Recent progress in QCD

La Thuile Conference 2019

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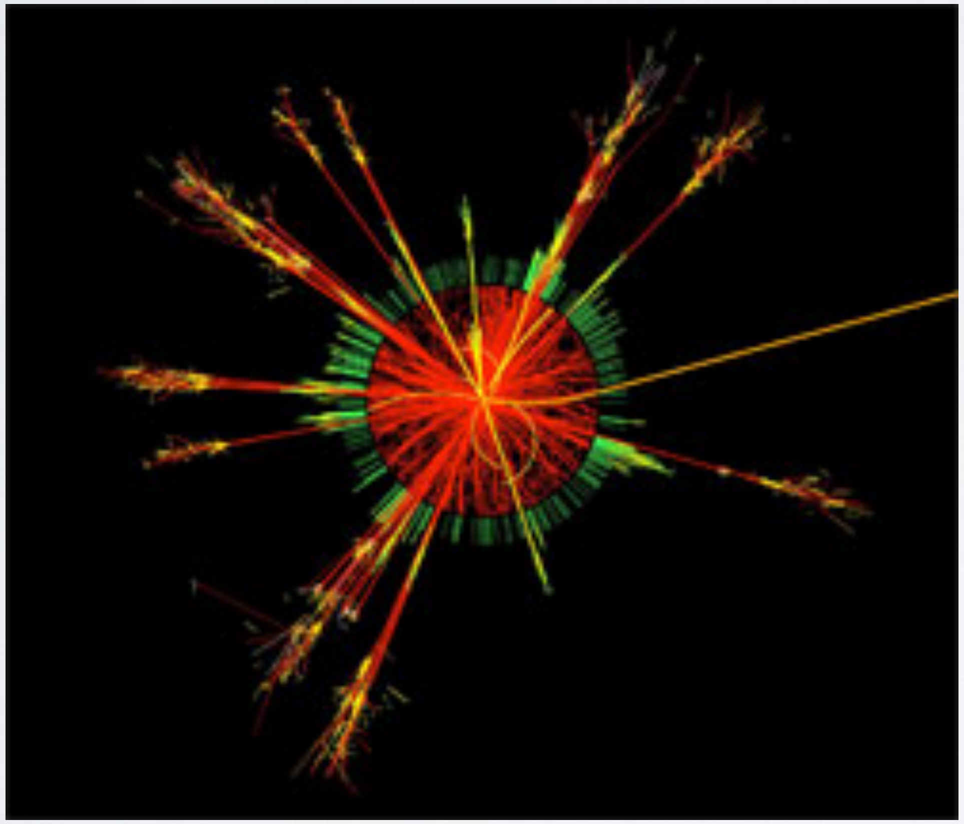
Talk partially inspired by input to ESPP, Anastasiou, Dittmeier, Gehrmann, Glover, Grazzini, Mangano, Pozzorini, Salam, GZ

Pre-LHC times …

Expectations from the LHC before its turn-on: direct production of new states resulting in clear signatures of New Physics in data



SUSY?
Black Hole production?
Z′?
Extra dimensions?
Composite theories?
…

Focus of phenomenological activity before 2008: how to reconstruct the underlying theory *given* striking deviations from SM predictions

About 12 years ago …

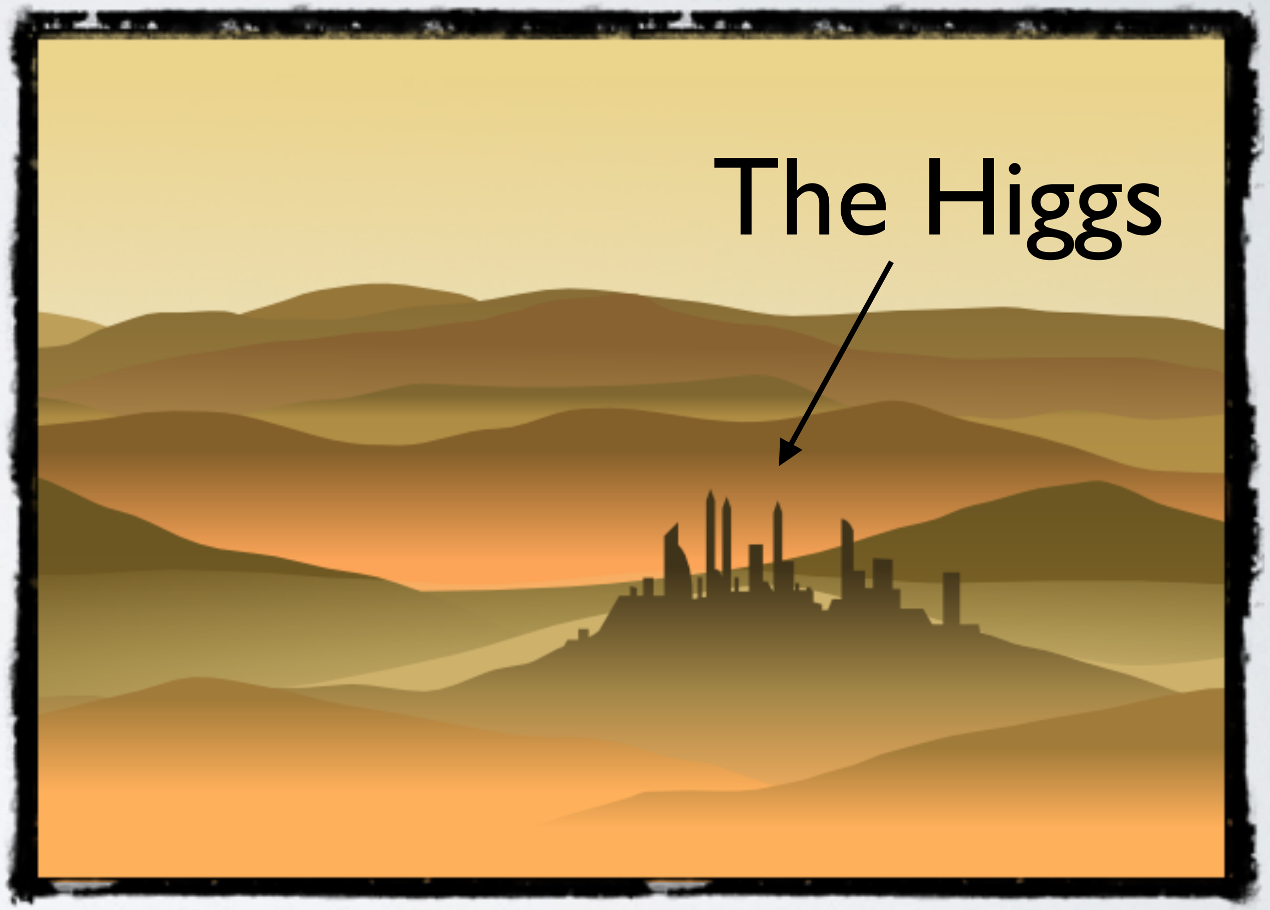
The abstract of a paper written before the LHC turned on:

We describe a coherent strategy and set of tools for reconstructing the fundamental theory of the TeV scale from LHC data. We show that On-Shell Effective Theories (OSETs) effectively characterize hadron collider data in terms of masses, production cross sections, and decay modes of candidate new particles. An OSET description of the data strongly constrains the underlying new physics, and sharply motivates the construction of its Lagrangian. Simulating OSETs allows efficient analysis of new-physics signals, especially when they arise from complicated production and decay topologies. To this end, we present MARMOSET, a Monte Carlo tool for simulating the OSET version of essentially any new-physics model. MARMOSET enables rapid testing of theoretical hypotheses suggested by both data and model-building intuition, which together chart a path to the underlying theory. We illustrate this process by working through a number of data challenges, where the most important features of TeV-scale physics are reconstructed with as little as 5 fb^{-1} of simulated LHC signals.

