



# BRIDGING THEORY WITH EXPERIMENTS

VALENTIN HIRSCHI

PHENO 2014, UNIVERSITY OF PITTSBURGH

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# OUTLINE

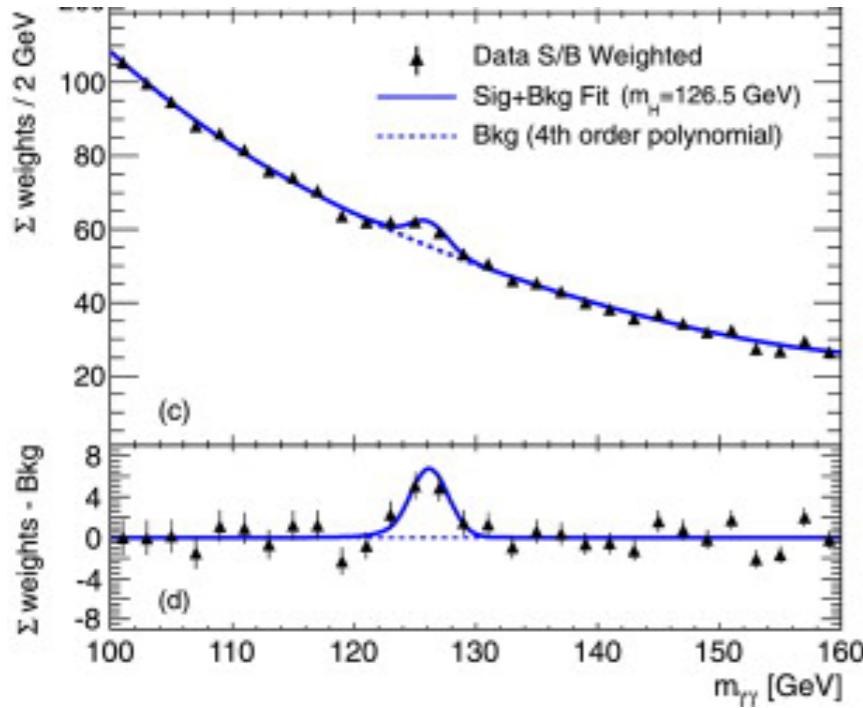
- ✚ **WHAT ROLE DO SIMULATIONS PLAY**
- ✚ **THE NEED FOR ACCURACY AND HOW TO GET IT**
- ✚ **TYPICAL SIMULATION WORKFLOW**
- ✚ **STATE-OF-THE ART TOOLS AND PROSPECTS**

# SIMULATION FOR DISCOVERY? THE HIGGS CASE

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PEAK

$H \rightarrow \gamma \gamma$



“EASY”

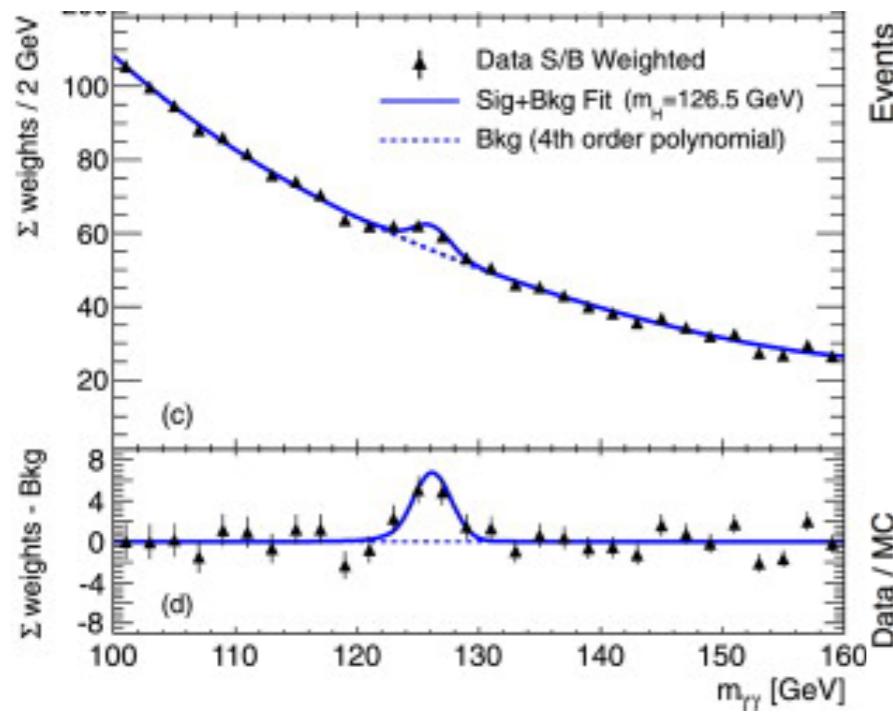
Background directly  
measured from **data**.  
Theory needed only for  
parameter extraction

# SIMULATION FOR DISCOVERY?

## THE HIGGS CASE

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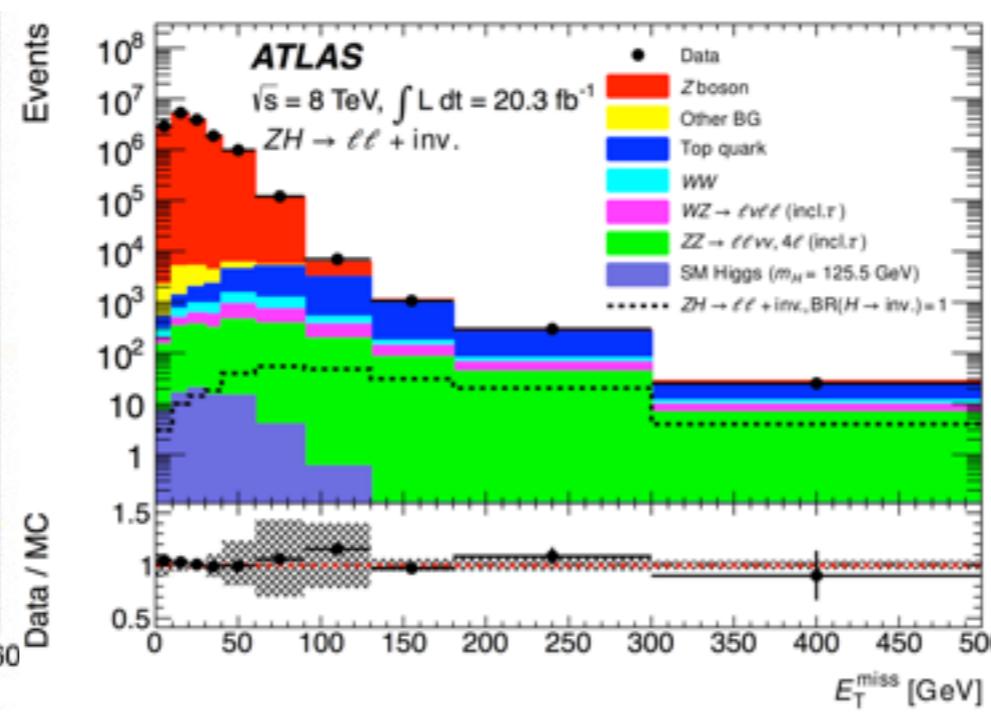


**“EASY”**

Background directly measured from **data**. Theory needed only for parameter extraction

### SHAPE

$$P P \rightarrow Z H \rightarrow \ell\ell + \text{inv.}$$



**“HARD”**

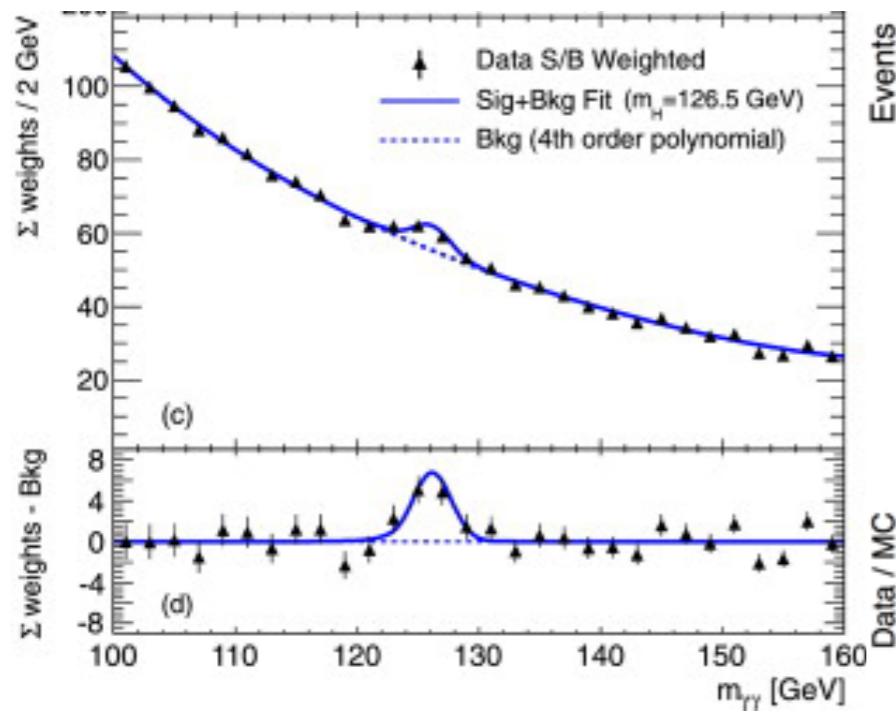
Background **SHAPE** needed. Flexible MC for both signal and background validated and tuned to data

# SIMULATION FOR DISCOVERY?

## THE HIGGS CASE

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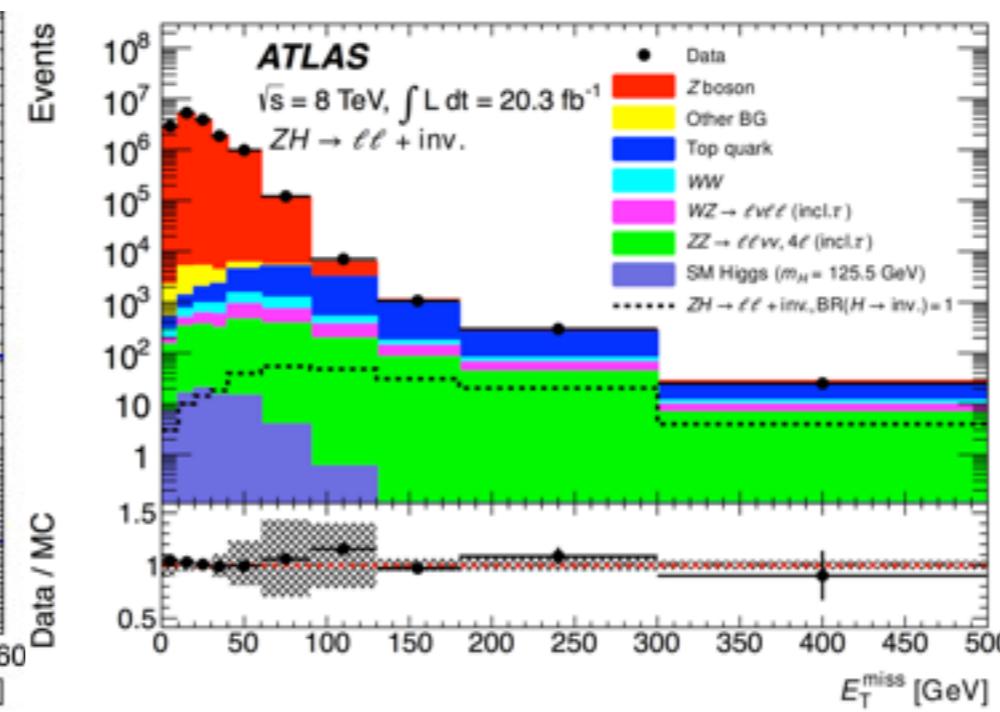


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### SHAPE

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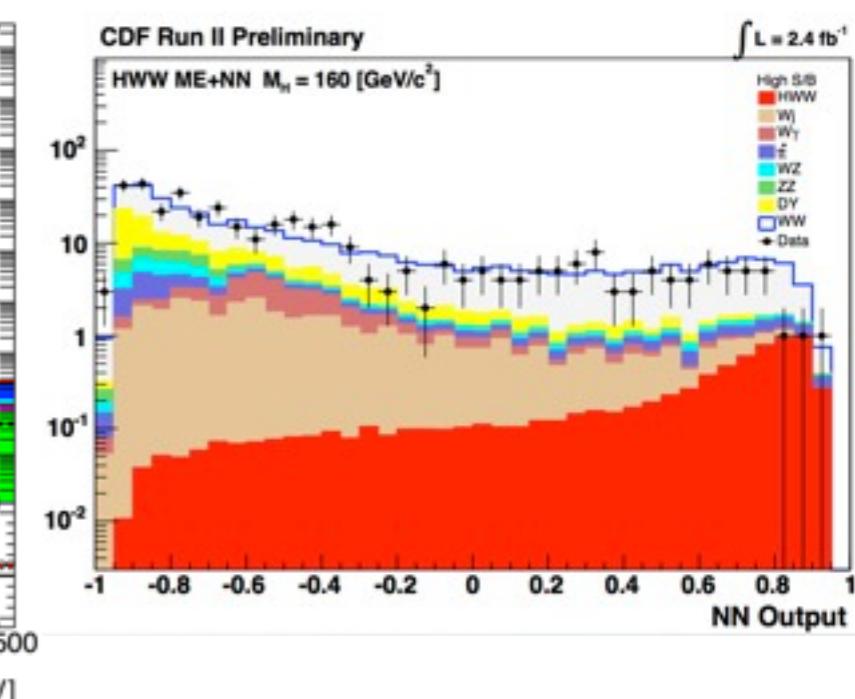


**“HARD”**

Background **SHAPE** needed. Flexible MC for both signal and background validated and tuned to data

### RATE

$$P P \rightarrow H \rightarrow W^+ W^-$$



**“VERY HARD”**

Relies on prediction for both **shape** and **normalization**. Complicated interplay of best simulations and data

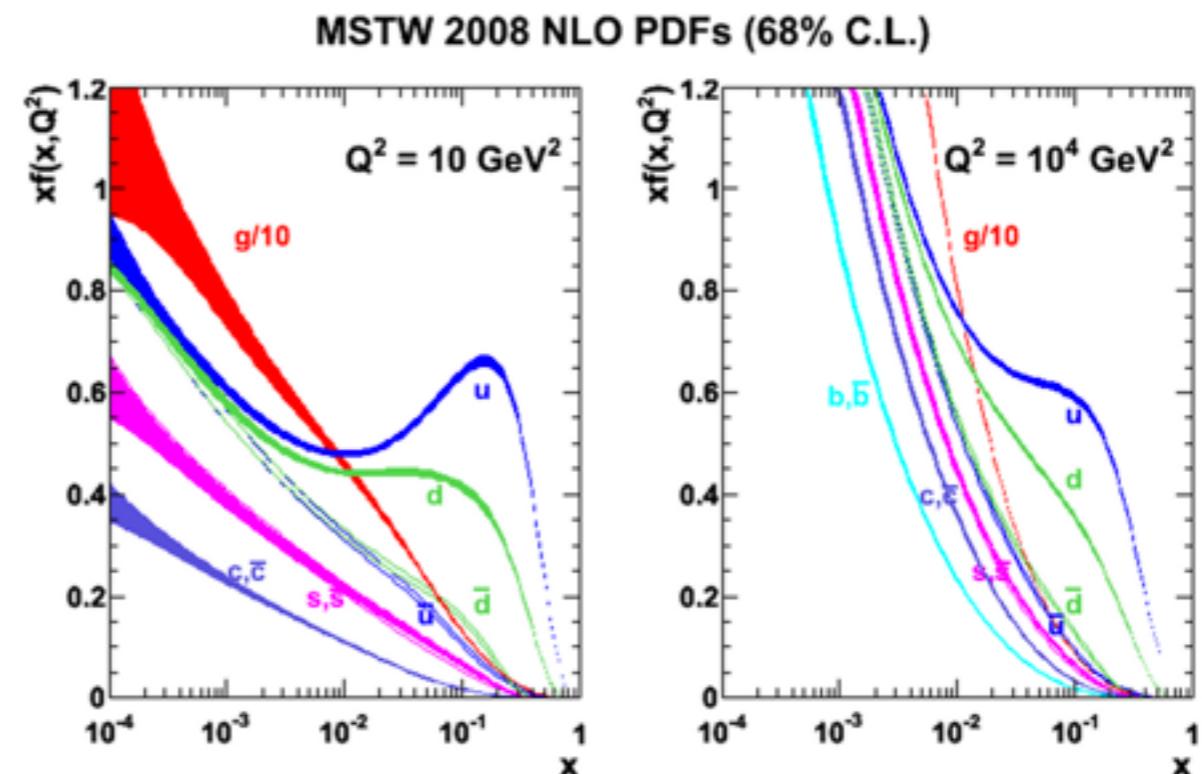
# SIMULATION FOR PDF

Experimental data sets  
used for fitting CTEQ10 NNLO

Experimental data set	$N_{\text{pt}}$	CT10NNLO	CT10W
Combined HERA1 NC and CC DIS [60]	579	1.07	1.17
BCDMS $F_2^p$ [61]	339	1.16	1.14
BCDMS $F_2^d$ [62]	251	1.16	1.12
NMC $F_2^p$ [63]	201	1.66	1.71
NMC $F_2^d/F_2^p$ [63]	123	1.23	1.28
CDHSW $F_2^p$ [64]	85	0.83	0.66
CDHSW $F_3^p$ [64]	96	0.81	0.75
CCFR $F_2^p$ [65]	69	0.98	1.02
CCFR $xF_3^p$ [66]	86	0.40	0.59
NuTeV neutrino dimuon SIDIS [67]	38	0.78	0.94
NuTeV antineutrino dimuon SIDIS [67]	33	0.86	0.91
CCFR neutrino dimuon SIDIS [68]	40	1.20	1.25
CCFR antineutrino dimuon SIDIS [68]	38	0.70	0.78
H1 $F_2^c$ [69]	8	1.17	1.26
H1 $\sigma_r^c$ for $c\bar{c}$ [70, 71]	10	1.63	1.54
ZEUS $F_2^c$ [72]	18	0.74	0.90
ZEUS $F_2^c$ [73]	27	0.62	0.76
E605 Drell-Yan process, $\sigma(pA)$ [74]	119	0.80	0.81
E866 Drell Yan process, $\sigma(pd)/(2\sigma(pp))$ [75]	15	0.65	0.64
E866 Drell-Yan process, $\sigma(pp)$ [76]	184	1.27	1.21
CDF Run-1 W charge asymmetry [77]	11	1.22	1.24
CDF Run-2 W charge asymmetry [78]	11	1.04	1.02
DØ Run-2 $W \rightarrow e\nu_e$ charge asymmetry [79]	12	2.17	2.11
DØ Run-2 $W \rightarrow \mu\nu_\mu$ charge asymmetry [80]	9	1.65	1.49
DØ Run-2 Z rapidity distribution [81]	28	0.56	0.54
CDF Run-2 Z rapidity distribution [82]	29	1.60	1.44
CDF Run-2 inclusive jet production [83]	72	1.42	1.55
DØ Run-2 inclusive jet production [84]	110	1.04	1.13
Total:	2641	1.11	1.13

[arXiv:1309.0025](https://arxiv.org/abs/1309.0025) [hep-ph]

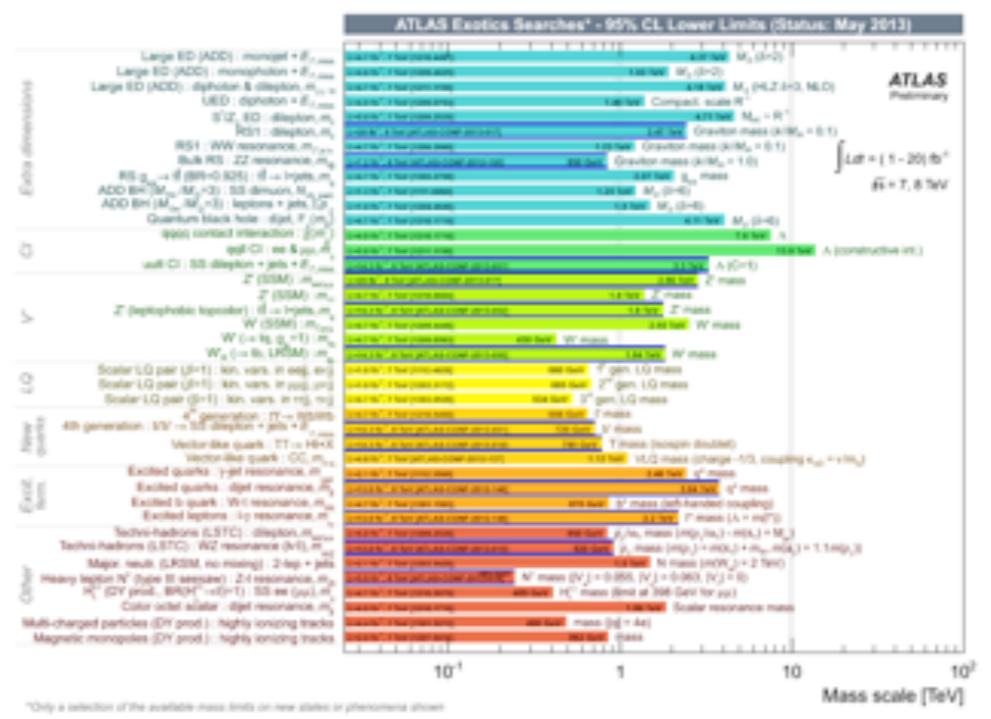
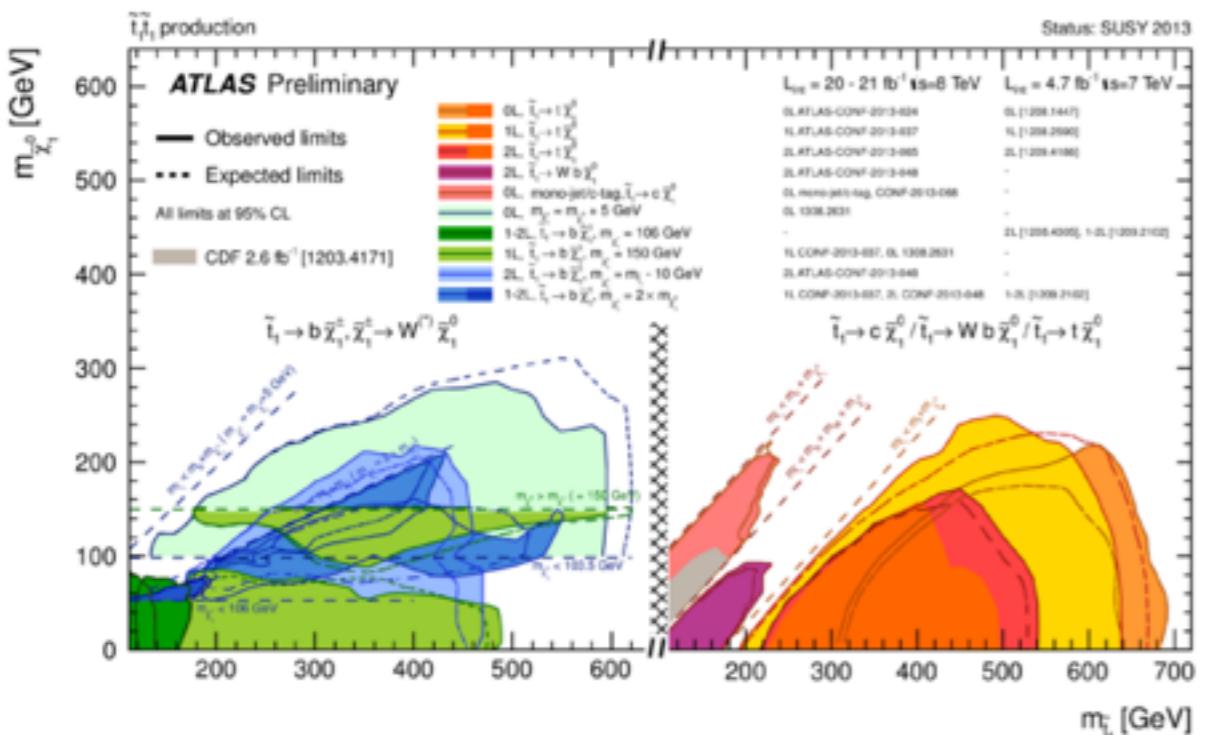
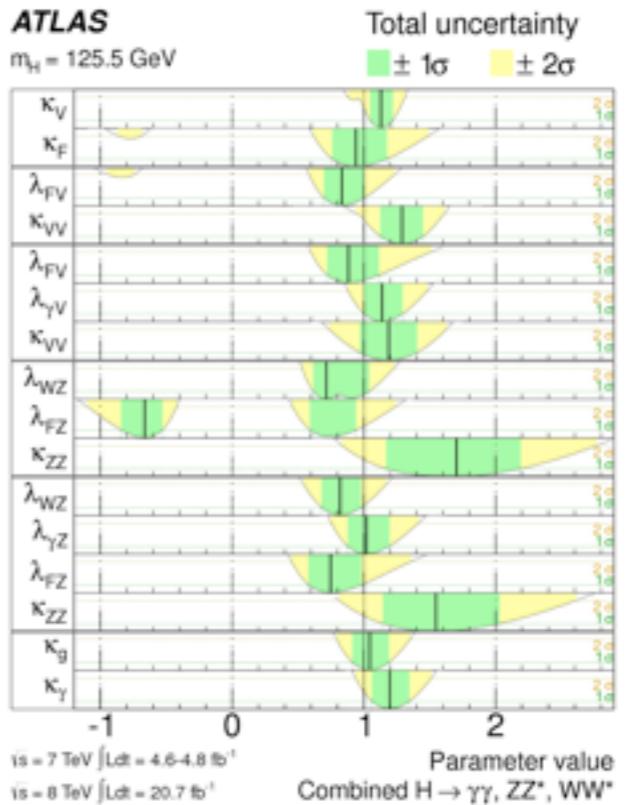
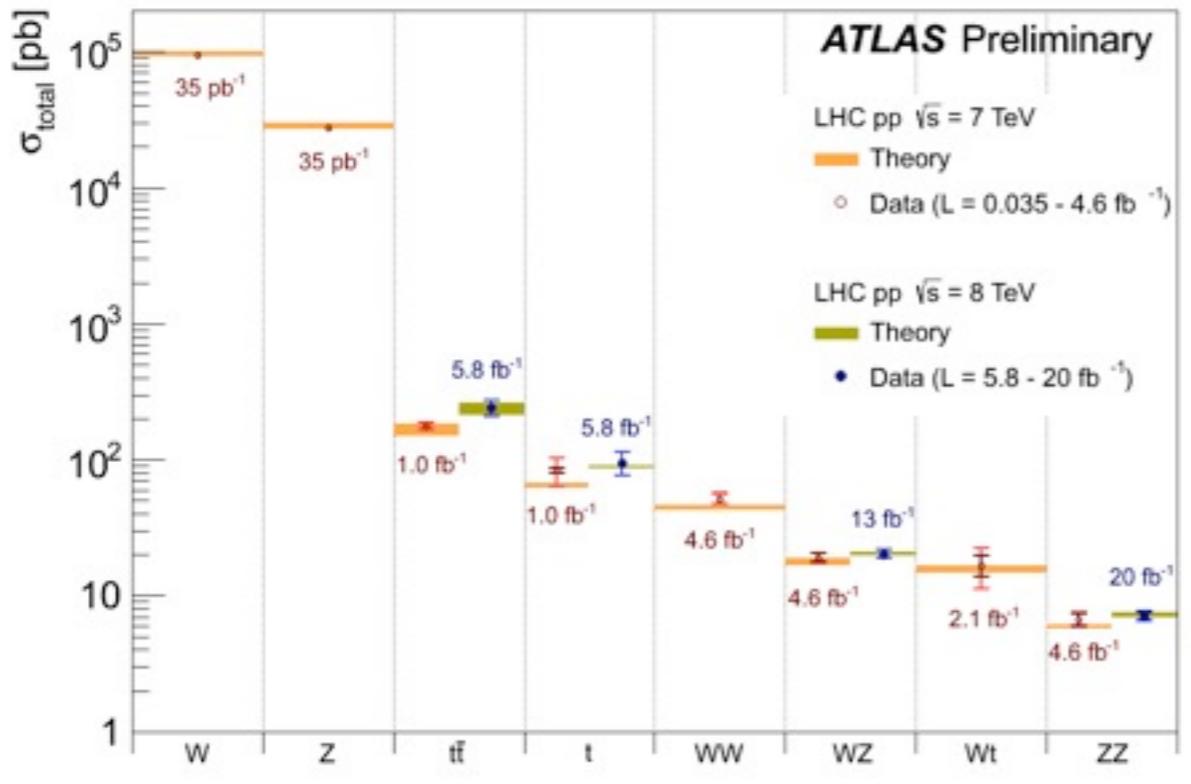
- Parton distribution functions are physical observables crucial for any hadron collider programme
- Obtained via a fitting procedure to existing data sets (especially  $e^+ p$  deep inelastic collisions)
- Simulation of all the experiments considered is indispensable for extracting these PDF

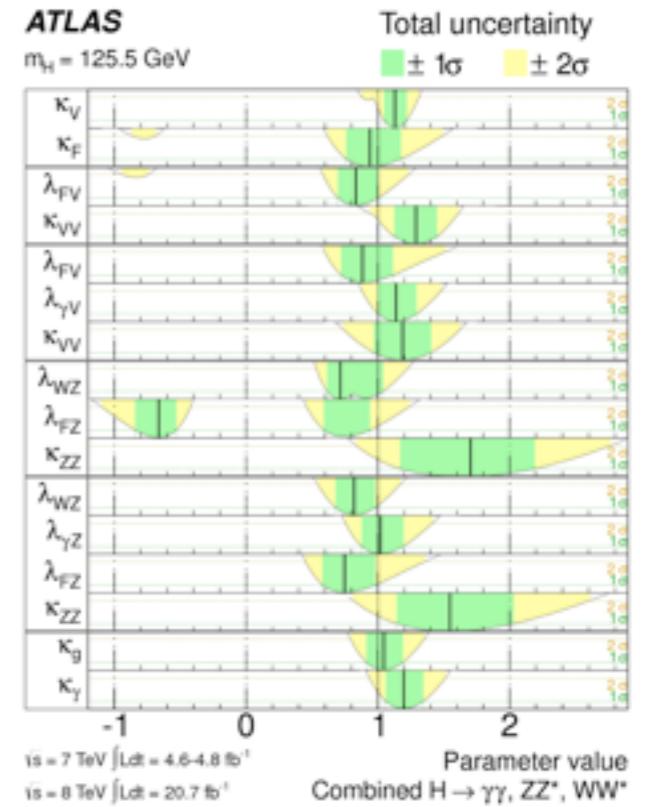
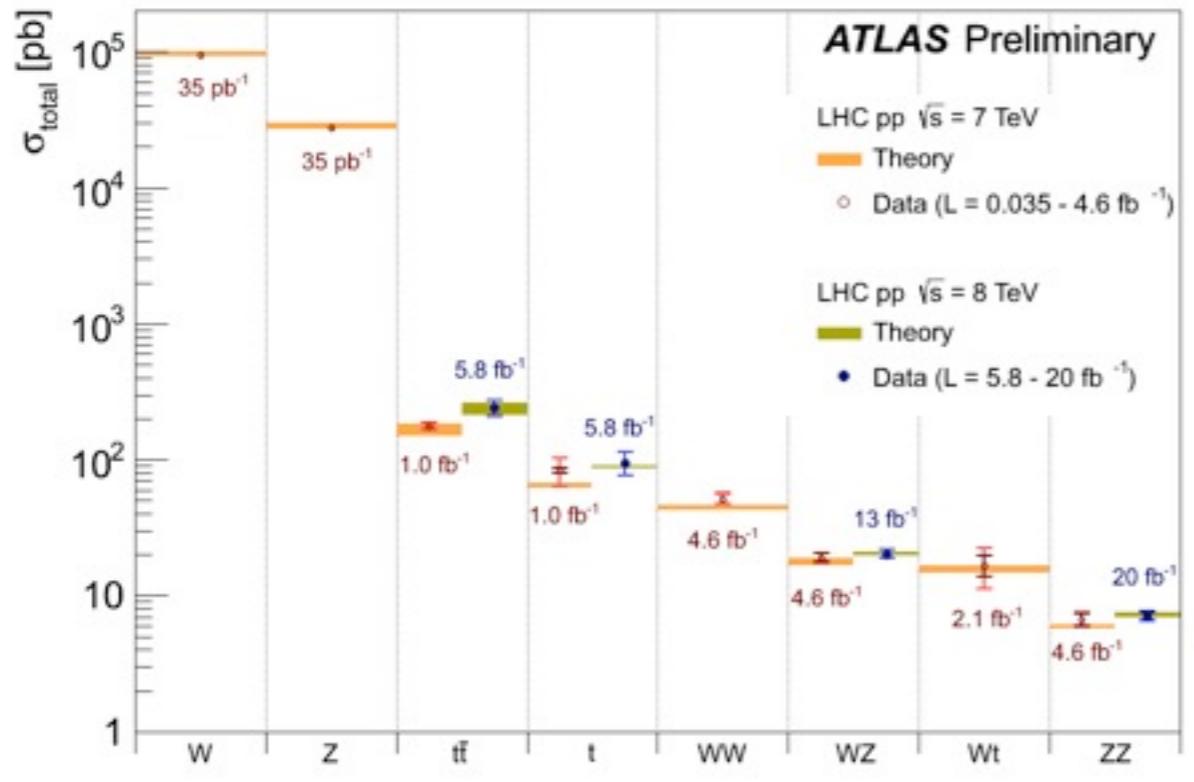


