Plan

- Field theory : a short reminder
    - free fields (KG details, Fermion)
    - Scattering matrix in perturbation
    - Wick theorem to Feynman rules
- Why Monte-Carlo/automated tools?
- Lagrangian to the Feynman rules
    - Model file : Parameters, fields, gauge group and Lagrangian
    - Running FeynRules
- Demo

C. Degrande

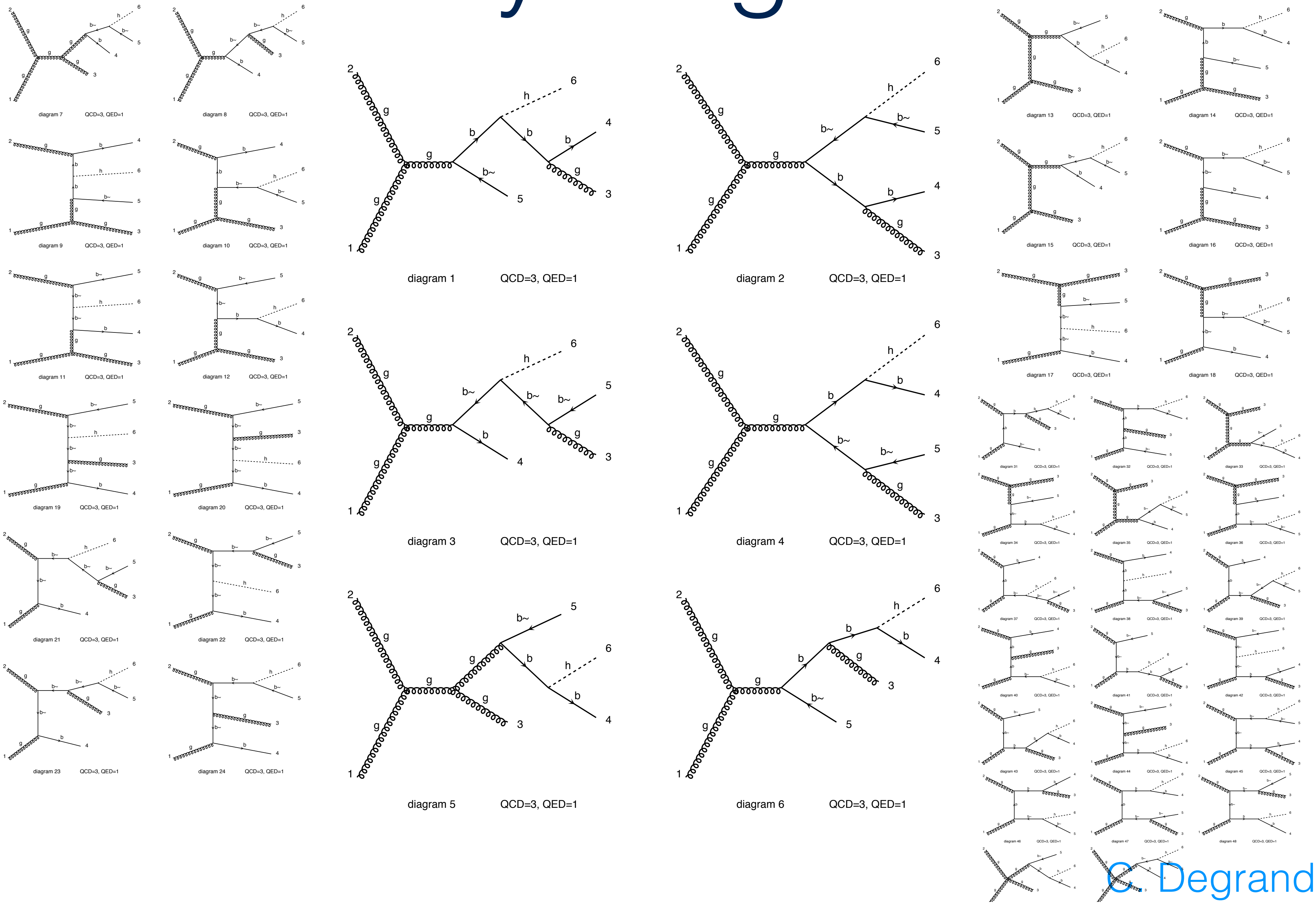
Why automated tools

- Algorithmic
- Less error prone
- Long $f^{abc}G^a_{\mu\nu}G^{b\nu\rho}G^{c\mu}_{\rho} \ni$ 4 gluons vertex

$$
\begin{aligned}
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_4}\mathrm{p}_2^{\mu_3}\eta_{\mu_1,\mu_2}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_3}\mathrm{p}_2^{\mu_4}\eta_{\mu_1,\mu_2}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_3}\mathrm{p}_3^{\mu_4}\eta_{\mu_1,\mu_2}+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_2^{\mu_3}\mathrm{p}_3^{\mu_4}\eta_{\mu_1,\mu_2}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_1^{\mu_4}\mathrm{p}_4^{\mu_3}\eta_{\mu_1,\mu_2}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_2^{\mu_4}\mathrm{p}_4^{\mu_3}\eta_{\mu_1,\mu_2}-\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\eta_{\mu_3,\mu_4}\mathrm{p}_1\cdot\mathrm{p}_3\eta_{\mu_1,\mu_2}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\eta_{\mu_3,\mu_4}\mathrm{p}_1\cdot\mathrm{p}_4\eta_{\mu_1,\mu_2}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\eta_{\mu_3,\mu_4}\mathrm{p}_2\cdot\mathrm{p}_3\eta_{\mu_1,\mu_2}-\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\eta_{\mu_3,\mu_4}\mathrm{p}_2\cdot\mathrm{p}_4\eta_{\mu_1,\mu_2}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_2}\mathrm{p}_2^{\mu_4}\eta_{\mu_1,\mu_3}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_4}\mathrm{p}_3^{\mu_2}\eta_{\mu_1,\mu_3}-\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_2^{\mu_4}\mathrm{p}_3^{\mu_2}\eta_{\mu_1,\mu_3}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_2}\mathrm{p}_3^{\mu_4}\eta_{\mu_1,\mu_3}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_1^{\mu_4}\mathrm{p}_4^{\mu_2}\eta_{\mu_1,\mu_3}+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_3^{\mu_4}\mathrm{p}_4^{\mu_2}\eta_{\mu_1,\mu_3}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_2}\mathrm{p}_2^{\mu_3}\eta_{\mu_1,\mu_4}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_3}\mathrm{p}_3^{\mu_2}\eta_{\mu_1,\mu_4}+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_1^{\mu_3}\mathrm{p}_4^{\mu_2}\eta_{\mu_1,\mu_4}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_2^{\mu_3}\mathrm{p}_4^{\mu_2}\eta_{\mu_1,\mu_4}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_1^{\mu_2}\mathrm{p}_4^{\mu_3}\eta_{\mu_1,\mu_4}-\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_3^{\mu_2}\mathrm{p}_4^{\mu_3}\eta_{\mu_1,\mu_4}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_4}\mathrm{p}_2^{\mu_1}\eta_{\mu_2,\mu_3}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_4}\mathrm{p}_3^{\mu_1}\eta_{\mu_2,\mu_3}+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_2^{\mu_4}\mathrm{p}_3^{\mu_1}\eta_{\mu_2,\mu_3}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_2^{\mu_1}\mathrm{p}_3^{\mu_4}\eta_{\mu_2,\mu_3}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_2^{\mu_4}\mathrm{p}_4^{\mu_1}\eta_{\mu_2,\mu_3}-\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_3^{\mu_4}\mathrm{p}_4^{\mu_1}\eta_{\mu_2,\mu_3}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_3}\mathrm{p}_2^{\mu_1}\eta_{\mu_2,\mu_4}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_2^{\mu_3}\mathrm{p}_3^{\mu_1}\eta_{\mu_2,\mu_4}-\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_1^{\mu_3}\mathrm{p}_4^{\mu_1}\eta_{\mu_2,\mu_4}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_2^{\mu_3}\mathrm{p}_4^{\mu_1}\eta_{\mu_2,\mu_4}-6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_2^{\mu_1}\mathrm{p}_4^{\mu_3}\eta_{\mu_2,\mu_4}+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_3^{\mu_1}\mathrm{p}_4^{\mu_3}\eta_{\mu_2,\mu_4}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_1^{\mu_2}\mathrm{p}_3^{\mu_1}\eta_{\mu_3,\mu_4}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_2^{\mu_1}\mathrm{p}_3^{\mu_2}\eta_{\mu_3,\mu_4}+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\mathrm{p}_1^{\mu_2}\mathrm{p}_4^{\mu_1}\eta_{\mu_3,\mu_4}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_3^{\mu_2}\mathrm{p}_4^{\mu_1}\eta_{\mu_3,\mu_4}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\mathrm{p}_2^{\mu_1}\mathrm{p}_4^{\mu_2}\eta_{\mu_3,\mu_4}-\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\mathrm{p}_3^{\mu_1}\mathrm{p}_4^{\mu_2}\eta_{\mu_3,\mu_4}+6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}\mathrm{p}_1\cdot\mathrm{p}_2-6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}\mathrm{p}_1\cdot\mathrm{p}_2+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}\mathrm{p}_1\cdot\mathrm{p}_3+6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}\mathrm{p}_1\cdot\mathrm{p}_4+6ig_s f_{\mathrm{a}_1,\mathrm{a}_4,a}f_{\mathrm{a}_2,\mathrm{a}_3,a}\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}\mathrm{p}_2\cdot\mathrm{p}_3+\\
&6ig_s f_{\mathrm{a}_1,\mathrm{a}_3,a}f_{\mathrm{a}_2,\mathrm{a}_4,a}\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}\mathrm{p}_2\cdot\mathrm{p}_4+6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}\mathrm{p}_3\cdot\mathrm{p}_4-6ig_s f_{\mathrm{a}_1,\mathrm{a}_2,a}f_{\mathrm{a}_3,\mathrm{a}_4,a}\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}\mathrm{p}_3\cdot\mathrm{p}_4
\end{aligned}
$$

