BSM II

AUTOMATION@NLO

Hua-Sheng Shao
CERN, PH-TH

Lecture BSM I given by Benjamin Fuks on Monday

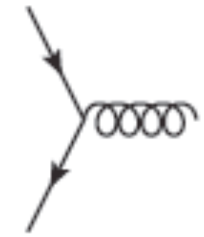
26 Nov 2015

PREDICTION CHAIN

slide stealing from Valentin Hirschi

SU(3)XSU(2)XU(1) • **Symmetries** $G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + \cdots$

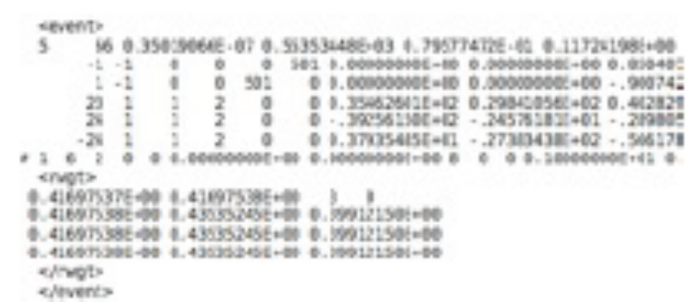
Standard Model • **Model**



$= \imath\gamma^\mu t^a_{ij} \quad , \cdots$

p p > j j QCD=2 • **Matrix Element** $\mathcal{M}^2_{gg\to d\bar{d}} \; , \cdots$

matrix.f • **Partonic Events**



events.lhe • **Hadron Level** $\{\pi^0, K^+, e^+, p, \cdots\}$

events.hep • **Detector Level**

BSM MODELS: READY FOR USE

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous	
NLO	Models ready for NLO computations

BSM MODELS: READY FOR USE

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-	
Strong theori	
Miscel	
NLO	

Available models

Model	Short Description	Contact	Status
Axigluon model	The SM plus a scalar gluon field.	S. Krastanov	**Available**
DY SM extension	The SM plus new spin-0, -1, and -2 bosons that contribute to Drell-Yan production of leptons at the LHC.	N. Christensen	**Available**
EFT mass basis	The SM EFT Lagrangian in the mass basis	B. Fuks, K. Mawatari	**Available**
FCNC Higgs interactions	The SM plus higher-dimensional flavor changing Higgs interactions.	S. Krastanov	**Available**
Fourth generation model	A fourth generation model including a t' and a b'	C. Duhr	**Available**
General 2HDM	The most general 2HDM, including all flavor violation and mixing terms.	C. Duhr, M. Herquet	**Available**
Hidden Abelian Higgs Model	A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings.	C. Duhr	**Available**
HiggsCharacterisation	The model file for the spin/parity characterisation of a 125 GeV resonance.	F. Demartin, K. Mawatari	**Available**
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	**Available**
Higgs Effective Lagrangian	Higgs effective Lagrangian including operators up-to dimension 6.	A. Alloul, B. Fuks and V. Sanz	**Available**
Hill Model	A model with an unusual extension of the SM Higgs sector.	P. de Aquino, C. Duhr	**Available**
Inert Doublet Model	A model with an additional complex scalar SU(2)L doublet and an unbroken Z2 symmetry under which all SM particles are even while the extra doublet is odd.	A. Goudelis, B. Herrmann, O. Stal	**Available**
Minimal Zp models	The minimal Z' extension of the SM.	L. Basso	**Available**
Monotops	The SM plus monotop effective Lagrangian.	B. Fuks	**Available**
Sextet diquarks	The SM plus sextet diquark scalars.	J. Alwall, C. Duhr	**Available**
Standard model + Scalars	The SM, together with a set of singlet scalar particles coupling only to the SM Higgs, and allowing it to decay invisibly into this new scalar sector.	C. Duhr	**Available**
TFCNC	The SM, plus FCNC top interactions.	M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi	**Available**
Triplet diquarks	The SM plus triplet diquark scalars.	J. Alwall, C. Duhr	**Available**

BSM MODELS: READY FOR USE

Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous	
NLO	Models ready for NLO computations

Available models

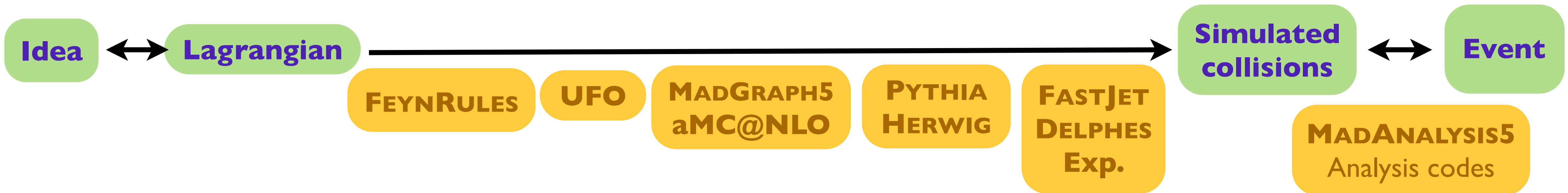
Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	-	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-

https://feynrules.irmp.ucl.ac.be/wiki/NLOModels

AUTOMATED LO CALCULATIONS

slide stealing from Benjamin Fuks

✦ A comprehensive approach to Monte Carlo simulations
[Example based on FEYNRULES and MADGRAPH5_aMC@NLO]



✦ Streamline the chain from the model Lagrangian to analyzed simulated collisions

✤ Works at the leading order
- ★ Implementation of the new physics Lagrangian into FEYNRULES
- ★ Generation of a UFO model file
- ★ Import of the model into MADGRAPH5_aMC@NLO
- ★ Hard scattering process with MADGRAPH5_aMC@NLO
- ★ Matching to parton showering, multiparton matrix element merging, hadronization, detector simulation, *etc.*

✤ Fully tested and validated in the context of large classes of new physics models

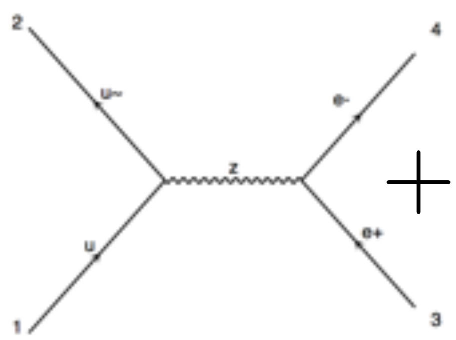
What about new physics event generation
at the next-to-leading order in QCD?

ANATOMY

$$\sigma_{pp\to e^+e^-} =$$

ANATOMY

$$\sigma^{\mathbf{LO}}_{pp\to e^+e^-} = \int_2 \left| \right.$$

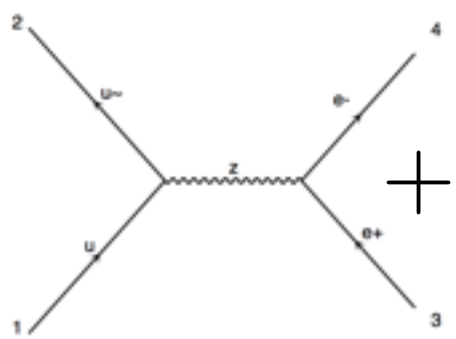


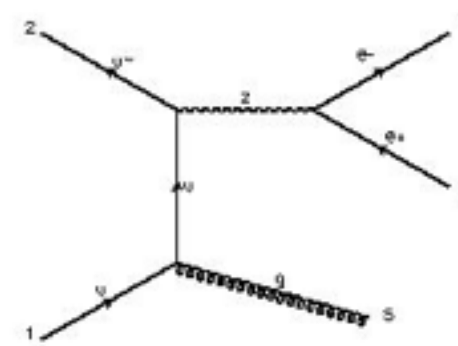
$$\left. + \cdots \right|^2$$

Wednesday, November 25, 15

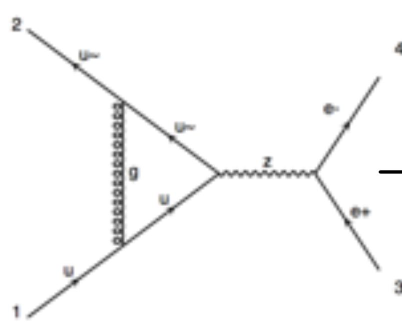
ANATOMY

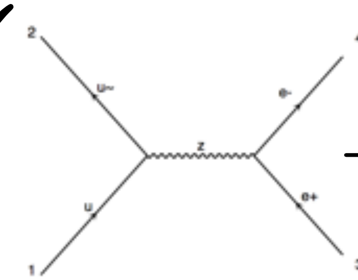
$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$ 

$$+\cdots\Bigg|^2 + \int_3 \Bigg|$$ 

$$+\cdots\Bigg|^2$$

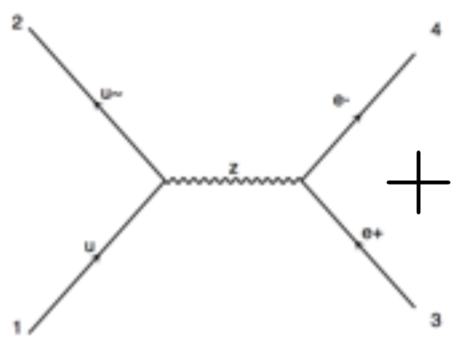
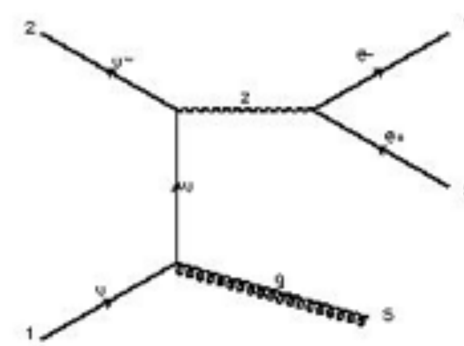
$$+ \int_2 \Bigg($$ 

$$+\cdots\Bigg) \times \Bigg($$ 

$$+\cdots\Bigg)^*$$

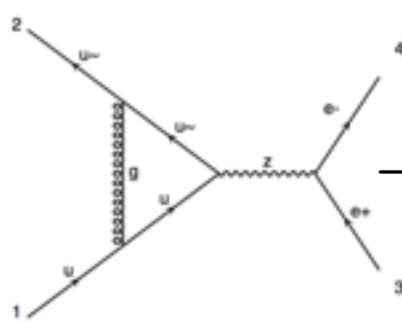
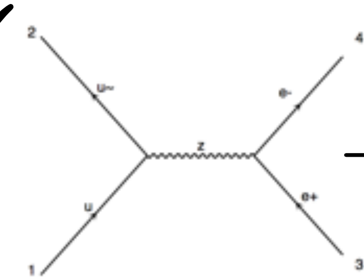
ANATOMY

$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$  $$+\cdots\Bigg|^2 + \int_3 \Bigg|$$  $$+\cdots\Bigg|^2$$

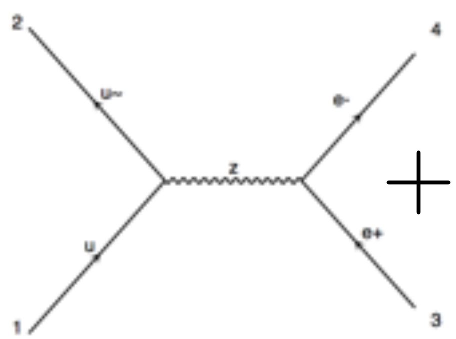
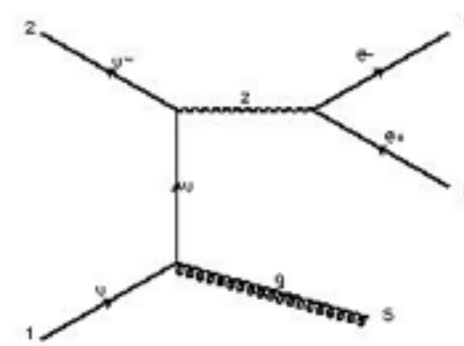
Infrared Div.

$$\frac{c_{-2}}{\epsilon_{\rm IR}^2}+\frac{c_{-1}}{\epsilon_{\rm IR}}$$

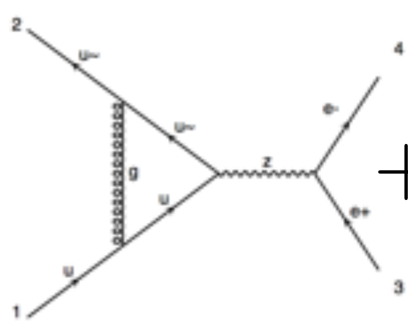
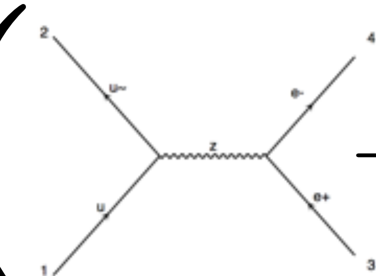
$$+\int_2 \Bigg($$  $$+\cdots\Bigg)\times\Bigg($$  $$+\cdots\Bigg)^*$$

ANATOMY

$$\sigma^{\mathbf{NLO}}_{pp\to e^+e^-} =$$

$$\int_2 \Bigg|$$  $$+\cdots\Bigg|^2 + \int_3 \Bigg|$$  $$+\cdots\Bigg|^2$$

Infrared Div. $\frac{c_{-2}}{\epsilon_{\rm IR}^2}+\frac{c_{-1}}{\epsilon_{\rm IR}}$

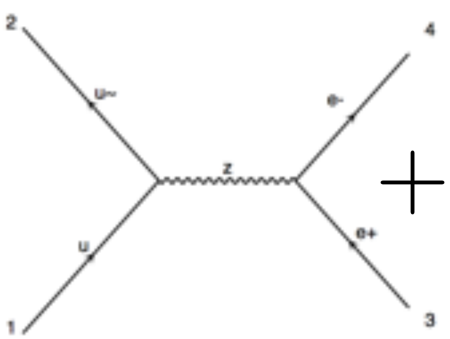
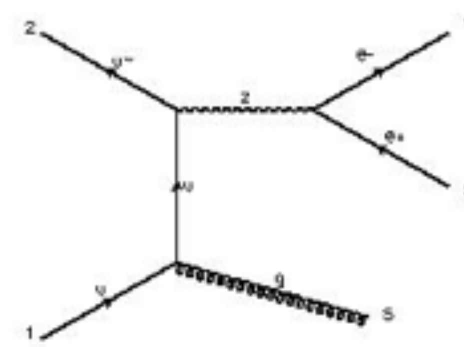
$$+\int_2 \Bigg($$  $$+\cdots\Bigg)\times\Bigg($$  $$+\cdots\Bigg)^*$$

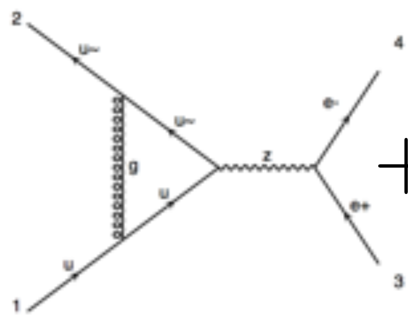
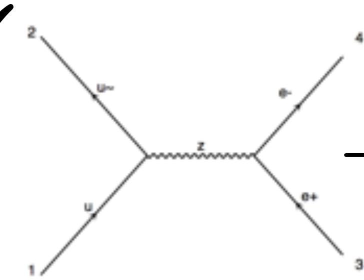
Ultraviolet Div. $\frac{a}{\epsilon_{\rm UV}}$

Infrared Div. $-\frac{c_{-2}}{\epsilon_{\rm IR}^2}-\frac{c_{-1}}{\epsilon_{\rm IR}}$

ANATOMY

$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$

$\int_2 \Big|$  $+\cdots\Big|^2 + \int_3 \Big|$  $+\cdots\Big|^2$

$+ \int_2 \Big($  $+\cdots\Big) \times \Big($  $+\cdots\Big)^*$

Infrared Div. $\frac{c_{-2}}{\epsilon_{\rm IR}^2} + \frac{c_{-1}}{\epsilon_{\rm IR}}$

Ultraviolet Div. $\frac{a}{\epsilon_{\rm UV}}$

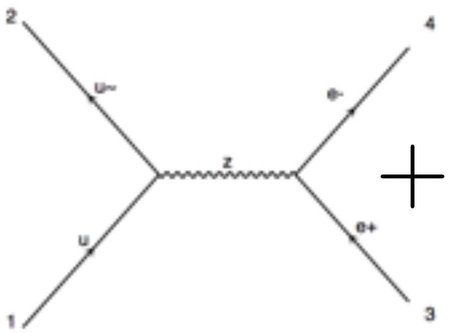
Infrared Div. $-\frac{c_{-2}}{\epsilon_{\rm IR}^2} - \frac{c_{-1}}{\epsilon_{\rm IR}}$

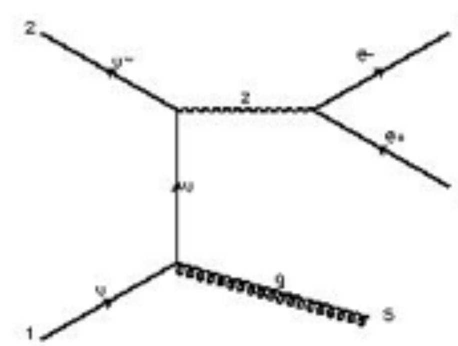
Kinoshita-Lee-Nauenberg theorem

Wednesday, November 25, 15

ANATOMY

$$\sigma^{\textbf{NLO}}_{pp\to e^+e^-} =$$

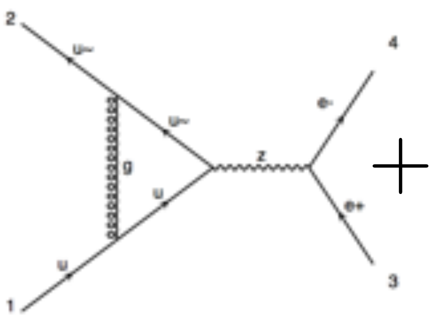
$$\int_2 \Bigg|$$ 

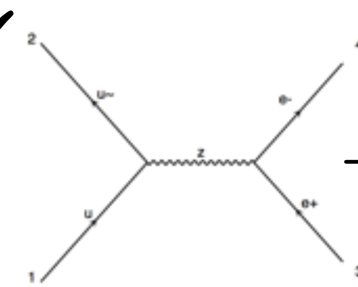
$$+\cdots \Bigg|^2 + \int_3 \Bigg|$$ 

$$+\cdots \Bigg|^2$$

Infrared Div.

$$\frac{c_{-2}}{\epsilon_{\rm IR}^2} + \frac{c_{-1}}{\epsilon_{\rm IR}}$$

$$+ \int_2 \Bigg($$ 

$$+\cdots \Bigg) \times \Bigg($$ 

$$+\cdots \Bigg)^*$$

Ultraviolet Div. $\frac{a}{\epsilon_{\rm UV}}$

Renormalization !

Infrared Div.

$$-\frac{c_{-2}}{\epsilon_{\rm IR}^2} - \frac{c_{-1}}{\epsilon_{\rm IR}}$$

Kinoshita-Lee-Nauenberg theorem

Wednesday, November 25, 15

ISSUES TO BE ADDRESSED @ NLO

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**
- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**
- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**
- Matching (avoid double counting) to PS: **MC@NLO**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**

LO

- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**
- Matching (avoid double counting) to PS: **MC@NLO**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**

LO

- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**

NLO

- Matching (avoid double counting) to PS: **MC@NLO**

ISSUES TO BE ADDRESSED @ NLO+PS

- Tree-level ME: **MadGraph**
- Resolved phase-space integration: **MadEvent**

LO

- Unresolved phase-space integration: **MadFKS**
- Loop ME: **MadLoop**
  - Amplitude: **ALOHA+MadLoop**
  - Loop integration: **OPP+TIR**
- Renormalization: **FeynRules->UFO->MadLoop**

NLO

- Matching (avoid double counting) to PS: **MC@NLO**

NLO+PS

JOINT EFFORTS FOR AUTOMATION AT NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'2014)

JOINT EFFORTS FOR AUTOMATION AT NLO

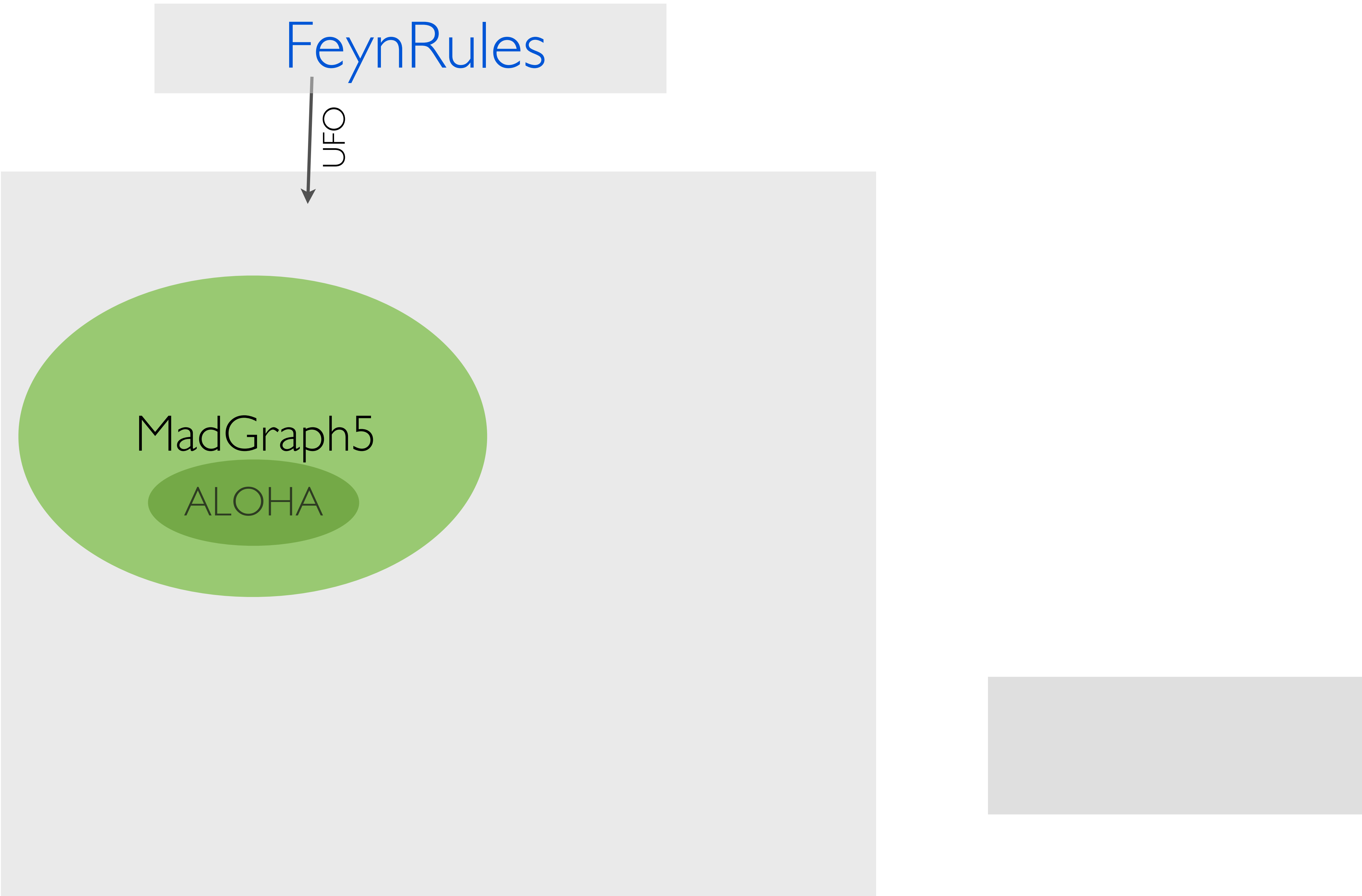
Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'2014)

FeynRules

UFO

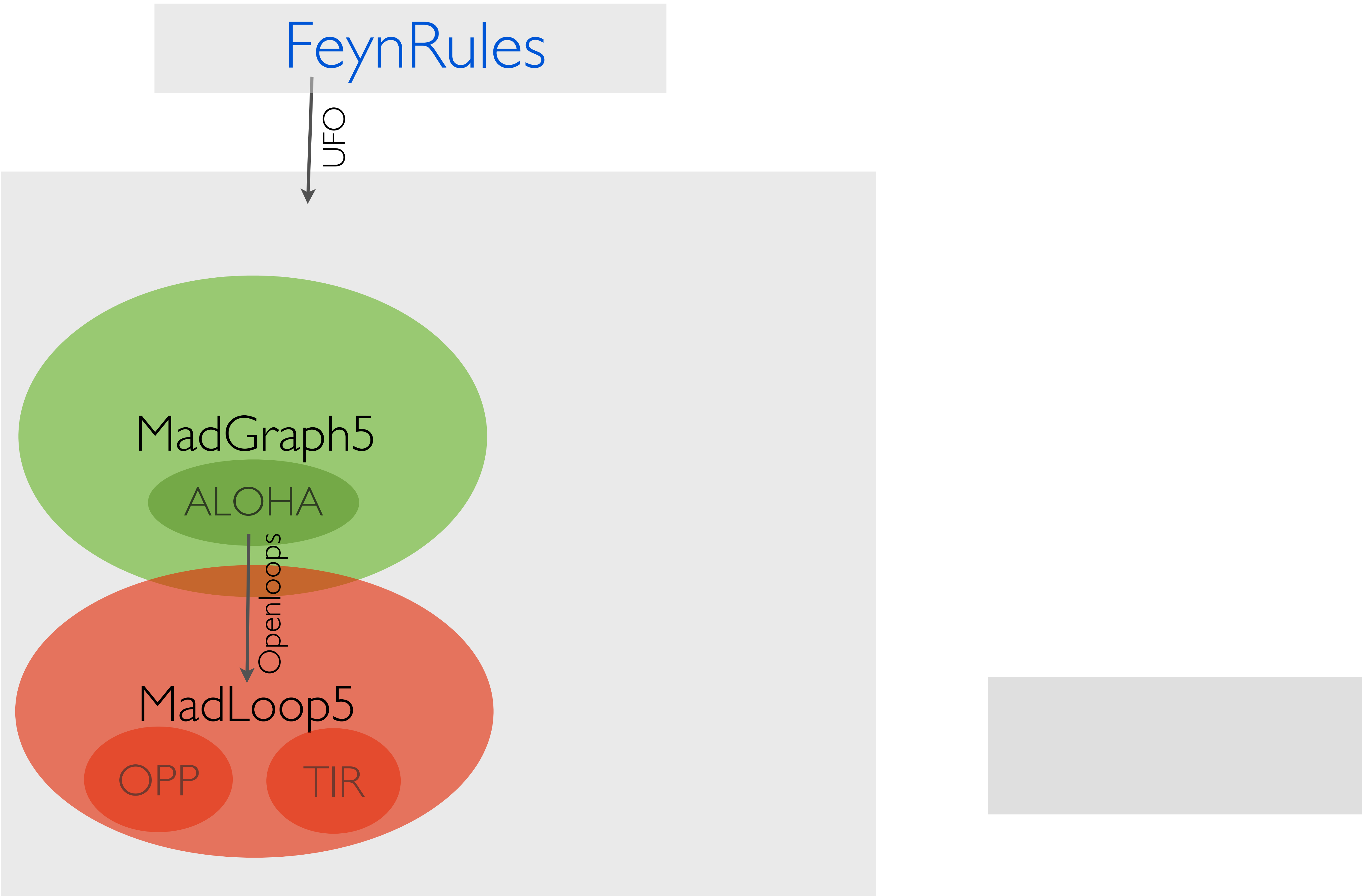
JOINT EFFORTS FOR AUTOMATION AT NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'2014)



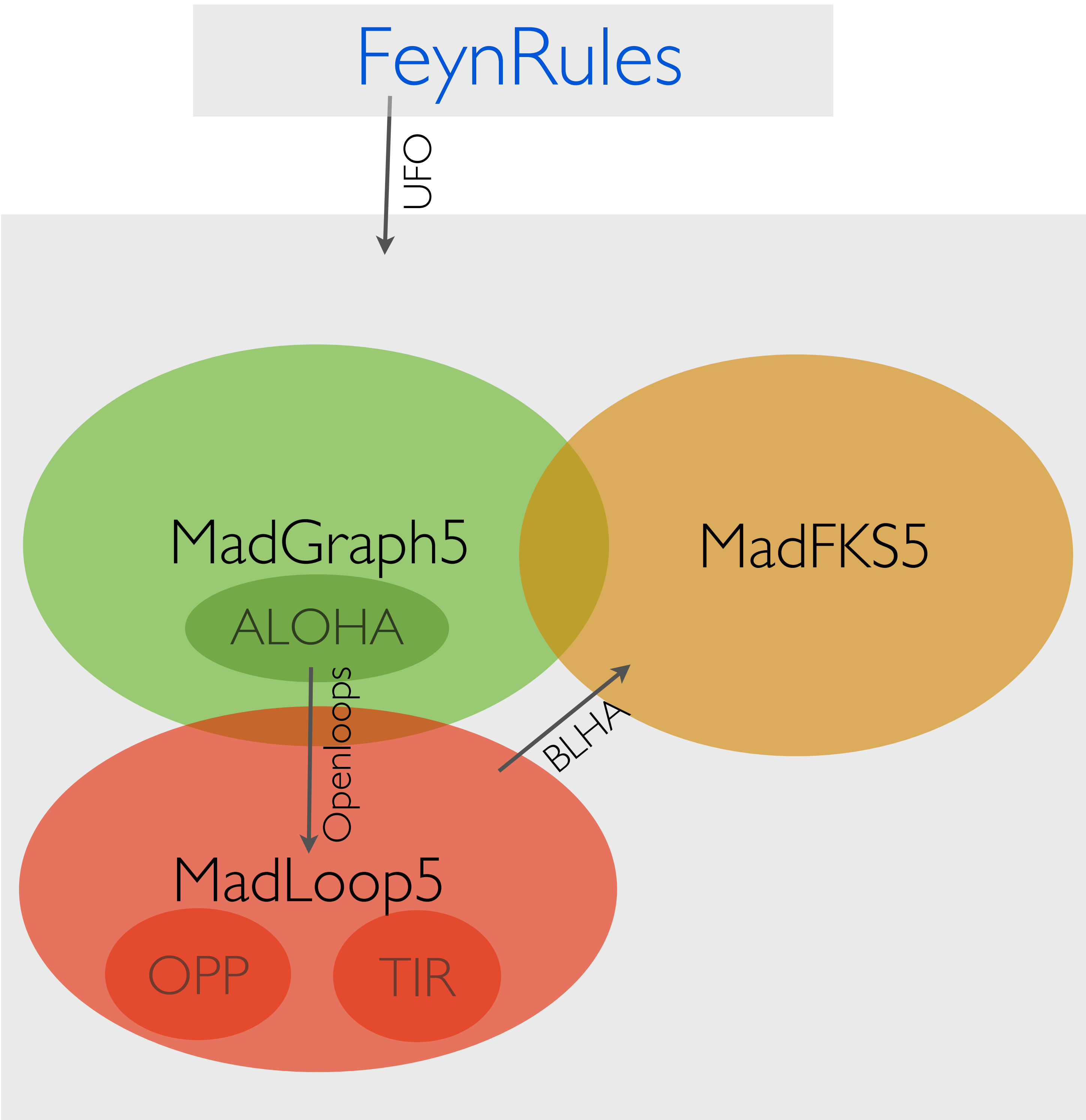
JOINT EFFORTS FOR AUTOMATION AT NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'2014)



