Theory improvements in view of HL-LHC

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Higgs Hunting 2016, LPNHE, 2nd September 2016

Many thanks to K. Melnikov and G. Salam for discussions on these topics

Some general remarks

- It is extremely hard to imagine what would happen in the next O(10) years…

- Nevertheless, it is clear that the HL-LHC would allow two kinds of investigations:

  - Look at rare processes (e.g. ttH, $H \to \mu\mu$, di-Higgs, exclusive decays, light quark Yukawa…) and specific kinematics regions ($\to$ unitarization, off-shell, high-p_t…)

    Will in general require some theoretical and experimental progress, but approach similar to current analysis

  - Aim to highest precision in ``standard'' processes

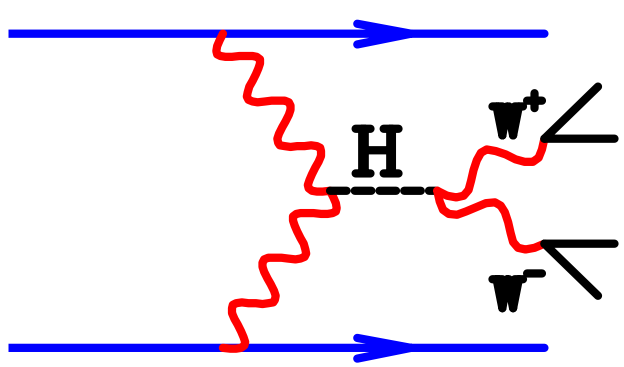
    Could possibly REQUIRE NEW APPROACH both from the THEORETICAL and the EXPERIMENTAL sides $\to$ focus of this talk

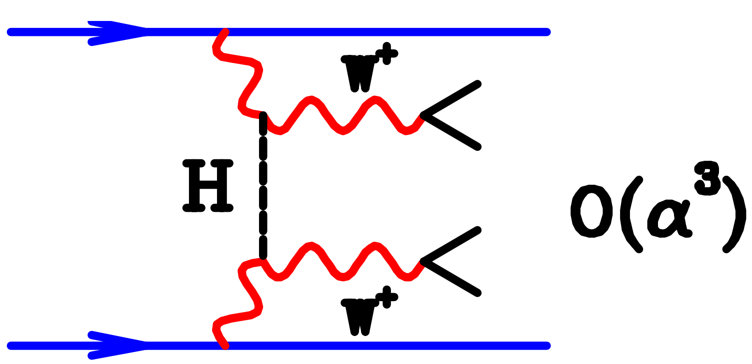
Rare processes / specific kinematics regions

Example 1: off-shell VBF studies

[Englert, Spannowski (2014); Campbell, Ellis (2015)]

- On Wednesday Raoul discussed off-shell studies in gluon fusion. A lot of potential but
  - Large K-factors, NNLO for bkg./int. extremely difficult
  - Interpretation e.g. in terms of Γ_H: some model dependence (ggH)
- One could largely circumvent these problems by considering off-shell VBF production





Anomalous couplings under reasonable control at the HL-LHC (see e.g. [Anderson et al. (2013) or ask Ulascan]), good theory control for signal/background (assuming improvements in ggH contaminations). Tiny rates

Example 1: off-shell VBF studies

[Campbell, Ellis (2015)]

Standard VBF selection cuts, extra off-shell m_T/m_{4l} cut

VBF pp→VVjj

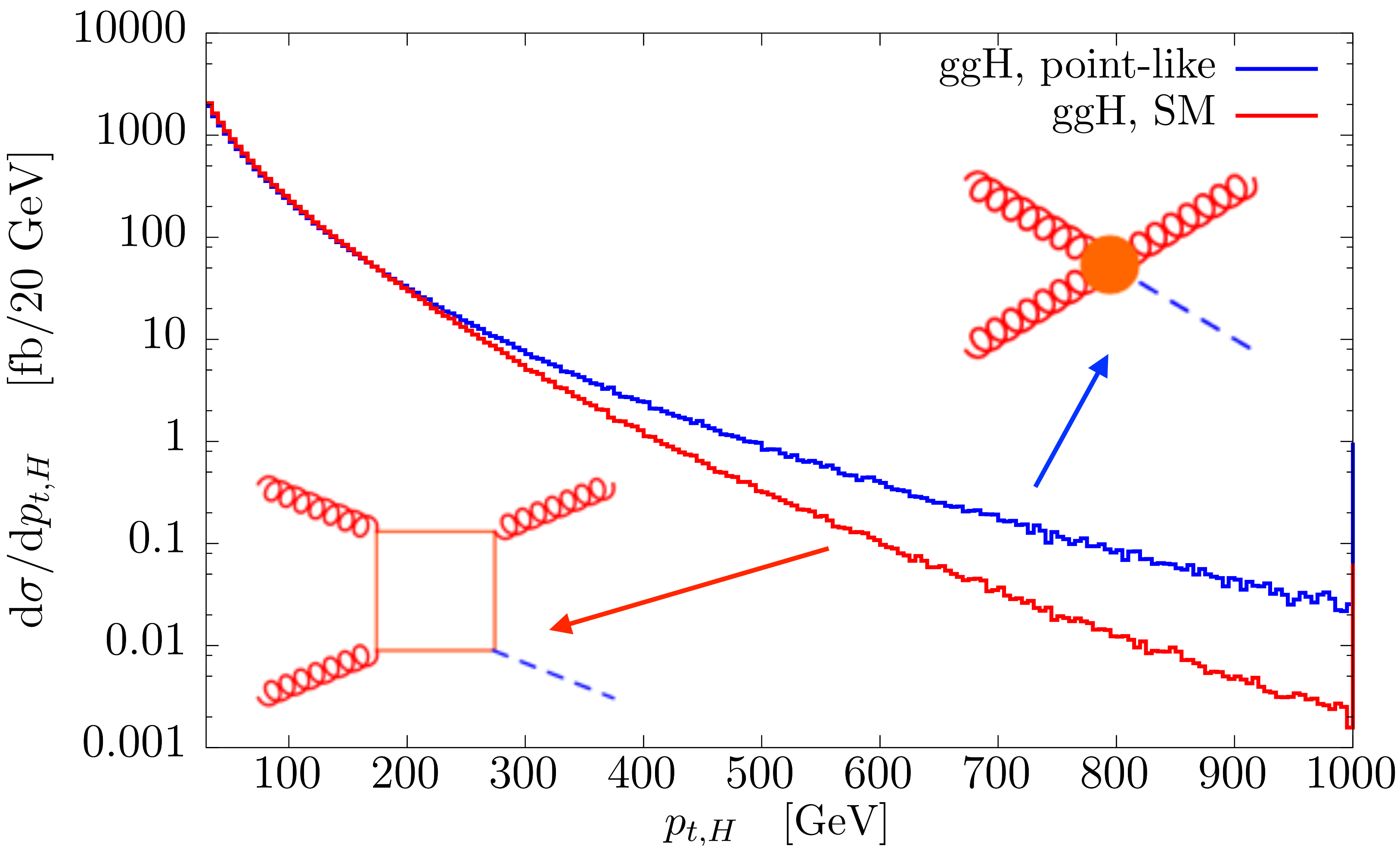
Nominal process	Cut	σ [fb] $O(\alpha^6)$	Factor	Events in 100 fb^{-1}
W^-W^+	$m_T^{WW} > 300$ GeV	0.2378	x4	95
W^+W^+	$m_T^{WW} > 300$ GeV	0.1358	x2	27
W^-W^-	$m_T^{WW} > 300$ GeV	0.0440	x2	9
W^+Z	$m_T^{WZ} > 300$ GeV	0.0492	x4	20
W^-Z	$m_T^{WZ} > 300$ GeV	0.0242	x4	10
ZZ	$m_T^{ZZ} > 300$ GeV	0.0225	x6	14
ZZ	$m_T^{WW} > 300$ GeV	0.0181	x6	11
ZZ	$m_{4l} > 300$ GeV	0.0218	x2	4

QCD pp→VVjj

Nominal process	Cut	σ [fb] $O(\alpha^4\alpha_s^2)$	Factor	Events in 100 fb^{-1}
W^-W^+	$m_T^{WW} > 300$ GeV	0.2227	x4	89
W^+W^+	$m_T^{WW} > 300$ GeV	0.0079	x2	2
W^-W^-	$m_T^{WW} > 300$ GeV	0.0025	x2	0
W^+Z	$m_T^{WZ} > 300$ GeV	0.0916	x4	37
W^-Z	$m_T^{WZ} > 300$ GeV	0.0454	x4	18
ZZ	$m_T^{ZZ} > 300$ GeV	0.0143	x6	9
ZZ	$m_T^{WW} > 300$ GeV	0.0118	x6	7
ZZ	$m_{4l} > 300$ GeV	0.0147	x2	3

- Small number of events, but W^+W^+ good S/B ratio
- At Run II/III: constraints ~ to Run I gluon fusion. Different theoretical systematics, complementary approach
- Can give interesting constraints at HL-LHC, especially if combined with gluon fusion and other coupling constraints

Example 2: high-p_t Higgs



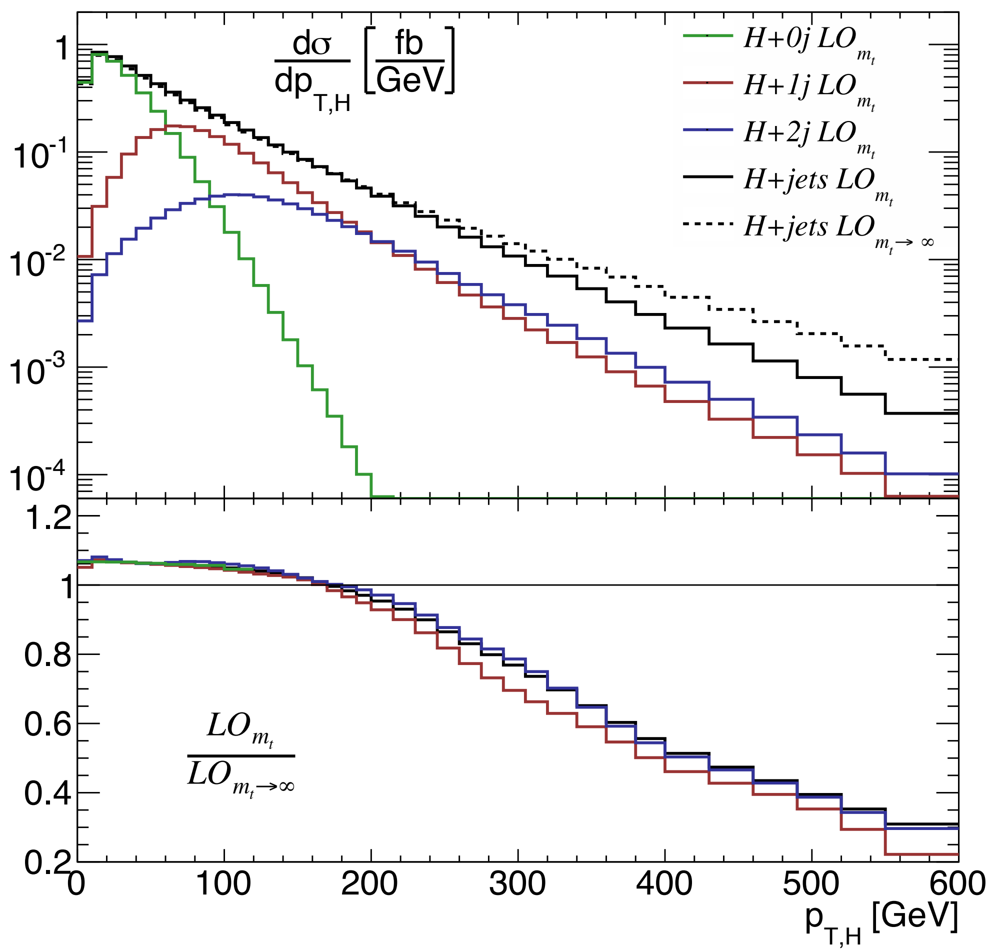
σ_{gg} (p_t>$p_{t,cut}$) =	1 fb	1 ab
bb	$p_{t,cut}$ ~ 600 GeV	$p_{t,cut}$ ~ 1.5 TeV
ττ	~ 400 GeV	~ 1.2 TeV
2l2ν	~ 300 GeV	~ 1 TeV
γγ	~ 200 GeV	~ 750 GeV
4l	~ 50 GeV	~ 450 GeV