C. Degrande

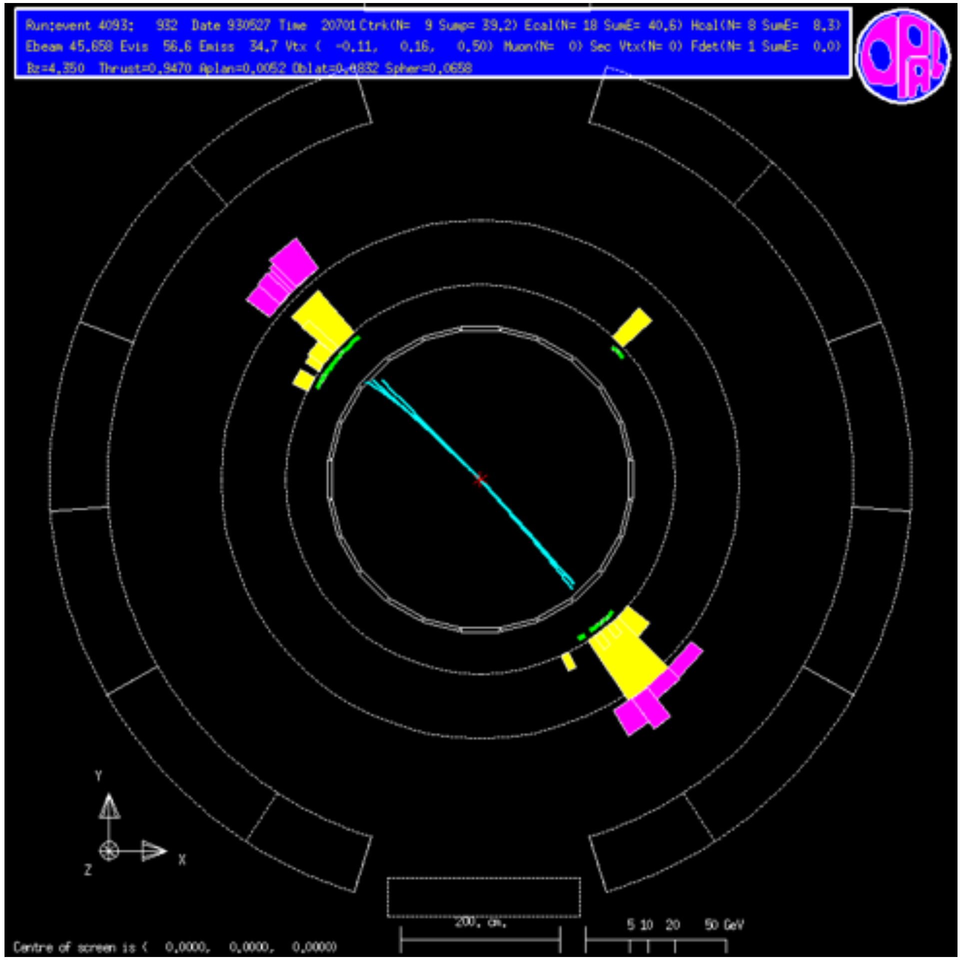
Many diagrams



C. Degrande

Hadron colliders

LEP



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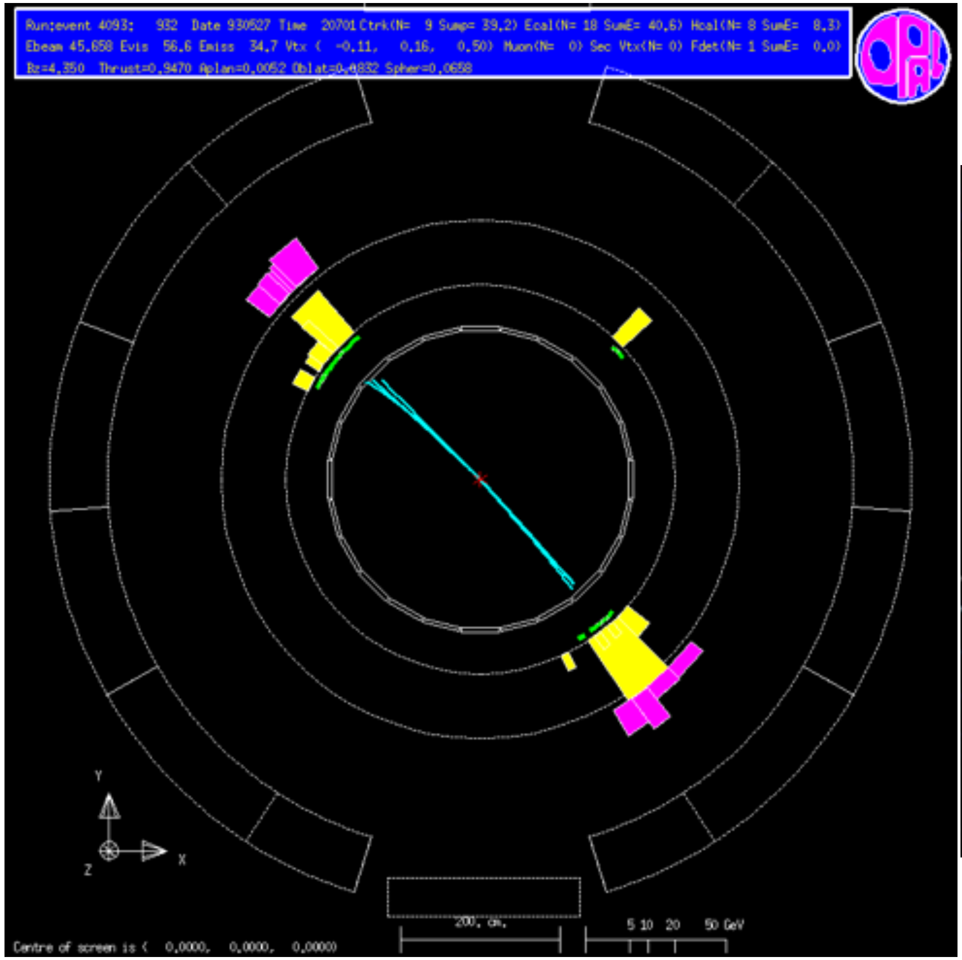
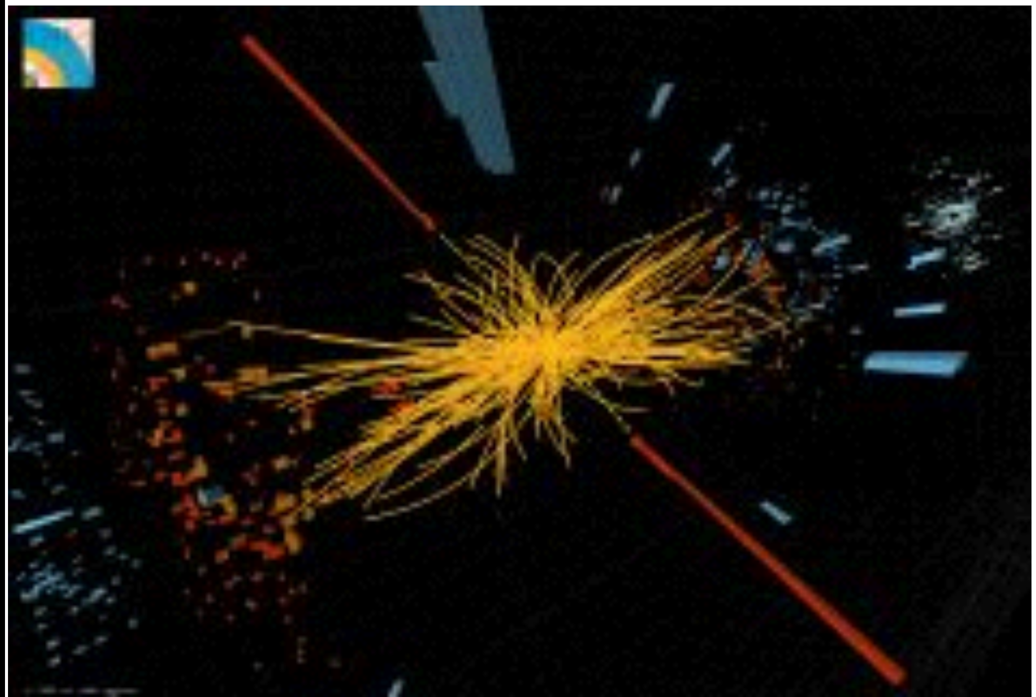
Hadron colliders

