MadGraph5_aMC@NLO

[https://launchpad.net/mg5amcnlo]

[arXiv:1405.0301]

Valentin Hirschi

MBI Workshop

25th August 2016

Foreword

University of Wisconsin - Madison   MAD/PH/813
January 1994

Automatic Generation of Tree Level
Helicity Amplitudes

```
Attempting Process: e- e-  -> e- e-

Enter the number of QCD vertices between 0 and 0 (0):

The number of QFD vertices is 2
Would you like to include the Weak sector (n)?

Enter a name to identify process (emem_emem):

 Generating diagrams for 4  external legs
 There are  2  graphs.
 Writing Feynman graphs in file emem_emem.ps
 Reduced color matrix 1 2
 Writing function emem_emem in file emem_emem.f.

 Standard Model particles include:
     Quarks:   d u s c b t d~ u~ s~ c~ b~ t~
     Leptons:  e- mu- ta- e+ mu+ ta+ ve vm vt ve~ vm~ vt~
     Bosons:   g a z w+ w- h

 Enter process you would like calculated in the form  e+ e- -> a.
 (<return> to exit MadGraph.)

 Thank you for using MadGraph
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Succeeding: ~~Attempting~~ Process: e- e- -> e- e-

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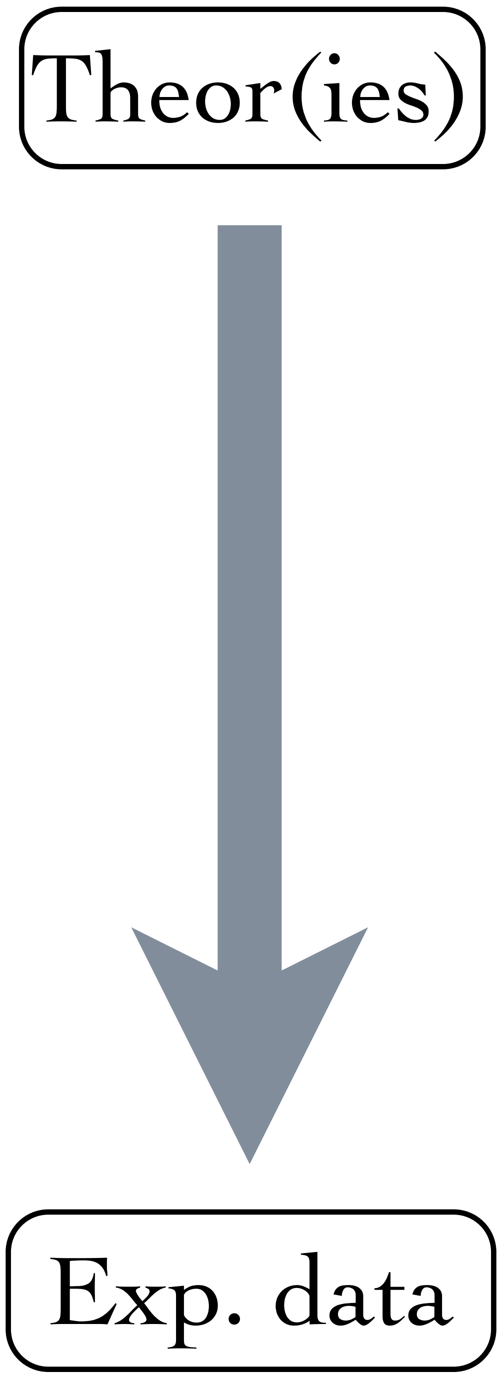
OUTLINE

- The ToolChain at NLO
- BSM@NLO : Two physics case
- Latest developments in MG5aMC

Prediction chain



Prediction chain

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

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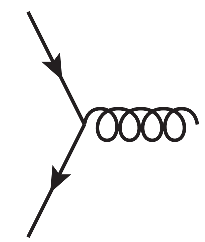
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**  $= \imath\gamma^\mu t^a_{ij}$, ...

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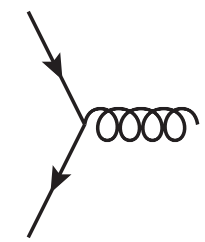
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**  $= \imath\gamma^\mu t^a_{ij}$, ...

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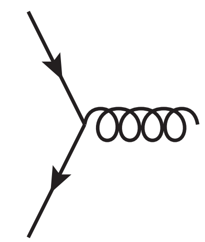
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**  $= \imath\gamma^\mu t^a_{ij}$, ...

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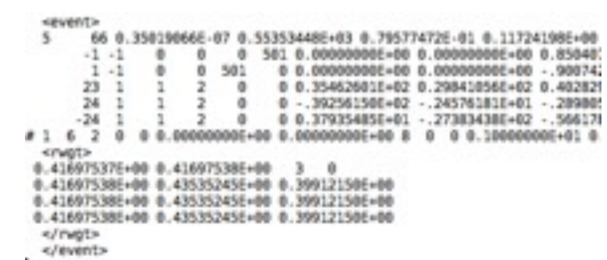
`matrix.f` **Partonic Events** 


```
<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 0.85040
       1 -1    0    0  501    0 0.00000000E+00 0.00000000E+00 -.90074
      23  1    1    2    0    0 0.35462601E+02 0.29841056E+02 0.40282
      24  1    1    2    0    0 -.39256150E+02 -.24576181E+01 -.28980
     -24  1    1    2    0    0 0.37935485E+01 -.27383438E+02 -.56617
# 1  6  2  0  0 0.00000000E+00 0.00000000E+00 8  0  0 0.10000000E+01 0.
<rwgt>
0.41697537E+00 0.41697538E+00   3   0
0.41697538E+00 0.43535245E+00 0.39912150E+00
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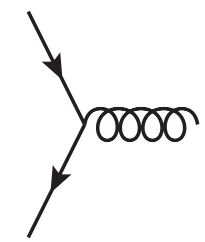
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**  $= \imath\gamma^\mu t^a_{ij}$, ...

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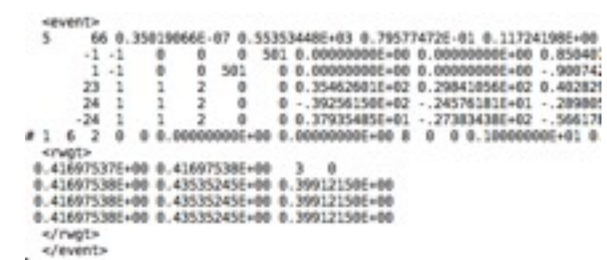
`matrix.f` **Partonic Events** 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       -1 -1    0    0    0  501 0.00000000E+00 0.00000000E+00 0.850402
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<rwgt>
0.41697537E+00 0.41697538E+00   3   0
0.41697538E+00 0.43535245E+00 0.39912150E+00
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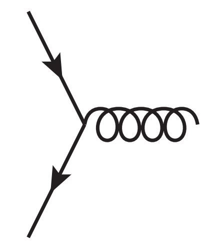
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**  $= \imath\gamma^\mu t^a_{ij}$, ...

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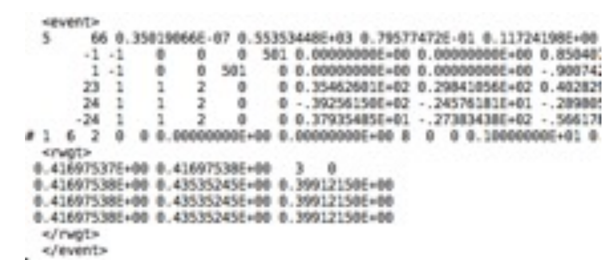
`matrix.f` **Partonic Events** 

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Prediction chain

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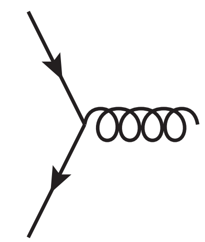
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ — **Model** —  $= \imath\gamma^\mu t^a_{ij}$, ...

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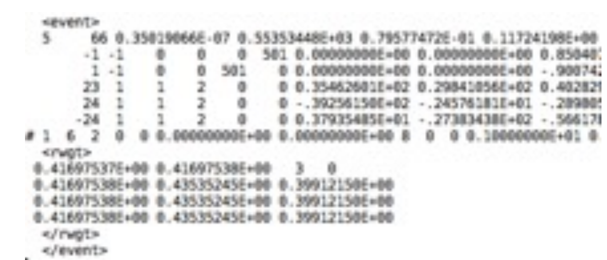
`matrix.f` — **Partonic Events** — 

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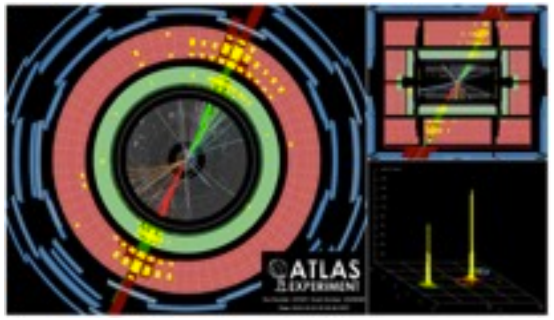
`events.hep` — **Detector level** — 

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FeynRules		Model
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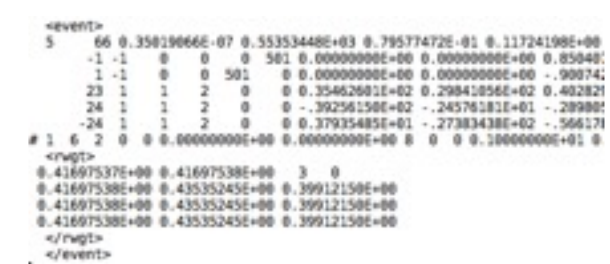
matrix.f	Partonic Events	
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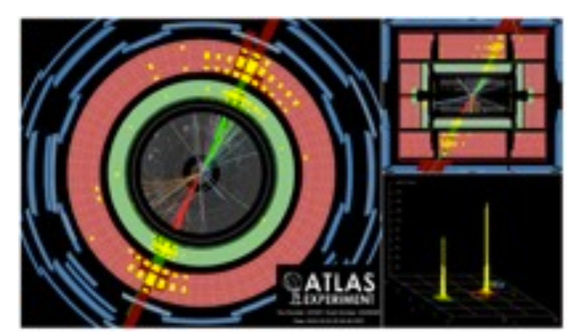
events.hep	Detector level	

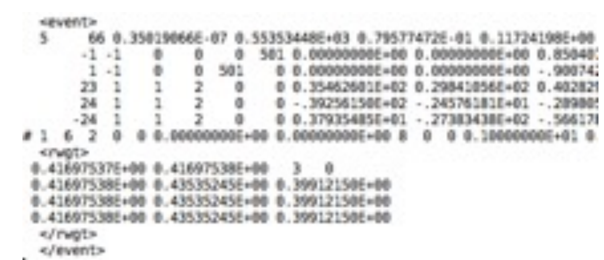
Prediction chain

? ? ? — Symmetries

FeynRules — Model

MadGraph 5 — Matrix Element

matrix.f — Partonic Events



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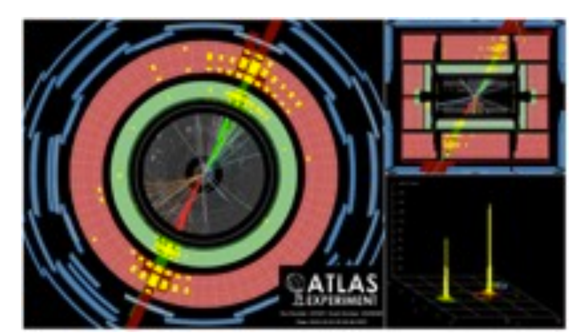

Prediction chain

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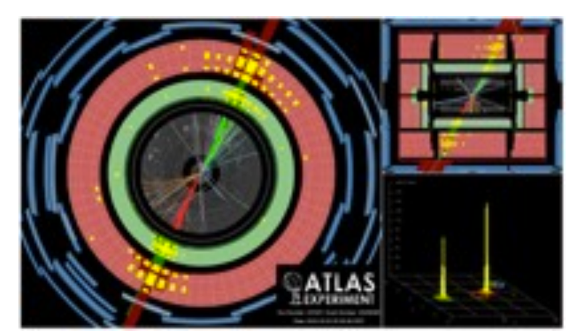

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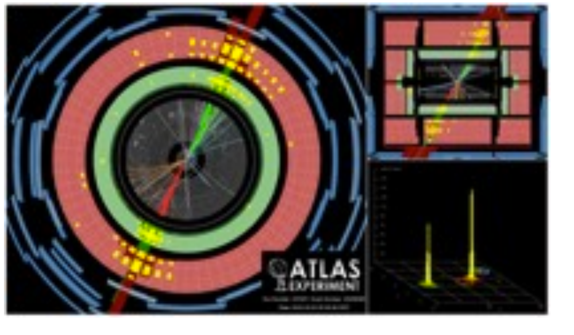
Pythia / Herwig	Hadron level

events.hep   Detector level



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MadAnalysis 5

Prediction chain

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FR + NLOCT	Model
MadGraph 5	Matrix Element
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Prediction chain

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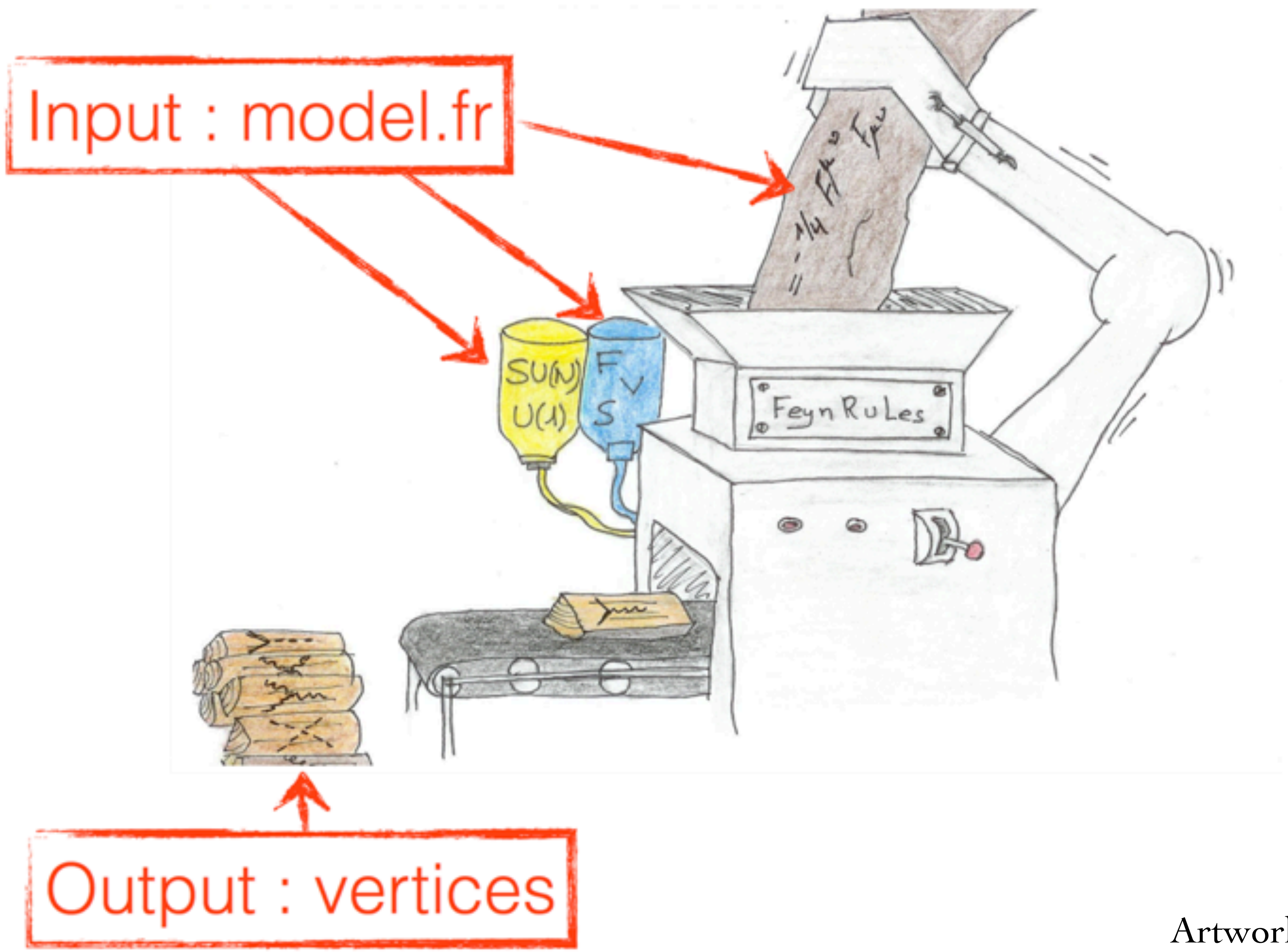
MadAnalysis 5

