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!

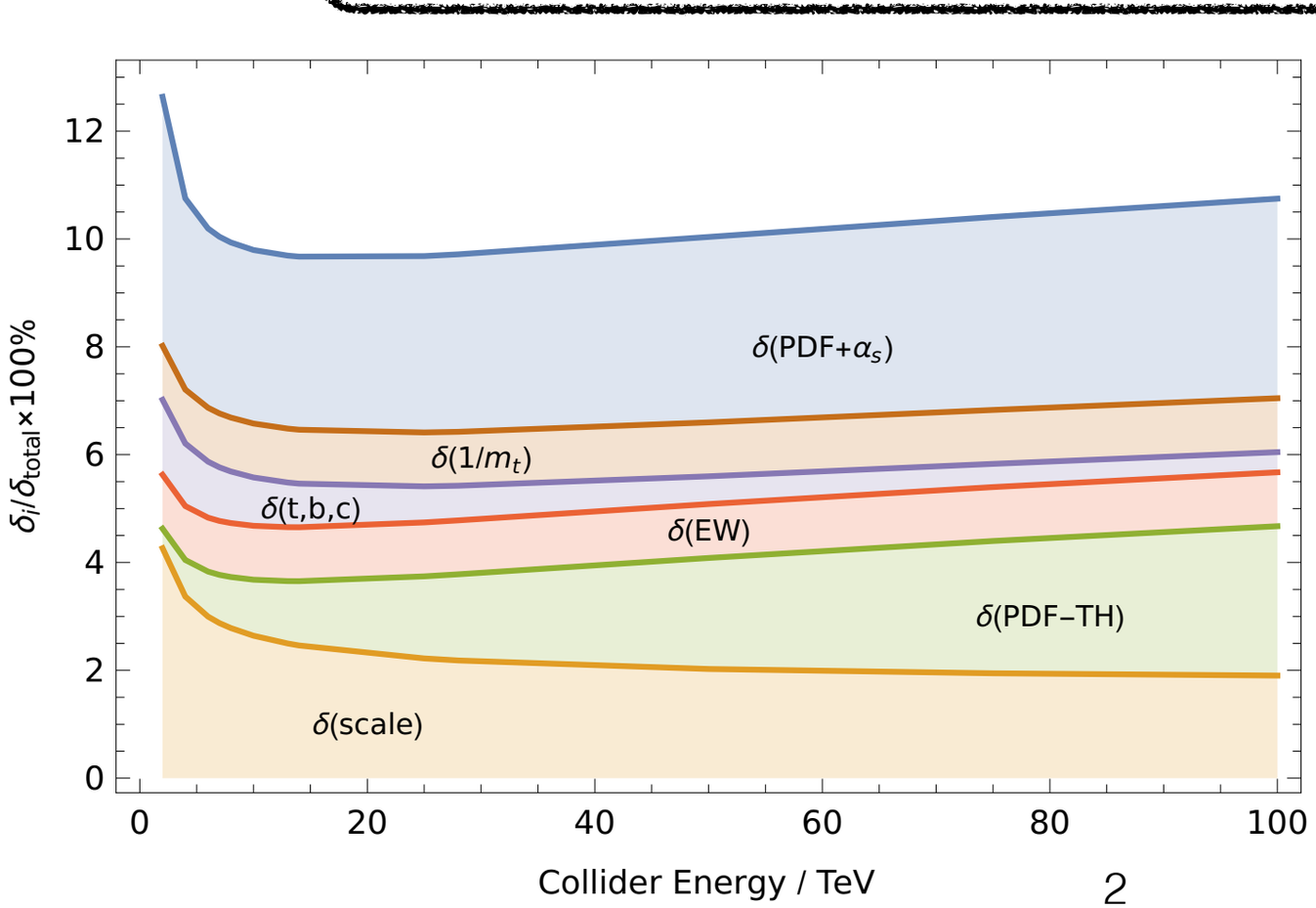
ggF: inclusive results

Already now, refined theoretical description

YR4-like predictions for HL/HE

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

[Mistlberger]



Breakdown of theoretical uncertainty

ggF: more on ``PDF'' effects

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

$\sqrt{s}$	$\sigma_{\mathrm{N^3LO+N^3LL+LL}x}$	$= \sigma_t + \Delta\sigma_{bc} + \Delta\sigma_{\mathrm{EW}}$	$\delta^{42\mathrm{var}}_{\mathrm{scale}}$	δ_{PDFs}	$\delta_{\mathrm{subl.logs}}$	$\frac{\sigma_{\mathrm{N^3LO+N^3LL+LL}x}}{\sigma_{\mathrm{N^3LO}}}$
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

[Bonvini, Marzani]

Change w.r.t. N^3LO

- Small impact of N^3LL_{soft} resummation on top of N^3LO (~1%)
- Larger ~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