LEP

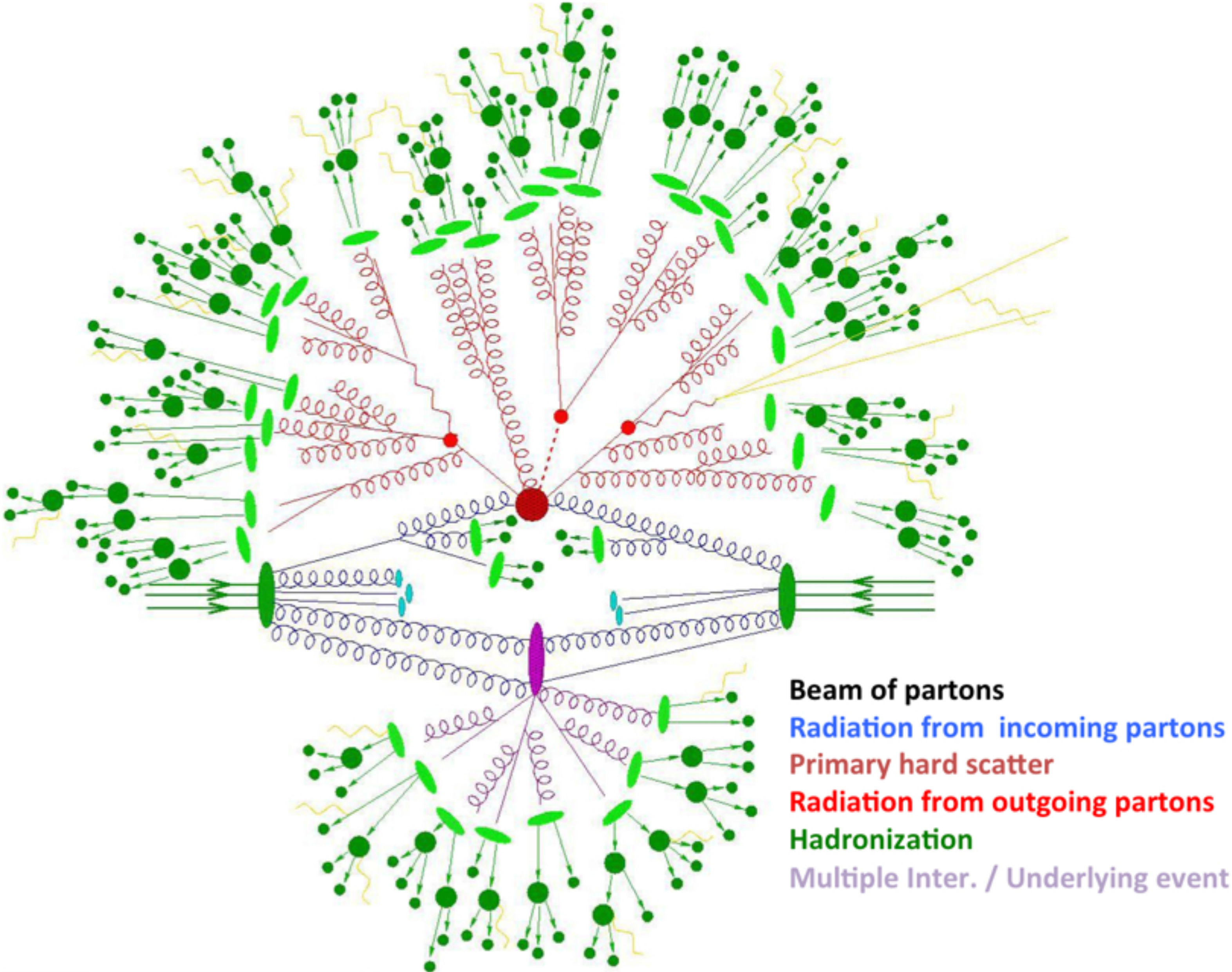


LHC



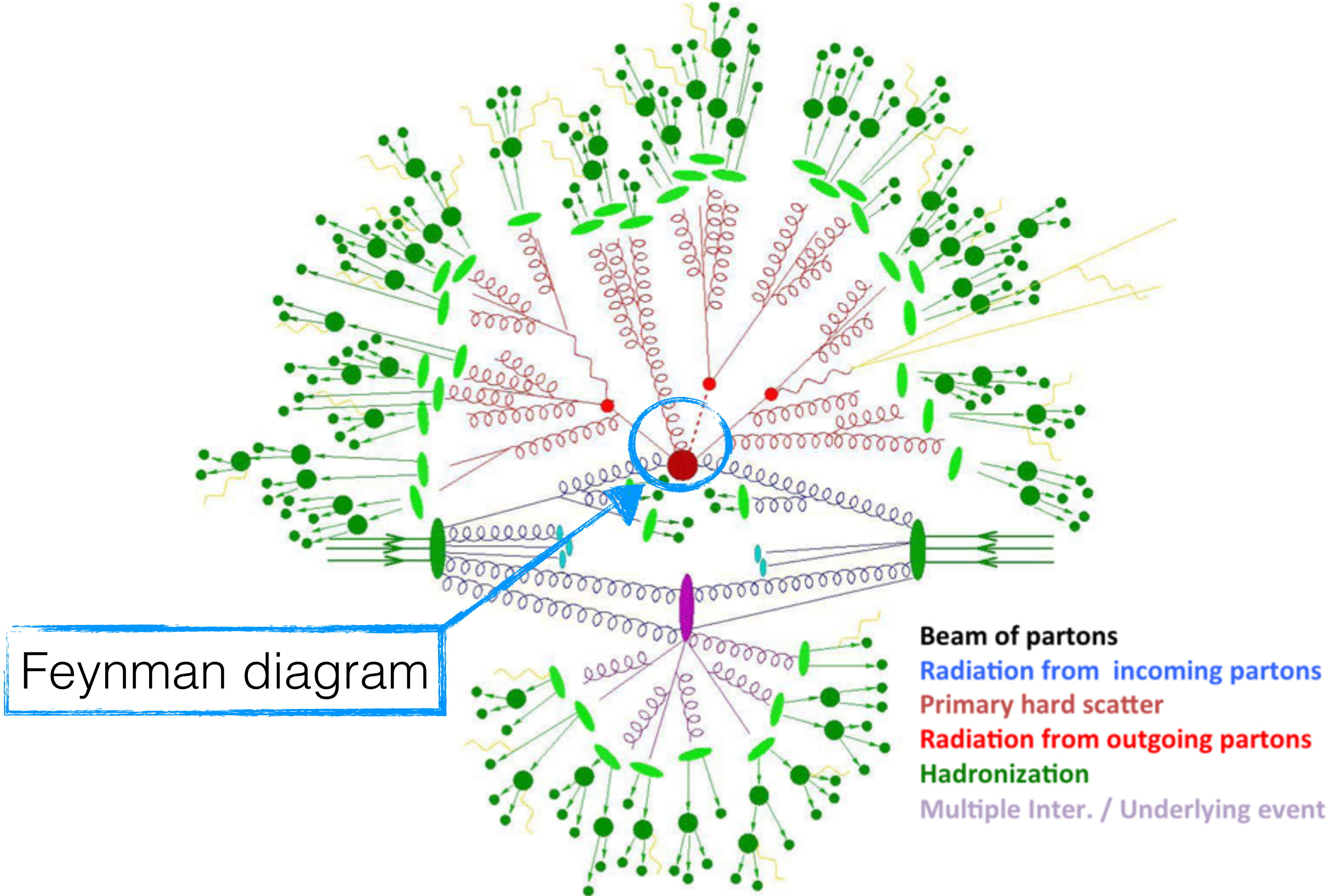
C. Degrande

Hadron collider event



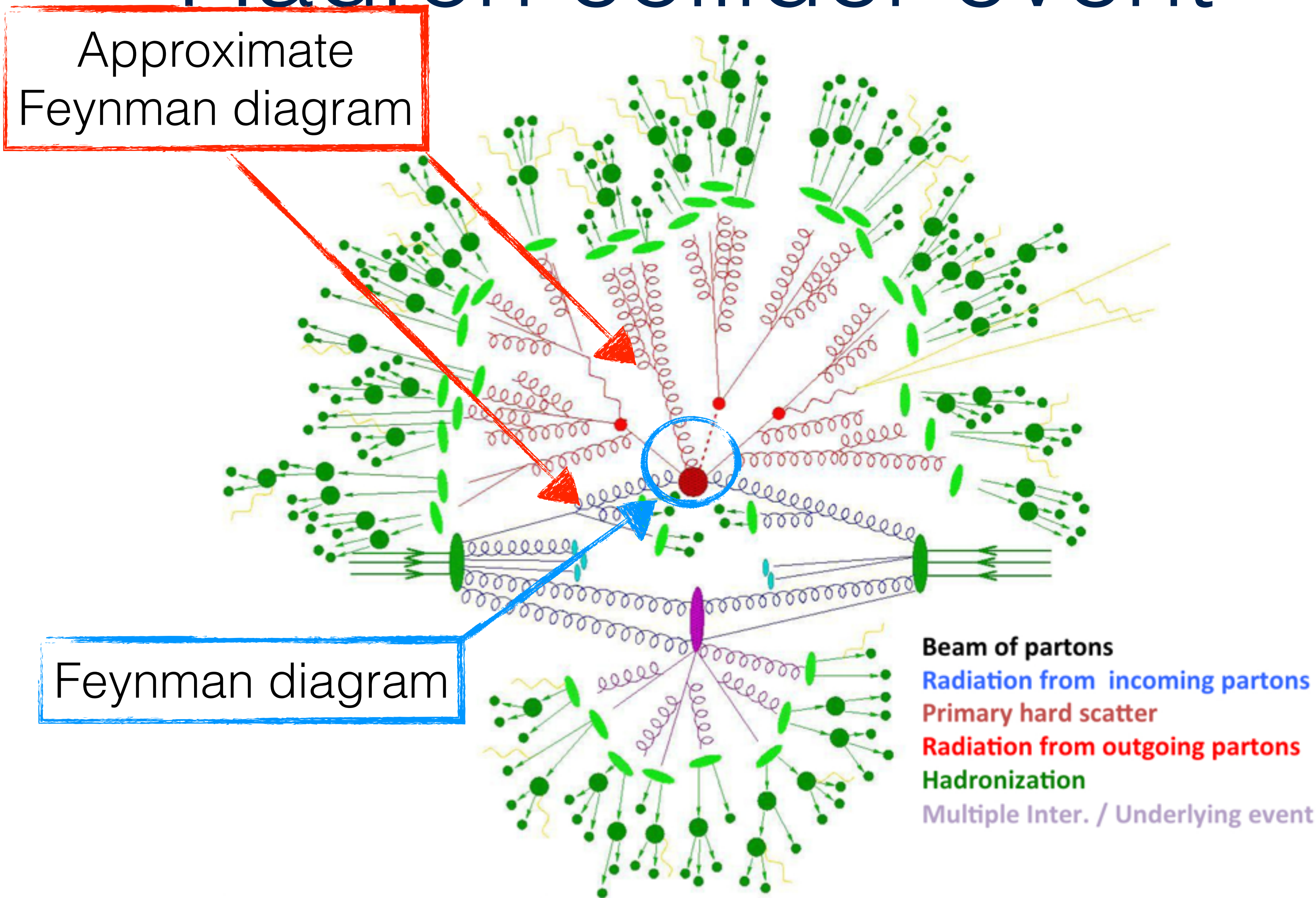
C. Degrande

Hadron collider event

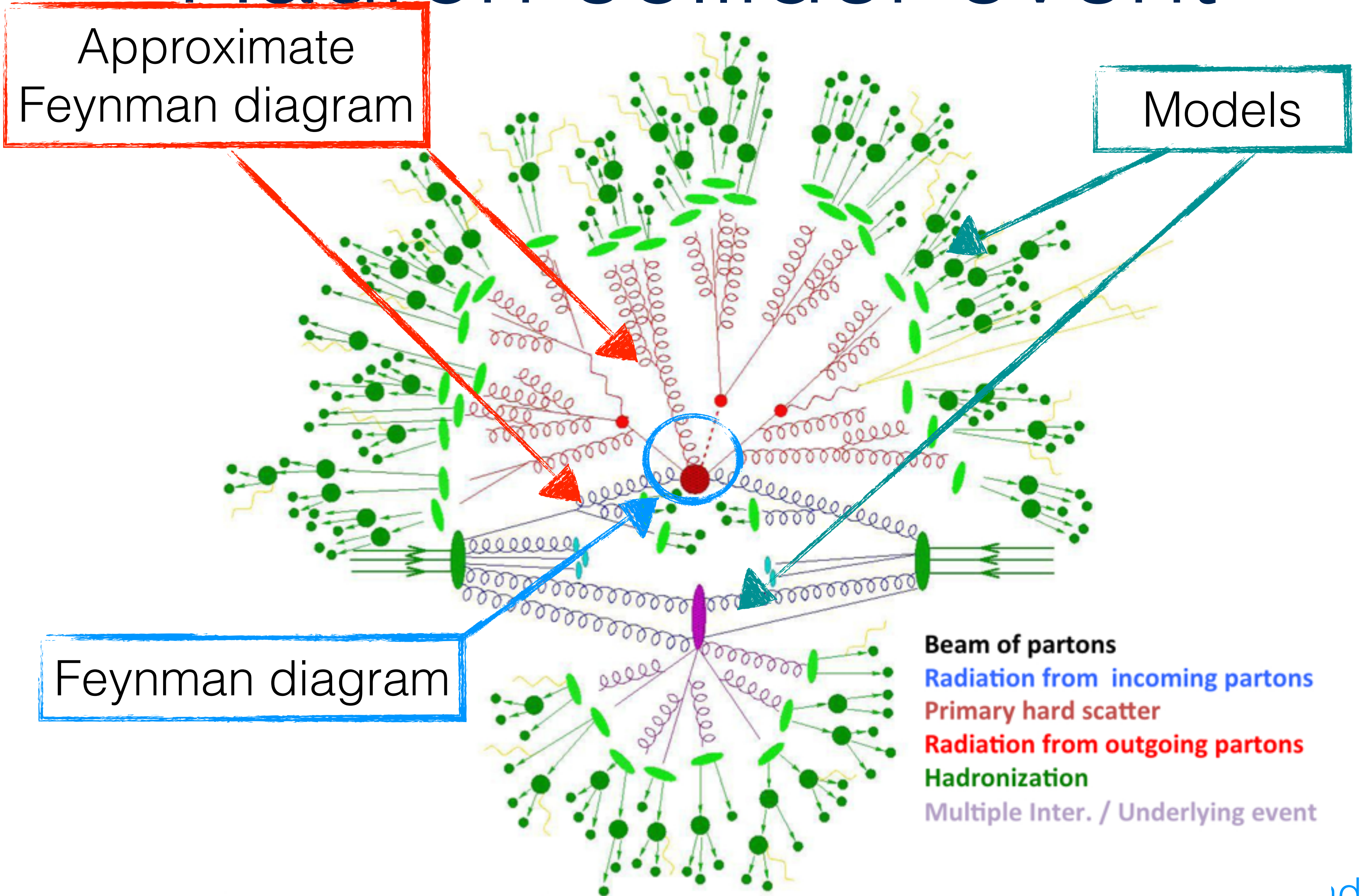


C. Degrande

Hadron collider event



Hadron collider event



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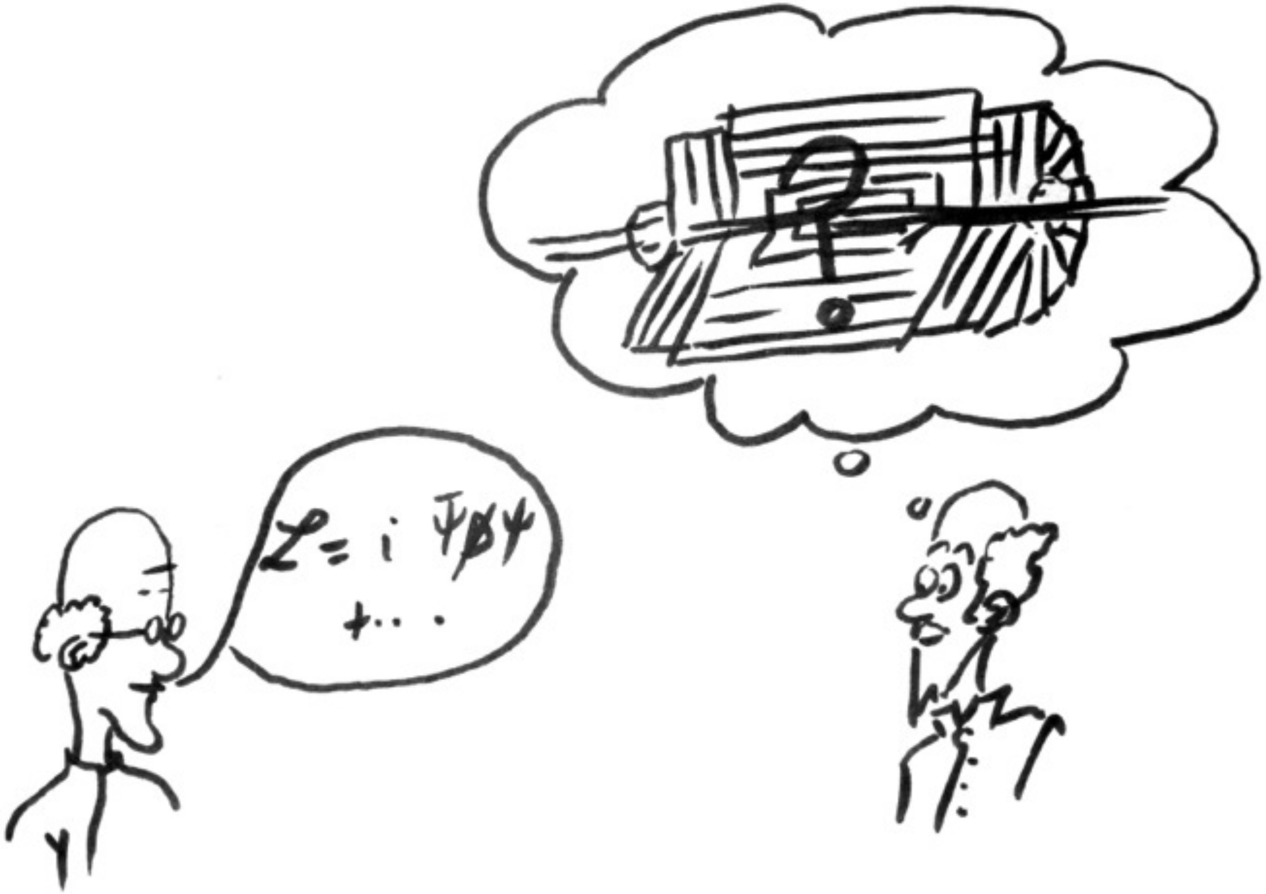
Why BSM simulation?



