[Degrassi, et al. '12]

refs are linked

NLO Monte Carlos for collider physics

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Goals of the SM LHC programme

1. Precise determination of the fundamental parameters of the dim=4 SM Lagrangian, such as masses (m_h, m_W, m_t), and couplings:

    - SM measurements of fundamental parameters provide information to be fed to the whole HEP community.

    - Range of validity of the SM.

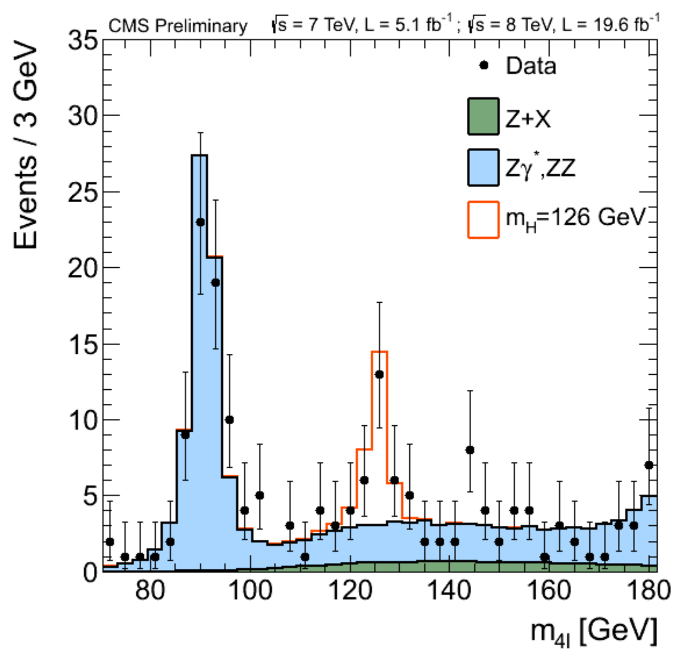
2. Search and quantification of deviations from the SM (New Physics).

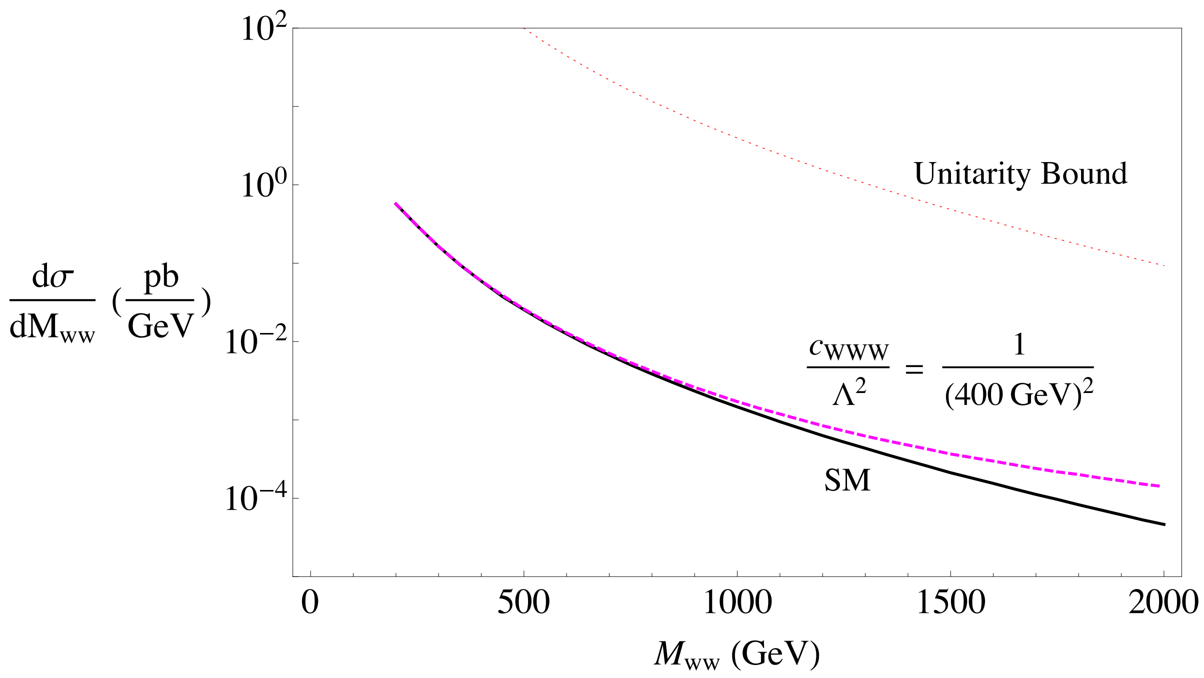
Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states

Search for new interactions

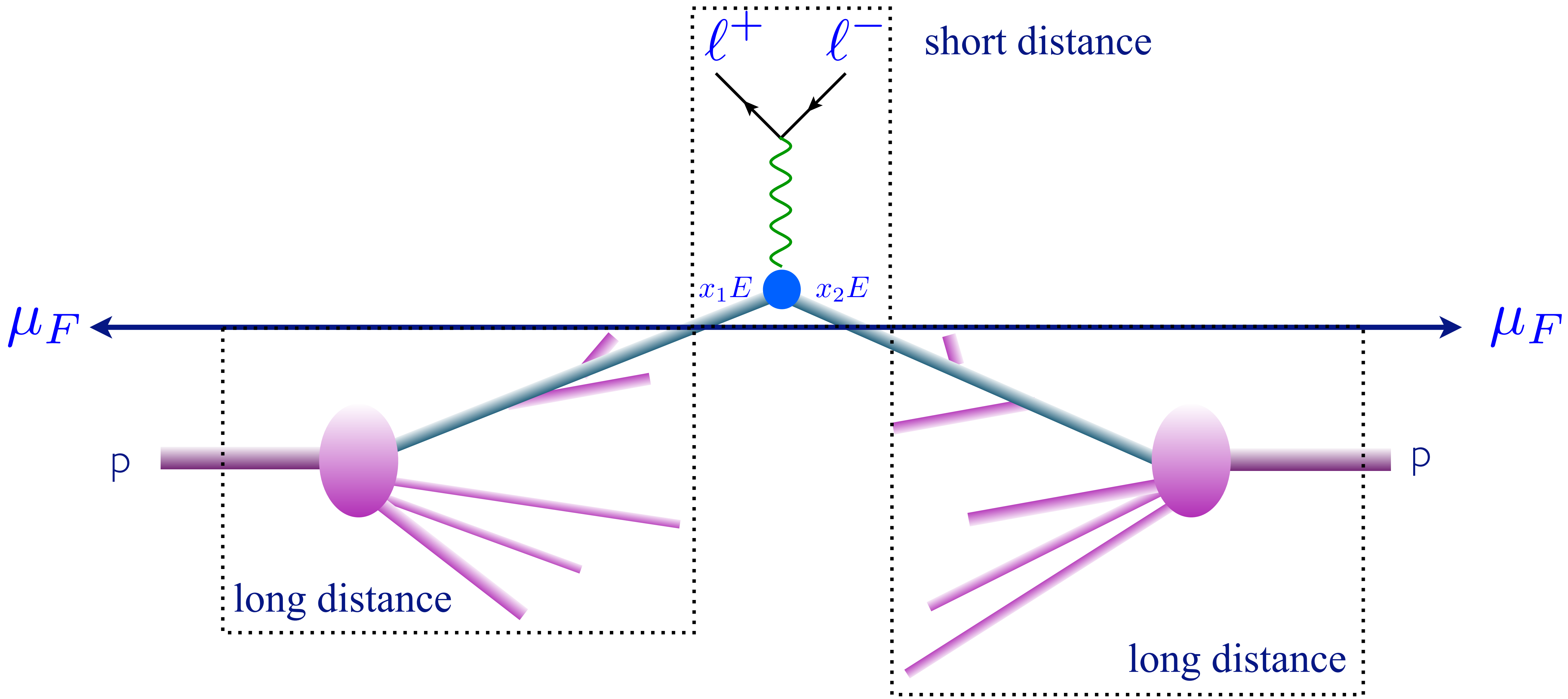




"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

Master formula for the LHC



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Accurate predictions for observables in hadronic collisions depend on the knowledge of both parton distribution functions and partonic cross sections.

Perturbative expansion

$\hat{\sigma}_{ab\to X}(\hat{s},\mu_F,\mu_R)$ 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

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

LO predictions — NLO corrections — NNLO corrections — NNNLO corrections

- Considering also the EW coupling leads to a double exp in α_s and α_W .

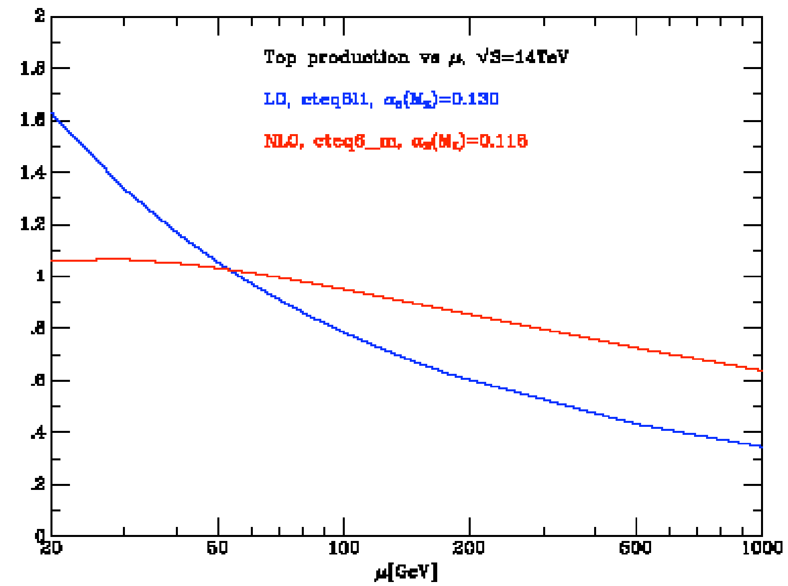
Perturbative expansion

- Leading order (LO) calculations typically give only the order of magnitude of cross sections and distributions

  - the scale of α_s is not defined
  - jets partons: jet structure starts to appear only beyond LO
  - Born topology might not be leading at the LHC

- To obtain reliable predictions at least NLO is needed

- NNLO allows to quantify uncertainties



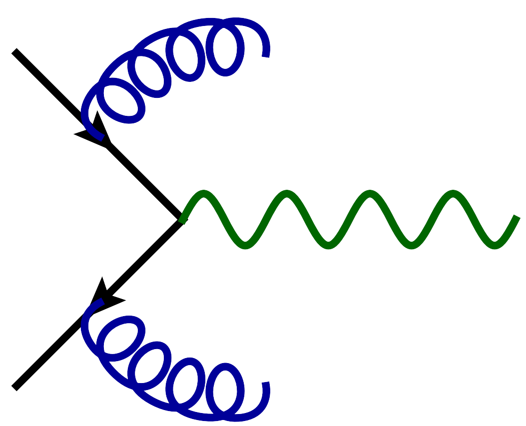
Furthermore:

- Resummation of the large logarithmic terms at phase space boundaries
- NLO ElectroWeak corrections ($\alpha_s^2 = \alpha_W$)
- Fully exclusive predictions available in terms of event simulation that can be used in experimental analysis

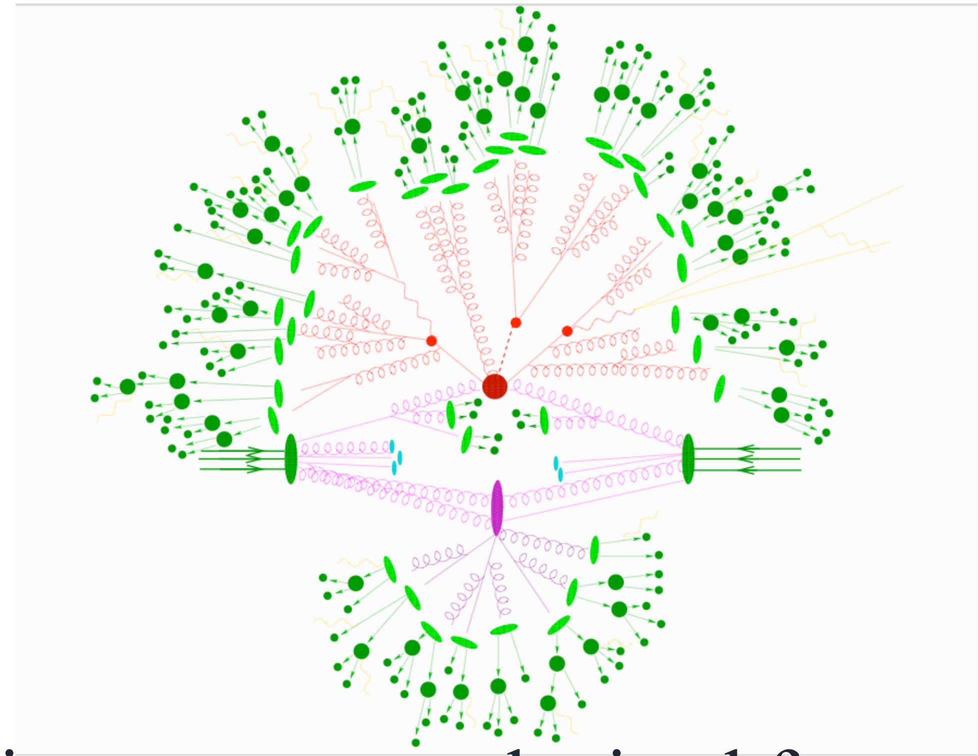
Predictive (NLO) Monte Carlo Generators

DEFINITION: A Monte Carlo generator is a code that can produce fully exclusive events (up to particle level) as distributed in Nature.

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2 \, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

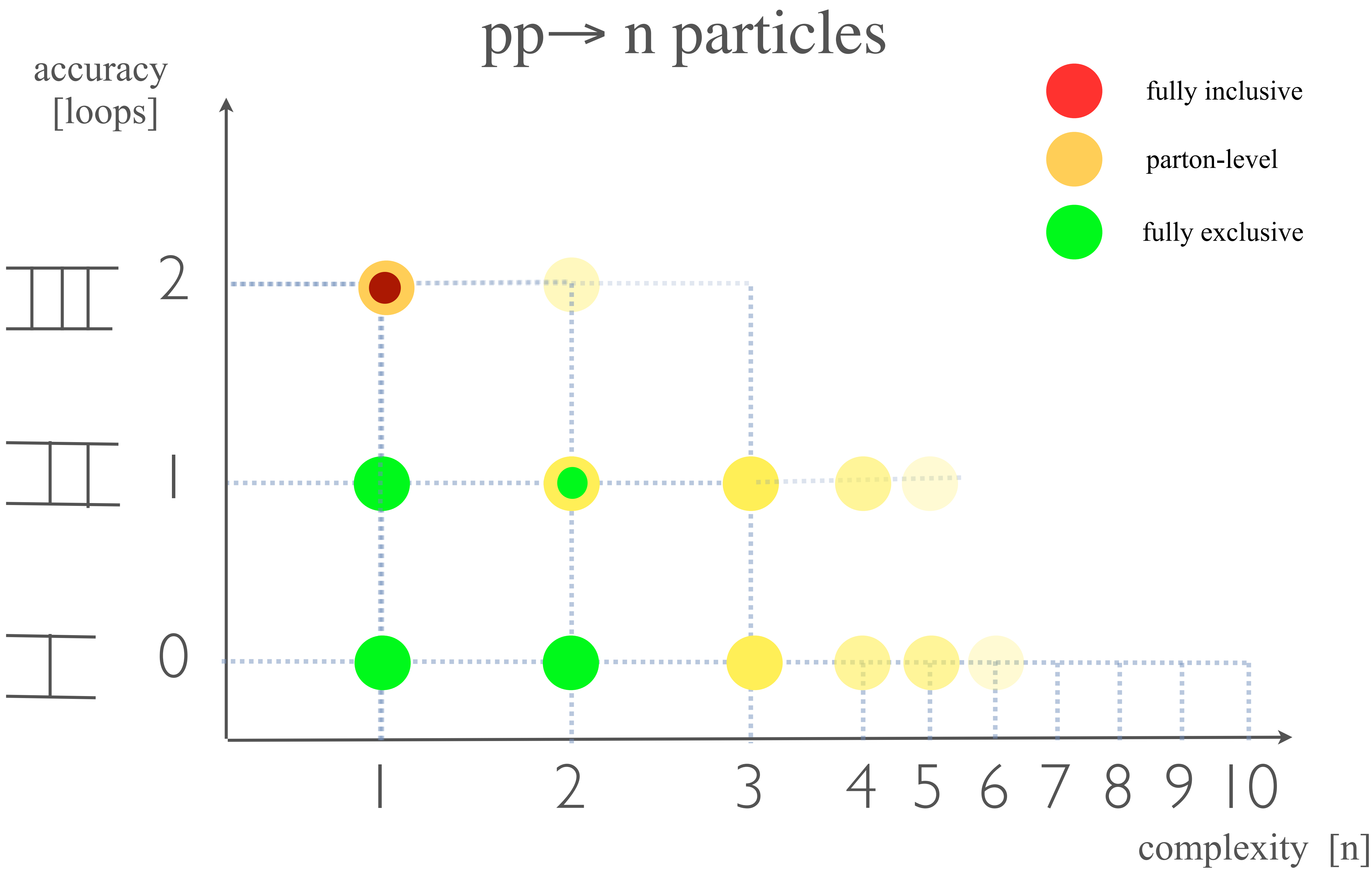


High Q^2

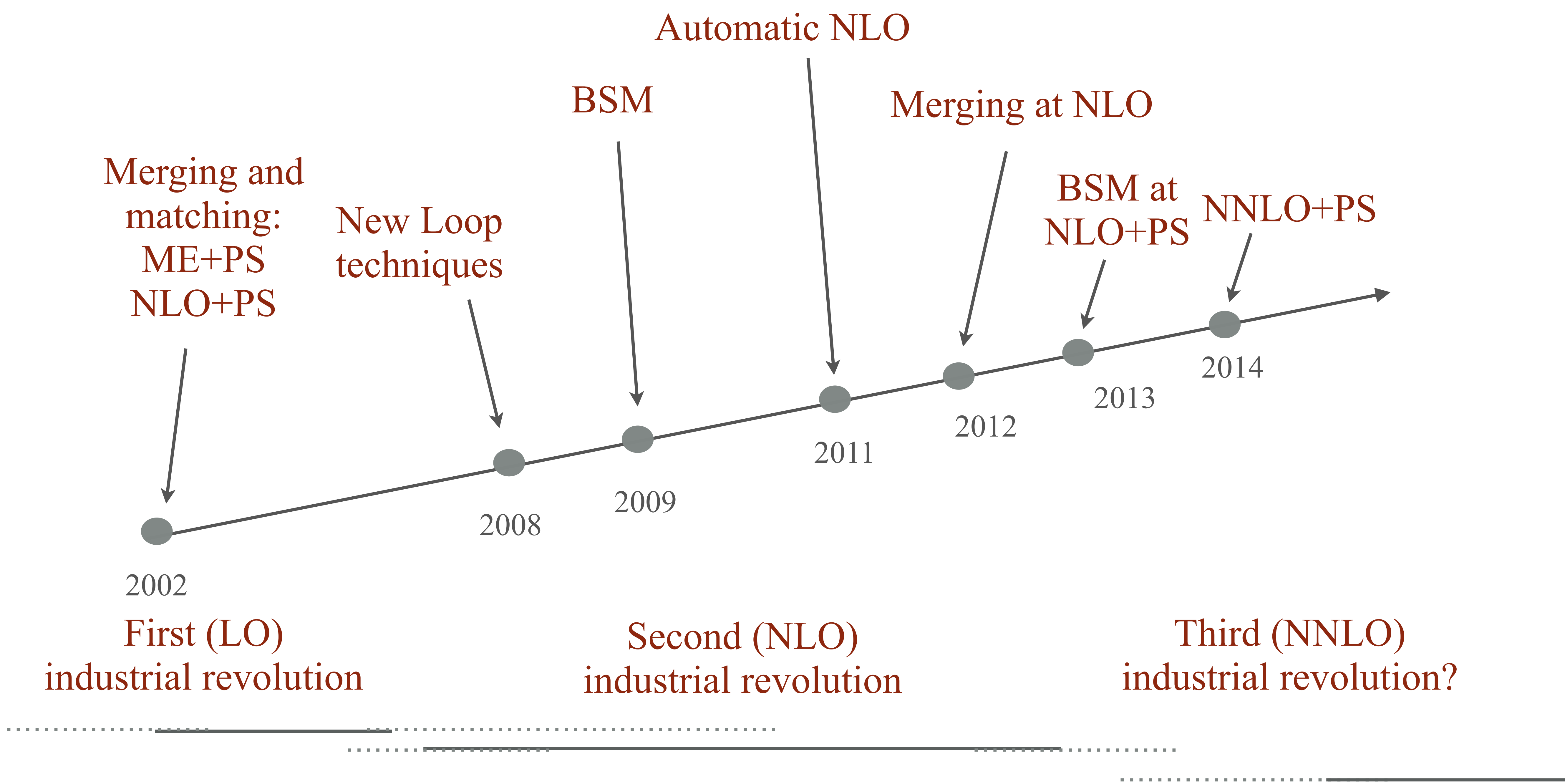


A **predictive** MC associates an history to short-distance events obtained from a parton-level (at least) next-to-leading order calculation avoid double counting and keeping the formal fixed-order accuracy.

Predictions in QCD: before the LHC

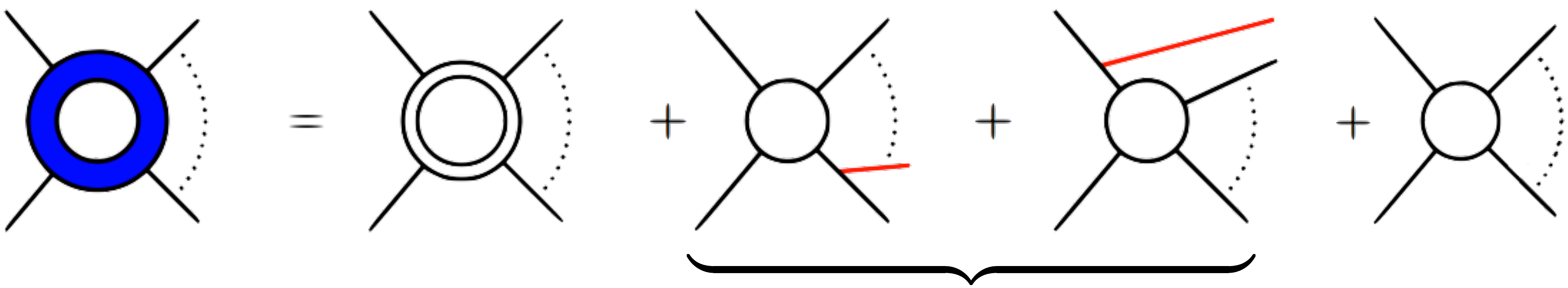


Predictive MC: progress



NLO Basics

NLO calculations have 3+1 parts



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

Virtual part — Real emission part — Born

- Loops have been for long the bottleneck of NLO computations
- Loop integration and integration of the reals over the m+1 phase space leads to Universal divergences that cancel when two contributions are added. A combination scheme is needed (Dipoles, FKS, Antenna's)
- A lot of work was necessary for each computation (see the MCFM project)

New Loop techniques

For the calculation of one-loop matrix elements, several methods have been established and public tools released:

•Generalized Unitarity (ex. BlackHat, Rocket,...)
[Bern, Dixon, Dunbar, Kosower,1994] [Ellis, Giele, Kunszt, 2007] [Ellis, Giele, Kunszt,Melnikov, 2008]

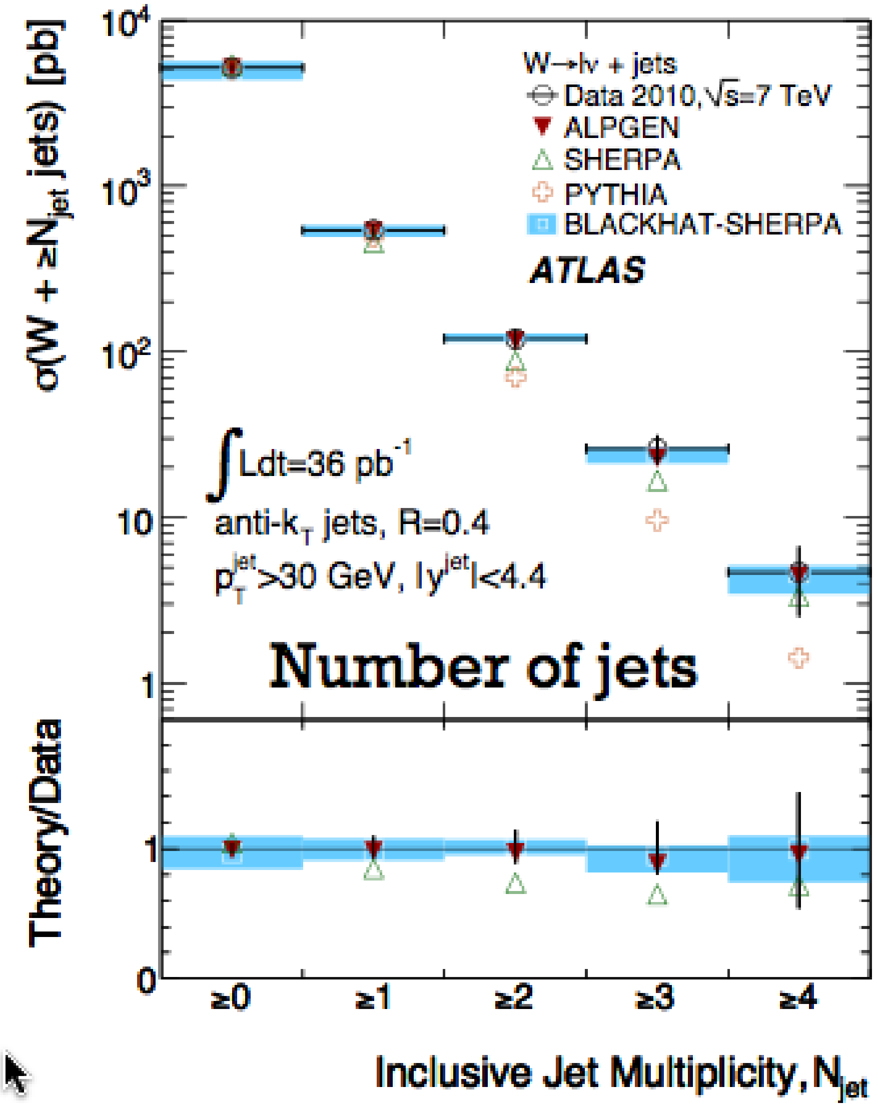
•Integrand Reduction (ex. CutTools, Samurai, Ninja)
[Ossola, Papadopolulos, Pittau,206] [del Aguila, Pittau, 2004] [Mastrolia, Ossola, Reiter, Tramontano, 2010] [Peraro, 2014]

•Tensor Reduction (ex. Golem, GoSam, MadLoop)
[Passarino, Veltman, 1979] [Denner, Dittmaier, 2005], [Binoth, Guillet, Heinrich, Pilon, Reiter, 2008]

All such techniques provide results in dim reg. UV renormalisation has to be taken care from the start, including the choice of schemes. Well-known for the SM. More difficult and involved for BSM. Additional model dependent counterterms are needed for some of the methods above.