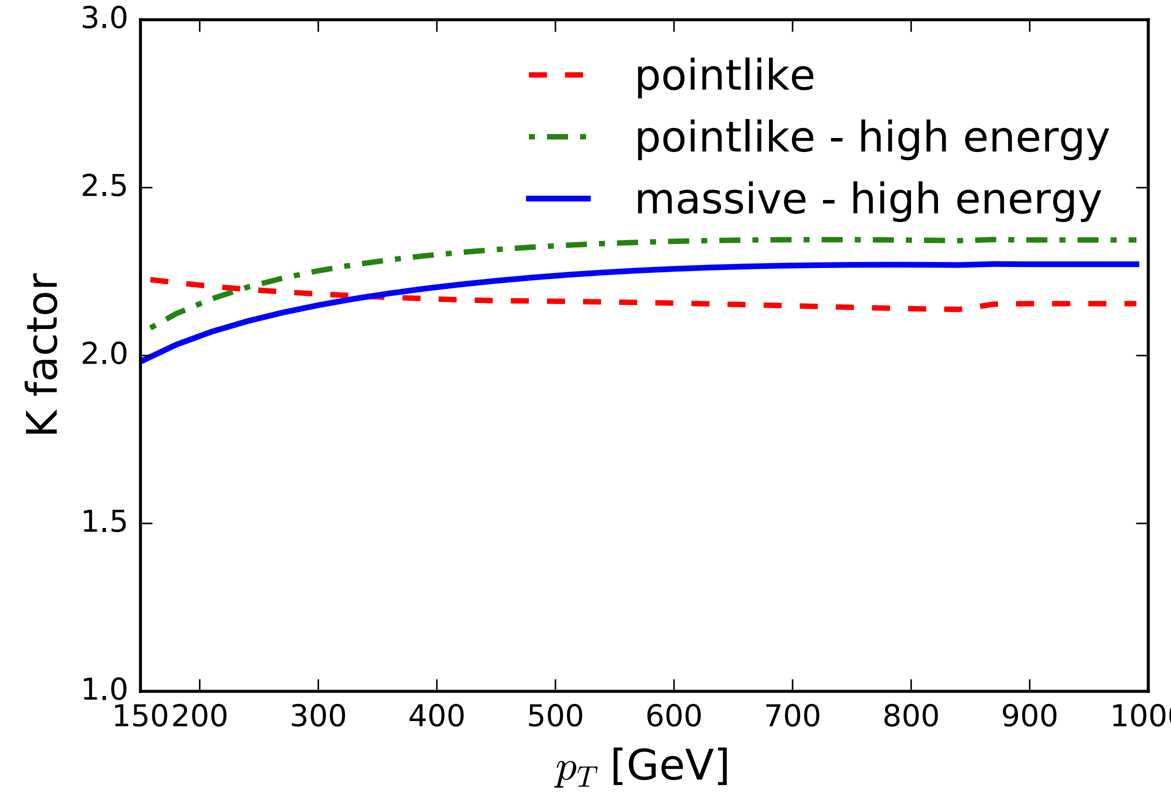
- Can investigate the structure of the ggH coupling, in a dynamical way
- Analysis non trivial
- Jet substructure techniques?
- Not unreasonable sensitivity expectation at high p_t ~ 10%
- DOES NOT REQUIRE PERFECT THEORETICAL CONTROL

Example 2: high-p_t Higgs

- Still, beyond what is actually known: LO
- Step 0: region dominated by real radiation (see F. Krauss' talk) → PS merging, resummation estimates

[Buschmann et al (2014)]



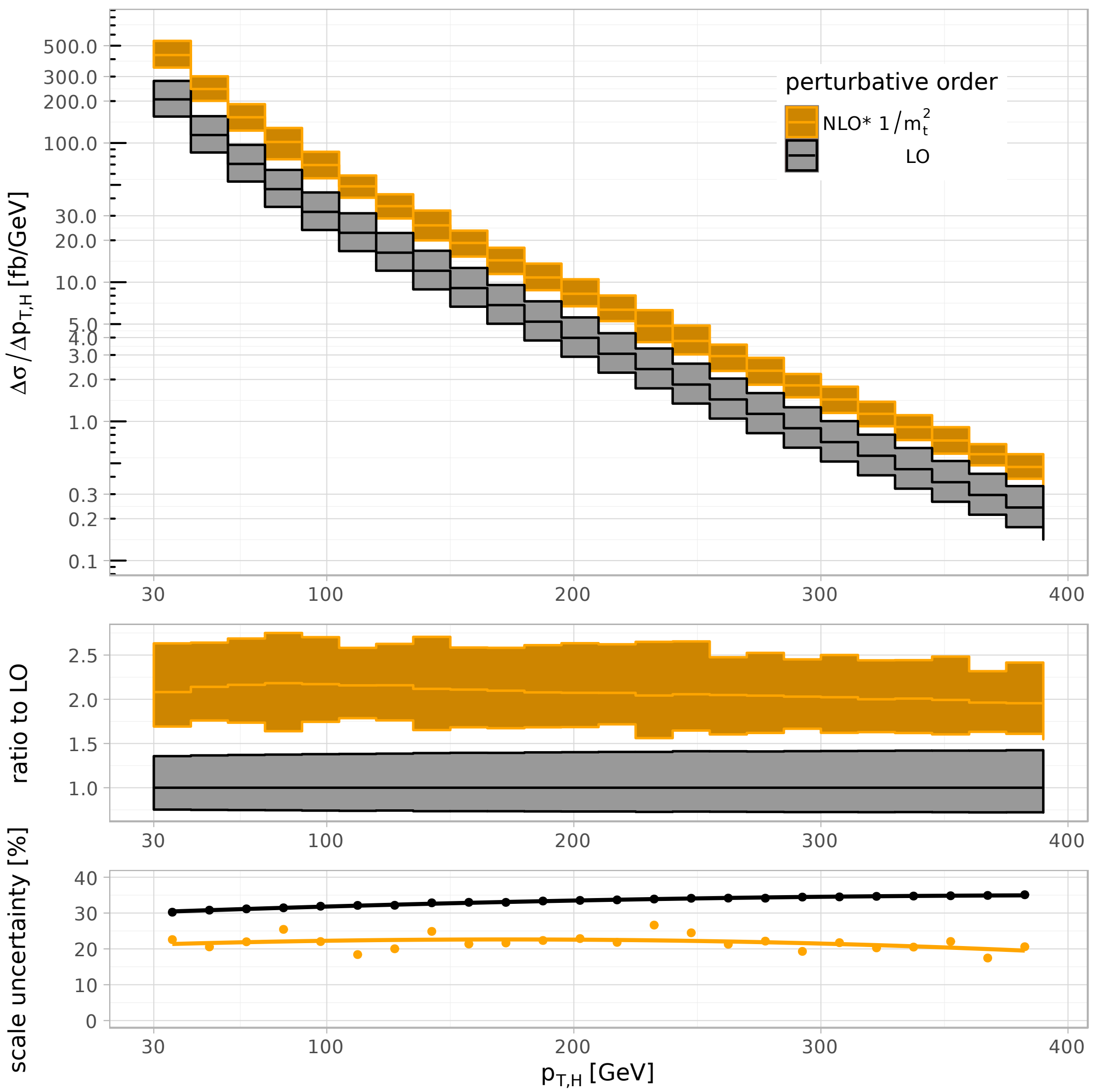


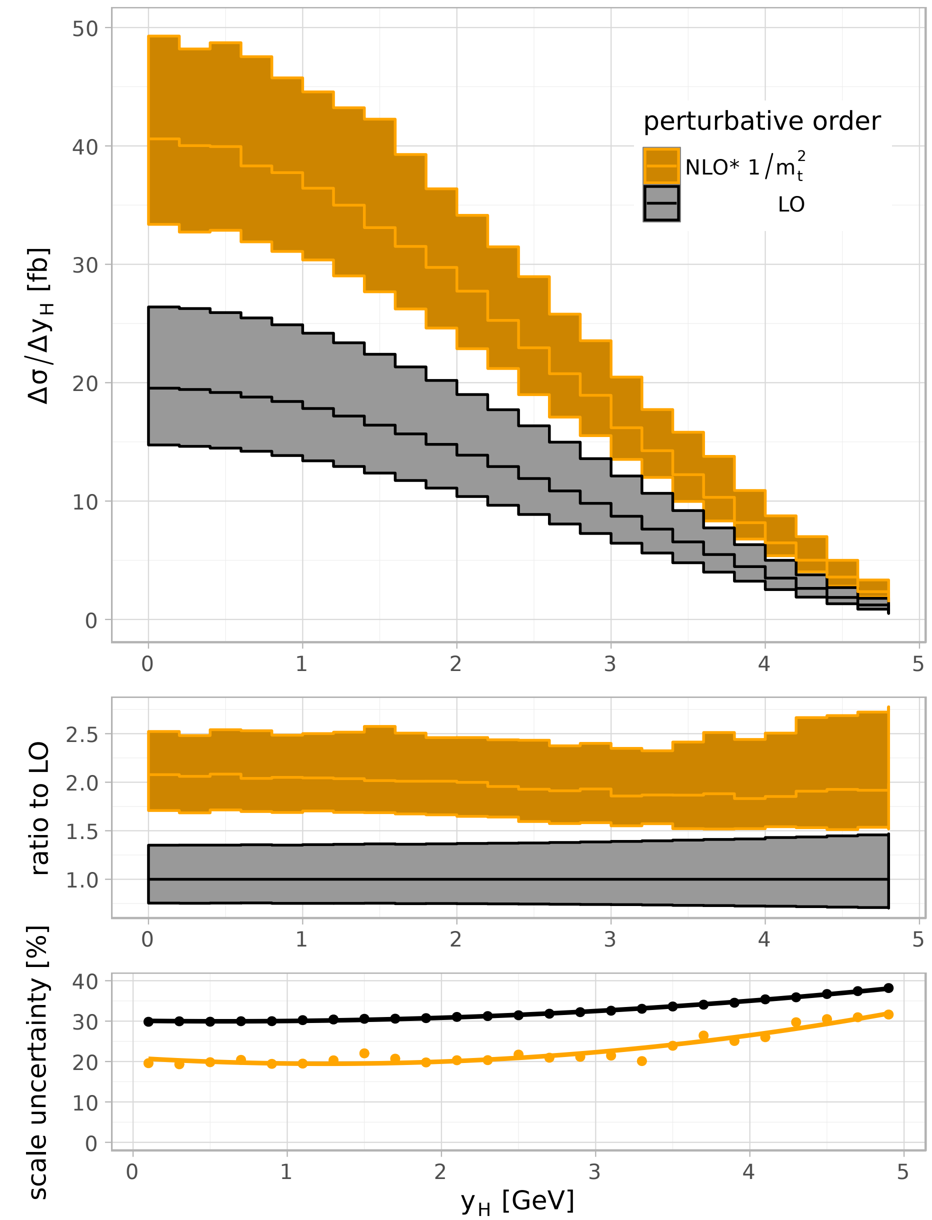
[Muselli et al (2016)]