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BSM simulation

Detector events

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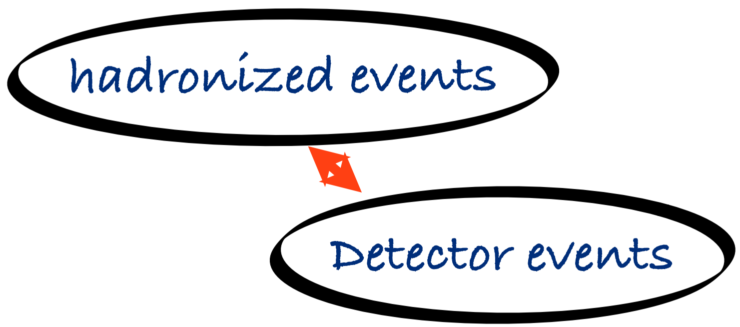
BSM simulation



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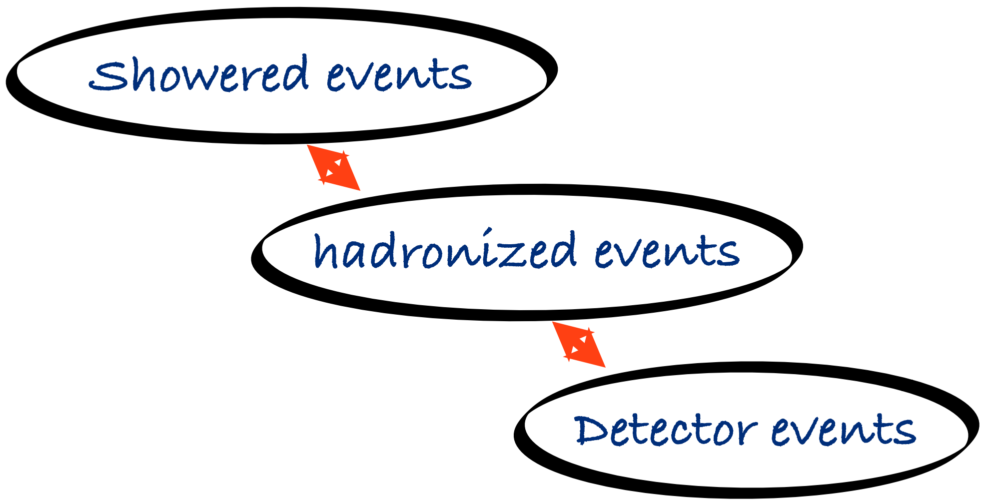
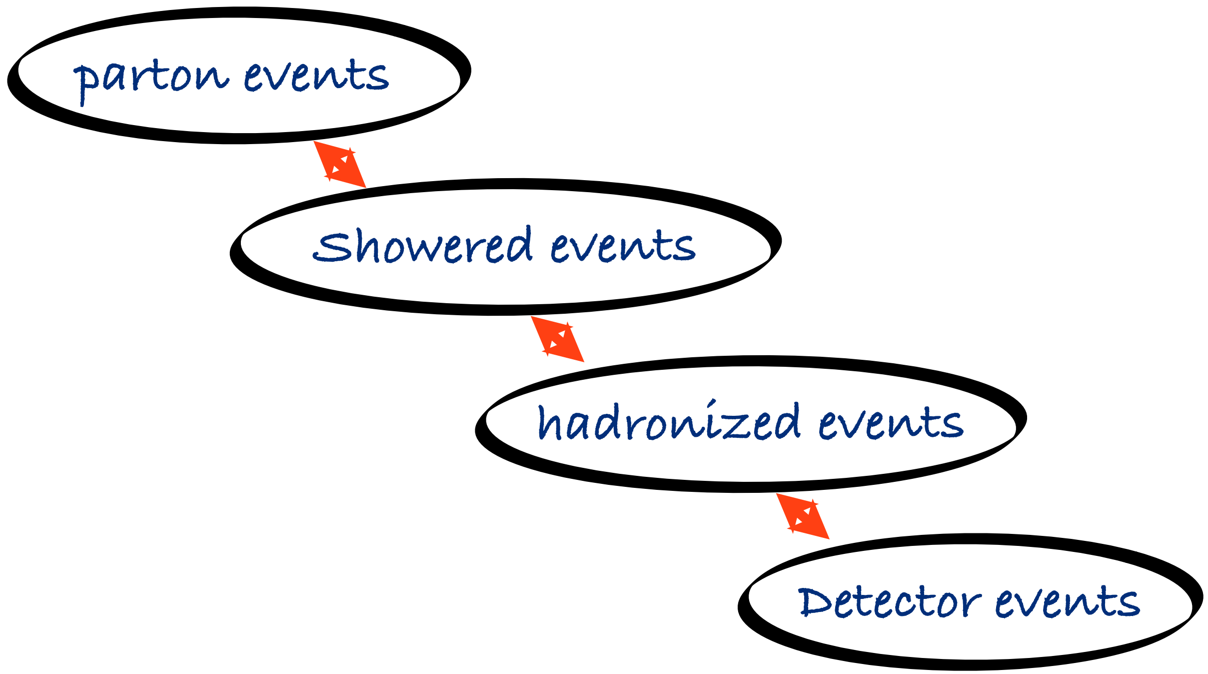
BSM simulation