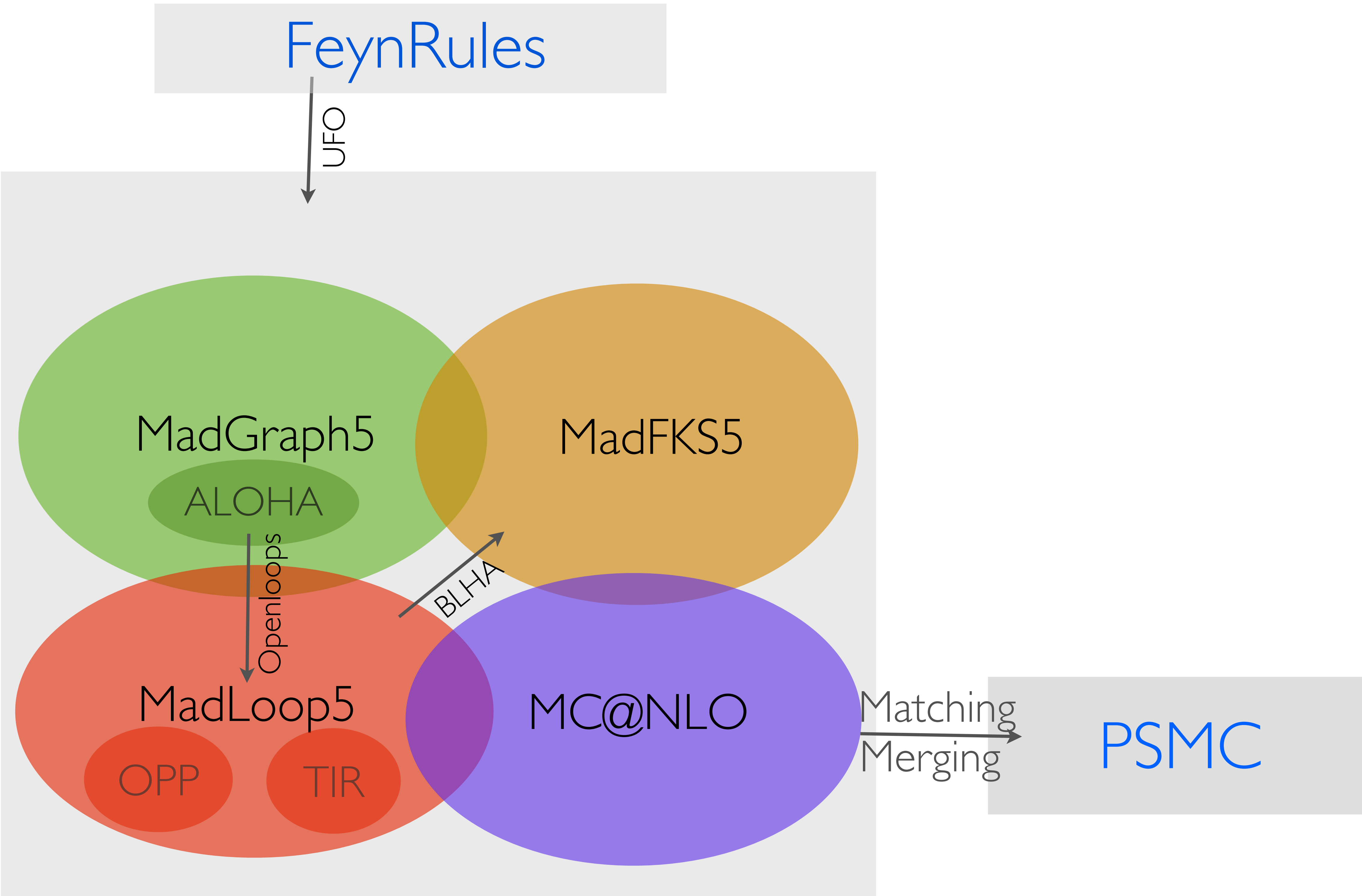
JOINT EFFORTS FOR AUTOMATION AT NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'2014)



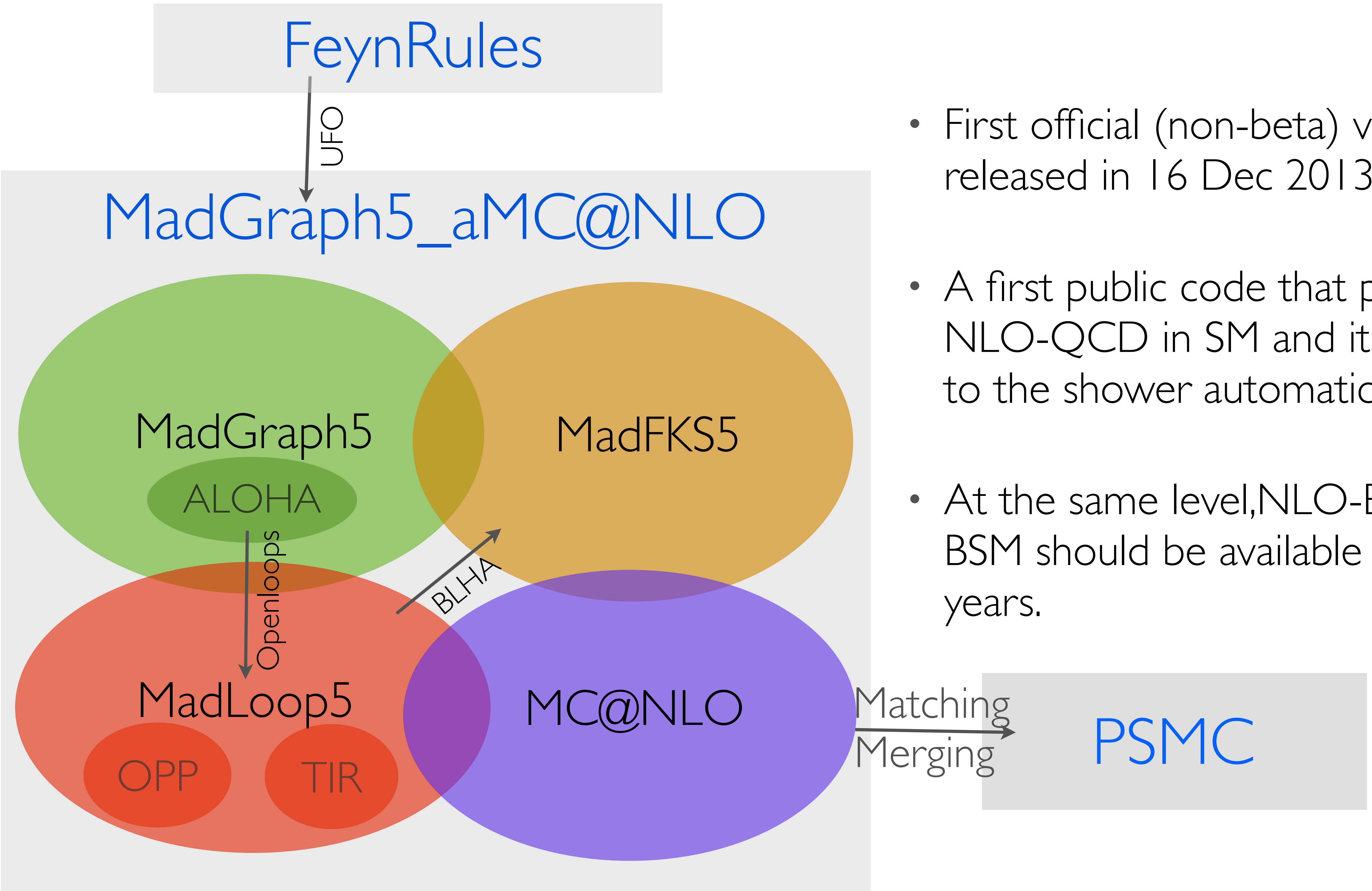
JOINT EFFORTS FOR AUTOMATION AT NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'2014)



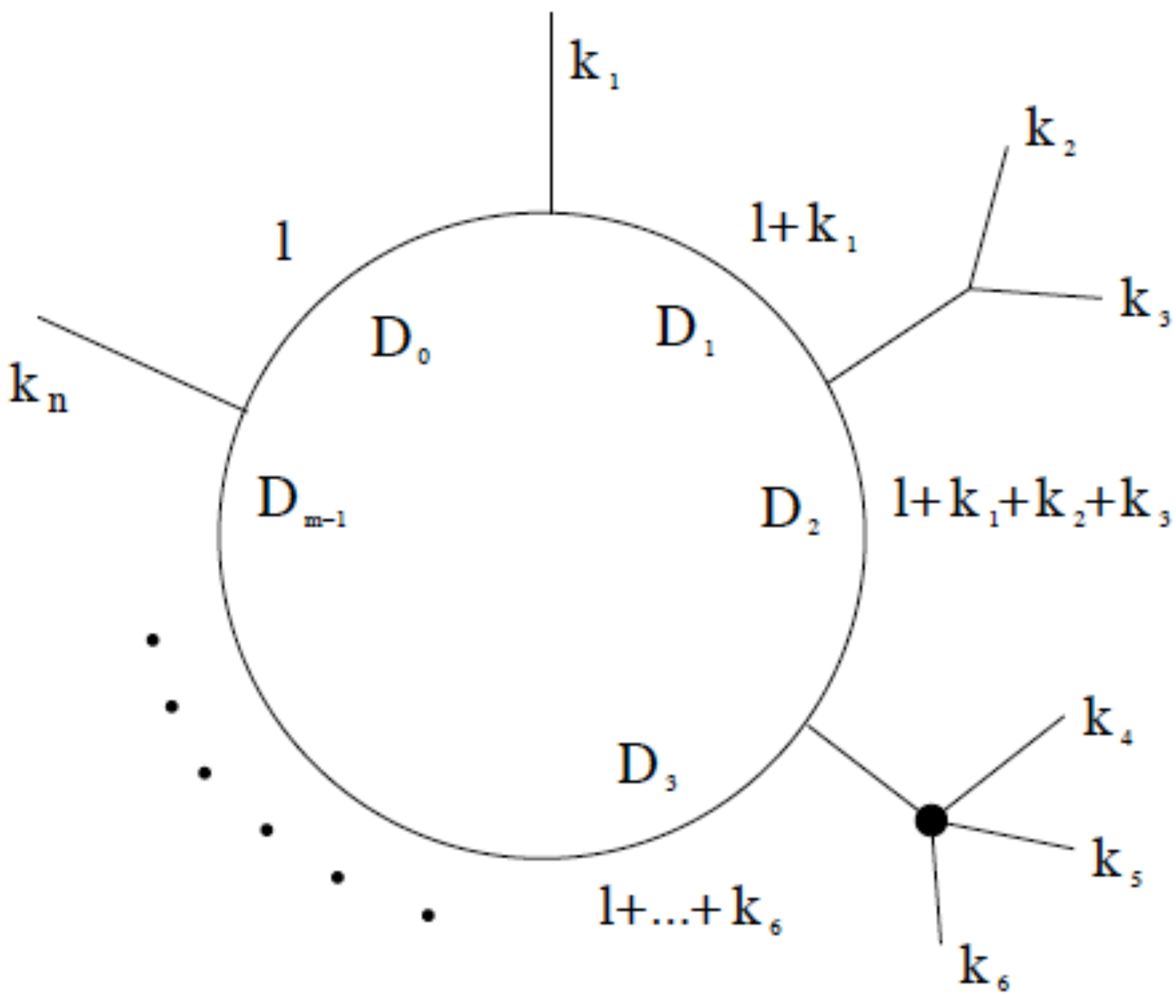
JOINT EFFORTS FOR AUTOMATION AT NLO

Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, HSS, Stelzer, Torrielli, Zaro (JHEP'2014)



- First official (non-beta) version was released in 16 Dec 2013.
- A first public code that provides NLO-QCD in SM and its interface to the shower automatically.
- At the same level,NLO-EW and BSM should be available in recent years.

A GENERAL LOOP INTEGRAL



- Consider a m-point loop diagram with n external momenta.
- The integral is

$$\int d^{(4-2\epsilon)}l \frac{N(l)}{D_0 D_1 D_2 \cdots D_{m-1}}$$

$$D_i = (l+p_i)^2 - m_i^2$$

A GENERAL LOOP INTEGRAL

$$\int d^{(4-2\epsilon)} \frac{N(l)}{D_0 D_1 D_2 \cdots D_{m-1}} =$$
$$\sum_{0\le i_0<i_1<i_2<i_3\le m-1} d_{i_0 i_1 i_2 i_3} \mathcal{I}_0(i_0 i_1 i_2 i_3) +$$
$$\sum_{0\le i_0<i_1<i_2\le m-1} c_{i_0 i_1 i_2} \mathcal{I}_0(i_0 i_1 i_2) +$$
$$\sum_{0\le i_0<i_1\le m-1} b_{i_0 i_1} \mathcal{I}_0(i_0 i_1) +$$
$$\sum_{0\le i_0\le m-1} a_{i_0} \mathcal{I}_0(i_0) +$$
$$R,$$

- Integral can be reduced to a minimal basis that was known.
- Rational term R is in general process dependent.

$$\mathcal{I}_0(i_0 i_1 i_2 i_3) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0} D_{i_1} D_{i_2} D_{i_3}},$$
$$\mathcal{I}_0(i_0 i_1 i_2) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0} D_{i_1} D_{i_2}},$$
$$\mathcal{I}_0(i_0 i_1) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0} D_{i_1}},$$
$$\mathcal{I}_0(i_0) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0}}.$$

A GENERAL LOOP INTEGRAL

$$\int d^{(4-2\epsilon)} \frac{N(l)}{D_0 D_1 D_2 \cdots D_{m-1}} = \sum_{0\leq i_0<i_1<i_2<i_3\leq m-1} d_{i_0 i_1 i_2 i_3} \mathcal{I}_0(i_0 i_1 i_2 i_3) + \sum_{0\leq i_0<i_1<i_2\leq m-1} c_{i_0 i_1 i_2} \mathcal{I}_0(i_0 i_1 i_2) + \sum_{0\leq i_0<i_1\leq m-1} b_{i_0 i_1} \mathcal{I}_0(i_0 i_1) + \sum_{0\leq i_0\leq m-1} a_{i_0} \mathcal{I}_0(i_0) + R,$$

Rational functions of external momentum and masses

- Integral can be reduced to a minimal basis that was known.
- Rational term R is in general process dependent.

$$\mathcal{I}_0(i_0 i_1 i_2 i_3) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0} D_{i_1} D_{i_2} D_{i_3}},$$

$$\mathcal{I}_0(i_0 i_1 i_2) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0} D_{i_1} D_{i_2}},$$

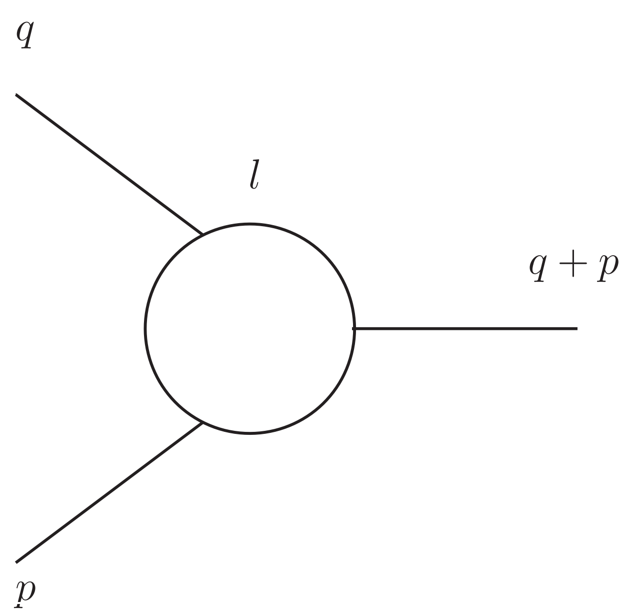
$$\mathcal{I}_0(i_0 i_1) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0} D_{i_1}},$$

$$\mathcal{I}_0(i_0) \equiv \int d^{(4-2\epsilon)} l \frac{1}{D_{i_0}}.$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Let us see an example:

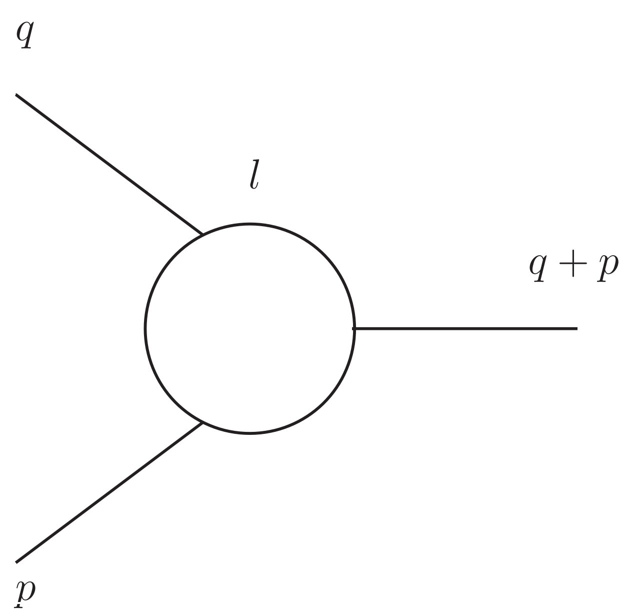


$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^\mu}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Let us see an example:



$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^\mu}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

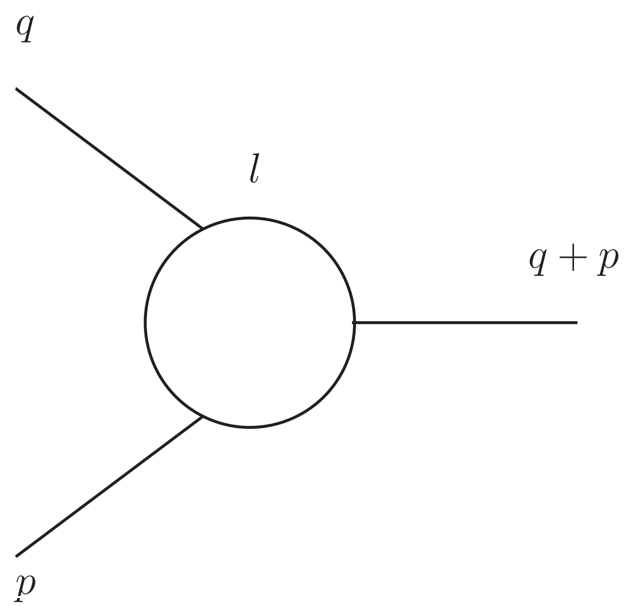
- Due to the Lorentz invariant, integral must be proportional to

$$\int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^\mu}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)} = (p^\mu \quad q^\mu) \begin{pmatrix} C_1 \\ C_2 \end{pmatrix}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Let us see an example:



$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^{\mu}}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)}$$

- Due to the Lorentz invariant, integral must be proportional to

$$\int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^{\mu}}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)} = (p^{\mu} \quad q^{\mu}) \begin{pmatrix} C_1 \\ C_2 \end{pmatrix}$$

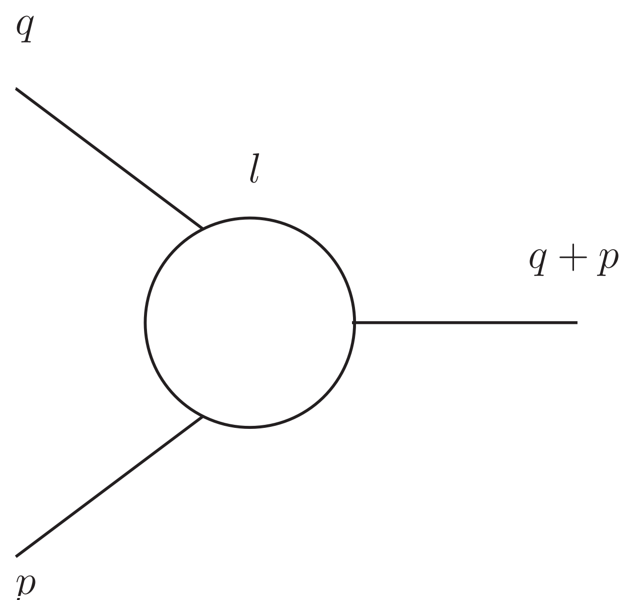
- Try to solve the equation by contracting the external momenta

$$[2l \cdot p] \equiv \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{1}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Let us see an example:



$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^\mu}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)}$$

- Due to the Lorentz invariant, integral must be proportional to

$$\int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^\mu}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)} = \begin{pmatrix} p^\mu & q^\mu \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix}$$

- Try to solve the equation by contracting the external momenta

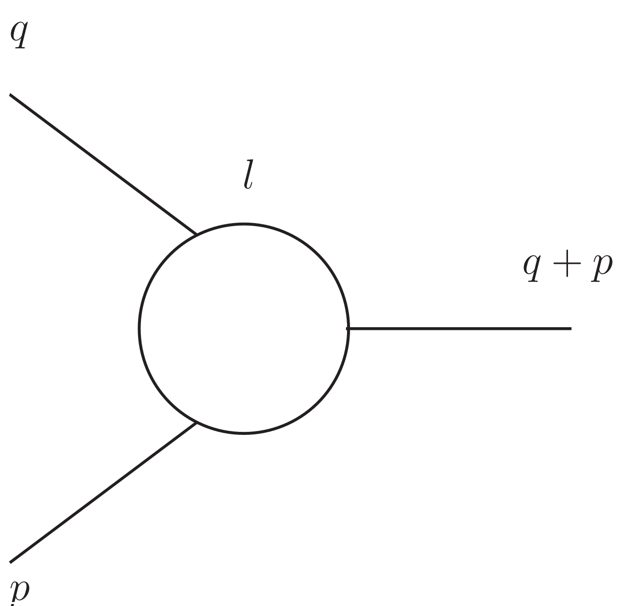
$$[2l \cdot p] \equiv \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{1}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)}$$

$$\Rightarrow \begin{pmatrix} 2p_\mu \\ 2q_\mu \end{pmatrix} \begin{pmatrix} p^\mu & q^\mu \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} 2p\cdot p & 2p\cdot q \\ 2p\cdot q & 2q\cdot q \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} [2l\cdot p] \\ [2l\cdot q] \end{pmatrix}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Let us see an example:



$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^\mu}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)}$$

Gram Determination

- Due to the Lorentz invariant, integral must be proportional to

$$\int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{l^\mu}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)} = \begin{pmatrix} p^\mu & q^\mu \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix}$$

- Try to solve the equation by contracting the external momenta

$$[2l \cdot p] \equiv \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{1}{(l^2 - m_1^2)\left((l+p)^2 - m_2^2\right)\left((l+q)^2 - m_3^2\right)}$$

$$\Rightarrow \begin{pmatrix} 2p_\mu \\ 2q_\mu \end{pmatrix} \begin{pmatrix} p^\mu & q^\mu \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} 2p \cdot p & 2p \cdot q \\ 2p \cdot q & 2q \cdot q \end{pmatrix} \begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} [2l \cdot p] \\ [2l \cdot q] \end{pmatrix}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- The numerator can be decomposed into denominators

$$[2l\cdot p]\equiv\int d^{(4-2\epsilon)}l\,\frac{1}{(2\pi)^{(4-2\epsilon)}}\,\frac{2l\cdot p}{(l^2-m_1^2)\,((l+p)^2-m_2^2)\,((l+q)^2-m_3^2)}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- The numerator can be decomposed into denominators

$$[2l\cdot p] \equiv \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{2l\cdot p}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{\left[(l+p)^2-m_2^2\right]-\left[l^2-m_1^2\right]+\left[-m_1^2+m_2^2-p^2\right]}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- The numerator can be decomposed into denominators

$$[2l\cdot p]\equiv\int d^{(4-2\epsilon)}l\frac{1}{(2\pi)^{(4-2\epsilon)}}\frac{2l\cdot p}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$=\int d^{(4-2\epsilon)}l\frac{1}{(2\pi)^{(4-2\epsilon)}}\frac{\left[(l+p)^2-m_2^2\right]-\left[l^2-m_1^2\right]+\left[-m_1^2+m_2^2-p^2\right]}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$=\int d^{(4-2\epsilon)}l\frac{1}{(2\pi)^{(4-2\epsilon)}}\frac{1}{(l^2-m_1^2)\left((l+q)^2-m_3^2\right)}$$

$$-\int d^{(4-2\epsilon)}l\frac{1}{(2\pi)^{(4-2\epsilon)}}\frac{1}{\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$+\int d^{(4-2\epsilon)}l\frac{1}{(2\pi)^{(4-2\epsilon)}}\frac{\left(-m_1^2+m_2^2-p^2\right)}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- The numerator can be decomposed into denominators

$$[2l\cdot p] \equiv \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{2l\cdot p}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{\left[(l+p)^2-m_2^2\right]-\left[l^2-m_1^2\right]+\left[-m_1^2+m_2^2-p^2\right]}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$= \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{1}{(l^2-m_1^2)\left((l+q)^2-m_3^2\right)}$$

$$- \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{1}{\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$+ \int d^{(4-2\epsilon)}l \frac{1}{(2\pi)^{(4-2\epsilon)}} \frac{\left(-m_1^2+m_2^2-p^2\right)}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$= \frac{1}{(2\pi)^{(4-2\epsilon)}}\left[\mathcal{I}_0(13)-\mathcal{I}_0(23)+\left(-m_1^2+m_2^2-p^2\right)\mathcal{I}_0(123)\right]$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Similarly

- The scalar integrals are known: QCDLoop [Ellis, Zanderighi (JHEP'2008)], OneLOop [Hameren (CPC'2011)]

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Similarly

$$[2l\cdot q]\equiv\int d^{(4-2\epsilon)}l\,\frac{1}{(2\pi)^{(4-2\epsilon)}}\,\frac{2l\cdot q}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$=\frac{1}{(2\pi)^{(4-2\epsilon)}}\left[\mathcal{I}_0\,(12)-\mathcal{I}_0\,(23)+\left(-m_2^2+m_1^2-q^2\right)\mathcal{I}_0(123)\right]$$

- The scalar integrals are known: QCDLoop [Ellis, Zanderighi (JHEP'2008)], OneLOop [Hameren (CPC'2011)]

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Similarly

$$[2l\cdot q]\equiv\int d^{(4-2\epsilon)}l\,\frac{1}{(2\pi)^{(4-2\epsilon)}}\frac{2l\cdot q}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)\left((l+q)^2-m_3^2\right)}$$

$$=\frac{1}{(2\pi)^{(4-2\epsilon)}}\left[\mathcal{I}_0\left(12\right)-\mathcal{I}_0\left(23\right)+\left(-m_2^2+m_1^2-q^2\right)\mathcal{I}_0(123)\right]$$

- The scalar integrals are known: QCDLoop [Ellis, Zanderighi (JHEP'2008)], OneLOop [Hameren (CPC'2011)]
- An example (an exercise for interested student):

$$\mathcal{I}_0(12)\equiv\int d^{(4-2\epsilon)}l\,\frac{1}{(l^2-m_1^2)\left((l+p)^2-m_2^2\right)}$$

$$=\frac{i\pi^2}{(2\pi\mu_R)^{2\epsilon}}\left(\frac{1}{\epsilon}-\gamma_E+2-\log\frac{p^2}{4\pi\mu_R^2}+\sum_{i=1}^{2}\gamma_i\log\frac{\gamma_i-1}{\gamma_i}-\log\gamma_i-1\right)$$

$$\gamma_{1,2}\equiv\frac{p^2-m_2^2+m_1^2\pm\sqrt{(p^2-m_2^2+m_1^2)^2-4p^2m_1^2}}{2p^2}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Solve the equation

$$=$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Solve the equation

$$\begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} 2p\cdot p & 2p\cdot q \\ 2p\cdot q & 2q\cdot q \end{pmatrix}^{-1} \begin{pmatrix} [2l\cdot p] \\ [2l\cdot q] \end{pmatrix}$$

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Solve the equation

$$\begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} 2p\cdot p & 2p\cdot q \\ 2p\cdot q & 2q\cdot q \end{pmatrix}^{-1} \begin{pmatrix} [2l\cdot p] \\ [2l\cdot q] \end{pmatrix}$$

known

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Solve the equation

$$\begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} 2p\cdot p & 2p\cdot q \\ 2p\cdot q & 2q\cdot q \end{pmatrix}^{-1} \begin{pmatrix} [2l\cdot p] \\ [2l\cdot q] \end{pmatrix}$$

- Two disadvantages:
  - It requires the determination of Gram matrix is not zero (need to improve stability)
  - The expression of the coefficients can be complicated (need to improve speed)

known

EXAMPLE: A LOOP INTEGRAL

Passarino, Veltman (NPB'1979)

- Solve the equation

$$\begin{pmatrix} C_1 \\ C_2 \end{pmatrix} = \begin{pmatrix} 2p \cdot p & 2p \cdot q \\ 2p \cdot q & 2q \cdot q \end{pmatrix}^{-1} \begin{pmatrix} [2l \cdot p] \\ [2l \cdot q] \end{pmatrix}$$

- Two disadvantages:
  - It requires the determination of Gram matrix is not zero (need to improve stability)
  - The expression of the coefficients can be complicated (need to improve speed)
- Three solutions:
  - improved tensor integral reduction (e.g. Denner, Dittmaier (NPB'2006))
  - integrand reduction (OPP reduction refer to Marco's talk on Wednesday)
  - generalized unitarity reduction (I will not talk about it, which is not used in MG5)

known

ONE SLIDE ON INTEGRAND REDUCTION

Ossola, Papadopoulos, Pittau (NPB'2006)

- The numerator (before integration) can be decomposed into:

$$
\begin{aligned}
N(l) =& \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d_{i_0i_1i_2i_3} + \tilde{d}_{i_0i_1i_2i_3}(l)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\
&+ \sum_{i_0<i_1<i_2}^{m-1} \left[c_{i_0i_1i_2} + \tilde{c}_{i_0i_1i_2}(l)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\
&+ \sum_{i_0<i_1}^{m-1} \left[b_{i_0i_1} + \tilde{b}_{i_0i_1}(l)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i \\
&+ \sum_{i_0}^{m-1} \left[a_{i_0} + \tilde{a}_{i_0}(l)\right] \prod_{i\neq i_0}^{m-1} D_i \\
&+ \tilde{P}(l) \prod_{i}^{m-1} D_i
\end{aligned}
$$

Details please refer to Marco's talk on Wednesday

ONE SLIDE ON INTEGRAND REDUCTION

Ossola, Papadopoulos, Pittau (NPB'2006)

- The numerator (before integration) can be decomposed into:

$$
\begin{aligned}
N(l) = & \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d_{i_0 i_1 i_2 i_3} + \tilde{d}_{i_0 i_1 i_2 i_3}(l)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\
& + \sum_{i_0<i_1<i_2}^{m-1} \left[c_{i_0 i_1 i_2} + \tilde{c}_{i_0 i_1 i_2}(l)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\
& + \sum_{i_0<i_1}^{m-1} \left[b_{i_0 i_1} + \tilde{b}_{i_0 i_1}(l)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i \\
& + \sum_{i_0}^{m-1} \left[a_{i_0} + \tilde{a}_{i_0}(l)\right] \prod_{i\neq i_0}^{m-1} D_i \\
& + \tilde{P}(l) \prod_{i}^{m-1} D_i
\end{aligned}
$$

To solve the OPP reduction, choosing special values for the loop momenta helps a lot

Details please refer to Marco's talk on Wednesday

ONE SLIDE ON INTEGRAND REDUCTION

Ossola, Papadopoulos, Pittau (NPB'2006)

