Theory predictions for Higgs-boson differential distributions

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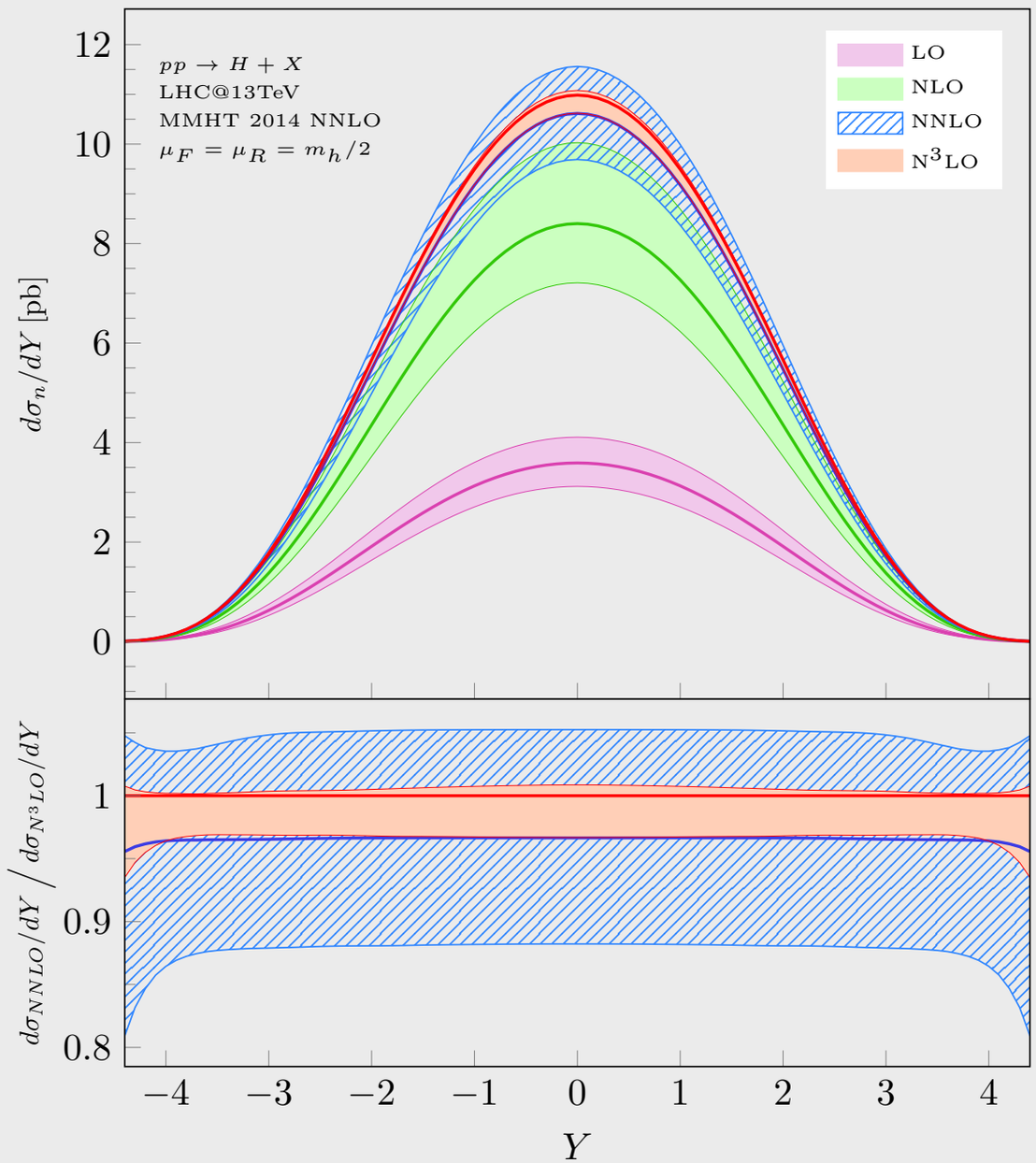
The Higgs rapidity distribution

Higgs predictions: *forefront of perturbative calculations*

[Dulat, Mistlberger & Pelloni (2018)]

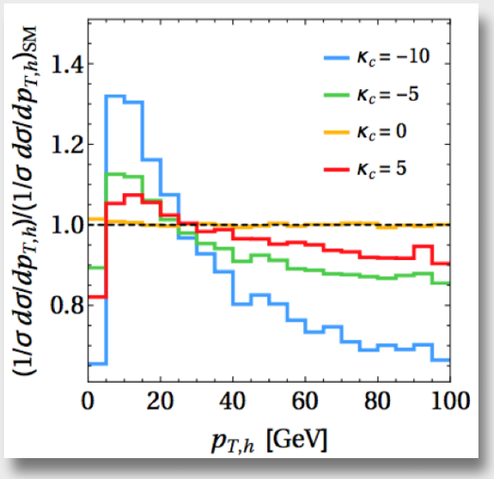


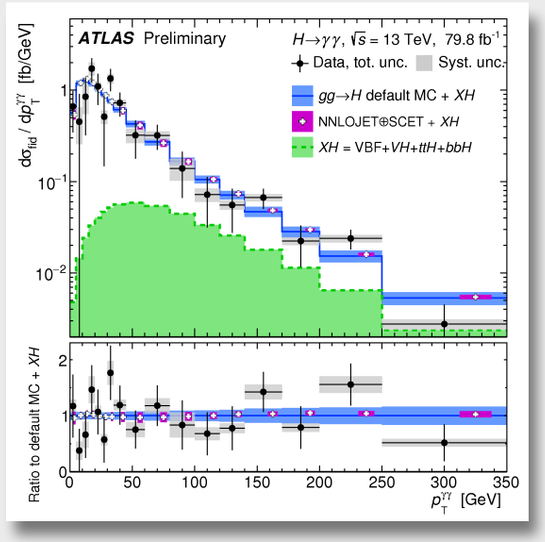
Higgs rapidity (ggF)

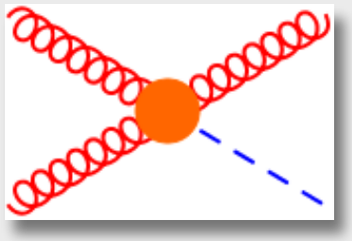
- Computed @N^{3}LO in a soft expansion (~*inclusive*)
- Expected to work very well. (*apart from end-points*)
- <u>Remarkably flat K-factor</u> (*as expected from previous orders*)
- Combined with p_t@NNLO, can give access to N^{3}LO fiducial volume

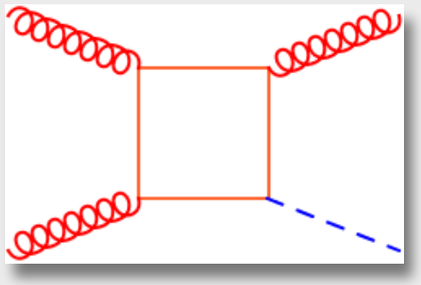
Also known at this order for (inclusive) VBF [Karlberg, Dreyer (2016)]

