QCD at colliders: Theoretical Results

Fabrizio Caola, CERN & IPPP Durham

The 28th International Symposium on Lepton Photon Interactions at High Energies

Sun Yat-Sen University, Guangzhou, Aug. 11th 2017

Disclaimer

Impressive experimental program at the LHC keeps pushing for further development in our understanding of QCD → a lot of recent progress

- Impossible / useless to cover everything in one talk
- In the following: more or less coherent overview of some key ingredients needed for precision physics at the LHC, with CHERRY-PICKED EXAMPLES OF NEW RESULTS
- Apologies if your favorite topic is not covered…

Precision QCD: Why?

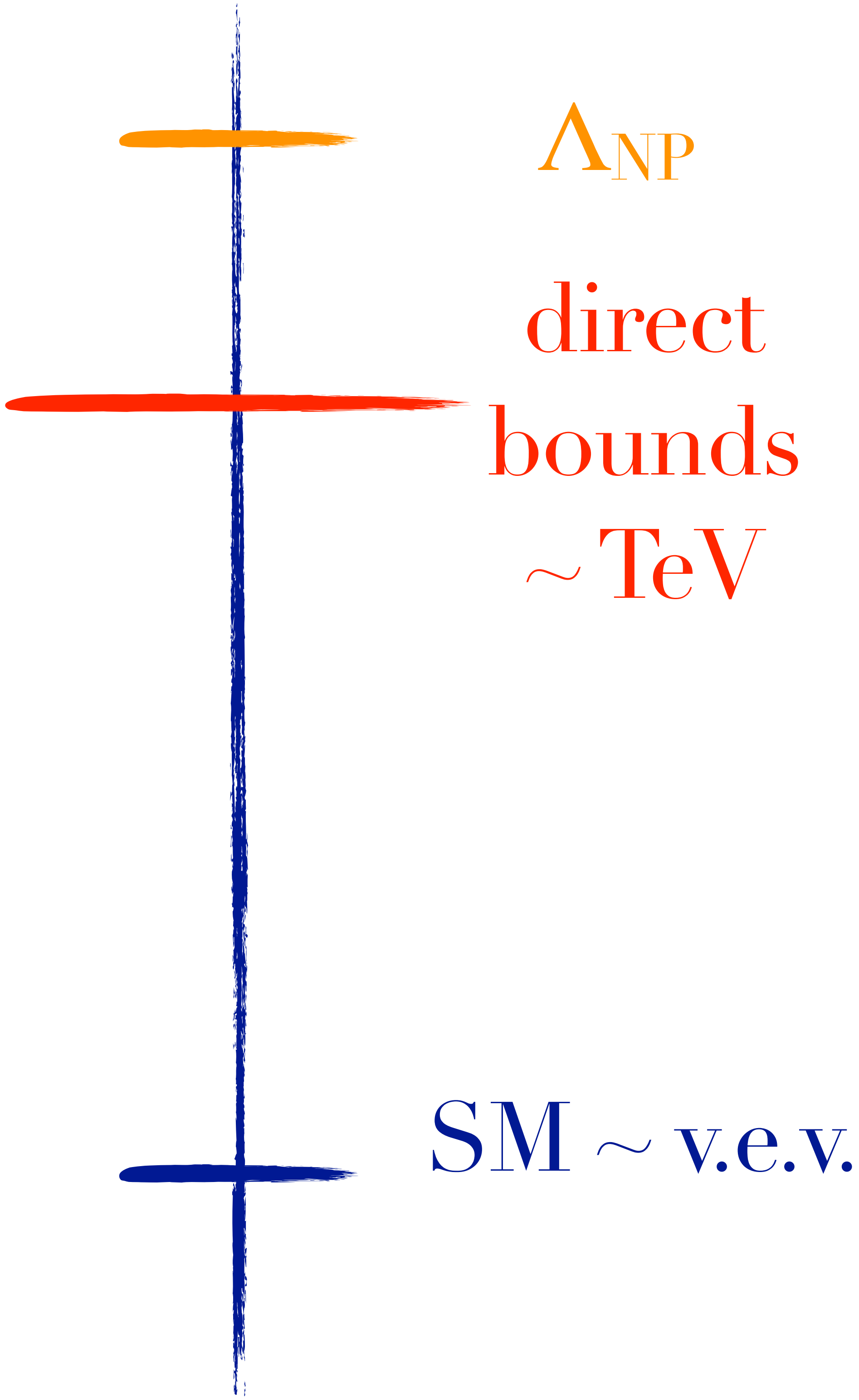
The LHC machine and experimental program are running extremely well. *Precision physics in a hadronic environment possible*

Why do we care about precision QCD:

- better understanding of the theory itself. Despite the framework being well known, many aspects still eluding (IR perturbative behavior, non perturbative effects…)
- NO SPECTACULAR NEW PHYSICS APPEARED SO FAR. Extremely good control on many different key observables may highlight (small) deviations from SM behavior → indication of new physics

PRECISION QCD IS NOW A PRIVILEGED TOOL FOR DISCOVERY AT THE LHC

What do we need to achieve?



Imagine to have new physics at a (heavish) scale Λ_{NP}

Typical modification to observable w.r.t. standard model prediction:

$$\delta O \sim Q^2 / \Lambda_{NP}^{\ 2}$$

To gain over direct bounds:

In the bulk:

$Q \sim M_H \rightarrow$ few percent

In the tail:

$Q \gtrsim 500$ GeV $\rightarrow$ ~10-20%

What do we need to achieve?

Λ_{NP}

direct

Imagine to have new physics at a (heavish) scale Λ_{NP}

Typical modification to observable

THESE KINDS OF ACCURACIES ARE WITHIN REACH OF LHC EXPERIMENTS CAPABILITIES.

WE SHOULD PUSH OUR UNDERSTANDING OF QCD TO MATCH THEM ON THE THEORY SIDE

SM ~ v.e.v.

IN THE BULK:

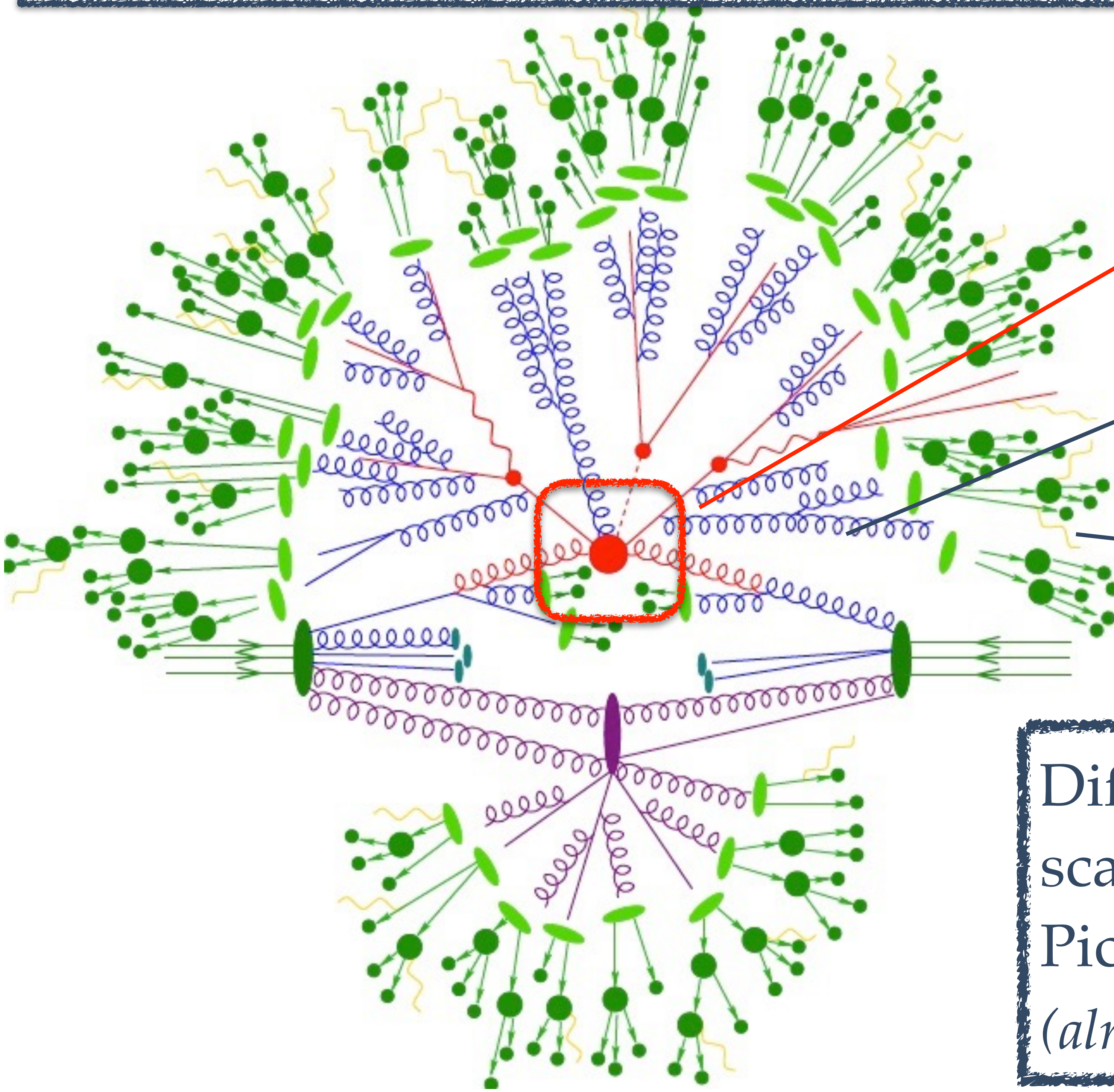
$Q \sim M_H \rightarrow$ few percent

IN THE TAIL:

$Q \gtrsim 500$ GeV $\rightarrow$ ~10-20%

QCD at colliders: factorization

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\text{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\text{QCD}}/Q))$$



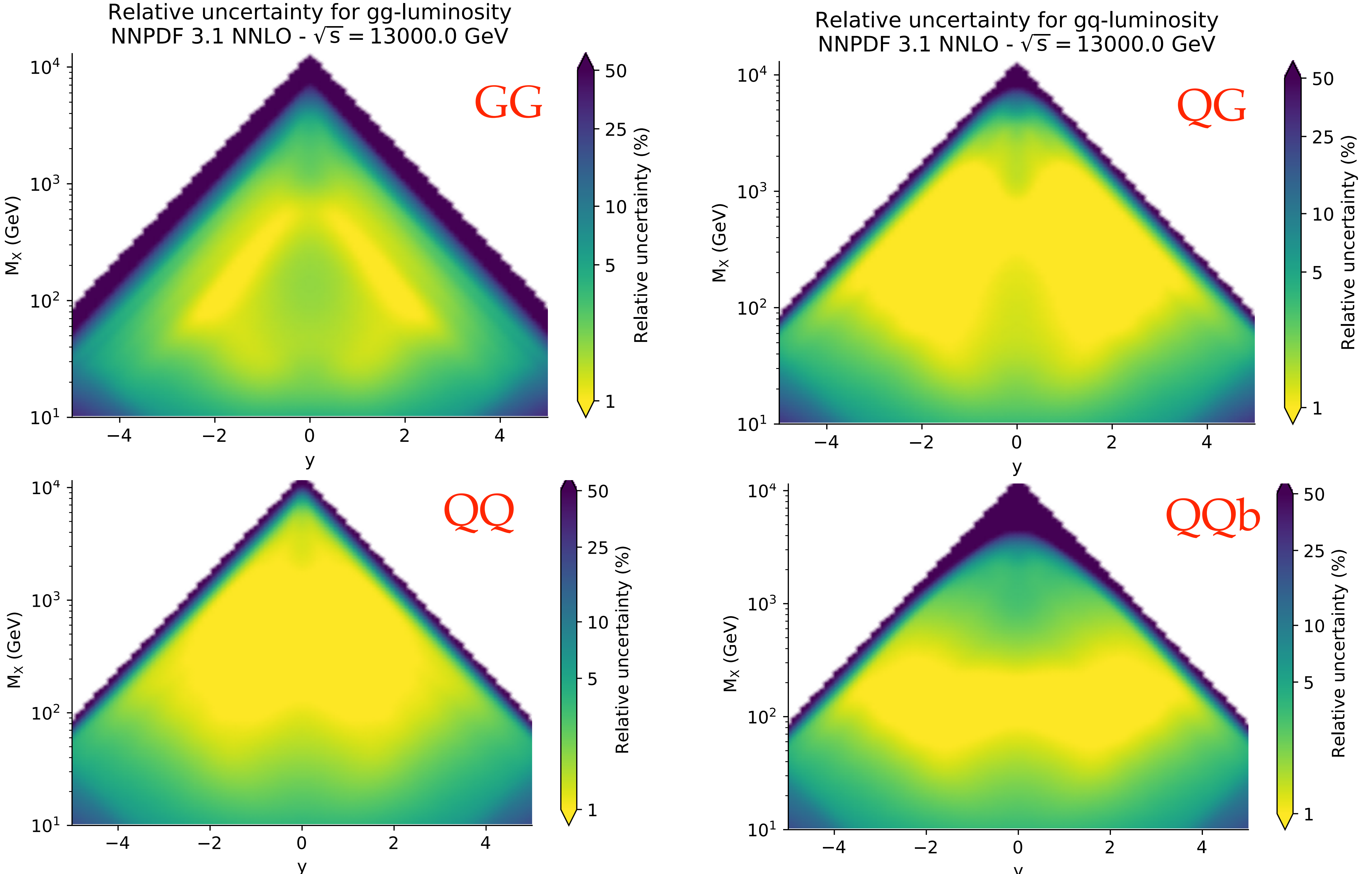
The ``interesting'' short distance cross-section

Extracting partons from protons: *Parton Distribution Functions*

The experimental world: hadrons / jets in the detector

Different physics at different scales, can be TREATED SEPARATELY.
Picture valid up to few percent
(already a limiting factor for $m_{t,W}$)

PDFs: the GPS plots



[NNPDF31, 2017]

- Big improvement w.r.t. few years ago (new methodology, LHC data)
- For Central EW Production: percent precision *(although be careful to take these uncertainties at face value)*
- This month: first steps towards even more precise evolution ([Moch et al (1017)])

The photon PDF

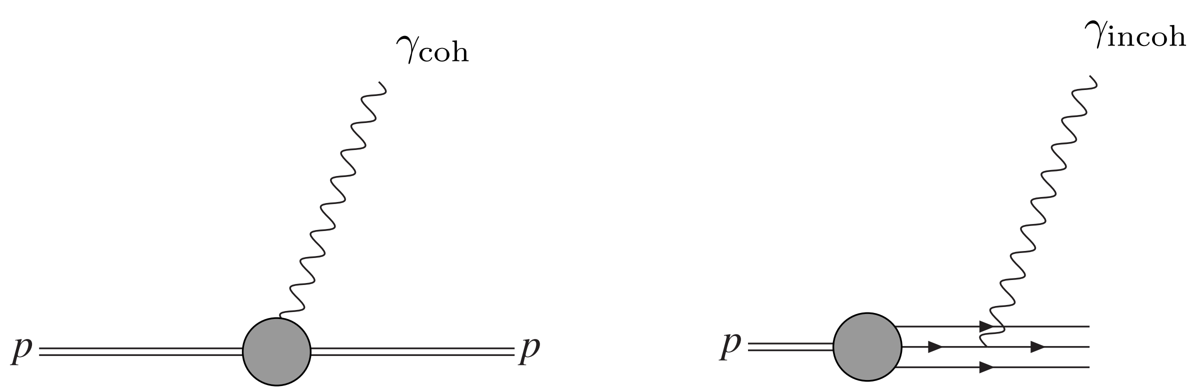
[Manohar, Nason, Salam, Zanderighi; Harland-Lang, Khoze, Ryskin (2016-17)]

THE PROBLEM:

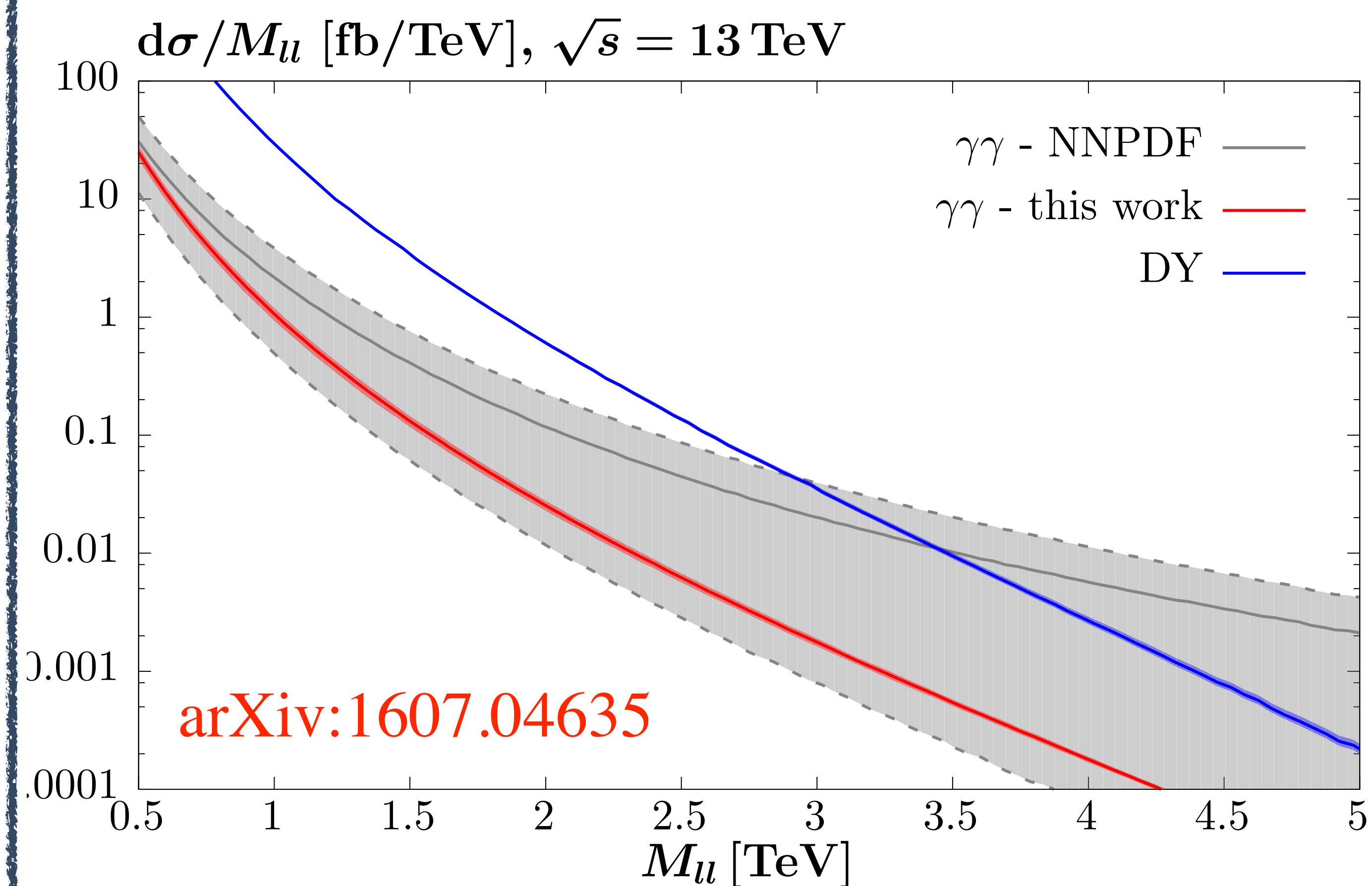
- Although the photon content of the proton is small, it could become relevant for production of high-mass resonances
- If considered on the same footing of other partons → large uncertainties

THE SOLUTION:

- The photon is *not* just another parton. QED is long range force → large coherent component



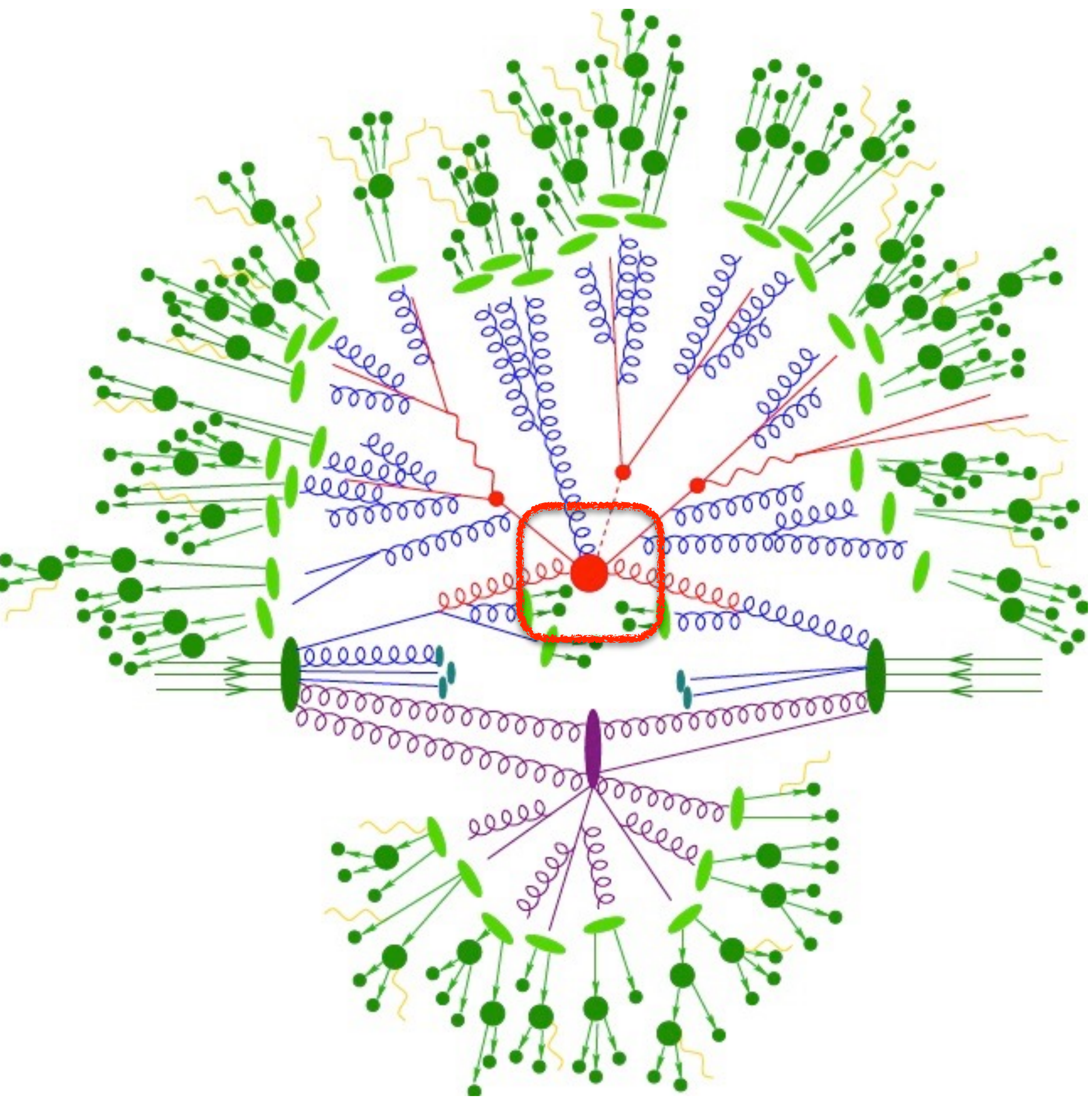
- Photon PDF can be constrained very precisely, model independently



Relatively small photon contribution

The hard process: precise computations

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 f(x_1) f(x_2) \mathrm{d}\sigma_{\mathrm{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q))$$



