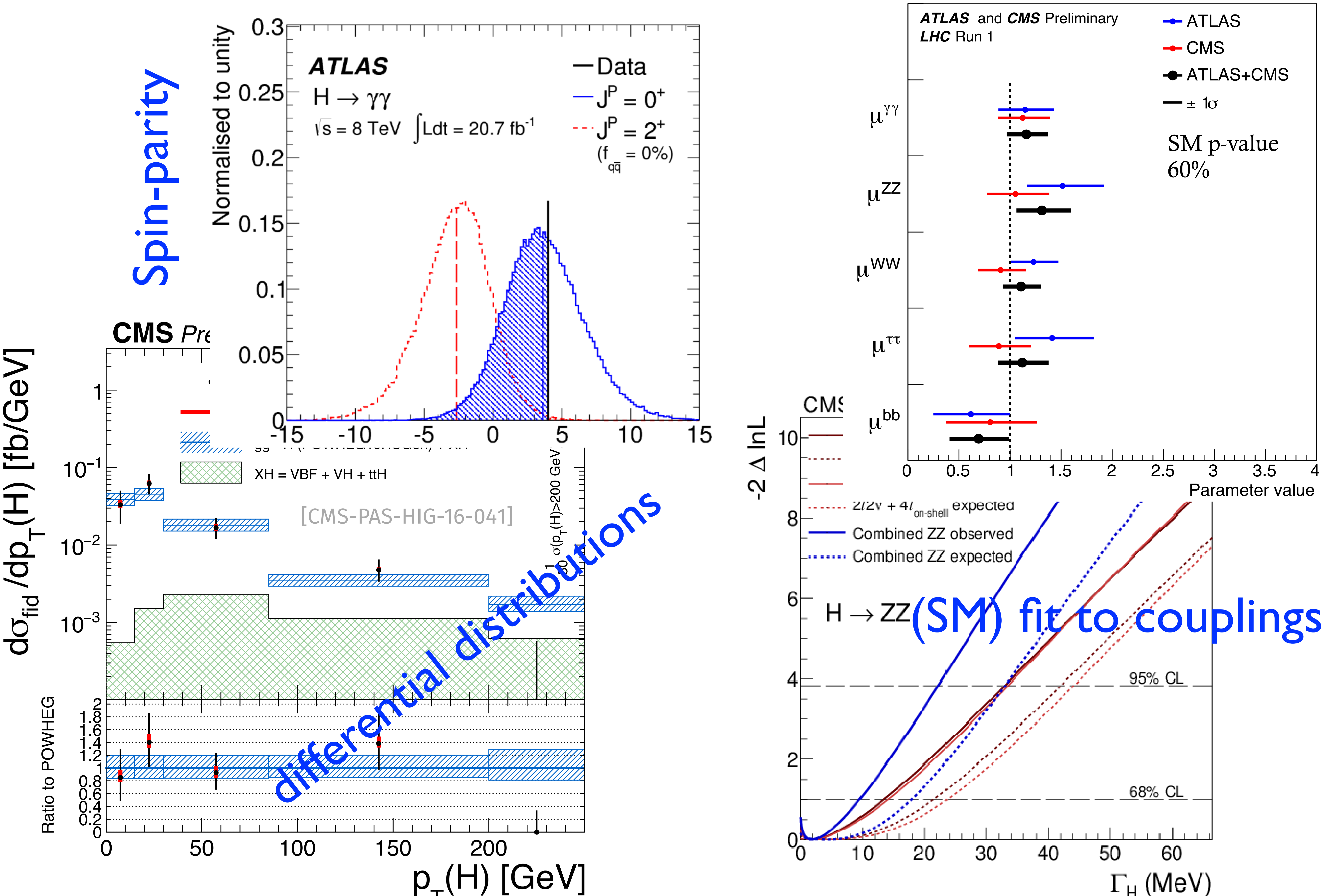
Higgs Theory

Conveners: FC, R. Harlander

Higgs ~ 2017: a lot of information



Higgs ~ 2017: a lot of information

After Run I / beginning of Run II:

- Scalar O^+ particle
- It couples to both fermions and bosons
- All main production mechanisms observed
- Mass known to 0.2% accuracy [→ implications for mass shift, Γ_H]
- Overall, good agreement ~10/20% with SM predictions

More data / Higher energy reach

- (Precise) differential distributions are coming in
- Access to tails of distributions (boosted $H \to bb$, $p_{t,H} > 450$ GeV)

SM Higgs redux

In the SM

- the Higgs is a neutral spin 0 particle ✔
- couplings to fermions ∝ masses ✔
- couplings to W/Z ∝ masses squared ✔
- couplings to photons/gluons loop-induced
- HHH coupling ∝ m_H^2

And beyond…

- in a ``typical'' BSM theory, this is no longer true
- in a ``natural'' BSM theory, expect O(1) modification of Higgs properties
- *(as a bonus: in any ``non pathological'' theory where m_H is computable, if Higgs is light new light d.o.f.)*

Precision in the Higgs sector

Looking for NP in the Higgs sector: *very roughly*, NP at a scale Λ induces modifications to SM predictions $\delta O \sim Q^2/\Lambda^2$.

To probe reasonably high ~ TeV scales:

- control to few percent in the bulk of the distributions ($Q \sim m_H$)
- control to ~10/20% (or better) in the tails (boosted/off-shell…)

While we are still far from such kind of accuracy from an exp. point of view, such accuracy is not unreasonable in the long run (Run II - HL)

We should match this on the theoretical side…

"*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: ~few percent

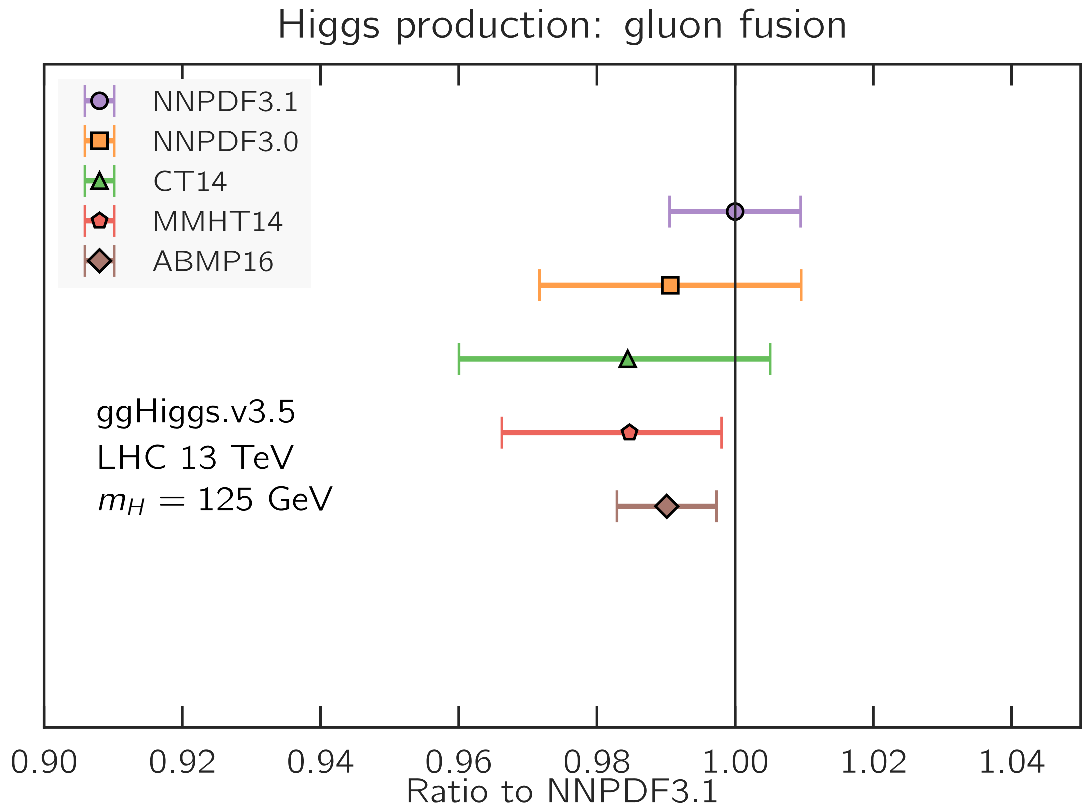
NP effects: ~ few percent
No good control/understanding of them at this level. LIMITING FACTOR FOR FUTURE DEVELOPMENT

