

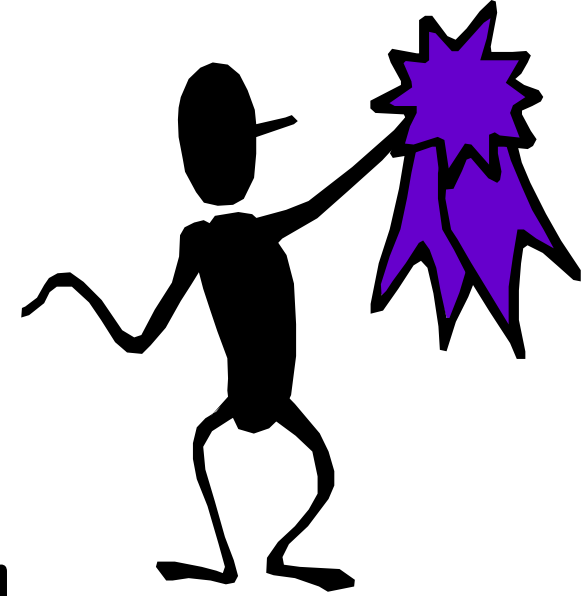
MadGraph5_aMC@NLO



**Automated Tree-Level and one loop
Feynman Diagram
and Event Generation at LO and NLO**

Valentin Hirschi and Olivier Mattelaer

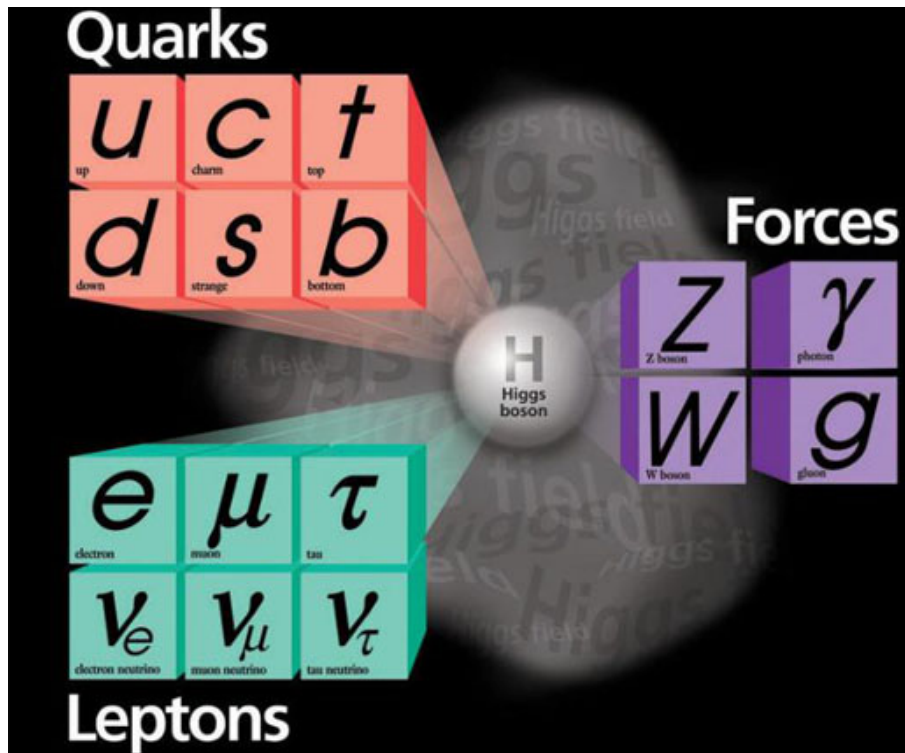
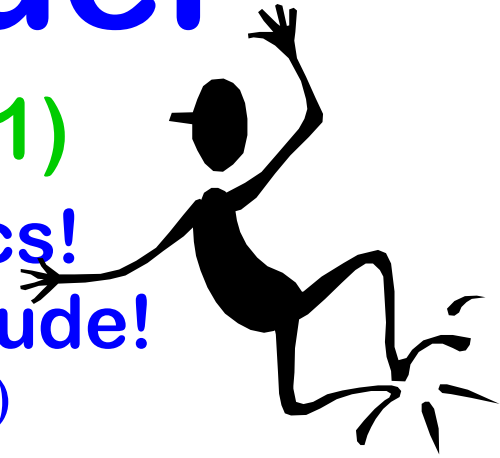
Plan



- **Overview of Standard Model**
 - Introduction to Particle Physics
 - The Standard Model
- **Parton level calculations**
- **Full Event Simulations**
- **Identify 3 Newly Discovered Particles**

Standard Model

- **Good News! $SU(3) \times SU_L(2) \times U(1)$**
 - Most successful theory in physics!
 - Tested over 30 orders of magnitude!
 - (photon mass $< 10^{-18}$ eV , LHC $> 10^{12}$ eV)



- All particles observed
 - Higgs (2012)
 - Top (1995)

Standard Model



- **Bad News!**
 - We can't solve it!

$$\begin{aligned}\mathcal{L}_{\text{QCD}} &= -\frac{1}{2} \text{Tr}(\mathbf{G}^{\mu\nu} \mathbf{G}_{\mu\nu}) + \bar{\mathbf{q}} [i \gamma^\mu \mathbf{D}_\mu - m_q] \mathbf{q} \\ &= -\frac{1}{4} (\partial^\mu G_\nu^a - \partial_\nu G_\mu^a) (\partial_\mu G_\nu^a - \partial_\nu G_\mu^a) + \sum_q \bar{q}_\alpha [i \gamma^\mu \partial_\mu - m_q] q_\alpha \\ &+ \frac{1}{2} \sum_q g_s [\bar{q}_\alpha (\lambda^a)_{\alpha\beta} \gamma^\mu q_\beta] G_\mu^a \\ &- \frac{1}{2} g_s f_{abc} (\partial_\mu G_\nu^a - \partial_\nu G_\mu^a) G_b^\mu G_c^\nu - \frac{1}{4} g_s^2 f_{abc} f_{ade} G_b^\mu G_c^\nu G_\mu^d G_\nu^e\end{aligned}$$

Predictions from SM



- **Cross Section:** $\sigma = \frac{1}{2s} \int |M|^2 d\Phi$

$$M = \left\langle \mu^+ \mu^- \left| T \left(e^{-i \int H_I dt} \right) \right| e^+ e^- \right\rangle$$

- Can't solve exactly because interactions change wave functions!
- **Perturbation Theory**
 - Start w/ Free Particle wave function
 - Assume interactions are small perturbation

$$M \approx \left\langle \mu^+ \mu^- \left| H_{\text{int}} \right| e^+ e^- \right\rangle + \frac{1}{2} \left\langle \mu^+ \mu^- \left| H_{\text{int}}^2 \right| e^+ e^- \right\rangle + \dots$$

Example: $e^+e^- \rightarrow \mu^+\mu^-$

- Scattering cross section

$$\sigma = \frac{1}{2s} \int |M|^2 d\Omega$$

$$M \approx \langle \mu^+ \mu^- | H_{int} | e^+ e^- \rangle$$

- Feynman Diagram

$\mathbf{W}_{\mu\nu} = \frac{i}{g} [\mathbf{D}_\mu, \mathbf{D}_\nu] = \frac{g}{2} \vec{W}_{\mu\nu} \rightarrow U_L \mathbf{W}_{\mu\nu} U_L^\dagger \quad ; \quad \mathbf{B}_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu \rightarrow B_{\mu\nu}$
 $W'_{\mu\nu} = \partial_\mu W'_\nu - \partial_\nu W'_\mu + g e^{ijk} W'_\mu W'_\nu$

$\mathcal{L}_K = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{2} \text{Tr}(\mathbf{W}_{\mu\nu} \mathbf{W}^{\mu\nu}) = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \vec{W}_{\mu\nu} \vec{W}^{\mu\nu} = \mathcal{L}_{K0} + \mathcal{L}_3 + \mathcal{L}_1$


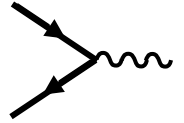


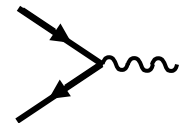


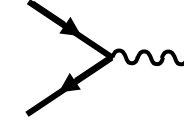
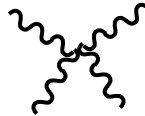