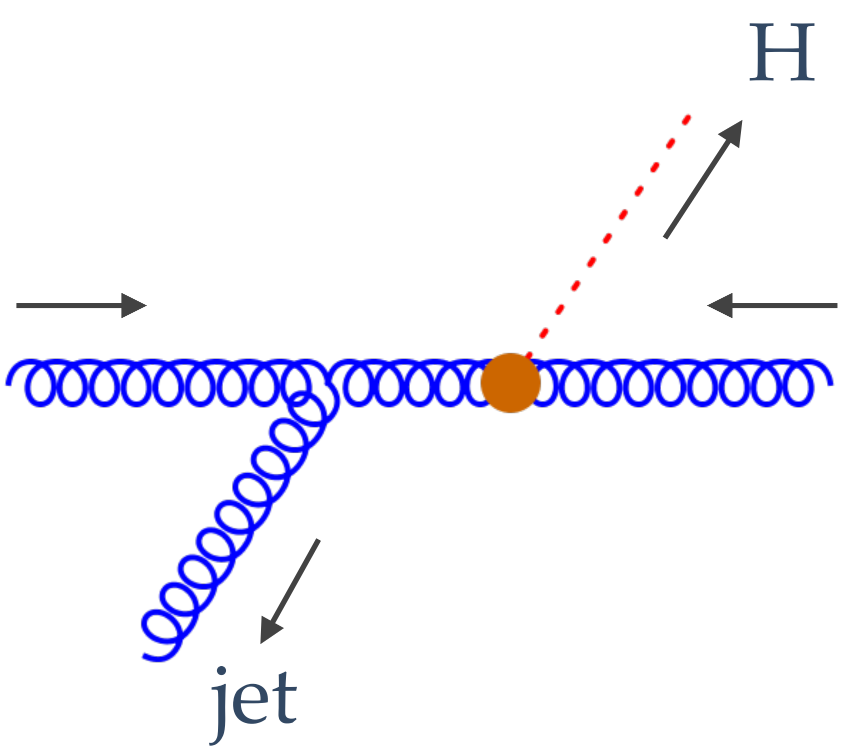
THE ``INTERESTING'' SHORT DISTANCE CROSS-SECTION

- Asymptotic freedom → at high scale QCD is perturbative
- Still, for typical EW scales $\alpha_S \sim 0.1$
- The path to precision: NLO ~ 10%, NNLO ~ 1%. Gluonic processes (e.g. Higgs): large color charges $\alpha_S C_A \sim 0.3$. Even higher orders may be required (N^3LO…)
- Must be able to compare with actual experimental result → keep information on all final state particles (fully exclusive)

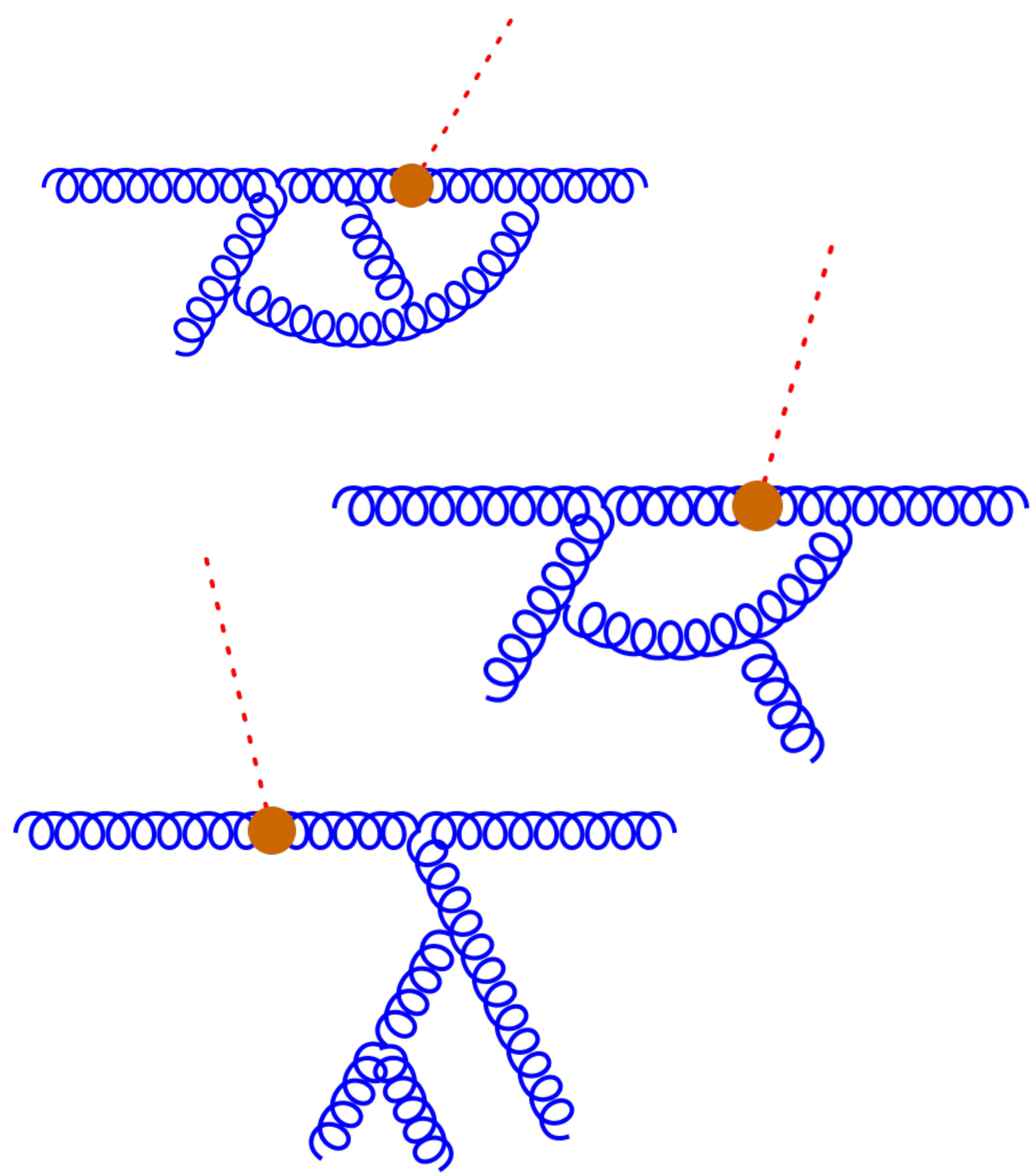
Fully exclusive NNLO: how to get there

Imagine you want to describe the Higgs boson p_T distribution

At LO:



At NNLO: two extra partons

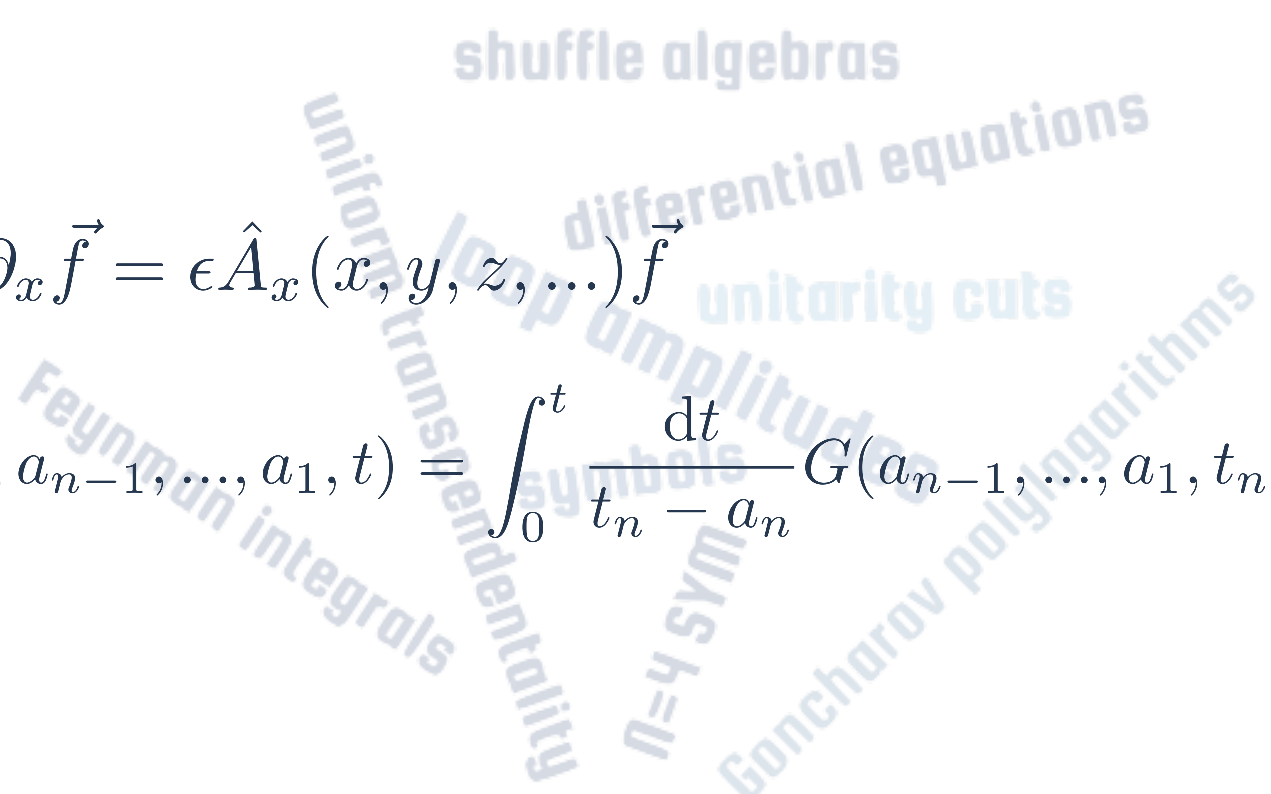


TWO BIG PROBLEMS:

- loop amplitudes
- IR structure of extra emission

Two-loop amplitudes

- Amplitude COMPLEXITY GROWS VERY FAST with the number of scales: invariants (~# legs) and particle masses
- Despite a lot of recent progress (some inspired by N=4 SYM ideas), still pretty limited knowledge. State of the art:
  - Analytically: 2 -> 2, external masses (pp->VV*) [FC, Henn, Melnikov, Smirnov, Smirnov (2014-15); Gehrmann, Manteuffel, Tancredi (2014-15)]
  - Numerically: 2->2, internal/external masses (pp-> tt, pp->HH) [Czakon; Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016)]



$$\partial_x \vec{f} = \epsilon \hat{A}_x(x, y, z, \ldots)\vec{f}$$

$$G(a_n, a_{n-1}, \ldots, a_1, t) = \int_0^t \frac{\mathrm{d}t}{t_n - a_n} G(a_{n-1}, \ldots, a_1, t_n)$$

- Important steps towards 2->3 and structure of massive amplitudes [Badger et al., Bonciani et al., Papadopoulos et al., Gehrmann et al., Melnikov et al…]
- *GOING BEYOND THAT MAY REQUIRE SUBSTANTIAL RETHINKING OF OUR APPROACH*

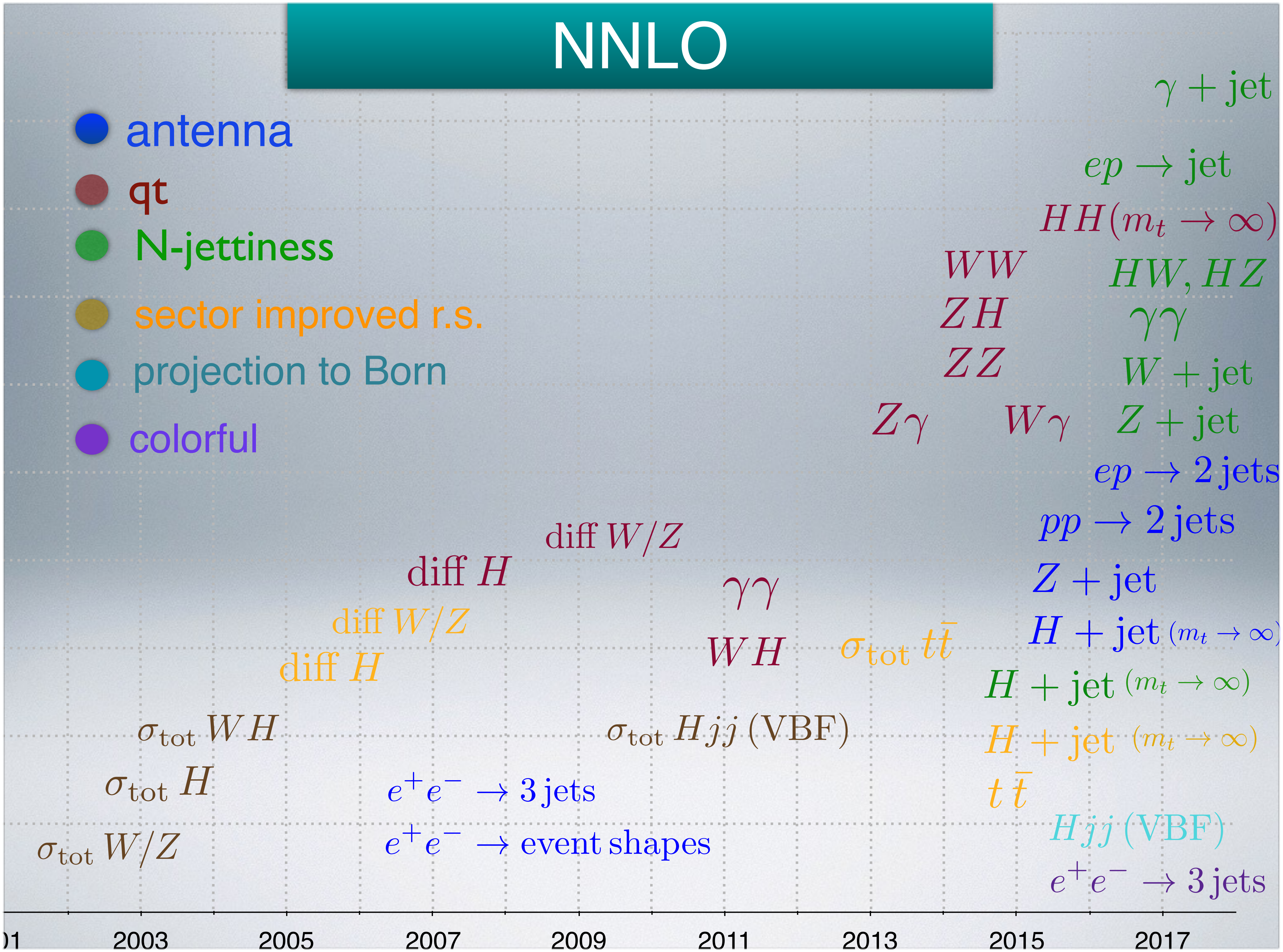
IR structure of real emission

- Even if all amplitudes are known, IR structure of real emission makes NNLO computations conceptually challenging, especially for processes with non trivial color flow and when taking into account proper experimental setup (*cuts, fiducial region > excl. predictions*)
- Recent past: conceptual progress that allows to overcome *in principle* this problem (*Antenna, Stripper, FKS+sector decomposition, P2B, q_T, N-jettiness, colorful NNLO…*)
- *In practice*, we can compute 2 → 2 processes, with large computer clusters (average time: ~100.000 CPU hours, *x1000 increase w.r.t. 2 →1*)

- Past year: from ``PROOF OF PRINCIPLE'' to ACTUAL PHENOMENOLOGY, for 2->2 processes
- Once again: *going beyond that may be problematic*

Fully inclusive: pheno predictions for H@N^{3}LO in gluon fusion [Anastasiou et al. (2016)] and VBF in the DIS^2 approx [Dreyer and Karlberg (2016)]

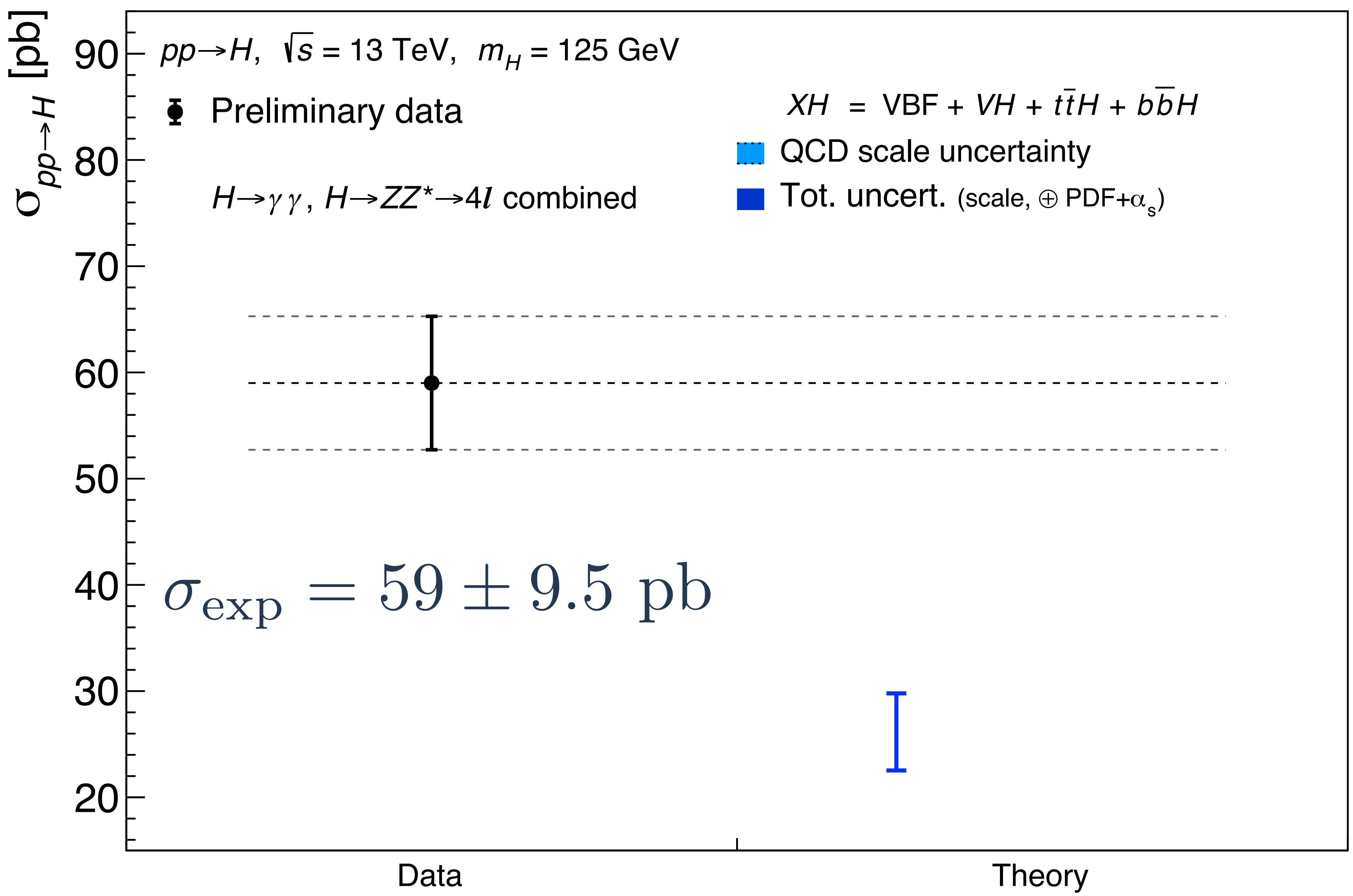
2016-17: 2→2 phenomenology at NNLO

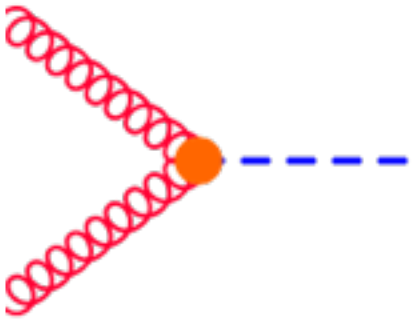


[G. Heinrich, CERN colloquium Jul. 2017]

Great progress, but going beyond hadronic 2→2 highly non trivial

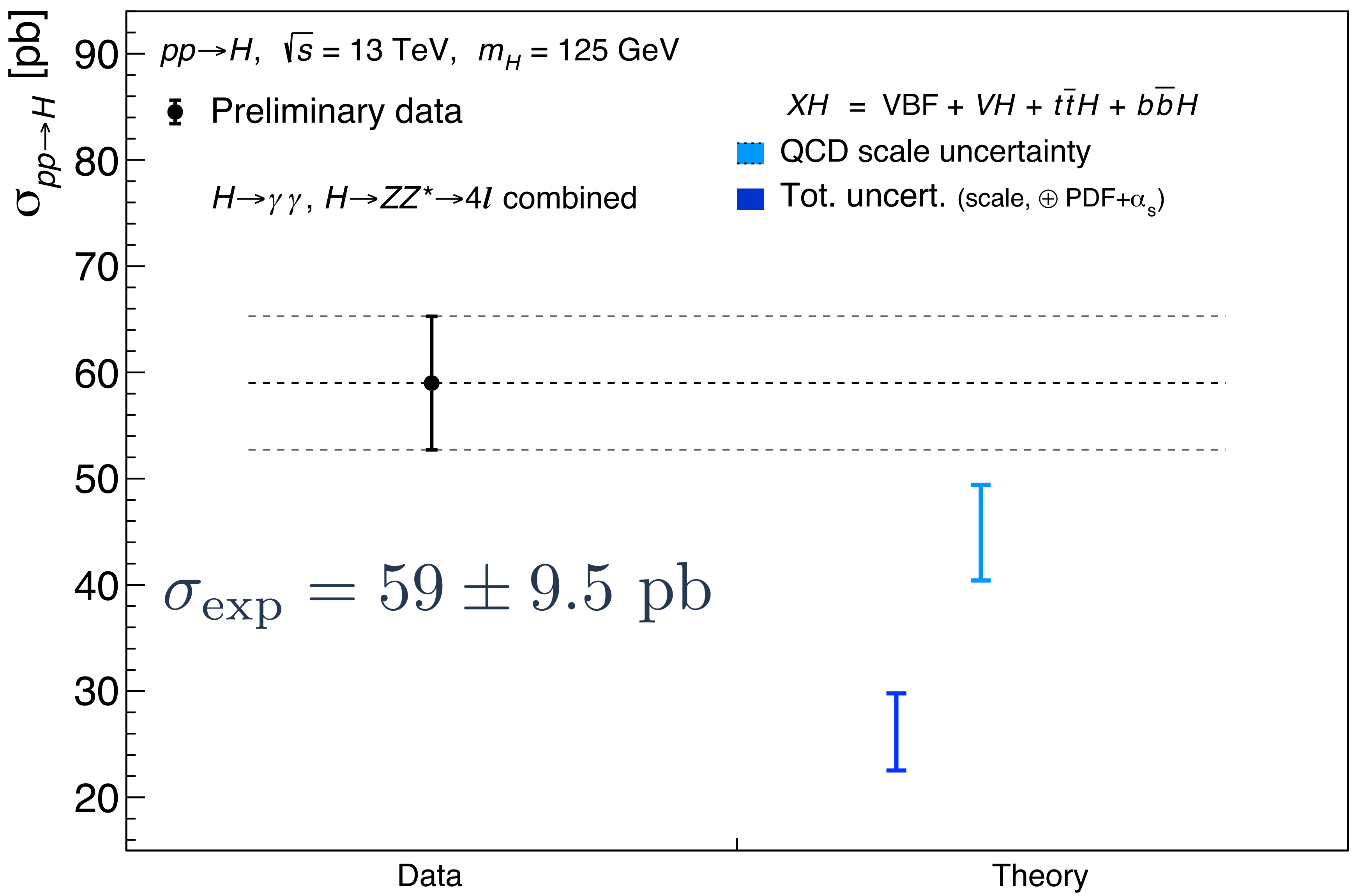
Results 1: *(high enough)* pert. theory is reliable