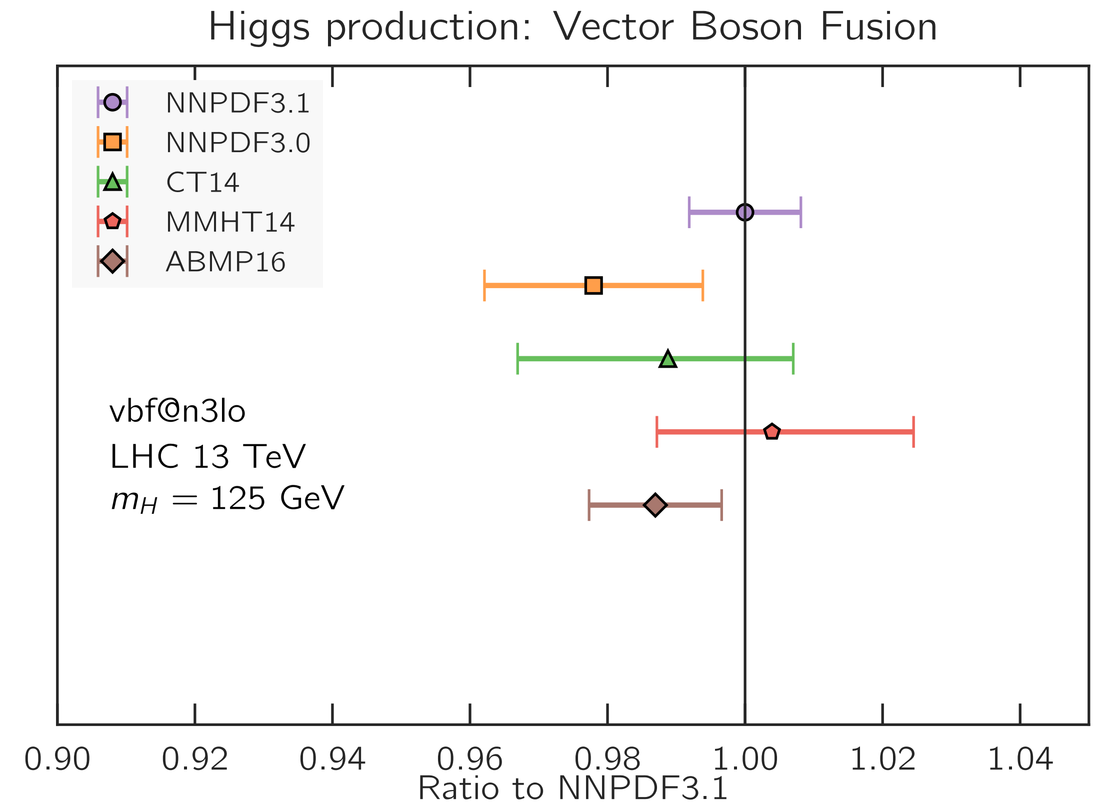
HARD SCATTERING MATRIX ELEMENT

- $\alpha_s \sim 0.1$ → For TYPICAL PROCESSES, we need Nxx for ~ 10% and NNxx for ~ 1 % accuracy. Processes with large color charges (ggF): $\alpha_s C_A \sim 0.3$ → N^3xx
- Going beyond that is neither particularly useful (exp. precision) NOR POSSIBLE GIVEN OUR CURRENT UNDERSTANDING OF QCD

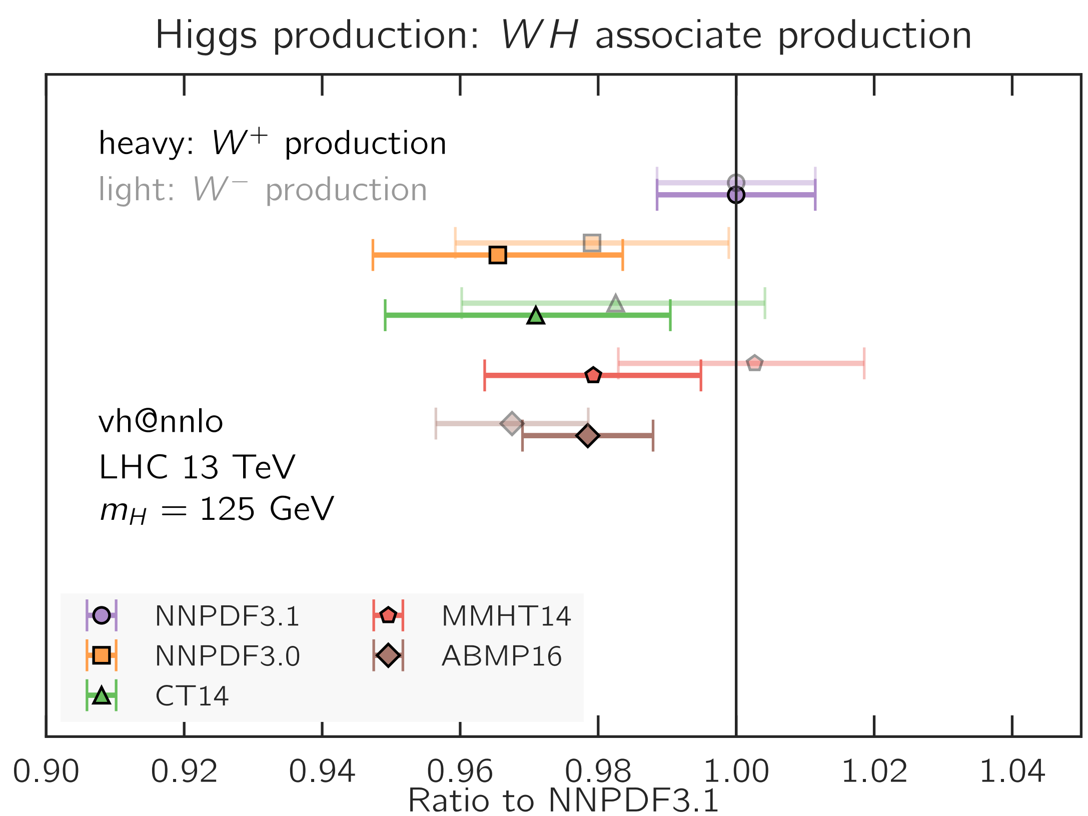
Input parameters: PDFs

Modern PDF sets, with LHC data to help constraining the gluon (top differential, Z p_t, di-jet…): substantial decrease in PDF error





arXiv: 1706.00428



- PDF error reduced to ~ percent in all main channels
- PDF sets seem consistent
- *Time for PDF community to start thinking at new source of errors (TH)?*
- *Do scale setting issues in di-jet affect this picture? How much?*

Inclusive quantities

[Cross section → S. Forte's talk; Rapidity distribution → M. Ebert's talk]

- At the few percent level, everything becomes relevant

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

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

- 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%

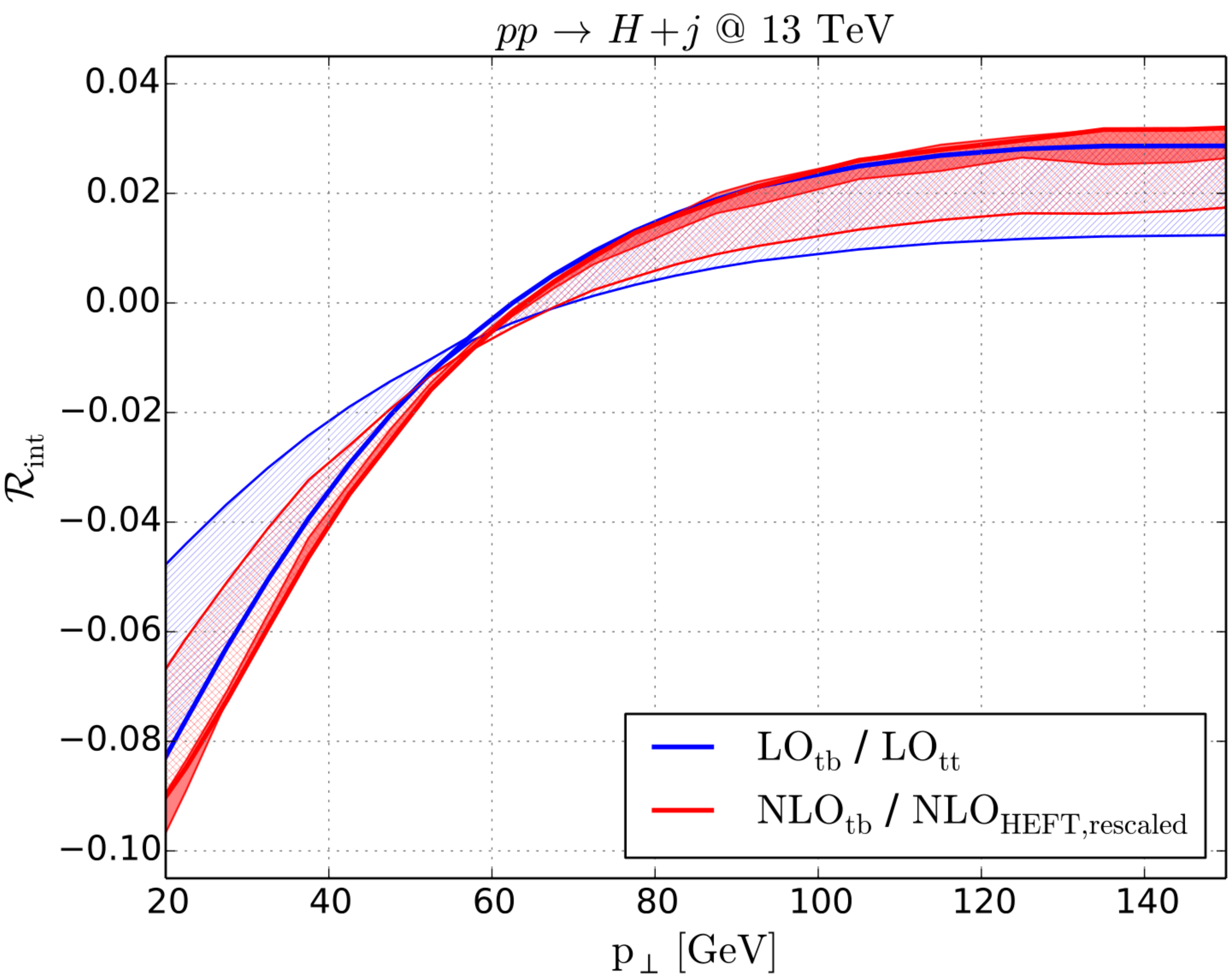
[Mistlberger, QCD@LHC2016]

- New developments: $N^3LO + N^3LL'$ $d\sigma/dy$, [Ebert, Michel, Tackmann (2017)] → *see Markus' talk*
  - Good ($N^3LO + N^3LL$) QCD control, in the HEFT approx
  - Mass (t,b) effects? → *see M. Wiesemann's talk*
  - EWxQCD?

