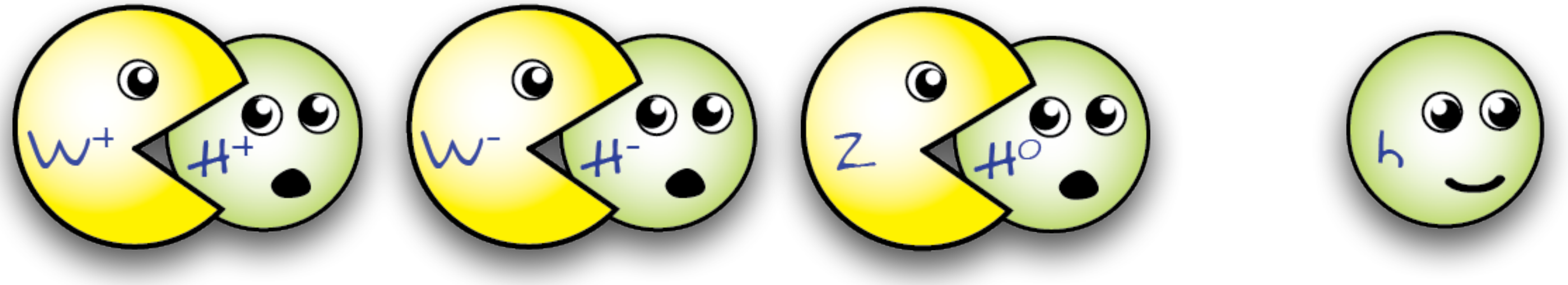
Higgs differential cross sections

Marius Wiesemann

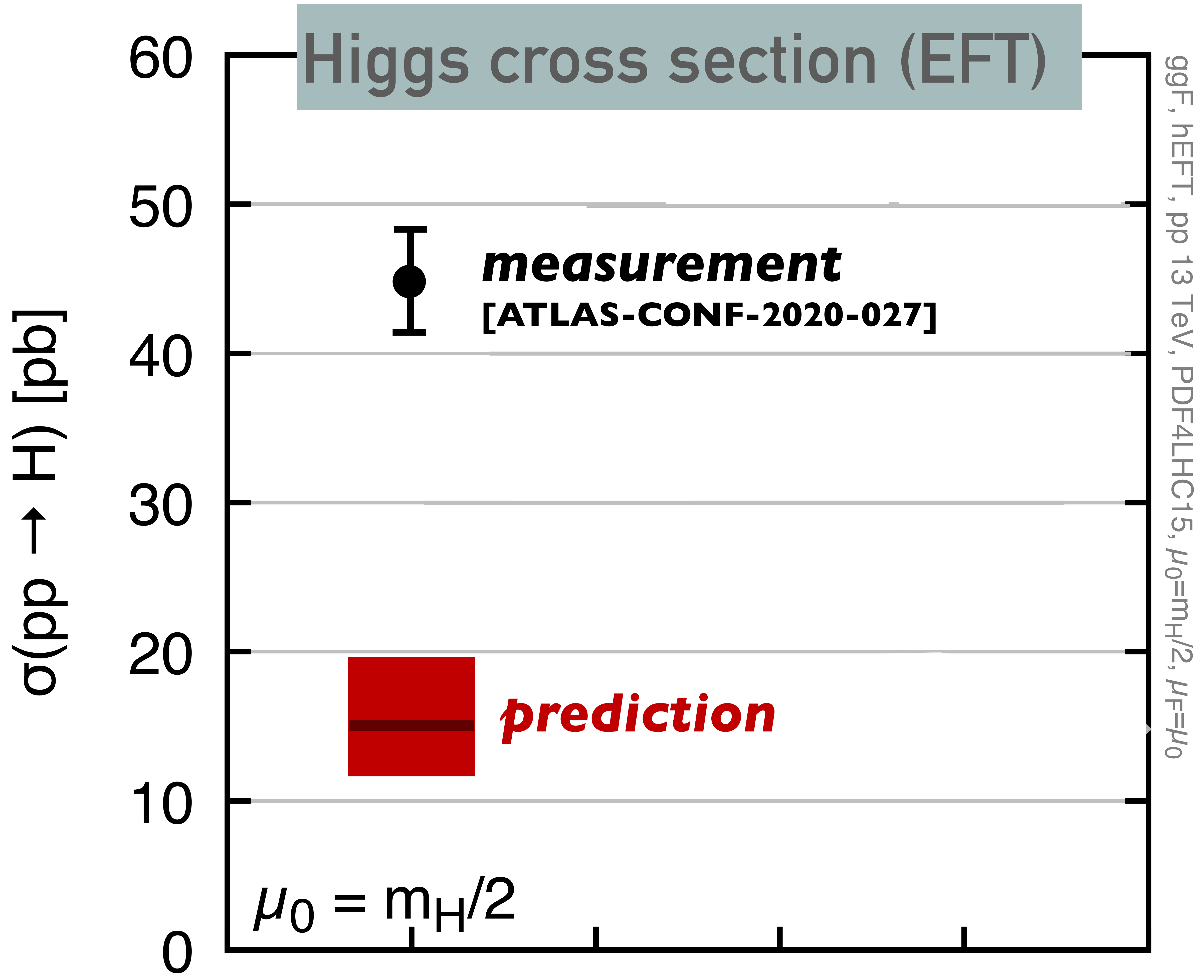
Max-Planck-Institut für Physik



Standard Model at the LHC 2022

CERN (Geneva, Switzerland), April 11-14, 2022

Why precision?



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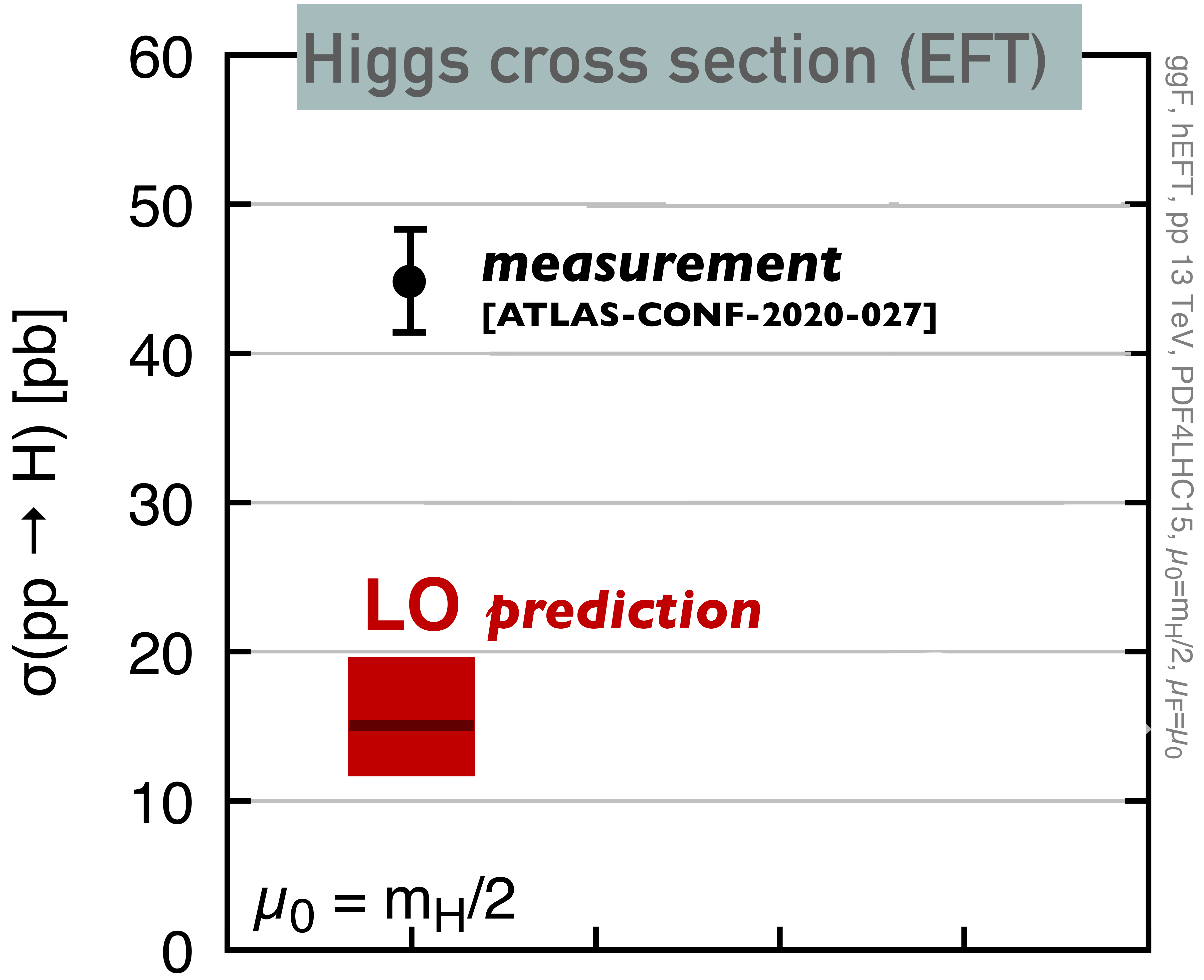

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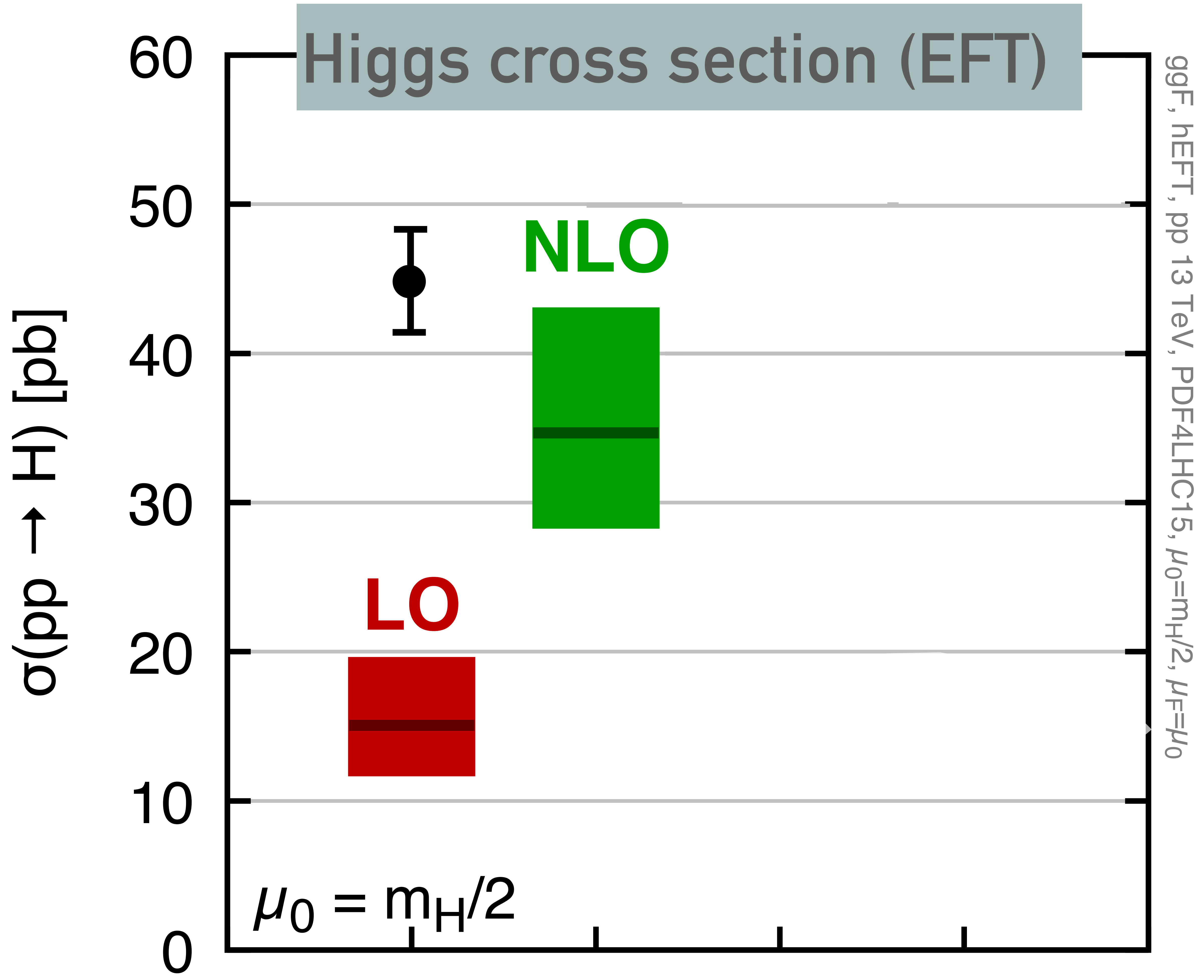

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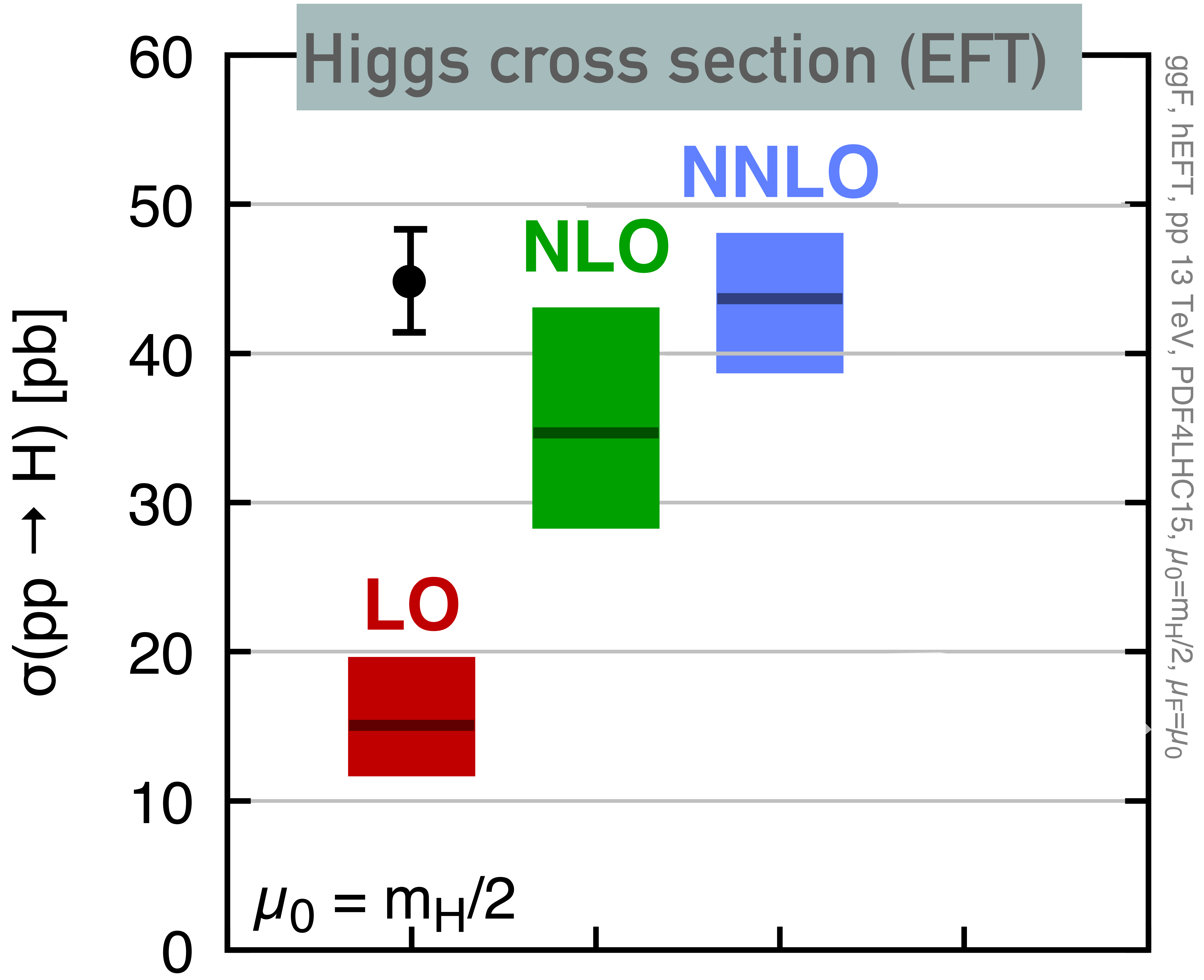

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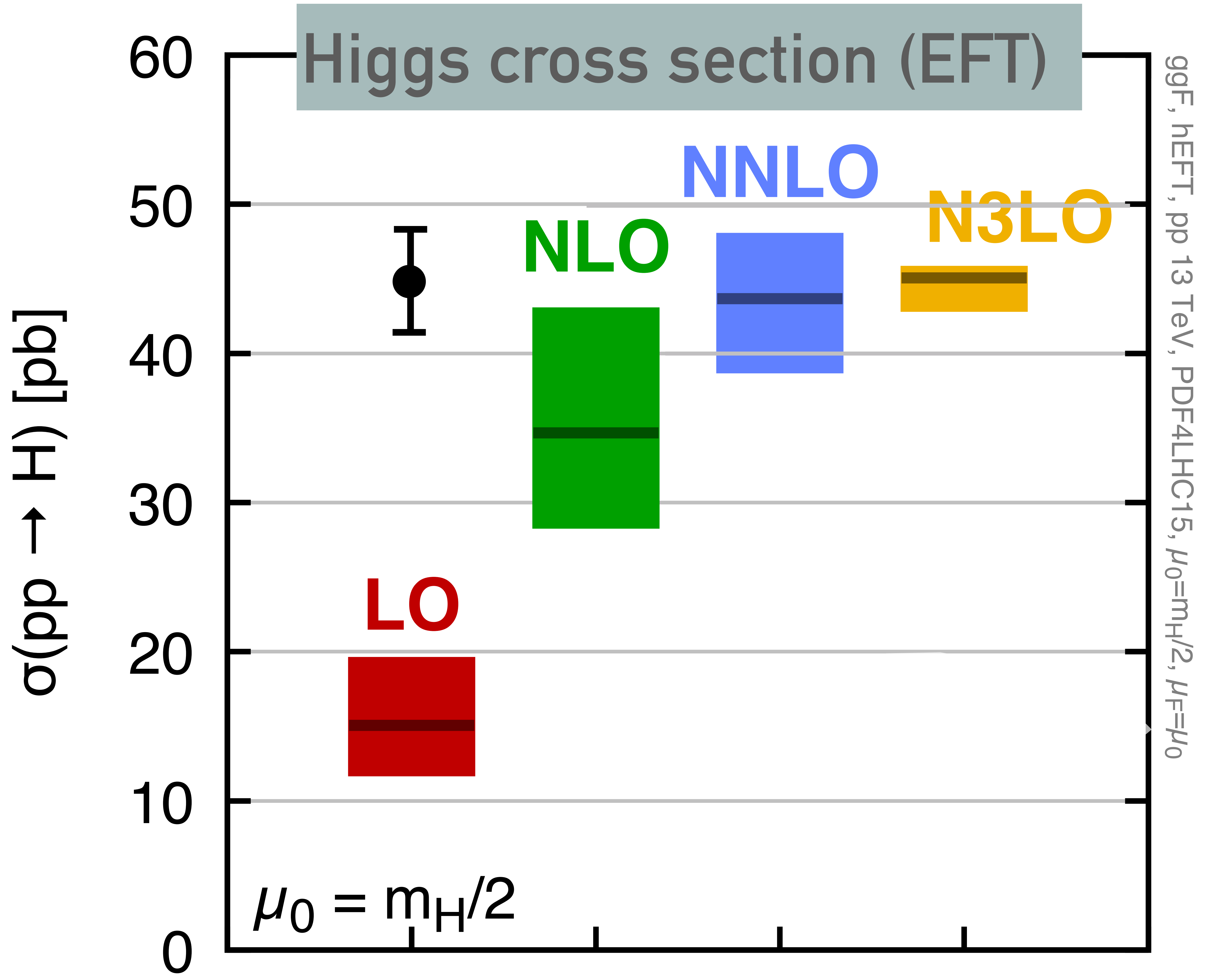
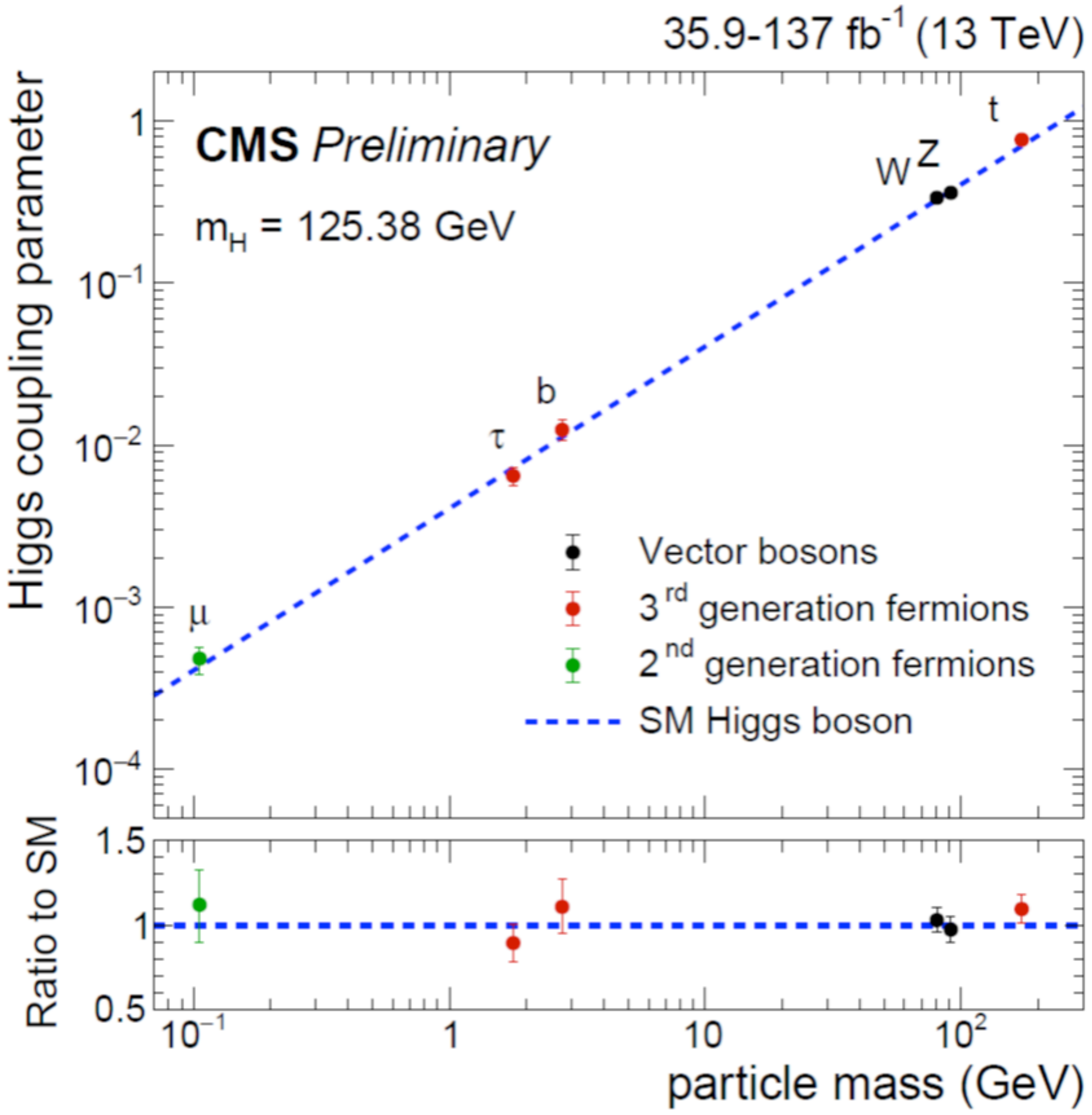


[Anastasiou et al. '15], [Mistlberger '18]

Why precision?

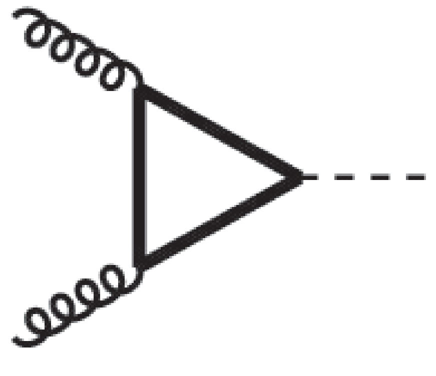
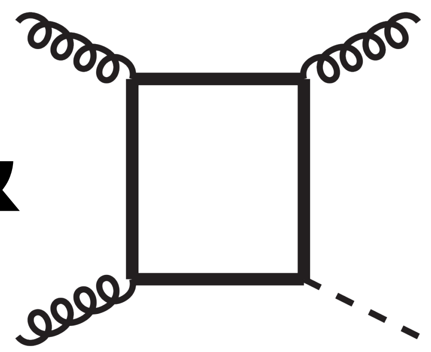
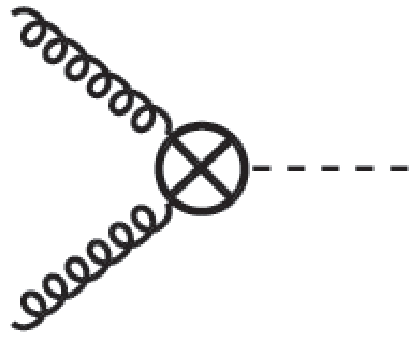
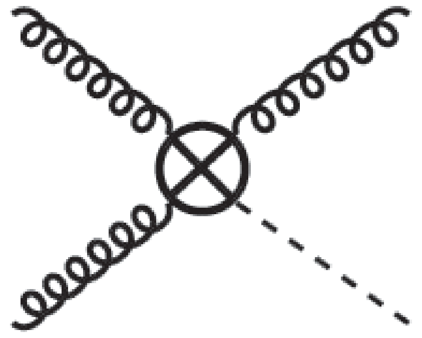
Higgs couplings



Why precision?

New Physics in small deviations, e.g. Higgs p_T:

How does the Higgs couple to gluons?

 **&**  **or**  **&**  **?**

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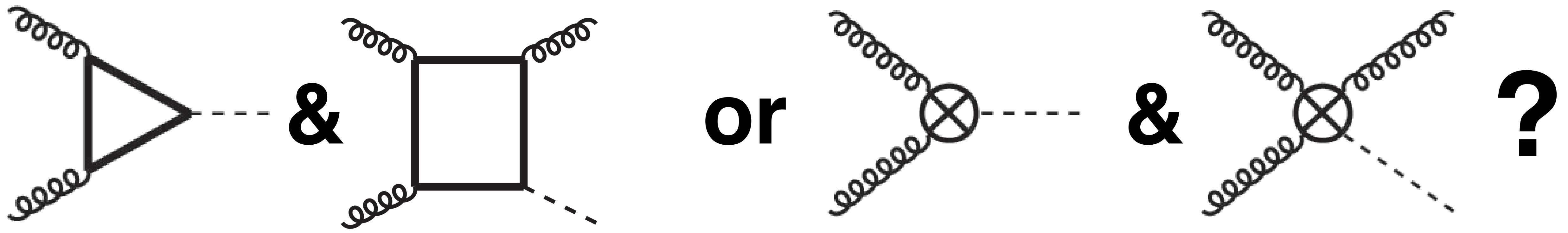
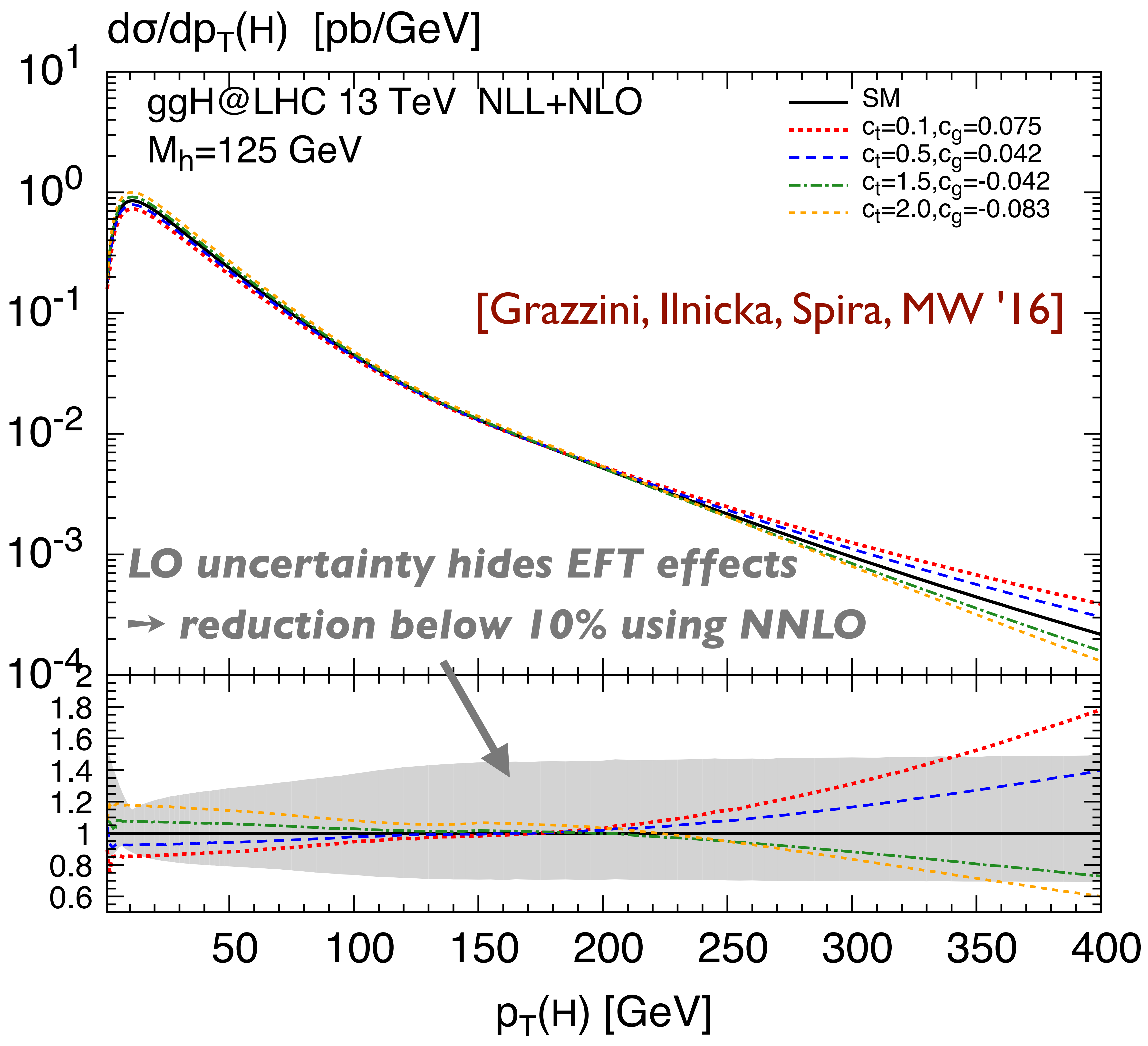
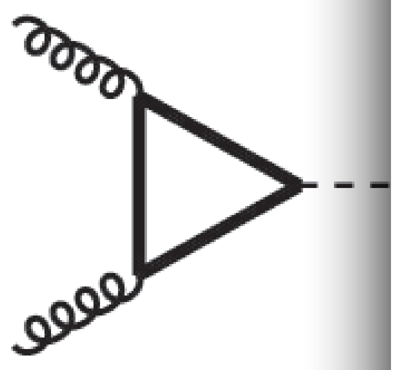


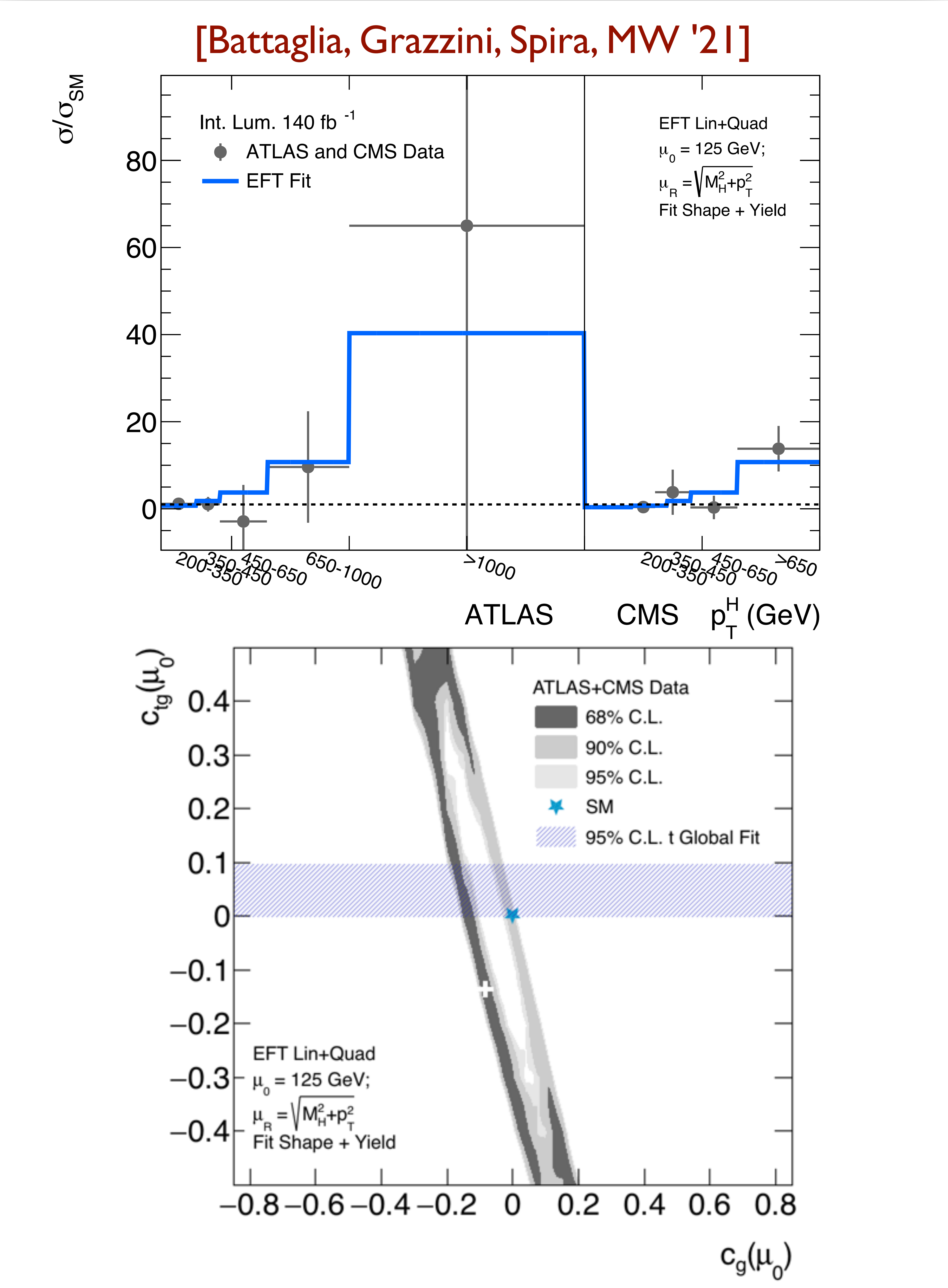


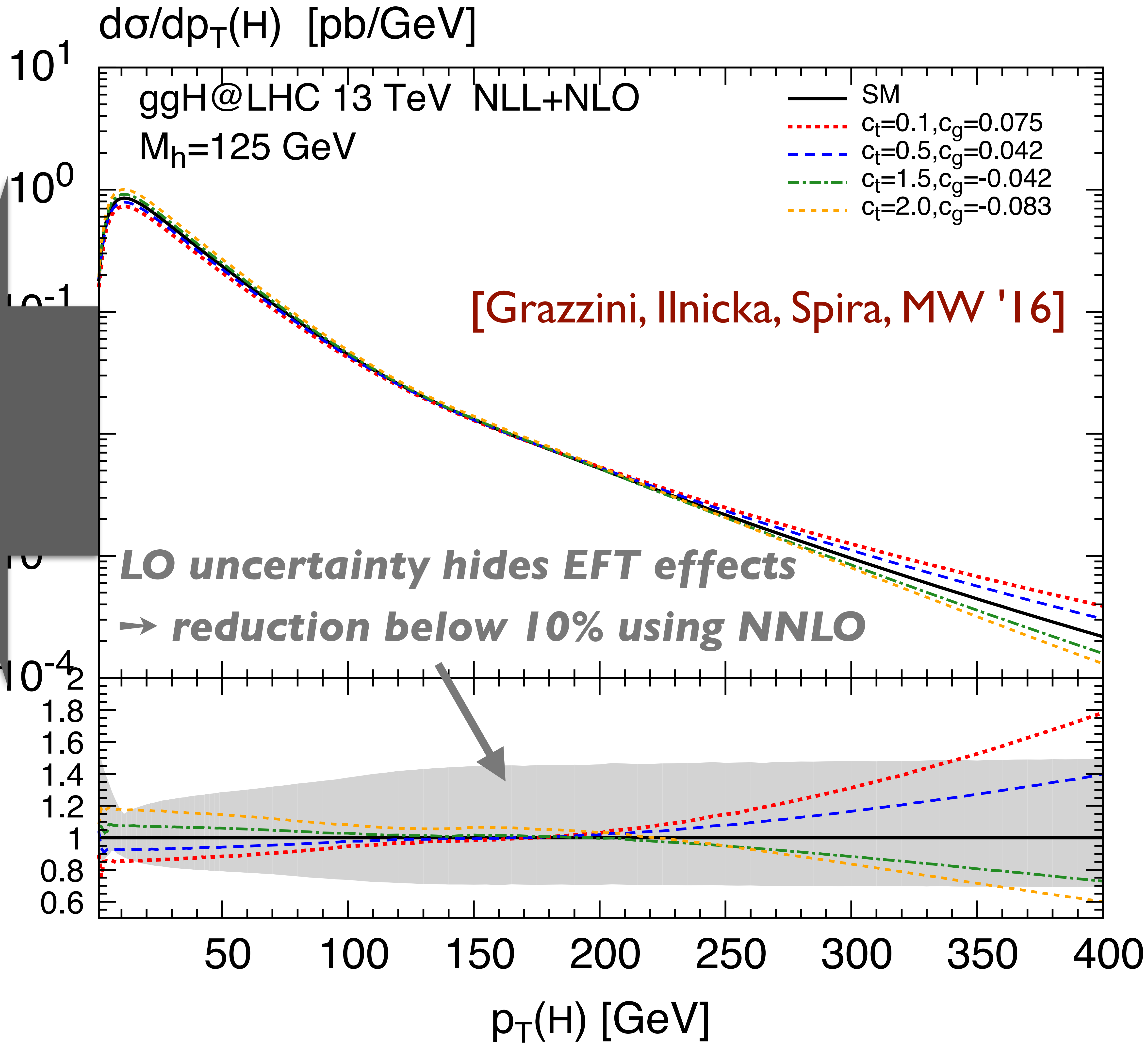
...recision?