Arkani-Hamed et al. hep-ph/0703088

LHC as a discovery machine: focus on how to interpret the abundant direct signatures of New Physics

Expectations vs. reality

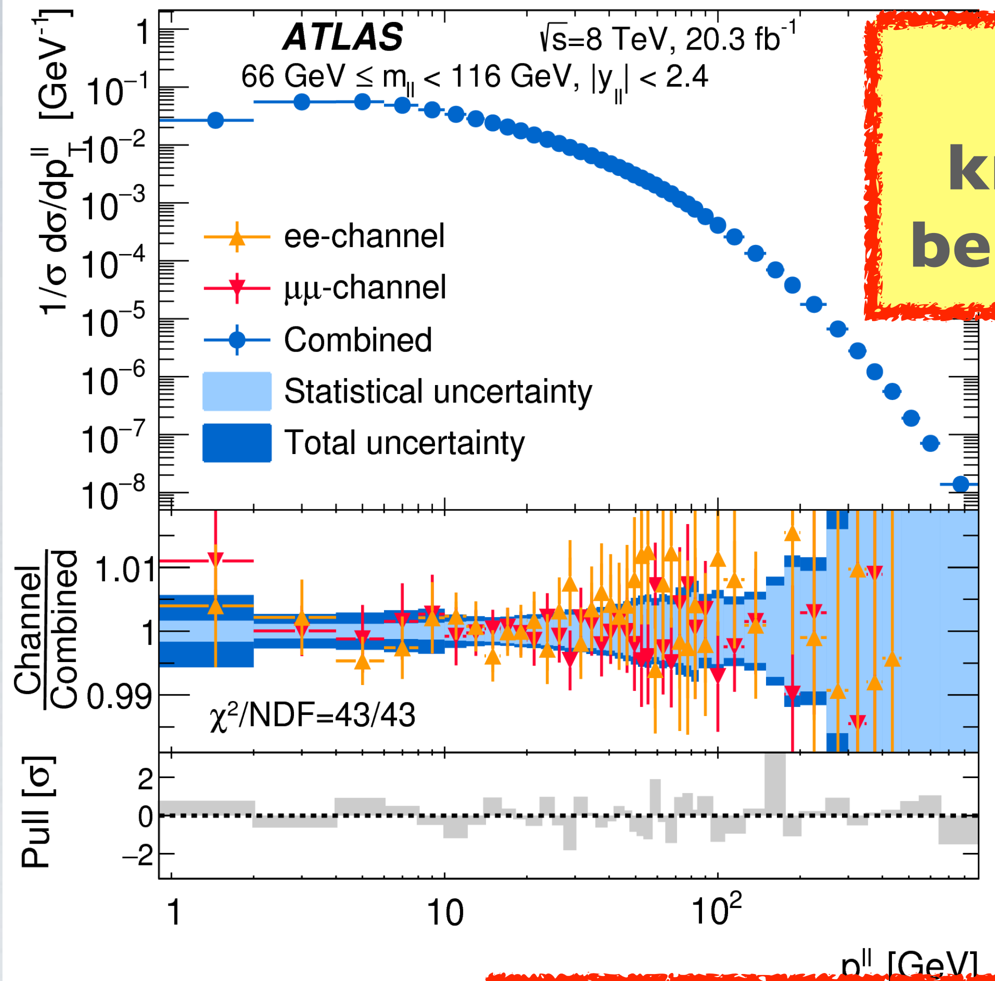


After more than 100 fb^{-1} no *direct compelling evidence* of New Physics

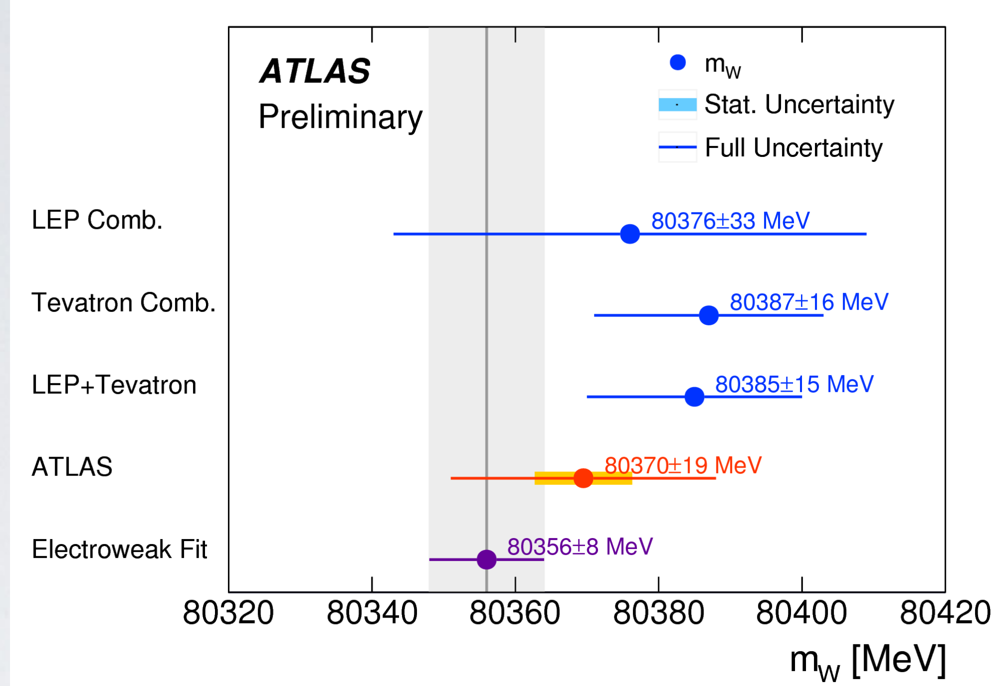
Facing reality

The LHC turned slowly into a precision machine.