# MOTIVATION: SUMMARY

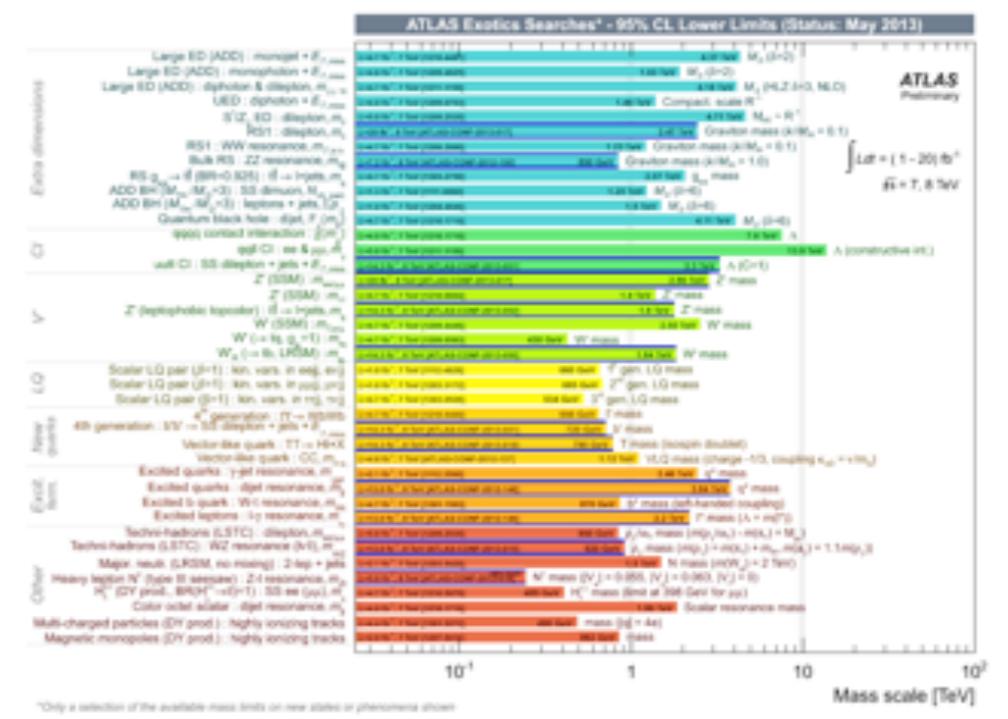
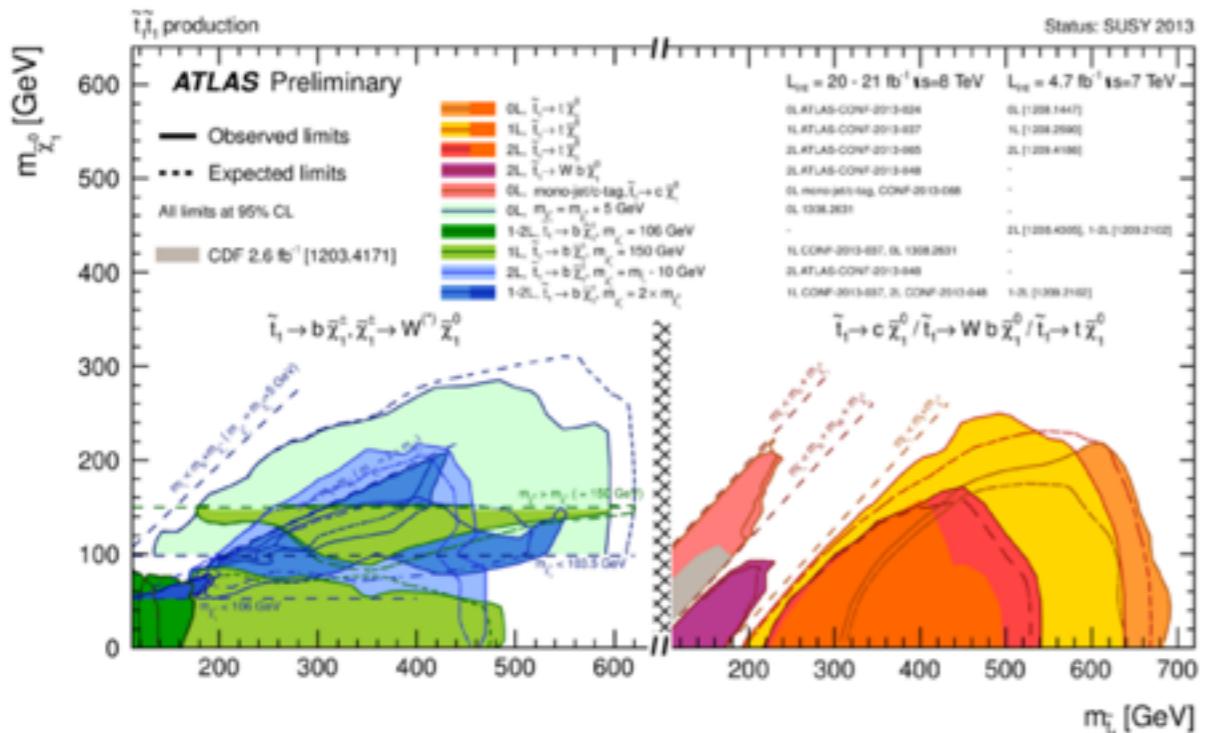
- Accurate and experimental friendly predictions for collider physics range from being very useful to strictly necessary.
- SM measurements and exclusions are particularly sensitive to the accuracy of the simulations
- New physics searches require predictions for both background and signal. SM and BSM simulations must be treated the same footing.
- Experimental analysis always involve a mixture of predictions and postdictions, and confidence in the findings rely on Monte-Carlo simulations. (i.e. PDFs)







# 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.

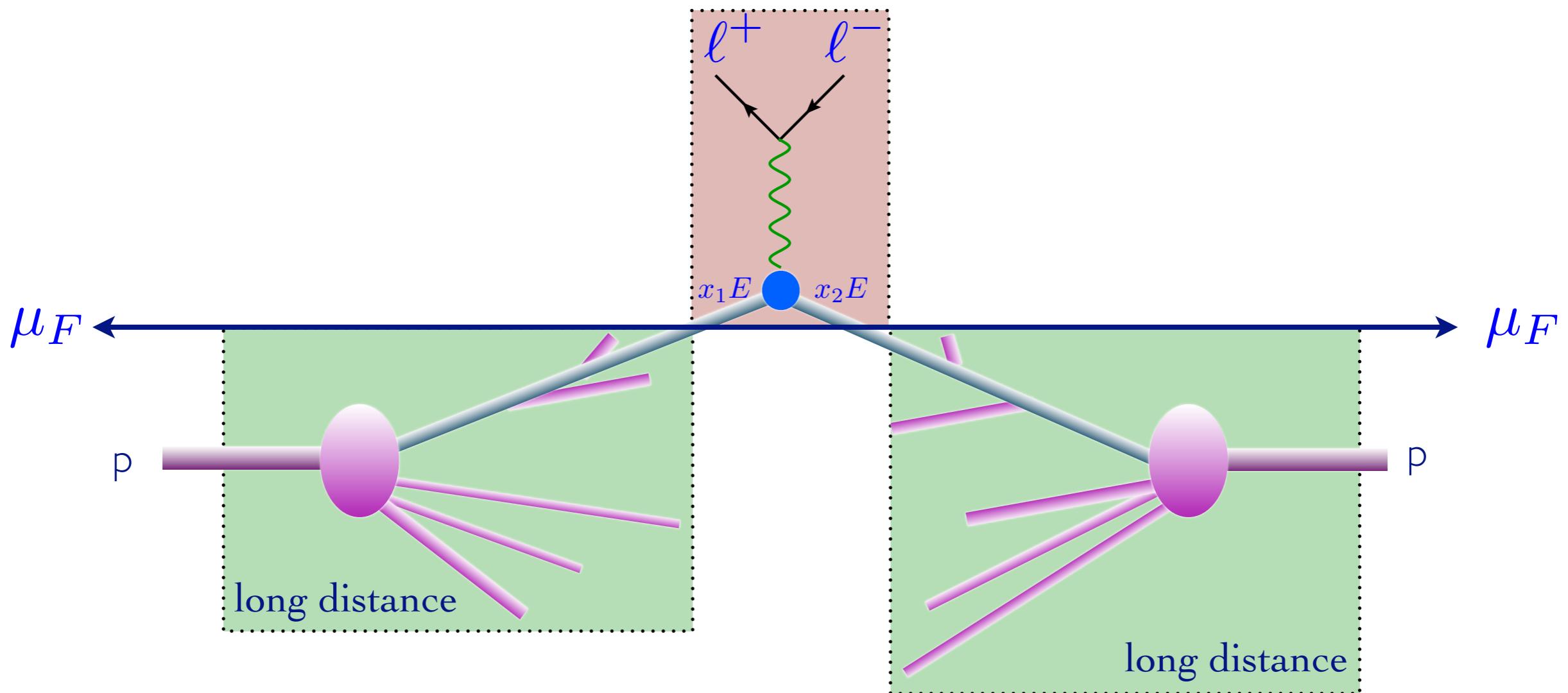
**WE NEED ACCURATE AND FLEXIBLE SIMULATIONS,  
FINE, BUT HOW DO YOU GET FROM**

Theory



TO Exp. data ?

# THE MASTER FORMULA



$$\sum_{a,b} \int dx_1 dx_2 d\Phi_{FS} f_a(x_1, \mu_F) f_b(x_2, \mu_F) \hat{\sigma}_{ab \rightarrow X}(\hat{s}, \mu_F, \mu_R)$$

Phase-space integral      Parton density functions      Parton-level cross section

## FIXED ORDER PERTURBATIVE EXPANSION

$\hat{\sigma}_{ab \rightarrow X}(\hat{s}, \mu_F, \mu_R)$  Parton-level cross section

- The parton-level cross section can be computed as a series in perturbation theory, using the coupling constant as an expansion parameter

$$\hat{\sigma} = \sigma^{\text{Born}} \left( 1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left( \frac{\alpha_s}{2\pi} \right)^2 \sigma^{(2)} + \left( \frac{\alpha_s}{2\pi} \right)^3 \sigma^{(3)} + \dots \right)$$

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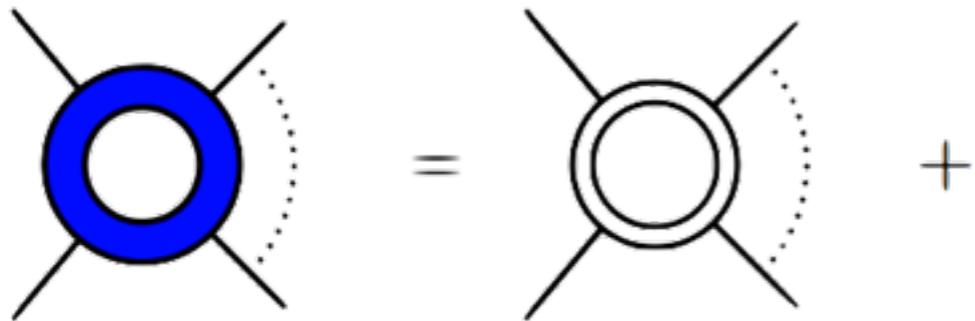
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- Theoretical uncertainty systematically decreases
- Fixed-order predictions is what for ex. MCFM provides; it does not generate events, so only quite inclusive comparison with data.
- Final description in fixed-order predictions is in terms of partons, so not directly useful for comparison with data

Fixed-order NLO contributions have **two** parts

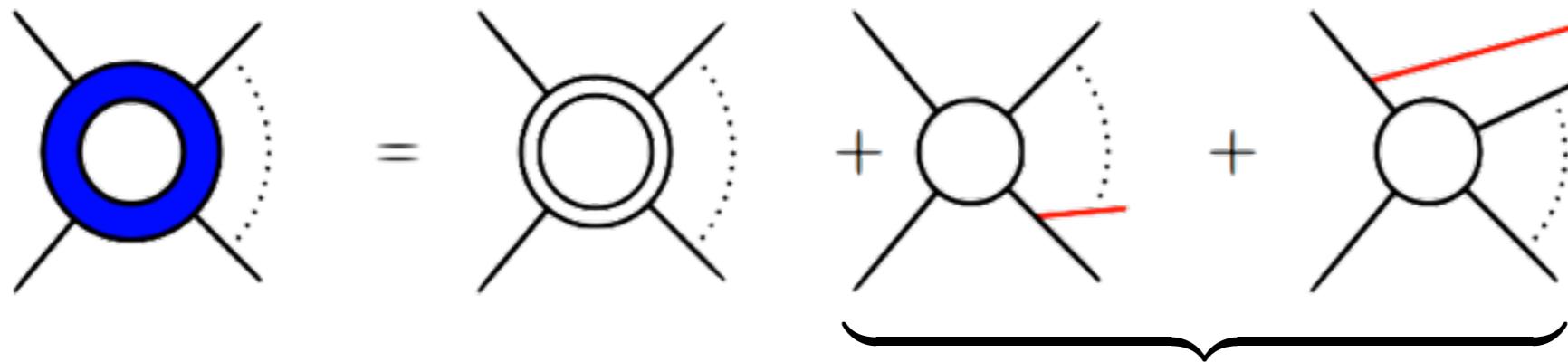
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$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V +$$

Virtual part

Fixed-order NLO contributions have **two** parts

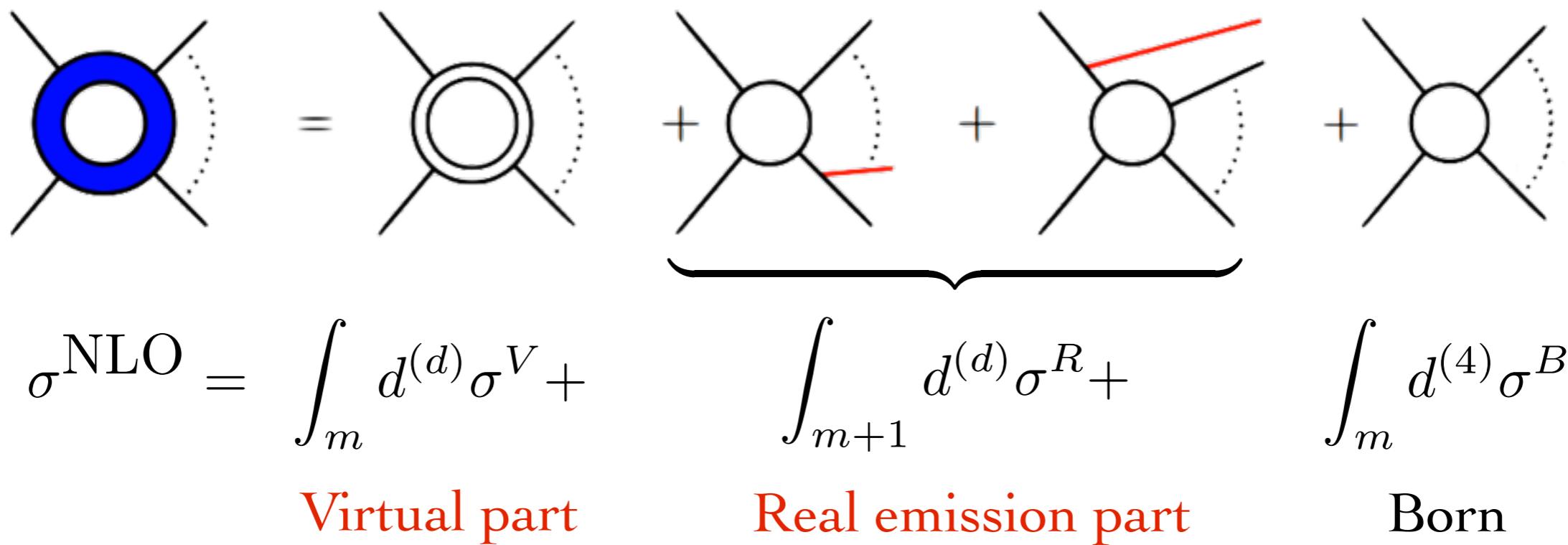


The diagram illustrates the decomposition of a fixed-order NLO cross-section. On the left, a blue shaded loop diagram represents the total NLO cross-section. An equals sign follows it, followed by a white loop diagram (the virtual part) and a sum symbol. To the right of the sum symbol is another sum symbol followed by a bracket under two diagrams: a white loop diagram with a red horizontal line extending from its bottom-left vertex (the real emission part) and a white loop diagram with a red diagonal line extending from its top-left vertex. This visualizes the decomposition into a virtual part and a real emission part.

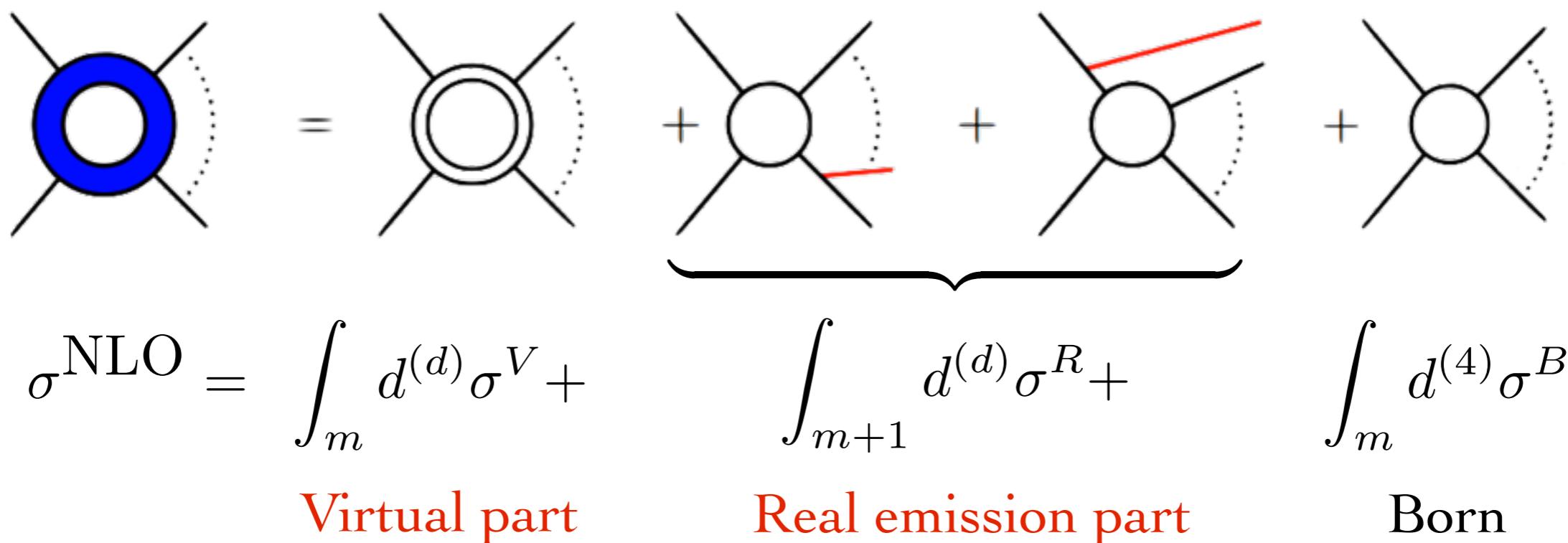
$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V + \underbrace{\int_{m+1} d^{(d)}\sigma^R +}_{\text{Real emission part}}$$

Virtual part

# Fixed-order NLO contributions have two parts

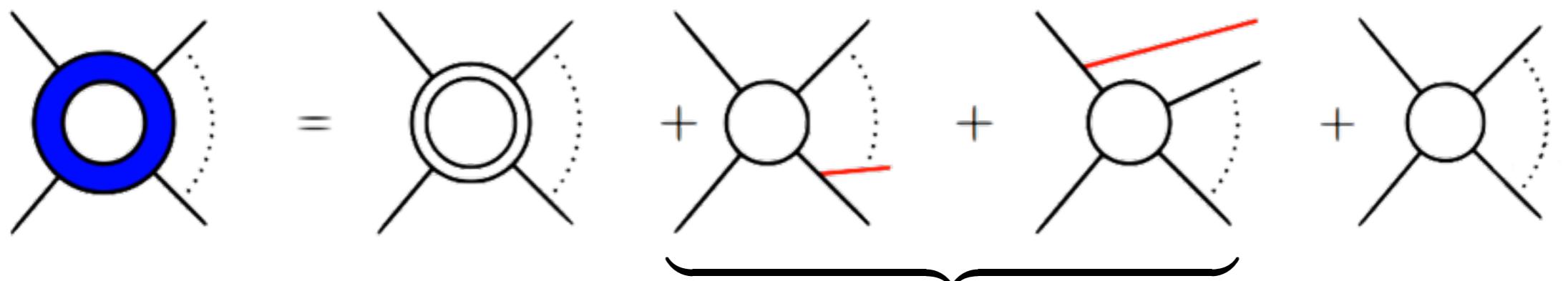


# Fixed-order NLO contributions have **two** parts



- One-Loop used to be the **most challenging** part, no longer!

# Fixed-order NLO contributions have **two** parts



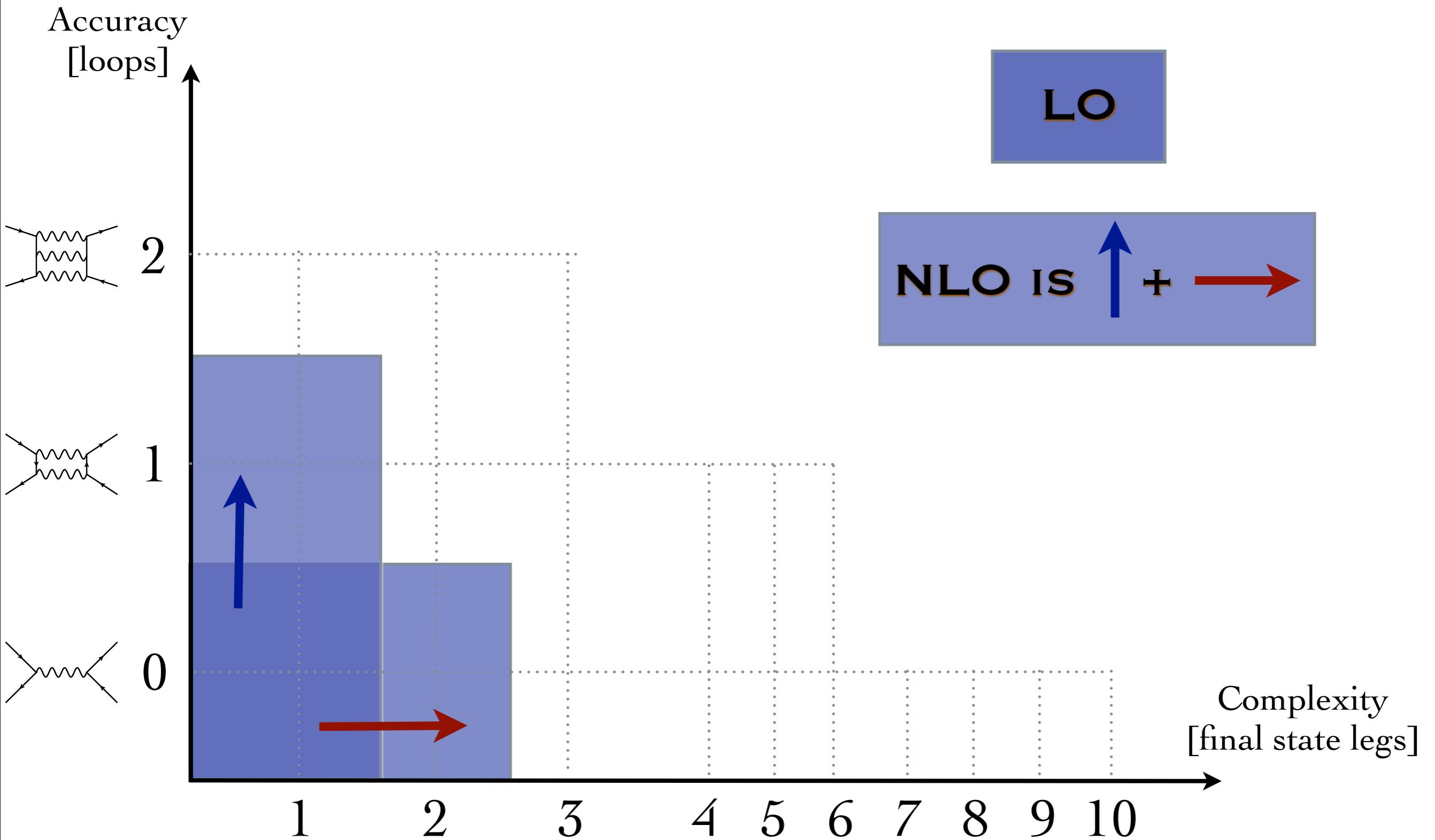
The diagram illustrates the decomposition of a one-loop Feynman diagram (a blue circle) into three parts. The first part is a bare tree-level diagram (a white circle). The second part is a real emission diagram where a red line is emitted from the tree-level vertex. The third part is a virtual correction diagram where a red line enters the tree-level vertex. A brace under the real emission and virtual correction diagrams indicates they are summed.

$$\sigma^{\text{NLO}} = \int_m d^{(d)}\sigma^V + \underbrace{\int_{m+1} d^{(d)}\sigma^R}_{\text{Real emission part}} + \int_m d^{(4)}\sigma^B$$

**Virtual part**                    **Real emission part**                    **Born**

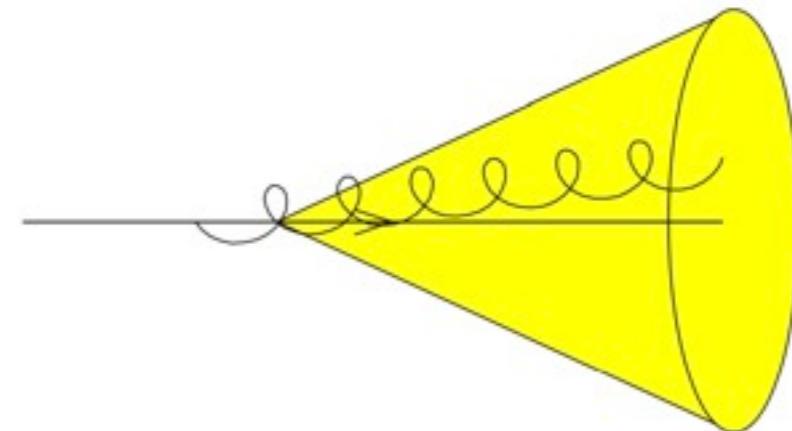
- One-Loop used to be the **most challenging** part, no longer!
- **Virtuels** and **reals** are **separately divergent**; sophisticated **subtraction techniques** necessary to regulate them (Dipoles, FKS)

# COMPUTING NLO



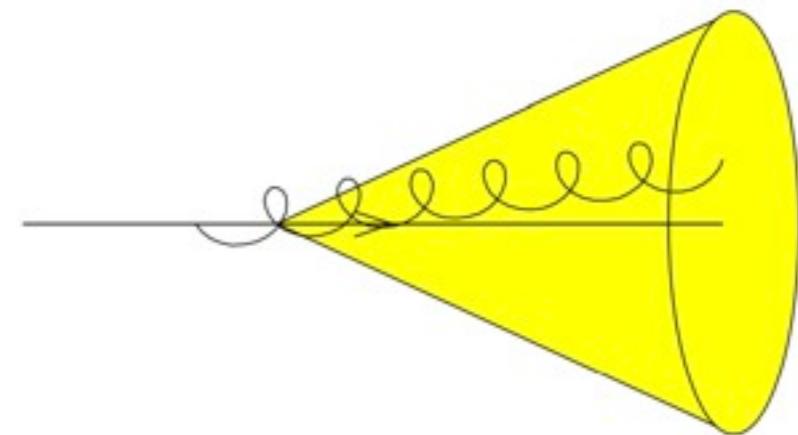
# BEYOND FIXED ORDER

Jet in a fixed-order NLO simulation:

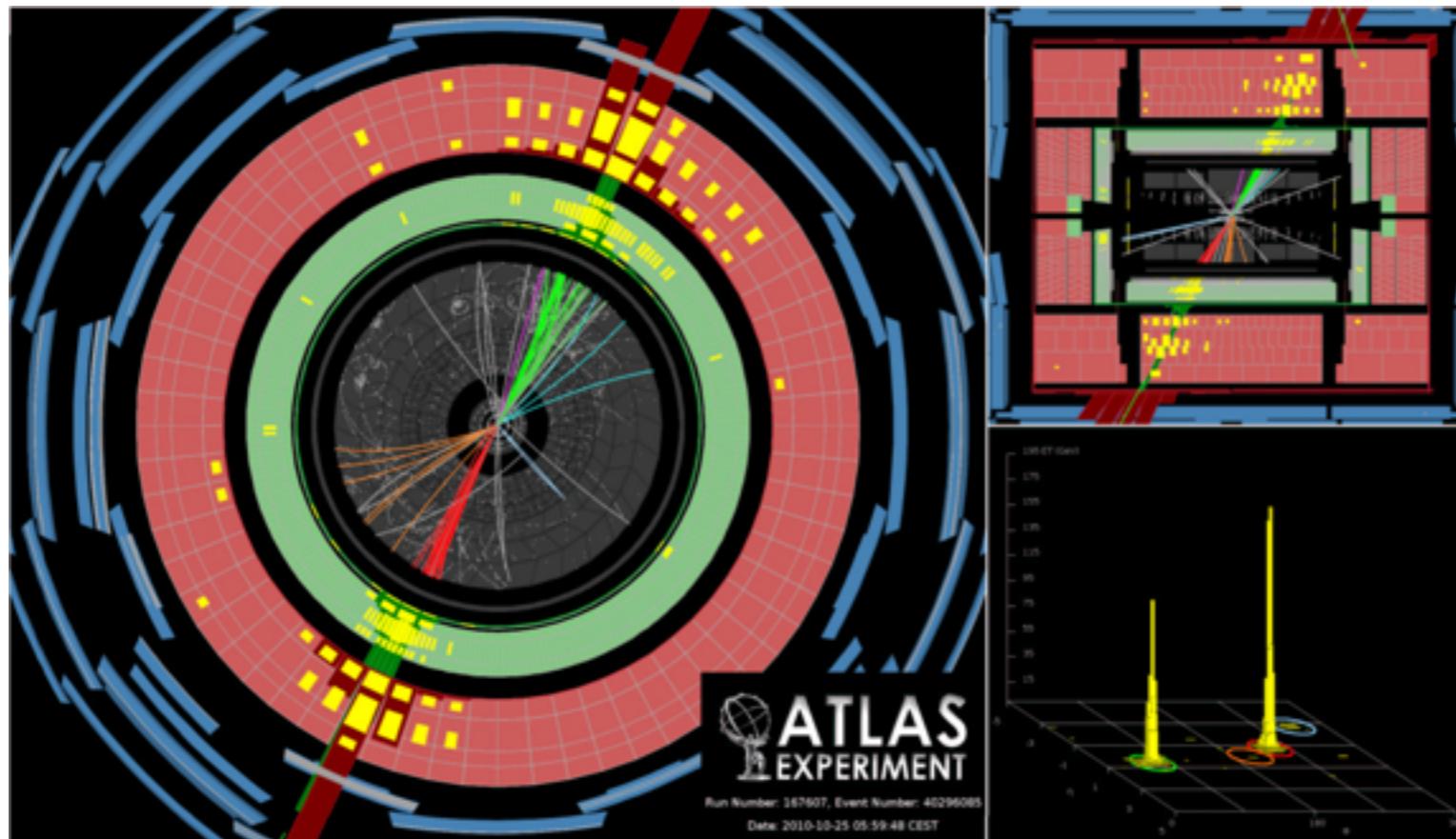


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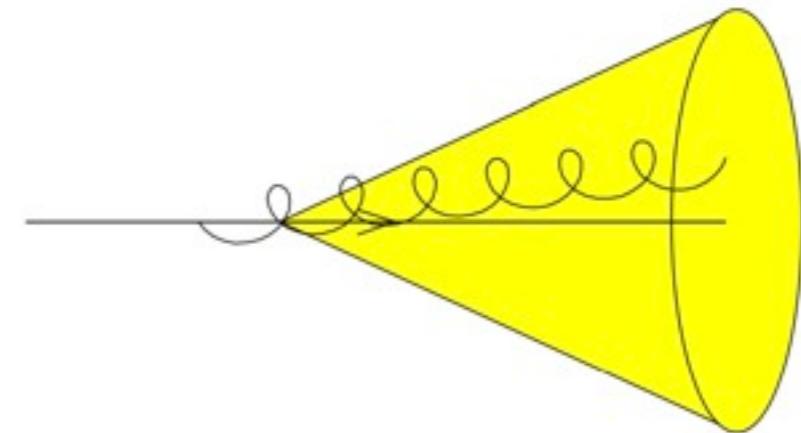


"Ouch"

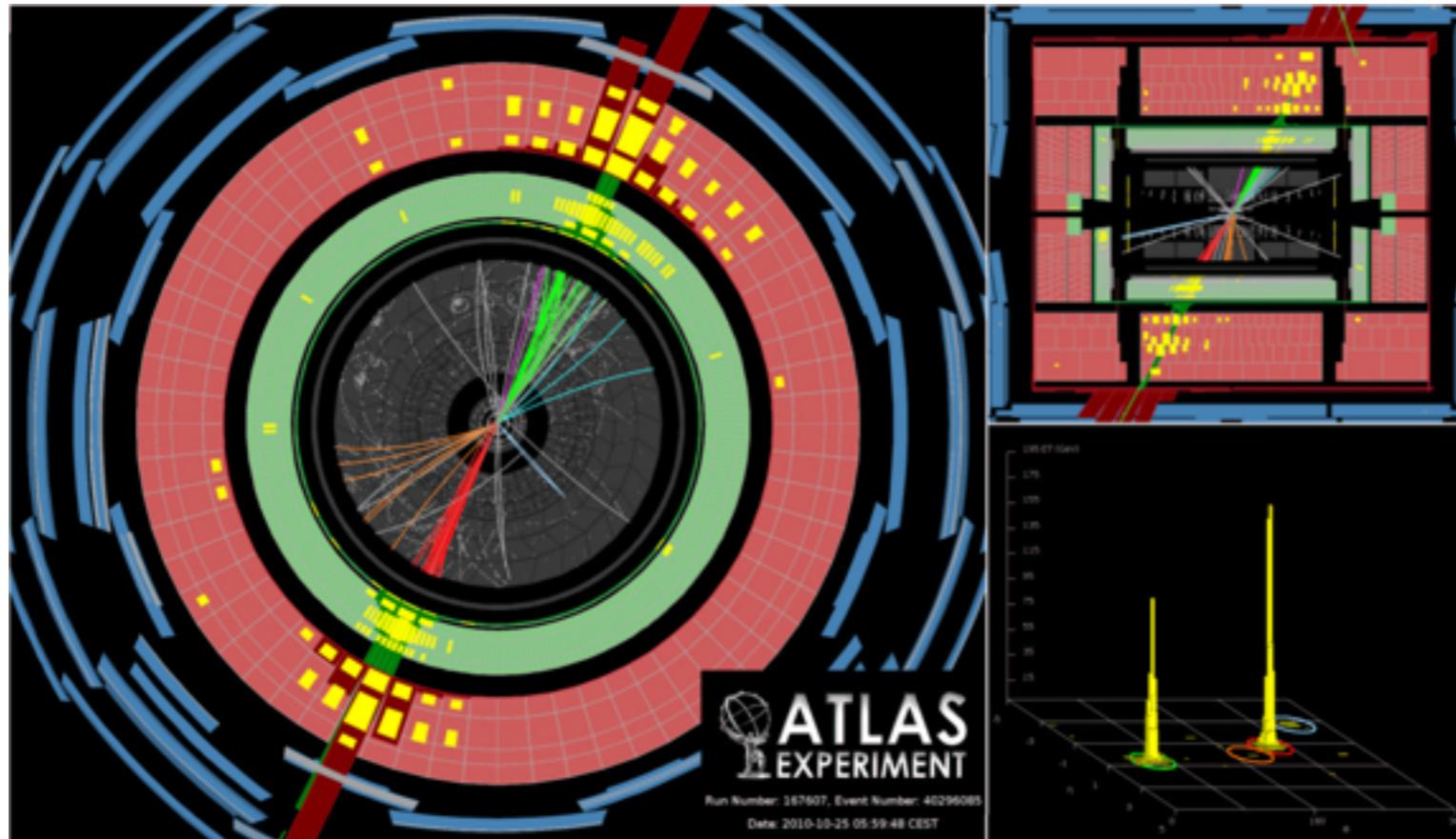


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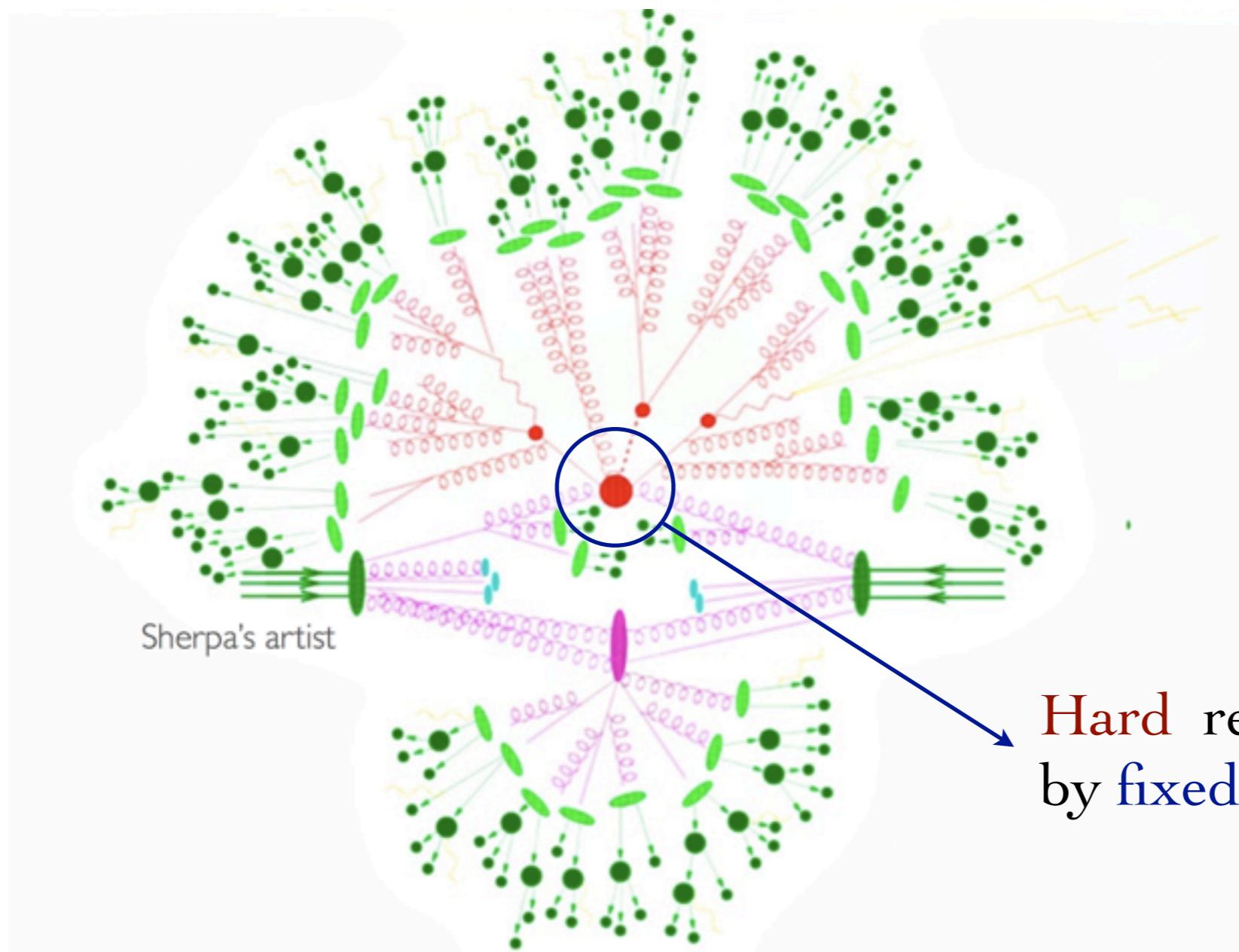


"Ouch"



We need a more **realistic** picture...