$\sqrt{s}$	$\sigma_{\mathrm{N^3LO+N^3LL+LL}x}$	$= \sigma_t + \Delta\sigma_{bc} + \Delta\sigma_{\mathrm{EW}}$	$\delta^{\mathrm{42var}}_{\mathrm{scale}}$	δ_{PDFs}	$\delta_{\mathrm{subl.logs}}$	$\frac{\sigma_{\mathrm{N^3LO+N^3LL+LL}x}}{\sigma_{\mathrm{N^3LO}}}$
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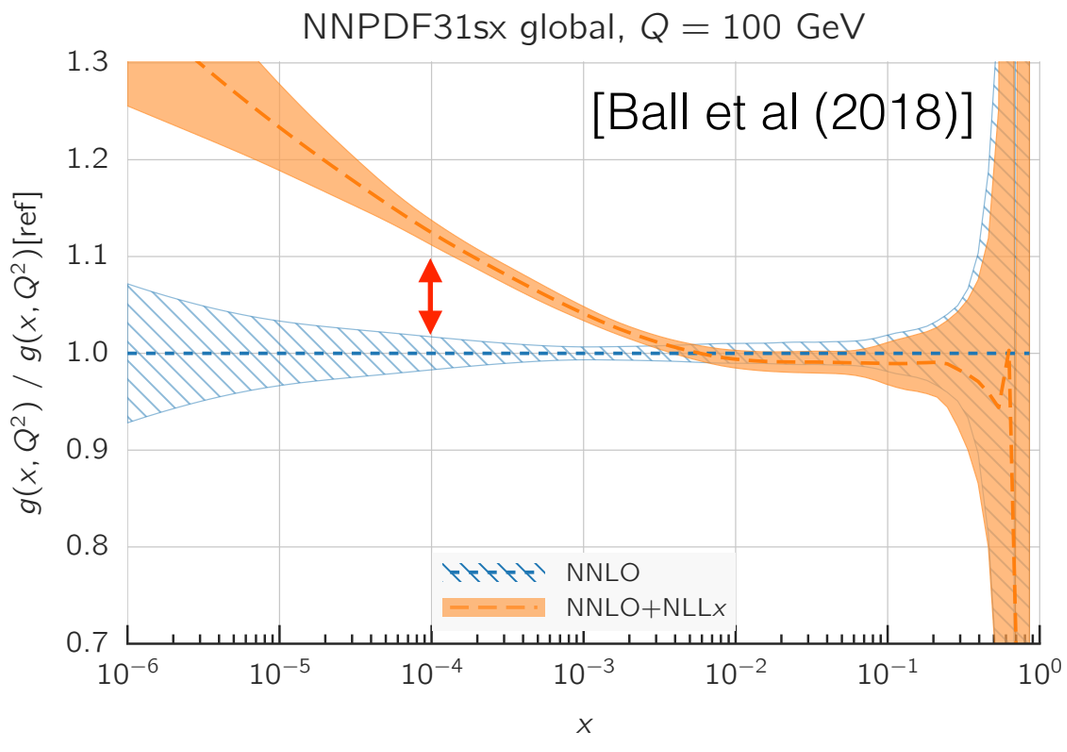

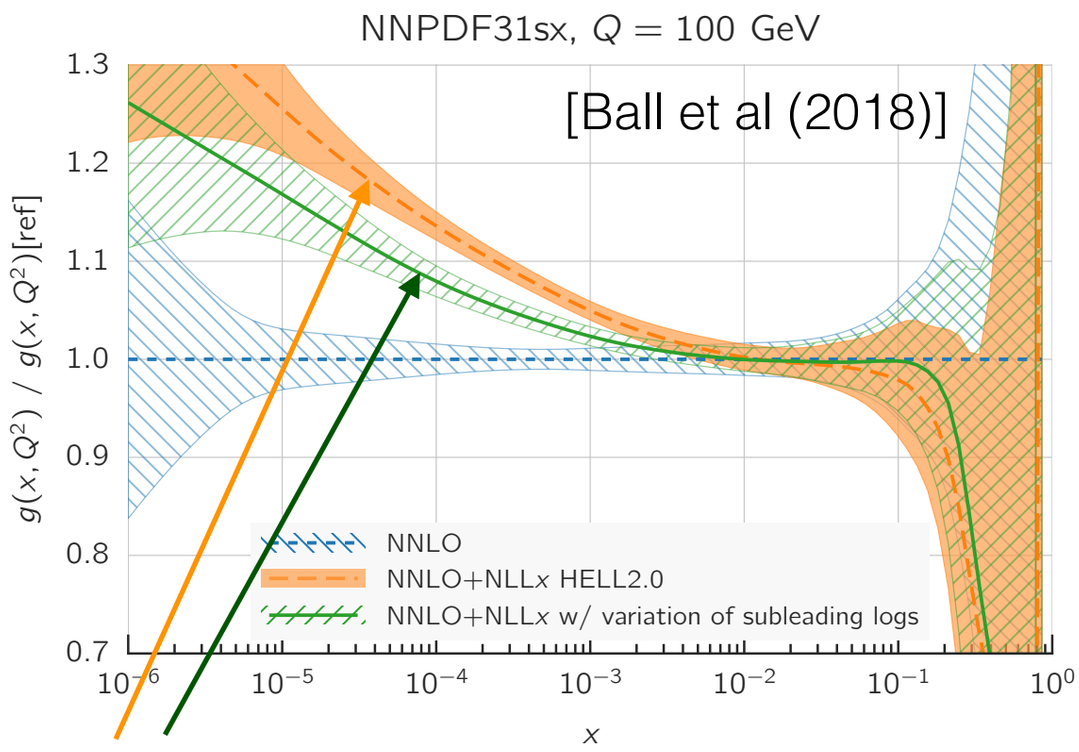

different treatment of subleading terms

Small-x resummation beyond LL$_x$ (≡first non-trivial order) unavailable

At this level of precision: theory error on PDF needed

many thanks to G. Salam for discussions on this topic

ggF: status and prospects

YR4, inclusive cross-section:

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

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

YR4, main sources of uncertainty

δ(scale)	δ(trunc)	δ(PDF-TH)	δ(EW)	$\delta(t,b,c)$	$\delta(1/m_t)$
$^{+0.10\text{ pb}}_{-1.15\text{ pb}}$	$\pm$0.18 pb	$\pm$0.56 pb	$\pm$0.49 pb	$\pm$0.40 pb	$\pm$0.49 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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\end{aligned}$$

known for NLO p_t distribution [1610.03747,1702.00426, 1712.06549, 1802.07977]

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$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

[1802.00833]

known in SV approximation [1801.10403]

ggF: status and prospects

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

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

$48.58\,\text{pb} =$ $16.00\,\text{pb}$ $(+32.9\%)$ (LO, rEFT)

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

Percent accuracy ~ current *theoretical* limit of pQCD

or NLO
bution
1702.00426,
802.07977]