New P... ...pT:

How c... ?

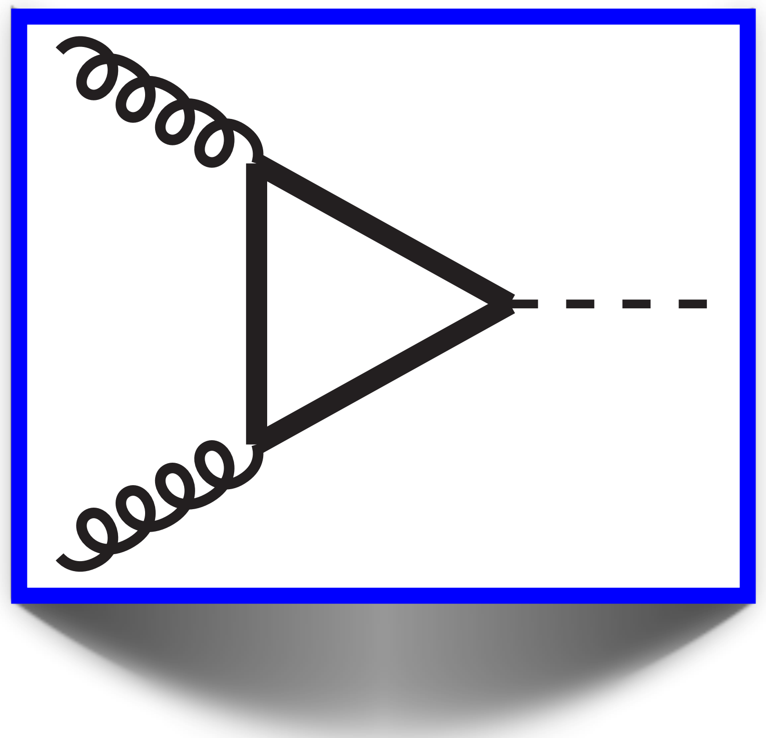




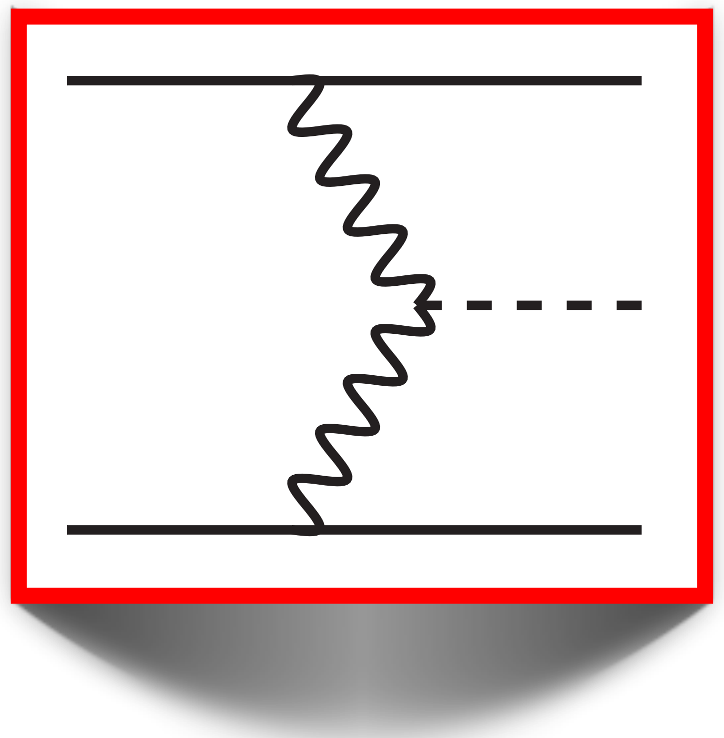


Higgs production

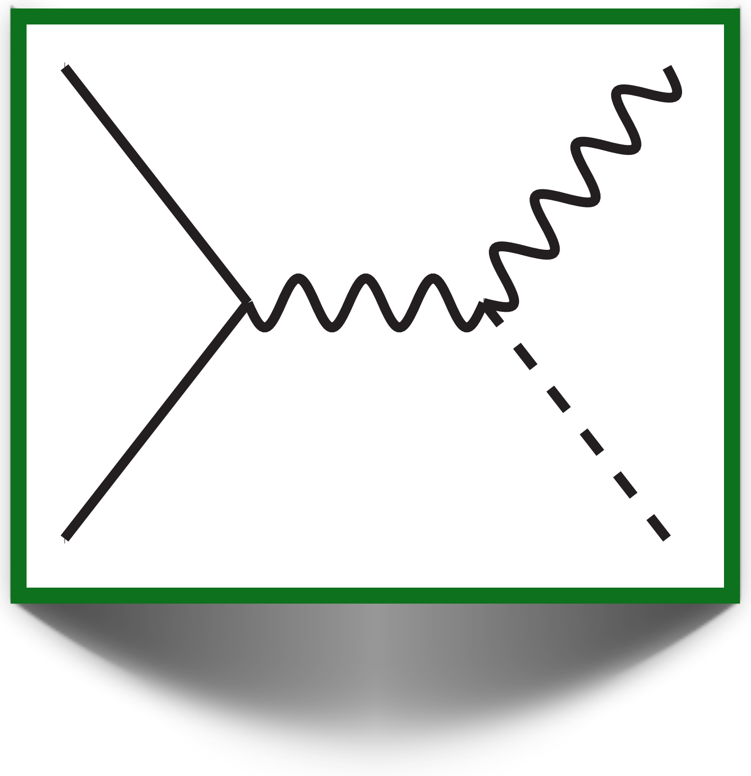
ggF ~ 87 %



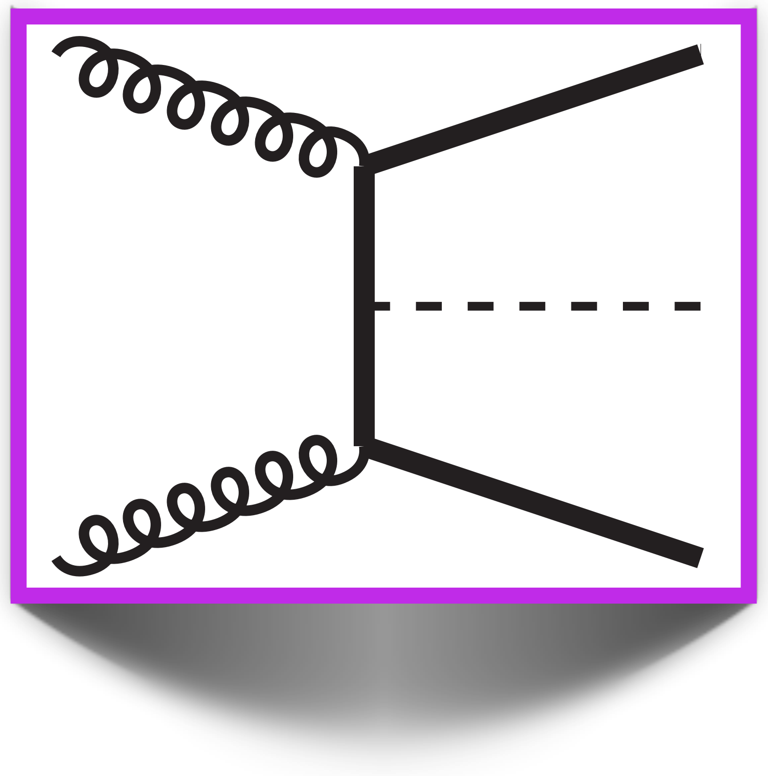
VBF ~ 7 %

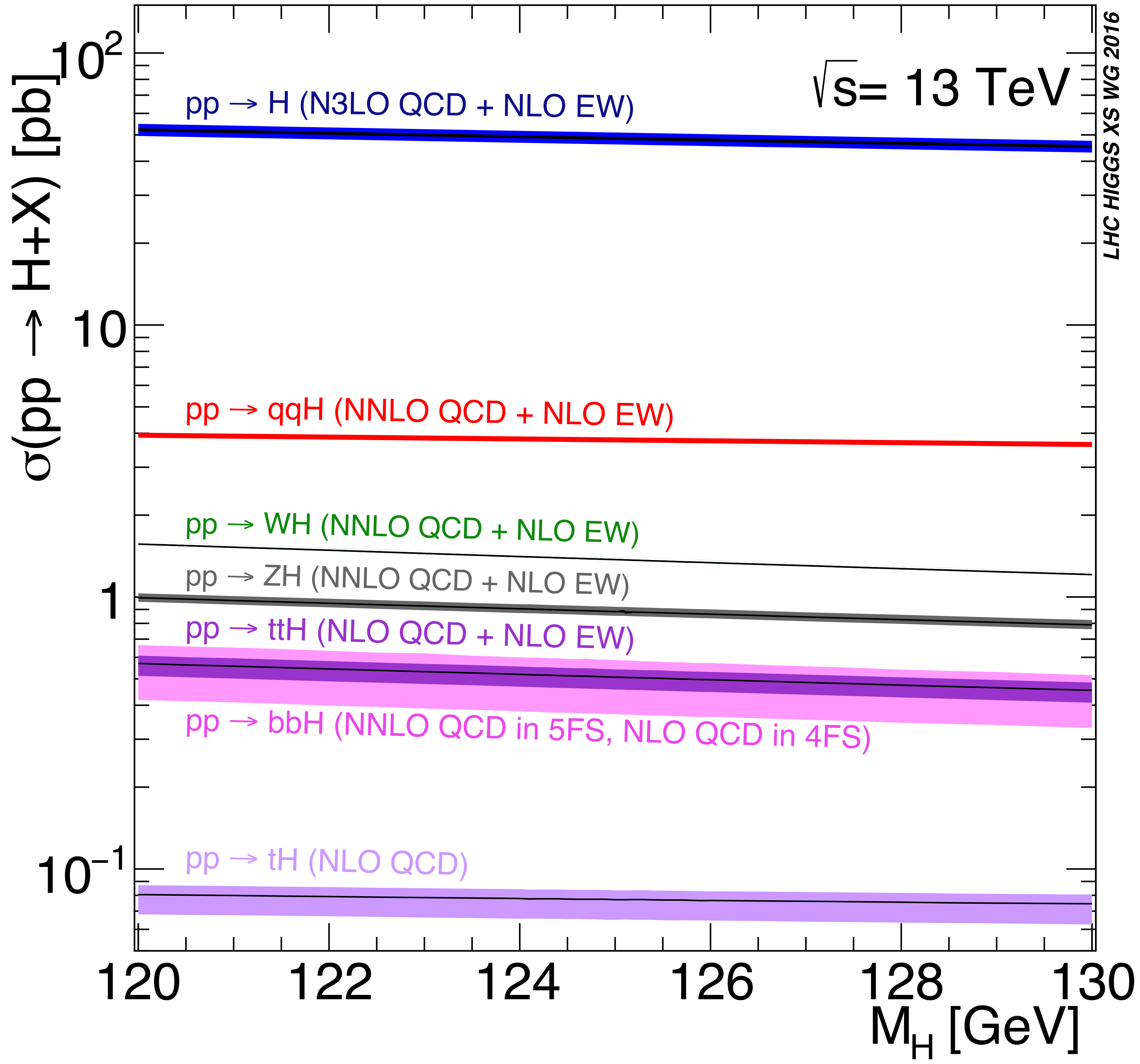


VH ~ 4 %



bbH, ttH ~ 1 %





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ggF ~ 87 %

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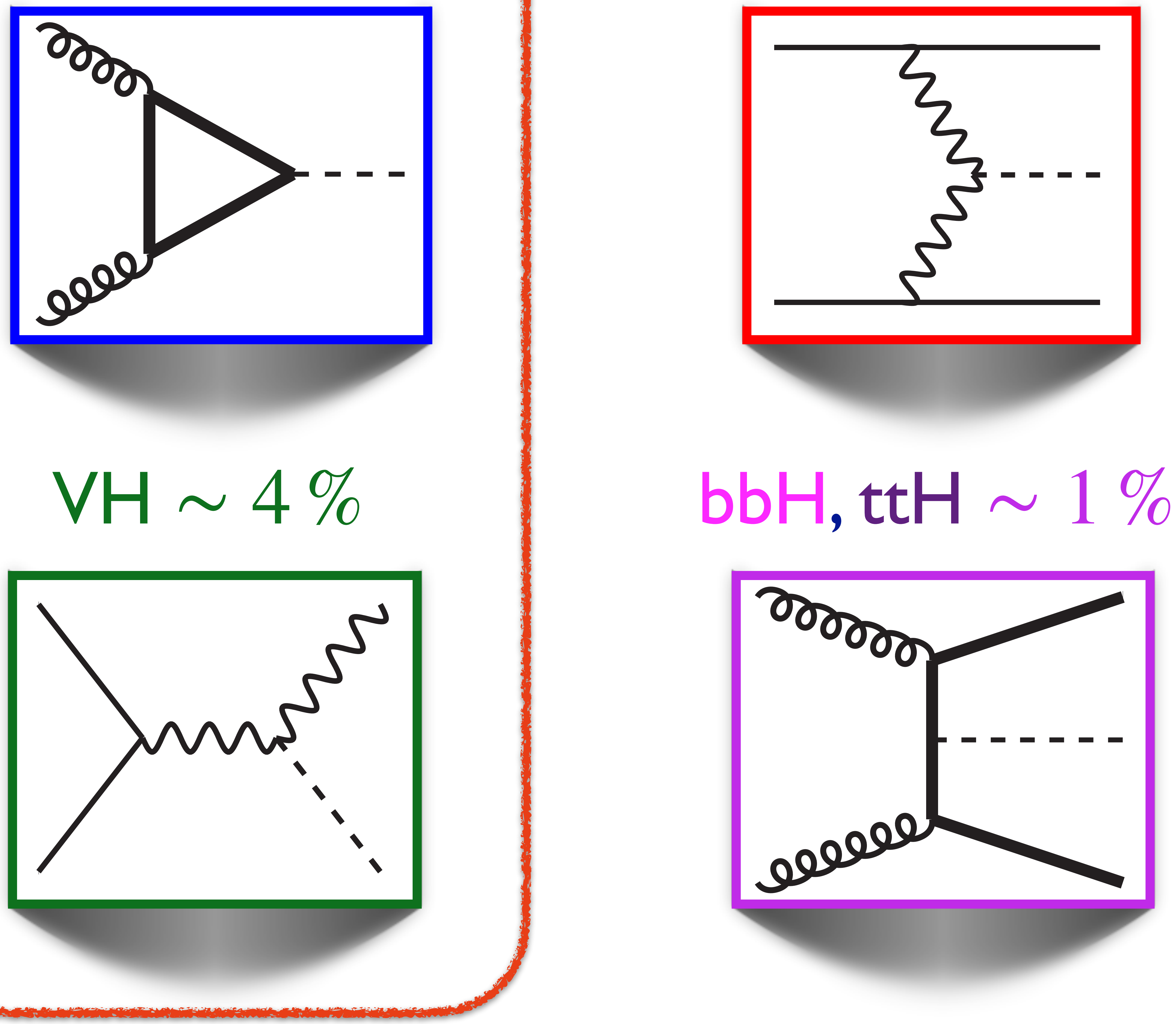
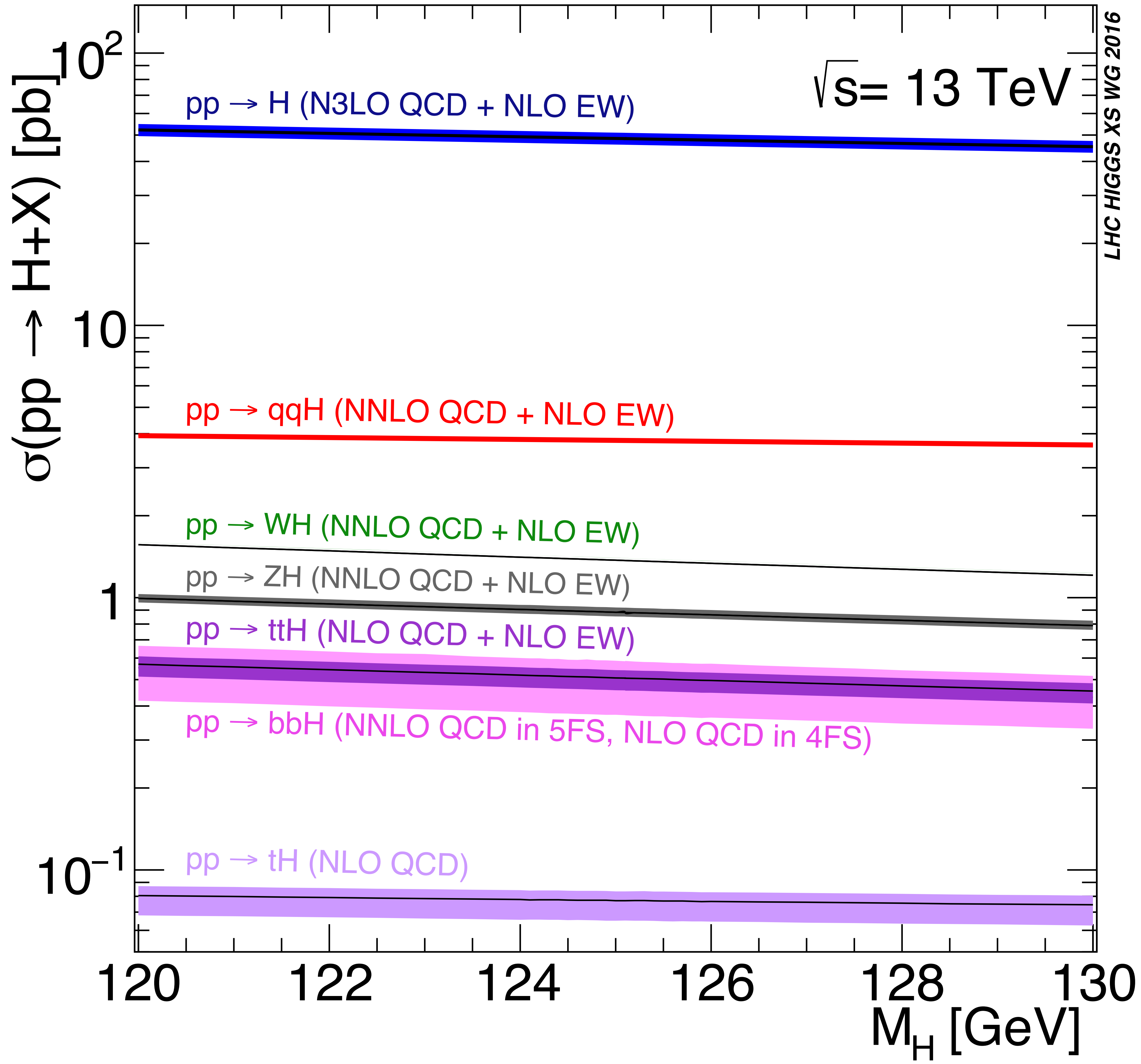
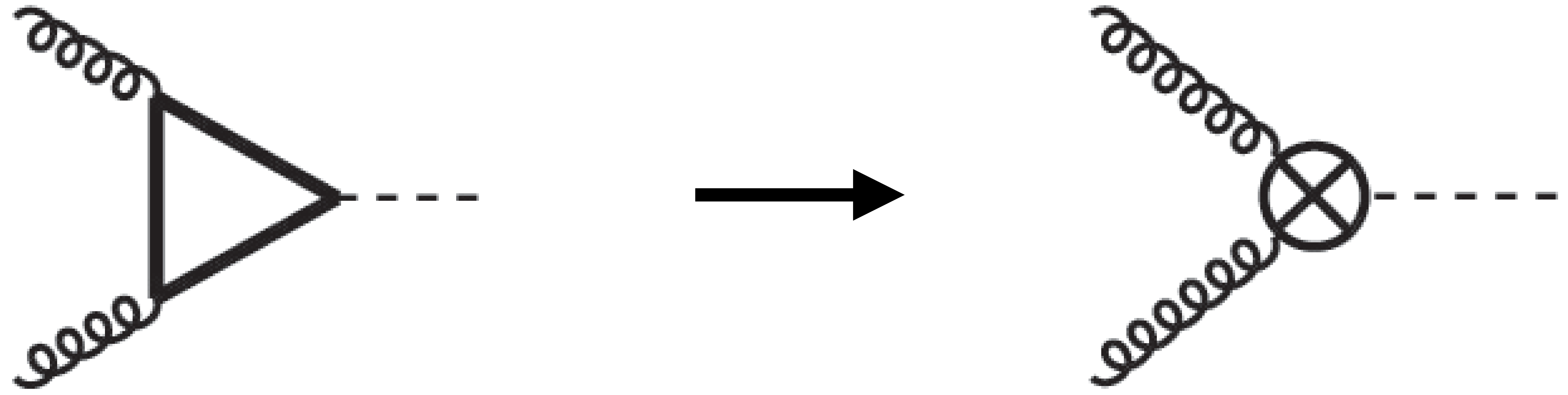


focus of this talk



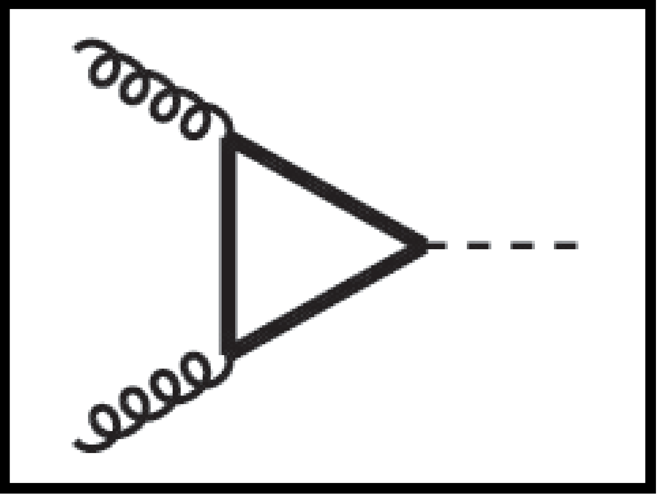
Disclaimer: will present a very incomplete and personal selection of results

Gluon Fusion (ggF)



Widely assumed EFT approximation "heavy-top limit" (HTL), by integrating out the top quark, for higher-order corrections.

(➙ need to compute effectively one loop less)



ggF @ N³LO differential

[Chen, Gehrmann, Glover, Huss, Mistlberger, Pelloni '21]

inclusive XS known for a while:

- soft expansion [Anastasiou et al. '15]
- full [Mistlberger '18]

differential:

- H+jet at NNLO
  [Chen, Gehrmann, Glover, Jaquier '14]
- Higgs rapidity at N³LO
  [Dulat, Mistlberger, Pelloni '18]

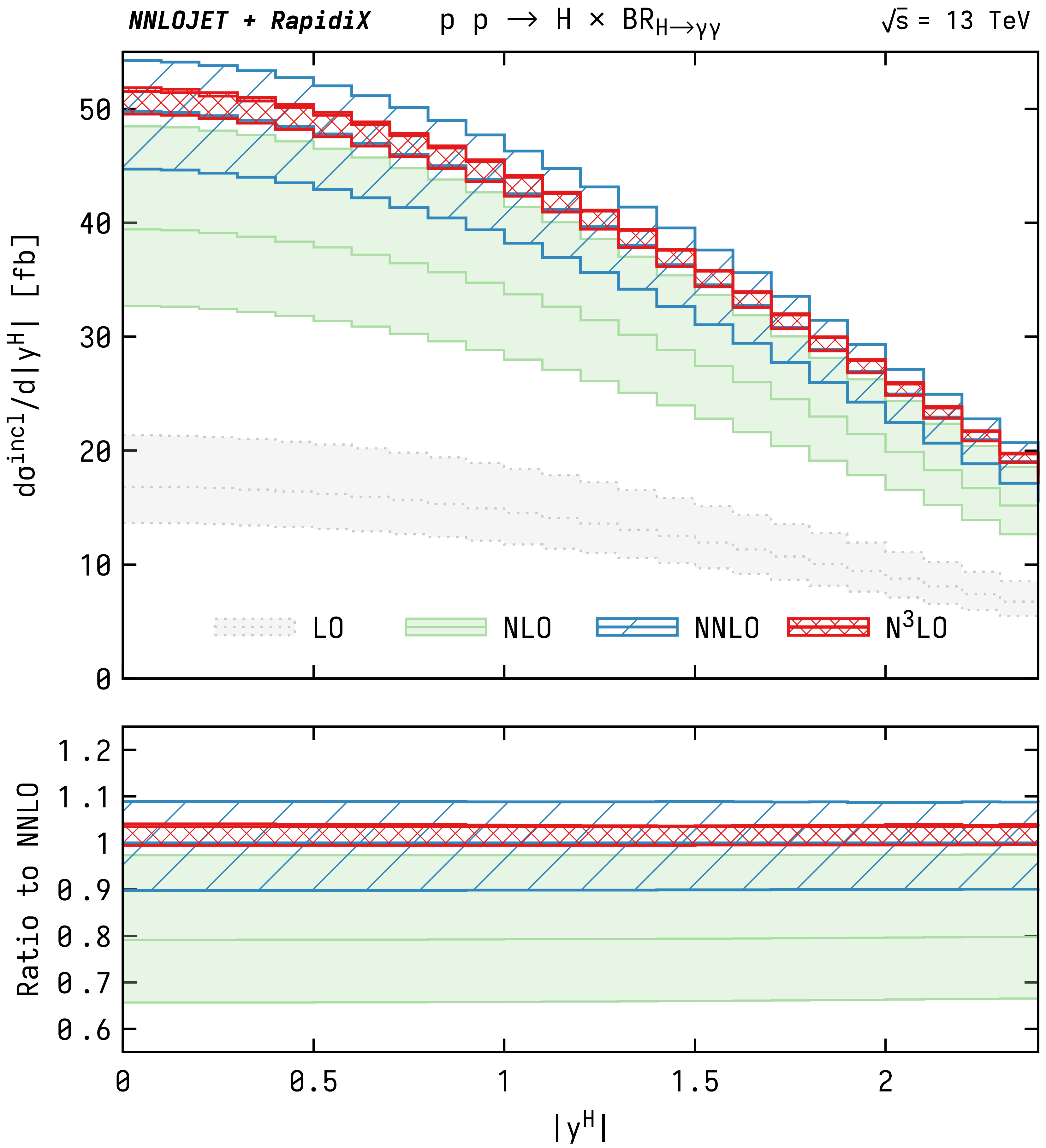
Projection-to-Born
[Cacciari, Dreyer, Karlberg, Salam, Zanderighi '15]

N³LO *for $gg \to H \to \gamma\gamma$*

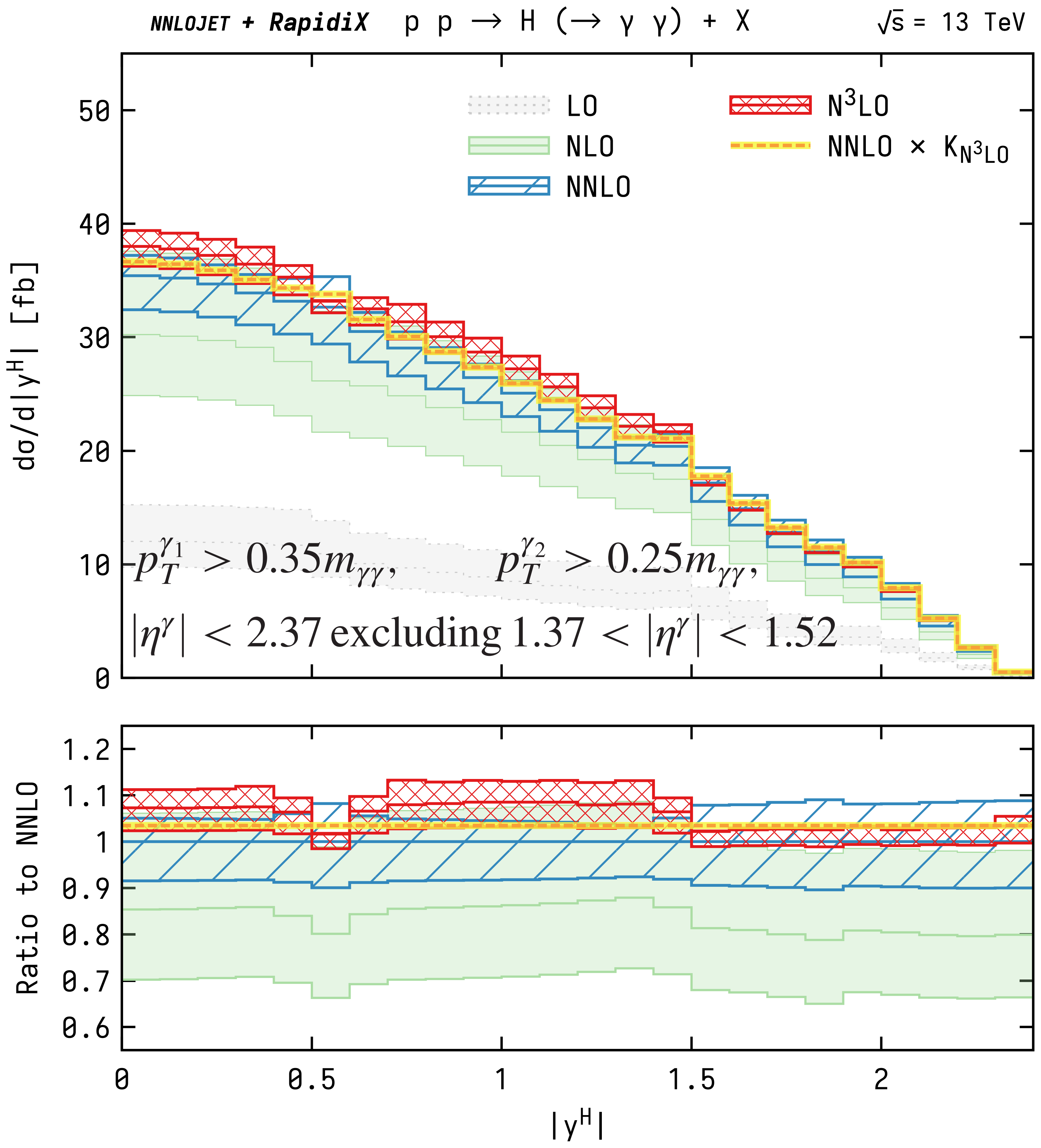
(fully differential)

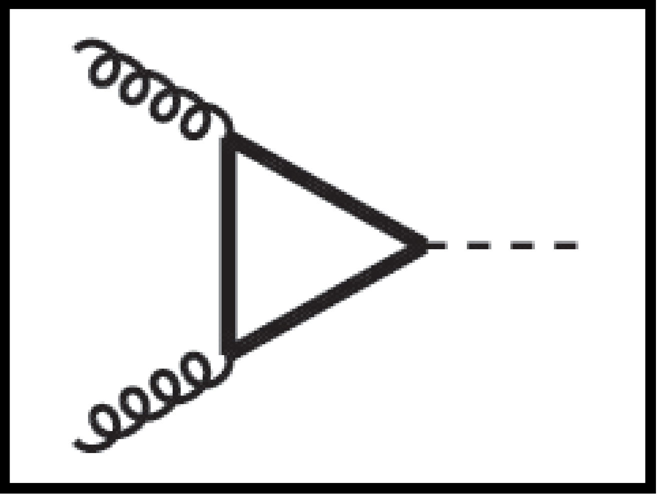
Higgs rapidity

no cuts (inclusive)

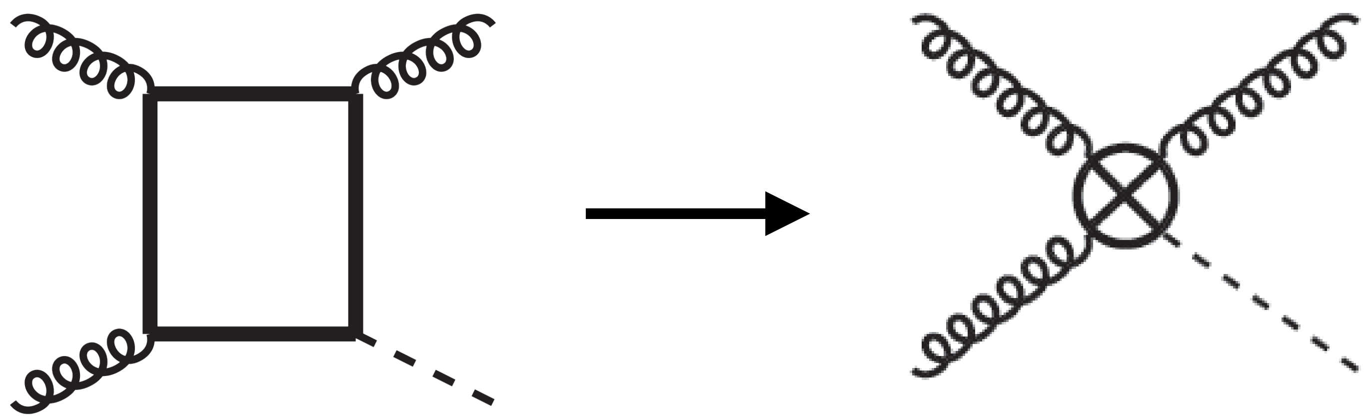


fiducial cuts (ATLAS)

