Higgs theoretical predictions in the precision era

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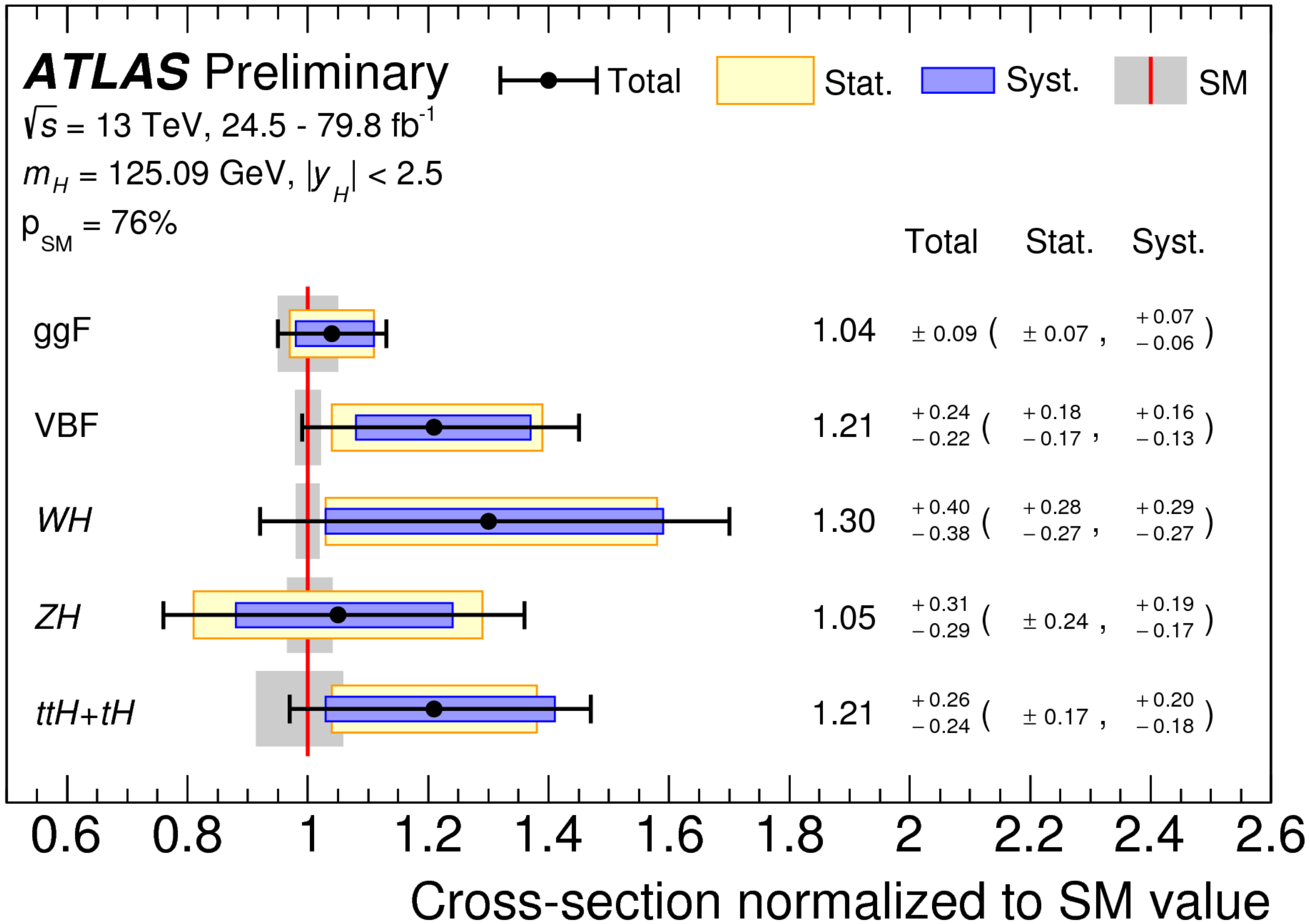
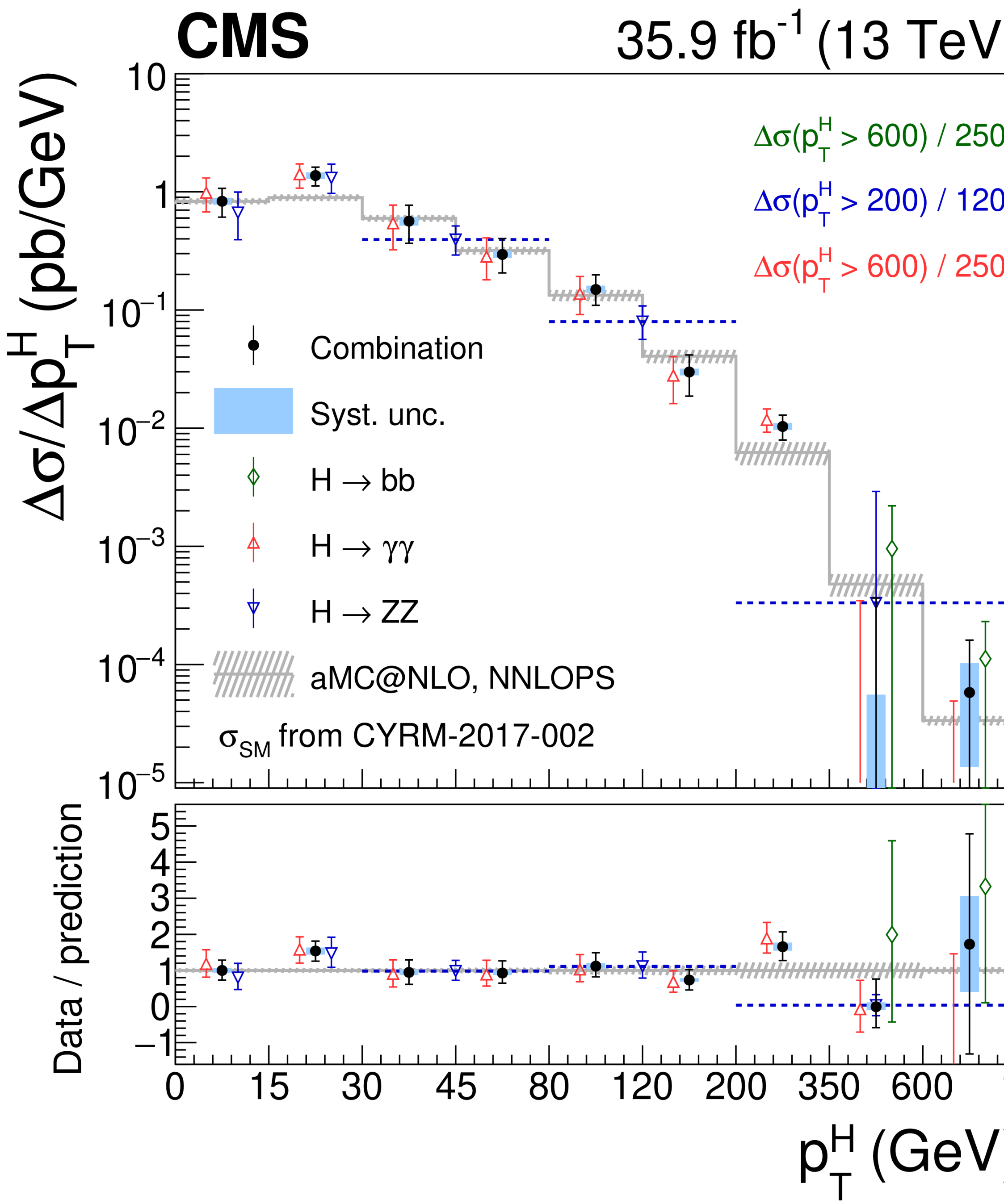
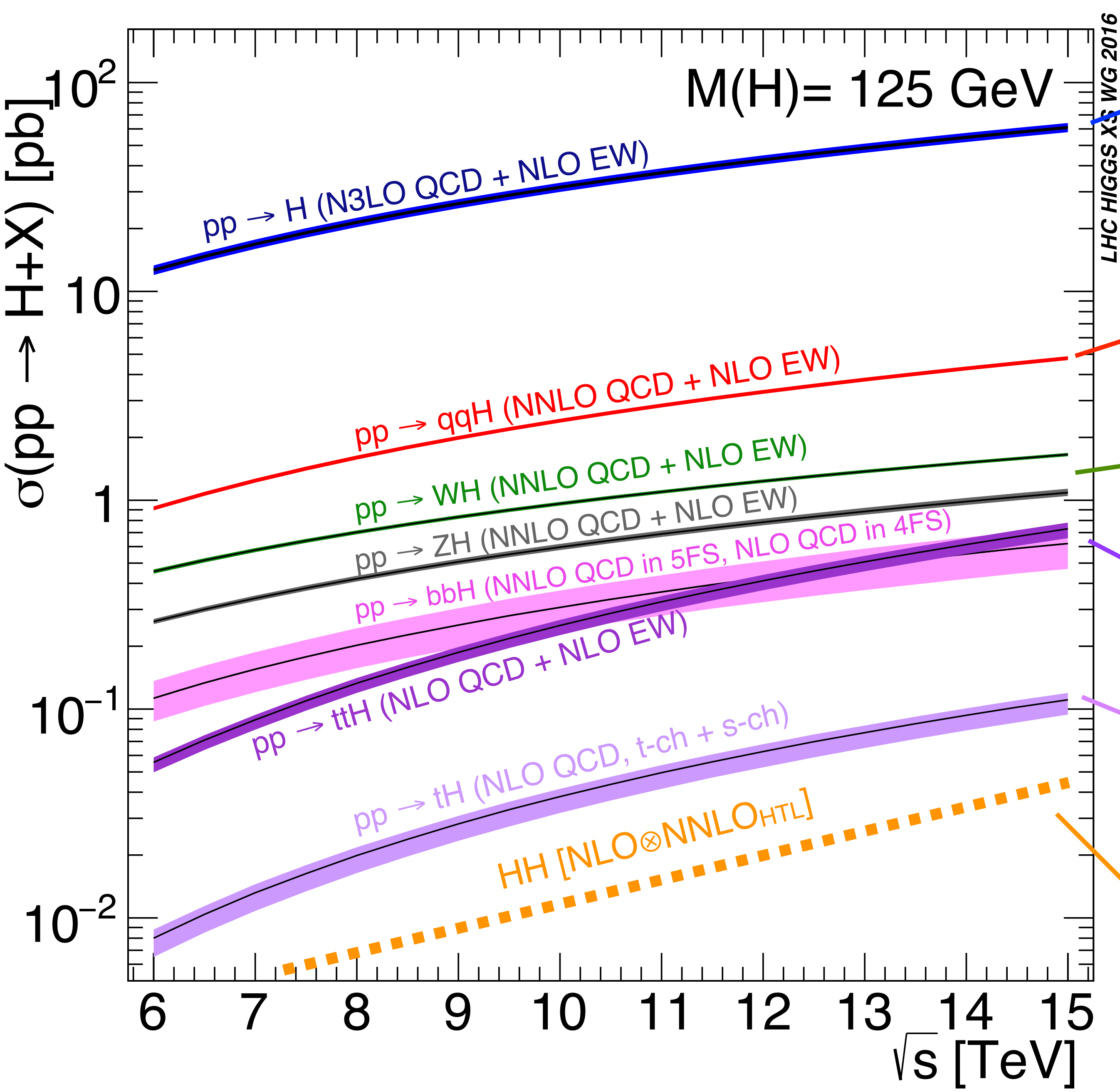
Higgs measurements: a snapshot





- All major channels observed
- More differential information is now available
- Precise studies of the Higgs sector well ongoing
- By and large, theoretical predictions in very good status… but experiments are catching up quickly

Higgs theoretical predictions



GGF: high precision, diff. distributions, extreme kin. regimes (boosted/off-shell) *ggH coupling, t,b,c couplings, Higgs width*

VBF: large yield. *Gauge/Higgs interactions*

VH: *gauge/Higgs interactions, unitarity structure of the SM, $H \to b\bar{b}$*

$t\bar{t}H$: *direct determination of top Yukawa*

TH: *top Yukawa, gauge vs fermion couplings pattern*

HH: *direct determination of Higgs self-coupling*

- Thorough investigations of the Higgs sector possible at the (HL-)LHC
- They require accurate predictions for several complex processes → highly non trivial
- Higgs was a key player in pushing forward collider phenomenology → in general, very refined predictions available

Gluon fusion: inclusive results

- SM prediction for ggF cross-section extremely advanced
- N³LO corrections to inclusive cross-section known [Anastasiou et al. (2015), Mistlberger (2018)]
- N³LO residual uncertainty: few percent. At this level, many other effects play a role…

[Mistlberger, QCD@LHC2016]

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

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

- 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 pb −1.15 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 (2018)]

progress: Melnikov, Penin (2016); Melnikov, et al. (2016-18); Jones, Kerner, Luisoni (2018)

progress: Bonetti, Melnikov, Tancredi (2017-18); Anastasiou et al (2018)

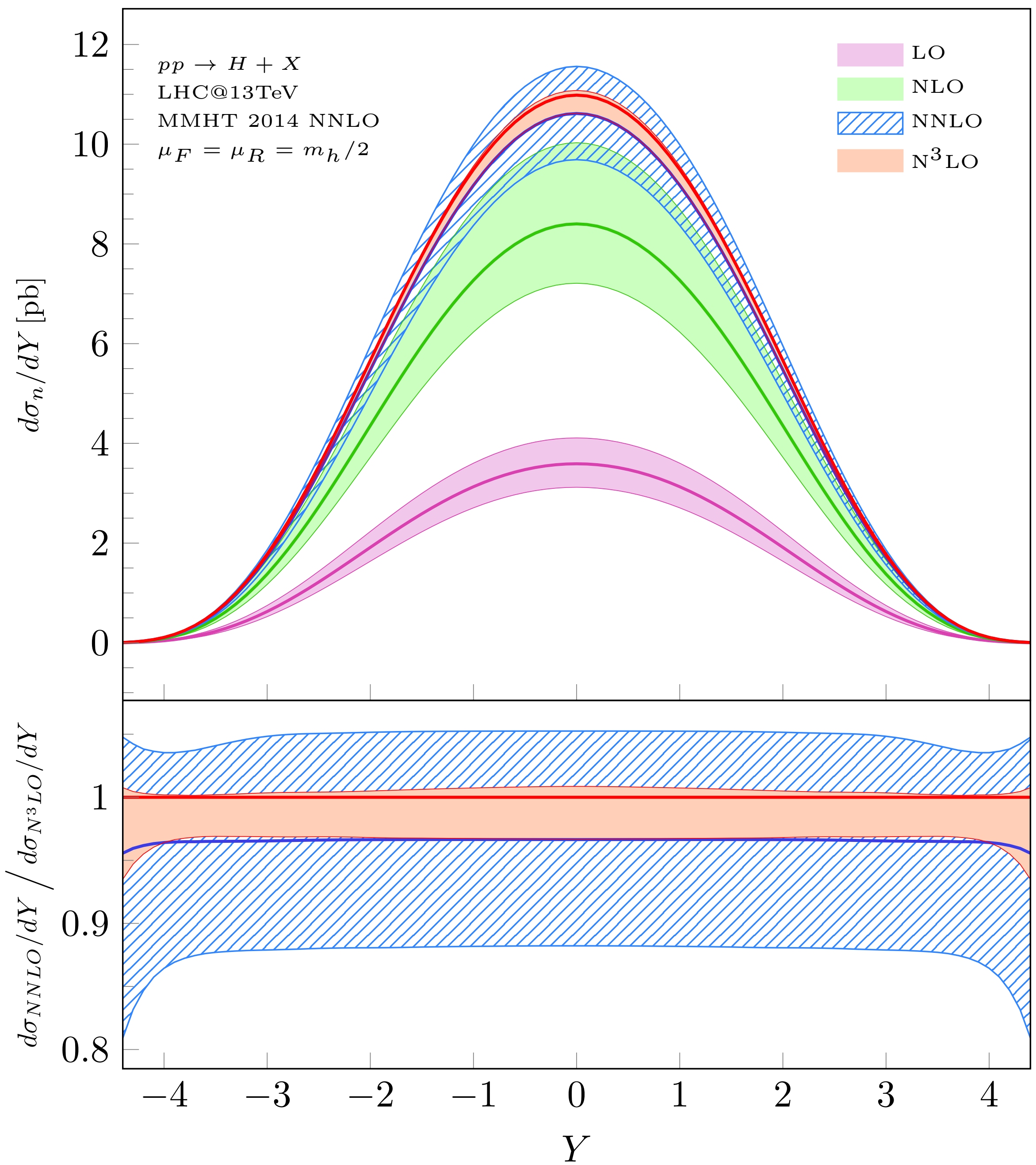
SEE E. FURLAN'S TALK

THIS AFTERNOON

Gluon fusion: going differential

- Inclusive cross section is an idealised quantity, very far from what we measure
- Reliable prediction: properly model fiducial volume of experiment → fully differential. Only known at NNLO [+PS]
- H is scalar: fully differential = p_t + rapidity