- These approaches agree, and lead to ~20-30% accuracy
- Beyond that: (merged) NLO IS REQUIRED
- At the boundary of our current technology (complicated 2-loop)
- *Will be there for HL-LHC…*

Example 2: high-p_t Higgs

[Neumann, Williams: arXiv 1609.00367 i.e. this morning]





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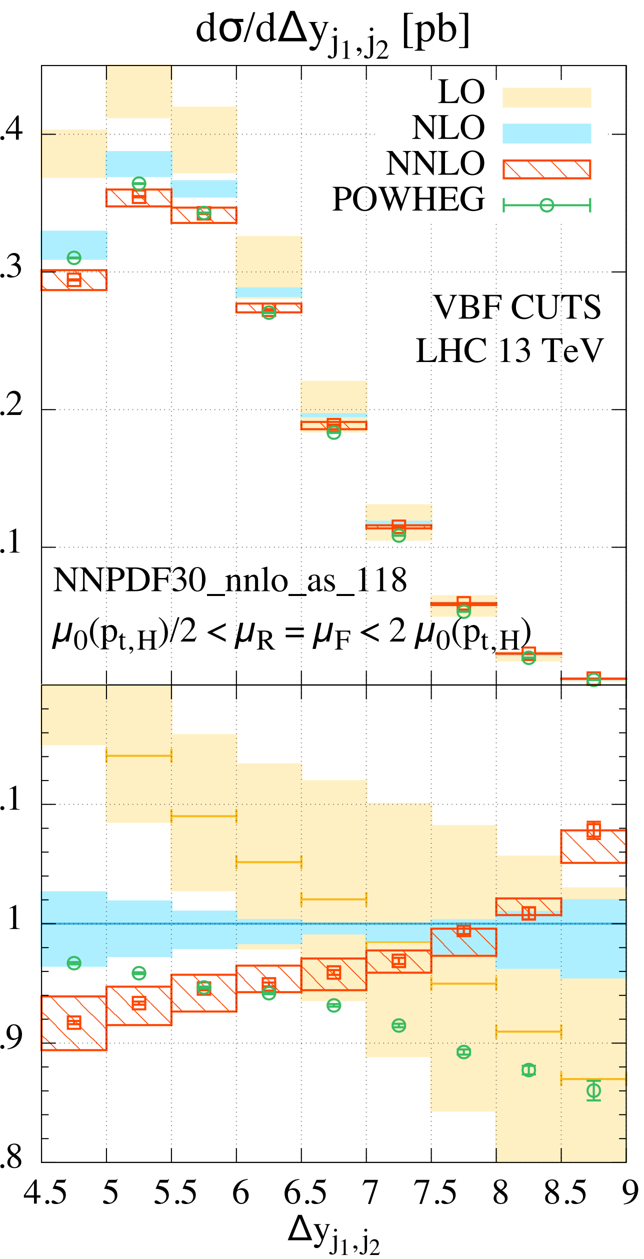
Highest precision for ``standard” analysis

The path to precision

- HL will allow us to perform extremely detailed investigations of the Higgs sector. REASONABLE TARGET: FEW PERCENT ACCURACY
- The goal: detect (small) tensions → precision throughout the full spectrum (signal and backgrounds), correlations
- To achieve this, we need to
  - focus on theoretically clean regions → high scale, IR-insensitive observables/cuts, minimal NonP contamination…
  - focus on experimentally clean regions → high quality…
  - be able to compare data/theory in a CONTROLLED ENVIRONMENT → ``cut and count'', minimize BDT, multivariate analysis, NN… Great tools to squeeze the most out of data, but VERY HARD TO CONTROL THEORETICALLY
  - be able to minimize underlying theoretical assumptions in experimental analysis → FIDUCIAL REGION, no (unnecessary) extrapolations, avoid reweightings…
  - be careful with ``standard'' practices. At ~1%, a lot of things can happen

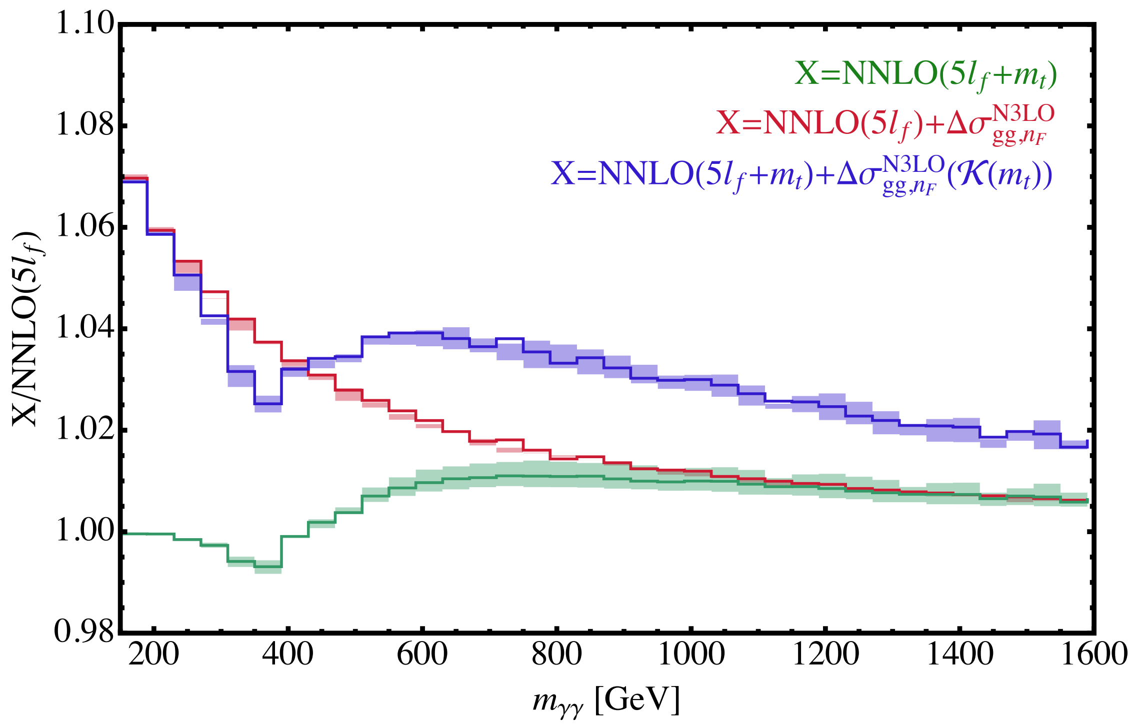
Examples of what can go wrong…

Reweighting: VBF@NNLO



- NNLO inclusive K-factor ~ 1%
- Actual correction ~ 10%
- Not captured by NLO or PS
- Non-trivial jet dynamics

Common practice: Data-driven background estimates



[Campbell, Ellis, Williams (2016)]

- top quark effects induce %-level shape distortion over smoothly falling pp→γγ background
- top quark effect, but it happens at ~ 750 GeV
- Not captured by MC

``Few percent": the theory side

The starting point: QCD factorization

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

``Few percent'': the theory side

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

INPUT PARAMETERS: α_s, PDFs, (m_q…)

- α_s: ~ 1% accuracy (PDG2016)
  - error *increased* w.r.t. previous PDG
  - tension with low DIS value (0.113)? *NP effects really under control?*
  - in a ~10 year timescale, should we expect improvements from lattice?
- PDFs: ~2-3% (PDF4LHC)
  - good agreement between different groups (*ABM discrepancies under control?*)
  - to which extent new LHC data can improve on this picture? Both experimental and theoretical issue. *(Z p_T: excellent data, excellent theory, the two are in tension…)*
  - PDFs for N^{3}LO?

``Few percent'': the theory side

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

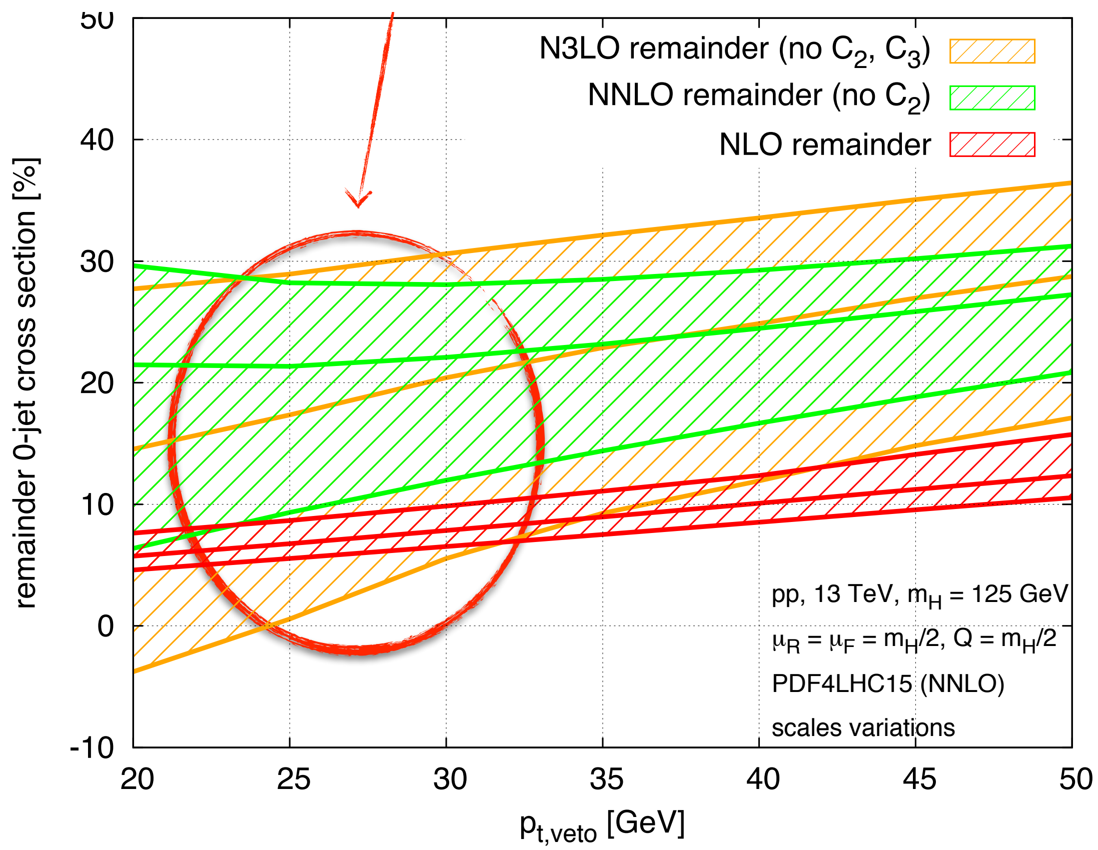
HARD SCATTERING MATRIX ELEMENT

- $\alpha_s \sim 0.1$ → For TYPICAL PROCESSES, we need NLO for ~ 10% and NNLO for ~ 1 % accuracy.
- $\alpha_s C_A \sim 0.3$ → For Higgs, we need N^{3}LO.