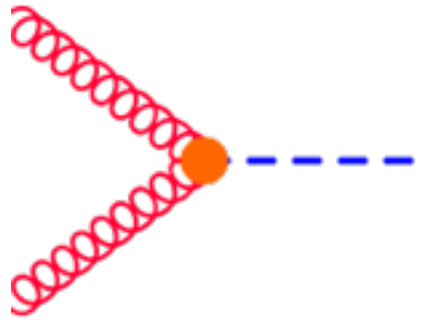


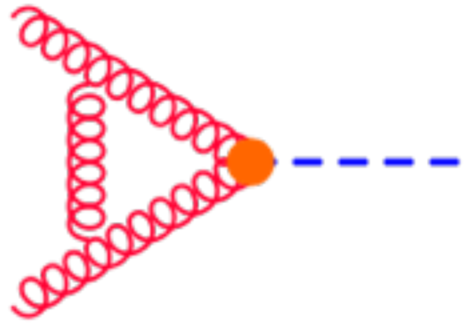


$\alpha_S{}^2$

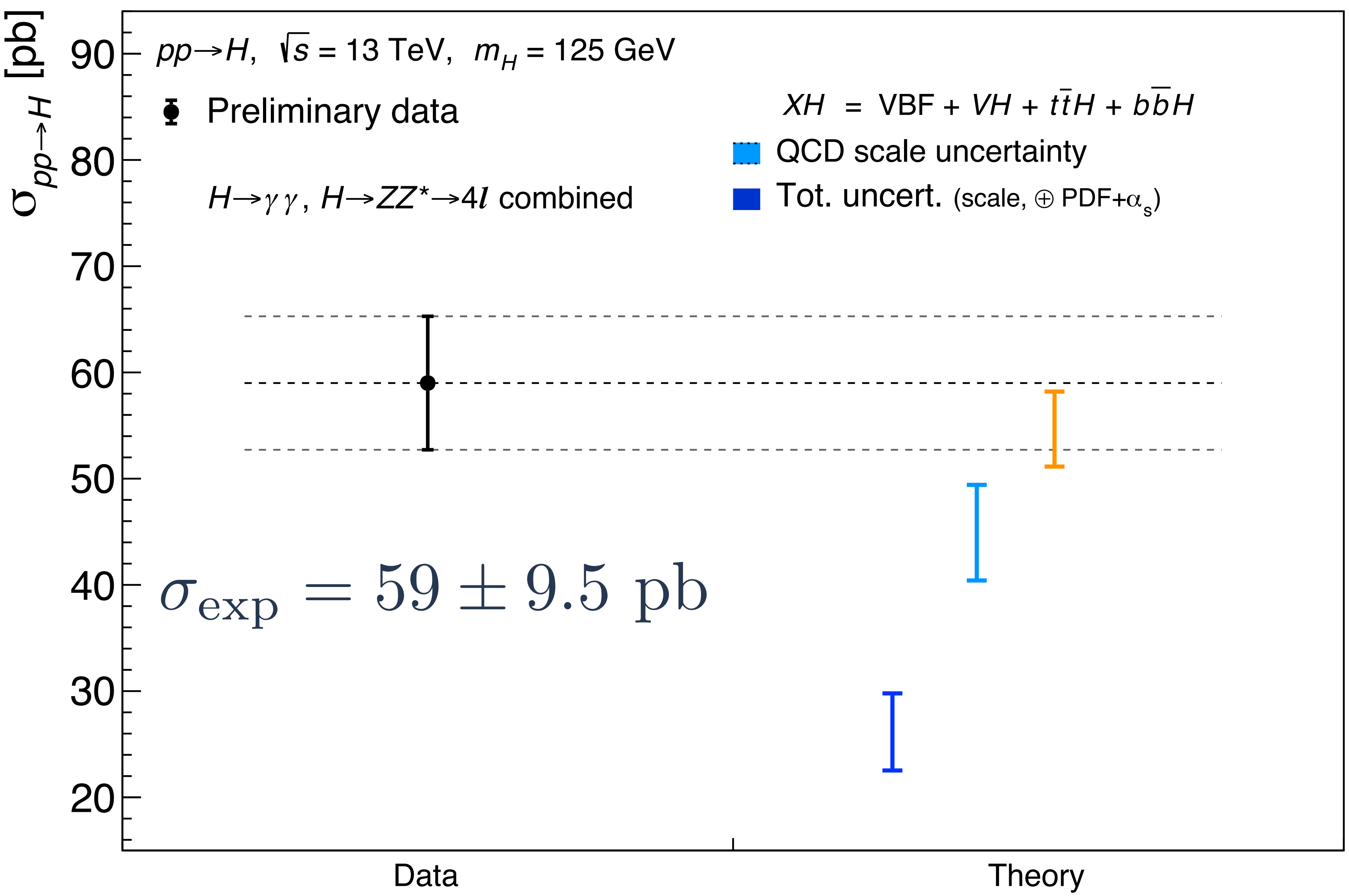
Results 1: *(high enough)* pert. theory is reliable

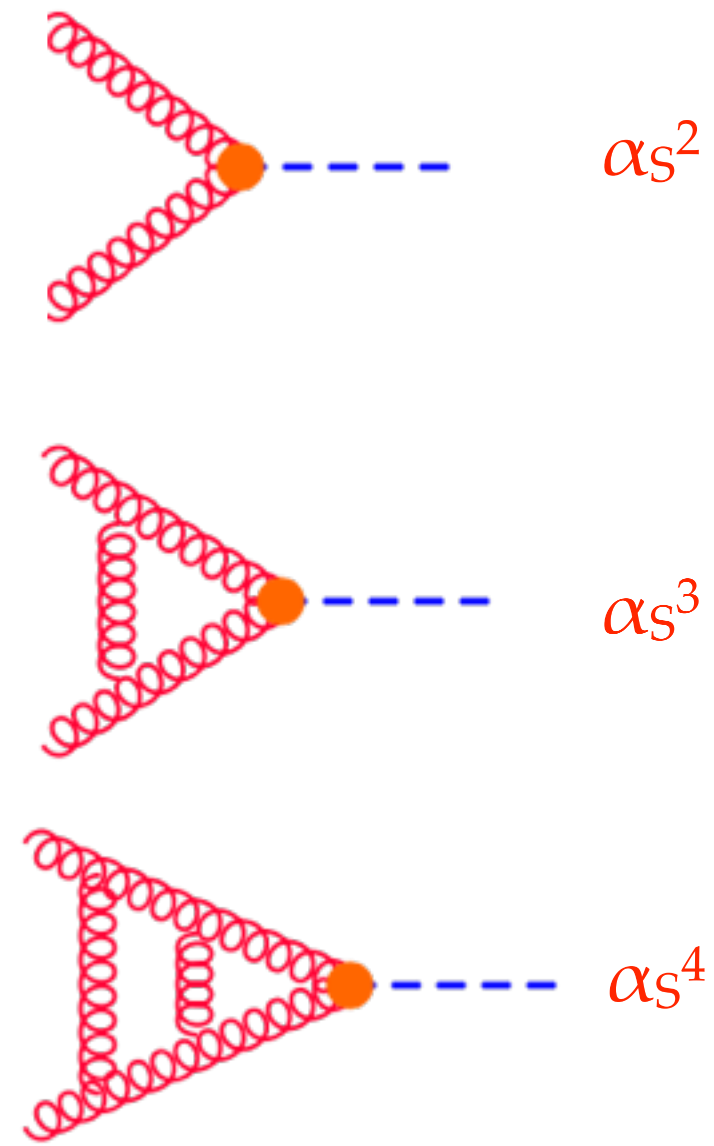






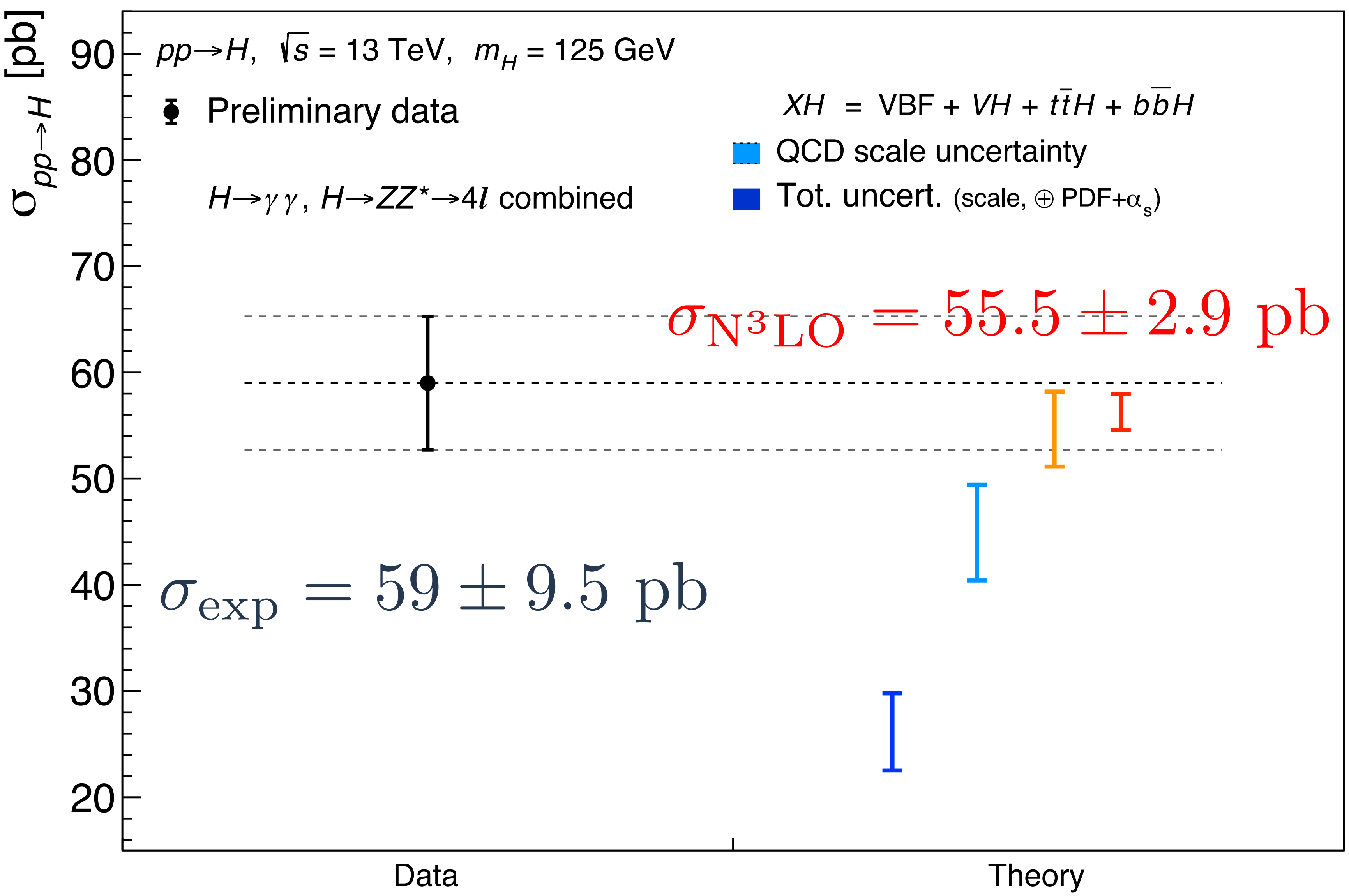
Results 1: *(high enough)* pert. theory is reliable

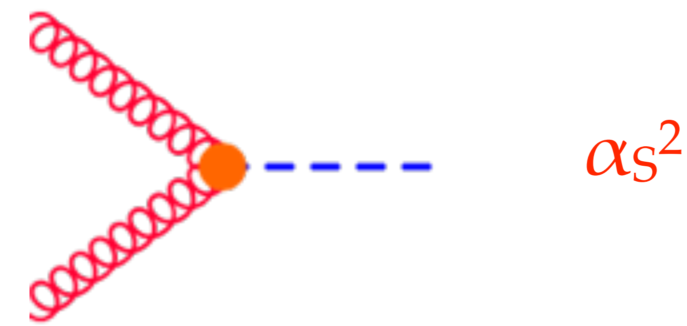


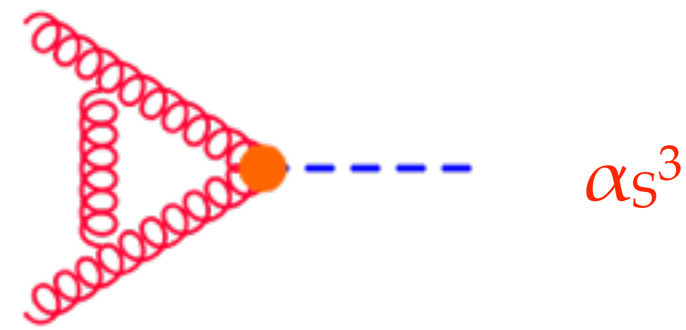


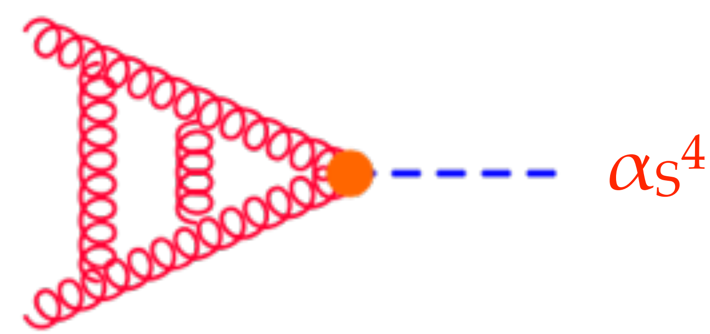
[Anastasiou, Melnikov; Harlander, Kilgore]

Results 1: *(high enough)* pert. theory is reliable



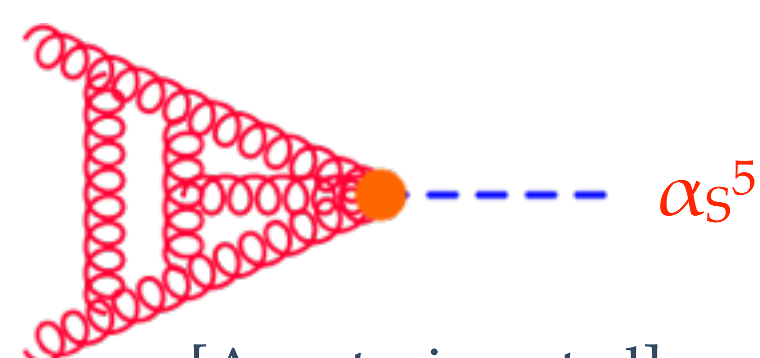






[Anastasiou, Melnikov; Harlander, Kilgore]

N^{3}LO results needed to establish perturbative convergence / reduce residual theoretical uncertainty

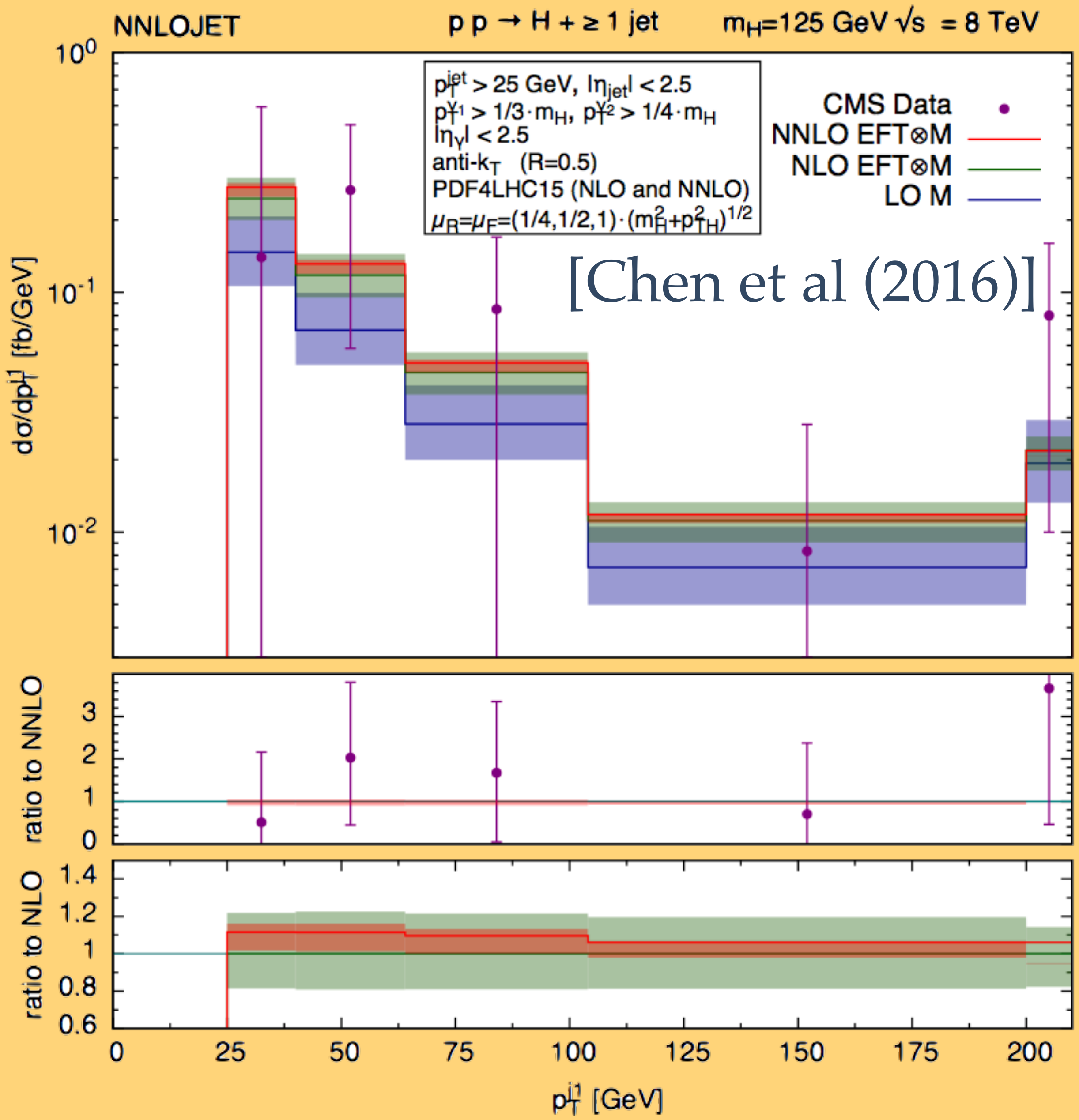


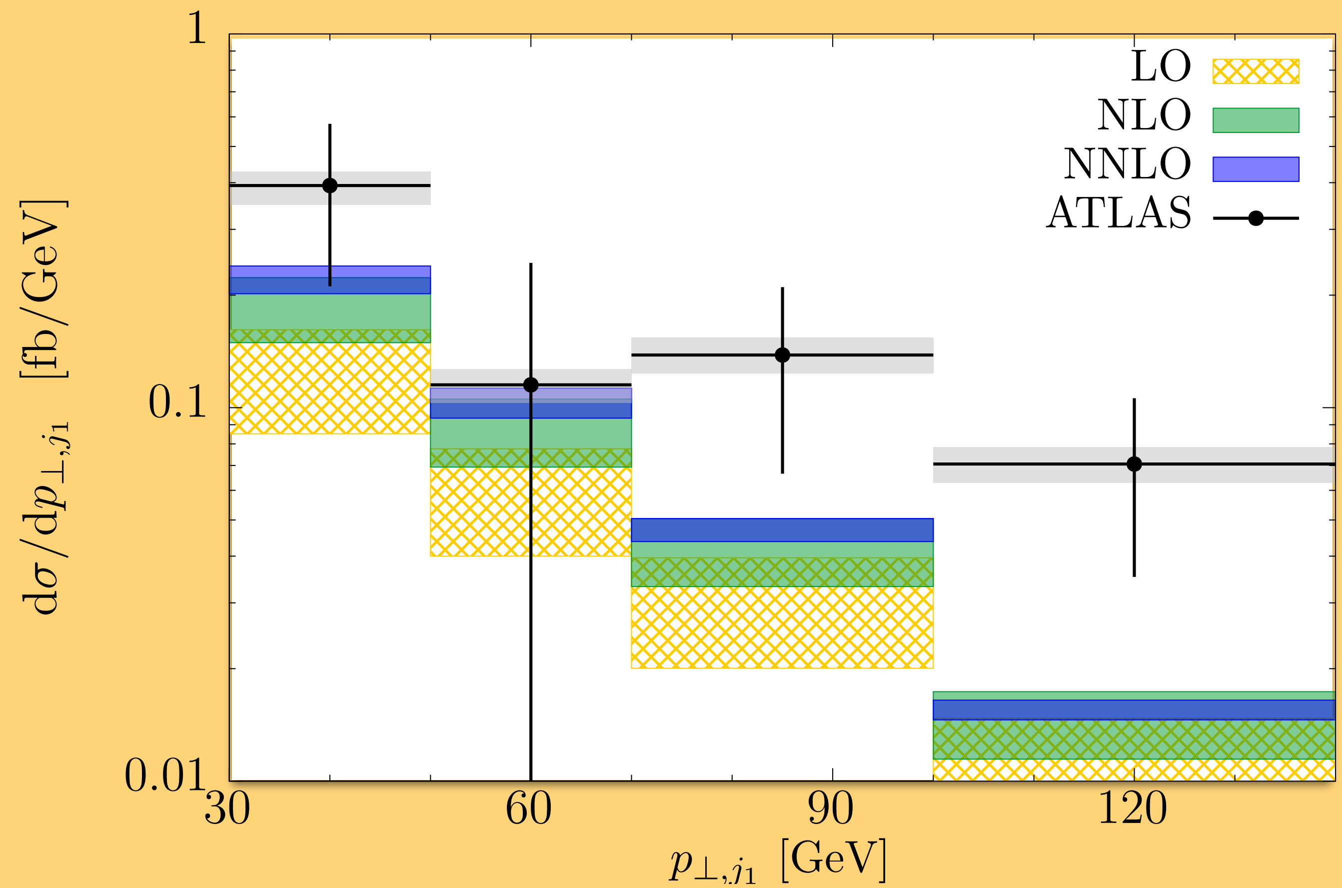
[Anastasiou et al]

Results 1: *(high enough)* pert. theory is reliable

Similar picture at the differential level:

$O(\alpha_s^5)$ [NNLO] needed to match exp. systematics



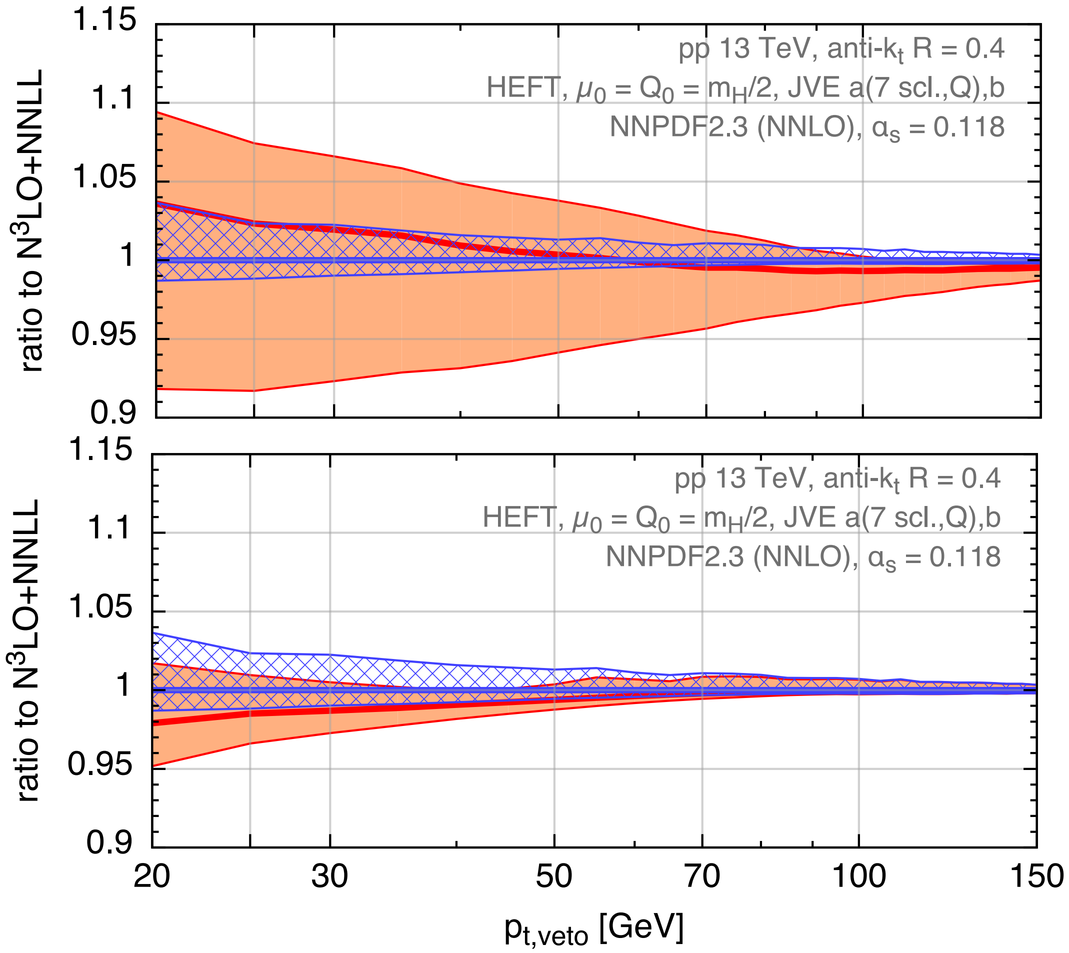


[FC, Melnikov, Schulze]