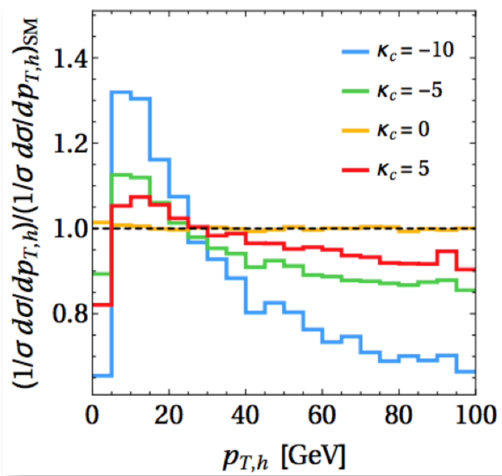
[Dulat, Mistlberger & Pelloni (2018)]

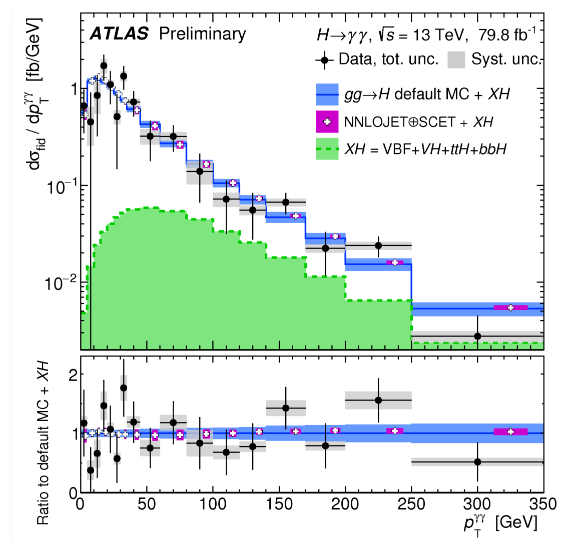


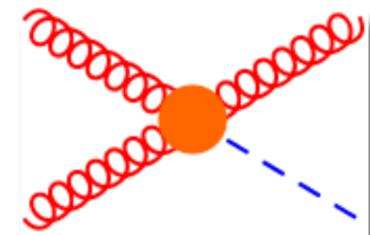
Higgs rapidity (ggF)

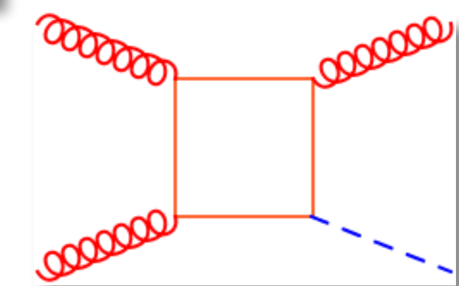
- Computed @N^{3}LO in a soft expansion (~*inclusive*)
- Expected to work very well (*apart from end-points*)
- Remarkably flat K-factor (*as expected from previous orders*)
- Combined with p_t@NNLO, can give access to N^{3}LO fiducial volume

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









Low p_t

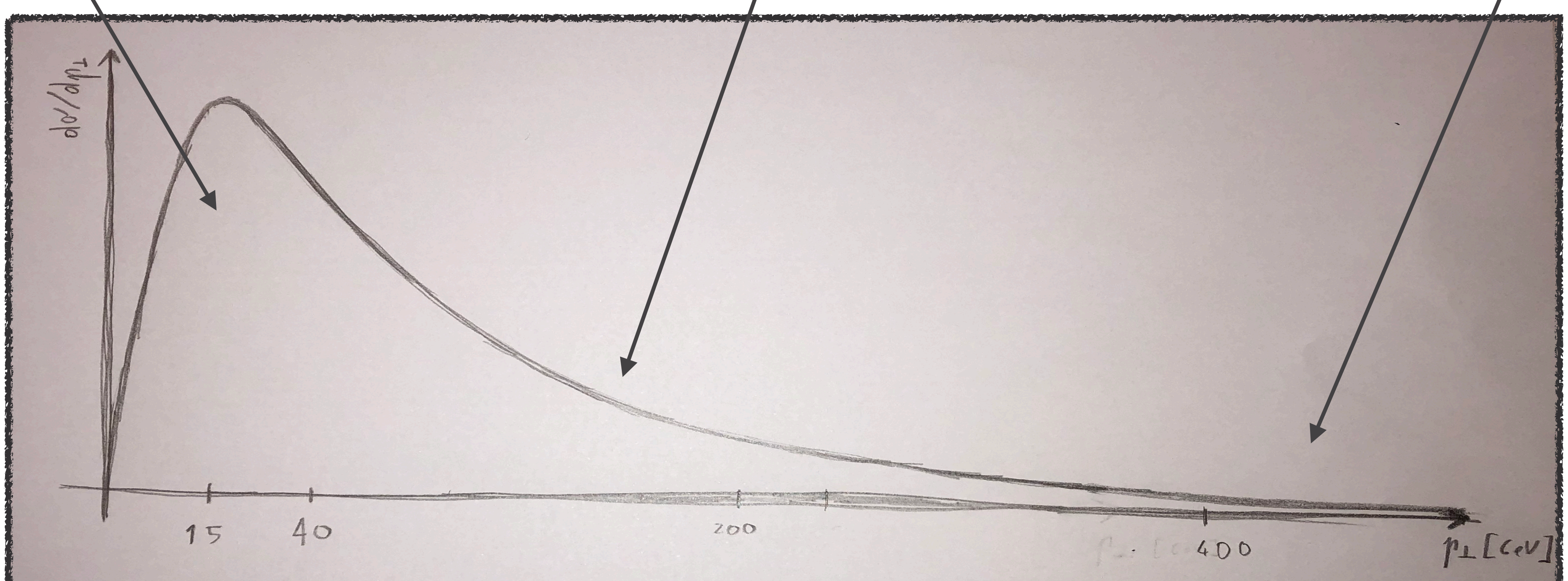
Light Yukawas…

Bulk of the distribution

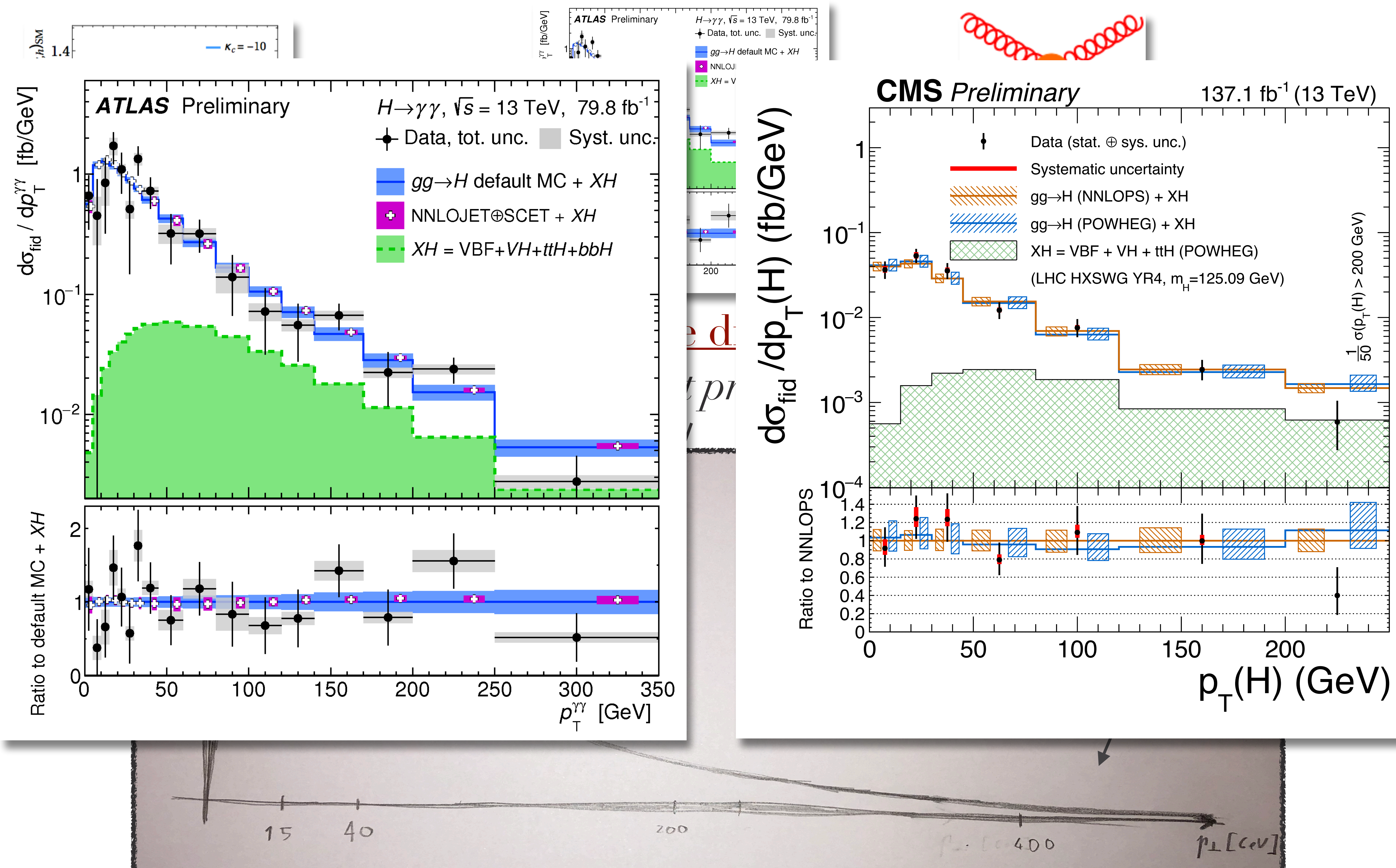
Highest precision

Boosted

ggH vs ttH, EFT…



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



Higgs p_t: the bulk of the distribution

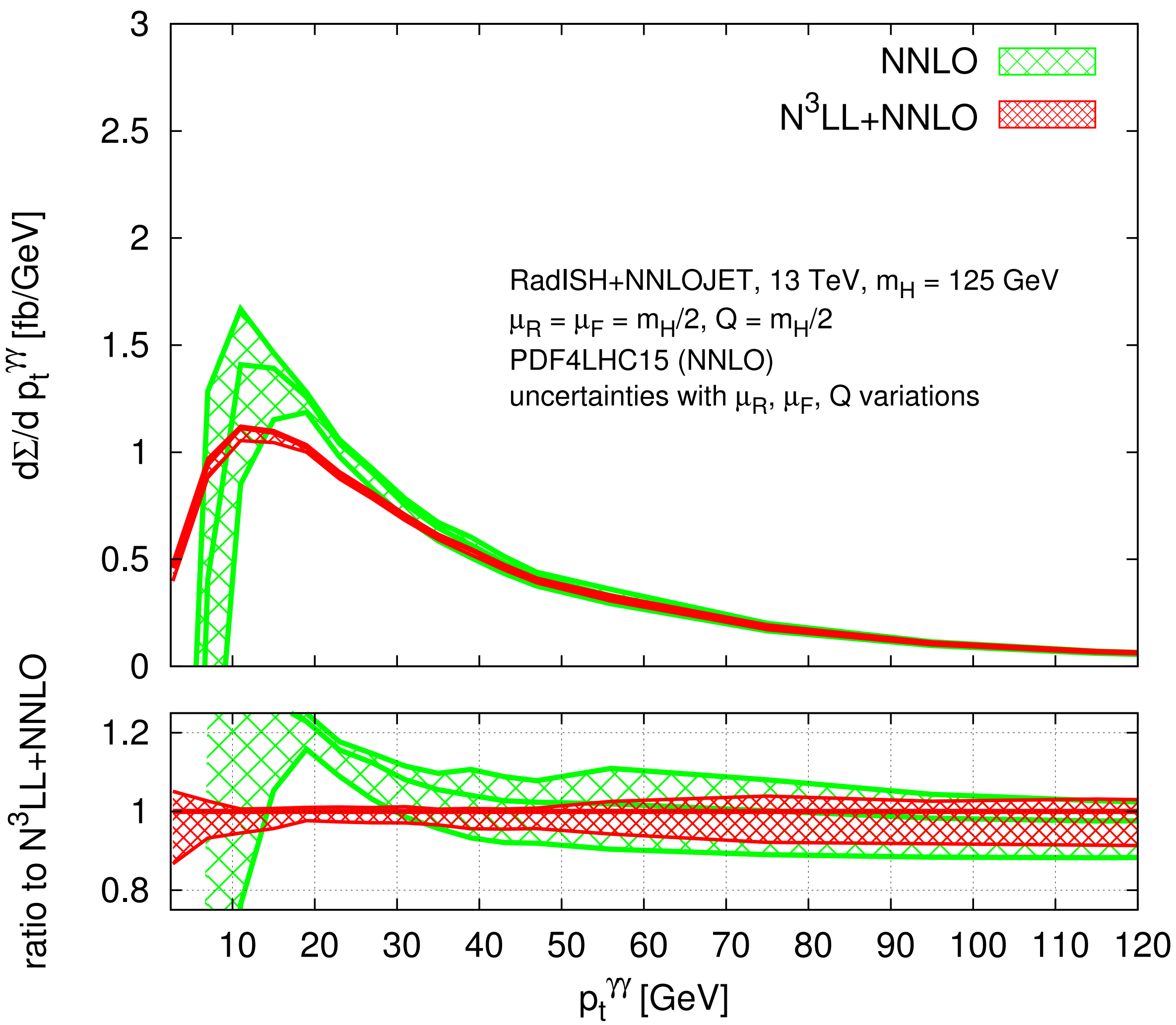
- In the region $p_t \ll m_t$: *ggF* effective vertex, point-like interaction → massive simplification for calculations

- m_t-suppressed terms under good control see e.g. [Neumann et al (2016)]

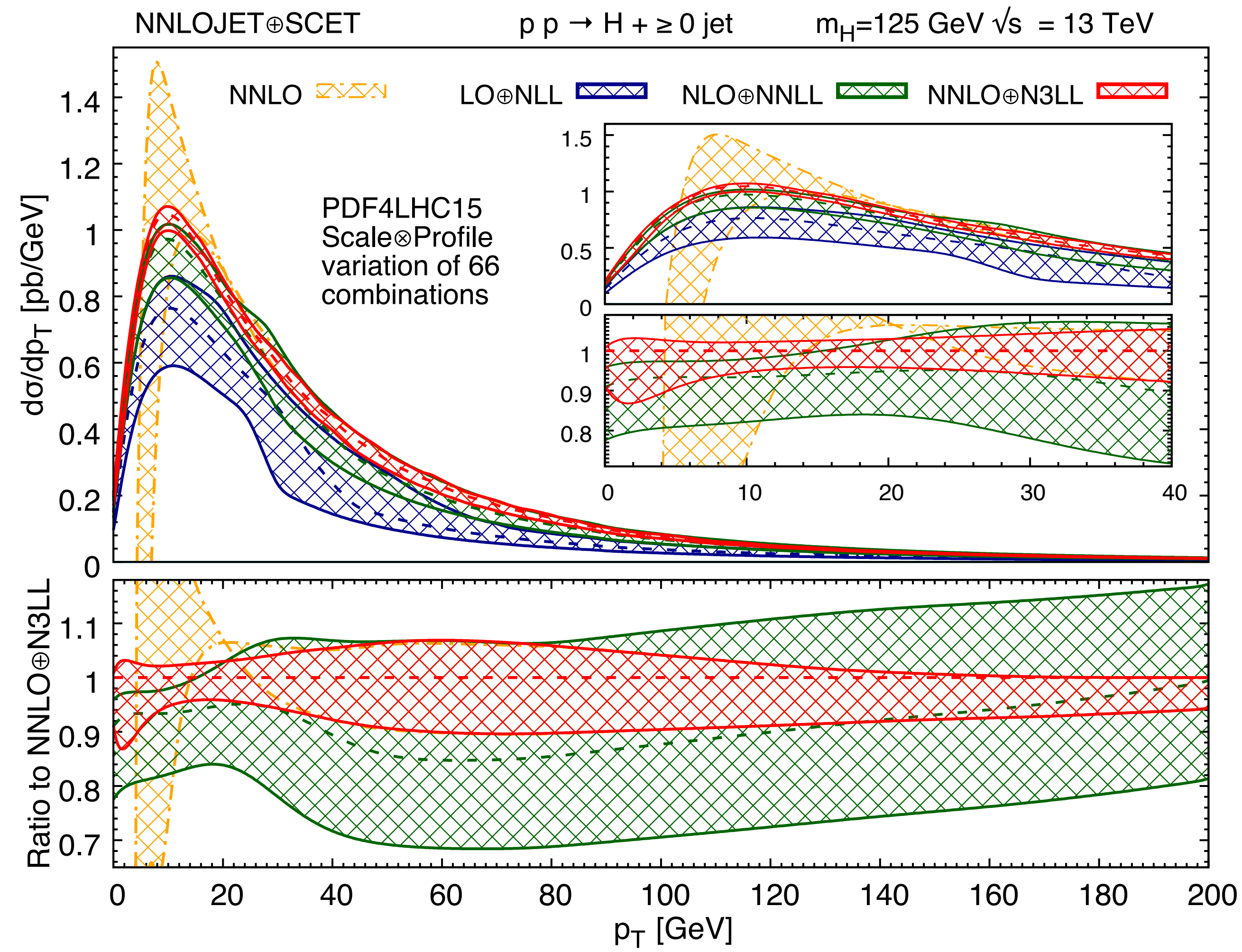
- In the HEFT approximation: fully differential NNLO p_t distribution known for quite a long time:
  - ✳ Boughezal, FC et al. (2015)
  - ✳ Boughezal et al., SCET-based (2015)
  - ✳ Chen, Gehrmann, Glover, Jaquier (2015)
  - ✳ Ellis, Campbell, Seth (2019) → *detailed validation of the different methods*