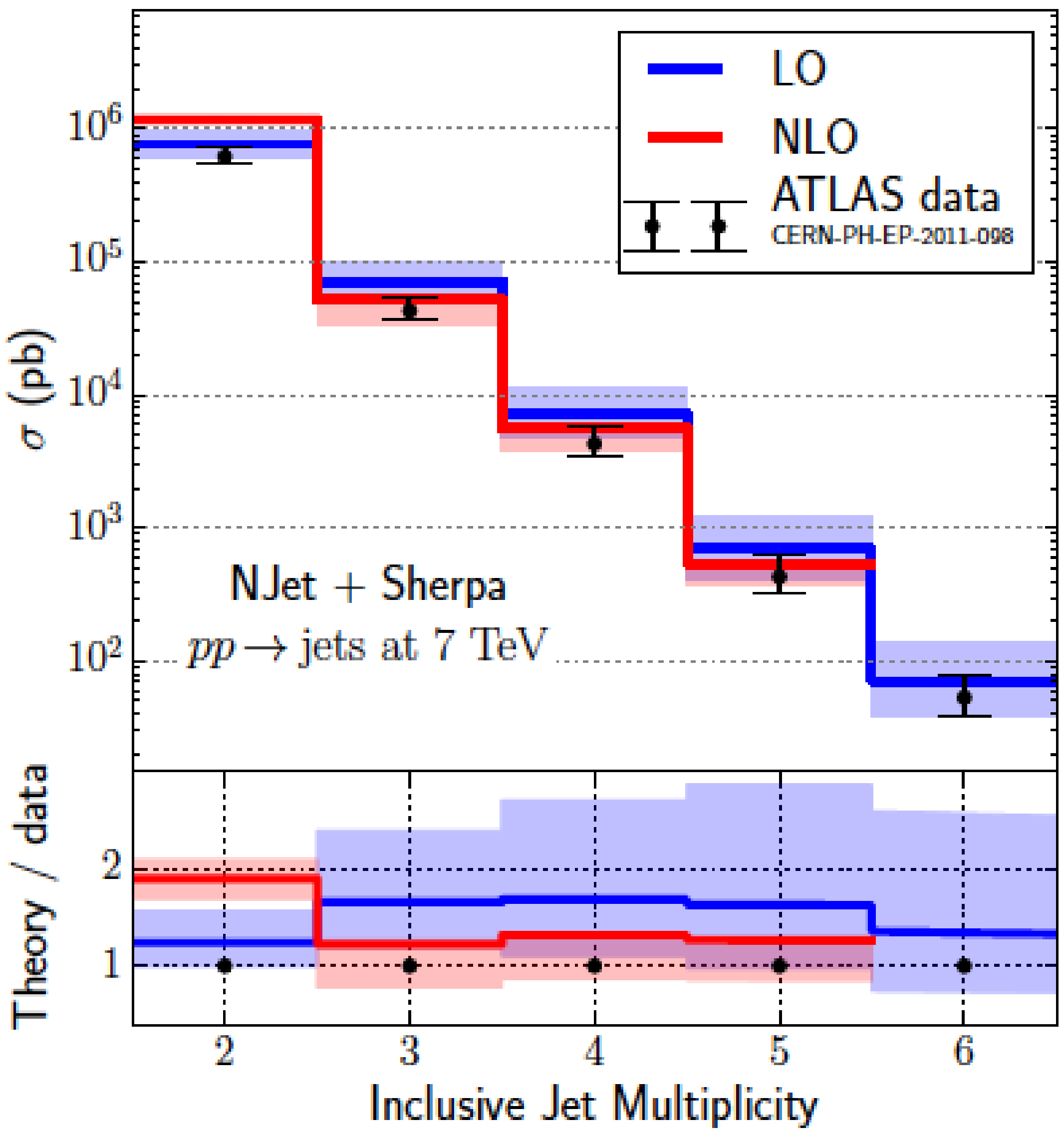
The NLO Guinness World Records

p p →W + 5 jets



[Bern et al., 2013]

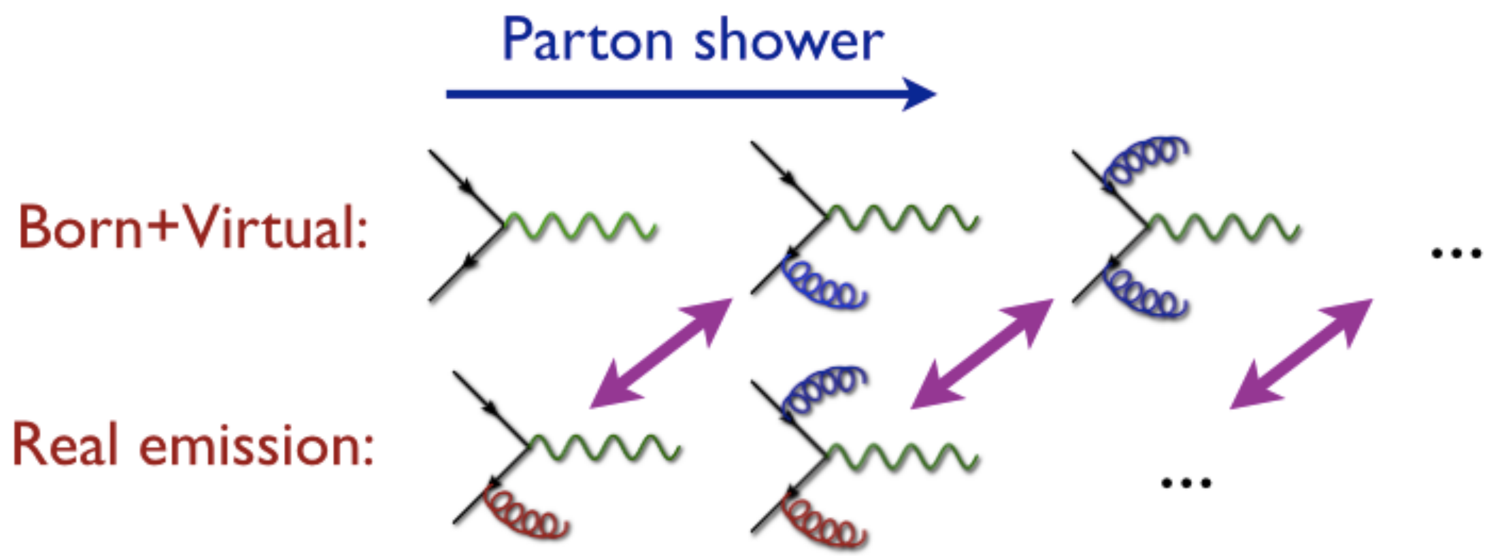
p p →5 jets

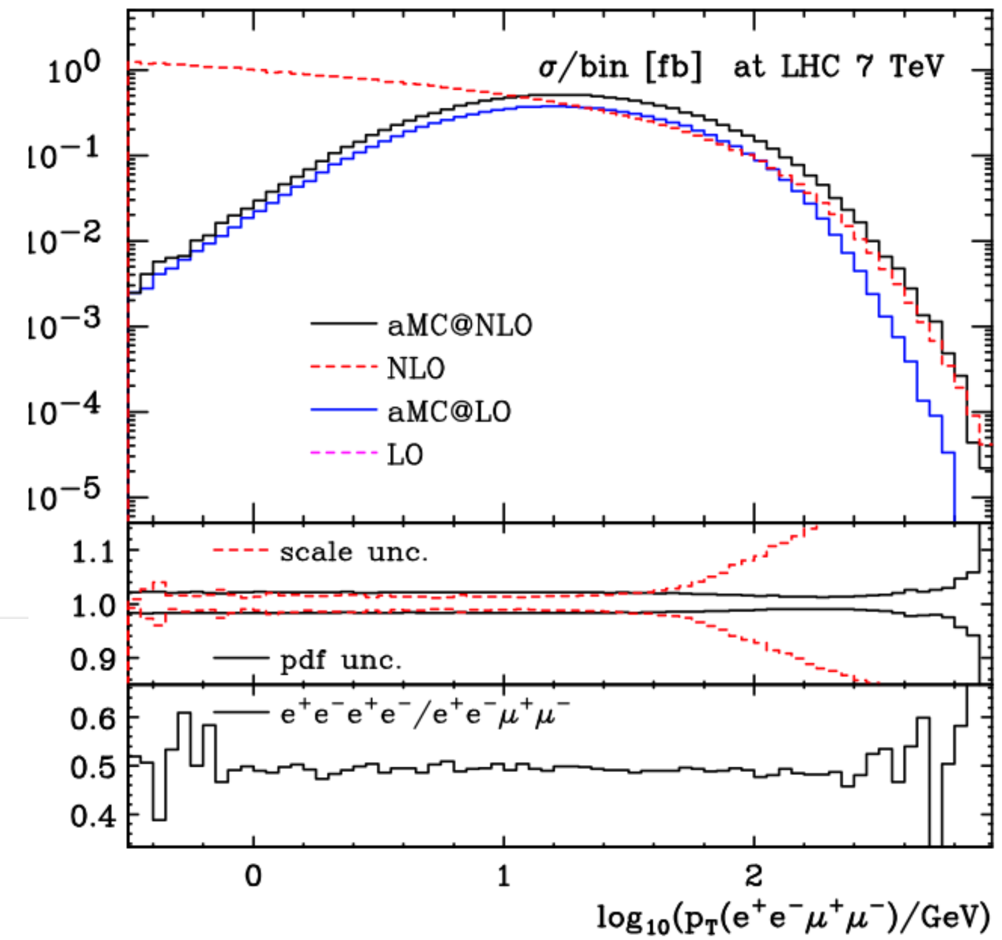


[Badger et al. 2013]

NLO+PS matching

Parton Shower Monte Carlo provide a simulation of all the stages of the hadronic collision: merge QCD matrix element + shower in the soft collinear approximation +hadronization model





The **MC@NLO** and **POWHEG** methods allow to combine NLO calculations with existing shower/ hadronisation programs such as PYTHIA8, HERWIG++, SHERPA….

The MC@NLO method has been extended to deal with samples of different jet multiplicity (merging) keeping NLO accuracy (FxFx in MG5aMC, ME@NLOPS in SHERPA).

The POWHEG method has been extended via the MINLO technique to obtain inclusive samples without merging scales.

MC@NLO and POWHEG

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

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 at fixed Born kinematics (If F=1).

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

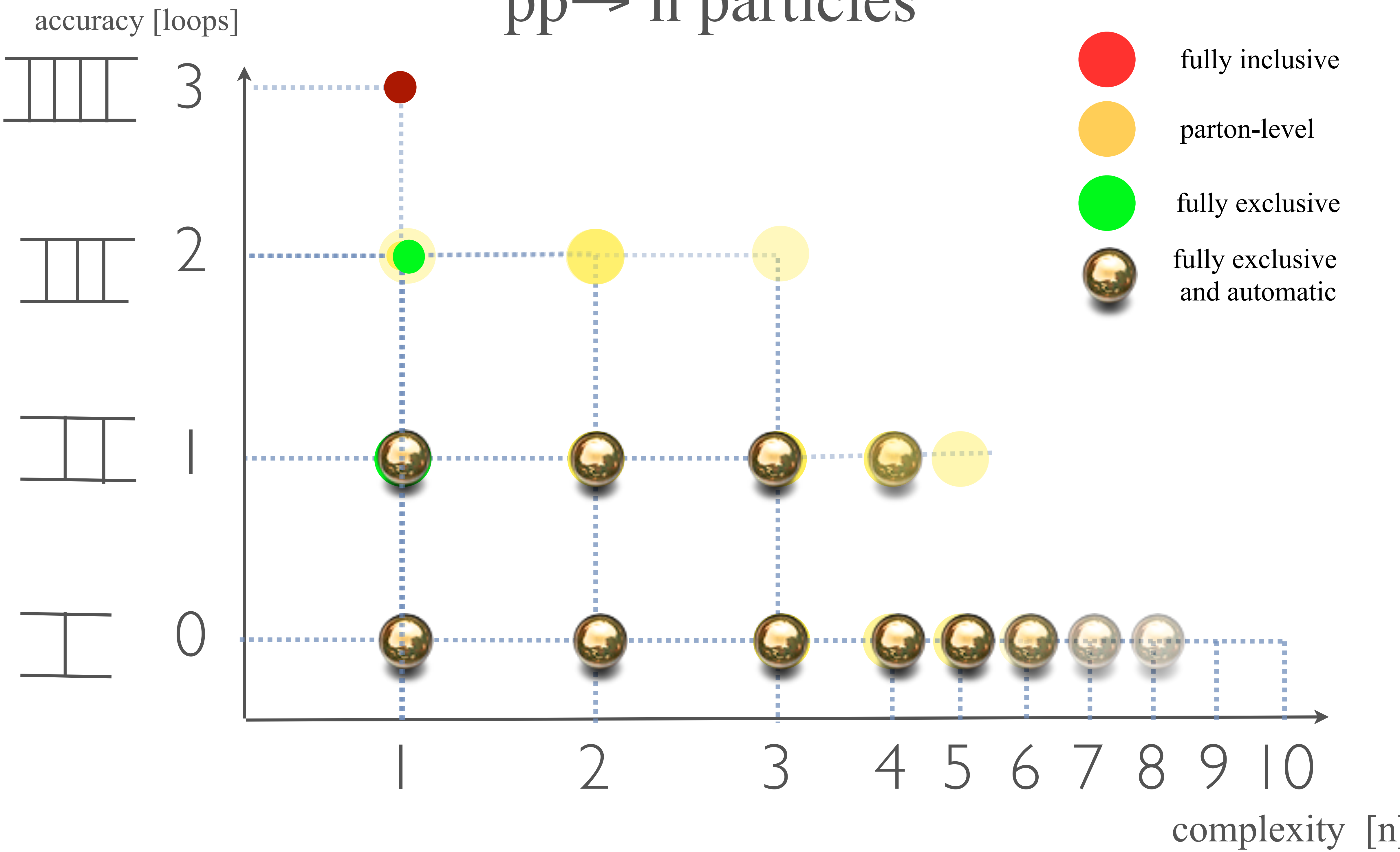
This formula is valid both for both MC@NLO and POWHEG

MC@NLO: $R^s(\Phi) = P(\Phi_{R|B})\, B(\Phi_B)$ — Needs exact mapping (ΦB,ΦR) →Φ

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.

Predictions in QCD for the LHC: status 2015

pp→ n particles



AAA level MCs

- **AVAILABILITY:** Several public frameworks (MG5_aMC, POWHEG-Box, Sherpa,…) are available that use public Parton Shower programs (Pythia8, Herwig, Sherpa) for matching with MC@NLO and POWHEG methods.
- **AUTOMATION:** All frameworks support automation to a different degree: the cost of implementation of processes in the SM at NLO in QCD is either quite low (or null) and the range of processes that can now be covered is very large. EW corrections have started to be automatically included (MG5aMC and Sherpa+OpenLoops). New Physics at NLO+PS is becoming also available automatically.
- **ACCURACY and PRECISION**: NLO in QCD is the standard, NLO in EW in the works. Extension to BSM being achieved. In addition, very handy possibilities are now widely available to all implementations, such as the automatic evaluation of the short-distance theoretical uncertainties (scale and pdfs). Different interfaces and techniques allow to make educated guesses of systematics associated to the matching methods, shower approximations and so on.

NLO+PS is widely available

- **MadGraph5_aMC@NLO** Alwall, Frederix, Frixione, FM, Mattelaer, Shao, Stelzer, Torrielli, Zaro and many collaborators…

  Fully automatic framework, where all the elements of a NLO+PS computation in the SM and (BSM) are automatically generated. FxFx is available for merging at NLO. Loop-induced available.

- **POWHEG-BOX** and applications: Alioli, Hamilton,Nason, Oleari, Re, Zanderighi and many others….

  Framework which allows to promote a standard NLO calculation into a MC at NLO generator. Very popular choice. Interfaces to automatic codes available. Tens of SM processes implemented. A lot of R&D and many new methods (EW macthing, MiNLO, NNLOPS, Res) developed in this framework.

- **SHERPA+OpenLoops** Krauss, Hoeche, Cascioli, Kellweit, Lindert, Pozzorini, Schonherr Siegert and many others…

  Flexible framework MC@NLO CS dipoles, MEPS@NLO, Fully automatic except for the virtuals which are mostly currently provided by OpenLoops….

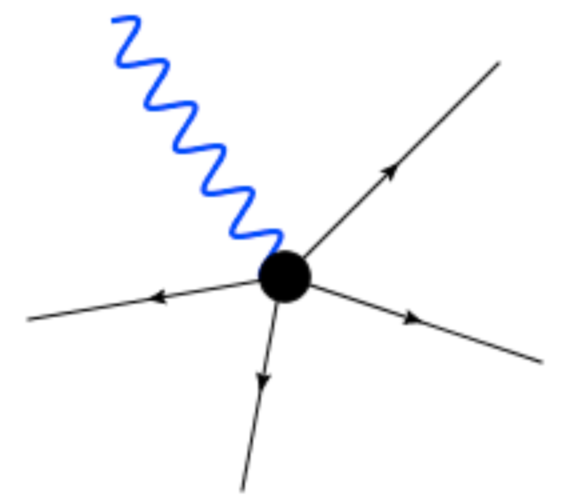
- **New Entries: HERWIG7, WHIZARD (e+e-)**

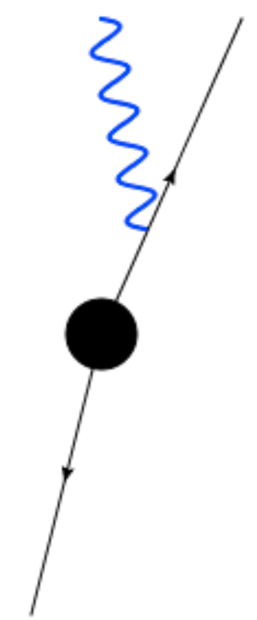
Outline

- Motivations & Status
- Selected applications and recent TH results :
  - V+jets
  - Top & Higgs
- Progress in BSM @ NLO+PS :
  - Full (2HDM, SUSY) and Simplified Models (DM)
  - EFT

V+jets : motivations

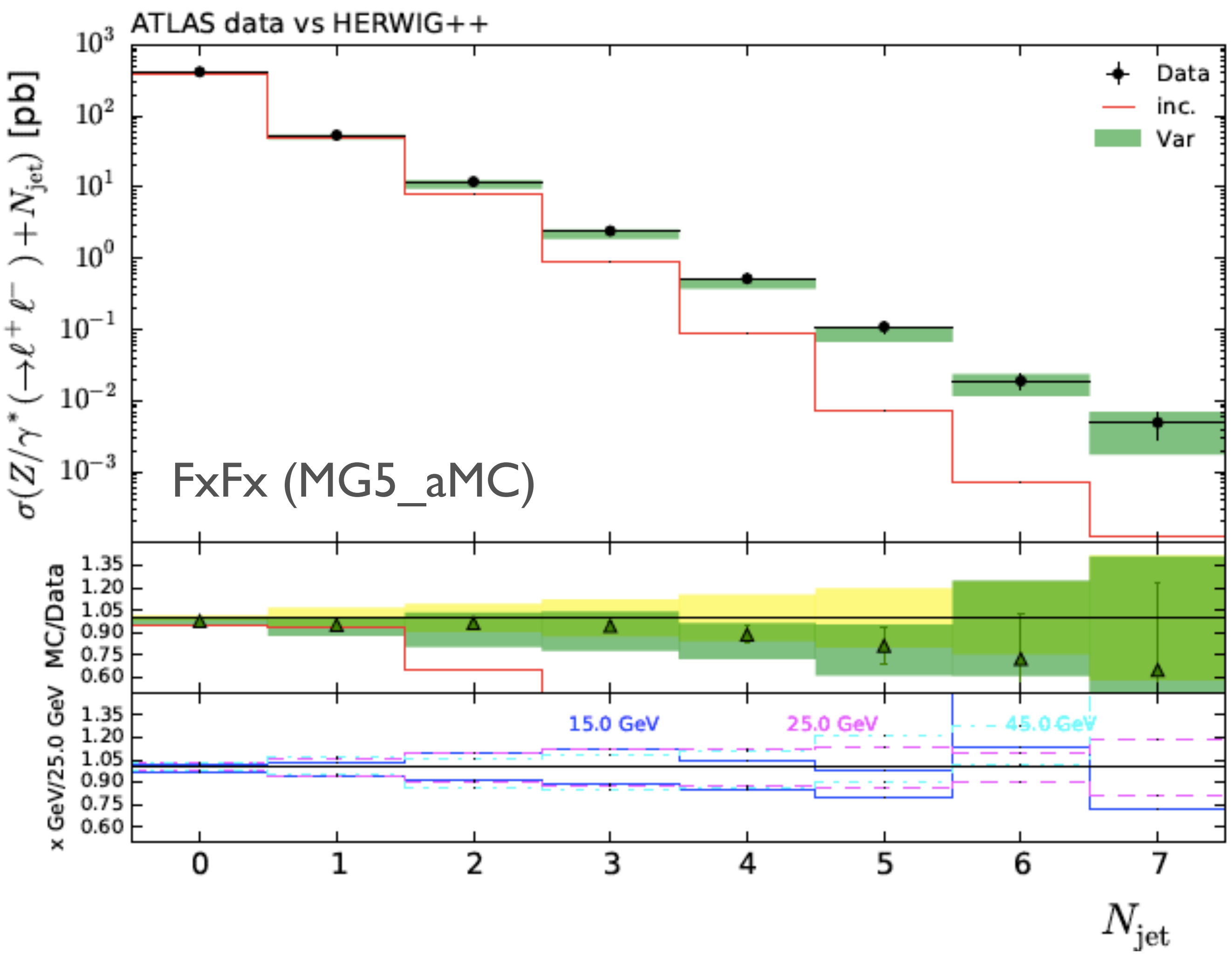
- Due to their large cross section Drell-Yan processes (Z or W) + jets provide
  - ubiquitous backgrounds to all final states that feature isolated leptons and/or missing energy + jets
  - precision EW and PDF measurements
  - a bench to test our understanding and ability to predict multi-jet final states in QCD
  - the possibility of testing the EW interactions at high-energy



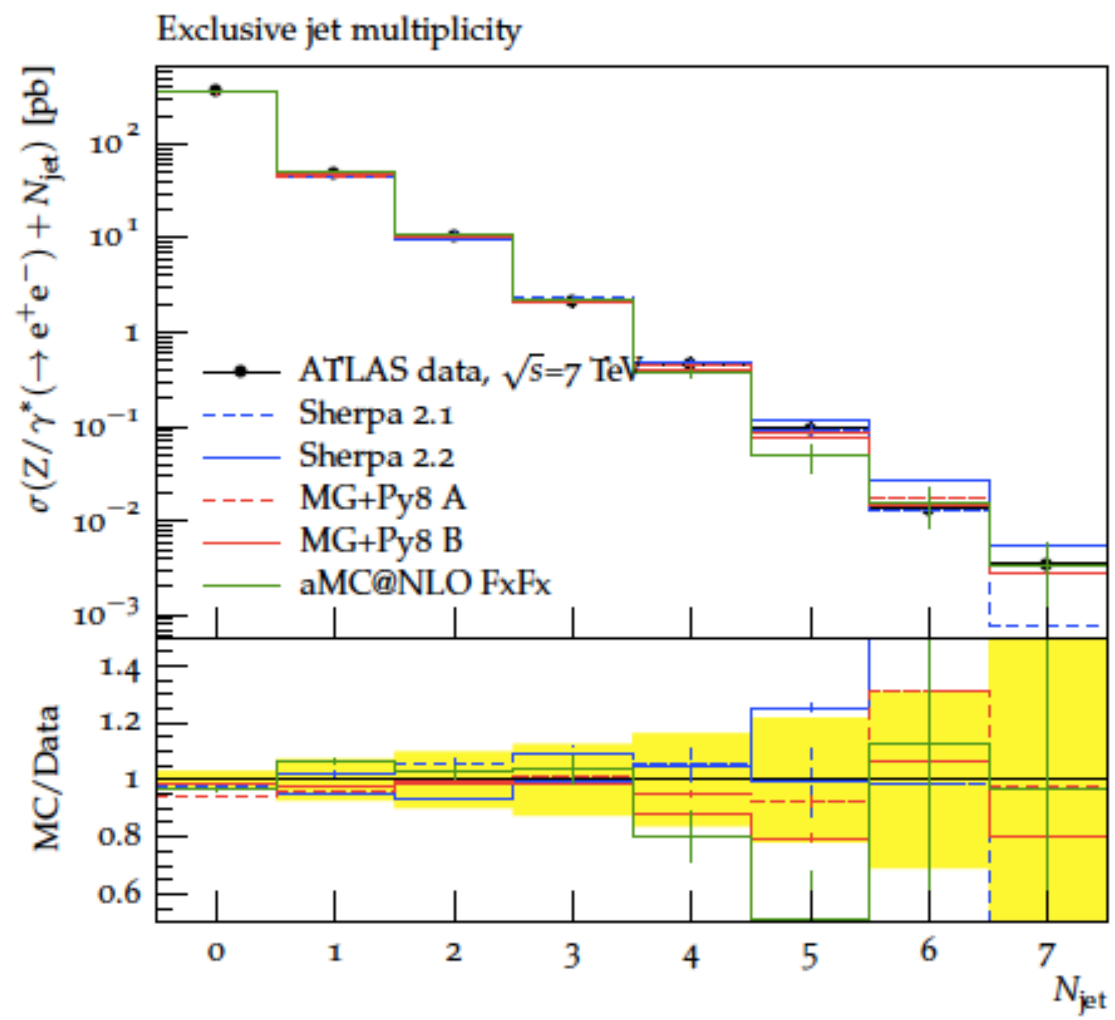


Z+jets comparison with ATLAS data

[Frederix et al., 2015]



