

# PRECISION SUSY WITH MADGRAPH5\_AMC<sup>A</sup>@NLO

VALENTIN HIRSCHI

IN A JOINT EFFORT WITH  
[[HTTP://ARXIV.ORG/ABS/1412.5589](http://arxiv.org/abs/1412.5589)]

CÉLINE DEGRANGE, BENJAMIN FUKS,  
JOSSELIN PROUDOM, HUA-SHENG SHAO

AND THE REST OF THE MG5\_AMC COLLABORATION.  
[[HTTP://ARXIV.ORG/ABS/1405.0301](http://arxiv.org/abs/1405.0301)]

SUSY, LAKE TAHOE  
08.28.2015

# PREDICTION CHAIN

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

**SYMMETRIES**

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

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

**MODEL**

$$\downarrow \\ \text{0000} = i\gamma^\mu t_{ij}^a , \dots$$

$pp \rightarrow jj$  QCD = 2

**MATRIX ELEMENT**

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

matrix.f

**PARTONIC EVENTS**

```
<event>
 5   66 0.35819066E-07 0.55353448E+03 0.79577472E-01 0.11724198E+00
    -1 -1 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 0.29841056E+02 0.402821
 24 1 1 2 0 0 -.39256150E+02 -.24576181E-01 -.209882
 -.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 0.38000000E+01 0
 </event>
 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
 </events>
</eventset>
```