In this endeavour, precise theory predictions crucial to enhance sensitivity

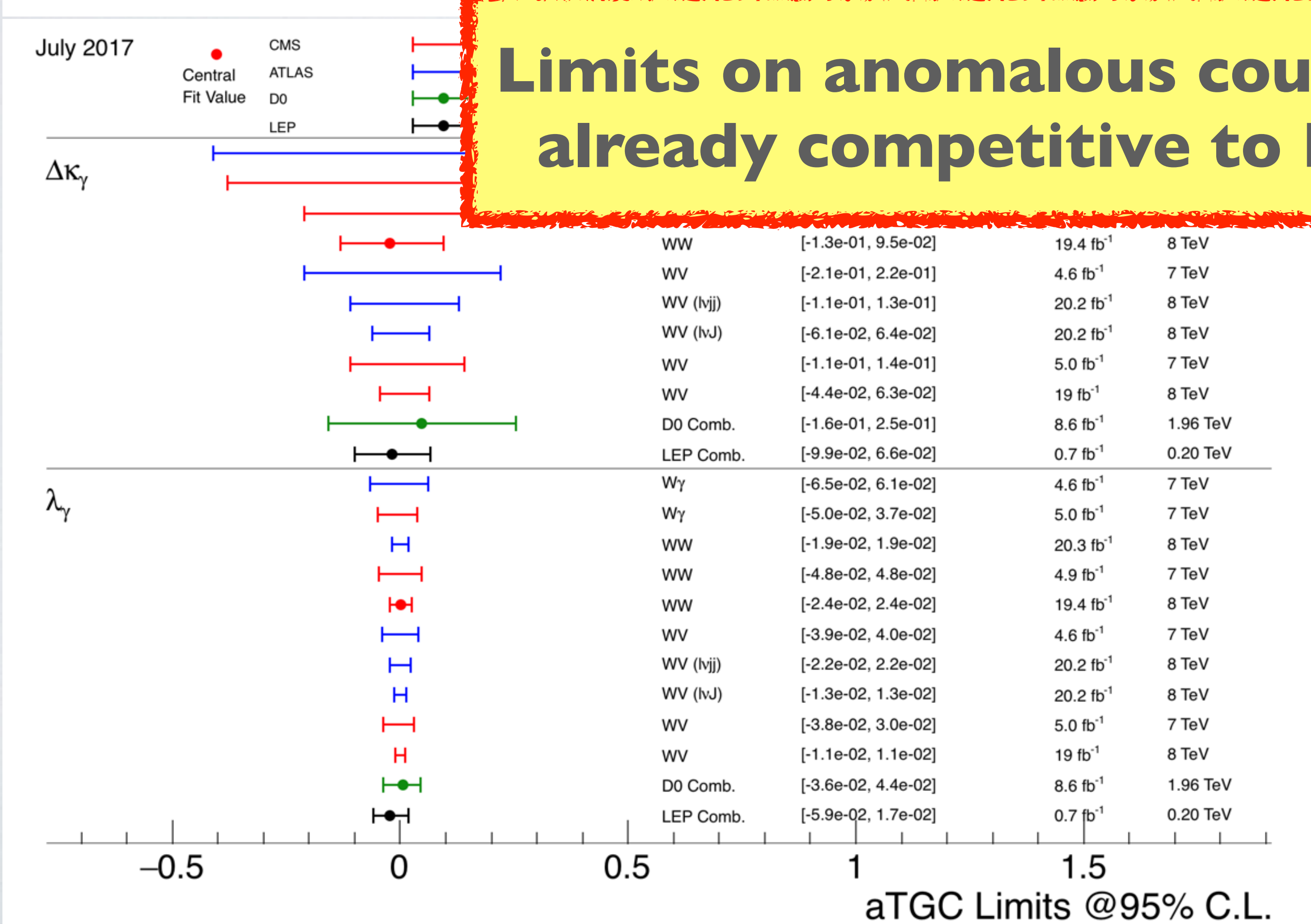


Z-boson kinematics to below a percent

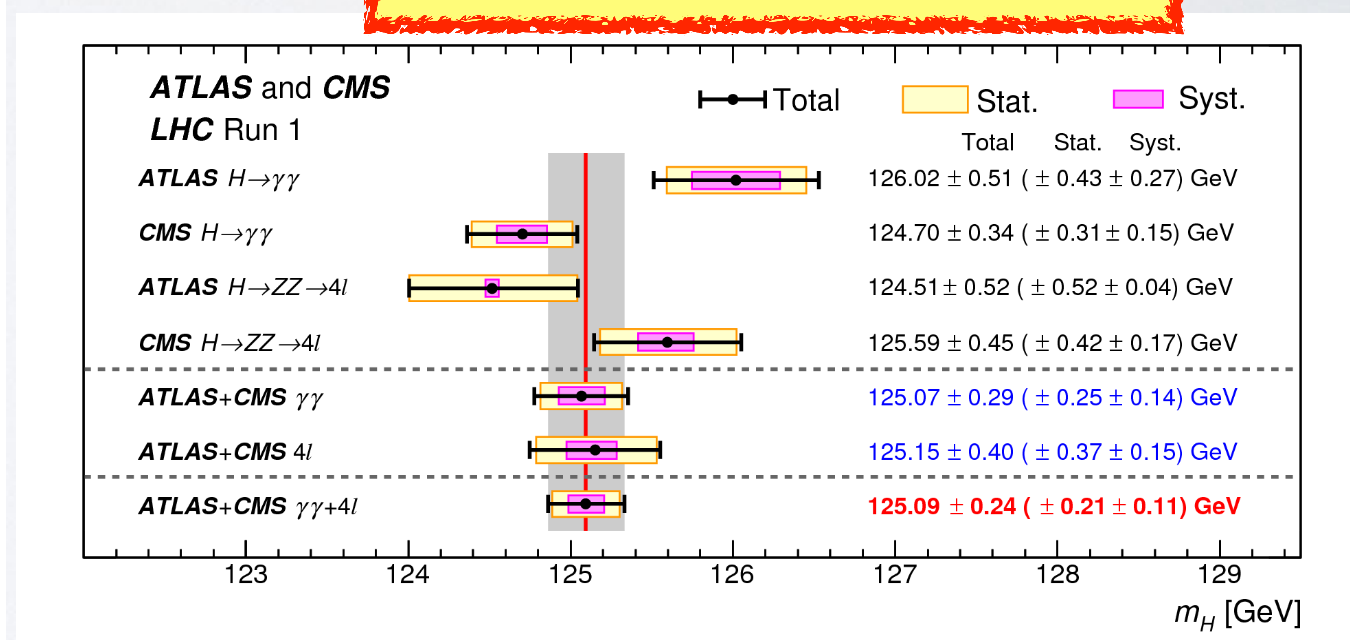


W-boson mass measured with 20 MeV precision (0.02%)

Limits on anomalous coupling already competitive to LEP



Higgs mass measured to 250 MeV (0.2%)



Roadmap for precision

Impressive, high-level precise measurements have already been carried out at the LHC in Run II, despite the very complex environment

In the light of detailed projections from the experiments **substantial further progress will be needed from theory calculations** if these are not to become a limiting factor in interpreting a wide range of High-Luminosity LHC data

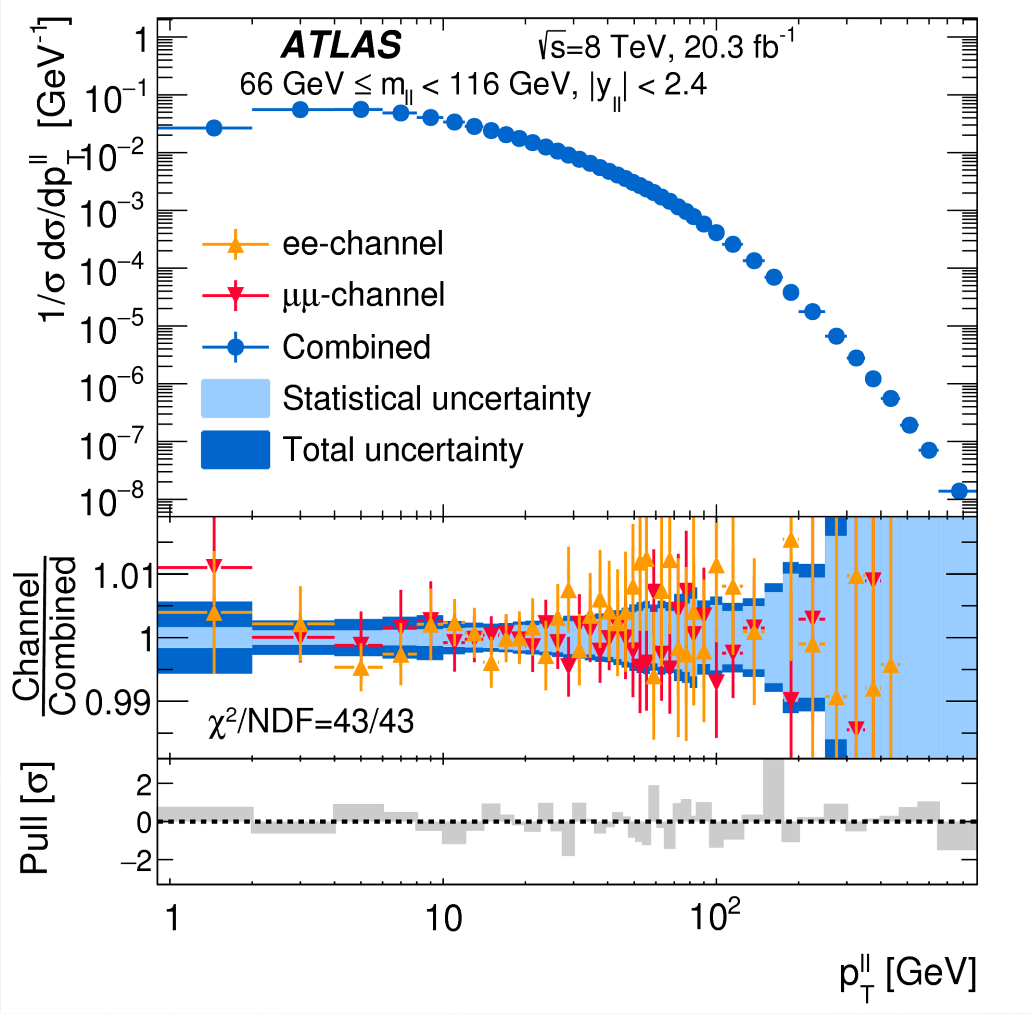
I will highlight **a few broad directions with substantial recent progress but still in need for improvements**
(NB: this is a personal selection, not an exhaustive list)

Roadmap for precision

1. Core processes at very high perturbative accuracy (N^3LO)

Experimental precision of core 2→1 and 2 → 2 processes likely to approach 1% precision over a substantial range of phase-space

NNLO predictions do not normally reach 1% precision
⇒ strong case for seeking N^3LO accuracy, also in the PDF extraction



Example:

$$\sigma_Z/\sigma_{ZZ} = O(100) \quad \mathcal{L}_{\mathrm{HL}}/\mathcal{L}_{\mathrm{RunI}} = O(100)$$

⇒ permille statistical error in ZZ at HL-LHC

Currently known at N^3LO

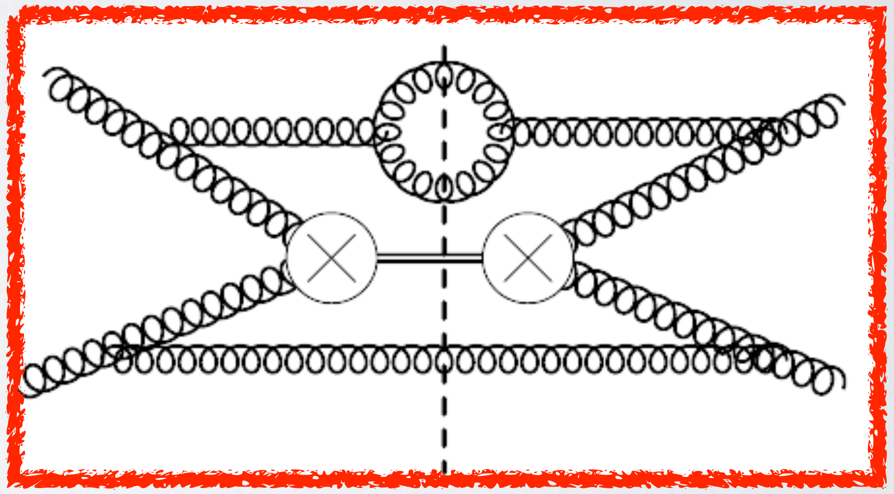
1. Inclusive Higgs production in the large m_t approximation

Anastasiou et al. 1602.00695
Mistlberger 1802.00833

Reminder: why is this so hard ?

