Glories of MadGraph_aMC@NLO

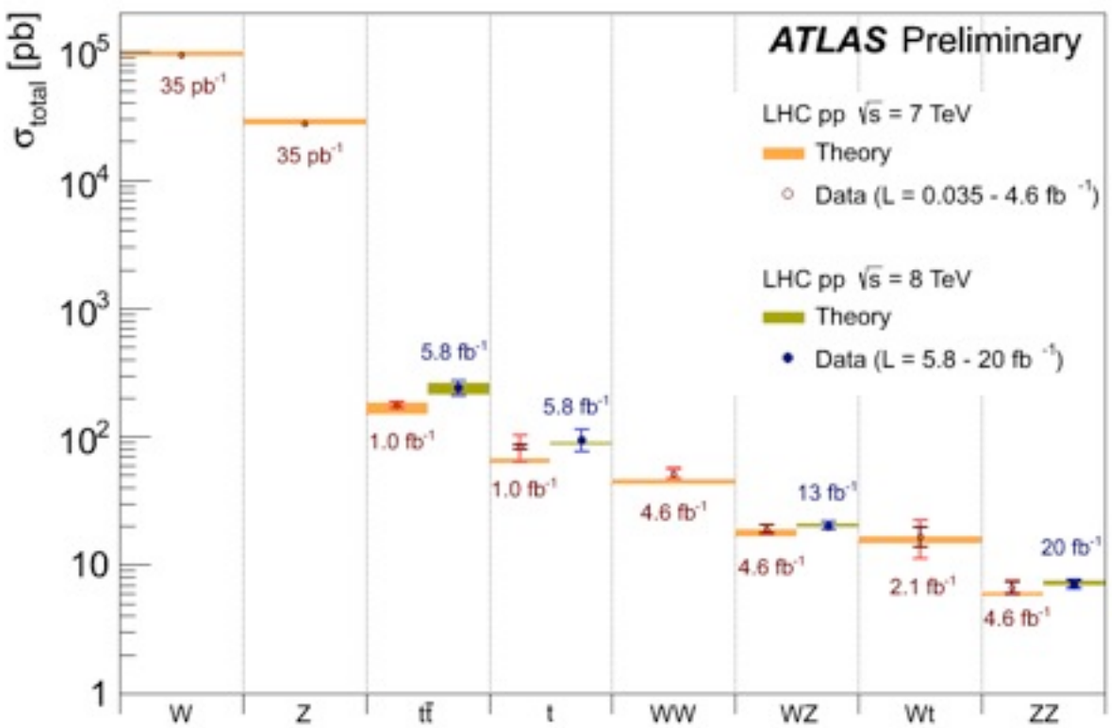
Valentin Hirschi

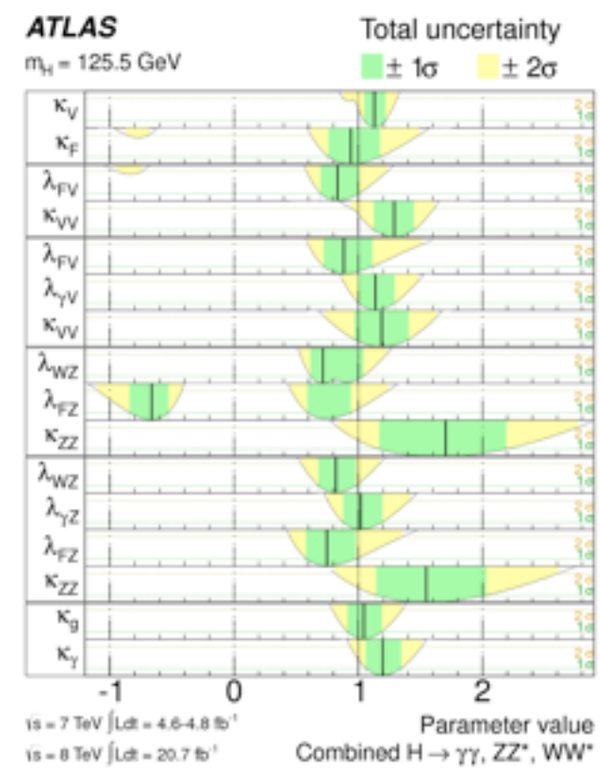
Atlas Jamboree Talks 2014, SLAC

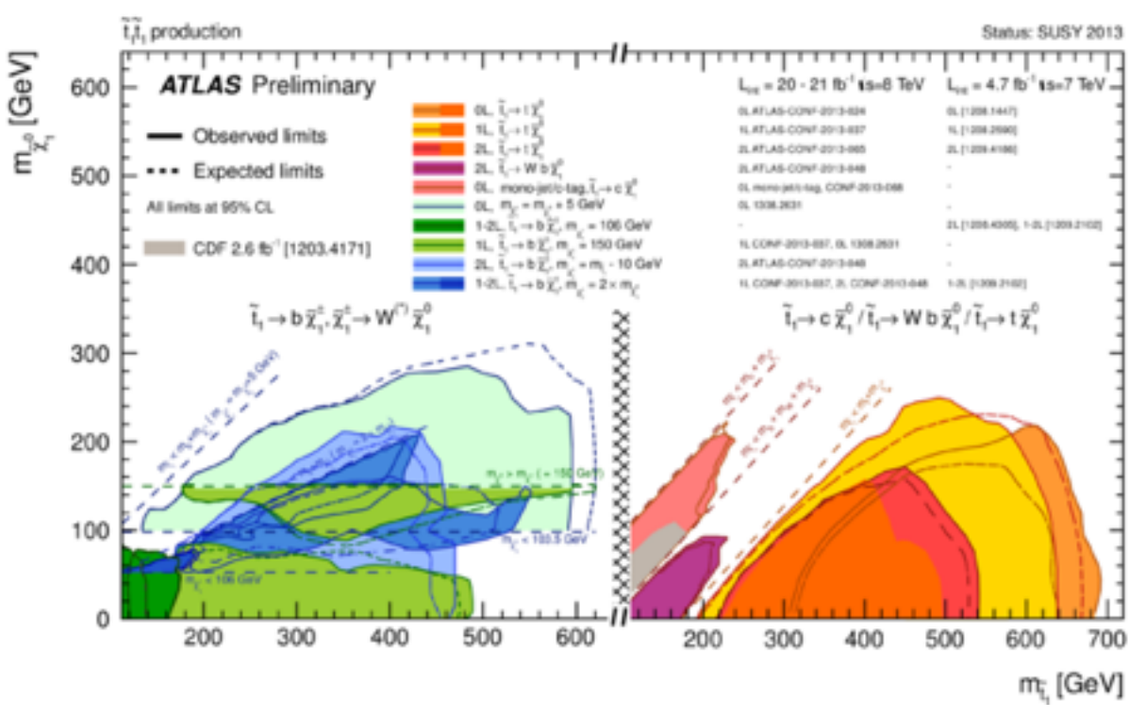
November 12th, 2014

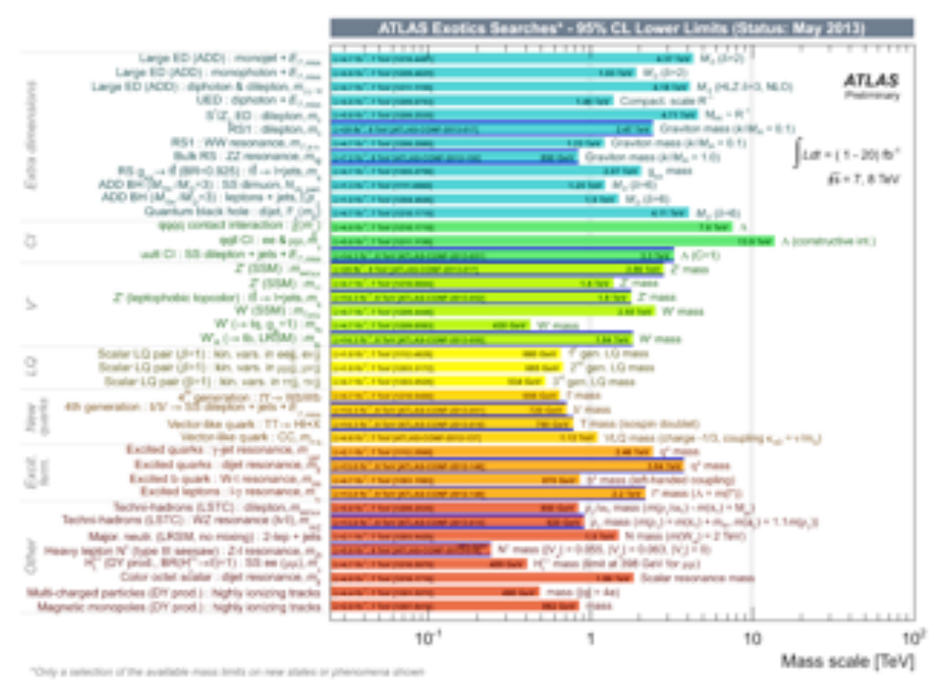
Outline

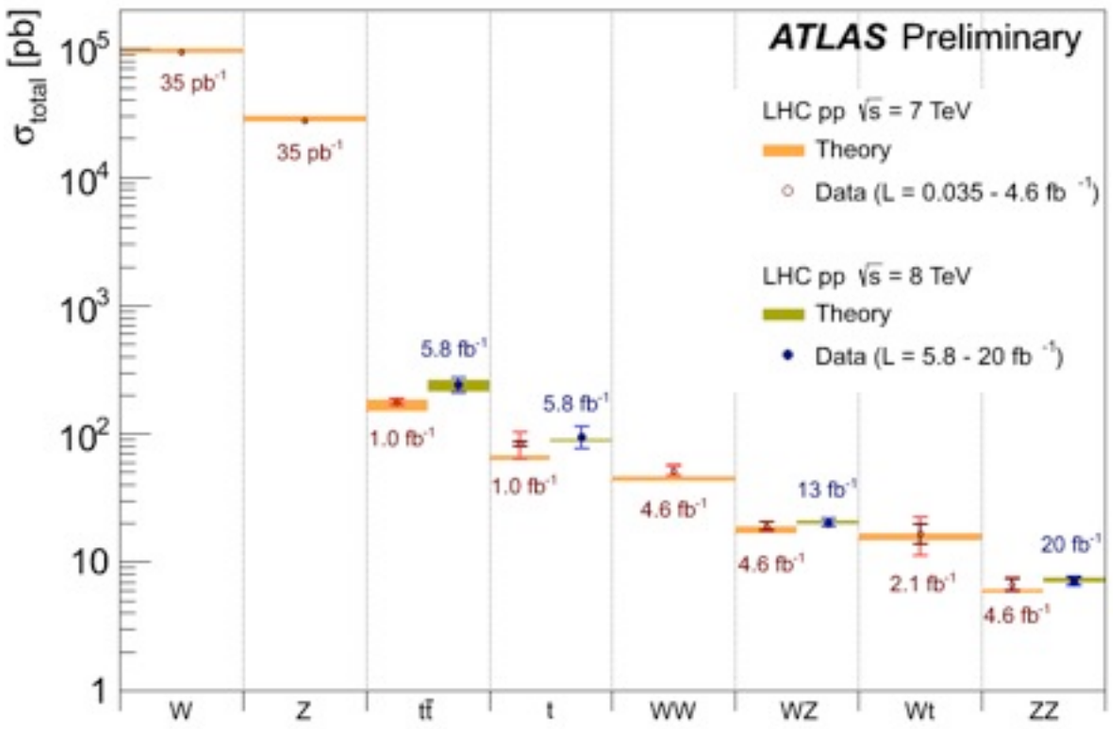
- MG5_aMC obsession of automation why?
- The need for accuracy and how to get it
- MG5_aMC tools and selected developments

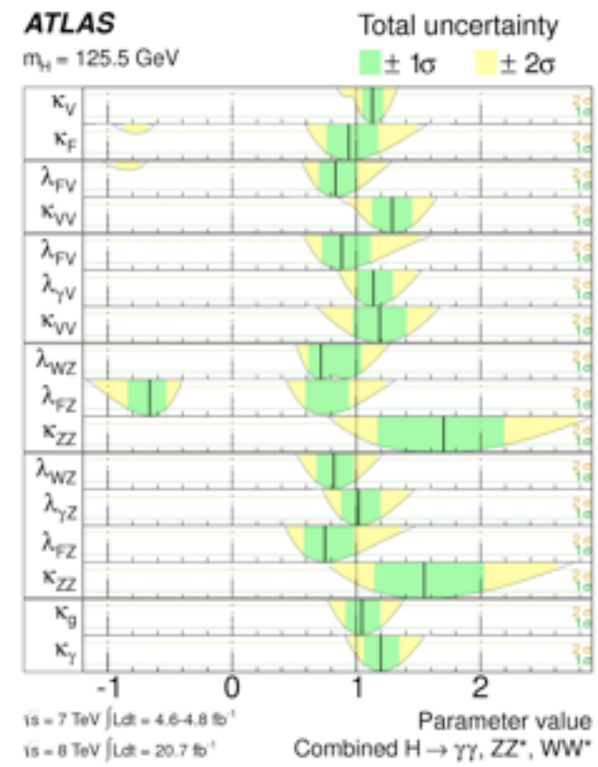

ATLAS Preliminary
LHC pp √s = 7 TeV
Theory
Data (L = 0.035 - 4.6 fb⁻¹)
LHC pp √s = 8 TeV
Theory
Data (L = 5.8 - 20 fb⁻¹)
σtotal [pb]
W
Z
tt̄
t
WW
WZ
Wt
ZZ


ATLAS
mH = 125.5 GeV
Total uncertainty
± 1σ
± 2σ
Parameter value
Combined H → γγ, ZZ*, WW*

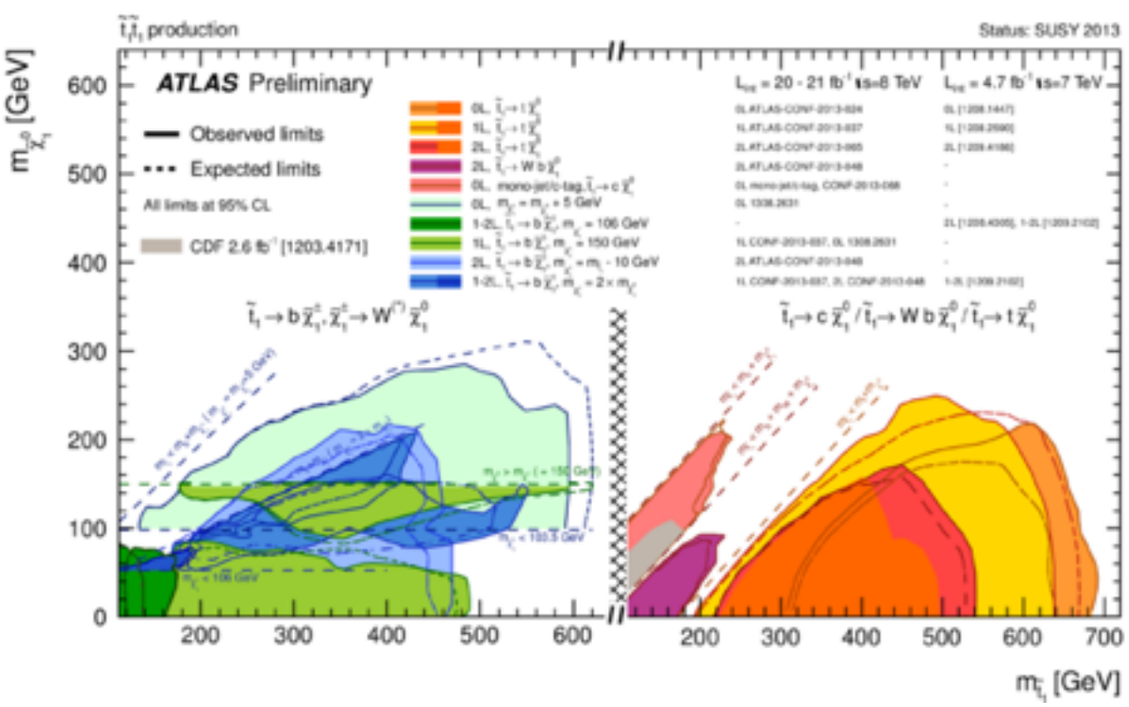

t̃1t̃1 production
Status: SUSY 2013
ATLAS Preliminary
Observed limits
Expected limits
All limits at 95% CL
CDF 2.6 fb⁻¹ [1203.4171]
mt̃1 [GeV]

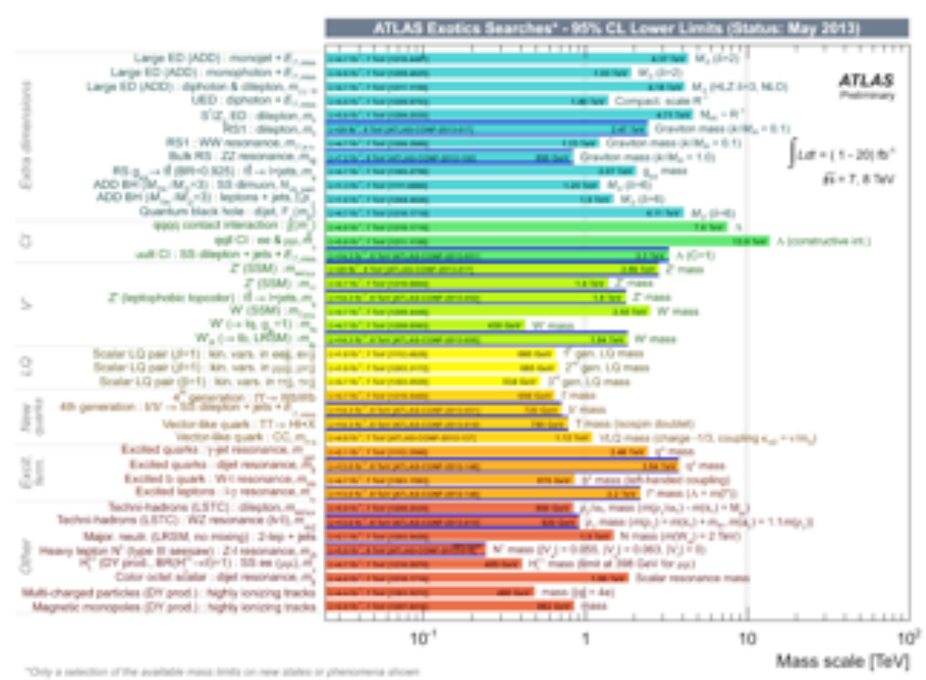

ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)
ATLAS
Mass scale [TeV]





No sign of new physics (so far)!





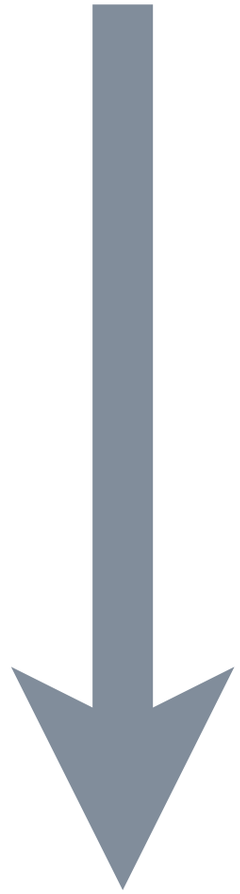
... BUT IT HAS GOOD ASPECTS TOO!

(AT LEAST FOR SOME MC DEVELOPERS)

- Optimism: New Physics could be hiding there already, just need to dig it out.
- Democratization: No evidence of most beaten BSM proposals, means more and more room for diversification. Possibility for small teams to make a big discovery.
- Ingenuity/Creativity: From new signatures to smart and new analysis techniques (MVA), and combination with non-collider searches (DM, Flavor...).
- BSM flexibility: We need MC that are able to predict the pheno of the Unexpected.
- Mass distribution: MC's in the hands of every th/exp might turn out to be the best overall strategy for discovering the Unexpected.

We need accurate and flexible simulations, fine, but how do you get from

Theory



to Exp. data ?

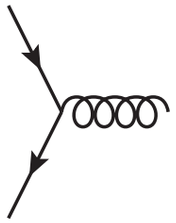
Prediction workflow

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

Prediction workflow

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

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

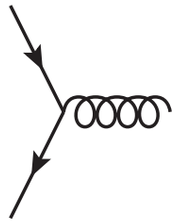


$= \imath\gamma^\mu t^a_{ij} \quad , \ldots$

Prediction workflow

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

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



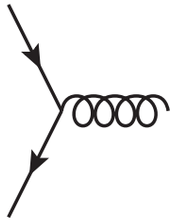
$= \imath\gamma^\mu t^a_{ij} \quad , \ldots$

$pp \to jj \quad \mathrm{QCD} = 2$ **Matrix Element** $\mathcal{M}^2_{gg\to d\bar{d}} \; , \ldots$

Prediction workflow

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

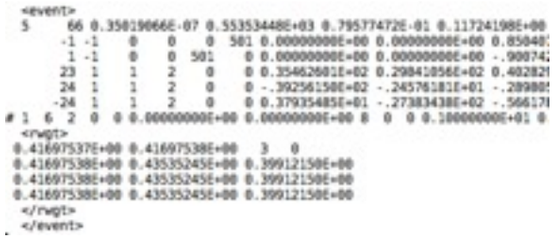
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**



$= \imath\gamma^\mu t^a_{ij} \quad , \ldots$

$pp \to jj \quad \mathrm{QCD} = 2$ **Matrix Element** $\mathcal{M}^2_{gg\to d\bar{d}} \ , \ldots$

`matrix.f` **Partonic Events**

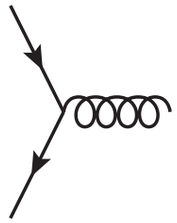


```
<event>
5     66 0.35019066E-07 0.55353448E+03 0.79577472E-01 0.11724198E+00
     -1 -1    0    0    0  501 0.00000000E+00 0.00000000E+00 0.85040
      1 -1    0    0  501    0 0.00000000E+00 0.00000000E+00 -.90074
     23  1    1    2    0    0 0.35462601E+02 0.29841056E+02 0.40282
     24  1    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
 0.41697538E+00 0.43535245E+00 0.39912150E+00
 0.41697538E+00 0.43535245E+00 0.39912150E+00
 </rwgt>
 </event>
```

Prediction workflow

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

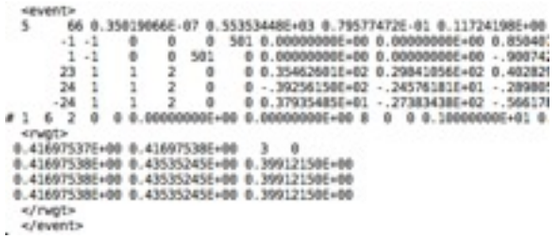
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**



$= \imath\gamma^\mu t^a_{ij} \quad , \ldots$

$pp \to jj \quad \mathrm{QCD} = 2$ **Matrix Element** $\mathcal{M}^2_{gg\to d\bar{d}} \ , \ldots$

`matrix.f` **Partonic Events**



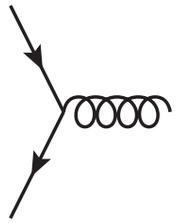
```
<event>
5     66 0.35019066E-07 0.55353448E+03 0.79577472E-01 0.11724198E+00
     -1 -1    0    0    0  501 0.00000000E+00 0.00000000E+00 0.85040
      1 -1    0    0  501    0 0.00000000E+00 0.00000000E+00 -.90074
     23  1    1    2    0    0 0.35462601E+02 0.29841056E+02 0.40282
     24  1    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
 0.41697538E+00 0.43535245E+00 0.39912150E+00
 0.41697538E+00 0.43535245E+00 0.39912150E+00
 </rwgt>
 </event>
```

`events.lhe` **Hadron level** $\{\pi^0, K^+, e^+, p, \cdots\}$

Prediction workflow

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

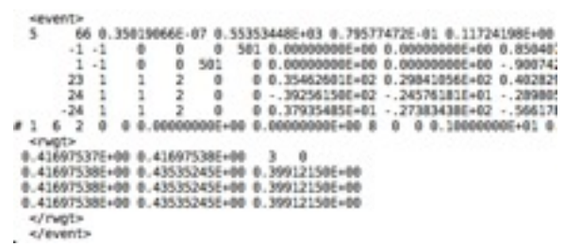
$G^{\mu\nu}G_{\mu\nu} + \imath\bar{q}_{(i)}D_\mu\gamma^\mu q_{(i)} + [\cdots]$ **Model**