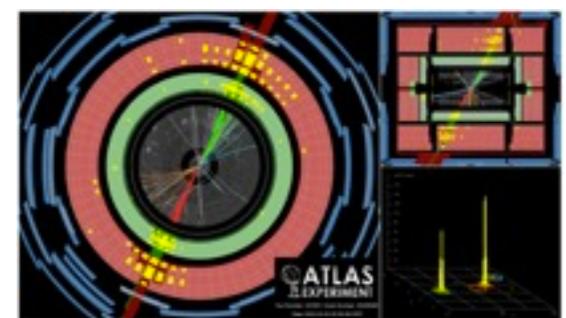
events.lhe

**HADRON LEVEL**

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

events.hep

**DETECTOR LEVEL**



# PREDICTION CHAIN

GALILEO

FEYNRULES

MG5 / MADLOOP

MADFKS / MADEVENT

PYTHIA / HERWIG

PGS / DELPHES

SYMMETRIES

MODEL

MATRIX ELEMENT

PARTONIC EVENTS

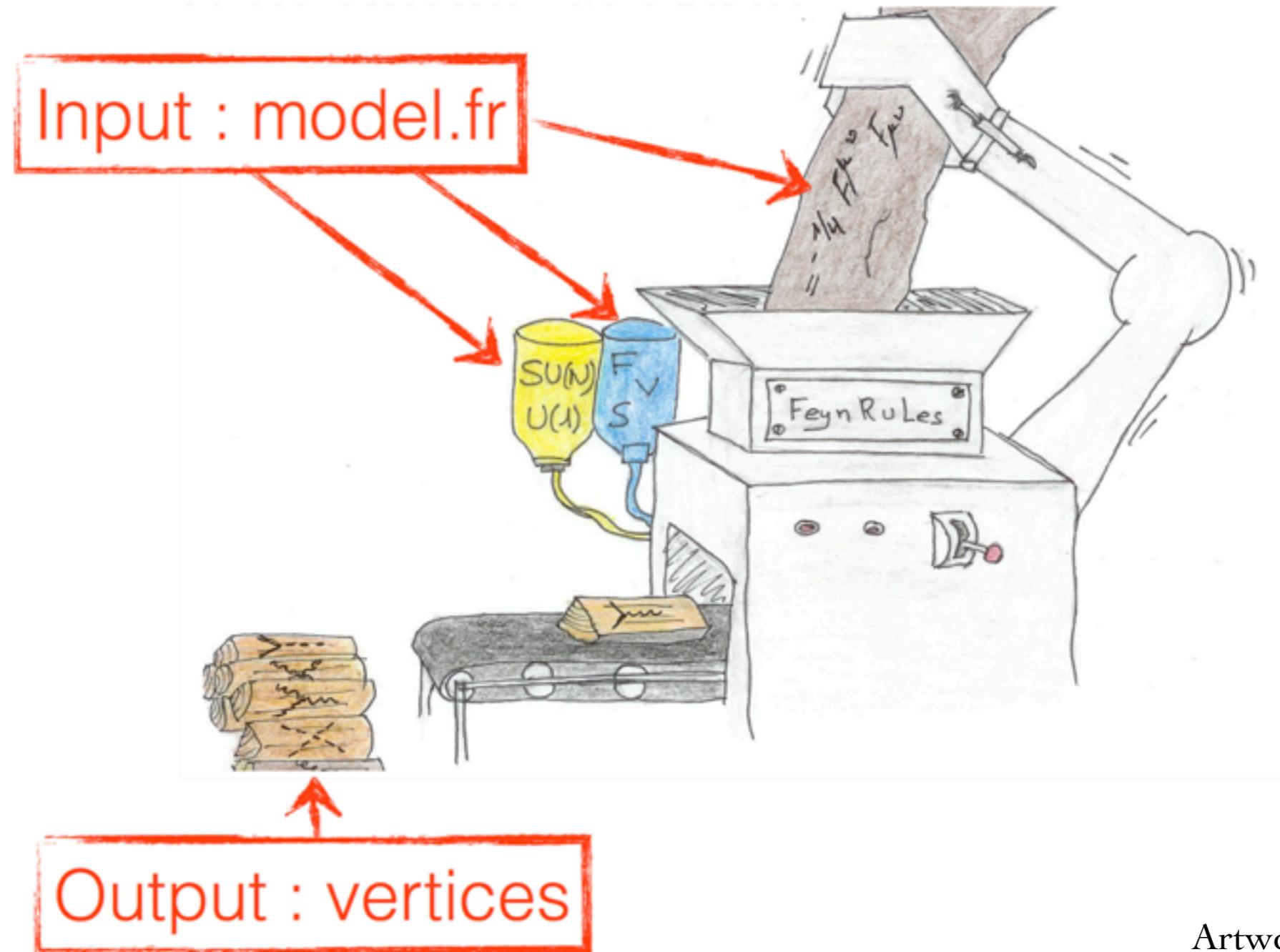
HADRON LEVEL

DETECTOR LEVEL

MADANALYSIS 5

# FEYNRULES

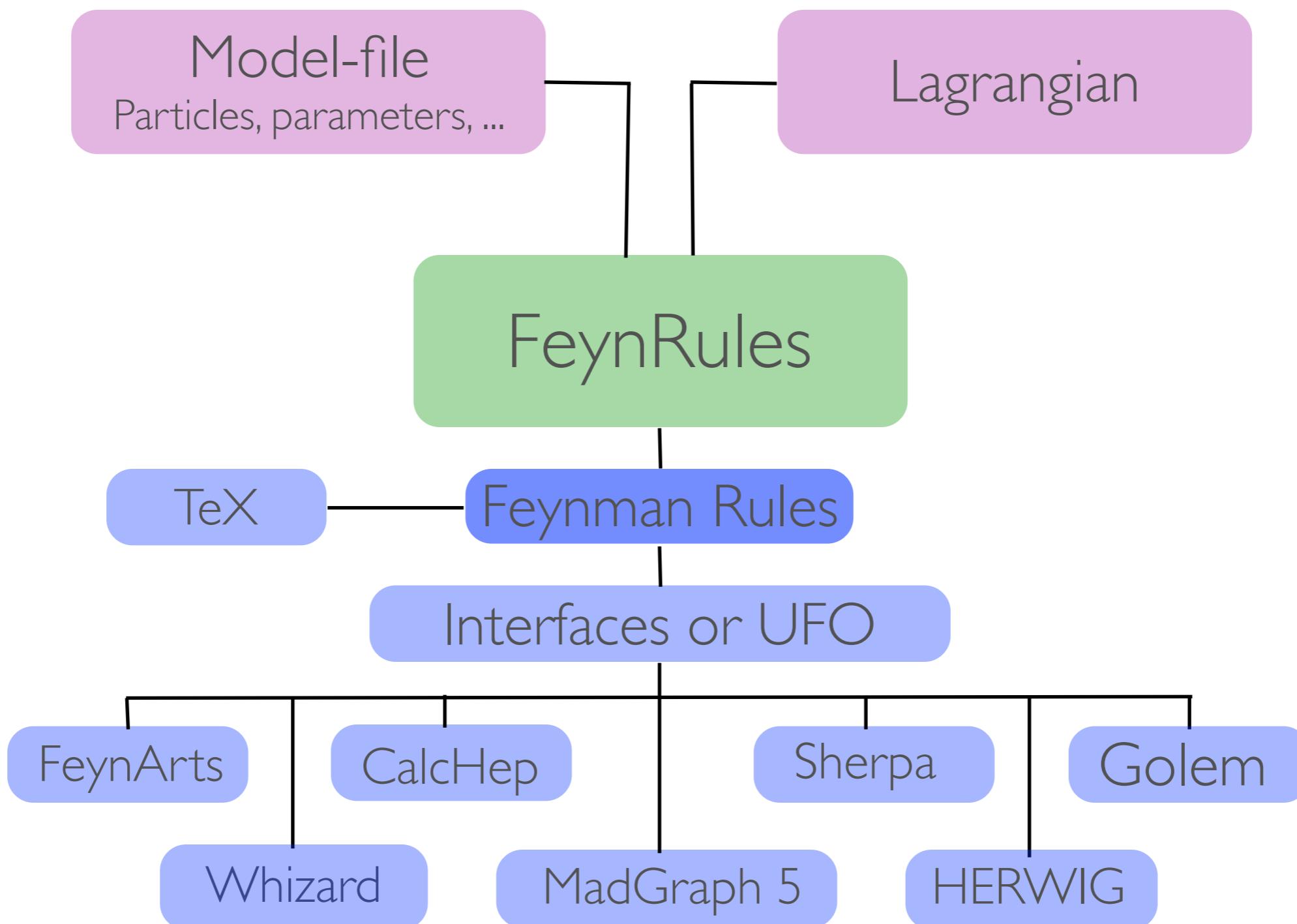
# MODEL



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

```
LoadModel[ <
```

## Extracting

```
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 ]  
WriteWOOOutput[ 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...

## coupling\_orders.py

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

## 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})
```

