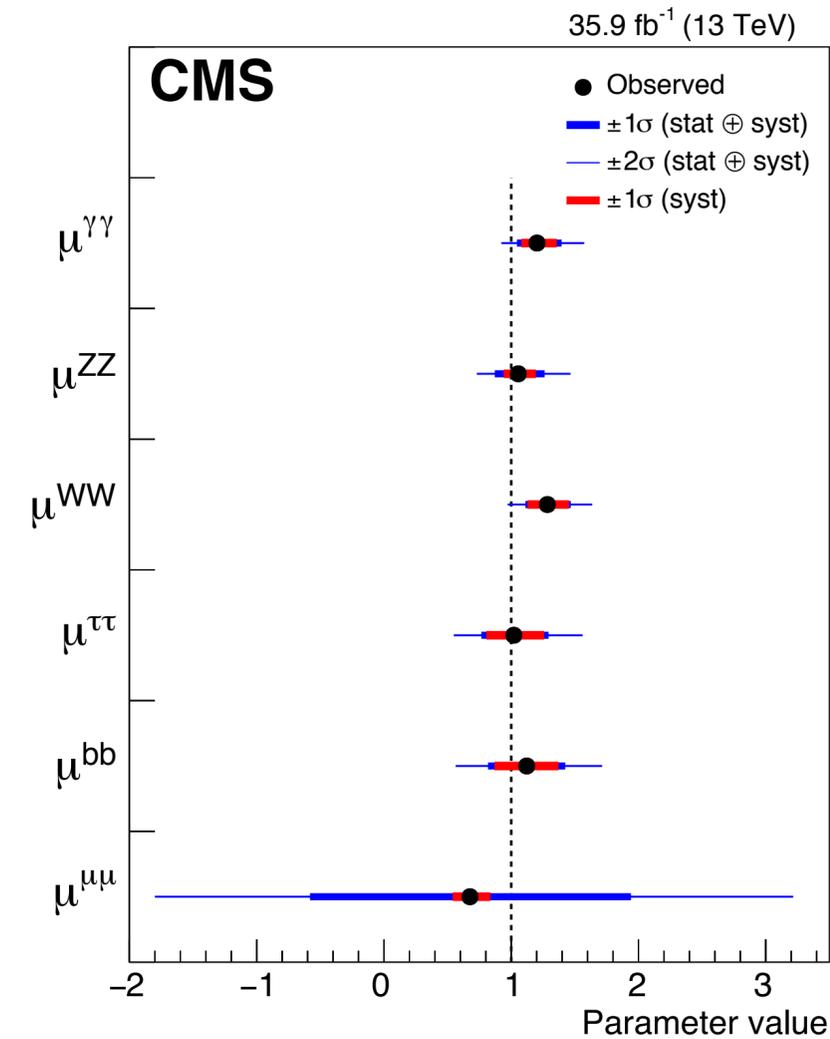
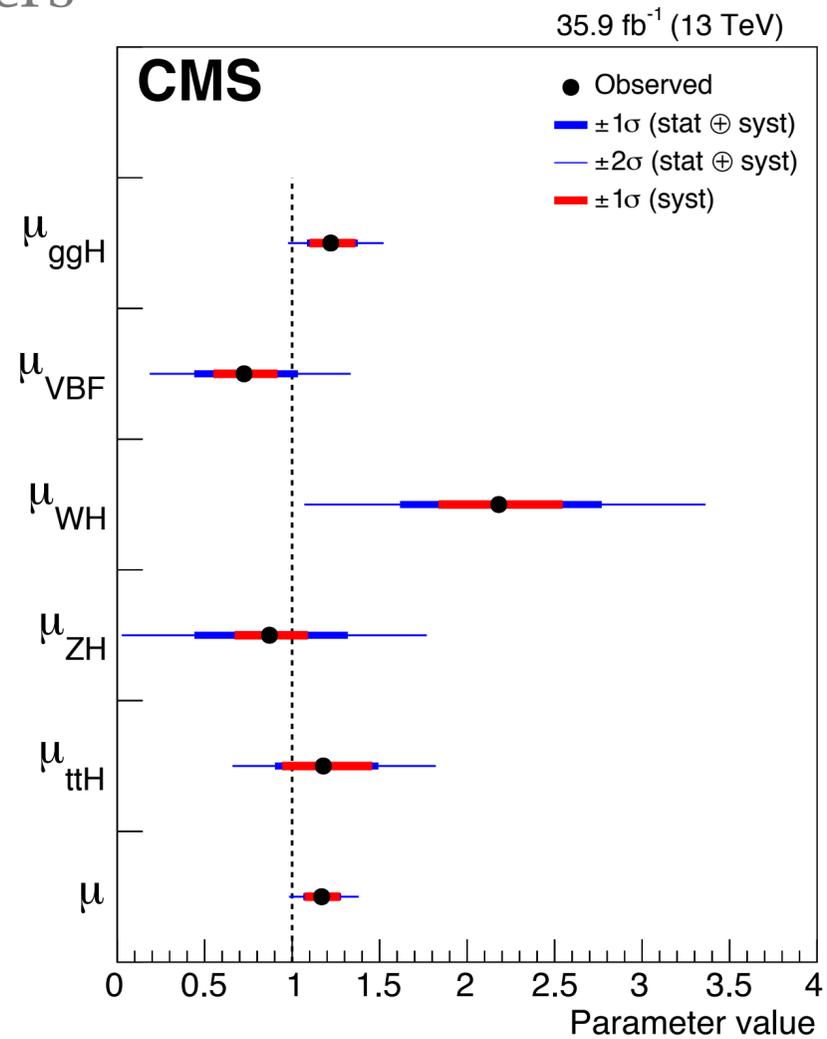
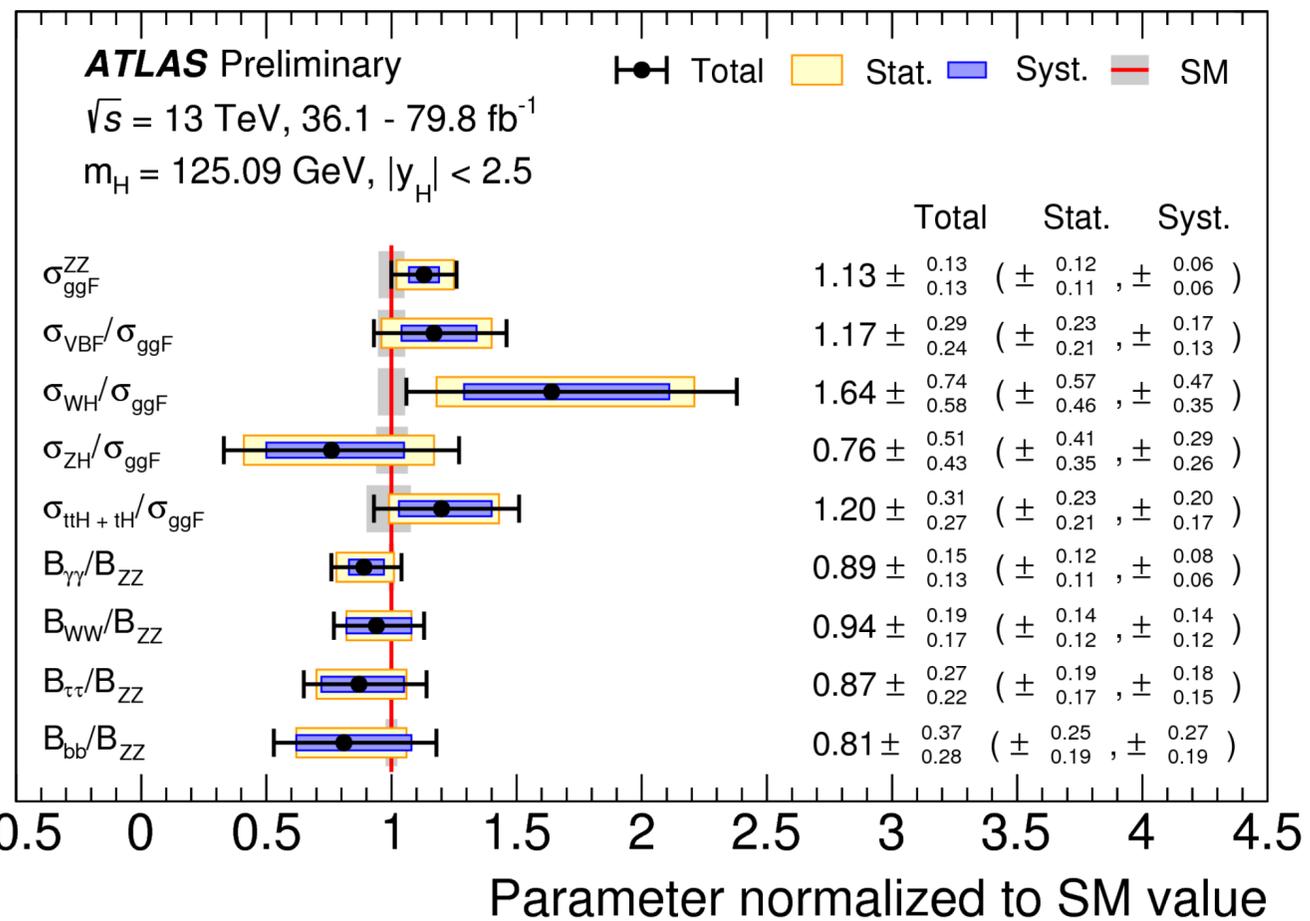


Recent progress in gluon fusion modelling

Pier Monni
CERN

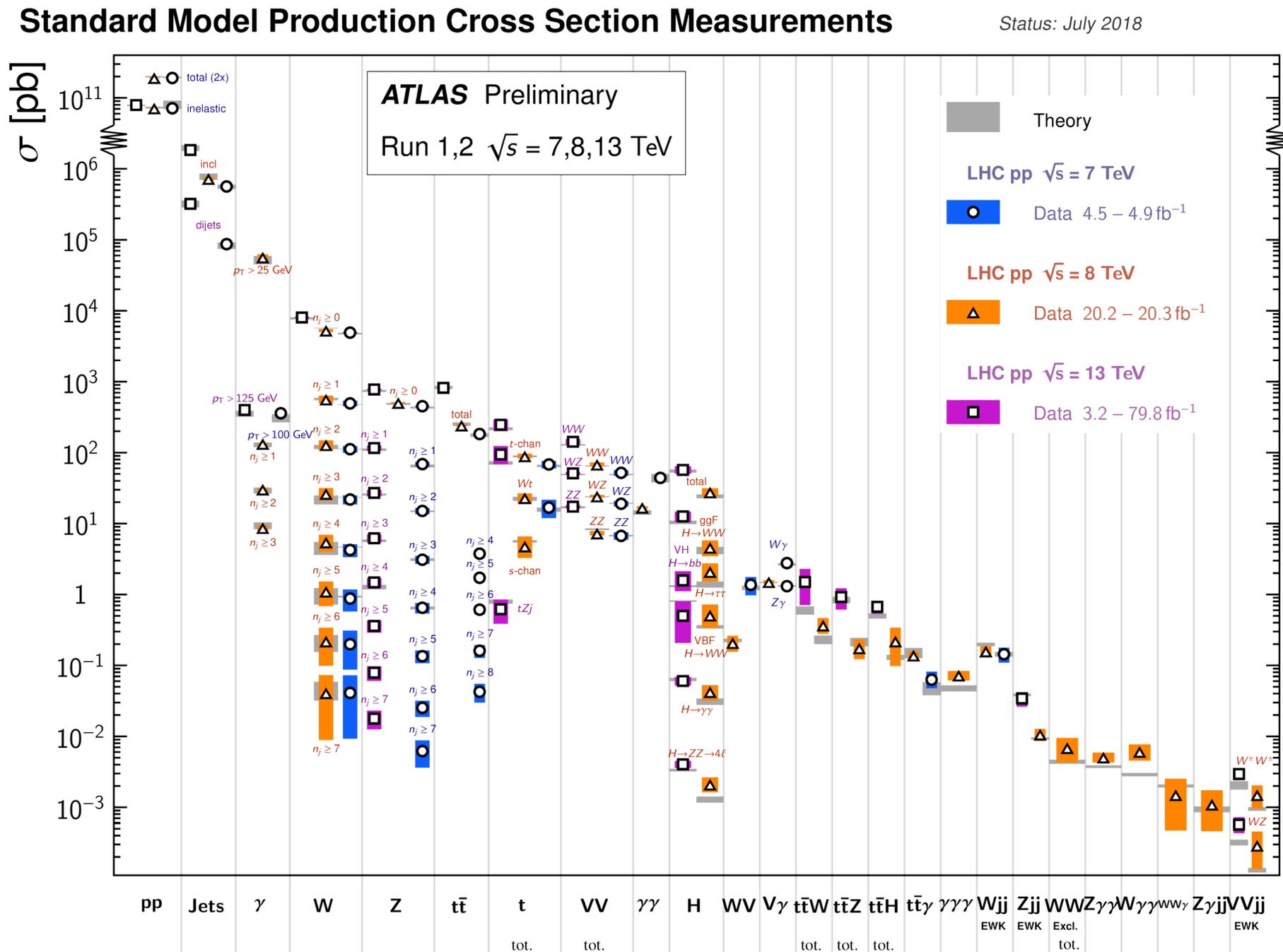
Higgs Physics at the LHC

- ▶ So far essentially all measurements are consistent with the SM. Future programme is twofold:
 - ▶ Measure precisely the known Higgs parameters
 - ▶ Constrain less established parts of the Higgs sector