$= \imath\gamma^\mu t^a_{ij} \quad , \ldots$

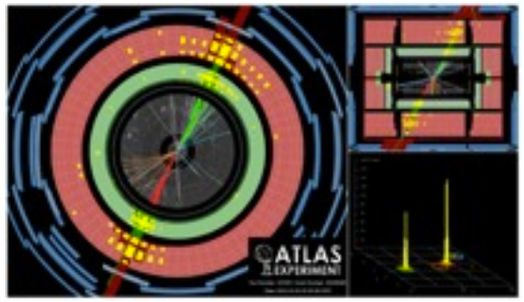
$pp \to jj \quad \mathrm{QCD} = 2$ **Matrix Element** $\mathcal{M}^2_{gg\to d\bar{d}} \ , \ldots$

matrix.f **Partonic Events**



events.lhe **Hadron level** $\{\pi^0, K^+, e^+, p, \cdots\}$

events.hep **Detector level**



IMPLEMENTATION

Galileo

Symmetries

IMPLEMENTATION

GALILEO	SYMMETRIES
FEYNRULES	MODEL

IMPLEMENTATION

GALILEO	SYMMETRIES
FEYNRULES	MODEL
MAD[GRAPH|LOOP] 5	MATRIX ELEMENT

IMPLEMENTATION

GALILEO	SYMMETRIES
FEYNRULES	MODEL
MAD[GRAPH|LOOP] 5	MATRIX ELEMENT
MAD[EVENT|FKS]	PARTONIC EVENTS

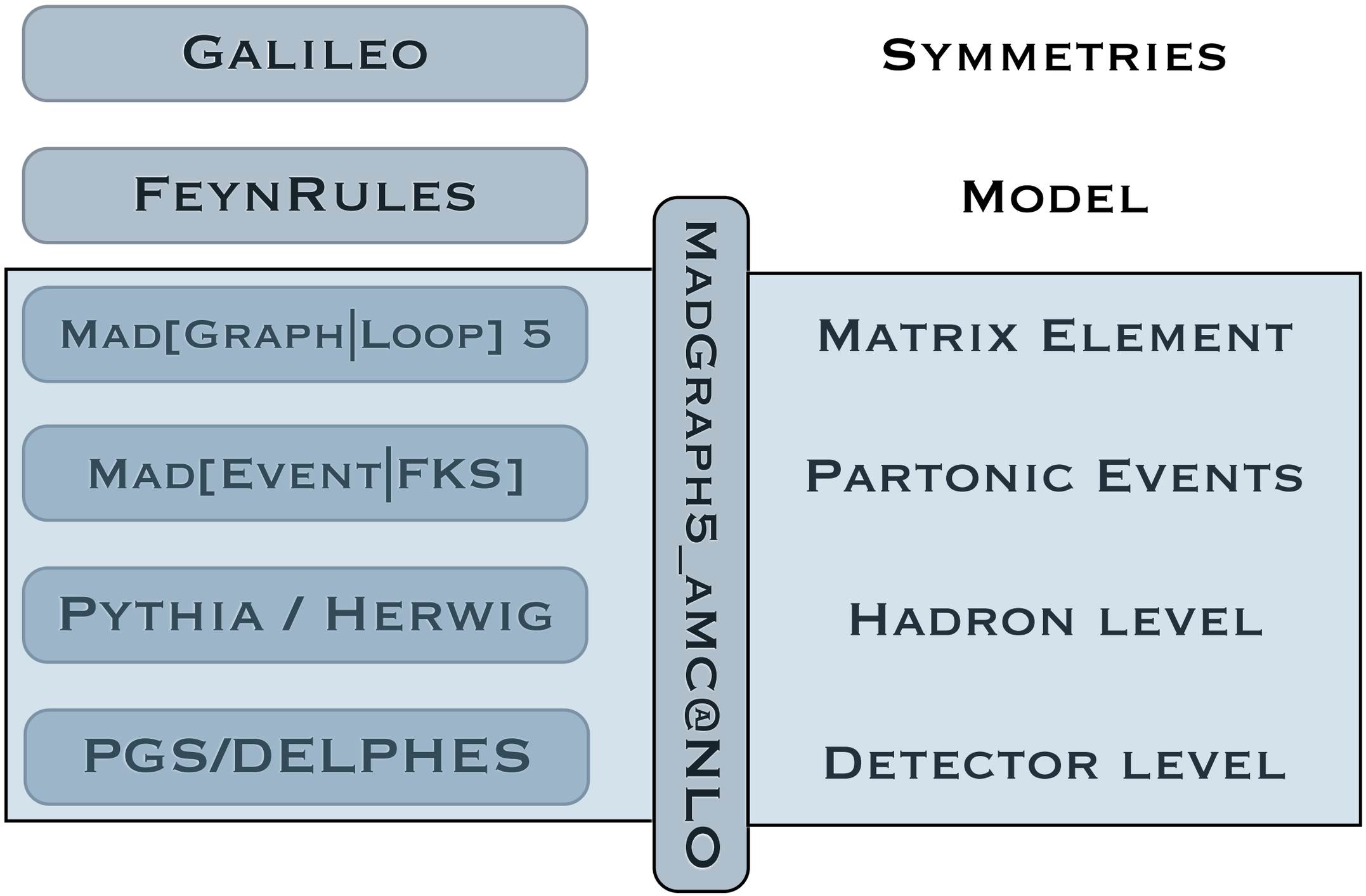
Implementation

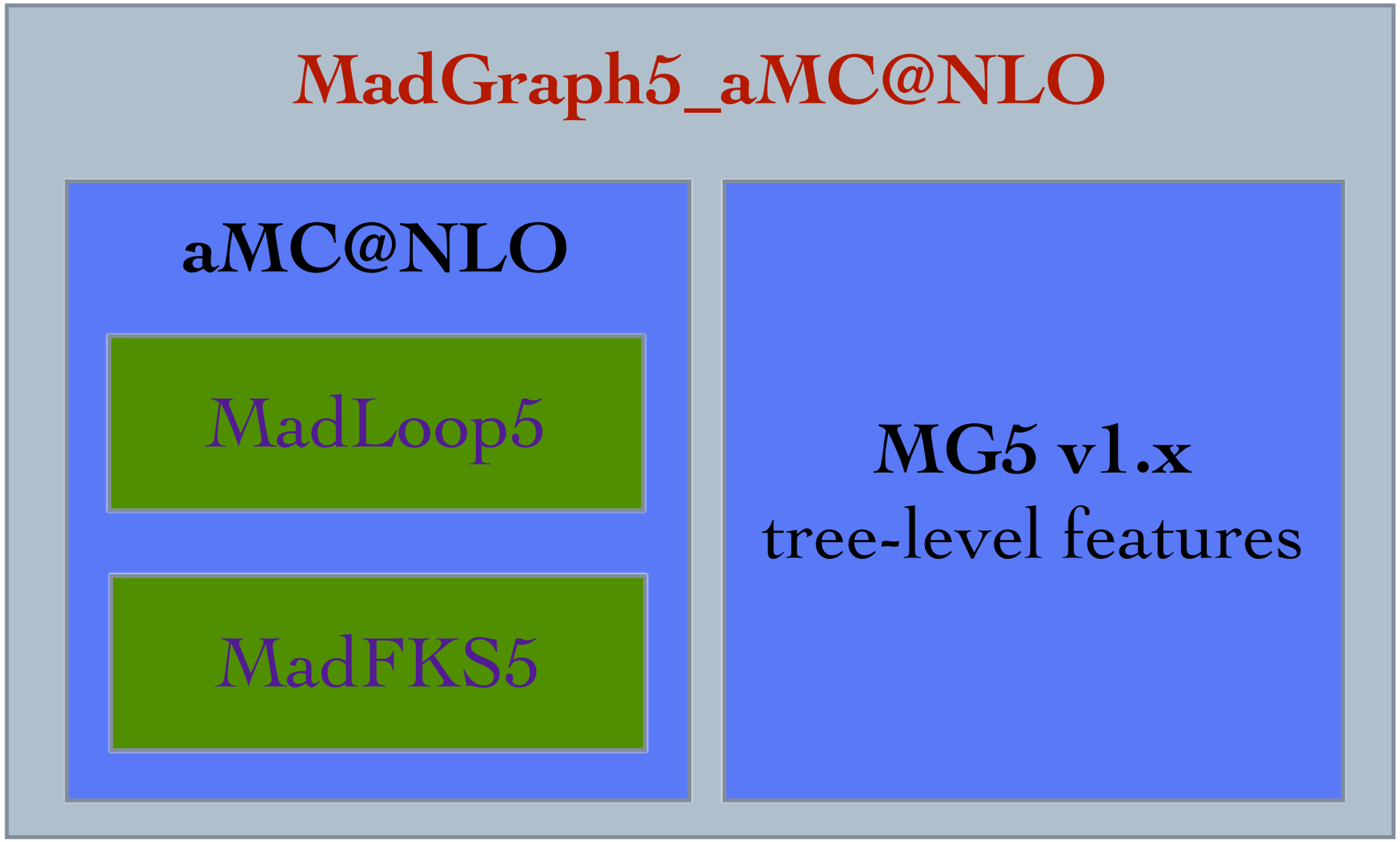
Galileo	Symmetries
FeynRules	Model
Mad[Graph|Loop] 5	Matrix Element
Mad[Event|FKS]	Partonic Events
Pythia / Herwig	Hadron level

IMPLEMENTATION

GALILEO	SYMMETRIES
FEYNRULES	MODEL
MAD[GRAPH|LOOP] 5	MATRIX ELEMENT
MAD[EVENT|FKS]	PARTONIC EVENTS
PYTHIA / HERWIG	HADRON LEVEL
PGS/DELPHES	DETECTOR LEVEL

IMPLEMENTATION





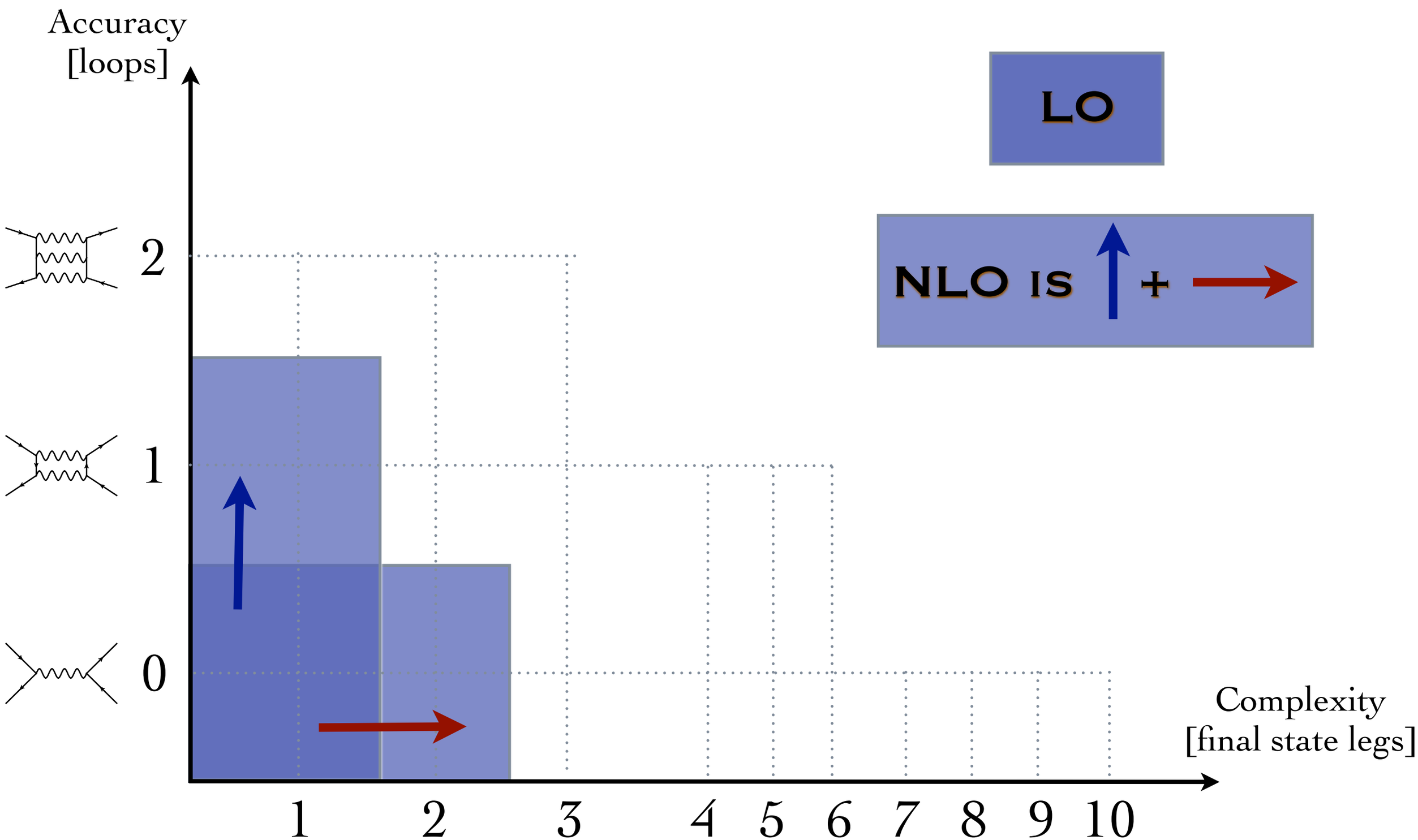
[J. Alwall, R. Frederix, S. Frixione, V. H, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, M. Zaro] [hep-ph/1405.0301]

Framework with many modules for specific tasks:

MadSpin, MadWidth, MadWeight, MadDM, ...

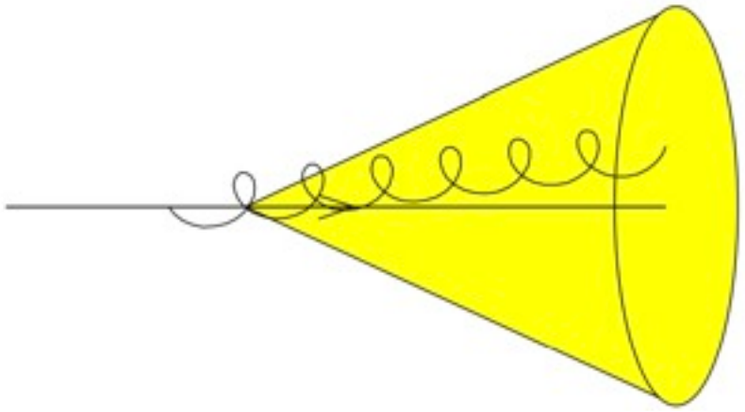
This separation and transitions transparent to the users.

MG5_aMC take on NLO



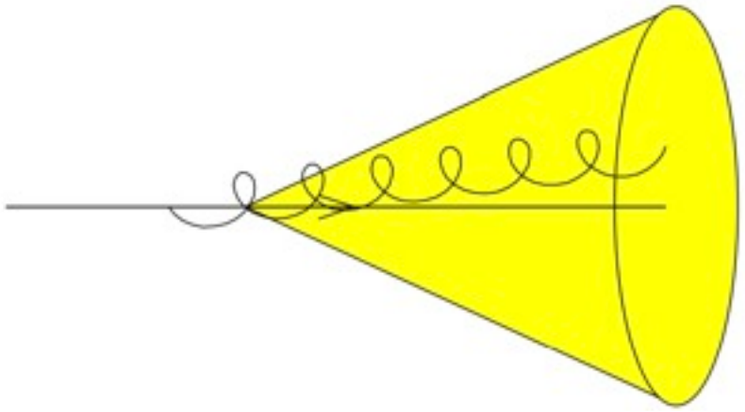
Beyond fixed order

Jet in a fixed-order NLO simulation:

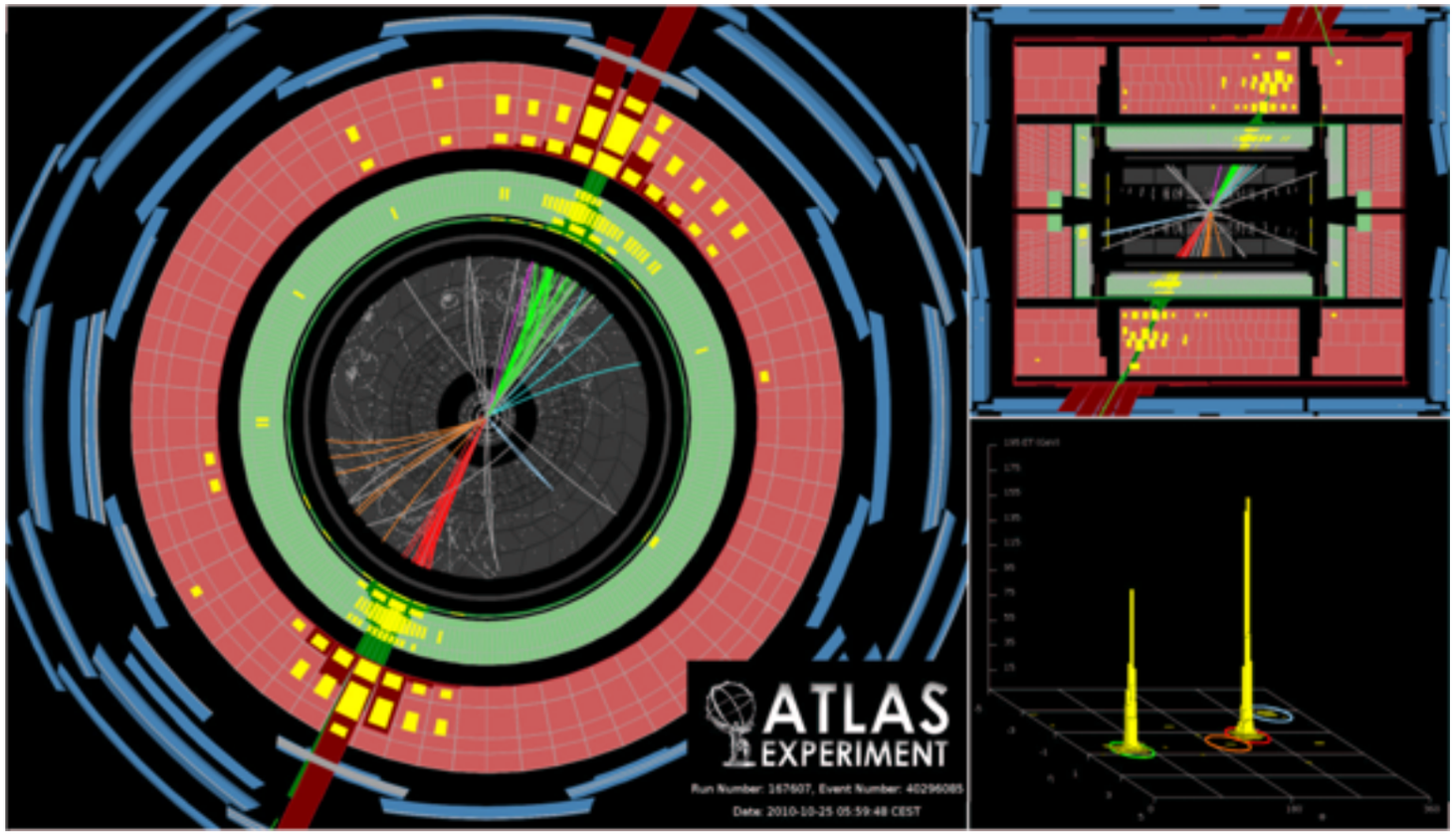


Beyond fixed order

Jet in a fixed-order NLO simulation:



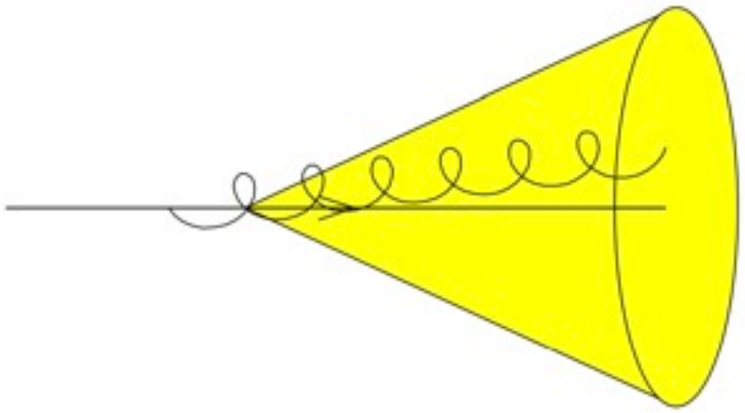
"Real" jet



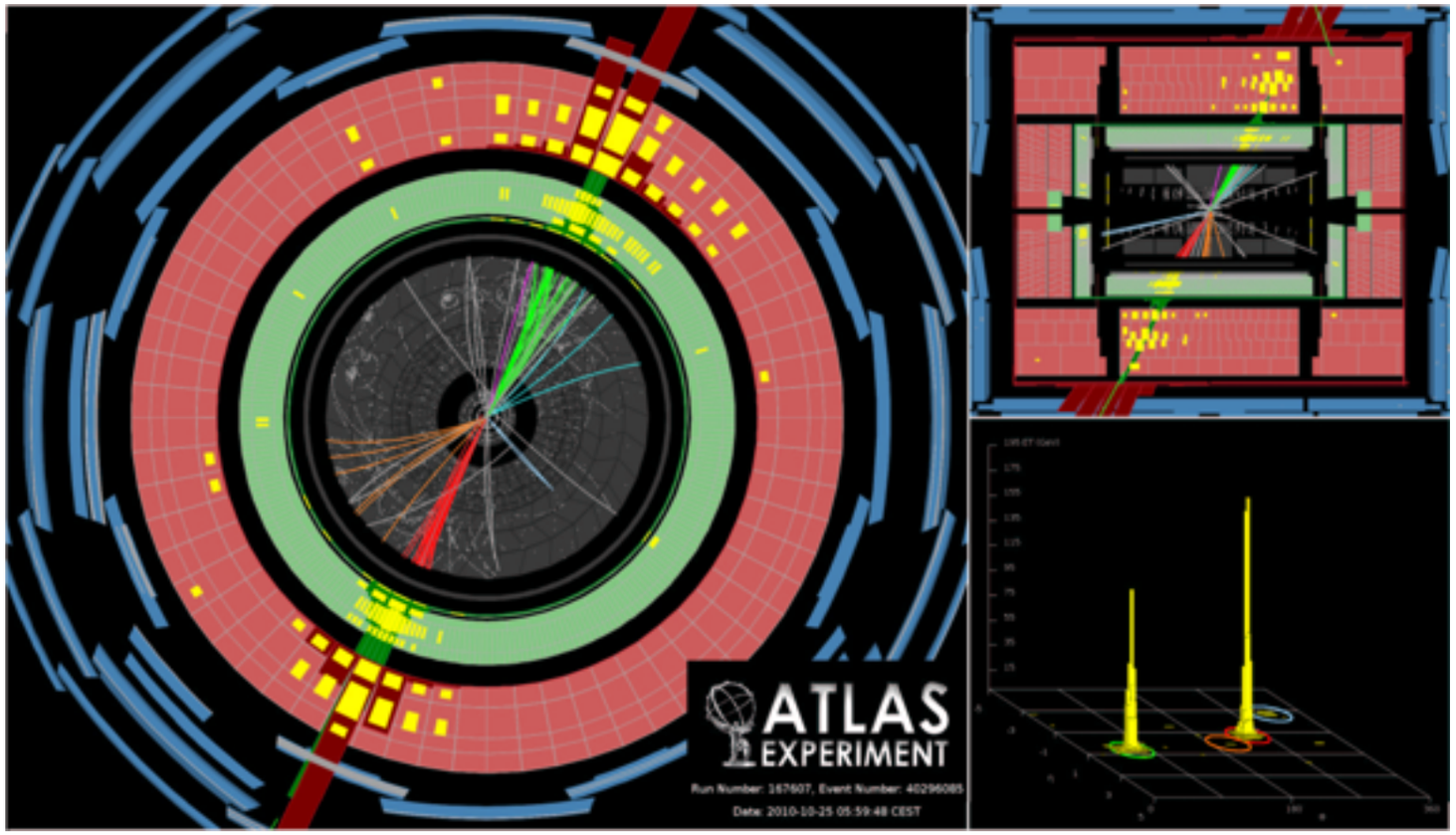
"Ouch"

Beyond fixed order

Jet in a fixed-order NLO simulation:



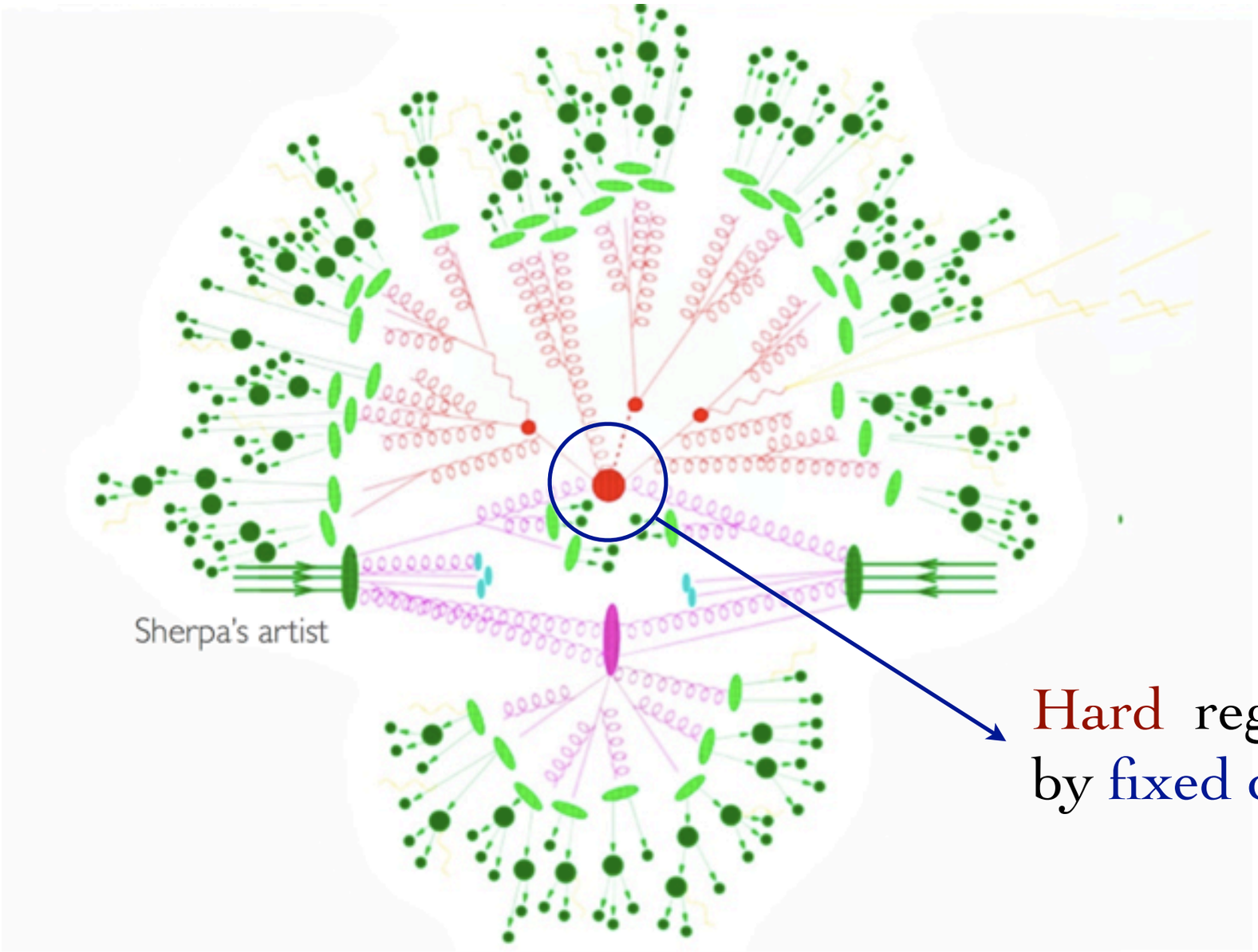
"Real" jet



"Ouch"

We need a more realistic picture...

Beyond fixed order



Hard region correctly described by fixed order simulations.

Fixed-order computations give us only part of the picture:
What about the soft regions? ☞ Parton Shower Monte Carlo

ME with PSMC

Matrix elements

1. Parton-level description
2. Fixed order expansion
3. Quantum interference exact
4. Valid when partons hard and well separated
5. Needed for multi-jet description

Parton Shower

1. Hadron-level description
2. Resums large logs
3. Only partial quantum interference (via angular ordering)
4. Valid when partons are collinear and/or soft
5. Needed for realistic studies

ME with PSMC

Matrix elements

1. Parton-level description
2. Fixed order expansion
3. Quantum interference exact
4. Valid when partons hard and well separated
5. Needed for multi-jet description

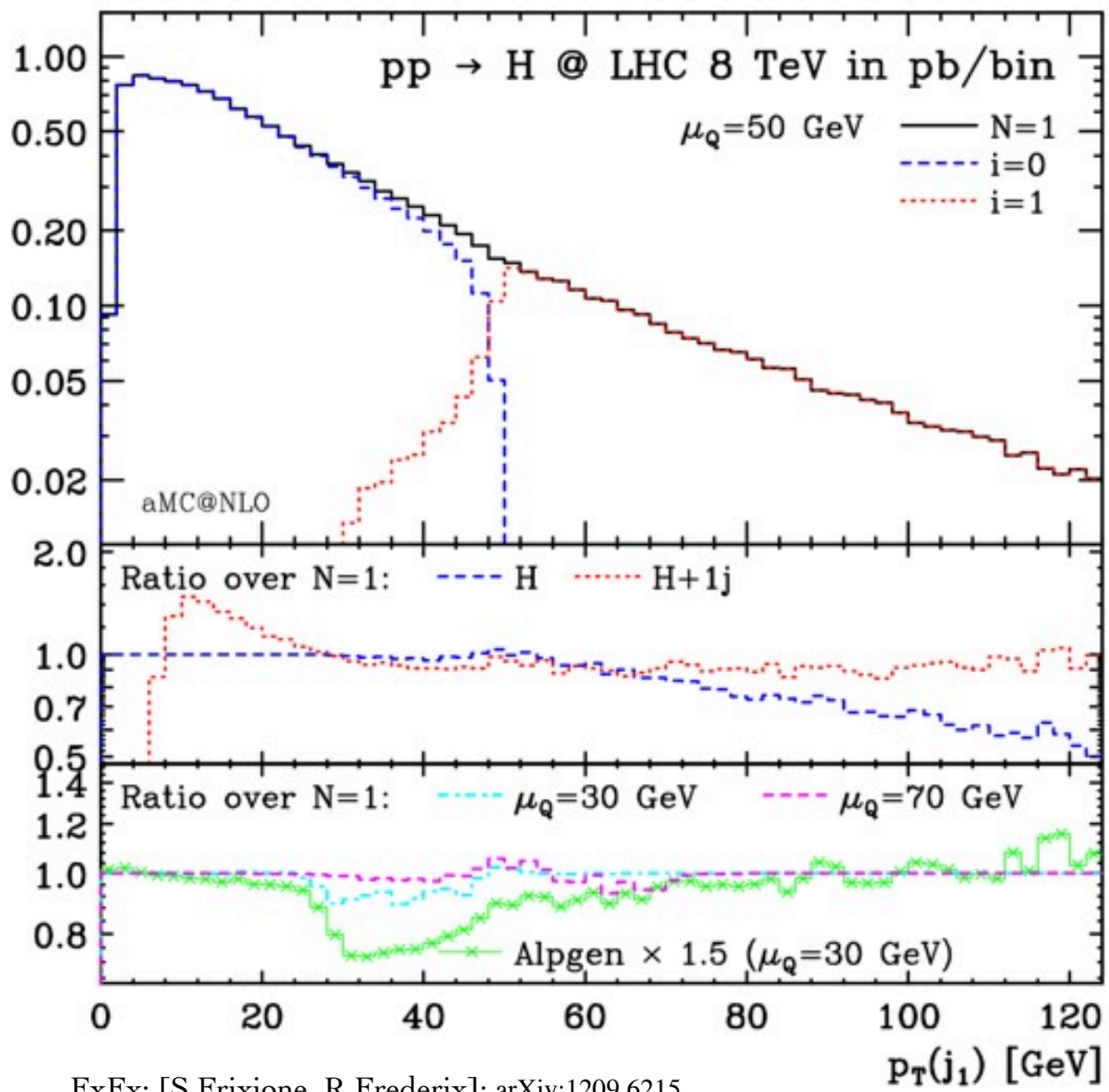
Parton Shower

1. Hadron-level description
2. Resums large logs
3. Only partial quantum interference (via angular ordering)
4. Valid when partons are collinear and/or soft
5. Needed for realistic studies

Complementary approaches: "merge/Match" them!