The calculation involves

- $O(10^5)$ interference diagrams
- $O(10^8)$ loop and phase space integrals
- $O(10^3)$ 3-loop master integrals



Currently known at N^3LO

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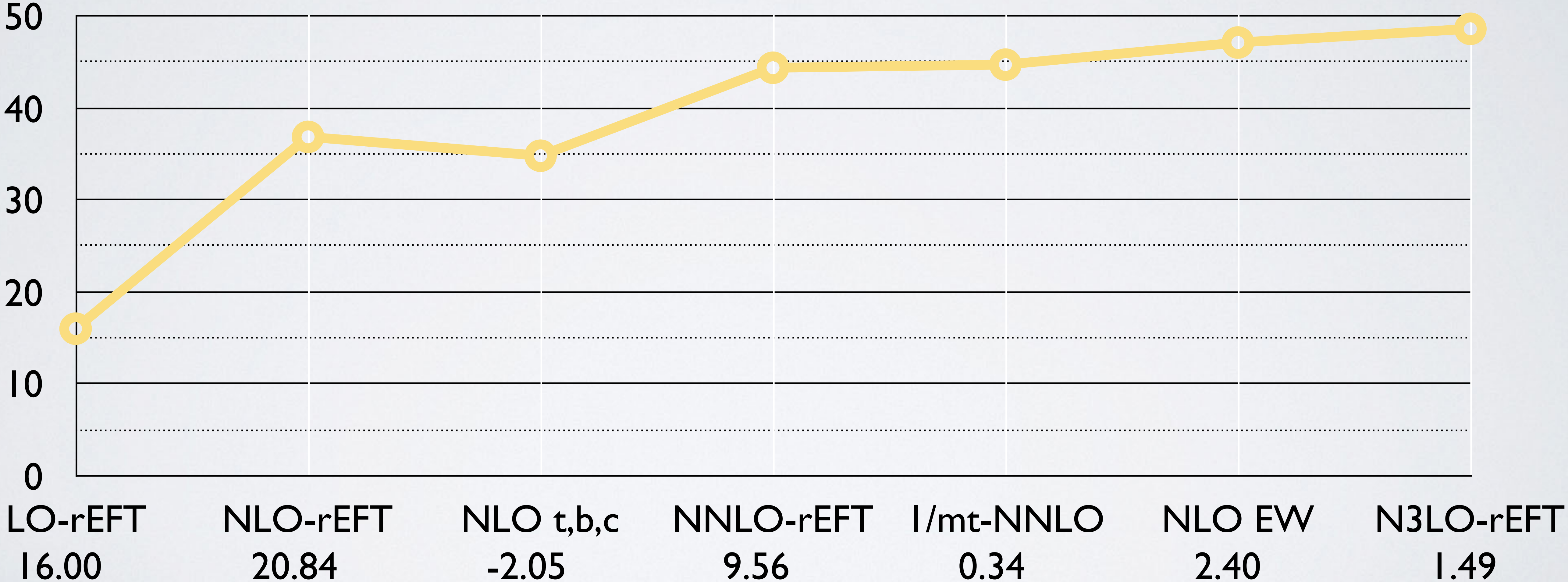
LHC 13 TeV: cross section in [pb] = 48.58 pb

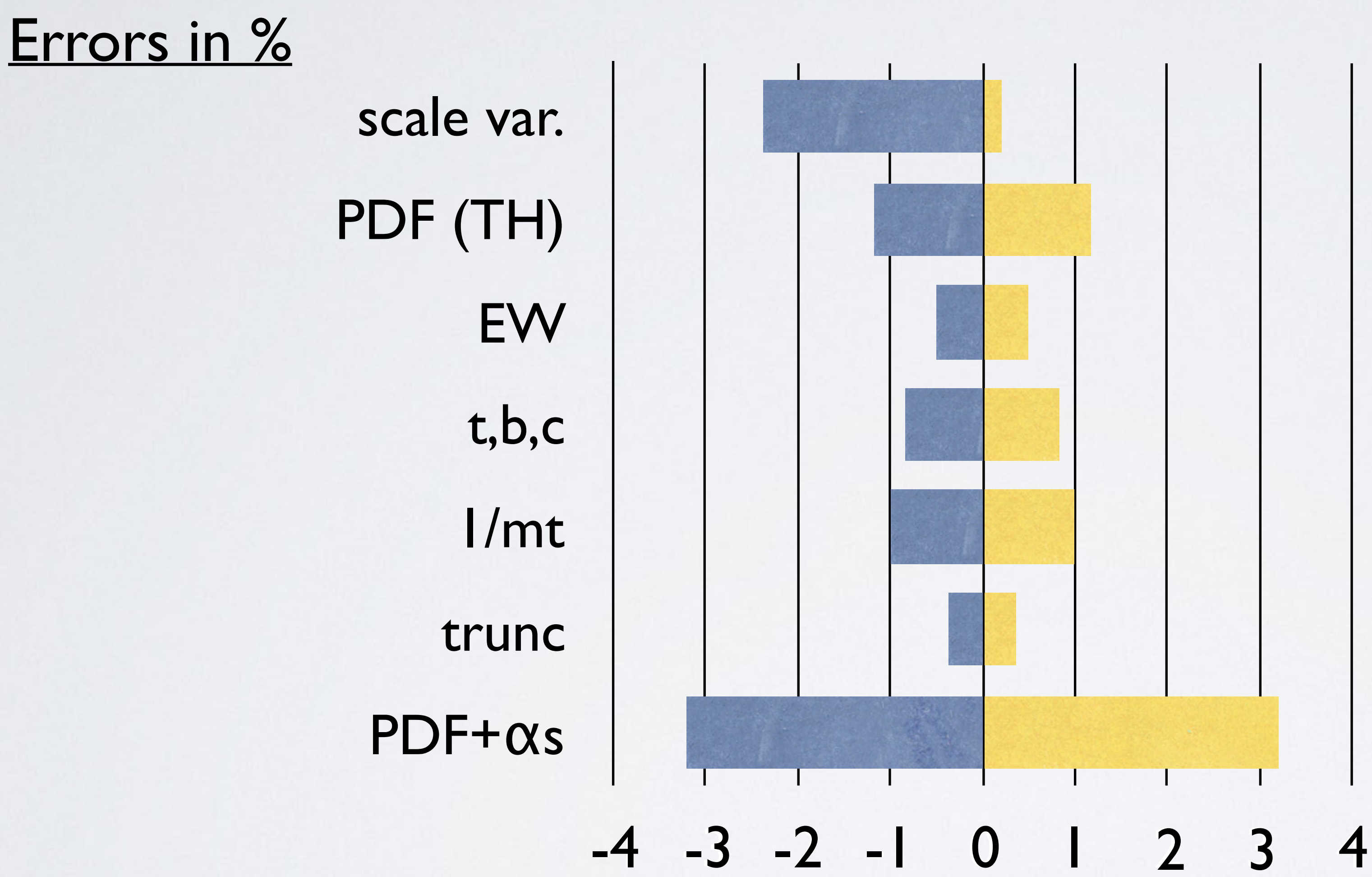


rEFT = EFT (i.e. heavy-top approximation) but rescaled by (exact Born) / (EFT Born) ≈ 1.07