Higgs Physics at the LHC

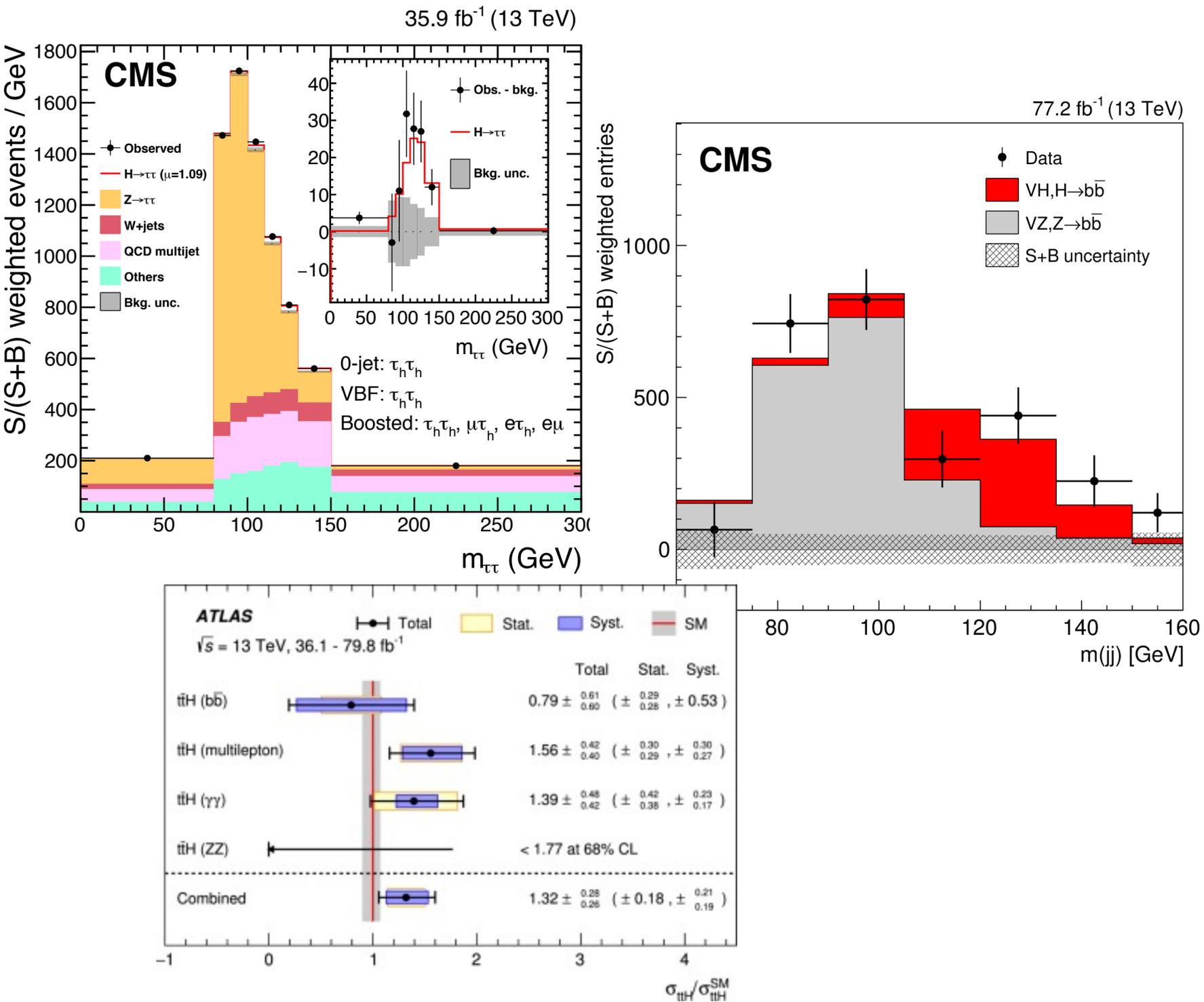
- ▶ Higgs sector still poorly established experimentally



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Higgs Physics at the LHC

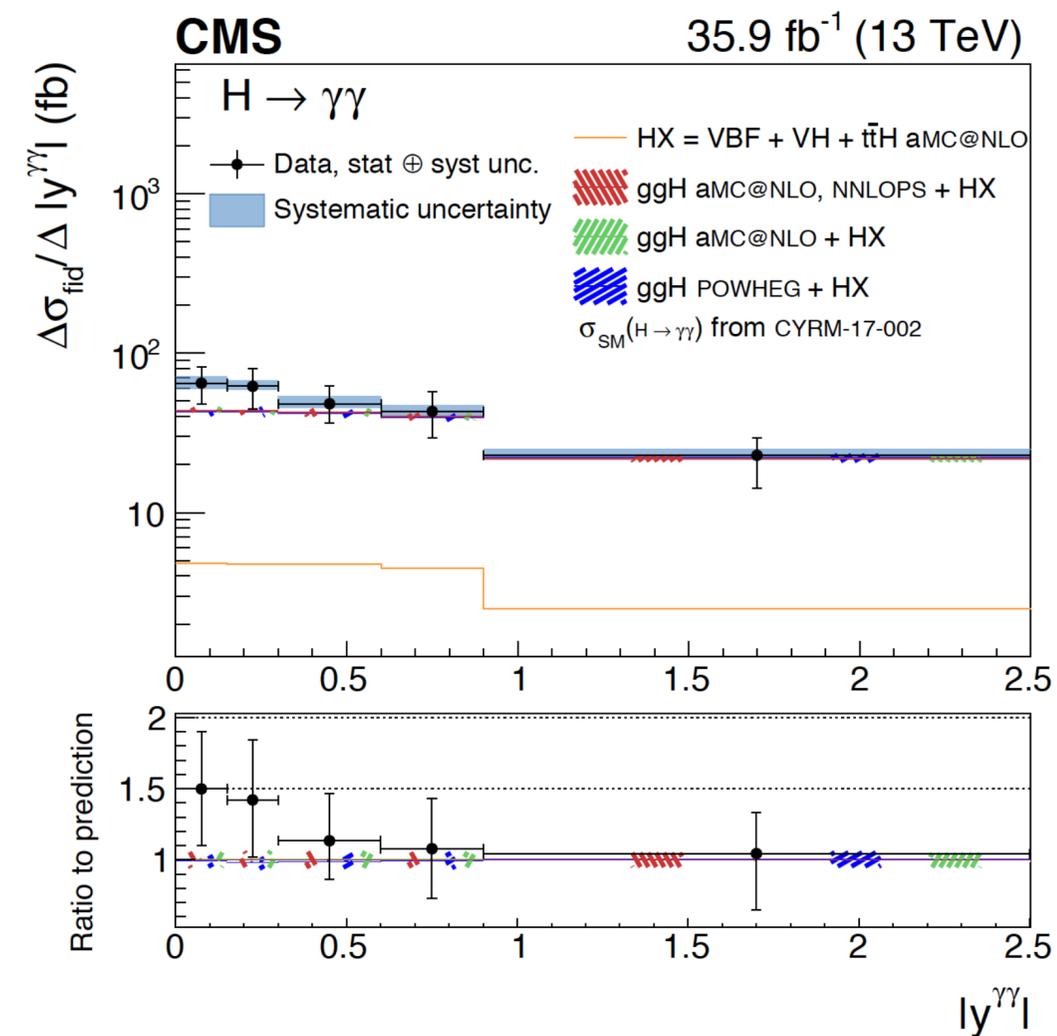
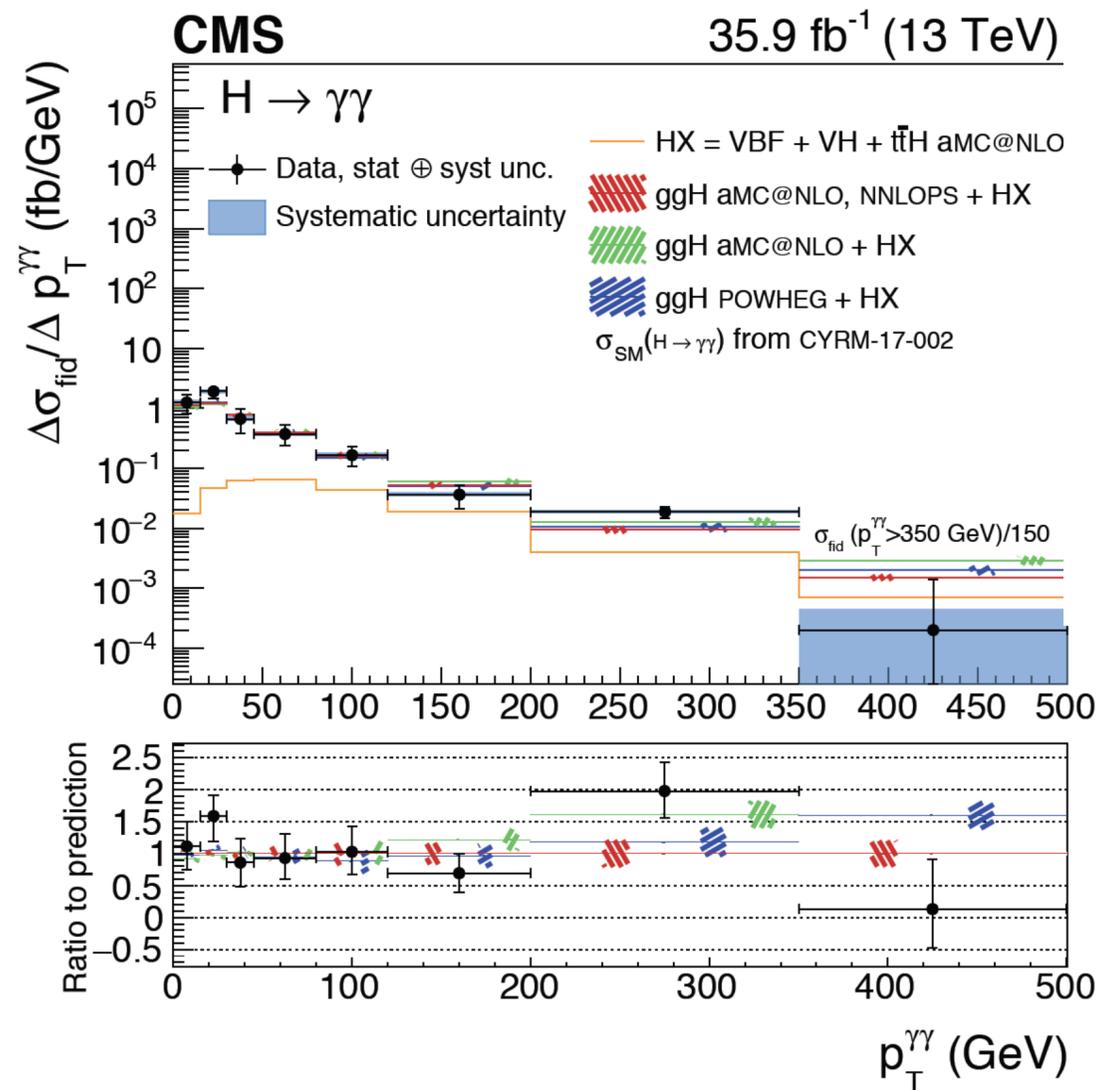
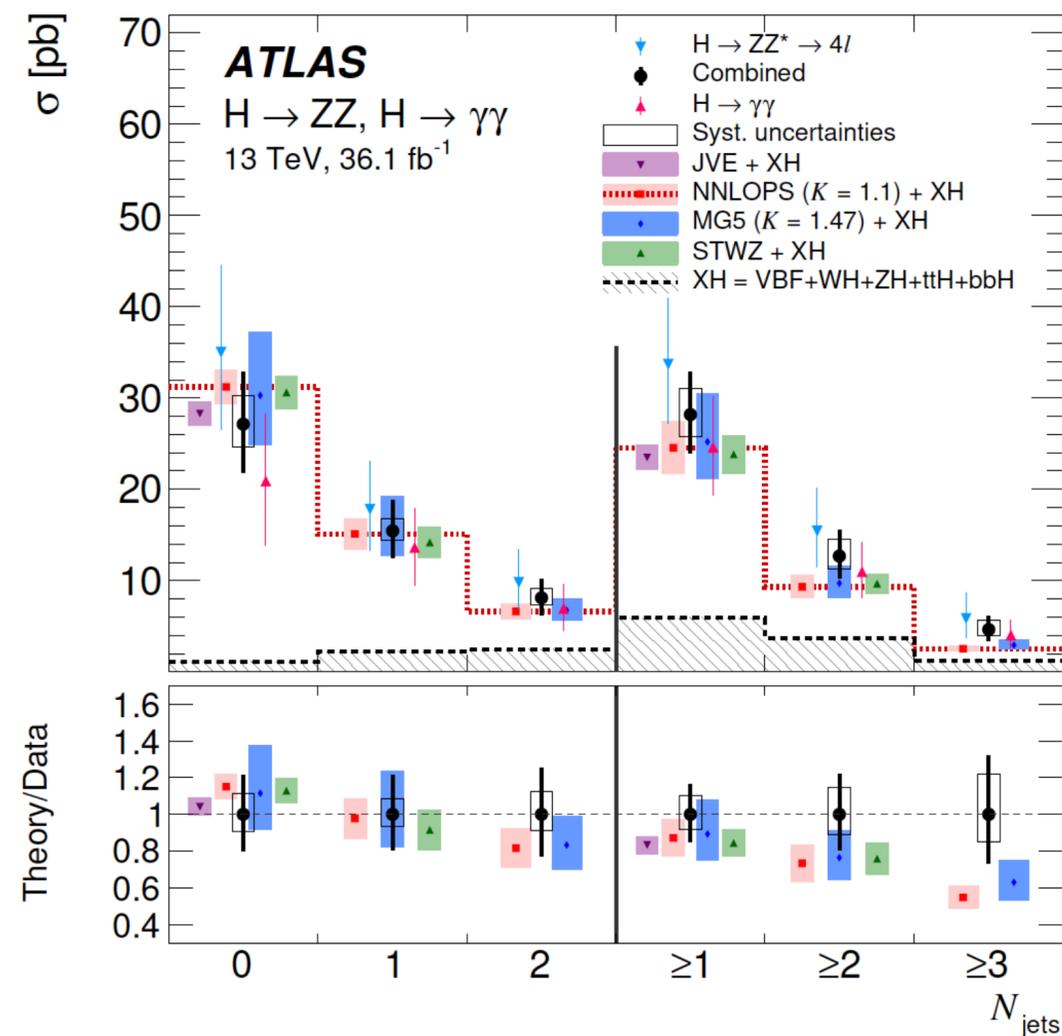
- ▶ Coupling to fermions directly observed only for 3rd generation (top, bottom, tau), in agreement with the SM



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + \text{h.c.} + \bar{\Psi}_i y_{ij} \Psi_j \phi + \text{h.c.} + |\mathcal{D}_\mu \phi|^2 - V(\phi)$$

Higgs Physics at the LHC

- ▶ Although direct access to such measurements is challenging, indirect constraints can be deduced from differential distributions in the long run
- ▶ Experimental errors expected to reduce to few-% level at HL-LHC



Theory precision is crucial

The inclusive ggH cross section

[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger '16]

- ▶ Currently total cross section known with ~6% accuracy

$$\sigma = 48.58 \text{ pb} \begin{matrix} +2.22 \text{ pb} (+4.56\%) \\ -3.27 \text{ pb} (-6.72\%) \end{matrix} (\text{theory}) \pm 1.56 \text{ pb} (3.20\%) (\text{PDF} + \alpha_s)$$

The inclusive ggH cross section

[Anastasiou, Duhr, Dulat, Furlan, Gehrmann, Herzog, Lazopoulos, Mistlberger '16]

- ▶ Currently total cross section known with $\sim 6\%$ accuracy
- ▶ theory uncertainty made of several small effects

$48.58 \text{ pb} =$	16.00 pb	$(+32.9\%)$	(LO, rEFT)
	$+ 20.84 \text{ pb}$	$(+42.9\%)$	(NLO, rEFT)
	$- 2.05 \text{ pb}$	(-4.2%)	$((t, b, c), \text{exact NLO})$
	$+ 9.56 \text{ pb}$	$(+19.7\%)$	(NNLO, rEFT)
	$+ 0.34 \text{ pb}$	$(+0.2\%)$	$(\text{NNLO, } 1/m_t)$
	$+ 2.40 \text{ pb}$	$(+4.9\%)$	(EW, QCD-EW)
	$+ 1.49 \text{ pb}$	$(+3.1\%)$	$(\text{N}^3\text{LO, rEFT})$
- ▶ Hard to improve on the total error
- ▶ However, **understanding of individual effects is important for the combination of uncertainties**

