Progress in perturbative QCD

Fabrizio Caola, IPPP Durham & CERN

University of Durham

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Disclaimer

A lot of progress in pQCD in the last year

- Impossible / useless to cover everything in 45 minutes
- 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 (=AFTER ANNUAL THEORY MEETING 2015) RESULTS
- Apologies if your favorite topic is not covered…

Physics at the LHC: need for precision

- Despite the standard model being 'complete', strong indications that new physics may be present at the LHC
- Before the LHC, some expectation of new physics beyond the corner (naturalness, fine tuning, WIMP miracle…): SUSY, extra dimensions… So far, this has not happened
- Discovering new physics turned out to be more challenging. No spectacular new signatures ⇒ new physics can be hiding in small deviations from SM behavior, or in unusual places
- To single them out: TEST THE (IN)CONSISTENCY OF THE SM AT THE LHC, as best as we can

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

Also, pushing the frontier of pQCD forward, we keep learning about the structure of a REAL-WORLD QFT.

Precision goals: some (rough) estimates

Imagine to have new physics at a scale Λ

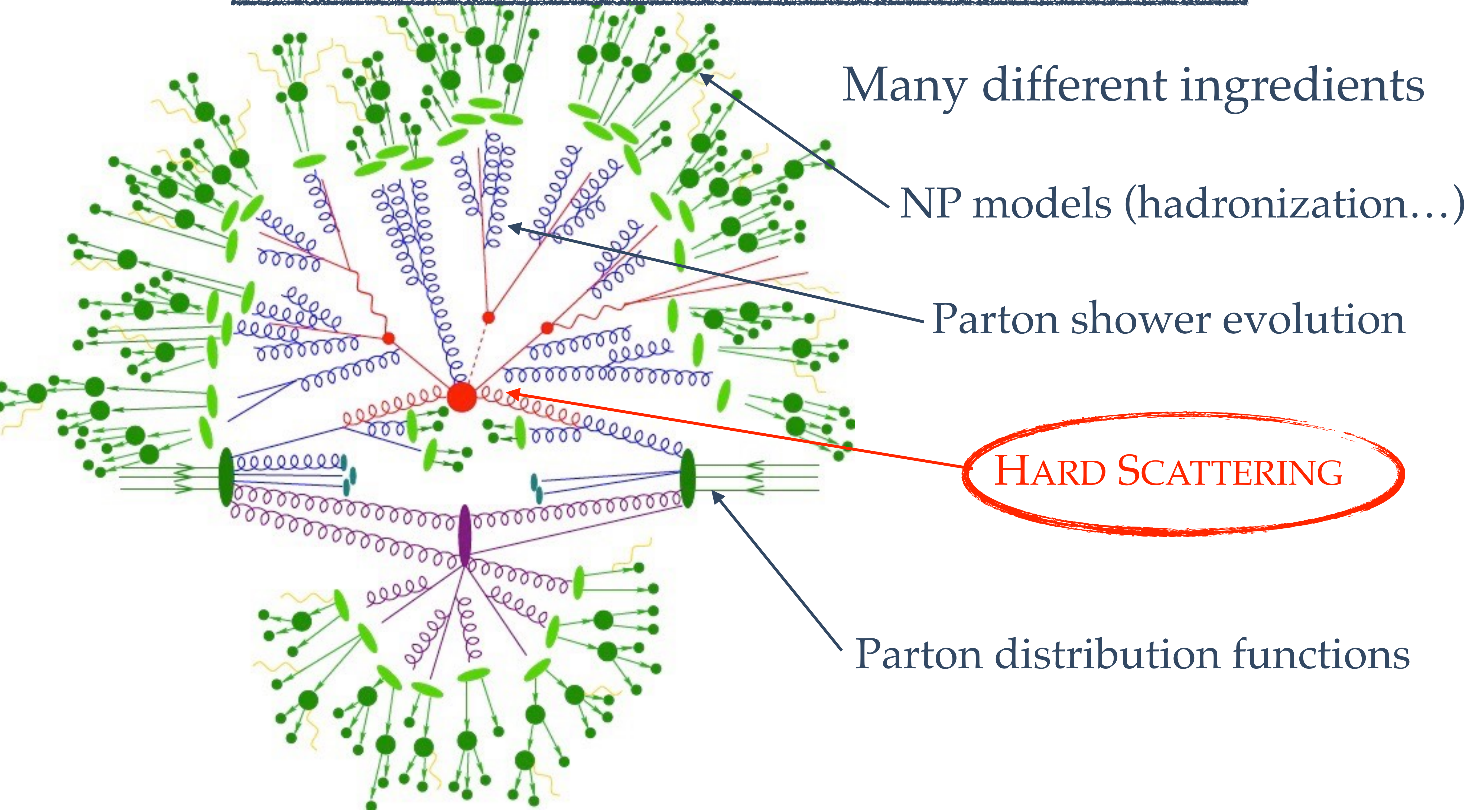
- if Λ small $\rightarrow$ should see it directly, bump hunting
- if Λ large, typical modification to observable w.r.t. standard model prediction: $\delta O \sim Q^2 / \Lambda^2$
- standard observables at the EW scale: to be sensitive to ~ TeV new physics, we need to control δO to few percent
- high 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 PQCD TO MATCH THEM ON THE THEORY SIDE

Precise predictions: requirements

THE GOAL: PRECISE MODELING OF THE ACTUAL EXPERIMENTAL SETUP



"Few percent": the theory side

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

Input parameters: ~few percent.
In principle improvable

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

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

NLO computations: status and recent progress

NLO computations: where do we stand

Thanks to a *very good understanding of one-loop amplitudes* and to *significant development in MC tools (→ real emission)* now

NLO IS THE STANDARD FOR LHC ANALYSIS

- Many publicly available codes allow anyone to perform NLO analysis for reasonably arbitrary [~ 4 particles (~ 3 colored) in the final state] LHC processes: MADGRAPH5_AMC@NLO, OPENLOOPS(+SHERPA), GOSAM(+SHERPA), RECOLA, HELAC…
- The next step for automation: NLO EW (basically there), arbitrary BSM

Dedicated codes allow for complicated final states, e.g.:

- V(V)+jets [BLACKHAT+SHERPA], jets [NJET+SHERPA], tt+jets [Höche et al. (2016)] → also allow for interesting theoretical analysis (mult. ratios predictions…)
- H+jets [GOSAM+SHERPA]. Recently: up to 3-jets at LO with full top-mass dependence [Greiner et al. (2016)] → investigate the high-p_t Higgs spectrum
- Off-shell effects in ttX processes: ttH [Denner and Feger (2015)], ttj [Bevilacqua et al. (2015)]

NLO computations: where do we stand

Thanks to a *very good understanding of one-loop amplitudes* and to *significant development in MC tools (→ real emission)* now

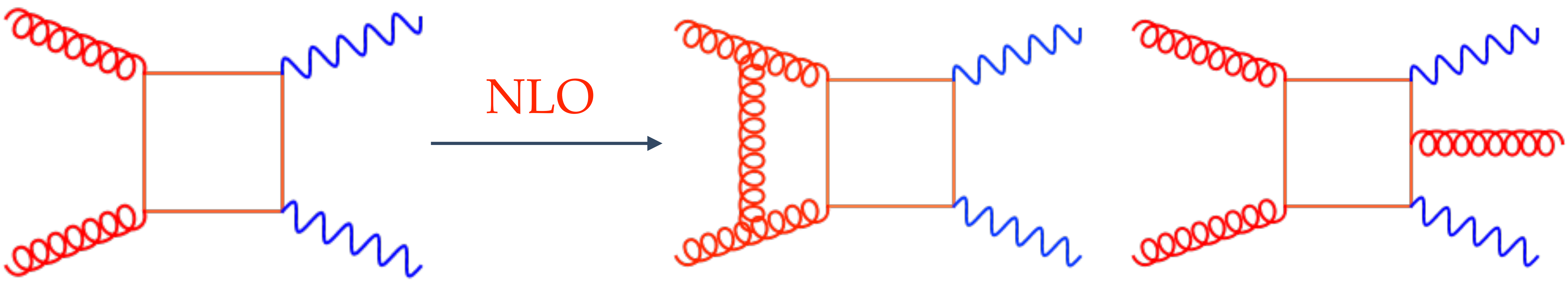
NLO IS THE STANDARD FOR LHC ANALYSIS

NLO RESULTS: SOME THEORETICAL SURPRISE

- NLO "revolution" triggered by new ideas for loop amplitude computation → unitarity, on-shell integrand reduction
- Sophisticated incarnations of traditional "Passarino-Veltman"-like tensor reduction proved to be COMPETITIVE WITH UNITARITY METHODS (COLLIER + OPENLOOPS)
- Amplitudes computed with numerical methods are fast and stable in degenerate kinematics → can be used in NNLO computations (so far established for color-singlet processes)

NLO: loop-induced processes

In the past year, significant progress for loop-induced processes



- Relevant examples: Higgs p_t, $gg \to VV$ (especially after $qq \to VV$@NNLO), $gg \to VH$ (especially after qq@NNLO), di-Higgs…
- Despite being loop-suppressed, the large gluon flux makes the yield for these processes sizable
- gluon-fusion processes → expect large corrections
- At NLO simple infrared structure, but virtual corrections require complicated two-loop amplitudes
- Real emission: one-loop multi-leg, in principle achievable with 1-loop tools

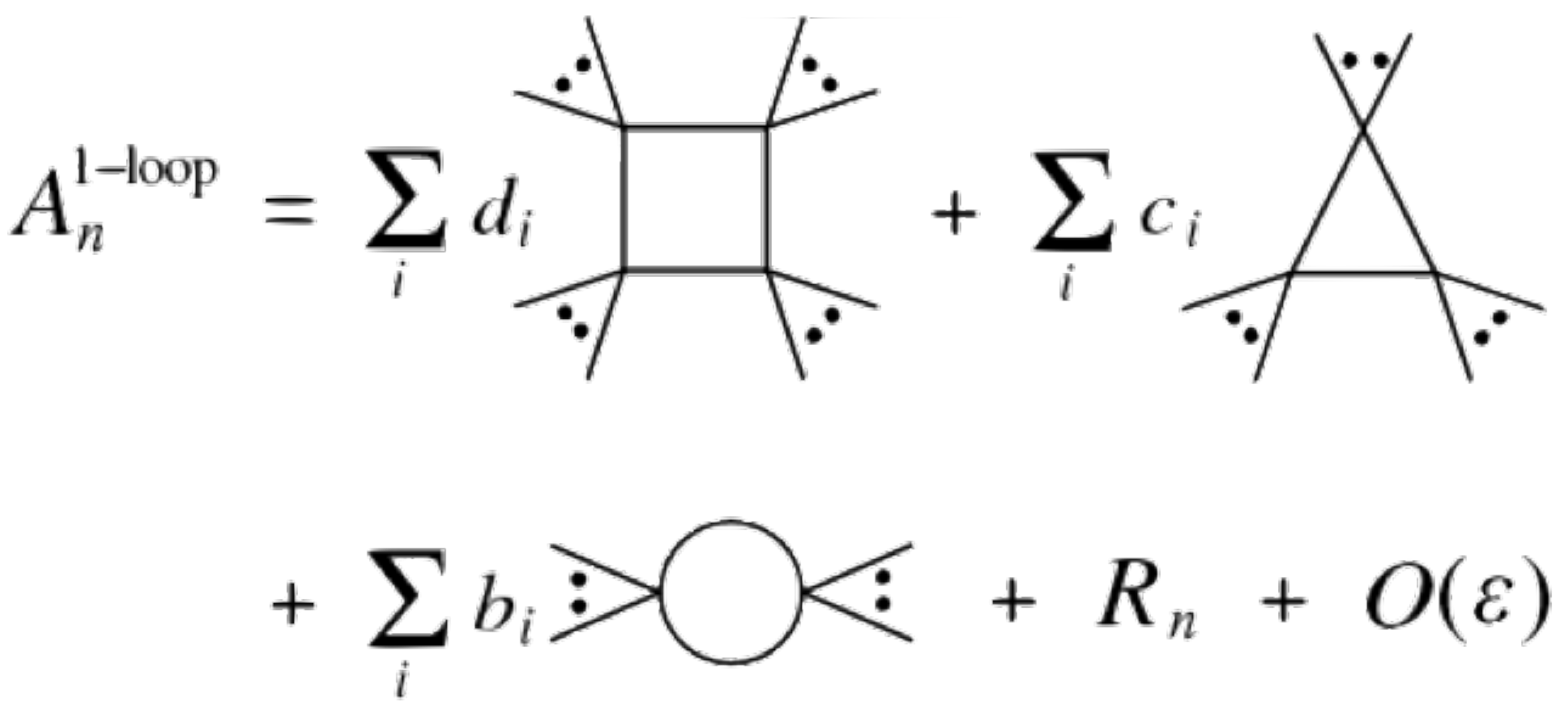
A small detour: loop amplitudes

Computation of loop-amplitudes in two steps:

1. reduce all the integrals of your amplitudes to a minimal set of independent `master' integrals
2. compute the independent integrals

At one-loop:

- independent integrals are always the same (box, tri., bub., tadpoles)
- only (1) is an issue. Very well-understood (tensor reduction, unitarity…)



Beyond one-loop: reduction not well understood, MI many and process-dependent (and difficult to compute…)

Two-loop: reduction

- So far: based on SYSTEMATIC ANALYSIS OF SYMMETRY RELATIONS between different integrals (IBP-LI RELATIONS [Tkachov; Chetyrkin and Tkachov (1981); Gehrmann and Remiddi (2000)] / LAPORTA ALGORITHM [Laporta (2000)])

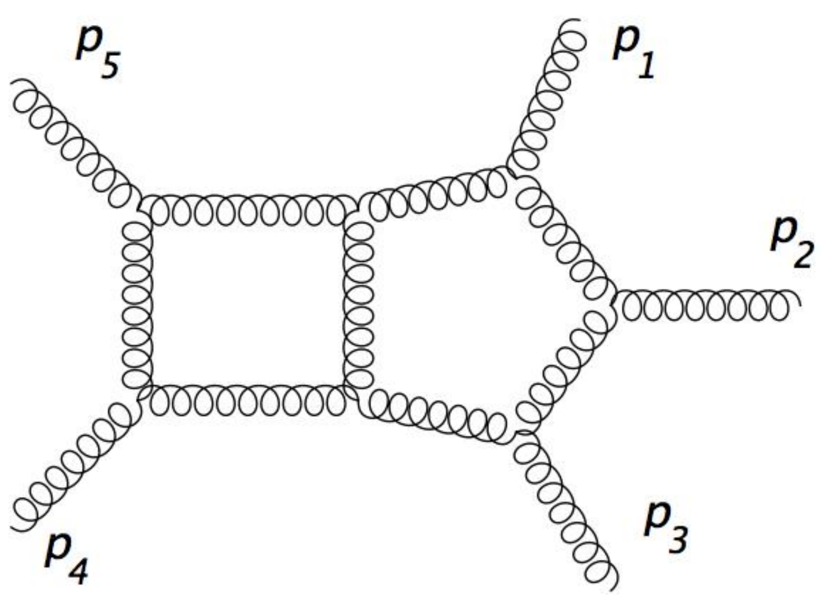
- State of the art for phenomenologically relevant amplitudes
  - 2 → 2 with massless internal particles (di-jet, H/V+jet, VV)
  - 2 → 2 with two mass scales: ttbar [Czakon et al. (2007)], H+JET WITH FULL TOP MASS DEPENDENCE [Melnikov et al. (2016)]

- Going beyond: significant improvements of tools, NEW IDEAS

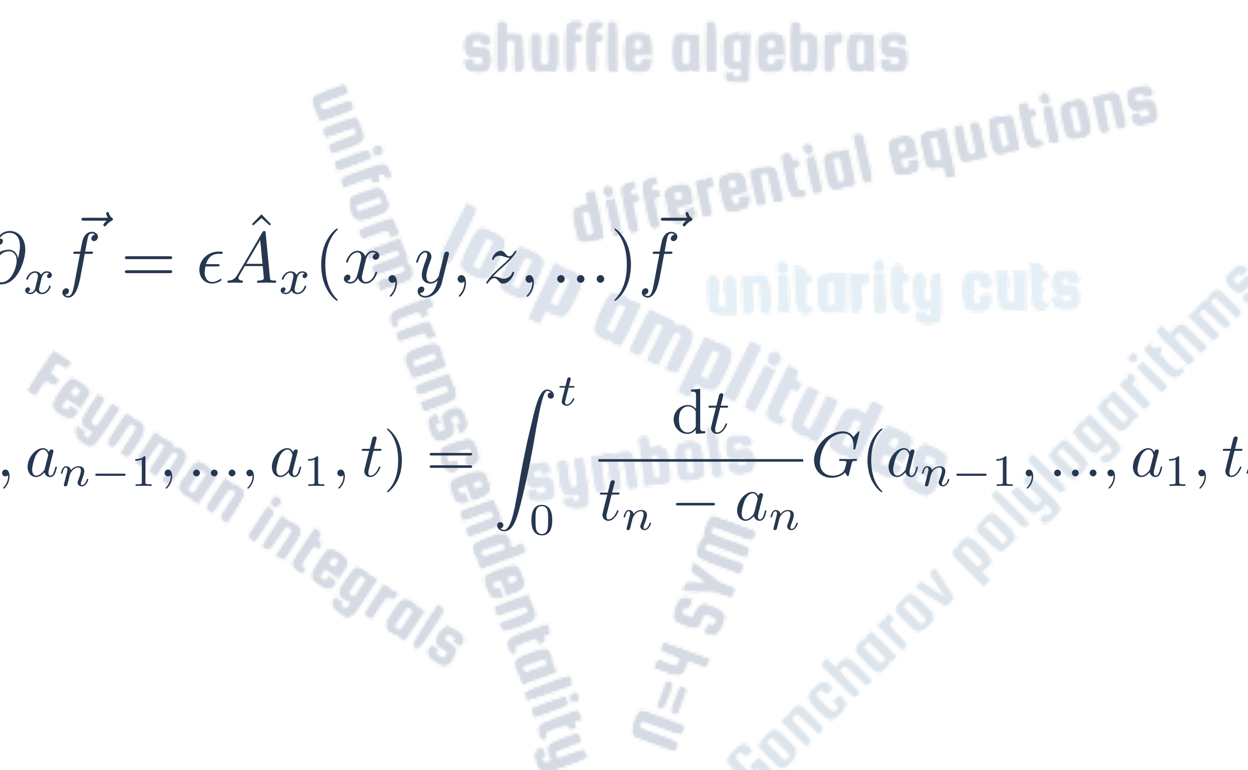
- Motivated by the one-loop success, many interesting attempts to generalize unitarity ideas / OPP approach to two-loop case
- We are still not there, but a lot of progress
- Interesting proof-of-concept for unitarity-based approaches: 5/6-gluon all-plus amplitudes at two-loops [Badger, Frellesvig, Zhang (2013); Badger, Mogull, Ochiruv, O'Connell (2015); Badger, Mogull, Peraro (2016)]