- We are after FIDUCIAL RESULTS (minimize hidden extrapolation error)
- We should focus on HIGH-Q the regime (minimize NP contamination)
  - In this regime, typically process is a multi-scale problem. However, no huge scale hierarchies → fixed (high enough) order predictions do not break down / / (high enough log) resummation provide good description → can tackle some issues from different perspectives. IN GENERAL, A COHERENT PICTURE IS EMERGING *(what about di-Higgs?)*

Examples: $p_{t,H}$, Jet-Veto

70-80% of the perturbative expansion comes from logs



[Monni, QCD@LHC2016]

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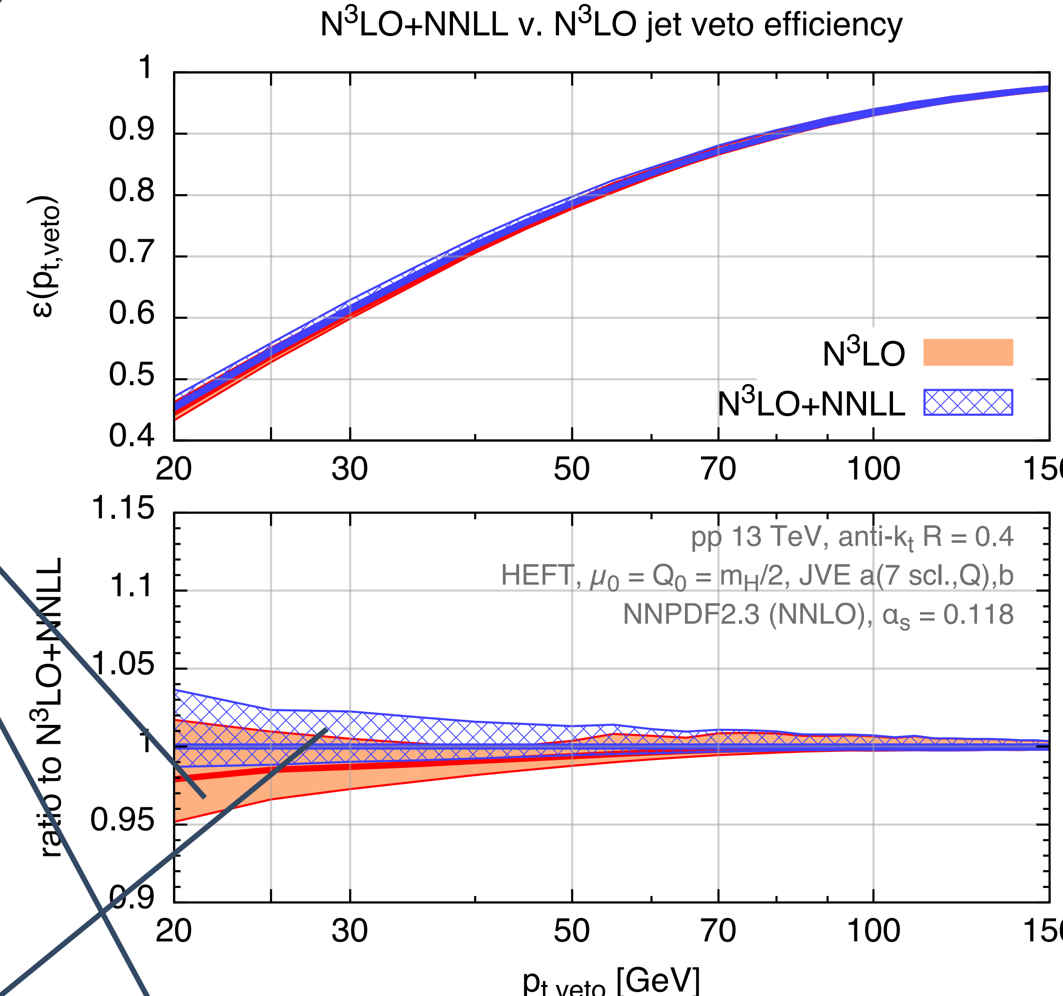
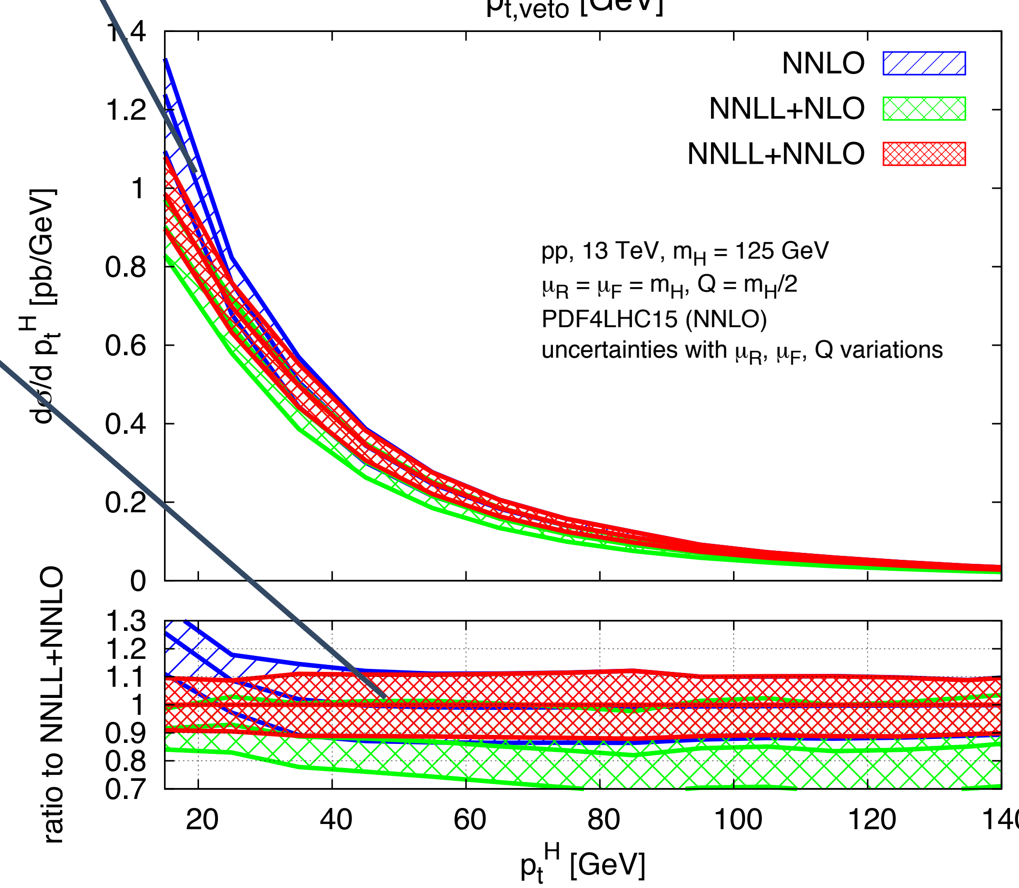


[Banfi et al, 2015]



[Monni, Re, Torrielli (2016)]

- From p_t ~ 40 GeV: fixed (NNLO) order under very good control
- CAN RELIABLY USE IT TO PREDICT FIDUCIAL VOLUMES AT THE FEW PERCENT LEVEL

Charting the progress

Process	~ 15 y ago	Now	What we want
ggH	towards NNLO$_{inc}$	N^{3}LO$_{inc}$, NNLOPS, NNLL	N^{3}LO(PS) +*small details*
VBF	NLO	N^{3}LO$_{inc}$, NNLO	N^{3}LO
VH	NLO	NNLO	gg→VH@NLO
ttH	LO	NLO	NNLO?
Hj	NLO	NNLO	mass effects
Hjj	LO	NLO	NNLO
pp→γγ	NLO	NNLO+gg@NLO	/ /
pp→VV	NLO	NNLO+gg@NLO	gg@NLO massive

- Many of the desiderata require significant theory improvements
- Nevertheless, given the trend: FAR FROM IMPOSSIBLE
- Quite remarkable precision ALREADY NOW

About the *small details*…

Physics at the few percent level: BASICALLY EVERYTHING IS RELEVANT

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

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

- 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
$^{+0.21\%}_{-2.37\%}$	±0.37%	±1.16%	±1%	±0.83%	±1%

[Mistlberger, QCD@LHC2016]

``Few percent": the theory side

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

NON PERTURBATIVE EFFECTS

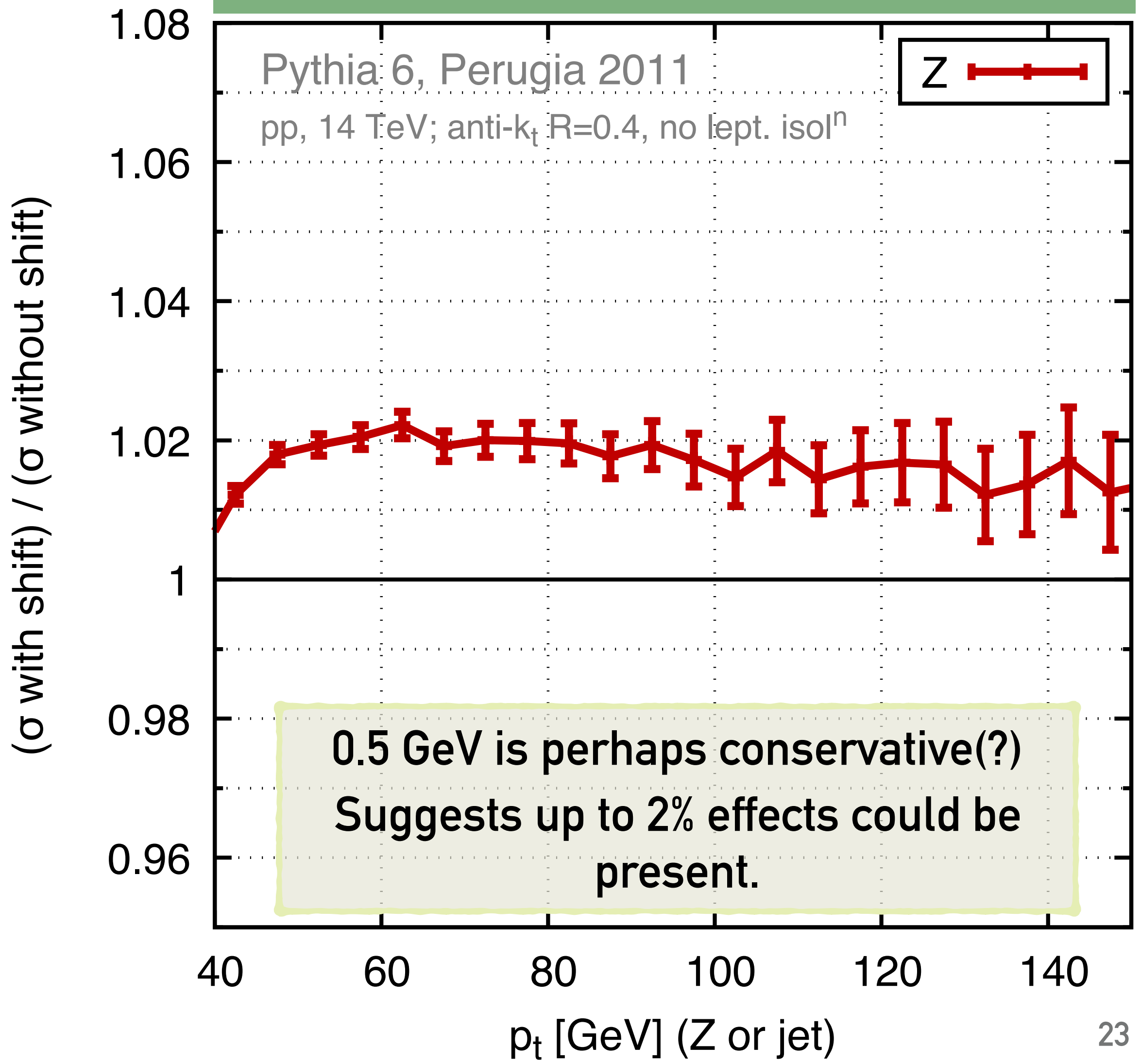
- $\Lambda_{\mathrm{QCD}}/\mathrm{Q} \sim 100$ GeV → PERCENT EFFECT
- NO GOOD UNDERSTANDING OF IT. LIMITING FACTOR FOR PRECISION
- To some extent it comes from ``normal" soft/collinear gluons → at least insight from resummation / PS… but not all of it
- To this level of precision, we could not assume that MC are getting this right. Much more exploration is needed
- Hadronic collisions → these effects are there, also for leptonic processes
- Ideally: design observables/cuts for which these effects are minimized (and more generically design IR-insensitive setups → symm./asymm. cuts…)
- Situation qualitatively different w.r.t. hard matrix element (we don't have a framework)