Recent progress: b-mass effects@NLO

Largish non-Sudakov double logs $m_b^2/m_h^2\left(\log^2(m_h^2/m_b^2), \log^2(p_\perp^2/m_b^2)\right) \sim 10^{-1}$

[Lindert, Melnikov, Tancredi, Wever (2017)]



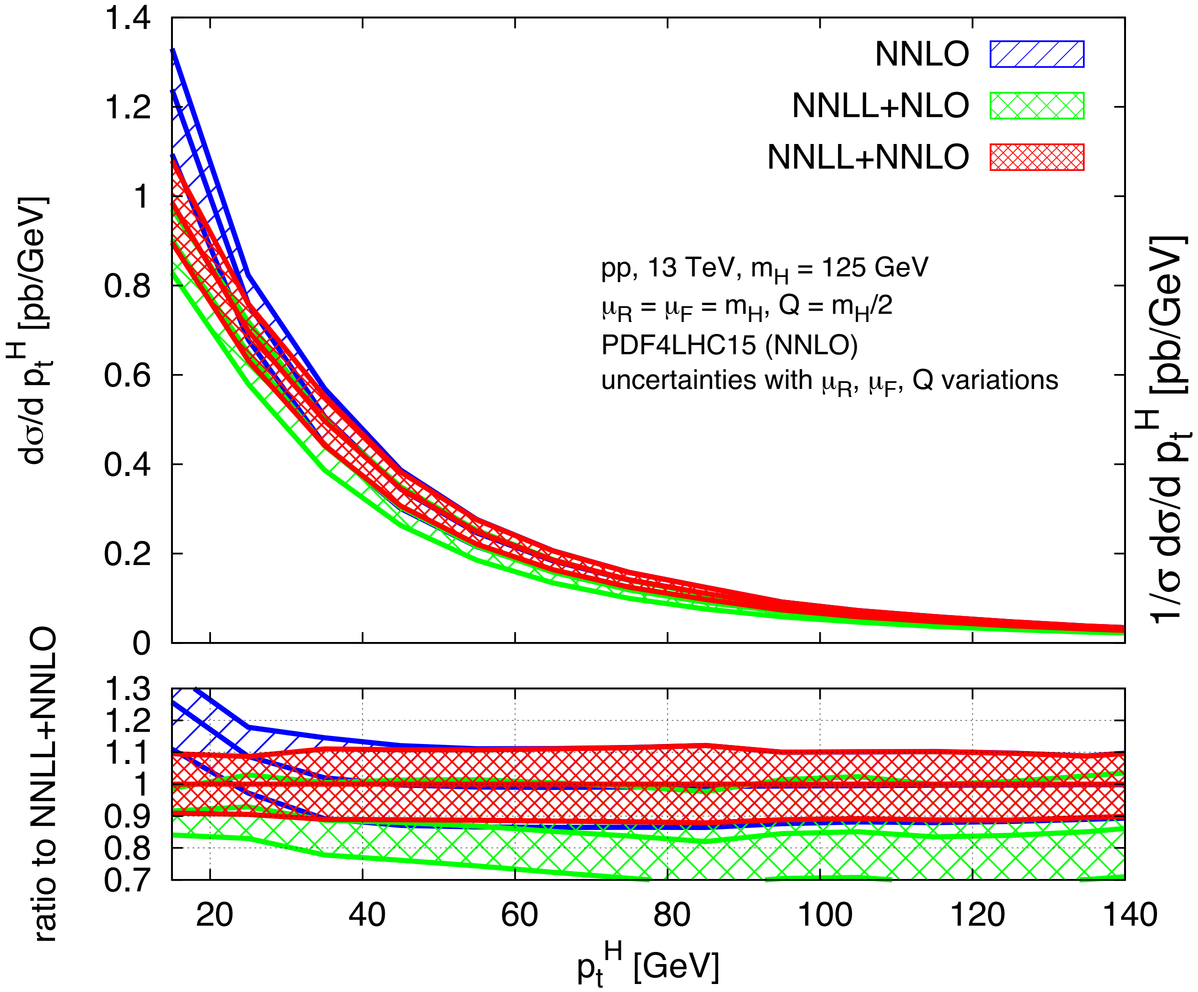
- Large corrections to tb interference, ~ to HEFT K-factor
- Logs do not seem to exponentiate, but not so big that resummation is necessary

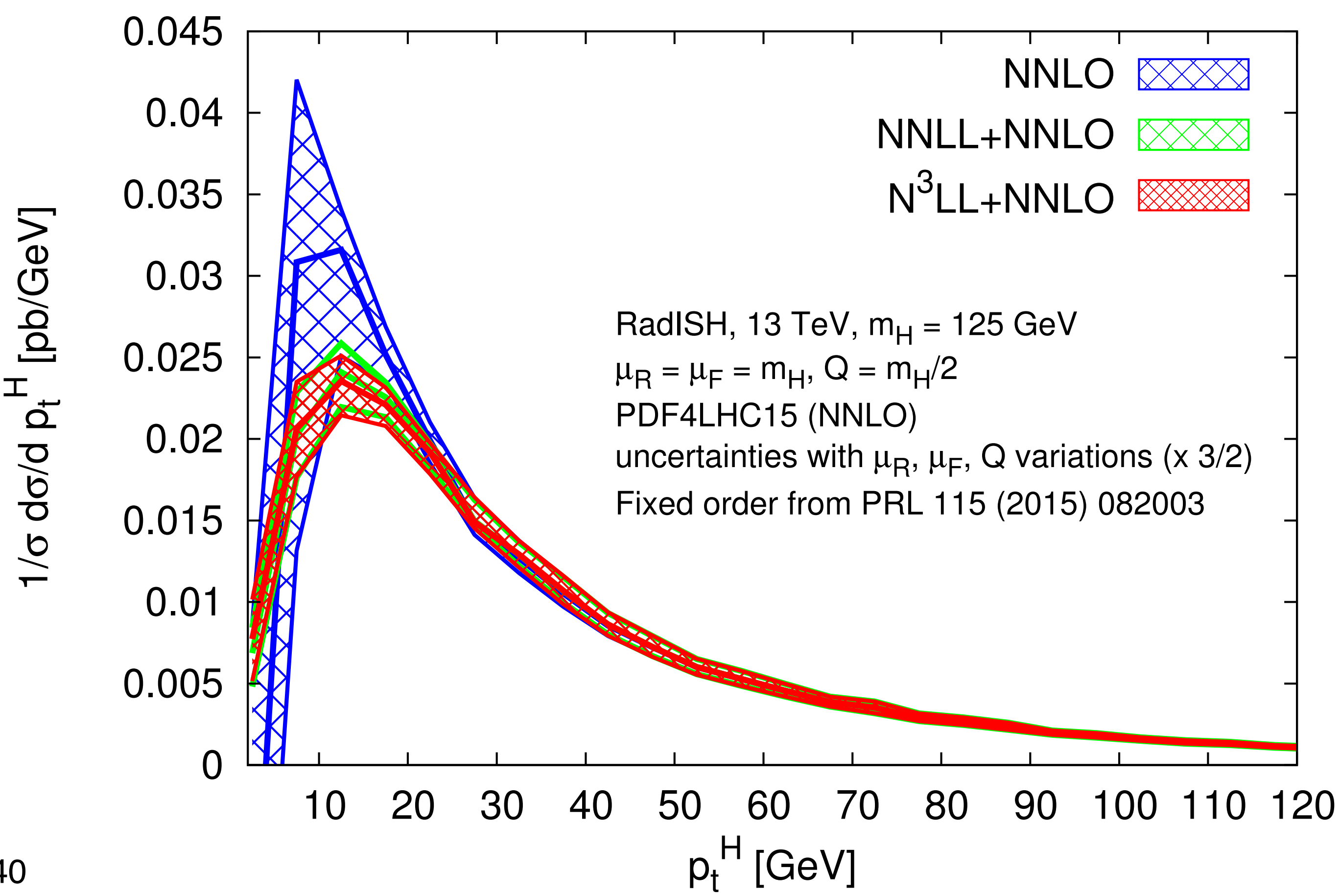
- *Best prediction for $p_{t,H}$ at small p_T? Interplay with p_t resummation…*
- *Best way to include these effects, e.g. for NNLOPS…*