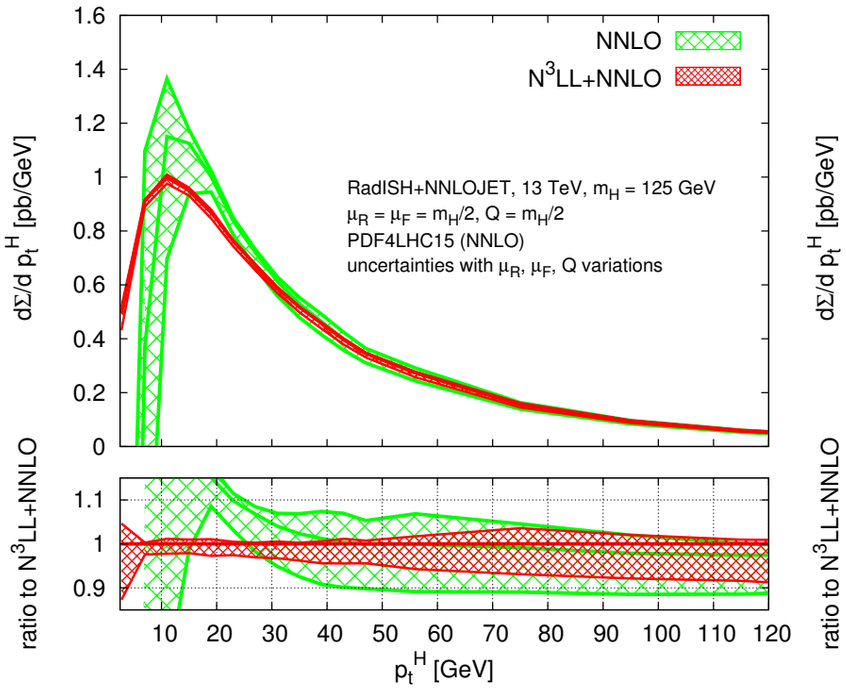
$^{+0.10\,\text{pb}}_{-1.15\,\text{pb}}$	± 0.18 pb	± 0.56 pb	± 0.49 pb	± 0.40 pb	± 0.49 pb
$^{+0.21\%}_{-2.37\%}$	$\pm 0.37\%$	$\pm 1.16\%$	$\pm 1\%$	$\pm 0.83\%$	$\pm 1\%$

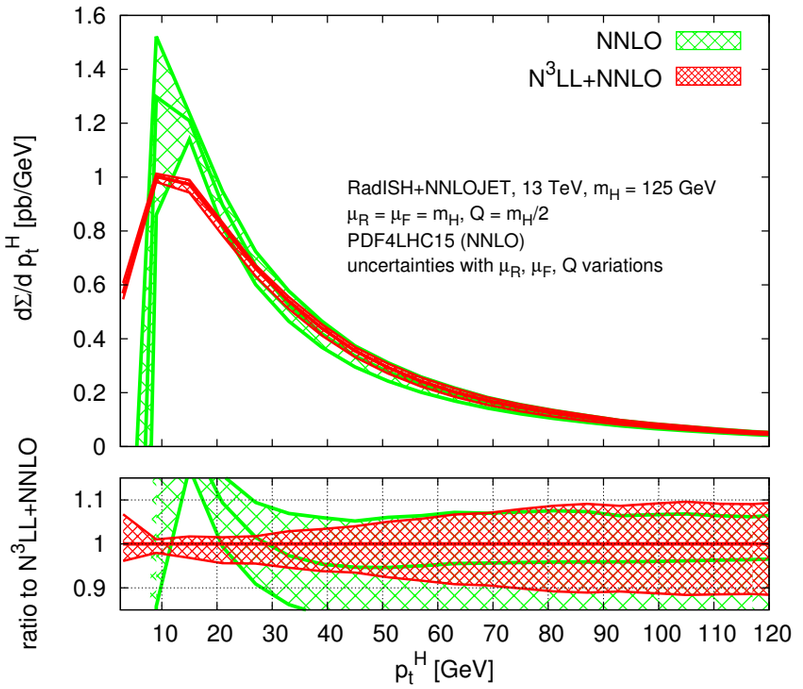
[1802.00833]

known in SV approximation [1801.10403]

ggF: more differential

Good control over Higgs p_t distribution

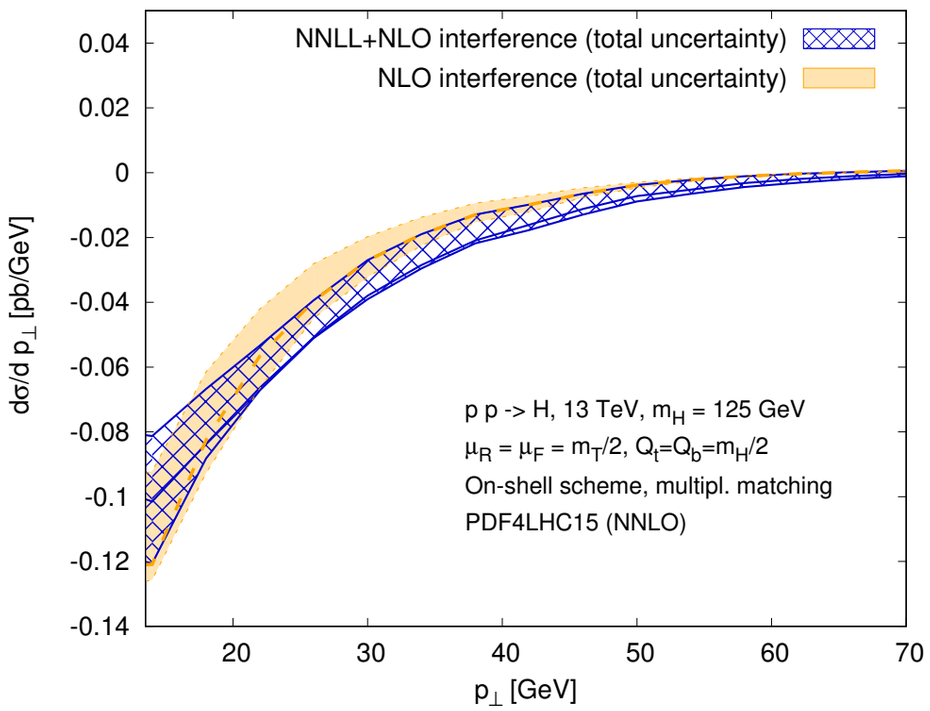




Pheno studies at NNLO+N³LL:

~ few percent in bulk of distribution

[1805.00736,1805.05916]