BSM @ NLO with FeynRules

FeynRules

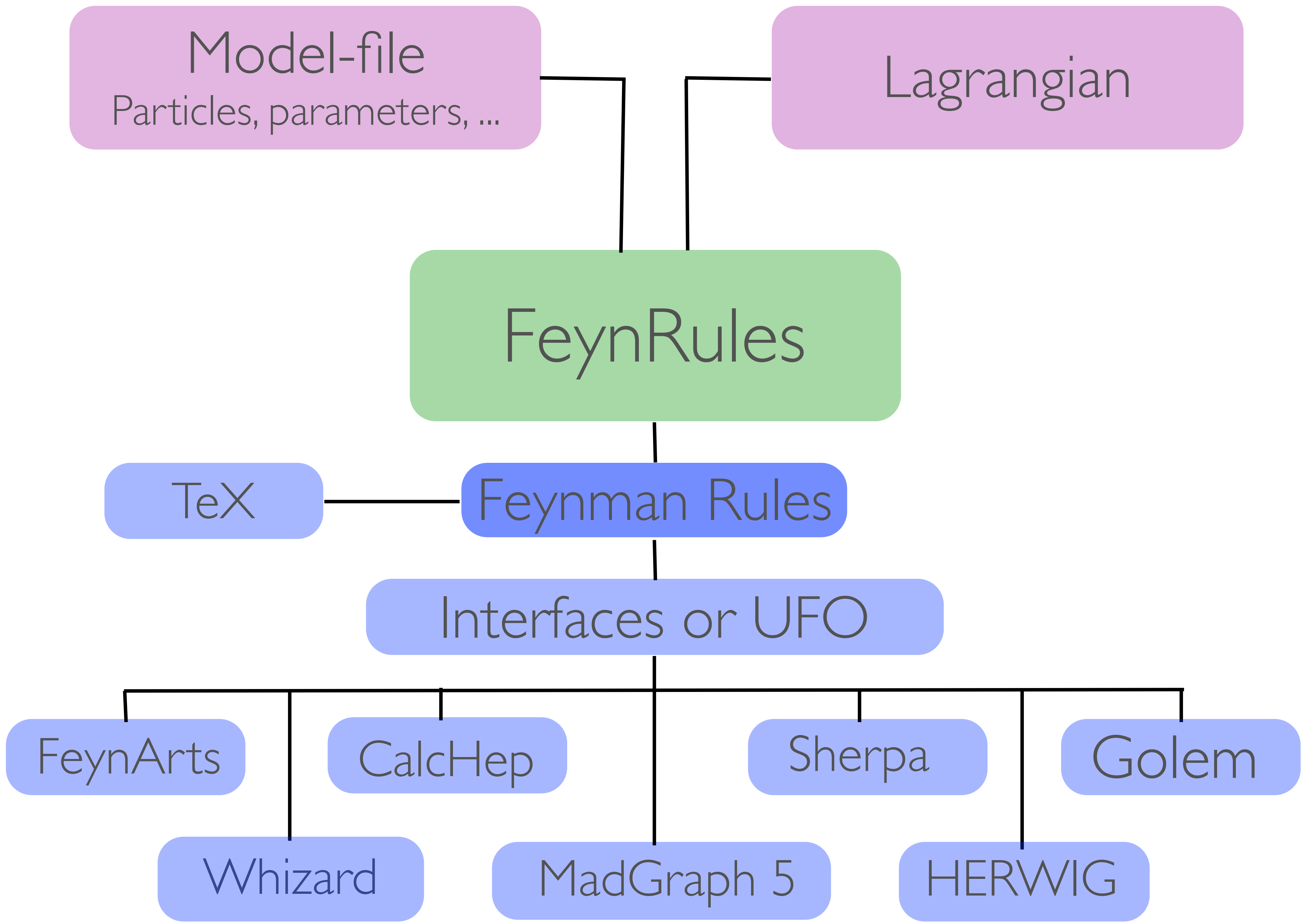
Model



Artwork by C. Degrande

FeynRules Structure

[Alloul, Christensen, Degrande, Duhr, Fuks]