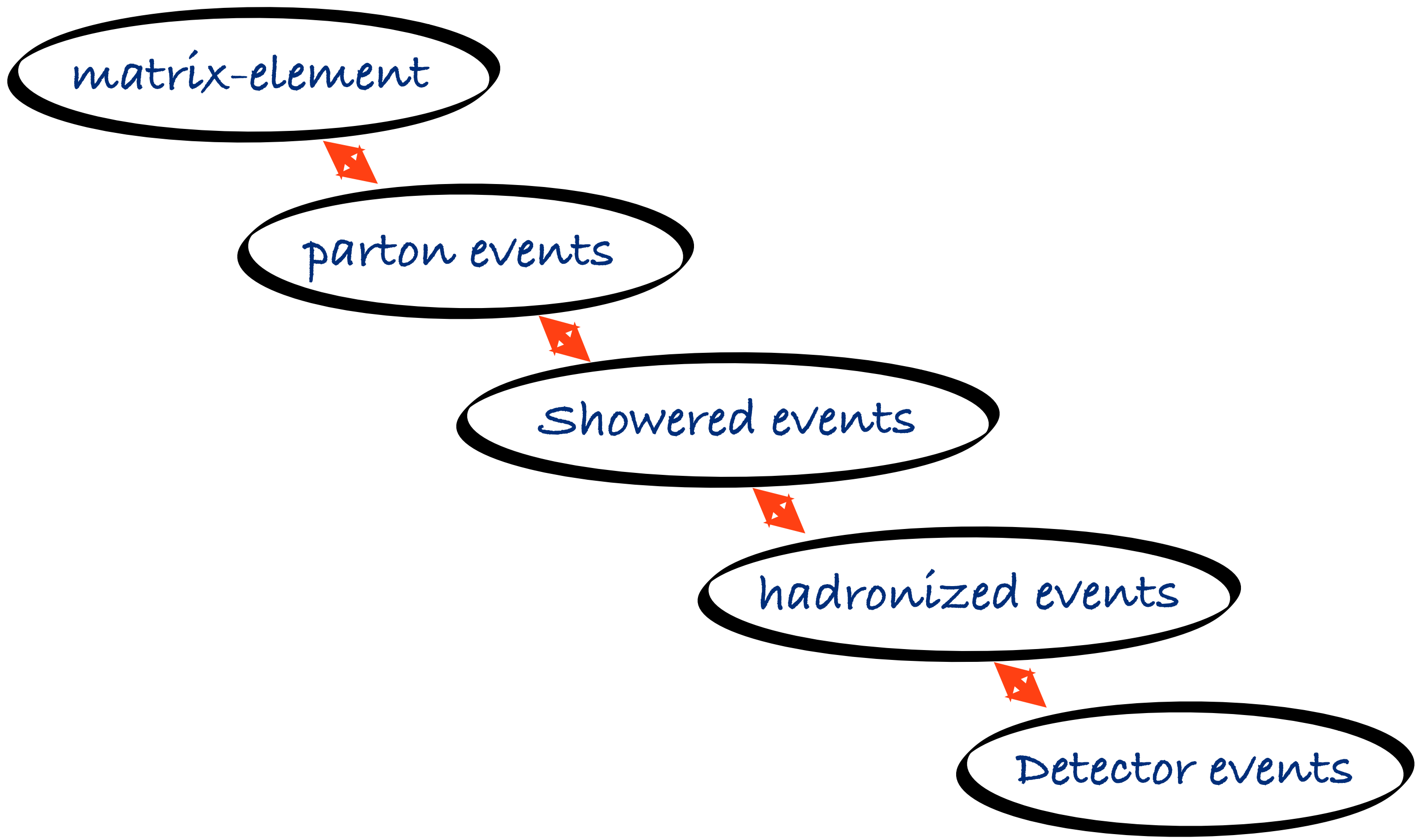
C. Degrande

BSM simulation



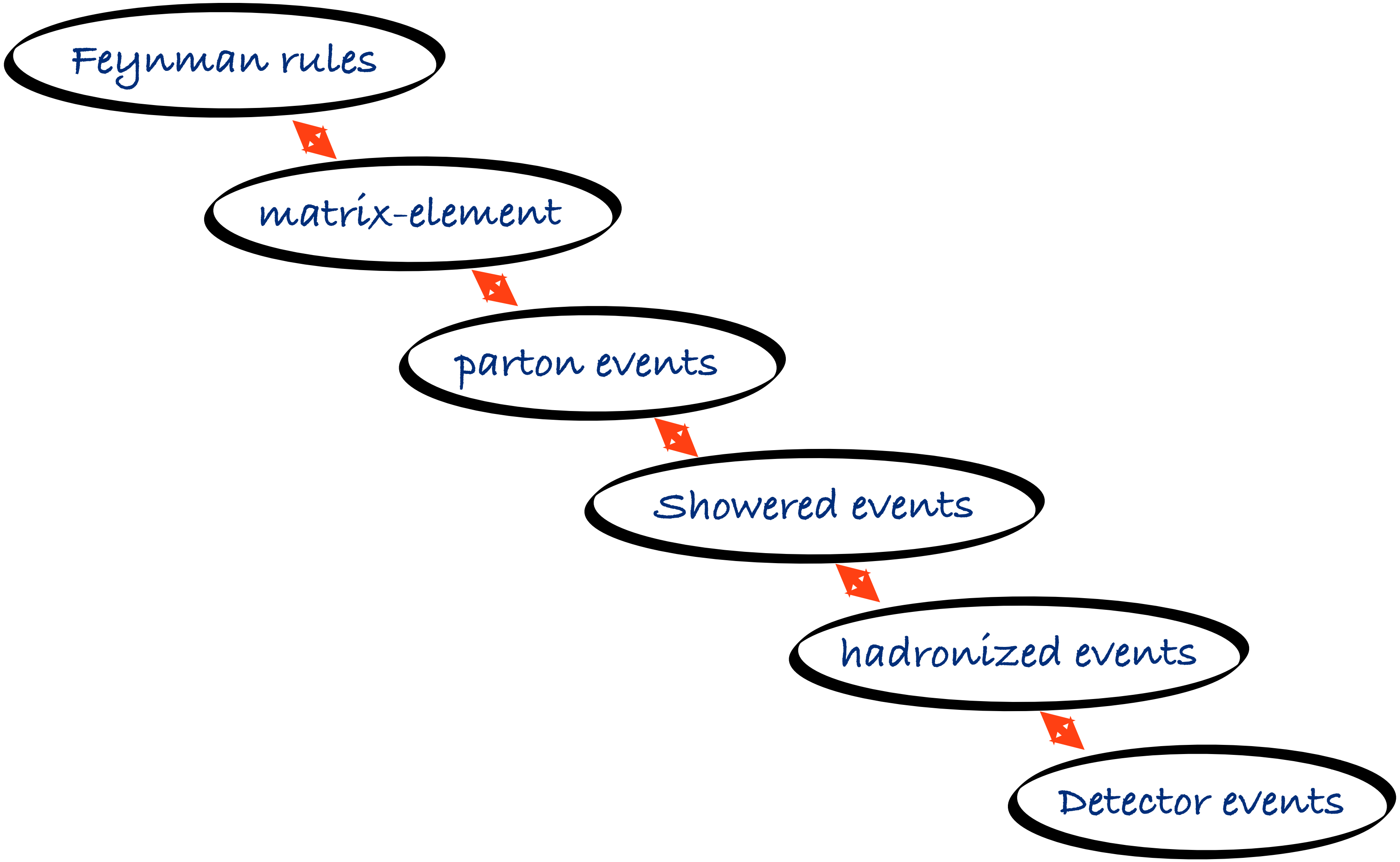
C. Degrande

BSM simulation



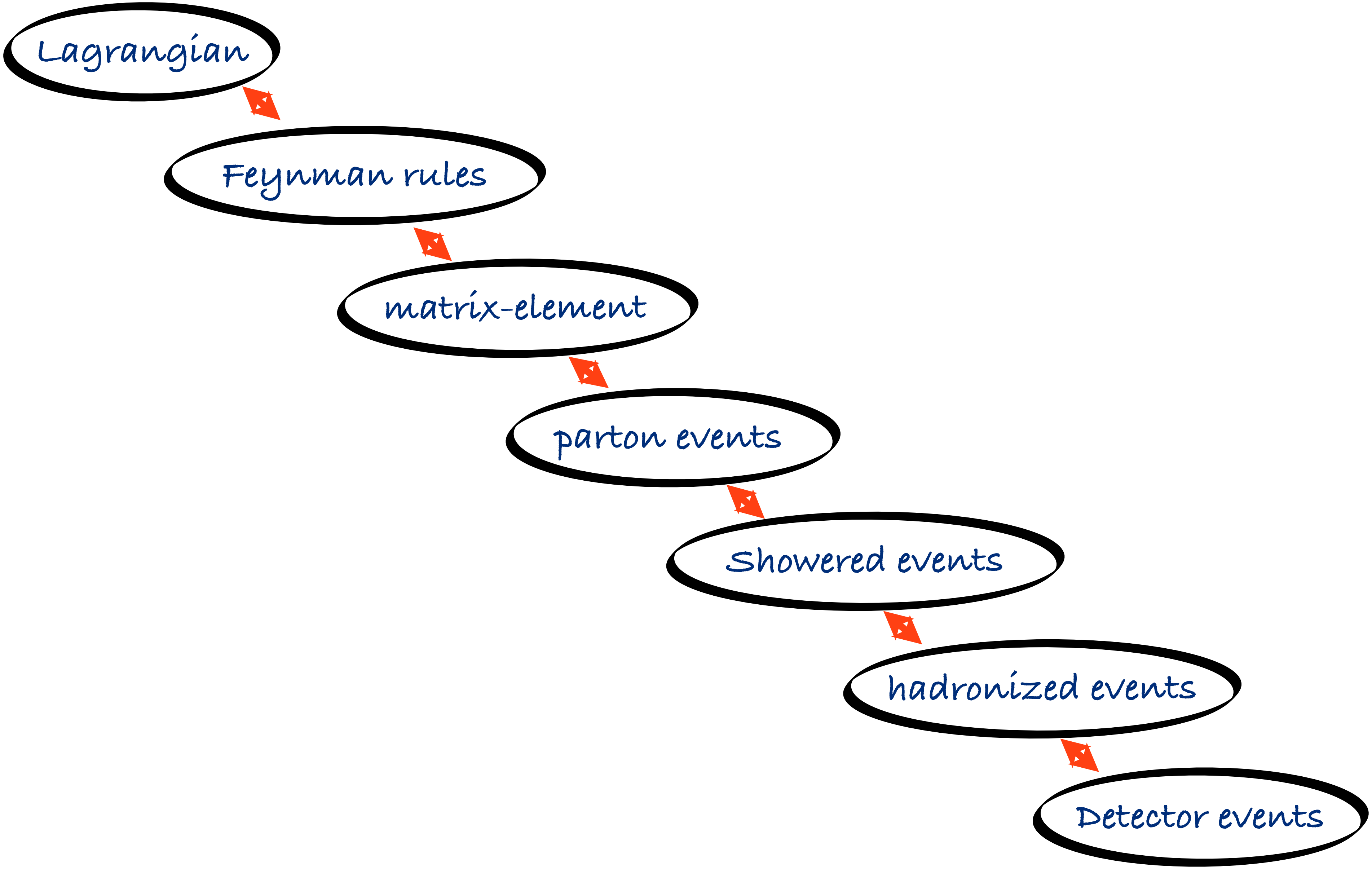
C. Degrande

BSM simulation



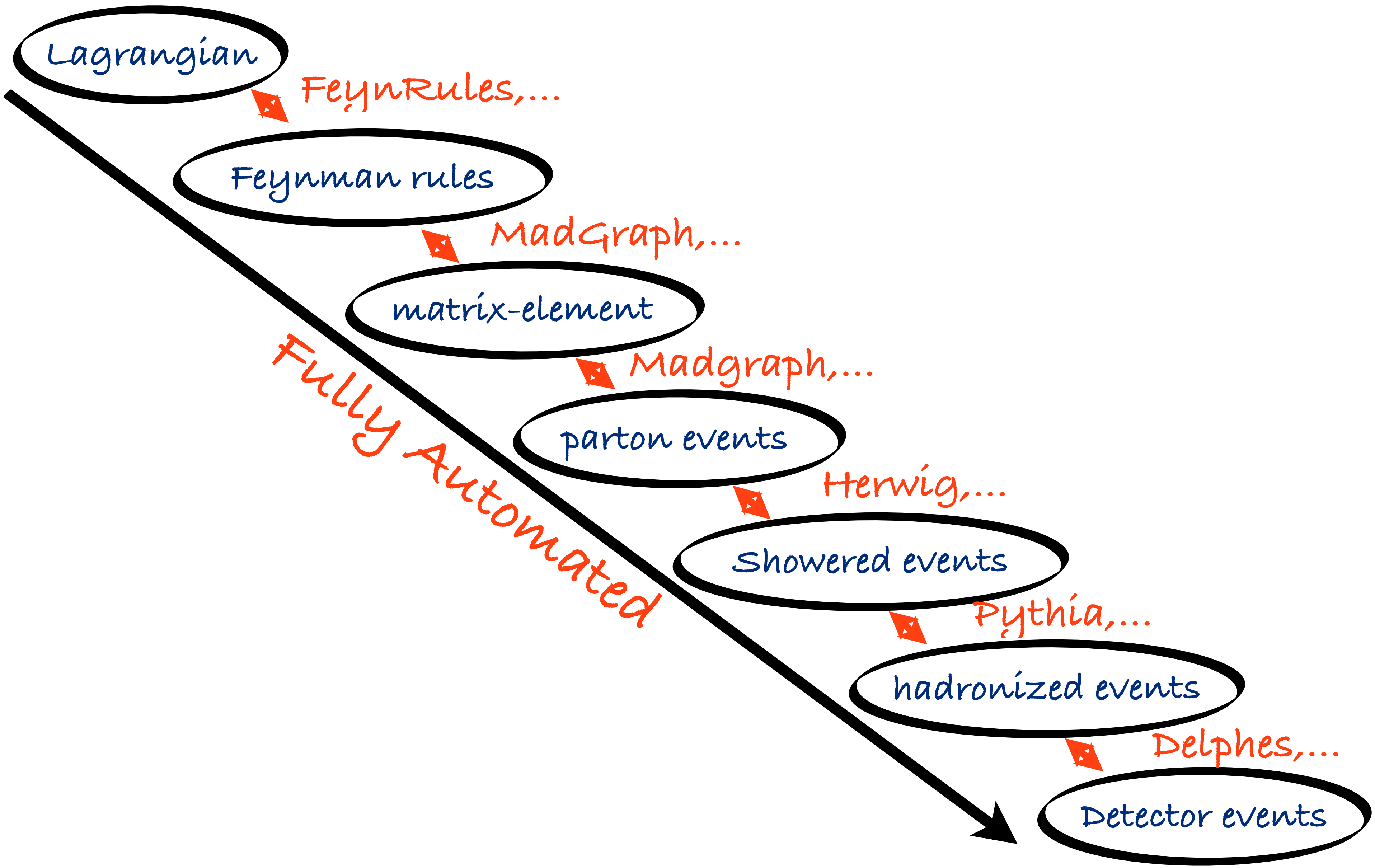
C. Degrande

BSM simulation



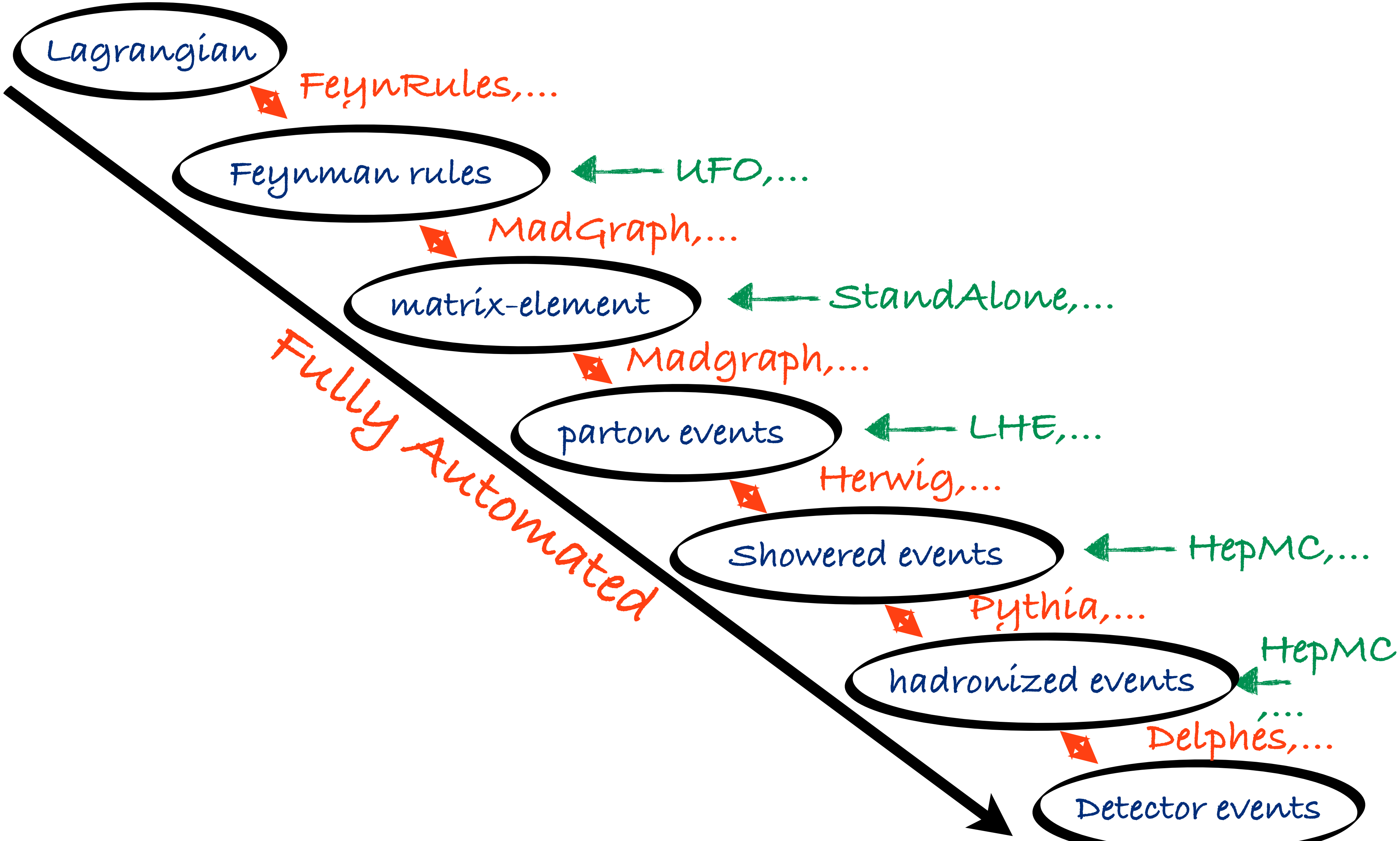
C. Degrande

BSM simulation



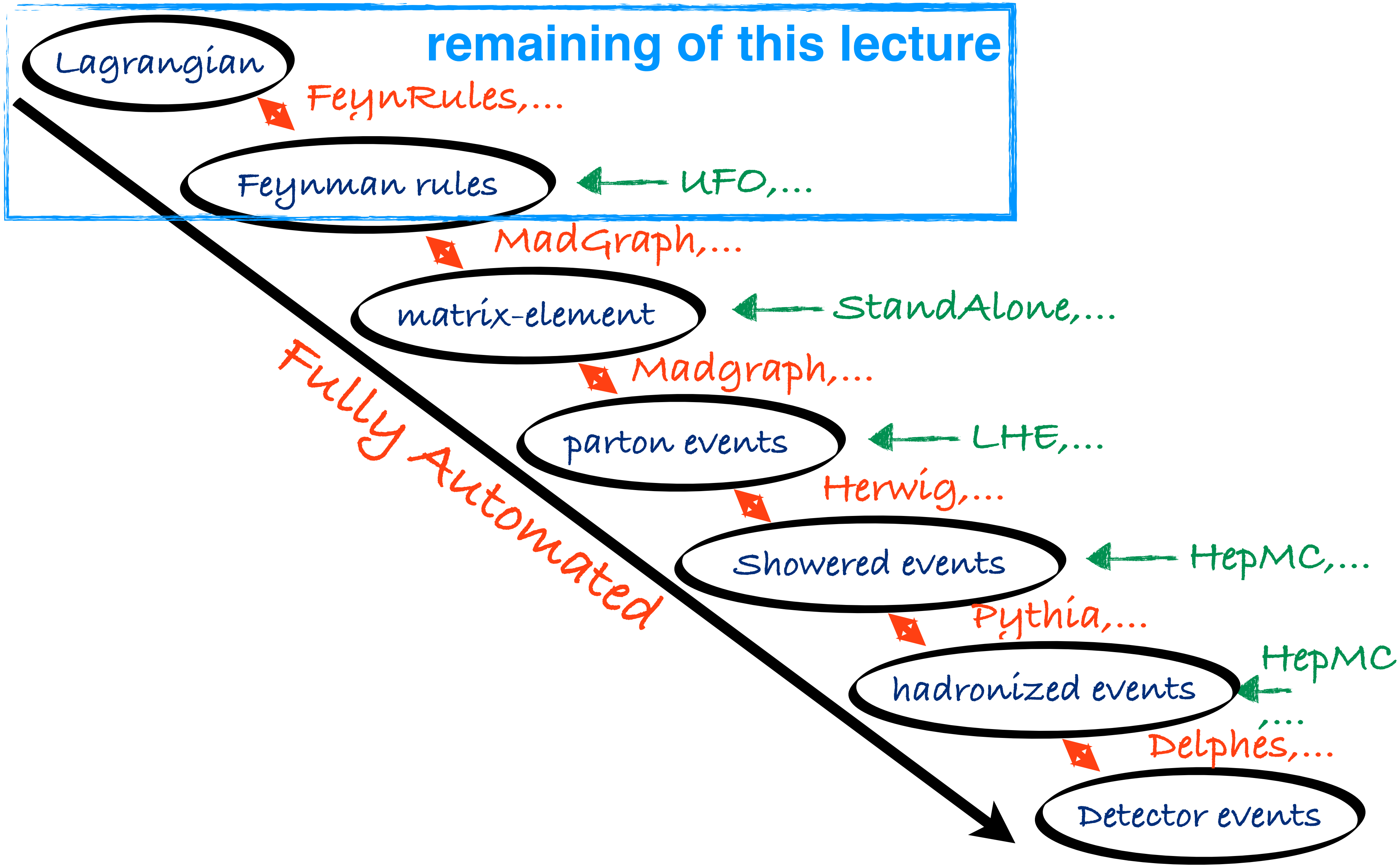
C. Degrande

BSM simulation



C. Degrande

BSM simulation



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Plan

- Field theory : a short reminder
    - free fields (KG details, Fermion)
    - Scattering matrix in perturbation
    - Wick theorem to Feynman rules
- Why Monte-Carlo/automated tools?
- Lagrangian to the Feynman rules
    - Model file : Parameters, fields, gauge group and Lagrangian
    - Running FeynRules
- Demo