- At small p_t: fixed-order non reliable → match with resummation

The bulk of the distribution: NNLO+N³LL



[Bizon et al. (2018)]

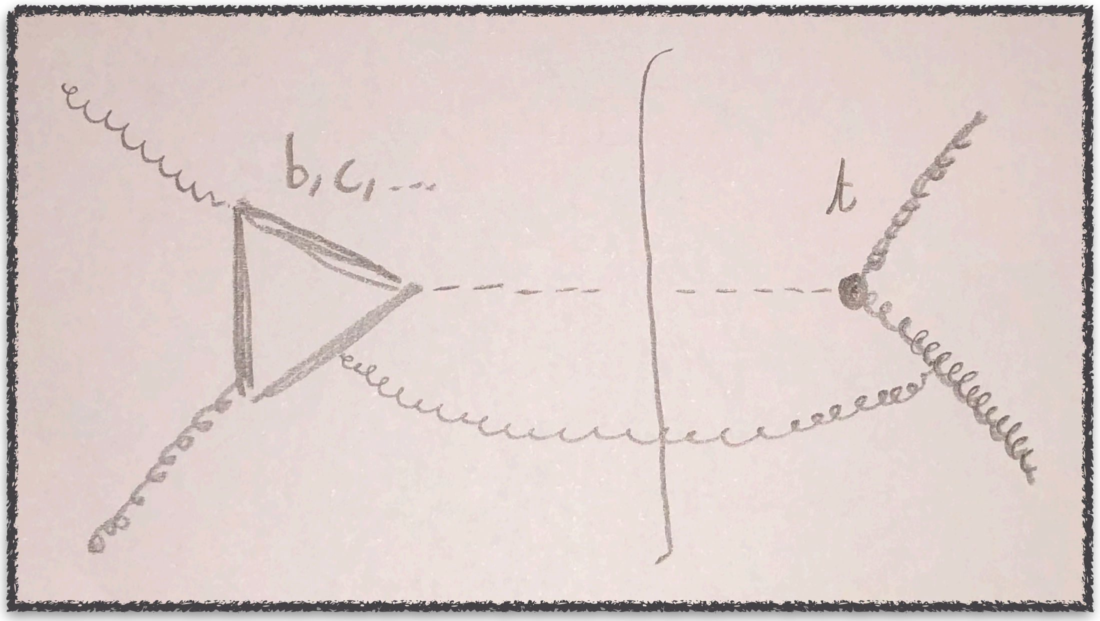


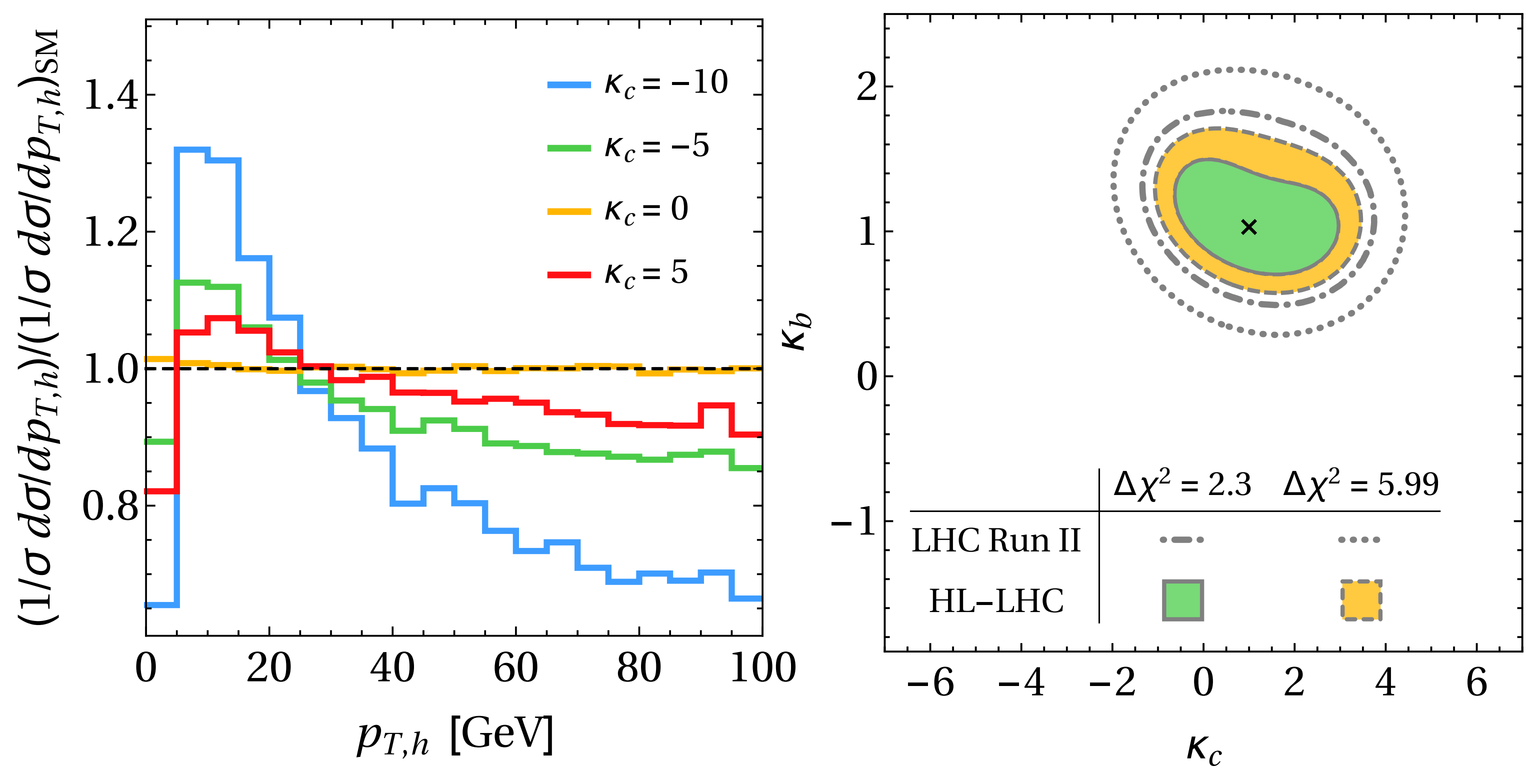
[Chen et al. (2018)]

- Sophisticated NNLO + N³LL results available, done in two different ways
- The two calculation have the same fixed-order and resummation accuracies
- They only differ by subleading effects (matching procedure…) → test for robustness
- By and large: very stable fixed-order result down to ~40 GeV → very good (fully differential) control of the bulk of the distribution

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 Yukawas!*
- Also: direct $q\bar{q} \to Hg$ impacts Higgs p_t → *powerful constraints for light Yukawas*





[Bishara et al. (2017)]

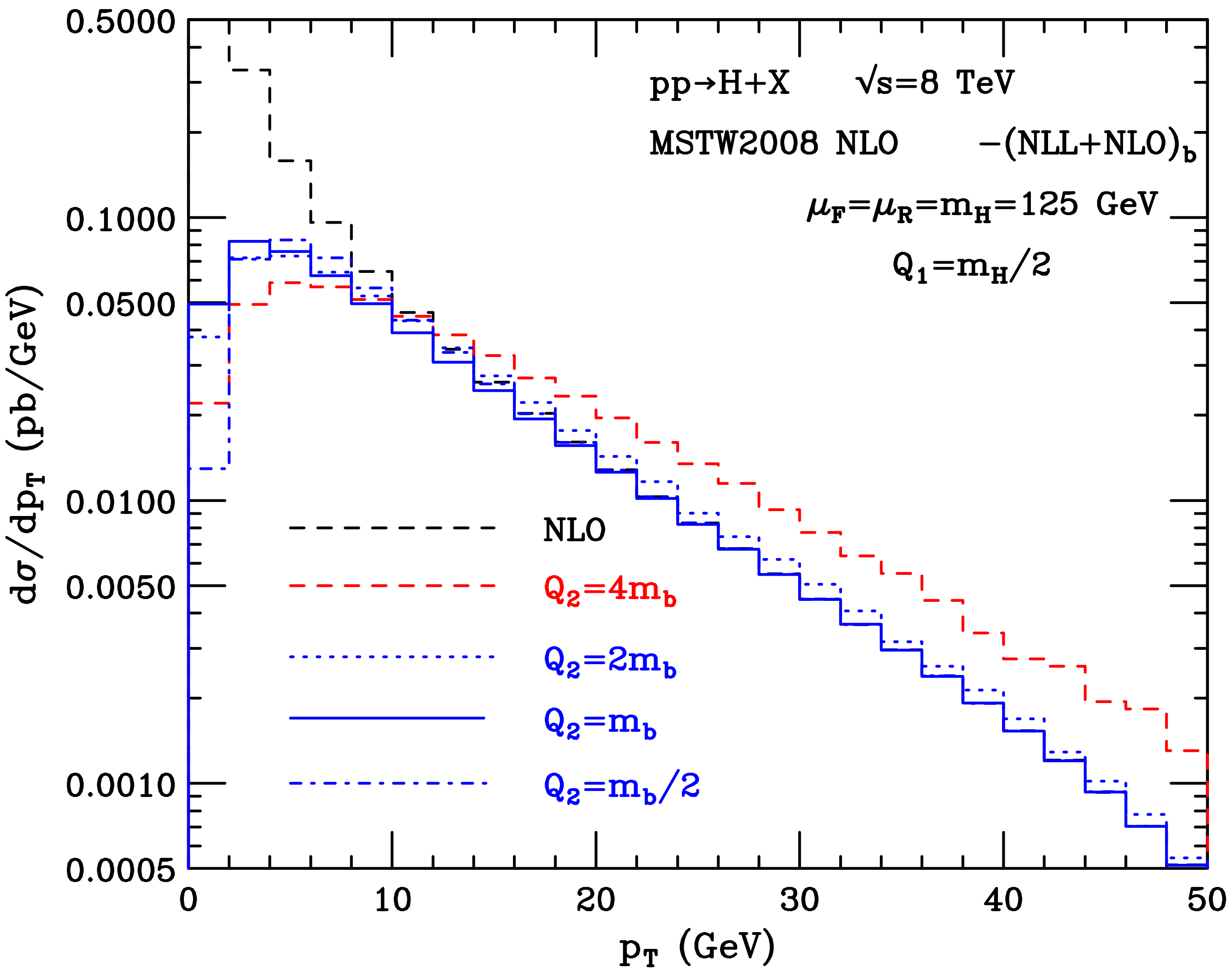
<u>PROBLEM: control over QCD corrections</u>

- Resolved quark loop → very difficult loop amplitudes
  - ✶ *beyond state-of-the-art for analytic calculations*
  - ✶ *large logs → numerical approached difficult*
- Low p_t, large logs → all-order effects must be considered

t/b interference: not so long ago

- *tb* interference only known at LO
- non trivial interplay with collinear gluons → ``standard" resummation machinery does not work. All-order effects non-trivial, and unknown
- not enough information for a proper fixed-order / resummation matching

[Grazzini, Sargsyan (2013)]



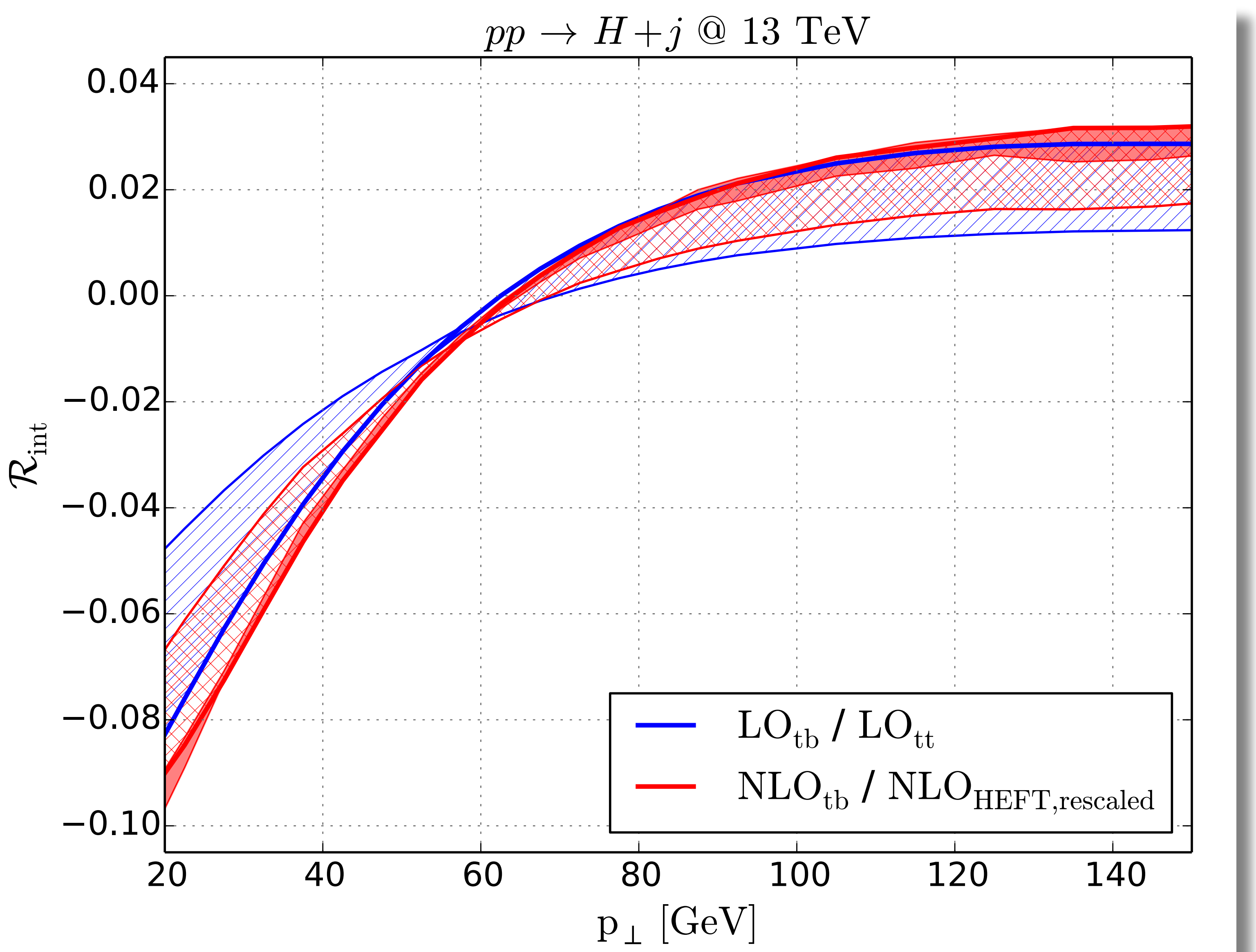
A pragmatic approach

- 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 $m_b \ll p_t \ll m_h$ [Melnikov, Tancredi, Wever (2016-17)]
- Approximation expected to be very good for all pheno applications

[Lindert et al. (2017)]