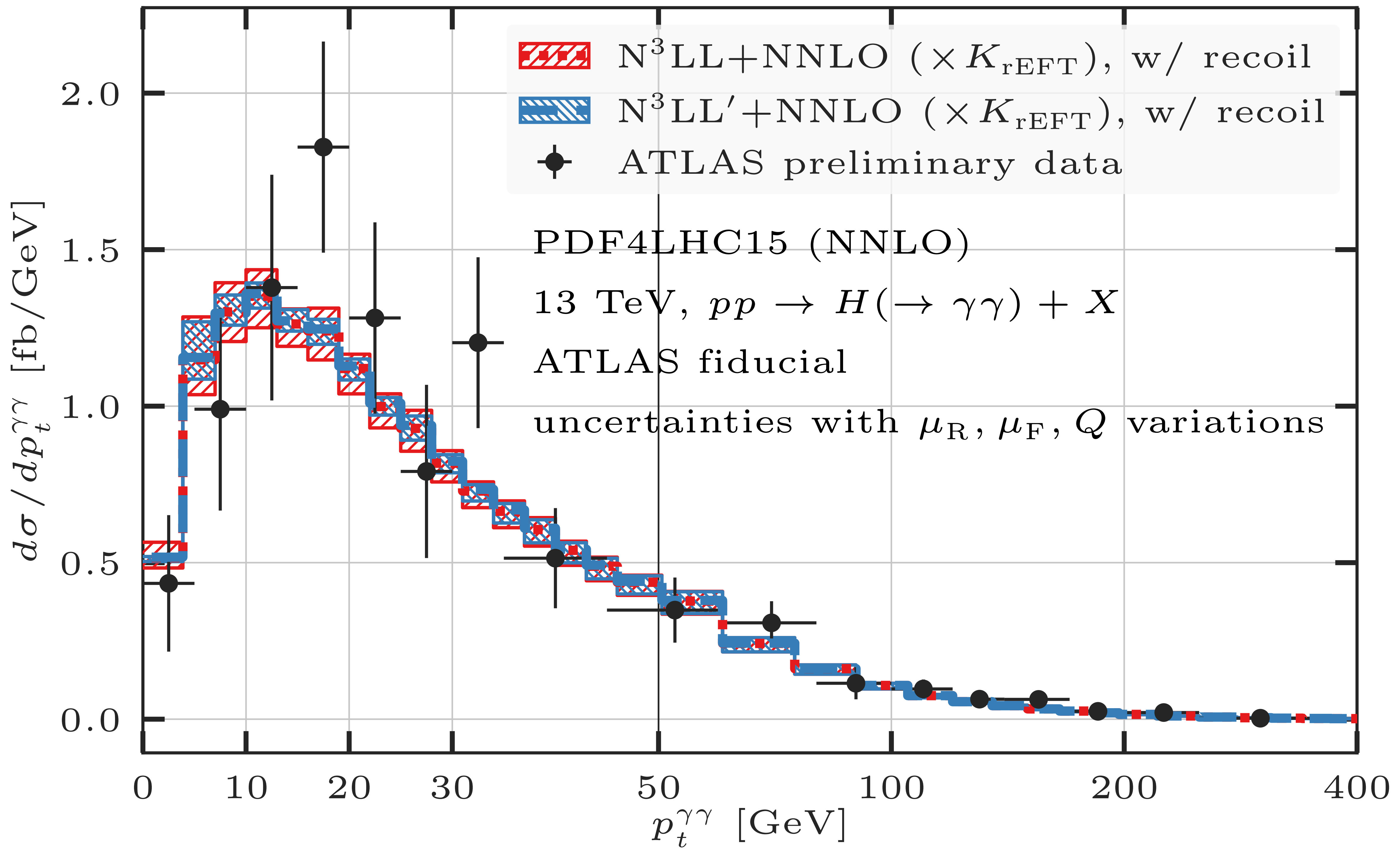




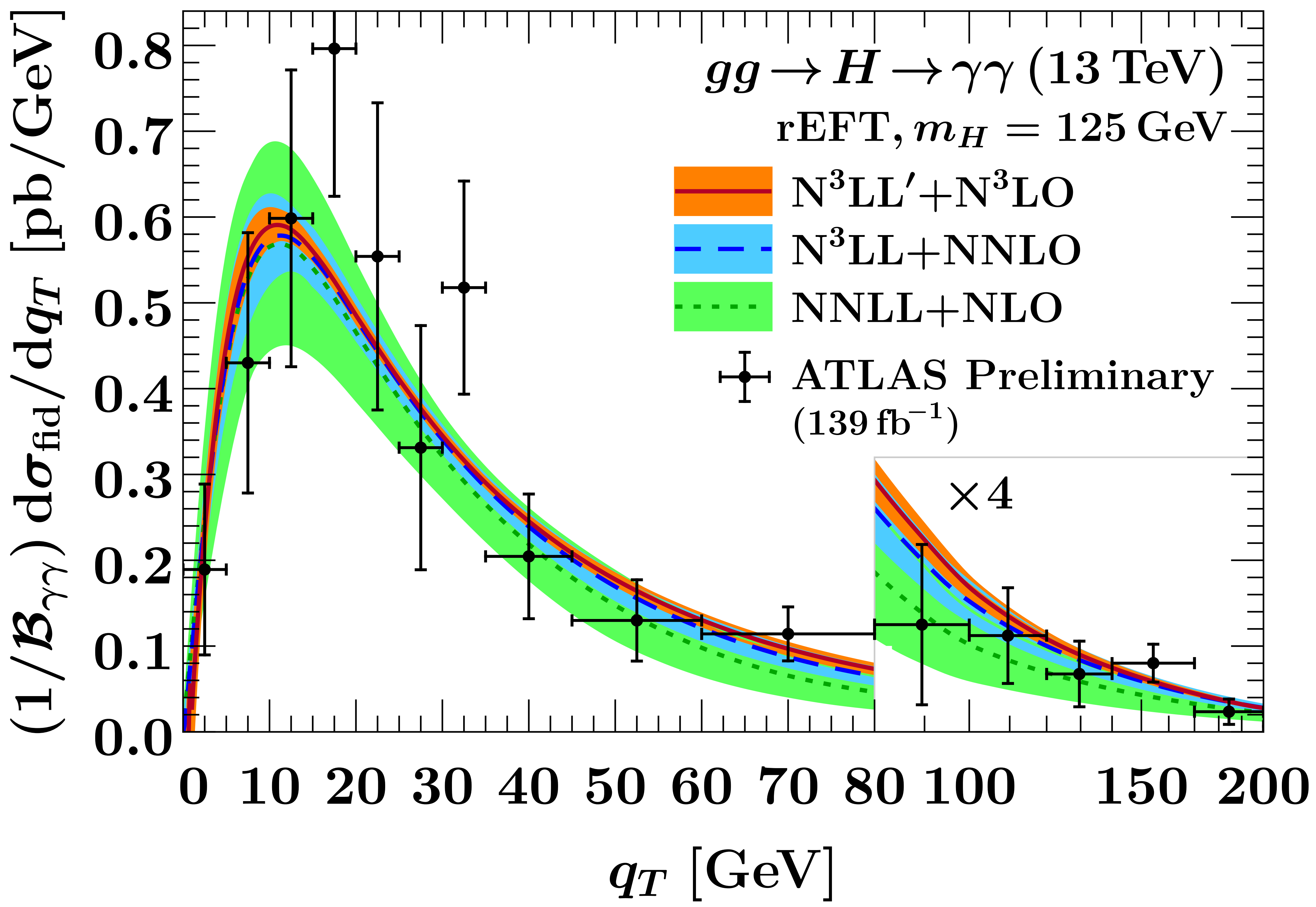
Higgs pT @ N³LL′+NNLO

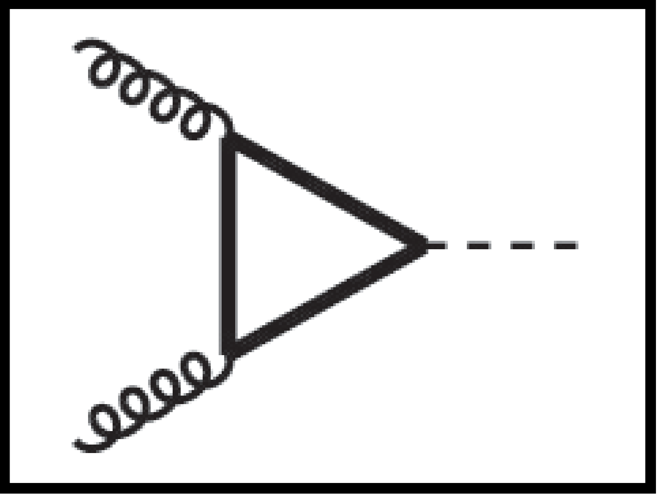


[Re, Rottoli, Torrieli '21]



[Billis, Dehnadi, Ebert, Michel, Tackmann '21]

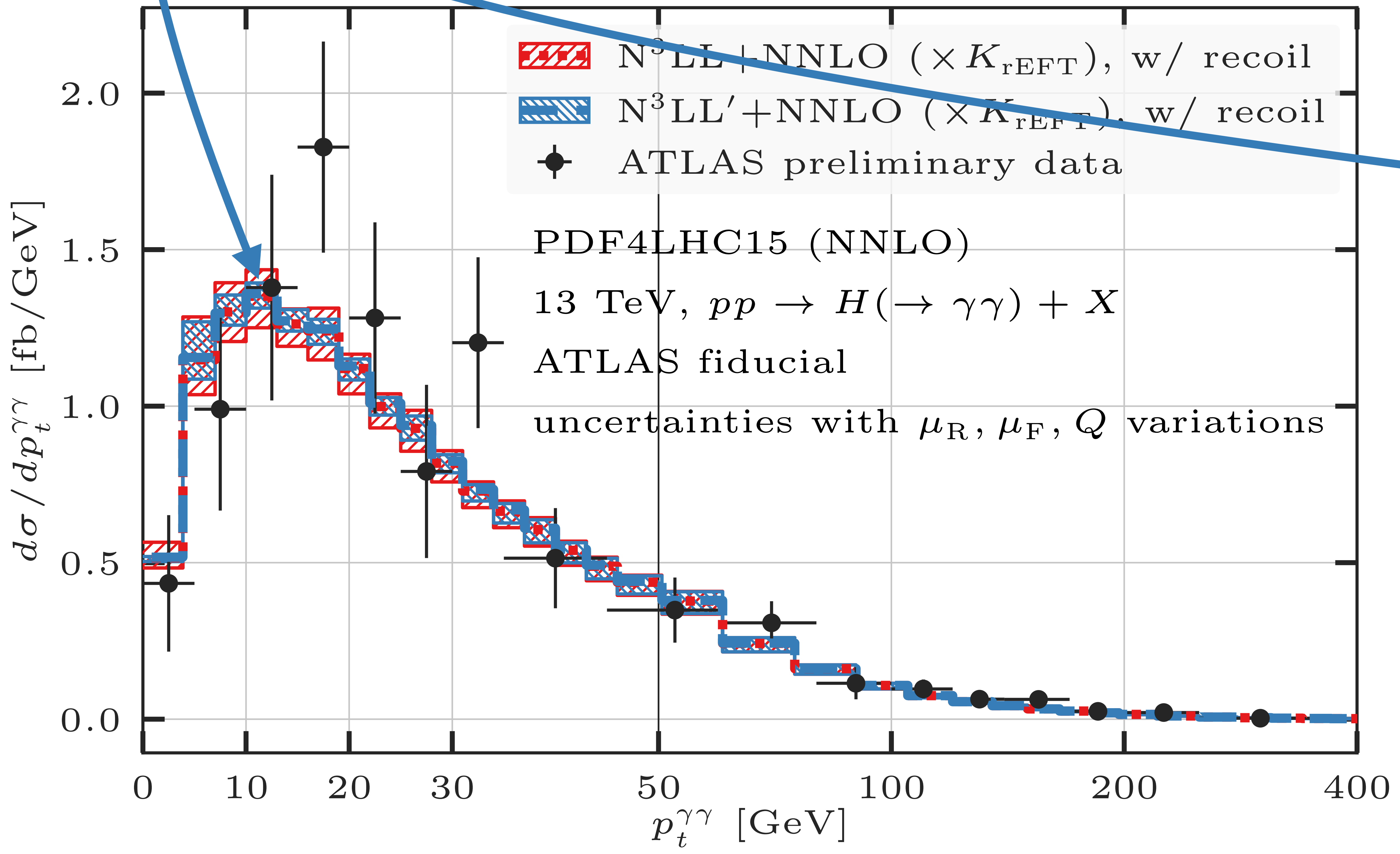


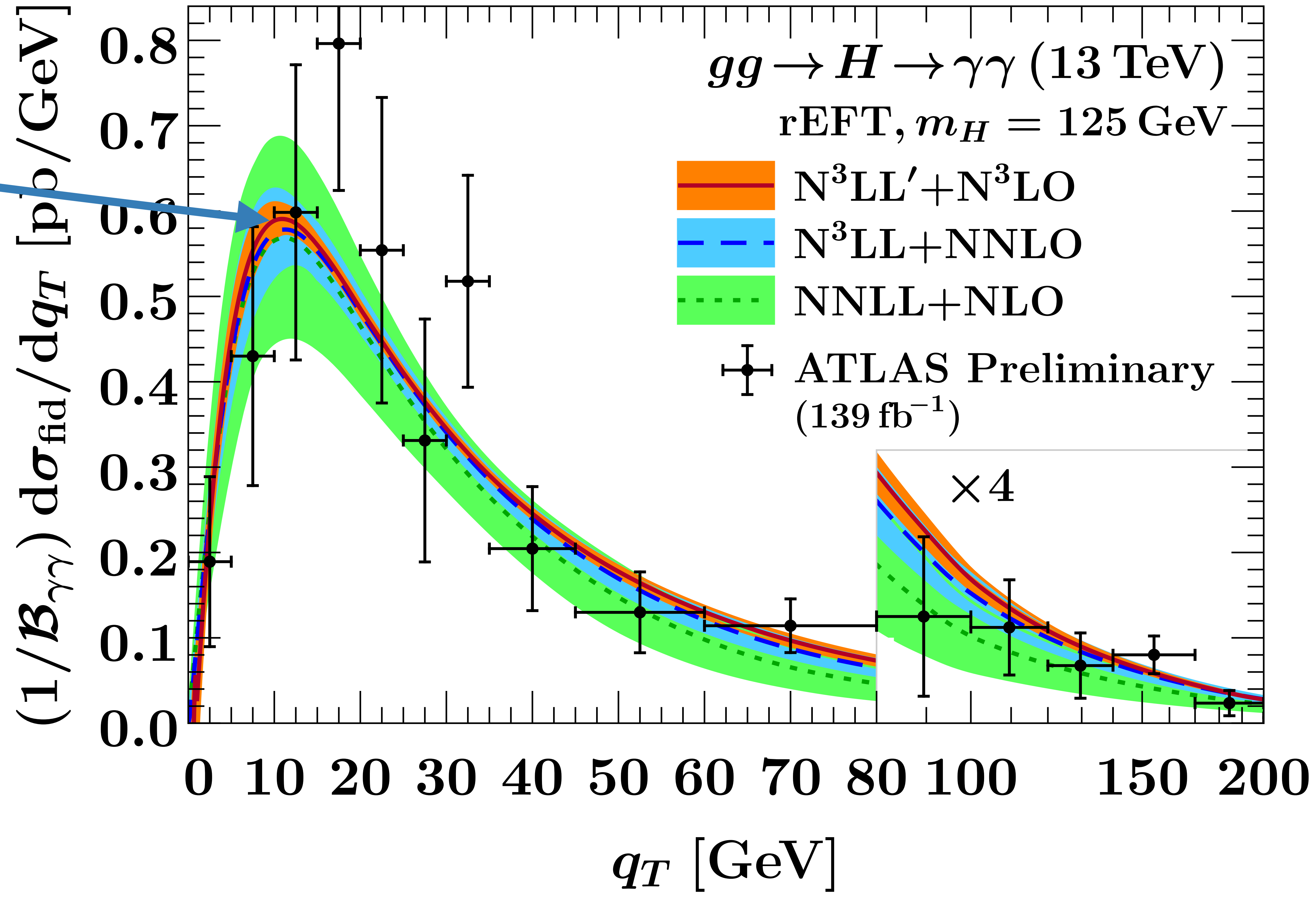


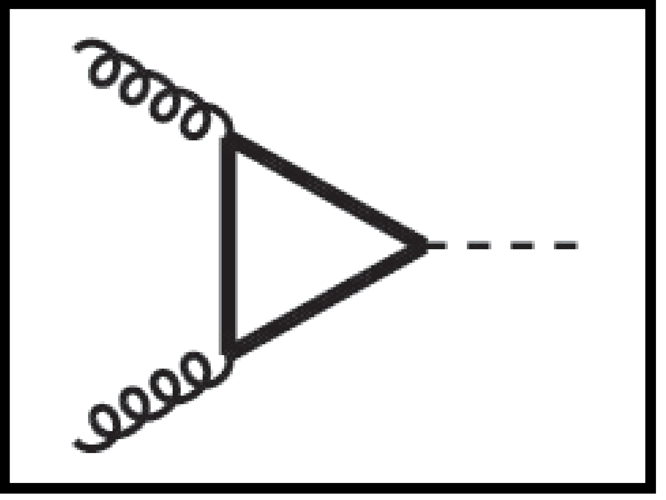
Higgs p_T @ N^3LL'+NNLO

***remarkably small theory uncertainties**, they will enable:*

- *at low p_T, the extraction of light-quark Yukawa couplings (bottom, charm)* [Bishara, Haisch, Monni, Re '16]







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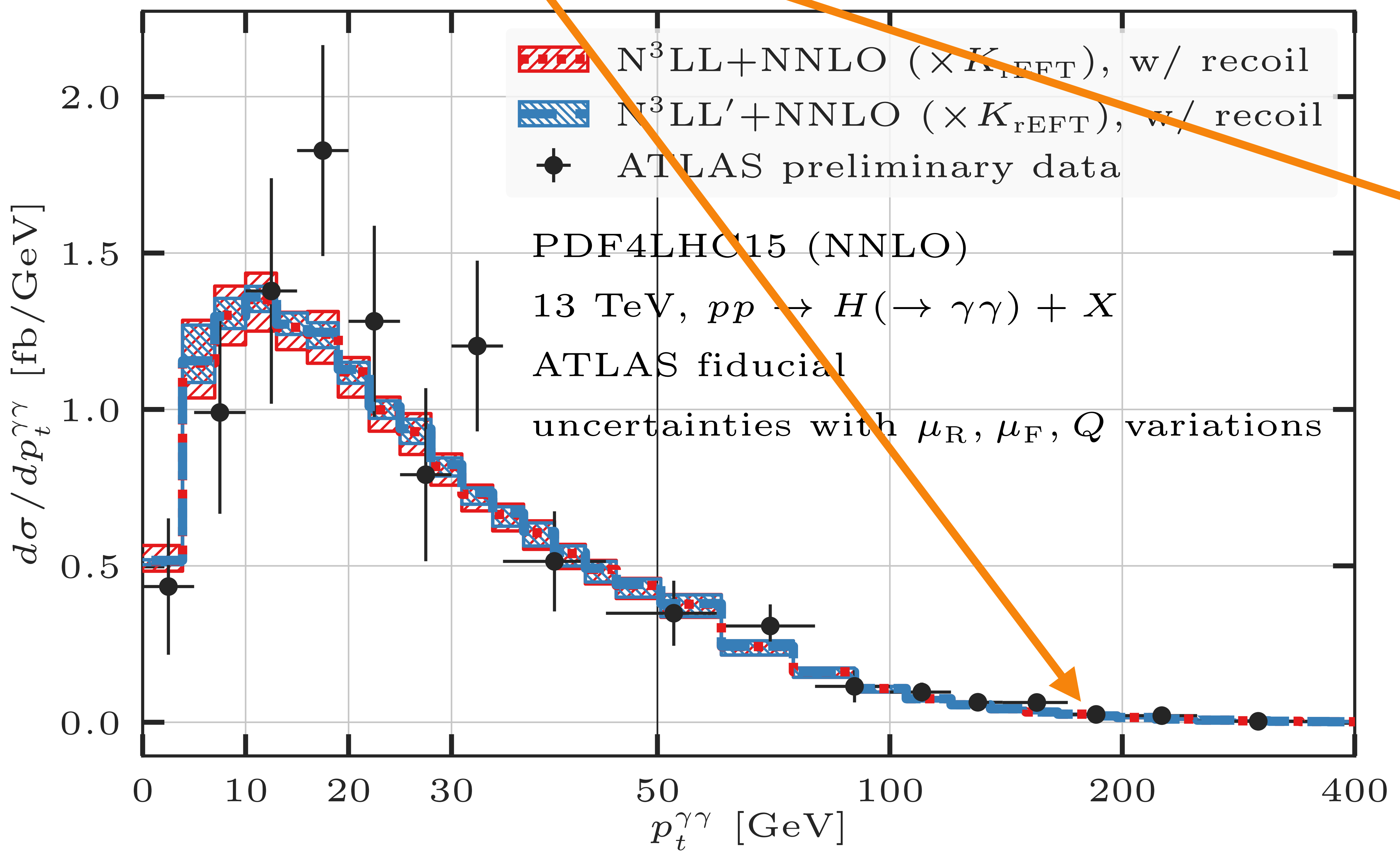
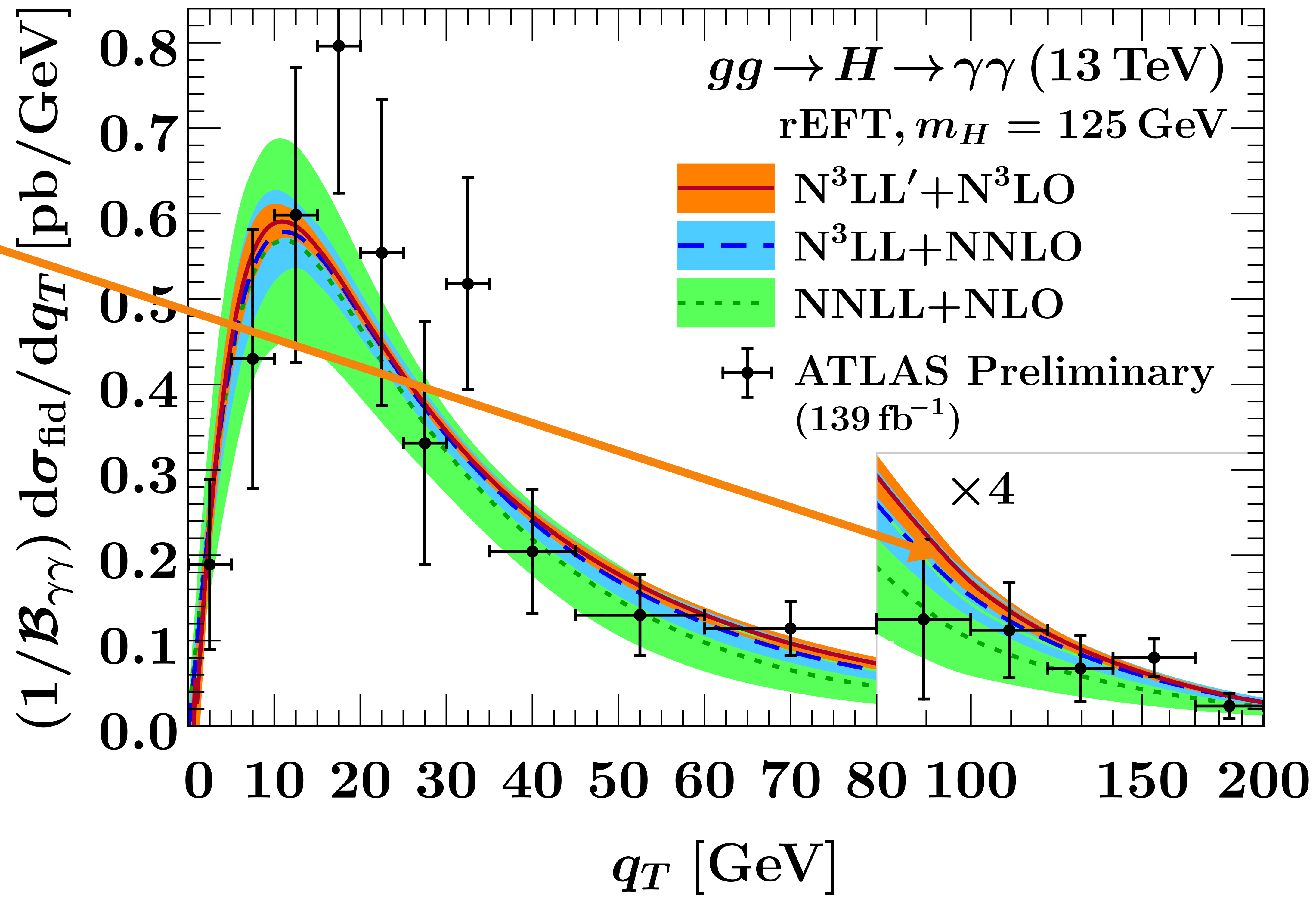
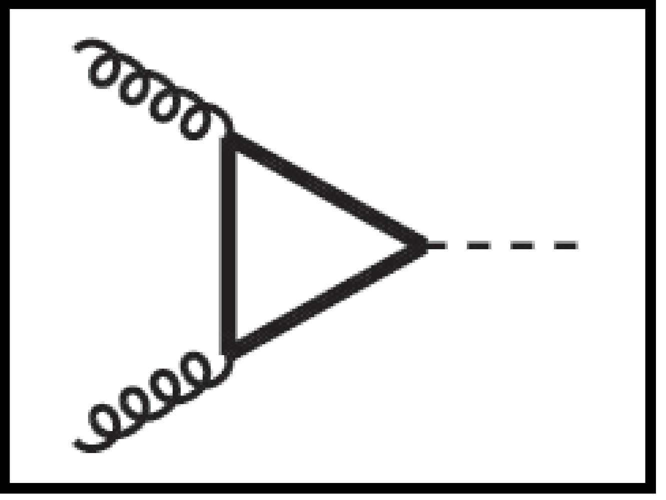
- *at low p_T, the extraction of light-quark Yukawa couplings (bottom, charm)* [Bishara, Haisch, Monni, Re '16]
- *at high p_T, the extraction of the Higgs coupling to gluons*, see e.g. [Battaglia, Grazzini, Spira, MW '21]



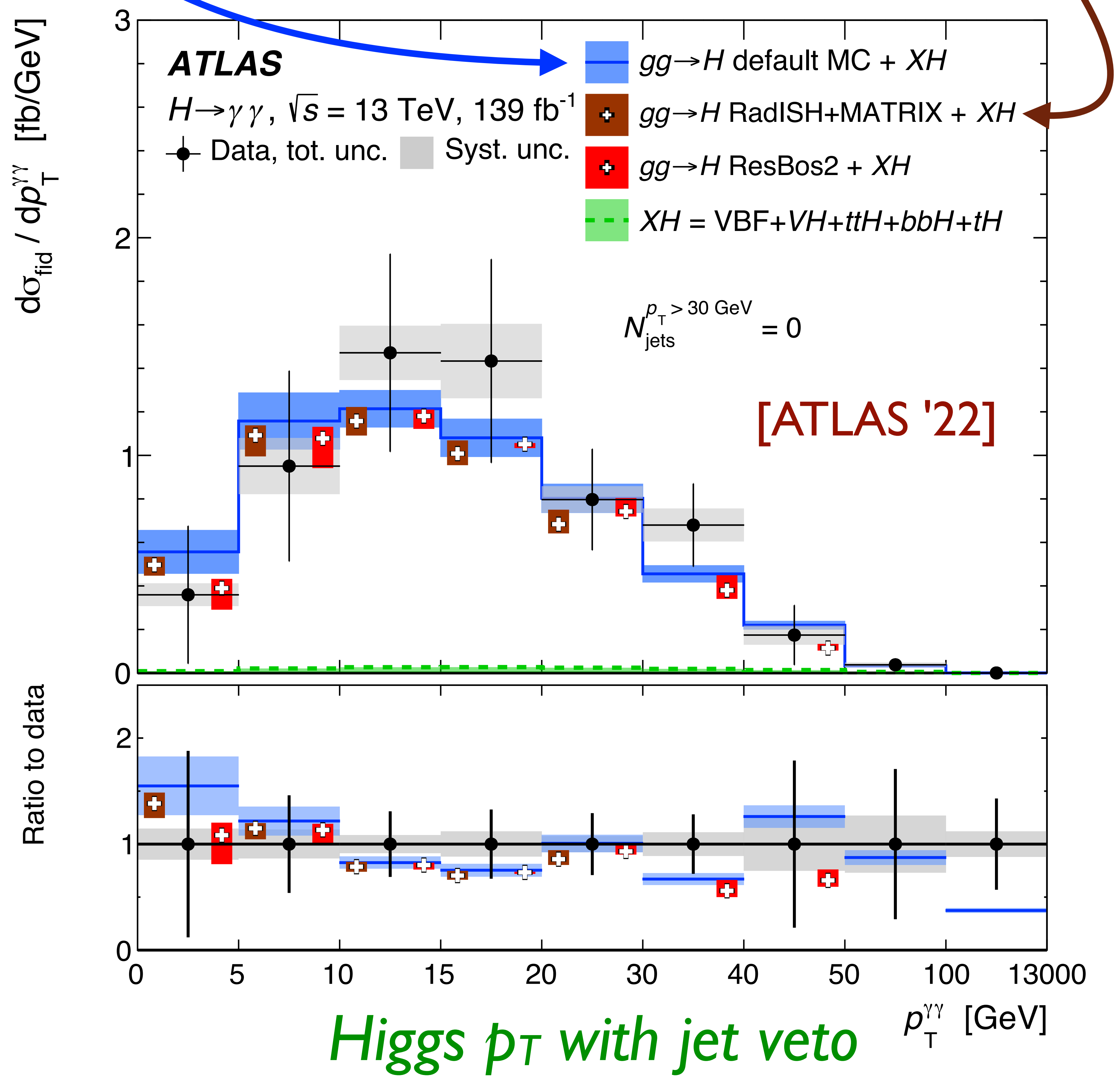




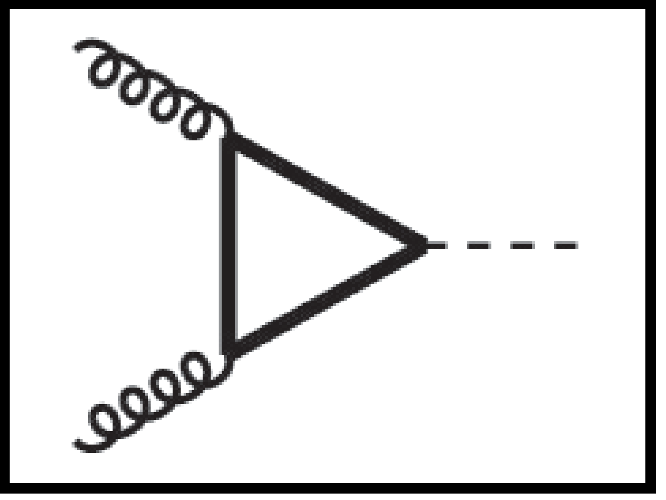
ggF @ NNLO+PS

baseline MC: MiNLO+reweighting to NNLO rapidity
[Hamilton, Nason, Re, Zanderighi '13]

agrees with NNLL from MATRIX+RadISH
[Kallweit, Re, Rottoli, MW '13]



Higgs p_T with jet veto



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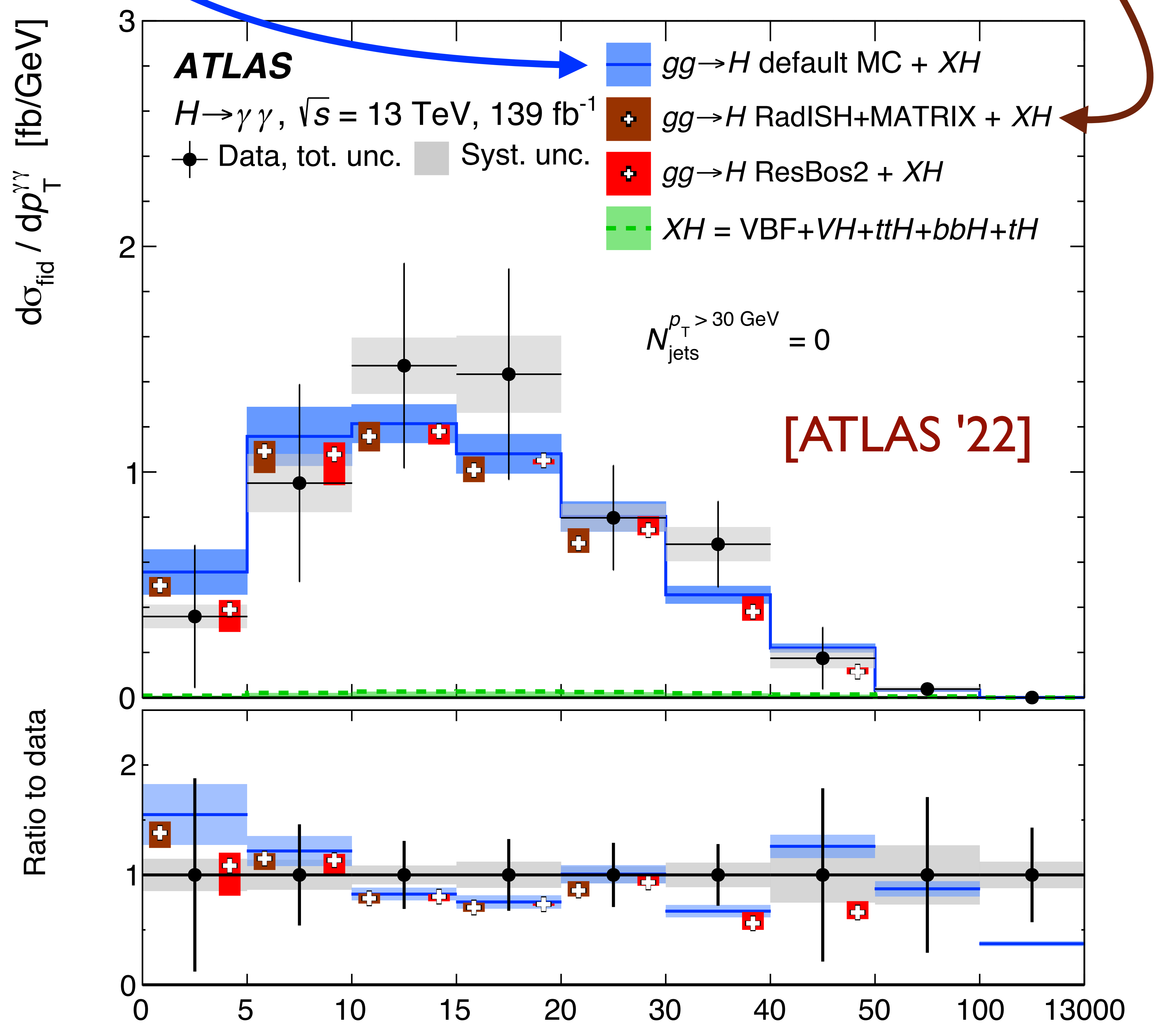
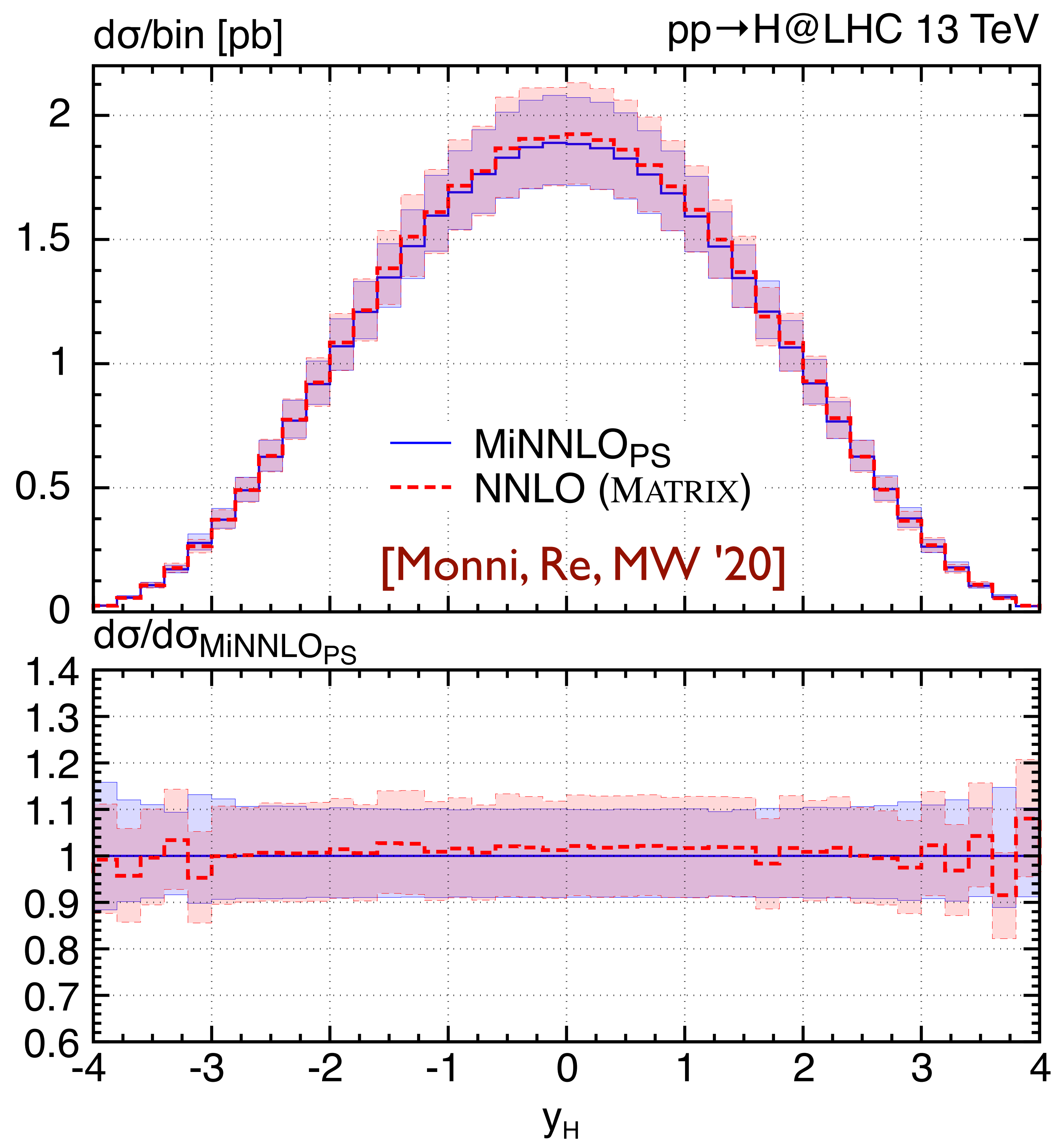
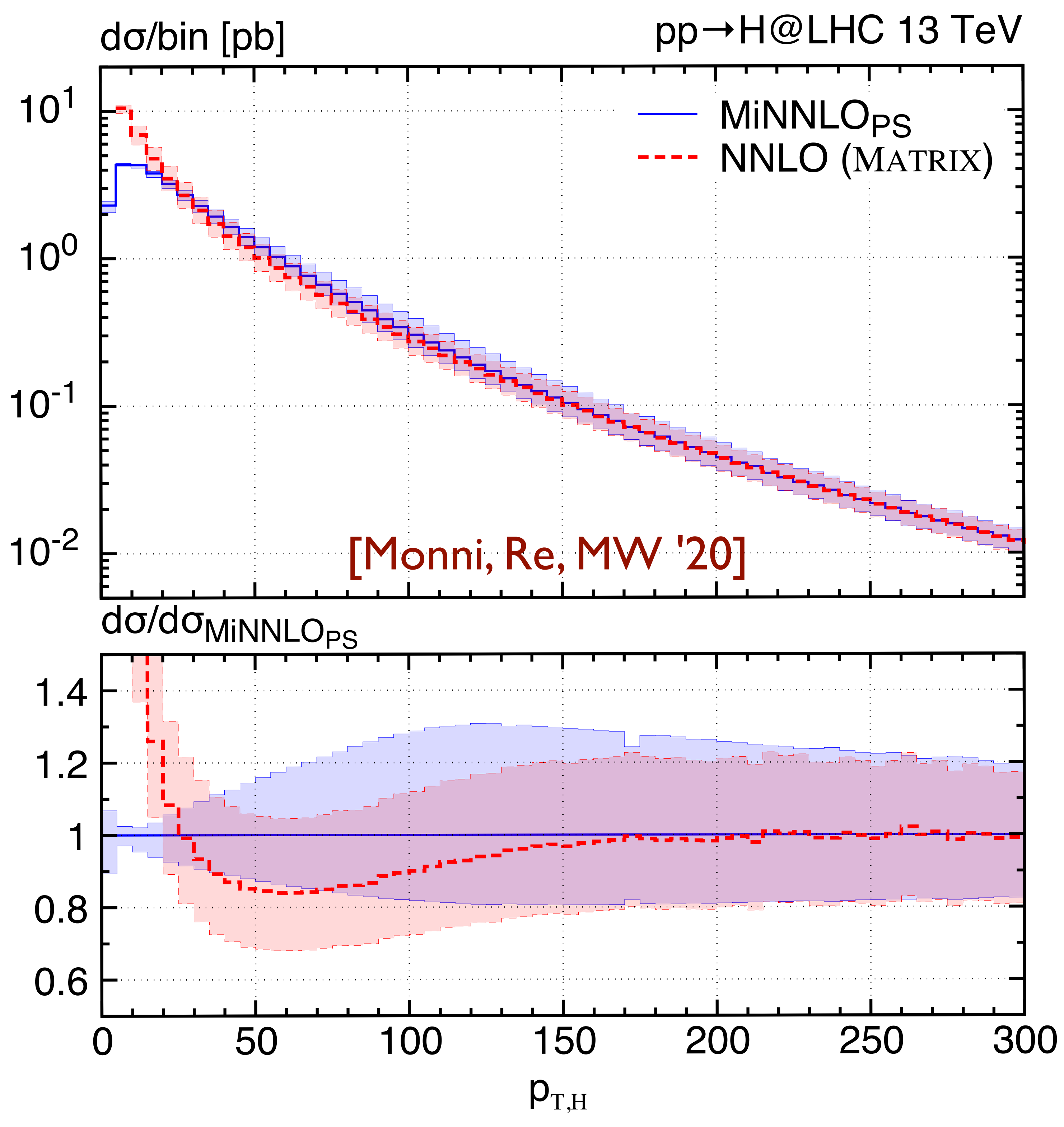


