

# BSM WITH FEYNRULES AND MG5\_AMC



VALENTIN HIRSCHI

# PREDICTION CHAIN

$SU(3) \times SU(2) \times U(1)$

**SYMMETRIES**

$G^{\mu\nu}G_{\mu\nu} + i\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + \dots$

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$$\begin{array}{c} \nearrow \\ \text{0000} = i\gamma^\mu t_{ij}^a , \dots \end{array}$$

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**MATRIX ELEMENT**

$\mathcal{M}_{gg \rightarrow d\bar{d}}^2 , \dots$

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matrix.f

**PARTONIC EVENTS**

```
<event>
 5   66 0.35819066E-07 0.55353448E+03 0.79577472E-01 0.11724198E+00
    -1 -1 0 0 0 501 0.00000000E+00 0.00000000E+00 0.850481
    1 -1 0 0 501 0.00000000E+00 0.00000000E+00 -.900741
  23 1 1 2 0 0 0.25462601E+02 0.29841856E+02 0.402821
  24 1 1 2 0 0 -.39256150E+02 -.24576181E+01 -.299881
  -24 1 1 2 0 0 0.37935485E+01 -.27383438E+02 -.566171
# 1 6 2 0 0 0.00000000E+00 0.00000000E+00 0 0 0.18000000E+01 0
<nuqt>
 0.41697537E+00 0.41697538E+00 3 0
 0.41697538E+00 0.43535245E+00 0.39912150E+00
 0.41697538E+00 0.43535245E+00 0.39912150E+00
 0.41697538E+00 0.43535245E+00 0.39912150E+00
</nuqt>
</event>
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 0.41697538E+00 0.43535245E+00 0.39912150E+00
 0.41697538E+00 0.43535245E+00 0.39912150E+00
</rwgt>
</event>
```

events.lhe

**HADRON LEVEL**

$\{\pi^0, K^+, e^+, p, \dots\}$

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```
<event>
 5   66 0.35019066E-07 0.55353448E+03 0.79577472E-01 0.11724198E+00
  -1 -1 0 0 0 501 0.00000000E+00 0.00000000E+00 0.850481
   1 -1 0 0 501 0.00000000E+00 0.00000000E+00 -.900741
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 0.41697538E+00 0.43535245E+00 0.39912150E+00
 0.41697538E+00 0.43535245E+00 0.39912150E+00
 </nuig>
</event>
```

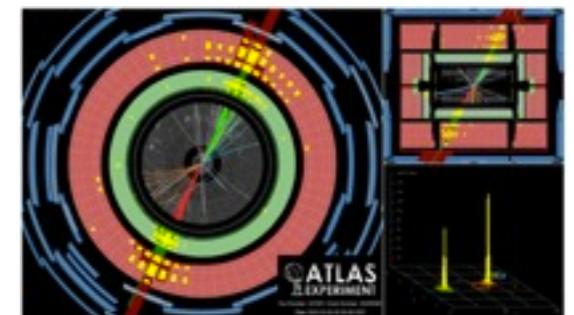
events.lhe

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$\{\pi^0, K^+, e^+, p, \dots\}$

events.hep

**DETECTOR LEVEL**



# PREDICTION CHAIN

GALILEO

$$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\dots]$$

MODEL

SYMMETRIES

$$\gamma^{0000} = \imath\gamma^\mu t_{ij}^a , \dots$$

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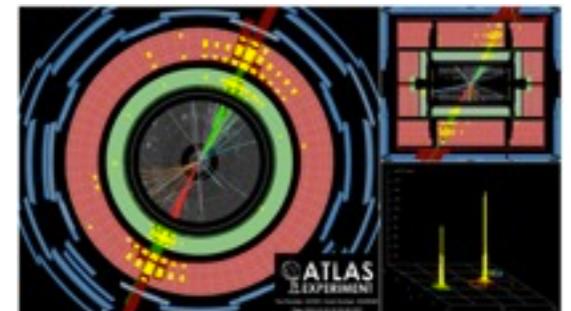
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$$\{\pi^0, K^+, e^+, p, \dots\}$$

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DETECTOR LEVEL



# PREDICTION CHAIN

GALILEO

FENYRULES

SYMMETRIES

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  0.41697537E+00 0.41697538E+00 3 0
  0.41697538E+00 0.43535245E+00 0.39912150E+00
  0.41697538E+00 0.43535245E+00 0.39912150E+00
  0.41697538E+00 0.43535245E+00 0.39912150E+00
</rwgt>
</event>
```

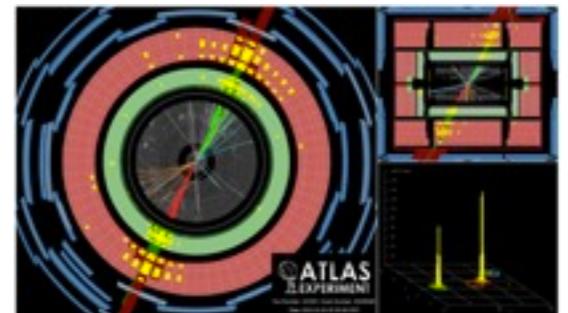
events.lhe

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# PREDICTION CHAIN

GALILEO

SYMMETRIES

FENYRULES

MODEL

MADGRAPH 5

MATRIX ELEMENT

matrix.f

PARTONIC EVENTS

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0.41697538E+00 0.43535245E+00 0.39912150E+00
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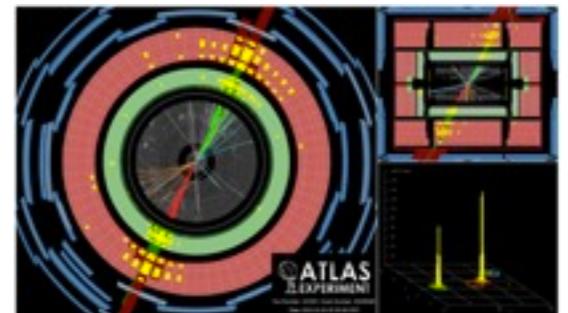
events.lhe