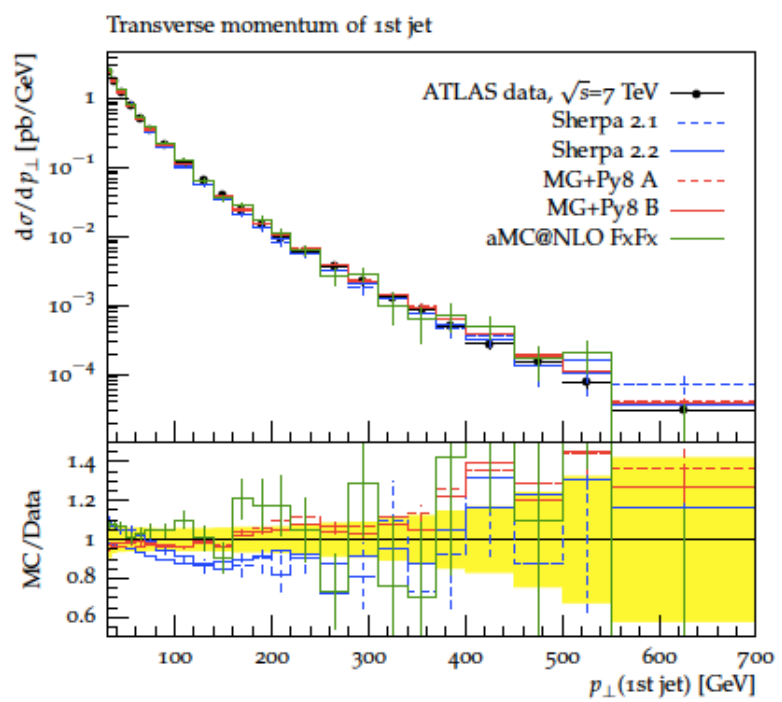
[ATLAS, 2016]

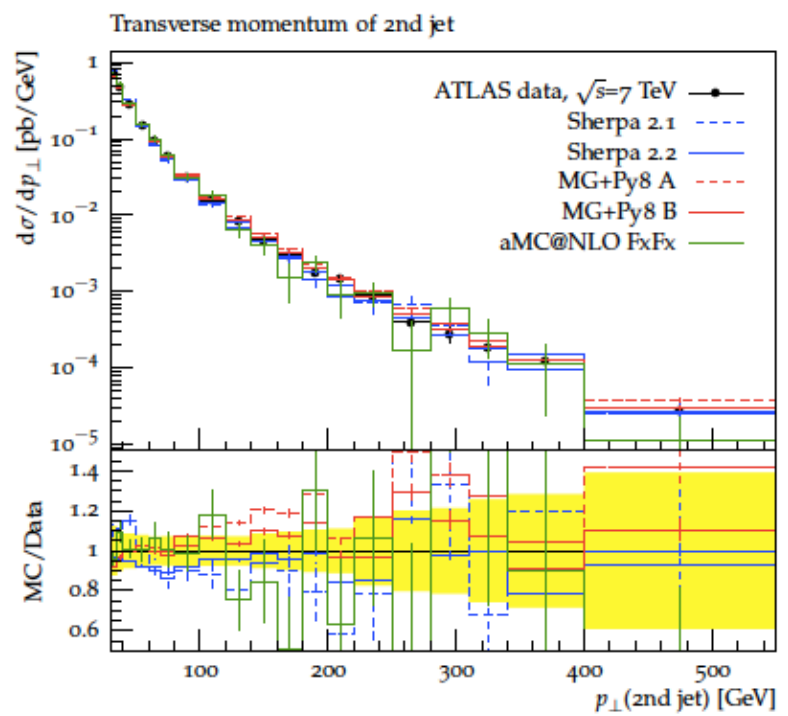


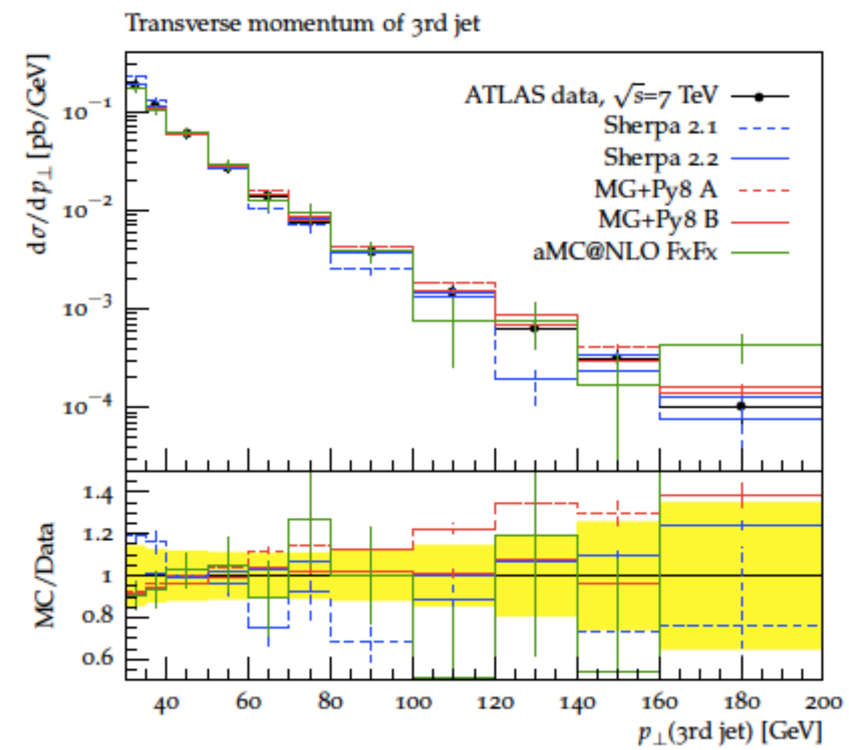
Exclusive jet rates for Z+jets. The NLO merged samples (Sherpa and aMC@NLO FxFx) have up to 2 jets at NLO and 3 (5 for Sherpa) jets at LO. The inclusive Z production at NLO+PS (red curve, left plot) falls short. Similar results hold for W+ jets.

Z+jets comparison with ATLAS data

[ATLAS, 2016]



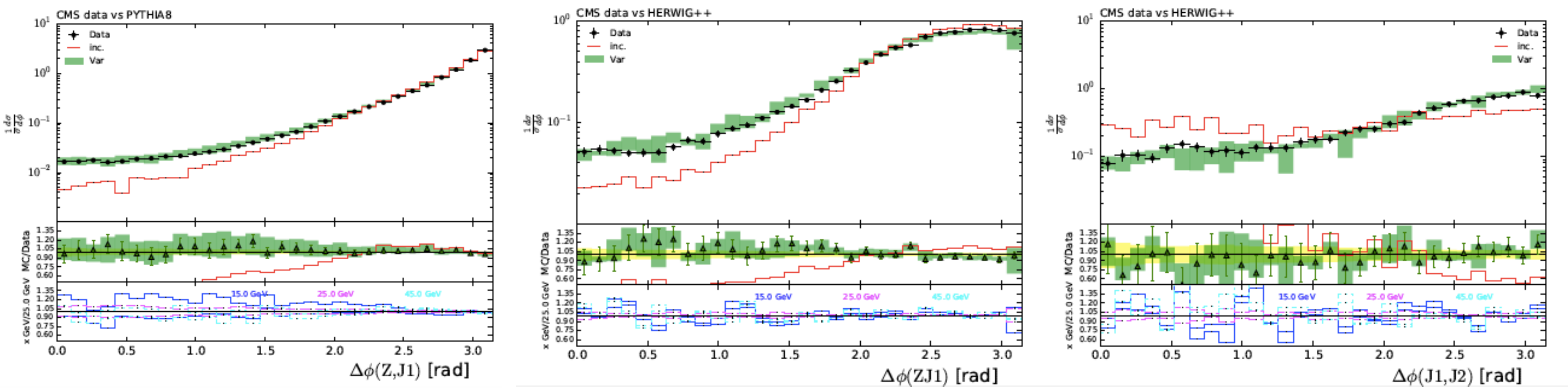




Transverse momentum of the first three jet in Z+jets. Similar results hold for W+ jets.

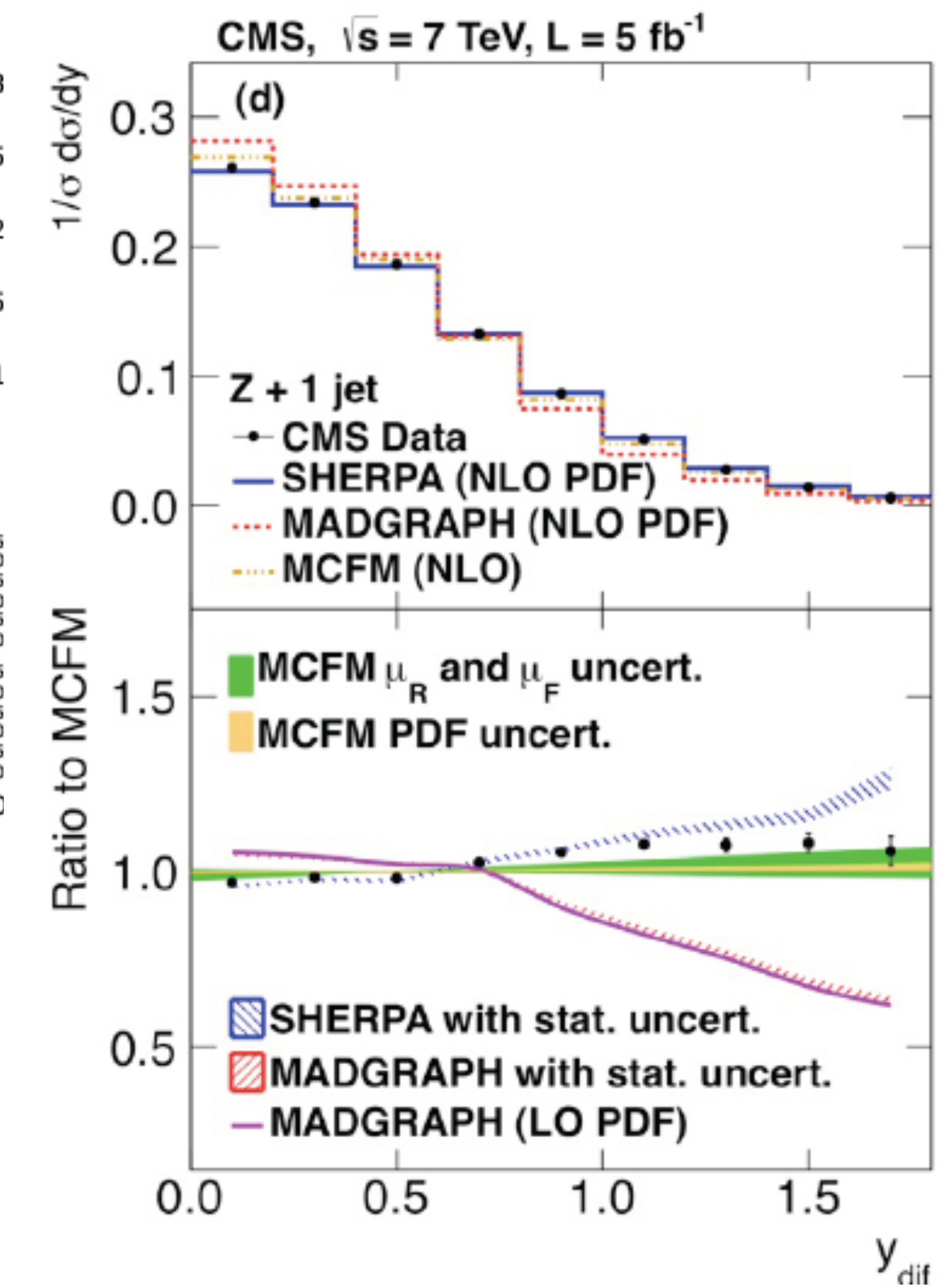
Z+jets comparison with CMS data

[Frederix et al., 2015]

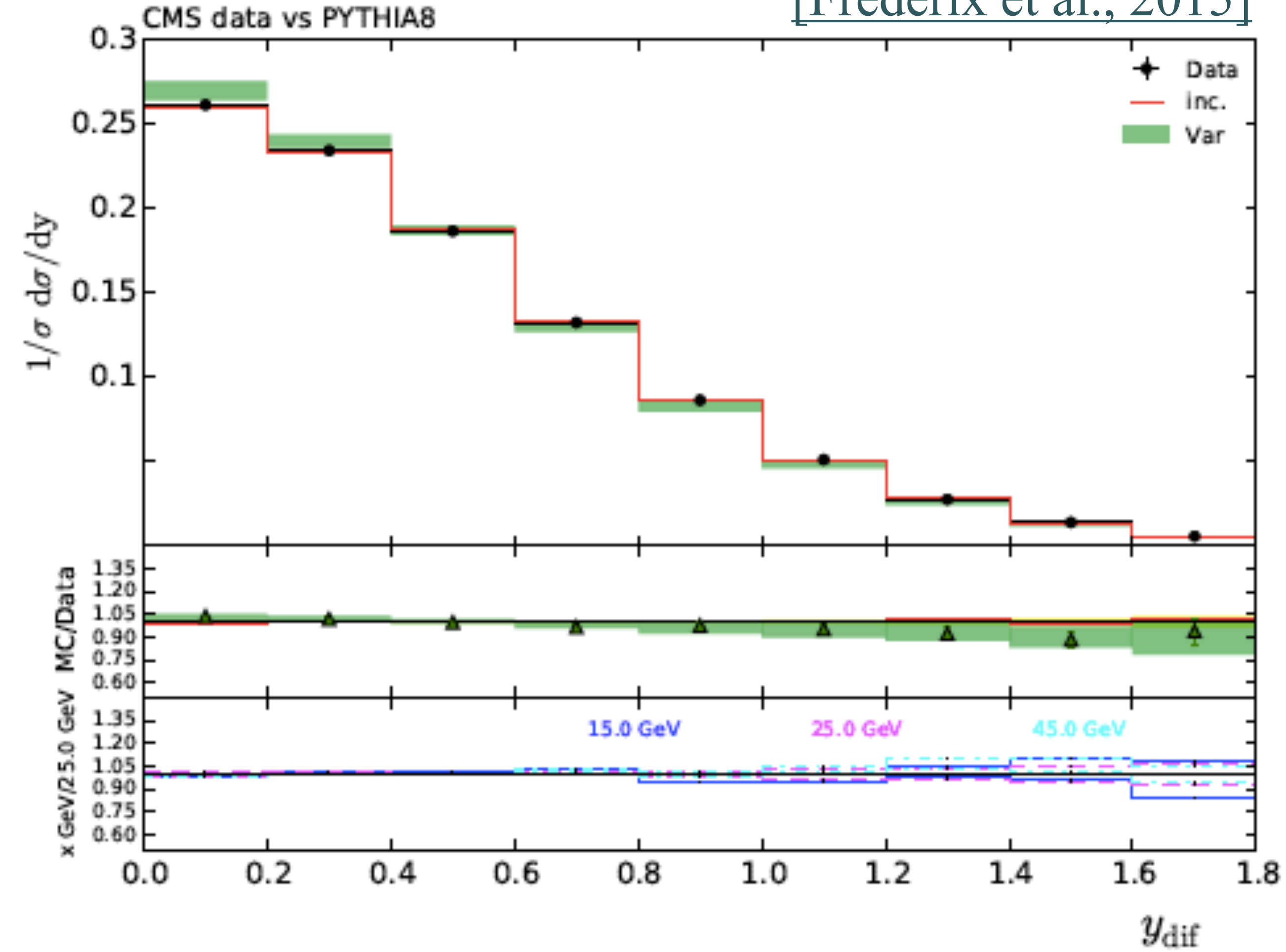


Correlations among final state objects provide sensitive observables to check the ability of the NLO merged sample to describe the data with respect to the NLO+PS inclusive sample.

Z+jets comparison with CMS data



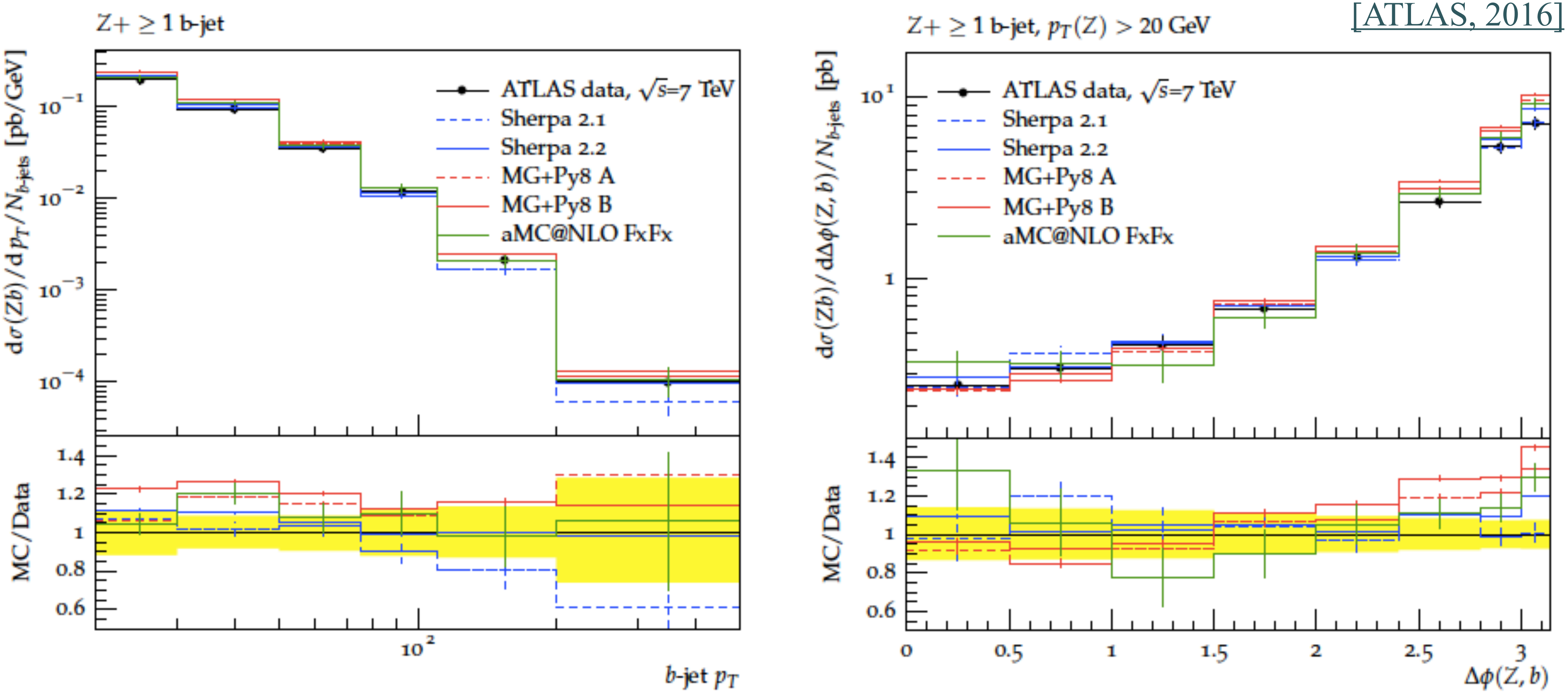
[Frederix et al., 2015]



Well-known limitations in describing the rapidity difference between the first jet and the Z are gone (also for Sherpa).

Z+b-jets comparison with ATLAS data

[ATLAS, 2016]

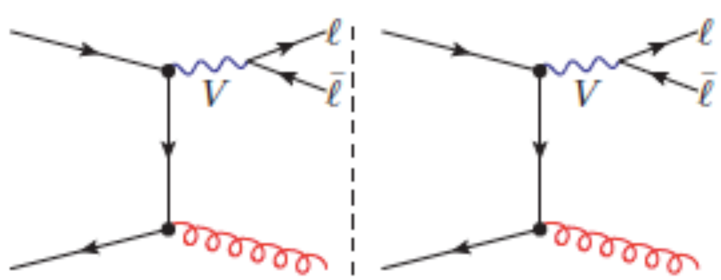


5F multijet samples give also the possibility to test the distributions in the case one jet is tagged as a b-quark. Opens up the possibility to study flavour scheme dependence of the predictions and gluon splitting.

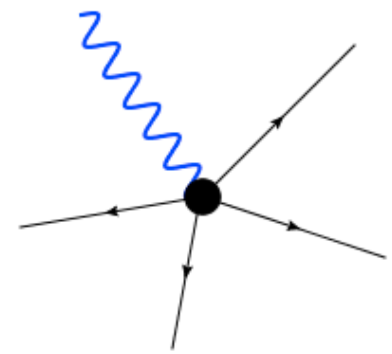
V+jets at NLO in EW and QCD

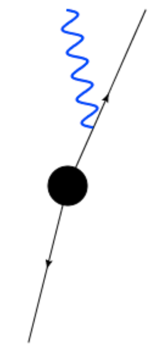
[Kallweit et al. 2014,2015]

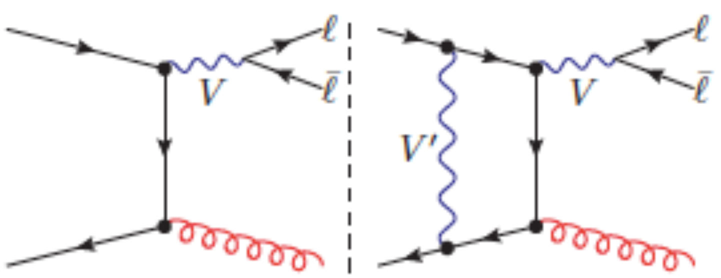
The first studies on including NLO QCD and EW corrections in W+jets appeared very recently in the fully automatic Sherpa+OpenLoops framework.



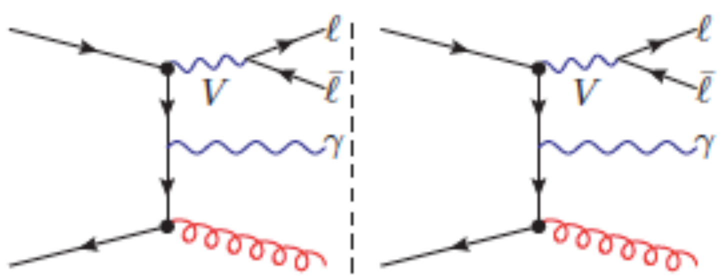
(a) $\mathcal{O}(\alpha_S\alpha^2)$ LO



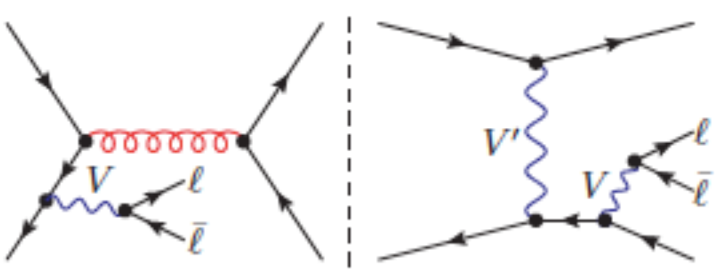




(a) Virtual $\mathcal{O}(\alpha_S\alpha^3)$ correction



(b) Real $\mathcal{O}(\alpha_S\alpha^3)$ correction



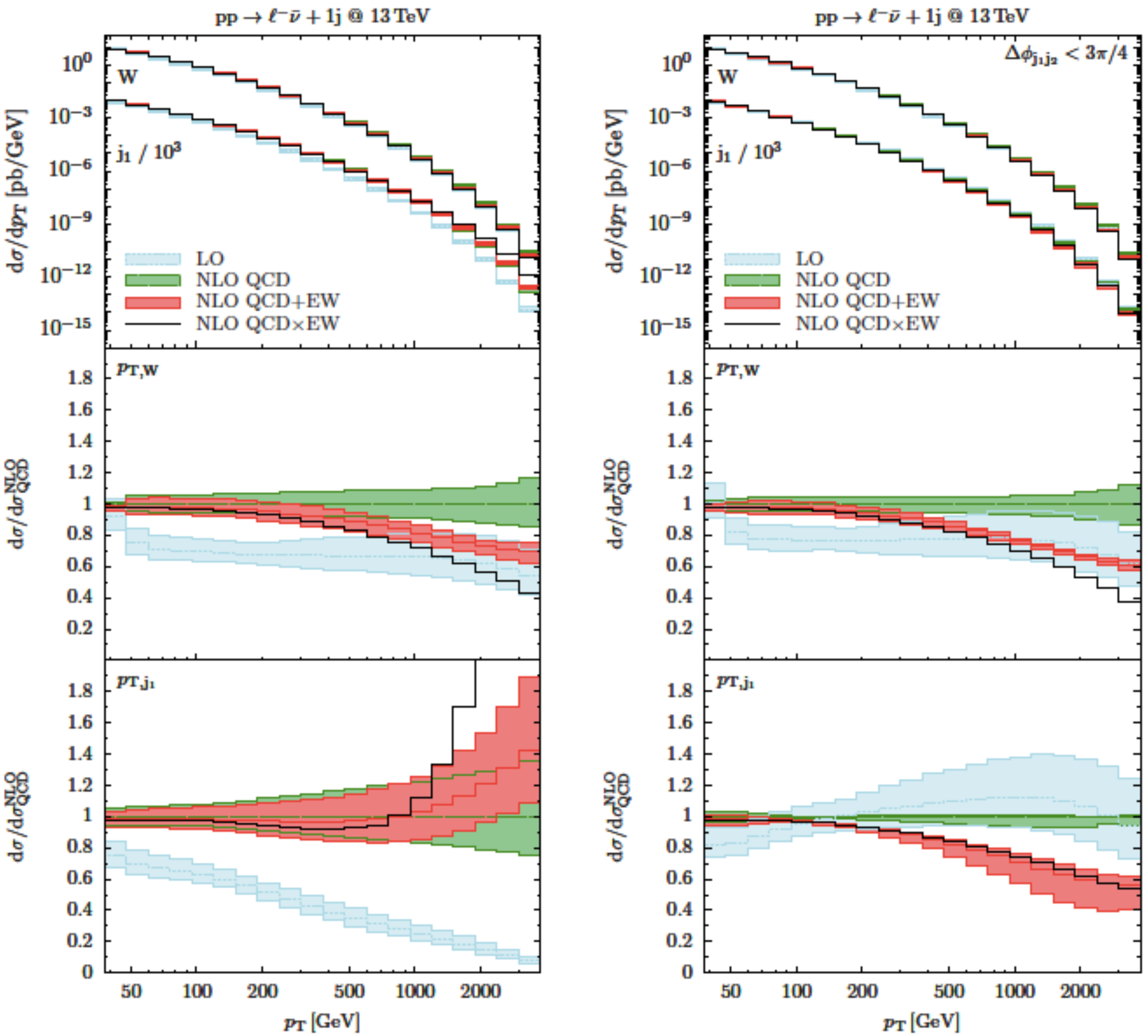
(c) Real $\mathcal{O}(\alpha_S\alpha^3)$ correction

$$\sigma^{\rm NLO}_{\rm QCD+EW} = \sigma^{\rm LO} + \delta\sigma^{\rm NLO}_{\rm QCD} + \delta\sigma^{\rm NLO}_{\rm EW}$$

$$\sigma^{\rm NLO}_{\rm QCD\times EW} = \sigma^{\rm NLO}_{\rm QCD}\left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right) = \sigma^{\rm NLO}_{\rm EW}\left(1+\frac{\delta\sigma^{\rm NLO}_{\rm QCD}}{\sigma^{\rm LO}}\right)$$