Example: DY transverse momentum

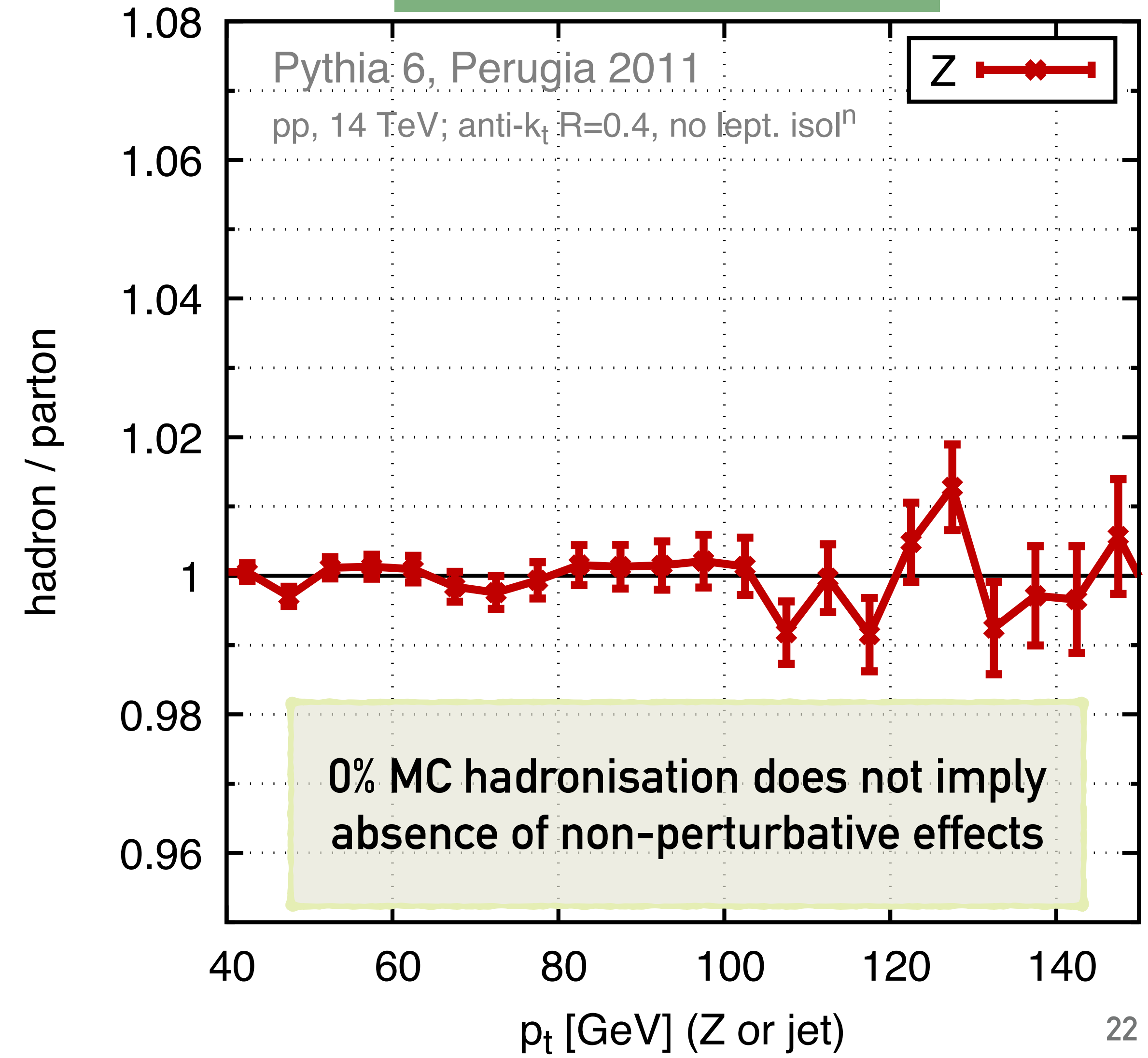
[G. Salam (2016)]

- Despite being a jet-free observable, non-vanishing p_{t,l^+l^-} comes from highly asymmetric color flow → expect linear behavior in Λ_{QCD}/Q

impact of 0.5 GeV shift of Z pT



MC hadronisation



Finite kick ~ 0.5 GeV to $p_{t,Z}$:
2% effect on the spectrum

MC does not get it

Dealing with NP effects: jets

- For jets, these issues are much more pronounced → quite some investigation already
- Many progress related to jet substructure studies. Analytical understanding of soft/collinear effects (new ideas, several techniques, traditional resummation, SCET…)

- A recent study: use the jet radius as a handle to disentangle different NP effects [Dasgupta et al. (2016)]
  - Basic idea: different contributions should scale differently (UE/MPI ~ R^2, Had ~ $1/R$, Pert ~ $\ln R$) [Dasgupta et al. (2007)]
  - If data for 3 different R are available, possible to gain some insight into these effects
  - Scaling agrees with simulations, but some features doesn't (p_t dependence) → more work is required

Conclusions

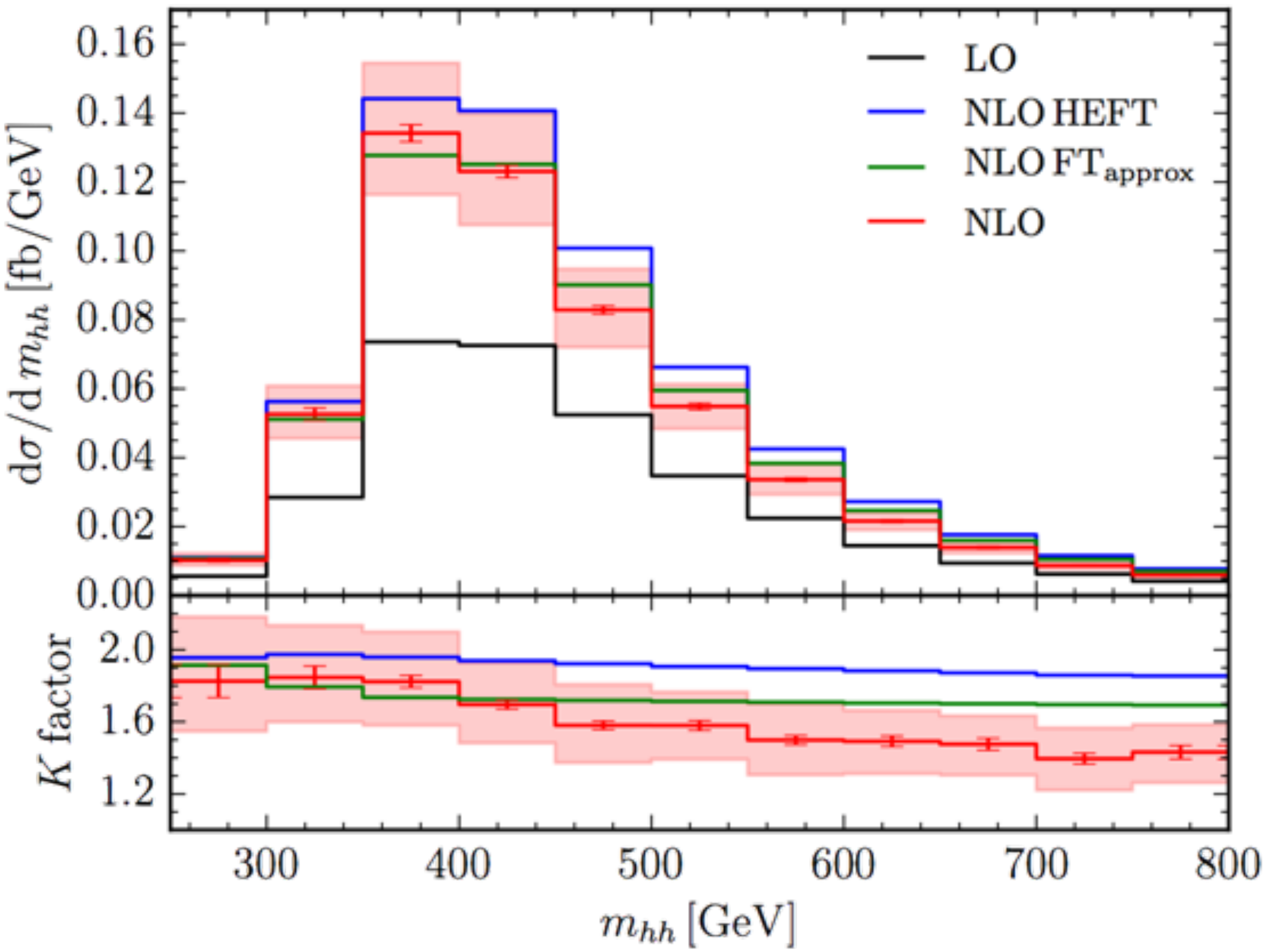
- The HL-LHC will open up new ways of exploring the Higgs sector
  - Investigate corners of phase space, to decent precision
  - Perform `standard' analysis to extremely high precision
- In both cases, we are SENSITIVE TO NEW PHYSICS EFFECTS
- To profit from this opportunity, a lot of work is needed
  - Continue the nice trend of ever improving our existing theoretical predictions (add loops/legs/logs…). It will require highly non-trivial progress, but no huge surprises are expected here. ~ known framework
  - At some point, we will hit against a wall: input parameters, NP effects. Progress in this direction is much more difficult to predict
  - Simultaneously, a slightly different experimental approach is required if we want to achieve very high precision (simple analysis, fiducial volumes, high-Q observables…)

EXCITING TIMES AHEAD!