## lorentz.py

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

## couplings.py

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

## parameters.py

```
aS = Parameter(name = 'aS',
                nature = 'external',
                type = 'real',
                value = 0.118,
                .pi),
                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-dimensions (1)</a>		
<a href="#">Strongly interacting theories (1)</a>		
<a href="#">Miscellaneous (1)</a>		
Model	Short Description	Contact
<a href="#">Axigluon model</a>	The SM plus a scalar gluon field.	S. Krastanov
<a href="#">DY SM extension</a>	The SM plus new spin-0, -1, and -2 bosons that contribute to Drell-Yan production of leptons at the LHC.	N. Christensen
<a href="#">FCNC Higgs interactions</a>	The SM plus higher-dimensional flavor changing Higgs interactions.	S. Krastanov
<a href="#">Fourth generation model</a>	A fourth generation model including a t' and a b'	C. Duhr
<a href="#">General 2HDM</a>	The most general 2HDM, including all flavor violation and mixing terms.	C. Duhr, M. Herquet
<a href="#">Hidden Abelian Higgs Model</a>	A Z' model where the Z' interacts with the SM through mixings, leading to very small non-SM like Z' couplings.	C. Duhr
<a href="#">HiggsCharacterisation</a>	The model file for the spin/parity characterisation of a 125 GeV resonance.	P. de Aquino, K. Mawatari
<a href="#">Higgs effective theory</a>	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr
<a href="#">Higgs Effective Lagrangian</a>	Higgs effective Lagrangian including operators up-to dimension 6.	A. Alloul, B. Fuks and V. Sanz
<a href="#">Hill Model</a>	A model with an unusual extension of the SM Higgs sector.	P. de Aquino, C. Duhr
<a href="#">Inert Doublet Model</a>	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
<a href="#">Minimal Zp models</a>	The minimal Z' extension of the SM.	L. Basso
<a href="#">Monotops</a>	The SM plus monotop effective Lagrangian.	B. Fuks
<a href="#">Sextet diquarks</a>	The SM plus sextet diquark scalars.	J. Alwall, C. Duhr
<a href="#">Standard model + Scalars</a>	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
<a href="#">Triplet diquarks</a>	The SM plus triplet diquark scalars.	J. Alwall, C. Duhr
<a href="#">Type III See-Saw Model</a>	The SM, including neutrino masses coming from a type III See-Saw mechanism.	C. Biggio, F. Bonnet
<a href="#">VLQ</a>	The SM, plus vector-like quarks, in a model-independent framework.	M. Buchkremer, G. Cacciapaglia, A. Deandrea, L. Panizzi

# TWO MISSING INGREDIENTS FOR NLO

- UV counterterms:

A) Renormalize the Lagrangian

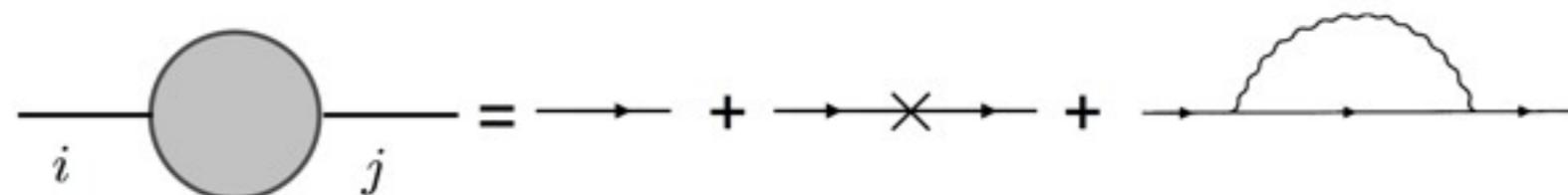
Fields	$\phi_0 \rightarrow (1 + \frac{1}{2}\delta Z_{\phi\phi}) + \sum_{\chi} \frac{1}{2}\delta Z_{\phi\chi}\chi$	}
ext. params	$x_0 \rightarrow x + \delta x$	
int. params	$g(x) \rightarrow g(x + \delta x)$	

$$\mathcal{L}_0 \rightarrow \mathcal{L} + \delta\mathcal{L}$$

B) Compute the defining loops

→ Done in **FeynArts**. Notice that for  $\overline{MS}$ , only poles are needed.

C) Solve for the counterterms by applying renormalization conditions



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}{\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}{\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( (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. \\
& + 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( (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) \\
& + 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}{\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}{\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( 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( 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. \\
& \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( 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}{\epsilon} + 1 - \log \left( \frac{M_b M_t}{\mu^2} \right) \right) \right) \right]
\end{aligned}$$

WITH

$$\begin{aligned}
l(m_1, m_2, m_3) = & \log \left( \frac{m_1^2 + m_2^2 - m_3^2 + \sqrt{(m_1^4 + (m_2^2 - m_3^2)^2 - 2m_1^2(m_2^2 + m_3^2))}}{2m_1 m_2} \right) \\
& \times \sqrt{(m_1^4 + (m_2^2 - m_3^2)^2 - 2m_1^2(m_2^2 + m_3^2))}.
\end{aligned}$$

**H<sup>+</sup> WAVEFUNCTION  
RENORMALIZATION  
CONSTANT IN 2HDM  
FOR QCD, QED AND  
EW CORRECTIONS...**

**... AUTOMATION IS  
MUCH NEEDED HERE**

# NLOCT: MISSING INGREDIENTS FOR NLO

- R2 counterterms:

Loop amplitude:

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

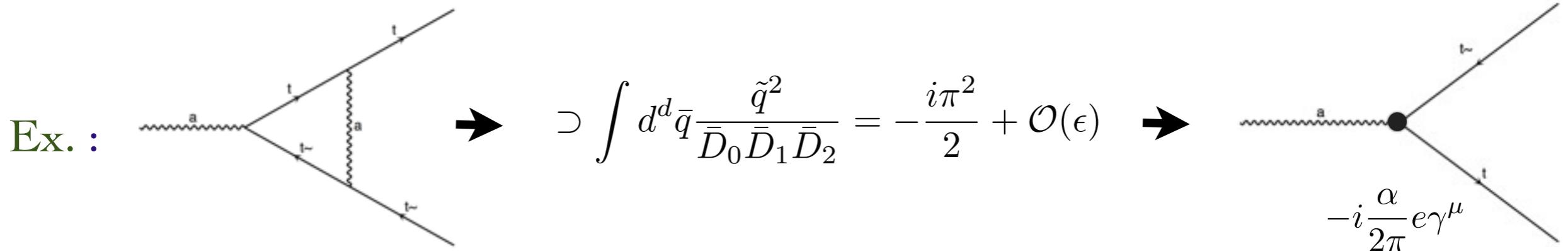
Problem : numerical technique can only evaluate the numerator in 4 dimensions

Solution : isolate the  $\epsilon$ -dim part of the numerator:

$$\underbrace{\bar{N}(\bar{q})}_{d\text{-dim}} = \underbrace{N(q)}_{4\text{-dim}} + \underbrace{\tilde{N}(\tilde{q}, q, \epsilon)}_{\epsilon\text{-dim}}$$

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**.

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



# EX: 4-GLUON VERTEX R2 IN THE SM

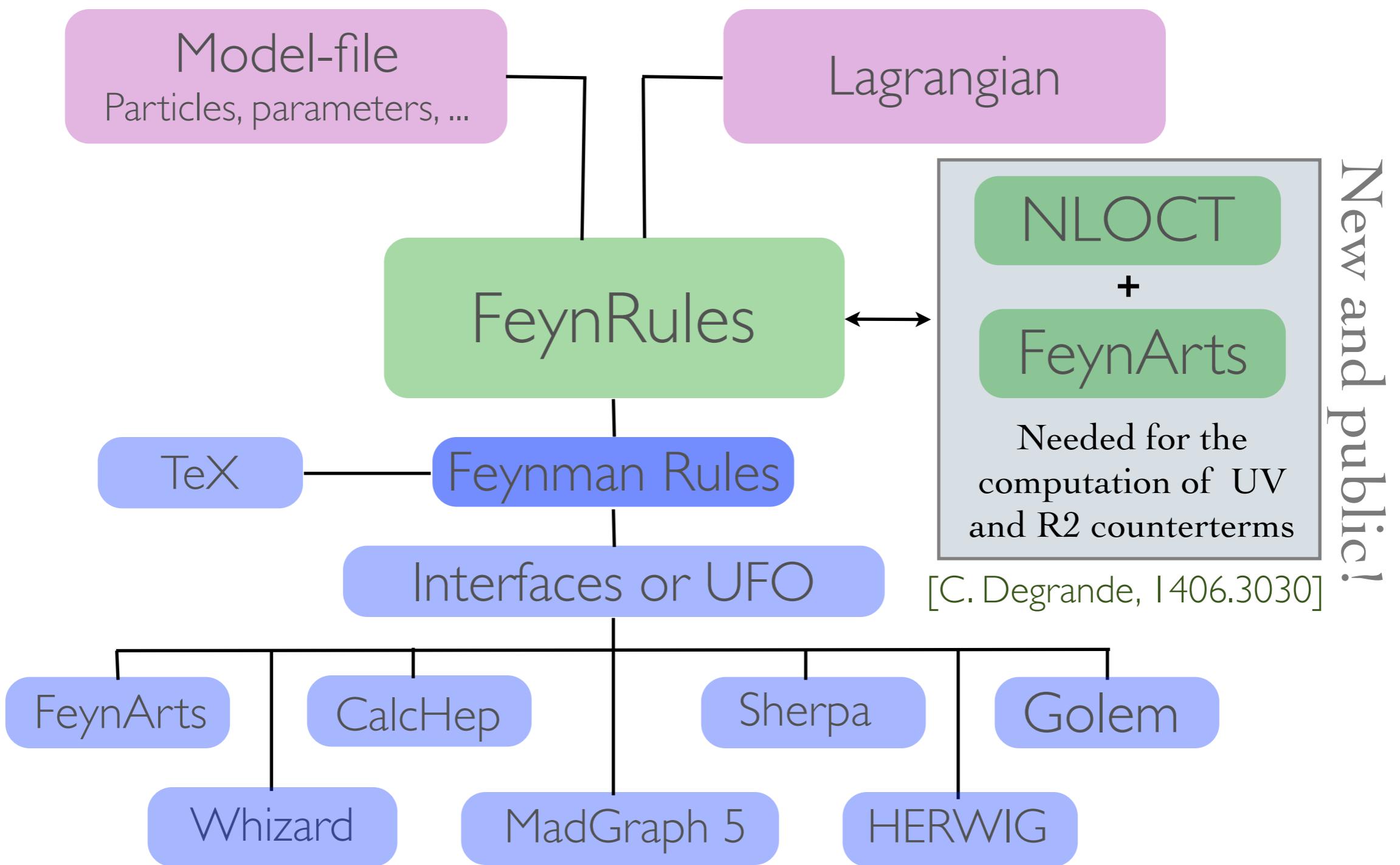
**R2 COUNTERTERMS TYPICALLY EXHIBIT A SIMPLER FORM, BUT CAN ALSO BECOME MORE COMPLICATED.**

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

**ONCE AGAIN AUTOMATION IS WELCOME.**

# FEYNRULES @ NLO (VERSION 2.1)

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



# 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,
                        (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),

# A LOOP MODEL DATABASE

## Available models

Standard Model	The SM implementation of FeynRules, included into the distribution of the FeynRules package.
Simple extensions of the SM (18)	Several models based on the SM that include one or more additional particles, like a 4th generation, a second Higgs doublet or additional colored scalars.
Supersymmetric Models (5)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more.
Extra-dimensional Models (4)	Extensions of the SM including KK excitations of the SM particles.
Strongly coupled and effective field theories (8)	Including Technicolor, Little Higgs, as well as SM higher-dimensional operators, vector-like quarks.
Miscellaneous (0)	

[NLO MODELS \(5\)](#)

**5 MODELS FOR NOW**

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

Dark matter simplified models ( <a href="#">more details</a> )	K. Mawatari	-	<a href="#">DMsimp_UFO.2.zip</a>
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_ufo.tgz</a>
Stop pair $\rightarrow t \bar{t} + \text{missing energy}$	B. Fuks	<a href="#">arXiv:1412.5589</a>	<a href="#">stop_ttmet_ufo.tgz</a>
Two-Higgs-Doublet Model ( <a href="#">more details</a> )	C. Degrande	<a href="#">arXiv:1406.3030</a>	<a href="#">2HDM_UFO.tar.gz</a>

- Many more BSM models in development and to be added to this list.
- Now, how to use these models in practice for producing NLO-accurate simulations?

# 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~  
> output  
> launch
```

[QCD]

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

- With some options specified:

```
> import model stop_ttmet_NLO  
> generate p p > sig3 sig3~ / t  
> output MyProc  
> launch -f
```

[QCD]

# BEGINNING OF A PARENTHESIS

**THE LO MEANING OF [QCD]:  
LOOP-INDUCED SIMULATION**

# LOOP-INDUCED PARENTHESIS

[V.H., O. Mattelaer 1507.00020]

- Can you compute this loop-induced process with MG5\_aMC?
  - Well... no, but MadLoop can give you the loop ME's!
- How does that help me?
  - It... does not.