V+jets at NLO in EW and QCD

[Kallweit et al. 2014,2015]

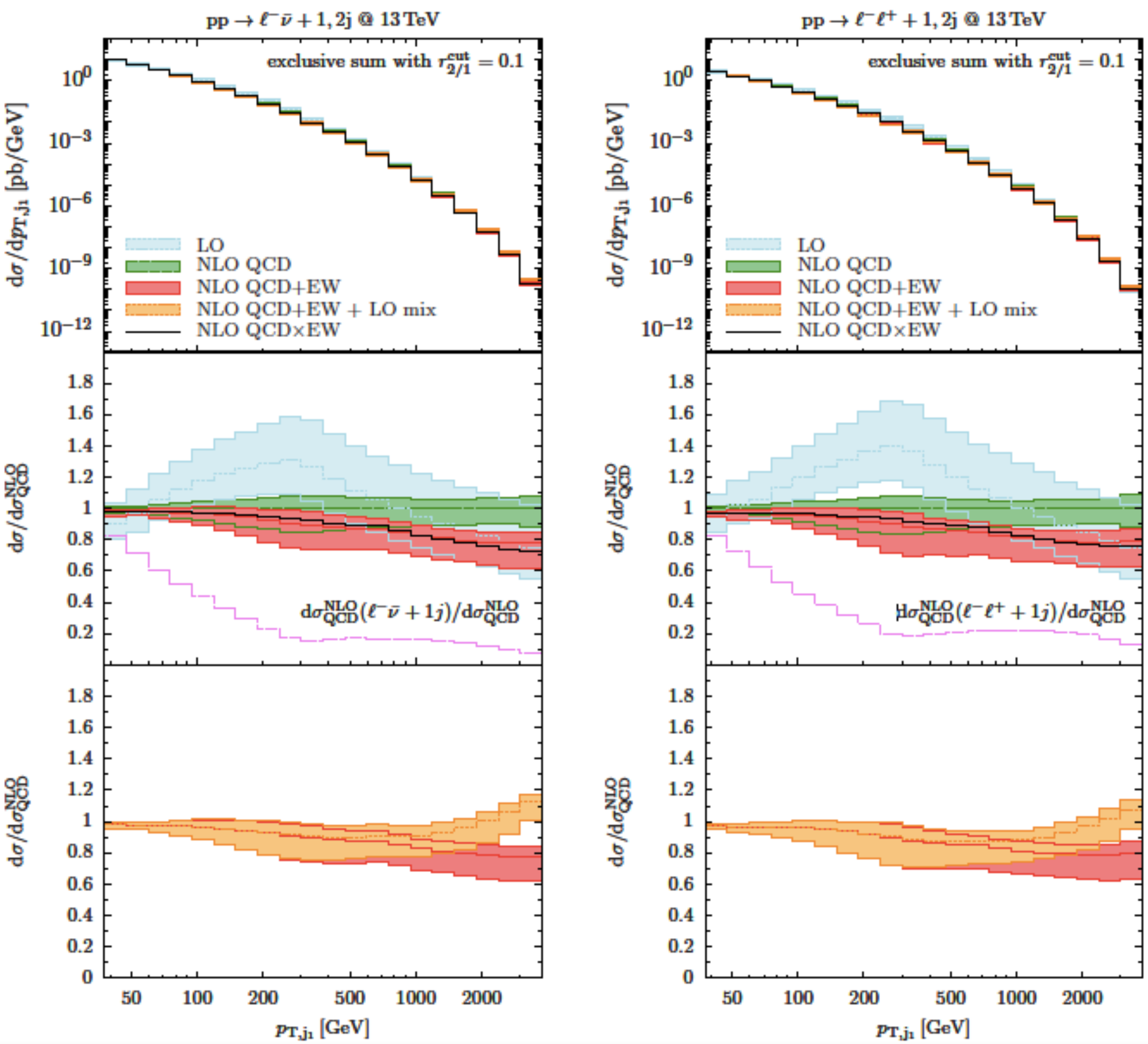


NLO corrections in QCD are important.

NLO corrections in EW are also important at high-energy due the presence of Sudakov logs.

Need for merging because of giant K-factors arising from 2 jet back-to-back configurations.

V+jets at NLO in EW and QCD: naive merging



[Kallweit et al. 2014,2015]

As a first step merging is realised at the parton-level by exclusive sums

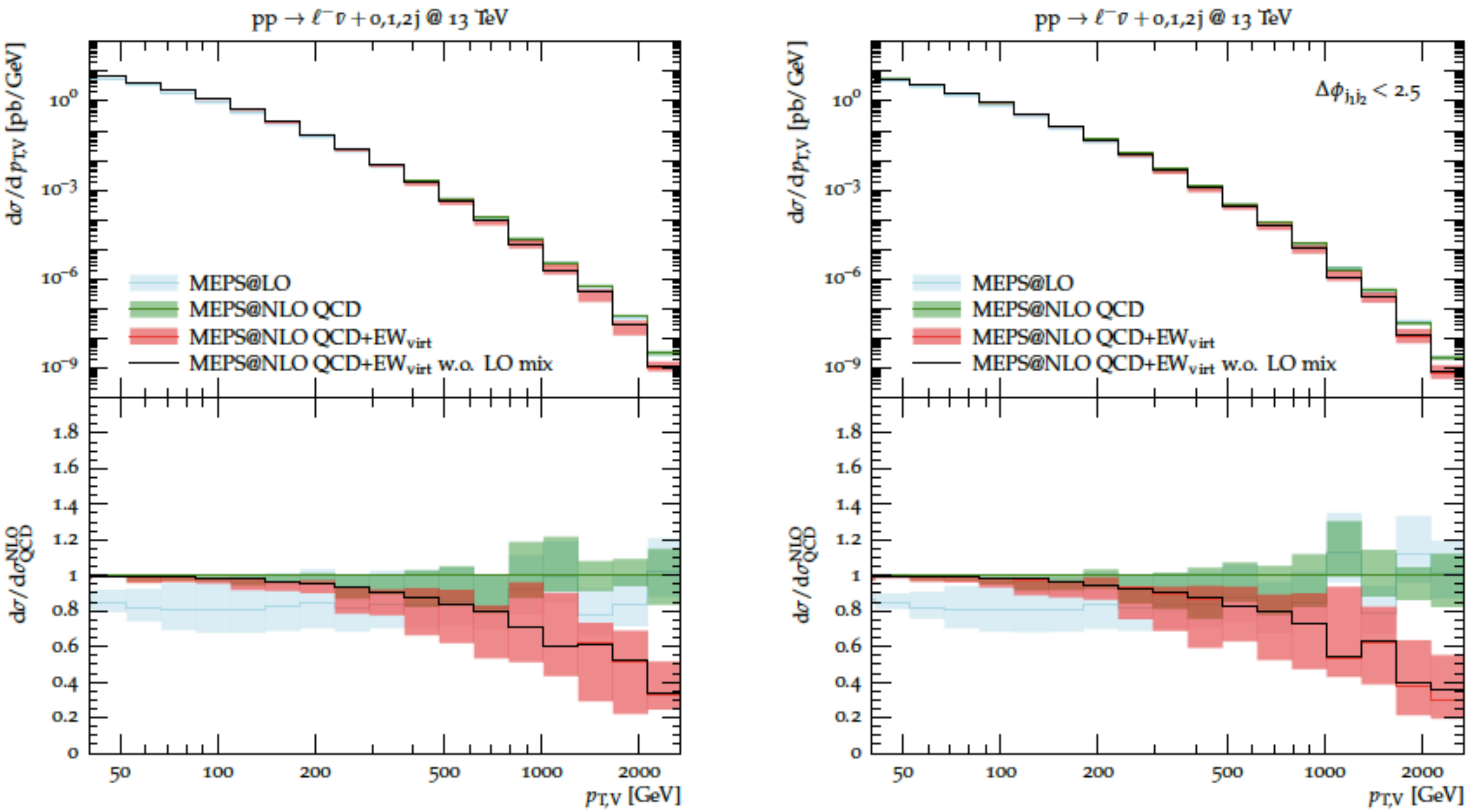
$$r_{2/1} = \frac{p_{T,j_2}}{p_{T,j_1}}$$

Behaviour of the perturbative series is tamed. This also allows to study the inclusion of EW corrections in an approximate way:

$$d\sigma_{n,\mathrm{NLO\,EW_{virt}}} = \left[B_n(\Phi_n) + V_{n,\mathrm{EW}}(\Phi_n) + I_{n,\mathrm{EW}}(\Phi_n)\right] d\Phi_n$$

V+jets at NLO in EW and QCD merged

[Kallweit et al. 2014,2015]



First effort:

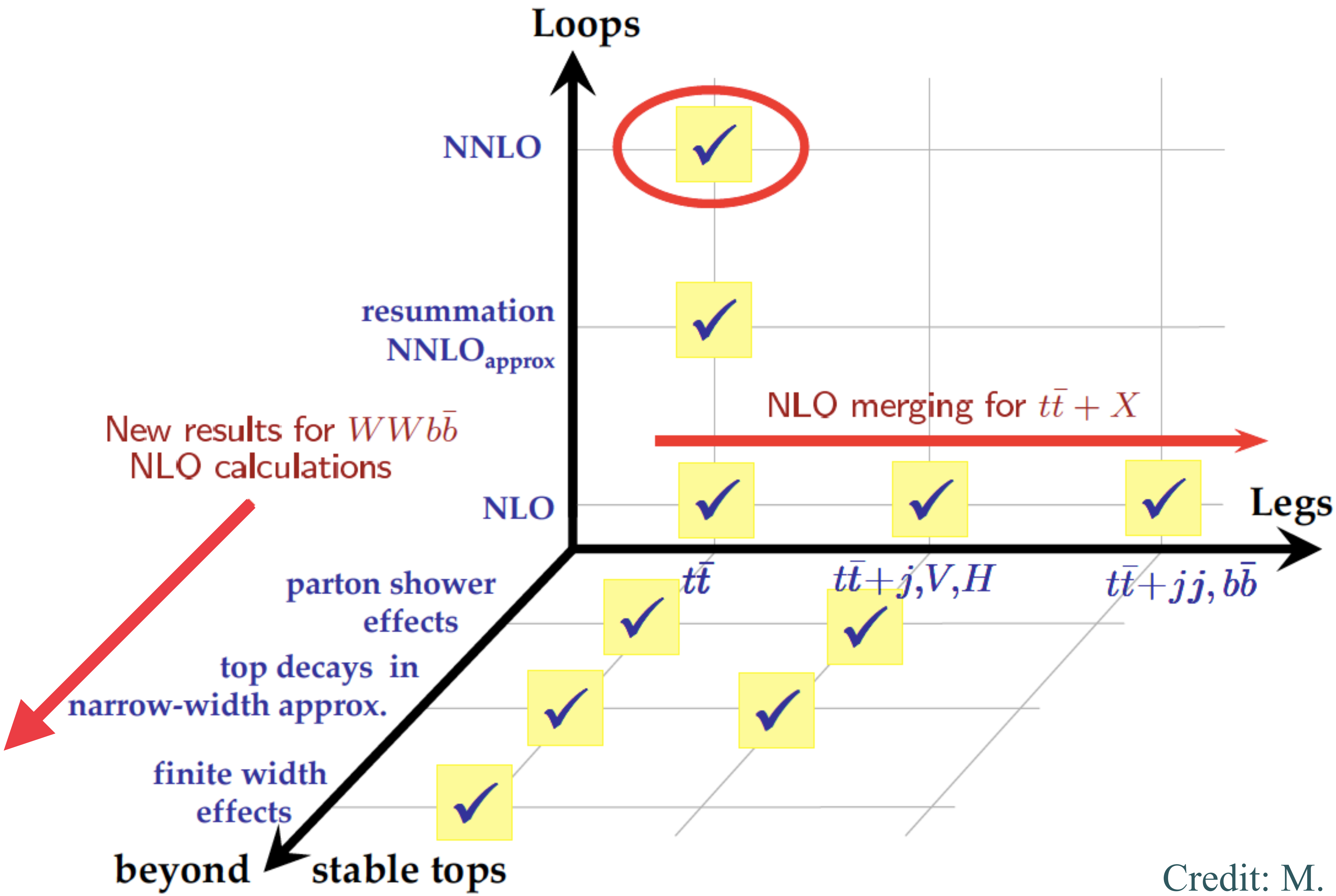
Approximated Born-type EW corrections, no QED shower and no matching with QED and consistent treatment of the QCD/EW terms needed.

$$\tilde{\mathrm{B}}_{n,\mathrm{QCD+EW}}(\Phi_n) = \tilde{\mathrm{B}}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

$$\mathrm{d}\sigma_n^{(\text{MEPS@NLO})} = \Big[\mathrm{d}\Phi_n\, \tilde{\mathrm{B}}_n(\Phi_n)\, \bar{\mathcal{F}}_n(\mu_Q^2\,; < Q_{\mathrm{cut}}) + \mathrm{d}\Phi_{n+1}\, \tilde{\mathrm{H}}_n(\Phi_{n+1})\, \Theta(Q_{\mathrm{cut}} - Q_{n+1})\, \mathcal{F}_{n+1}(\mu_Q^2\,; < Q_{\mathrm{cut}})\Big]\, \Theta(Q_n - Q_{\mathrm{cut}})$$

Top and Higgs

Top quark predictions

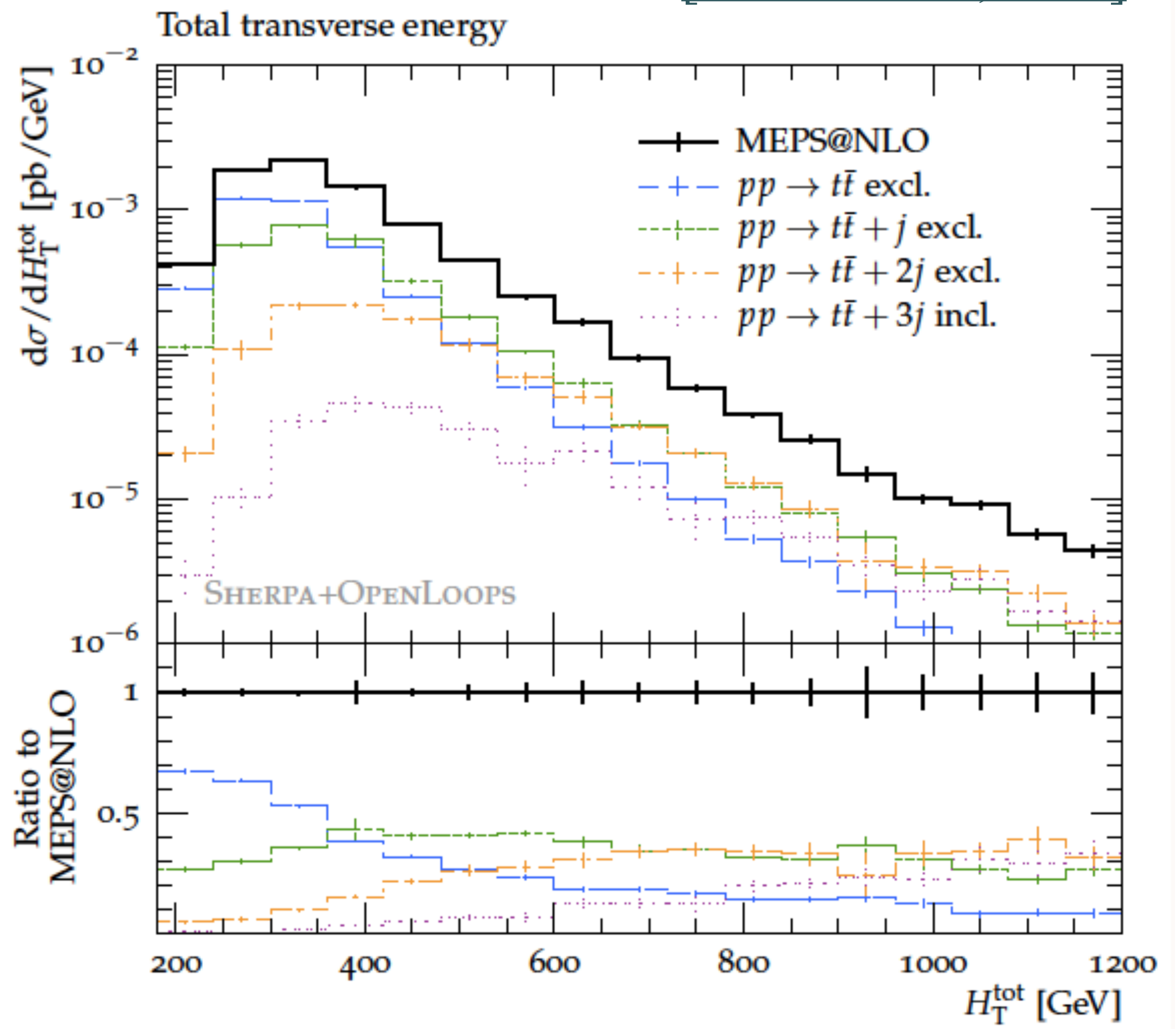


Credit: M. Schulze

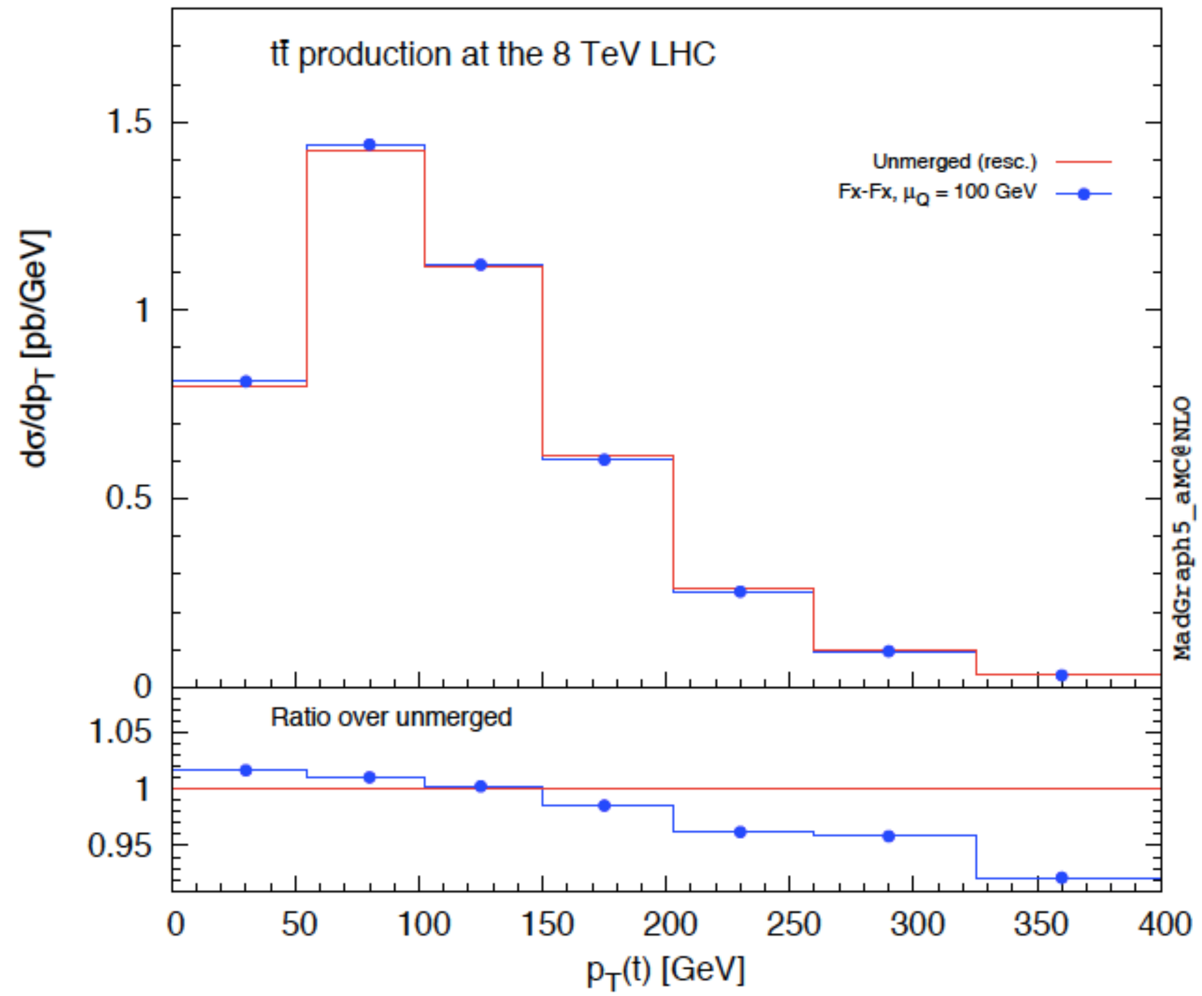
Top pair production with jets

Same methods shown in action for V+jets (MEPS@NLO, FxFx, UNLOPS) can be applied to top pair production in association with jets.

[Hoeche et al., 2014]



[Frixione et al, 2014]

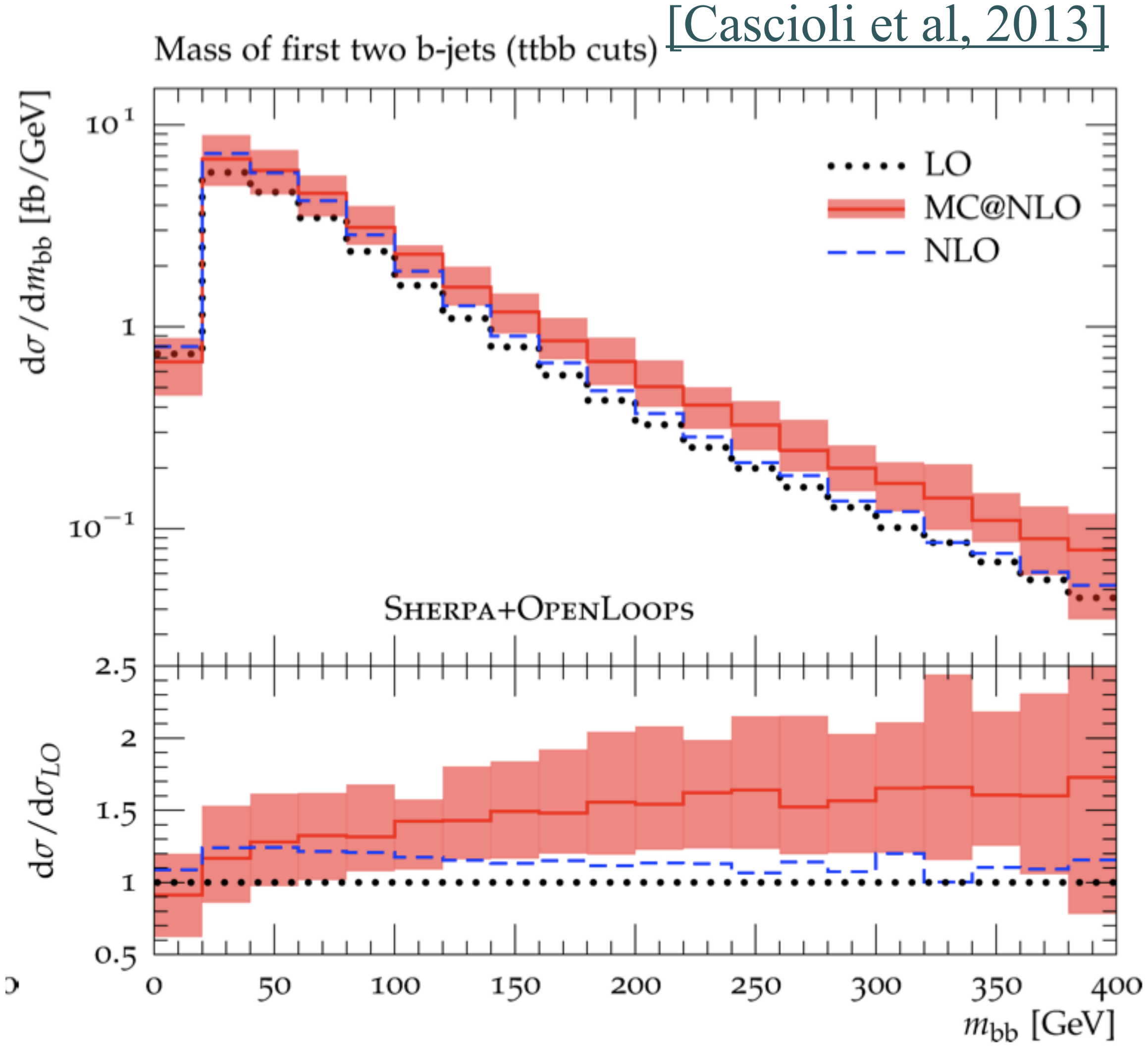


ttbb and tttt production at NLO in QCD

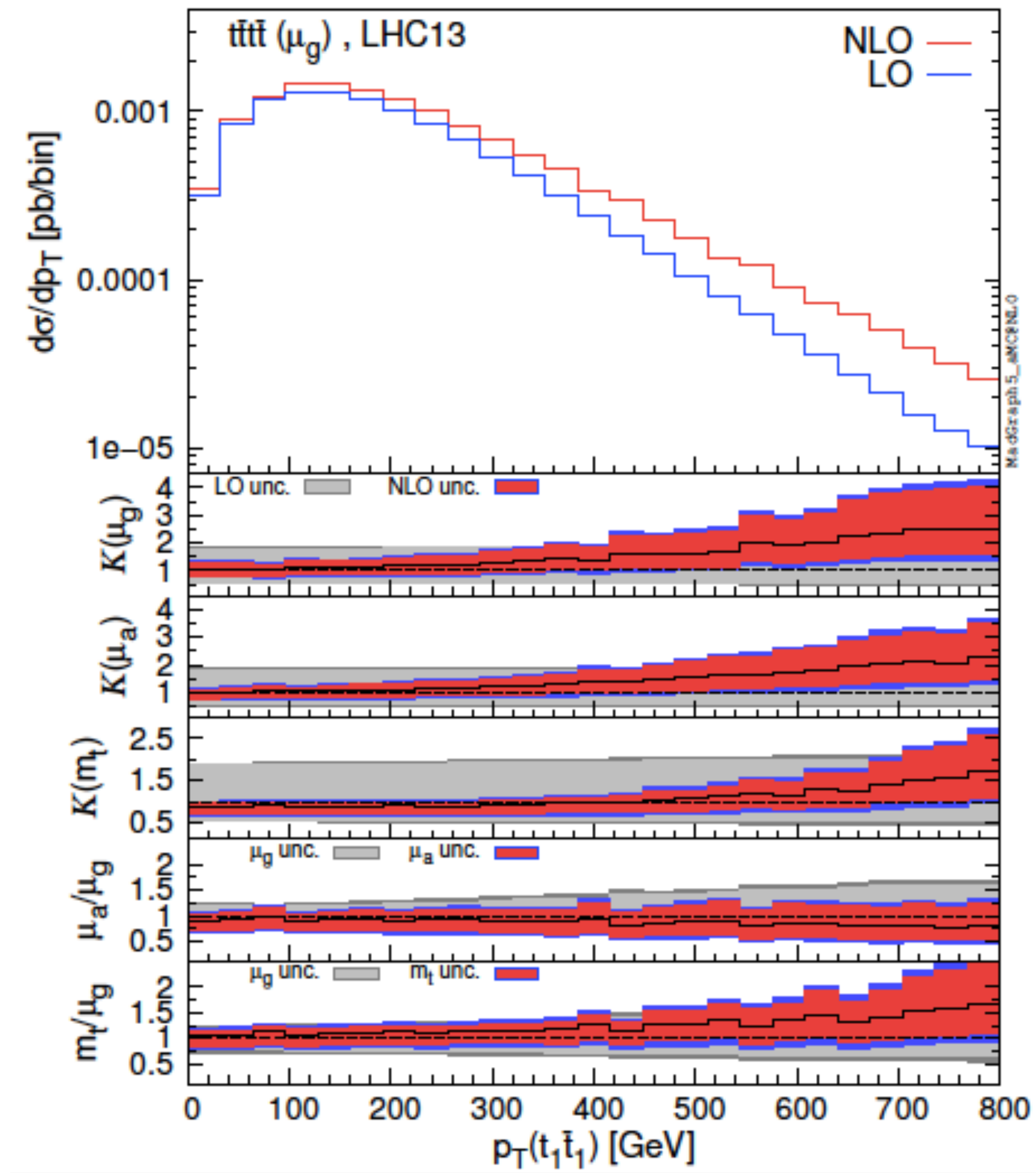
$$pp \to t\bar{t}b\bar{b}$$

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

[Cascioli et al, 2013]