$\delta(\text{scale})$	$\delta(\text{trunc})$	$\delta(\text{PDF-TH})$	$\delta(\text{EW})$	$\delta(t, b, c)$	$\delta(1/m_t)$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
+0.10 pb -1.15 pb	$\pm 0.18 \text{ pb}$	$\pm 0.56 \text{ pb}$	$\pm 0.49 \text{ pb}$	$\pm 0.40 \text{ pb}$	$\pm 0.49 \text{ pb}$	$\pm 0.90 \text{ pb}$	+1.27pb -1.25pb
+0.21% -2.37%	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$	$\pm 1.86\%$	+2.61% -2.58%

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[Mistlberger '18]

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+0.21% −2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%	±1.86%	+2.61% −2.58%

The inclusive ggH cross section

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$\pm 0.90 \text{ pb}$	$+1.27 \text{ pb}$ -1.25 pb
$\pm 1.86\%$	$+2.61\%$ -2.58%

Mixed QCD-EW corrections

- ▶ Estimate of the $\mathcal{O}(\alpha_s^2\alpha)$ corrections to ggH: full virtual corrections + reals in the (improved) soft limit
- ▶ Further corrections could arise from the emission of hard radiation that probes the EW structure of the loop

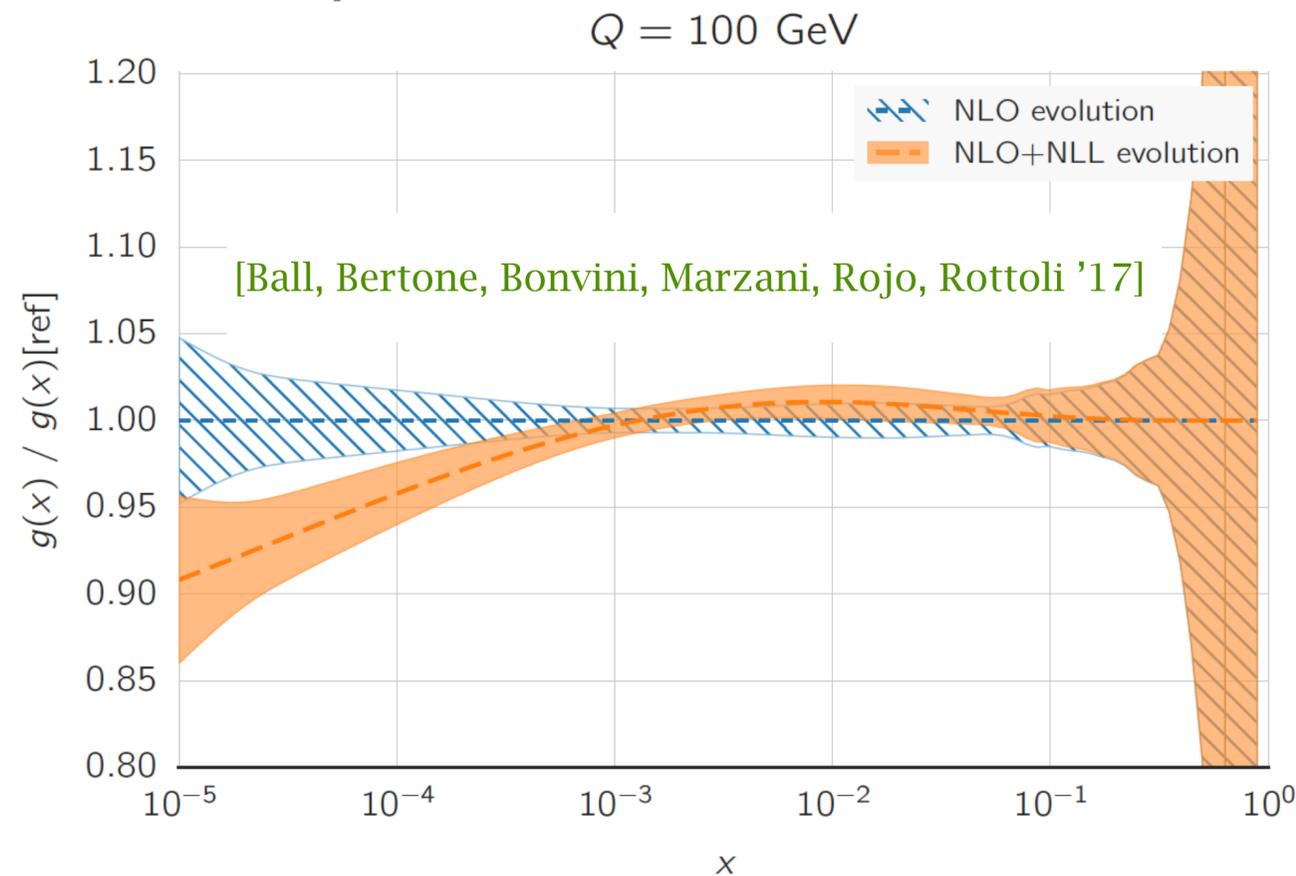
[Bonetti, Melnikov, Tancredi '18]

$$\begin{array}{ccc} \sigma_{\text{QCD}}^{\text{LO}} = 20.6 \text{ pb}, & \xrightarrow{\sim 5\%} & \sigma_{\text{QCD/EW}}^{\text{LO}} = 21.7 \text{ pb}, \\ \sigma_{\text{QCD}}^{\text{NLO}} = 32.66 \text{ pb}, & & \sigma_{\text{QCD/EW}}^{\text{NLO}} = 34.41 \text{ pb}. \end{array}$$

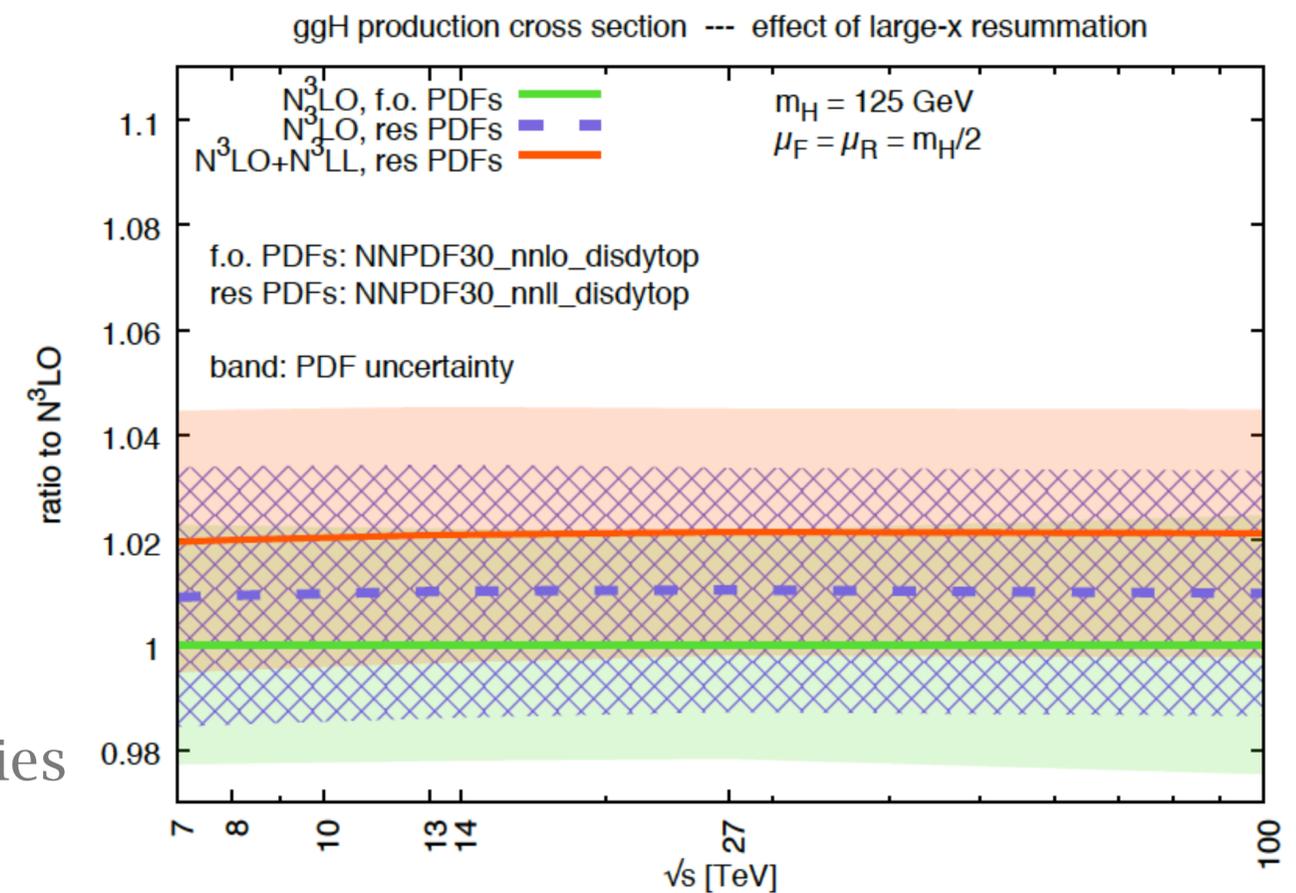
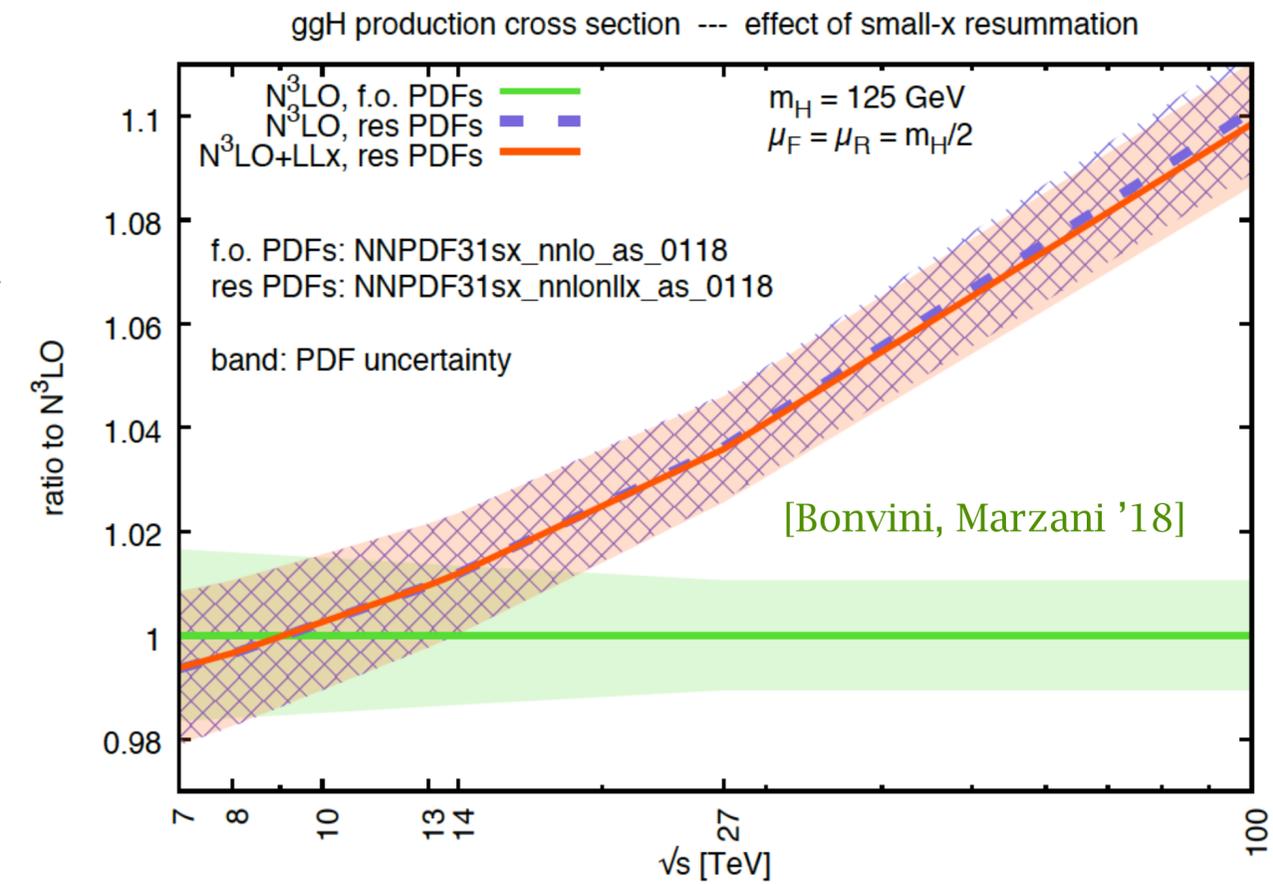
- ▶ The result suggests that QCD and EW corrections factorise, and provides insight on the combination of uncertainties
- ▶ confirms mixed EW-QCD NLO estimate used in the inclusive cross section

Extra corrections: large and small x

- ▶ Additional perturbative corrections due to all-order radiation have a moderate ($\sim 2\%$) impact at current energies
- ▶ *Small-x* effects become sizeable at higher energies
- ▶ Effect almost **entirely due to PDF evolution**. Do we have a robust control over small-x dynamics ?