There is a wide range of interest for loop-induced processes, but no automated efficient way of **integrating** them.

Need to bring a definitive solution to this.

# SIMPLEST EXAMPLE

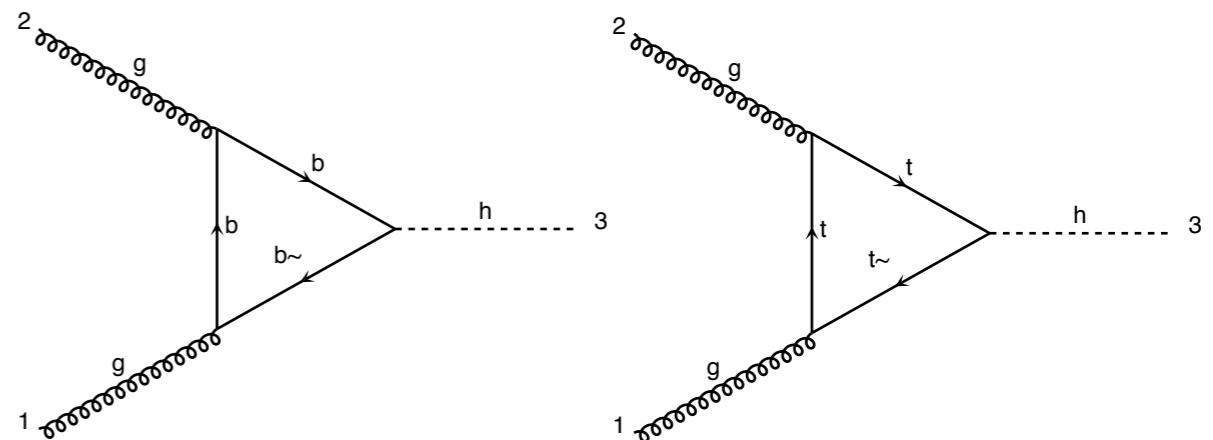
[V.H., O. Mattelaer 1507.00020]

## User Input

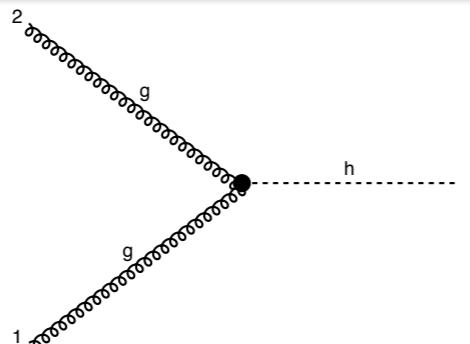
- generate  $g\ g > h$  [QCD]
- output
- launch

## Loop Induced

$$\sigma_{loop} = 15.74(2) pb$$

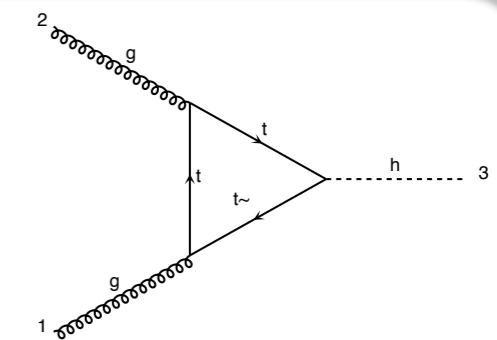


## HEFT



$$\sigma_{heft} = 17.63(2) pb$$

## No bottom loop



$$\sigma_{toploop} = 17.65(2) pb$$

# IMPROVED PARALLELIZATION

[V.H., O. Mattelaer 1507.00020]

## MadEvent

$$\int |M|^2 = \int \frac{|M_1|^2}{|M_1|^2 + |M_2|^2} |M|^2 + \int \frac{|M_2|^2}{|M_1|^2 + |M_2|^2} |M|^2$$

- Iteration 1
- Grid Refinement
- Iteration 2
- Grid Refinement

- Iteration 1
- Grid Refinement
- Iteration 2
- Grid Refinement

# IMPROVED PARALLELIZATION

[V.H., O. Mattelaer 1507.00020]

## New MadEvent

$$\int |M|^2 = \int \frac{|M_1|^2}{|M_1|^2 + |M_2|^2} |M|^2 + \int \frac{|M_2|^2}{|M_1|^2 + |M_2|^2} |M|^2$$

- Iteration 1

- Grid Refinement

- Iteration 2

- Grid Refinement

- Iteration 1

- Grid Refinement

- Iteration 2

- Grid Refinement

# AUTOMATE AND CONQUER

[V.H., O. Mattelaer 1507.00020]

- Extract from a **semi-exhaustive list** of all loop-induced SM processes

Process	Syntax	Cross section (pb)	$\Delta_{\bar{\mu}}$	$\Delta_{PDF}$
			$\sqrt{s} = 13 \text{ TeV}$	
<b>Triple bosons</b>				
*c.1 $pp \rightarrow HHH$	$p\ p > h\ h\ h \text{ [QCD]}$	$3.968 \pm 0.010 \cdot 10^{-5}$	+31.8% -22.6%	+1.4% -1.4%
†c.2 $gg \rightarrow HHZ$	$g\ g > h\ h\ z \text{ [QCD]}$	$5.260 \pm 0.009 \cdot 10^{-5}$	+31.2% -22.2%	+1.3% -1.3%
†c.3 $gg \rightarrow HZZ$	$g\ g > h\ z\ z \text{ [QCD]}$	$1.144 \pm 0.004 \cdot 10^{-4}$	+31.1% -22.2%	+1.2% -1.3%
†c.4 $gg \rightarrow HZ\gamma$	$g\ g > h\ z\ a \text{ [QCD]}$	$6.190 \pm 0.020 \cdot 10^{-6}$	+29.3% -21.2%	+1.0% -1.2%
†c.5 $pp \rightarrow H\gamma\gamma$	$p\ p > h\ a\ a \text{ [QCD]}$	$6.058 \pm 0.004 \cdot 10^{-6}$	+30.3% -21.8%	+1.1% -1.3%
*c.6 $pp \rightarrow HW^+W^-$	$g\ g > h\ w^+\ w^- \text{ [QCD]}$	$2.670 \pm 0.007 \cdot 10^{-4}$	+31.0% -22.2%	+1.2% -1.3%
†c.7 $gg \rightarrow ZZZ$	$g\ g > z\ z\ z \text{ [QCD]}$	$6.964 \pm 0.009 \cdot 10^{-5}$	+30.9% -22.1%	+1.2% -1.3%
†c.8 $gg \rightarrow ZZ\gamma$	$g\ g > z\ z\ a \text{ [QCD]}$	$3.454 \pm 0.010 \cdot 10^{-6}$	+28.7% -20.9%	+0.9% -1.1%
*c.9 $gg \rightarrow Z\gamma\gamma$	$g\ g > z\ a\ a \text{ [QCD]}$	$3.079 \pm 0.005 \cdot 10^{-4}$	+28.0% -20.9%	+0.7% -1.0%
†c.10 $gg \rightarrow ZW^+W^-$	$g\ g > z\ w^+\ w^- \text{ [QCD]}$	$8.595 \pm 0.020 \cdot 10^{-3}$	+26.9% -19.5%	+0.6% -0.6%
†c.12 $gg \rightarrow \gamma W^+W^-$	$g\ g > a\ w^+\ w^- \text{ [QCD]}$	$1.822 \pm 0.005 \cdot 10^{-2}$	+28.7% -20.9%	+0.9% -1.1%

★ : Published but **not publicly** available.