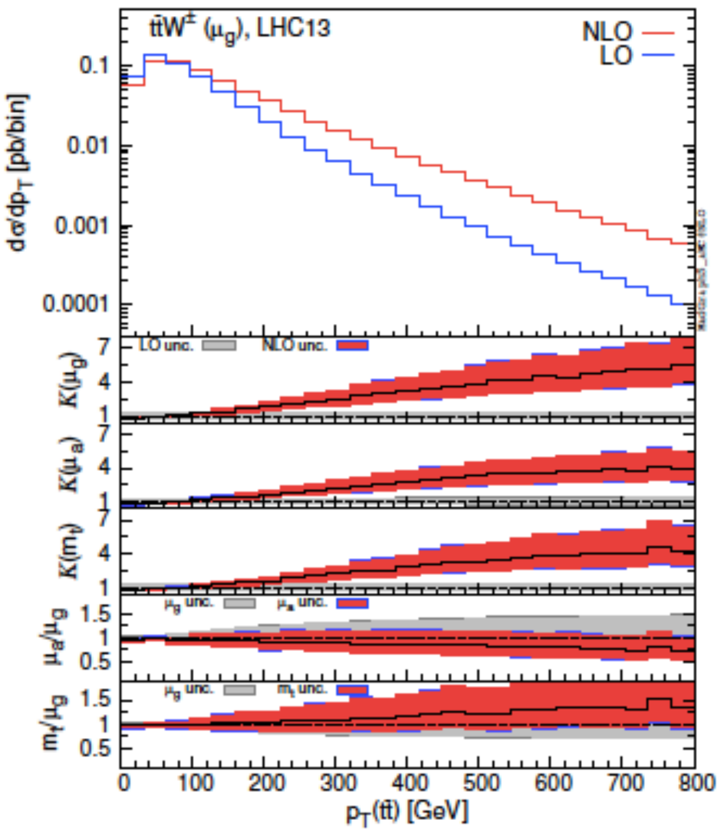
[Pagani et al, 2015]

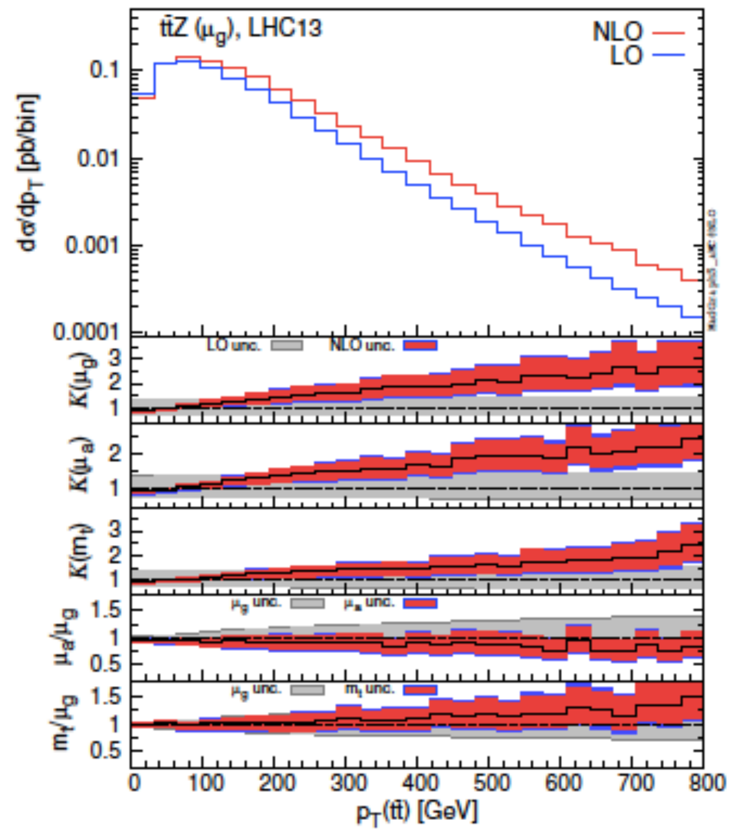


See also [Kardos and Trocsanyi, 2013]

See also [Bevilacqua and Worek, 2012]

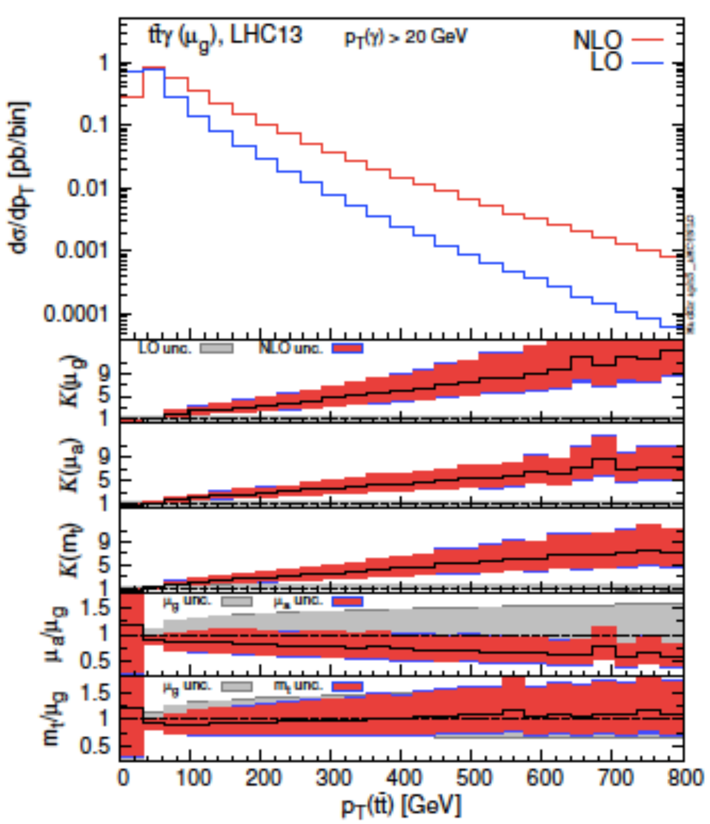
ttV at NLO(+PS)

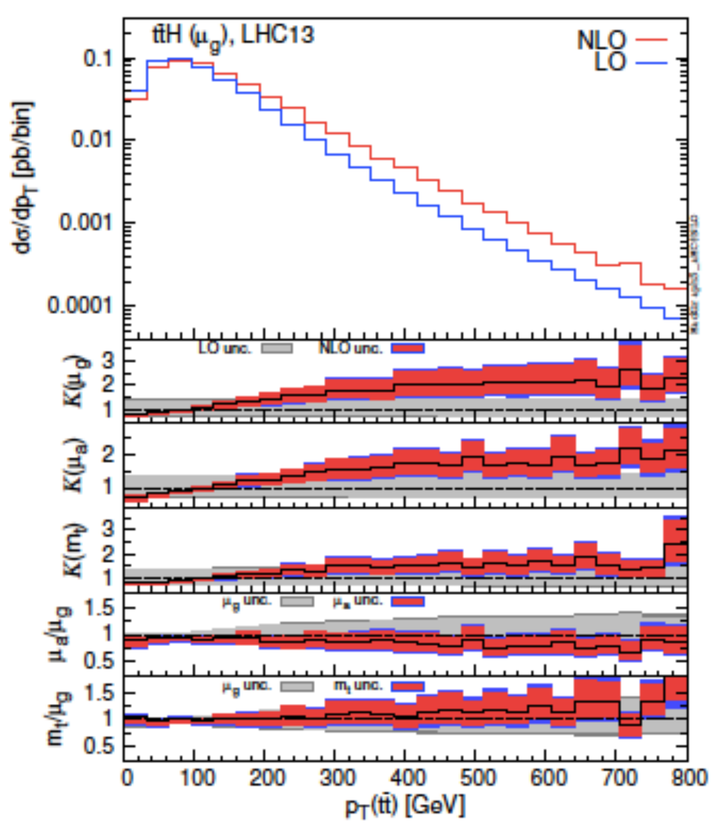


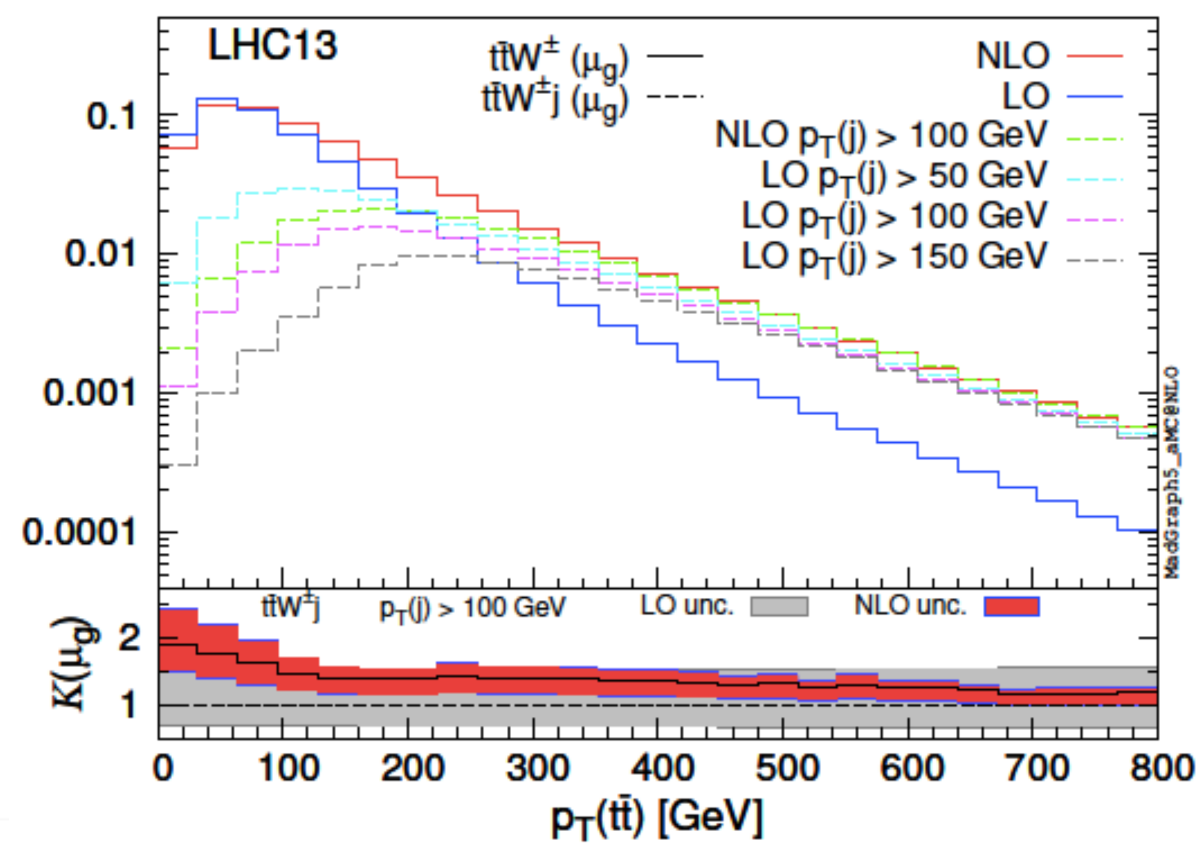


Giant K-factors at high pt(tt) are due to a soft-collinear double log (same situation as in Vjj) especially for quark initiated production. ttVj is instead stable.

[Pagani et al, 2015]

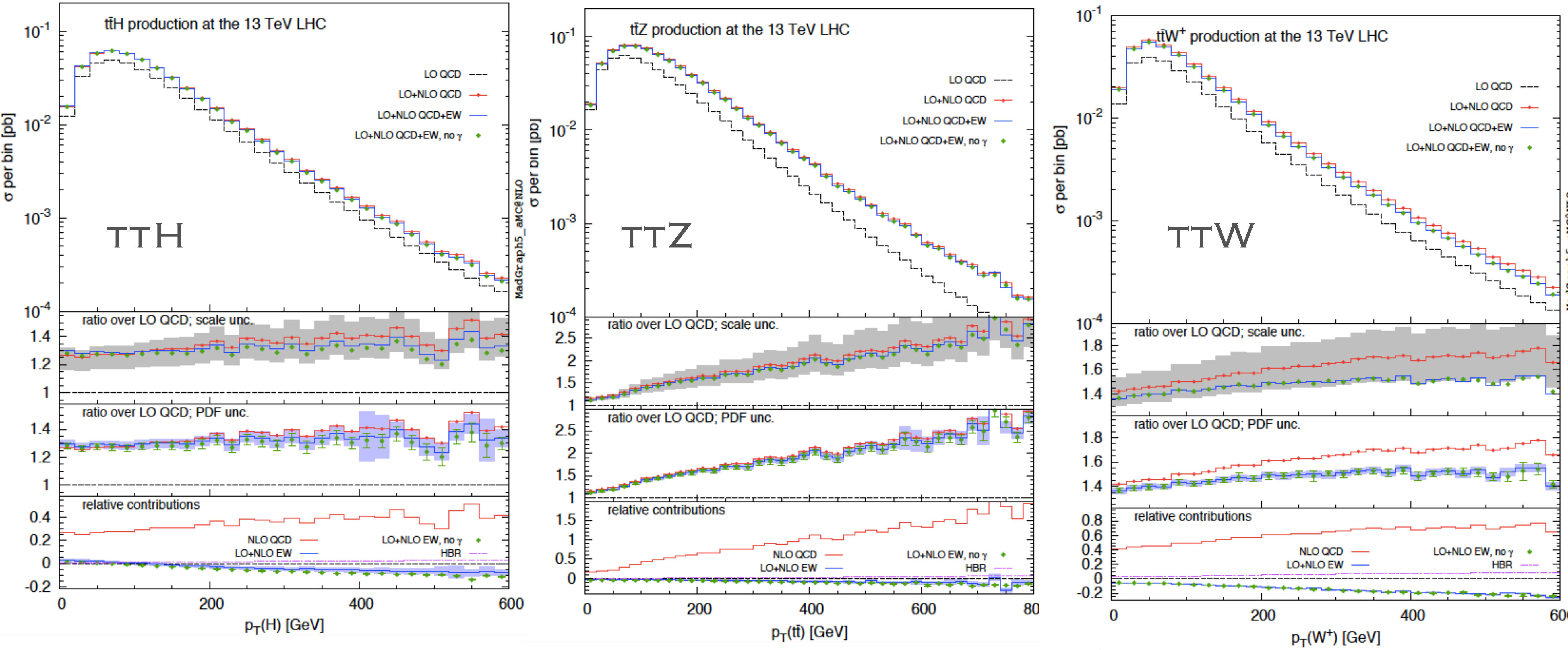






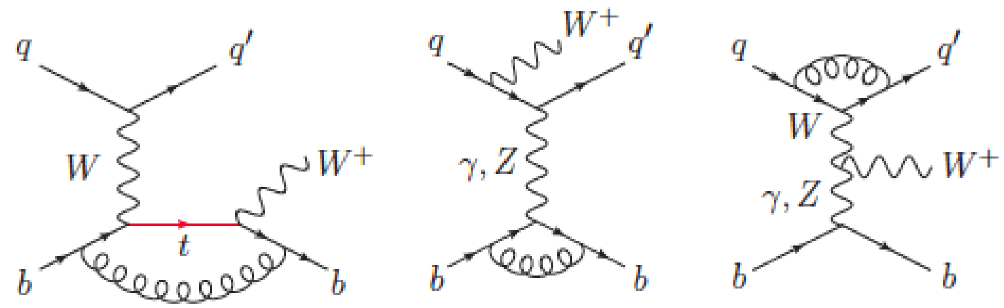
ttV production at NLO in QCD and EW

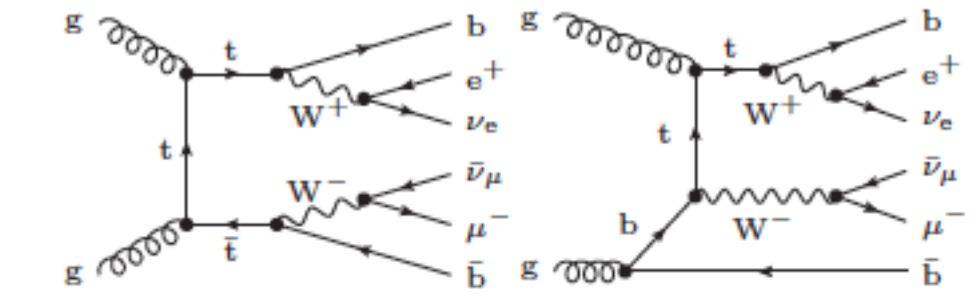
[Frixione et al, 2015]

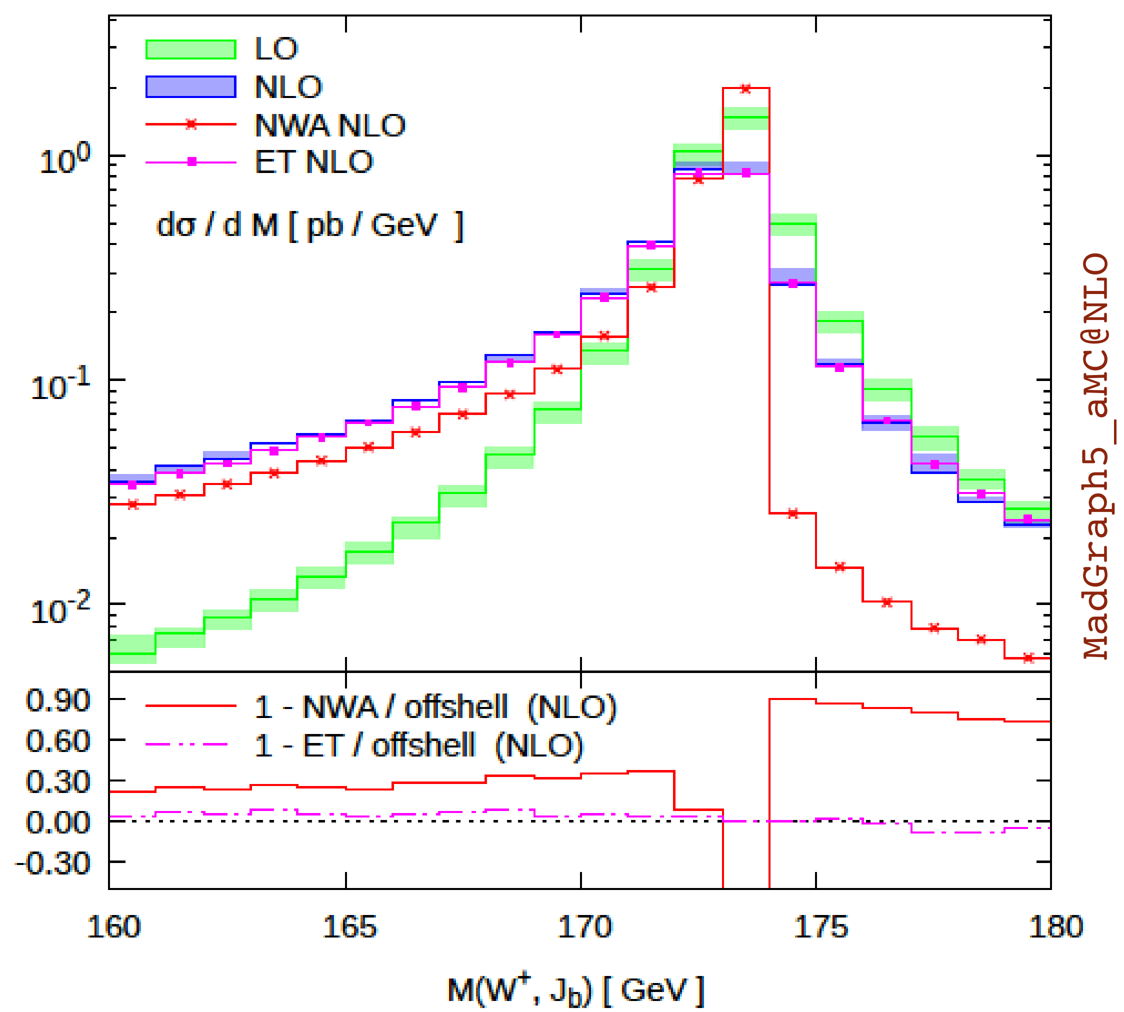


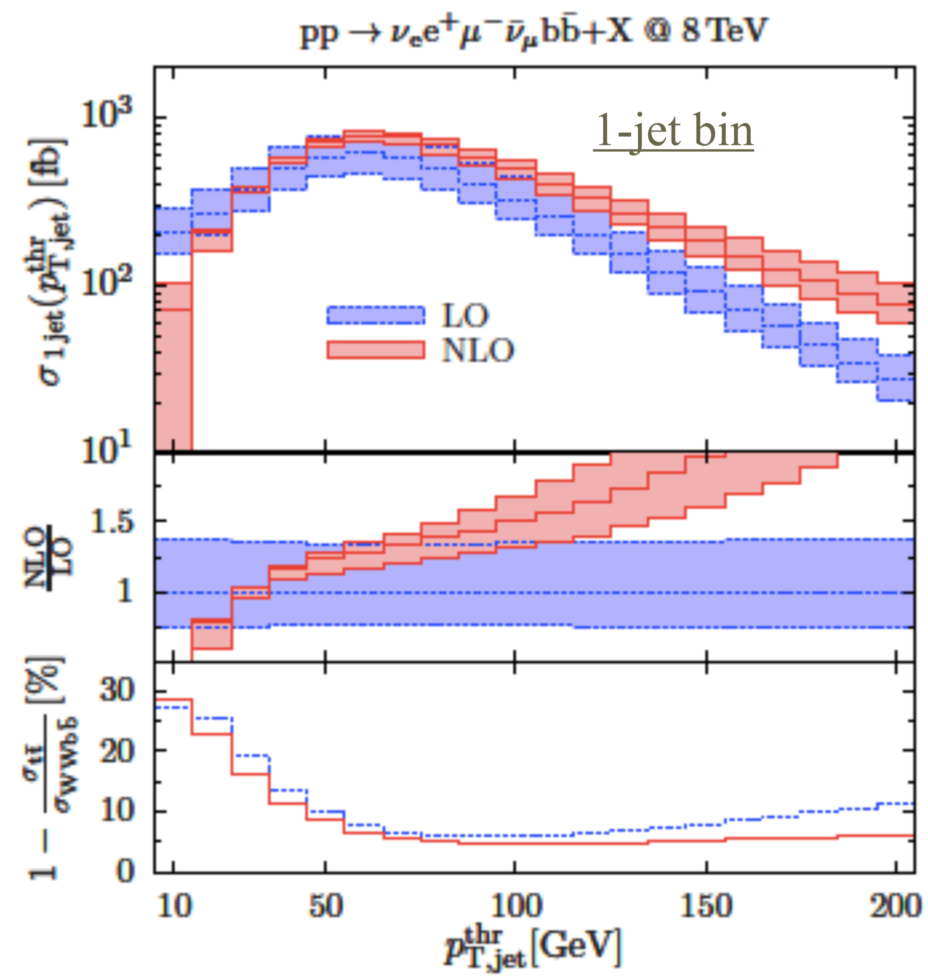
NLO for QCD & EW corrections included. QCD effects need to be taken into account for precision and accuracy. EW ones for accuracy.