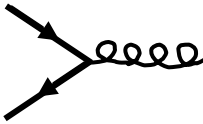
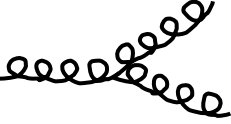
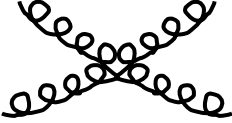
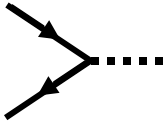
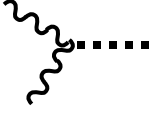
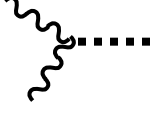
$\mathcal{L}_3 = -ie \cot \theta_w \{ (\partial^\mu W^\nu - \partial^\nu W^\mu) W_\mu^\dagger Z_\nu - (\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}) W_\nu Z_\mu + W_\mu W_\nu^\dagger (\partial^\mu Z^\nu - \partial^\nu Z^\mu) \}$
 $-ie \{ (\partial^\mu W^\nu - \partial^\nu W^\mu) W_\mu^\dagger A_\nu - (\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}) W_\nu A_\mu + W_\mu W_\nu^\dagger (\partial^\mu A^\nu - \partial^\nu A^\mu) \}$

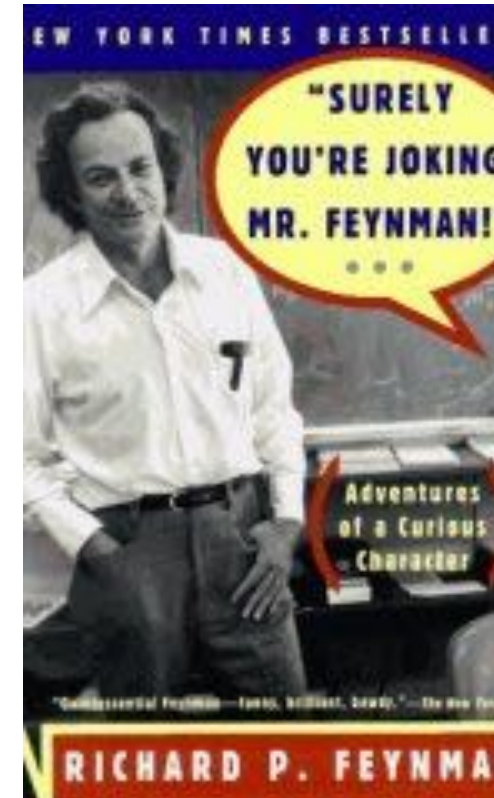
$\mathcal{L}_1 = -\frac{e^2}{2 \sin^2 \theta_w} \{ (W_\mu^\dagger W^\mu)^2 - W_\mu^\dagger W^{\mu\dagger} W_\nu W^\nu \} - e^2 \cot^2 \theta_w \{ W_\mu^\dagger W^\mu Z_\nu Z^\nu - W_\mu^\dagger Z^\mu W_\nu Z^\nu \}$
 $-e^2 \cot \theta_w \{ 2W_\mu^\dagger W^\mu Z_\nu A^\nu - W_\mu^\dagger Z^\mu W_\nu A^\nu - W_\mu^\dagger A^\mu W_\nu Z^\nu \} - e^2 \{ W_\mu^\dagger W^\mu A_\nu A^\nu - W_\mu^\dagger A^\mu W_\nu A^\nu \}$

The Standard Model A. Pich - CERN - Summer lectures 2005

$$M \approx \bar{v}(e^+) (-iq\gamma^\mu) v(e^-) \frac{\delta^{\mu\nu}}{p^2} \bar{u}(\mu^+) (-iq\gamma^\nu) u(\mu^-)$$

Feynman Rules!

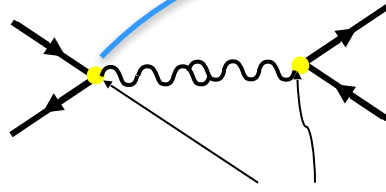
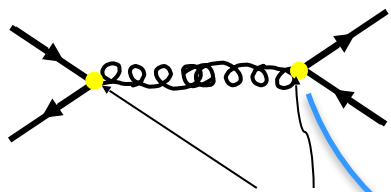
γ		QED	 $q\bar{q}\gamma \quad l-l^+\gamma$	 $W^+W^-\gamma$	
Z		QED	 $q\bar{q}Z \quad l\bar{l}Z$	 W^+W^-Z	
W^{+-}		QED	 $q\bar{q}'W \quad l\nu W$	 $WWWW$	
g		QCD	 $q\bar{q}g$	 ggg	 $gggg$
h	QED (m)	 $q\bar{q}h \quad l\bar{l}h$	 W^+W^-h	 ZZh



Feynman Rules!

- These are basic building blocks, combine to form “allowed” diagrams

– e.g. $u u^{\sim} \rightarrow t t^{\sim}$



Order is QCD²

Order is QED²

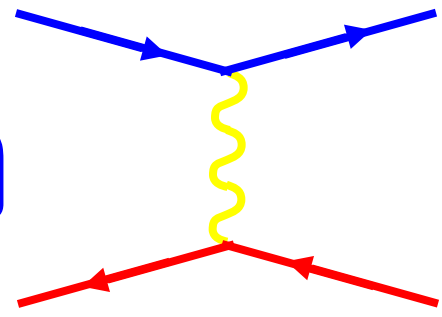
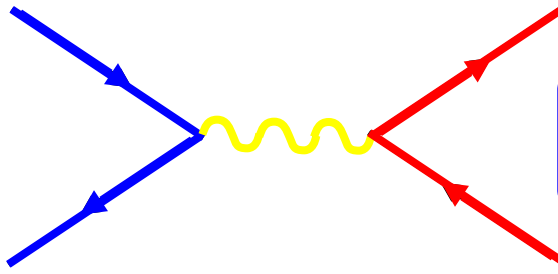
- Draw Feynman diagrams:

- $gg \rightarrow t t^{\sim}$
- $gg \rightarrow t t^{\sim} h$
- $gg \rightarrow h h$
- $dd^{\sim} \rightarrow uu^{\sim} Z$

$\gamma \sim$	QED			
$Z \sim$	QED			
$W \sim$	QED			
$g \sim$	QCD			
$h \dots$	QED (m)			

- Determine “order” for each diagram

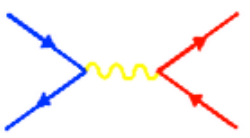
MadGraph



- User Requests:
 - $g g \rightarrow t \bar{t} h$ QCD ≤ 4
- MadGraph Returns
 - Feynman diagrams
 - Self-Contained Fort

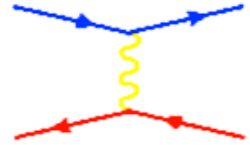
```
SUBROUTINE SMATRIX(P1,ANS)
C
C Generated by MadGraph II Version 3.83. Updated 06/13/05
C RETURNS AMPLITUDE SQUARED SUMMED/AVG OVER COLORS
C AND HELICITIES
C FOR THE POINT IN PHASE SPACE P(0:3,NEXTERNAL)
C
C FOR PROCESS : g g -> t t~ b b~
C
C Crossing 1 is g g -> t t~ b b~
  IMPLICIT NONE
C
C CONSTANTS
C
  Include "genps.inc"
  INTEGER      NCOMB,  NCROSS
  PARAMETER (      NCOMB= 64, NCROSS= 1)
  INTEGER  THEL
  PARAMETER (THEL=NCOMB*NCROSS)
C
C ARGUMENTS
C
  REAL*8 P1(0:3,NEXTERNAL),ANS(NCROSS)
C
```

Check your answer



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[UCL UIUC Launchpad](#)
by the [MG/ME Development team](#)



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Generate processes online using MadGraph5_aMC@NLO

To improve our web services we request that you register. Registration is quick and free. You may register for a password by clicking [here](#). Please note the correct reference for MadGraph5_aMC@NLO, [arXiv:1405.0301 \[hep-ph\]](#).