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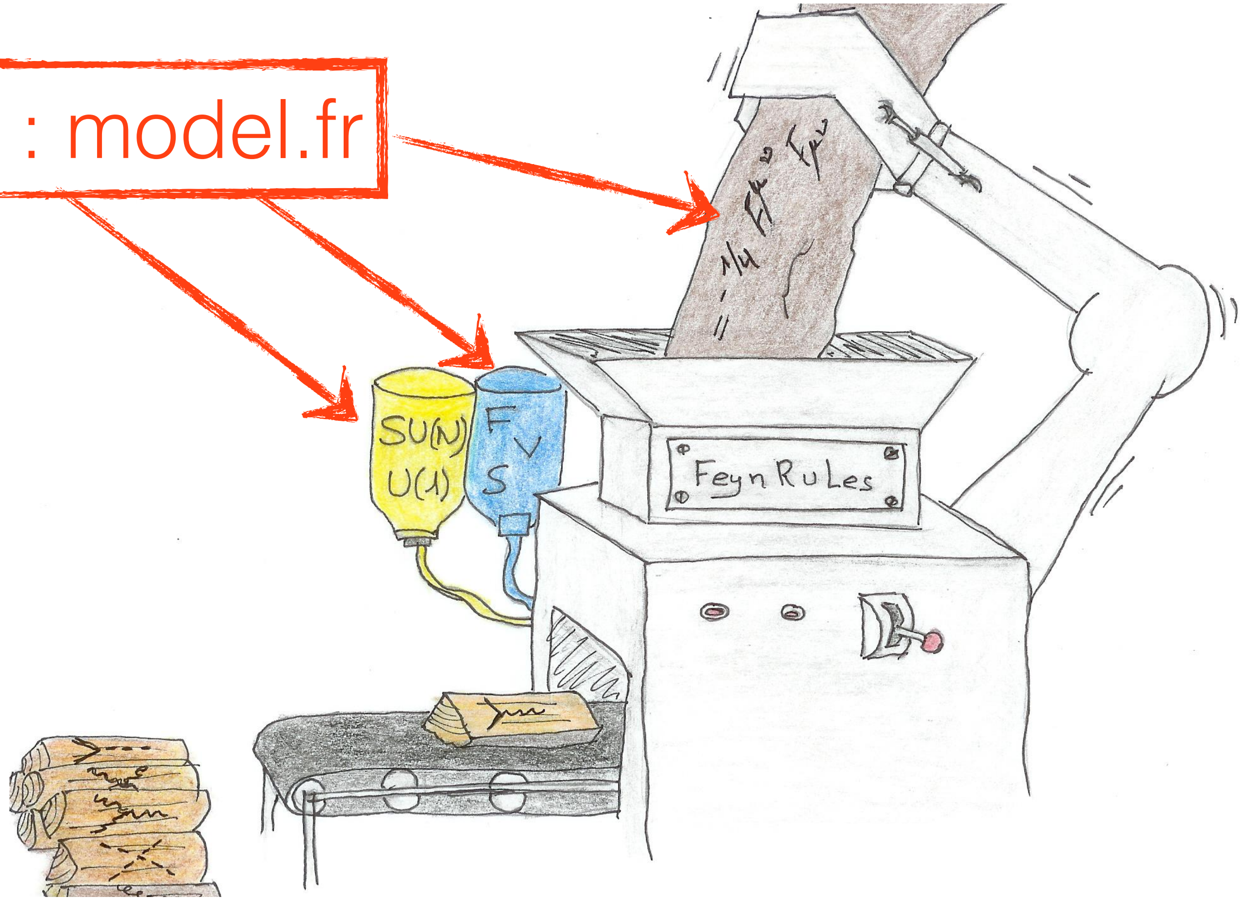
FeynRules in a nutshell

Input : model.fr



Output : vertices

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FeynRules structure

FeynRules

- Core: Main functions
- Interfaces: Translation to ME
- Models
- FeynRules.m
- FeynRulesPackage.m
- ToolBox.m
- FRPalette.nb

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FeynRules structure

FeynRules

- Core: Main functions
- Interfaces: Translation to ME
- Models
  - SM
  - template.fr
- FeynRules.m
- FeynRulesPackage.m
- ToolBox.m
- FRPalette.nb

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model file

```
(**************** This is a template model file for FeynRules ***********)

(********** Index definition *********)

IndexRange[ Index[Generation] ] = Range[3]

IndexFormat[Generation, f]

(***** Parameter list ******)

M$Parameters = {
}
(***** Gauge group list ******)

M$GaugeGroups = {
}
(***** Particle classes list ******)

M$ClassesDescription = {
}
```

Definition of variables
in Mathematica syntaxe

C. Degrande

Model information

```
M$ModelName = "my_new_model";

M$Information = {
          Authors      -> {"Mr. X", "Ms. Y"},
          Institutions -> {"UC Louvain"},
          Emails       -> {"X@uclouvain.be", "Y@uclouvain.be},
          Date         -> "01.03.2013",
          References   -> {"reference 1", "reference 2"},
          URLs         -> {"http://feynrules.irmp.ucl.ac.be"},
          Version      -> "1.0"
                };
```

Good practice for credit, issue(s) tracking

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Indices definition

Used in parameters, gauge groups and fields

Tells FR to remplace summed indices by the explicite sum

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

C. Degrande

Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

Format:

```
IndexStyle[ Colour, i ];
IndexStyle[ Gluon, a ];
```

Indices definition

Used in parameters, gauge groups and fields

```
IndexRange[ Index[Colour] ] = Range[3];
IndexRange[ Index[SU2W] ]  = Unfold[ Range[3] ];
IndexRange[ Index[Gluon] ]  = NoUnfold[ Range[8] ];
```

Tells FR to remplace summed indices by the explicite sum

Tells FA/FC **not** to remplace summed indices by the explicite sum

Format:

```
IndexStyle[ Colour, i ];
IndexStyle[ Gluon, a ];
```

Predefined indices: Lorentz, Spin, Spin1, Spin2

C. Degrande

Parameters definition

```
M$Parameters = {
   param1 == { options1 },
   param2 == { options2 },
              ...
};
```

```
aEWM1 == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 1,
   Value            -> 127.9,
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
  },
```

Numerical value

Compulsory!

C. Degrande

Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
            ...
};
```

```
MW == {
  ParameterType -> Internal,
  Value       -> Sqrt[MZ^2/2+Sqrt[MZ^4/4-Pi/Sqrt[2]*aEW/
Gf*MZ^2]],
  TeX         -> Subscript[M,W],
  Description -> "W mass"
 },
```

Expression

Parameters definition

```
M$Parameters = {
   param1 == { options1 },
   param2 == { options2 },
              ...
};
```

```
aEWM1 == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 1,
   Value            -> 127.9,
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z
pole"
  },
```

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Parameters definition

```
M$Parameters = {
   param1 == { options1 },
   param2 == { options2 },
              ...
};
```

```
aEWM1 == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 1,
   Value            -> 127.9,
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
  },
```

For the LHA cards

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Parameters definition

```
M$Parameters = {
   param1 == { options1 },
   param2 == { options2 },
              ...
};
```

```
aEWM1 == {
   ParameterType    -> External,
   BlockName        -> SMINPUTS,
   OrderBlock       -> 1,
   Value            -> 127.9,
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
  },
```

Dependence in the expansion parameters

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Parameters definition

```
M$Parameters = {
  param1 == { options1 },
  param2 == { options2 },
            ...
};
```

```
aEWM1 == {
  ParameterType    -> External,
  BlockName        -> SMINPUTS,
  OrderBlock       -> 1,
  Value            -> 127.9,
  InteractionOrder -> {QED,-2},
  Description      -> "Inverse of the EW coupling constant at the Z pole"
 },
```

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Parameters definition

Tensor parameters

```
CKM == {
   ParameterType -> Internal,
   Indices       -> {Index[Generation], Index[Generation]},
   ComplexParameter -> True,
   Unitary       -> True,
   Value         -> {CKM[1,1] -> Cos[cabi],  CKM[1,2] -> Sin[cabi],
CKM[1,3] -> 0,
                  CKM[2,1] -> -Sin[cabi], CKM[2,2] -> Cos[cabi],
CKM[2,3] -> 0,
                  CKM[3,1] -> 0,  CKM[3,2] -> 0,  CKM[3,3] -> 1},
   TeX         -> Superscript[V,CKM],
   Description -> "CKM-Matrix"}
```

C. Degrande

Parameters definition

Tensor parameters

```
CKM == {
   ParameterType -> Internal,
   Indices       -> {Index[Generation], Index[Generation]},
   ComplexParameter -> True,
   Unitary       -> True,
   Value         -> {CKM[1,1] -> Cos[cabi],  CKM[1,2] -> Sin[cabi],
CKM[1,3] -> 0,
                     CKM[2,1] -> -Sin[cabi], CKM[2,2] -> Cos[cabi],
CKM[2,3] -> 0,
                     CKM[3,1] -> 0,  CKM[3,2] -> 0,  CKM[3,3] -> 1},
   TeX           -> Superscript[V,CKM],
   Description -> "CKM-Matrix"}
```

C. Degrande

Parameters definition

Tensor parameters

```
CKM == {
   ParameterType -> Internal,
   Indices       -> {Index[Generation], Index[Generation]},
   ComplexParameter -> True,
   Unitary       -> True,
   Value         -> {CKM[1,1] -> Cos[cabi],  CKM[1,2] -> Sin[cabi],
CKM[1,3] -> 0,
                  CKM[2,1] -> -Sin[cabi], CKM[2,2] -> Cos[cabi],
CKM[2,3] -> 0,
                  CKM[3,1] -> 0,  CKM[3,2] -> 0,  CKM[3,3] -> 1},
   TeX         -> Superscript[V,CKM],
   Description -> "CKM-Matrix"}
```

Default: Tensor is True, scalar is False

C. Degrande

Parameters definition

Tensor parameters

```
CKM == {
   ParameterType -> Internal,
   Indices       -> {Index[Generation], Index[Generation]},
   ComplexParameter -> True,
   Unitary       -> True,                Hermitian, Orthogonal
   Value        -> {CKM[1,1] -> Cos[cabi],  CKM[1,2] -> Sin[cabi],
CKM[1,3] -> 0,
                 CKM[2,1] -> -Sin[cabi], CKM[2,2] -> Cos[cabi],
CKM[2,3] -> 0,
                 CKM[3,1] -> 0,  CKM[3,2] -> 0,  CKM[3,3] -> 1},
   TeX         -> Superscript[V,CKM],
   Description -> "CKM-Matrix"}
```

C. Degrande

Interaction order

In the SM : QCD the power of g_s

QED the power of e