Two-loop: master integrals

- For a large class of processes (~ phenomenologically relevant scattering amplitudes with massless internal lines) we think we know (at least in principle) how to compute the (very complicated) MI. E.g.: DIFFERENTIAL EQUATIONS [Kotikov (1991); Remiddi (1997); HENN (2013); Papadopoulos (2014)]
- Recent results for very complicated processes: planar 3-jet [Gehrmann, Henn, Lo Presti (2015)], towards planar Vjj/Hjj [Papadopoulos, Tommasini, Wever (2016)]
- In these cases, the basis function for the result is very well-known (Goncharov PolyLogs) and several techniques allow to efficiently handle the result (symbol, co-products…) and numerically evaluate it



$$s_{ij} = (p_i + p_j)^2$$
$$\vec{x} = \{s_{12}, s_{23}, s_{34}, s_{45}, s_{51}\}$$



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

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

Two-loop: master integrals

- Unfortunately, we know that GPL are not the end of the story. For pheno-relevant processes, we typically exit from this class when we consider amplitudes with internal massive particles (e.g. ttbar, H+J)
- Progress in this cases as well (e.g. [Tancredi, Remiddi (2016); Adams, Bogner, Weinzierl (2015-16)]) but we are still far from a satisfactory solution → real conceptual bottleneck for further development

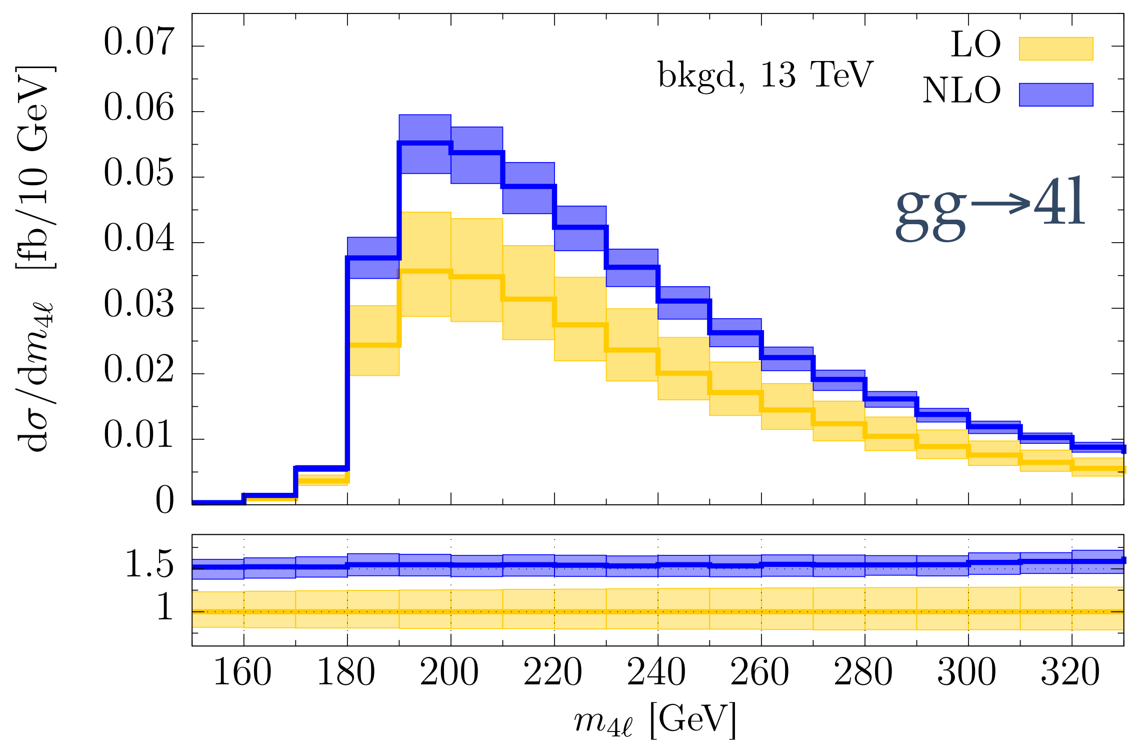
- FIRST STEP TOWARDS A SOLUTION: planar results for H+J with full top mass effects. Solution as 1-fold integrals. Elliptic functions. [Bonciani et al. (2016)]

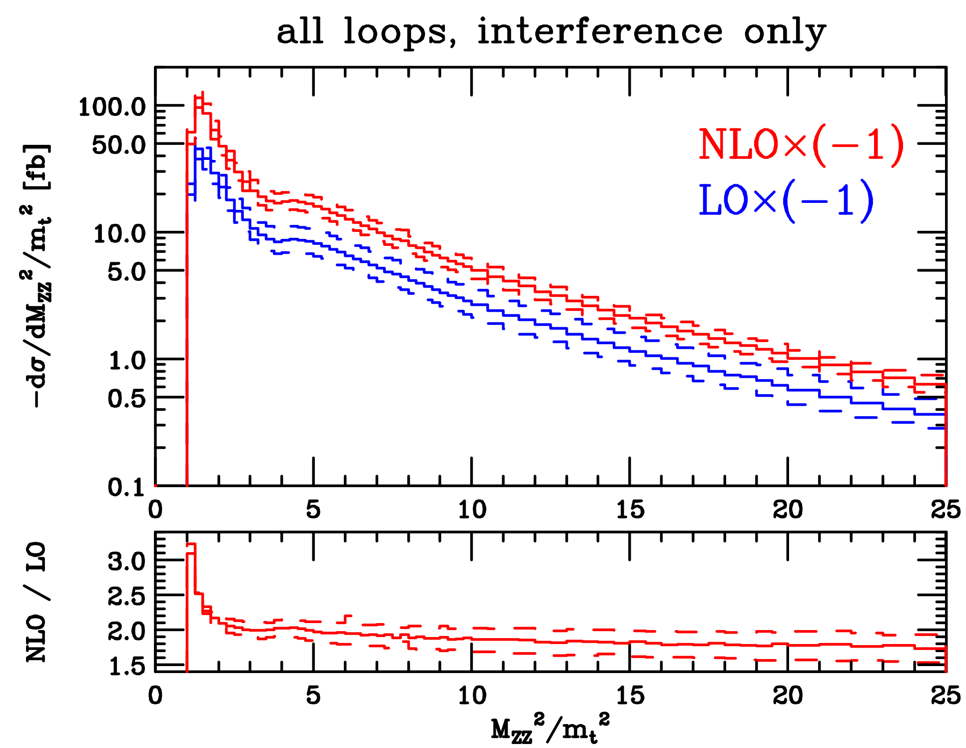
- *Side note: some times physics come and help you. b-quark mass effects for Higgs p_t relevant in the region $m_b \ll p_t \ll m_H$. Using this condition massively simplify the computation of integrals* → *AMPLITUDE IN THIS REGIME RECENTLY COMPUTED* [Melnikov et al. (2016)]. *But result cannot be extended for $p_t \gg m_H$*

Back to loop induced: NLO for gg → VV

Thanks to the progress in loop-amplitude computations, NLO corrections to gg→WW/ZZ and to gg→(H)→VV signal/background interference

[FC, Melnikov, Röntsch, Tancredi (2015-16); Campbell, Ellis, Czakon, Kirchner (2016)]

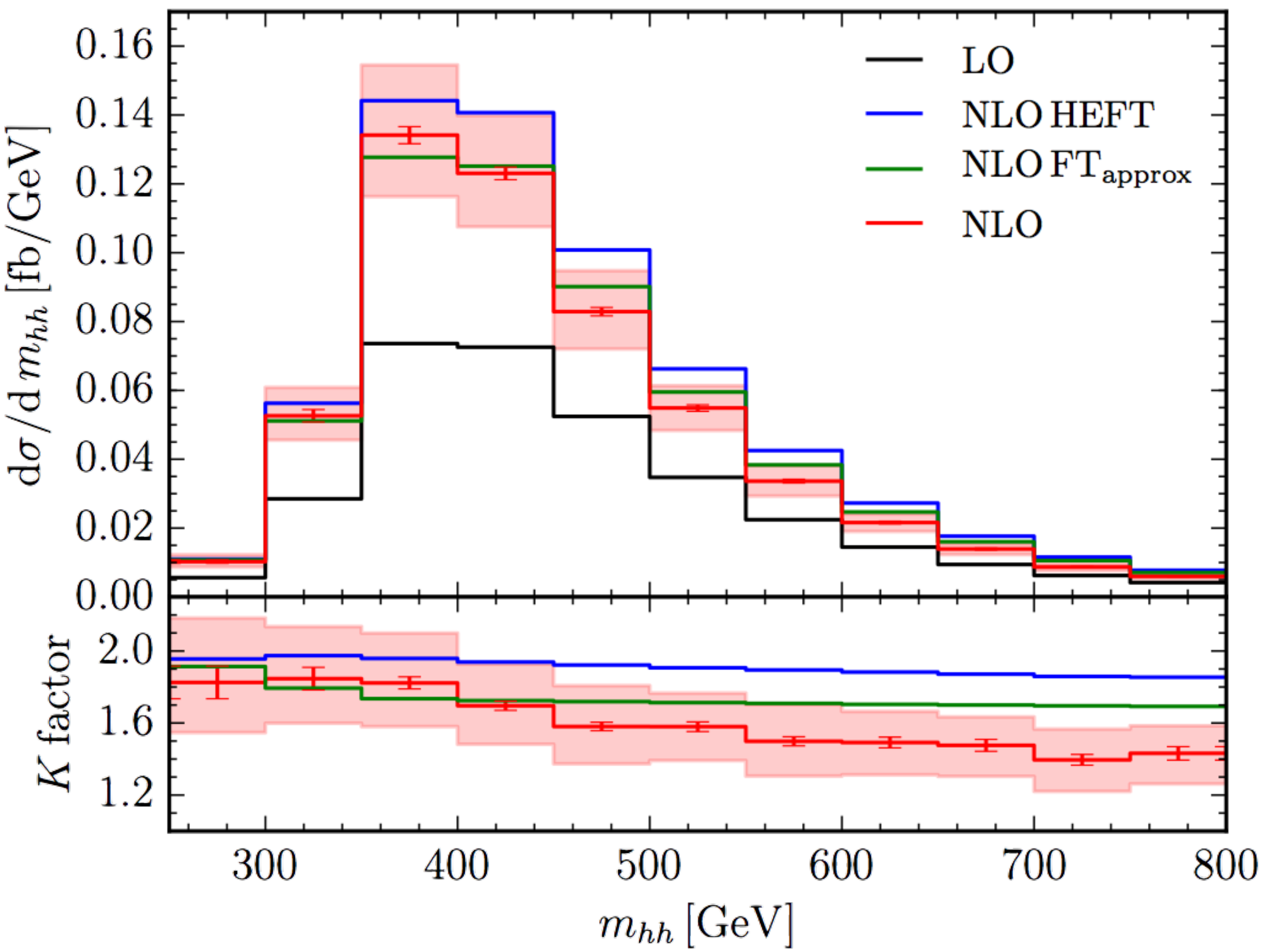




- Large corrections (relevant especially for precision pp→ZZ cross-section)
- Higgs interference: large, but as expected (K_{sig}~K_{bkg}~K_{int})
- Top mass effects (important for interference) through $1/m_t$ expansion → reliable only below threshold (although some hope for past-threshold extension via Padé approximations)

Loop induced: di-Higgs@NLO

[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016)]



- 2-loop amplitude beyond current reach (reduction and for MI)
- Completely different approach: *FULLY NUMERICAL INTEGRATION OF EACH INDIVIDUAL INTEGRAL*
- Table of 665 phase-space points
- Highly non-trivial computer-science component (GPUs, very delicate numerical integration…)

Lessons from the Exact Computation:

- Reasonable approximations to extend $1/m_t$ result beyond the top threshold (rescaled Born, exact real radiation) can fail quite significantly
- Exact K-factor much less flat than for m_t approximations

Loop induced: di-Higgs@NLO

[Borowka, Greiner, Heinrich, Jones, Kerner, Schlenk, Schubert, Zirke (2016)]

Now that we know the exact result, many interesting questions:

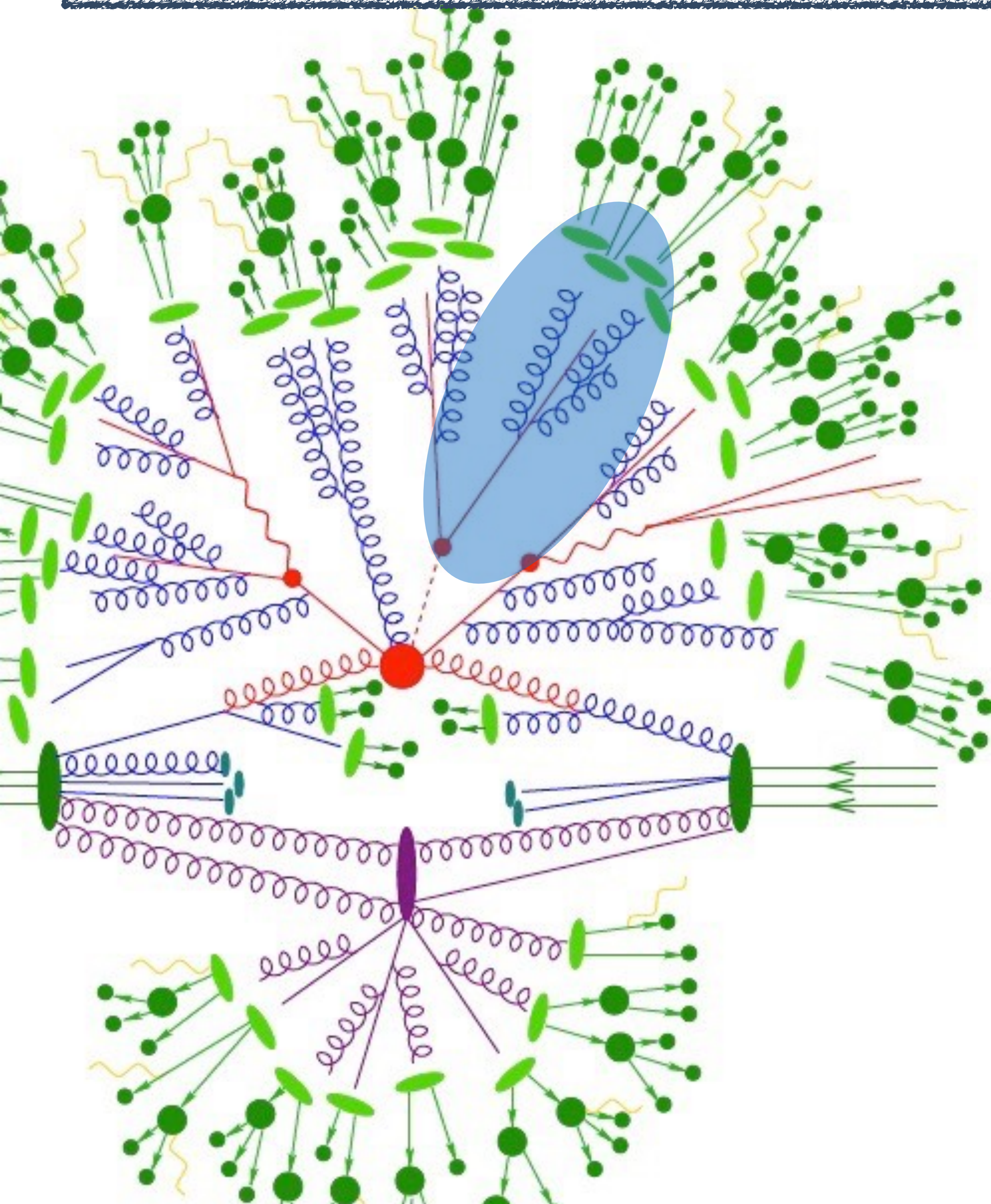
- do we understand why the approximate m_t result fails so miserably (high energy matching, genuinely large two-loop components…)?
  - ideal playground for approximation testing. Can we find something which works? Can we study e.g. the Padé approximation used to extend the $1/m_t$ expansion in $gg \to VV$?
  - especially relevant because we now know FULLY DIFFERENTIAL NNLO CORRECTIONS IN THE $M_T \to \infty$ LIMIT [de Florian et al (2016)] → Would like to know best way to combine the results

CAN THIS FULLY NUMERICAL APPROACH BE APPLIED TO MORE GENERAL CASES?

