Theoretical predictions for Higgs physics: status and prospects

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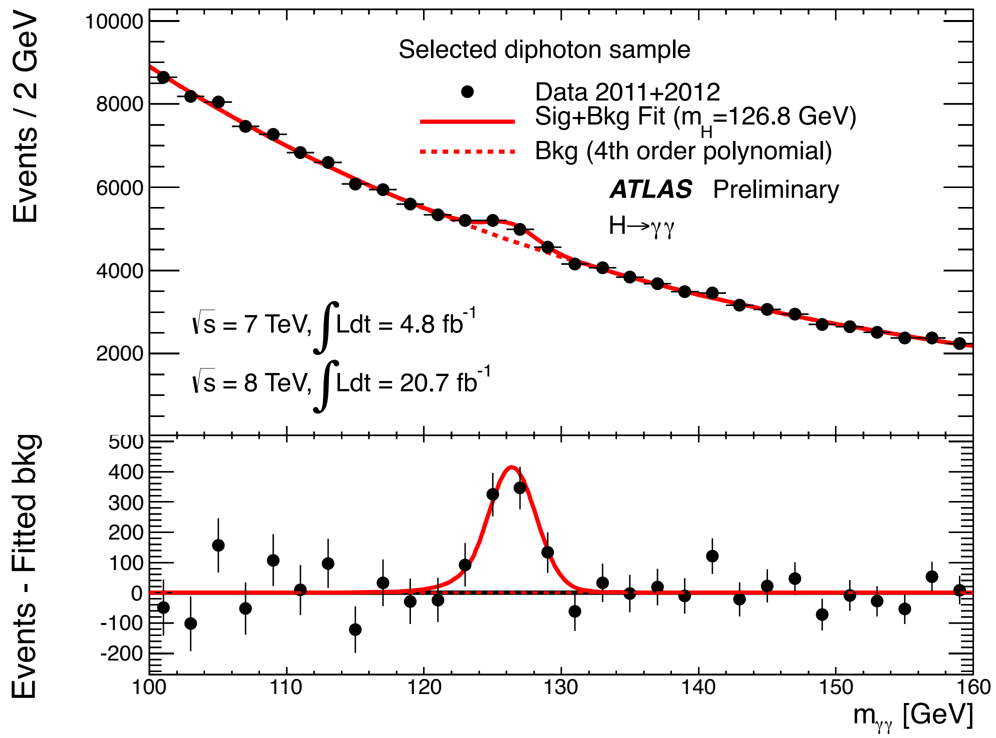
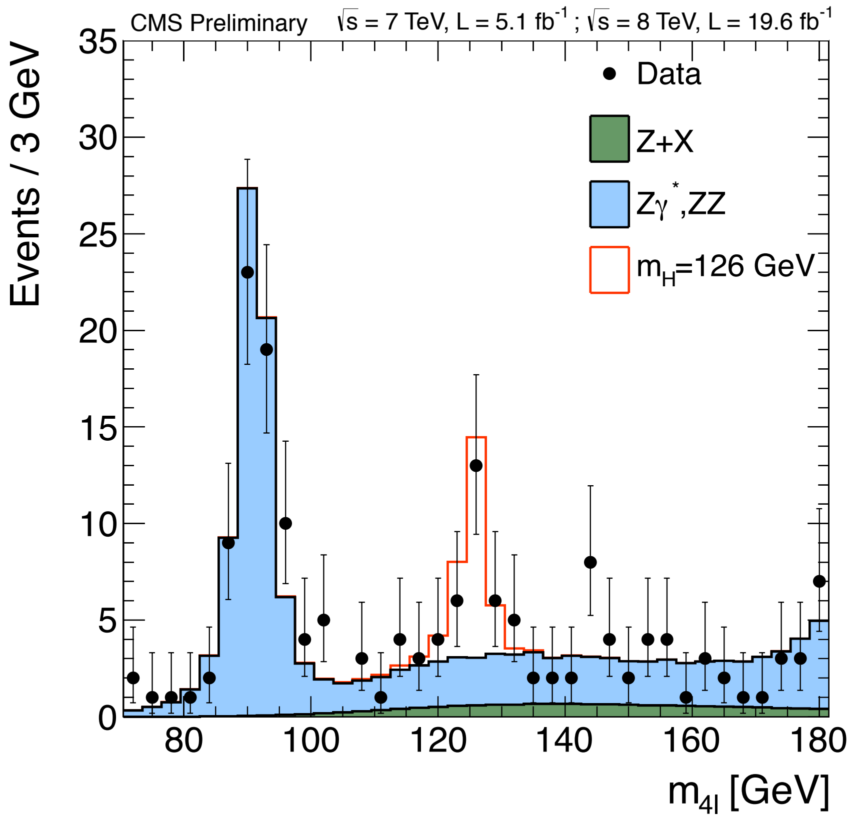
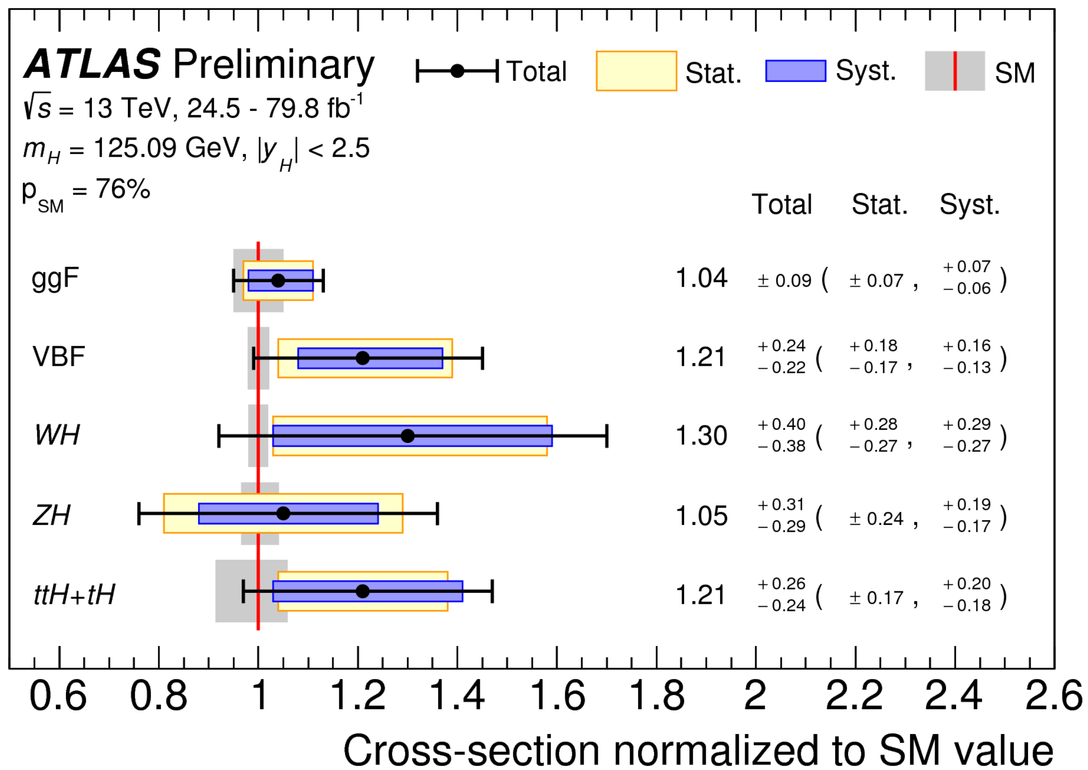
Higgs at the LHC: a very short childhood

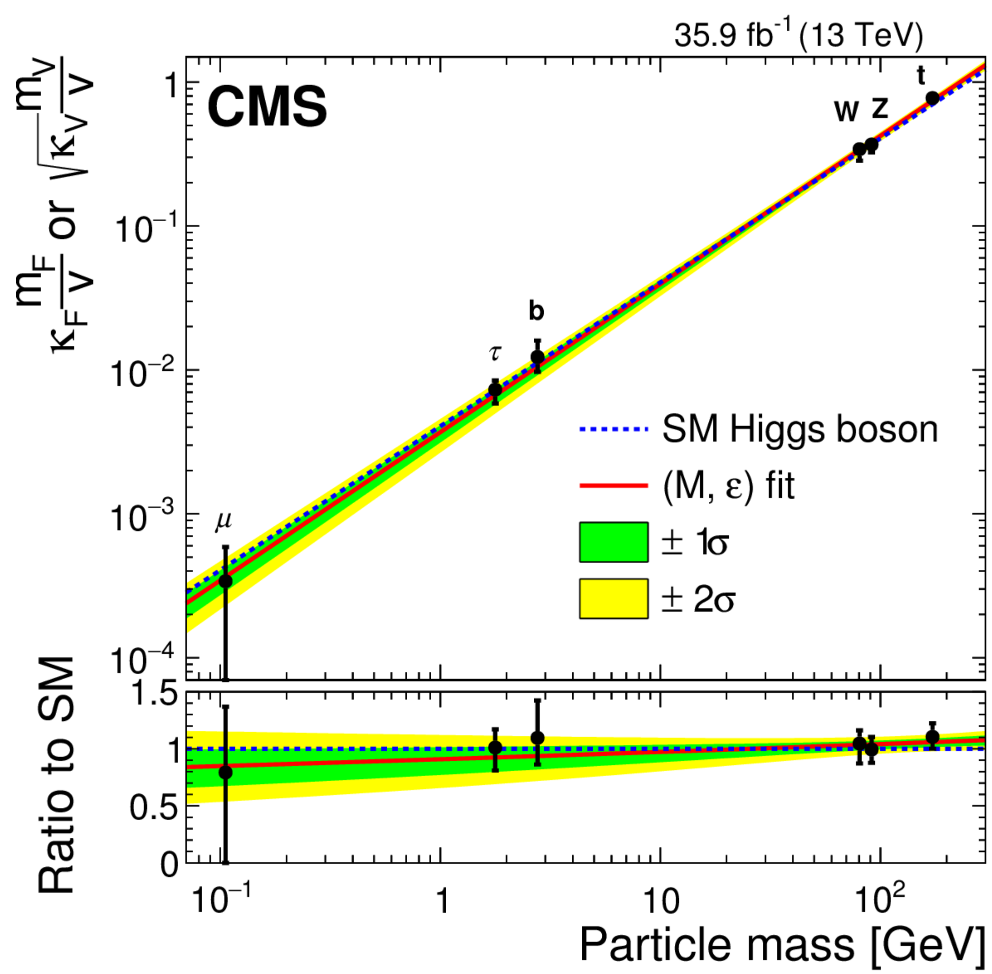




2012

Higgs at the LHC: a very short childhood





H^0 $J = 0$

H^0 MASS

VALUE (GeV)

125.10±0.14 OUR AVERAGE

H^0 DECAY WIDTH

VALUE (GeV)	*CL%*
<0.0144	95
<1.10	95
<0.013	95
<1.7	95
>3.5 $\times 10^{-12}$	95
<5.0	95
<2.6	95

H^0 SIGNAL STRENGTHS

Combined Final States

VALUE

1.10±0.11 OUR AVERAGE

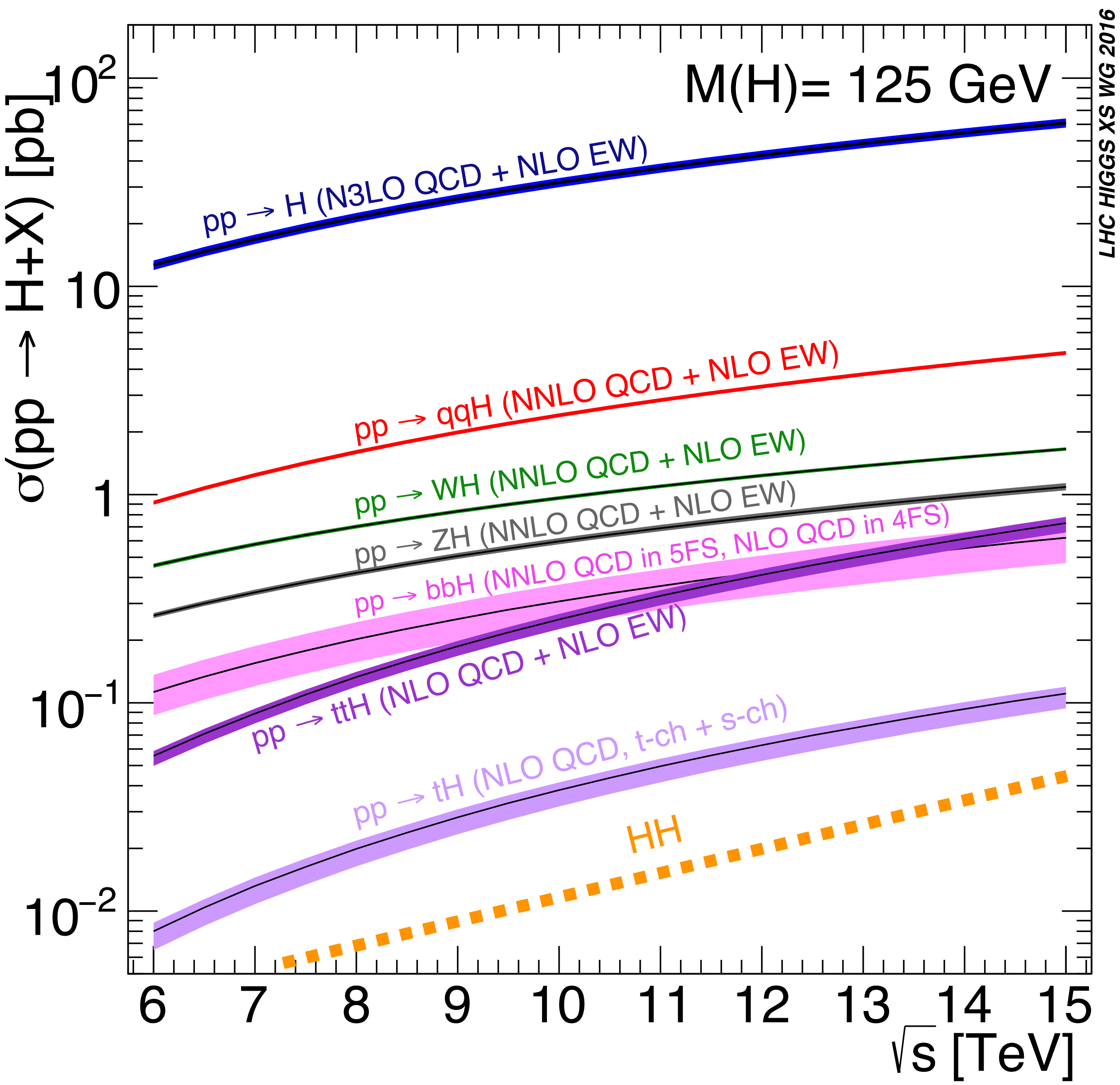
• • •

[PDG 2018]

