LHC phenomenology with MadGraph5_aMC@NLO

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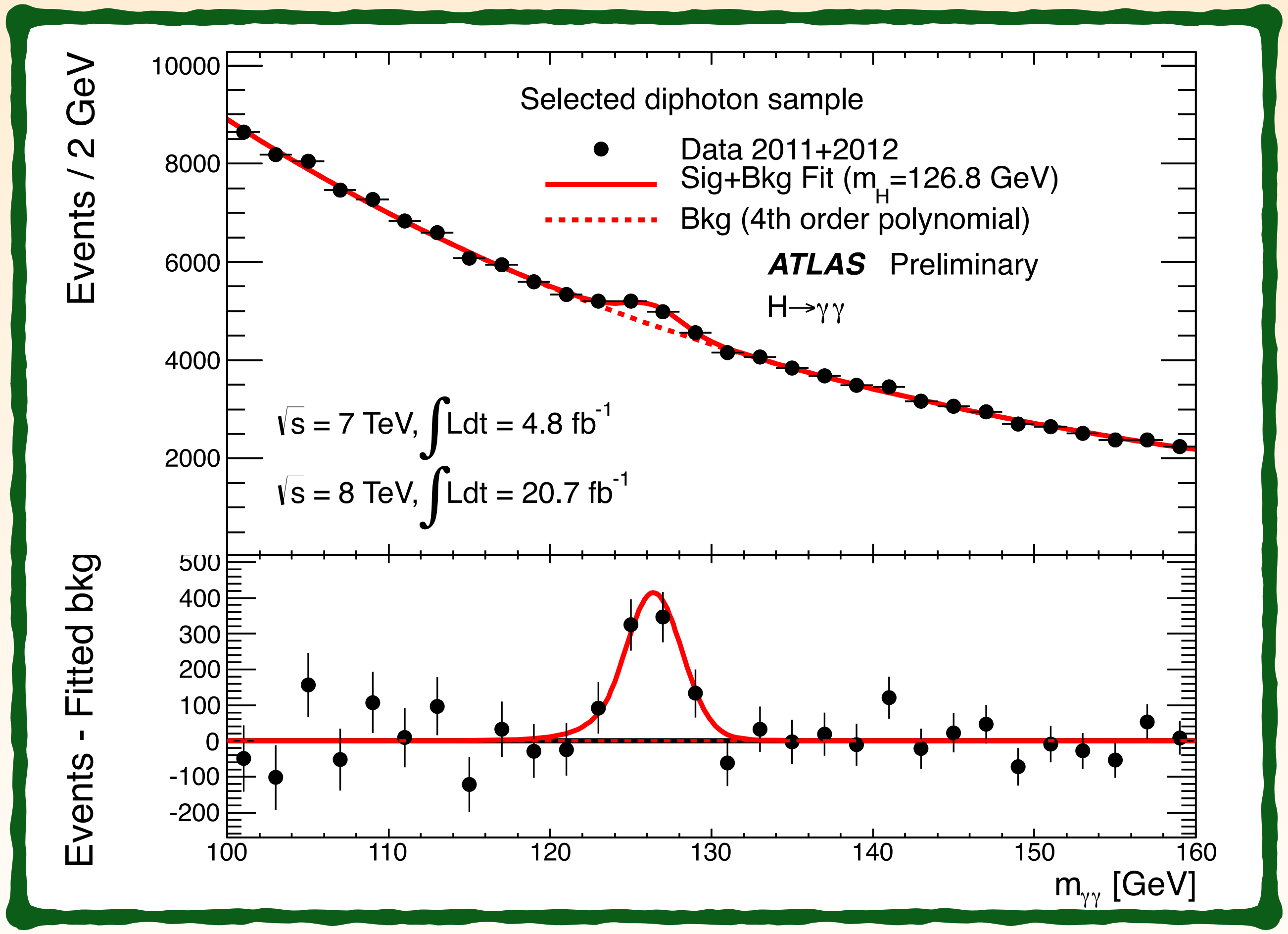
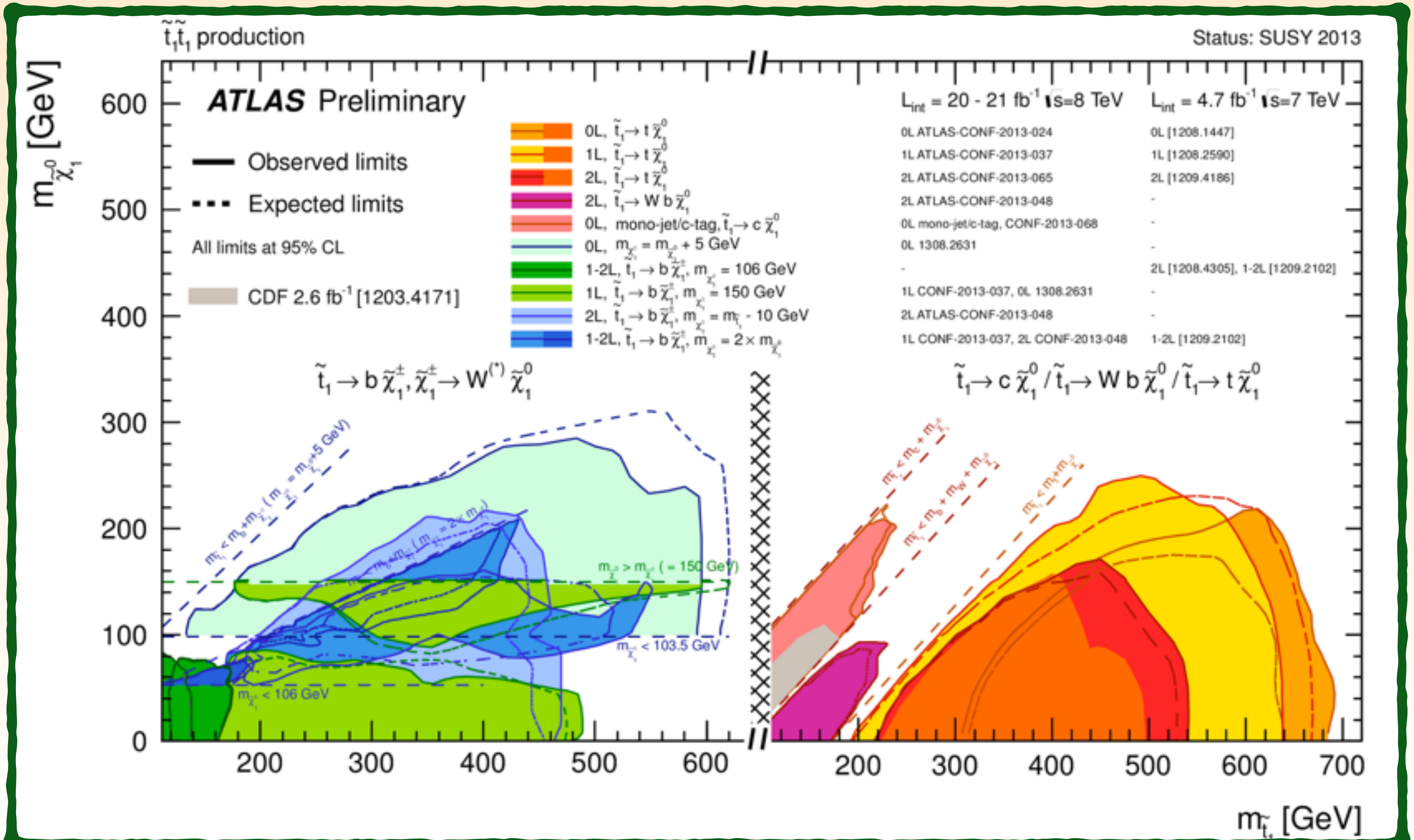
Large Hadron Collider

- The world's largest particle accelerator, the LHC, has been running extremely well during the last couple of years
- Higgs boson discovery!
- LHC has been running now with nearly doubled collision energy (13-14 TeV)
- Is the Higgs responsible for generating the masses of all fundamental particles?
    - ➡Need to measure its coupling strength to all massive particles
    - ➡This includes the Higgs self-coupling, of which we have no information so far

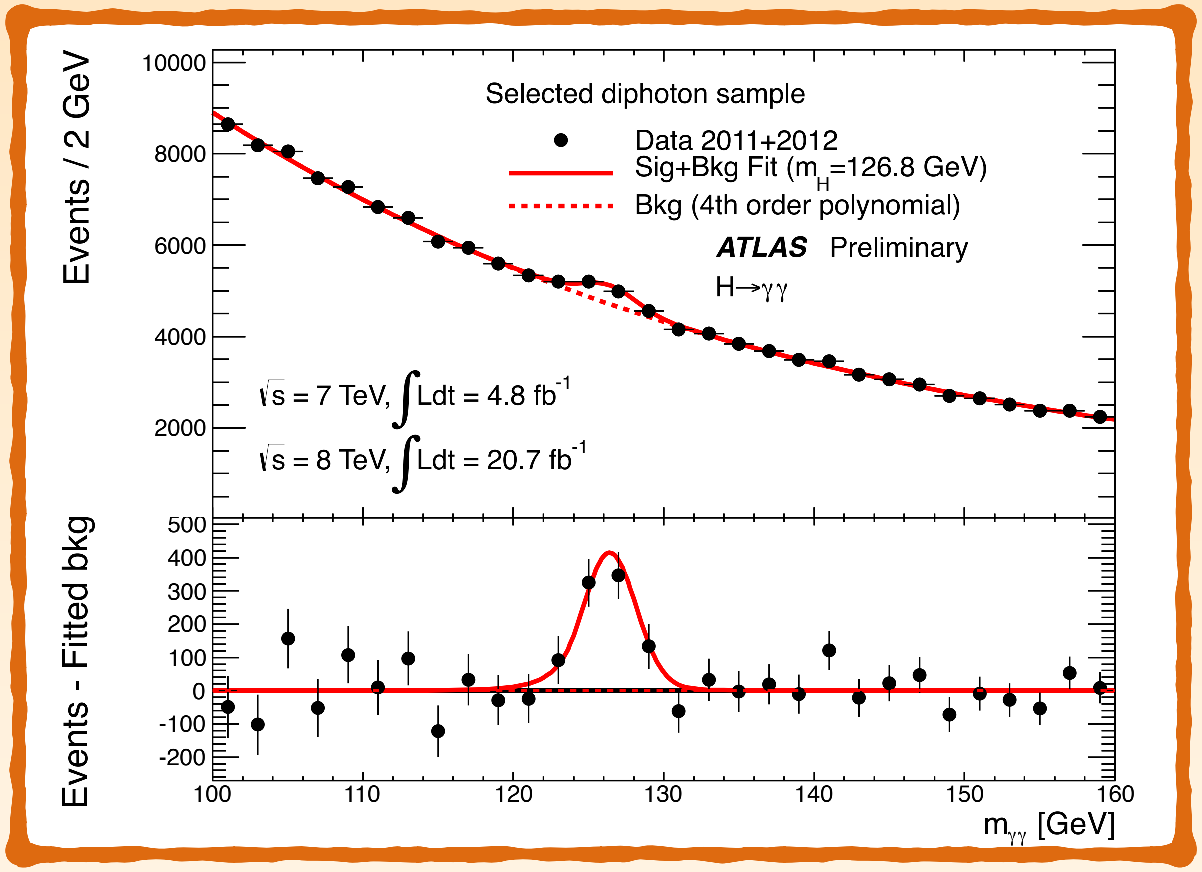


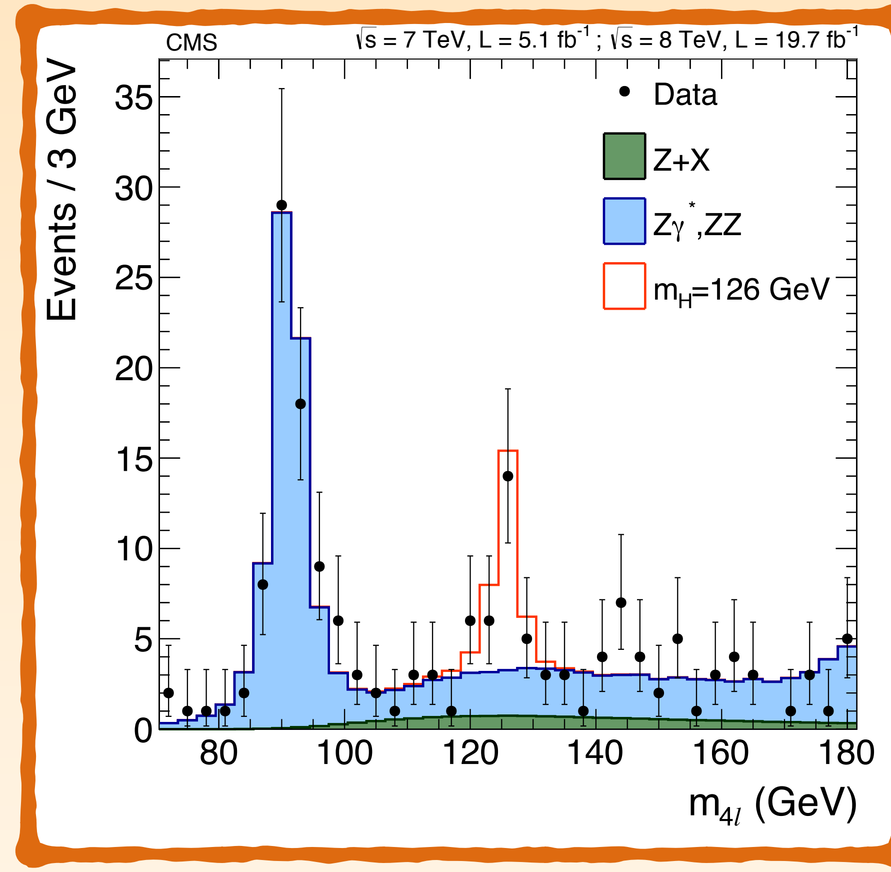
MORE!