† : Computed here for the **first time**.

# **BACK TO BSM AT NLO:**

## **THE WHOLE AUTOMATED CHAIN APPLIED TO SUSY.**

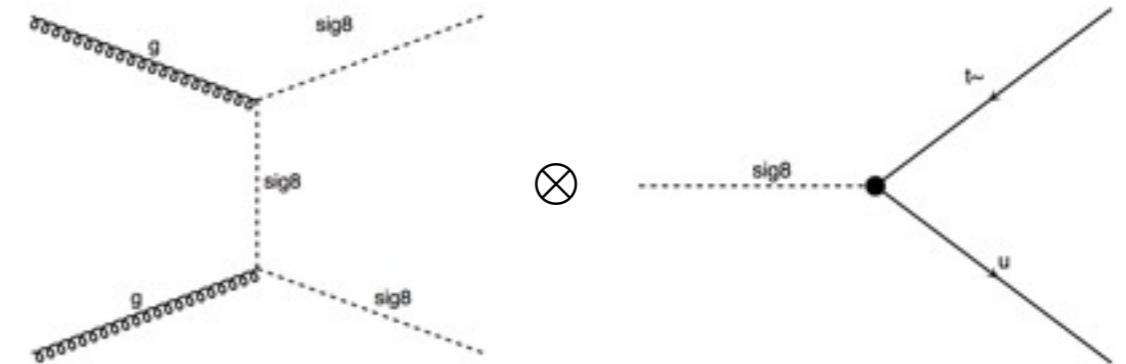
**WARM-UP ROUND:  
COLORED SCALARS PAIR-PRODUCTION  
IN A SIMPLIFIED MODEL**

# COLORED SCALAR OCTET PAIR PRODUCTION

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

- sgluon pair production

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



- Counterterms derived by FR+NLOCT :

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

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

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

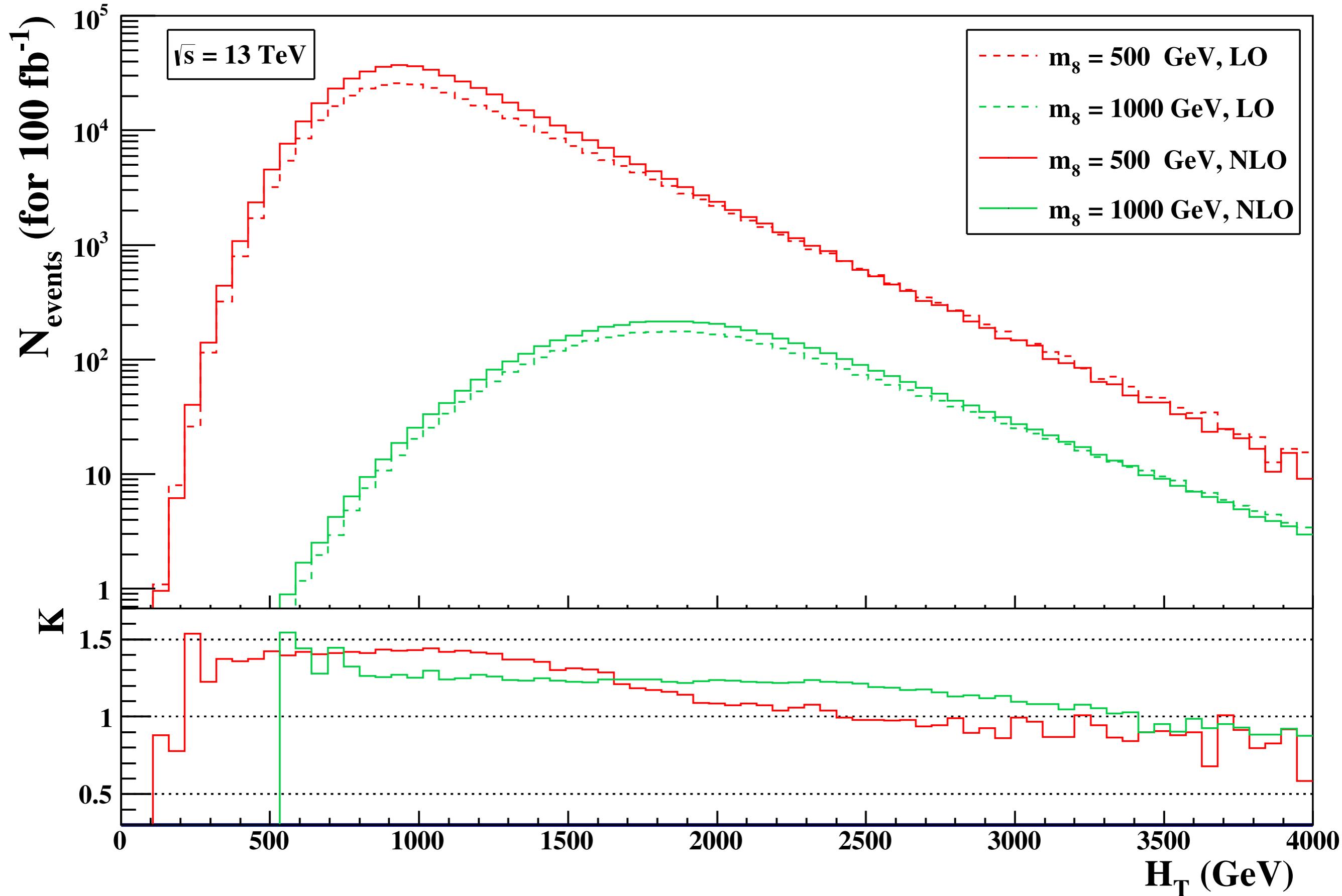
UV

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

R2

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

# SCALAR COLOR OCTET PAIR PRODUCTION

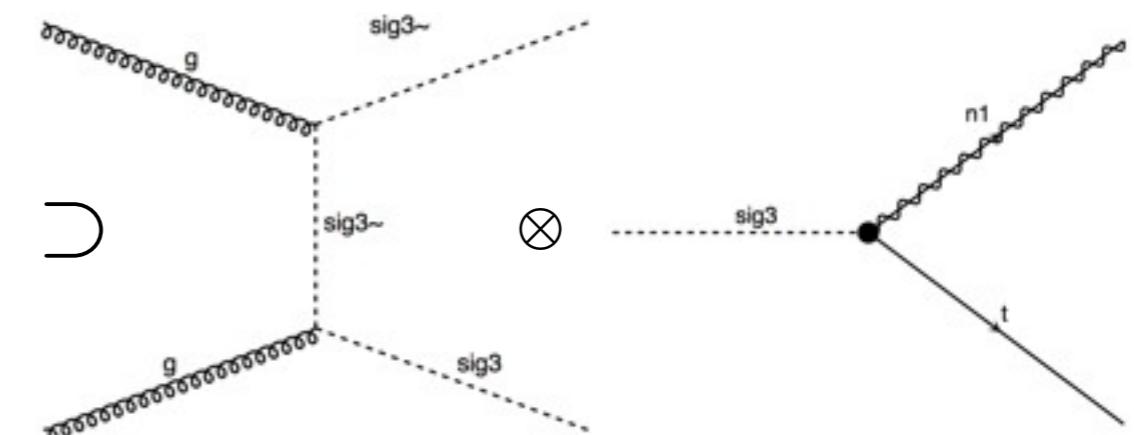


# SCALAR COLOR TRIPLET PAIR PRODUCTION

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

- Squark pair production

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



- Counterterms derived by FR+NLOCT :