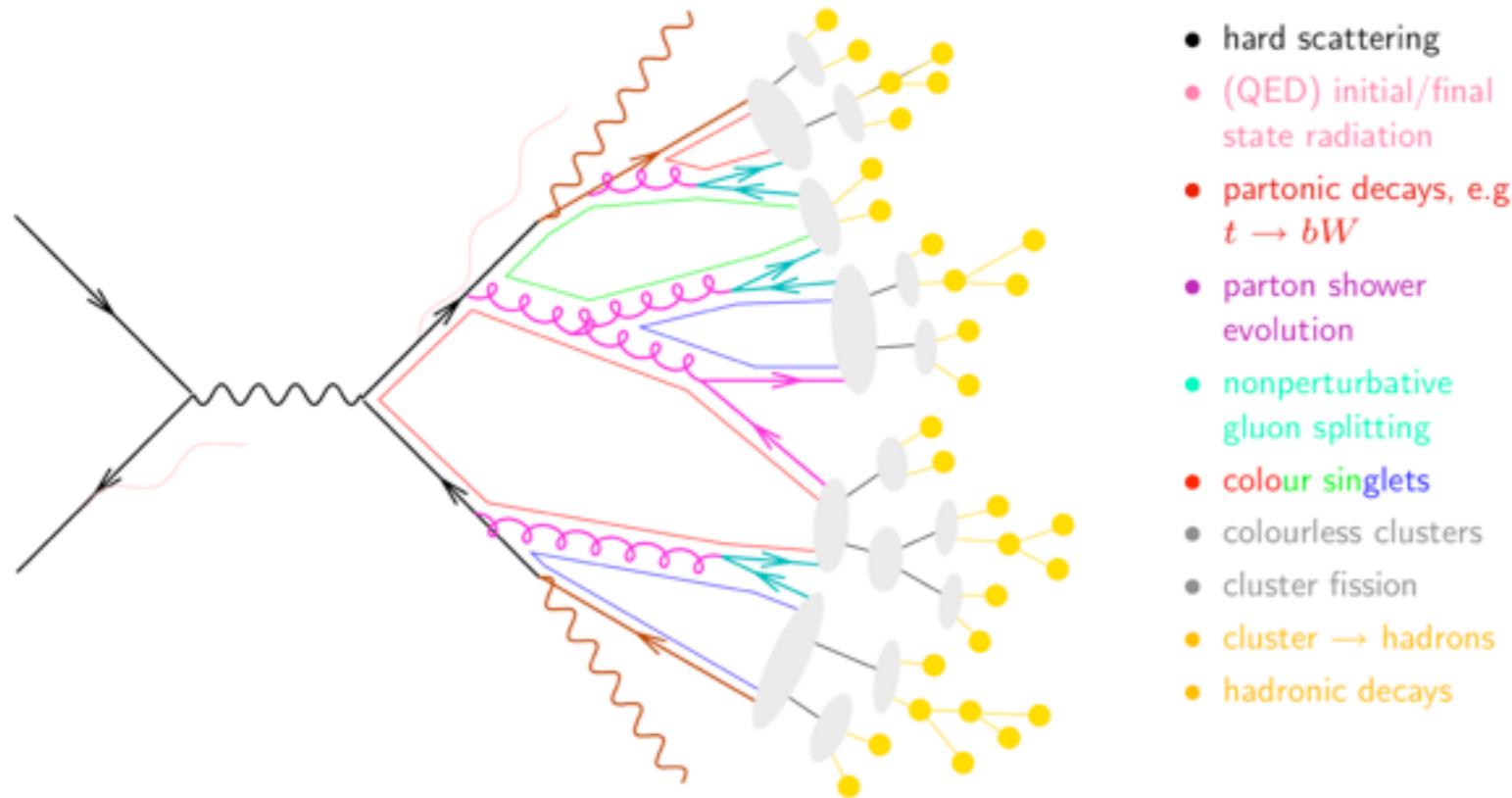
# BEYOND FIXED ORDER



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

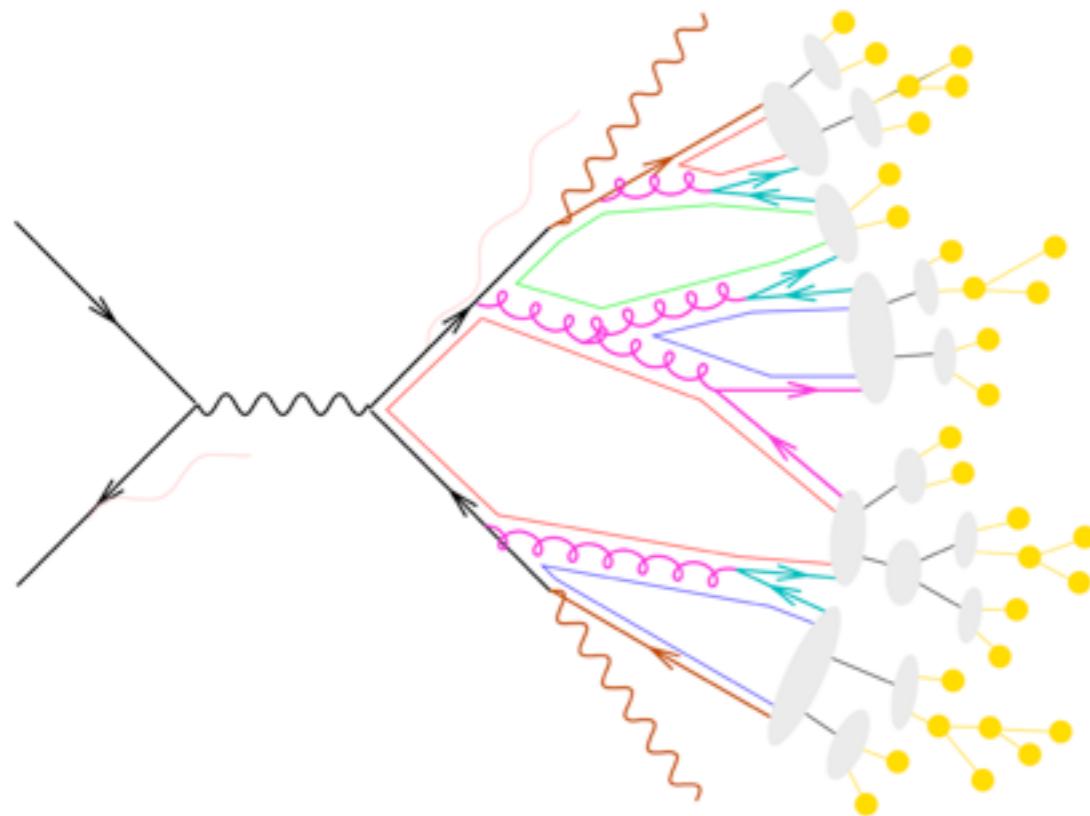
# PARTON SHOWER MONTE-CARLO

- Soft physics describing the radiation of the partons emitted in the hard region of the interaction can be simulated by Parton Shower Monte-Carlo (PSMC)

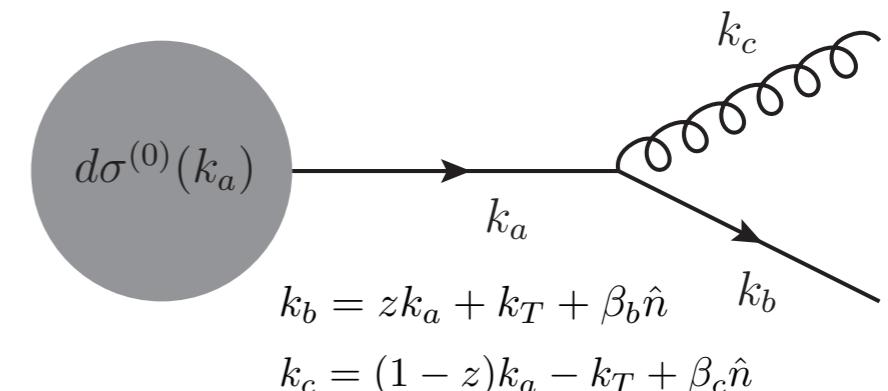


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- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g.  $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster  $\rightarrow$  hadrons
- hadronic decays



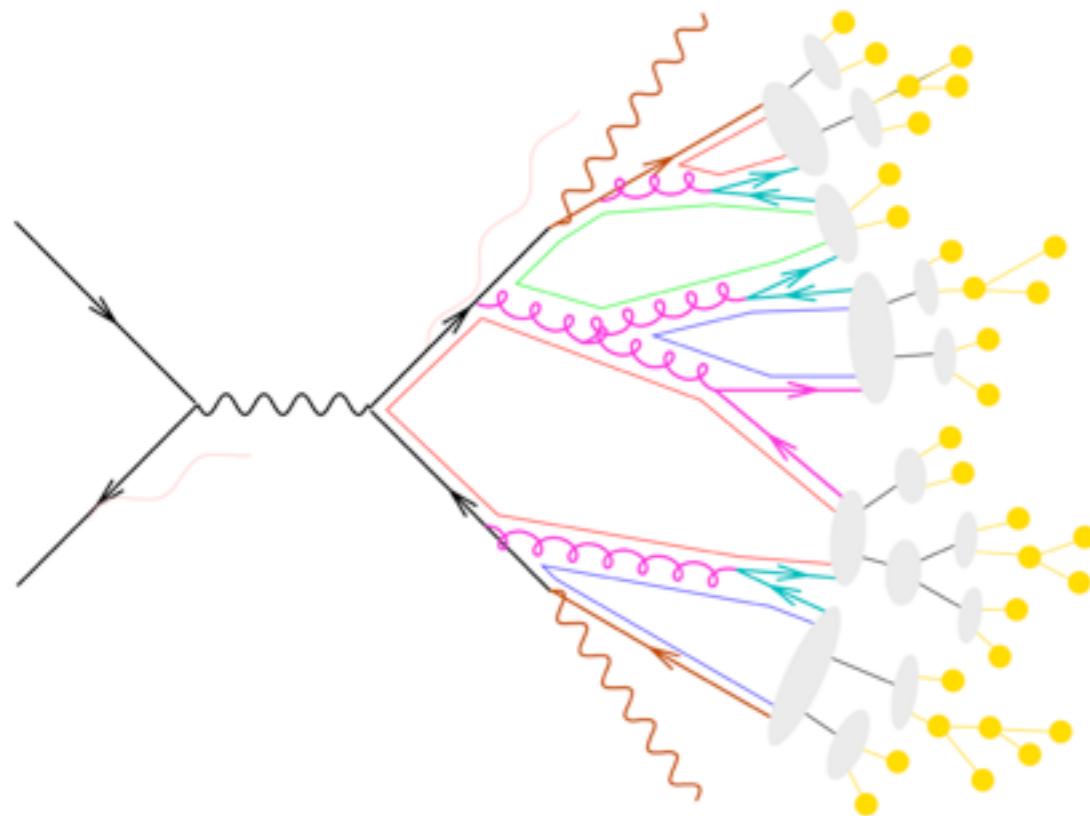
$$d\sigma^{(1,R)} \simeq \mathcal{K} \otimes d\sigma^{(0)}(k_a)$$

$$\left( \mathcal{K} = \frac{\alpha_s}{2\pi} \int dk_T^2 \int_0^1 dz C_F \frac{1+z^2}{1-z} \frac{1}{k_T^2} \right)$$

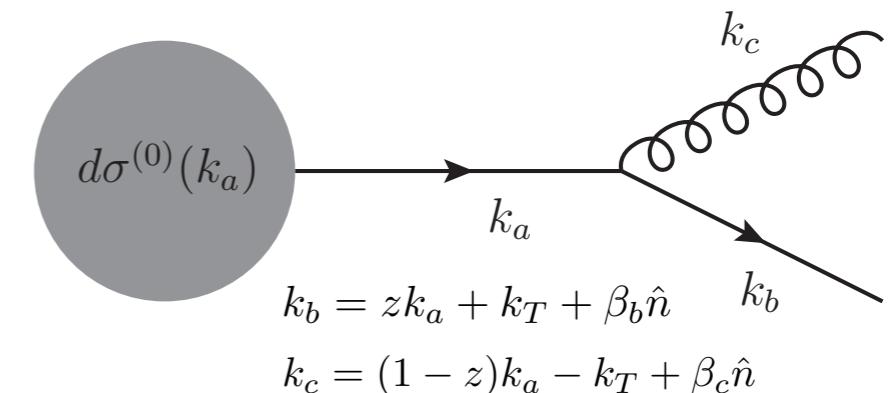
- Start from a 2 $\rightarrow$ 1 or 2 $\rightarrow$ 2 hard process and quasi-classically splits partons with probabilities given by the limiting behavior of QCD in the soft and/or collinear regime. Finally hadronize the many partons using a semi-empirical model.

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- The final products are hadrons which are physical observable. Fully exclusive predictions can then be compared to data.

# 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)
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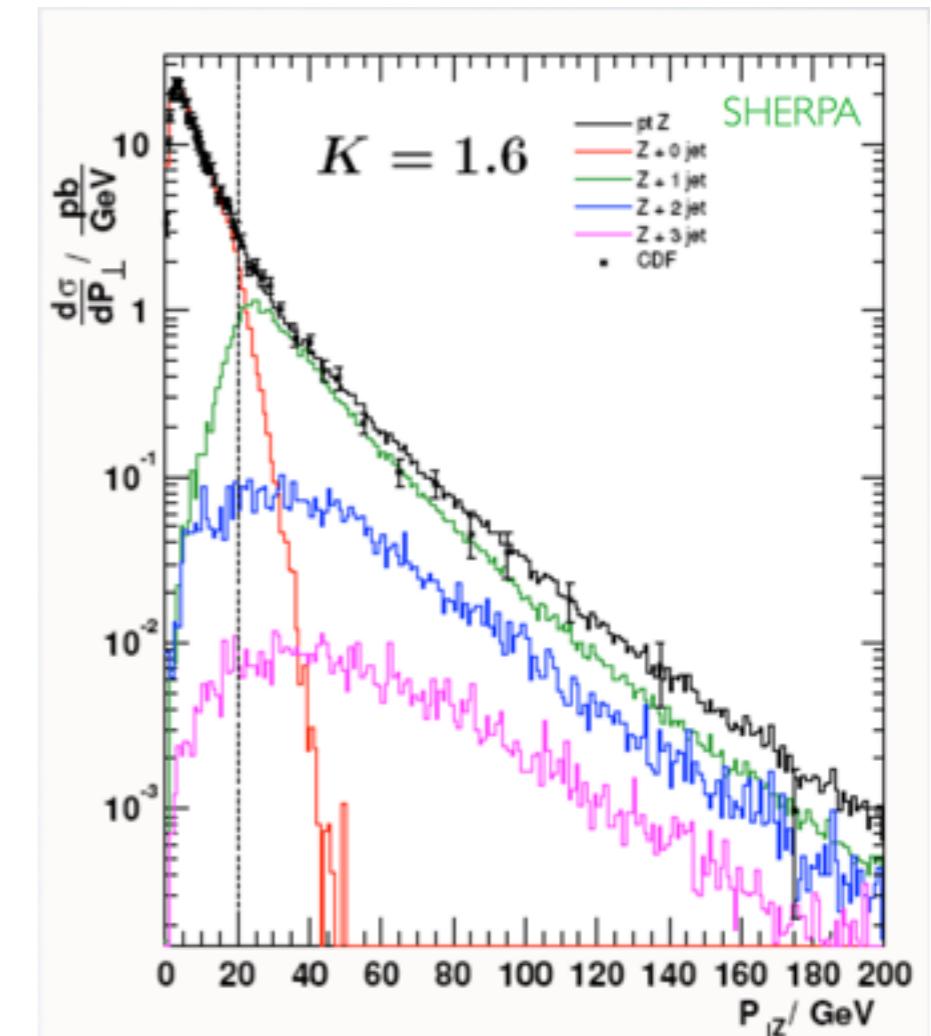
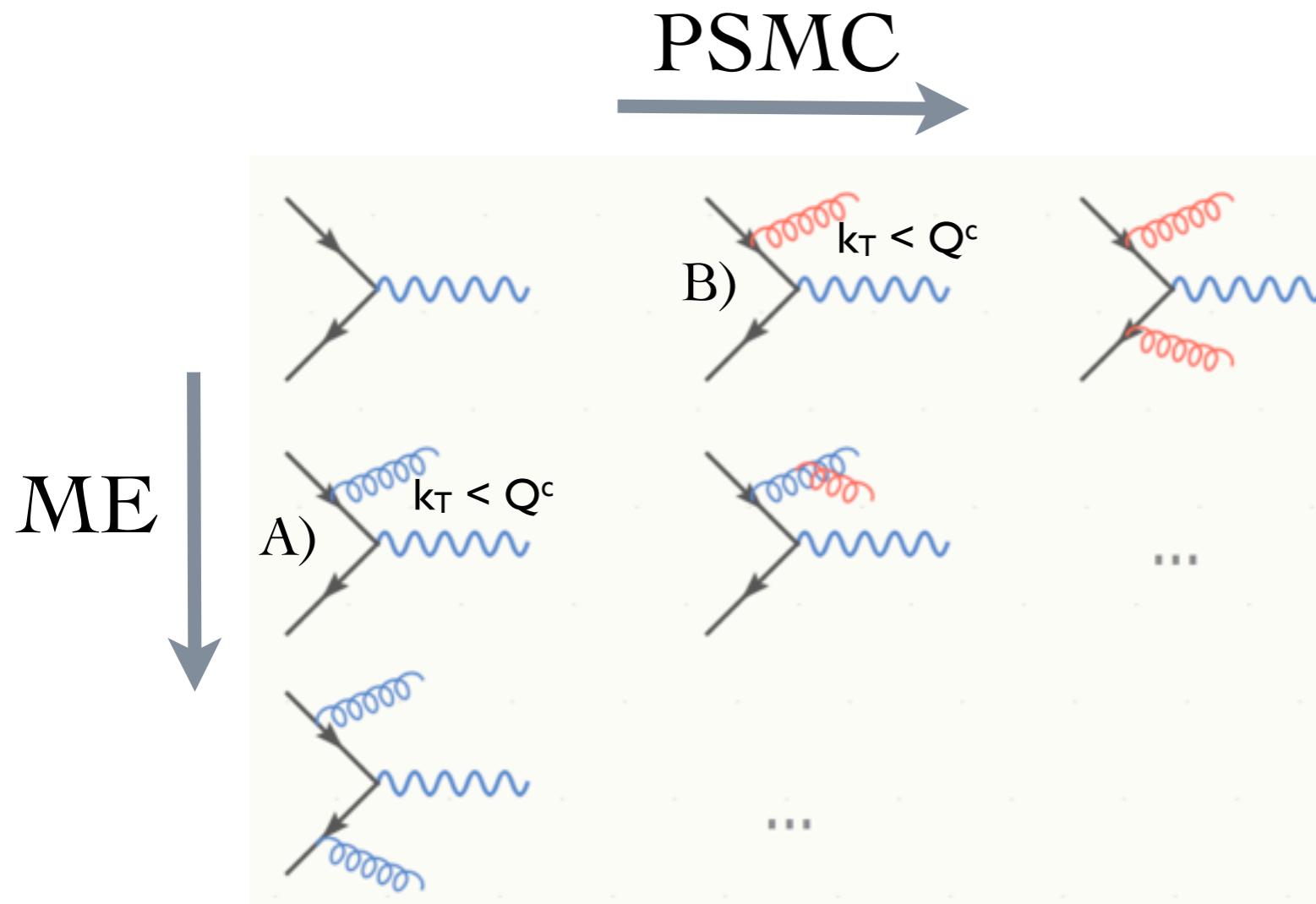
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**COMPLEMENTARY APPROACHES: “MERGE” THEM!**

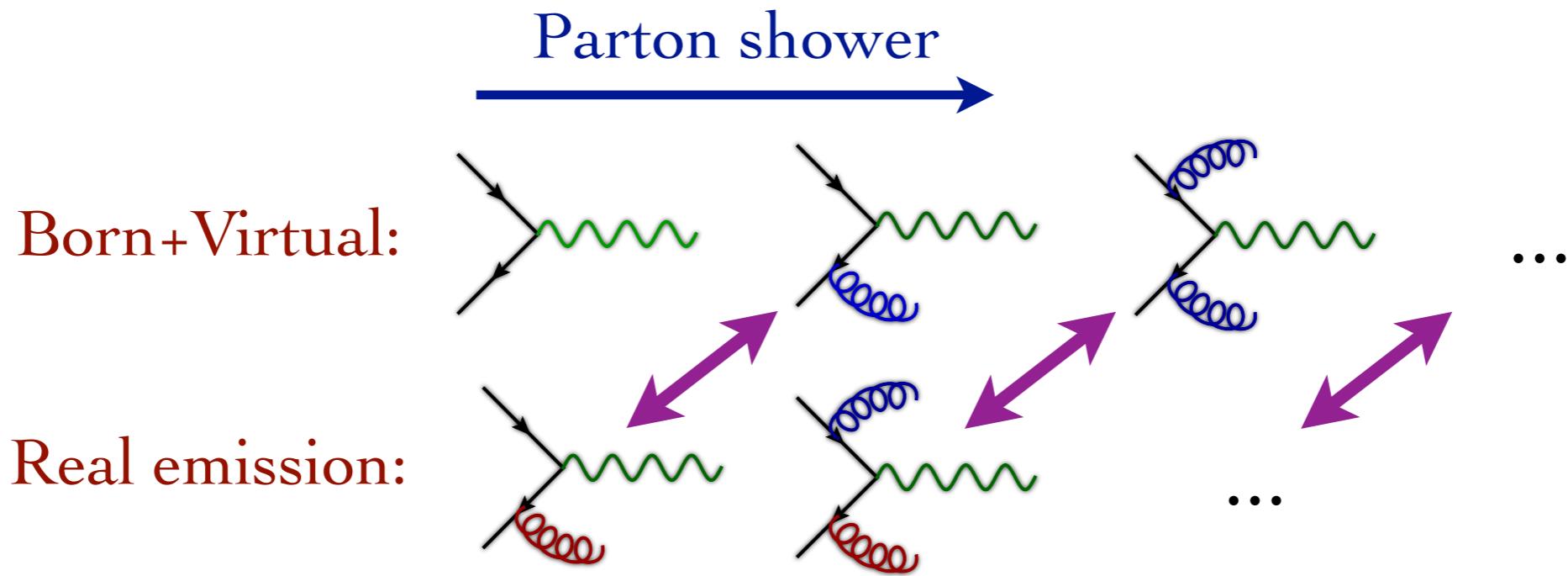
# MERGING ME WITH PSMC



Double counting of **configurations** which can be obtained in different ways (i.e. A and B for ex.) is **avoided** by using matching algorithms (**CKKW**, **MLM**, ...) selecting only one possibility depending on the event kinematic and **a merging scale  $\mu_q$** . The exclusive samples can the be added together into an inclusive one. **Distribution is accurate, but rate is still LO.**

# MATCHING ME WITH PSMC AT NLO

- At NLO one faces even more severe double-counting issues:



- And also part of the virtual contribution is double counted through the definition of the Sudakov factor  $\Delta$

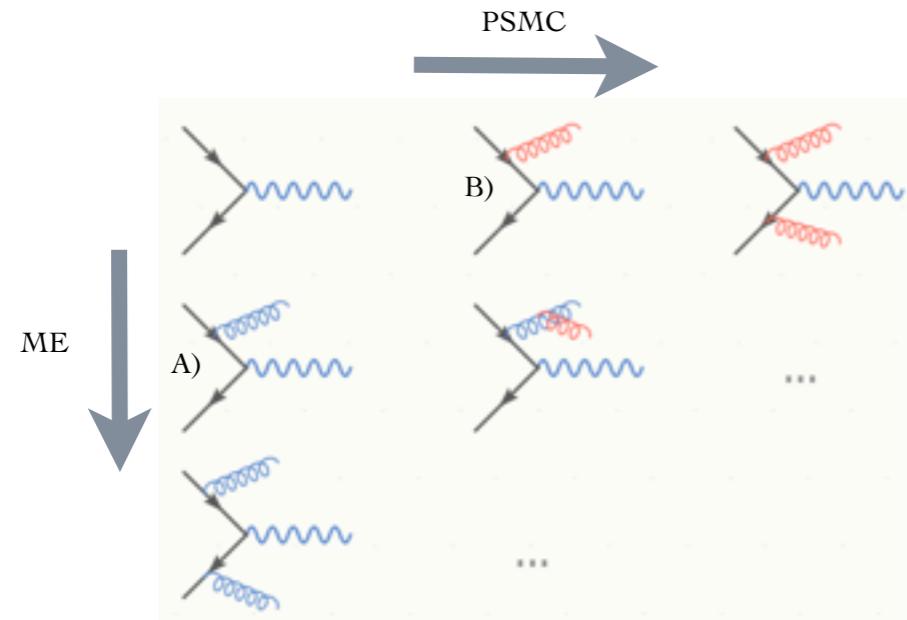
## MC@NLO

1. PSMC dependent
2. Some negative weighted events
3. Quantum interference exact
4. Used by both MG5\_aMC and Sherpa.

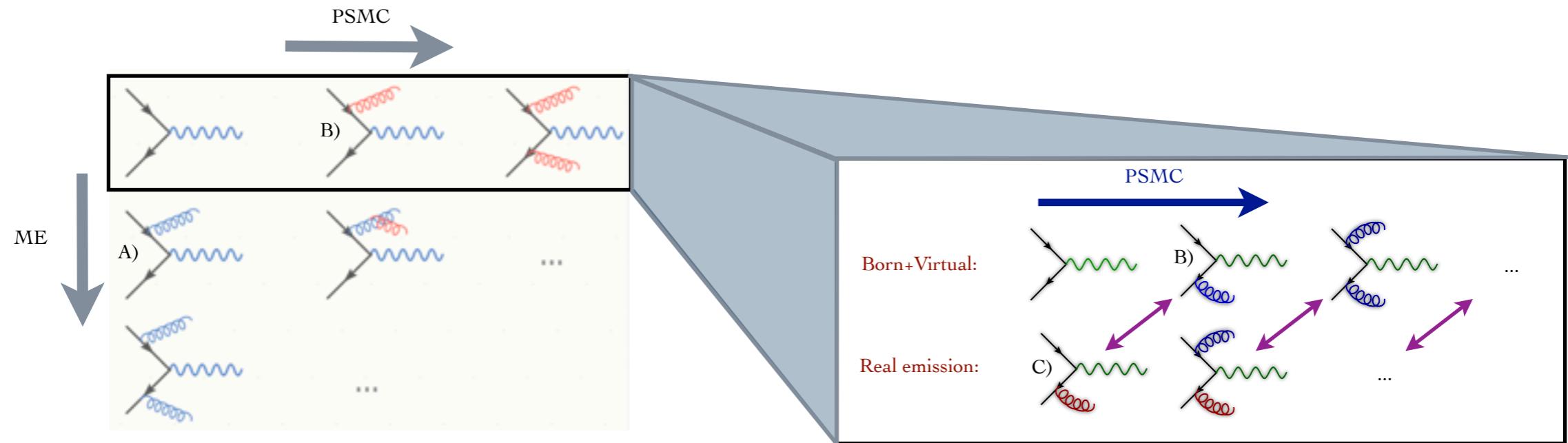
## POWHEG

1. PSMC independent
2. Only positive unit weight
3. Can use existing NLO results via the POWHEG-Box
4. Used by HELAC

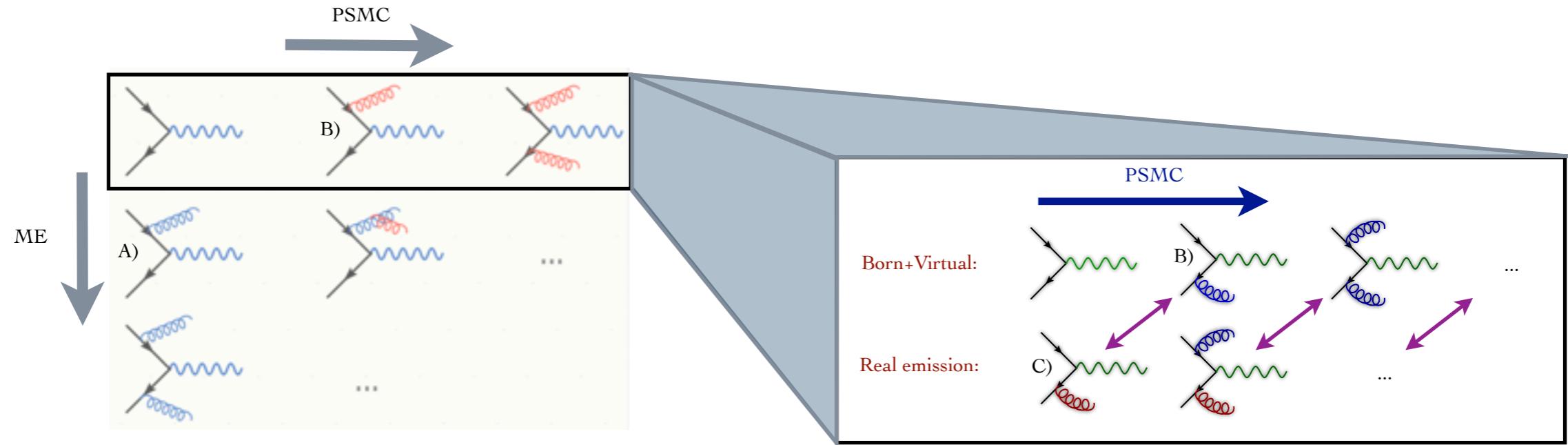
# MATCHING MEETS MERGING



# MATCHING MEETS MERGING

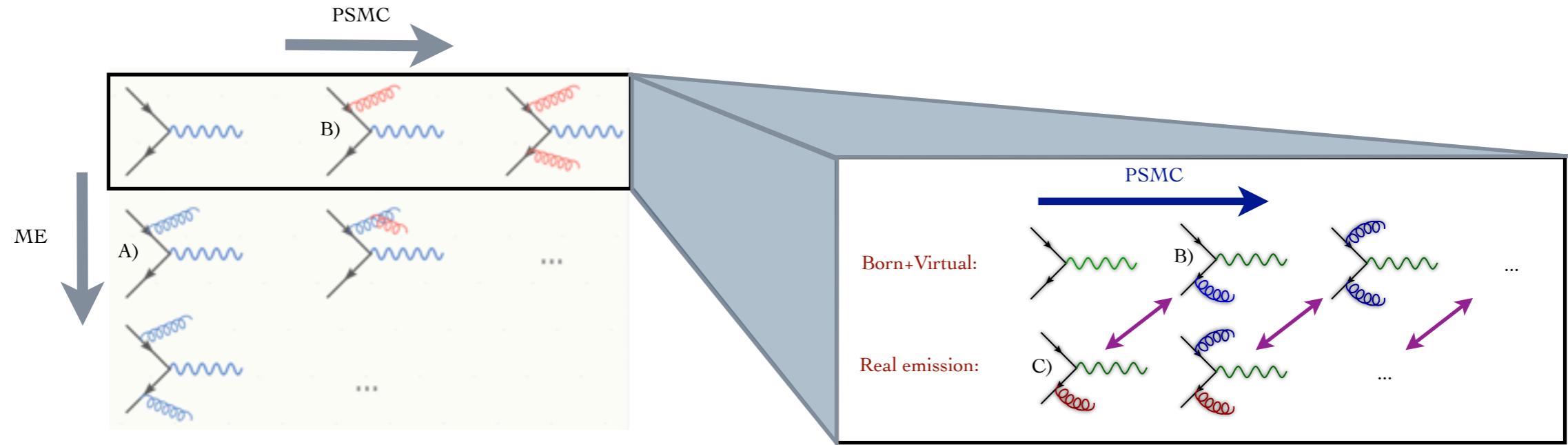


# MATCHING MEETS MERGING



NLO ME of different final state multiplicities interfaced to PSMC. In this case, both of the double counting issues presented before must be addressed together. ( A vs B and B vs C)

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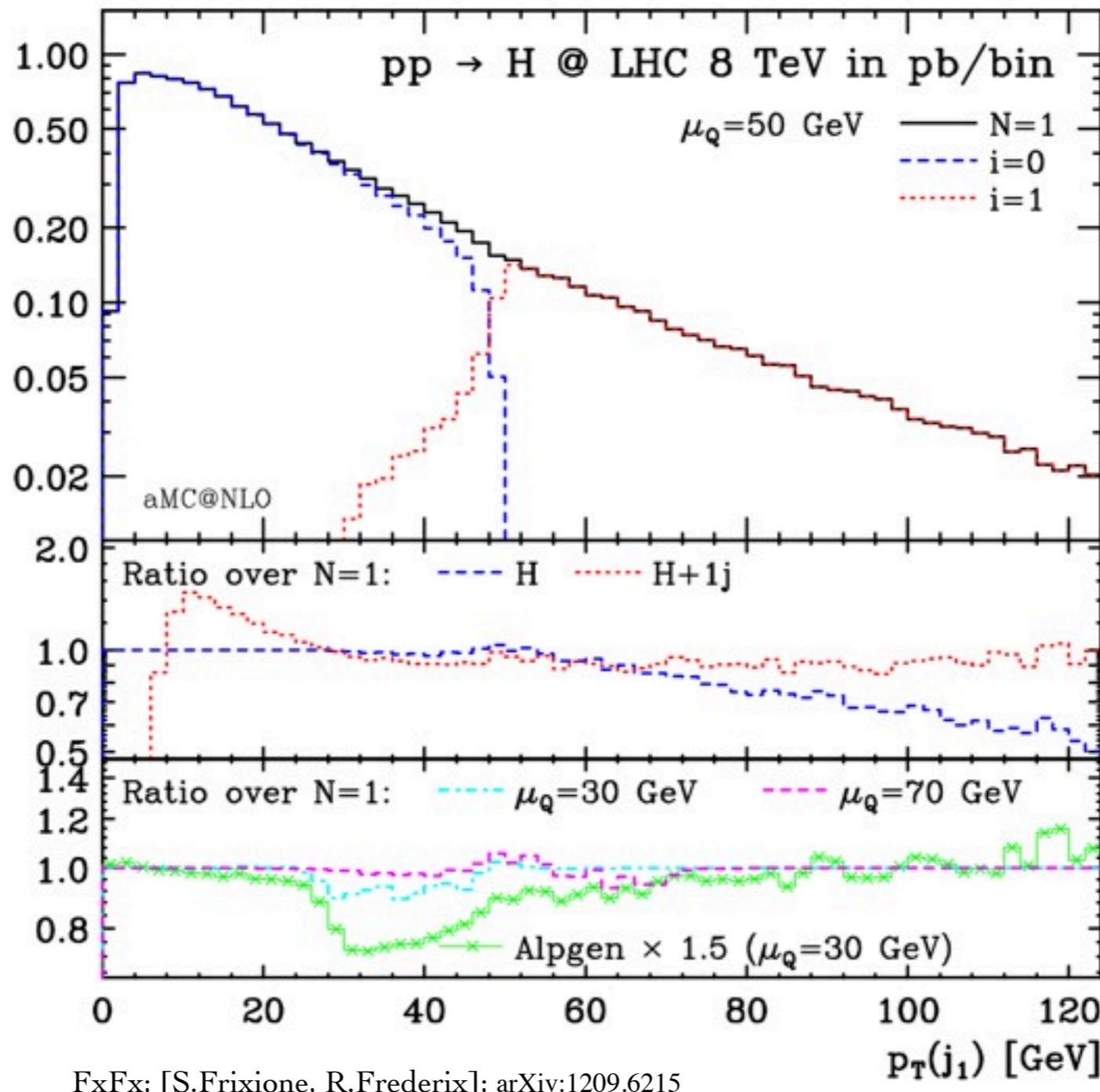
Two main solutions implemented:

FxFx in aMC@NLO

MEPS@NLO in Sherpa

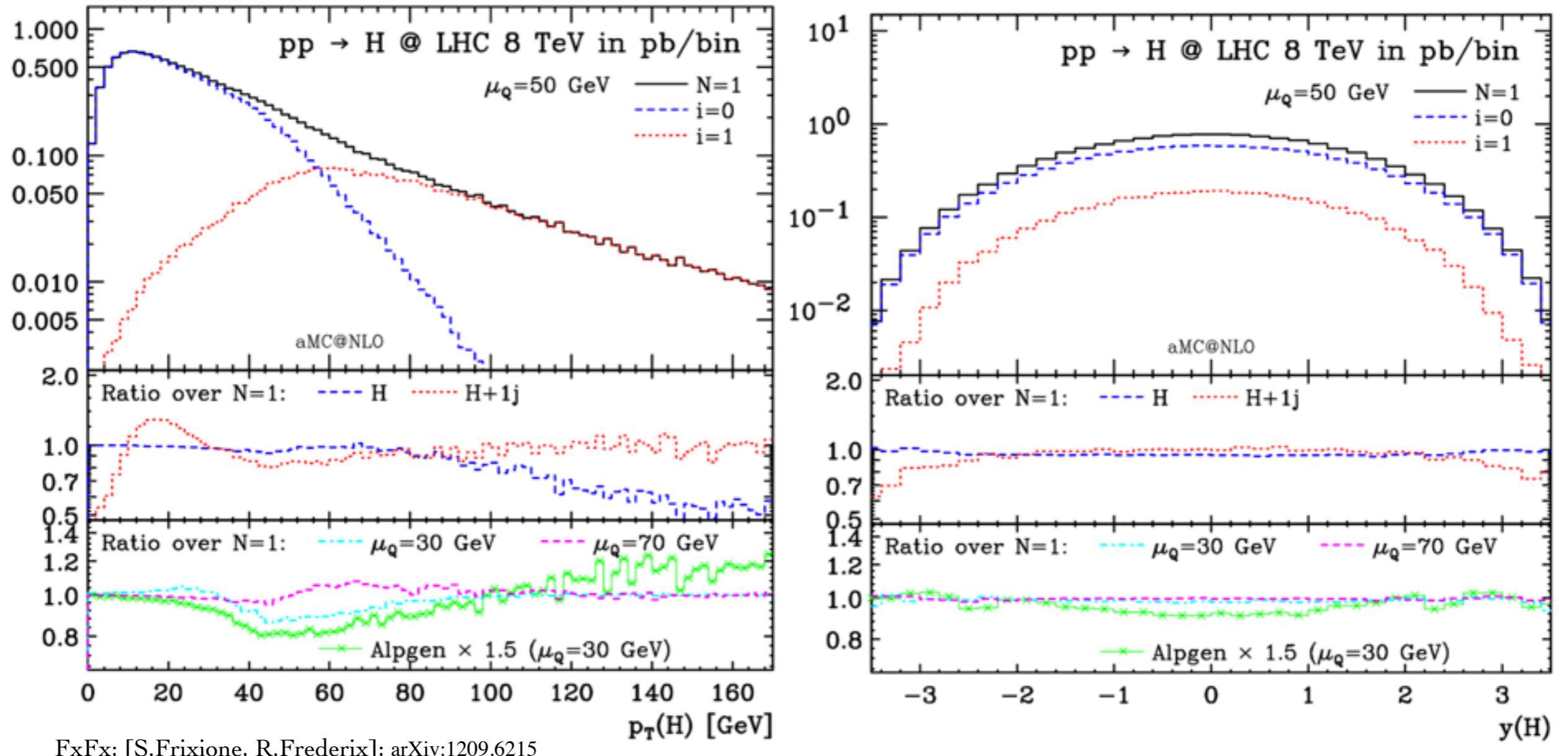
Same philosophy and very similar performances

# MATCHING MEETS MERGING



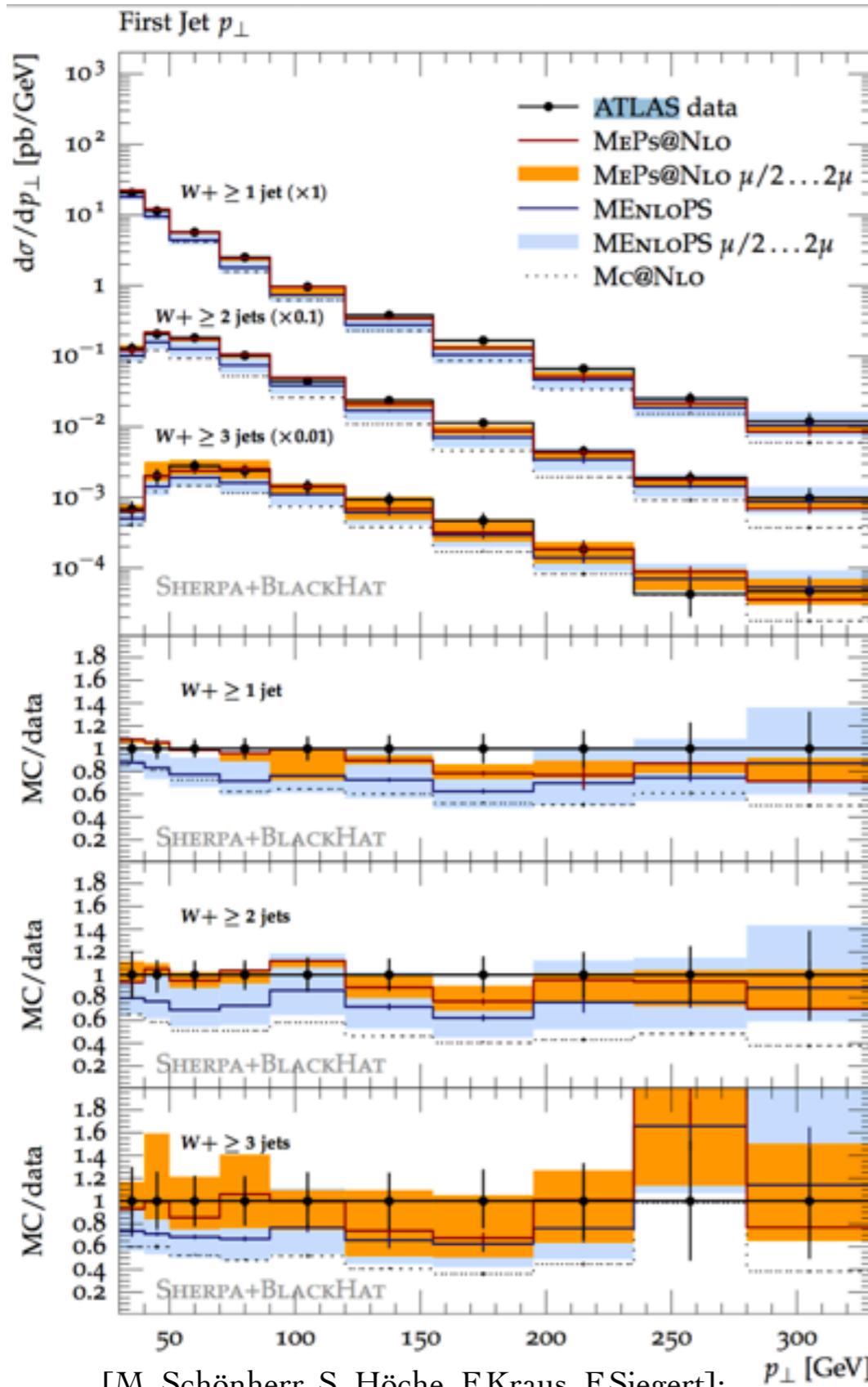
NLO reduces merging scale uncertainties

# MATCHING MEETS MERGING



Transition across descriptions of different multiplicities not necessarily sharp.

# MATCHING MEETS MERGING



## MEPS@NLO:

n={0,1,2} : NLO ME  
n={3,4} : LO ME  
n>4 : PSMC

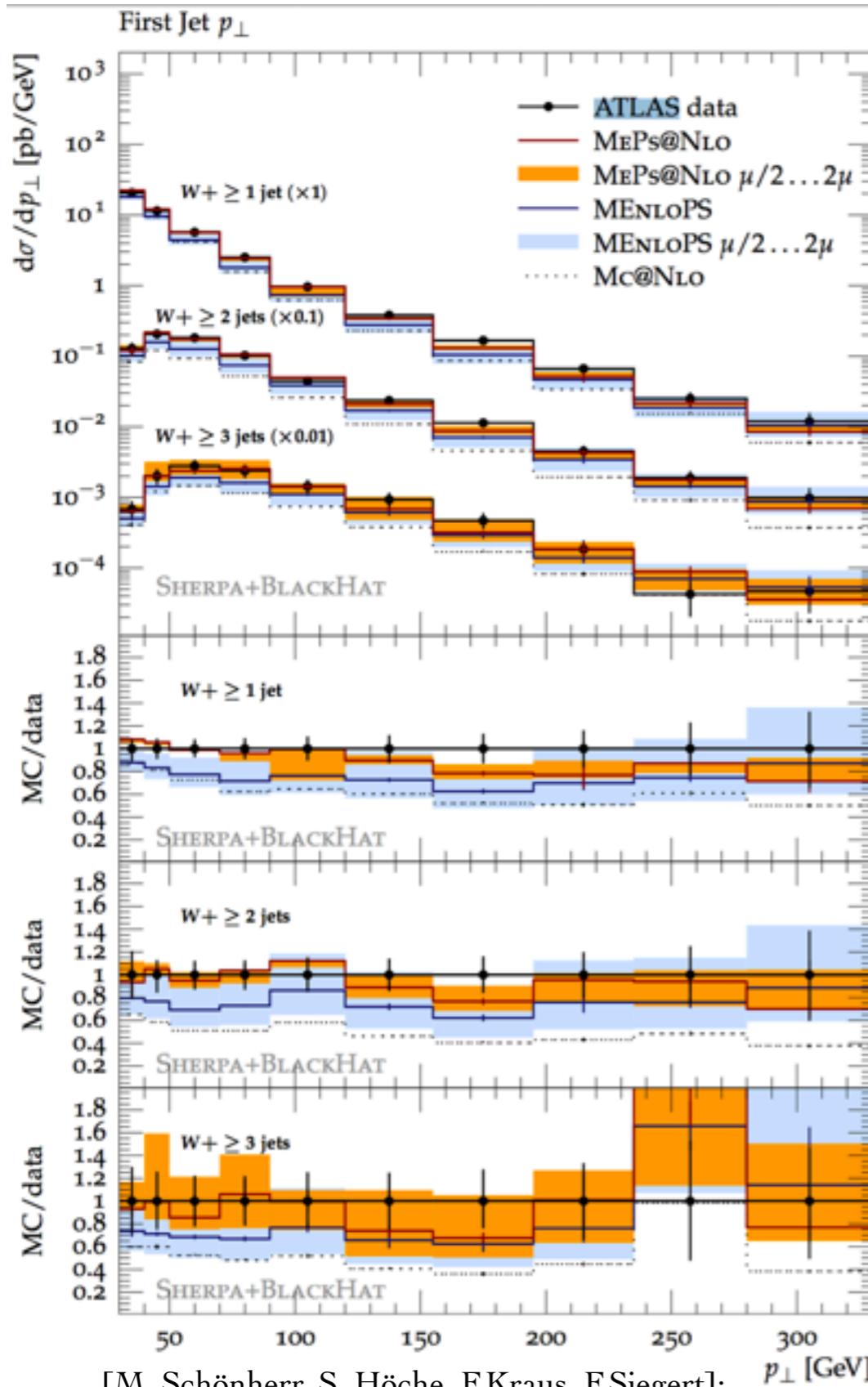
## MENloPS:

n=0 : NLO ME  
n={1→4} : LO ME  
n>4 : PSMC

## MC@NLO:

n=0 : NLO ME  
n>0 : PSMC

# MATCHING MEETS MERGING



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- n={0,1,2} : NLO ME
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MENloPS:

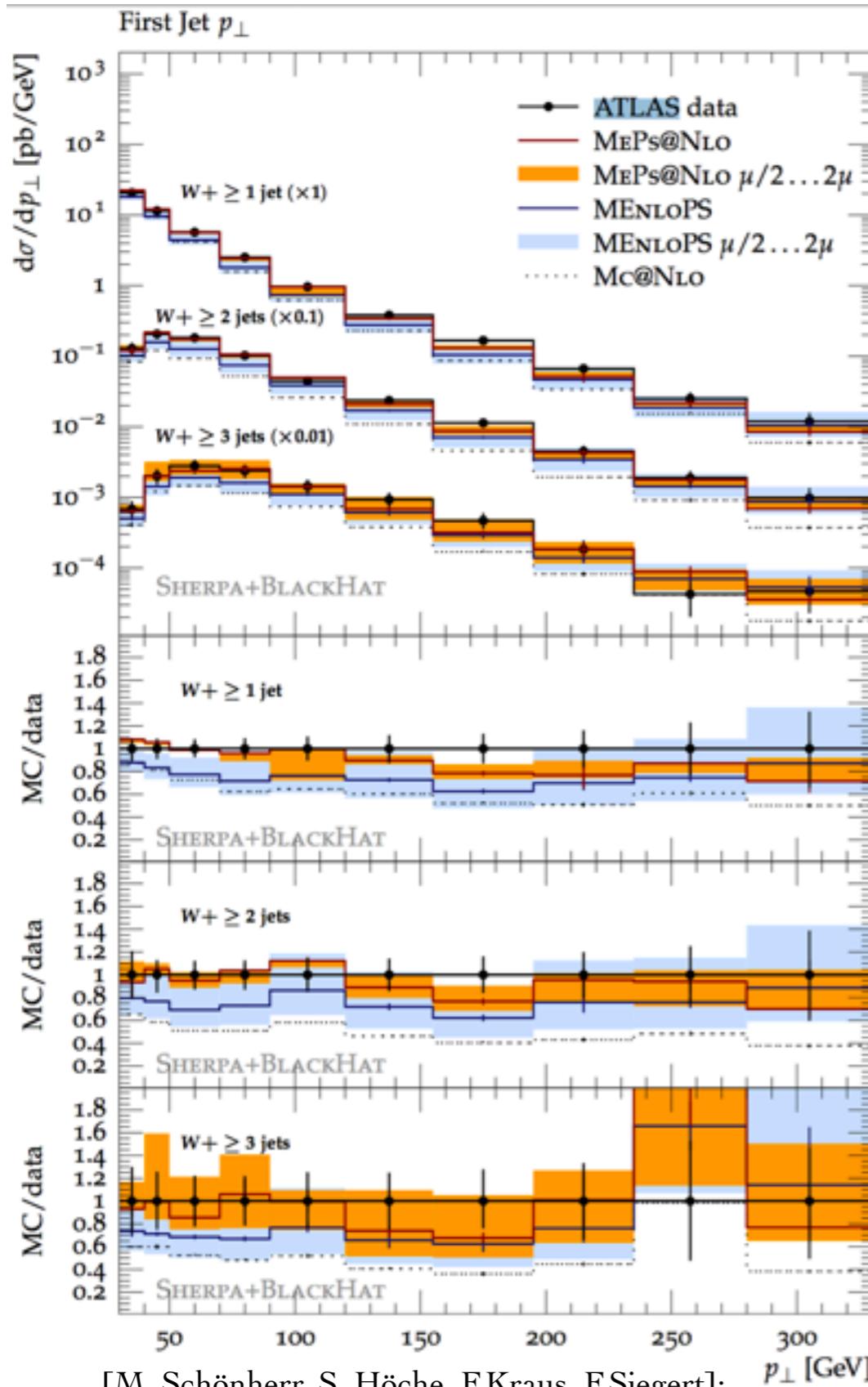
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MC@NLO:

- n=0 : NLO ME
- n>0 : PSMC

NLO reduces scale uncertainties

# MATCHING MEETS MERGING



[M. Schönherr, S. Höche, F.Kraus, F.Siegert];

arXiv:1311.3634

$$p p \rightarrow W^+ + n j$$

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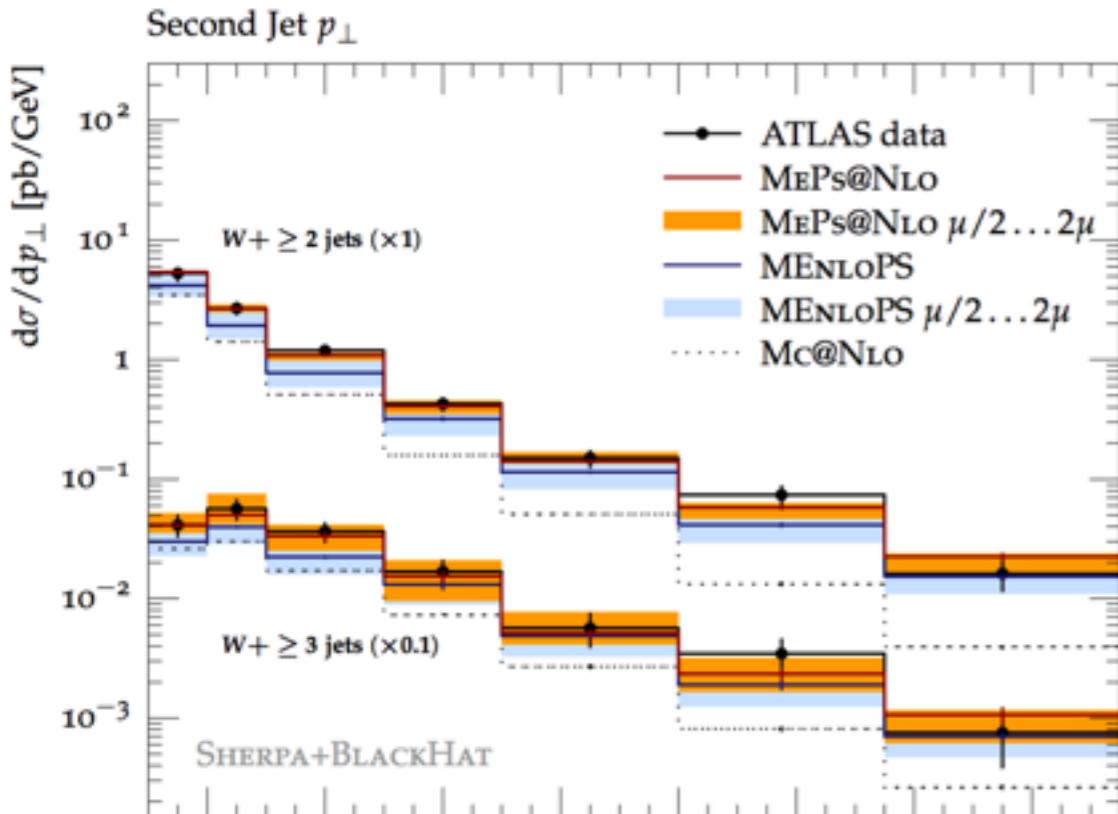
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NLO reduces scale uncertainties

NLO improves on normalization

# MATCHING MEETS MERGING

$$p p \rightarrow W^+ + n j$$



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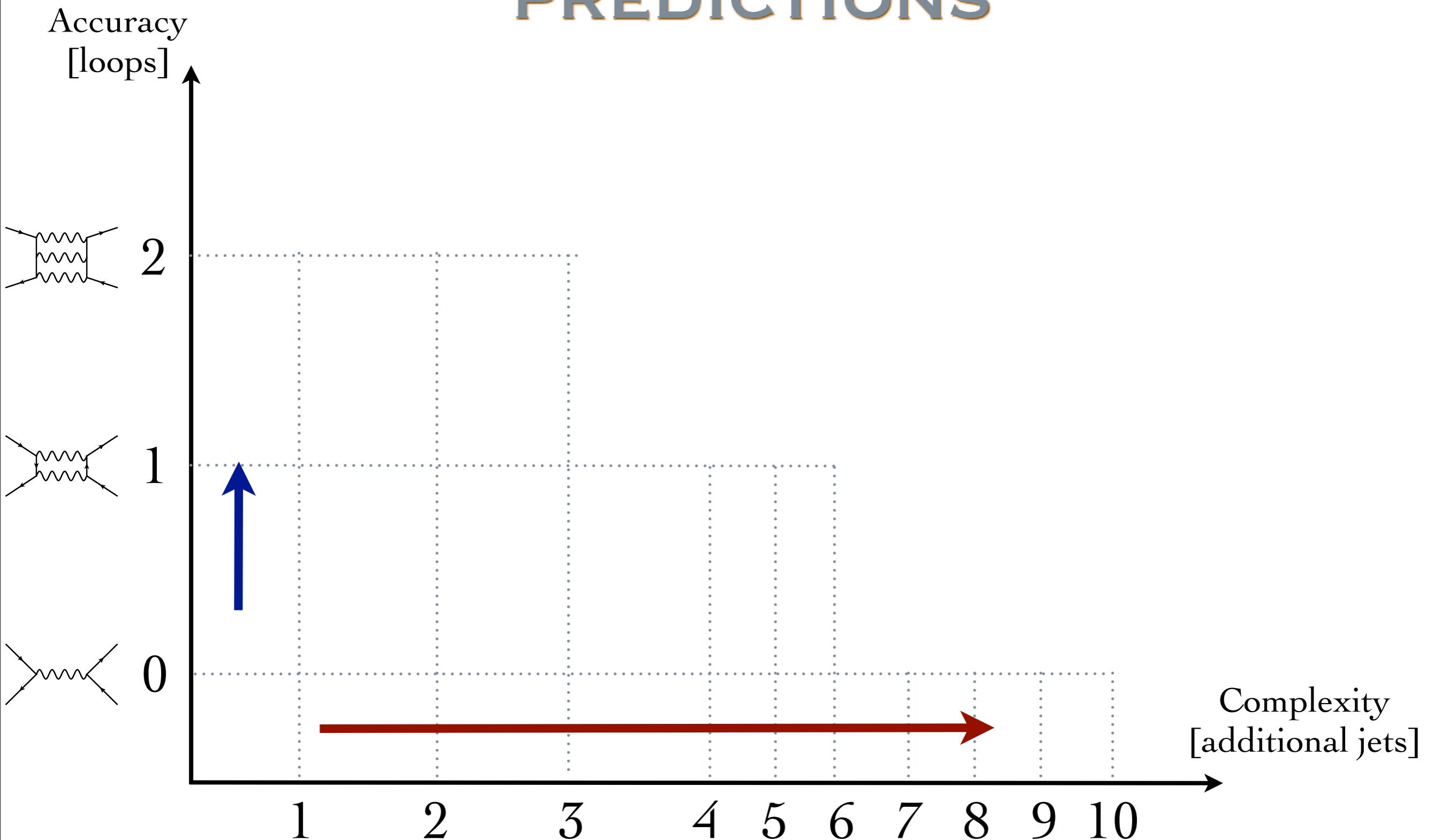
## MC@NLO:

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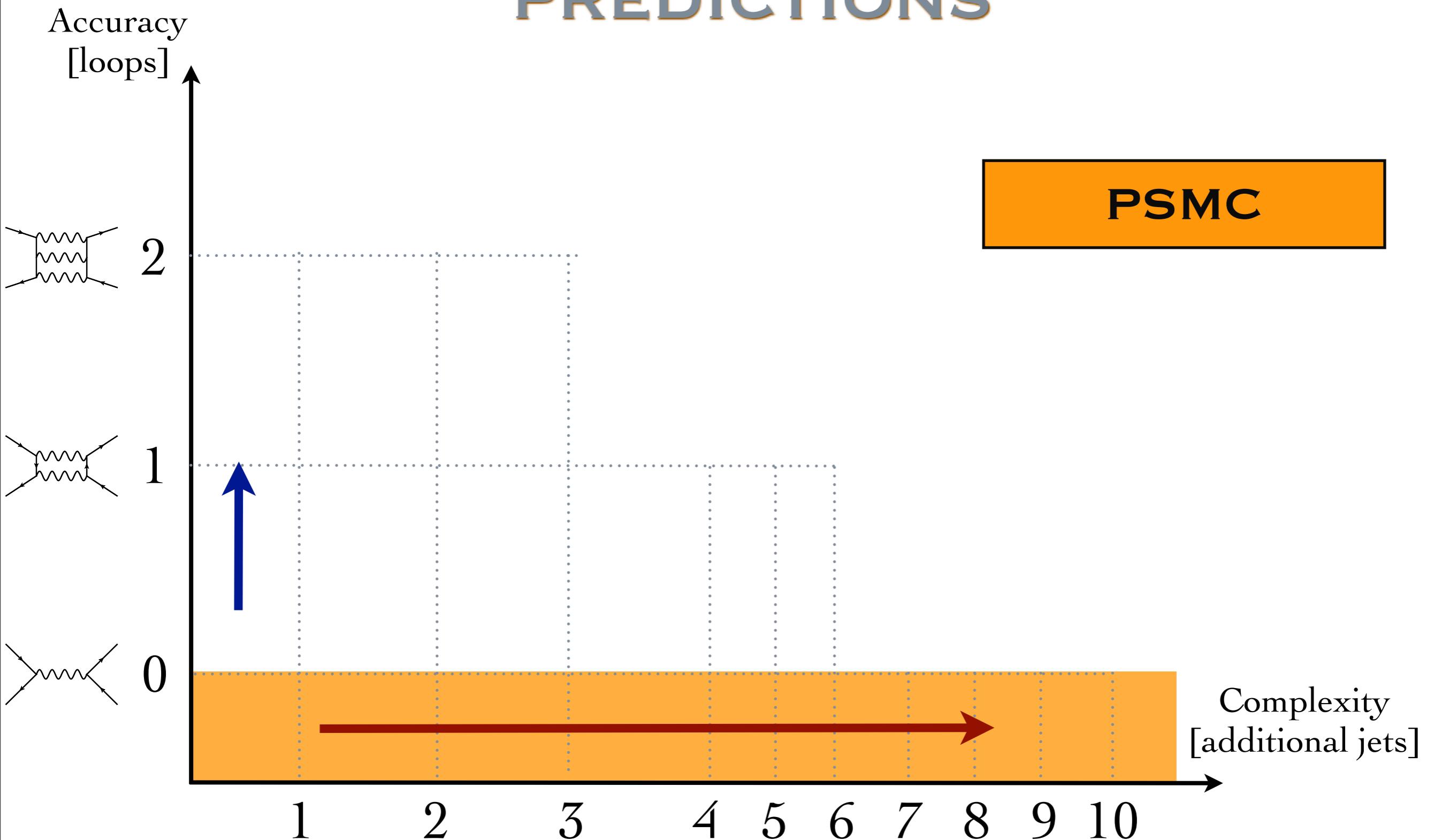
NLO reduces scale uncertainties  
 NLO improves on normalization  
 and trees sculpt shapes !

[M. Schönherr, S. Höche, F.Kraus, F.Siegert];  
 arXiv:1311.3634

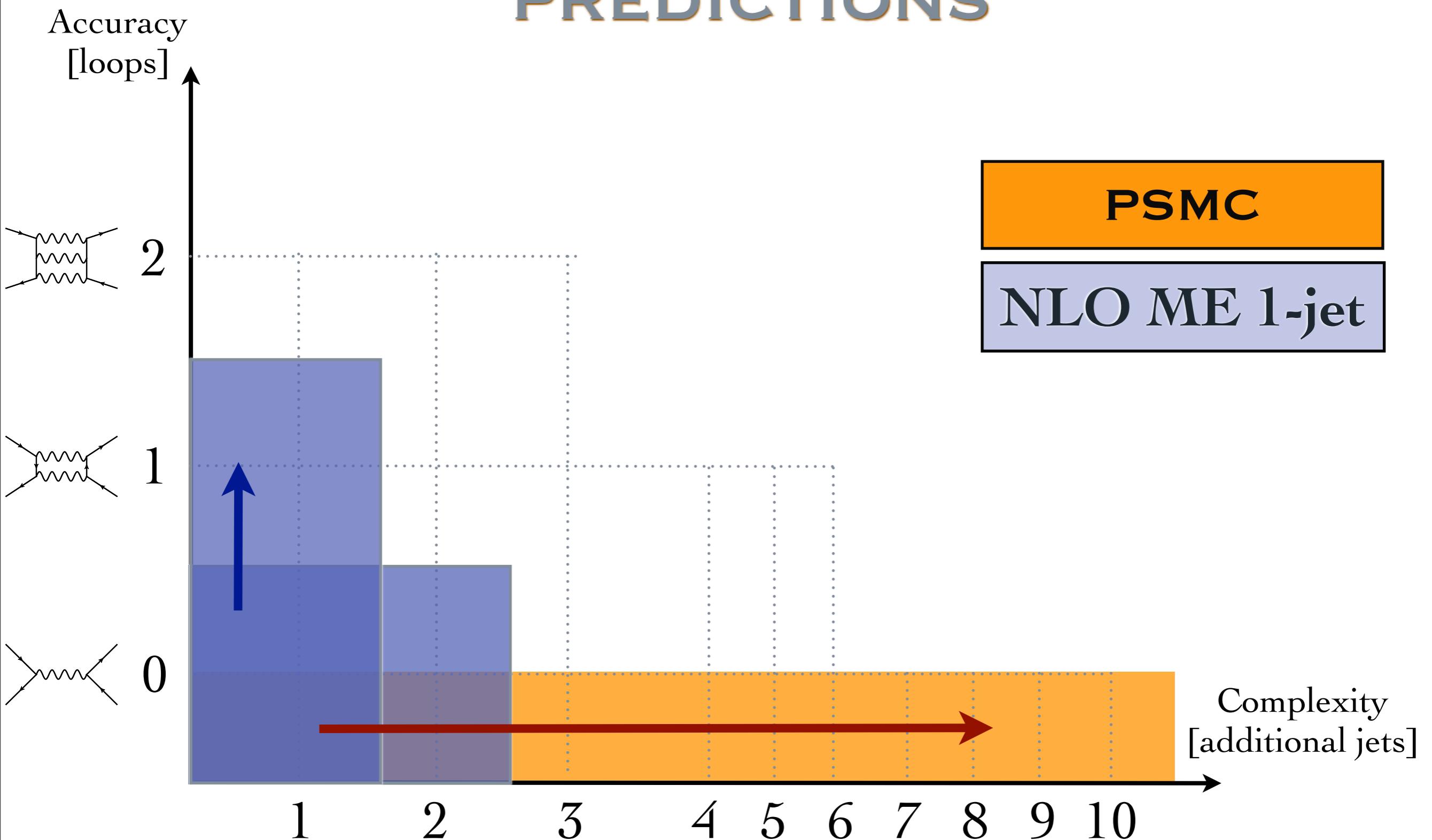
# MATCHED AND MERGED PREDICTIONS



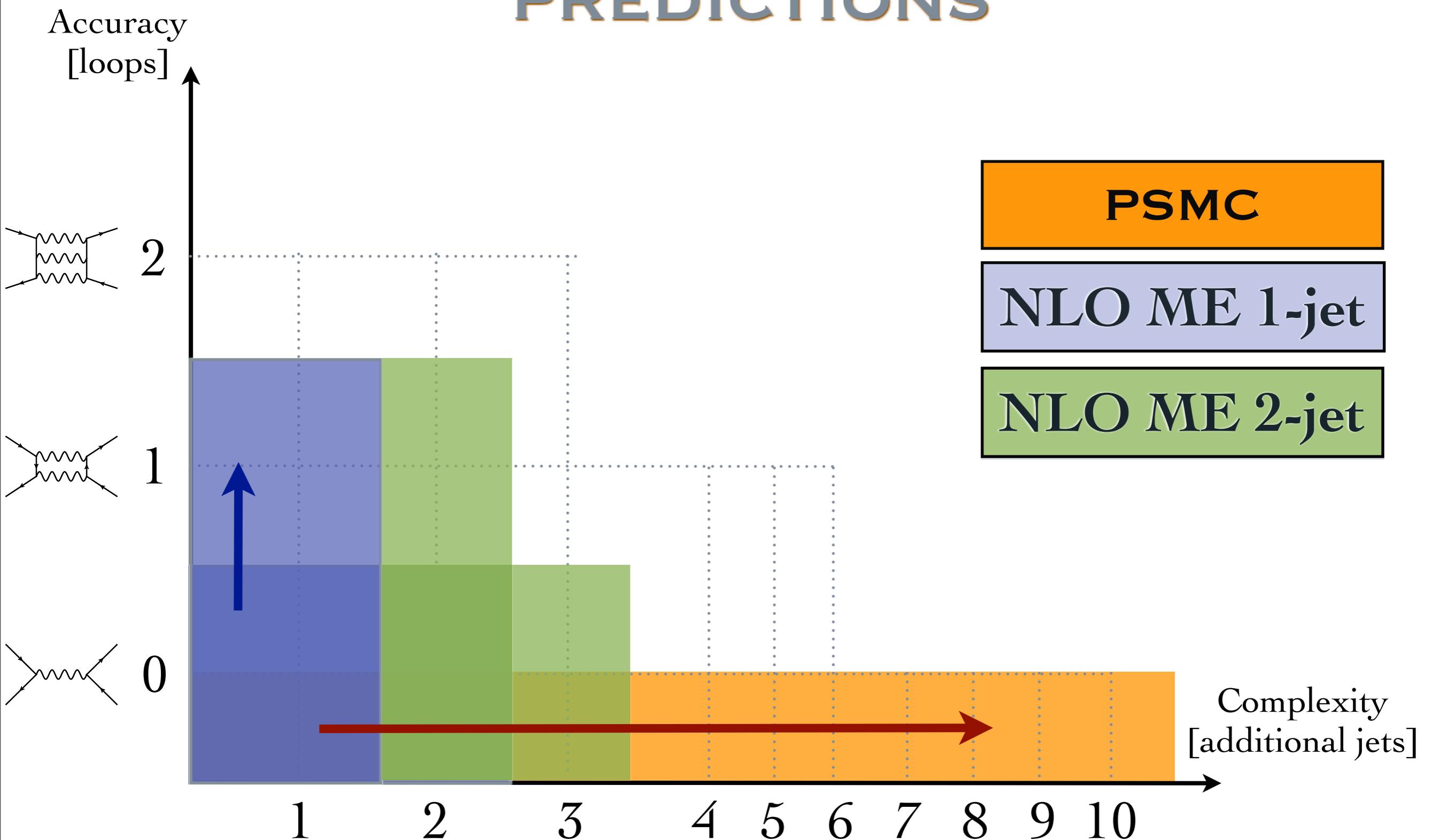
# MATCHED AND MERGED PREDICTIONS



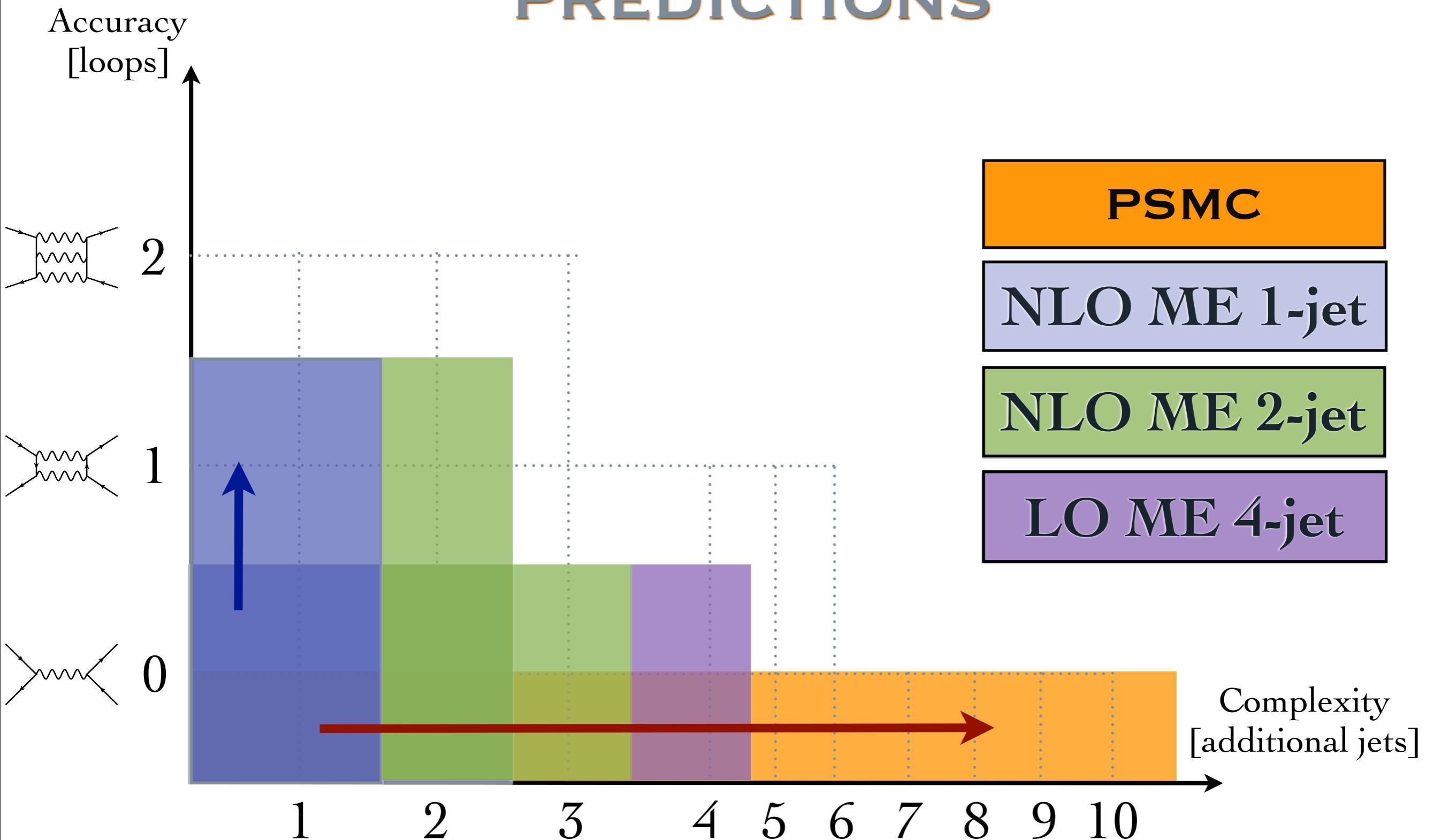
# MATCHED AND MERGED PREDICTIONS



# MATCHED AND MERGED PREDICTIONS



# MATCHED AND MERGED PREDICTIONS



# 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 ( $\mu_R$ ,  $\mu_F$ ,  $\mu_Q$ )
- Credible total rates predictions
- Necessary for parameters extraction from measurements (*i.e* precision physics)
- Treat loop-induced processes without effective theories

# NEED FOR AUTOMATION

- Merging trees is **easy** comparatively to computing loops , and they bring most of the interesting higher order features: needs **incentive** for not sticking to them!