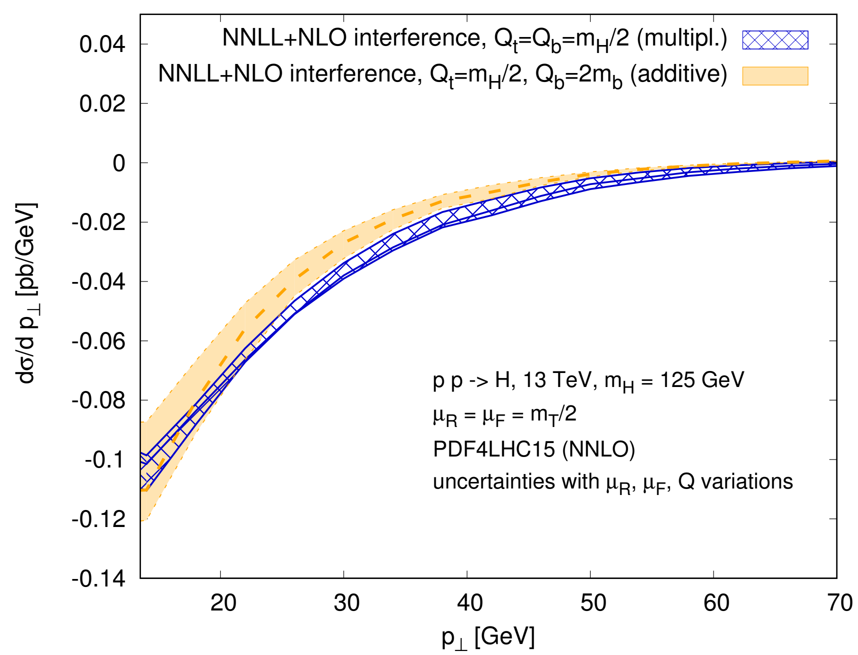


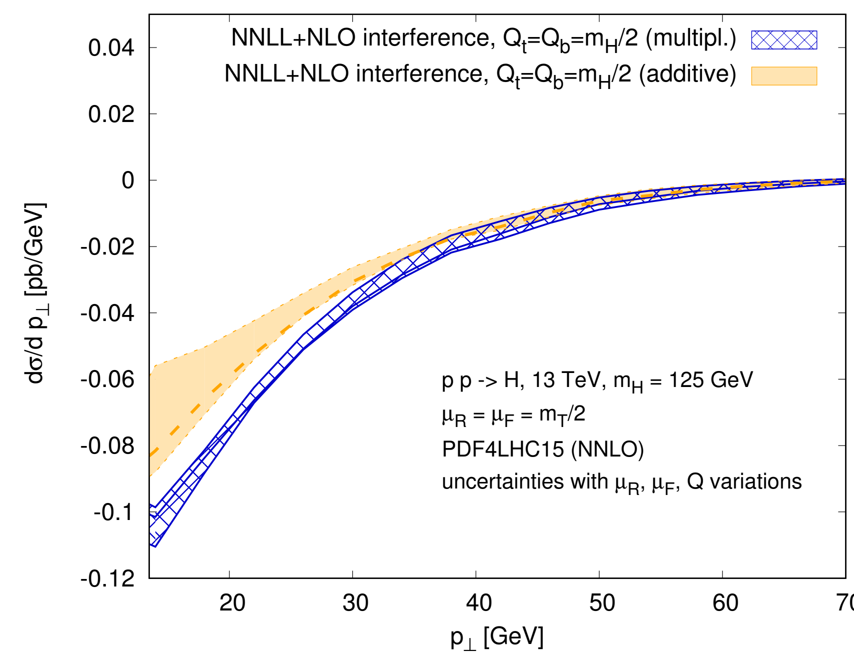
- Large K-factor…
- … but similar to HEFT
- Large source of unc. from b-mass scheme
- Non-trivial logarithmic structure
- Still don't know how to resum [some work in this direction: Melnikov, Penin (2016); Forte et al (2016); Penin, Liu (2018)]

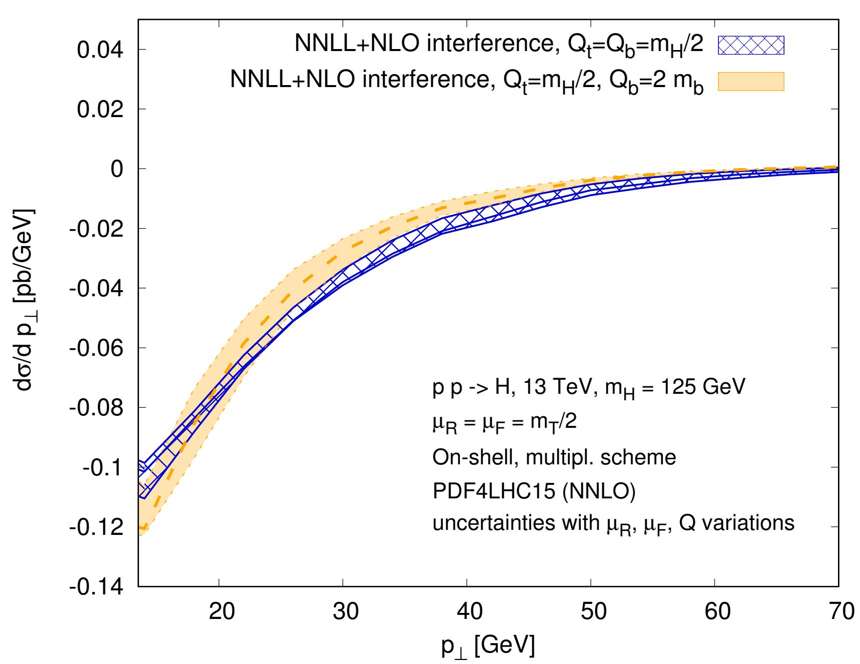
t/b interference: matching with resummation

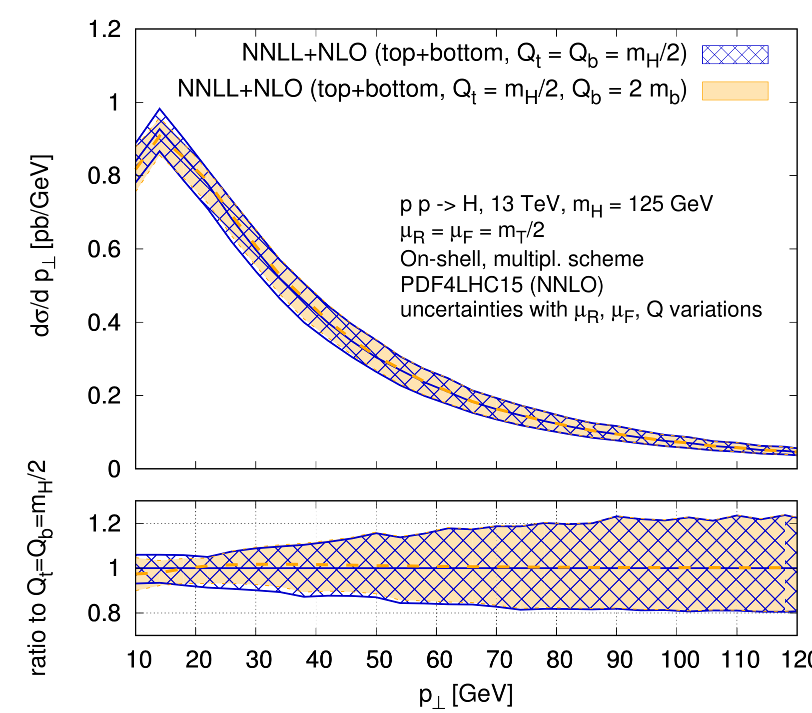
[FC, Monni et al. (2018)]

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





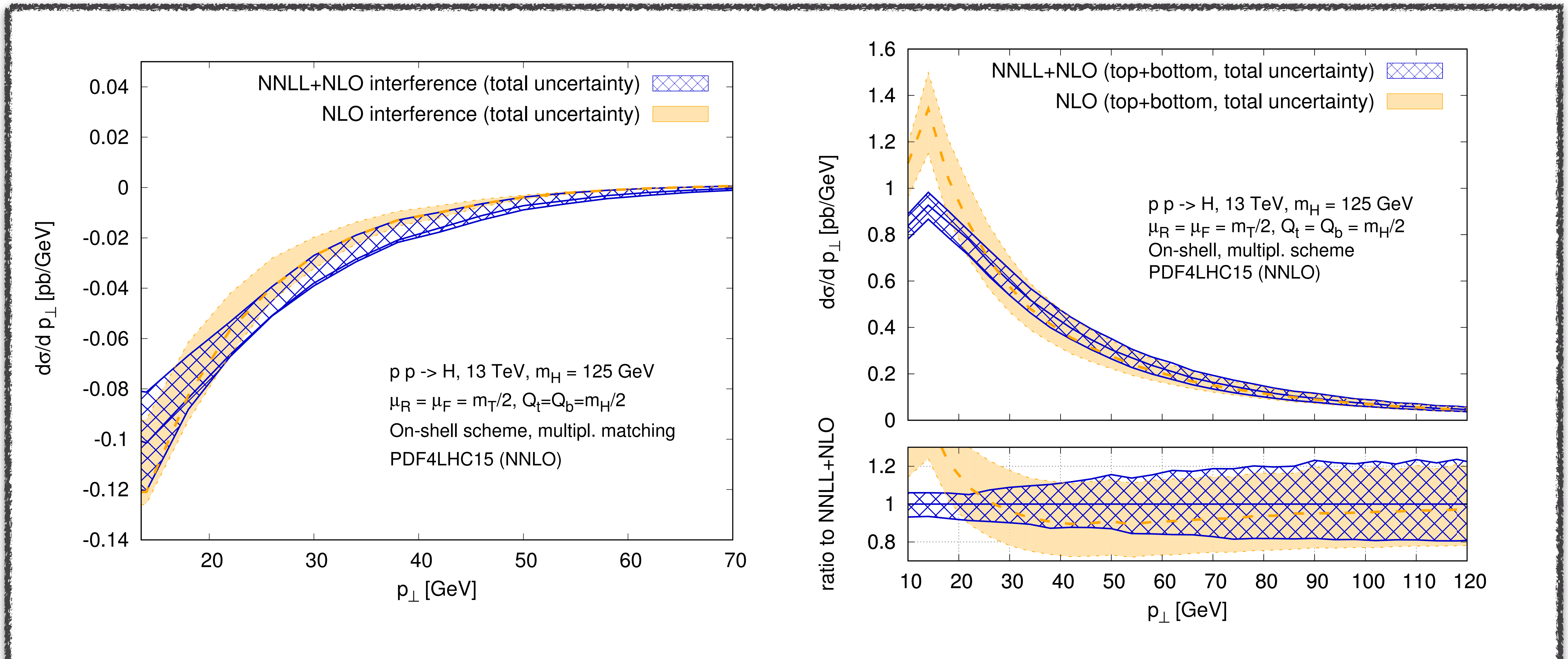




t/b interference: matching with resummation

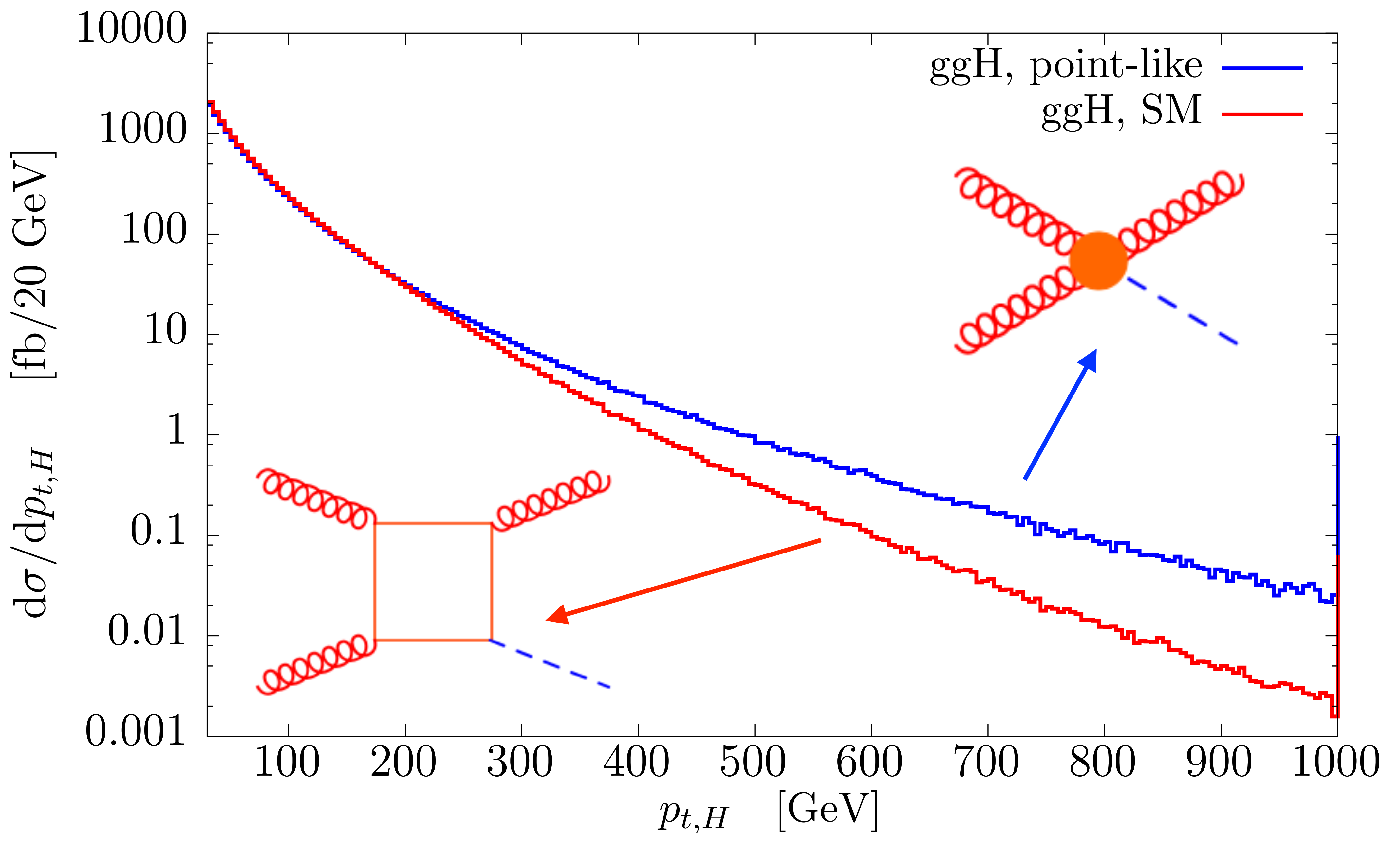
[FC, Monni et al. (2018)]

Reasonable control over *t/b* interference

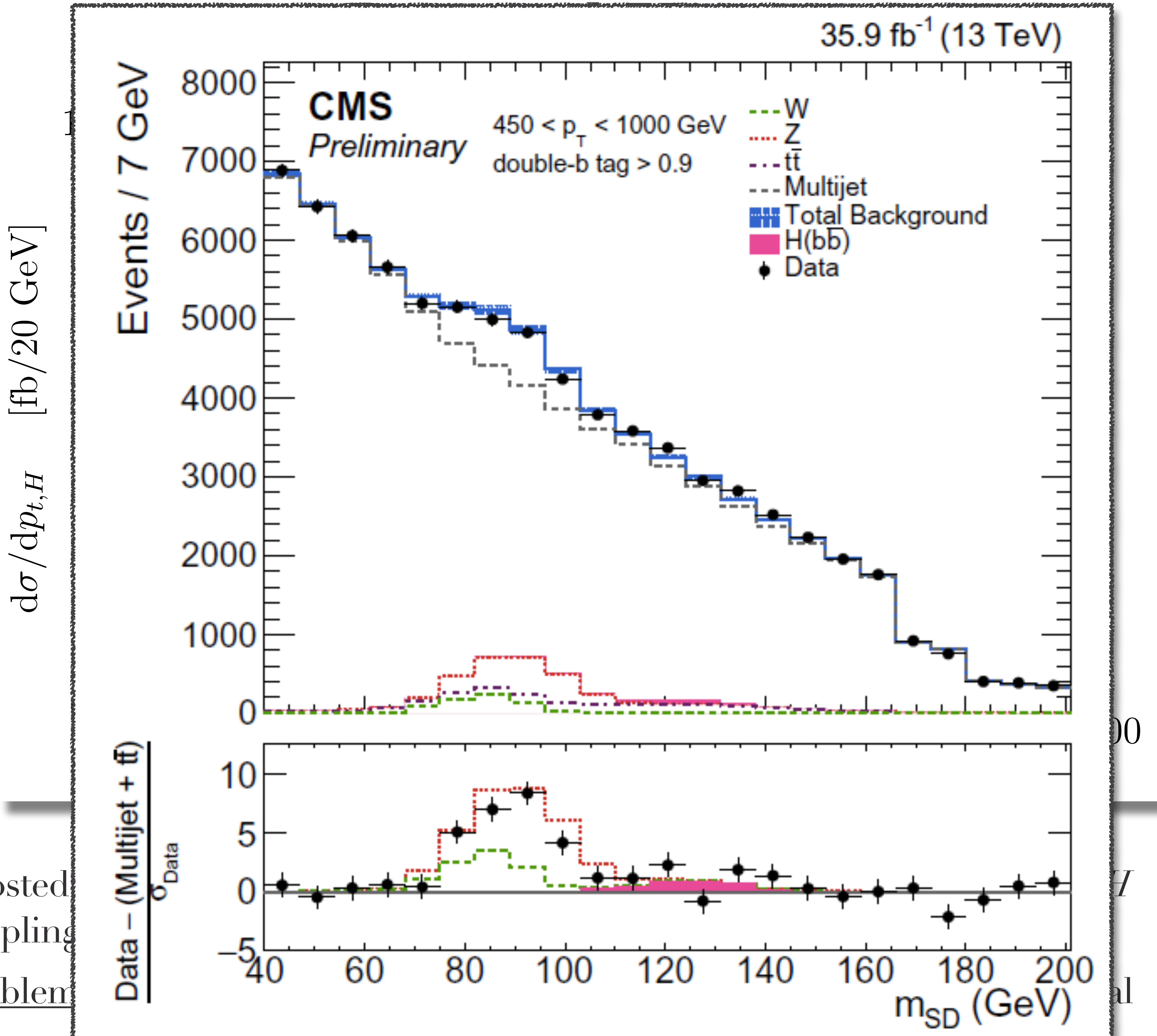


- Major source of uncertainty from b-mass scheme → can only be improved with higher order calculation
- It will be very hard to improve in this direction
- A common feature of processes involving (active) massive virtual quarks…

