Status and future prospects of precision computations for Higgs Physics at the LHC

Fabrizio Caola

Rudolf Peierls Centre for Theoretical Physics & Wadham College

PANIC 2021, Sep 5 2021

UNIVERSITY OF OXFORD

erc

Higgs physics: a snapshot

Higgs: at the forefront of high-precision calculations in the SM

Current situation: theory

- all but one (ttH) channels known at NNLO. ggF and VBF known at N^3LO
- in many cases (leading) EW corrections known
- most important decay channels under control

Current situation: experiment

- most production/decay channels known at 20% or better
- so far, Higgs very SM-like

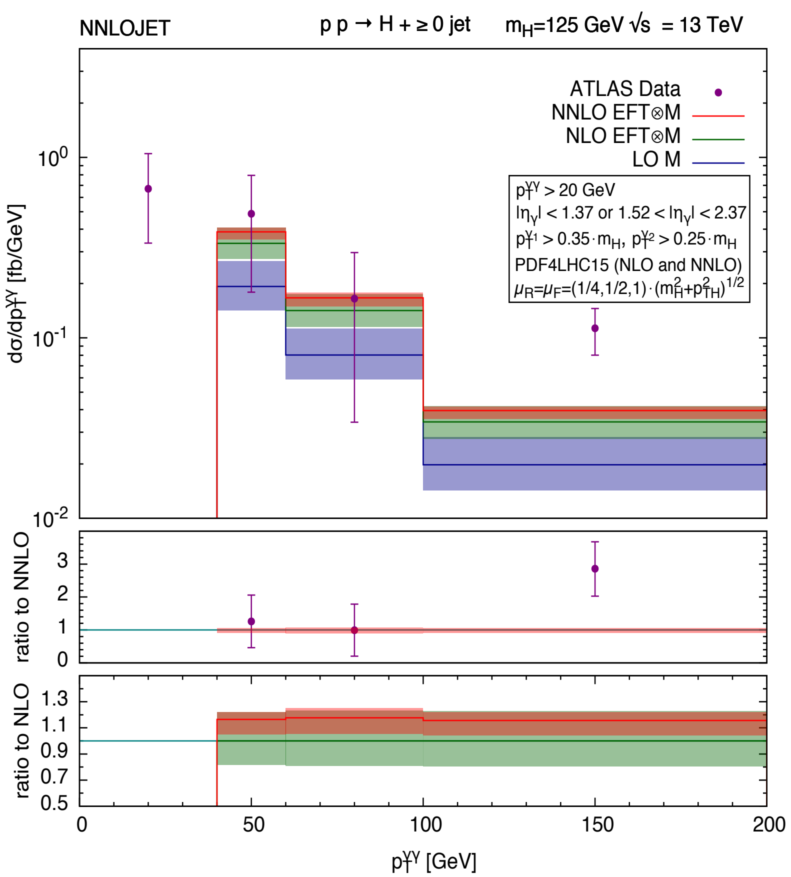
Goals: investigations at the few-percent level

- in many cases possible experimentally
- no new-physics at the TeV scale → deviations from SM of order $Q^2/\Lambda^2_{BSM} \sim 0.1$
- $\alpha_{EW} \sim 0.1$ → investigate quantum structure of the SM
- at least in principle, should be possible from TH point of view (much beyond that: non-perturbative effects…)

ggF: N^{3}LO differential

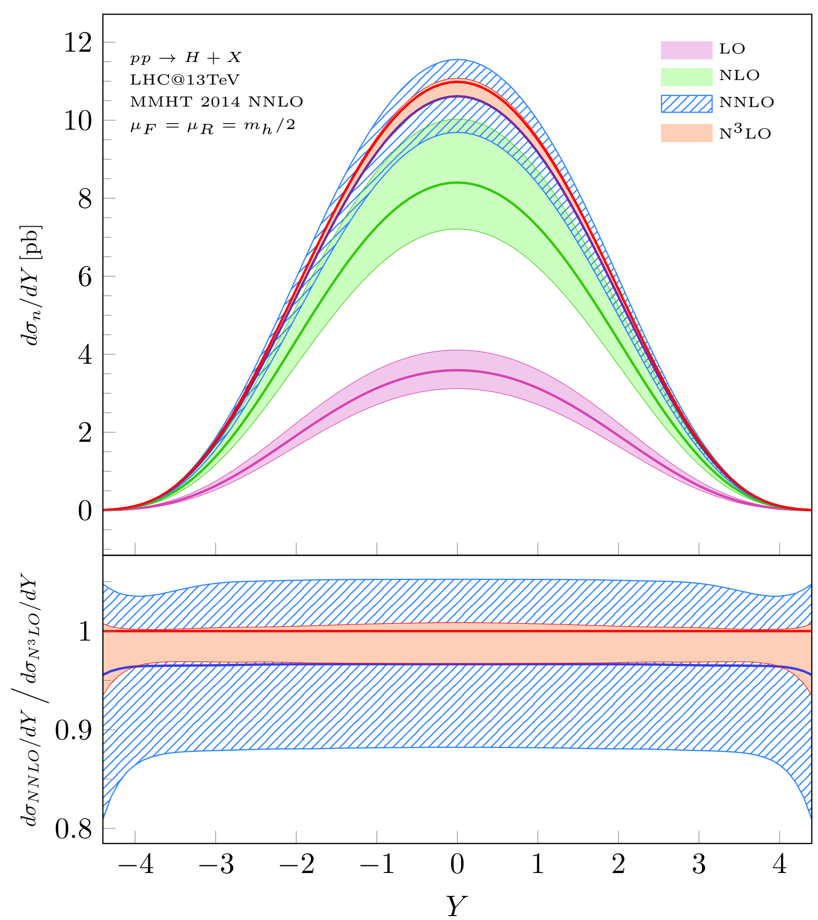
Color-singlet production: in principle knowing
a) V+J@NNLO
b) the V N^{3}LO rapidity distribution or its ``small-p_t (universal) limit"
is enough to obtain fully-differential N^{3}LO

H+j



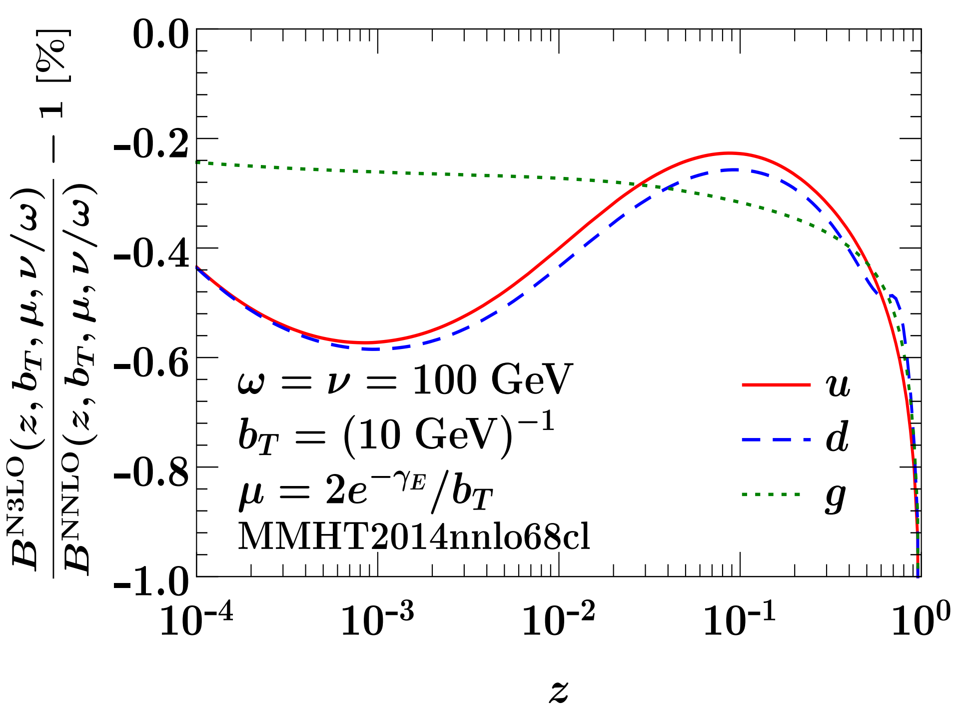
[Chen, Cruz-Martinez, Glover, Gehrmann, Huss, Jaquier; FC, Melnikov, Schulze; Boughezal, Focke, Liu, Petriello (2015-...)]

dσ/dy



[Dulat, Mistlberger, Pelloni (2018)]