HADRON LEVEL

$\{\pi^0, K^+, e^+, p, \dots\}$

events.hep

DETECTOR LEVEL



# PREDICTION CHAIN

GALILEO

SYMMETRIES

FEYNRULES

MODEL

MADGRAPH 5

MATRIX ELEMENT

MADEVENT 5

PARTONIC EVENTS

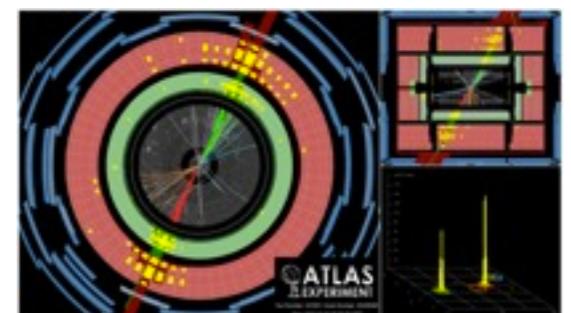
events.lhe

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GALILEO

SYMMETRIES

FEYNRULES

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MADGRAPH 5

MATRIX ELEMENT

MADEVENT 5

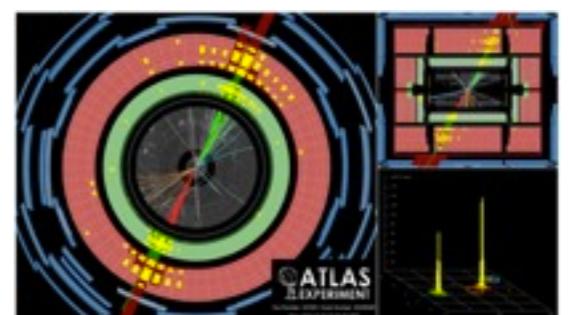
PARTONIC EVENTS

PYTHIA / HERWIG

HADRON LEVEL

events.hep

DETECTOR LEVEL



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GALILEO

SYMMETRIES

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MADGRAPH 5

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# PREDICTION CHAIN

GALILEO

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MADGRAPH 5

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MADANALYSIS 5

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GALILEO

FEYNRULES

MG5 INC. MADLOOP

MADEVENT 5

PYTHIA / HERWIG

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MADANALYSIS 5

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GALILEO

FEYNRULES

MG5 INC. MADLOOP

MADFKS INC. MC<sup>A</sup>NLO

PYTHIA / HERWIG

PGS/DELPHES

SYMMETRIES

MODEL

MATRIX ELEMENT

PARTONIC EVENTS

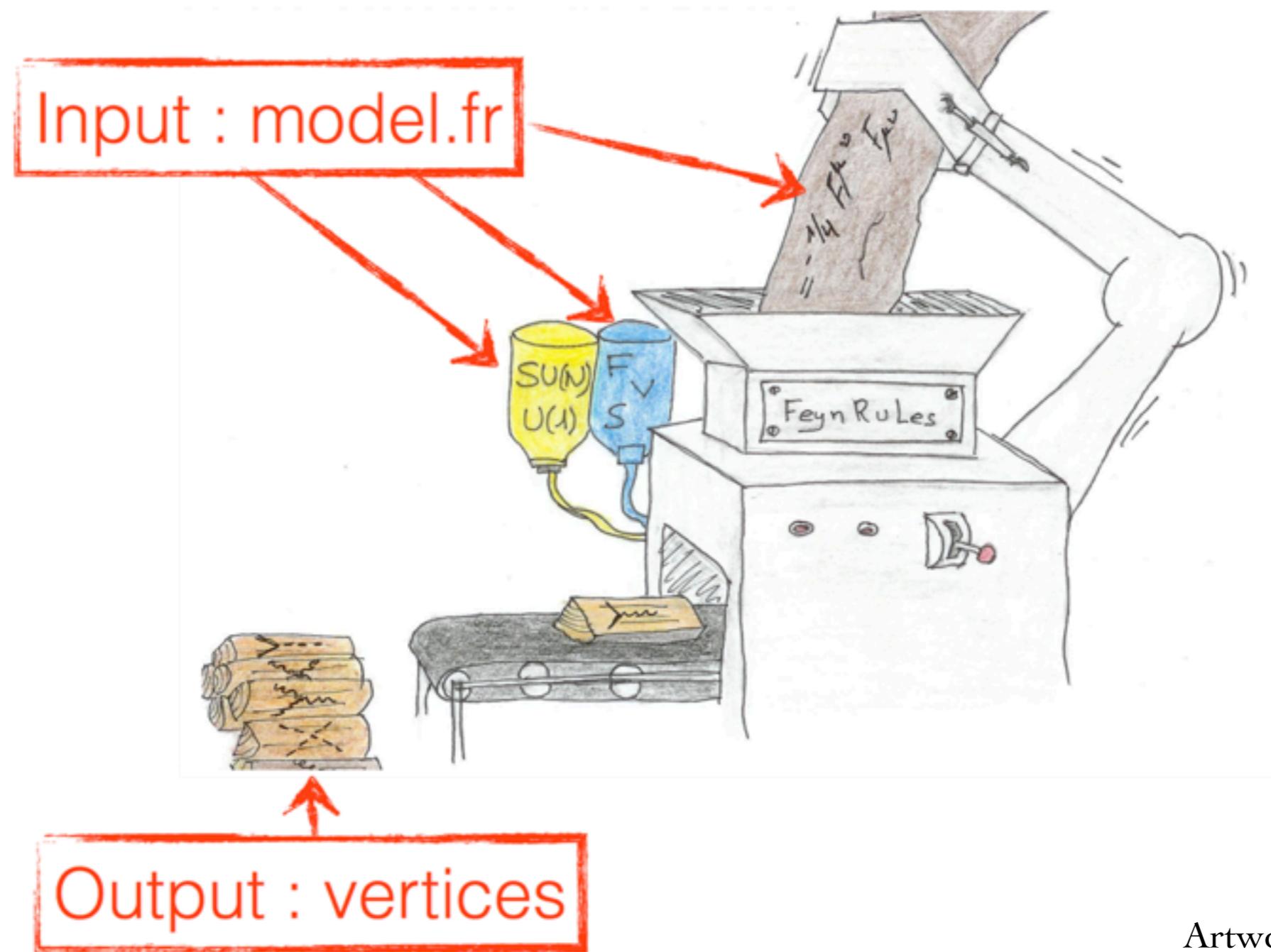
HADRON LEVEL

DETECTOR LEVEL

MADANALYSIS 5

# FEYNRULES

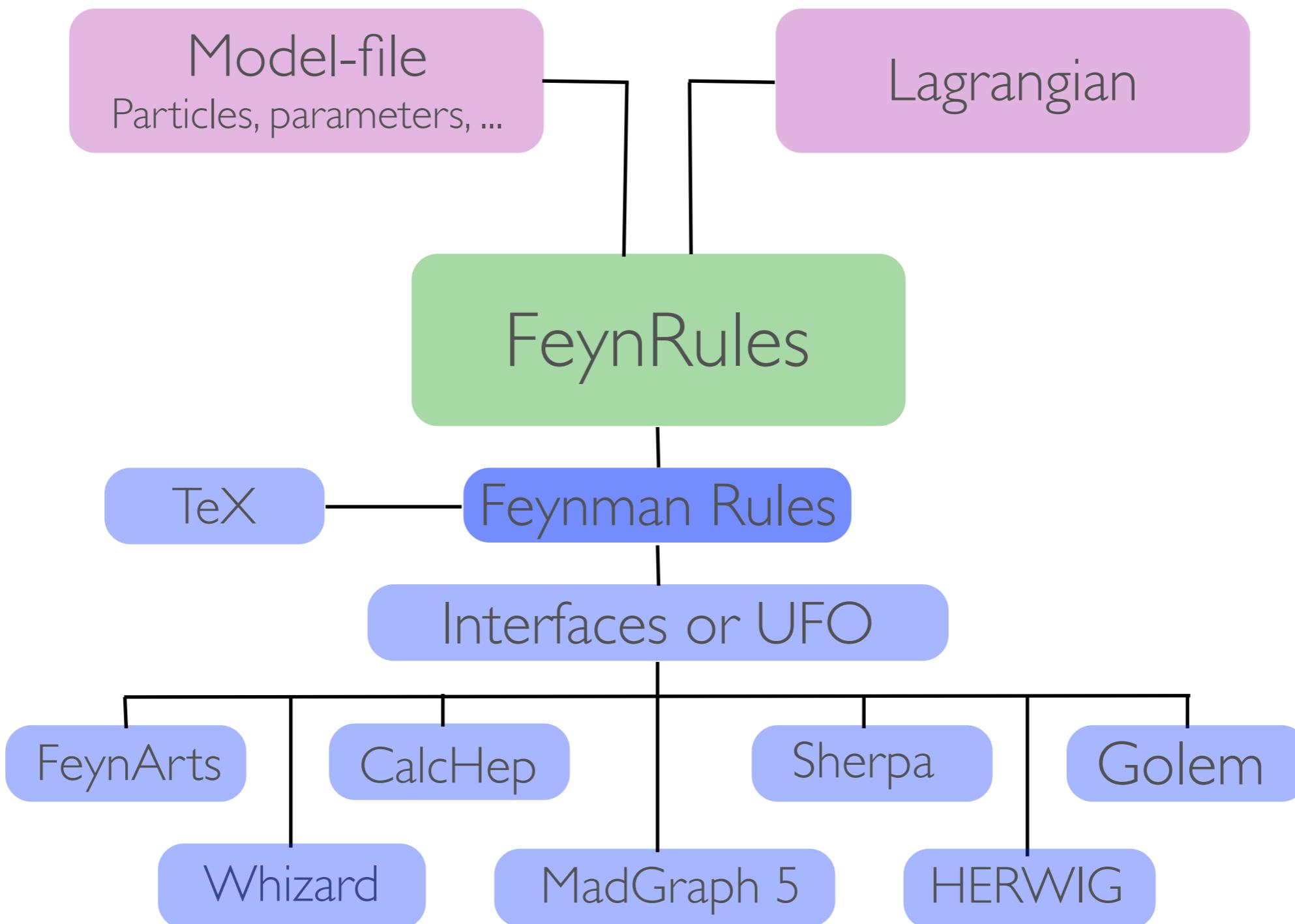
# MODEL



Artwork by C. Degrande

# FEYNRULES STRUCTURE

[Alloul, Christensen, Degrande, Duhr, Fuks]



# FEYNRULES: THE BASICS

- Start with the **definition** of the **abstract objects** entering the Lagrangian

```
(***** 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 = {  
}
```

Fields, Lagrangian and other variables defined in the **model.fr** file using Mathematica syntax.

# FEYNRULES: THE BASICS

## 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 ];  $\longleftrightarrow$  < 0 |  $i\mathcal{L}_I$  | fields >
```

## Checking the Lagrangian

```
CheckKineticTermNormalisation[ L ]
```

```
CheckMassSpectrum[ L ]
```

## Output



{

- WriteCHOutput[ L ]
- WriteFeynArtsOutput[ L ]
- WriteSHOutput[ L ]
- WriteWOOOutput[ L ]
- WriteUFO[ L ]

# FEYNRULES: THE BASICS

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## Loading the

```
LoadModel[ <
```

## Extracting

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vertsQCD = FeynmanRules[ LQCD ];  $\longleftrightarrow \langle 0 | i\mathcal{L}_I | \text{fields} \rangle$ 
```

The UFO format has become the **standard**, as it is now being used by **MG5\_aMC, Sherpa, GoSam**

## Checking the Lagrangian

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

## Output



```
{ WriteCHOutput[ L ]  
WriteFeynArtsOutput[ L ]  
WriteSHOutput[ L ]  
WriteWOOutput[ L ]  
WriteUFO[ L ]
```

# THE UFO STANDARD

[ C. Degrande, C. Duhr, B. Fuks, D. Grellscheid, O. Mattelaer, T. Reiter in 1108.2040v1 ]

- A **python** module containing the **full** model information, consisting of the files...

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## `coupling_orders.py`

- In the SM: QCD, QED
- name
- hierarchy

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## vertices.py

```
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.VVVV1, L.VVVV3, L.VVVV4 ],
               couplings = {(0,0):C.GC_12,
                            (1,1):C.GC_12,
                            (2,2):C.GC_12})
```

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```

## lorentz.py

```
VVVV1 = Lorentz(name = 'VVVV1',
                  spins = [ 3, 3, 3, 3 ],
                  structure = 'Metric(1,4)*Metric(2,3) '+
                             '- Metric(1,3)*Metric(2,4)')
```

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```

## couplings.py

```
GC_12 = Coupling(name = 'GC_12',
                  value = 'complex(0,1)*G**2',
                  order = {'QCD':2})
```

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                         'f(-1,1,4)*f(2,3,-1)' ],
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                  structure = 'Metric(1,4)*Metric(2,3) '+
                             '- Metric(1,3)*Metric(2,4)')
```

## parameters.py

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

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```
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```
GC_12 = Coupling(name = 'GC_12',
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                  order = {'QCD':2})
```

## parameters.py

```
aS = Parameter(name = 'aS',
                nature = 'external',
                type = 'real',
                value = 0.118,
                texname = '\\alpha_s',
                lhablock = 'SMINPUTS',
                lhacode = [ 3 ])
```

# FR+UFO: BIG SUCCESS AT LO

## Available models

<a href="#">Standard Model</a>	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
<a href="#">Simple extensions of the SM (18)</a>	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.
<a href="#">Supersymmetric Models (5)</a>	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
<a href="#">Extra-dimensional Models (4)</a>	Extensions of the SM including KK excitations of the SM particles.
<a href="#">Strongly coupled and effective field theories (8)</a>	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
<a href="#">Miscellaneous (0)</a>	

# FR+UFO: BIG SUCCESS AT LO

## Available models

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Extra-dir			
Strongly theories			
Miscellan			
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
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.	P. de Aquino, 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
Triplet diquarks	The SM plus triplet diquark scalars.	J. Alwall, C. Duhr	Available
Type III See-Saw Model	The SM, including neutrino masses coming from a type III See-Saw mechanism.	C. Biggio, F. Bonnet	Available
VLO	The SM, plus vector-like quarks, in a model-independent framework.	M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi	Available

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- UV counterterms:

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$$\left. \begin{array}{ll} \text{Fields} & \phi_0 \rightarrow (1 + \frac{1}{2}\delta Z_{\phi\phi}) + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi \\ \text{ext. params} & x_0 \rightarrow x + \delta x \\ \text{int. params} & g(x) \rightarrow g(x + \delta x) \end{array} \right\} \mathcal{L}_0 \rightarrow \mathcal{L} + \delta\mathcal{L}$$

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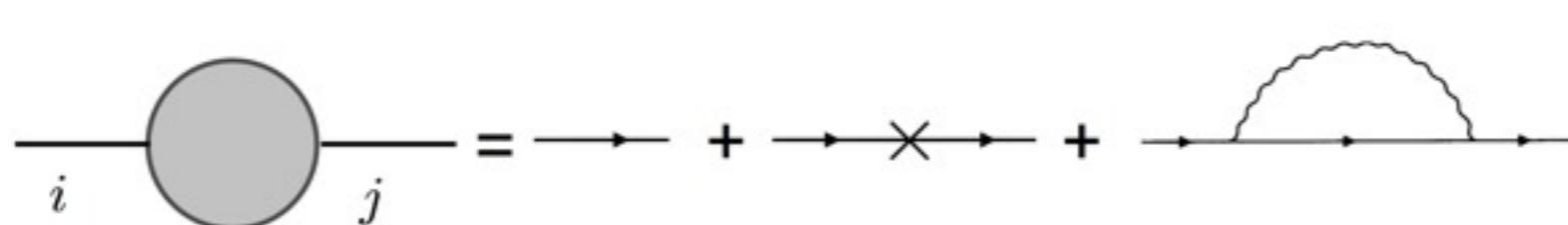
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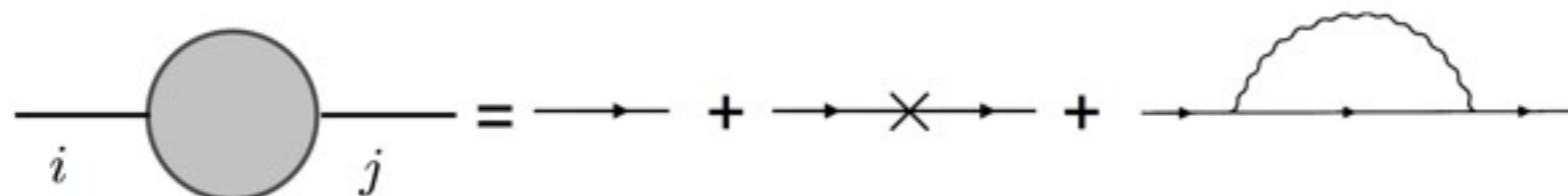
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D) Derive and output the corresponding UV counterterms.

# EX.: RENORMALIZING THE TWO HIGGS DOUBLET MODEL

$$\begin{aligned}
\delta Z_{H^+H^+} = & \frac{1}{16\pi^2} \left[ -\frac{e^2 c_w^2}{4c_w^2 s_w^2 m_{H^+}^4} \left( 2m_{H^+}^4 \left( \log \left( \frac{M_Z m_{H^+}}{\mu^2} \right) - \frac{1}{\bar{\epsilon}} \right) - m_{H^+}^2 M_Z^2 \right. \right. \\
& + (m_{H^+}^2 - M_Z^2) \left( l(m_{H^+}, M_Z, m_{H^+}) + (2m_{H^+}^2 - M_Z^2) \log \left( \frac{M_Z}{m_{H^+}} \right) \right) \Big) \\
& + \left\{ \frac{e^2 s_w^2}{4s_w^2 m_{H^+}^4} \left( \frac{l(M_W, m_{h_1}, m_{H^+})}{((m_{h_1} - M_W)^2 - m_{H^+}^2)((m_{h_1} + M_W)^2 - m_{H^+}^2)} \right. \right. \\
& (+M_W^2 (m_{h_1}^2 m_{H^+}^2 - 2m_{H^+}^4 + 5m_{h_1}^4) - 2(m_{h_1}^2 - m_{H^+}^2)(m_{H^+}^4 + m_{h_1}^4) + M_W^6 \\
& - M_W^4 (m_{H^+}^2 + 4m_{h_1}^2)) + m_{H^+}^2 \left( 2m_{H^+}^2 \left( \frac{1}{\bar{\epsilon}} + 1 - \log \left( \frac{M_W m_{h_1}}{\mu^2} \right) \right) - 2m_{h_1}^2 + M_W^2 \right) \\
& + \log \left( \frac{m_{h_1}}{M_W} \right) (M_W^4 - 3m_{h_1}^2 M_W^2 + 2m_{h_1}^4) \Big) + \frac{v^2 (\lambda_4 s_1 - 2c_1 \lambda_6)^2}{4m_{H^+}^4} \\
& \left. \left. \left( \frac{M_W^4 - m_{h_1}^2 (m_{H^+}^2 + 2M_W^2) - M_W^2 m_{H^+}^2 + m_{h_1}^4}{(m_{h_1}^4 - 2m_{h_1}^2 (m_{H^+}^2 + M_W^2) + (m_{H^+}^2 - M_W^2)^2} l(M_W, m_{h_1}, m_{H^+}) \right. \right. \right. \\
& - \left. \left. \left. \left( (m_{h_1}^2 - M_W^2) \log \left( \frac{m_{h_1}}{M_W} \right) - m_{H^+}^2 \right) \right) + h_1 \rightarrow h_2, c_1 \rightarrow s_1, s_1 \rightarrow -c_1 \right. \right. \\
& + h_1 \rightarrow h_3, c_1 \rightarrow 0, s_1 \rightarrow 1 \Big) + \left\{ \frac{v^2 (c_1 \lambda_3 - \lambda_7 s_1)^2}{m_{H^+}^4} \right. \\
& \left. \left( \left( (m_{H^+}^2 - m_{h_1}^2) \log \left( \frac{m_{h_1}}{m_{H^+}} \right) - m_{H^+}^2 \right) - \frac{(m_{h_1}^2 - 3m_{H^+}^2)}{4m_{H^+}^2 - m_{h_1}^2} l(m_{H^+}, m_{h_1}, m_{H^+}) \right) \right. \\
& + h_1 \rightarrow h_2, c_1 \rightarrow s_1, s_1 \rightarrow -c_1 \Big) - \sum_l G_l^2 \left( -\log \left( \frac{m_{H^+}^2}{\mu^2} \right) + \frac{1}{\bar{\epsilon}} + i\pi + 1 \right) \\
& - 3 \sum_{light} (G_d^2 + G_u^2) \left( -\log \left( \frac{m_{H^+}^2}{\mu^2} \right) + \frac{1}{\bar{\epsilon}} + i\pi + 1 \right) \\
& - \frac{12G_b G_t M_b M_t}{m_{H^+}^4} \left( \frac{M_b^2 (m_{H^+}^2 + 2M_t^2) + M_t^2 m_{H^+}^2 - M_b^4 - M_t^4}{-2M_b^2 (m_{H^+}^2 + M_t^2) + (m_{H^+}^2 - M_t^2)^2 + M_b^4} l(M_t, M_b, m_{H^+}) \right. \\
& - \left. \left. \left( m_{H^+}^2 - (M_b^2 - M_t^2) \left( \log \left( \frac{M_b}{M_t} \right) \right) \right) \right) - \frac{3(G_b^2 + G_t^2)}{m_{H^+}^4} \left( l(M_t, M_b, m_{H^+}) \right. \\
& \left. \left. \left( M_b^2 + M_t^2 \right) \left( -M_b^2 (m_{H^+}^2 + 2M_t^2) - M_t^2 m_{H^+}^2 - m_{H^+}^4 + M_b^4 + M_t^4 \right) + m_{H^+}^6 \right. \right. \\
& \left. \left. - 2M_b^2 (m_{H^+}^2 + M_t^2) + (m_{H^+}^2 - M_t^2)^2 + M_b^4 \right) \right. \\
& + \left. \left. \left. \left( M_b^2 + M_t^2 \right) \left( m_{H^+}^2 - (M_b^2 - M_t^2) \log \left( \frac{M_b}{M_t} \right) \right) + m_{H^+}^4 \left( \frac{1}{\bar{\epsilon}} + 1 - \log \left( \frac{M_b M_t}{\mu^2} \right) \right) \right) \right]
\end{aligned}$$