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



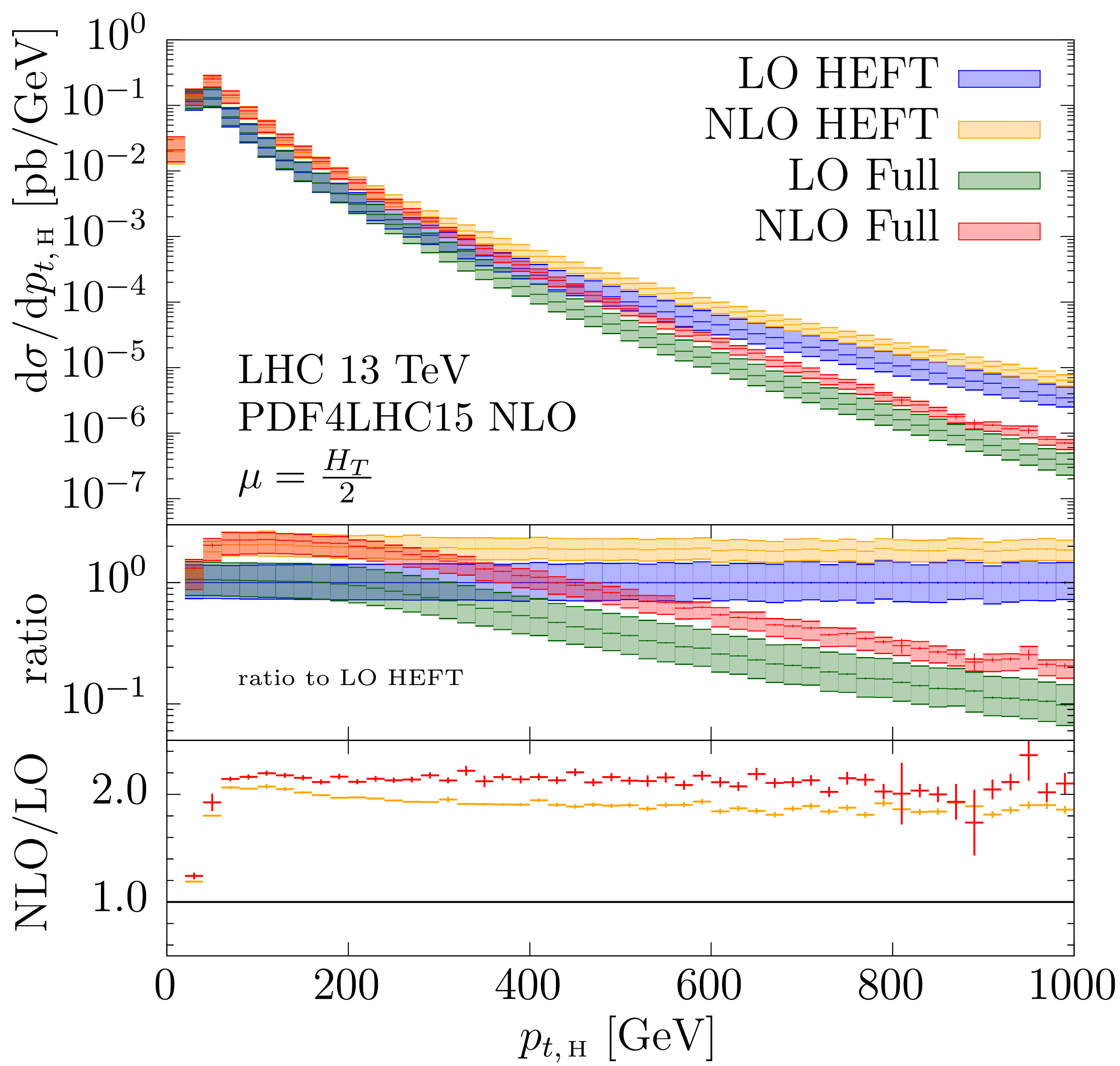
- Boosted ... H
  coupling ...
- Problem ... al

Boosted Higgs: NLO

NLO is finally known. 2 approaches:

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

They agree within expectation → important validation



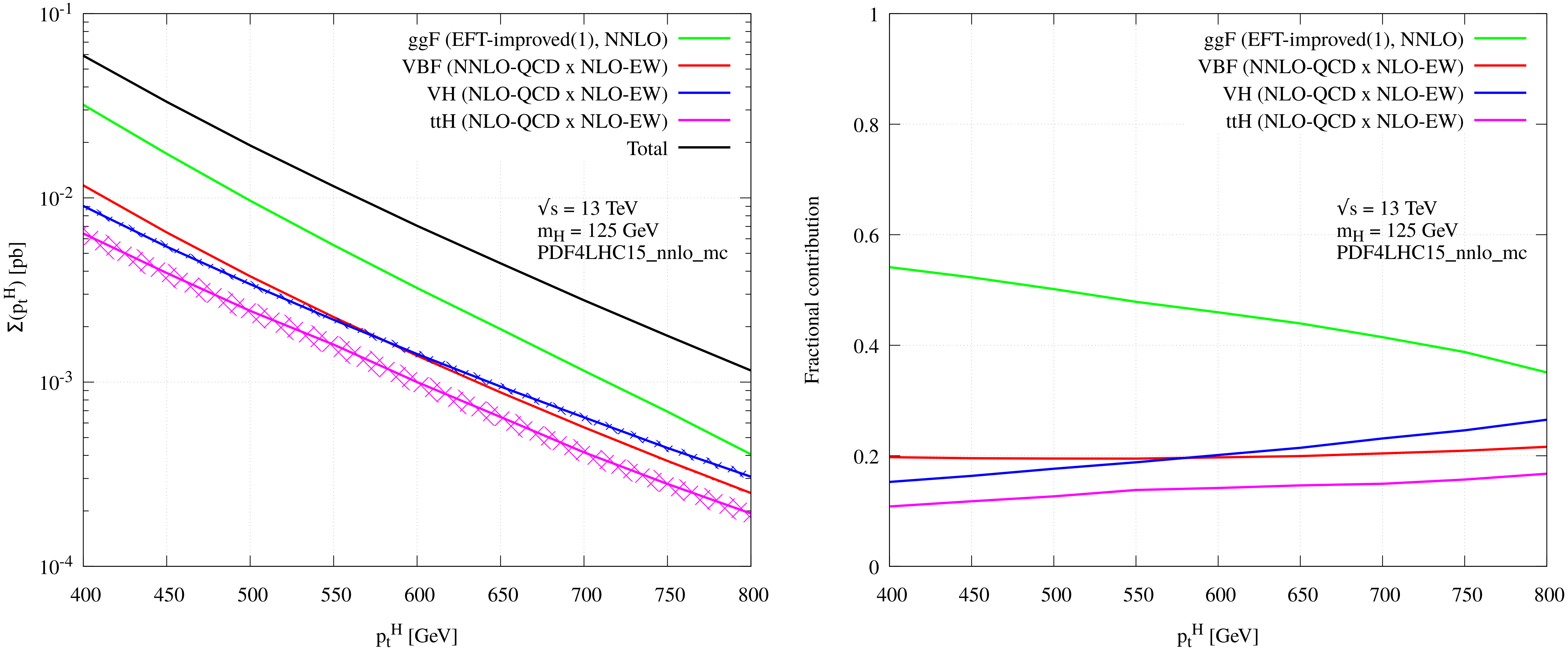
- Large *K-factor*
- Very similar to HEFT *K-factor.* As expected from
  - ✳*merged samples approach* [see e.g. Frederix et al (2016), Greiner et al (2016)]
  - ✳*approximate m_t treatment* [see e.g. Neumann and Williams (2016)]
  - ✳*resummation analysis* [see e.g. Muselli et al (2016)]

↓

Can combine with NNLO HEFT K-factor

Boosted Higgs: all channels

At large p_t, the ggF dominance becomes less pronounced → important to include all channels.

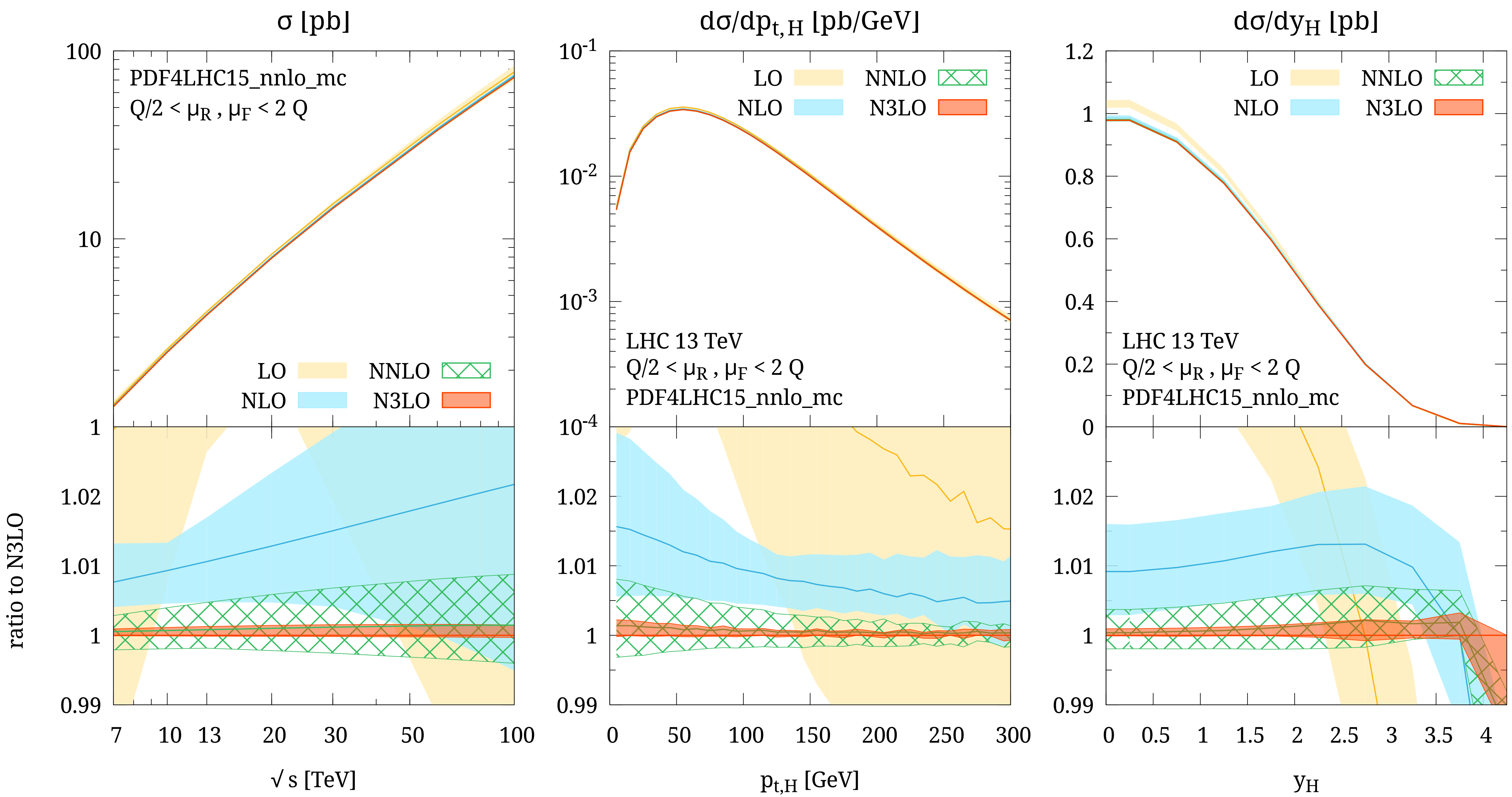


LHCHXSWG (2019)

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

Beyond ggF: vector boson fusion

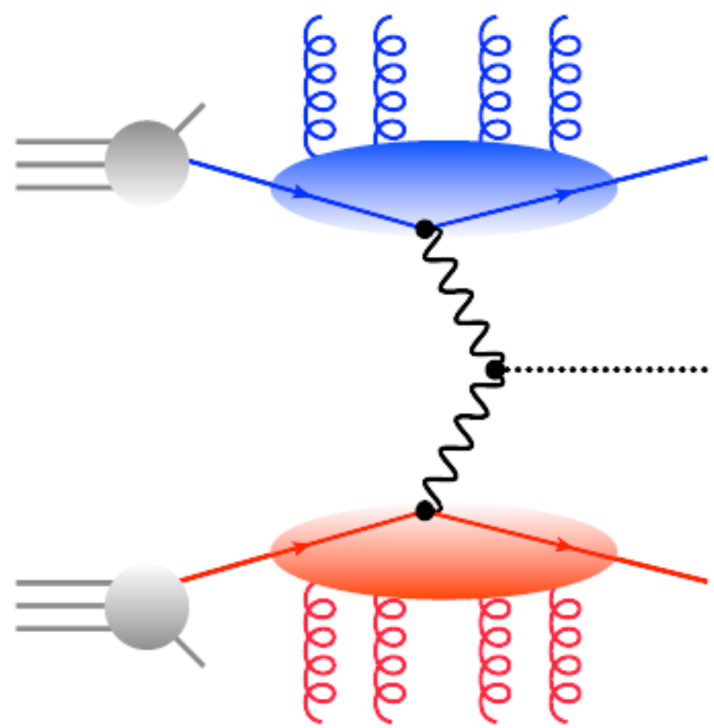
Also in this case, N³LO predictions are known for quantities inclusive over jet activity (not jet requirement/cut possible) [Dreyer, Karlberg (2016)]



- Tiny corrections ~ few permill
- No kinematic feature on top of NNLO
- Is it the end of it? Not so fast…

VBF beyond the DIS approximation

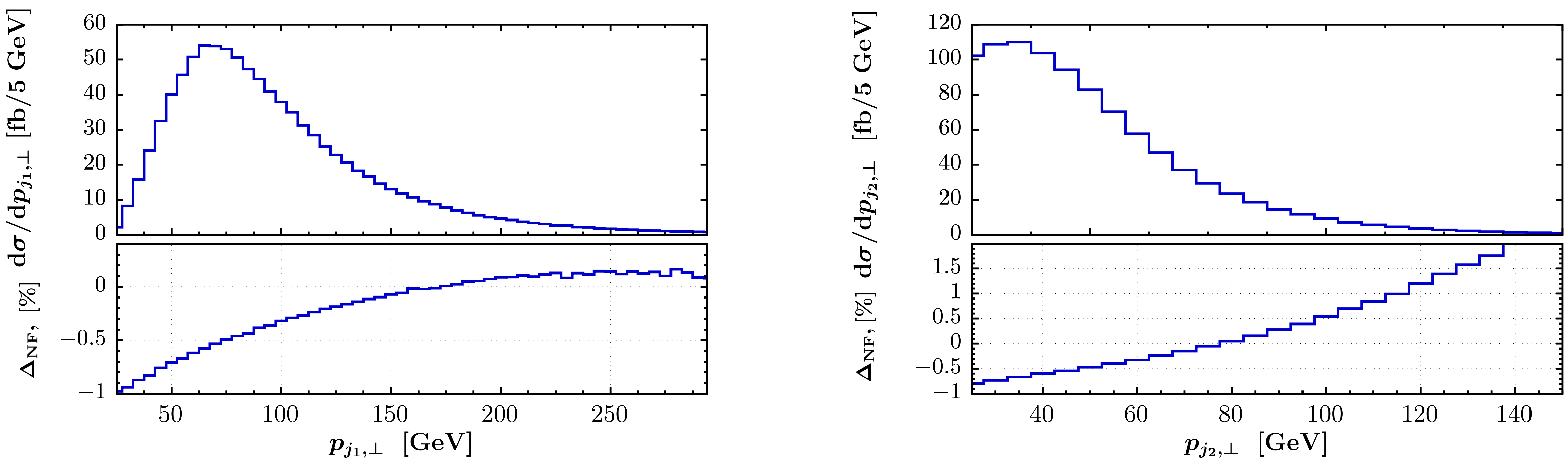
- Typically, VBF predictions are computed in the DIS/ ``structure functions”/ ``factorized” approximation [Han, Valencia, Willenbrock (1992)]
- In this approximation, one consider emission from the two quark legs independently, without considering any cross talk



- Results can be borrowed from DIS → much simpler
- Corrections to this approximation expected to be small after VBF cuts (first appear at NNLO, color/kinematics suppression)
- … but are they small compared to (inclusive) precision (~per mill)?