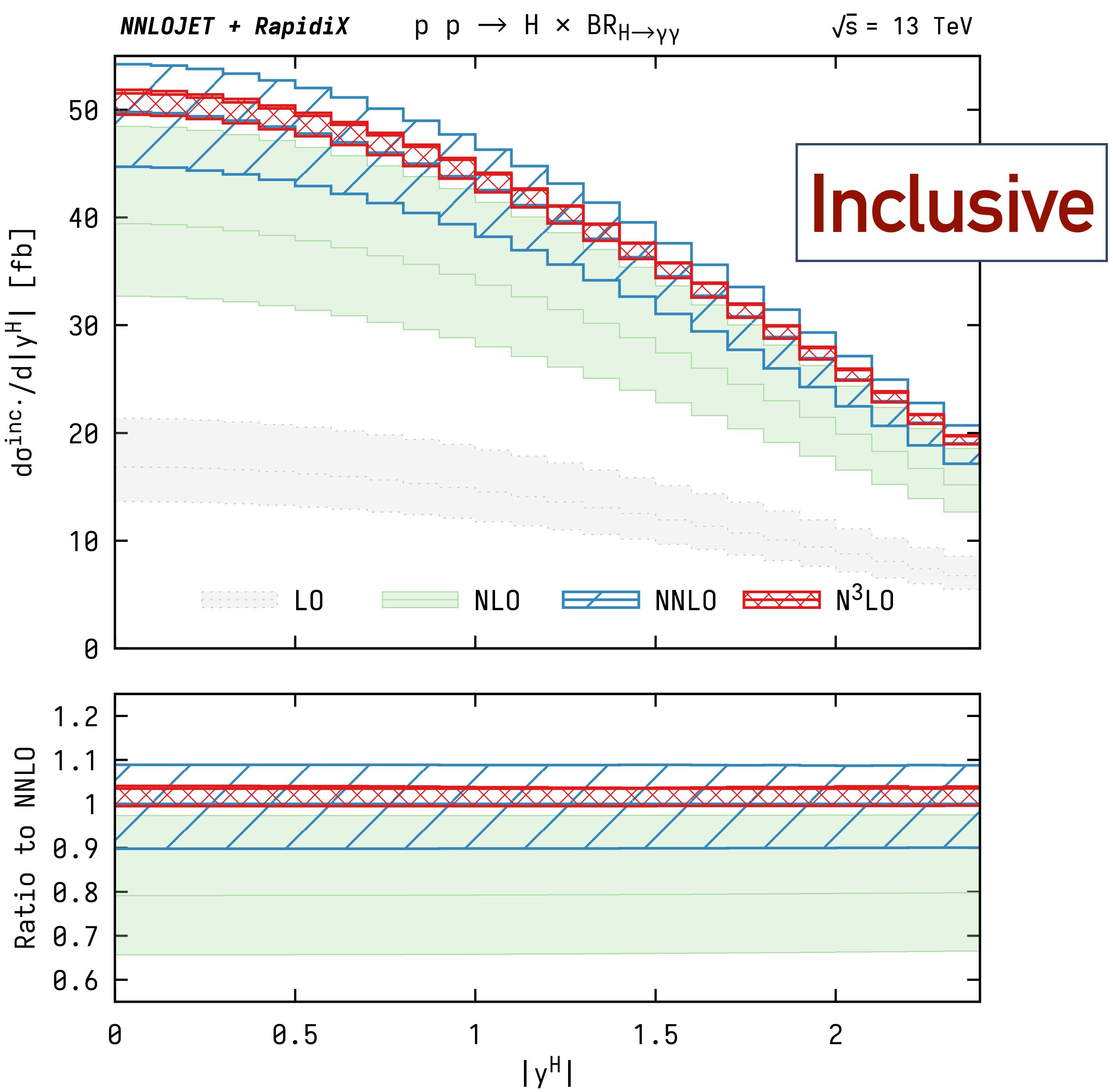
N^{3}LO beam functions

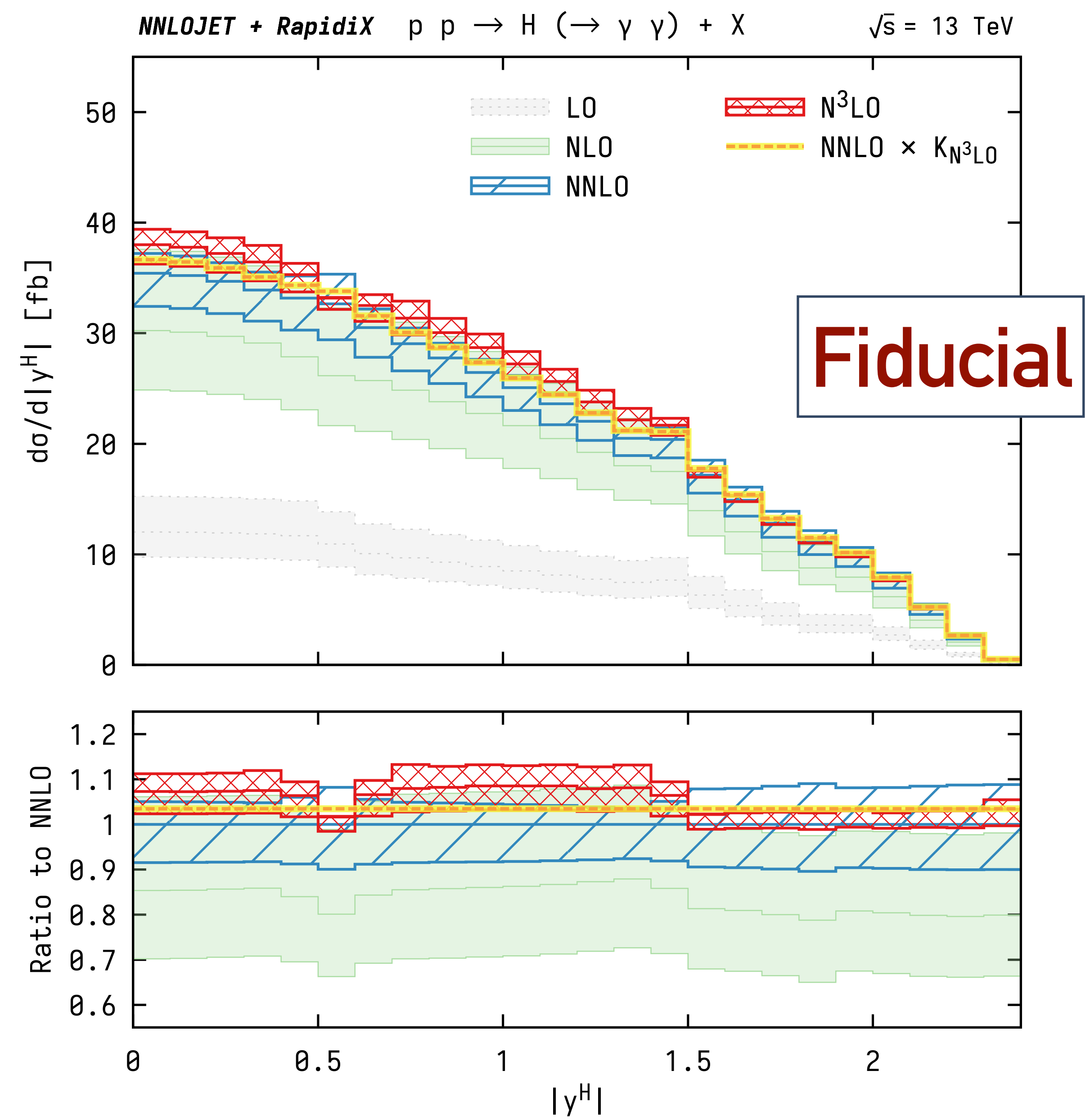


[Ebert, Mistlberger, Vita (2020); Luo, Zhang, Zhu, Zhu (2019)]

Fully-differential Higgs @ N³LO: P2B

[Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni (2021)]

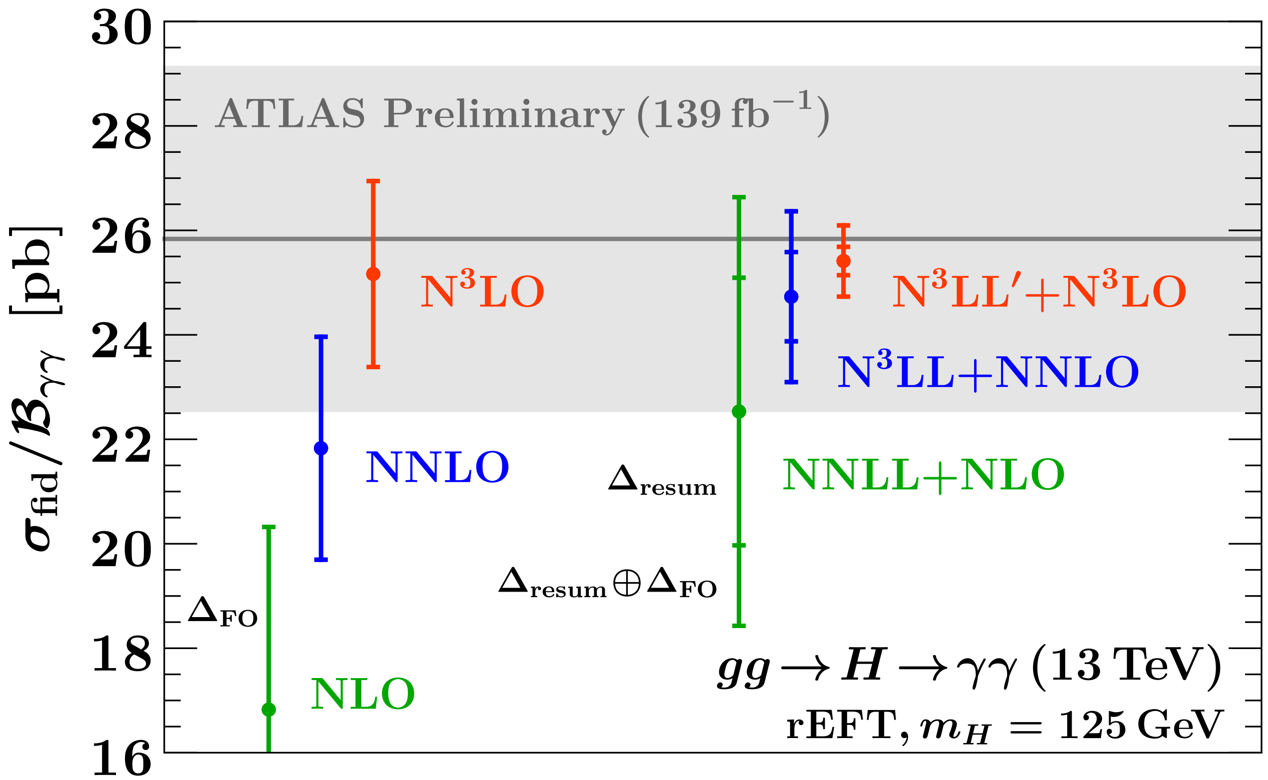




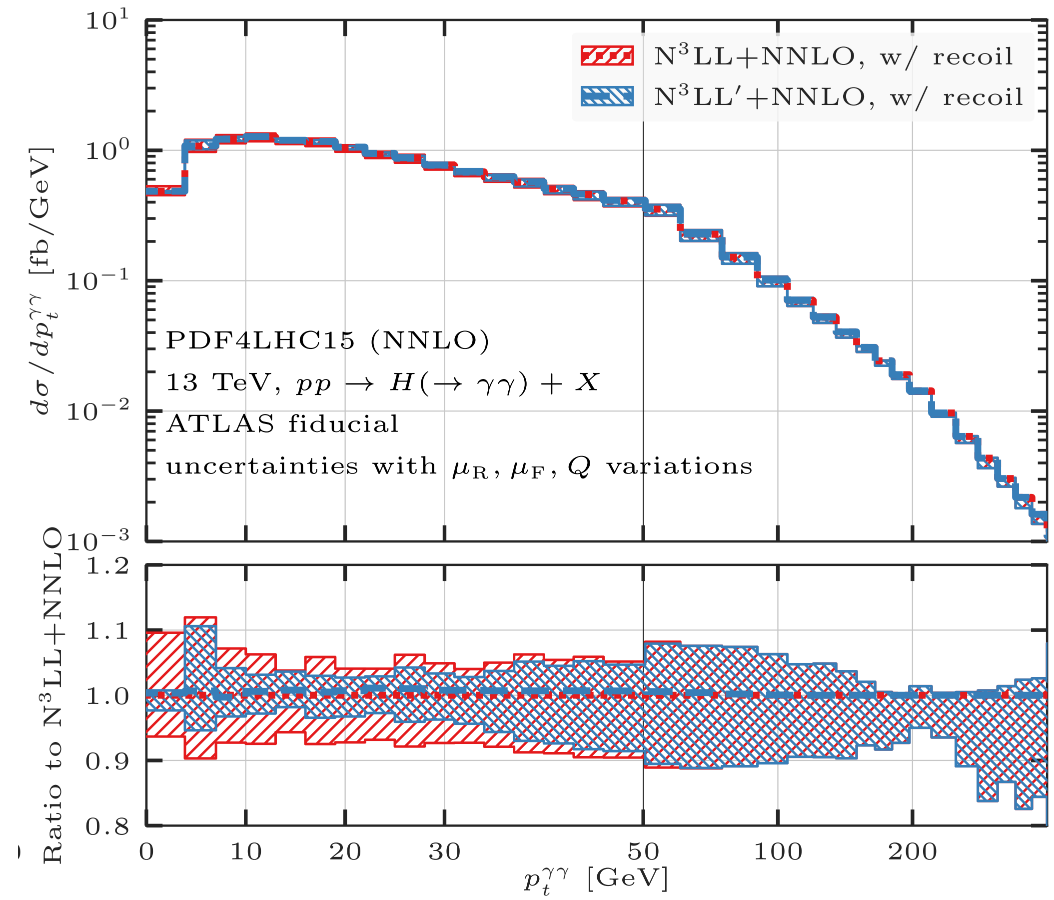
- Higgs rapidity distribution [Dulat, Mistlberger, Pelloni (2018)]
- Exquisite numerical control of H+j@NNLO [NNLOjet, 2015-2021]
- Combined using P2B [Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015)]

Fiducial results at N³LO+N³LL

[V+jet@NNLO: NNLOjet, extremely stable down to p_t ~ 0.5 GeV]



[Billis, Dehnadi, Ebert, Michel, Tackmann (2021)]



[Re, Rottoli, Torrielli (2021)]

Fixed-order: large spurious fiducial correction effects

At N³LO: as large as correction itself

$$\sigma^{\rm FO}_{\rm incl} = 13.80\,[1 + 1.291 + 0.783 + 0.299]\,\text{pb}\,,$$