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

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

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

$$+ \frac{\alpha_s}{24\pi} \left[ \frac{1}{\bar{\epsilon}} - \log \frac{m_3^2}{\mu_R^2} \right].$$

UV

$$R_2^{\sigma_3^\dagger \sigma_3} = \frac{ig_s^2}{72\pi^2} \delta_{c_1 c_2} \left[ 3m_3^2 - p^2 \right],$$

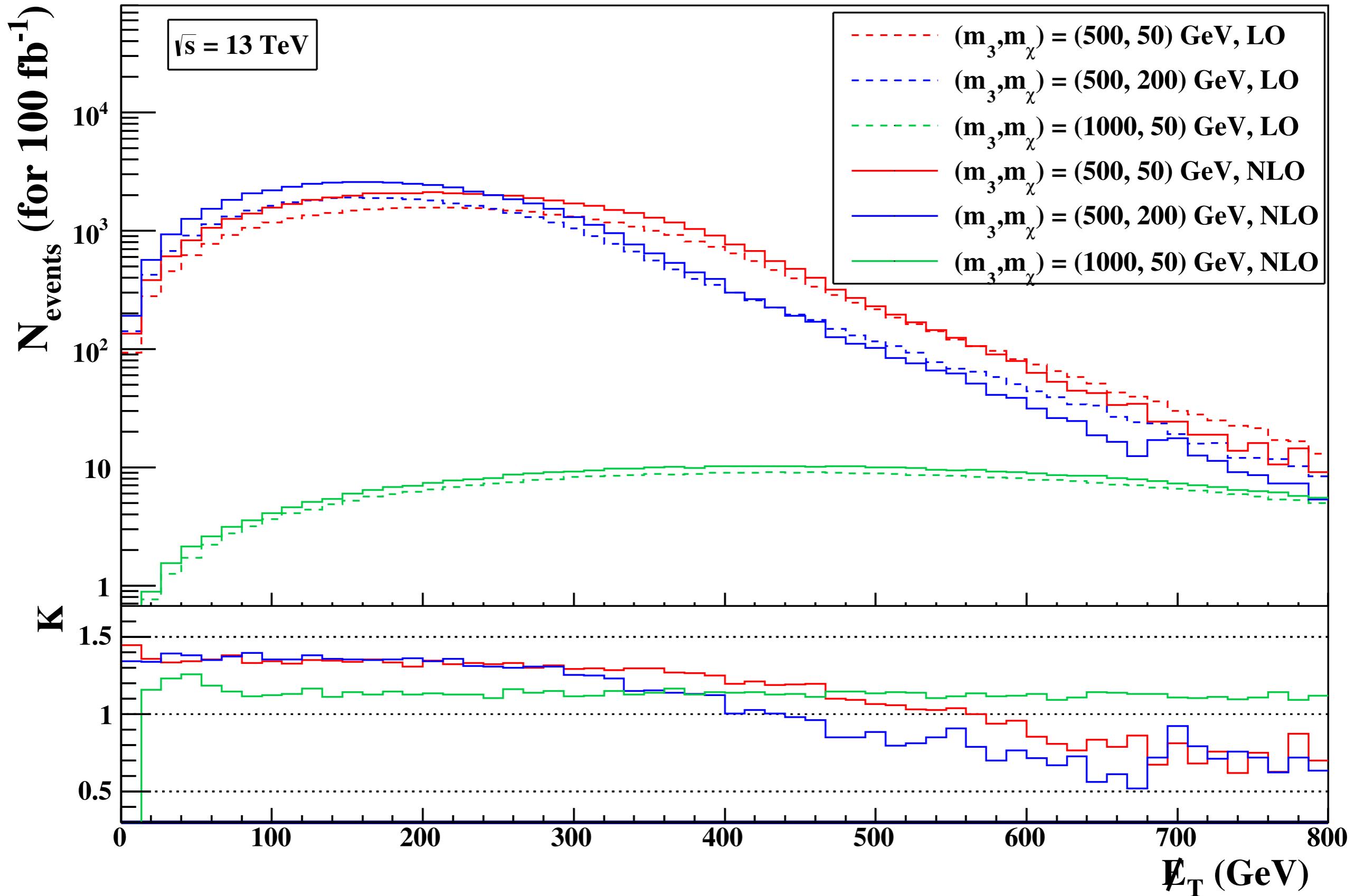
$$R_2^{g \sigma_3^\dagger \sigma_3} = \frac{53ig_s^3}{576\pi^2} T_{c_2 c_3}^{a_1} (p_2 - p_3)^{\mu_1},$$

$$R_2^{gg \sigma_3^\dagger \sigma_3} = \frac{ig_s^4}{1152\pi^2} \eta^{\mu_1 \mu_2} [3\delta^{a_1 a_2} - 187\{T^{a_1}, T^{a_2}\}]_{c_3 c_4}$$

R2

- Analytical cross-checks and numerical comparison vs Prospino :