- processes with more than two (m_{HH}, y_{HH}) variables ($gg \to 4l$)
- processes with a more complicated tensor structure (H+J)

NLO computations: NLO+PS

Thanks to a *understanding of one-loop amplitudes* and to *significant development in MC tools (→ real emission, all order soft/collinear emission)* now NLO + PS IS THE STANDARD FOR LHC ANALYSIS



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…)

NLO computations: NLO+PS

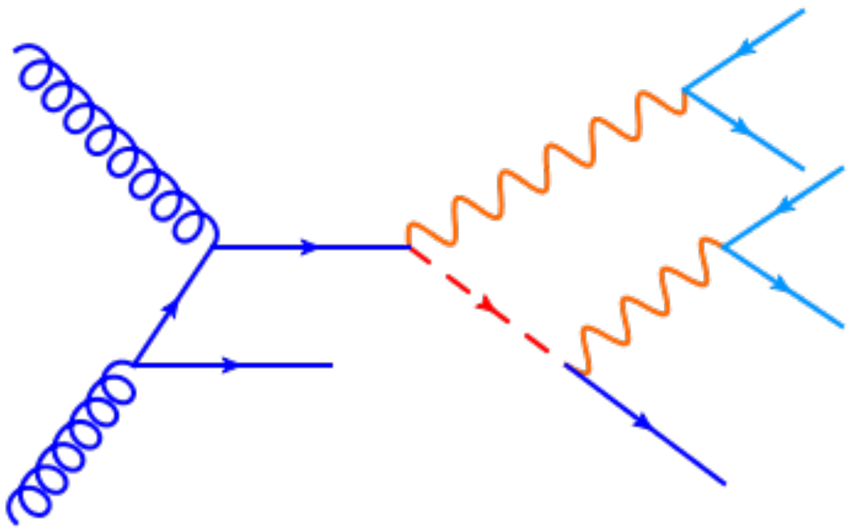
Ideally: combine NLO and PS

- Methods to combine NLO computations and fixed order ("matching") now standard: MC@NLO (~exponentiate soft radiation), POWHEG (~exponentiate full real emission), GENEVA (~SCET matching) NEW KID IN TOWN: KrkNLO [Jadach et al (2016)] (~redefine PDF to contain "nasty" universal bits of NLO)

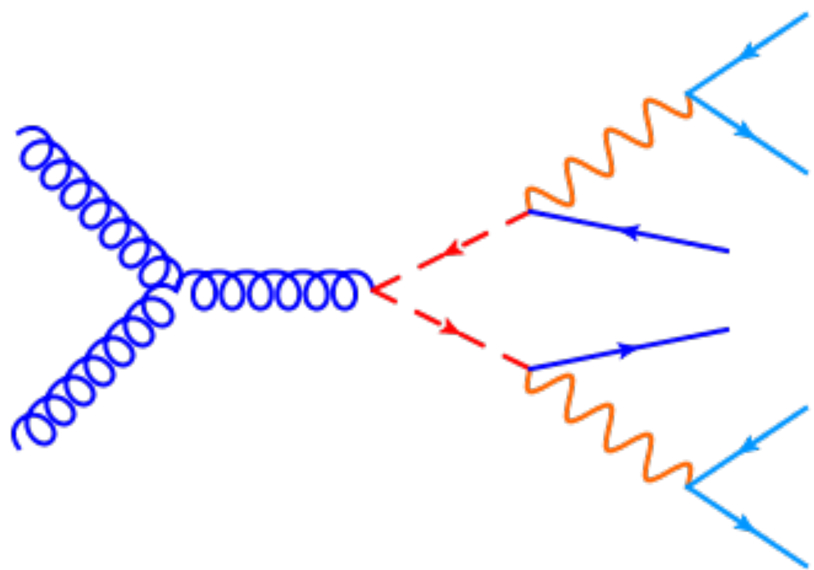
- Improved accuracy pushed for improvement in parton shower
  - better control of evolution, e.g. DIRE [Höche, Prestel (2015)]
  - better control of some logarithmic structure, e.g. HEJ for high-energy logs [Andersen, Smillie (2011-…)], DEDUCTOR [Nagy, Soper (2016)] for threshold logs
  - beyond purely classical evolution (try and introduce some quantum corrections), e.g. [Nagy, Soper (2014-…)]
  - better control of resonance structure of the process [Ježo, Nason (2015), Frederix et al. (2016)]

Example: unified treatment of WWbb

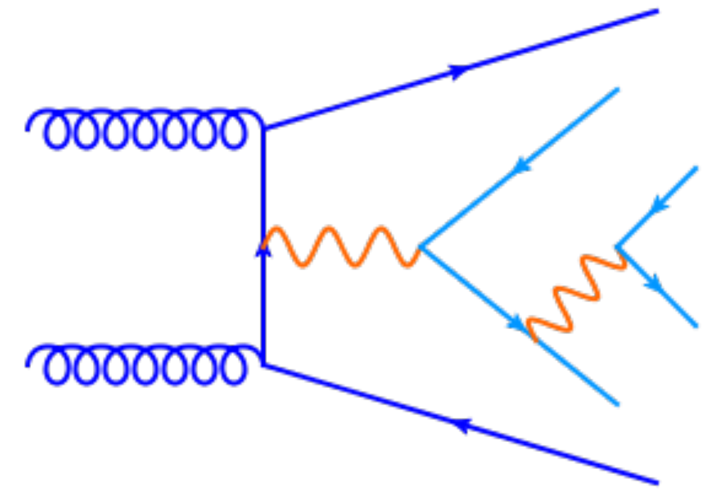
“Single-top”



“Top-pair”



“WW”

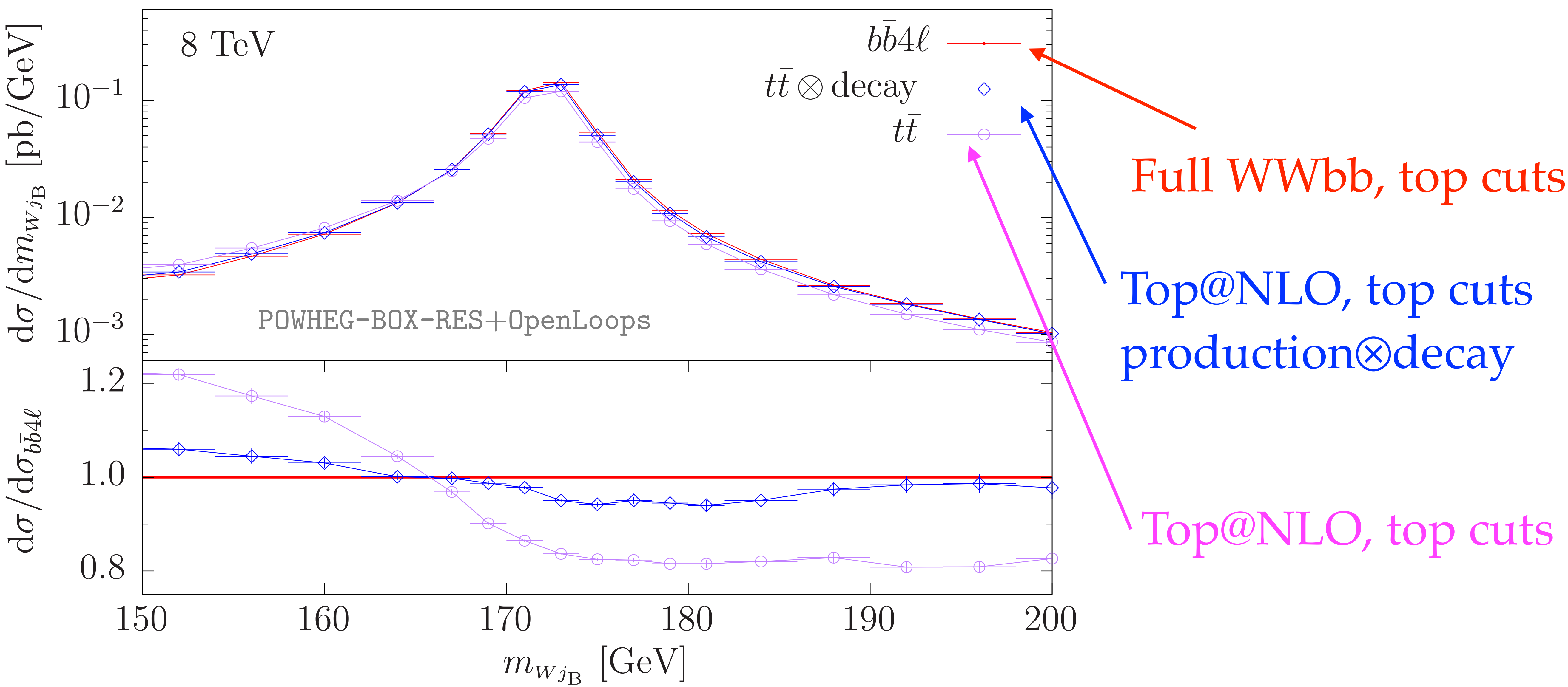


These 3 “processes” share the same initial/final state → THEIR SEPARATION IS UNPHYSICAL (quantum interference)

- 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

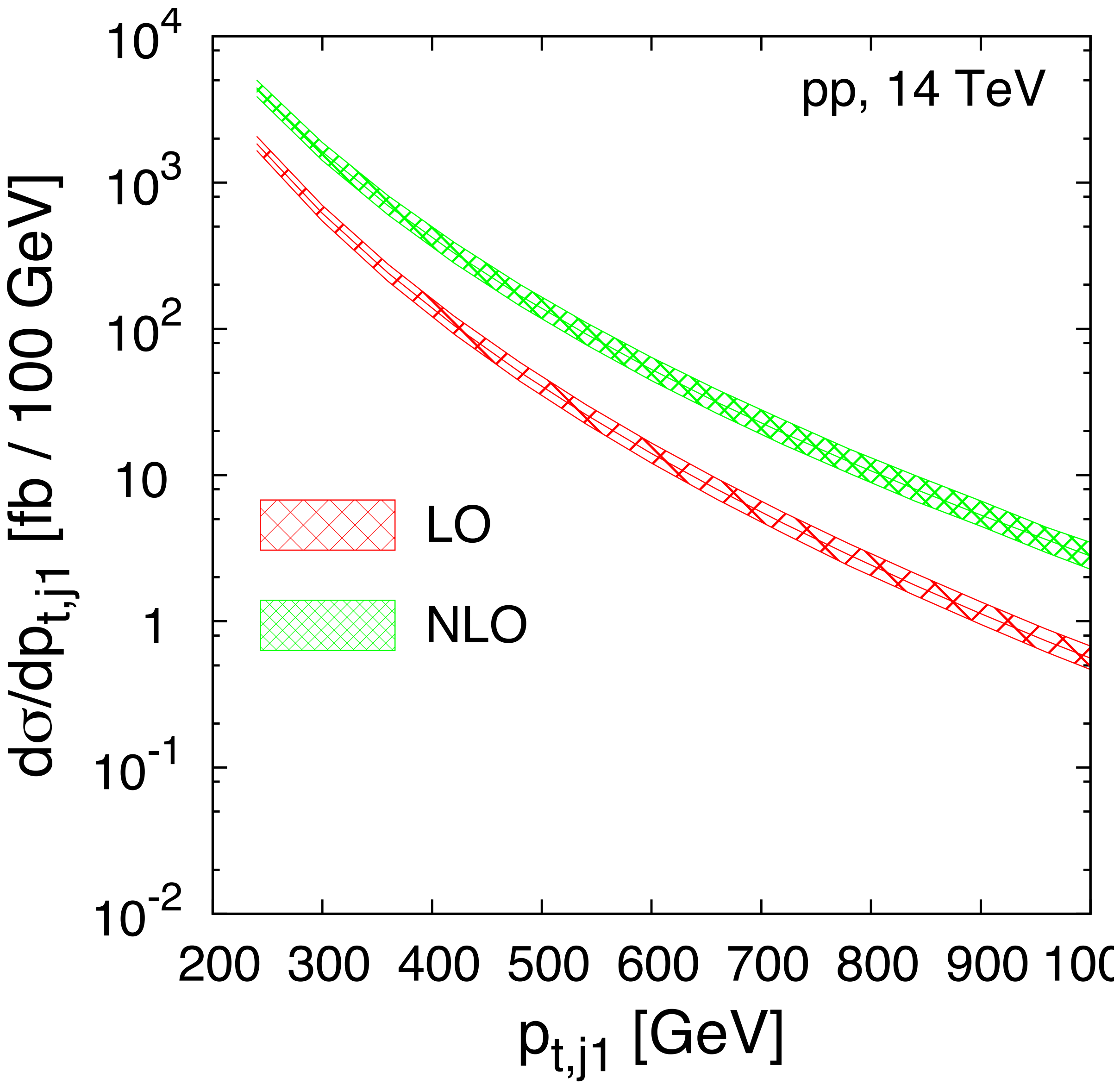
[Ježo, Lindert, Nason, Oleari, Pozzorini (2016)]

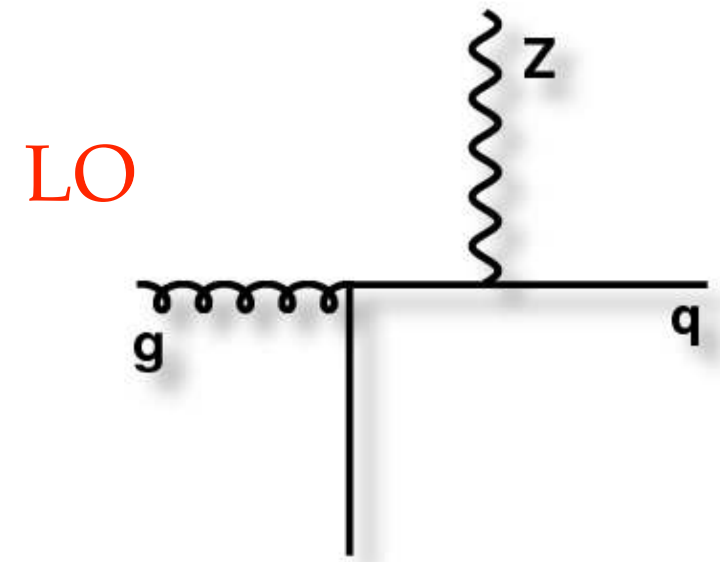


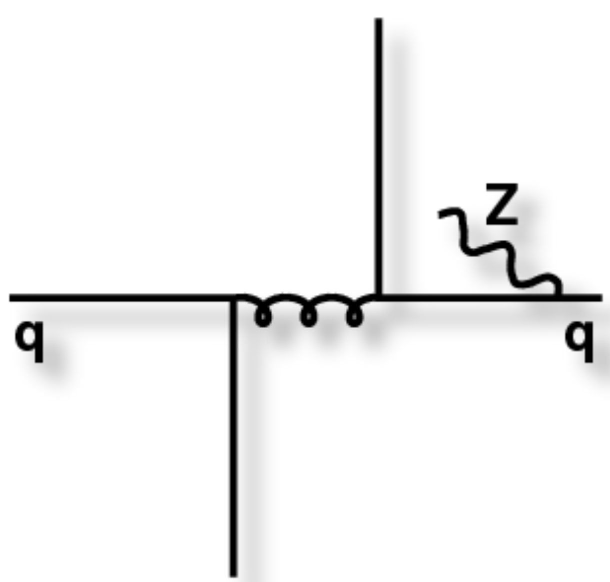
- **Radiation in the decay crucial** for the reconstructed top mass
- **After top selection cuts**, naive expectation WWbb~ top production⊗decay **works well** ($\Gamma_t \ll m_t \rightarrow$ factorization) → NNLO!
- Shift in **reconstructed top mass: ~ 100 MeV** (WWbb vs top prod⊗decay)

A bonus of PS: merging

Often, radiative corrections are dominated by real emission: new channels/new topologies opening up. The classic example: DY production, leading jet p_t [slide from G.P. Salam (2011)]







NLO: new channel, topology responsible for the large corrections

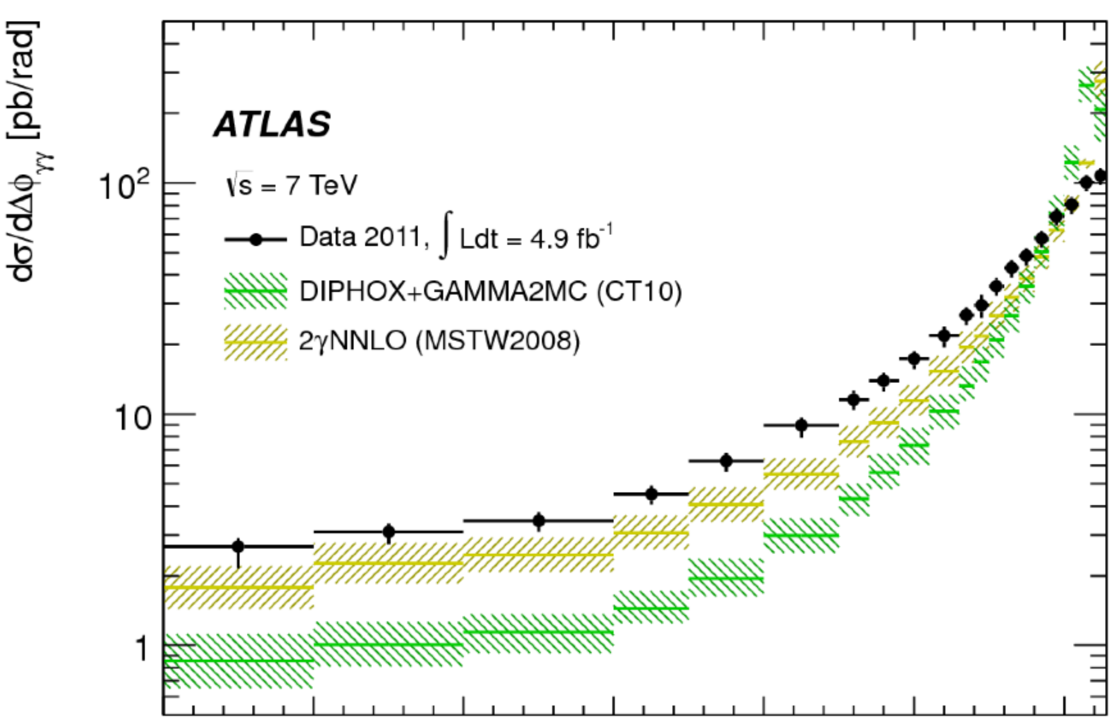
Bulk of corrections ~ trivial (= no loop, LO at higher multiplicity).

CAN WE CAPTURE THEM?

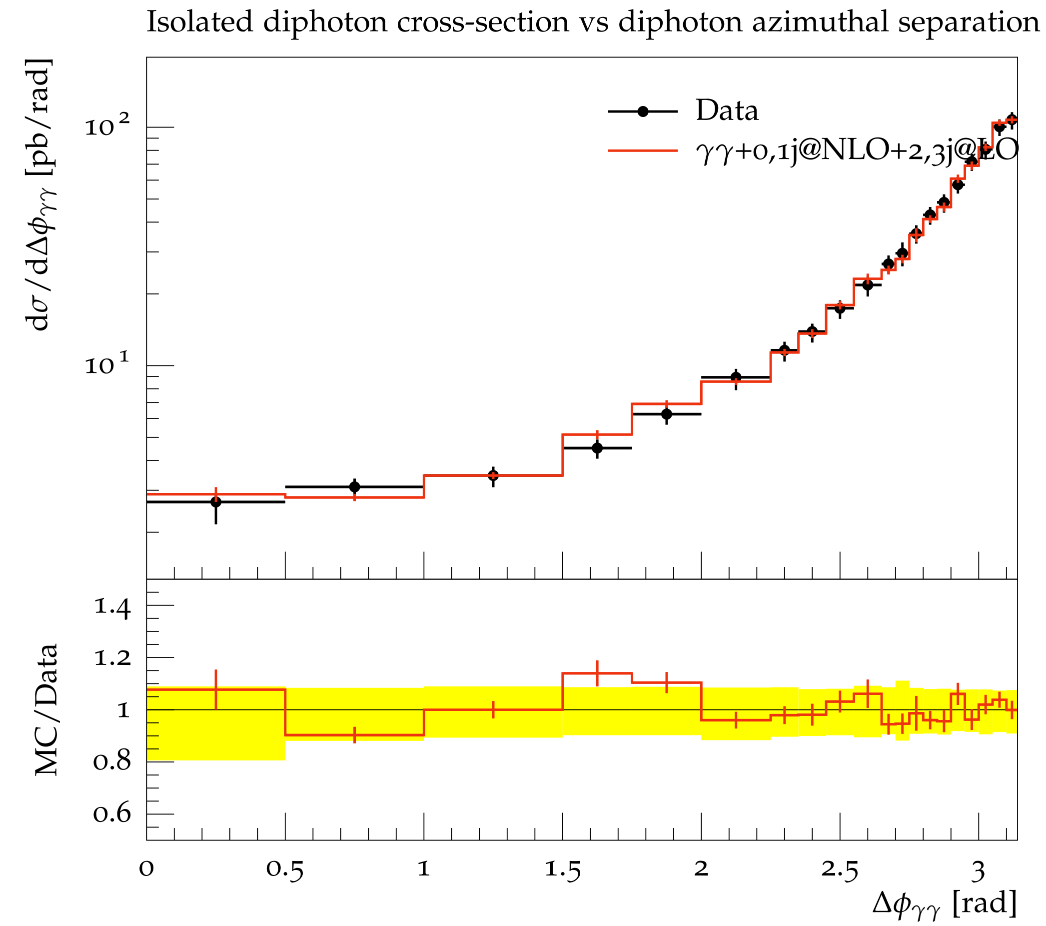
A bonus of PS: merging

- Parton shower MC provide an ideal framework to perform such combination
- "Merge" together samples of different multiplicities. Well established techniques to LO (CKKW, MLM), and a lot of different approaches to NLO accuracy (NLOPS, MEPS, MENLOPS, MEPS@NLO, FXFX, MINLO, GENEVA…)