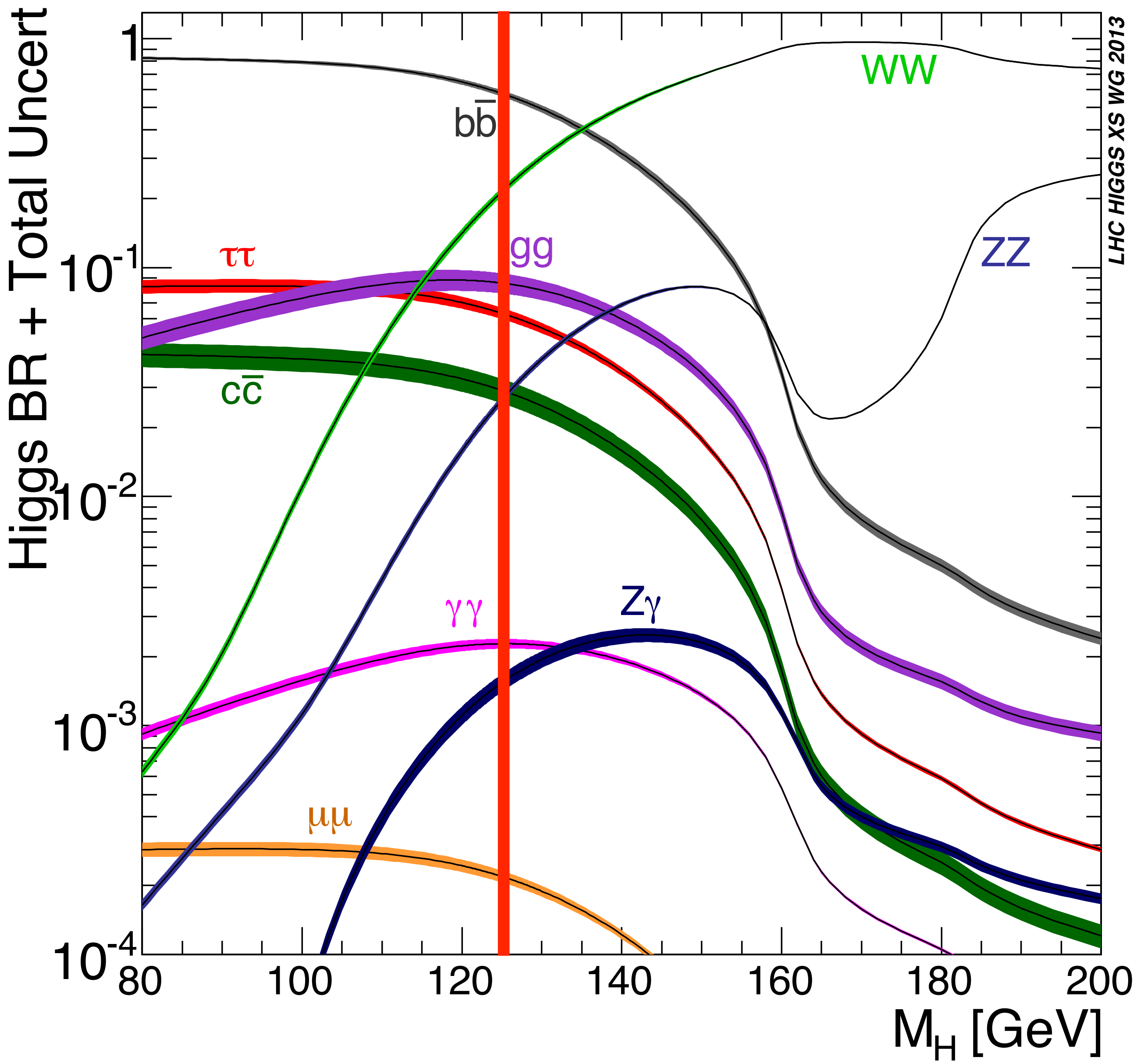
After LHC Run II

Higgs125 at the LHC: a sweet spot

Production modes

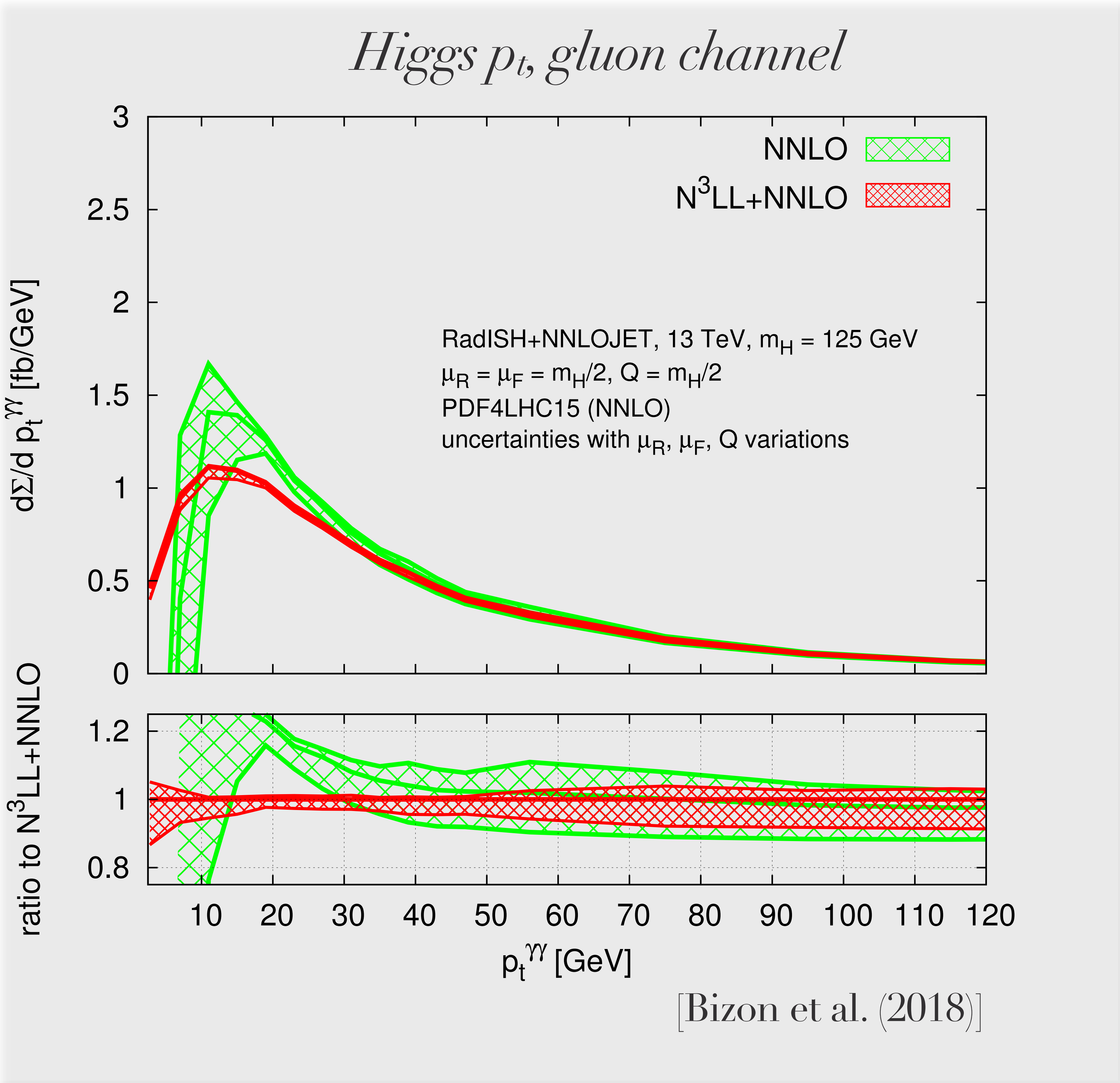


Decay channels



- Comprehensive studies at the LHC are possible, in many different channels
- ``*Nature has been kind*"