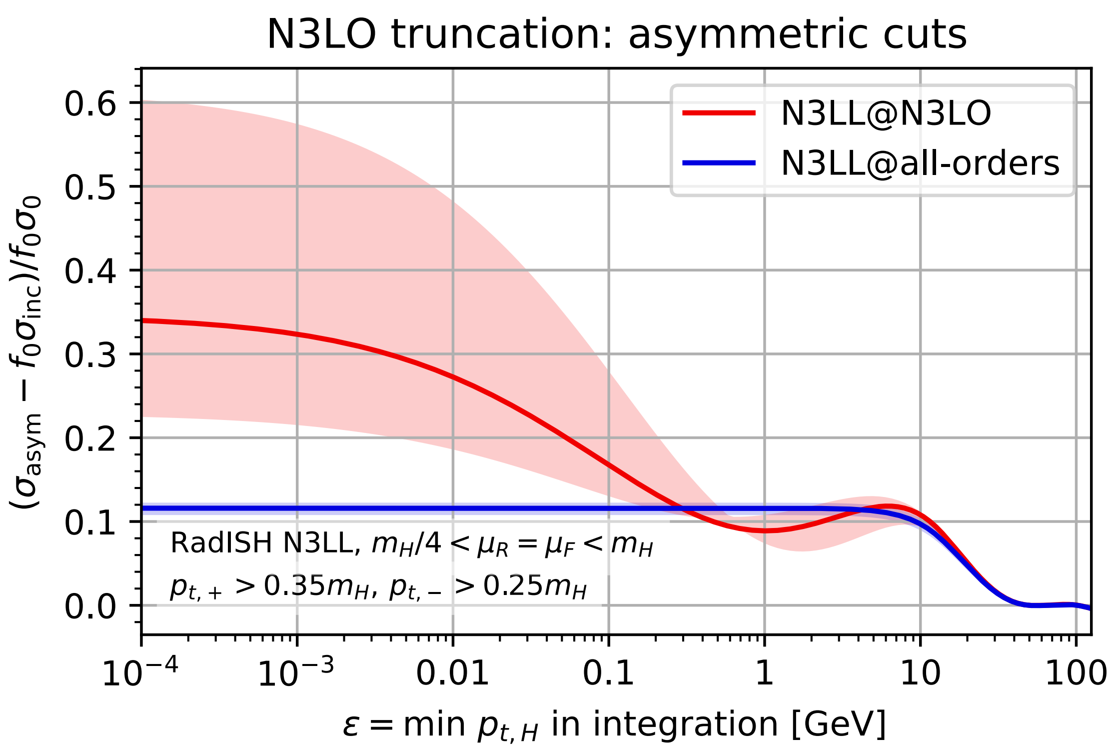
$$\begin{aligned}\sigma^{\rm FO}_{\rm fid}/\mathcal{B}_{\gamma\gamma} = 6.928\,[1 &+ (1.300 + 0.129_{\rm fpc}) \\ &+ (0.784 - 0.061_{\rm fpc}) \\ &+ (0.331 + 0.150_{\rm fpc})]\,\text{pb}\,.\end{aligned}$$

Spurious fiducial-correction effects

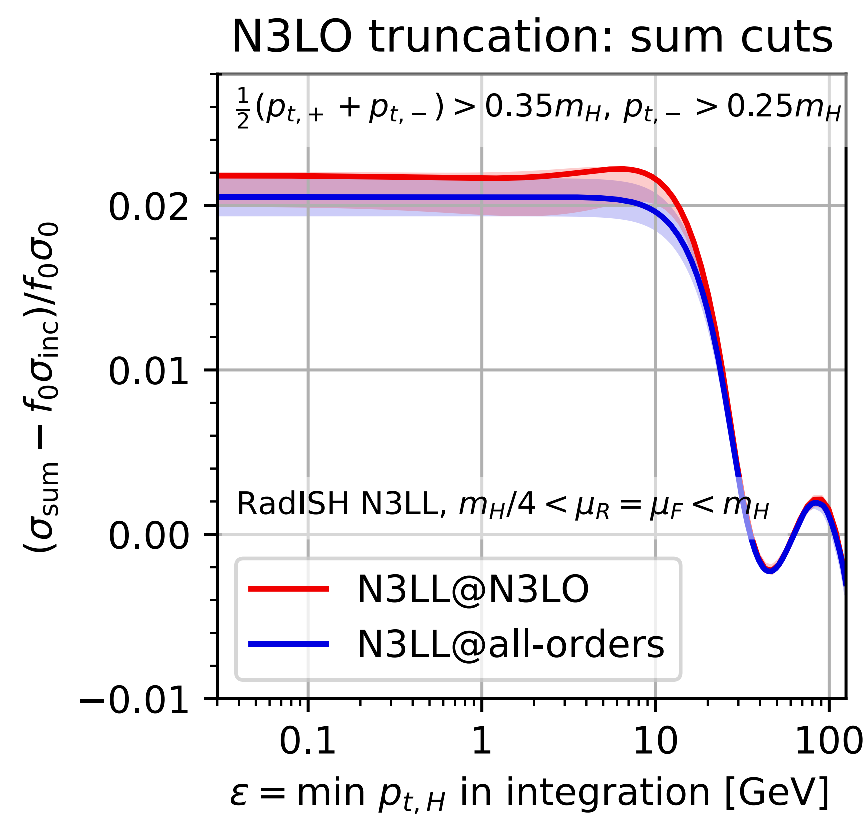
The issue: ATLAS / CMS fiducial cuts induce sensitivity to IR physics in f.o. calculations [Catani, Cieri, de Florian, Ferrera, Grazzini (2018); Ebert, Michel, Tackmann + Billis, Dehnadi (2017-2021); Salam + Slade (2015, 2021)]

Two options:

- abandon fixed-order calculation (resummation is well under-control)
- design sets of cuts that do not induce such sensitivity, while still being practical and retaining good S/B ratio[Salam, Slade (2021)]



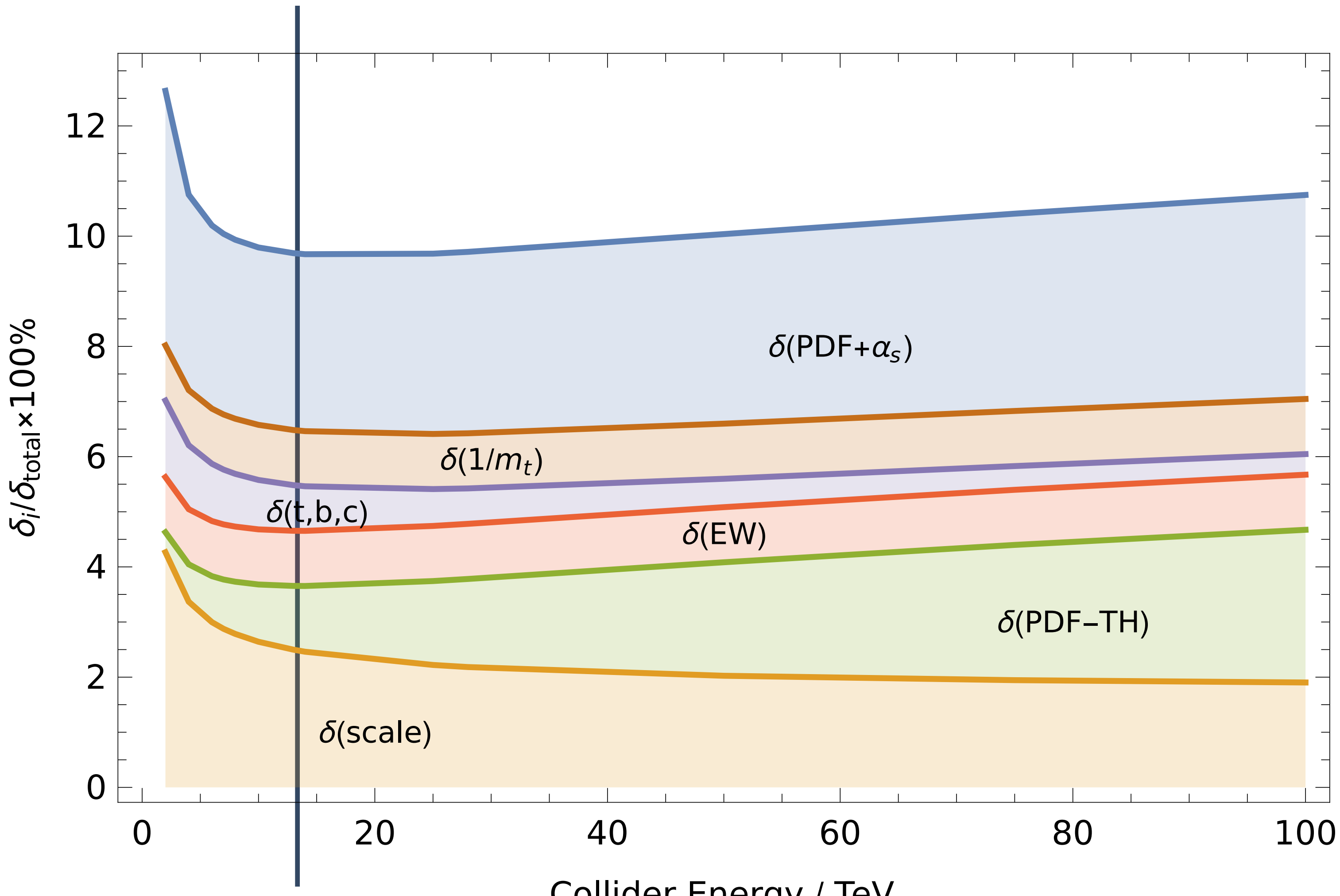
$$p_{t,1} > 0.35 m_H\,, p_{t,2} > 0.25 m_H$$



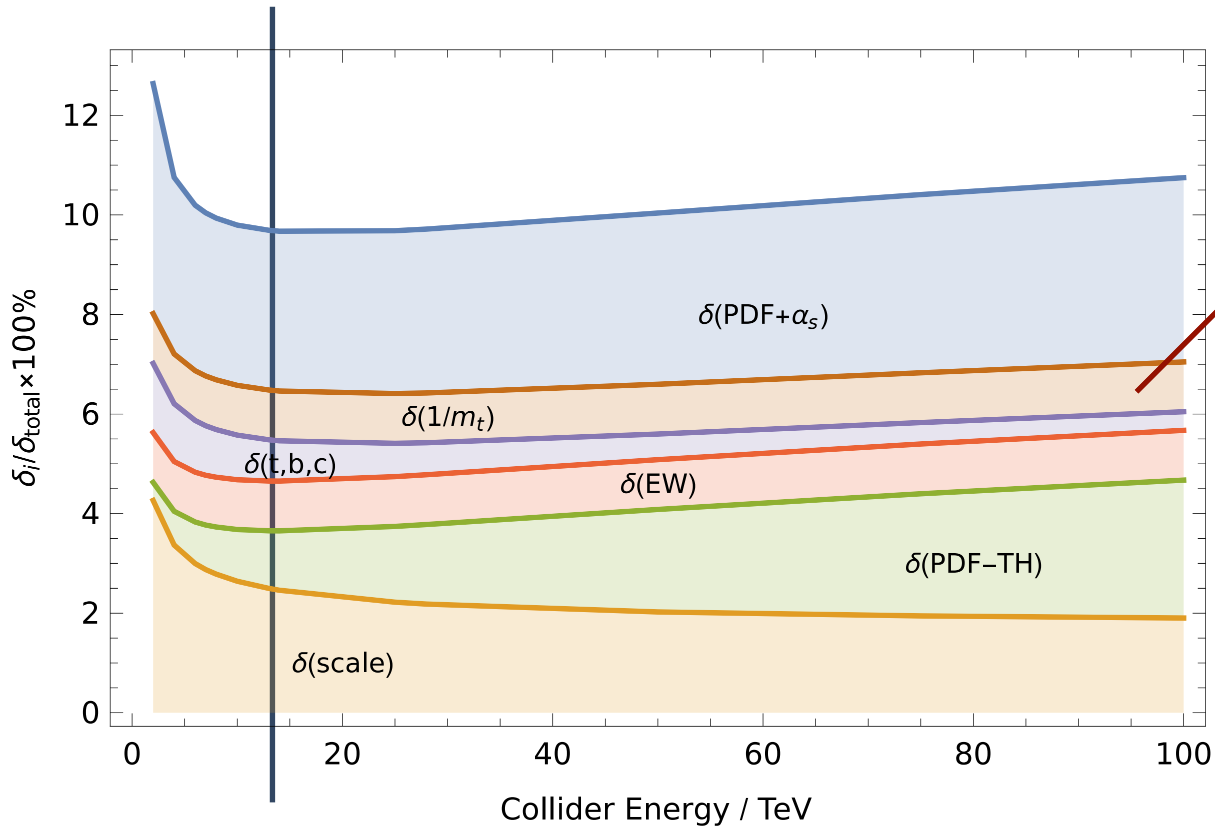
$$p_{t,2} > 0.25 m_H\,, \frac{p_{t,1}+p_{t,2}}{2} > 0.35 m_H$$