$p_{t,H}$: a major probe for Higgs physics









Low p_t

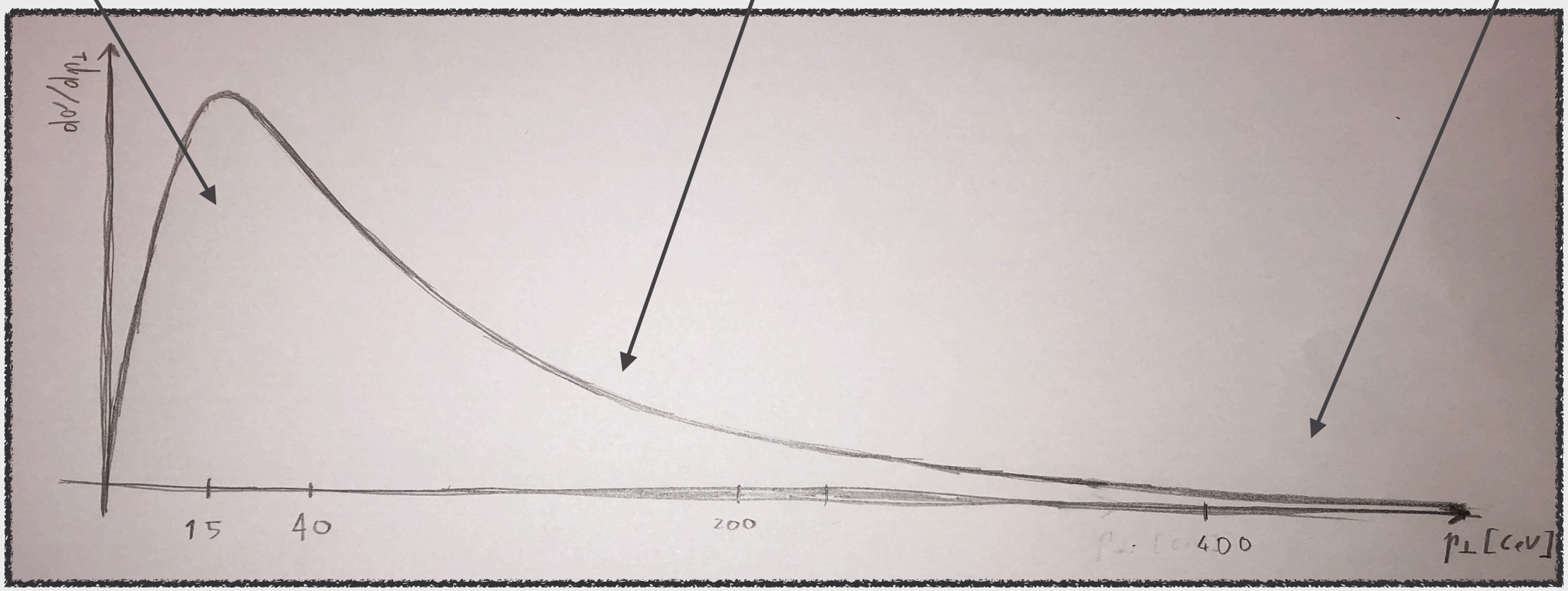
Light Yukawas…

Bulk of the distribution

Highest precision

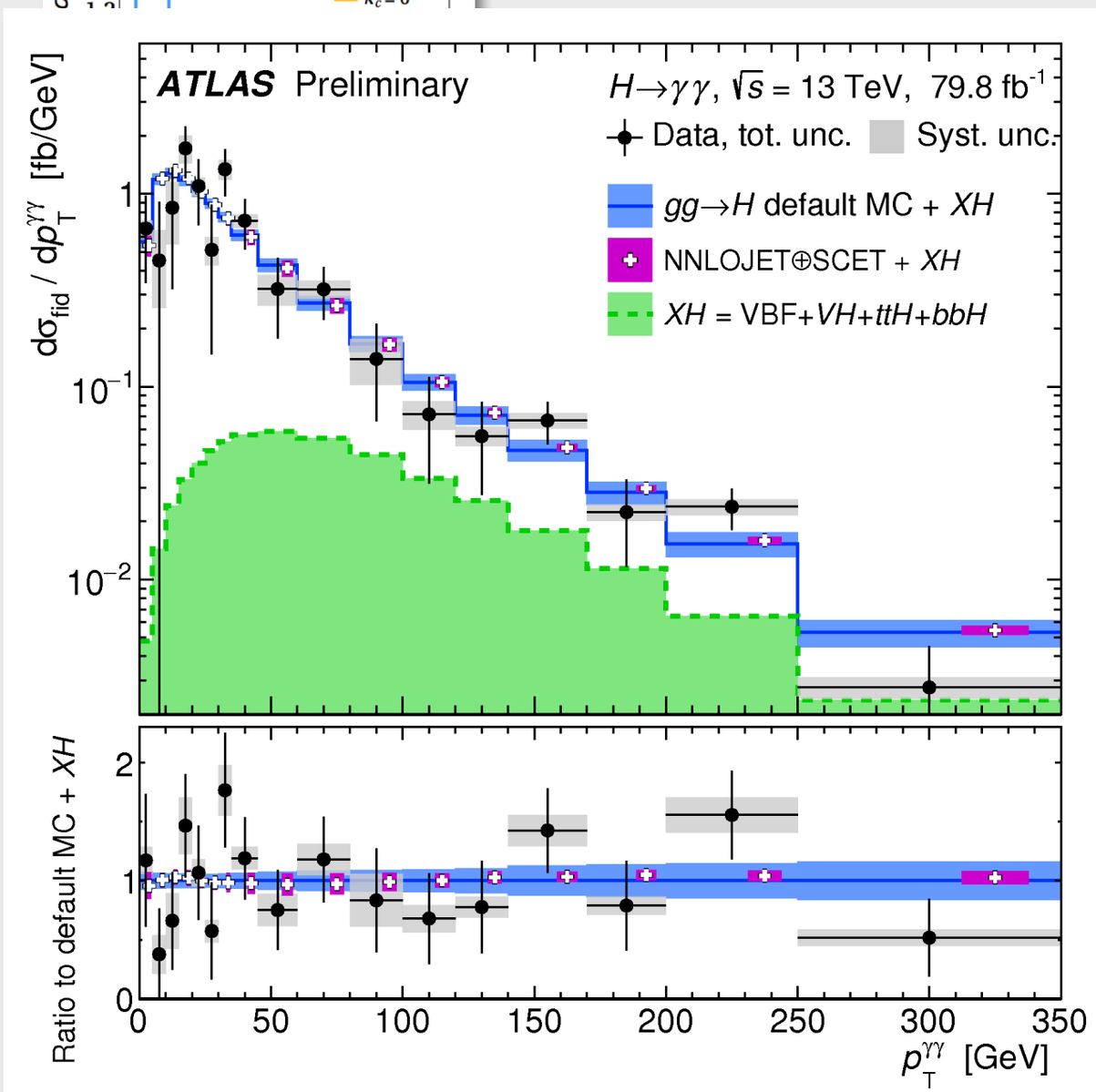
Boosted

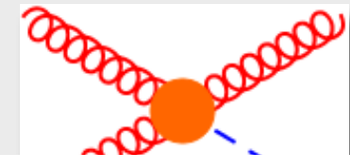
ggH vs ttH, EFT…

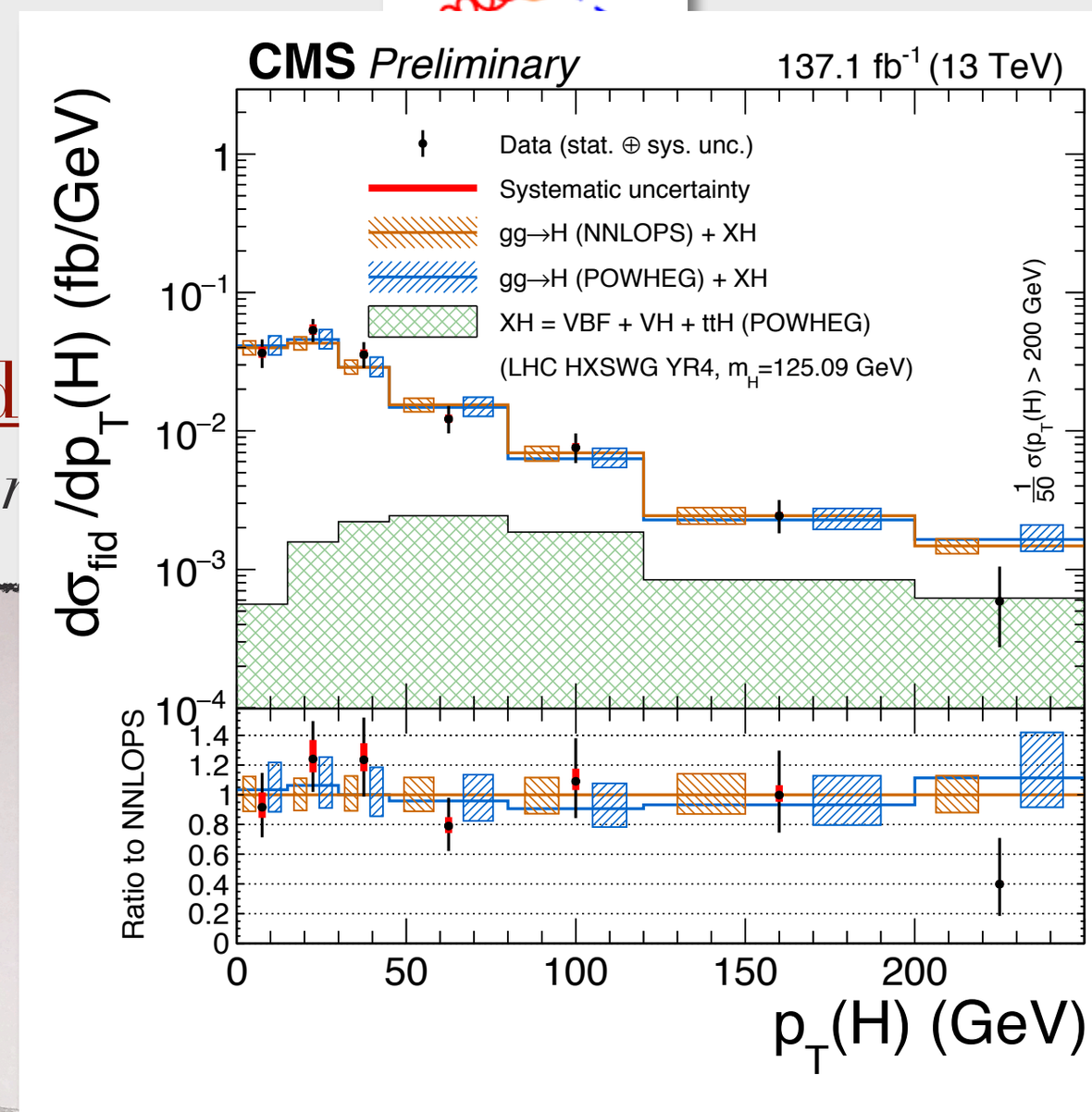


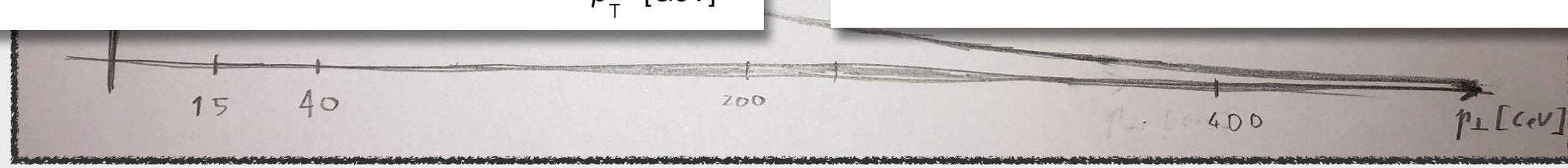
Disclaimer: *some illustration from each region, mostly focusing on ggF*

$p_{t,H}$: a major probe for Higgs physics









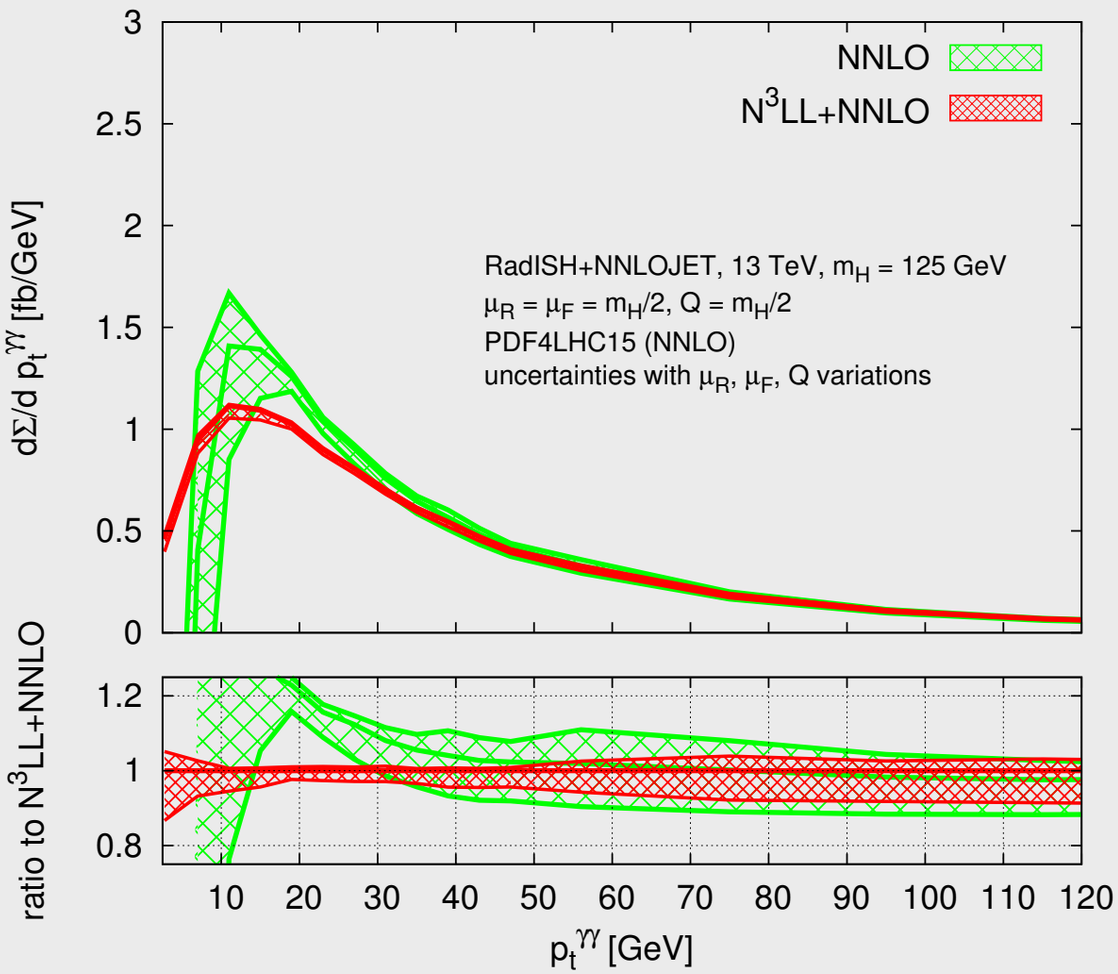
<u>Disclaimer</u>: *some illustration from each region, mostly focusing on ggF*

The bulk of the distribution: NNLO+N³LL

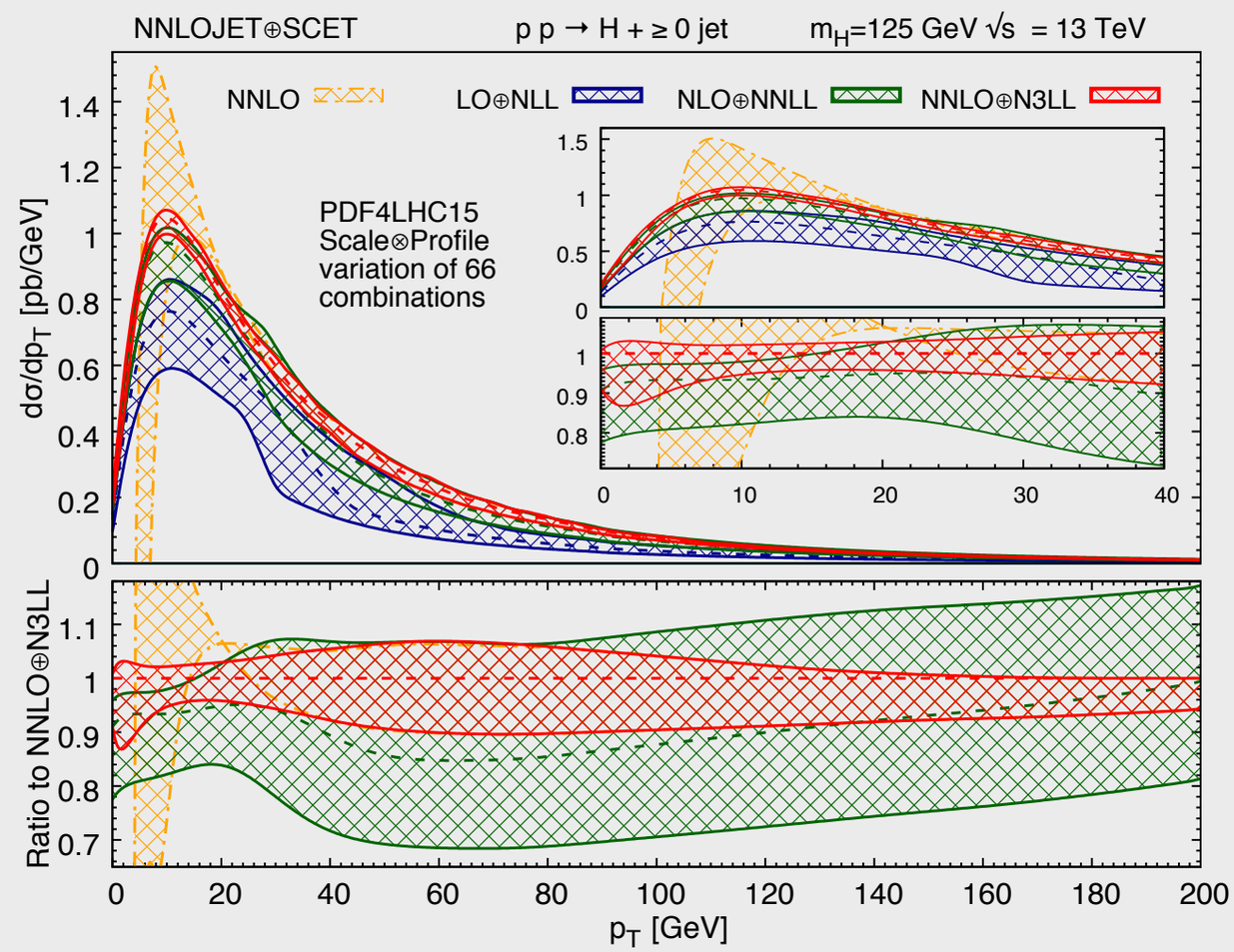
- $p_t \ll m_t$: *ggF*, point-like interaction
  (*m_t-suppressed terms under good control see e.g.* [Neumann et al (2016)])

- Very refined theoretical predictions
  - $p_{t,H}$ known at NNLO QCD [Boughezal et al. (2015) x2, Chen et al (2015)].
    Fully validated
  - small p_t: matched against resummation to extend down to $p_t \sim 0$.
    Two different methods

The bulk of the distribution: NNLO+N³LL



[Bizon et al. (2018)]