- The numerator (before integration) can be decomposed into:

$$
\begin{aligned}
N(l) = &\sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d_{i_0i_1i_2i_3} + \tilde{d}_{i_0i_1i_2i_3}(l)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i \\
&+ \sum_{i_0<i_1<i_2}^{m-1} \left[c_{i_0i_1i_2} + \tilde{c}_{i_0i_1i_2}(l)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i \\
&+ \sum_{i_0<i_1}^{m-1} \left[b_{i_0i_1} + \tilde{b}_{i_0i_1}(l)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i \\
&+ \sum_{i_0}^{m-1} \left[a_{i_0} + \tilde{a}_{i_0}(l)\right] \prod_{i\neq i_0}^{m-1} D_i \\
&+ \tilde{P}(l) \prod_{i}^{m-1} D_i
\end{aligned}
$$

To solve the OPP reduction, choosing special values for the loop momenta helps a lot

For example, choosing *l* such that

$$
\begin{aligned}
D_0(l^\pm) &= D_1(l^\pm) = \\
&= D_2(l^\pm) = D_3(l^\pm) = 0
\end{aligned}
$$

sets all the terms in this equation to zero except the first line

Details please refer to Marco's talk on Wednesday

ONE SLIDE ON INTEGRAND REDUCTION

Ossola, Papadopoulos, Pittau (NPB'2006)

- The numerator (before integration) can be decomposed into:

$$N(l) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d_{i_0i_1i_2i_3} + \tilde{d}_{i_0i_1i_2i_3}(l)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i$$
$$+ \sum_{i_0<i_1<i_2}^{m-1} \left[c_{i_0i_1i_2} + \tilde{c}_{i_0i_1i_2}(l)\right] \prod_{i\neq i_0,i_1,i_2}^{m-1} D_i$$
$$+ \sum_{i_0<i_1}^{m-1} \left[b_{i_0i_1} + \tilde{b}_{i_0i_1}(l)\right] \prod_{i\neq i_0,i_1}^{m-1} D_i$$
$$+ \sum_{i_0}^{m-1} \left[a_{i_0} + \tilde{a}_{i_0}(l)\right] \prod_{i\neq i_0}^{m-1} D_i$$
$$+\tilde{P}(l) \prod_{i}^{m-1} D_i$$

To solve the OPP reduction, choosing special values for the loop momenta helps a lot

For example, choosing *l* such that

$$D_0(l^\pm) = D_1(l^\pm) = \\ = D_2(l^\pm) = D_3(l^\pm) = 0$$

sets all the terms in this equation to zero except the first line

There are two (complex) solutions to this equation due to the quadratic nature of the propagators

Details please refer to Marco's talk on Wednesday

ONE SLIDE ON INTEGRAND REDUCTION

Ossola, Papadopoulos, Pittau (NPB'2006)

- The numerator (before integration) can be decomposed into:

$$N(l) = \sum_{i_0<i_1<i_2<i_3}^{m-1} \left[d_{i_0 i_1 i_2 i_3} + \tilde{d}_{i_0 i_1 i_2 i_3}(l)\right] \prod_{i\neq i_0,i_1,i_2,i_3}^{m-1} D_i$$

$$+ \sum^{m-1} \left[c \ldots + \tilde{c} \ldots (l)\right] \prod^{m-1} D \ldots$$

$$\ldots \sum_{i_0<i_1} \ldots \prod_{i\neq i_0,i_1} \ldots$$

$$+ \sum_{i_0}^{m-1} \left[a_{i_0} + \tilde{a}_{i_0}(l)\right] \prod_{i\neq i_0}^{m-1} D_i$$

$$+\tilde{P}(l) \prod_{i}^{m-1} D_i$$

Recently, we have CutTools, Samurai, Ninja working in MadGraph5_aMC@NLO

To solve the OPP reduction, choosing special values for the loop momenta helps a lot

... that

$$\ldots = D_2(l^{\ldots}) = D_3(l^{\ldots}) = 0$$

sets all the terms in this equation to zero except the first line

There are two (complex) solutions to this equation due to the quadratic nature of the propagators

Details please refer to Marco's talk on Wednesday

ONE SLIDE ON TENSOR INTEGRAL REDUCTION REDUCTION

- Instead, one can also write the numerator into

$$N(l) = \sum_{r=0}^{r_{\max}} c_{\mu_1\cdots\mu_r} l^{\mu_1}\ldots l^{\mu_r}$$

- Tensor integral reduction tries to work in

$$\int d^{(4-2\epsilon)}l \frac{N(l)}{D_0 D_1 D_2 \cdots D_{m-1}} = \sum_{r=0}^{r_{\max}} c_{\mu_1\cdots\mu_r}\mathcal{I}^{\mu_1\cdots\mu_r}$$

- Tensor integral reduction tries to reduce

$$\{[g]^1[p_0]^0[p_1]^2\}^{\mu_1\cdots\mu_4} \equiv g^{\mu_1\mu_2}p_1^{\mu_3}p_1^{\mu_4} + g^{\mu_1\mu_3}p_1^{\mu_2}p_1^{\mu_4} + g^{\mu_1\mu_4}p_1^{\mu_2}p_1^{\mu_3}$$

$$\mathcal{I}^{\mu_1\cdots\mu_r} \equiv \int d^{(4-2\epsilon)}l \frac{l^{\mu_1}\ldots l^{\mu_r}}{D_0 D_1 D_2 \cdots D_{m-1}}$$

$$= \sum_{2j+i_0+i_1+\cdots+i_{m-1}=r} \left\{[g]^j[p_0]^{i_0}\cdots[p_{m-1}]^{i_{m-1}}\right\}^{\mu_1\cdots\mu_r}\mathcal{I}_{ji_0\cdots i_{m-1}}$$

ONE SLIDE ON TENSOR INTEGRAL REDUCTION REDUCTION

- Instead, one can also write the numerator into

$$N(l) = \sum_{r=0}^{r_{\max}} c_{\mu_1 \cdots \mu_r} l^{\mu_1} \dots l^{\mu_r}$$

- Te

We have PJFry++, IREGI, Golem95 working in MadGraph5_aMC@NLO

$$\int \quad D_0 D_1 D_2 \cdots D_{m-1} \quad \sum_{r=0}$$

- Tensor integral reduction tries to reduce

$$\{[g]^1[p_0]^0[p_1]^2\}^{\mu_1\cdots\mu_4} \equiv g^{\mu_1\mu_2}p_1^{\mu_3}p_1^{\mu_4} + g^{\mu_1\mu_3}p_1^{\mu_2}p_1^{\mu_4} + g^{\mu_1\mu_4}p_1^{\mu_2}p_1^{\mu_3}$$

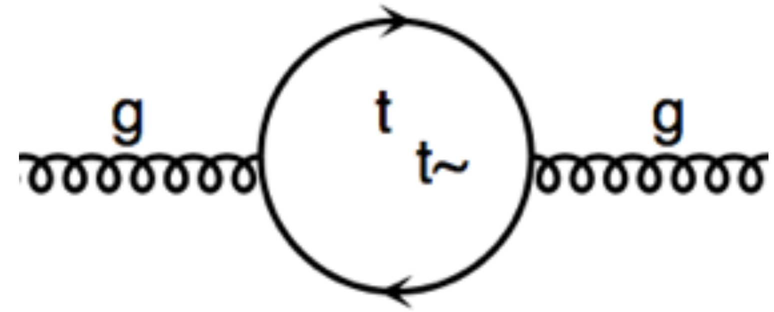
$$\mathcal{I}^{\mu_1\cdots\mu_r} \equiv \int d^{(4-2\epsilon)}l \frac{l^{\mu_1} \dots l^{\mu_r}}{D_0 D_1 D_2 \cdots D_{m-1}}$$

$$= \sum_{2j+i_0+i_1+\cdots+i_{m-1}=r} \left\{[g]^j[p_0]^{i_0}\cdots[p_{m-1}]^{i_{m-1}}\right\}^{\mu_1\cdots\mu_r} \mathcal{I}_{j i_0 \cdots i_{m-1}}$$

R2

- The numerator N(l) is a complicated function (Clifford algebra etc) in d- and 4-dimensional quantities.
- It is usually conv. to work N(l) in 4-dim --> super useful for numerical calculations.
- We need a special rational term R2 !

- For example, gluon SE:



$$N(l) = -\frac{\alpha_S}{(2\pi)^3}\delta_{ab}\mathrm{Tr}[\gamma^\mu(\not{l}+m_t)\gamma^\nu(\not{l}+\not{p}+m_t)]\varepsilon_\mu\varepsilon_\nu$$

- Dirac algebra gives the (d-4) numerator

$$\tilde{N}(\tilde{l}) = 4\frac{\alpha_S}{(2\pi)^3}\delta_{ab}g^{\mu\nu}\tilde{l}^2\varepsilon_\mu\varepsilon_\nu$$

- With the integration

$$\int d^{(4-2\epsilon)}l\frac{\tilde{l}^2}{(l^2-m_t^2)((l+p)^2-m_t^2)} = -\frac{i\pi^2}{2}\left(2m_t^2-\frac{p^2}{3}\right)+\mathcal{O}(\epsilon)$$

- The corresponding R2 term

$$R_2 = -\frac{i\alpha_S}{4\pi}(2m_t^2-\frac{p^2}{3})\delta_{ab}g^{\mu\nu}\varepsilon_\mu\varepsilon_\nu$$

R2

Draggiotis, Garzelli, Papadopoulos, Pittau (JHEP'09); HSS, Zhang, Chao (JHEP'11)

- It was proven that R2 is only UV related, hence universal (i.e. model dependent only), which can be derived by R2 counterterm Feynman rules and should be derived once for all in each model.

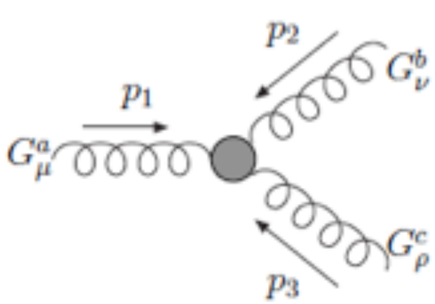
R2

Draggiotis, Garzelli, Papadopoulos, Pittau (JHEP'09); HSS, Zhang, Chao (JHEP'11)

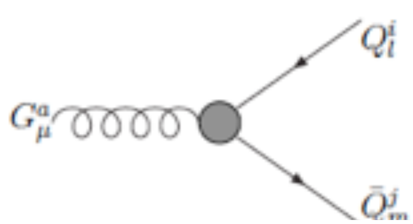
- It was proven that R2 is only UV related, hence universal (i.e. model dependent only), which can be derived by R2 counterterm Feynman rules and should be derived once for all in each model.

$= \mathrm{Vert}(G^a_\mu, G^b_\nu)$

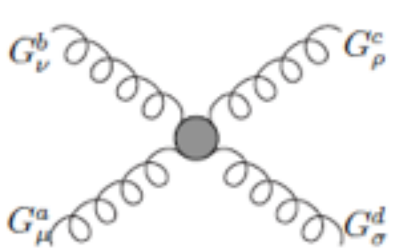
$= \mathrm{Vert}(Q^i_l, \bar{Q}^j_m)$



$= \mathrm{Vert}(G^a_\mu, G^b_\nu, G^c_\rho)$



$= \mathrm{Vert}(G^a_\mu, Q^i_l, \bar{Q}^j_m)$



$= \mathrm{Vert}\left(G^a_\mu, G^b_\nu, G^c_\rho, G^d_\sigma\right)$

$$\mathrm{Vert}(G^a_\mu, G^b_\nu) = \frac{i g_s^2 N_c}{48\pi^2}\,\delta^{ab}\left[\frac{p^2}{2} g_{\mu\nu} + \lambda_{HV}\left(g_{\mu\nu}p^2 - p_\mu p_\nu\right) + \sum_Q \frac{p^2 - 6m_Q^2}{N_c} g_{\mu\nu}\right]$$

$$\mathrm{Vert}(Q^i_l, \bar{Q}^j_m) = \frac{i g_s^2}{16\pi^2}\,\frac{N_c^2-1}{2N_c}\,\delta^{ij}\,\delta_{lm}\,\left(-\not{p} + 2m_{Q_l}\right)\lambda_{HV}.$$

$$\mathrm{Vert}(G^a_\mu, G^b_\nu, G^c_\rho) = -\frac{g_s^3 N_c}{48\pi^2}\left(\frac{7}{4} + \lambda_{HV} + \frac{2N_f}{N_c}\right) f^{abc}\, V_{\mu\nu\rho}(p_1, p_2, p_3)$$

$$V_{\mu\nu\rho}(p_1, p_2, p_3) = g_{\mu\nu}(p_2 - p_1)_\rho + g_{\nu\rho}(p_3 - p_2)_\mu + g_{\rho\mu}(p_1 - p_3)_\nu.$$

$$\mathrm{Vert}(G^a_\mu, Q^i_l, \bar{Q}^j_m) = \delta_{lm}\,\frac{i g_s^3}{16\pi^2}\,T^a_{ji}\,\frac{N_c^2-1}{2N_c}\,\gamma_\mu\left(1 + \lambda_{HV}\right)$$

$$\mathrm{Vert}\left(G^a_\mu, G^b_\nu, G^c_\rho, G^d_\sigma\right) = \frac{i g_s^4}{48\pi^2}\left(C_1\, g_{\mu\nu}g_{\rho\sigma} + C_2\, g_{\mu\rho}g_{\nu\sigma} + C_3\, g_{\mu\sigma}g_{\nu\rho}\right),$$

$$\begin{aligned} C_1 = {} & Tr(\{T^a, T^b\}\{T^c, T^d\})\ (5N_c + 2\lambda_{HV}N_c + 6N_f) \\ & - \left(Tr(T^aT^cT^bT^d) + Tr(T^aT^dT^bT^c)\right)(12N_c + 4\lambda_{HV}N_c + 10N_f) \\ & - \left(\delta^{ab}\delta^{cd} + \delta^{ac}\delta^{bd} + \delta^{ad}\delta^{bc}\right),\quad C_2 = C_1(b \leftrightarrow c) \qquad C_3 = C_1(b \leftrightarrow d) \end{aligned}$$

MADLOOP

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau (JHEP'11)

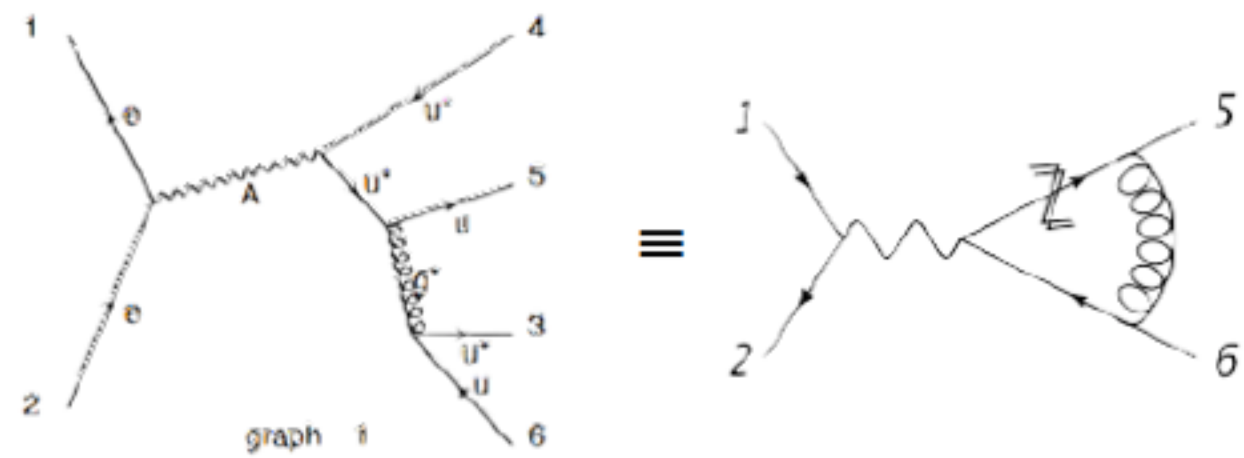
- Instead of using an external tool for loop diagram generation, we recycle MadGraph algorithms for tree-level diagram generation.

- A loop diagrams with the loop cut open has two extra external particles. Consider e^+e^- > u u~ u u~ (loop particle are in red).MadLoop will generate 8 L-cut diagrams. Here are two of them:

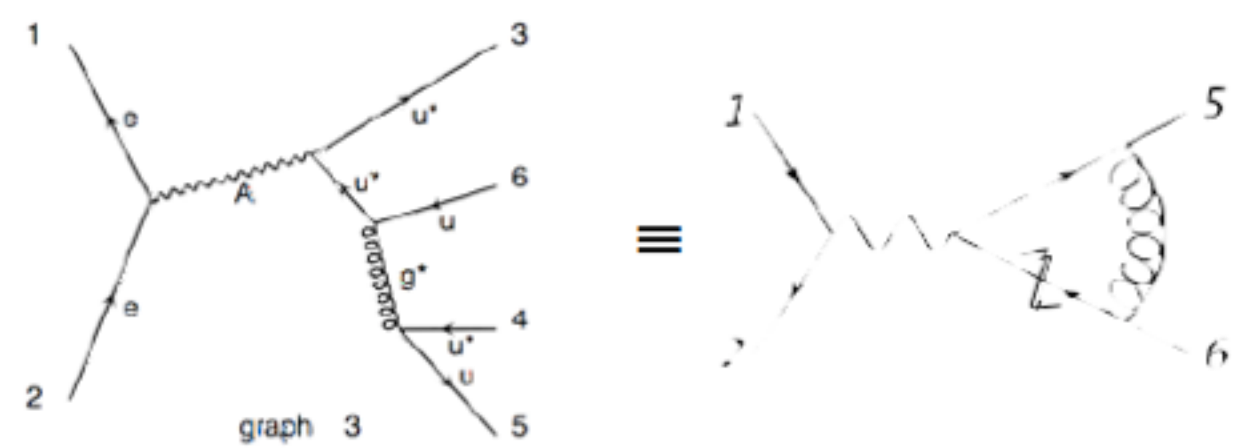
- All diagrams with two extra particles generated and the ones that are redundant need be filtered out

- Each diagram gets an unique tag:
any mirror and/or cyclic permutations of tags of diagrams already in the set are taken out

- Additional filter to eliminate tadpole and bubbles attached to external lines.



$\text{Diag}_1 = [u^*(6)g^*(5)u^*(A)]$

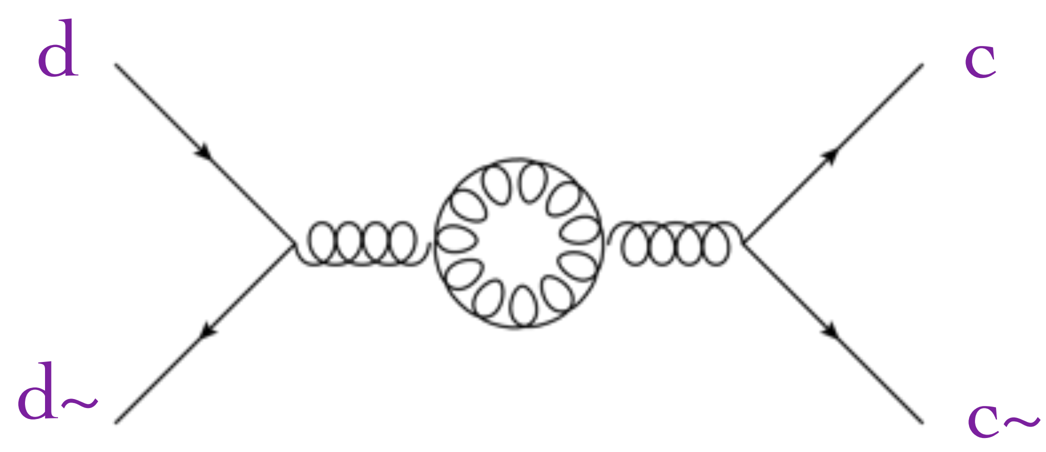


$\text{Diag}_3 = [u^*(A)u^*(6)g^*(5)]$

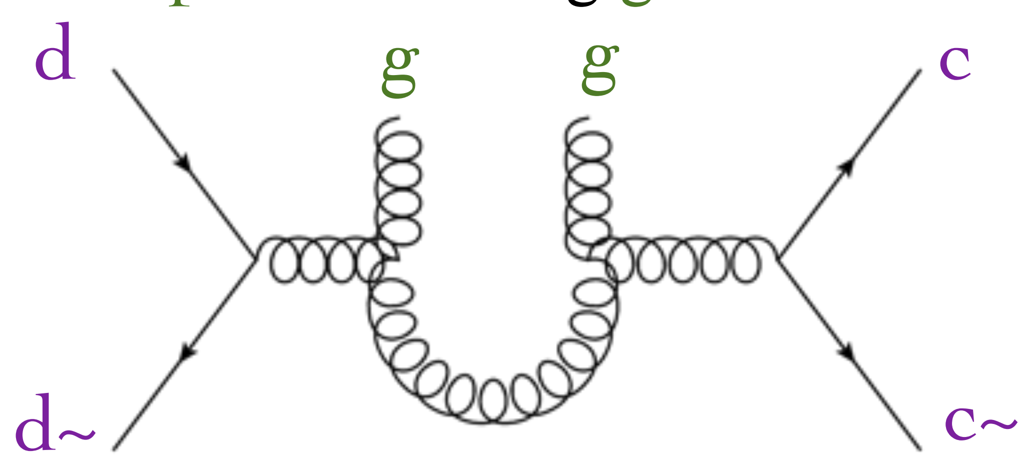
MADLOOP

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau (JHEP'11)

- It is clear though that d d~ ➞ c c~ u u~ will not get you this loop :



- For this one you necessarily need to generate the born process with the additional two L-cut particles being gluons!

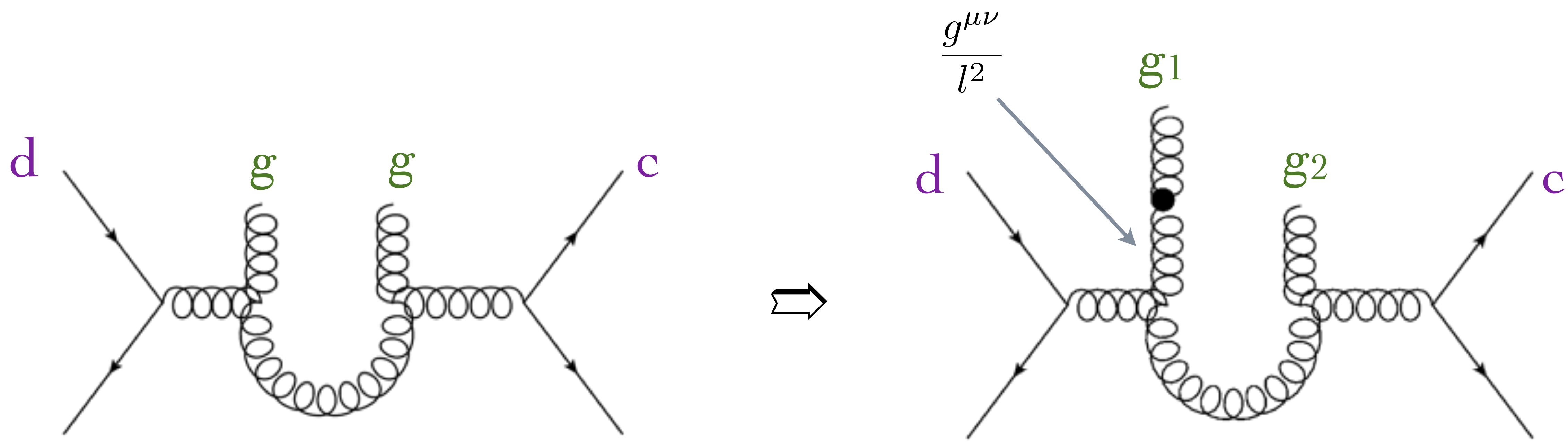


- Loops including a u-quark were already generated with d d~ ➞ c c~ u u~, so you can speed up the d d~ ➞ c c~ g g generation forbidding u in the loop!

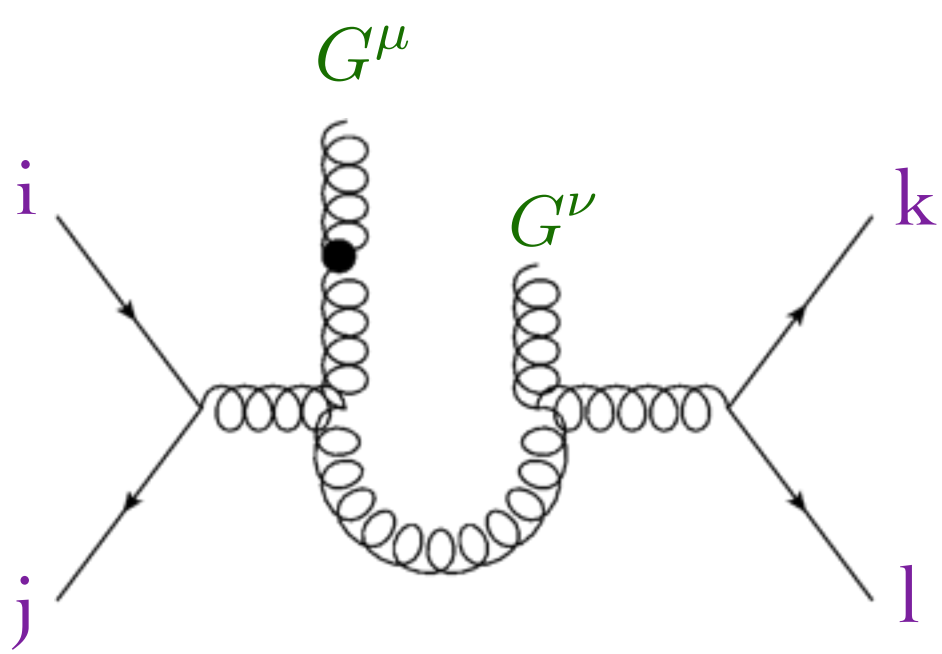
MADLOOP

Hirschi, Frederix, Frixione, Garzelli, Maltoni, Pittau (JHEP'11)

- We want to use (modified) HELAS method



- Closing the Lorentz trace :



$$\delta^{\mu\nu} = \sum_{i=0}^{4} \underbrace{\delta^{\mu i}}_{G^\mu} \underbrace{\delta^{i\nu}}_{G^\nu}$$

External Wavefunction for HELAS

RENORMALIZATION

- Renormalization is a non-trivial task in principle.
- In QFT, renormalization is widely used to absorb (the divergence from) the high-momentum mode.
- The renormalization of some theories is quite well known, such as QCD (or the Standard Model).

RENORMALIZATION

- Renormalization is a non-trivial task in principle.
- In QFT, renormalization is widely used to absorb (the divergence from) the high-momentum mode.
- The renormalization of some theories is quite well known, such as QCD (or the Standard Model).
- In general, the UV divergences should be absorbed by a redefinition of
  - the free parameters (such as mass, couplings, mixing angles etc

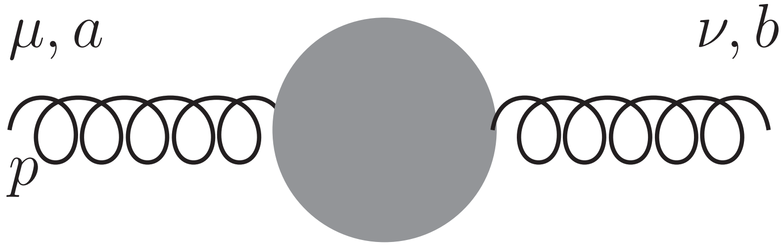
$$x_0 \to x + \delta x$$

  - the fields

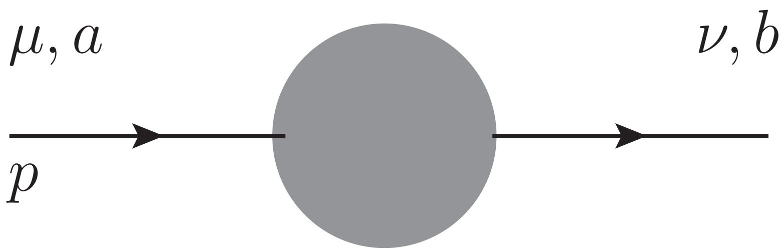
$$\phi_0 \to (1 + \frac{1}{2}\delta Z_{\phi\phi})\phi + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi$$

EXAMPLE: RENORMALIZATION

- One-particle irreducible two-point functions ('t Hooft-Veltman)



$$= -i g_{\mu\nu} p^2 \delta_{ab} - i \left(g_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) \Sigma_T^{ab}(p^2) - i \frac{p_\mu p_\nu}{p^2} \Sigma_L^{ab}(p^2)$$



$$= i(\not{p} - m_Q)\delta_{ab} + i \left[\not{p}\Omega_- \Sigma_L^{Q,ab}(p^2) + \not{p}\Omega_+ \Sigma_R^{Q,ab}(p^2) + (m_Q \Omega_- + m_Q \Omega_+) \Sigma_S^{Q,ab}(p^2) \right]$$

- On-shell mass and wavefunction renormalization

$$\delta Z_g \delta^{ab} = - \left. \frac{\partial \Sigma_T^{ab}(p^2)}{\partial p^2} \right|_{p^2=0}$$

$$\delta m_Q \delta^{ab} = \frac{m_Q}{2} \left(\Sigma_L^{Q,ab}(m_Q^2) + \Sigma_R^{Q,ab}(m_Q^2) + 2\Sigma_S^{Q,ab}(m_Q^2) \right)$$

$$\delta Z_Q^{L/R} \delta^{ab} = -\Sigma^{L/R}(m_Q^2) - m_Q^2 \frac{\partial}{\partial p^2} \left. \left[\Sigma_L^{Q,ab}(p^2) + \Sigma_R^{Q,ab}(p^2) + 2\Sigma_S^{Q,ab}(p^2) \right] \right|_{p^2=m_Q^2}$$

EXAMPLE: RENORMALIZATION

- Coupling constant renormalization (match to PDF)
  - Keep scale dependence of massive mode to gluon self-energy
  - MSbar renormalize for massless mode to gluon self-energy

$$\delta g_s^{\overline{\rm MS}} = \delta V_{q\bar{q}G}^{\overline{\rm MS}} - \delta Z_q^{\overline{\rm MS}} - \frac{\delta Z_g^{\rm ZS}}{2}$$

$$\delta Z_g^{\rm ZS} = \delta Z_g^{\rm OS}(\text{massive loop}) + \delta Z_g^{\overline{\rm MS}}(\text{massless loop})$$

EXAMPLE: RENORMALIZATION

- Coupling constant renormalization (match to PDF)
  - Keep scale dependence of massive mode to gluon self-energy
  - MSbar renormalize for massless mode to gluon self-energy

$$\delta g_s^{\overline{\mathrm{MS}}} = \delta V_{q\bar{q}G}^{\overline{\mathrm{MS}}} - \delta Z_q^{\overline{\mathrm{MS}}} - \frac{\delta Z_g^{\mathrm{ZS}}}{2}$$

$$\delta Z_g^{\mathrm{ZS}} = \delta Z_g^{\mathrm{OS}}(\mathrm{massive\ loop}) + \delta Z_g^{\overline{\mathrm{MS}}}(\mathrm{massless\ loop})$$

- Renormalization with UV counterterm

$$\mathcal{L}_{Q\bar{Q}G} = \bar{Q}(i\partial\!\!\!/ - m_Q + g_s T^a G\!\!\!/)Q$$

$$\Rightarrow \quad \mathcal{L}_{Q\bar{Q}G} + \delta\mathcal{L}_{Q\bar{Q}G}^{\mathrm{UV}}$$ where

$$\delta\mathcal{L}_{Q\bar{Q}G}^{\mathrm{UV}} = \bar{Q}((i\partial\!\!\!/ - m_Q)\delta Z_Q - \delta m_Q + (\delta g_s + \delta Z_Q + \frac{\delta Z_g}{2})g_s T^a G\!\!\!/)Q$$