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 ];
```

$\longleftrightarrow \quad < 0|i\mathcal{L}_I|\text{fields} >$

Checking the Lagrangian

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

Output $\longrightarrow \left\{ \begin{array}{l} \texttt{WriteCHOuput[L]} \\ \texttt{WriteFeynArtsOutput[L]} \\ \texttt{WriteSHOutput[L]} \\ \texttt{WriteWOOutput[L]} \\ \texttt{WriteUFO[L]} \end{array} \right.$

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Loading th

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```

The UFO format has become the standard, as it is now being used by MG5_aMC, Sherpa, GoSam, Whizard,HW7

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

Two missing ingredients for NLO

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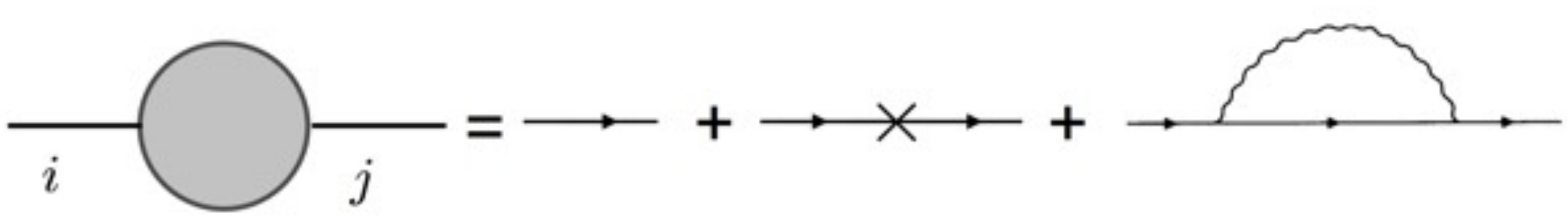

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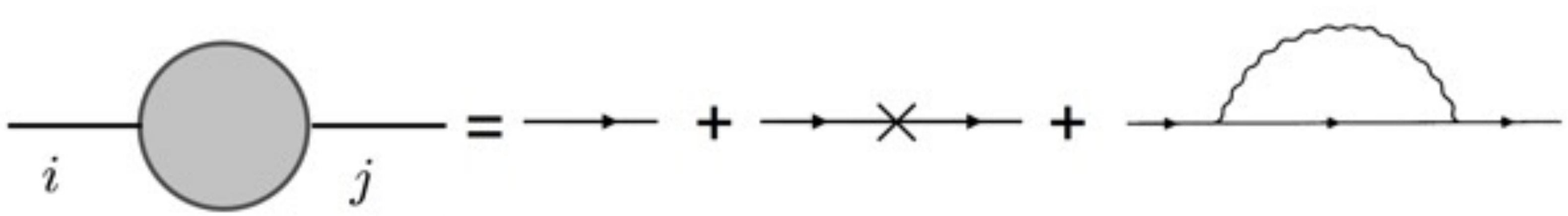

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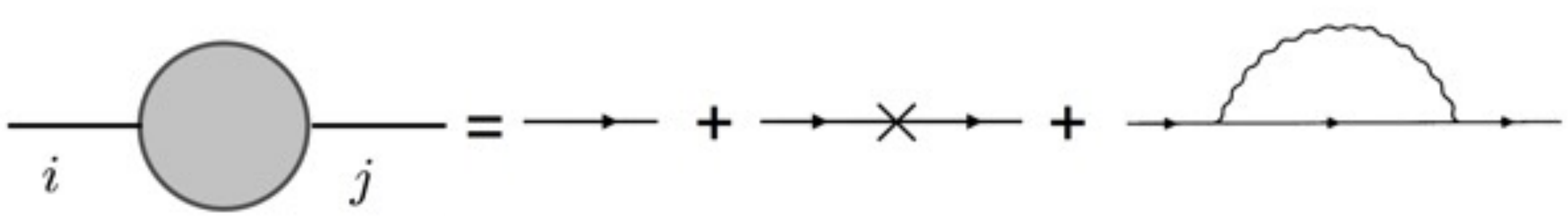

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- R2 counterterms, what are they?

$\mathbf{R_2}$

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

R_2

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Solution : isolate the ε-dim part of the numerator: $$\underbrace{\bar{N}(\bar{q})}_{\text{d-dim}} = \underbrace{N(q)}_{\text{4-dim}} + \underbrace{\tilde{N}(\tilde{q},q,\epsilon)}_{\epsilon-dim}$$

R2

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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.

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

R2

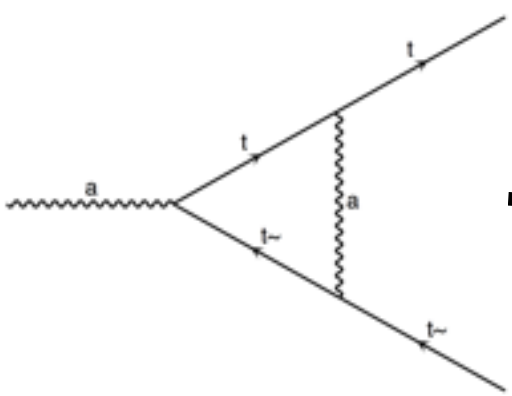
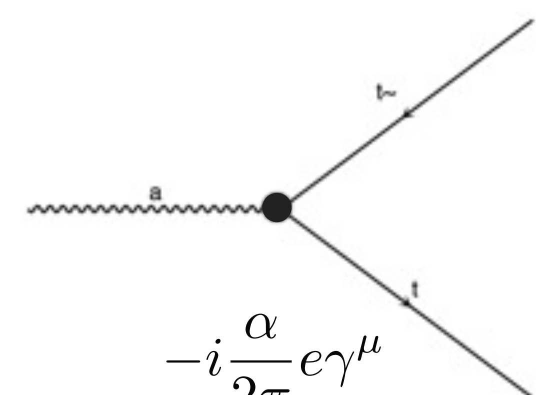
Loop amplitude: $\frac{1}{(2\pi)^4}\int d^d\bar{q}\frac{\bar{N}(\bar{q})}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}$, $\bar{D}_i = (\bar{q}+p_i)^2 - m_i^2$

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

Solution : isolate the ε-dim part of the numerator: $\underbrace{\bar{N}(\bar{q})}_{\text{d-dim}} = \underbrace{N(q)}_{\text{4-dim}} + \underbrace{\tilde{N}(\tilde{q},q,\epsilon)}_{\epsilon-dim}$

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.

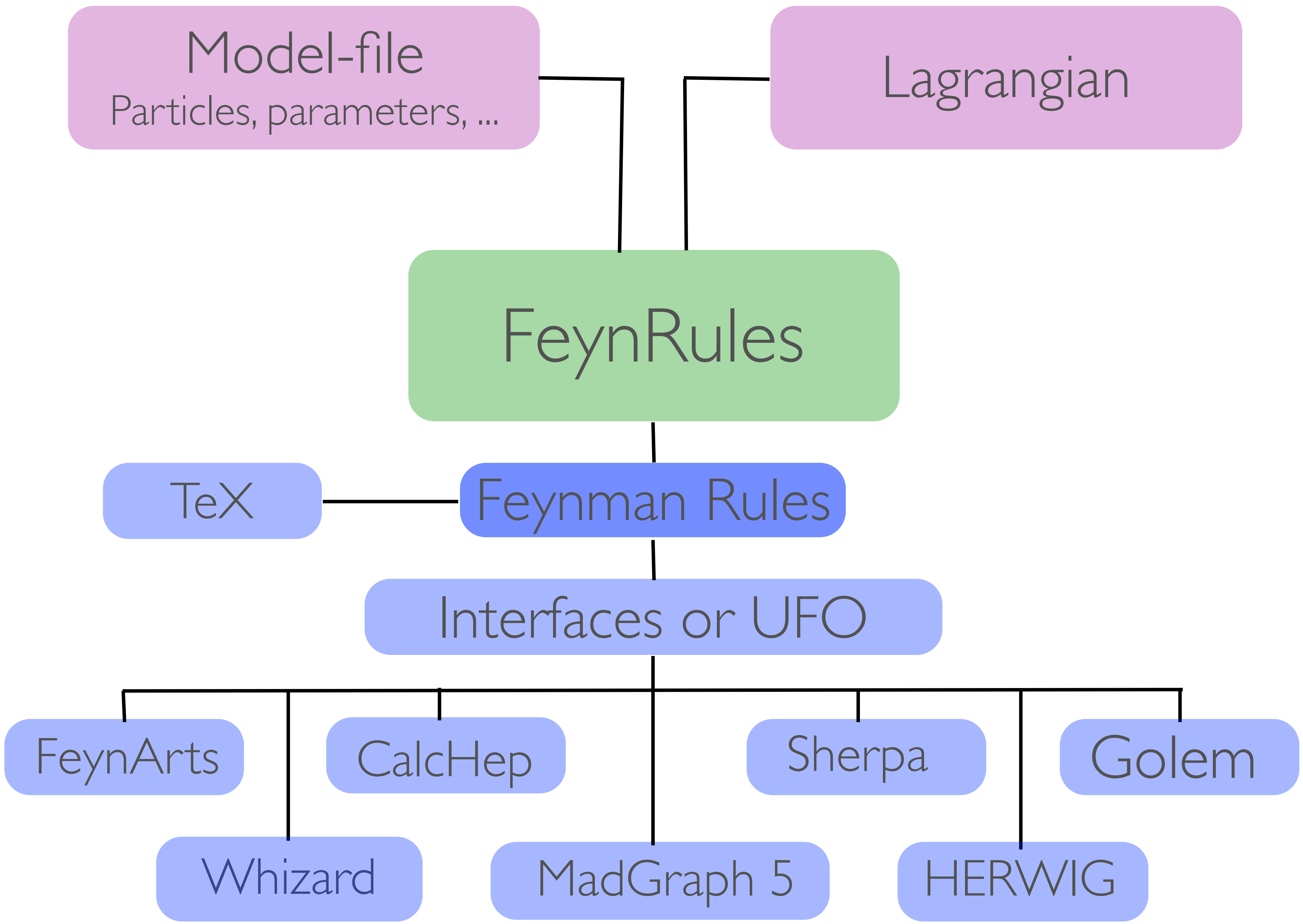
$$\boxed{R2 \equiv \lim_{\epsilon\to 0}\frac{1}{(2\pi)^4}\int d^d\bar{q}\frac{\tilde{N}(\tilde{q},q,\epsilon)}{\bar{D}_0\bar{D}_1\cdots\bar{D}_{m-1}}}$$

