

NNLO + PS Higgs-pair production in MiNNLO_{PS}

Francesco Garosi

Oxford, QCD@LHC, 01.10.2026

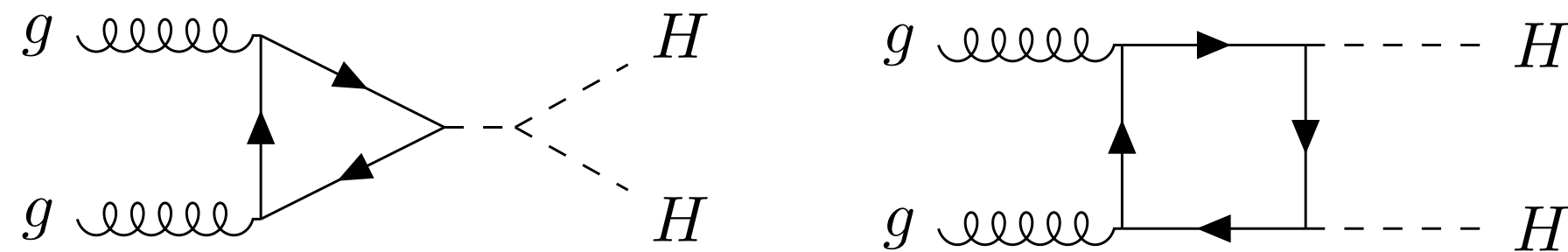
From Garosi, Wiesemann, Zanderighi [[2606.05300](#)]

HH production at the LHC

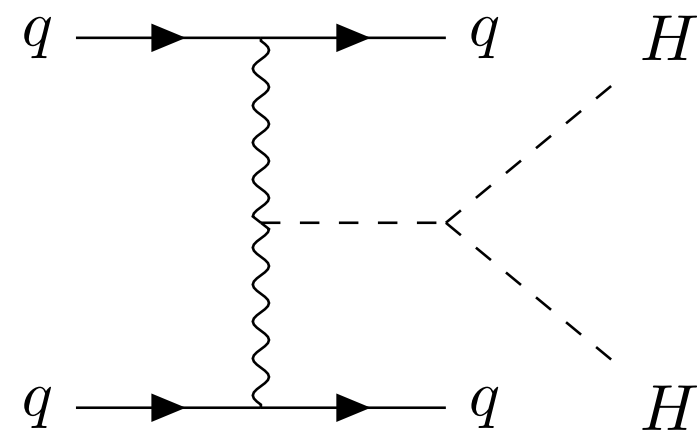
See talks by J. Chang, K. Schönwald,
B. Lawrence-Sanderson, M. Vassilev (Tue)



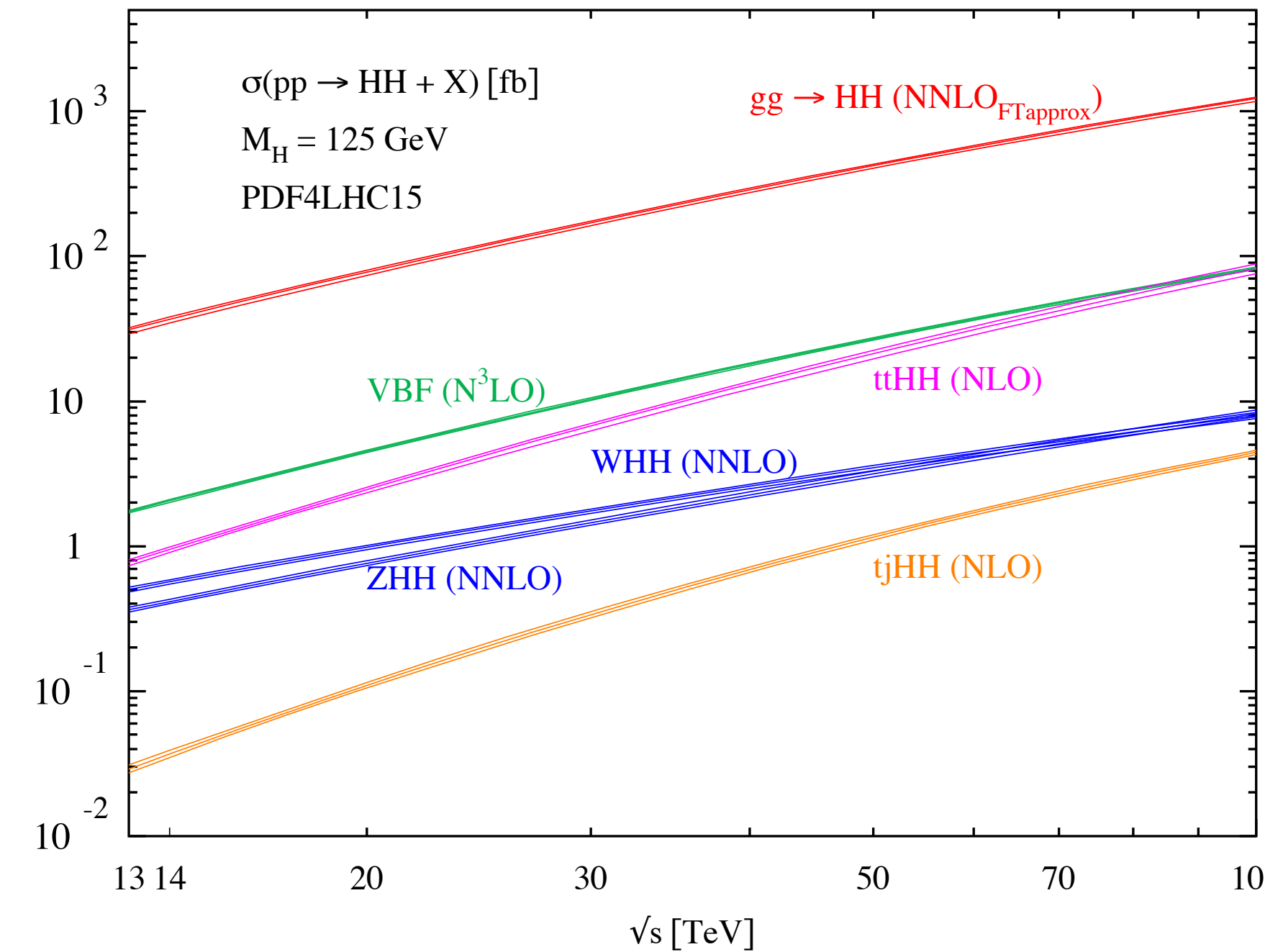
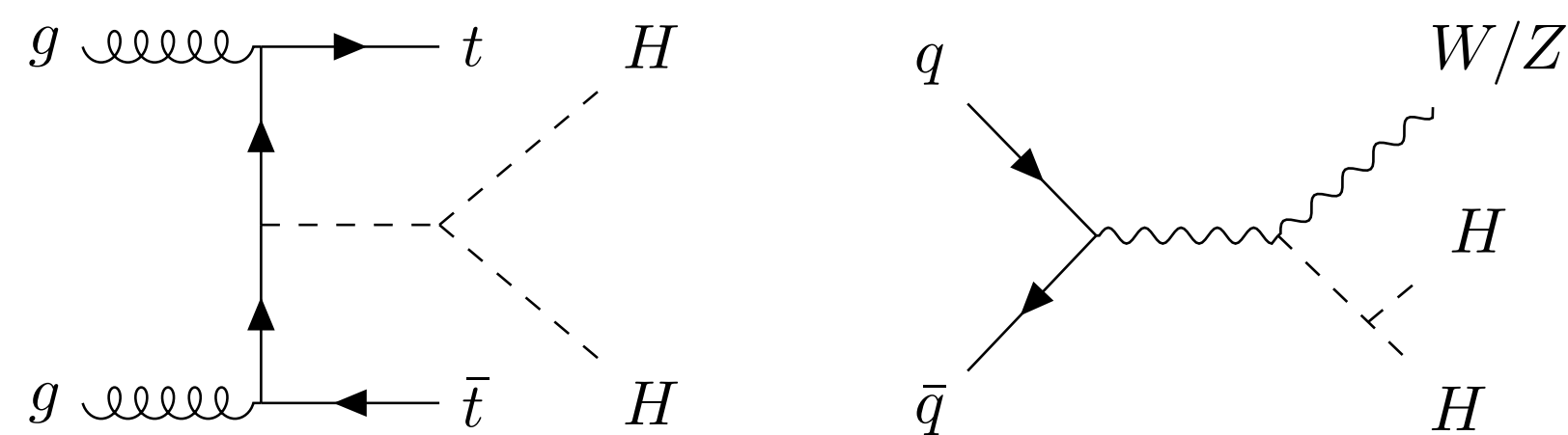
Gluon fusion



Vector Boson Fusion (VBF)



Associated production



[di Micco et al. [1910.00012](#)]

$$\sigma_{HH} \sim 35 \text{ fb} \sim 10^{-3} \sigma_H \quad (13 \text{ TeV})$$

Access to the trilinear Higgs coupling

The MiNNLO_{PS} method



$$d\sigma_F^{\text{MiNNLO}_{\text{PS}}} = d\Phi_{\text{FJ}} \bar{B}^{\text{MiNNLO}_{\text{PS}}} \times \left\{ \Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + d\Phi_{\text{rad}} \Delta_{\text{pwg}}(p_{\text{T,rad}}) \frac{R_{\text{FJ}}}{B_{\text{FJ}}} \right\}$$

See talk by C. Savoini (Thu)

$$\bar{B}^{\text{MiNNLO}_{\text{PS}}} = e^{-\tilde{S}} \left\{ \frac{d\sigma_{\text{FJ}}^{(1)}}{d\Phi_{\text{FJ}}} \left(1 + \tilde{S}^{(1)} \right) + \frac{d\sigma_{\text{FJ}}^{(2)}}{d\Phi_{\text{FJ}}} + \left(D - D^{(1)} - D^{(2)} \right) \times F^{\text{corr}} \right\}$$

[Monni et al.
[1908.06987](#), [2006.04133](#)]

The MiNNLO_{PS} method

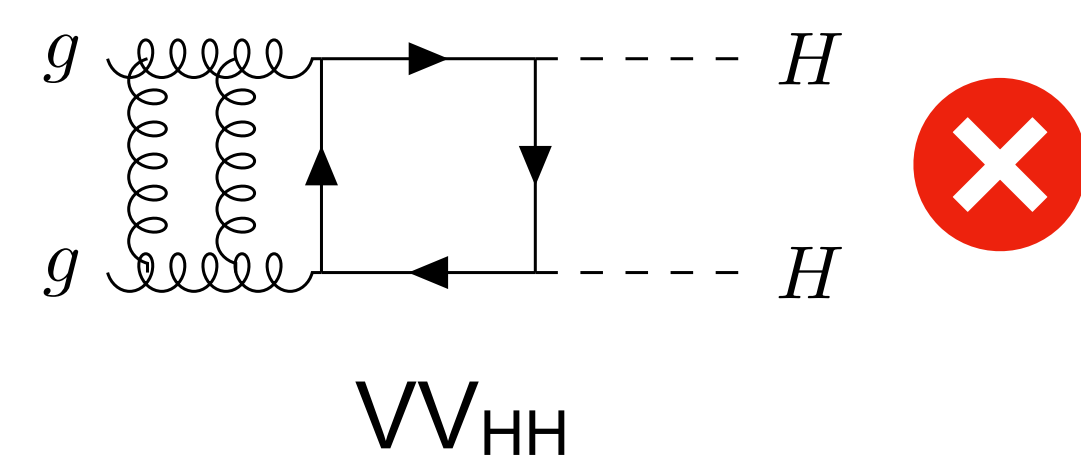
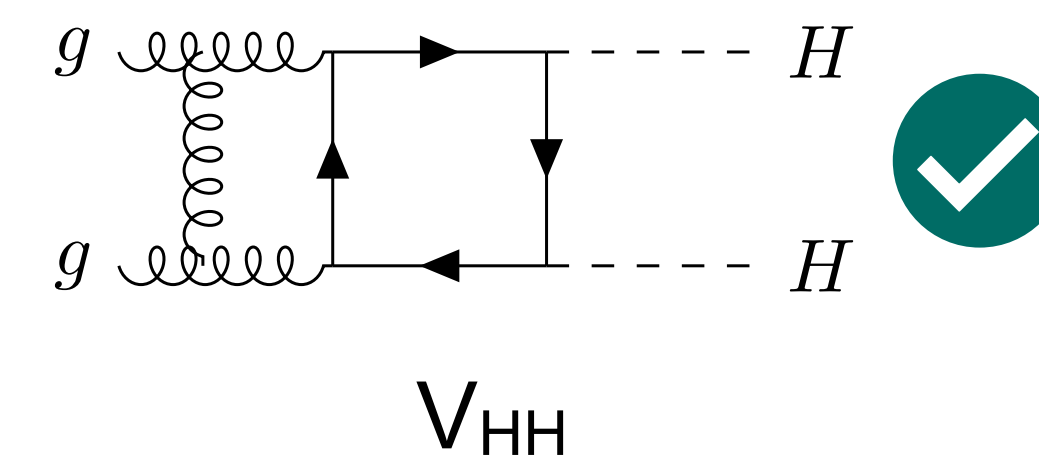
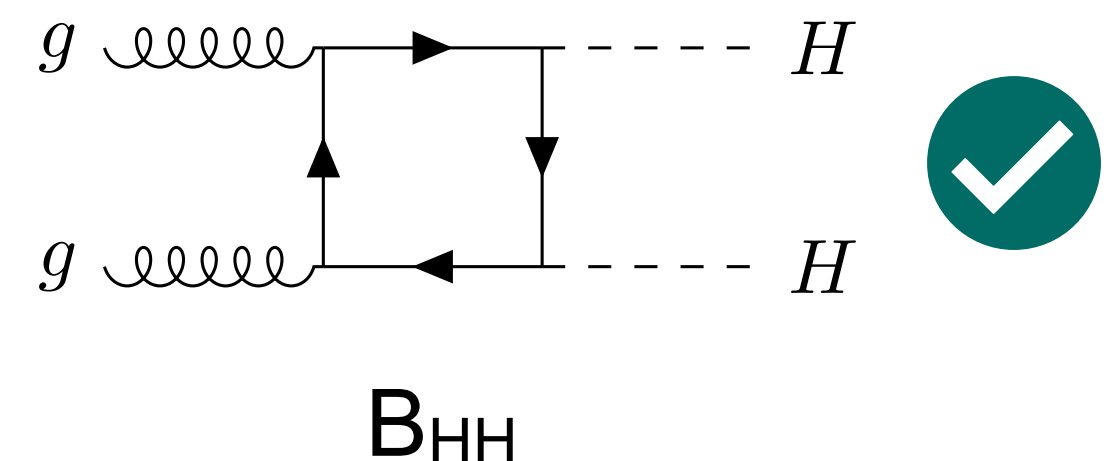
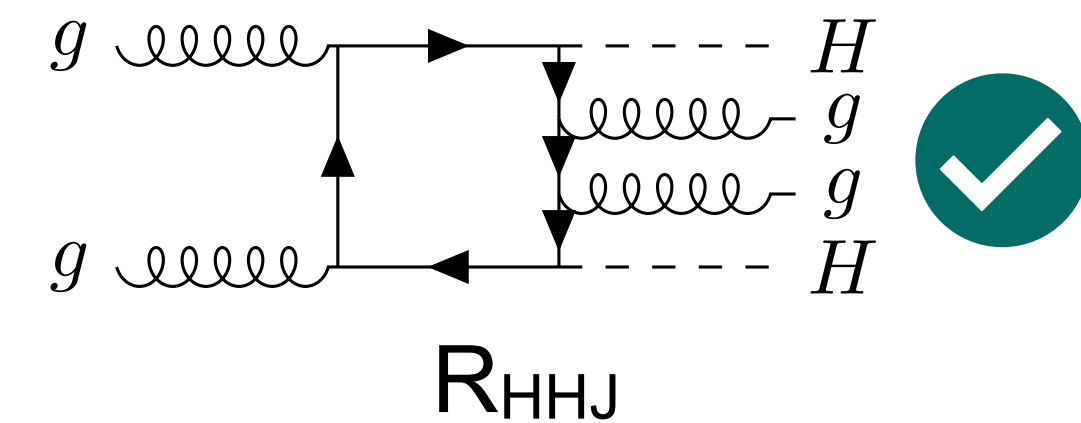
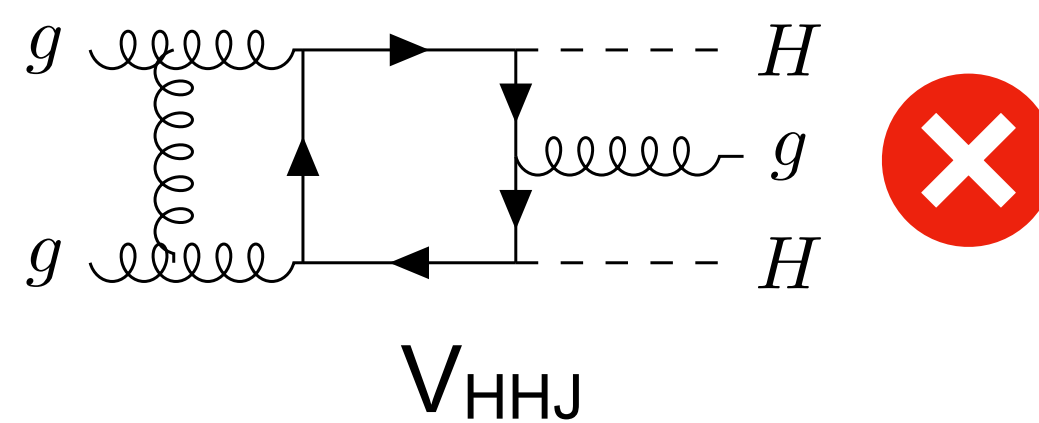
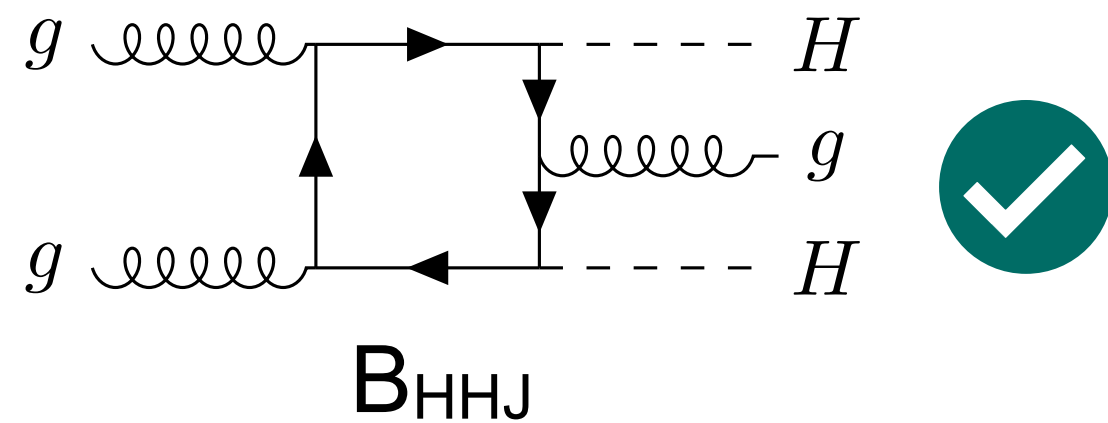


$$d\sigma_F^{\text{MiNNLO}_{\text{PS}}} = d\Phi_{\text{FJ}} \bar{B}^{\text{MiNNLO}_{\text{PS}}} \times \left\{ \Delta_{\text{pwg}}(\Lambda_{\text{pwg}}) + d\Phi_{\text{rad}} \Delta_{\text{pwg}}(p_{\text{T,rad}}) \frac{R_{\text{FJ}}}{B_{\text{FJ}}} \right\}$$

