Boosted Higgs production: theory overview

P. Monni [for the ggF WG]

ggF Working Group meeting - CERN, 12 Apr 2019

- Study of inclusive boosted Higgs regime
  - State of the art perturbative predictions for gluon fusion
  - Validation of Monte Carlo event generators
  - Impact of other production modes (VBF, VH, ttH)
  - size of EW corrections
- Draft on CDS for the next ~month at

https://cds.cern.ch/record/2669113

Some refinements ongoing

Recommended predictions for the boosted-Higgs cross section

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Abstract: In this note we study the inclusive production of a Higgs boson with large transverse momentum. We provide a recommendation for the inclusive cross section based on a combination of state of the art QCD predictions for the gluon-fusion and vector-boson-fusion channels. Moreover, we compare such predictions to those obtained with commonly used event generators. We observe that the description of the considered kinematic regime provided by these tools is in good agreement with state of the art QCD predictions.

Theory predictions for ggF

- Predictions at large p_T obtained by combining state of the art results:
  - NLO corrections with top-mass effects (13 TeV)

    [Kudashkin, Lindert, Melnikov, Wever '18; Jones, Kerner, Luisoni '18]

    - Flat correction as in the heavy top EFT, with slightly larger K factor
      - mass effects seem to factorise w.r.t. QCD corrections

BR(H->bb) not included

$p_\perp^{\text{cut}}$	LO [fb]	NLO[6] [fb]	K
400 GeV	$11.9^{+43.7\%}_{-28.9\%}$	$25.5^{+6.4\%}_{-17.0\%}$	2.14
430 GeV	$8.2^{+44\%}_{-29.1\%}$	$17.6^{+6.2\%}_{-17.0\%}$	2.14
450 GeV	$6.5^{+44\%}_{-29\%}$	$13.9^{+6.4\%}_{-17.1\%}$	2.14
500 GeV	$3.6^{+44.2\%}_{-29.4\%}$	$7.7^{+6.2\%}_{-17.2\%}$	2.12
550 GeV	$2.1^{+44.7\%}_{-29.1\%}$	$4.4^{+6.2\%}_{-17.0\%}$	2.12
600 GeV	$1.2^{+44.9\%}_{-29.5\%}$	$2.6^{+6.7\%}_{-17.5\%}$	2.10

- **Combine NLO full QCD with NNLO results in the heavy-top EFT**

$$\boxed{\frac{d\sigma^{\text{EFT-improved (1), NNLO}}}{dp_\perp} = \frac{\frac{d\sigma^{\text{QCD, NLO}}}{dp_\perp}}{\frac{d\sigma^{\text{EFT, NLO}}}{dp_\perp}} \frac{d\sigma^{\text{EFT, NNLO}}}{dp_\perp}}$$

[Boughezal, Caola, Melnikov, Petriello, Schulze '15; Boughezal, Focke, Giele, Liu, Petriello '15; Chen, Cruz-Martinez, Gehrmann, Glover, Jaquier '16]

Uncertainties (ggF)

- Estimate of uncertainties:
  - scale variation by a factor of 2 with muR = muF in the NNLO cross section
  - Assume *relative* uncertainties due to mass effects *identical* at NLO & NNLO:

$$\frac{d\sigma^{\text{EFT-improved (0), NNLO}}}{dp_\perp} = \frac{\frac{d\sigma^{\text{QCD, LO}}}{dp_\perp}}{\frac{d\sigma^{\text{EFT, LO}}}{dp_\perp}} \frac{d\sigma^{\text{EFT, NNLO}}}{dp_\perp}$$

$$\begin{aligned}\delta_{\text{NNLO}, m_t} &= \frac{\delta\Sigma^{\text{QCD, NLO}} - \delta\Sigma^{\text{improved(0), NLO}}}{\delta\Sigma^{\text{improved(0), NLO}}} \times \delta\Sigma^{\text{improved(0), NNLO}} \\ &\sim \frac{\mathrm{K_{QCD}} - \mathrm{K_{EFT}}}{\mathrm{K_{EFT}} - 1} \times \delta\Sigma^{\text{improved(0), NNLO}} \\ &\sim 0.2 \times \delta\Sigma^{\text{improved(0), NNLO}}.\end{aligned}$$

