Progress in QCD for the LHC

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Disclaimer

A lot of progress in QCD in the last year

- 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

Precision goals: some (rough) estimates

Imagine to have new physics at a scale Λ

- if Λ small $\rightarrow$ should see it directly, bump hunting
- if Λ large, typical modification to observable w.r.t. standard model prediction: $\delta O \sim Q^2/\Lambda^2$
- standard observables at the EW scale: to be sensitive to ~ TeV new physics, we need to control δO to few percent
- high scale processes (large p_T, large invariant masses…): sensitive to ~TeV if we control δO to 10-20%

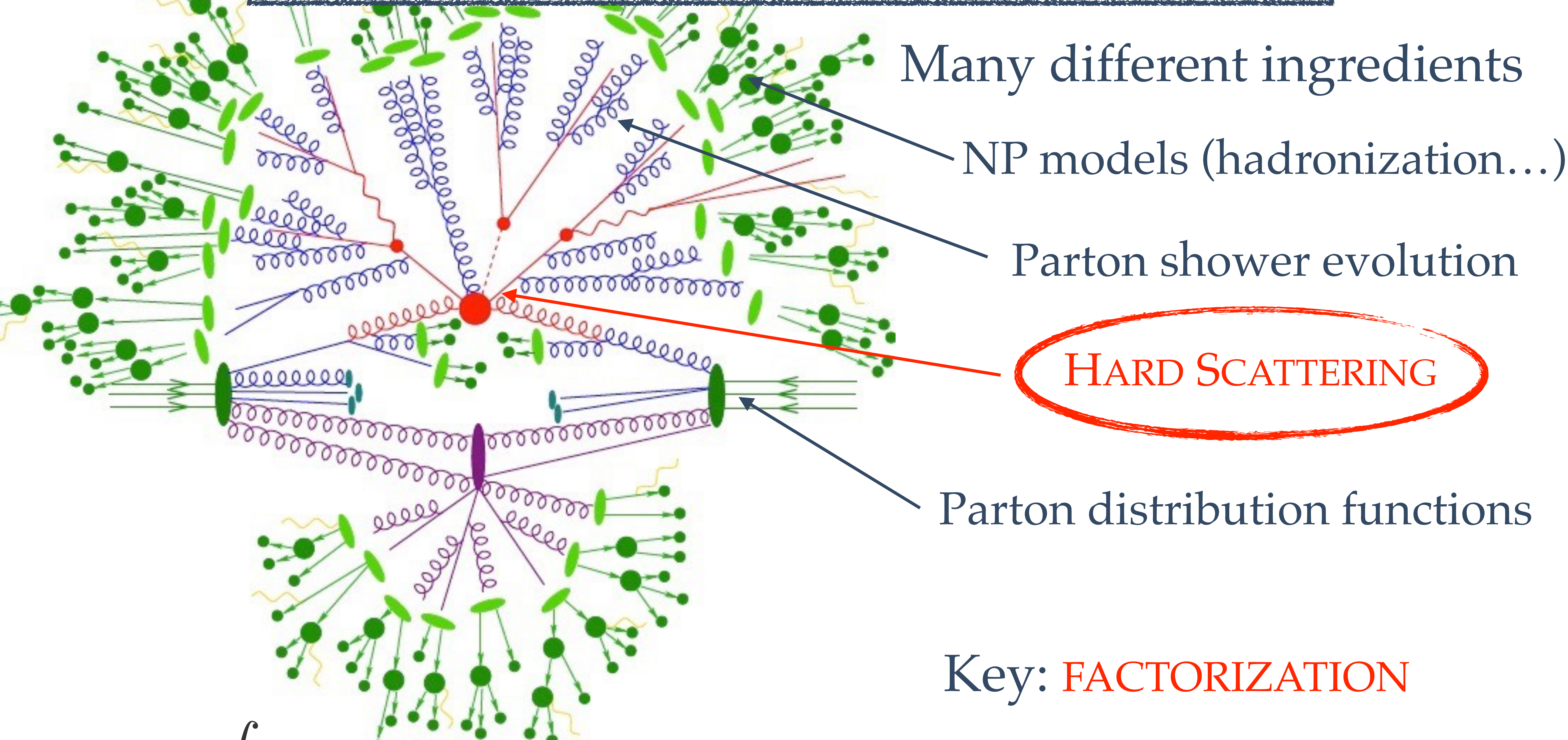
THESE KINDS OF ACCURACIES ARE WITHIN REACH OF LHC EXPERIMENT CAPABILITIES.

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

Precise predictions: requirements

THE GOAL: PRECISE MODELING OF THE ACTUAL EXPERIMENTAL SETUP

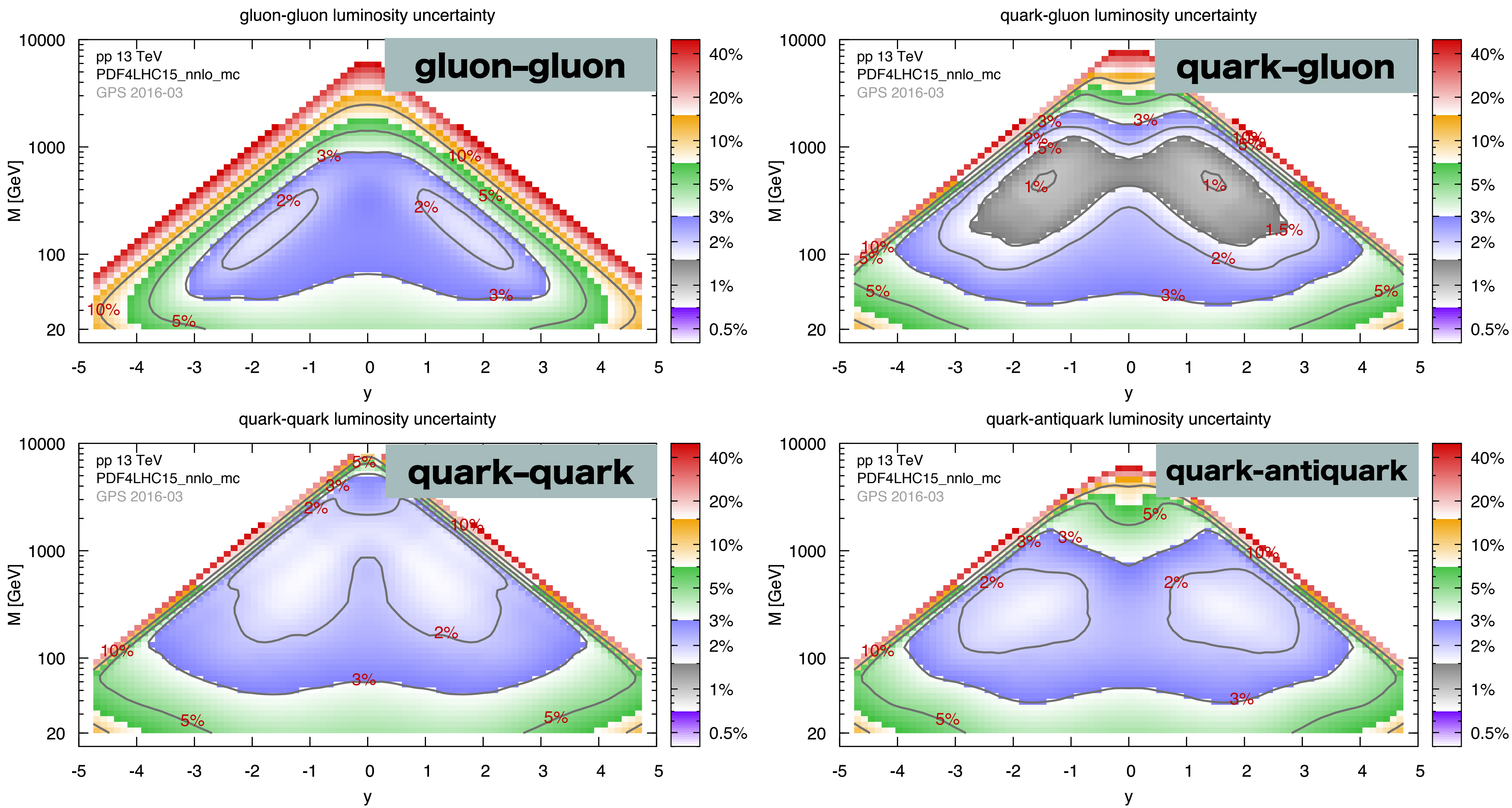
Many different ingredients



Key: FACTORIZATION

$$d\sigma = \int dx_1 dx_2 f(x_1) f(x_2) d\sigma_{\text{part}}(x_1, x_2) F_J (1 + \mathcal{O}(\Lambda_{\text{QCD}}/Q))$$

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 photon PDF

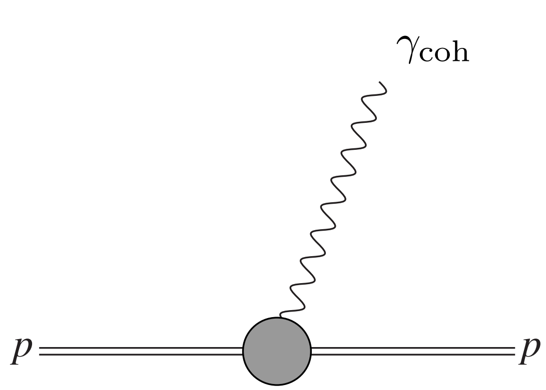
[Manohar, Nason, Salam, Zanderighi; Harland-Lang, Khoze, Ryskin (2016)]

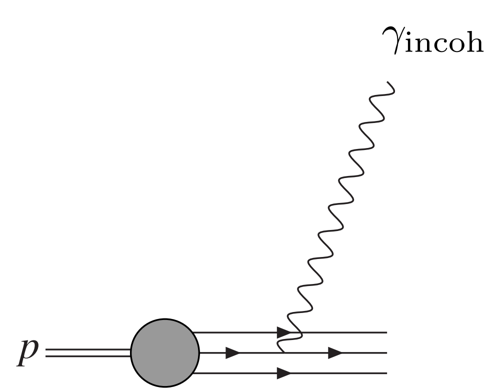
THE PROBLEM:

- 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

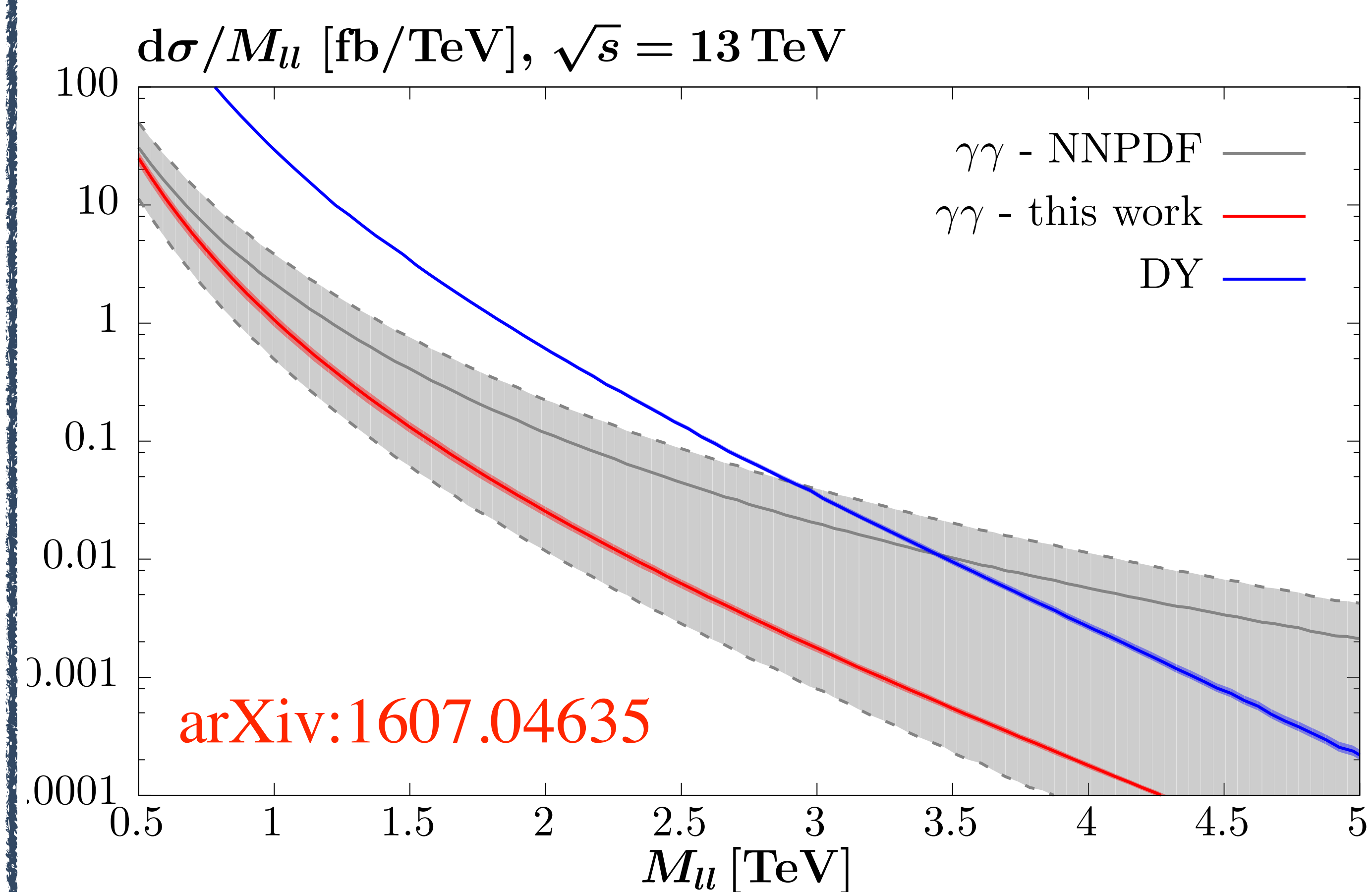
THE SOLUTION:

- 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

"*Few percent*": the hard matrix element

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

HARD SCATTERING MATRIX ELEMENT

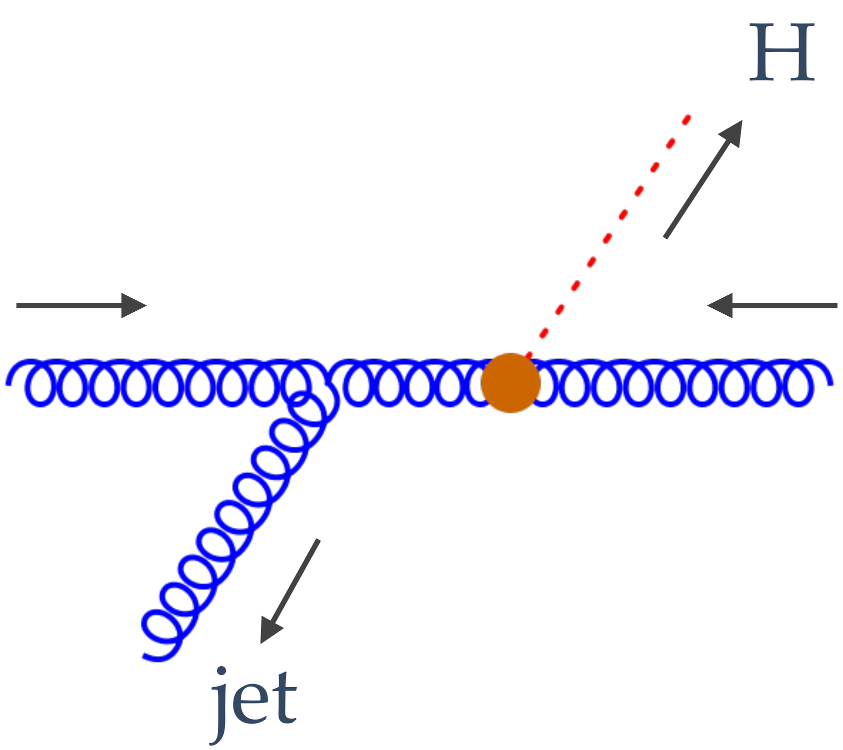
- large Q → most interesting and theoretically clean
- $\alpha_s \sim 0.1$ → For TYPICAL PROCESSES, we need NLO for ~ 10% and NNLO for ~ 1 % accuracy. Processes with large perturbative corrections (Higgs): N^3LO
- Going beyond that is neither particularly useful (exp. precision) NOR POSSIBLE GIVEN OUR CURRENT UNDERSTANDING OF QCD

NP effects: ~ few percent
No good control / understanding of them at this level. LIMITING FACTOR FOR FUTURE DEVELOPMENT

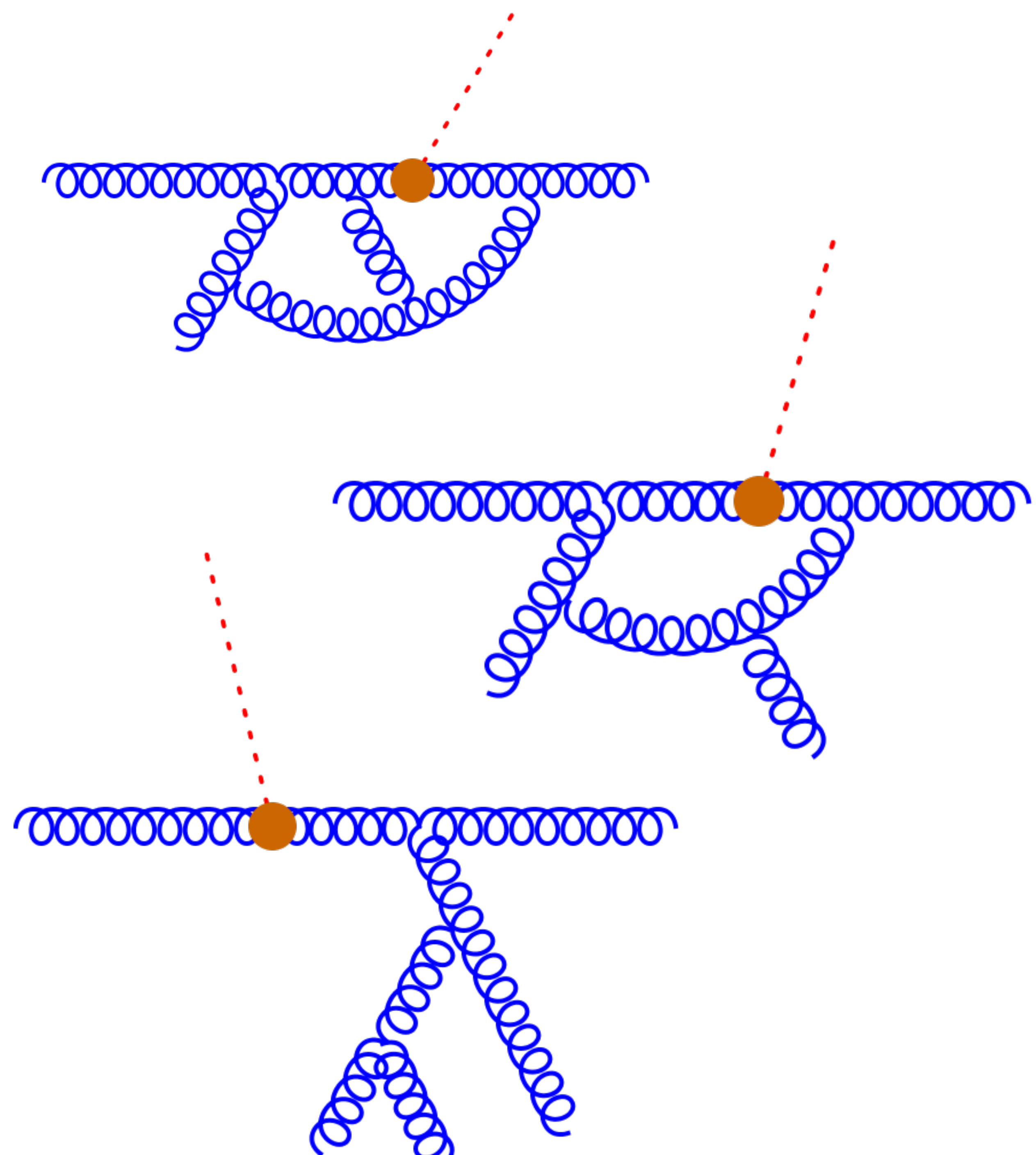
Fully exclusive NNLO: how to get there

Imagine you want to describe the Higgs boson p_T distribution

At LO:



At NNLO: two extra partons



TWO BIG PROBLEMS:

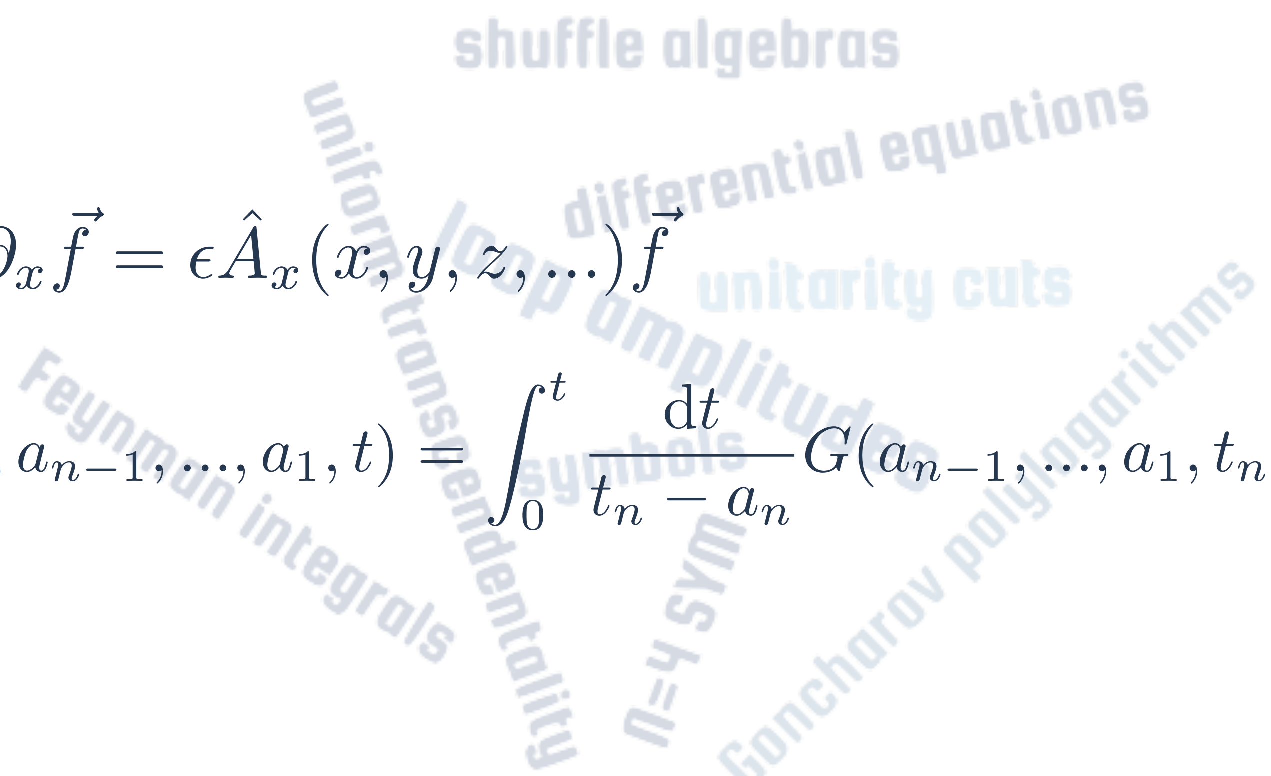
- loop amplitudes
- IR structure of extra emission

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)