Thank you very much
for your attention

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 WITH SECDEC*
- Table of 665 phase-space points
- Highly non-trivial computer-science component (GPUs, very delicate numerical integration…)

- 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)]

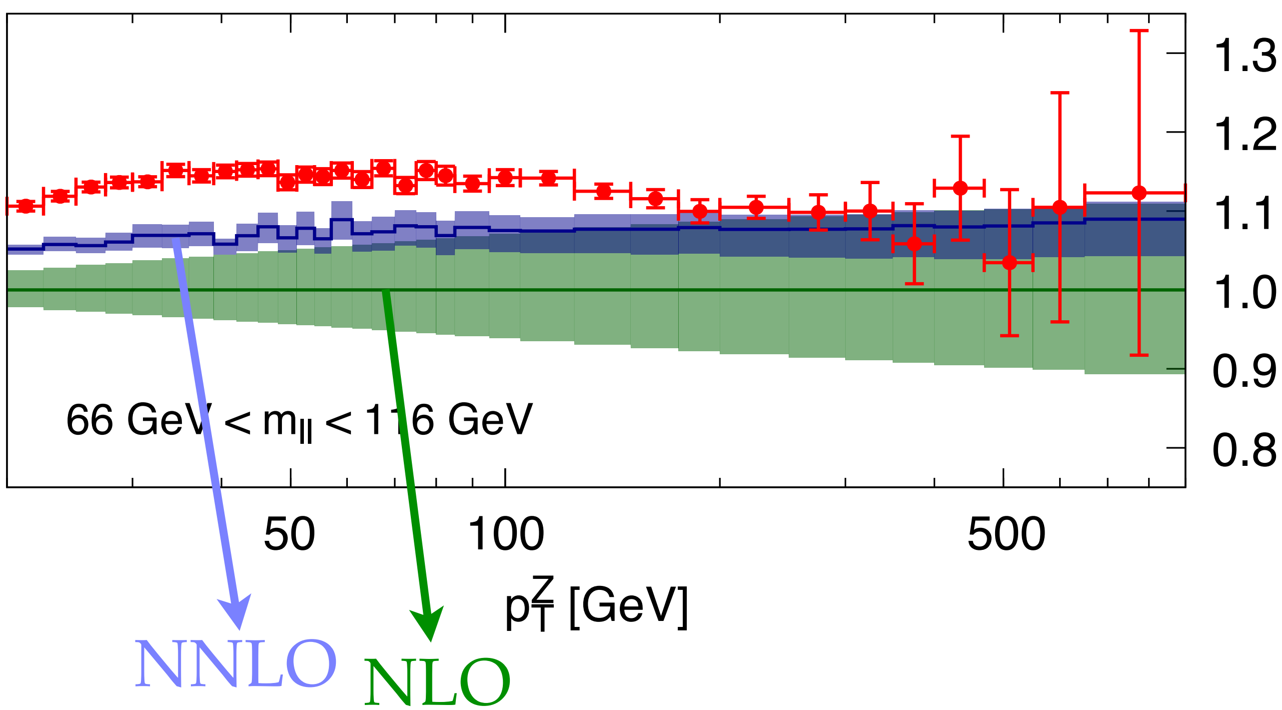
Now that we know the exact result, many interesting questions:

- 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), see Jonas' talk on Thursday) → 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)

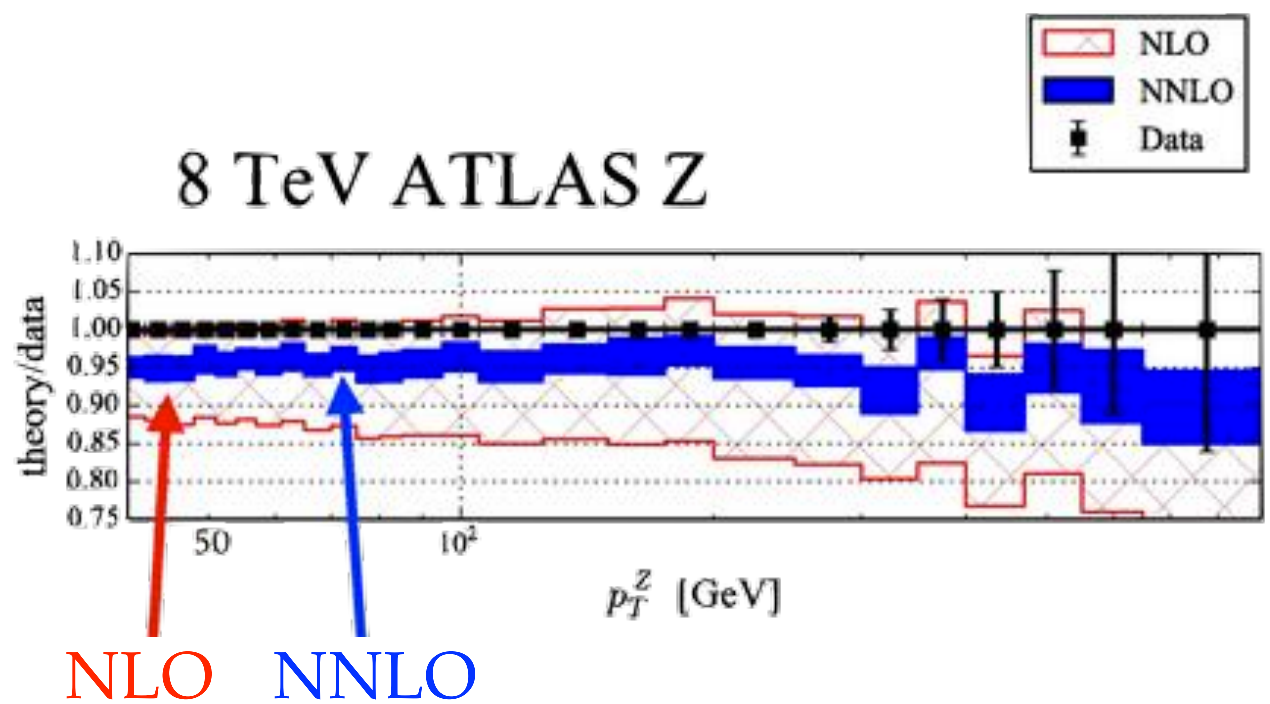
Recent NNLO results: V+J phenomenology

Data / theory ratio, Z+jet

Antenna [Gehrmann-de Ridder et al (2016)]



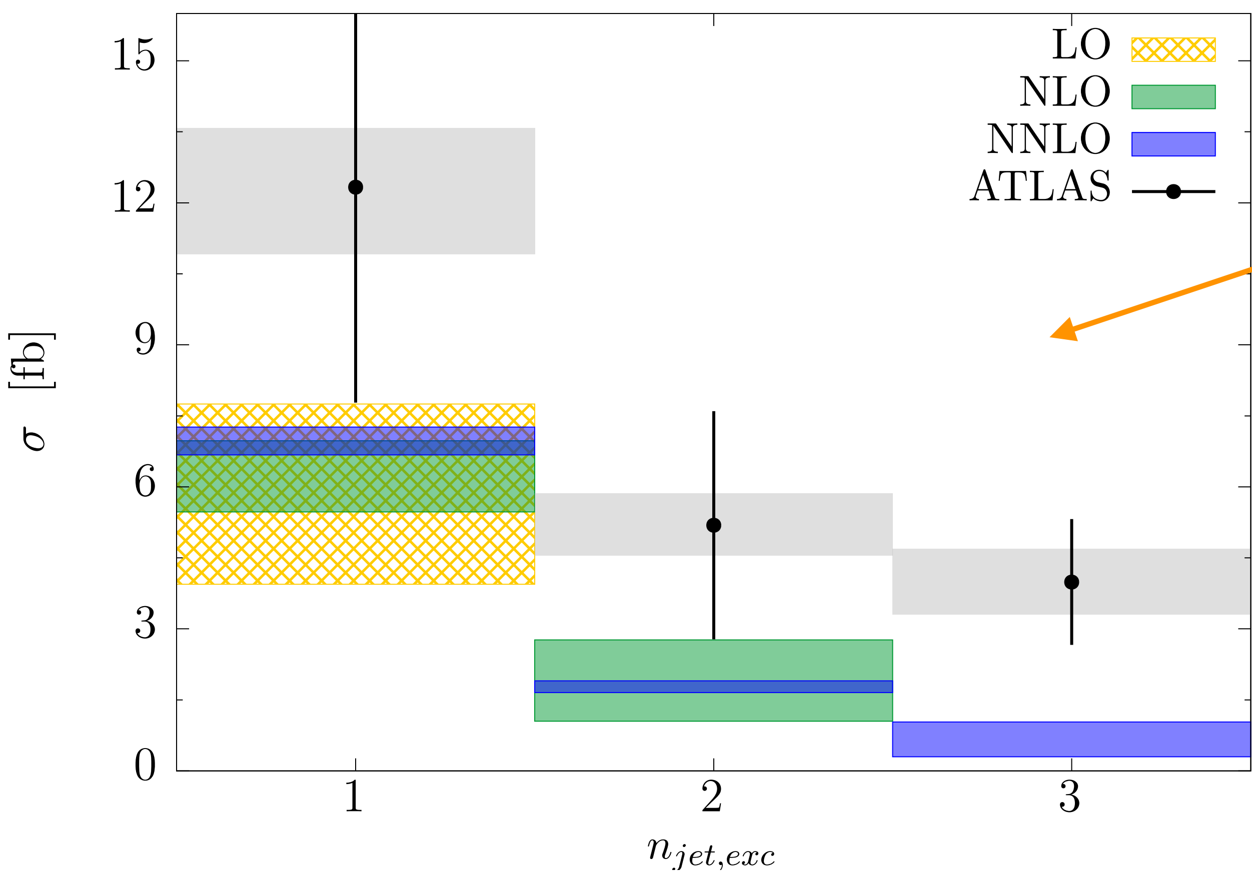
N-Jettiness [Boughezal et al (2016)]



- Also at NNLO, slight data/theory tension
- Disappears for normalized ratios, but not accounted for systematics / luminosity uncertainties
- The cleanest possible measurement… SHOULD WE BE WORRIED?