13 TeV data are coming in…

Results 2: *(high enough)* pert. theory is robust

HIGGS WITH JET VETO



[Banfi et al (2015)]

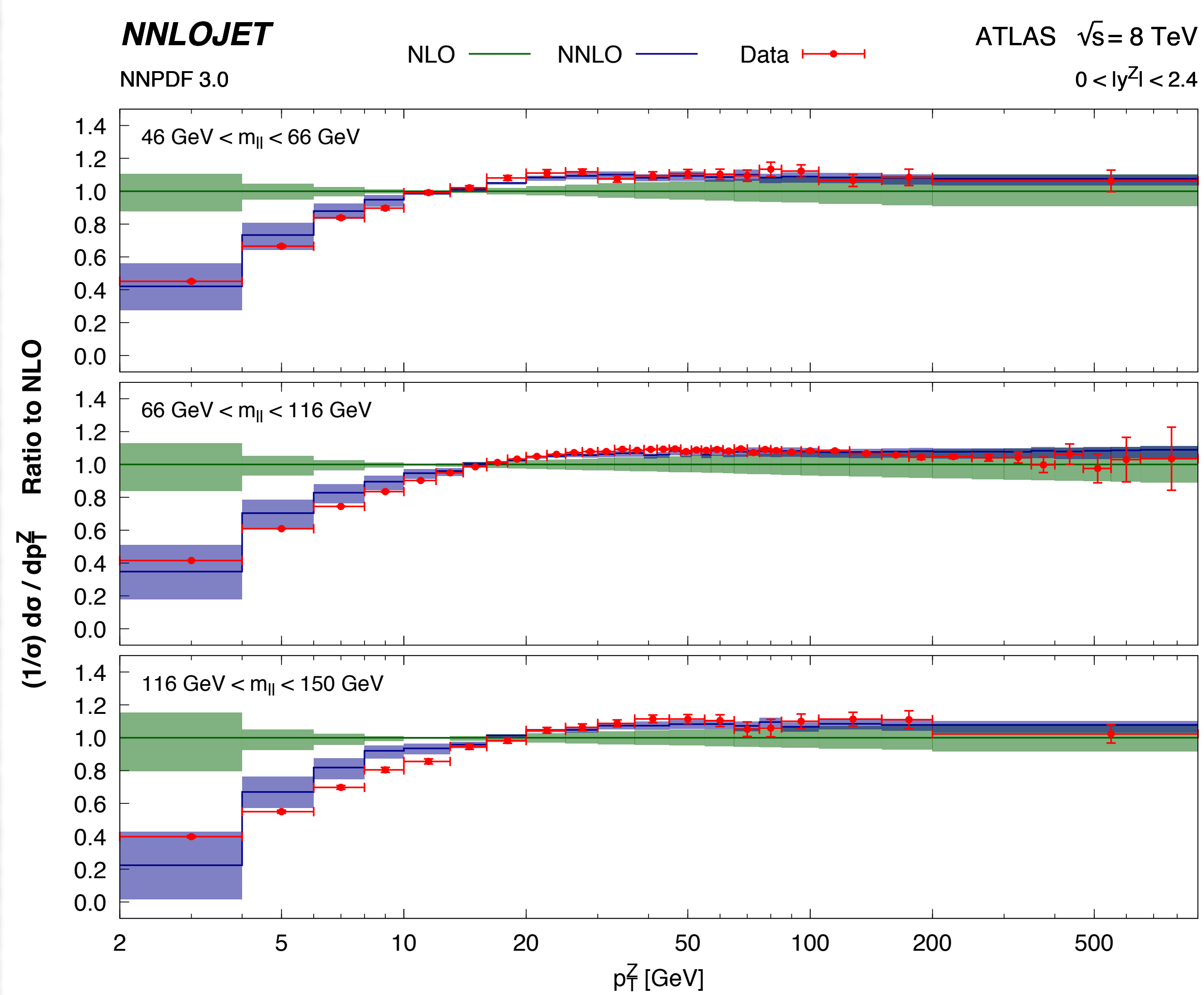
- Adding NNLL$^+$ to N^{3}LO: no big effect for $p_t \gtrsim 25$ GeV
- Adding N^{3}LO to NNLO+NNLL$^+$: drastic reduction in uncertainties

$$C_A \ln^2 (25/m_h) \sim C_F \ln^2 (5/m_Z)$$

Z p_T: DATA/THEORY

NNLO works down to ~5 GeV

(NLO: ~ 40 GeV)

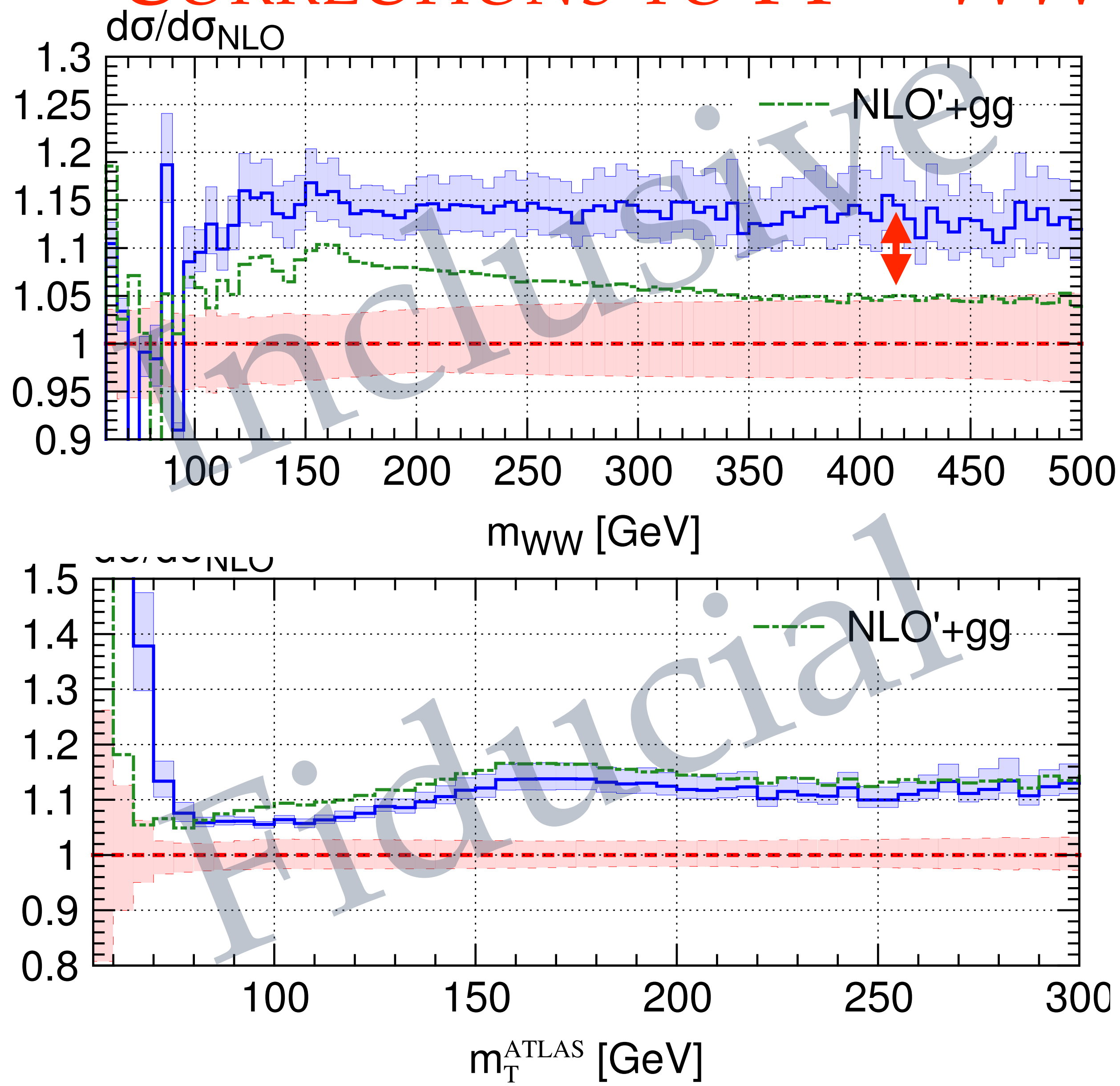


[Gehrmann-De Ridder et al. (2016-17)]

Results 3: *fiducial comparisons are crucial*

Especially for processes / obs. / cuts involving jets

CORRECTIONS TO PP→WW



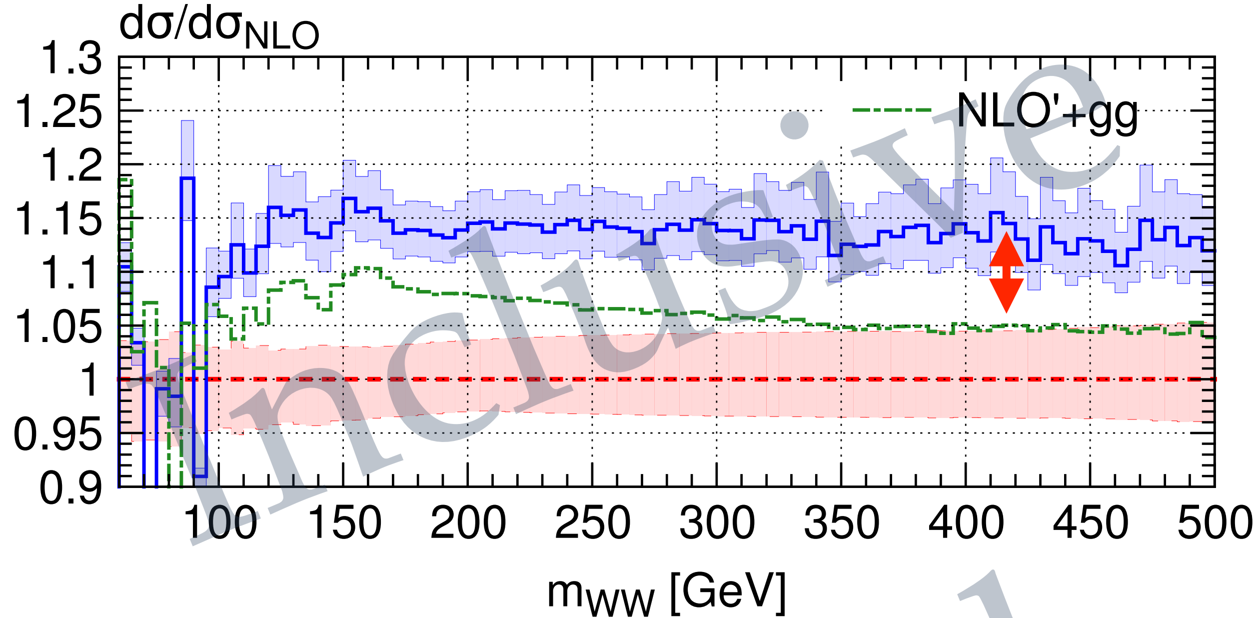
[Grazzini et al (2016)]

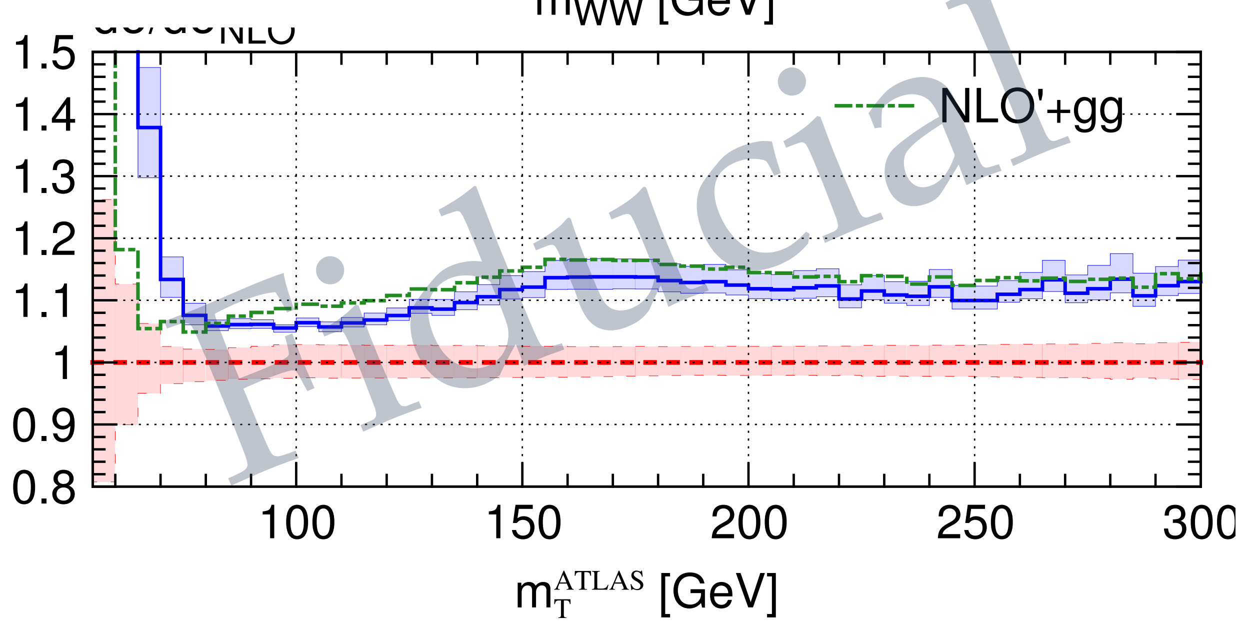
- Inclusive: gg→VV small
- Fiducial: gg → VV dominates *(higher order corrections in* [FC, Dowling, Melnikov, Röntsch, Tancredi (2016)])

Results 3: *fiducial comparisons are crucial*

Especially for processes / obs. / cuts involving jets

Corrections to pp→WW

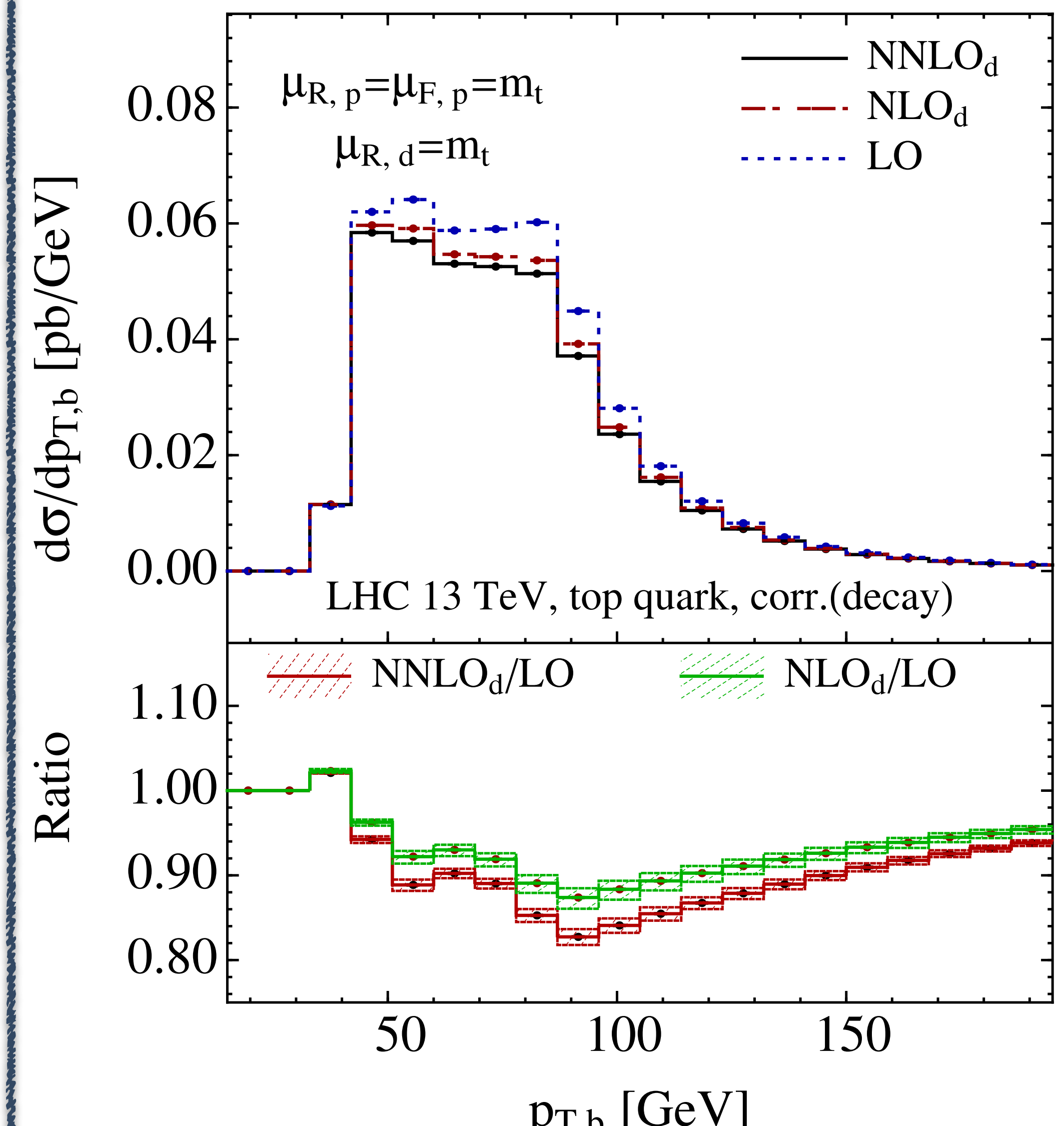




[Grazzini et al (2016)]

- Inclusive: gg→VV small
- Fiducial: gg → VV dominates *(higher order corrections in* [FC, Dowling, Melnikov, Röntsch, Tancredi (2016)])

(t- chan.) Single-top



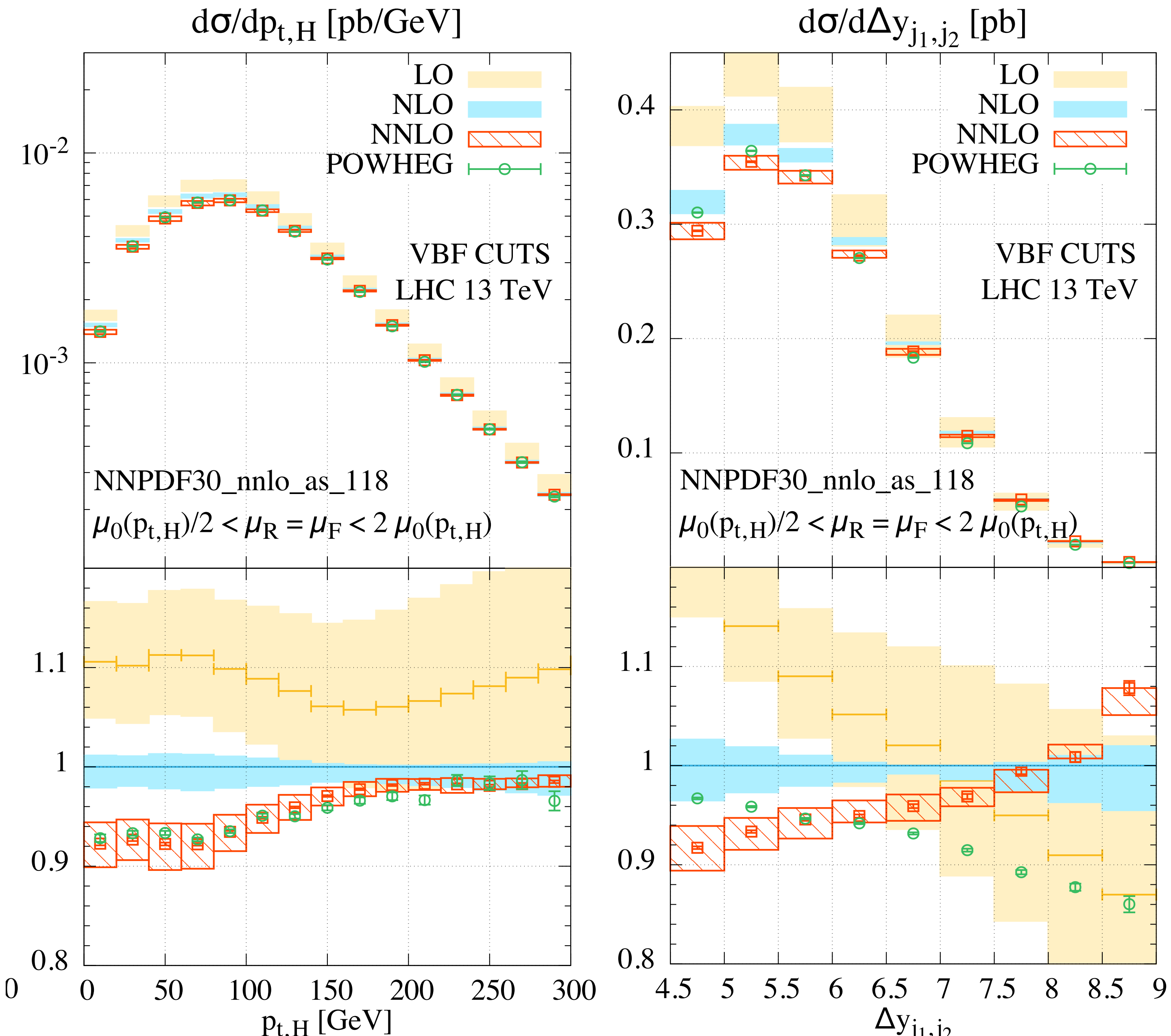
[Berger, Gao, Yuan, Zhu (2016)]

Corrections: small in σ_{TOT}, larger in differential distr.