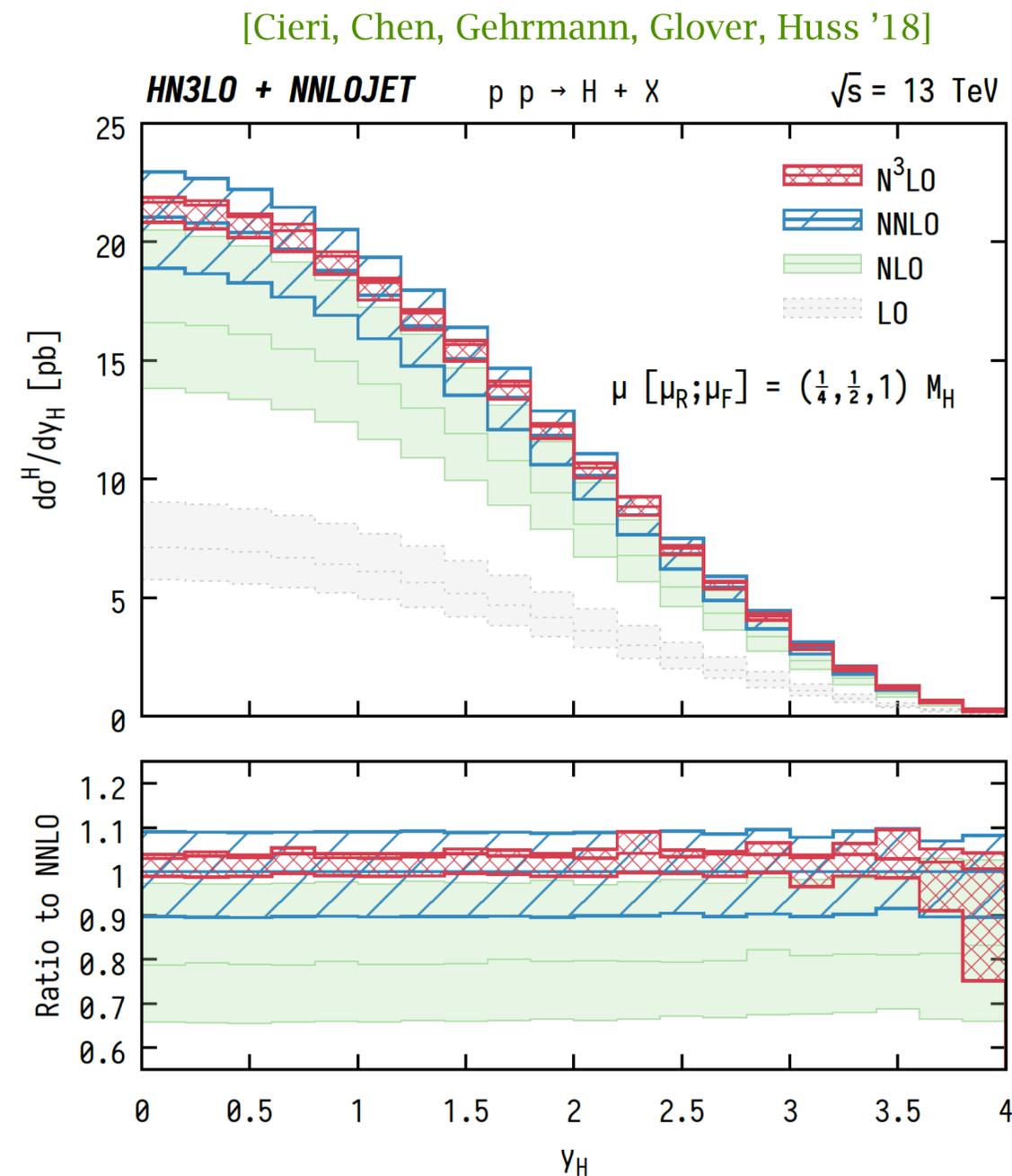
- ▶ Difficult to access relevant x region at current LHC energies *accurately* (e.g. high-rapidity/low mass DY)



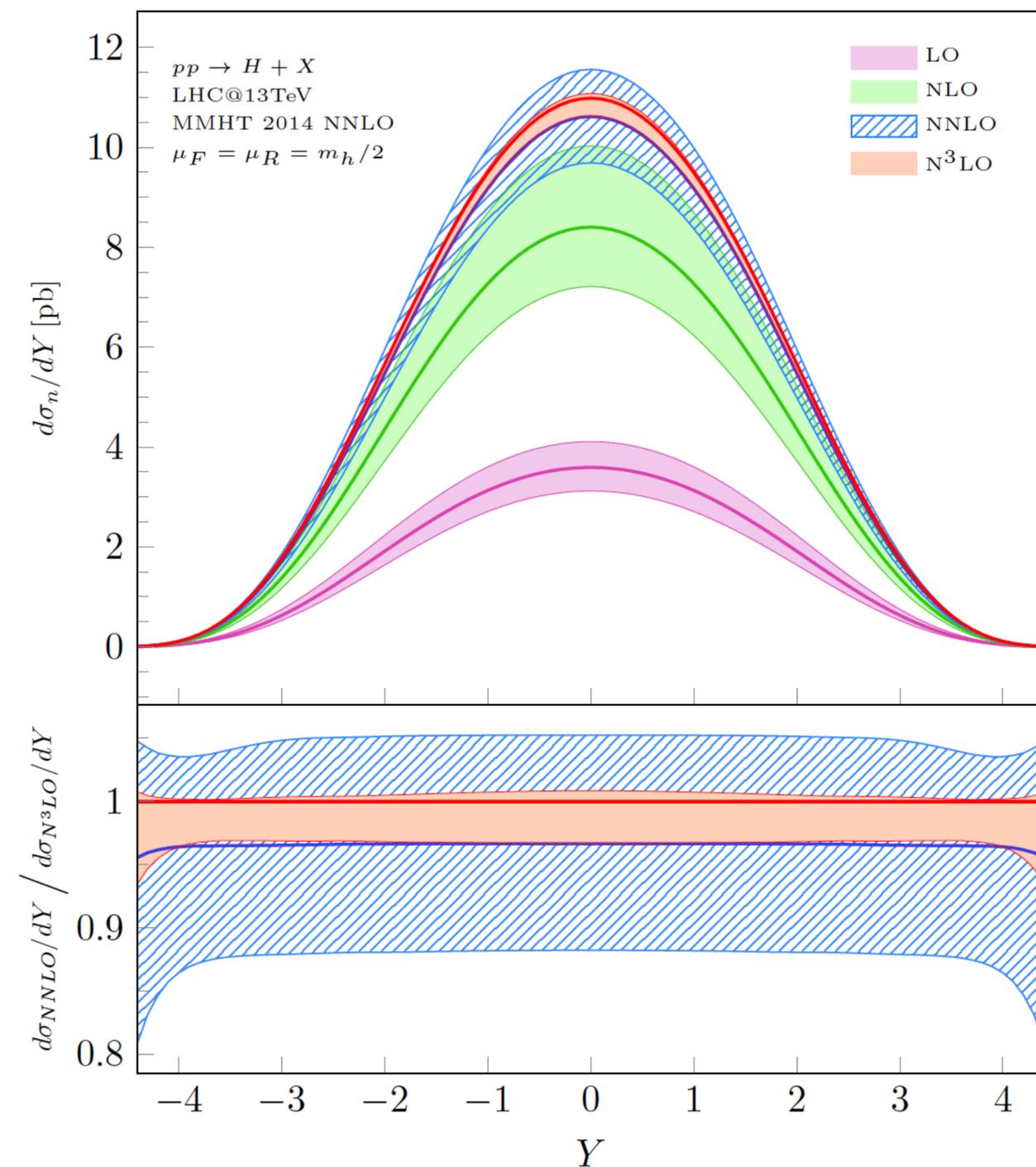
Rapidity distribution

- ▶ Rapidity distribution features a constant K factor
- ▶ Perturbative uncertainties reduced to $\sim 3\text{-}4\%$

- ▶ $N^3\text{LO}$ distribution well reproduced by assuming a flat correction
- ▶ Fully exclusive $N^3\text{LO}$ now accessible

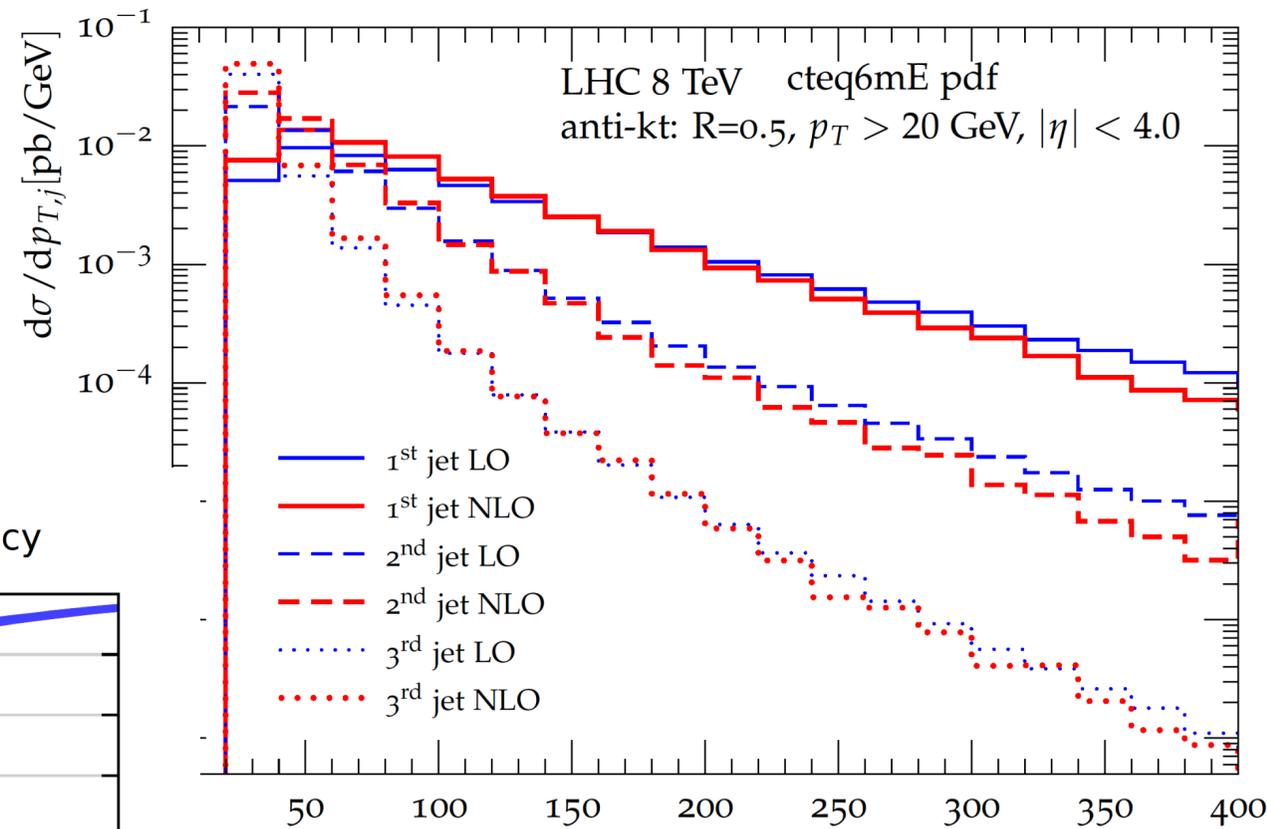
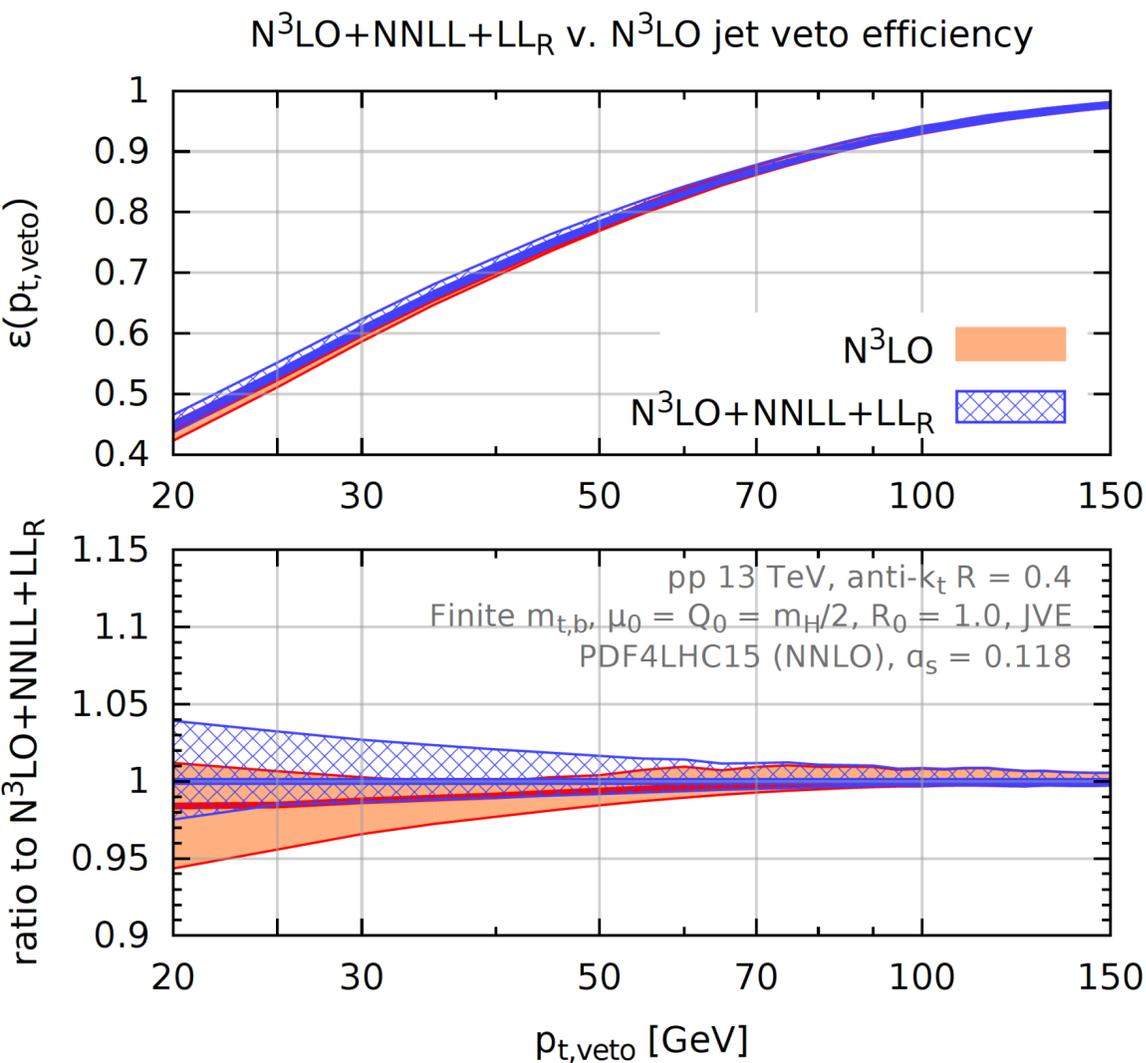


[Dulat, Mistlberger, Pelloni '18]



Kinematic distributions & production with jets

- Great progress in past year in the understanding of jet dynamics in ggH



H+3 jets @ NLO

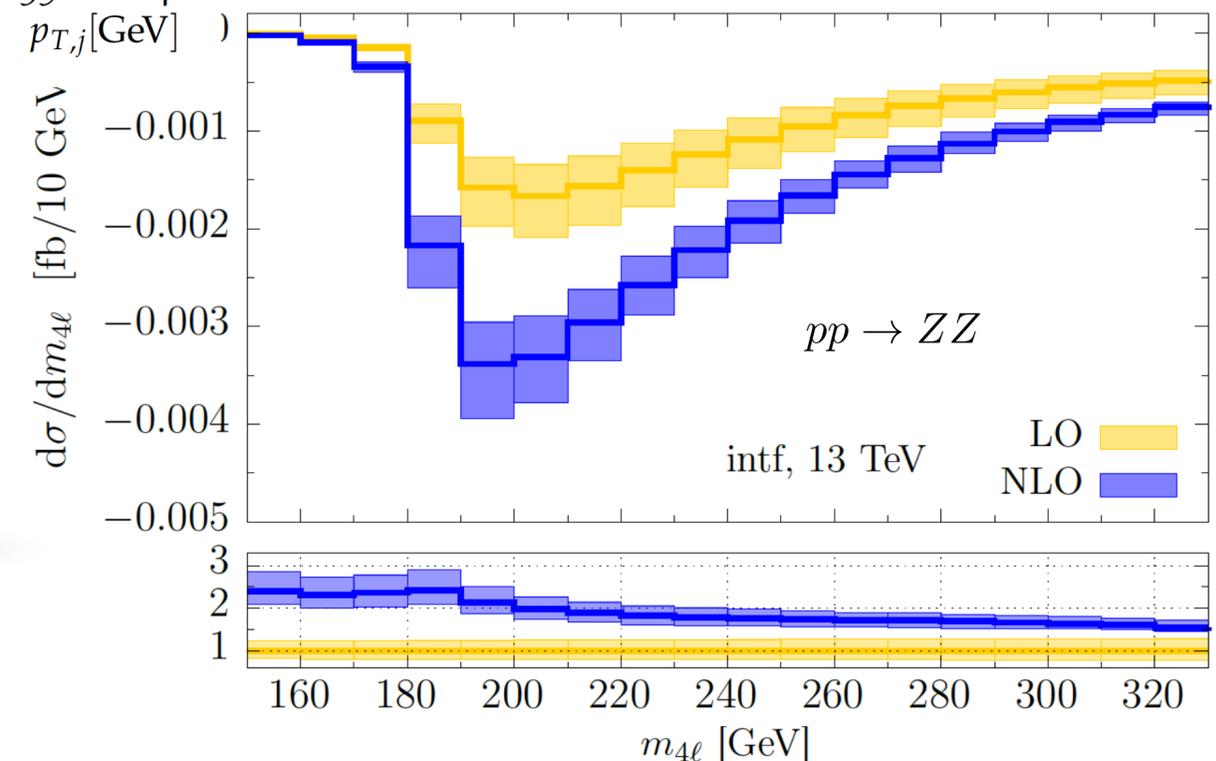
[Cullen et al. '13]