Code can be generated either by (only LO process can be generated online):

I. Fill the form:

Model:

[Model descriptions](#)

Input Process:

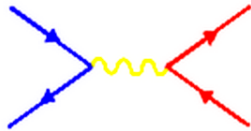
[Examples/format](#)

Example: $p p > w+ j j$ QED=3, $w+ > l+ \nu l$

p and j definitions:

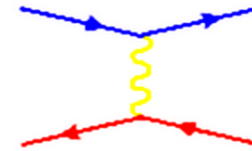
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I High Energy Physics
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MadGraph5_aMC Registration

Please complete the form below. Your username and password will be sent to the e-mail address you enter.

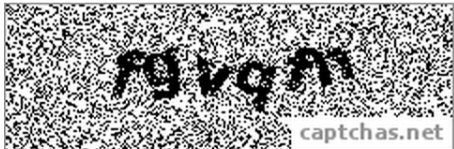
First Name

Family Name

Name of your institution

Your e-mail address

The letter sequence you can read on the following image:



captchas.net

SUBMIT

<http://madgraph.hep.uiuc.edu/>

SummerCERN17

OR install it on your laptop

<https://launchpad.net/mg5amcnlo>

The screenshot shows the Launchpad.net project page for MadGraph5_aMC@NLO. The browser address bar shows the URL <https://launchpad.net/mg5amcnlo>. The page title is "MadGraph5_aMC@NLO" and it is registered on 2009-09-11 by Michael Herquet. The page content includes a description of the framework, download instructions, and a series of milestones. A download link for "MCS_aMC_v1.5.5 merge" is circled in orange. The "Series and milestones" section shows a timeline from 2009 to 2016, with milestones for "alpha1", "1.0beta", "1.0x", "2.1.x", "2.2.x", "2.3.x", "1.5x", "2.1x", "1.0", "1.1.0", "1.2.0", "1.3.0", and "1.4.0". The "Announcements" section mentions the "Official Release of MadGraph5_aMC@NLO on 2016-11-16".

MadGraph5_aMC@NLO

Registered 2009-09-11 by Michael Herquet

MadGraph5_aMC@NLO is a framework that aims at providing all the elements necessary for SM and BSM phenomenology, such as the computations of cross sections, the generation of hard events and their matching with event generators, and the use of a variety of tools relevant to event manipulation and analysis. Processes can be simulated to LO accuracy for any user defined Lagrangian, and the NLO accuracy in the case of QCD corrections to SM processes. Matrix elements at the tree- and one-loop-level can also be obtained.

MadGraph5_aMC@NLO is the new version of both MadGraph5 and aMC@NLO that unifies the LO and NLO lines of development of automated tools within the MadGraph Family. It therefore supersedes all the MadGraph5 1.5.x versions and all the beta versions of aMC@NLO.

The standard reference for the use of the code is: J. Alwall et al. "The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations", arXiv:1405.0301 [hep-ph]. A more complete list of references can be found here: http://amc@nlo.web.cern.ch/amc@nlo/list_refs.htm

Download

The latest stable release can be downloaded as a tar.gz package (see the right of this page) or through the Docker versioning system, using the branch [jmg5amcnlo](#)

Installation

MadGraph5_aMC@NLO needs Python version 2.6 or 2.7 (gfortran/gcc 4.4 or higher is required for NLO calculations/simulations).

Getting started

Run `bin/mg5_aMC` and type `?help?` to learn how to run MadGraph5_aMC@NLO using the command interface, or run the interactive quick-start tutorial by typing `tutorial`. Some third party packages can be installed using the MCS_aMC shell command `!install`. LO generation can also be done directly online at: <http://madgraph.phy.ucl.ac.be> or <http://madgraph.hep.uvic.edu>

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Project information

Maintainer: MadTeam

Also known as: madoraahi

Servers: MadTeam

Series and milestones

View full history

Timeline: 2009 (alpha1), 2010 (1.0beta), 2010 (1.0x), 2011 (2.1.x), 2011 (2.2.x), 2011 (2.3.x), 2012 (1.5x), 2012 (2.1x), 2013 (1.0), 2013 (1.1.0), 2013 (1.2.0), 2013 (1.3.0), 2014 (1.4.0)

Downloads

MG5_aMC version 1.5.1

MCS_aMC_v1.5.5 merge (circled in orange)

Downloaded on 2016-09-08

Announcements

Official Release of MadGraph5_aMC@NLO on 2016-11-16

We would like to announce the public release of the new code MadGraph5_aMC@NLO...

aMC@NLO On MadGraph5 on 2015-11-08

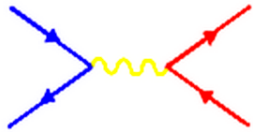
On Nov 08 2015, version 2.0 beta of MadGraph5 has been released. This is a B...



Status

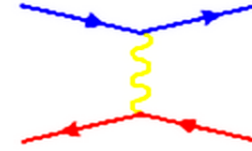


- **Good News**
 - MadGraph generates all tree-level and one loop diagrams
 - MadGraph generates fortran/C++/Python code to calculate $\Sigma|M|^2$
- **Bad News**
 - Madgraph generates code....
 - Hadron colliders are tough!
- **Good News**
 - There's a cool animation next!



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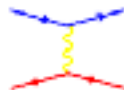
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Physics applications

[Experiments and Codes](#)

Events library

[MadGraph5_Samples for the LHC](#)



MadGraph

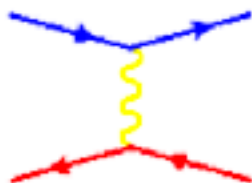


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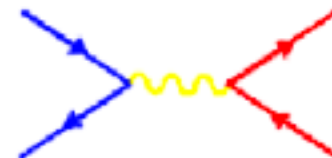
wiki: MGTutorial

Lectures on the MadGraph framework

- 2017 Cern Summer School, by Valentin Hirschi and Olivier Mattelaer.
- 2017 MCNET2017, by O. Mattelaer, V. Hirschi, E. Vryonidou
- 2017 MC4SSM16, by O. Mattelaer, B. Fuks, L. Moore
- 2016 MC4SSM16, by O. Mattelaer.



MadGraph

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wiki: [CernSummerSchool17](#)

2017 CERN Summer student workshop

Animations

- [Interactive Flash version](#) Note you may want to zoom in!
- [Fast movie \(.avi\) of collision](#)
- [Guided movie \(.mov\) of collision](#)



What are the MC for?