  - Combine the above errors either *linearly* or in *quadrature* **(default)**

BR(H->bb) not included

$p_\perp^{\text{cut}}$	$\text{NNLO}^{\text{approximate}}_{\text{quad.unc.}}$ [fb]	$\text{NNLO}^{\text{approximate}}_{\text{lin.unc.}}$ [fb]
400 GeV	$32.0^{+9.1\%}_{-11.6\%}$	$32.0^{+9.4\%}_{-11.9\%}$
430 GeV	$22.1^{+9\%}_{-11.4\%}$	$22.1^{+9.3\%}_{-11.8\%}$
450 GeV	$17.4^{+8.9\%}_{-11.5\%}$	$17.4^{+9.3\%}_{-11.9\%}$

Event Generators

- Comparison to simulations from event generators: MG5_aMC@NLO & HJ MiNLO
  - **Good agreement between MC and approximate NNLO for gluon fusion**

BR(H->bb) not included

$p_T^{\rm cut}$	$\rm NNLO^{approximate}_{quad.unc.}$ [fb]	HJ-MINLO [fb]	MG5_MC@NLO [fb]
400 GeV	$32.0^{+9.1\%}_{-11.6\%}$	$29^{+24\%}_{-21\%}$	$31.5^{+31\%}_{-25\%}$
430 GeV	$22.1^{+9\%}_{-11.4\%}$	-	$21.8^{+31\%}_{-25\%}$
450 GeV	$17.4^{+8.9\%}_{-11.5\%}$	$16.1^{+22\%}_{-21\%}$	$17.1^{+31\%}_{-25\%}$

HJ-MINLO w/ mass effects [Hamilton, Nason, Zanderighi '15]

NB: HJ-MINLO identical to NNLOPS in the considered phase space region

[Frederix, Frixione, Vryonidou, Wiesemann '16]

- HJ-MiNLO [9]: NLO for inclusive gluon fusion and NLO in the $p_\perp$ spectrum. μ_R and μ_F are always set to $p_\perp$. Born events with one jet terms are proportional to $\alpha_s^2(m_H)\alpha_s(p_\perp)$, while NLO corrections are proportional to $\alpha_s^2(m_H)\alpha_s^2(p_\perp)$.

- MG5_MC@NLO [10]: predictions obtained by merging samples of 0,1, and 2 jets. The scale is set following the FxFx [19] prescription and the merging scale is set to 30 GeV

Parton Shower effects

Fixed order level	Total	$p_T^H > 400$	$p_T^H > 450$	$p_T^H > 500$
$\mathrm{gg\_h}^{\mathrm{hfact}=104}_{\mathrm{m_t}=\infty}$	$30.3^{36.4}_{25.6}$	0.0730	0.0507	0.0362
HJ $m_t = \infty$ 5 GeV gen cut	–	0.0643	0.0413	0.0278
HJ $m_t = \infty$ 50 GeV gen cut	–	0.0644	0.0416	0.0277
HJ-MiNLO $m_t = \infty$	$32.1^{43.1}_{27.2}$	0.0778	0.0509	0.0343
HJ-MiNLO $m_t = 171.3$	$33.8^{45.2}_{28.6}$	0.0281	0.0153	0.0089

HJ-MINLO results from Keith Hamilton

PS-level	Total	$p_T^H > 400$	$p_T^H > 450$	$p_T^H > 500$
$\mathrm{gg\_h}^{\mathrm{hfact}=104}_{\mathrm{m_t}=\infty}$	$30.3^{36.4}_{25.6}$	$0.0829^{0.1280}_{0.0563}$	$0.0577^{0.0902}_{0.0387}$	$0.0408^{0.0644}_{0.0271}$
HJ $m_t = \infty$ 5 GeV gen.cut	–	$0.0651^{0.0807}_{0.0520}$	$0.0417^{0.0517}_{0.0333}$	$0.0279^{0.0346}_{0.0222}$
HJ $m_t = \infty$ 50 GeV gen.cut	–	$0.0651^{0.0807}_{0.0520}$	$0.0418^{0.0518}_{0.0333}$	$0.0278^{0.0344}_{0.0222}$
HJ-MiNLO $m_t = \infty$	$32.1^{43.1}_{27.2}$	$0.0803^{0.0989}_{0.0639}$	$0.0524^{0.0642}_{0.0417}$	$0.0353^{0.0431}_{0.0281}$
HJ-MiNLO $m_t = 171.3$	$33.7^{45.2}_{28.6}$	$0.029^{0.036}_{0.023}$	$0.0161^{0.0197}_{0.0128}$	$0.0091^{0.0112}_{0.0073}$