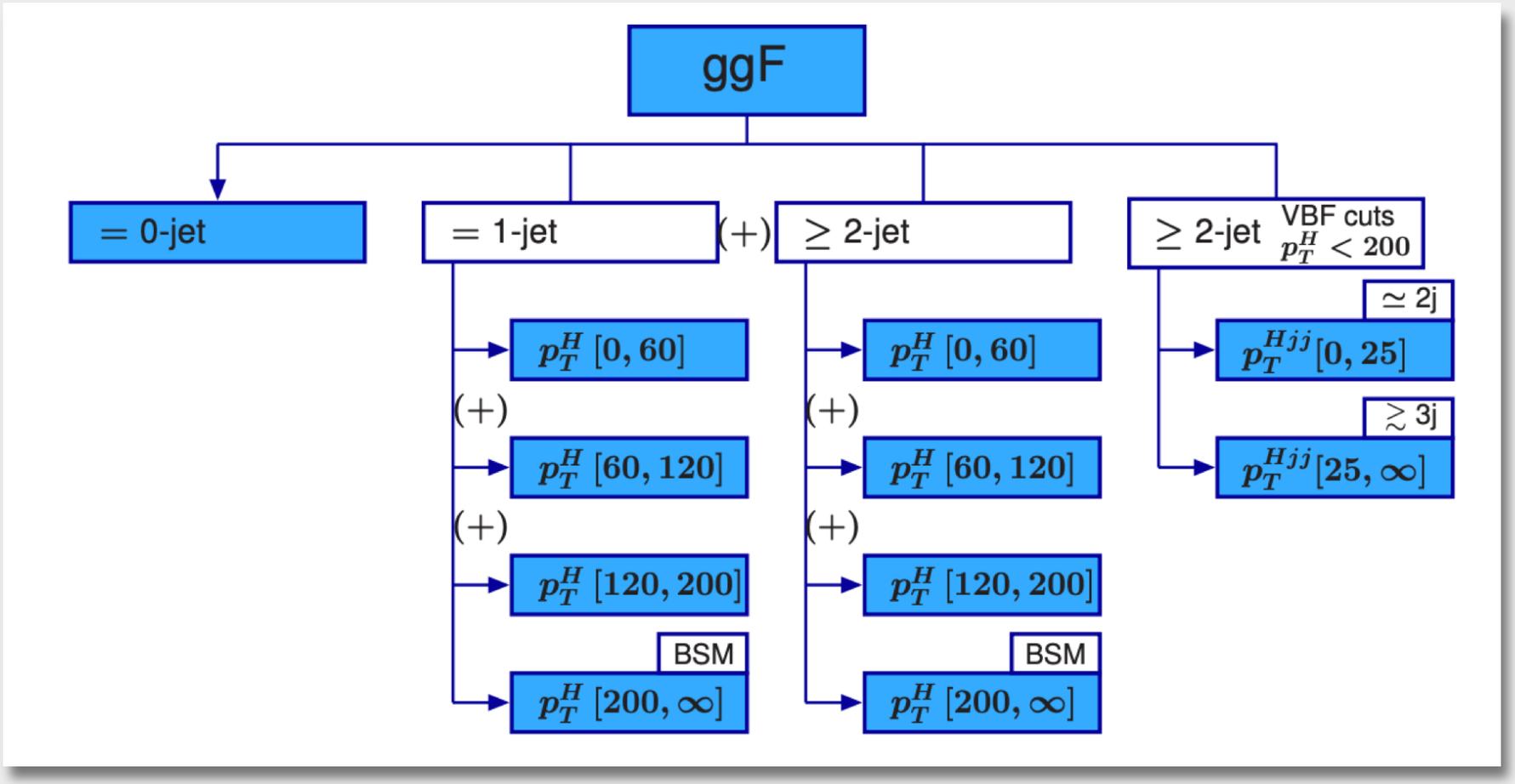


[Chen et al. (2018)]

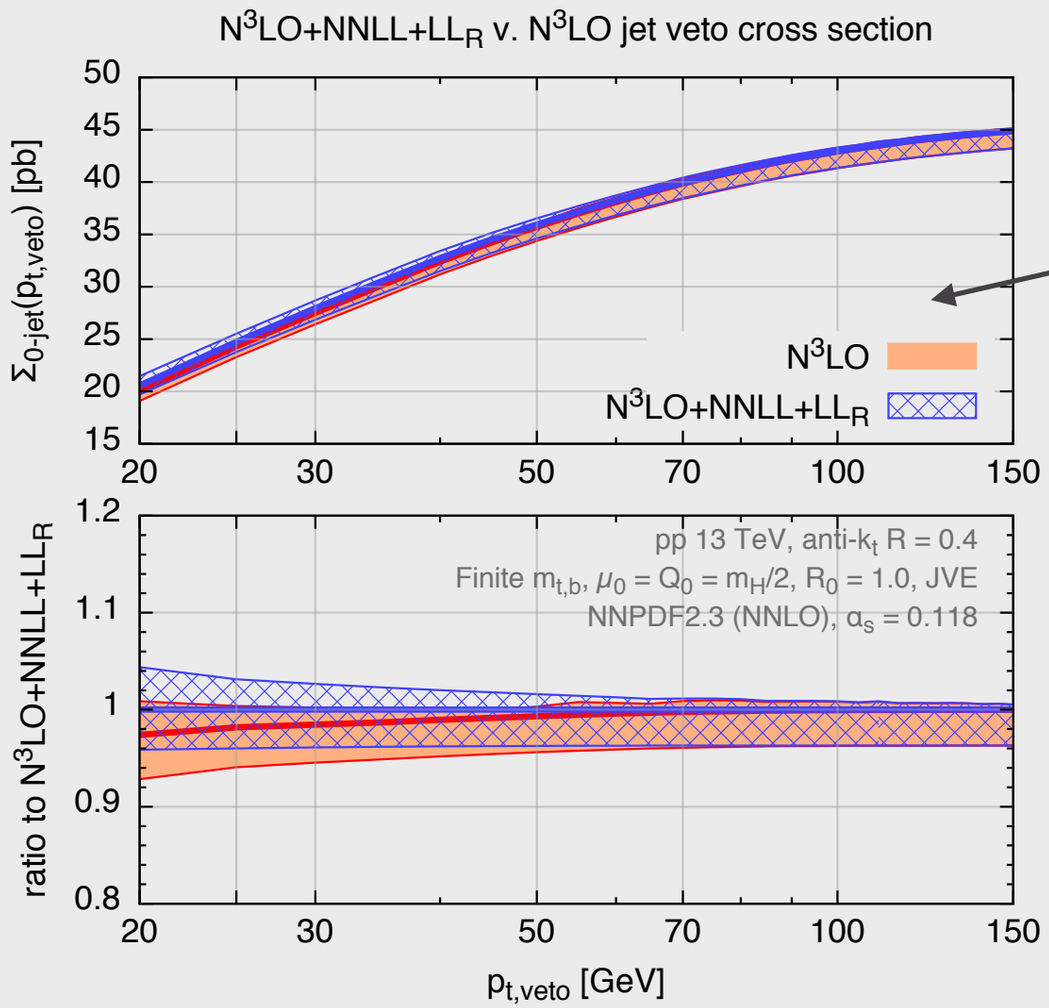
- Same f.o. + resummation accuracy, different matching procedure → test for robustness
- By and large: very stable result, f.o. OK down to ~40 GeV → very good control in the bulk of the distribution

Not the end of the story I: more differential

Eventually interested in more differential information, e.g. jet-binned p_t distributions



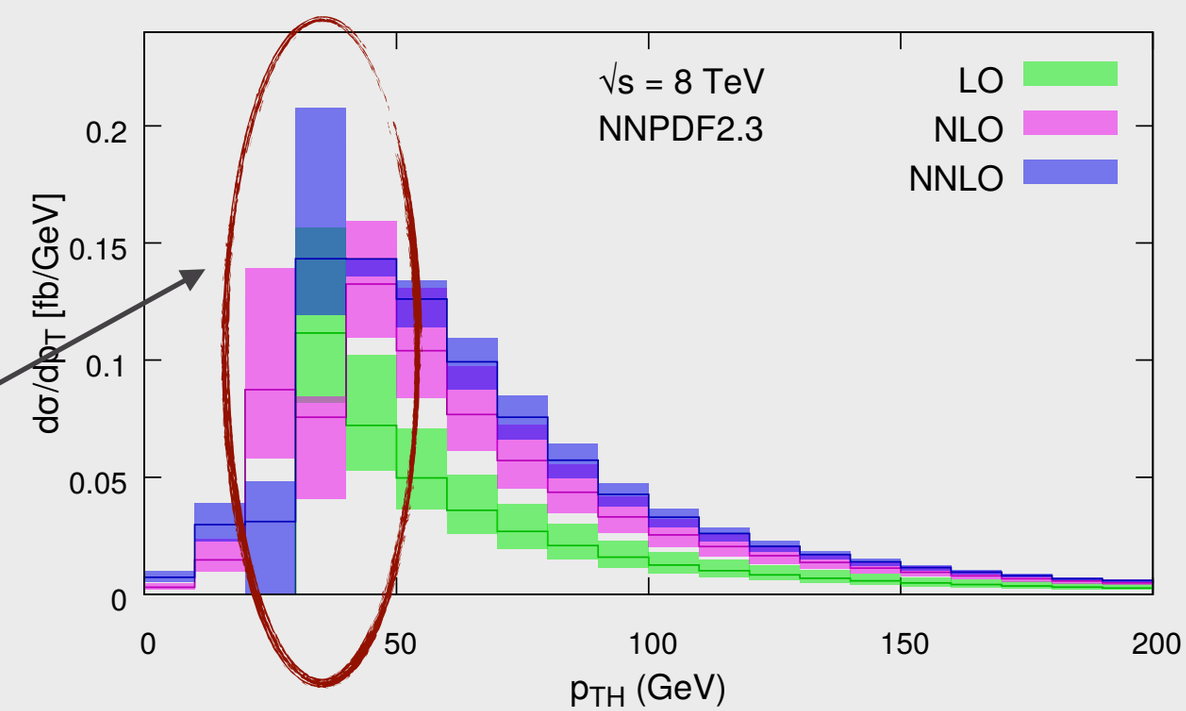
Not the end of the story I: more differential



Jet-vetoed cross-section under very good theoretical control…
[Banfi et al. (2015)]

… but f.o. jet-binned $d\sigma/dp_t$ has unphysical features *(would require all-order considerations)*

[some work in this direction: Sun et al (2016)]

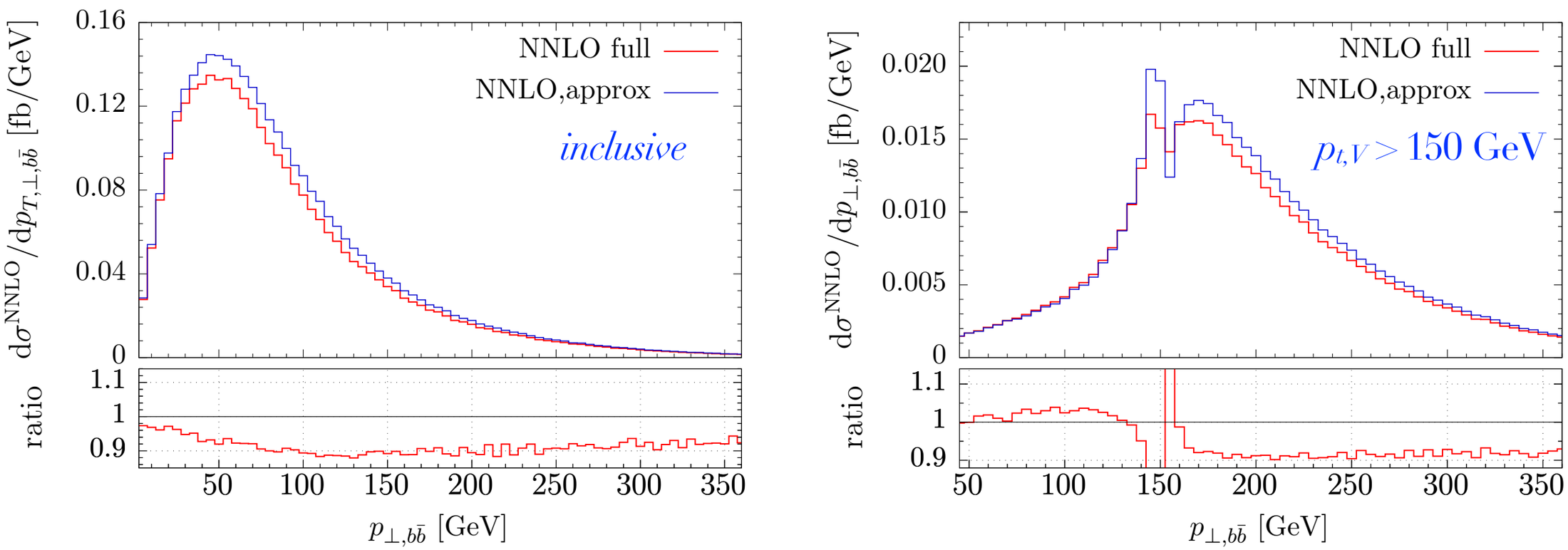


Not the end of the story II: realistic final states

Consider VH, H → $b\bar{b}$

- Typical $p_{t,V}$ ~ 150-250 GeV → Higgs only semi-boosted
- QCD radiation pattern from H→$b\bar{b}$ non trivial
- $NNLO_{prod}$ x $NNLO_{dec}$ known [Ferrera et al.; FC et al. (2018)]→ *can explore*

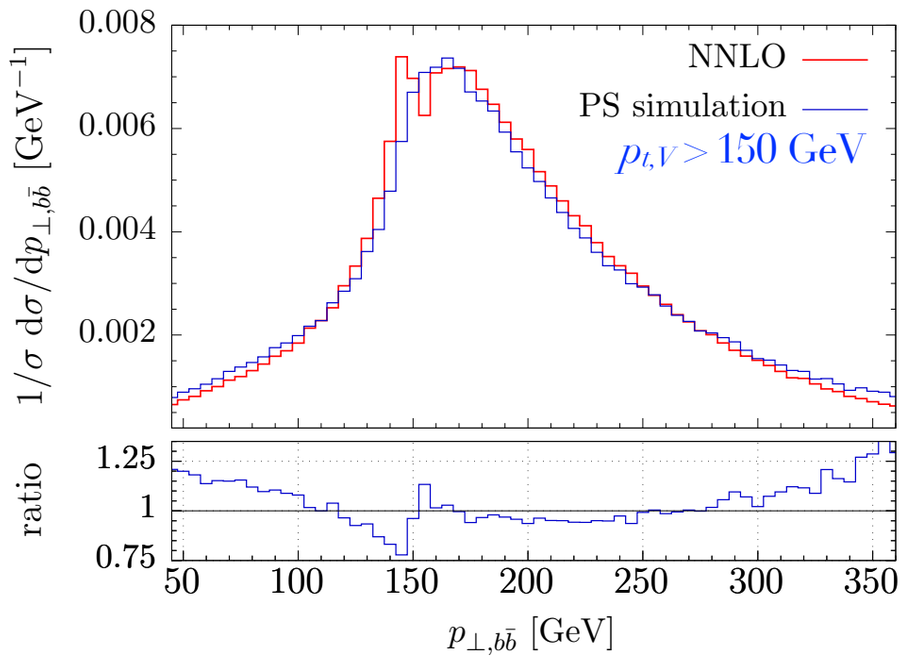
WH, Reconstructed Higgs p_t, NLO_{dec} vs $NNLO_{dec}$