NLO with intermediate top resonances









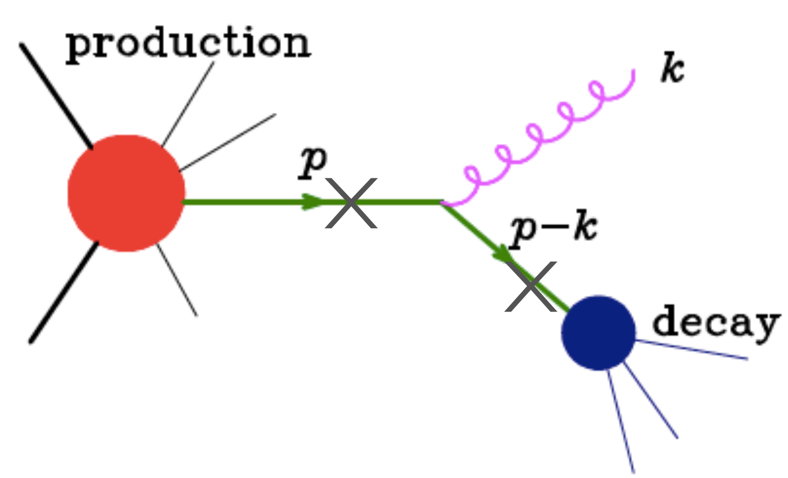
[Papanastasiou et al., 2013]

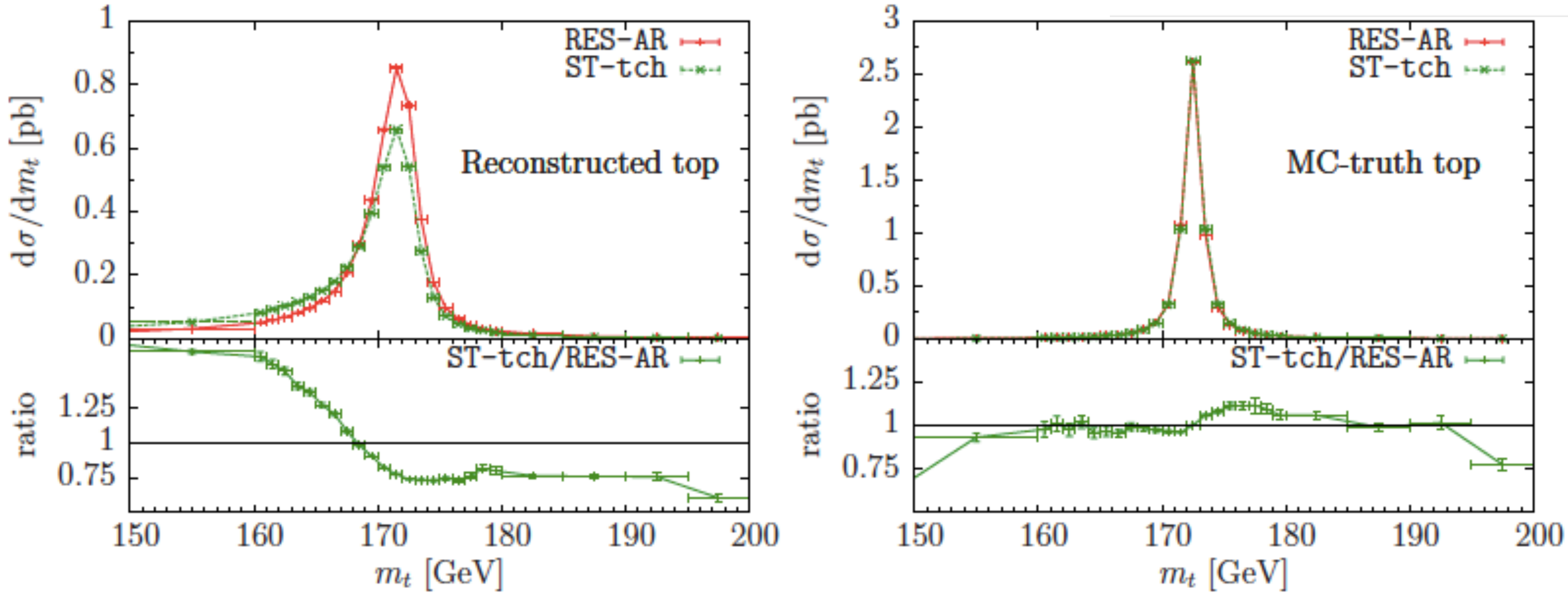
[Cascioli et al., 2014]

NLO+PS with intermediate resonances

[Jezo and Nason, 2015]

Amplitudes squared are expressed in terms of sum of contributions from the BW's. A modified FKS method has been proposed that deals correctly with double logs of Γ in POWHEG. Soft single logs Γ are left to cancel on their own in the B tilde function.

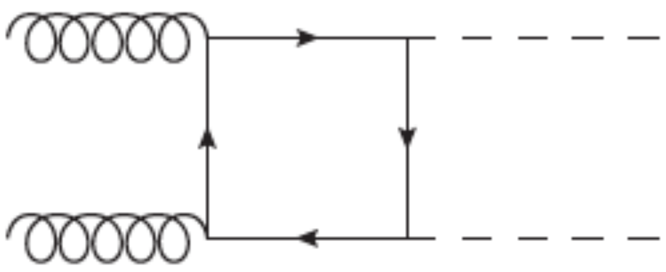




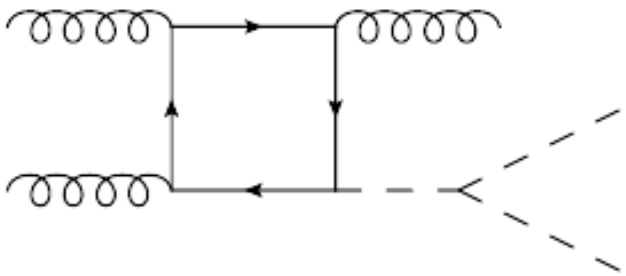
Shift in the reconstructed top mass due to differences in the final state radiation treatment of the b quark. Impact on the top mass reconstruction to be investigated.

Loop-Induced Processes in MCs

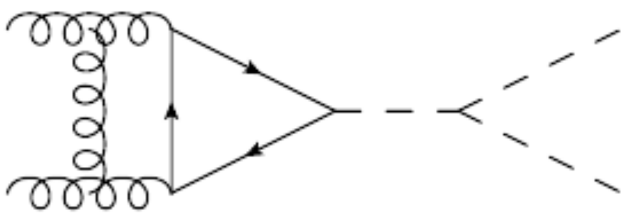
Many important processes at the LHC, mostly related to Higgs physics, are mediated by loops. Sometimes they are dominant (such as gg>h) more often they are part of NNLO corrections, but enhanced by gluon pdfs (gg>ZH, gg>VV).



One loop processes are Born level and therefore can treated exactly as tree-level processes when merging to the shower. Sherpa+OpenLoops and MG5_aMC (and now also Herwig7) have the out-of-the box capability to have MC generators with merging implemented (see eg. [Hirschi and Mattelaer 2015]).

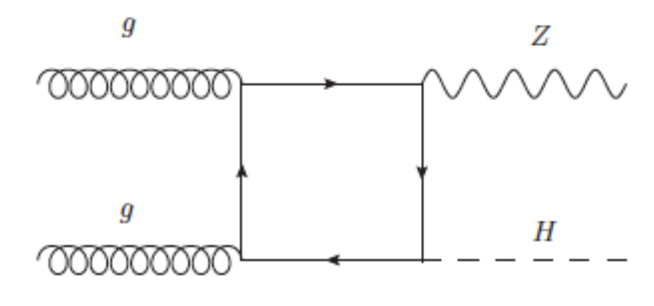


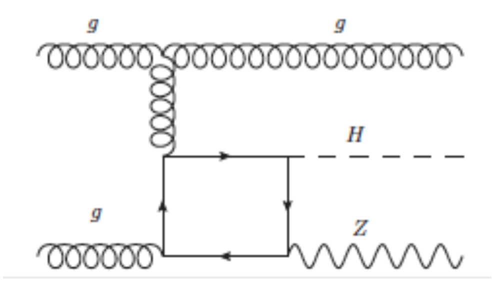
Going NLO+PS is straightforward (the IR structure is NLO) apart from the fact that very difficult two-loop amplitudes need to be calculated, which are presently mostly unknown (see Johannes and Kirill talks).



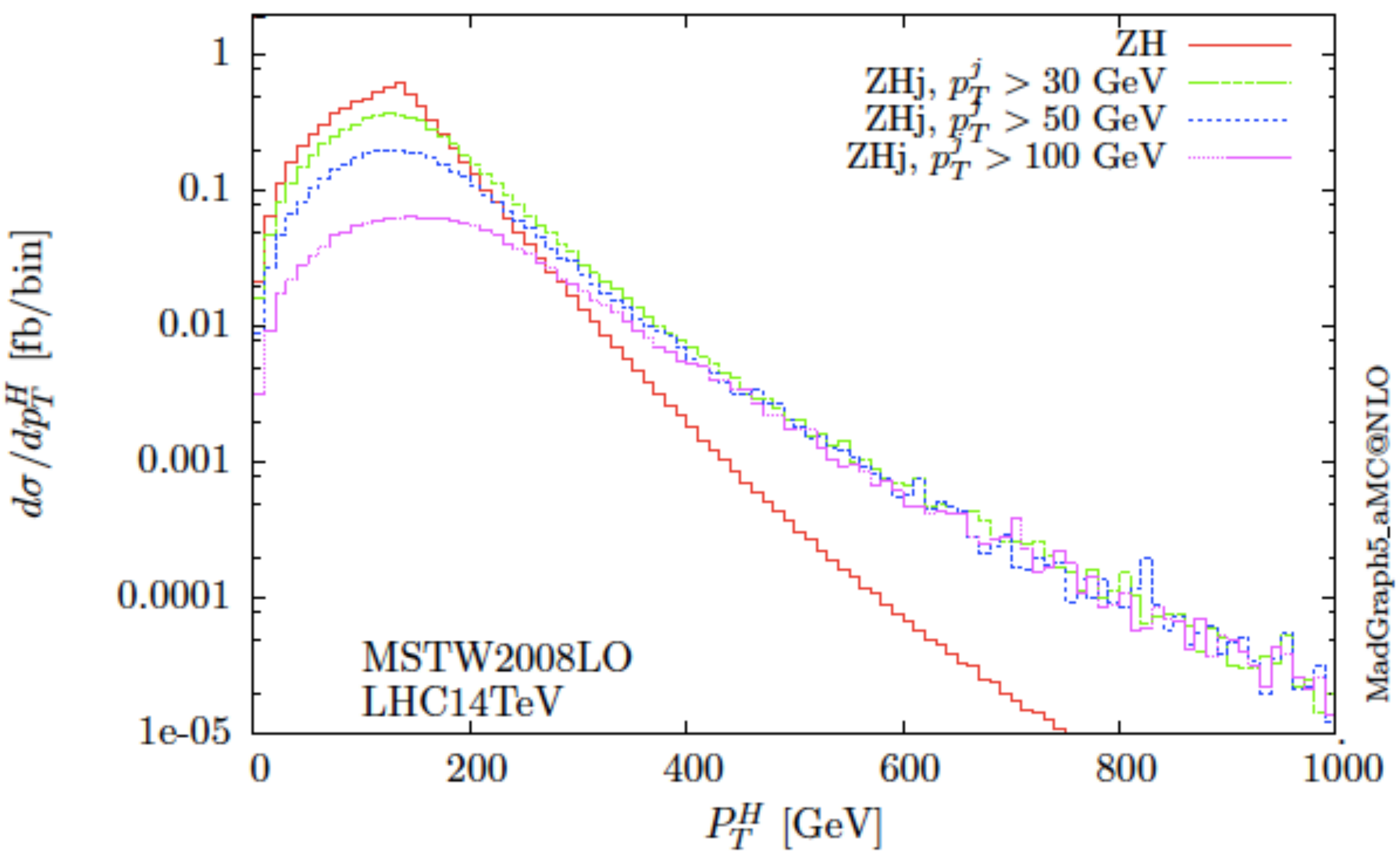
Loop Induced : ZH

ZH production goes through Drell-Yan but also gg fusion. Results for LI processes merged at LO show the importance of 2→3 for high-pT.

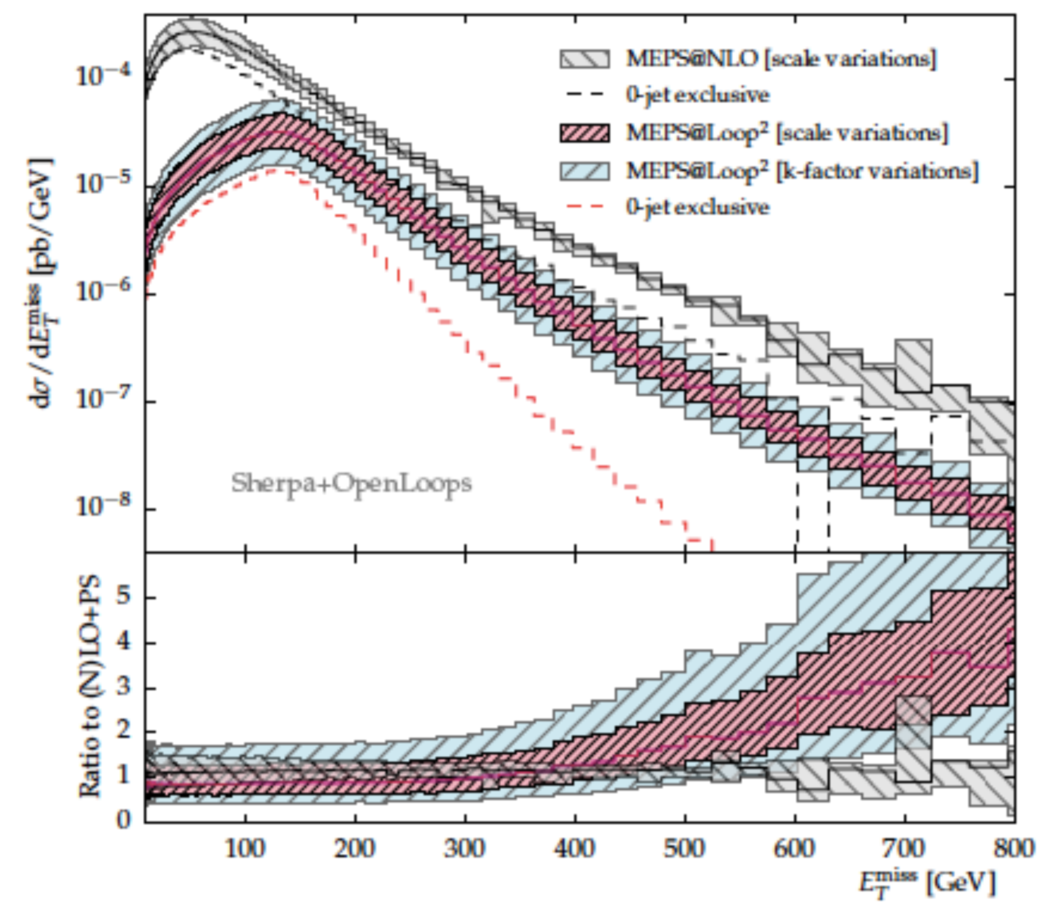




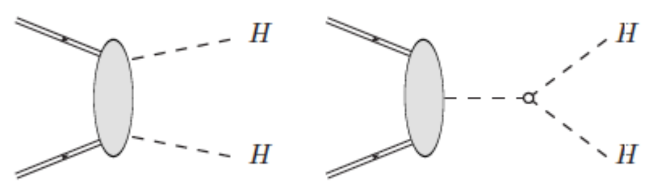
[Hespel et al 2015]



[Buschmann et al 2015]



Loop Induced : HH at NLO+PS$_{\text{approx}}$



For double Higgs, only the two-loop box diagrams are not known, while two-loop triangle and the one-loop real are all known. This allows to obtain an approximated result at NLO accuracy including top mass effects by reweighting the EFT at NLO:

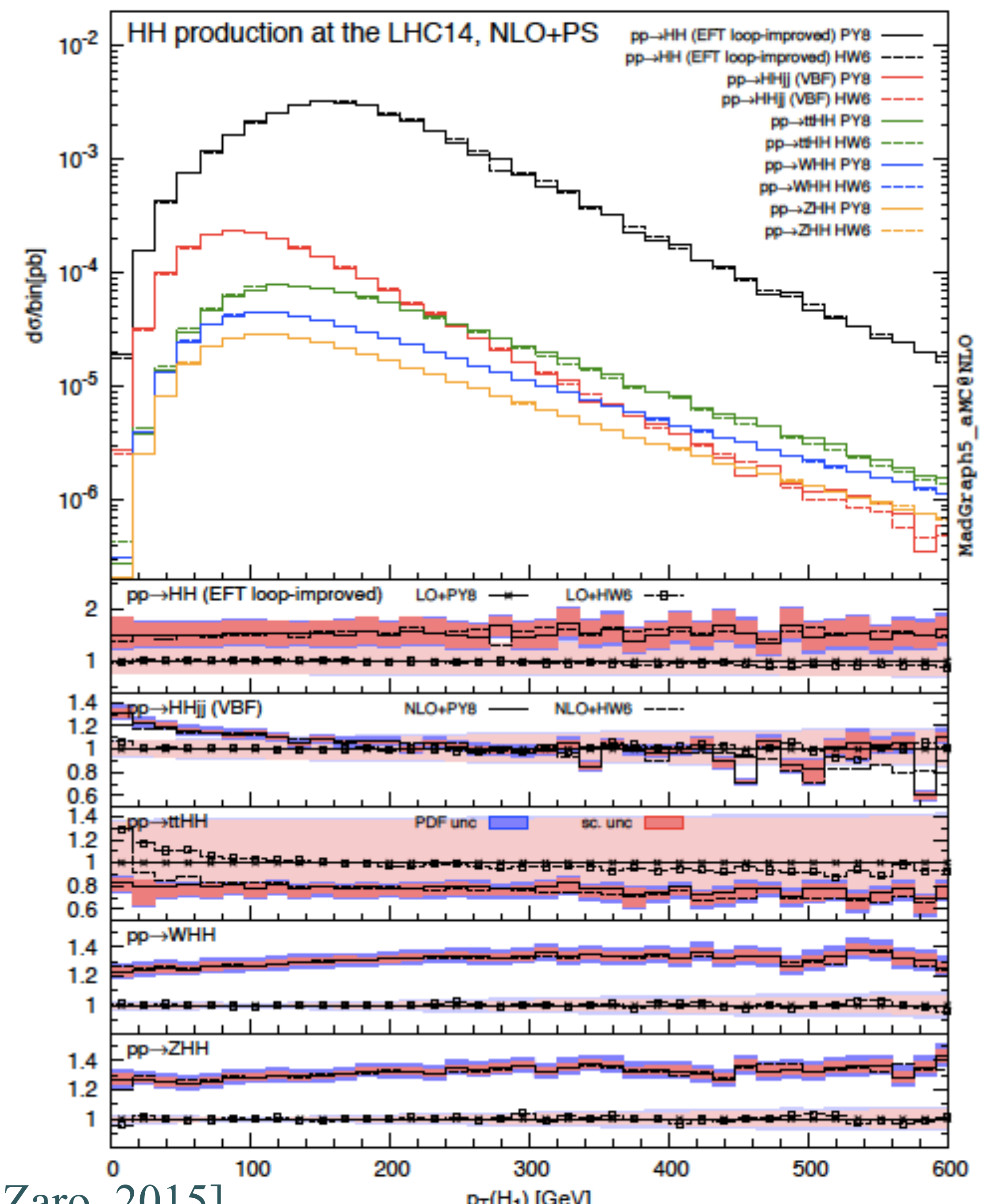
$$d\sigma^{(\mathbb{H})} = d\phi_{n+1}\left(\mathcal{R} - \mathcal{C}_{MC}\right),$$

$$d\sigma^{(\mathbb{S})} = d\phi_{n+1}\left[\left(\mathcal{B} + \mathcal{V} + \mathcal{C}^{int}\right)\frac{d\phi_n}{d\phi_{n+1}} + \left(\mathcal{C}_{MC} - \mathcal{C}\right)\right]$$

HH production in gluon-gluon fusion at 14 TeV		Cross section [fb]
LO	HEFT	$19.2^{+35.2+2.8\%}_{-24.3-2.9\%}$
	FT, $\Gamma_t = 0$ GeV	$23.2^{+32.3+2.0\%}_{-22.9-2.3\%}$
	FT, $\Gamma_t = 1.5$ GeV	$22.7^{+32.3+2.0\%}_{-22.9-2.3\%}$
NLO	HEFT	$32.9^{+18.1+2.9\%}_{-15.5-3.7\%}$
	HEFT Born-improved	$38.5^{+18.4+2.0\%}_{-15.1-2.4\%}$
	FT$_{\text{approx}}$ (virtuals: Born-rescaled HEFT)	$34.3^{+15.0+1.5\%}_{-13.4-2.4\%}$
	FT$'_{\text{approx}}$ (virtuals: estimated from single Higgs in FT)	$35.0^{+15.7+2.0\%}_{-13.7-2.4\%}$

[FM, Vryonidou and Zaro, 2015]

[Frederix et al 2014]



BSM @ NLO+PS

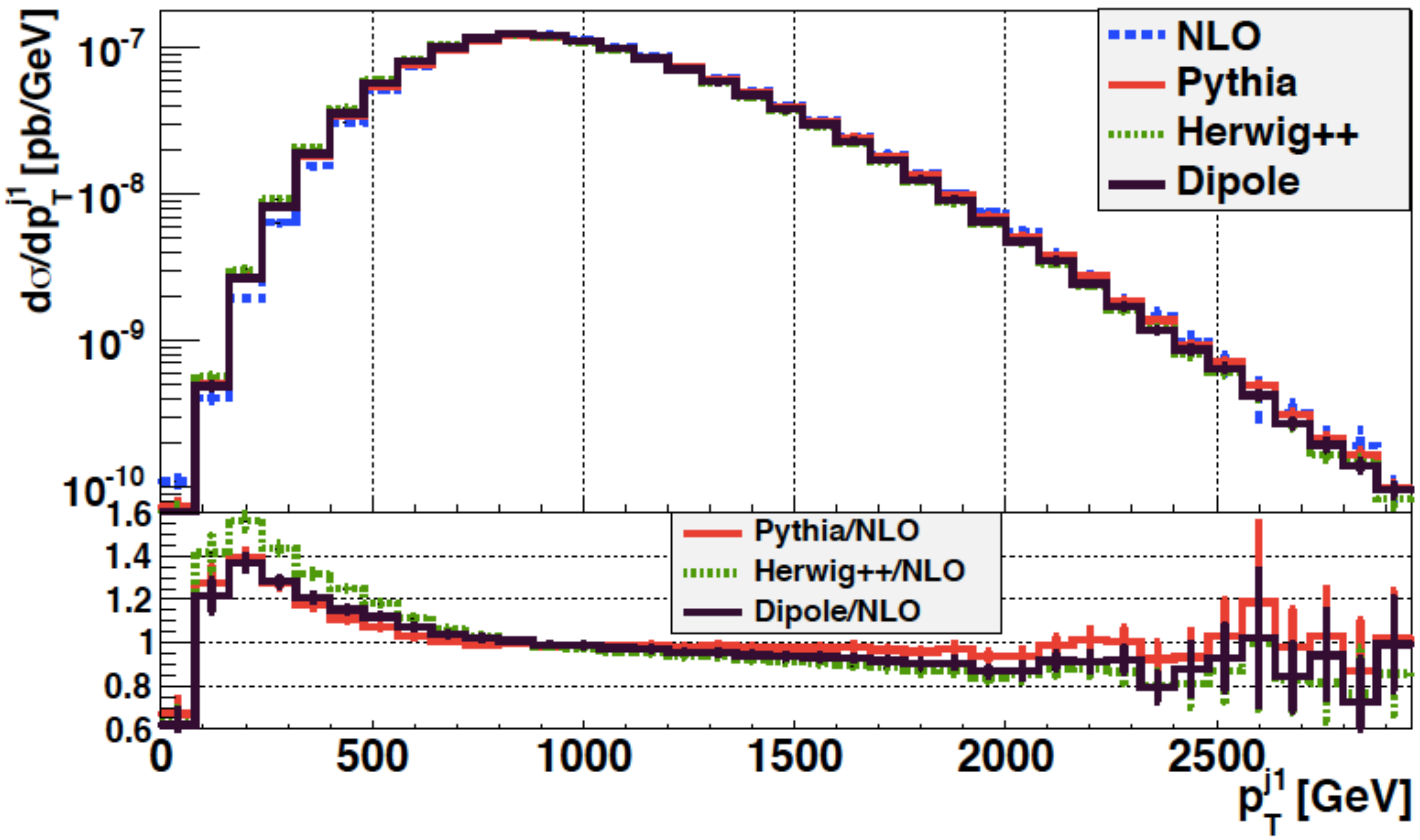
Going NLO+PS for BSM brings additional complications:

- Renormalization of the $\mathscr{L}_{\mathrm{NP}}$ needs to be performed and in case of use of numerical loop techniques the full set of counteterms is needed.
- At NLO, processes mix with LO resonant contributions and in order to keep NLO accuracy in inclusive samples a MC friendly procedure to subtract real resonant diagrams must be in place.
- If non-renormalizable operators appear, higher-dimensional rank in the integrals appear as well as extra UV divergences and full mixing RGE are needed.

Not to mention that given the plethora of models that are conceivable and/or the complexity of the EFT, at least a minimal level automation is needed.

SUSY at NLO+PS

First work in this direction by [Gavin, Hangst, Kraemer, Muhlleinter, Pellen, Popenda, Spira, 2013] where they used the known analytic results collected in PROSPINO and implement them by hand in the POWHEG-Box. Only issue to solve the separation of resonant contributions appearing at NLO (similar situation as in the SM for tW at NLO which is interfering with tt at NLO).