Recent progress: the Higgs p_t spectrum

[Talks by C. Muselli and L. Rottoli, M. Wiesemann for EFT]

NNLO prediction at high p_t matched to N^3LL resummation, HEFT

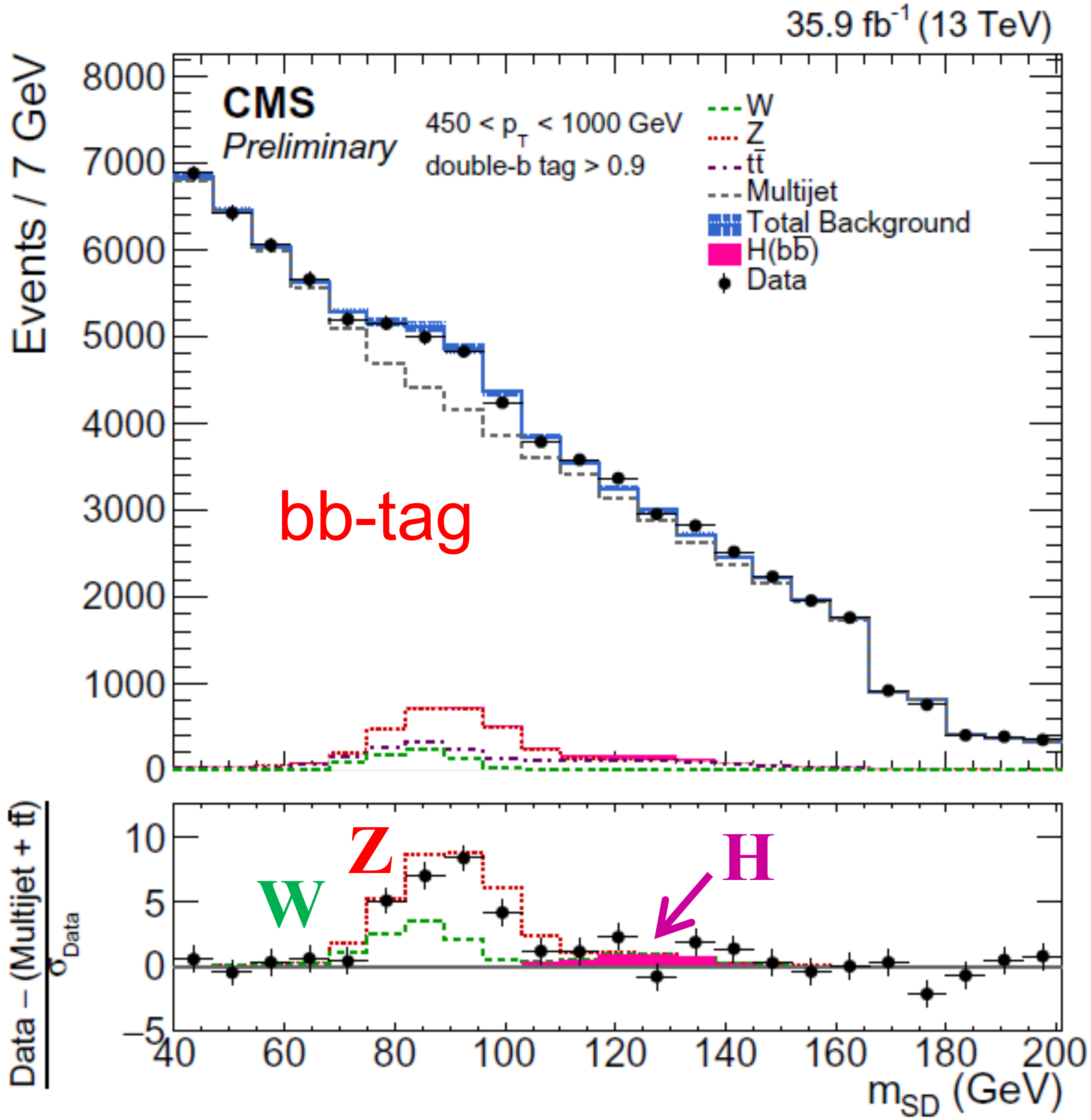




[Bizon, Monni, Re, Rottoli, Torrielli (2017)]

- Perturbative results very stable (resummation effects: 25% at p_T = 15 GeV, ~0% at p_T = 40 GeV). Similar pattern for jet veto (and Z p_t)
- Significant reduction of perturbative uncertainties from NLO+NNLL to NNLO+NNLL. *Addition of N^3LL effects does not lead to substantial error decrease. Is this understood? How do these predictions compare to e.g. NNLOPS?*

Exploring the tails: boosted Higgs



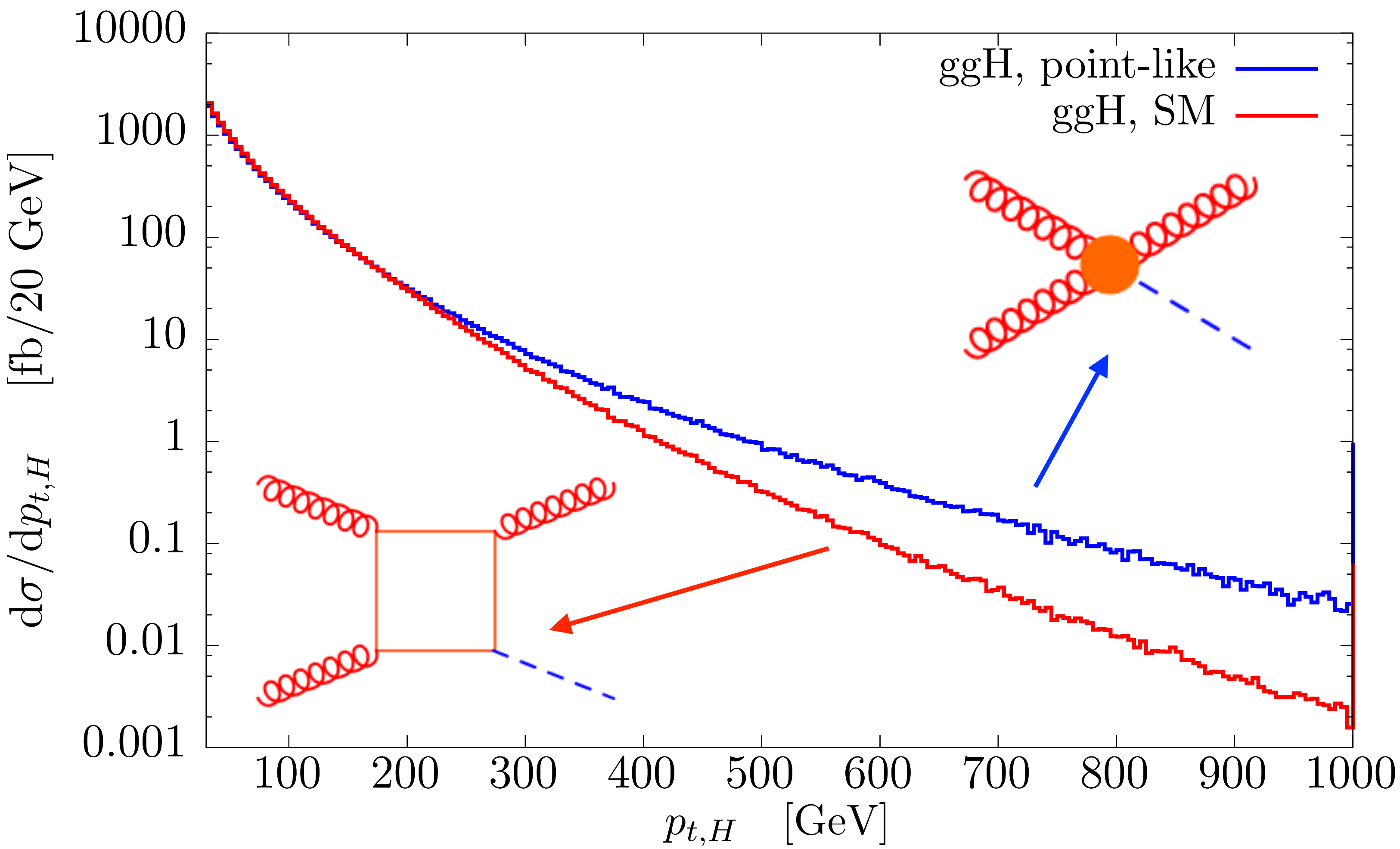
CMS-PAS-HIG-17-010

- Very recent CMS analysis for boosted H→bb
- Very nice result for boosted Z, robust analysis
- Jet substructure…

[Discussion about it on Saturday]