ggF: N³LO QCD is not enough…

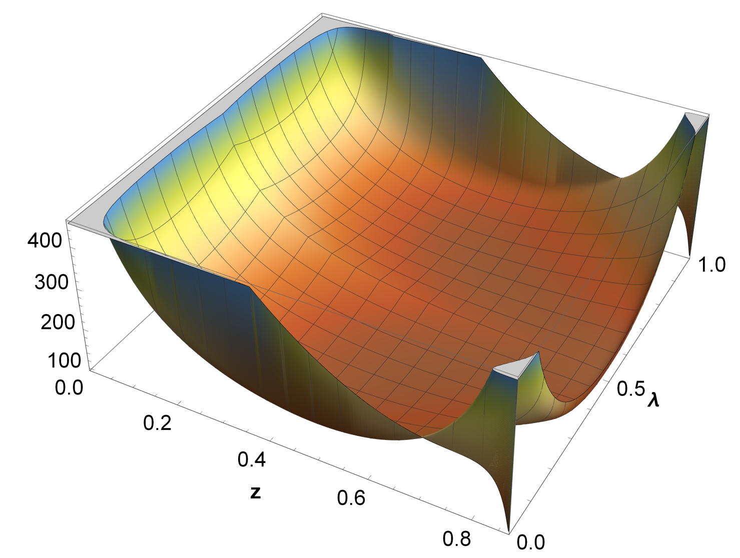
[HE-HL LHC report, 2019]



ggF: N^{3}LO QCD is not enough…



Exact NNLO top-mass effects

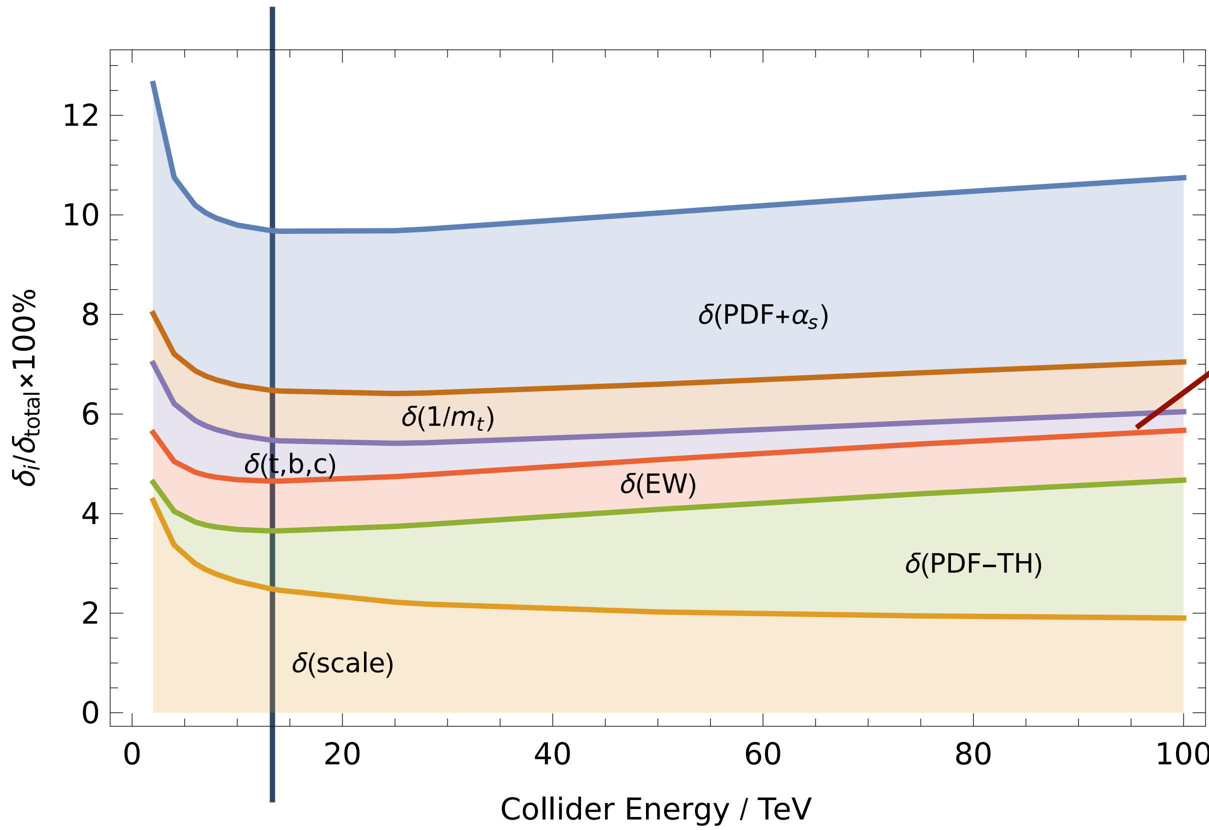


[Czakon, Harlander, Klappert, Niggetiedt (2021)]

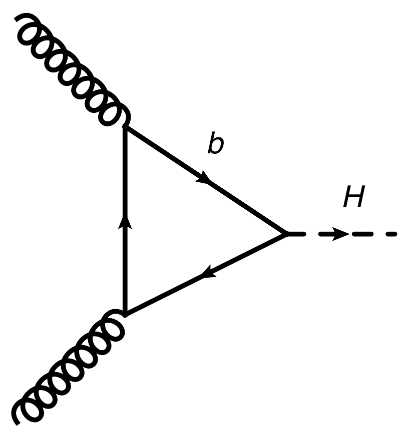
channel	$\sigma^{\text{NNLO}}_{\text{HEFT}}$ [pb] $\mathcal{O}(\alpha_s^2)+\mathcal{O}(\alpha_s^3)+\mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}}-\sigma^{\text{NNLO}}_{\text{HEFT}})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\text{NNLO}}_{\text{exact}}/\sigma^{\text{NNLO}}_{\text{HEFT}}-1)$ [%]
		$\sqrt{s}=8\,\text{TeV}$		
gg	$7.39+8.58+3.88$	$+0.0353$	$+0.0879\pm0.0005$	$+0.62$
qg	$0.55+0.26$	-0.1397	-0.0021 ± 0.0005	-18
qq	$0.01+0.04$	$+0.0171$	-0.0191 ± 0.0002	-4
total	$7.39+9.15+4.18$	-0.0873	$+0.0667\pm0.0007$	-0.10
		$\sqrt{s}=13\,\text{TeV}$		
gg	$16.30+19.64+8.76$	$+0.0345$	$+0.2431\pm0.0020$	$+0.62$
qg	$1.49+0.84$	-0.3696	-0.0115 ± 0.0010	-16
qq	$0.02+0.10$	$+0.0322$	-0.0501 ± 0.0006	-15
total	$16.30+21.15+9.79$	-0.3029	$+0.1815\pm0.0023$	-0.26

Confirmed expectations, source of uncertainty removed

ggF: N³LO QCD is not enough…



Bottom contribution



$$\sim -\frac{3}{2}\frac{m_b^2}{m_H^2}\ln^2\frac{m_H^2}{m_b^2}\,\mathcal{M}^t_{gg\to H}$$

Exact result at NNLO (yet) unknown, information from resummation

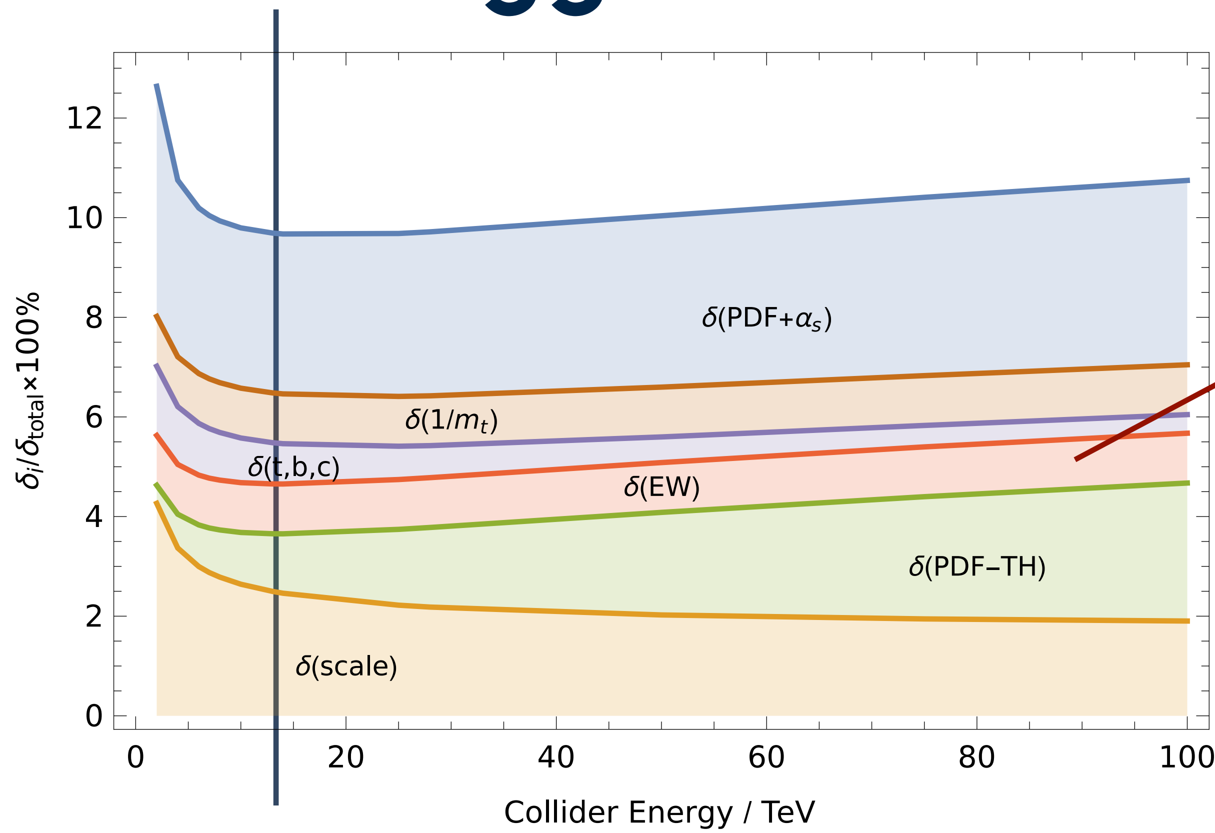
[Anastasiou and Penin (2020); Liu, Mecaj, Neubert, Wang (2020)]

	LO	NLO	NNLO	N^{3}LO
$\delta\sigma^{\rm LL}_{pp\to H+X}$	-1.420	-1.640	-1.667	-1.670
$\delta\sigma^{\rm NLL}_{pp\to H+X}$	-1.420	-2.048	-2.183	-2.204
$\delta\sigma_{pp\to H+X}$	-1.023	-2.000	?	

