Progress on NNLO+PS matching

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NNLO+PS: What do we want to achieve?

- NNLO accuracy for observables inclusive on radiation. $[d\sigma/dy_F]$
- NLO(LO) accuracy for $F+1(2)$ jet observables (in the hard region). $[d\sigma/dp_{T,j_1}]$
  - appropriate scale choice for each kinematics regime
- resummation from the Parton Shower (PS) $[\sigma(p_{T,j} < p_{T,\text{veto}})]$
- preserve the PS accuracy (leading log - LL)

- possibly, no merging scale required.

	X	X+jet	X+2jets	X+nj (n>2)
XJ (NLO)	—	NLO	LO	—
XJ-MiNLO	NLO	NLO	LO	PS
X@NNLO	NNLO	NLO	LO	—
X@NNLOPS	NNLO	NLO	LO	PS

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X@NNLOPS	NNLO	NLO	LO	PS

not talking about recent progress in improving parton showers to (N)NLL

[Forshaw, Holguin, Plätzer '20] [Nagy, Soper '19], [Dasgupta, et al. '20; Hamilton, et al. '20; Karlberg, et al. '21]

NNLO+PS methods

✦ seminal approaches for NLO+PS many years ago (POWHEG, MC@NLO)

MiNLO+reweighting

[Hamilton, Nason, Oleari, Zanderighi '12, + Re '13], [Karlberg, Re, Zanderighi '14]

- ✦ no new unphysical scale (i.e. physically sound)
- ✦ numerically very intensive
- ✦ applied beyond 2→1 processes

Geneva

[Alioli, Bauer, Berggren, Tackmann, Walsh '15 + Zuberi '13]

- ✦ slicing cutoff (missing power corrections)
- ✦ numerical cancellations in slicing parameter
- ✦ applied beyond 2→1 processes

MiNNLO$_{PS}$

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

- ✦ no new unphysical scale (i.e. physically sound)
- ✦ numerically efficient
- ✦ applied beyond 2→1 and even beyond colour singlet