- And there should be more!
- Dark matter, fine tuning problem, matter anti-matter asymmetry, etc., suggest the **existence of new particles and phenomena** that have not yet been discovered



Higgs as example for BSM searches?

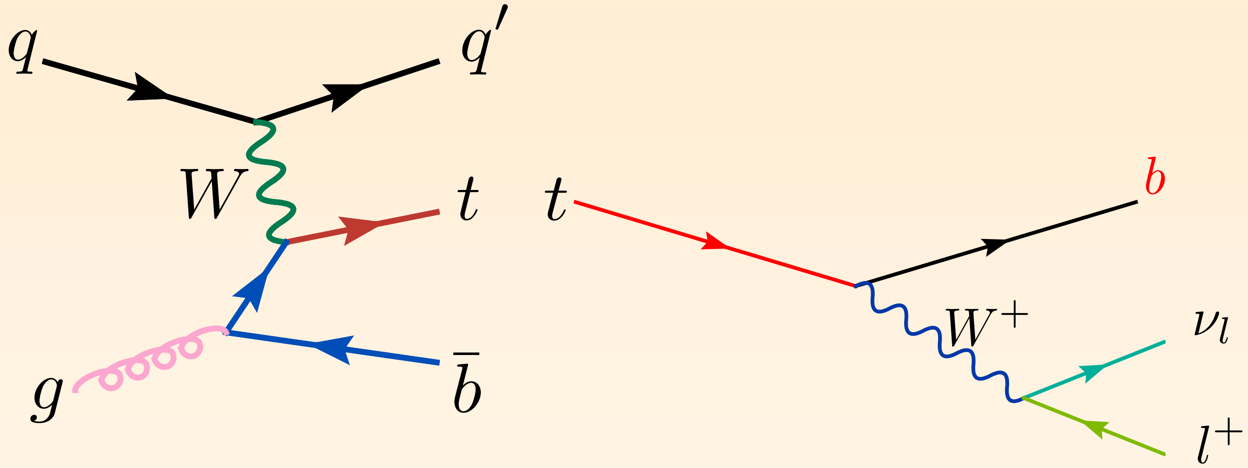


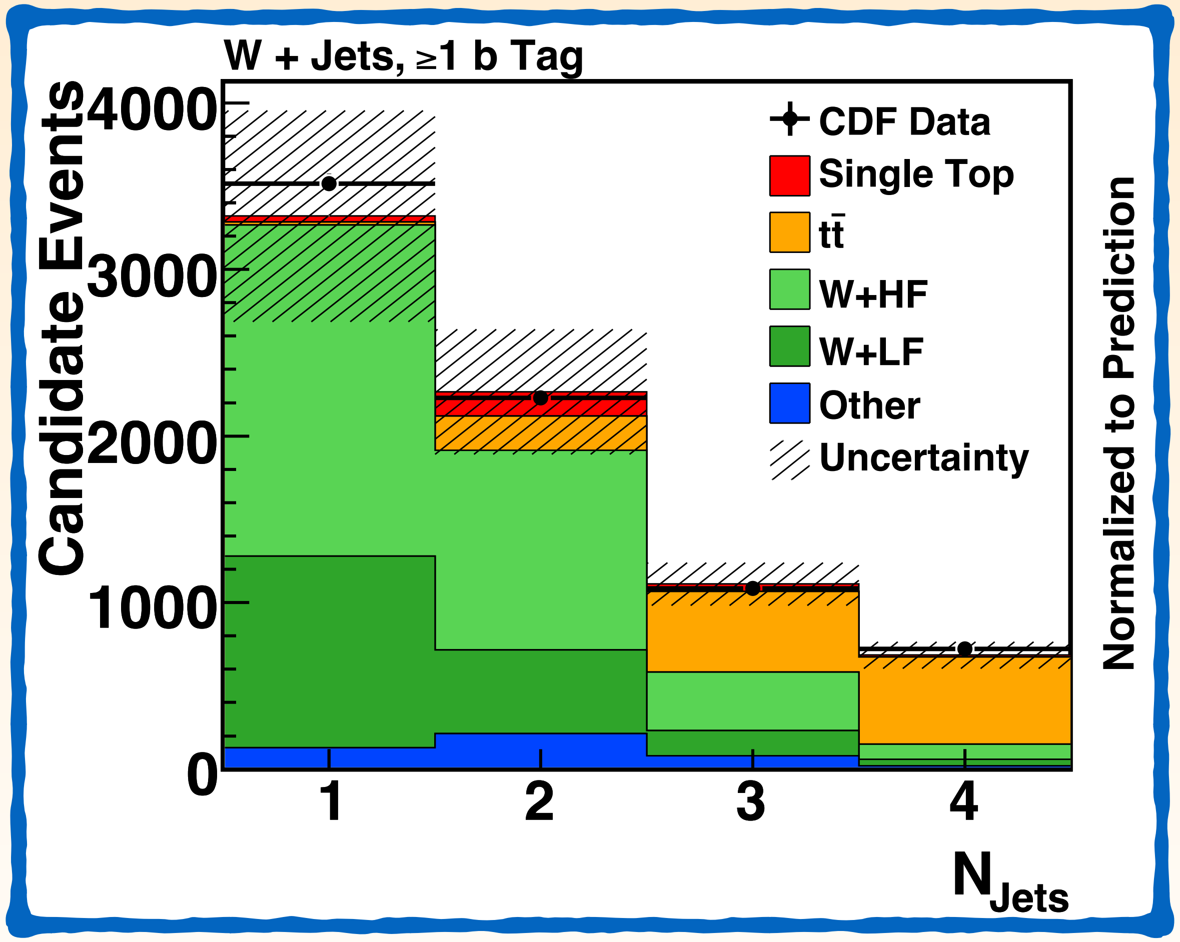


- Higgs is **NOT** a typical example of most New Physics searches
  - Higgs was "easy": plot invariant mass and a peak appears. No advanced analysis techniques nor any theory input needed for discovery (but needed for the measurements of the rates, spin, etc.)
- For New Physics it is usually not possible to reconstruct an invariant mass peak: dark matter candidate escapes the detector
- This makes it much more difficult to disentangle it from backgrounds

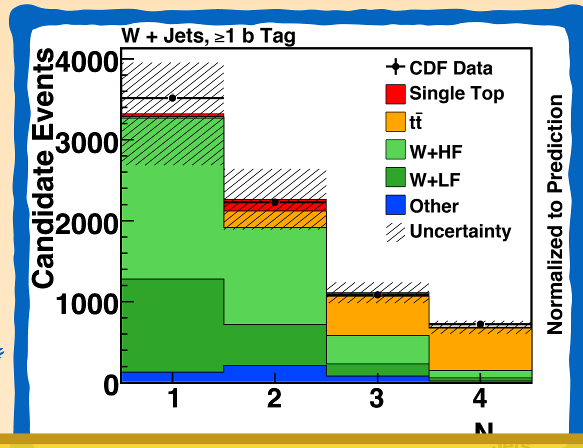
Single top as example!

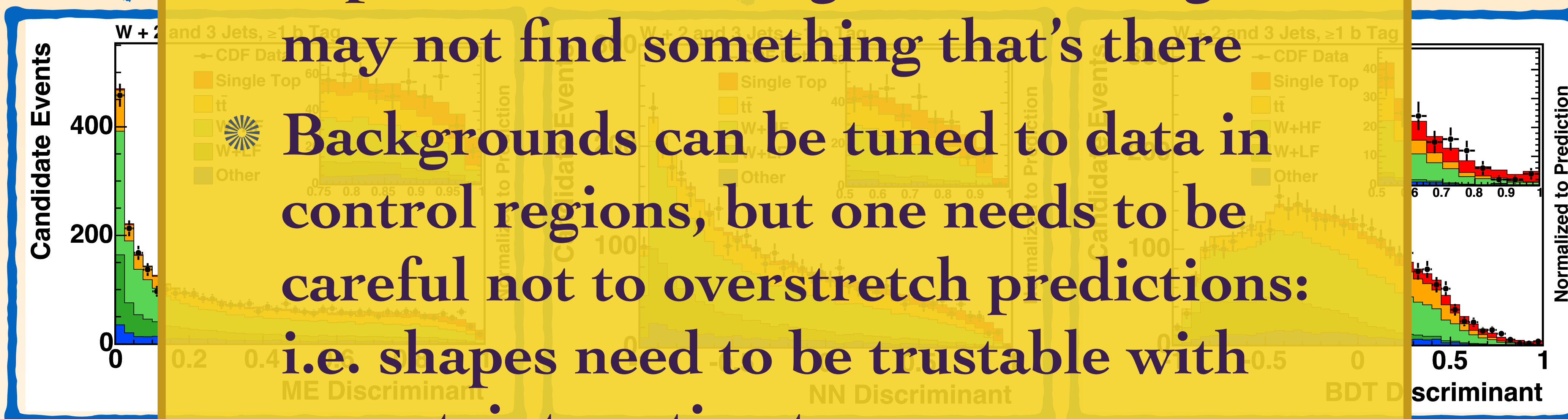
- The Single Top observation (5 sigma) at the Tevatron is a better example of what to expect:
  - small signal over a very large background



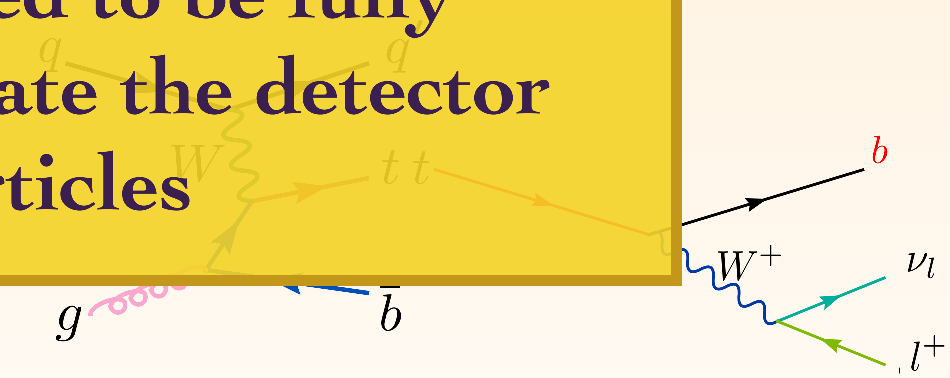


- Signature is a lepton, jets and missing energy
- Large background from W+jets and top pair production
- Cut and count measurement not possible due to large uncertainties