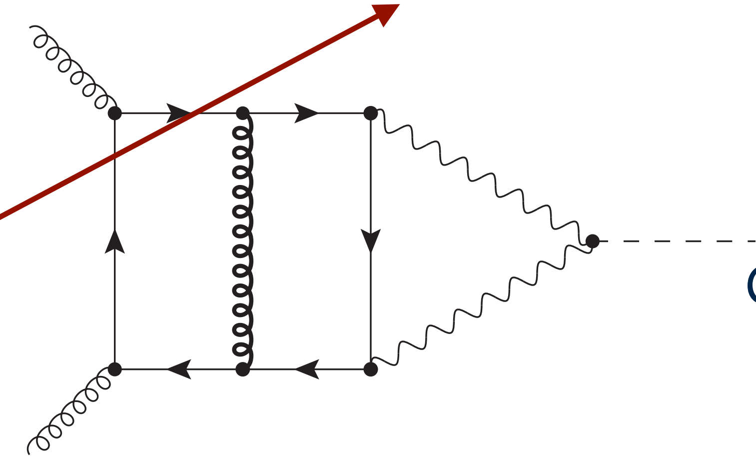
[Anastasiou, Penin (2020)]

Exact top result [Czakon, Harlander, Klappert, Niggetiedt (2021)] could be extended to this case as well

ggF: N^3LO QCD is not enough…



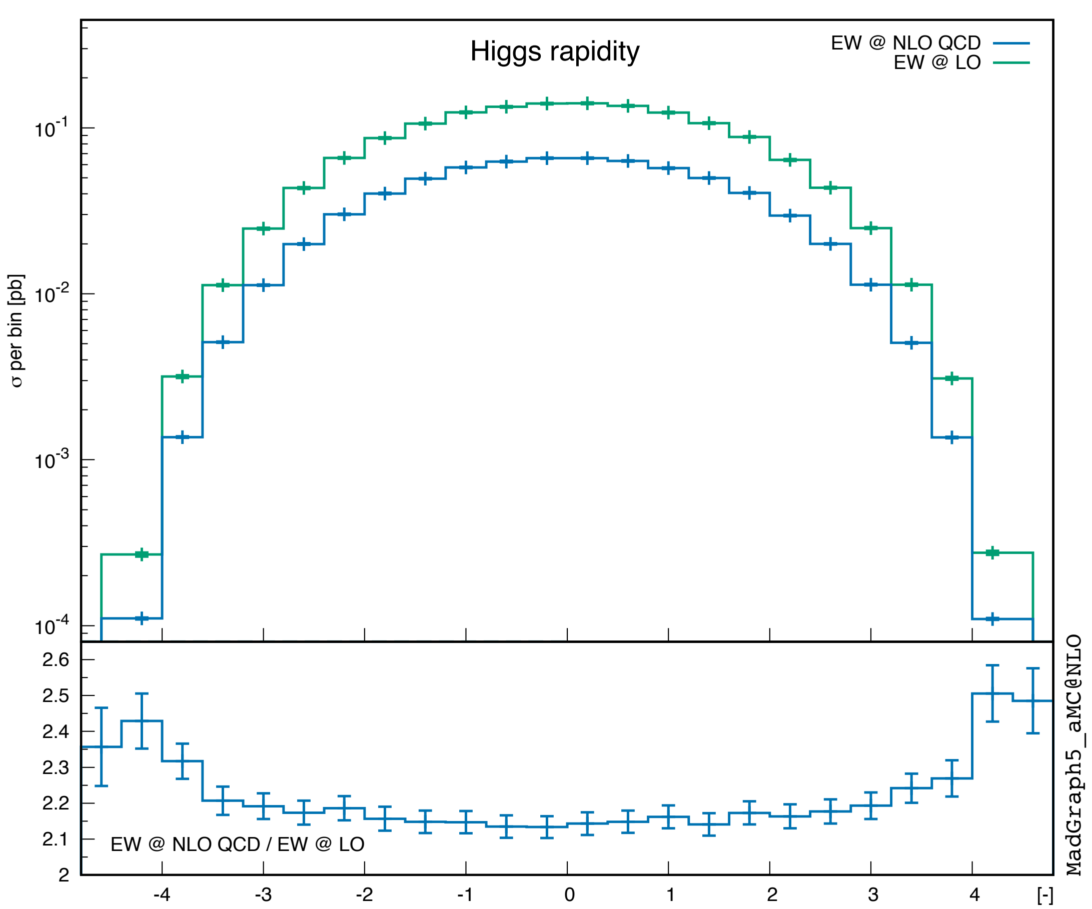
EW contributions



Leading EW corrections recently computed

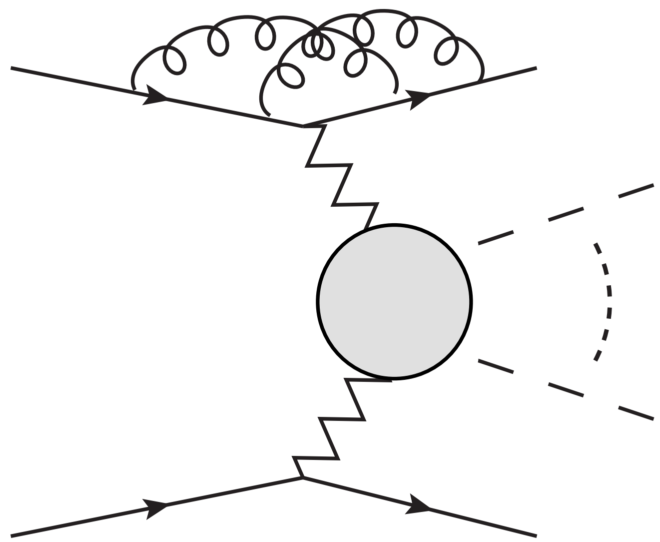
[Bonetti, Melnikov, Tancredi (2017); Bonetti, Panzer, Smirnov, Tancredi (2020); Bacchetti, Bonciani, del Duca, Hirschi, Moriello, Schweitzer (2020)]

[Bacchetti, Bonciani, del Duca, Hirschi, Moriello, Schweitzer (2020)]

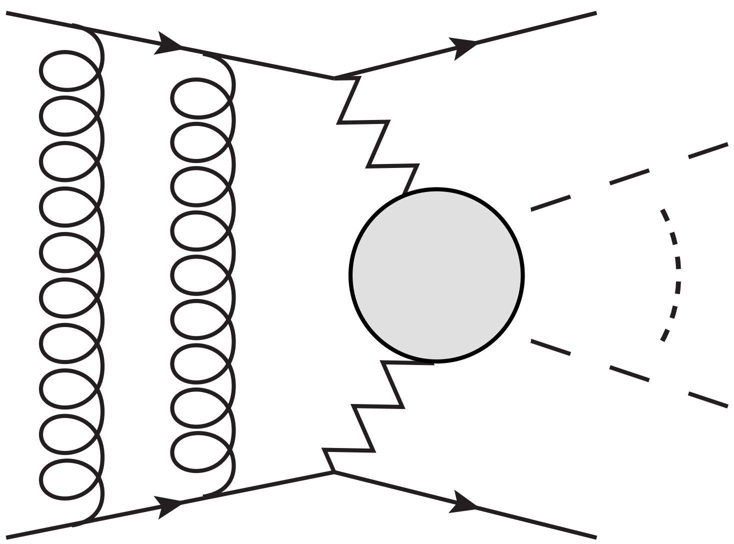


Expectations largely confirmed, still 1% residual uncertainty on Higgs cross-section

VBF: factorizable vs non factorizable



VS



Dominant, known at NNLO (diff) + N^3LO (inclusive)

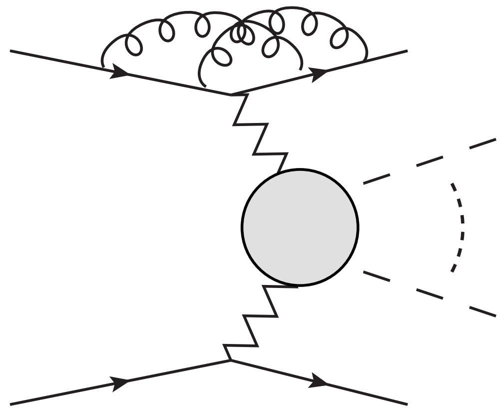
[Cacciari, Dreyer, Karlberg, Salam, Zanderighi (2015); Cruz-Martinez, Glover, Gehrmann, Huss (2018); Dreyer, Karlberg (2016)]

Starts at NNLO; kinematic suppressed in VBF region, color-suppressed (but π^2 enhanced)

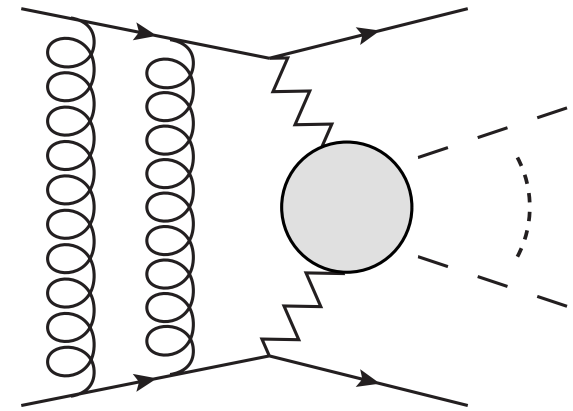
Only recently leading contribution has been computed

[Liu, Melnikov, Penin (2019)]