- ACCESS TO THE HIGH-P_T HIGGS SEEMS FEASIBLE

Boosted Higgs: theoretical picture



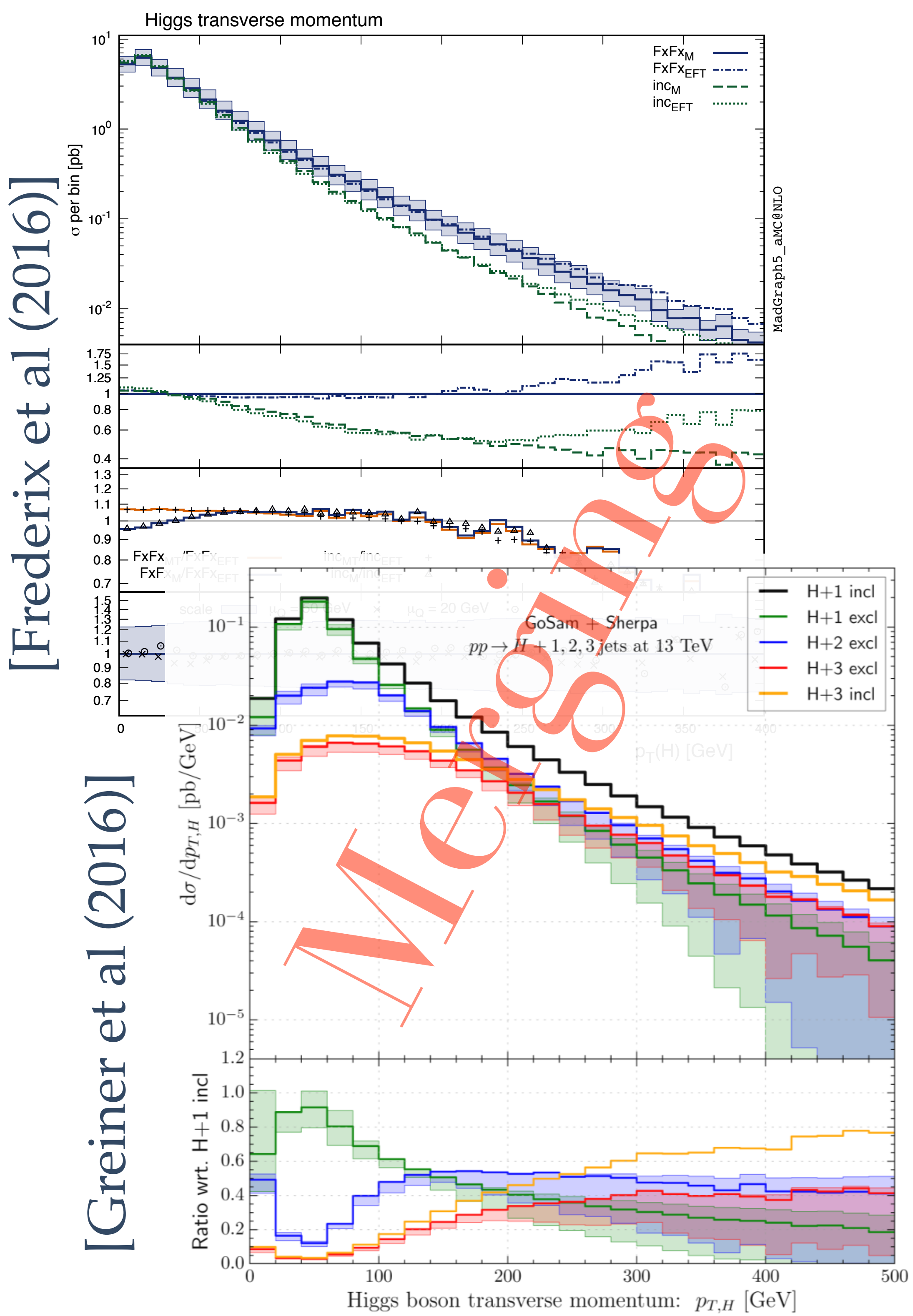
σ_{gg} ($p_t > p_{t,cut}$) =	1 fb	1 ab
bb	$p_{t,cut}$ ~ 600 GeV	$p_{t,cut}$ ~ 1.5 TeV
ττ	~ 400 GeV	~ 1.2 TeV
2l2ν	~ 300 GeV	~ 1 TeV
γγ	~ 200 GeV	~ 750 GeV
4l	~ 50 GeV	~ 450 GeV

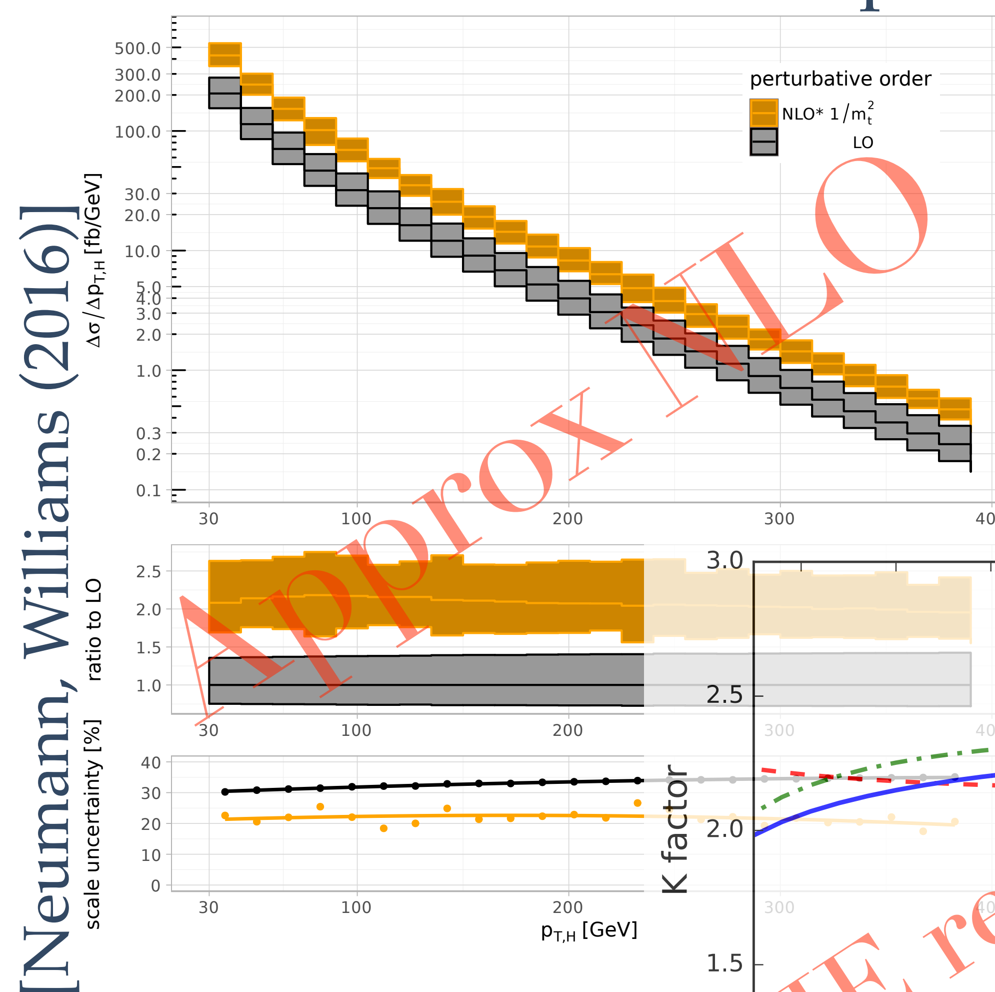
- Rates are low, but not insignificant
- Very sensitive to anomalous ggH coupling
- Can help resolving flat directions in ggH, ttH couplings
- UNFORTUNATELY, WE ONLY KNOW IT AT LO
- NLO would require complicated 2-loop amplitudes, currently under investigation → *J. Henn*

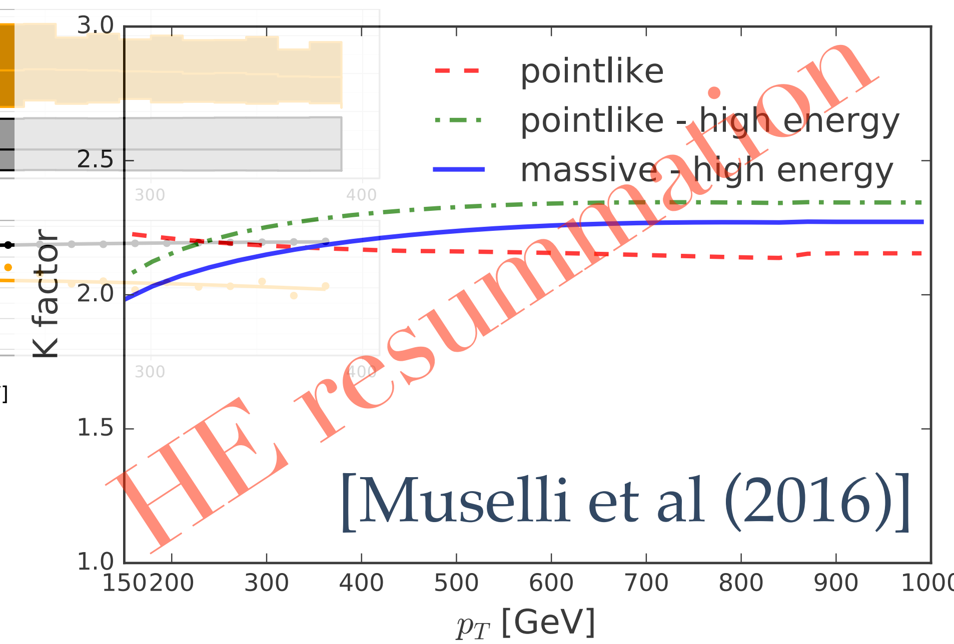
Boosted Higgs: what can we say

[Talks by C. Muselli and L. Rottoli]