$VH, H \to b\bar{b}$

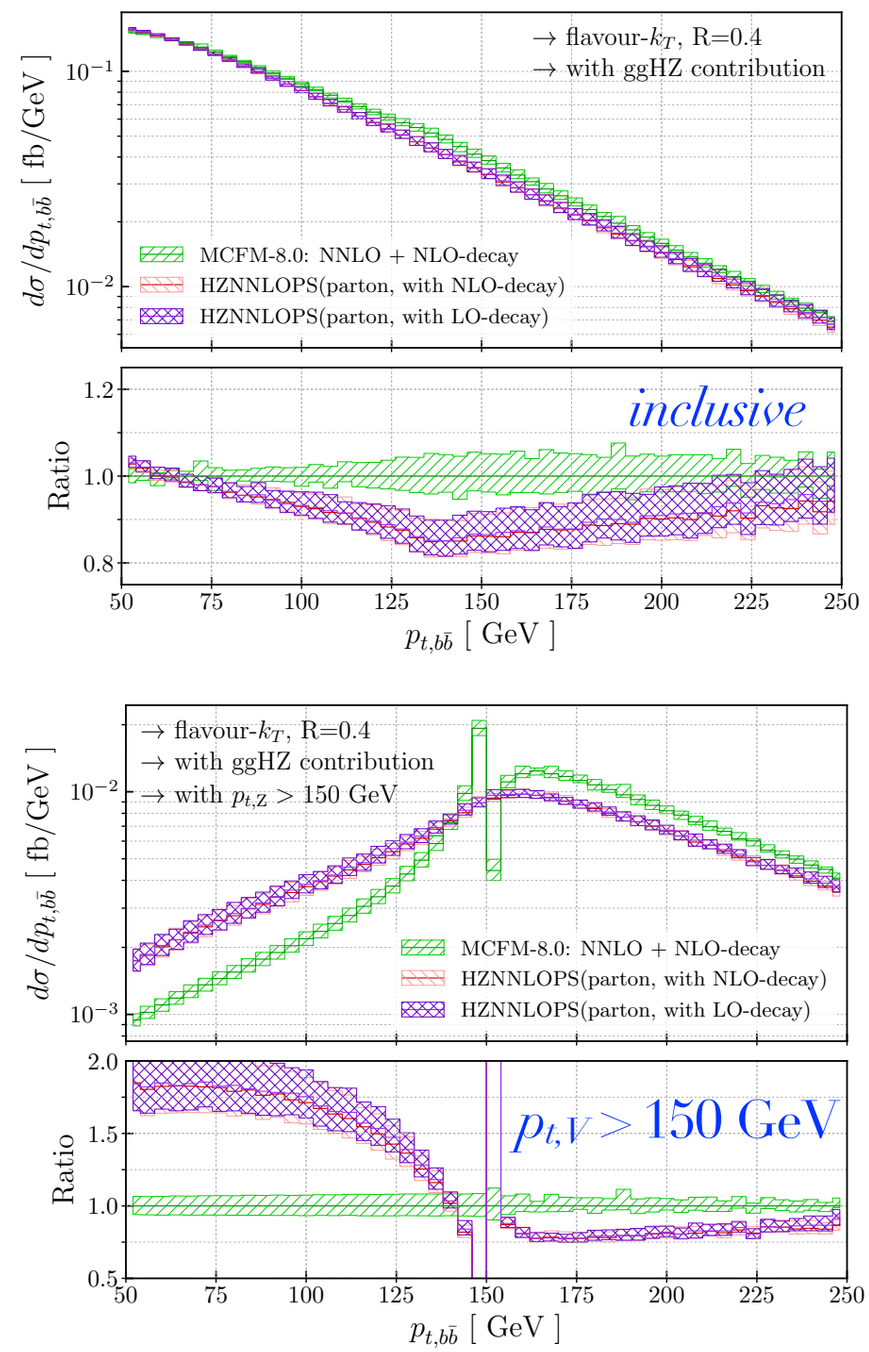
How well is the radiation pattern described by PS?

WH, NNLO vs *off-the-shelf* PS



[FC et al (2018)]

ZH, NNLOPS + NLO$_{dec}$ vs f.o.

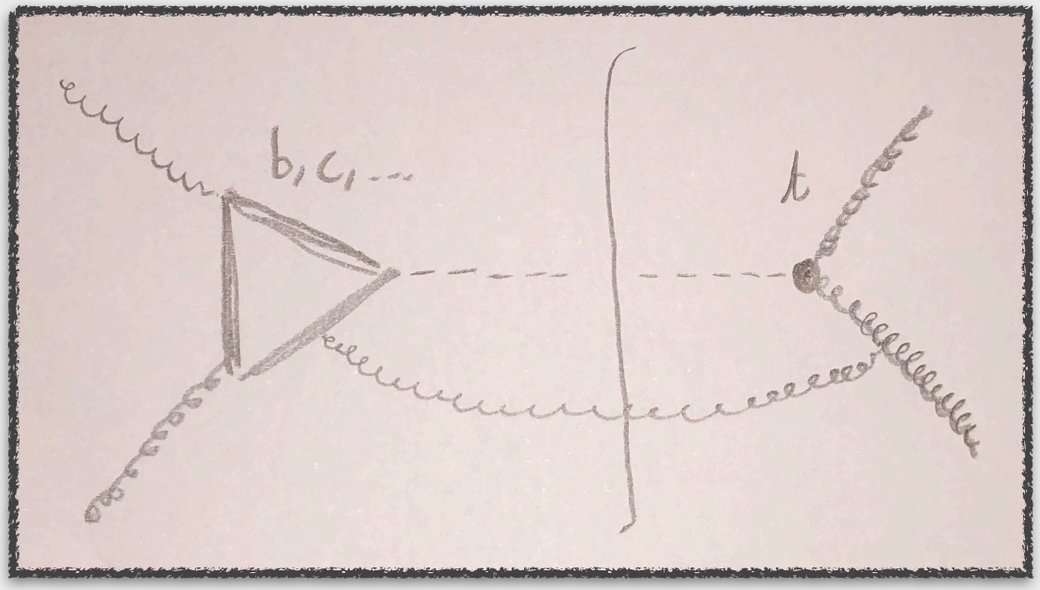


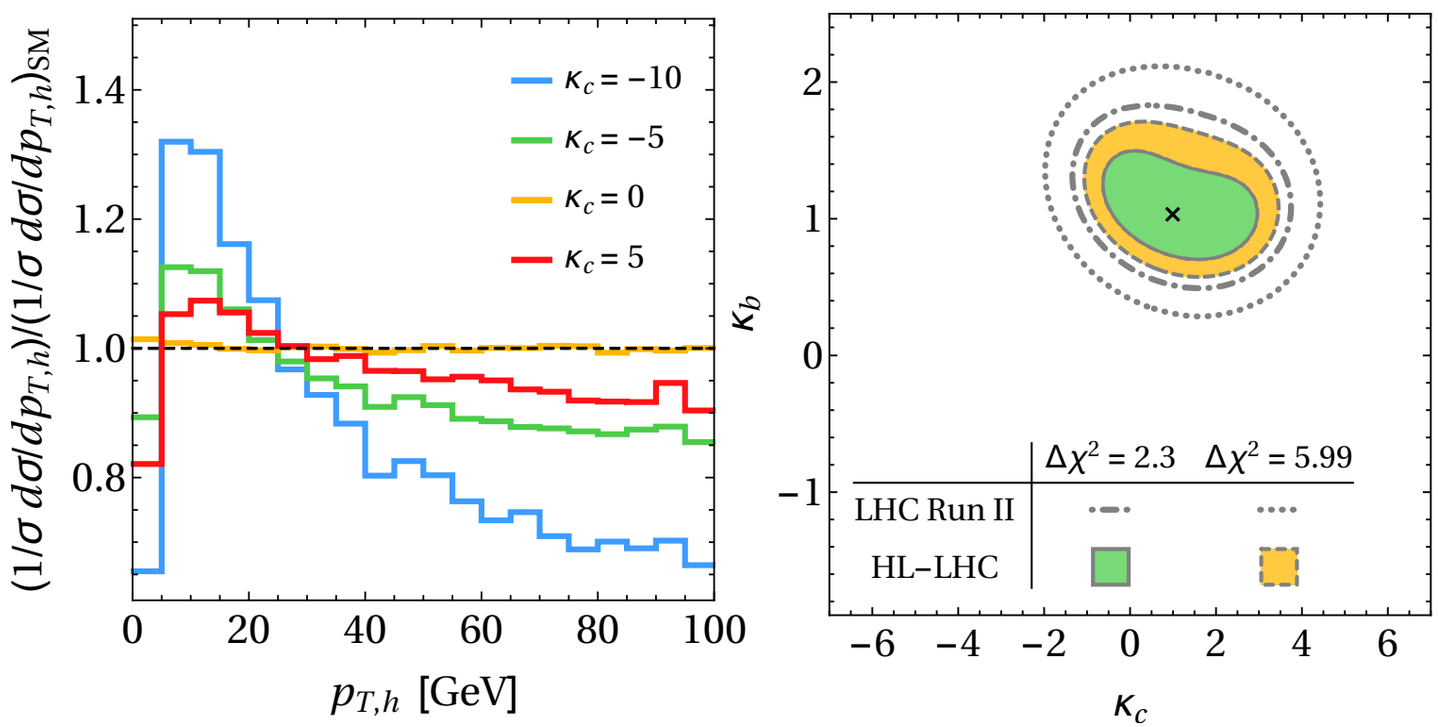
[Astill et al (2018)]

- PS seems to capture *some* of the radiation pattern
- Delicate issues about HF-identification (b-tagging vs flavour k_t)
- More apple-to-apple investigations desirable (*massive b*…)

Low p_t: light quark effects

- For $m_q \ll p_t \ll m_H$: amplitude develops non-Sudakov double logs
  $y_q m_q / m_H \left[\ln^2(m_H^2/m_q^2), \ln^2(p_t^2/m_q^2) \right]$
- Despite $y_{b,c\ldots} \ll y_t$, interference effects may be visible → *constrain light Yukawas!*





[Bishara et al. (2017)]

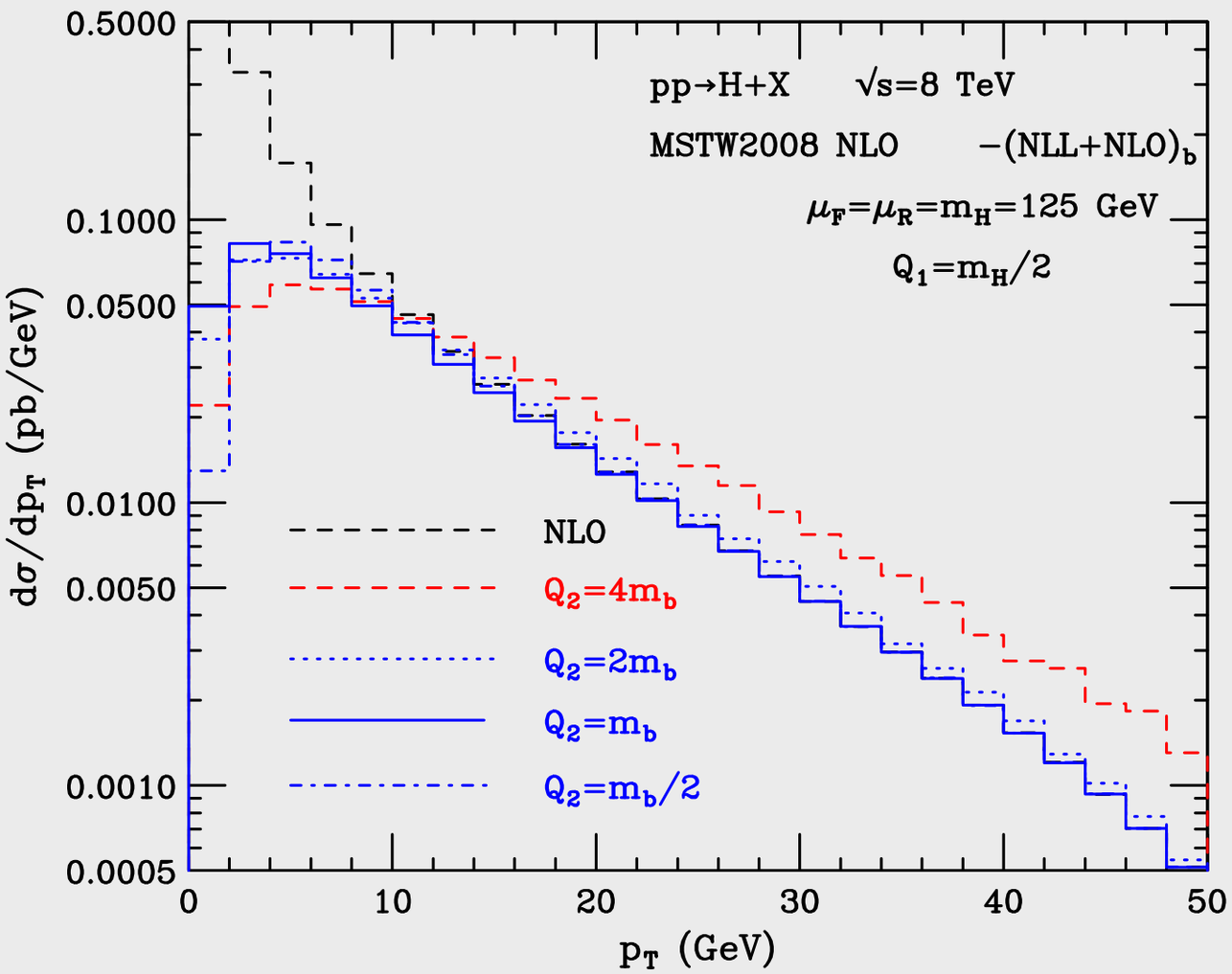
PROBLEM: control over QCD corrections

- resolved quark loop → difficult loop amplitudes
- low p_t → all-order effects

t/b interference: not so long ago

- *tb* interference only known at LO
- non trivial interplay with collinear gluons → don't know how to resume all-order effects at low p_t
- not enough information for a proper f.o. / resummation matching