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[Monni et al.
[1908.06987](#), [2006.04133](#)]



All one-loop amplitudes taken from [OpenLoops](#) [Buccioni et al. [1907.13071](#)].

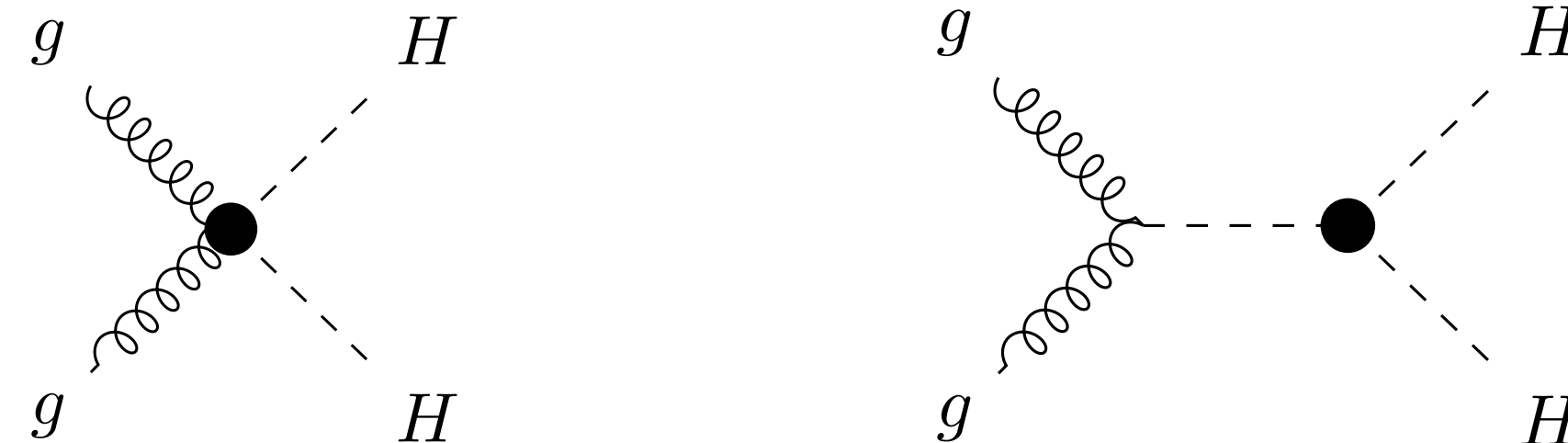
Exact V_{HH} from [HHgrid](#) [[1604.06447](#), [1608.04798](#), [1703.09252](#), [1907.06408](#)] and [ggxy](#) [Davis et al. [2506.04323](#)].

See talk by K. Schönwald (Tue)

Top-quark mass approximations



Heavy Top Limit (HTL): all amplitudes computed in the effective theory with the top integrated out



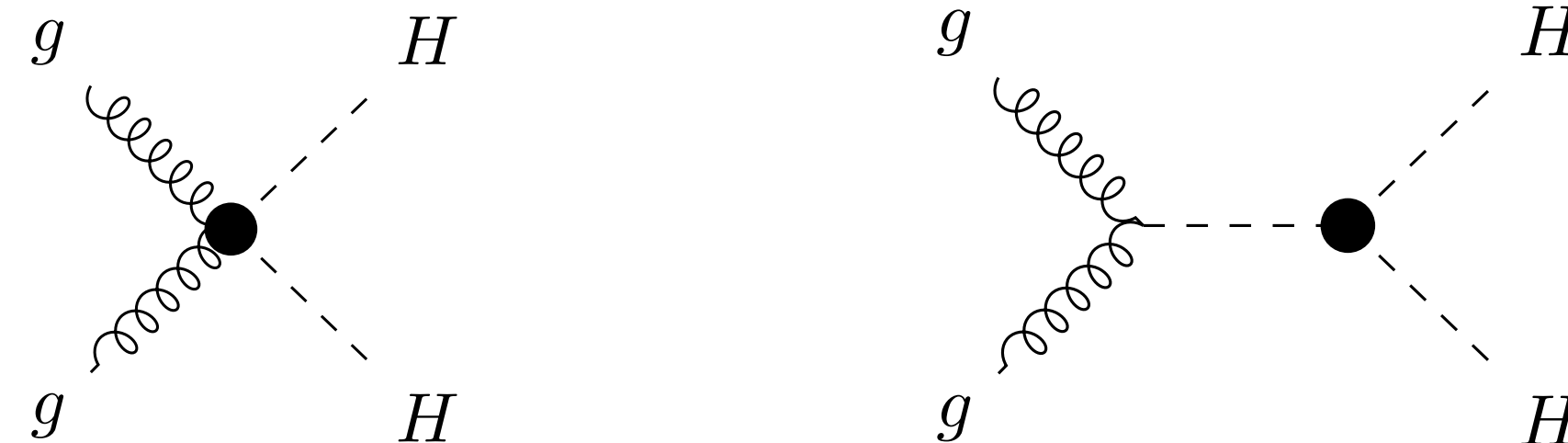
Analytical HH amplitudes in HTL

[de Florian, Mazzitelli [1305.5206](#)]

Top-quark mass approximations



Heavy Top Limit (HTL): all amplitudes computed in the effective theory with the top integrated out.



Analytical HH amplitudes in HTL

[de Florian, Mazzitelli [1305.5206](#)]

NLO Improved (NLO-I): rescale NLO **distributions** with the higher-order corrections in HTL:

$$d\sigma_{\text{NLO-I}}^{\text{NNLO}} = d\sigma_{\text{FT}}^{\text{NLO}} \cdot \frac{d\sigma_{\text{HTL}}^{\text{NNLO}}}{d\sigma_{\text{HTL}}^{\text{NLO}}}$$

Not well suited for event generation: better something **point-by-point in phase space**.



The tower of approximations

Born Improved (Born-I): everything rescaled with the exact B_{HH} at squared matrix level.

$$X_{\text{BI}} = X_{\text{HTL}} \frac{B_{HH}^{\text{FT}}}{B_{HH}^{\text{HTL}}}$$



The tower of approximations

Born Improved (Born-I): everything rescaled with the exact B_{HH} at squared matrix level.

$$X_{BI} = X_{HTL} \frac{B_{HH}^{FT}}{B_{HH}^{HTL}}$$

Full theory approximations (FT-approx): add exact Born and real amplitudes for HHJ, rescale the virtual by the Born.

Three possibilities for the virtual corrections:

- **FT-approx-0**: same as in Born-I;
- **FT-approx**: add exact V_{HH} , VV_{HH} as in Born-I;
- **FT-approx-2**: rescale VV_{HH} by V_{HH} .

Change **mt-approx** in the input card to run in the different approximations.

Total cross sections



Inputs:

$$m_H = 125 \text{ GeV}, \quad G_F = 1.1663787 \times 10^{-5} \text{ GeV}^{-2}, \quad m_t = 173 \text{ GeV}, \quad \Gamma_H = \Gamma_t = 0$$

PDF set: PDF4LHC21_40 (93100)

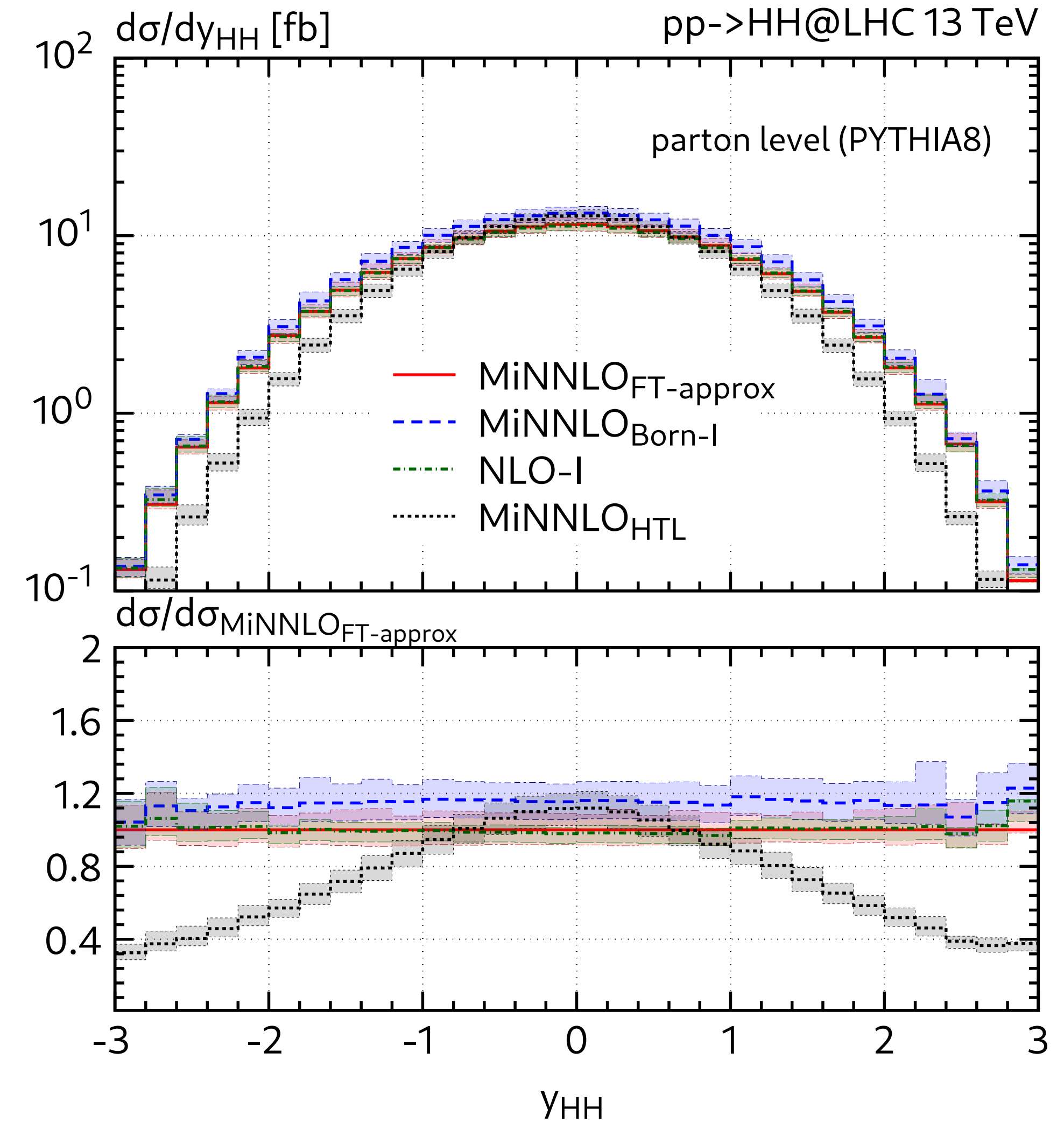
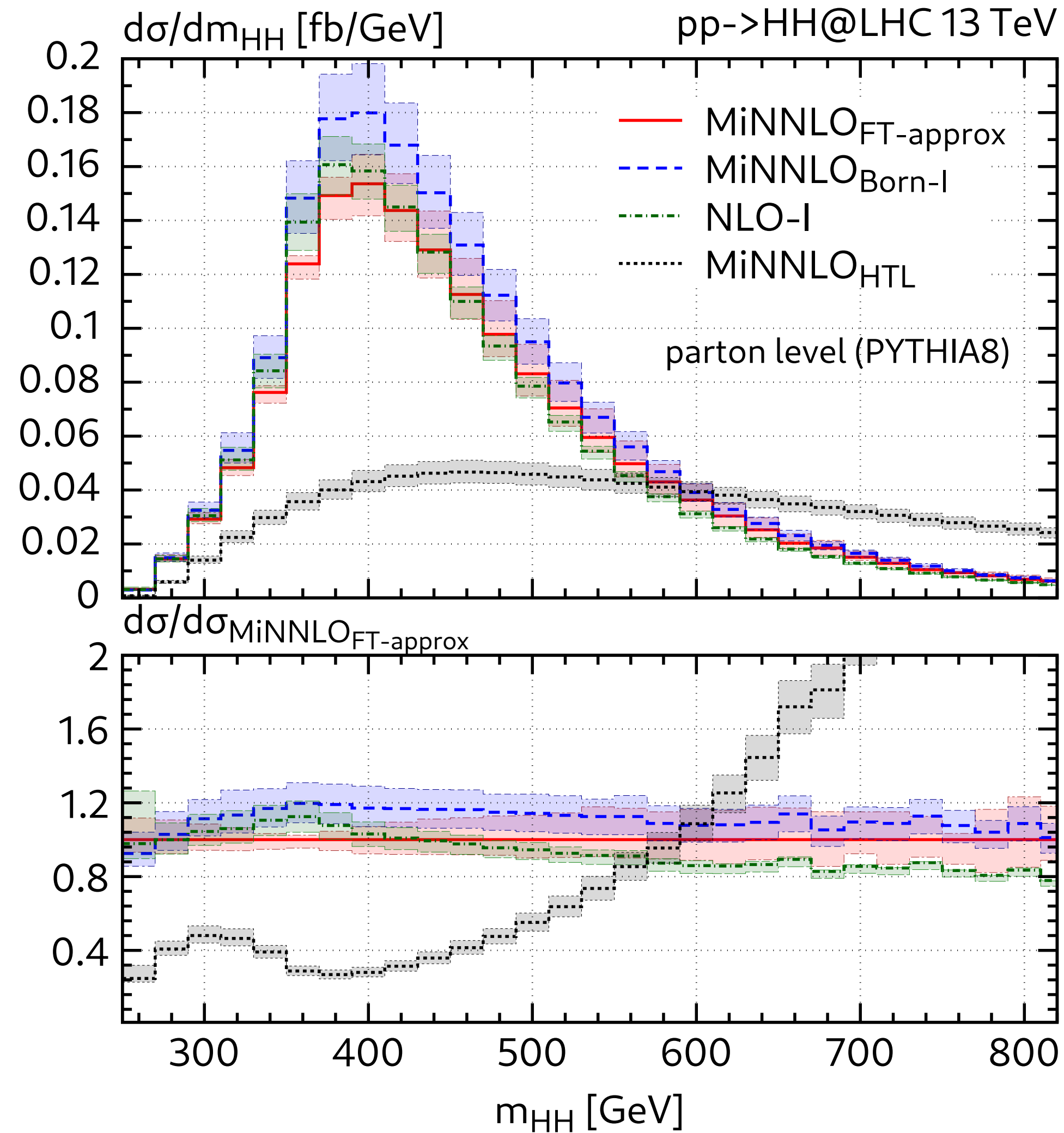
HTL	Born-I	NLO-I	FT-approx-0	FT-approx	FT-approx-2
$30.08^{+8.1\%}_{-8.5\%}$	$37.34^{+9.2\%}_{-8.7\%}$	$31.98^{+4.4\%}_{-5.8\%}$	$32.04^{+6.1\%}_{-6.6\%}$	$32.32^{+9.5\%}_{-8.1\%}$	$31.88^{+8.6\%}_{-7.7\%}$

The **three FT-approx** are **close** to each other and to **NLO-I**.