VBF beyond the DIS approximation

- NNLO exact VBF calculation out of reach *(two-loop 2→3 amplitudes well beyond what we can imagine doing in the near future)*
- However, possible to estimate the leading non-factorizable contributions the VBF region (two forward/backward tagging jets) [Liu, Melnikov, Penin (2019)]

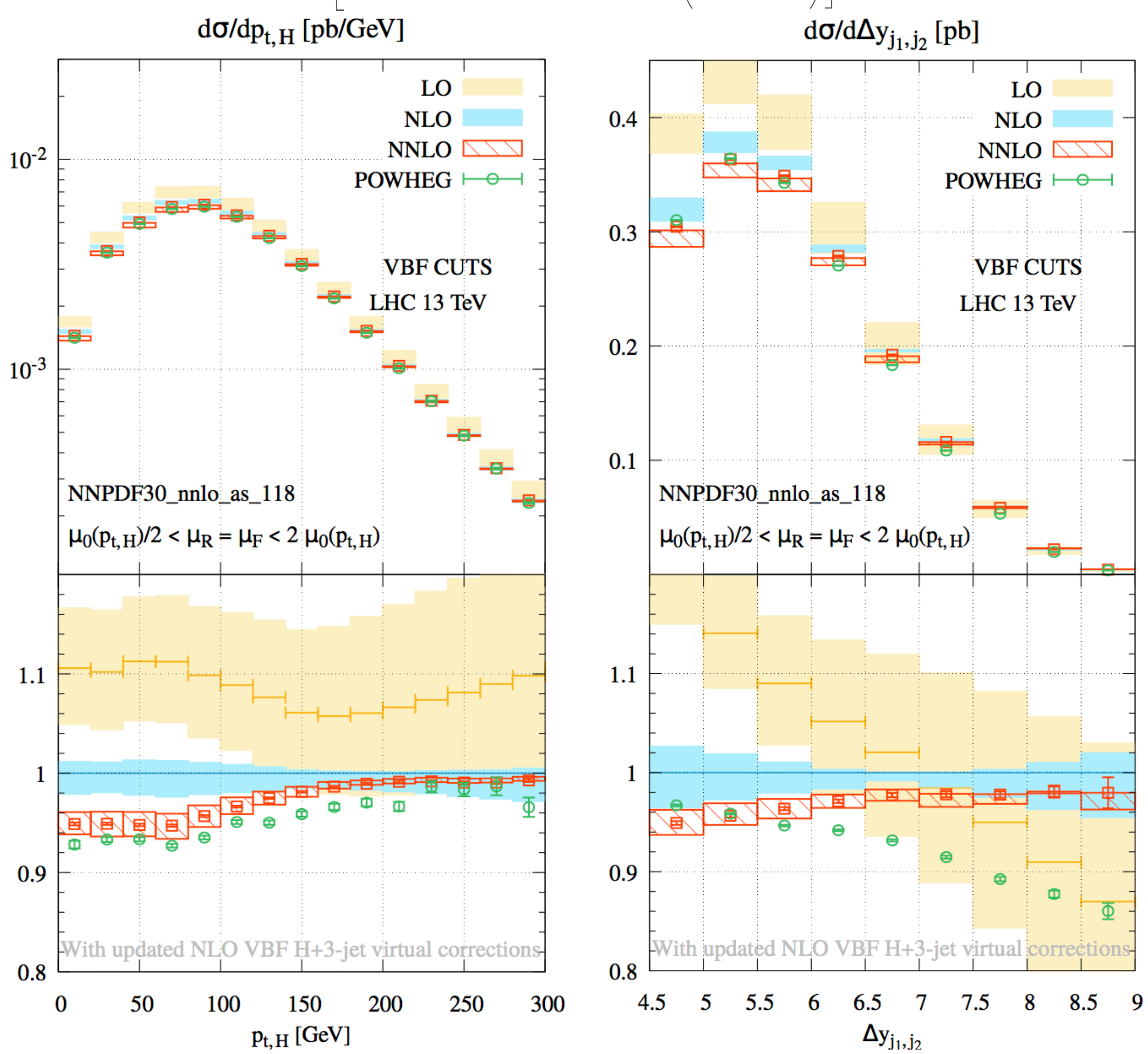


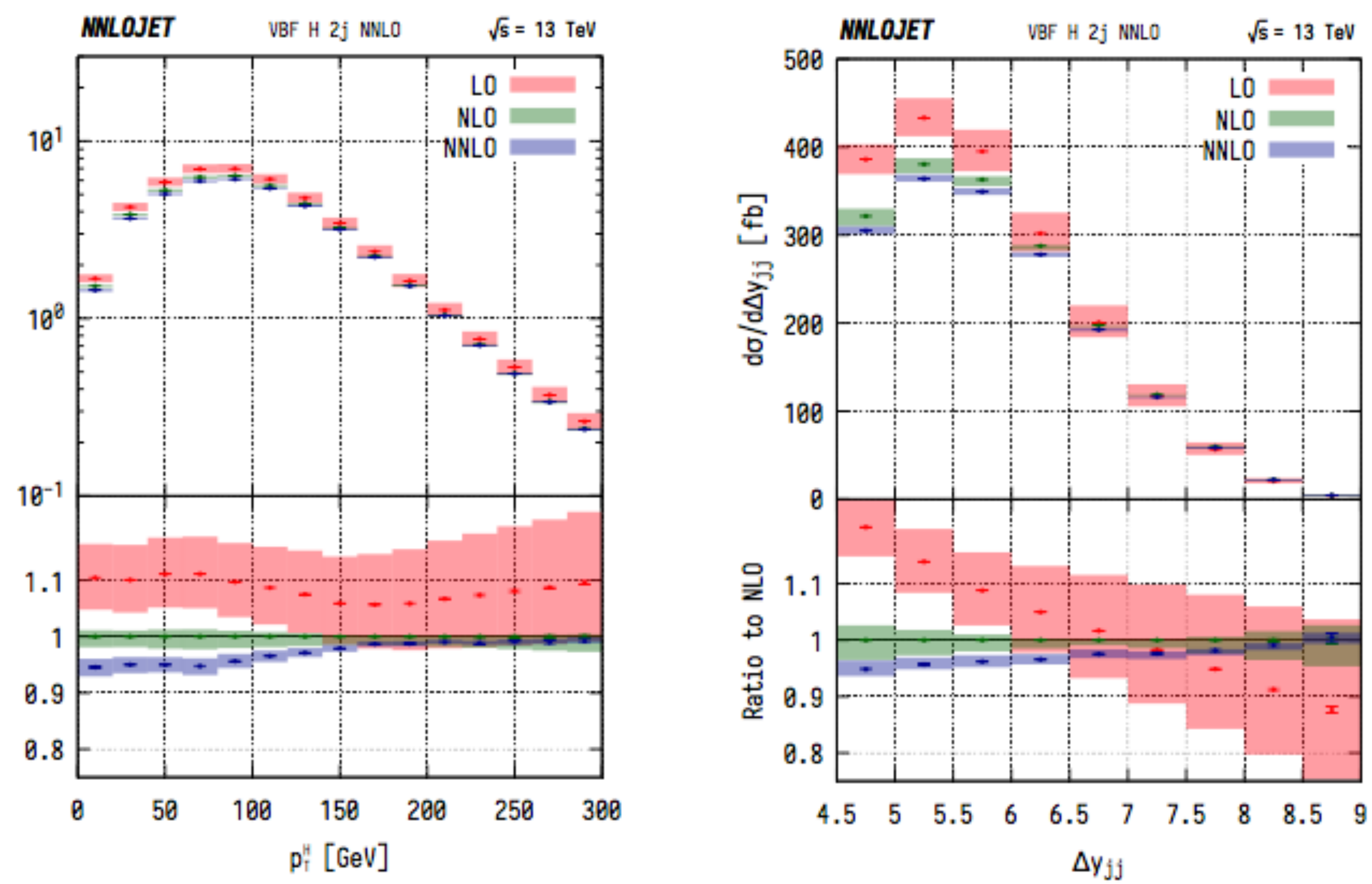
- As expected, corrections to inclusive quantities small (~4 permill), although larger than N^3LO
- Interestingly, small corrections come as a cancellation between positive and negative corrections to differential distributions → can reach percent-level in differential distributions

VBF: fully differential results

- For VBF, crucial to proper model the experimental setup (jet requirements)
- Full NNLO(+NLO EW) results in the DIS approximation known

[Cacciari et al (2015)]



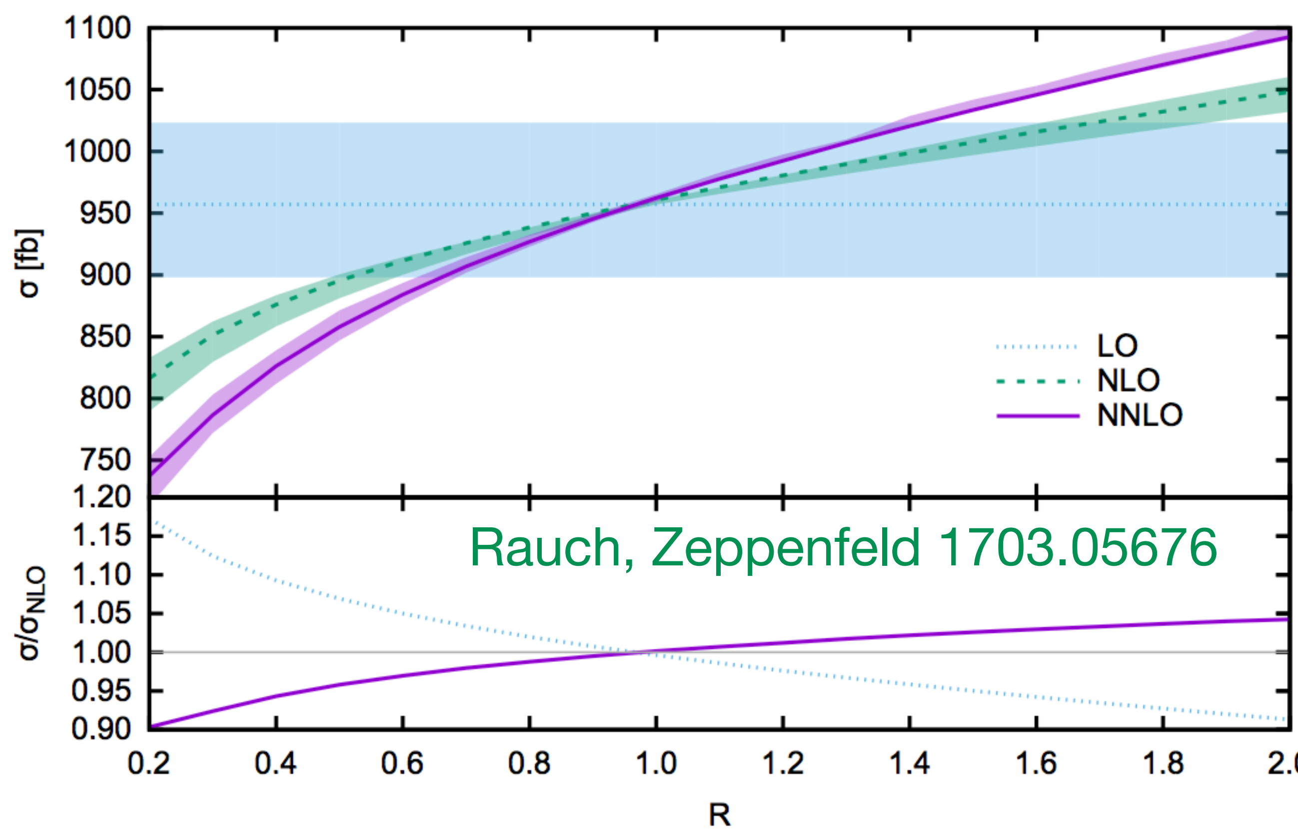


[Cruz-Martinez, Glover, Gehrmann, Huss (2018)]

- Corrections in the VBF region much larger than for the inclusive case (most likely due to non-trivial jet dynamics)
- Residual uncertainty ~2-3% → non-factorizable contributions smaller, but barely
- For some distribution, bad disagreement with PS → NNLOPS?

VBF: fully differential results

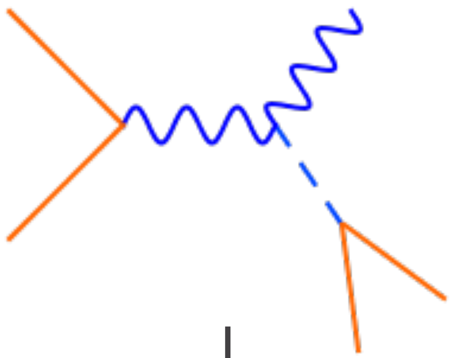
- For VBF, crucial to proper model the experimental setup (jet requirements)
- Large differential corrections: VBF very sensitive to tagging jet cuts and jet radius

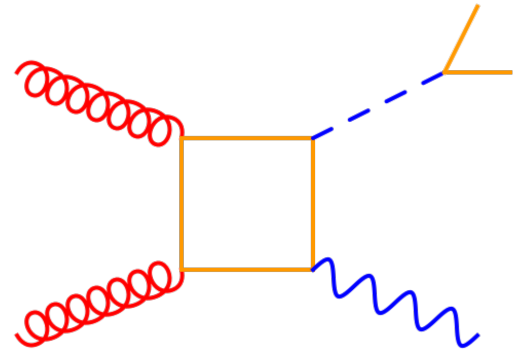


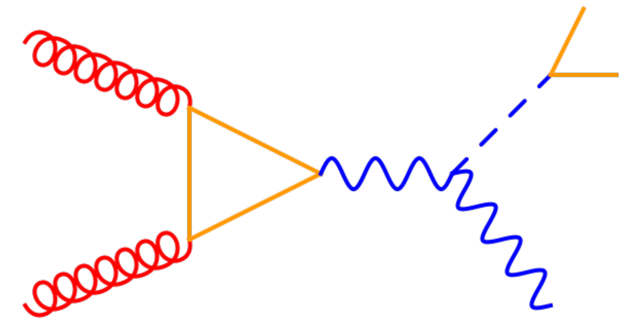
- NNLO corrections change by ~20% from R=0.1 to R=1.0
- It would be interesting to understand it better
  - ✶NNLO for VBF+j
  - ✶NNLOPS *[only major channel where this is missing…]*

VH: status

- VH: known at NNLO QCD + NLO EW for quite some time







DY-like: very good control

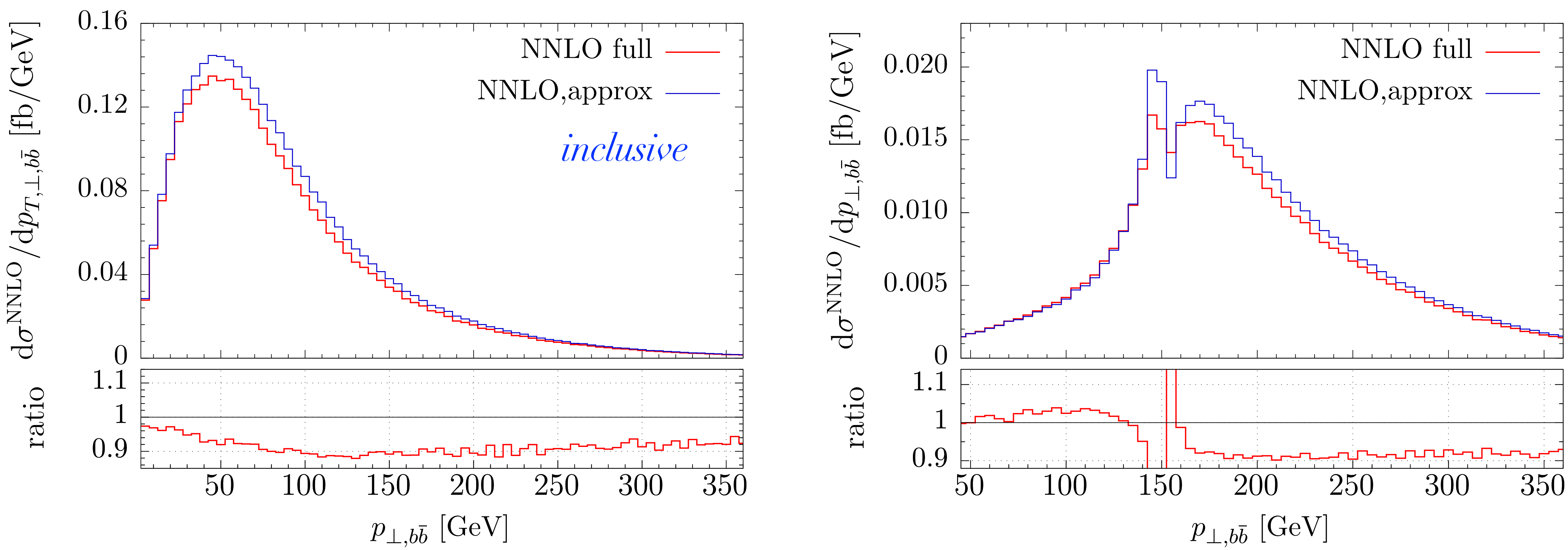
gg→ZH

- delicate SM unitarity cancellations between box/triangle → very good probe for new physics [see e.g. Englert, McCullough, Spannowsky (2013), Harlander et al (2019)]
- formally, it starts contributing at NNLO, but enhanced by gluon flux (~10/20% of total NNLO cross-section)
- only known to LO → large residual uncertainties
- currently, only approximate result [Hasselhuhn, Luthe, Steinhauser (2016)], but simplest yet-to-be-computed gg→XY process mediated by top loop. Within current (numerical) technology → expect results soon?