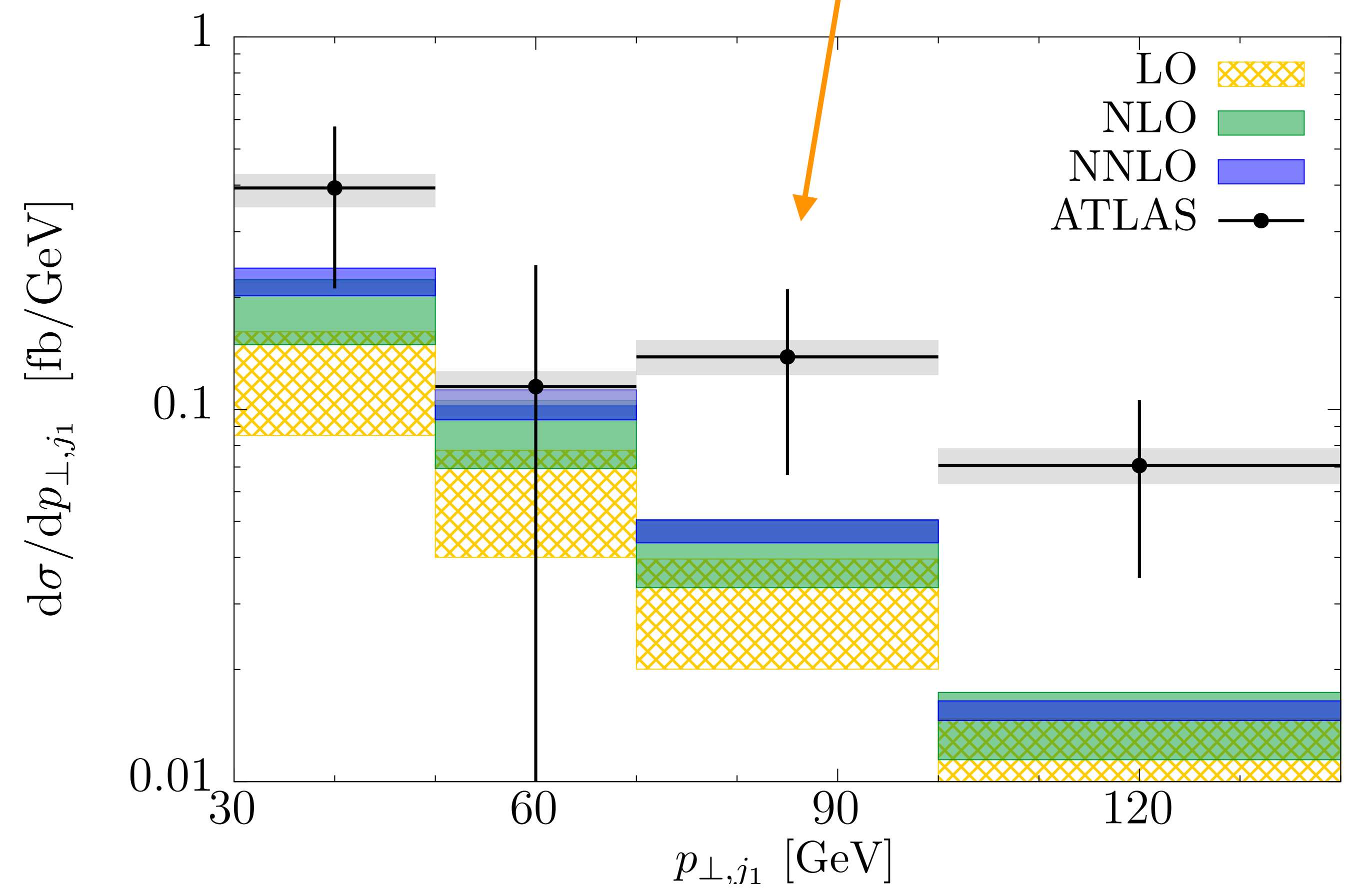
Fiducial analysis: H→γγ

[FC, Melnikov, Schulze (2015)]



Exclusive Jet bins, ATLAS8

Leading jet p_T, ATLAS8



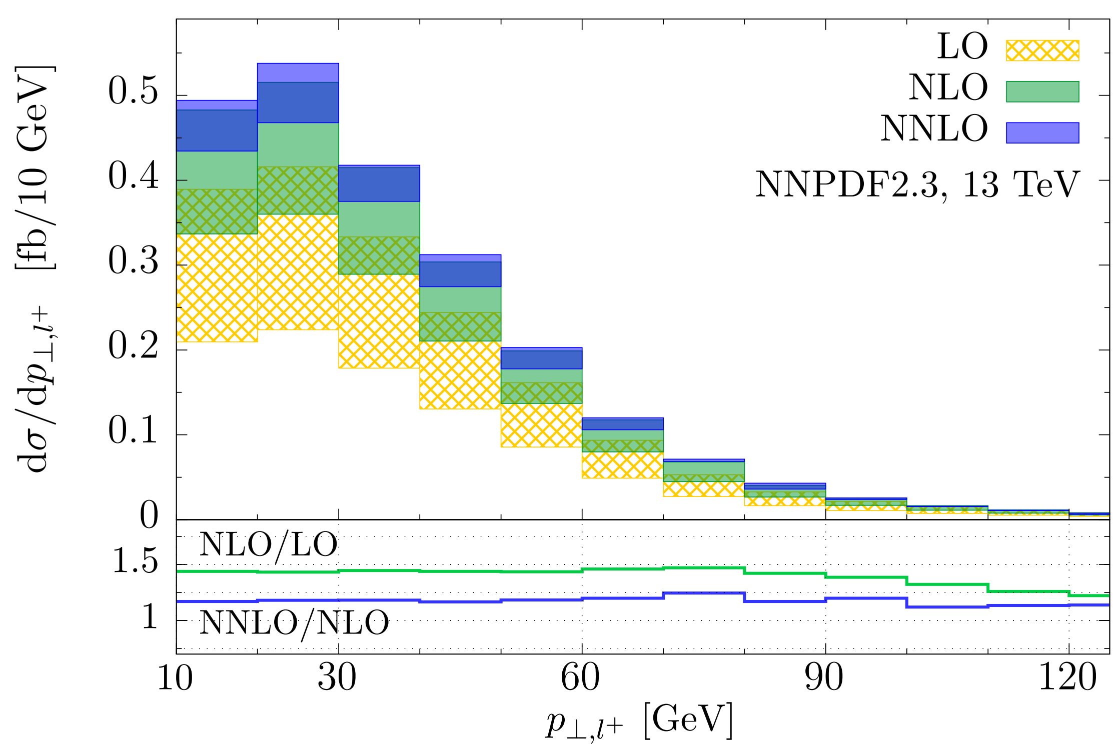
Still very large statistical fluctuations for these analysis to mean much, but NNLO theory error ~ systematic error

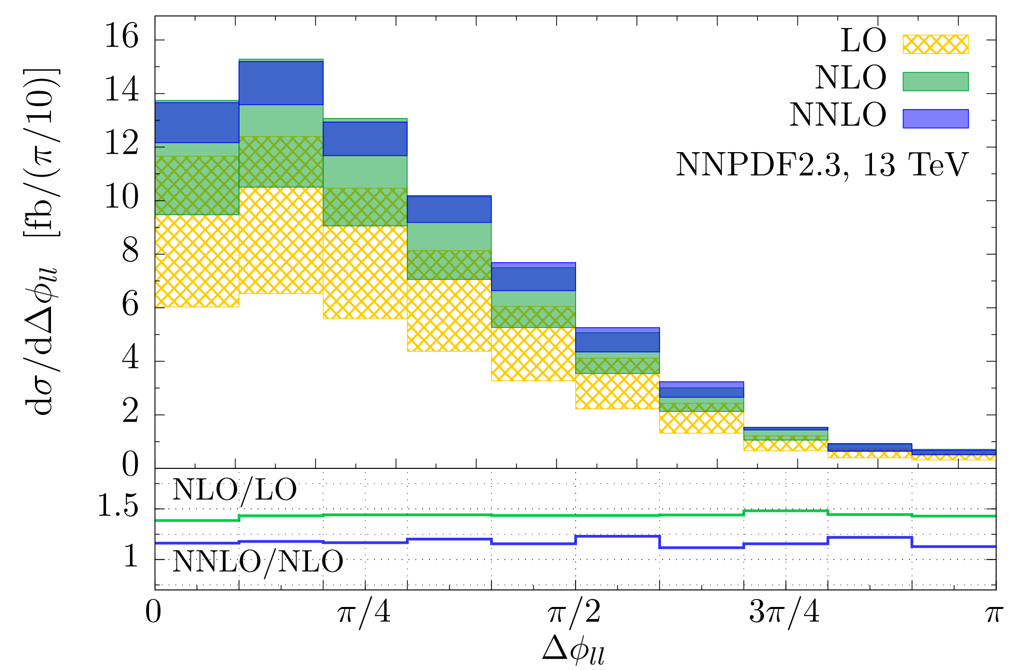
Fiducial analysis: H→2l2ν

[FC, Melnikov, Schulze (2015)]

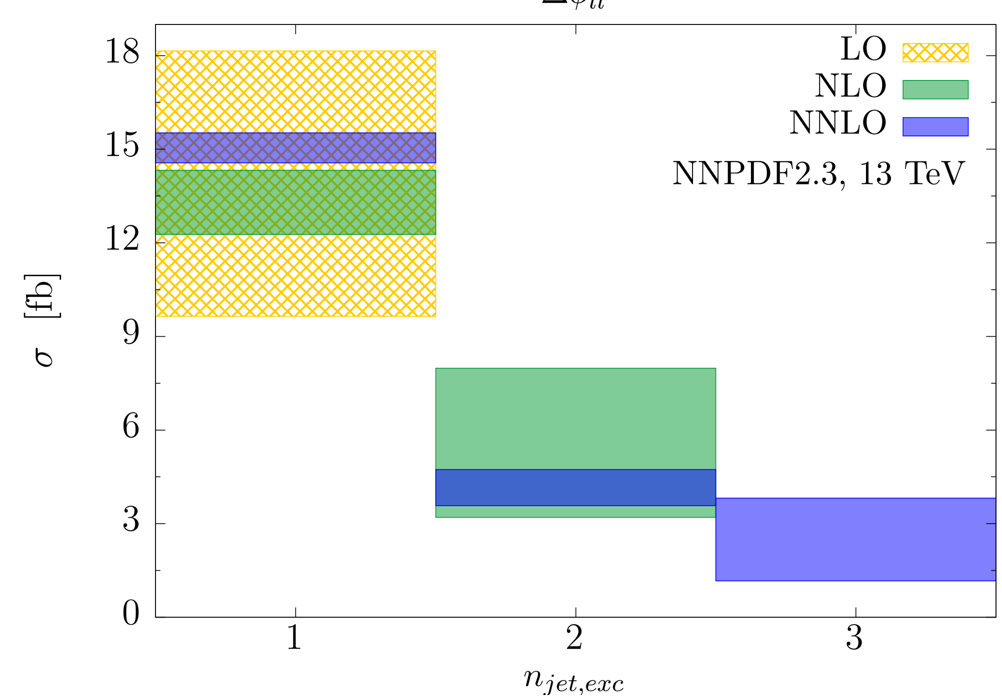
SETUP: CMS-LIKE ANALYSIS, 13 TEV

Anti-k_t with R=0.4, $p_{t,j} > 30$ GeV, $|y_j| < 4.7$, $p_{t,l} > 20/10$ GeV, $E_{t,miss} > 20$ GeV, $m_{ll} > 12$ GeV, $p_{t,ll} > 30$ GeV, $m_{t,WW} > 30$ GeV