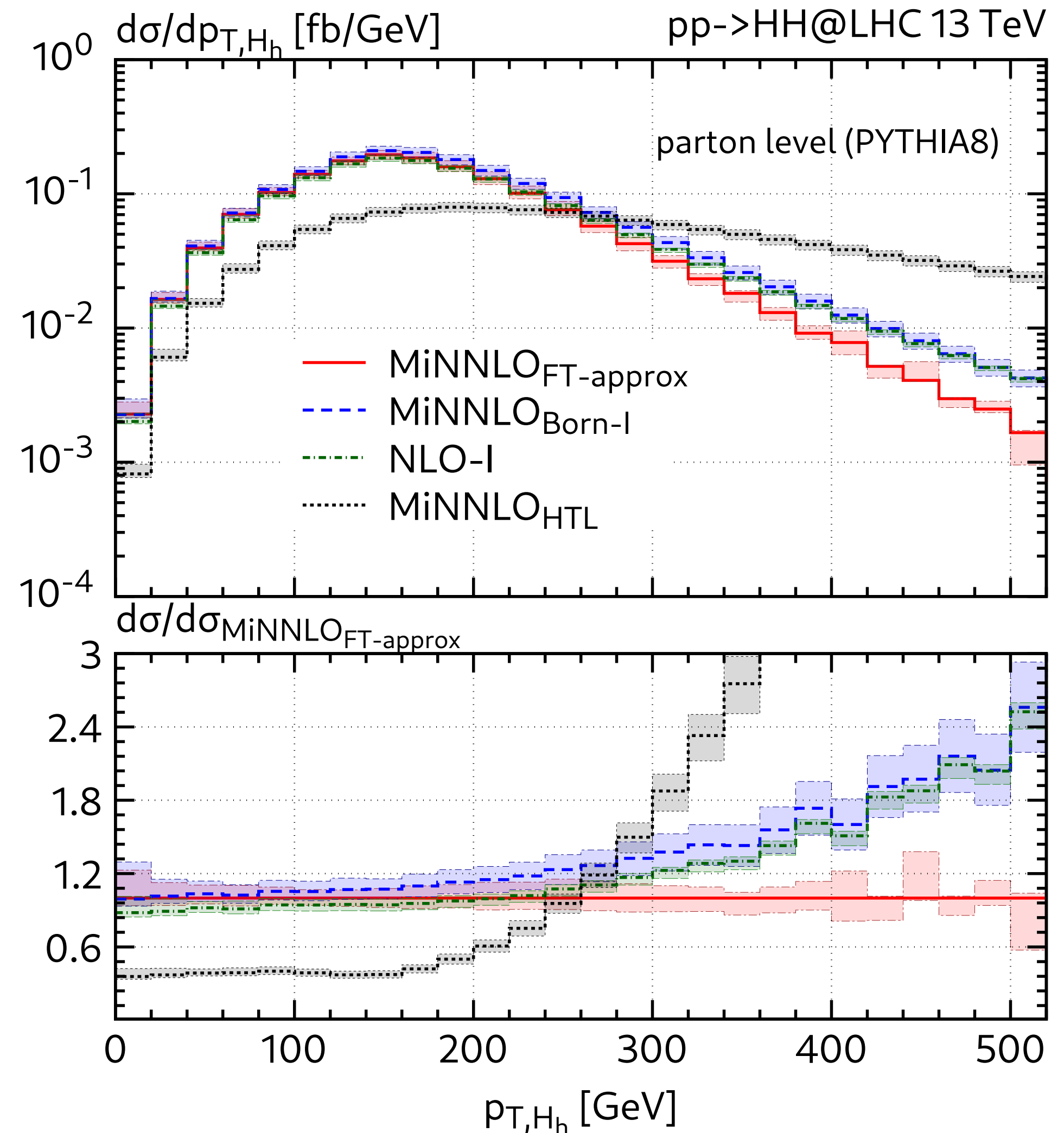
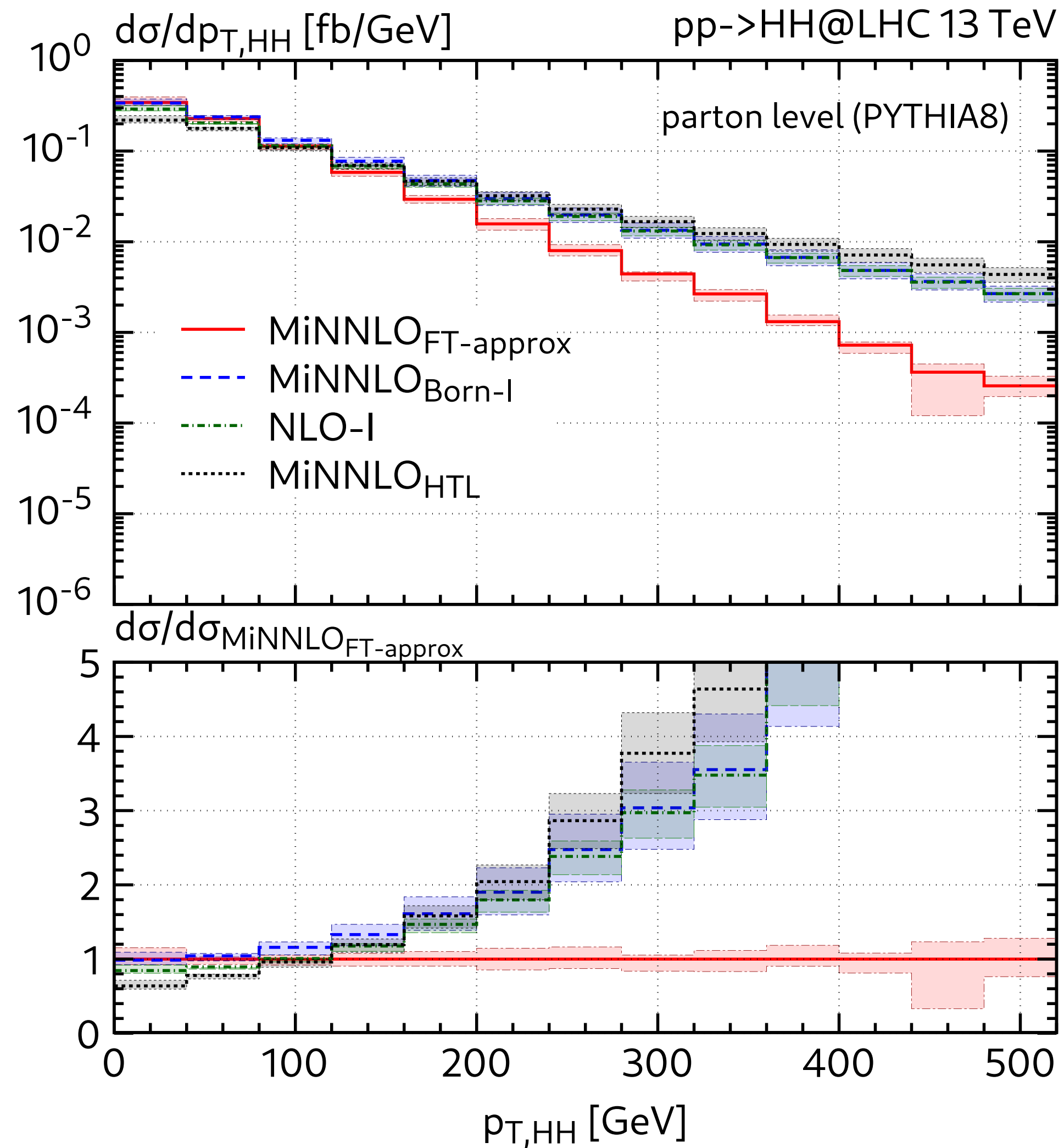
Sizeable **positive mass effects** not captured by HTL.

Born-I overestimates mass effects in the inclusive cross section.

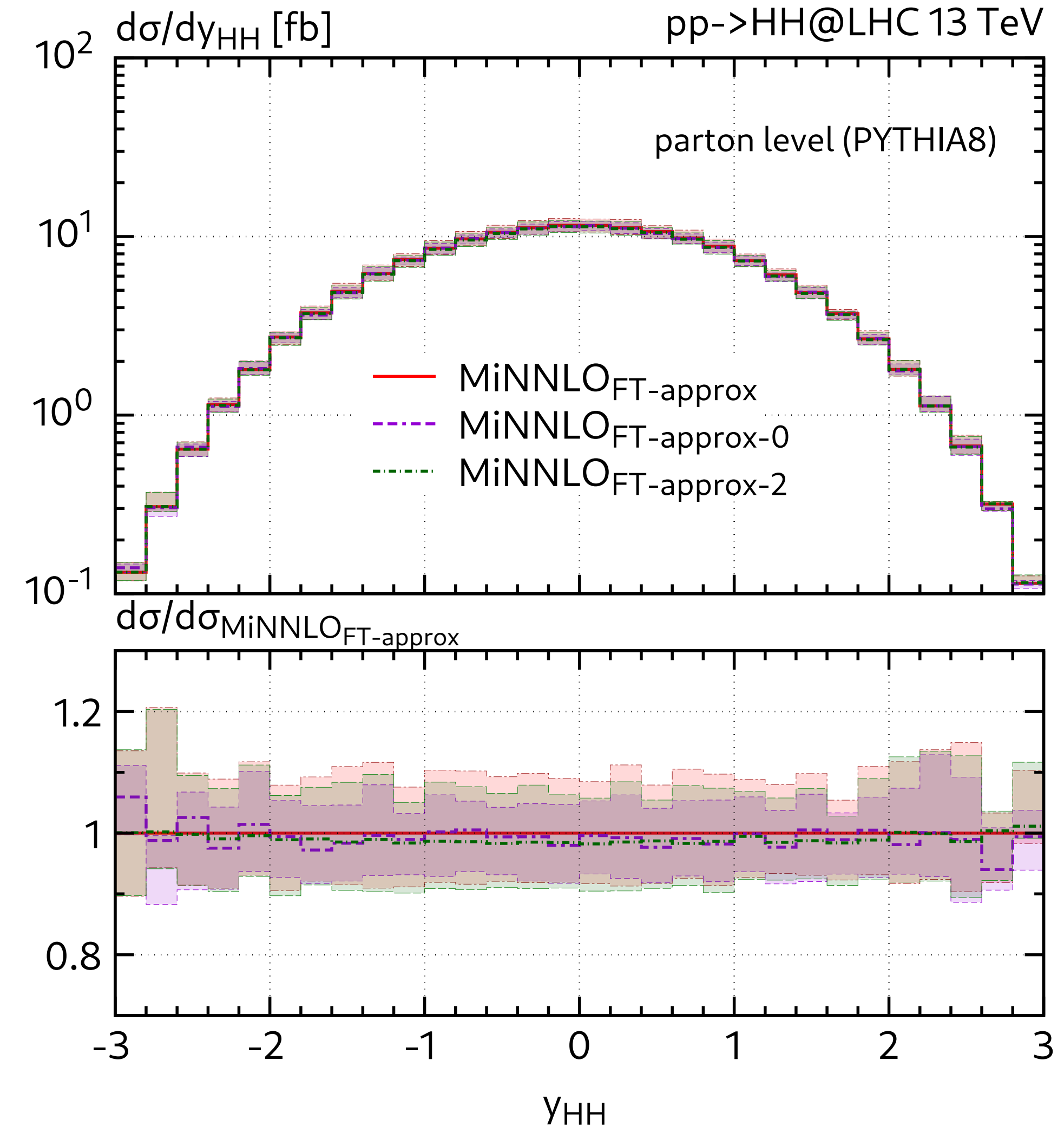
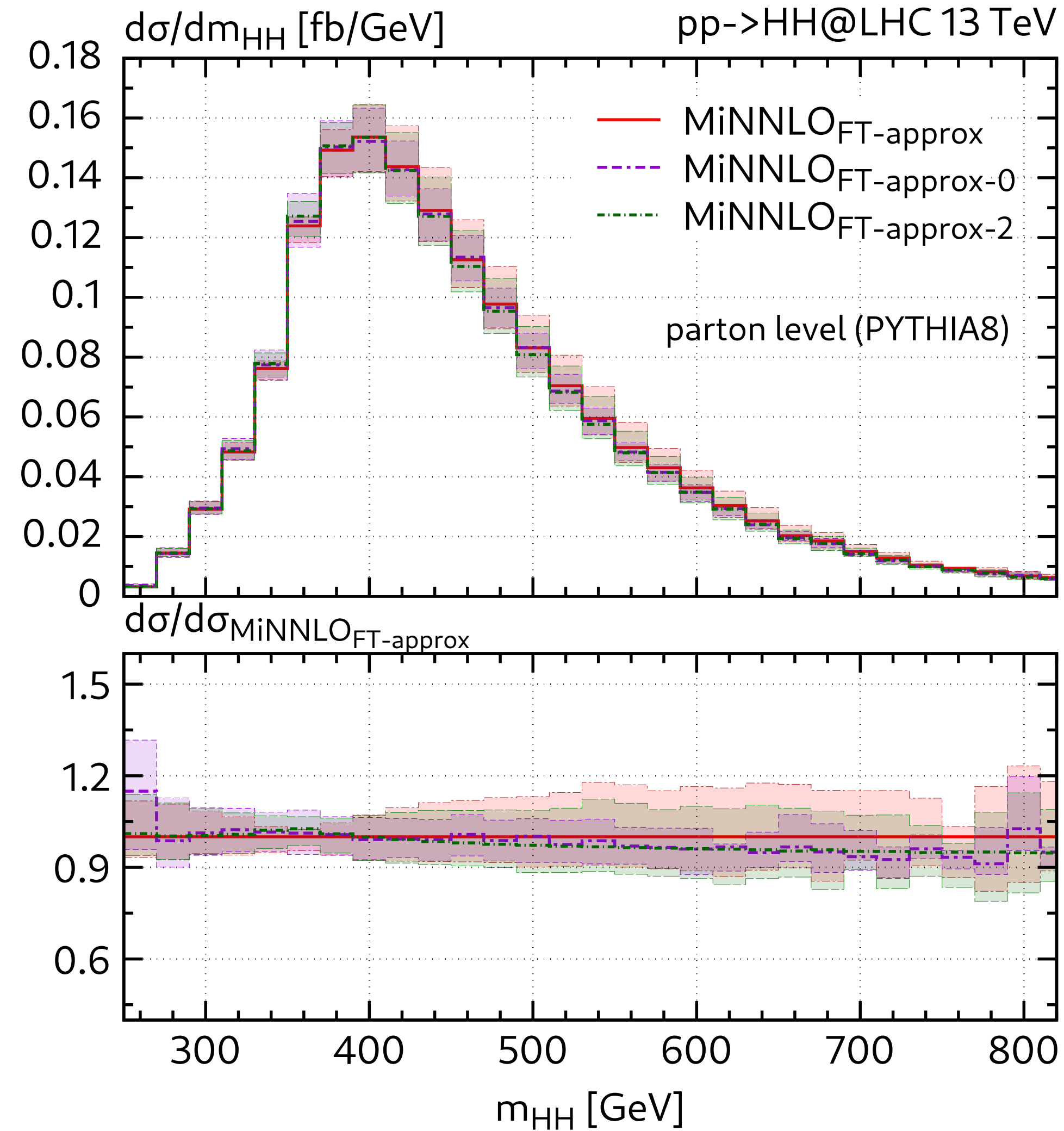
Mass effects for inclusive observables