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

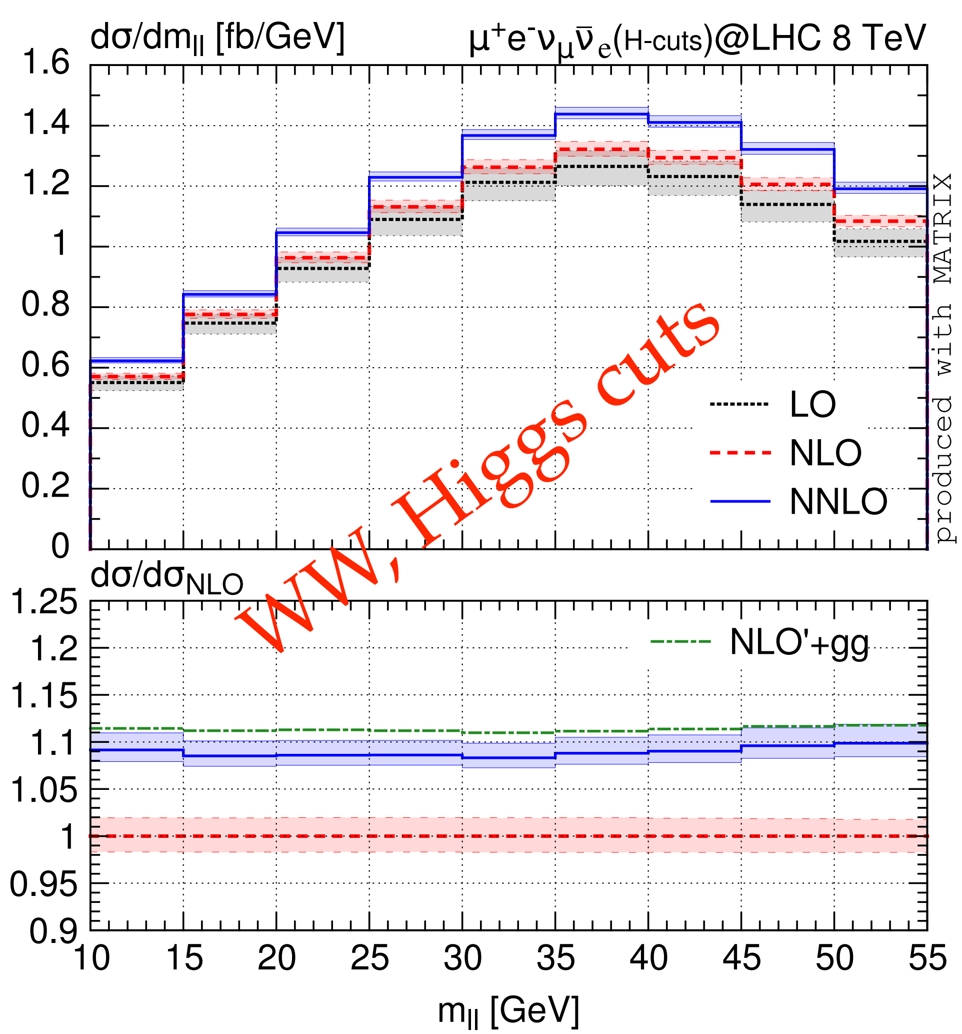
Fully inclusive: pheno predictions for H@N^{3}LO [Anastasiou et al. (2016)]

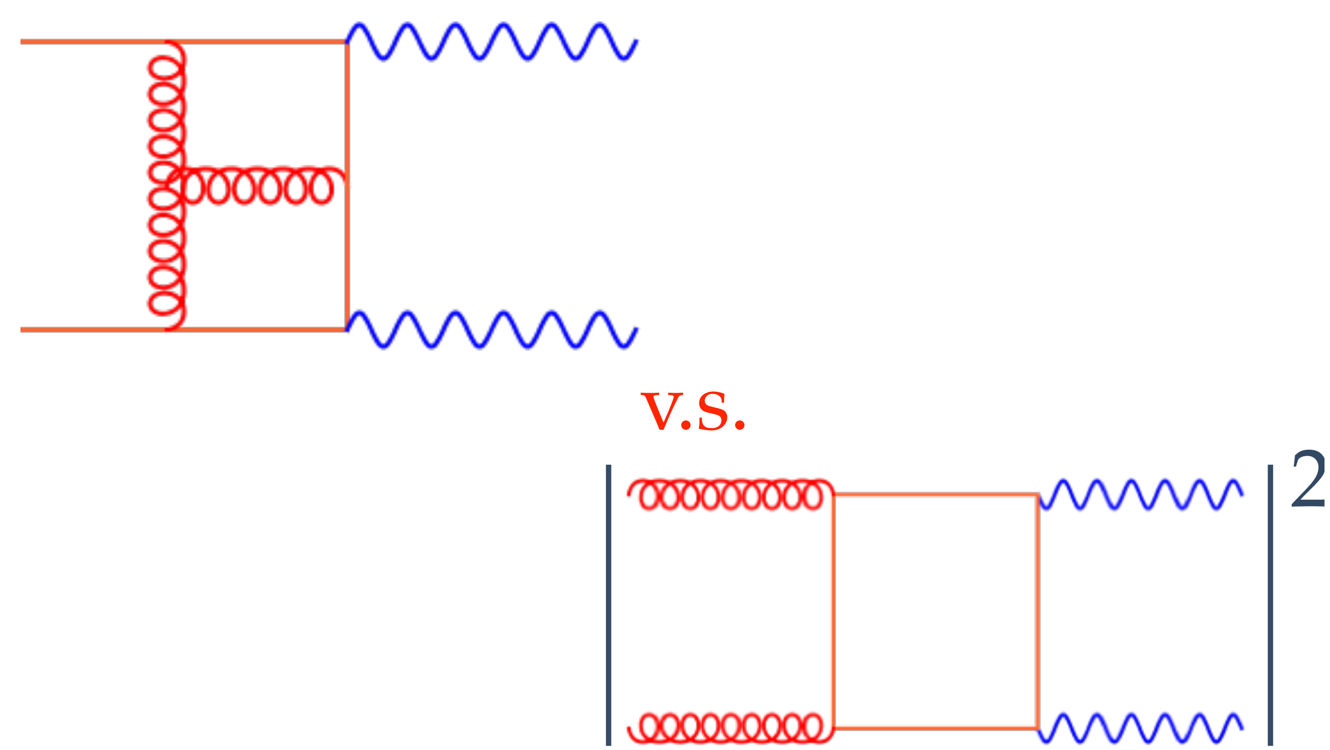
Recent NNLO results: di-bosons

[Grazzini et al. (2015-2016)]

In the last year, the PROGRAM OF COMPUTING FULLY DIFFERENTIAL NNLO CORRECTION TO DI-BOSON PROCESSES HAS BEEN COMPLETED

- General picture: GOOD AGREEMENT DATA / NNLO (with some possible room for discussion for WW jet-veto, see [Dawson et al (2016)])
- Corrections strongly cut-sensitive → FIDUCIAL REGION comparisons important (jet veto, interplay of qqb / gg contributions…)

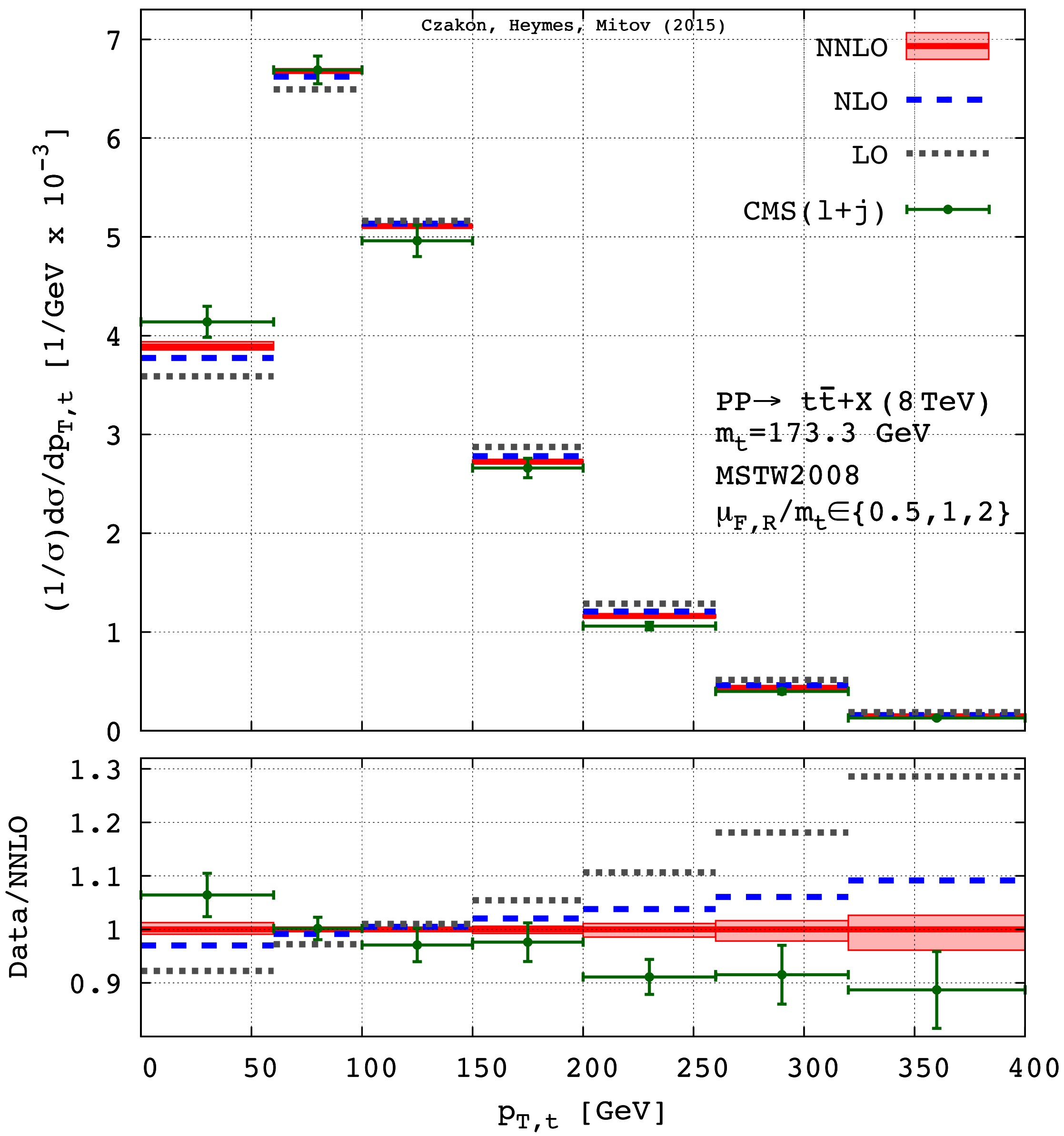




[Corrections computed in FC, Melnikov, Röntsch, Tancredi (2015)]

Recent NNLO results: top

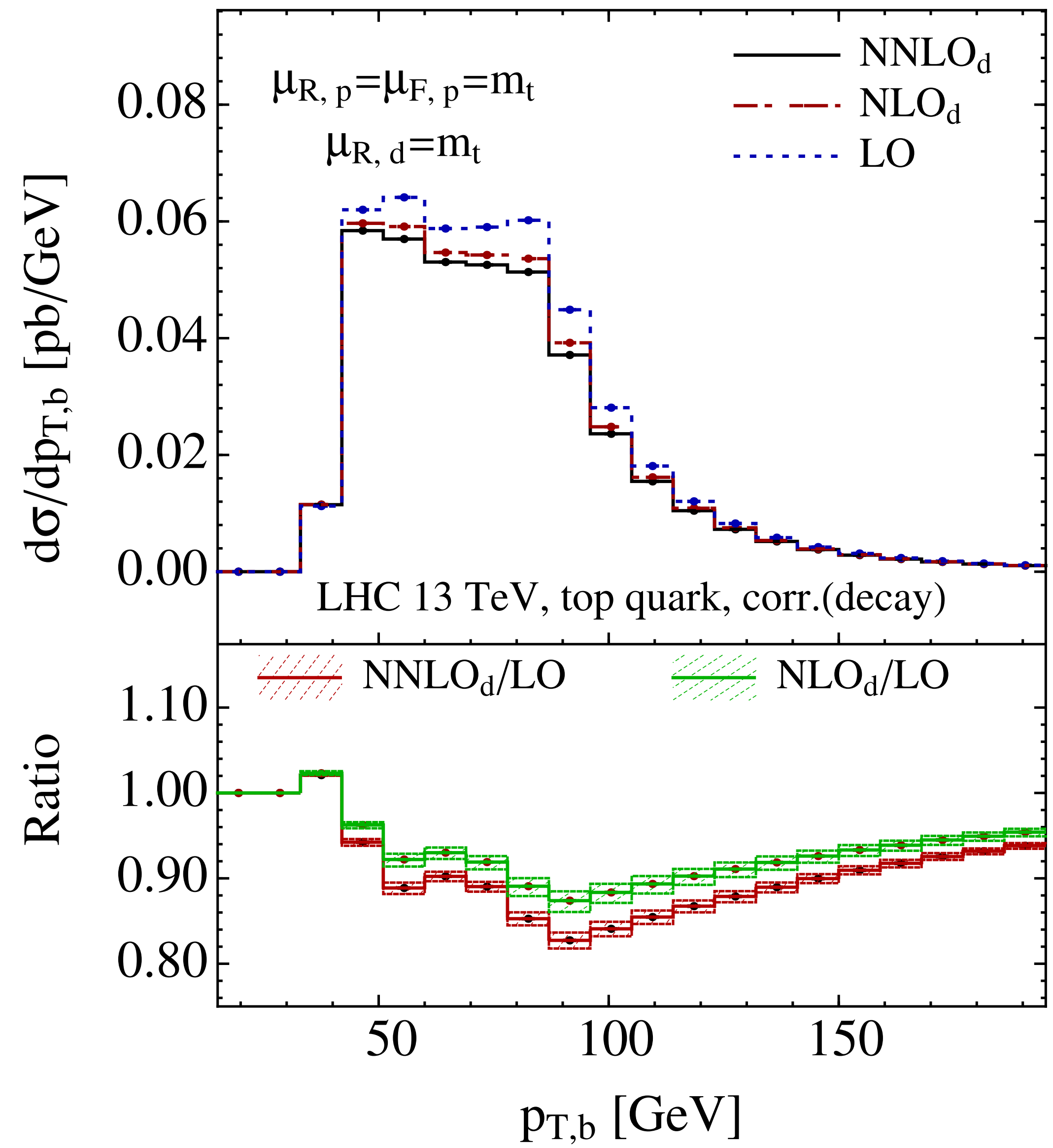
TTBAR DIFFERENTIAL DISTRIBUTIONS



[Czakon, Heymes, Mitov (2016)]