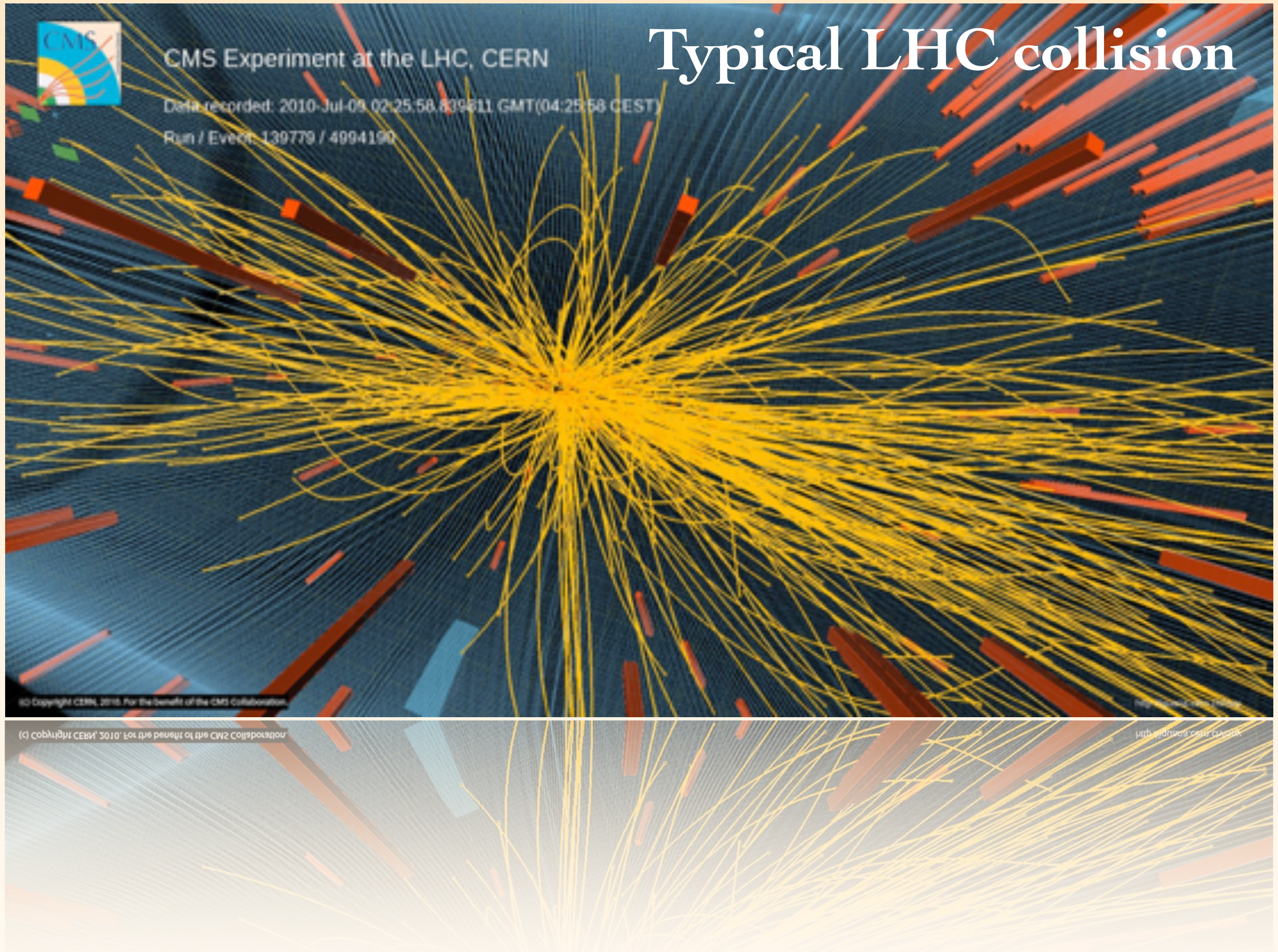
Single Top at CMS (2010) PRD82 112005



- If predictions for signal are wrong: one may not find something that's there
- Backgrounds can be tuned to data in control regions, but one needs to be careful not to overstretch predictions: i.e. shapes need to be trustable with uncertainty estimates
- Theory predictions need to be fully exclusive to also simulate the detector response on all the particles

- Advanced analysis techniques used to discriminate signal from background
- Impossible without trustable theory predictions
- Top quark already known
- Maybe not such advanced techniques possible for discovery of BSM, because very model dependent, but certainly needed for measuring its properties!

QCD RADIATION



✦ Need to match the fixed order calculation to a parton shower to be able to describe all this radiation, so that detector response can be properly accounted for

This means?

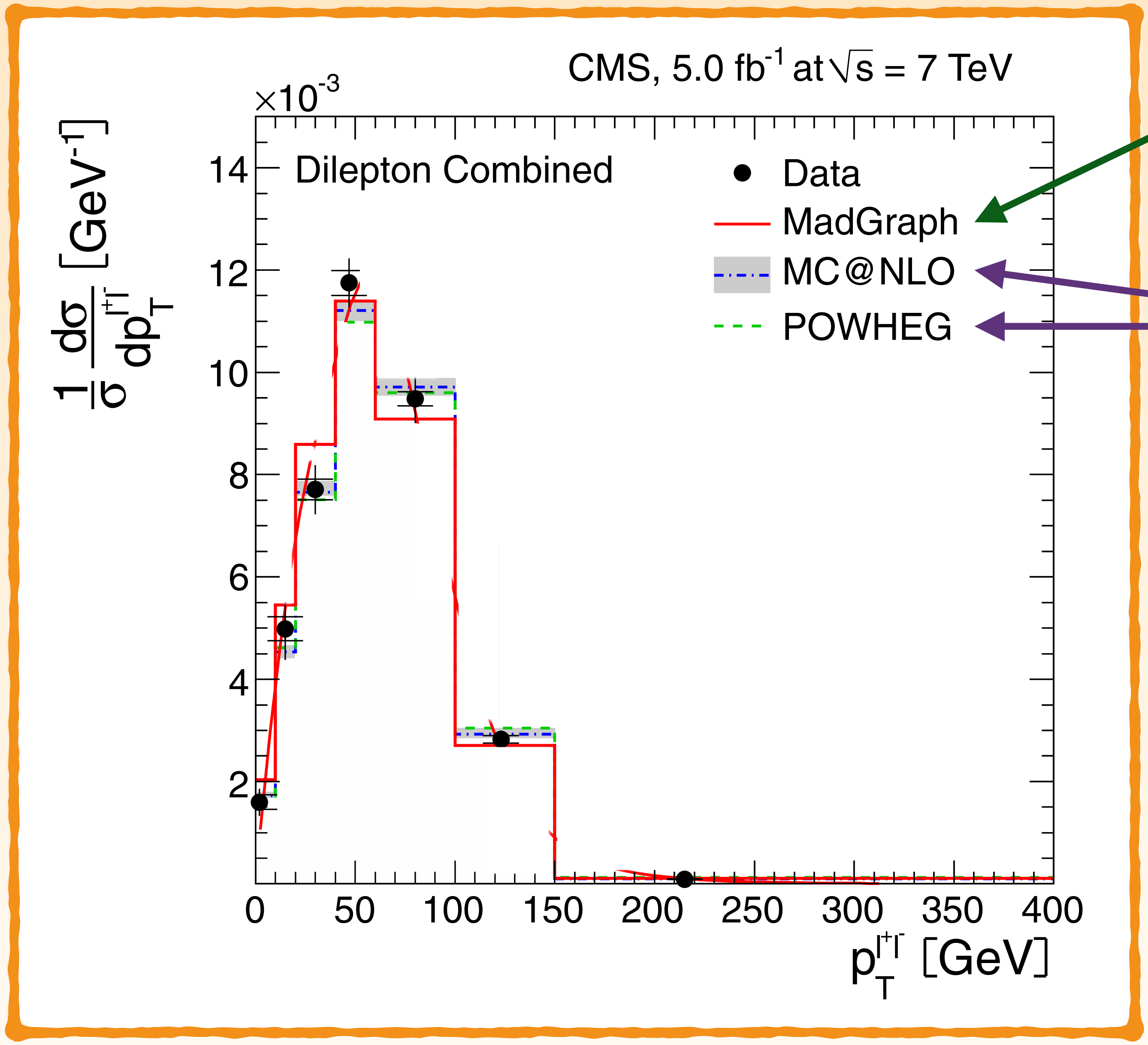
This means that in analyses accurate, quantitative, hadron-level predictions will play an important role

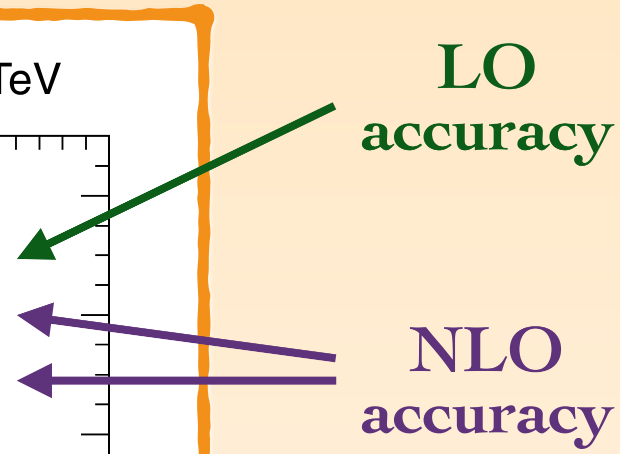
Hence, we need (at least)

NLO+PS

(Next-to-leading Order matched to a parton shower)

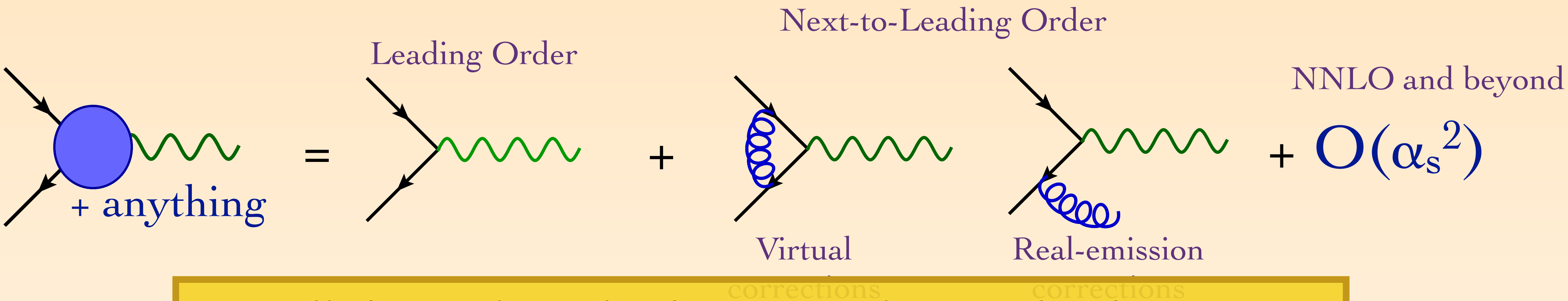
Quantitative predictions





For precise, quantitative comparisons between theory and data, (at least) Next-to-Leading-Order corrections are a must

Next-to-leading order



- All these obstacles have now been solved in completely general ways
- They have all been cast in the form of algorithms that are implemented in computer code
- This brings that making predictions at NLO accuracy, has become as simple as LO accuracy

- Computing next-to-leading order corrections used to be difficult:
  - **Virtual corrections**: how to compute the loops automatically in a reasonable amount of time
  - How to deal with **infra-red divergences**: virtual corrections and real-emission corrections are separately divergent, only their sum is finite (for IR-safe observables) according to the KLN theorem
  - How to **match** these processes to a **parton shower** without double counting
- Due to these difficulties, it used to take at least several months to be able to compute a new process at NLO accuracy

Automation

- Although the formal solutions have existed for quite some time, finding practical implementations that allow the generation of processes with 1000s of diagrams at NLO accuracy is fairly difficult
- I started working on NLO automation in 2008; we were less than 10 people working on this back then
- The field has grown and is still developing at a high pace

MadFKS (RF, Frixione, Maltoni, Stelzer, 0908.4272), HELAC (Czakon, Papadopoulos, Worek 0905.0883), MadDipole (RF, Gehrmann, Greiner 1004.2905, 0808.2128), SHERPA (Gleisberg, Krauss 0709.2881), MadLoop (Hirschi, RF, Frixione, Garzelli, Maltoni, Pittau, 1103.0621), BlackHat (Berger, Bern, Dixon, Febres Cordero, Forde, Gleisberg, Ita, Kosower, Maitre 1009.2338), Rocket (Ellis, Giele, Kunszt, Melnikov, Zanderighi 0810.2762), HELAC-NLO (Bevilacqua, Czakon, Garzelli, van Hameren, Kardos, Papadopoulos, Pittau, Worek, 1110.1499), GoSam (Cullen, Greiner, Heinrich, Luisoni, Mastrolia, Ossola, Reiter, Tramontano, 1111.2034), OpenLoops (Cascioli, Maierhofer, Pozzorini, 1111.5206), NJET (Badger, Biedermann, Uwer, Yundin, 1309.6585), RECOLA (Actis, Denner, Hofer, Scharf, Uccirati, 1211.6316), POWHEG-BOX (Nason, Oleari) etc.