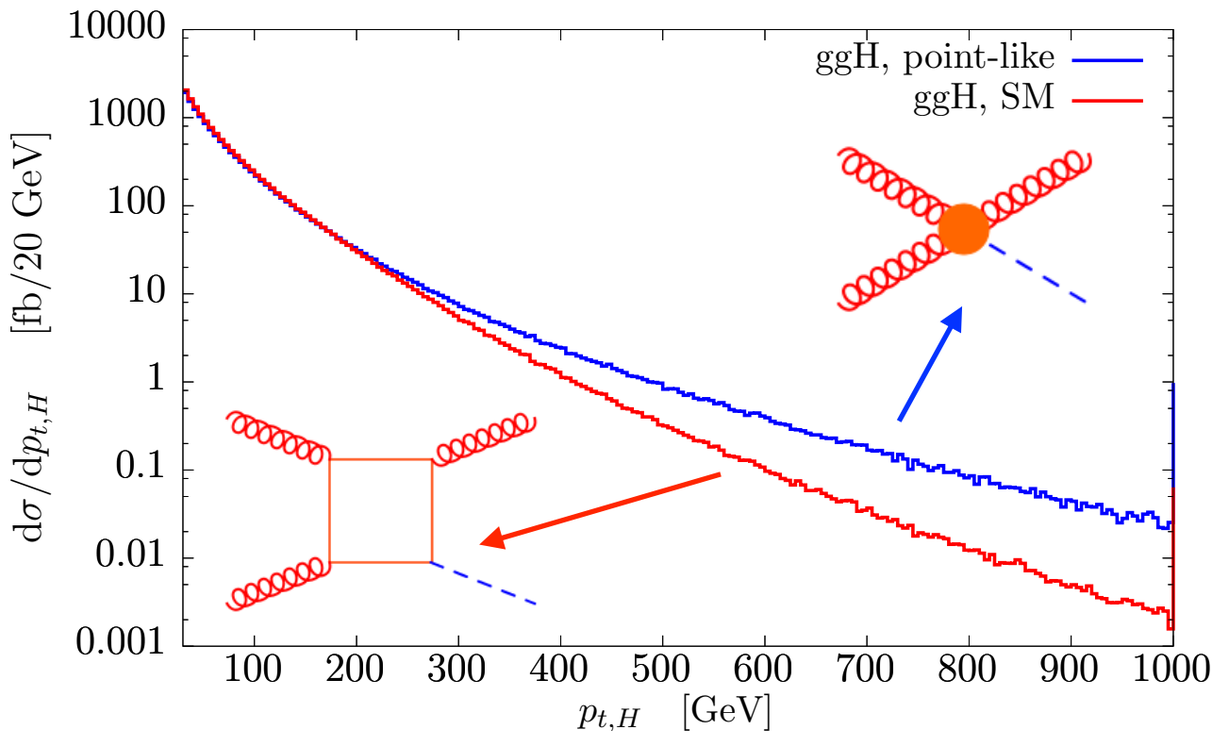
~20% on t/b contribution

[=~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:

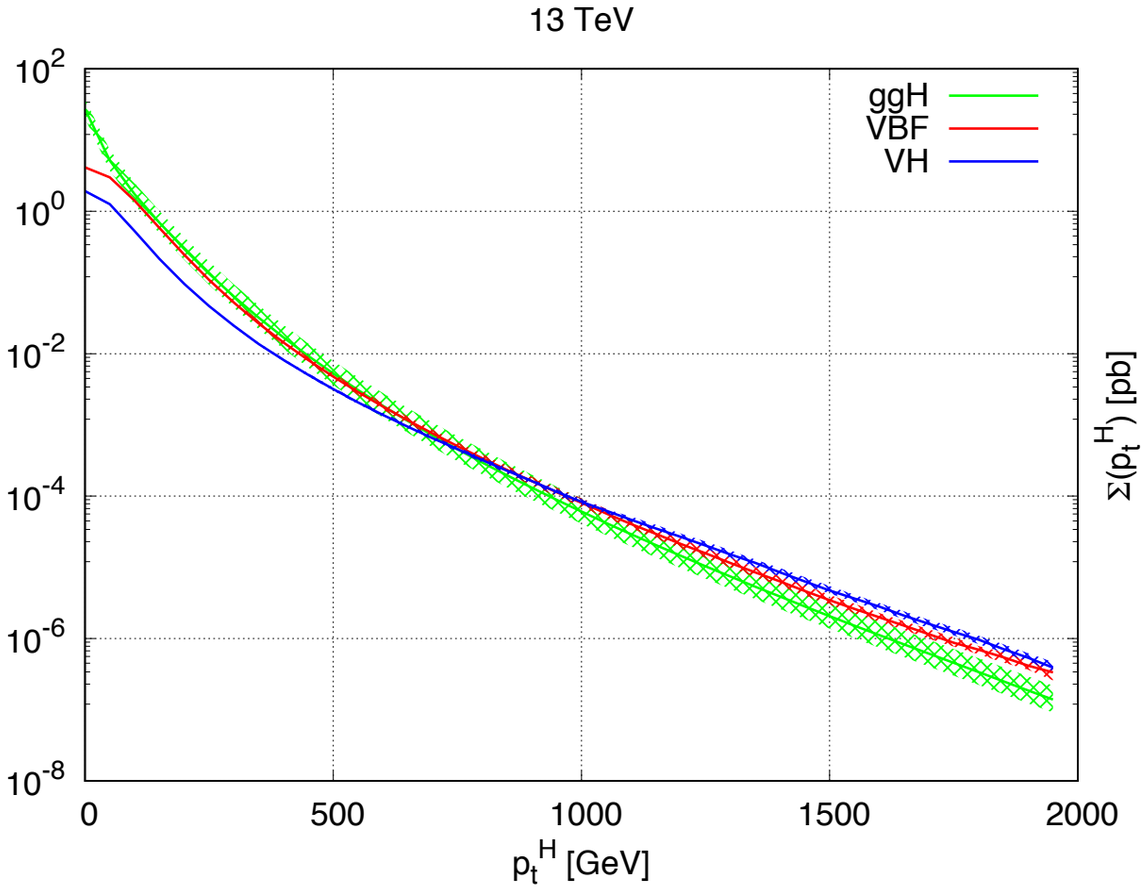
<u>rough</u> idea for inclusive rates

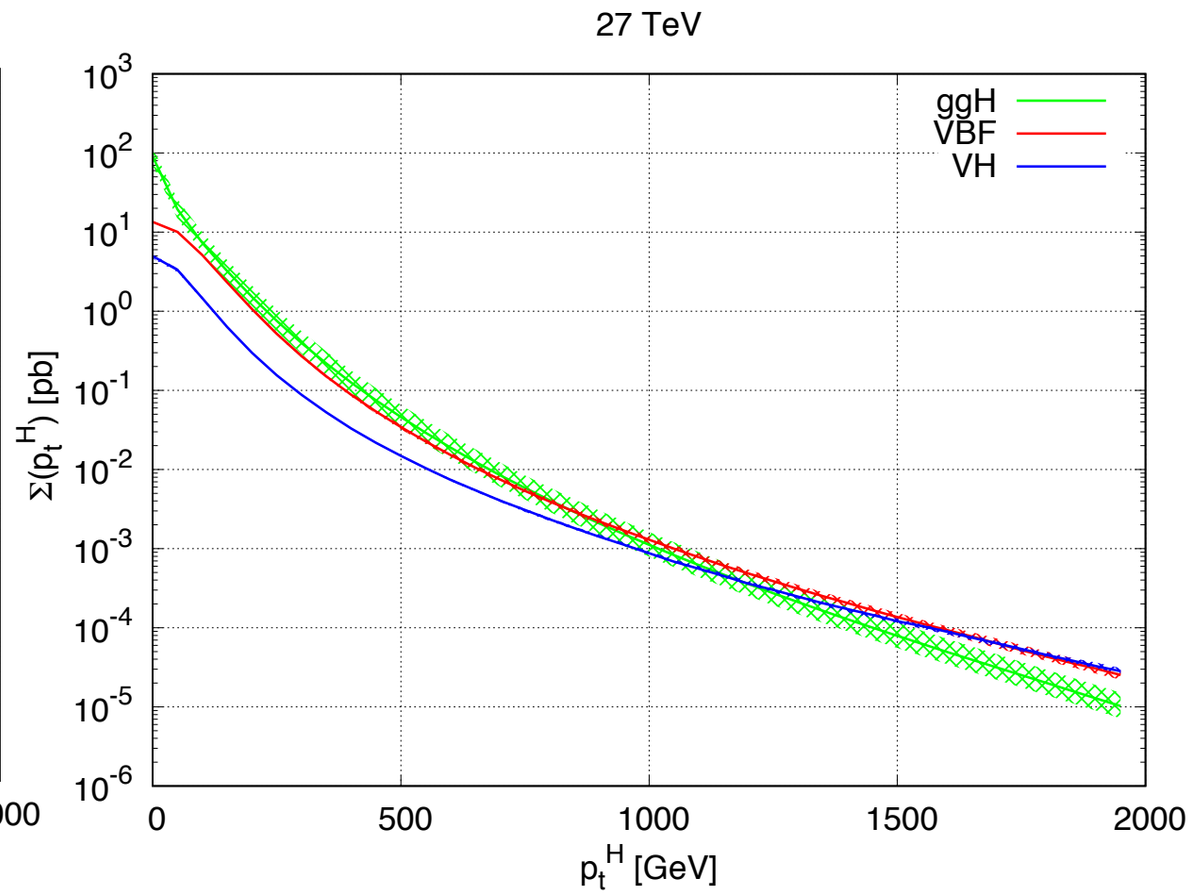
(here: gg-only)

$\sigma_{gg}(p_\perp > p_{\perp,cut})$ =	1 fb	1 ab
bb	~900 GeV	~2.4 TeV
ττ	~600 GeV	~1.8 TeV
eμνν	~300 GeV	~1.1 TeV
γγ	~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 conveners]

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

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

slides from A. Karlberg

VBF Higgs Production at the HL-/HE-LHC

Alexander Karlberg

In collaboration with Juan M. Cruz-Martinez
CERN

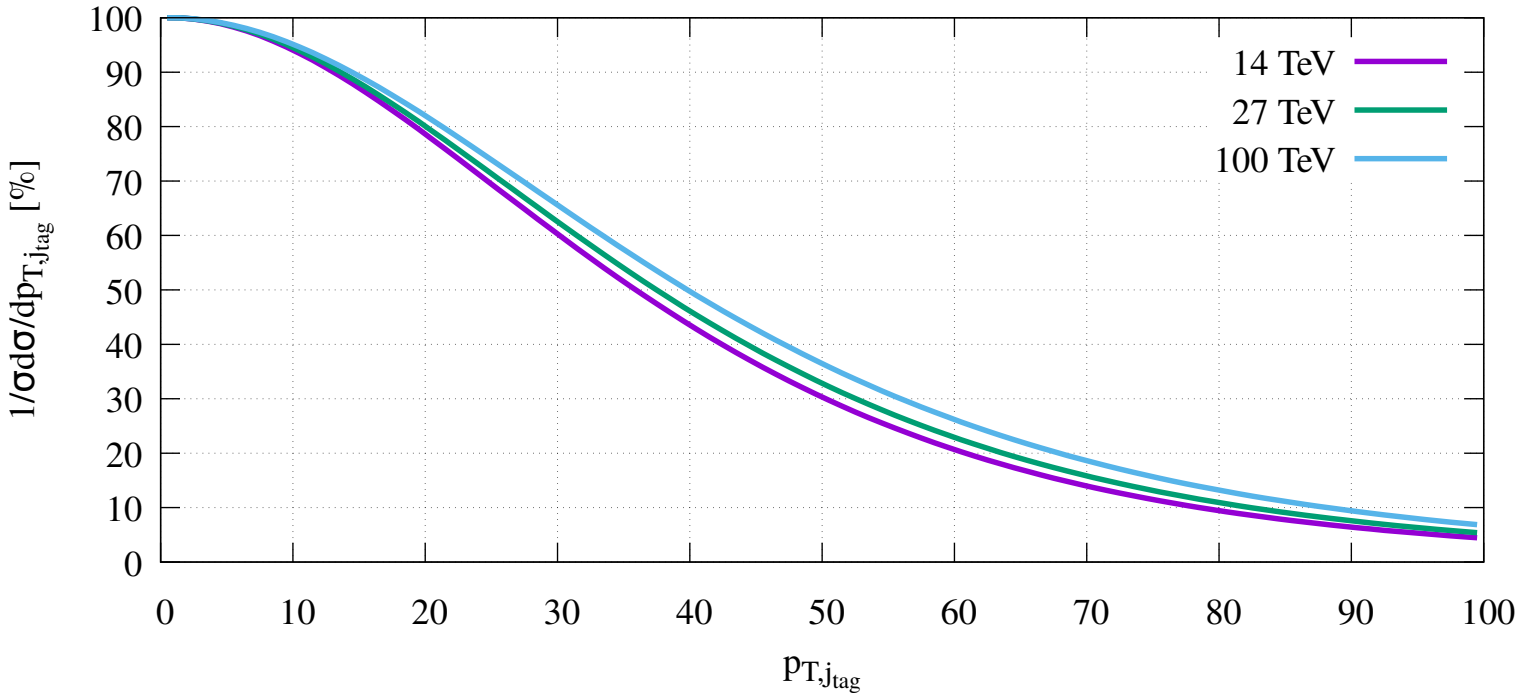
Inclusive results[1]