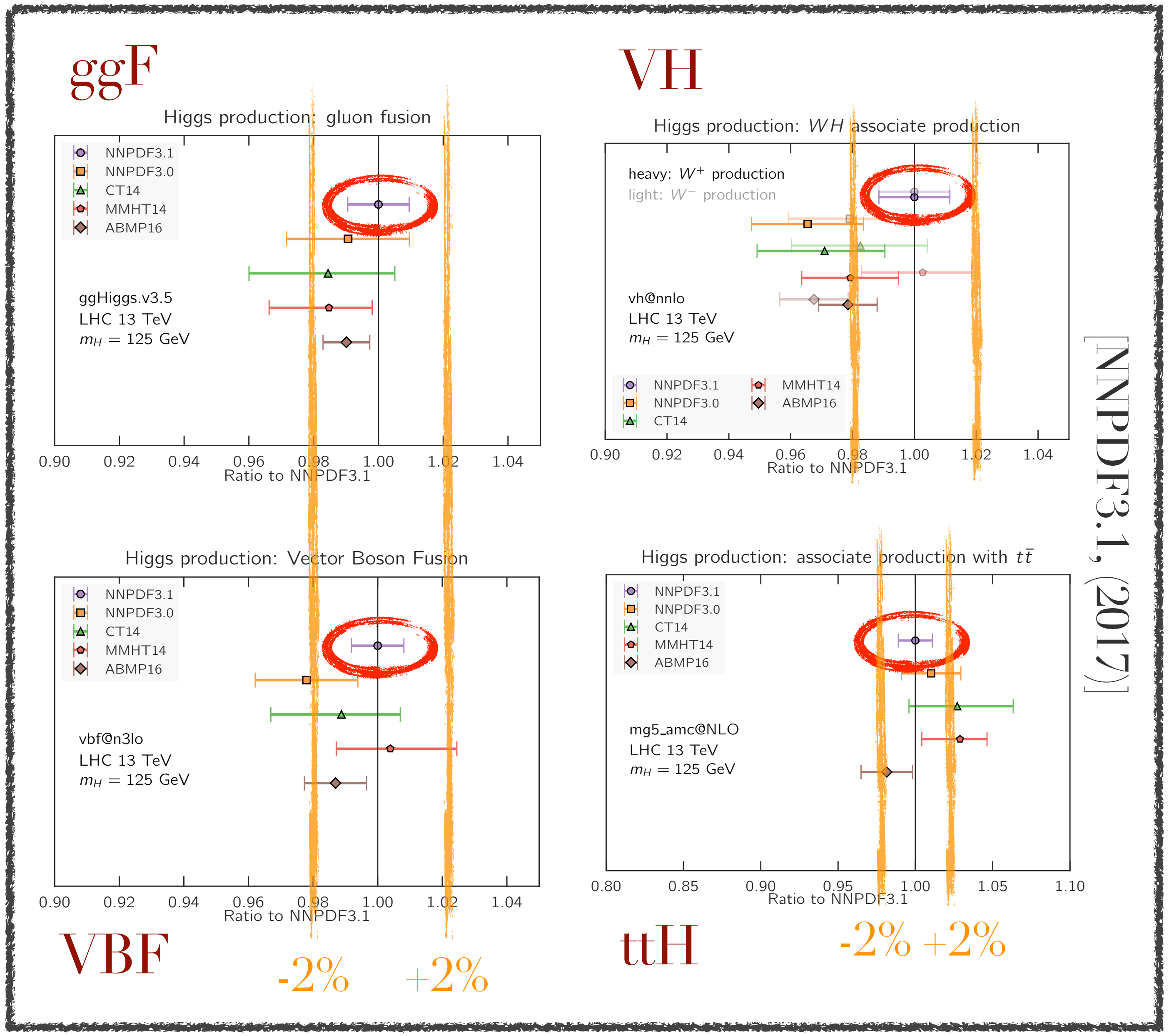
Higgs$_{125}$ and QCD: a sweet spot

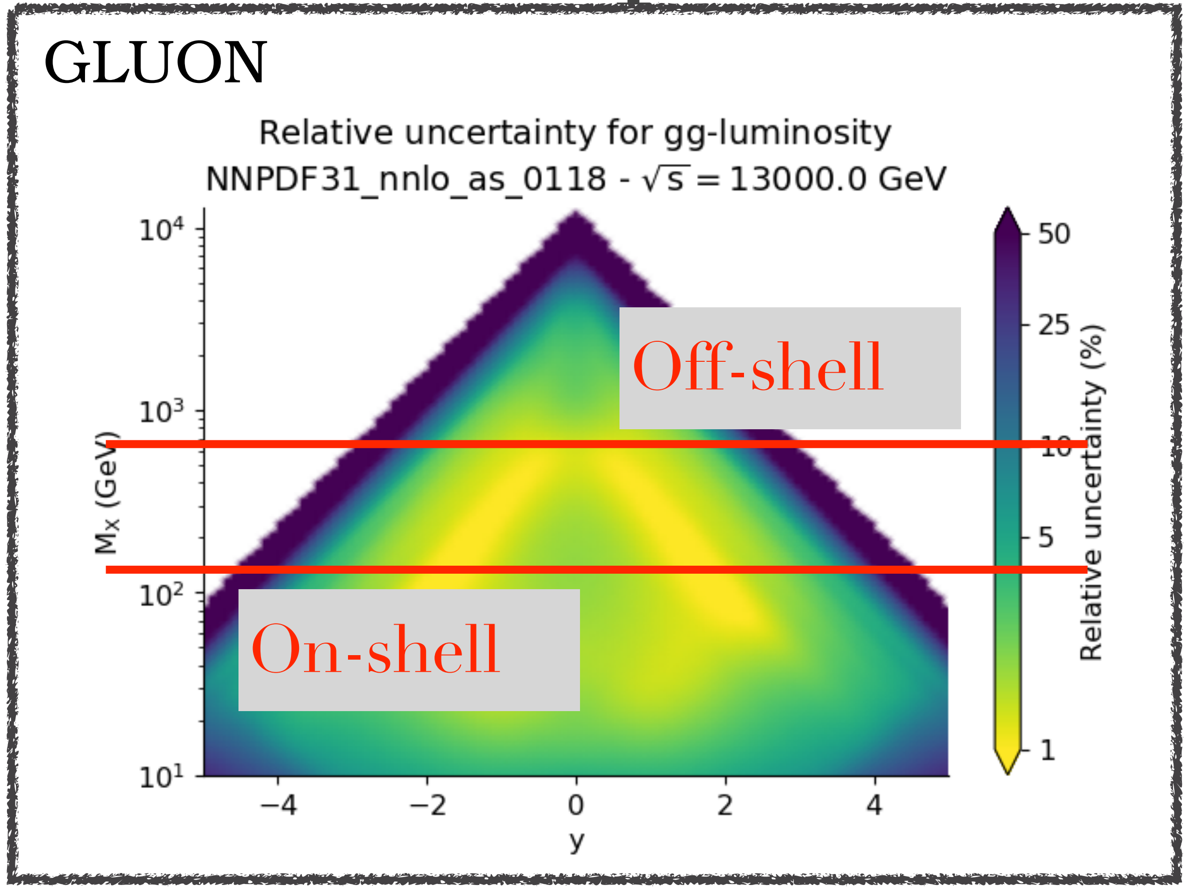


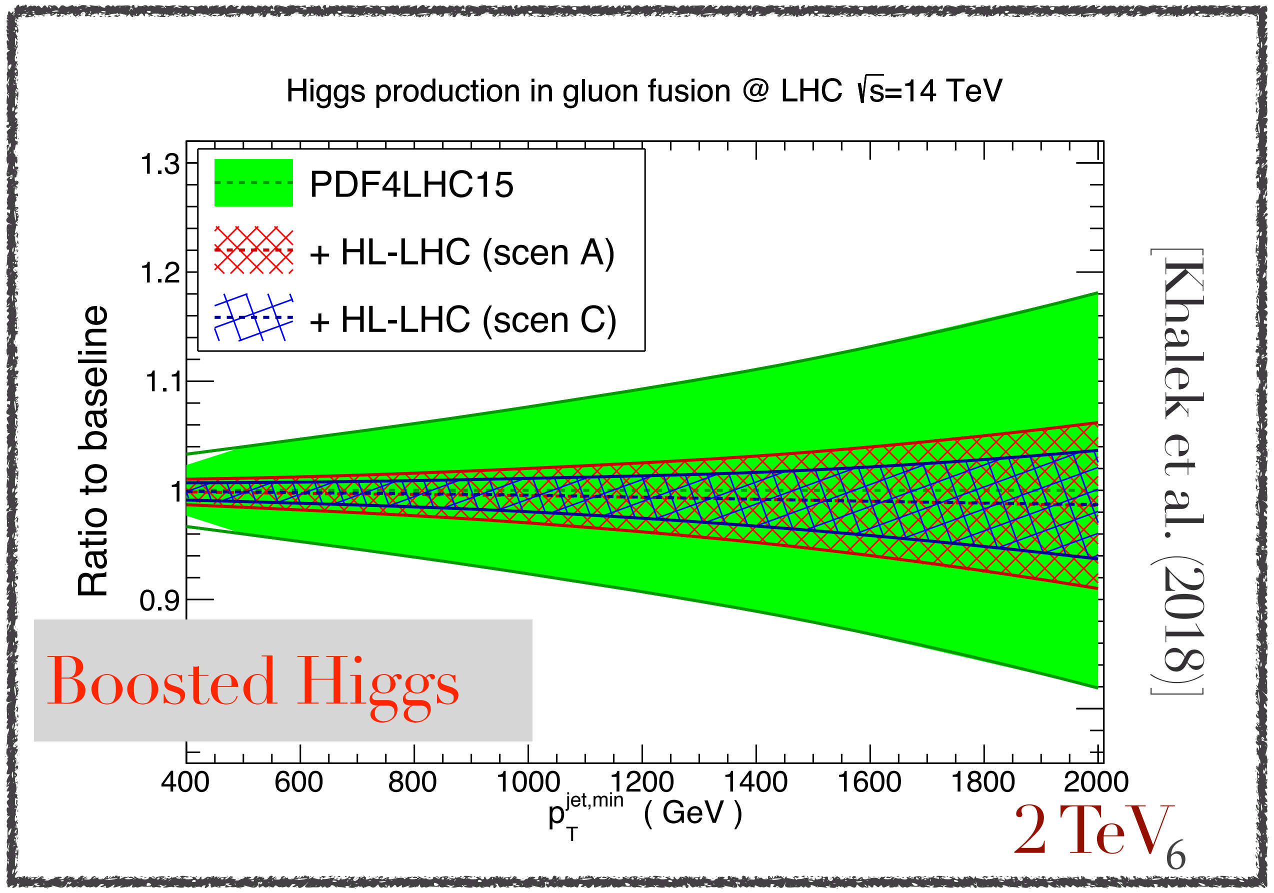
By and large, most of the Higgs cross section accessible with perturbative QCD methods

Large part of the cross section in a region with little contamination from soft physics

Higgs125 and QCD: a sweet spot

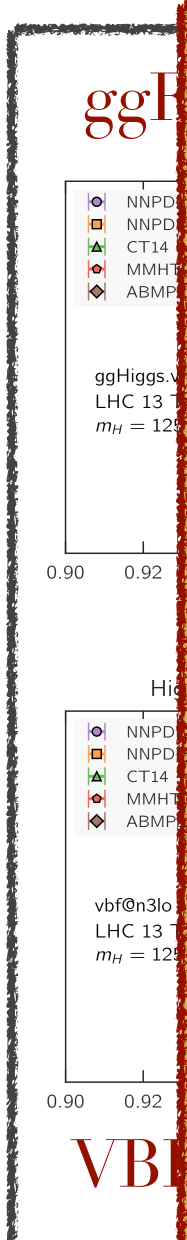


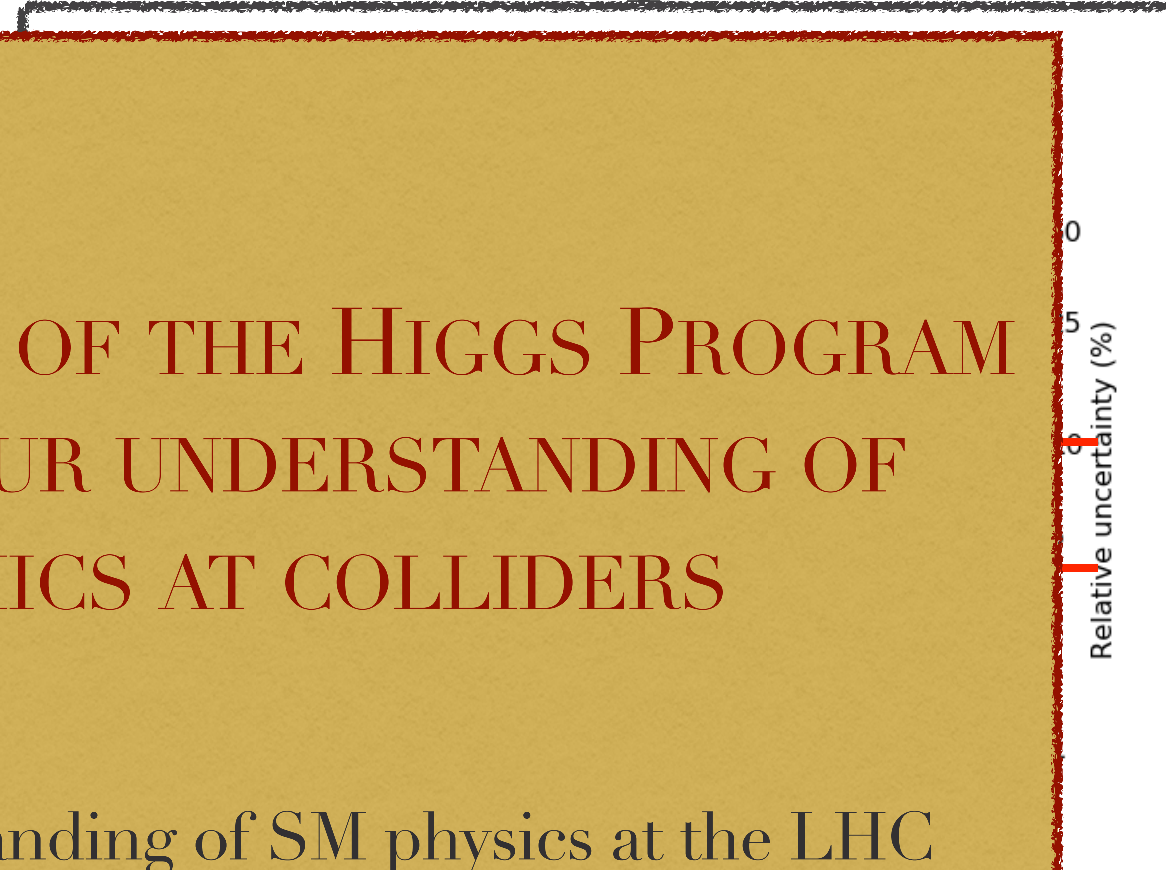


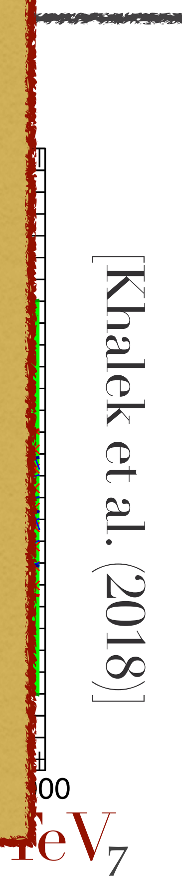


- Good knowledge of relevant PDFs
- A lot of experimental (LHC data) and theoretical progress (*see S. Forte's talk*)

Higgs$_{125}$ and QCD: a sweet spot





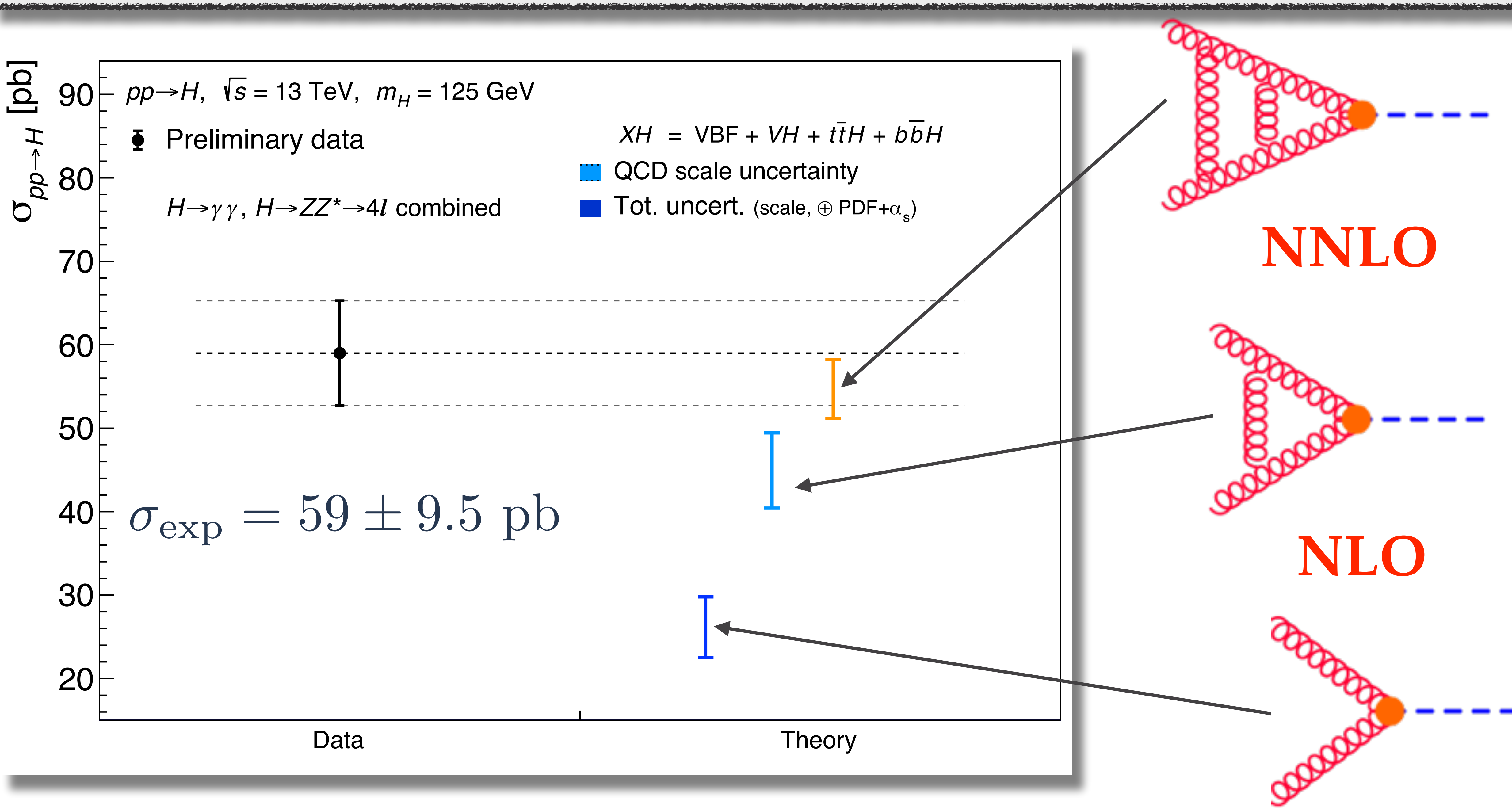


To a large Extent, success of the Higgs Program at the LHC depends on our understanding of (p)QCD and SM dynamics at colliders

- Higgs: a drive towards better understanding of SM physics at the LHC
- Higgs: behind many breakthrough *(first N³LO calculation, first NNLO "+j" calculation, multi-differential resummations, new generation of PS…)*
- At the forefront of theoretical developments in QCD
- In the following: some illustrative examples
- *Disclaimer:* not a comprehensive review!