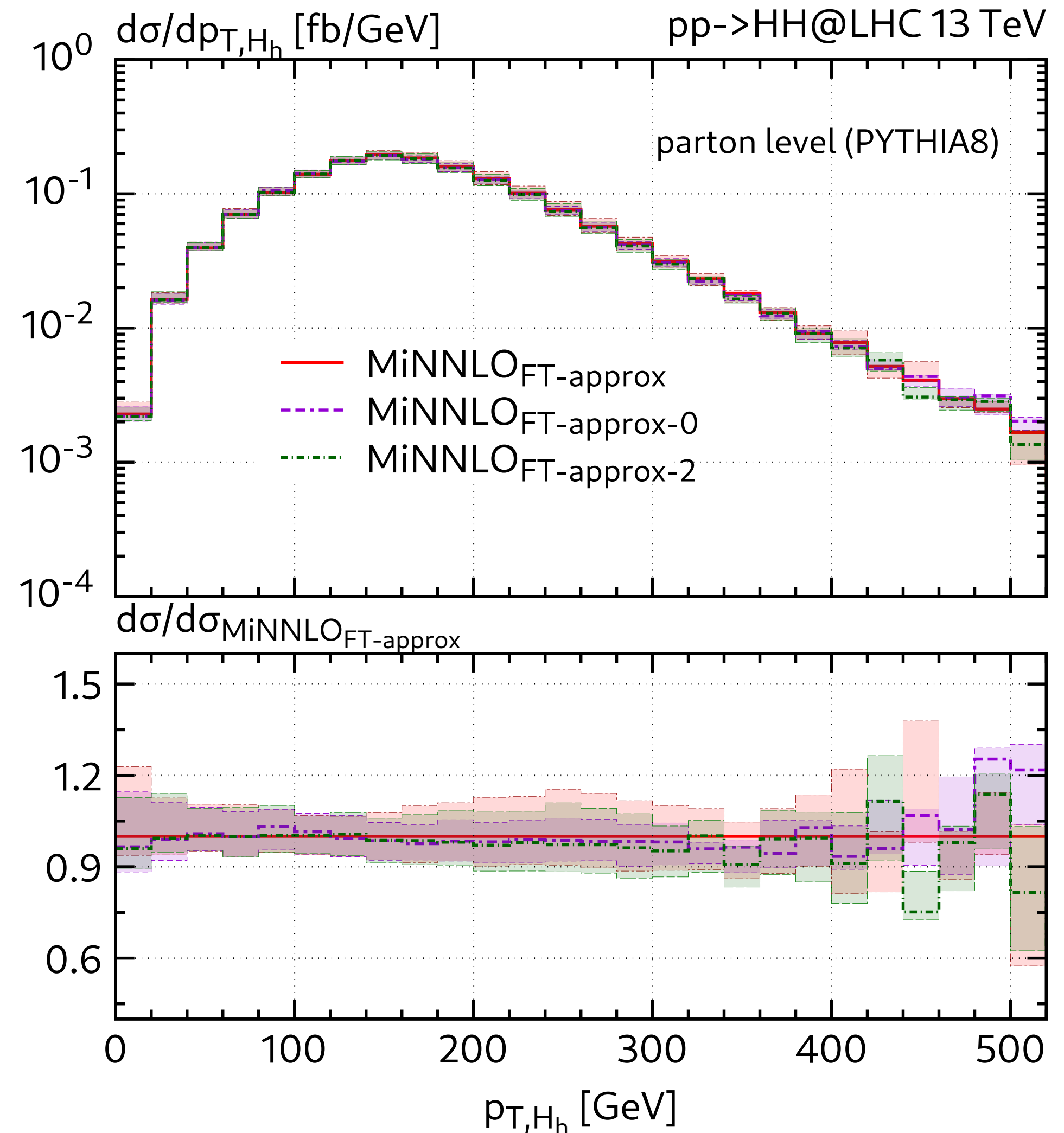
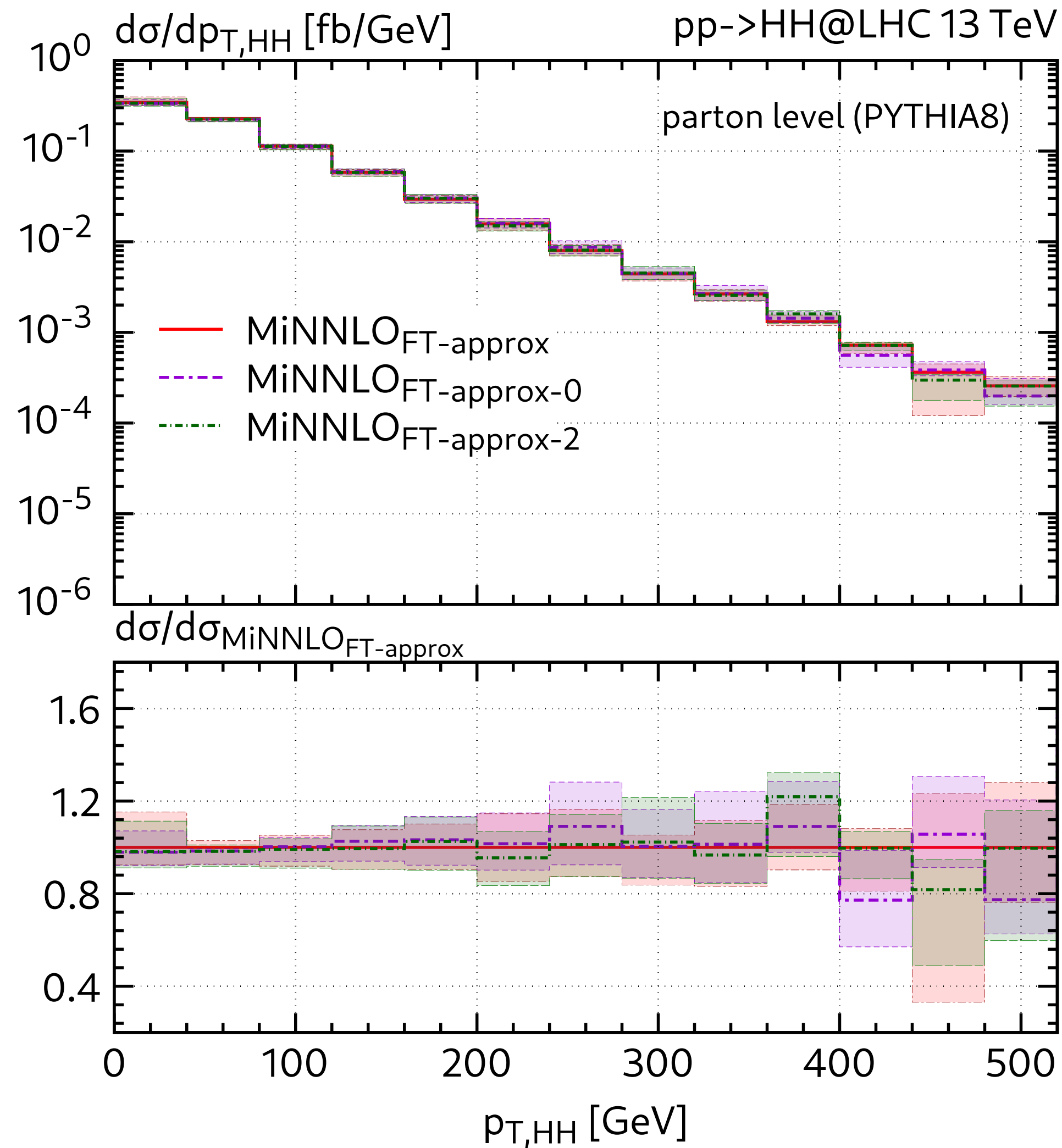
Mass effects for radiation-sensitive observables



Comparison of the three FT-approx



Comparison of the three FT-approx



Comparison with GENEVA

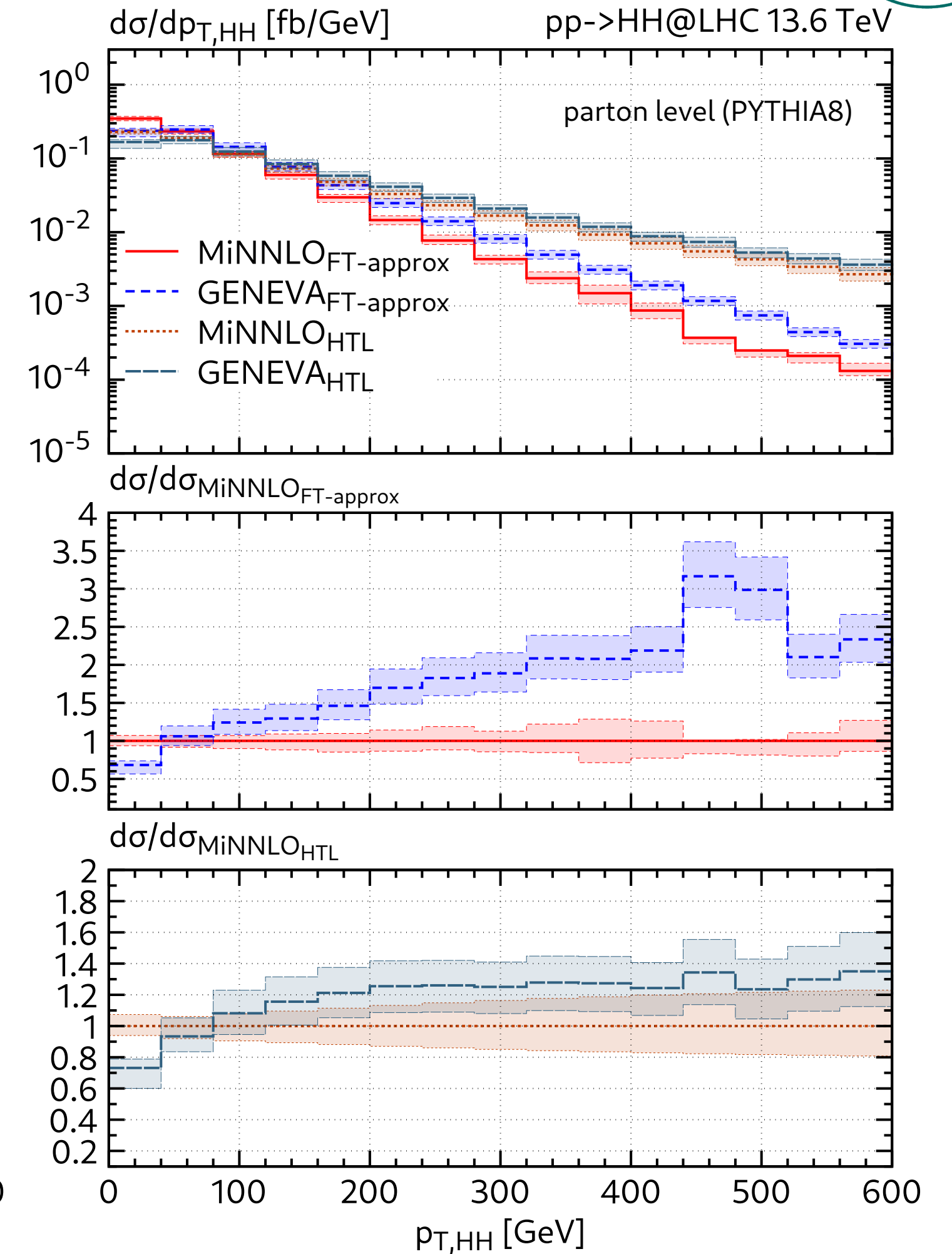
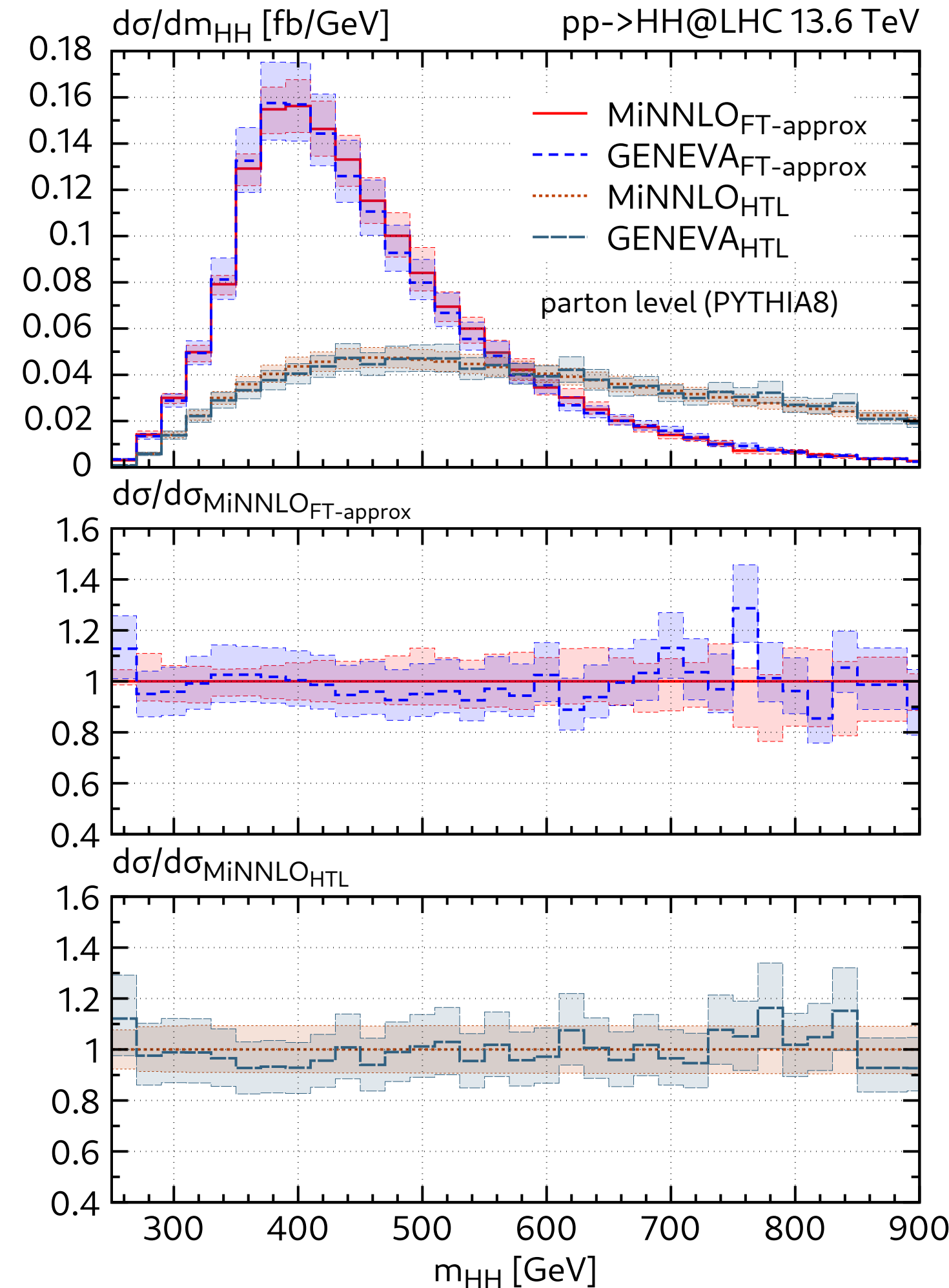
[Alioli, Marinelli, Napolitano [2507.08558](#)]



σ (fb)	HTL	Born-I	FT-approx
MINNLO _{PS}	$31.32^{+9.2\%}_{-9.4\%}$	$37.92^{+9.3\%}_{-9.2\%}$	$32.72^{+7.7\%}_{-8.5\%}$
GENEVA	$30.69^{+7.1\%}_{-8.5\%}$	$37.65^{+7.3\%}_{-8.4\%}$	$32.34^{+6.8\%}_{-5.3\%}$

Good agreement for the total cross section and inclusive observables.

Large discrepancies for p_T , possibly due to the different resummation (p_T vs zero-jettiness) and different treatment of some matrix elements (needs future work).





Variation of the trilinear Higgs coupling

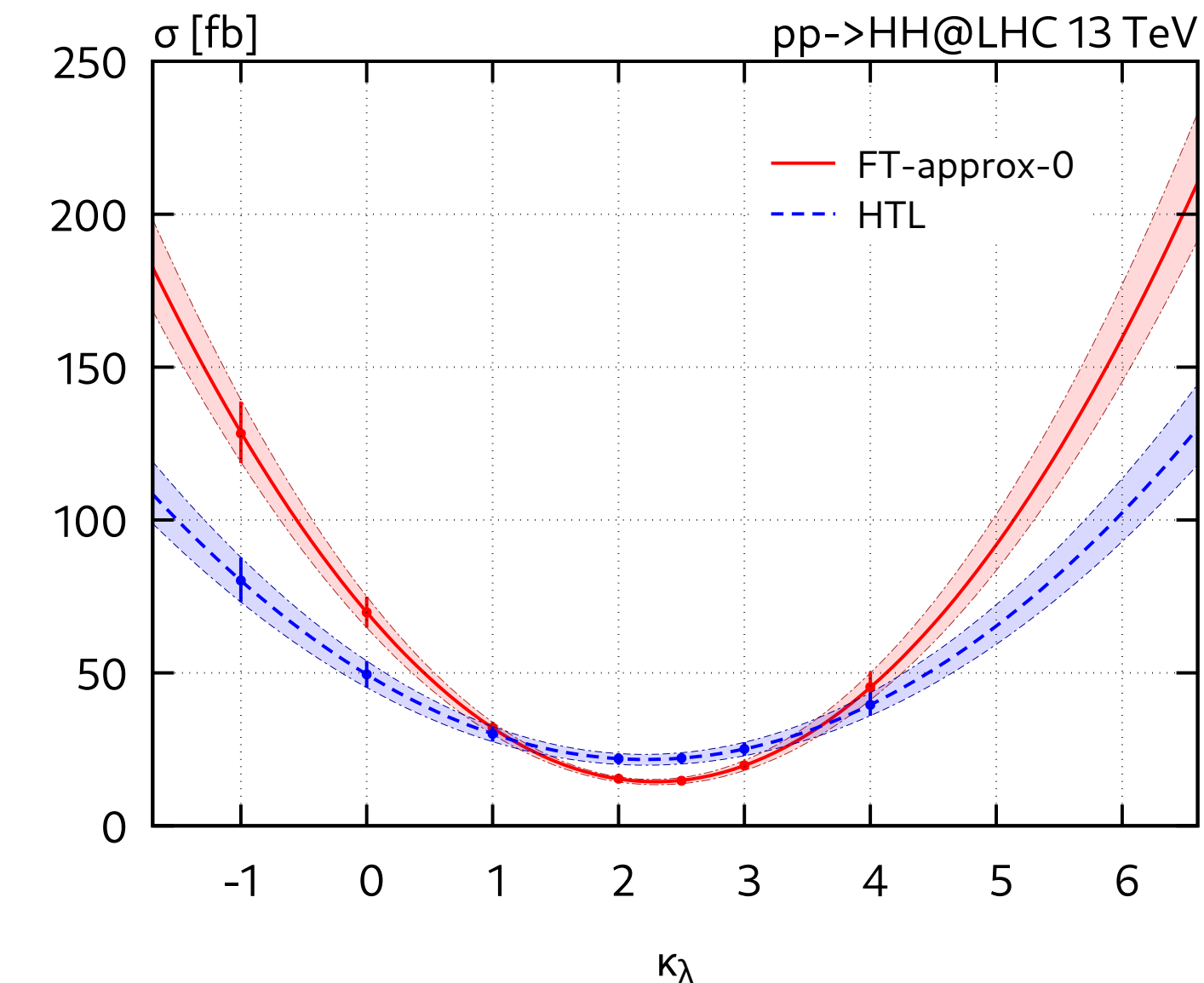
Allow for **deviations from the SM**: $\lambda_3 = \kappa_\lambda \lambda_3^{\text{SM}} = \kappa_\lambda \frac{m_H^2}{2v}$

Change **kl** in the input card.