Signal-background interference @ NLO

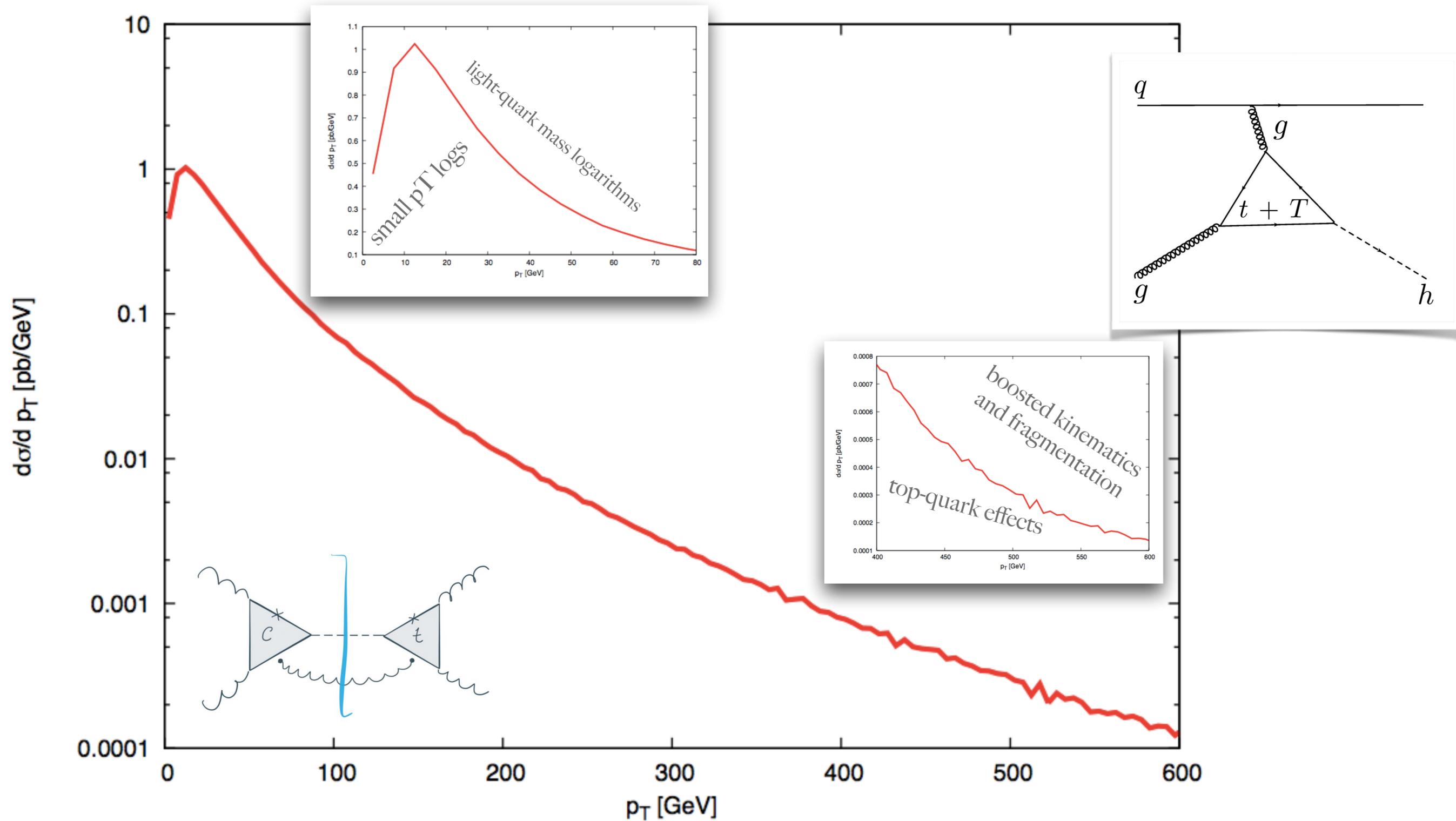
[Caola et al. '16]

0-jet cross section @ N³LO+NNLL+LL_R

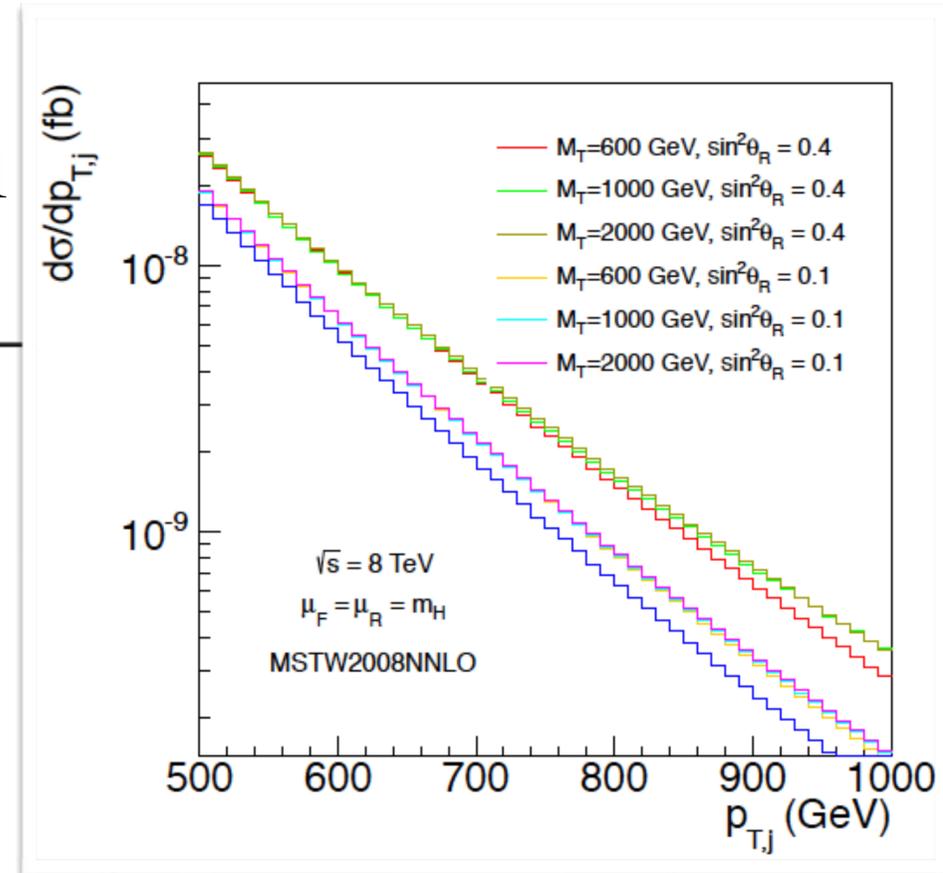
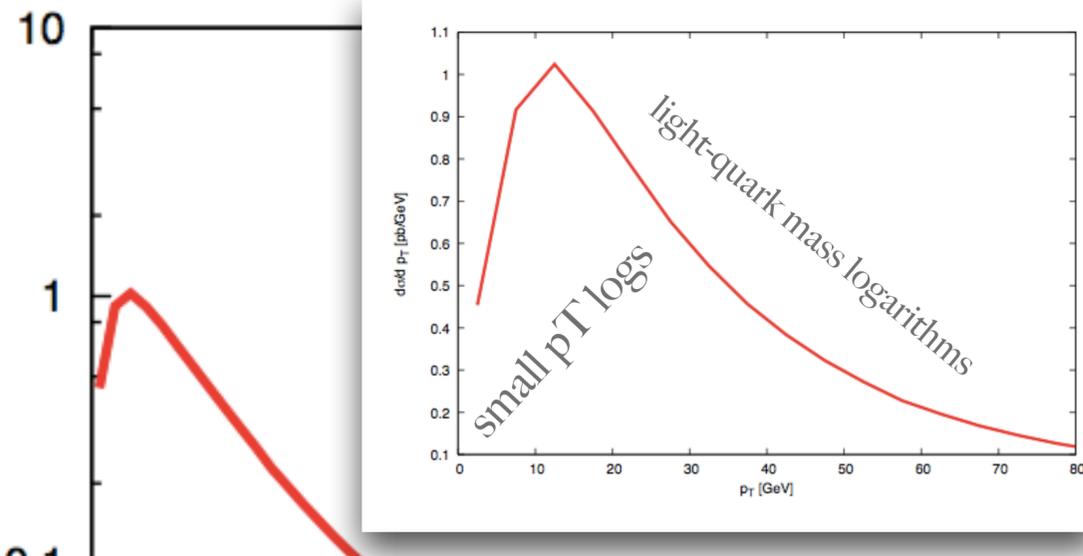
[Banfi et al. '15]



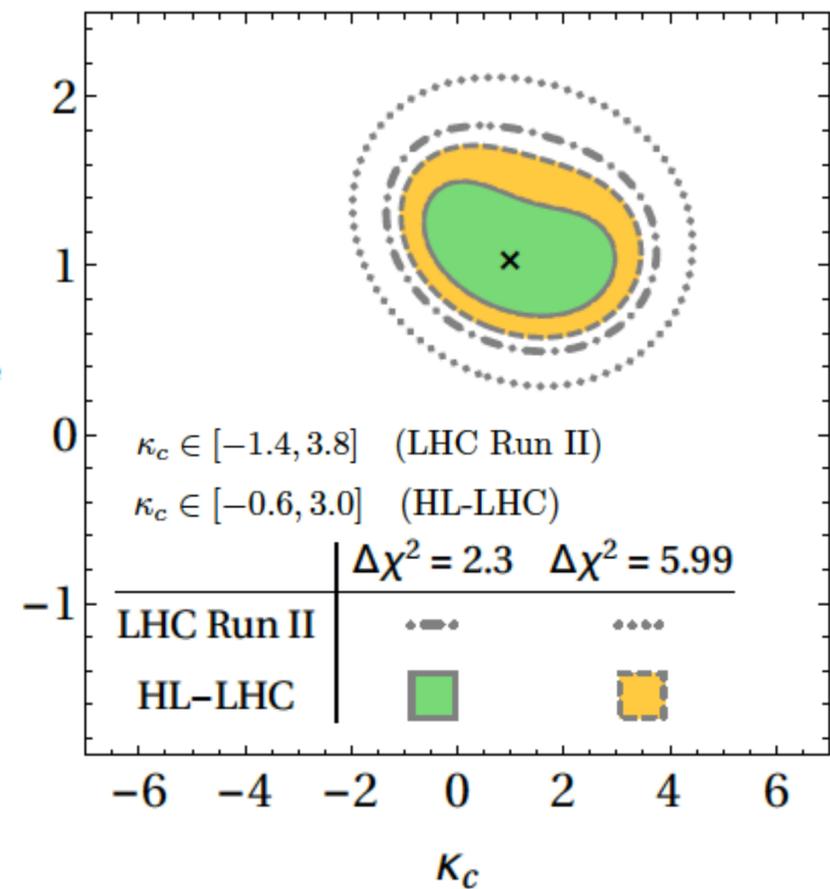
An example: the p_T spectrum



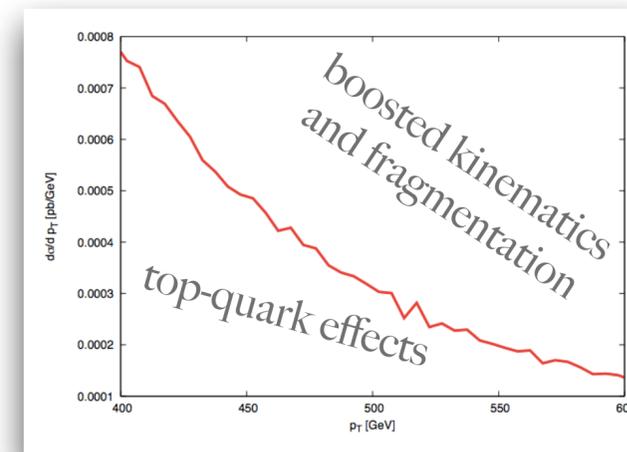
An example: the p_T spectrum



assume combination of $h \rightarrow \gamma\gamma, 4\ell, 2\ell 2\nu$



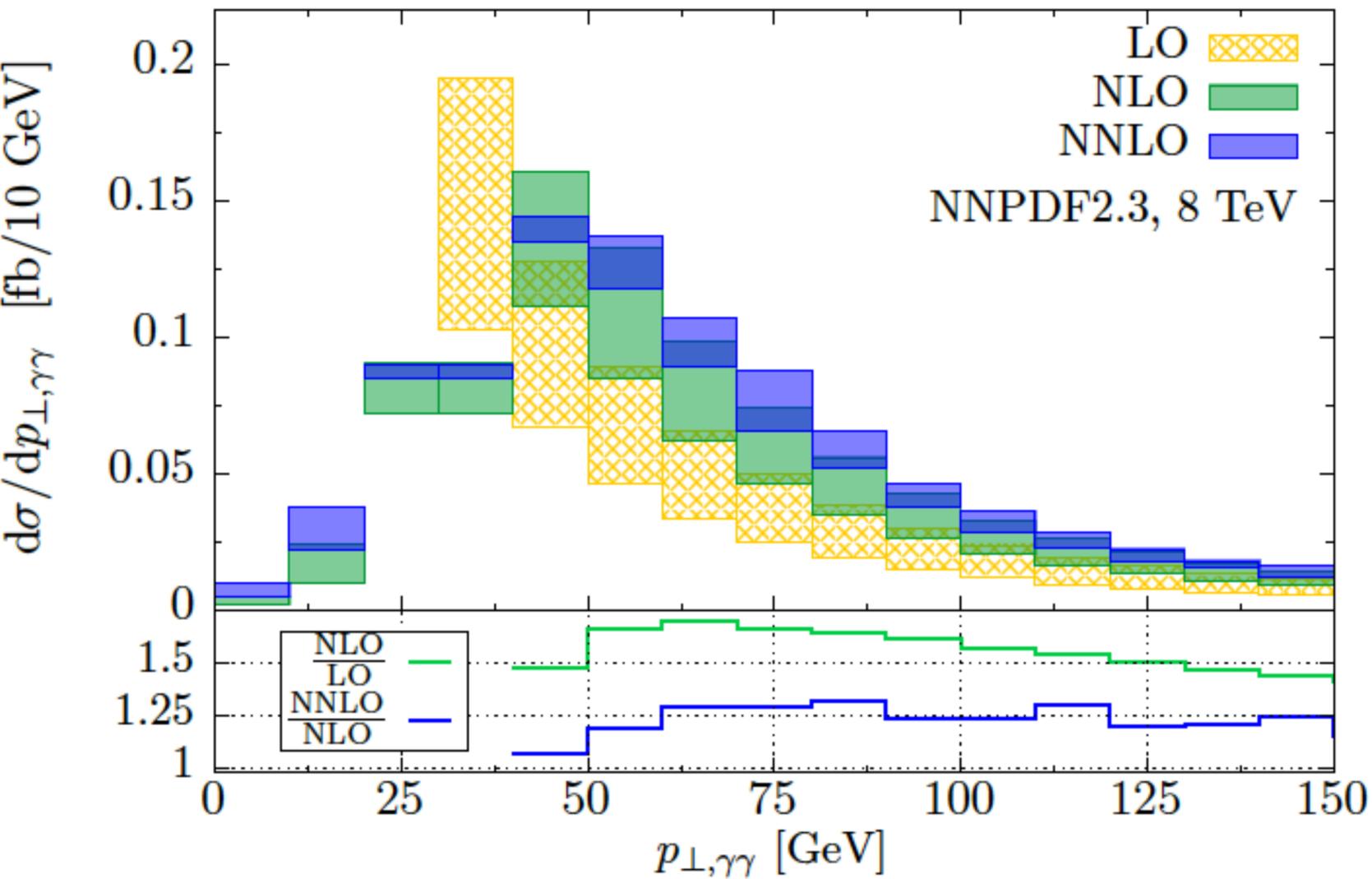
[Bishara, Haisch, Re, PM '16;
 see also Soreq, Zhu, Zupan '16]