```
aEWM1 == { ...
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
  },

vev == {...
   InteractionOrder -> {QED,-1},
   Description      -> "Higgs vacuum expectation value"
  },
```

C. Degrande

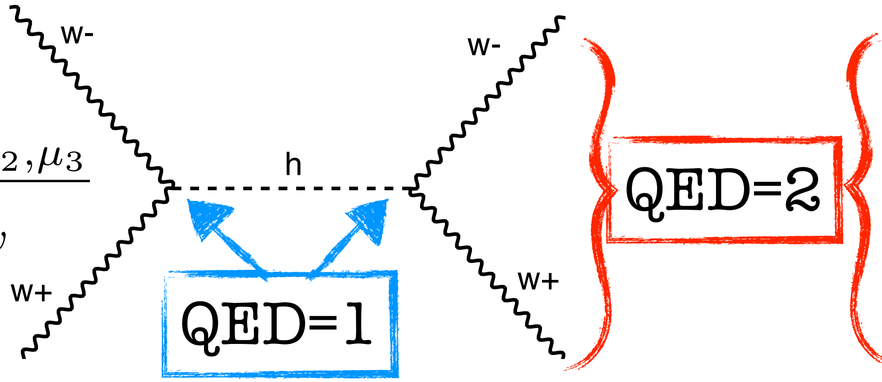
Interaction order

In the SM : QCD the power of g_s

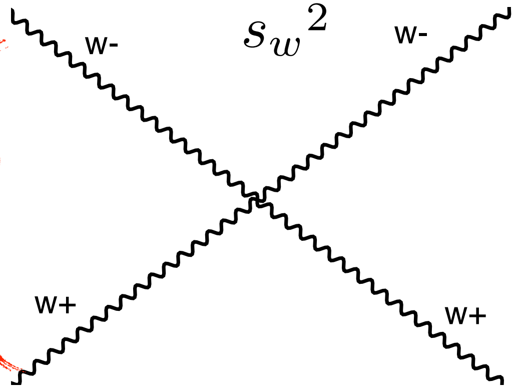
QED the power of e

```
aEWM1 == { ...
   InteractionOrder -> {QED,-2},
   Description      -> "Inverse of the EW coupling constant at the Z pole"
 },

vev == {...
   InteractionOrder -> {QED,-1 },
   Description      -> "Higgs vacuum expectation value"
 },
```

$$\frac{ie^2 v \eta_{\mu_2,\mu_3}}{2s_w^2}$$



$$-\frac{ie^2\left(\eta_{\mu_1,\mu_4}\eta_{\mu_2,\mu_3}+\eta_{\mu_1,\mu_3}\eta_{\mu_2,\mu_4}-2\eta_{\mu_1,\mu_2}\eta_{\mu_3,\mu_4}\right)}{s_w{}^2}$$



C. Degrande

Interaction order

In the SM : QCD the power of g_s

QED the power of e

```
vev == {...
   InteractionOrder -> {QED,-1},
   Description      -> "Higgs vacuum expectation value"
  },

yu == {...
   InteractionOrder -> {QED, 1},
   Description      -> "Up-type Yukawa couplings"
  },
```

Such that masses have QED=0

C. Degrande

Interaction order

In the SM : `QCD` the power of g_s

`QED` the power of e

```
vev == {...
   InteractionOrder -> {QED,-1},
   Description      -> "Higgs vacuum expectation value"
  },

yu == {...
   InteractionOrder -> {QED, 1},
   Description      -> "Up-type Yukawa couplings"
  },
```

Such that masses have `QED=0`

However y_t is not a small parameter!

C. Degrande

Interaction order

```
M$InteractionOrderHierarchy = {  {QCD, 1},
                                  {QED, 2}};
```

$$g_s \sim e^2$$

C. Degrande

Interaction order

M$InteractionOrderHierarchy = { {QCD, 1},
{QED, 2}};

,{NP, 2}

$$g_s \sim e^2$$

$$\mathcal{L} = \mathcal{L} + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

NP the power of Λ^{-2}

C. Degrande

Interaction order

M$InteractionOrderHierarchy = { {QCD, 1},
{QED, 2}};

,{NP, 2}

$$g_s \sim e^2$$

$$\mathcal{L} = \mathcal{L} + \sum_i \frac{1}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

NP the power of Λ^{-2}

M$InteractionOrderLimit = {{NP,1}};

Max power per diagram of Λ^{-2} is 1

C. Degrande

Fields definition I

```
M$ClassesDescription = {
    spin1[1] == { options1 },
    spin1[2] == { options2 },
    spin2[1] == { options3 },
    ...}
```

C. Degrande

Fields definition I

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
   spin1[1] == { options1 },
   spin1[2] == { options2 },
   spin2[1] == { options3 },
   ...}
```

C. Degrande

Fields definition I

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
   spin1[1] == { options1 },
   spin1[2] == { options2 },
   spin2[1] == { options3 },
   ...}
```

Unique Id

C. Degrande

Fields definition I

ClassName->..., SelfConjugate->...,
Indices->...,QuantumNumbers->...,
FlavorIndex->..., ClassMembers,
Mass->..., Witdh->..., PDG->...,
Definitions->..., Unphysical->...,
Chirality->..., MajoranaPhase->...,
WeylComponents->...,
Goldstone->..., Ghost->..., ...(Format)

S	0
W,F	1/2
V	1
RW,R	3/2
T	2
U	-1

```
M$ClassesDescription = {
   spin1[1] == { options1 },
   spin1[2] == { options2 },
   spin2[1] == { options3 },
   ...}
```

Unique Id

C. Degrande

Fields definition II

```
F[3] == {    ClassName         -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

C. Degrande

Fields definition II

Spin index

```
F[3] == {   ClassName        -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

C. Degrande

Fields definition II

Generation index distinguishes the class members

```
F[3] == {   ClassName        -> uq,
   ClassMembers      -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

C. Degrande

Fields definition II

```
F[3] == {    ClassName        -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

Same representation

C. Degrande

Fields definition II

```
F[3] == {    ClassName         -> uq,
   ClassMembers      -> {u, c, t},
   Indices           -> {Index[Generation], Index[Colour]},
   FlavorIndex       -> Generation,
   SelfConjugate     -> False,
   Mass              -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width             -> {0, 0, {WT,1.50833649}},
   QuantumNumbers    -> {Q -> 2/3},
   PDG               -> {2, 4, 6},
   ...
  }
```

External parameters

C. Degrande

Fields definition II

```
F[3] == {    ClassName         -> uq,
   ClassMembers     -> {u, c, t},
   Indices          -> {Index[Generation], Index[Colour]},
   FlavorIndex      -> Generation,
   SelfConjugate    -> False,
   Mass             -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width            -> {0, 0, {WT,1.50833649}},
   QuantumNumbers   -> {Q -> 2/3},
   PDG              -> {2, 4, 6},
   ...
  }
```

External parameters

Generic label

```
Mass -> {MW, Internal}
Mass -> {MZ, 91.188}
Mass -> {{MU,0}, {MC,0}, {MT, 174.3}}
Mass -> {Mu, {MU, 0}, {MC, 0}, {MT, 174.3}}
```

C. Degrande

Fields definition II

```
F[3] == {    ClassName          -> uq,
   ClassMembers      -> {u, c, t},
   Indices           -> {Index[Generation], Index[Colour]},
   FlavorIndex       -> Generation,
   SelfConjugate     -> False,
   Mass              -> {Mu, {MU, 2.55*^-3}, {MC,1.27}, {MT,172}},
   Width             -> {0, 0, {WT,1.50833649}},
   QuantumNumbers    -> {Q -> 2/3},
   PDG               -> {2, 4, 6},
   ...
  }
```

Not used in FR but by following codes

C. Degrande

Fields definition III

Interaction eigenstates

```
V[12] == {
   ClassName     -> Wi,
   Unphysical    -> True,
   SelfConjugate -> True,
   Indices       -> {Index[SU2W]},
   FlavorIndex   -> SU2W,
   Definitions   -> { Wi[mu_,1] -> (Wbar[mu]+W[mu])/Sqrt[2],
Wi[mu_,2] -> (Wbar[mu]-W[mu])/(I*Sqrt[2]), Wi[mu_,3] -> cw
Z[mu] + sw A[mu]}
  }
```

FR does not export them to matrix element code

Physical fields

C. Degrande

Fields definition IV

```
U[11] == {
   ClassName     -> ghB,
   Unphysical    -> True,
   SelfConjugate -> False,
   Ghost         -> B,
   Definitions   -> { ghB -> -sw ghZ + cw ghA}
  },

S[2] == {
   ClassName       -> G0,
   SelfConjugate   -> True,
   Goldstone       -> Z,
   ...
  },
```

ClassName of the boson

C. Degrande

Gauge Groups

```
M$GaugeGroups = {
 U1Y  == {
   Abelian          -> True,
   CouplingConstant -> g1,
   GaugeBoson       -> B,
   Charge           -> Y
  },...
 SU3C == {
   Abelian           -> False,
   CouplingConstant  -> gs,
   GaugeBoson        -> G,
   StructureConstant -> f,
   Representations   -> {T,Colour},
   SymmetricTensor   -> dSUN
  }
};
```

C. Degrande

Gauge Groups

```
M$GaugeGroups = {
 U1Y  == {
   Abelian          -> True,
   CouplingConstant -> g1,
   GaugeBoson       -> B,
   Charge           -> Y
 },...
 SU3C == {
   Abelian           -> False,
   CouplingConstant  -> gs,
   GaugeBoson        -> G,
   StructureConstant -> f,
   Representations   -> {T,Colour},
   SymmetricTensor   -> dSUN
 }
};
```

C. Degrande

Gauge Groups

```
M$GaugeGroups = {
 U1Y == {
  Abelian          -> True,
  CouplingConstant -> g1,
  GaugeBoson       -> B,
  Charge           -> Y
 },...
 SU3C == {
  Abelian           -> False,
  CouplingConstant  -> gs,
  GaugeBoson        -> G,
  StructureConstant -> f,
  Representations   -> {T,Colour},
  SymmetricTensor   -> dSUN
 }
};
```

C. Degrande

Gauge Groups

```
M$GaugeGroups = {
 U1Y  == {
   Abelian          -> True,
   CouplingConstant -> g1,
   GaugeBoson       -> B,
   Charge           -> Y
 },...
 SU3C == {
   Abelian           -> False,
   CouplingConstant  -> gs,
   GaugeBoson        -> G,
   StructureConstant -> f,
   Representations   -> {T,Colour}
   SymmetricTensor   -> dSUN
 }
};
```

Associated index

Generator label

C. Degrande

Gauge groups

- Predefined strength tensor

`FS[ A, mu, nu( , a )]` ⇒ $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^a{}_{bc} A^b_\mu A^c_\nu$

abelian

- Predefined covariant derivative (from the Indices and QuantumNumbers of the fields)

DC[phi, mu] ⇒ $D_\mu \phi = \partial_\mu \phi - i g A^a_\mu T_a \phi$

C. Degrande

Lagrangian

$$\mathcal{L}^{\mathcal{QCD}} \equiv -\frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + i\bar{d}\not{D} d$$

```
L = -1/4 FS[G, mu, nu, a] FS[G, mu, nu, a]
          + I dqbar.Ga[mu].DC[dq, mu]
```

FeynRules creates the “anti”-particle name

Dot to avoid commuting the fermions

```
dqbar.Ga[mu].T[a].dq
         → Ga[mu,s,r] T[a,i,j] dqbar[s,f,i].dq[r,f,j]
```

FeynRules restores the indices internally

C. Degrande

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

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

Extracting the Feynman rules

```
vertsQCD = FeynmanRules[ LQCD ];
```

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

C. Degrande

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

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

All the model files should be loaded at once

Extracting the Feynman rules

```
vertsQCD = FeynmanRules[ LQCD ];
```

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

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

Extracting the Feynman rules

```
vertsQCD = FeynmanRules[ LQCD ];
```

$$\left\{ \left\{ \begin{pmatrix} A & 1 \\ GP & 2 \\ GP^\dagger & 3 \end{pmatrix}, ie\,(\mathrm{p}_2^{\mu_1} - \mathrm{p}_3^{\mu_1}) \right\} \\ \ldots \right\}$$

$$\langle 0 |\, i\mathcal{L}_I \,| \mathrm{fields} \rangle$$

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

All momenta are incoming

C. Degrande

Running FeynRules

In Mathematica :

Loading Feynrules

```
$FeynRulesPath = SetDirectory[ <the address of the package> ];
<< FeynRules`
```

Loading the model

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

Extracting the Feynman rules

```
vertsQCD = FeynmanRules[ LQCD ];
```

$$\left\{ \left\{ \begin{pmatrix} A & 1 \\ GP & 2 \\ GP^\dagger & 3 \end{pmatrix}, ie\,(p_2^{\mu_1} - p_3^{\mu_1}) \right\} \atop \ldots \right\}$$

$$\langle 0 | \, i\mathcal{L}_I \, | \text{fields} \rangle$$

Off-shell

Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
CheckMassSpectrum[ L ]
```

All momenta are incoming

C. Degrande

Checks

CheckHermiticity[L, options]

