

Higgs predictions for the HL/HE-LHC: LHCHXSWG1 activities

Fabrizio Caola, IPPP Durham, for the WG1 conveners



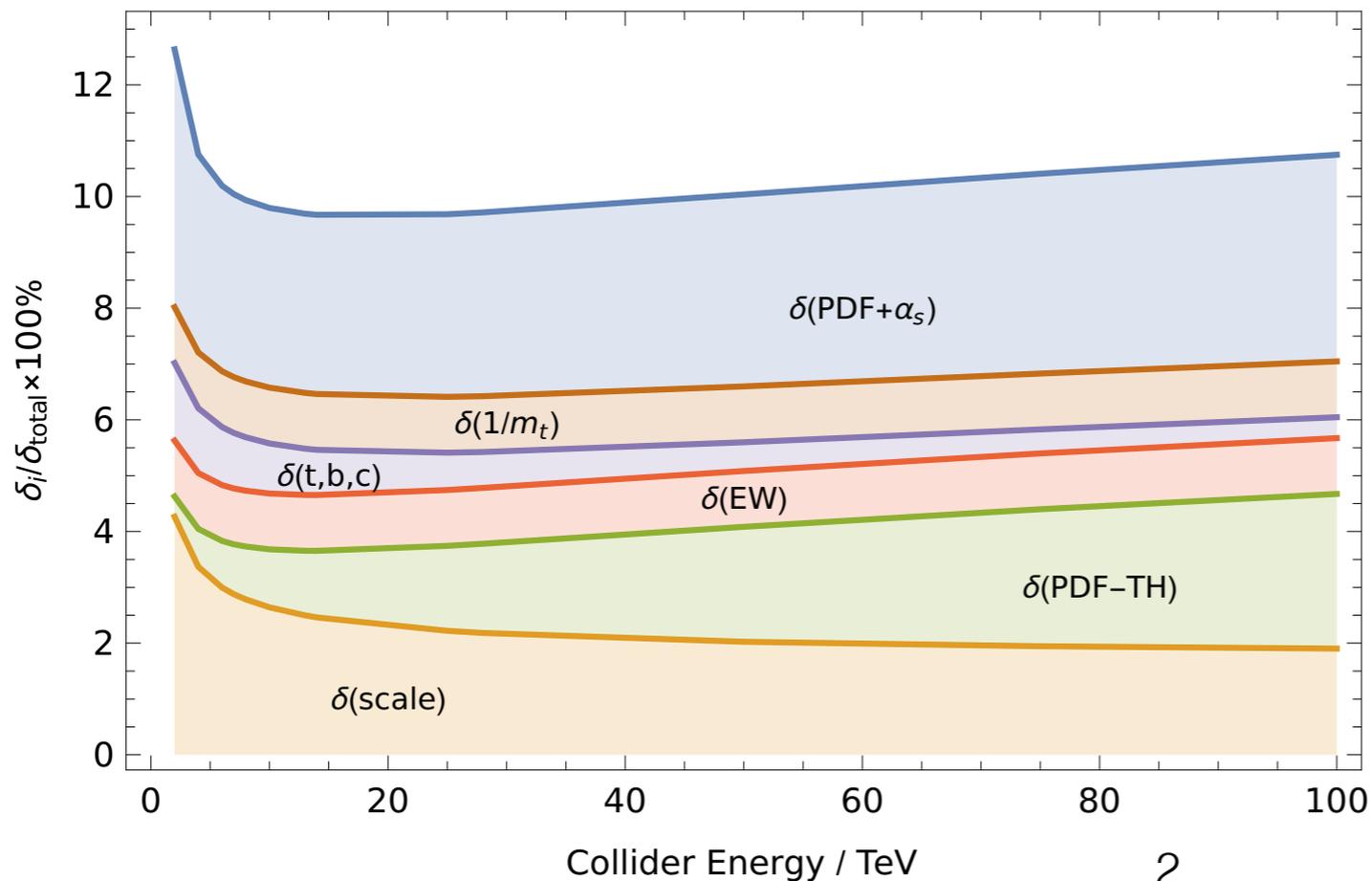
*Slides based on input from the subgroup conveners.
Many thanks for their work!*

ggF: inclusive results

Already now, refined theoretical description

YR4-like predictions for HL/HE

E_{CM}	σ	$\delta(\text{theory})$	$\delta(\text{PDF})$	$\delta(\alpha_s)$
13 TeV	48.61 pb	$+2.08\text{pb} \left(+4.27\% \right)$ $-3.15\text{pb} \left(-6.49\% \right)$	$\pm 0.89 \text{ pb} \left(\pm 1.85\% \right)$	$+1.24\text{pb} \left(+2.59\% \right)$ $-1.26\text{pb} \left(-2.62\% \right)$
14 TeV	54.72 pb	$+2.35\text{pb} \left(+4.28\% \right)$ $-3.54\text{pb} \left(-6.46\% \right)$	$\pm 1.00 \text{ pb} \left(\pm 1.85\% \right)$	$+1.40\text{pb} \left(+2.60\% \right)$ $-1.41\text{pb} \left(-2.62\% \right)$
27 TeV	146.65 pb	$+6.65\text{pb} \left(+4.53\% \right)$ $-9.44\text{pb} \left(-6.43\% \right)$	$\pm 2.81 \text{ pb} \left(\pm 1.95\% \right)$	$+3.88\text{pb} \left(+2.69\% \right)$ $-3.82\text{pb} \left(-2.64\% \right)$