Shower corrections moderate for the inclusive cumulative spectrum

Other production modes

Substantial fraction of the boosted cross section from VBF, VH and ttH

$p_\perp^{\rm cut}$ [GeV]	$\Sigma_{\rm ggF}^{\rm NNLO_{approx}}(p_\perp^{\rm cut})$ [fb]	$\Sigma_{\rm VBF}^{\rm NNLO}(p_\perp^{\rm cut})$ [fb]	$\Sigma_{\rm VH}^{\rm NLO}(p_\perp^{\rm cut})$ [fb]	$\Sigma_{\rm t\bar{t}H}^{\rm NLO}(p_\perp^{\rm cut})$ [fb]
400	$32.03^{+9.09\%}_{-11.55\%}$	$14.23^{+0.15\%}_{-0.19\%}$	$11.16^{+4.12\%}_{-3.68\%}$	$6.89^{+12.62\%}_{-12.97\%}$
450	$17.37^{+8.90\%}_{-11.50\%}$	$8.06^{+0.24\%}_{-0.23\%}$	$6.87^{+4.6\%}_{-3.49\%}$	$4.24^{+12.84\%}_{-13.15\%}$
500	$9.66^{+8.86\%}_{-11.49\%}$	$4.75^{+0.33\%}_{-0.29\%}$	$4.39^{+4.43\%}_{-4.04\%}$	$2.66^{+12.85\%}_{-13.22\%}$
550	$5.54^{+8.76\%}_{-11.45\%}$	$2.90^{+0.34\%}_{-0.36\%}$	$2.87^{+4.44\%}_{-3.74\%}$	$1.76^{+14.23\%}_{-13.93\%}$
600	$3.24^{+8.73\%}_{-11.28\%}$	$1.82^{+0.41\%}_{-0.39\%}$	$1.91^{+5.22\%}_{-4.71\%}$	$1.11^{+12.99\%}_{-13.4\%}$
650	$1.94^{+8.66\%}_{-11.28\%}$	$1.17^{+0.49\%}_{-0.39\%}$	$1.30^{+4.67\%}_{-4.28\%}$	$0.72^{+12.6\%}_{-13.26\%}$
700	$1.15^{+8.56\%}_{-11.24\%}$	$0.77^{+0.57\%}_{-0.45\%}$	$0.90^{+4.15\%}_{-5.4\%}$	$0.47^{+11.42\%}_{-12.74\%}$
750	$0.69^{+8.53\%}_{-11.27\%}$	$0.51^{+0.69\%}_{-0.56\%}$	$0.62^{+5.15\%}_{-4.66\%}$	$0.32^{+11.53\%}_{-12.84\%}$
800	$0.41^{+8.47\%}_{-11.18\%}$	$0.35^{+0.71\%}_{-0.6\%}$	$0.44^{+5.64\%}_{-4.13\%}$	$0.22^{+11.42\%}_{-13.3\%}$

[this note] [Alexander Karlberg] POWHEG @ NLO [Emanuele Re] Sherpa + OpenLoops [Jonas Lindert, Stefano Pozzorini et al.]