VH: a faithful description of measurements

- VH: important channel for $H \rightarrow b\bar{b}$
- Ideally: boosted region. In practice: semi-boosted ($p_{t,V} > 150$ GeV)
- In the boosted region, decay should be very collinear → well described by PS
- Interesting to study the interplay fixed-order/PS in the semi-boosted region…
- Fixed-order: full NNLO (production⊗decay) [Ferrera, Grazzini Tramontano (2017); FC, Luisoni, Melnikov, Röntsch (2017); Gauld, Gehrmann-de Ridder, Glover, Huss, Majer (2019)]

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

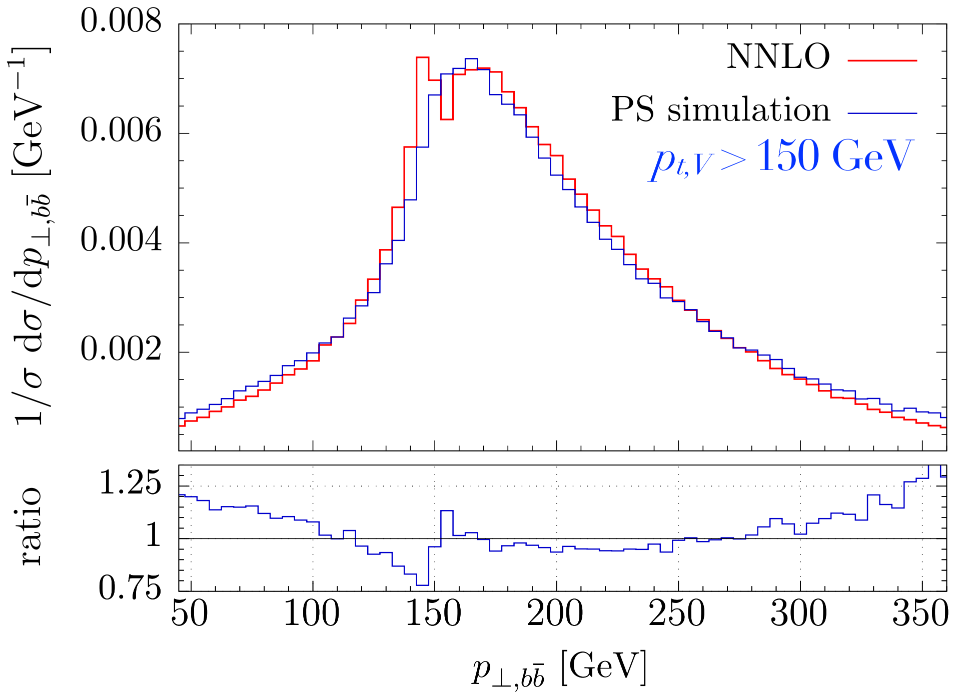


Large impact of radiation from final state bs

VH: a faithful description of measurements

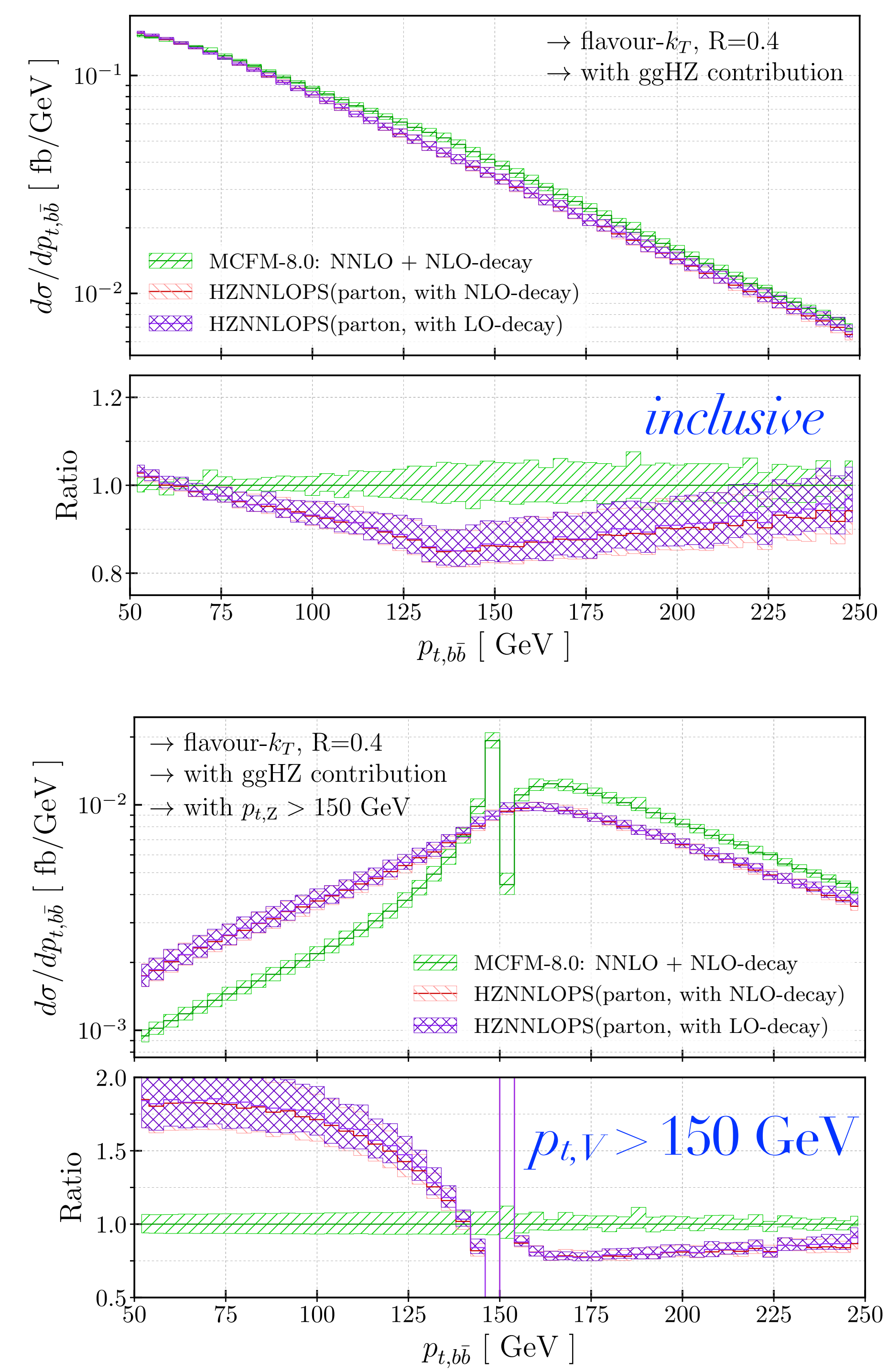
How well is the radiation pattern described by PS?

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



[FC et al (2018)]

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



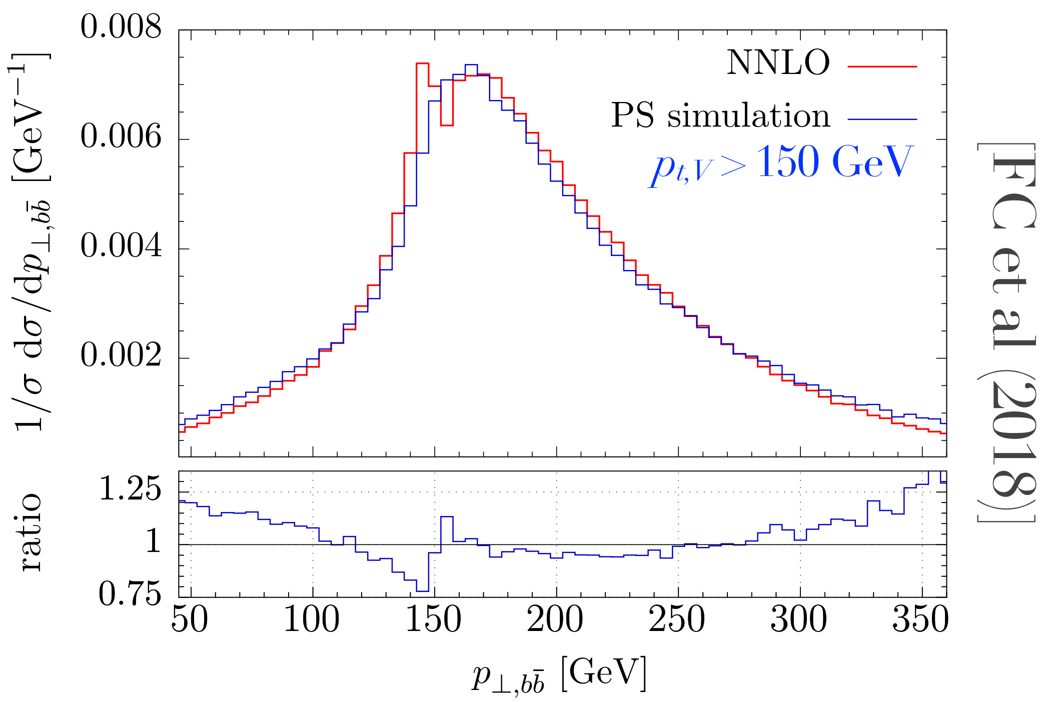
[Astill et al (2018)]

- Off-the shelf PS seems to capture *some* of the radiation pattern
- Now very sophisticated NNLOPS$_{prod}$⊗NLOPS$_{dec}$ available [Astill et al (2018)]. Similar pattern
- Delicate issues about HF-identification (b-tagging vs flavour k_t)
- More apple-to-apple investigations desirable (*massive b…*)

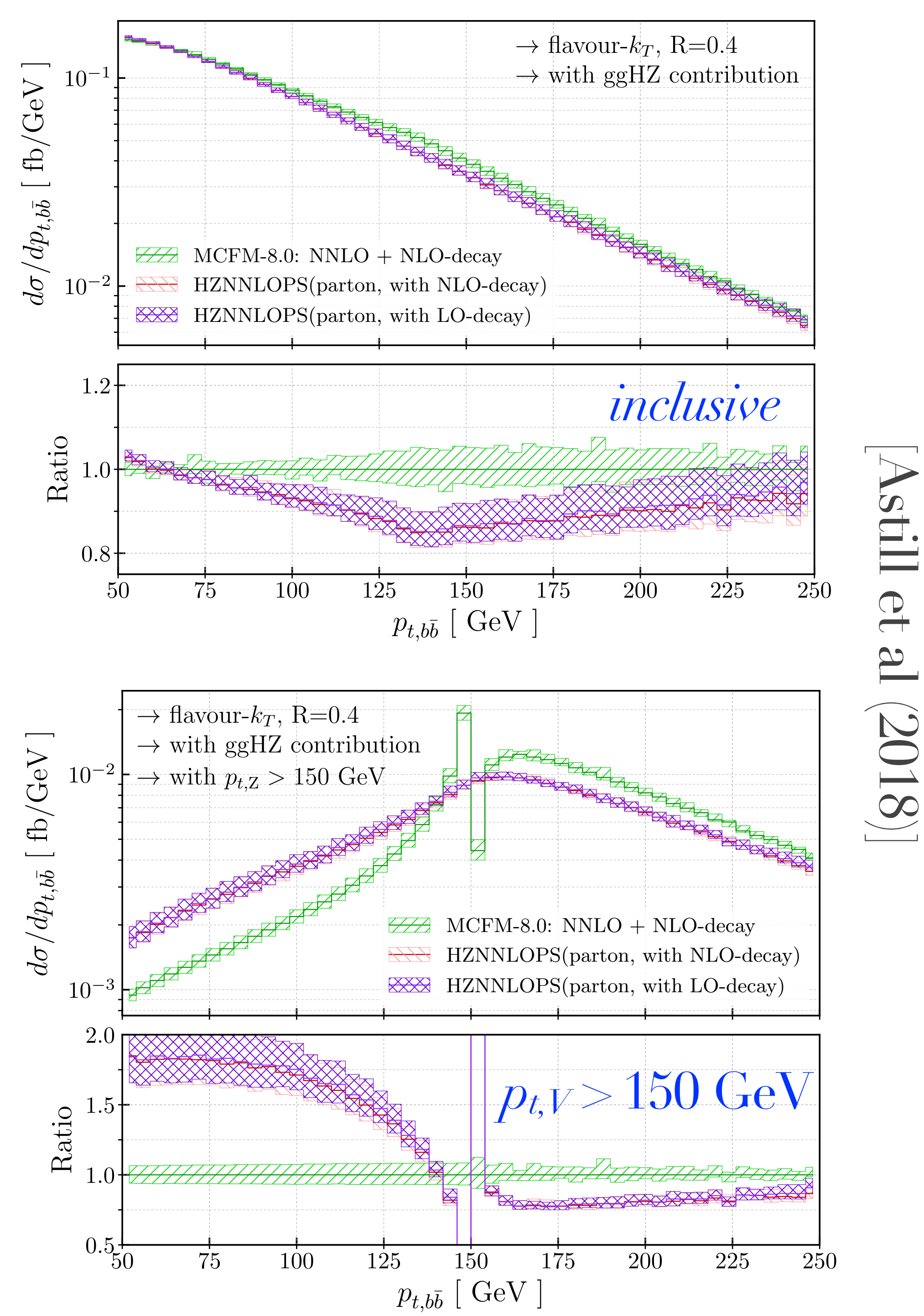
VH: a faithful description of measurements

How well is the radiation pattern described by PS?