← Breakdown of theoretical uncertainty

[Mistlberger]

ggF: more on ``PDF'' effects

Results including $N^3LL_{\text{soft}} + LL_x$ resummation

\sqrt{s}	$\sigma_{N^3LO+N^3LL+LLx}$	$= \sigma_t + \Delta\sigma_{bc} + \Delta\sigma_{EW}$	$\delta_{\text{scale}}^{42\text{var}}$	δ_{PDFs}	$\delta_{\text{subl.logs}}$	$\frac{\sigma_{N^3LO+N^3LL+LLx}}{\sigma_{N^3LO}}$
13 TeV	48.93 pb	(49.26 - 2.66 + 2.33) pb	$+4.0\%$ -3.8%	$\pm 1.2\%$	$\pm 1.8\%$	1.020
14 TeV	55.22 pb	(55.56 - 2.96 + 2.63) pb	$+4.0\%$ -3.8%	$\pm 1.1\%$	$\pm 1.9\%$	1.023
27 TeV	151.6 pb	(151.6 - 7.2 + 7.2) pb	$+4.0\%$ -4.0%	$\pm 1.0\%$	$\pm 2.3\%$	1.046

Change w.r.t. N³LO

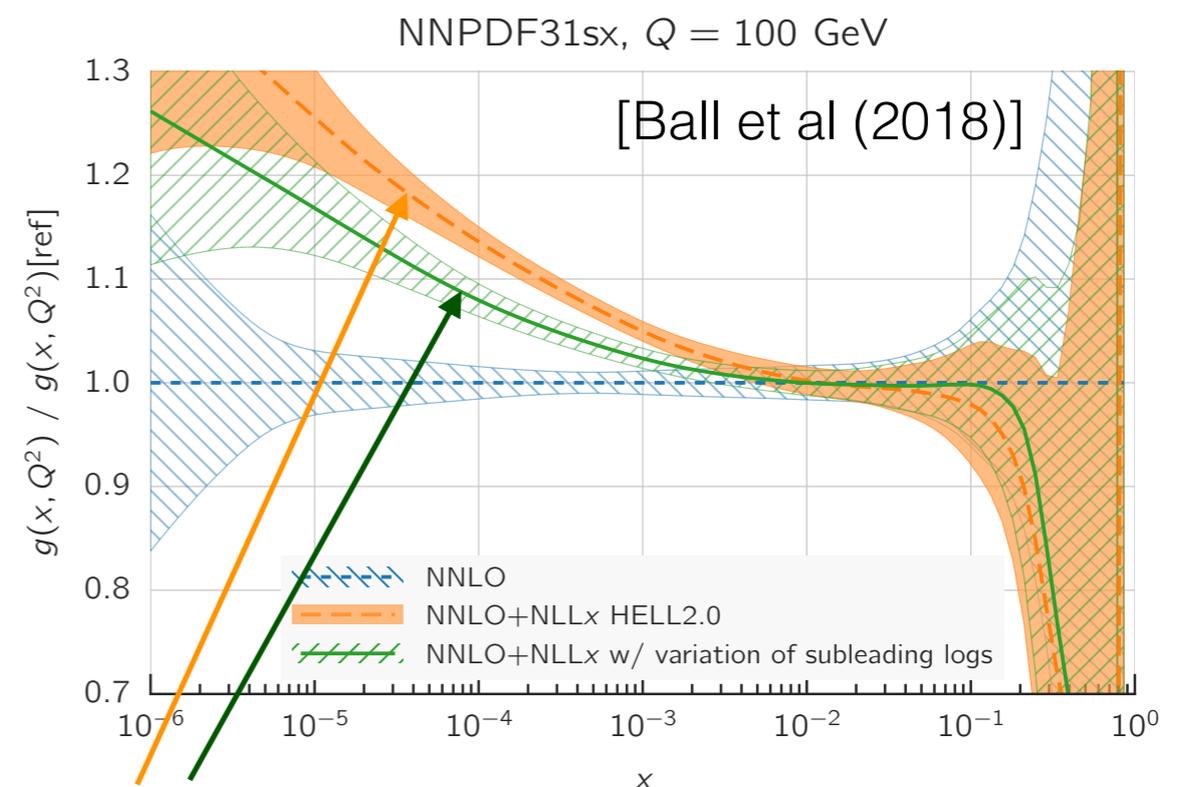
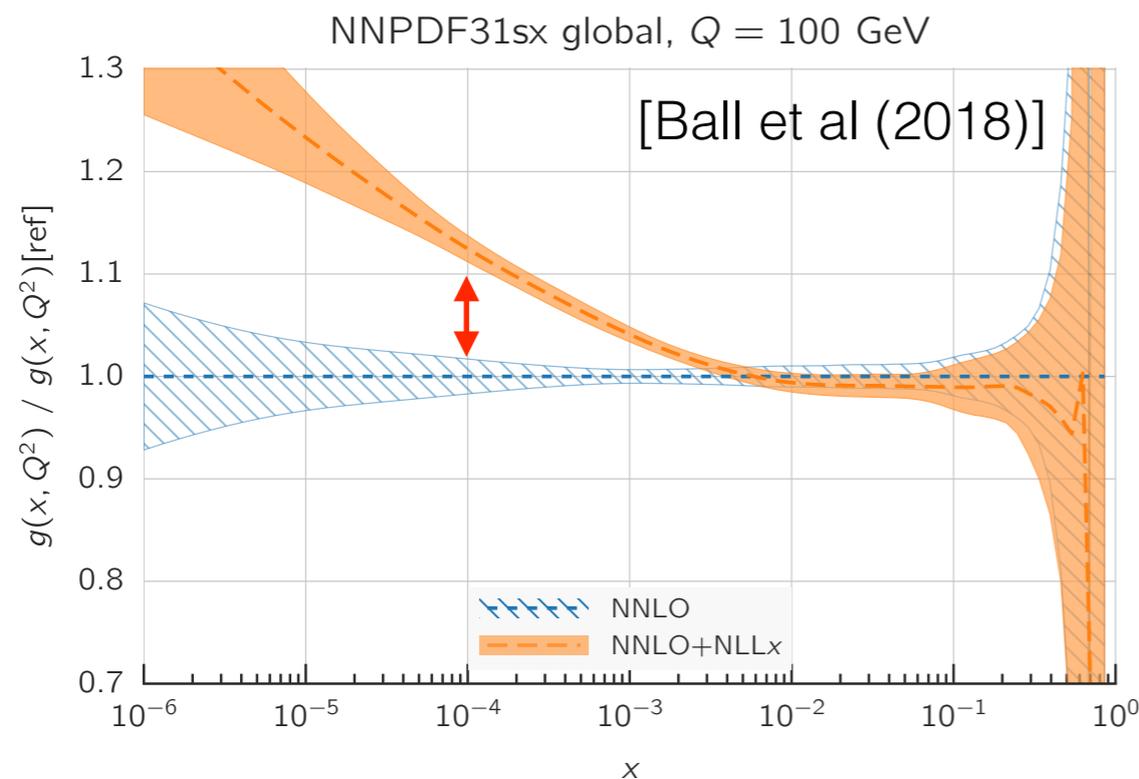
[Bonvini, Marzani]