Automation

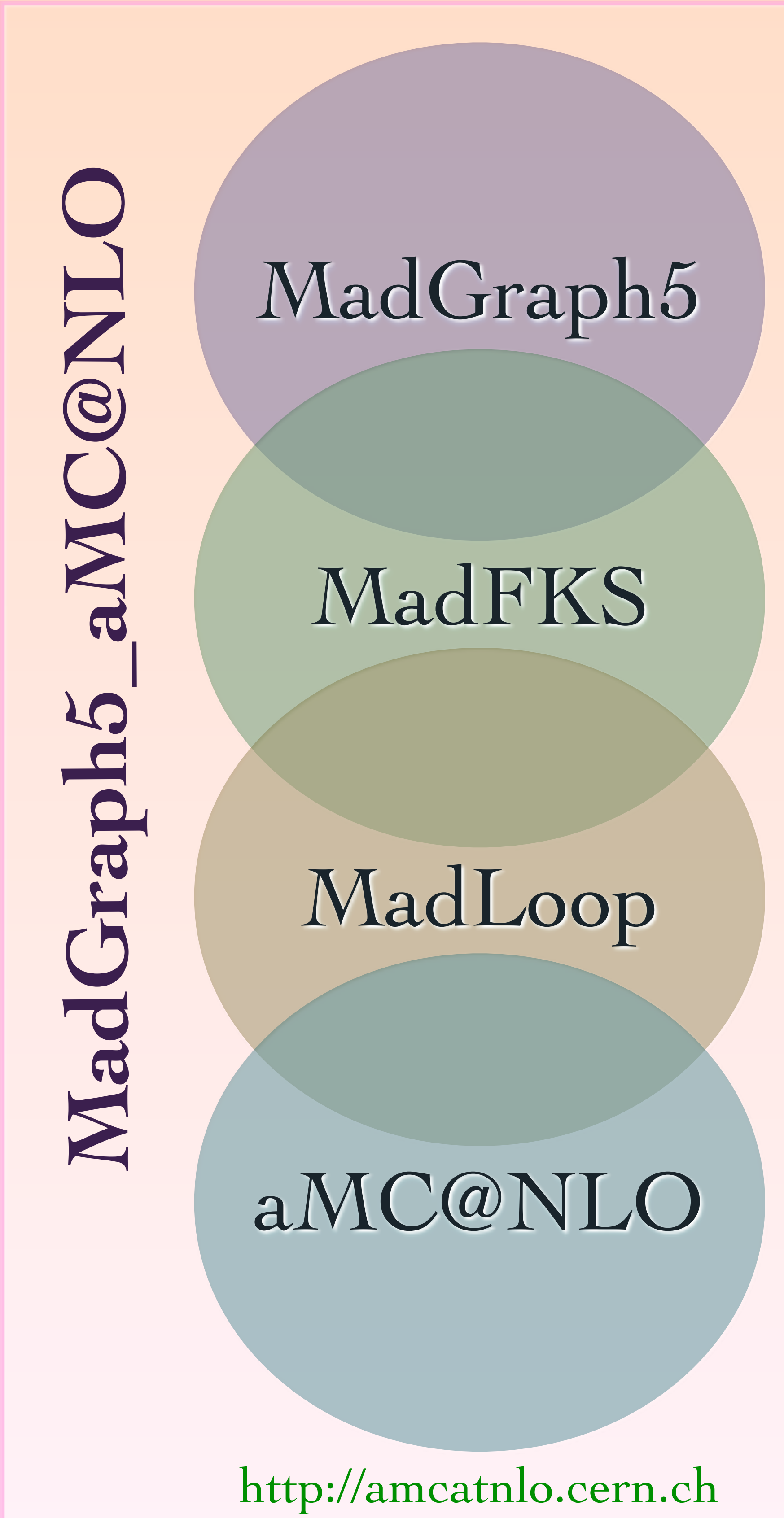
- Good news: a lot of progress has been made!
- There are now frameworks that allows for collider physics predictions at (N)LO and (N)LO+PS accuracy
- Personally, I'm involved in

Alwall, RF, S.Frixione, V.Hirschi, F.Maltoni, O.Mattelaer, H-S.Shao, T.Stelzer, P.Torrielli, M.Zaro, arXiv:1405.0301

MadGraph5_aMC@NLO

- For NLO(+PS) currently limited to the SM and QCD corrections only, but improvements to allow for any type of corrections in any BSM model ongoing

MadGraph5_aMC@NLO



- Modular structure:
  - Use MadGraph5 for LO and steering
  - MadFKS for factoring out Infrared singularities
  - MadLoop for the virtual corrections
  - aMC@NLO for matching to the parton shower
- Even though there is no other single code on the market than can do all these, the various components can be taken from different codes and put together, e.g. Sherpa+GoSam
  (for references see previous slides)

Level of automation

- To make predictions easy in MadGraph5_aMC@NLO we have inherited the user-friendly interface from the MadGraph5 code
- NLO predictions are really as simple as:

```
$ ./bin/mg5
MG5_aMC> generate p p > h h t t~ [QCD]
MG5_aMC> output my_NLO_hhtt_process
MG5_aMC> launch
```

- Ready for phenomenology!

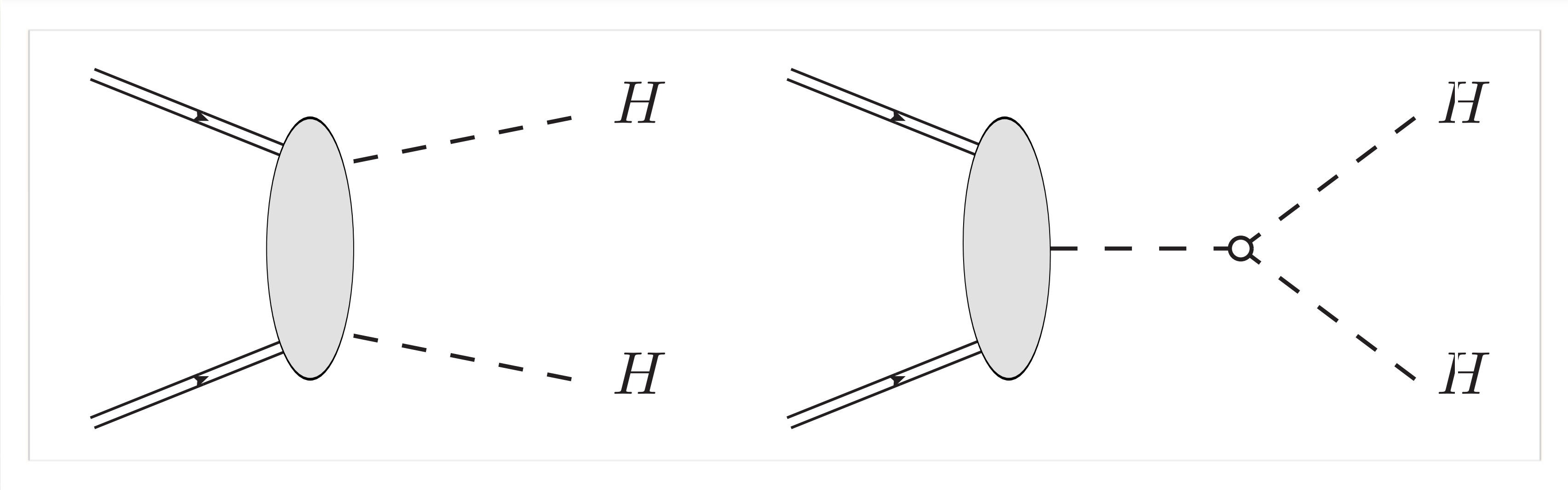
LHC phenomenology

- What I mean by phenomenology is the following:
  - To try to **understand** possible **discrepancies** between data and theoretical predictions
  - To suggest experimentalists to search for **new interesting features** of quantum field theory
  - To show **how improved predictions** might **affect** current and future **measurements**
  - To check the **self-consistency** between various levels of sophistication **within theory predictions**
  - To show how **experimentalists** could **improve their measurements** by using specific features of collider signatures
  - To develop **new methods** for making predictions
  - …

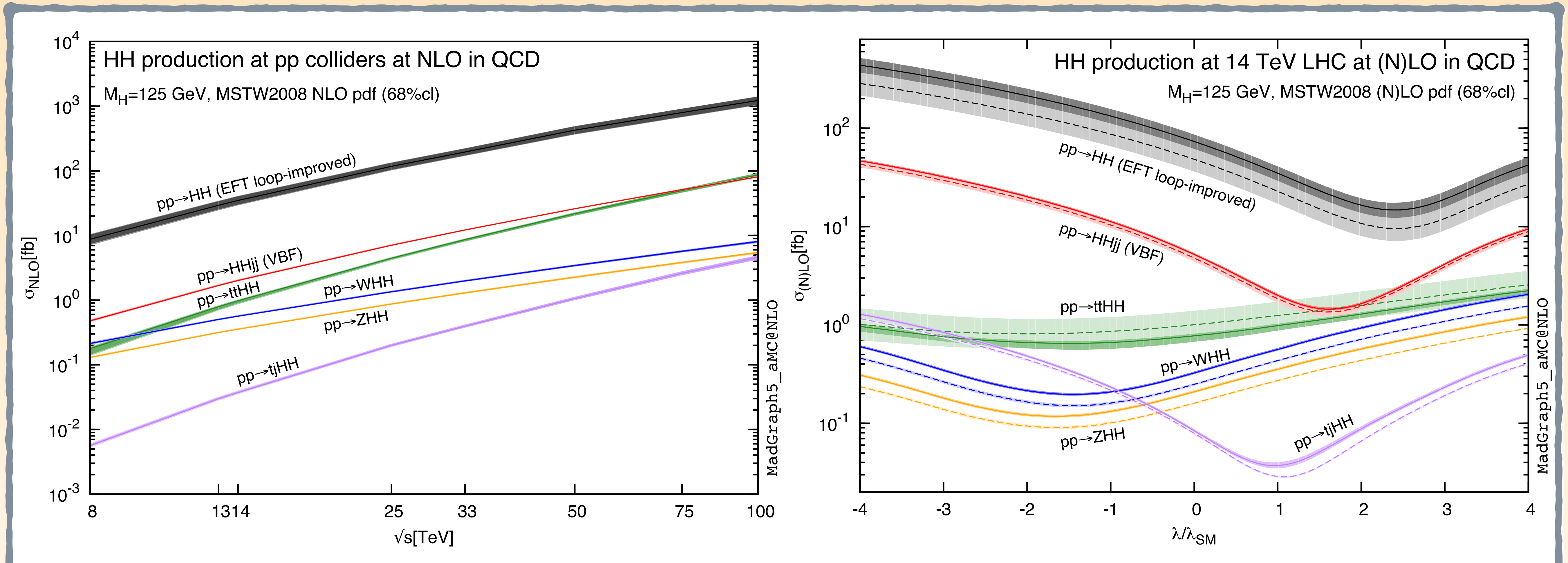
A COUPLE OF EXAMPLES

- Predictions for Higgs pair production
  [RF et al. Phys.Lett. B732 (2014) 142-149]
- T-odd asymmetry in W+jet events
  [RF et al. Phys.Rev.Lett. 113 (2014) 152001]
- Top quark induced backgrounds to Higgs production
  [RF Phys.Rev.Lett. 112 (2014) 8, 082002]
- Automated NNLL + NLO jet-veto predictions
  [T. Becher et al. EPJC 75 (2015) 4, 154]
- Multi-jet production in association with a EW vector boson
  [RF et al. arXiv:1511.00847]