At high p_t, real emission dominance. Can use this to improve description





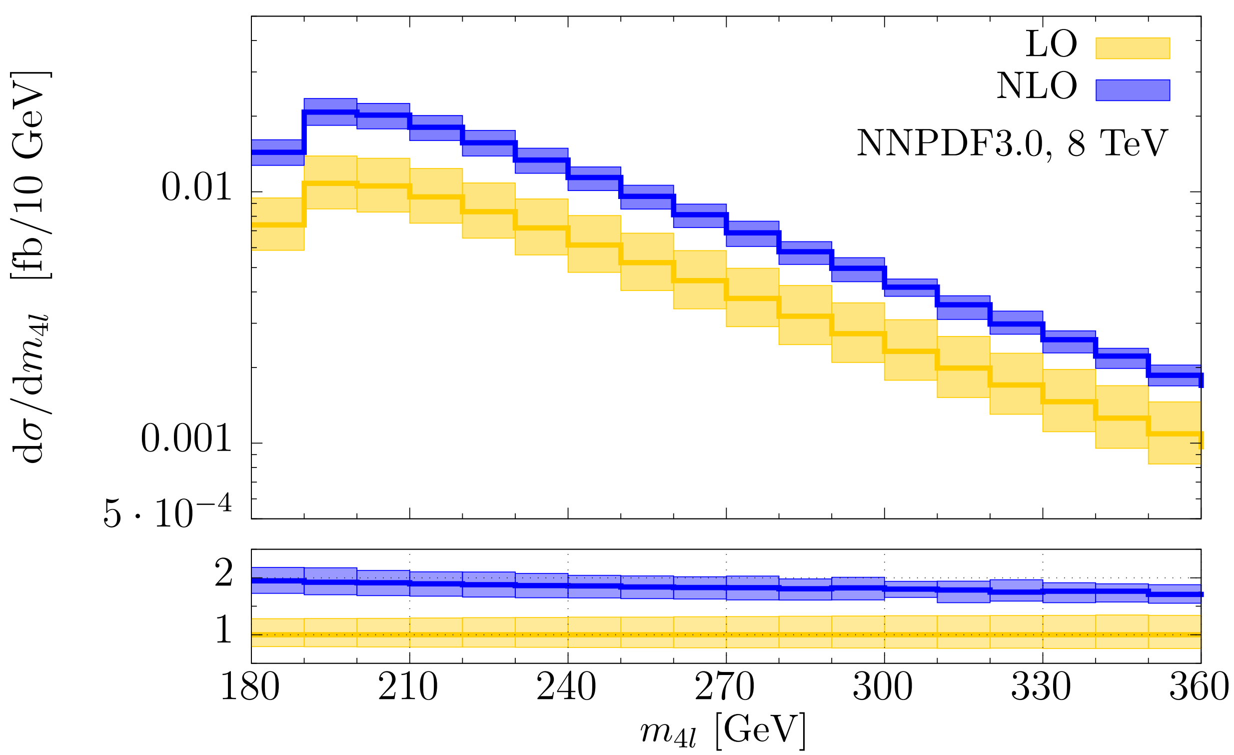


Very different methods obtain qualitatively similar result ($K_{full} \sim K_{HEFT}$). Can we be more quantitative? Detailed comparisons?

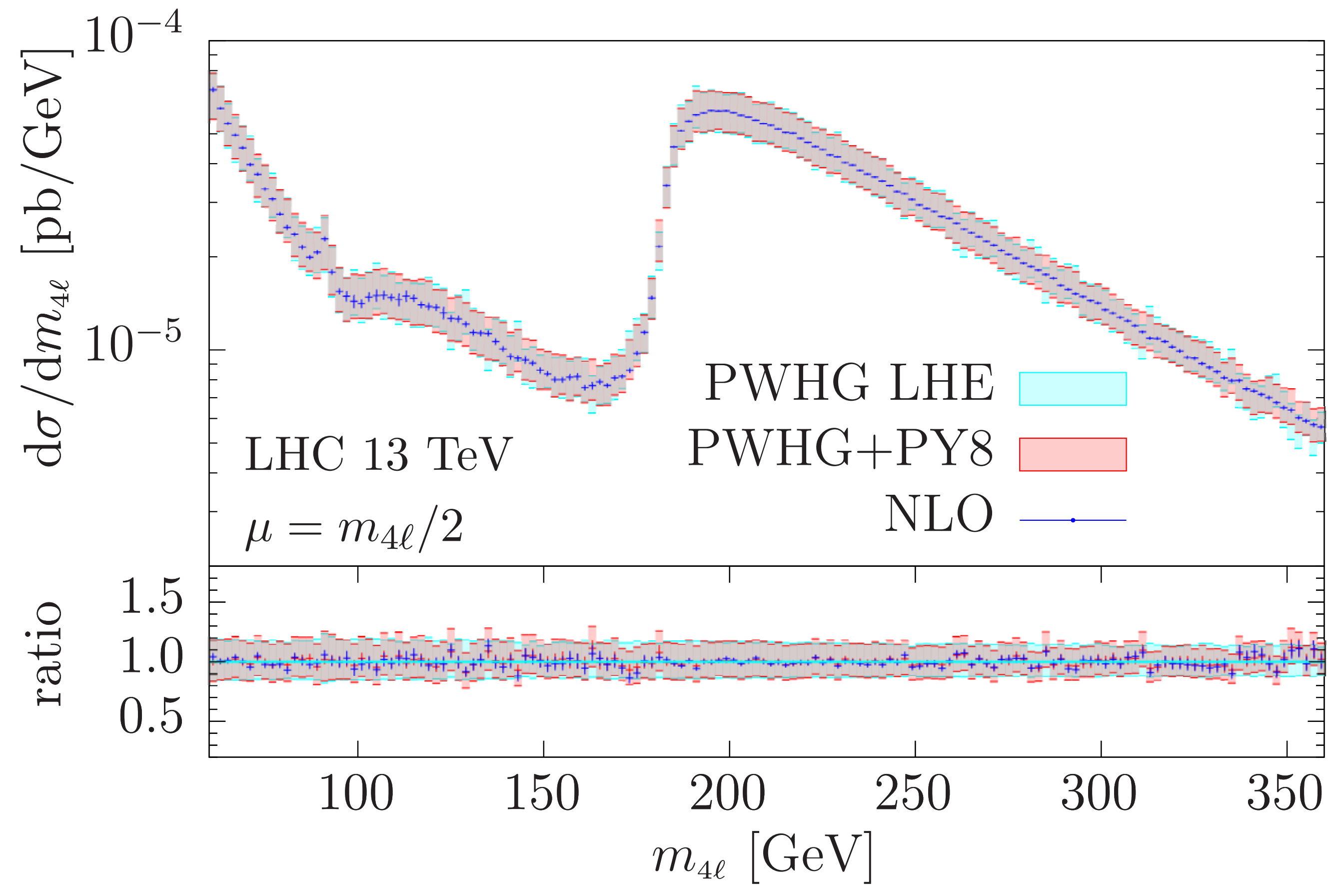
Another tail: off-shell Higgs

[Talk by N. Kauer]

Recent result: signal H→VV, bkd gg→VV and interference @NLO.
Background@NLOPS



[FC, Melnikov, Röntsch, Tancredi (2015)]