- Small impact of N^3LL_{soft} resummation on top of N^3LO ($\sim 1\%$)
- Larger \sim few percent impact of small- x resummation
- It seems (to me) that the bulk of the effect comes from large modifications of the gluon in the HERA region
- Effect washed out by evolution, but not completely
- LL_x analysis, potentially large subleading effects

many thanks to G. Salam for discussions on this topic

ggF: more on ``PDF'' effects

\sqrt{s}	$\sigma_{N^3LO+N^3LL+LLx}$	$= \sigma_t + \Delta\sigma_{bc} + \Delta\sigma_{EW}$	δ_{scale}^{42var}	δ_{PDFs}	$\delta_{subl.logs}$	$\frac{\sigma_{N^3LO+N^3LL+LLx}}{\sigma_{N^3LO}}$
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different treatment of subleading terms

Small-x resummation beyond LL_x (\equiv first non-trivial order) unavailable

At this level of precision: **theory error on PDF needed**

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ggF: status and prospects

YR4, inclusive cross-section:

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

48.58 pb =	16.00 pb	(+32.9%)	(LO, rEFT)
	+ 20.84 pb	(+42.9%)	(NLO, rEFT)
	- 2.05 pb	(-4.2%)	((t, b, c), exact NLO)
	+ 9.56 pb	(+19.7%)	(NNLO, rEFT)
	+ 0.34 pb	(+0.7%)	(NNLO, 1/m _t)
	+ 2.40 pb	(+4.9%)	(EW, QCD-EW)
	+ 1.49 pb	(+3.1%)	(N ³ LO, rEFT)

YR4, main sources of uncertainty

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

ggF: status and prospects

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48.58 pb =

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+ 20.84 pb	(+42.9%)	(NLO, rEFT)	
- 2.05 pb	(-4.2%)	((<i>t, b, c</i>), exact NLO)	← known for NLO p_t distribution
+ 9.56 pb	(+19.7%)	(NNLO, rEFT)	
+ 0.34 pb	(+0.7%)	(NNLO, $1/m_t$)	← [1610.03747, 1702.00426, 1712.06549, 1802.07977]
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[1802.00833]

known in SV approximation [1801.10403]

ggF: status and prospects

YR4, ~~inclusive~~ differential cross-section:

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

48.58 pb = 16.00 pb (+32.9%) (LO, rEFT)