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\end{aligned}$$

WITH

$$\begin{aligned}
l(m_1, m_2, m_3) = & \log \left( \frac{m_1^2 + m_2^2 - m_3^2 + \sqrt{(m_1^4 + (m_2^2 - m_3^2)^2 - 2m_1^2(m_2^2 + m_3^2))}}{2m_1 m_2} \right) \\
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# NLOCT: MISSING INGREDIENTS FOR NLO

- R2 counterterms:

Loop amplitude:

$$\frac{1}{(2\pi)^4} \int d^d \bar{q} \frac{\bar{N}(\bar{q})}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}} , \quad \bar{D}_i = (\bar{q} + p_i)^2 - m_i^2$$

Then : compute **analytically** the finite set of loops for which its contribution does **not vanish**, and re-express it in terms of an **R2 Feynman rules**.

$$R2 \equiv \lim_{\epsilon \rightarrow 0} \frac{1}{(2\pi)^4} \int d^d \bar{q} \frac{\tilde{N}(\tilde{q}, q, \epsilon)}{\bar{D}_0 \bar{D}_1 \cdots \bar{D}_{m-1}}$$

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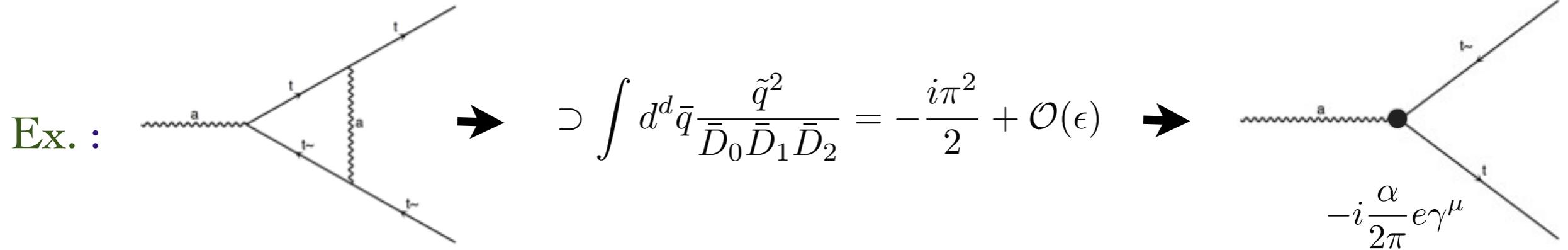
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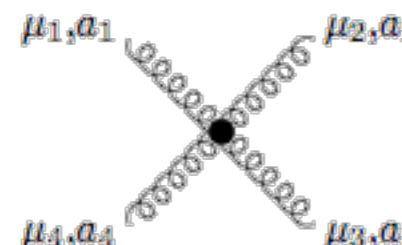
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# EX: 4-GLUON VERTEX R2 IN THE SM

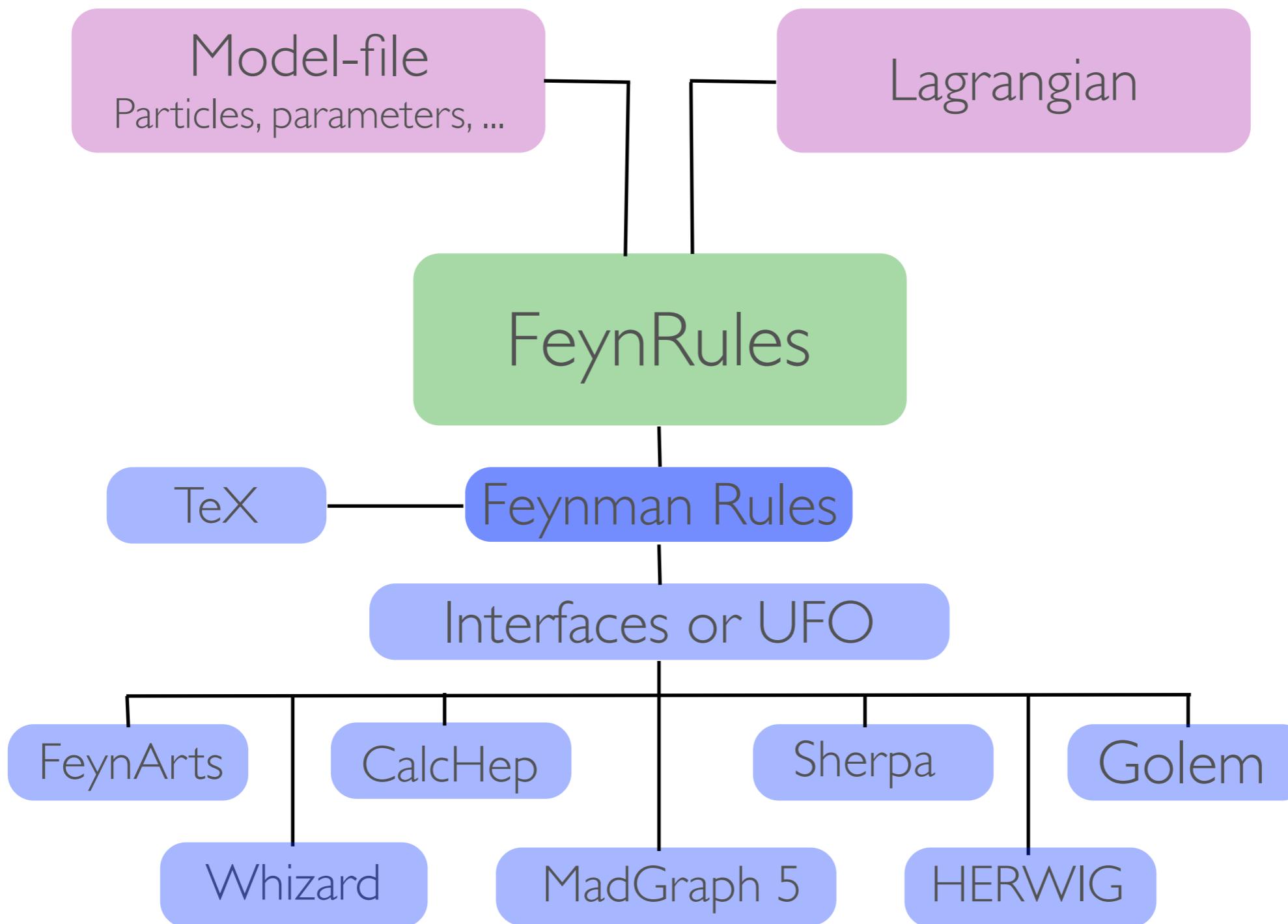
R2 COUNTERTERMS TYPICALLY EXHIBIT A SIMPLER FORM, BUT CAN ALSO BECOME MORE COMPLICATED.


$$= -\frac{ig^4 N_{col}}{96\pi^2} \sum_{P(234)} \left\{ \left[ \frac{\delta_{a_1 a_2} \delta_{a_3 a_4} + \delta_{a_1 a_3} \delta_{a_4 a_2} + \delta_{a_1 a_4} \delta_{a_2 a_3}}{N_{col}} \right. \right. \\ + 4 \text{Tr}(t^{a_1} t^{a_3} t^{a_2} t^{a_4} + t^{a_1} t^{a_4} t^{a_2} t^{a_3}) (3 + \lambda_{HV}) \\ \left. \left. - \text{Tr}(\{t^{a_1} t^{a_2}\} \{t^{a_3} t^{a_4}\}) (5 + 2\lambda_{HV}) \right] g_{\mu_1 \mu_2} g_{\mu_3 \mu_4} \right. \\ \left. + 12 \frac{N_f}{N_{col}} \text{Tr}(t^{a_1} t^{a_2} t^{a_3} t^{a_4}) \left( \frac{5}{3} g_{\mu_1 \mu_3} g_{\mu_2 \mu_4} - g_{\mu_1 \mu_2} g_{\mu_3 \mu_4} - g_{\mu_2 \mu_3} g_{\mu_1 \mu_4} \right) \right\}$$

ONCE AGAIN AUTOMATION IS WELCOME.

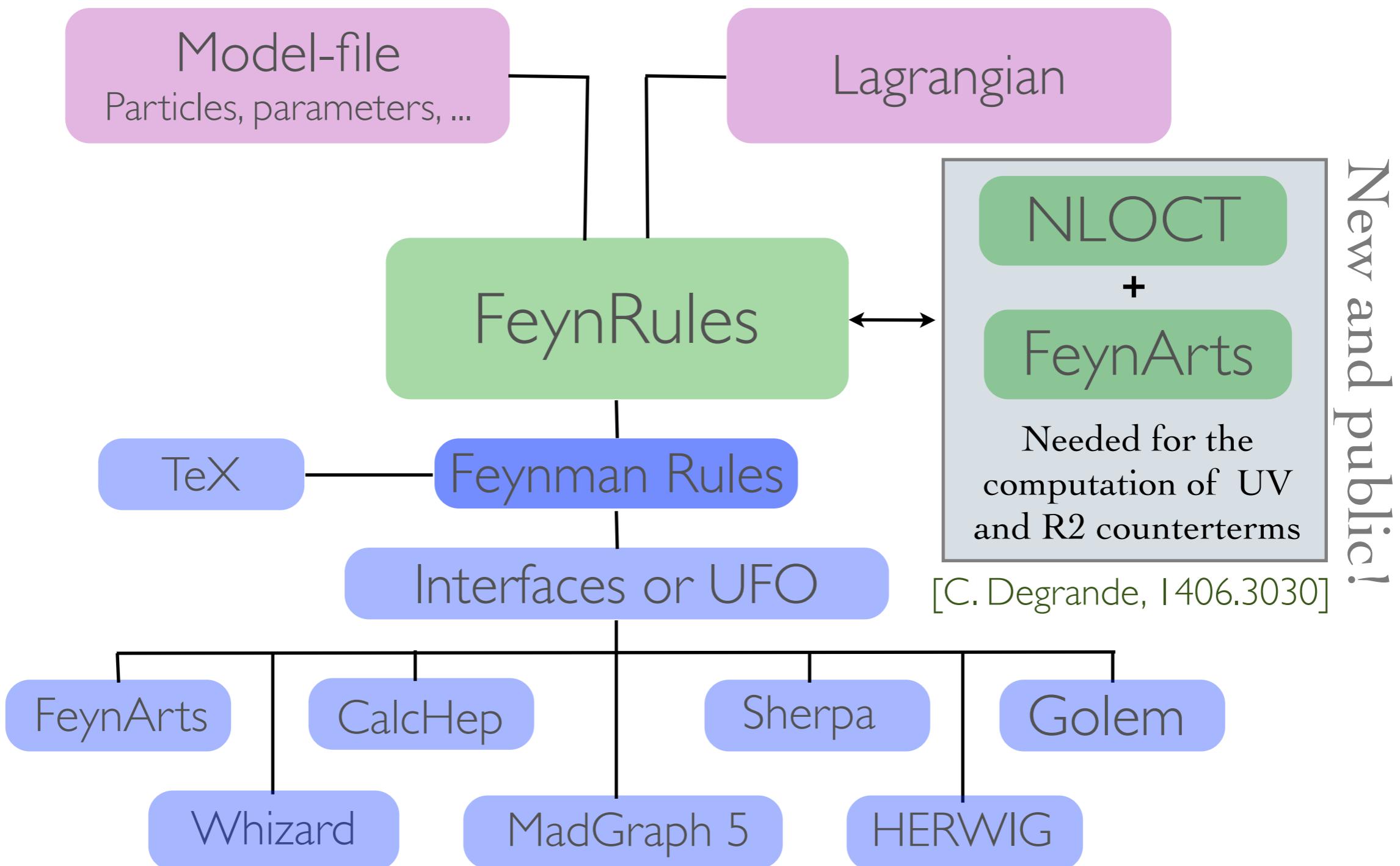
# FEYNRULES @ NLO (VERSION 2.1)

[Alloul, N. Christensen, C. Degrande, C. Duhr, B. Fuks, in 1310.1921]



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# UFO @ NLO

- A couple modifications to the tree-level UFO Standard.