$\sqrt{s}$	$\sigma_{\mathrm{DIS}}^{(\mathrm{incl})}$ [pb]	δ_{EW}[%]	σ_{γ}[fb]	$\sigma_{\mathrm{s-channel}}$[fb]
13 TeV	3.928	-5.3	35.3	1412
14 TeV	4.461	-5.4	40.7	1555
27 TeV	12.41	-6.2	129	3495

- Growth of electroweak corrections with energy as expected.
- γ contribution at 1% at all energies. Reduction compare to YR4.
- s-channel contribution relatively smaller at 27 TeV

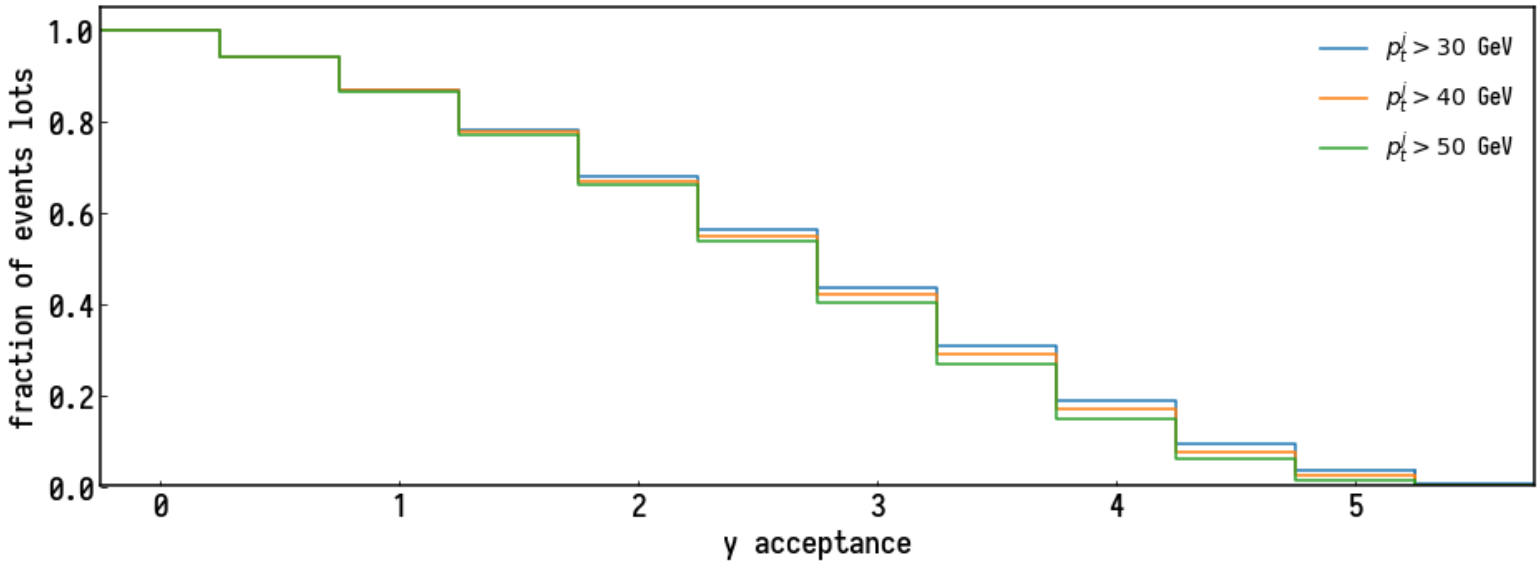
[1] Thanks to Alexander Mueck et al. for EW results from HAWK

VBF cuts



- The VBF cross section is very sensitive to the jet definition (here anti-k_t, $R = 0.4$)
- This is due to $p_{t,j} \sim m_W$ for all collider energies
- With 30 GeV jets, $\sim 30\%$ of the signal is lost
- With 50 GeV jets, that increases to almost 70%