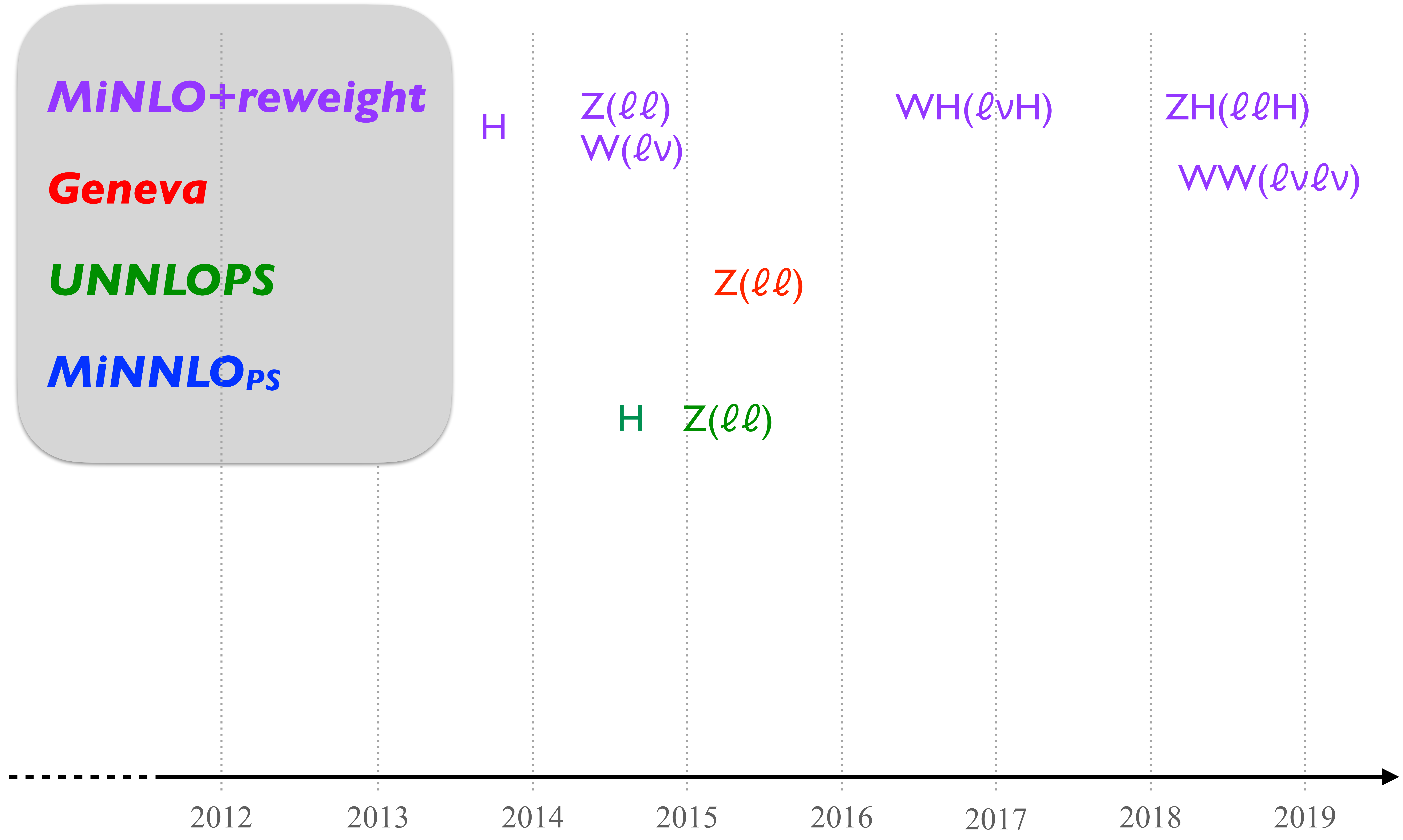
UNNLOPS

[Höche, Prestel '14 '15]

- ✦ extension of UNLOPS merging of event samples
- ✦ two-loop corrections entirely in 0-jet bin
- ✦ only applied to 2→1 processes

there was also some recent progress on NNLO+PS for sector showers [Campbell, Höche, Li, Preuss, Slands '21]