EXAMPLE: RENORMALIZATION

- Coupling constant renormalization (match to PDF)
  - Keep scale dependence of massive mode to gluon self-energy
  - MSbar renormalize for massless mode to gluon self-energy

$$\delta g_s^{\overline{\rm MS}} = \delta V_{q\bar{q}G}^{\overline{\rm MS}} - \delta Z_q^{\overline{\rm MS}} - \frac{\delta Z_g^{\rm ZS}}{2}$$

$$\delta Z_g^{\rm ZS} = \delta Z_g^{\rm OS}(\text{massive loop}) + \delta Z_g^{\overline{\rm MS}}(\text{massless loop})$$

- Renormalization with UV counterterm

Propagator

$$\mathcal{L}_{Q\bar{Q}G} = \bar{Q}(i\partial\!\!\!/ - m_Q + g_s T^a G\!\!\!/)Q$$

$$\Rightarrow \quad \mathcal{L}_{Q\bar{Q}G} + \delta\mathcal{L}_{Q\bar{Q}G}^{\rm UV} \quad \text{where}$$

$$\delta\mathcal{L}_{Q\bar{Q}G}^{\rm UV} = \bar{Q}((i\partial\!\!\!/ - m_Q)\delta Z_Q - \delta m_Q + (\delta g_s + \delta Z_Q + \frac{\delta Z_g}{2})g_s T^a G\!\!\!/)Q$$

EXAMPLE: RENORMALIZATION

- Coupling constant renormalization (match to PDF)
  - Keep scale dependence of massive mode to gluon self-energy
  - MSbar renormalize for massless mode to gluon self-energy

$$\delta g_s^{\overline{\rm MS}} = \delta V_{q\bar{q}G}^{\overline{\rm MS}} - \delta Z_q^{\overline{\rm MS}} - \frac{\delta Z_g^{\rm ZS}}{2}$$

$$\delta Z_g^{\rm ZS} = \delta Z_g^{\rm OS}(\text{massive loop}) + \delta Z_g^{\overline{\rm MS}}(\text{massless loop})$$

- Renormalization with UV counterterm

Vertex

$$\mathcal{L}_{Q\bar{Q}G} = \bar{Q}(i\partial\!\!\!/ - m_Q + g_s T^a G\!\!\!/)Q$$

$$\mathcal{L}_{Q\bar{Q}G} + \delta\mathcal{L}_{Q\bar{Q}G}^{\rm UV}$$ where

$$\delta\mathcal{L}_{Q\bar{Q}G}^{\rm UV} = \bar{Q}((i\partial\!\!\!/ - m_Q)\delta Z_Q - \delta m_Q + (\delta g_s + \delta Z_Q + \frac{\delta Z_g}{2})g_s T^a G\!\!\!/)Q$$

EXAMPLE: RENORMALIZATION

- Coupling constant renormalization (match to PDF)
  - Keep scale dependence of massive mode to gluon self-energy
  - MSbar renormalize for massless mode to gluon self-energy

$$\delta g_s^{\overline{\rm MS}} = \delta V_{q\bar{q}G}^{\overline{\rm MS}} - \delta Z_q^{\overline{\rm MS}} - \frac{\delta Z_g^{\rm ZS}}{2}$$

$$\delta Z_g^{\rm ZS} = \delta Z_g^{\rm OS}(\text{massive loop}) + \delta Z_g^{\overline{\rm MS}}(\text{massless loop})$$

- Renormalization with UV counterterm

Vertex

$$\mathcal{L}_{Q\bar{Q}G} = \bar{Q}(i\not{\partial} - m_Q + g_s T^a \not{G})Q$$

$$\Rightarrow \quad \mathcal{L}_{Q\bar{Q}G} + \delta\mathcal{L}_{Q\bar{Q}G}^{\rm UV} \quad \text{where}$$

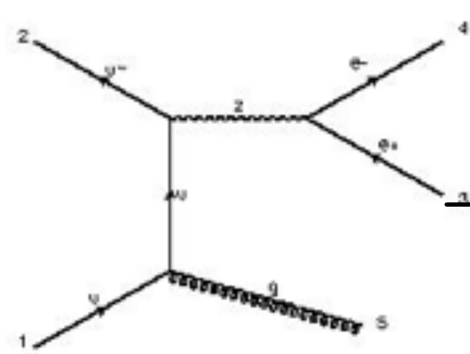
UV Vertex

$$\delta\mathcal{L}_{Q\bar{Q}G}^{\rm UV} = \bar{Q}((i\not{\partial} - m_Q)\delta Z_Q - \delta m_Q + (\delta g_s + \delta Z_Q + \frac{\delta Z_g}{2})g_s T^a \not{G})Q$$

Wednesday, November 25, 15

REAL SUBTRACTION

- Because of IR div, difficult to integrate real phase-space !
- Subtraction the IR piece by a constructed function S



$$\underbrace{\int_3 \left(\left| \quad + \cdots \right|^{2}}_{R} - S \right) + \int_3 S$$

- Requirement:
  - The IR singularity of **R** and **S** are completely same (i.e. local)
  - **S** is much easier to integrate analytically at least one particle's phase space for NLO computation.

Details please refer to Marco's talk on Wednesday

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i} \frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

Details please refer to Marco's talk on Wednesday

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i} \frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

$\chi_i \to 0$ **soft**

Details please refer to Marco's talk on Wednesday

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \overset{\text{IR sing.}}{\longrightarrow} \frac{1}{\chi_i}\frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

$y_{ij} \to 1$ **collinear**

Details please refer to Marco's talk on Wednesday

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i} \frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

- Divide phase-space so that each partition has at most one soft and one collinear singularity

$$\int_3 R = \sum_{i,j} \int_3 S_{ij} R \qquad \sum_{i,j} S_{ij} = 1$$

Details please refer to Marco's talk on Wednesday

REAL SUBTRACTION

Frixione, Kunszt, Signer (NPB'96); Frederix, Frixione, Maltoni, Stelzer (JHEP'09)

- MG5_aMC used Frixione-Kunszt-Signer (FKS) subtraction of **S**
- The real IR singular form is

$$R \xrightarrow{\text{IR sing.}} \frac{1}{\chi_i}\frac{1}{1-y_{ij}}$$

where $\chi_i \equiv \frac{E_i}{\sqrt{\hat{s}}}, y_{ij} \equiv \cos\theta_{ij}$

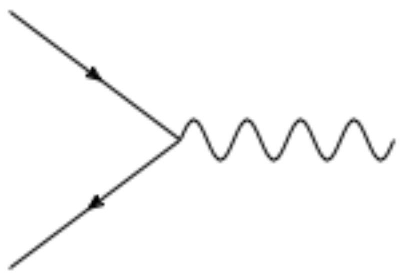
- Divide phase-space so that each partition has at most one soft and one collinear singularity

$$\int_3 R = \sum_{i,j} \int_3 S_{ij} R \qquad \sum_{i,j} S_{ij} = 1$$

- The real can be regulated as $\sum_{i,j}\int_3 \left(\frac{1}{\chi_i}\right)_+ \left(\frac{1}{1-y_{ij}}\right)_+ \chi_i \left(1-y_{ij}\right) S_{ij} R$
- Soft counterterm is blind of spin, but the splitting kernel in collinear counterterm is dependent of spin/gauge/...

Details please refer to Marco's talk on Wednesday

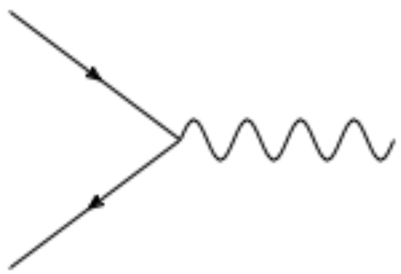
MATCHING TO PARTON SHOWER



Details please refer to Marco's talk on Wednesday

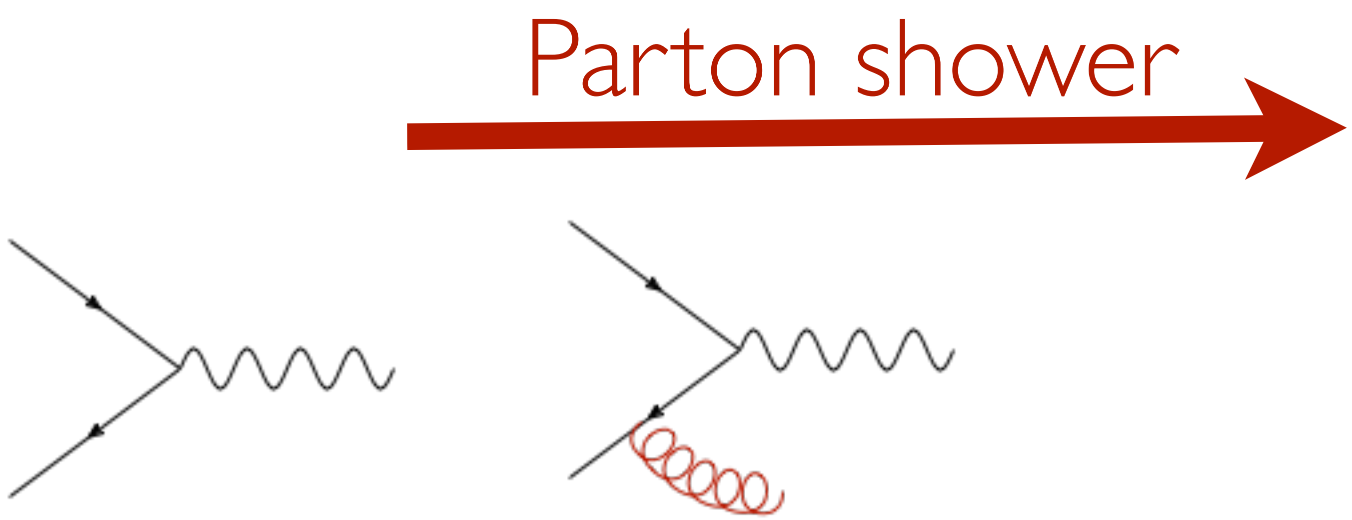
MATCHING TO PARTON SHOWER

Parton shower



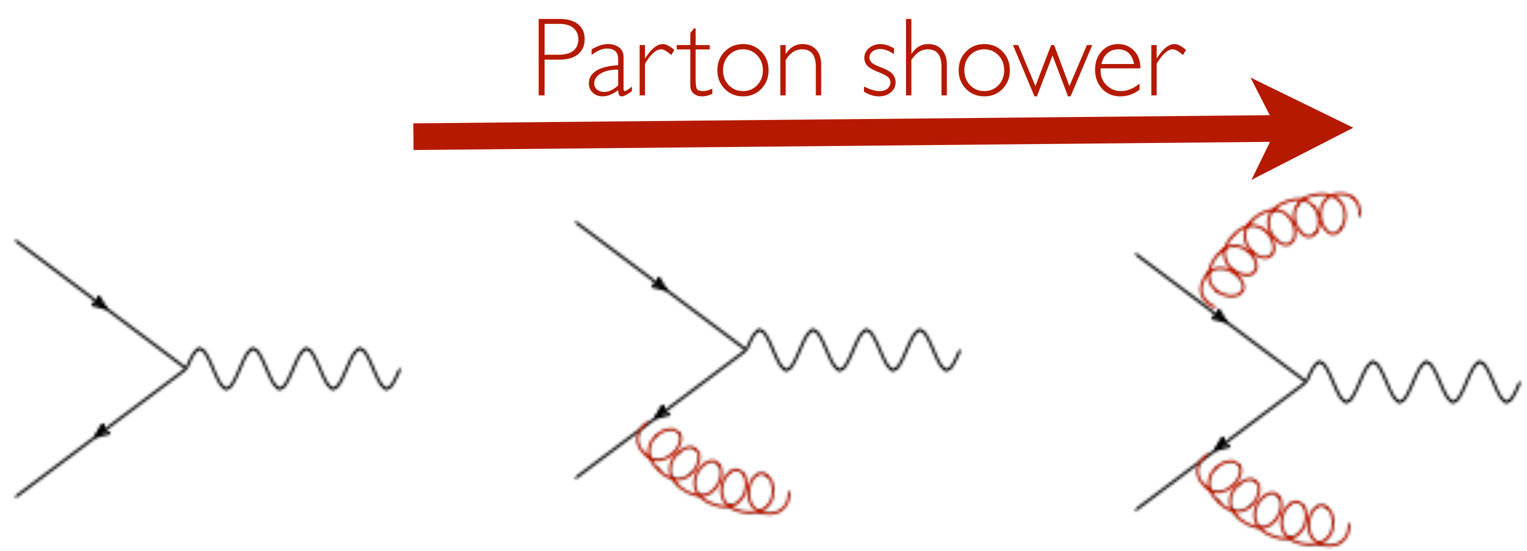
Details please refer to Marco's talk on Wednesday

MATCHING TO PARTON SHOWER



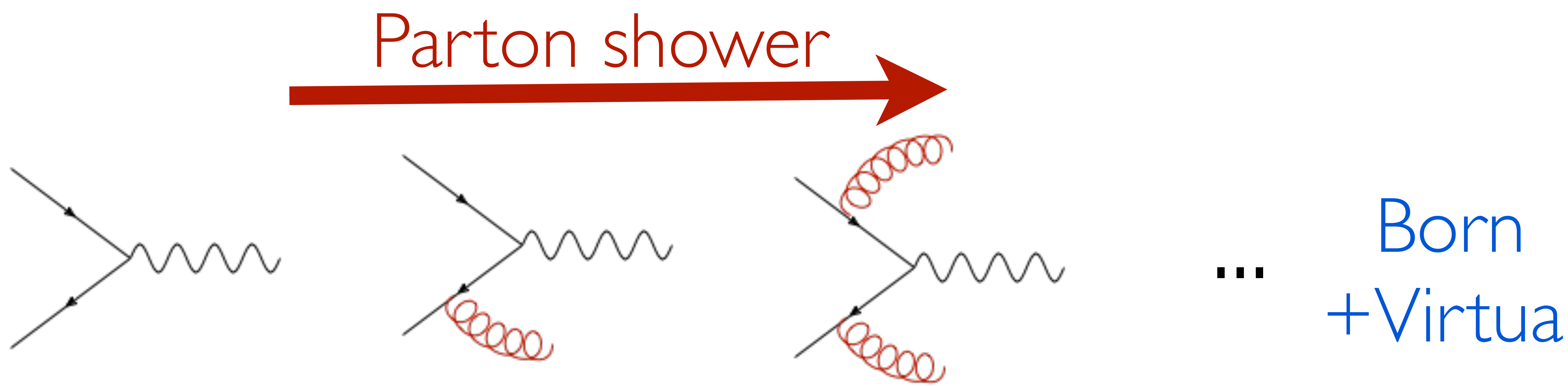
Details please refer to Marco's talk on Wednesday

MATCHING TO PARTON SHOWER



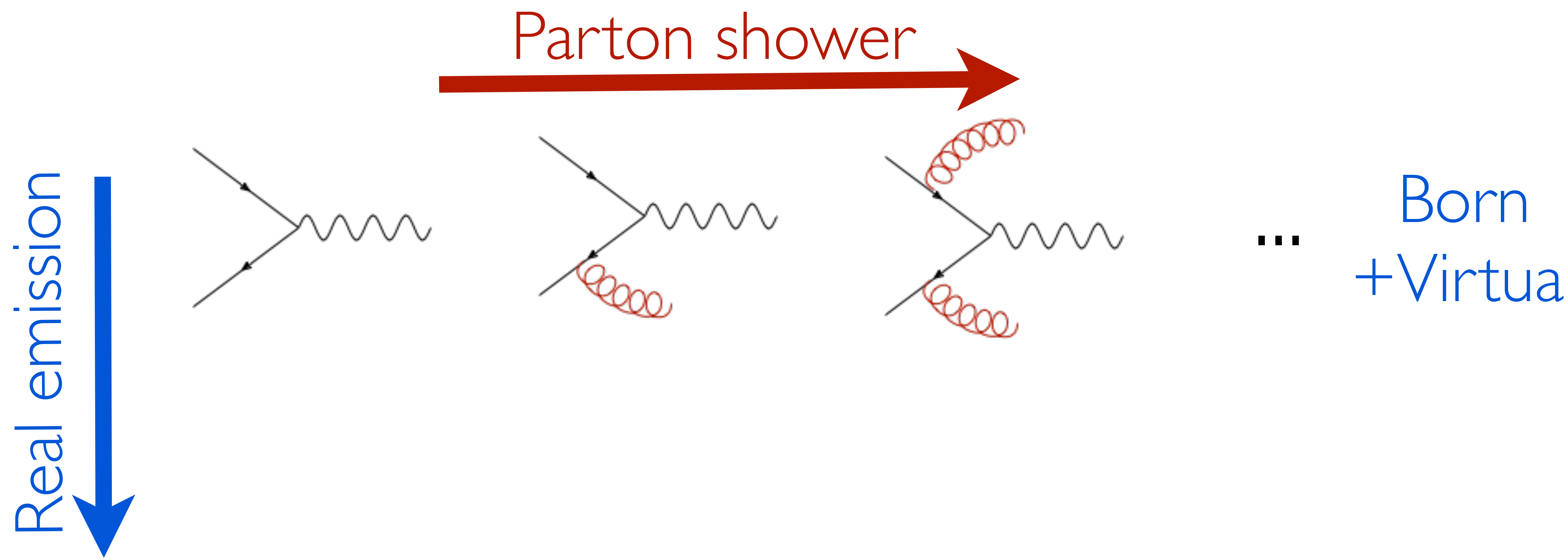
Details please refer to Marco's talk on Wednesday

MATCHING TO PARTON SHOWER



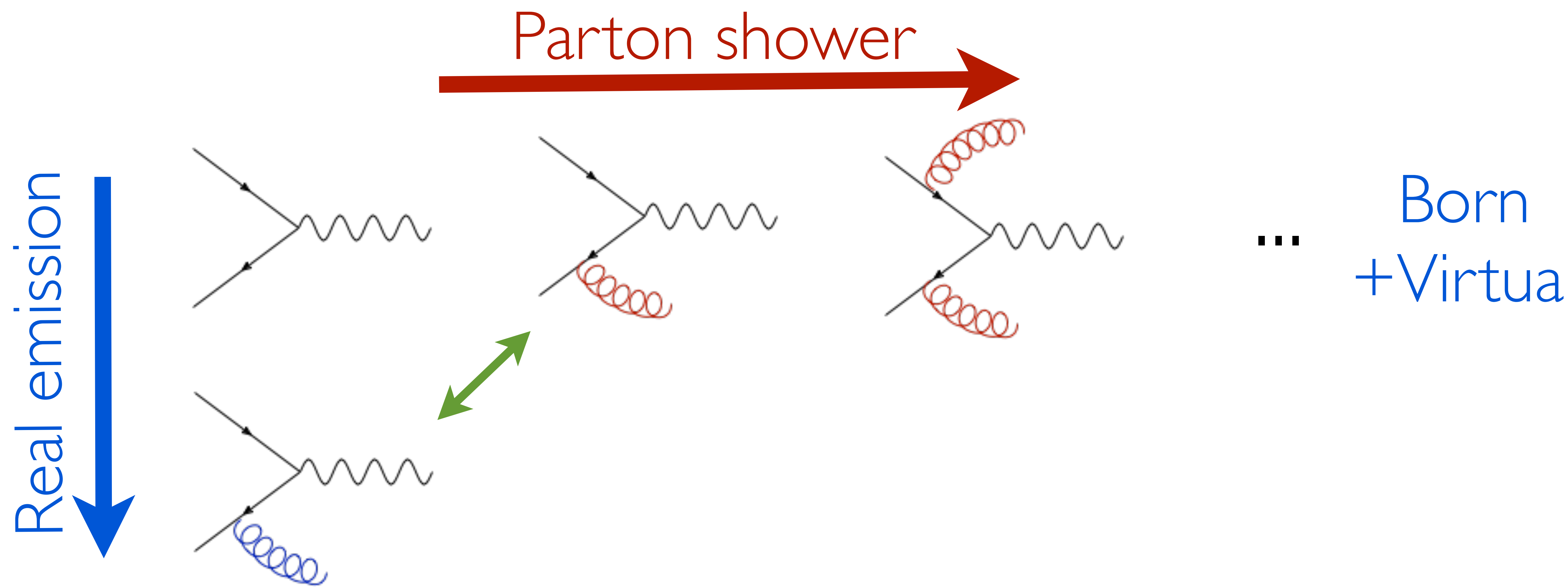
Details please refer to Marco's talk on Wednesday

MATCHING TO PARTON SHOWER



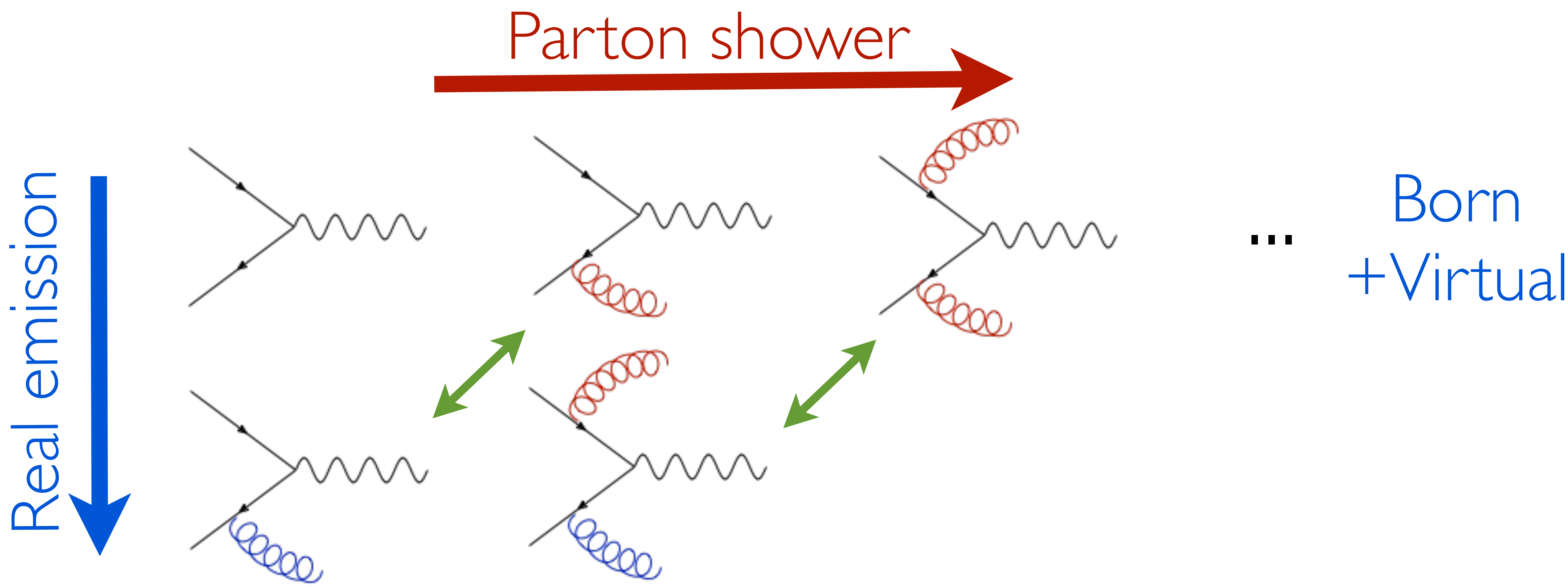
Details please refer to Marco's talk on Wednesday

MATCHING TO PARTON SHOWER



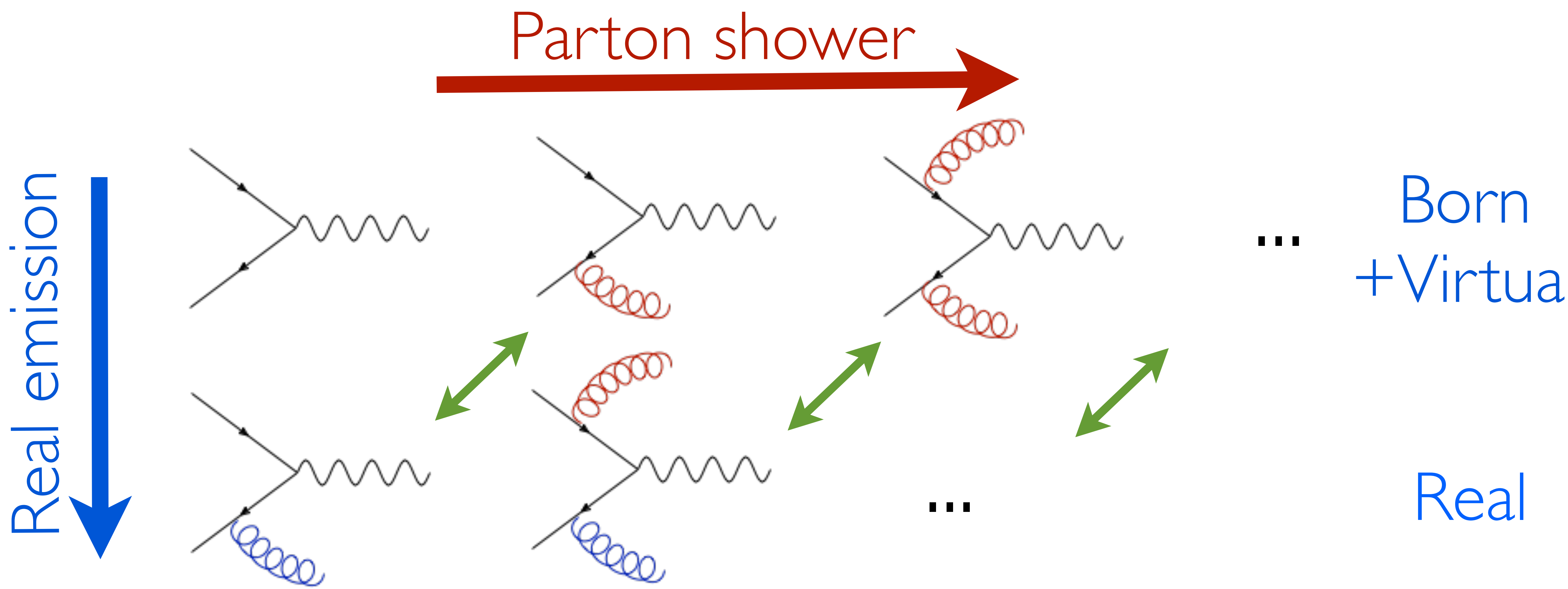
Details please refer to Marco's talk on Wednesday

MATCHING TO PARTON SHOWER



Details please refer to Marco's talk on Wednesday

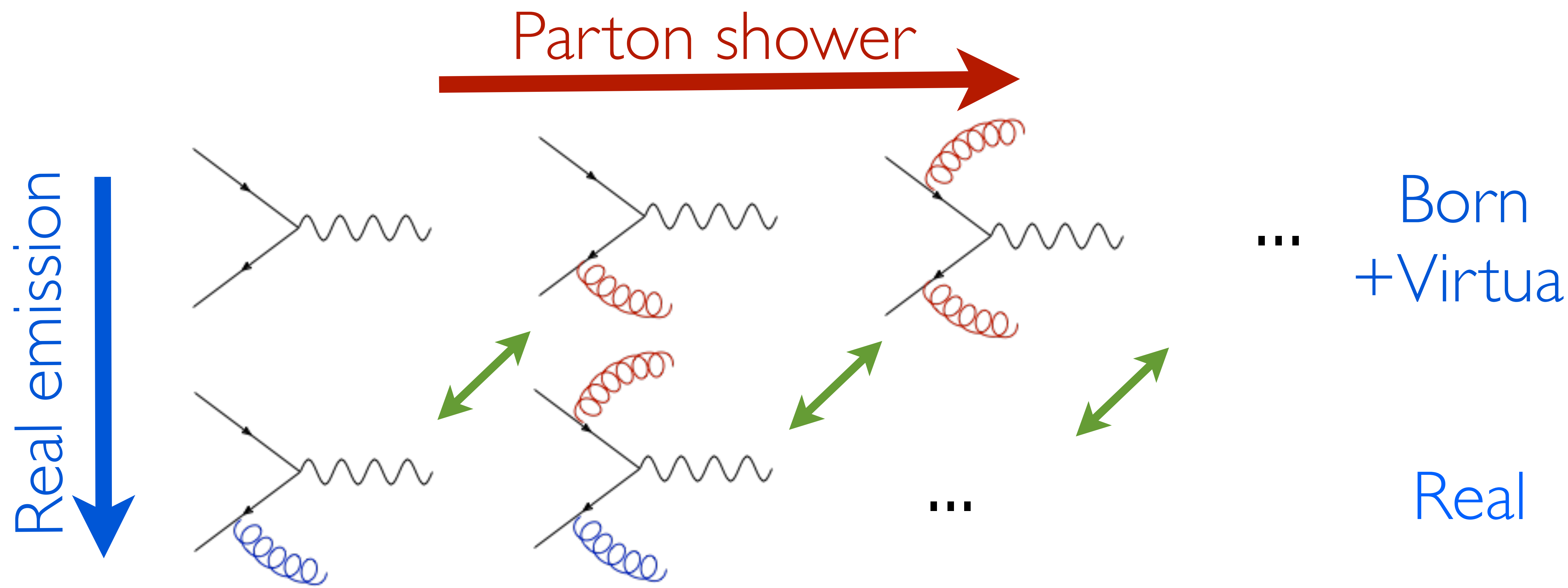
MATCHING TO PARTON SHOWER



- When matching NLO events to PS, one faces double counting issues.
- And also part of the virtual contribution is double counted through the definition of the Sudakov factor.
- Two ways out have been proposed: POWHEG and MC@NLO

Details please refer to Marco's talk on Wednesday

MATCHING TO PARTON SHOWER



- When matching NLO events to PS, one faces double counting issues.
- And also part of the virtual contribution is double counted through the definition of the Sudakov factor.

used by MG5_aMC

- Two ways out have been proposed: POWHEG and MC@NLO

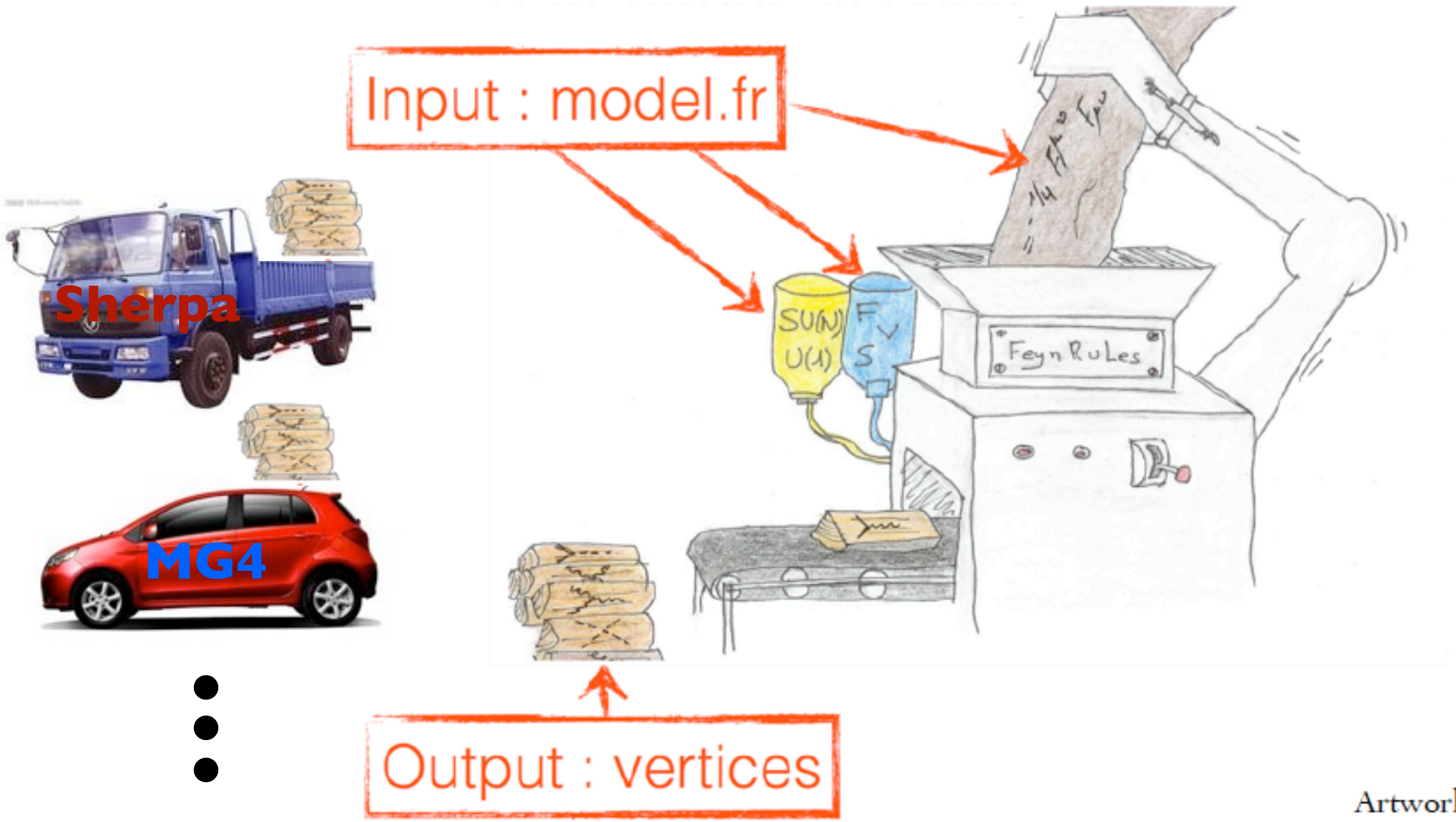
Details please refer to Marco's talk on Wednesday

FEYNRULES

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- How to incorporate all of above information in a model file ?