Results 3: *fiducial comparisons are crucial*

Especially for processes /

VFB HIGGS PRODUCTION



[Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2016)]

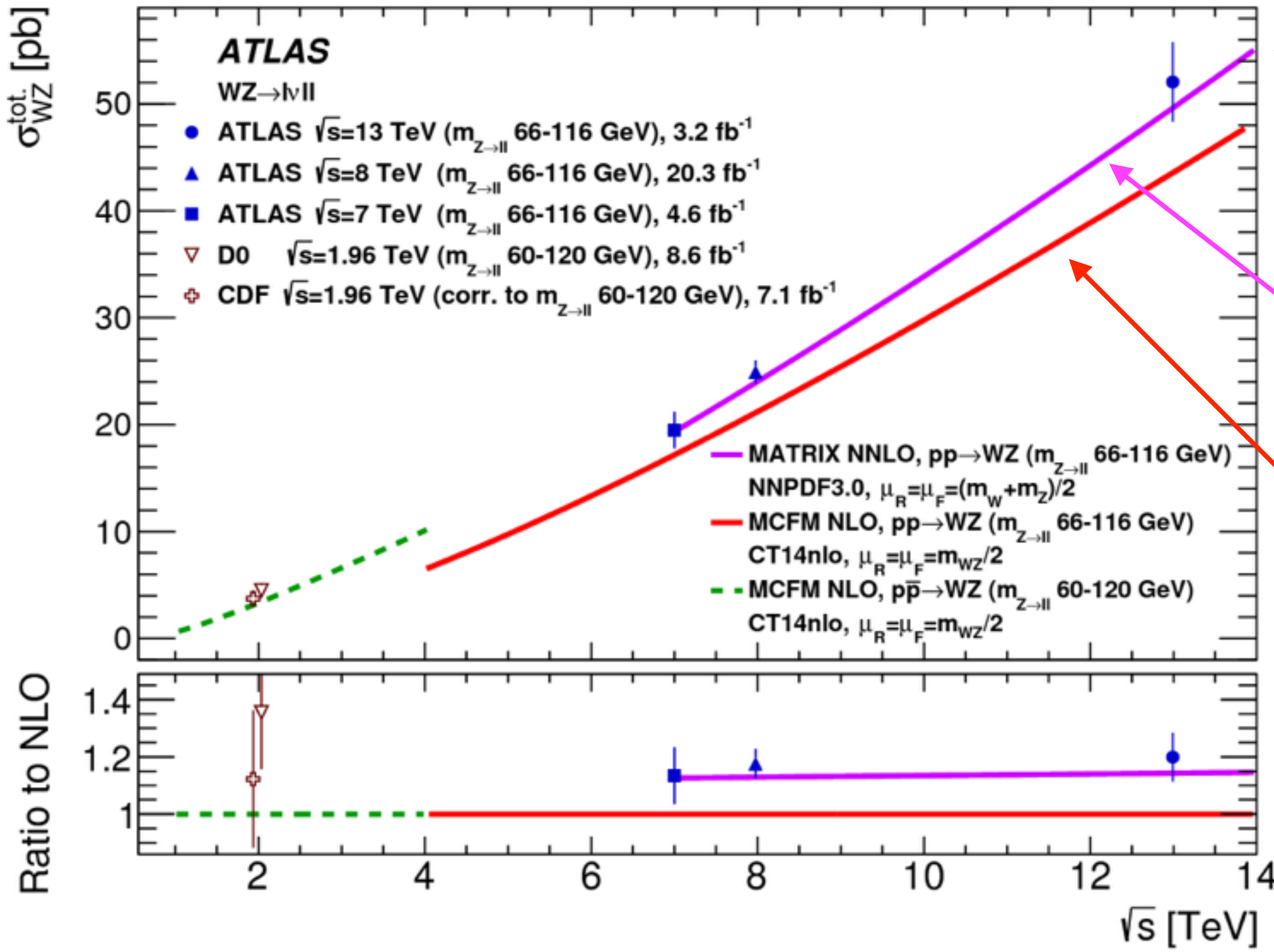
- small ~ 1% corrections to total cross-section
- large ~5-10% corrections to important observables
- non trivial jet dynamics at play [Rauch and Zeppenfeld (2017)]

[Berger, Gao, Yuan, Zhu (2016)]

Röntsch, Tancredi (2016)])

High precision already relevant now

[Grazzini et al. (2017)]



WZ cross-section:

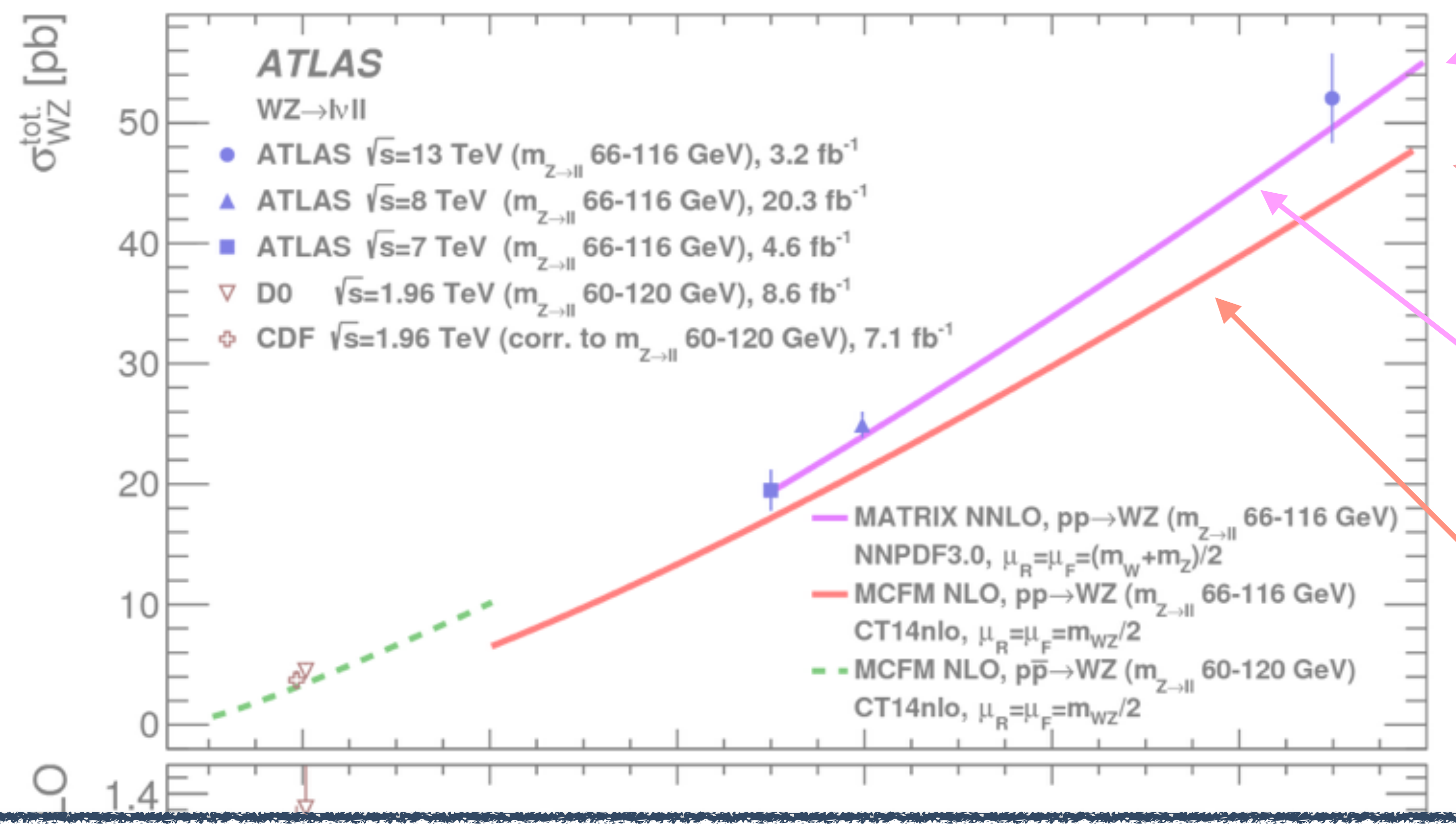
Data vs. Theory

NNLO

NLO

Anomalous couplings…

High precision already relevant now



[Grazzini et al. (2017)]

WZ cross-section: Data vs. Theory

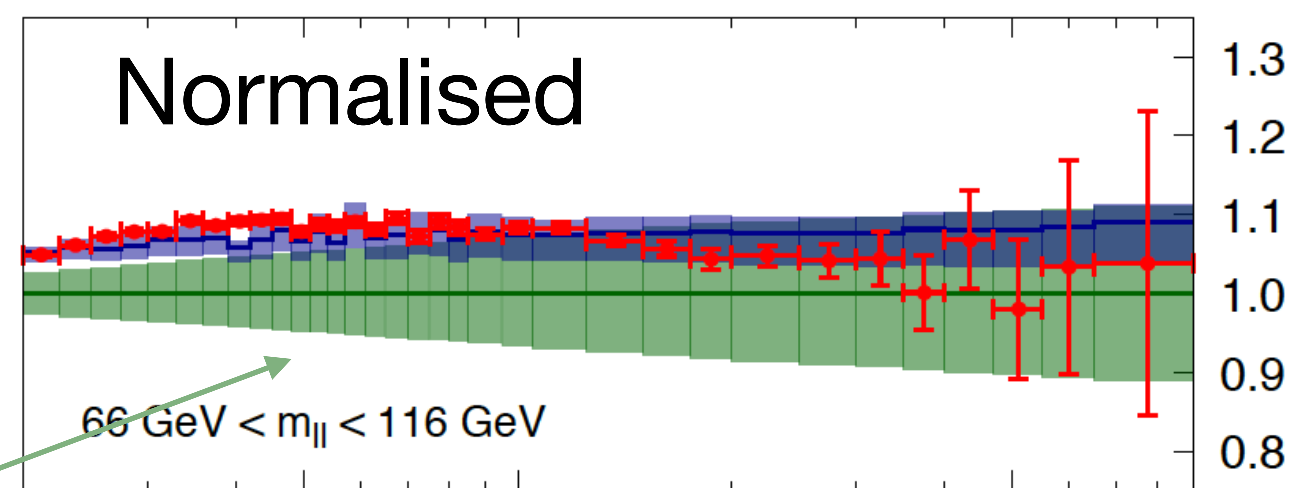
NNLO

NLO

DY di-lepton p_T spectrum: data/theory

NNLO

NLO



[Gehrmann-De Ridder et al. (2016-17)]

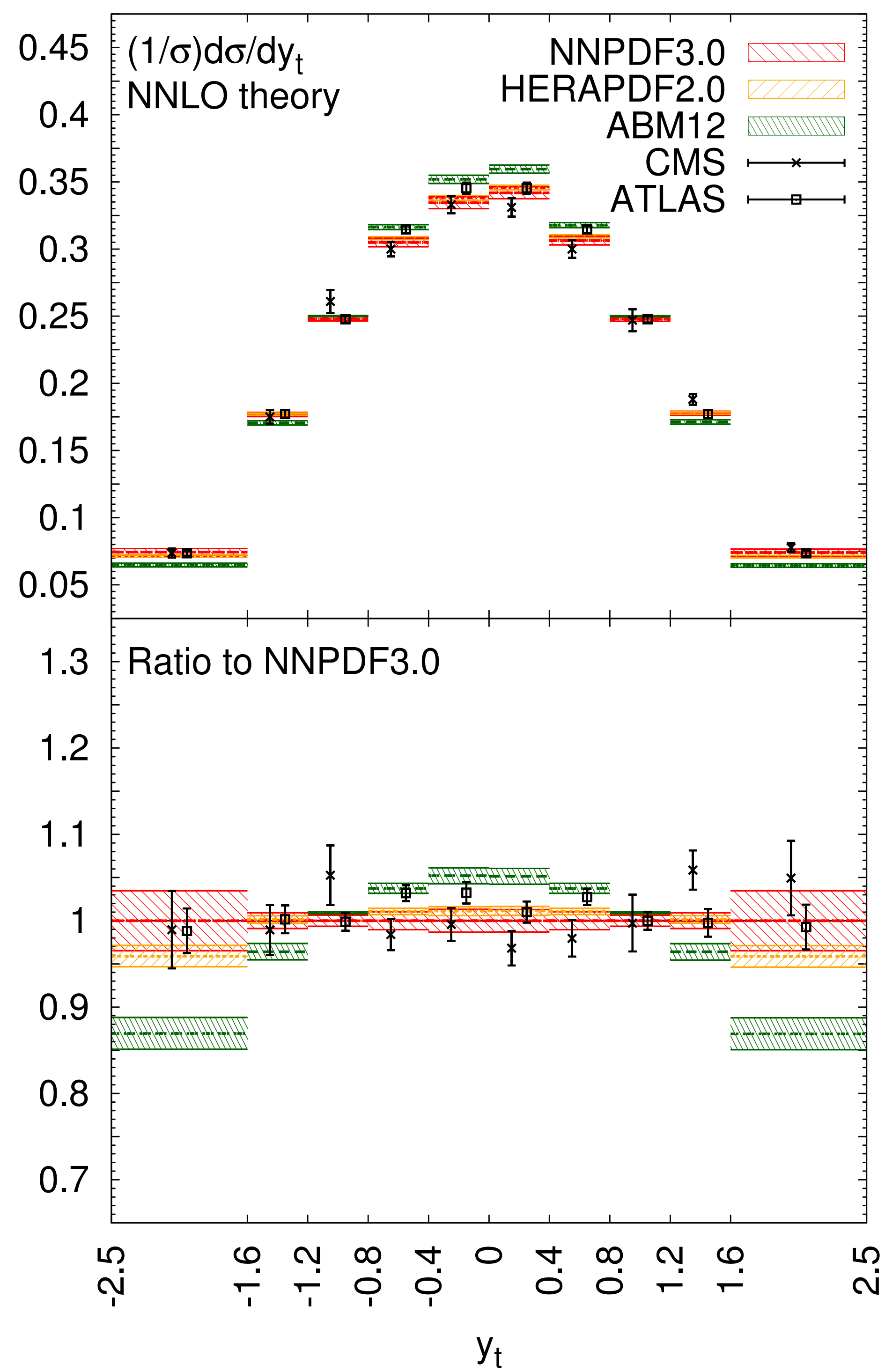
PDF fits, calibrations…

High precision already relevant now

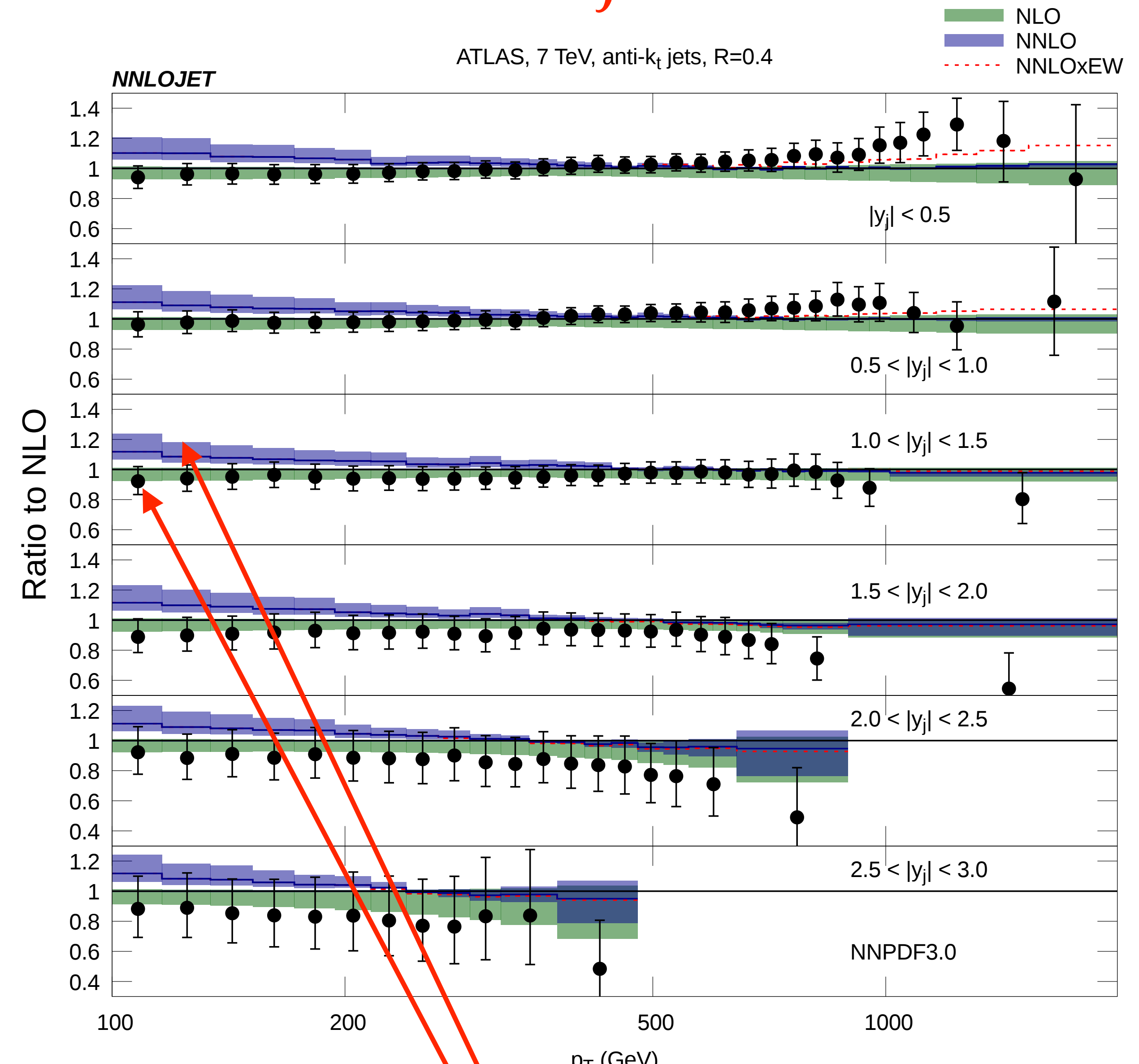
More on the (gluon) PDF…

Top pairs

[Czakon et al (2017)]



Inclusive Jet Spectrum



[Currie, Glover, Pires et al (2016-17)]

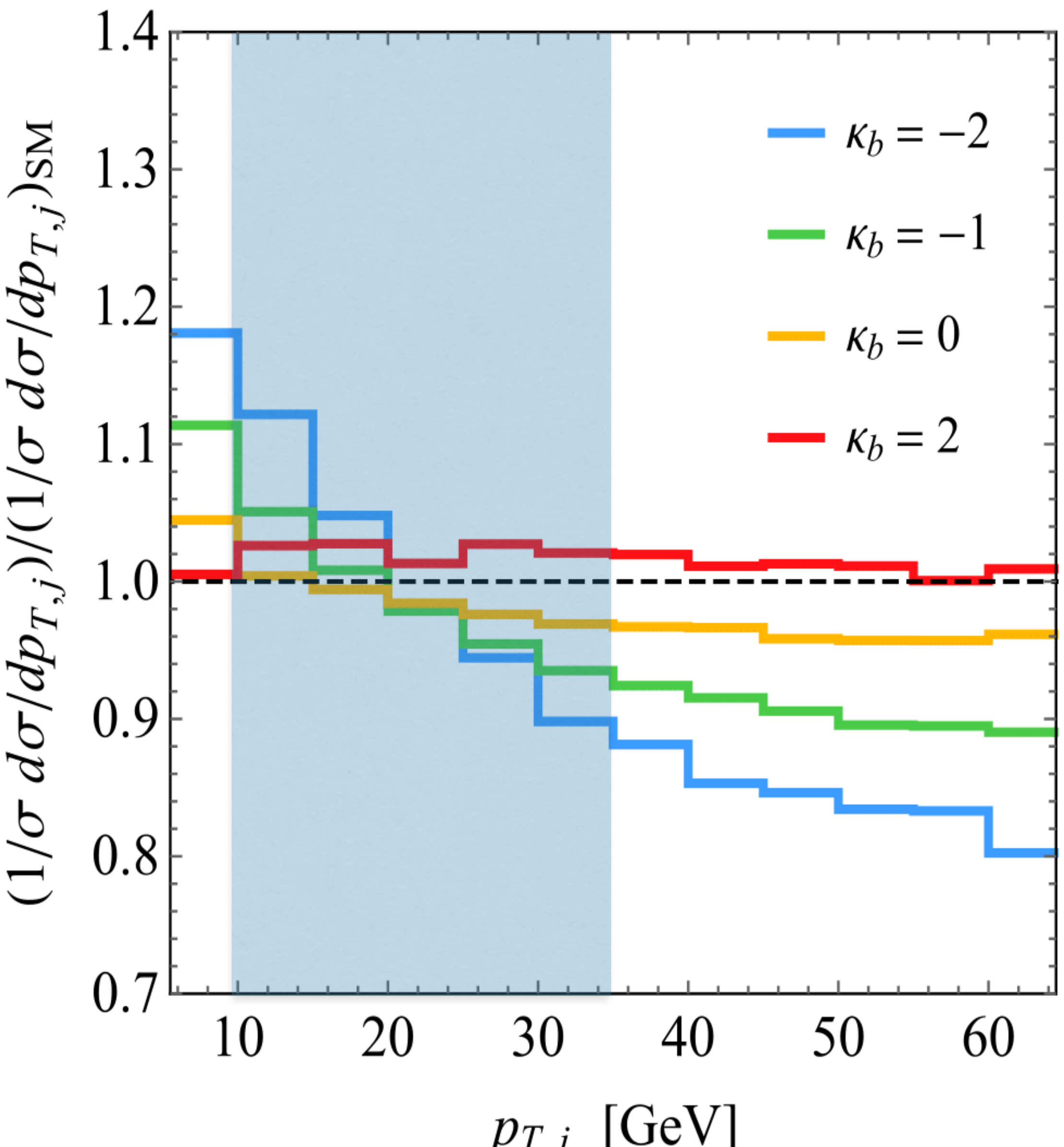
Some features begs for a better understanding. Entering an unchartered territory, explorations just started!

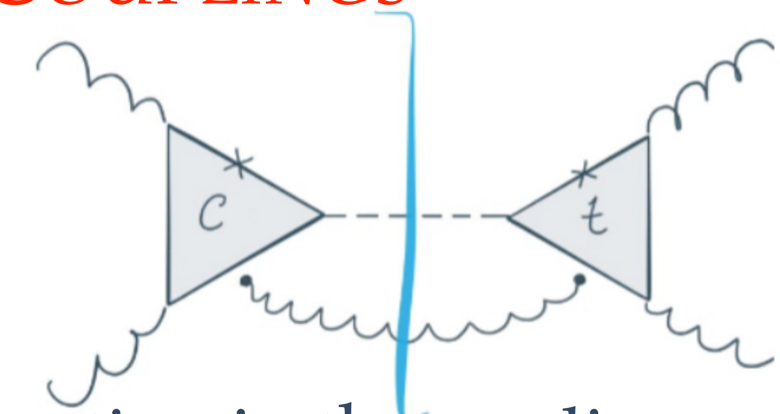
Moving away from the ``safe zone”

- In an ideal world, we would only consider high-Q observables, insensitive to IR radiation → ``standard” f.o. perturbation theory
- In a real world, this is often non possible. FOR EXAMPLE:

CONSTRAINING THE LIGHT YUKAWA COUPLINGS

[Soreq et al; Bishara et al (2016)]



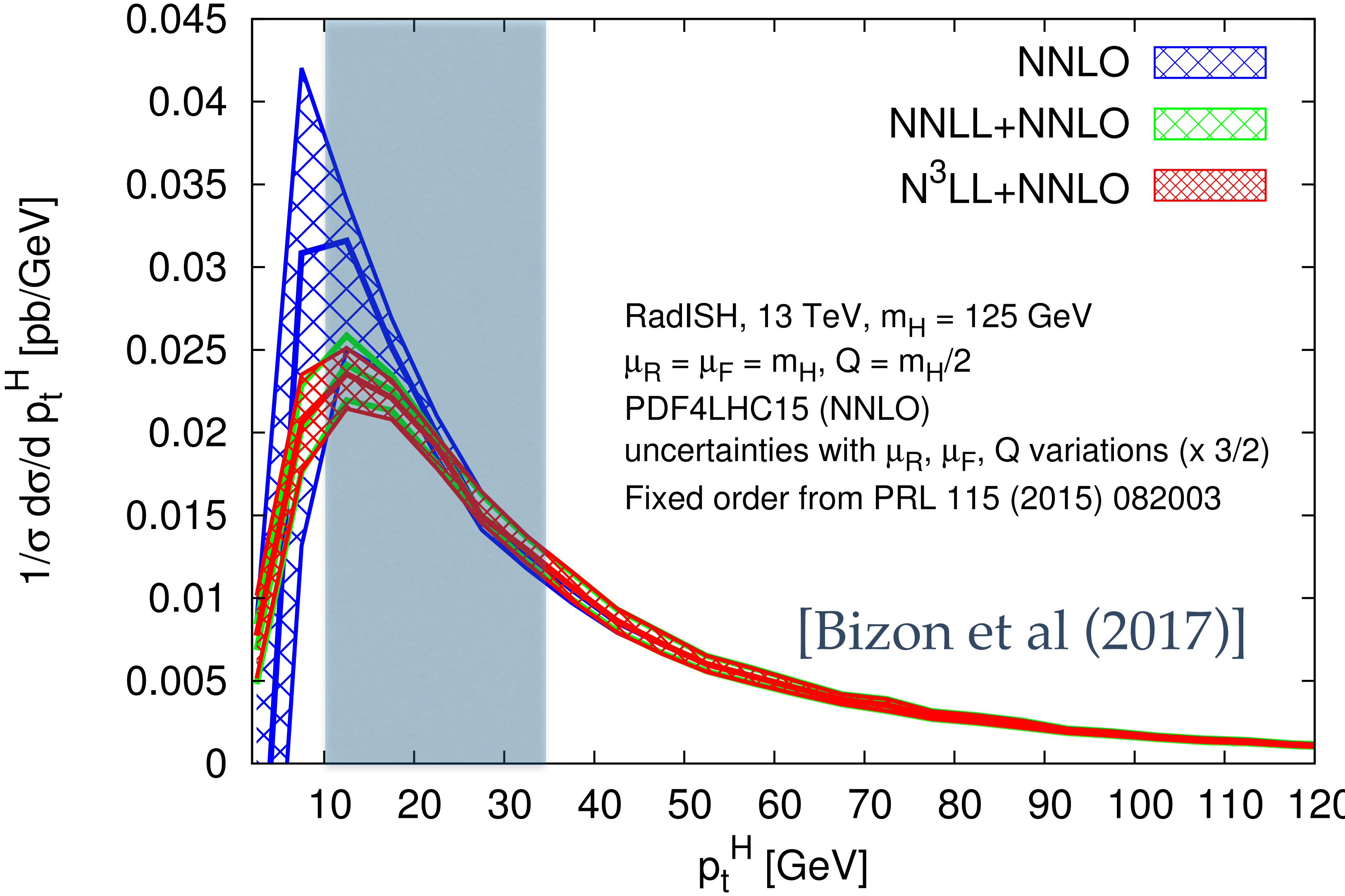


- Interesting information in the medium-low p_t region
- Internal details of (virtual) quark dynamics cannot be neglected (≠top) → highly non trivial loop amplitudes
- NLO EFFECTS COMPUTED ONLY RECENTLY [Melnikov, Tancredi, Wever + Lindert (2017)]
- Soft / collinear extra emission can distort the picture → *must be under control*