## `coupling_orders.py`

- `perturbative_expansion`

Specifies the kind of loops  
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## CT\_vertices.py

```
V_R2GUU = CTVertex(name = 'V_R2GUU',
                     particles = [ P.u_tilde_, P.u, P.G ],
                     color = [ 'T(3,2,1)' ],
                     lorentz = [ L.FFV1 ],
                     loop_particles = [[[P.u,P.G]]],
                     couplings = {(0,0,0):C.R2_GQQ},
                     type = 'R2')

V_UVGUU = CTVertex(name = 'V_UVGUU',
                     particles = [ P.u_tilde_, P.u, P.G ],
                     color = [ 'T(3,2,1)' ],
                     lorentz = [ L.FFV1 ],
                     loop_particles = [[[P.u],[P.d],[P.s]],
                                      [[P.c]],[[P.b]],[[P.t]],[[P.G]]],
                     couplings = {
                         (0,0,0):C.UV_GQQq,(0,0,1):C.UV_GQQc,
                         (0,0,2):C.UV_GQQb,(0,0,3):C.UV_GQQt,(0,0,4):C.UV_GQQg},
                     type = 'UV')
```

# UFO @ NLO

- A couple modifications to the tree-level UFO Standard.

## coupling\_orders.py

- `perturbative_expansion`

Specifies the kind of loops supported by the model

## CT\_parameters.py

```
P = CTPParameter(name = 'MyUVCTParam',
                  type = 'complex',
                  value = {-1:'singlePoleExpression',
                            0:'finitePart'},
                  texname = 'MadRules')
```

## CT\_vertices.py

```
V_R2GUU = CTVertex(name = 'V_R2GUU',
                     particles = [ P.u_tilde_, P.u, P.G ],
                     color = [ 'T(3,2,1)' ],
                     lorentz = [ L.FFV1 ],
                     loop_particles = [[[P.u,P.G]]],
                     couplings = {(0,0,0):C.R2_GQQ},
                     type = 'R2')

V_UVGUU = CTVertex(name = 'V_UVGUU',
                     particles = [ P.u_tilde_, P.u, P.G ],
                     color = [ 'T(3,2,1)' ],
                     lorentz = [ L.FFV1 ],
                     loop_particles = [[[P.u],[P.d],[P.s]],
                                      [[P.c]],[[P.b]],[[P.t]],[[P.G]]],
                     couplings = {
                        (0,0,0):C.UV_GQQq,(0,0,1):C.UV_GQQc,
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                     type = 'UV')
```

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- A couple modifications to the tree-level UFO Standard.