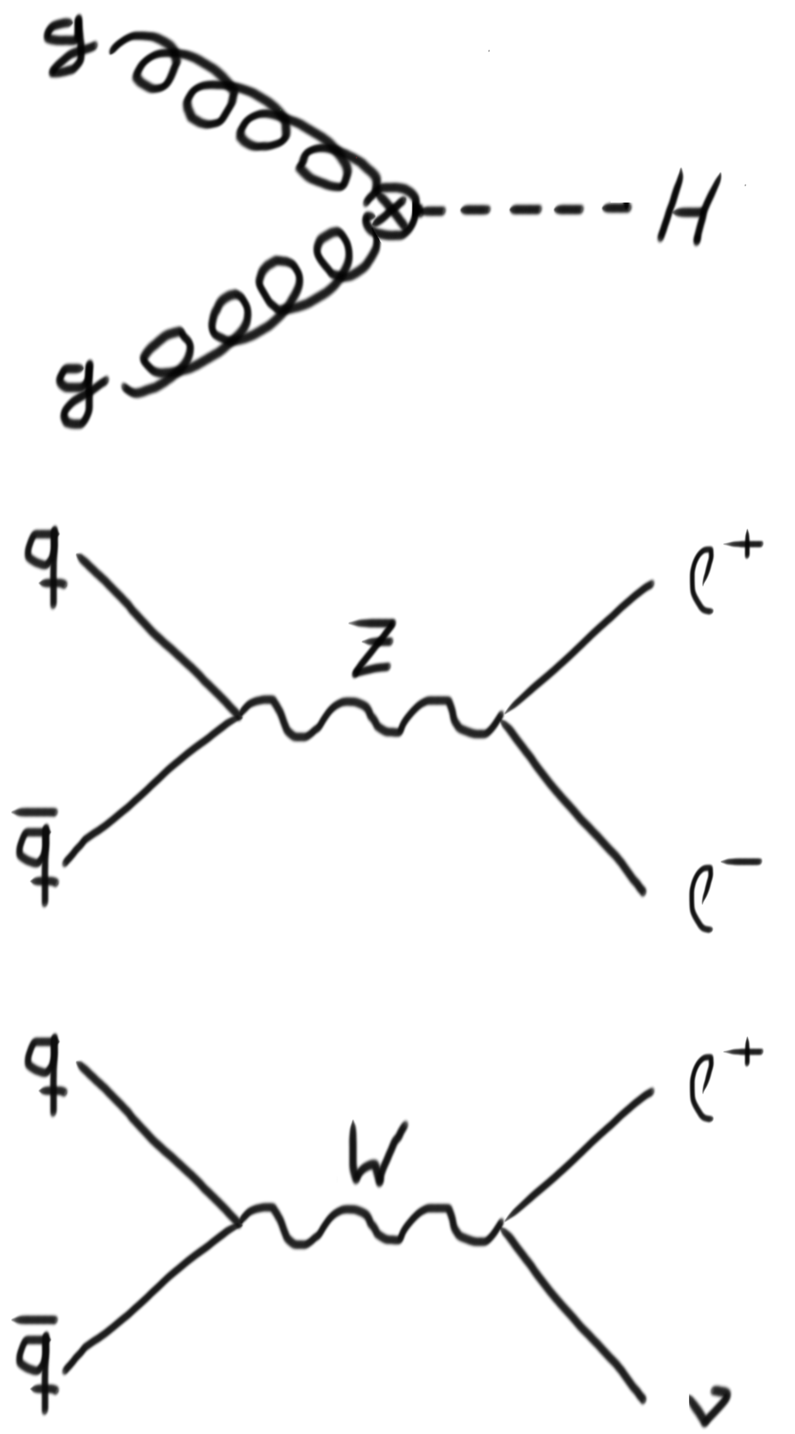
NNLO+PS timeline



NNLO+PS timeline

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

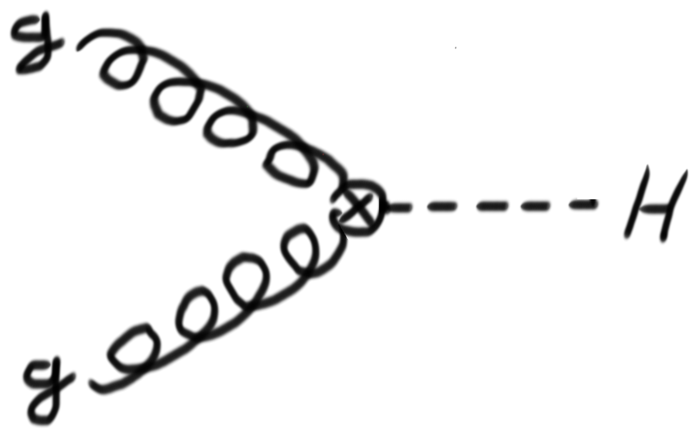
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

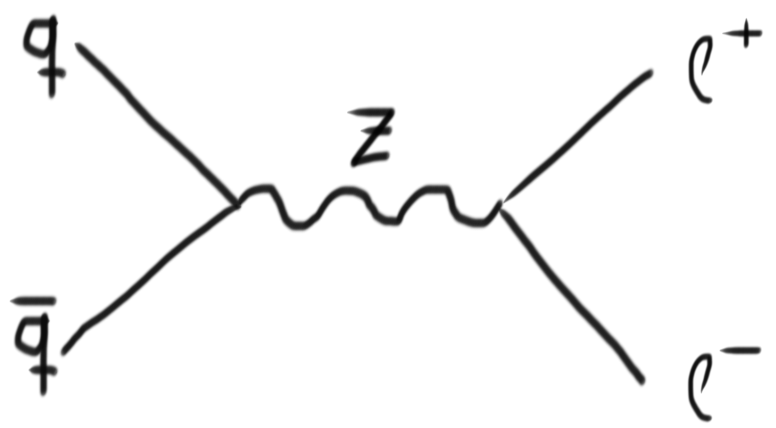


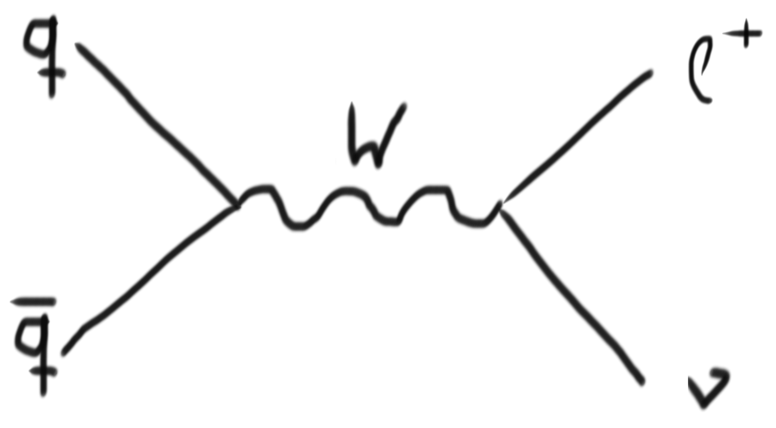
Process	NNLO (MATRIX)	MiNNLO$_{PS}$	Ratio
$pp \to H$	$39.64(1)^{+10.7\%}_{-10.4\%}$ pb	$39.1(5)^{+10.2\%}_{-9.0\%}$ pb	0.987
$pp \to \ell^+\ell^-$	$1919(1)^{+0.8\%}_{-1.1\%}$ pb	$1917(1)^{+1.4\%}_{-1.1\%}$ pb	0.999
$pp \to \ell^-\bar{\nu}_\ell$	$8626(4)^{+1.0\%}_{-1.2\%}$ pb	$8643(4)^{+1.7\%}_{-1.5\%}$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