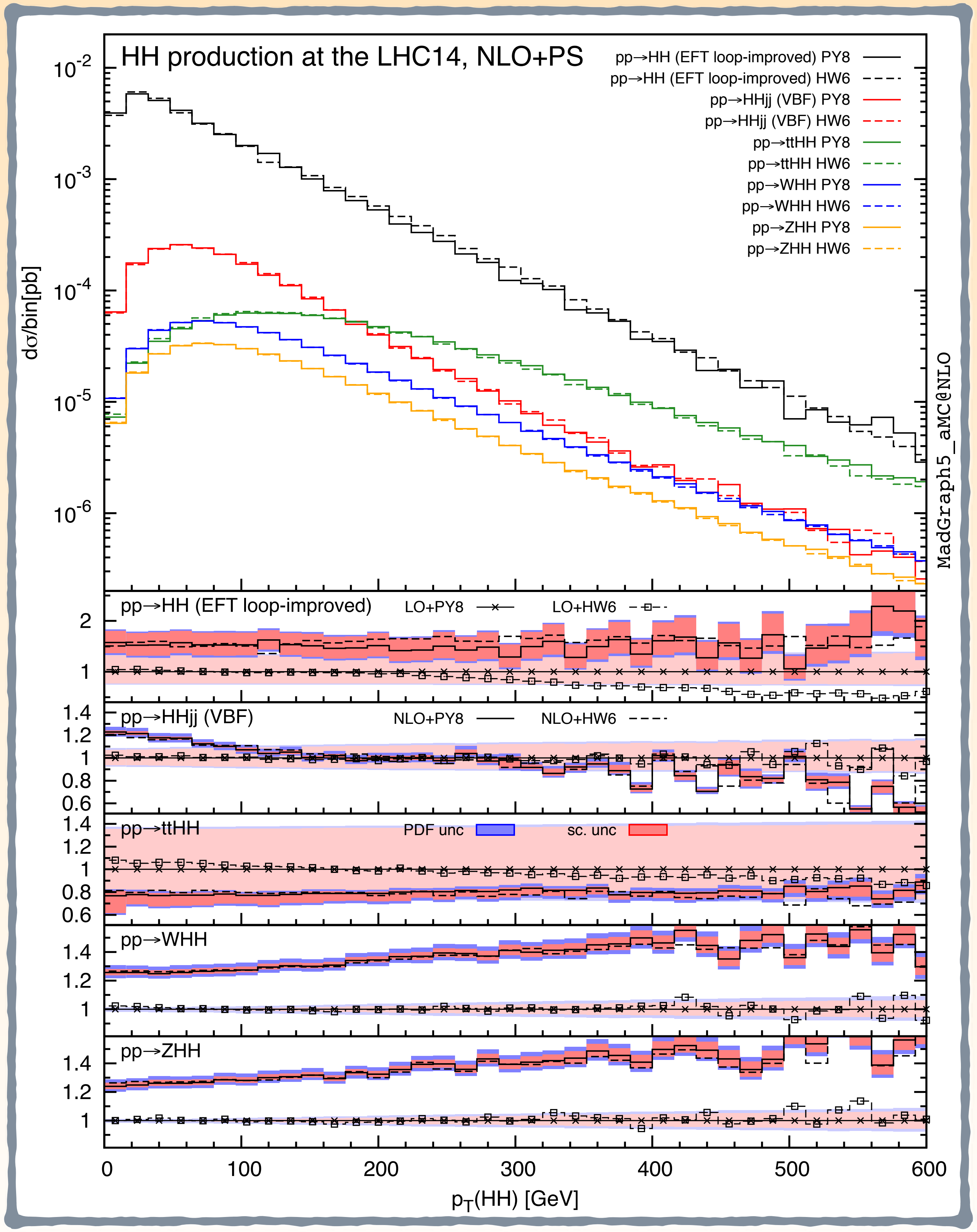
Predictions for Higgs pair production



- To confirm that the found Higgs boson is indeed the SM Higgs boson and responsible for the masses of all the SM particles, the coupling strength to all massive particles need to be measured
  - In particular the Higgs self coupling is extremely important here
- Higgs pair production is the only way to get direct information on the Higgs self-coupling
- Producing Higgs pair in association with other particles reduces the cross section, but increases the handles to tag it



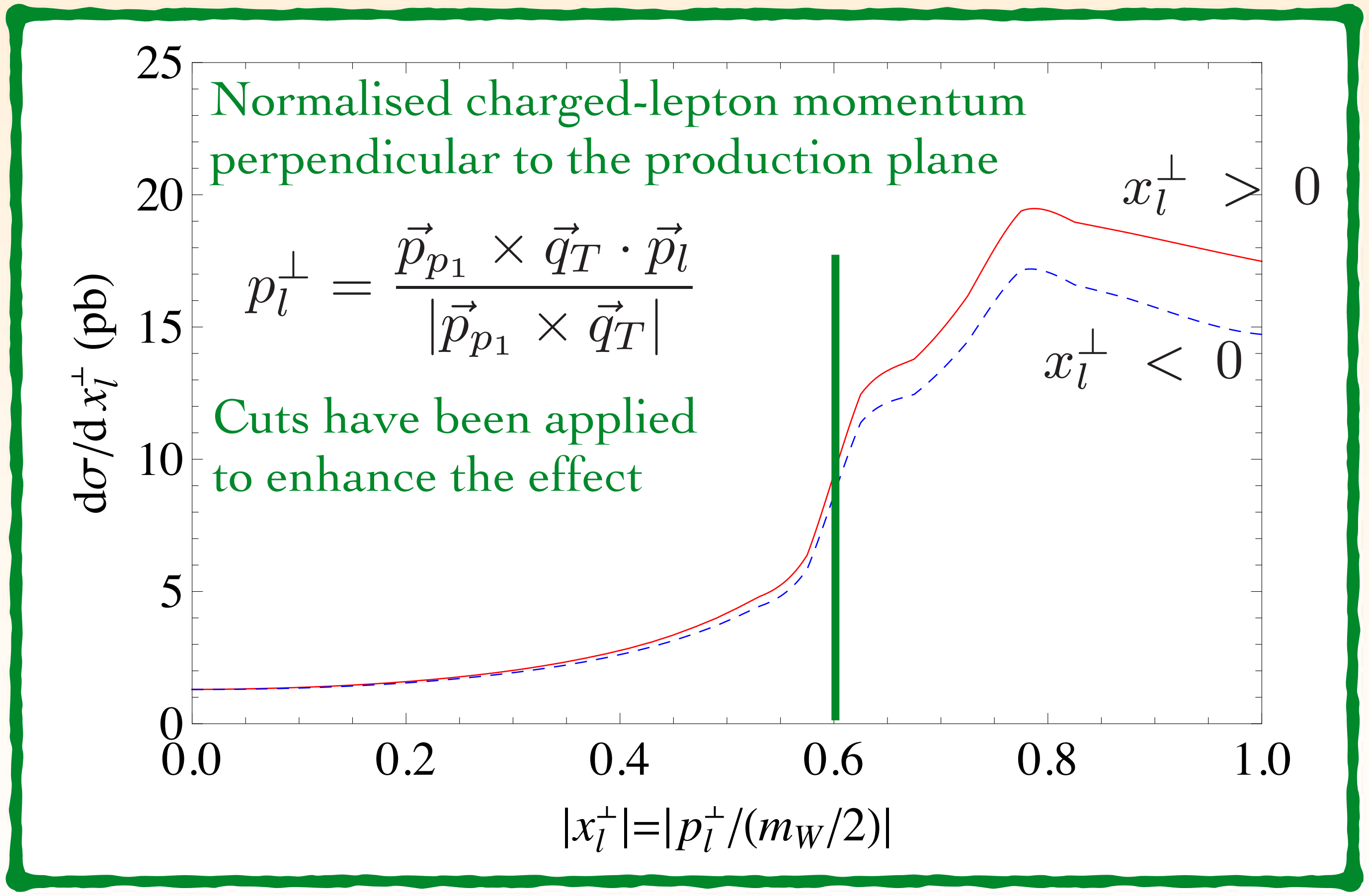
- ✦ Higgs pair production cross sections as a function of the collider energy (left) and Higgs triple coupling (right)
- ✦ Width of the bands are uncertainty estimates



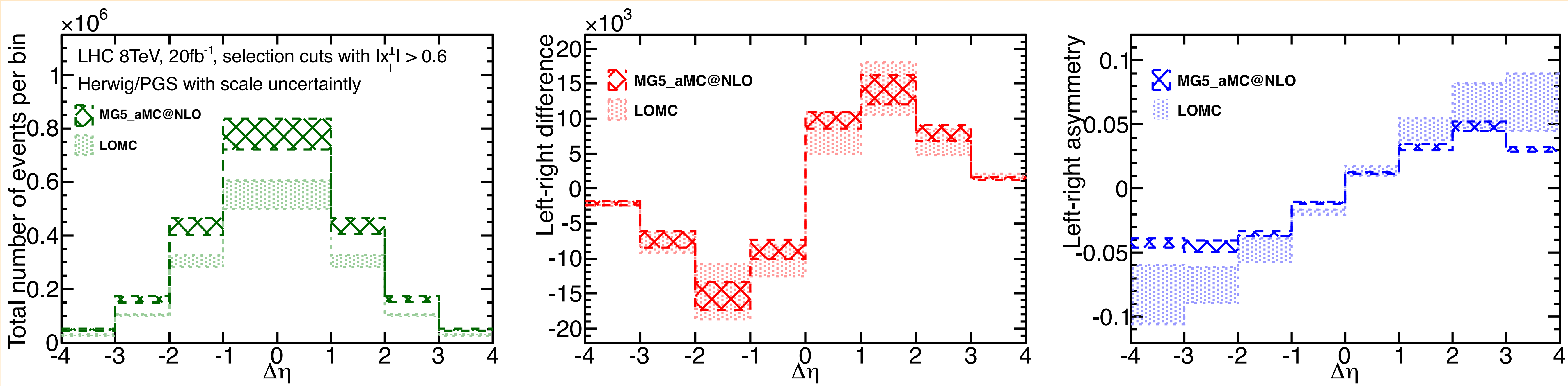
- Transverse momentum of the Higgs pairs
- Matched to Herwig6 and Pythia8 parton showers
- Differences between parton showers rather small
- NLO corrections reasonable; left-over uncertainties under control
- For some of the HH channels, these are currently the most precise predictions available

T-odd asymmetry in W+jet events

- W-bosons produced at high transverse momentum can have a polarisation along the direction perpendicular to the production plane, which is odd under T-reversal (where both the three-momenta and the angular momenta are reversed)
  - T-odd asymmetry has never been measured, even though it is know to exist in the theory for more than 30 years
  - Small effect and therefore large statistical uncertainties
- The **leptons** from the W-boson decay **inherit the polarisation information** in their angular distributions
- Perturbative QCD predicts a non-zero contribution to this asymmetry at the **one-loop level**



$$A \equiv \frac{\sigma(x_l^\perp > 0) - \sigma(x_l^\perp < 0)}{\sigma(x_l^\perp > 0) + \sigma(x_l^\perp < 0)}$$

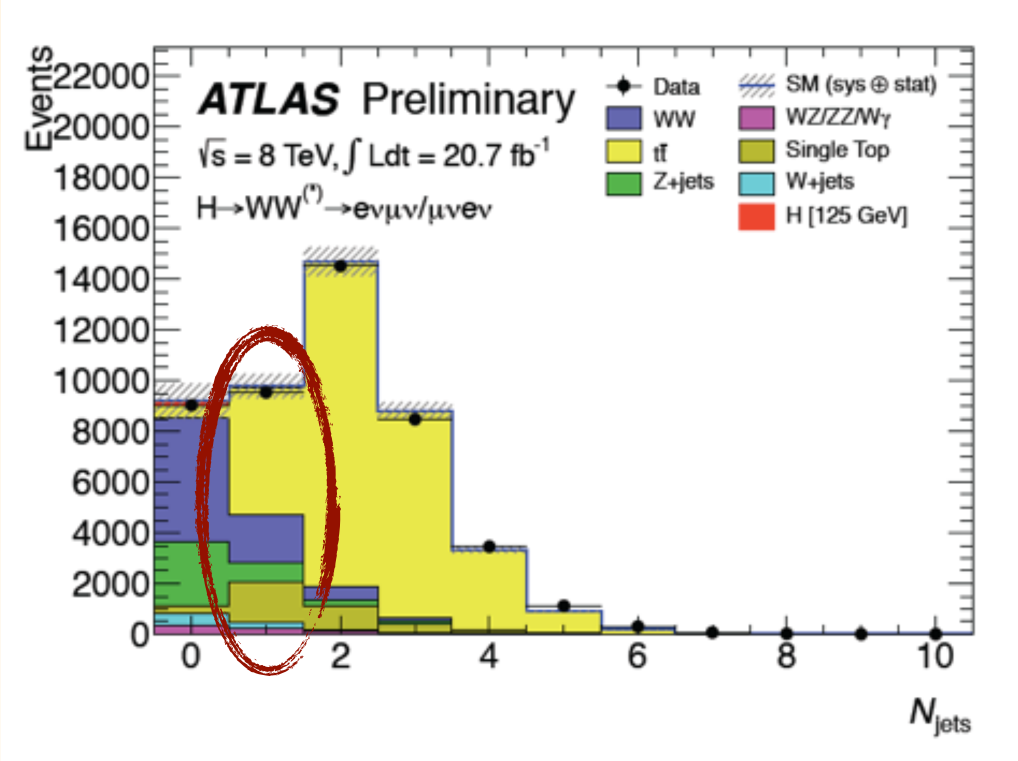


$$\Delta\eta \equiv \eta_\mu - \eta_j$$

- Realistic setup: including detector simulation, experimental cuts, W-boson reconstruction and backgrounds from taus
- More than 2 million events: statistical uncertainty small enough to measure the asymmetry
- **Interesting feature of QFT: should be possible to measure it with the current data set!**