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- Merging trees is **easy** comparatively to computing loops , and they bring most of the interesting higher order features: needs **incentive** for not sticking to them!
- 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)
- Byproducts of automating MC simulations :
  - \* More time available for physics and phenomenology
  - \* All-in-one software hence wide accessibility
  - \* Reliability ( new results exploit the same elementary building blocks and are therefore correct almost by construction )

# SO WHAT'S NEEDED, REALLY?

- Having the possibility of carrying on any **collider study**, in the **SM and beyond**, starting from the **Lagrangian** only
- To have these **EXP/TH** results directly usable by the **TH/EXP** colleagues. A framework  then.
- Benefit from both the accuracy of **NLO predictions** and at the same time the **flexibility of parton shower Monte-Carlo**.
- Only **physics input** should be provided, the technicalities must be under the hood.
- A framework of **flexible usage** but retaining **maximal simplicity**.

# PREDICTION WORKFLOW

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

**SYMMETRIES**

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

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**MODEL**

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

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

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**MODEL**

$$\text{graph TD} \nabla0000 --> 0000$$

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

$pp \rightarrow jj$  QCD = 2

**MATRIX ELEMENT**

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

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

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

matrix.f

**PARTONIC EVENTS**

```
<event>
 5   66 0.35819066E-07 0.55353448E+03 0.79577472E-01 0.11724198E+00
    -1 -1 0 0 0 501 0.00000000E+00 0.00000000E+00 0.850481
    1 -1 0 0 501 0.00000000E+00 0.00000000E+00 -.900741
  23 1 1 2 0 0 0.25462601E+02 0.29841856E+02 0.402821
  24 1 1 2 0 0 -.39256150E+02 -.24576181E+01 -.299881
  -24 1 1 2 0 0 0.37935485E+01 -.27383438E+02 -.566171
# 1 6 2 0 0 0.00000000E+00 0.00000000E+00 8 0 0 0.18000000E+01 0
<rwgt>
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 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>
```

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

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

events.lhe

**HADRON LEVEL**

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

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

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$pp \rightarrow jj \quad \text{QCD} = 2$