Taming logs: the low-p_t Higgs spectrum

$$\alpha_s \ln^2 \frac{p_{t,H}}{M_H} \sim 0.5, \qquad p_t \sim 15 \text{ GeV}$$

- In the low p_t region, perturbation theory develops largish logs
- Universal effects → *can be resummed to all orders*
- RECENTLY, INGREDIENTS FOR VERY PRECISE RESUMMATION COMPUTED [Li and Zhu (2017)]
- THIS ALLOWED FOR N^3LL RESUMMATION → VERY GOOD CONTROL OF THE QCD PART [Bizon, Monni, Re, Rottoli, Torrielli (2017)]



Study of the transition between (recently computed) NLO and resummation under way

Learning from logs: jet dynamics

A better understanding of the soft / collinear structure of QCD can give interesting information on underlying dynamics. Especially true for jets

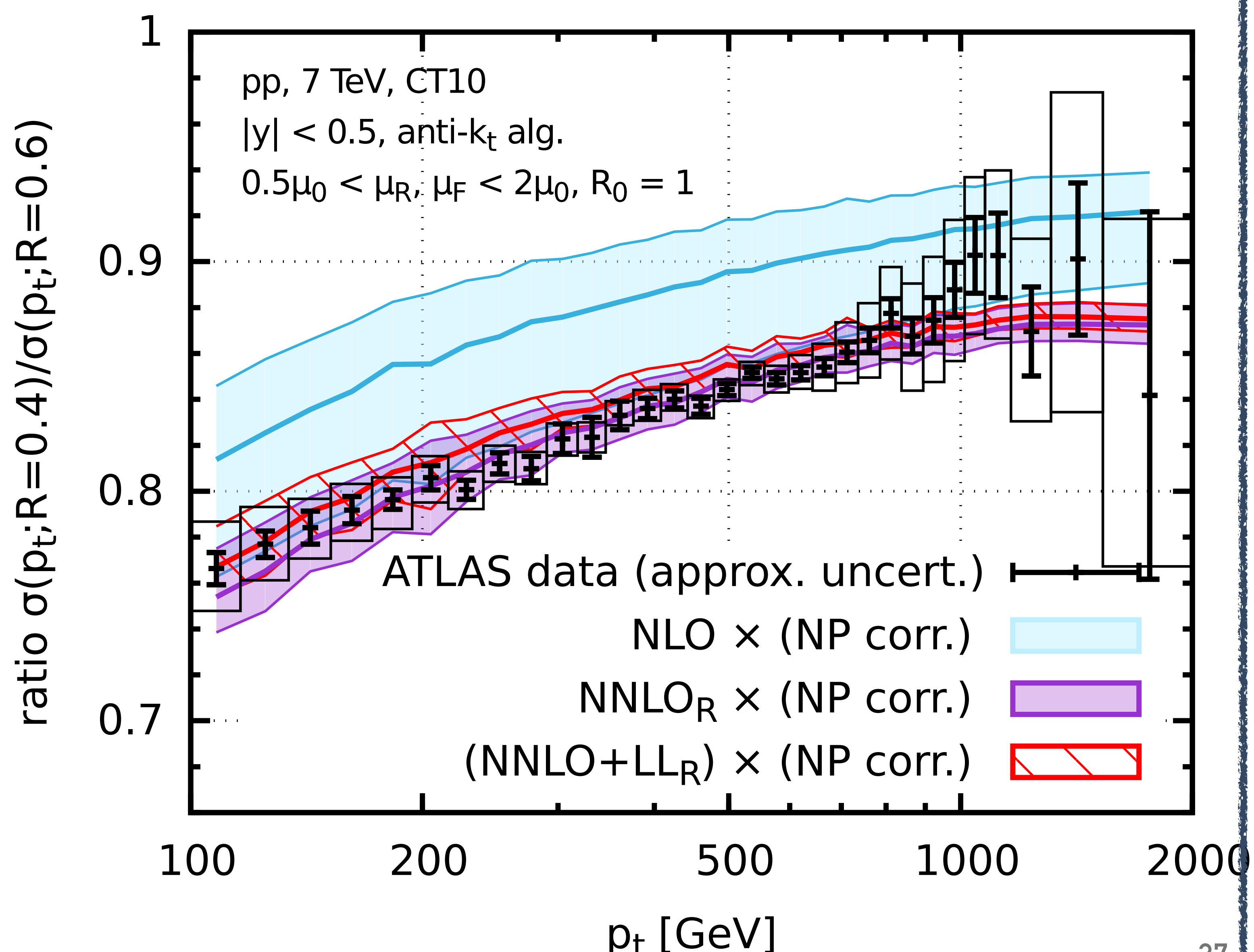
3 effects:

- ➤ perturbative (~ ln R)
- ➤ hadronisation (~ 1/R)
- ➤ MPI/UE (~ R^2)

To disentangle them, need ≥3 R values:

- ➤ 0.6–0.7: large MPI/UE
- ➤ 0.4: non-pert. effects cancel?
- ➤ 0.2–0.3: large hadronisation

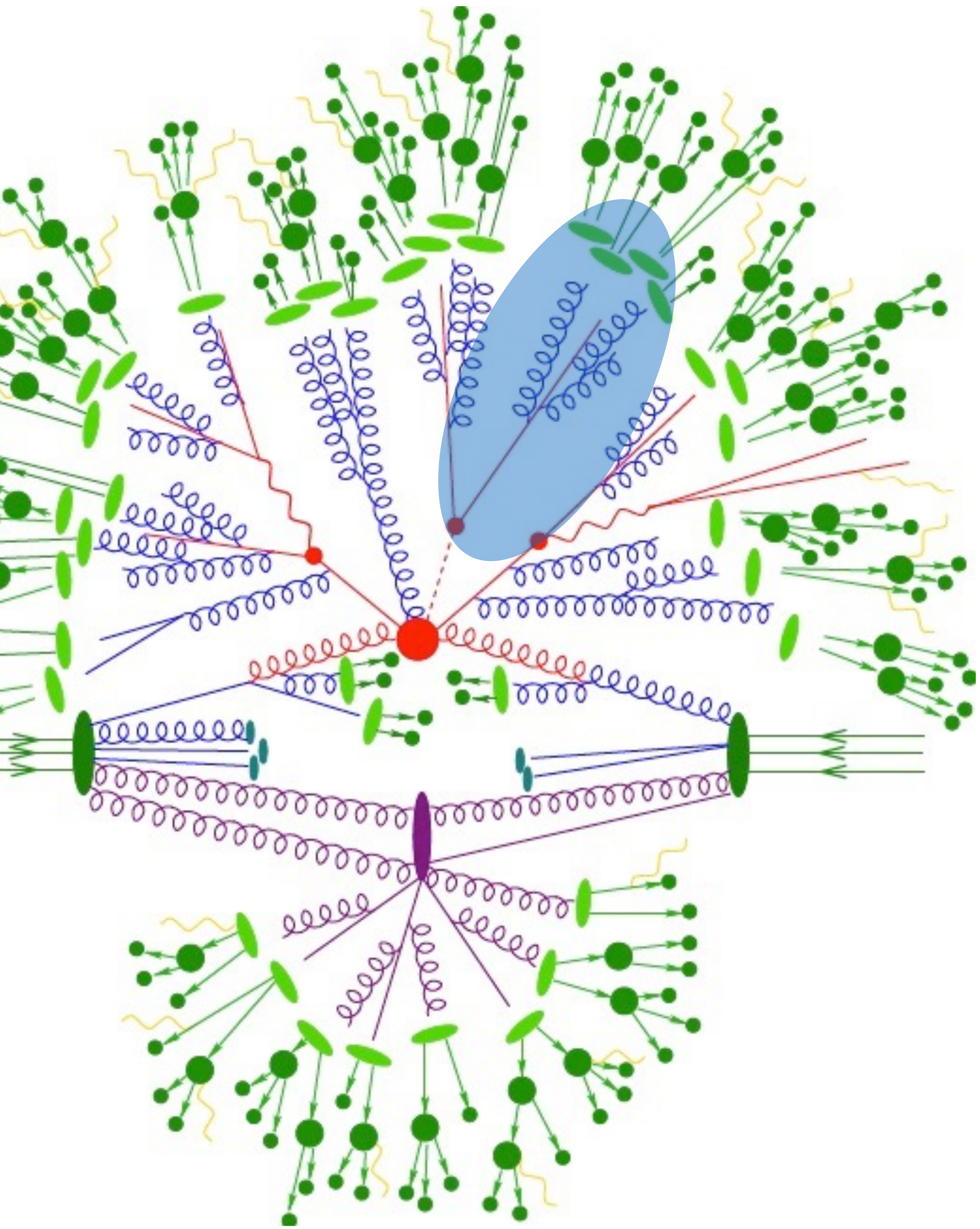
ratio of inclusive jet spectra at R=0.4 and 0.6



[*G.P. Salam, "Future challenges for perturbative QCD" 2016*]

other examples: new observables, jet substructure…

Towards realistic final states: PS



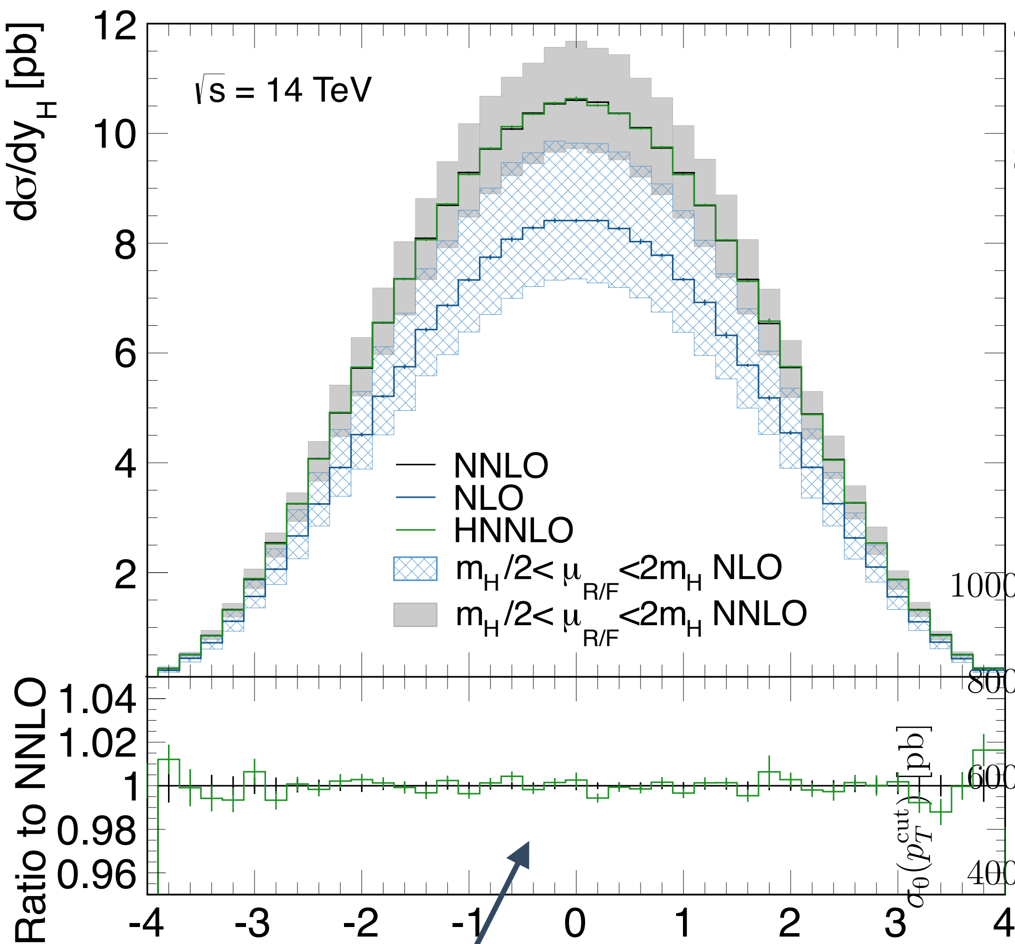
PARTON SHOWER EVOLUTION

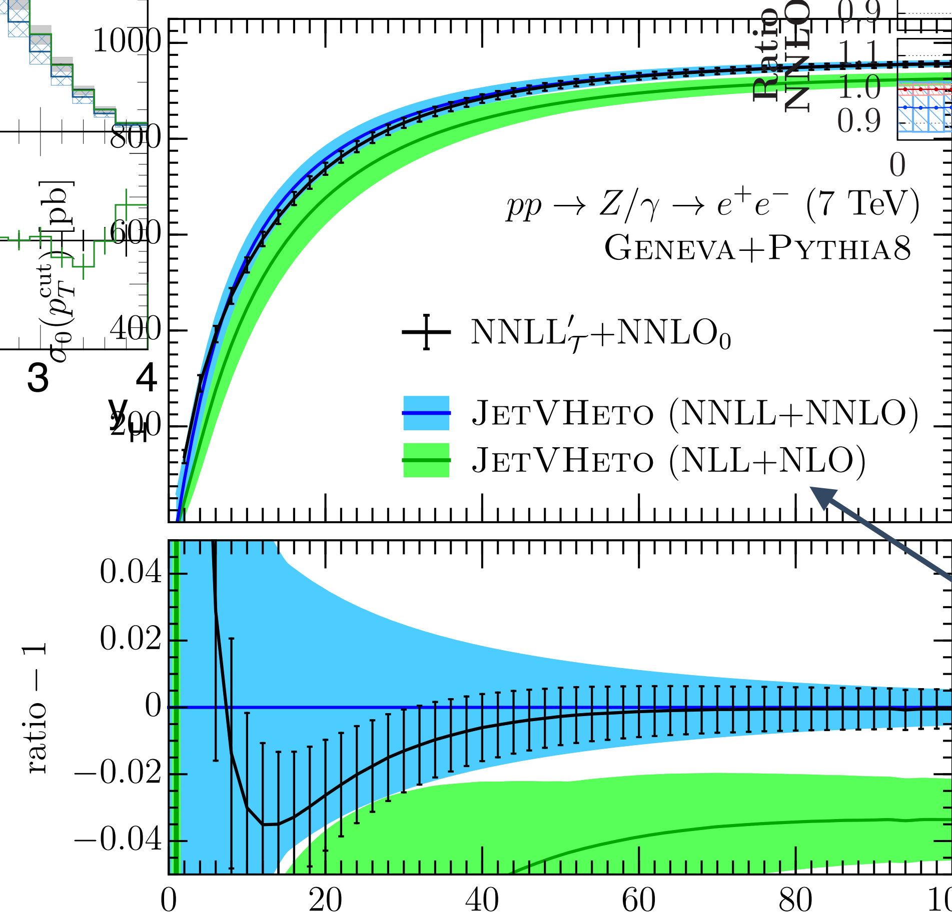
- All order-emission of soft / collinear partons
- Does not capture hard emission / virtual corrections
- As such, IRRELEVANT FOR HIGH-Q PHYSICS
- CAN GENERATE FULL EVENTS → HADRONIZATION† → DETECTOR SIMULATIONS
- Also, although in the (N)LL approximation only, capture multi-parton dynamics (e.g. jet structure…)
- A lot of recent developments…

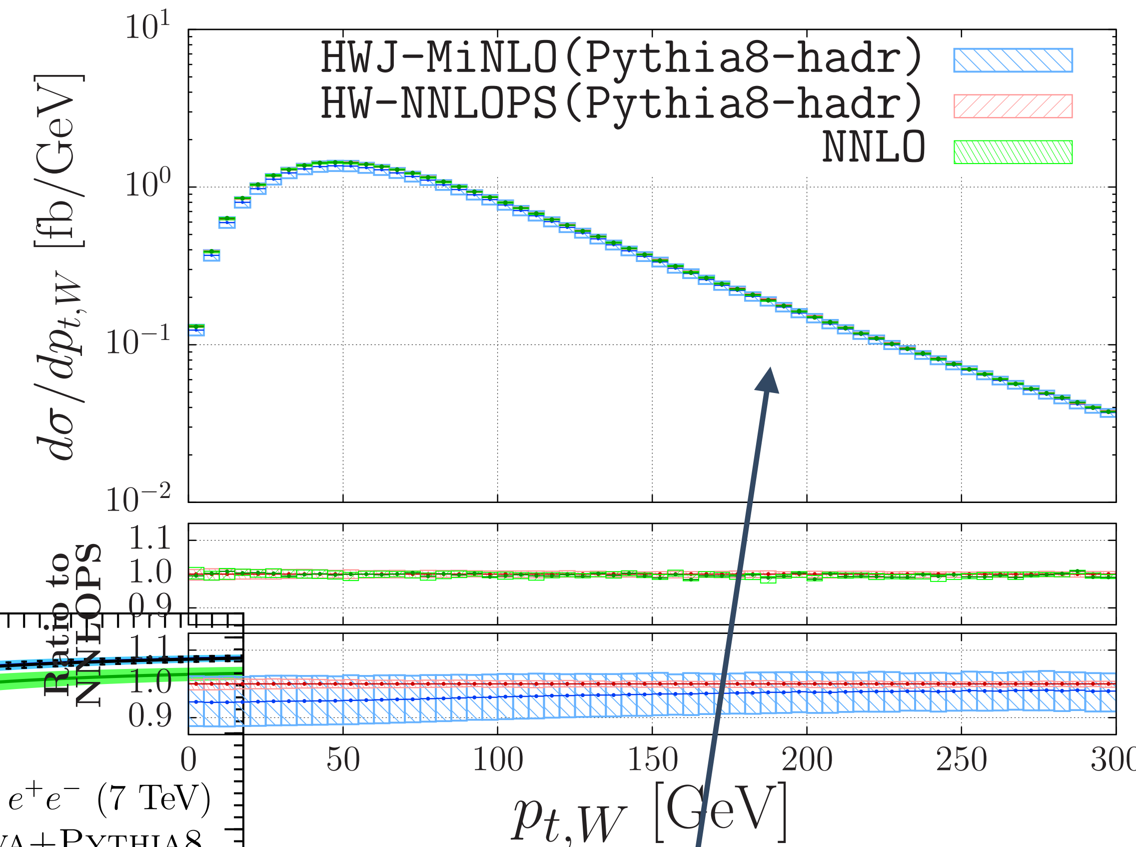
†*here is where we wave goodbye to first principle QFT computations*

The best from both worlds: NNLOPS

Would like to combine very accurate predictions (N^kLO…) to realistic description of final states (hadronization…). First ideas / results on how to achieve this are emerging!







Higgs

[Höche et al, UN²LOPS (2014)]

Drell-Yan

[Alioli et al, GENEVA (2015)]

WH

[Astill et al, MINLO (2016)]

Conclusions and outlook

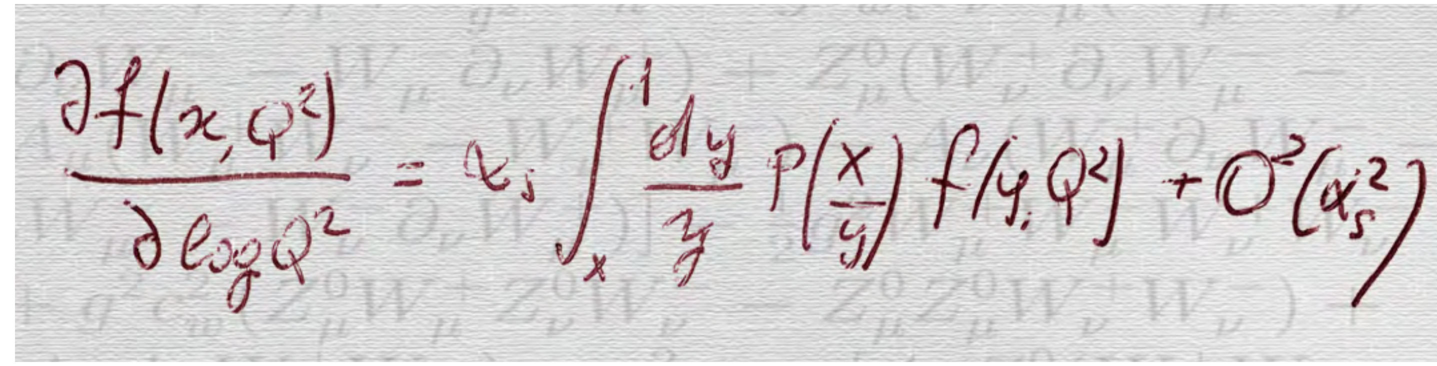
- LHC is driving amazing progress in perturbative QCD
- "LHC as a precision machine": possible!
  - Sophisticated higher order computations achievable
  - Big progress in multi-loop computations
  - Better understanding of logarithmic structures / PS
  - Reliable theory-experiment comparison possible (fiducial region…)
- Many other aspects not covered here
  - NLO improvements (automation, EW automation, BSM…)
  - Progress in input parameters: α_s fits, evolution…
  - Input parameters: the top mass…
  - EW corrections, mixed QCD-EW…
  - Resummation: non global observables, IR structures at higher orders…
- Going beyond state of the art: quite hard (technical/conceptual problems)

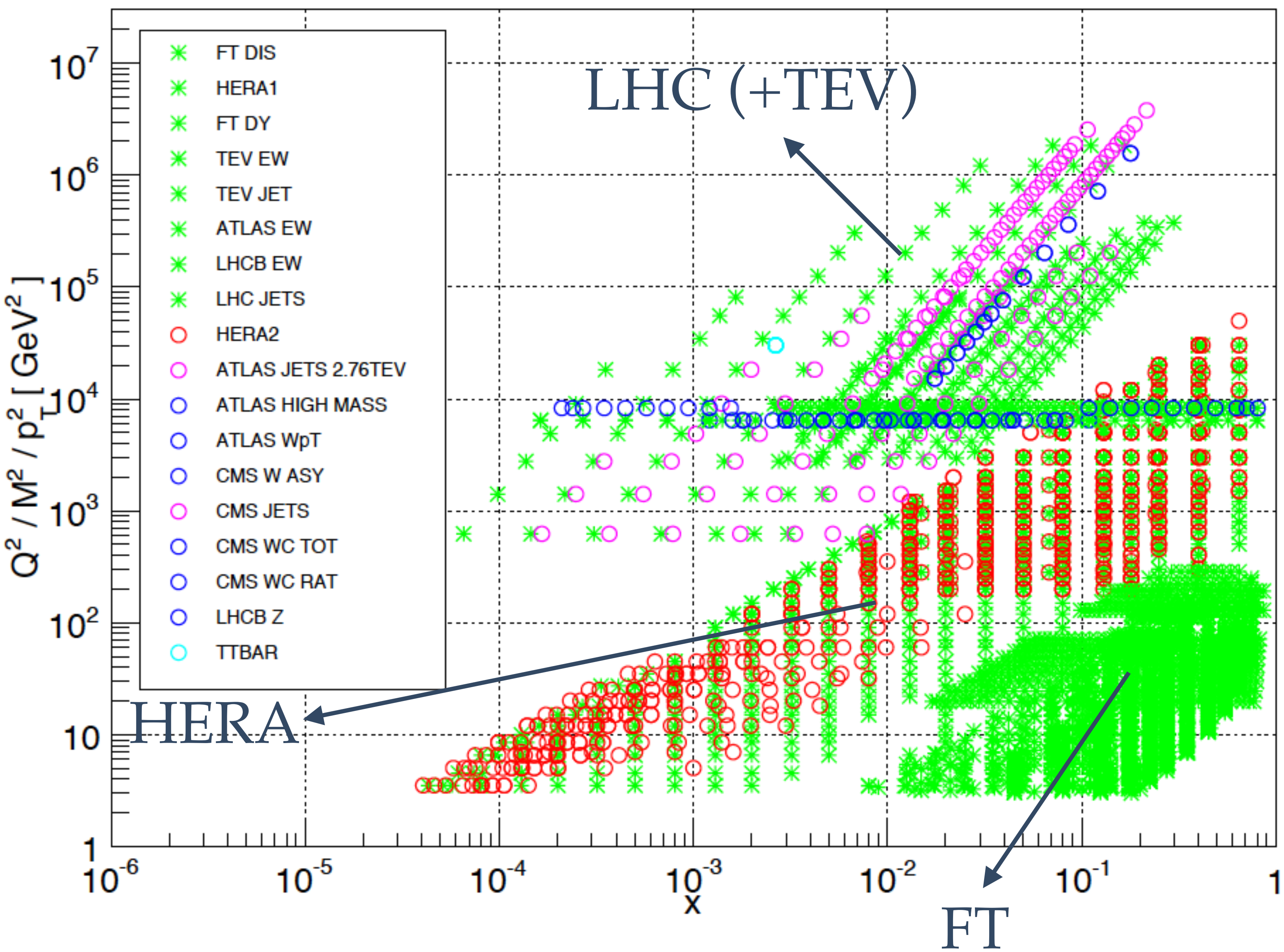
A LOT OF THEORETICAL FUN AHEAD, DIRECTLY RELEVANT FOR LHC PHENOMENOLOGY!