The golden channel: ggF

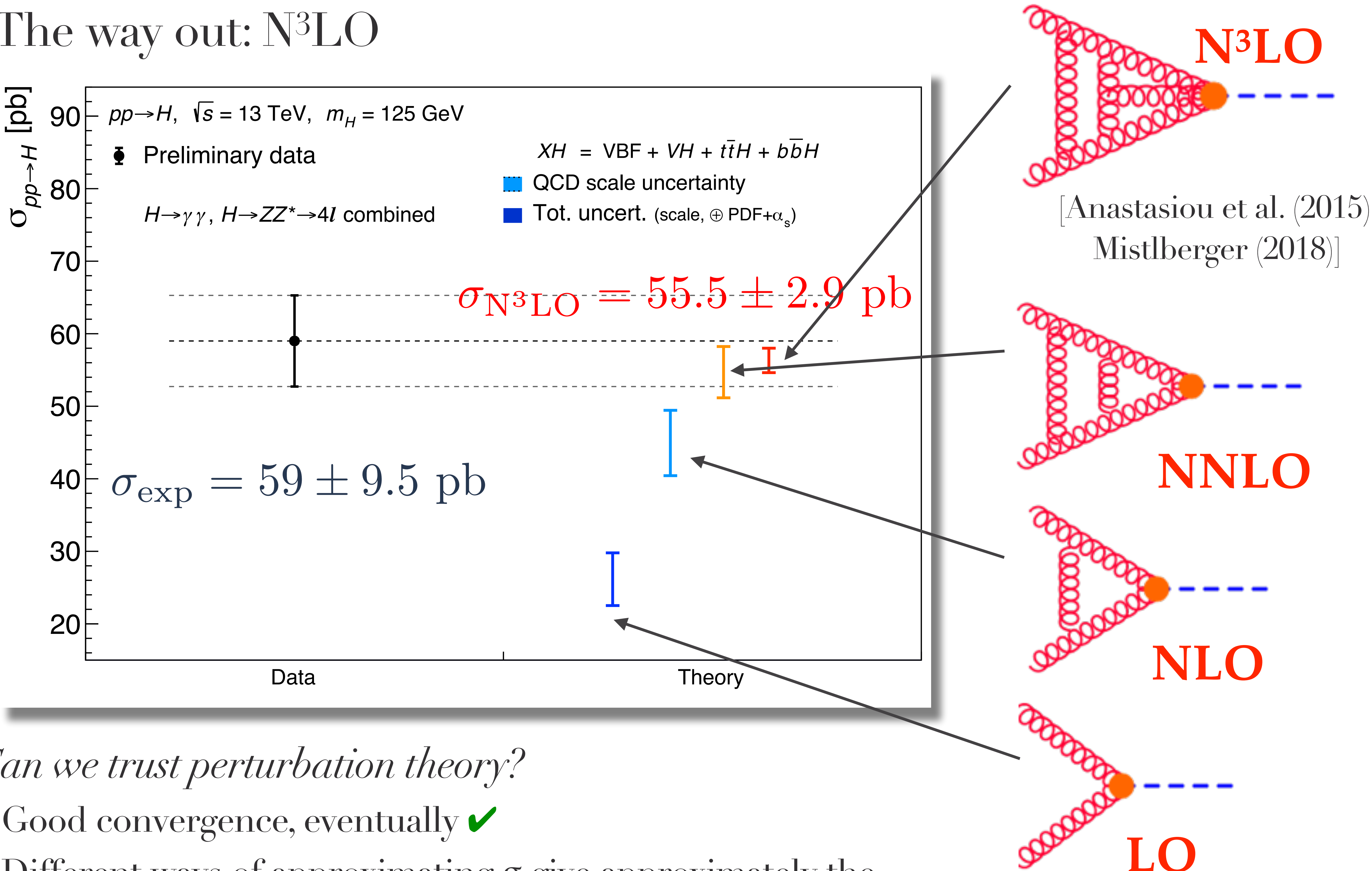
> *"In QFT, corrections are typically either large and then trivial, or small and then irrelevant"*, a celebrated quantum-field theorist



Despite some arguments, and a lot of experience, ggF K-factor is still something we do not really understand in pQCD…

The golden channel: ggF

The way out: N^{3}LO



Can we trust perturbation theory?

- Good convergence, eventually ✔
- Different ways of approximating σ give approximately the same result ✔

Life beyond N^{3}LO

N^{3}LO residual uncertainty: few percent. At this level, many other effects play a role…

[Mistlberger, QCD@LHC2016]

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

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

- Todo List:
  - Full mass dependent NNLO
  - Mixed $\mathcal{O}(\alpha\alpha_S)$ corrections
  - N3LO PDFs
  - ….

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	~~±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 (2018)]

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

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

Slight change in the perspective: no longer ``one big contribution", many (very difficult to control) small effects…

N^3LO: going differential

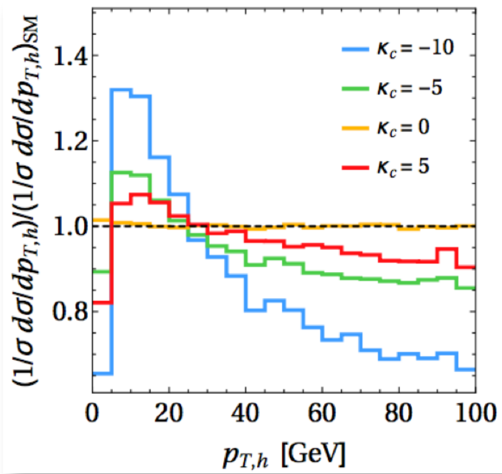
- Inclusive cross section is an idealised quantity, very far from what we measure
- Reliable prediction: properly model fiducial volume of experiment → fully differential. Only known at NNLO [+PS]
- Although fiducial volume seem relatively stable under perturbative corrections, desirable + very interesting QCD problem
- H is scalar: fully differential:
  - p_t → known since quite some time ``H+J@NNLO"
  - y → (very reliable) approximate results appeared [Dulat, Mistlberger, Pelloni (2018)]

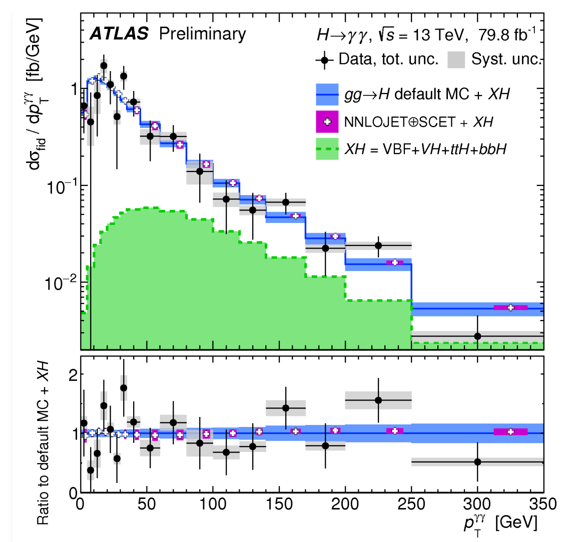
→ *see X. Chen's talk tomorrow*

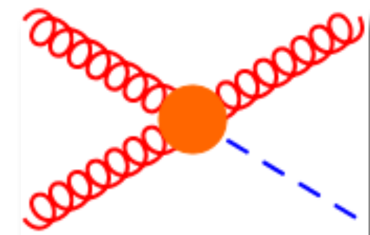
Is the full rapidity dependence required for N^3LO differential?

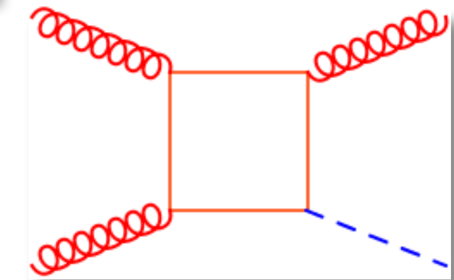
- No: if you know NNLO p_t distribution, you only need to know N^3LO rapidity at zero p_t → ``beam function"
- Very recently: first results (for DY) appeared [Behring, Melnikov, Rietkerk, Tancredi, Wever (2019); Luo, Yang, Zhu, Zhu (2019)]

Why going differential?