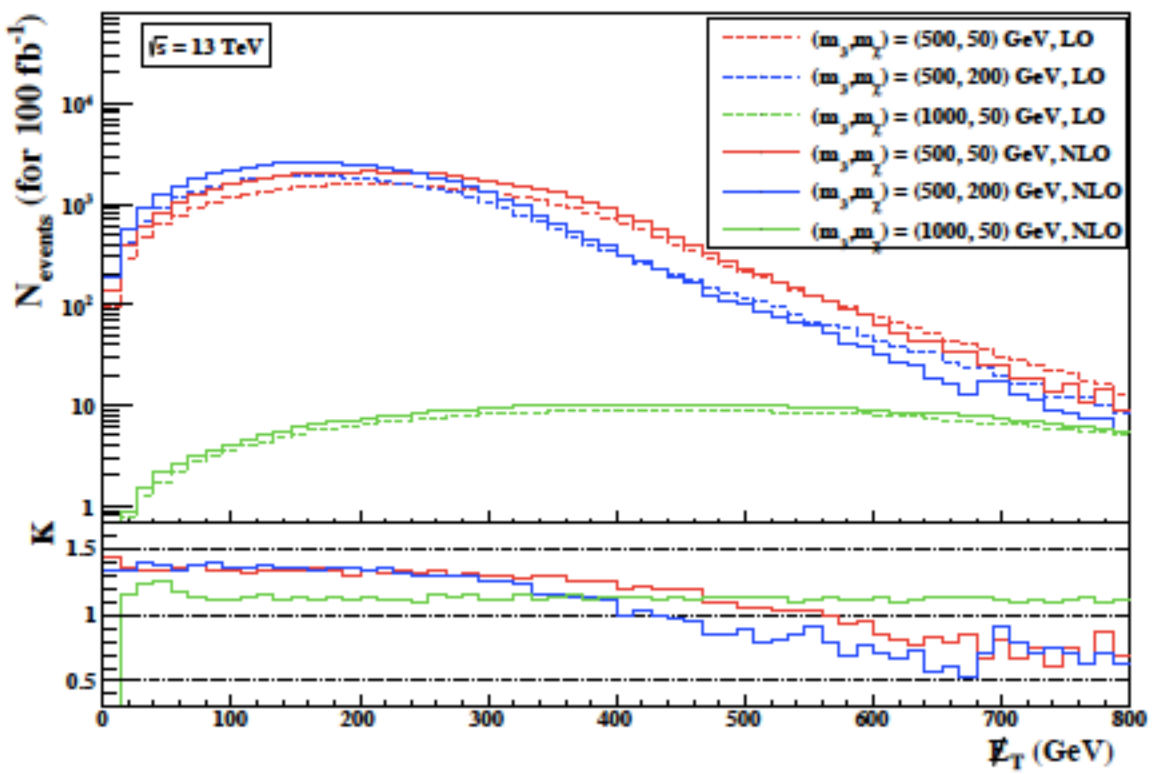


Only squark pair production implemented

SUSY colored scalar production

[Degrande et al., 2015]

The full chain from the SUSY Lagrangian to the computation of the counter terms done automatically and UFO model available. Full automation of SUSY at NLO+PS achieved.



m_3 [GeV]	8 TeV $\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$389.3^{+34.2\%}_{-23.9\%}$	$554.8^{+14.9\%\,+1.6\%}_{-13.5\%\,-1.6\%}$
250	$4.118^{+40.4\%}_{-27.2\%}$	$5.503^{+13.1\%\,+3.7\%}_{-13.7\%\,-3.7\%}$
500	$(6.594\times10^{-2})^{+45.5\%}_{-29.1\%}$	$(7.764\times10^{-2})^{+12.1\%\,+6.7\%}_{-14.1\%\,-6.7\%}$
750	$(3.504\times10^{-3})^{+48.8\%}_{-30.5\%}$	$(3.699\times10^{-3})^{+12.3\%\,+10.2\%}_{-14.6\%\,-10.2\%}$
1000	$(2.875\times10^{-4})^{+51.5\%}_{-31.5\%}$	$(2.775\times10^{-4})^{+13.1\%\,+15.5\%}_{-15.2\%\,-15.5\%}$

m_8 [GeV]	8 TeV $\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
100	$3854^{+34.4\%}_{-24.1\%}$	$5573^{+14.9\%\,+1.6\%}_{-13.6\%\,-1.6\%}$
250	$38.89^{+41.3\%}_{-27.7\%}$	$54.32^{+14.5\%\,+3.9\%}_{-14.6\%\,-3.9\%}$
500	$0.5878^{+47.6\%}_{-30.0\%}$	$0.7431^{+15.8\%\,+7.6\%}_{-16.2\%\,-7.6\%}$
750	$(2.977\times10^{-2})^{+52.0\%}_{-31.9\%}$	$(3.353\times10^{-2})^{+17.2\%\,+12.1\%}_{-17.3\%\,-12.1\%}$
1000	$(2.328\times10^{-3})^{+55.9\%}_{-33.4\%}$	$(2.398\times10^{-3})^{+19.0\%\,+19.1\%}_{-18.4\%\,-19.1\%}$

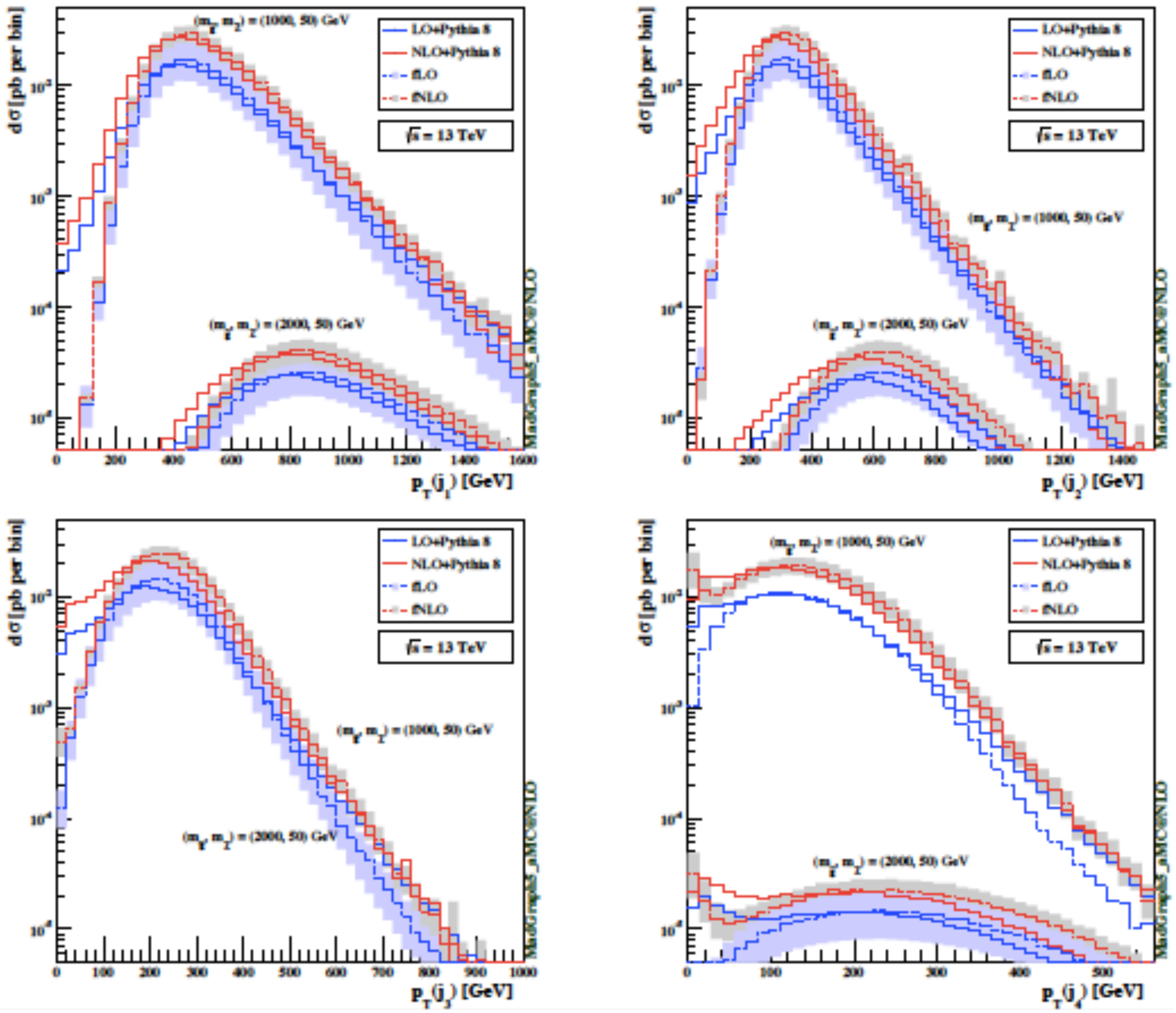
$$\mathcal{L}_3 = D_\mu\sigma_3^\dagger D^\mu\sigma_3 - m_3^2\sigma_3^\dagger\sigma_3 + \frac{i}{2}\bar\chi\partial\!\!\!/\chi - \frac{1}{2}m_\chi\bar\chi\chi + \left[\sigma_3\bar t(\tilde g_L P_L + \tilde g_R P_R)\chi + \text{h.c.}\right],$$

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

SUSY gluino pair production

[Degrande et al., 2015]

..including gluino pair production which technically very challenging (Majorana nature of the gluinos).



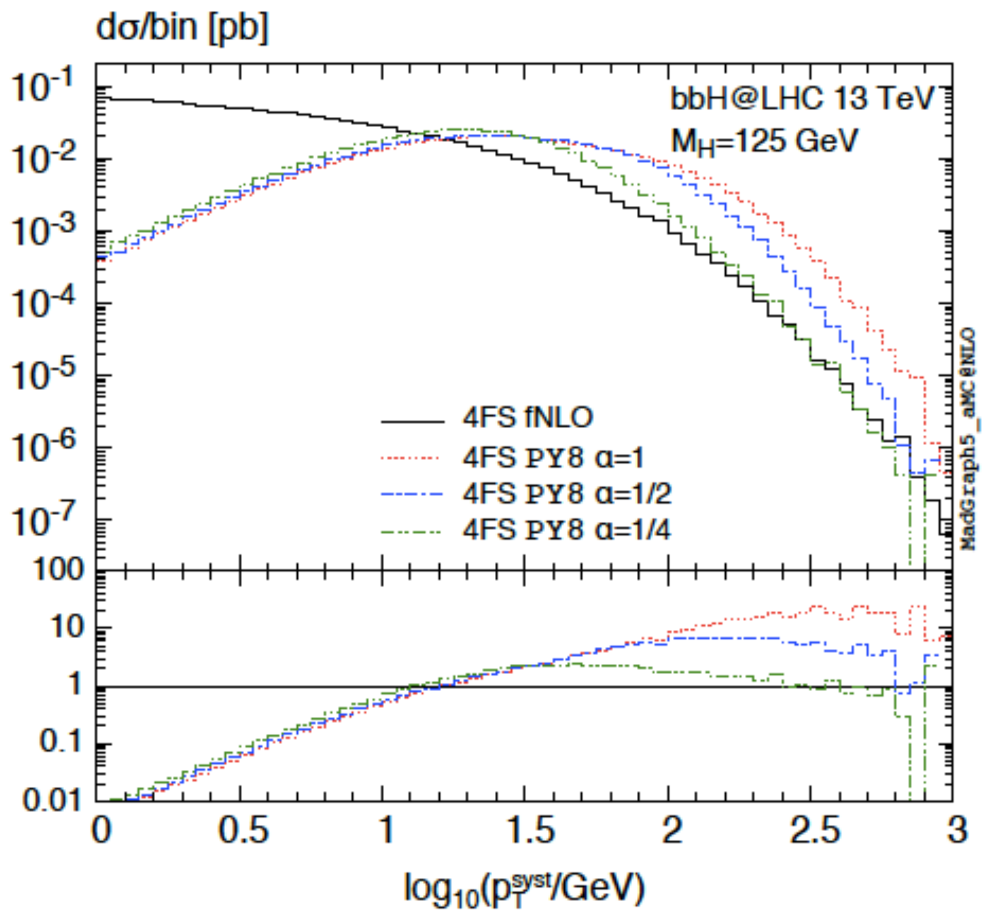
$m_{\tilde{g}}$ [GeV]	$\sigma^{\rm LO}$ [pb]	$\sigma^{\rm NLO}$ [pb]
200	$2104^{+30.3\%\,+14.0\%}_{-21.9\%\,-14.0\%}$	$3183^{+10.8\%\,+1.8\%}_{-11.6\%\,-1.8\%}$
500	$15.46^{+34.7\%\,+19.5\%}_{-24.1\%\,-19.5\%}$	$24.90^{+12.5\%\,+3.7\%}_{-13.4\%\,-3.7\%}$
750	$1.206^{+35.9\%\,+23.5\%}_{-24.6\%\,-23.5\%}$	$2.009^{+13.5\%\,+5.5\%}_{-14.1\%\,-5.5\%}$
1000	$1.608 \cdot 10^{-1}{}^{+36.3\%\,+26.4\%}_{-24.8\%\,-26.4\%}$	$2.743 \cdot 10^{-1}{}^{+14.4\%\,+7.3\%}_{-14.8\%\,-7.3\%}$
1500	$6.264 \cdot 10^{-3}{}^{+36.2\%\,+29.4\%}_{-24.7\%\,-29.4\%}$	$1.056 \cdot 10^{-2}{}^{+16.1\%\,+11.3\%}_{-15.8\%\,-11.3\%}$
2000	$4.217 \cdot 10^{-4}{}^{+35.6\%\,+29.8\%}_{-24.5\%\,-29.8\%}$	$6.327 \cdot 10^{-4}{}^{+17.7\%\,+17.8\%}_{-16.6\%\,-17.8\%}$

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

H^0bb and H^+tb production at NLO+PS

[Wiesemann et al., 2014] [Degrande et al., 2015]

Within FeynRules/MG5_aMC the 2HDM Lagrangian has been implemented in two different QCD schemes (4 and 5 flavour) and production of neutral Hbb and charged H+tb final states.



- Choice of the shower starting scale for processes with initial state b's is important. It should be chosen with the same criteria that are used for the renormalisation and factorisation scales.
- Reasonable agreement between 4F and 5F schemes for observables at the same accuracy.

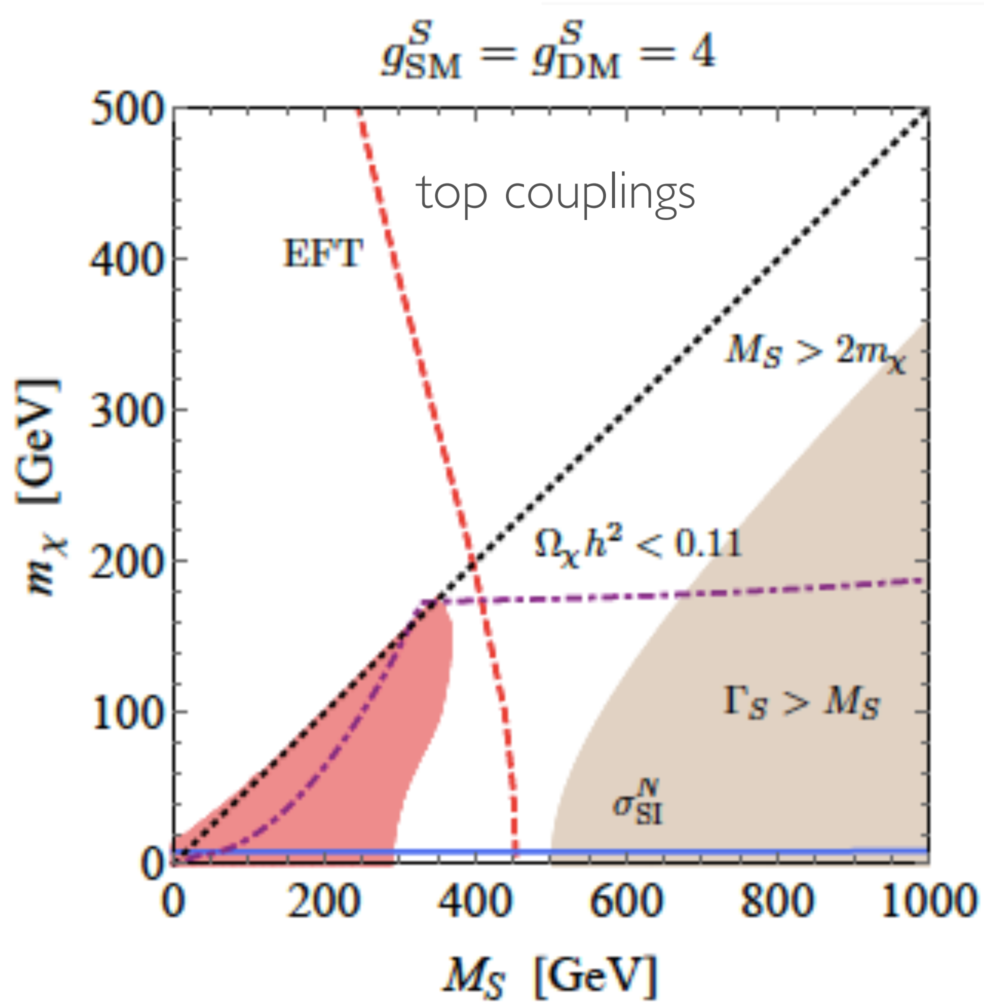
H^0bb and tH^+ (5F) are also available in the POWHEG-BOX

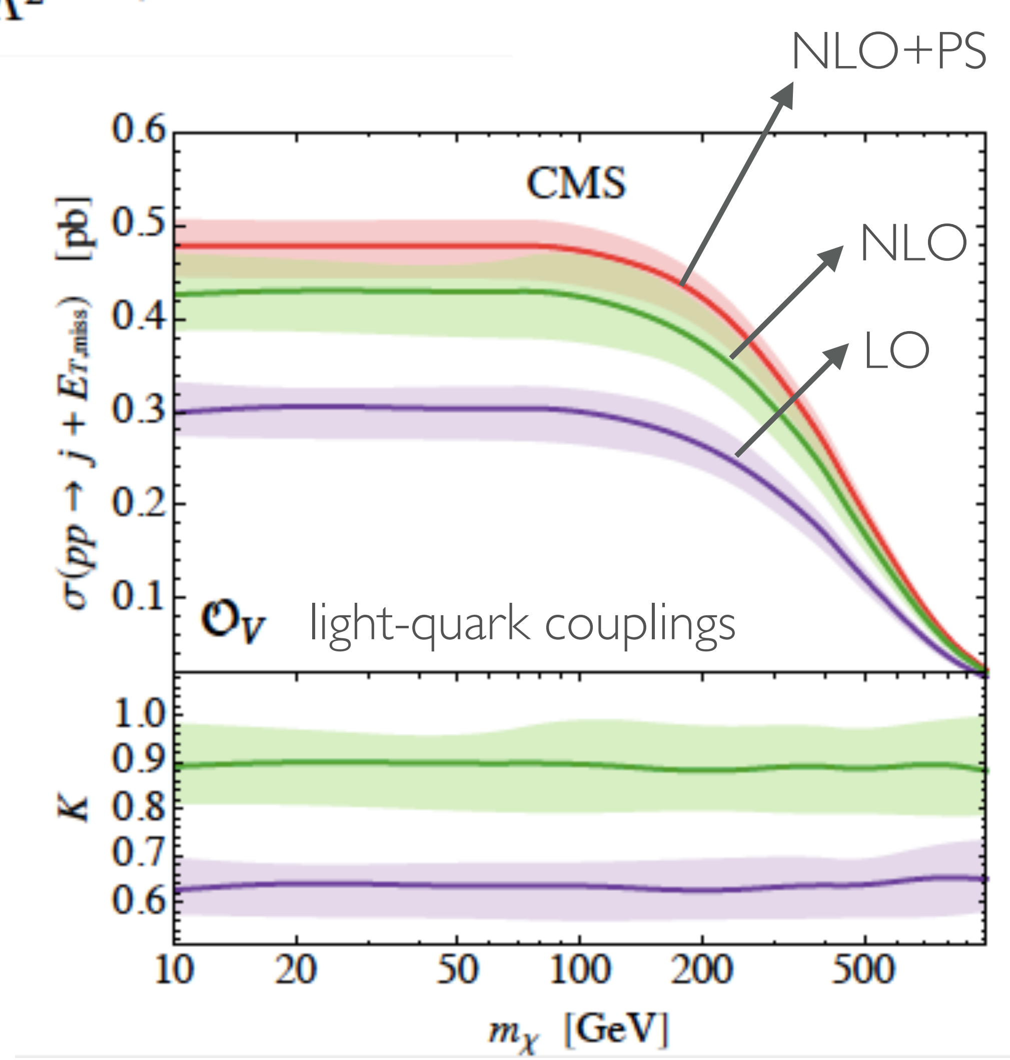
[Klasen et al, 2015]
[Jeager and Reina, 2015]

Dark Matter at NLO+PS (& Loop-Induced)

First work in this direction by [Haisch et al., 2013] [Haisch et al., 2013] [Haisch et al., 2014] [Crivellin et al., 2015] [Haisch and Re, 2015] where they used the known analytic results collected in MCFM and also implemented some of them by hand in the POWHEG-Box.

$$\mathcal{O}_V = \frac{1}{\Lambda^2}\left(\bar{q}\gamma_\mu q\right)\left(\bar{\chi}\gamma^\mu\chi\right), \qquad \mathcal{O}_A = \frac{1}{\Lambda^2}\left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)$$





Dark Matter production at NLO+PS and LI

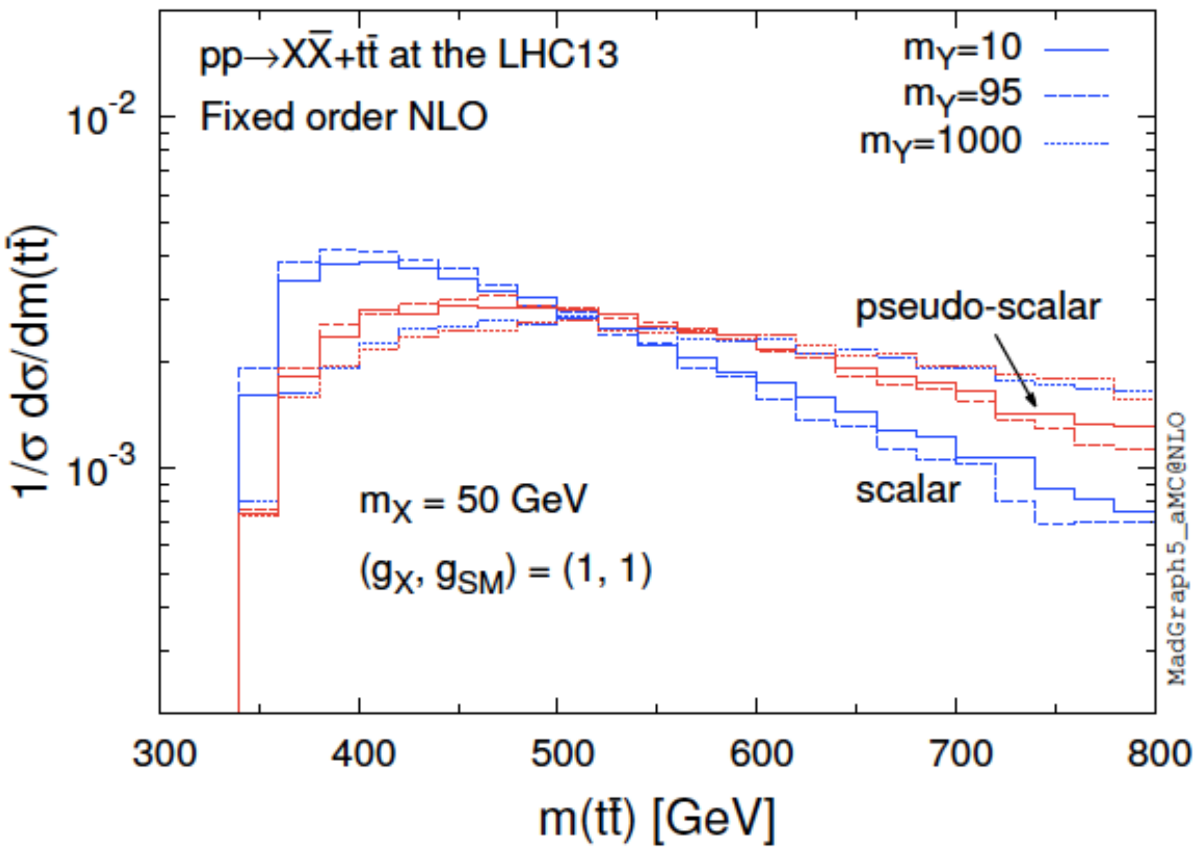
A Simplified Model Lagrangian has been implemented in FeynRules and counter terms obtained automatically with NLOCT. Full automation of Simplified Models possible for Loop-Induced and NLO+PS.