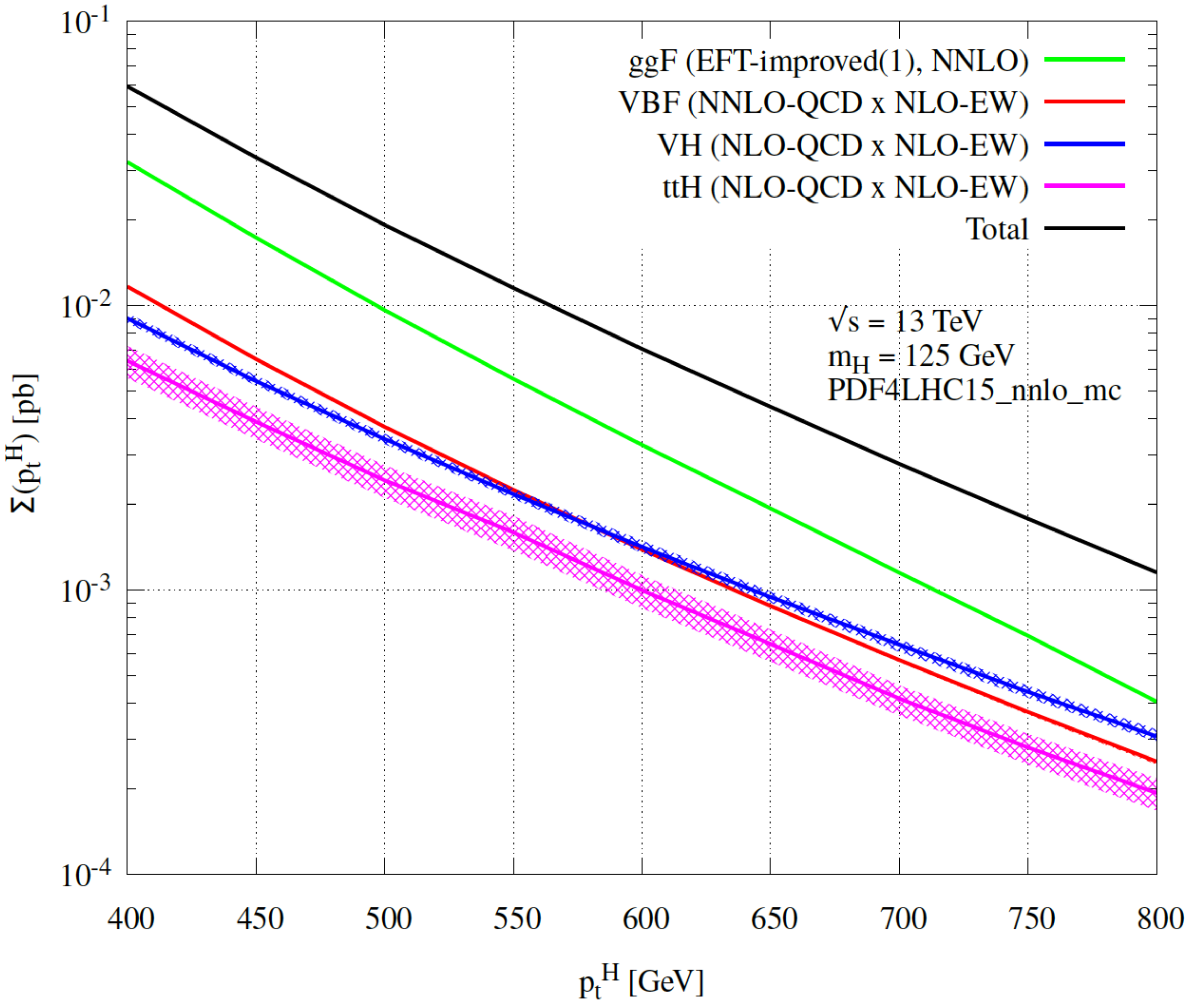
Other production modes: EW corrections

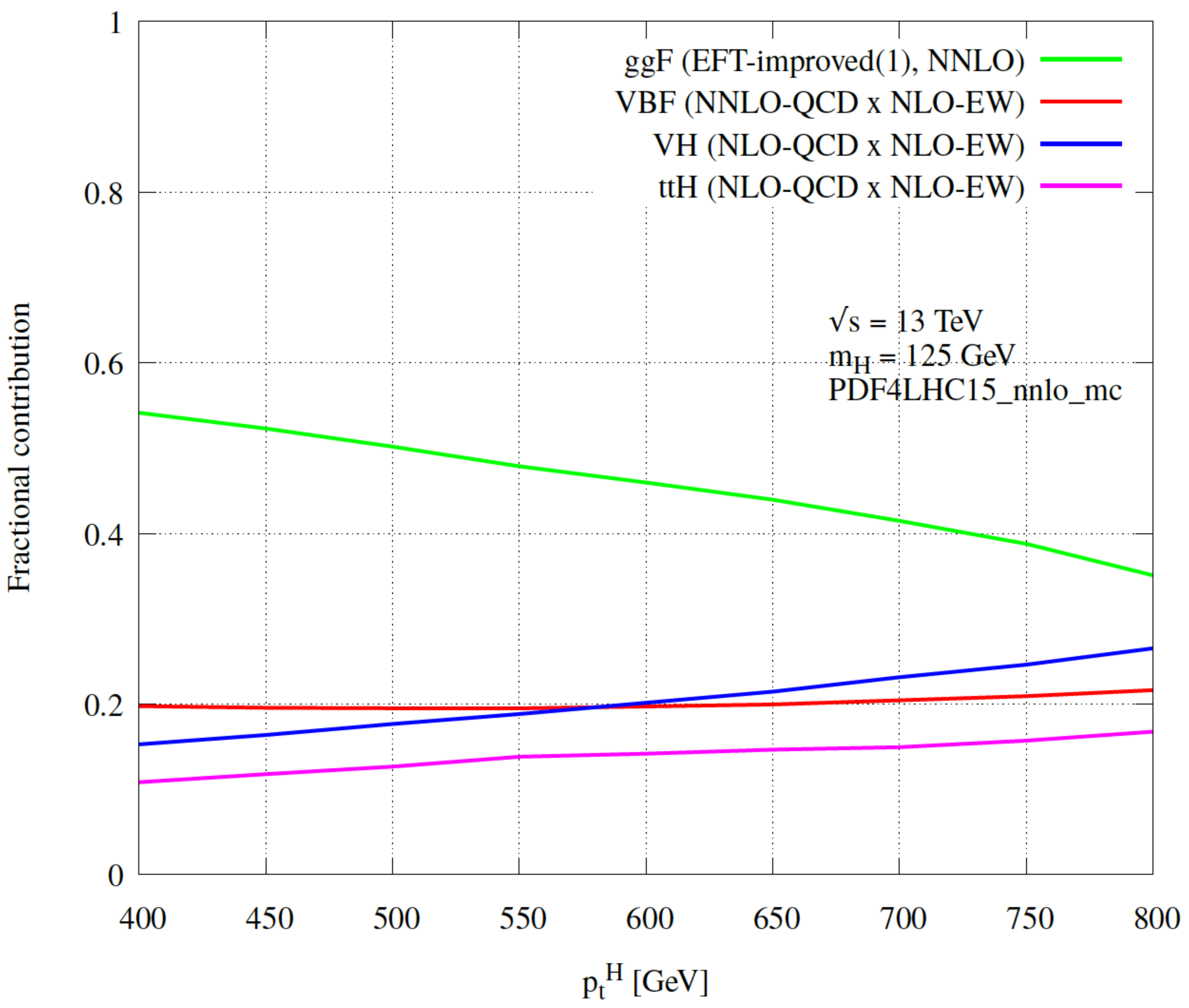
$p_\perp^{\mathrm{cut}}$ [GeV]	VBF	VH	$\mathrm{t\bar{t}H}$
400	-17.80%	-19.05%	-6.95%
450	-19.43%	-20.83%	-7.75%
500	-21.05%	-22.50%	-8.49%
550	-22.34%	-24.07%	-9.11%
600	-23.73%	-25.56%	-9.91%
650	-25.03%	-26.98%	-10.67%
700	-26.29%	-28.30%	-11.37%
750	-27.35%	-29.60%	-11.94%
800	-28.42%	-30.83%	-12.51%

Substantial percentage decrease in the XS due to the inclusion of electroweak corrections

Sherpa + OpenLoops
[Kallweit, Lindert, Maierhoefer, Pozzorini, Schoenherr ’14]

All channels





Conclusions & Outlook

- Note on CDS for about another month, then arXiv upon approval from the SC
  - feedback welcome !
  - The ggF predictions are being refined by using a consistent combination of the full NLO and the NNLO EFT results. We will provide a precise recommendation for the approximate NNLO cross section

- Important findings:
  - The considered event generators agree well with the more accurate result for ggF. The uncertainties from the MC should be adopted (some relevant elements of the analysis — e.g. substructure — were ignored in this analysis) !
  - Contribution from other channels significant
  - EW corrections at the - 10% / -30% level