Currently known at N^{3}LO

1. Inclusive Higgs production in the large m_t approximation

Anastasiou et al. 1602.00695
Mistlberger 1802.00833



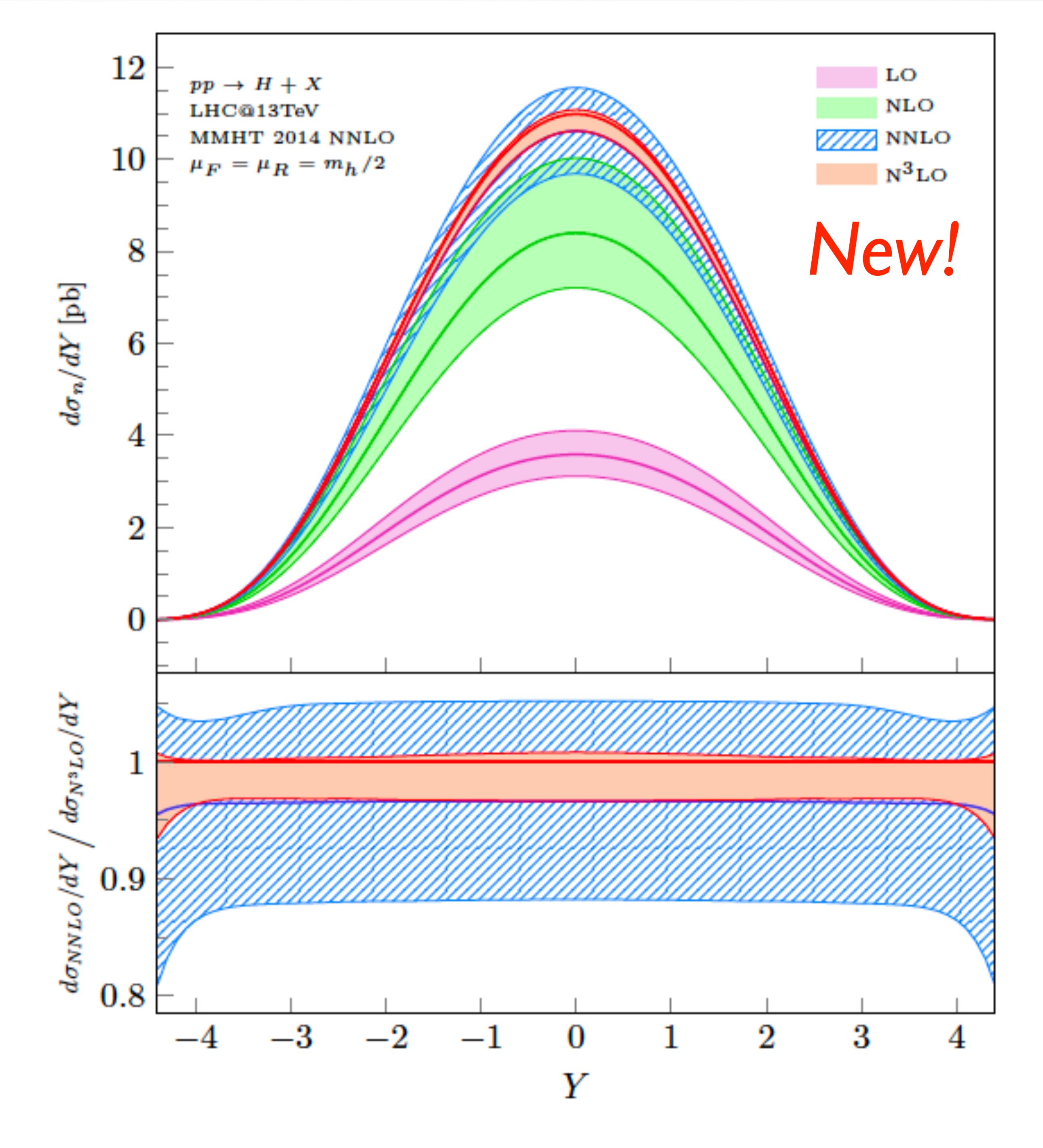
⇒ PDF and α_s dominate the error

$$\sigma = 48.58\text{pb}^{+2.22\text{pb}(4.56\%)}_{-3.27\text{pb}(-6.72\%)}\,\text{theory} \pm 1.56\text{pb}(3.2\%)(\text{PDF}+\alpha_s)$$

Currently known at N^3LO

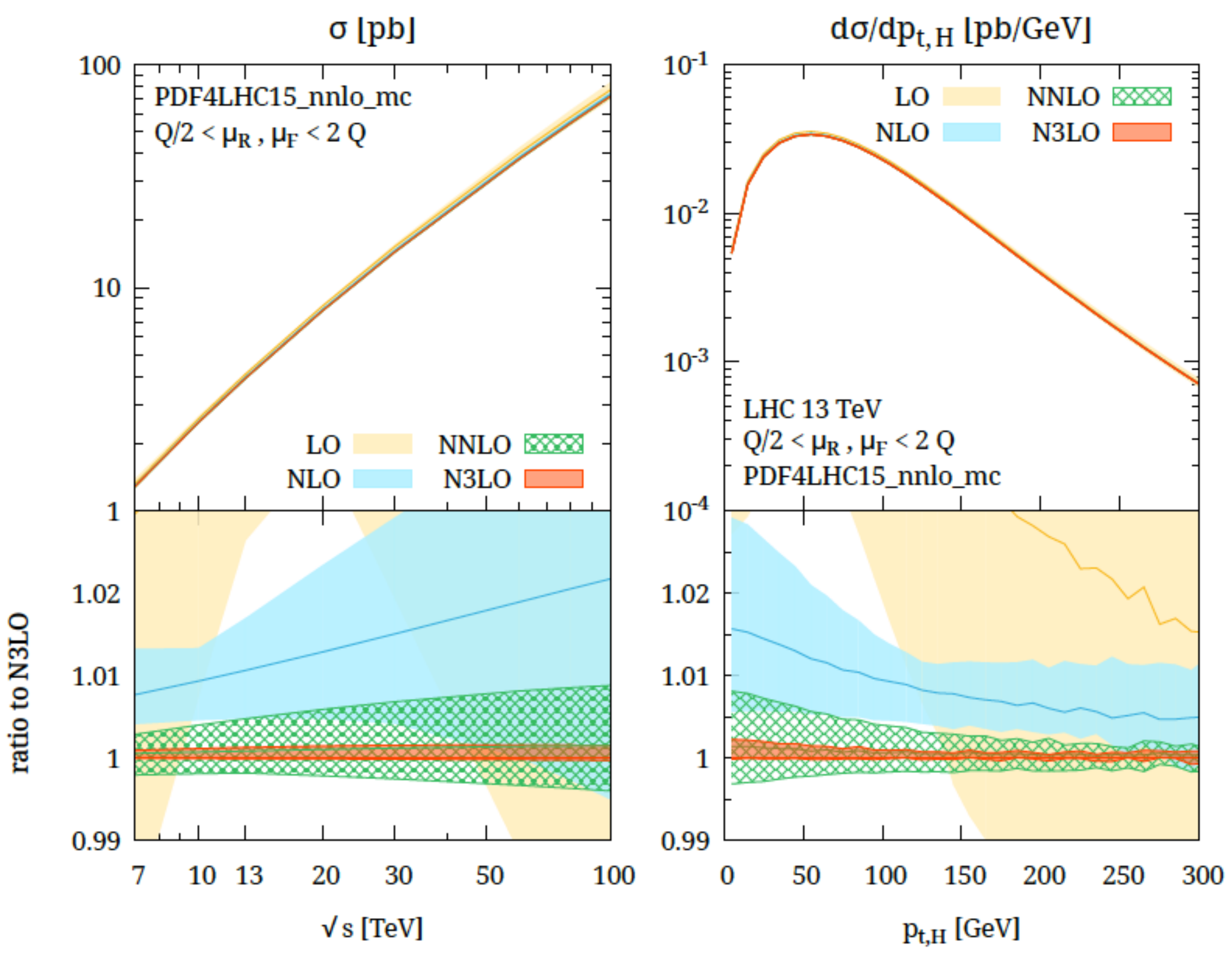
Recently even the Higgs rapidity has been computed at N^3LO (using a threshold expansion)

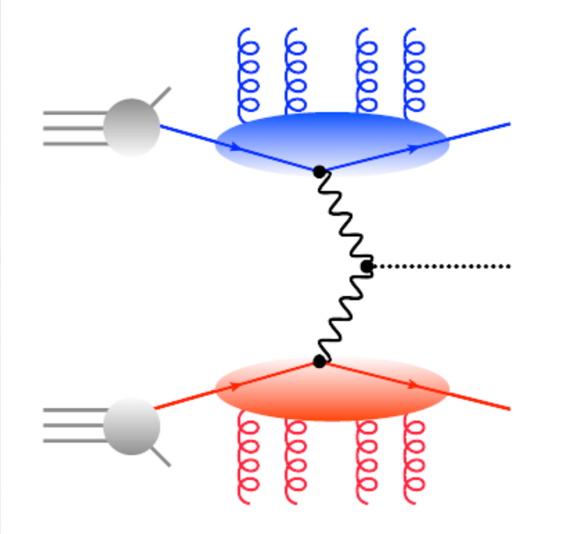
Dulat, Mistlberger, Pelloni 1810.09462



Currently known at N^3LO

2. Total Vector Boson Fusion Higgs cross-section in the DIS approx.





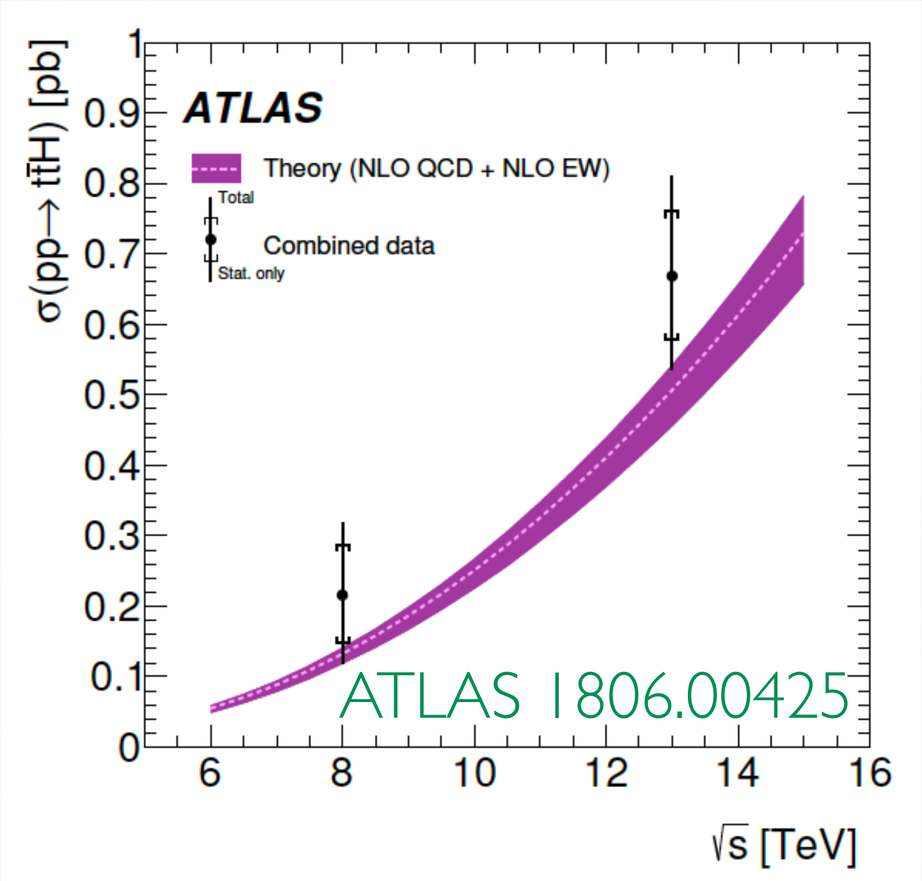
- N^3LO fully in NNLO band (same for gluon-fusion production)
- no realistic cuts at N^3LO