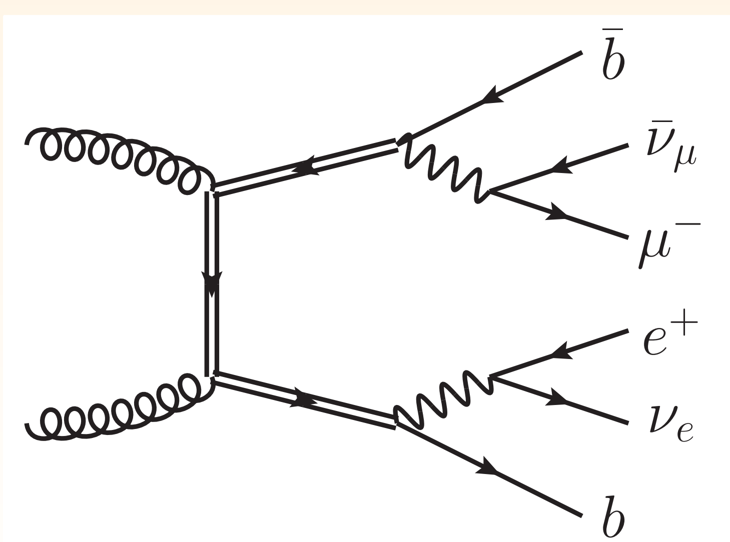
Top quark induced backgrounds to Higgs production

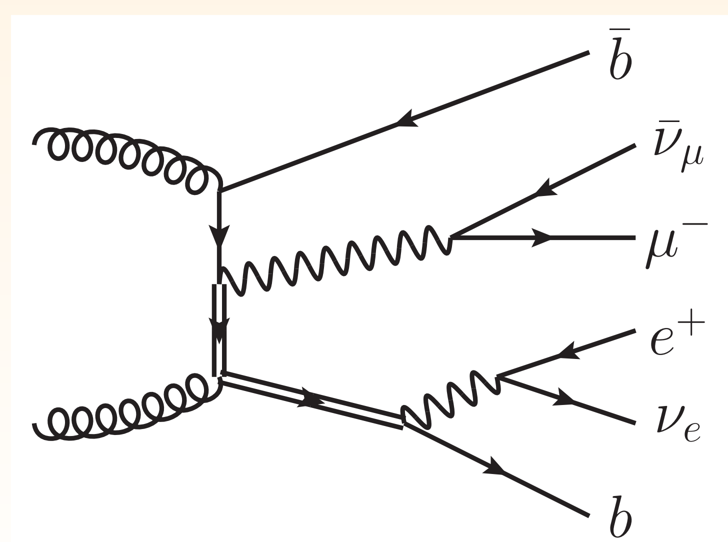
- Large ttbar and single-top (mostly Wt) backgrounds for H ->WW* in the 1-jet bin
- To improve the significance of the signal, stringent cuts are applied to suppress top quark backgrounds
- Question:
  Does on-shell top production give a reasonable estimation of the top induced backgrounds under these stringent cuts that have been designed to remove top quark contributions?
- Important not only for Higgs production, but for any process for which top quarks are a background

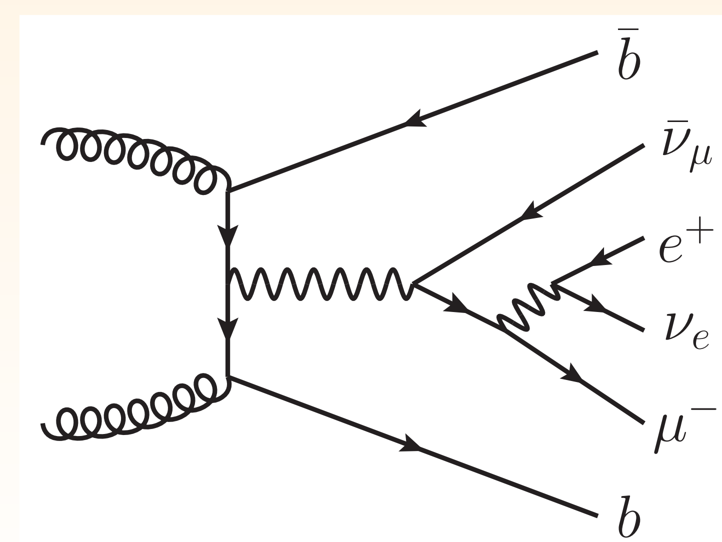


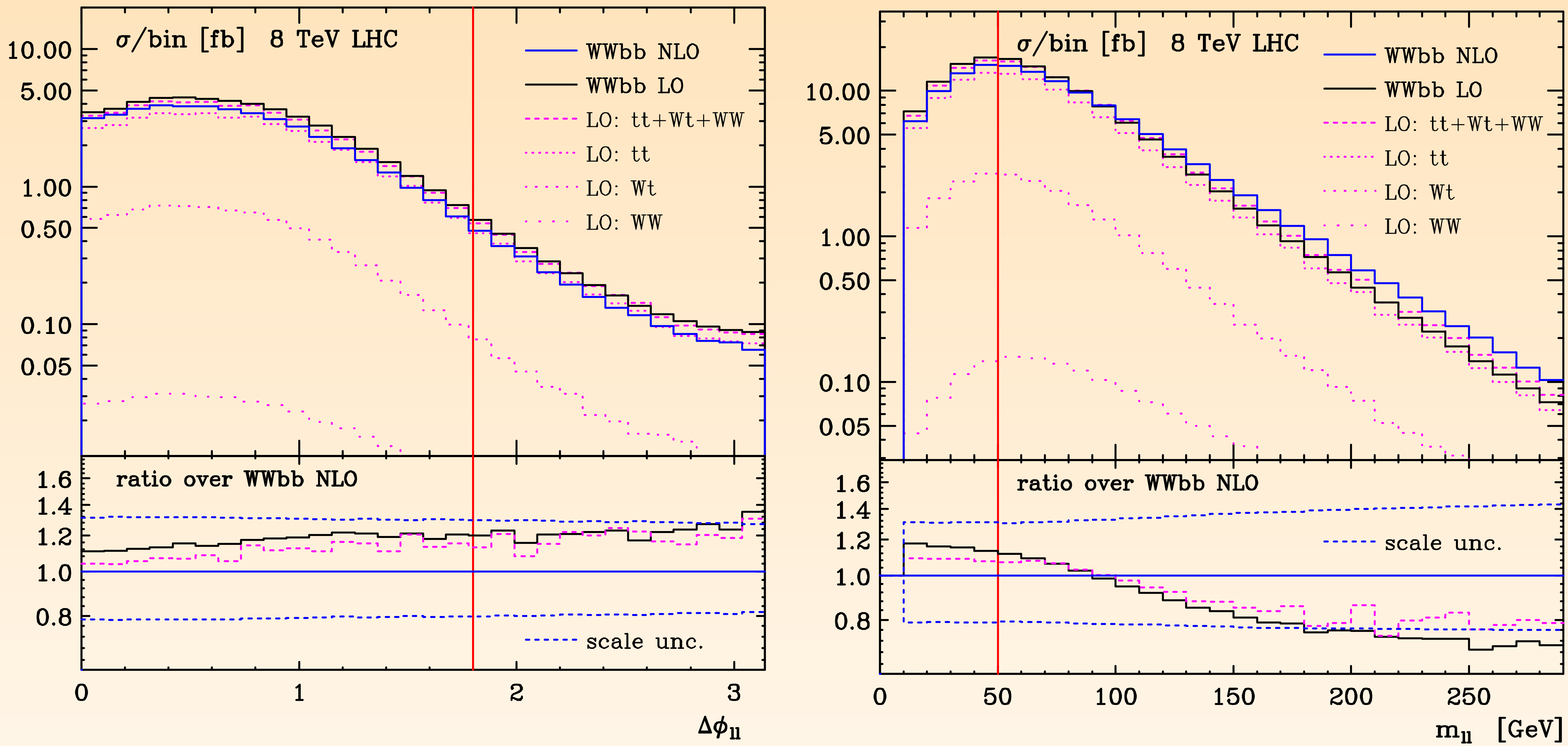
- Need precise (i.e. NLO) predictions for the full 2->6 process, pp -> $e^+\nu_e\mu^-\nu_\mu bb$, including all double, single and non-resonant contributions and their interference

- We need to apply a jet-veto (we are in the 1-jet bin), hence we need a 4FS calculation with massive b quarks
- The b-quark mass will regulate the singularities, which means that one can apply a jet-veto without hitting divergences
- Also the complete Wt associated single top contributions are included in the calculation
    - No separation between top pair and single top needed
    - Also some overlap with the WW background, which complicates the situation
- Extremely though calculation with thousands of one-loop diagrams and many scales & masses!





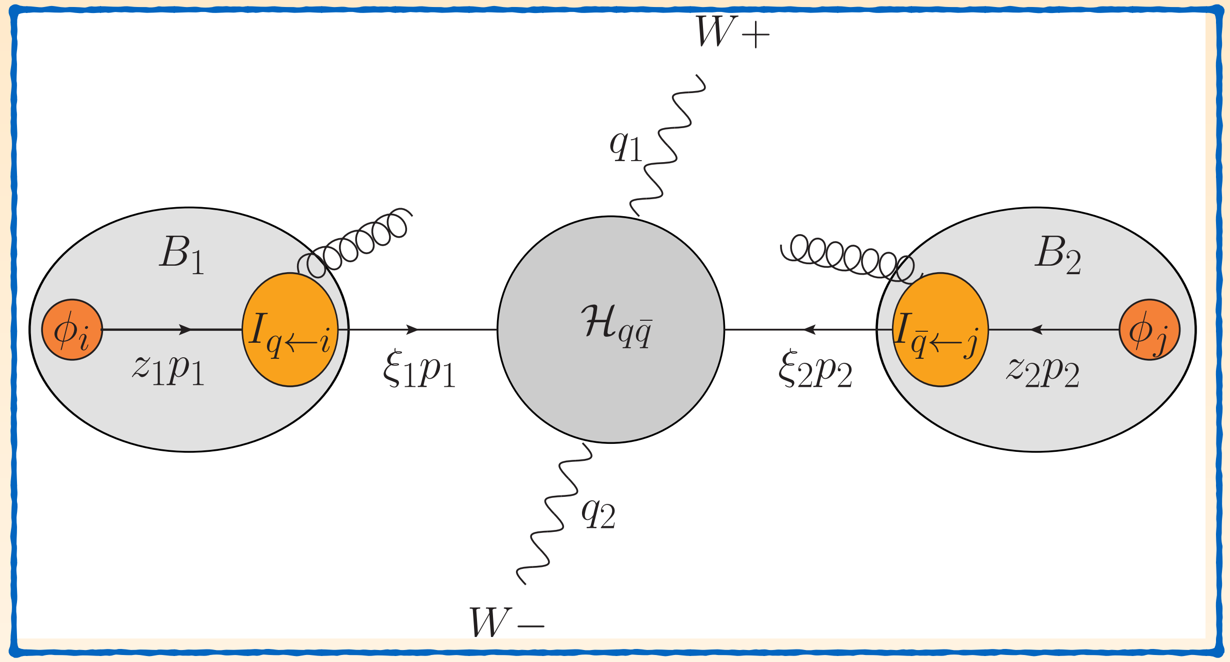




- ✦ di-lepton invariant mass and azimuthal difference
- ✦ NLO corrections are not an overall rescaling
- ✦ Uncertainty is large, even at NLO
- ✦ Using separate calculations for ttbar and Wt yields a fair approximation, within the left-over theoretical uncertainties