Reasonable to expect progress on all these issues within HL-LHC timeframe

Percent accuracy ~ current *theoretical* limit of pQCD

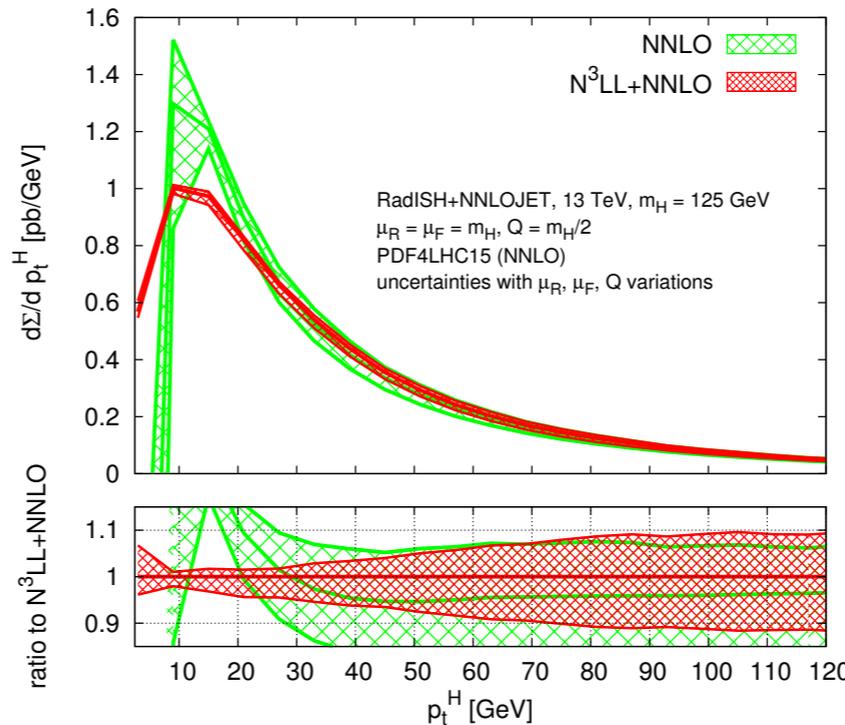
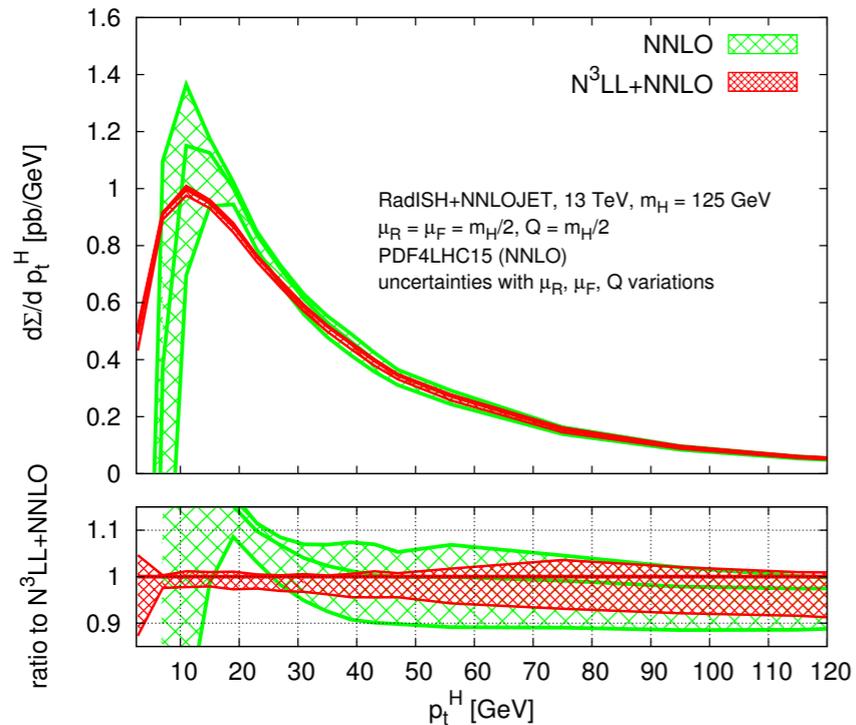
+0.10 pb -1.15 pb	±0.18 pb	±0.56 pb	±0.49 pb	±0.40 pb	±0.49 pb
+0.21% -2.37%	±0.37%	±1.16%	±1%	±0.83%	±1%

[1802.00833]

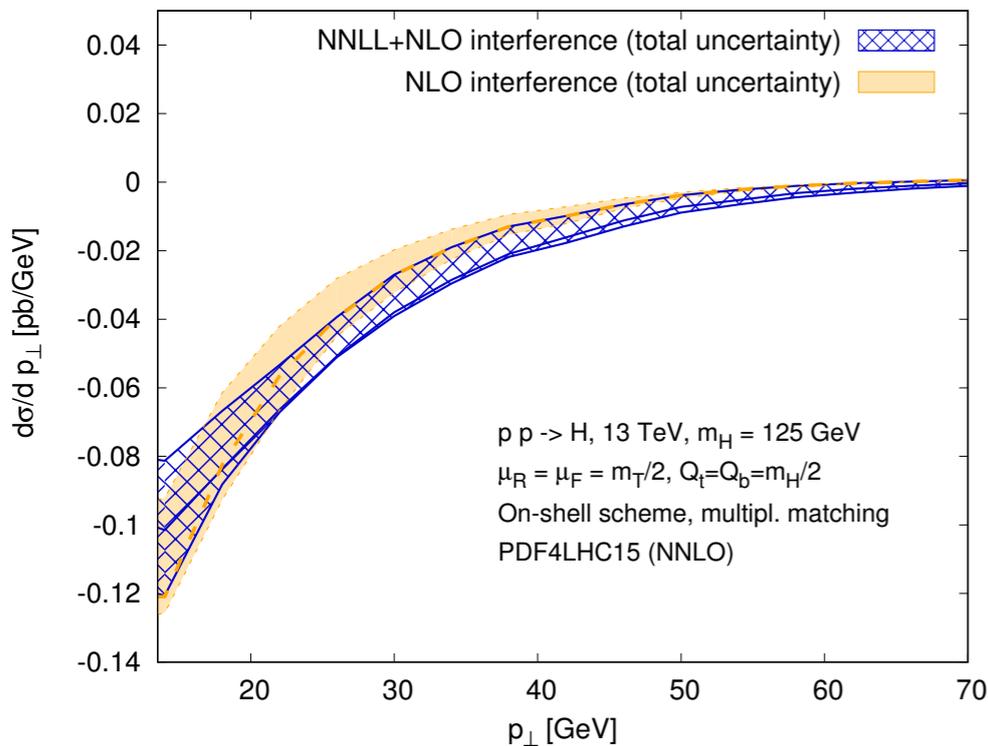
known in SV approximation [1801.10403]