Ex. :  ➔ $\supset \int d^d\bar{q}\frac{\tilde{q}^2}{\bar{D}_0\bar{D}_1\bar{D}_2} = -\frac{i\pi^2}{2} + \mathcal{O}(\epsilon)$ ➔ 

$-i\frac{\alpha}{2\pi}e\gamma^{\mu}$

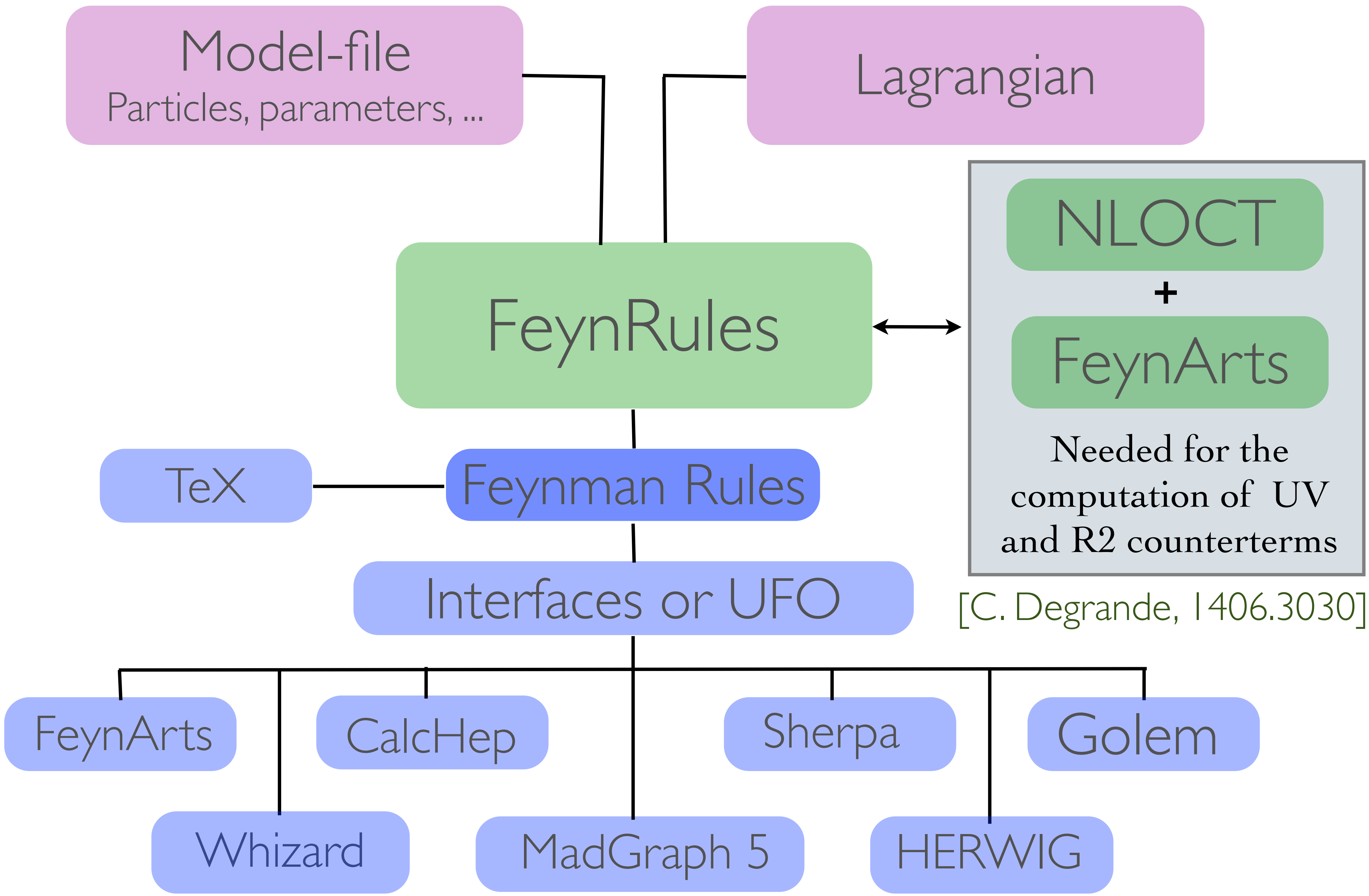
FEYNRULES @ NLO (VERSION 2.1)

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



FeynRules @ NLO (version 2.1)

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



[C. Degrande, 1406.3030]

Loop models database

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

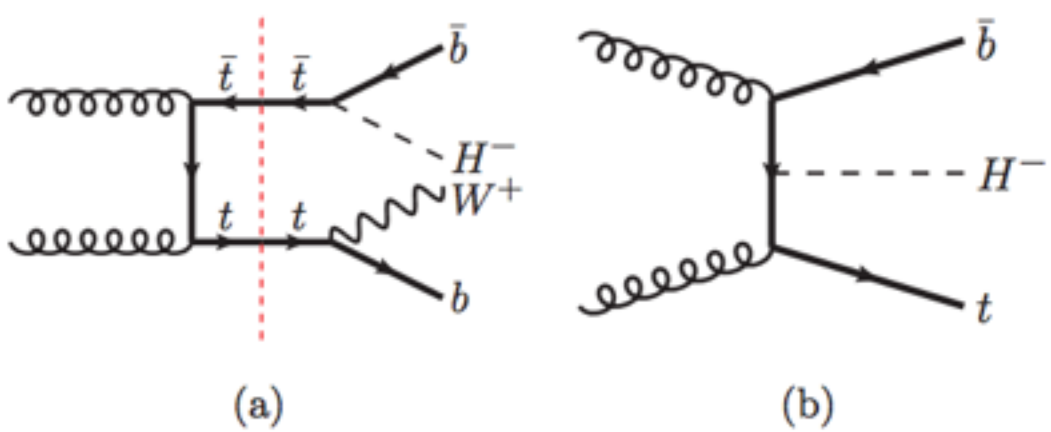
NLO models (10)	10 models for now

Description	Contact	Reference	FeynRules model files	UFO libraries
Dark matter simplified models (more details)	K. Mawatari	arXiv:1508.00564 , arXiv: 1508.05327 , arXiv: 1509.05785	-	DMsimp_UFO.2.zip
Gluino pair production (SUSY-QCD)	B. Fuks	arXiv:1510.00391	-	susyqcd_ufo.tgz
Higgs characterisation (more details)	K. Mawatari	arXiv:1311.1829 , arXiv:1407.5089 , arXiv: 1504.00611	-	HC_NLO_X0_UFO.zip
Inclusive sgluon pair production	B. Fuks	arXiv:1412.5589	sgluons.fr	sgluons_ufo.tgz
Stop pair -> t tbar + missing energy	B. Fuks	arXiv:1412.5589	stop_ttmet.fr	stop_ttmet_ufo.tgz
Two-Higgs-Doublet Model (more details)	C. Degrande	arXiv:1406.3030	-	2HDM_NLO
Top FCNC Model (more details)	C. Zhang	arXiv:1412.5594	TopEFTFCNC.fr	TopFCNC UFO
GM (more details)	A. Peterson	arXiv:1512.01243	-	GM_NLO UFO
Heavy Neutrino (more details)	R. Ruiz	-	heavyN.fr	HeavyN NLO UFO
Spin-2 (more details)	C. Degrande	http://arxiv.org/abs/1605.09359	dm_s_spin2.fr	SMspin2 NLO UFO

- Many more BSM models in development and to be added to this list.
- What can do with these loop-models? NLO-accurate simulations and loop-induced phenomenology.

H^{+} PROD. @ NLO, $M_H \sim M_T$

[1607.05291]



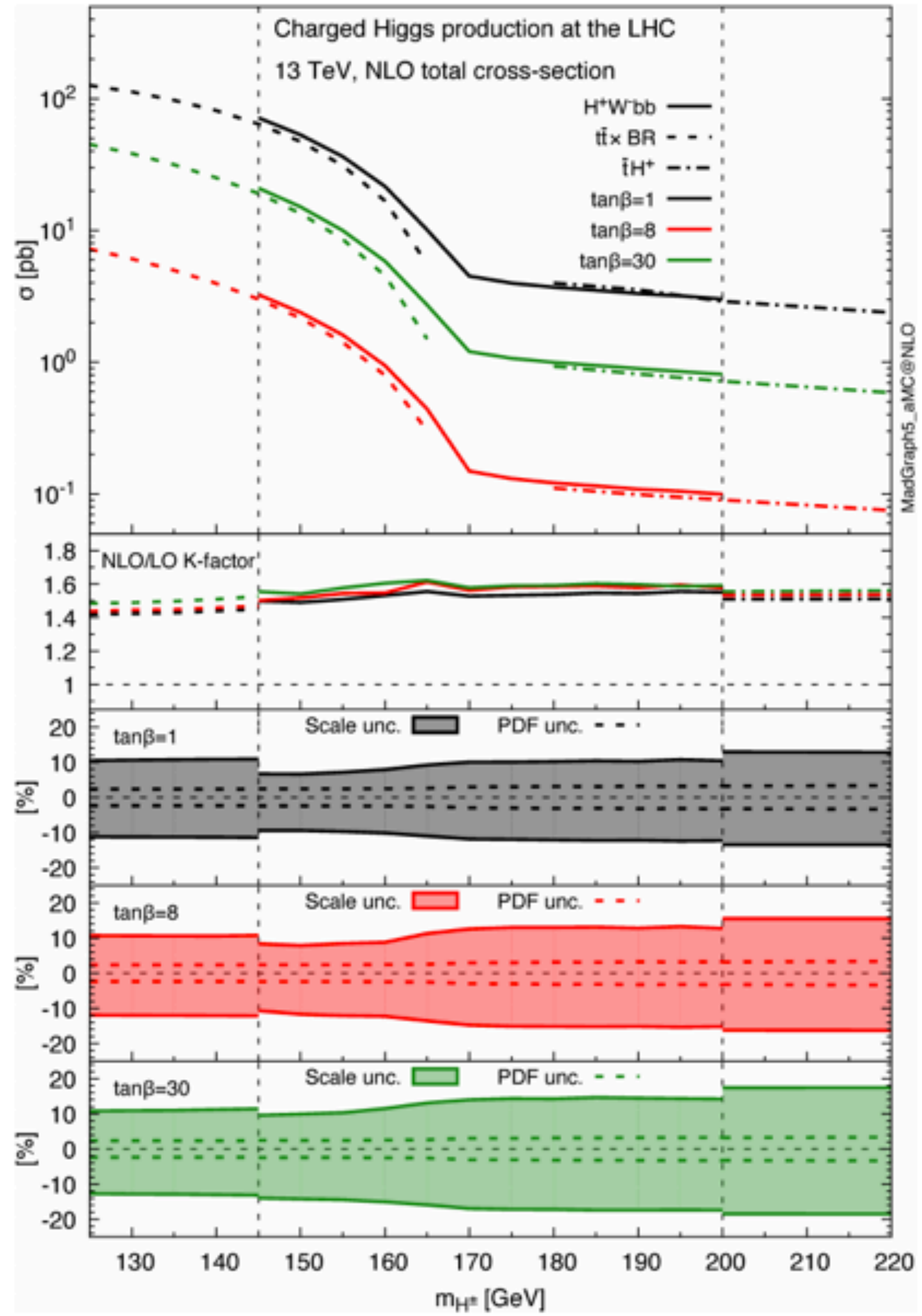
a) dominates for $m_H < 145$ GeV

b) dominates for $m_H > 200$ GeV

a)+b) For 145 GeV$< m_H <$ 200 GeV

-> Requires to honestly compute:

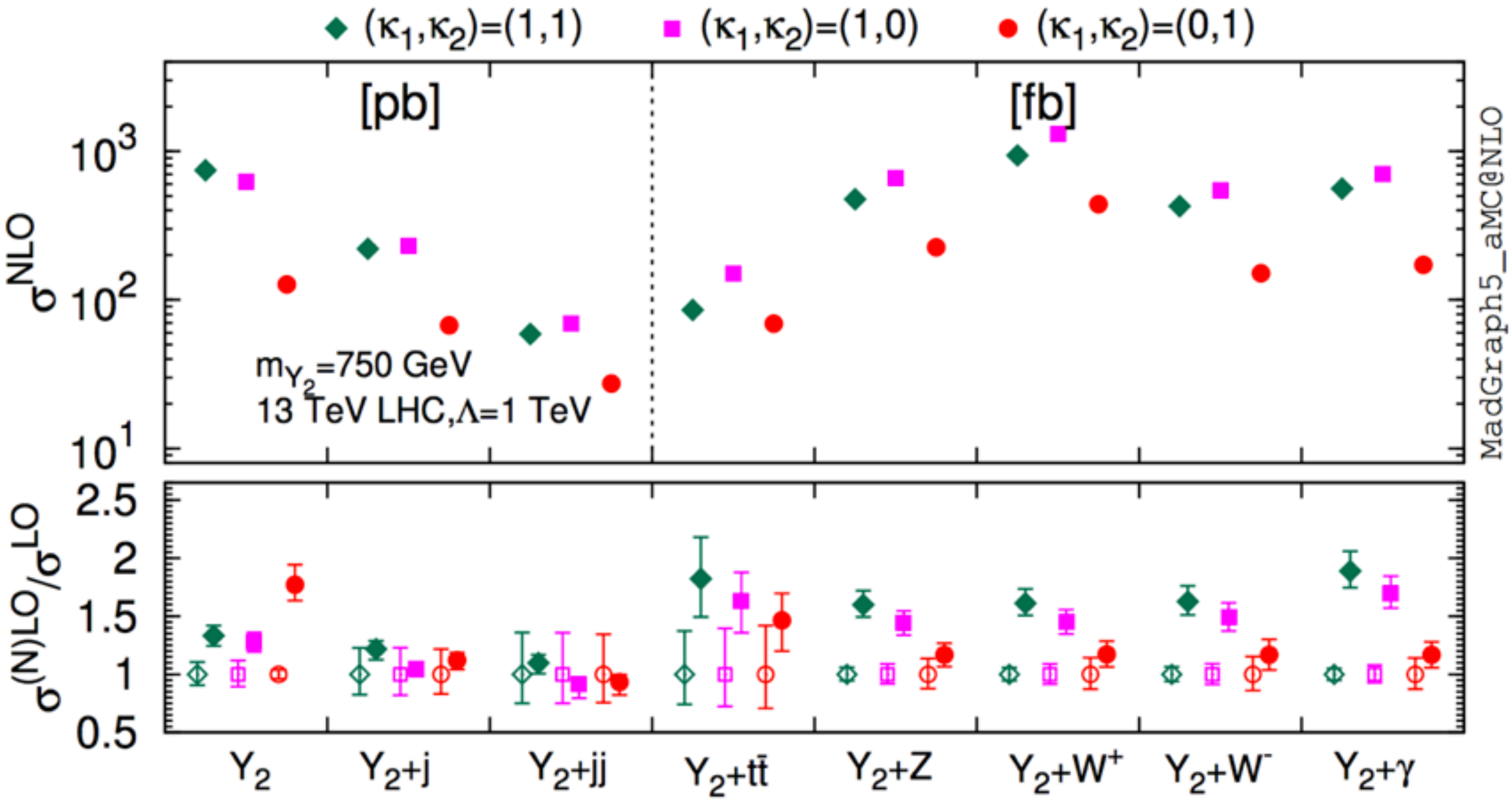
p p > H^{+} W^{-} b b



Spin-2 production @ NLO

[1605.09359]

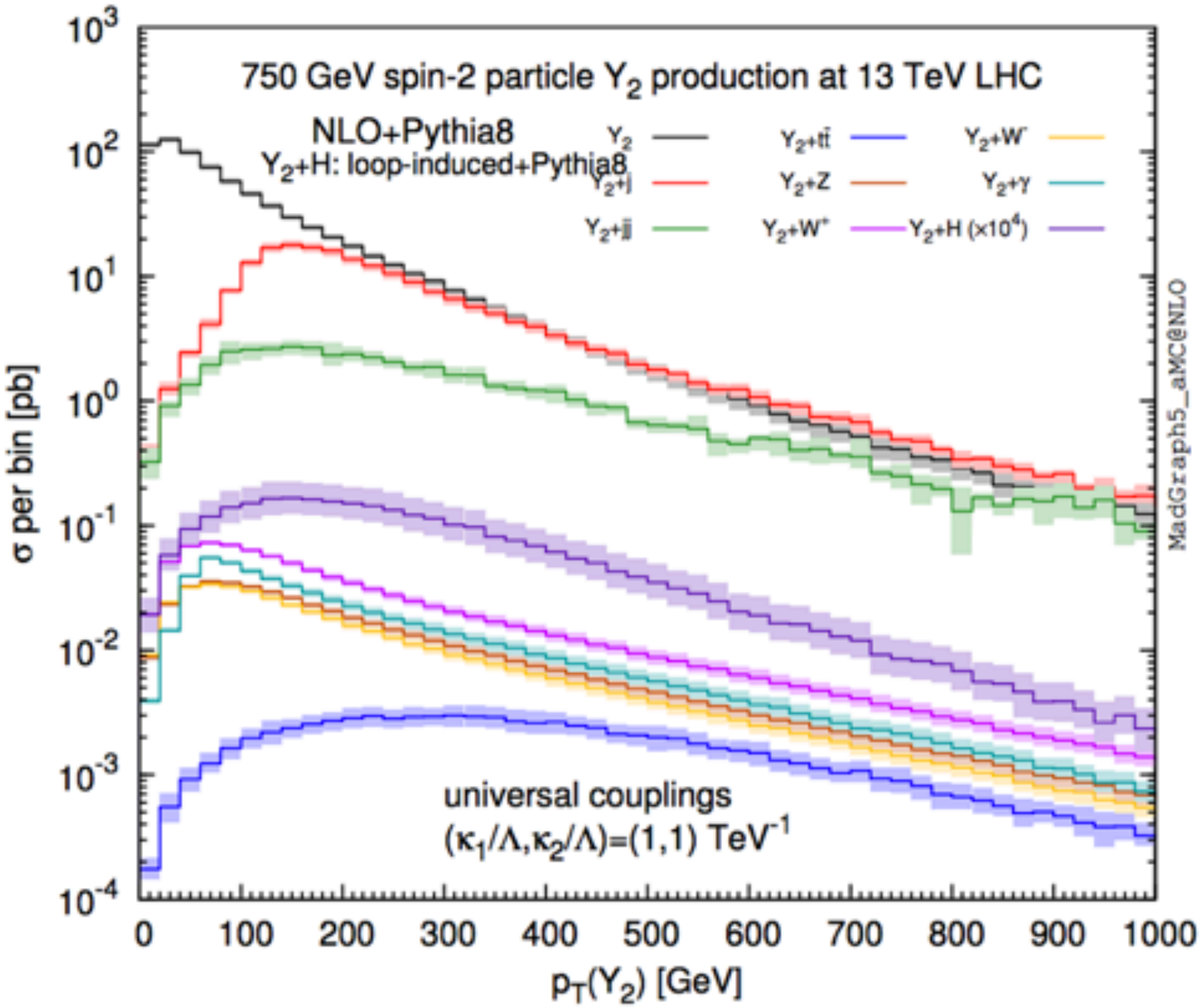
Simplified model: $\mathcal{L}^{Y_2}_{\mathrm{V,f}} = -\frac{\kappa_{V,f}}{\Lambda} T^{V,f}_{\mu\nu} Y^{\mu\nu}_2$



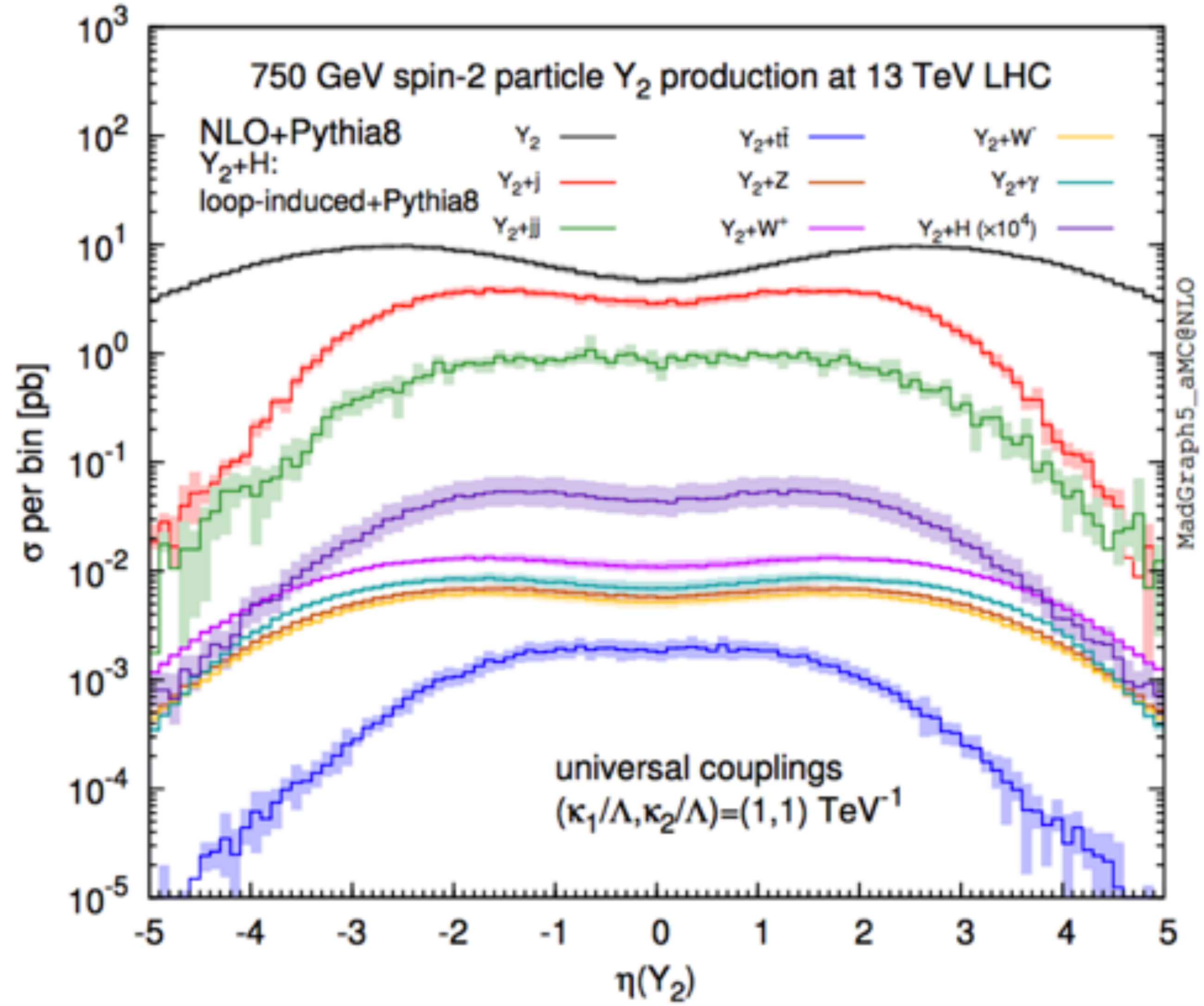
Large K-factors, unreliable uncertainties at LO.

Spin-2 : NLO QCD matched

[1605.09359]



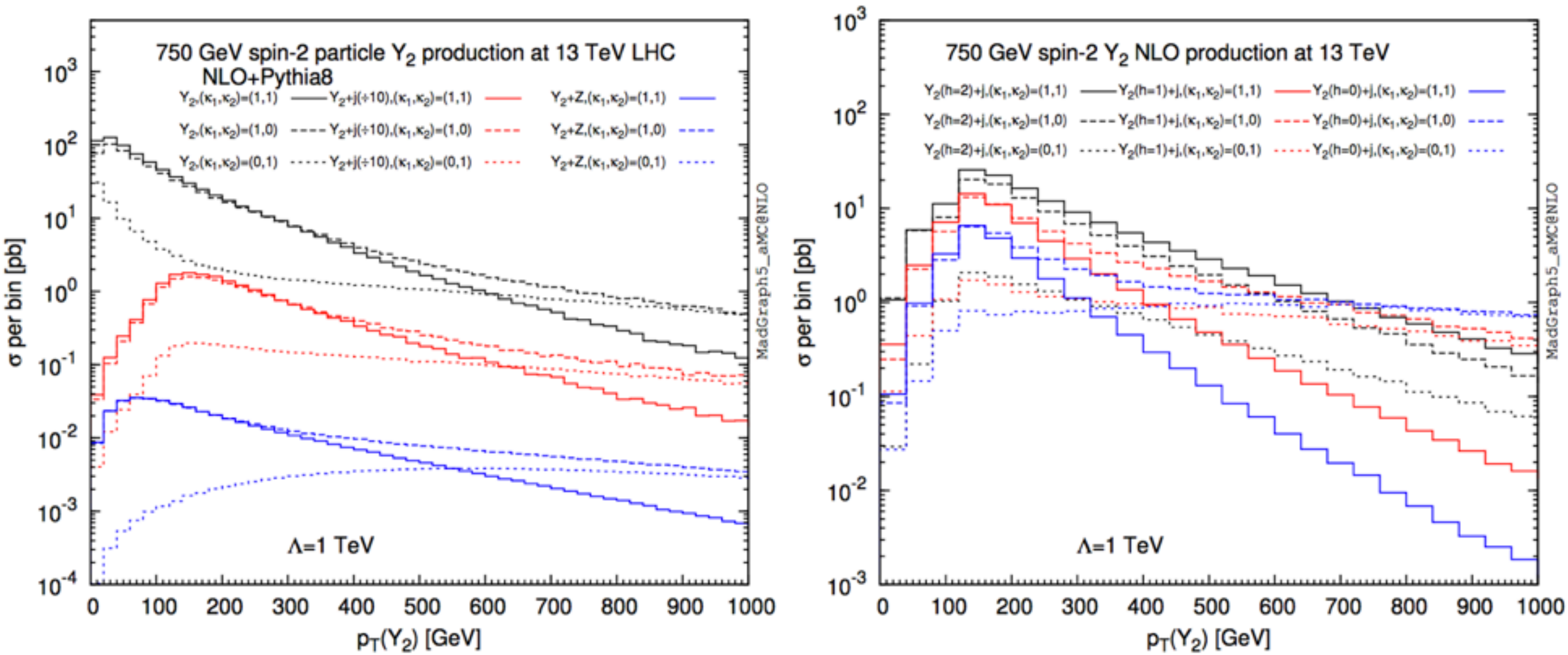