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



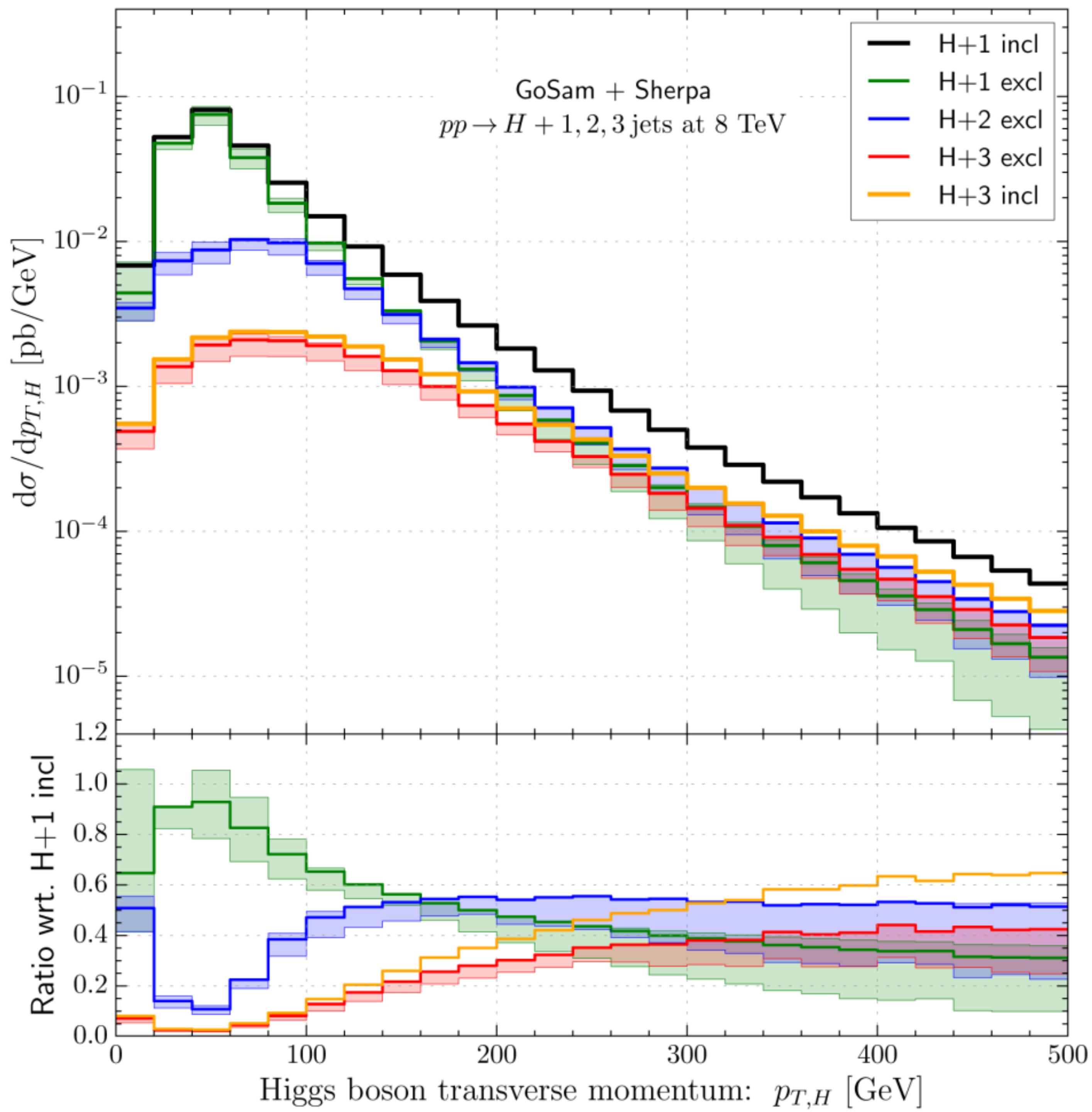
[Catani et al, pp→γγ @NNLO]



[Höche and Siegert, SHERPA merged NLO]

Merging: Higgs p_t with finite top mass effects

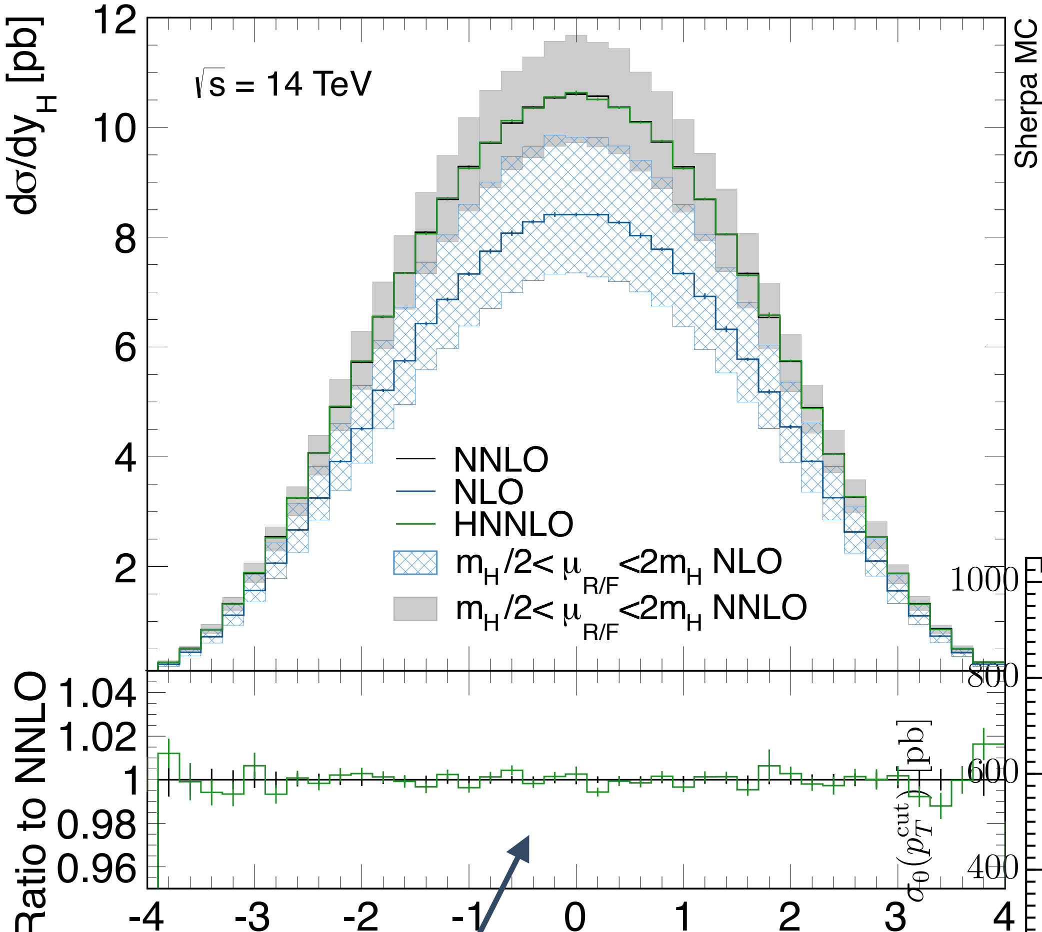
Complete NLO corrections with full top-quark mass dependence: still unavailable (2-loop amplitudes) (*NNLO in the HEFT*)



- 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…)

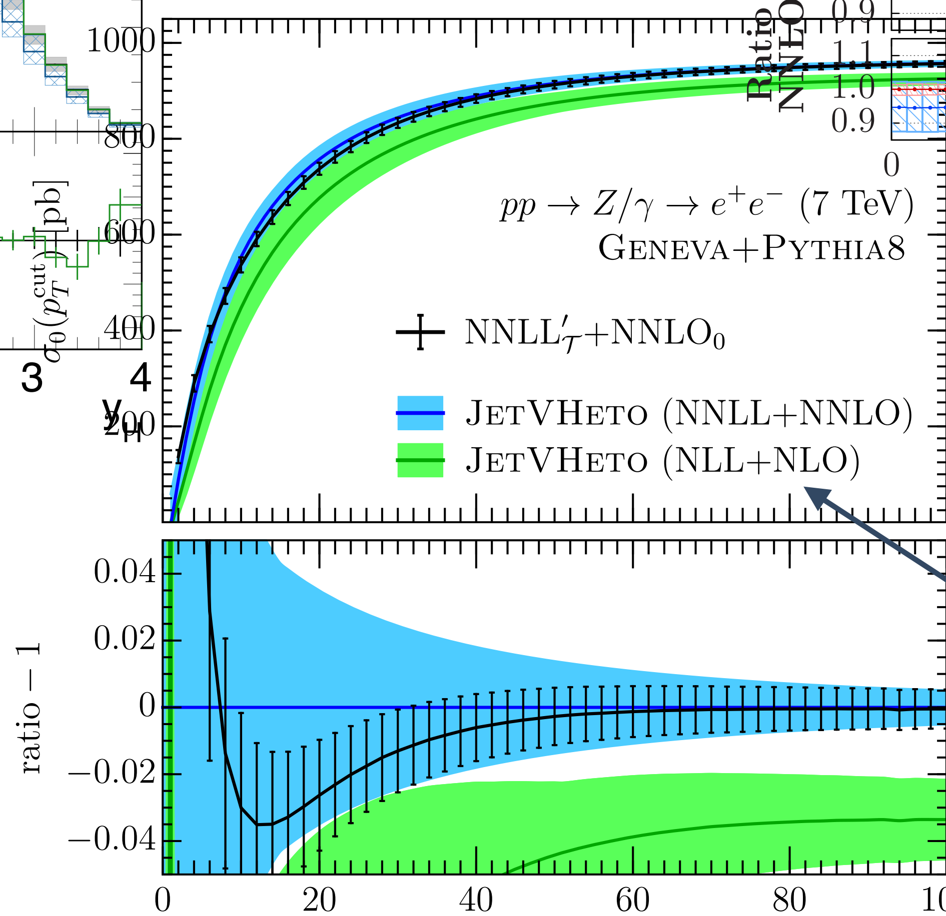
From merging to NNLOPS

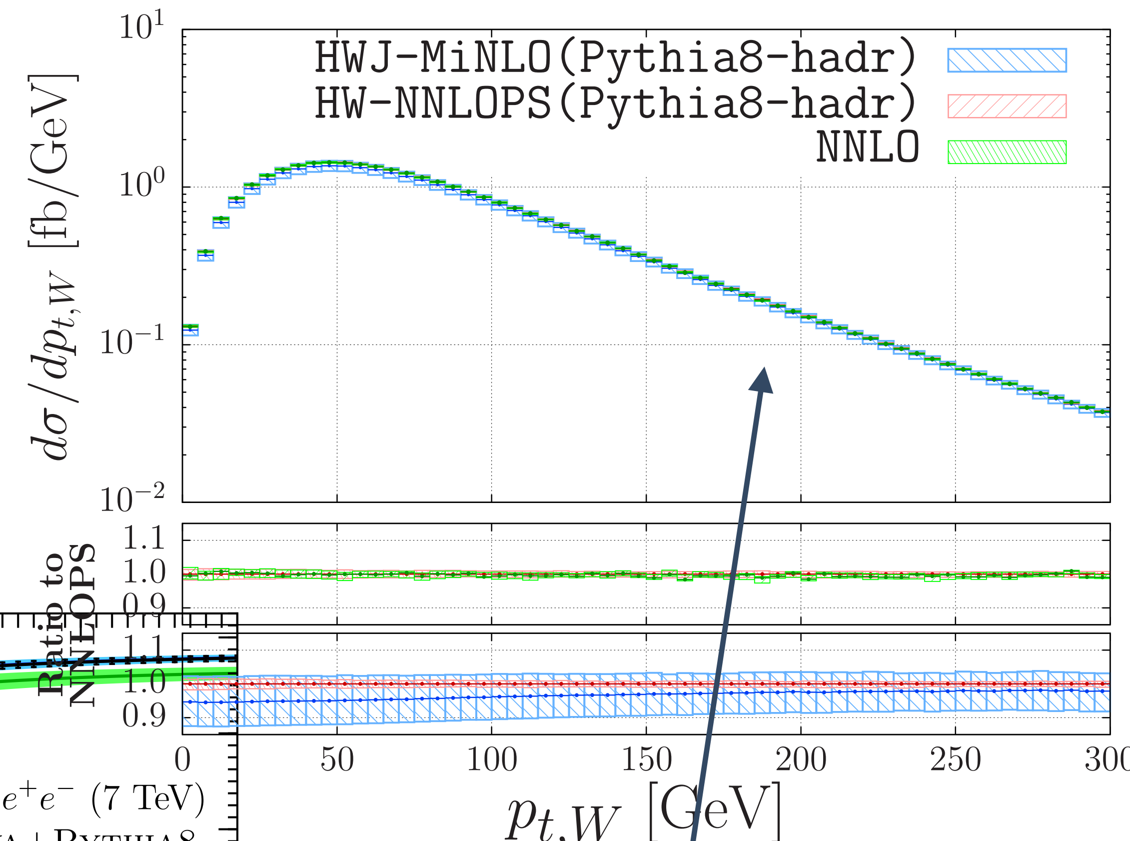
Merged sample close to full NNLO computation (~right real emission, missing virtual corrections). For color-singlet processes, extension of merging ideas led to combination of NNLO + PS



Higgs

[Höche et al, UN²LOPS (2014)]





WH

[Astill et al, MINLO (2016)]

Drell-Yan

[Alioli et al, GENEVA (2015)]

Logs beyond Parton Shower: progress in resummation

Logs and resummation

- Often, at the LHC we are dealing with multi-scale processes → large ratios → large soft/collinear logs, resummation at least desirable
- At high Q, very far from soft/collinear regions → effects should be irrelevant
- But: often in intermediate regions (statistics…)
- Also, often fiducial cuts / analysis strategies force us into soft-sensitive regions (jet veto, jet substructure…)
- Finally, understanding all-order structure of perturbative soft/collinear emission can give glimpse into non-perturbative regime of QCD (and help singling out genuine non perturbative effects, hadronization, UE…)

Resummation: recent progress

The past year saw many interesting development, obtained with different frameworks (SCET, ordinary QCD…). Impossible to summarize in few slides (even to enumerate…).

SOME examples

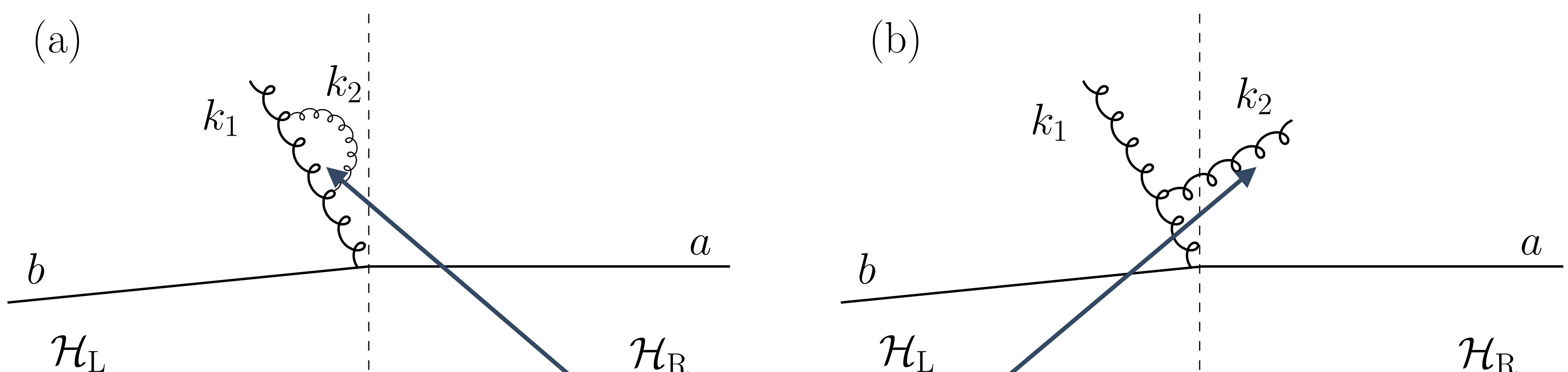
- Forward scattering and Glauber gluons, next-to-leading-power resummation, non-global logarithms, automatic NNLL for IRC observables, jet radius logs, Higgs quark mass logs…
- Progress in automation / resummation for generic observables (two-loop soft function, ttH, ttW resummations…), high precision phenomenology (Higgs/DY p_t, Jet Veto…)
- One loop soft function with arbitrarily many soft gluons, three-loop soft anomalous dimension, three-loop double differential soft function/rapidity an. dim. (and N^3LL p_t resummation)
- Jet substructure, better understanding, better observables…

Non global logs

If observable sensitive only to radiation in PART OF THE PHASE SPACE: complicated "non global" logarithmic structure, non-exponentiation [Dasgupta, Salam (2001)]

- Example: hemisphere jet mass

[Dasgupta, Salam (2001)]



spoil real / virtual cancellation

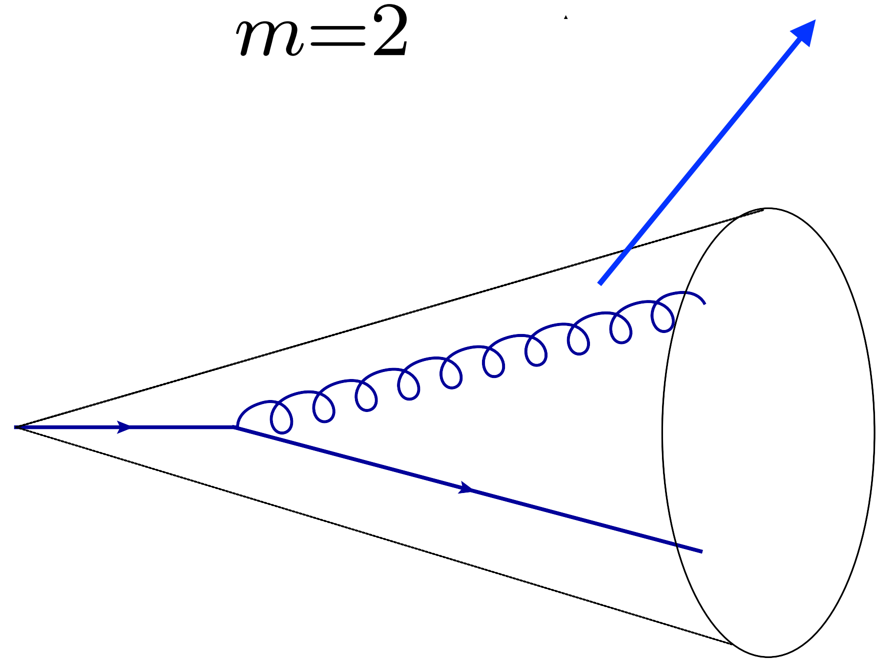
Every time we are dealing with exclusive jets, gaps, isolation…