NNLL resummation matched to NLO

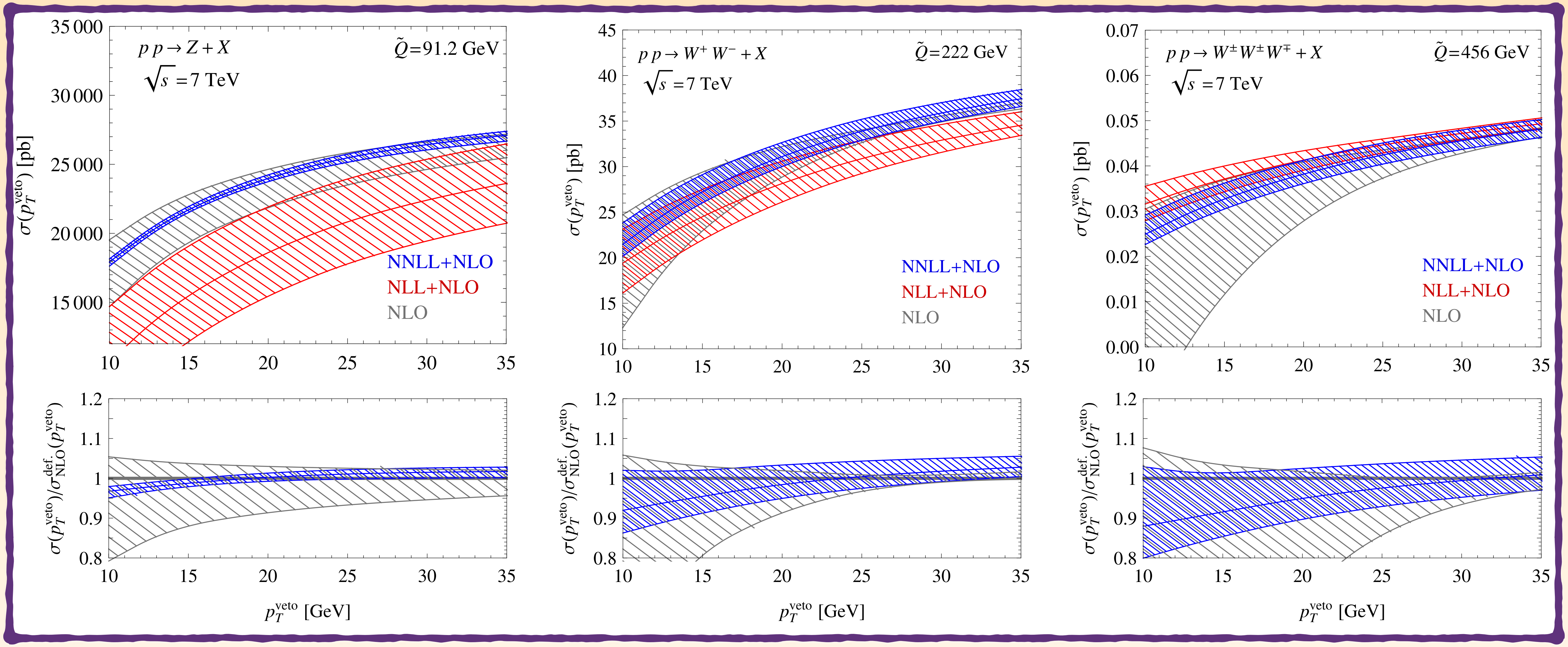
- Jet-veto cross sections resumed to NNLL and matched to NLO, based on SCET
- Implementations in 2 schemes
  - **A**: NNLL from reweighting unweighted LO events
  - **B**: Automated computation of beam functions and matching corrections



$$d\sigma_{ij}^{\mathrm{NNLL+NLO}}(p_T^{\mathrm{veto}}) = P_{ij}(Q^2,\hat{t},p_T^{\mathrm{veto}}) \times d\tilde{\sigma}_{ij}(p_T^{\mathrm{veto}})$$

$$= \left(1+\frac{\alpha_s(\mu_h)}{4\pi}\mathcal{H}_{ij}^{(1)}(Q^2,\hat{t},\mu_h)\right) E_i(Q^2,p_T^{\mathrm{veto}},\mu_h,\mu,R)$$

$$\times\left[d\sigma_{ij}^{\mathrm{NLO}}(p_T^{\mathrm{veto}},\mu) - \frac{\alpha_s(\mu)}{4\pi}\left(\mathcal{H}_{ij}^{(1)}(Q^2,\hat{t},\mu) + E_i^{(1)}(Q^2,p_T^{\mathrm{veto}},\mu)\right) d\sigma_{ij}^{0}(\mu)\right]$$



- ✦ Any colour-singlet final state possible
- ✦ For Z, WW, and WWW resummation effects at NNLL are small compared to NLO

Multi-jet production in association with an EW boson

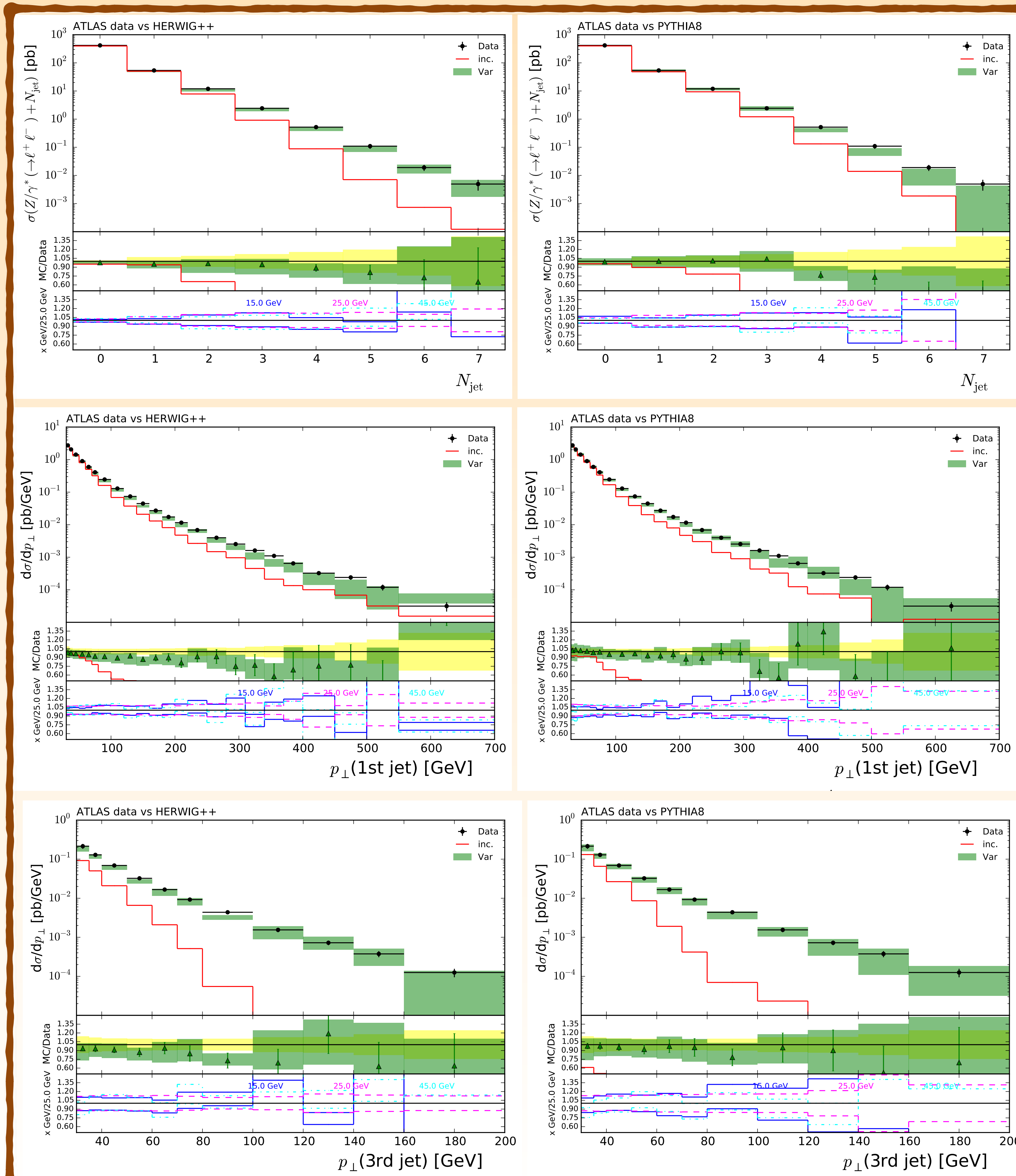
- Combine various multiplicity final states at NLO accuracy using the FxFx merging method
- To remove double counting between matrix elements and the shower:
  - Matrix elements are augmented with Sudakov form factors, à la MiNLO [Hamilton, Nason, Zanderighi]
  - On top of that there is an MLM-type rejection at the shower stage
  - Similar methods on the market: MEPS@NLO [Hoeche et al], UNLOPS [Lonnblad, Prestel], MiNLO
- Use and validate the FxFx merging method with matching to Herwig++ and Pythia8
- Merging for W and Z plus up to 2 jets at NLO for LHC 7 TeV

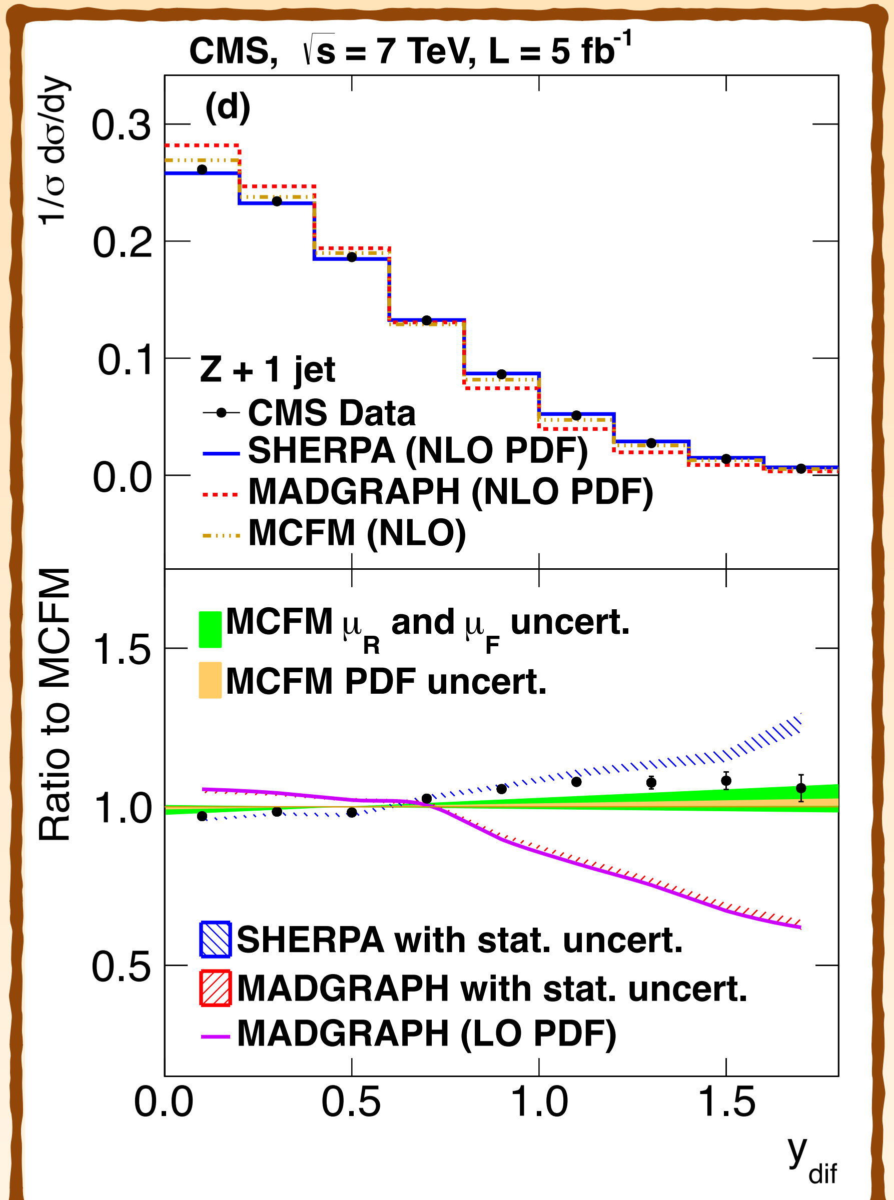
	$\mu_Q = 15$ GeV	$\mu_Q = 25$ GeV	$\mu_Q = 45$ GeV	inclusive	
Z+jets	2.055(−0.9%)	2.074	2.085(+0.5%)	2.012(−3.0%)	HW++
	2.168(+0.8%)	2.150	2.117(−1.5%)	2.011(−6.5%)	PY8
W+jets	20.60(−0.9%)	20.78	20.87(+0.4%)	19.96(−3.9%)	HW++
	21.71(+1.0%)	21.50	21.18(−1.5%)	19.97(−7.1%)	PY8