- Tension in $p_{t,top}$ alleviated
- Allow for precision physics in the top sector

T-CHANNEL SINGLE-TOP PLUS TOP-DECAY (NWA)

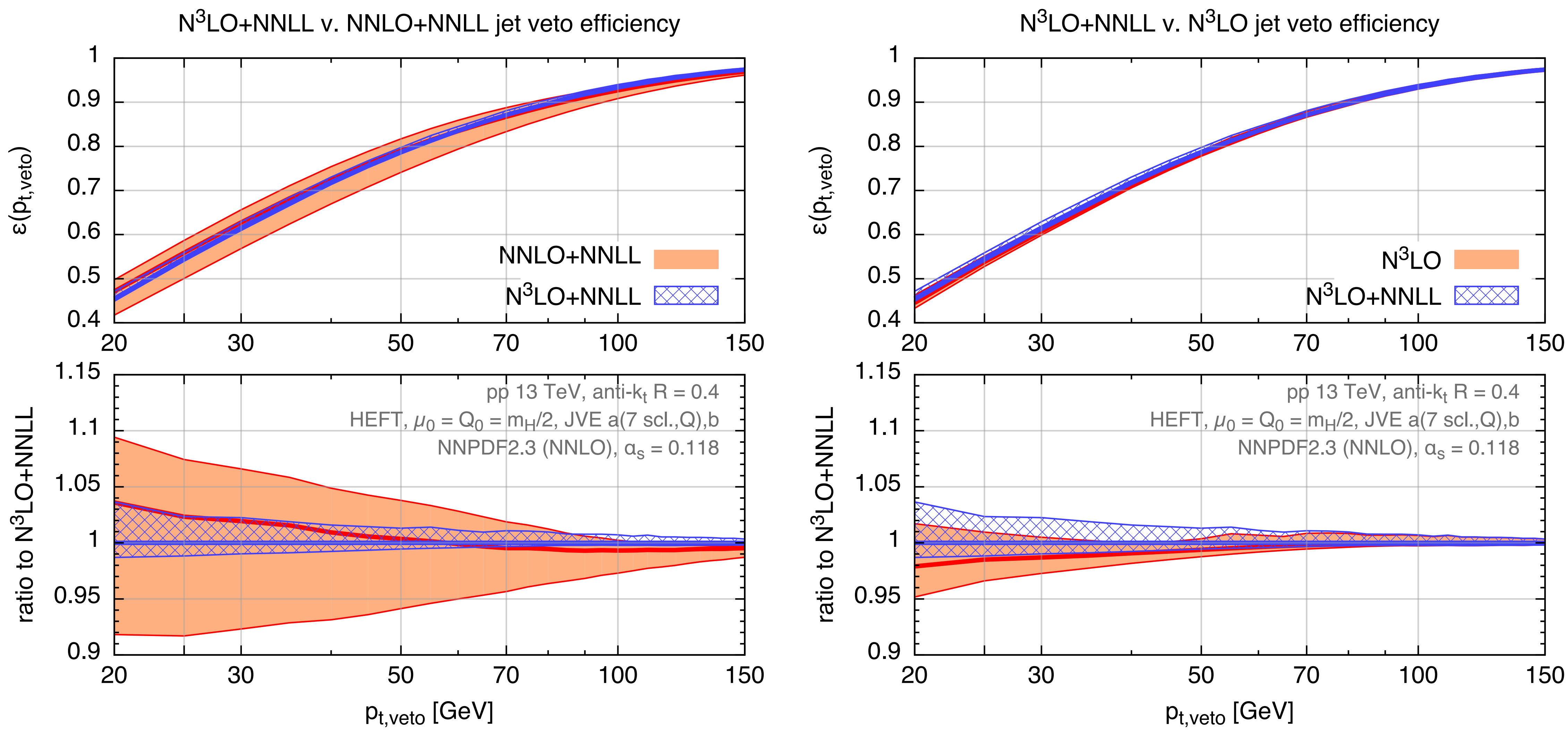


[Berger, Gao, Yuan, Zhu (2016)]

- Small inclusive corrections
- LARGE CORRECTIONS in exclusive region
- Similar behavior observed in Higgs in VBF [Cacciari et al (2015)]

Application of f.o. results: H and jet vetoes

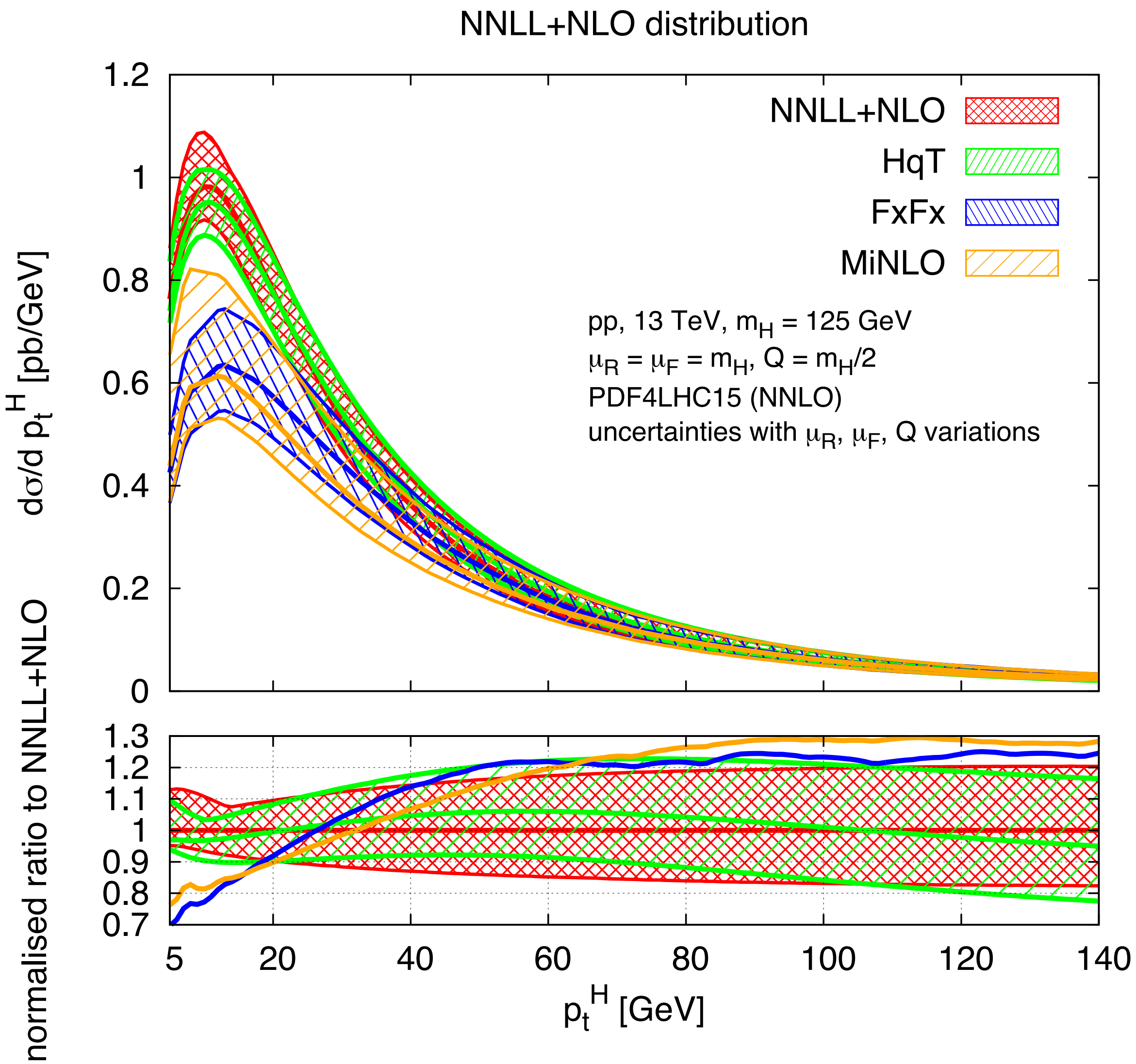
[Banfi, FC, Dreyer, Monni, Salam, Zanderighi, Dulat (2015)]

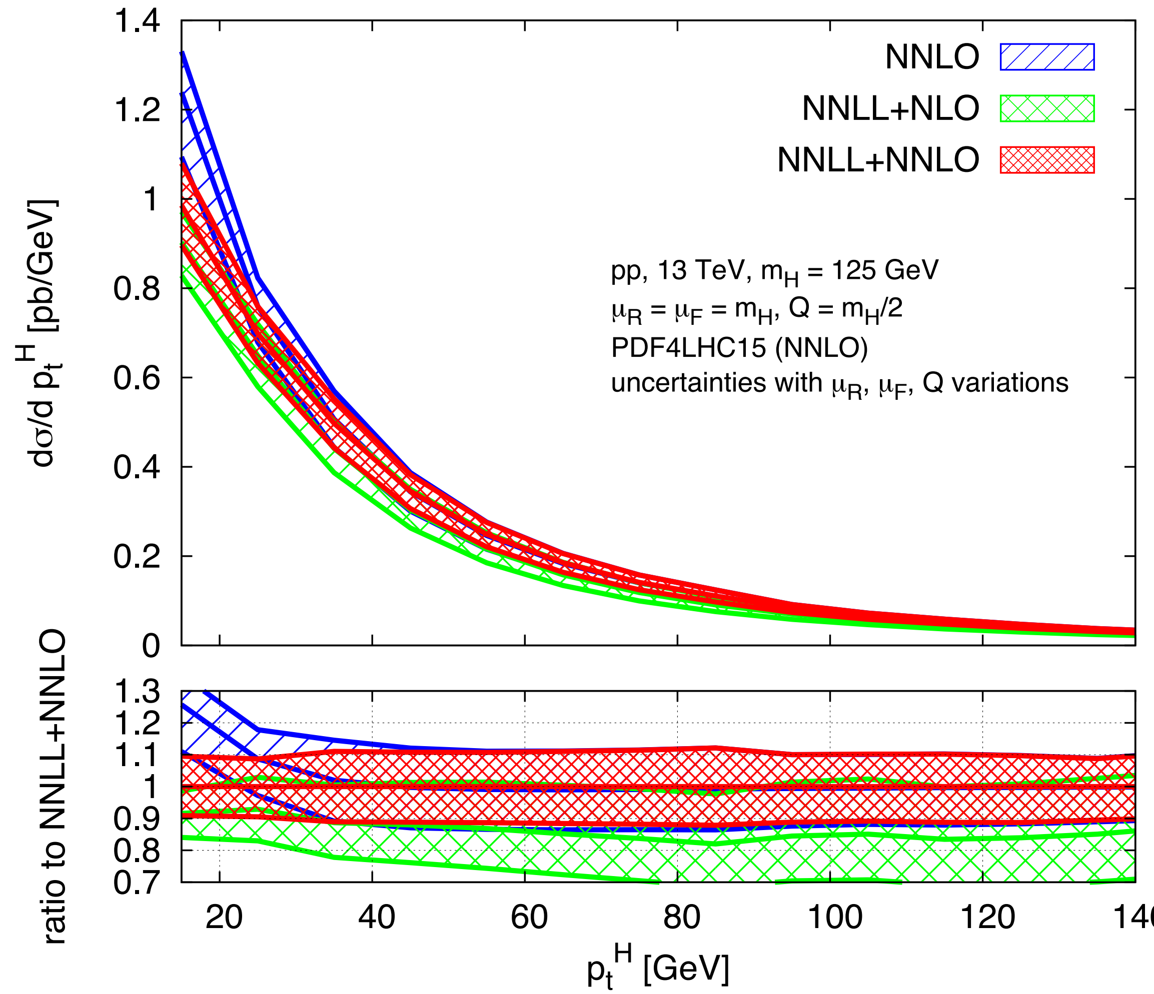


- Combination of f.o. N^{3}LO (Higgs inclusive) and NNLO (H+J exclusive) with NNLL resummation, LL$_R$ resummation, mass effects…
- No breakdown of fixed (high) order till very low scales
- Even more so for Z+jet [Gerhmann-De Ridder et al (2016)]