$\boxed{\text{PROBLEMATIC TO RESUM BEYOND LL}}$

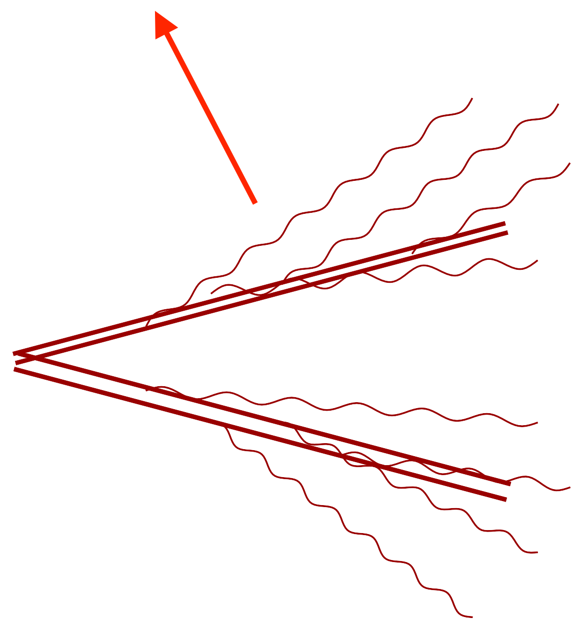
Non global logs: a factorization theorem

[Becher et al (2016)]

$$\sigma(\beta) = \sum_{m=2}^{\infty} \left\langle \boldsymbol{\mathcal{H}}_m(\{\underline{n}\}, Q, \mu) \otimes \boldsymbol{\mathcal{S}}_m(\{\underline{n}\}, Q\beta, \mu) \right\rangle$$



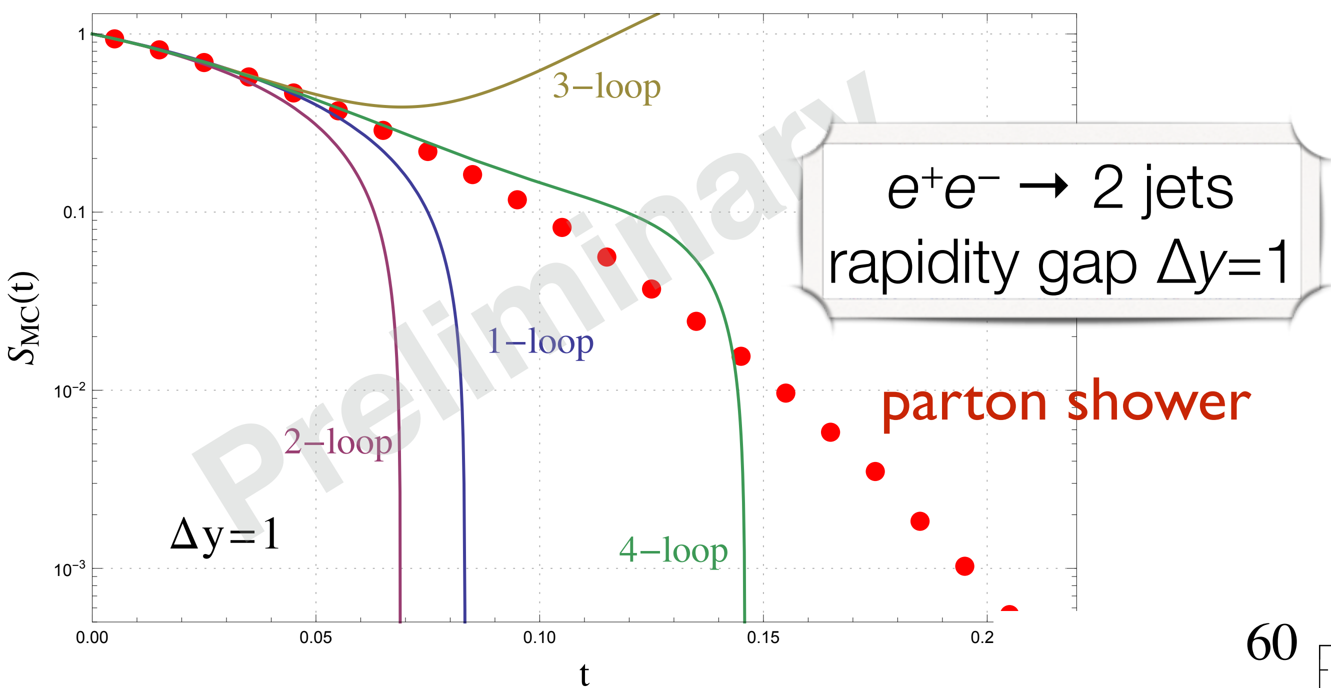
Hard emission, “inside”



Soft emission, everywhere

FACTORIZATION SEEMS UNDER CONTROL $\rightarrow$
CAN EXTEND BEYOND LL

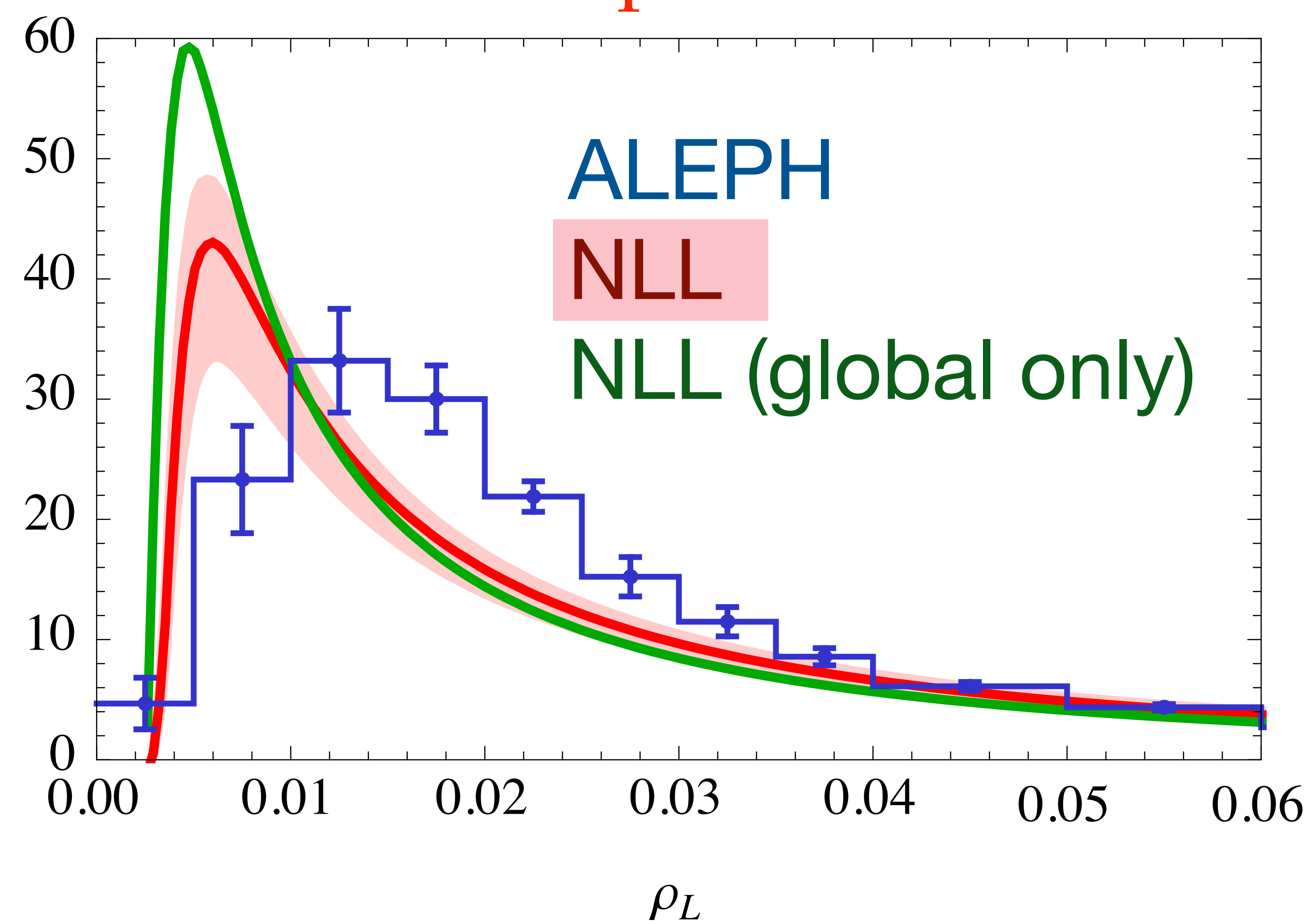
Non global logs: examples



[Becher, QCD@LHC2016]

First Non Trivial Results Recently Appeared

Hemisphere mass



[Becher, Pecjak, Shao (2016)]

- Equations can be solved numerically, in a PS-like approach
- Sizable effect (needed to understand NP contamination)
- See also [Caron-Huot (2015), Larkoski, Moult, Neill (2016)]

Jet radius logs

[Dasgupta et al (2016), Chen et al (2015) Kolodrubetz et al (2016), Kang et al (2016)]

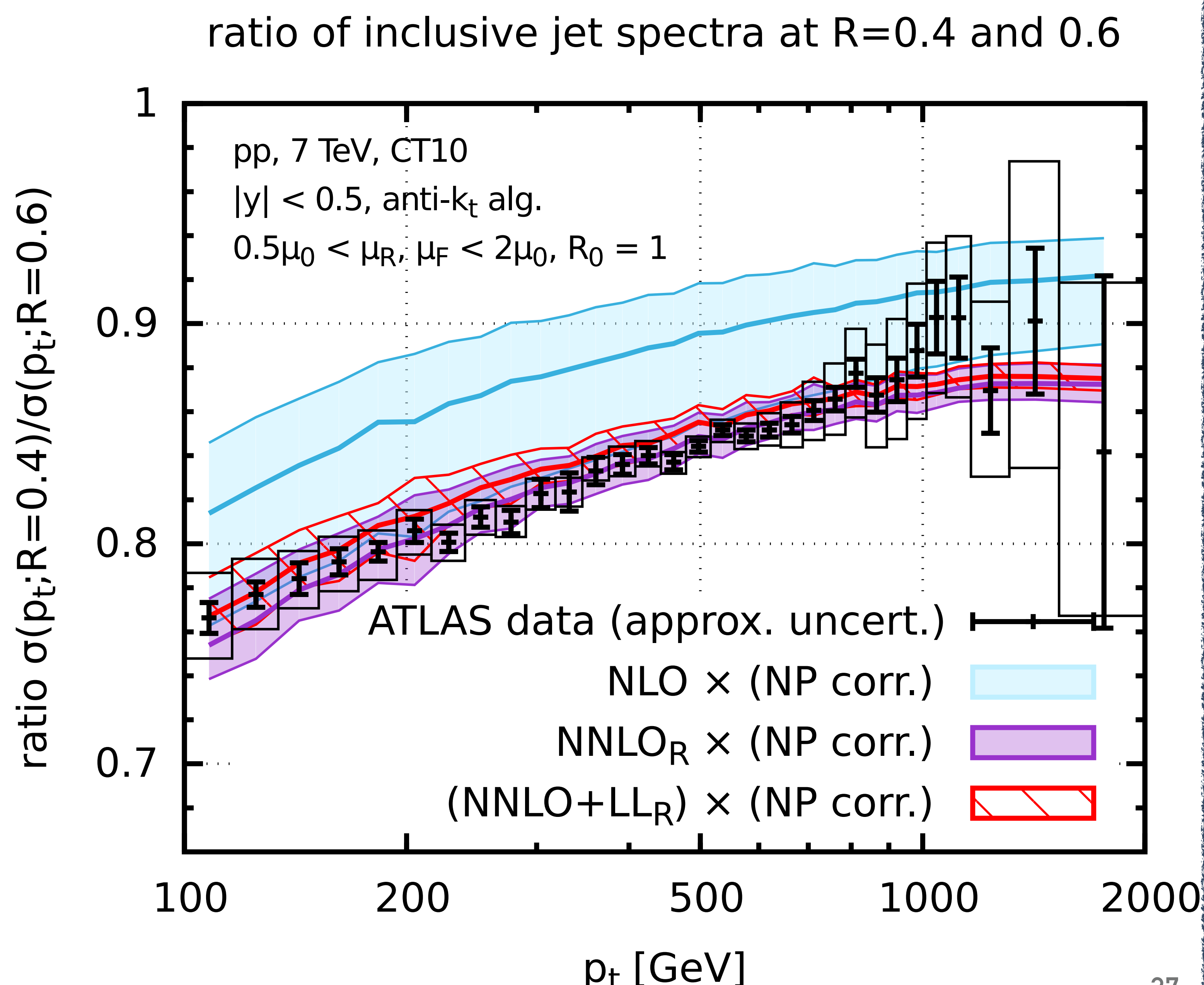
- Clustering logs now to all orders, at LL → small R accessible
- LL ↔ PS… but here disentangled

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]

Highest precision for standard candles: N^3LO/NNLO predictions

Fully inclusive: Higgs N^{3}LO phenomenology

- Monumental computation: perturbative QCD under control
- Physics at the few percent level: BASICALLY EVERYTHING IS RELEVANT

$$\boxed{\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\ (\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\ (\text{PDF}+\alpha_s)\,.}$$

$$\begin{aligned}
48.58\,\text{pb} = {} & \ 16.00\,\text{pb} & (+32.9\%) & \quad (\text{LO, rEFT}) \\
& + 20.84\,\text{pb} & (+42.9\%) & \quad (\text{NLO, rEFT}) \\
& - \ 2.05\,\text{pb} & (-4.2\%) & \quad ((t,b,c),\ \text{exact NLO}) \\
& + \ 9.56\,\text{pb} & (+19.7\%) & \quad (\text{NNLO, rEFT}) \\
& + \ 0.34\,\text{pb} & (+0.7\%) & \quad (\text{NNLO}, 1/m_t) \\
& + \ 2.40\,\text{pb} & (+4.9\%) & \quad (\text{EW, QCD-EW}) \\
& + \ 1.49\,\text{pb} & (+3.1\%) & \quad (\text{N}^3\text{LO, rEFT})
\end{aligned}$$

- Todo List:
  - Full mass dependent NNLO
  - Mixed $\mathcal{O}(\alpha\alpha_S)$ corrections
  - N3LO PDFs
  - ....

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

[Mistlberger, QCD@LHC2016]

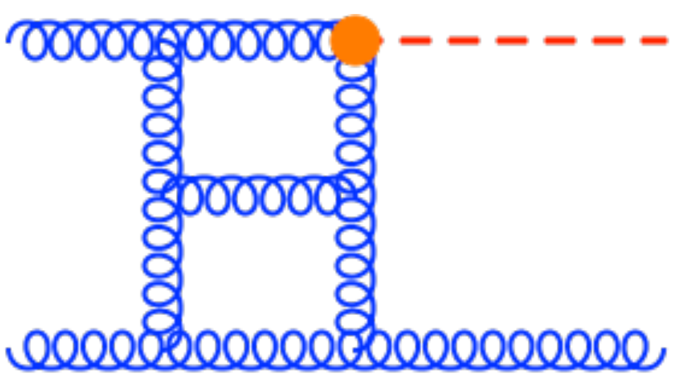
(inclusive VBF@N^{3}LO: [Dreyer, Karlberg (2016)])

Beyond fully inclusive: NNLO differential

Apart from complicated multi-loop amplitudes, the big problem of higher order computations is how to consistently handle IR singularities

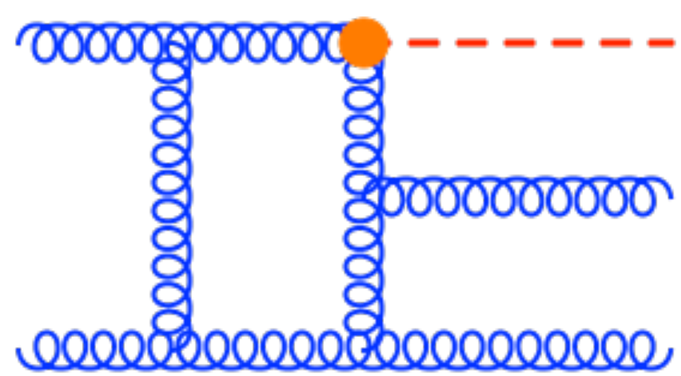
NNLO: 3 ingredients, separately divergent

VV



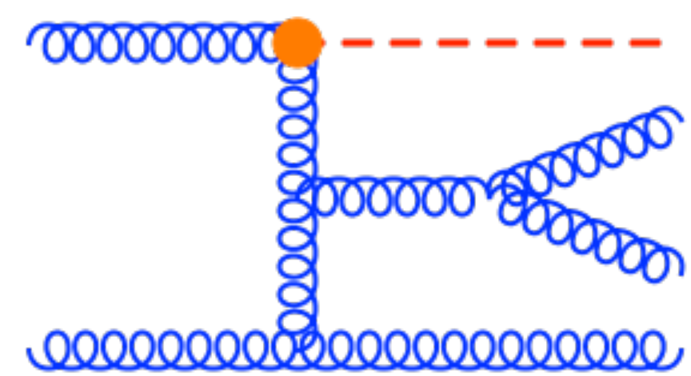
$$\int \left[\frac{\mathrm{vv}_4}{\epsilon^4} + \frac{\mathrm{vv}_3}{\epsilon^3} + \frac{\mathrm{vv}_2}{\epsilon^2} + \frac{\mathrm{vv}_1}{\epsilon} + \mathrm{vv}_0\right] d\phi_2$$

RV



$$\int \left[\frac{\mathrm{rv}_2}{\epsilon^2} + \frac{\mathrm{rv}_1}{\epsilon} + \mathrm{rv}_0\right] d\phi_3$$

RR

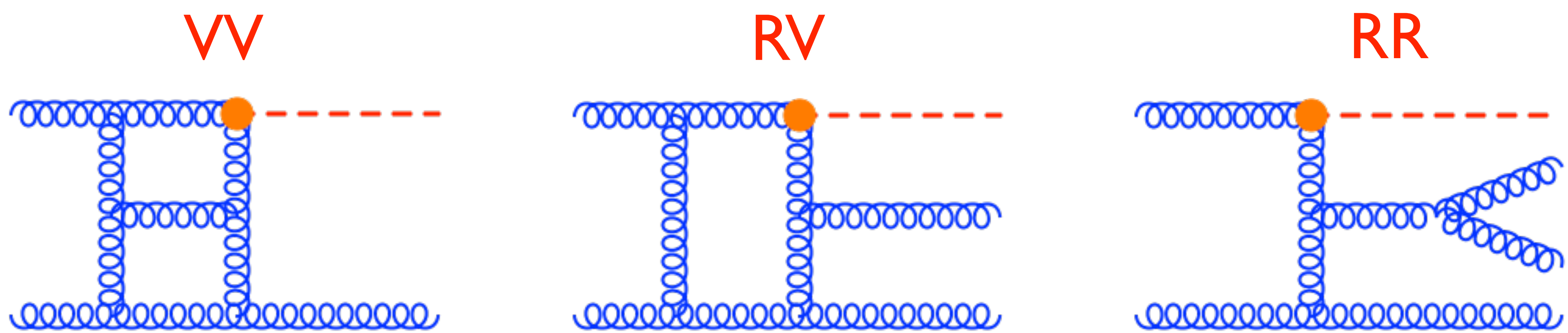


$$\int [\mathrm{rr}_0]\, d\phi_4$$

COMPLICATED IR STRUCTURE HIDDEN IN THE PHASE SPACE INTEGRATION

The problems with NNLO computations

Apart from complicated two-loop amplitudes, the big problem of NNLO computations is how to consistently handle IR singularities



- IR divergences hidden in PS integrations
- After integrations, all singularities are manifest and cancel (KLN)
- We are interested in realistic setup (arbitrary cuts, arbitrary observables) → we need fully differential results, we are not allowed to integrate over the PS
- The challenge is to EXTRACT PS-INTEGRATION SINGULARITIES WITHOUT ACTUALLY PERFORMING THE PS-INTEGRATION

NNLO differential: solutions

Thanks to multi-year effort of the whole community: we now have DIFFERENT WAYS TO DEAL WITH THIS PROBLEM. Each has its own merits/problems.