Thank you
very much for
your attention!

Input parameters: PDFs in the LHC era

- Parton content of the proton non pert → fitted to data
- Data at different scales related by first-principle computable AP evolution → universality

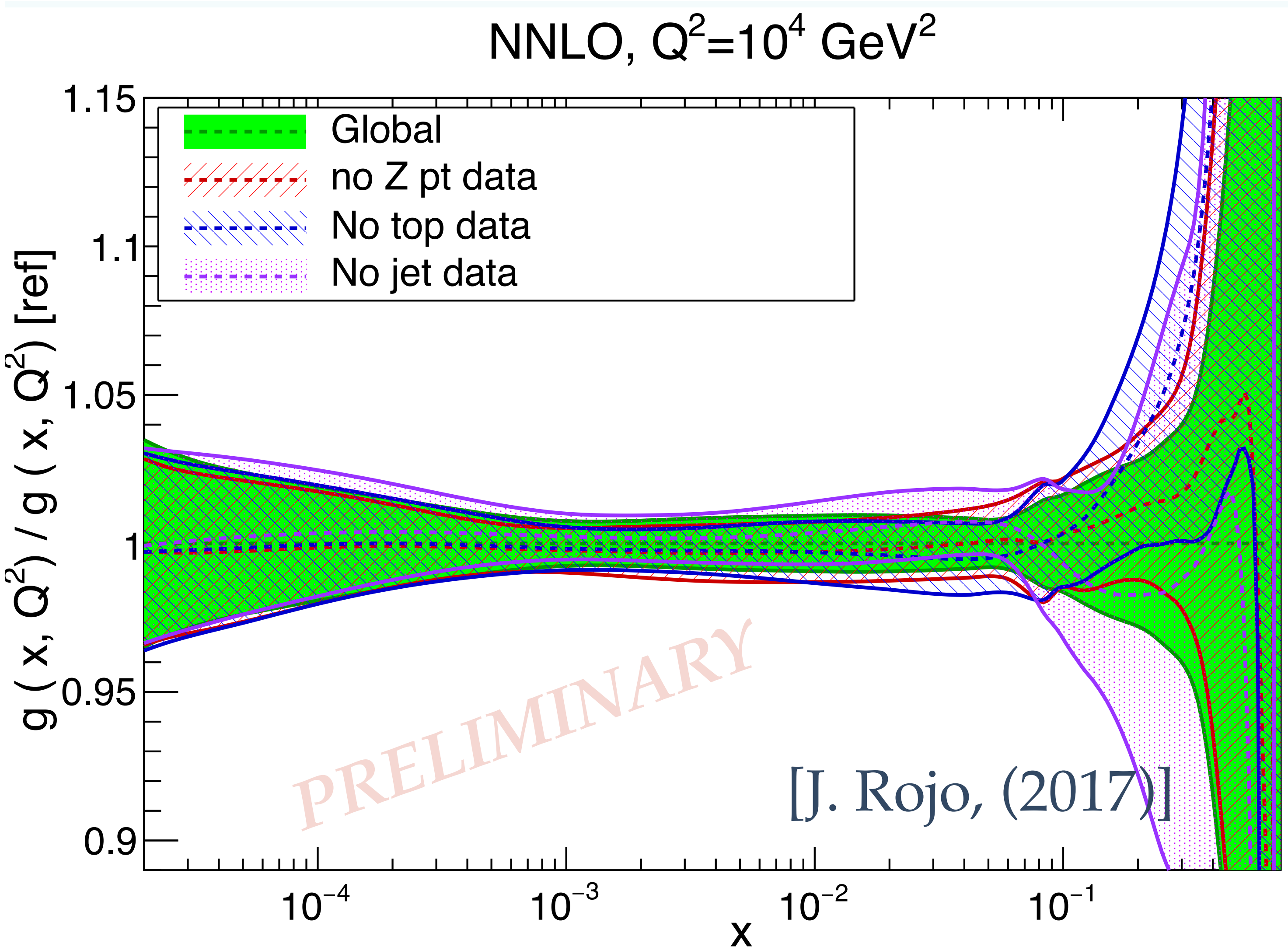




- Results consistent over many orders of magnitude → great test of pQCD
- A lot of precise data from the LHC are already now having great impact (tt, jj, Z/W…)
- We may soon discard `old' low-Q data with limited theoretical control (*nuclear corrections*…)
- SOLID, ROBUST AND `CLEAN' DETERMINATIONS

PDFs: sanity checks

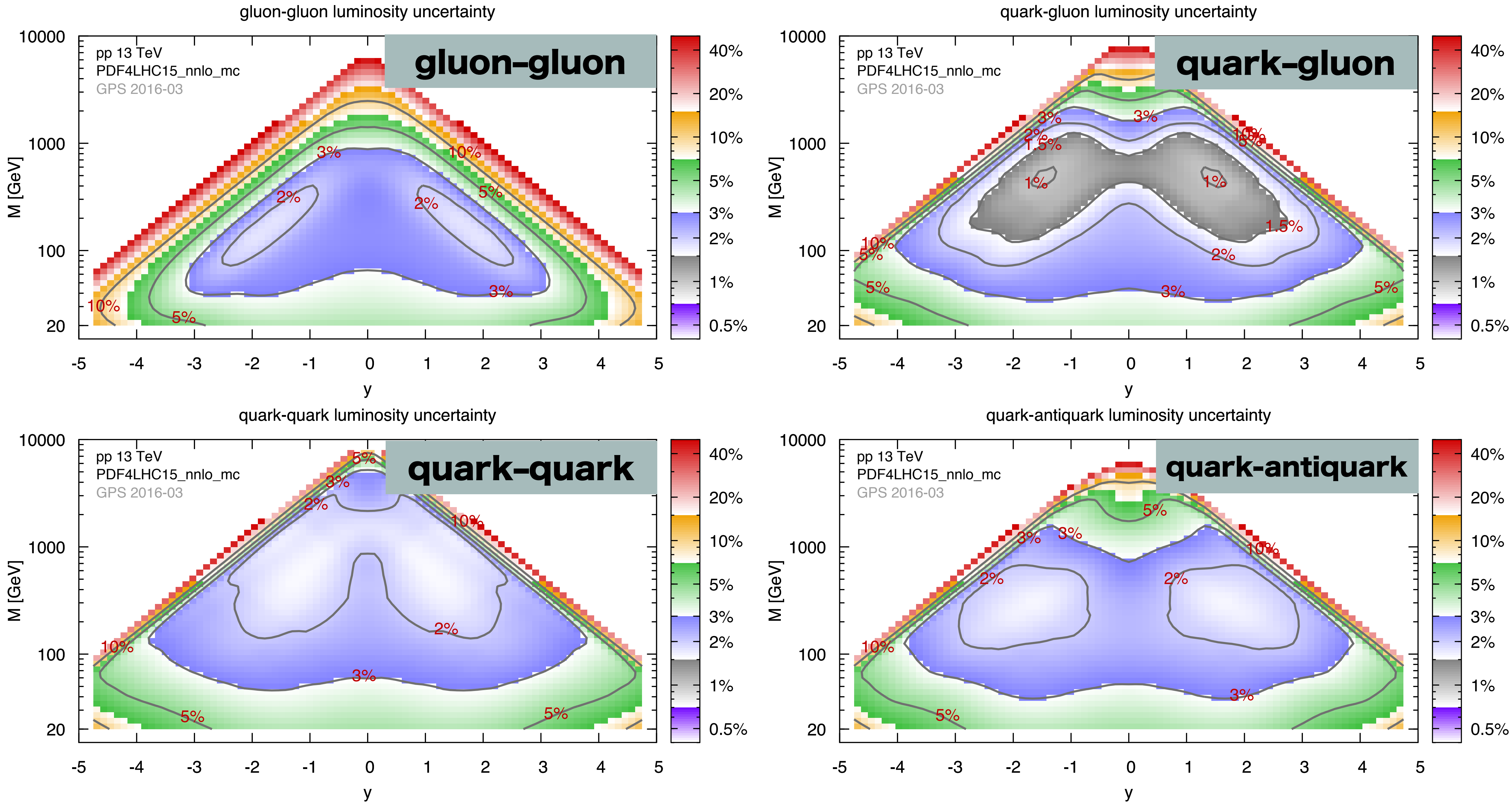
or how do we make sure we are not fitting new physics away…



- Fits are stable under inclusion/exclusion of extra data-set
- Effect of new data: mostly reduction in uncertainty, small change in the central value

- With more and more data, can also try to fit ``safest'' PDF from PS regions which should be free from NP contaminations (e.g. forward jets…)…

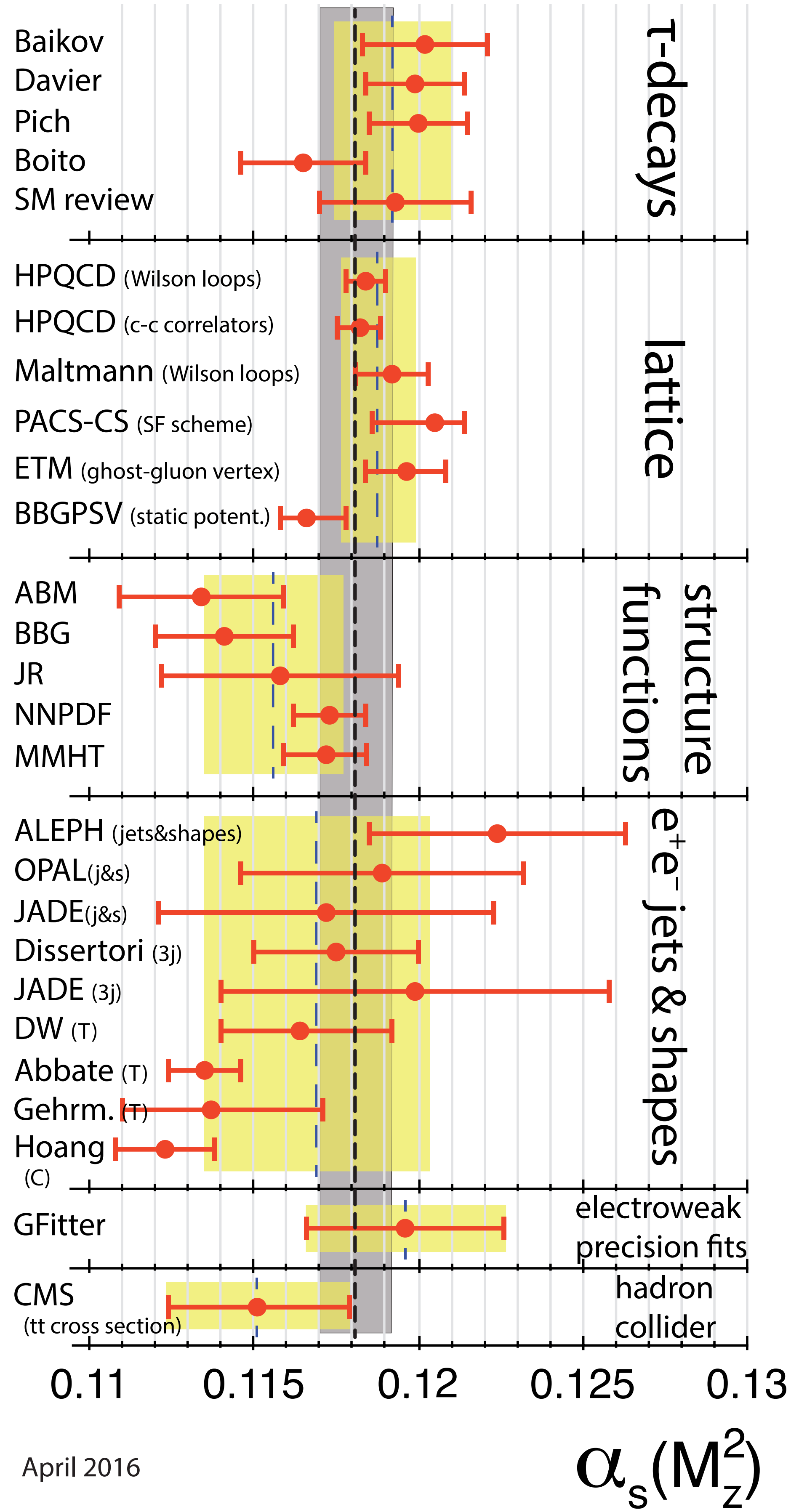
Parton distribution functions circa 2016



[plots by G. Salam]

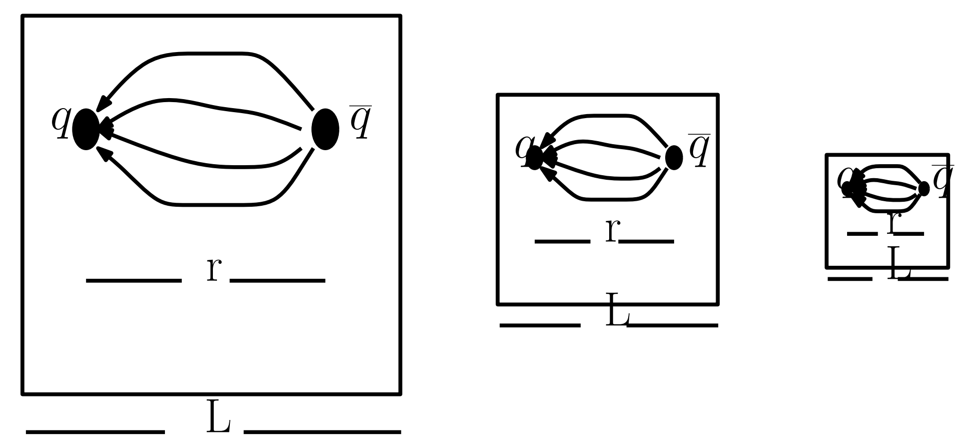
- Big improvement w.r.t. few years ago [better handling on fit, larger data coverage (LHC)]. Reasonable consensus among different groups
- FOR CENTRAL EW PRODUCTION: 2/3% PRECISION
- *Going below may require some rethinking of PDF uncertainty*

The precision on input parameters: α_S



$$\alpha_s(m_Z) = 0.118 \pm 1\%$$

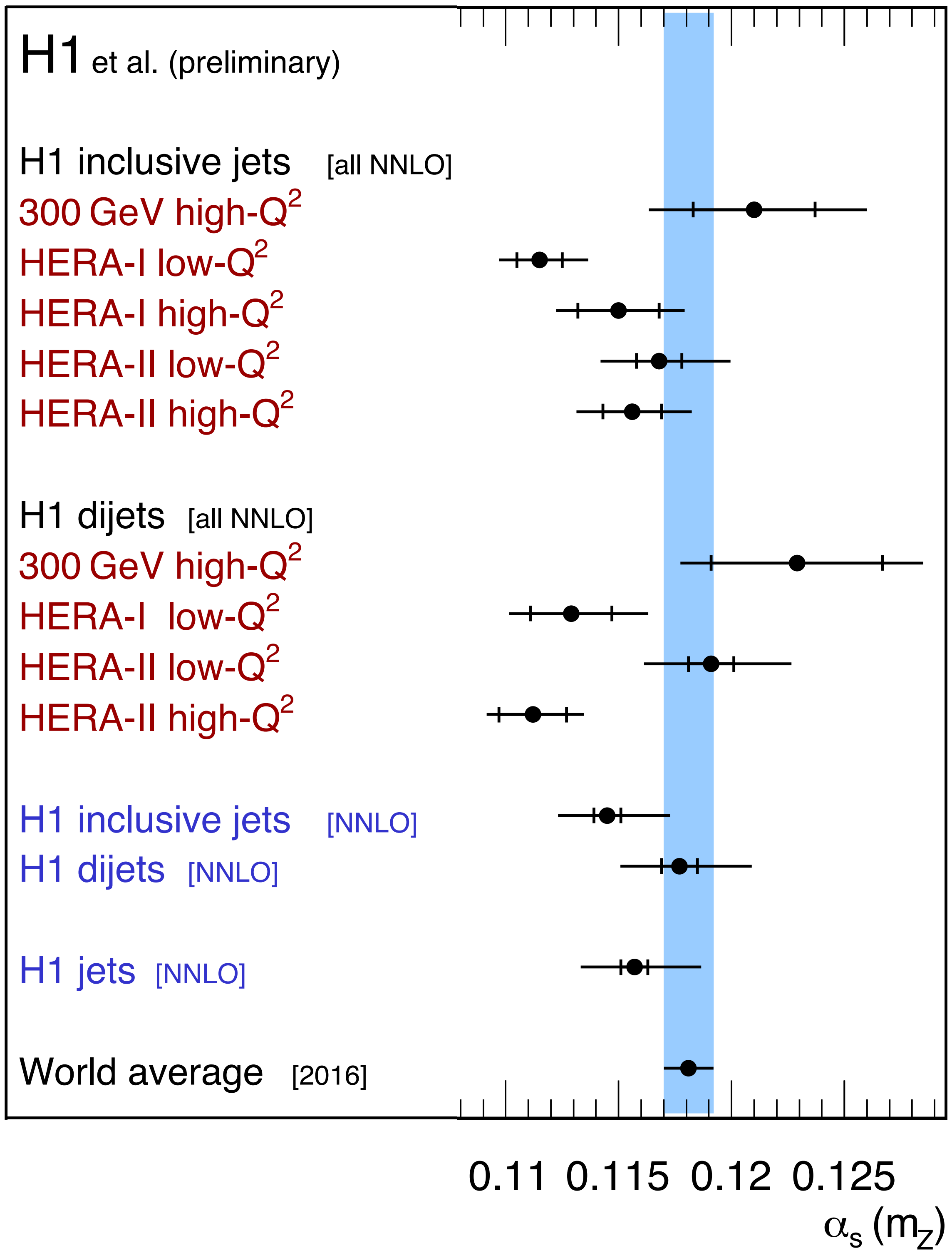
- Many different determinations, (more or less) consistent
- Lattice: the best hope for improvement?
- A lot of recent developments to properly connect the non-perturbative to the perturbative regime (finite size scaling…)

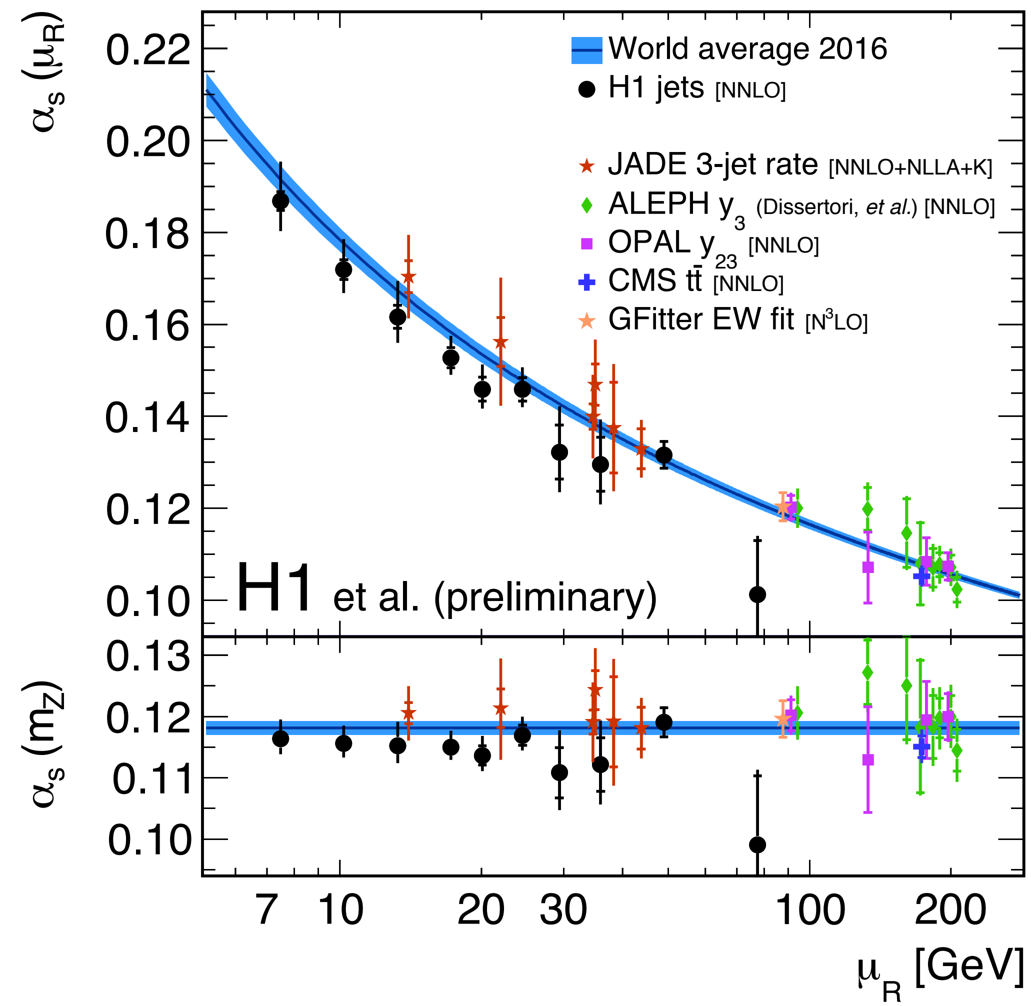


[Lüscher et al (1991), ALPHA (2017)]

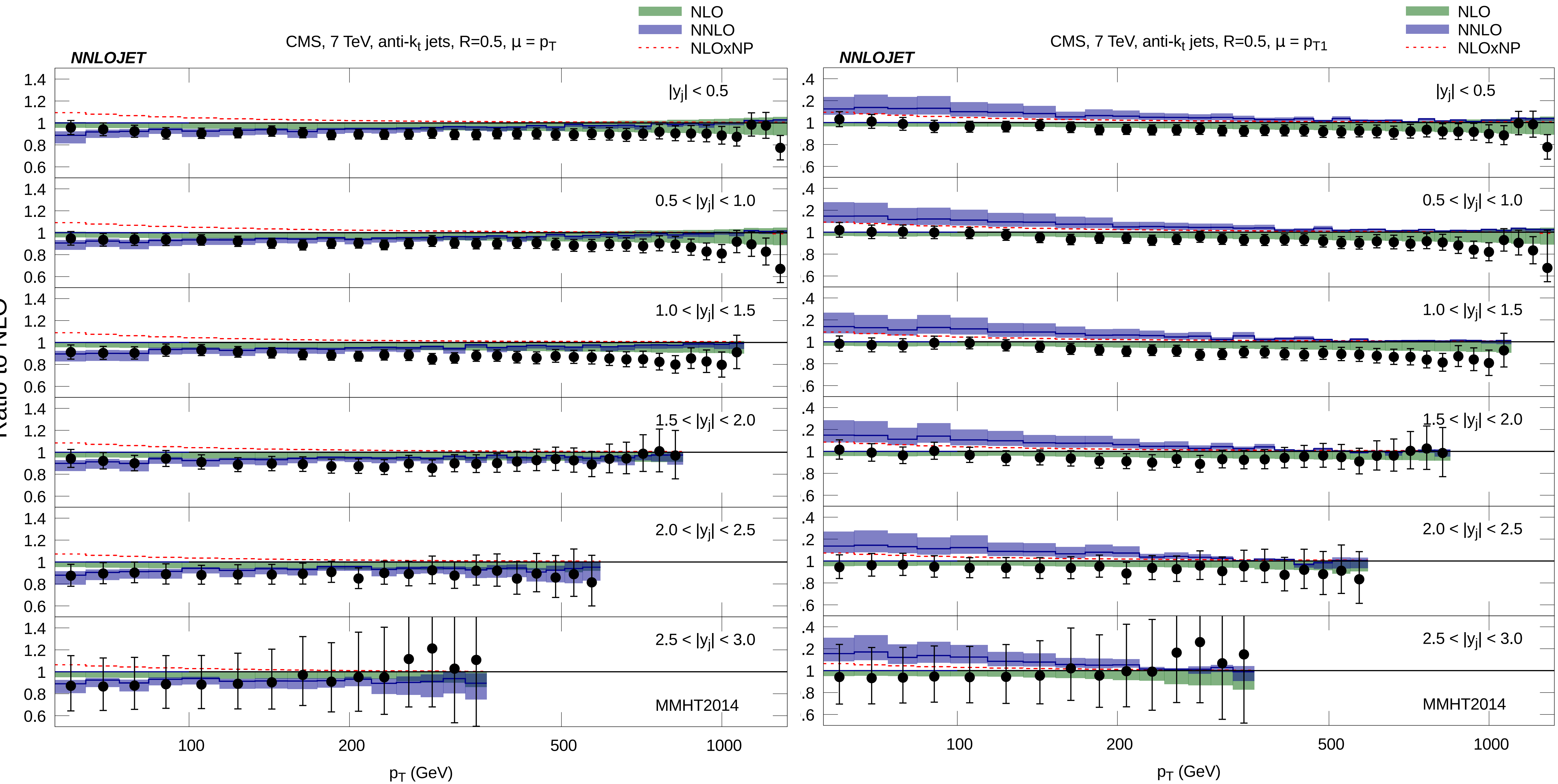
0.5% precision may be possible?