ggF: more differential

Good control over Higgs p_t distribution



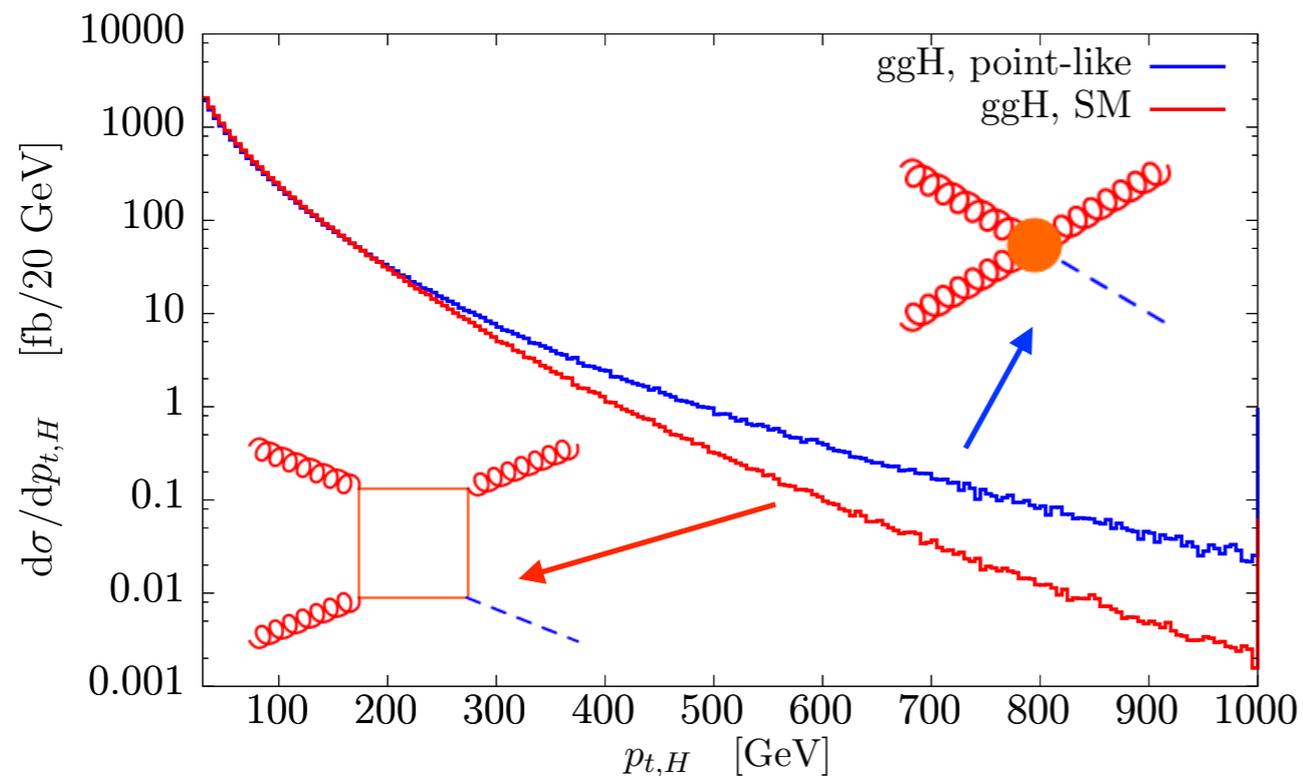
Pheno studies at
 NNLO+N³LL:
 ~ few percent in
 bulk of distribution
 [1805.00736, 1805.05916]



~20% on t/b
 contribution
 [= ~few percent of
 full distribution]
 [1804.07632]

- Ongoing work: LHC13 recommendation
- Extending to HL easy
- Progress w.r.t. what shown here: likely very slow...

ggF: boosted



HE-LHC reach:
rough idea for inclusive rates
(here: gg-only)