Dreyer & Karlberg 1606.00840

Roadmap for precision

2. Complex processes at few-percent accuracy

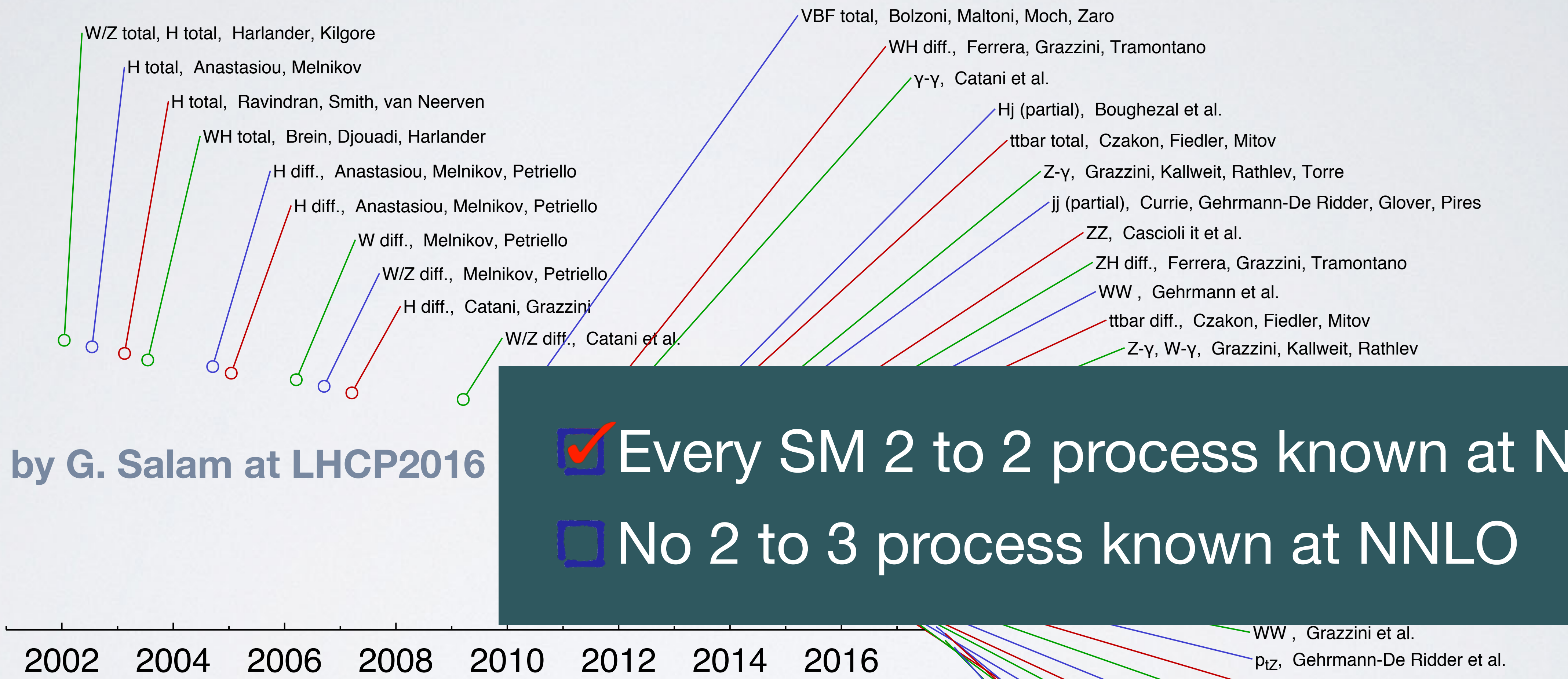
A number of crucial processes involving a 2→3 structure beyond today's state-of-the-art for NNLO calculations (e.g. 3-jet, ttH, ttV, H+2jets, …)



Example:
ttH expected to have 2% statistical precision at the end of the HL-LHC. Without NNLO and NLO EW calculations this experimental precision can not be fully exploited

NNLO: current status

An explosion of NNLO results in the last years



Talk given by G. Salam at LHCP2016

- ☑ Every SM 2 to 2 process known at NNLO
- ☐ No 2 to 3 process known at NNLO

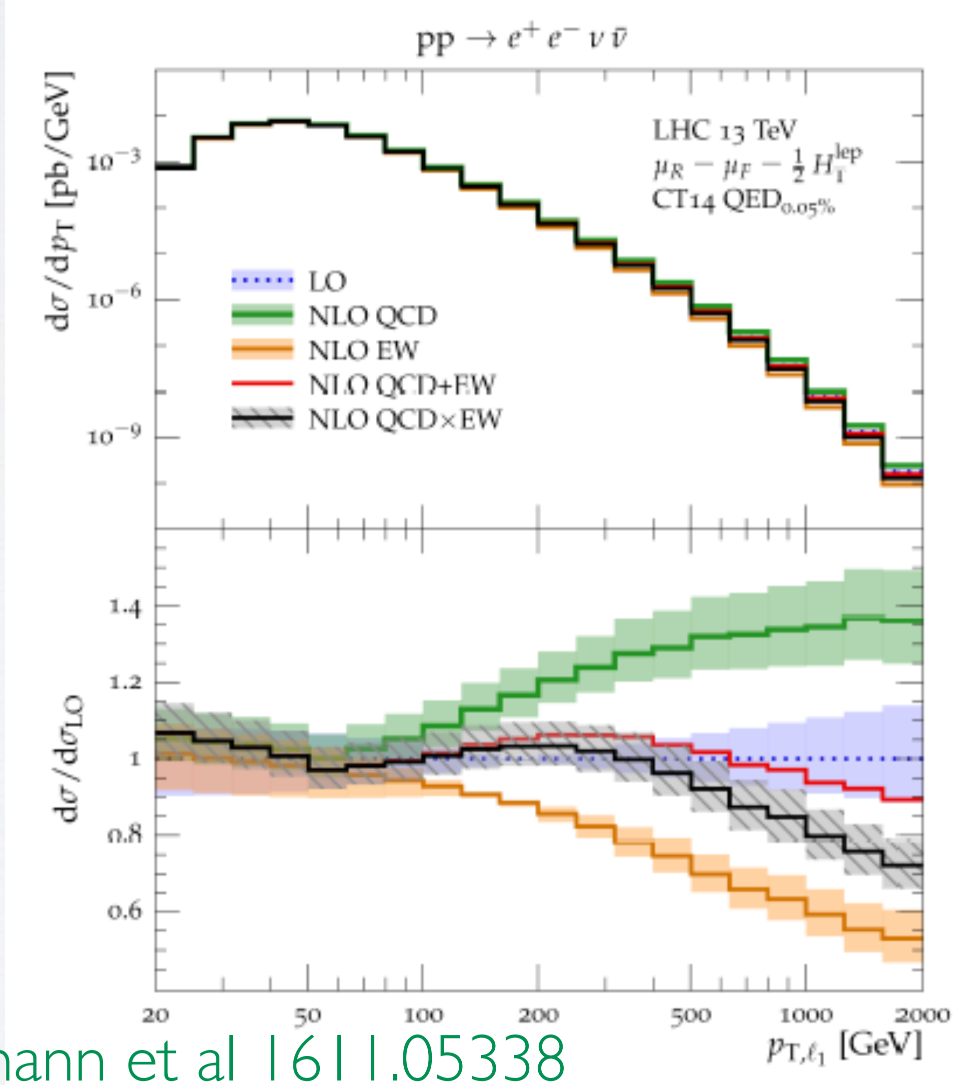
Things are developing rapidly, but a **number of conceptual and technical challenges** remain to be faced

Roadmap for precision

3. Accuracy at high p_t

Understanding logarithmically enhanced electroweak effects at high p_t, also in relevant background processes, will be crucial to fully exploit future data

Plot also high-lights importance of genuine mixed QCD+EW effects (combining corrections multiplicatively or additively leads to large ambiguities)