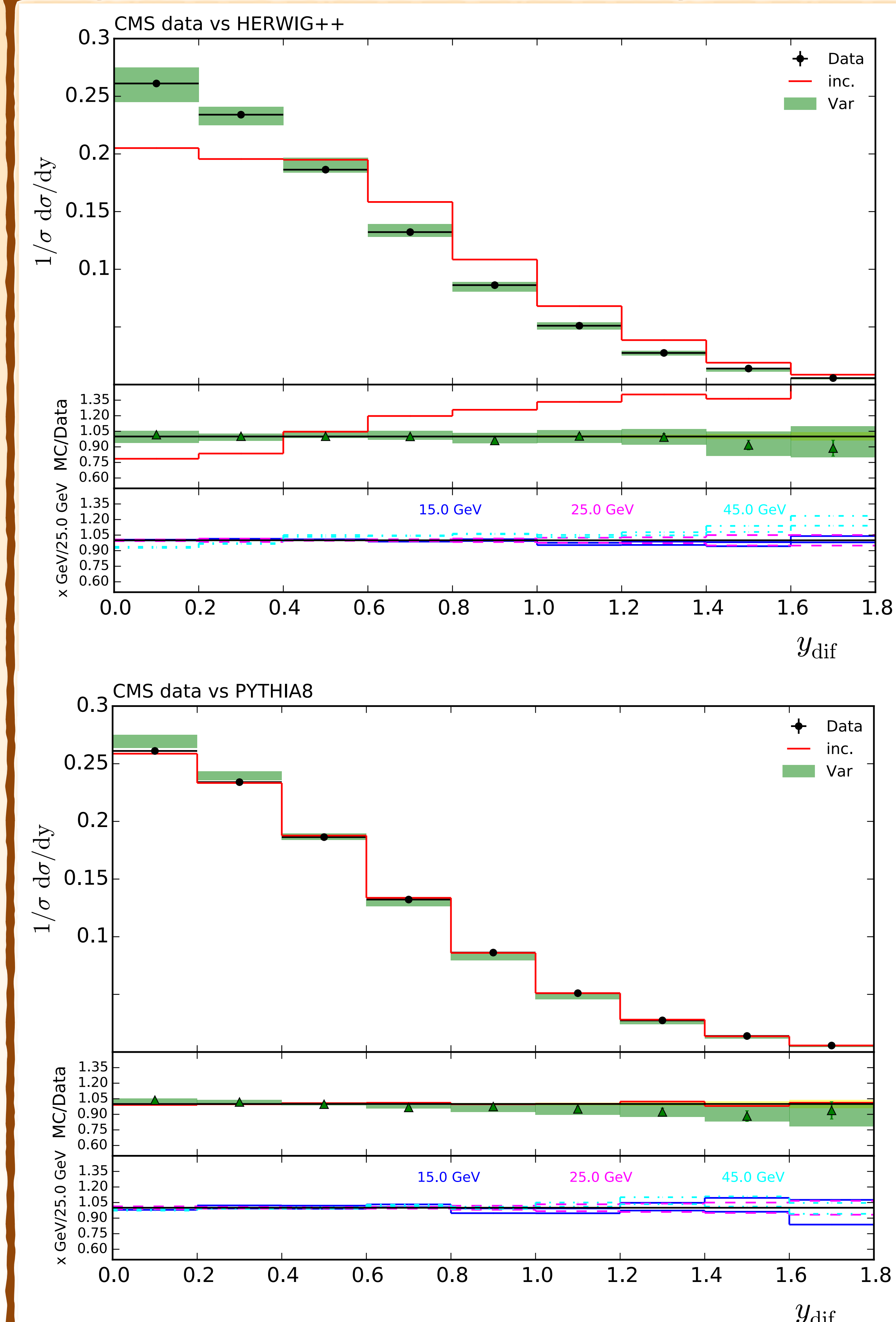
- FxFx Merged results close to the NLO inclusive cross sections
- Order 1% dependence on the merging scale for total rates
  - slightly smaller for HW++ than for PY8
- Slightly larger cross section for PY8 than for HW++

- For comparisons to data (next slides) no normalisation factors applied: the normalisation of the predictions is as they come out of the code

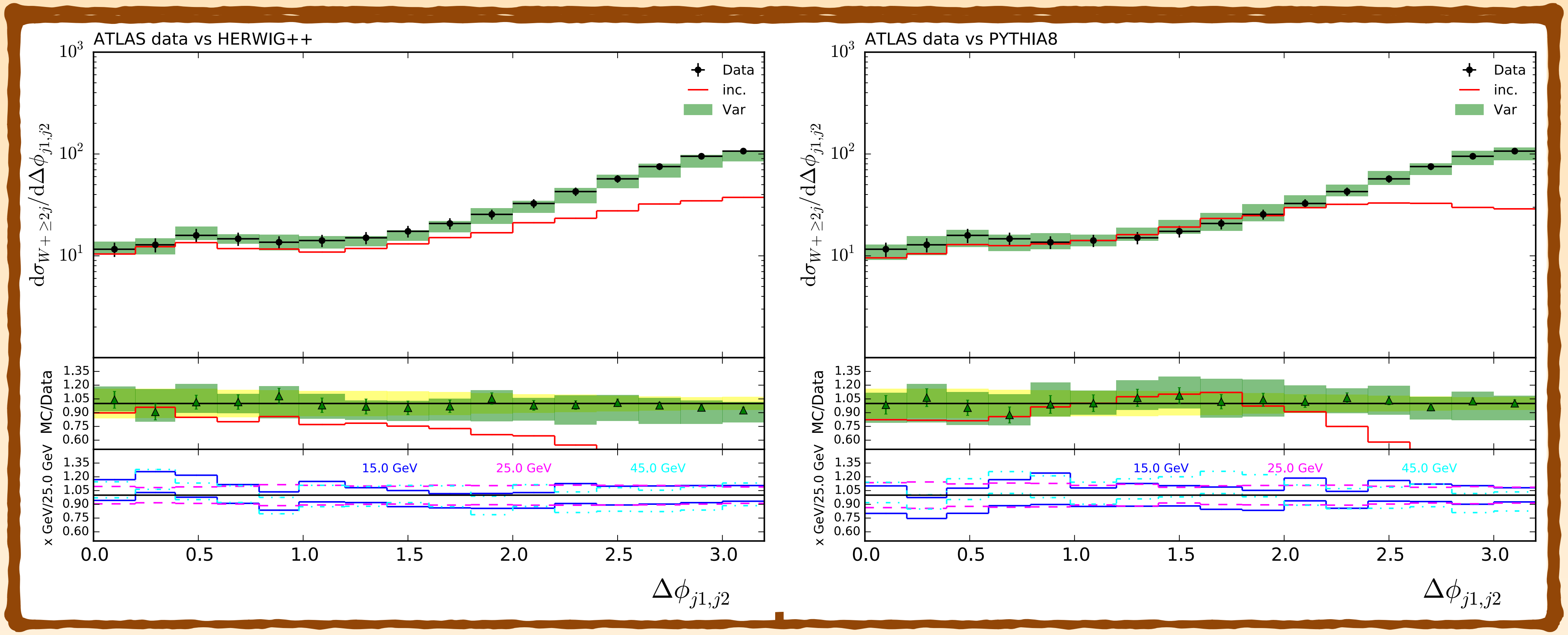
- ✦ Z+jets
- ✦ Exclusive jet multiplicity and hardest and 3rd hardest jet pT spectra
- ✦ Uncertainty band contains ren. & fac. scale, PDF & merging scale dependence
- ✦ Rather good agreement between data and theory





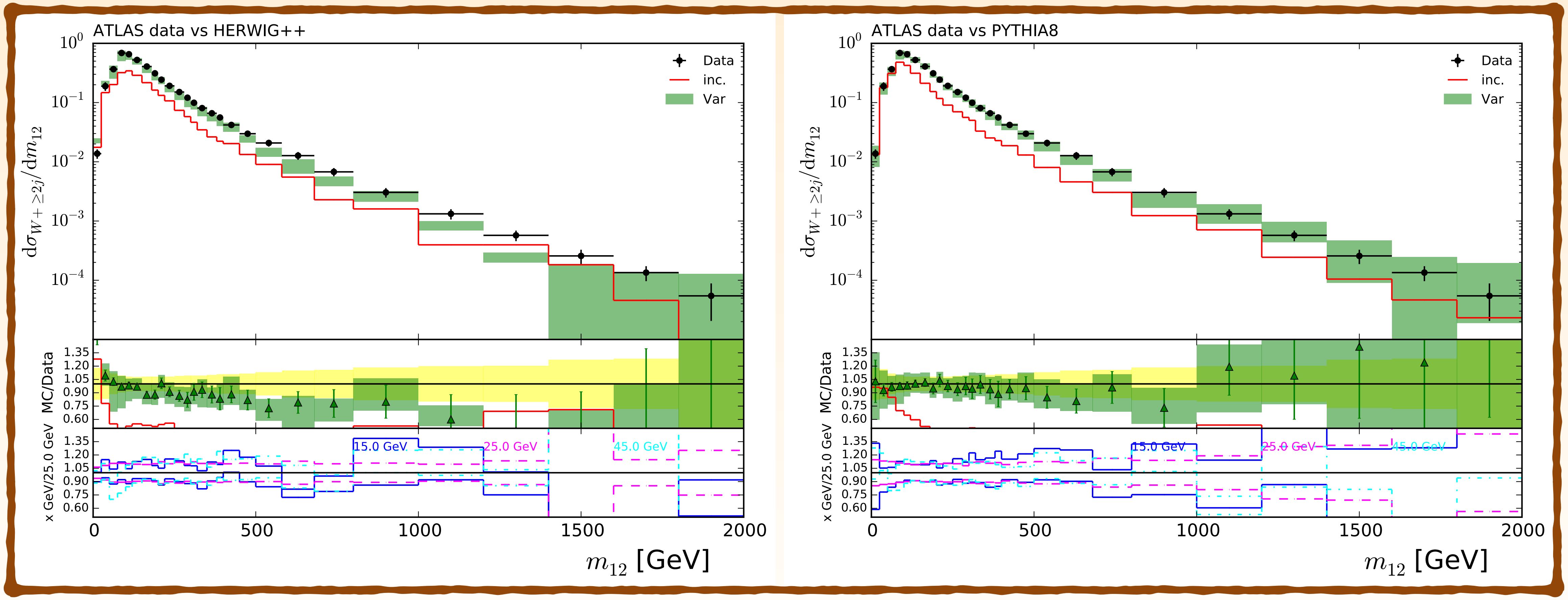


- ✦ Rapidity difference between Z-boson and hardest jet.
- ✦ Sensitive to higher multiplicity matrix elements
- ✦ LO predictions off (in particular MadGraph)
- ✦ No discrepancies at NLO



- W+jets
- Azimuthal correlation between the two hardest jets
- Agreement quite good apart from the bin around pi
- Turned out to be a problem in the analysis routine (from rivet), which gave the wrong theory prediction
- We were contacted by ATLAS immediately after we had put out the paper and were provided with a fix

- Agreement between FxFx merged results, matched to Herwig++ and Pythia8, and Atlas and CMS data is rather good
- Where data and theory differ, also differences between the results matched to HW++ and PY8 differ



Conclusions

- Difficult theoretical problems in NLO calculations have been thoroughly understood and solved. This paved the way for automation
- NLO calculations are now almost at the same footing as LO calculations: NLO QCD corrections in the SM have been solved
- Regarding **MadGraph5_aMC@NLO**:
  - I've shown 5 examples on how MG5_aMC can be used for phenomenology
  - Probably in a couple of months, EW corrections and BSM will be at the same level
  - Emphasis will shift towards (developing) analysis tools and on phenomenology that build upon the implementation of NLO