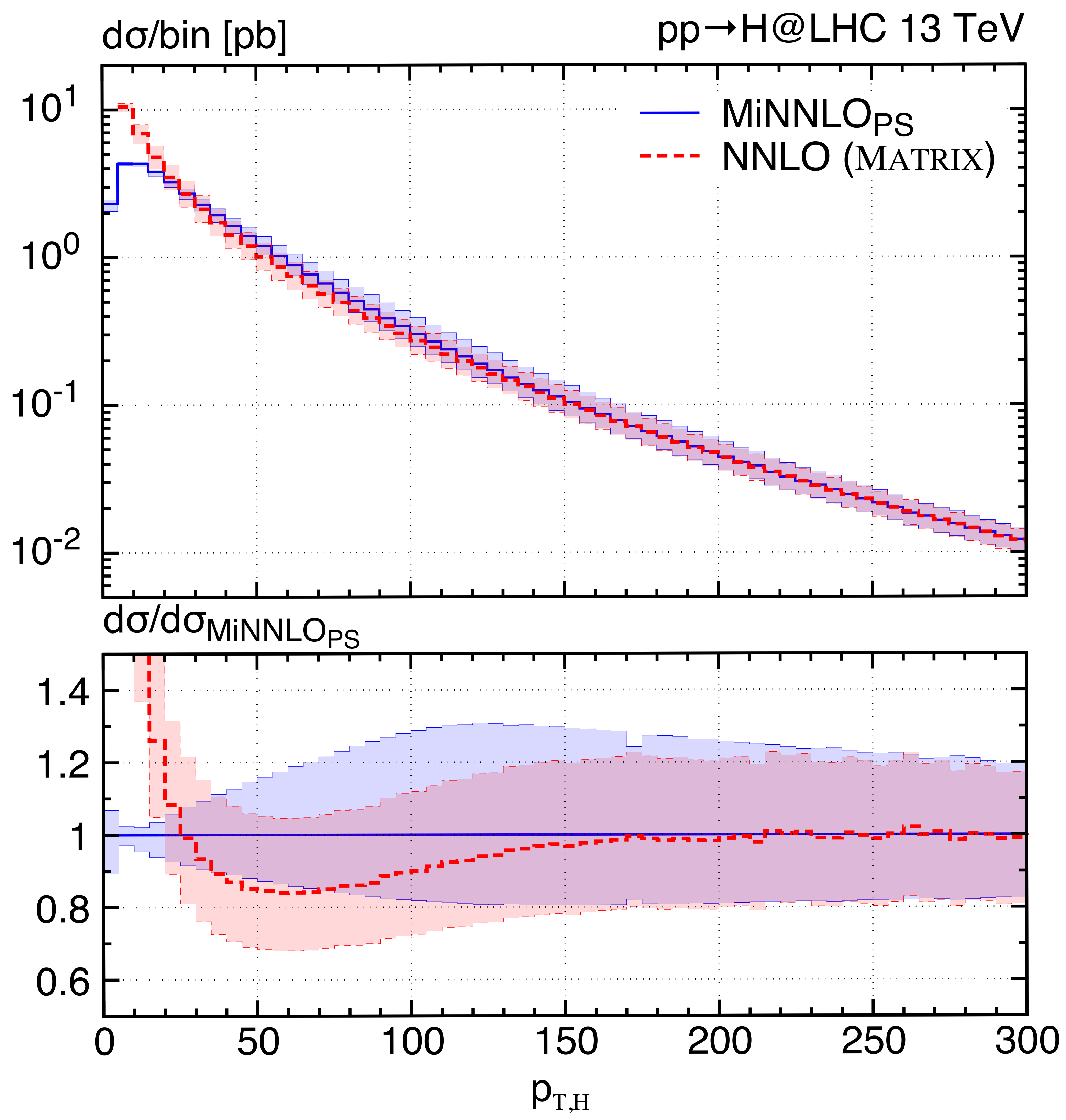
$\textit{MiNNLO}_{\textit{PS}}$: 2→1 colour-singlet processes