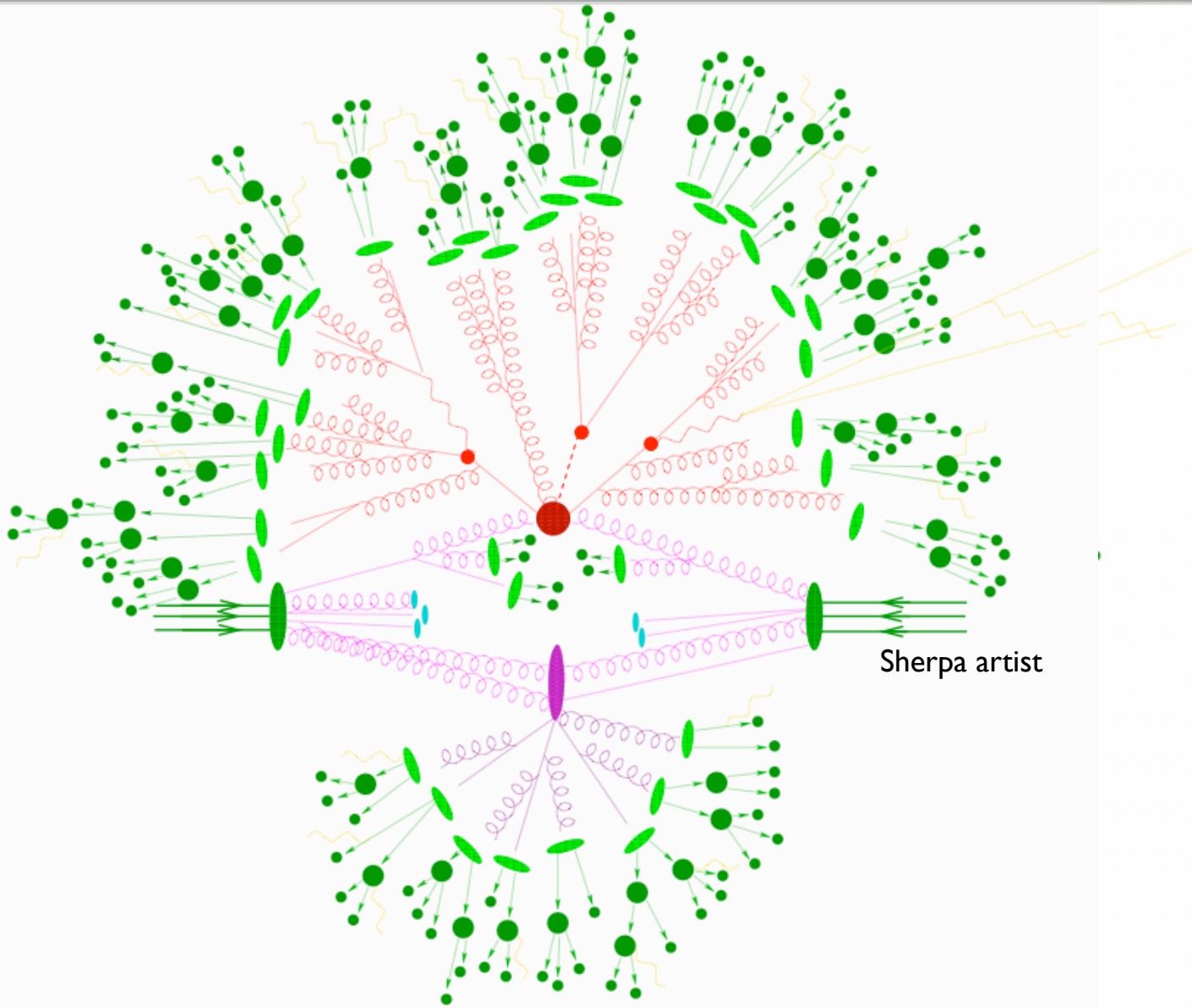
Scales



TeV

GeV

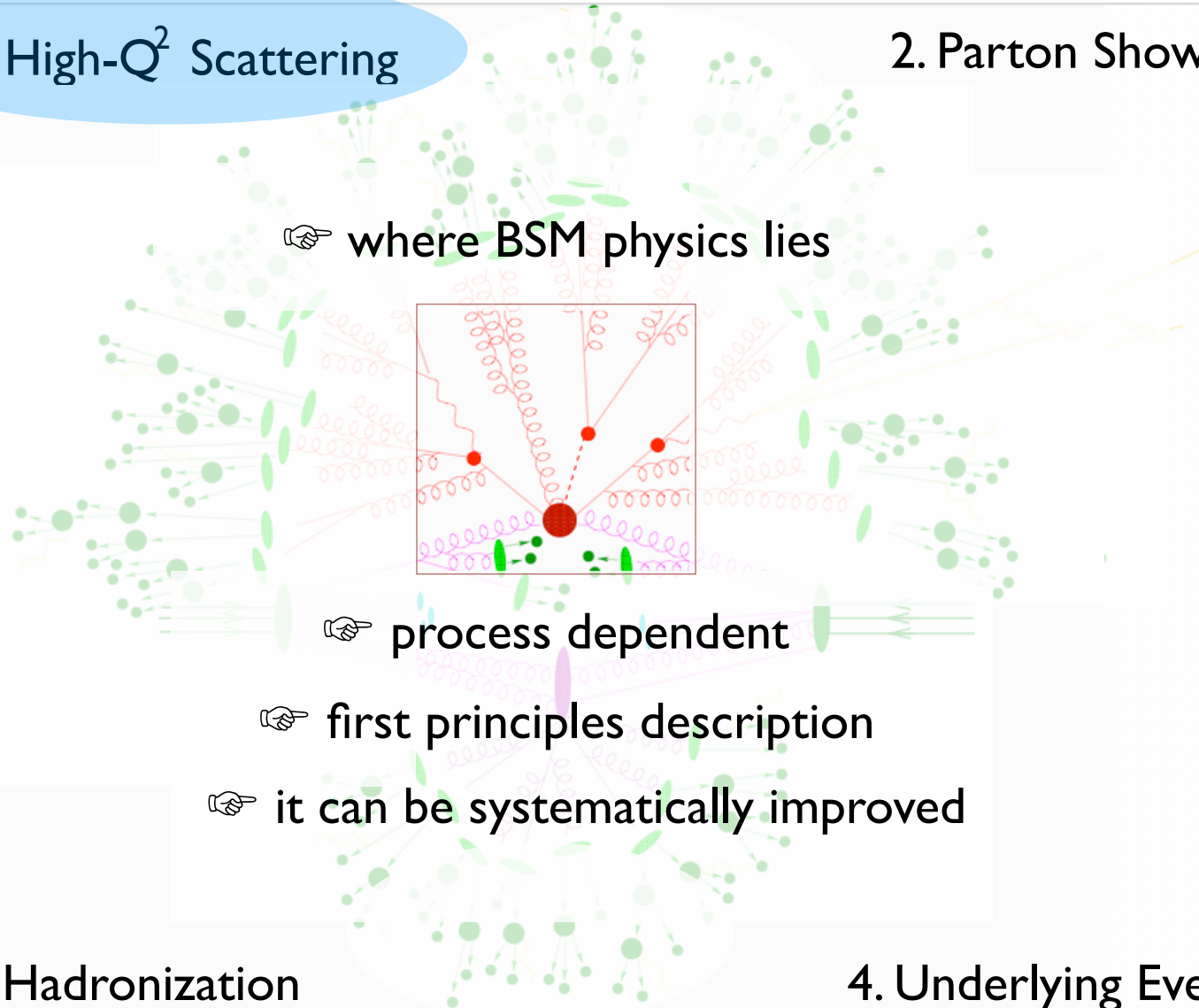
MeV



What are the MC for?