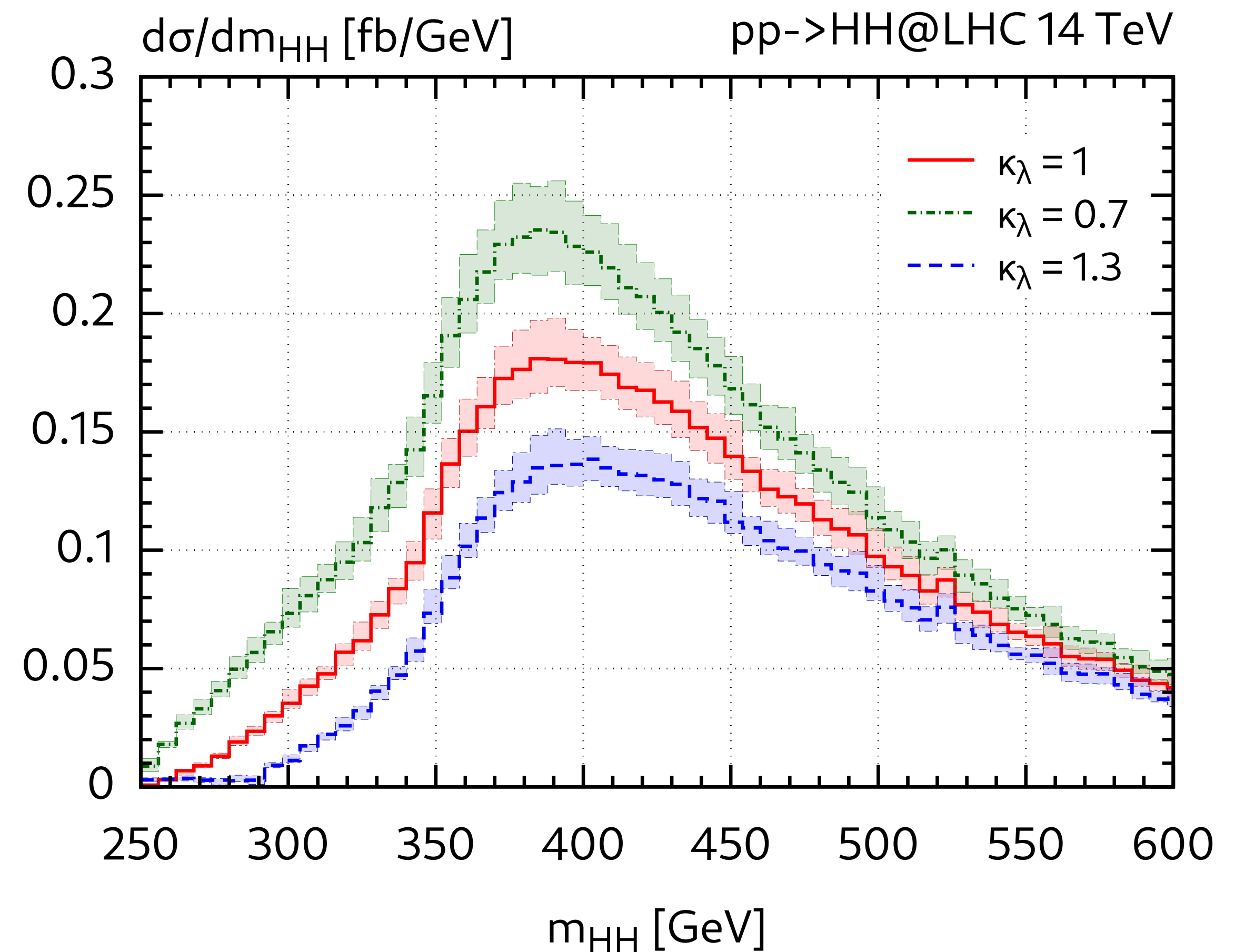
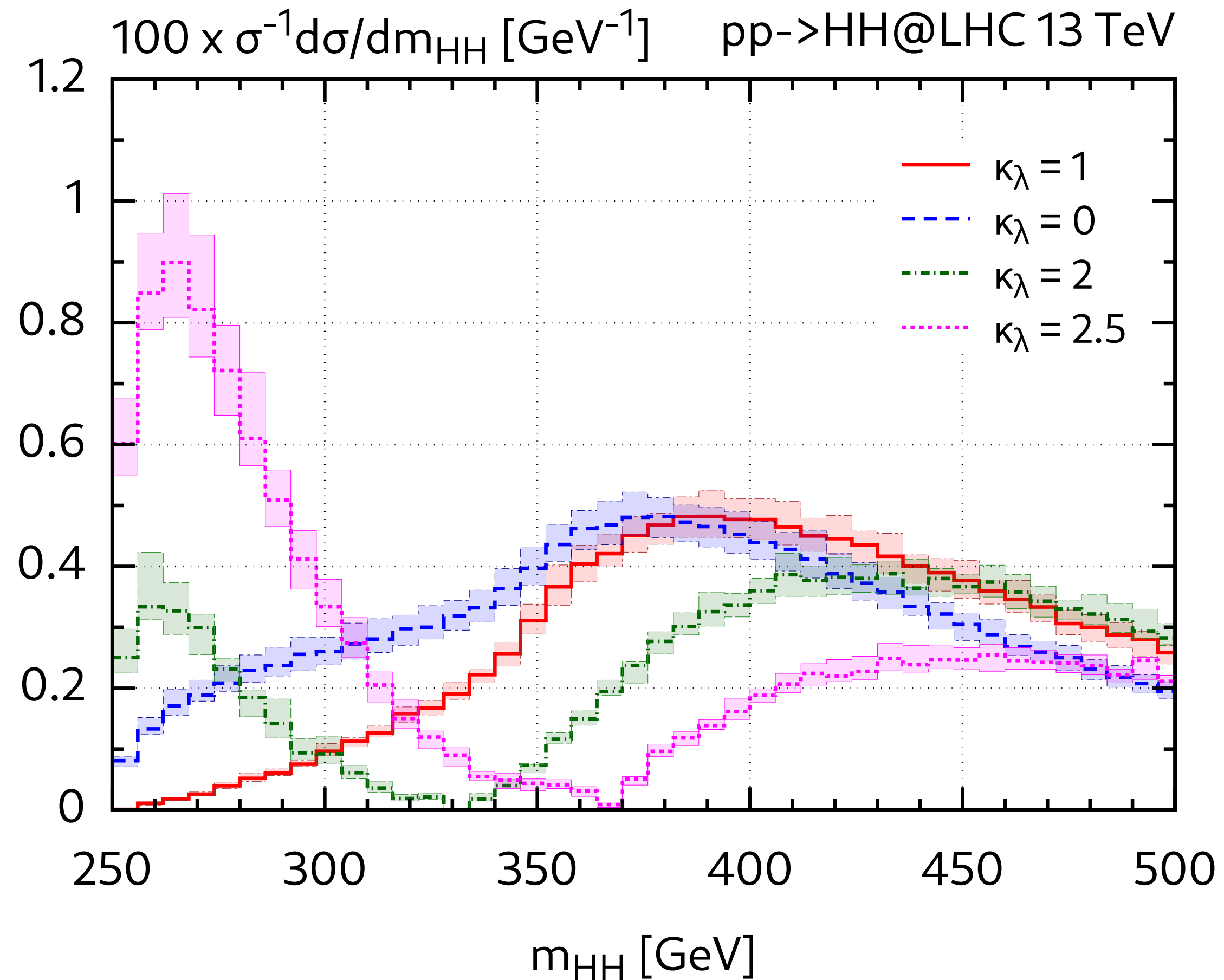
Bounds from **[ATLAS Collaboration 2507.03495]**: $-1.7 < \kappa_\lambda < 6.6$

κ_λ	-1	0	1 (SM)	2	2.5	4
σ_{HTL} (fb)	$80.21^{+9.3\%}_{-8.8\%}$	$49.52^{+8.9\%}_{-8.7\%}$	$30.08^{+8.1\%}_{-8.5\%}$	$21.96^{+8\%}_{-8.5\%}$	$22.13^{+8.6\%}_{-8.6\%}$	$39.57^{+10\%}_{-9\%}$
$\sigma_{\text{FT-approx-0}}$ (fb)	$128.29^{+7.5\%}_{-8.1\%}$	$69.82^{+7.3\%}_{-7.2\%}$	$32.04^{+6.1\%}_{-6.6\%}$	$15.38^{+4.2\%}_{-6.5\%}$	$14.74^{+6.4\%}_{-7.3\%}$	$45.39^{+10.9\%}_{-9.3\%}$

$$\sigma = |\Box|^2 + 2\text{Re}(\Box^* \Delta) \kappa_\lambda + |\Delta|^2 \kappa_\lambda^2$$



Variation of the trilinear Higgs coupling



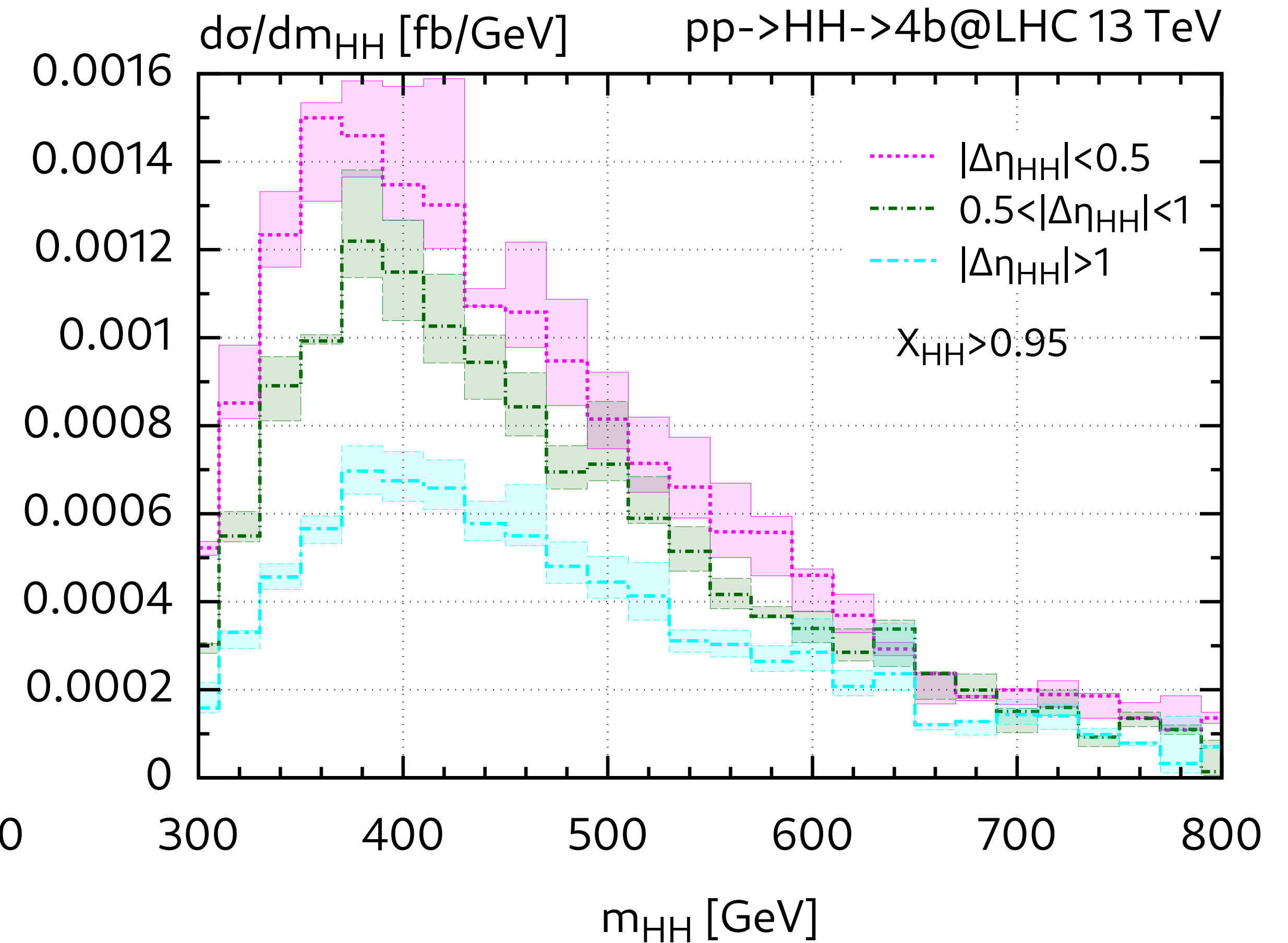
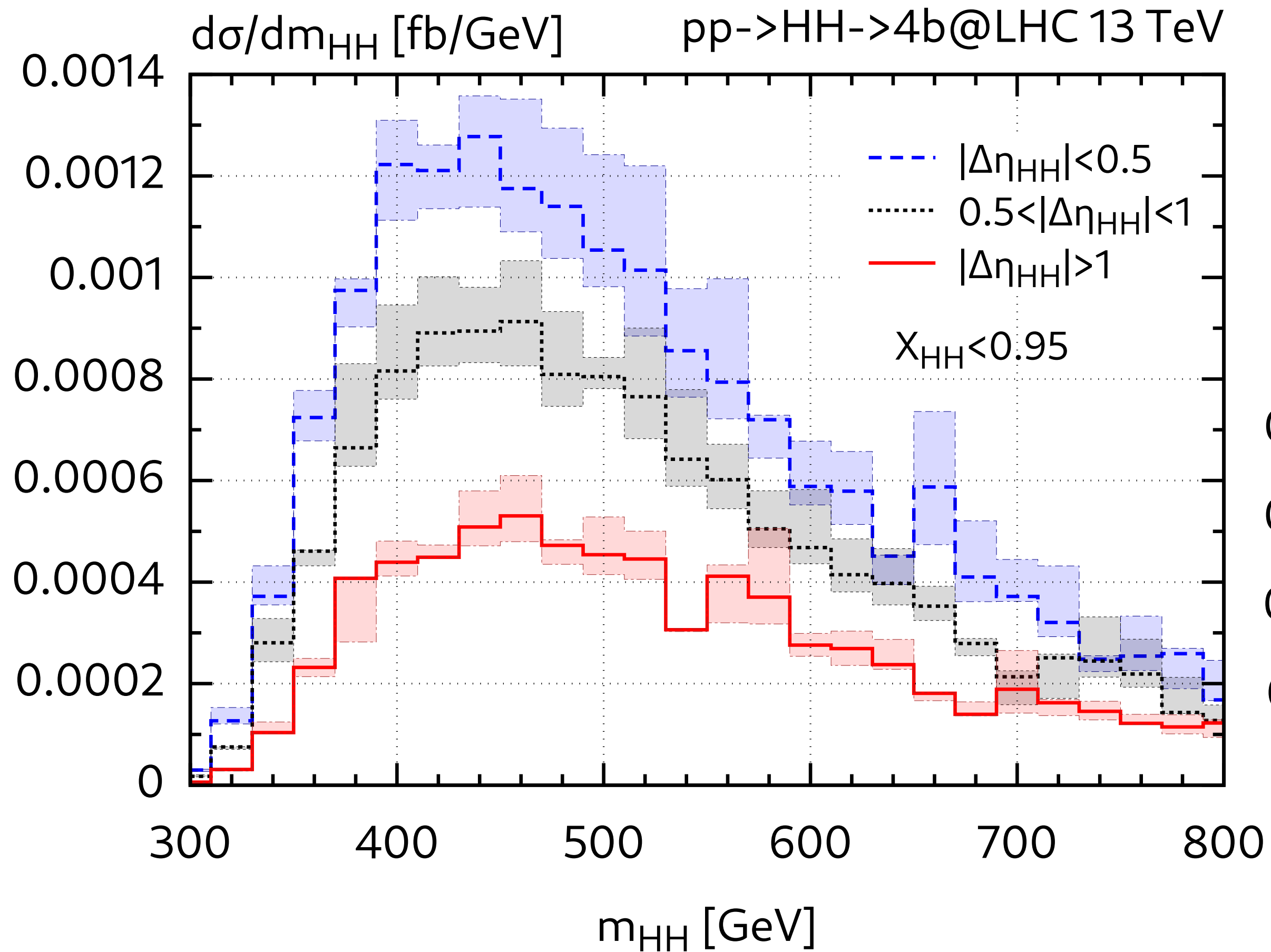
Expected HL-LHC sensitivity

[ATLAS and CMS collaborations [2504.00672](#)]