At LO : CKKW, MLM
At NLO : FxFx

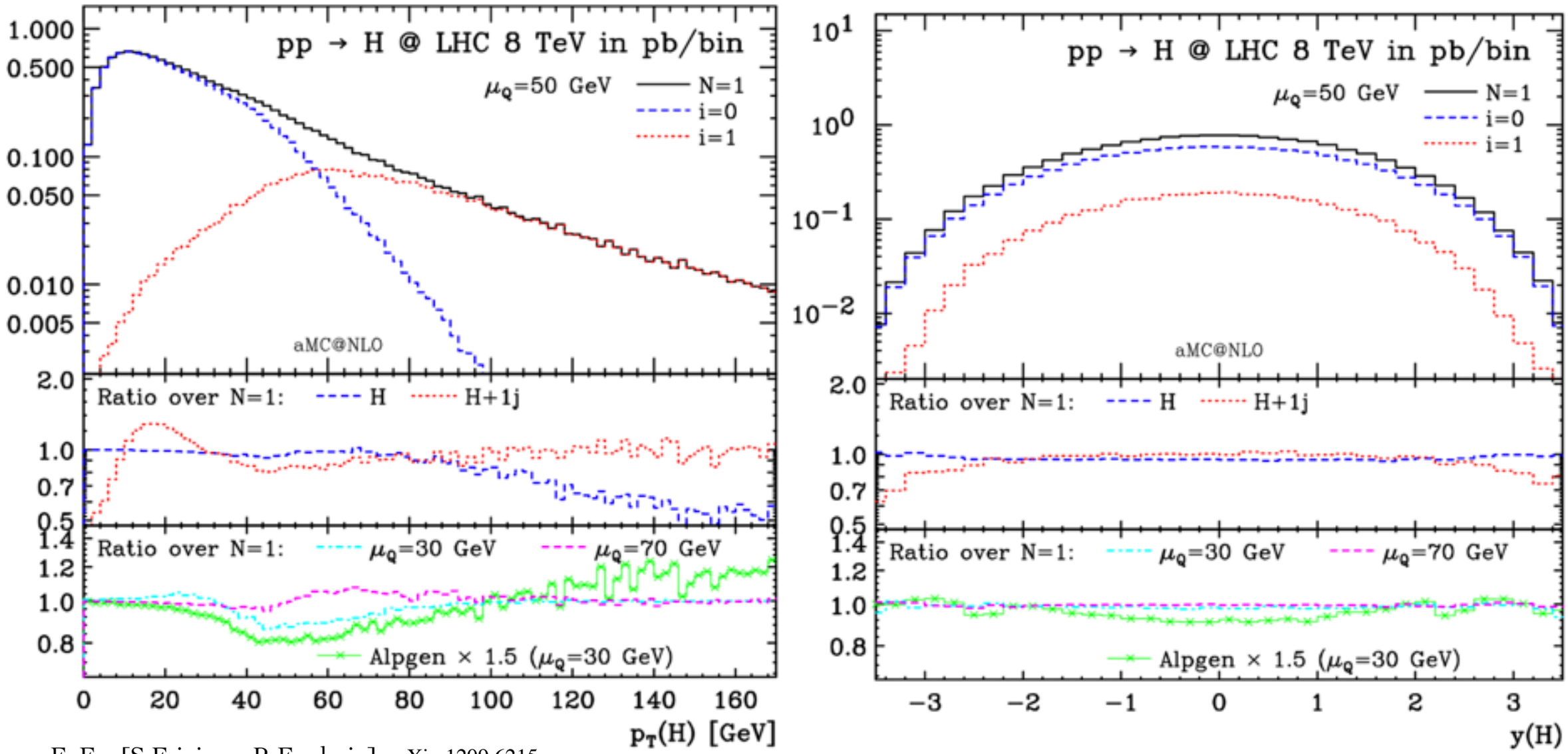
Matching meets merging



FxFx; [S.Frixione, R.Frederix]; arXiv:1209.6215

NLO reduces merging scale uncertainties

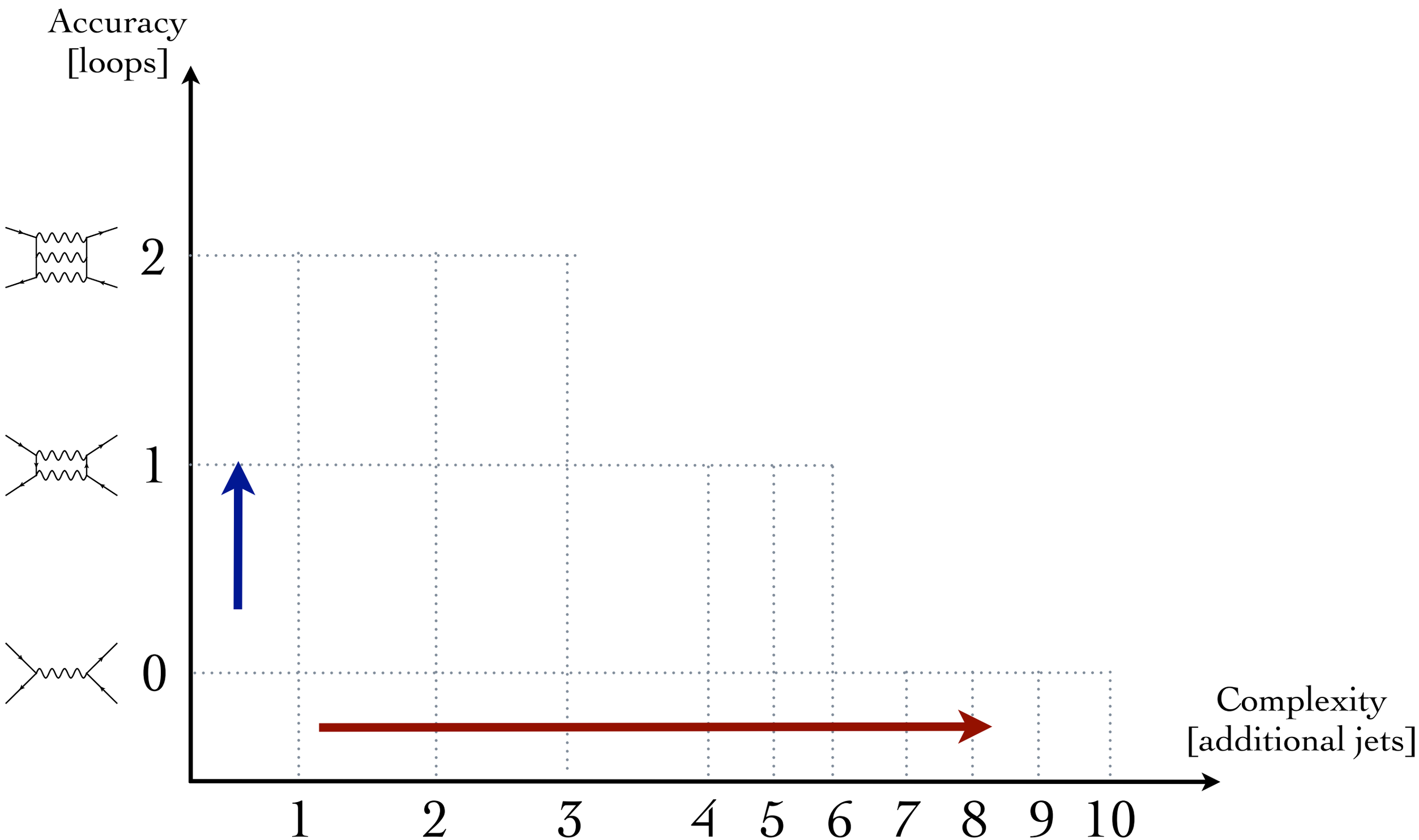
Matching meets merging



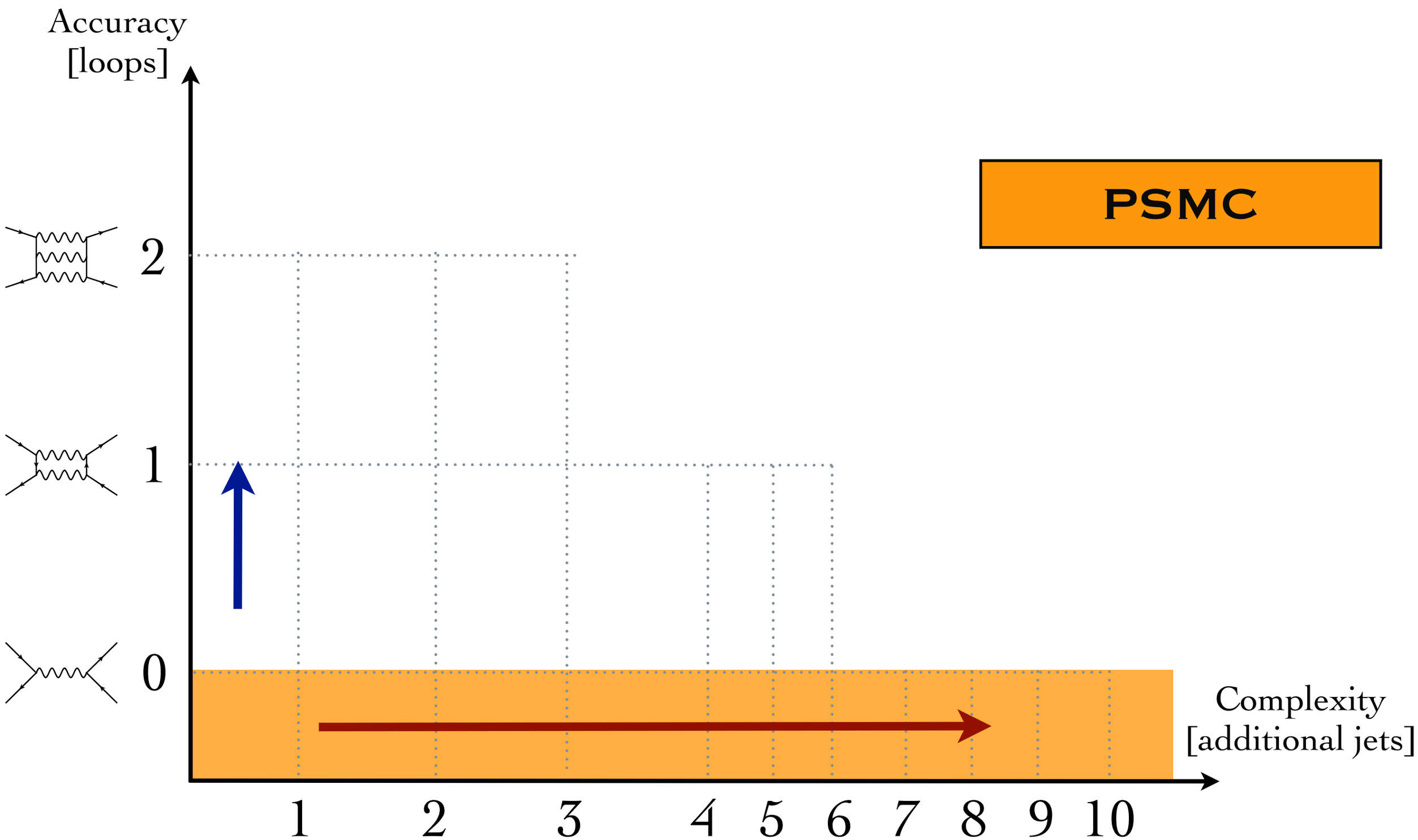
FxFx; [S.Frixione, R.Frederix]; arXiv:1209.6215

Transition across descriptions of different multiplicities not necessarily sharp.

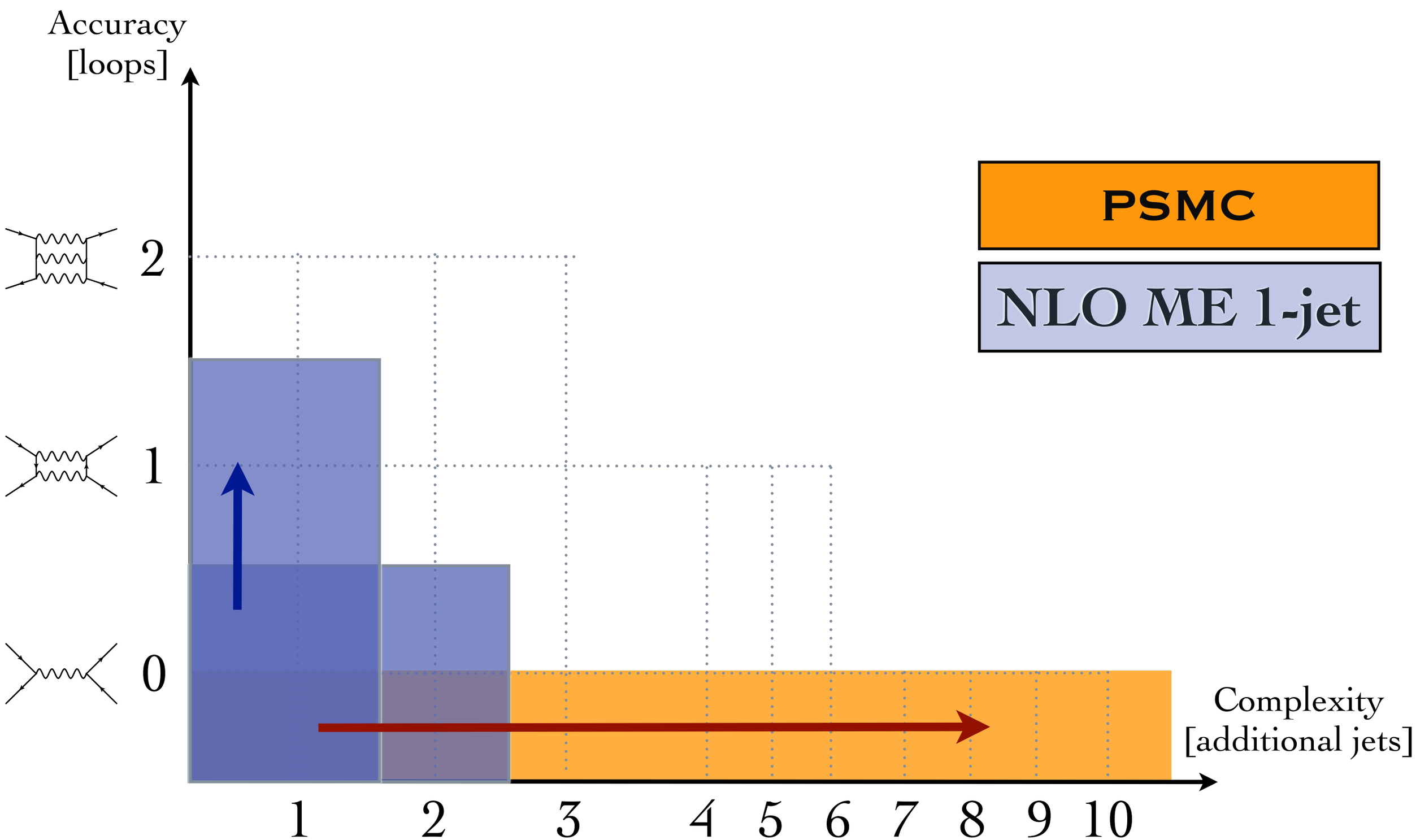
Matching meets merging



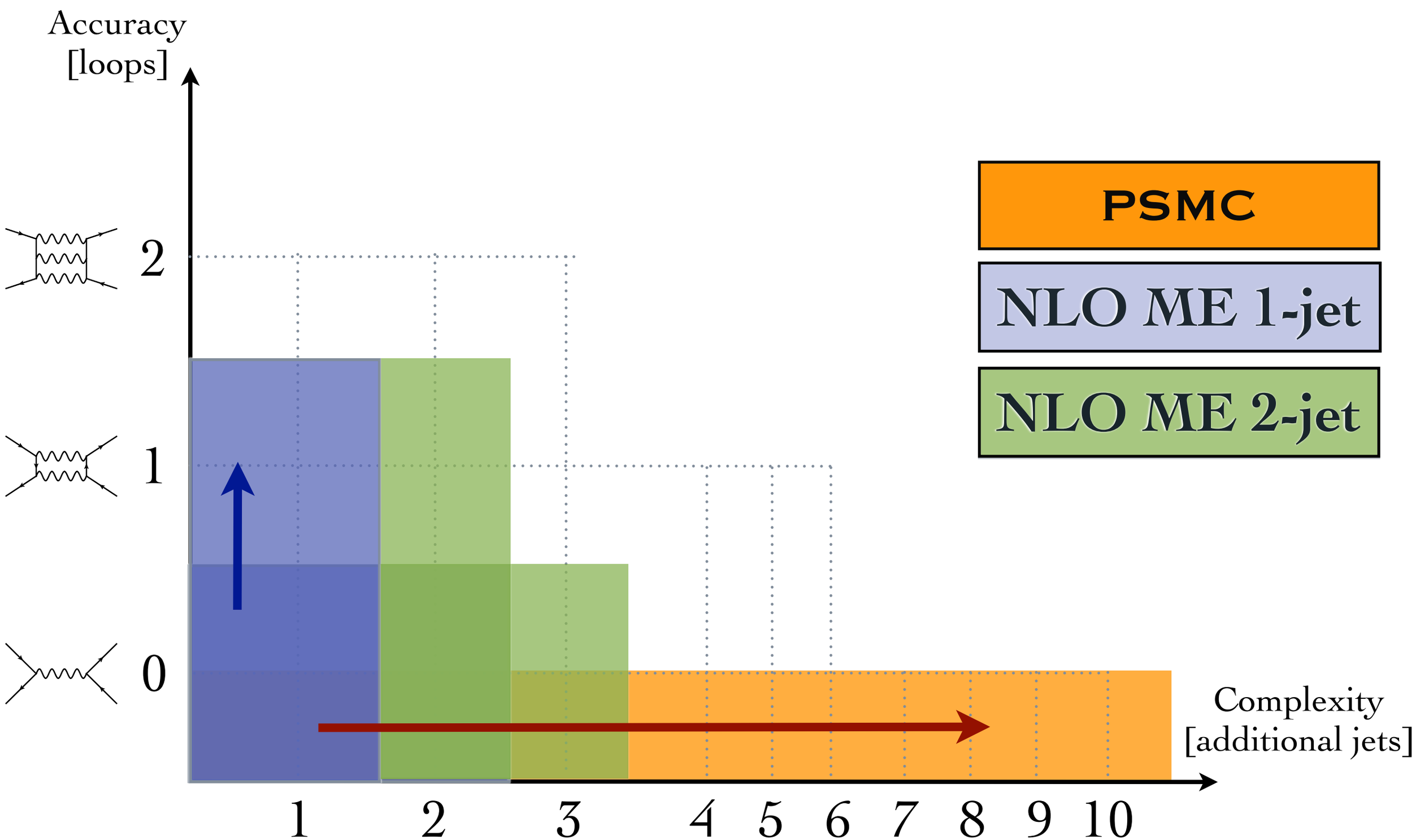
Matching meets merging



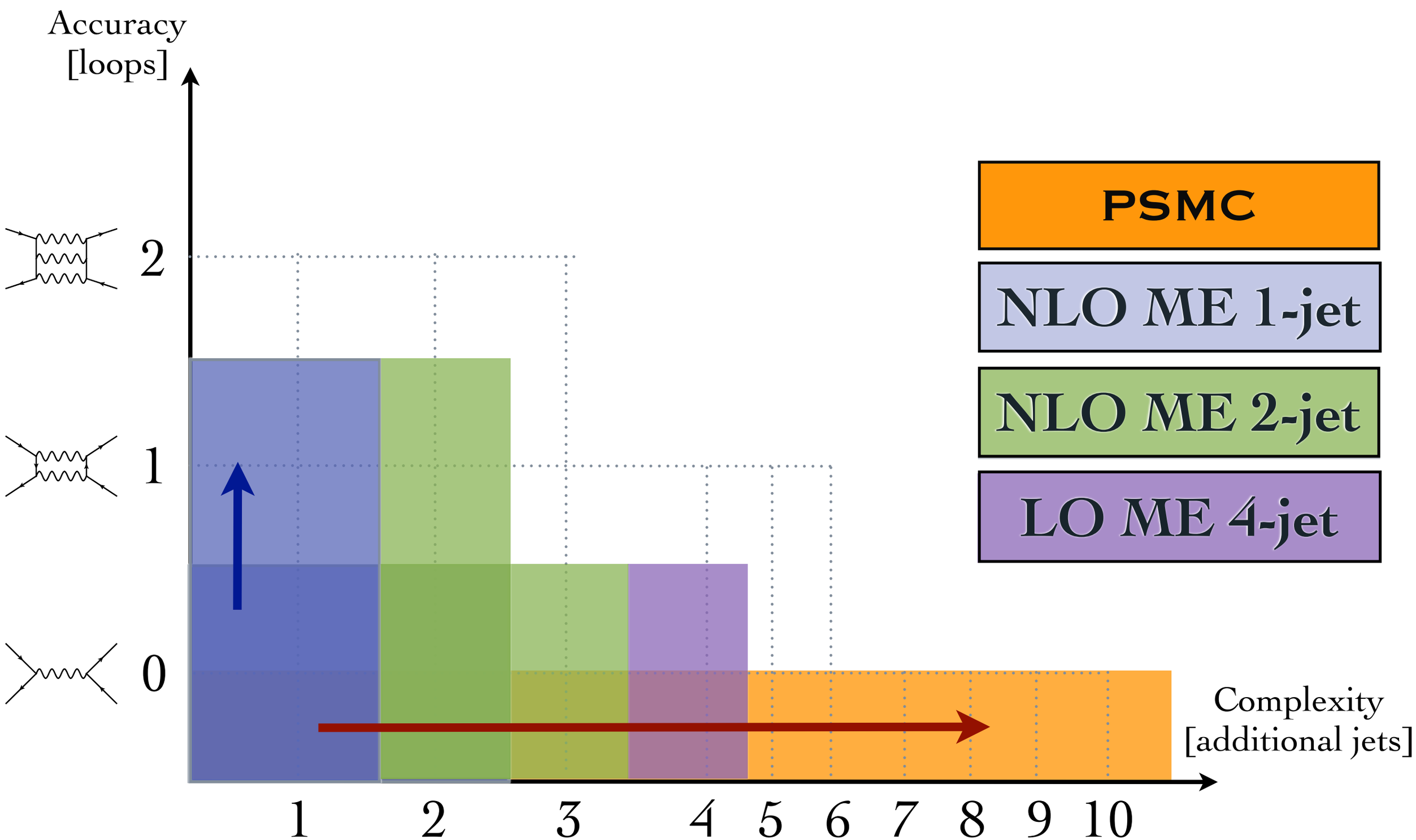
Matching meets merging



Matching meets merging



Matching meets merging



Higher ME multiplicities ?

- Better jet description

- Probing of new initial state channels opening up

- Most of the NLO impact on the shape of distributions comes from the real-emissions diagrams, *i.e.* trees

Adding Loops (i.e. using NLO ME)?

- Meaningful assessment of theoretical uncertainties with scales variation (μ_R , μ_F, μ_Q)

- Credible total rates predictions

- Necessary for parameters extraction from measurements (*i.e* precision physics)

- Treat loop-induced processes without effective theories

Need for Automation

Need for Automation

- Trees are easy and they bring most of the interesting higher order features

Need for Automation

- Trees are easy and they bring most of the interesting higher order features

- Loops and full NLO simulations in general are hard and have milder effects.

Need for Automation

- Trees are easy and they bring most of the interesting higher order features

- Loops and full NLO simulations in general are hard and have milder effects.

- So, the advantage of having more precise results when also considering loops will only outweigh their considerable technical difficulties if their implementation is FULLY AUTOMATED (*i.e.* at zero human cost)

MADGRAPH5_AMC@NLO

FRIEND OF USERS

- 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:

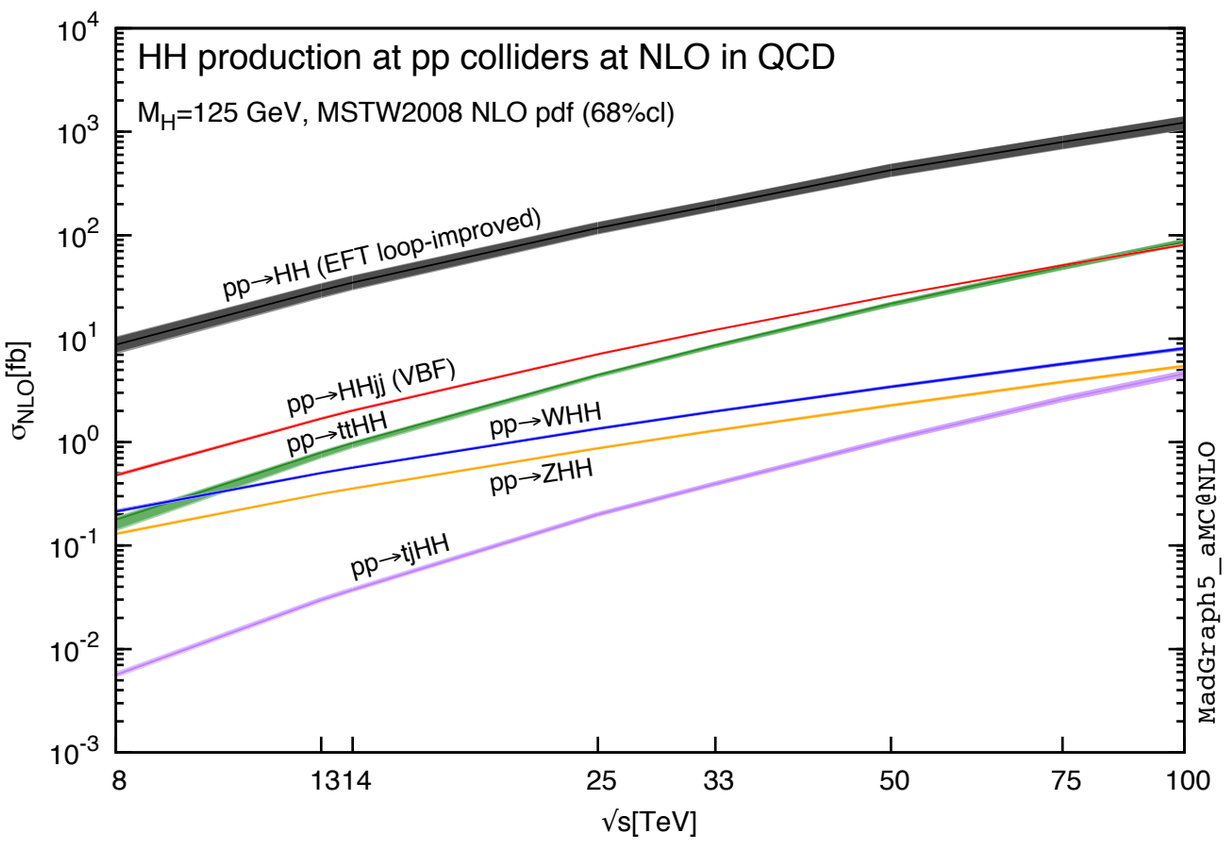
```
> generate p p > t t~ [QCD]
> output
> launch
```

  - With options specified:

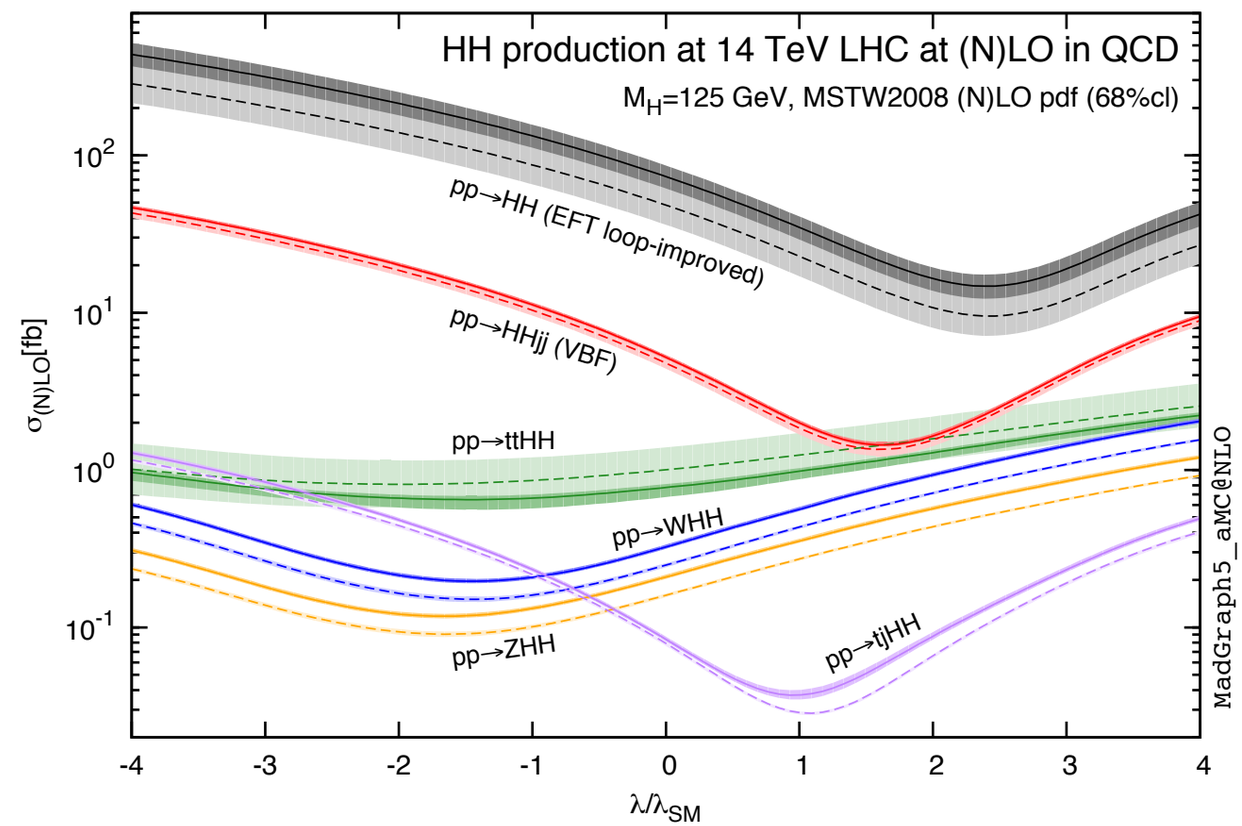
```
> import model loop_sm-no_hwidth
> set complex_mass_scheme
> generate p p  > e+ ve mu- vm~ b b~ / h QED=2 [QCD]
> output MyProc
> launch -f
```

[Frederix et al. 1401.7340]

HH production at PP colliders



Total cross sections at NLO for the various channels



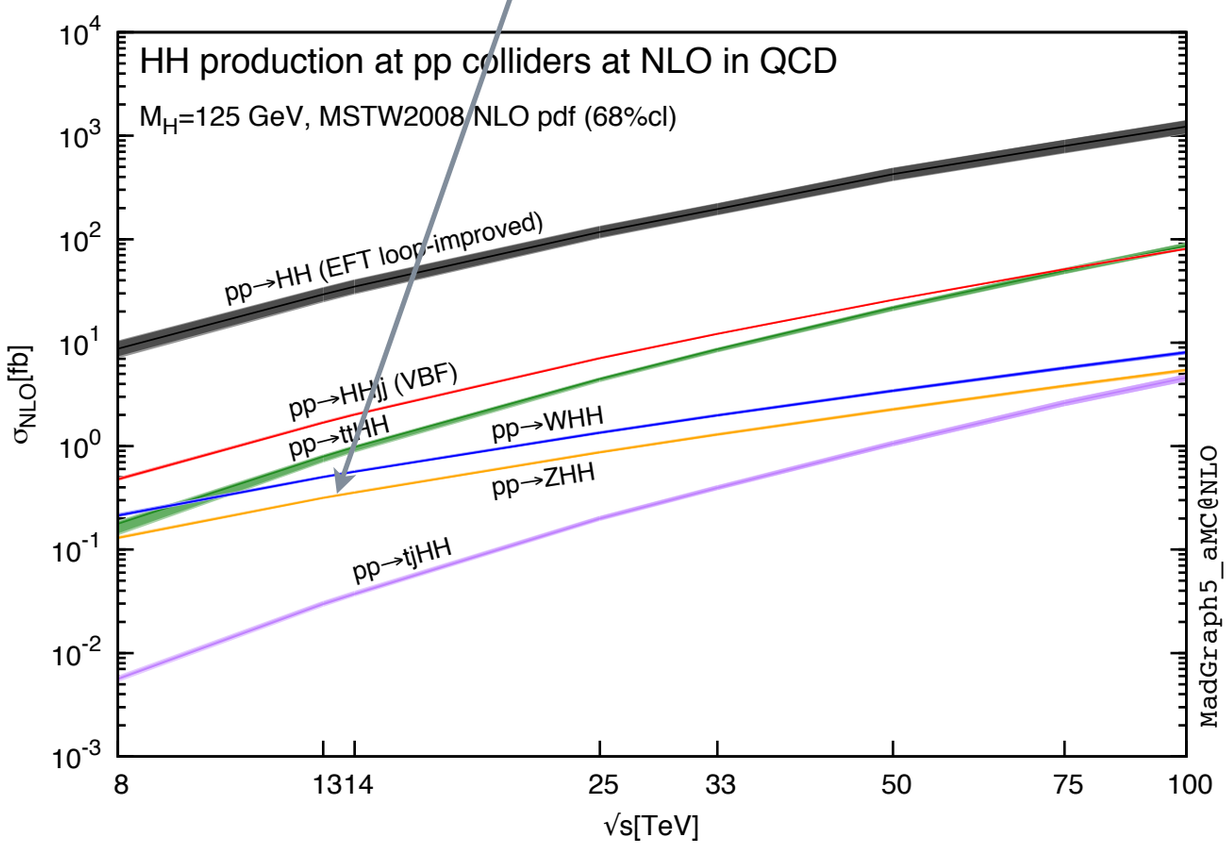
Trilinear coupling sensitivity

[Frederix et al. 1401.7340]

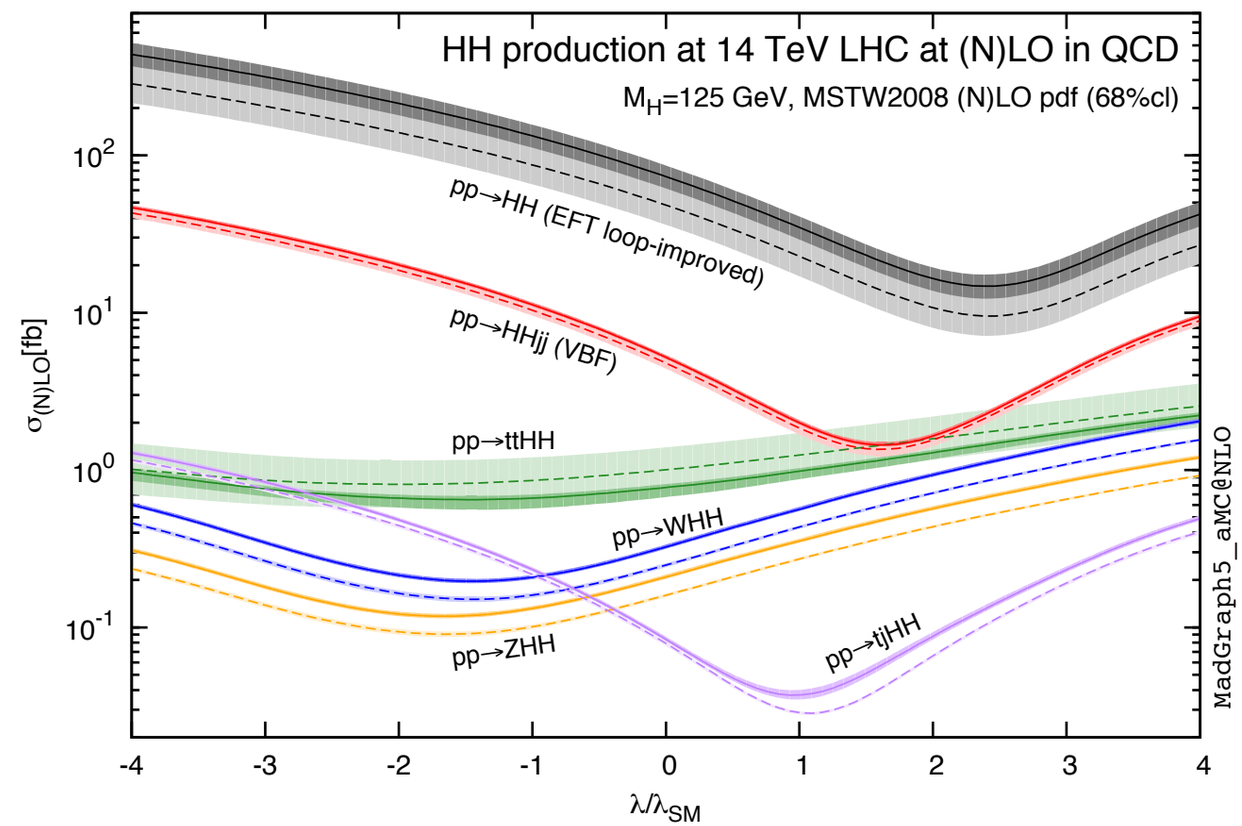
HH production at pp colliders

You don't believe this particular data point? Then just type:

```
> generate p p > z h h [QCD]
> output
> launch
```



Total cross sections at NLO for the various channels



Trilinear coupling sensitivity

[J. Alwall et al. 1405.0301]

Automatic NLO in the SM (2014)

Process		Syntax	Cross section (pb)					
Vector-boson pair +jets			LO 13 TeV			NLO 13 TeV		
b.1	$pp \to W^+W^-$ (4f)	`p p > w+ w-`	$7.355 \pm 0.005 \cdot 10^1$	$^{+5.0\%}_{-6.1\%}$	$^{+2.0\%}_{-1.5\%}$	$1.028 \pm 0.003 \cdot 10^2$	$^{+4.0\%}_{-4.5\%}$	$^{+1.9\%}_{-1.4\%}$
b.2	$pp \to ZZ$	`p p > z z`	$1.097 \pm 0.002 \cdot 10^1$	$^{+4.5\%}_{-5.6\%}$	$^{+1.9\%}_{-1.5\%}$	$1.415 \pm 0.005 \cdot 10^1$	$^{+3.1\%}_{-3.7\%}$	$^{+1.8\%}_{-1.4\%}$
b.3	$pp \to ZW^\pm$	`p p > z wpm`	$2.777 \pm 0.003 \cdot 10^1$	$^{+3.6\%}_{-4.7\%}$	$^{+2.0\%}_{-1.5\%}$	$4.487 \pm 0.013 \cdot 10^1$	$^{+4.4\%}_{-4.4\%}$	$^{+1.7\%}_{-1.3\%}$
b.4	$pp \to \gamma\gamma$	`p p > a a`	$2.510 \pm 0.002 \cdot 10^1$	$^{+22.1\%}_{-22.4\%}$	$^{+2.4\%}_{-2.1\%}$	$6.593 \pm 0.021 \cdot 10^1$	$^{+17.6\%}_{-18.8\%}$	$^{+2.0\%}_{-1.9\%}$
b.5	$pp \to \gamma Z$	`p p > a z`	$2.523 \pm 0.004 \cdot 10^1$	$^{+9.9\%}_{-11.2\%}$	$^{+2.0\%}_{-1.6\%}$	$3.695 \pm 0.013 \cdot 10^1$	$^{+5.4\%}_{-7.1\%}$	$^{+1.8\%}_{-1.4\%}$
b.6	$pp \to \gamma W^\pm$	`p p > a wpm`	$2.954 \pm 0.005 \cdot 10^1$	$^{+9.5\%}_{-11.0\%}$	$^{+2.0\%}_{-1.7\%}$	$7.124 \pm 0.026 \cdot 10^1$	$^{+9.7\%}_{-9.9\%}$	$^{+1.5\%}_{-1.3\%}$
b.7	$pp \to W^+W^-j$ (4f)	`p p > w+ w- j`	$2.865 \pm 0.003 \cdot 10^1$	$^{+11.6\%}_{-10.0\%}$	$^{+1.0\%}_{-0.8\%}$	$3.730 \pm 0.013 \cdot 10^1$	$^{+4.9\%}_{-4.9\%}$	$^{+1.1\%}_{-0.8\%}$
b.8	$pp \to ZZj$	`p p > z z j`	$3.662 \pm 0.003 \cdot 10^0$	$^{+10.9\%}_{-9.3\%}$	$^{+1.0\%}_{-0.8\%}$	$4.830 \pm 0.016 \cdot 10^0$	$^{+5.0\%}_{-4.8\%}$	$^{+1.1\%}_{-0.9\%}$
b.9	$pp \to ZW^\pm j$	`p p > z wpm j`	$1.605 \pm 0.005 \cdot 10^1$	$^{+11.6\%}_{-10.0\%}$	$^{+0.9\%}_{-0.7\%}$	$2.086 \pm 0.007 \cdot 10^1$	$^{+4.9\%}_{-4.8\%}$	$^{+0.9\%}_{-0.7\%}$
b.10	$pp \to \gamma\gamma j$	`p p > a a j`	$1.022 \pm 0.001 \cdot 10^1$	$^{+20.3\%}_{-17.7\%}$	$^{+1.2\%}_{-1.5\%}$	$2.292 \pm 0.010 \cdot 10^1$	$^{+17.2\%}_{-15.1\%}$	$^{+1.0\%}_{-1.4\%}$
b.11*	$pp \to \gamma Zj$	`p p > a z j`	$8.310 \pm 0.017 \cdot 10^0$	$^{+14.5\%}_{-12.8\%}$	$^{+1.0\%}_{-1.0\%}$	$1.220 \pm 0.005 \cdot 10^1$	$^{+7.3\%}_{-7.4\%}$	$^{+0.9\%}_{-0.9\%}$
b.12*	$pp \to \gamma W^\pm j$	`p p > a wpm j`	$2.546 \pm 0.010 \cdot 10^1$	$^{+13.7\%}_{-12.1\%}$	$^{+0.9\%}_{-1.0\%}$	$3.713 \pm 0.015 \cdot 10^1$	$^{+7.2\%}_{-7.1\%}$	$^{+0.9\%}_{-1.0\%}$
b.13	$pp \to W^+W^+jj$	`p p > w+ w+ j j`	$1.484 \pm 0.006 \cdot 10^{-1}$	$^{+25.4\%}_{-18.9\%}$	$^{+2.1\%}_{-1.5\%}$	$2.251 \pm 0.011 \cdot 10^{-1}$	$^{+10.5\%}_{-10.6\%}$	$^{+2.2\%}_{-1.6\%}$
b.14	$pp \to W^-W^-jj$	`p p > w- w- j j`	$6.752 \pm 0.007 \cdot 10^{-2}$	$^{+25.4\%}_{-18.9\%}$	$^{+2.4\%}_{-1.7\%}$	$1.003 \pm 0.003 \cdot 10^{-1}$	$^{+10.1\%}_{-10.4\%}$	$^{+2.5\%}_{-1.8\%}$
b.15	$pp \to W^+W^-jj$ (4f)	`p p > w+ w- j j`	$1.144 \pm 0.002 \cdot 10^1$	$^{+27.2\%}_{-19.9\%}$	$^{+0.7\%}_{-0.5\%}$	$1.396 \pm 0.005 \cdot 10^1$	$^{+5.0\%}_{-6.8\%}$	$^{+0.7\%}_{-0.6\%}$
b.16	$pp \to ZZjj$	`p p > z z j j`	$1.344 \pm 0.002 \cdot 10^0$	$^{+26.6\%}_{-19.6\%}$	$^{+0.7\%}_{-0.6\%}$	$1.706 \pm 0.011 \cdot 10^0$	$^{+5.8\%}_{-7.2\%}$	$^{+0.8\%}_{-0.6\%}$
b.17	$pp \to ZW^\pm jj$	`p p > z wpm j j`	$8.038 \pm 0.009 \cdot 10^0$	$^{+26.7\%}_{-19.7\%}$	$^{+0.7\%}_{-0.5\%}$	$9.139 \pm 0.031 \cdot 10^0$	$^{+3.1\%}_{-5.1\%}$	$^{+0.7\%}_{-0.5\%}$
b.18	$pp \to \gamma\gamma jj$	`p p > a a j j`	$5.377 \pm 0.029 \cdot 10^0$	$^{+26.2\%}_{-19.8\%}$	$^{+0.6\%}_{-1.0\%}$	$7.501 \pm 0.032 \cdot 10^0$	$^{+8.8\%}_{-10.1\%}$	$^{+0.6\%}_{-1.0\%}$
b.19*	$pp \to \gamma Zjj$	`p p > a z j j`	$3.260 \pm 0.009 \cdot 10^0$	$^{+24.3\%}_{-18.4\%}$	$^{+0.6\%}_{-0.6\%}$	$4.242 \pm 0.016 \cdot 10^0$	$^{+6.5\%}_{-7.3\%}$	$^{+0.6\%}_{-0.6\%}$
b.20*	$pp \to \gamma W^\pm jj$	`p p > a wpm j j`	$1.233 \pm 0.002 \cdot 10^1$	$^{+24.7\%}_{-18.6\%}$	$^{+0.6\%}_{-0.6\%}$	$1.448 \pm 0.005 \cdot 10^1$	$^{+3.6\%}_{-5.4\%}$	$^{+0.6\%}_{-0.7\%}$

Etc...

Selected developments in MadGraph5_aMC@NLO

(E)W corrections

(E)W corrections

- Does not always matter, but here is an example of where it does:

Numerical values

The best-fit results for independent signal strengths corresponding to the four main production processes, ggH, VBF, VH, and ttH; the expected sensitivities and observed significances with respect to background-only hypothesis ($\mu = 0$), and the pull of the observation with respect to the SM hypothesis ($\mu = 1$). These results assume that the relative values of the branching fractions are those predicted by the SM.

Parameter	Best fit result (68% CL) for full combination	Observed significance (σ)	Expected sensitivity (σ)	Pull to SM hypothesis (σ)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
μ_{VBF}	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
μ_{VH}	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0.0
μ_{ttH}	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1

(E)W corrections

- Does not always matter, but here is an example of where it does:

Numerical values

The best-fit results for independent signal strengths corresponding to the four main production processes, ggH, VBF, VH, and ttH; the expected sensitivities and observed significances with respect to background-only hypothesis ($\mu = 0$), and the pull of the observation with respect to the SM hypothesis ($\mu = 1$). These results assume that the relative values of the branching fractions are those predicted by the SM.

Parameter	Best fit result (68% CL) for full combination	Observed significance (σ)	Expected sensitivity (σ)	Pull to SM hypothesis (σ)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
μ_{VBF}	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
μ_{VH}	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0.0
μ_{ttH}	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1

- Need good probe for ttH; also ttZ recently observed at 3.1σ :

$$\sigma_{t\bar{t}Z} = 200^{+80}_{-70}(stat)^{+40}_{-30}(syst)fb$$

[arXiv: 1406.7830]

(E)W corrections

- Does not always matter, but here is an example of where it does:

Numerical values

The best-fit results for independent signal strengths corresponding to the four main production processes, ggH, VBF, VH, and ttH; the expected sensitivities and observed significances with respect to background-only hypothesis ($\mu = 0$), and the pull of the observation with respect to the SM hypothesis ($\mu = 1$). These results assume that the relative values of the branching fractions are those predicted by the SM.

Parameter	Best fit result (68% CL) for full combination	Observed significance (σ)	Expected sensitivity (σ)	Pull to SM hypothesis (σ)
μ_{ggH}	$0.85^{+0.19}_{-0.17}$	6.5	7.5	-0.8
μ_{VBF}	$1.15^{+0.37}_{-0.35}$	3.6	3.3	0.4
μ_{VH}	$1.00^{+0.40}_{-0.40}$	2.7	2.7	0.0
μ_{ttH}	$2.93^{+1.04}_{-0.97}$	3.5	1.2	2.1

- Need good probe for ttH; also ttZ recently observed at 3.1σ :

$$\sigma_{t\bar{t}Z} = 200^{+80}_{-70}(stat)^{+40}_{-30}(syst)fb$$

[arXiv: 1406.7830]

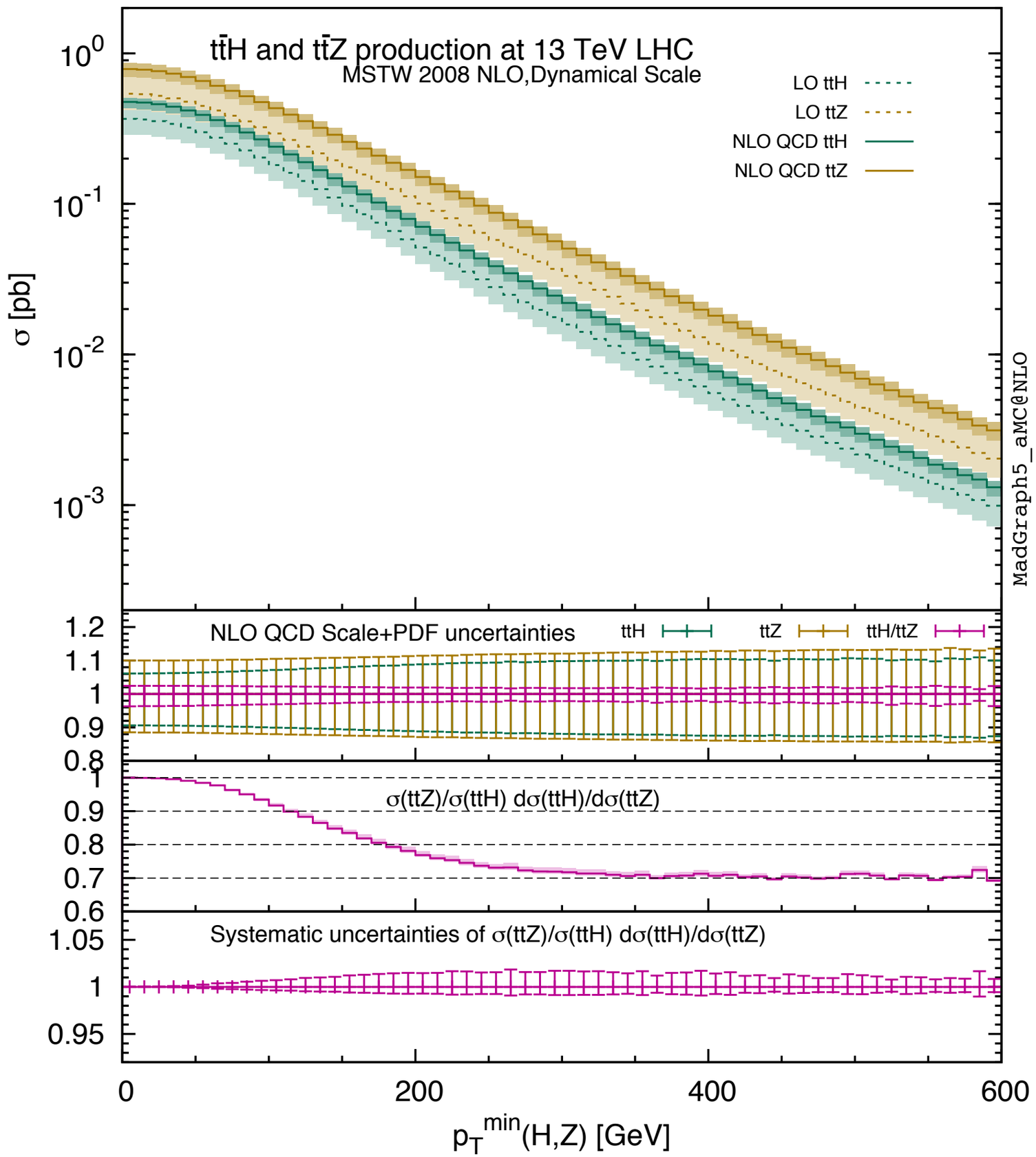
- Harvest on these rare processes, using the ratio ttH/ttZ as a probe for the top yukawa!

Weak corrections

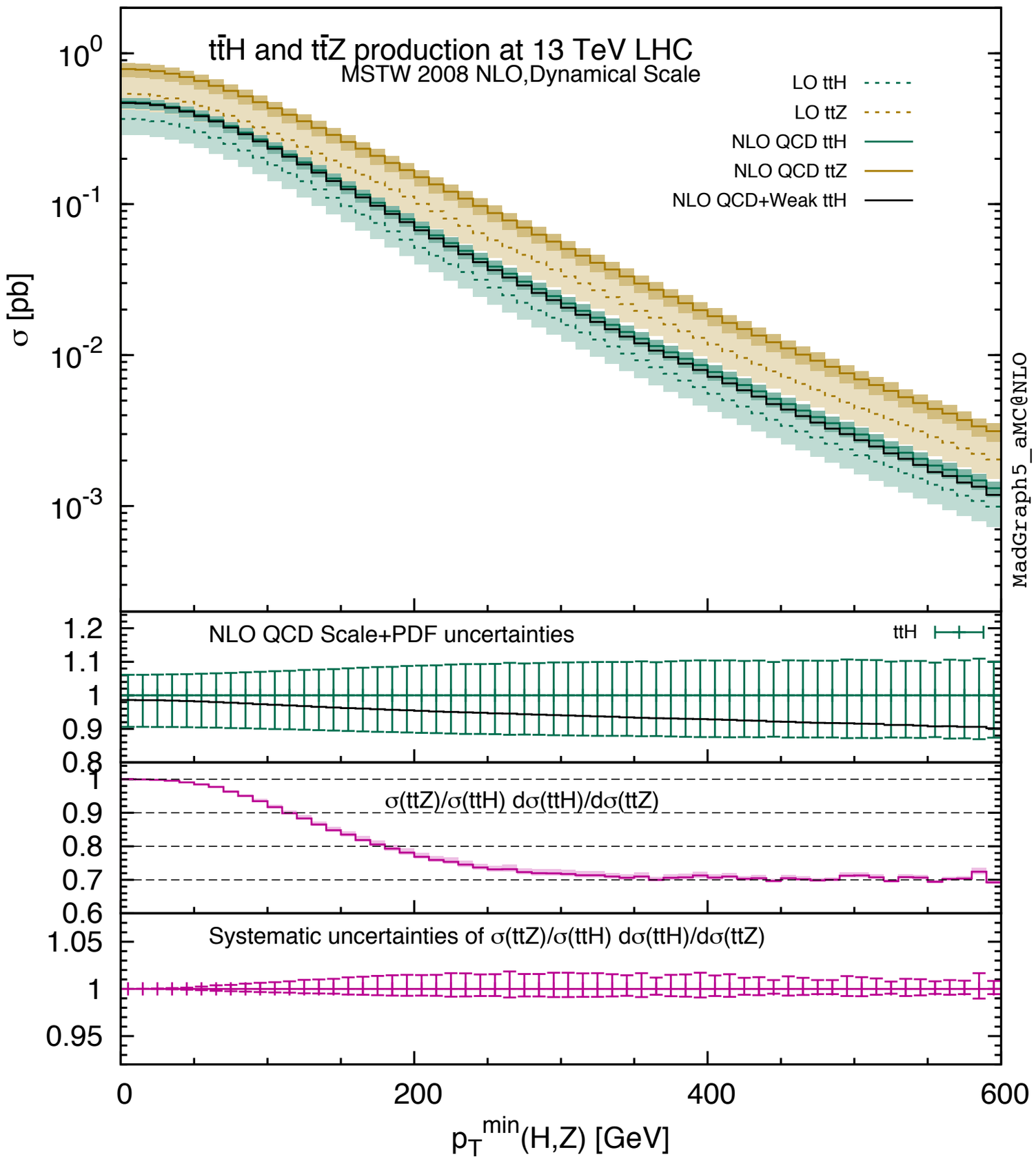
- Why the ratio? Same production mechanism for the dominating g g channel, scale dependences and corrections drop:

MSTW2008NLO, $\mu_0 = H_T/2$*, LHC13*

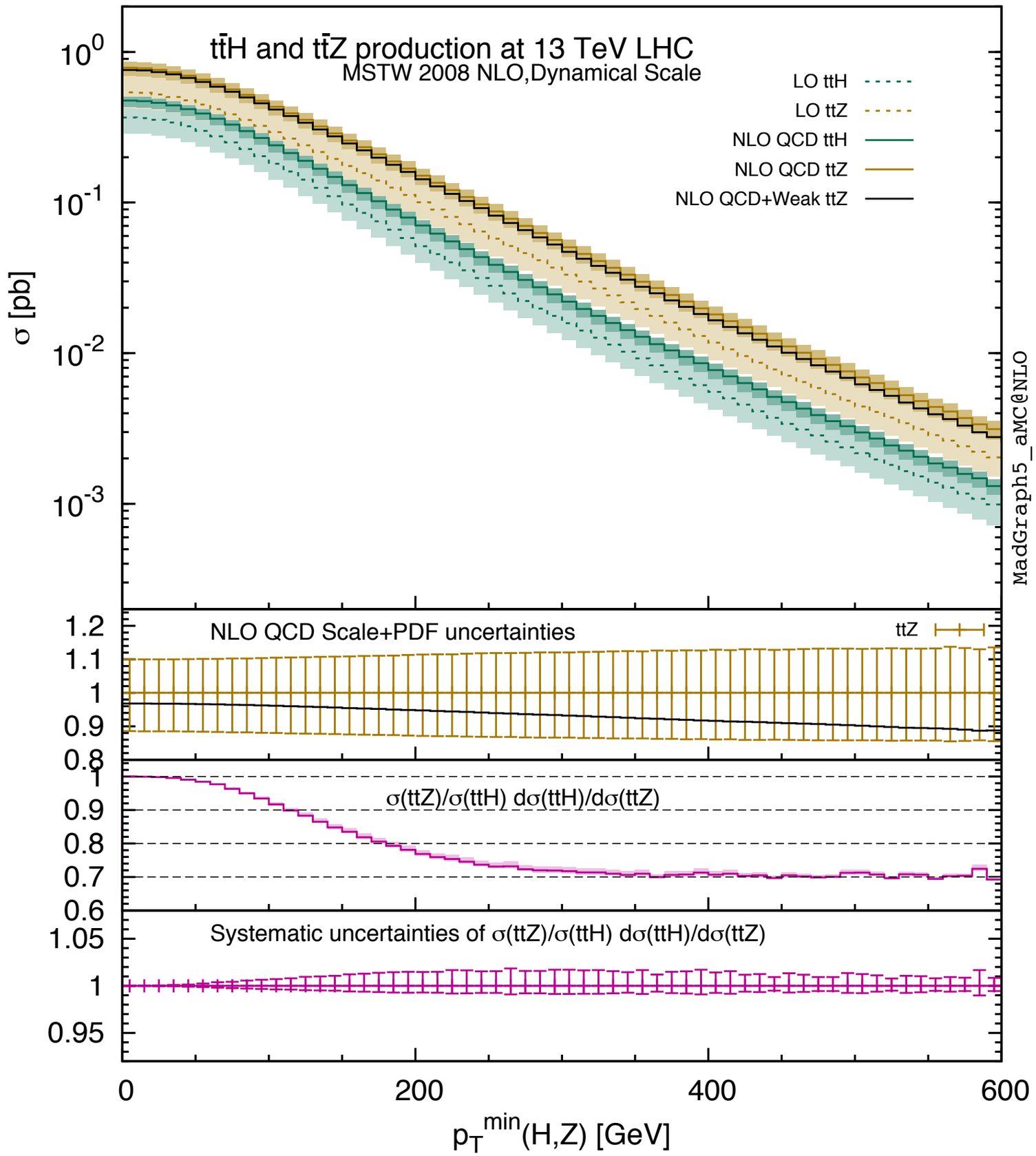
	ttH (pb)	ttZ (pb)	**ttH / ttZ**
LO	0.367 $[^{+30.0\%}_{-21.5\%}]$Scale $[^{+1.78\%}_{-2.18\%}]$PDF	0.540 $[^{+30.5\%}_{-21.8\%}]$Scale $[^{+1.83\%}_{-2.25\%}]$PDF	**0.682** $[^{+0.361\%}_{-0.446\%}]$**Scale +PDF**
NLO QCD	0.475 $[^{+5.79\%}_{-9.04\%}]$Scale $[^{+2.02\%}_{-2.50\%}]$PDF	0.785 $[^{+9.81\%}_{-11.2\%}]$Scale $[^{+1.93\%}_{-2.39\%}]$PDF	**0.606** $[^{+2.46\%}_{-3.66\%}]$**Scale+PDF**
Weak	-0.00659	-0.0252	**0.263**



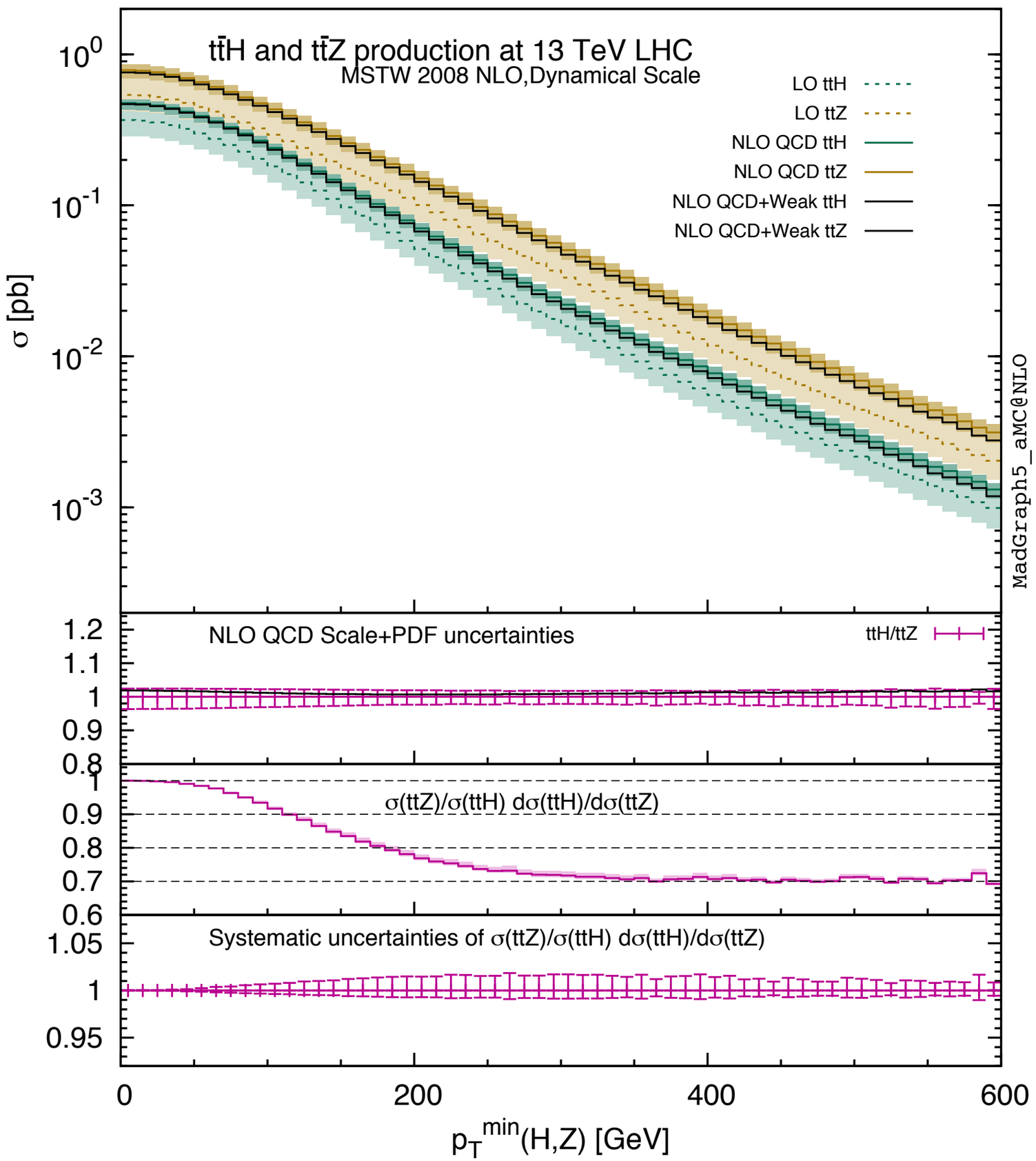
- QCD corrections + ratio reduce theoretical uncertainties by a lot.



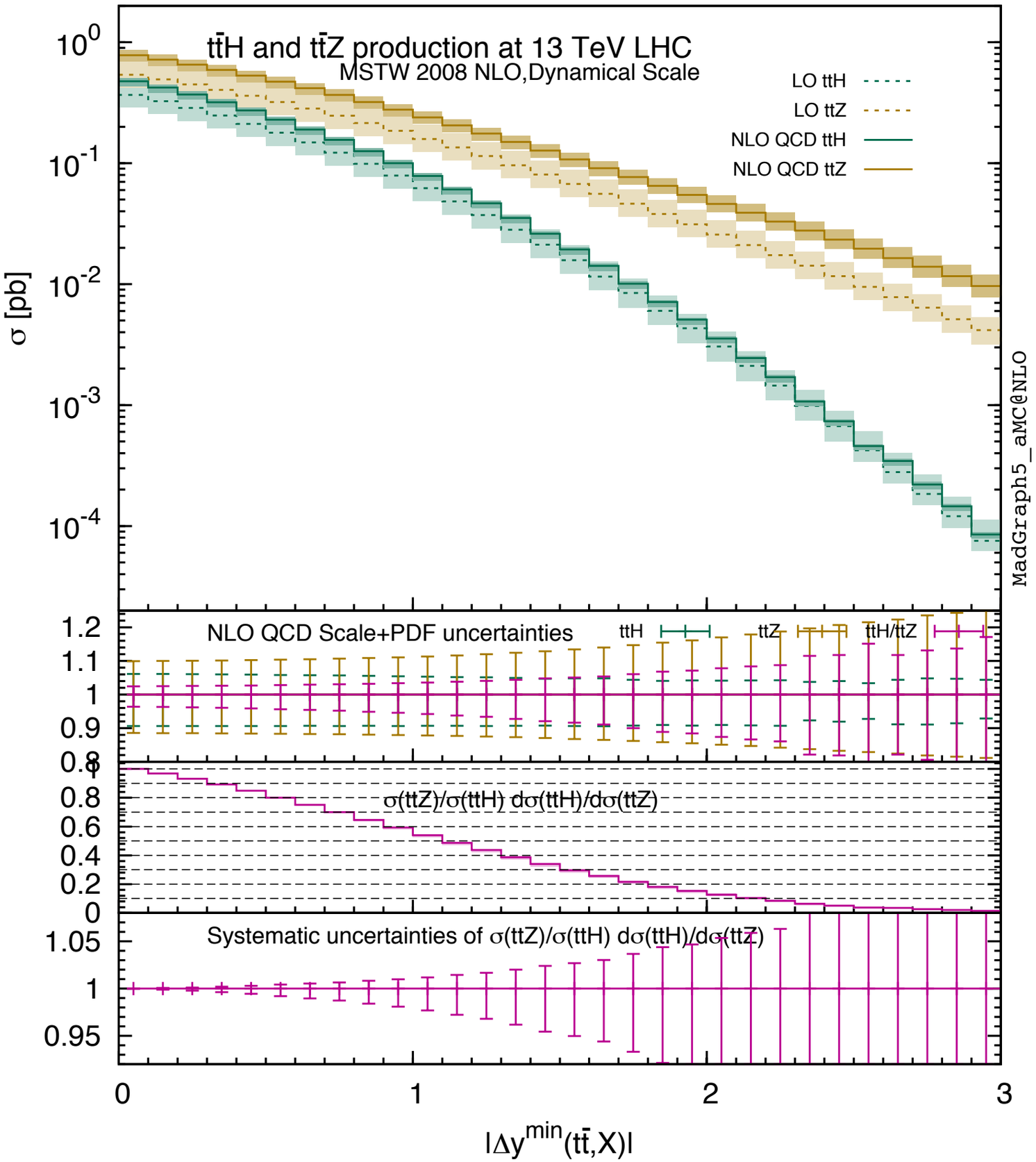
- QCD corrections + ratio reduce theoretical uncertainties by a lot.

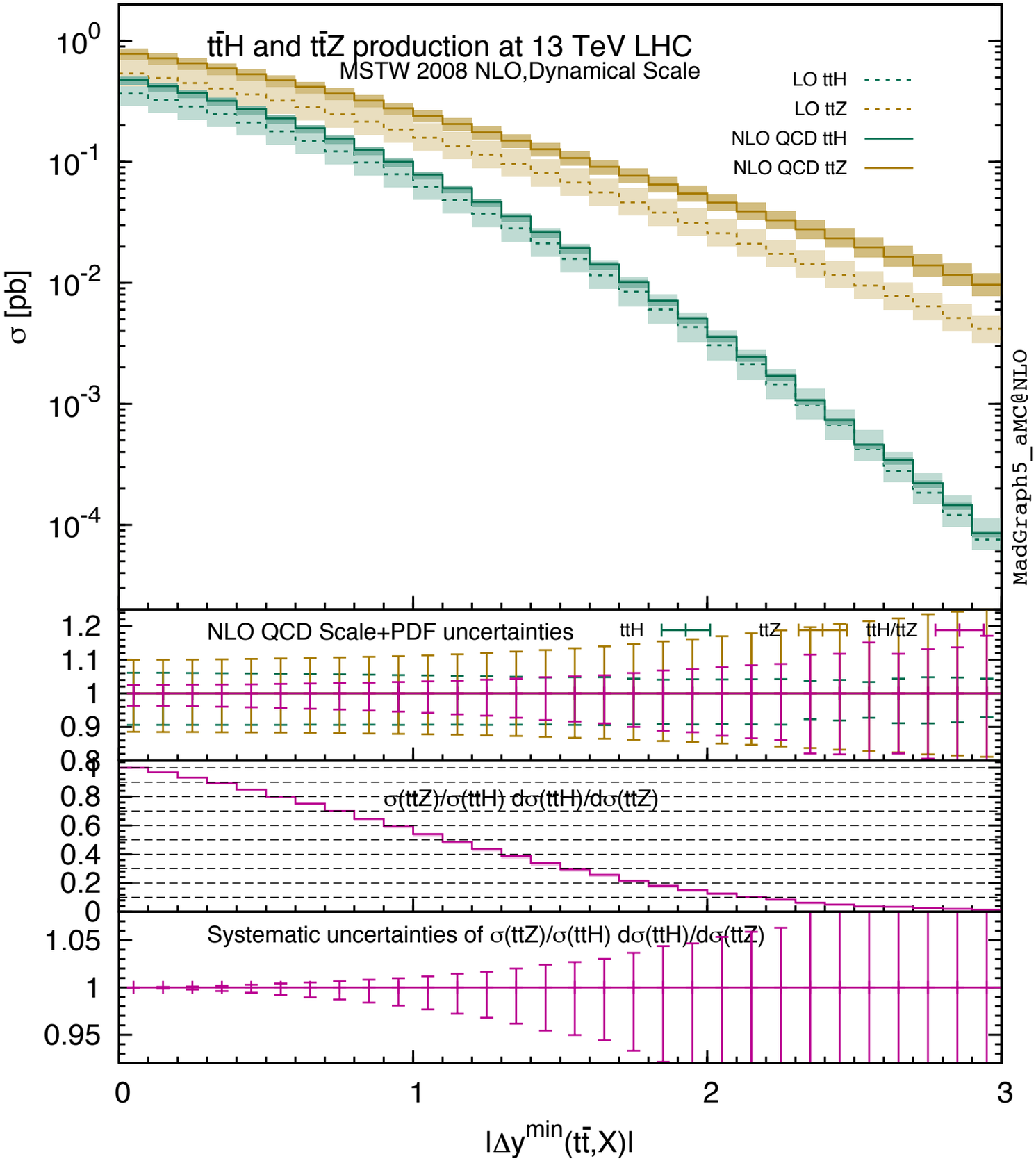


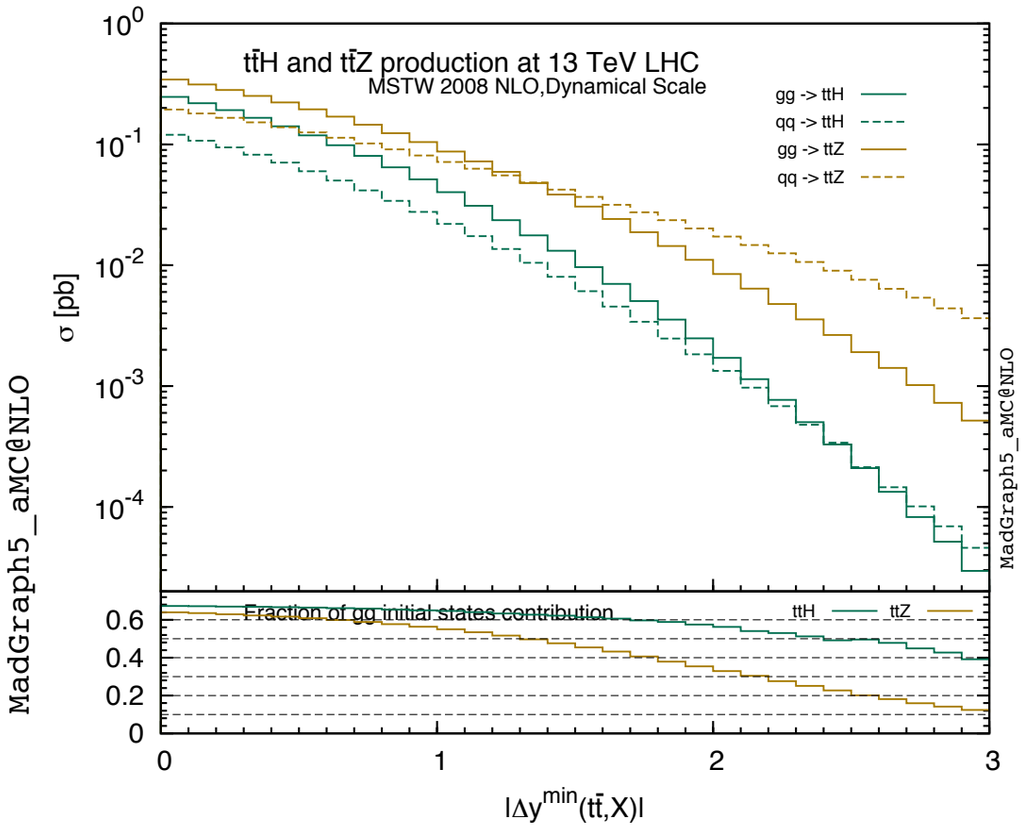
- QCD corrections + ratio reduce theoretical uncertainties by a lot.



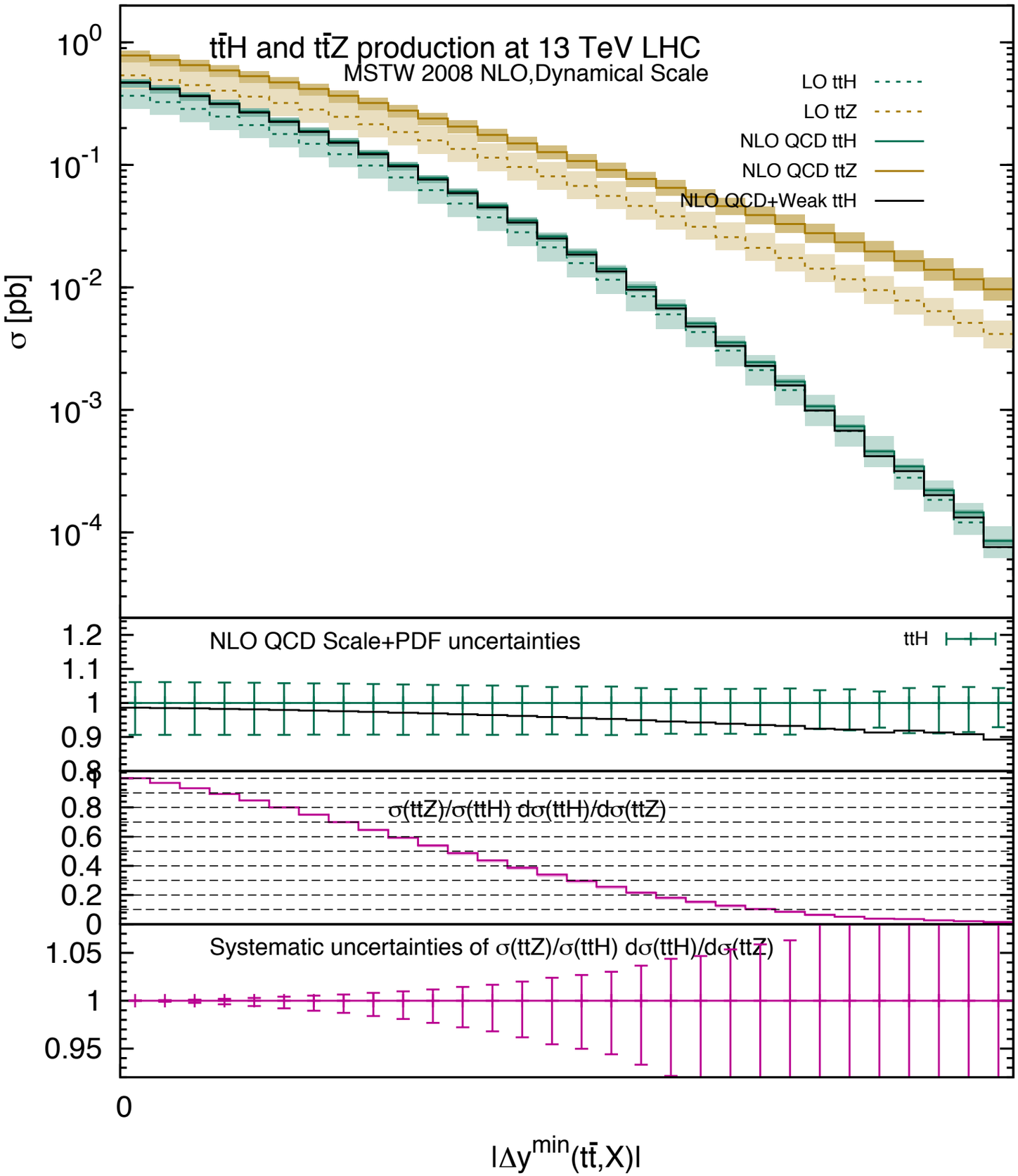
- QCD corrections + ratio reduce theoretical uncertainties by a lot.
- Weak corrections are only important in the boost region for ttH as well as ttZ.
- Weak corrections are important (~syst. uncer.) in the ratio.

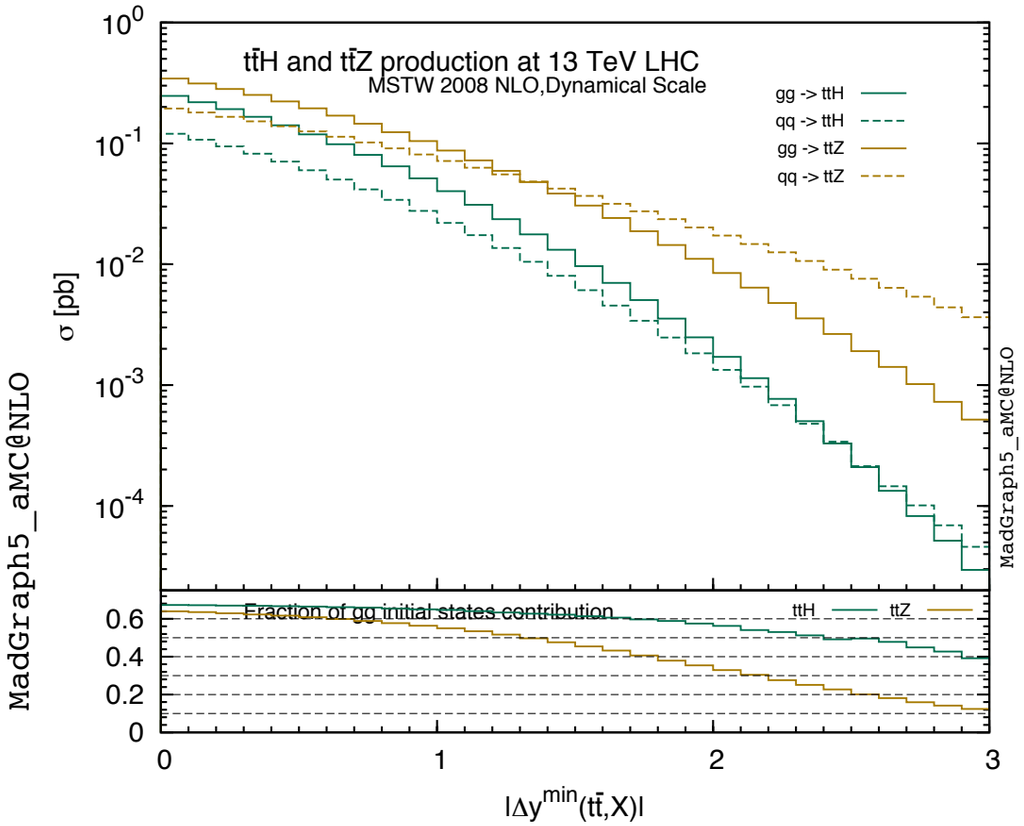

$t\bar{t}H$ and $t\bar{t}Z$ production at 13 TeV LHC
MSTW 2008 NLO,Dynamical Scale
LO ttH
LO ttZ
NLO QCD ttH
NLO QCD ttZ
σ [pb]
MadGraph5_aMC@NLO
NLO QCD Scale+PDF uncertainties
ttH
ttZ
ttH/ttZ
σ(ttZ)/σ(ttH) dσ(ttH)/dσ(ttZ)
Systematic uncertainties of σ(ttZ)/σ(ttH) dσ(ttH)/dσ(ttZ)
$|\Delta y^{min}(t\bar{t},X)|$



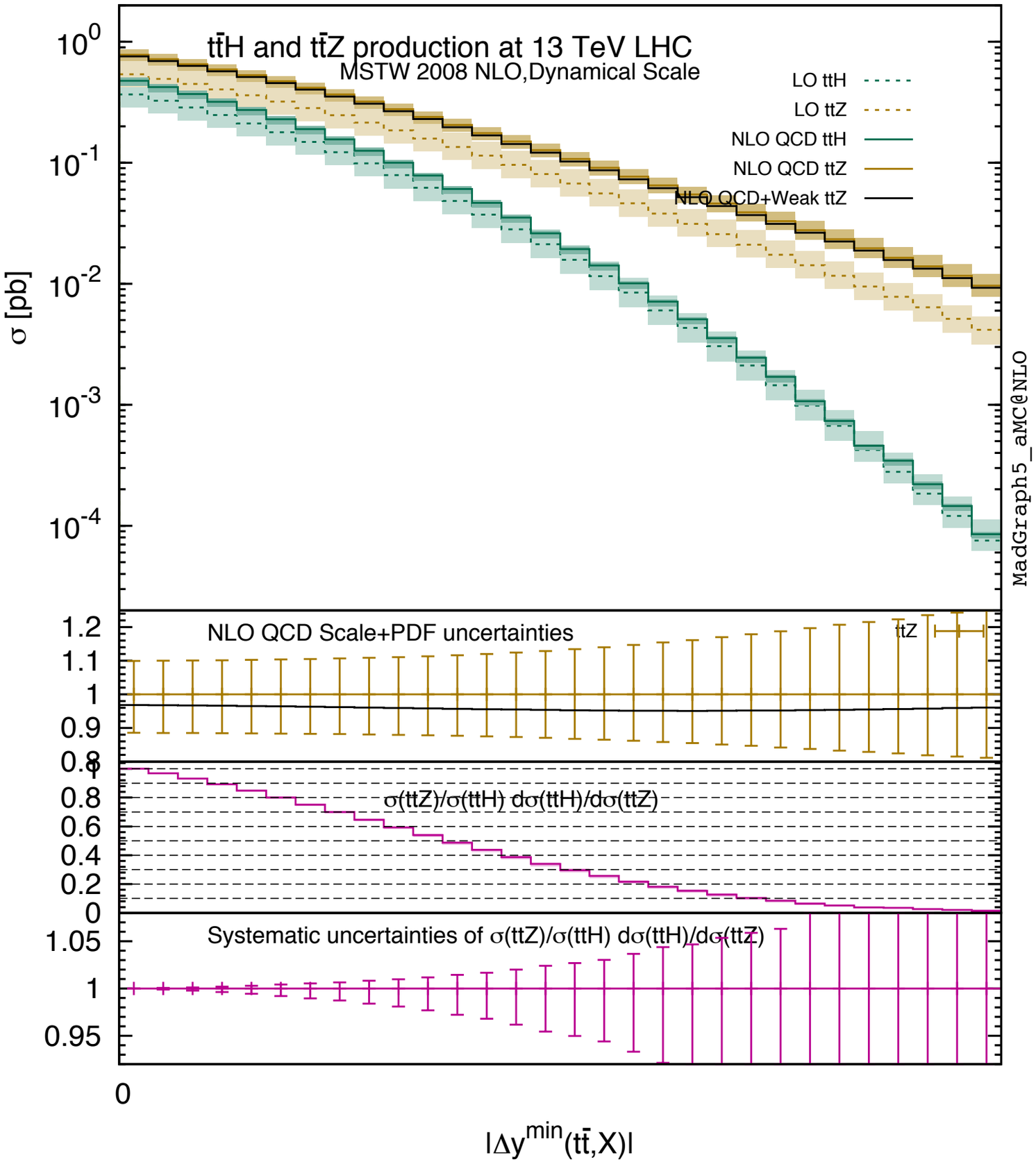


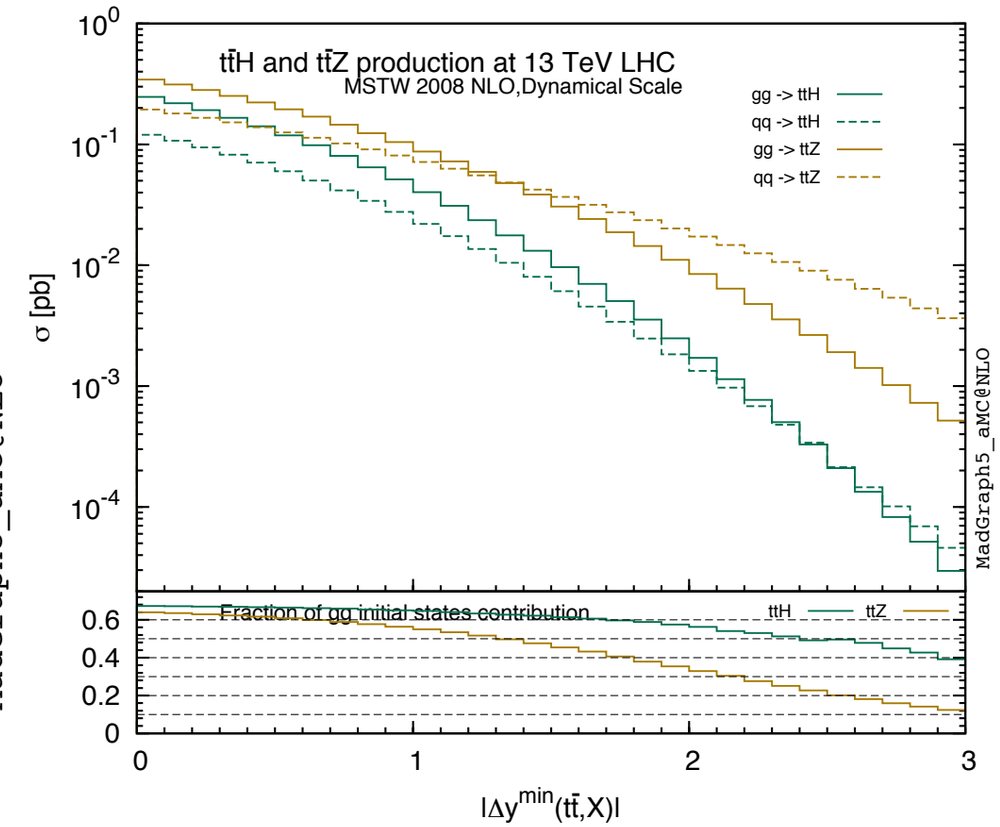
- quark channel is crucial to understand the difference between ttH and ttZ.