(a) Transverse momentum distribution



(b) Pseudorapidity distribution

Spin-2 : Unitarity violation

[1605.09359]



(a) (b)

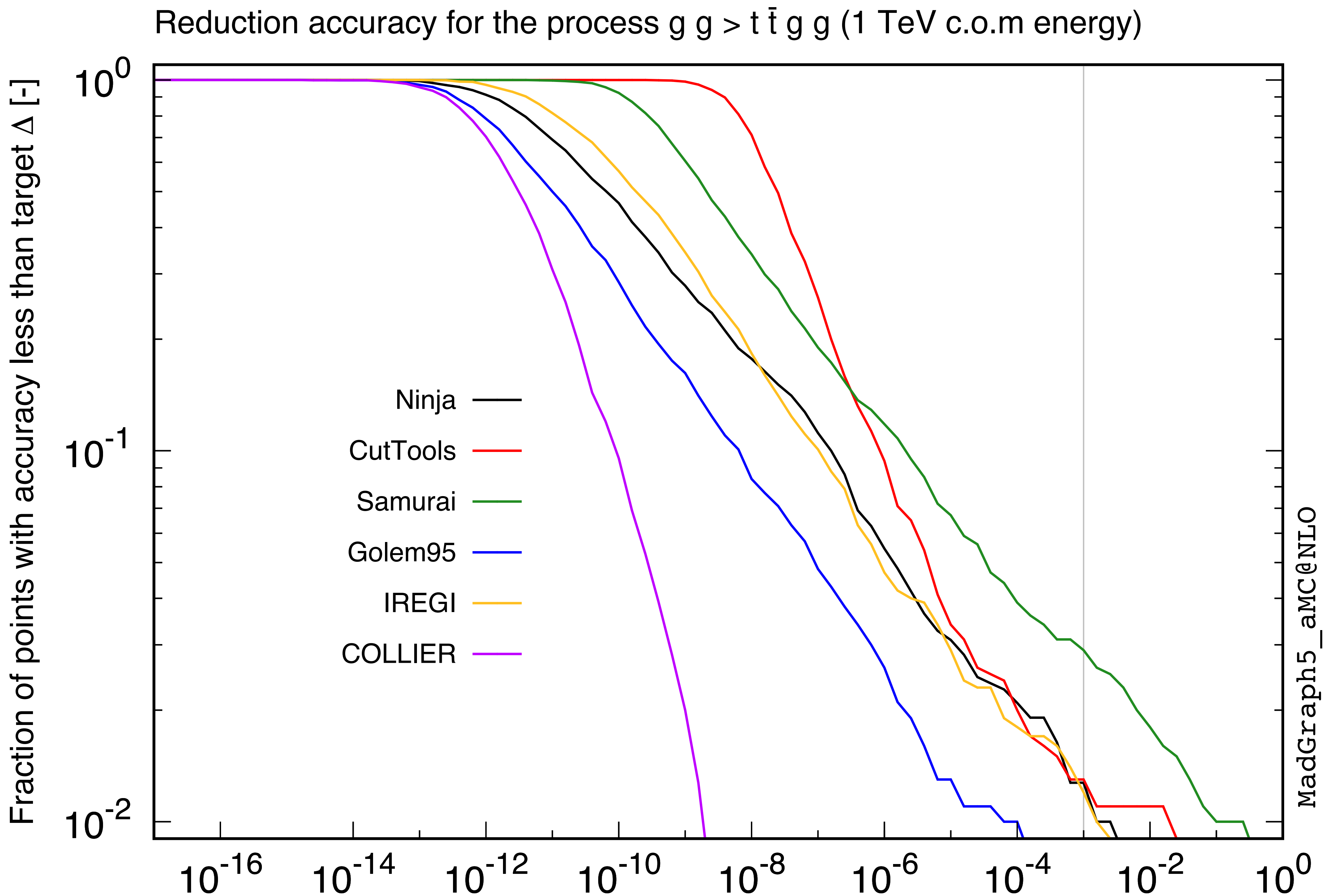
- In $pp \to Y_2 j$: Unitary violation for helicity modes 0 and 1, and $\kappa_g \neq \kappa_q$
- Already present at **LO** . How to restore it? Stay for Marco Sekulla's talk.

Latest developments in MG5aMC

- NINJA and COLLIER interfaced to MadLoop
- Event generation for loop-induced processes
- Reweighting framework (for both LO and NLO)
- Pythia8 LO MLM, CKKW-L merging systematics
- User-defined MG5aMC Plugins
- NLO EW (+QCD) computations

New Loop Reductions in MadLoop

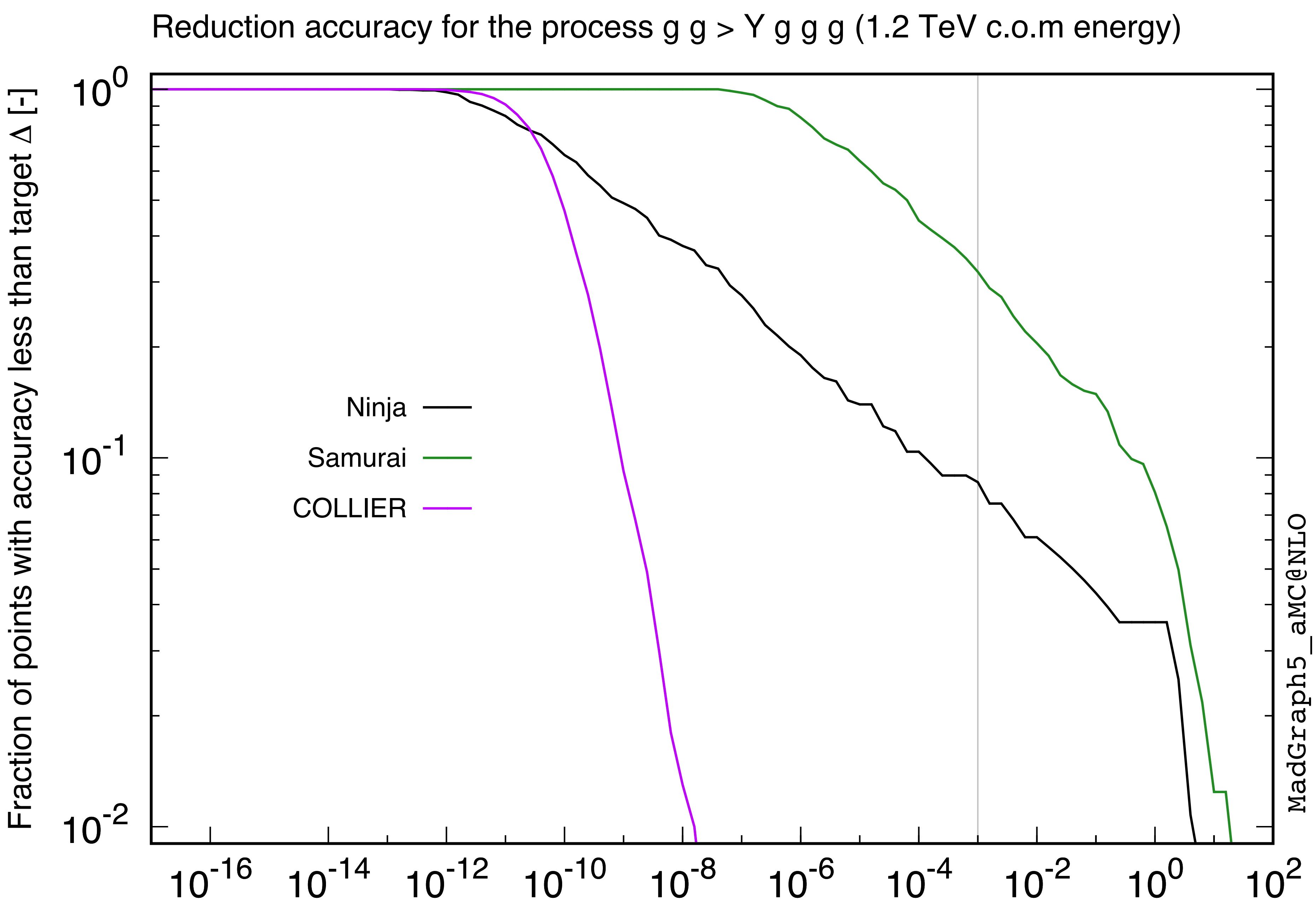
[1604.01363] NINJA and COLLIER interfaced to MadLoop



Unmatched numerical stability with COLLIER

New Loop Reductions in MadLoop

[1604.01363]



And it can be very relevant.

New Loop Reductions in MadLoop

Add. scales and larg mult.	$gg \to t\bar{t}$	$gg \to t\bar{t}g$	$gg \to t\bar{t}gg$	$uu \to t\bar{t}b\bar{b}d\bar{d}$
Max. loop num. rank	3	4	5	4
Integrand computation time	0.26 ms	4.8 ms	170 ms	99 ms
Ninja reduction time	0.40 ms	5.3 ms	78 ms	104 ms
COLI and (DD)	0.83 (0.72)	13.6 (16.4)	220 (322)	1120 (N/A)
CutTools reduction time	1.3 ms	23.2 ms	330 ms	301 ms
COLLIER/ Ninja	2.1	2.6	2.8	10.8

Saturated rank (LI)	$gg \to 2 \cdot Z$	$gg \to 3 \cdot Z$	$gg \to 4 \cdot Z$
Max. loop num. rank	4	5	6
Integrand computation time	0.60 ms	7.2 ms	81 ms
Ninja reduction time	1.6 ms	21 ms	310 ms
COLI and (DD)	1.6 (1.6)	25 (46)	590 (661)
CutTools reduction time	4.1 ms	59 ms	1080 ms
COLLIER/ Ninja	1.0	1.2	1.9

Eff. theory, Y≡spin-2	$gg \to Yg$	$gg \to Ygg$	$gg \to Yggg$
Max. loop num. rank	5	6	7
Integrand computation time	2.2 ms	33 ms	1.4 s
Ninja reduction time	1.5 ms	20 ms	0.32 s
COLI reduction time	1.9 ms	57 ms	1.8 s
COLLIER/ Ninja	1.3	2.9	5.6

Table 1: All timings refer to the computation of the colour-summed loop amplitude for a single helicity and kinematic configuration . The test machine is using a single core of an Intel Core i7 CPU (2.7 GHz) and the MadLoop is compiled with GNU `gfortran -O2` (v4.8.2).

NINJA slightly faster (ratio > 2) for large multiplicity processes.

MadLoop in MG5aMC

- 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 default MG5aMC interface
  - Very simple one (in this case, generates the full code for NLO computations) :