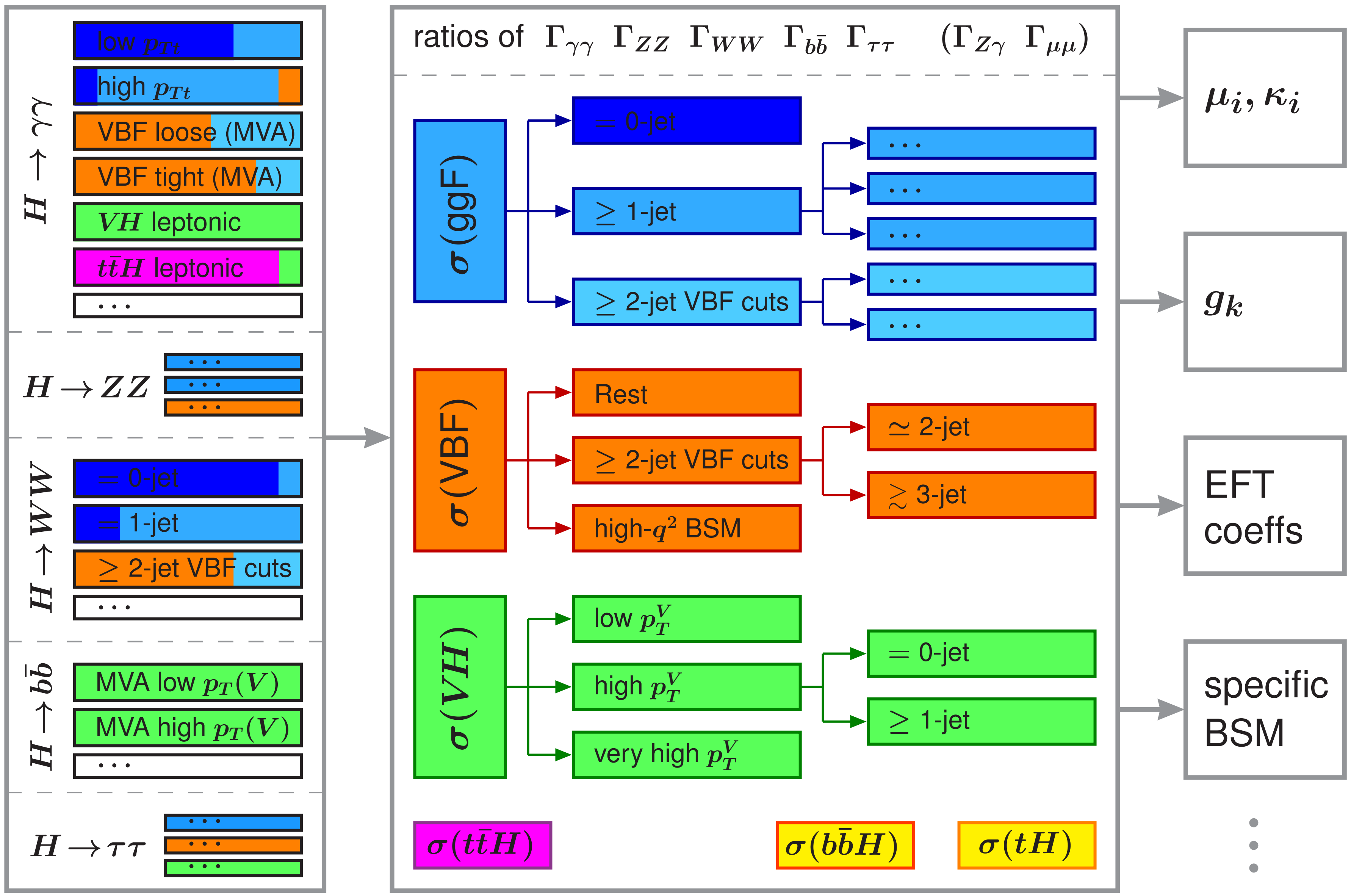


[Alioli, FC, Luisoni, Röntsch (2016)]

- *NLOPS vs merged LOPS comparisons*
- *qg effects@NLO*
- *Moving past the top threshold [see e.g. Czakon et al (2016)]*
- *EW corrections?*

Going differential: fiducial, STXS, jets…

[several talks in the next days]

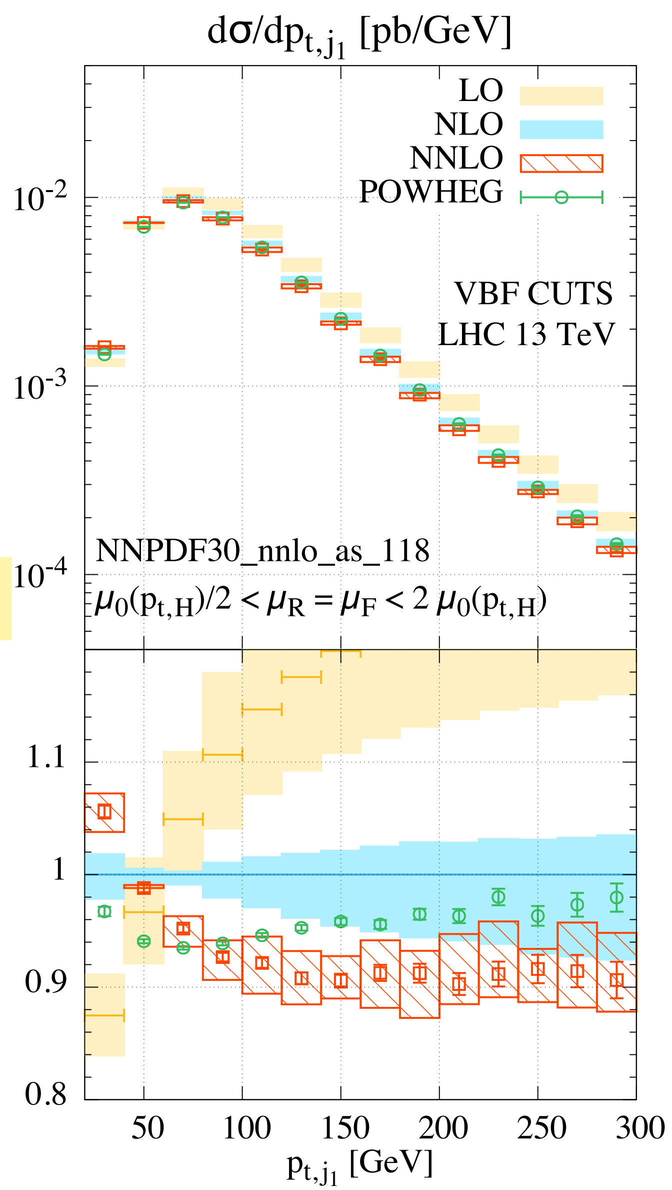


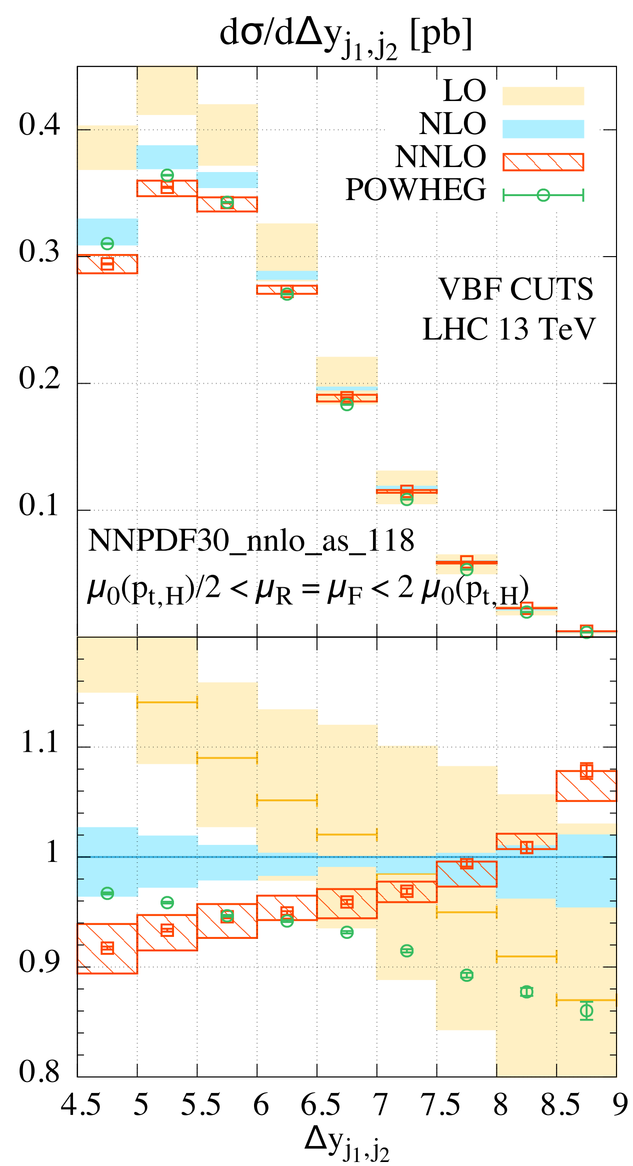
- *Model dependence of the acceptances*
- *Best tools for acceptances, errors, correlations…*
- *NNLOPS seems to work remarkably well, also when it is not supposed to (e.g. H+3j@NLO…). Further studies?*

Other channels: VBF

[Talk by F. Dreyer]