CheckDiagonalKineticTerms[L, options]

CheckDiagonalMassTerms[L, options]

CheckDiagonalQuadraticTerms[L, options]

CheckKineticTermNormalisation[L, options]

$$\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 \qquad \frac{1}{2}\bar{\lambda}i\partial\!\!\!/\lambda - \frac{1}{2}m\bar{\lambda}\lambda \qquad -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2A_\mu A^\mu$$

$$\partial_\mu\phi^\dagger\partial^\mu\phi - m^2\phi^\dagger\phi \qquad \bar{\psi}i\partial\!\!\!/\psi - m\bar{\psi}\psi \qquad -\frac{1}{2}F^\dagger_{\mu\nu}F^{\mu\nu} - m^2A^\dagger_\mu A^\mu$$

CheckMassSpectrum[L, options]

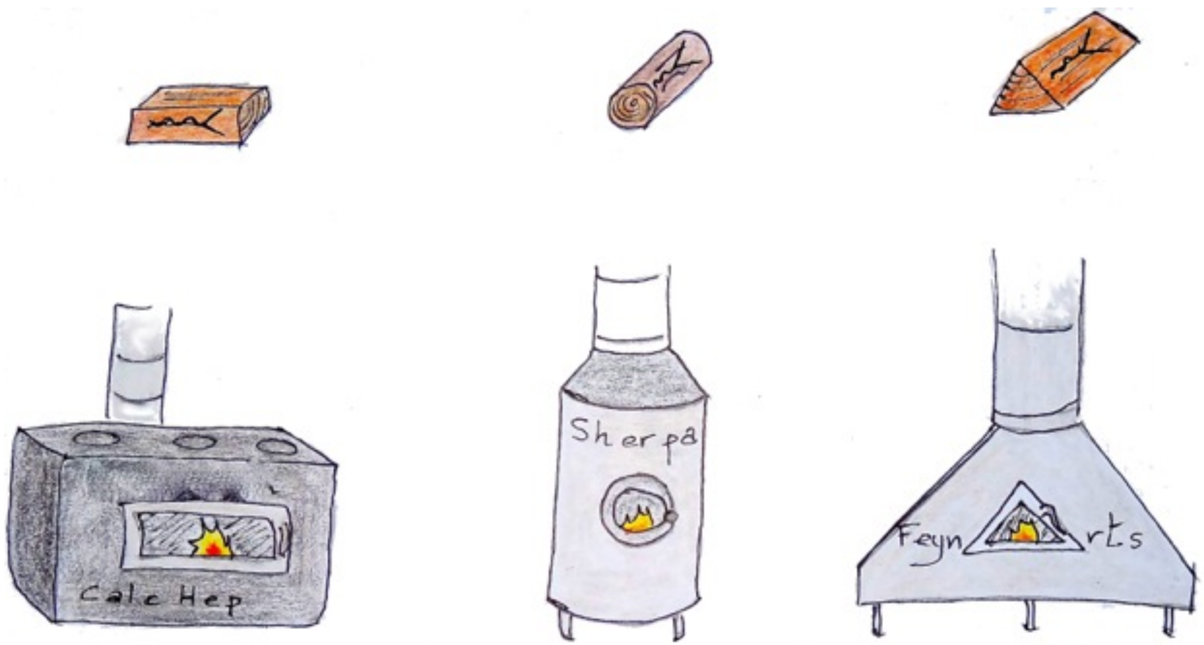
C. Degrande

Toolbox

```
ExpandIndices[L, options]

GetKineticTerms[L, options]

GetMassTerms[L, options]

GetQuadraticTerms[L, options]

GetInteractionTerms[L, options]

SelectFieldContent[L, list]
```

C. Degrande

FeynRules outputs



FeynRules outputs can be used directly by event generators

UFO : output with the full information used by several generators

C. Degrande

Conventions

- FeynRules does not care which symbol is used
- However there are conventions for the translation to matrix element computation tools
  - α_S is hardcoded in most code (running) as well as other SM parameters (α_{EW}^{-1}, G_F)
  - SU(3) representations
  - PDG numbering scheme, LHA block, …

C. Degrande

FeynRules outputs

Generating the output

```
WriteCHOuput[ L ]
WriteFeynArtsOutput[ L ]
WriteSHOutput[ L ]
WriteWOOutput[ L ]
WriteUFO[ L ]
```

FeynRules takes care of all the conventions

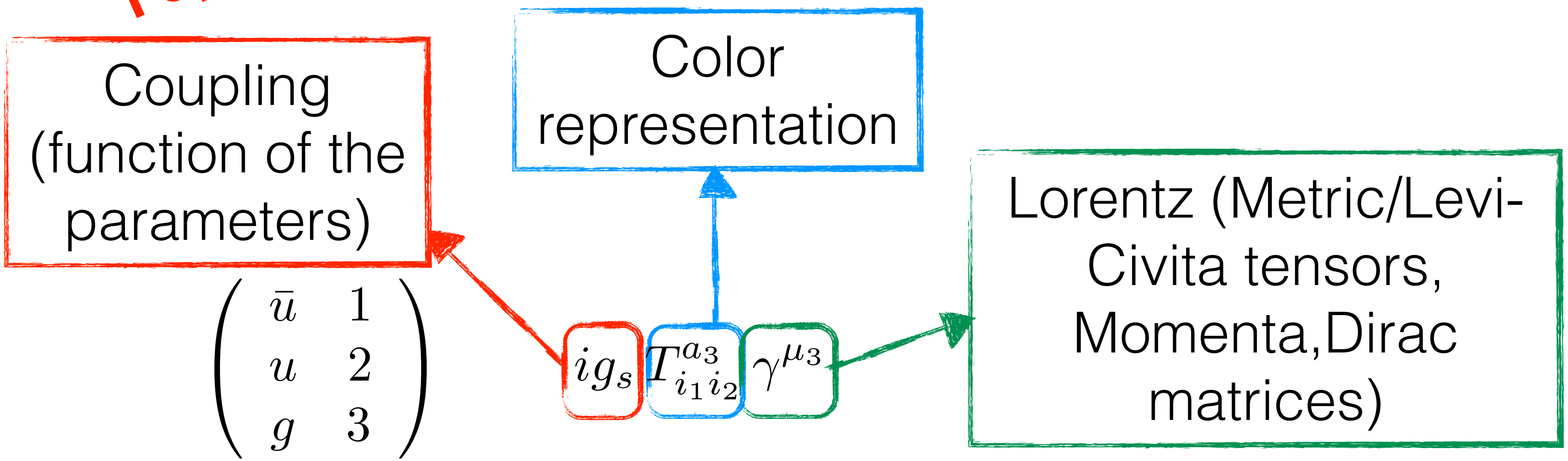
C. Degrande

FeynRules outputs

Generating the output

```
WriteCHOuput[ L ]
WriteFeynArtsOutput[ L ]
WriteSHOutput[ L ]
WriteWOOutput[ L ]
WriteUFO[ L ]
```

FeynRules takes care of all the conventions



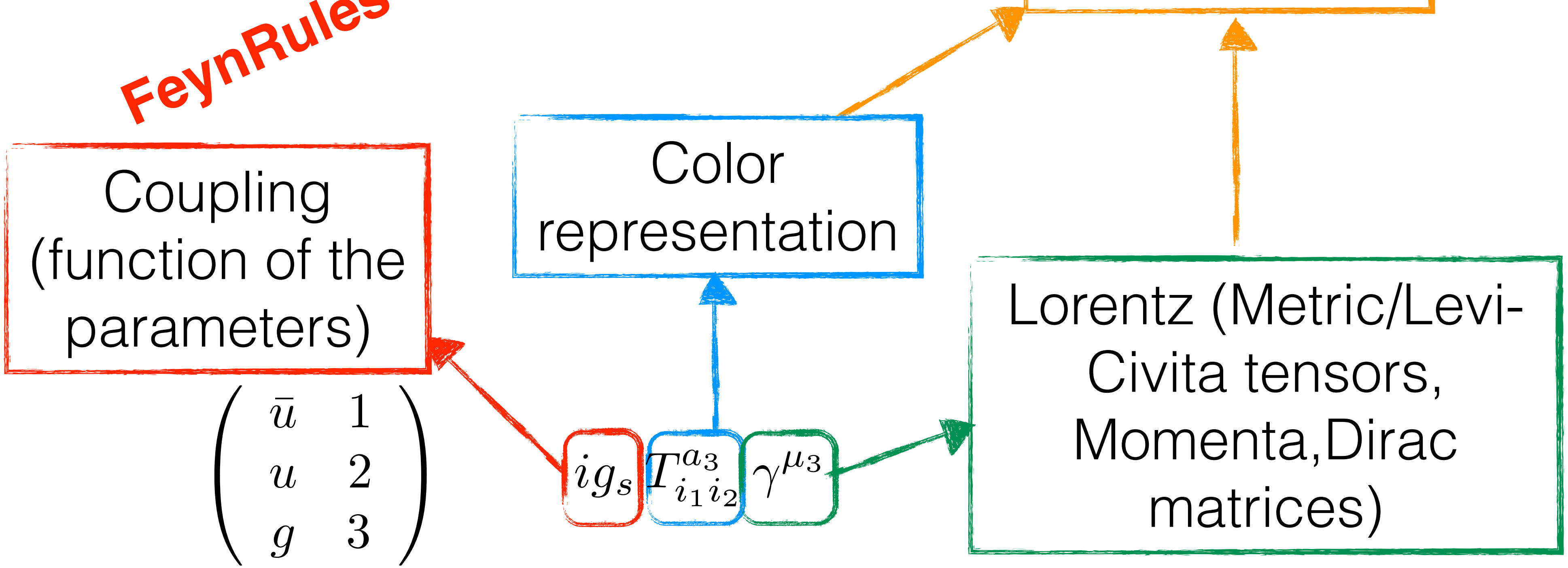
C. Degrande

FeynRules outputs

Generating the output

```
WriteCHOuput[ L ]
WriteFeynArtsOutput[ L ]
WriteSHOutput[ L ]
WriteWOOutput[ L ]
WriteUFO[ L ]
```

FeynRules takes care of all the conventions



C. Degrande

Sherpa output

feynrules.dat: A static file, setting up the model in Sherpa.

Particle.dat: The list of all particles together with their properties.

param_card.dat: LH-like file defining the numerical values of the external parameters.

ident_card.dat: File linking the entries in param_card.dat to the variables used in the Sherpa code.

param_definition.dat: File containing analytical expressions for all the internal parameters.

Interactions.dat: File defining all the interaction vertices with their couplings.

Sherpa output

feynrules.dat: A static file, setting up the model in Sherpa.

Particle.dat: The list of all particles together with their properties.

param_card.dat: LH-like file defining the numerical values of the external parameters.

ident_card.dat: File linking the entries in param_card.dat to the variables used in the Sherpa code.

param_definition.d
the internal para

Interactions.dat: F
couplings.

```
VERTEX 5 22 5   # b a b
  1 -0.3333333333333333*ee*(0,1)  # right-handed coupling
  2 -0.3333333333333333*ee*(0,1)  # left-handed coupling
  3 D[1,3]  # colour structure
  4 FFV  # Lorentz structure
```

$$-\frac{i}{3}e\delta_{ij}\gamma^{\mu}\gamma_{+} - \frac{i}{3}e\delta_{ij}\gamma^{\mu}\gamma_{-}$$

Color or Lorentz structures of the SM and MSSM only

C. Degrande

UFO

- Generic output with the **full** model information
  - coupling_orders.py, parameters.py, particles.py, write_param_card.py, __init__.py,
  - vertices.py, couplings.py, lorentz.py

    $ig_s T^a \gamma^\mu$

    No basis, all the lorentz structures of the model
  - decays.py
  - CT_vertices.py, CT_couplings.py (For NLO)
- Python module used in MadGraph, Herwig, Gosam(, Sherpa)

C. Degrande

UFO

vertices.py

```
V_135 = Vertex(name = 'V_135',
               particles = [ P.u__tilde__, P.u, P.g ],
               color = [ 'T(3,2,1)' ],
               lorentz = [ L.FFV1 ],
               couplings = {(0,0):C.GC_11})
```

Lorentz.py

```
FFV1 = Lorentz(name = 'FFV1',
               spins = [ 2, 2, 3 ],
               structure = 'Gamma(3,2,1)')
```

couplings.py

```
GC_11 = Coupling(name = 'GC_11',
                 value = 'complex(0,1)*G',
                 order = {'QCD':1})
```

C. Degrande

Plan

- Field theory : a short reminder
    - free fields (KG details, Fermion)
    - Scattering matrix in perturbation
    - Wick theorem to Feynman rules
- Why Monte-Carlo/automated tools?
- Lagrangian to the Feynman rules
    - Model file : Parameters, fields, gauge group and Lagrangian
    - Running FeynRules
- Demo

C. Degrande