Details please refer to Claude's talk on Tuesday



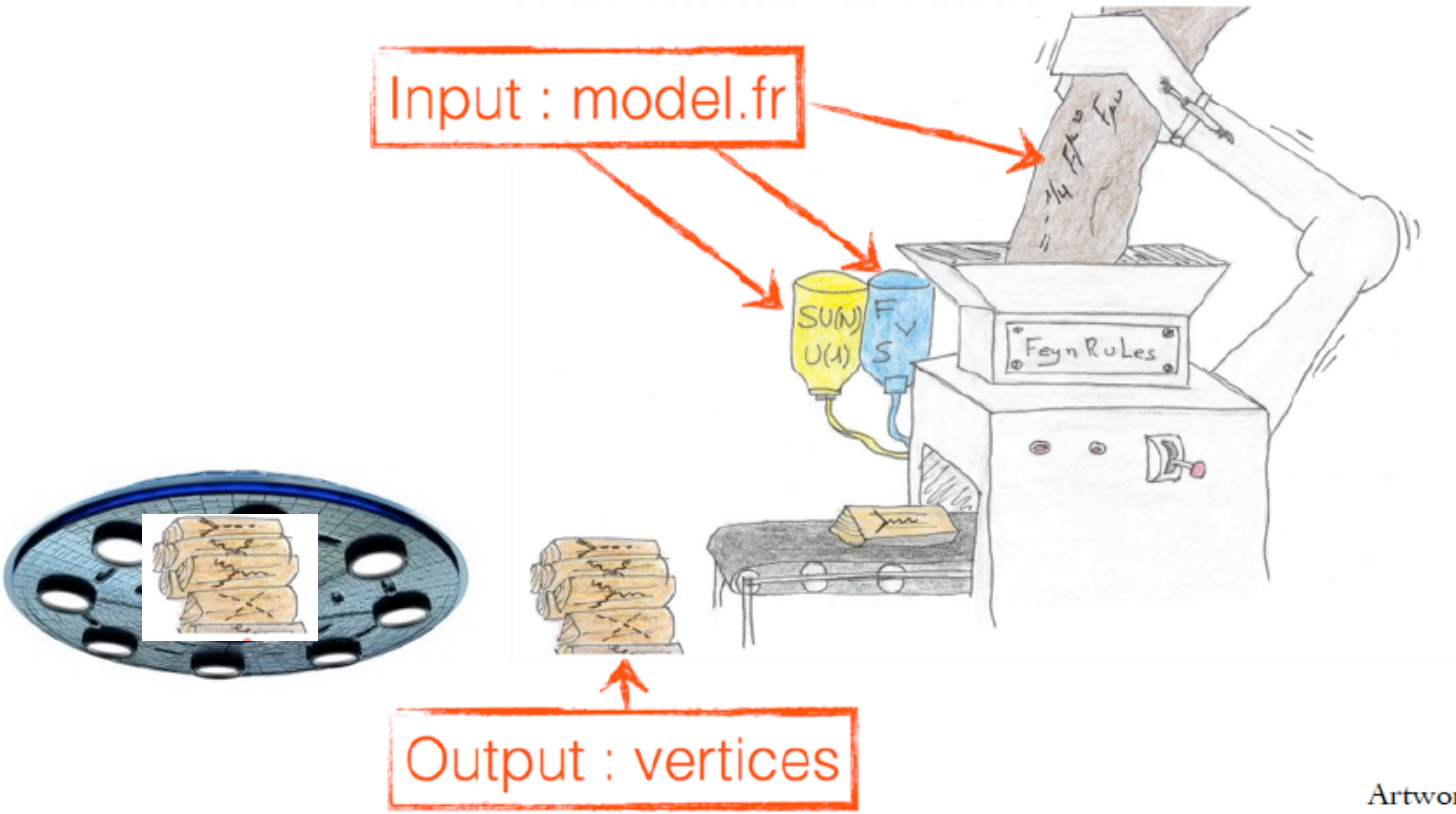
Artwork by C. Degrande

FEYNRULES

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- How to incorporate all of above information in a model file ?

Details please refer to Claude's talk on Tuesday



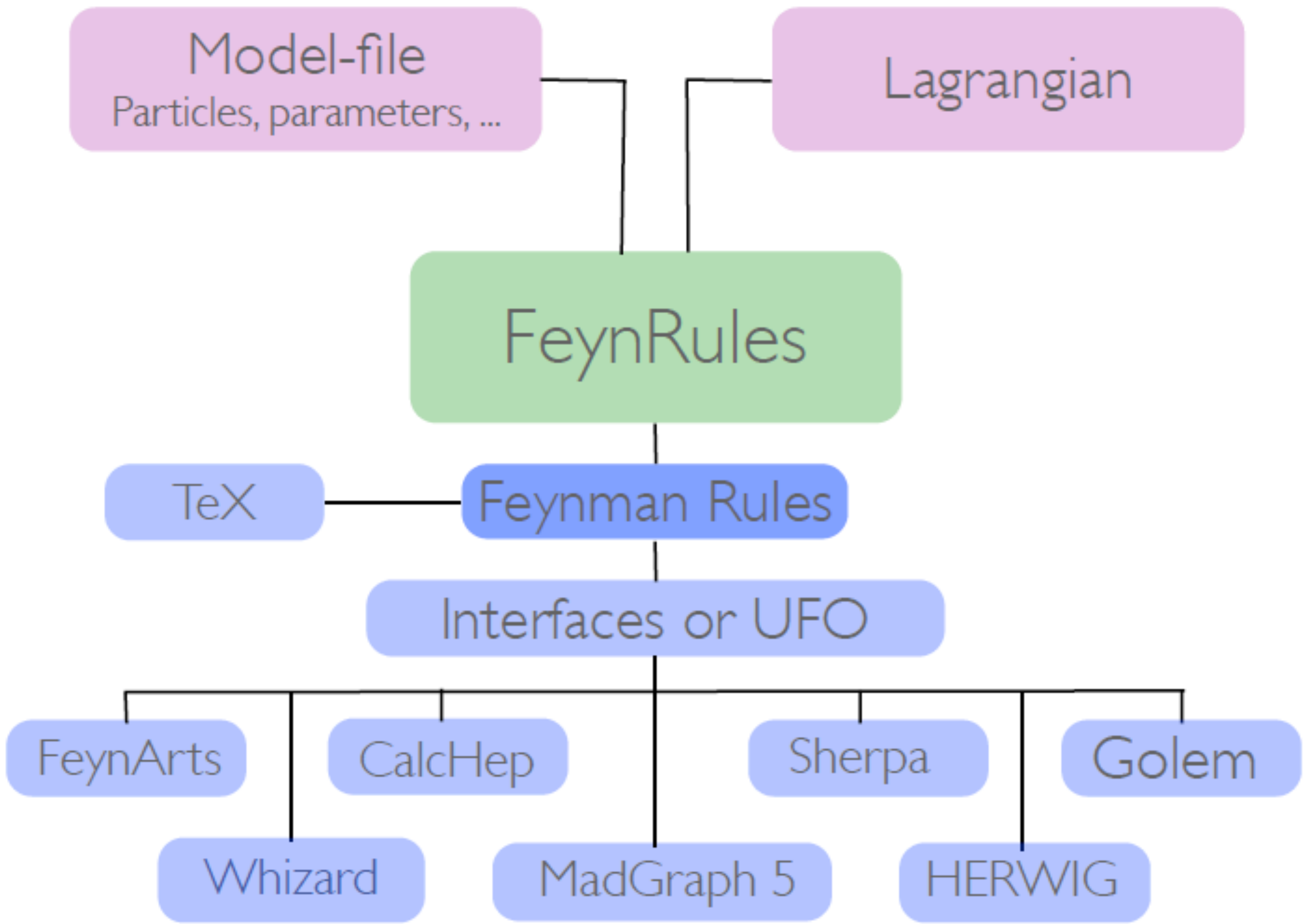
Artwork by C. Degrande

- UFO stands for Universal FeynRules Output:

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

FEYNRULES: STRUCTURE

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)



FEYNRULES: INPUT

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

FEYNRULES: INPUT

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles

```
(* ************************** *)
(* **** Particle classes **** *)
(* ************************** *)
M$ClassesDescription = {
            . . .
   V[4] == {
     ClassName        -> G,
     SelfConjugate    -> True,
     Indices          -> {Index[Gluon]},
     Mass             -> 0,
     Width            -> 0,
     ParticleName     -> "g",
     PDG              -> 21,
     PropagatorLabel  -> "G",
     PropagatorType   -> C,
     PropagatorArrow  -> None,
     FullName         -> "G"
   },
            . . .
 };
```

FEYNRULES: INPUT

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles

```
(* ************************** *)
(* **** Particle classes **** *)
(* ************************** *)
M$ClassesDescription = {
                ...
   V[4] == {
     ClassName        -> G,
     SelfConjugate    -> True,
     Indices          -> {Index[Gluon]},
     Mass             -> 0,
     Width            -> 0,
     ParticleName     -> "g",
     PDG              -> 21,
     PropagatorLabel  -> "G",
     PropagatorType   -> C,
     PropagatorArrow  -> None,
     FullName         -> "G"
   },
                ...
 };
```

- Definitions of parameters

```
(* ************************** *)
(* *****   Parameters   ***** *)
(* ************************** *)
M$Parameters = {
                ...
     aS     == {
       ParameterType    -> External,
       BlockName        -> SMINPUTS,
       OrderBlock       -> 3,
       Value            -> 0.1184,
       InteractionOrder -> {QCD,2},
       TeX              -> Subscript[\[Alpha],s],
       Description      -> "Strong coupling constant at the Z p
     },
                ...
};
```

FEYNRULES: INPUT

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles

```
(* ************************* *)
(* **** Particle classes **** *)
(* ************************* *)
M$ClassesDescription = {
              ...
   V[4] == {
     ClassName        -> G,
     SelfConjugate    -> True,
     Indices          -> {Index[Gluon]},
     Mass             -> 0,
     Width            -> 0,
     ParticleName     -> "g",
     PDG              -> 21,
     PropagatorLabel  -> "G",
     PropagatorType   -> C,
     PropagatorArrow  -> None,
     FullName         -> "G"
   },
              ...
};
```

- Definitions of parameters

```
(* ************************* *)
(* *****   Parameters   ***** *)
(* ************************* *)
M$Parameters = {
              ...
     aS     == {
       ParameterType    -> External,
       BlockName        -> SMINPUTS,
       OrderBlock       -> 3,
       Value            -> 0.1184,
       InteractionOrder -> {QCD,2},
       TeX              -> Subscript[\[Alpha],s],
       Description      -> "Strong coupling constant at the Z p
     },
              ...
};
```

- Definitions of gauge groups

```
(* ************************* *)
(* *****  Gauge groups  ***** *)
(* ************************* *)
M$GaugeGroups = {

        SU3C == {
          Abelian           -> False,
          CouplingConstant  -> gs,
          GaugeBoson        -> G,
          StructureConstant -> f,
          Representations   -> {T,Colour},
          SymmetricTensor   -> dSUN
        }
       };
```

FEYNRULES: INPUT

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Definitions of particles

```
(* ************************* *)
(* **** Particle classes **** *)
(* ************************* *)
M$ClassesDescription = {
             ...
   V[4] == {
     ClassName          -> G,
     SelfConjugate      -> True,
     Indices            -> {Index[Gluon]},
     Mass               -> 0,
     Width              -> 0,
     ParticleName       -> "g",
     PDG                -> 21,
     PropagatorLabel    -> "G",
     PropagatorType     -> C,
     PropagatorArrow    -> None,
     FullName           -> "G"
   },        ...
};
```

- Definitions of gauge groups

```
(* ************************* *)
(* *****  Gauge groups  ***** *)
(* ************************* *)
M$GaugeGroups = {
          SU3C == {
            Abelian           -> False,
            CouplingConstant  -> gs,
            GaugeBoson        -> G,
            StructureConstant -> f,
            Representations   -> {T,Colour},
            SymmetricTensor   -> dSUN
          }
        };
```

- Definitions of parameters

```
(* ************************* *)
(* *****   Parameters  ***** *)
(* ************************* *)
M$Parameters = {
             ...
    aS     == {
      ParameterType    -> External,
      BlockName        -> SMINPUTS,
      OrderBlock       -> 3,
      Value            -> 0.1184,
      InteractionOrder -> {QCD,2},
      TeX              -> Subscript[\[Alpha],s],
      Description      -> "Strong coupling constant at the Z p
    },       ...
};
```

- The Lagrangian

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4}G^a_{\mu\nu}G^{a,\mu\nu} + i\bar{q}\gamma^\mu D_\mu q - M_q\bar{q}q$$

L =
-1/4 FS[G,mu,nu,a] FS[G,mu,nu,a]
+ I qbar.Ga[mu].DC[q,mu]
- MQ qbar.q

FEYNRULES: DERIVATION

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Above information can be incorporated in .fr files and load the file via

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

- Extracting the Feynman rules

```
FeynmanRules[ L ]
```

- Output the model files for various generators

WriteCHOutput[L] ⟶ CalcHep

WriteFeynArtsOutput[L] ⟶ FeynArts

WriteSHOutput[L] ⟶ Sherpa

WriteWOOutput[L] ⟶ Whizard

WriteUFO[L] ⟵ { MadGraph5_aMC@NLO, Sherpa, GoSam }

FEYNRULES: DERIVATION

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14)

- Above information can be incorporated in .fr files and load the file via

```
LoadModel[ < file.fr >, < file2.fr >, ... ]
```

- Extracting the Feynman rules

```
FeynmanRules[ L ]
```

- Output the model files for various generators

WriteCHOutput[L]	⟶	CalcHep
WriteFeynArtsOutput[L]	⟶	FeynArts
WriteSHOutput[L]	⟶	Sherpa
WriteWOOutput[L]	⟶	Whizard

WriteUFO[L] ⟵ { MadGraph5_aMC@NLO, Sherpa, GoSam }

NEW Standard !

WHY IS THE UFO NOW A STANDARD ?

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

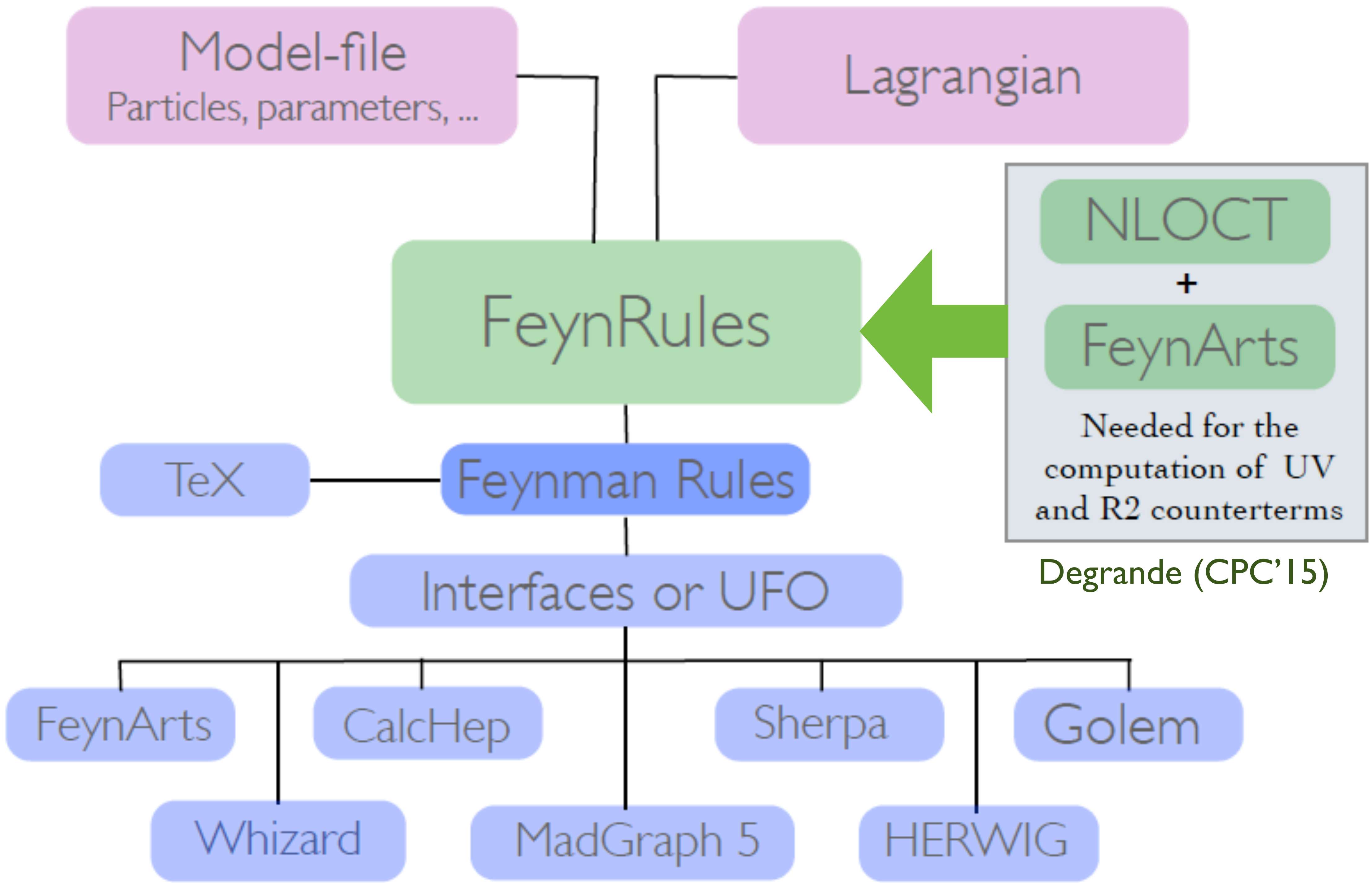
- Color structures: not supported in full generality by Monte Carlo generators
  - The treatment of the color information is hard-coded
  - The interfaces to a specific tool discard all non-supported vertices
  - Representations usually handled: 1, 3, 8 (limited in CALCHEP), sometimes 6

- Lorentz structures and spins not supported in full generality by Monte Carlo programs
  - The treatment of the Lorentz structures of the different vertices is hard-coded
  - The possible spins for the particles are restricted
  - The interfaces discard all non-supported vertices
  - Spin representations usually handled: 0, 1/2, 1; sometimes 3/2, 2
  - Lorentz structures usually handled: MSSM-like; sometimes any

Each interface dedicated to a given tool is specific
★ Removal of vertices not compliant with the tool
★ Translation to a specific format and programming language
⇒ **not efficient**
⇒ **better: one translation and the tools parse it**

FEYNRULES: STRUCTURE

Christensen, Duhr (CPC'09); Alloul, Christensen, Duhr, Degrande, Fuks (CPC'14); Degrande (CPC'15)



Degrande (CPC'15)

FEYNRULES: DERIVATION@NLO I

Degrande (CPC'15)

Load FeynRules and Model file

```
$FeynRulesPath = SetDirectory["~/feynrules/trunk/feynrules-development"]; << FeynRules`
LoadModel["~/feynrules/trunk/feynrules-development/Models/SM/SM.fr",
  "~/Dropbox/aMCatNLO-MSSM/FeynRulesInput/coloredscalars.fr"];
```

Load restrict card

```
LoadRestriction["~/feynrules/trunk/feynrules-development/Models/SM/Masslessbuttb.rst"]
LoadRestriction["~/feynrules/trunk/feynrules-development/Models/SM/DiagonalCKM.rst"]
```

Derive Feynman rule (optional)

```
FeynmanRules[LSM + LagNP]
```

Get renormalization Lagrangian

```
Lren = OnShellRenormalization[LSM + LagNP (*ExpandIndices[LSM,FlavorExpand→True]/.
     {u[__]→0,c[__]→0,d[__]→0,s[__]→0,ve[__]→0,vm[__]→0,e[__]→0,mu[__]→0}*), QCDOnly → True, FlavorMixing → False]; //
 Timing
```

Generate NLO FeynArts Model

```
SetDirectory["~/FeynArts-3.8/Models"];
WriteFeynArtsOutput[Lren, Output → "colscalarsnomixgs"]
```

Tutorial this afternoon !

FEYNRULES: DERIVATION@NLO II

Degrande (CPC'15)

Quit kernel

```
Quit[]
```

Load FeynArts and NLOCT

```
SetDirectory["~/FeynArts-3.8"];
<< FeynArts`
SetDirectory["~/feynrules/trunk/feynrules-development"];
<< NLOCT`
SetDirectory["~/feynrules/trunk/R2"];
```

Compute UV and R2 CT

```
WriteCT["colscalarsnomix/colscalarsnomix", "colscalarsnomix/colscalarsnomix", Output -> "colscalartest",
  LabelInternal → True, QCDOnly → True, CTparameters → False, KeptIndices → {}, ZeroMom → {{aS, {F[7], V[4], -F[7]}, C
  Assumptions -> {MT > 0},
  GenericVertexList → {{F, F}, {S, S}, {V, V}, {F, F, V}, {F, F, S}, {F, F, V, V}(*,{V,V,S},{V,S,S},{S,S,S},{V,V,V},
    {V,V,V,V},{V,V,S,S}*)}, MaxDim → 5, EvenOnly → False, IsFeynmanGauge → False] // Timing
```

Tutorial this afternoon !

FEYNRULES: DERIVATION@NLO III

Degrande (CPC'15)

Quit kernel

```
Quit[]
```

Load FeynRules and Model file again

```
$FeynRulesPath = SetDirectory["~/feynrules/trunk/feynrules-development"]; << FeynRules`
LoadModel["~/feynrules/trunk/feynrules-development/Models/SM/SM.fr",
  "~/Dropbox/aMCatNLO-MSSM/FeynRulesInput/coloredscalars.fr"];
```

Load restrict card again

```
LoadRestriction["~/feynrules/trunk/feynrules-development/Models/SM/DiagonalCKM.rst"]
LoadRestriction["~/feynrules/trunk/feynrules-development/Models/SM/Masslessbuttb.rst"]
```

Get the UV and R2 computed by NLOCT

```
SetDirectory["~/feynrules/trunk/R2"];
Get["colscalartest.nlo"];
```

Write out NLO UFO model

```
FR$Loop = False;
SetDirectory["~/2.2.0/models"];
WriteUFO[LSM + LagNP, UVCounterterms → (UV$vertlist /. FR$IR → 1), R2Vertices → R2$vertlist, Output → "ColScalarFull",
 Debug → False]
```

Tutorial this afternoon !

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD

```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py         SUSYQCD_CTprm_UFO.log   couplings.py            object_library.py       propagators.py
CT_parameters.py        __init__.py             function_library.py     parameters.py           vertices.py
CT_vertices.py          coupling_orders.py      lorentz.py              particles.py            write_param_card.py
```

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD

```
bogon:SUSYQCD_CTprm_UFO erdissshaw$ ls
CT_couplings.py      SUSYQCD_CTprm_UFO.log   couplings.py          object_library.py    propagators.py
CT_parameters.py     __init__.py             function_library.py   parameters.py        vertices.py
CT_vertices.py       coupling_orders.py      lorentz.py            particles.py         write_param_card.py
```

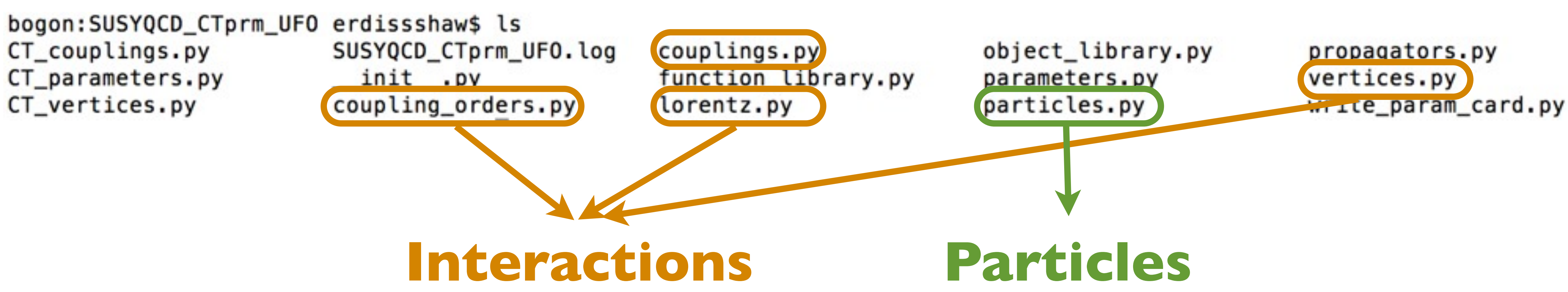
Particles

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD

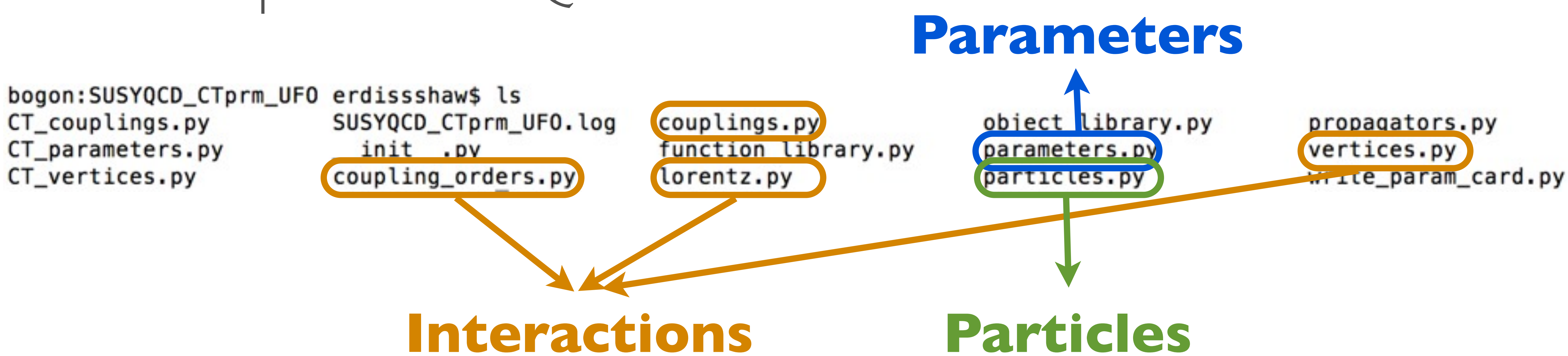


UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD

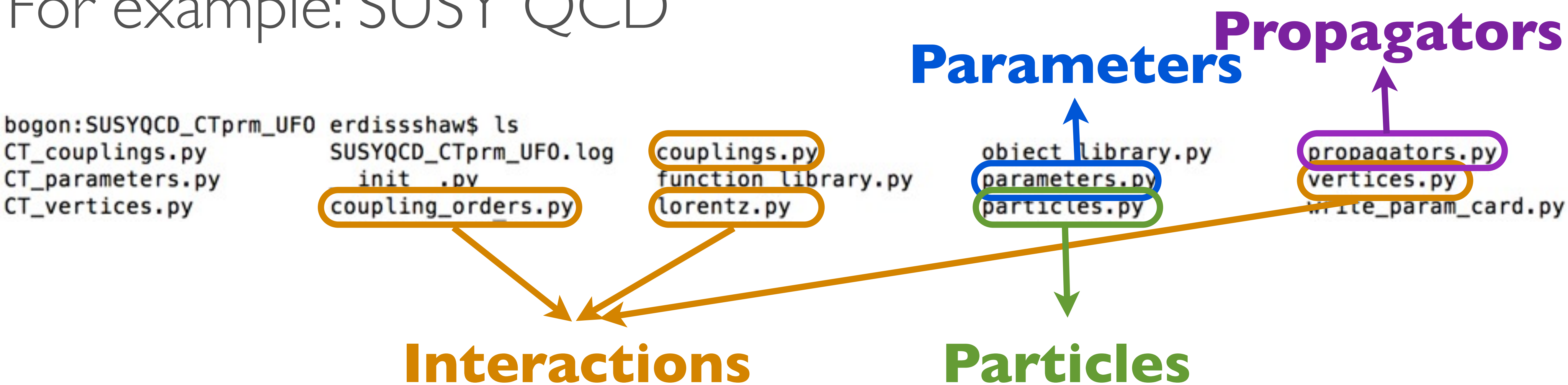


UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD

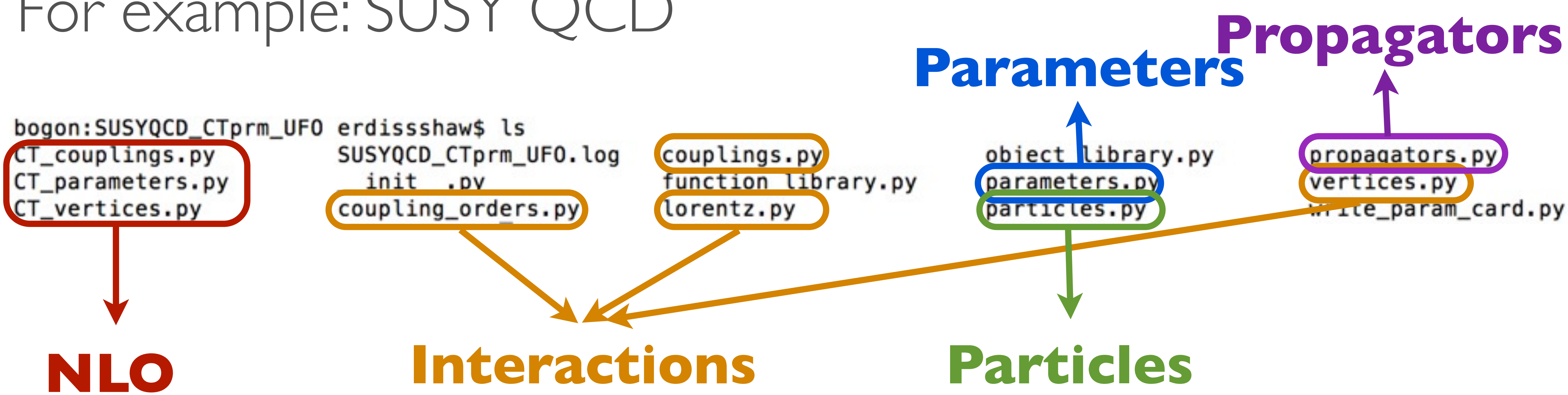


UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- The UFO is a set of PYTHON files
  - Particle information (particles.py)
  - Interaction information (vertices.py, couplings.py, lorentz.py, couplings_orders.py)
  - Parameter information (parameters.py)
  - Propagator information (propagators.py)
  - Tools (function_library.py, object_library.py, write_param_card.py, decays.py)
  - NLO counterterms (CT_couplings.py, CT_parameters.py, CT_vertices.py)