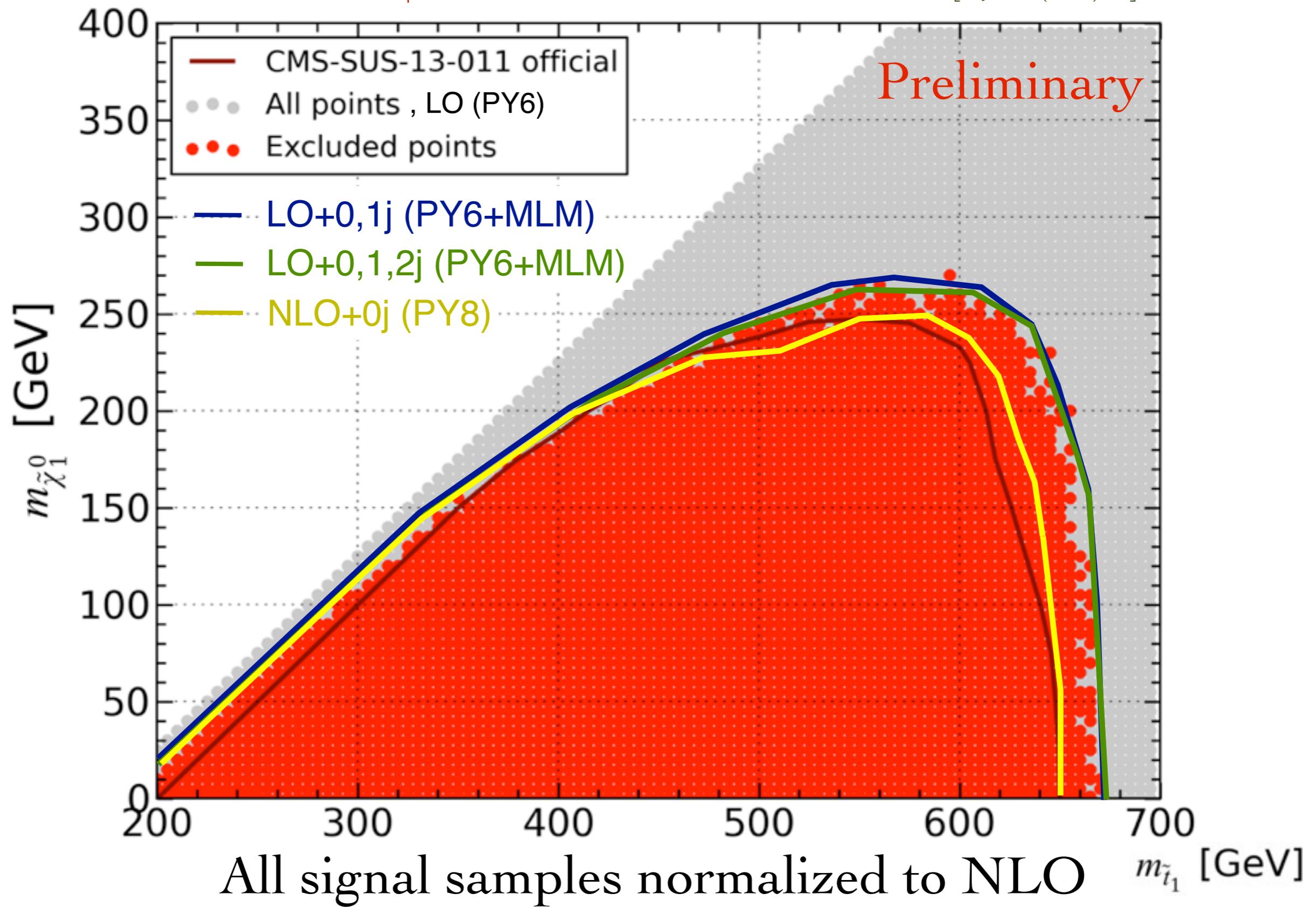
# SCALAR COLOR TRIPLET PAIR PRODUCTION



# MADANALYSIS5 RECASTING

Recasting in MA5: Conte, Dumont, Fuks, Wymant [EPJC 74 (2014) 3103]

CMS-SUS-13-011 implementation in MA5: Dumont, Fuks, Kraml et al [EPJC 75 (2015) 56]

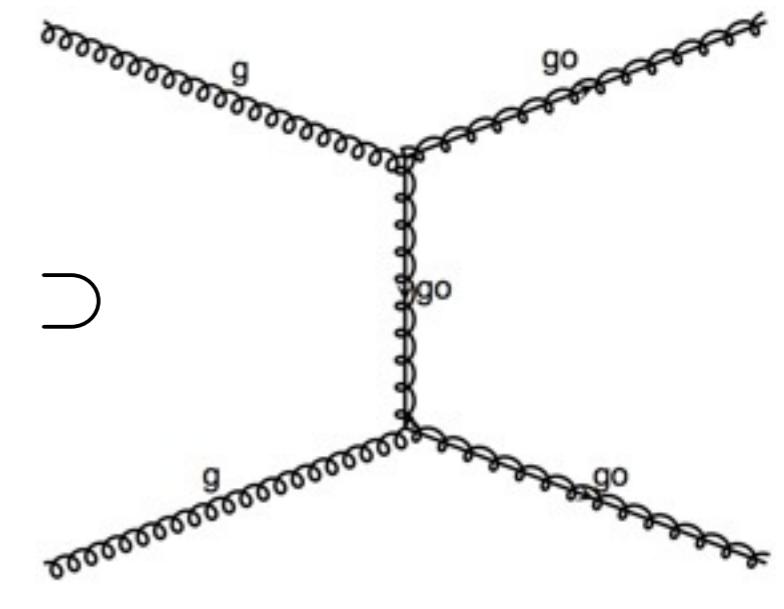


# A LOOK AHEAD : GLUINO PAIR PRODUCTION

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

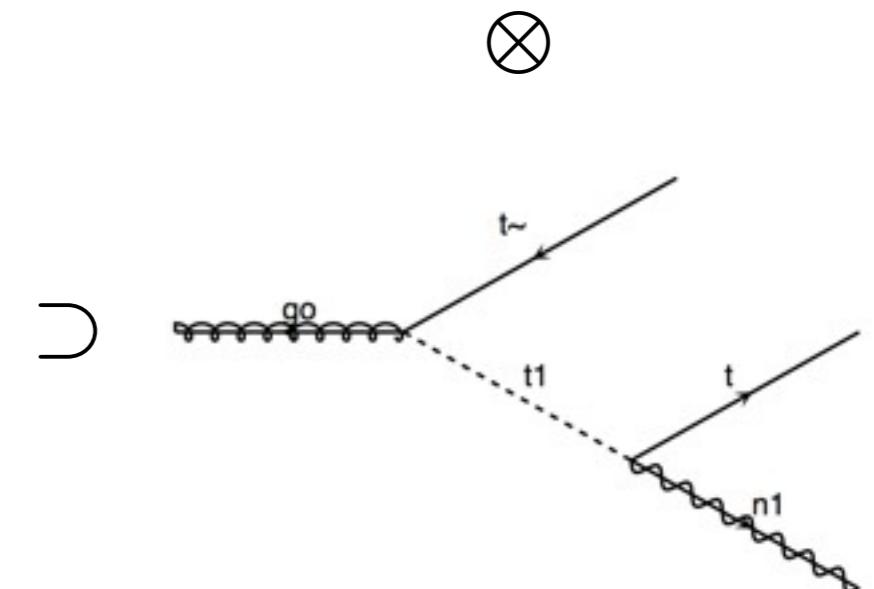
- Gluinos pair production...

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



- ... including the squark decay.

$$\begin{aligned} \mathcal{L}_{\text{decay}} = & \frac{i}{2} \bar{\chi} \not{D} \chi - \frac{1}{2} m_\chi \bar{\chi} \chi \\ & + \sqrt{2} g' \left[ - \tilde{q}_L^\dagger Y_q (\bar{\chi} P_L q) + (\bar{q} P_L \chi) Y_q \tilde{q}_R + \text{h.c.} \right] \end{aligned}$$