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                     couplings = {
                        (0,0,0):C.UV_GQQq,(0,0,1):C.UV_GQQc,
                        (0,0,2):C.UV_GQQb,(0,0,3):C.UV_GQQt,(0,0,4):C.UV_GQQg},
                     type = 'UV')
```

- The **one-to-one correspondence** between a loop and its “corresponding counterterms” is kept as far as possible, guaranteeing **consistency** for any process definition.

[See sect. 2.4.2 of MG5\_aMC ref paper for details, i.e. 1405.0301v2 ]

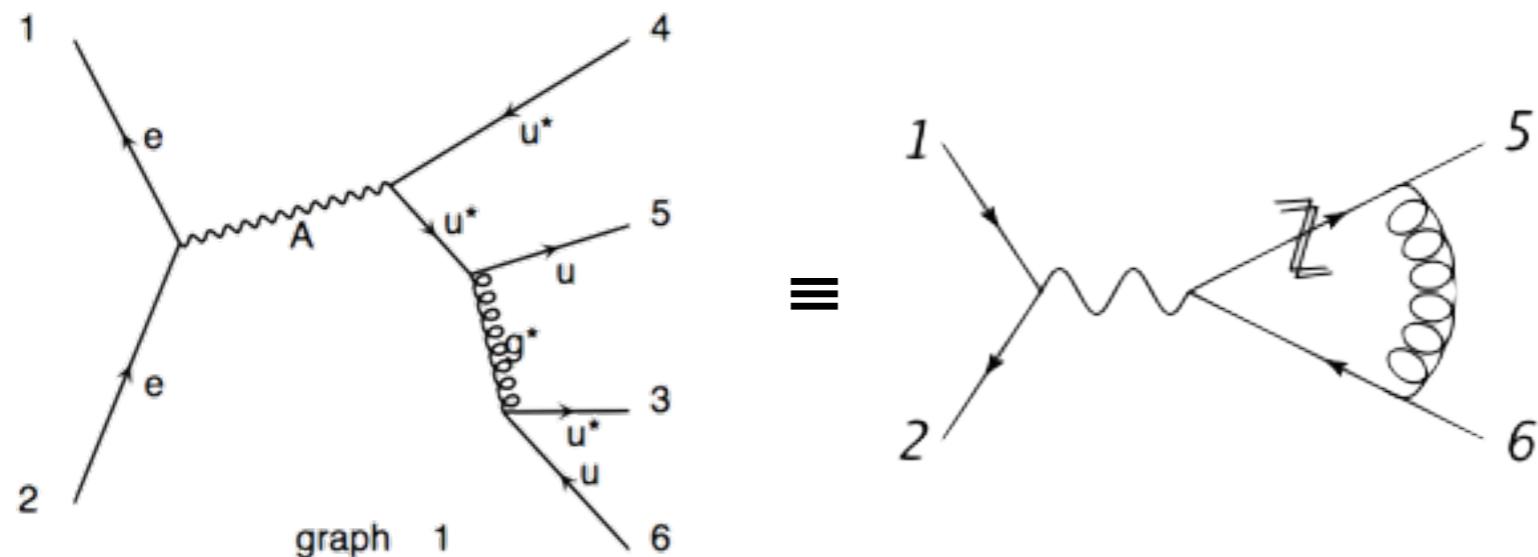
# NLOCT LIMITATIONS / ASSUMPTIONS

[C. Degrande, 1406.3030]

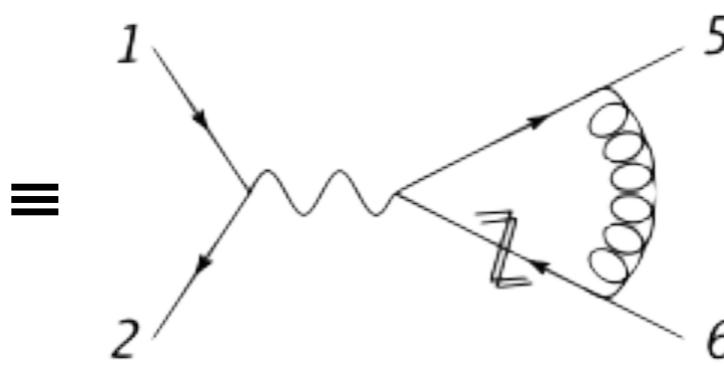
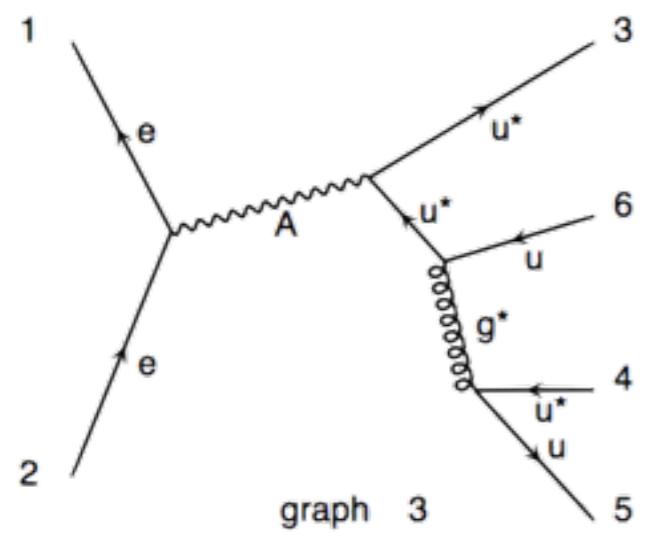
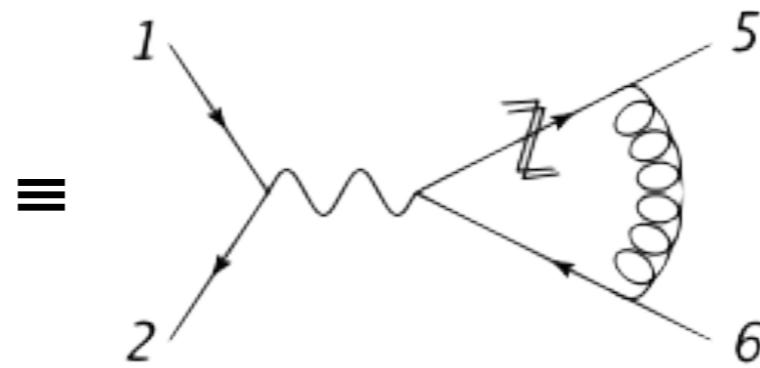
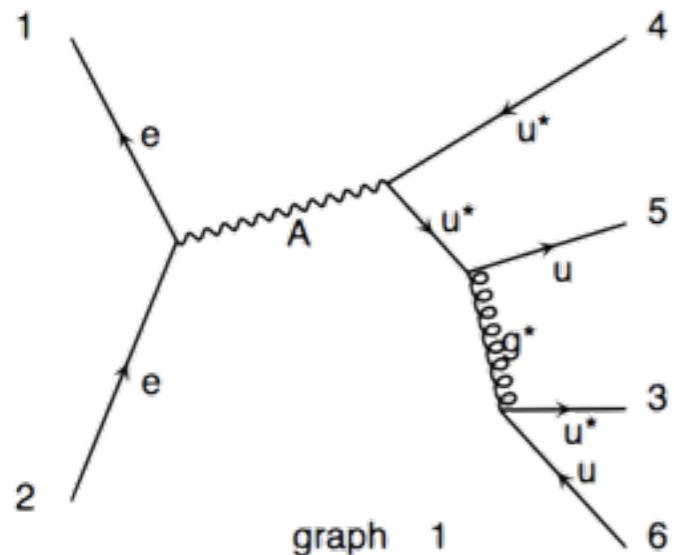
- Renormalizable Lagrangian, i.e. maximum operator dimension is 4.
- Feynman gauge
- t'Hooft-Veltman scheme
- Onshell renormalization condition for wavefunctions and masses
- $\overline{MS}$  everywhere else (zero momentum subtraction possible for couplings of massive fermions to gauge bosons).

• The **generalization of the renormalization conditions** considered is an important ongoing effort as it is necessary for:  
EW corrections,  
full MSSM,  
complex-mass scheme (partially supported already),  
...

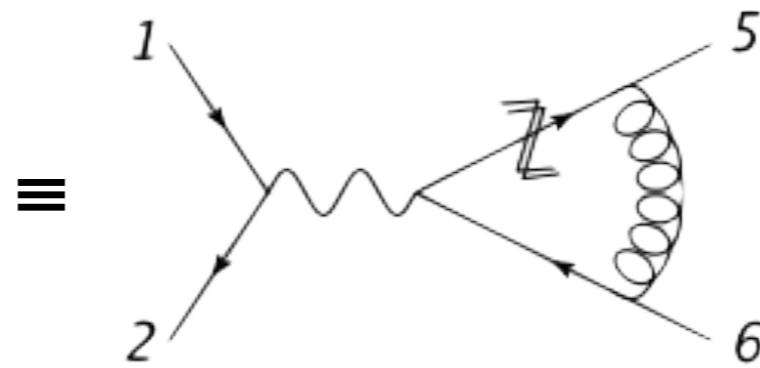
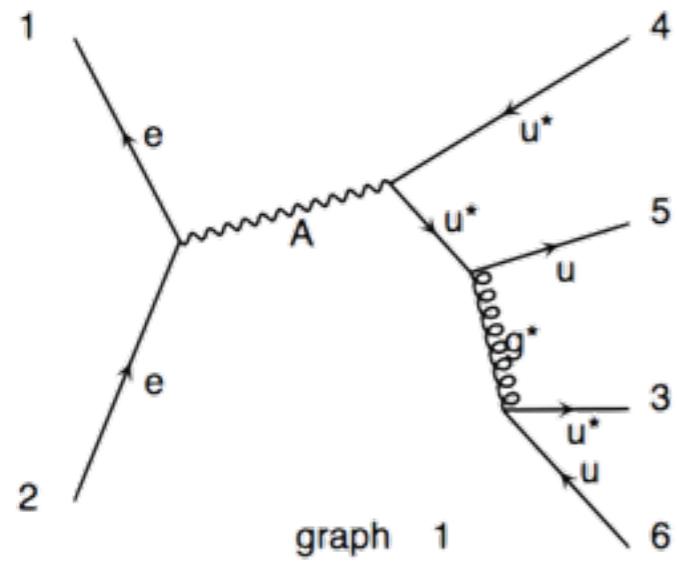
- Instead of using an external tool for loop diagram generation, we recycle MadGraph5 algorithm for tree level diagram generation.
- A loop diagrams with the loop cut open has two extra external particles. Consider  $e^+e^- \rightarrow u\bar{u} u\bar{u}$  (loop particles are in green).



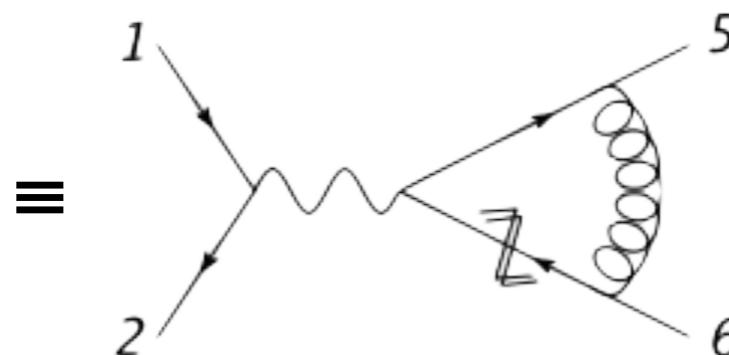
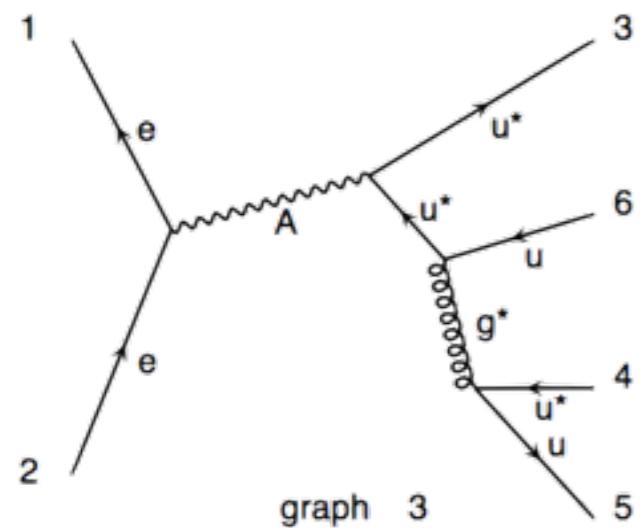
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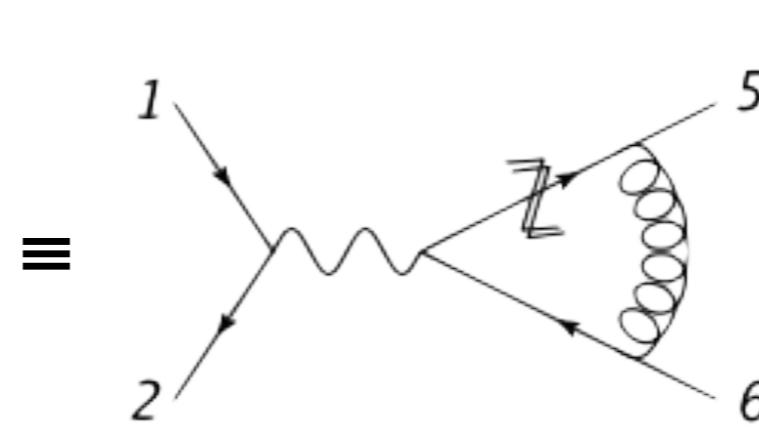
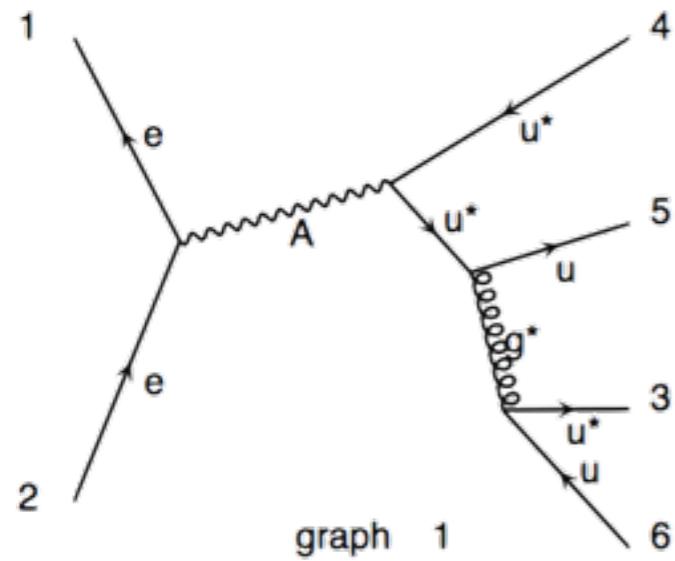


$$\text{Diag}_1 = [u^*(6)g^*(5)u^*(A)]$$

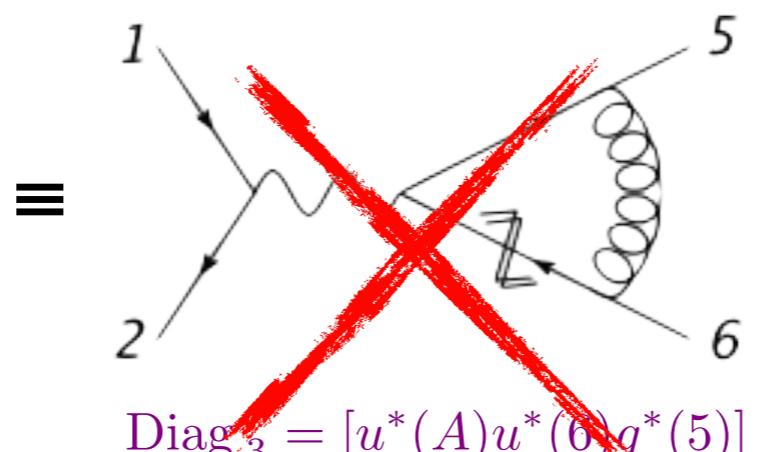
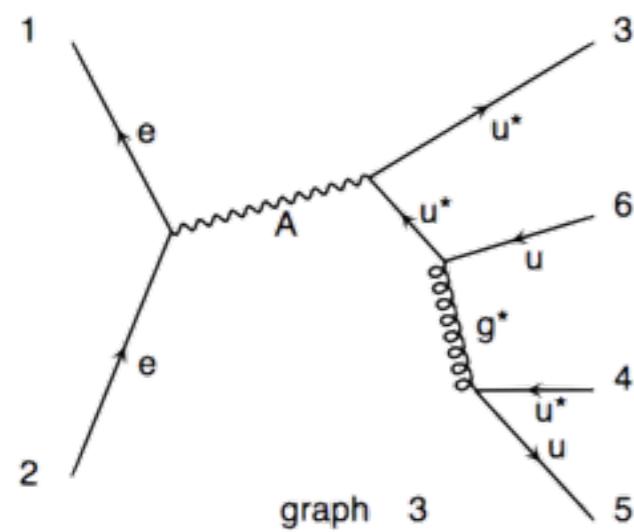
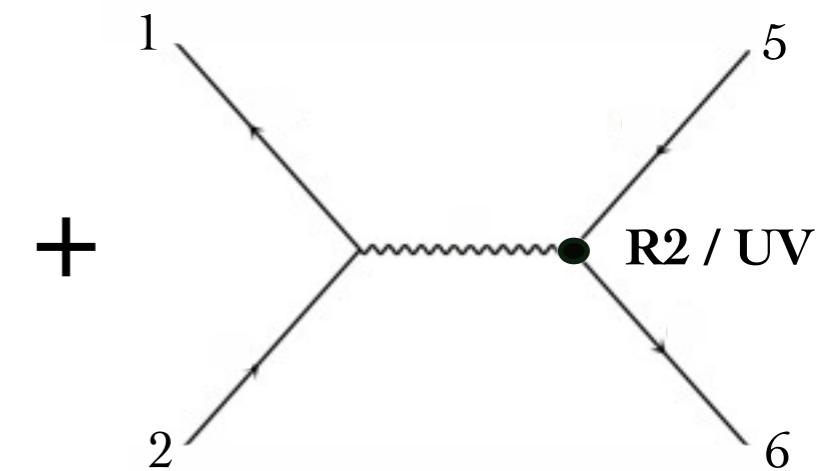


$$\text{Diag}_3 = [u^*(A)u^*(6)g^*(5)]$$

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



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

- Robust towards complicated one-loop ME which can be generated, and computed for a single phase space point (with standalone mode [virt=])
  - Can easily create a ML dynamic library to interface to other Monte-Carlo generator (as it is done in a still private plugin to Sherpa).

Process	$t_{\text{generation}}$	$t_{\text{run}} / \text{PS} / \text{hel. conf.}$	$n_{\text{loops}}   n_{\text{loop\_groups}}$
$g g \rightarrow d d^{\sim} b b^{\sim} t t^{\sim} [\text{virt}=QCD]$	15 h	18.6 s	5'4614   8'190
$u u^{\sim} \rightarrow d d^{\sim} t t^{\sim} [\text{virt}=QCD \text{ QED}]$	28 min	895 ms	10'947   811
$u d^{\sim} \rightarrow d d^{\sim} W^+ Z H [\text{virt}=QCD \text{ QED}]$	25 h	26.4 s	187'138   8'098

Details in 1405.0301

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Details in 1405.0301

- No reason not to cross-check alternative computations of loop ME's vs MadLoop
- MadLoop has, in practice, no limitations on the kind of models it can handle, hence making the ability to build the corresponding UFO@NLO model the major current obstacle towards full general higher order corrections for BSM physics.

# MADGRAPH5\_AMC@NLO

[J. Alwall, R. Frederix, S. Frixione, V.H., F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, 1405.0301]

## EVENT GENERATION FOLLOWS AT NLO LIKE AT LO

- Process generation