[Banfi, Martin, Sanz '13]

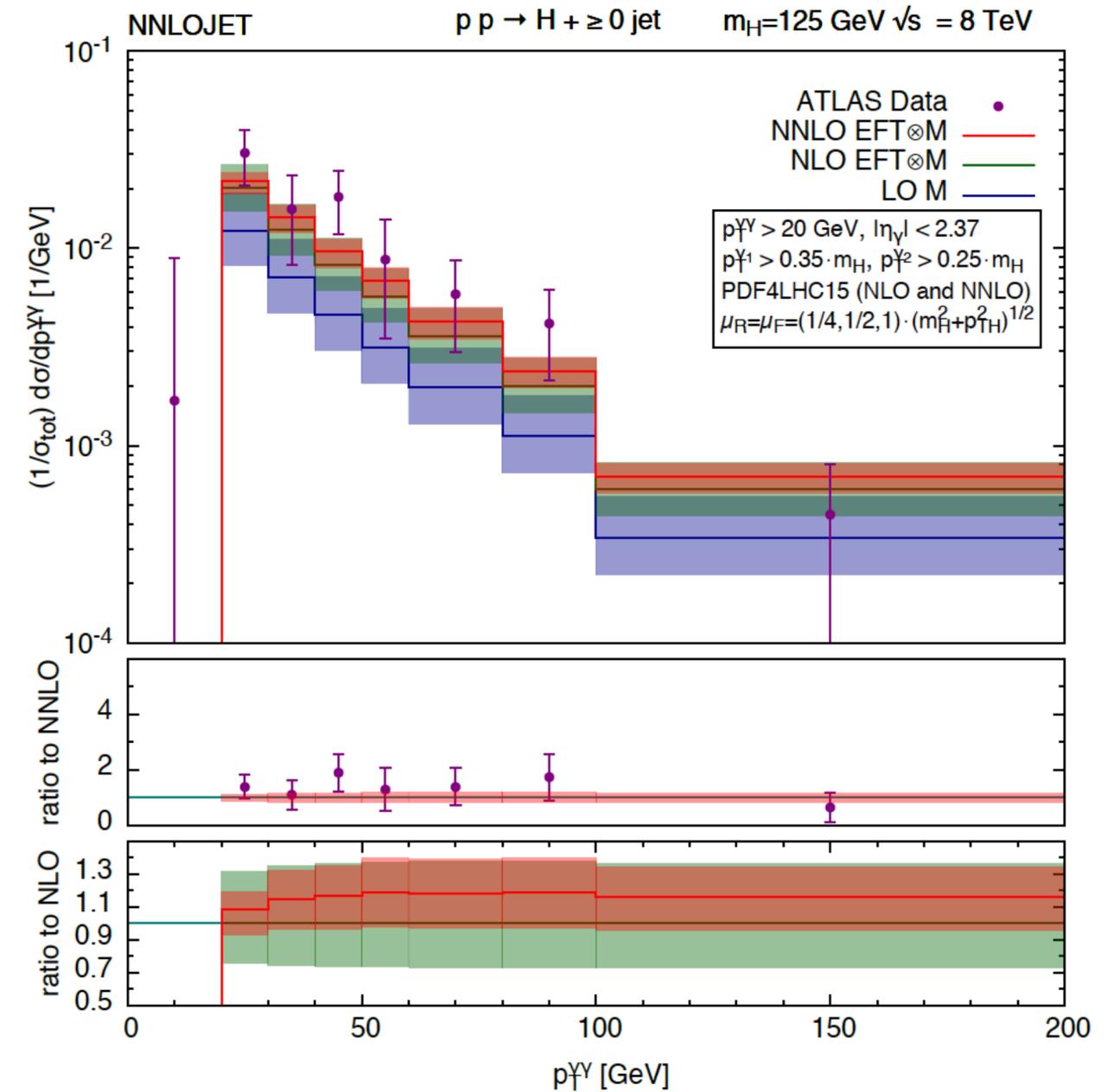
Fiducial distributions at NNLO

- ▶ NNLO QCD well established, including exclusive decay into EW final states



[Caola, Melnikov, Schulze '15]

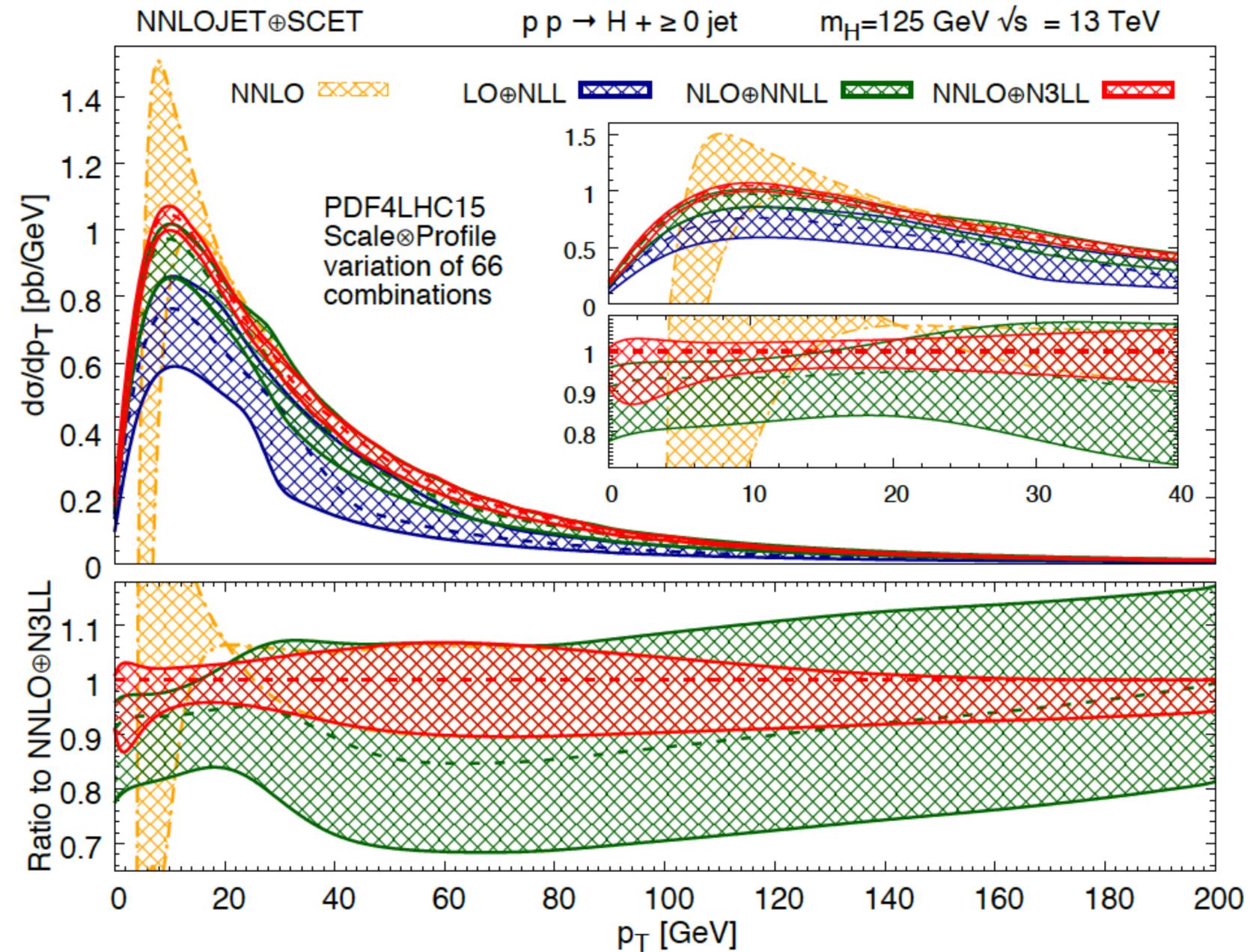
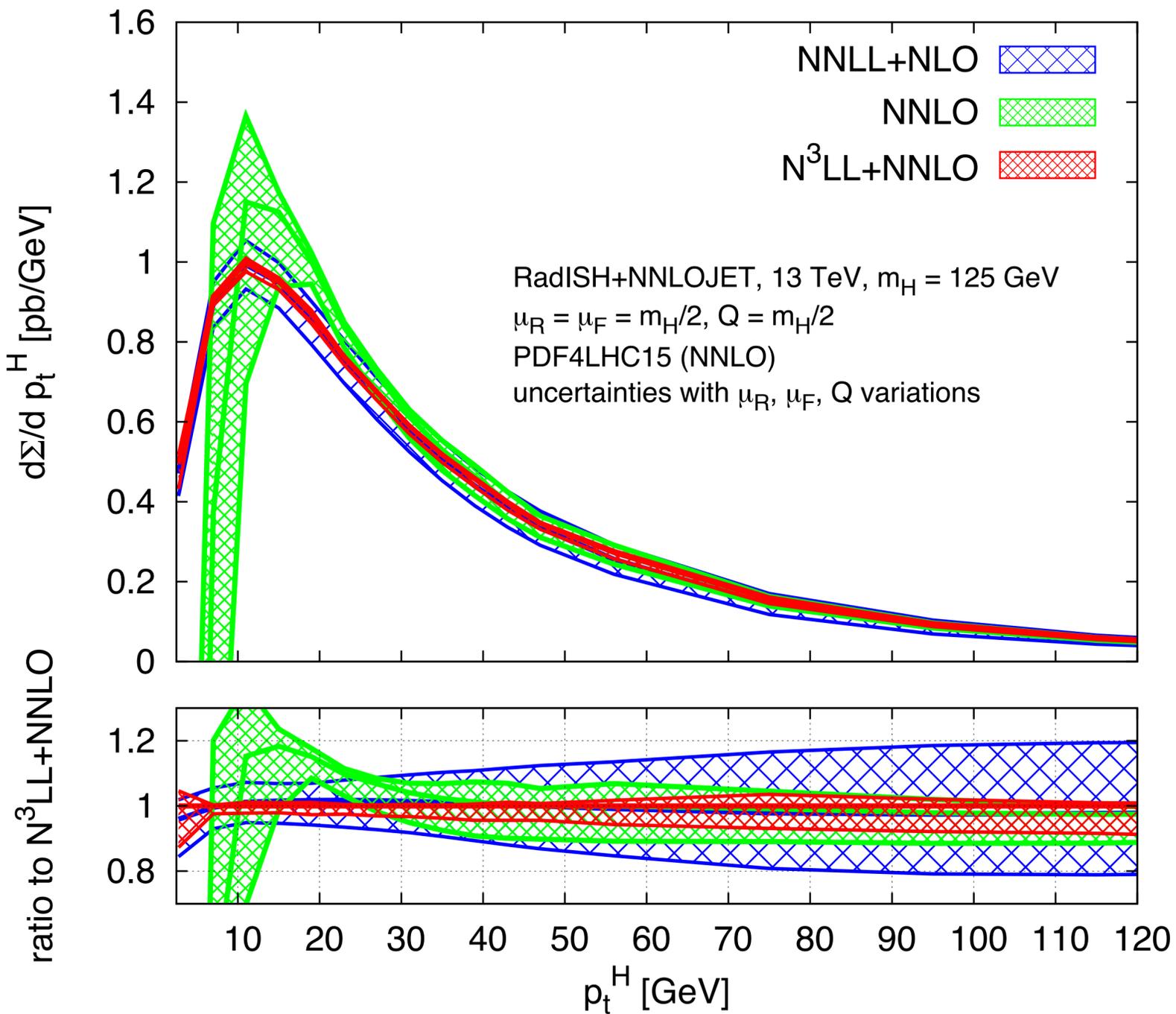
[see also Boughezal, Focke, Giele, Liu, Petriello '15]



[Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '16]