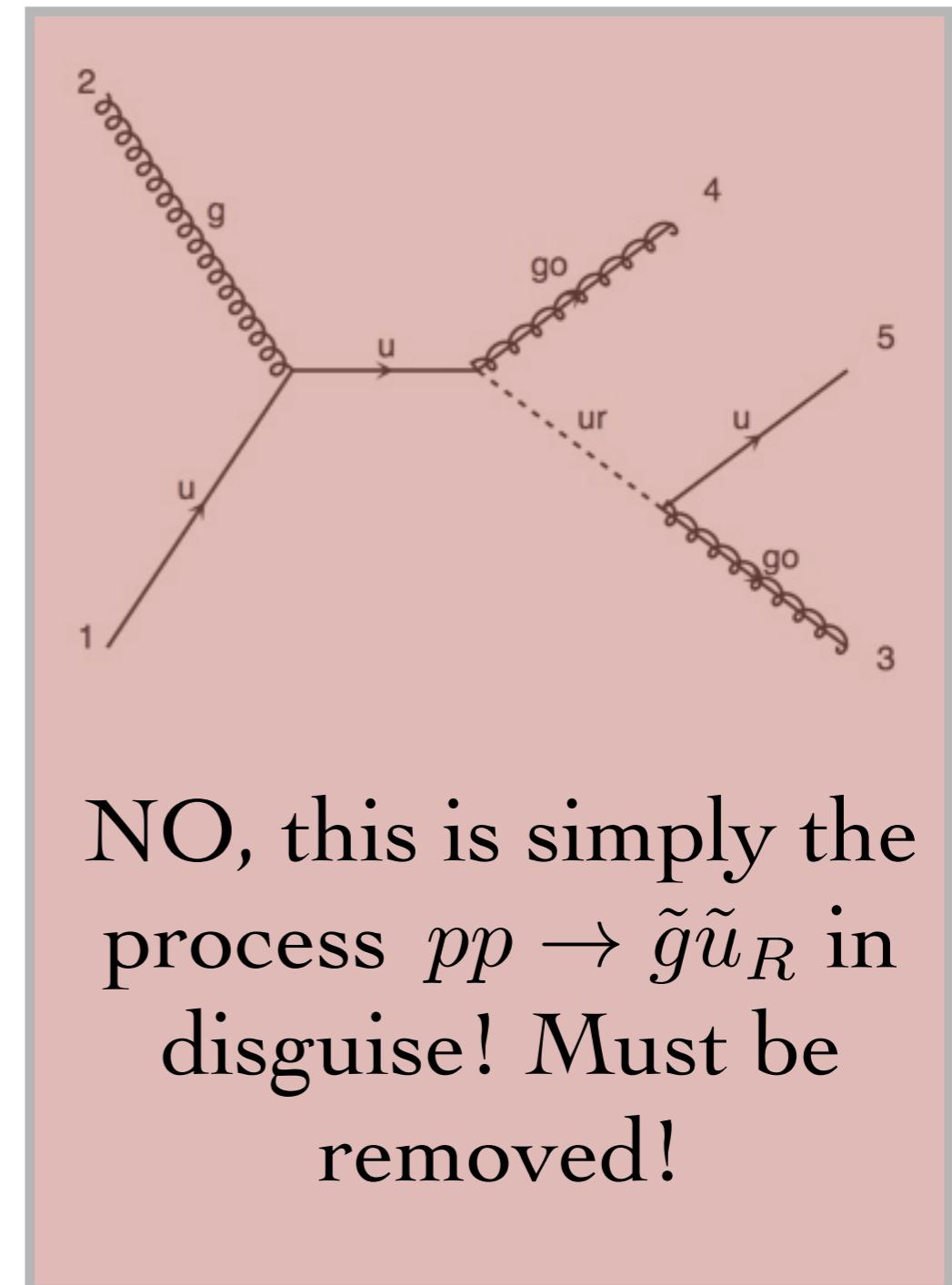
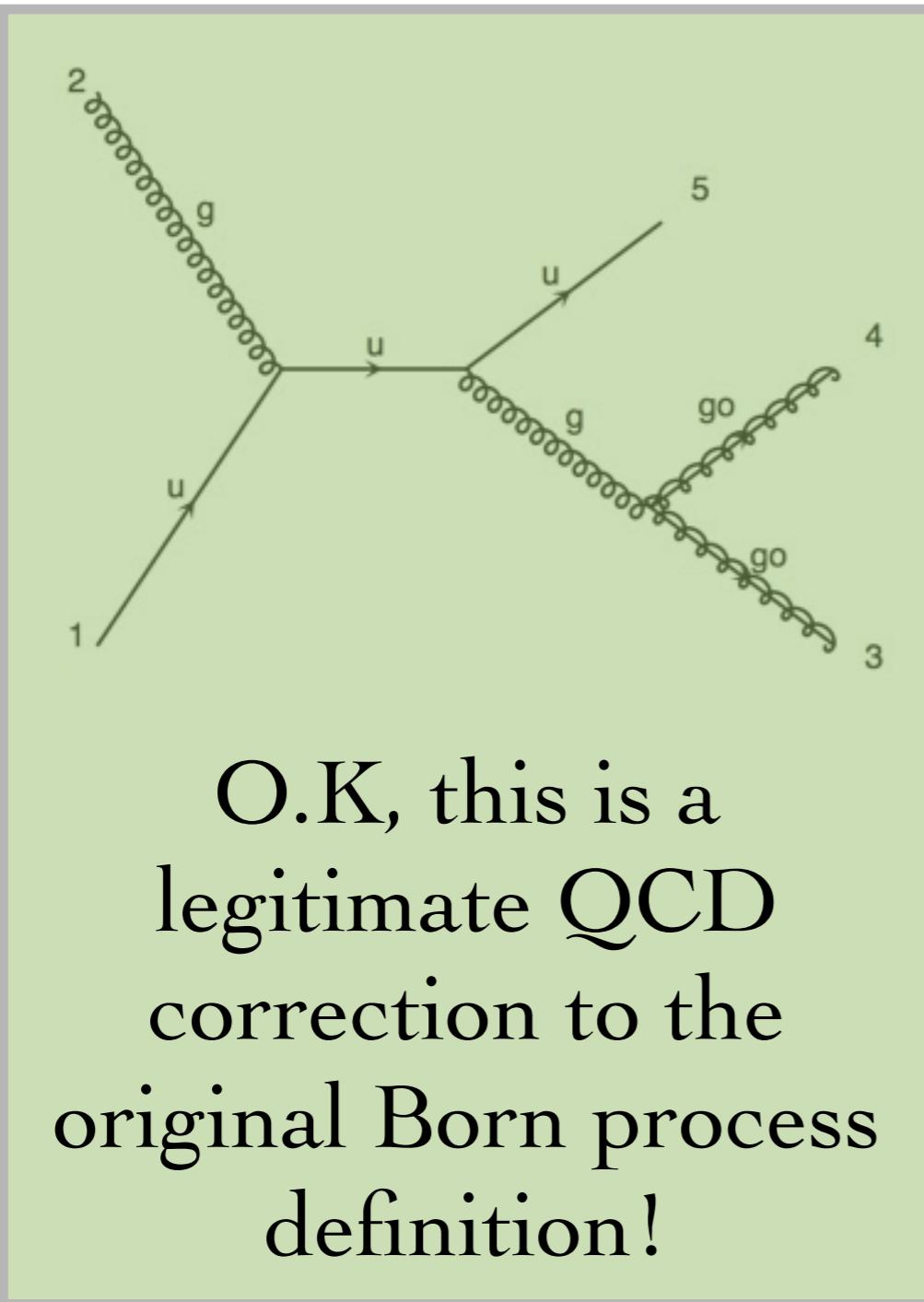


**Well underway; already full agreement with Prospino.**

Majorana flow, top quark mixing matrix renorm, SUSY restoring CT: Solved.  
Onshell subtraction : Work in progress...

# ONSHELL SUBTRACTION

- Real-emission diagrams to the process  $pp \rightarrow \tilde{g}\tilde{g}$  :



- Problematic for the MC integration since squark resonance is not mapped.
- Different solutions currently under investigation.

**THE NEXT STEP WILL THEN BE  
FULL MSSM@<sup>A</sup>(QCD)NLO!**

# THE LONGED-FOR CONCLUSION

- Loop-induced simulation now streamlined in MG5\_aMC.
- Automatic BSM@NLO is a thing! See already available models at:  
<http://feynrules.irmp.ucl.ac.be/wiki/NLOModels>  
...or build your own UFO NLO model with FeynRules if not already available.
- Full MSSM@(QCD)NLO soon available (as well as automated MA5 recasting).

MadGraph Home Page [madgraph.hep.uiuc.edu](http://madgraph.hep.uiuc.edu)

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.

   
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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](#)

Input Process:   NLO [Examples/format](#)

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

p and j definitions:

sum over leptons:

Soon !