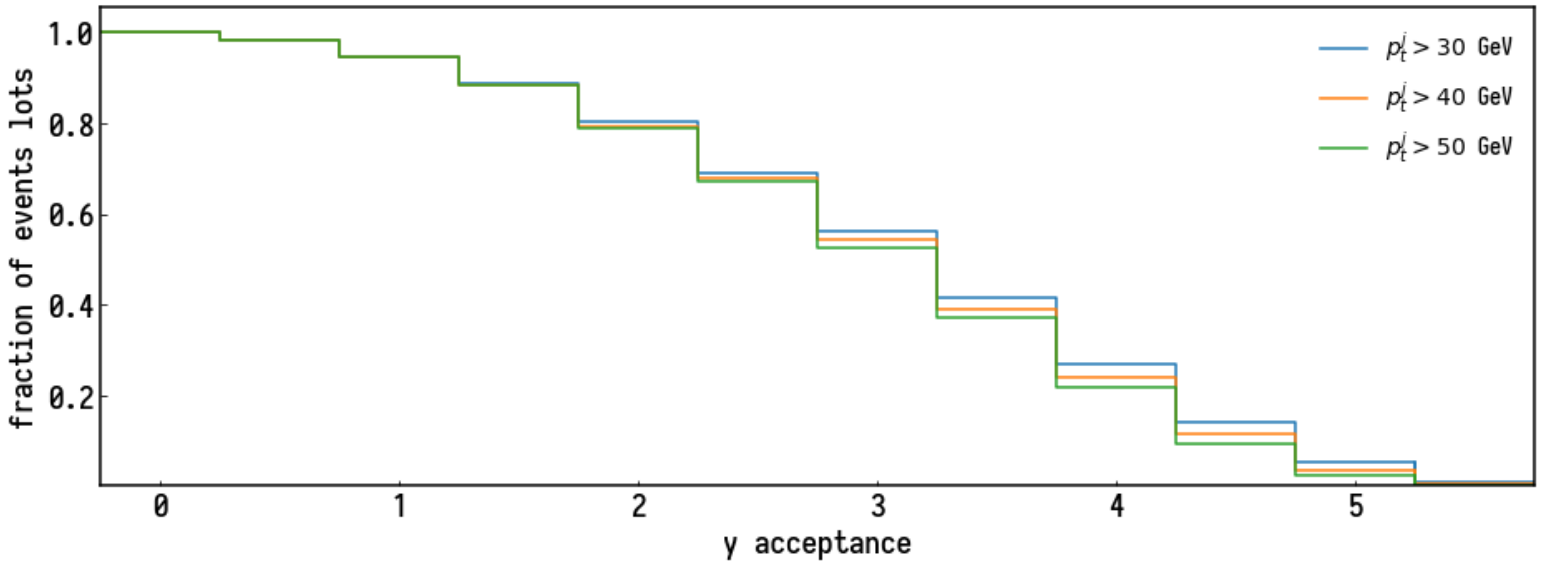
Detector acceptance



- The typical VBF topology consists of two forward jets
- The higher the collider energy the more forward they tend to be
- With current CMS and ATLAS detectors $\sim 20\%$[2] of the jets will be lost at 27 TeV

[2] At 14 TeV the number is $\sim 5\%$

Detector acceptance



- Imposing "typical" VBF cuts of $m_{jj} > 600$ GeV, $\Delta y_{jj} > 4.5$ and $y_{j_1} y_{j_2} < 0$ makes the situation even worse
- This is expected as we now force the jets to be forward
- With current CMS and ATLAS detectors $\sim 30\%$ of the VBF events will be lost at 27 TeV

VBF conclusion

- The VBF program at HE-LHC will be very dependent on the jet definition and rapidity reach of the ATLAS and CMS detectors
  - In a "worst case" scenario of $p_{\mathrm{T},j} > 50$ GeV and no increase in rapidity reach compared to now, $\sim 80-85\%$ of the VBF signal is lost before VBF cuts are applied
- One thing we are currently considering: Will "typical" VBF cuts change a lot at 27 TeV?
  - We have already carried out some studies for signal, but i is curcial to also study the ggHjj background in detail

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%	wo γ
W^-H	**0.59**	+0.6% - 0.7%	2.0%	**1.4**	+0.4% - 0.9%	2.0%	
$l^+\nu$ 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}**			with γ
$l^-\bar{\nu}$ 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}**			

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

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	14 TeV			27 TeV		
	σ [pb]	Δ_{μ_r,μ_f}	$\Delta_{\rm PDF}$	σ [pb]	Δ_{μ_r,μ_f}	$\Delta_{\rm PDF}$
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 LOx$K_{NLO,\ HEFT}$ + NLL_{soft}

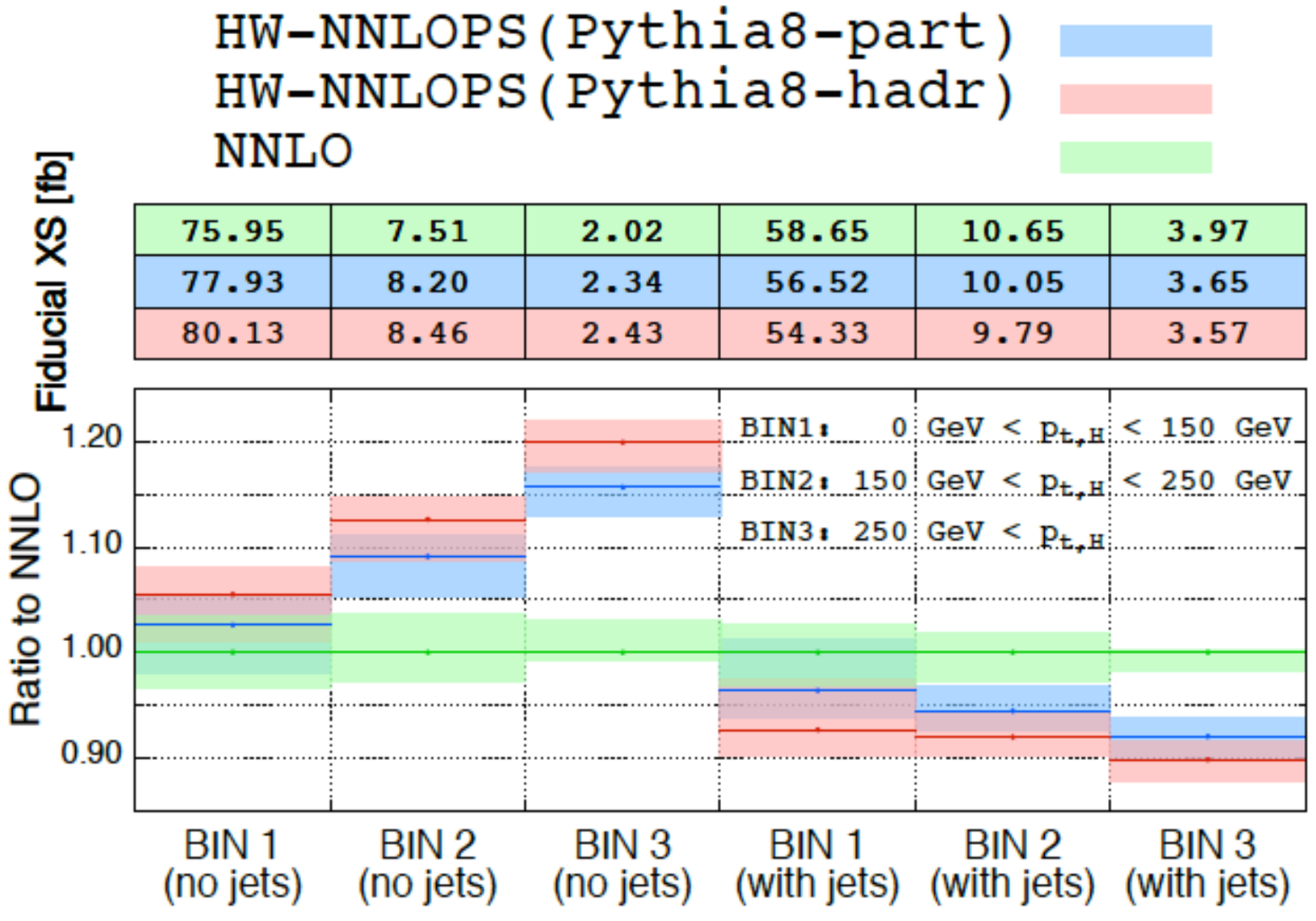
Lessons from di-Higgs:
- NLO reduces error from ~20-25% to ~15%
- $K_{NLO,\ HEFT}$ overestimates K-factor of ~20-25%