Application of NNLO results: H p_T

[Monni, Re, Torrielli (2016)]



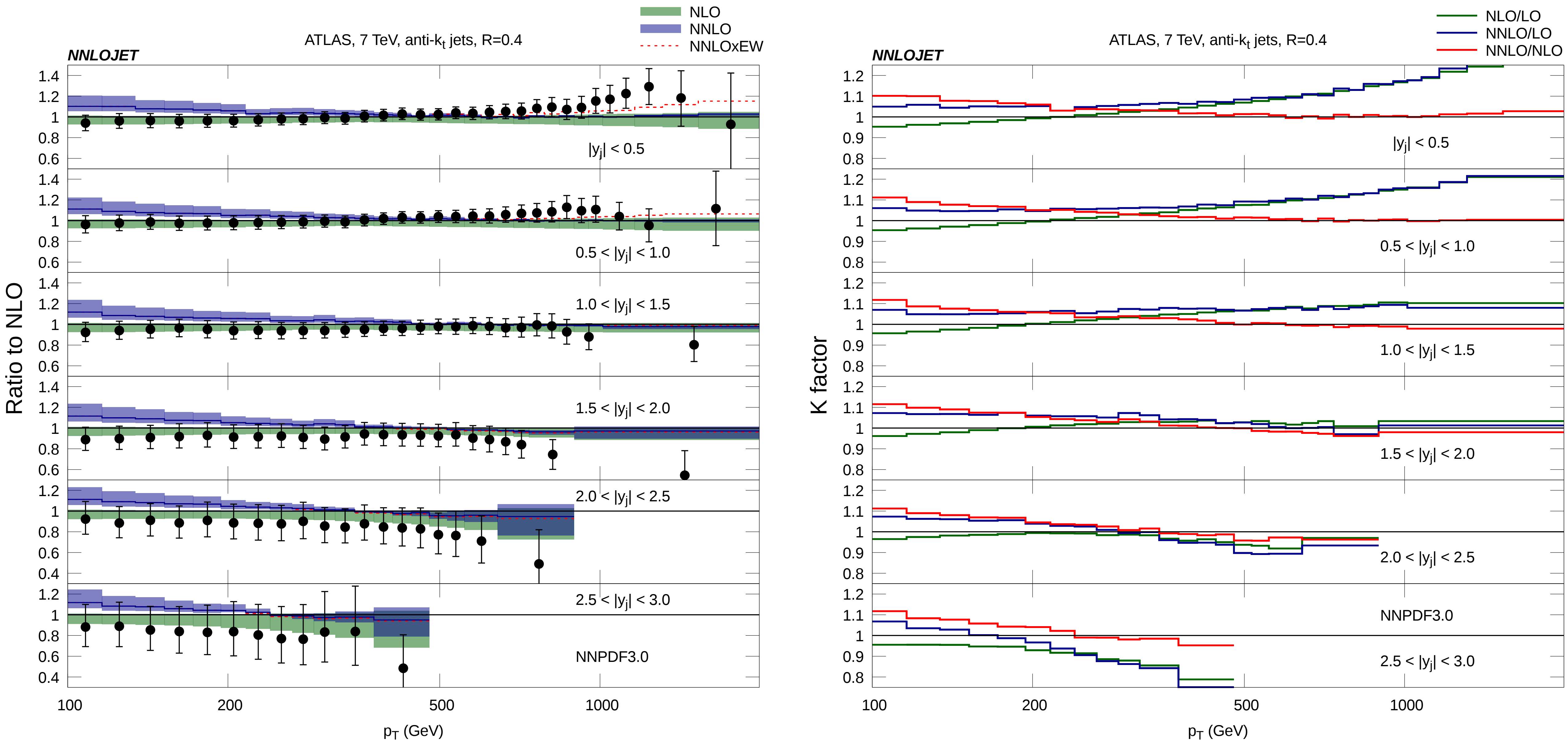


- Matching of NNLO H+J with NNLL Higgs p_T resummation
- Significant reduction of perturbative uncertainties
- Again, no breakdown of perturbation theory (resummation effects: 25% at $p_T = 15$ GeV, ~0% at $p_T = 40$ GeV)

Recent NNLO results: dijet

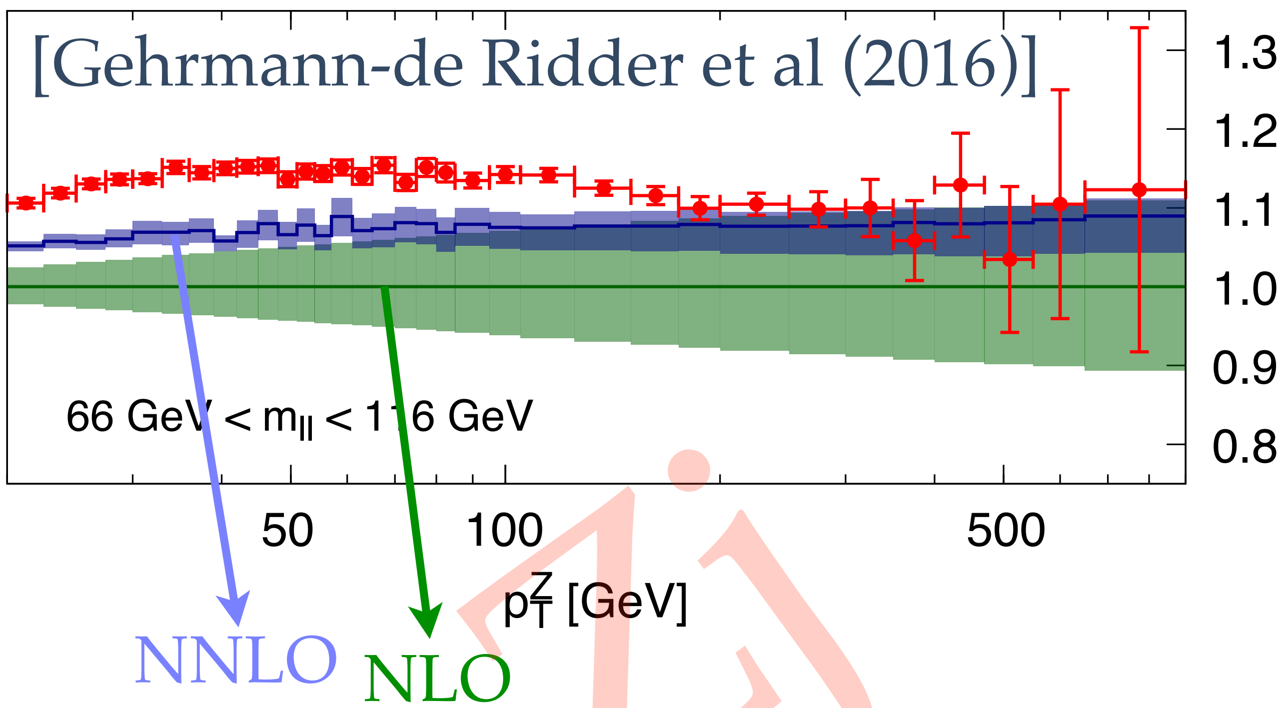
[Currie, Glover, Pires (2016)]

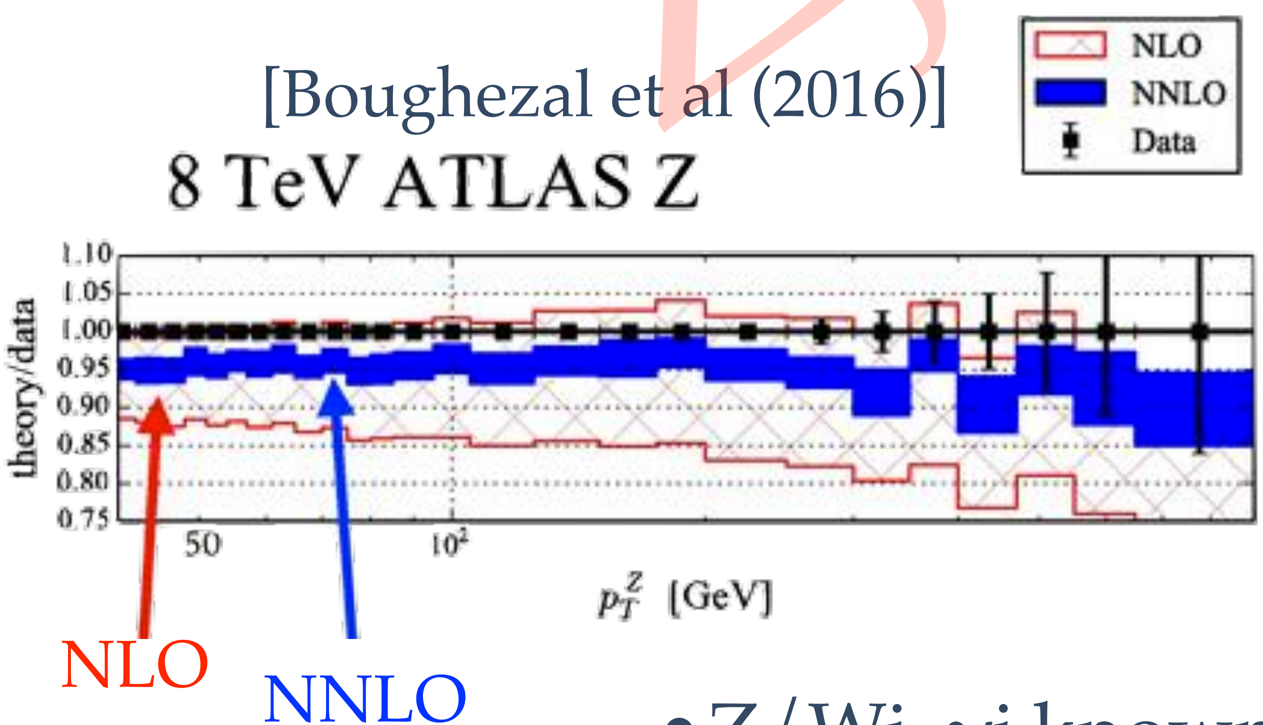
~40 partonic channels, highly non-trivial color flow. Realistic jet