For example: SUSY QCD



Wednesday, November 25, 15

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Particles are in** particles.py
  - Instances of the particle class
  - spin, color, mass, width, PDG etc

```
go = Particle(pdg_code = 1000021,
              name = 'go',
              antiname = 'go',
              spin = 2,
              color = 8,
              mass = Param.Mgo,
              width = Param.Wgo,
              texname = 'go',
              antitexname = 'go',
              charge = 0,
              GhostNumber = 0,
              LeptonNumber = 0,
              Y = 0)
```

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Particles are in** particles.py
  - Instances of the particle class
  - spin, color, mass, width, PDG etc

```
go = Particle(pdg_code = 1000021,
              name = 'go',
              antiname = 'go',
              spin = 2,
              color = 8,
              mass = Param.Mgo,
              width = Param.Wgo,
              texname = 'go',
              antitexname = 'go',
              charge = 0,
              GhostNumber = 0,
              LeptonNumber = 0,
              Y = 0)
```

- **Parameters are in** parameters.py
  - External parameters are in LHA-like
  - Python-compliant formula for int. para

```
aS = Parameter(name = 'aS',
               nature = 'external',
               type = 'real',
               value = 0.1184,
               texname = '\\alpha _s',
               lhablock = 'SMINPUTS',
               lhacode = [ 3 ])

G = Parameter(name = 'G',
              nature = 'internal',
              type = 'real',
              value = '2*cmath.sqrt(aS)*cmath.sqrt(cmath.pi)',
              texname = 'G')
```

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Interactions are in** vertices.py, couplings.py, lorentz.py, coupling_orders,py
  - Vertices are decomposed in a spin x color basis, coupling being coordinates
  - Example: the quartic gluon vertex can be written as

$$
\begin{aligned}
&i g_s^2\, f^{a_1 a_2 b} f^{b a_3 a_4} \left(\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4}\right)\\
&+ i g_s^2\, f^{a_1 a_3 b} f^{b a_2 a_4} \left(\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}\right)\\
&+ i g_s^2\, f^{a_1 a_4 b} f^{b a_2 a_3} \left(\eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}\right)
\end{aligned}
\Rightarrow
\begin{aligned}
&\left(f^{a_1 a_2 b} f^{b a_3 a_4},\ f^{a_1 a_3 b} f^{b a_2 a_4},\ f^{a_1 a_4 b} f^{b a_2 a_3}\right)\\
&\times \begin{pmatrix} i g_s^2 & 0 & 0 \\ 0 & i g_s^2 & 0 \\ 0 & 0 & i g_s^2 \end{pmatrix}
\begin{pmatrix} \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} \\ \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \\ \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \end{pmatrix}
\end{aligned}
$$

- vertices.py: define all Feynman rules for vertices in the model

```
V_37 = Vertex(name = 'V_37',
              particles = [ P.g, P.g, P.g, P.g ],
              color = [ 'f(-1,1,2)*f(3,4,-1)', 'f(-1,1,3)*f(2,4,-1)', 'f(-1,1,4)*f(2,3,-1)' ],
              lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
              couplings = {(1,0):C.GC_20,(0,0):C.GC_20,(2,1):C.GC_20,(0,1):C.GC_19,(2,2):C.GC_19,(1,2):C.GC_19})
```

- lorentz.py: define the Lorentz structure in the model

```
VVVV2 = Lorentz(name = 'VVVV2',
                spins = [ 3, 3, 3, 3 ],
                structure = 'Metric(1,4)*Metric(2,3)')
```

- couplings.py: define the coupling constant in the model

```
GC_20 = Coupling(name = 'GC_20',
                 value = 'complex(0,1)*G**2',
                 order = {'QCD':2})
```

- coupling_orders.py: define the coupling orders in the model

```
QCD = CouplingOrder(name = 'QCD',
                    expansion_order = 99,
                    hierarchy = 1,
                    perturbative_expansion = 1)
```

UFO

Degrande, Duhr, Fuks, Grellscheid, Mattelaer, Reiter (CPC'12)

- **Interactions are in** vertices.py, couplings.py, lorentz.py, coupling_orders,py
  - Vertices are decomposed in a spin x color basis, coupling being coordinates
  - Example: the quartic gluon vertex can be written as

$$\begin{aligned} & ig_s^2\, f^{a_1a_2b} f^{ba_3a_4}\,(\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4}) \\ & + ig_s^2\, f^{a_1a_3b} f^{ba_2a_4}\,(\eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}) \\ & + ig_s^2\, f^{a_1a_4b} f^{ba_2a_3}\,(\eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4}) \end{aligned} \Rightarrow \begin{aligned} & \left(f^{a_1a_2b} f^{ba_3a_4},\ f^{a_1a_3b} f^{ba_2a_4},\ f^{a_1a_4b} f^{ba_2a_3}\right) \\ & \times \begin{pmatrix} ig_s^2 & 0 & 0 \\ 0 & ig_s^2 & 0 \\ 0 & 0 & ig_s^2 \end{pmatrix} \begin{pmatrix} \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} \\ \eta^{\mu_1\mu_4}\eta^{\mu_2\mu_3} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \\ \eta^{\mu_1\mu_3}\eta^{\mu_2\mu_4} - \eta^{\mu_1\mu_2}\eta^{\mu_3\mu_4} \end{pmatrix} \end{aligned}$$

- vertices.py: define all Feynman rules for vertices in the model

```
V_37 = Vertex(name = 'V_37',
              particles = [ P.g, P.g, P.g, P.g ],
              color = [ 'f(-1,1,2)*f(3,4,-1)', 'f(-1,1,3)*f(2,4,-1)', 'f(-1,1,4)*f(2,3,-1)' ],
              lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
              couplings = {(1,0):C.GC_20,(0,0):C.GC_20,(2,1):C.GC_20,(0,1):C.GC_19,(2,2):C.GC_19,(1,2):C.GC_19})
```

- lorentz.py: define the Lorentz structure in the model

```
VVVV2 = Lorentz(name = 'VVVV2',
                spins = [ 3, 3, 3, 3 ],
                structure = 'Metric(1,4)*Metric(2,3)')
```

- couplings.py: define the coupling constant in the model

```
GC_20 = Coupling(name = 'GC_20',
                 value = 'complex(0,1)*G**2',
                 order = {'QCD':2})
```

- coupling_orders.py: define the coupling orders in the model

```
QCD = CouplingOrder(name = 'QCD',
                    expansion_order = 99,
                    hierarchy = 1,
                    perturbative_expansion = 1)
```

Make sure > 0 for NLO QCD

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

```
V_2 = CTVertex(name = 'V_2',
               type = 'R2',
               particles = [ P.g, P.g, P.g, P.g ],
               color = [ 'd(-1,1,3)*d(-1,2,4)', 'd(-1,1,3)*f(-1,2,4)', 'd(-1,1,4)*d(-1,2,3)', 'd(-1,1,4)*f(-1,2,3)', 'd(-1,2,3)*f(-1,1,4)', 'd(-1,2,4)*f(-1,1,3)', 'f(-1,1\
,2)*f(-1,3,4)', 'f(-1,1,3)*f(-1,2,4)', 'f(-1,1,4)*f(-1,2,3)', 'Identity(1,2)*Identity(3,4)', 'Identity(1,3)*Identity(2,4)', 'Identity(1,4)*Identity(2,3)' ],
               lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
               loop_particles = [ [ [P.b], [P.c], [P.d], [P.s], [P.t], [P.u] ], [ [P.g] ], [ [P.go] ] ],
               couplings = {(2,0,0):C.R2GC_101_4,(2,0,1):C.R2GC_100_3,(2,0,2):C.R2GC_100_2,(0,0,0):C.R2GC_101_4,(0,0,1):C.R2GC_100_3,(0,0,2):C.R2GC_100_2,(4,0,0):C.R2GC_9\
9_171,(4,0,1):C.R2GC_99_172,(4,0,2):C.R2GC_99_173,(3,0,0):C.R2GC_99_171,(3,0,1):C.R2GC_99_172,(3,0,2):C.R2GC_99_173,(8,0,0):C.R2GC_100_1,(8,0,1):C.R2GC_100_2,(8,0,2):C.R2\
GC_100_3,(6,0,0):C.R2GC_110_22,(6,0,1):C.R2GC_112_26,(6,0,2):C.R2GC_110_23,(7,0,0):C.R2GC_111_24,(7,0,1):C.R2GC_105_11,(7,0,2):C.R2GC_111_25,(5,0,0):C.R2GC_99_171,(5,0,1)\
:C.R2GC_99_172,(5,0,2):C.R2GC_99_173,(1,0,0):C.R2GC_99_171,(1,0,1):C.R2GC_99_172,(1,0,2):C.R2GC_99_173,(11,0,0):C.R2GC_103_7,(11,0,1):C.R2GC_103_8,(11,0,2):C.R2GC_103_9,(\
10,0,0):C.R2GC_103_7,(10,0,1):C.R2GC_103_8,(10,0,2):C.R2GC_103_9,(9,0,1):C.R2GC_102_5,(9,0,2):C.R2GC_102_6,(2,1,0):C.R2GC_101_4,(2,1,1):C.R2GC_100_3,(2,1,2):C.R2GC_100_2,\
(0,1,0):C.R2GC_101_4,(0,1,1):C.R2GC_100_3,(0,1,2):C.R2GC_100_2,(4,1,0):C.R2GC_99_171,(4,1,1):C.R2GC_99_172,(4,1,2):C.R2GC_99_173,(3,1,0):C.R2GC_99_171,(3,1,1):C.R2GC_99_1\
72,(3,1,2):C.R2GC_99_173,(8,1,0):C.R2GC_100_1,(8,1,1):C.R2GC_105_11,(8,1,2):C.R2GC_100_3,(6,1,0):C.R2GC_115_29,(6,1,1):C.R2GC_115_30,(6,1,2):C.R2GC_115_31,(7,1,0):C.R2GC_\
111_24,(7,1,1):C.R2GC_100_2,(7,1,2):C.R2GC_111_25,(5,1,0):C.R2GC_99_171,(5,1,1):C.R2GC_99_172,(5,1,2):C.R2GC_99_173,(1,1,0):C.R2GC_99_171,(1,1,1):C.R2GC_99_172,(1,1,2):C.\
R2GC_99_173,(11,1,0):C.R2GC_103_7,(11,1,1):C.R2GC_103_8,(11,1,2):C.R2GC_103_9,(10,1,0):C.R2GC_103_7,(10,1,1):C.R2GC_103_8,(10,1,2):C.R2GC_103_9,(9,1,1):C.R2GC_102_5,(9,1,\
2):C.R2GC_102_6,(0,2,0):C.R2GC_101_4,(0,2,1):C.R2GC_100_3,(0,2,2):C.R2GC_100_2,(2,2,0):C.R2GC_101_4,(2,2,1):C.R2GC_100_3,(2,2,2):C.R2GC_100_2,(5,2,0):C.R2GC_99_171,(5,2,1\
):C.R2GC_99_172,(5,2,2):C.R2GC_99_173,(1,2,0):C.R2GC_99_171,(1,2,1):C.R2GC_99_172,(1,2,2):C.R2GC_99_173,(7,2,0):C.R2GC_114_27,(7,2,1):C.R2GC_104_10,(7,2,2):C.R2GC_114_28,\
(4,2,0):C.R2GC_99_171,(4,2,1):C.R2GC_99_172,(4,2,2):C.R2GC_99_173,(3,2,0):C.R2GC_99_171,(3,2,1):C.R2GC_99_172,(3,2,2):C.R2GC_99_173,(8,2,0):C.R2GC_100_1,(8,2,1):C.R2GC_10\
4_10,(8,2,2):C.R2GC_100_3,(6,2,0):C.R2GC_110_22,(6,2,2):C.R2GC_110_23,(11,2,0):C.R2GC_103_7,(11,2,1):C.R2GC_103_8,(11,2,2):C.R2GC_103_9,(10,2,0):C.R2GC_103_7,(10,2,1):C.R\
2GC_103_8,(10,2,2):C.R2GC_103_9,(9,2,1):C.R2GC_102_5,(9,2,2):C.R2GC_102_6})
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

```
V_351 = CTVertex(name = 'V_351',
                 type = 'UV',
                 particles = [ P.g, P.g, P.g, P.g ],
                 color = [ 'd(-1,1,3)*d(-1,2,4)', 'd(-1,1,3)*f(-1,2,4)', 'd(-1,1,4)*d(-1,2,3)', 'd(-1,1,4)*f(-1,2,3)', 'd(-1,2,3)*f(-1,1,4)', 'd(-1,2,4)*f(-1,1,3)', 'f(-1,1,2)*f(-1,3,4)', 'f(-1,1,3)*f\
(-1,2,4)', 'f(-1,1,4)*f(-1,2,3)', 'Identity(1,2)*Identity(3,4)', 'Identity(1,3)*Identity(2,4)', 'Identity(1,4)*Identity(2,3)' ],
                 lorentz = [ L.VVVV2, L.VVVV3, L.VVVV4 ],
                 loop_particles = [ [ [P.b] ], [ [P.b], [P.c], [P.d], [P.s], [P.sbL], [P.sbR], [P.scL], [P.scR], [P.sdL], [P.sdR], [P.ssL], [P.ssR], [P.stL], [P.stR], [P.suL], [P.suR], [P.t], [P.u] ],\
 [ [P.b], [P.c], [P.d], [P.s], [P.t], [P.u] ], [ [P.c] ], [ [P.d] ], [ [P.g] ], [ [P.ghG] ], [ [P.go] ], [ [P.s] ], [ [P.sbL] ], [ [P.sbL], [P.sbR], [P.scL], [P.scR], [P.sdL], [P.sdR], [P.ssL], [P.ssR\
], [P.stL], [P.stR], [P.suL], [P.suR] ], [ [P.sbR] ], [ [P.scL] ], [ [P.scR] ], [ [P.sdL] ], [ [P.sdR] ], [ [P.ssL] ], [ [P.ssR] ], [ [P.stL] ], [ [P.stR] ], [ [P.suL] ], [ [P.suR] ], [ [P.t] ], [ [P.\
u] ] ],
                 couplings = {(2,0,5):C.UVGC_100_2,(2,0,6):C.UVGC_100_1,(0,0,5):C.UVGC_100_2,(0,0,6):C.UVGC_100_1,(4,0,5):C.UVGC_99_1085,(4,0,6):C.UVGC_99_1086,(3,0,5):C.UVGC_99_1085,(3,0,6):C.UVGC_99\
_1086,(8,0,5):C.UVGC_100_1,(8,0,6):C.UVGC_100_2,(6,0,0):C.UVGC_112_137,(6,0,3):C.UVGC_112_138,(6,0,4):C.UVGC_112_139,(6,0,5):C.UVGC_112_140,(6,0,6):C.UVGC_112_141,(6,0,7):C.UVGC_112_142,(6,0,8):C.UVGC\
_112_143,(6,0,9):C.UVGC_112_144,(6,0,11):C.UVGC_112_145,(6,0,12):C.UVGC_112_146,(6,0,13):C.UVGC_112_147,(6,0,14):C.UVGC_112_148,(6,0,15):C.UVGC_112_149,(6,0,16):C.UVGC_112_150,(6,0,17):C.UVGC_112_151,\
(6,0,18):C.UVGC_112_152,(6,0,19):C.UVGC_112_153,(6,0,20):C.UVGC_112_154,(6,0,21):C.UVGC_112_155,(6,0,22):C.UVGC_112_156,(6,0,23):C.UVGC_112_157,(7,0,0):C.UVGC_112_137,(7,0,3):C.UVGC_112_138,(7,0,4):C.\
UVGC_112_139,(7,0,5):C.UVGC_105_31,(7,0,6):C.UVGC_113_158,(7,0,7):C.UVGC_112_142,(7,0,8):C.UVGC_112_143,(7,0,9):C.UVGC_112_144,(7,0,11):C.UVGC_112_145,(7,0,12):C.UVGC_112_146,(7,0,13):C.UVGC_112_147,(\
7,0,14):C.UVGC_112_148,(7,0,15):C.UVGC_112_149,(7,0,16):C.UVGC_112_150,(7,0,17):C.UVGC_112_151,(7,0,18):C.UVGC_112_152,(7,0,19):C.UVGC_112_153,(7,0,20):C.UVGC_112_154,(7,0,21):C.UVGC_112_155,(7,0,22):\
C.UVGC_112_156,(7,0,23):C.UVGC_112_157,(5,0,5):C.UVGC_99_1085,(5,0,6):C.UVGC_99_1086,(1,0,5):C.UVGC_99_1085,(1,0,6):C.UVGC_99_1086,(11,0,5):C.UVGC_103_5,(11,0,6):C.UVGC_103_6,(10,0,5):C.UVGC_103_5,(10\
,0,6):C.UVGC_103_6,(9,0,5):C.UVGC_102_3,(9,0,6):C.UVGC_102_4,(2,1,5):C.UVGC_100_2,(2,1,6):C.UVGC_100_1,(0,1,5):C.UVGC_100_2,(0,1,6):C.UVGC_100_1,(4,1,5):C.UVGC_99_1085,(4,1,6):C.UVGC_99_1086,(3,1,5):C\
.UVGC_99_1085,(3,1,6):C.UVGC_99_1086,(8,1,0):C.UVGC_105_28,(8,1,3):C.UVGC_105_29,(8,1,4):C.UVGC_105_30,(8,1,5):C.UVGC_105_31,(8,1,6):C.UVGC_105_32,(8,1,7):C.UVGC_105_33,(8,1,8):C.UVGC_105_34,(8,1,9):C\
.UVGC_105_35,(8,1,11):C.UVGC_105_36,(8,1,12):C.UVGC_105_37,(8,1,13):C.UVGC_105_38,(8,1,14):C.UVGC_105_39,(8,1,15):C.UVGC_105_40,(8,1,16):C.UVGC_105_41,(8,1,17):C.UVGC_105_42,(8,1,18):C.UVGC_105_43,(8,\
1,19):C.UVGC_105_44,(8,1,20):C.UVGC_105_45,(8,1,21):C.UVGC_105_46,(8,1,22):C.UVGC_105_47,(8,1,23):C.UVGC_105_48,(6,1,0):C.UVGC_114_159,(6,1,3):C.UVGC_114_160,(6,1,4):C.UVGC_114_161,(6,1,5):C.UVGC_115_\
179,(6,1,6):C.UVGC_115_180,(6,1,7):C.UVGC_114_163,(6,1,8):C.UVGC_114_164,(6,1,9):C.UVGC_115_181,(6,1,11):C.UVGC_115_182,(6,1,12):C.UVGC_115_183,(6,1,13):C.UVGC_115_184,(6,1,14):C.UVGC_115_185,(6,1,15)\
:C.UVGC_115_186,(6,1,16):C.UVGC_115_187,(6,1,17):C.UVGC_115_188,(6,1,18):C.UVGC_115_189,(6,1,19):C.UVGC_115_190,(6,1,20):C.UVGC_115_191,(6,1,21):C.UVGC_115_192,(6,1,22):C.UVGC_114_177,(6,1,23):C.UVGC_\
114_178,(7,1,1):C.UVGC_110_133,(7,1,5):C.UVGC_100_1,(7,1,6):C.UVGC_111_136,(7,1,7):C.UVGC_110_134,(5,1,5):C.UVGC_99_1085,(5,1,6):C.UVGC_99_1086,(1,1,5):C.UVGC_99_1085,(1,1,6):C.UVGC_99_1086,(11,1,5):C\
.UVGC_103_5,(11,1,6):C.UVGC_103_6,(10,1,5):C.UVGC_103_5,(10,1,6):C.UVGC_103_6,(9,1,5):C.UVGC_102_3,(9,1,6):C.UVGC_102_4,(0,2,5):C.UVGC_100_2,(0,2,6):C.UVGC_100_1,(2,2,5):C.UVGC_100_2,(2,2,6):C.UVGC_10\
0_1,(5,2,5):C.UVGC_99_1085,(5,2,6):C.UVGC_99_1086,(1,2,5):C.UVGC_99_1085,(1,2,6):C.UVGC_99_1086,(7,2,0):C.UVGC_114_159,(7,2,3):C.UVGC_114_160,(7,2,4):C.UVGC_114_161,(7,2,5):C.UVGC_104_10,(7,2,6):C.UVG\
C_114_162,(7,2,7):C.UVGC_114_163,(7,2,8):C.UVGC_114_164,(7,2,9):C.UVGC_114_165,(7,2,11):C.UVGC_114_166,(7,2,12):C.UVGC_114_167,(7,2,13):C.UVGC_114_168,(7,2,14):C.UVGC_114_169,(7,2,15):C.UVGC_114_170,(\
7,2,16):C.UVGC_114_171,(7,2,17):C.UVGC_114_172,(7,2,18):C.UVGC_114_173,(7,2,19):C.UVGC_114_174,(7,2,20):C.UVGC_114_175,(7,2,21):C.UVGC_114_176,(7,2,22):C.UVGC_114_177,(7,2,23):C.UVGC_114_178,(4,2,5):C\
.UVGC_99_1085,(4,2,6):C.UVGC_99_1086,(3,2,5):C.UVGC_99_1085,(3,2,6):C.UVGC_99_1086,(8,2,0):C.UVGC_104_7,(8,2,3):C.UVGC_104_8,(8,2,4):C.UVGC_104_9,(8,2,5):C.UVGC_104_10,(8,2,6):C.UVGC_104_11,(8,2,7):C.\
UVGC_104_12,(8,2,8):C.UVGC_104_13,(8,2,9):C.UVGC_104_14,(8,2,11):C.UVGC_104_15,(8,2,12):C.UVGC_104_16,(8,2,13):C.UVGC_104_17,(8,2,14):C.UVGC_104_18,(8,2,15):C.UVGC_104_19,(8,2,16):C.UVGC_104_20,(8,2,1\
7):C.UVGC_104_21,(8,2,18):C.UVGC_104_22,(8,2,19):C.UVGC_104_23,(8,2,20):C.UVGC_104_24,(8,2,21):C.UVGC_104_25,(8,2,22):C.UVGC_104_26,(8,2,23):C.UVGC_104_27,(6,2,2):C.UVGC_110_133,(6,2,6):C.UVGC_102_3,(\
6,2,7):C.UVGC_110_134,(6,2,10):C.UVGC_110_135,(11,2,5):C.UVGC_103_5,(11,2,6):C.UVGC_103_6,(10,2,5):C.UVGC_103_5,(10,2,6):C.UVGC_103_6,(9,2,5):C.UVGC_102_3,(9,2,6):C.UVGC_102_4})
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices
- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2

```
FRCTdeltaZxttLxtG = CTParameter(name = 'FRCTdeltaZxttLxtG',
                                type = 'complex',
                                value = {-1:'-G**2/(6.*cmath.pi**2)',0:'-G**2/(3.*cmath.pi**2) + (G**2*reglog(MT/MU_R))/(2.*cmath.pi**2)'},
                                texname = 'FRCTdeltaZxttLxtG')
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2

```
FRCTdeltaZxttLxtG = CTParameter(name = 'FRCTdeltaZxttLxtG',
                                type = 'complex',
                                value = {-1:'-G**2/(6.*cmath.pi**2)',0:'-G**2/(3.*cmath.pi**2) + (G**2*reglog(MT/MU_R))/(2.*cmath.pi**2)'},
                                texname = 'FRCTdeltaZxttLxtG')
```

coefficient of $\frac{1}{\epsilon}$

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

CERN

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py: UV, R2 counter term vertices
- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2

```
FRCTdeltaZxttLxtG = CTParameter(name = 'FRCTdeltaZxttLxtG',
                                type = 'complex',
                                value = {-1:'-G**2/(6.*cmath.pi**2)',0:'-G**2/(3.*cmath.pi**2) + (G**2*reglog(MT/MU_R))/(2.*cmath.pi**2)'},
                                texname = 'FRCTdeltaZxttLxtG')
```

coefficient of $\frac{1}{\epsilon}$ finite piece

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2

```
FRCTdeltaZxttLxgostL = CTParameter(name = 'FRCTdeltaZxttLxgostL',
                                   type = 'complex',
                                   value = {0:'( 0 if 2*Mgo*MstL + MT**2>=Mgo**2 + MstL**2 and MT**2<=(Mgo + MstL)**2 else ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT else \
(G**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/(12.*cmath.pi**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4\
 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) + (G**2*Mgo**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2\
))/MU_R**2))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) - (G**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**\
2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 \
- MT**2/MU_R**2)**2)) - (G**2*Mgo**4*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12.*cm\
ath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) + (G**2*Mgo**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + \
MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(6.*cmath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R*\
*2 - MT**2/MU_R**2)**2)) - (G**2*MstL**4*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12\
.*cmath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) - (G**2*Mgo**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**\
2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 \
- MT**2/MU_R**2)**2)) + (G**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12.*c\
math.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) ) ) ) ) + ( ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT el\
se (G**2*Mgo*MstL*re((-(MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*\
Mgo*MstL) - (MU_R**2*(-(Mgo**2/MU_R**2) - MstL**2/MU_R**2 + MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL\
))*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL))))/\
(12.*cmath.pi**2*MT**2) ) ) ) if 2*Mgo*MstL + MT**2>=Mgo**2 + MstL**2 and MT**2<(Mgo + MstL)**2 else 0 ) + ( ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT else (MU_R**2*G**2*\
Mgo**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/MU_R**2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R\
**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL) + (MstL**4/MU_R**4 + (Mgo**2*(Mgo**2/MU_\
R**2 - MT**2/MU_R**2))/MU_R**2 - (MstL**2*((2*Mgo**2)/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2\
)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL)))/cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(12\
.*cmath.pi**2*MT**4) - (MU_R**2*G**2*MstL**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/MU_R*\
*2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL) + \
(MstL**4/MU_R**4 + (Mgo**2*(Mgo**2/MU_R**2 - MT**2/MU_R**2))/MU_R**2 - (MstL**2*((2*Mgo**2)/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/M\
U_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL)))/cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL\
**2/MU_R**2 - MT**2/MU_R**2)**2)))/(12.*cmath.pi**2*MT**4) + (MU_R**2*G**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + M\
T**2/MU_R**2))/MU_R**2))/MU_R**2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2)\
```

UFO@NLO

Degrande, Duhr, Fuks, Grellscheid, Hirschi, Mattelaer, Reiter, HSS ... (in preparation)

- Provide renormalization scale in parameters.py

```
MU_R = Parameter(name = 'MU_R',
                 nature = 'external',
                 type = 'real',
                 value = 91.188,
                 texname = '\\text{\\mu_r}',
                 lhablock = 'LOOP',
                 lhacode = [1])
```

- CT_vertices.py:UV, R2 counter term vertices

- CT_couplings.py: couplings for UV and R2 counter terms

```
UVGC_104_23 = Coupling(name = 'UVGC_104_23',
                       value = '-((FRCTdeltaxaSxstR*complex(0,1)*G**2)/aS) - 2*FRCTdeltaZxGGxstR*complex(0,1)*G**2 + (complex(0,1)*G**4*invFREps)/(32.*cmath.pi**2)',
                       order = {'QCD':4})
```

- CT_parameters.py: parameters for UV and R2