Low p_t

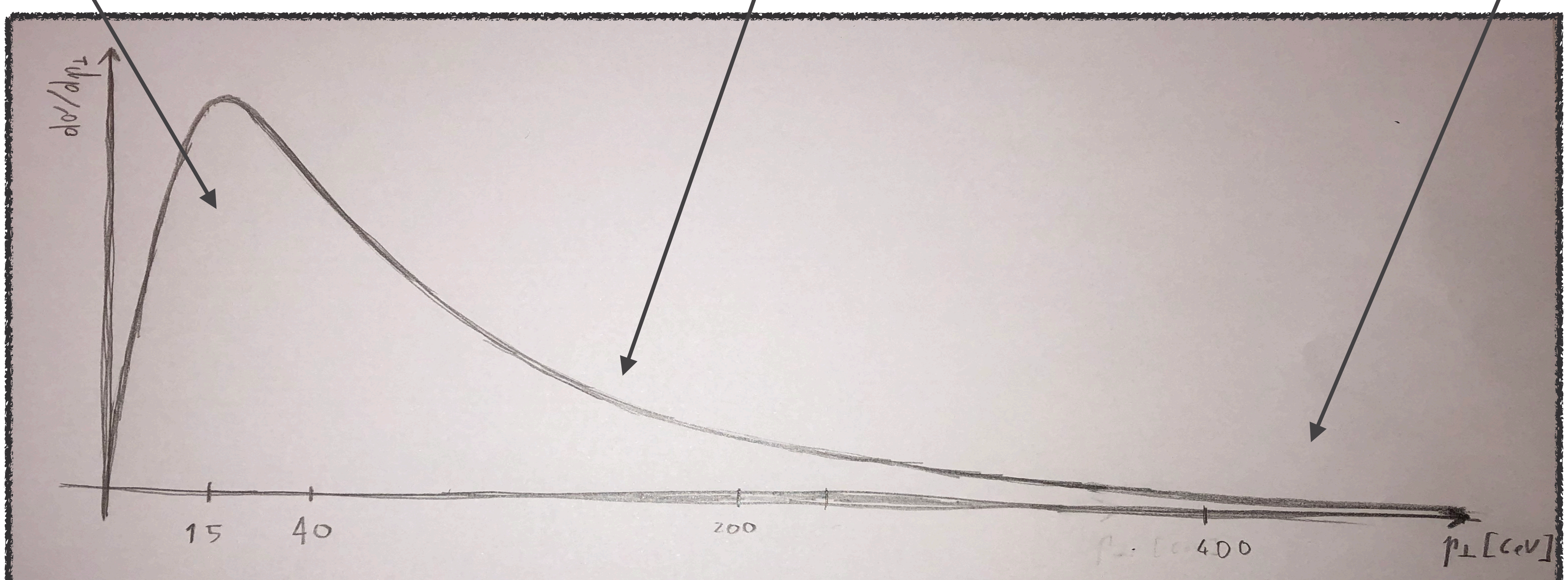
Light Yukawas…

Bulk of the distribution

Highest precision

Boosted

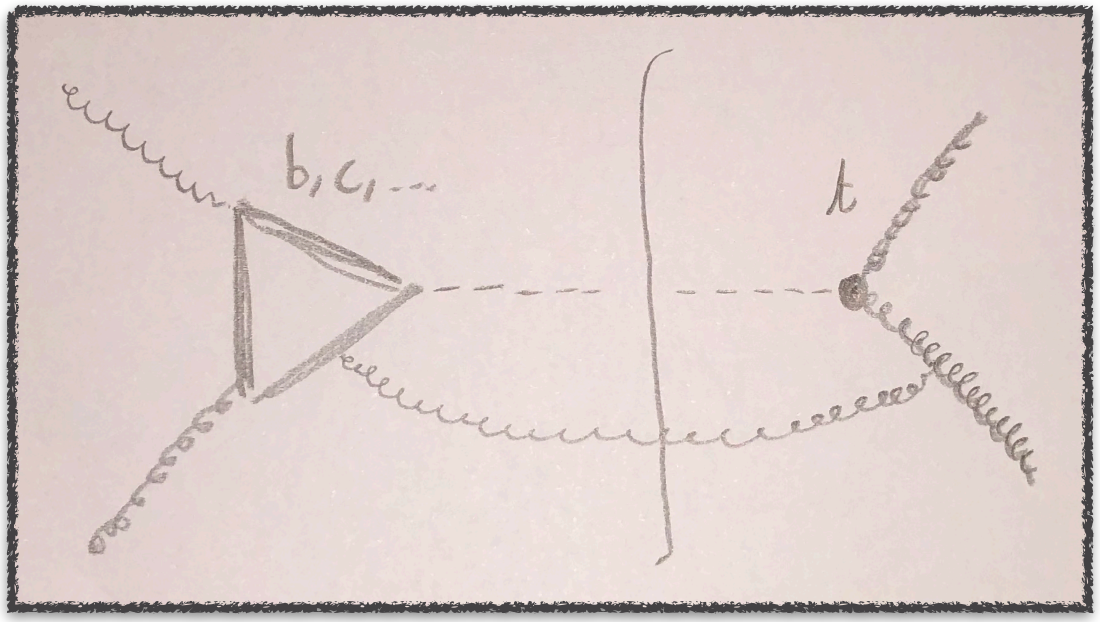
ggH vs ttH, EFT…

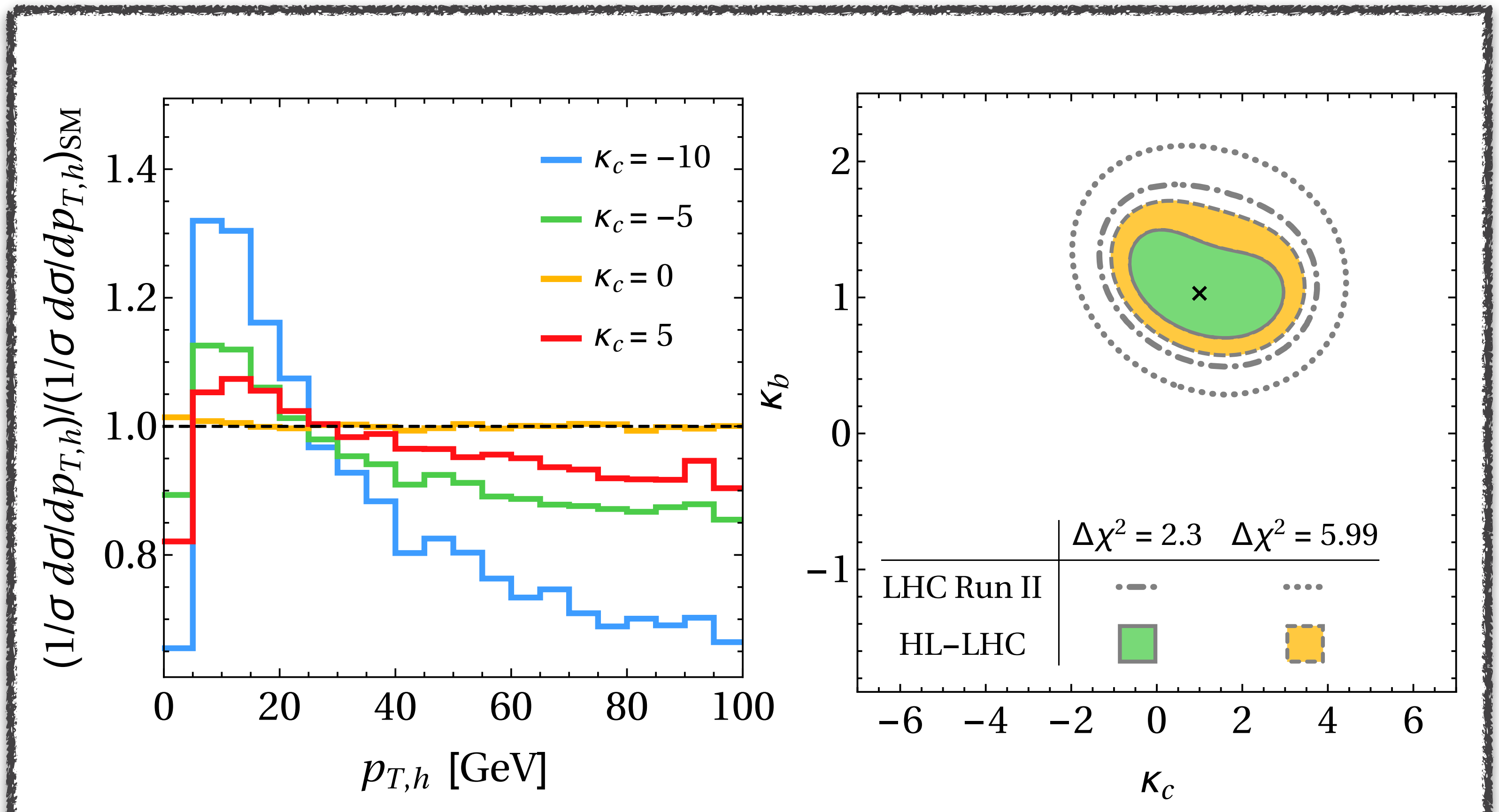


see X. Chen's talk tomorrow

Low pt: 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>

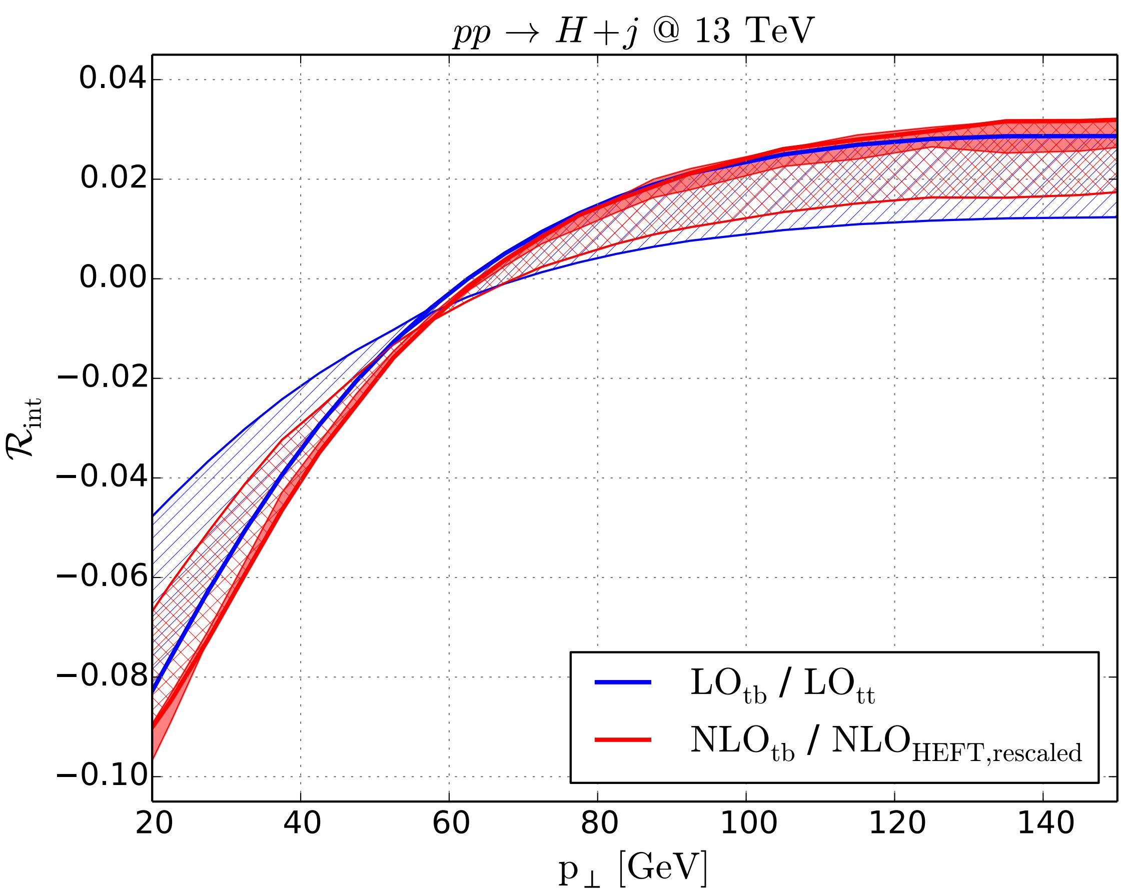
- Resolved quark loop → very difficult loop amplitudes
  - ✴ *beyond state-of-the-art for analytic calculations*
  - ✴ *large logs → numerical approached difficult*
- Low p_t, large logs → all-order effects must be considered?

Low p_t: light quark effects

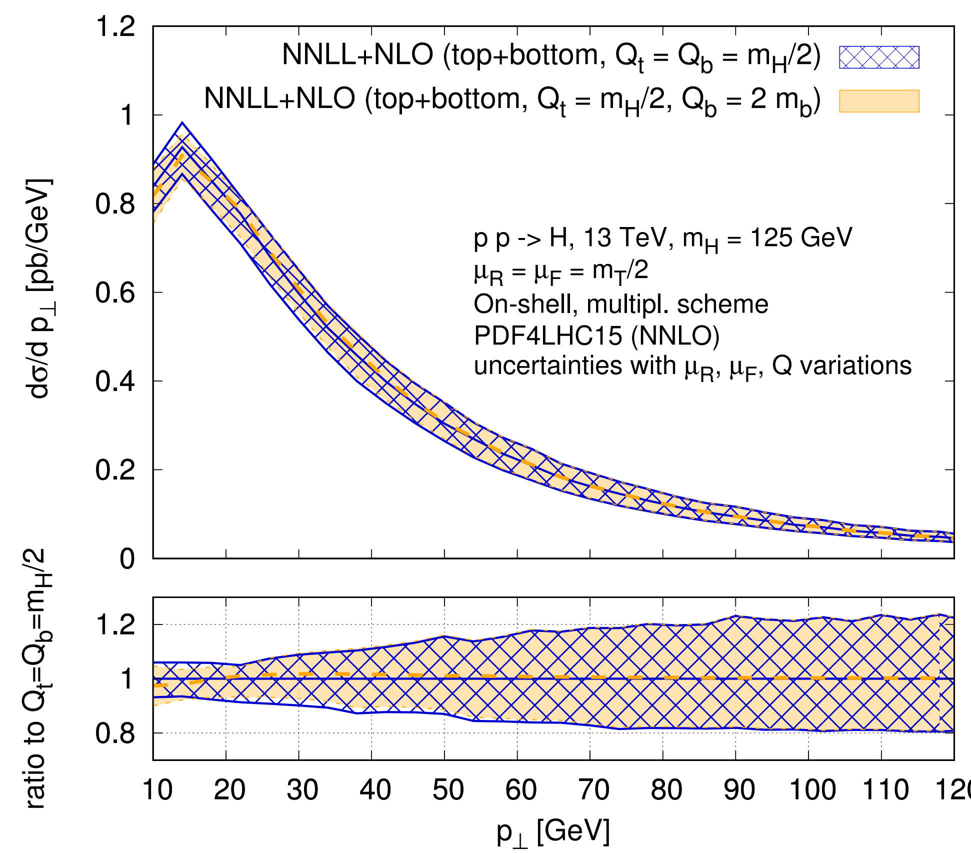
- Key idea: exploit the physics → large hierarchies $m_q \ll p_t \ll m_H$
- THIS CAN BE SYSTEMATICALLY USE TO MASSIVELY SIMPLIFY MULTI-LOOP AMPLITUDE CALCULATIONS [Melnikov, Tancredi, Wever (2016-18); see also Mueller and Öztürk (2016)]

t/b interference

[Lindert et al. (2017)]



p_t spectrum



[FC, Lindert, Melnikov, Monni, Tancredi, Wever (2018)]

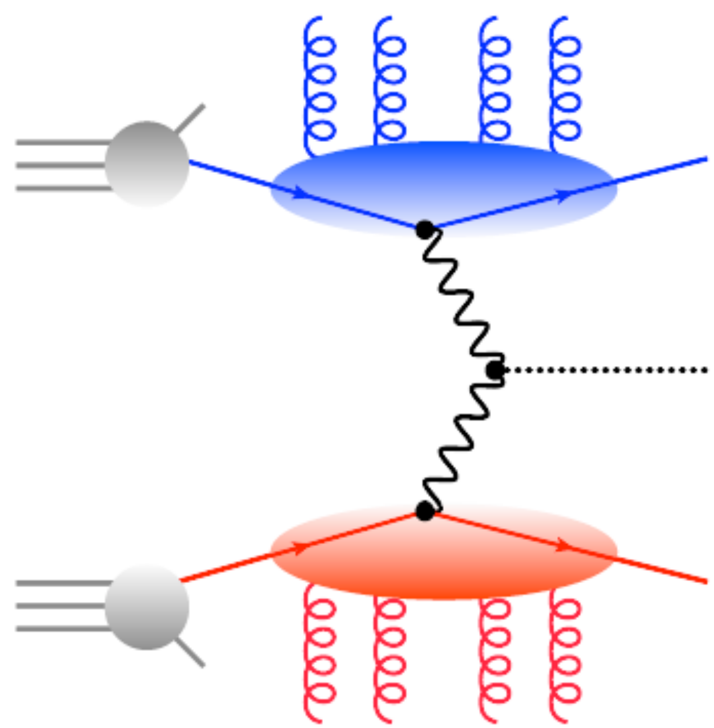
- Reasonable f.o. control
- All-order structure still elusive, beyond ``standard" resummation toolkit [some work in this direction: Melnikov, Penin (2016); Forte et al (2016); Penin, Liu (2018)]

Beyond ggF: vector boson fusion

- VBF has a much more complex kinematical structure w.r.t. gluon fusion ($2\to3$ vs $2\to1$). Very rich phenomenology, very difficult to calculate in pQCD

- However: two very forward/backward color lines, linked by color-singlet exchange → expect little cross-talk between the two quark lines

- Neglecting cross-talk: VBF = DIS^2, much simpler. ``Factorized approach, DIS/structure function approach” [Han, Valencia, Willenbrock (1992)]

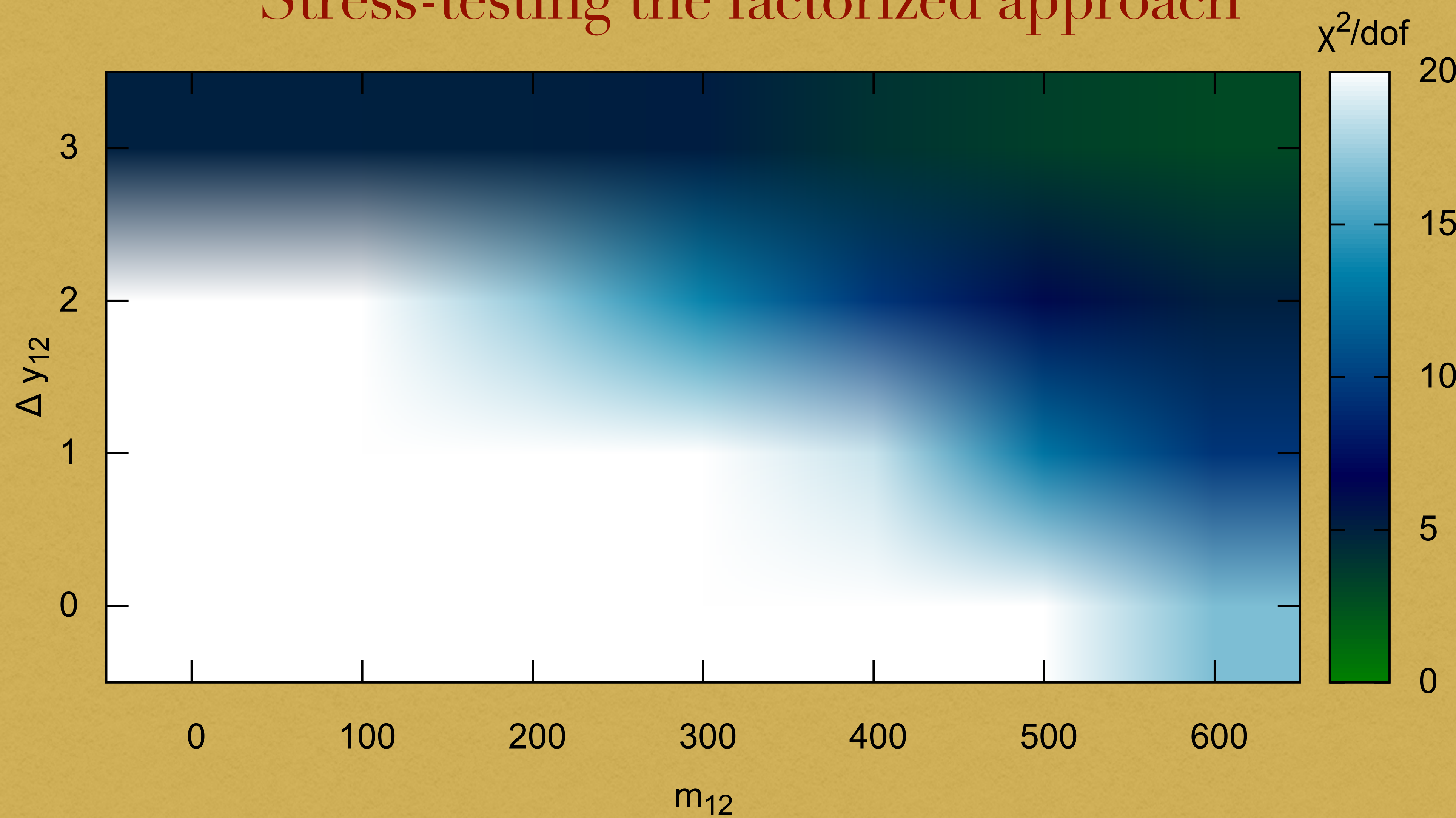


- Exact at NLO (1-L amplitude: color octet, no interference with color-singlet LO)
- Beyond NLO: non-factorized corrections color and kinematics suppressed in the deep VBF region

Beyond ggF: vector boson fusion

- VBF has a much more complex kinematical structure w.r.t. gluon fusion (2→3 vs 2→1). Very
- How … →
  expe
- Negl … ure
  funct

Stress-testing the factorized approach



[Campanario et al (2018)]