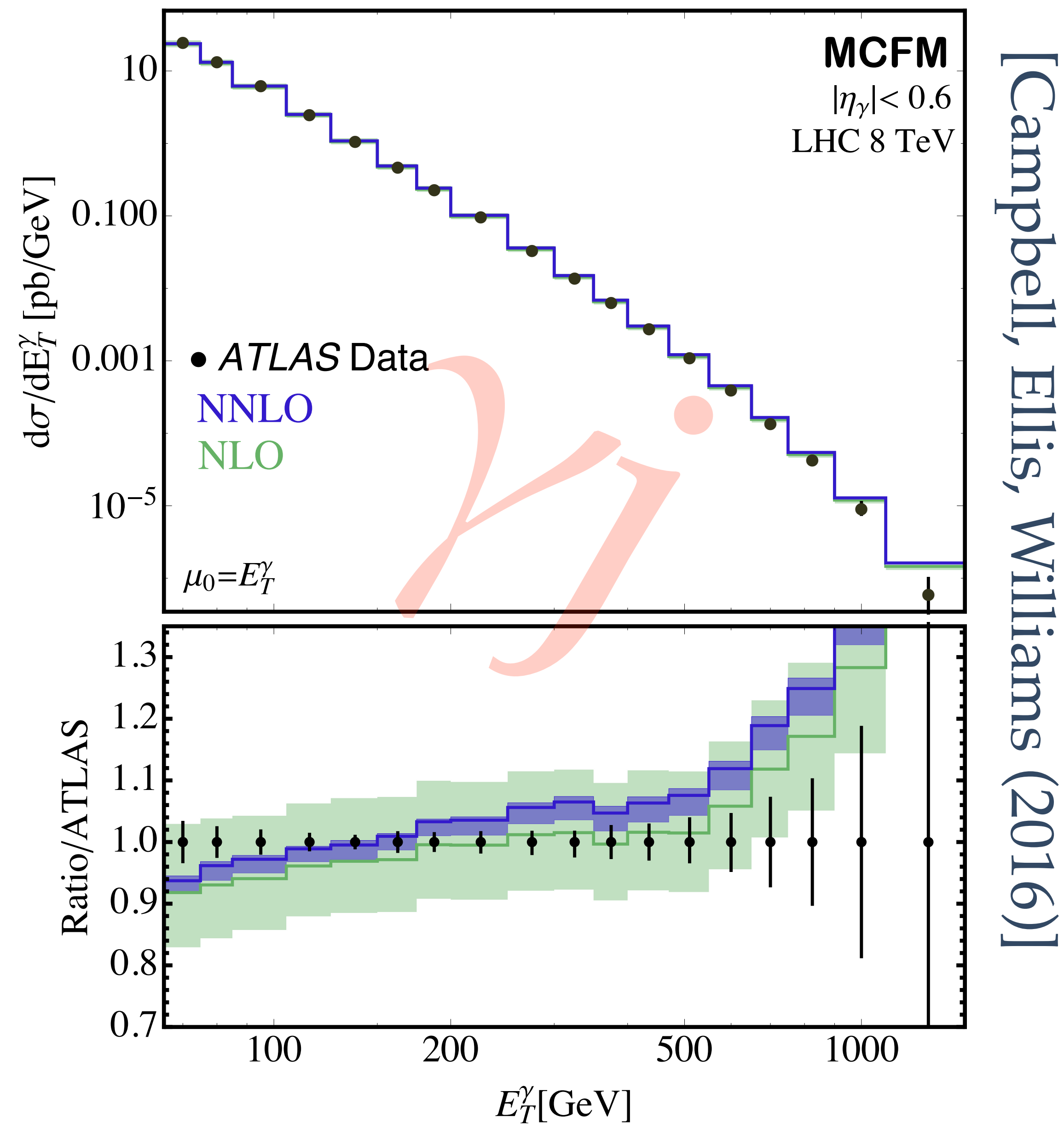


- Non trivial shape correction (NLO scale choice?), sizable effect
- Large effect on PDF? (see also jj in DIS [Niehues, Currie, Gehrmann (2016)])

Recent NNLO results: VJ

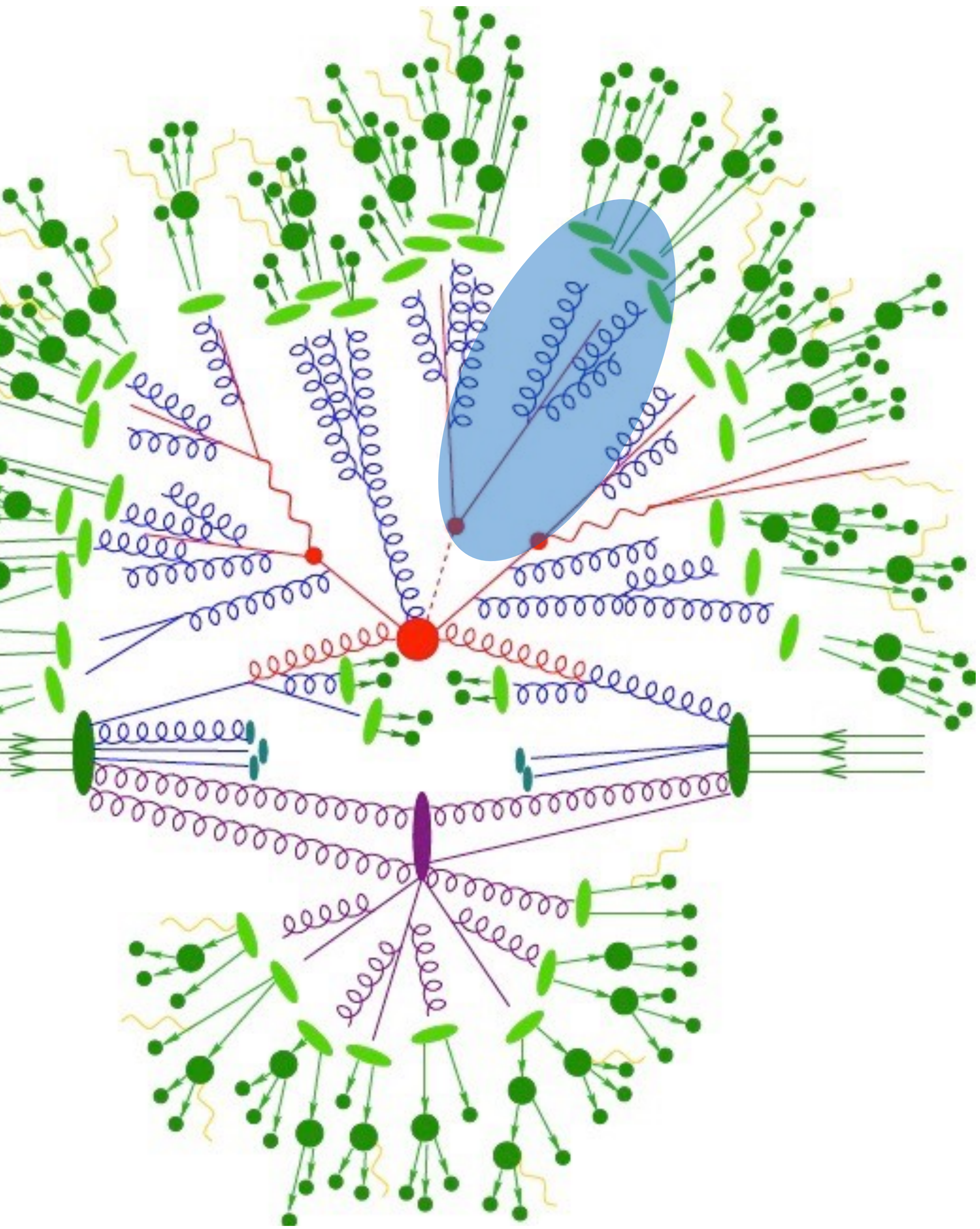






- Z/Wj, γj known. Zj: independent computations
- Highly improved theoretical accuracy (~exp error)
- Small deviations evident (PDFs? NP? Isolation?)

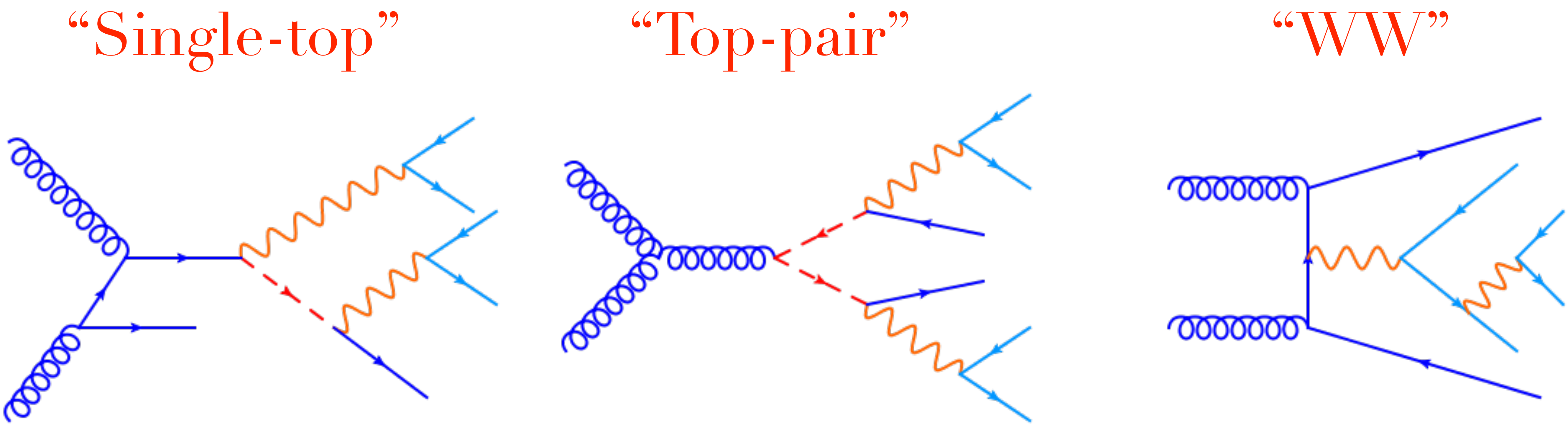
From partons to hadrons: PS



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…

Example: unified treatment of WWbb

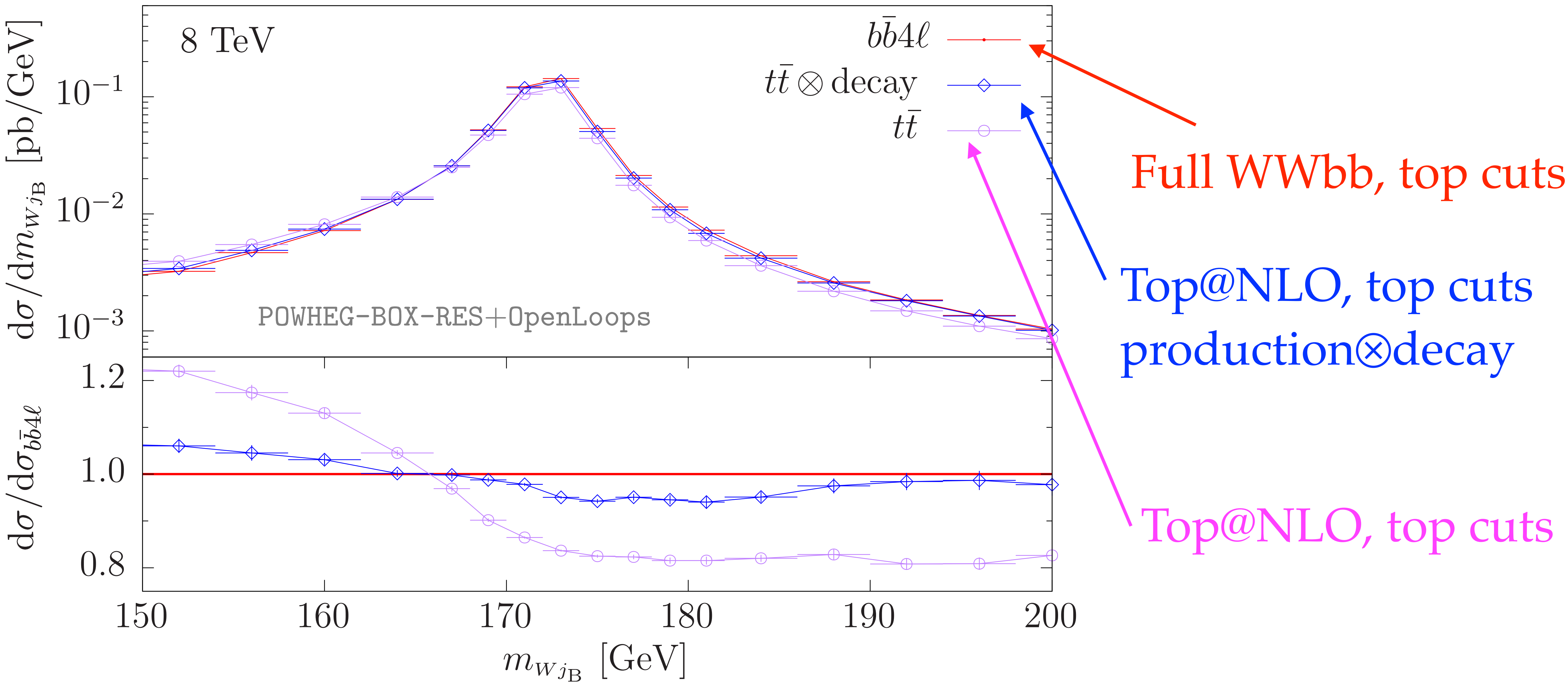


These 3 “processes” share the same initial/final state → THEIR SEPARATION IS UNPHYSICAL (quantum interference)