Local subtractions (cancellations point by point in the phase-space)

- antenna [Gehrmann-de Ridder, Gehrmann, Glover] → jj, Hj, Vj
- Sector-decomposition+FKS [Czakon; Boughezal, Melnikov, Petriello; Czakon, Heymes] → ttbar, single-top, Hj
- P2B [Cacciari, Dreyer, Karlberg, Salam, Zanderighi] → VBF_H, single-top
- *Colorful NNLO [Del Duca, Somogyi, Tocsanyi, Duhr, Kardos]: only e^+e^- so far*

Non-local subtractions (cancellation globally after integration)

- q_t subtraction [Catani, Grazzini] → H, V, VH, VV, HH
- N-jettiness [Boughezal et al; Gaunt et al] → H, V, $\gamma\gamma$, VH, Vj, Hj, single-top

NNLO differential: solutions

Some of these techniques are quite generic

IN PRINCIPLE, they allow for ARBITRARY COMPUTATIONS

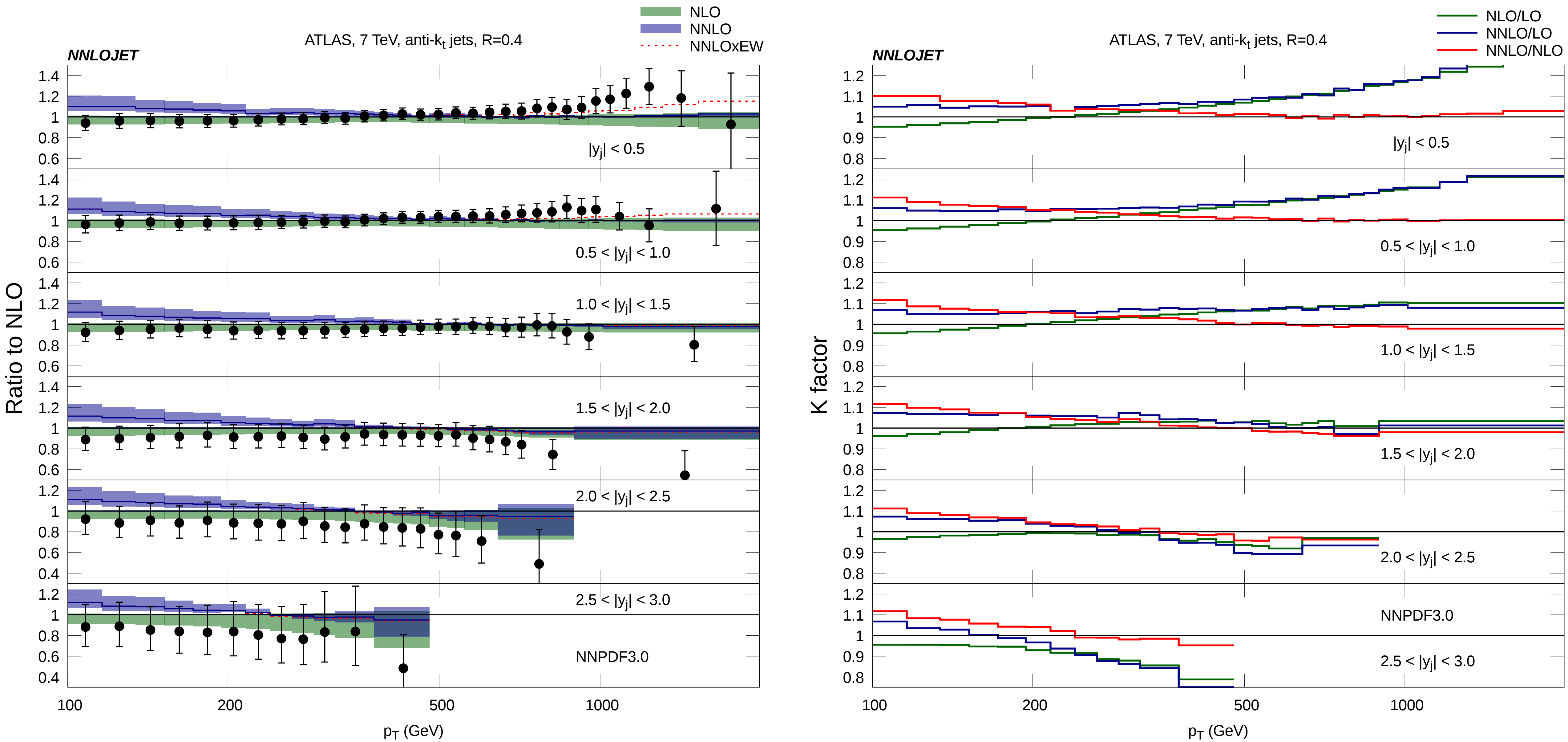
IN PRACTICE: `genuine' 2→2 REACTIONS, with big computer farms

2016: from "PROOF OF CONCEPT" to PHENOMENOLOGY

Recent NNLO results: dijet

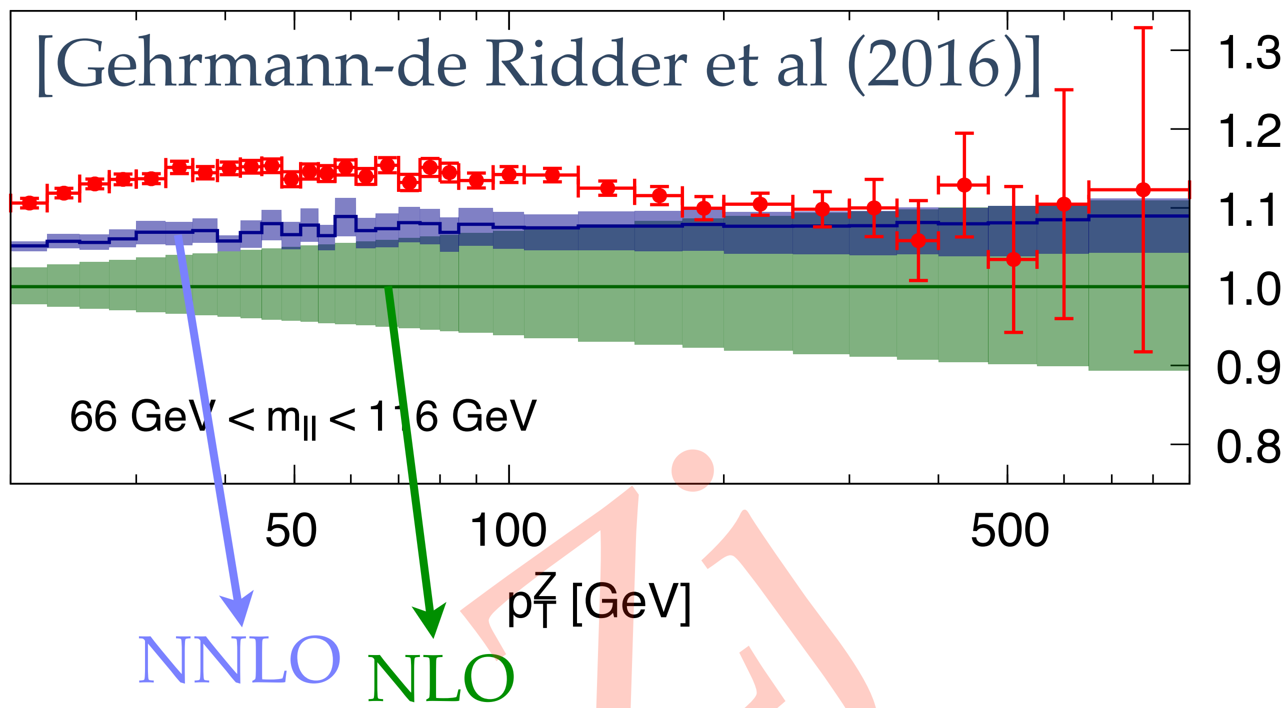
[Currie, Glover, Pires (2016)]

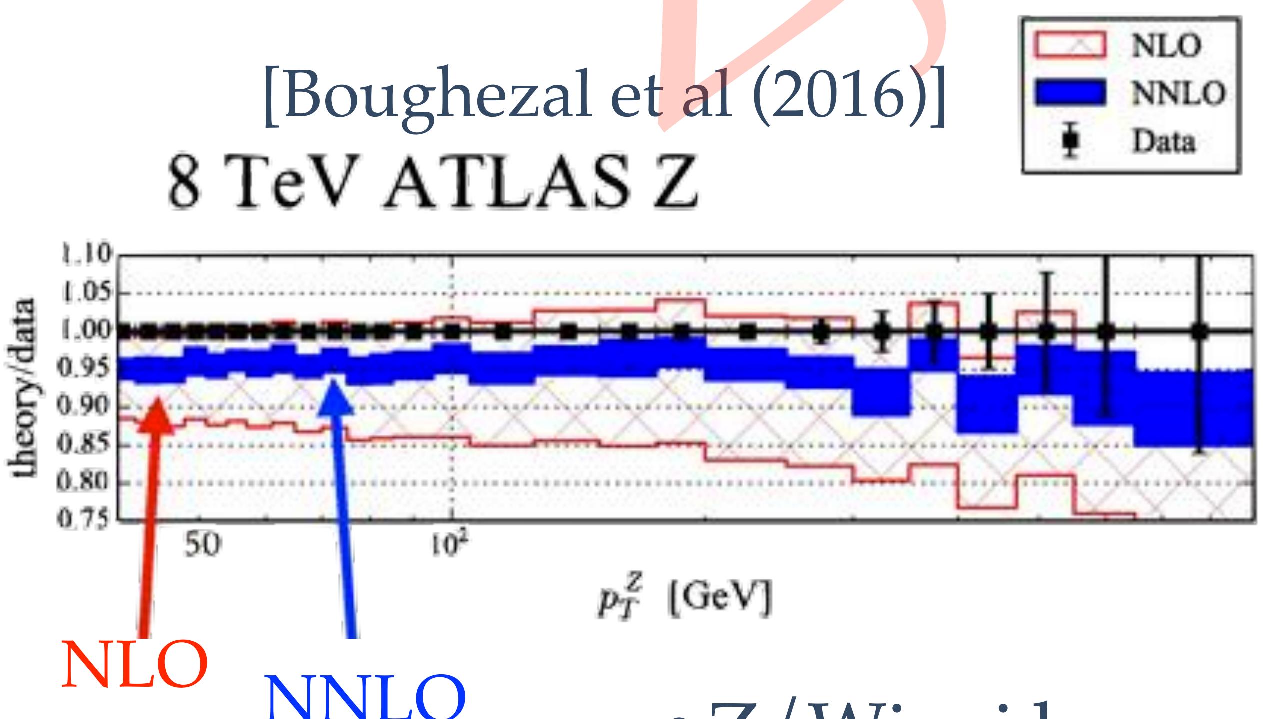
~40 partonic channels, highly non-trivial color flow. Realistic jet

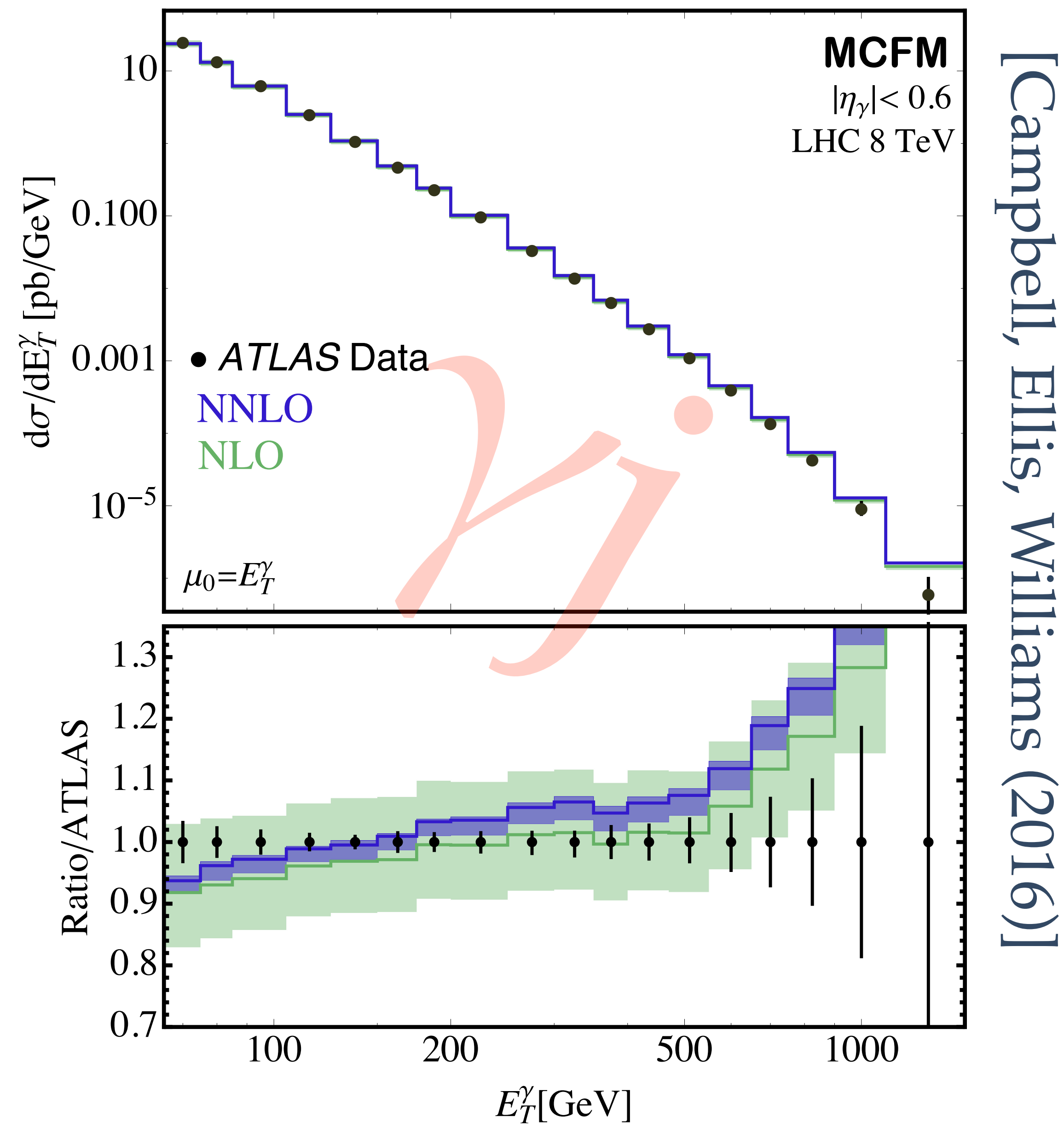


- Non trivial shape correction (NLO scale choice?), sizable effect
- Large effect on PDF? (see also jj in DIS [Niehues, Currie, Gehrmann (2016)])