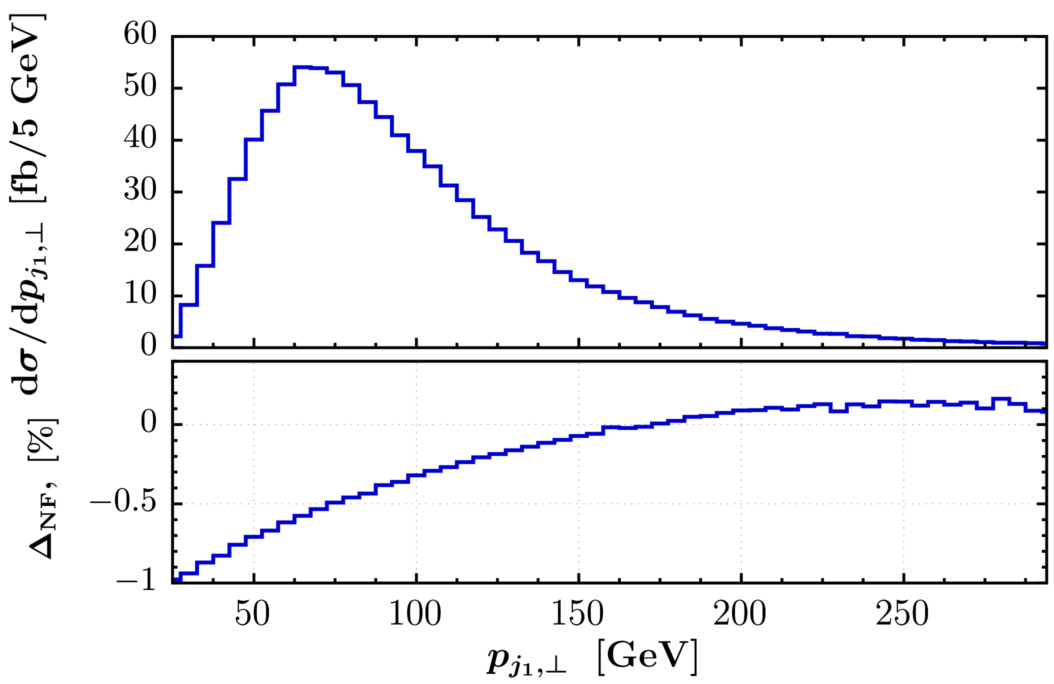
Valid if tight VBF cuts applied

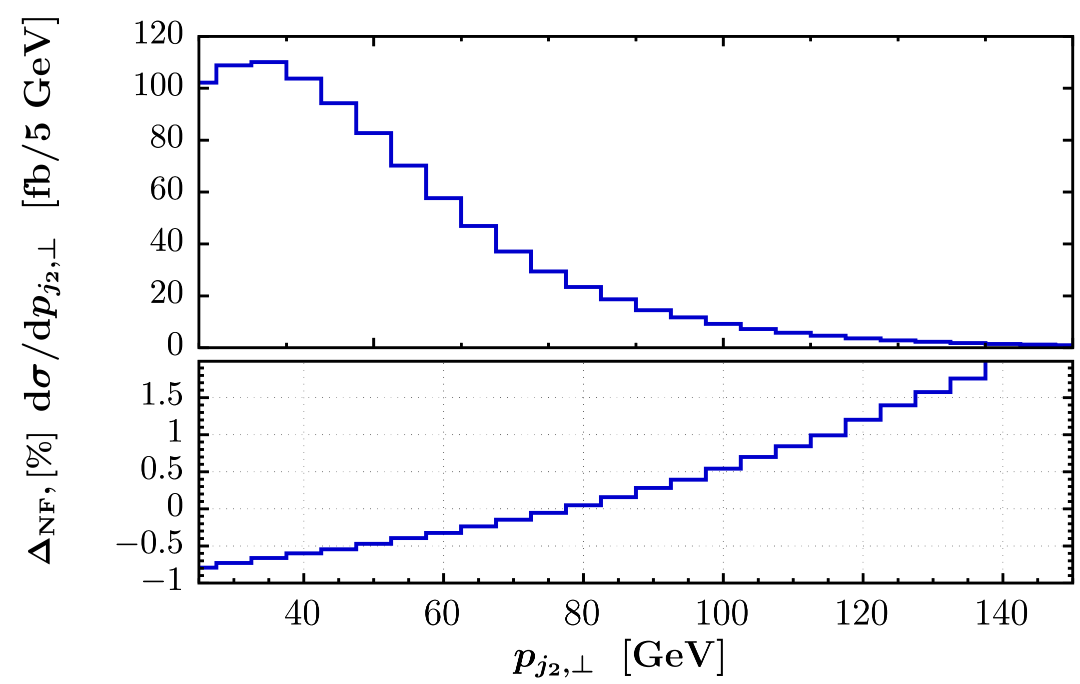
- Exac
- Beyond NLO: non-factorized corrections color and kinematics suppressed in the deep VBF region

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)]



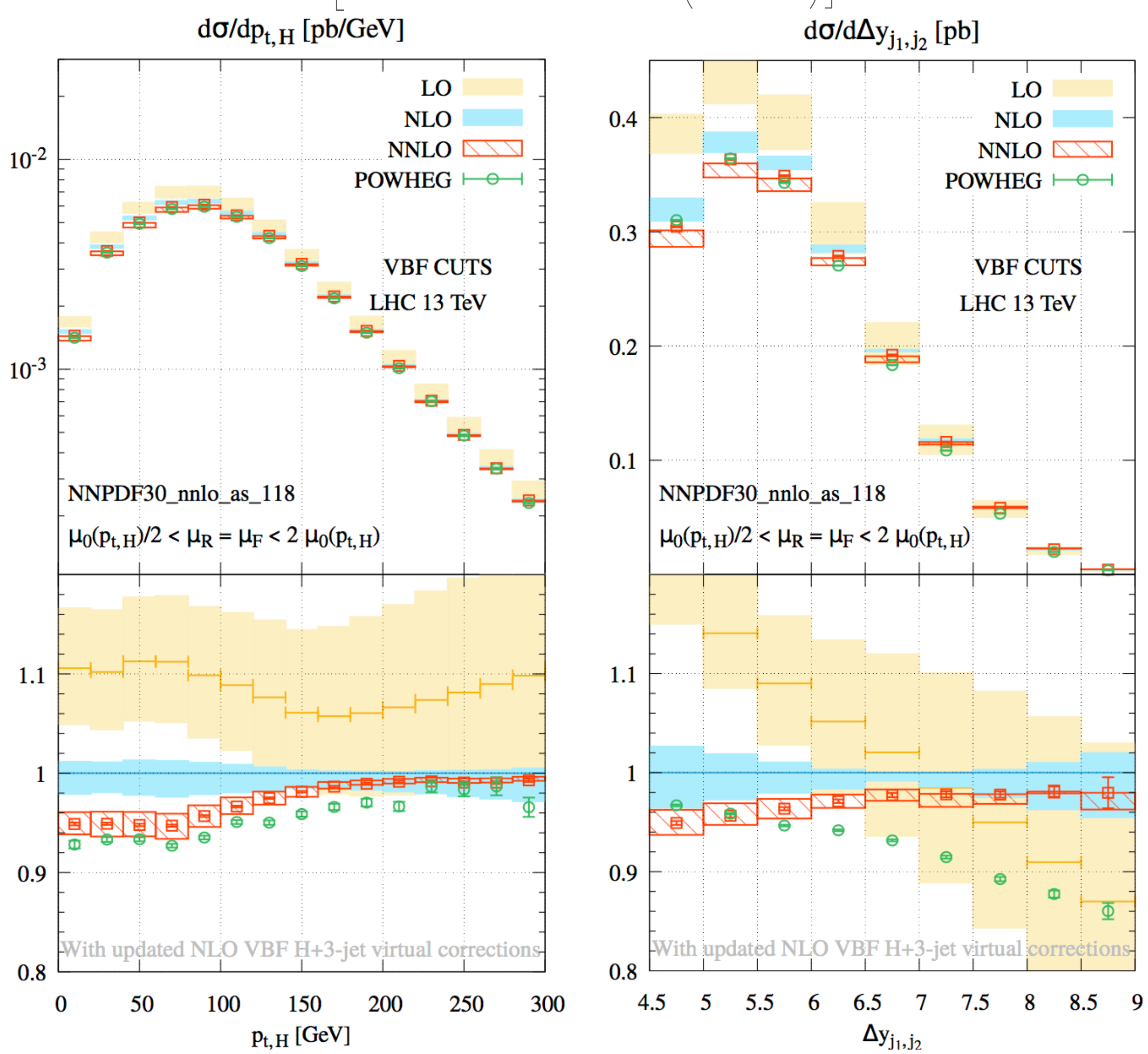


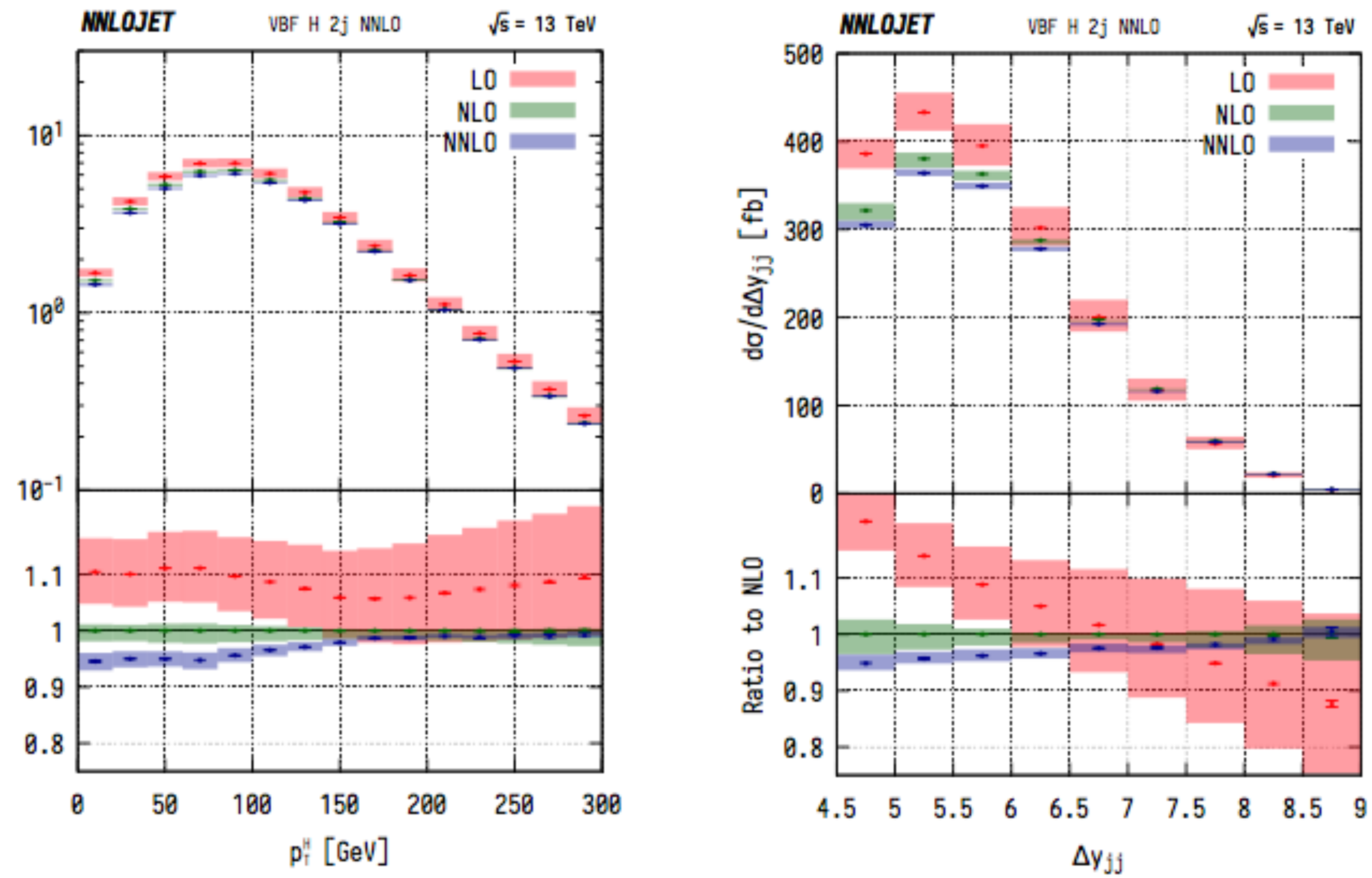
- As expected, corrections to inclusive quantities small (~4 permill), although larger than inclusive N^{3}LO [Dreyer, Karlberg (2016)]
- Interestingly, small corrections come as a cancellation between positive and negative corrections to differential distributions → can reach percent-level in differential distributions. Color suppressed, but π^2-enhanced

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)]



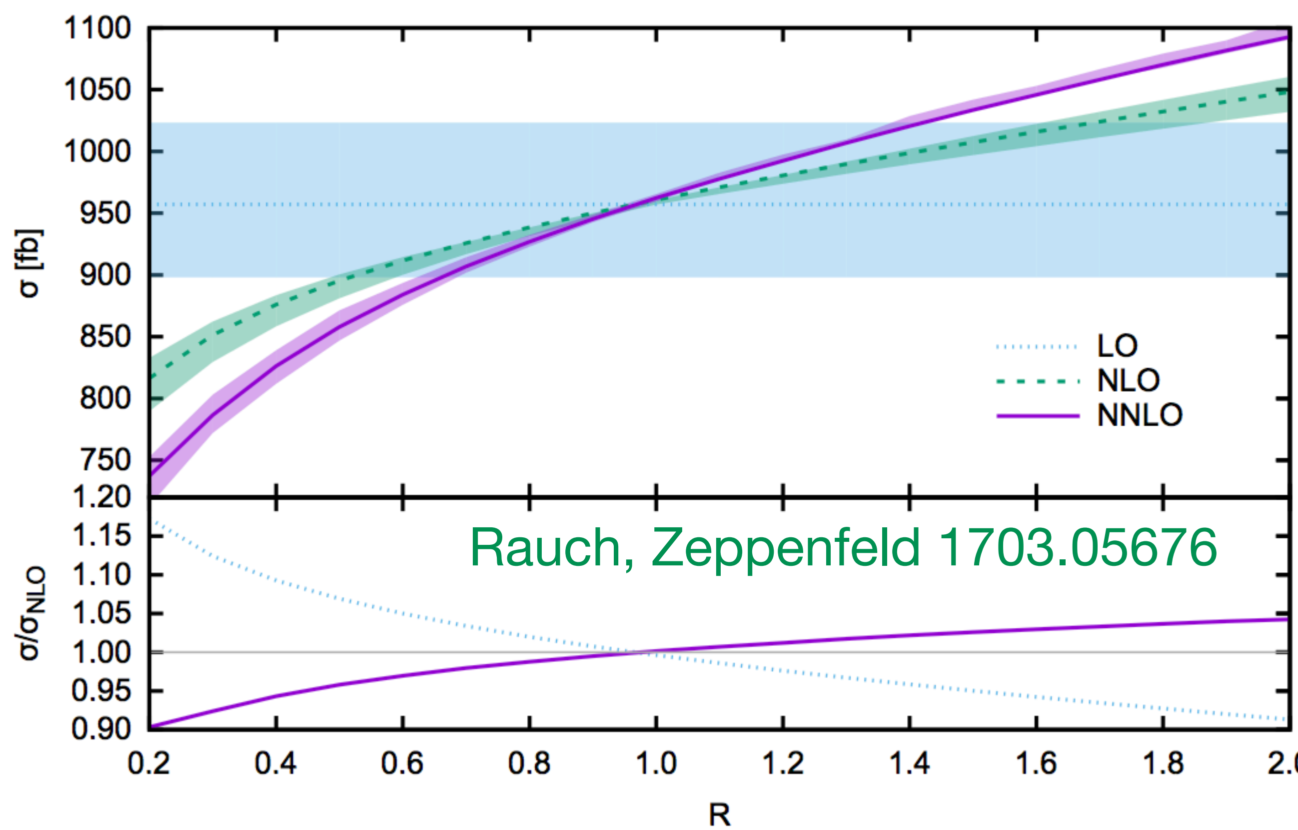


[Cruz-Martinez, Glover, Gehrmann, Huss (2018)]