- import model <model\_name>-<restrictions>
  - generate <process> <amp\_orders\_and\_option> [<mode>=<pert\_orders>] <squared\_orders>
  - output <format> <folder\_name>
  - launch <options>

- Examples, starting from a blank MG5 interface.

- Very simple one:

- > generate p p > t t~ [QCD]
    - > output
    - > launch

- With options specified:

- > import model loop\_sm-no\_hwidth
    - > set complex\_mass\_scheme
    - > generate p p > e+ ve mu- vm~ b b~ / h QED=2 [QCD]
    - > output MyProc
    - > launch -f

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[J. Alwall, R. Frederix, S. Frixione, V.H., F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, 1405.0301]

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    - > output MyProc
    - > launch -f

The only difference between LO and NLO  
from the user perspective!

# A LOOP MODEL DATABASE

## Available models

<a href="#">Standard Model</a>	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
<a href="#">Simple extensions of the SM (18)</a>	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.
<a href="#">Supersymmetric Models (5)</a>	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
<a href="#">Extra-dimensional Models (4)</a>	Extensions of the SM including KK excitations of the SM particles.
<a href="#">Strongly coupled and effective field theories (8)</a>	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
<a href="#">Miscellaneous (0)</a>	

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Miscellaneous (0)	

[NLO MODELS \(100000\)](#)

**3 MODELS FOR NOW**

<http://feynrules.irmp.ucl.ac.be/wiki/NLOModels>

## Available models

Description	Contact	Reference	FeynRules model files	UFO libraries
Higgs characterisation ( <a href="#">more details</a> )	K. Mawatari	<a href="#">arXiv:1311.1829</a> , <a href="#">arXiv:1407.5089</a>	-	<a href="#">HC_NLO_X0_UFO.zip</a>
Inclusive sgluon pair production	B. Fuks	<a href="#">arXiv:1412.5589</a>	<a href="#">sgluons.fr</a>	<a href="#">sgluons_ufo.tgz</a>
Stop pair $\rightarrow t \bar{t} + \text{missing energy}$	B. Fuks	<a href="#">arXiv:1412.5589</a>	<a href="#">stop_ttmet.fr</a>	<a href="#">stop_ttmet_ufo.tgz</a>

- Many more BSM models in development and to be added to this list.
- Now to a practical illustration : simplified model for colored scalar pair production.

# SCALAR COLOR TRIPLET PAIR PRODUCTION

[C. Degrande, B. Fuks, V.H., J. Proudom, H.S. Shao in 1412.5589 ]

- Squark pair production

$$\begin{aligned}\mathcal{L}_3 = & D_\mu \sigma_3^\dagger D^\mu \sigma_3 - m_3^2 \sigma_3^\dagger \sigma_3 + \frac{i}{2} \bar{\chi} \not{D} \chi - \frac{1}{2} m_\chi \bar{\chi} \chi \\ & + \left[ \sigma_3 \bar{t} (\tilde{g}_L P_L + \tilde{g}_R P_R) \chi + \text{h.c.} \right],\end{aligned}$$

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- Counterterms derived by FR+NLOCT :

$$\begin{aligned}\delta Z_g &= \delta Z_g^{(SM)} - \frac{g_s^2}{96\pi^2} \left[ \frac{1}{\bar{\epsilon}} - \log \frac{m_3^2}{\mu_R^2} \right], \\ \delta Z_{\sigma_3} &= 0 \quad \text{and} \quad \delta m_3^2 = -\frac{g_s^2 m_3^2}{12\pi^2} \left[ \frac{3}{\bar{\epsilon}} + 7 - 3 \log \frac{m_3^2}{\mu_R^2} \right] \\ \frac{\delta \alpha_s}{\alpha_s} &= \frac{\alpha_s}{2\pi\bar{\epsilon}} \left[ \frac{n_f}{3} - \frac{11}{2} \right] + \frac{\alpha_s}{6\pi} \left[ \frac{1}{\bar{\epsilon}} - \log \frac{m_t^2}{\mu_R^2} \right] \\ &\quad + \frac{\alpha_s}{24\pi} \left[ \frac{1}{\bar{\epsilon}} - \log \frac{m_3^2}{\mu_R^2} \right].\end{aligned}$$