[Grazzini, Sargsyan (2013)]



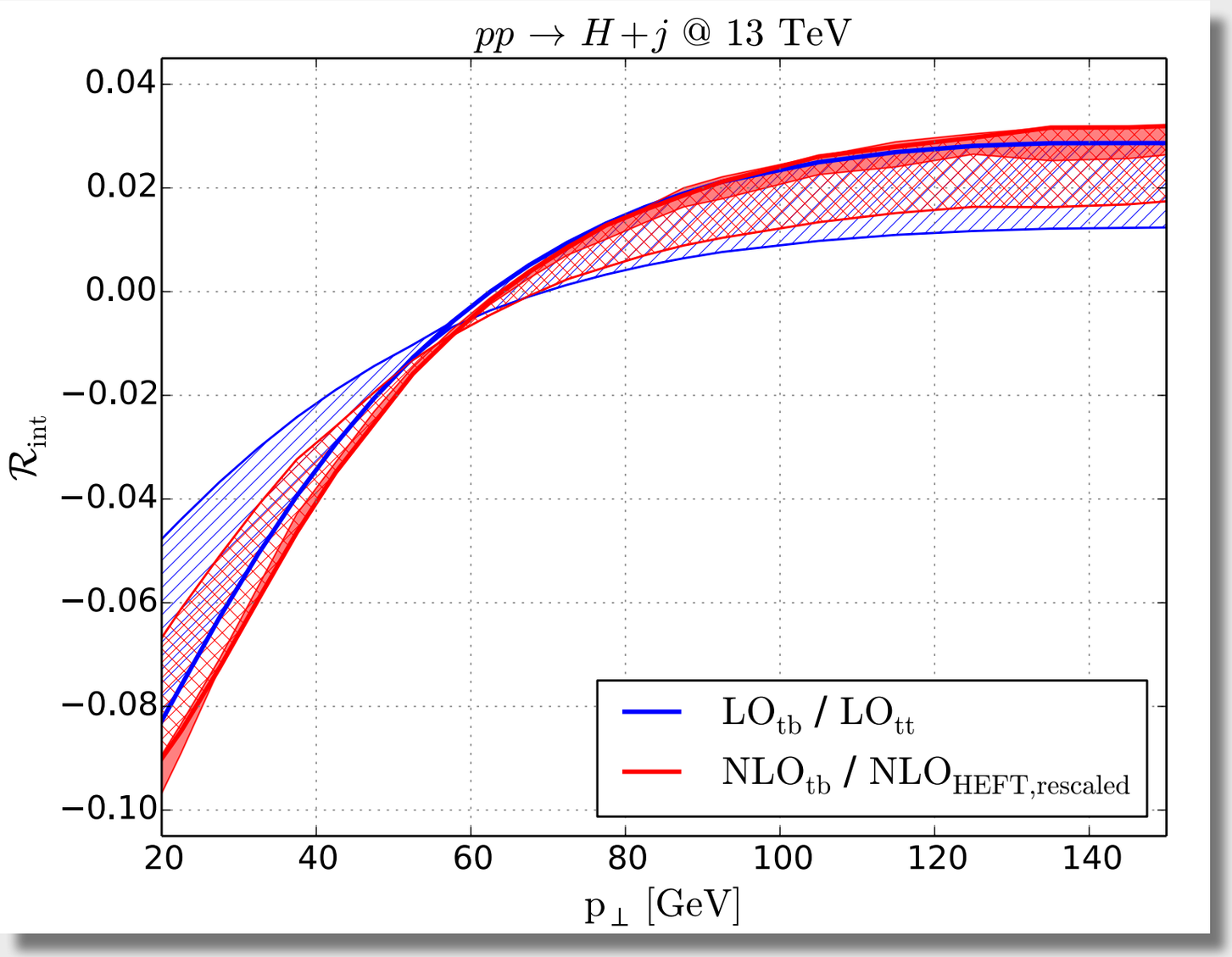
A pragmatic approach

- use all the available information
- resum under 2 extreme assumptions:
  - ✳*b/t* contributions on the same footing
  - ✳*no resummation after* $p_t \sim m_b$
- Large residual uncertainties

t/b interference: NLO

- 2-loop amplitude for b contribution computed in the limit $m_b \ll p_t \ll m_h$
- Approximation expected to be very good for all pheno applications

[Lindert et al. (2017)]

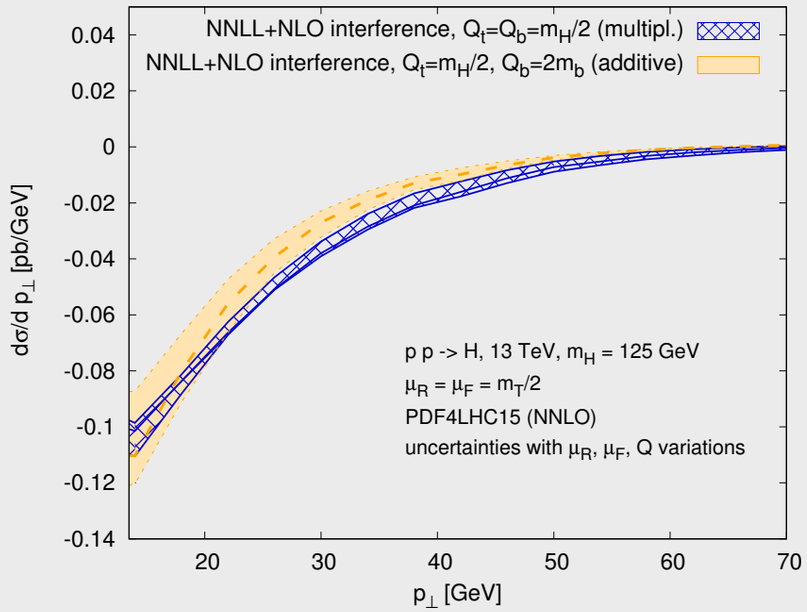


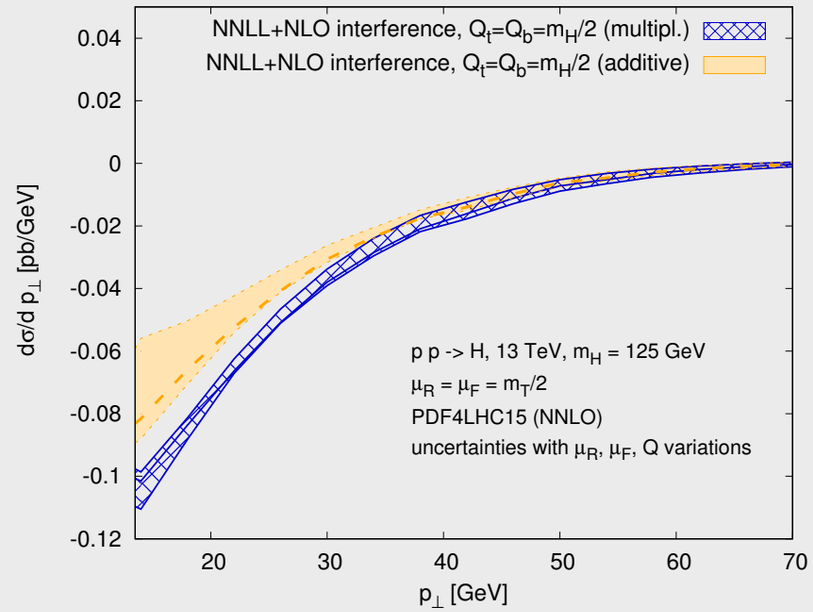
- Large K-factor…
- … but similar to HEFT
- Large source of unc. from b-mass scheme
- Non-trivial logarithmic structure
- <u>Still don't know how to resum</u> [some work in this direction: Melnikov, Penin (2016); Forte et al (2016); Penin, Liu (2018)]

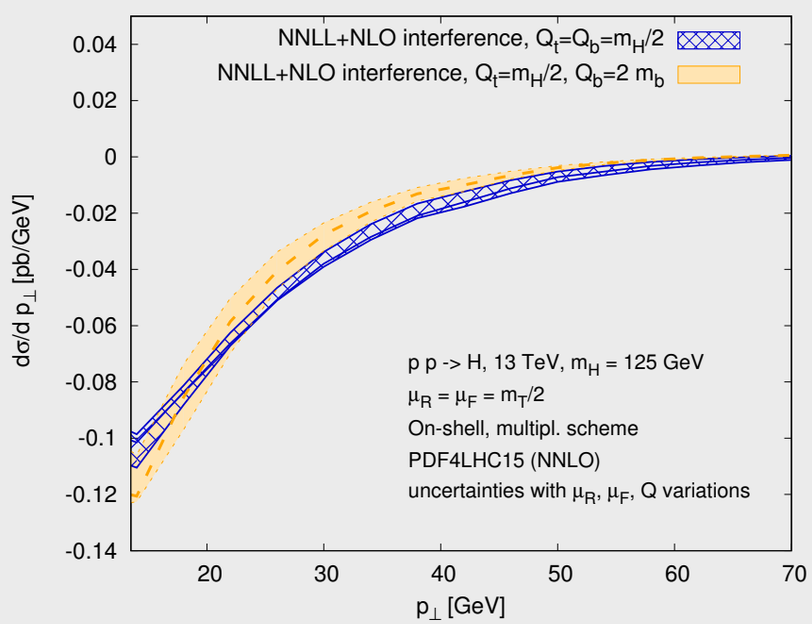
t/b interference: matching with resummation

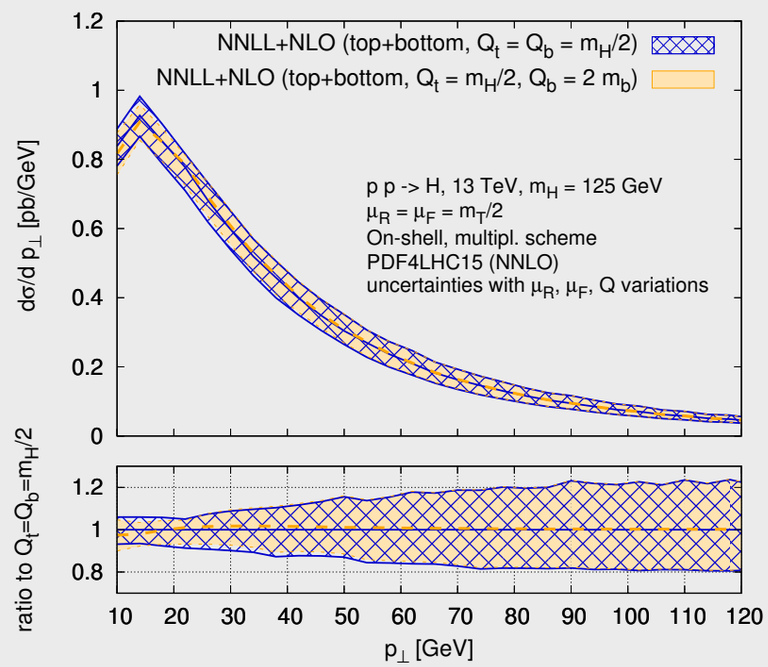
[FC, Monni et al. (2018)]

NLO result allows for a proper matching → resummation ambiguities much less severe