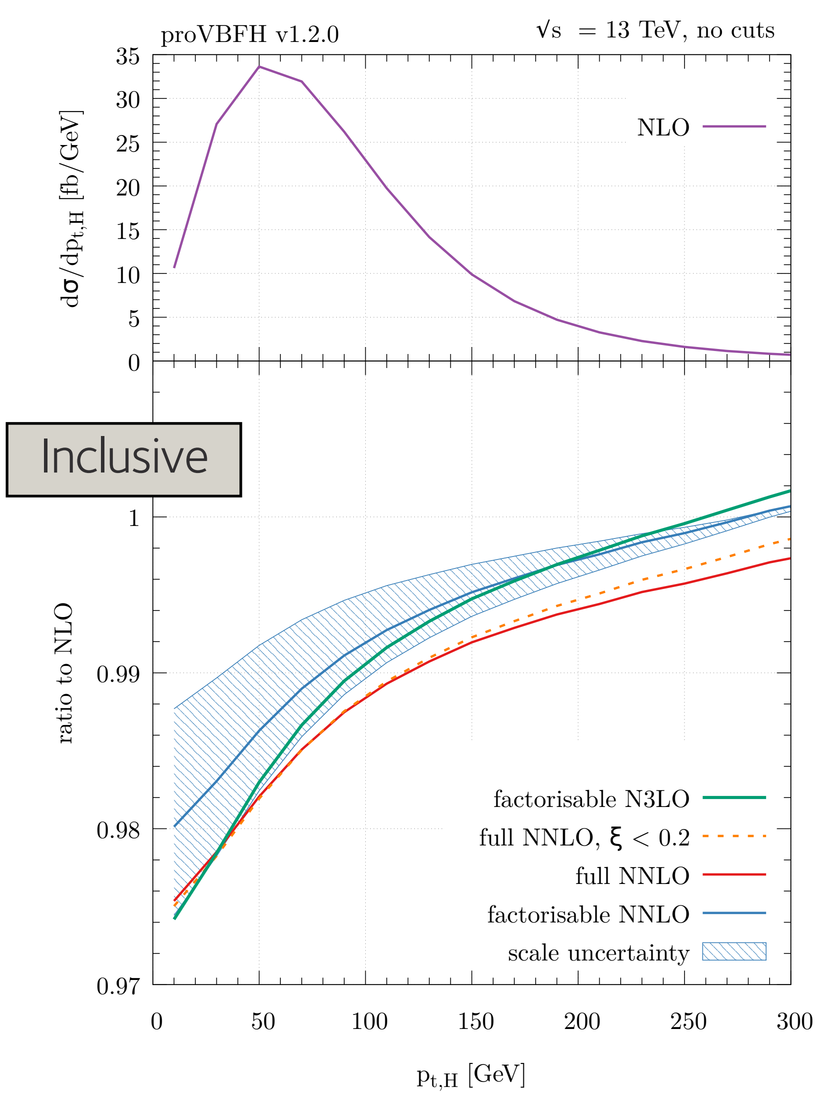
VBF: factorizable vs non factorizable

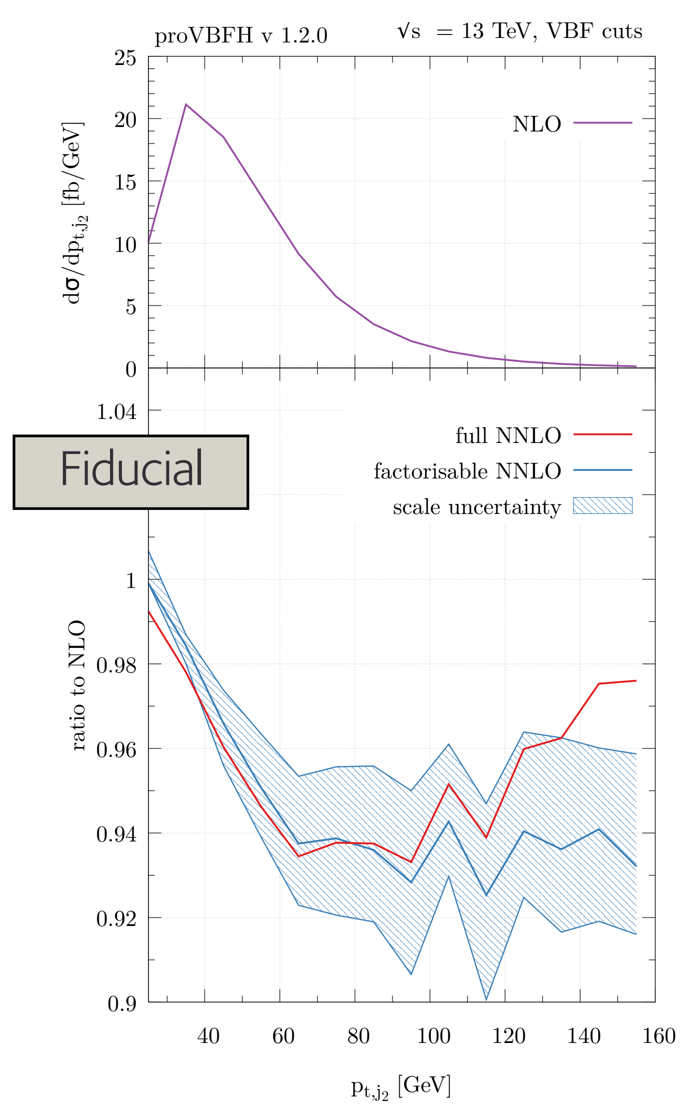


VS



Recent phenomenological study for H and HH [Dreyer, Karlberg, Tancredi (2020)]

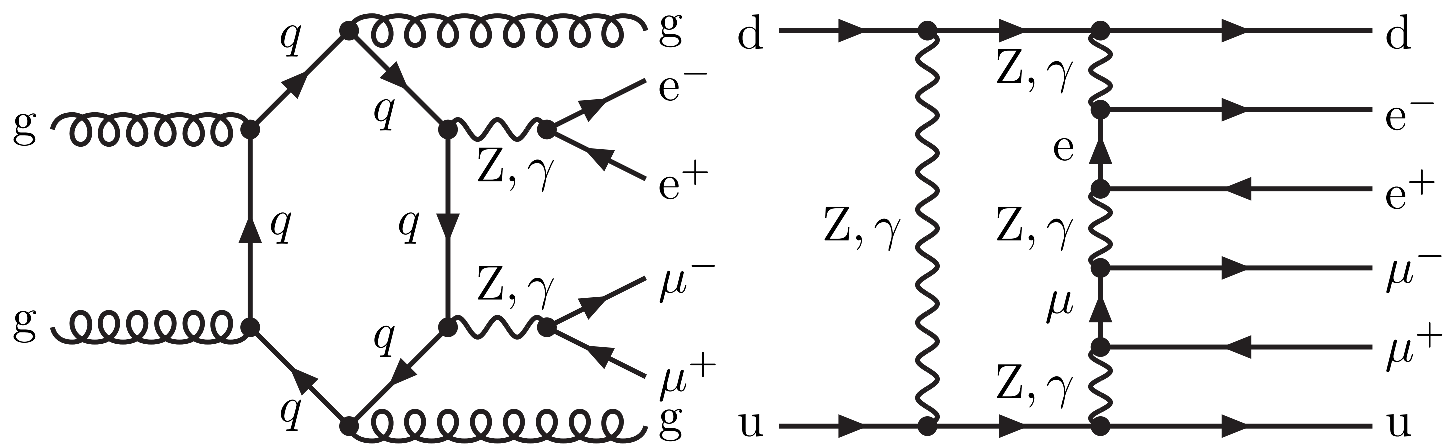


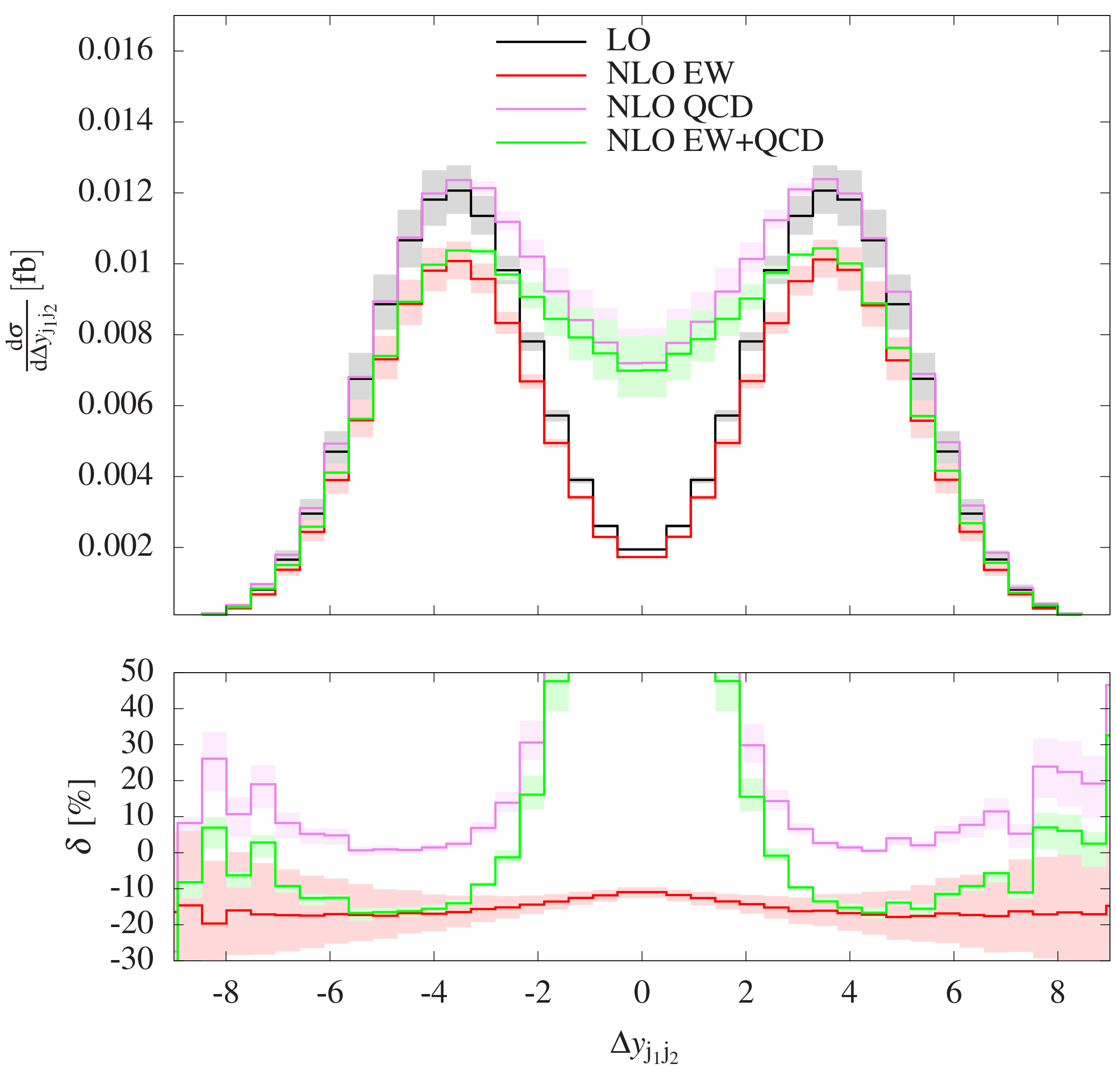


- Inclusive: non-factorizable corrections can be large
- Fiducial: typically suppressed, however non-trivial shapes
- Become important at large $p_{t,H}$, $p_{t,J}$. EFT/BSM studies?

VBF: not only QCD

Results at NLO QCD+EW for VBF, H → 4l [Denner, Pellen, Franken, Schmidt (2020)]



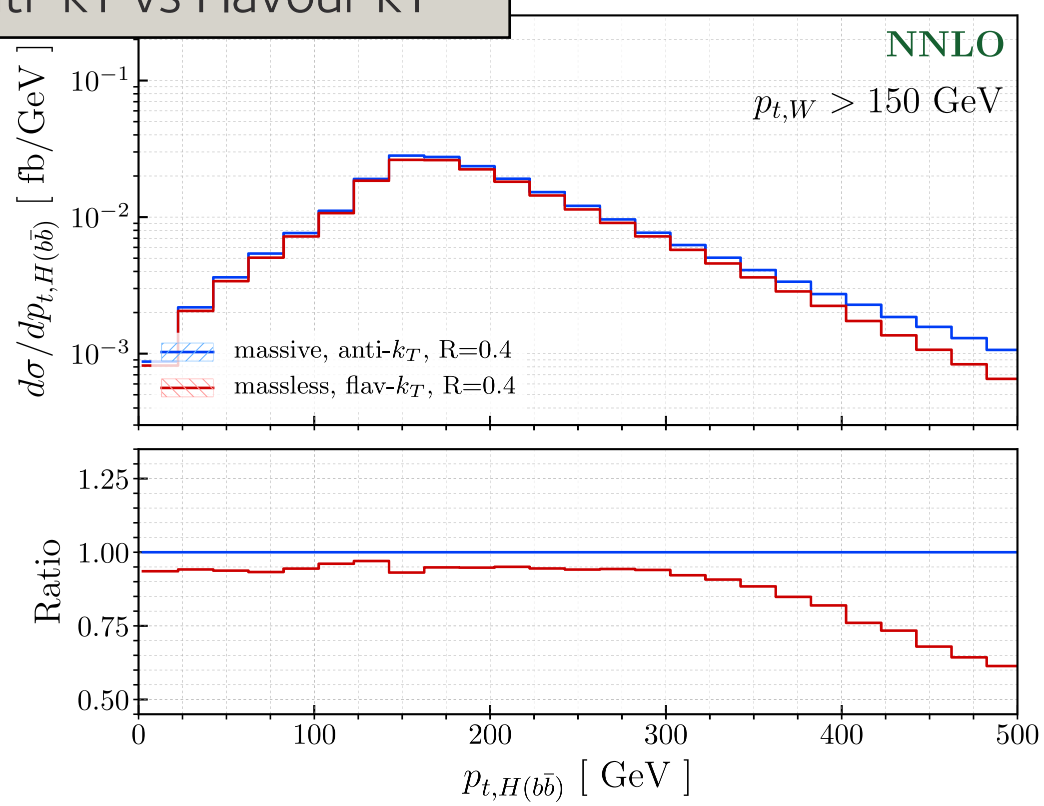


- Large ~ -16% EW corrections in the fiducial region (Sudakov logs)
- Treat di-boson and tri-boson contributions on an equal footing
- Careful when using MC for inclusive extrapolations...