Recent NNLO results: VJ





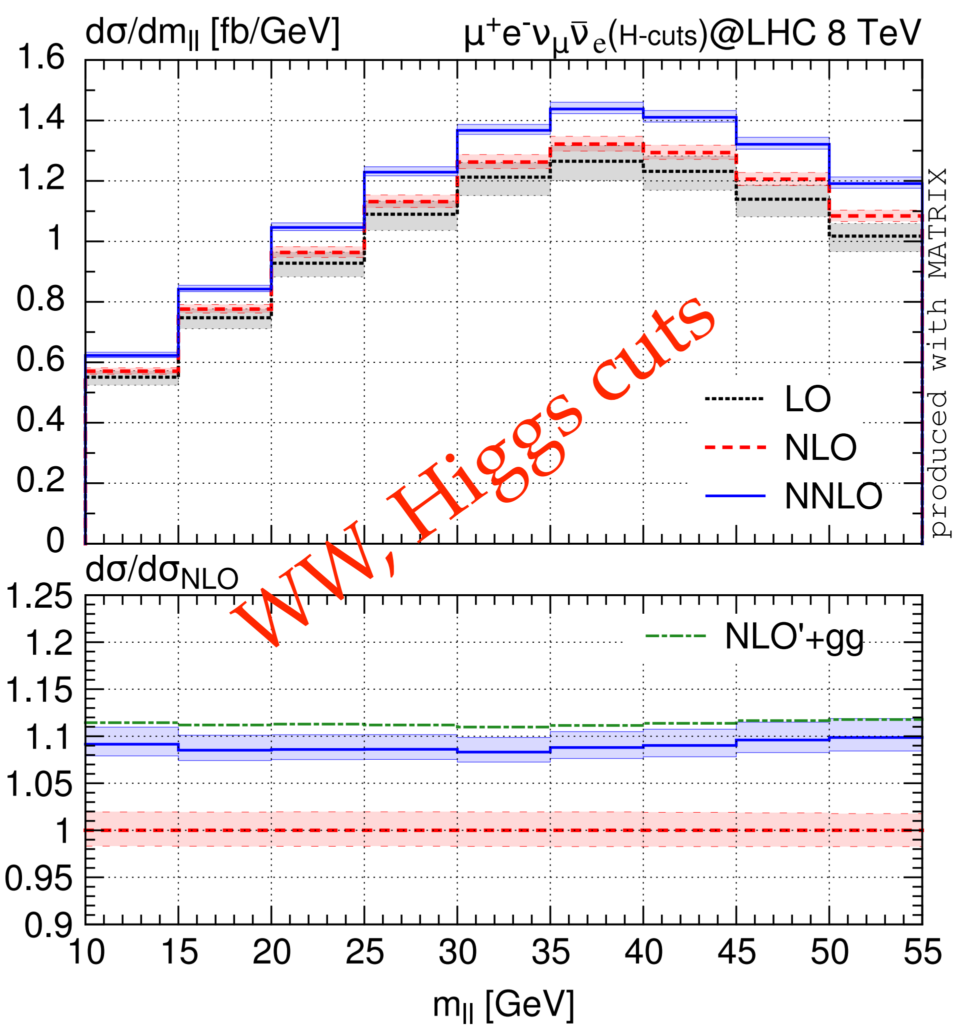


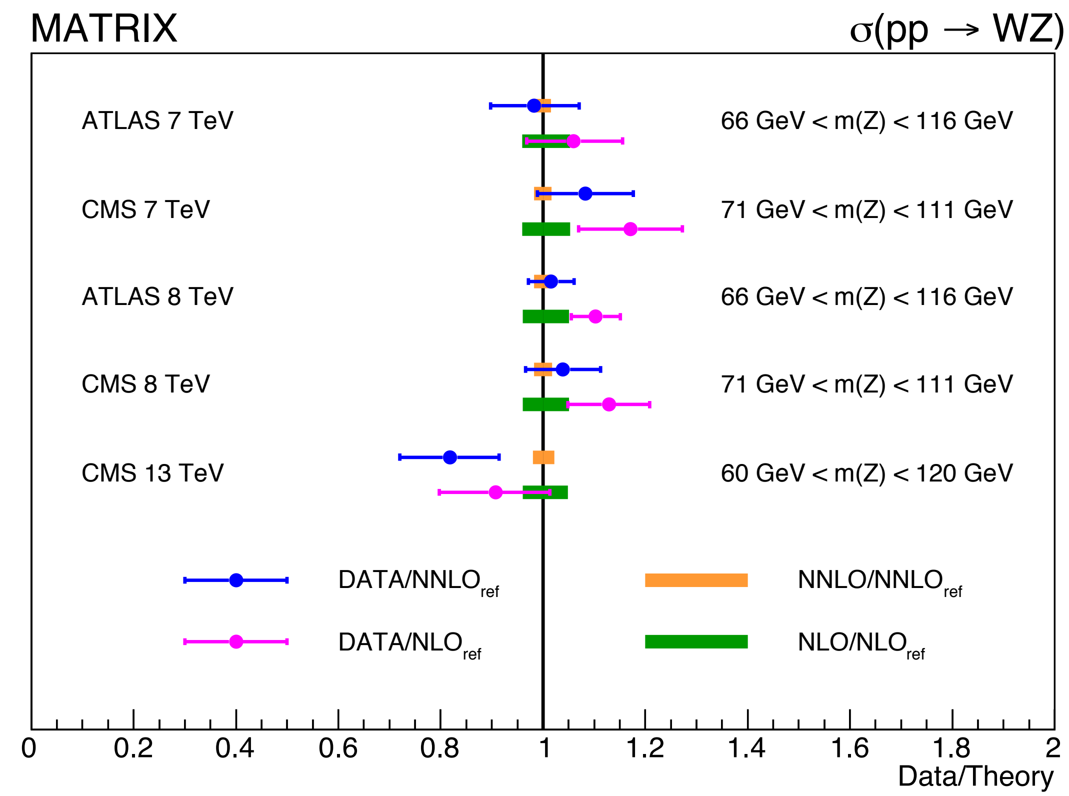
- Z/Wj, γj known. Zj: independent computations
- Highly improved theoretical accuracy (~exp error)
- Small deviations evident (PDFs? Calibration?)

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



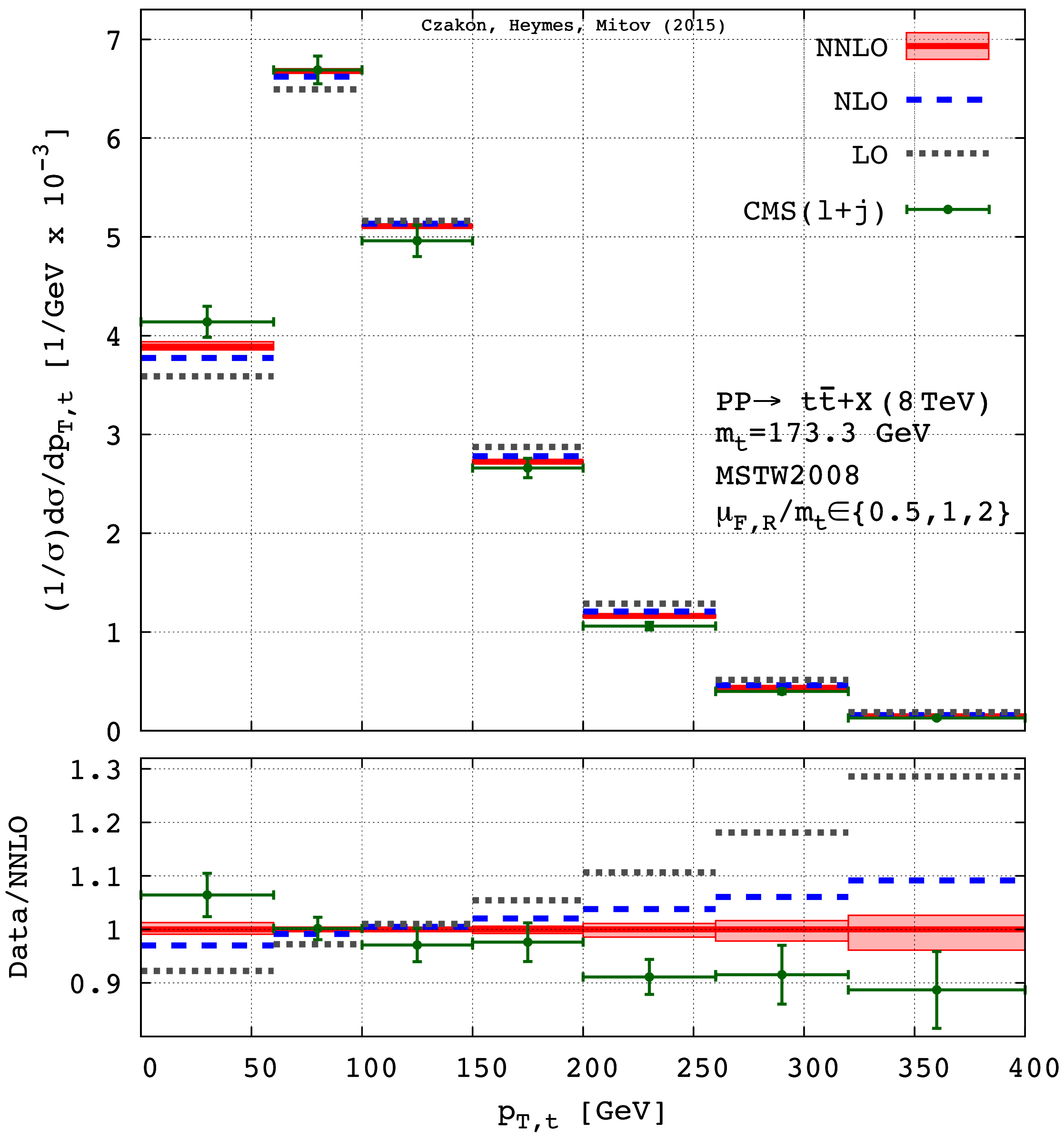


WZ vs data

- Fully exclusive analysis possible. Corrections strongly cut-sensitive → FIDUCIAL REGION comparisons (jet veto, gg contribution…)
- General picture: GOOD AGREEMENT DATA / NNLO (with some possible room for discussion for WW jet-veto, see [Dawson et al (2016)])

Recent NNLO results: top

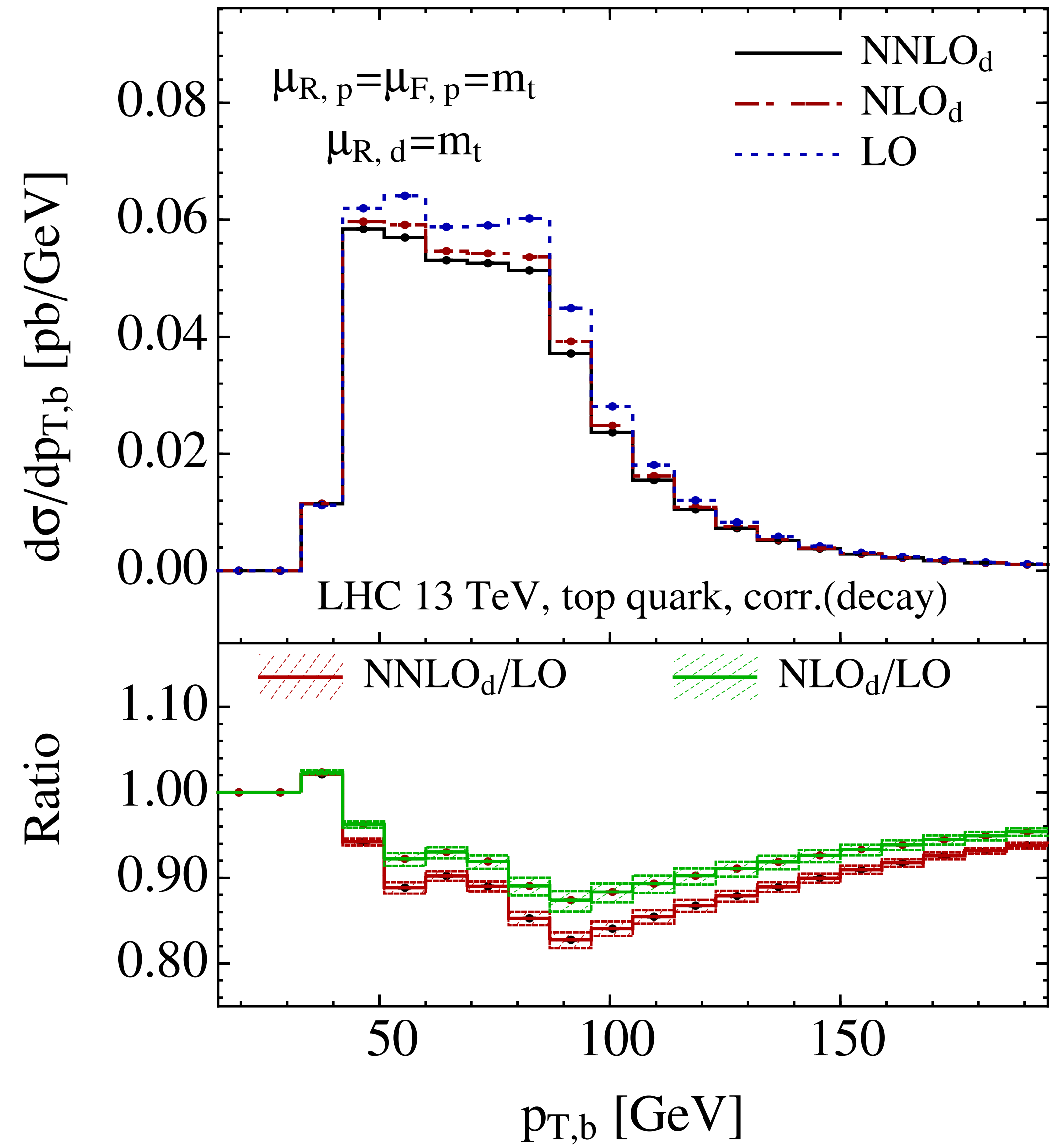
TTBAR DIFFERENTIAL DISTRIBUTIONS



[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)

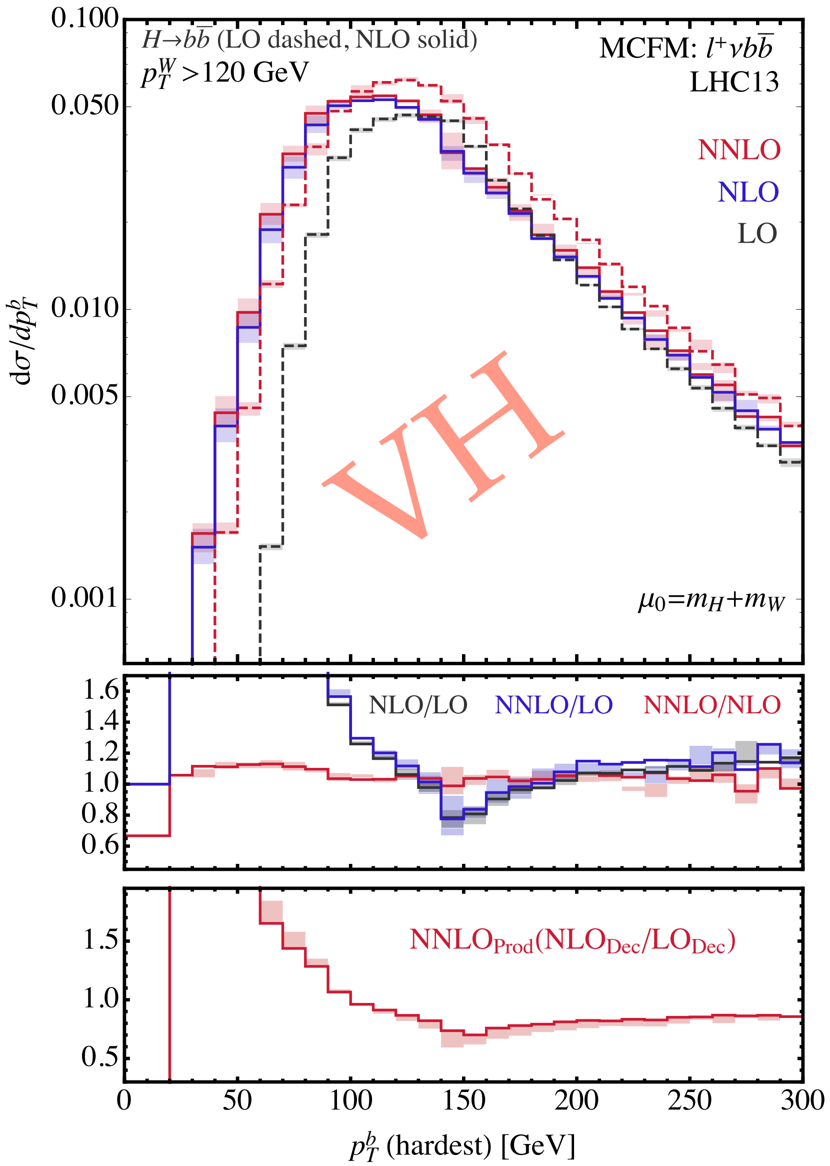


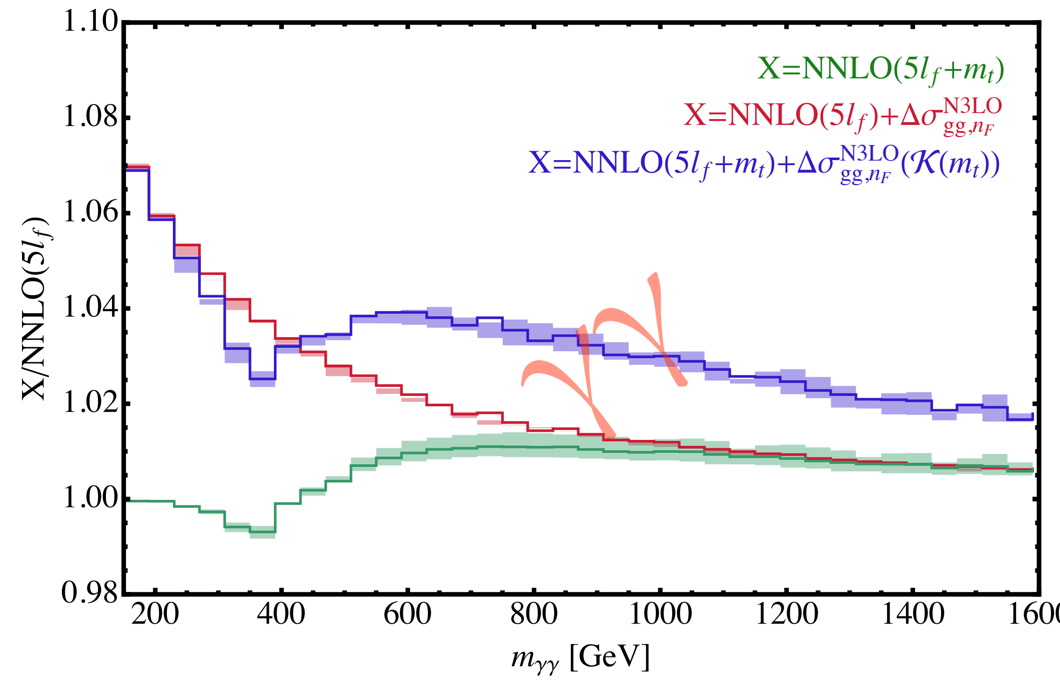
[Berger, Gao, Yuan, Zhu (2016)]

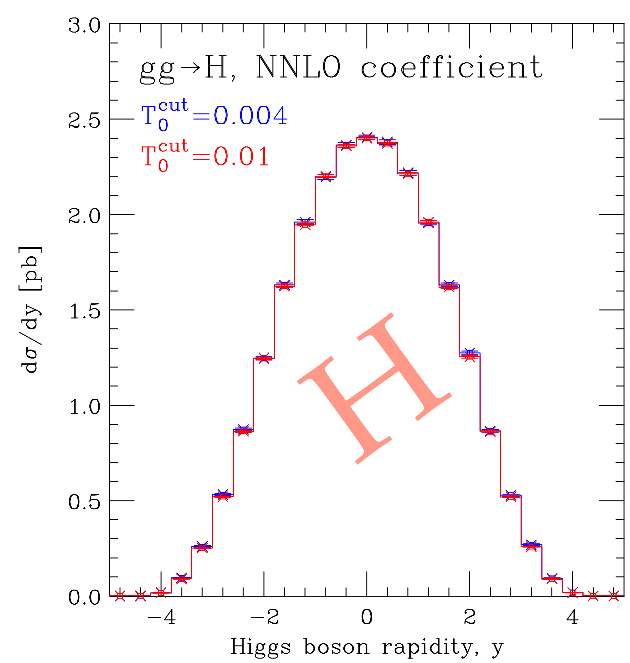
- Small inclusive corrections
- LARGE CORRECTIONS in exclusive region
- Similar behavior observed in Higgs in VBF [Cacciari et al (2015)]

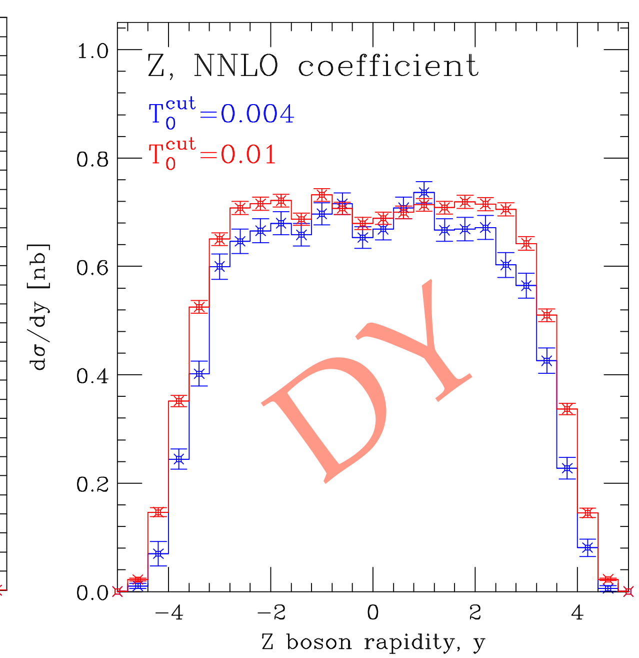
Recent NNLO results: MCFM@NNLO

[Campbell, Ellis, Williams (2016); Campbell et al (2016); Boughezal et al (2016)]