I. High- Q^2 Scattering

2. Parton Shower



3. Hadronization

4. Underlying Event

Scales



TeV

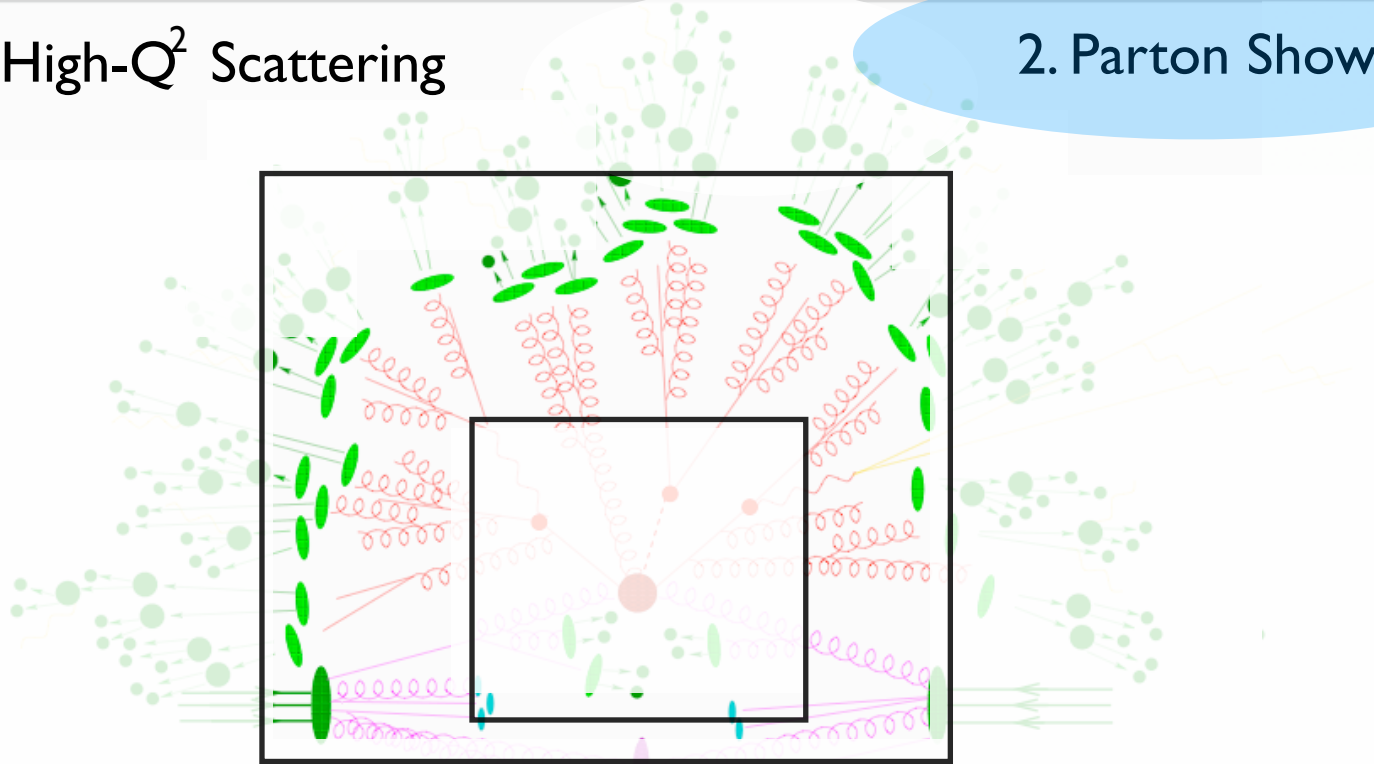
GeV

MeV

What are the MC for?

I. High- Q^2 Scattering

2. Parton Shower



☞ QCD - "known physics"

☞ universal/ process independent

☞ first principles description

3. Hadronization

4. Underlying Event

Scales



TeV

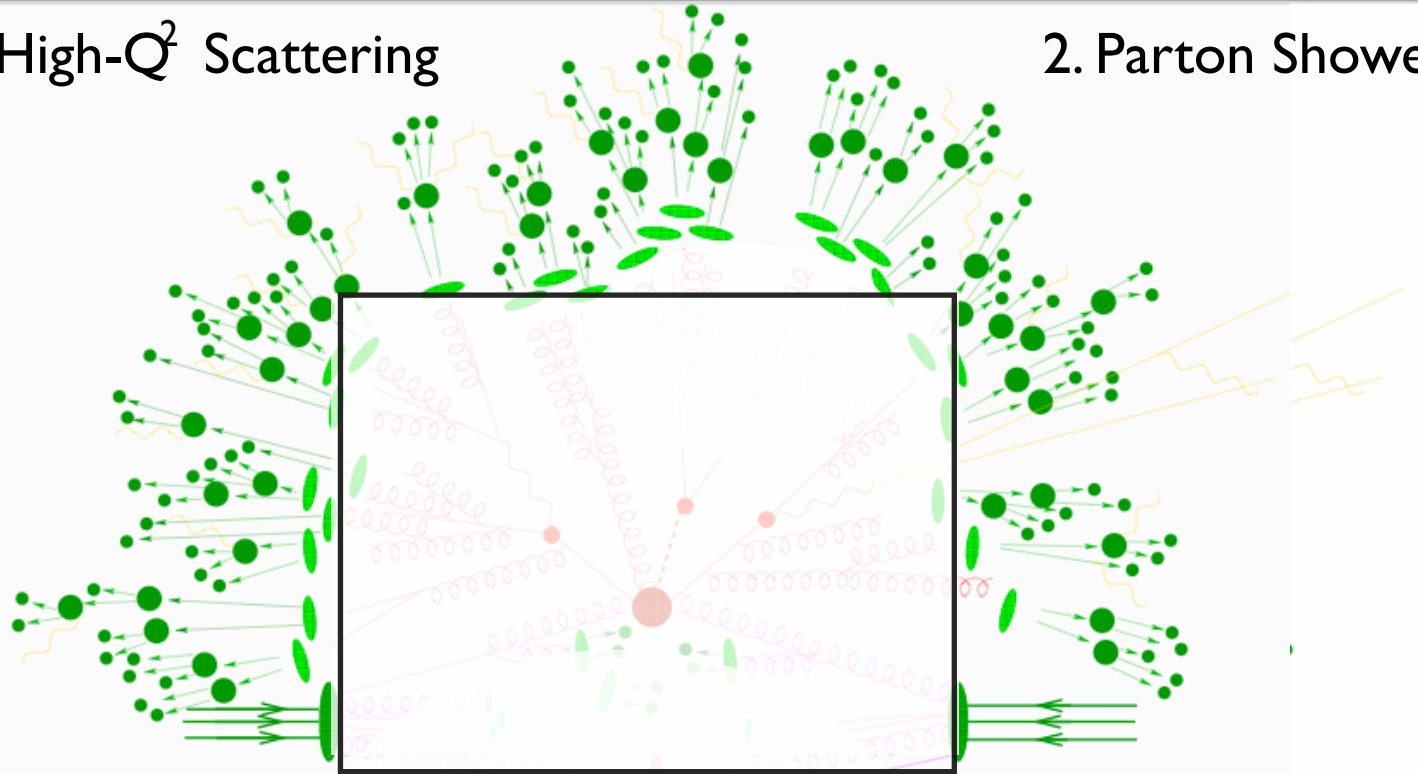
GeV

MeV

What are the MC for?

1. High- Q^2 Scattering

2. Parton Shower



low Q^2 physics

universal/ process independent

model-based description

3. Hadronization

4. Underlying Event

Scales



TeV

GeV

MeV

What are the MC for?