Higgs p_T with jet veto

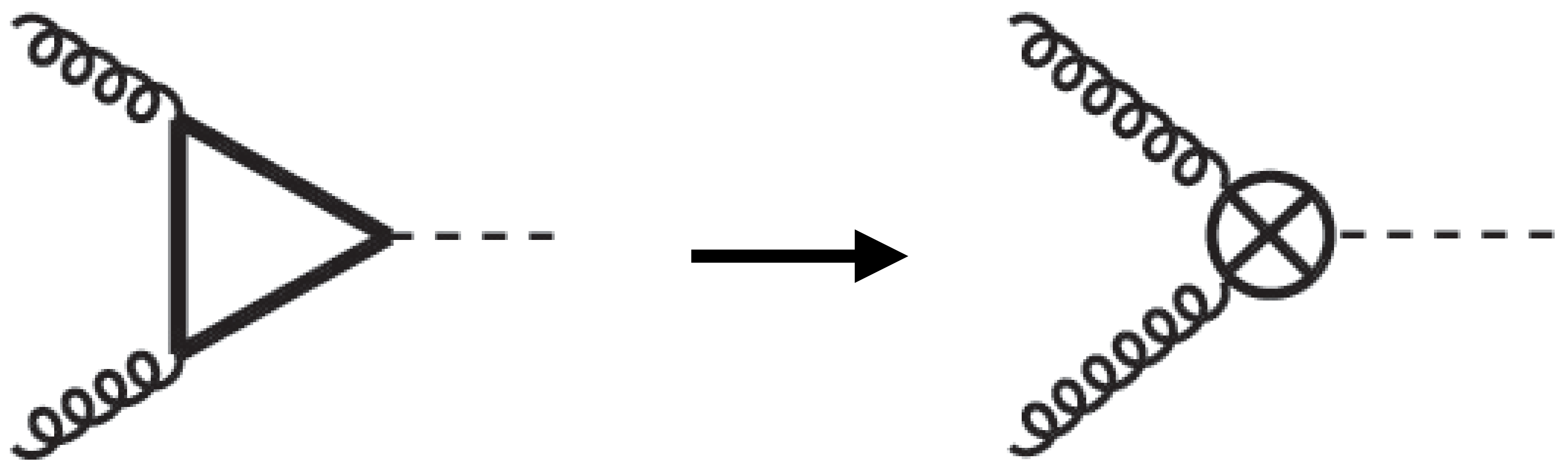
MiNNLO$_{PS}$: direct NNLO in event generation (no reweight)
[Monni, Nason, Re, Zanderighi, MW '19], [Monni, Re, MW '20]

Process	NNLO (MATRIX)	MiNNLO$_{PS}$	Ratio
$pp \rightarrow H$	$39.64(1)^{+10.7\%}_{-10.4\%}$ pb	$39.1(5)^{+10.2\%}_{-9.0\%}$ pb	0.987



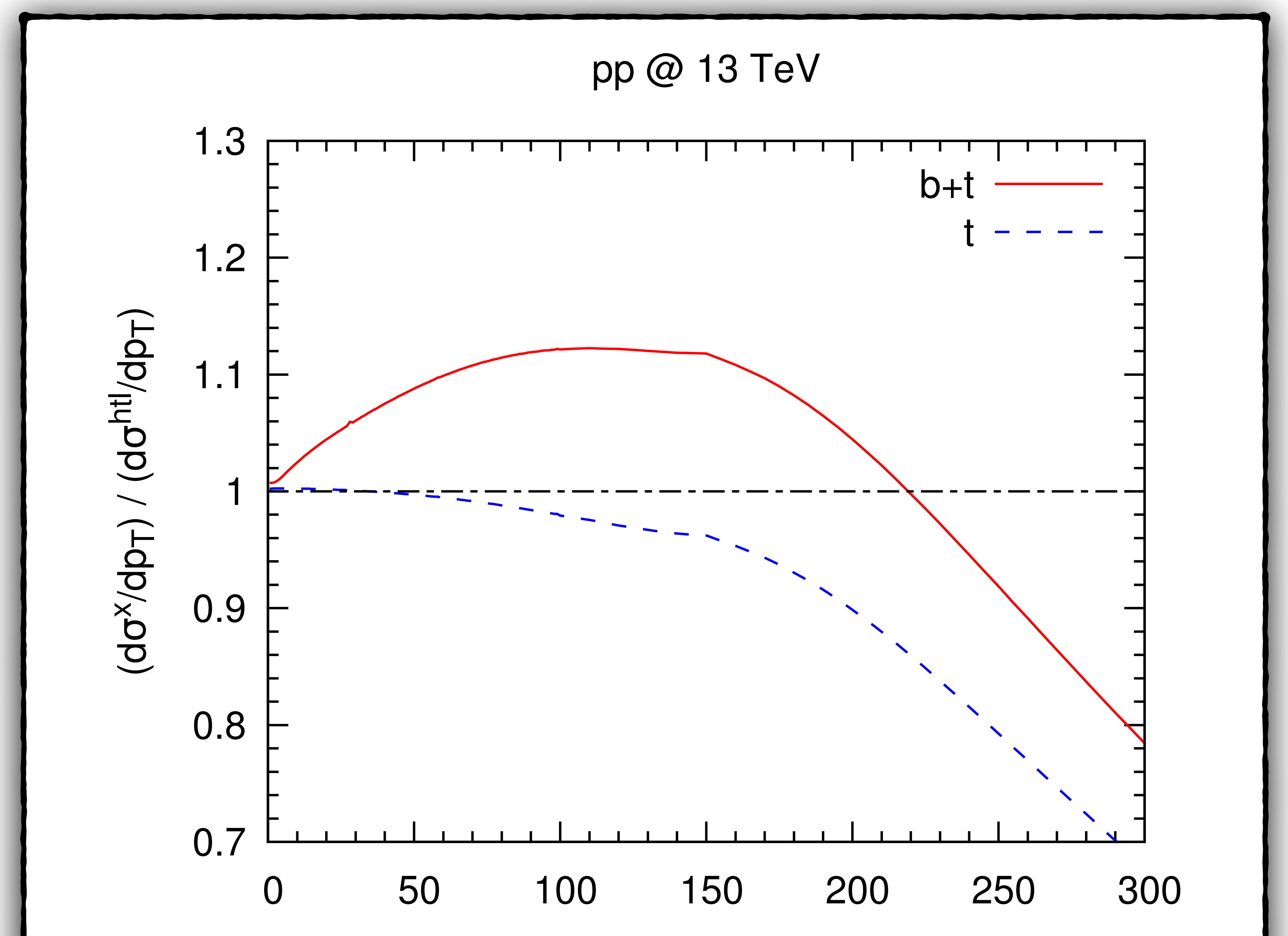


All based on HTL approximation



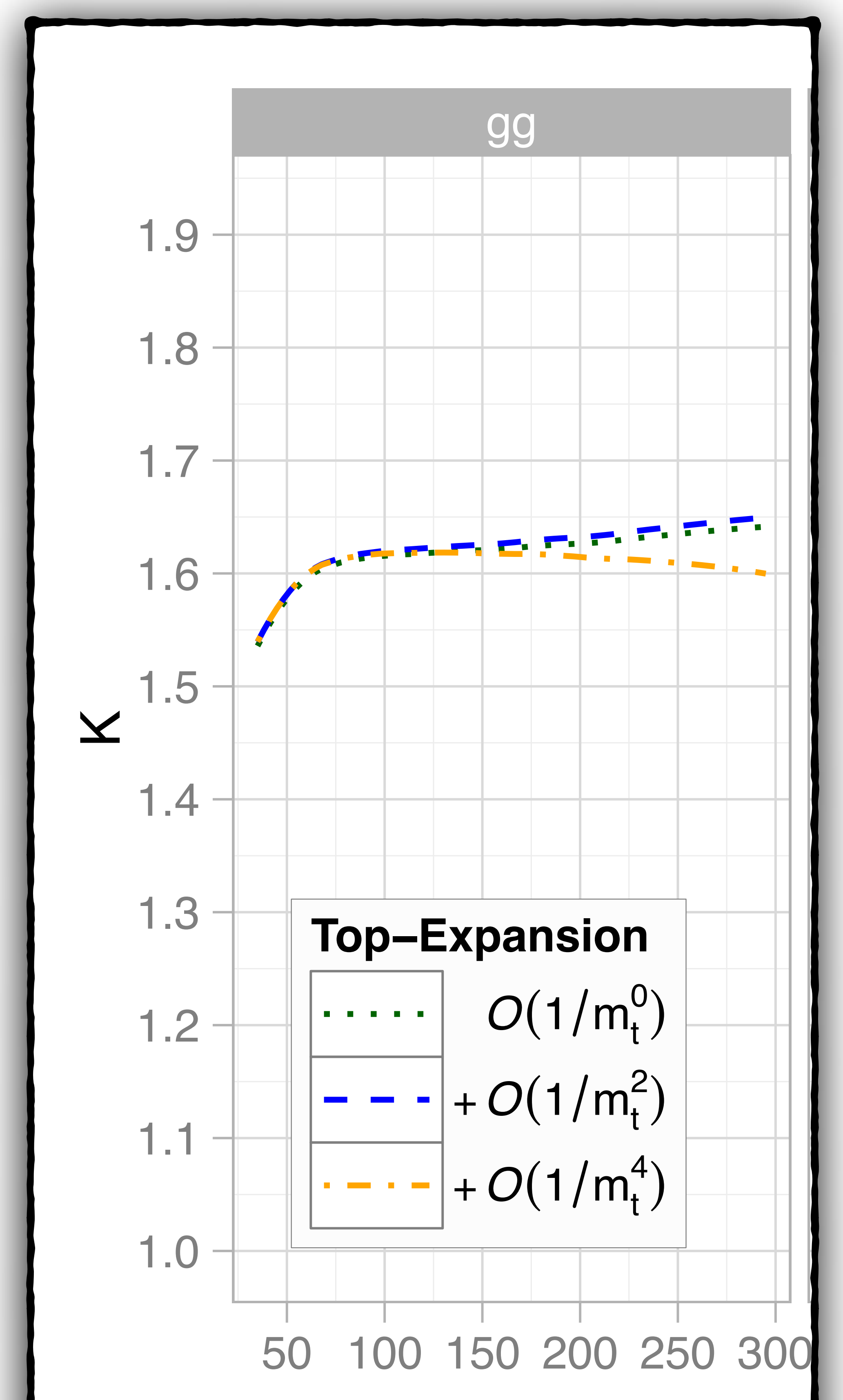
top and bottom mass effects?

p_T @ NLL+LO

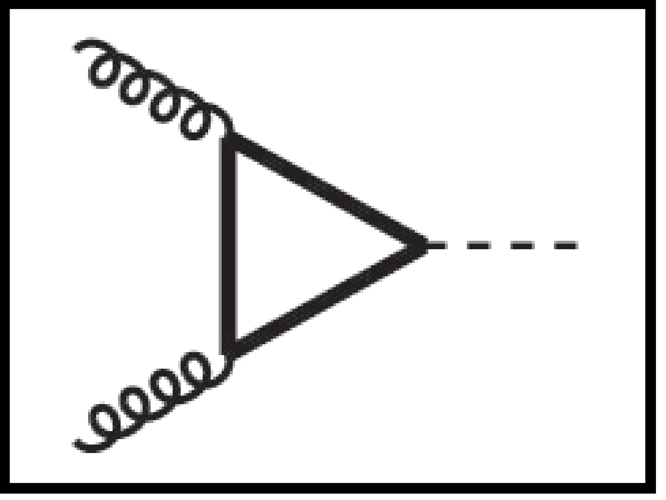


[Mantler, MW '12]

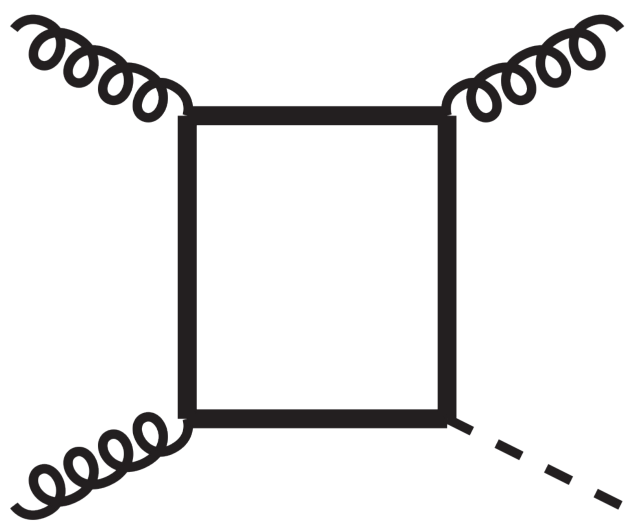
p_T @ NLO ($1/m_t$)



[Neumann, MW '14]

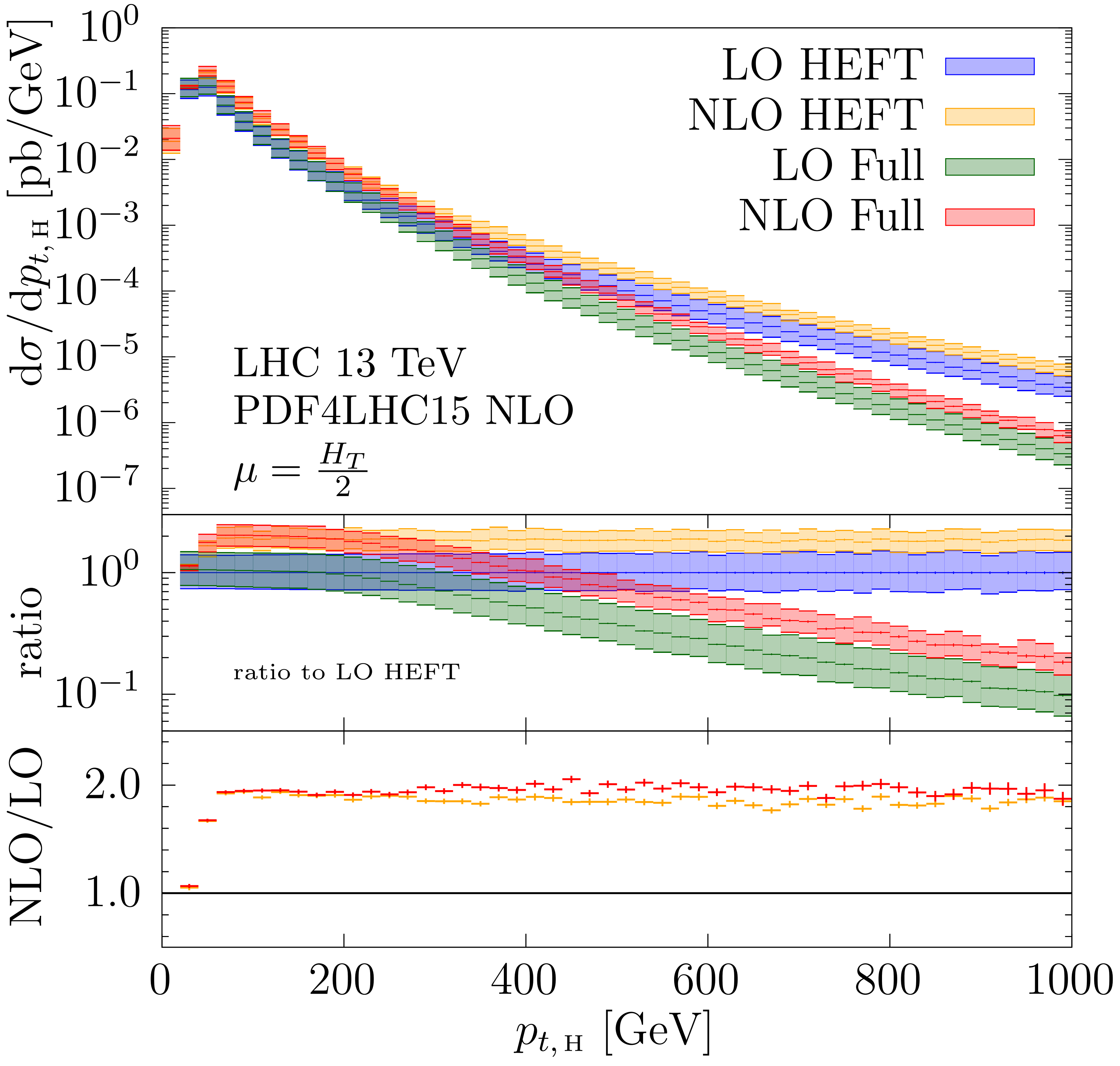


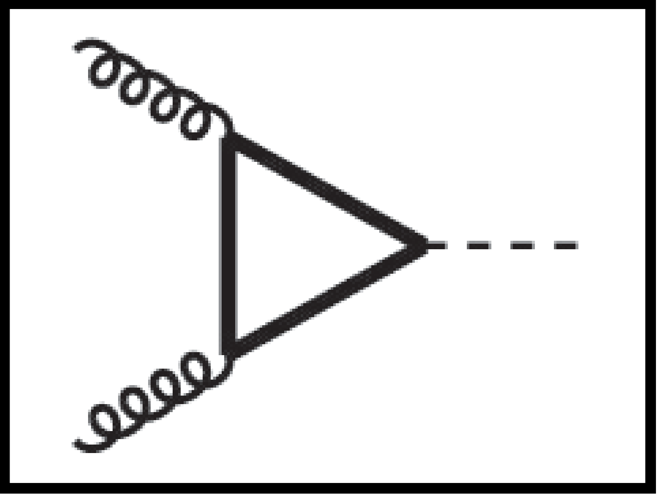
Mass effects for Higgs+jets @ NLO(+PS)



H+jet @ NLO in full theory

[Jones, Kerner, Luisoni '18]





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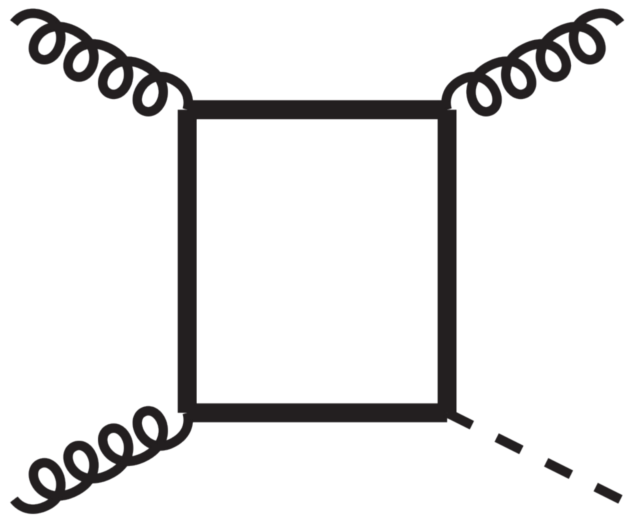

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State-of-the-art mass effects in Higgs MC:

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1. H+0/1/2-jets @ NLO+PS (FxFx, MG5)
2. full m_{top} and m_{bottom} for H+0-jet
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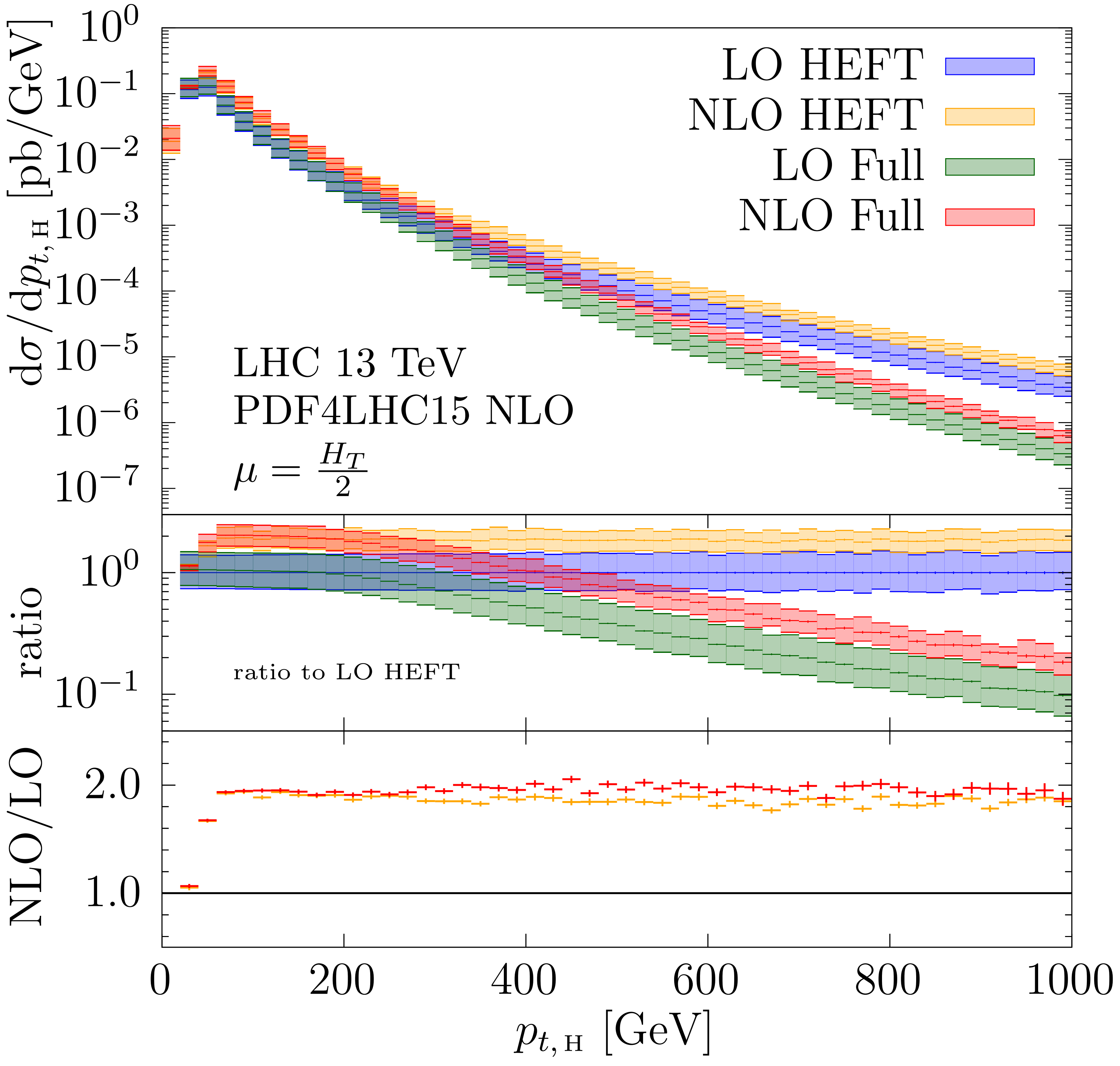
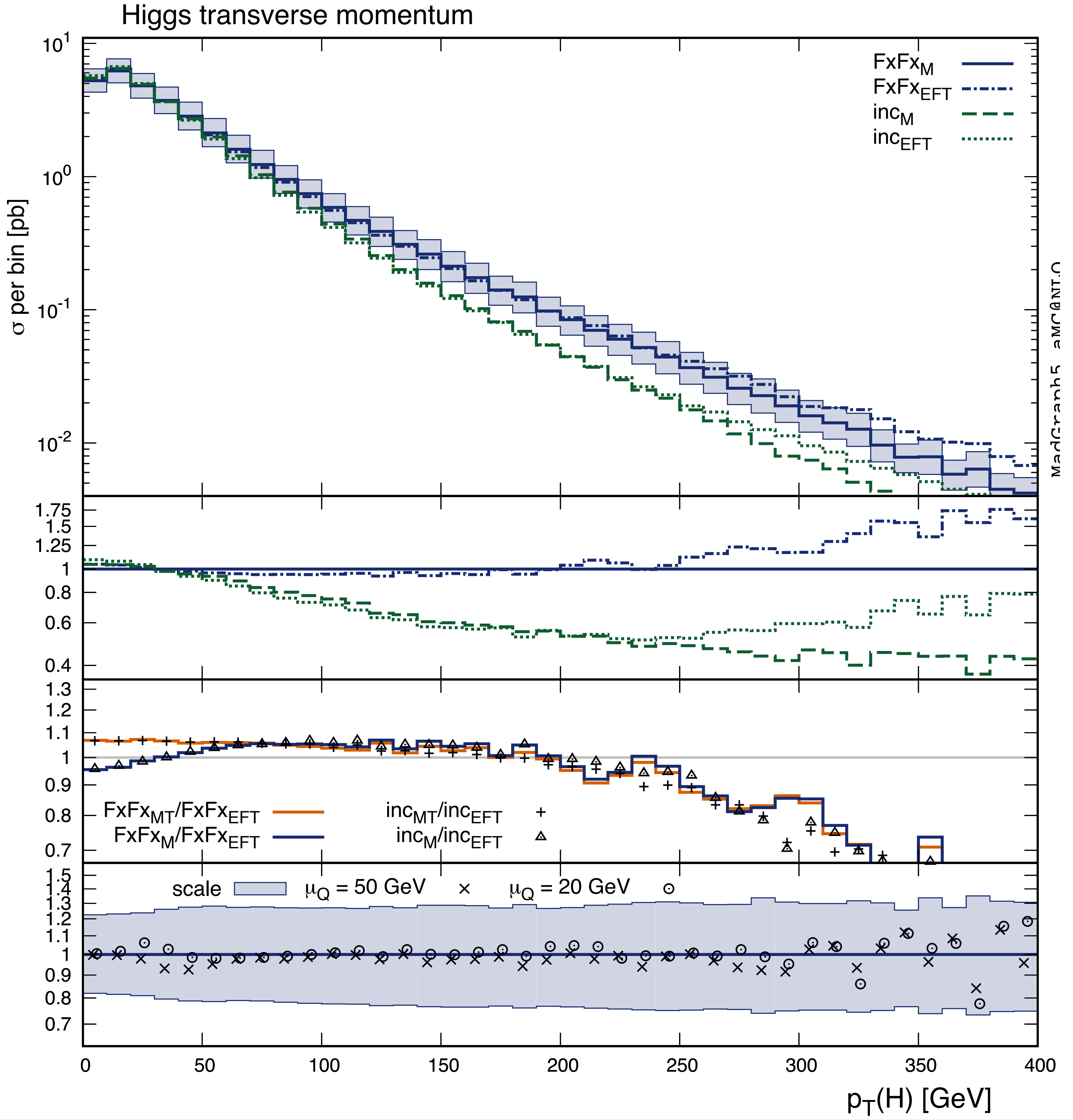
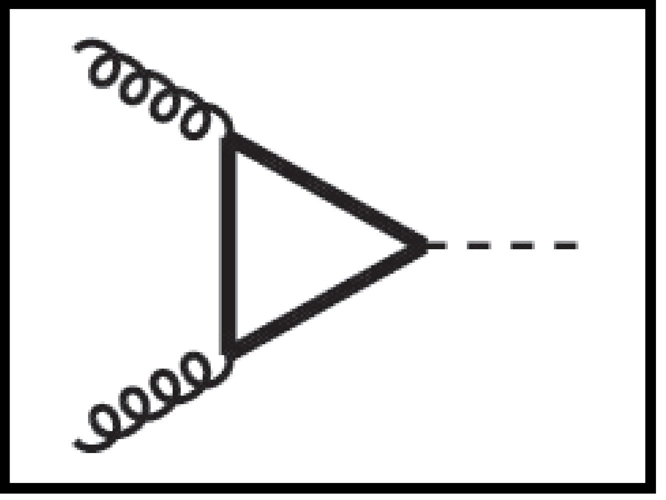
FTapprox: full born & real, virtual reweighted:

$$\mathrm{virt}(m_t) \approx \mathrm{born}(m_t) \cdot \mathrm{virt(HTL)}/\mathrm{born(HTL)}$$







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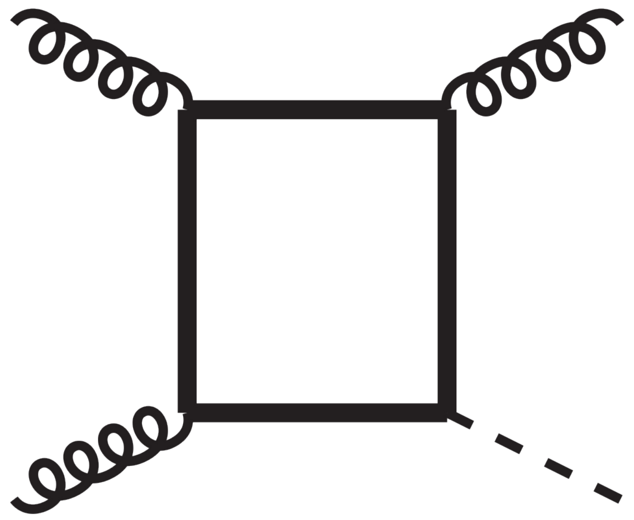

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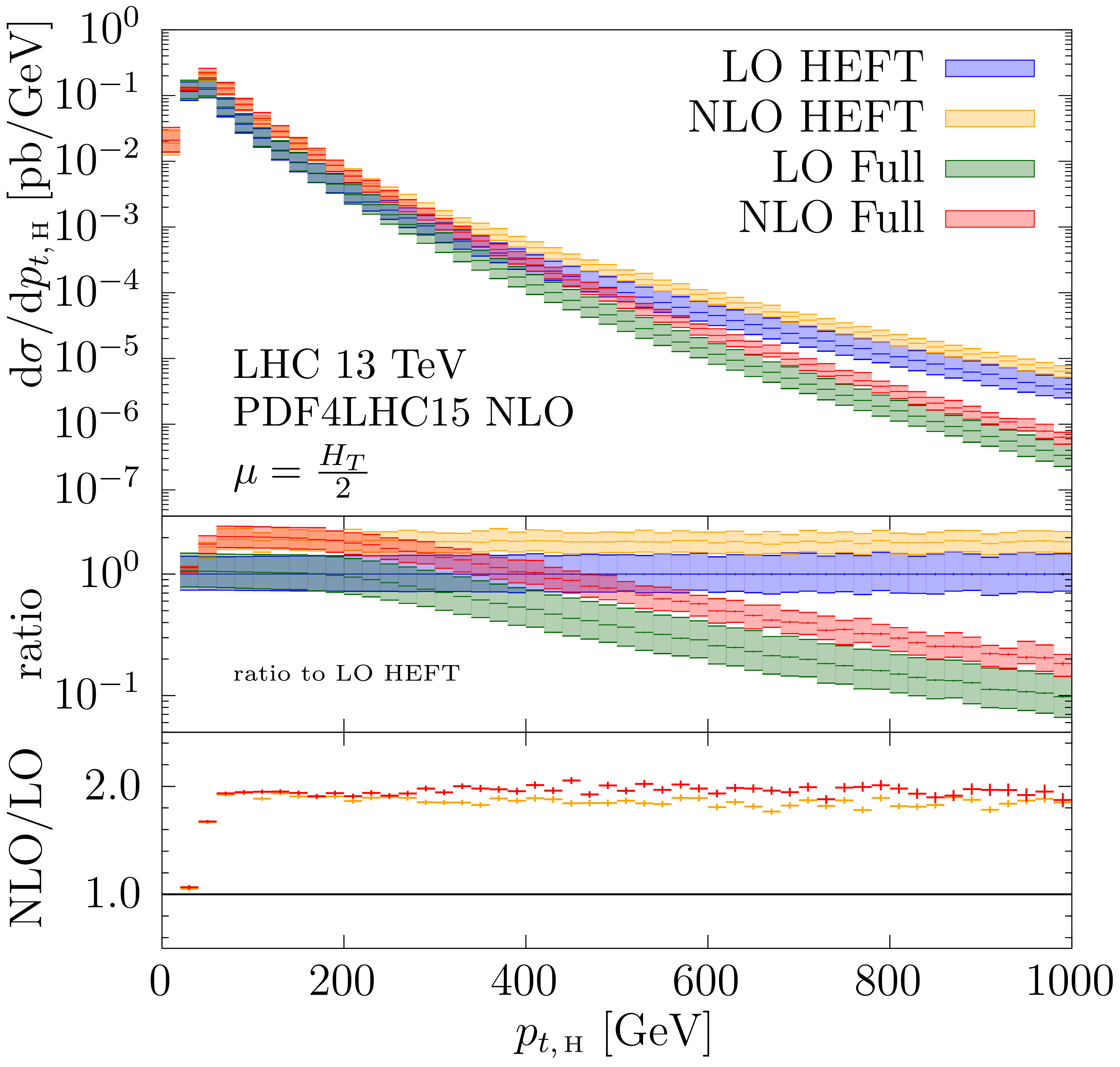