```
FRCTdel FRCTdeltaZxttLxgostL = CTParameter(name = 'FRCTdeltaZxttLxgostL',
                       type = 'complex',
                       value = {0:'( 0 if 2*Mgo*MstL + MT**2>=Mgo**2 + MstL**2 and MT**2<=(Mgo + MstL)**2 else ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT else \
(G**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/(12.*cmath.pi**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4\ *2)'},
 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) + (G**2*Mgo**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2\
))/MU_R**2))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) - (G**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**\
2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2))/(12.*cmath.pi**2*MT**2*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 \
- MT**2/MU_R**2)**2)) - (G**2*Mgo**4*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12.*cm\
ath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) + (G**2*Mgo**2*MstL**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + \
MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(6.*cmath.pi**2*MT**4*cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R\
**2 - MT**2/MU_R**2)**2)) - (G**2*MstL**4*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL))/(12\
.*cmath.pi**2[illegible]cmath.sqrt((-4*Mgo**2[illegible]**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)) - [illegible] + MT**\
2/MU_R**2)**2 [illegible] MU_R**2 \
- MT**2/MU_R[illegible]/(12.*c\
math.pi**2*MT**2*cmath.sqrt((-4*Mgo[illegible]MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R[illegible] ( 0 if Mgo==MstL else ( 0 if Mgo==MT else ( 0 if MstL==MT el\
se (G**2*Mgo*MstL*re((-(MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*\
Mgo*MstL) - (MU_R**2*(-(Mgo**2/MU_R[illegible]stL**2/MU_R**2 + MT**2/MU_R**2 + cmath.sqrt([illegible]**2)/MU_R**4 + [illegible]o**2/MU_R**2 + [illegible]**2/MU_R**2)**2)))/(2.*Mgo*MstL\
))*reglog((MU_R**2*(Mgo**2/MU_R**2 [illegible]R**2)**2)))/(2.*Mgo*MstL))))/\
(12.*cmath.pi**2*MT**2) ) ) ) if 2*M[illegible] if MstL==MT else (MU_R**2*G**2*\
Mgo**2*re(((MT**2*cmath.sqrt(MstL**4/[illegible]Mgo**2/MU_R**2) + MstL**2/MU_R\
**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL)) + (MstL**4/MU_R**4 + (Mgo**2*(Mgo**2/MU_\
R**2 - MT**2/MU_R**2))/MU_R**2 - (MstL**2*((2*Mgo**2)/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2\
)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL)))/cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(12\
.*cmath.pi**2*MT**4) - (MU_R**2*G**2*MstL**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)))/MU_R\
**2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog(Mgo/MstL) + \
(MstL**4/MU_R**4 + (Mgo**2*(Mgo**2/MU_R**2 - MT**2/MU_R**2))/MU_R**2 - (MstL**2*((2*Mgo**2)/MU_R**2 + MT**2/MU_R**2))/MU_R**2)*reglog((MU_R**2*(Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/M\
U_R**2 + cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL**2/MU_R**2 - MT**2/MU_R**2)**2)))/(2.*Mgo*MstL)))/cmath.sqrt((-4*Mgo**2*MstL**2)/MU_R**4 + (Mgo**2/MU_R**2 + MstL\
**2/MU_R**2 - MT**2/MU_R**2)**2)))/(12.*cmath.pi**2*MT**4) + (MU_R**2*G**2*re(((MT**2*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + M\
T**2/MU_R**2))/MU_R**2))/MU_R**2 + (-(Mgo**2/MU_R**2) + MstL**2/MU_R**2)*cmath.sqrt(MstL**4/MU_R**4 + (-(Mgo**2/MU_R**2) + MT**2/MU_R**2)**2 - (2*MstL**2*(Mgo**2/MU_R**2 + MT**2/MU_R**2)\
```

Complicated mass spectrum makes the computation heavy !!!

CERN

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	-	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model stop_ ttmet_ufo
5. > generate p p > sig3 sig3~ [QCD]
6. > output pp2t1t1QCD
7. > launch

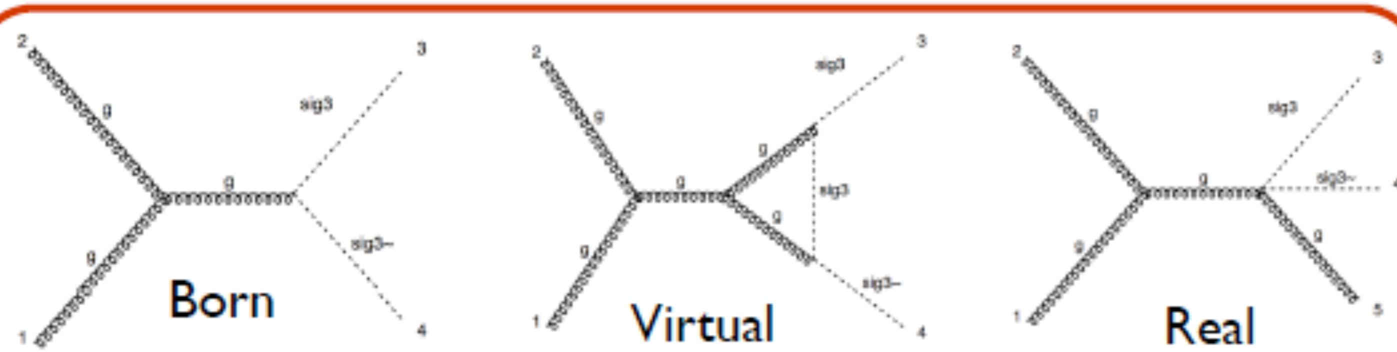
✦ The stop (σ_3) / bino (χ) model

$$\mathcal{L}_3 = D_\mu \sigma_3^\dagger D^\mu \sigma_3 - m_3^2 \sigma_3^\dagger \sigma_3 + \frac{i}{2}\bar{\chi}\partial\!\!\!/ \chi - \frac{1}{2} m_\chi \bar{\chi}\chi + \left[\sigma_3 \bar{t}(\tilde{g}_L P_L + \tilde{g}_R P_R)\chi + \text{h.c.}\right]$$

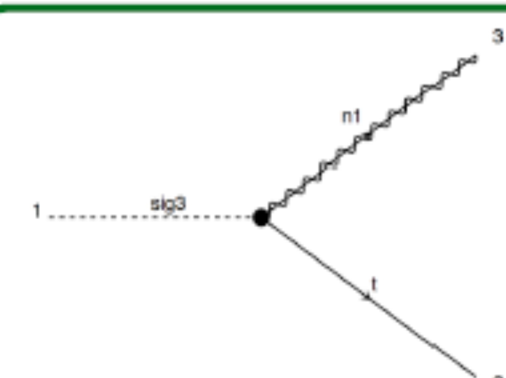
Production — Decay

- ✤ One scalar field in the fundamental representation (σ_3)
- ✤ One gauge-singlet Majorana fermion (χ) coupling the stop to the top

✦ Representative Feynman diagrams (yielding a top-antitop plus missing energy signature)



Production



Decay

Wednesday, November 25, 15

APPLICATION 1: A STOP SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

Analytical validation

✤ Analytical checks are important (the fully automated approach is new)

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{96\pi^2}\left[\frac{1}{\bar\epsilon} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$\delta Z_{\sigma_3} = 0 \quad \text{and} \quad \delta m_3^2 = -\frac{g_s^2 m_3^2}{12\pi^2}\left[\frac{3}{\bar\epsilon} + 7 - 3\log\frac{m_3^2}{\mu_R^2}\right]$$

$$\frac{\delta\alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar\epsilon}\left[\frac{n_f}{3} - \frac{11}{2}\right] + \frac{\alpha_s}{6\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_t^2}{\mu_R^2}\right] + \frac{\alpha_s}{24\pi}\left[\frac{1}{\bar\epsilon} - \log\frac{m_3^2}{\mu_R^2}\right]$$

$$R_2^{\sigma_3^\dagger\sigma_3} = \frac{ig_s^2}{72\pi^2}\delta_{c_1c_2}\left[3m_3^2 - p^2\right]$$

$$R_2^{g\sigma_3^\dagger\sigma_3} = \frac{53ig_s^3}{576\pi^2}T^{a_1}_{c_2c_3}(p_2 - p_3)^{\mu_1}$$

$$R_2^{gg\sigma_3^\dagger\sigma_3} = \frac{ig_s^4}{1152\pi^2}\eta^{\mu_1\mu_2}\left[3\delta^{a_1a_2} - 187\{T^{a_1}, T^{a_2}\}\right]_{c_3c_4}$$

✦ Total rates at 8 TeV and 13 TeV

Numerical validation

m_3 [GeV]	$\sigma^{\rm LO}$ [pb] (8 TeV)	$\sigma^{\rm NLO}$ [pb] (8 TeV)	$\sigma^{\rm LO}$ [pb] (13 TeV)	$\sigma^{\rm NLO}$ [pb] (13 TeV)
100	$3.893 \pm 0.0095 \cdot 10^{2}\ ^{+34.2\%}_{-23.9\%}$	$5.548 \pm 0.018 \cdot 10^{2}\ ^{+14.9\%}_{-13.5\%}\ ^{+1.6\%}_{-1.6\%}$	$1.066 \pm 0.0025 \cdot 10^{3}\ ^{+29.1\%}_{-21.4\%}$	$1.497 \pm 0.0054 \cdot 10^{3}\ ^{+14.1\%}_{-12.1\%}\ ^{+1.2\%}_{-1.2\%}$
250	$4.118 \pm 0.0096 \cdot 10^{0}\ ^{+40.4\%}_{-27.2\%}$	$5.503 \pm 0.017 \cdot 10^{0}\ ^{+13.1\%}_{-13.7\%}\ ^{+3.7\%}_{-3.7\%}$	$1.553 \pm 0.0037 \cdot 10^{1}\ ^{+35.2\%}_{-24.8\%}$	$2.156 \pm 0.0067 \cdot 10^{1}\ ^{+12.1\%}_{-12.3\%}\ ^{+2.4\%}_{-2.4\%}$
500	$6.594 \pm 0.016 \cdot 10^{-2}\ ^{+45.5\%}_{-29.1\%}$	$7.764 \pm 0.025 \cdot 10^{-2}\ ^{+12.1\%}_{-14.1\%}\ ^{+6.7\%}_{-6.7\%}$	$3.890 \pm 0.0093 \cdot 10^{-1}\ ^{+39.6\%}_{-26.4\%}$	$5.062 \pm 0.015 \cdot 10^{-1}\ ^{+11.2\%}_{-12.8\%}\ ^{+4.4\%}_{-4.4\%}$
750	$3.504 \pm 0.0084 \cdot 10^{-3}\ ^{+48.8\%}_{-30.5\%}$	$3.699 \pm 0.012 \cdot 10^{-3}\ ^{+12.3\%}_{-14.6\%}\ ^{+10.2\%}_{-10.2\%}$	$3.306 \pm 0.0081 \cdot 10^{-2}\ ^{+41.8\%}_{-27.5\%}$	$4.001 \pm 0.012 \cdot 10^{-2}\ ^{+10.8\%}_{-12.9\%}\ ^{+6.1\%}_{-6.1\%}$
1000	$2.875 \pm 0.0067 \cdot 10^{-4}\ ^{+51.5\%}_{-31.5\%}$	$2.775 \pm 0.0087 \cdot 10^{-4}\ ^{+13.1\%}_{-15.2\%}\ ^{+15.5\%}_{-15.5\%}$	$4.614 \pm 0.011 \cdot 10^{-3}\ ^{+43.6\%}_{-28.3\%}$	$5.219 \pm 0.016 \cdot 10^{-3}\ ^{+10.9\%}_{-13.2\%}\ ^{+7.9\%}_{-7.9\%}$

8 TeV　　13 TeV

✤ NNPDF2.3; scales set to the stop mass

✤ Agrees with PROSPINO [Beenakker, Kramer, Plehn, Spira & Zerwas (NPB'98)]

✤ Scale varied by a factor of two up and down

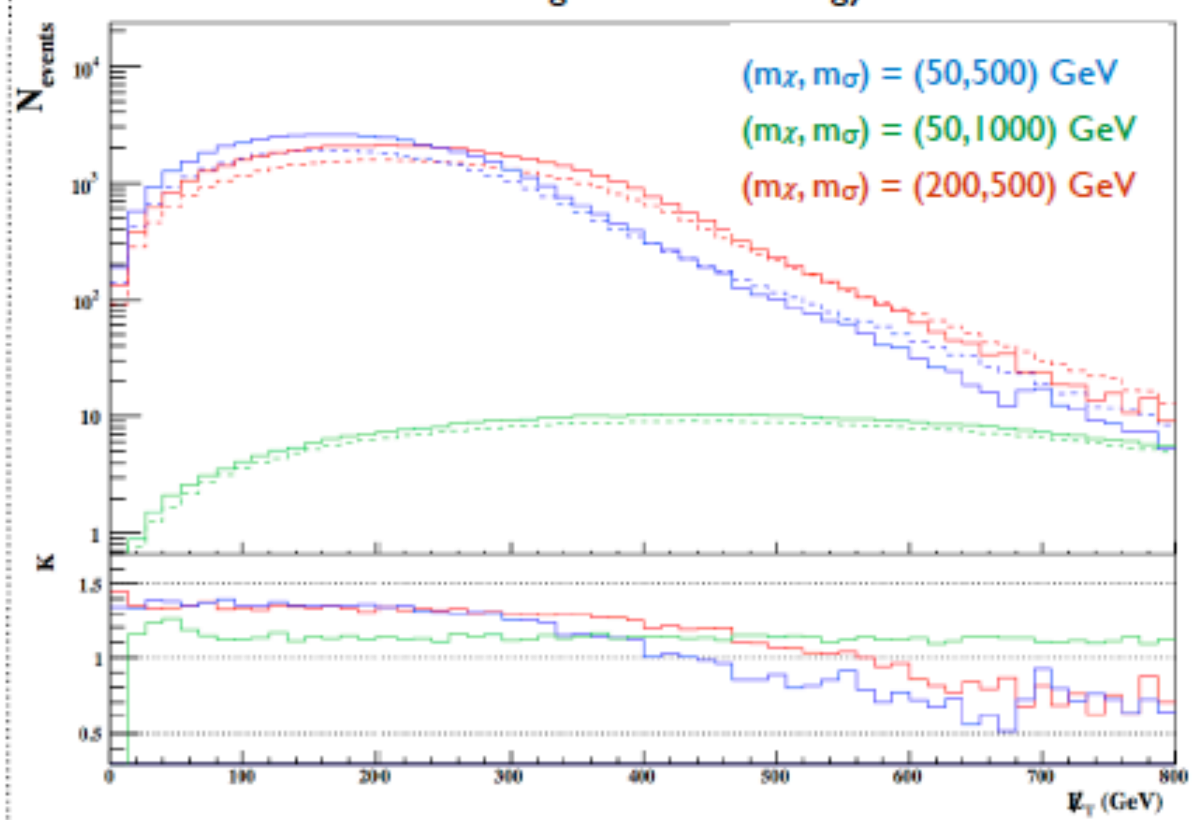
✤ PDF variations obtained with the 100 NNPDF replica provided with the central set of densities

APPLICATION 1: A STOP SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

- NLO matrix elements matched to parton showering: differential distributions
  - Test case: 500/1000 GeV stop; 50/200 GeV bino; 13 TeV collisions
  - Standard coupling strengths for a maximally mixing stop and a bino
  - Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands (CPC'08)]
  - Jet reconstruction: anti-k_T & FASTJET [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]
  - Analysis (single lepton case) & figures: MADANALYSIS 5 [Conte, BF, Serret (CPC'13)]

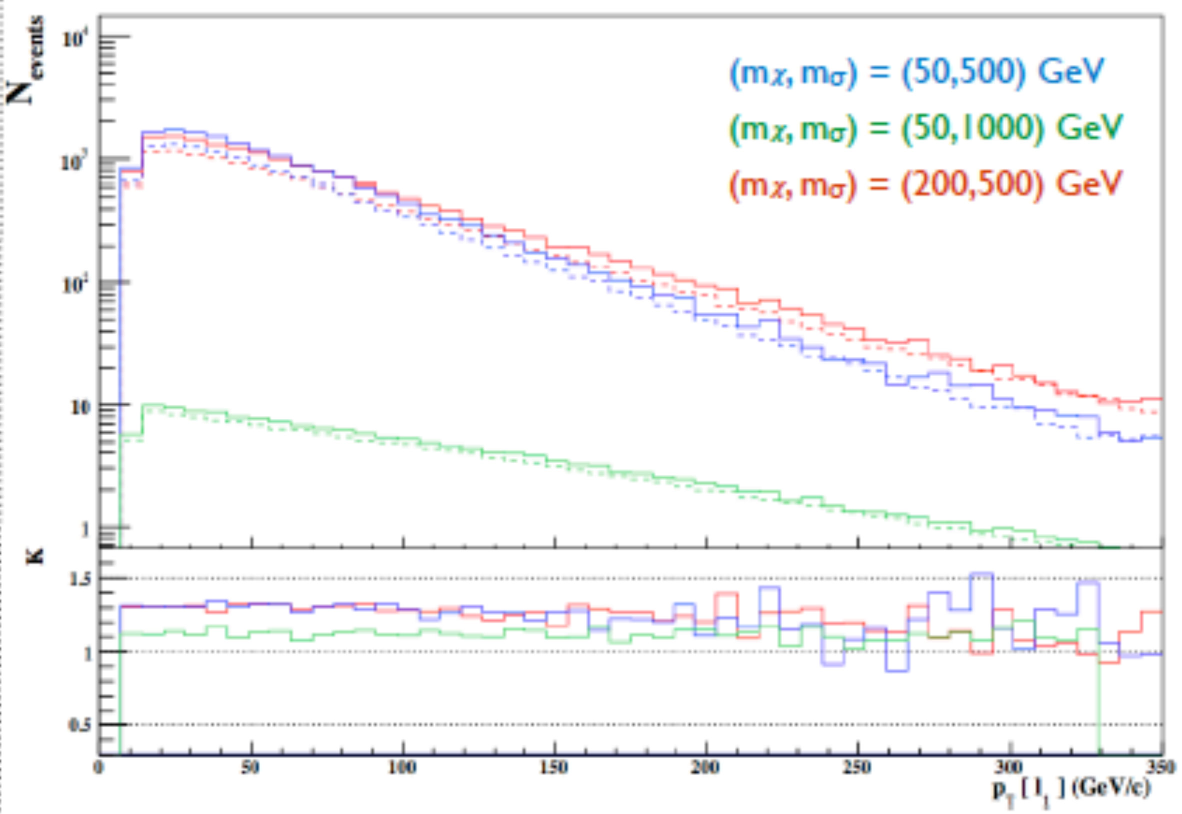
Missing transverse energy



★ Constant *K*-factors not suitable

★ The K-factor depends on the scenario

Leading lepton transverse momentum (single lepton signature)



★ Constant *K*-factors okayish

★ The K-factor depends on the scenario

APPLICATION 2: A SGLUON SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	-	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model sgluon_ ufo
5. > generate p p > sig8 sig8~ [QCD]
6. > output pp2sig8sig8QCD
7. > launch

✦ The sgluon (σ_8) model

$$\mathcal{L}_8 = \frac{1}{2}D_\mu\sigma_8 D^\mu\sigma_8 - \frac{1}{2}m_8^2\sigma_8\sigma_8 + \frac{\hat{g}_g}{\Lambda}\sigma_8 G_{\mu\nu}G^{\mu\nu} + \sum_{q=u,d}\left[\sigma_8\bar{q}(\hat{g}_q^L P_L + \hat{g}_q^R P_R)q + \text{h.c.}\right]$$

Production — Decay

- ✤ One scalar field in the adjoint representation (σ_8)
- ✤ Effective couplings (g): only for the decay that is enforced to be at the leading order
- ✤ g couplings at NLO: a consistent effective theory is required for a proper renormalization

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

- ✤ Analytical checks

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{32\pi^2}\left[\frac{1}{\bar{\epsilon}} - \log\frac{m_8^2}{\mu_R^2}\right] ,$$

$$\delta Z_{\sigma_8} = 0 \quad \text{and} \quad \delta m_8^2 = -\frac{3g_s^2 m_8^2}{16\pi^2}\left[\frac{3}{\bar{\epsilon}} + 7 - 3\log\frac{m_8^2}{\mu_R^2}\right]$$

$$\frac{\delta\alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar{\epsilon}}\left[\frac{n_f}{3} - \frac{11}{2}\right] + \frac{\alpha_s}{6\pi}\left[\frac{1}{\bar{\epsilon}} - \log\frac{m_t^2}{\mu_R^2}\right] + \frac{\alpha_s}{8\pi}\left[\frac{1}{\bar{\epsilon}} - \log\frac{m_8^2}{\mu_R^2}\right]$$

$$R_2^{\sigma_8\sigma_8} = \frac{ig_s^2}{32\pi^2}\delta_{a_1a_2}\left[3m_8^2 - p^2\right] ,$$

$$R_2^{g\sigma_8\sigma_8} = \frac{7g_s^3}{64\pi^2}f_{a_1a_2a_3}(p_2 - p_3)^{\mu_1} ,$$

$$R_2^{gg\sigma_8\sigma_8} = \frac{ig_s^4}{384\pi^2}\eta^{\mu_1\mu_2}\Big[72(d_{a_1a_4e}d_{a_2a_3e} + d_{a_1a_3e}d_{a_2a_4e}) - 141 d_{a_1a_2e}d_{a_3a_4e} - 92\delta_{a_1a_2}\delta_{a_3a_4} + 50(\delta_{a_1a_3}\delta_{a_2a_4} + \delta_{a_1a_4}\delta_{a_2a_3})\Big] ,$$

APPLICATION 2: A SGLUON SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	-	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model sgluon_ ufo
5. > generate p p > sig8 sig8~ [QCD]
6. > output pp2sig8sig8QCD
7. > launch

Non-renormalizable operator

✦ The sgluon (σ_8) model

$$\mathcal{L}_8 = \frac{1}{2} D_\mu \sigma_8 D^\mu \sigma_8 - \frac{1}{2} m_8^2 \sigma_8 \sigma_8 + \frac{\hat{g}_g}{\Lambda} \sigma_8 G_{\mu\nu} G^{\mu\nu} + \sum_{q=u,d} \left[\sigma_8 \bar{q} (\hat{g}_q^L P_L + \hat{g}_q^R P_R) q + \text{h.c.} \right]$$

Production — Decay

- One scalar field in the adjoint representation (σ_8)
- Effective couplings (g): only for the decay that is enforced to be at the leading order
- g couplings at NLO: a consistent effective theory is required for a proper renormalization

✦ UV behavior (on-shell scheme, zero-momentum subtraction for α_s)

- Analytical checks

$$\delta Z_g = \delta Z_g^{(SM)} - \frac{g_s^2}{32\pi^2} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_8^2}{\mu_R^2} \right] ,$$

$$\delta Z_{\sigma_8} = 0 \quad \text{and} \quad \delta m_8^2 = - \frac{3 g_s^2 m_8^2}{16\pi^2} \left[\frac{3}{\bar{\epsilon}} + 7 - 3 \log \frac{m_8^2}{\mu_R^2} \right]$$

$$\frac{\delta \alpha_s}{\alpha_s} = \frac{\alpha_s}{2\pi\bar{\epsilon}} \left[\frac{n_f}{3} - \frac{11}{2} \right] + \frac{\alpha_s}{6\pi} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_t^2}{\mu_R^2} \right] + \frac{\alpha_s}{8\pi} \left[\frac{1}{\bar{\epsilon}} - \log \frac{m_8^2}{\mu_R^2} \right]$$

$$R_2^{\sigma_8 \sigma_8} = \frac{i g_s^2}{32\pi^2} \delta_{a_1 a_2} \left[3 m_8^2 - p^2 \right] ,$$

$$R_2^{g \sigma_8 \sigma_8} = \frac{7 g_s^3}{64\pi^2} f_{a_1 a_2 a_3} (p_2 - p_3)^{\mu_1} ,$$

$$R_2^{g g \sigma_8 \sigma_8} = \frac{i g_s^4}{384\pi^2} \eta^{\mu_1 \mu_2} \Big[72 (d_{a_1 a_4 e} d_{a_2 a_3 e} + d_{a_1 a_3 e} d_{a_2 a_4 e}) - 141 d_{a_1 a_2 e} d_{a_3 a_4 e} - 92 \delta_{a_1 a_2} \delta_{a_3 a_4} + 50 (\delta_{a_1 a_3} \delta_{a_2 a_4} + \delta_{a_1 a_4} \delta_{a_2 a_3}) \Big] ,$$

APPLICATION 2: A SGLUON SIMPLIFIED MODEL

Degrande, Fuks, Hirschi, Proudom, HSS (PRD'15)

✦ Total rates at 8 TeV and 13 TeV

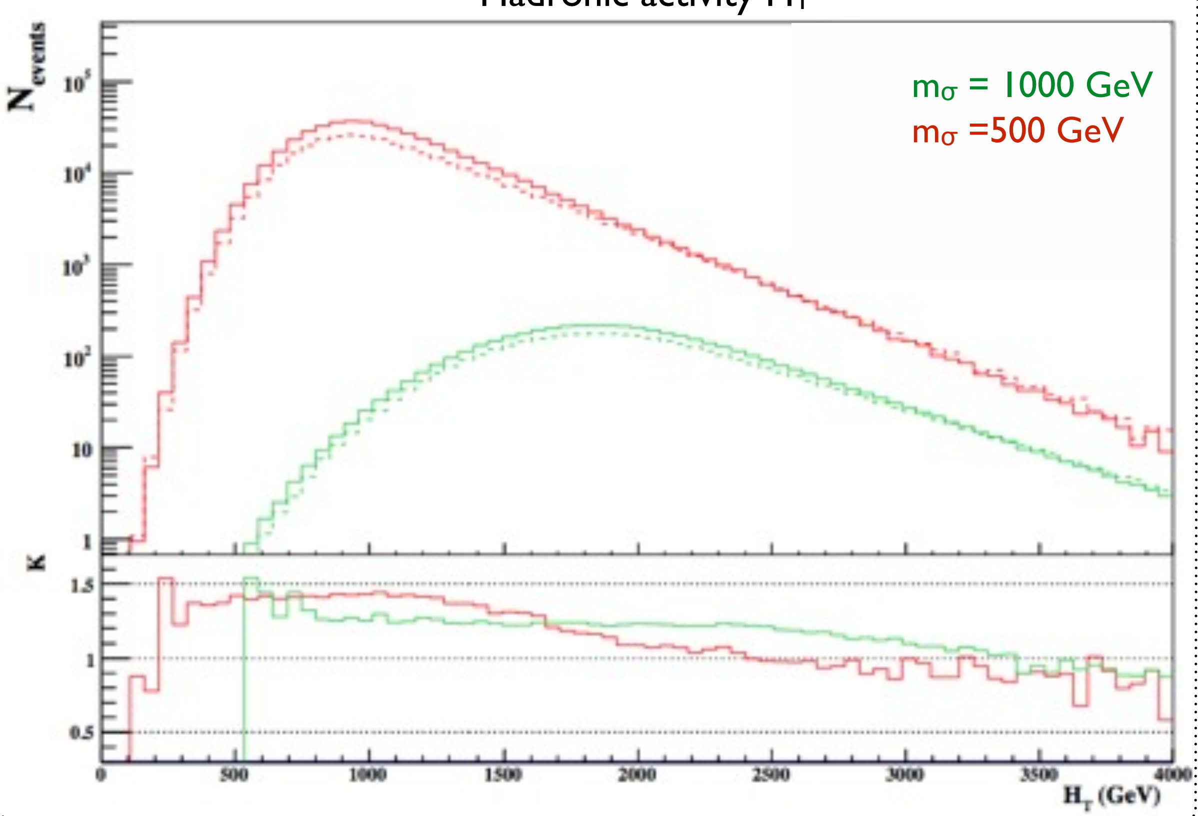
Numerically validated

m_8 [GeV]	σ^{LO} [pb] (8 TeV)	σ^{NLO} [pb] (8 TeV)	σ^{LO} [pb] (13 TeV)	σ^{NLO} [pb] (13 TeV)