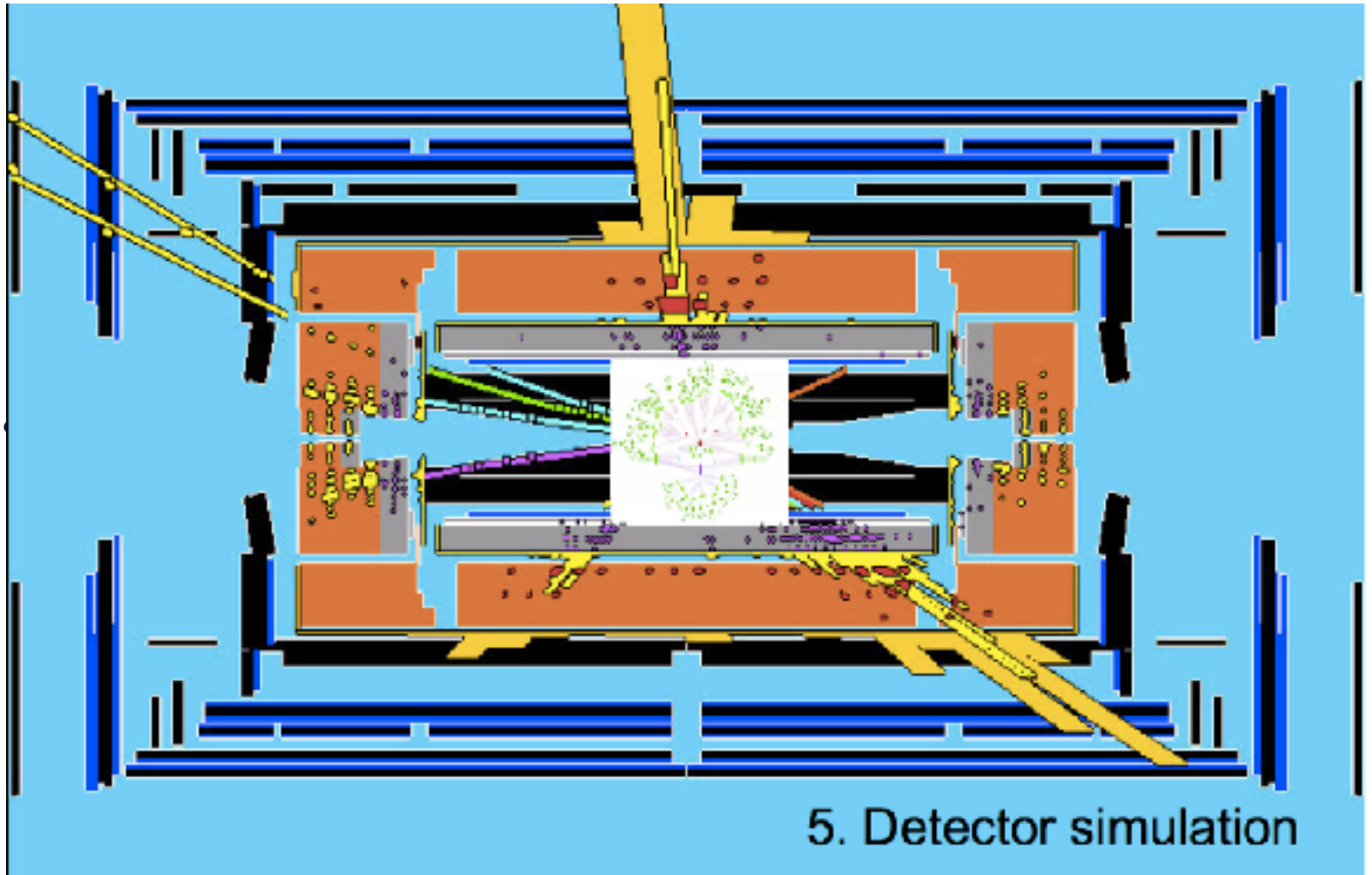
Scales



TeV

GeV

MeV



5. Detector simulation

Protons

- **Simple Model**
 - 3 “Valence” quarks u u d
 - 2/3 chance of getting up quark
 - 1/3 chance of getting down quark
 - Guess each carries 1/3 of momentum
- **Deep Inelastic Scattering Results**
 - Short time scales “sea” partons
 - u and d. but also $u\sim d\sim s$, c and g with varying amounts of momentum
- **Need to multiple matrix element by probability $f(x)$ of finding parton i with fraction of momentum x**
$$\sigma = \frac{1}{2s} \sum \int f_u(x_1) f_{\bar{u}}(x_2) |M|^2 d\Phi dx_1 dx_2$$
- **Many parton level sub processes contribute to same hadron level event (e.g. $pp \rightarrow e^+ \nu jjj$)**

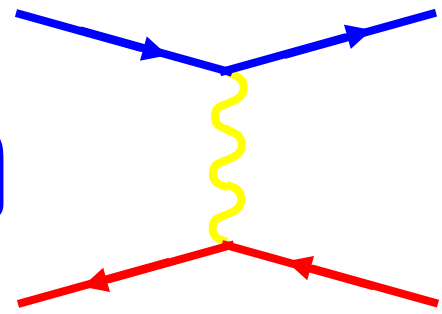
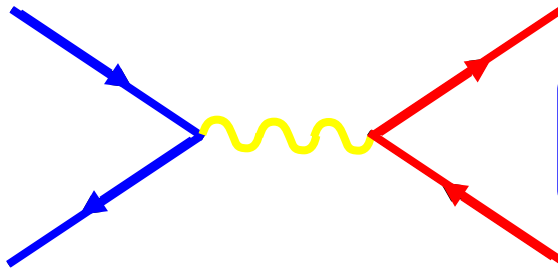


Exercise



- List processes for signal $pp \rightarrow t \bar{t} h$ with Higgs decaying to $b \bar{b}$
 - e.g. $uu \rightarrow t \bar{t} h$
- List process for background $pp \rightarrow t \bar{t} b \bar{b}$
 - e.g. $uu \rightarrow t \bar{t} b \bar{b}$
- List process for reducible background $pp \rightarrow t \bar{t} j j$
 - e.g. $uu \rightarrow t \bar{t} g g$

MadGraph



- **User Requests:**

- $pp \rightarrow bb \sim tt \sim \text{QCD} \leq 4$

- **MadGraph Returns:**

- Feynman diagrams

- Fortran Code for $|M|^2$

- Summed over all sub processes w/ pdf

```
DOUBLE PRECISION FUNCTION DSIG(PP,WGT)
C *****
C Generated by MadGraph II Version 3.83. Updated
06/13/05
C RETURNS DIFFERENTIAL CROSS SECTION
C Input:
C   pp  4 momentum of external particles
C   wgt  weight from Monte Carlo
C Output:
C   Amplitude squared and summed
C *****
```

```
-----
IPROC=IPROC+1   ! u u~ -> t t~ b b~
PD(IPROC)=PD(IPROC-1) + u1 * ub2
IPROC=IPROC+1   ! d d~ -> t t~ b b~
PD(IPROC)=PD(IPROC-1) + d1 * db2
IPROC=IPROC+1   ! s s~ -> t t~ b b~
PD(IPROC)=PD(IPROC-1) + s1 * sb2
IPROC=IPROC+1   ! c c~ -> t t~ b b~
PD(IPROC)=PD(IPROC-1) + c1 * cb2
CALL SMATRIX(PP,DSIGUU)
```

```
dsig = pd(iproc)*conv*dsiguu
```


Hadronic Collision Cross Sections

- **Good News**

- Automatically determine sub processes and Feynman diagrams
- Automatically create function needed to integrate

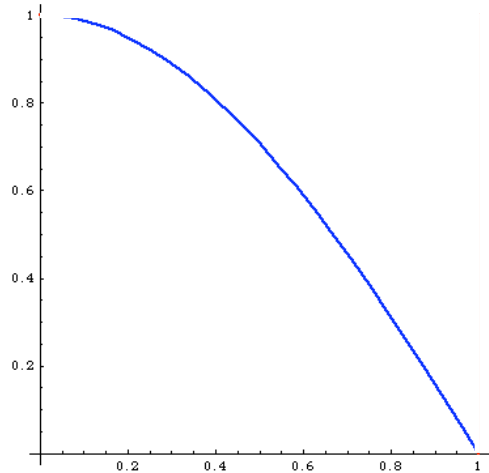
$$\sigma = \frac{1}{2s} \int f(x_1) f(x_2) |M|^2 d^3 P_1 \dots d^3 P_n \delta^4(P - p_1 - p_2 \dots - p_n)$$

- **Bad News**

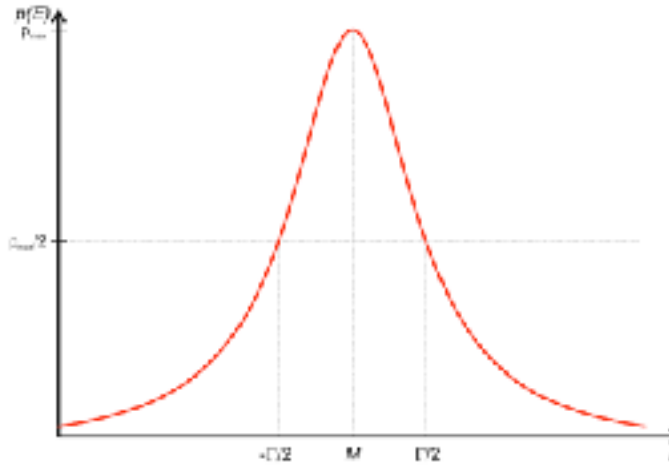
- Hard to integrate!
- $3N-4+2$ dimensions

Integration

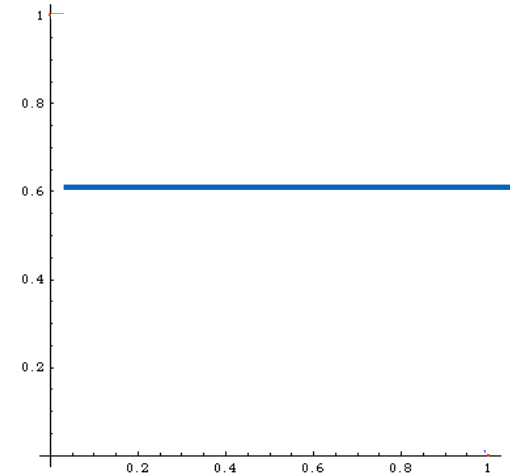
$$I = \int_0^1 dx \cos \frac{\pi}{2} x$$