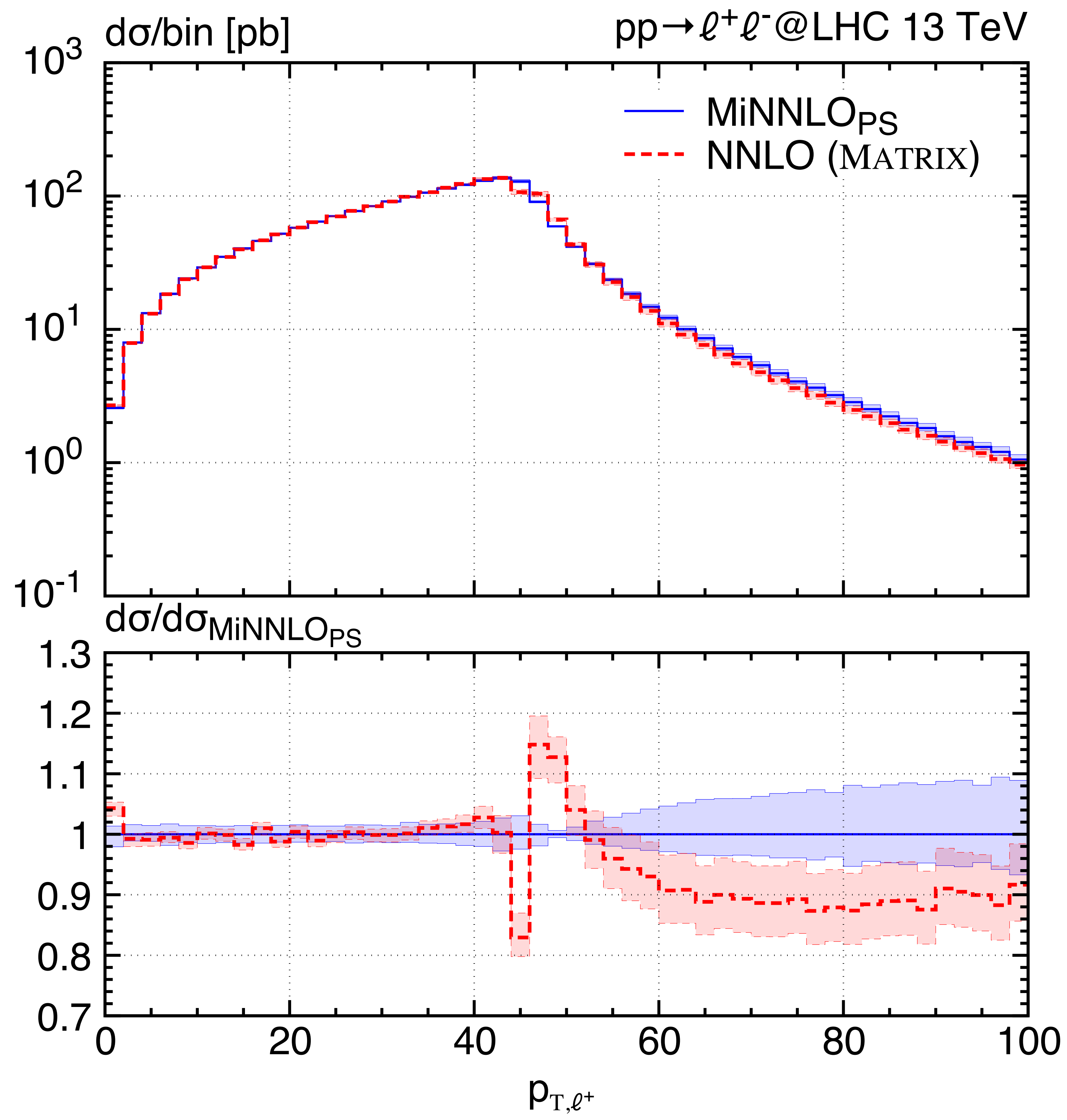
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