Resummation effects: $N^3LL + NNLO$

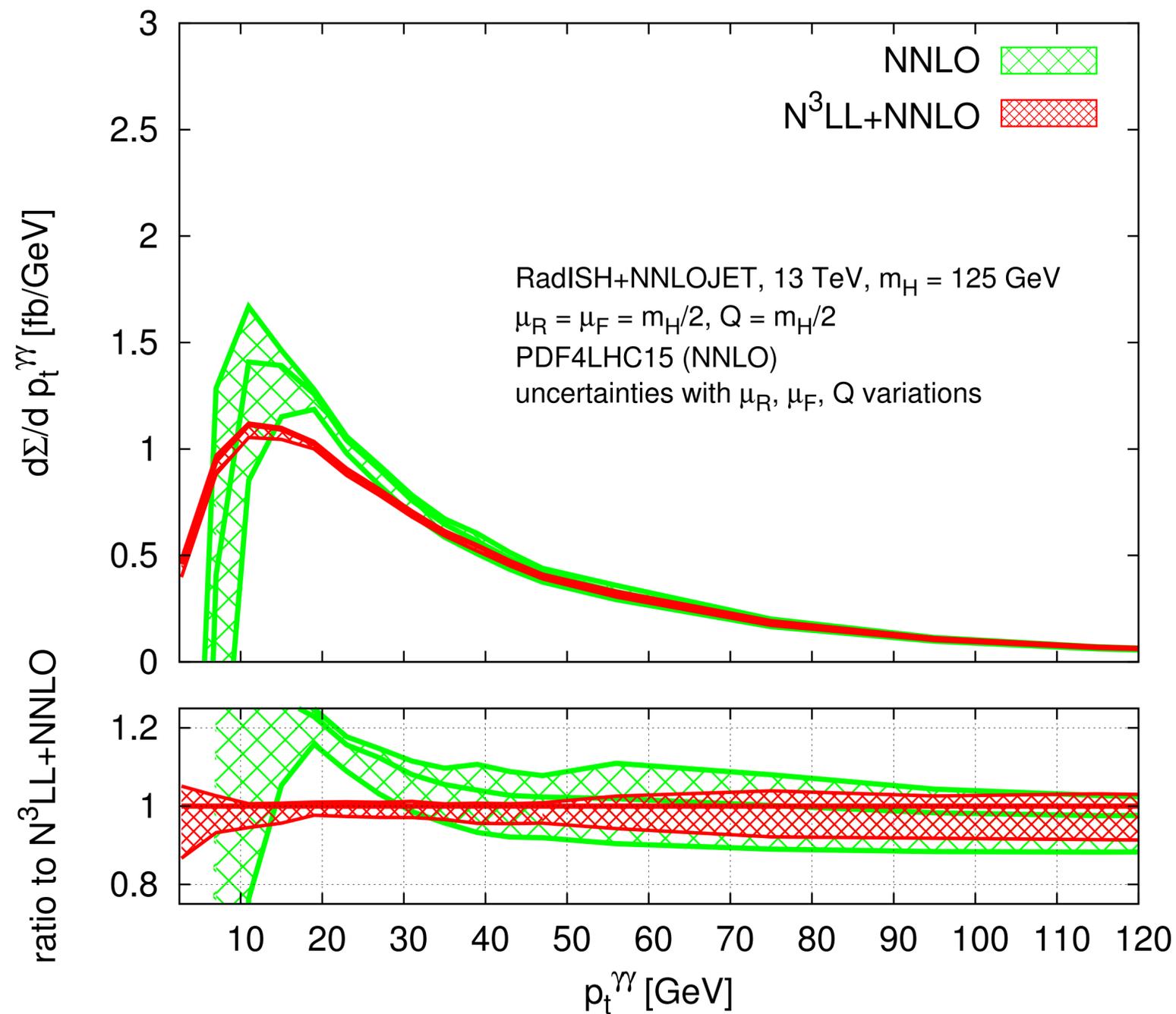
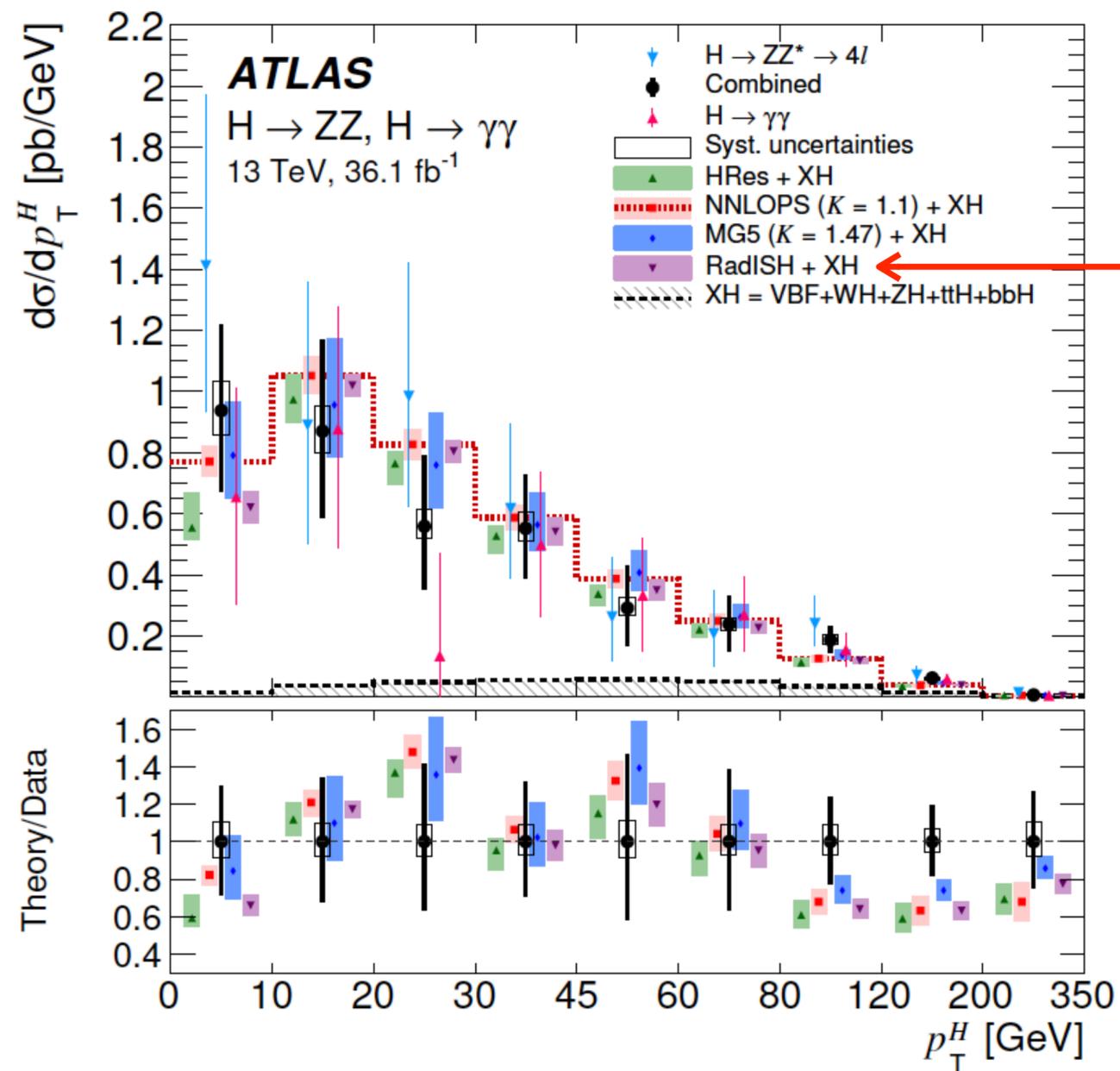
- Large logarithmic corrections under very good control in the small p_T regime



Resummation effects: fiducial distribution

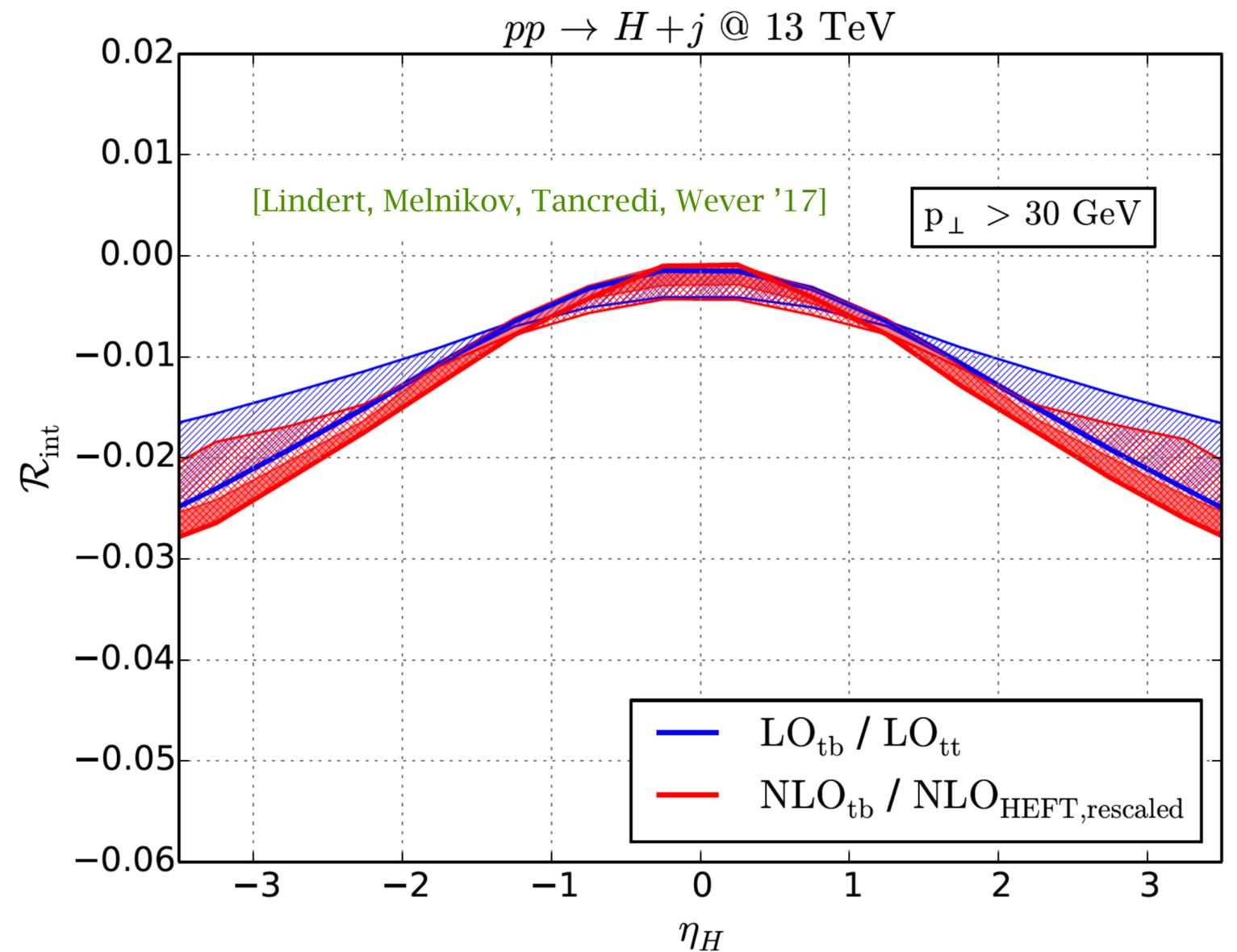
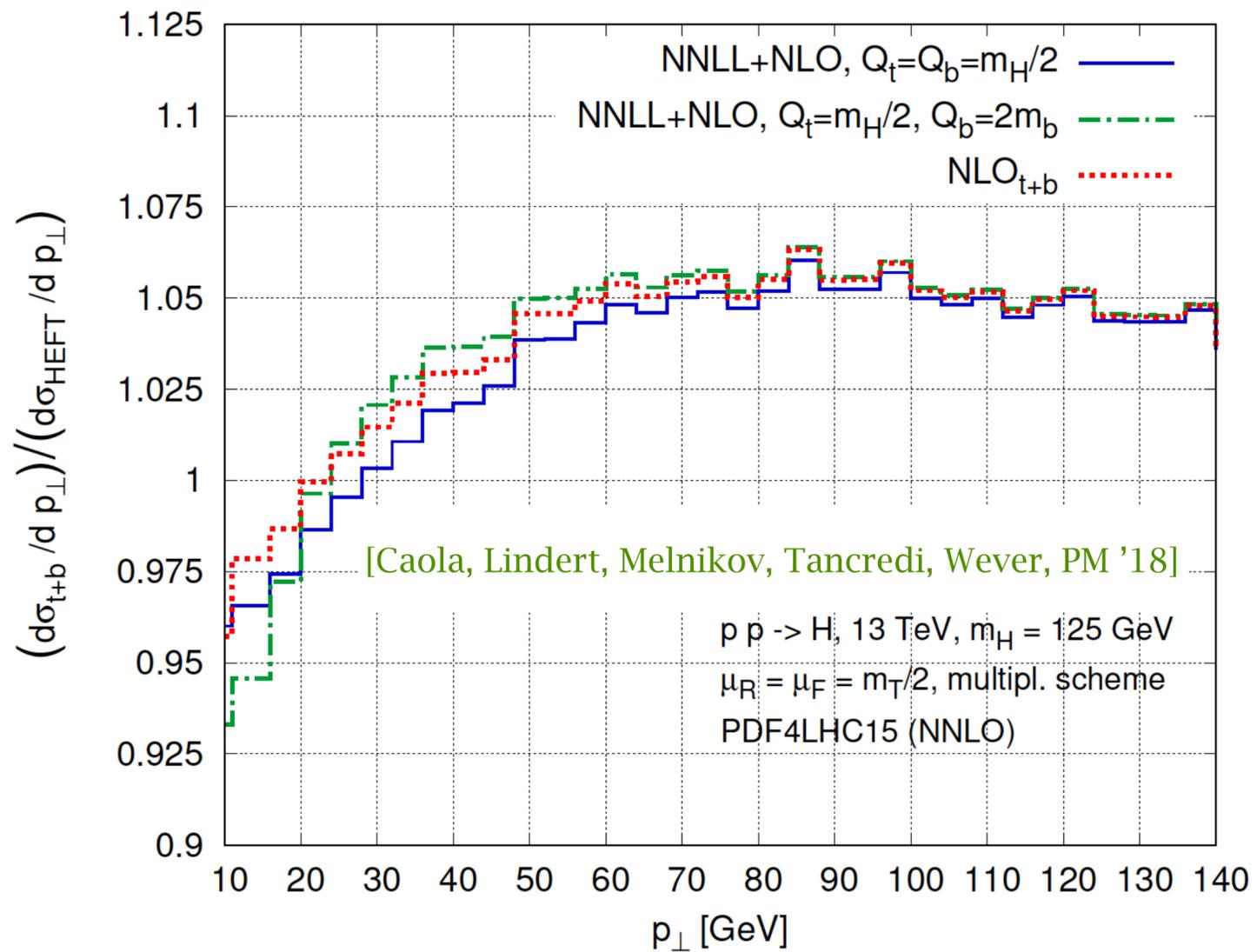
- ▶ $\sim 5\%$ residual uncertainty in the spectrum for ggH production via heavy top loop
- ▶ Exclusive description of decay products

[ATLAS 1805.10197]