$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$



$$\int dx C$$



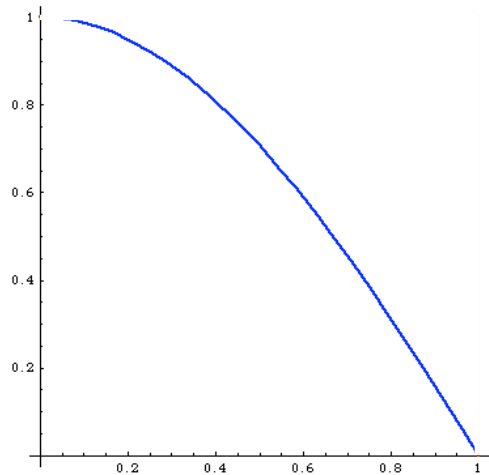
	simpson	MC
3	0,638	0,3
5	0,6367	0,8
20	0,63662	0,6
100	0,636619	0,65
1000	0,636619	0,636

Method of evaluation

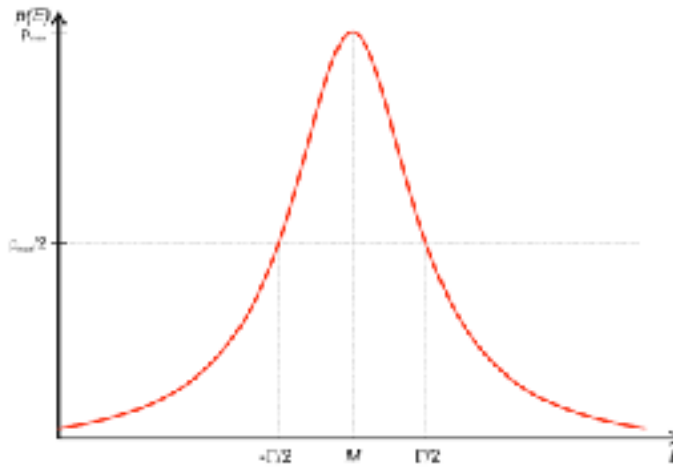
- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

Integration

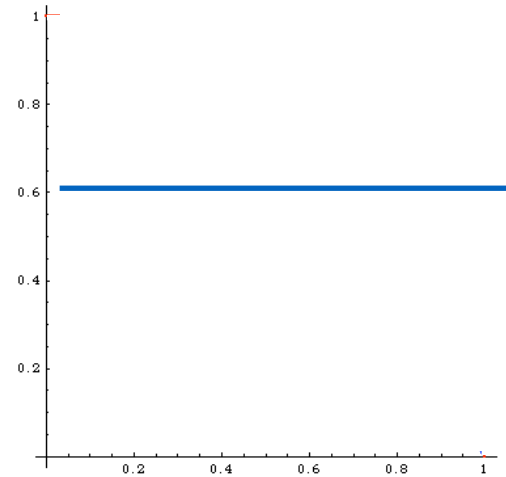
$$I = \int_0^1 dx \cos \frac{\pi}{2} x$$



$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$



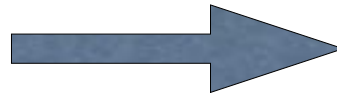
$$\int dx C$$



Method of evaluation

- MonteCarlo $1/\sqrt{N}$
- Trapezium $1/N^2$
- Simpson $1/N^4$

More Dimension



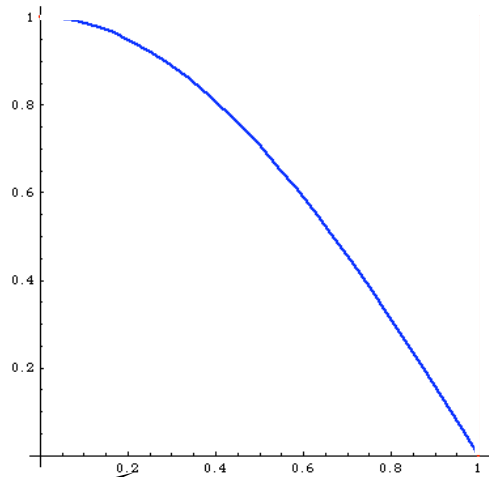
$$1/\sqrt{N}$$

$$1/N^{2/d}$$

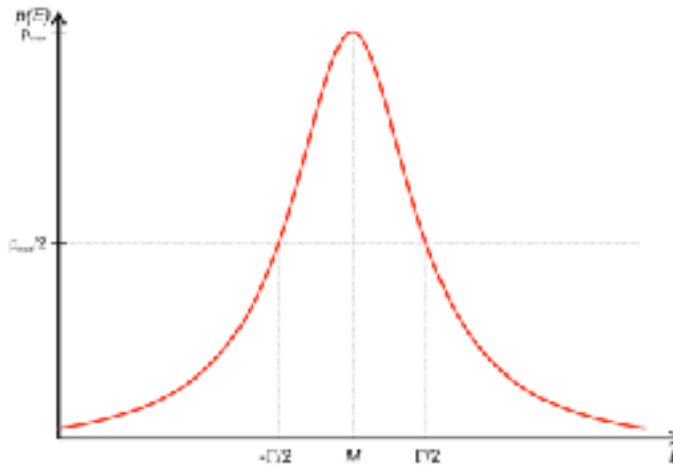
$$1/N^{4/d}$$

Integration

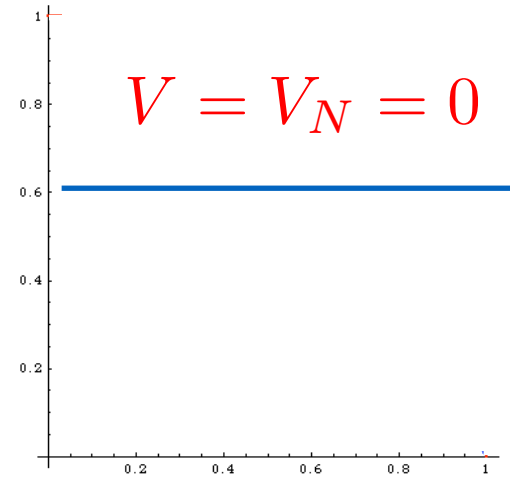
$$I = \int_0^1 dx \cos \frac{\pi}{2} x$$



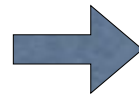
$$\int \frac{dq^2}{(q^2 - M^2 + iM\Gamma)^2}$$



$$\int dx C$$

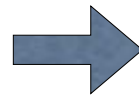


$$I = \int_{x_1}^{x_2} f(x) dx$$



$$I_N = (x_2 - x_1) \frac{1}{N} \sum_{i=1}^N f(x)$$

$$V = (x_2 - x_1) \int_{x_1}^{x_2} [f(x)]^2 dx - I^2$$

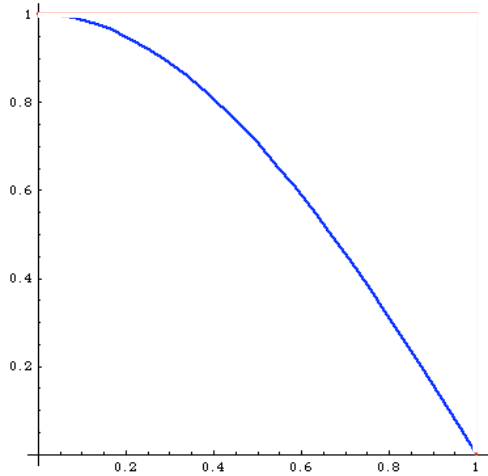


$$V_N = (x_2 - x_1)^2 \frac{1}{N} \sum_{i=1}^N [f(x)]^2 - I_N^2$$

$$I = I_N \pm \sqrt{V_N/N}$$

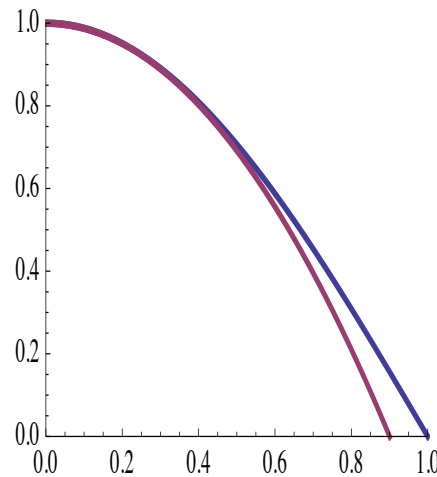
Can be minimized!