VH: realistic jet algorithm in the bb channel

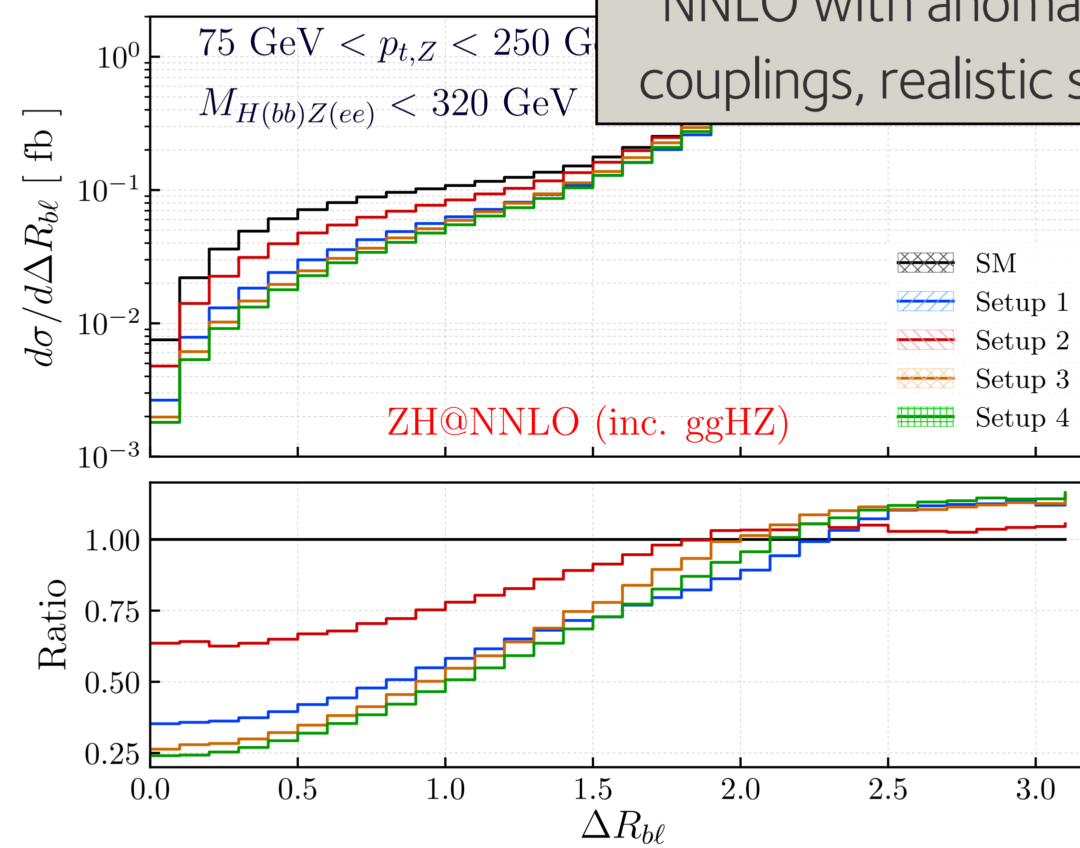
- VH@NNLO well-known, as well as fully differential H→bb, for massless b
- Starting from NNLO: tagged massless b IR unsafe with anti-kT, needs to use dedicated algorithm [Banfi, Salam, Zanderighi (2006)]. Different behaviour w.r.t. anti-kT, impossible to make clean TH-EXP comparisons
- Recently: H→bb with massive b [Bernreuther, Chen, Si (2018); Behring, Bizon (2020)] → realistic TH-EXP comparison possible

anti-kT vs Flavour kT



[Behring, Bizon, FC, Melnikov, Röntsch (2020)]

NNLO with anomalous couplings, realistic setup

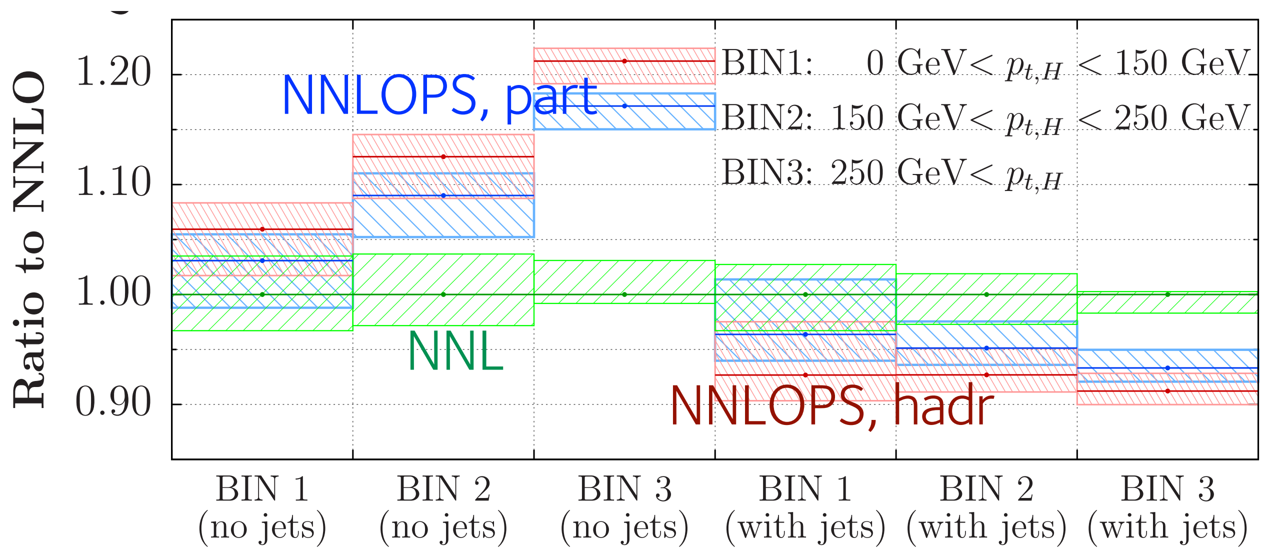


[Behring, Bizon, FC, Melnikov, Röntsch (2020)]

NNLOPS also available [Astill, Bizon, Re, Zanderighi (2020)]

WH: precise results for jet-bins

For WH: jet-binned cross section very important for signal/background discrimination. Non-trivial to properly describe

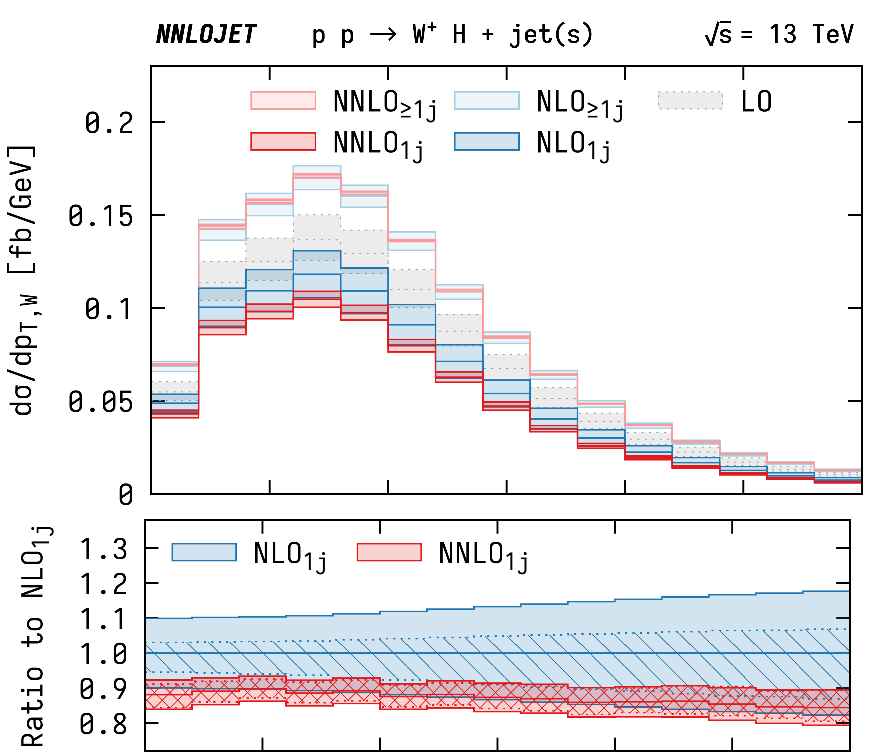


Large residual uncertainties

[Astill, Bizon, Re, Zanderighi (2016)]

Recently: WH+J@NNLO

[Gauld, Gerhmann-de Ridder, Glover, Huss, Majer (2020)]



- Large NNLO corrections in exclusive bins (expected)
- Jet-binned cross-section under much better control

ZH: towards gg→ZH@NLO

A serious problem for ZH: gg→ZH. Formally: NNLO, but new channel and gluon induced → expect very large corrections

W+H

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.831	$^{+0.74}_{-0.73}$	1.79

ZH, full

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.880	$^{+3.50}_{-2.68}$	1.65

ZH, no gg

$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.758	$^{+0.49}_{-0.61}$	1.78

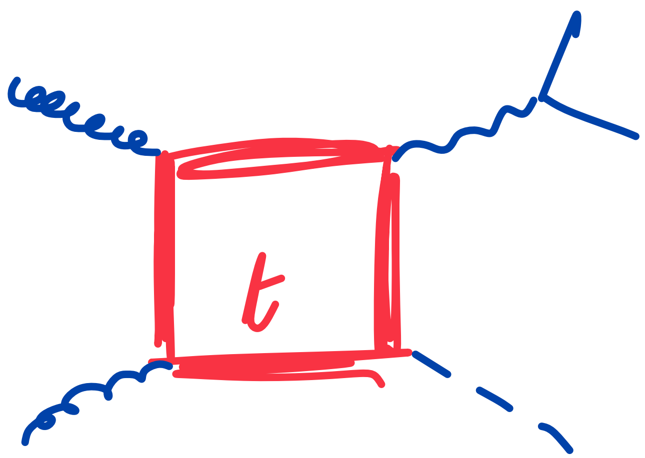
ZH, gg only

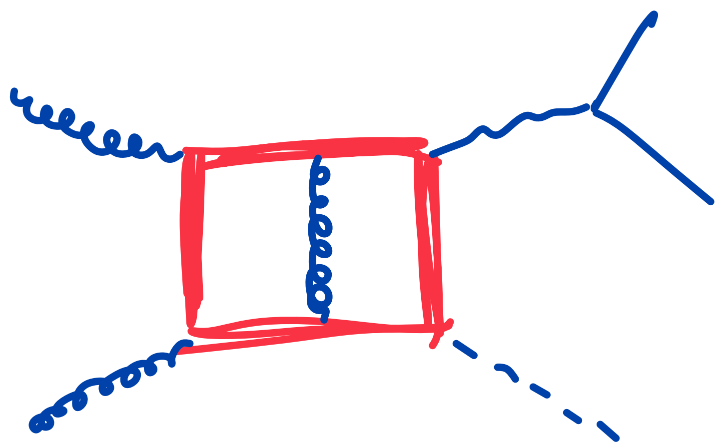
$\sqrt{s}$ [TeV]	$\sigma_{\text{NNLO QCD}\otimes\text{NLO EW}}$ [pb]	Δ_{scale} [%]	$\Delta_{\text{PDF}\oplus\alpha_s}$ [%]
13	0.123	$^{+24.9}_{-18.8}$	4.37

ZH@NLO: desirable…

ZH: towards gg→ZH@NLO

ZH@NLO: complicated 2L scattering amplitudes involving virtual top loops





Computation recently done, either numerically or using suitable approximation [Davies, Mishima, Steinhauser (2020); Chen, Heinrich, Jones, Kerner, Klappert, Schlenk (2020); Alasfar, Degrassi, Giardino, Gröber, Vitti (2021)]

After a long time: all ingredients for gg→ZH@NLO available!