Biedermann et al 1611.05338

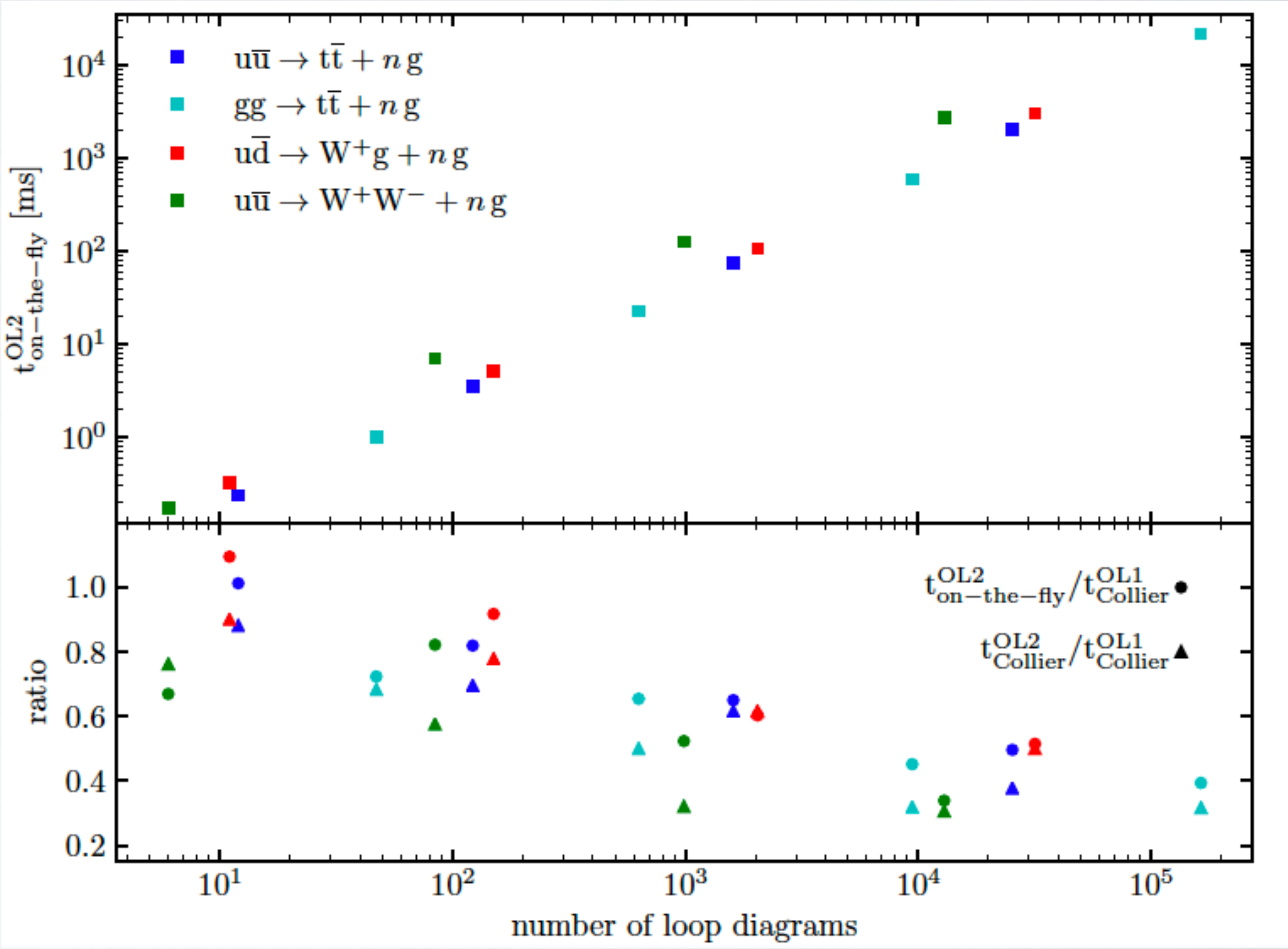
Examples:
Two most important examples are high-p_t Higgs production and Dark Matter searches

Roadmap for precision

4. NLO for high-multiplicity processes

NLO QCD has been automated but

- NLO high-multiplicity HL-LHC signals and backgrounds requires an order of magnitude efficiency improvement
- NLO QCD and EW to BSM processes (e.g. in EFT approach) desirable



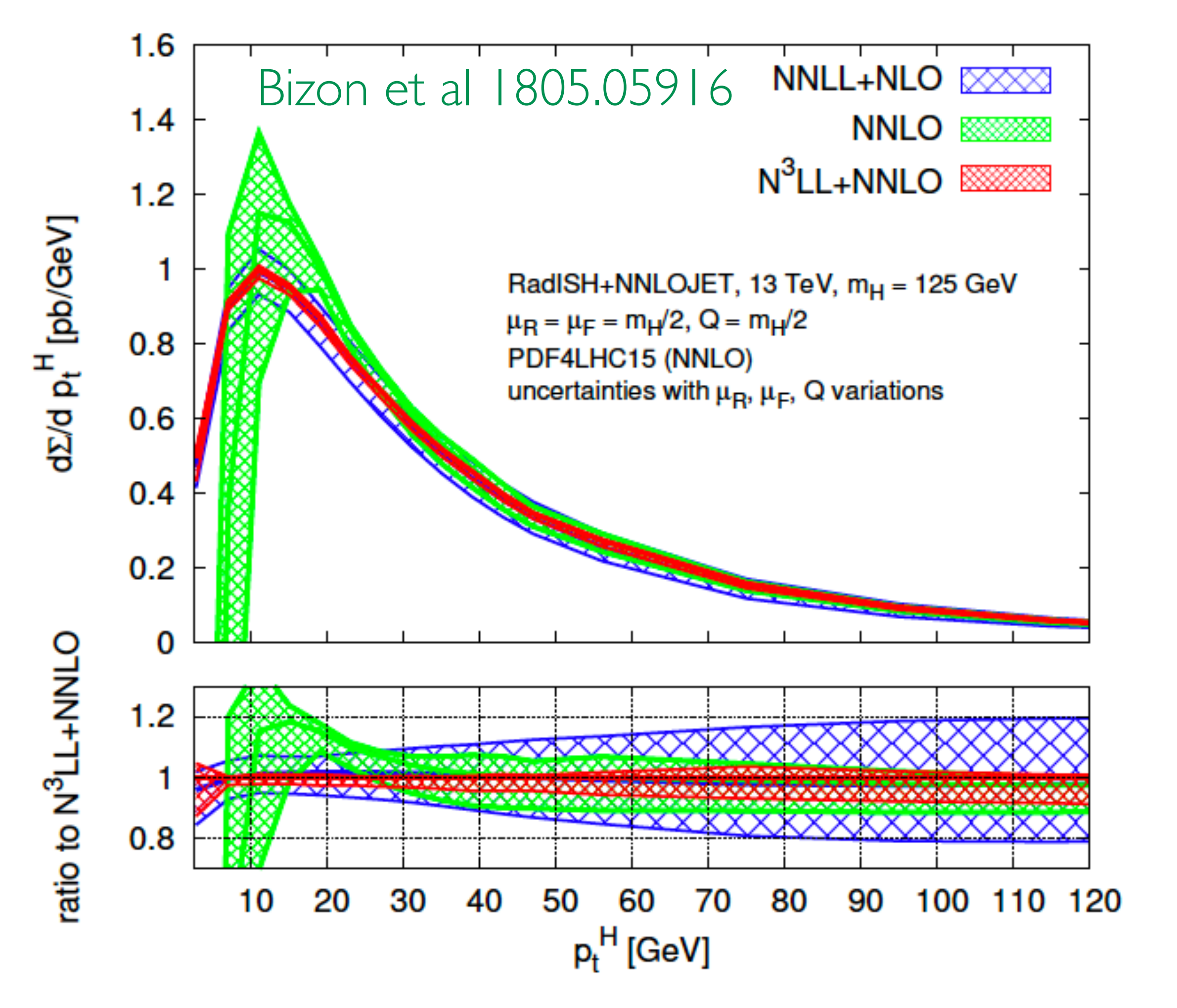
Buccioni, Pozzorini, Zoller 1710.11452

Roadmap for precision

5. All-order resummed calculations

N^{3}LL achieved for few selected processes, NNLL available for a large class of processes (mostly colour-singlet)