Reconstructed di-Higgs invariant mass in 4b final state



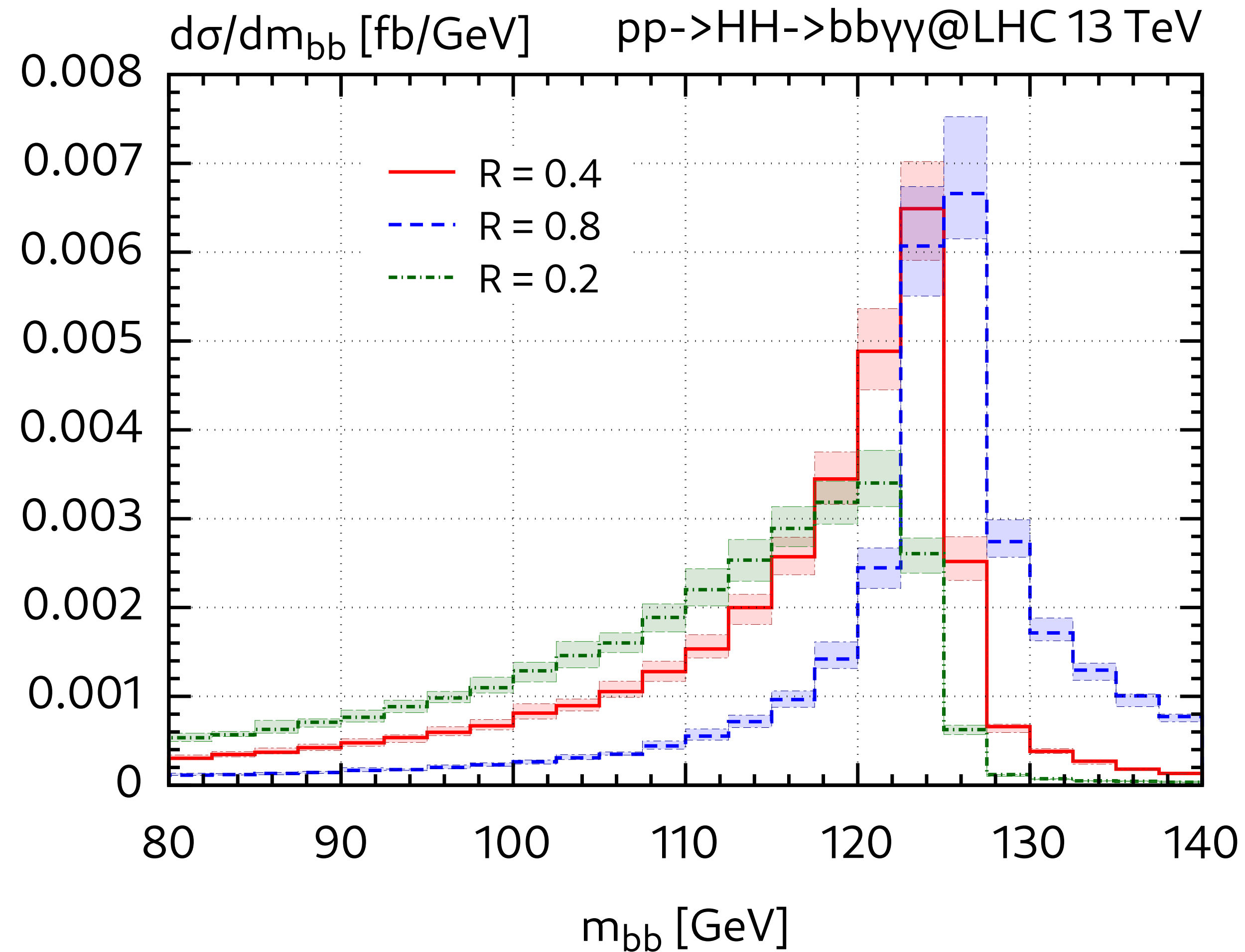
Inspired by [\[ATLAS Collaboration 2301.03212\]](#)



Di-jet invariant mass in 2b2 γ final state



Inspired by [\[ATLAS Collaboration 2507.03495\]](#)



Summary



- We provided a **NNLO+PS event generator** for Higgs pair production in the MiNNLOPS framework.
- The HHJ code is **publicly available** at <https://gitlab.com/POWHEG-BOX/RES/POWHEG-BOX-RES>.
- It allows for **different implementations of the top-quark mass effects**, with the three **FT-approx** representing the best we can achieve at the moment.
The code is written to directly accomodate the missing matrix elements.
- We found unexpected **discrepancies with GENEVA** when introducing mass effects.
Their understanding is still work in progress.
- The code allows for the **variation of the trilinear Higgs coupling**.
- We implemented **analysis** inspired by the ones by **ATLAS**.

THANK YOU FOR YOUR ATTENTION!



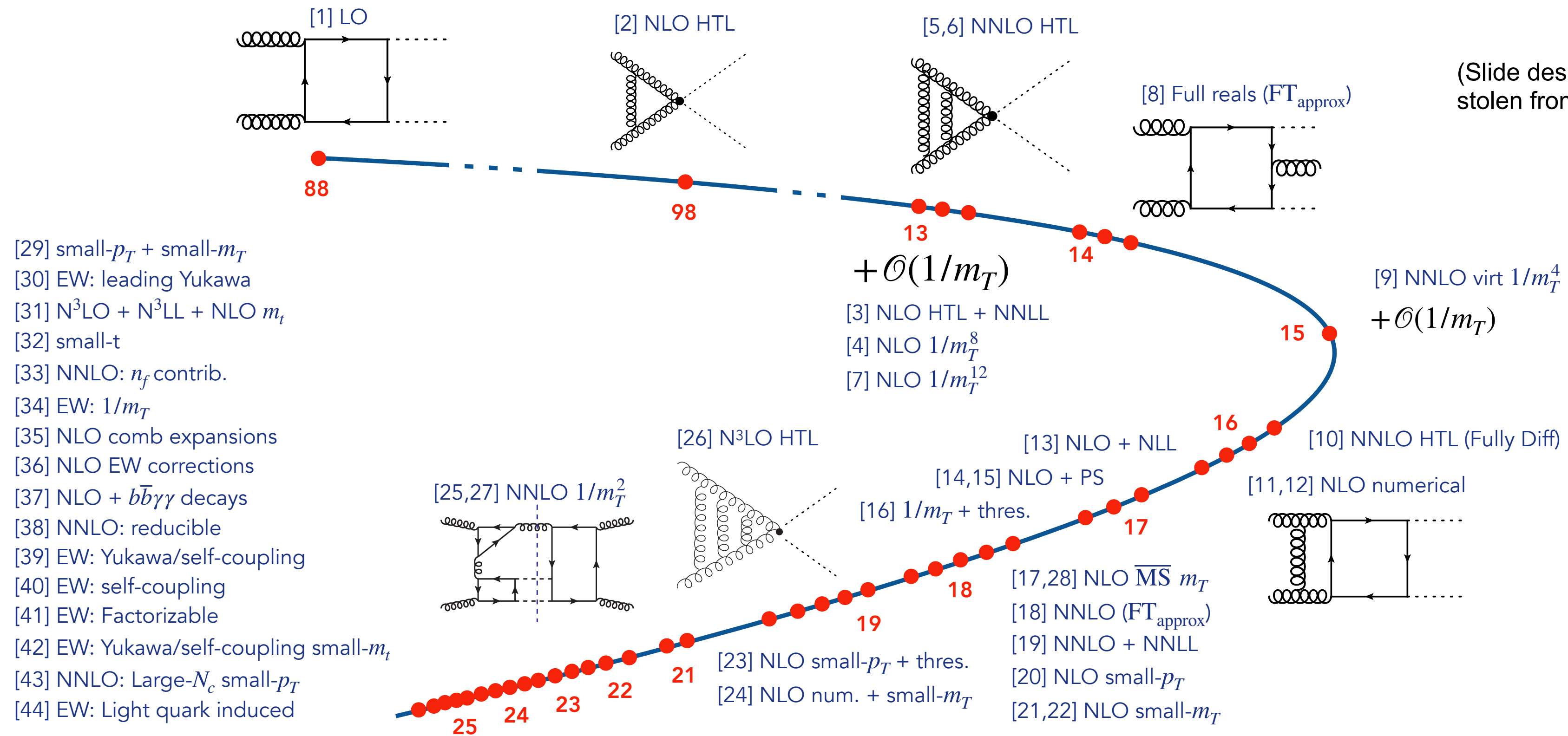
BACKUP SLIDES

Theory status

(Slide stolen from S. Jones)



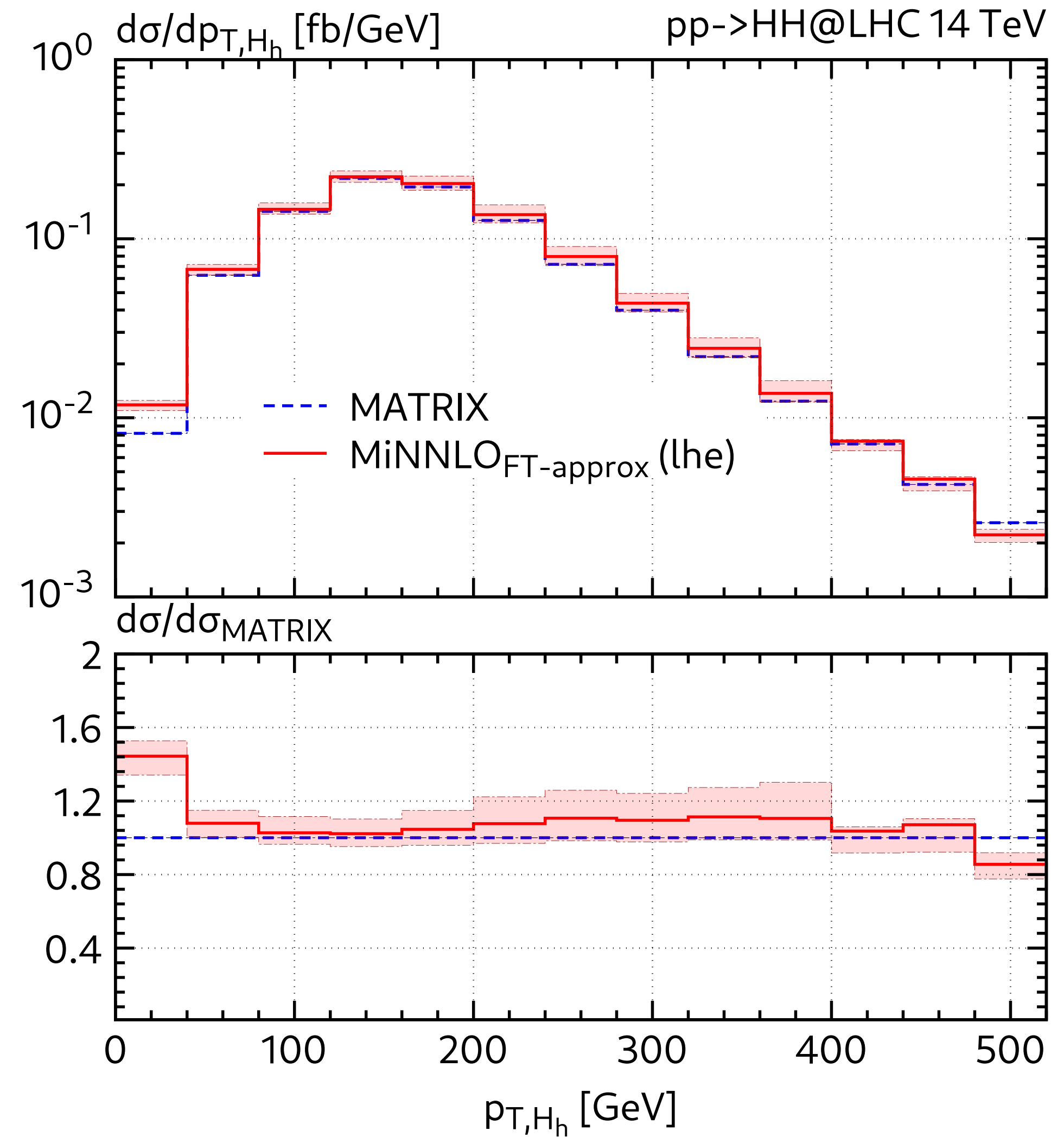
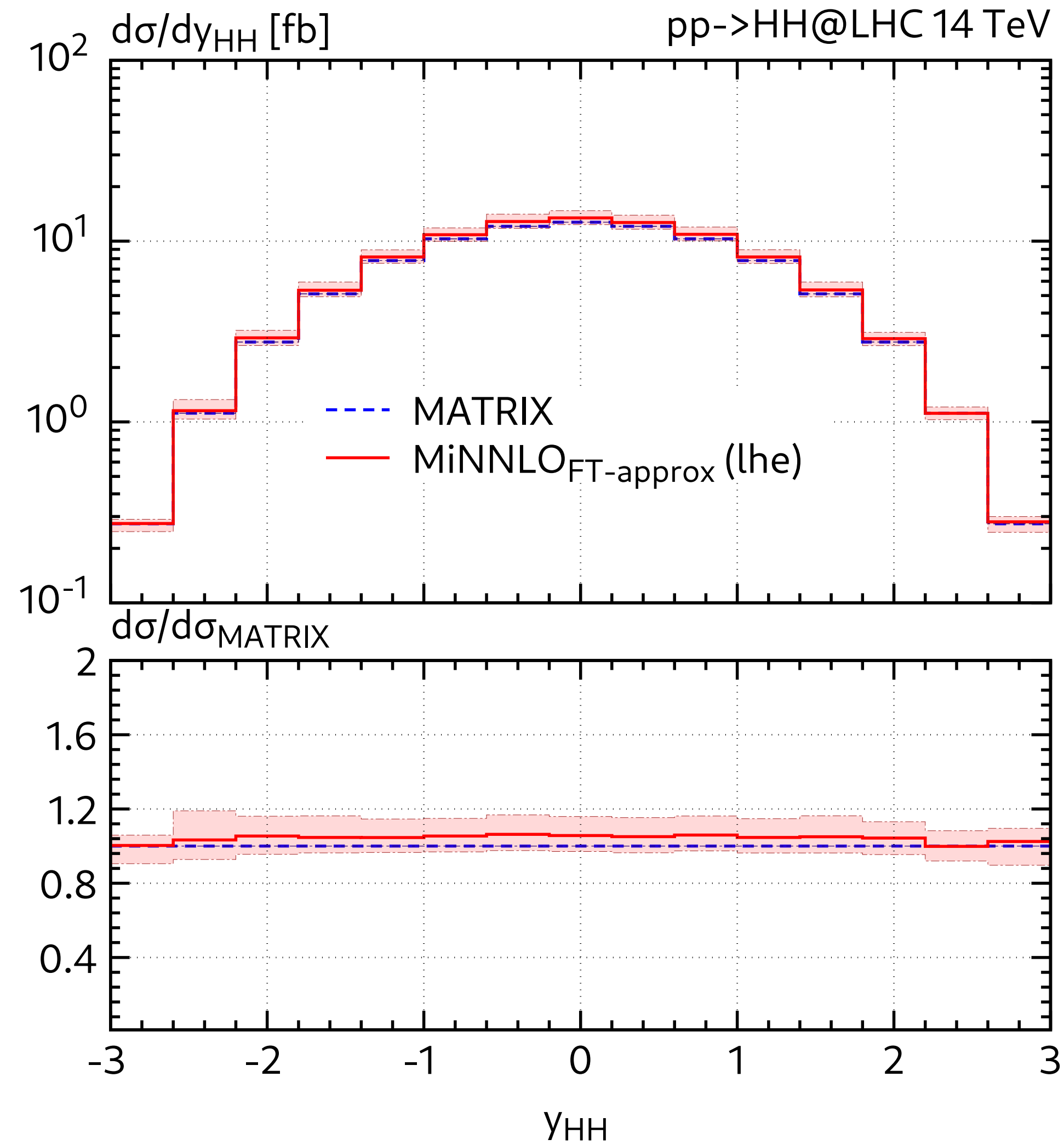
(Slide design shamelessly stolen from G. Salam)



[1] Glover, van der Bij 88; [2] Dawson, Dittmaier, Spira 98; [3] Shao, Li, Li, Wang 13; [4] Grigo, Hoff, Melnikov, Steinhauser 13; [5] de Florian, Mazzitelli 13; [6] Grigo, Melnikov, Steinhauser 14; [7] Grigo, Hoff 14; [8] Maltoni, Vryonidou, Zaro 14; [9] Grigo, Hoff, Steinhauser 15; [10] de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; [11] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; [12] Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Zirke 16; [13] Ferrera, Pires 16; [14] Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; [15] SPJ, Kuttimalai 17; [16] Gröber, Maier, Rauh 17; [17] Baglio, Campanario, Glaus, Mühlleitner, Spira, Streicher 18; [18] Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18; [19] de Florian, Mazzitelli 18; [20] Bonciani, Deggrasi, Giardino, Gröber 18; [21] Davies, Mishima, Steinhauser, Wellmann 18, 18; [22] Mishima 18; [23] Gröber, Maier, Rauh 19; [24] Davies, Heinrich, SPJ, Kerner, Mishima, Steinhauser, David Wellmann 19; [25] Davies, Steinhauser 19; [26] Chen, Li, Shao, Wang 19, 19; [27] Davies, Herren, Mishima, Steinhauser 19, 21; [28] Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira 21; [29] Bellafronte, Deggrasi, Giardino, Gröber, Vitti 22; [30] Davies, Mishima, Schönwald, Steinhauser, Zhang 22; [31] Ajath, Shao 22; [32] Davies, Mishima, Schönwald, Steinhauser 23; [33] Davies, Schönwald, Steinhauser 23; [34] Davies, Schönwald, Steinhauser, Zhang 23; [35] Bagnaschi, Deggrasi, Gröber 23; [36] Bi, Huang, Huang, Ma Yu 23; [37] Li, Si, Wang, Zhang, Zhao 24; [38] Davies, Schönwald, Steinhauser, Vitti 24; [39] Heinrich, SPJ, Kerner, Stone, Vestner 24; [40] Li, Si, Wang, Zhang, Zhao 24; [41] Davies, Schönwald, Steinhauser, Zhang 24; [42] Davies, Schönwald, Steinhauser, Zhang 25; [43] Davies, Schönwald, Steinhauser 25; [44] Bonetti, Rendler, Bobadilla 25;