```
[ 2.5s   ] generate p p > t t~ [QCD]
[ 6.1s   ] output
[ ~ mins*] launch
    * timing for 10k unweighted events on a laptop
```

  - With options specified (in this case, generates the one-loop matrix element code only):

```
[ 0.01s ] import model loop_sm-no_hwidth
[ 0.01s ] set complex_mass_scheme
[ 5min  ] generate g g > e+ ve mu- vm~ b b~ / h QED=2 [virt=QCD]
[ 2min  ] output MyProc
[ ~1 s* ] launch -f
    * time per phase-space point, summed over helicity configurations and colors.
```

Details on how to generate and use a MadLoop standalone library available @

cp3.irmp.ucl.ac.be/projects/madgraph/wiki/MadLoopStandaloneLibrary

MadLoop in MG5aMC

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  - `import model <model_name>-<restrictions>`
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[ 0.01s ] set complex_mass_scheme
[ 5min  ] generate g g > e+ ve mu- vm~ b b~ / h QED=2 [virt=QCD]
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```

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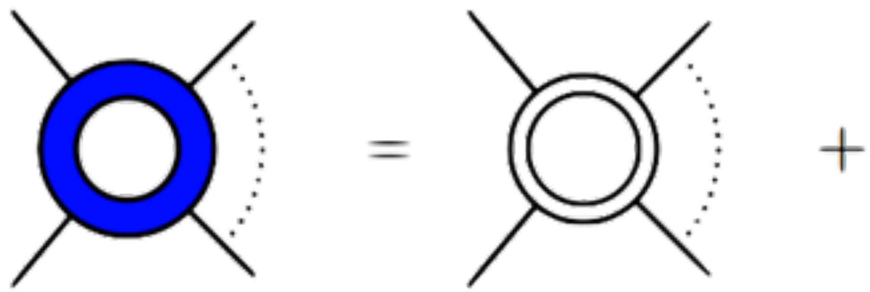
Loop-Induced (LI) Event generation

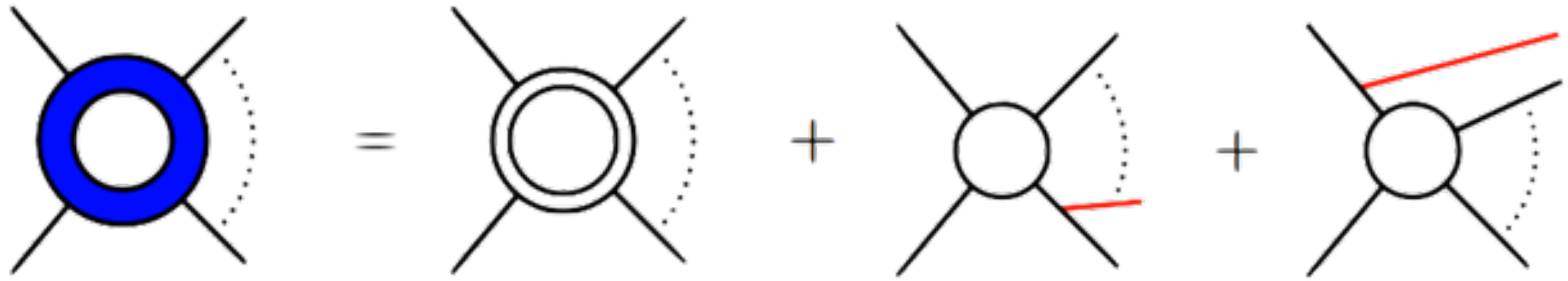
[1507.00020]



$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V +$$

Loop-Induced (LI) Event generation

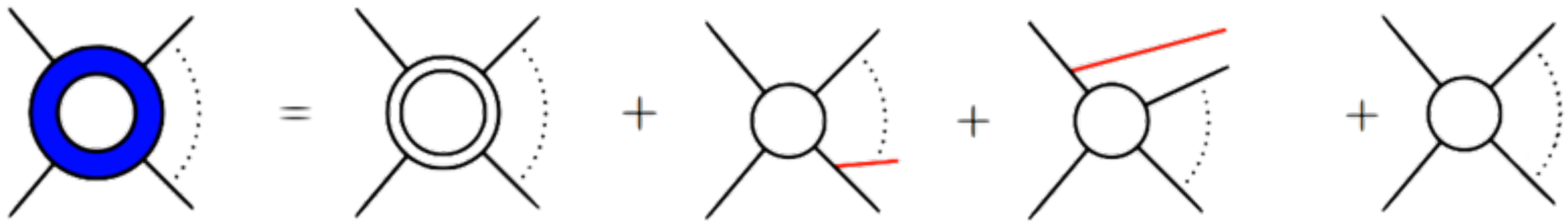
[1507.00020]



$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \qquad \int_{m+1} d^{(d)}\sigma^R +$$

Loop-Induced (LI) Event generation

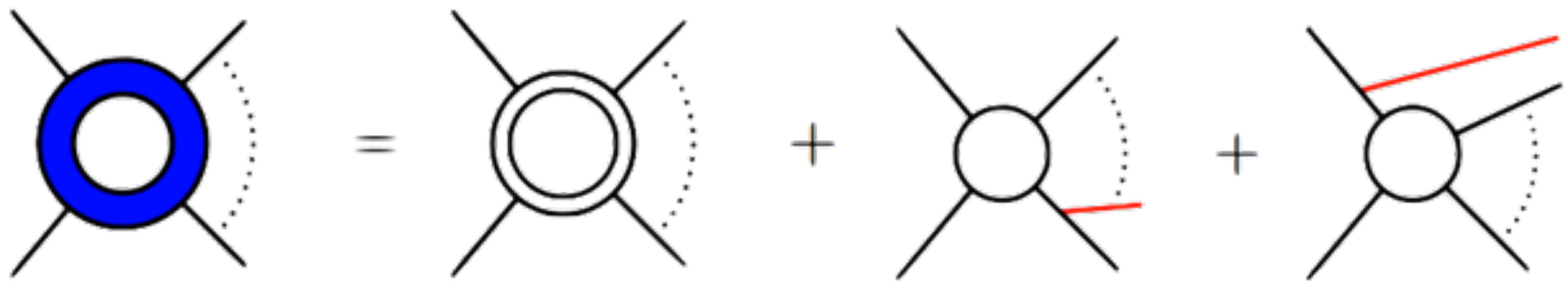
[1507.00020]



$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

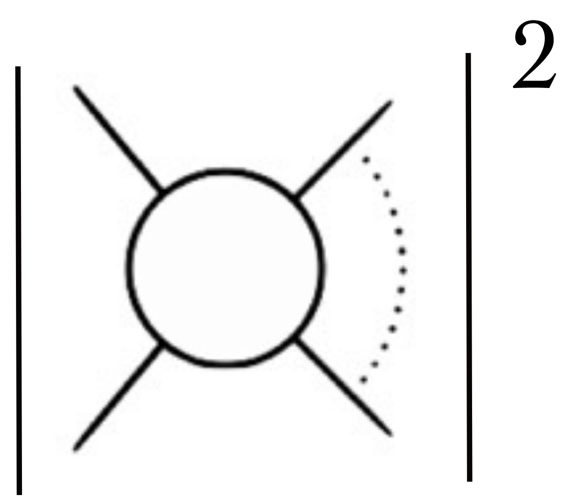
Loop-Induced (LI) Event generation

[1507.00020]



$$\sigma^{\mathrm{NLO}} = \int_m d^{(d)}\sigma^V + \int_{m+1} d^{(d)}\sigma^R + \int_m d^{(4)}\sigma^B$$

$\sigma^{\mathrm{LI}} =$



$$= \int_m d^{(d)} \left|\mathcal{A}^{(1)}\right|^2$$

Two difficulties for LI

[1507.00020]

- No approximation of the virtual is available and slow ME
  - ↳ $\mathcal{A}^{(1)}$ must be evaluated for each PS point.
  - ↳ We improved parallelization of MadEvent.

- Reduction must be done at the amplitude level
  - ↳ Loop red. must be performed for each helicity config.
  - ↳ Using [TIR] or [MC over Helicity + OPP] helps.

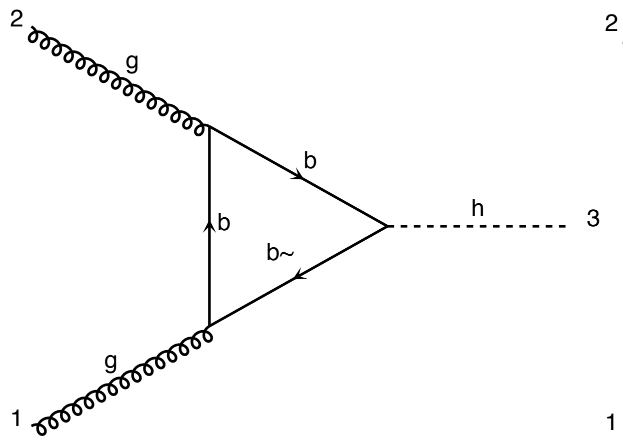
Simplest example

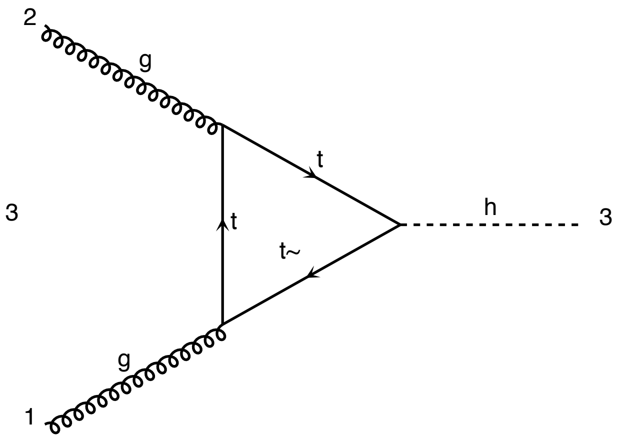
User Input

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

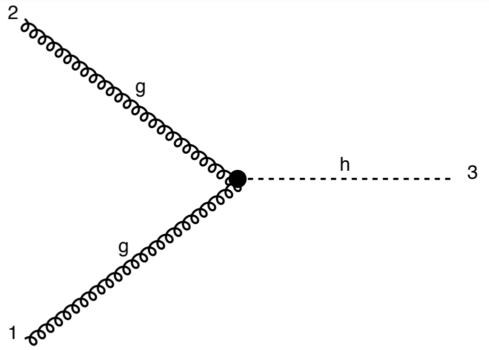
Loop Induced

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





HEFT



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

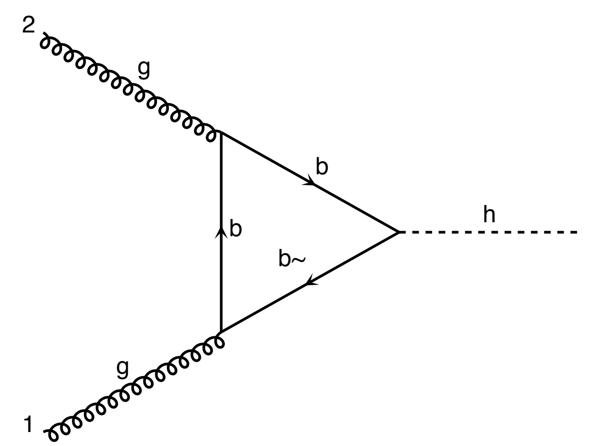
Simplest example

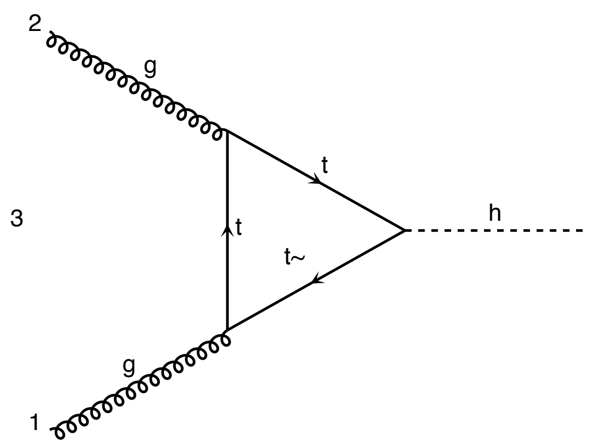
User Input

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

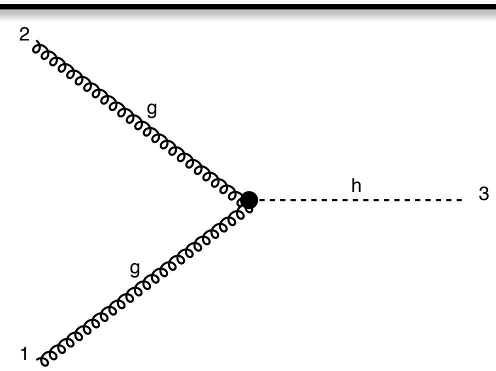
Loop Induced

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



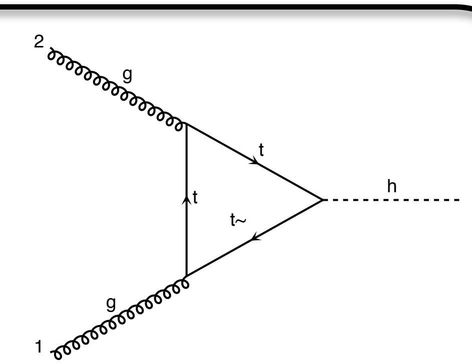


HEFT



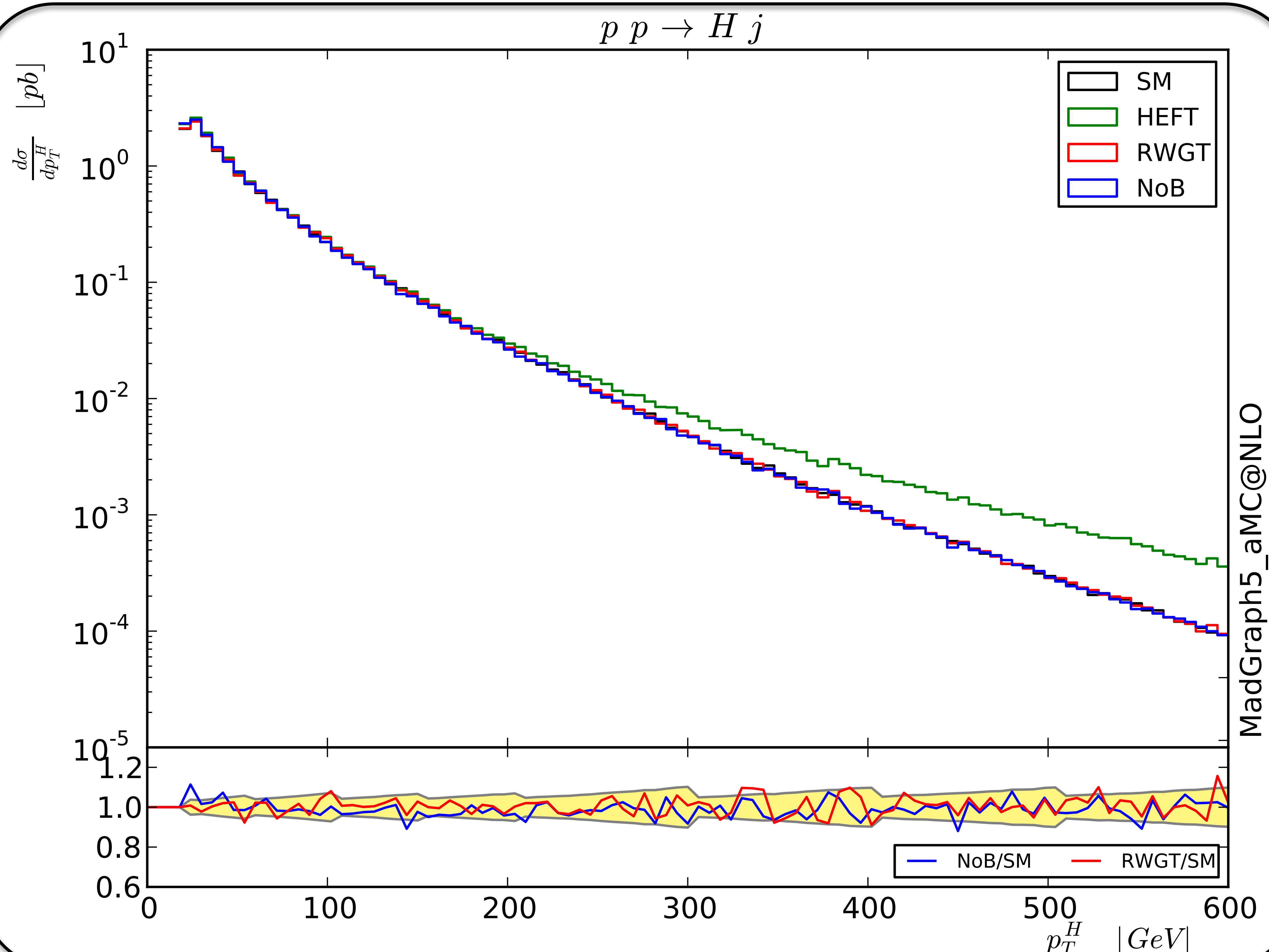
$$\sigma_{heft} = 17.63(2)pb$$

No bottom loop



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

Validation p p > h j



SM Tables (I)

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}
Single boson + jets			$\sqrt{s} = 13$ TeV		
a.1	$pp \to H$	`p p > h [QCD]`	17.79 ± 0.060	$^{+31.3\%}_{-23.1\%}$	$^{+0.5\%}_{-0.9\%}$
a.2	$pp \to Hj$	`p p > h j [QCD]`	12.86 ± 0.030	$^{+42.3\%}_{-27.7\%}$	$^{+0.6\%}_{-0.9\%}$
a.3	$pp \to Hjj$	`p p > h j j QED=1 [QCD]`	6.175 ± 0.020	$^{+61.8\%}_{-35.6\%}$	$^{+0.7\%}_{-0.9\%}$
⋆a.4	$gg \to Zg$	`g g > z g [QCD]`	43.05 ± 0.060	$^{+43.7\%}_{-28.4\%}$	$^{+0.7\%}_{-1.0\%}$
†a.5	$gg \to Zgg$	`g g > z g g [QCD]`	20.85 ± 0.030	$^{+64.5\%}_{-36.5\%}$	$^{+1.0\%}_{-1.1\%}$
†a.6	$gg \to \gamma g$	`g g > a g [QCD]`	75.61 ± 0.200	$^{+73.8\%}_{-41.6\%}$	$^{+0.7\%}_{-1.1\%}$
†a.7	$gg \to \gamma gg$	`g g > a g g [QCD]`	14.50 ± 0.030	$^{+76.2\%}_{-40.7\%}$	$^{+0.6\%}_{-1.0\%}$

⋆ : **Not publicly** available.

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

SM Tables (II)

Process Double bosons + jet		Syntax	Cross section (pb) $\sqrt{s}=13$ TeV	$\Delta_{\hat{\mu}}$	Δ_{PDF}
b.1	$pp \to HH$	`p p > h h [QCD]`	$1.641 \pm 0.002 \cdot 10^{-2}$	$^{+30.2\%}_{-21.7\%}$	$^{+1.1\%}_{-1.2\%}$
b.2	$pp \to HHj$	`p p > h h j [QCD]`	$1.758 \pm 0.003 \cdot 10^{-2}$	$^{+45.7\%}_{-29.2\%}$	$^{+1.2\%}_{-1.2\%}$
*b.3	$pp \to H\gamma j$	`p p > h a j [QCD]`	$4.225 \pm 0.006 \cdot 10^{-3}$	$^{+38.6\%}_{-25.9\%}$	$^{+0.4\%}_{-0.7\%}$
*b.4	$gg \to HZ$	`g g > h z [QCD]`	$6.537 \pm 0.030 \cdot 10^{-2}$	$^{+29.4\%}_{-21.3\%}$	$^{+1.0\%}_{-1.1\%}$
*b.5	$gg \to HZg$	`g g > h z g [QCD]`	$5.465 \pm 0.020 \cdot 10^{-2}$	$^{+46.0\%}_{-29.4\%}$	$^{+1.2\%}_{-1.3\%}$
b.6	$gg \to ZZ$	`g g > z z [QCD]`	1.313 ± 0.004	$^{+27.1\%}_{-20.1\%}$	$^{+0.7\%}_{-1.0\%}$
*b.7	$gg \to ZZg$	`g g > z z g [QCD]`	0.6361 ± 0.002	$^{+45.4\%}_{-29.1\%}$	$^{+1.0\%}_{-1.2\%}$
b.8	$gg \to Z\gamma$	`g g > z a [QCD]`	1.265 ± 0.0007	$^{+30.2\%}_{-22.2\%}$	$^{+0.6\%}_{-1.0\%}$
†b.9	$gg \to Z\gamma g$	`g g > z a g [QCD]`	0.4604 ± 0.001	$^{+43.7\%}_{-28.4\%}$	$^{+0.8\%}_{-1.1\%}$
b.10	$gg \to \gamma\gamma$	`g g > a a [QCD]`	$5.182 \pm 0.010 \cdot 10^{+2}$	$^{+72.3\%}_{-43.4\%}$	$^{+1.0\%}_{-1.3\%}$
*b.11	$gg \to \gamma\gamma g$	`g g > a a g [QCD]`	19.22 ± 0.030	$^{+59.7\%}_{-35.7\%}$	$^{+0.7\%}_{-1.0\%}$
b.12	$gg \to W^+W^-$	`g g > w+ w- [QCD]`	4.099 ± 0.010	$^{+26.5\%}_{-19.7\%}$	$^{+0.7\%}_{-1.0\%}$
*b.13	$gg \to W^+W^-g$	`g g > w+ w- g [QCD]`	1.837 ± 0.004	$^{+45.2\%}_{-29.0\%}$	$^{+0.9\%}_{-1.1\%}$

$\star$: **Not publicly** available.

$\dagger$: Computed here for the **first time**.

SM Tables (III)

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

★ : **Not publicly** available.

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

SM Tables (IV)

Process		Syntax	Cross section (pb)	$\Delta_{\hat{\mu}}$	Δ_{PDF}
Selected $2 \to 4$			$\sqrt{s} = 13$ TeV		
†d.1	$pp \to Hjjj$	`p p > h j j j QED=1 [QCD]`	2.519 ± 0.005	$^{+75.1\%}_{-39.8\%}$	$^{+0.6\%}_{-0.6\%}$
*d.2	$pp \to HHjj$	`p p > h h j j QED=1 [QCD]`	$1.085 \pm 0.002 \cdot 10^{-2}$	$^{+62.1\%}_{-35.8\%}$	$^{+1.2\%}_{-1.3\%}$
†d.3	$pp \to HHHj$	`p p > h h h j [QCD]`	$4.981 \pm 0.008 \cdot 10^{-5}$	$^{+46.3\%}_{-29.6\%}$	$^{+1.4\%}_{-1.4\%}$
†d.3	$pp \to HHHH$	`p p > h h h h [QCD]`	$1.080 \pm 0.003 \cdot 10^{-7}$	$^{+33.3\%}_{-23.4\%}$	$^{+1.7\%}_{-1.7\%}$
d.4	$gg \to e^+e^-\mu^+\mu^-$	`g g > e+ e- mu+ mu- [QCD]`	$2.022 \pm 0.003 \cdot 10^{-3}$	$^{+26.4\%}_{-19.4\%}$	$^{+0.7\%}_{-1.1\%}$
†d.5	$pp \to HZ\gamma j$	`g g > h z a g [QCD]`	$4.950 \pm 0.008 \cdot 10^{-6}$	$^{+45.8\%}_{-29.3\%}$	$^{+1.2\%}_{-1.3\%}$
Non-hadronic processes			$\sqrt{s} = 500$ GeV, no PDF		
†e.1	$e^+e^- \to ggg$	`e+ e- > g g g [QED]`	$2.526 \pm 0.004 \cdot 10^{-6}$	$^{+31.2\%}_{-22.0\%}$	
†e.2	$e^+e^- \to HH$	`e+ e- > h h [QED]`	$1.567 \pm 0.003 \cdot 10^{-5}$	$^{+0.0\%}_{-0.0\%}$	
†e.3	$e^+e^- \to HHgg$	`e+ e- > h h g g [QED]`	$6.629 \pm 0.010 \cdot 10^{-11}$	$^{+19.2\%}_{-14.8\%}$	
*e.4	$\gamma\gamma \to HH$	`a a > h h [QED]`	$3.198 \pm 0.005 \cdot 10^{-4}$	$^{+0.0\%}_{-0.0\%}$	
Miscellaneous			$\sqrt{s} = 13$ TeV		
†f.1	$pp \to tt$	`p p > t t [QED]`	$4.045 \pm 0.007 \cdot 10^{-15}$	$^{+0.2\%}_{-0.8\%}$	$^{+0.9\%}_{-1.0\%}$

★ : **Not publicly** available.

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

SM Tables (V)

Process		Syntax	Partial width (GeV)
Bosonic decays			
g.1	$H \to jj$	`h > j j [QCD]`	$1.740 \pm 0.0006 \cdot 10^{-4}$
*g.2	$H \to jjj$	`h > j j j [QCD]`	$3.413 \pm 0.010 \cdot 10^{-4}$
†g.3	$H \to jjjj$	`h > j j j j QED=1 [QCD]`	$1.654 \pm 0.004 \cdot 10^{-4}$
g.4	$H \to \gamma\gamma$	`h > a a [QED]`	$9.882 \pm 0.002 \cdot 10^{-6}$
†g.5	$H \to \gamma\gamma jj$	`h > a a j j [QCD]`	$7.448 \pm 0.030 \cdot 10^{-13}$
*g.7	$Z \to ggg$	`z > g g g [QCD]`	$3.986 \pm 0.010 \cdot 10^{-6}$

$\star$: **Not publicly** available.

$\dagger$: Computed here for the **first time**.

Reweighting framework (LO and NLO)

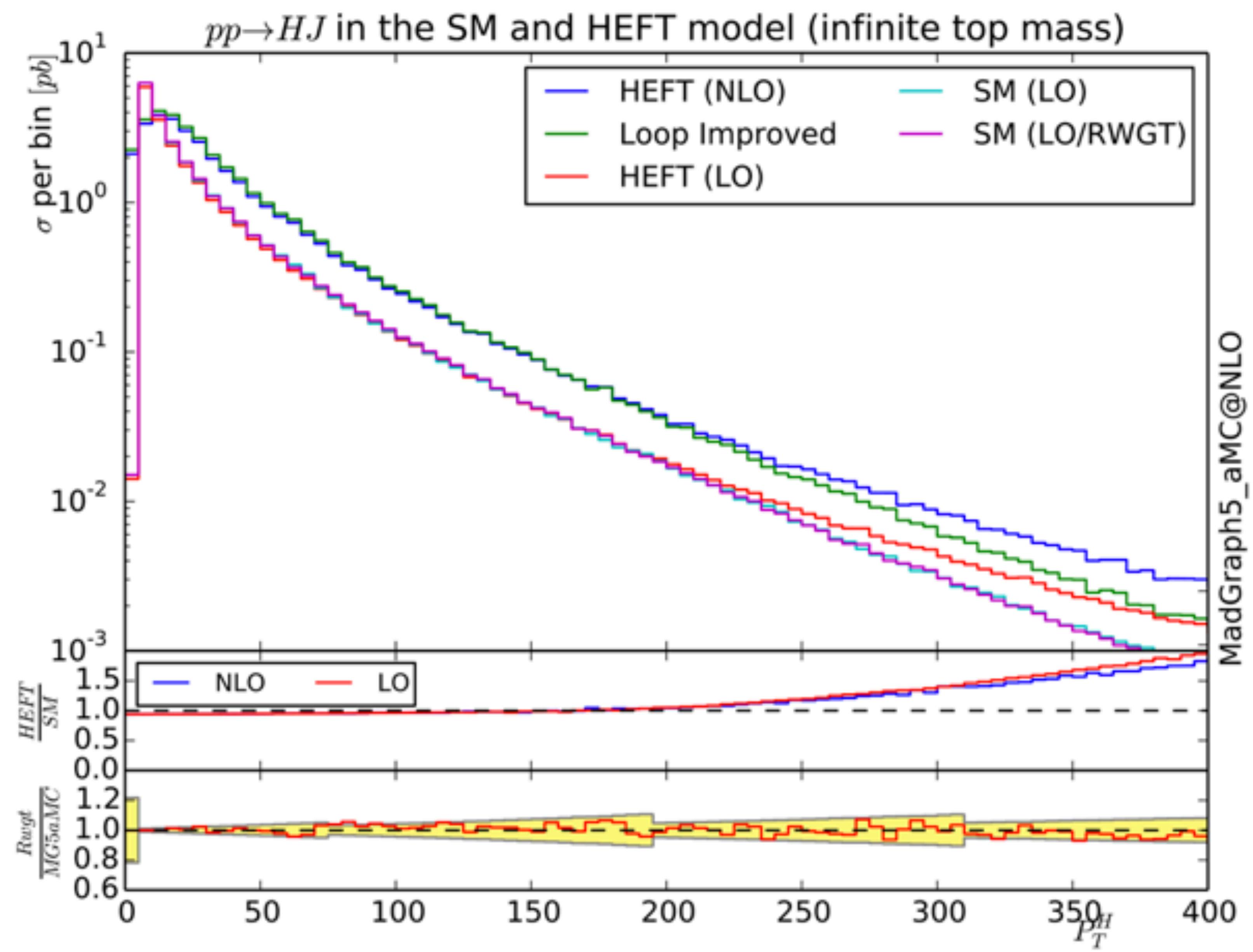
[O. Mattelaer, 1607.00763]

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Reweight

At LO: simple

$$W_{new} = \frac{|M_{new}|^2}{|M_{orig}|^2} W_{orig}$$

At NLO: more involved
but conceptually the same



A non-trivial example: Reweighting HEFT@NLO with exact loop-induced MEs.

Pythia8 Merging systematics at LO

[S. Prestel, V. H, O.Mattelaer, to appear]

- Streamlined PYTHIA8 installation and steering