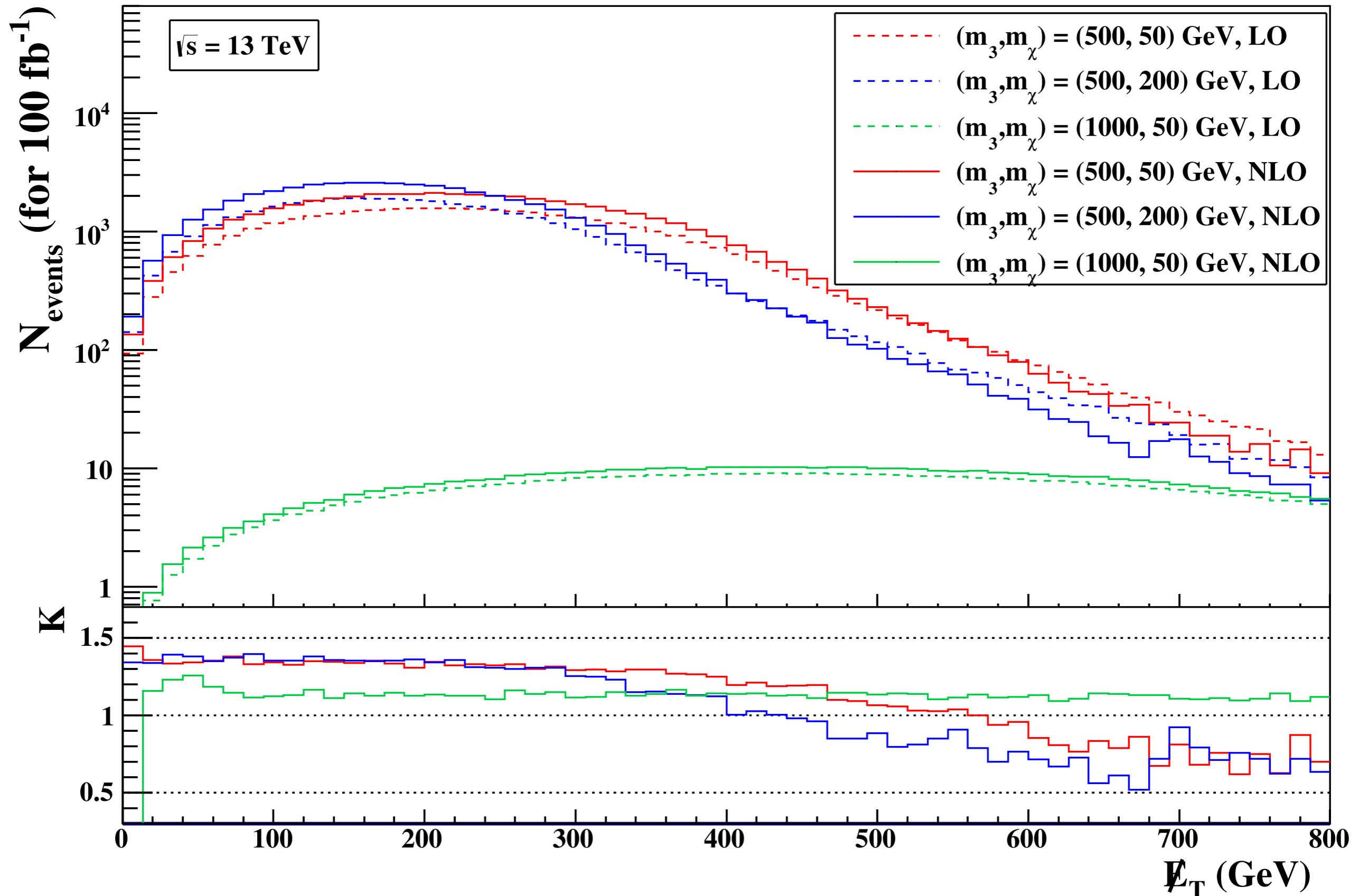
UV

$$\begin{aligned}R_2^{\sigma_3^\dagger \sigma_3} &= \frac{ig_s^2}{72\pi^2} \delta_{c_1 c_2} \left[ 3m_3^2 - p^2 \right], \\ R_2^{g\sigma_3^\dagger \sigma_3} &= \frac{53ig_s^3}{576\pi^2} T_{c_2 c_3}^{a_1} (p_2 - p_3)^{\mu_1}, \\ R_2^{gg\sigma_3^\dagger \sigma_3} &= \frac{ig_s^4}{1152\pi^2} \eta^{\mu_1 \mu_2} [3\delta^{a_1 a_2} - 187\{T^{a_1}, T^{a_2}\}]_{c_3 c_4}\end{aligned}$$

R2

- Analytical cross-checks and numerical comparison vs Prospino :

# SCALAR COLOR TRIPLET PAIR PRODUCTION



# COLORED SCALAR OCTET PAIR PRODUCTION

[C. Degrande, B. Fuks, V.H., J. Proudom, H.S. Shao in 1412.5589 ]

- sgluon pair production

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

# COLORED SCALAR OCTET PAIR PRODUCTION

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- Counterterms derived by FR+NLOCT :

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

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

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

$$+ \frac{\alpha_s}{8\pi} \left[ \frac{1}{\bar{\epsilon}} - \log \frac{m_8^2}{\mu_R^2} \right].$$

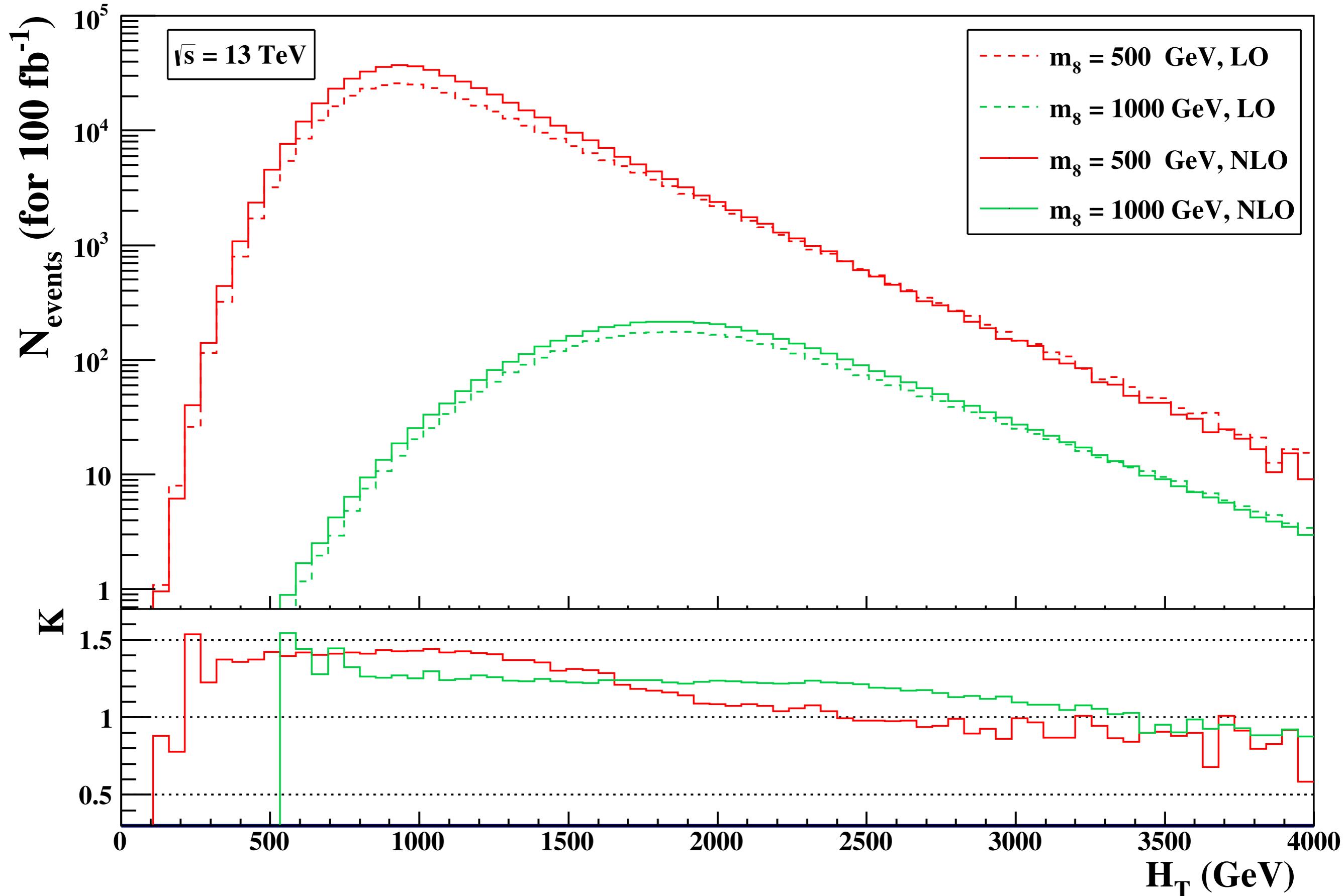
UV

$$\begin{aligned}R_2^{\sigma_8\sigma_8} &= \frac{ig_s^2}{32\pi^2} \delta_{a_1 a_2} \left[ 3m_8^2 - p^2 \right], \\ R_2^{g\sigma_8\sigma_8} &= \frac{7g_s^3}{64\pi^2} f_{a_1 a_2 a_3} (p_2 - p_3)^{\mu_1}, \\ R_2^{gg\sigma_8\sigma_8} &= \frac{ig_s^4}{384\pi^2} \eta^{\mu_1 \mu_2} \left[ 72(d_{a_1 a_4 e} d_{a_2 a_3 e} + d_{a_1 a_3 e} d_{a_2 a_4 e}) \right. \\ &\quad \left. - 141 d_{a_1 a_2 e} d_{a_3 a_4 e} - 92 \delta_{a_1 a_2} \delta_{a_3 a_4} \right. \\ &\quad \left. + 50(\delta_{a_1 a_3} \delta_{a_2 a_4} + \delta_{a_1 a_4} \delta_{a_2 a_3}) \right],\end{aligned}$$

R2

- Analytical cross-checks and numerical comparison for local phase-space points vs MadGolem.

# SCALAR COLOR OCTET PAIR PRODUCTION



Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

The MadGraph homepage  
UCL UIUC Fermi  
by the MG/ME Development team

Generate Process Register Tools My Database Cluster Status Downloads (needs registration) Wiki/Docs Admin

## Generate processes online using MadGraph 5

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 MadGraph 5, [JHEP 1106\(2011\)128, arXiv:1106.0522 \[hep-ph\]](#). You can still use MadGraph 4 [here](#).

Code can be generated either by:

I. Fill the form:

Model:   LO [Model descriptions](#)  
 NLO [Examples/format](#)

Input Process:

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

$p$  and  $j$  definitions:

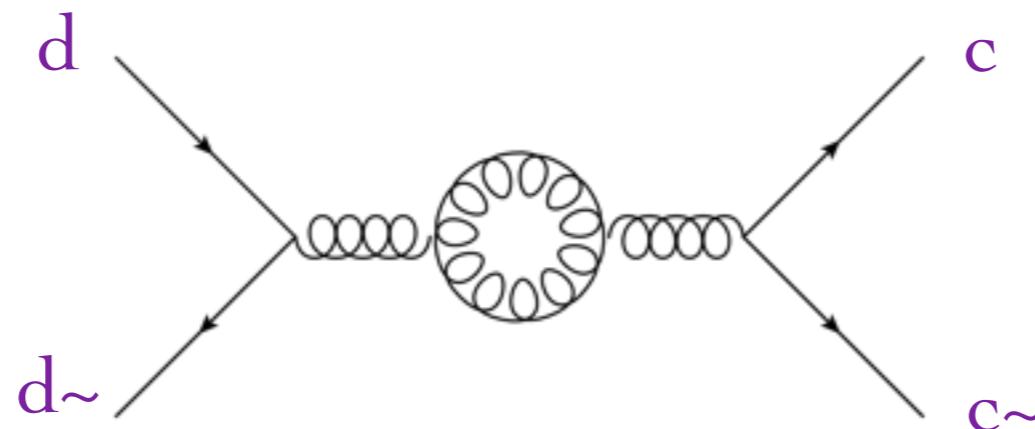
sum over leptons:

Soon !

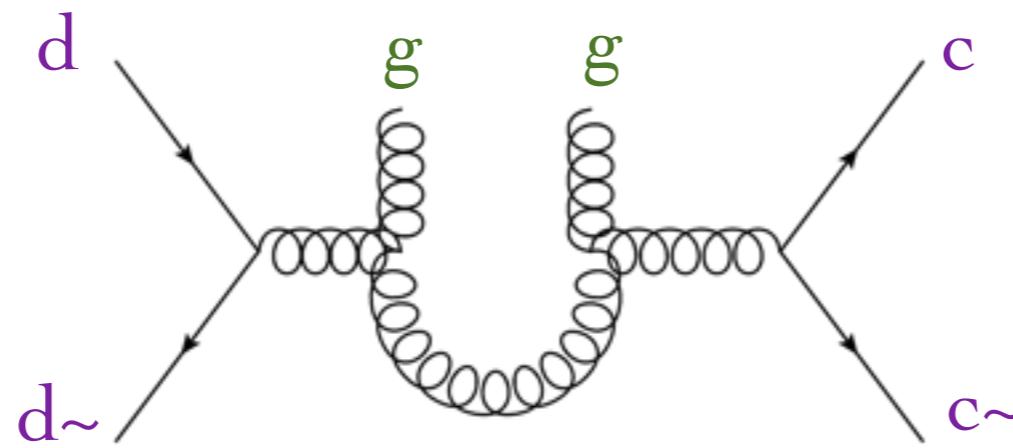
# ADDITIONAL SLIDES

# GENERATING LOOP DIAGRAMS

- It is clear though that  $d\bar{d} \rightarrow c\bar{c} u\bar{u}$  will not get you this loop :



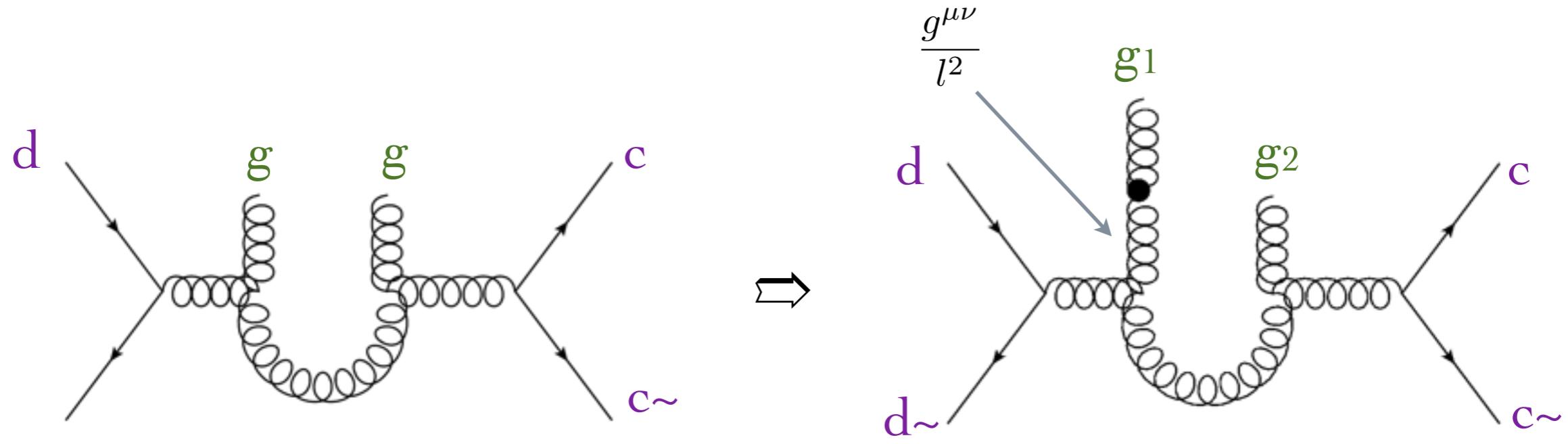
- For this one you necessarily need to generate the born process with the additional two L-cut particles being gluons!



- Loops including a  $u$ -quark were already generated with  $d\bar{d} \rightarrow c\bar{c} u\bar{u}$ , so you can speed up the  $d\bar{d} \rightarrow c\bar{c} gg$  generation forbidding  $u$  in the loop!

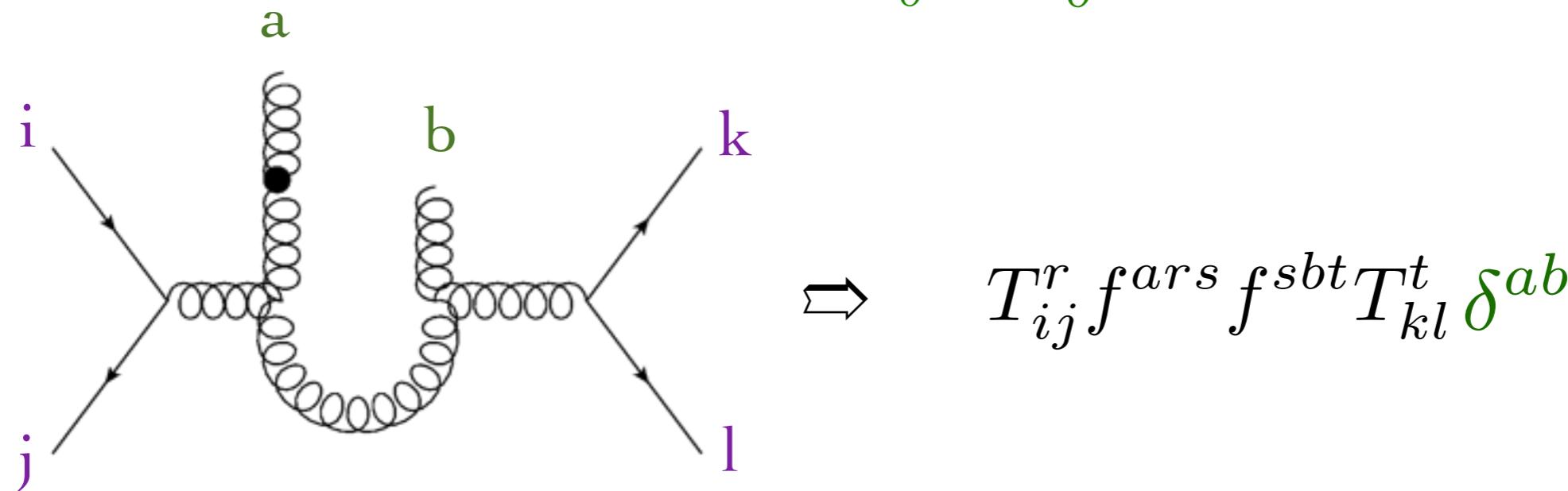
# GENERATING LOOP DIAGRAMS

- It is not yet what we want, we are missing the l-cut propagator



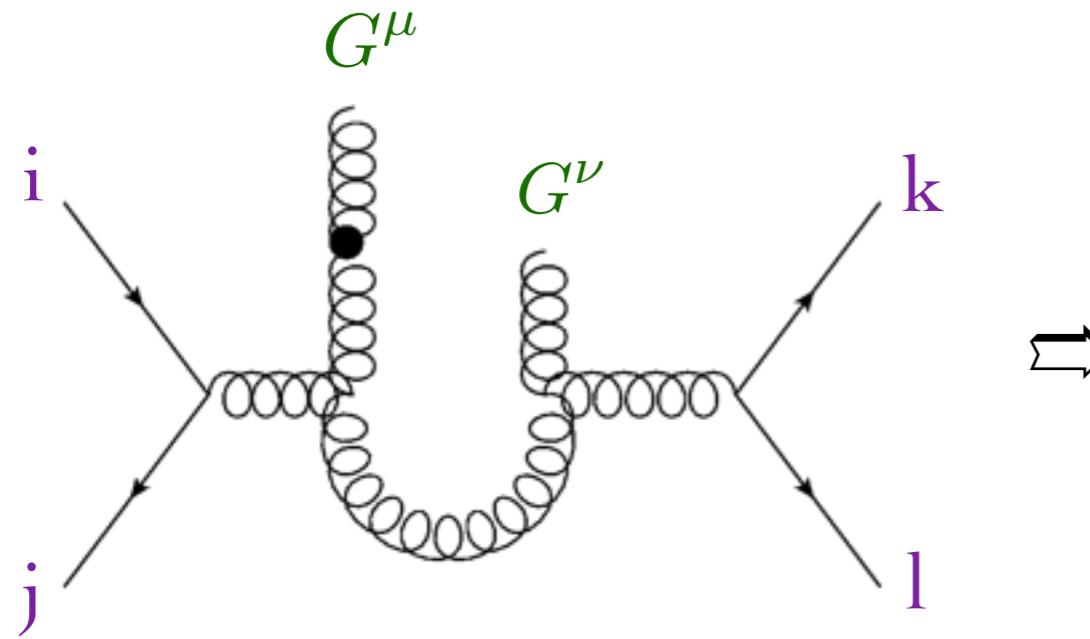
$d \sim$

- Also close the color trace  $\rightarrow$  insert a  $\delta^{ab}$  or  $\delta^{ij}$  to the color chain



# GENERATING LOOP DIAGRAMS

- Closing the Lorentz trace :