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 ~2/3% shower effects
- Larger corrections to exclusive observables
- Jet bins still poorly understood



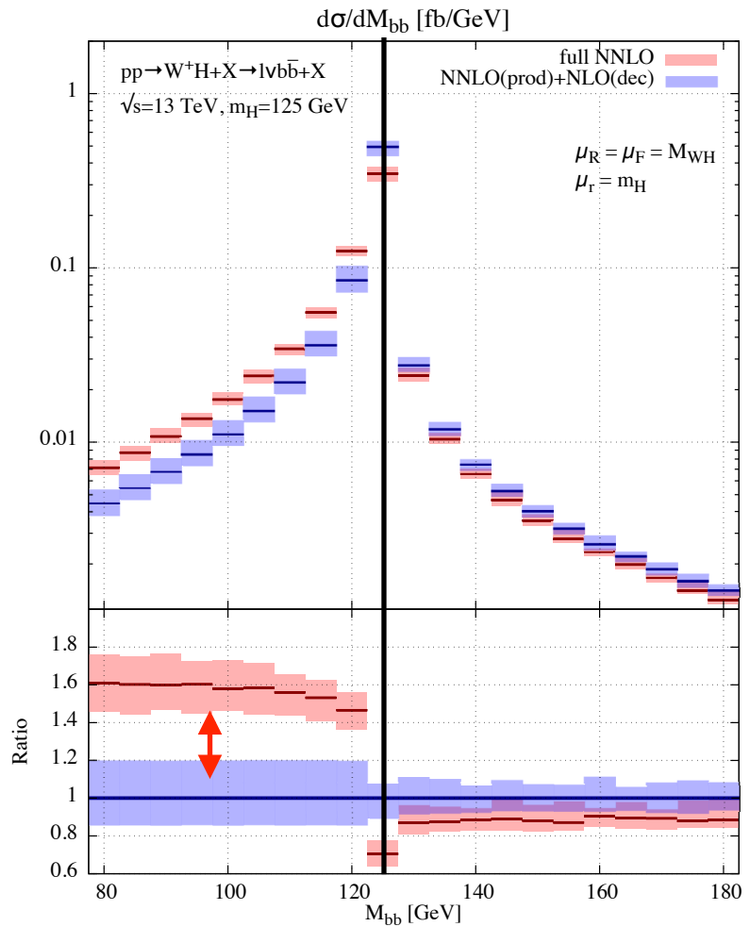
[Astill, Bizon, Re Zanderighi (2016)]

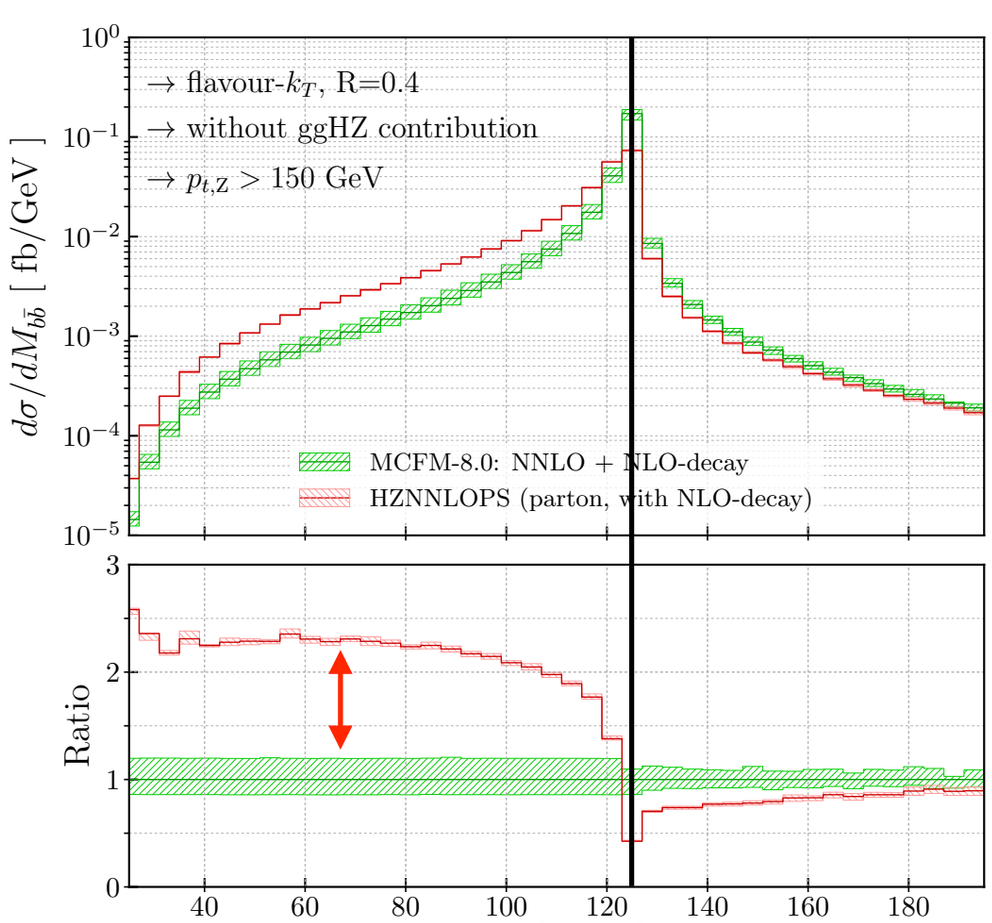
VH: more differential results

Semi-boosted region: shape corrections from radiation off H→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

$M_{\rm H}$[GeV]	$\sigma^{\rm NLO}_{\rm QCD+EW}$[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.

$M_{\rm H}$[GeV]	$\sigma^{\rm NLO}_{\rm QCD+EW}$[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 → 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]	$\sigma_{\mathrm{NLO+PS}}$ [fb]	$\sigma_{\mathrm{NLO+PS}}/\sigma_{\mathrm{NLO}}$
$n_b \geq 1$	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