Importance Sampling



$$I = \int_0^1 dx \cos \frac{\pi}{2} x$$

$$I_N = 0.637 \pm 0.307/\sqrt{N}$$



$$I = \int_0^1 dx (1 - cx^2) \frac{\cos(\frac{\pi}{2}x)}{(1 - cx^2)} = \int_{\xi_1}^{\xi_2} d\xi \frac{\cos \frac{\pi}{2} x[\xi]}{1 - x[\xi]^2 c}$$

→ ≈ 1

$$I_N = 0.637 \pm 0.031/\sqrt{N} \quad \text{100 times faster}$$

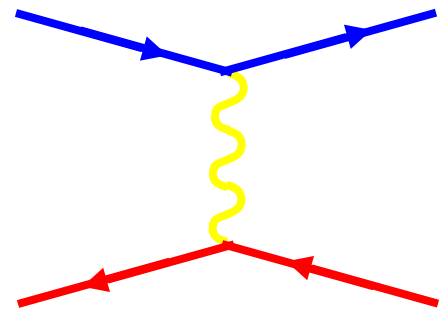
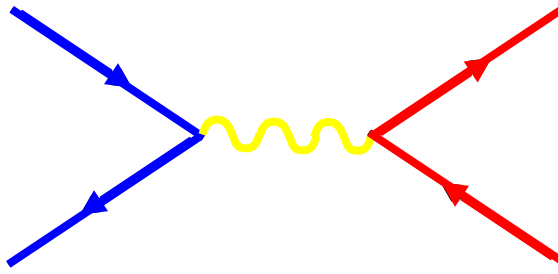
The Phase-Space parametrization is important to have an efficient computation!

Single Diagram Enhanced MadEvent

$$\sigma = \int |a_1 + a_2|^2 d(PS) = \int \frac{|a_1 + a_1|^2}{|a_1|^2 + |a_1|^2} |a_1|^2 d(PS) + \int \frac{|a_1 + a_1|^2}{|a_1|^2 + |a_1|^2} |a_2|^2 d(PS)$$

- **Key Idea**
 - Any single diagram is “easy” to integrate
 - Divide integration into pieces, based on diagrams
- **Get N independent integrals**
 - Errors add in quadrature so no extra cost
 - No need to calculate “weight” function from other channels.
 - Can optimize # of points for each one independently
 - Parallel in nature

MadEvent



- **User Requests:**

- Model (HiggsHeft)
- $pp \rightarrow a a$
- Cuts + Parameters

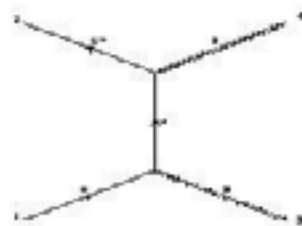
- **MadEvent Returns:**

- Feynman diagrams
- Complete package for event generation
- Events/Plots on line!



Created: Tue Jul 25 03:21:21 CDT 2017

Process: $p p > a a$
Model: sm



Links

[Process Information](#)

[Code Download](#)

[On-line Event Generation](#)

[Results and Event Database](#)

Status

Generation Complete

Available

Available (access restricted)

No runs available

Notes:

pp > a a

- **Generate SubProcesses+Diagrams**
 - **Use HiggsEFT model**
- **Generate Parton Level Plots**

Exercise



- **Generate parton level plot for the Higgs production to four lepton**
 - e.g. $g g \rightarrow h \rightarrow e^+ e^- \mu^+ \mu^-$ (use HiggsEFT)
- **List process for background and generate the associate partonic plot**
- **What is a strategy to observe the Higgs?**

Final Project

- Good News....we have discovered 3 new particles at the LHC (Z' , H , W^+) Your job is to determine their mass using the plots provided.
- Go to the wiki page to get the plots and determine which sample is which model:
- <https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/CernSummerSchool17>

Advice

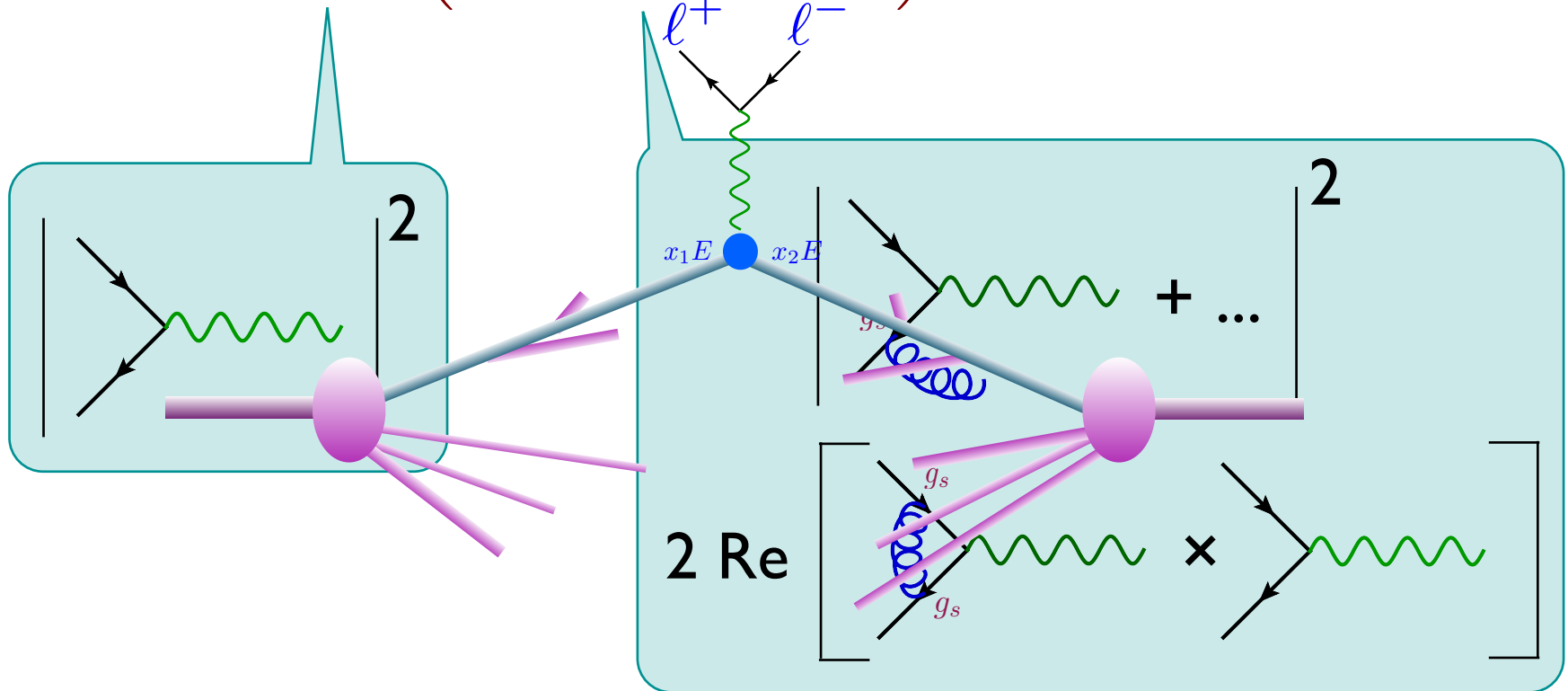
- A person who can efficiently calculate cross sections can be useful to a collaboration
- A person who can efficiently calculate the **CORRECT** cross section is **ESSENTIAL** to a collaboration

NLO predictions

- As an example, consider **Drell-Yan Z/γ^* production**

$$M \approx \langle \mu^+ \mu^- | H_{\text{int}} | e^+ e^- \rangle + \frac{1}{2} \langle \mu^+ \mu^- | H_{\text{int}}^2 | e^+ e^- \rangle + \dots$$

$$\hat{\sigma} = \sigma^{\text{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \dots \right)$$



Conclusions

- Standard Model is Amazing (good news)
- S.M. is tough to Solve (good news!)
 - Factorization allows use of Perturbation Theory
 - Feynman Diagrams help
 - MG5aMC can help too
- LHC requires NLO (at least for the SM)
 - MG5aMC can help here too !!
- Good Luck!