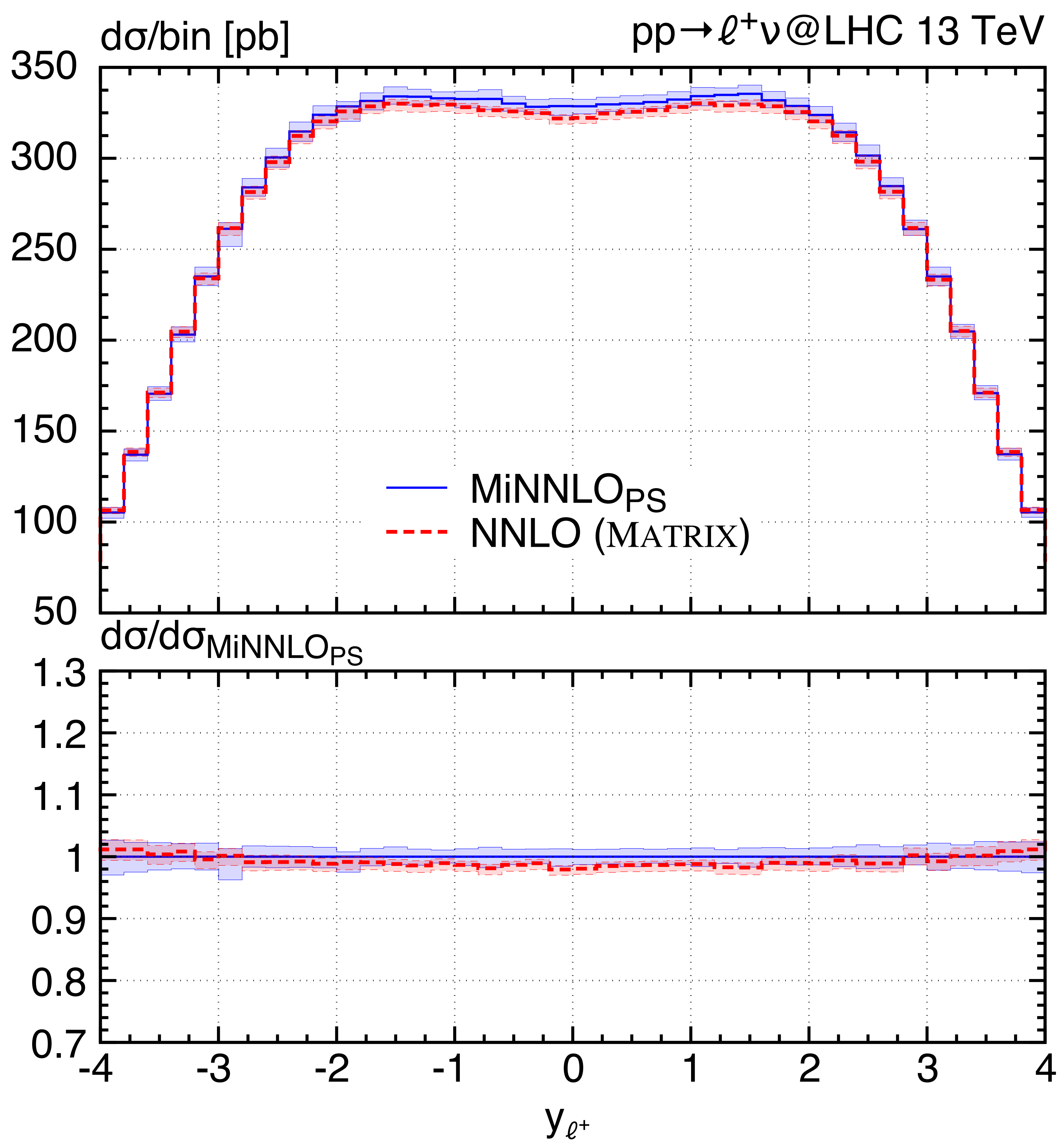






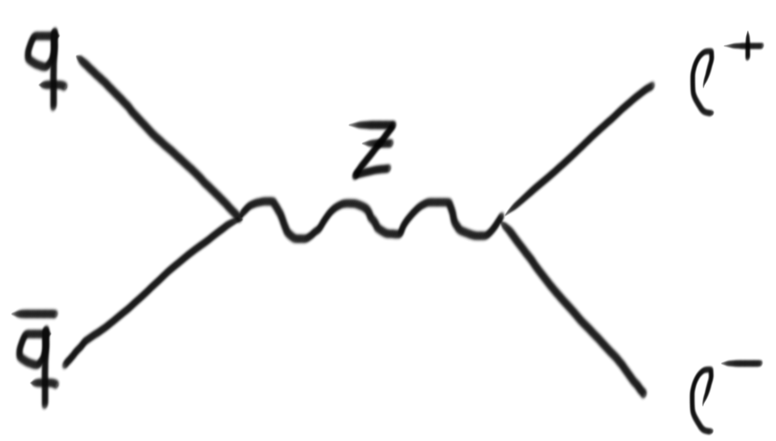