Light quarks contribution at NLO

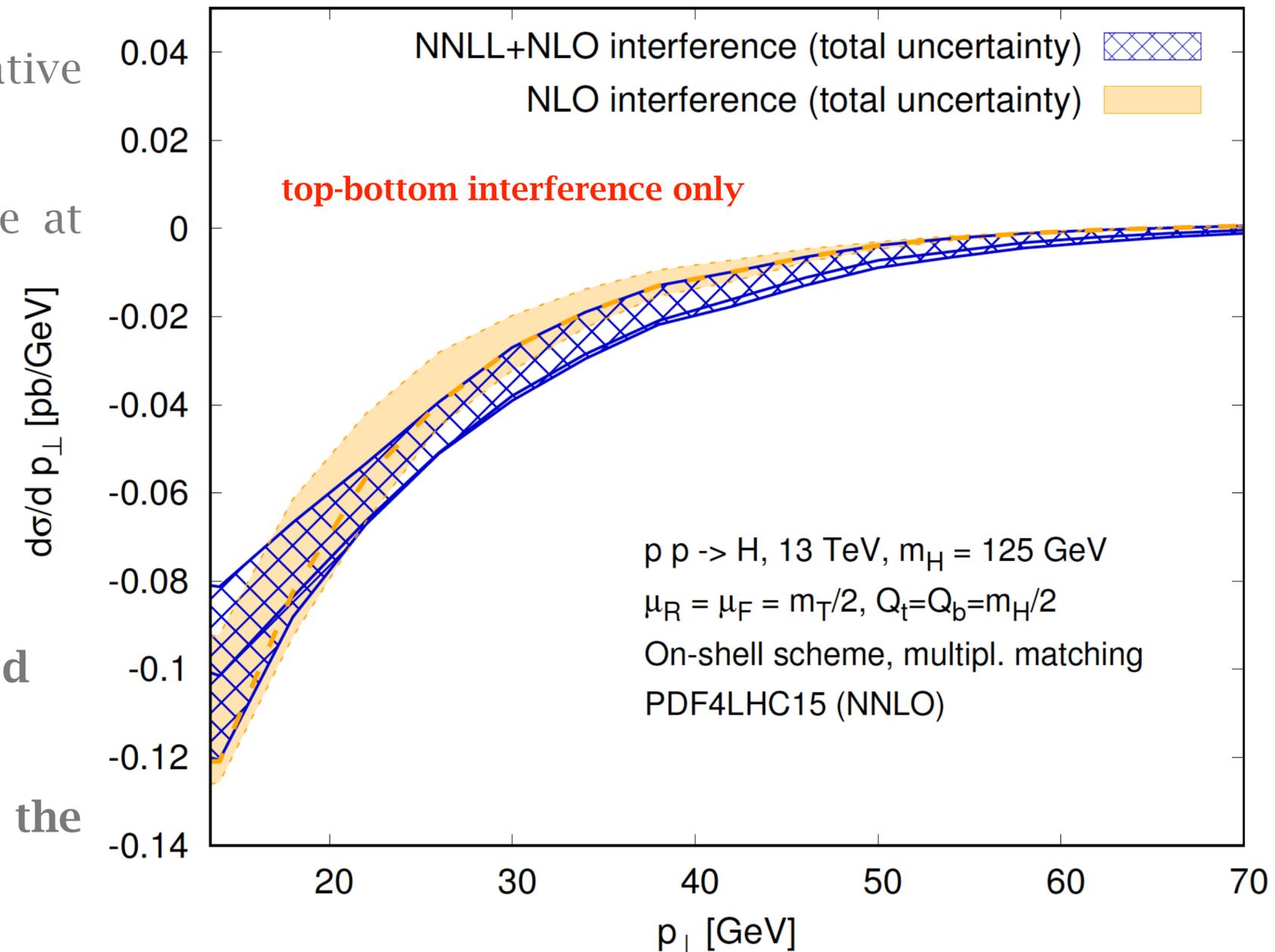
- Impact of light quarks (notably bottom) relevant in the intermediate p_T regime
- Relative bottom effects largely preserved by NLO and resummation corrections



Resummation ambiguities

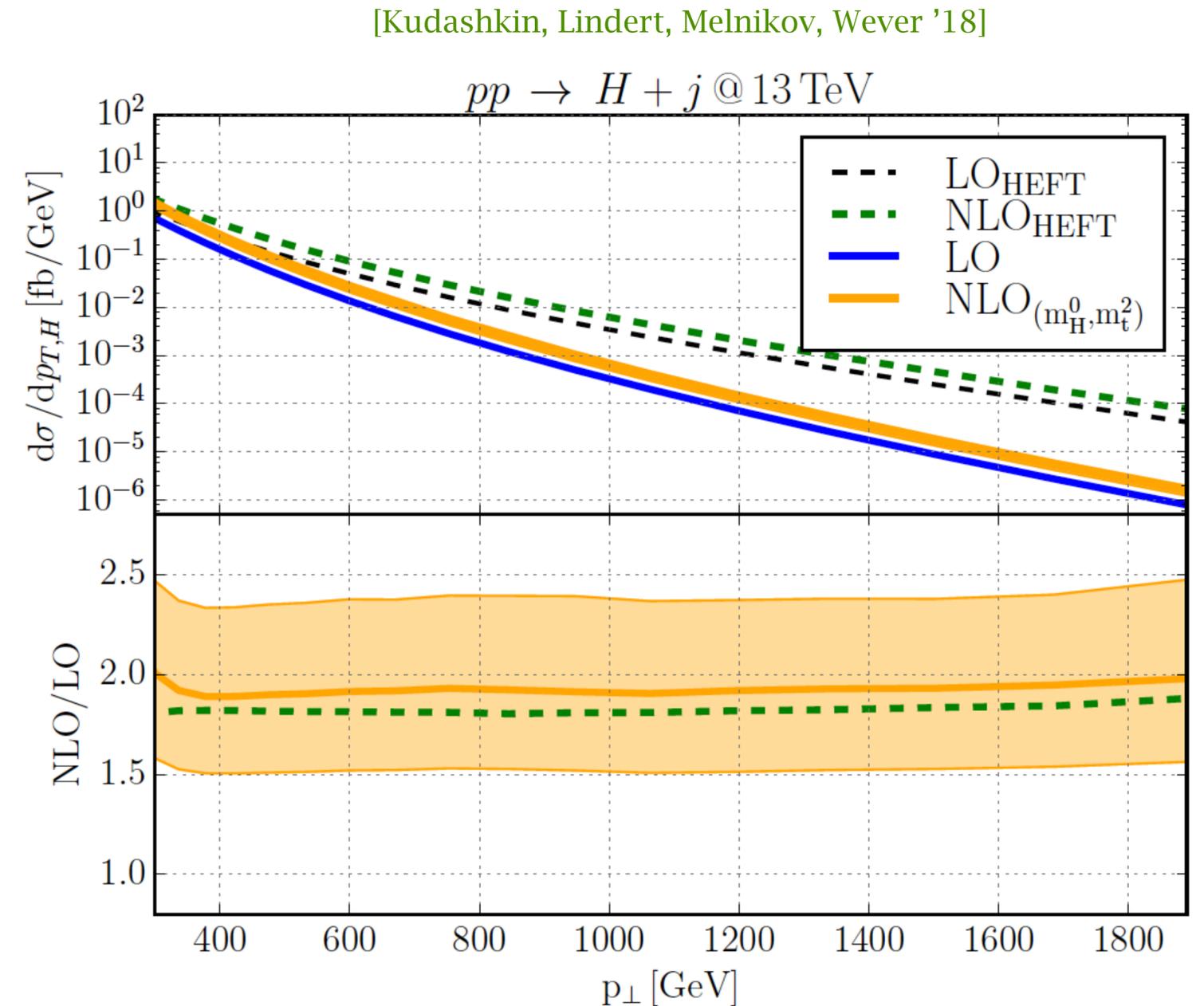
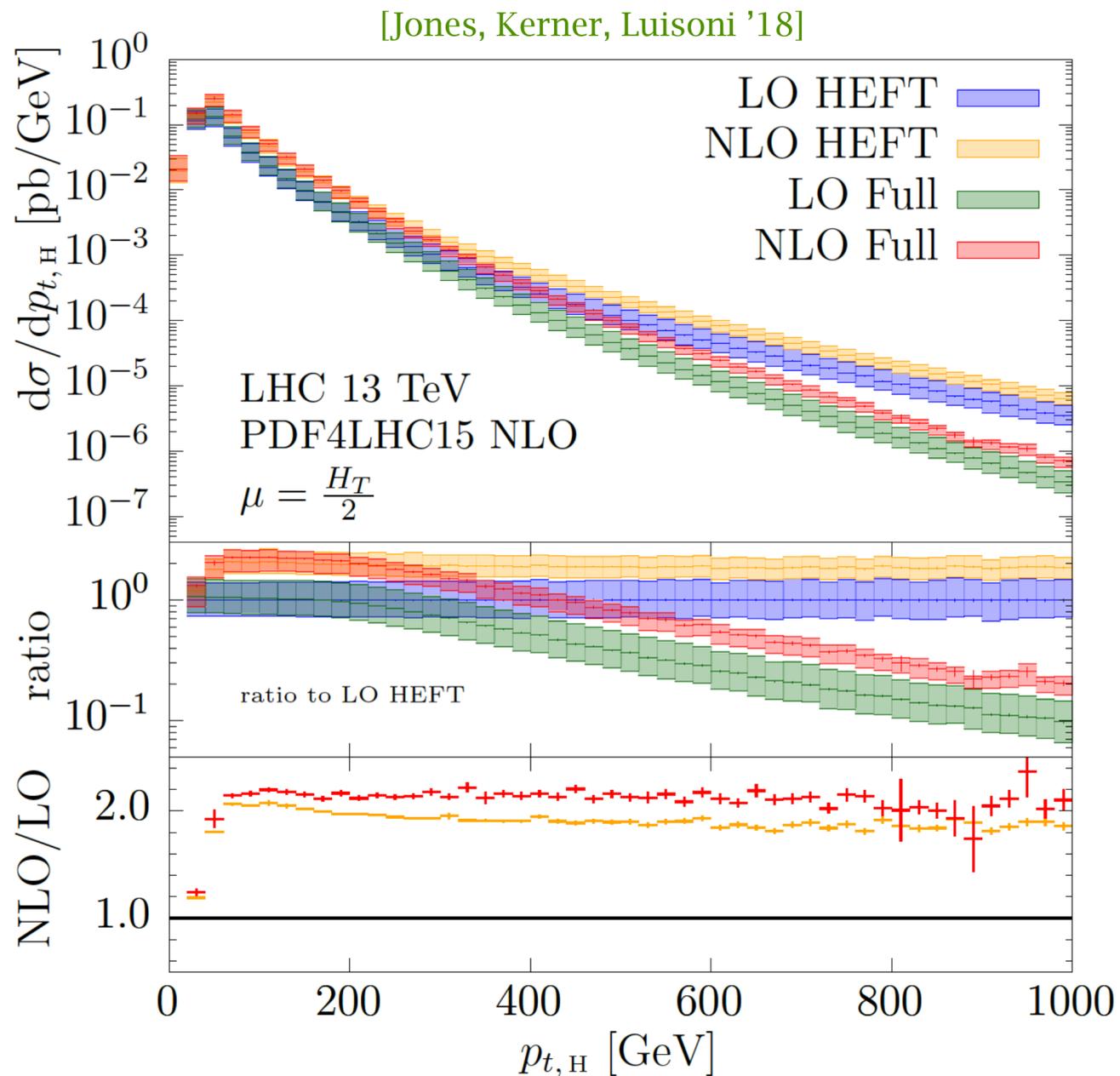
- ▶ The presence of the bottom (or lighter) quark leads to complications in the radiation structure that cannot be understood with the known approaches to resummation
- ▶ One can be very conservative to estimate radiative corrections:
 - ▶ switch off resummation in top-bottom interference at disparate p_T scales (from $\sim m_b$ to $m_H/2$)
 - ▶ Vary scales & matching scheme
 - ▶ Change scheme of light quark mass
- ▶ **Total uncertainty in the interference $\sim 20\%$, dominated by mass scheme perturbative ambiguities**
- ▶ **Translates in an error in the full SM prediction at the $\sim 1\%$ level**

[Caola, Lindert, Melnikov, Tancredi, Wever, PM '18]



Boosted Higgs: NLO corrections

- Recently two-loop amplitudes obtained either in a high- p_T expansion or numerically
 - NLO corrections show slightly larger K factor than the HEFT, with a very similar pattern (not completely understood why)



Boosted Higgs: Monte Carlo generators

- Accurate MC simulation desirable for measurements via substructure techniques (shower effects might be subtle)

[CMS 1709.05543]

Inclusive search for a highly boosted Higgs boson decaying to a bottom quark-antiquark pair

The CMS Collaboration*

35.9 fb^{-1} . A highly Lorentz-boosted Higgs boson decaying to $b\bar{b}$ is reconstructed as a single, large radius jet and is identified using jet substructure and dedicated b tagging techniques. The method is validated with $Z \rightarrow b\bar{b}$ decays. The $Z \rightarrow b\bar{b}$ process is

is 1.5σ (0.7σ). The observed μ_H implies a measured ggF cross section times H(bb) branching fraction for jet $p_T > 450 \text{ GeV}$ and $|\eta| < 2.5$ of 74 ± 48 (stat) $_{-10}^{+17}$ (syst) fb, assuming the SM values for the ratios of the different H($b\bar{b}$) production modes. This measurement is consistent within uncertainties with the SM ggF cross section times H($b\bar{b}$) branching fraction of 31.7 ± 9.5 fb.

Boosted Higgs: Monte Carlo generators

- ▶ Boosted regime dominated by real corrections
 - ▶ MC (currently w/o virtual corrections) expected to do a good job
 - ▶ **Standard generators simulate boosted regime correctly**

NB: numbers in the previous slide refer to reconstruction level results

[In preparation ...]

Recommended predictions for the boosted-Higgs cross section

p_T^{cut}	NNLO _{quad.unc.} ^{approximate} [fb]	HJ-MINLO [fb]	MG5_MC@NLO [fb]
400 GeV	$32.0^{+9.1\%}_{-11.6\%}$	$29^{+24\%}_{-21\%}$	$31.5^{+31\%}_{-25\%}$
430 GeV	$22.1^{+9\%}_{-11.4\%}$	-	$21.8^{+31\%}_{-25\%}$
450 GeV	$17.4^{+8.9\%}_{-11.5\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

Conveners of the gluon-fusion Working Group:

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In collaboration with:

X. Chen,^f S. Frixione,^g T. Gehrmann,^f N. Glover,^c K. Hamilton,^h S. P. Jones,ⁱ A. Karlberg,^f M. Kerner,ⁱ K. Kudashkin,^l J. M. Lindert,^c G. Luisoni,ⁱ M. L. Mangano,^e K. Melnikov,^l G. P. Salam,^e E. Vryonidou,^e C. Wever.^l

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^eCenter for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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^gINFN, Sezione di Genova, Via Dodecaneso 33, I-16146, Genoa, Italy

^hDepartment of Physics and Astronomy, University College London, London, WC1E 6BT, UK

ⁱMax-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany

^lInstitute for Theoretical Particle Physics (TTP), KIT, Karlsruhe, Germany

$$\frac{d\sigma^{\text{EFT-improved (1), NNLO}}}{dp_{\perp}} = \frac{\frac{d\sigma^{\text{QCD, NLO}}}{dp_{\perp}}}{\frac{d\sigma^{\text{EFT, NLO}}}{dp_{\perp}}} \frac{d\sigma^{\text{EFT, NNLO}}}{dp_{\perp}}$$

[Jones et al. '18] [Chen et al. '16]

Conclusions

- ▶ Great progress in understanding strong dynamics in Higgs production via gluon-fusion
- ▶ Advancements in different areas (amplitudes, IR subtraction, resummations, (N)NLO + Parton Shower) have led to few-% accurate predictions for several observables central to the LHC programme
- ▶ Besides the mentioned perturbative calculations, an important role is also played by the development of better observables (e.g. substructure), which often arise from the advanced knowledge of radiation dynamics developed in recent years
- ▶ This outstanding progress is crucial to establish solid grounds for the future exploitation of LHC data to effectively deepen our knowledge of the Higgs sector

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Thank you for listening