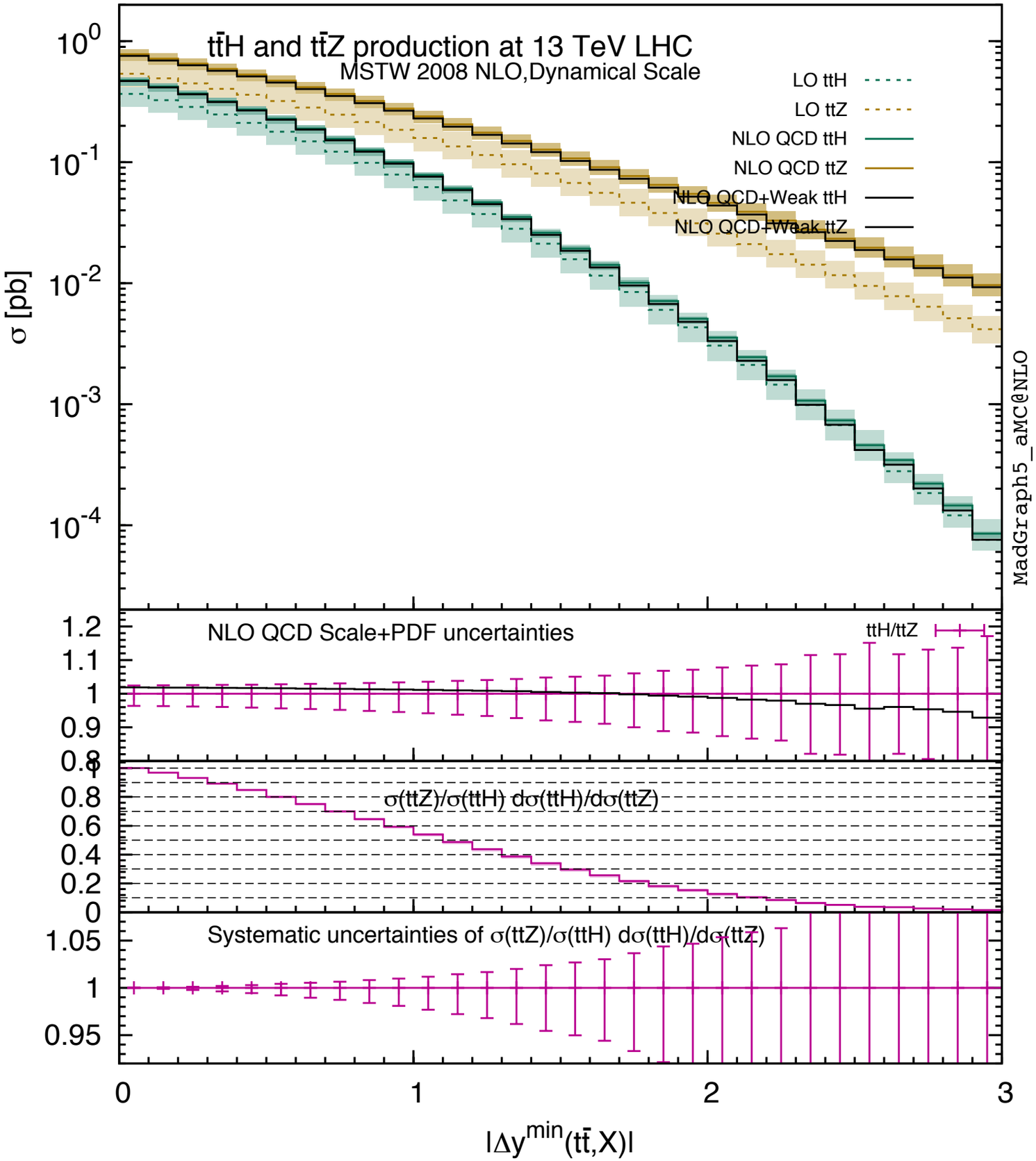


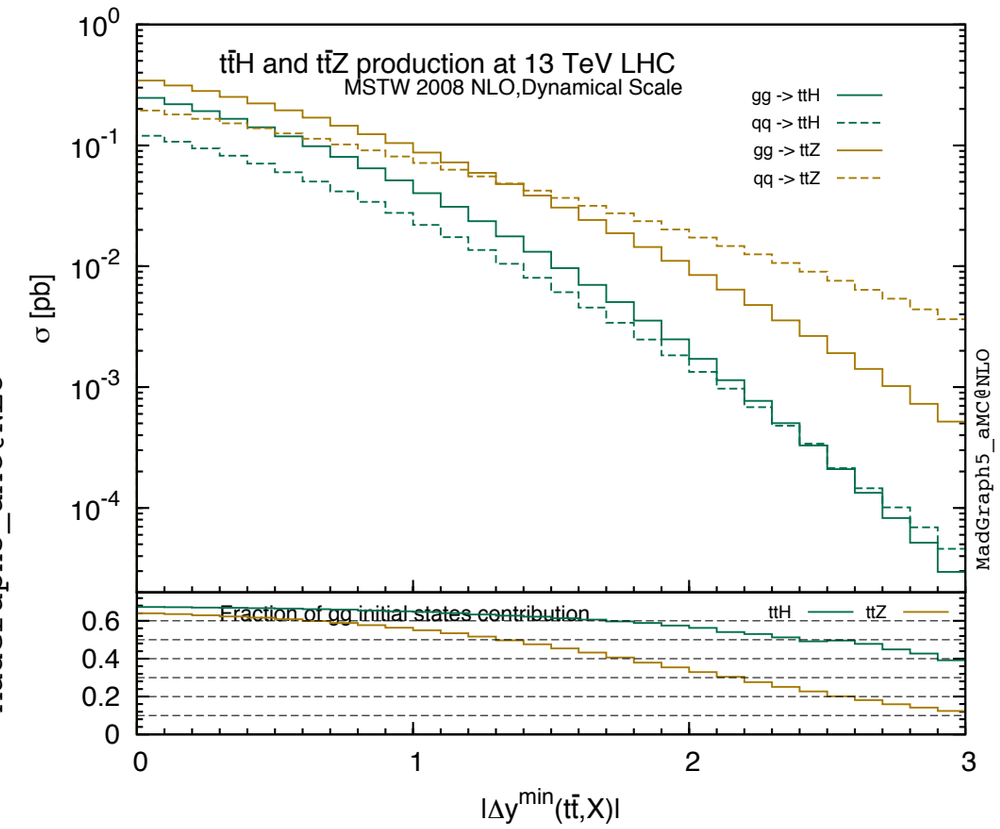
- quark channel is crucial to understand the difference between ttH and ttZ.





- quark channel is crucial to understand the difference between ttH and ttZ.
- Weak is mild in ttZ while it is important in ttH.





- quark channel is crucial to understand the difference between ttH and ttZ.
- Weak is mild in ttZ while it is important in ttH.

Interference computation

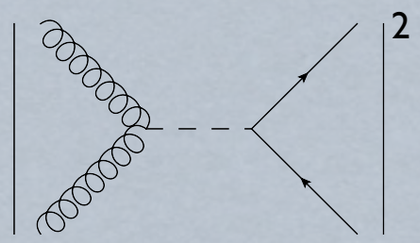
A)

- Simulate only the signal when its leading contribution comes through its interference with the background

Interference computation

- Simulate only the signal when its leading contribution comes through its interference with the background

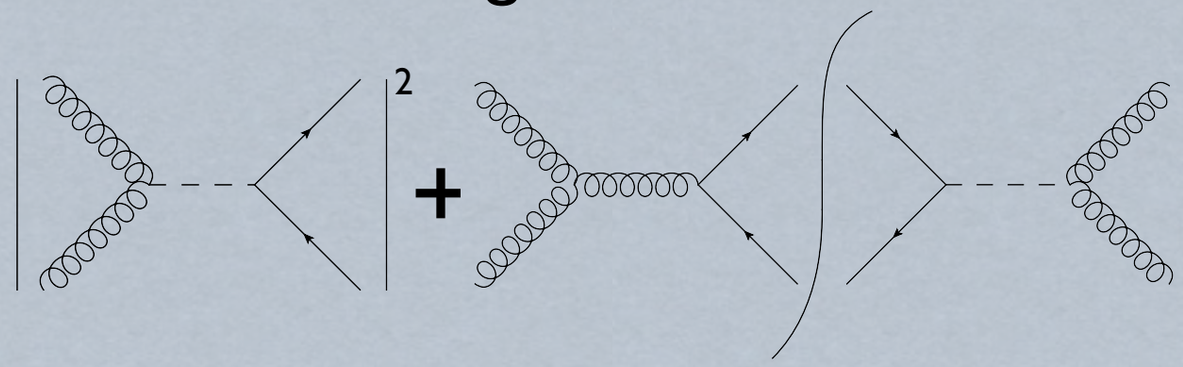
A)



Interference computation

A)

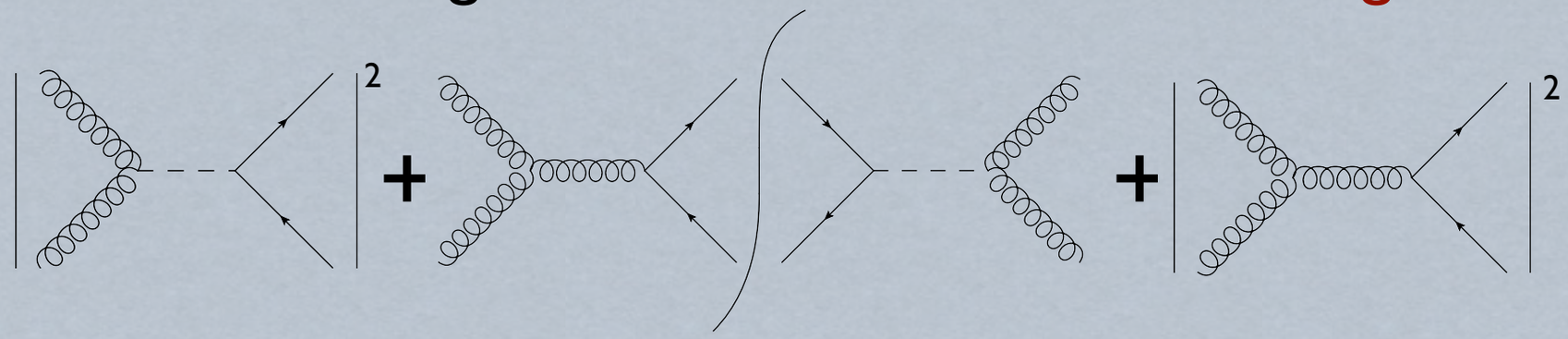
- Simulate only the signal when its leading contribution comes through its interference with the background



Interference computation

A)

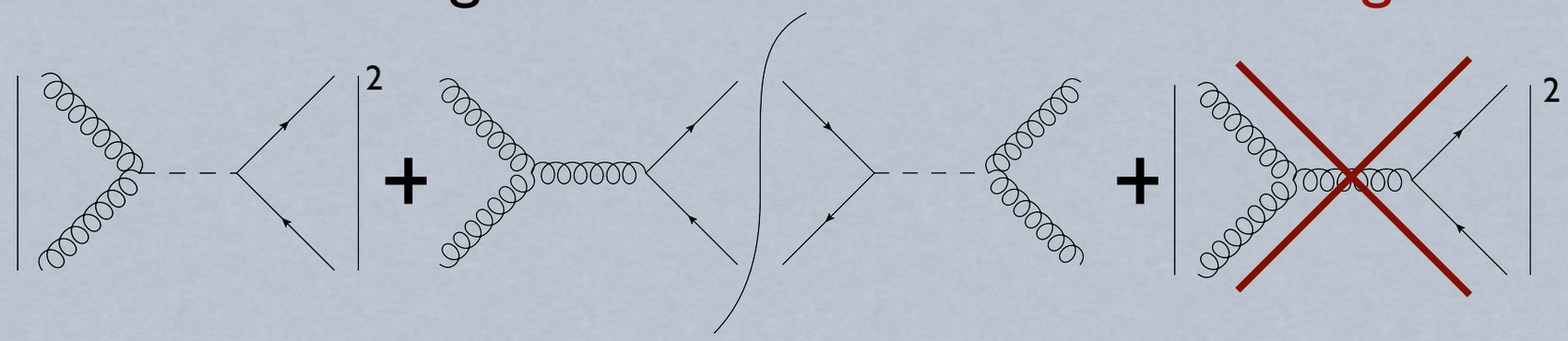
- Simulate only the signal when its leading contribution comes through its interference with the background



Interference computation

A)

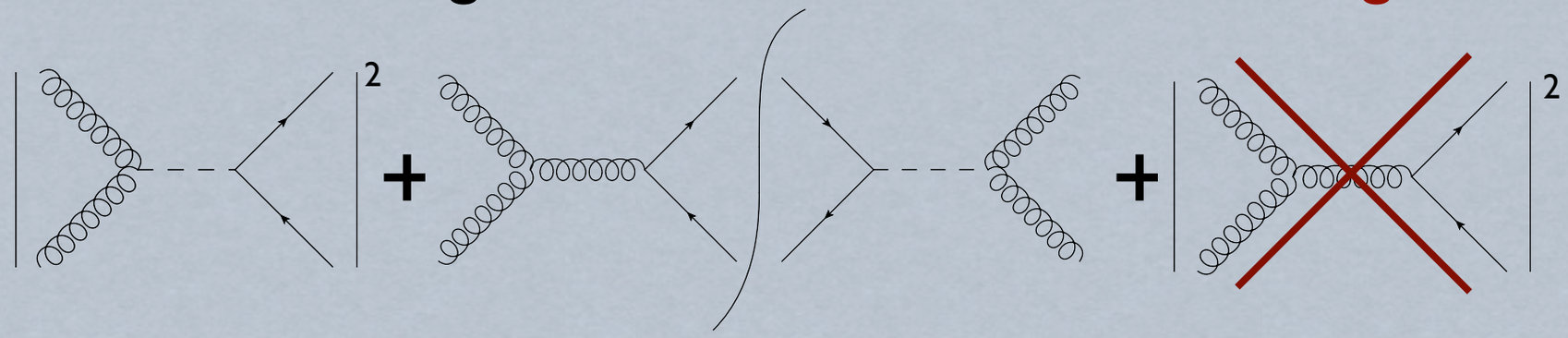
- Simulate only the signal when its leading contribution comes through its interference with the background



Interference computation

A)

- Simulate only the signal when its leading contribution comes through its interference with the background



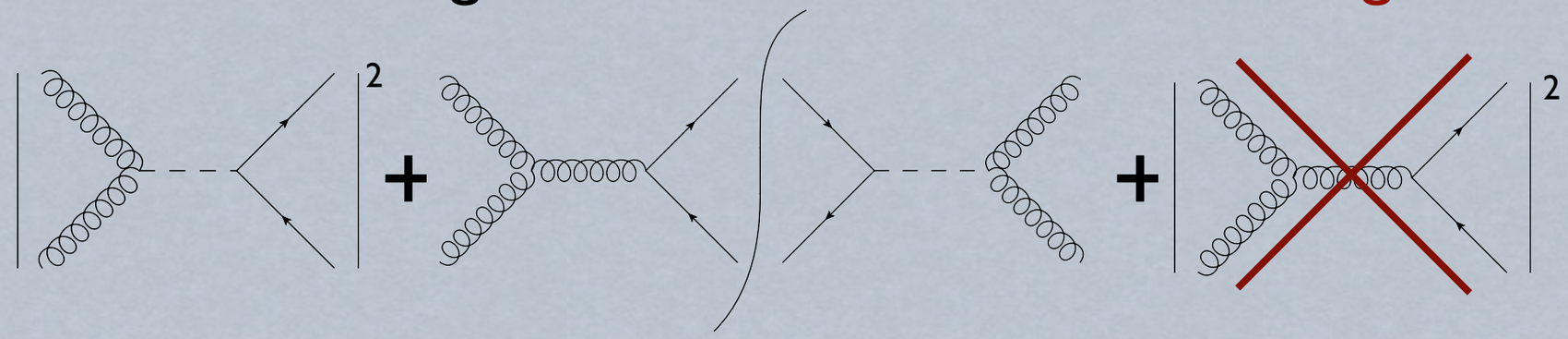
B)

- Exclude higher order contributions in the cutoff $\Lambda = \lambda^{-1}$ when studying effective theories for example

Interference computation

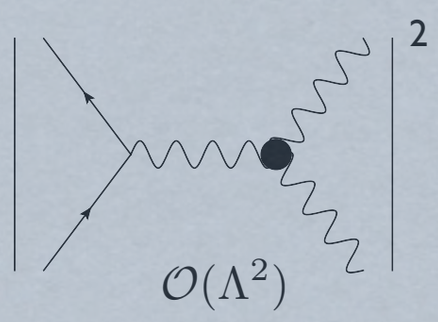
A)

- Simulate only the signal when its leading contribution comes through its interference with the background



B)

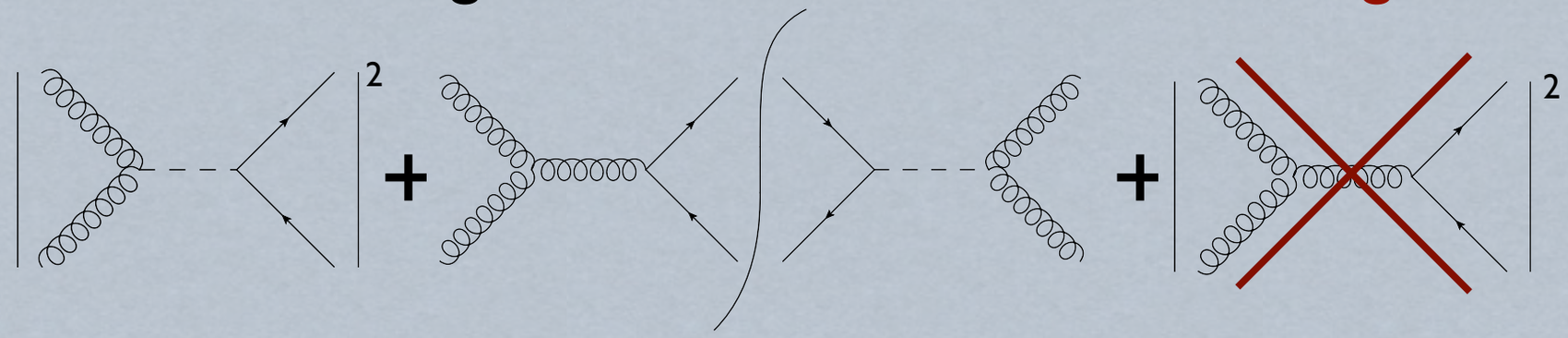
- Exclude higher order contributions in the cutoff $\Lambda = \lambda^{-1}$ when studying effective theories for example



Interference computation

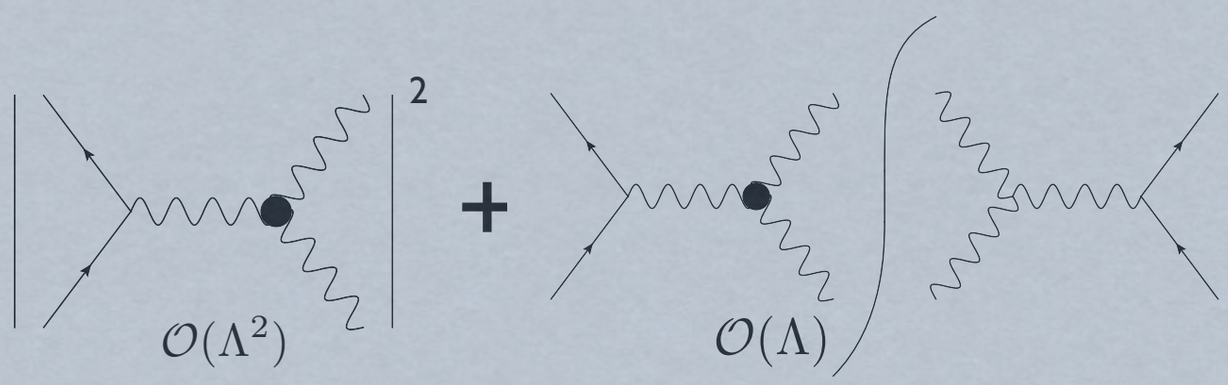
A)

- Simulate only the signal when its leading contribution comes through its interference with the background



B)

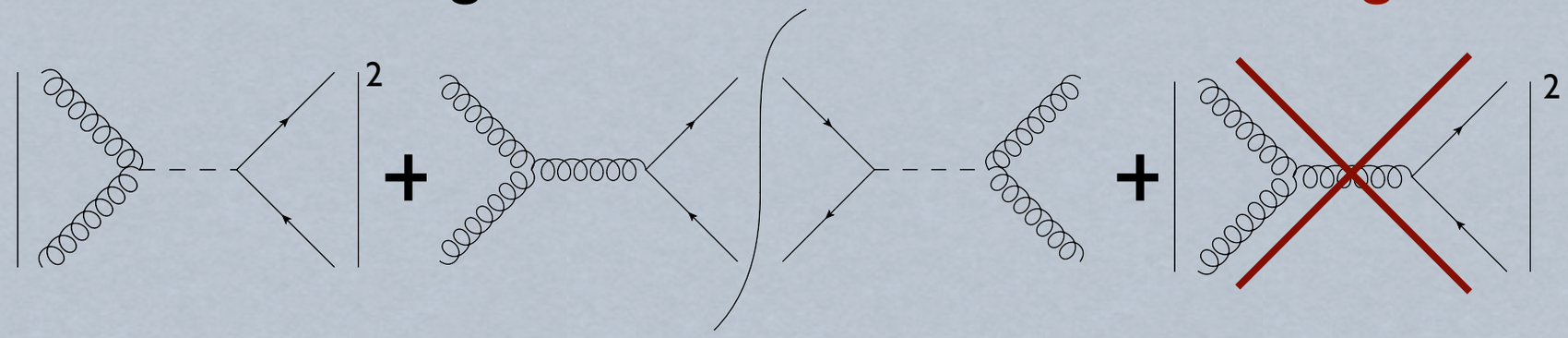
- Exclude higher order contributions in the cutoff $\Lambda = \lambda^{-1}$ when studying effective theories for example



Interference computation

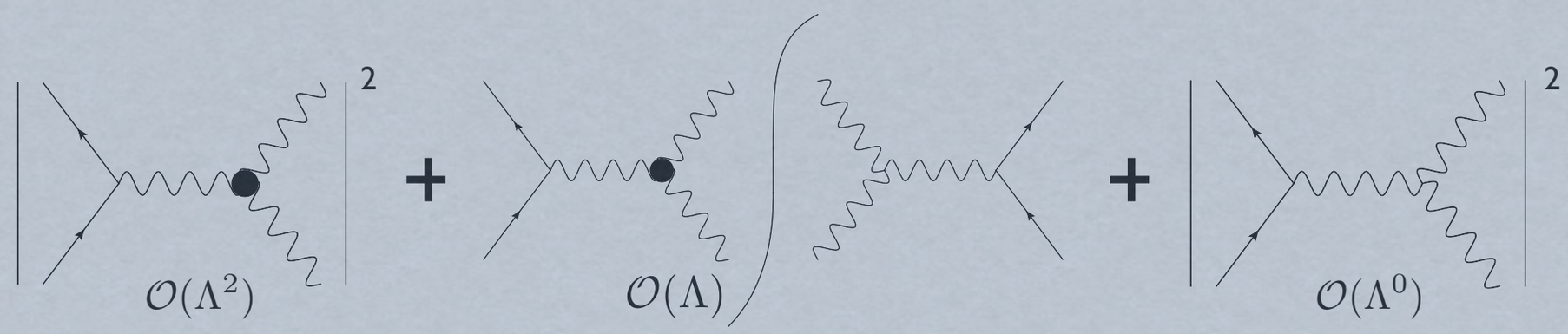
A)

- Simulate only the signal when its leading contribution comes through its interference with the background



B)

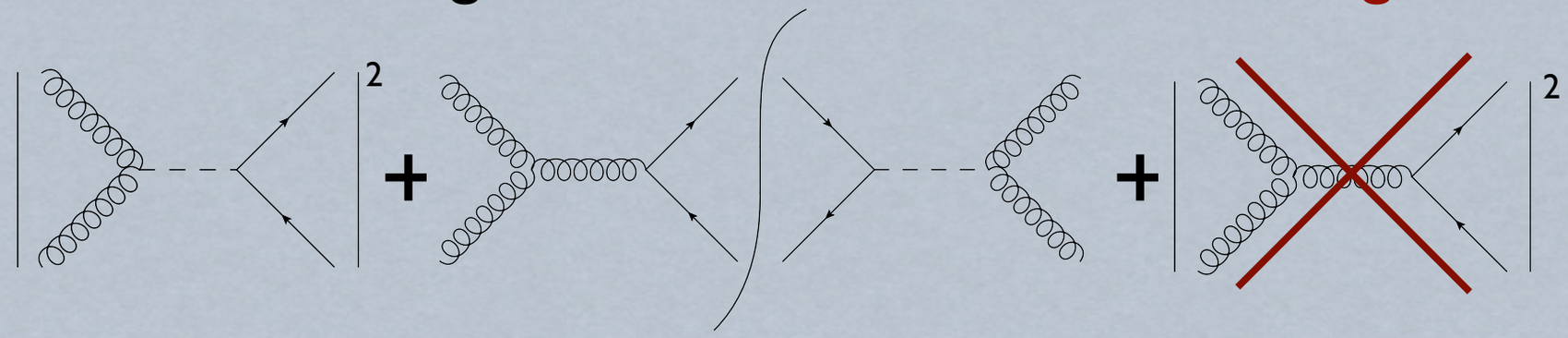
- Exclude higher order contributions in the cutoff $\Lambda = \lambda^{-1}$ when studying effective theories for example