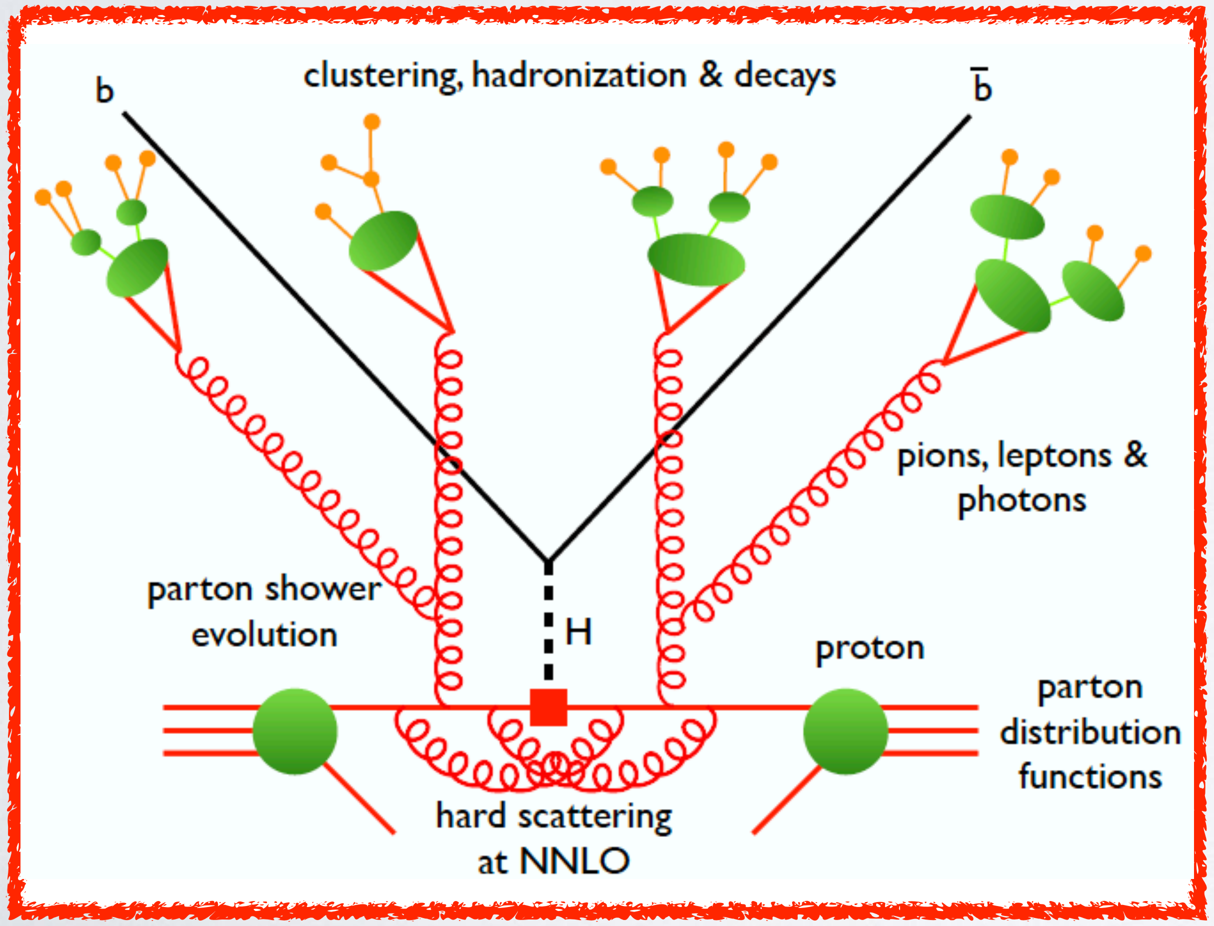
- better resummation accuracy for more generic processes (important in exclusive regions)
- numerical/automated resummation approches
- insight on resummation likely to play a big role in further improvements of parton shower and NNLOPS methods



Roadmap for precision

6. Matching of NNLO and patron shower (NNLOPS)

NNLOPS is a must to have the best perturbative accuracy with a realistic description of final state



NNLOPS: currently three methods exist (UNNLOPS, Geneva, MiNLO) but hard to extend to generic 2 → 2 processes

Hoeche, Li,Prestel [UNNLOPS]
Astill, Bizon, Hamilton, Karlberg, Nason, Re, GZ [MiNLO]
Alioli, Bauer, Berggren, Guns, Tackmann, Walsh [Geneva]

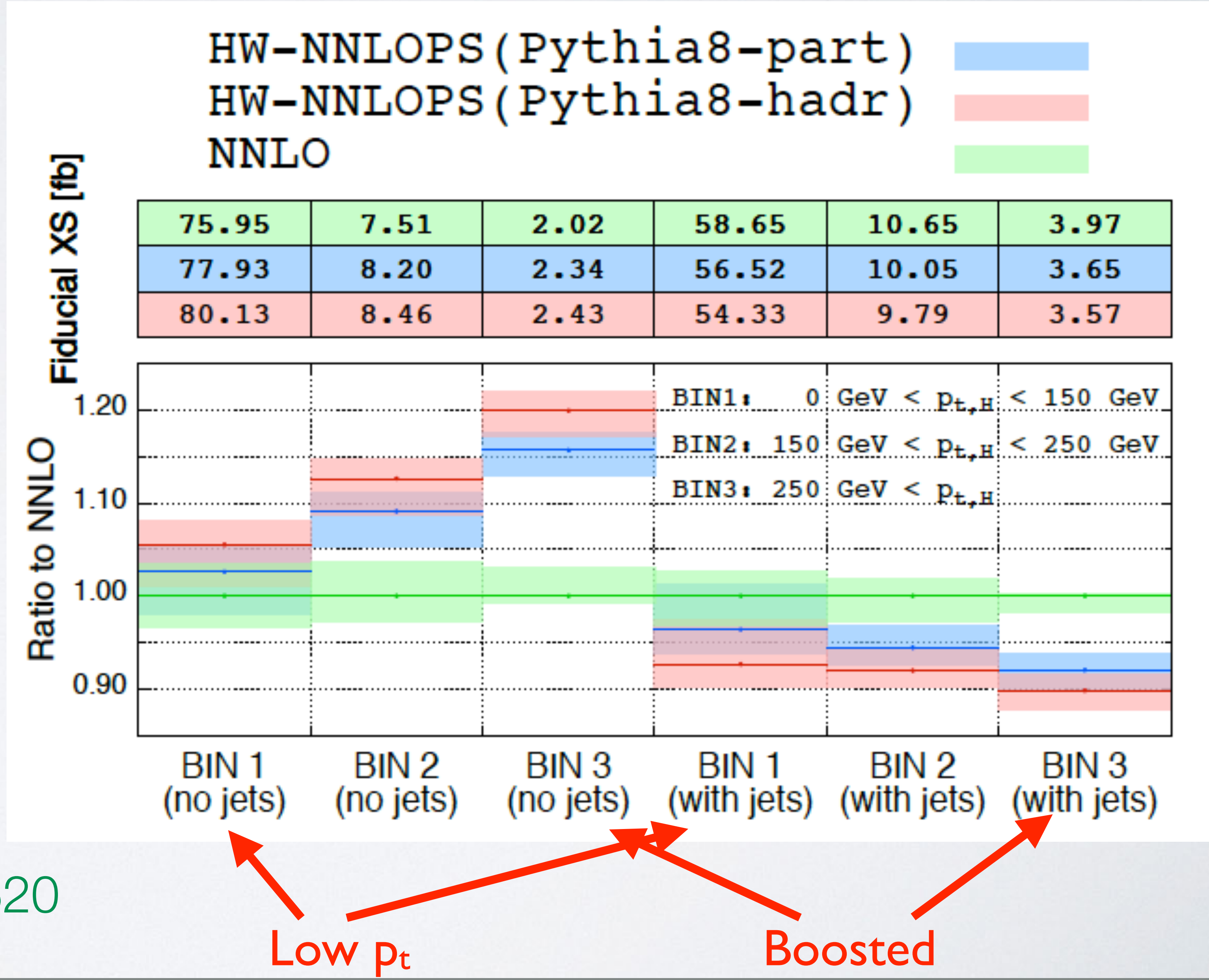
Roadmap for precision

6. Matching of NNLO and patron shower (NNLOPS)

One sample NNLOPS result: associated HW production with cuts suggested by HXSWG

- Parton shower and hadronization cause migration between jet-bins
- Difficult to reach high accuracy in jet-binned observables

Astill, Bizon, Re, GZ 1603.01620



	BIN 1 (no jets)	BIN 2 (no jets)	BIN 3 (no jets)	BIN 1 (with jets)	BIN 2 (with jets)	BIN 3 (with jets)
NNLO	75.95	7.51	2.02	58.65	10.65	3.97
HW-NNLOPS(Pythia8-part)	77.93	8.20	2.34	56.52	10.05	3.65
HW-NNLOPS(Pythia8-hadr)	80.13	8.46	2.43	54.33	9.79	3.57

Roadmap for precision

7. Multivariate analyses and Monte Carlo uncertainties

Estimating theory uncertainties for sophisticated multi-variate analyses is a very challenging and poorly studied task

- often MC predictions are constrained to data through profile likelihood fits of kinematic distributions in different event categories
- related uncertainties at the level of NLO matrix elements, parton shower, NLO matching need to be identified, modelled, correlated in a realistic way
- assessment of Monte Carlo uncertainties is alone a very hard task (insights likely to come from resummed calculations)

Progress likely to come from a close collaboration of experts in the different theoretical and experimental aspects of the problem

Conclusion

Precision is crucial to enhance the sensitivity in the search for BSM. The hope is that any deviation will point us to the way forward.

- amazing progress in precision QCD over the last years (N^3LO, NNLO, automated NLO, resummations, matching to parton shower …)
- still, even more precise results are needed to match upcoming measurements at the LHC and HL-LHC
- precision QCD is not only about computing more orders in α_s. Reaching precision in all regions of phase space, with a robust theoretical error, is a multi-lateral challenge

Precision QCD will play a crucial role in the years to come