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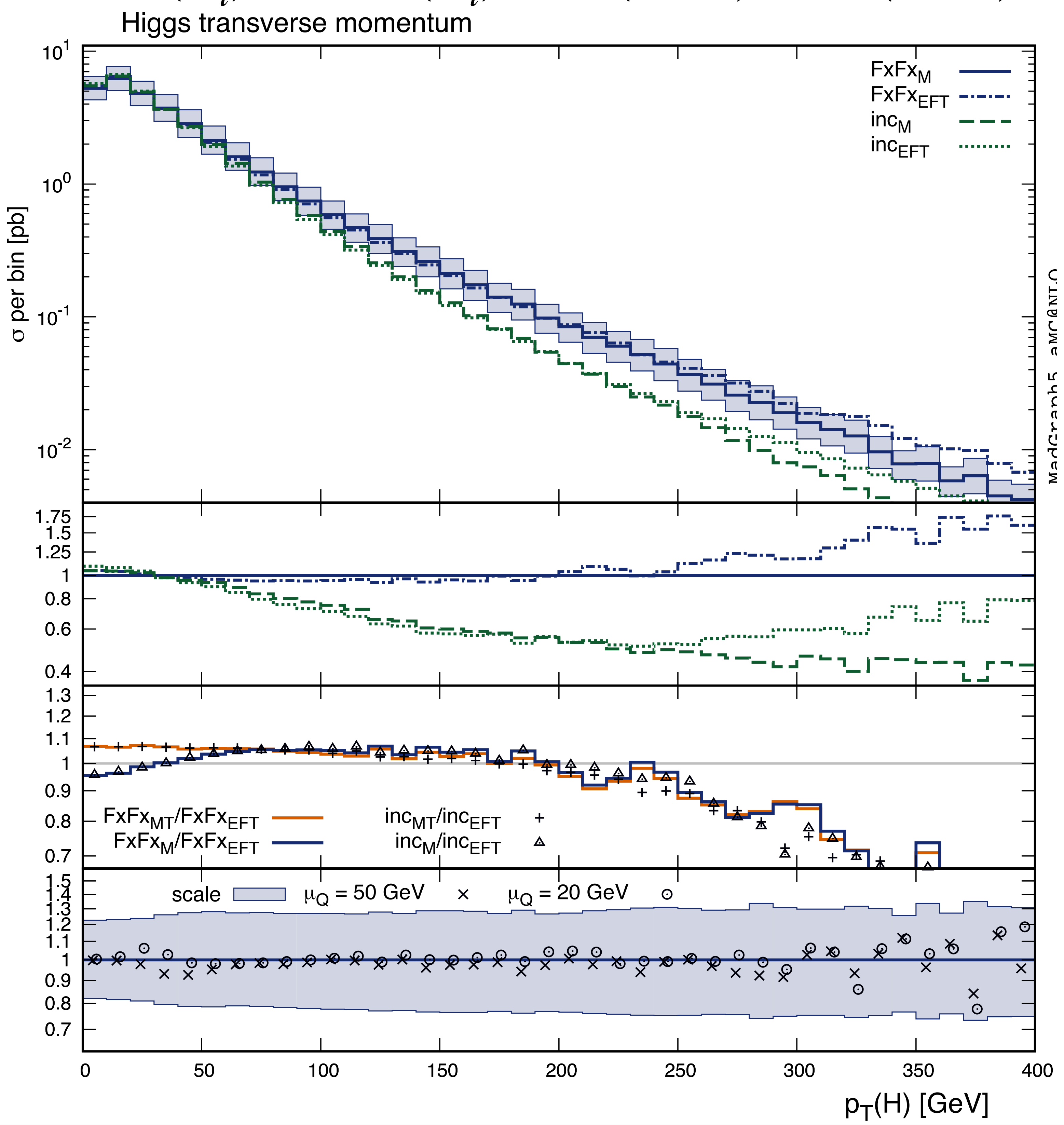
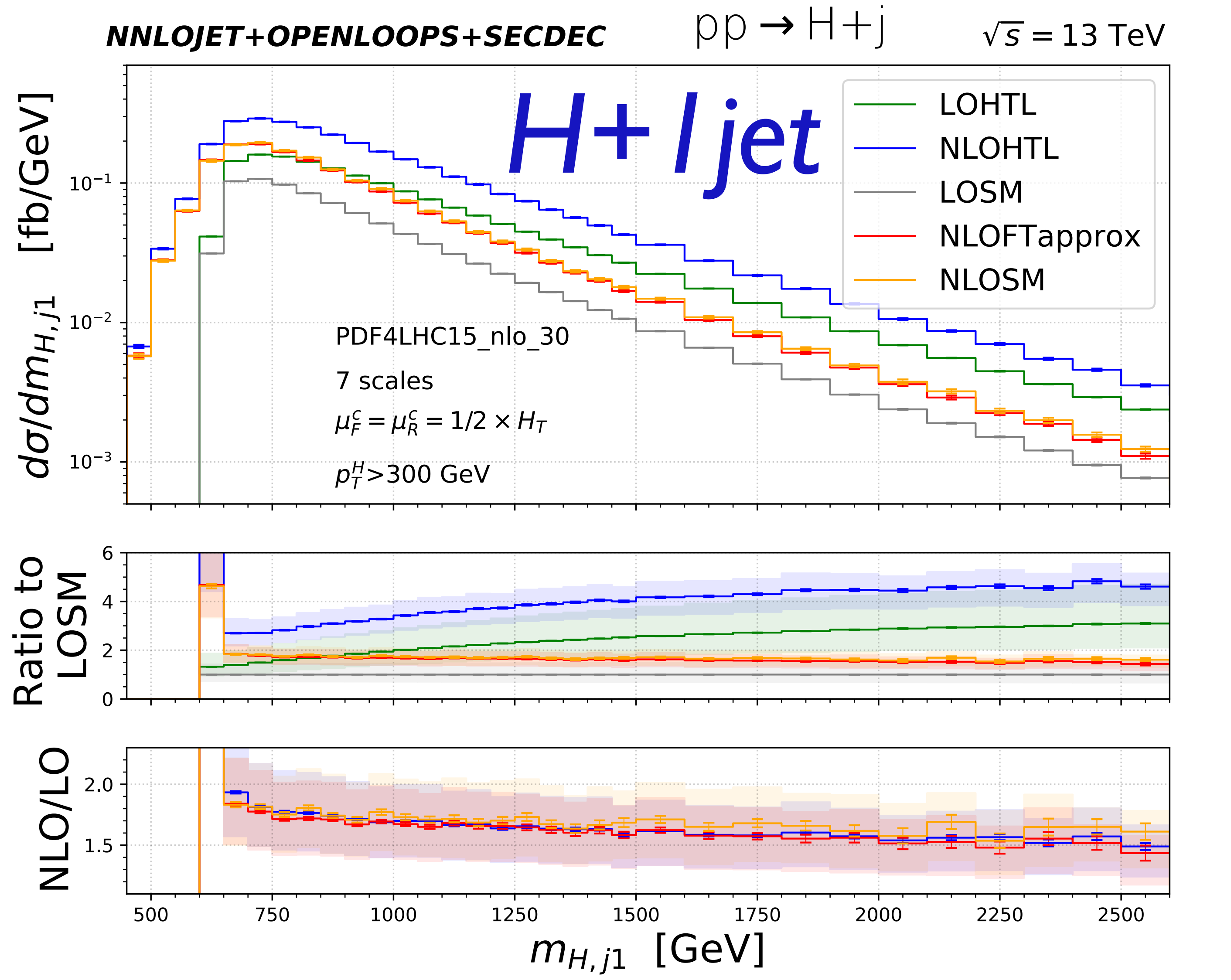
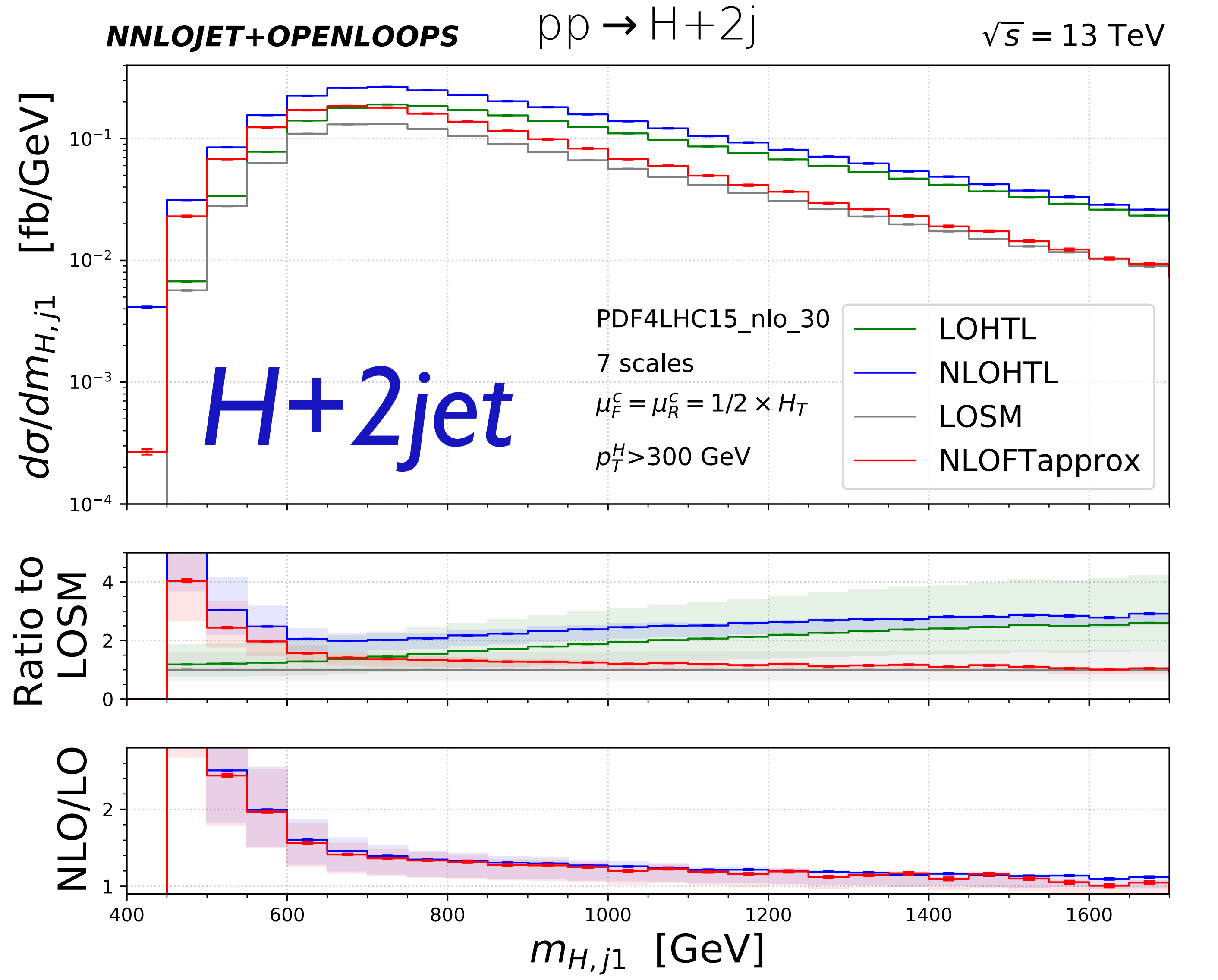
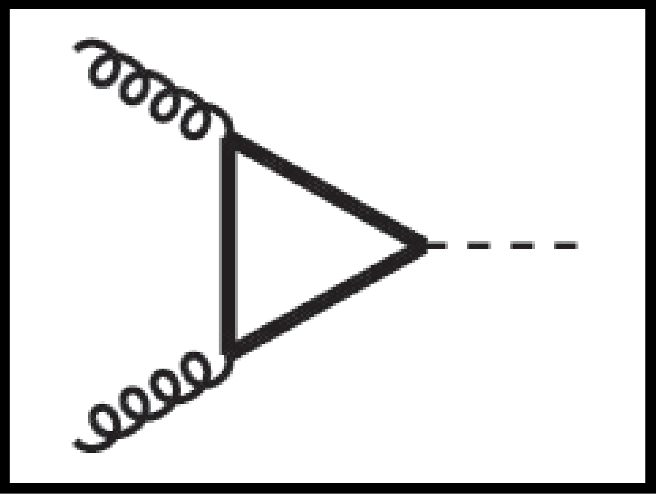


[Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang '21]







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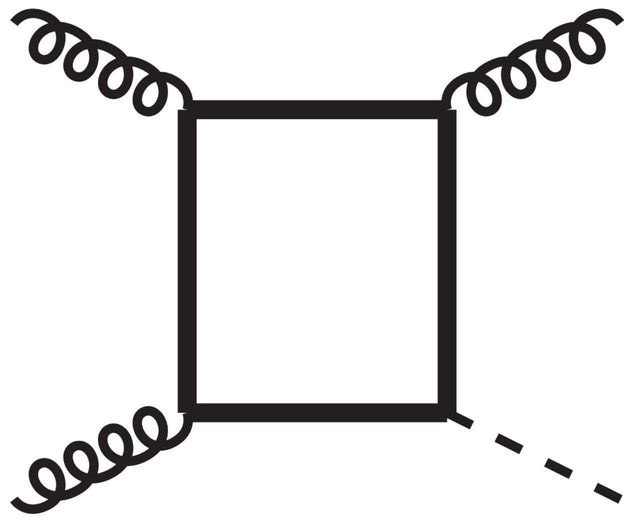

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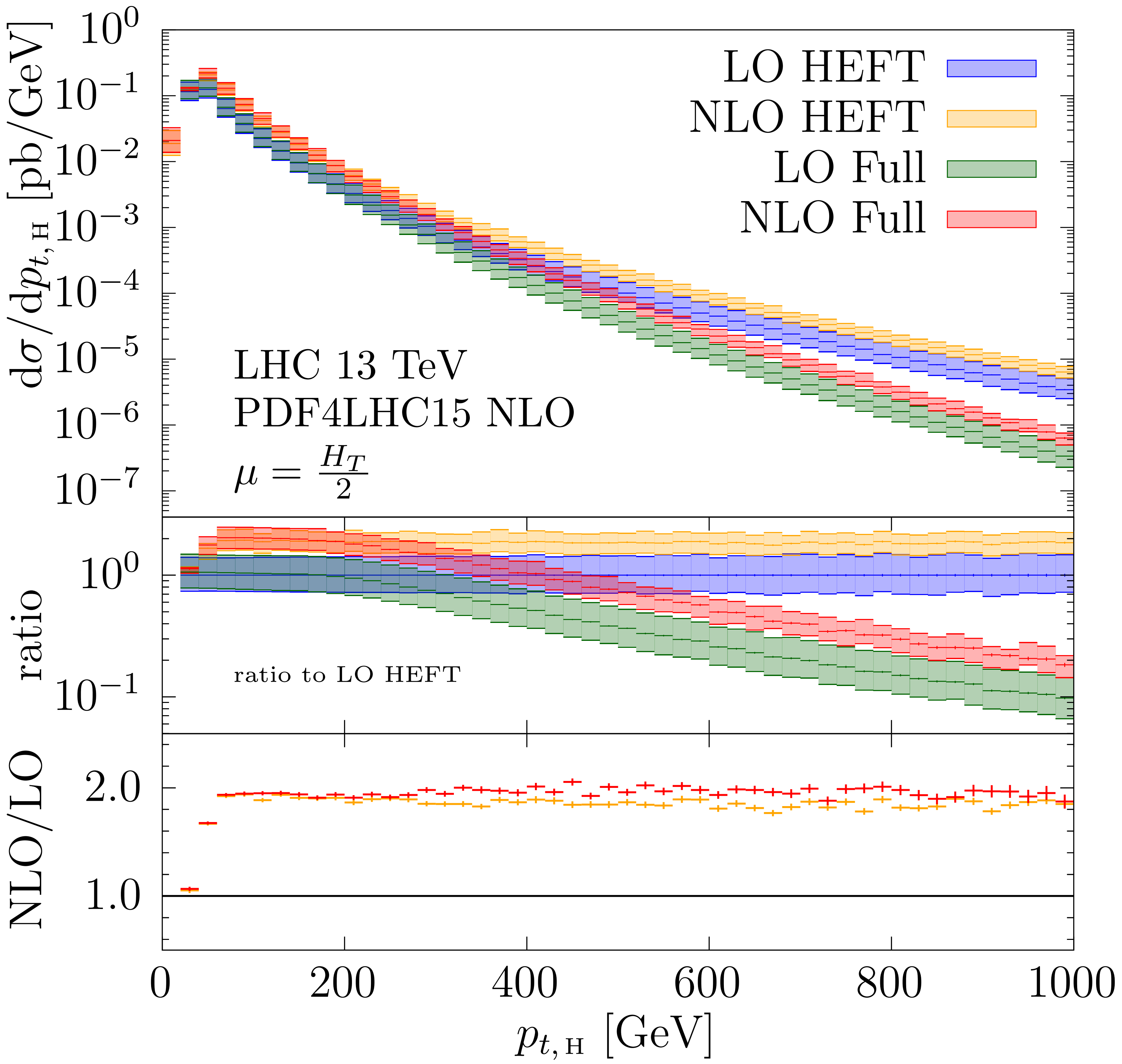

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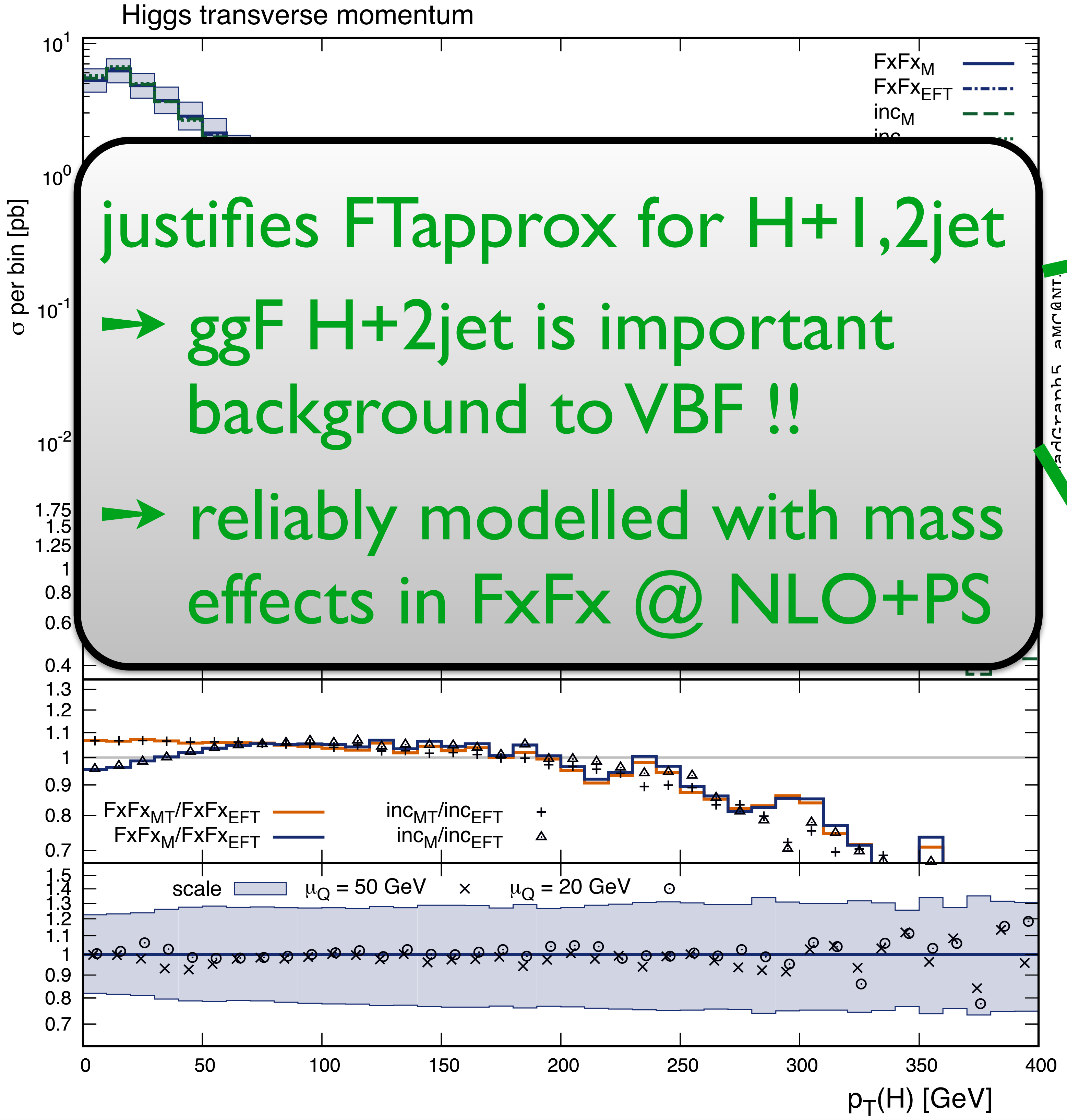
3. m_{top} through FTapprox for H+1,2-jets

FTapprox: full born & real, virtual reweighted:

$$\mathrm{virt}(m_t) \approx \mathrm{born}(m_t) \cdot \mathrm{virt(HTL)}/\mathrm{born(HTL)}$$

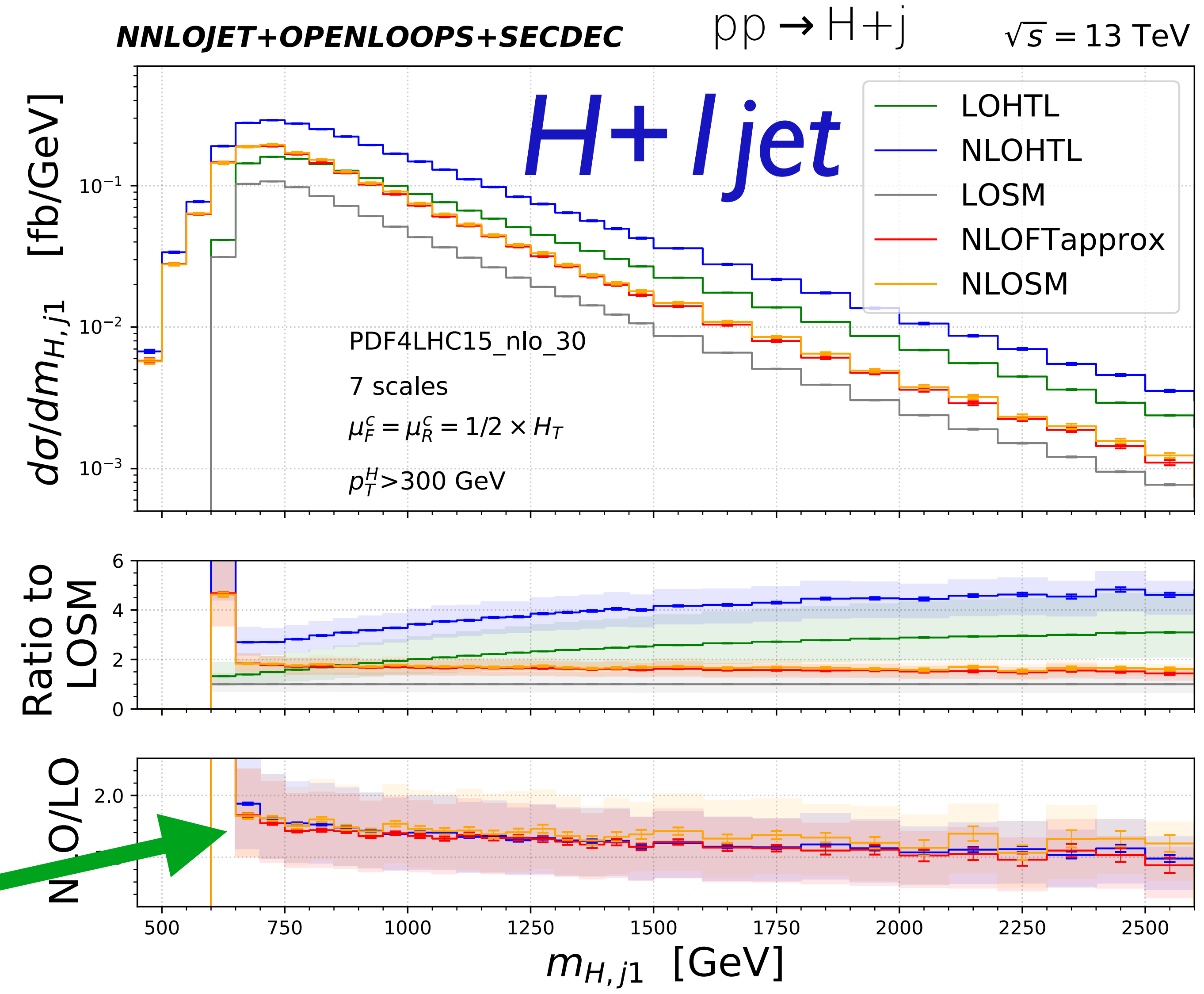


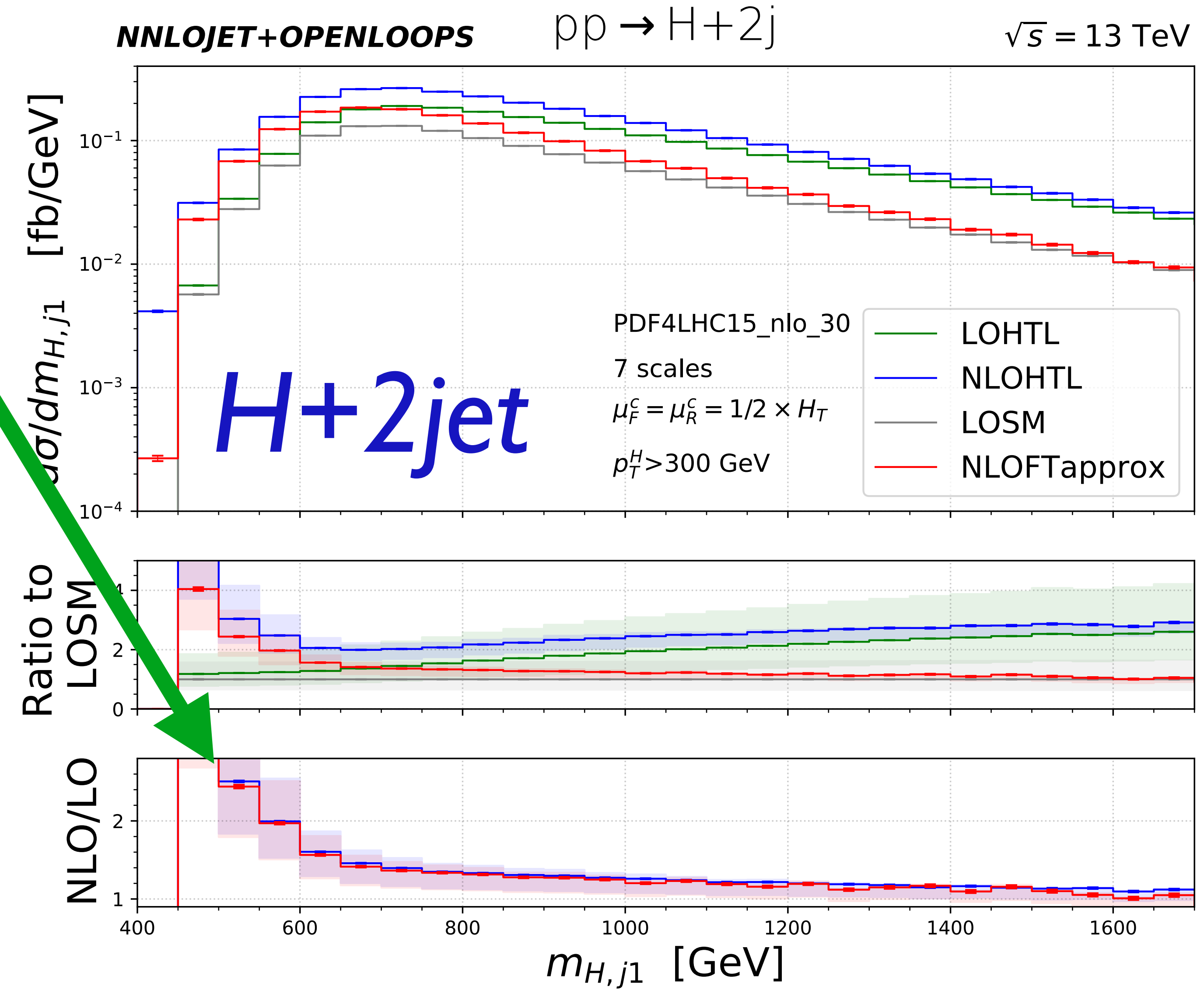
justifies FTapprox for H+1,2jet

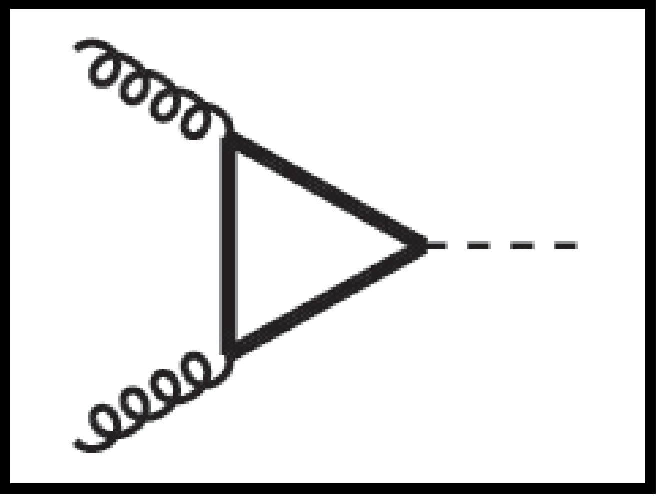
→ ggF H+2jet is important background to VBF !!

→ reliably modelled with mass effects in FxFx @ NLO+PS

[Chen, Huss, Jones, Kerner, Lang, Lindert, Zhang '21]







inclusive ggF @ NNLO in full theory

[Czakon, Harlander, Klappert, Niggetiedt '20]

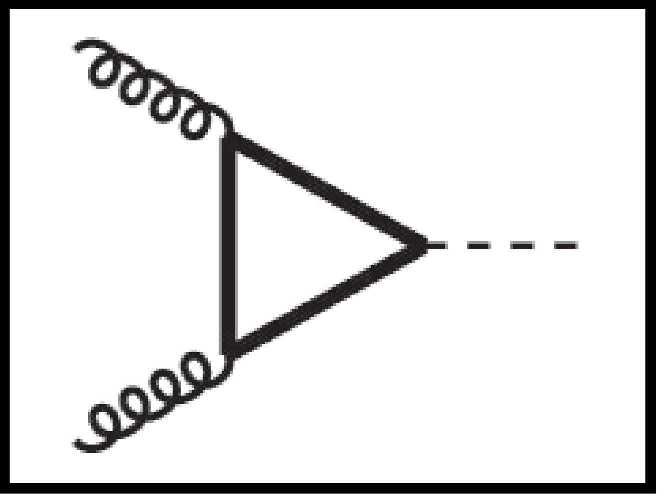
remarkable calculation!

includes full m_t 1,2,3-loop for H+0-jet, full m_t 1,2-loop for H+jet and full m_t 1-loop for H+2jet

channel	$\sigma^{\rm NNLO}_{\rm HEFT}$ [pb] $\mathcal{O}(\alpha_s^2)+\mathcal{O}(\alpha_s^3)+\mathcal{O}(\alpha_s^4)$	$(\sigma^{\rm NNLO}_{\rm exact}-\sigma^{\rm NNLO}_{\rm HEFT})$ [pb] $\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^4)$	$(\sigma^{\rm NNLO}_{\rm exact}/\sigma^{\rm NNLO}_{\rm HEFT}-1)$ [%]
		$\sqrt{s}=8$ 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
		$\sqrt{s}=13$ 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

→ $-0.26\,\%$ *top-mass effects on total inclusive cross section (note: large cancellations)*

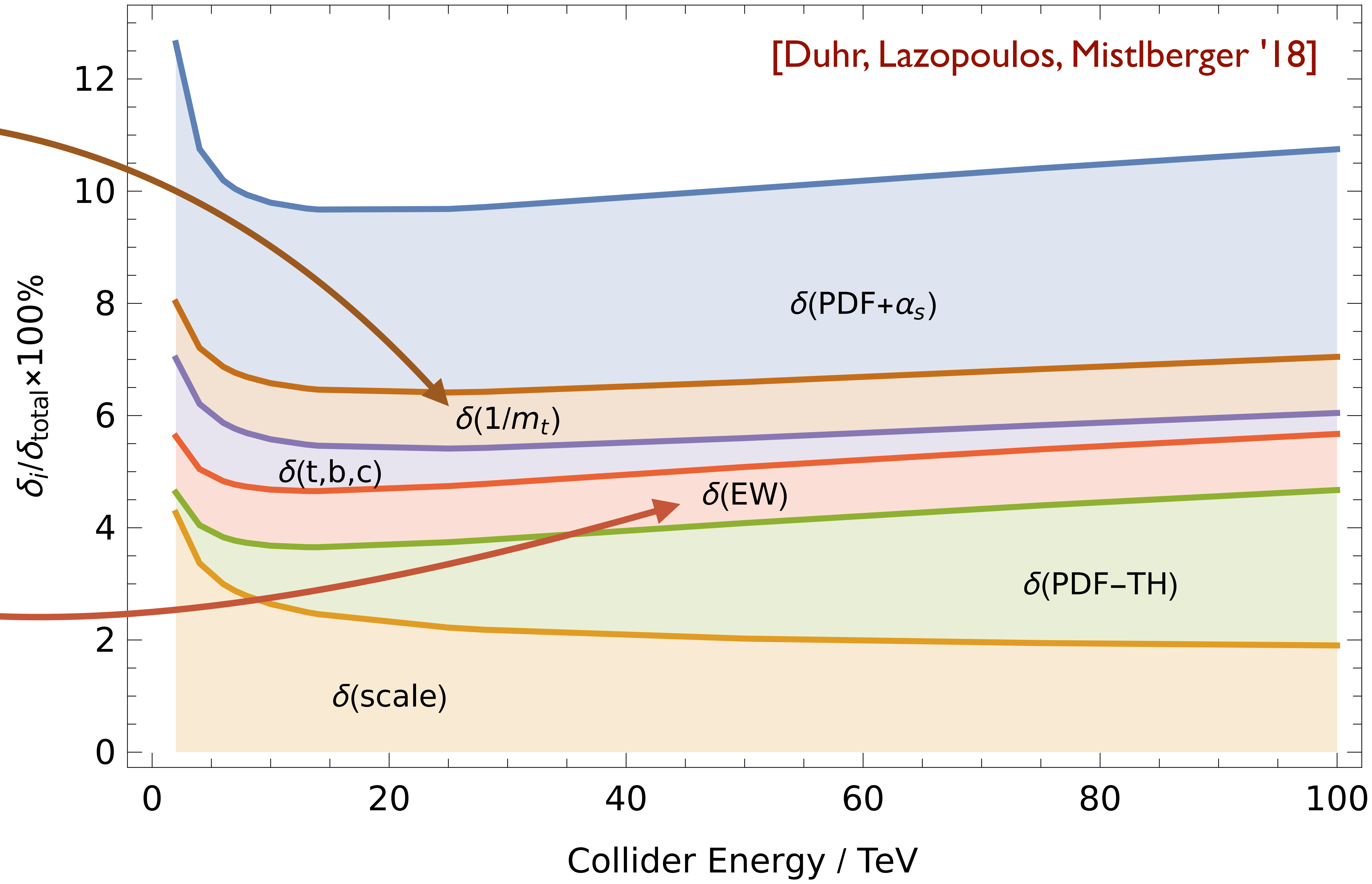
in the future: extension to differential NNLO and NNLO+PS possible