- in the past: we were unable to properly generate the WWbb final state
- more or less ad-hoc ways of separating the three (IDEA: selection cuts should clearly select one of the 3 topologies)
- thanks to recent advance we can consider WWbb as a whole, putting these analysis on solid theoretical grounds

Example: unified treatment of WWbb

[Iežo, Lindert, Nason, Oleari, Pozzorini (2016)]

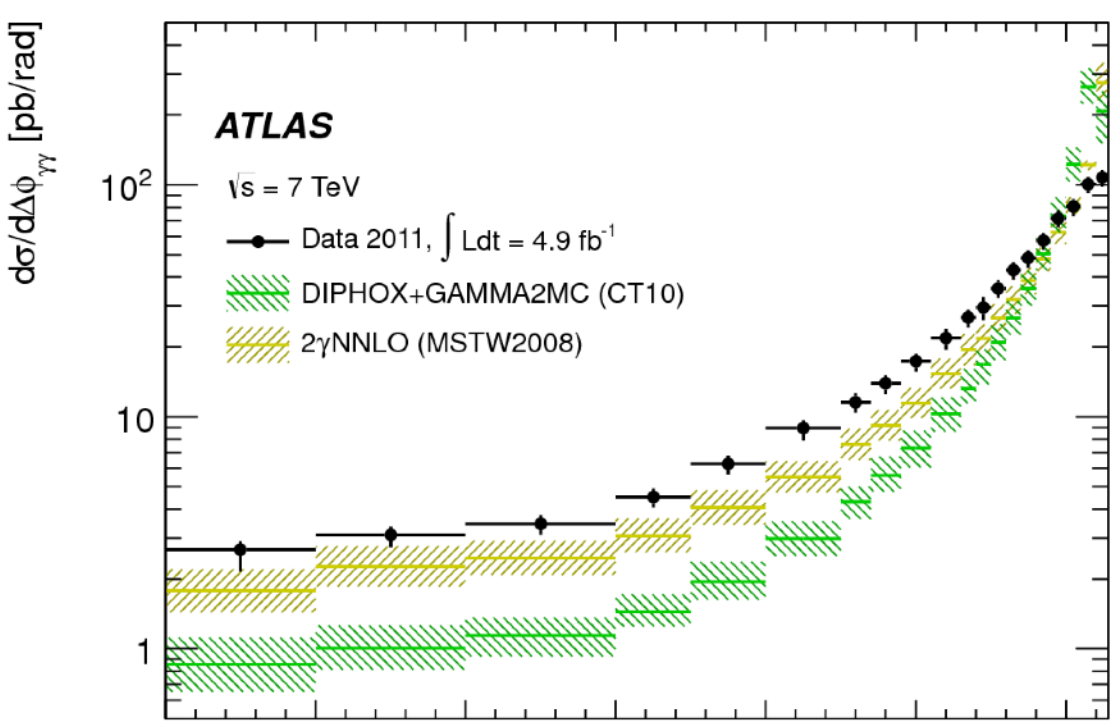


- Radiation in the decay crucial for the reconstructed top mass
- After top selection cuts, naive expectation WWbb~ top production⊗decay works well ($\Gamma_t \ll m_t \rightarrow$ factorization) → NNLO!
- Shift in reconstructed top mass: ~ 100 MeV (WWbb vs top prod⊗decay)

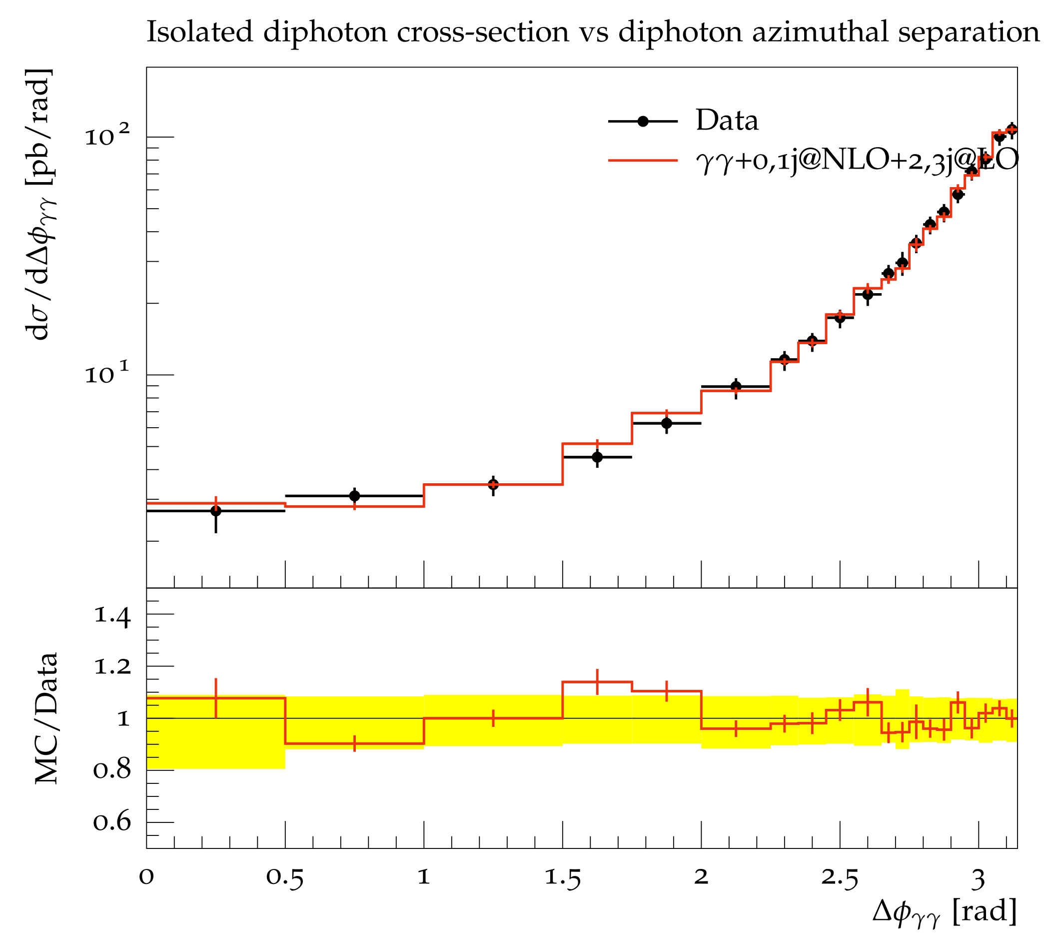
A bonus of PS: merging

- Often, radiative corrections are dominated by real emission: new channels / new topologies opening up.
- Parton shower MC provide an ideal framework to perform such combination
- "Merge" together samples of different multiplicities (CKKW, MLM, NLOPS, MEPS, MENLOPS, MEPS@NLO, FXFX, MINLO, GENEVA…)

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



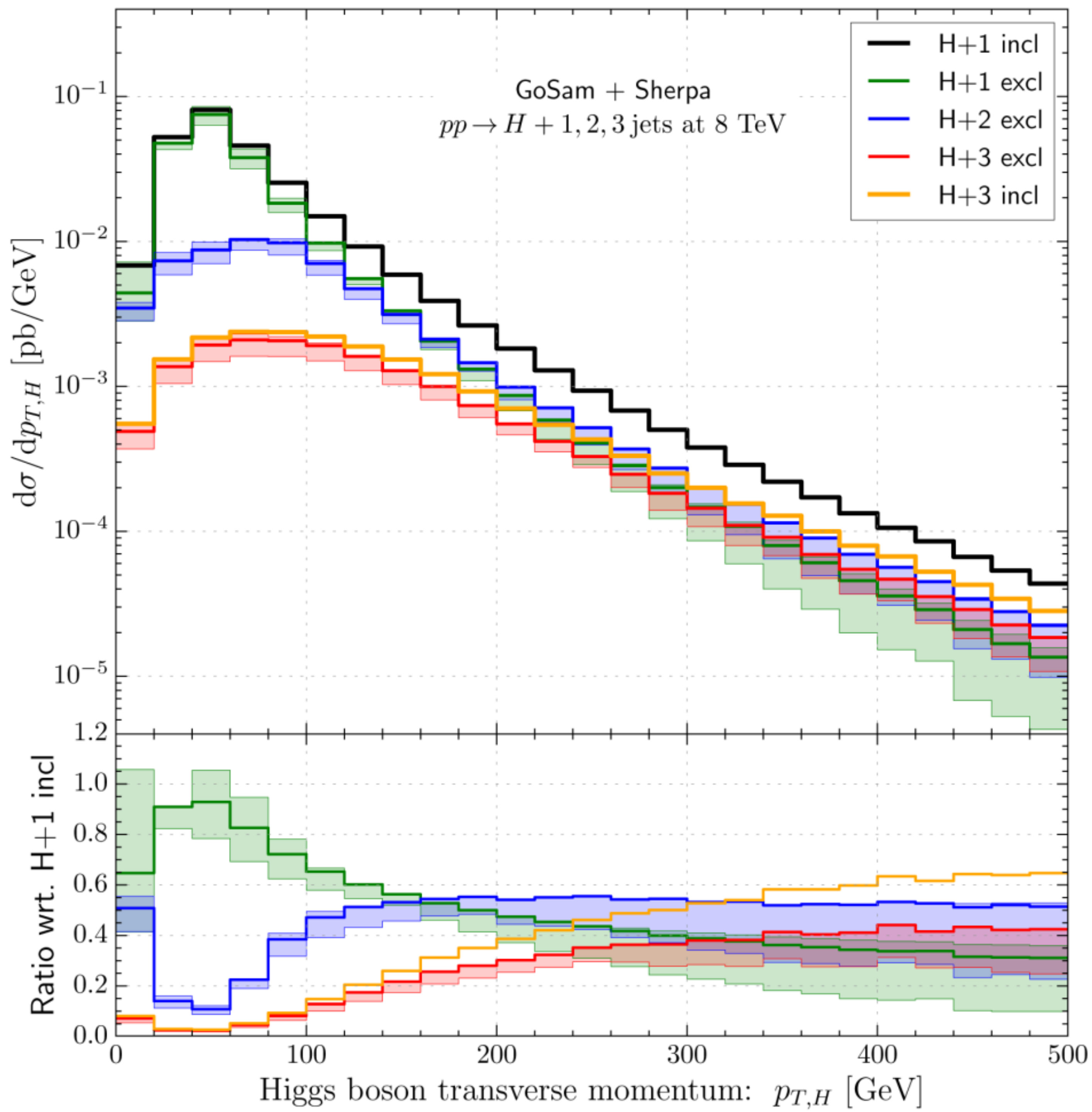
[Catani et al, $pp \to \gamma\gamma$ @NNLO]



[Höche and Siegert, SHERPA merged NLO]