Interference computation

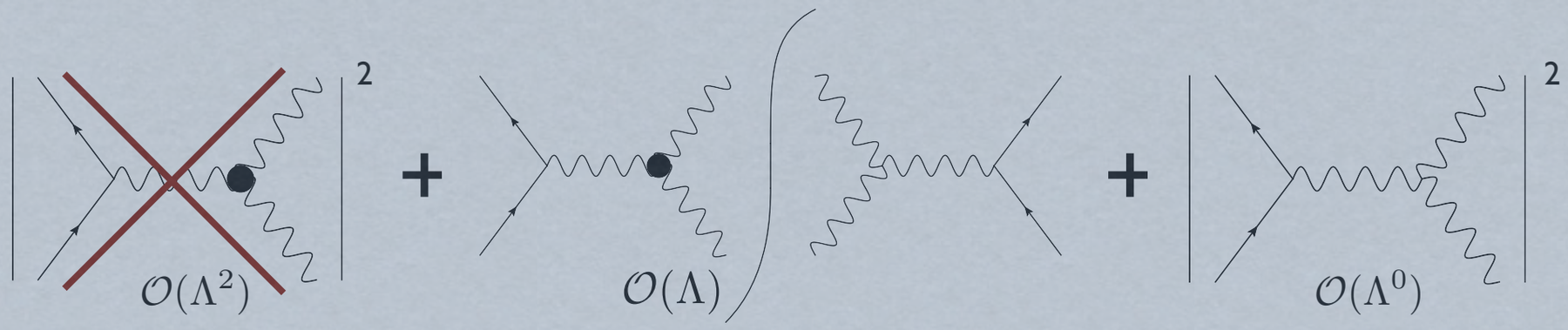
A)

- Simulate only the signal when its leading contribution comes through its interference with the background



B)

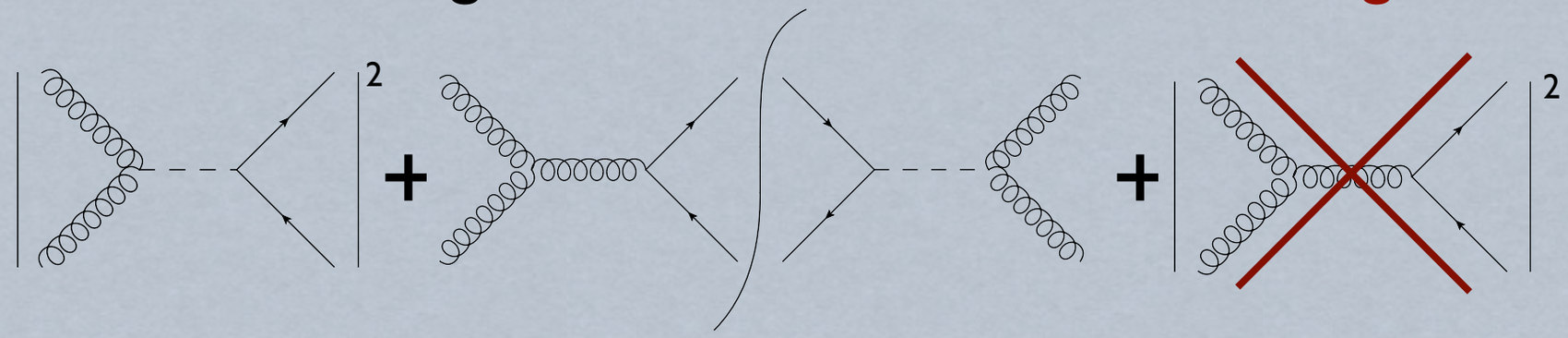
- Exclude higher order contributions in the cutoff $\Lambda = \lambda^{-1}$ when studying effective theories for example



Interference computation

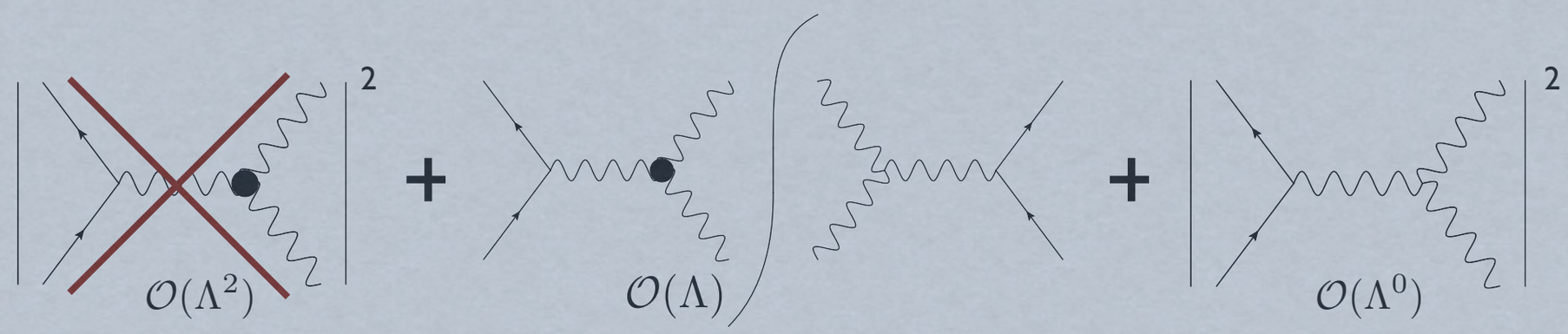
A)

- Simulate only the signal when its leading contribution comes through its interference with the background



B)

- Exclude higher order contributions in the cutoff $\Lambda = \lambda^{-1}$ when studying effective theories for example



We do NOT want to make use of the identity

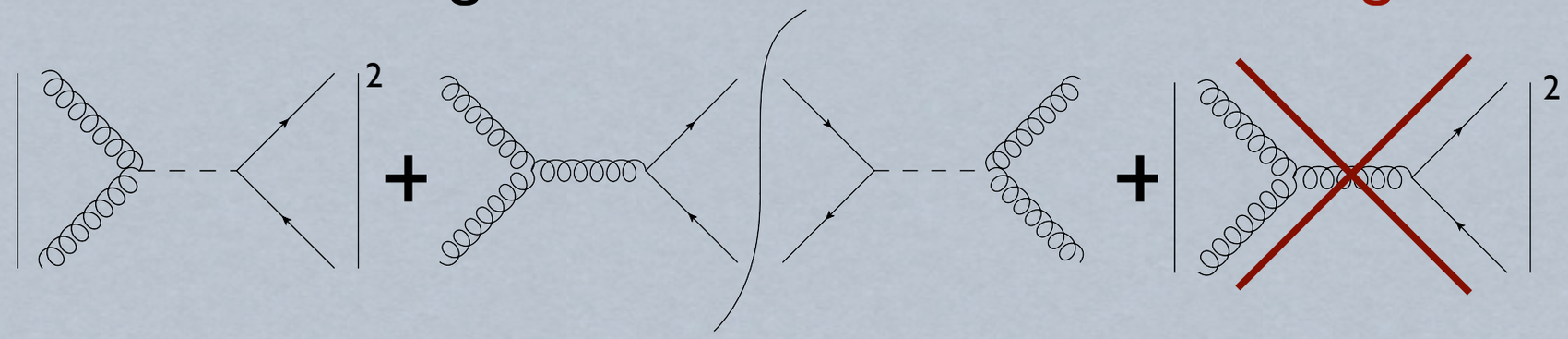
$$2Re(\mathcal{A}^a \mathcal{A}^{b*}) = \mathcal{M}^{a+b} - \mathcal{M}^a - \mathcal{M}^b$$

Because it is very Inefficient for generation (especially mass production)

Interference computation

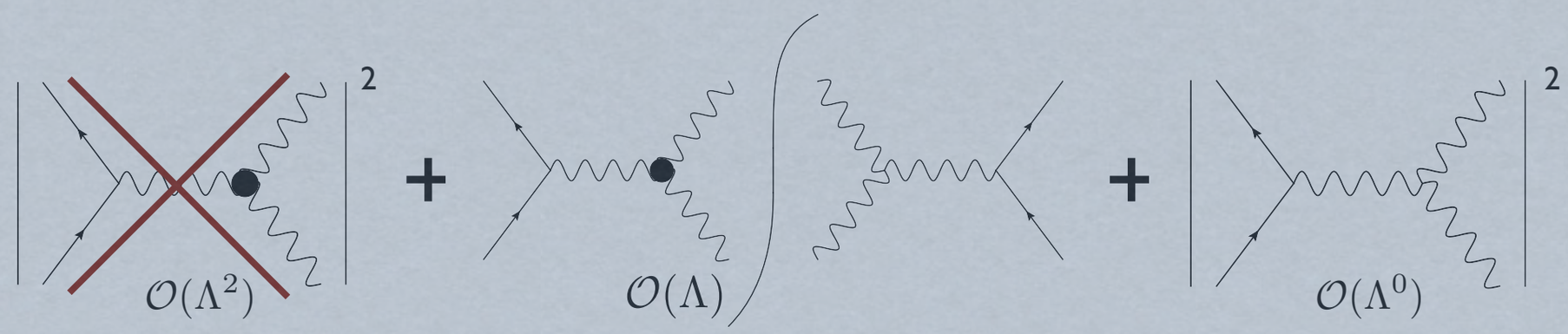
A)

- Simulate only the signal when its leading contribution comes through its interference with the background



B)

- Exclude higher order contributions in the cutoff $\Lambda = \lambda^{-1}$ when studying effective theories for example



We do NOT want to make use of the identity

$$2Re(\mathcal{A}^a \mathcal{A}^{b*}) = \mathcal{M}^{a+b} - \mathcal{M}^a - \mathcal{M}^b$$

Because it is very Inefficient for generation (especially mass production)

New syntax : `> generate process NP^2==2`

Loop induced processes

Idea

- We can evaluate the loops with MadLoop5
- We can efficiently integrate trees with MadEvent
  - ➡ Contract the loop and use the resulting tree-topology to drive the integration

- Automation at the same level as with conventional tree processes :

```
> generate p p > h [QCD]
> launch -f
```

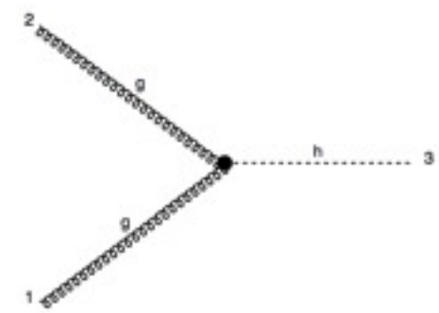
- Many LO MadGraph5 features also available in this context (matching/merging, MadSpin, gridpacks, etc...)
- Anticipated multiplicity reach: **2 → 4**
- Should be under the tree before Christmas !

Loop induced: Training ground

g g → H

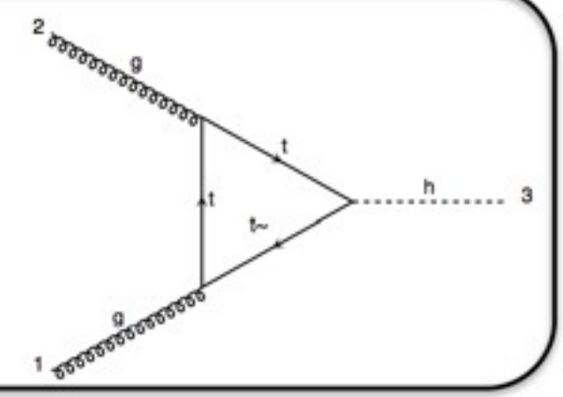
HEFT

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



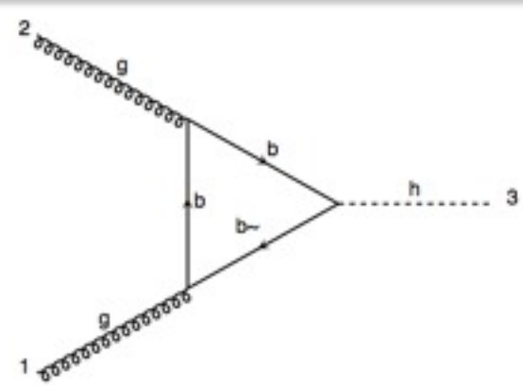
No bottom loop

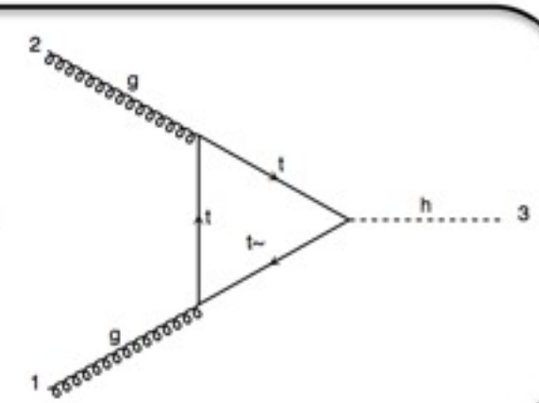
$$\sigma_{toploop} = 17.65(2)pb$$



Loop Induced

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



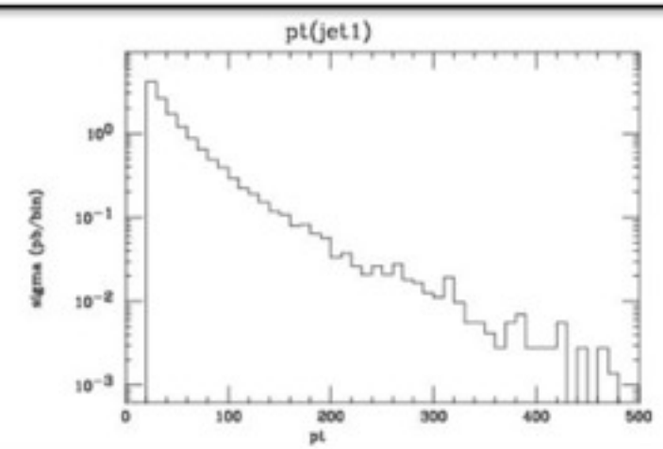


Loop induced: Moving on

Preliminary! No refund for wrong LHC x-sec...

HEFT

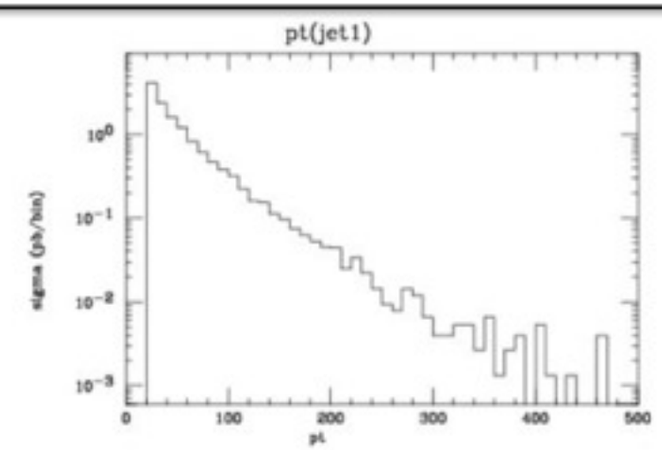
$$\sigma_{heft} = 13.87(3)pb$$



Loop Induced

$$\sigma_{loop} = 13.24(2)pb$$

$$\sigma_{toploop} = 13.56(2)pb$$

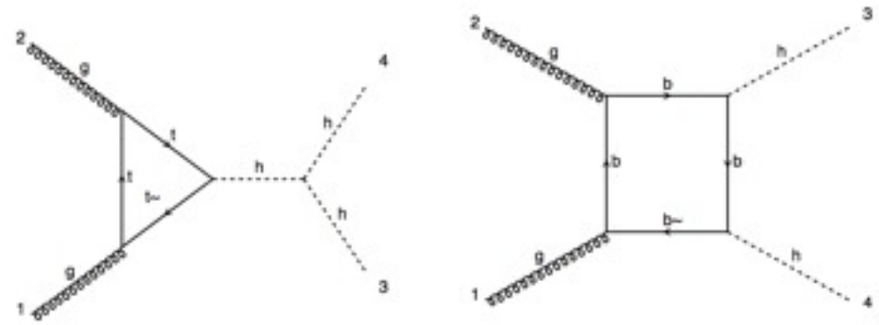


Loop induced: Moving on

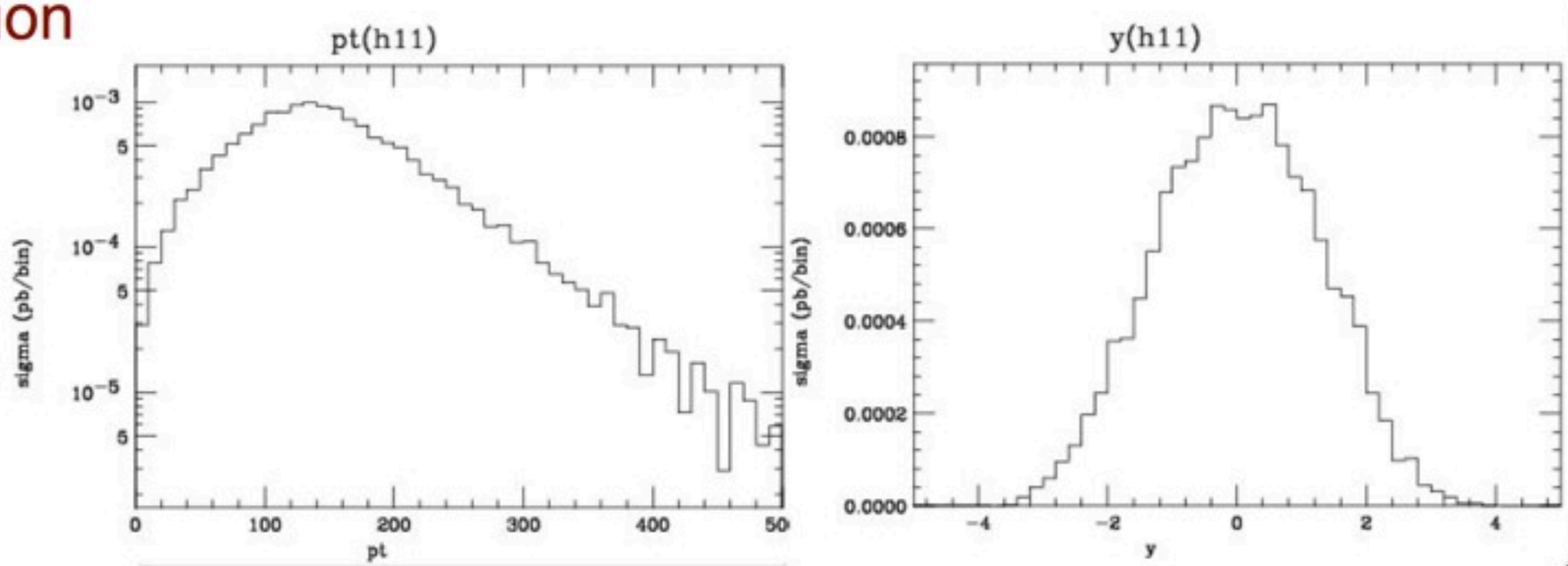
Preliminary! No refund for wrong LHC x-sec...

Loop

$$\sigma_{loop} = 0.01453(1)pb$$



Distribution

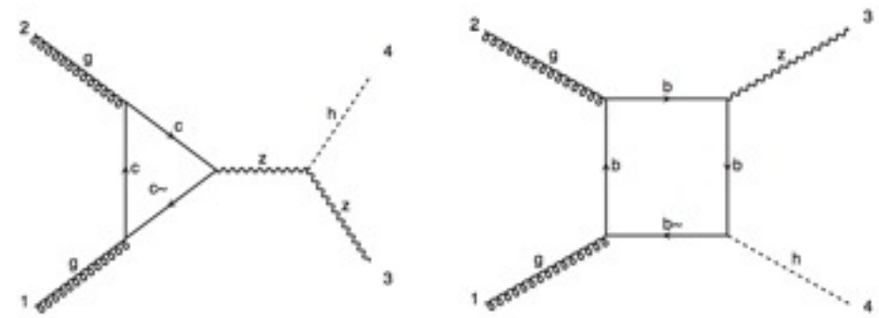


Loop induced: Moving on

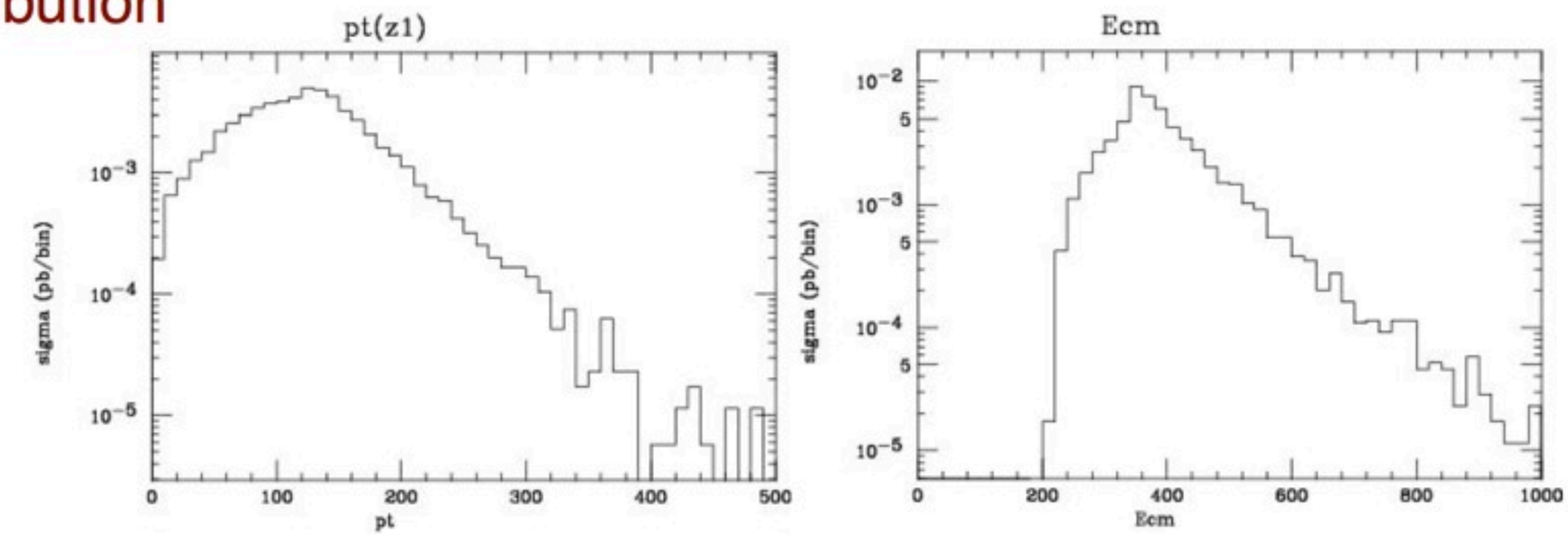
Preliminary! No refund for wrong LHC x-sec...

Loop

$$\sigma_{loop} = 0.05765(2)pb$$



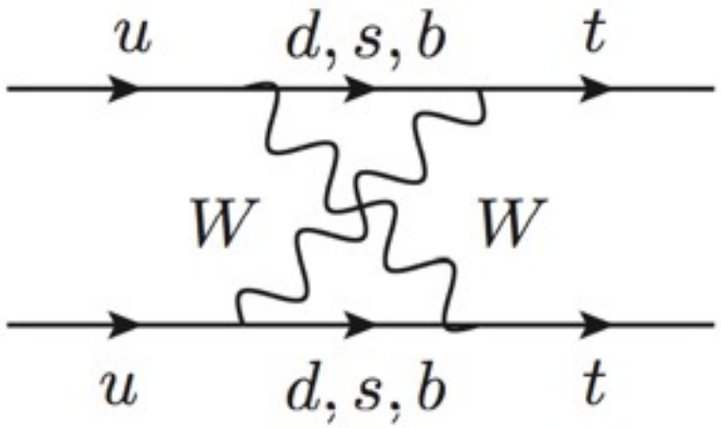
Distribution



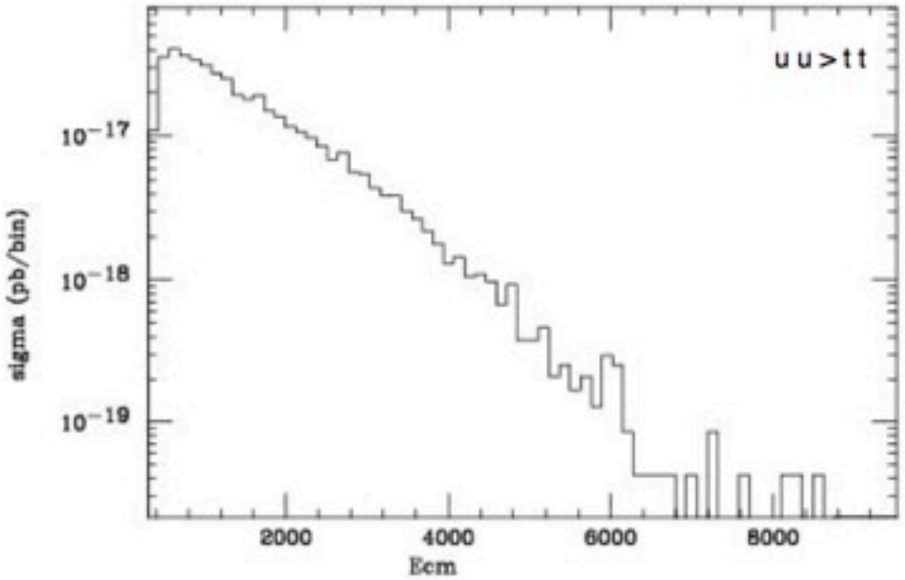
Loop induced: Moving on

Some Fun... Still no refund

- Same-sign top pair events would be New Physics smoking guns... but the process exists in the SM!
- Weak loops, doubly CKM-suppressed:
- Has never been computed (maybe rightfully so)



$$\sigma_{loop} = 2.23(1)10^{-15} pb$$



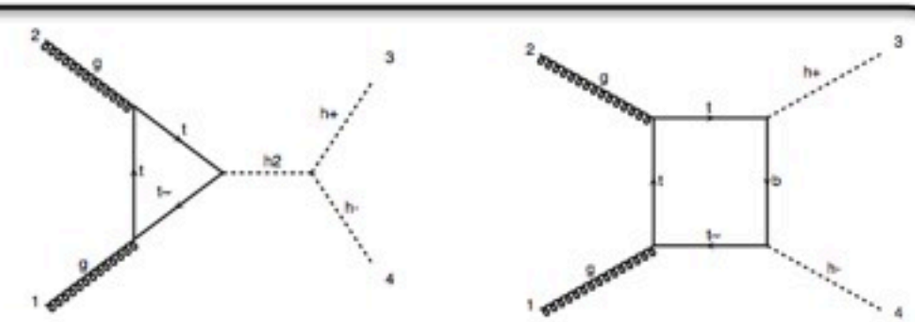
Loop induced: Moving on

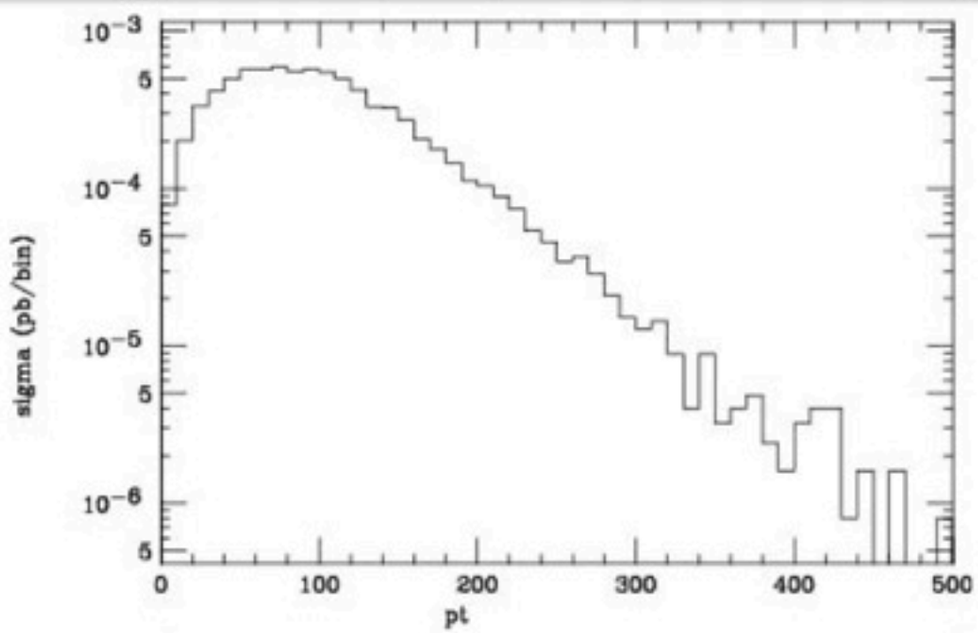
BSM too! ... Still no refund

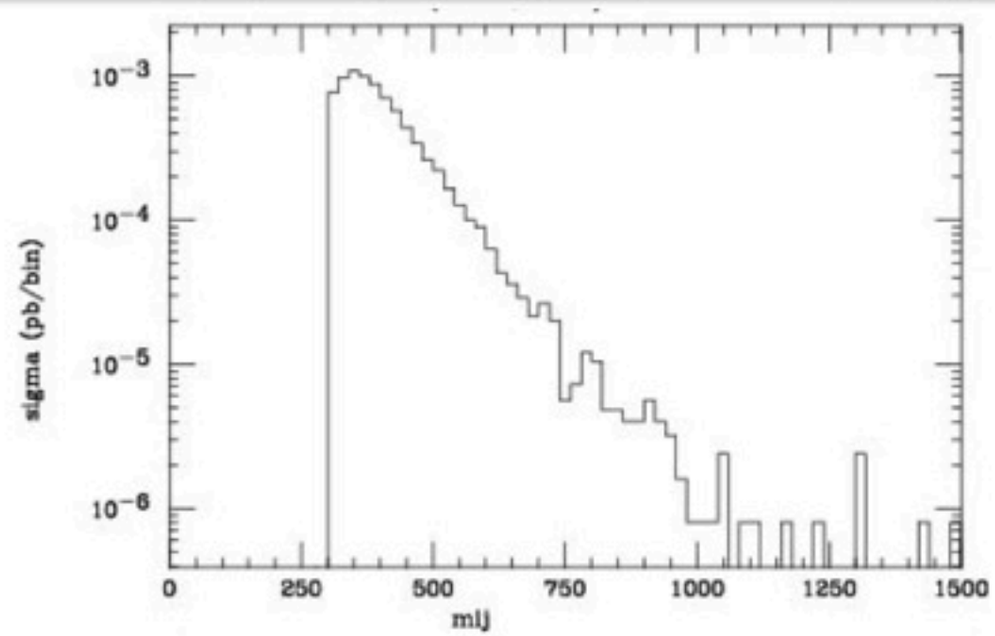
- Using the NLOCT module of FeynRules to produce the UFO for this typeII 2HDM.