Inclusive rate known to N^{3}LO [Dreyer, Karlberg (2016)]. Moderate corrections



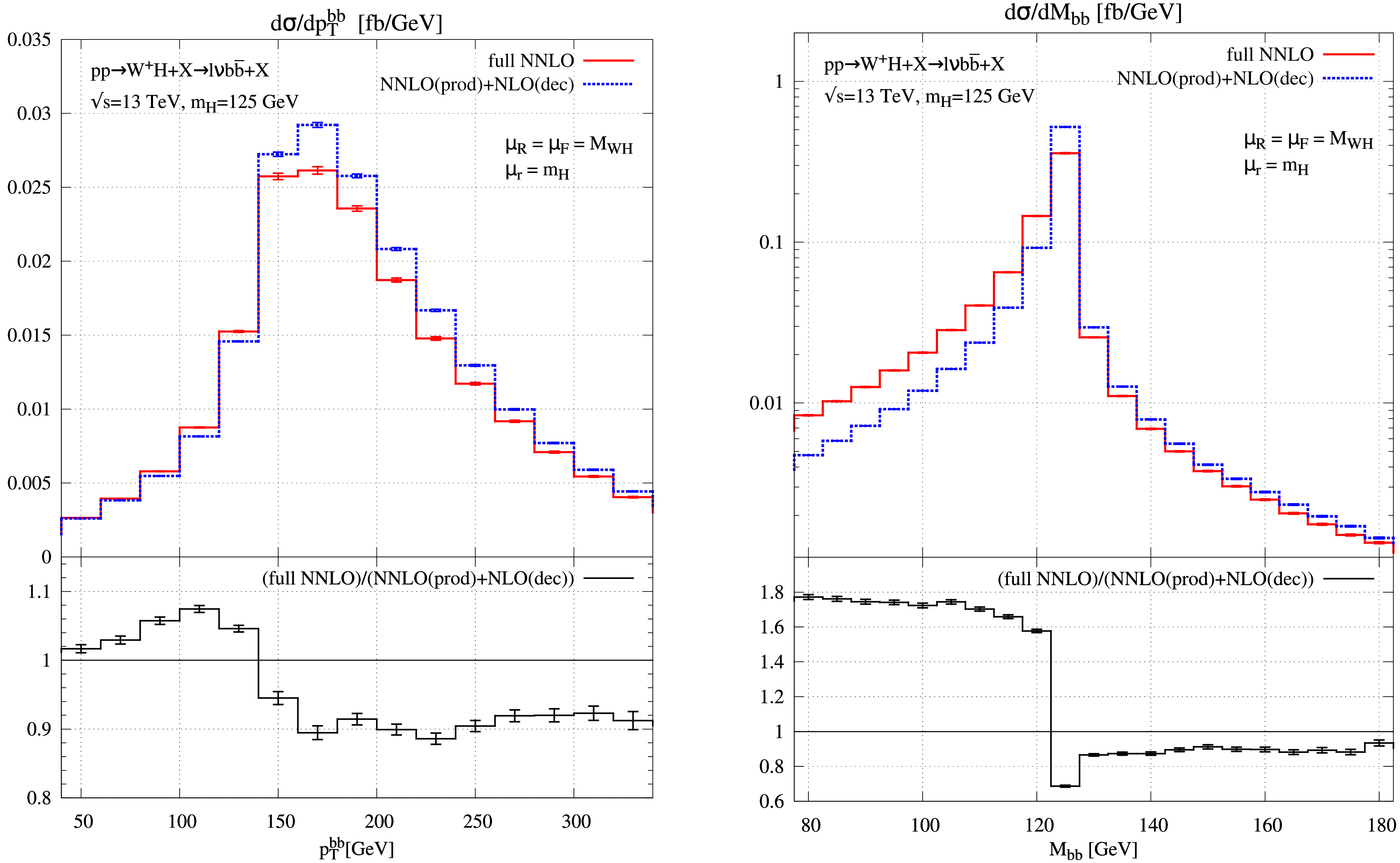


- Large corrections in the VBF fiducial region [Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2016)]
- Not always captured by PS. Most striking example: Δy_{jj}
- Partially understood as non-trivial jet dynamics [Rauch, Zeppenfeld (2017)]

- *Are these observables under control? More PS comparisons?*
- *To which extent do we control non-factorizable effects?*
- *ggF contamination to VBF? (→ Andersen et al, arXiv: 1706.01002)*

Other channels: VH

Recent results: NNLO production x NNLO decay, massless *b*



[Ferrera, Somogyi, Tramontano (2017)]

- *Large effect of NNLO decay (gluon radiation)*
- *Massless vs massive decays*
- *Unrelated: gg→HZ@NLO with full m_t dependence (e.g. with HH technology?)*

Other channels: ttH

- Known to NLOQCD (+NNLL) + NLOEW, including off-shellness and interference
- Fiducial cuts enhance tails → NLOEW
- $d\sigma \propto y_t^2$ no longer true @NLOEW

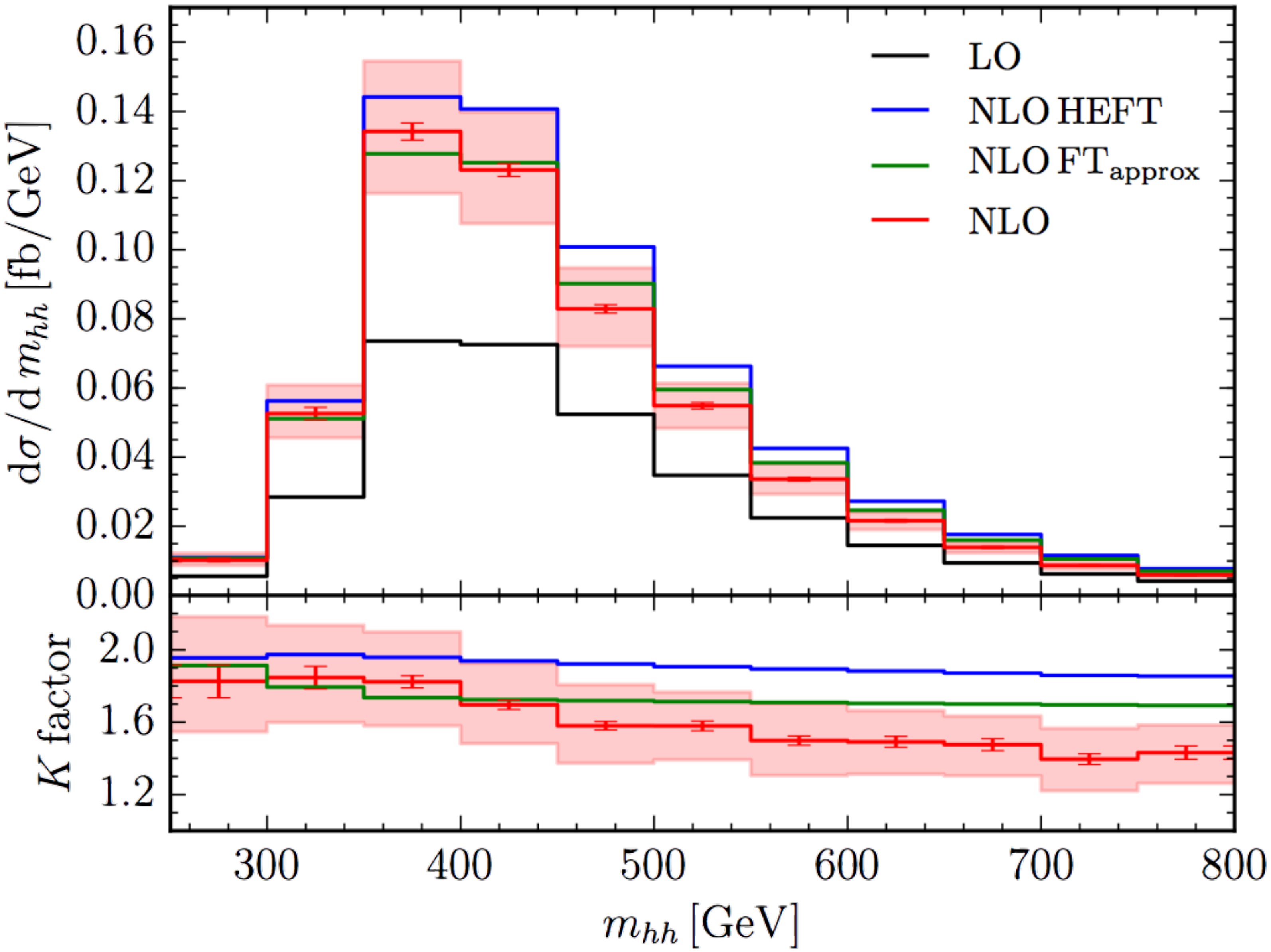
- Proper description of background problematic. Most famous example: ttbb

Selection	Tool	σ_{NLO} [fb]	$\sigma_{\mathrm{NLO+PS}}$ [fb]	$\sigma_{\mathrm{NLO+PS}}/\sigma_{\mathrm{NLO}}$
$n_b \geq 1$	SHERPA+OPENLOOPS	$12820^{+35\%}_{-28\%}$	$12939^{+30\%}_{-27\%}$	1.01
	MADGRAPH5_AMC@NLO		$13833^{+37\%}_{-29\%}$	1.08
	POWHEL		$10073^{+45\%}_{-29\%}$	0.79
$n_b \geq 2$	SHERPA+OPENLOOPS	$2268^{+30\%}_{-27\%}$	$2413^{+21\%}_{-24\%}$	1.06
	MADGRAPH5_AMC@NLO		$3192^{+38\%}_{-29\%}$	1.41
	POWHEL		$2570^{+35\%}_{-28\%}$	1.13

- Shower effects enhanced in the Higgs region…

Beyond single H: di-Higgs

- Full NLO result, with exact top mass dependence [Borowka et al (2016)]
- NNLO in the $m_t \rightarrow$ limit [de Florian et al (2016)]



- 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

- *Can we understand why approx fail (e.g. large box/triangle cancellations?)*
- *Best way to include NNLO$_{HEFT}$?*
- *Use this technology for other processes, and gain extra information?*

Final remarks

- A lot of progress for Higgs sector predictions. Many new results from last LH
- Still, many issues still need to be solved / investigated
- According to interests / expertise of the participants, try to tackle some of them
- Ideally, coordination with LHCHXSWG and CERN Theory Institute

ENJOY LES HOUCHES!