- 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

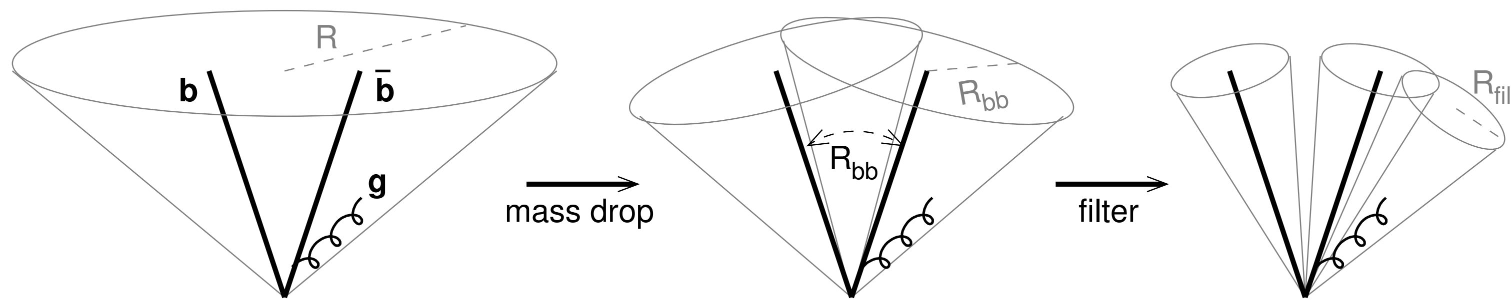
- For VBF, crucial to proper model the experimental setup (jet requirements)
- Large differential corrections: VBF very sensitive to tagging jet cuts and jet radius



- 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…]*

The path towards H→bb: VH

- At large p_t: tagging V allows for H→bb reconstruction [Butterworth et al (2008)]

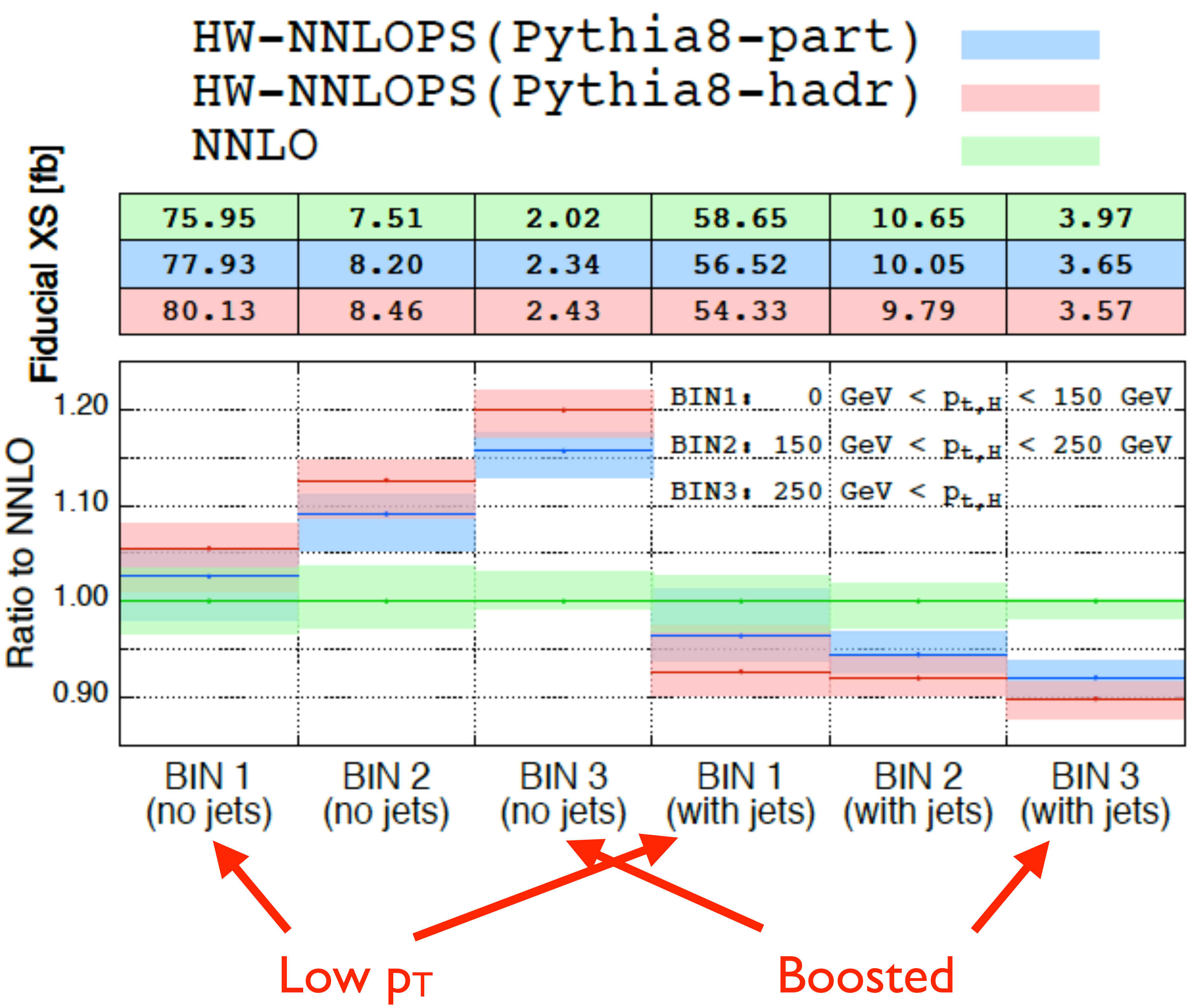


- Currently: $p_{t,V}$ > 150 GeV, not yet asymptotic → concurrence of many interesting subtle effects (fixed-order hard dynamics, sub-leading logs, improved parton shower…)
- H→bb: *see W. Bizon's talk*
- *VH: at the forefront of PS developments. Very recently: new generation of NNLO PS, theoretically nicer → much more efficient [Monni, Nason, Re, Zanderighi (2019)]*

VH: is NNLOPS enough?

With realistic cuts: large bin-to-bin migration…

[Bizon et al (2016)]

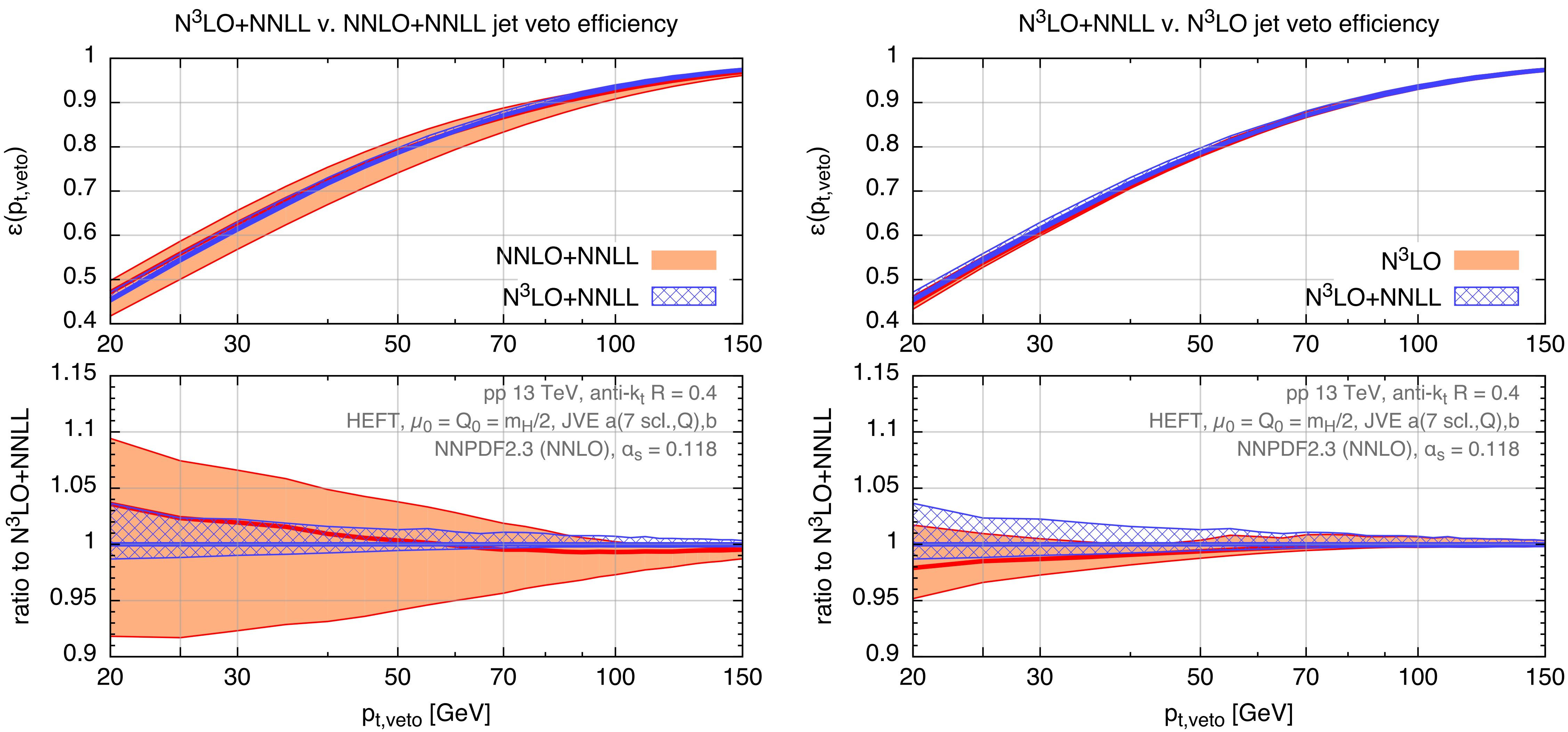


- Jet rates difficult to predict
- Is it the end of it?
- Recall: NNLOPS is NLO for jet rates…

VH: is NNLOPS enough?

Lessons from ggF: control extra jet dramatically improves the situation

ggF Higgs production with jet veto: H+J@NNLO + N³LO



[Banfi, FC, Dreyer, Monni, Salam, Zanderighi, Dulat (2015)]

- VH: quark-induced → should be even better behaved
- NNLO for VH+J? N³LO?

$t\bar{t}H$: 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
- Better signal predictions: *see A. Kulesza's talk*

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

Selection	Tool	σ_{NLO} [fb]	$\sigma_{\text{NLO+PS}}$ [fb]	$\sigma_{\text{NLO+PS}}/\sigma_{\text{NLO}}$
$n_b \geq 1$	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

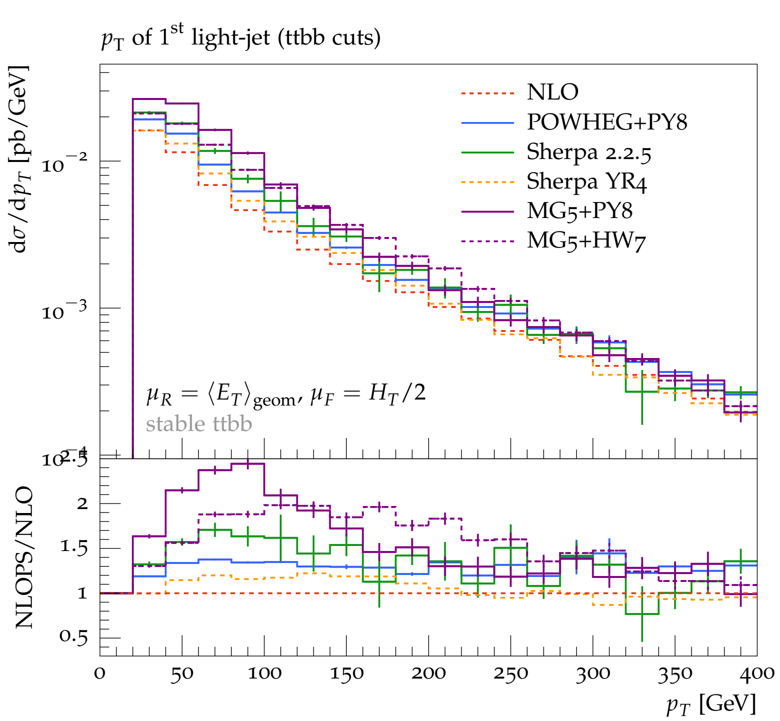
- Shower effects enhanced in the Higgs region…