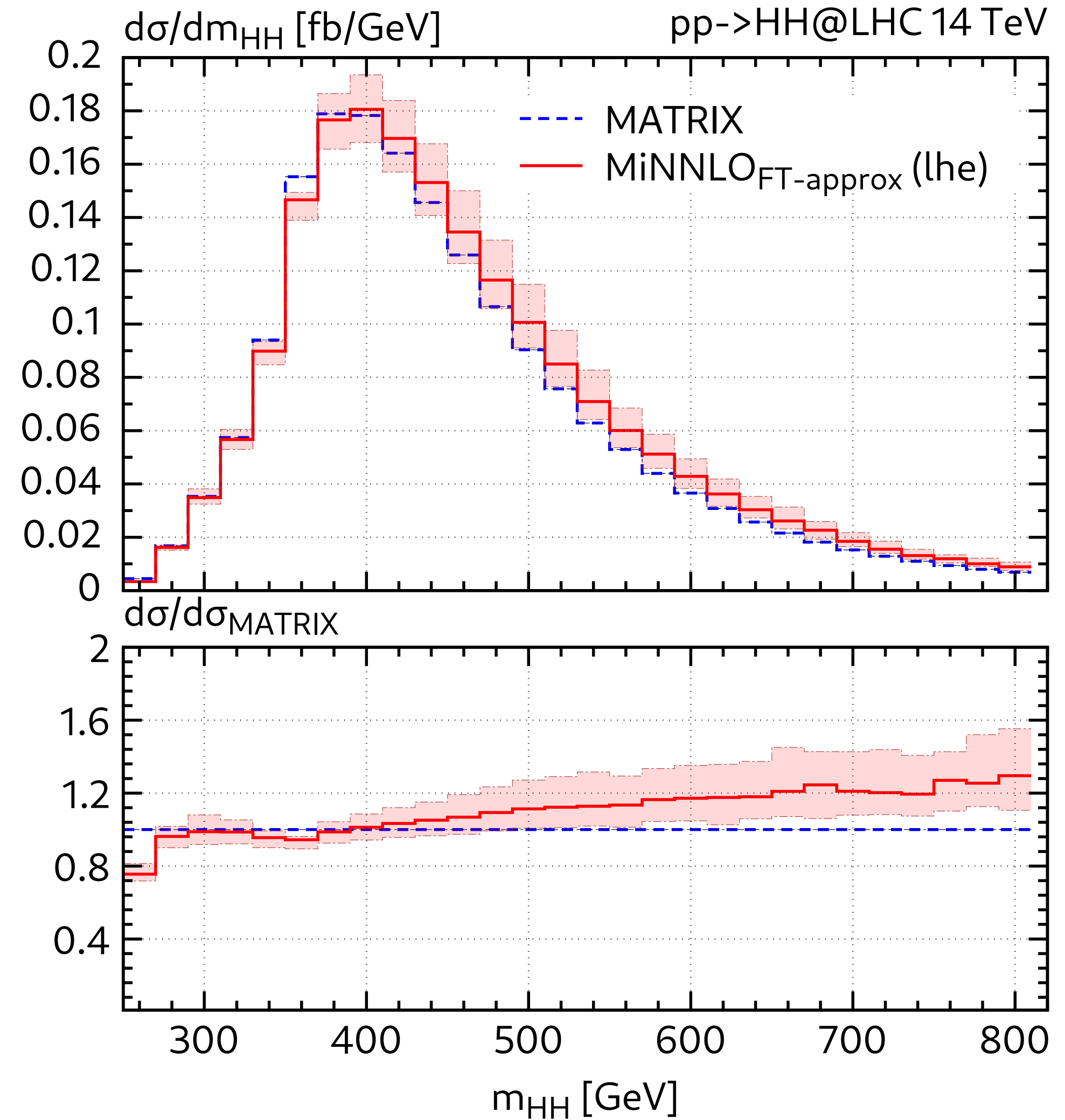
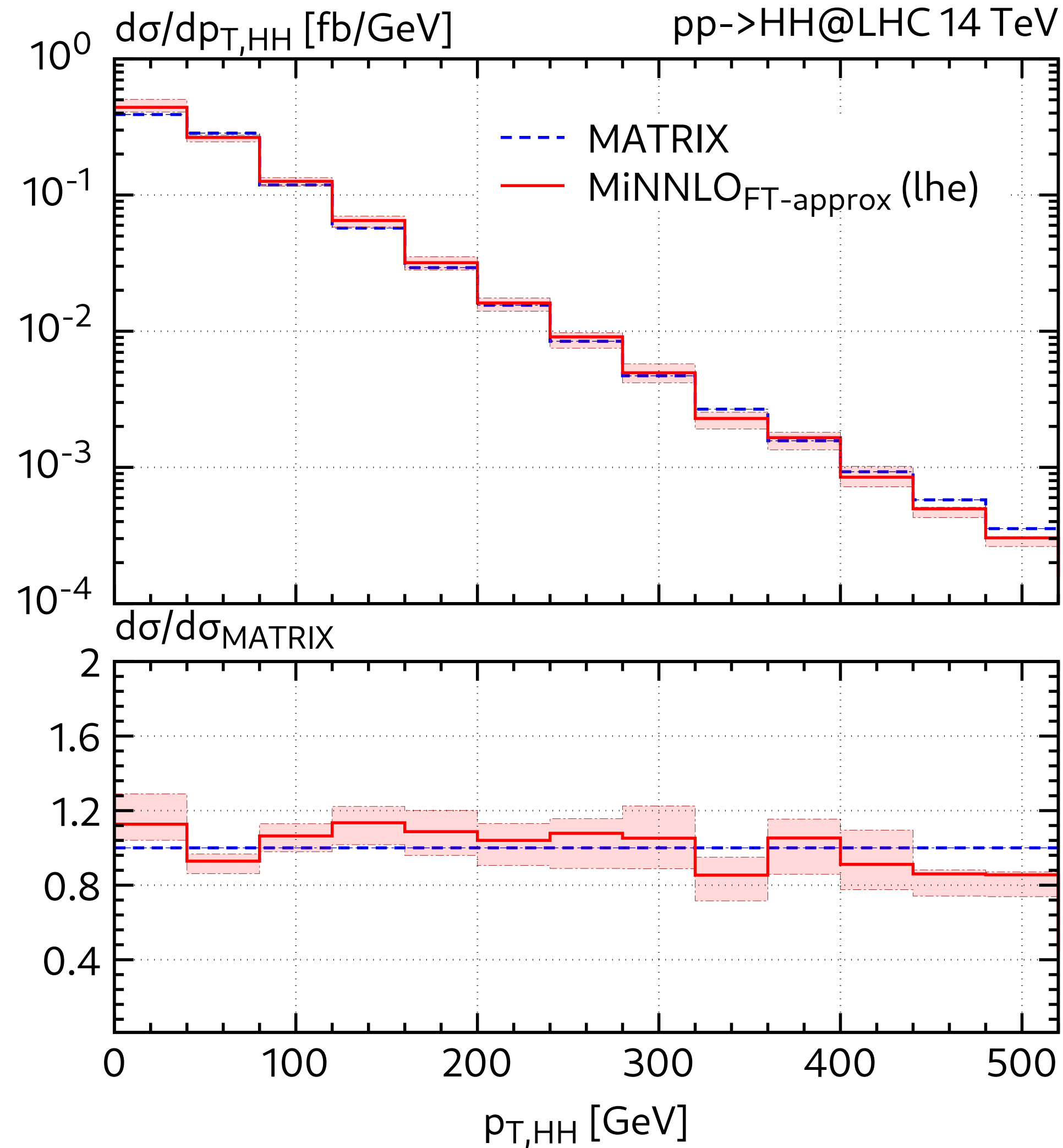
Validation against fixed-order

[Grazzini et al. [1803.02463](#)]