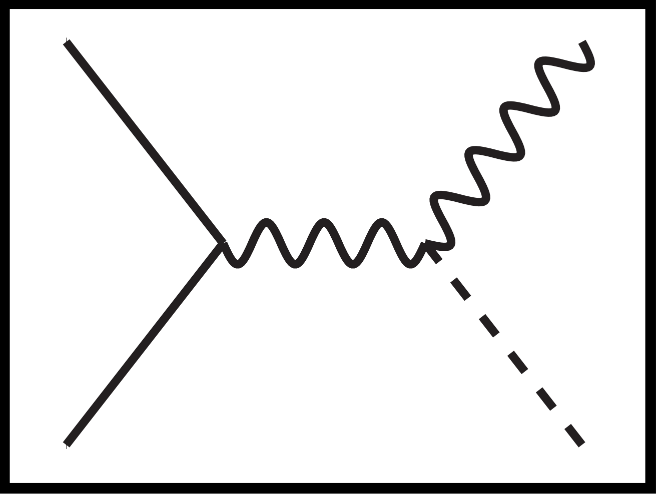


ggF error budget of inclusive XS

essentially removed
[Czakon, Harlander, Klappert, Niggetiedt '20]

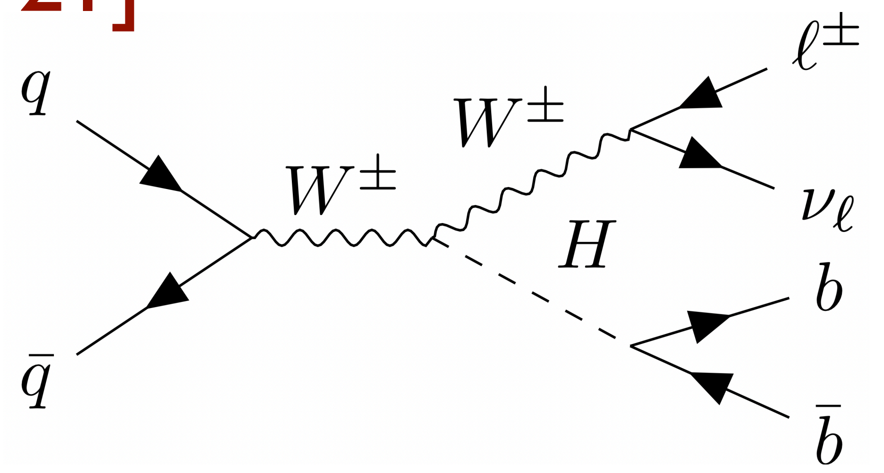
reduced to ~0.6% through mixed QCDxEW corrections
[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]

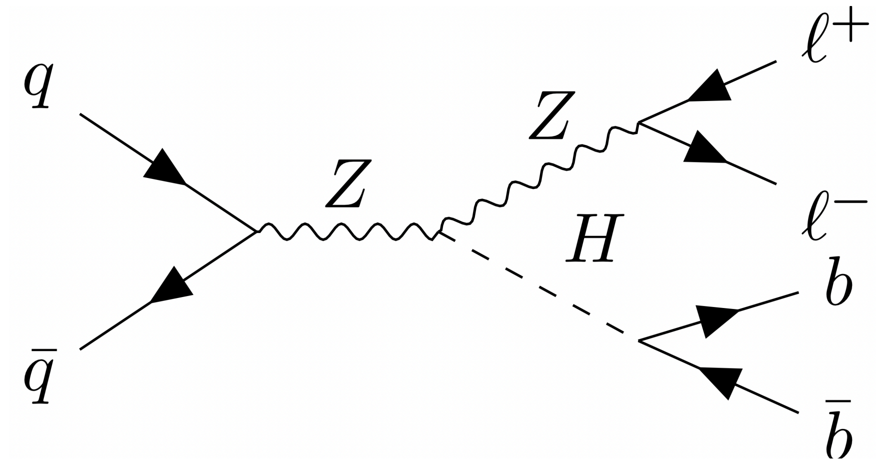




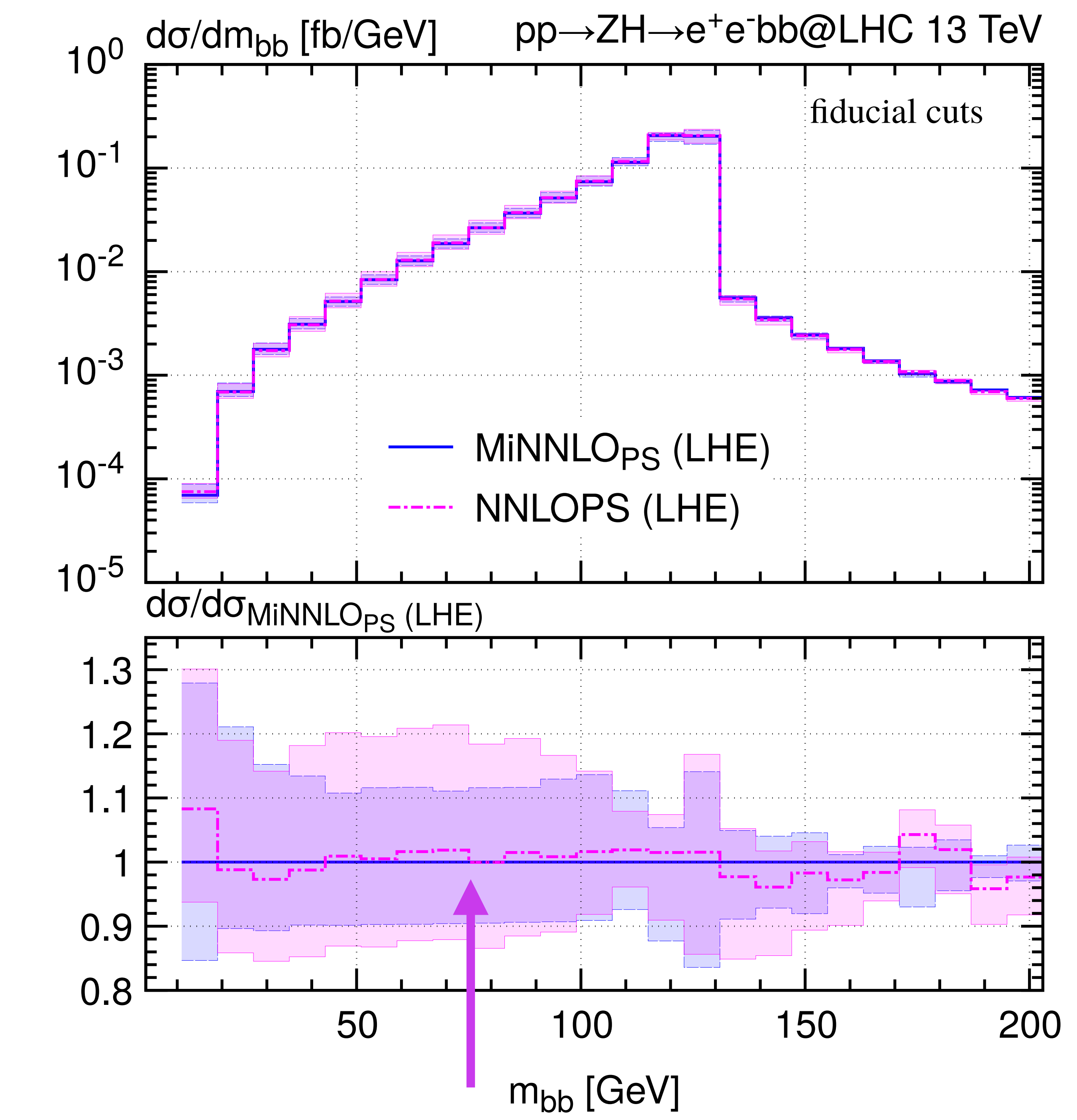
VH x H→bb @ NNLO+PS

[Zanoli, Chiesa, Re, MW, Zanderighi '21]

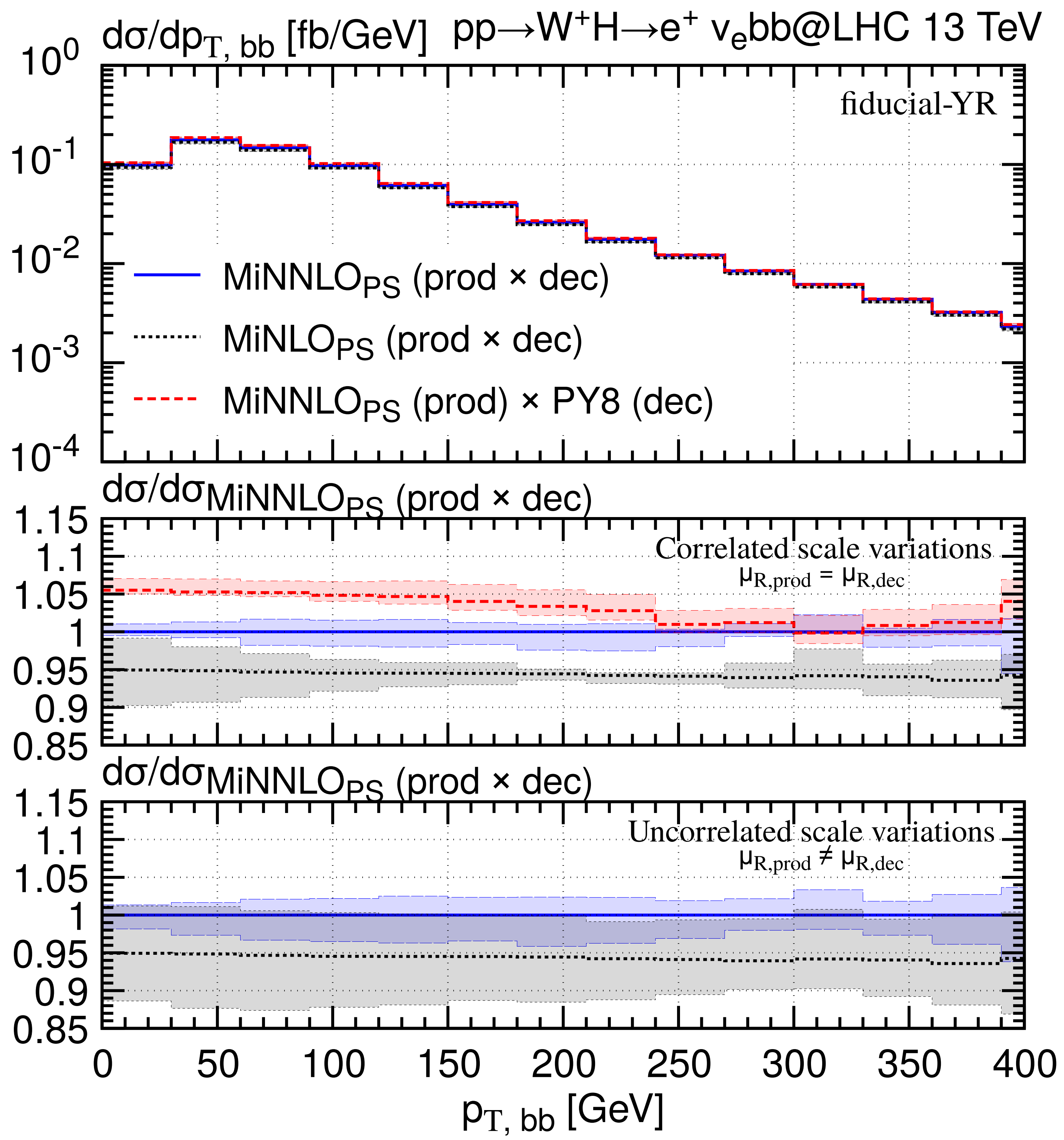


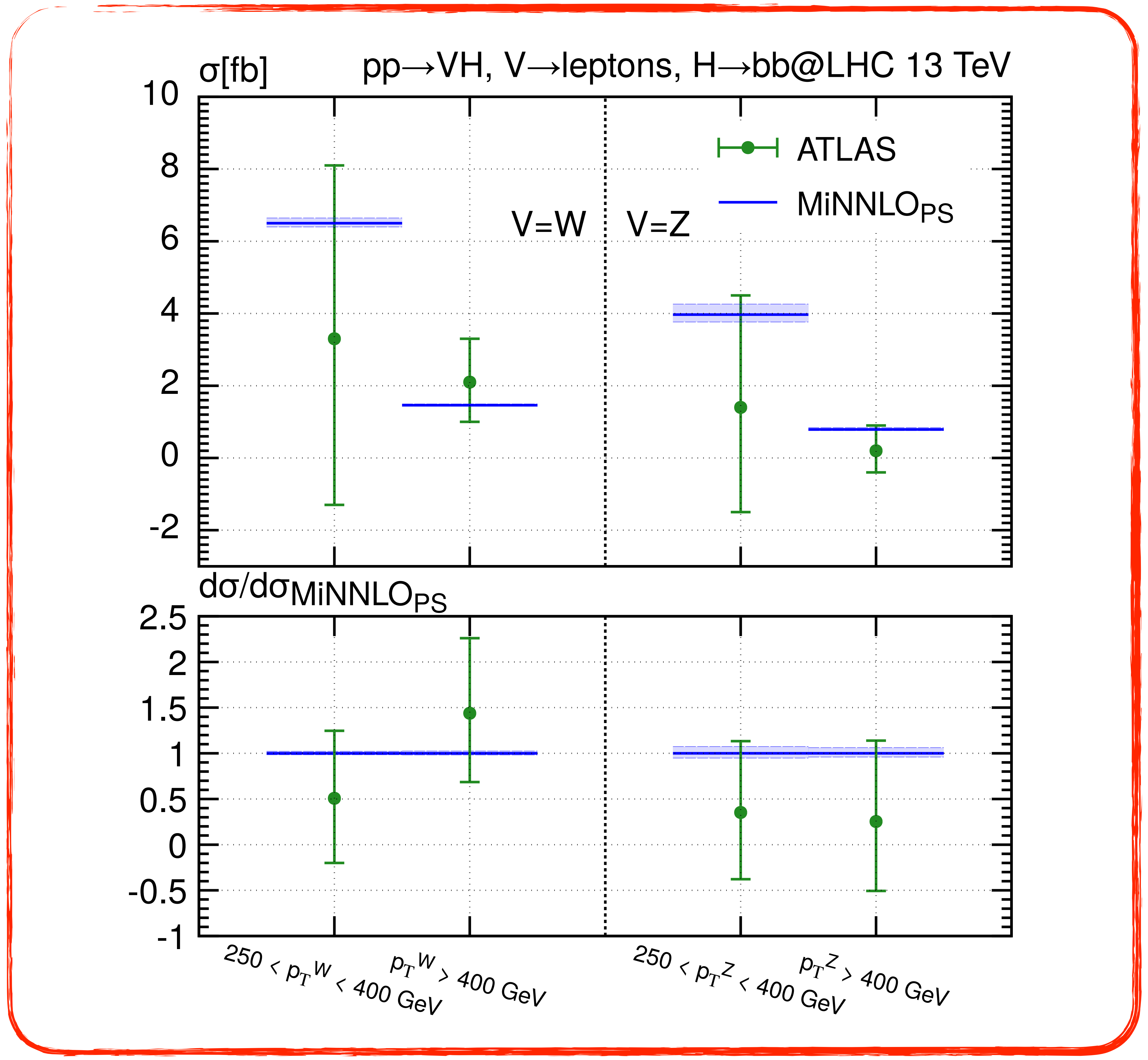


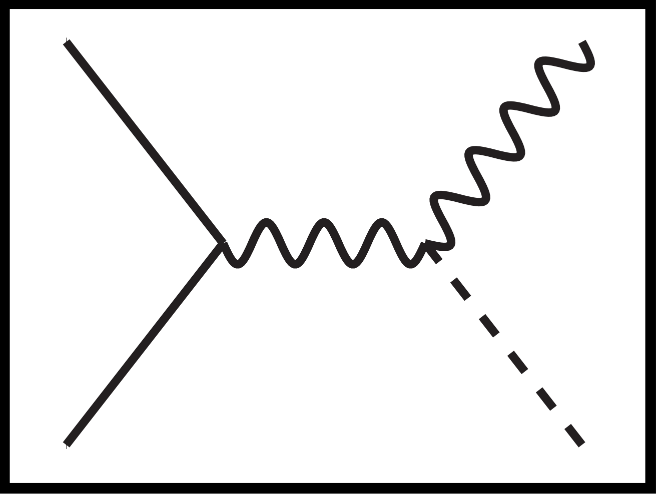
- ***NNLO+PS** accuracy in both **production** and **decay***
  see also [Alioli et al. '19] see also [Alioli et al. '20]
- *includes NNLO directly in event generation through **MiNNLO$_{PS}$ method***
  [Monni, Nason, Re, Zanderighi, MW '19], [Monni, Re, MW '20]
- *main production channel to observe $H \to b\bar{b}$ (largest branching fraction)*



agrees well with **NNLOPS** (MiNLO+reweighting)
[Bizoń, Re, Zanderighi '19]



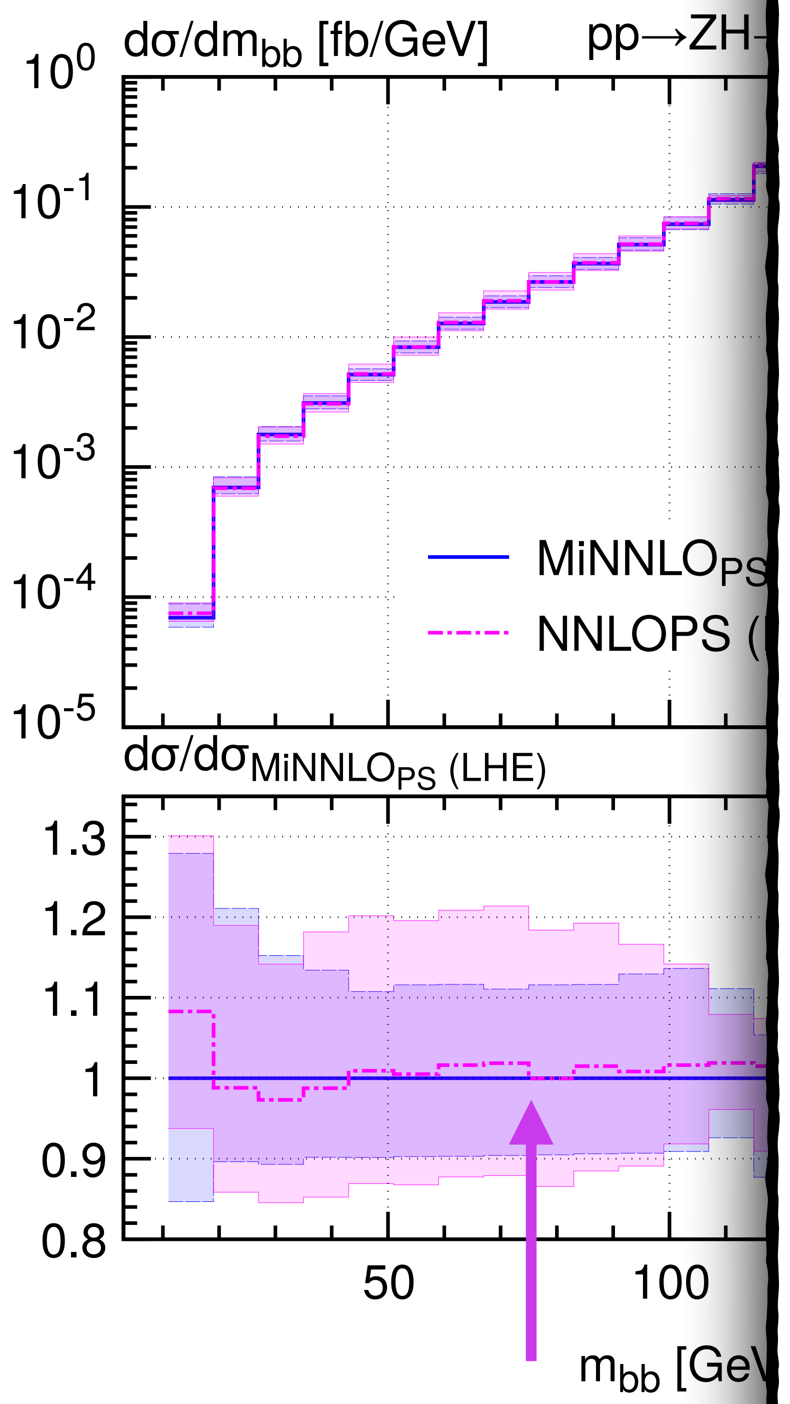




❖ ***NNLO+PS*** *acc*

❖ *includes NNLO d*

❖ *main production c*

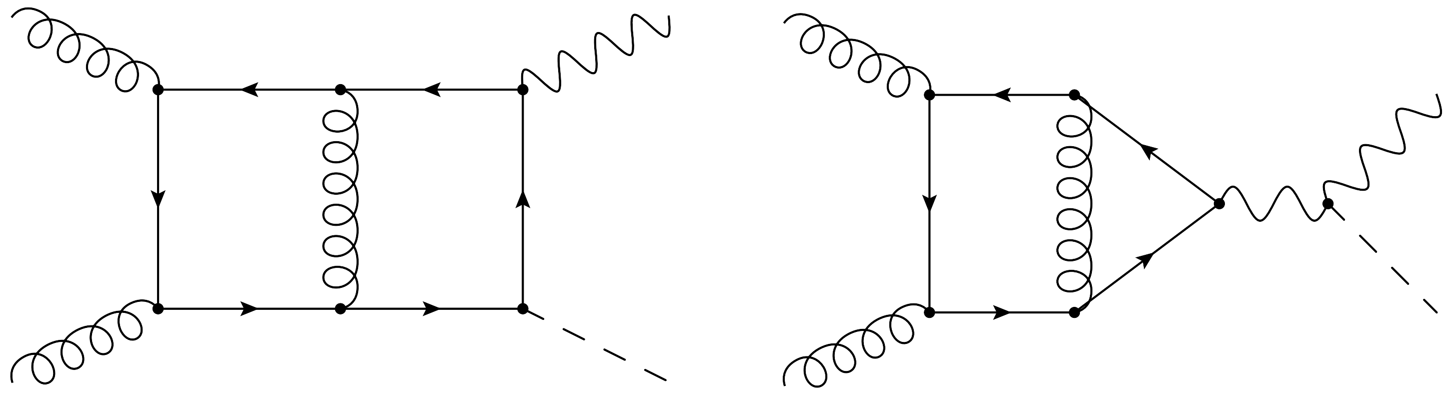


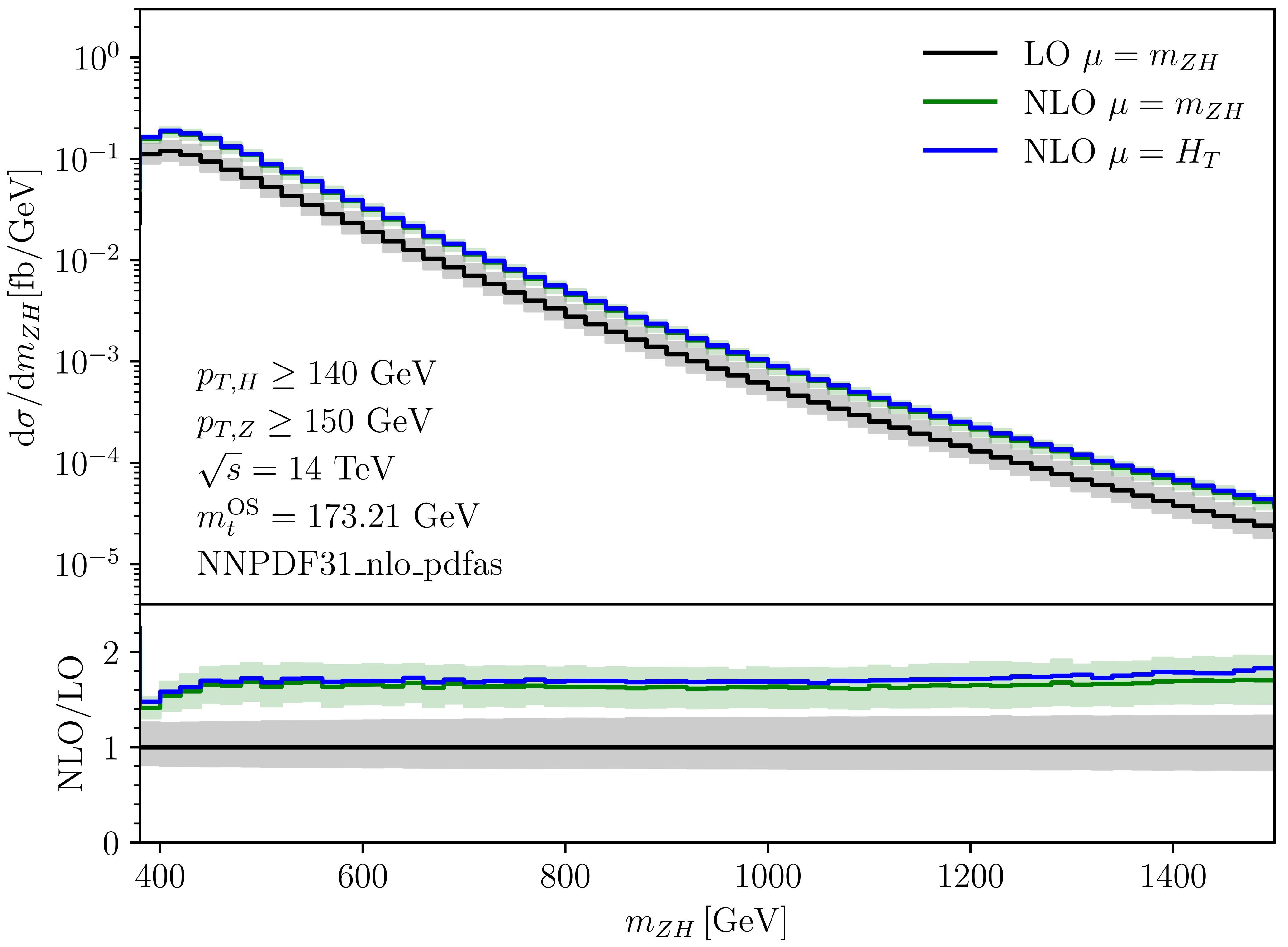
agrees well with **NNLOPS** (

[Bizoń, Re, Za

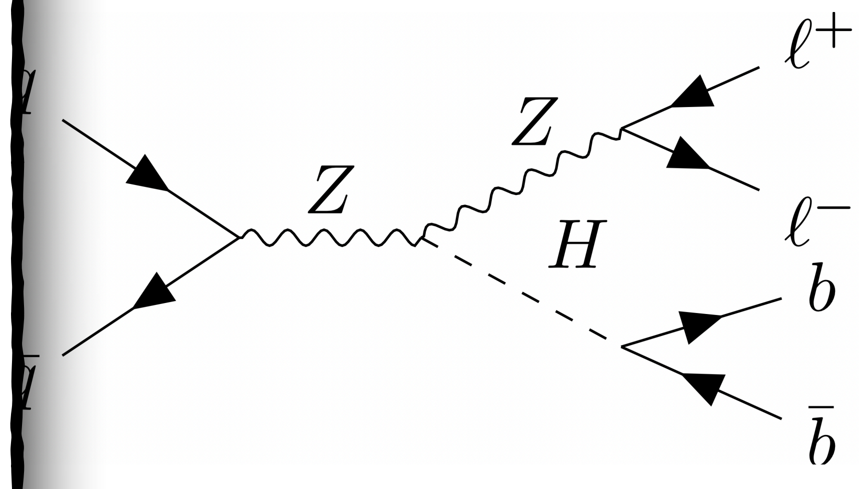
just today: gg → ZH @ NLO

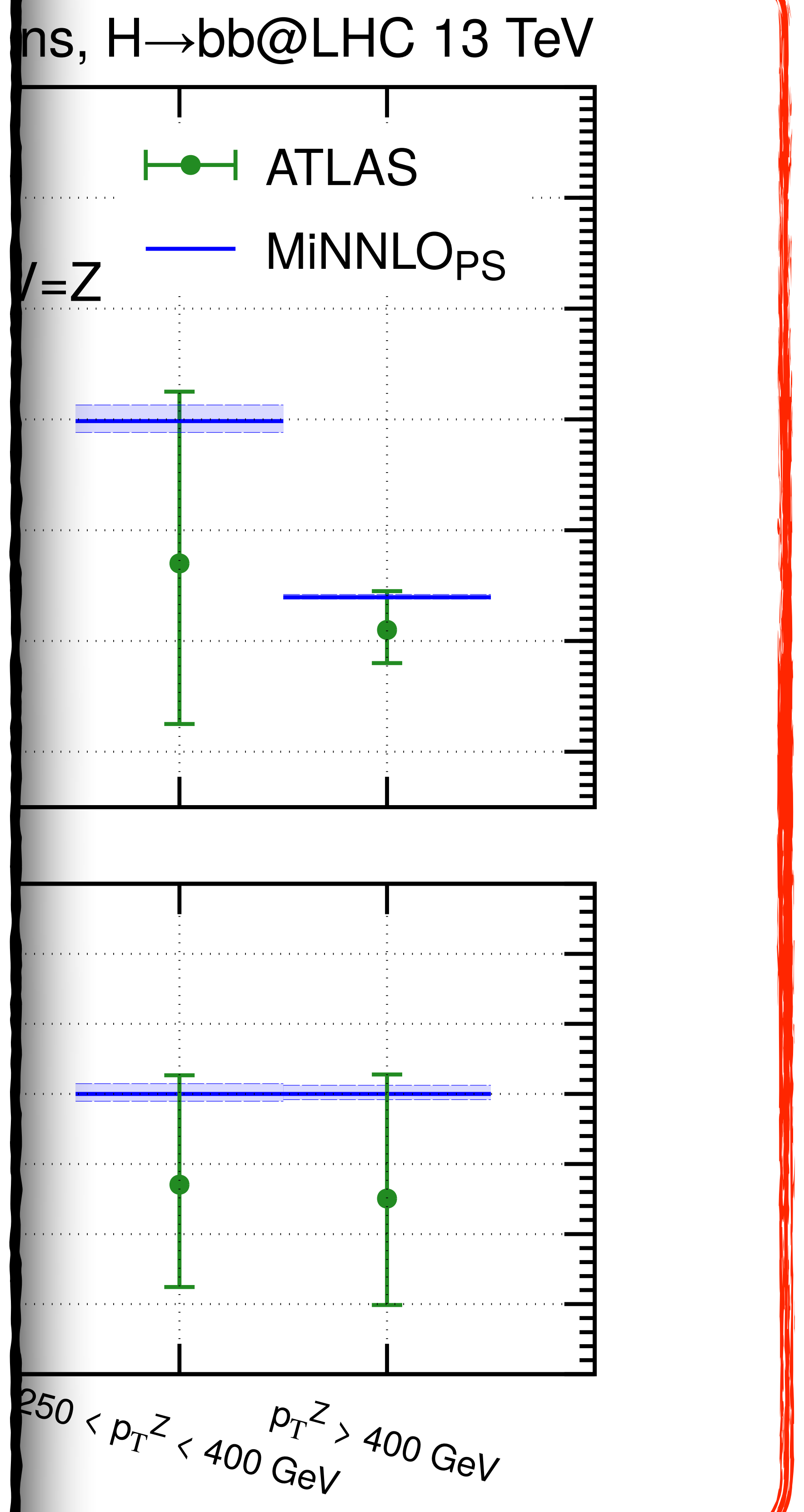
[Chen, Davies, Heinrich, Jones, Kerner, Mishima, Schlenk, Steinhauser '22]

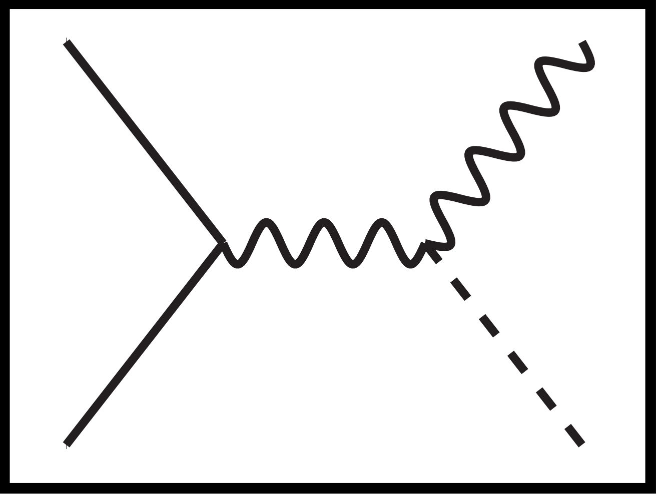




→ K-factor of almost 2!