```
MG5_aMC> install pythia8
MG5_aMC> generate p p > z > e+ e-; launch;

The following switches determine which programs are run:
 1 Choose the shower/hadronization program:                        shower = PYTHIA8
 2 Choose the detector simulation program:                       detector = OFF
 3 Decay particles with the MadSpin module:                       madspin = OFF
 4 Add weights to the events based on changing model parameters:  reweight = OFF
 [0,shower=PYTHIA6, shower=PYTHIA8, detector=OFF, detector=PGS,... ][60s to answer]
>
```

- Support for MLM and CKKW-L merging
- Merging scale variation systematics form a single run.

- **No excuse anymore for theorists using MG5+Pythia6 at LO!**

USER-DEFINED PLUGIN

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/Plugin

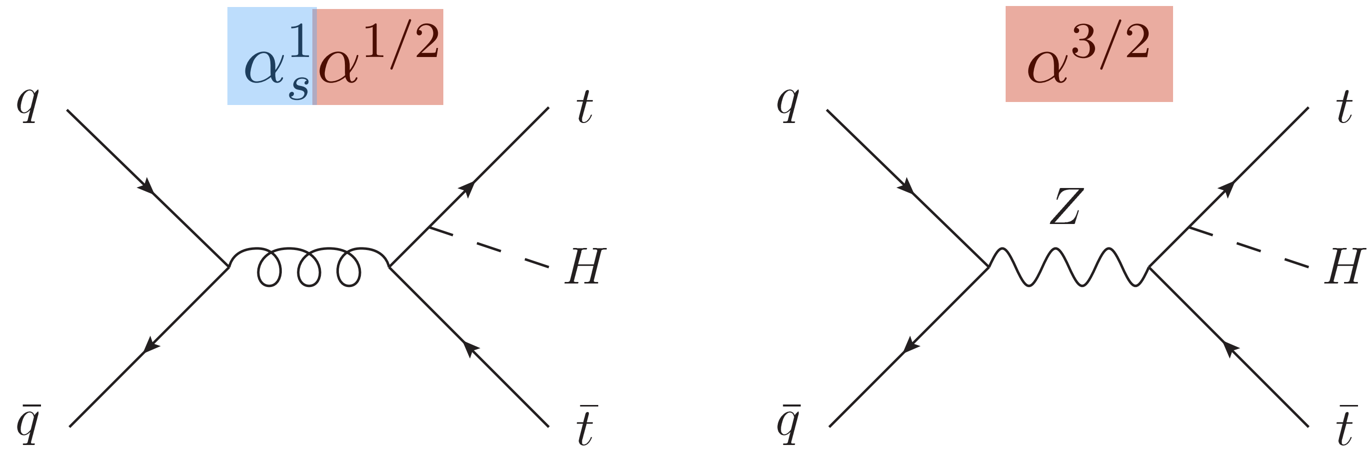
Allows for:

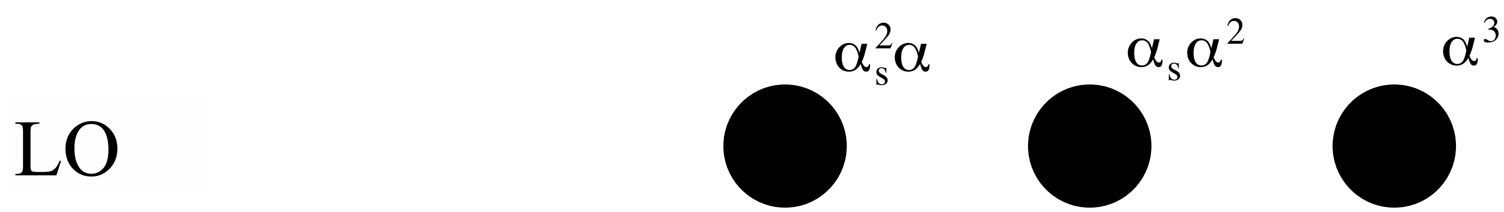
- `Custom commands in MG5aMC interface`
- `Customized format for the matrix element output at LO`
- `Custom cluster job submission implementation`

Useful for robust tweaks of MG5_aMC

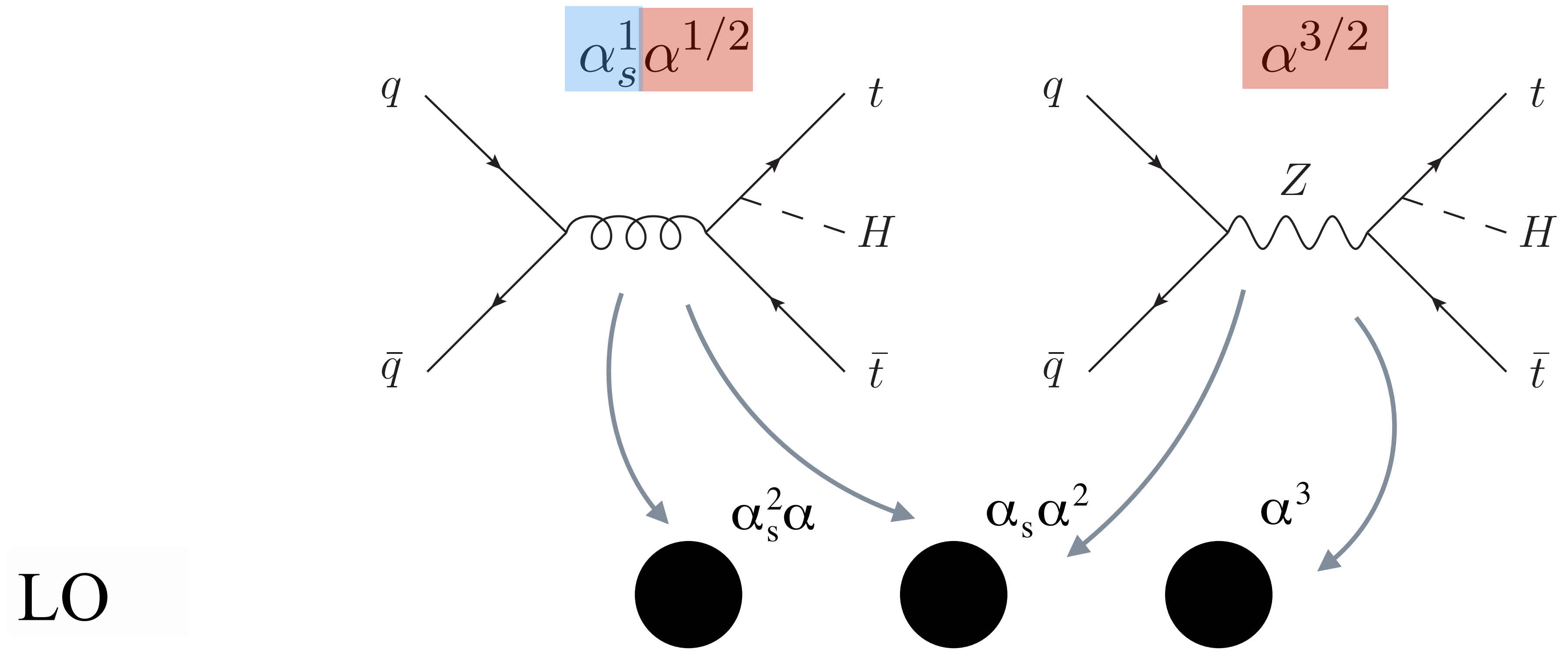
NLO QCD $\oplus$ EW Corrections

Structure of NLO EW-QCD corrections: ttH case

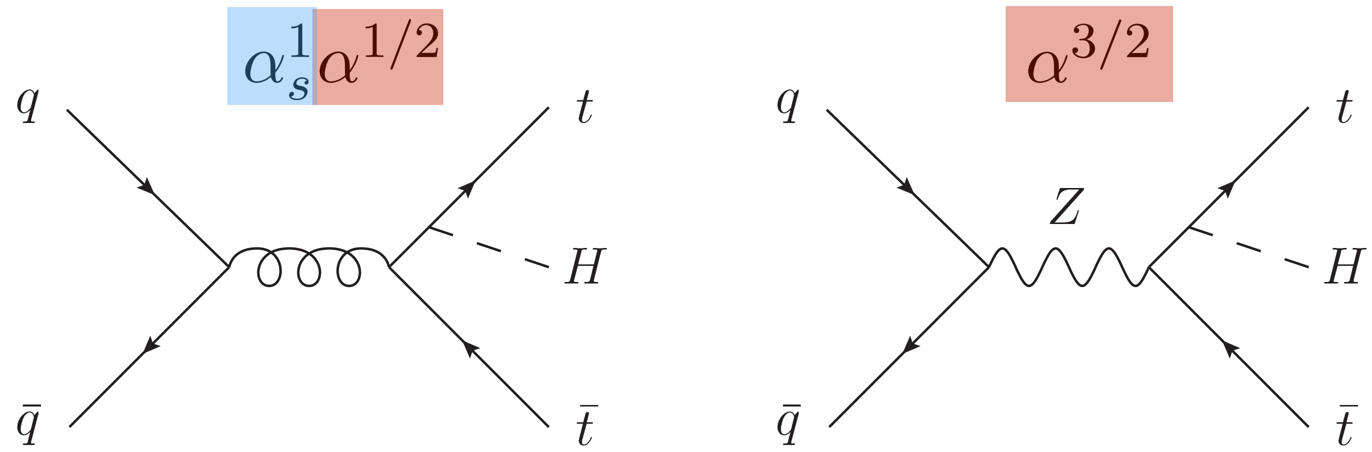


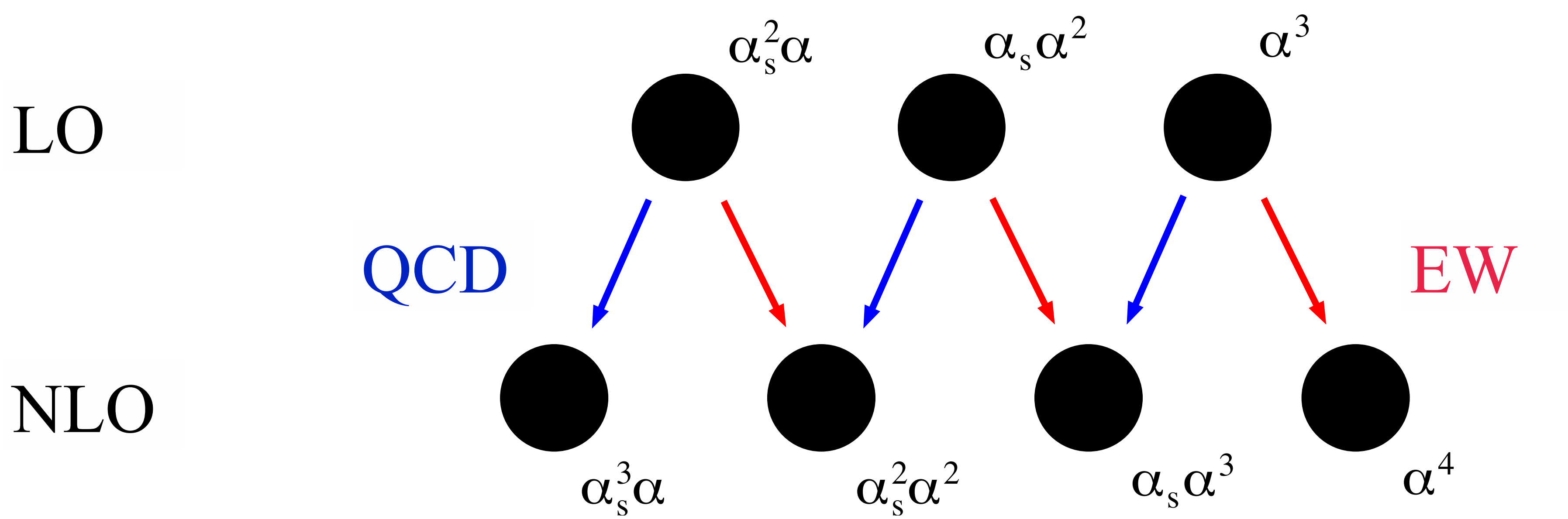


Structure of NLO EW-QCD corrections: ttH case

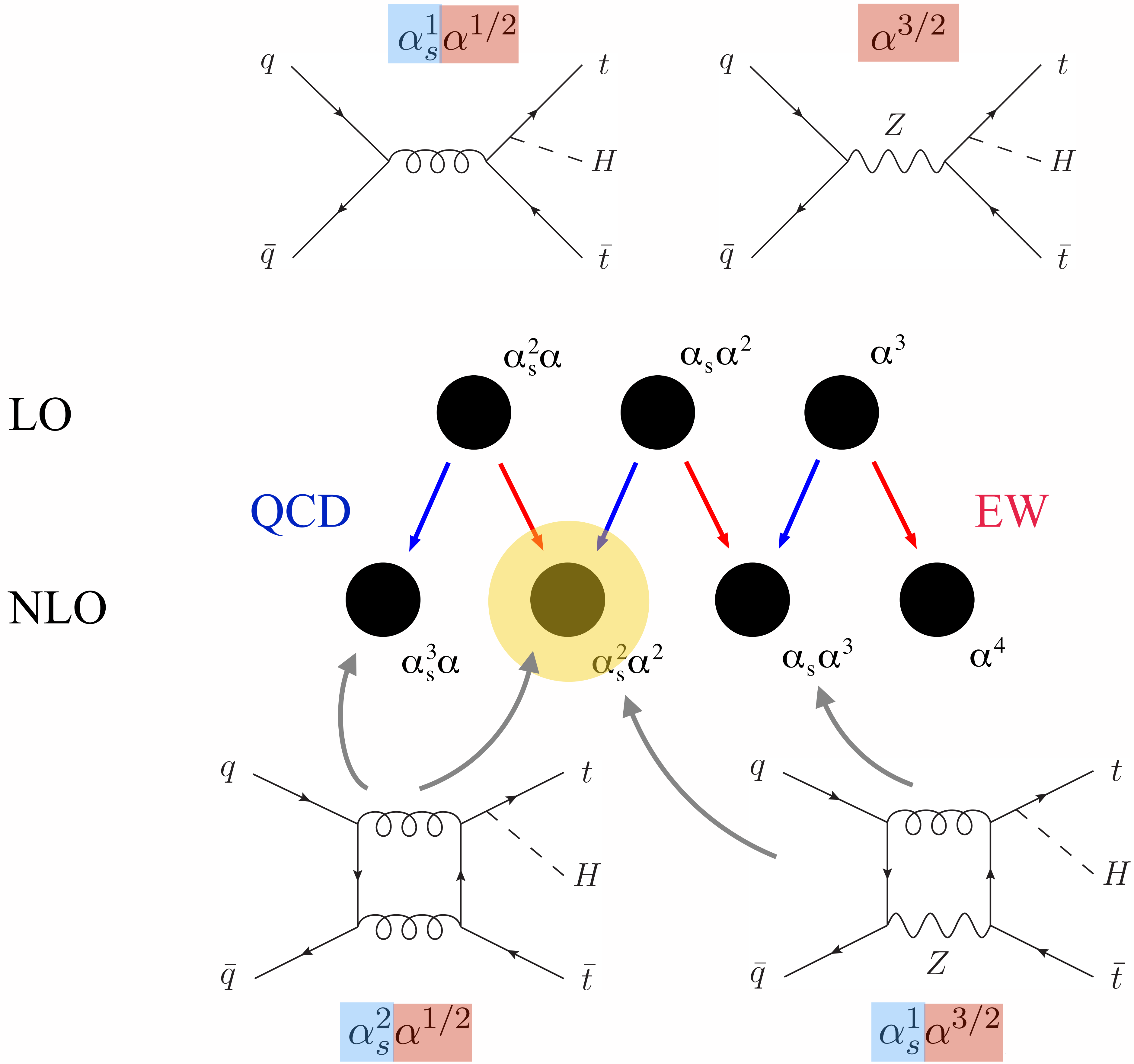


Structure of NLO EW-QCD corrections: ttH case

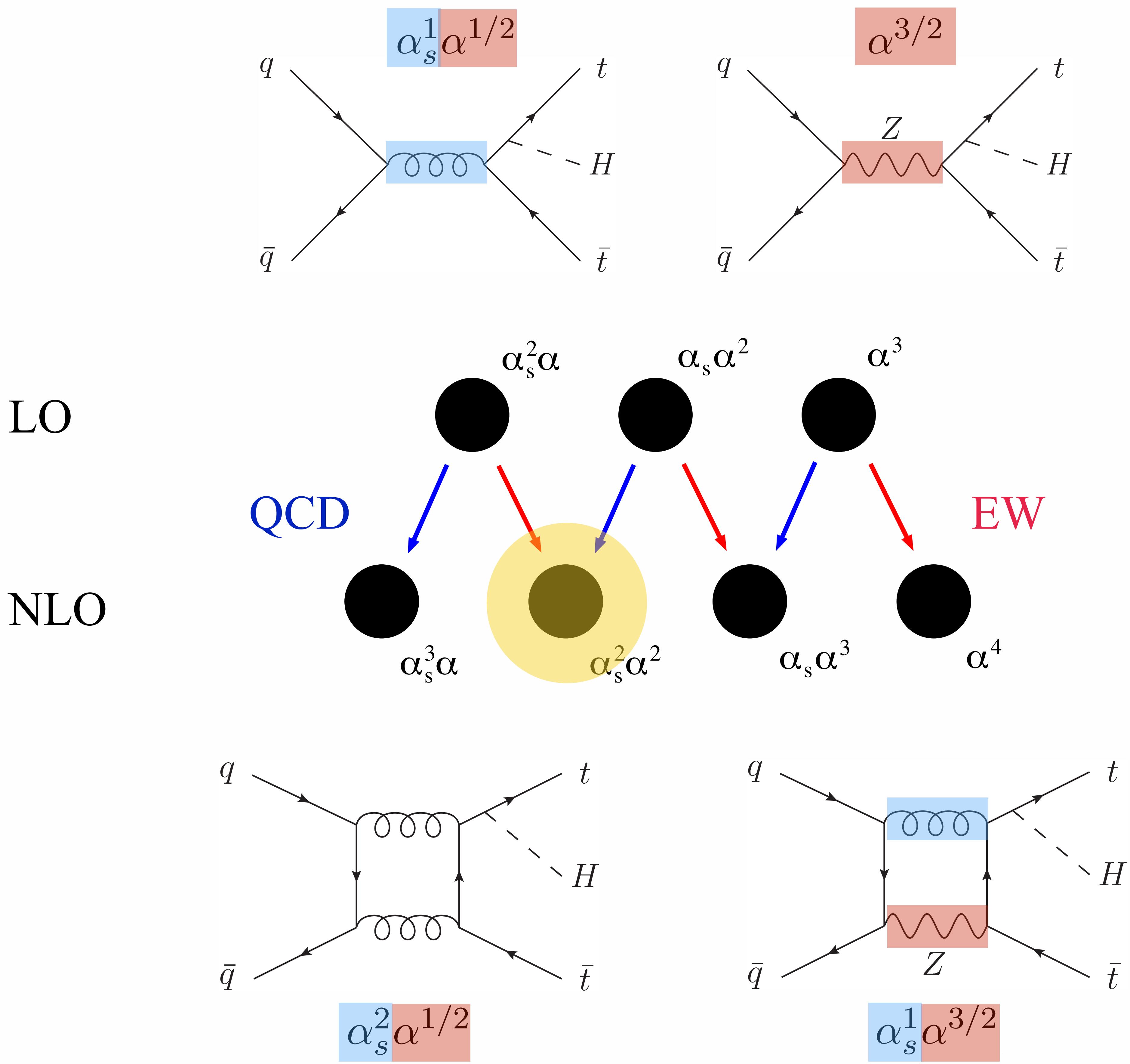




Structure of NLO EW-QCD corrections: ttH case

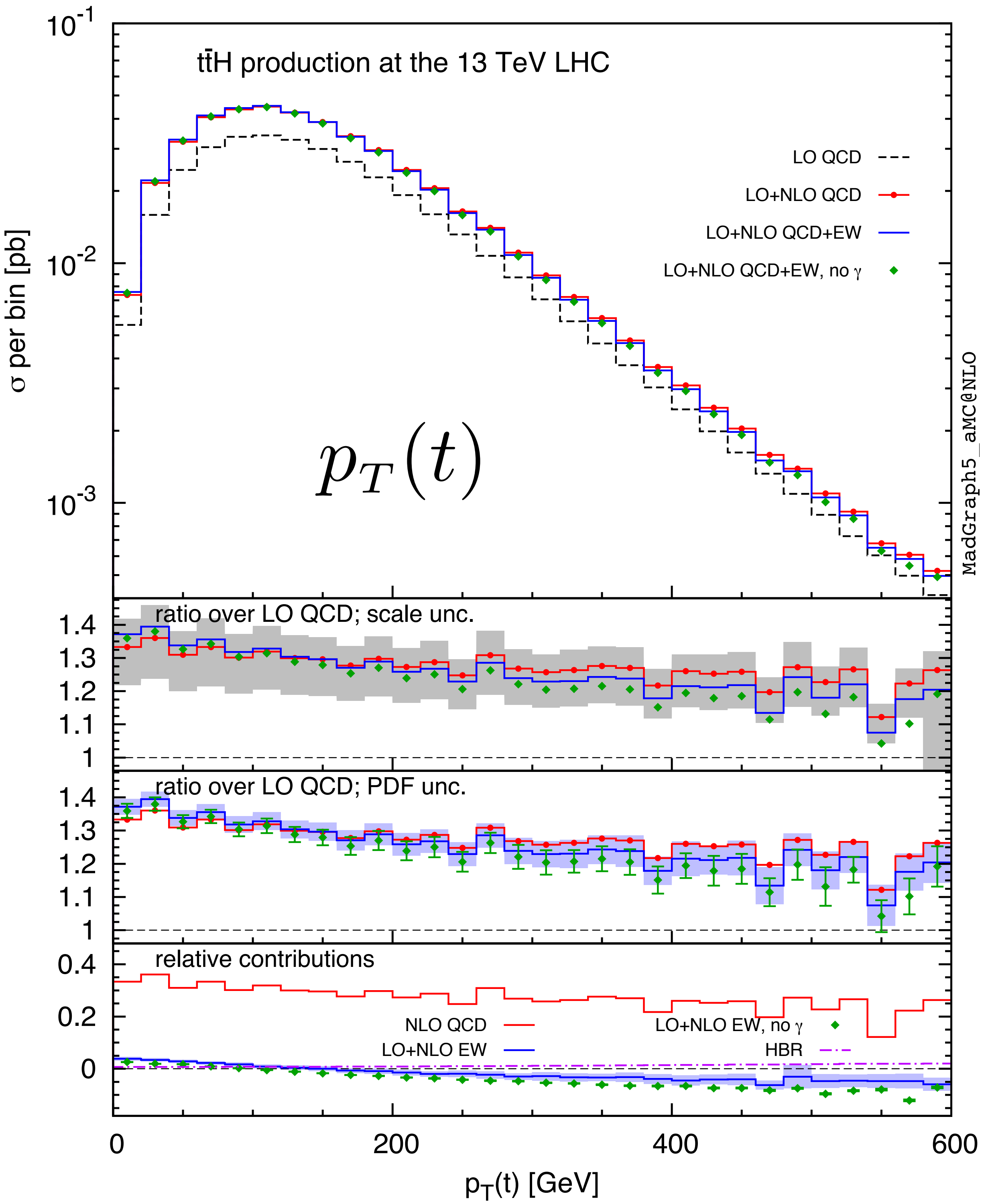


Structure of NLO EW-QCD corrections: ttH case



Top pair + heavy boson @QCD+EW NLO

[1504.03446]



$t\bar{t}H$: $\delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$25.9^{+5.4}_{-11.1}$	$\boxed{29.7^{+6.8}_{-11.1}\ (24.2^{+4.8}_{-10.6})}$	$40.8^{+9.3}_{-9.1}$
LO EW	1.8 ± 1.3	$1.2 \pm 0.9\ (2.8 \pm 2.0)$	0.0 ± 0.2
LO EW no γ	-0.3 ± 0.0	$-0.4 \pm 0.0\ (-0.2 \pm 0.0)$	-0.6 ± 0.0
NLO EW	-0.6 ± 0.1	$\boxed{-1.2 \pm 0.1\ (-8.2 \pm 0.3)}$	-2.7 ± 0.0
NLO EW no γ	-0.7 ± 0.0	$-1.4 \pm 0.0\ (-8.5 \pm 0.2)$	-2.7 ± 0.0
HBR	0.88	0.89 (1.87)	0.91

(Boosted regime in brackets)

$$p_T(t) \geq 200\ \text{GeV}, \quad p_T(\bar{t}) \geq 200\ \text{GeV}, \quad p_T(H) \geq 200\ \text{GeV}$$

$$t\bar{t}H$$

Comparison between different renormalization schemes

$$m_W = 80.385 \ \text{GeV}\,, \qquad m_Z = 91.188 \ \text{GeV}$$

$\alpha(m_Z)$ scheme → $\dfrac{1}{\alpha(m_Z)} = 128.93$

G_μ scheme → $G_\mu = 1.16639 \cdot 10^{-5} \longrightarrow \dfrac{1}{\alpha} = 132.23$

	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W^+$	$t\bar{t}W^-$
$\sigma_{\text{LO QCD}}(\text{pb})$	$3.617 \cdot 10^{-1}$	$5.282 \cdot 10^{-1}$	$2.496 \cdot 10^{-1}$	$1.265 \cdot 10^{-1}$
$\sigma^{G_\mu}_{\text{LO QCD}}(\text{pb})$	$3.527 \cdot 10^{-1}$	$5.152 \cdot 10^{-1}$	$2.433 \cdot 10^{-1}$	$1.234 \cdot 10^{-1}$
$\Delta^{G_\mu}_{\text{LO QCD}}(\%)$	2.5	2.5	2.5	2.5
$\delta_{\text{LO EW}}(\%)$	1.2	0.0	0	0
$\delta^{G_\mu}_{\text{LO EW}}(\%)$	1.2	0.0	0	0
$\Delta^{G_\mu}_{\text{LO EW}}(\%)$	2.5	2.5	2.5	2.5
$\delta_{\text{NLO EW}}(\%)$	-1.2	-3.8	-7.7	-6.7
$\delta^{G_\mu}_{\text{NLO EW}}(\%)$	1.8	-0.7	-4.5	-3.5
$\Delta^{G_\mu}_{\text{NLO EW}}(\%)$	-0.5	-0.7	-0.9	-0.9

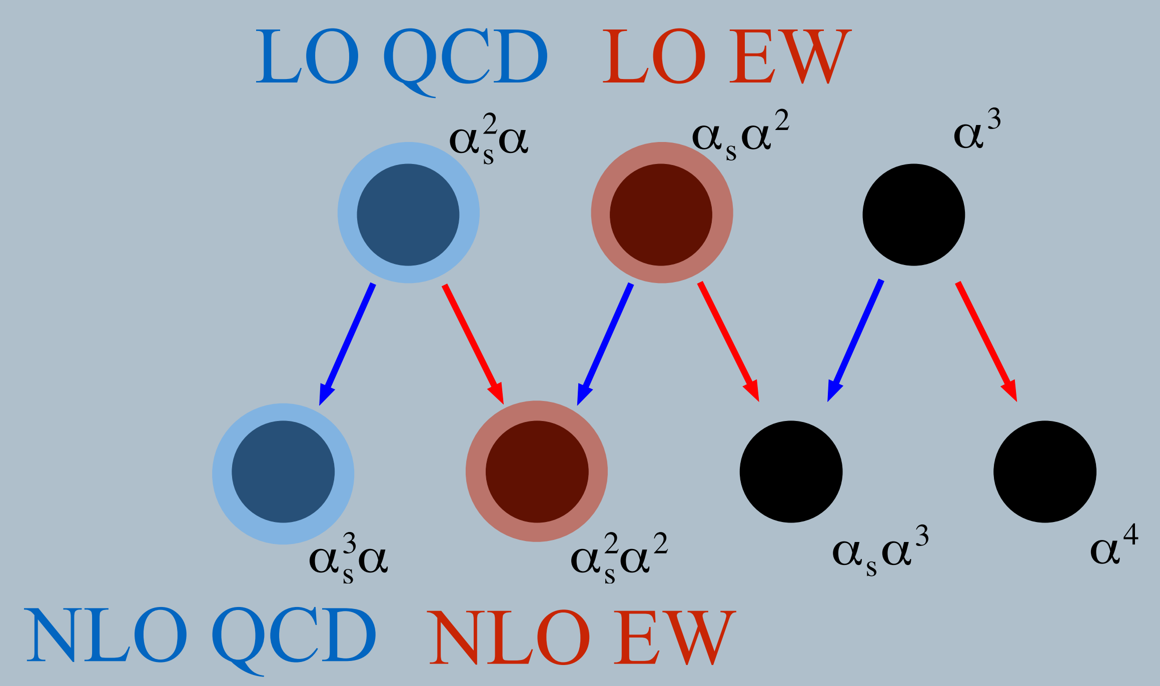
Table 11: Comparison between results in the $\alpha(m_Z)$ and G_μ scheme, at 13 TeV.

$$\Delta^{G_\mu}_{\text{LO QCD}} = \frac{\sigma_{\text{LO QCD}} - \sigma^{G_\mu}_{\text{LO QCD}}}{\sigma_{\text{LO QCD}}}$$

$$\delta_{\text{X}} = \frac{\sigma_{\text{X}}}{\sigma_{\text{LO QCD}}}$$

The midterm goal