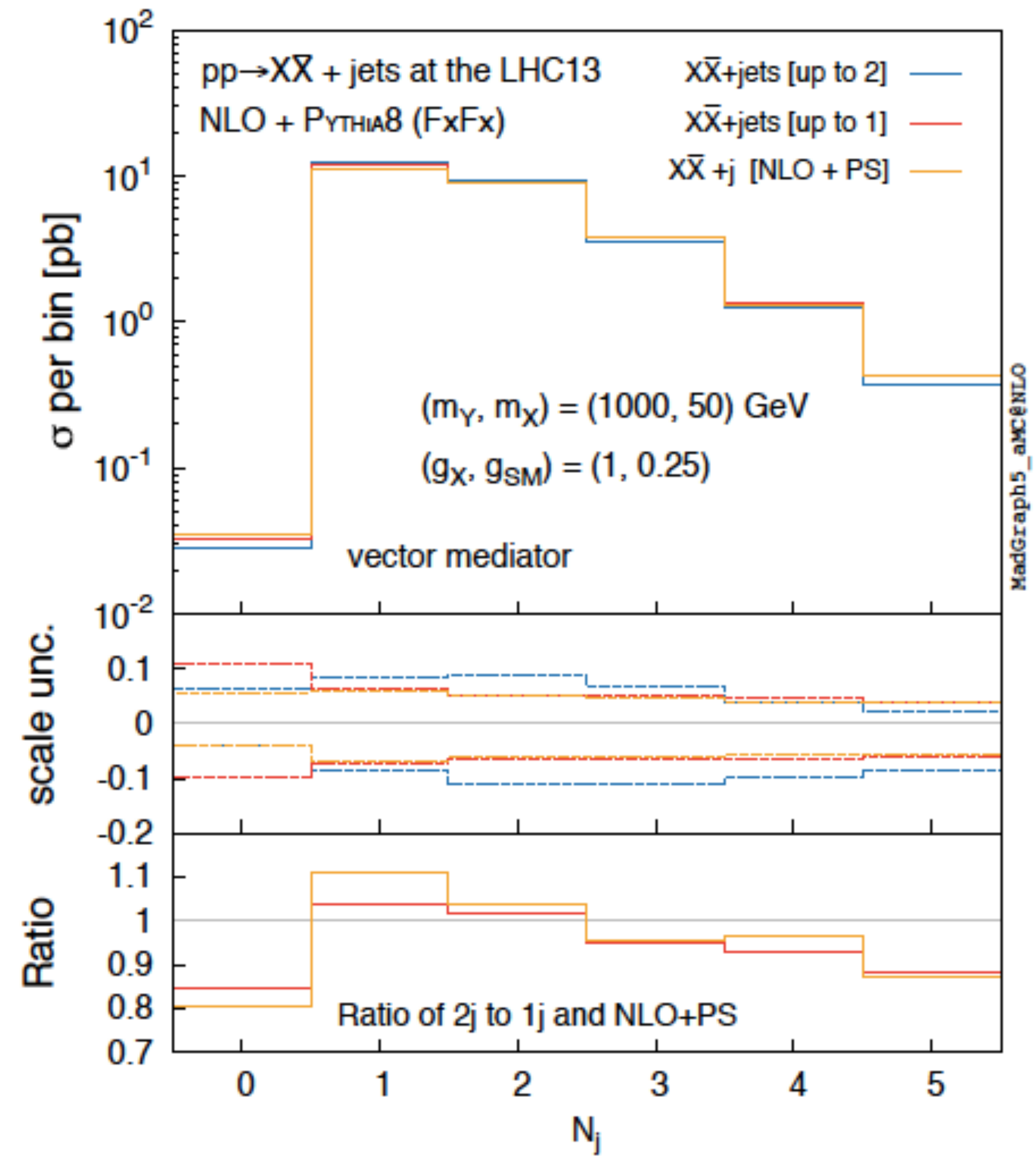
- s-channel scalar and vector mediators coupling to quarks, NLO+PS [Backovic et al., 2015]
- s-channel models with coupling to the top, loop-induced processes. [Mattelaer and Vryonidou, 2015]
- s-channel scalar and vector mediators coupling to quarks and vector bosons [M. Neubert, J. Wang, C. Zhang, 2015]

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

Dark Matter production at NLO+PS

[Backovic et al., 2015]

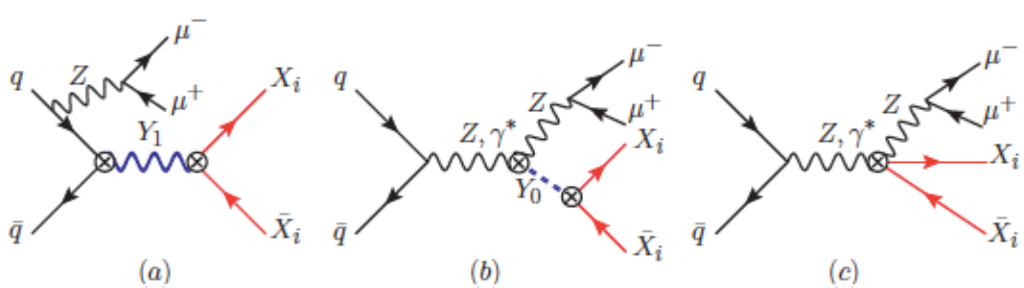


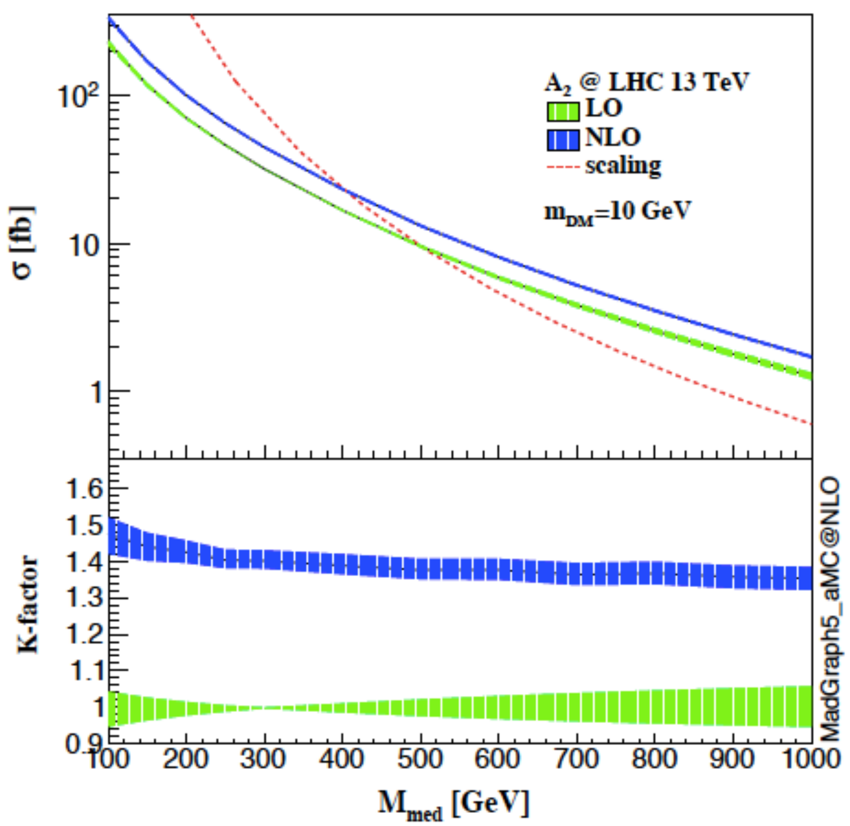


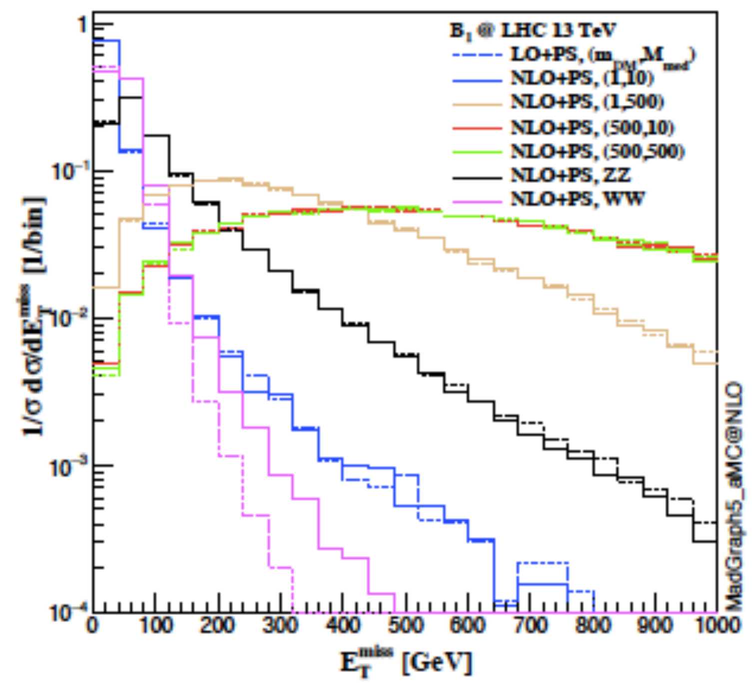
- tt+$X_{DM}X_{DM}$ with (pseudo-)scalar mediator is calculated at NLO+PS. Different shapes.
- $X_{DM}X_{DM}$ + (0,)1,2 jets is merged at NLO (FxFx) : no significant changes with respect to the NLO +PS sample for 1 jet at NLO.

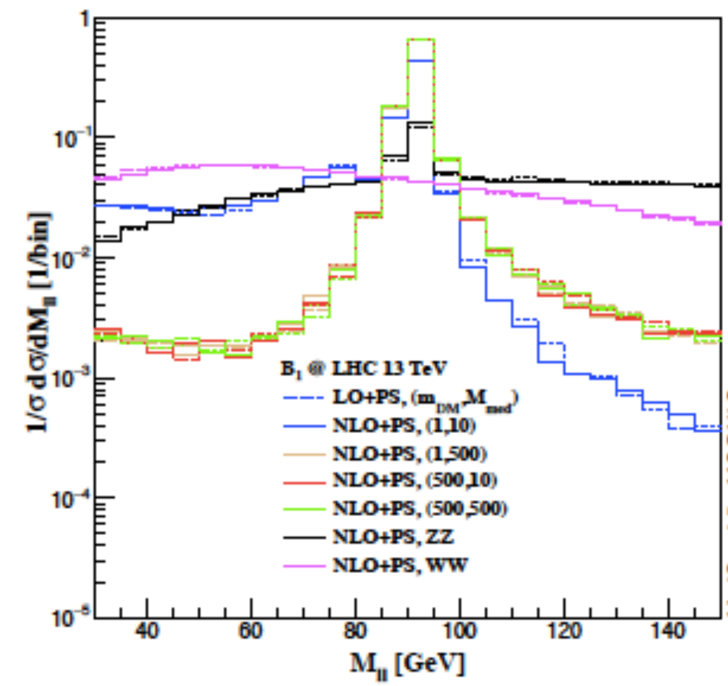
Dark Matter production at NLO+PS : Z+mET

[M. Neubert, J. Wang, C. Zhang, 2015]





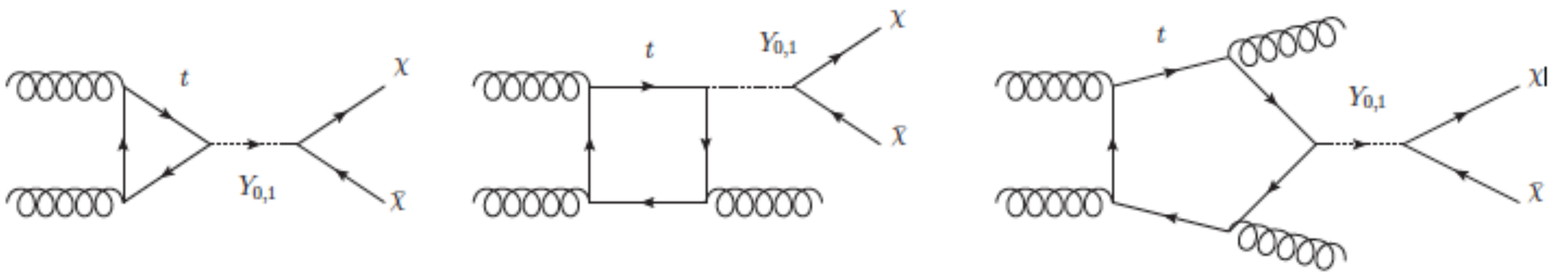


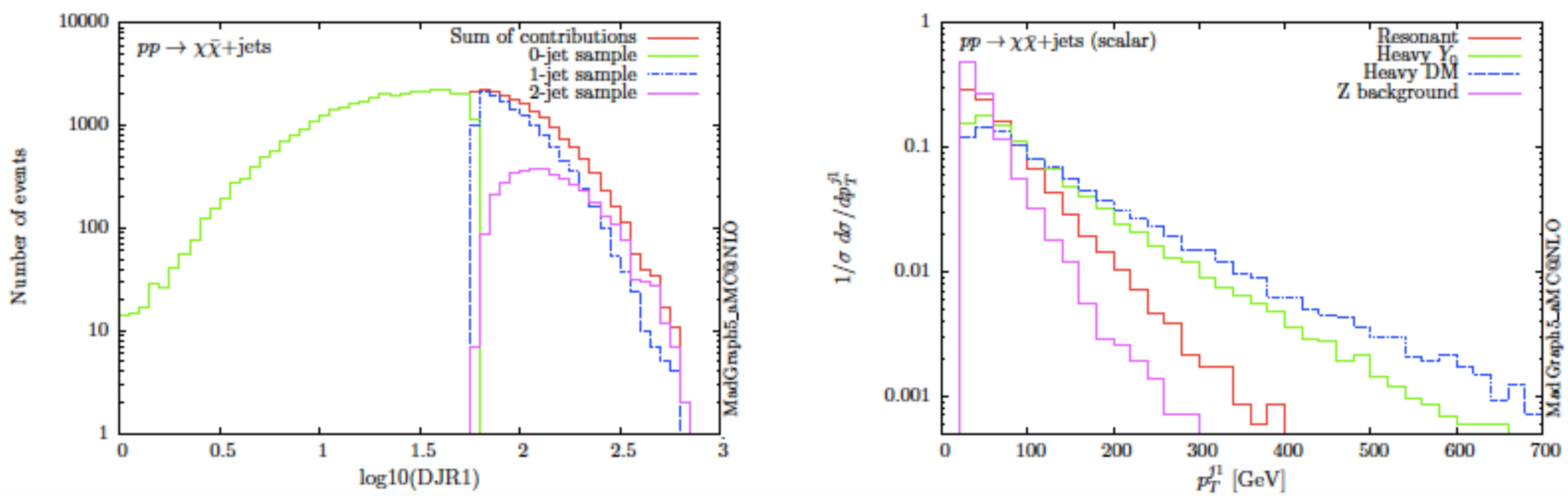


- Significant effects due to NLO corrections
- Comparison with SM backgrounds also calculated at NLO+PS

Loop-Induced X_{DM} X_{DM} + jets merged

[Mattelaer and Vryonidou, 2015]

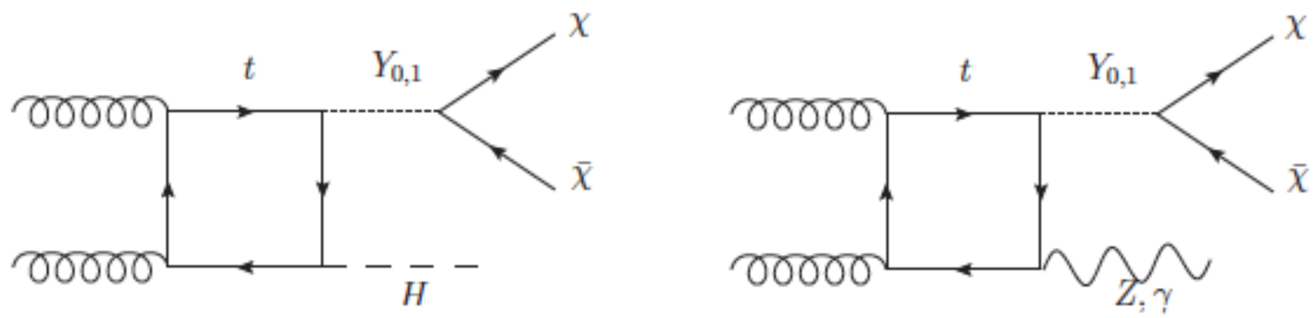


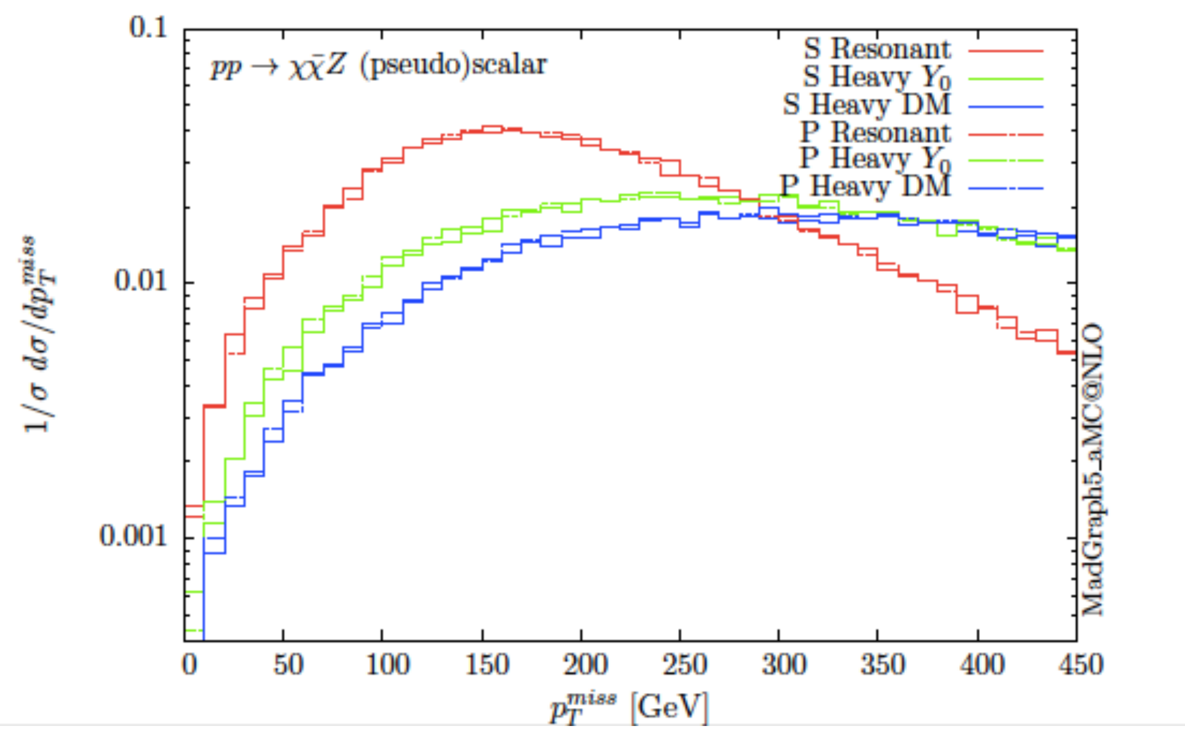


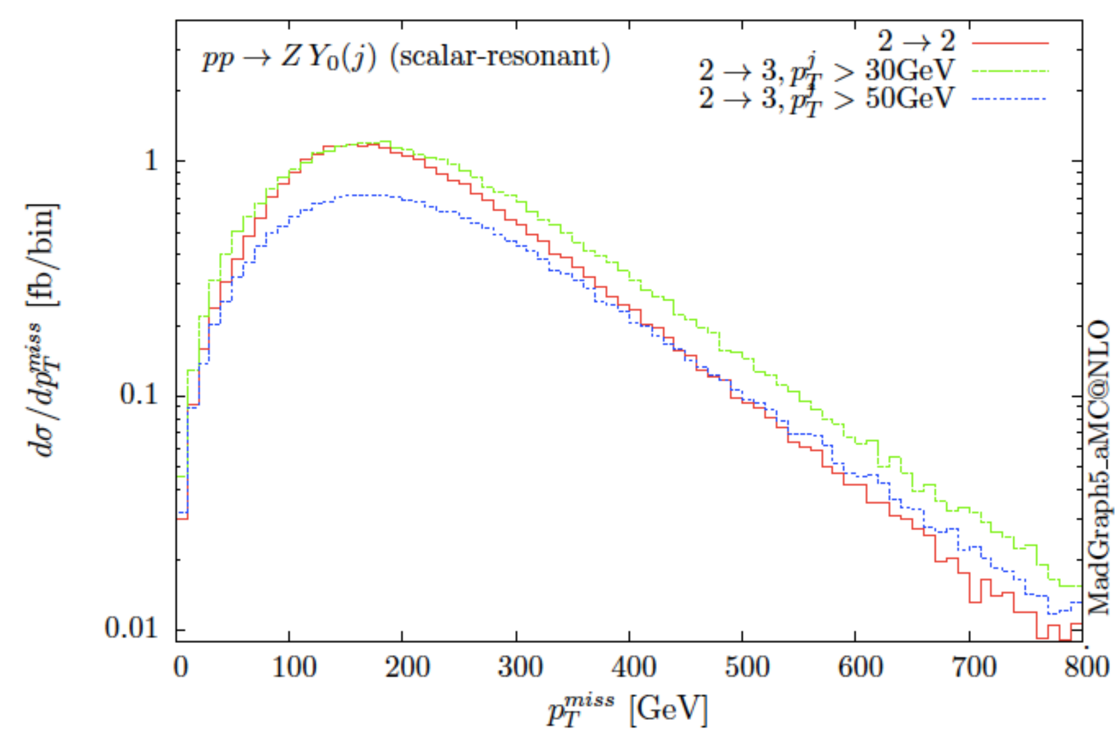
Scalar mediator coupled to the top leads to X_{DM} X_{DM} + jets via loops. Merged samples built automatically and compared to SM at NLO+PS.

Loop-induced X_{DM} X_{DM} + (H, Z, ɣ)

[Mattelaer and Vryonidou, 2015]







Scalar mediator coupled to the top leads to X_{DM} X_{DM} + H, Z or ɣ. Very different shapes of Etmiss depending on the associated production. The effect of extra gluon radiation on the shape Etmiss can also be studied.

BSM goals of the SM LHC programme

Two main strategies for searching new physics

Search for new states ⟷ Search for new interactions

SUSY, EXOTICS, BSM HIGGS — SM

The matter content of SM has been experimentally verified and evidence for light states is not present. SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions.

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

BSM goal of the SM LHC program:

determination of the couplings of the SM lagrangian at DIM=6

Dim=6 SM Lagrangian

[Grzadkowski et al, 10]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
		Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
		Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
		Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu \tau^I q_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu \tau^I l_r)(\bar q_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

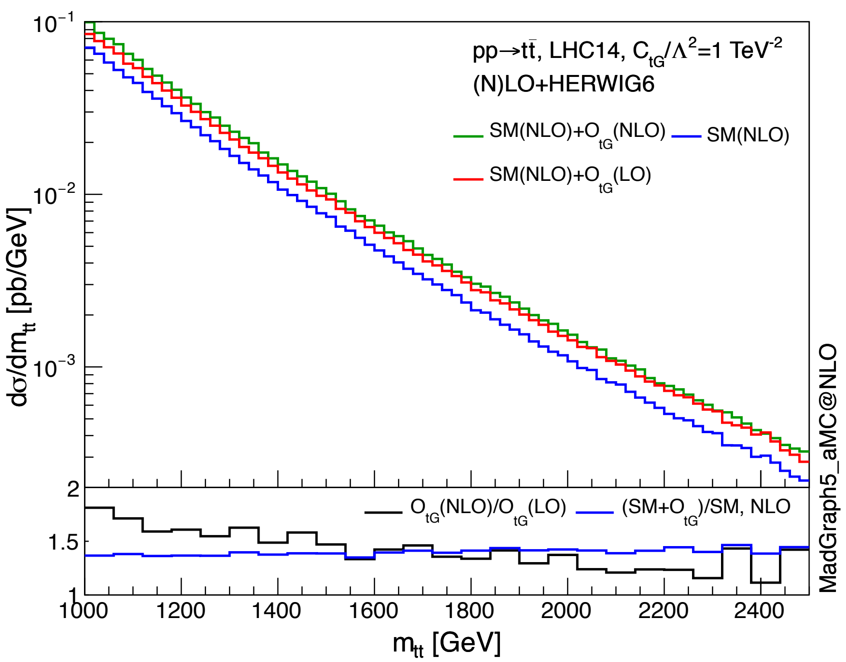
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalizable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ

Status of the NLO+PS for the SM@dim6

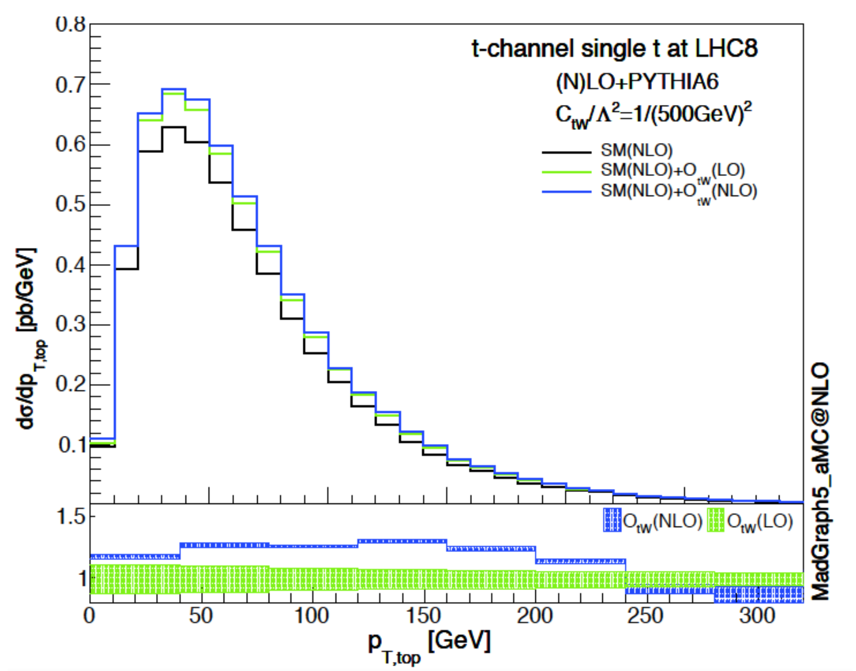
- The ambitious program of measuring all coefficients of the $\mathscr{L}_{\mathrm{EFT}}$ relies on our ability of making accurate predictions for the SM and also for the EFT. This is especially try for the top and the Higgs at the LHC.
- The structure of the theory at NLO in QCD becomes non-trivial, with mixing and RGE of the couplings to be considered.
- The SM@dim6 is implemented and available at LO via FeynRules and is being extended at NLO in QCD. Many results already available relevant Higgs and top quark at NLO.

[Franzosi and Zhang, 2015]



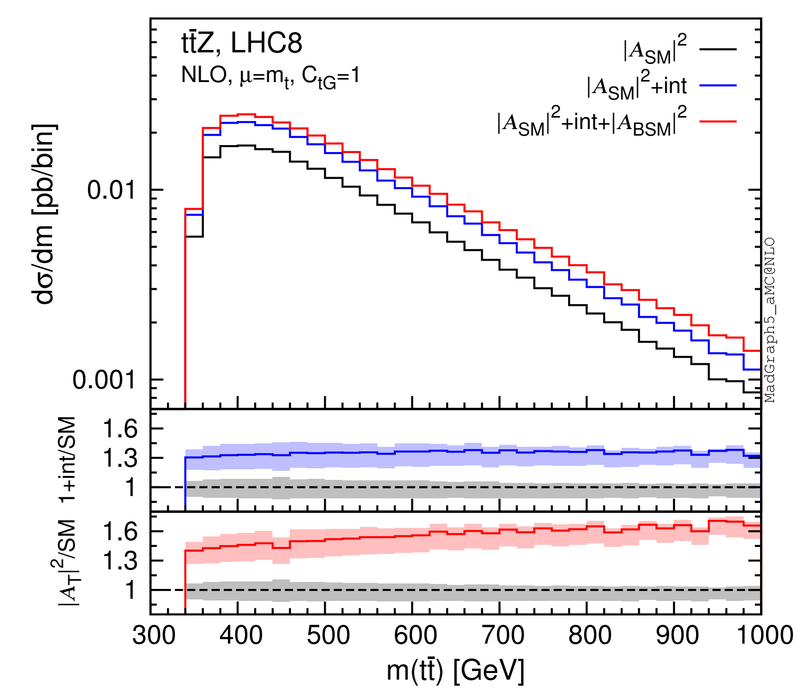
pp→tt with O_{tG}

[Zhang to appear, 2015]



pp→tj with O_{tW}

[Bylund to appear, 2015]



pp→ttZ with O_{tG}

Summary

- The LHC physics program demands predictions at an unprecedented level of accuracy and precision.
- Rapid and impressive progress in techniques in the last years has lead to:
  - Full automation of the computation of NLO QCD corrections in the SM.
  - New techniques and their general (process-independent) implementation of matching/ merging with parton shower programs.
  - A new generation of MC generators that are NLO accurate.
- New results are being obtained for:
  - EW corrections and their combination into MC.
  - NLO in QCD for BSM (resonant and in EFTs).
- Main outcome: NLO MC can provide baseline simulations, SM and BSM, for the Run II LHC Physics program.