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matrix.f

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```
<event>
 5 66 0.35019066E-07 0.55353448E+03 0.79577472E-01 0.11724198E+00
  -1 -1 0 0 501 0.00000000E+00 0.00000000E+00 0.850484
   1 -1 0 0 501 0.00000000E+00 0.00000000E+00 -.90074
  23 1 1 2 0 0 0.25462601E+02 0.2984056E+02 0.402821
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 -.24 1 1 2 0 0 0.37935485E+01 -.27383438E+02 -.566171
 # 1 6 2 0 0 0.00000000E+00 0.00000000E+00 8 0 0 0.10000000E+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
 </rwgt>
</event>
```

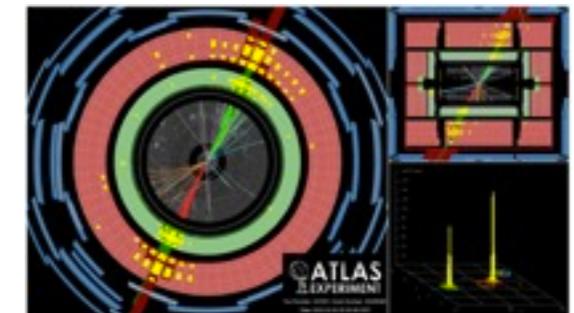
events.lhe

**HADRON LEVEL**

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

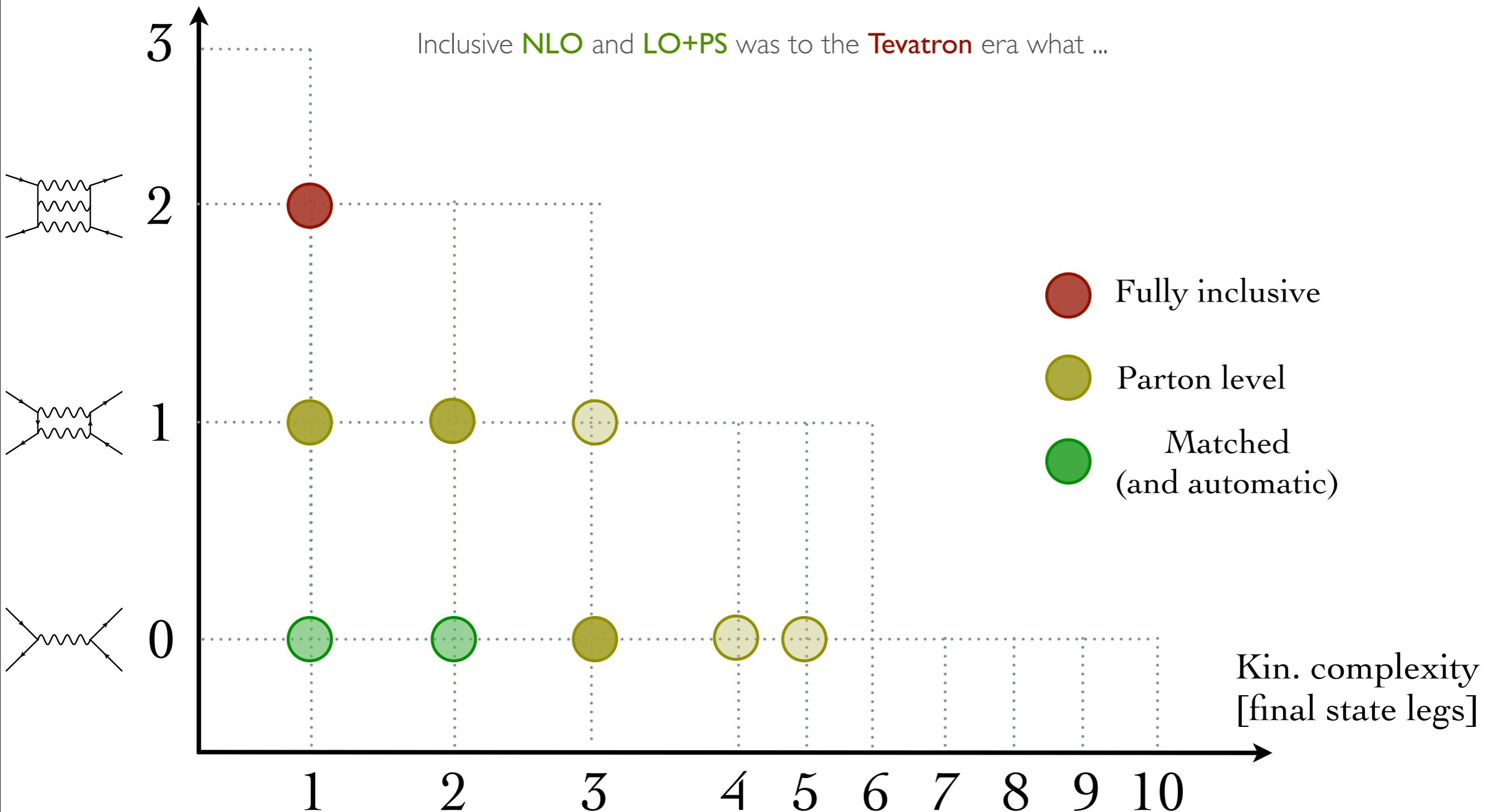
events.hep

**DETECTOR LEVEL**



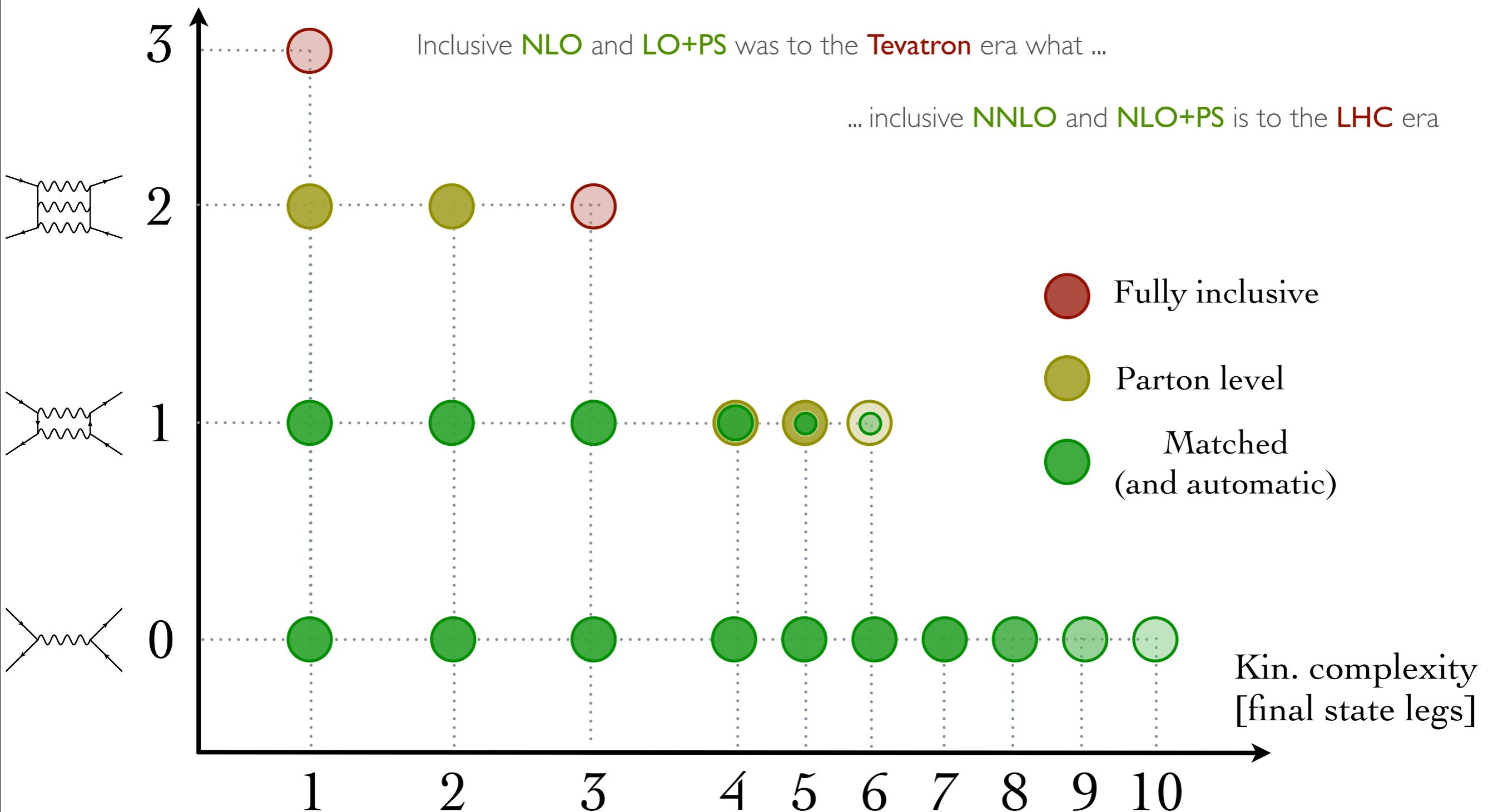
# STATE OF THE ART IN 2000

Accuracy  
[loops]



# STATE OF THE ART IN 2014

Accuracy  
[loops]



# IMPLEMENTATION

GALILEO

SYMMETRIES

# IMPLEMENTATION

**GALILEO**

**SYMMETRIES**

**FEYNRULES**

**MODEL**

# IMPLEMENTATION

**GALILEO**

**SYMMETRIES**

**FEYNRULES**

**MODEL**

**MADGRAPH 5**

**MATRIX ELEMENT**

# IMPLEMENTATION

**GALILEO**

**SYMMETRIES**

**FEYNRULES**

**MODEL**

**MADGRAPH 5**

**MATRIX ELEMENT**

**MADEVENT 5**

**PARTONIC EVENTS**

# IMPLEMENTATION

GALILEO

SYMMETRIES

FEYNRULES

MODEL

MADGRAPH 5

MATRIX ELEMENT

MADEVENT 5

PARTONIC EVENTS

PYTHIA / HERWIG

HADRON LEVEL

# IMPLEMENTATION

GALILEO

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FEYNRULES

MODEL

MADGRAPH 5

MATRIX ELEMENT

MADEVENT 5

PARTONIC EVENTS

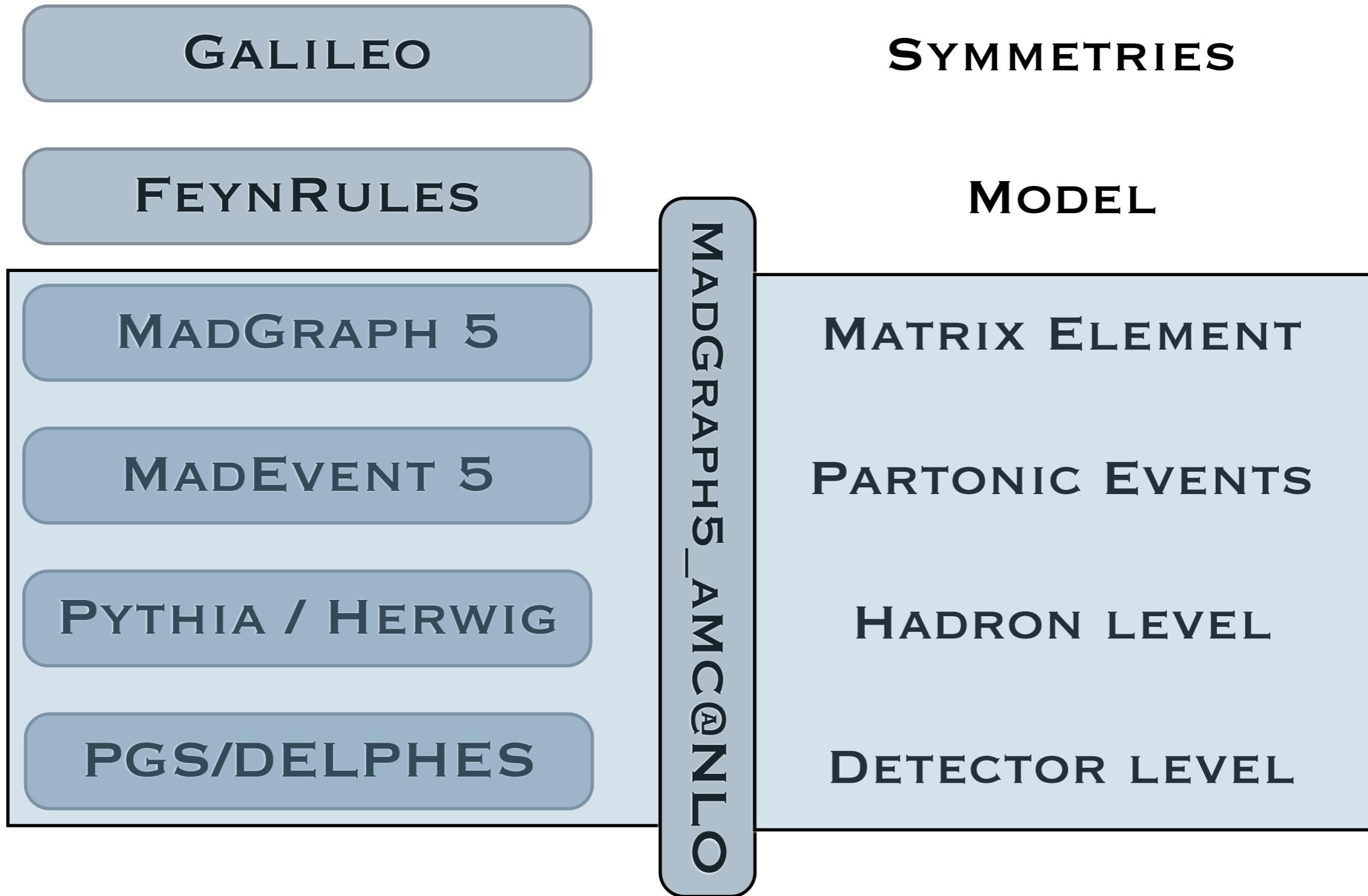
PYTHIA / HERWIG

HADRON LEVEL

PGS/DELPHES

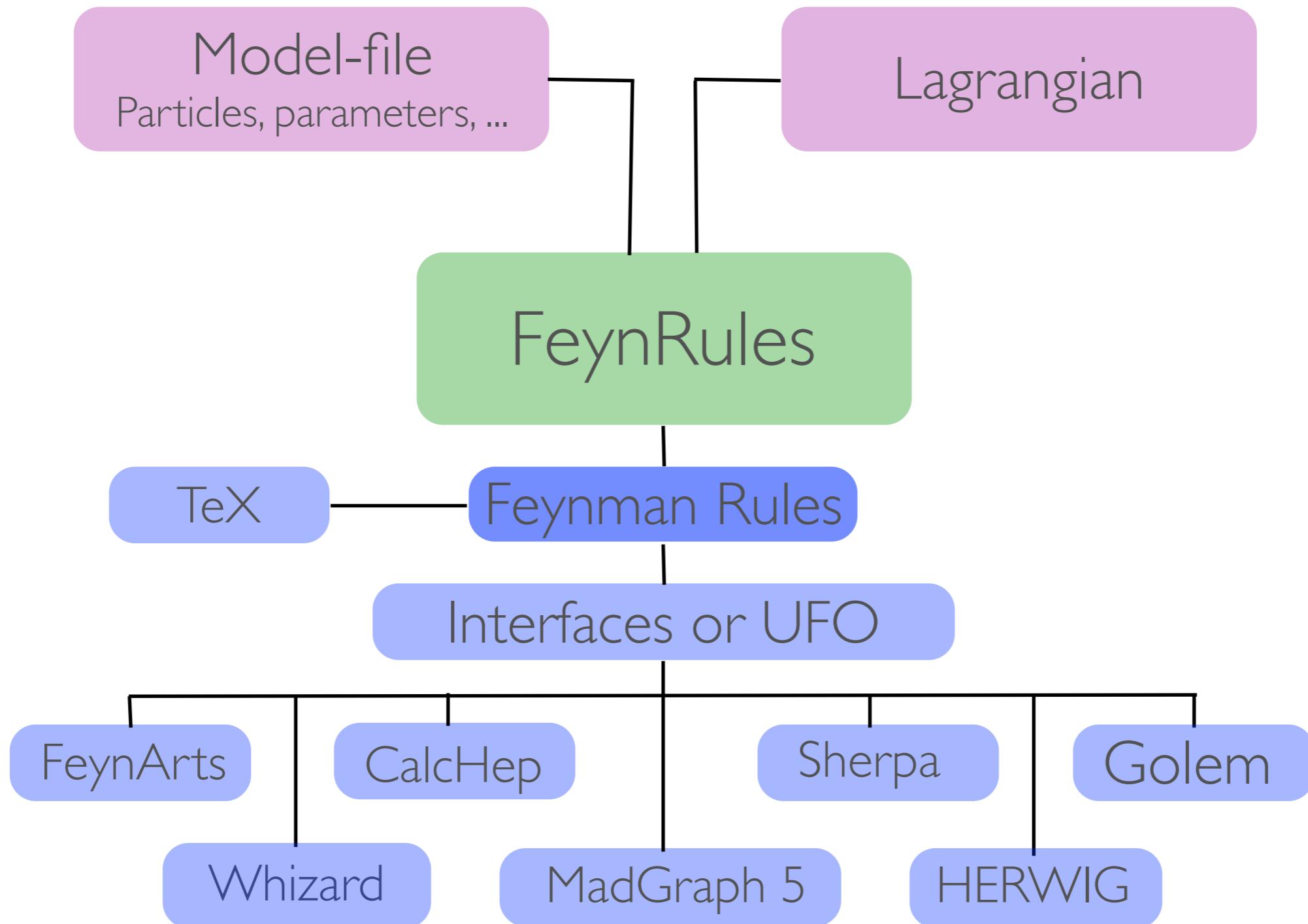
DETECTOR LEVEL

# IMPLEMENTATION



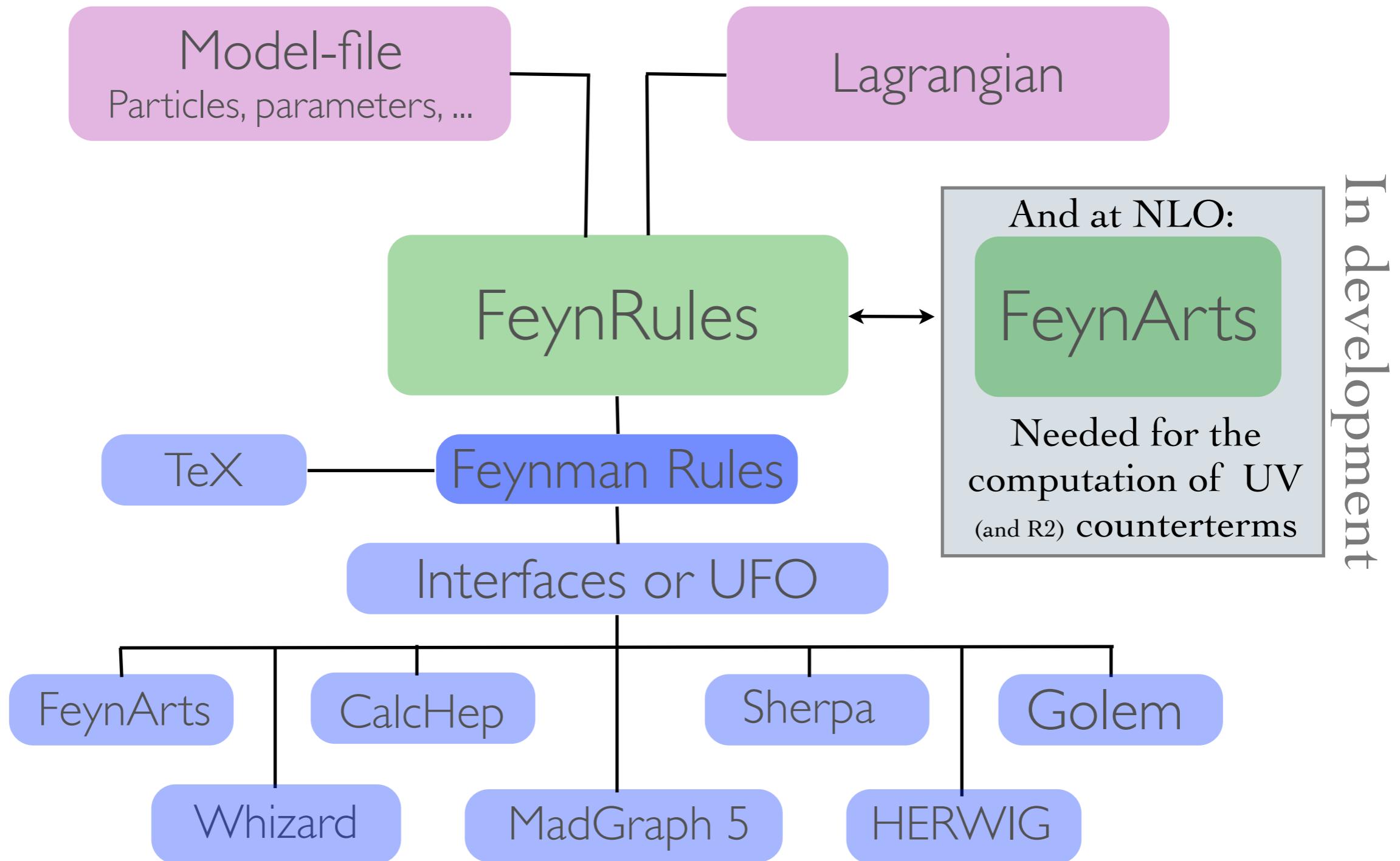
# THE FEYNRULES PROJECT

[Alloul, Christensen, Degrande, Duhr, Fuks]



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## Available models

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

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Supersymmetric Models (5)	Various supersymmetric extensions of the SM, including the MSSM, the NMSSM and many more		
Extra-dim	Extractions of the SM including various extensions of the SM		
Strongly coupled theories (1)			
Axigluon model	The SM plus a scalar gluon field.	S. Krastanov	Available
DY SM extension	The SM plus new spin-0, -1, and -2 bosons that contribute to Drell-Yan production of leptons at the LHC.	N. Christensen	Available
FCNC Higgs interactions	The SM plus higher-dimensional flavor changing Higgs interactions.	S. Krastanov	Available
Fourth generation model	A fourth generation model including a $t'$ and a $b'$	C. Duhr	Available
General 2HDM	The most general 2HDM, including all flavor violation and mixing terms.	C. Duhr, M. Herquet	Available
Hidden Abelian Higgs Model	A $Z'$ model where the $Z'$ interacts with the SM through mixings, leading to very small non-SM like $Z'$ couplings.	C. Duhr	Available
HiggsCharacterisation	The model file for the spin/parity characterisation of a 125 GeV resonance.	P. de Aquino, K. Mawatari	Available
Higgs effective theory	An add-on for the SM implementation containing the dimension 5 gluon fusion operator.	C. Duhr	Available
Higgs Effective Lagrangian	Higgs effective Lagrangian including operators up-to dimension 6.	A. Alloul, B. Fuks and V. Sanz	Available
Hill Model	A model with an unusual extension of the SM Higgs sector.	P. de Aquino, C. Duhr	Available
Inert Doublet Model	A model with an additional complex scalar SU(2)L doublet and an unbroken $Z_2$ symmetry under which all SM particles are even while the extra doublet is odd.	A. Goudelis, B. Herrmann, O. Stal	Available
Minimal Zp models	The minimal $Z'$ extension of the SM.	L. Basso	Available
Monotops	The SM plus monotop effective Lagrangian.	B. Fuks	Available
Sextet diquarks	The SM plus sextet diquark scalars.	J. Alwall, C. Duhr	Available
Standard model + Scalars	The SM, together with a set of singlet scalar particles coupling only to the SM Higgs, and allowing it to decay invisibly into this new scalar sector.	C. Duhr	Available
Triplet diquarks	The SM plus triplet diquark scalars.	J. Alwall, C. Duhr	Available
Type III See-Saw Model	The SM, including neutrino masses coming from a type III See-Saw mechanism.	C. Biggio, F. Bonnet	Available

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[Alloul, Christensen, Degrande, Duhr, Fuks]

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<a href="#">Miscellaneous (0)</a>	
<a href="#"><b>NLO MODELS (100000)</b></a>	<b>SOON!</b>

# MadGraph5\_aMC@NLO



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

This separation is transparent to the users.

Publicly available since 8<sup>th</sup> Nov. 2012

(Reference paper came out today! [hep-ph/1405.0301] )

# 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.

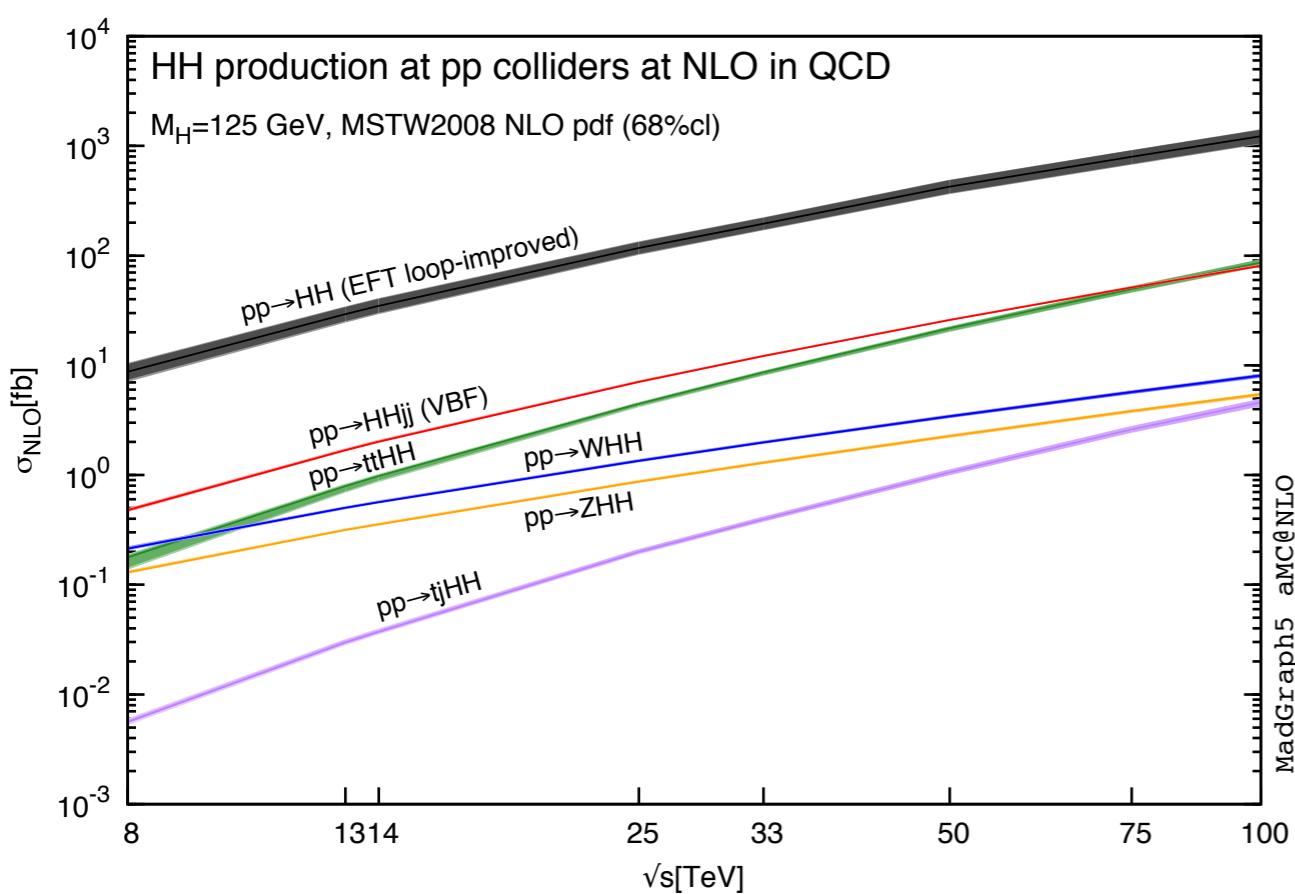
- Very simple one:

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

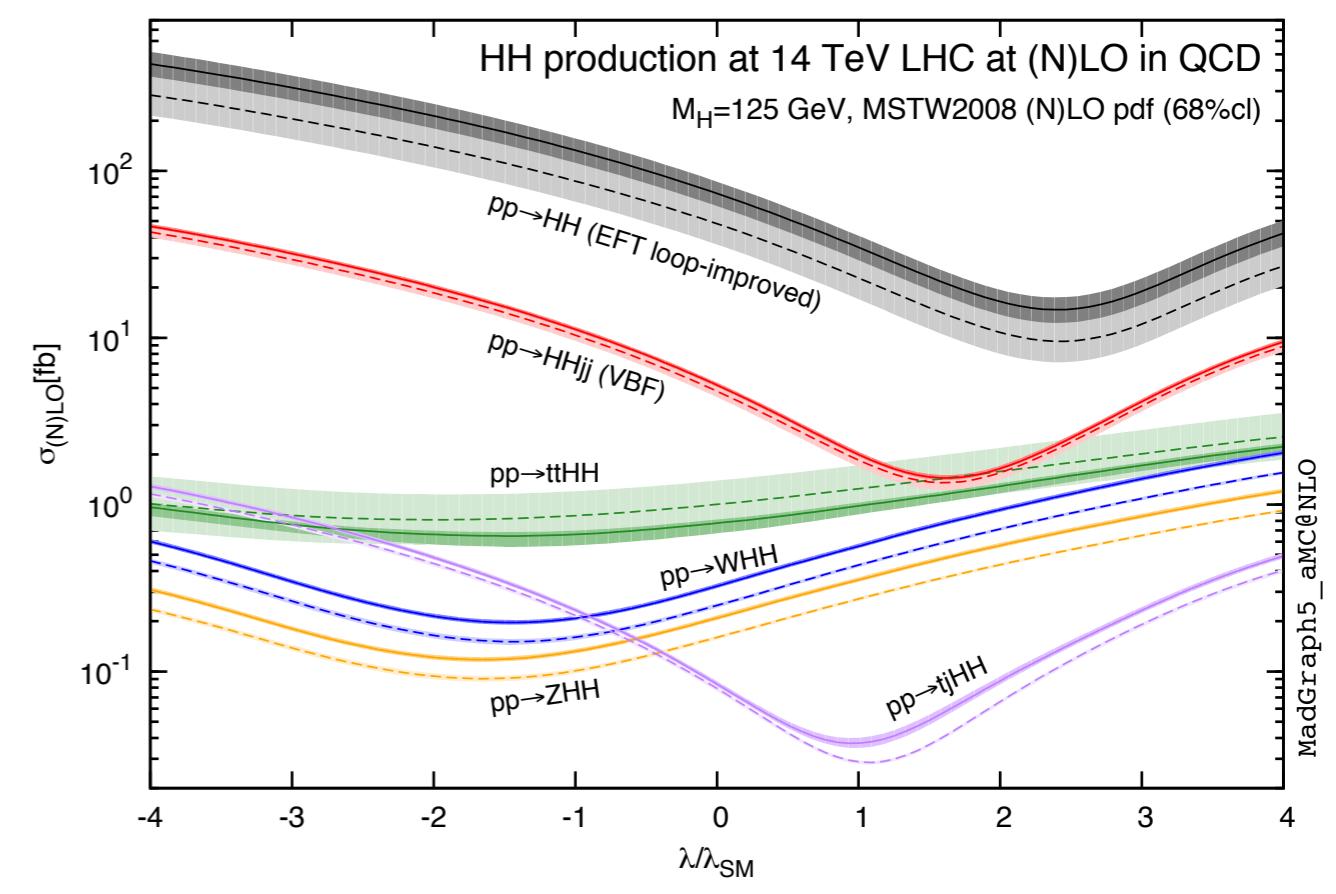
- With options specified:

- > 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

# HH PRODUCTION AT PP COLLIDERS



Total cross sections at NLO for the various channels

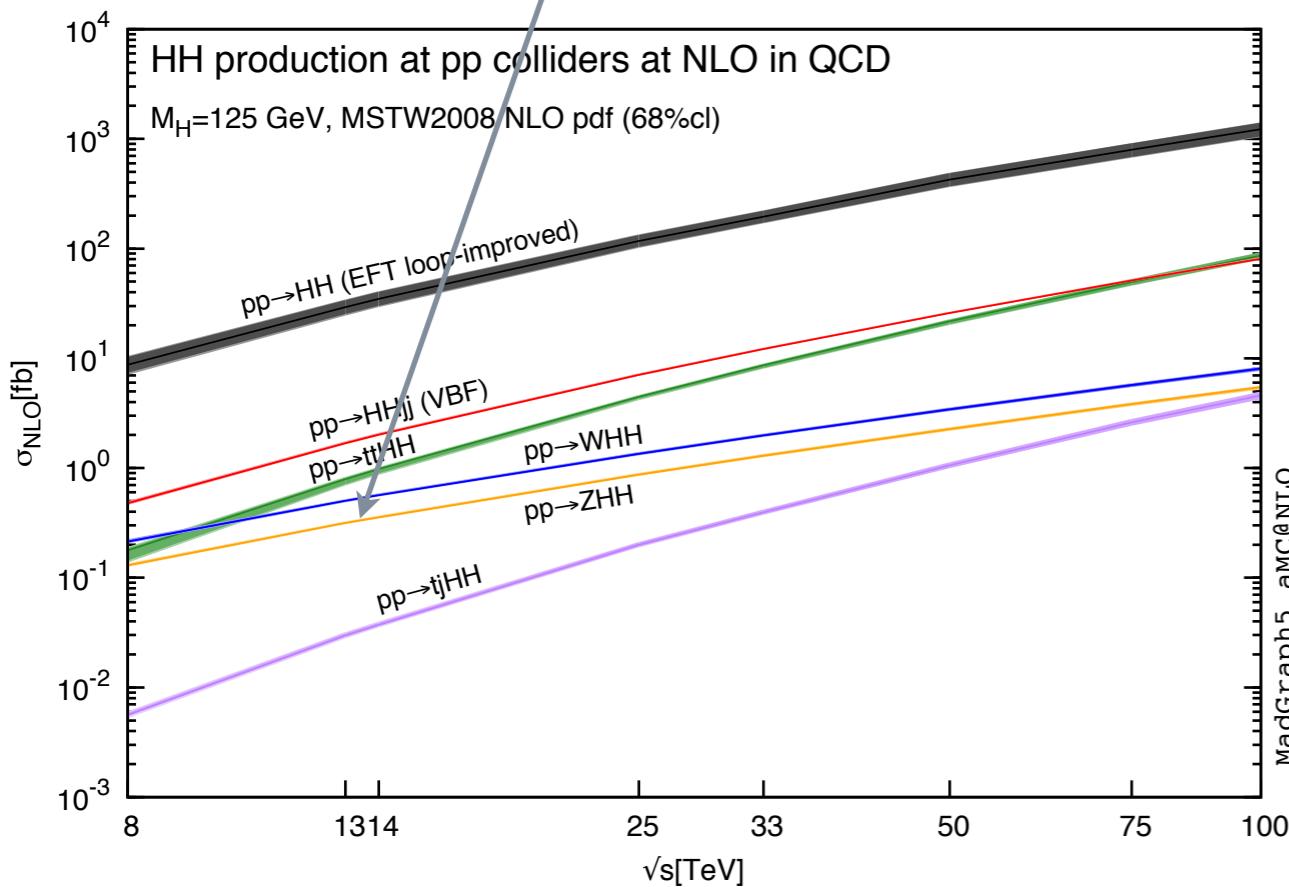


Trilinear coupling sensitivity

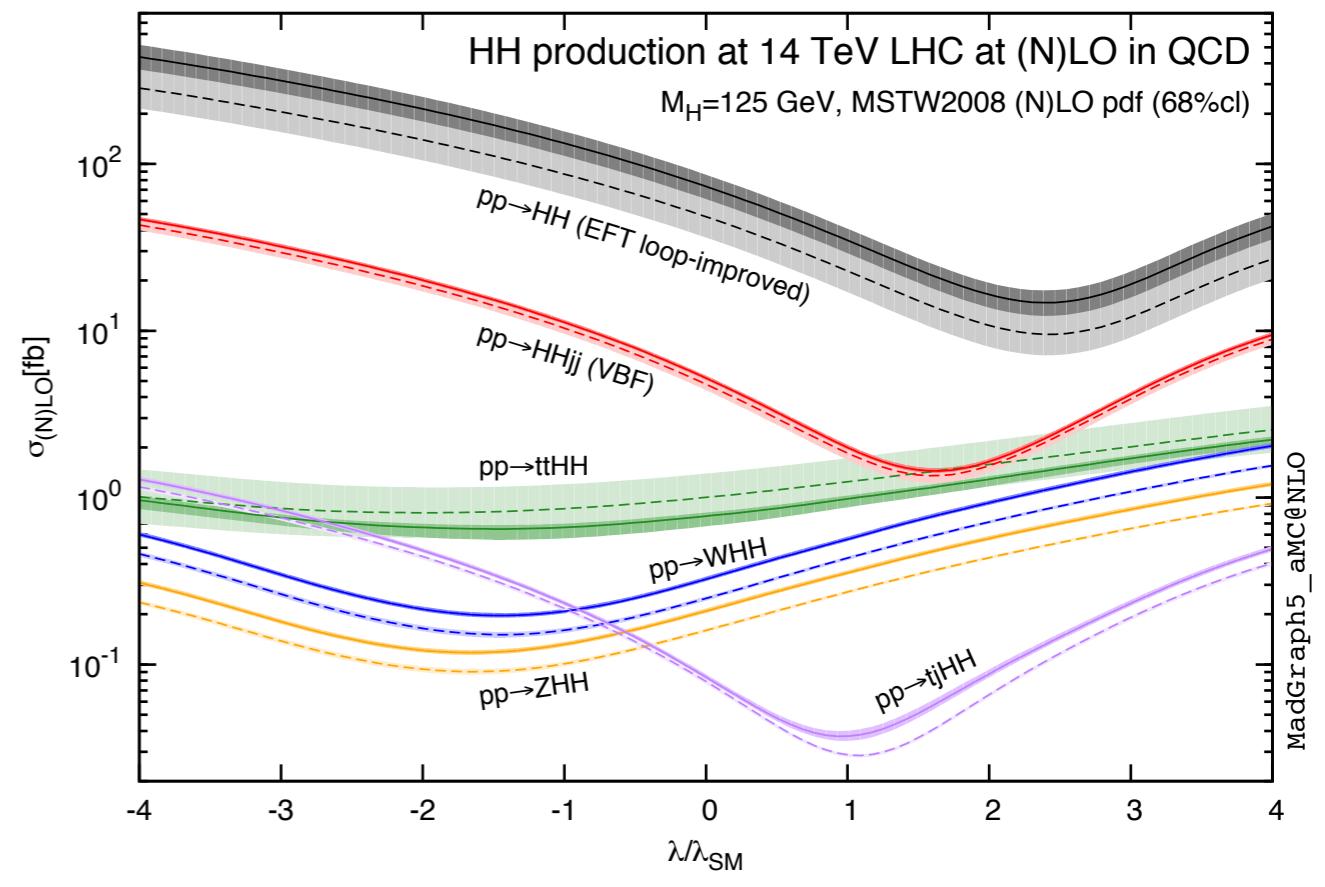
# HH PRODUCTION AT PP COLLIDERS

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

- > generate  $p\ p \rightarrow z\ h\ h$  [QCD]
- > output
- > launch

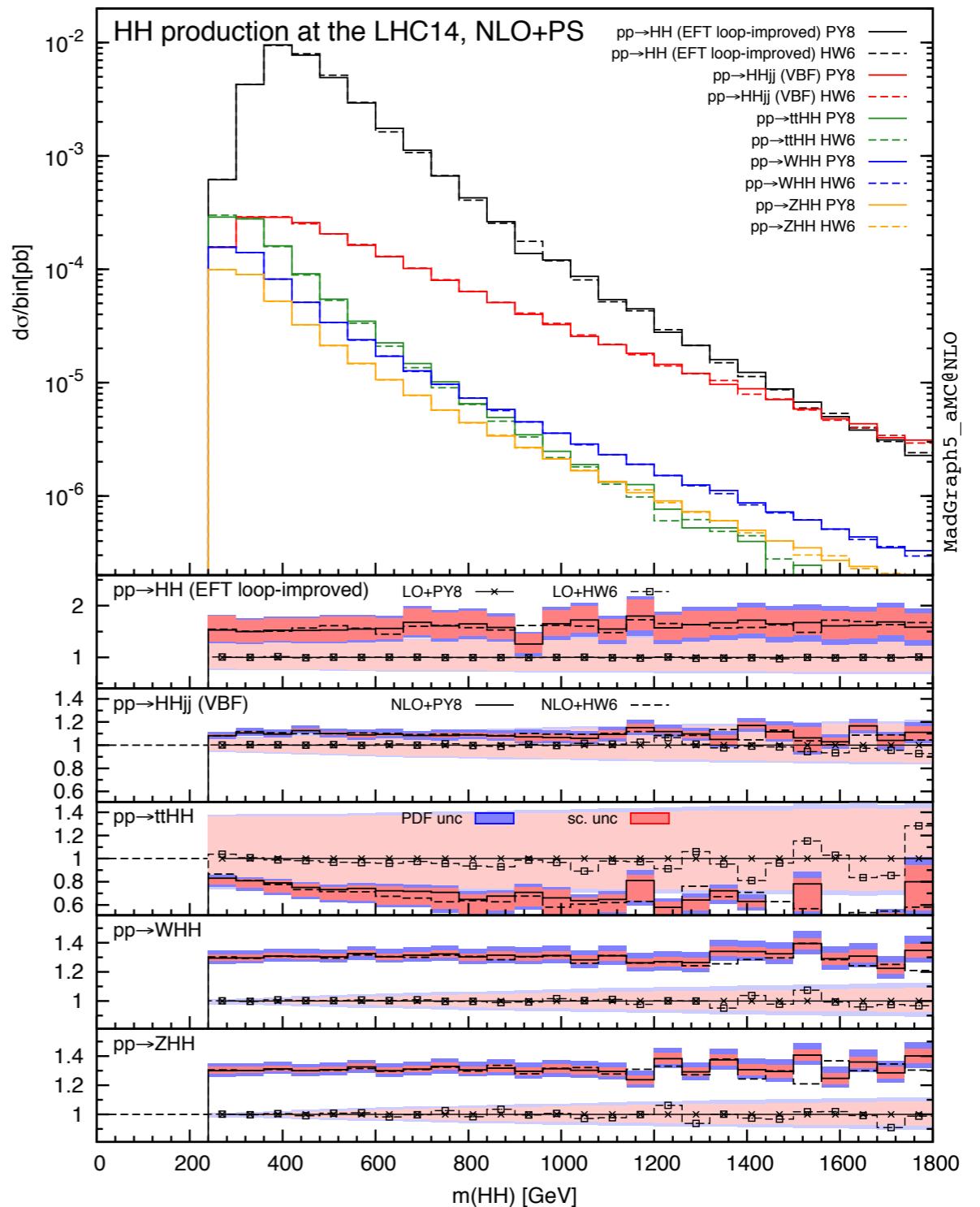
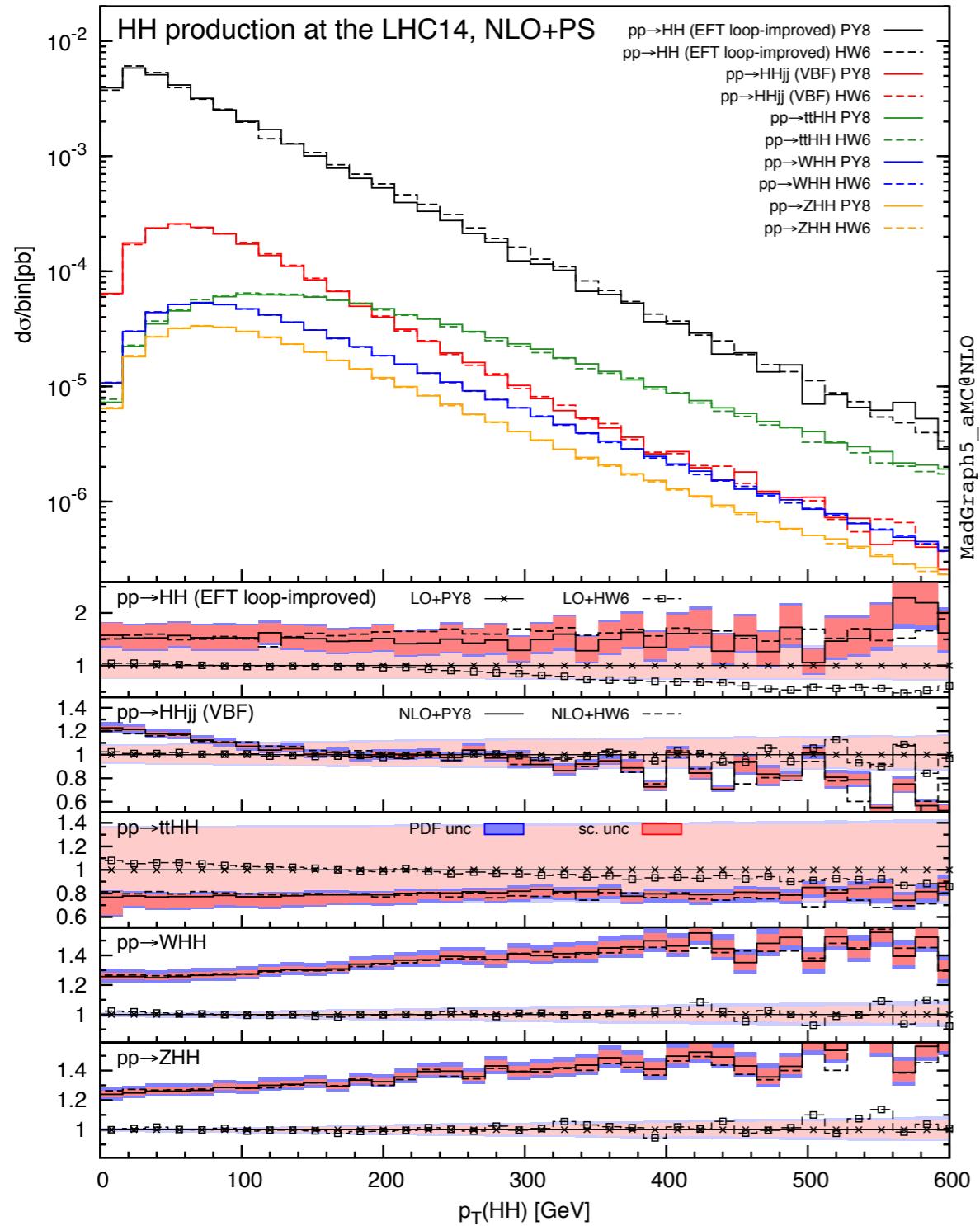


Total cross sections at NLO for the various channels



Trilinear coupling sensitivity

# HH PRODUCTION AT PP COLLIDERS



# AUTOMATIC NLO IN THE SM (2014)



Process	Syntax	Cross section (pb)					
		LO 13 TeV		NLO 13 TeV			
<b>Vector boson +jets</b>							
a.1 $pp \rightarrow W^\pm$	$p\ p > wpm$	$1.375 \pm 0.002 \cdot 10^5$	+15.4% -16.6%	+2.0% -1.6%	$1.773 \pm 0.007 \cdot 10^5$	+5.2% -9.4%	+1.9% -1.6%
a.2 $pp \rightarrow W^\pm j$	$p\ p > wpm\ j$	$2.045 \pm 0.001 \cdot 10^4$	+19.7% -17.2%	+1.4% -1.1%	$2.843 \pm 0.010 \cdot 10^4$	+5.9% -8.0%	+1.3% -1.1%
a.3 $pp \rightarrow W^\pm jj$	$p\ p > wpm\ j\ j$	$6.805 \pm 0.015 \cdot 10^3$	+24.5% -18.6%	+0.8% -0.7%	$7.786 \pm 0.030 \cdot 10^3$	+2.4% -6.0%	+0.9% -0.8%
a.4 $pp \rightarrow W^\pm jjj$	$p\ p > wpm\ j\ j\ j$	$1.821 \pm 0.002 \cdot 10^3$	+41.0% -27.1%	+0.5% -0.5%	$2.005 \pm 0.008 \cdot 10^3$	+0.9% -6.7%	+0.6% -0.5%
a.5 $pp \rightarrow Z$	$p\ p > z$	$4.248 \pm 0.005 \cdot 10^4$	+14.6% -15.8%	+2.0% -1.6%	$5.410 \pm 0.022 \cdot 10^4$	+4.6% -8.6%	+1.9% -1.5%
a.6 $pp \rightarrow Zj$	$p\ p > z\ j$	$7.209 \pm 0.005 \cdot 10^3$	+19.3% -17.0%	+1.2% -1.0%	$9.742 \pm 0.035 \cdot 10^3$	+5.8% -7.8%	+1.2% -1.0%
a.7 $pp \rightarrow Zjj$	$p\ p > z\ j\ j$	$2.348 \pm 0.006 \cdot 10^3$	+24.3% -18.5%	+0.6% -0.6%	$2.665 \pm 0.010 \cdot 10^3$	+2.5% -6.0%	+0.7% -0.7%
a.8 $pp \rightarrow Zjjj$	$p\ p > z\ j\ j\ j$	$6.314 \pm 0.008 \cdot 10^2$	+40.8% -27.0%	+0.5% -0.5%	$6.996 \pm 0.028 \cdot 10^2$	+1.1% -6.8%	+0.5% -0.5%
a.9 $pp \rightarrow \gamma j$	$p\ p > a\ j$	$1.964 \pm 0.001 \cdot 10^4$	+31.2% -26.0%	+1.7% -1.8%	$5.218 \pm 0.025 \cdot 10^4$	+24.5% -21.4%	+1.4% -1.6%
a.10 $pp \rightarrow \gamma jj$	$p\ p > a\ j\ j$	$7.815 \pm 0.008 \cdot 10^3$	+32.8% -24.2%	+0.9% -1.2%	$1.004 \pm 0.004 \cdot 10^4$	+5.9% -10.9%	+0.8% -1.2%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)					
		LO 13 TeV		NLO 13 TeV			
Vector-boson pair + jets							
b.1 $pp \rightarrow W^+W^-$ (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 $pp \rightarrow ZZ$	$p\ p > z\ z$	$1.097 \pm 0.002 \cdot 10^1$	+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 $pp \rightarrow ZW^\pm$	$p\ p > z\ wpm$	$2.777 \pm 0.003 \cdot 10^1$	+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 $pp \rightarrow \gamma\gamma$	$p\ p > a\ a$	$2.510 \pm 0.002 \cdot 10^1$	+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 $pp \rightarrow \gamma Z$	$p\ p > a\ z$	$2.523 \pm 0.004 \cdot 10^1$	+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 $pp \rightarrow \gamma W^\pm$	$p\ p > a\ wpm$	$2.954 \pm 0.005 \cdot 10^1$	+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 $pp \rightarrow W^+W^- j$ (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 $pp \rightarrow ZZj$	$p\ p > z\ z j$	$3.662 \pm 0.003 \cdot 10^0$	+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 $pp \rightarrow ZW^\pm j$	$p\ p > z\ wpm\ j$	$1.605 \pm 0.005 \cdot 10^1$	+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 $pp \rightarrow \gamma\gamma j$	$p\ p > a\ a j$	$1.022 \pm 0.001 \cdot 10^1$	+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* $pp \rightarrow \gamma Z j$	$p\ p > a\ z j$	$8.310 \pm 0.017 \cdot 10^0$	+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* $pp \rightarrow \gamma W^\pm j$	$p\ p > a\ wpm\ j$	$2.546 \pm 0.010 \cdot 10^1$	+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 $pp \rightarrow W^+W^+jj$	$p\ p > w^+ w^+ j\ j$	$1.484 \pm 0.006 \cdot 10^{-1}$	+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 $pp \rightarrow W^-W^-jj$	$p\ p > w^- w^- j\ j$	$6.752 \pm 0.007 \cdot 10^{-2}$	+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 $pp \rightarrow W^+W^-jj$ (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 $pp \rightarrow ZZjj$	$p\ p > z\ z j\ j$	$1.344 \pm 0.002 \cdot 10^0$	+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 $pp \rightarrow ZW^\pm jj$	$p\ p > z\ wpm\ j\ j$	$8.038 \pm 0.009 \cdot 10^0$	+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 $pp \rightarrow \gamma\gamma jj$	$p\ p > a\ a j\ j$	$5.377 \pm 0.029 \cdot 10^0$	+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* $pp \rightarrow \gamma Z jj$	$p\ p > a\ z j\ j$	$3.260 \pm 0.009 \cdot 10^0$	+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* $pp \rightarrow \gamma W^\pm jj$	$p\ p > a\ wpm\ j\ j$	$1.233 \pm 0.002 \cdot 10^1$	+24.7% -18.6%	+0.6% -0.6%	$1.448 \pm 0.005 \cdot 10^1$	+3.6% -5.4%	+0.6% -0.7%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)					
		LO 13 TeV			NLO 13 TeV		
Three vector bosons +jet							
c.1 $pp \rightarrow W^+W^-W^\pm$ (4f)	$p\ p > w^+ w^- wpm$	$1.307 \pm 0.003 \cdot 10^{-1}$	+0.0% -0.3%	+2.0% -1.5%	$2.109 \pm 0.006 \cdot 10^{-1}$	+5.1% -4.1%	+1.6% -1.2%
c.2 $pp \rightarrow ZW^+W^-$ (4f)	$p\ p > z\ w^+\ w^-$	$9.658 \pm 0.065 \cdot 10^{-2}$	+0.8% -1.1%	+2.1% -1.6%	$1.679 \pm 0.005 \cdot 10^{-1}$	+6.3% -5.1%	+1.6% -1.2%
c.3 $pp \rightarrow ZZW^\pm$	$p\ p > z\ z\ wpm$	$2.996 \pm 0.016 \cdot 10^{-2}$	+1.0% -1.4%	+2.0% -1.6%	$5.550 \pm 0.020 \cdot 10^{-2}$	+6.8% -5.5%	+1.5% -1.1%
c.4 $pp \rightarrow ZZZ$	$p\ p > z\ z\ z$	$1.085 \pm 0.002 \cdot 10^{-2}$	+0.0% -0.5%	+1.9% -1.5%	$1.417 \pm 0.005 \cdot 10^{-2}$	+2.7% -2.1%	+1.9% -1.5%
c.5 $pp \rightarrow \gamma W^+W^-$ (4f)	$p\ p > a\ w^+\ w^-$	$1.427 \pm 0.011 \cdot 10^{-1}$	+1.9% -2.6%	+2.0% -1.5%	$2.581 \pm 0.008 \cdot 10^{-1}$	+5.4% -4.3%	+1.4% -1.1%
c.6 $pp \rightarrow \gamma\gamma W^\pm$	$p\ p > a\ a\ wpm$	$2.681 \pm 0.007 \cdot 10^{-2}$	+4.4% -5.6%	+1.9% -1.6%	$8.251 \pm 0.032 \cdot 10^{-2}$	+7.6% -7.0%	+1.0% -1.0%
c.7 $pp \rightarrow \gamma ZW^\pm$	$p\ p > a\ z\ wpm$	$4.994 \pm 0.011 \cdot 10^{-2}$	+0.8% -1.4%	+1.9% -1.6%	$1.117 \pm 0.004 \cdot 10^{-1}$	+7.2% -5.9%	+1.2% -0.9%
c.8 $pp \rightarrow \gamma ZZ$	$p\ p > a\ z\ z$	$2.318 \pm 0.004 \cdot 10^{-2}$	+2.0% -2.8%	+1.9% -1.5%	$3.177 \pm 0.015 \cdot 10^{-2}$	+3.1% -2.9%	+1.8% -1.4%
c.9 $pp \rightarrow \gamma\gamma Z$	$p\ p > a\ a\ z$	$3.077 \pm 0.008 \cdot 10^{-2}$	+5.7% -6.8%	+1.9% -1.6%	$4.571 \pm 0.017 \cdot 10^{-2}$	+4.2% -4.8%	+1.7% -1.4%
c.10 $pp \rightarrow \gamma\gamma\gamma$	$p\ p > a\ a\ a$	$1.269 \pm 0.003 \cdot 10^{-2}$	+9.8% -11.0%	+2.0% -1.8%	$3.441 \pm 0.012 \cdot 10^{-2}$	+11.8% -11.6%	+1.4% -1.5%
c.11* $pp \rightarrow W^+W^-W^\pm j$ (4f)	$p\ p > w^+ w^- wpm\ j$	$9.167 \pm 0.010 \cdot 10^{-2}$	+15.0% -12.2%	+1.0% -0.7%	$1.197 \pm 0.004 \cdot 10^{-1}$	+5.2% -5.6%	+1.0% -0.8%
c.12* $pp \rightarrow ZW^+W^- j$ (4f)	$p\ p > z\ w^+\ w^- j$	$8.340 \pm 0.010 \cdot 10^{-2}$	+15.6% -12.6%	+1.0% -0.7%	$1.066 \pm 0.003 \cdot 10^{-1}$	+4.5% -5.3%	+1.0% -0.7%
c.13* $pp \rightarrow ZZW^\pm j$	$p\ p > z\ z\ wpm\ j$	$2.810 \pm 0.004 \cdot 10^{-2}$	+16.1% -13.0%	+1.0% -0.7%	$3.660 \pm 0.013 \cdot 10^{-2}$	+4.8% -5.6%	+1.0% -0.7%
c.14* $pp \rightarrow ZZZj$	$p\ p > z\ z\ z\ j$	$4.823 \pm 0.011 \cdot 10^{-3}$	+14.3% -11.8%	+1.4% -1.0%	$6.341 \pm 0.025 \cdot 10^{-3}$	+4.9% -5.4%	+1.4% -1.0%
c.15* $pp \rightarrow \gamma W^+W^- j$ (4f)	$p\ p > a\ w^+\ w^- j$	$1.182 \pm 0.004 \cdot 10^{-1}$	+13.4% -11.2%	+0.8% -0.7%	$1.233 \pm 0.004 \cdot 10^3$	+18.9% -19.9%	+1.0% -1.5%
c.16 $pp \rightarrow \gamma\gamma W^\pm j$	$p\ p > a\ a\ wpm\ j$	$4.107 \pm 0.015 \cdot 10^{-2}$	+11.8% -10.2%	+0.6% -0.8%	$5.807 \pm 0.023 \cdot 10^{-2}$	+5.8% -5.5%	+0.7% -0.7%
c.17* $pp \rightarrow \gamma ZW^\pm j$	$p\ p > a\ z\ wpm\ j$	$5.833 \pm 0.023 \cdot 10^{-2}$	+14.4% -12.0%	+0.7% -0.6%	$7.764 \pm 0.025 \cdot 10^{-2}$	+5.1% -5.5%	+0.8% -0.6%
c.18* $pp \rightarrow \gamma ZZj$	$p\ p > a\ z\ z\ j$	$9.995 \pm 0.013 \cdot 10^{-3}$	+12.5% -10.6%	+1.2% -0.9%	$1.371 \pm 0.005 \cdot 10^{-2}$	+5.6% -5.5%	+1.2% -0.9%
c.19* $pp \rightarrow \gamma\gamma Zj$	$p\ p > a\ a\ z\ j$	$1.372 \pm 0.003 \cdot 10^{-2}$	+10.9% -9.4%	+1.0% -0.9%	$2.051 \pm 0.011 \cdot 10^{-2}$	+7.0% -6.3%	+1.0% -0.9%
c.20* $pp \rightarrow \gamma\gamma\gamma j$	$p\ p > a\ a\ a\ j$	$1.031 \pm 0.006 \cdot 10^{-2}$	+14.3% -12.6%	+0.9% -1.2%	$2.020 \pm 0.008 \cdot 10^{-2}$	+12.8% -11.0%	+0.8% -1.2%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)						
		LO 13 TeV			NLO 13 TeV			
		Four vector bosons						
c.21*	$pp \rightarrow W^+W^-W^+W^-$ (4f)	$p\ p > w^+ w^- w^+ w^-$	$5.721 \pm 0.014 \cdot 10^{-4}$	+3.7% -3.5%	+2.3% -1.7%	$9.959 \pm 0.035 \cdot 10^{-4}$	+7.4% -6.0%	+1.7% -1.2%
c.22*	$pp \rightarrow W^+W^-W^\pm Z$ (4f)	$p\ p > w^+ w^- wpm\ z$	$6.391 \pm 0.076 \cdot 10^{-4}$	+4.4% -4.1%	+2.4% -1.8%	$1.188 \pm 0.004 \cdot 10^{-3}$	+8.4% -6.8%	+1.7% -1.2%
c.23*	$pp \rightarrow W^+W^-W^\pm\gamma$ (4f)	$p\ p > w^+ w^- wpm\ a$	$8.115 \pm 0.064 \cdot 10^{-4}$	+2.5% -2.5%	+2.2% -1.7%	$1.546 \pm 0.005 \cdot 10^{-3}$	+7.9% -6.3%	+1.5% -1.1%
c.24*	$pp \rightarrow W^+W^-ZZ$ (4f)	$p\ p > w^+ w^- z\ z$	$4.320 \pm 0.013 \cdot 10^{-4}$	+4.4% -4.1%	+2.4% -1.7%	$7.107 \pm 0.020 \cdot 10^{-4}$	+7.0% -5.7%	+1.8% -1.3%
c.25*	$pp \rightarrow W^+W^-Z\gamma$ (4f)	$p\ p > w^+ w^- z\ a$	$8.403 \pm 0.016 \cdot 10^{-4}$	+3.0% -2.9%	+2.3% -1.7%	$1.483 \pm 0.004 \cdot 10^{-3}$	+7.2% -5.8%	+1.6% -1.2%
c.26*	$pp \rightarrow W^+W^-\gamma\gamma$ (4f)	$p\ p > w^+ w^- a\ a$	$5.198 \pm 0.012 \cdot 10^{-4}$	+0.6% -0.9%	+2.1% -1.6%	$9.381 \pm 0.032 \cdot 10^{-4}$	+6.7% -5.3%	+1.4% -1.1%
c.27*	$pp \rightarrow W^\pm ZZZ$	$p\ p > wpm\ z\ z\ z$	$5.862 \pm 0.010 \cdot 10^{-5}$	+5.1% -4.7%	+2.4% -1.8%	$1.240 \pm 0.004 \cdot 10^{-4}$	+9.9% -8.0%	+1.7% -1.2%
c.28*	$pp \rightarrow W^\pm ZZ\gamma$	$p\ p > wpm\ z\ z\ a$	$1.148 \pm 0.003 \cdot 10^{-4}$	+3.6% -3.5%	+2.2% -1.7%	$2.945 \pm 0.008 \cdot 10^{-4}$	+10.8% -8.7%	+1.3% -1.0%
c.29*	$pp \rightarrow W^\pm Z\gamma\gamma$	$p\ p > wpm\ z\ a\ a$	$1.054 \pm 0.004 \cdot 10^{-4}$	+1.7% -1.9%	+2.1% -1.7%	$3.033 \pm 0.010 \cdot 10^{-4}$	+10.6% -8.6%	+1.1% -0.8%
c.30*	$pp \rightarrow W^\pm\gamma\gamma\gamma$	$p\ p > wpm\ a\ a\ a$	$3.600 \pm 0.013 \cdot 10^{-5}$	+0.4% -1.0%	+2.0% -1.6%	$1.246 \pm 0.005 \cdot 10^{-4}$	+9.8% -8.1%	+0.9% -0.8%
c.31*	$pp \rightarrow ZZZZ$	$p\ p > z\ z\ z\ z$	$1.989 \pm 0.002 \cdot 10^{-5}$	+3.8% -3.6%	+2.2% -1.7%	$2.629 \pm 0.008 \cdot 10^{-5}$	+3.5% -3.0%	+2.2% -1.7%
c.32*	$pp \rightarrow ZZZ\gamma$	$p\ p > z\ z\ z\ a$	$3.945 \pm 0.007 \cdot 10^{-5}$	+1.9% -2.1%	+2.1% -1.6%	$5.224 \pm 0.016 \cdot 10^{-5}$	+3.3% -2.7%	+2.1% -1.6%
c.33*	$pp \rightarrow ZZ\gamma\gamma$	$p\ p > z\ z\ a\ a$	$5.513 \pm 0.017 \cdot 10^{-5}$	+0.0% -0.3%	+2.1% -1.6%	$7.518 \pm 0.032 \cdot 10^{-5}$	+3.4% -2.6%	+2.0% -1.5%
c.34*	$pp \rightarrow Z\gamma\gamma\gamma$	$p\ p > z\ a\ a\ a$	$4.790 \pm 0.012 \cdot 10^{-5}$	+2.3% -3.1%	+2.0% -1.6%	$7.103 \pm 0.026 \cdot 10^{-5}$	+3.4% -3.2%	+1.6% -1.5%
c.35*	$pp \rightarrow \gamma\gamma\gamma\gamma$	$p\ p > a\ a\ a\ a$	$1.594 \pm 0.004 \cdot 10^{-5}$	+4.7% -5.7%	+1.9% -1.7%	$3.389 \pm 0.012 \cdot 10^{-5}$	+7.0% -6.7%	+1.3% -1.3%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)					
		LO 13 TeV			NLO 13 TeV		
<b>Heavy quarks and jets</b>							
d.1 $pp \rightarrow jj$	$p\ p > j\ j$	$1.162 \pm 0.001 \cdot 10^6$	+24.9%	+0.8%	$1.580 \pm 0.007 \cdot 10^6$	+8.4%	+0.7%