Merging: Higgs p_t with finite top mass effects

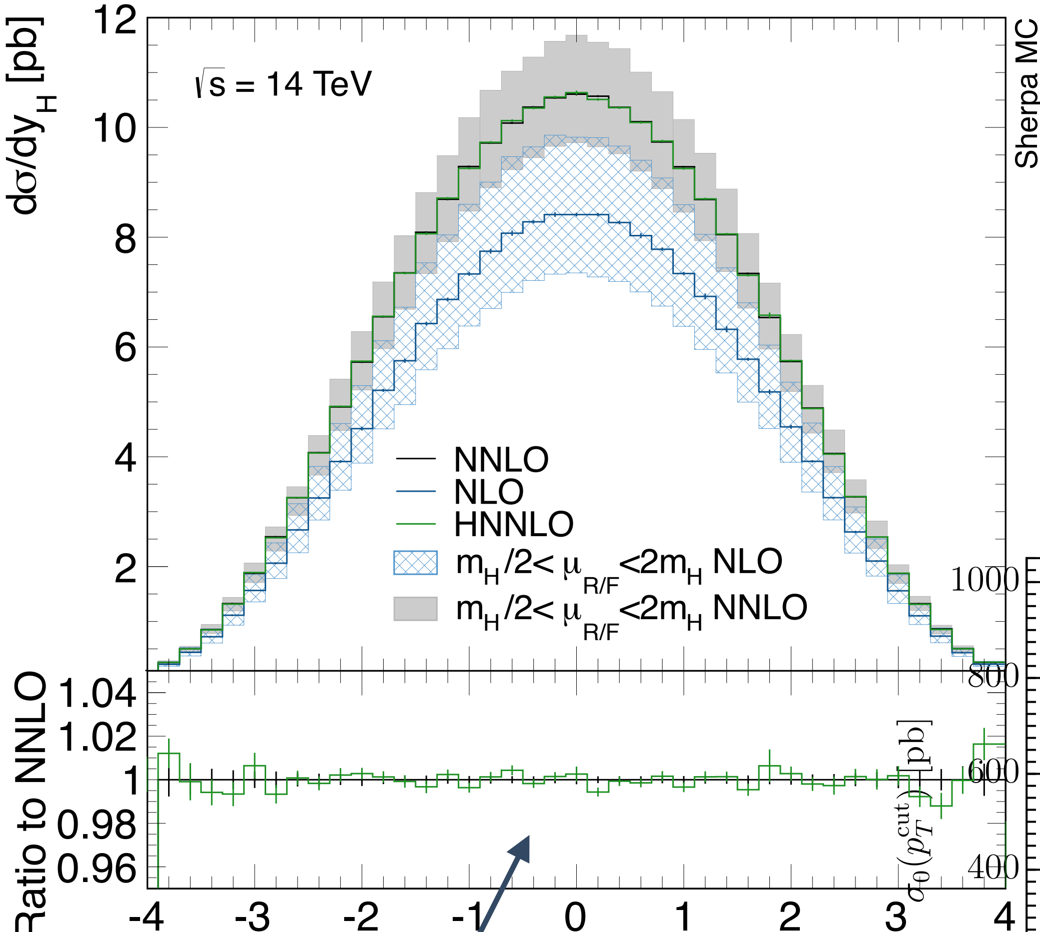
Complete NLO corrections with full top-quark mass dependence: still unavailable (2-loop amplitudes) (*NNLO in the HEFT*)



- 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…)

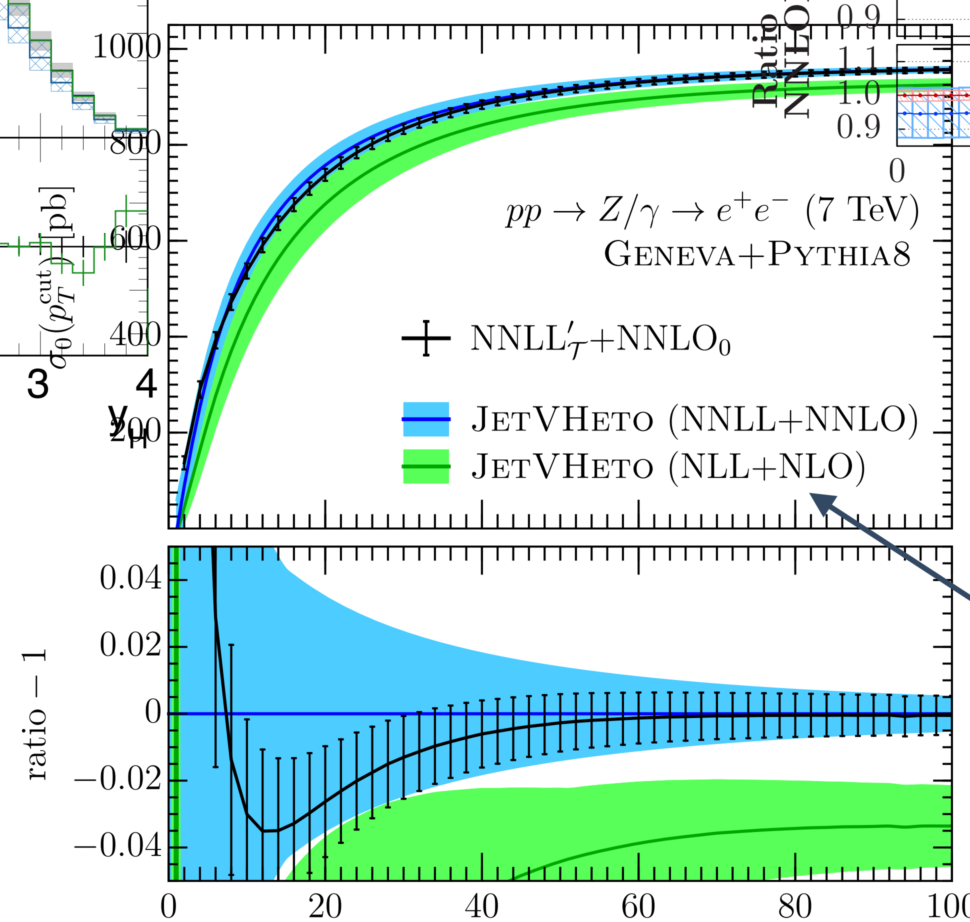
From merging to NNLOPS

Merged sample close to full NNLO computation (~right real emission, missing virtual corrections). For color-singlet processes, extension of merging ideas led to combination of NNLO + PS



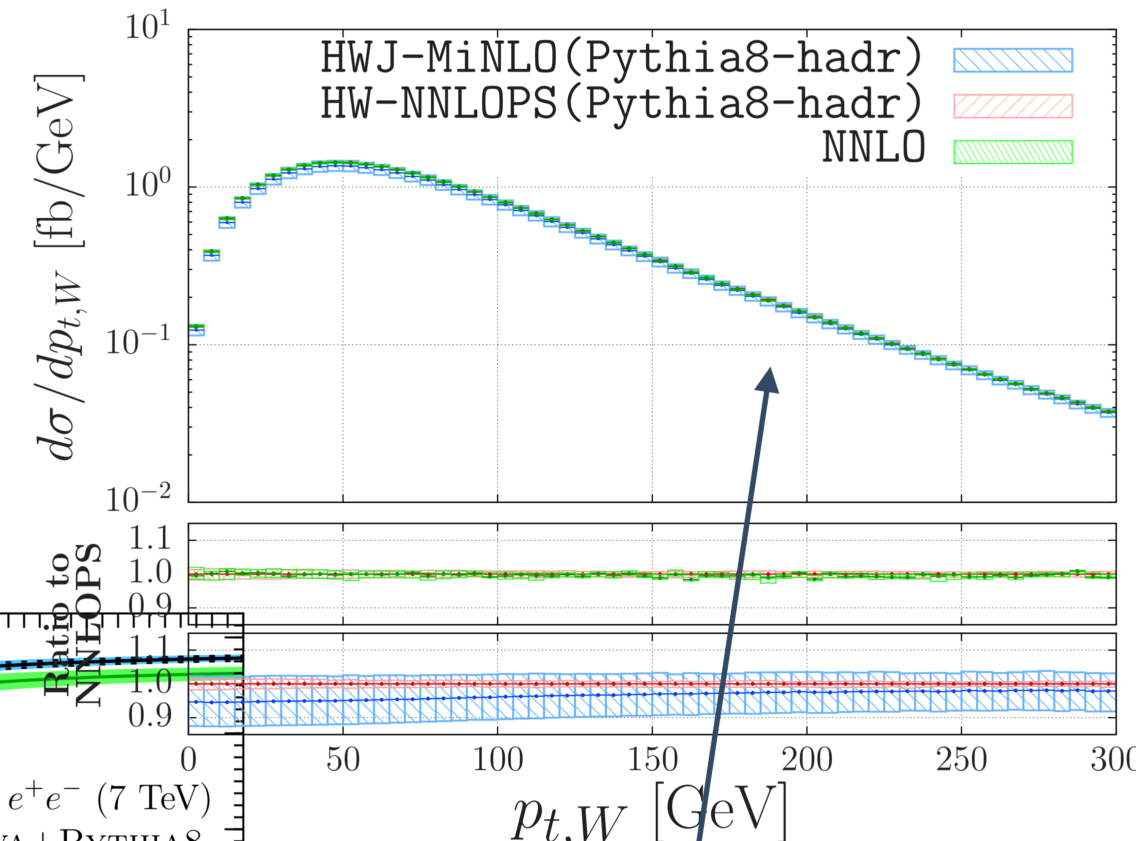
Higgs

[Höche et al, UN²LOPS (2014)]



Drell-Yan

[Alioli et al, GENEVA (2015)]



WH

[Astill et al, MINLO (2016)]

Logs beyond PS: resummation

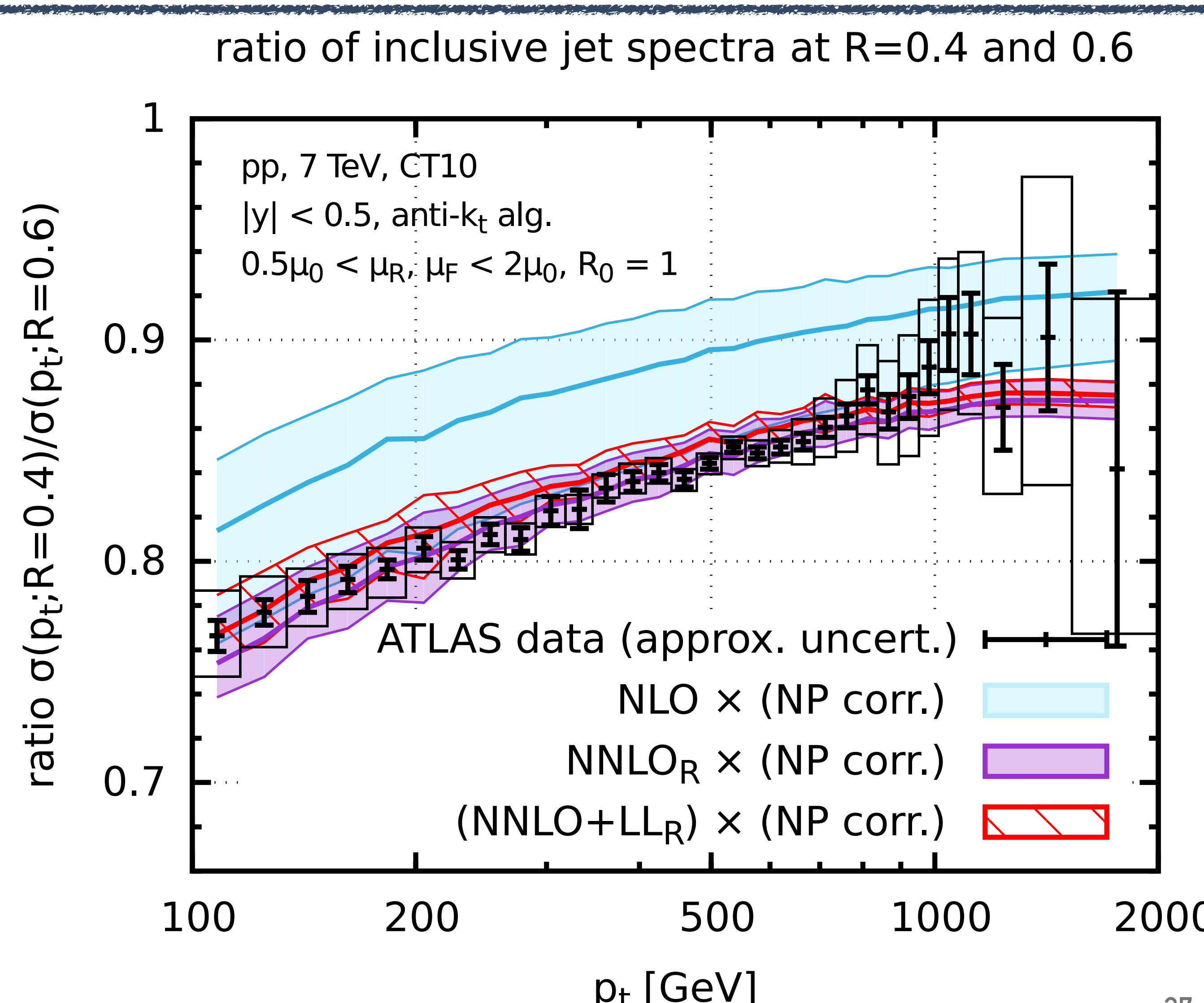
- PS gives an approximate description of multi-particle emission in the soft/collinear limit. More theoretical control: resummation
- Example: STUDY THE DEPENDENCE ON JET RADIUS R
[Dasgupta et al (2016), Chen et al (2015) Kolodrubetz et al (2016), Kang et al (2016)]

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



[G.P. Salam, "Future challenges for perturbative QCD" 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!