```
MG5_aMC> define p = p b b~ a
MG5_aMC> generate p p > t t~ h [QCD QED]
MG5_aMC> output ttbarh_QCD_QED
MG5_aMC> launch
```



The midterm goal

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MG5_aMC> define p = p b b~ a
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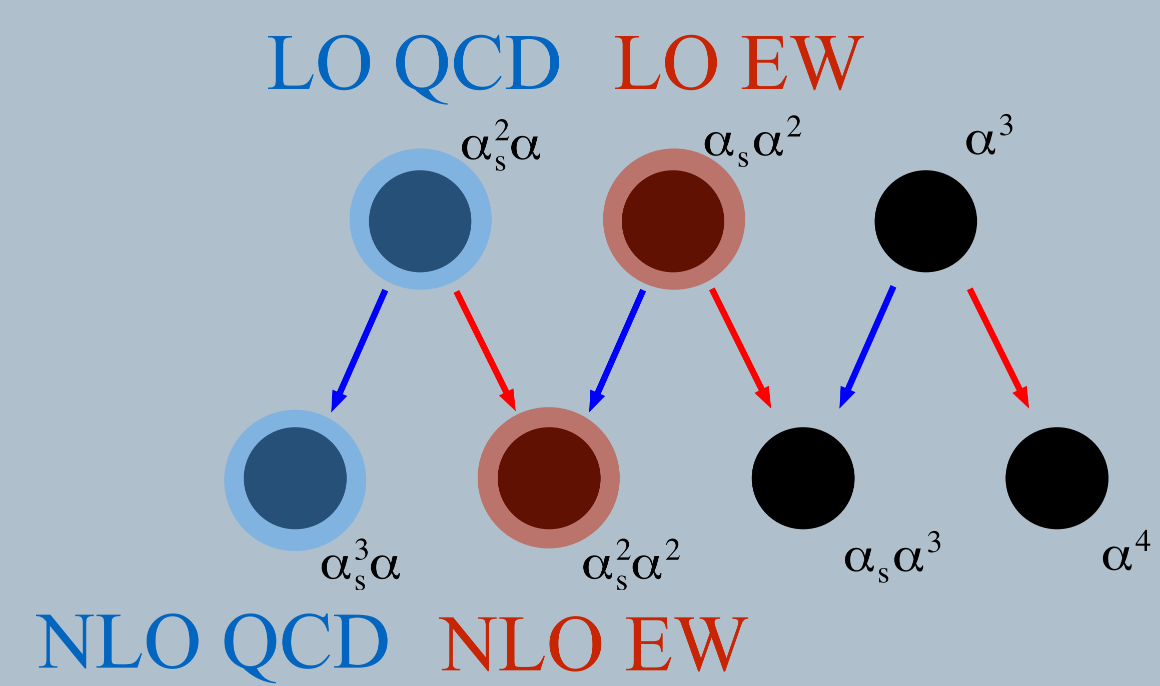
```



Additional difficulties appear when computing all the blobs and other processes:

> complex mass scheme
> isolated photon definition
> book-keeping of Born topologies

currently under development using dijet as a case-study

Thank you for using MadGraph.

Additional Slides

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),

P P > T T, THE ANSWER