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

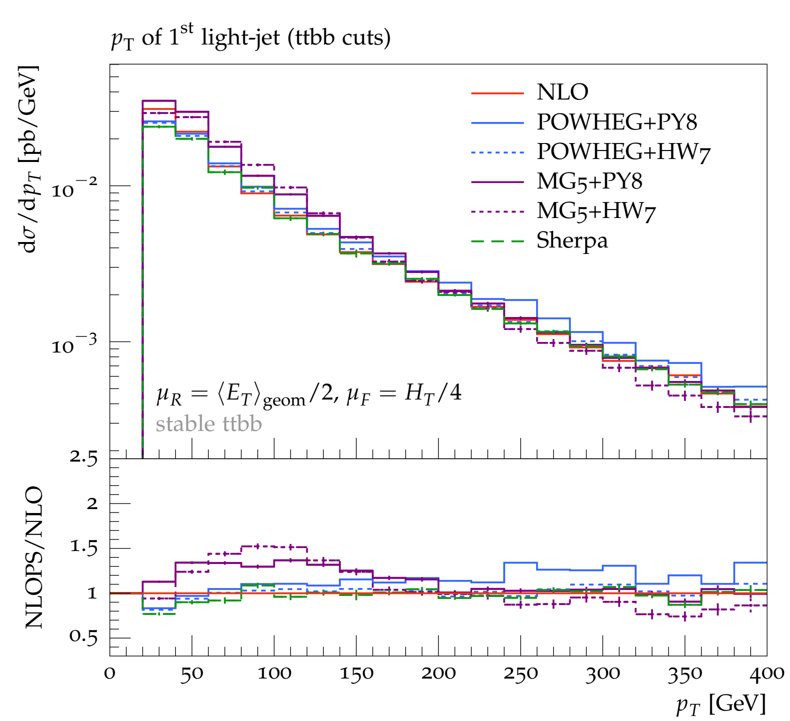
- An heroic ongoing effort to understand / fix the NLO vs NLOPS issue
  [S. Pozzorini, L. Reina, F. Buccioni, M.V. Garzelli, T. Jezo, J. Krause, A. Kardos, J. Lindert, R. Podskubka, C. Reuschle, F. Siegert, M. Zaro, M. Zoller, *ongoing*]
- A lot of complex delicate issues… cannot make justice to it in 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

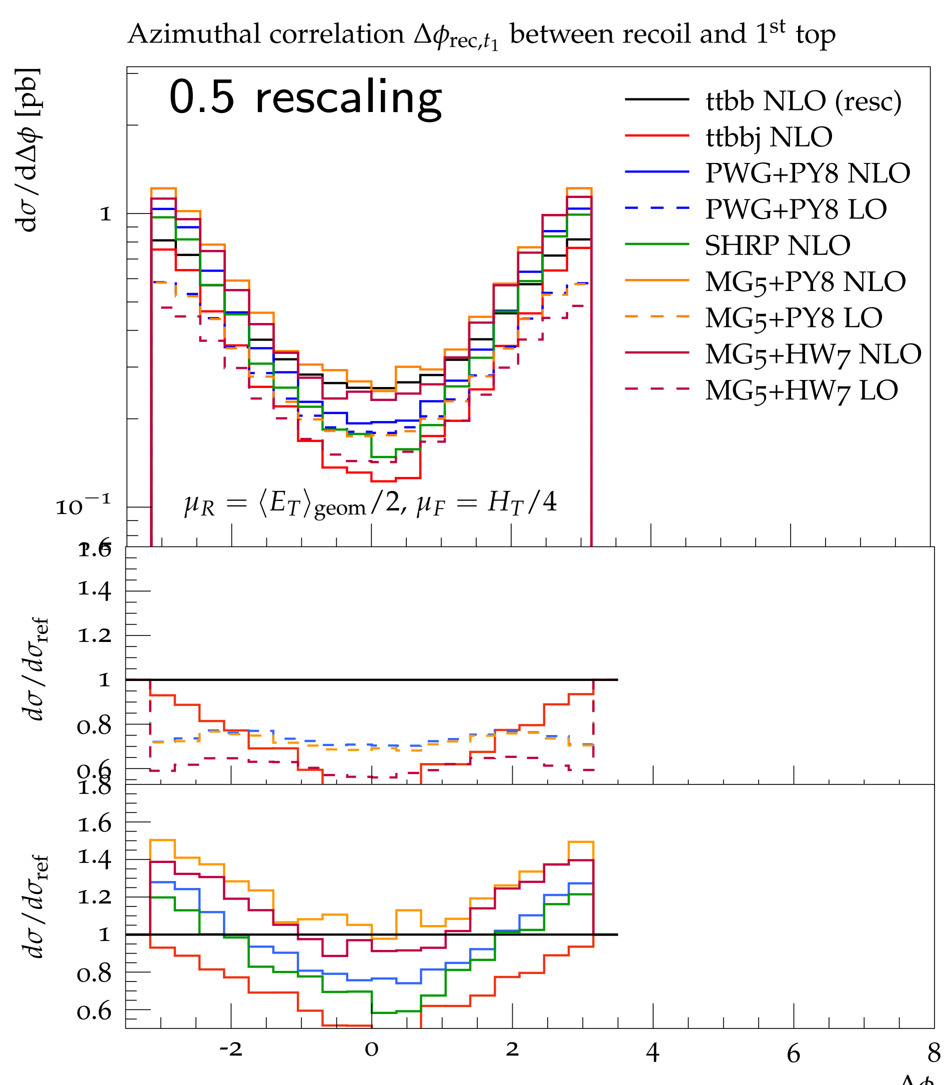


- The good news: a more appropriate scale choice removes part of the issue
- The bad news: this does not remove large shower corrections in the N_b=2 bin

$t\bar{t}H$: 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



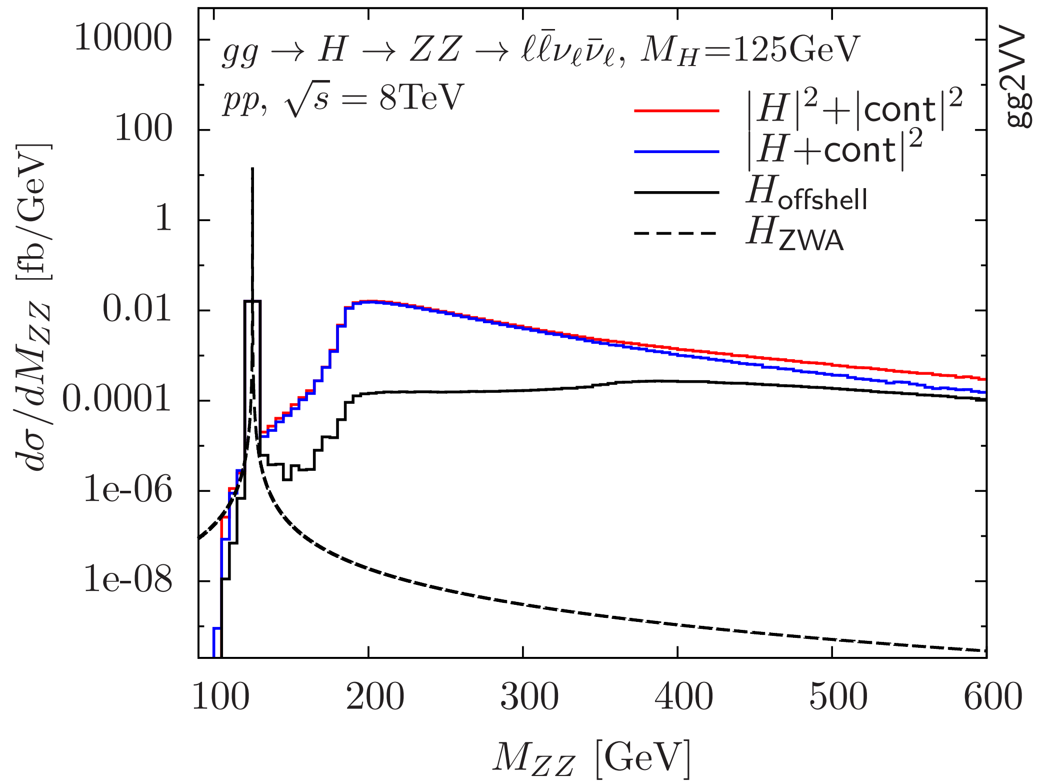
Once again, it would be crucial to better understand jet dynamics, $g \to b\bar{b}$ splitting etc…

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

Beyond standard channels: off-shell

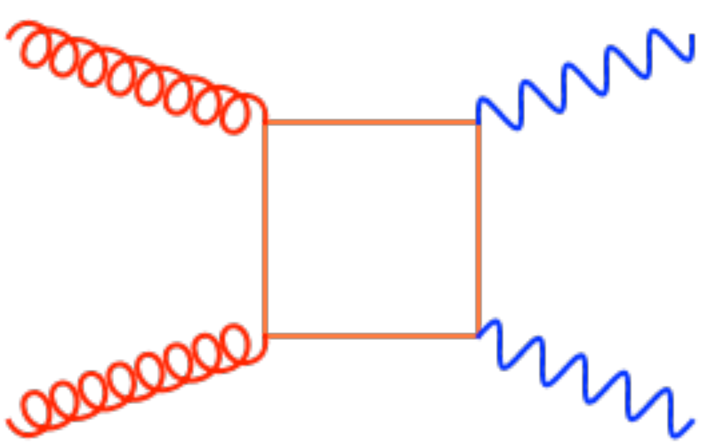
- An interesting probe of Higgs properties (ggH vs ttH, off-shell couplings, width…)

[Kauer, Passarino (2012)]

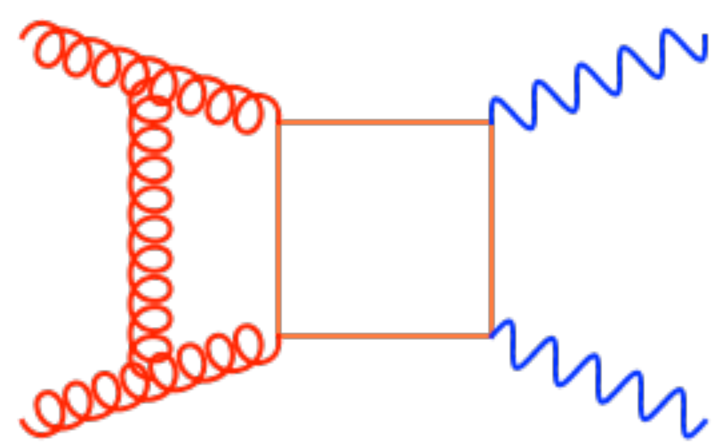


- Large ~10% off-shell tail in the VV channel
- Non-trivial interplay with gg→VV SM background (unitarity cancellations…)

- Very difficult to predict: 2-loop amplitudes with internal masses… we cannot compute it analytically (although within reach numerically…)



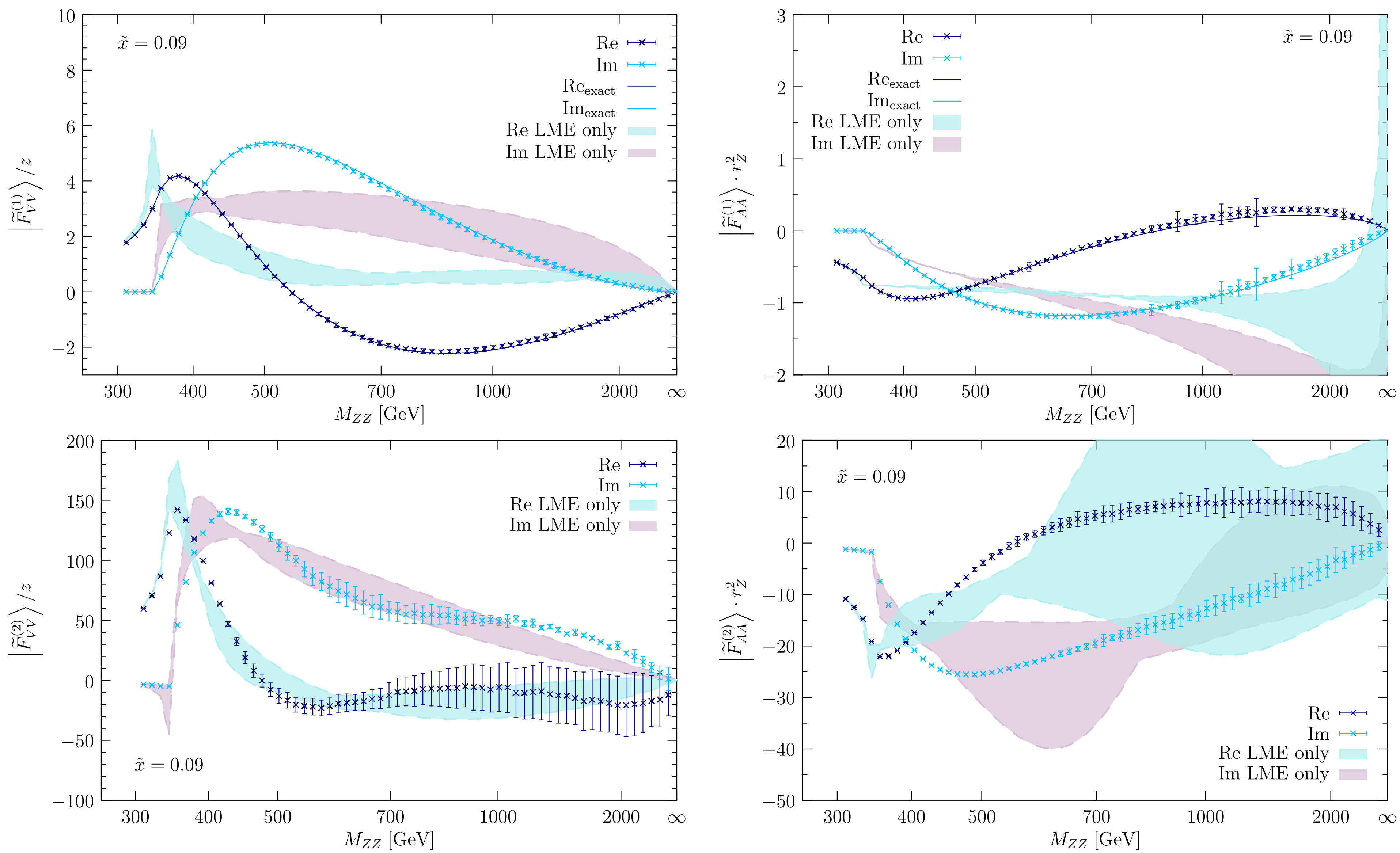
LO



NLO → ? *(non-rational alphabet, elliptic integrals…)*

Towards 2L: *divide et impera*

- We cannot obtain exact 2L result, but we can compute it in many different limits (low m_{VV}, threshold) → join all the knowledge together



[Davies et al (2019)]

- Validated with HH

- ``*An analytic multi-loop result is a result which can give you a number*'' E. Remiddi

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, virtually in any field of QCD and collider pheno (PDFs, fixed-order, resummations, PS…) → could not make justice to it
- A pattern is emerging:
  - No longer ``one big issue''. Several small effects
  - New ideas, ingenuity can achieve results unreachable by brute force methods
  - In several cases, this requires a good and wide knowledge of pQFT

- Summing up: non-trivial improvement in our understanding of QFT/QCD/EW/collider pheno, that would have actual implication for real-world Higgs explorations → EXCITING TIMES AHEAD!

Thank you very much!