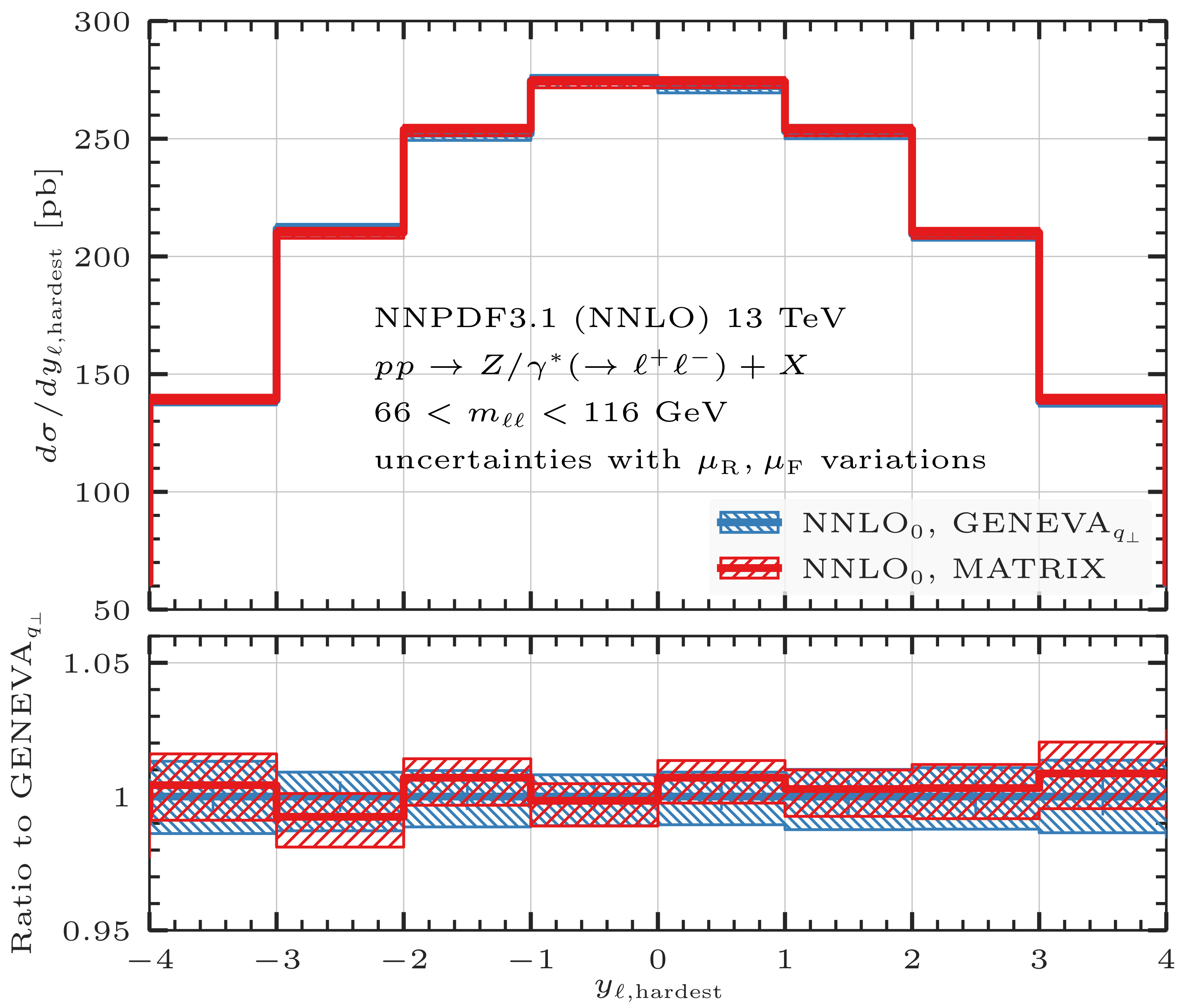


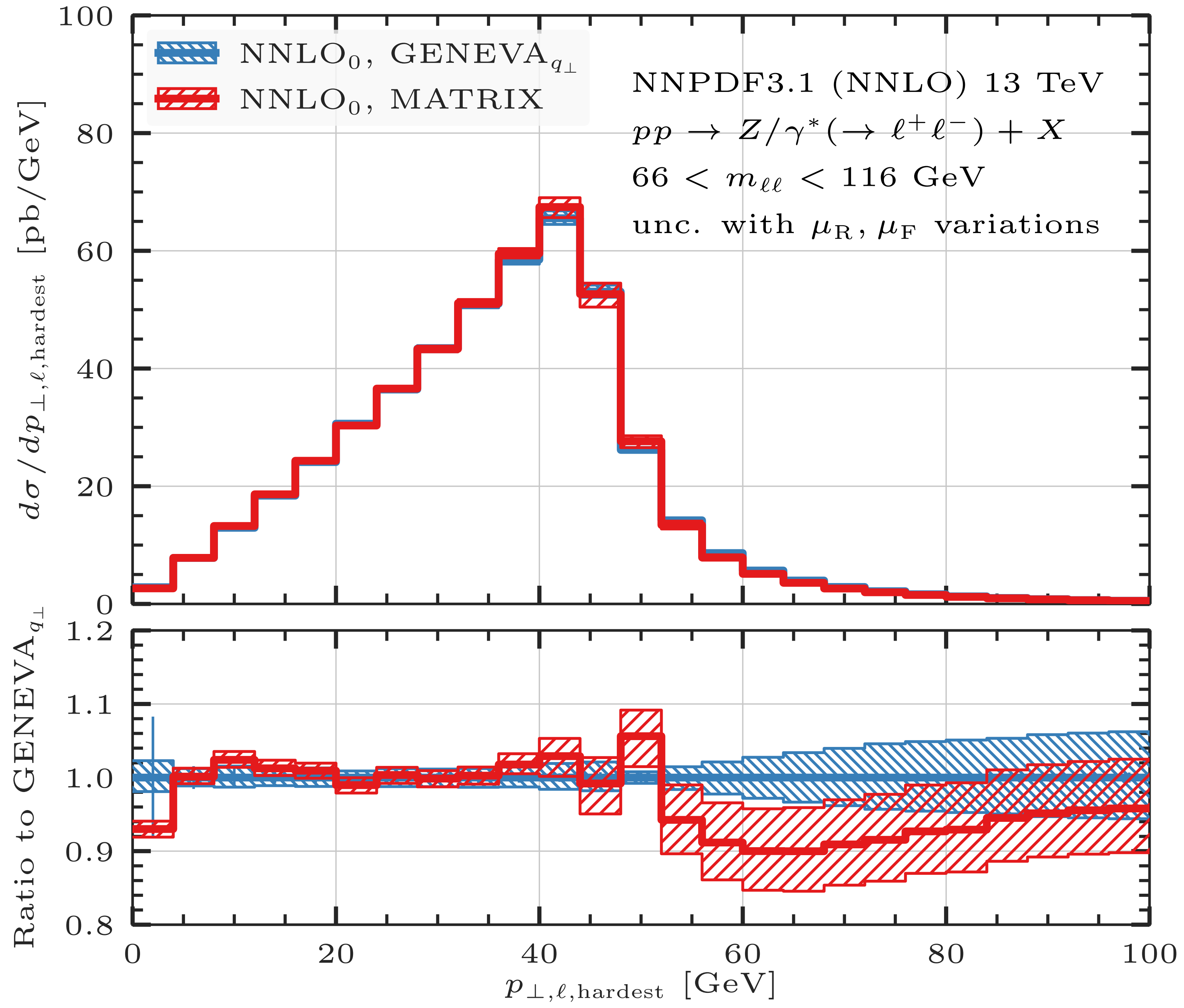