α_S from DIS+J





dijet: p_t vs $p_{t,1}$

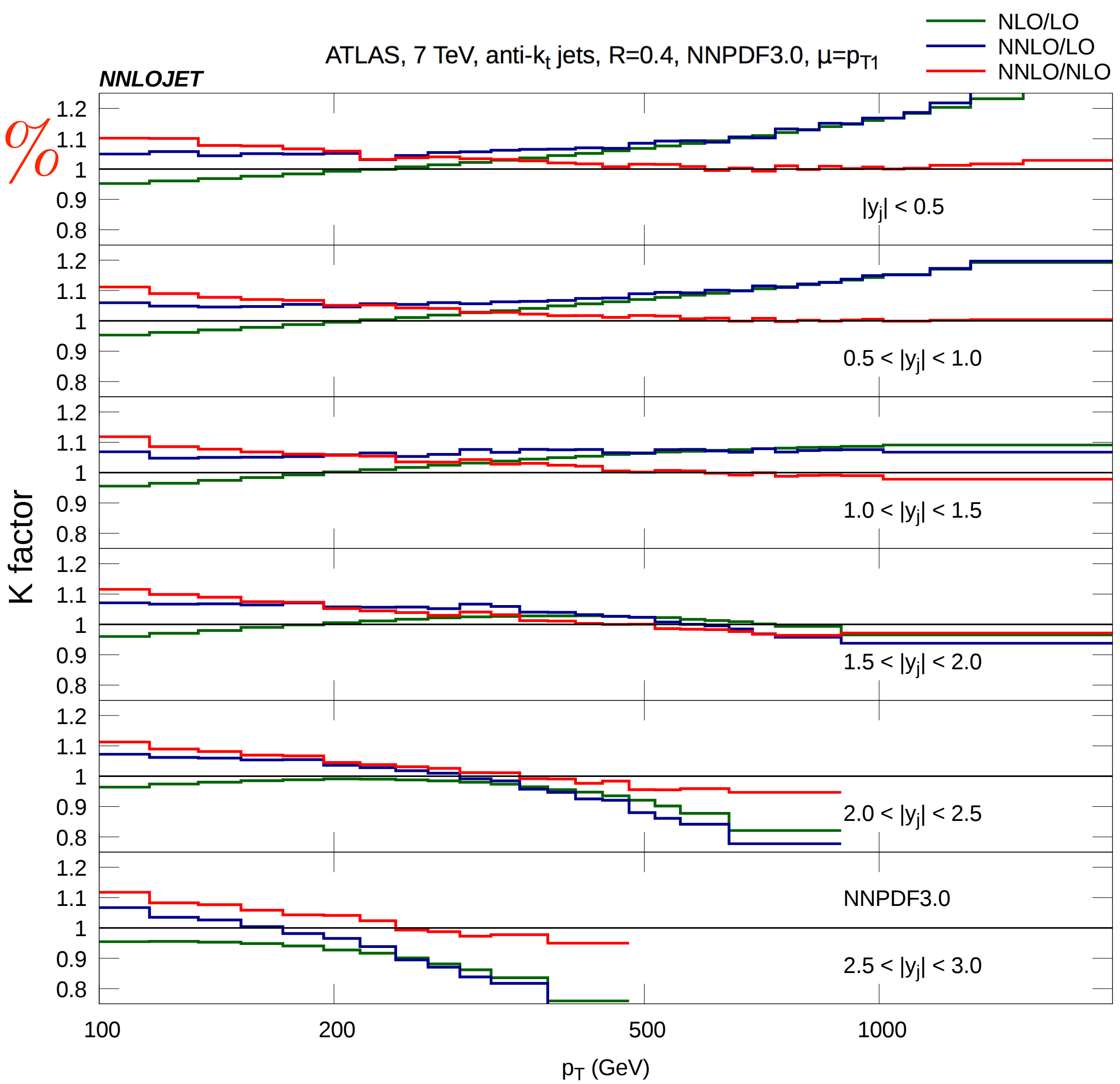


[J. Currie, CMS workshop Jan. 2017]

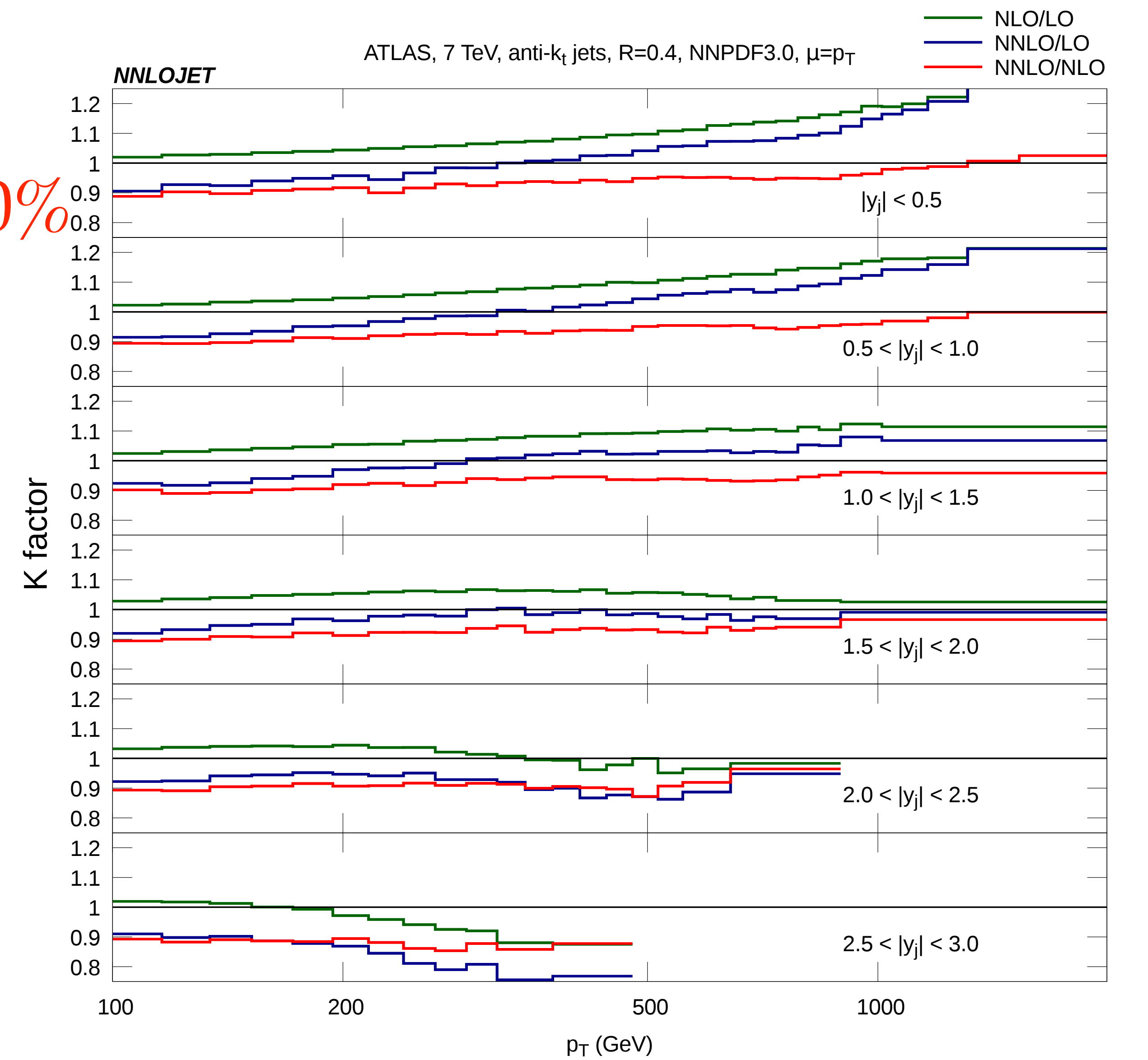
NNLO: open puzzles

- Inclusive jet spectrum: $\mu = p_{t,L}$ vs p_t

+10%



-10%



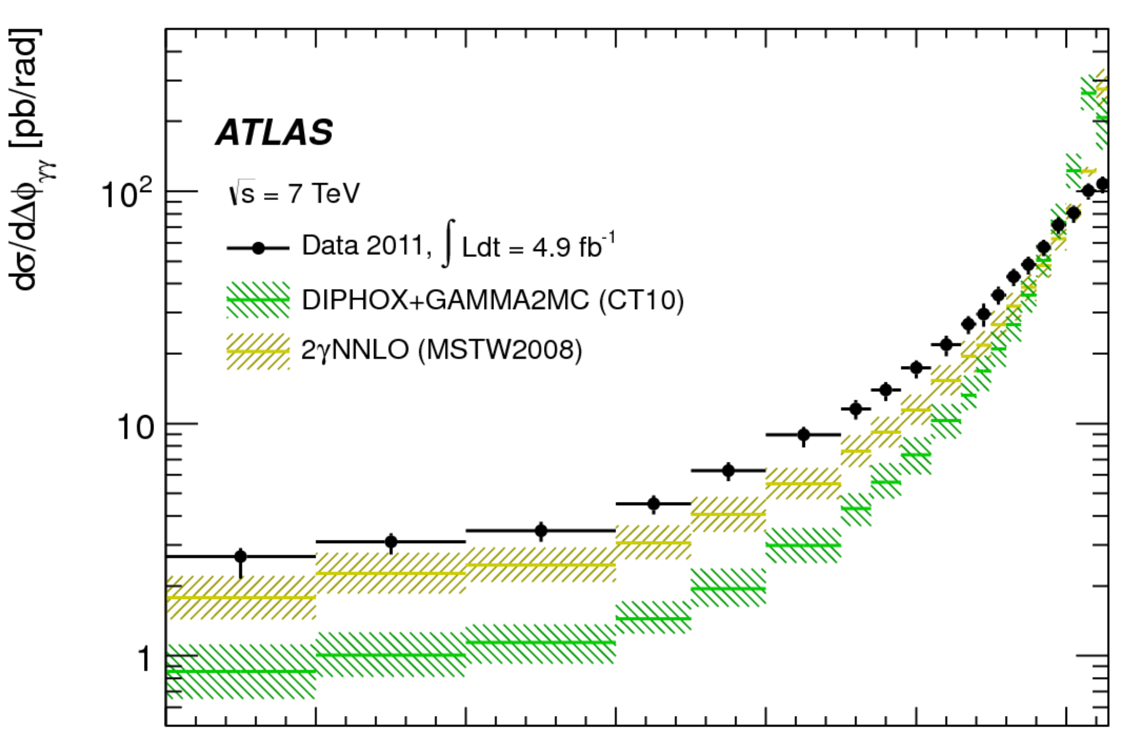
[Currie, Glover, Gehrmann, Gehrmann-de Ridder, Huss, Pires (2017)]

- Despite small scale variation, very large dependence on scale choice (hardest jet in the event vs individual jet). Non trivial jet dynamics to be understood

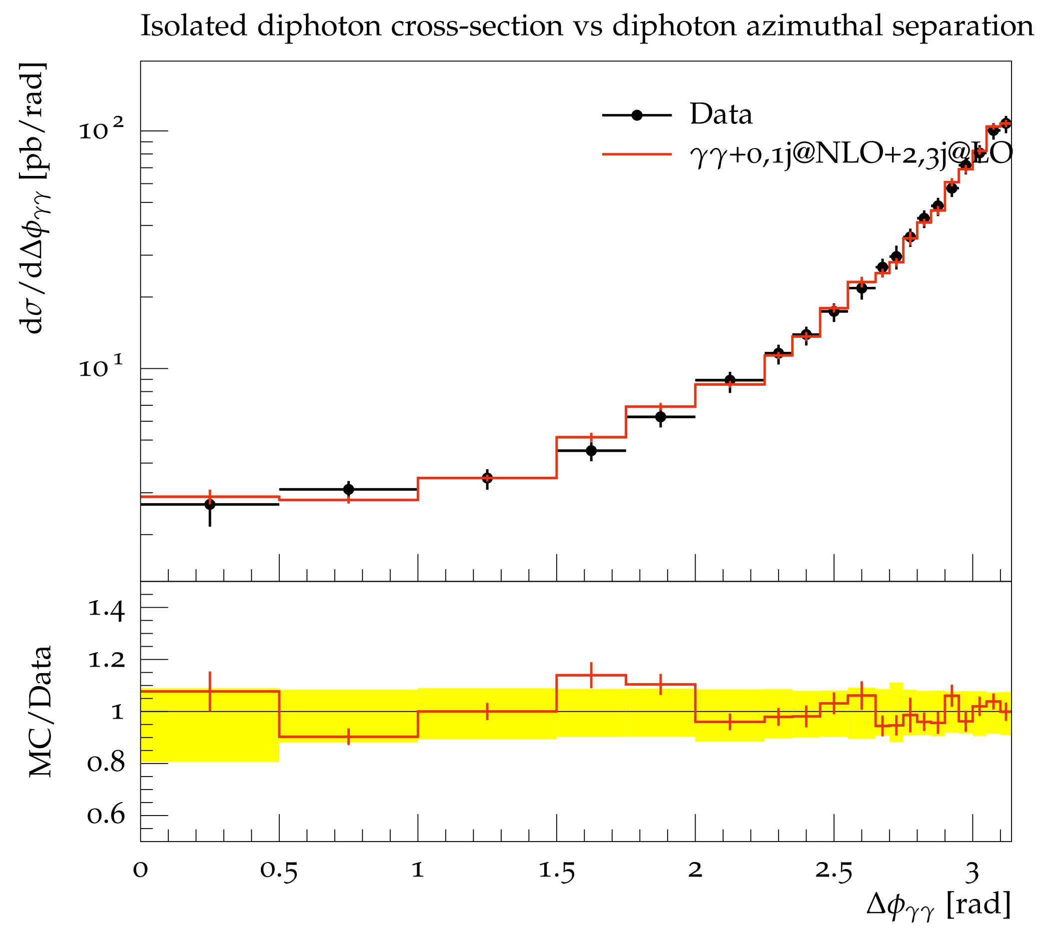
A bonus of PS: merging

- Often, radiative corrections are dominated by real emission: new channels/new topologies opening up.
- Parton shower MC provide an ideal framework to perform ``merge together'' processes with different jet multiplicities (CKKW, MLM, NLOPS, MEPS, MENLOPS, MEPS@NLO, FXFX, MINLO, GENEVA…)
- Because of (approx.) multi-parton emission, the result does not depend too much on the details of the merging

POSTER CHILD FOR "MERGING": DI-PHOTON OPENING ANGLE



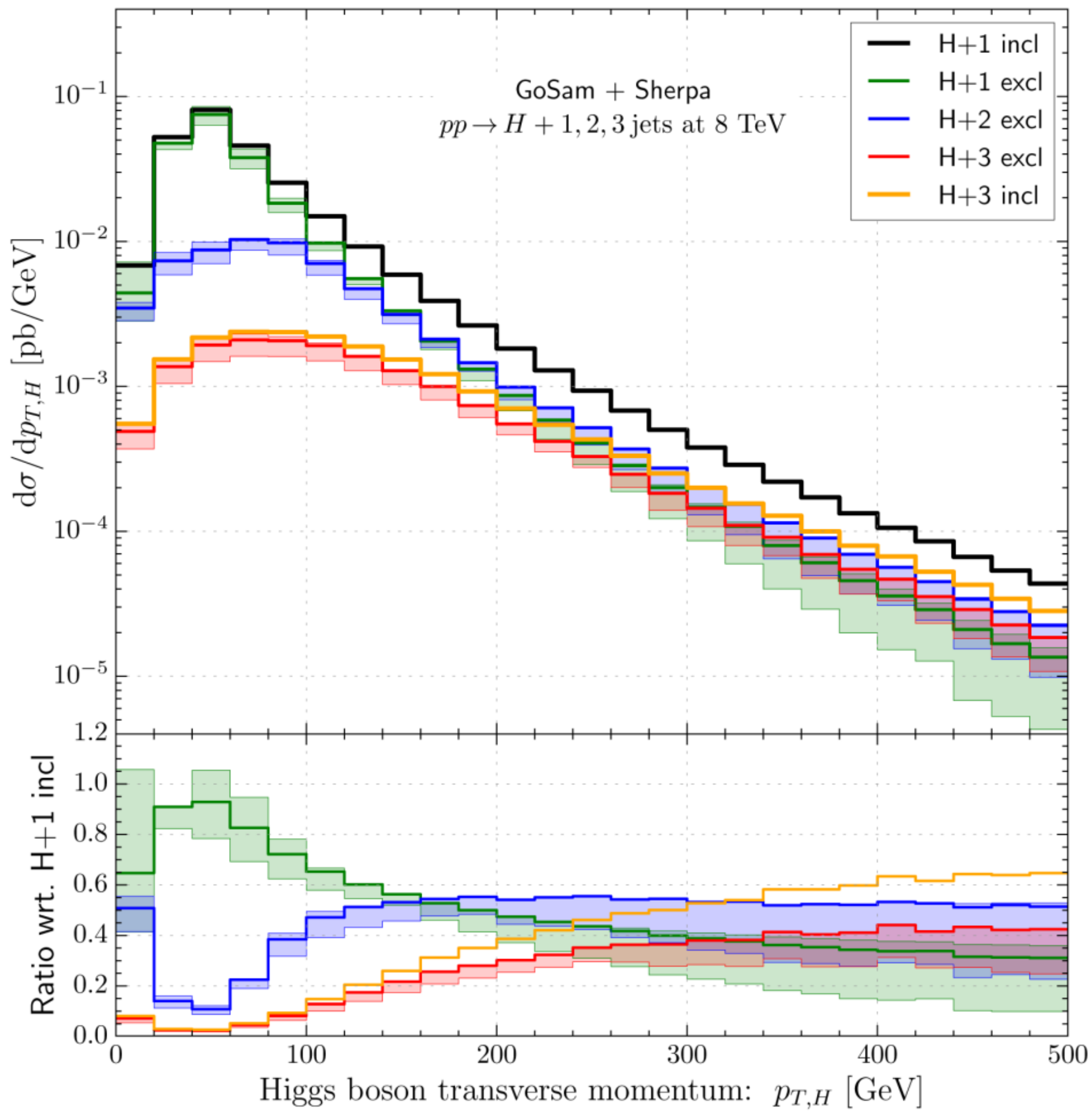
[Catani et al, pp→γγ @NNLO]



[Höche and Siegert, SHERPA merged NLO]

Merging: Higgs p_t with finite top mass effects

Complete NLO corrections with full top-quark mass dependence: still unavailable (2-loop amplitudes) (*NNLO in the HEFT*)



- At high p_t merged samples can give a good idea of the corrections [Frederix et al (2016), Greiner et al (2016)]
- Give similar result of approximate NLO of [Neumann, Williams (2016)]
- Same behavior as predicted by high energy resummation [Muselli et al (2016)]
- COHERENT PICTURE (waiting for the NLO result…)

Example: the mass of a quark…

At the LHC, top mass reconstructed from template fit to observables. Experimental reach ~ 500 MeV

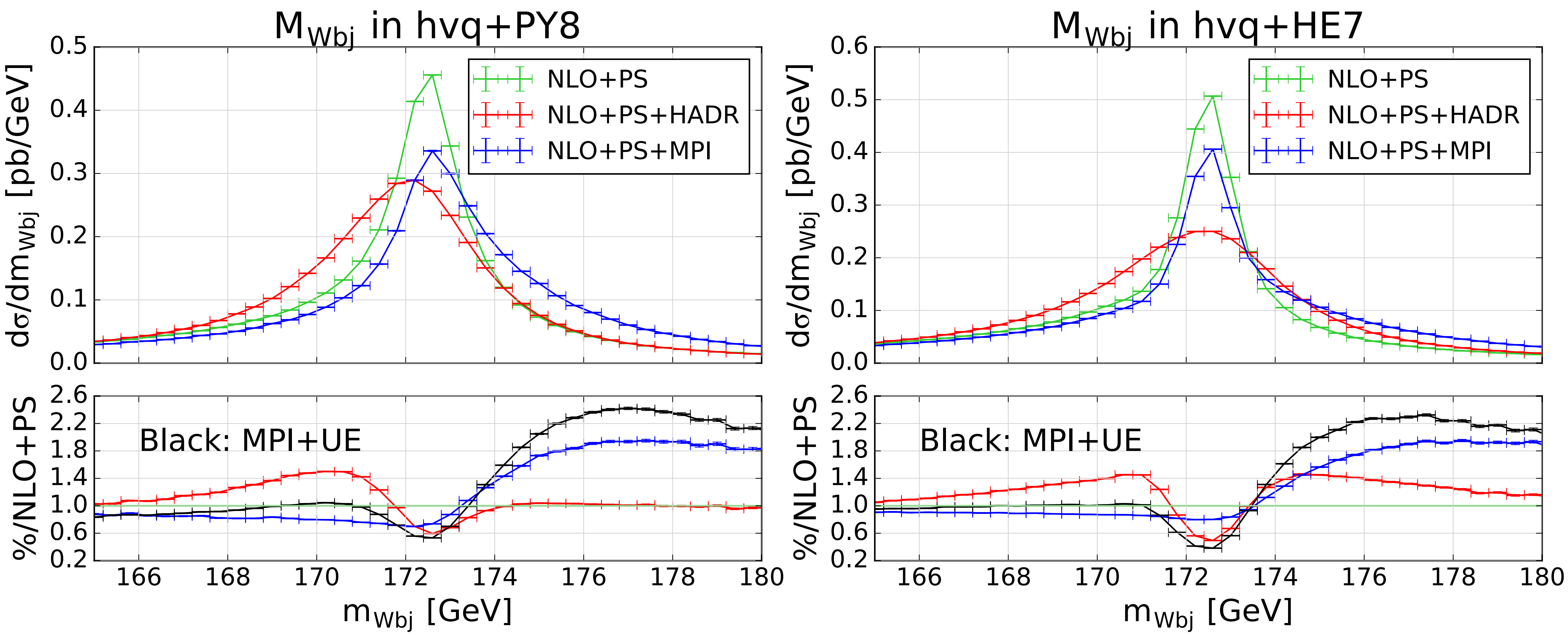
Quarks don't exist as asymptotic state. As such, the definition of their mass is subtle. Normal `pole of the propagator' definitions suffer from inherent theoretical ambiguities. Nevertheless, this ambiguity is estimated to be (much) less than 500 MeV

Still, tops are created in an hadronic environment. At this level of precision, our understanding of it is hampered by our lack of understanding of it from first principles → phenomenological models for hadronization, underlying event, MPI…

PS Monte Carlos are an ideal playground to test the robustness of top quark mass restrictions under known perturbative and (modeled) non perturbative effects

Example: the mass of a quark…

Hadronization and MPI



[P. Nason, talk at the TOP Working group (2017)]

- Hadronization: wider peak, raised tail below peak (Py8).
- MPI: raised tail above peak.

Some preliminary results…

		Extracted m_{Wbj} peak [GeV]			
		Full		Parton level (no MPI)	
		PY8	HE7	PY8	HE7
No smearing	$b\bar{b}4\ell$	172.828	172.935	172.527	172.497
	hvq	172.780	173.039	172.488	172.497
15 GeV smearing	$b\bar{b}4\ell$	173.052	172.355	171.803	171.102
	hvq	172.613	172.375	171.385	171.279