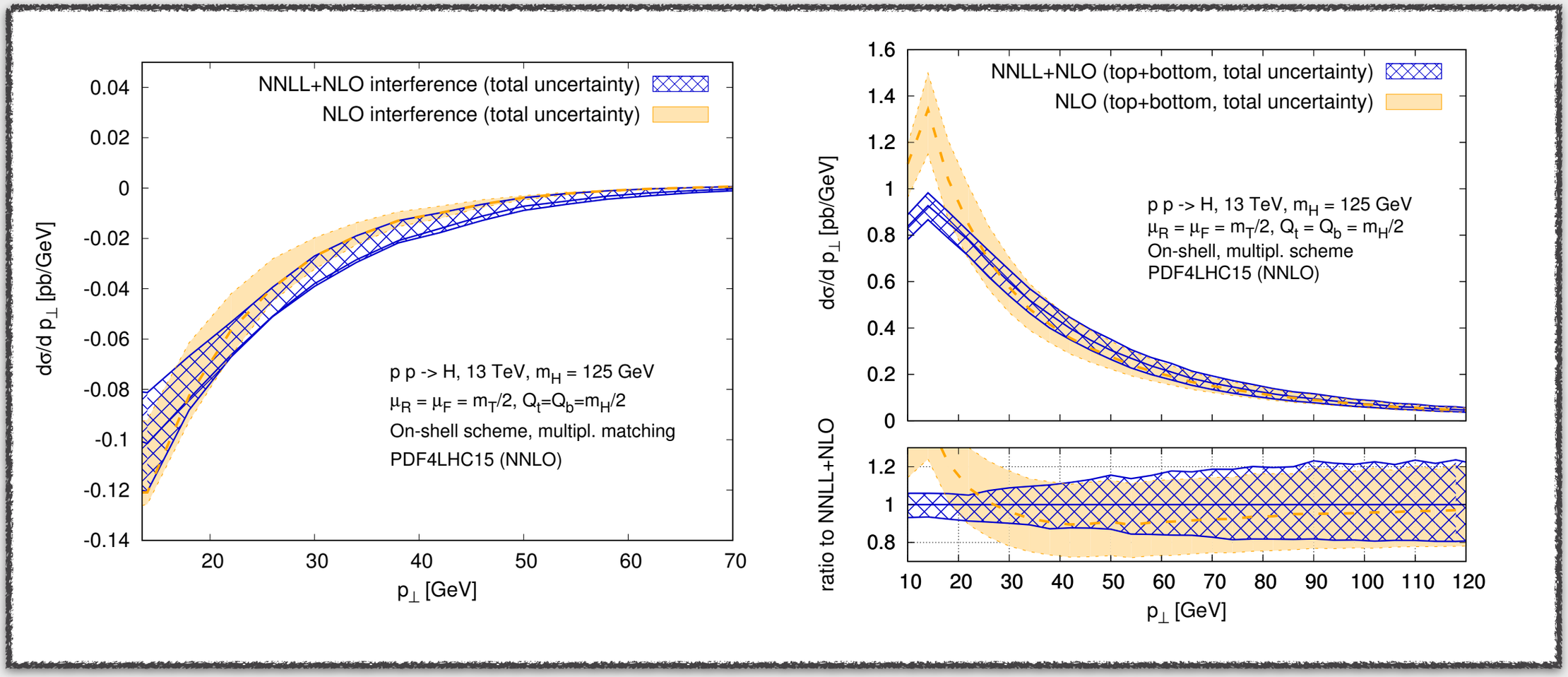




t/b interference: matching with resummation

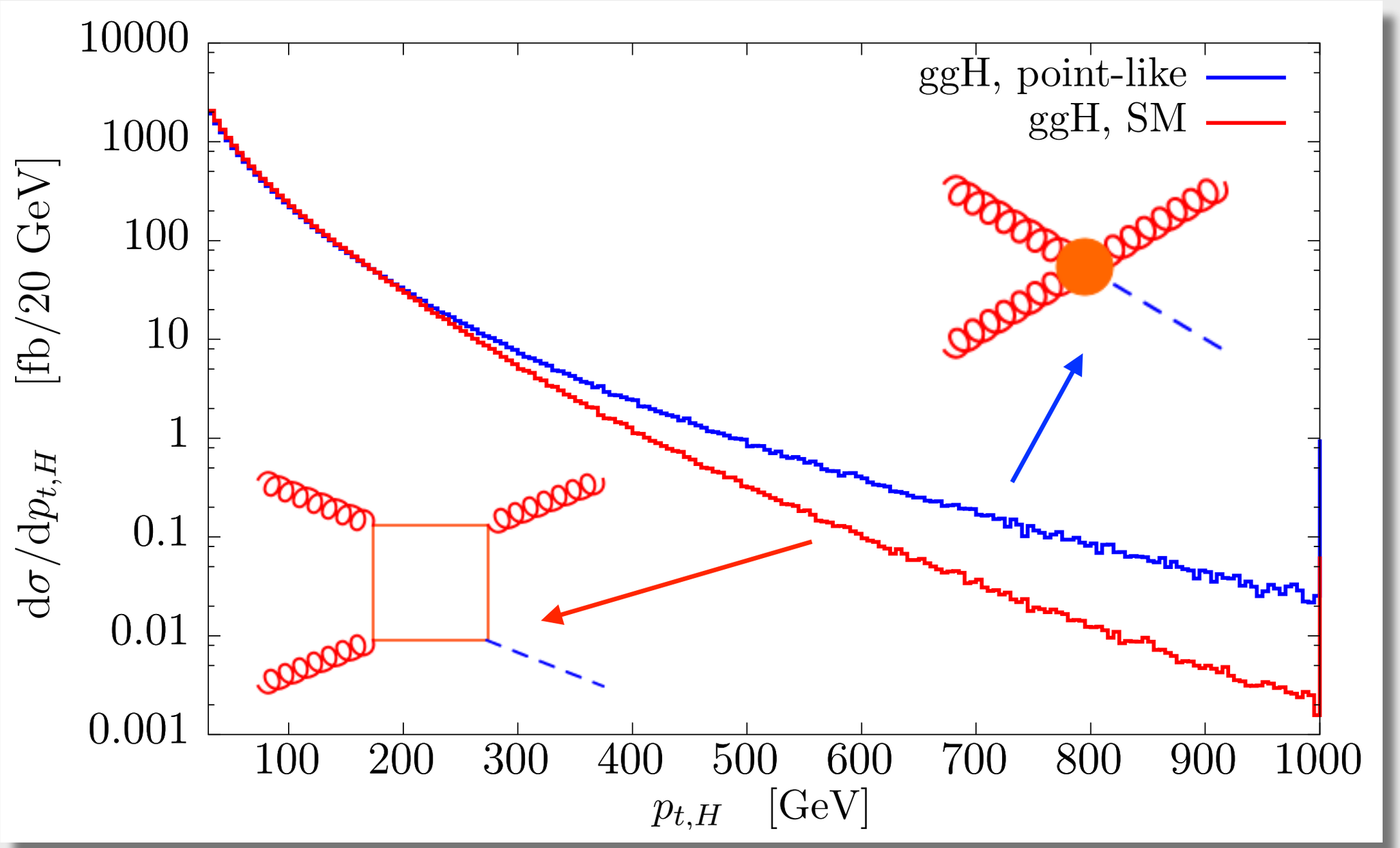
[FC, Monni et al. (2018)]

Reasonable control over *t/b* interference

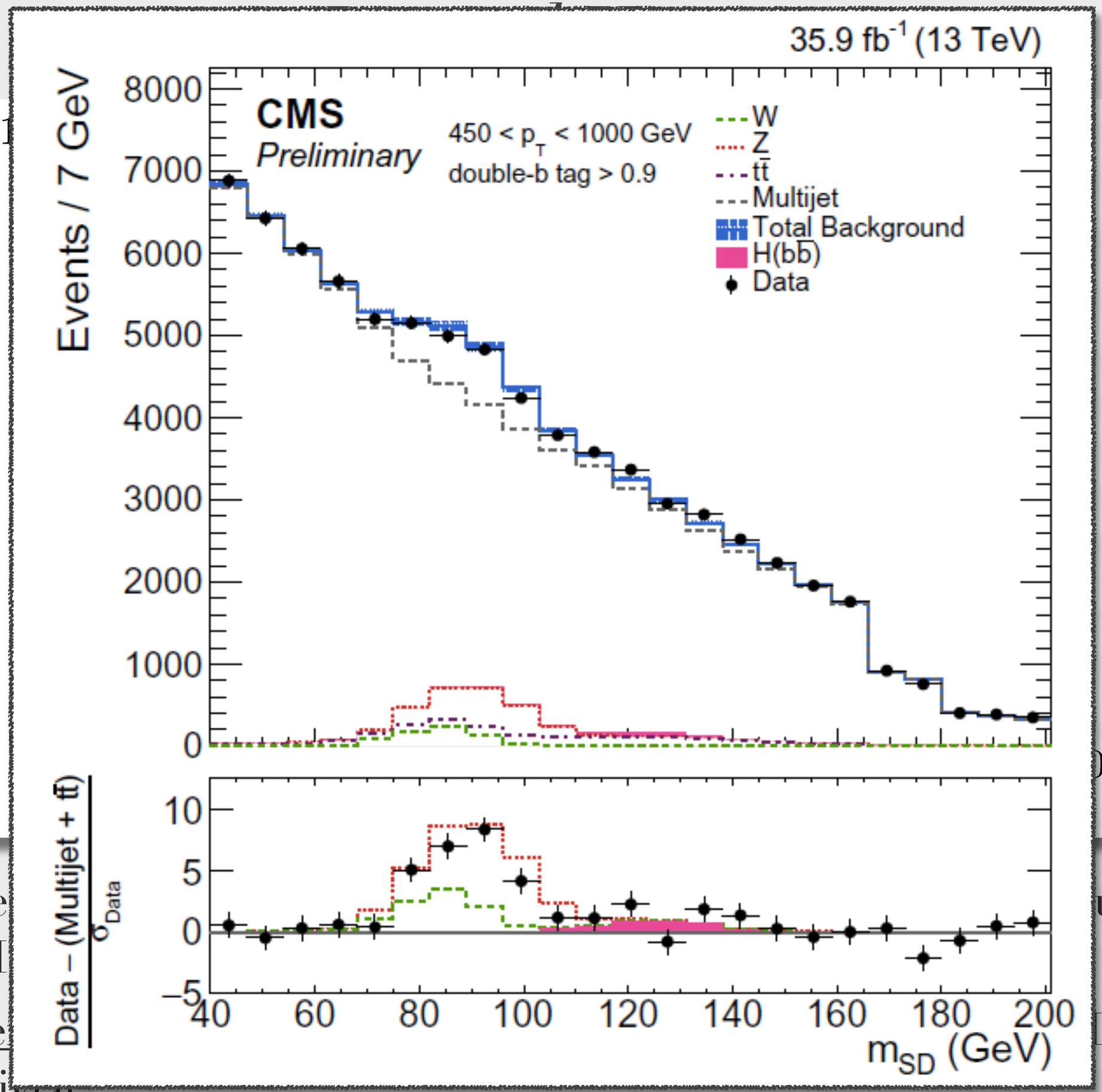


- Major source of uncertainty from *b*-mass scheme → can only be improved with higher order calculation
- <u>It will be very hard to improve in this direction</u>

Boosted Higgs



- Boosted Higgs very sensitive to BSM contributions, internal structure of ggH coupling
- <u>Problem</u>: very difficult (multi)-loop amplitudes. Going beyond LO non trivial



$d\sigma/dp_{t,H}$ [fb/20 GeV]

00

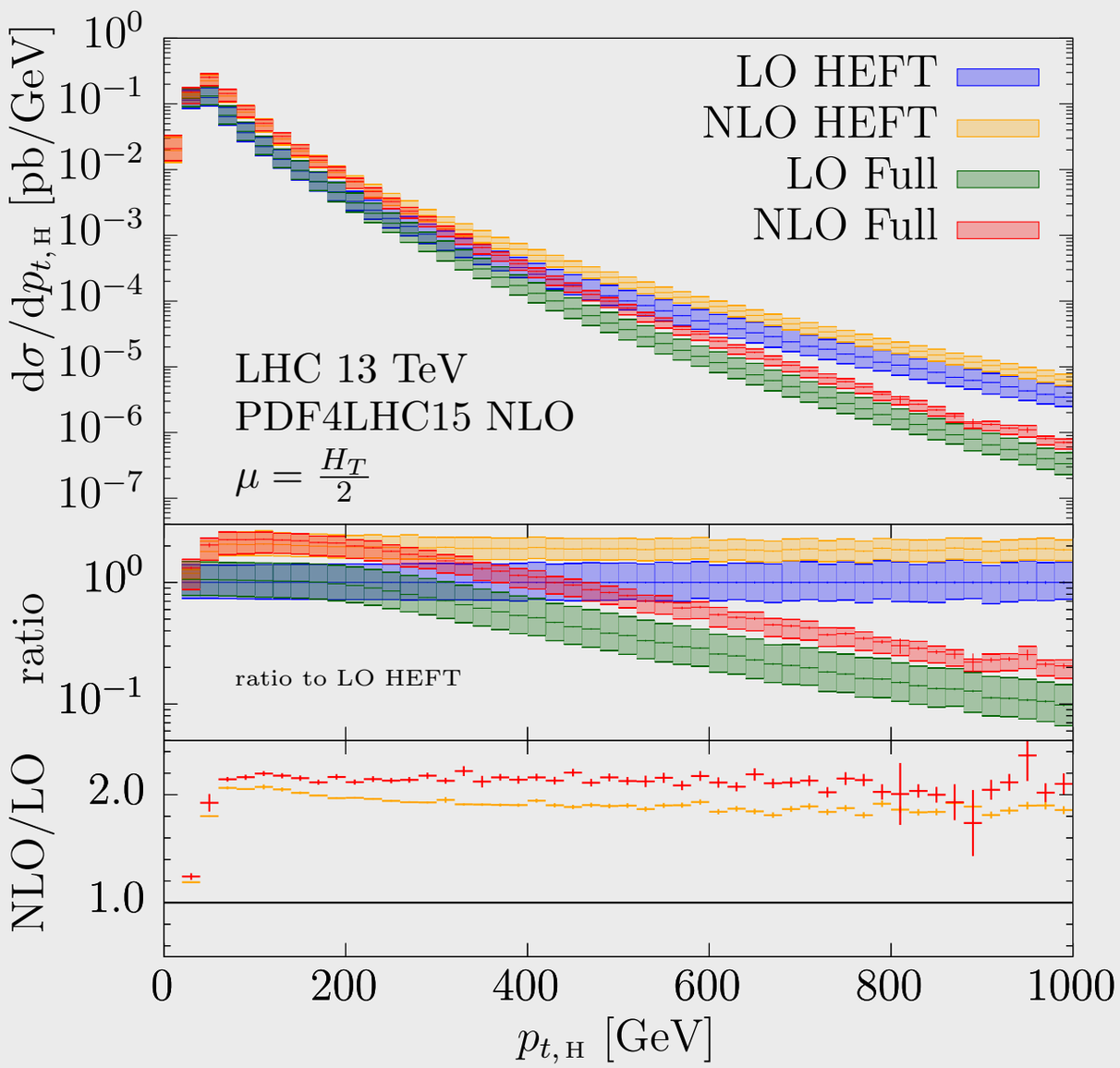
- Booste ucture of ggH
- Proble LO non trivi

Boosted Higgs: NLO

NLO is finally known. 2 approaches:

- analytic result under the assumption $m_{t,h} \ll p_t$ [Kudashkin et al. (2017-18)]
- exact numerical result [Jones, Kerner, Luisoni (2018)]

They agree within expectation → important validation

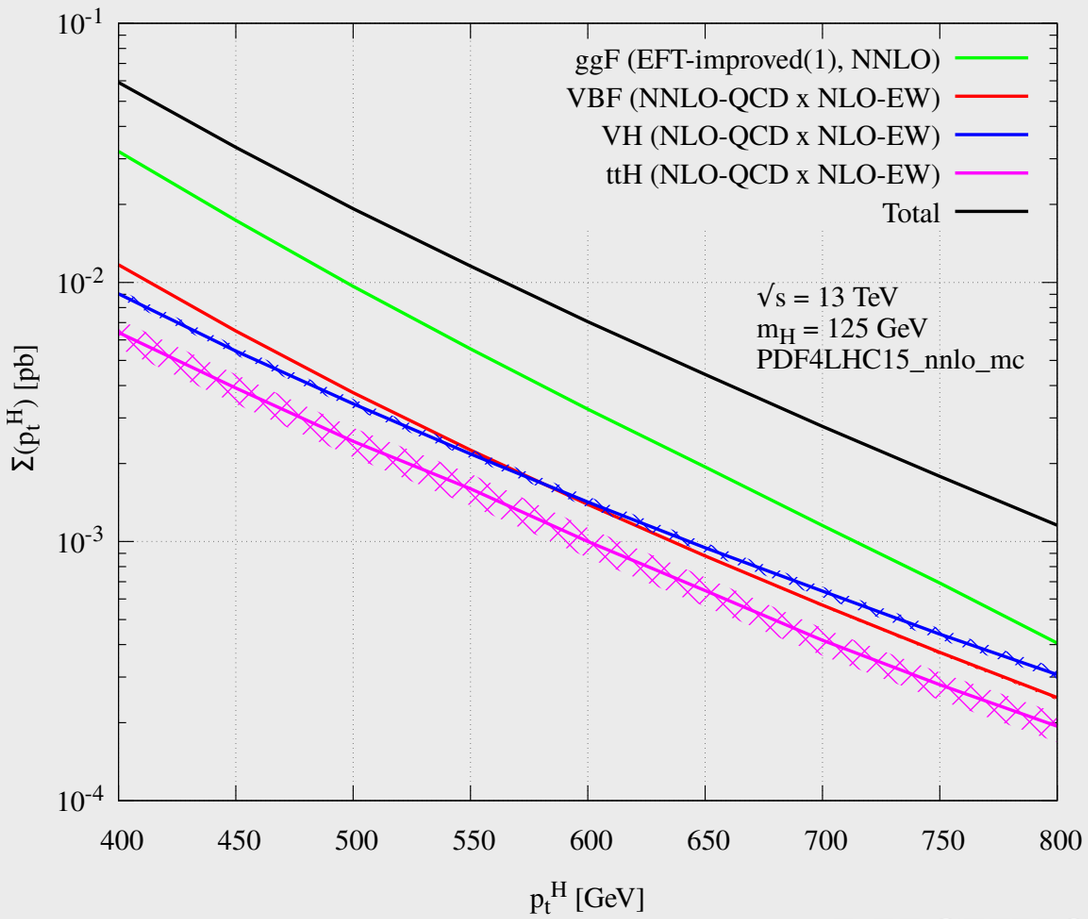


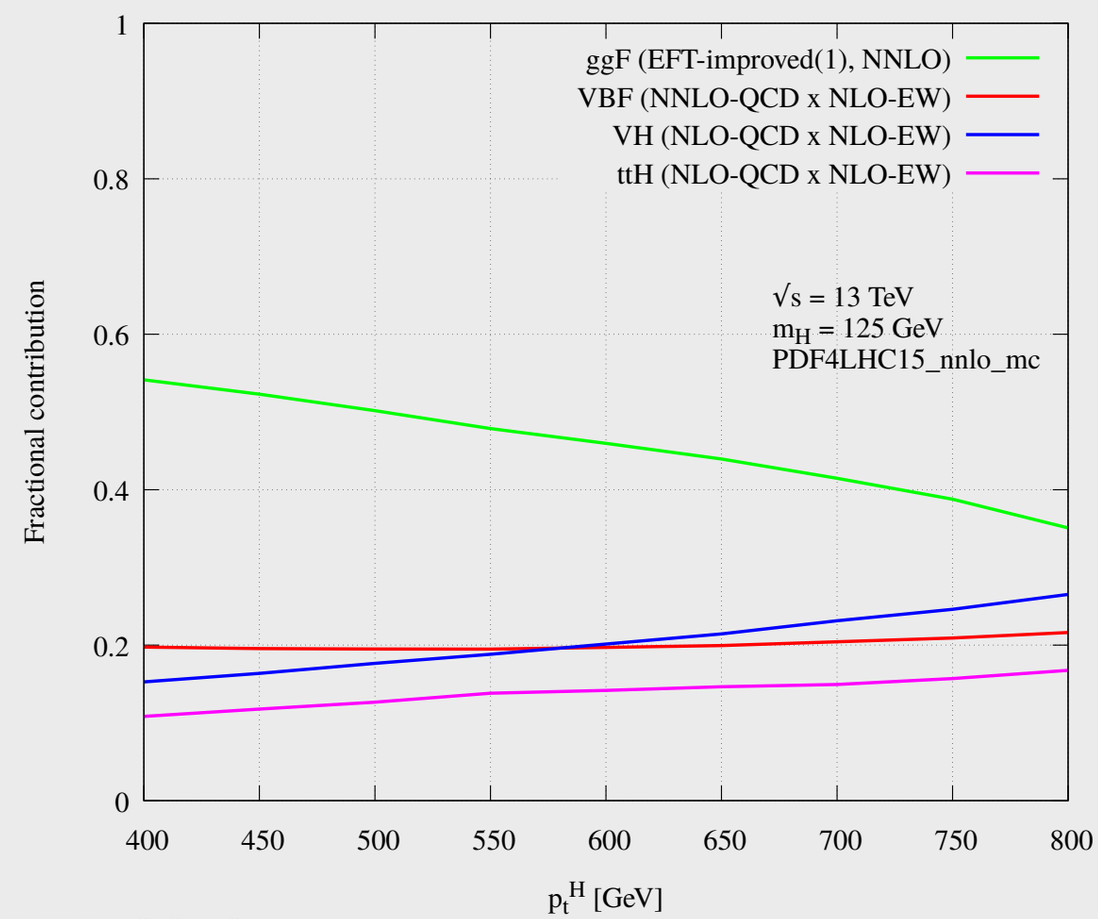
- Large *K-factor*
- Very similar to HEFT *K-factor* *confirming expectations from merged samples approach* [see e.g. Frederix et al (2016), Greiner et al (2016)], *approximate m_t treatment* [see e.g. Neumann and Williams (2016)] *and resummation analysis* [see e.g. Muselli et al (2016)]

Can combine with NNLO HEFT K-factor

Boosted Higgs: all channels

Boosted Higgs: other channels become more relevant





LHCHXSWH (2019)

- Interesting interplay of different channels. Different pattern of radiative corrections
- <u>NLO EW corrections in ggF? $\ln^2(p_t/m_t)$?</u>

Boosted Higgs: state of the art vs practice

Shower effects small, as they should

	Fixed order level	Total	$p_T^H > 400$	$p_T^H > 450$	$p_T^H > 500$
1	$\mathrm{gg\_h}^{\mathrm{hfact=104}}_{\mathrm{m_t=\infty}}$	$30.3^{36.4}_{25.6}$	0.0730	0.0507	0.0362
2	HJ $m_t = \infty$ 5 GeV gen cut	–	0.0643	0.0413	0.0278
3	HJ $m_t = \infty$ 50 GeV gen cut	–	0.0644	0.0416	0.0277
4	HJ-MiNLO $m_t = \infty$	$32.1^{43.1}_{27.2}$	0.0778	0.0509	0.0343
5	HJ-MiNLO $m_t = 171.3$	$33.8^{45.2}_{28.6}$	0.0281	0.0153	0.0089

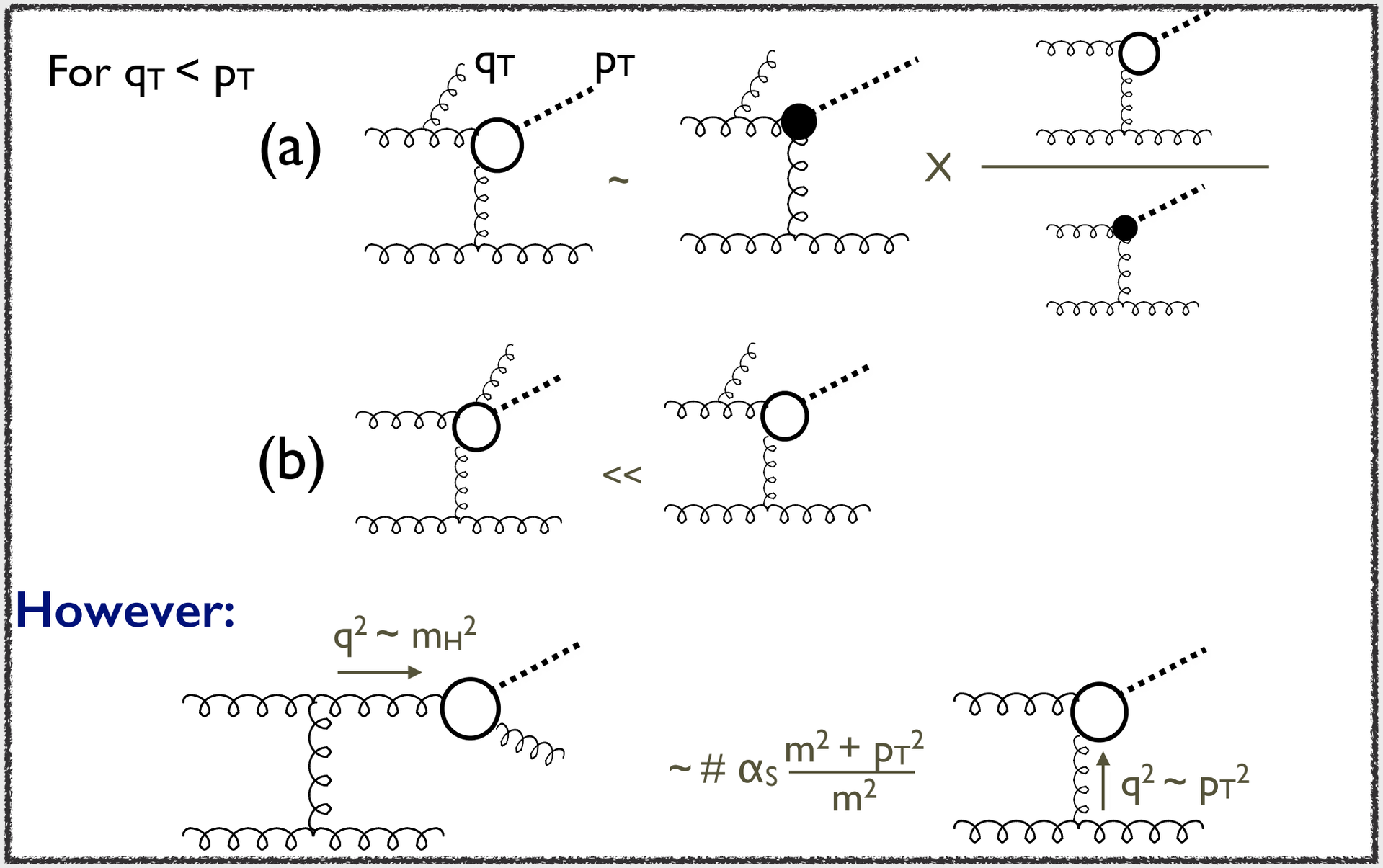
	PS-level	Total	$p_T^H > 400$	$p_T^H > 450$	$p_T^H > 500$
1	$\mathrm{gg\_h}^{\mathrm{hfact=104}}_{\mathrm{m_t=\infty}}$	$30.3^{36.4}_{25.6}$	$0.0829^{0.1280}_{0.0563}$	$0.0577^{0.0902}_{0.0387}$	$0.0408^{0.0644}_{0.0271}$
2	HJ $m_t = \infty$ 5 GeV gen.cut	–	$0.0651^{0.0807}_{0.0520}$	$0.0417^{0.0517}_{0.0333}$	$0.0279^{0.0346}_{0.0222}$
3	HJ $m_t = \infty$ 50 GeV gen.cut	–	$0.0651^{0.0807}_{0.0520}$	$0.0418^{0.0518}_{0.0333}$	$0.0278^{0.0344}_{0.0222}$
4	HJ-MiNLO $m_t = \infty$	$32.1^{43.1}_{27.2}$	$0.0803^{0.0989}_{0.0639}$	$0.0524^{0.0642}_{0.0417}$	$0.0353^{0.0431}_{0.0281}$
5	HJ-MiNLO $m_t = 171.3$	$33.7^{45.2}_{28.6}$	$0.029^{0.036}_{0.023}$	$0.0161^{0.0197}_{0.0128}$	$0.0091^{0.0112}_{0.0073}$

Central value for merged samples (✔) and PS (?) in good agreement with state-of-the-art predictions

p_T^{cut}	$\mathrm{NNLO}^{\mathrm{approximate}}_{\mathrm{quad.unc.}}$ [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	$17.4^{+8.9\%}_{-11.5\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