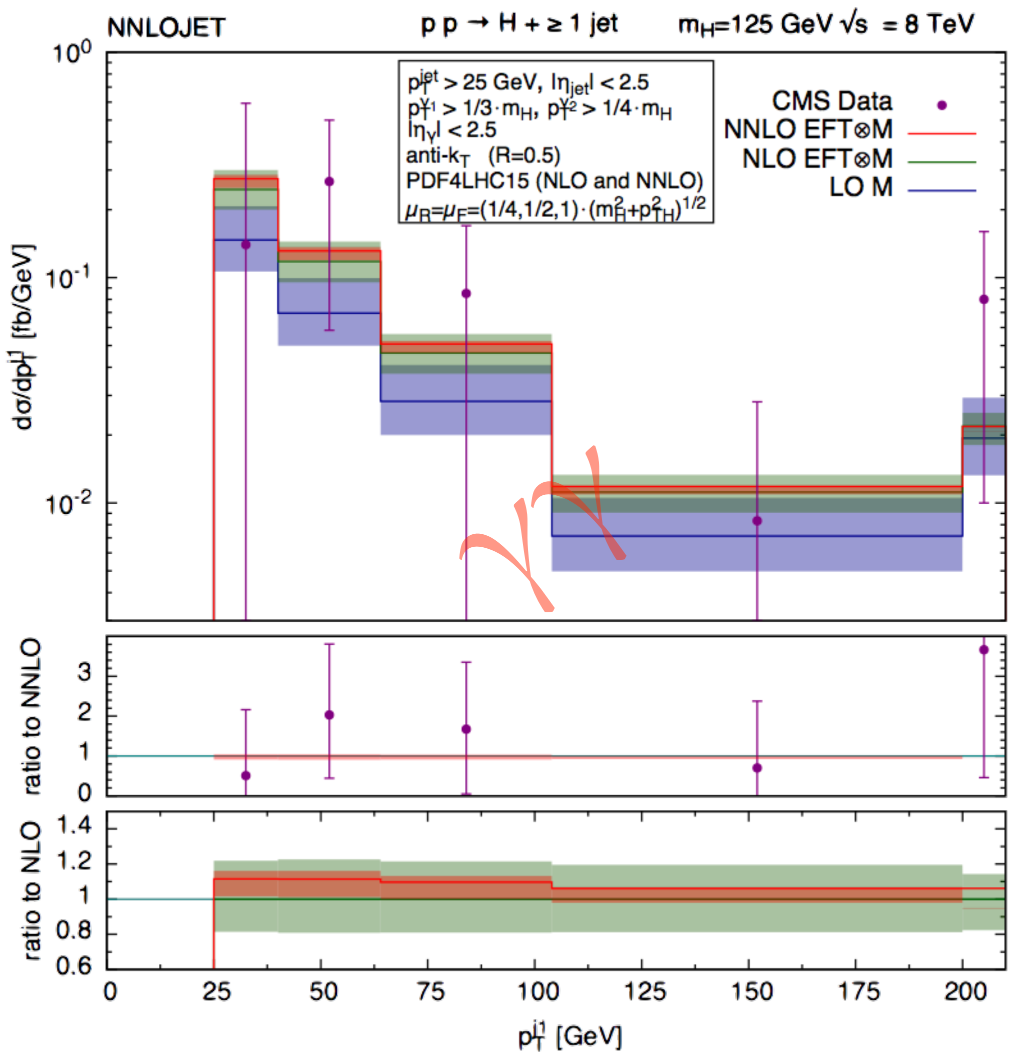




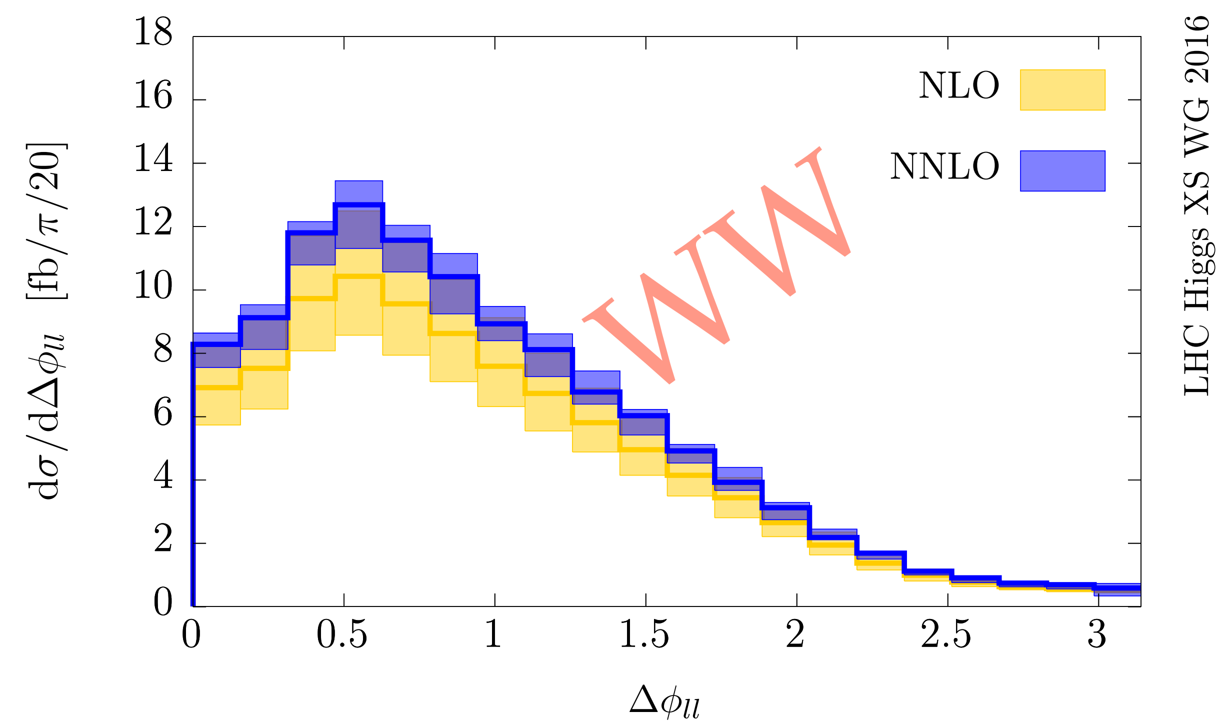
- NNLO slicing available for some color-singlet processes in MCFM
- V/H+J will be next?

Recent NNLO results: H+J phenomenology

[Chen et al (2016)]



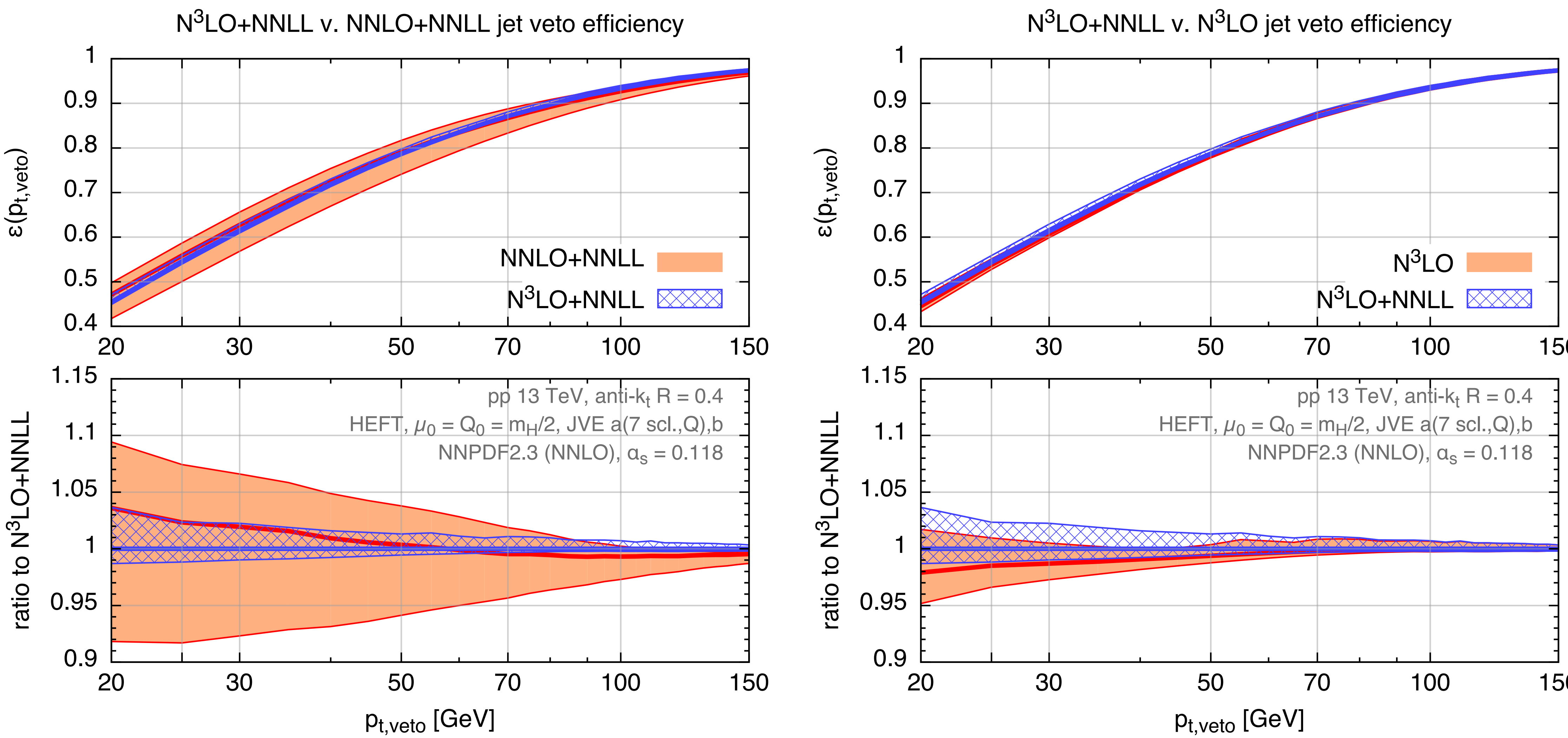
[FC, Melnikov, Schulze (2015+YR4)]



- Realistic final states → fiducial region
- Important benchmarking between different computations
- Non-trivial final states possible

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

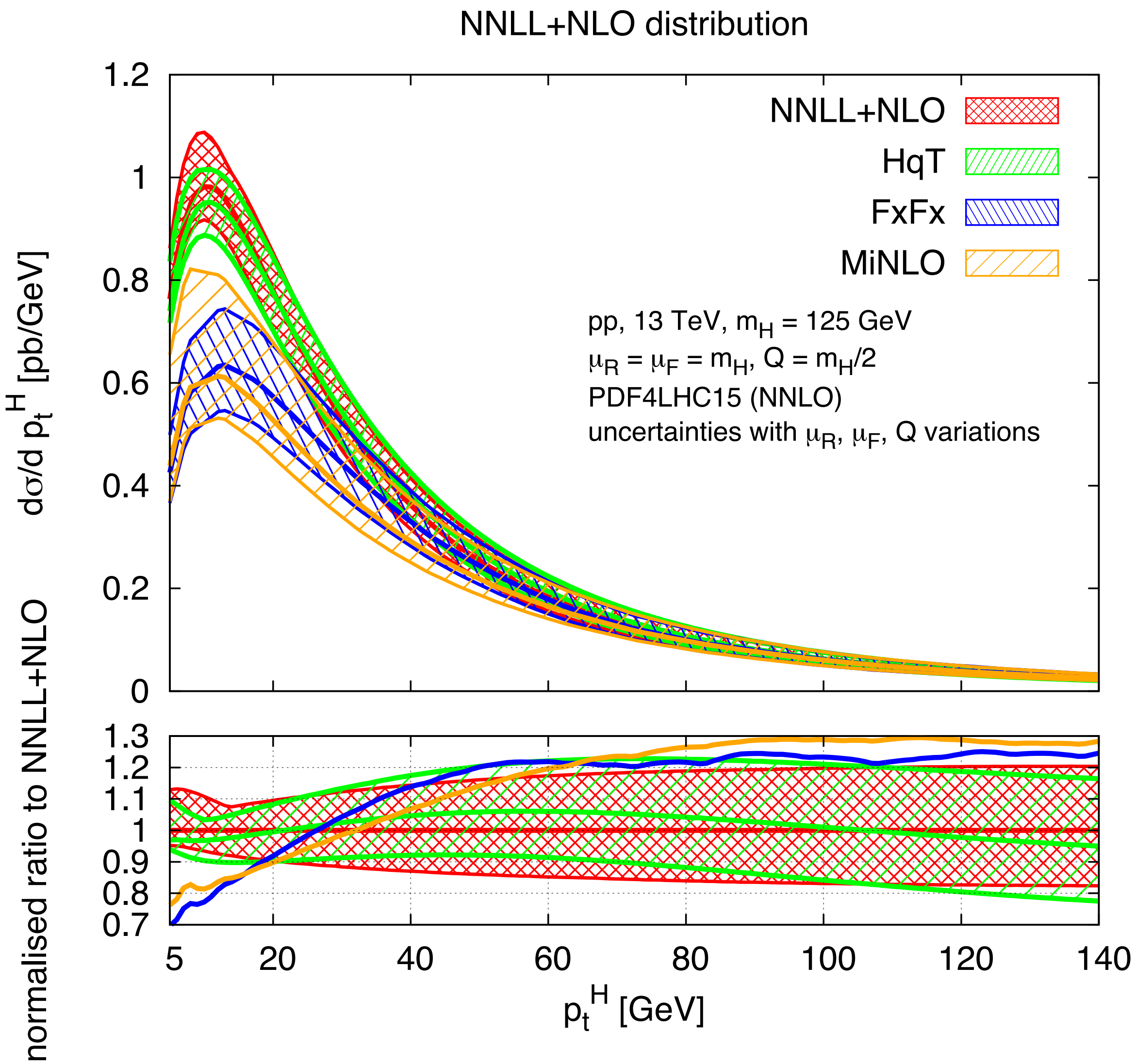
[Banfi, FC, Dreyer, Monni, Salam, Zanderighi, Dulat (2015)]

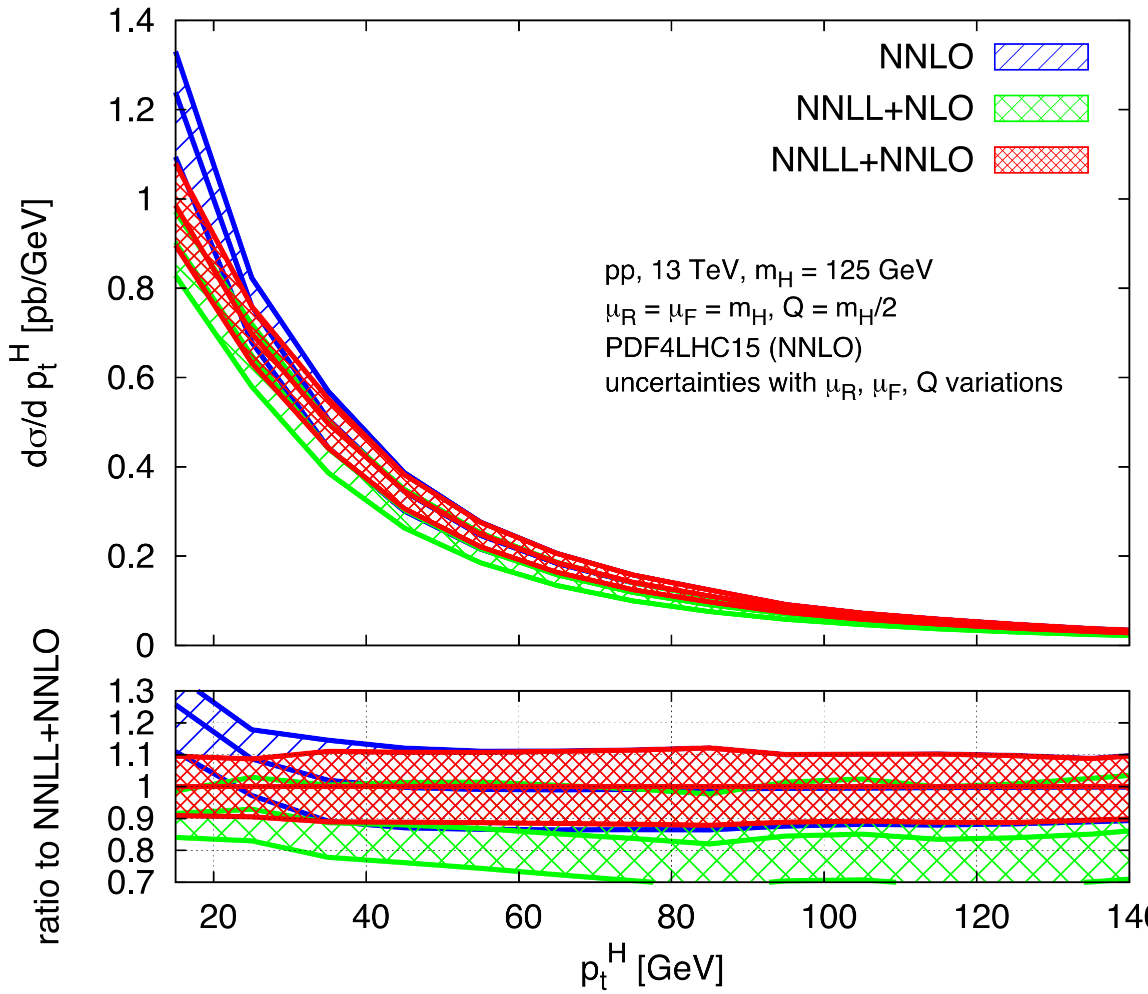


- Combination of f.o. N^{3}LO (Higgs inclusive) and NNLO (H+J exclusive) with NNLL resummation, LL$_R$ resummation, mass effects…
- No breakdown of fixed (high) order till very low scales
- Even more so for Z+jet [Gerhmann-De Ridder et al (2016)]

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)

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
  - Progress in input parameters: α_s fits, PDFs improvement. Photon PDF [Manohar, Nason, Salam, Zanderighi (2016), Harland, Khoze, Ryskin (2016)]
  - 5-loop evolution of α_s [Baikov, Chetyrkin, Kühn (2016)]
  - Input parameters: the top mass [Beneke et al, Hoang et al (2016)]
  - EW corrections, mixed QCD-EW…
- 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!