$$\sigma_{gg}(p_{\perp} > p_{\perp, \text{cut}}) =$$

1 fb

1 ab

bb

~900 GeV

~2.4 TeV

$\tau\tau$

~600 GeV

~1.8 TeV

$e\mu\nu\nu$

~300 GeV

~1.1 TeV

$\gamma\gamma$

~300 GeV

~1.1 TeV

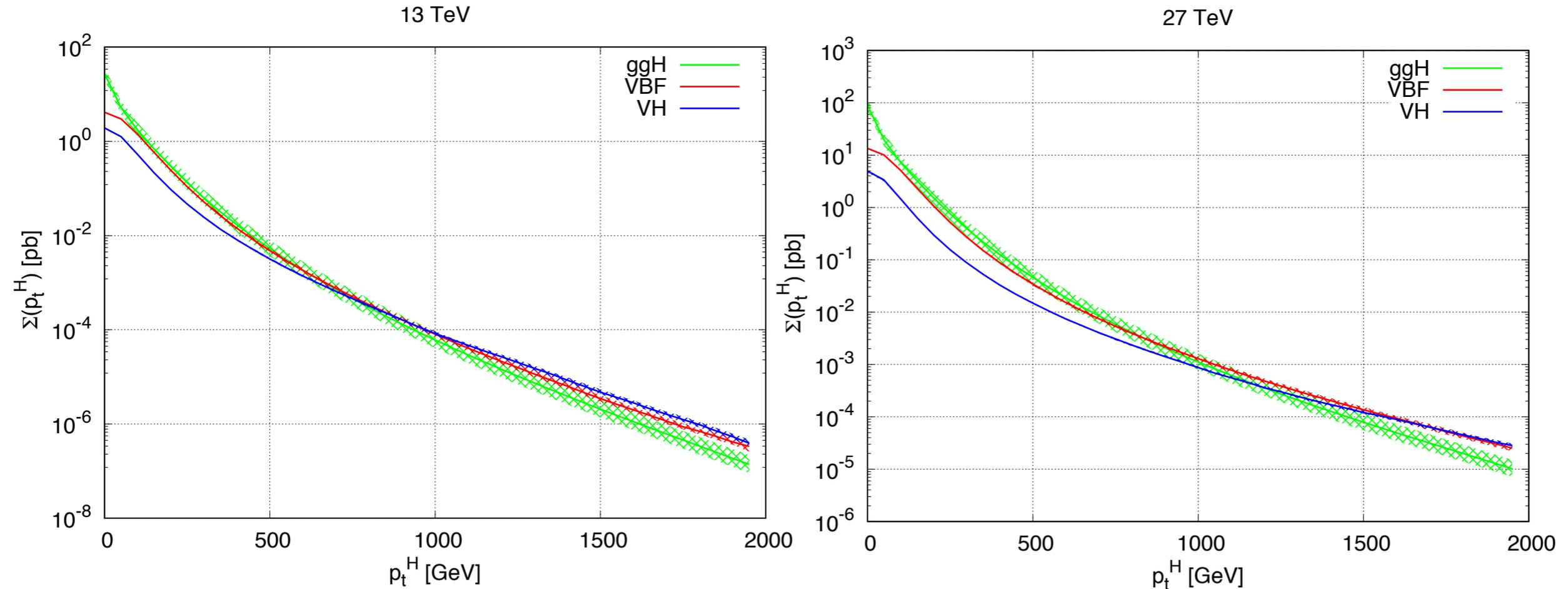
$e^+e^-\mu^+\mu^-$

~60 GeV

~600 GeV

ggF: boosted

Ongoing work: predictions including all channels



[many thanks to the ggF,
VBF, VH converters]

- Recent result: NLO predictions with top-mass effects.
Scale variation: $\sim 20\%$ [1801.08226, 1802.02981, 1802.00349]
- Ongoing work for LHC13 recommendation
- Studies can be extended to HL/HE
- Significant progress beyond this: likely very slow...

VBF: ~~see A. Karlberg's talk~~

slides from A. Karlberg

VH: predictions for total rates

- NNLO QCD + NLOEW [thanks to R. Harlander, S. Dittmaier & collaborators for providing input]
- Same baseline of YR4, but LUXqed_plus_PDF4LHC15_nnlo PDF set
- $m_H=125.09$ GeV [124.59, 125.59 available]

	14 TeV			27 TeV		
	σ [pb]	Δ_{μ_r, μ_f}	Δ_{PDF}	σ [pb]	Δ_{μ_r, μ_f}	Δ_{PDF}
W ⁺ H	0.91	+0.6% - 0.8%	1.8%	2.0	+0.4% - 1.0%	1.8%
W ⁻ H	0.59	+0.6% - 0.7%	2.0%	1.4	+0.4% - 0.9%	2.0%
I+v H	0.10	+0.6% - 0.7%	1.7%	0.23	+0.4% - 1.0%	1.7%
γ -induced only	4.6 10⁻³			1.5 10⁻²		
I- $\bar{\nu}$ H	0.07	+0.5% - 0.6%	1.9%	0.16	+0.3% - 0.9%	1.9%
γ -induced only	3.1 10⁻³			1.1 10⁻²		

wo γ

with γ

- Photon contribution under full control
- Marginally larger impact at 27 TeV
- Good perturbative control, but beware of tiny error in inclusive numbers

VH: predictions for total rates

- NNLO QCD + NLOEW [thanks to R. Harlander, S. Dittmaier & collaborators for providing input]
- Same baseline of YR4, but LUXqed_plus_PDF4LHC15_nnlo PDF set
- $m_H = 125.09$ GeV [124.59, 125.59 available]

	14 TeV			27 TeV		
	σ [pb]	Δ_{μ_r, μ_f}	Δ_{PDF}	σ [pb]	Δ_{μ_r, μ_f}	Δ_{PDF}
ZH, no gg	0.84	+0.5% - 0.6%	1.8%	1.94	+0.6% - 0.7%	2.4%
ZH, gg	0.14	+24% - 20%	7.5%	0.53	+25% - 19%	6%

↑
Particularly interesting/
important at large m_{ZH}

Exact $\text{LO} \times \text{K}_{\text{NLO, HEFT}} + \text{NLL}_{\text{soft}}$

Lessons from di-Higgs:

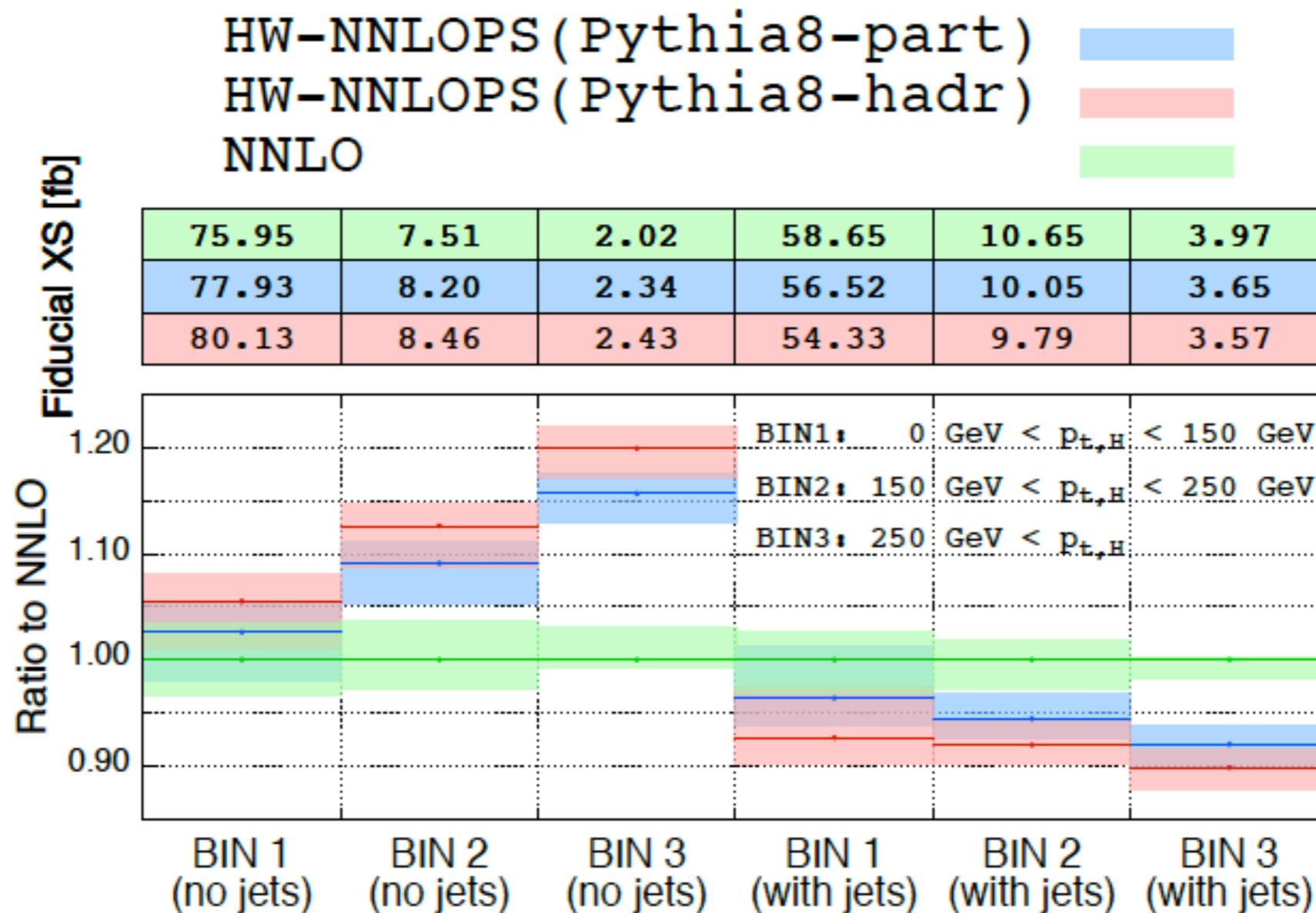
- NLO reduces error from $\sim 20\text{-}25\%$ to $\sim 15\%$
- $\text{K}_{\text{NLO, HEFT}}$ overestimates K-factor of $\sim 20\text{-}25\%$

However be careful, both in HH and VH delicate cancellation patterns

NLO likely to come in the near future

VH: more differential results

- NNLOPS available. In most cases small $\sim 2/3\%$ shower effects
- Larger corrections to exclusive observables
- Jet bins still poorly understood



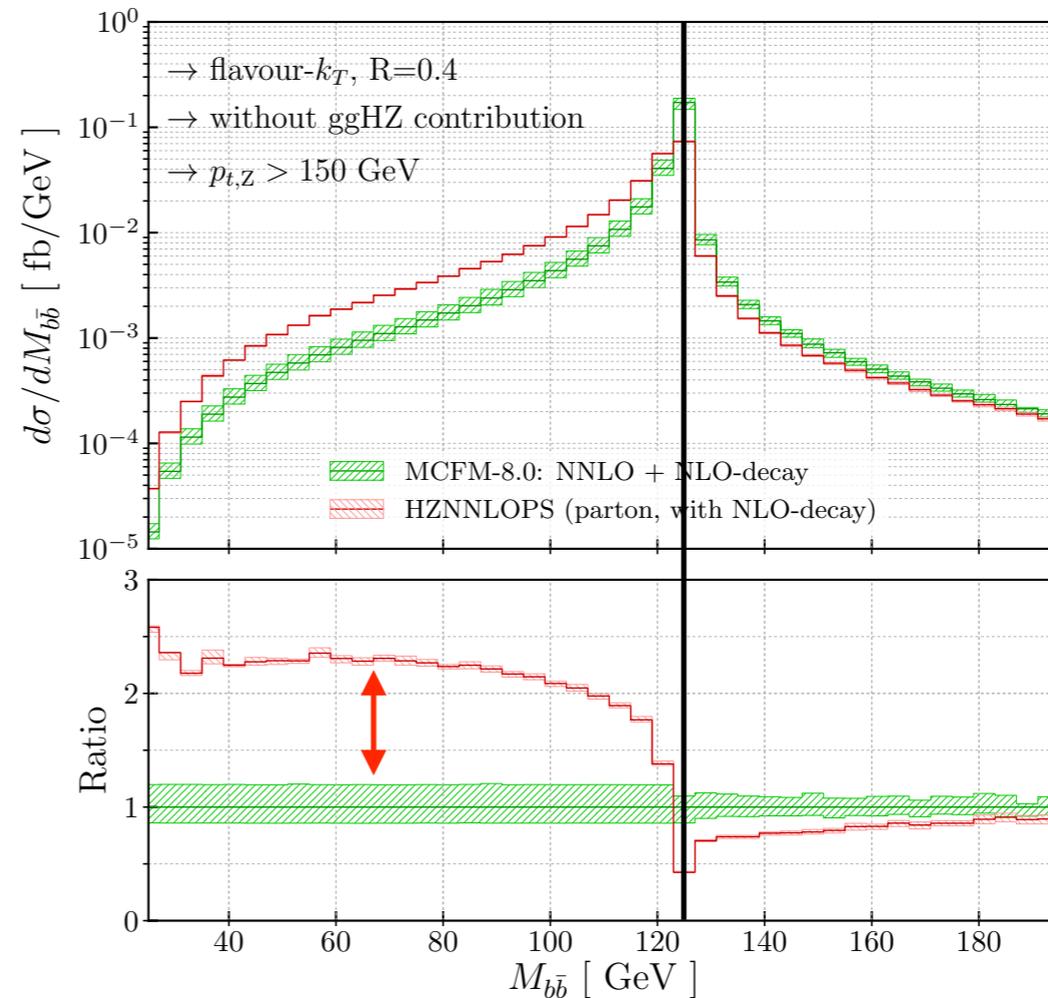
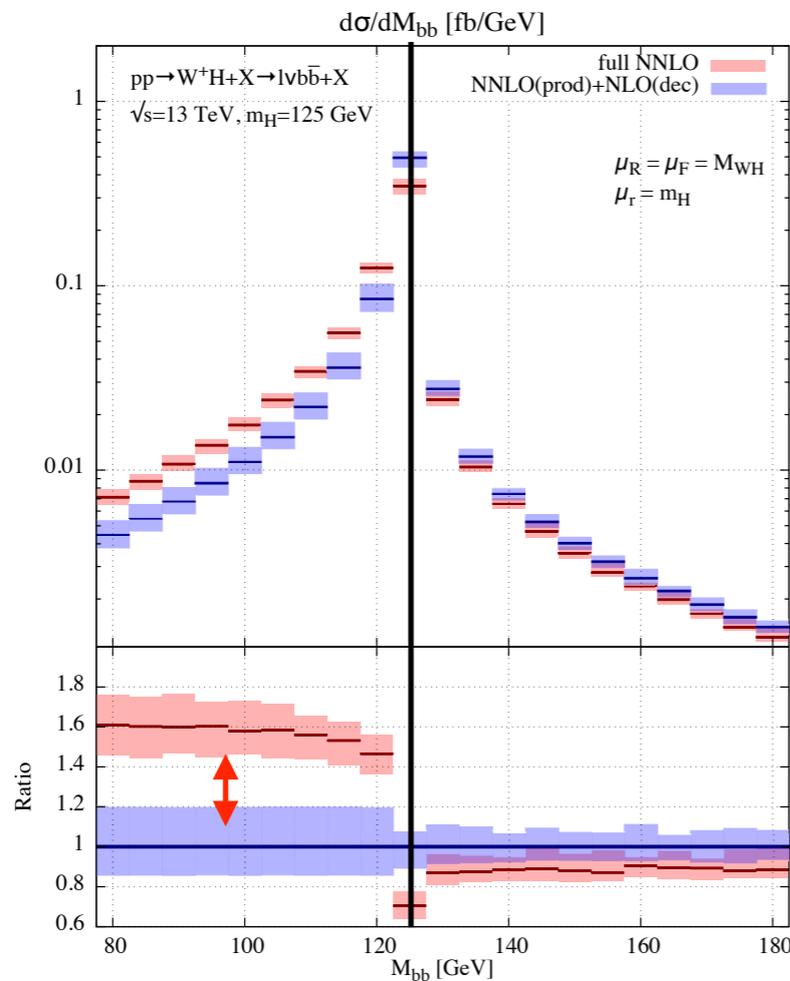
[Astill, Bizon, Re Zanderighi (2016)]