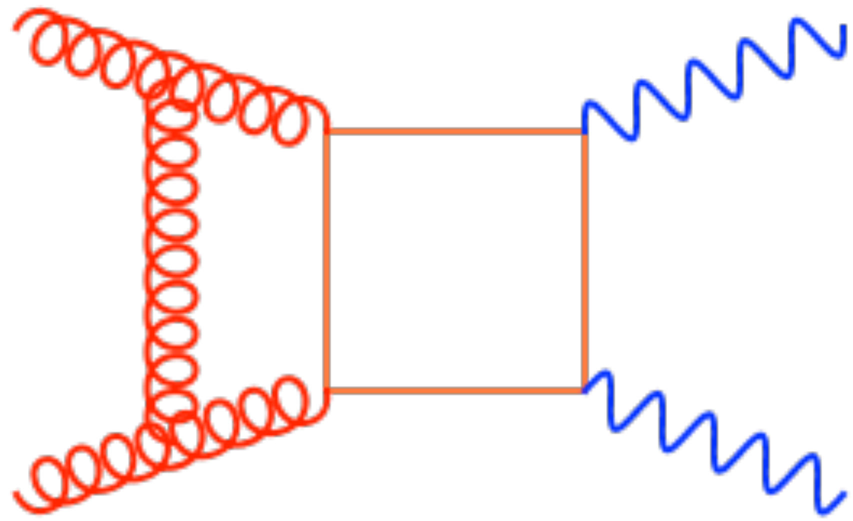




NNLO able to cope with complicated final states (up to 7 particles)

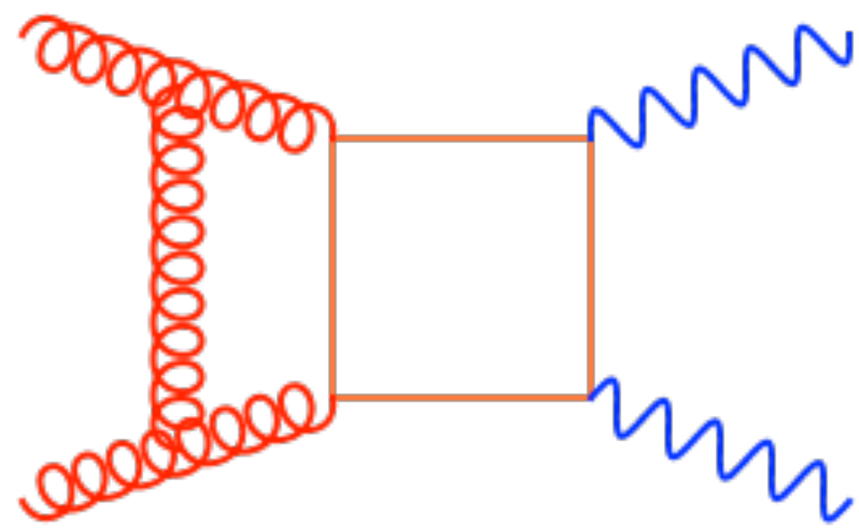


The problem of (two) loop amplitudes



- As a rule of thumb, complexity of multi-loop amplitudes grows very rapidly
  - as we move away from the massless limit
  - as we increase the number of scales of the process
- Here: 4 scales ($s,t,m_{ee},m_{\mu\mu}$) → several orders of magnitude more complicated than di-jet, H+j,…
- With internal top masses: prohibitively complicated

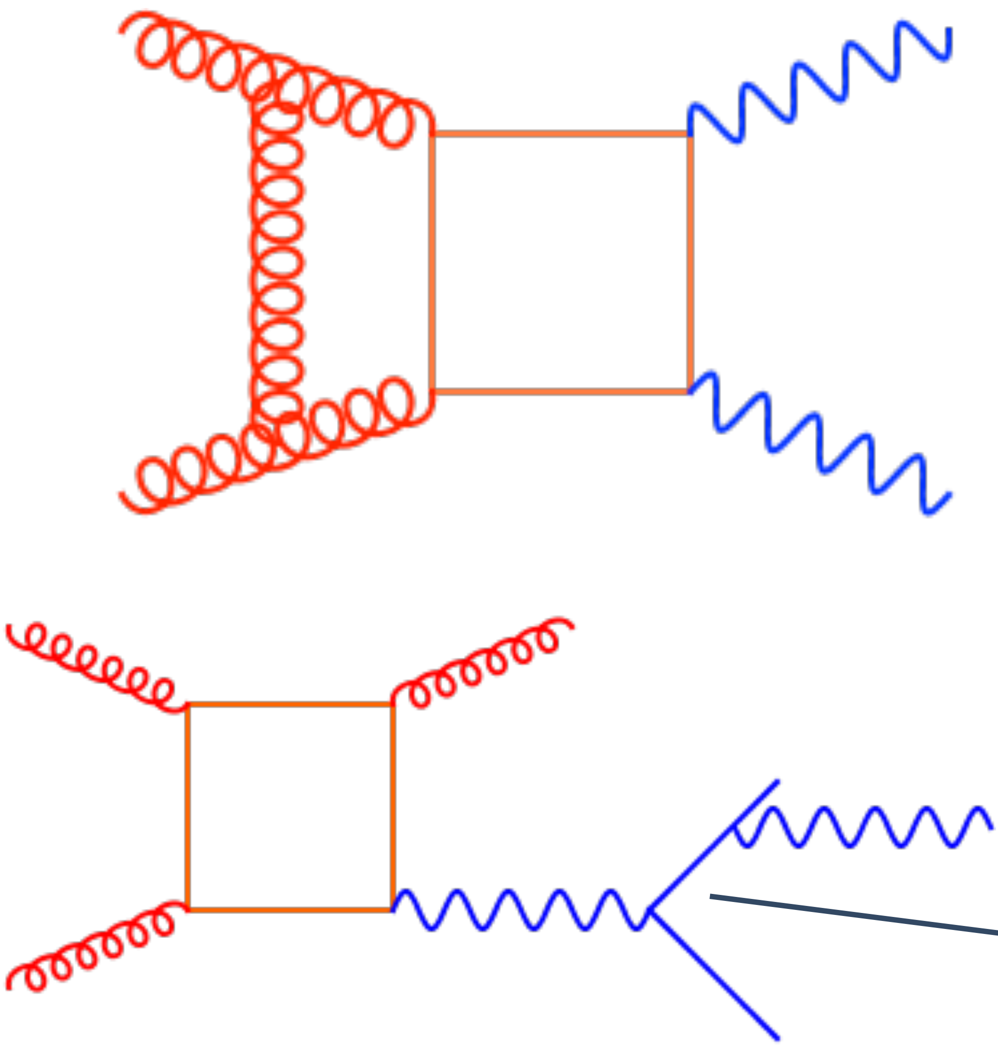
The problem of (two) loop amplitudes



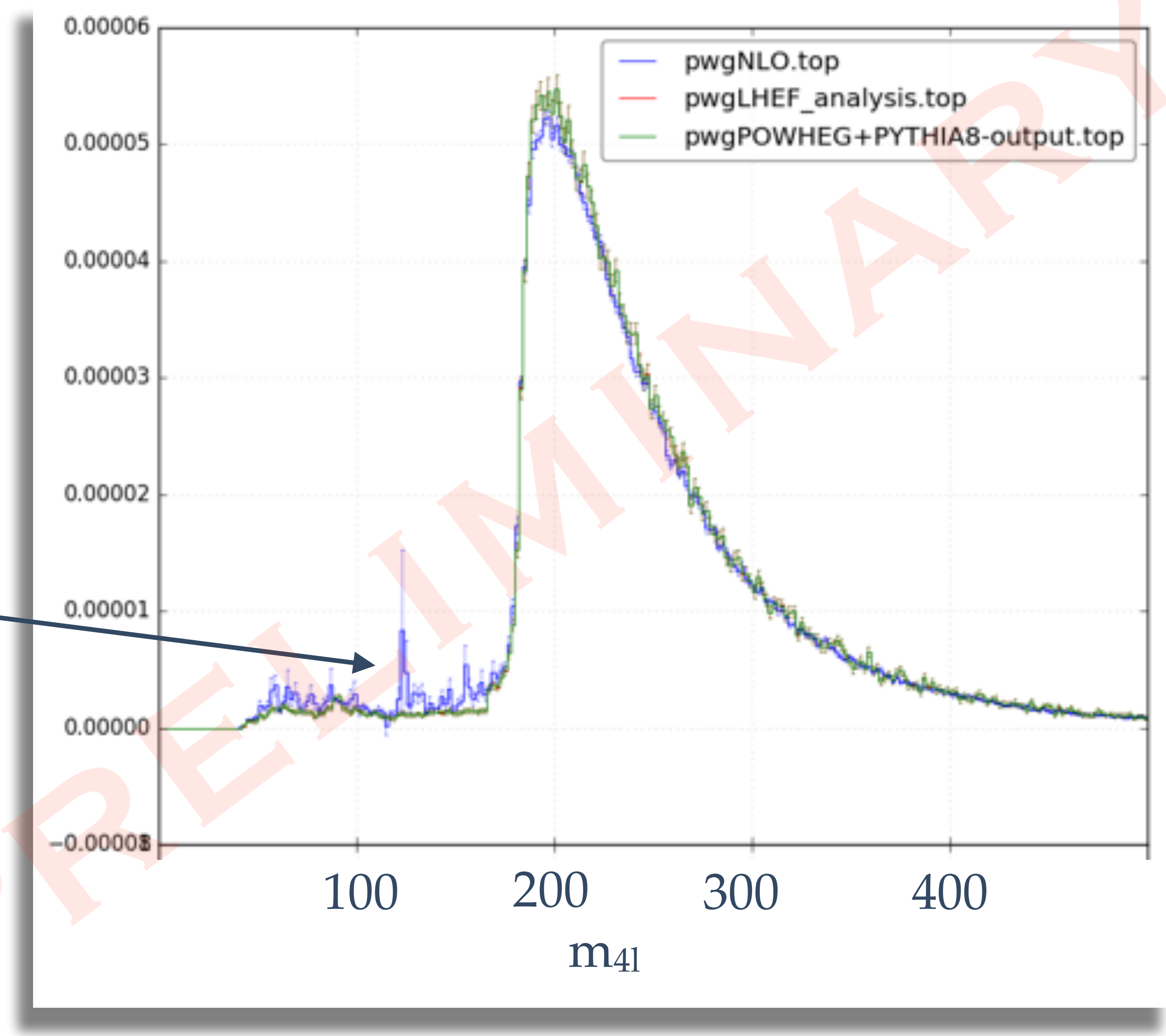
- Combining traditional techniques with new ideas inspired by more formal $\mathcal{N} = 4$ SYM studies, powerful new methods allowed to obtain amplitudes for massless quarks
  [FC, Henn, Melnikov, Smirnov, Smirnov (2015); Tancredi, v. Manteuffel, Gehrmann (2015); Tancredi, v. Manteuffel (2015); FC, Melnikov, Röntsch, Tancredi (2015)]
- For massive quarks: expand in the top mass below threshold (~ higher dim operators) [FC, Dowling, Melnikov, Röntsch, Tancredi (2016)]
- Results above top threshold still missing (although some approximations available [Campbell, Ellis, Czakon, Kirchner (2016)])
- *Full result could be obtained via brute force numerical methods?*

One step closer to reality: PS matching

[Alioli, FC, Luisoni, Röntsch et al, work in progress]



Powheg + Pythia8, background only



Z off-shellness and $Z\gamma^*$ interference fully taken into account