d.2 $pp \rightarrow jjj$	$p\ p > j\ j\ j$	$8.940 \pm 0.021 \cdot 10^4$	+43.8%	+1.2%	$7.791 \pm 0.037 \cdot 10^4$	+2.1%	+1.1%
d.3 $pp \rightarrow b\bar{b}$	$p\ p > b\ b\sim$	$3.743 \pm 0.004 \cdot 10^3$	+25.2%	+1.5%	$6.438 \pm 0.028 \cdot 10^3$	+15.9%	+1.5%
d.4* $pp \rightarrow b\bar{b}j$	$p\ p > b\ b\sim j$	$1.050 \pm 0.002 \cdot 10^3$	+44.1%	+1.6%	$1.327 \pm 0.007 \cdot 10^3$	+6.8%	+1.5%
d.5* $pp \rightarrow b\bar{b}jj$	$p\ p > b\ b\sim j\ j$	$1.852 \pm 0.006 \cdot 10^2$	+61.8%	+2.1%	$2.471 \pm 0.012 \cdot 10^2$	+8.2%	+2.0%
d.6 $pp \rightarrow b\bar{b}bb$	$p\ p > b\ b\sim b\ b\sim$	$5.050 \pm 0.007 \cdot 10^{-1}$	+61.7%	+2.9%	$8.736 \pm 0.034 \cdot 10^{-1}$	+20.9%	+2.9%
d.7 $pp \rightarrow t\bar{t}$	$p\ p > t\ t\sim$	$4.584 \pm 0.003 \cdot 10^2$	+29.0%	+1.8%	$6.741 \pm 0.023 \cdot 10^2$	+9.8%	+1.8%
d.8 $pp \rightarrow t\bar{t}j$	$p\ p > t\ t\sim j$	$3.135 \pm 0.002 \cdot 10^2$	+45.1%	+2.2%	$4.106 \pm 0.015 \cdot 10^2$	+8.1%	+2.1%
d.9 $pp \rightarrow t\bar{t}jj$	$p\ p > t\ t\sim j\ j$	$1.361 \pm 0.001 \cdot 10^2$	+61.4%	+2.6%	$1.795 \pm 0.006 \cdot 10^2$	+9.3%	+2.4%
d.10 $pp \rightarrow t\bar{t}t\bar{t}$	$p\ p > t\ t\sim t\ t\sim$	$4.505 \pm 0.005 \cdot 10^{-3}$	+63.8%	+5.4%	$9.201 \pm 0.028 \cdot 10^{-3}$	+30.8%	+5.5%
d.11 $pp \rightarrow t\bar{t}bb\bar{b}$	$p\ p > t\ t\sim b\ b\sim$	$6.119 \pm 0.004 \cdot 10^0$	+62.1%	+2.9%	$1.452 \pm 0.005 \cdot 10^1$	+37.6%	+2.9%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)						
		LO 13 TeV			NLO 13 TeV			
<b>Heavy quarks+vector bosons</b>								
e.1	$pp \rightarrow W^\pm b\bar{b}$	$p\ p > wpm\ b\ b\sim$	$3.074 \pm 0.002 \cdot 10^2$	+42.3% -29.2%	+2.0% -1.6%	$8.162 \pm 0.034 \cdot 10^2$	+29.8% -23.6%	+1.5% -1.2%
e.2	$pp \rightarrow Z b\bar{b}$	$p\ p > z\ b\ b\sim$	$6.993 \pm 0.003 \cdot 10^2$	+33.5% -24.4%	+1.0% -1.4%	$1.235 \pm 0.004 \cdot 10^3$	+19.9% -17.4%	+1.0% -1.4%
e.3	$pp \rightarrow \gamma b\bar{b}$	$p\ p > a\ b\ b\sim$	$1.731 \pm 0.001 \cdot 10^3$	+51.9% -34.8%	+1.6% -2.1%	$4.171 \pm 0.015 \cdot 10^3$	+33.7% -27.1%	+1.4% -1.9%
e.4*	$pp \rightarrow W^\pm b\bar{b} j$	$p\ p > wpm\ b\ b\sim\ j$	$1.861 \pm 0.003 \cdot 10^2$	+42.5% -27.7%	+0.7% -0.7%	$3.957 \pm 0.013 \cdot 10^2$	+27.0% -21.0%	+0.7% -0.6%
e.5*	$pp \rightarrow Z b\bar{b} j$	$p\ p > z\ b\ b\sim\ j$	$1.604 \pm 0.001 \cdot 10^2$	+42.4% -27.6%	+0.9% -1.1%	$2.805 \pm 0.009 \cdot 10^2$	+21.0% -17.6%	+0.8% -1.0%
e.6*	$pp \rightarrow \gamma b\bar{b} j$	$p\ p > a\ b\ b\sim\ j$	$7.812 \pm 0.017 \cdot 10^2$	+51.2% -32.0%	+1.0% -1.5%	$1.233 \pm 0.004 \cdot 10^3$	+18.9% -19.9%	+1.0% -1.5%
e.7	$pp \rightarrow t\bar{t} W^\pm$	$p\ p > t\ t\sim\ wpm$	$3.777 \pm 0.003 \cdot 10^{-1}$	+23.9% -18.0%	+2.1% -1.6%	$5.662 \pm 0.021 \cdot 10^{-1}$	+11.2% -10.6%	+1.7% -1.3%
e.8	$pp \rightarrow t\bar{t} Z$	$p\ p > t\ t\sim\ z$	$5.273 \pm 0.004 \cdot 10^{-1}$	+30.5% -21.8%	+1.8% -2.1%	$7.598 \pm 0.026 \cdot 10^{-1}$	+9.7% -11.1%	+1.9% -2.2%
e.9	$pp \rightarrow t\bar{t} \gamma$	$p\ p > t\ t\sim\ a$	$1.204 \pm 0.001 \cdot 10^0$	+29.6% -21.3%	+1.6% -1.8%	$1.744 \pm 0.005 \cdot 10^0$	+9.8% -11.0%	+1.7% -2.0%
e.10*	$pp \rightarrow t\bar{t} W^\pm j$	$p\ p > t\ t\sim\ wpm\ j$	$2.352 \pm 0.002 \cdot 10^{-1}$	+40.9% -27.1%	+1.3% -1.0%	$3.404 \pm 0.011 \cdot 10^{-1}$	+11.2% -14.0%	+1.2% -0.9%
e.11*	$pp \rightarrow t\bar{t} Z j$	$p\ p > t\ t\sim\ z\ j$	$3.953 \pm 0.004 \cdot 10^{-1}$	+46.2% -29.5%	+2.7% -3.0%	$5.074 \pm 0.016 \cdot 10^{-1}$	+7.0% -12.3%	+2.5% -2.9%
e.12*	$pp \rightarrow t\bar{t} \gamma j$	$p\ p > t\ t\sim\ a\ j$	$8.726 \pm 0.010 \cdot 10^{-1}$	+45.4% -29.1%	+2.3% -2.6%	$1.135 \pm 0.004 \cdot 10^0$	+7.5% -12.2%	+2.2% -2.5%
e.13*	$pp \rightarrow t\bar{t} W^- W^+ (4f)$	$p\ p > t\ t\sim\ w^+\ w^-$	$6.675 \pm 0.006 \cdot 10^{-3}$	+30.9% -21.9%	+2.1% -2.0%	$9.904 \pm 0.026 \cdot 10^{-3}$	+10.9% -11.8%	+2.1% -2.1%
e.14*	$pp \rightarrow t\bar{t} W^\pm Z$	$p\ p > t\ t\sim\ wpm\ z$	$2.404 \pm 0.002 \cdot 10^{-3}$	+26.6% -19.6%	+2.5% -1.8%	$3.525 \pm 0.010 \cdot 10^{-3}$	+10.6% -10.8%	+2.3% -1.6%
e.15*	$pp \rightarrow t\bar{t} W^\pm \gamma$	$p\ p > t\ t\sim\ wpm\ a$	$2.718 \pm 0.003 \cdot 10^{-3}$	+25.4% -18.9%	+2.3% -1.8%	$3.927 \pm 0.013 \cdot 10^{-3}$	+10.3% -10.4%	+2.0% -1.5%
e.16*	$pp \rightarrow t\bar{t} ZZ$	$p\ p > t\ t\sim\ z\ z$	$1.349 \pm 0.014 \cdot 10^{-3}$	+29.3% -21.1%	+1.7% -1.5%	$1.840 \pm 0.007 \cdot 10^{-3}$	+7.9% -9.9%	+1.7% -1.5%
e.17*	$pp \rightarrow t\bar{t} Z\gamma$	$p\ p > t\ t\sim\ z\ a$	$2.548 \pm 0.003 \cdot 10^{-3}$	+30.1% -21.5%	+1.7% -1.6%	$3.656 \pm 0.012 \cdot 10^{-3}$	+9.7% -11.0%	+1.8% -1.9%
e.18*	$pp \rightarrow t\bar{t} \gamma\gamma$	$p\ p > t\ t\sim\ a\ a$	$3.272 \pm 0.006 \cdot 10^{-3}$	+28.4% -20.6%	+1.3% -1.1%	$4.402 \pm 0.015 \cdot 10^{-3}$	+7.8% -9.7%	+1.4% -1.4%

# AUTOMATIC NLO IN THE SM (2014)



Process	Syntax	Cross section (pb)					
		LO 13 TeV			NLO 13 TeV		
Single-top							
f.1 $pp \rightarrow tj$ (t-channel)	$p\ p > tt\ j\ \$\$ w^+ w^-$	$1.520 \pm 0.001 \cdot 10^2$	+9.4%	+0.4%	$1.563 \pm 0.005 \cdot 10^2$	+1.4%	+0.4%
f.2 $pp \rightarrow t\gamma j$ (t-channel)	$p\ p > tt\ a\ j\ \$\$ w^+ w^-$	$9.956 \pm 0.014 \cdot 10^{-1}$	+6.4%	+0.9%	$1.017 \pm 0.003 \cdot 10^0$	+1.3%	+0.8%
f.3 $pp \rightarrow tZj$ (t-channel)	$p\ p > tt\ z\ j\ \$\$ w^+ w^-$	$6.967 \pm 0.007 \cdot 10^{-1}$	+3.5%	+0.9%	$6.993 \pm 0.021 \cdot 10^{-1}$	+1.6%	+0.9%
f.4 $pp \rightarrow tbj$ (t-channel)	$p\ p > tt\ bb\ j\ \$\$ w^+ w^-$	$1.003 \pm 0.000 \cdot 10^2$	+13.8%	+0.4%	$1.319 \pm 0.003 \cdot 10^2$	+5.8%	+0.4%
f.5* $pp \rightarrow tbj\gamma$ (t-channel)	$p\ p > tt\ bb\ j\ a\ \$\$ w^+ w^-$	$6.293 \pm 0.006 \cdot 10^{-1}$	+16.8%	+0.8%	$8.612 \pm 0.025 \cdot 10^{-1}$	+6.2%	+0.8%
f.6* $pp \rightarrow tbjZ$ (t-channel)	$p\ p > tt\ bb\ j\ z\ \$\$ w^+ w^-$	$3.934 \pm 0.002 \cdot 10^{-1}$	+18.7%	+1.0%	$5.657 \pm 0.014 \cdot 10^{-1}$	+7.7%	+0.9%
f.7 $pp \rightarrow tb$ (s-channel)	$p\ p > w^+ > t\ b\sim, p\ p > w^- > t\sim\ b$	$7.489 \pm 0.007 \cdot 10^0$	+3.5%	+1.9%	$1.001 \pm 0.004 \cdot 10^1$	+3.7%	+1.9%
f.8* $pp \rightarrow tb\gamma$ (s-channel)	$p\ p > w^+ > t\ b\sim\ a, p\ p > w^- > t\sim\ b\ a$	$1.490 \pm 0.001 \cdot 10^{-2}$	+1.2%	+1.9%	$1.952 \pm 0.007 \cdot 10^{-2}$	+2.6%	+1.7%
f.9* $pp \rightarrow tbZ$ (s-channel)	$p\ p > w^+ > t\ b\sim\ z, p\ p > w^- > t\sim\ b\ z$	$1.072 \pm 0.001 \cdot 10^{-2}$	+1.3%	+2.0%	$1.539 \pm 0.005 \cdot 10^{-2}$	+3.9%	+1.9%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)						
		LO 13 TeV			NLO 13 TeV			
<b>Single Higgs production</b>								
g.1	$pp \rightarrow H$ (HEFT)	$p\ p \rightarrow h$	$1.593 \pm 0.003 \cdot 10^1$	+34.8% -26.0%	+1.2% -1.7%	$3.261 \pm 0.010 \cdot 10^1$	+20.2% -17.9%	+1.1% -1.6%
g.2	$pp \rightarrow Hj$ (HEFT)	$p\ p \rightarrow h\ j$	$8.367 \pm 0.003 \cdot 10^0$	+39.4% -26.4%	+1.2% -1.4%	$1.422 \pm 0.006 \cdot 10^1$	+18.5% -16.6%	+1.1% -1.4%
g.3	$pp \rightarrow Hjj$ (HEFT)	$p\ p \rightarrow h\ j\ j$	$3.020 \pm 0.002 \cdot 10^0$	+59.1% -34.7%	+1.4% -1.7%	$5.124 \pm 0.020 \cdot 10^0$	+20.7% -21.0%	+1.3% -1.5%
g.4	$pp \rightarrow Hjj$ (VBF)	$p\ p \rightarrow h\ j\ j\ \$(w^+ w^- z)$	$1.987 \pm 0.002 \cdot 10^0$	+1.7% -2.0%	+1.9% -1.4%	$1.900 \pm 0.006 \cdot 10^0$	+0.8% -0.9%	+2.0% -1.5%
g.5	$pp \rightarrow Hjjj$ (VBF)	$p\ p \rightarrow h\ j\ j\ j\ \$(w^+ w^- z)$	$2.824 \pm 0.005 \cdot 10^{-1}$	+15.7% -12.7%	+1.5% -1.0%	$3.085 \pm 0.010 \cdot 10^{-1}$	+2.0% -3.0%	+1.5% -1.1%
g.6	$pp \rightarrow HW^\pm$	$p\ p \rightarrow h\ wpm$	$1.195 \pm 0.002 \cdot 10^0$	+3.5% -4.5%	+1.9% -1.5%	$1.419 \pm 0.005 \cdot 10^0$	+2.1% -2.6%	+1.9% -1.4%
g.7	$pp \rightarrow HW^\pm j$	$p\ p \rightarrow h\ wpm\ j$	$4.018 \pm 0.003 \cdot 10^{-1}$	+10.7% -9.3%	+1.2% -0.9%	$4.842 \pm 0.017 \cdot 10^{-1}$	+3.6% -3.7%	+1.2% -1.0%
g.8*	$pp \rightarrow HW^\pm jj$	$p\ p \rightarrow h\ wpm\ j\ j$	$1.198 \pm 0.016 \cdot 10^{-1}$	+26.1% -19.4%	+0.8% -0.6%	$1.574 \pm 0.014 \cdot 10^{-1}$	+5.0% -6.5%	+0.9% -0.6%
g.9	$pp \rightarrow HZ$	$p\ p \rightarrow h\ z$	$6.468 \pm 0.008 \cdot 10^{-1}$	+3.5% -4.5%	+1.9% -1.4%	$7.674 \pm 0.027 \cdot 10^{-1}$	+2.0% -2.5%	+1.9% -1.4%
g.10	$pp \rightarrow HZ j$	$p\ p \rightarrow h\ z\ j$	$2.225 \pm 0.001 \cdot 10^{-1}$	+10.6% -9.2%	+1.1% -0.8%	$2.667 \pm 0.010 \cdot 10^{-1}$	+3.5% -3.6%	+1.1% -0.9%
g.11*	$pp \rightarrow HZ jj$	$p\ p \rightarrow h\ z\ j\ j$	$7.262 \pm 0.012 \cdot 10^{-2}$	+26.2% -19.4%	+0.7% -0.6%	$8.753 \pm 0.037 \cdot 10^{-2}$	+4.8% -6.3%	+0.7% -0.6%
g.12*	$pp \rightarrow HW^+ W^-$ (4f)	$p\ p \rightarrow h\ w^+ w^-$	$8.325 \pm 0.139 \cdot 10^{-3}$	+0.0% -0.3%	+2.0% -1.6%	$1.065 \pm 0.003 \cdot 10^{-2}$	+2.5% -1.9%	+2.0% -1.5%
g.13*	$pp \rightarrow HW^\pm \gamma$	$p\ p \rightarrow h\ wpm\ a$	$2.518 \pm 0.006 \cdot 10^{-3}$	+0.7% -1.4%	+1.9% -1.5%	$3.309 \pm 0.011 \cdot 10^{-3}$	+2.7% -2.0%	+1.7% -1.4%
g.14*	$pp \rightarrow HZW^\pm$	$p\ p \rightarrow h\ z\ wpm$	$3.763 \pm 0.007 \cdot 10^{-3}$	+1.1% -1.5%	+2.0% -1.6%	$5.292 \pm 0.015 \cdot 10^{-3}$	+3.9% -3.1%	+1.8% -1.4%
g.15*	$pp \rightarrow HZZ$	$p\ p \rightarrow h\ z\ z$	$2.093 \pm 0.003 \cdot 10^{-3}$	+0.1% -0.6%	+1.9% -1.5%	$2.538 \pm 0.007 \cdot 10^{-3}$	+1.9% -1.4%	+2.0% -1.5%
g.16	$pp \rightarrow Ht\bar{t}$	$p\ p \rightarrow h\ t\ t\sim$	$3.579 \pm 0.003 \cdot 10^{-1}$	+30.0% -21.5%	+1.7% -2.0%	$4.608 \pm 0.016 \cdot 10^{-1}$	+5.7% -9.0%	+2.0% -2.3%
g.17	$pp \rightarrow Htj$	$p\ p \rightarrow h\ tt\ j$	$4.994 \pm 0.005 \cdot 10^{-2}$	+2.4% -4.2%	+1.2% -1.3%	$6.328 \pm 0.022 \cdot 10^{-2}$	+2.9% -1.8%	+1.5% -1.6%
g.18	$pp \rightarrow Hb\bar{b}$ (4f)	$p\ p \rightarrow h\ b\ b\sim$	$4.983 \pm 0.002 \cdot 10^{-1}$	+28.1% -21.0%	+1.5% -1.8%	$6.085 \pm 0.026 \cdot 10^{-1}$	+7.3% -9.6%	+1.6% -2.0%
g.19	$pp \rightarrow Ht\bar{t}j$	$p\ p \rightarrow h\ t\ t\sim\ j$	$2.674 \pm 0.041 \cdot 10^{-1}$	+45.6% -29.2%	+2.6% -2.9%	$3.244 \pm 0.025 \cdot 10^{-1}$	+3.5% -8.7%	+2.5% -2.9%
g.20*	$pp \rightarrow Hb\bar{b}j$ (4f)	$p\ p \rightarrow h\ b\ b\sim\ j$	$7.367 \pm 0.002 \cdot 10^{-2}$	+45.6% -29.1%	+1.8% -2.1%	$9.034 \pm 0.032 \cdot 10^{-2}$	+7.9% -11.0%	+1.8% -2.2%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)				
		LO 13 TeV		NLO 13 TeV		
<b>Multiple Higgs production</b>						
h.1	$pp \rightarrow HH$ (Loop improved)	$p\ p > h\ h$	$1.772 \pm 0.006 \cdot 10^{-2}$	+29.5% +2.1% -21.4% -2.6%	$2.763 \pm 0.008 \cdot 10^{-2}$	+11.4% +2.1% -11.8% -2.6%
h.2	$pp \rightarrow HHjj$ (VBF)	$p\ p > h\ h\ j\ j\ \$\$ w^+ w^- z$	$6.503 \pm 0.019 \cdot 10^{-4}$	+7.2% +2.3% -6.4% -1.6%	$6.820 \pm 0.026 \cdot 10^{-4}$	+0.8% +2.4% -1.0% -1.7%
h.3	$pp \rightarrow HHW^\pm$	$p\ p > h\ h\ wpm$	$4.303 \pm 0.005 \cdot 10^{-4}$	+0.9% +2.0% -1.3% -1.5%	$5.002 \pm 0.014 \cdot 10^{-4}$	+1.5% +2.0% -1.2% -1.6%
h.4*	$pp \rightarrow HHW^\pm j$	$p\ p > h\ h\ wpm\ j$	$1.922 \pm 0.002 \cdot 10^{-4}$	+14.2% +1.5% -11.7% -1.1%	$2.218 \pm 0.009 \cdot 10^{-4}$	+2.7% +1.6% -3.3% -1.1%
h.5*	$pp \rightarrow HHW^\pm \gamma$	$p\ p > h\ h\ wpm\ a$	$1.952 \pm 0.004 \cdot 10^{-6}$	+3.0% +2.2% -3.0% -1.6%	$2.347 \pm 0.007 \cdot 10^{-6}$	+2.4% +2.1% -2.0% -1.6%
h.6*	$pp \rightarrow HHHW^\pm$	$p\ p > h\ h\ h\ wpm$	$3.989 \pm 0.009 \cdot 10^{-7}$	+3.9% +2.2% -3.8% -1.7%	$4.590 \pm 0.012 \cdot 10^{-7}$	+1.8% +2.2% -1.7% -1.7%
h.7	$pp \rightarrow HHZ$	$p\ p > h\ h\ z$	$2.701 \pm 0.007 \cdot 10^{-4}$	+0.9% +2.0% -1.3% -1.5%	$3.130 \pm 0.008 \cdot 10^{-4}$	+1.6% +2.0% -1.2% -1.5%
h.8*	$pp \rightarrow HHZj$	$p\ p > h\ h\ z\ j$	$1.211 \pm 0.001 \cdot 10^{-4}$	+14.1% +1.4% -11.7% -1.1%	$1.394 \pm 0.006 \cdot 10^{-4}$	+2.7% +1.5% -3.2% -1.1%
h.9*	$pp \rightarrow HHZ\gamma$	$p\ p > h\ h\ z\ a$	$1.397 \pm 0.003 \cdot 10^{-6}$	+2.4% +2.2% -2.5% -1.7%	$1.604 \pm 0.005 \cdot 10^{-6}$	+1.7% +2.3% -1.4% -1.7%
h.10*	$pp \rightarrow HHHZ$	$p\ p > h\ h\ h\ z$	$2.735 \pm 0.006 \cdot 10^{-7}$	+3.9% +2.2% -3.7% -1.7%	$3.154 \pm 0.007 \cdot 10^{-7}$	+1.7% +2.2% -1.6% -1.7%
h.11*	$pp \rightarrow HHZZ$	$p\ p > h\ h\ z\ z$	$2.309 \pm 0.005 \cdot 10^{-6}$	+3.9% +2.2% -3.8% -1.7%	$2.754 \pm 0.009 \cdot 10^{-6}$	+2.3% +2.3% -2.0% -1.7%
h.12*	$pp \rightarrow HHZW^\pm$	$p\ p > h\ h\ z\ wpm$	$3.708 \pm 0.013 \cdot 10^{-6}$	+4.8% +2.3% -4.5% -1.7%	$4.904 \pm 0.029 \cdot 10^{-6}$	+3.7% +2.2% -3.2% -1.6%
h.13*	$pp \rightarrow HHW^+W^-$ (4f)	$p\ p > h\ h\ w^+ w^-$	$7.524 \pm 0.070 \cdot 10^{-6}$	+3.5% +2.3% -3.4% -1.7%	$9.268 \pm 0.030 \cdot 10^{-6}$	+2.3% +2.3% -2.1% -1.7%
h.14	$pp \rightarrow HHt\bar{t}$	$p\ p > h\ h\ t\ t\sim$	$6.756 \pm 0.007 \cdot 10^{-4}$	+30.2% +1.8% -21.6% -1.8%	$7.301 \pm 0.024 \cdot 10^{-4}$	+1.4% +2.2% -5.7% -2.3%
h.15	$pp \rightarrow HHtj$	$p\ p > h\ h\ tt\ j$	$1.844 \pm 0.008 \cdot 10^{-5}$	+0.0% +1.8% -0.6% -1.8%	$2.444 \pm 0.009 \cdot 10^{-5}$	+4.5% +2.8% -3.1% -3.0%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)				
		LO 1 TeV	NLO 1 TeV			
<b>Heavy quarks and jets</b>						
i.1	$e^+e^- \rightarrow jj$	$e^+ e^- > j\ j$	$6.223 \pm 0.005 \cdot 10^{-1}$	+0.0% -0.0%	$6.389 \pm 0.013 \cdot 10^{-1}$	+0.2% -0.2%
i.2	$e^+e^- \rightarrow jjj$	$e^+ e^- > j\ j\ j$	$3.401 \pm 0.002 \cdot 10^{-1}$	+9.6% -8.0%	$3.166 \pm 0.019 \cdot 10^{-1}$	+0.2% -2.1%
i.3	$e^+e^- \rightarrow jjjj$	$e^+ e^- > j\ j\ j\ j$	$1.047 \pm 0.001 \cdot 10^{-1}$	+20.0% -15.3%	$1.090 \pm 0.006 \cdot 10^{-1}$	+0.0% -2.8%
i.4	$e^+e^- \rightarrow jjjjj$	$e^+ e^- > j\ j\ j\ j\ j$	$2.211 \pm 0.006 \cdot 10^{-2}$	+31.4% -22.0%	$2.771 \pm 0.021 \cdot 10^{-2}$	+4.4% -8.6%
i.5	$e^+e^- \rightarrow t\bar{t}$	$e^+ e^- > t\ t\sim$	$1.662 \pm 0.002 \cdot 10^{-1}$	+0.0% -0.0%	$1.745 \pm 0.006 \cdot 10^{-1}$	+0.4% -0.4%
i.6	$e^+e^- \rightarrow t\bar{t}j$	$e^+ e^- > t\ t\sim j$	$4.813 \pm 0.005 \cdot 10^{-2}$	+9.3% -7.8%	$5.276 \pm 0.022 \cdot 10^{-2}$	+1.3% -2.1%
i.7*	$e^+e^- \rightarrow t\bar{t}jj$	$e^+ e^- > t\ t\sim j\ j$	$8.614 \pm 0.009 \cdot 10^{-3}$	+19.4% -15.0%	$1.094 \pm 0.005 \cdot 10^{-2}$	+5.0% -6.3%
i.8*	$e^+e^- \rightarrow t\bar{t}jjj$	$e^+ e^- > t\ t\sim j\ j\ j$	$1.044 \pm 0.002 \cdot 10^{-3}$	+30.5% -21.6%	$1.546 \pm 0.010 \cdot 10^{-3}$	+10.6% -11.6%
i.9*	$e^+e^- \rightarrow t\bar{t}t\bar{t}$	$e^+ e^- > t\ t\sim t\ t\sim$	$6.456 \pm 0.016 \cdot 10^{-7}$	+19.1% -14.8%	$1.221 \pm 0.005 \cdot 10^{-6}$	+13.2% -11.2%
i.10*	$e^+e^- \rightarrow t\bar{t}t\bar{t}j$	$e^+ e^- > t\ t\sim t\ t\sim j$	$2.719 \pm 0.005 \cdot 10^{-8}$	+29.9% -21.3%	$5.338 \pm 0.027 \cdot 10^{-8}$	+18.3% -15.4%
i.11	$e^+e^- \rightarrow b\bar{b}$ (4f)	$e^+ e^- > b\ b\sim$	$9.198 \pm 0.004 \cdot 10^{-2}$	+0.0% -0.0%	$9.282 \pm 0.031 \cdot 10^{-2}$	+0.0% -0.0%
i.12	$e^+e^- \rightarrow b\bar{b}j$ (4f)	$e^+ e^- > b\ b\sim j$	$5.029 \pm 0.003 \cdot 10^{-2}$	+9.5% -8.0%	$4.826 \pm 0.026 \cdot 10^{-2}$	+0.5% -2.5%
i.13*	$e^+e^- \rightarrow b\bar{b}jj$ (4f)	$e^+ e^- > b\ b\sim j\ j$	$1.621 \pm 0.001 \cdot 10^{-2}$	+20.0% -15.3%	$1.817 \pm 0.009 \cdot 10^{-2}$	+0.0% -3.1%
i.14*	$e^+e^- \rightarrow b\bar{b}jjj$ (4f)	$e^+ e^- > b\ b\sim j\ j\ j$	$3.641 \pm 0.009 \cdot 10^{-3}$	+31.4% -22.1%	$4.936 \pm 0.038 \cdot 10^{-3}$	+4.8% -8.9%
i.15*	$e^+e^- \rightarrow b\bar{b}b\bar{b}$ (4f)	$e^+ e^- > b\ b\sim b\ b\sim$	$1.644 \pm 0.003 \cdot 10^{-4}$	+19.9% -15.3%	$3.601 \pm 0.017 \cdot 10^{-4}$	+15.2% -12.5%
i.16*	$e^+e^- \rightarrow b\bar{b}b\bar{b}j$ (4f)	$e^+ e^- > b\ b\sim b\ b\sim j$	$7.660 \pm 0.022 \cdot 10^{-5}$	+31.3% -22.0%	$1.537 \pm 0.011 \cdot 10^{-4}$	+17.9% -15.3%
i.17*	$e^+e^- \rightarrow t\bar{t}b\bar{b}$ (4f)	$e^+ e^- > t\ t\sim b\ b\sim$	$1.819 \pm 0.003 \cdot 10^{-4}$	+19.5% -15.0%	$2.923 \pm 0.011 \cdot 10^{-4}$	+9.2% -8.9%
i.18*	$e^+e^- \rightarrow t\bar{t}b\bar{b}j$ (4f)	$e^+ e^- > t\ t\sim b\ b\sim j$	$4.045 \pm 0.011 \cdot 10^{-5}$	+30.5% -21.6%	$7.049 \pm 0.052 \cdot 10^{-5}$	+13.7% -13.1%



# AUTOMATIC NLO IN THE SM (2014)

Process	Syntax	Cross section (pb)				
		LO 1 TeV	NLO 1 TeV			
Top quarks +bosons						
j.1	$e^+e^- \rightarrow t\bar{t}H$	$e^+ e^- > t\bar{t} h$	$2.018 \pm 0.003 \cdot 10^{-3}$	+0.0% -0.0%	$1.911 \pm 0.006 \cdot 10^{-3}$	+0.4% -0.5%
j.2*	$e^+e^- \rightarrow t\bar{t}Hj$	$e^+ e^- > t\bar{t} h j$	$2.533 \pm 0.003 \cdot 10^{-4}$	+9.2% -7.8%	$2.658 \pm 0.009 \cdot 10^{-4}$	+0.5% -1.5%
j.3*	$e^+e^- \rightarrow t\bar{t}Hjj$	$e^+ e^- > t\bar{t} h jj$	$2.663 \pm 0.004 \cdot 10^{-5}$	+19.3% -14.9%	$3.278 \pm 0.017 \cdot 10^{-5}$	+4.0% -5.7%
j.4*	$e^+e^- \rightarrow t\bar{t}\gamma$	$e^+ e^- > t\bar{t} a$	$1.270 \pm 0.002 \cdot 10^{-2}$	+0.0% -0.0%	$1.335 \pm 0.004 \cdot 10^{-2}$	+0.5% -0.4%
j.5*	$e^+e^- \rightarrow t\bar{t}\gamma j$	$e^+ e^- > t\bar{t} a j$	$2.355 \pm 0.002 \cdot 10^{-3}$	+9.3% -7.9%	$2.617 \pm 0.010 \cdot 10^{-3}$	+1.6% -2.4%
j.6*	$e^+e^- \rightarrow t\bar{t}\gamma jj$	$e^+ e^- > t\bar{t} a jj$	$3.103 \pm 0.005 \cdot 10^{-4}$	+19.5% -15.0%	$4.002 \pm 0.021 \cdot 10^{-4}$	+5.4% -6.6%