Loop

$$\sigma_{loop} = 0.00803(1)pb$$

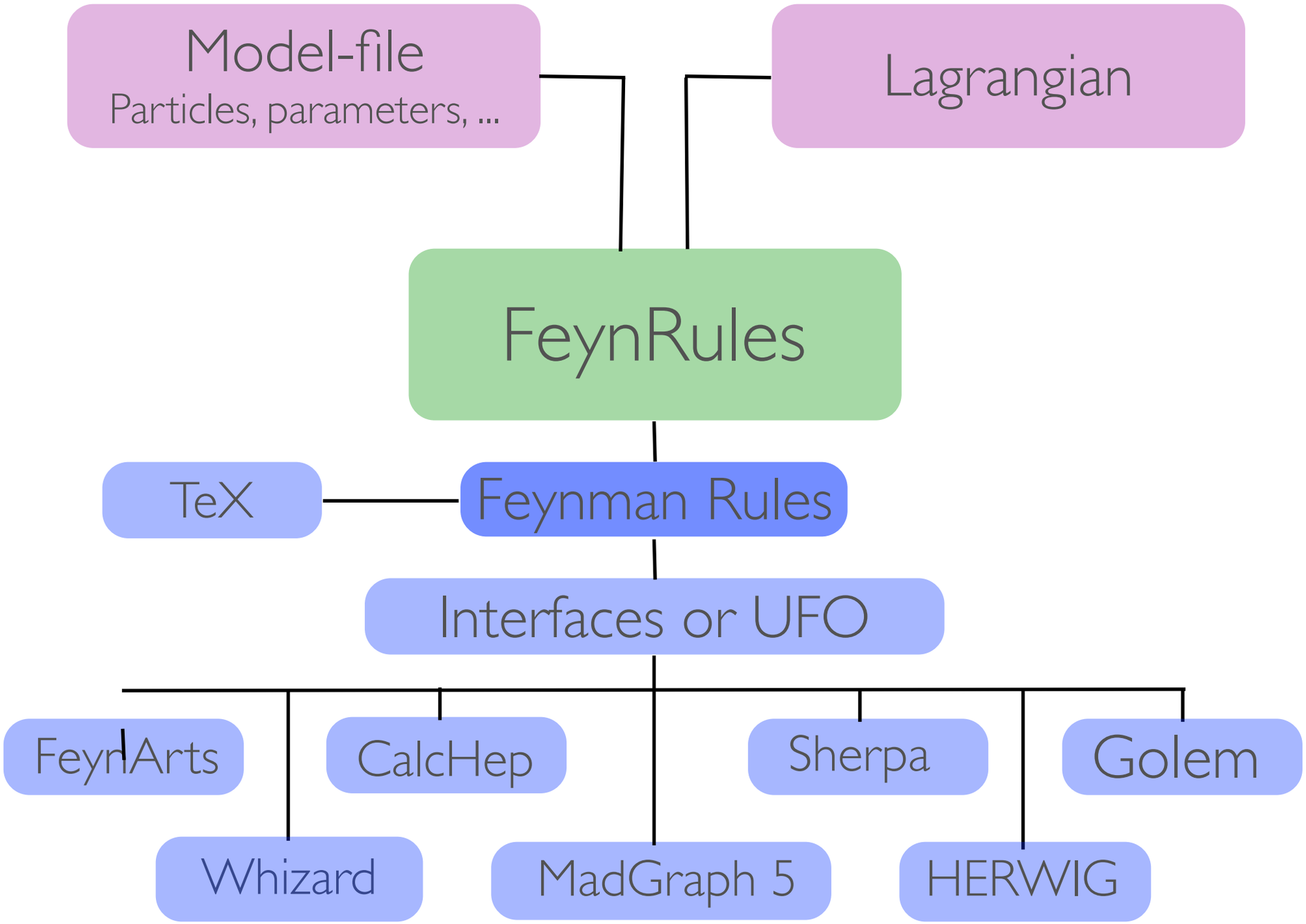






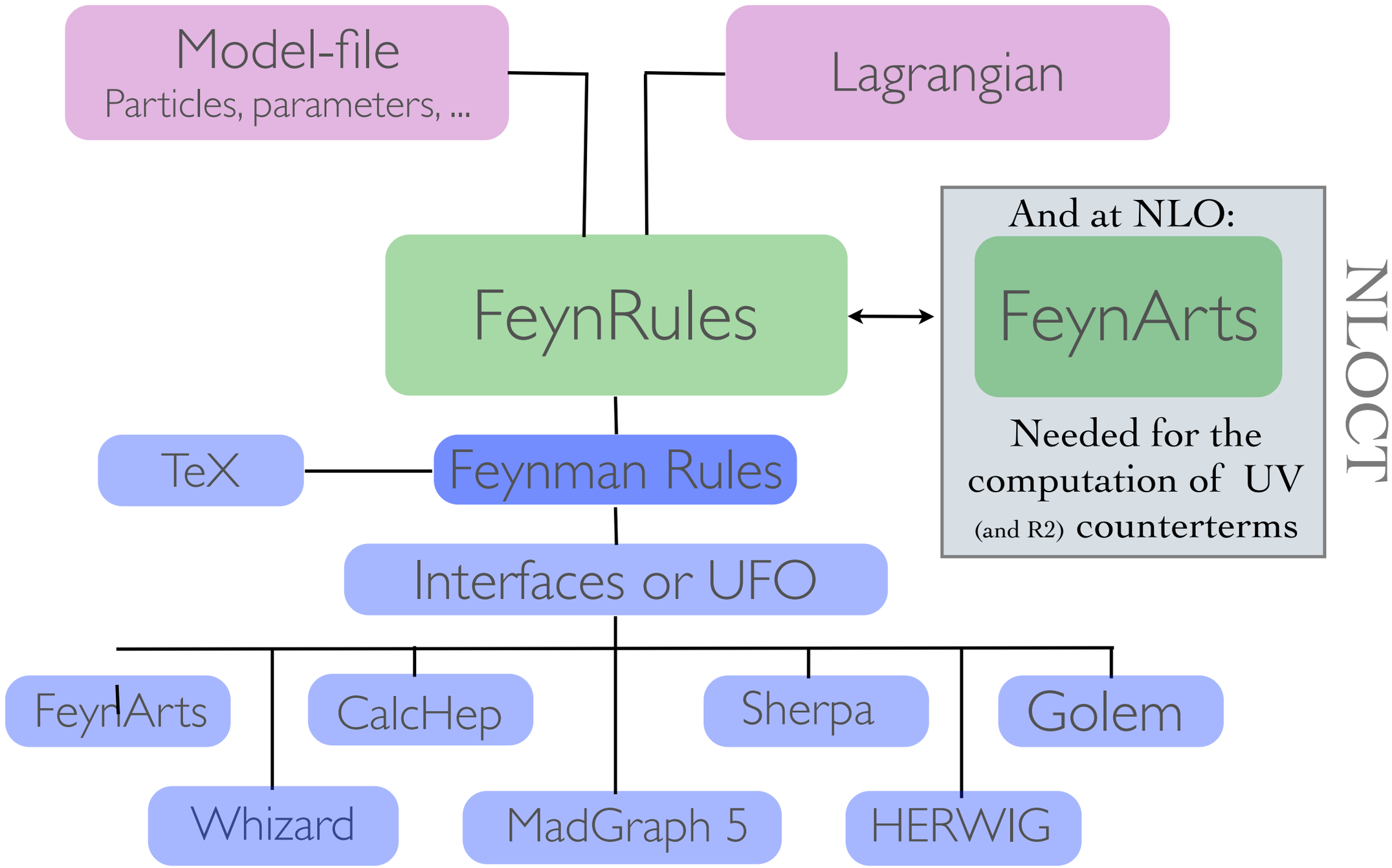
Automating BSM@NLO

[Alloul, Christensen, Degrande, Duhr, Fuks]



Automating BSM@NLO

[Alloul, Christensen, Degrande, Duhr, Fuks]



Automating BSM@NLO

Simplified MSSM-like model

- UFO model from the NLOCT module of FeynRules, with Lagrangian :

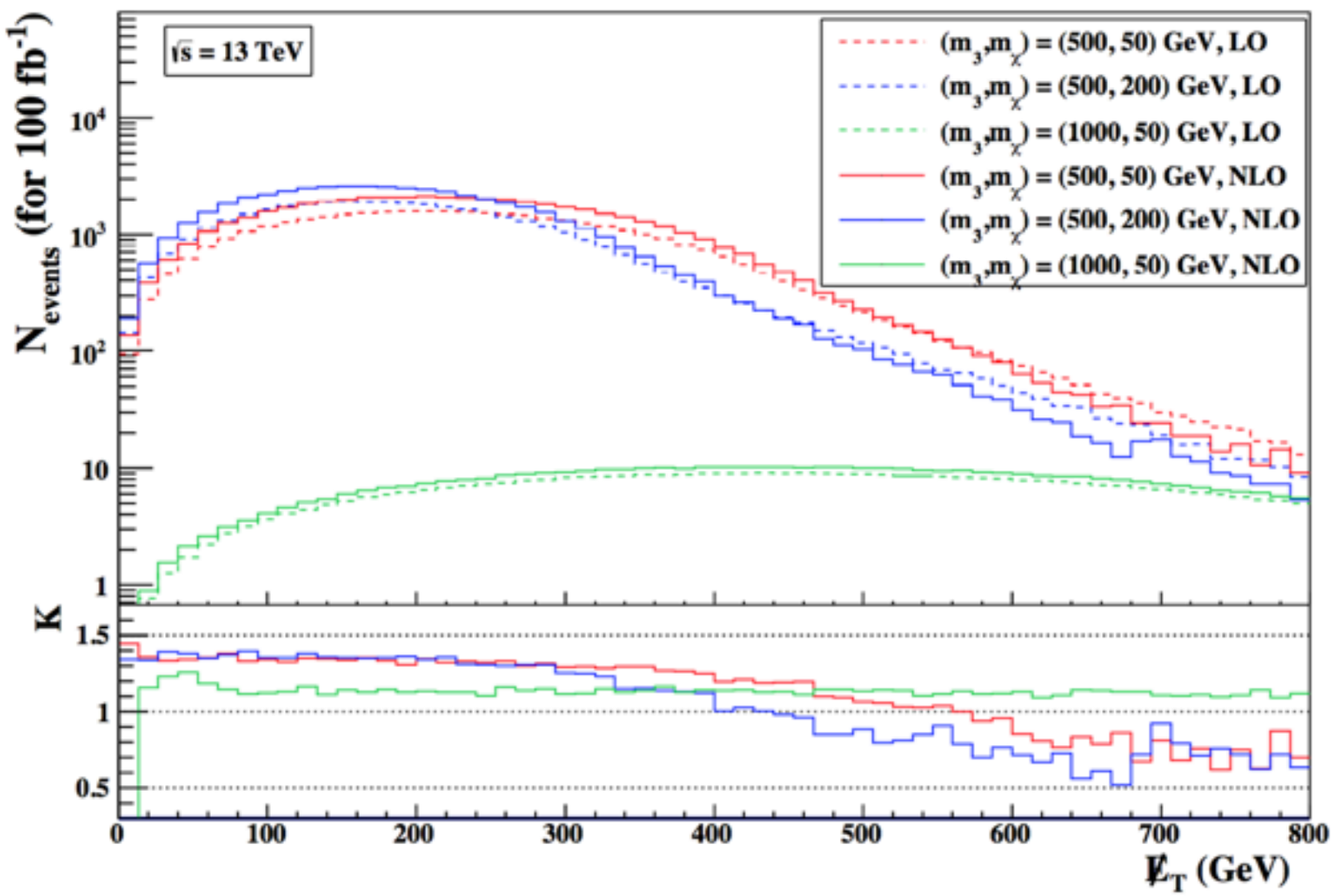
$$\mathcal{L}_3 = D_\mu \sigma_3^\dagger D^\mu \sigma_3 - m_3^2 \sigma_3^\dagger \sigma_3 + \frac{i}{2}\bar{\chi}\partial\!\!\!/\chi - \frac{1}{2} m_\chi \bar{\chi}\chi$$
$$+ \left[\sigma_3 \bar{t}(\tilde{g}_L P_L + \tilde{g}_R P_R)\chi + \text{h.c.}\right],$$

Automating BSM@NLO

Simplified MSSM-like model

- UFO model from the NLOCT module of FeynRules, with Lagrangian :

$$\mathcal{L}_3 = D_\mu \sigma_3^\dagger D^\mu \sigma_3 - m_3^2 \sigma_3^\dagger \sigma_3 + \frac{i}{2}\bar{\chi}\partial\!\!\!/\chi - \frac{1}{2} m_\chi \bar{\chi}\chi + \left[\sigma_3 \bar{t}(\tilde{g}_L P_L + \tilde{g}_R P_R)\chi + \text{h.c.}\right],$$



[C. Degrande, B. Fuchs, VH, J.Proudom, S.Shao, to appear]

$$pp \to \sigma_3\sigma_3 \to t\bar{t}\chi\bar{\chi}$$

- Core process at NLO
- Decay at LO with MadSpin.
- Simple K-factor rescaling not always right.
- Matched to Pythia 8
- Validation with Prospino

Automating BSM@NLO

- Now considering colored scalars with effective Lagrangian :

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

NLOCT $\Longrightarrow$

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

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

[C. Degrande, B. Fuchs, VH, J.Proudom, S.Shao, to appear]

Automating BSM@NLO

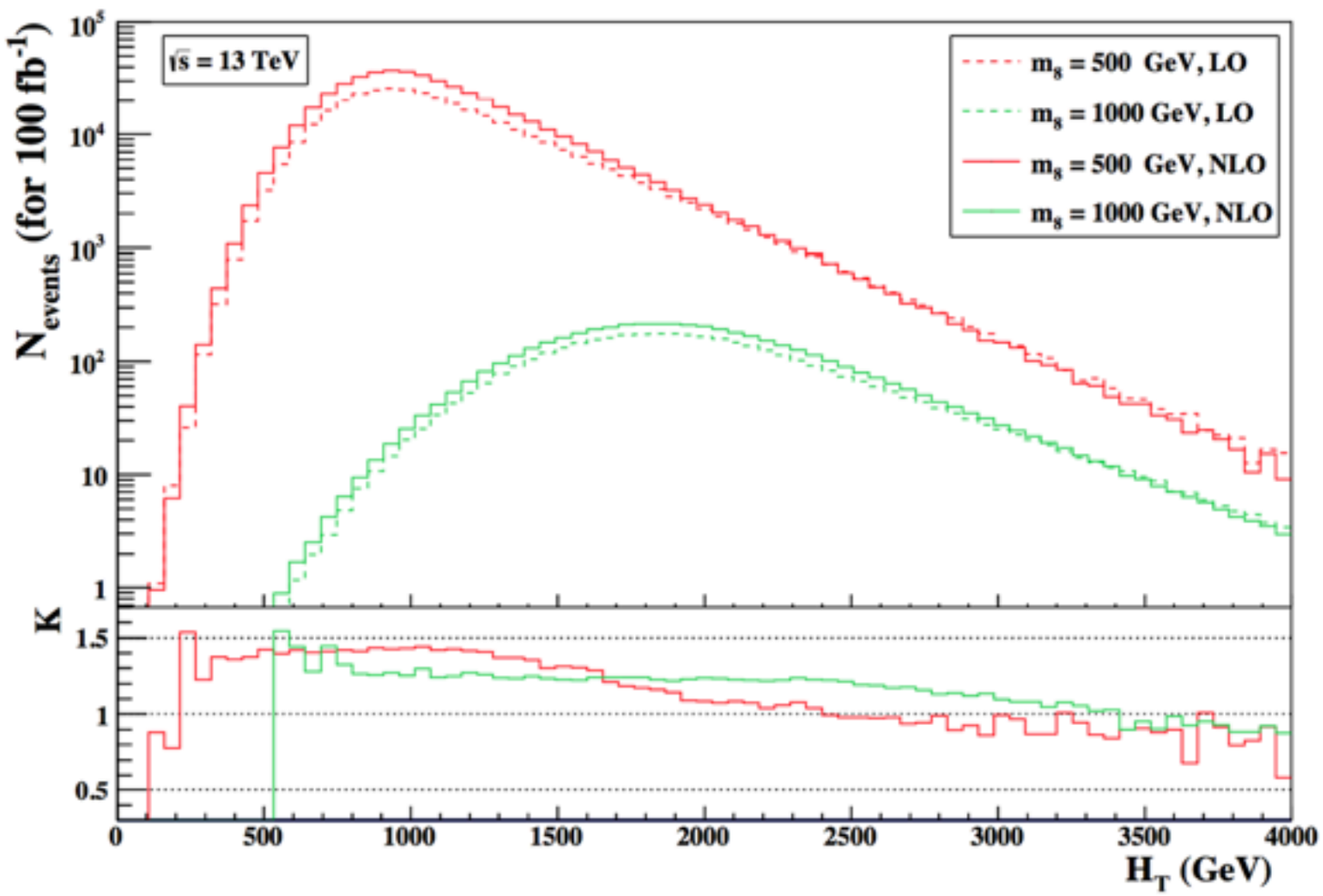
- Now considering colored scalars with effective Lagrangian :

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

NLOCT $\Longrightarrow$

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

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

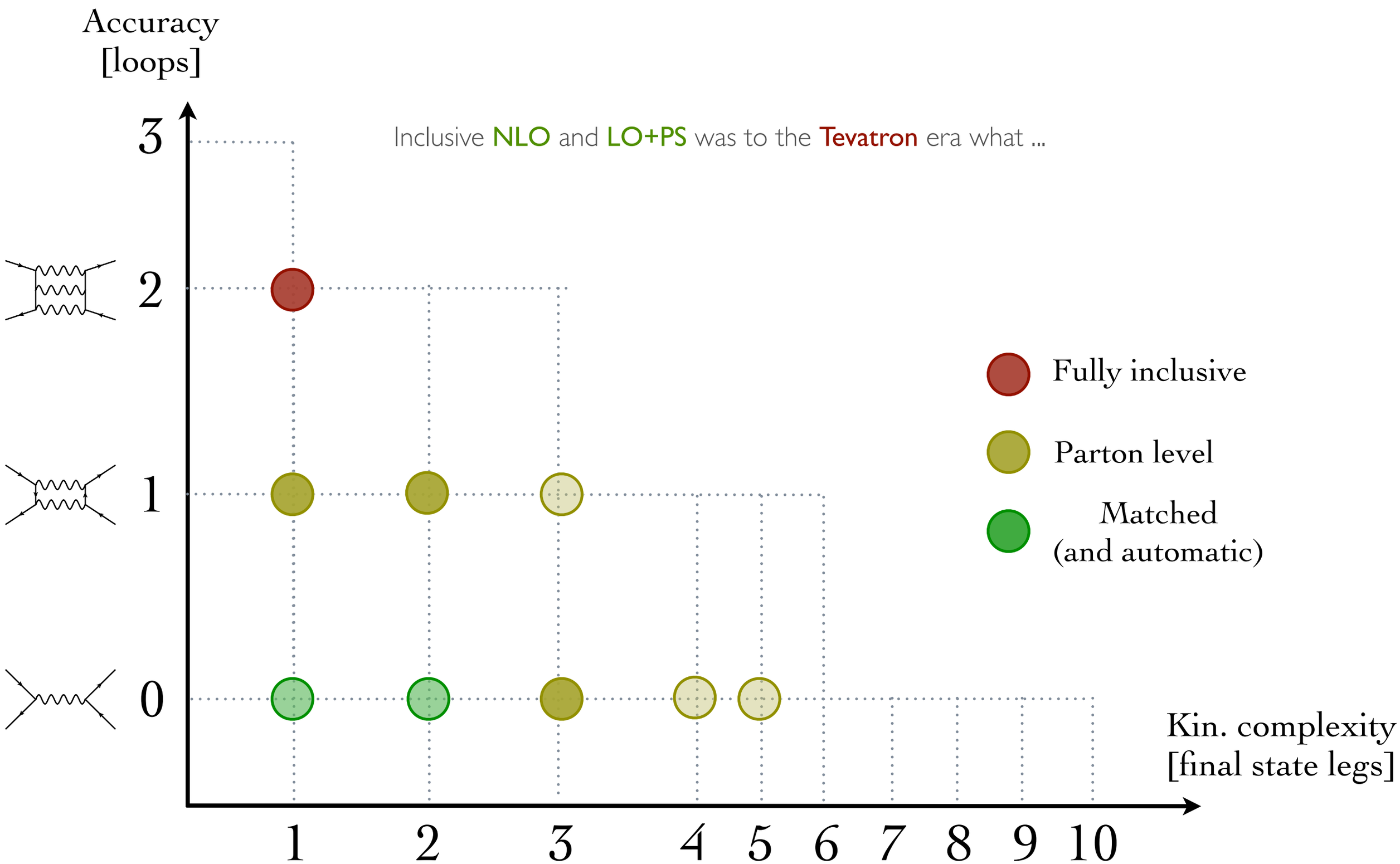


[C. Degrande, B. Fuchs, VH, J.Proudom, S.Shao, to appear]

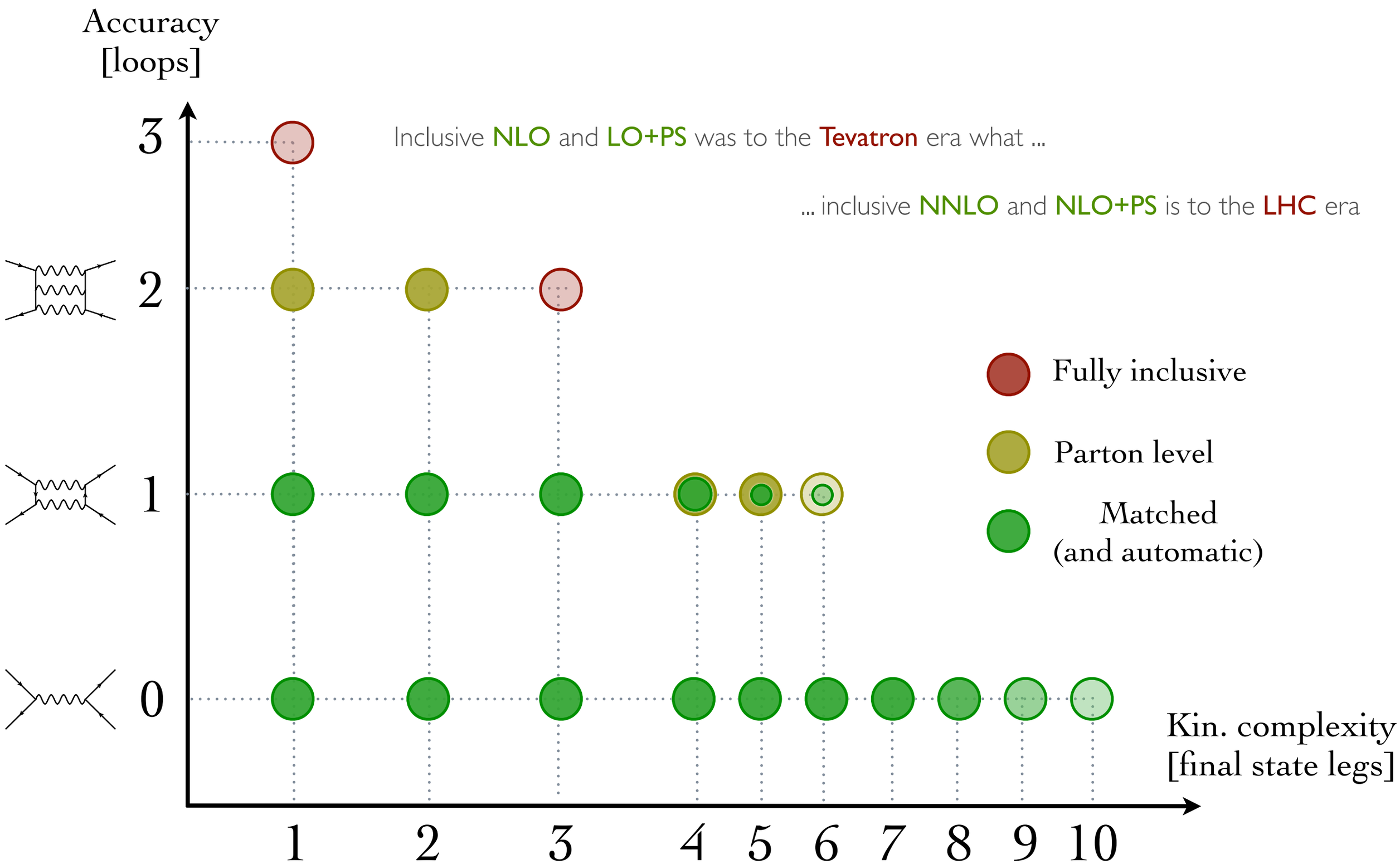
$$pp \to \sigma_8 \sigma_8 \to jjjj$$

- Core process at NLO
- Decay at LO with MadSpin.
- Matched to Pythia 8
- Validation with MadGolem

State of the art in 2000



State of the art in 2014



AUTOMATIC, ACCURATE AND AUGMENTING
MC'S AT COLLIDERS

Free to Run II !