Similar situation for gg→VV at high-mass

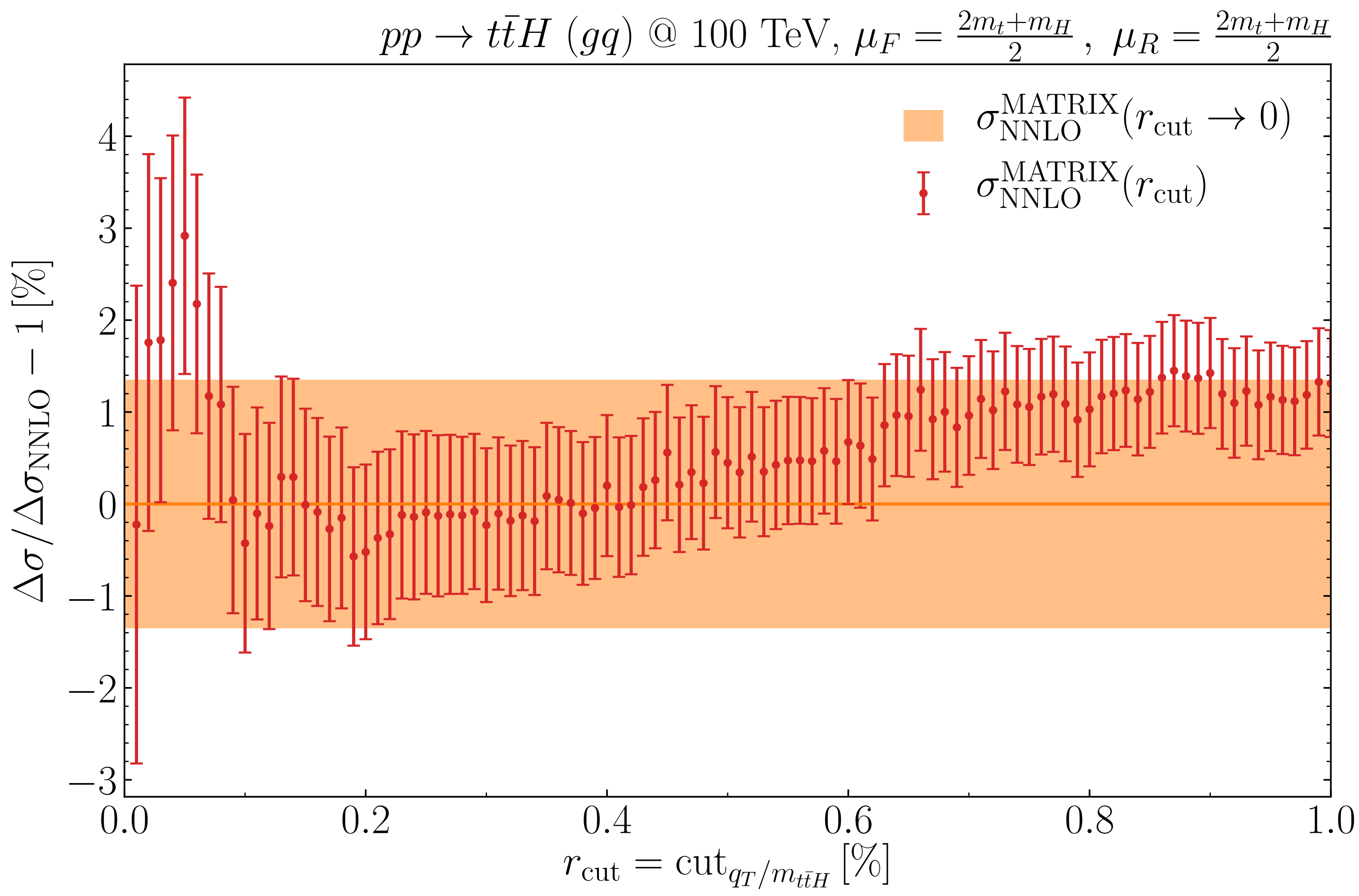
Brønnum-Hansen, Chen (2020-2021); Davies, Mishima, Steinhauser, Weller (2020); Agarwal, von Manteuffel, Jones (2020)]

Stay tuned for results!

Towards ttH@NNLO

Bottleneck: 2L virtual amplitude (non-trivial, but progress….)

In the meantime: getting ready for it. ttH@NNLO in the off-diagonal channels (qg,qq,qq') [Catani, Fabre, Grazzini, Kallweit (2021)]

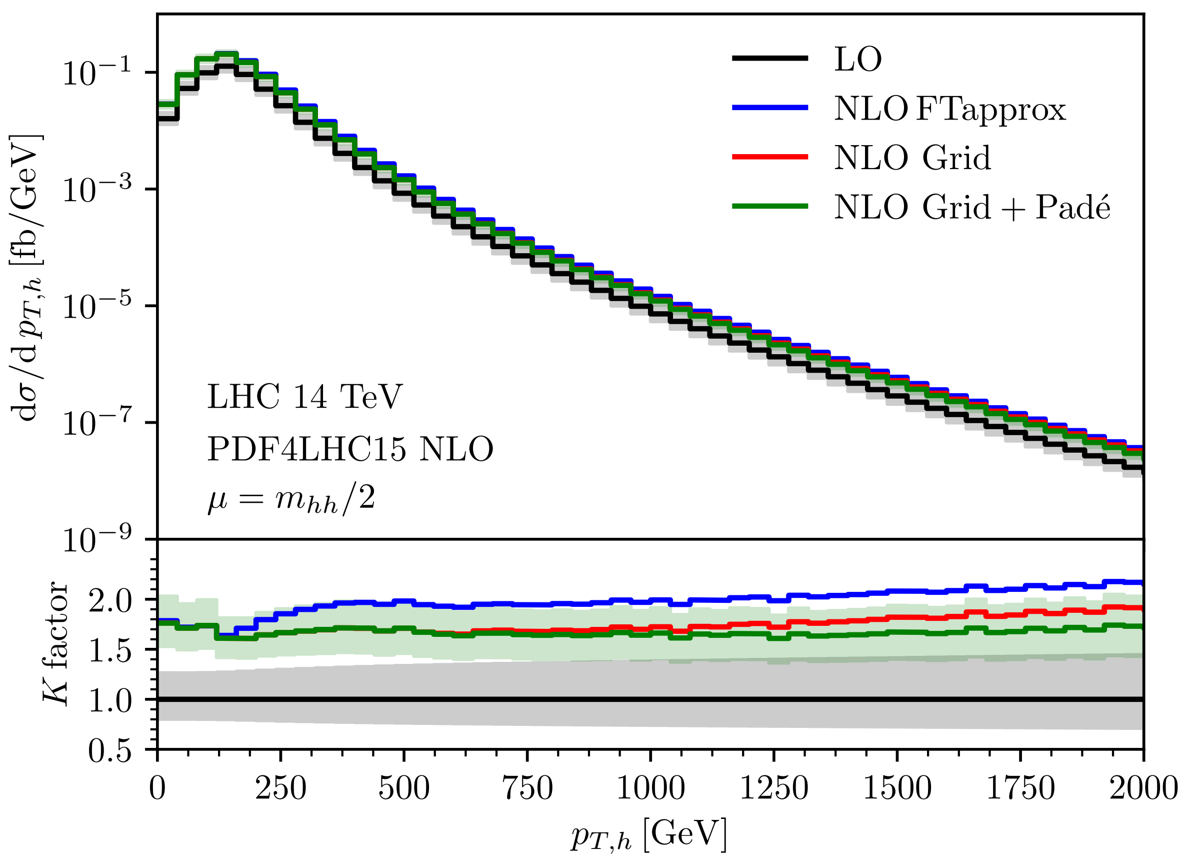


Difficult calculation, but no major obstacle if 2L amplitude is known

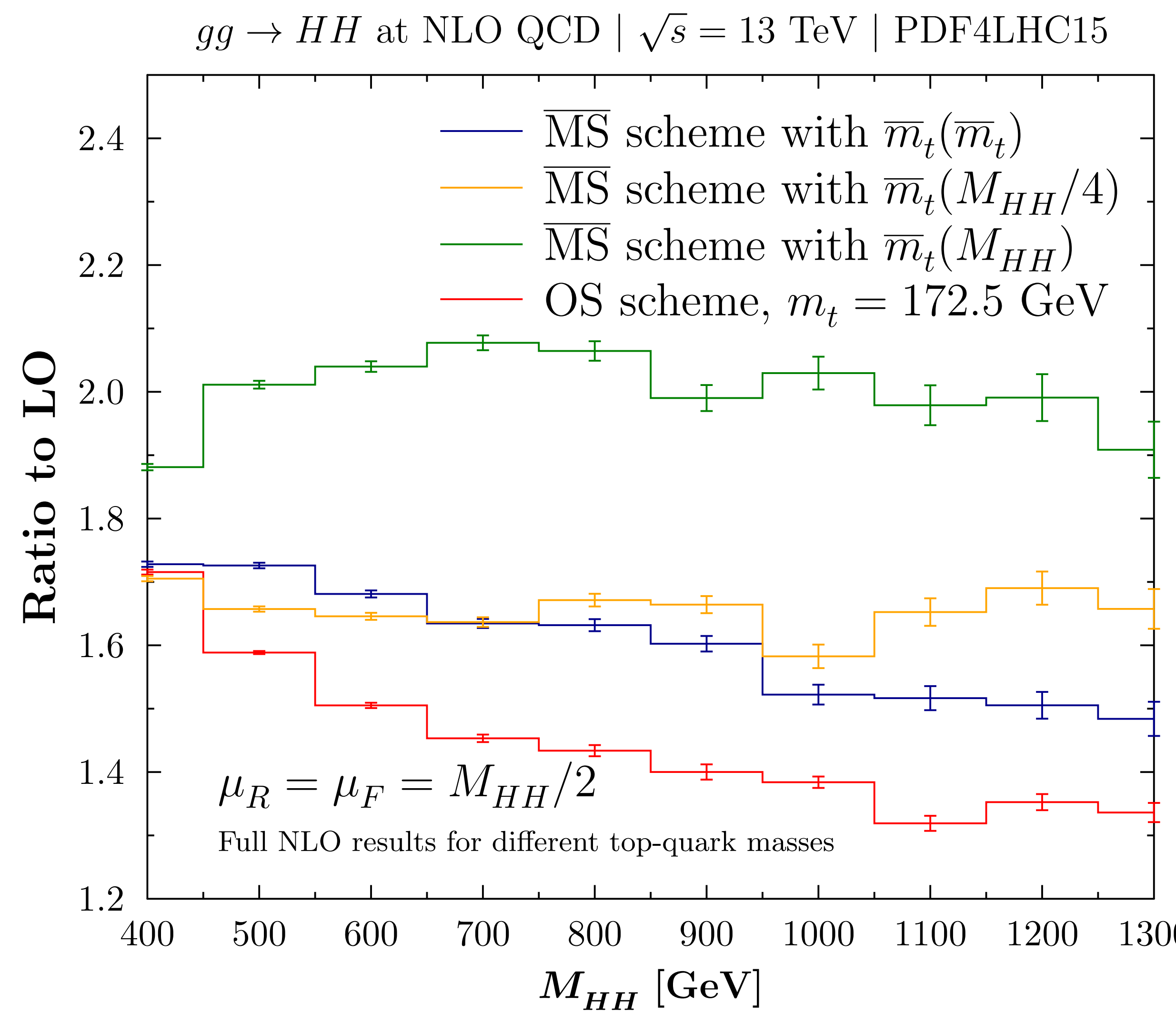
Backgrounds (ttbb) remain a major problem

HH:

gg➝HH@NLO now known (highly non trivial). Careful investigation of uncertainties underway



[Davies, Heinrich, Jones, Kerner, Mishima, Steinhauser, Wellmann (2019)]



[Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira (2020)]

Large ambiguities from top mass scheme. Should affect all loop induced processes at high-scale (gg➝VV, ggF…). Careful studies required

Conclusion

Higgs keeps pushing forward our understanding of collider pheno

Very sophisticated calculations

- N^3LO, multi-leg EW, complex loop scattering amplitudes
- refined shower predictions, resummations…

Higgs program is well underway, but getting to the few percent highly non-trivial. Many small subtle effects playing

- good definition of fiducial region
- ggF: heavy quark effects, non-trivial EW corrections…
- VBF: factorizable vs non factorizable
- At some point: non-perturbative corrections?

Another important chapter: input parameters (α_s, PDFs…)

… a lot of progress, but a lot still to be done → interesting times ahead

Thank you very much for your attention!