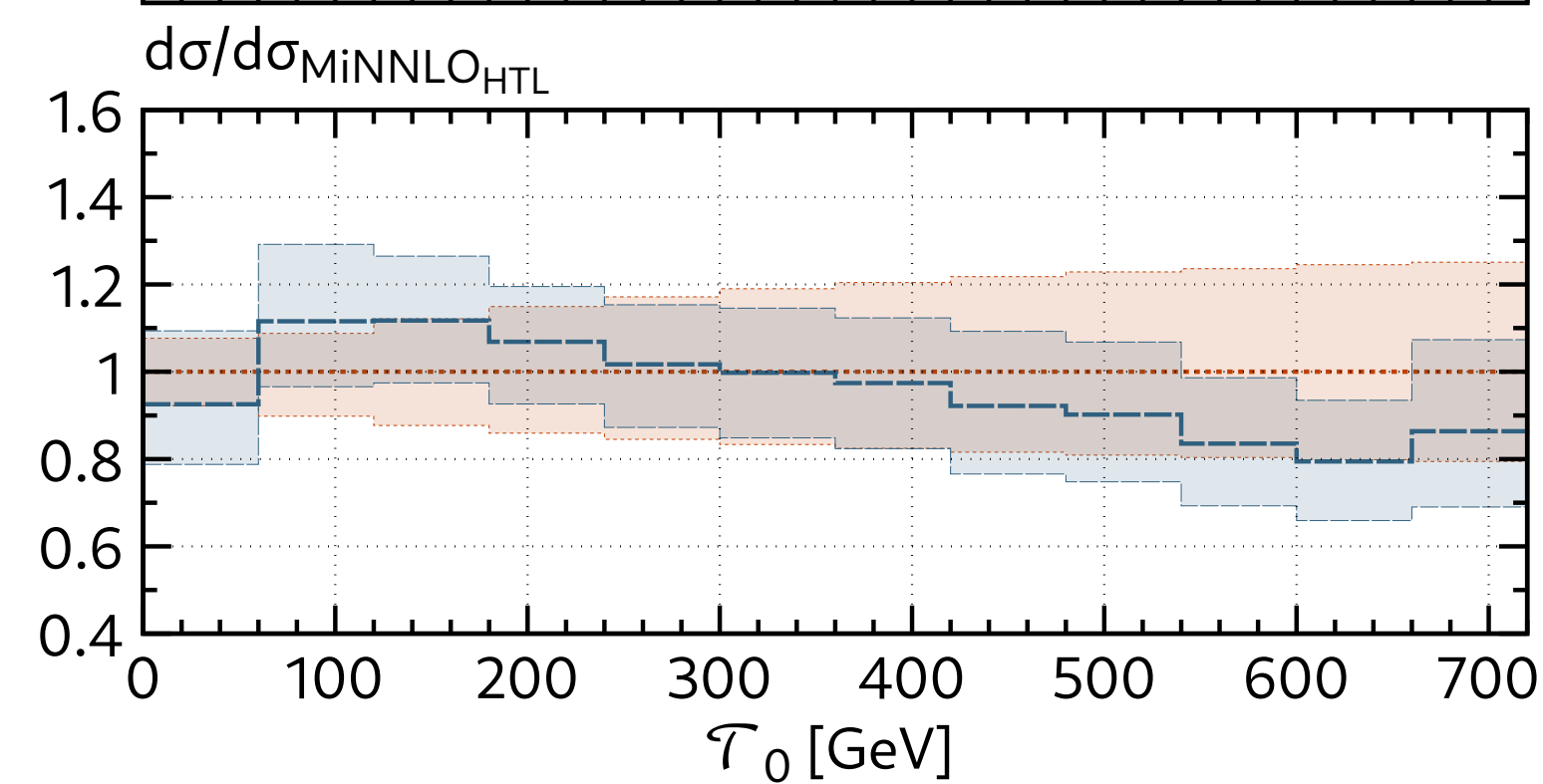
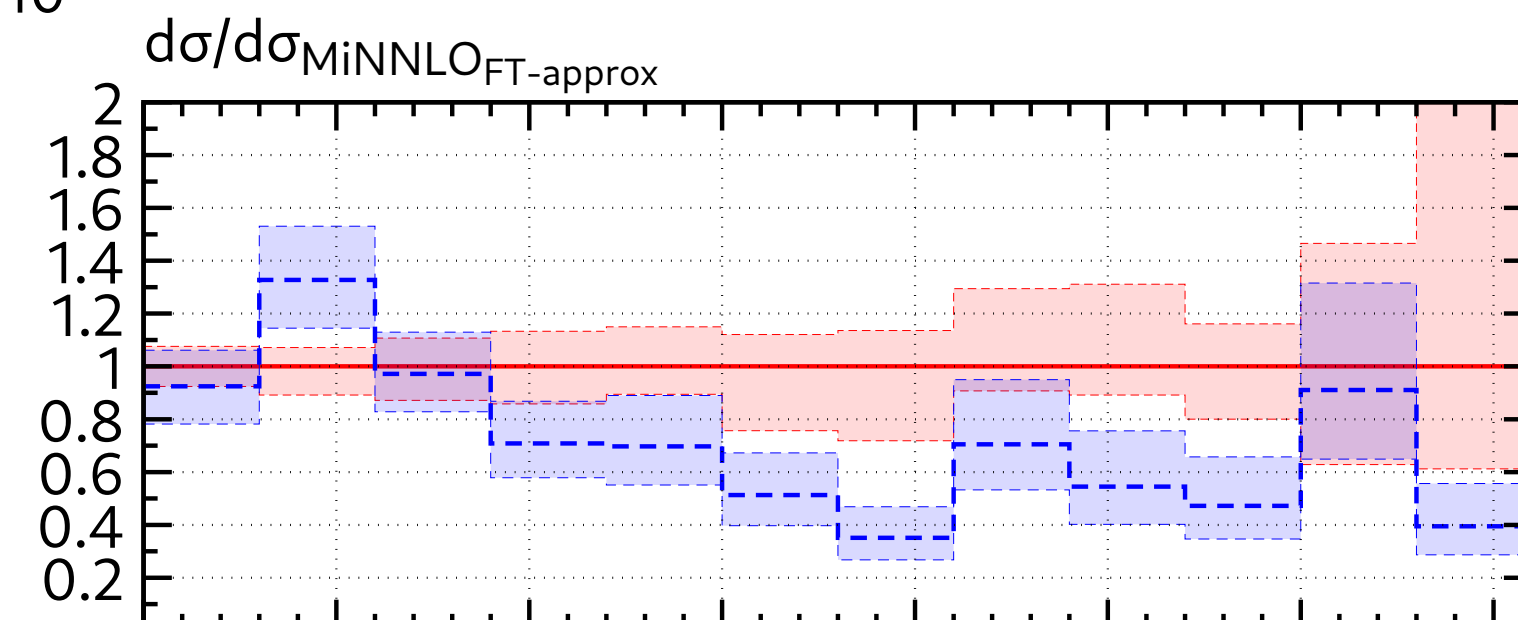
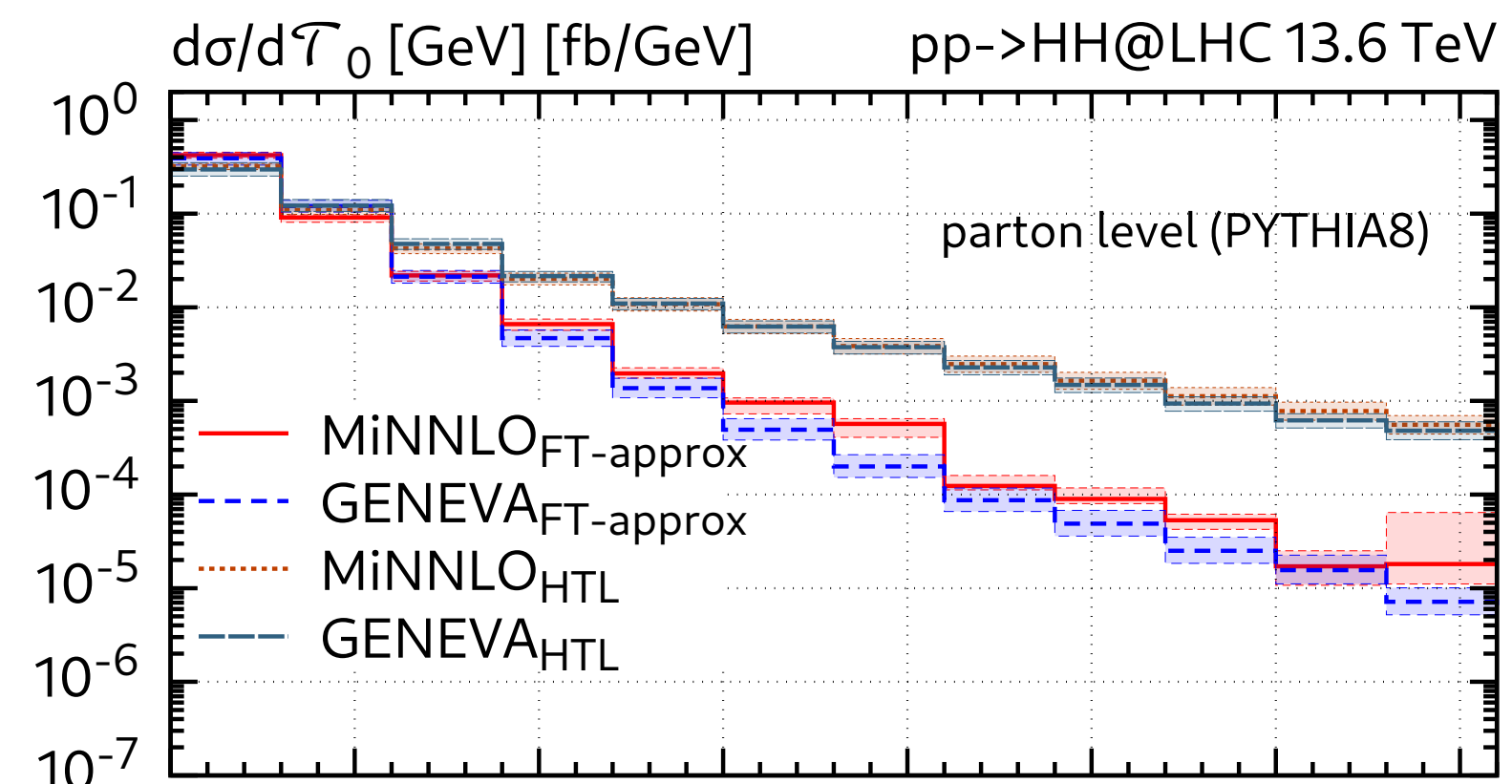
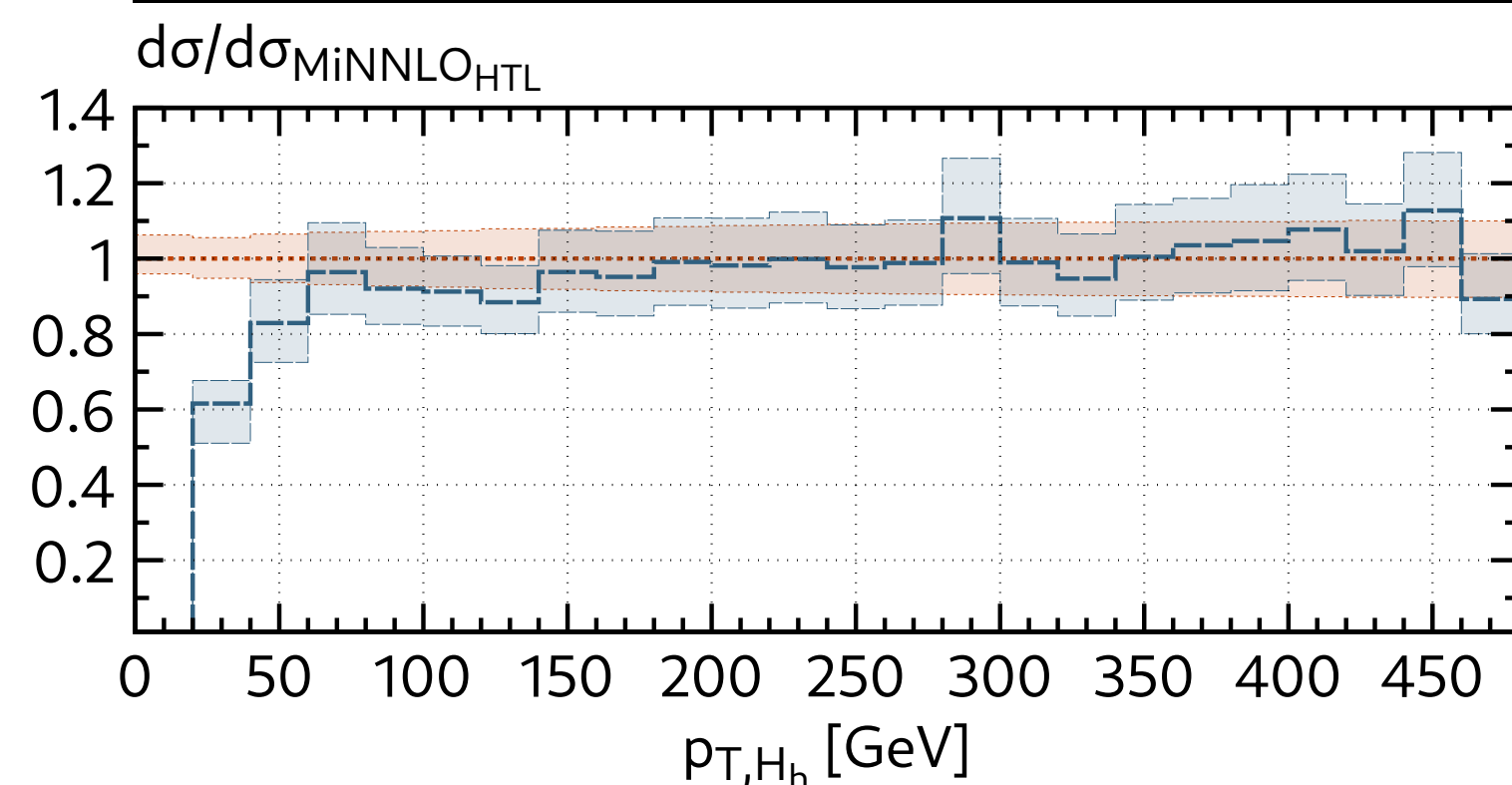
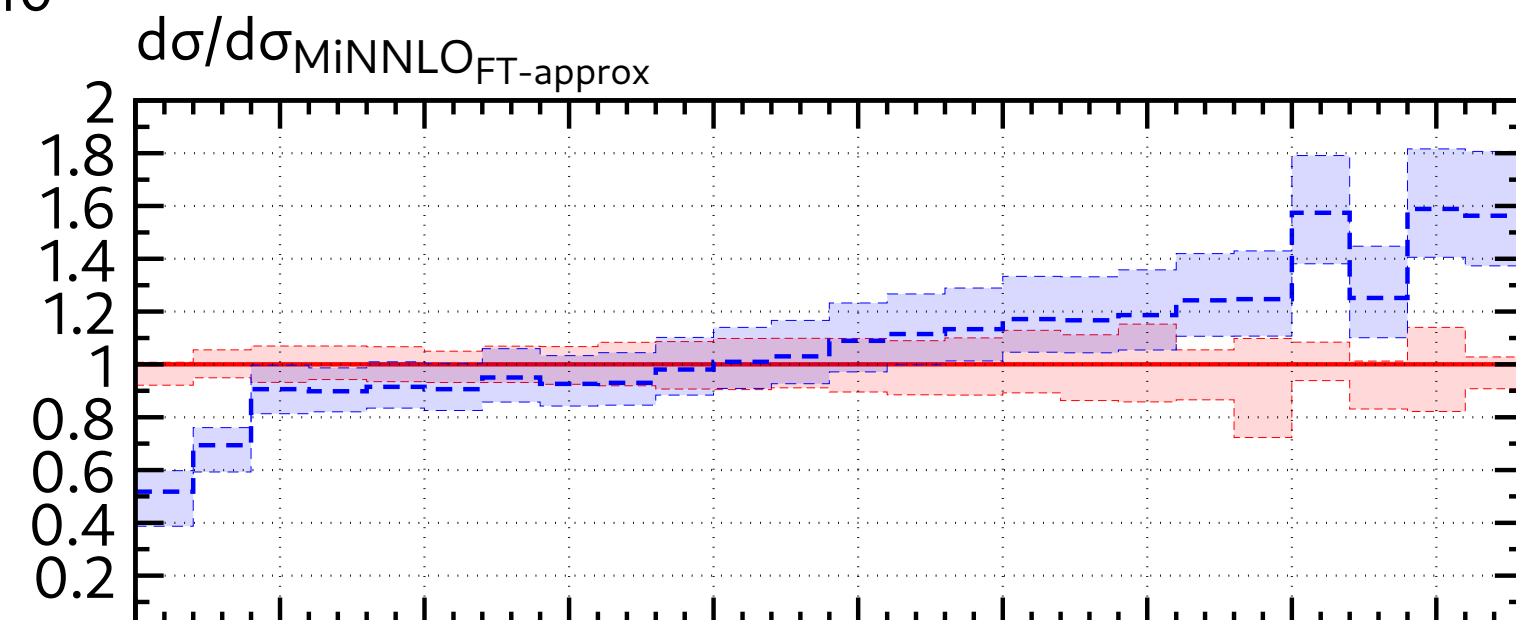
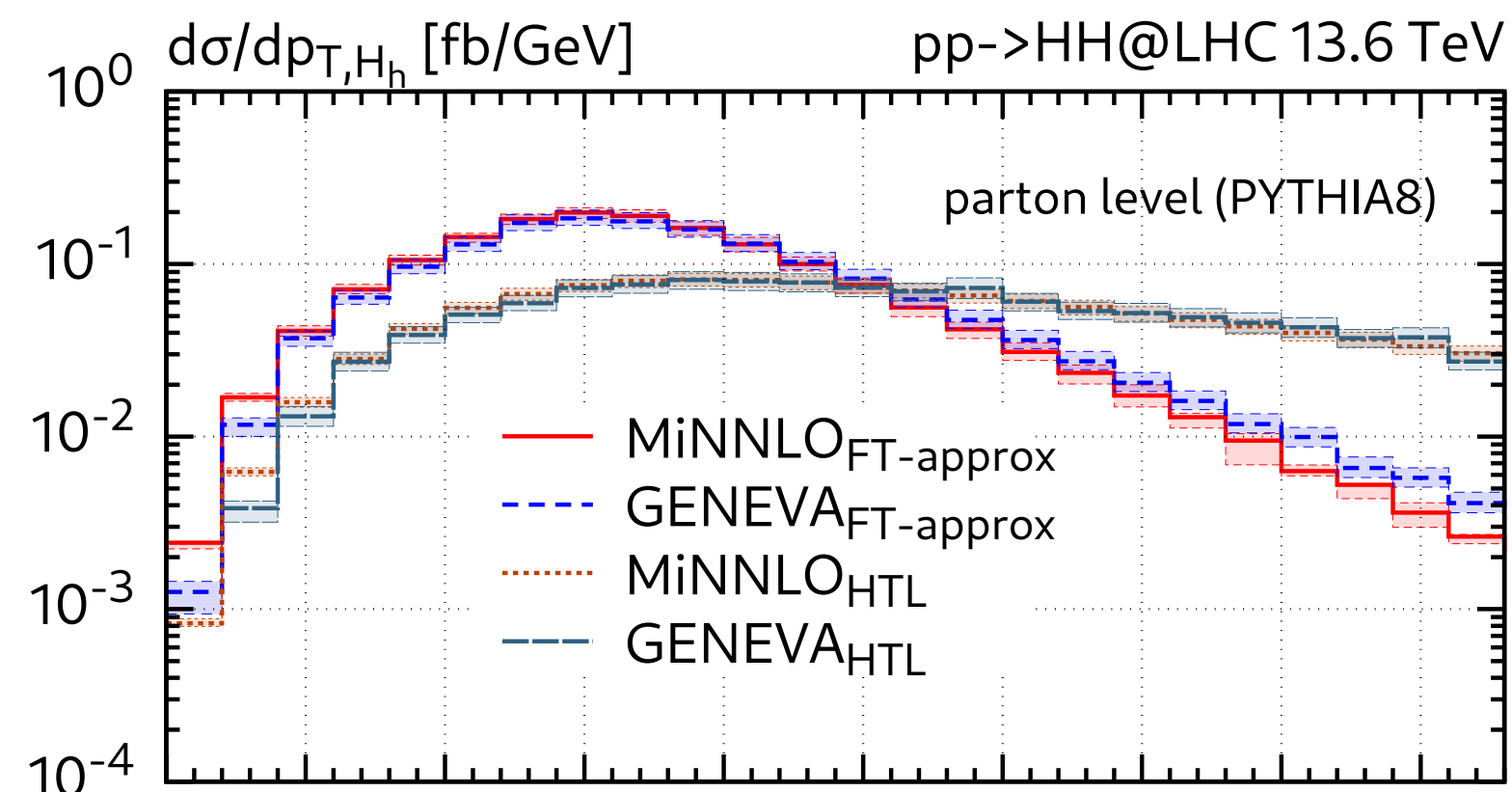


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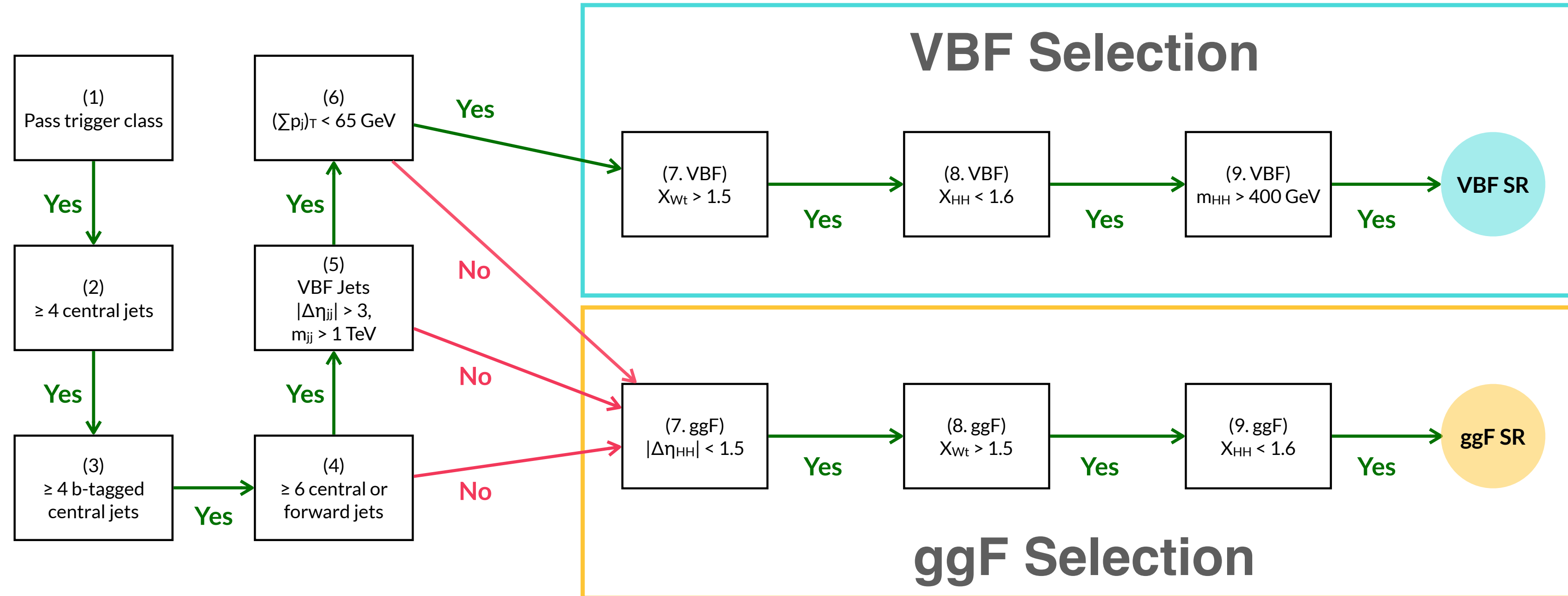


MiNNLO vs GENEVA (2)



ATLAS analysis in the 4b final state

[ATLAS Collaboration [2301.03212](#)]



Higgs bosons reconstructed from the **4 hardest b-jets**.
Pair them so that the hardest pair has the **smallest R separation**.

central jets: $|\eta| < 2.5, \quad p_T > 40 \text{ GeV};$
forward jets: $2.5 < |\eta| < 4.5, \quad p_T > 30 \text{ GeV}.$

$$x_{Wt} = \min \left[\sqrt{\left(\frac{m_{jj} - m_W}{0.1 m_{jj}} \right)^2 + \left(\frac{m_{jjb} - m_t}{0.1 m_{jjb}} \right)^2} \right]$$

$$X_{HH} = \sqrt{\left(\frac{m_{H_1} - 124 \text{ GeV}}{0.1 m_{H_1}} \right)^2 + \left(\frac{m_{H_2} - 117 \text{ GeV}}{0.1 m_{H_2}} \right)^2}$$

ATLAS analysis in the 2b2 γ final state

[ATLAS Collaboration [2507.03495](#)]



Cuts on the photons:

$$p_{\text{T}}(\gamma_1) > 35 \text{ GeV}, \quad p_{\text{T}}(\gamma_2) > 25 \text{ GeV}, \quad 105 \text{ GeV} < m_{\gamma\gamma} < 160 \text{ GeV},$$
$$|\eta(\gamma_{1,2})| < 2.37, \quad \frac{p_{\text{T}}(\gamma_1)}{m_{\gamma\gamma}} > 0.35, \quad \frac{p_{\text{T}}(\gamma_2)}{m_{\gamma\gamma}} > 0.25.$$

Cuts on the b-jets (anti- k_{T}):

$$p_{\text{T}}(j) > 25 \text{ GeV}, \quad |\eta(j)| < 2.5$$

Cut on the reconstructed Higgs invariant mass:

$$80 \text{ GeV} < m_{bb} < 140 \text{ GeV}$$