j.7*	$e^+e^- \rightarrow t\bar{t}Z$	$e^+ e^- > t\bar{t} z$	$4.642 \pm 0.006 \cdot 10^{-3}$	+0.0% -0.0%	$4.949 \pm 0.014 \cdot 10^{-3}$	+0.6% -0.5%
j.8*	$e^+e^- \rightarrow t\bar{t}Zj$	$e^+ e^- > t\bar{t} z j$	$6.059 \pm 0.006 \cdot 10^{-4}$	+9.3% -7.8%	$6.940 \pm 0.028 \cdot 10^{-4}$	+2.0% -2.6%
j.9*	$e^+e^- \rightarrow t\bar{t}Zjj$	$e^+ e^- > t\bar{t} z jj$	$6.351 \pm 0.028 \cdot 10^{-5}$	+19.4% -15.0%	$8.439 \pm 0.051 \cdot 10^{-5}$	+5.8% -6.8%
j.10*	$e^+e^- \rightarrow t\bar{t}W^\pm jj$	$e^+ e^- > t\bar{t} w^\pm jj$	$2.400 \pm 0.004 \cdot 10^{-7}$	+19.3% -14.9%	$3.723 \pm 0.012 \cdot 10^{-7}$	+9.6% -9.1%
j.11*	$e^+e^- \rightarrow t\bar{t}HZ$	$e^+ e^- > t\bar{t} h z$	$3.600 \pm 0.006 \cdot 10^{-5}$	+0.0% -0.0%	$3.579 \pm 0.013 \cdot 10^{-5}$	+0.1% -0.0%
j.12*	$e^+e^- \rightarrow t\bar{t}\gamma Z$	$e^+ e^- > t\bar{t} a z$	$2.212 \pm 0.003 \cdot 10^{-4}$	+0.0% -0.0%	$2.364 \pm 0.006 \cdot 10^{-4}$	+0.6% -0.5%
j.13*	$e^+e^- \rightarrow t\bar{t}\gamma H$	$e^+ e^- > t\bar{t} a h$	$9.756 \pm 0.016 \cdot 10^{-5}$	+0.0% -0.0%	$9.423 \pm 0.032 \cdot 10^{-5}$	+0.3% -0.4%
j.14*	$e^+e^- \rightarrow t\bar{t}\gamma\gamma$	$e^+ e^- > t\bar{t} a a$	$3.650 \pm 0.008 \cdot 10^{-4}$	+0.0% -0.0%	$3.833 \pm 0.013 \cdot 10^{-4}$	+0.4% -0.4%
j.15*	$e^+e^- \rightarrow t\bar{t}ZZ$	$e^+ e^- > t\bar{t} z z$	$3.788 \pm 0.004 \cdot 10^{-5}$	+0.0% -0.0%	$4.007 \pm 0.013 \cdot 10^{-5}$	+0.5% -0.5%
j.16*	$e^+e^- \rightarrow t\bar{t}HH$	$e^+ e^- > t\bar{t} h h$	$1.358 \pm 0.001 \cdot 10^{-5}$	+0.0% -0.0%	$1.206 \pm 0.003 \cdot 10^{-5}$	+0.9% -1.1%
j.17*	$e^+e^- \rightarrow t\bar{t}W^+W^-$	$e^+ e^- > t\bar{t} w^+ w^-$	$1.372 \pm 0.003 \cdot 10^{-4}$	+0.0% -0.0%	$1.540 \pm 0.006 \cdot 10^{-4}$	+1.0% -0.9%

# PHILOSOPHY DIFFERENT FROM MCFM

Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]



# PHILOSOPHY DIFFERENT FROM MCFM

Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]

8.1	$W$ -boson production, processes 1,6 . . . . .	30
8.2	$W +$ jet production, processes 11,16 . . . . .	30
8.3	$W + b$ production, processes 12,17 . . . . .	31
8.4	$W + c$ production, processes 13,18 . . . . .	31
8.5	$W + c$ production ( $m_c = 0$ ), processes 14,19 . . . . .	31
8.6	$W + b\bar{b}$ production, processes 20,25 . . . . .	31
8.7	$W + b\bar{b}$ production ( $m_b = 0$ ), processes 21,26 . . . . .	32
8.8	$W + 2$ jets production, processes 22,27 . . . . .	32
8.9	$W + 3$ jets production, processes 23,28 . . . . .	33
8.10	$W + b\bar{b} +$ jet production ( $m_b = 0$ ), processes 24,29 . . . . .	33
8.11	$Z$ -boson production, processes 31–33 . . . . .	33
8.12	$Z$ -boson production decaying to jets, processes 34–35 . . . . .	33
8.13	$t\bar{t}$ production mediated by $Z/\gamma^*$ -boson exchange, process 36 . . . . .	34
8.14	$Z +$ jet production, processes 41–43 . . . . .	34
8.15	$Z + 2$ jets production, processes 44, 46 . . . . .	34
8.16	$Z + 3$ jets production, processes 45, 47 . . . . .	34

# PHILOSOPHY DIFFERENT FROM MCFM

Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]

8.1	<i>W</i> -boson production processes	1–6						
8.17	$Z + b\bar{b}$ production, process	50	35	.	.	.	30	
8.18	$Z + b\bar{b}$ production ( $m_b = 0$ ), processes	51–53	35	.	.	.	30	
8.19	$Z + b\bar{b}$ + jet production ( $m_b = 0$ ), process	54	35	.	.	.	31	
8.20	$Z + c\bar{c}$ production ( $m_c = 0$ ), process	56	35					
8.21	Di-boson production, processes	61–89	36	.	.	.	31	
8.21.1	$WW$ production, processes	61–64, 69	36	.	.	.	31	
8.21.2	$WW$ +jet production, process	66	37	.	.	.	31	
8.21.3	$WZ$ production, processes	71–80	37	.	.	.		
8.21.4	$ZZ$ production, processes	81–84, 86–90	37	.	.	.	32	
8.21.5	$ZZ$ +jet production, process	85	38	.	.	.	32	
8.21.6	Anomalous couplings		38					
8.22	$WH$ production, processes	91–94, 96–99	39	.	.	.	33	
8.23	$ZH$ production, processes	101–109	39	.	.	.	33	
8.24	Higgs production, processes	111–121	40	.	.	.	33	
8.25	$H \rightarrow W^+W^-$ production, processes	126, 127	41	.	.	.		
8.26	$H + b$ production, processes	131–133	42	.	.	.	33	
8.27	$t\bar{t}$ production with 2 semi-leptonic decays, processes	141–145	42	36	.	.	34	
8.28	$t\bar{t}$ production with decay and a gluon, process	143	43					
8.29	$t\bar{t}$ production with one hadronic decay, processes	146–151	43	.	.	.	34	
8.30	$Q\bar{Q}$ production, processes	157–159	44	.	.	.	34	
8.31	$t\bar{t}$ + jet production, process	160	44	.	.	.	34	
8.32	Single top production, processes	161–177	45					
8.33	$Wt$ production, processes	180–187	46					
8.34	$H +$ jet production, processes	201–210	47					
8.35	Higgs production via WBF, processes	211–217	48					
8.36	$\tau^+\tau^-$ production, process	221	48					
8.37	$t$ -channel single top with an explicit $b$ -quark, processes	231–240	48					
8.38	$W^+W^+$ +jets production, processes	251, 252	49					
8.39	$Z + Q$ production, processes	261–267	49					
8.40	$H + 2$ jet production, processes	270–274	50					
8.41	$H + 3$ jet production, processes	275–278	50					
8.42	Direct $\gamma$ production, processes	280–282	51					
8.43	Direct $\gamma +$ heavy flavour production, processes	283–284	51					
8.44	$\gamma\gamma$ production, processes	285–286	51					
8.45	$W\gamma$ production, processes	290–297	52					
8.45.1	Anomalous $WW\gamma$ couplings		52					
8.46	$Z\gamma$ , production, processes	300, 305	53					
8.46.1	Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings		53					

# PHILOSOPHY DIFFERENT FROM MCFM

Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]

8.1	<i>W</i> -boson production processes 1–6	30
8.17	$Z + b\bar{b}$ production, process 50	35
8.18	$Z + b\bar{b}$ production ( $m_b = 0$ ), processes 51–53	35
8.19	$Z + b\bar{b}$ + jet production ( $m_b = 0$ ), process 54	35
8.20	$Z + c\bar{c}$ production ( $m_c = 0$ ), process 56	35
8.21	Di-boson production, processes 61–89	36
8.21.1	$WW$ production, processes 61–64, 69	36
8.21.2	$WW$ +jet production, process 66	37
8.21.3	$WZ$ production, processes 71–80	37
8.21.4	$ZZ$ production, processes 81–84, 86–90	37
8.21.5	$ZZ$ +jet production, process 85	38
8.21.6	Anomalous couplings	38
8.22	$WH$ production, processes 91–94, 96–99	39
8.23	$ZH$ production, processes 101–109	54
8.24	Higgs production, processes 111–121	54
8.25	$H \rightarrow W^+W^-$ production, processes 1	54
8.26	$H + b$ production, processes 131–133	55
8.27	$t\bar{t}$ production with 2 semi-leptonic de	55
8.28	$t\bar{t}$ production with decay and a gluon	55
8.29	$t\bar{t}$ production with one hadronic deca	55
8.30	$Q\bar{Q}$ production, processes 157–159	56
8.31	$t\bar{t}$ + jet production, process 160	56
8.32	Single top production, processes 161–	57
8.33	$Wt$ production, processes 180–187	58
8.34	$H$ + jet production, processes 201–210	58
8.35	Higgs production via WBF, processes	58
8.36	$\tau^+\tau^-$ production, process 221	58
8.37	$t$ -channel single top with an explicit $t$	58
8.38	$W^+W^+$ +jets production, processes 21	58
8.39	$Z + Q$ production, processes 261–267	59
8.40	$H + 2$ jet production, processes 270–	59
8.41	$H + 3$ jet production, processes 275–2	60
8.42	Direct $\gamma$ production, processes 280–2	60
8.43	Direct $\gamma$ + heavy flavour production,	60
8.44	$\gamma\gamma$ production, processes 285–286	61
8.45	$W\gamma$ production, processes 290–297	52
8.45.1	Anomalous $WW\gamma$ couplings	52
8.46	$Z\gamma$ , production, processes 300, 305	53
8.46.1	Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings	53

# PHILOSOPHY DIFFERENT FROM MCFM

Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]

8.1	<i>W</i> -boson production processes	1–6			
8.17	$Z + b\bar{b}$ production, process	50	35	30	
8.18	$Z + b\bar{b}$ production ( $m_b = 0$ ), processes	51–53	35	30	
8.19	$Z + b\bar{b}$ + jet production ( $m_b = 0$ ), process	54	35	31	
8.20	$Z + c\bar{c}$ production ( $m_c = 0$ ), process	56	35		
8.21	Di-boson production, processes	61–89	36	31	
8.21.1	$WW$ production, processes	61–64, 69	36	31	
8.21.2	$WW$ +jet production, process	66	37	31	
8.21.3	$WZ$ production, processes	71–80	37		
8.21.4	$ZZ$ production, processes	81–84, 86–90	37	32	
8.21.5	$ZZ$ +jet production, process	85	38	32	
8.21.6	Anomalous couplings		38		
8.22	$WH$ production, processes	91–94, 96–99	39	33	
8.23	$ZH$ production, processes	101–109	8.47	$Z\gamma\gamma$ production processes, 301, 306	54
8.24	Higgs production, processes	111–121	8.48	$Z\gamma j$ , production, processes 302, 307	54
8.25	$H \rightarrow W^+W^-$ production, processes	1	8.49	$Z\gamma\gamma j$ and $Z\gamma jj$ , 303, 304, 308 and 309	55
8.26	$H + b$ production, processes	131–133	8.50	$W + Q$ + jet production processes 311–326	55
8.27	$t\bar{t}$ production with 2 semi-leptonic de		8.51	$W + c$ + jet production, processes 331, 336	55
8.28	$t\bar{t}$ production with decay and a gluon		8.52	$Z + Q$ +jet production, processes 341–357	56
8.29	$t\bar{t}$ production with one hadronic deca		8.53	$c\bar{s} \rightarrow W^+$ , processes 361–363	56
8.30	$Q\bar{Q}$ production, processes	157–159	8.54	$W + Q$ production in the 4FNS, processes 401–408	57
8.31	$t\bar{t}$ + jet production, process	160	8.55	$W + Q$ production in the 5FNS, processes 411, 416	58
8.32	Single top production, processes	161–	8.56	$W + Q$ production in the combined 4FNS/5FNS, processes	
8.33	$Wt$ production, processes	180–187	8.57	$W + b\bar{b}$ + jet production, processes 431, 436	58
8.34	$H$ + jet production, processes	201–210	8.58	$W + t\bar{t}$ processes 500–516	58
8.35	Higgs production via WBF, processes		8.59	$Zt\bar{t}$ production, processes 529–533	59
8.36	$\tau^+\tau^-$ production, process	221	8.60	$Ht$ and $H\bar{t}$ production, processes 540–557	59
8.37	$t$ -channel single top with an explicit $t$		8.61	$Zt$ and $Z\bar{t}$ production, processes 560–569	60
8.38	$W^+W^+$ +jets production, processes	21	8.62	$Ht\bar{t}$ production, processes 640–660	60
8.39	$Z + Q$ production, processes	261–267	8.63	Dark Matter Processes Mono-jet and Mono-photon 800–848	61
8.40	$H + 2$ jet production, processes	270–1	8.45	$W\gamma$ production, processes 290–297	52
8.41	$H + 3$ jet production, processes	275–2	8.45.1	Anomalous $WW\gamma$ couplings	52
8.42	Direct $\gamma$ production, processes	280–21	8.46	$Z\gamma$ , production, processes 300, 305	53
8.43	Direct $\gamma$ + heavy flavour production,		8.46.1	Anomalous $ZZ\gamma$ and $Z\gamma\gamma$ couplings	53

- overall 50+ processes
- First results implemented in 1998 ...this is 13 years worth of work of several people (**~5M\$**)
- Cross sections and parton-level distributions at NLO are provided
- One framework, however, each process implemented by hand.

# PHILOSOPHY DIFFERENT FROM MCFM

Downloadable general purpose NLO code [Campbell, Ellis, Williams+collaborators]

8.1	<i>W</i> -boson production processes	1–6			
8.17	$Z + b\bar{b}$ production, process	50	35	30	
8.18	$Z + b\bar{b}$ production ( $m_b = 0$ ), processes	51–53	35	30	
8.19	$Z + b\bar{b}$ + jet production ( $m_b = 0$ ), process	54	35	31	
8.20	$Z + c\bar{c}$ production ( $m_c = 0$ ), process	56	35		
8.21	Di-boson production, processes	61–89	36	31	
8.21.1	$WW$ production, processes	61–64, 69	36	31	
8.21.2	$WW$ +jet production, process	66	37	31	
8.21.3	$WZ$ production, processes	71–80	37		
8.21.4	$ZZ$ production, processes	81–84, 86–90	37	32	
8.21.5	$ZZ$ +jet production, process	85	38	32	
8.21.6	Anomalous couplings		38		
8.22	$WH$ production, processes	91–94, 96–99	39	33	
8.23	$ZH$ production, processes	101–109	8.47	$Z\gamma\gamma$ production processes, 301, 306	54
8.24	Higgs production, processes	111–121	8.48	$Z\gamma j$ , production, processes 302, 307	54
8.25	$H \rightarrow W^+W^-$ production, processes	1	8.49	$Z\gamma\gamma j$ and $Z\gamma jj$ , 303, 304, 308 and 309	55
8.26	$H + b$ production, processes	131–133	8.50	$W + Q +$ jet production processes 311–326	55
8.27	$t\bar{t}$ production with 2 semi-leptonic de		8.51	$W + c +$ jet production, processes 331, 336	55
8.28	$t\bar{t}$ production with decay and a gluon		8.52	$Z + Q +$ jet production, processes 341–357	56
8.29	$t\bar{t}$ production with one hadronic deca		8.53	$c\bar{s} \rightarrow W^+$ , processes 361–363	56
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8.32	Single top production, processes	161–	8.56	$W + Q$ production in the combined 4FNS/5FNS, processes	
8.33	$Wt$ production, processes	180–187	8.35	Higgs production via WBF, processes 421, 426	58
8.34	$H +$ jet production, processes	201–210	8.36	$\tau^+\tau^-$ production, process 221	58
8.35			8.37	$t$ -channel single top with an explicit $t$	58
8.36			8.38	$W^+W^+$ +jets production, processes 21	58
8.37			8.39	$Z + Q$ production, processes 261–267	59
8.38			8.40	$H + 2$ jet production, processes 270–	59
8.39			8.41	$H + 3$ jet production, processes 275–2	60
8.40			8.42	Direct $\gamma$ production, processes 280–2	60
8.41			8.43	Direct $\gamma +$ heavy flavour production,	60
8.42			8.44	$\gamma\gamma$ production, processes 285–286	60
8.43			8.45	$W\gamma$ production, processes 290–297	61
8.44			8.45.1	Anomalous $WW\gamma$ couplings	52
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8.21.4	$ZZ$ production, processes 81–84, 86–90	37
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8.24	Higgs production, processes 111–121	54
8.25	$H \rightarrow W^+W^-$ production, processes 1	54
8.26	$H + b$ production, processes 131–133	55
8.27	$t\bar{t}$ production with 2 semi-leptonic de	55
8.28	$t\bar{t}$ production with decay and a gluon	55
8.29	$t\bar{t}$ production with one hadronic deca	55
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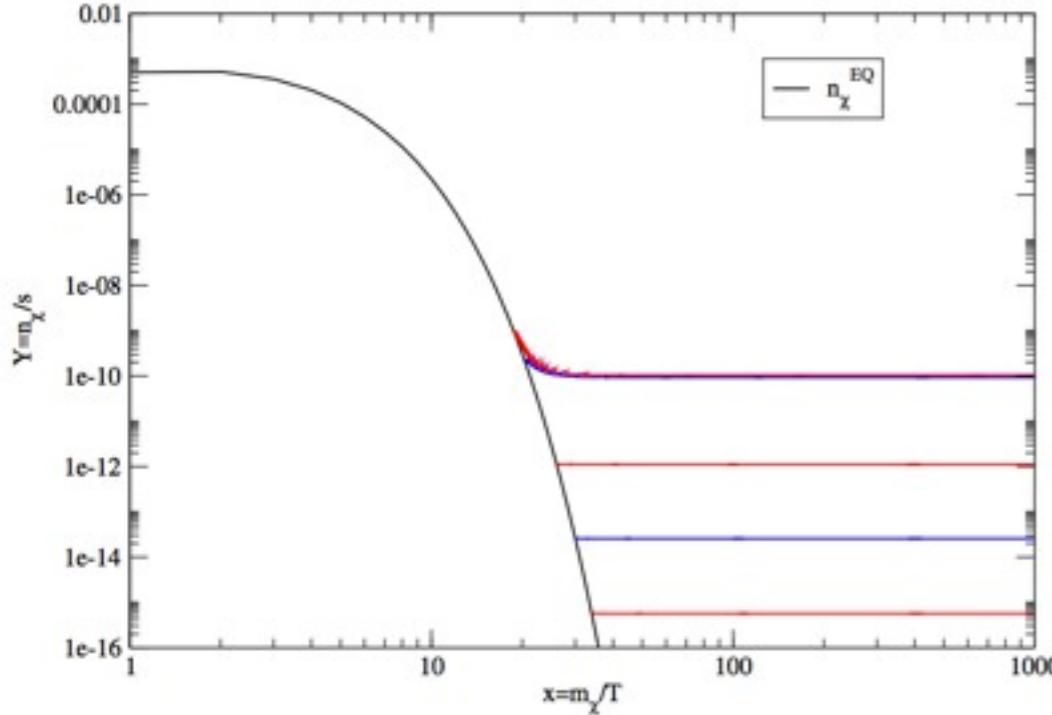
- overall 50+ processes
- First results implemented in 1998 ...this is 13 years worth of work of several people (**~5M\$**)
- Cross sections and parton-level distributions at NLO are provided
- One framework, however, each process implemented by hand.

# IT'S NOT ALL ABOUT COLLIDERS:

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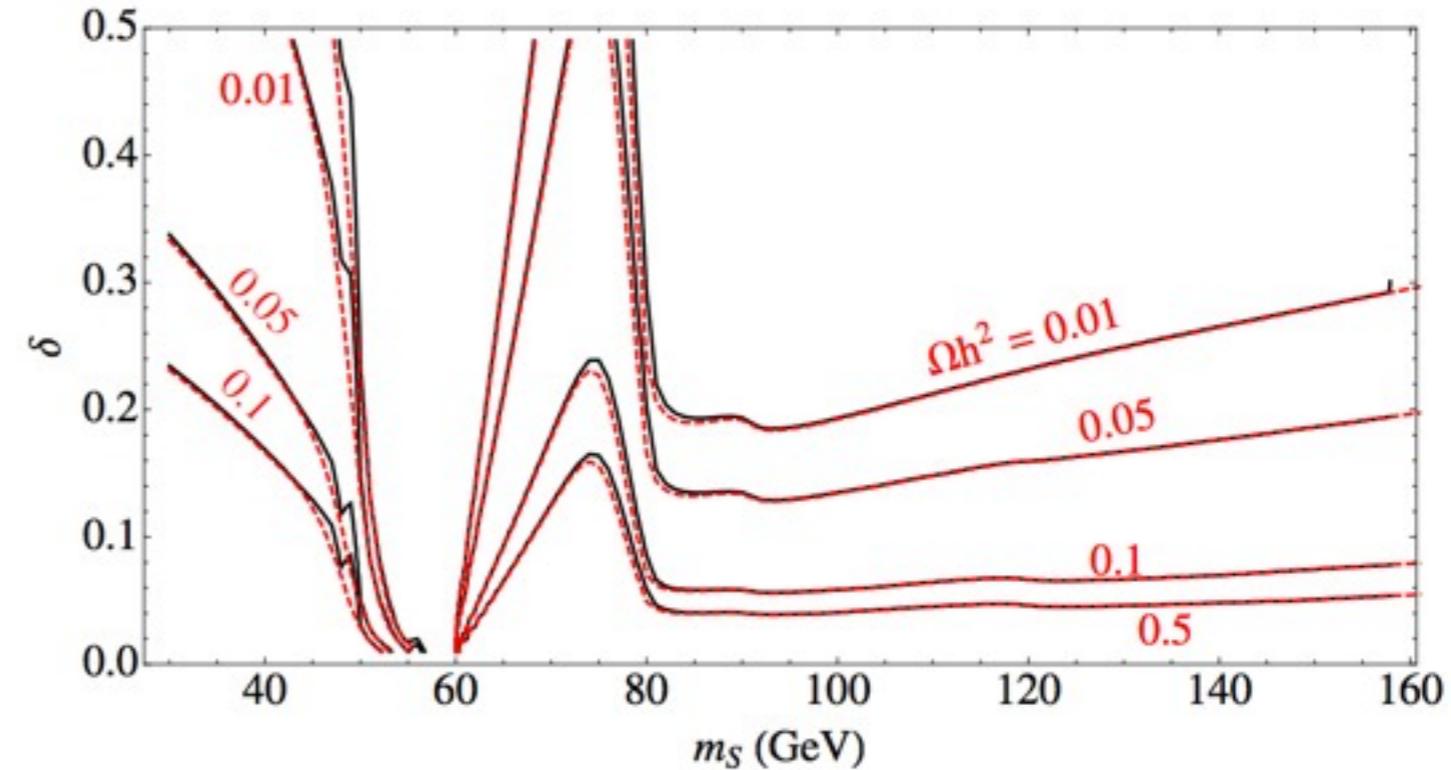
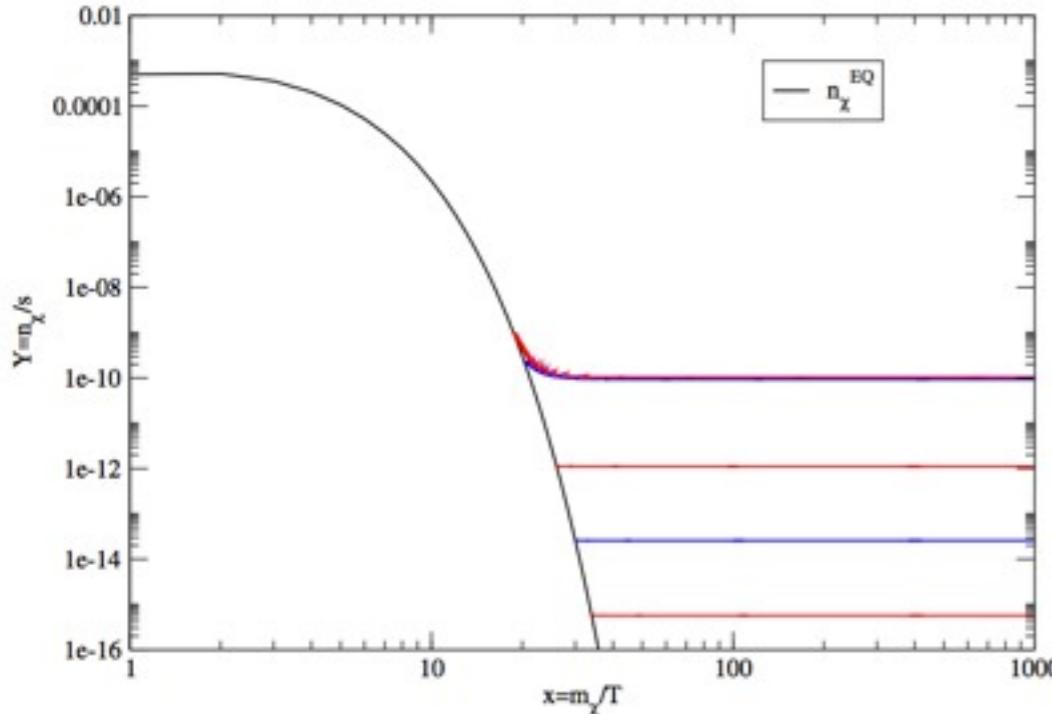
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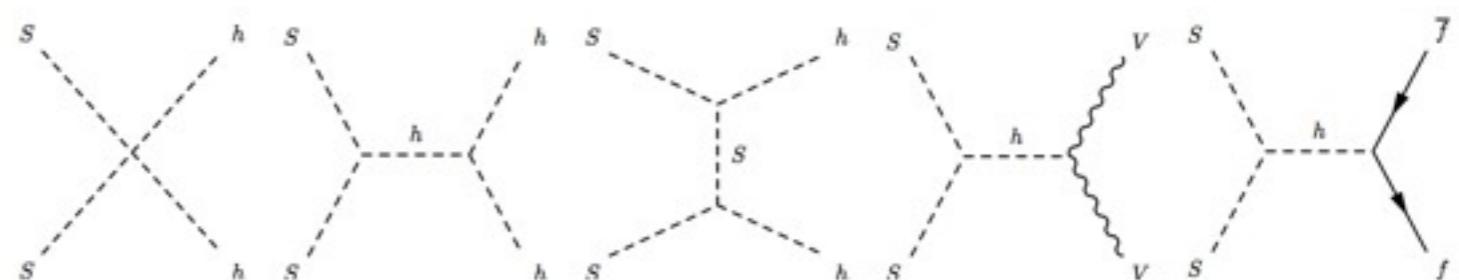
MadDM can compute the freeze-out temperature

( by iteratively computing the dark matter number density at progressively lower temperatures )

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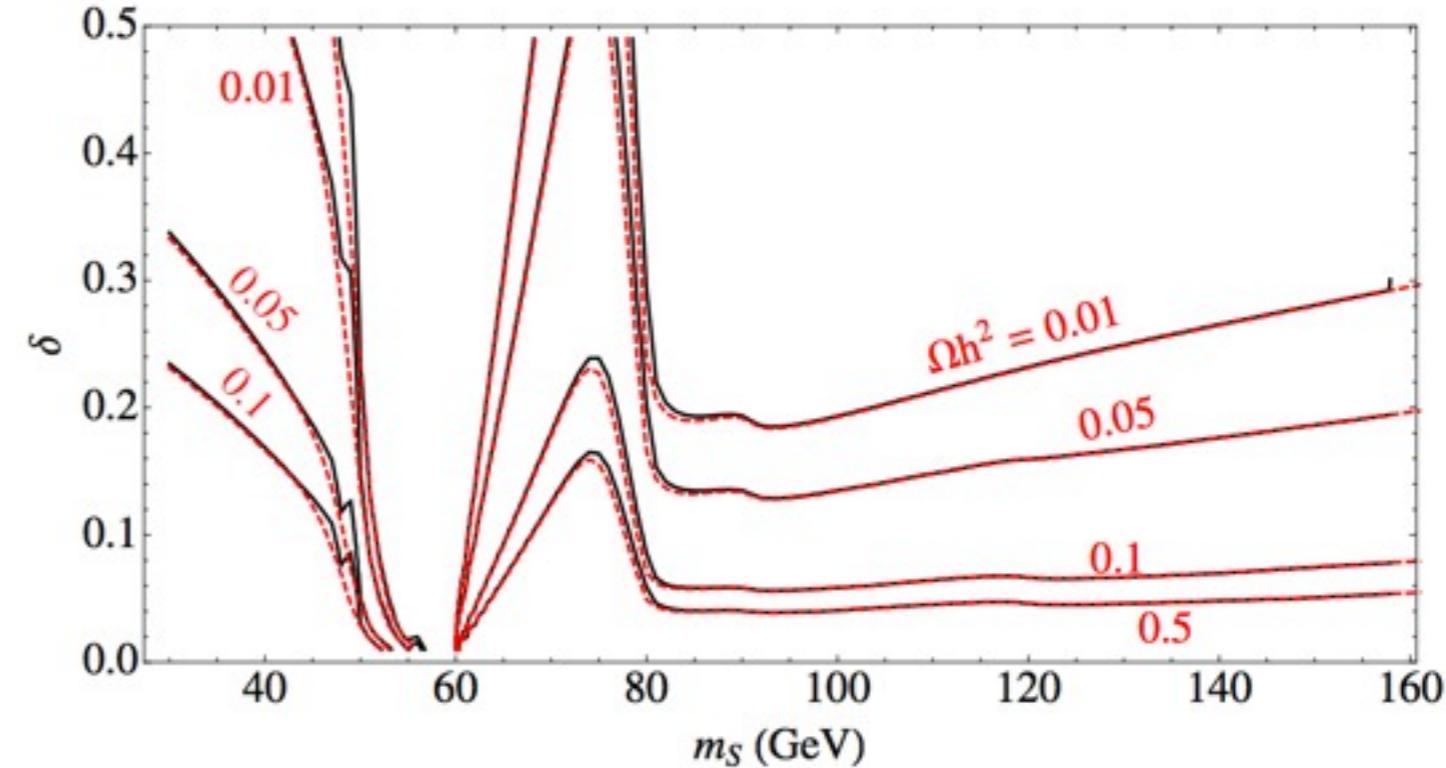
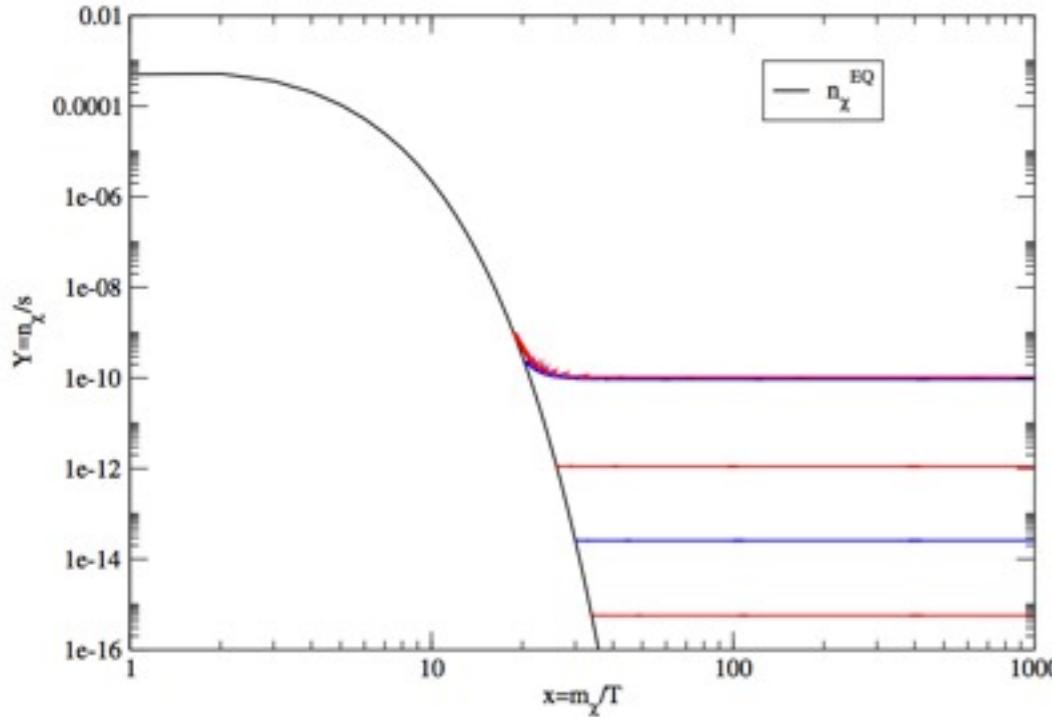


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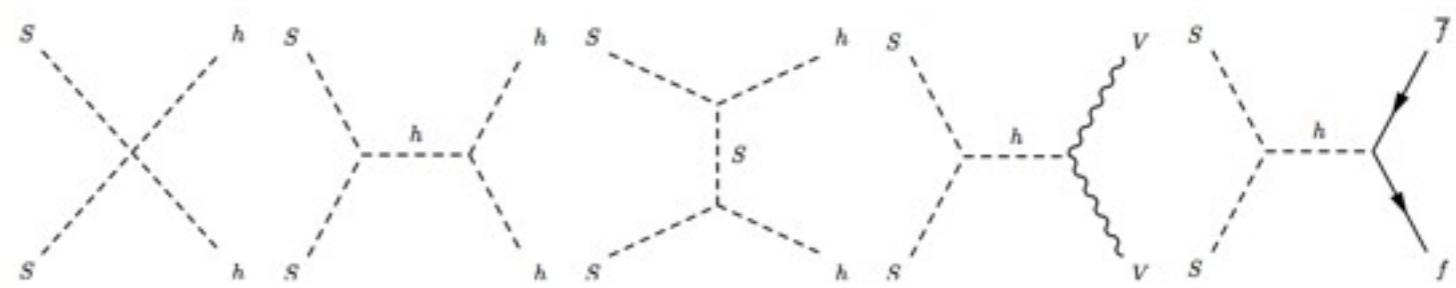
The dark matter relic density computed by MadDM (in black) is compared to the one obtained by MICROMEGAS (in red) for this case-study of the SM plus a real scalar of mass  $m_S$  and coupling  $\delta$ .

# IT'S NOT ALL ABOUT COLLIDERS:



MadDM can compute the freeze-out temperature  
( by iteratively computing the dark matter number density at progressively lower temperatures )

- Model dependent piece are the annihilation process **matrix elements by MG5\_aMC**:
  - BSM flexibility comes “for free”
  - Soon loop-induced annihilation supported too (or even NLO accuracy in decays :)



The dark matter relic density computed by MadDM (in black) is compared to the one obtained by MICROMEGAS (in red) for this case-study of the SM plus a real scalar of mass  $m_S$  and coupling  $\delta$ .

# A LOOK AHEAD

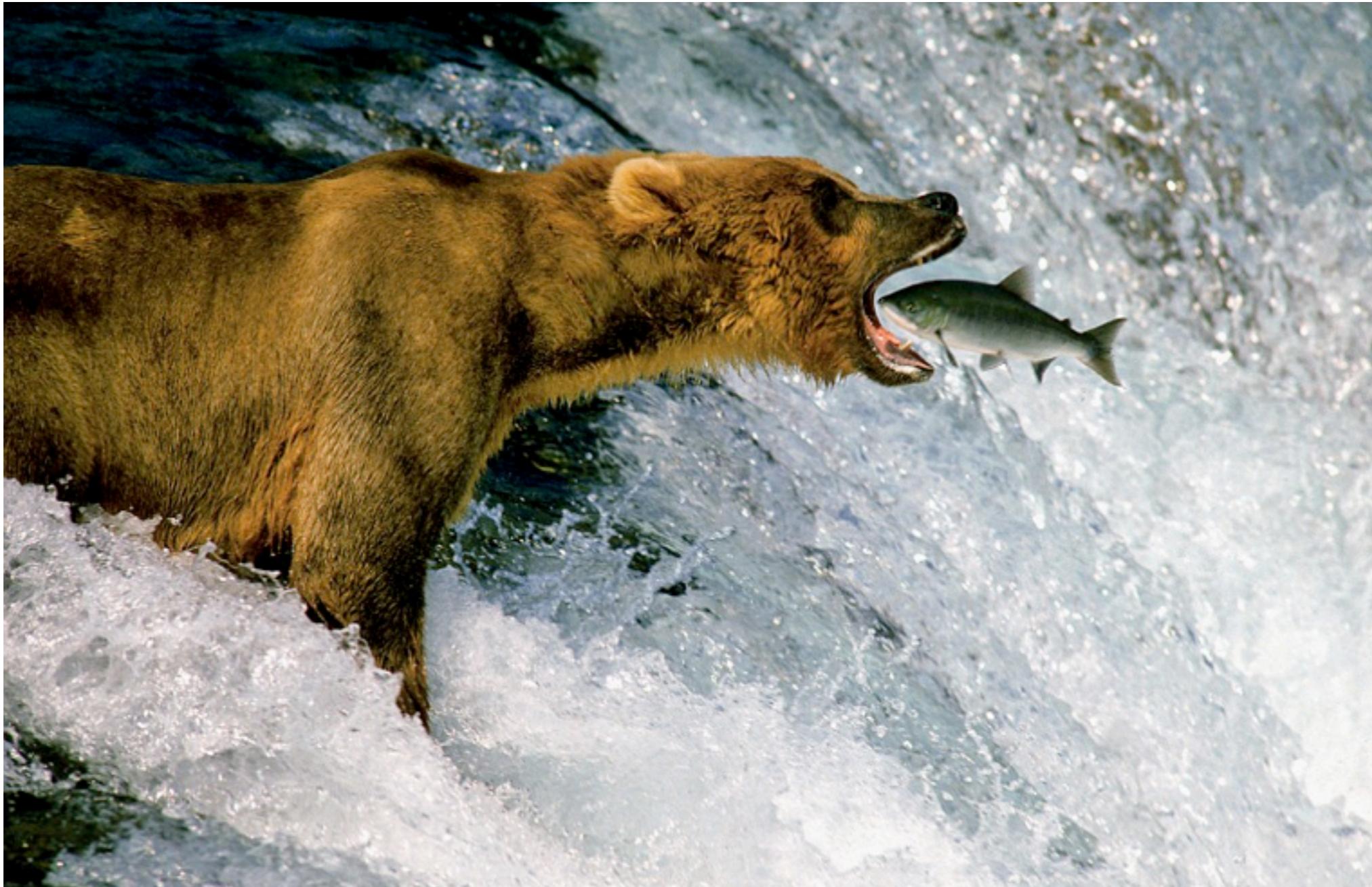
- On-going developments :
  - automatic BSM including EFT
  - automatic computation of EW corrections
- On a longer term perspective, NNLO is the big challenge.
- On-going applications (just a taste):
  - PDF fits and extraction with NLO and NLO+PS (via APPLgrid)
  - Study of loop-induced processes
  - Dark Matter Pheno : loops and NLO

# AUTOMATIC, ACCURATE AND AUGMENTING MC'S AT COLLIDERS



## Free to Pheno

# AUTOMATIC, ACCURATE AND AUGMENTING MC'S AT COLLIDERS



Free to lunch!

# **BACK UP SLIDES**

# NLO+PS IN A NUTSHELL

$$d\sigma^{\text{NLO+PS}} = d\Phi_B \bar{B}^s(\Phi_B) \left[ \Delta^s(p_\perp^{\min}) + d\Phi_{R|B} \frac{R^s(\Phi_R)}{B(\Phi_B)} \Delta^s(p_T(\Phi)) \right] + d\Phi_R R^f(\Phi_R)$$

← →  
integrates to 1 (unitarity)

with

$$\bar{B}^s = B(\Phi_B) + \left[ V(\Phi_B) + \int d\Phi_{R|B} R^s(\Phi_{R|B}) \right]$$

Full cross section (if  $F=1$ ) at fixed Born kinematics

$$R(\Phi_R) = R^s(\Phi_R) + R^f(\Phi_R)$$

This formula is valid both for both MC@NLO and POWHEG

MC@NLO:  $R^s(\Phi) = P(\Phi_{R|B}) B(\Phi_B)$       Needs exact mapping  $(\Phi_B, \Phi_R) \rightarrow \Phi$

POWHEG:  $R^s(\Phi) = F R(\Phi), R^f(\Phi) = (1 - F) R(\Phi)$        $F=1$  = Exponentiates the Real.  
It can be damped by hand.