VH: more differential results

Semi-boosted region: shape corrections from radiation off $H \rightarrow bb$

Reconstructed Higgs mass

[Ferrera, Somogyi,
Tramontano (2017)]



[Astill, Bizon, Re
Zanderighi (2018)]

- Bulk of the effect captured by PS
- Interesting (non-trivial) dependence on y_b [arXiv:1712.06954]
- Recent results, more studies needed

ttH: prediction for total rates

NLO QCD + NLOEW results

M_H [GeV]	$\sigma_{\text{QCD+EW}}^{\text{NLO}}$ [fb]	Scale[%]	α_s [%]	PDF[%]	PDF+ α_s [%]
124.59	619.3	+6.1 - 9.2	± 1.9	± 2.9	± 3.5
125.09	612.8	+6.0 - 9.2	± 1.9	± 2.9	± 3.5
125.59	605.6	+6.1 - 9.2	± 1.9	± 2.9	± 3.5

Table 1: NLO QCD+EW cross sections for $t\bar{t}H$ production at the 14 TeV LHC.

M_H [GeV]	$\sigma_{\text{QCD+EW}}^{\text{NLO}}$ [pb]	Scale[%]	α_s [%]	PDF[%]	PDF+ α_s [%]
124.59	2.90	+7.9 - 9.0	± 1.8	± 2.1	± 2.8
125.09	2.86	+7.8 - 9.0	± 1.8	± 2.1	± 2.8
125.59	2.84	+7.8 - 9.0	± 1.8	± 2.1	± 2.8

Table 2: NLO QCD+EW cross sections for $t\bar{t}H$ production at the 27 TeV LHC.

- Dominant ambiguity: scale variation
- Can only be improved by NNLO calculation \rightarrow well beyond what we can do today
- Although unrealistic in the near future, foreseeable on HL-LHC timescales
- Reasonable expectation: factor of 2 improvement on theoretical prediction

ttH: main problem

Poor theoretical modeling of ttbb and ttW+jets backgrounds via Monte Carlo generators

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

YR4

Shower effects enhanced in the signal region

- Big ongoing effort of the ttH subgroup to investigate this issue (uncertainty estimate, improvements...)
- Unrealistic to expect major developments for the report
- Estimate on a 5-10y timescale: background uncertainties reduced by a factor 2~3.

Conclusions

- Cross-section predictions for all the main channels available for HL/HE-LHC
- Major obstacles / estimates for improvement are becoming clear
- Several LHC13 studies going on, many could be easily extended to HL(HE)-LHC
- Other studies ongoing (off-shell, differential distributions, detector reach, fiducial region definition...)

Many thanks to the subgroup conveners and all the people who contributed for providing these results