Boosted Higgs: an interesting theoretical puzzle

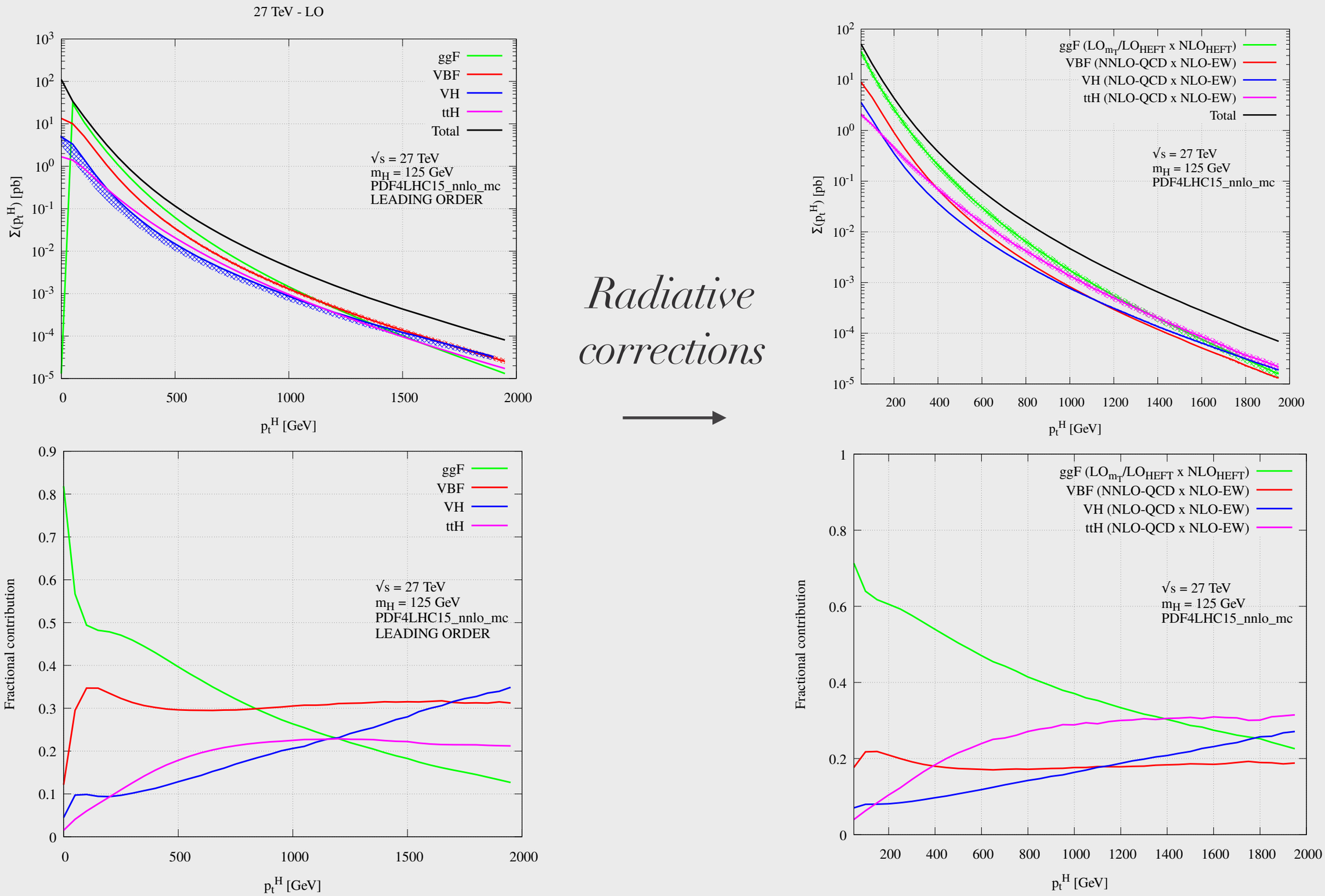
[M. Mangano, Higgs Couplings 2016]



- Eventually, $K_{full} \neq K_{heft}$
- We don't see it yet… visible at the (HL/HE)-LHC?

Boosted Higgs: a glimpse in the future?

Boosted Higgs at a 27 TeV LHC [LHCHXSWG (2019)]



Conclusions

- By and large, Higgs differential distributions under good theoretical control
- <u>There are caveats though</u>
  - going multi-differential
  - complex final states, proper reconstruction
  - loop amplitudes involving massive quarks (low p_t, boosted Higgs). All-order structure, higher order corrections…
  - Non-trivial interplays of different channels at high p_t, non-trivial patterns of radiative corrections → estimate NLO EW for Higgs p_t in ggF?
- Many of these issues not immediately relevant for phenomenology in 2019, but can become issues at the HL-(HE)-LHC…
- … and very interesting from a theoretical point of view

Conclusions

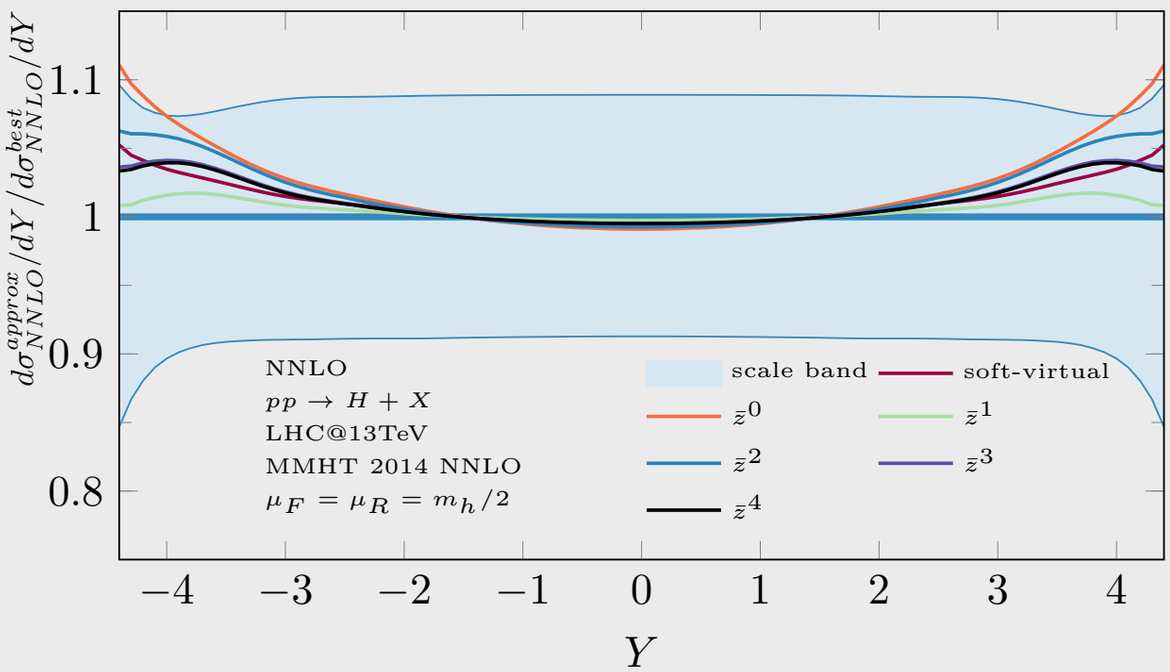
- By and la … retical control
- <u>There ar</u>
  - going m
  - comple
  - loop an … ggs). All-ord
  - Non-tri … al patterns … s p_t in ggF?
- Many of t … gy in 2019, but
- … and very interesting from a theoretical point of view

Backup

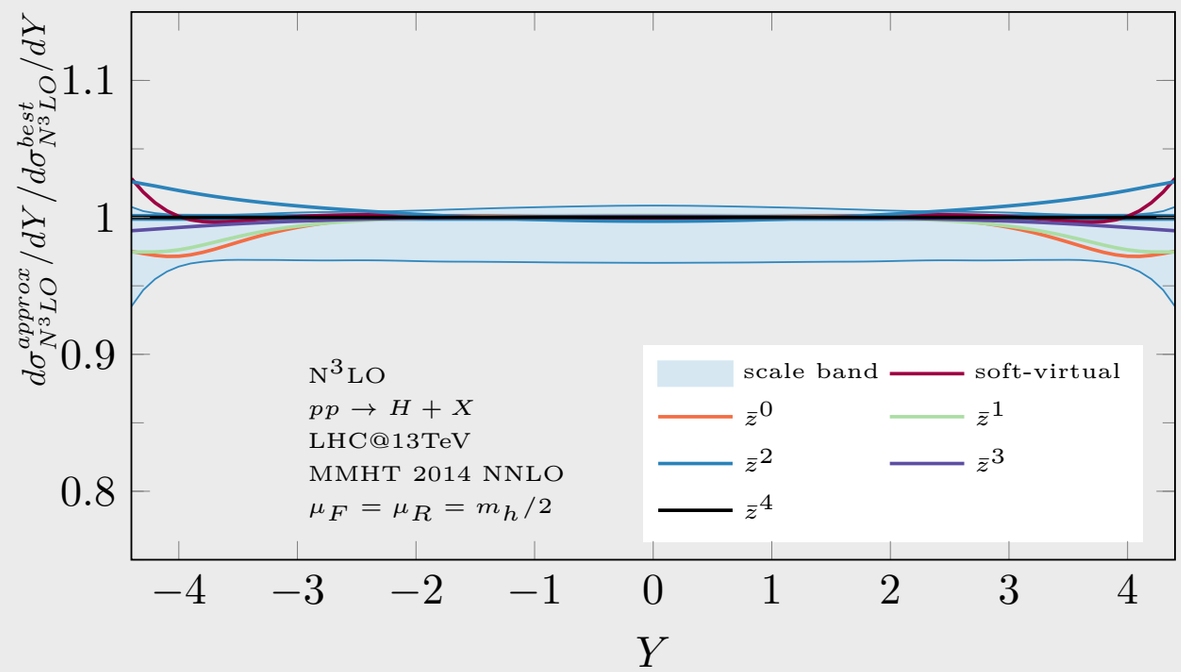
Higgs differential: rapidity

Soft expansion

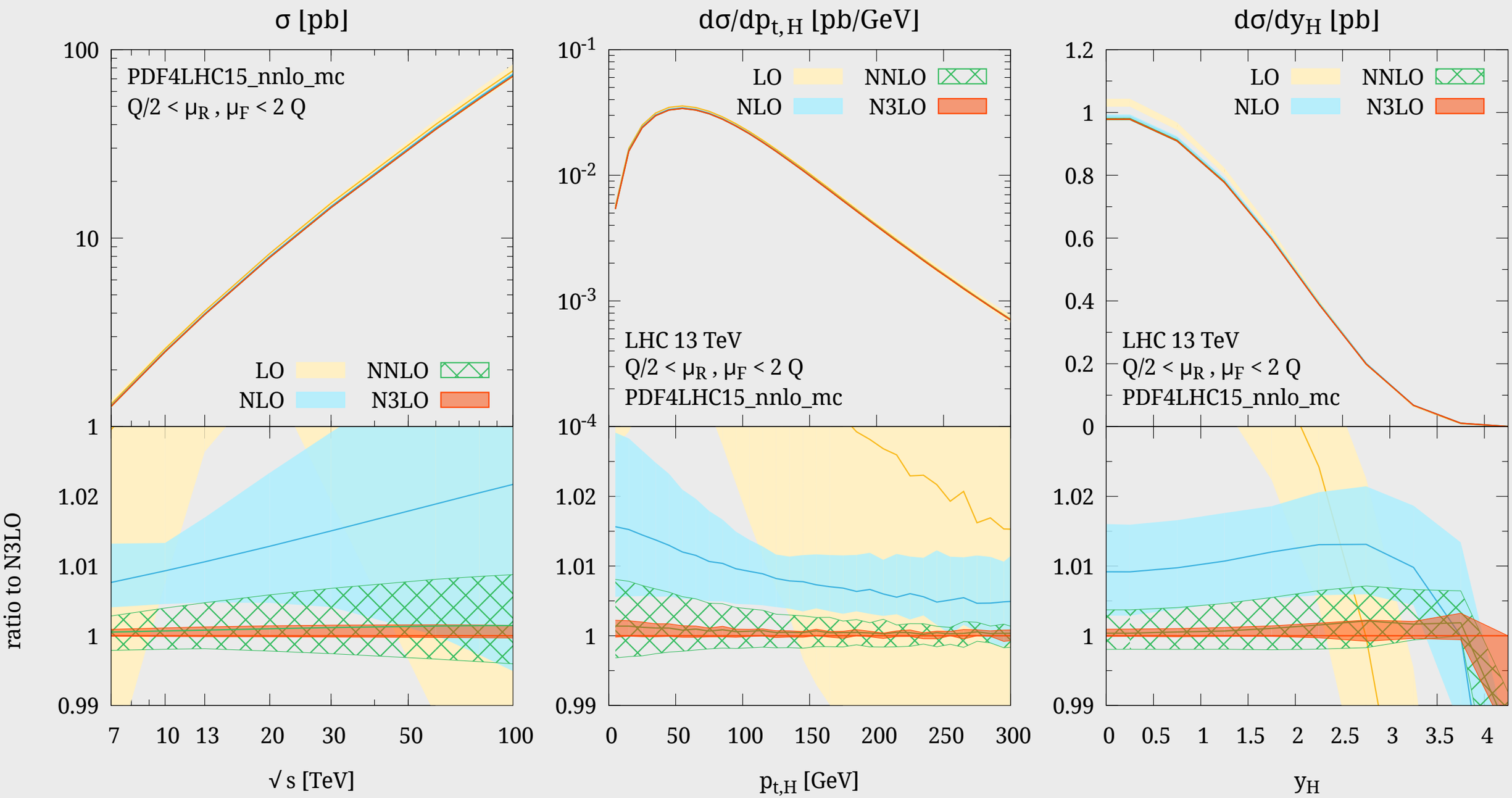
NNLO



N^{3}LO



VBF@N³LO


σ [pb]
PDF4LHC15_nnlo_mc
Q/2 < μR , μF < 2 Q
LO
NLO
NNLO
N3LO
ratio to N3LO
√ s [TeV]
dσ/dpt,H [pb/GeV]
LHC 13 TeV
Q/2 < μR , μF < 2 Q
PDF4LHC15_nnlo_mc
pt,H [GeV]
dσ/dyH [pb]
yH