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



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



- Massive b calculation available [Berneuther, Chen, Si (2018); Primo, Sasso, Somogyi, Tramontano (2018)] → *jet algorithm/full b-reconstruction studies*
- Furthermore: fully differential H→b$\bar{\text{b}}$ available [Mondini, Schiavi, Williams (2019)] → *more detailed studies on radiation patterns*

$t\bar{t}H$: the devil in the background…

- Direct probe of top Yukawa coupling
- 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	$\sigma_{\rm NLO}$ [fb]	$\sigma_{\rm NLO+PS}$ [fb]	$\sigma_{\rm NLO+PS}/\sigma_{\rm NLO}$
$n_b \geq 1$	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

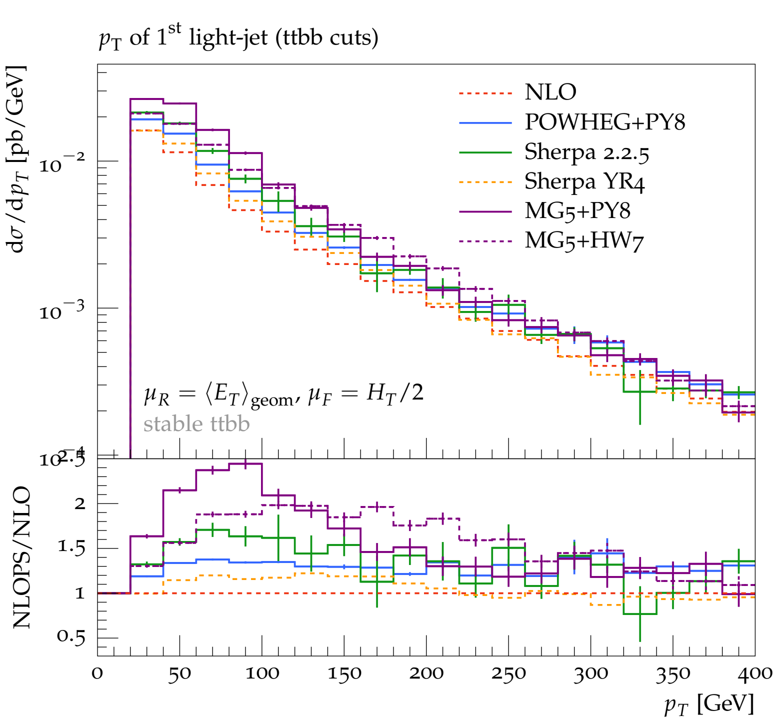
- Shower effects enhanced in the Higgs region…

$t\bar{t}H$: the devil in the background…

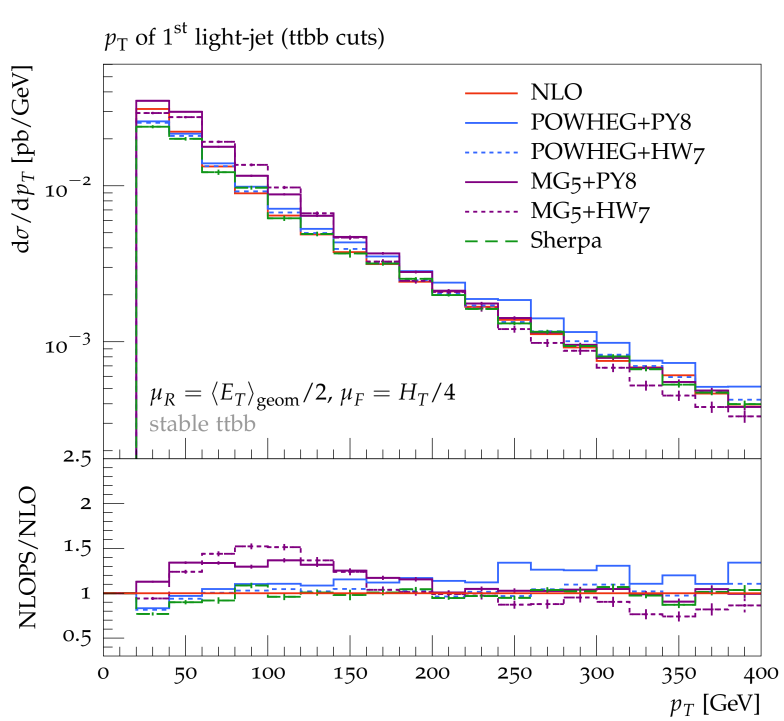
- An heroic ongoing effort to understand / fix the NLO vs NLOPS issue
  [S. Pozzorini, L. Reina, F. Buccioni, M.V. Garzelli, T. Jezo, J. Krause, A. Kardos, J. Lindert, R. Podskubka, C. Reuschle, F. Siegert, M. Zaro, M. Zoller, *ongoing*]
- A lot of complex delicate issues… cannot make justice to it in a few minutes. Just few highlights, see talks by S. Pozzorini at the HXSWG meetings for more details

Most likely cause of bad behavior: LARGE K-FACTOR ENHANCED BY SHOWER

NLOPS YR4 scales



NLOPS 0.5 rescaling

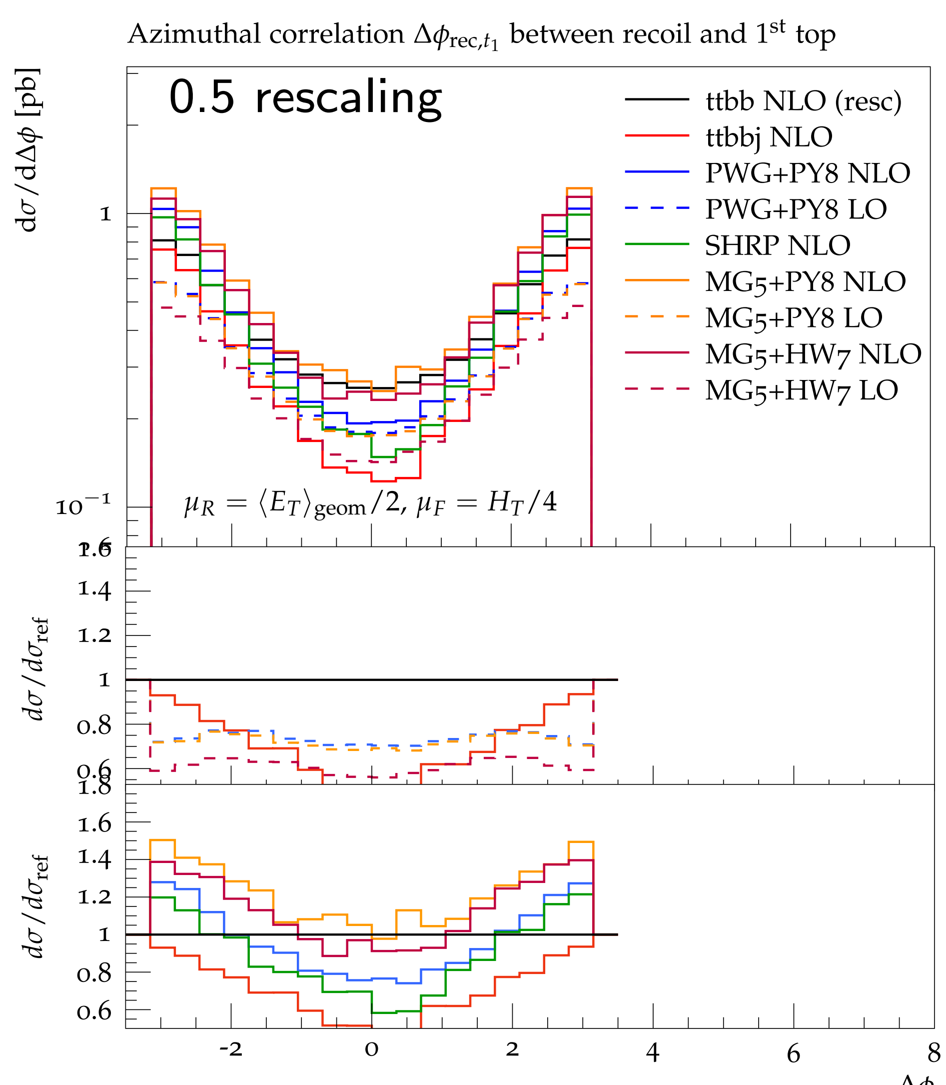


- The good news: a more appropriate scale choice removes part of the issue
- The bad news: this does not remove large shower corrections in the N_b=2 bin

$t\bar{t}H$: the devil in the background…

Most likely cause of bad behavior: LARGE K-FACTOR ENHANCED BY SHOWER

- The bad news: clever scale choice does not remove large shower corrections in the N_b=2 bin
- Most likely culprit: large recoil effect / bin migration
- To fix it: need to understand better QCD radiation pattern, find good observables sensitive to it

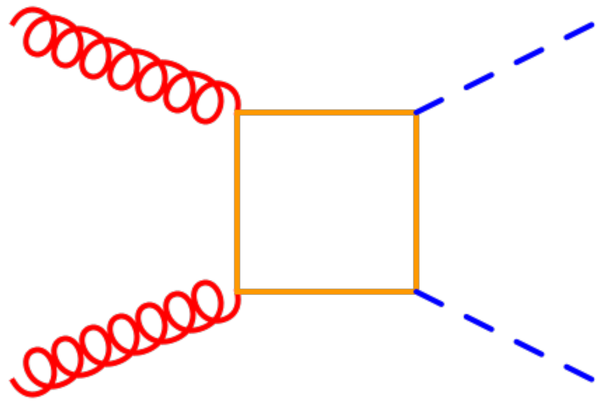


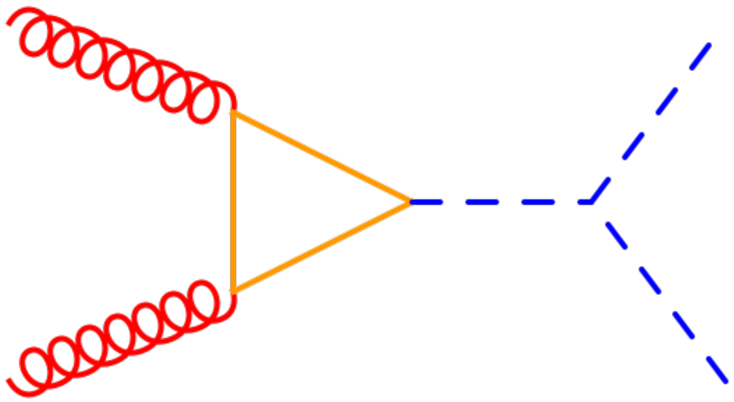
Once again, it would be crucial to better understand jet dynamics, $g \to b\bar{b}$ splitting etc…

Very interesting theoretical problem, not limited to $t\bar{t}H$ (e.g.: V+HF for VH…)

HH: good theory, but difficult to improve…

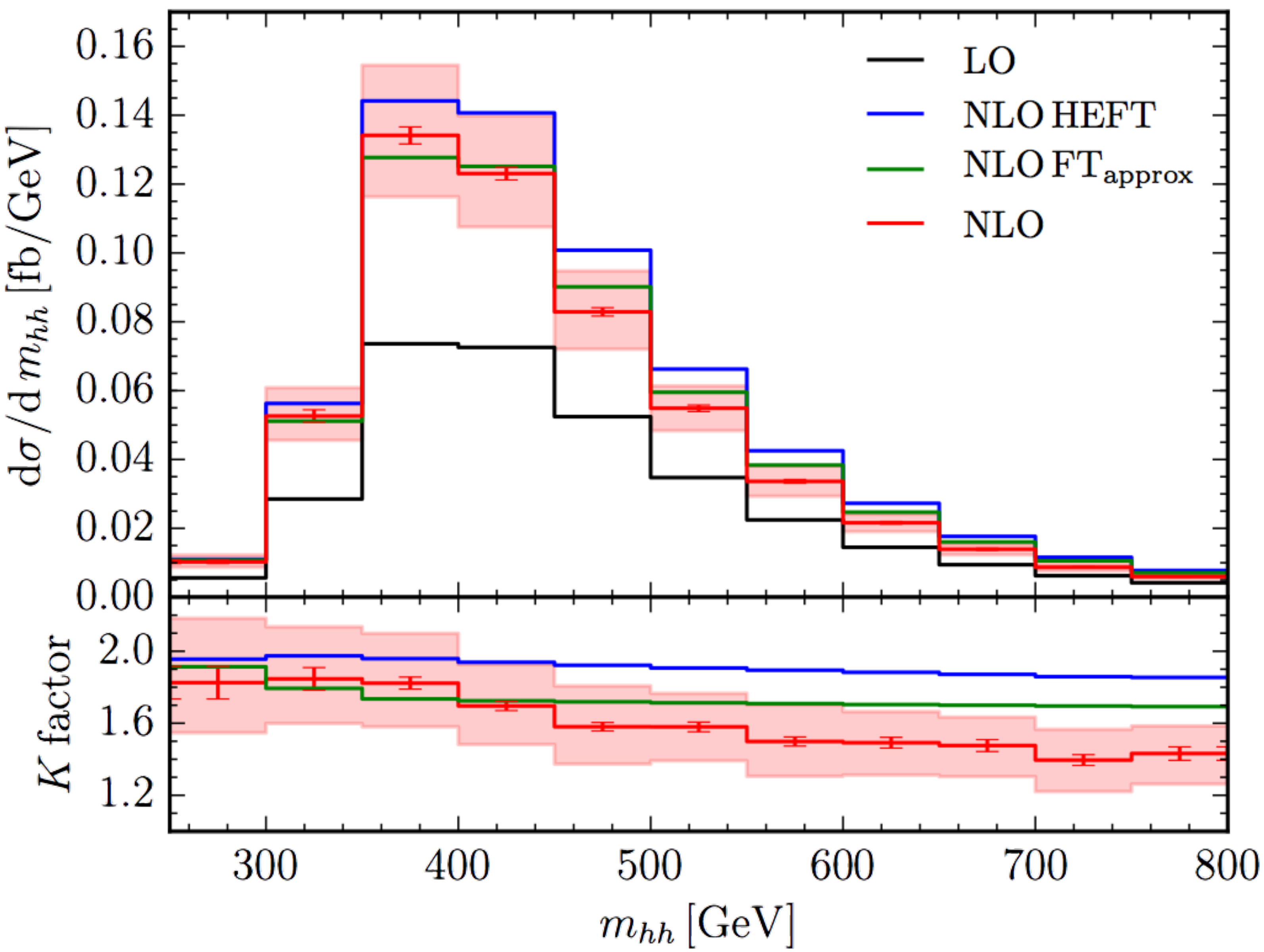
- HH production: direct probe of Higgs self-coupling





- Still far from measurements, but still important to have good theoretical control.
- The (usual) problem: LO is loop-induced → NLO is already 2-loop, with massive virtual fermions → cannot do it analytically yet (although a lot of progress…)
- Same problem of boosted Higgs, gg→ZH, gg→VV / off-shell interference…
- In some sense, the ``simplest'' process in this class → a lot of attention.
- Analytic side: several approximations.
- Numerical techniques developed, we now have full NLO result [Borowka et al (2016), Baglio et al (2018)]

HH@NLO: lesson learned



- 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

Still unclear why this is happening

- It would be interesting to study different approximations, to understand better what is going on [see e.g. Xu, Yang (2018)]
- It would be interesting to study other processes, to gain extra information (ZZ, Hj, VH)

HH@NLO: applications

- NLO calculations used as a basis for several applications. For example:
  - NLOPS [Heinrich et al. (2017)]
  - Informing analytic approximations to extend calculation at high invariant mass [Davies et al. (2019)]
  - NLO+NNLO$_{\mathrm{mt}\to\infty}$ [de Florian et al. (2016), Grazzini et al (2018)], +NNLL$_{\mathrm{soft}}$ [de Florian, Mazzitelli (2018)]

<u>A very good control…</u>

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
NLO [fb]	$27.78^{+13.8\%}_{-12.8\%}$	$32.88^{+13.5\%}_{-12.5\%}$	$127.7^{+11.5\%}_{-10.4\%}$	$1147^{+10.7\%}_{-9.9\%}$
$\mathrm{NLO}_{\mathrm{FTapprox}}$ [fb]	$28.91^{+15.0\%}_{-13.4\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$134.1^{+12.7\%}_{-11.1\%}$	$1220^{+11.9\%}_{-10.6\%}$
$\mathrm{NNLO}_{\mathrm{NLO-i}}$ [fb]	$32.69^{+5.3\%}_{-7.7\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$149.3^{+4.8\%}_{-6.7\%}$	$1337^{+4.1\%}_{-5.4\%}$
$\mathrm{NNLO}_{\mathrm{B-proj}}$ [fb]	$33.42^{+1.5\%}_{-4.8\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$154.2^{+0.7\%}_{-3.8\%}$	$1406^{+0.5\%}_{-2.8\%}$
$\mathrm{NNLO}_{\mathrm{FTapprox}}$ [fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$
M_t unc. $\mathrm{NNLO}_{\mathrm{FTapprox}}$	±2.6%	±2.7%	±3.4%	±4.6%
$\mathrm{NNLO}_{\mathrm{FTapprox}}$/NLO	1.118	1.116	1.096	1.067

<u>… with a very big caveat</u>

HH@NLO: mass-scheme dependence

- Result depends non-trivially on the renormalisation scheme and scale for the top quark mass [Baglio et al (2019)]
- Ambiguities substantially larger than ``standard'' uncertainties (careful in identify TH uncertainty with ``naive'' scale variation…)

$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=300\text{ GeV}} = 0.0298(7)^{+6\%}_{-34\%}\,\text{fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=400\text{ GeV}} = 0.1609(4)^{+0\%}_{-13\%}\,\text{fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=600\text{ GeV}} = 0.03204(9)^{+0\%}_{-30\%}\,\text{fb/GeV},$$
$$\left.\frac{d\sigma(gg\to HH)}{dQ}\right|_{Q=1200\text{ GeV}} = 0.000435(4)^{+0\%}_{-35\%}\,\text{fb/GeV},$$

- Unfortunately, natural to expect (and also seen in *b*-contribution to the Higgs p_t spectrum [Melnikov, Tancredi, Wever (2017)])
- For bulk ggF: top is not active → effect not there (*this is the exception!*)
- Honest solution: one order higher, i.e. NNLO for a process for which we can only barely compute NLO… quite some fun ahead…

Conclusions

- A 125 GeV Higgs: sweet spot for thorough studies of its properties
- LHC measurements progressing very fast
- Higgs has always been one of the main player in pushing our understanding of QCD and collider phenomenology
- A lot of recent progress → could not make justice to it. Among missing items
  - Off-shell
  - Background issues (ggF contamination to VBF, PS/UE effects…)
  - EW
  - Higgs and complex final states
  - EFT/BSM. Future colliders…
- Apologies if I skipped your favourite topic!

- The general picture: theory in a pretty good shape, but still a lot to be done
- In many cases, this requires some non-trivial improvement in our understanding of QCD/EW/collider pheno, that would have actual implication for real-world Higgs explorations → EXCITING TIMES AHEAD!

Thank you very much!