SMEFT: VH x H→bb @ NNLO+PS

[Haisch, Scott, MW, Zanderighi, Zanoli '22]

$$Q_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)\,, \qquad Q_{HD} = (H^\dagger D_\mu H)^*\,(H^\dagger D^\mu H)\,,$$

$$Q_{bH} = y_b\,(H^\dagger H)\,\bar{q}_L b_R H\,, \qquad Q_{bG} = \frac{g_s^3}{(4\pi)^2}\,y_b\,\bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu}\,,$$

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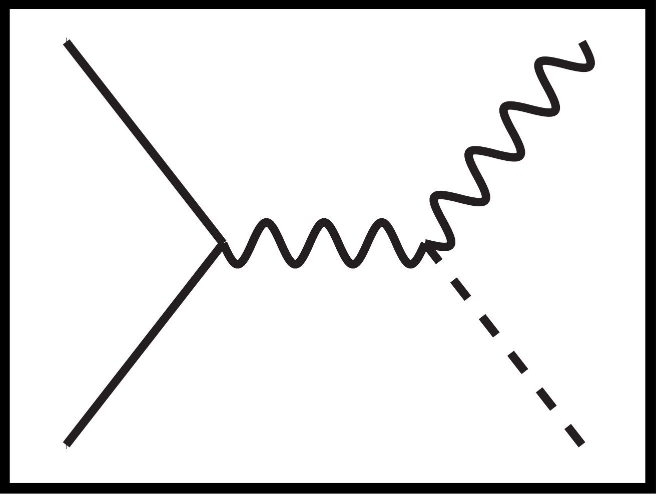

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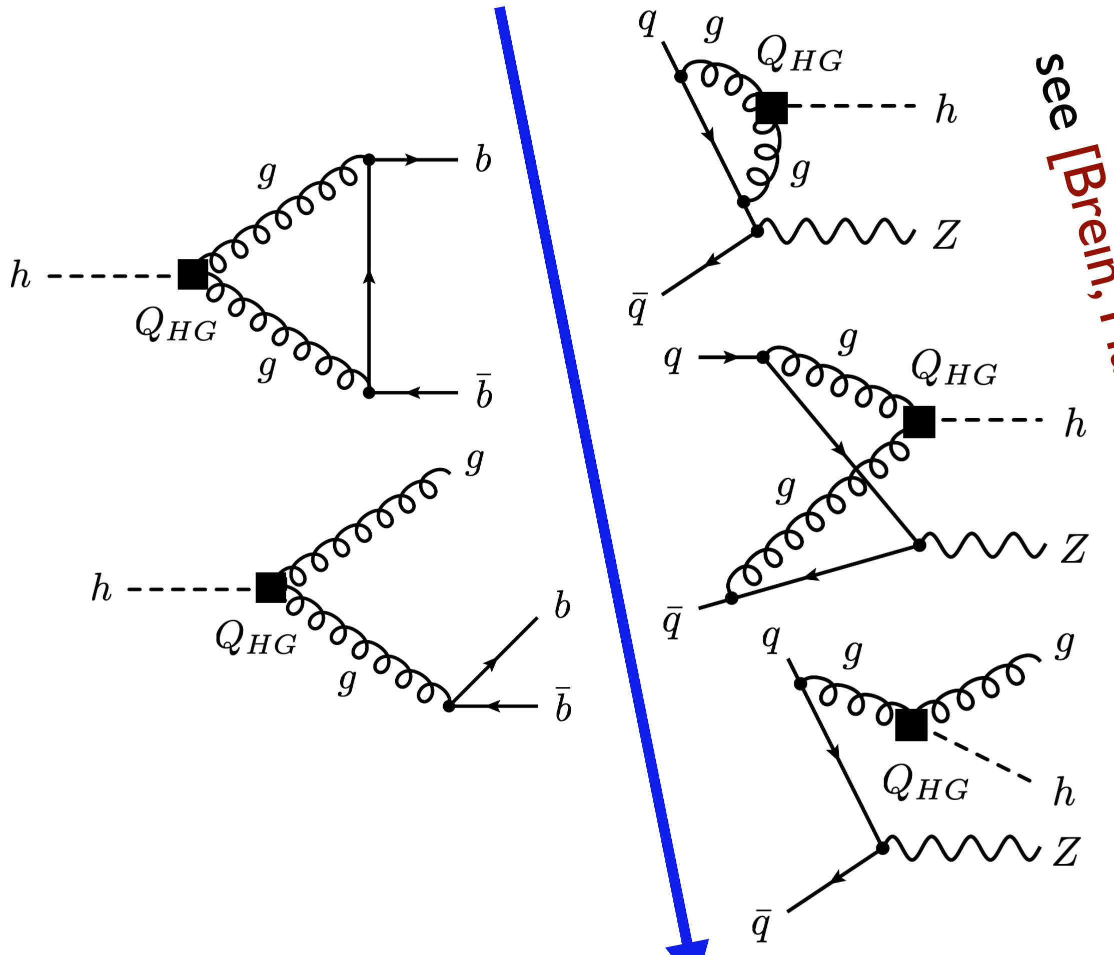
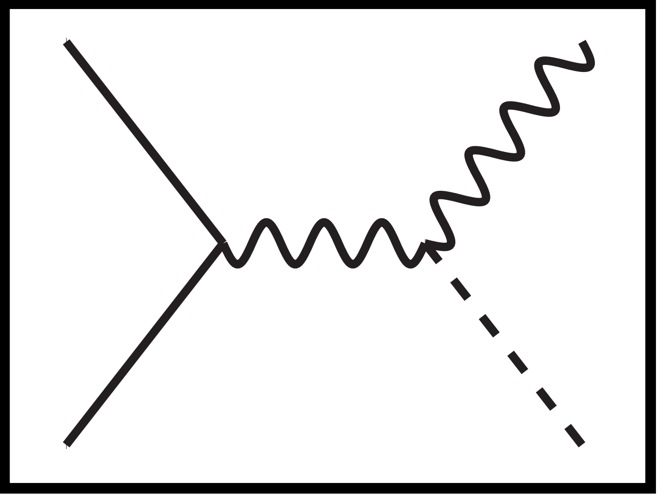


see [Brein, Harlander, MW, Zirke '11]

negligible impact already with current constraints



SMEFT: VH x H→bb @ NNLO+PS

[Haisch, Scott, MW, Zanderighi, Zanoli '22]

factorizable contributions, included through: $y_b^2 \to y_b^2\,(1+2c_{\rm fac})\,, \quad c_{\rm fac} = c_{\rm kin} - c_{bH}\,, \quad c_{\rm kin} = \frac{v^2}{\Lambda^2}\left[C_{H\Box} - \frac{C_{HD}}{4}\right]\,, \quad c_{bH} = \frac{v^2}{\Lambda^2}{\rm Re}\,(C_{bH})$

$$Q_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)\,, \qquad Q_{HD} = (H^\dagger D_\mu H)^*\,(H^\dagger D^\mu H)\,,$$

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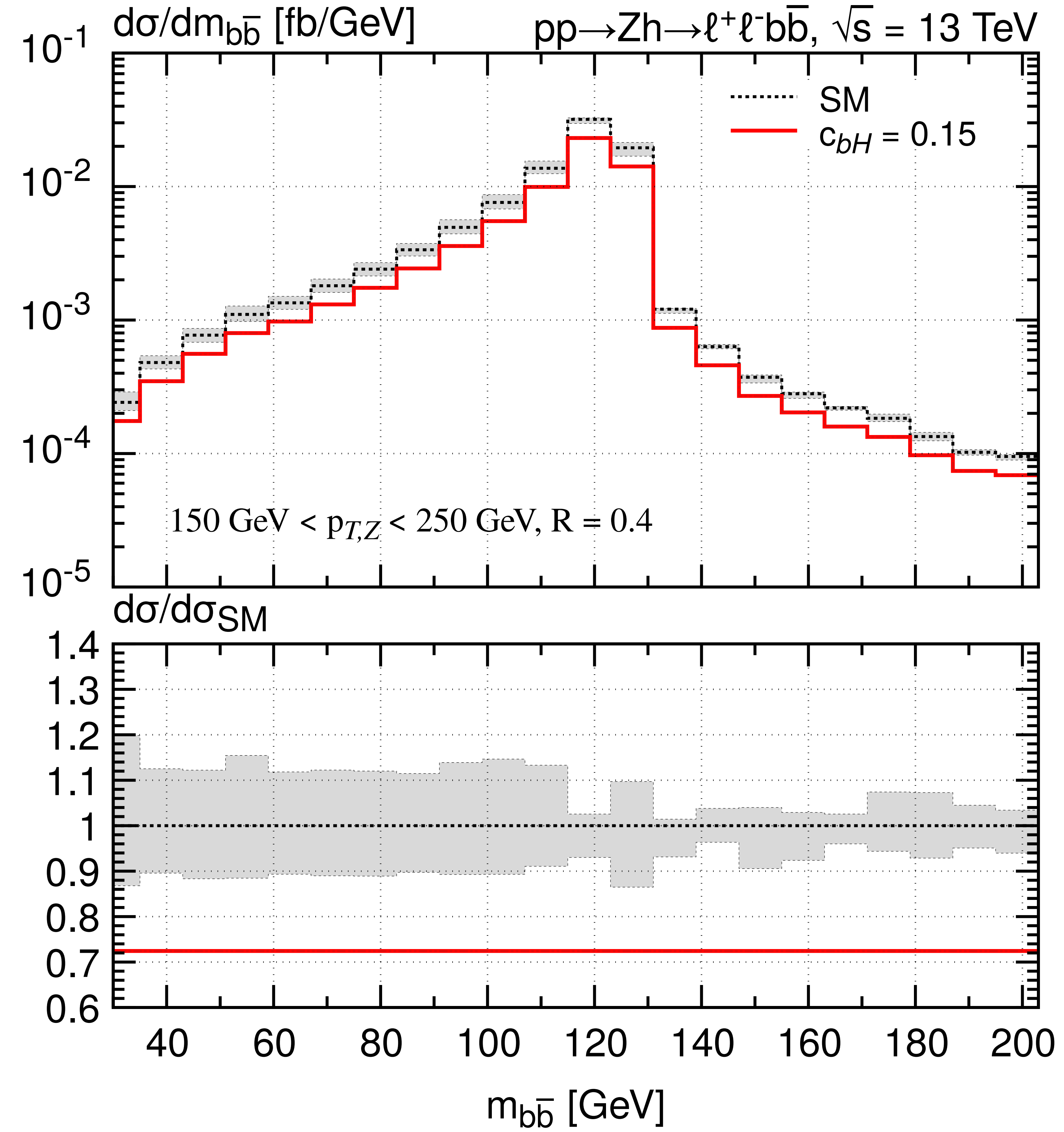
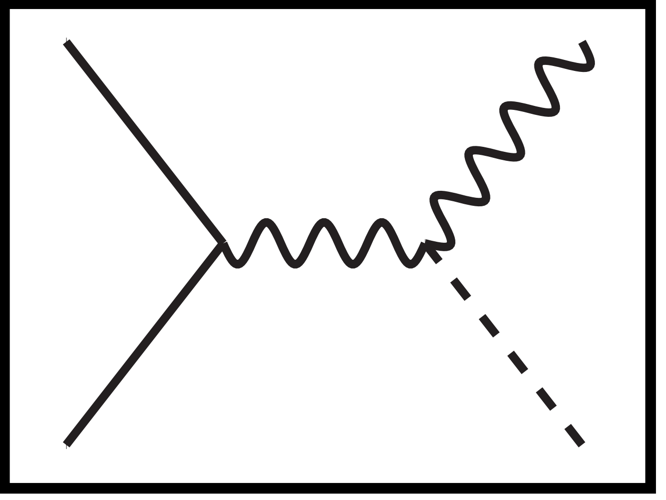
corrected Higgs width: $\Gamma_h^{\rm SMEFT} = (1+2c_{\rm kin})\left[\Gamma_h^{\rm SM} - (2\Delta c_{bH} - K_{bG}\,\Delta_{\rm non}\,c_{bG})\,\Gamma(h\to b\bar b)^{\rm LO}_{\rm SM} + 6K_{HG}c_{HG}\Gamma(h\to gg)^{\rm LO}_{\rm SM}\right].$

$$d\sigma^{\rm SMEFT}_{\rm NNLO+PS} = (1+2c_{\rm kin})^2\left\{\left[1-2c_{bH}\right]d\sigma^{\rm SM}_{\rm NNLO+PS}\right\}\frac{\Gamma_h^{\rm SM}}{\Gamma_h^{\rm SMEFT}}\,,$$





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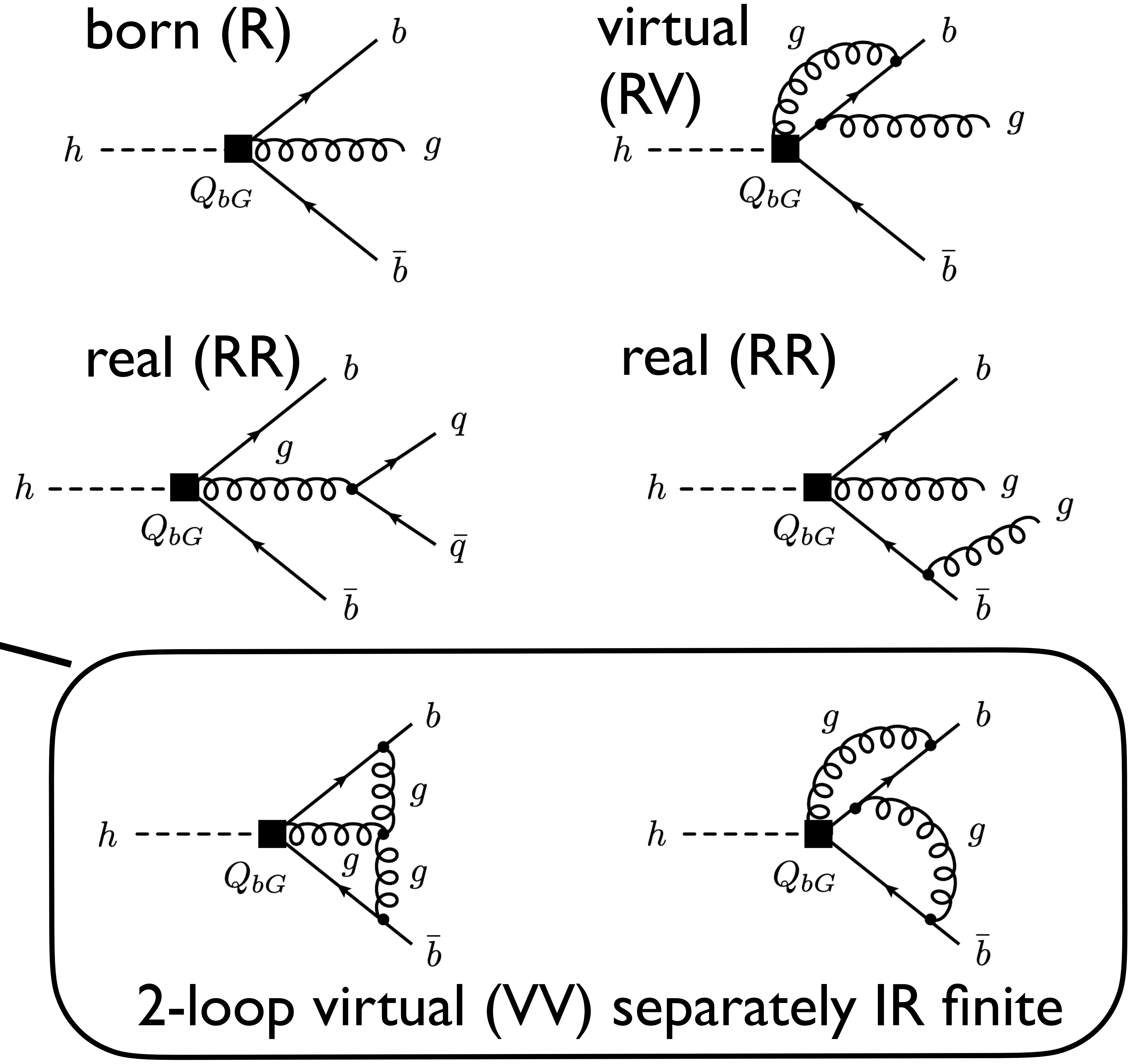
non-factorizable contributions from $\mathcal{O}(\alpha_s^2)$, included through NLO+PS, i.e. $\mathcal{O}(\alpha_s^3)$, effectively N³LO correction:



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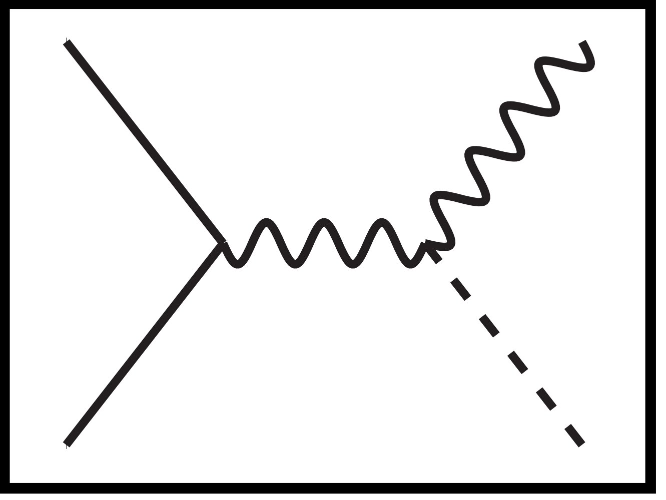

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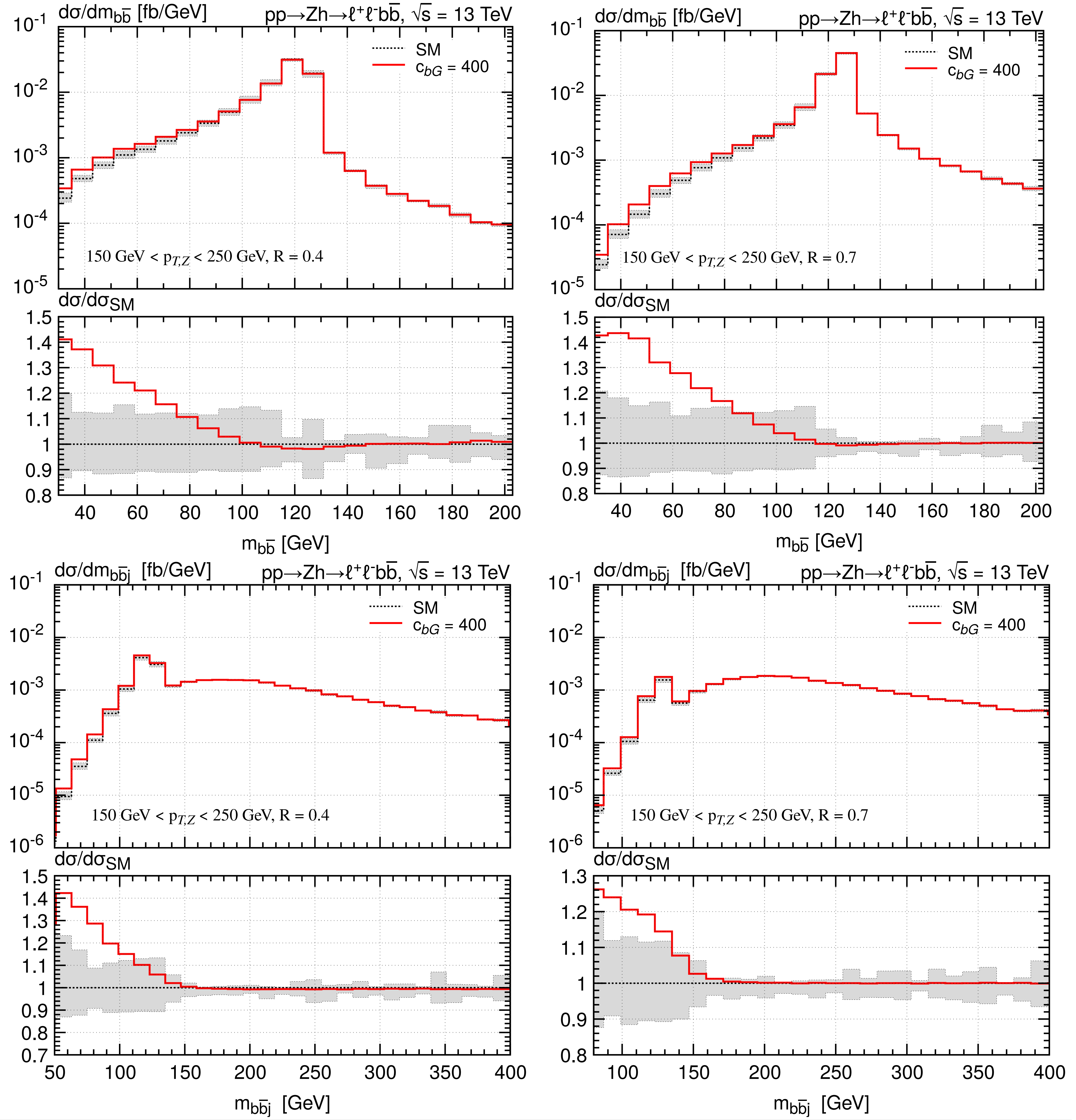
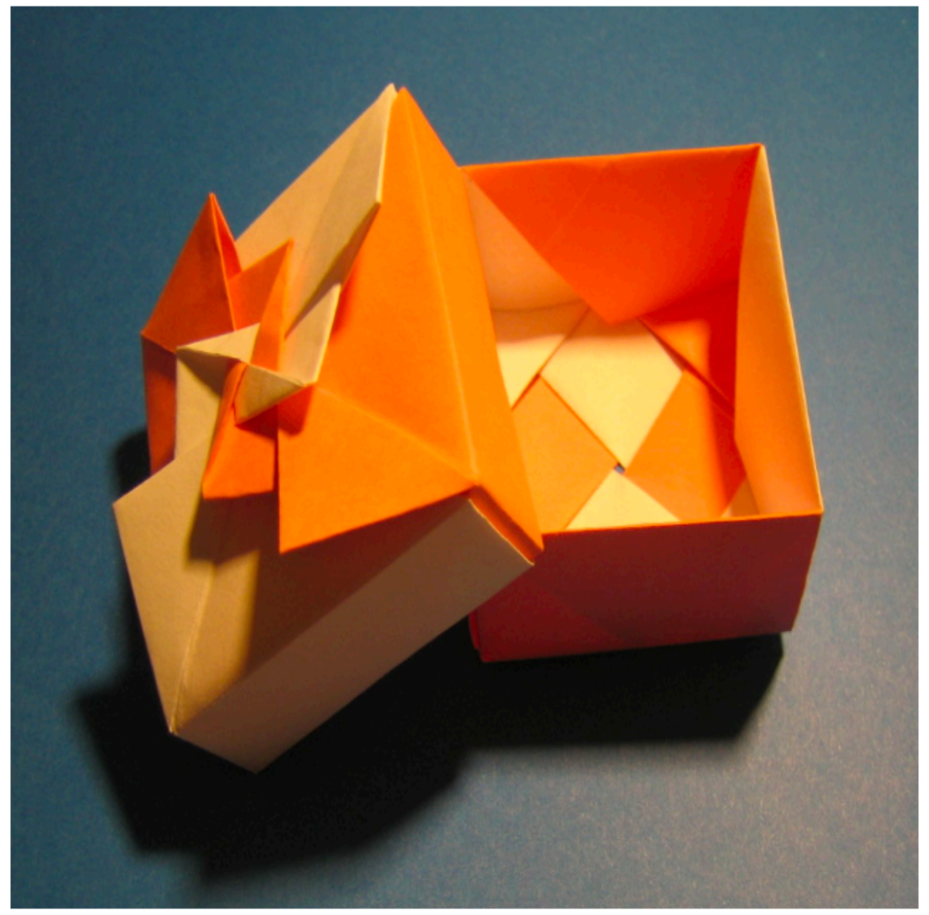


H production & background generators @ NNLO+PS

The POWHEG BOX



Project

The POWHEG BOX is a general computer framework for implementing NLO calculations in shower Monte Carlo programs according to the POWHEG method. It is also a library, where previously included processes are made available to the users. It can be interfaced with all modern shower Monte Carlo programs that support the Les Houches Interface for User Generated Processes.

Index:

- Available NLO+PS processes
- NNLOps using MiNNLOps
- Proper references
- Downloads
- Version 2
- Version RES
- Bugs
- Licence
- Contributing Authors

ggF Higgs production in POWHEG-BOX-V2
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

NEW ***Top-quark pair*** *generator now available*
[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

MiNNLO$_{PS}$ has been extended to $2 \to 2$ colour-singlet processes (built in POWHEG-BOX-RES).
[Lombardi, MW, Zanderighi '20]

NEW ***WW*** *generator [Lombardi, MW, Zanderighi '21]*

NEW ***ZZ*** *generator with incoherent combination of $q\bar{q}$ and gg channels*
[Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]

NEW ***VH*** *generator interfaced with* ***H→bb*** *decay (t.b.a.)*
[Zanoli, Chiesa, Re, MW, Zanderighi '21]

NEW $\gamma\gamma$ *generator (t.b.a.) [Gavardi, Oleari, Re 'to appear]*

More to come …

Summary

★ enormous progress on Higgs predictions in past years

★ in HTL: N^3LO inclusive and fully differential; NNLO+PS and merged NLO+PS MCs

★ NNLO cross section in full theory; quark-mass dependence in distributions at NLO(+PS)

★ VH production and H → bb decay at NNLO+PS in SM and SMEFT

Outlook

★ differential NNLO(+PS) in full theory

★ N^3LO for Higgsstrahlung (similar to Drell Yan), inclusive & differential? (VH+jet at NNLO known)

★ beyond NLO(+PS) for ttH and bbH

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Outlook

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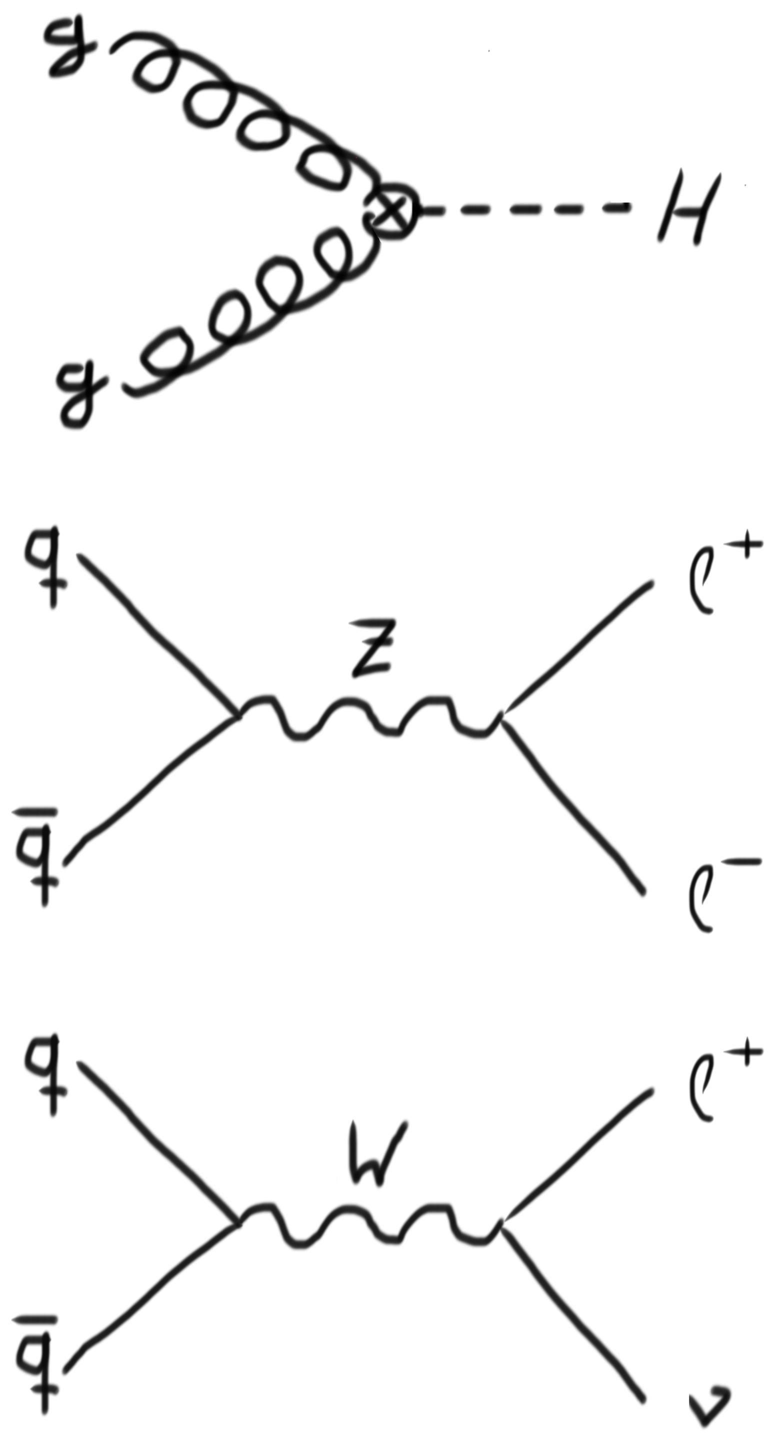
Stay tuned !

Back Up

MiNNLO$_{PS}$: 2→1 colour-singlet processes

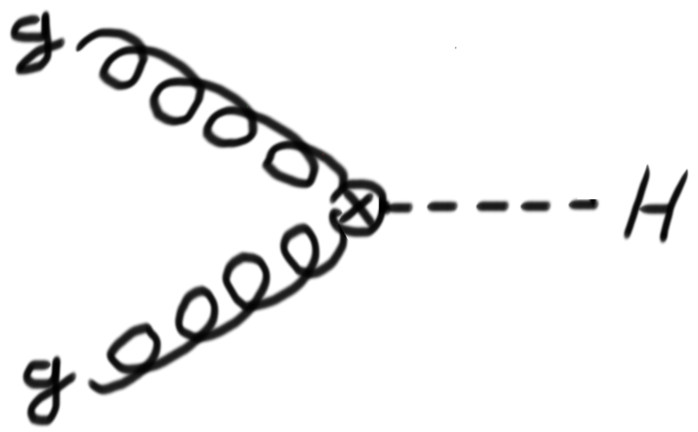
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

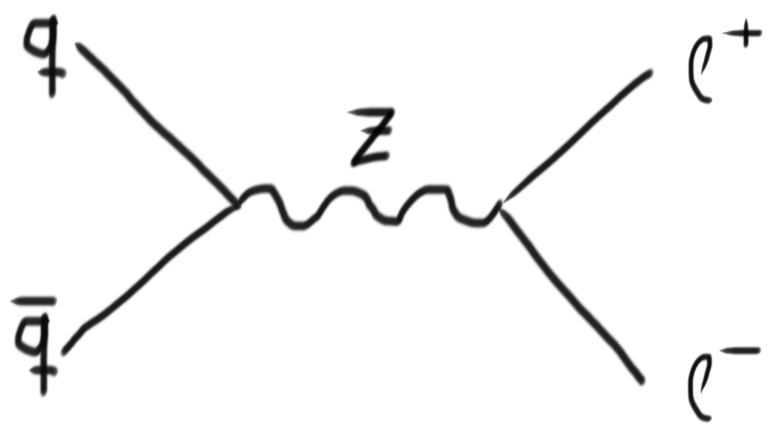


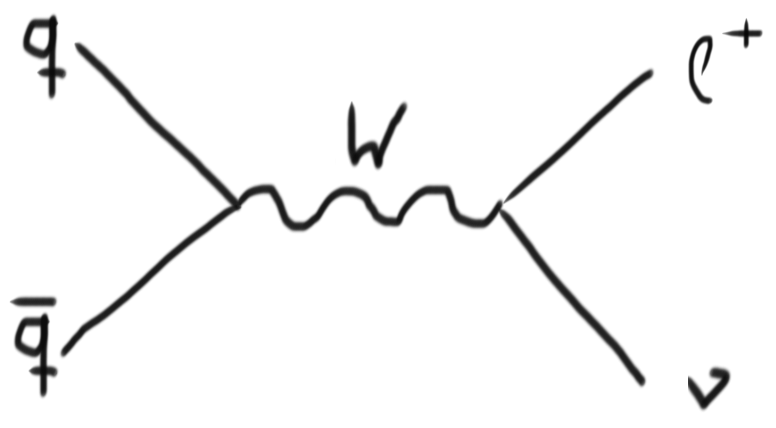
Process	NNLO (MATRIX)	MiNNLO$_{PS}$	Ratio
$pp \to H$	$39.64(1)^{+10.7\%}_{-10.4\%}$ pb	$39.1(5)^{+10.2\%}_{-9.0\%}$ pb	0.987
$pp \to \ell^+\ell^-$	$1919(1)^{+0.8\%}_{-1.1\%}$ pb	$1917(1)^{+1.4\%}_{-1.1\%}$ pb	0.999
$pp \to \ell^-\bar{\nu}_\ell$	$8626(4)^{+1.0\%}_{-1.2\%}$ pb	$8643(4)^{+1.7\%}_{-1.5\%}$ pb	1.002
$pp \to \ell^+\nu_\ell$	$11677(5)^{+0.9\%}_{-1.3\%}$ pb	$11693(5)^{+1.5\%}_{-1.6\%}$ pb	1.001

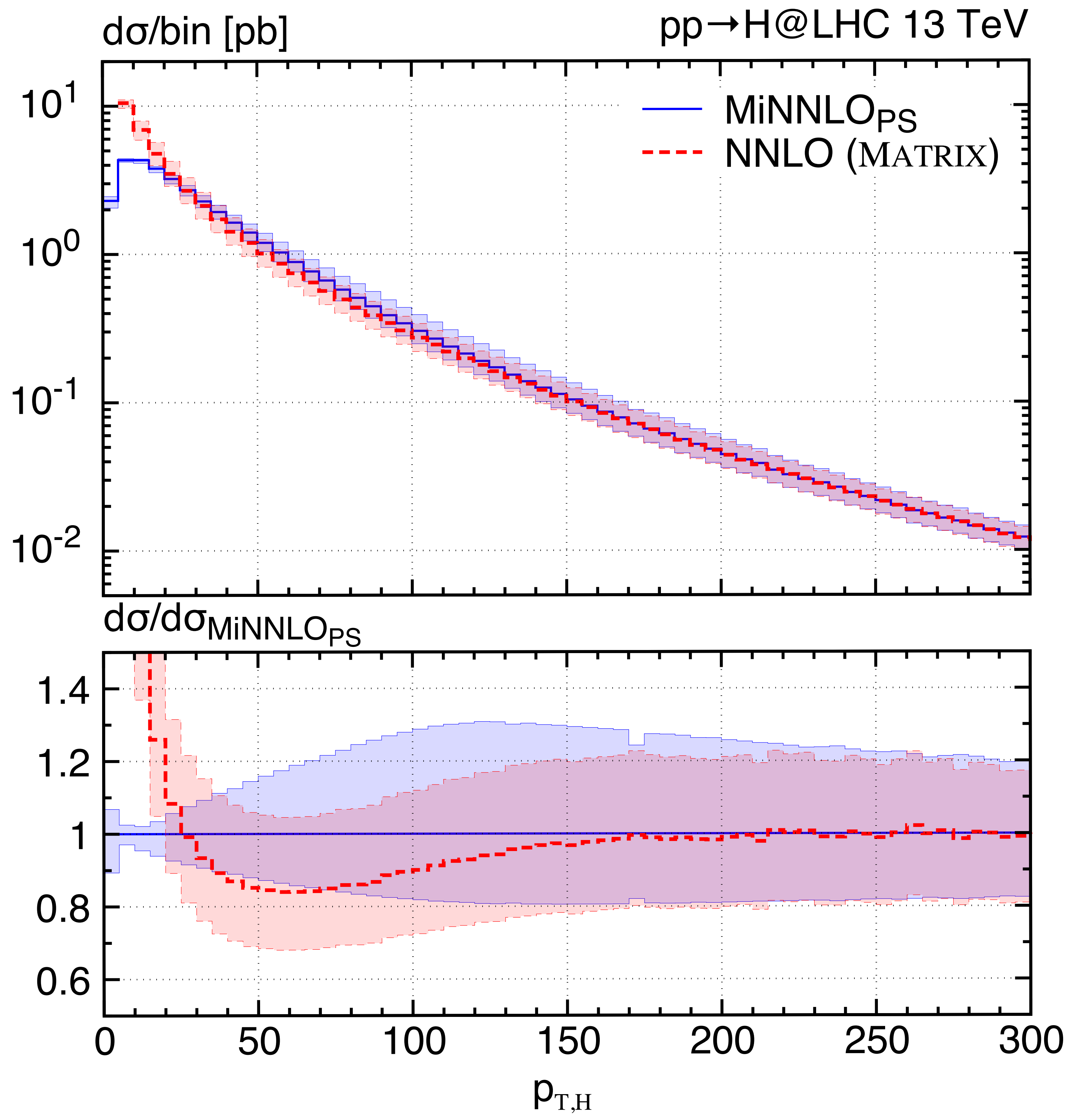
MiNNLO$_{PS}$: 2→1 colour-singlet processes

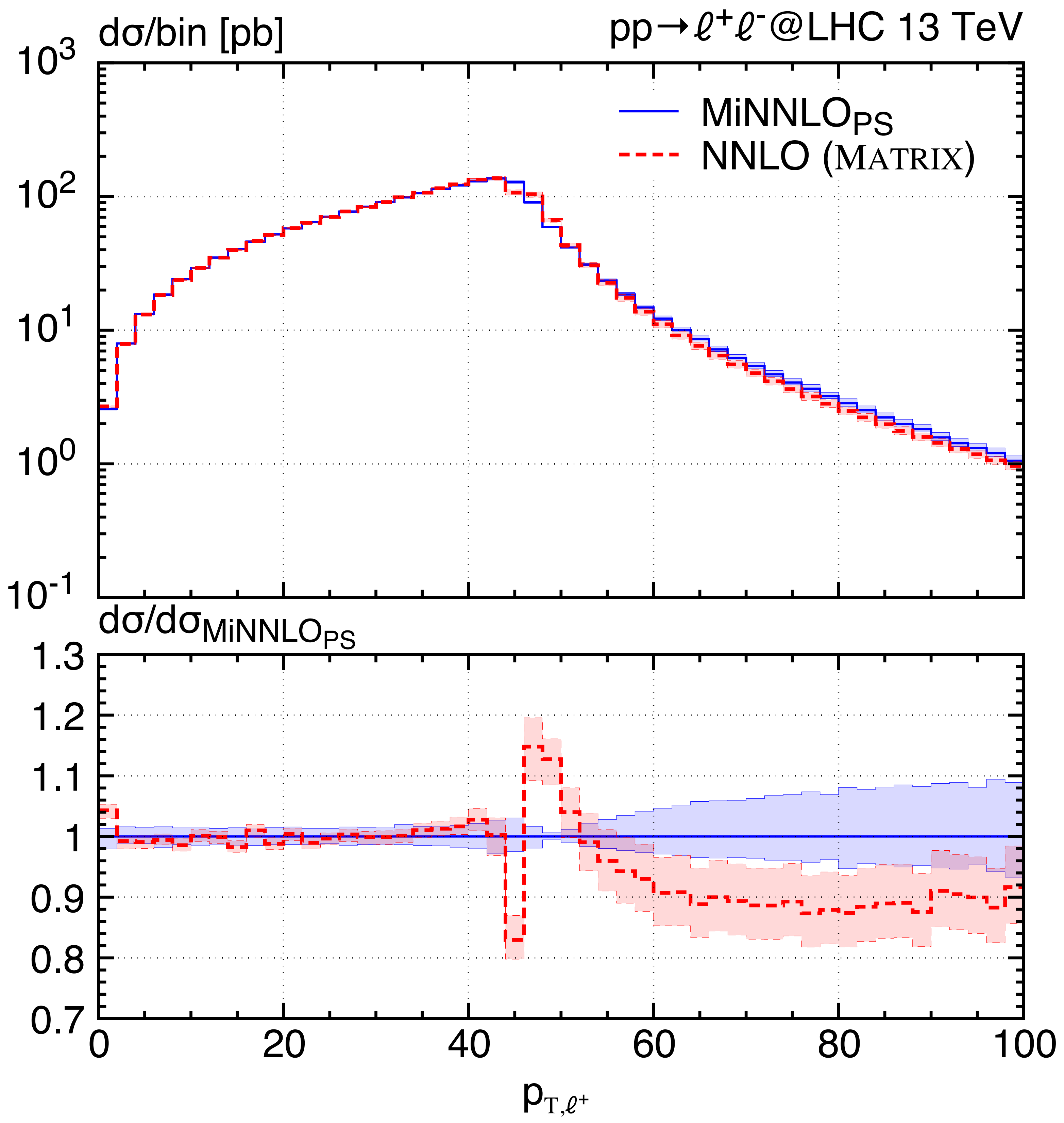
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