100	$3.854 \pm 0.0094 \cdot 10^3\ ^{+34.4\%}_{-24.1\%}$	$5.573 \pm 0.02 \cdot 10^3\ ^{+14.9\%}_{-13.6\%}\ ^{+1.6\%}_{-1.6\%}$	$1.056 \pm 0.0029 \cdot 10^4\ ^{+29.2\%}_{-21.5\%}$	$1.470 \pm 0.0058 \cdot 10^4\ ^{+13.6\%}_{-11.9\%}\ ^{+1.2\%}_{-1.2\%}$
250	$3.889 \pm 0.010 \cdot 10^1\ ^{+41.3\%}_{-27.7\%}$	$5.432 \pm 0.019 \cdot 10^1\ ^{+14.5\%}_{-14.6\%}\ ^{+3.9\%}_{-3.9\%}$	$1.504 \pm 0.0034 \cdot 10^2\ ^{+35.7\%}_{-25.1\%}$	$2.145 \pm 0.0077 \cdot 10^2\ ^{+12.9\%}_{-12.9\%}\ ^{+2.5\%}_{-2.5\%}$
500	$5.878 \pm 0.015 \cdot 10^{-1}\ ^{+47.6\%}_{-30.0\%}$	$7.431 \pm 0.028 \cdot 10^{-1}\ ^{+15.8\%}_{-16.2\%}\ ^{+7.6\%}_{-7.6\%}$	$3.619 \pm 0.0079 \cdot 10^0\ ^{+40.8\%}_{-27.0\%}$	$4.977 \pm 0.018 \cdot 10^0\ ^{+13.3\%}_{-14.1\%}\ ^{+4.7\%}_{-4.7\%}$
750	$2.977 \pm 0.0073 \cdot 10^{-2}\ ^{+52.0\%}_{-31.9\%}$	$3.353 \pm 0.012 \cdot 10^{-2}\ ^{+17.2\%}_{-17.3\%}\ ^{+12.1\%}_{-12.1\%}$	$2.951 \pm 0.0065 \cdot 10^{-1}\ ^{+43.6\%}_{-28.4\%}$	$3.817 \pm 0.015 \cdot 10^{-1}\ ^{+14.0\%}_{-14.8\%}\ ^{+6.9\%}_{-6.9\%}$
1000	$2.328 \pm 0.0058 \cdot 10^{-3}\ ^{+55.9\%}_{-33.4\%}$	$2.398 \pm 0.0099 \cdot 10^{-3}\ ^{+19.0\%}_{-18.4\%}\ ^{+19.1\%}_{-19.1\%}$	$3.983 \pm 0.0087 \cdot 10^{-2}\ ^{+46.1\%}_{-29.5\%}$	$4.822 \pm 0.017 \cdot 10^{-2}\ ^{+15.1\%}_{-15.6\%}\ ^{+9.3\%}_{-9.3\%}$

8 TeV 13 TeV

- ✤ NNPDF2.3; scales set to the sgluon mass; uncertainties evaluated as for the stop case
- ✤ Validation with MADGOLEM
  - ★ Discrepancy of a 1-3 % for central scale choices; larger for other scale setups
  - ★ MADGOLEM is overestimating the numerical uncertainties

Hadronic activity H_T



✦ Differential distributions at NLO

- ✤ Test case: 500/1000 GeV sgluons; 13 TeV collisions
- ✤ Tetratop decays
- ✤ Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands
- ✤ Jet reconstruction: anti-k_T & FASTJET [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]
- ✤ Analysis & figure: MADANALYSIS 5 [Conte, BF, Serret

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

✦ SUSY QCD: Production of gluino-pair

$$\mathcal{L}_{\rm SQCD} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}} \not{D} \tilde{g} - m_{\tilde{q}_L}^2 \tilde{q}_L^\dagger \tilde{q}_L - m_{\tilde{q}_R}^2 \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2} m_{\tilde{g}} \bar{\tilde{g}} \tilde{g}$$

$$+ \sqrt{2} g_s \Big[-\tilde{q}_L^\dagger T (\bar{\tilde{g}} P_L q) + (\bar{q} P_L \tilde{g}) T \tilde{q}_R + \text{h.c.} \Big] - \frac{g_s^2}{2} \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big]$$

- ✤ Besides new UV and R2 (I will not listed here), we also need some special counter terms
- ✤ Mixing angle renormalization (mass and wavefunction)

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \to \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \delta Z_{\tilde{t}_L} & \delta Z_{\tilde{t},\rm LR} \\ \delta Z_{\tilde{t},\rm RL} & \delta Z_{\tilde{t}_R} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$\delta \mathcal{L}_{\rm off} = -\delta m_{\tilde{t},\rm LR}^2 (\tilde{t}_L^\dagger \tilde{t}_R + \tilde{t}_R^\dagger \tilde{t}_L)$$

- ✤ SUSY restoring counter terms

$$\mathcal{L}_{\rm SCT} = \sqrt{2} g_s \frac{\alpha_s}{3\pi} \Big[-\tilde{q}_L^\dagger T_a (\bar{\tilde{g}}^a P_L q) + (\bar{q} P_L \tilde{g}^a) T_a \tilde{q}_R + \text{h.c.} \Big]$$

$$+ \frac{g_s^2}{2} \frac{\alpha_s}{4\pi} \Big[\tilde{q}_R^\dagger \{T_a, T_b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T_a, T_b\} \tilde{q}_L \Big] \times \Big[\tilde{q}_R^\dagger \{T^a, T^b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T^a, T^b\} \tilde{q}_L \Big]$$

$$- \frac{g_s^2}{2} \frac{\alpha_s}{4\pi} \Big[\tilde{q}_R^\dagger T_a \tilde{q}_R - \tilde{q}_L^\dagger T_a \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T^a \tilde{q}_R - \tilde{q}_L^\dagger T^a \tilde{q}_L \Big]$$

✦ Decay of gluino

$$\mathcal{L}_{\rm decay} = \frac{i}{2} \bar{\chi} \not{\partial} \chi - \frac{1}{2} m_\chi \bar{\chi} \chi + \sqrt{2} g' \Big[-\tilde{q}_L^\dagger Y_q (\bar{\chi} P_L q) + (\bar{q} P_L \chi) Y_q \tilde{q}_R + \text{h.c.} \Big]$$

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

Majorana: fermion-flow violation

- SUSY QCD: Production of gluino-pair

$$\mathcal{L}_{\rm SQCD} = D_\mu \tilde{q}_L^\dagger D^\mu \tilde{q}_L + D_\mu \tilde{q}_R^\dagger D^\mu \tilde{q}_R + \frac{i}{2}\bar{\tilde{g}} \not{D} \tilde{g} - m_{\tilde{q}_L}^2 \tilde{q}_L^\dagger \tilde{q}_L - m_{\tilde{q}_R}^2 \tilde{q}_R^\dagger \tilde{q}_R - \frac{1}{2} m_{\tilde{g}} \bar{\tilde{g}} \tilde{g}$$
$$+ \sqrt{2} g_s \Big[- \tilde{q}_L^\dagger T (\bar{\tilde{g}} P_L q) + (\bar{q} P_L \tilde{g}) T \tilde{q}_R + {\rm h.c.} \Big] - \frac{g_s^2}{2} \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T \tilde{q}_R - \tilde{q}_L^\dagger T \tilde{q}_L \Big]$$

  - Besides new UV and R2 (I will not listed here), we also need some special counter terms
  - Mixing angle renormalization (mass and wavefunction)

$$\begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \to \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \delta Z_{\tilde{t}_L} & \delta Z_{\tilde{t},{\rm LR}} \\ \delta Z_{\tilde{t},{\rm RL}} & \delta Z_{\tilde{t}_R} \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}$$

$$\delta \mathcal{L}_{\rm off} = -\delta m_{\tilde{t},{\rm LR}}^2 (\tilde{t}_L^\dagger \tilde{t}_R + \tilde{t}_R^\dagger \tilde{t}_L)$$

  - SUSY restoring counter terms

$$\mathcal{L}_{\rm SCT} = \sqrt{2} g_s \frac{\alpha_s}{3\pi} \Big[- \tilde{q}_L^\dagger T_a (\bar{\tilde{g}}^a P_L q) + (\bar{q} P_L \tilde{g}^a) T_a \tilde{q}_R + {\rm h.c.} \Big]$$
$$+ \frac{g_s^2}{2} \frac{\alpha_s}{4\pi} \Big[\tilde{q}_R^\dagger \{T_a, T_b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T_a, T_b\} \tilde{q}_L \Big] \times \Big[\tilde{q}_R^\dagger \{T^a, T^b\} \tilde{q}_R + \tilde{q}_L^\dagger \{T^a, T^b\} \tilde{q}_L \Big]$$
$$- \frac{g_s^2}{2} \frac{\alpha_s}{4\pi} \Big[\tilde{q}_R^\dagger T_a \tilde{q}_R - \tilde{q}_L^\dagger T_a \tilde{q}_L \Big] \Big[\tilde{q}_R^\dagger T^a \tilde{q}_R - \tilde{q}_L^\dagger T^a \tilde{q}_L \Big]$$

- Decay of gluino

$$\mathcal{L}_{\rm decay} = \frac{i}{2} \bar{\chi} \not{\partial} \chi - \frac{1}{2} m_\chi \bar{\chi} \chi + \sqrt{2} g' \Big[- \tilde{q}_L^\dagger Y_q (\bar{\chi} P_L q) + (\bar{q} P_L \chi) Y_q \tilde{q}_R + {\rm h.c.} \Big]$$

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

Available models

Description	Contact	Reference	FeynRules model files	UFO libraries	Validation material
Dark matter simplified models (more details)	K. Mawatari	-	-	DMsimp_UFO.2.zip	-
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz	All figures available from the arxiv
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089	-	HC_NLO_X0_UFO.zip	-
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz	sgluons_validation.pdf ; sgluons_validation_root.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz	stop_ttmet_validation.pdf ; stop_ttmet_validation_root.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO	-

1. Download UFO from FR Wiki
2. Put the UFO model in models
3. ./bin/mg5_aMC
4. > import model susyqcd_ufo
5. > generate p p > go go [QCD]
6. > output pp2gogoQCD
7. > launch

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

✦ Total rates at 8 TeV and 13 TeV

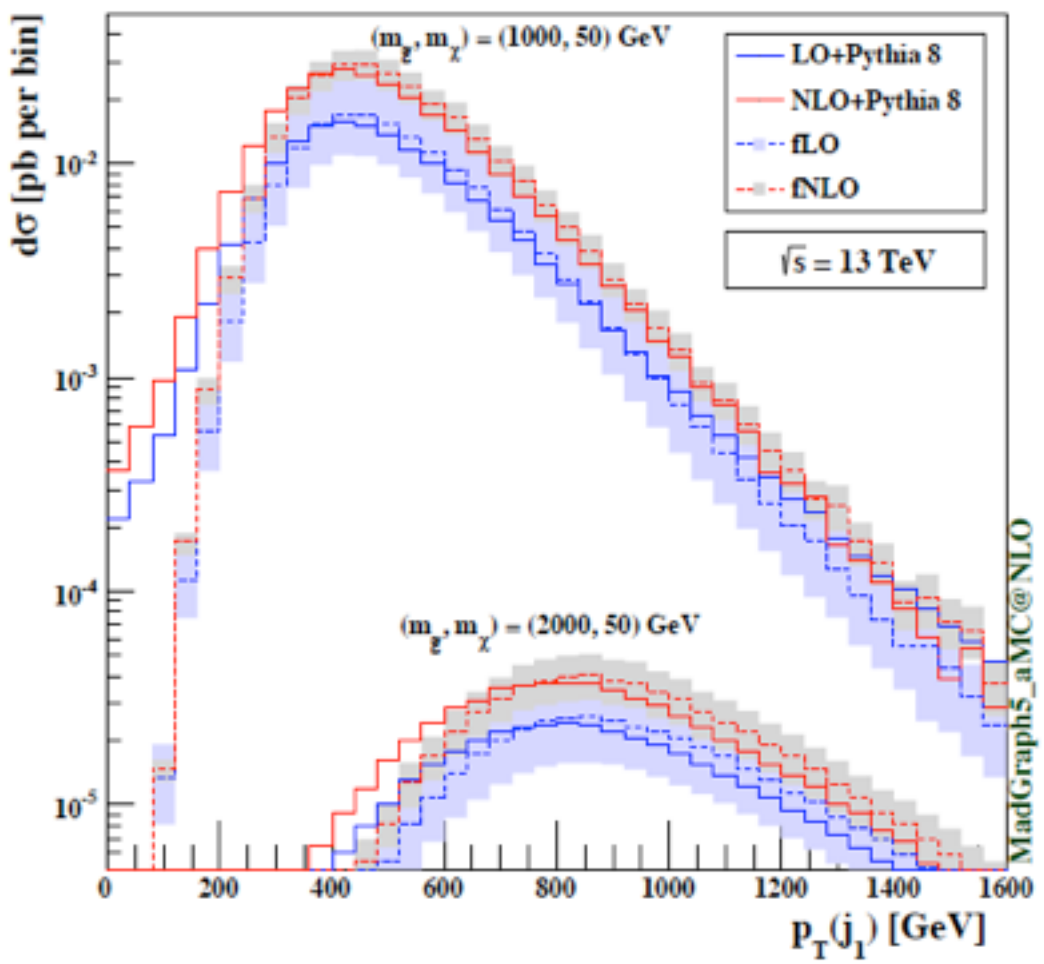
Splitting SUSY

Numerically validated

$m_{\tilde{g}}$ [GeV]	σ^{LO} [pb]	σ^{NLO} [pb]
200	$2104^{+30.3\%+14.0\%}_{-21.9\%-14.0\%}$	$3183^{+10.8\%+1.8\%}_{-11.6\%-1.8\%}$
500	$15.46^{+34.7\%+19.5\%}_{-24.1\%-19.5\%}$	$24.90^{+12.5\%+3.7\%}_{-13.4\%-3.7\%}$
750	$1.206^{+35.9\%+23.5\%}_{-24.6\%-23.5\%}$	$2.009^{+13.5\%+5.5\%}_{-14.1\%-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%+26.4\%}_{-24.8\%-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%+7.3\%}_{-14.8\%-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%+29.4\%}_{-24.7\%-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%+11.3\%}_{-15.8\%-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%+29.8\%}_{-24.5\%-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%+17.8\%}_{-16.6\%-17.8\%}$

✤ NNPDF3.0; scales set to the HT/2; uncertainties evaluated as for the stop case

✤ Validation with PROSPINO 2.1



✦ Differential distributions at NLO

✤ Test case: 1000/2000 GeV gluino; 13 TeV collisions

✤ Gluino decays: MadSpin

✤ Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands

✤ Jet reconstruction: anti-k_T & FASTJET

[Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]

✤ Analysis & figure: MADANALYSIS 5

[Conte, BF, Serret

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

✦ Total rates at 8 TeV and 13 TeV

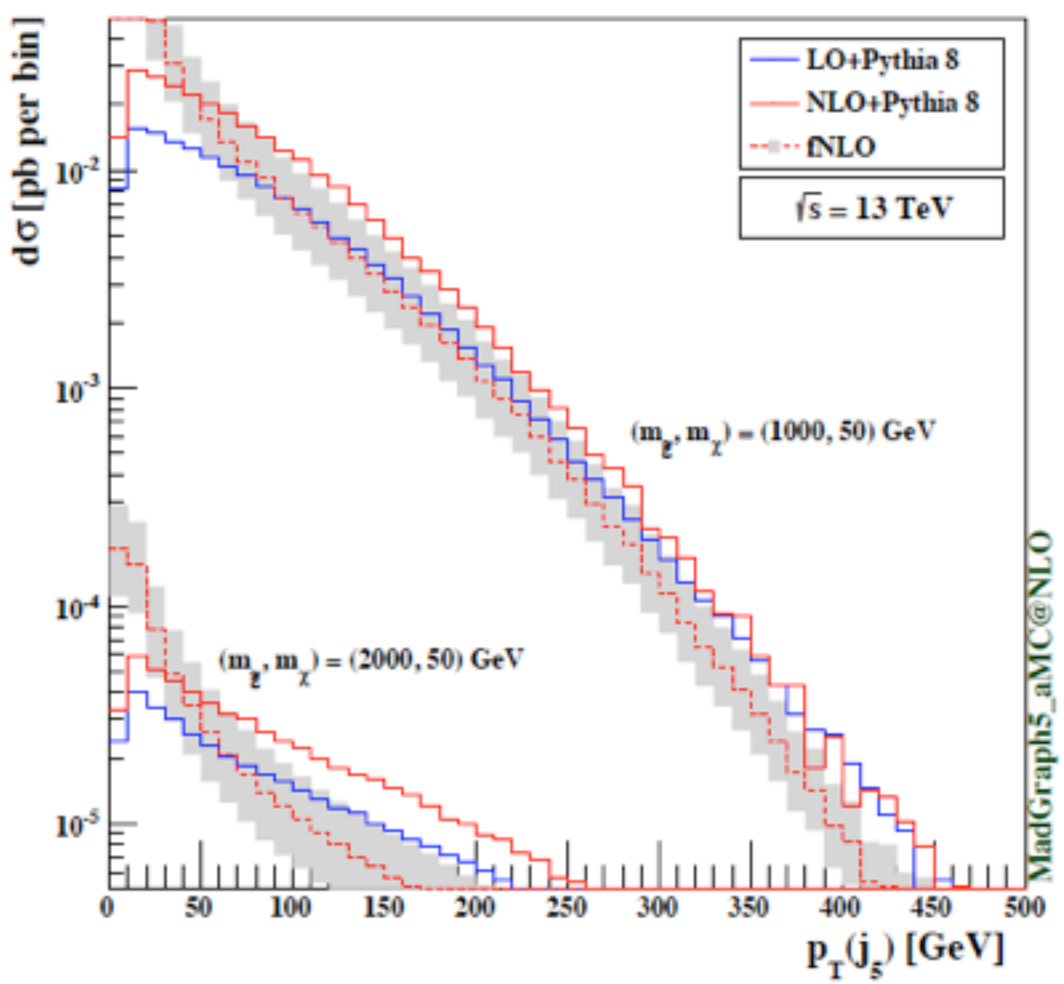
Splitting SUSY

Numerically validated

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%+14.0\%}_{-21.9\%-14.0\%}$	$3183^{+10.8\%+1.8\%}_{-11.6\%-1.8\%}$
500	$15.46^{+34.7\%+19.5\%}_{-24.1\%-19.5\%}$	$24.90^{+12.5\%+3.7\%}_{-13.4\%-3.7\%}$
750	$1.206^{+35.9\%+23.5\%}_{-24.6\%-23.5\%}$	$2.009^{+13.5\%+5.5\%}_{-14.1\%-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%+26.4\%}_{-24.8\%-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%+7.3\%}_{-14.8\%-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%+29.4\%}_{-24.7\%-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%+11.3\%}_{-15.8\%-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%+29.8\%}_{-24.5\%-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%+17.8\%}_{-16.6\%-17.8\%}$

✤ NNPDF3.0; scales set to the HT/2; uncertainties evaluated as for the stop case

✤ Validation with PROSPINO 2.1



✦ Differential distributions at NLO

✤ Test case: 1000/2000 GeV gluino; 13 TeV collisions

✤ Gluino decays: MadSpin

✤ Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands

✤ Jet reconstruction: anti-k_T & FASTJET [Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]

✤ Analysis & figure: MADANALYSIS 5 [Conte, BF, Serret

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Hirschi, Proudom, HSS (arXiv:1510.00391)

✦ Total rates at 8 TeV and 13 TeV

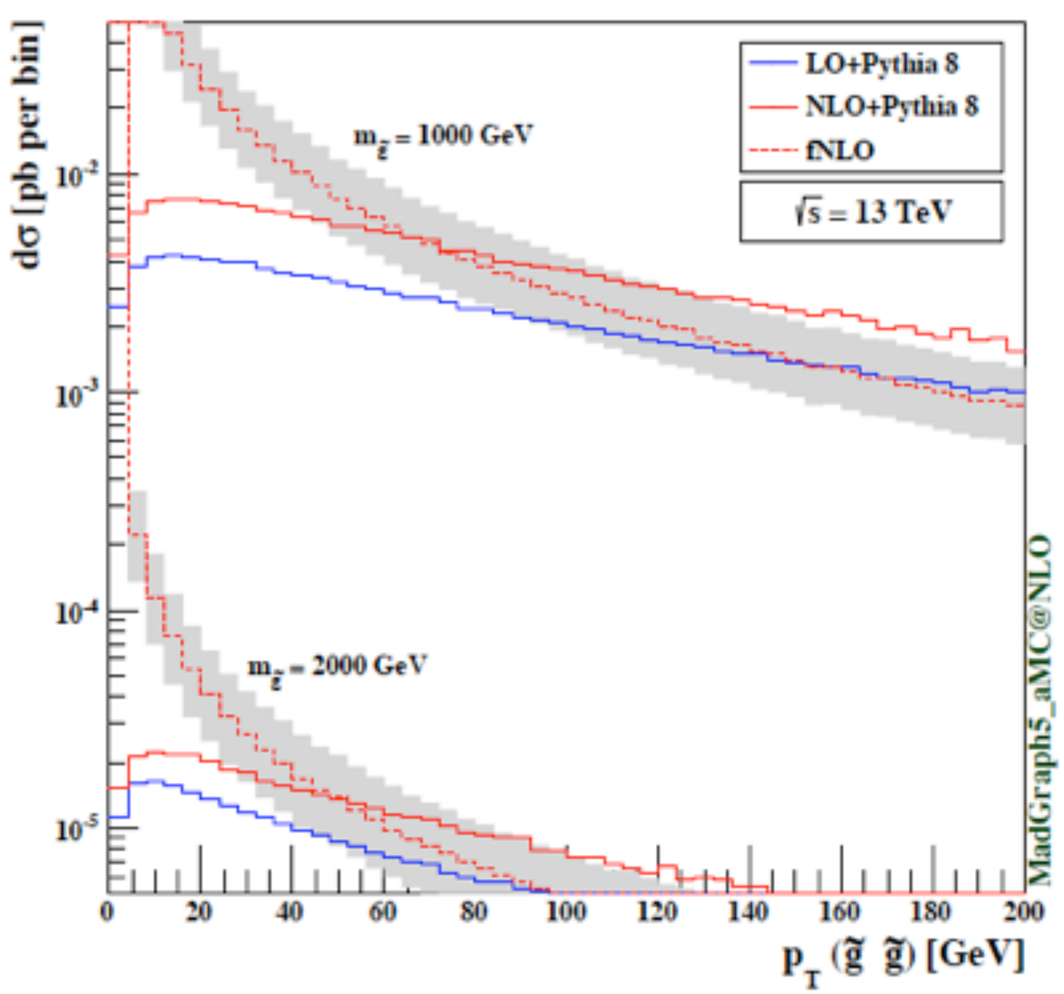
Splitting SUSY

Numerically validated

$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%}_{-21.9\%}{}^{+14.0\%}_{-14.0\%}$	$3183^{+10.8\%}_{-11.6\%}{}^{+1.8\%}_{-1.8\%}$
500	$15.46^{+34.7\%}_{-24.1\%}{}^{+19.5\%}_{-19.5\%}$	$24.90^{+12.5\%}_{-13.4\%}{}^{+3.7\%}_{-3.7\%}$
750	$1.206^{+35.9\%}_{-24.6\%}{}^{+23.5\%}_{-23.5\%}$	$2.009^{+13.5\%}_{-14.1\%}{}^{+5.5\%}_{-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%}_{-24.8\%}{}^{+26.4\%}_{-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%}_{-14.8\%}{}^{+7.3\%}_{-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%}_{-24.7\%}{}^{+29.4\%}_{-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%}_{-15.8\%}{}^{+11.3\%}_{-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%}_{-24.5\%}{}^{+29.8\%}_{-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%}_{-16.6\%}{}^{+17.8\%}_{-17.8\%}$

✤ NNPDF3.0; scales set to the HT/2; uncertainties evaluated as for the stop case

✤ Validation with PROSPINO 2.1



✦ Differential distributions at NLO

✤ Test case: 1000/2000 GeV gluino; 13 TeV collisions

✤ Gluino decays: MadSpin

✤ Shower: PYTHIA 8.2 [Sjostrand, Mrenna & Skands

✤ Jet reconstruction: anti-k_T & FASTJET

[Cacciari, Salam & Soyez (JHEP'08, EPJC'12)]

✤ Analysis & figure: MADANALYSIS 5

[Conte, BF, Serret

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

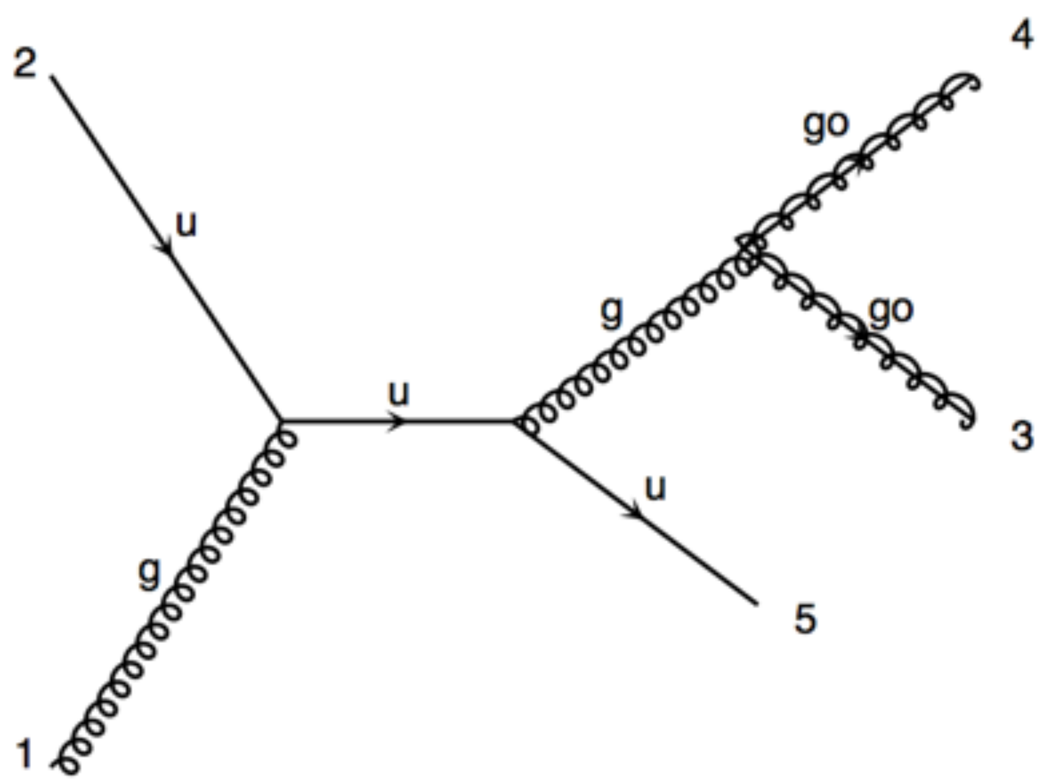
Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions

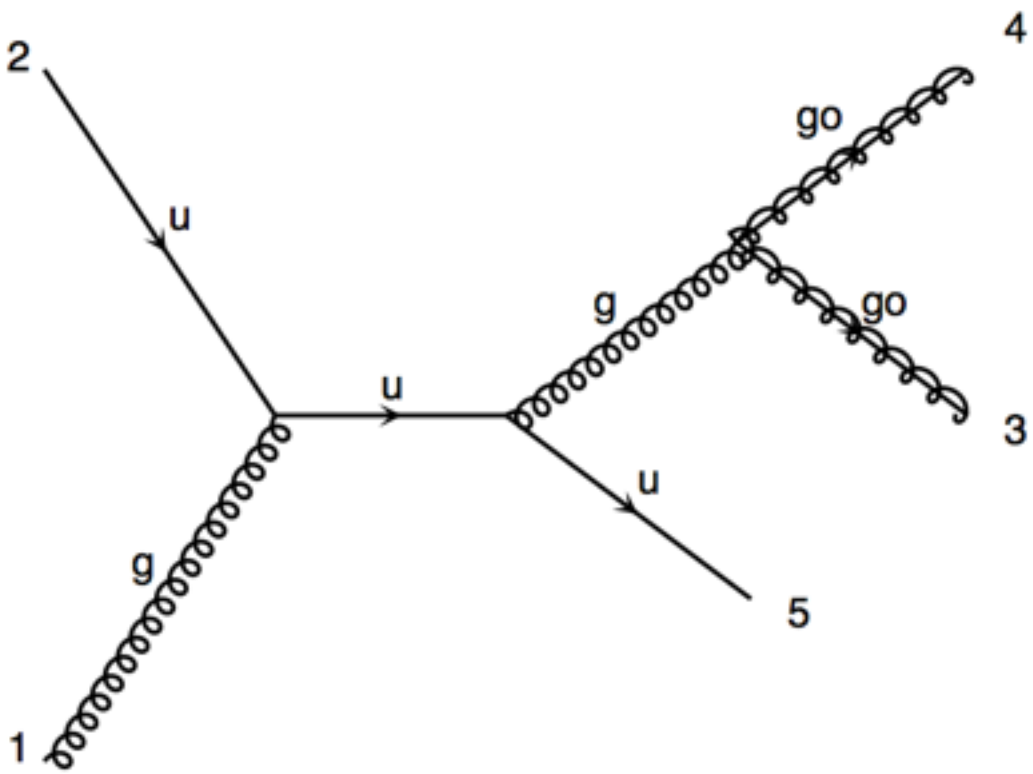


NLO diagram for gluino-pair

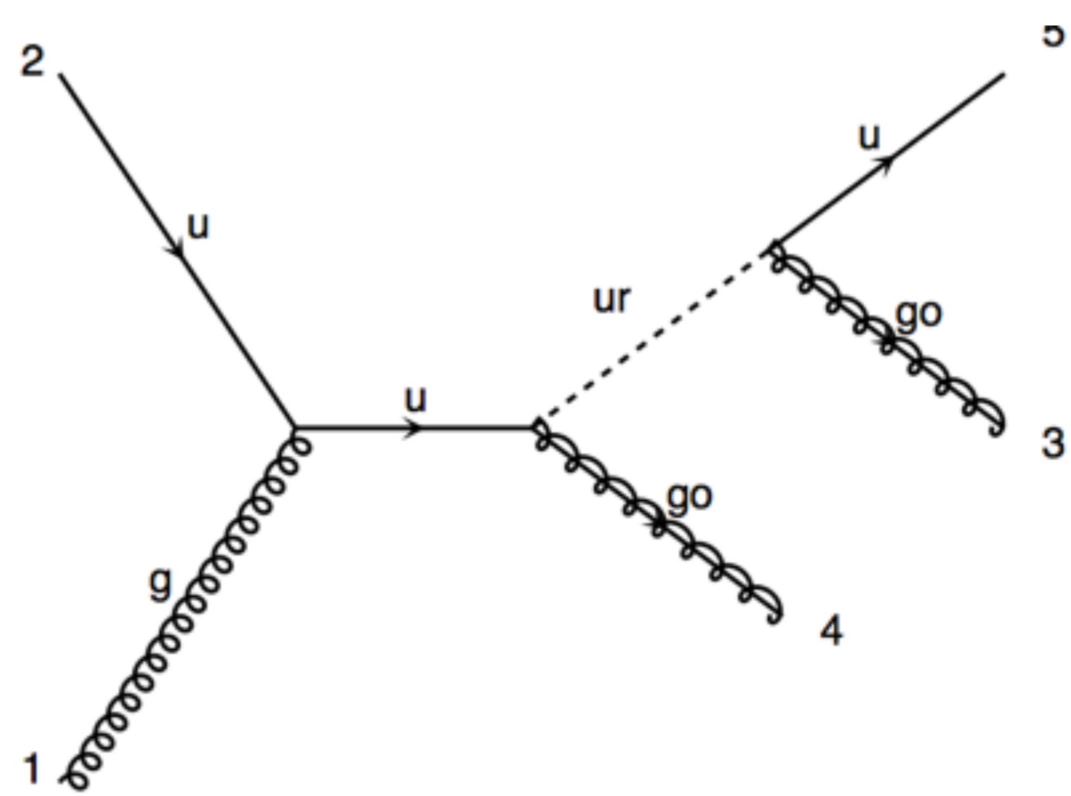
APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions



NLO diagram for gluino-pair

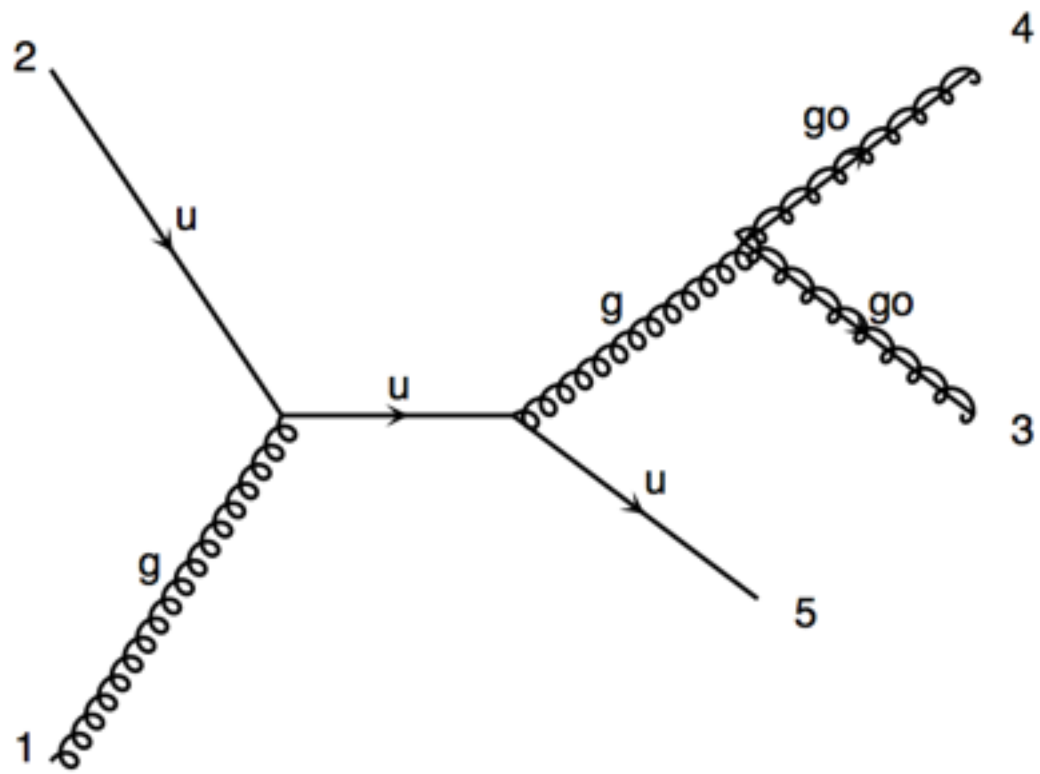


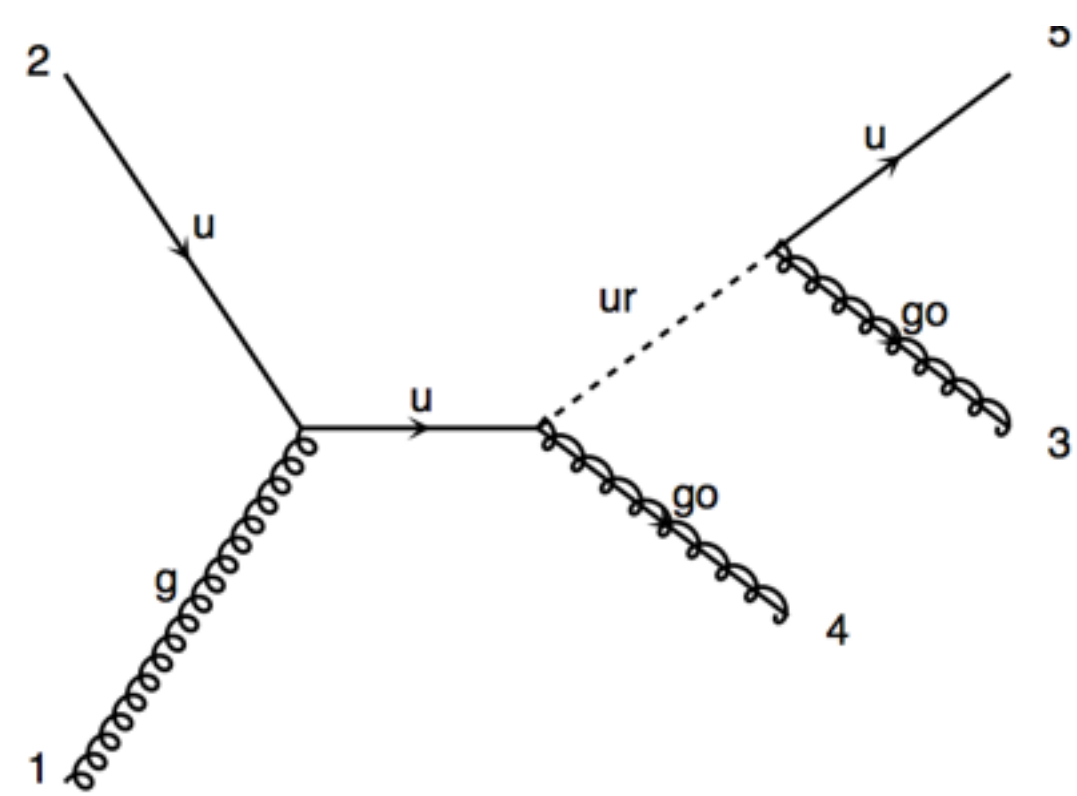
LO diagram for gluino-squark with squark decay

APPLICATION 3: GLUINO-PAIR IN SUSY QCD

Degrande, Fuks, Goncalves-Netto, Hirschi, Lopez-Val, Mawatari, Pagani, Proudom, HSS, Zaro (in preparation)

- Explore full spectrum (in the future):
  - New hadron states (R-hadron, gluinonium etc)
  - Separate resonance and non-resonance contributions





NLO diagram for gluino-pair **LO diagram for gluino-squark with squark decay**

On-Shell subtraction **MadOS**

OTHER EFFORTS IN FR/MG5AMC @ NLO

- Top FCNC Degrande, Maltoni, Wang, Zhang (PRD'15)
- DM with spin-0/1 s-channel mediator Backovic, Kramer, Maltoni, Martini, Mawatari, Pellen (EPJC'15); Neubert, Wang, Zhang (arXiv:1509.05785)
- Other simple extension of SM: 2HDM etc Degrande (CPC'15)
- More efforts are ongoing
- We welcome the interested young students to join us.