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

- Two other modifications :
  - Allow for the loop momentum to be complex
  - Remove the denominator of the loop propagators
- Ok, now this gives you  $\mathcal{N}(l^\mu)$ , the **integrand numerator** to be fed to OPP!

# OPEN-LOOPS

[S. Pozzorini & al. hep-ph/1111.5206]

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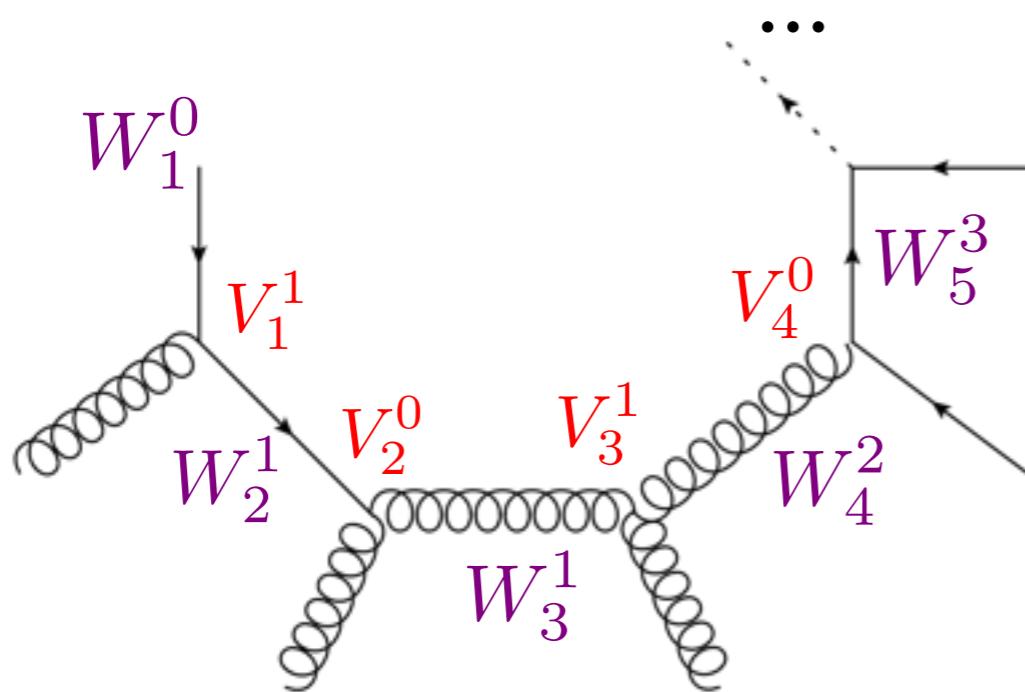
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- How to get these coefficients? (Wavefunction and 4-momenta indices now omitted)



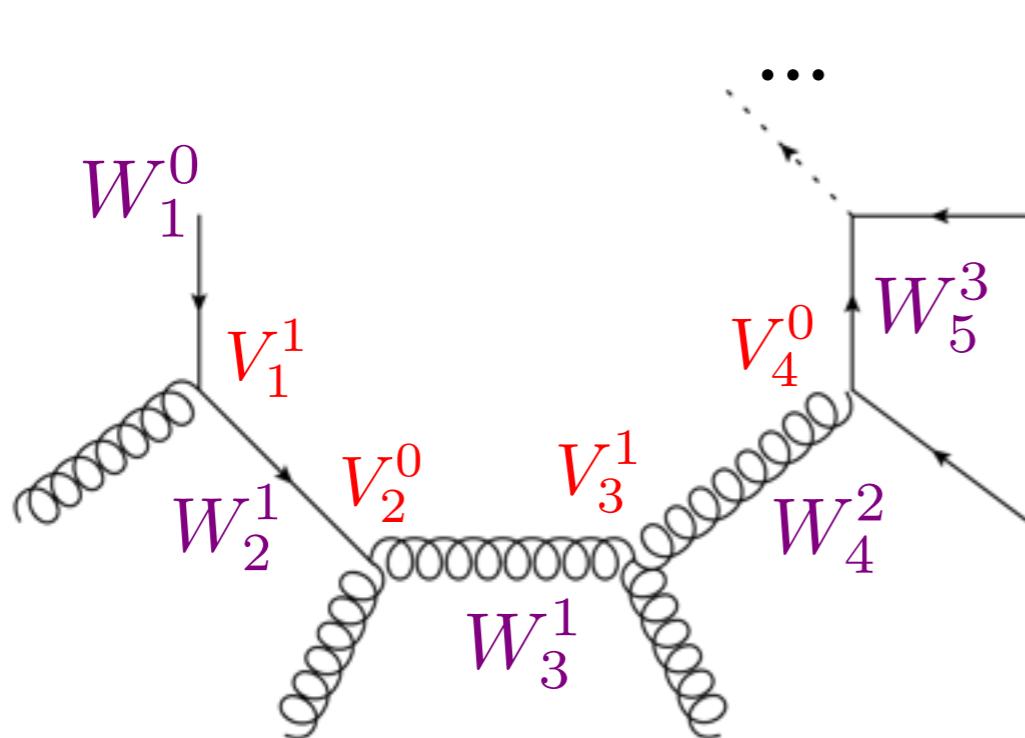
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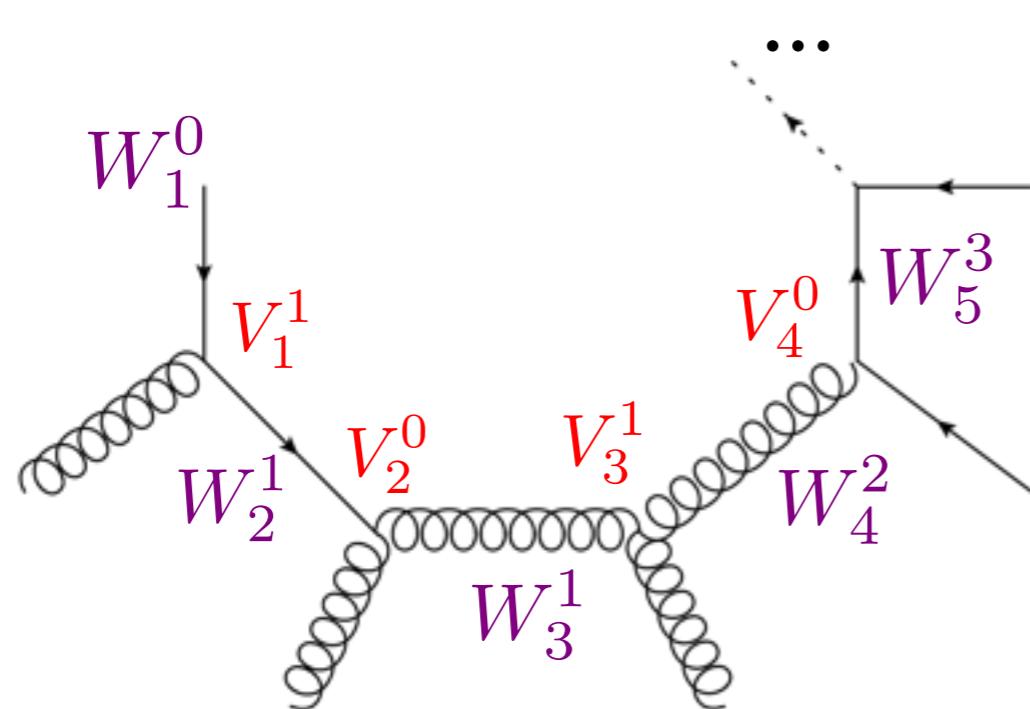
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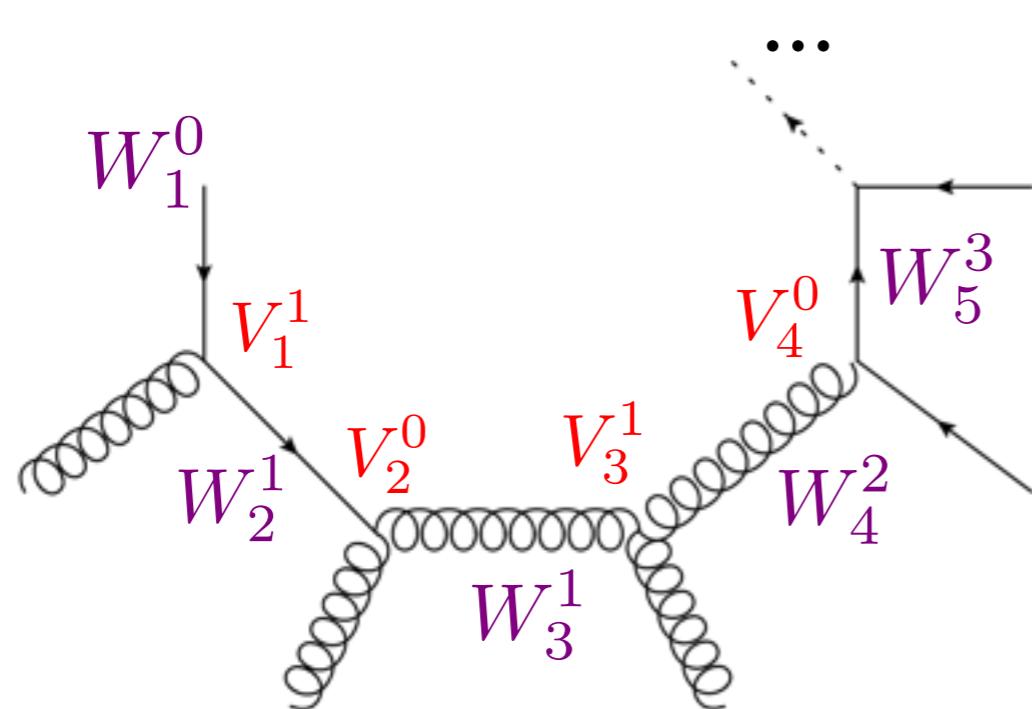
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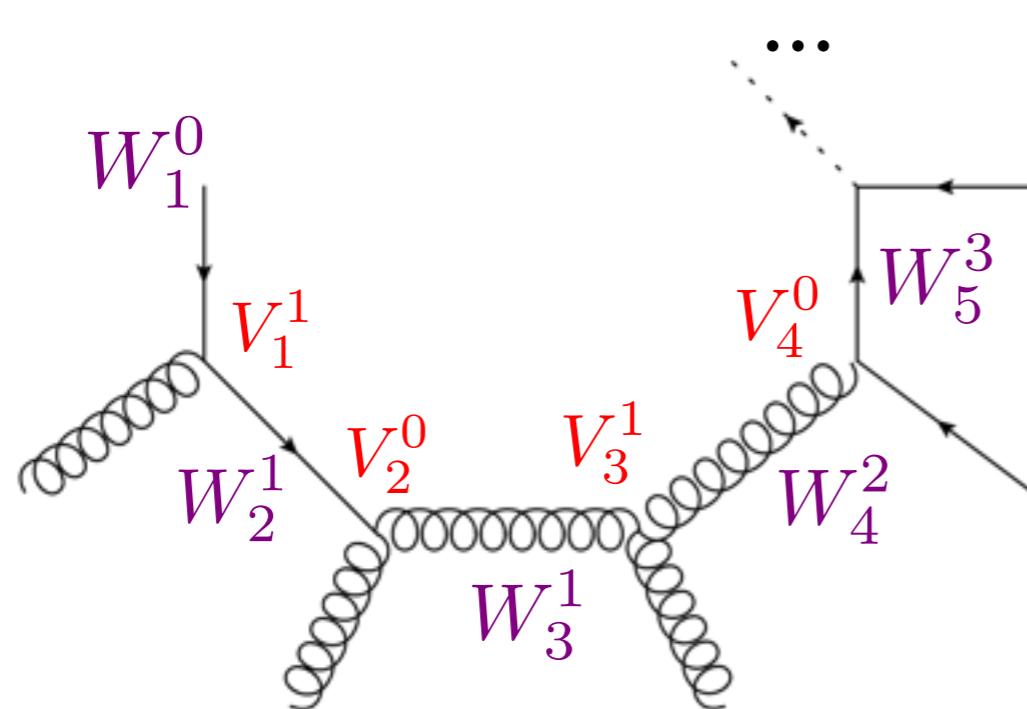
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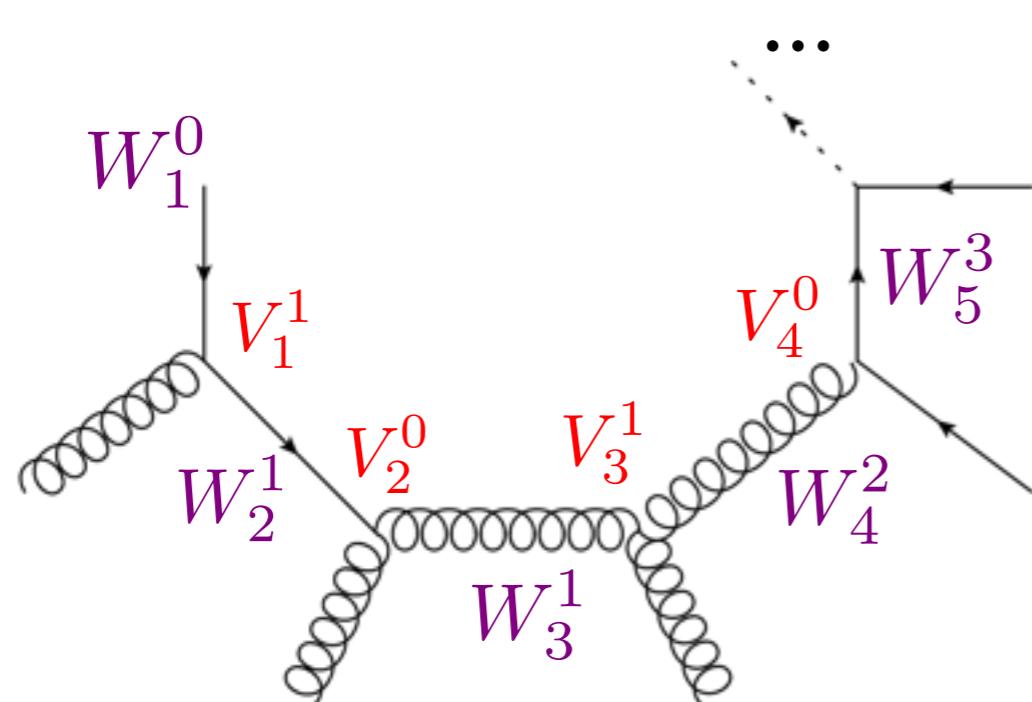
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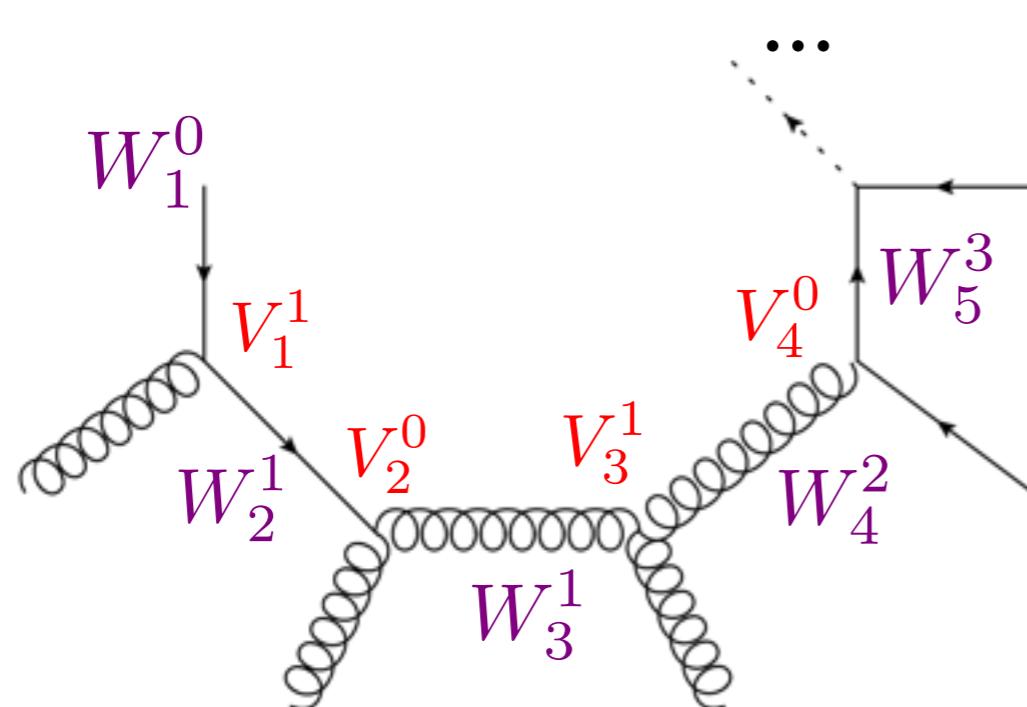
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... or end of loop and  $C^{(2)} = v_3^1 v_2^0 v_1^1 w_1^0, C^{(1)} = v_2^0 w_1^0 (v_3^1 v_0^1 + v_3^0 v_1^1), C^0 = \dots$

# PROCESS DETAILS

Process	unpol $t_{\text{coef}} / t_{\text{tot}}$	pol $t_{\text{coef}} / t_{\text{tot}}$	$n_{\text{loops}} / n_{\text{loop\_groups}}$
$u \ u \sim \rightarrow t \ t \sim$	42%	20%	8 / 14
$u \ u \sim \rightarrow w^+ w^-$	69%	21%	5 / 6
$u \ d \sim \rightarrow w^+ g$	52%	16%	9 / 11
$g \ g \rightarrow t \ t \sim$	66%	25%	26 / 45
$u \ u \sim \rightarrow t \ t \sim \ g$	78%	18%	54 / 128
$u \ u \sim \rightarrow w^+ w^- \ g$	91%	24%	40 / 98
$u \ d \sim \rightarrow w^+ g \ g$	69%	17%	61 / 144
$g \ g \rightarrow t \ t \sim \ g$	92%	29%	164 / 556
$u \ u \sim \rightarrow t \ t \sim \ g \ g$	88%	22%	374 / 1530
$u \ u \sim \rightarrow w^+ w^- \ g \ g$	95%	25%	260 / 1108
$u \ d \sim \rightarrow w^+ g \ g \ g$	84%	20%	405 / 1827
$g \ g \rightarrow t \ t \sim \ g \ g$	97%	35%	1168 / 7356
$u \ d \sim \rightarrow w^+ g \ g \ g \ g$	94%	21%	3255 / 25666

# RUNNING SPEED OF ONE-LOOP AMPLITUDES

## COLOR SUMMED, WITH OPP

Process	$t_{\text{pol}}$ [ms]	$n_{\text{hel}}$	$t_{\text{unpol}}$ [ms]
$u \ u \sim \rightarrow t \ t \sim$	0.52	<b>3/16</b>	0.72
$u \ u \sim \rightarrow w^+ w^-$	0.43	<b>10/36</b>	1.00
$u \ d \sim \rightarrow w^+ g$	0.87	<b>6/24</b>	1.51
$g \ g \rightarrow t \ t \sim$	2.51	<b>6/16</b>	5.42
$u \ u \sim \rightarrow t \ t \sim g$	7.44	<b>16/32</b>	27.5
$u \ u \sim \rightarrow w^+ w^- g$	9.3	<b>36/72</b>	81.8
$u \ d \sim \rightarrow w^+ g \ g$	13.5	<b>12/48</b>	36.9
$g \ g \rightarrow t \ t \sim g$	40.8	<b>32/32</b>	381
$u \ u \sim \rightarrow t \ t \sim g \ g$	142	<b>32/64</b>	1010
$u \ u \sim \rightarrow w^+ w^- g \ g$	166	<b>72/144</b>	2820
$u \ d \sim \rightarrow w^+ g \ g \ g$	260	<b>24/96</b>	1'310
$g \ g \rightarrow t \ t \sim g \ g$	826	<b>64/64</b>	16'900
$u \ d \sim \rightarrow w^+ g \ g \ g \ g$	9400	<b>48/192</b>	90'900

Polarized timing **competitive**

$t_{2 \rightarrow 2} : t_{2 \rightarrow 3} : t_{2 \rightarrow 4} \lesssim 1 : 40 : 800$  ms

Unpolarized timing

Good enough for  $2 \rightarrow 3$

Might need further improvement for  $2 \rightarrow 4$

Higher multiplicity  
 $2 \rightarrow 5$  generation feasible

But evaluation is slow, so only useful to cross-check other codes  
 (Ex.  $gg \rightarrow gggg$  successfully cross-checked vs NGluon<sup>[S. Badger]</sup>)