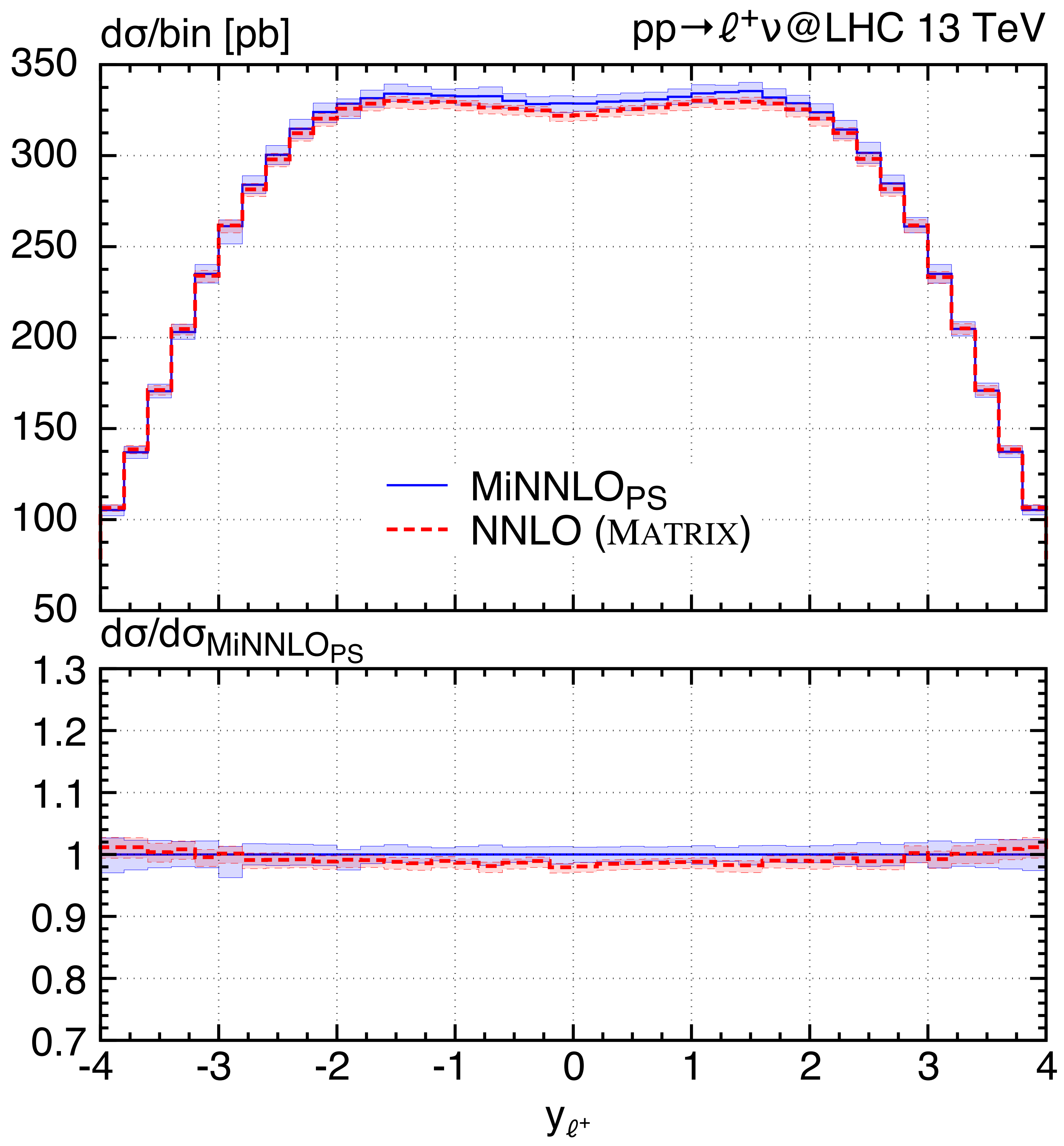




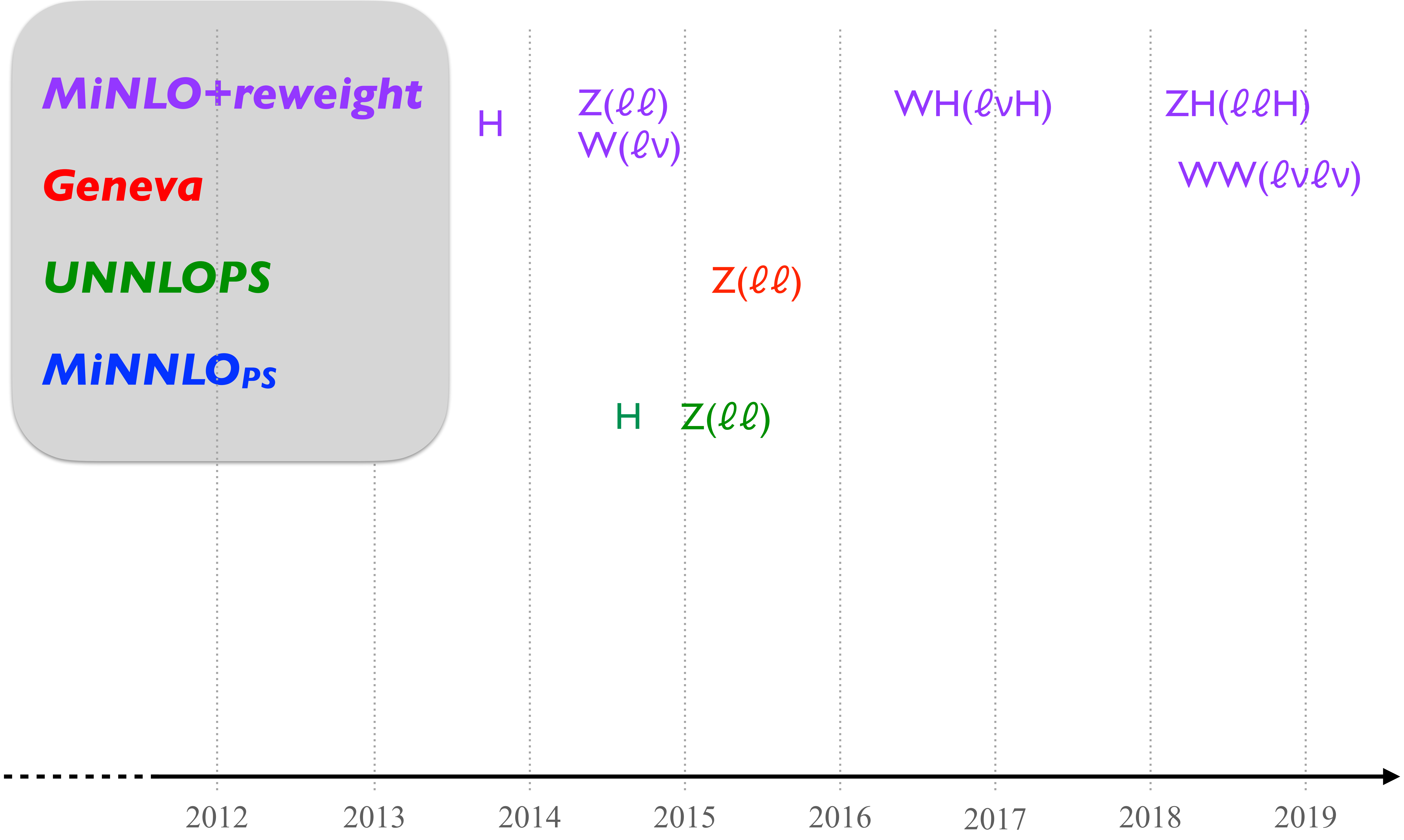






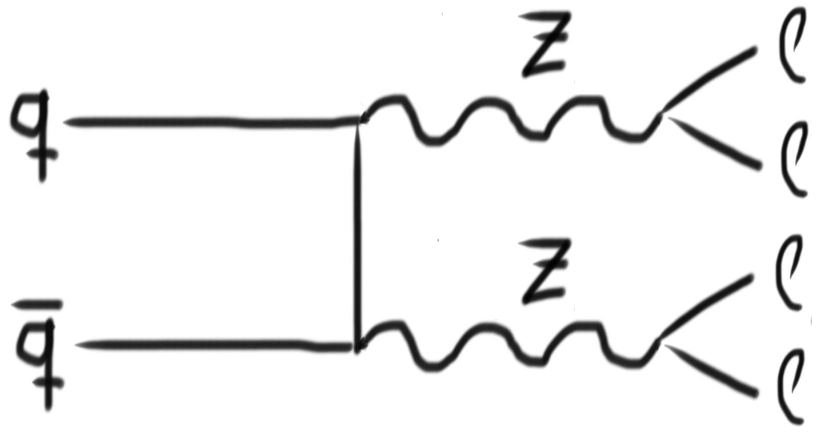


NNLO+PS timeline



NNLO+PS timeline

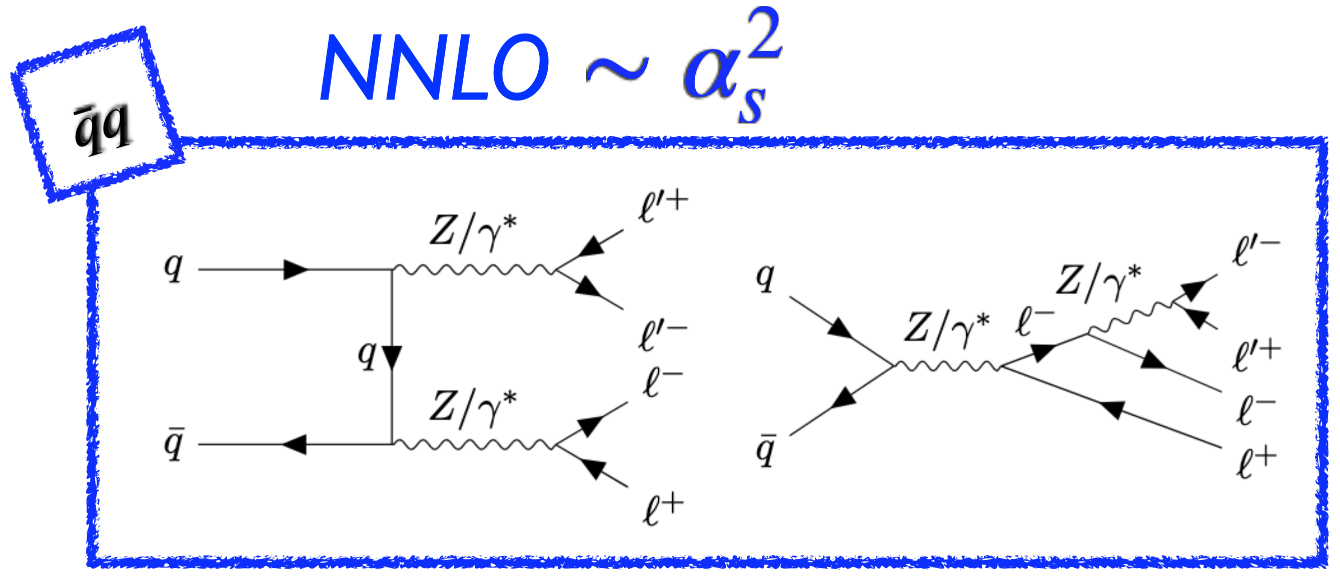
MiNNLO$_{PS}$: nNNLO+PS (x EW) for $ZZ(\ell\ell\ell'\ell')$

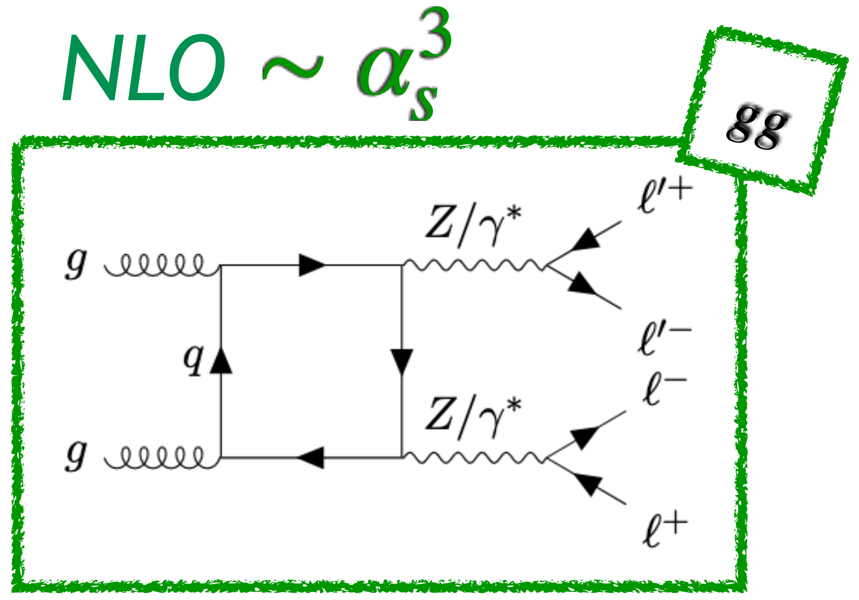


[Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]

- ✦ smallest cross section of massive VV, but very clean
- ✦ relevant background for Higgs and BSM

NNLO $\sim \alpha_s^2$ *NLO* $\sim \alpha_s^3$



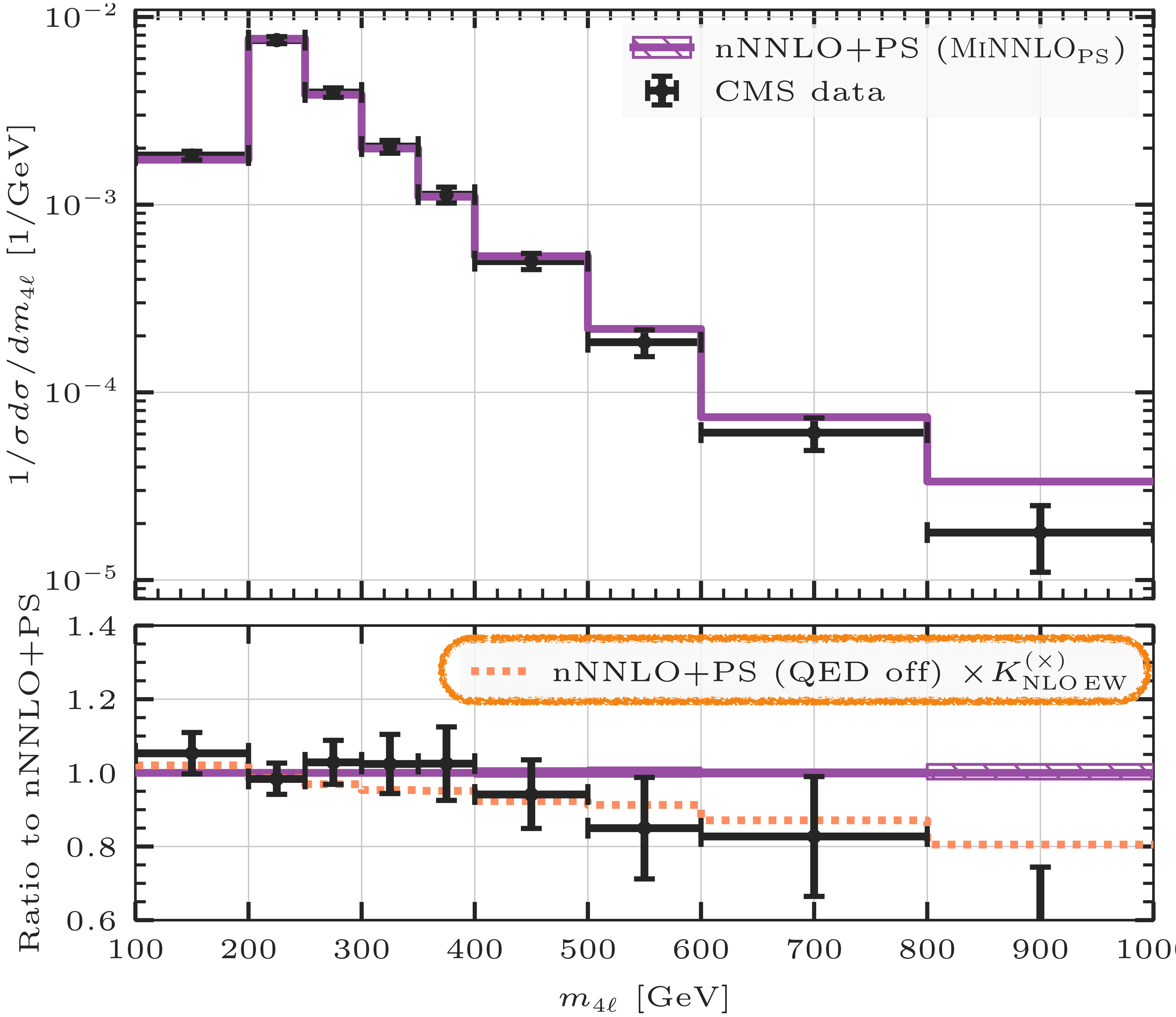


NNLO+PS using MiNNLO$_{PS}$* ***NLO+PS with POWHEG****

$$pp \to \ell^+\ell^-\ell^{(\prime)+}\ell^{(\prime)-}$$

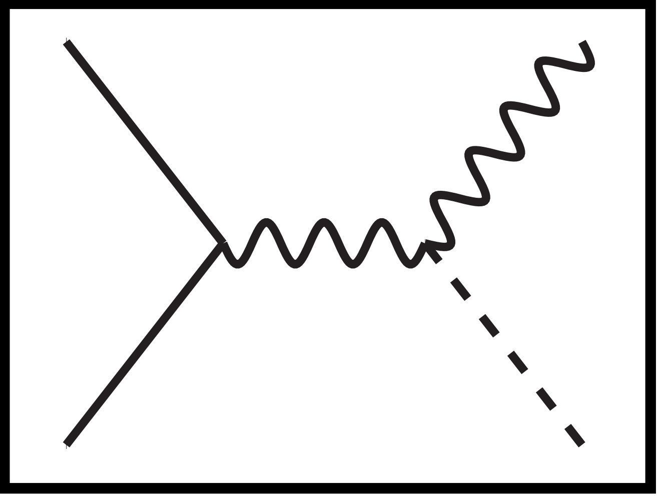
Incoherent combination ⟶ ***nNNLO+PS***

* *also in* [Alioli et al. '21] * *also in* [Alioli, Ferrario Ravasio, Lindert, Röntsch '21]



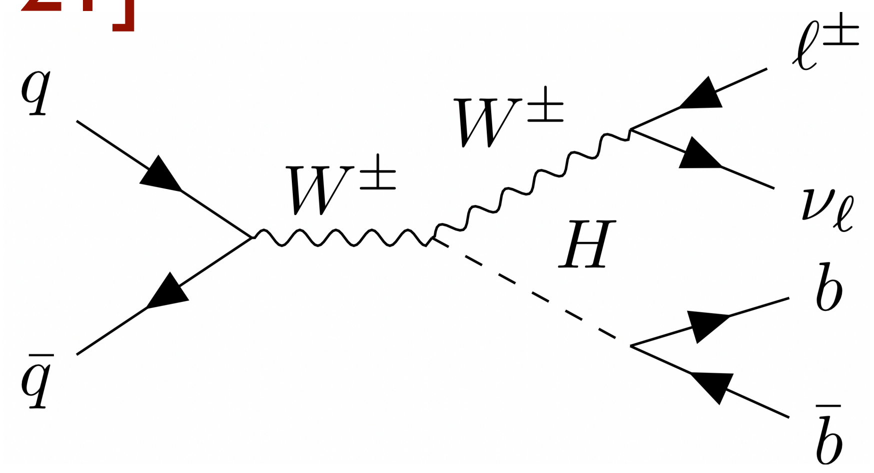
✓ *nNNLO+PS in good agreement with CMS results (137fb^{-1} 13TeV)*

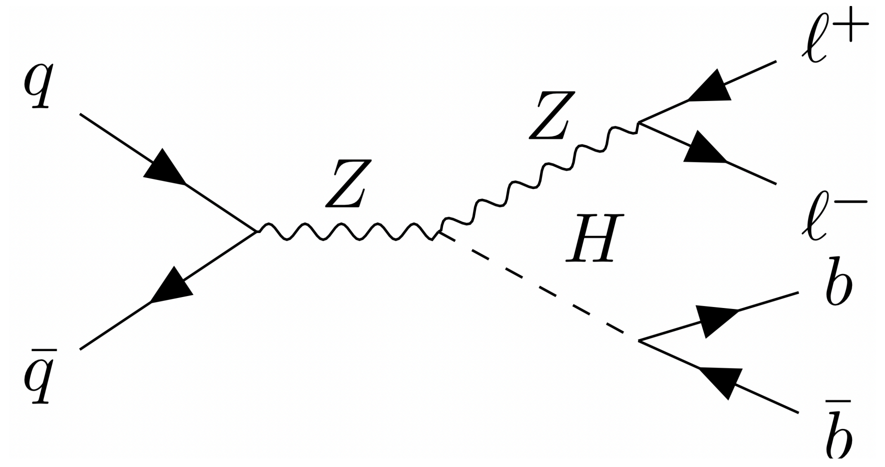
✓ *EW corrections (through NLO K factor) to describe tails*



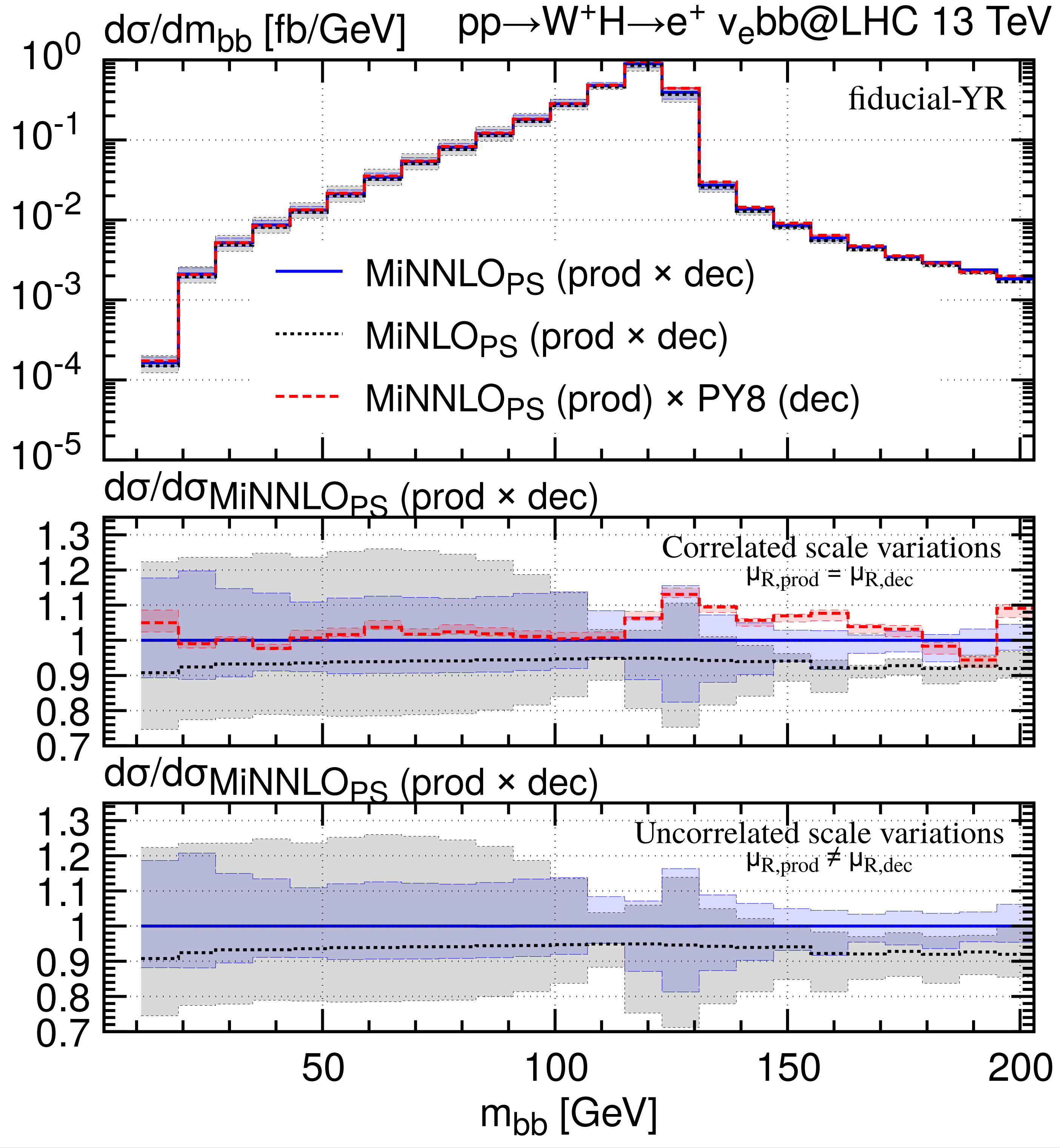
VH x H→bb @ NNLO+PS

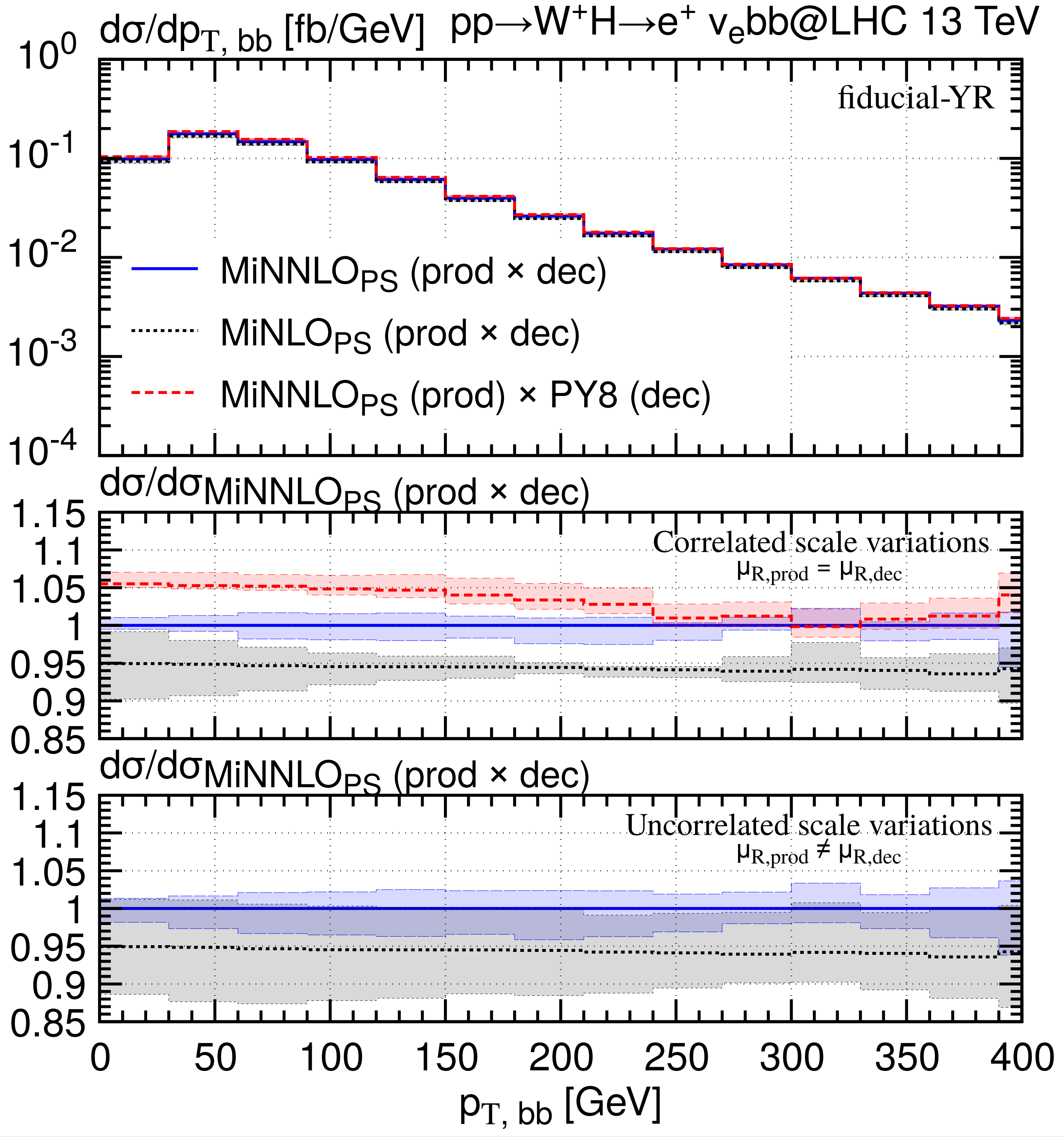
[Zanoli, Chiesa, Re, MW, Zanderighi '21]

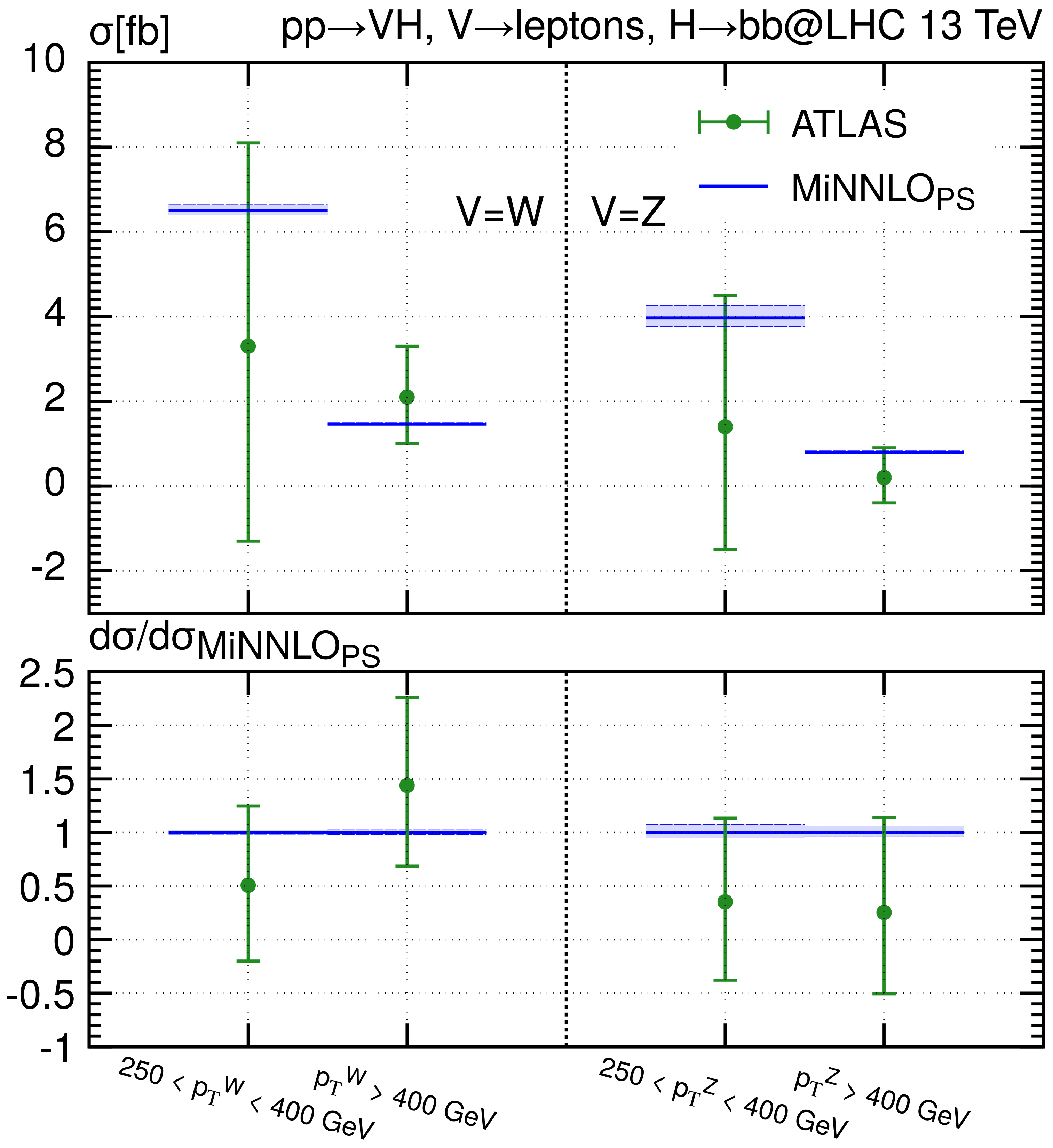


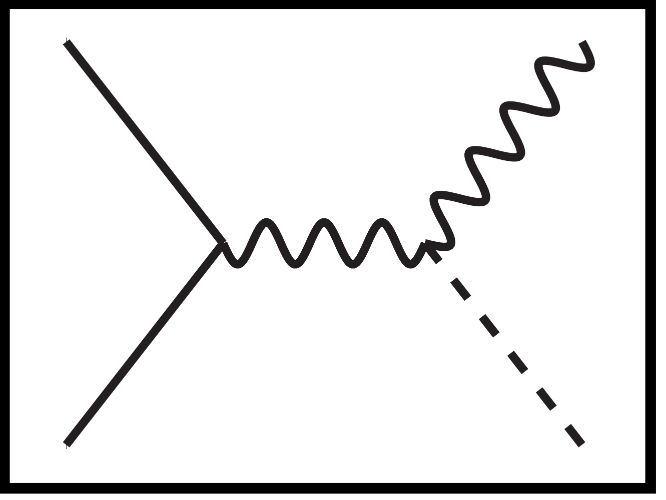


- ***NNLO+PS*** *accuracy in both* ***production*** ***and*** ***decay***
  see also [Alioli et al. '19] see also [Alioli et al. '20]
- *includes NNLO directly in event generation through* ***MiNNLO$_{PS}$ method***
  [Monni, Nason, Re, Zanderighi, MW '19], [Monni, Re, MW '20]
- *main production channel to observe* $H \to b\bar{b}$ *(largest branching fraction)*









SMEFT: VH x H➞bb @ NNLO+PS

[Haisch, Scott, MW, Zanderighi, Zanoli '22]

$$Q_{H\Box} = (H^\dagger H)\,\Box\,(H^\dagger H)\,, \qquad Q_{HD} = (H^\dagger D_\mu H)^*\,(H^\dagger D^\mu H)\,,$$

$$Q_{bH} = y_b\,(H^\dagger H)\,\bar{q}_L b_R H\,, \qquad Q_{bG} = \frac{g_s^3}{(4\pi)^2}\,y_b\,\bar{q}_L \sigma_{\mu\nu} T^a b_R H G^{a,\mu\nu}\,,$$

$$Q_{HG} = \frac{g_s^2}{(4\pi)^2}\,(H^\dagger H)\,G^a_{\mu\nu} G^{a,\mu\nu}\,, \qquad Q_{3G} = \frac{g_s^3}{(4\pi)^2}\,f^{abc} G_\mu^{a,\nu} G_\nu^{b,\sigma} G_\sigma^{c,\mu}\,,$$

N³LO QCD inclusive H ➞ bb decay width:

$$\Gamma(h \to b\bar{b})^{\mathrm{N^3LO}}_{\mathrm{SMEFT}} = \left\{ (1 + 2c_{\mathrm{fac}}) \left[1 + \frac{\alpha_s}{\pi}\,5.67 + \left(\frac{\alpha_s}{\pi}\right)^2 29.15 + \left(\frac{\alpha_s}{\pi}\right)^3 41.76 \right] + \left(\frac{\alpha_s}{\pi}\right)^2 \frac{m_h^2}{3v^2} \left[1 + \frac{\alpha_s}{\pi}\,17.32 \right] c_{bG} \right\} \Gamma(h \to b\bar{b})^{\mathrm{LO}}_{\mathrm{SM}}\,,$$

corrected Higgs width: $\Gamma_h^{\mathrm{SMEFT}} = (1 + 2c_{\mathrm{kin}}) \left[\Gamma_h^{\mathrm{SM}} - (2\Delta\, c_{bH} - K_{bG}\,\Delta_{\mathrm{non}}\, c_{bG})\,\Gamma(h \to b\bar{b})^{\mathrm{LO}}_{\mathrm{SM}} + 6 K_{HG}\, c_{HG}\,\Gamma(h \to gg)^{\mathrm{LO}}_{\mathrm{SM}} \right].$

$$d\sigma^{\mathrm{SMEFT}}_{\mathrm{NNLO+PS}} = (1 + 2c_{\mathrm{kin}})^2 \left\{ \left[1 - 2c_{bH} + \frac{\Gamma(h \to b\bar{b})^{\mathrm{non,VV}}_{\mathrm{SMEFT}}}{\Gamma(h \to b\bar{b})^{\mathrm{NNLO}}_{\mathrm{SM}}} \right] d\sigma^{\mathrm{SM}}_{\mathrm{NNLO+PS}} + d\sigma^{\mathrm{non,R+RV+RR}}_{\mathrm{NNLO+PS}} \right\} \frac{\Gamma_h^{\mathrm{SM}}}{\Gamma_h^{\mathrm{SMEFT}}}\,,$$