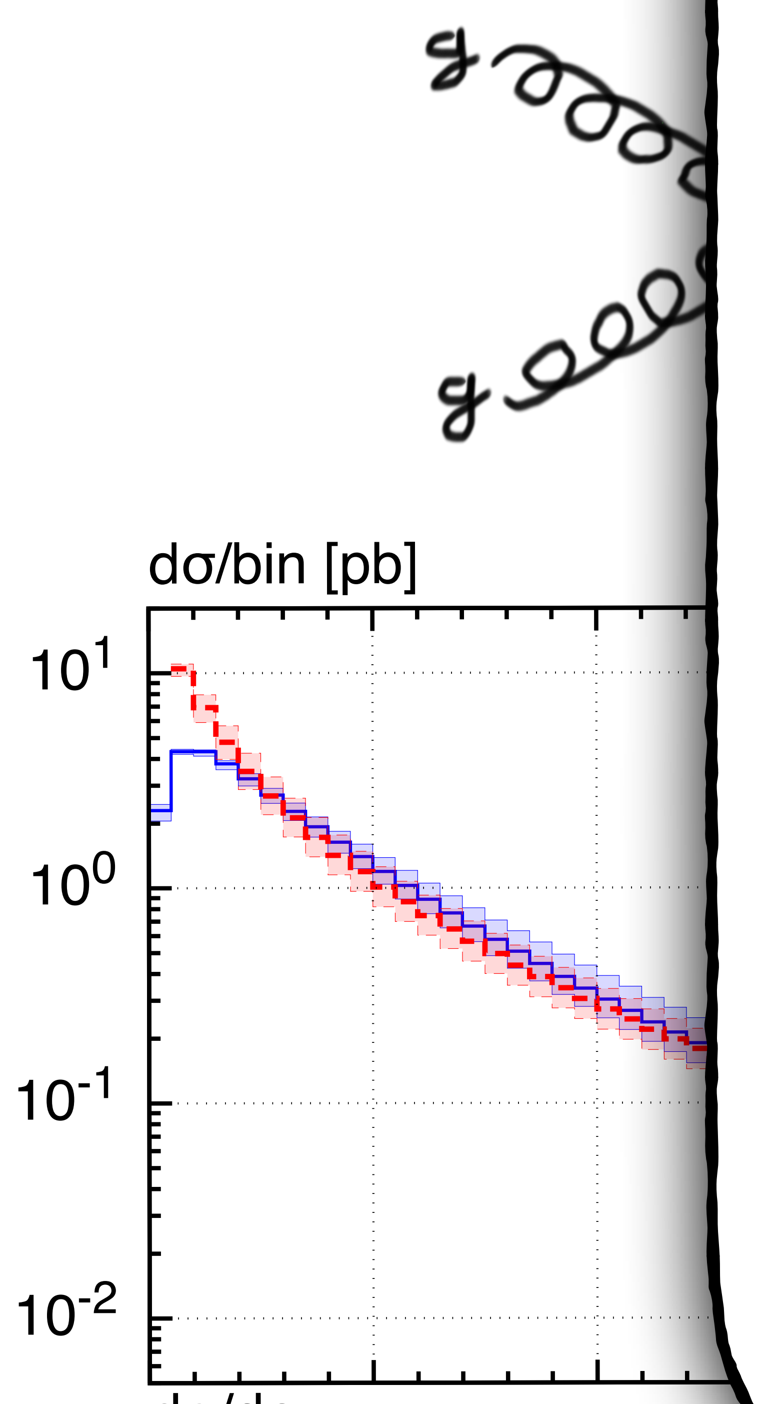
similarly for **Geneva**, e.g.:

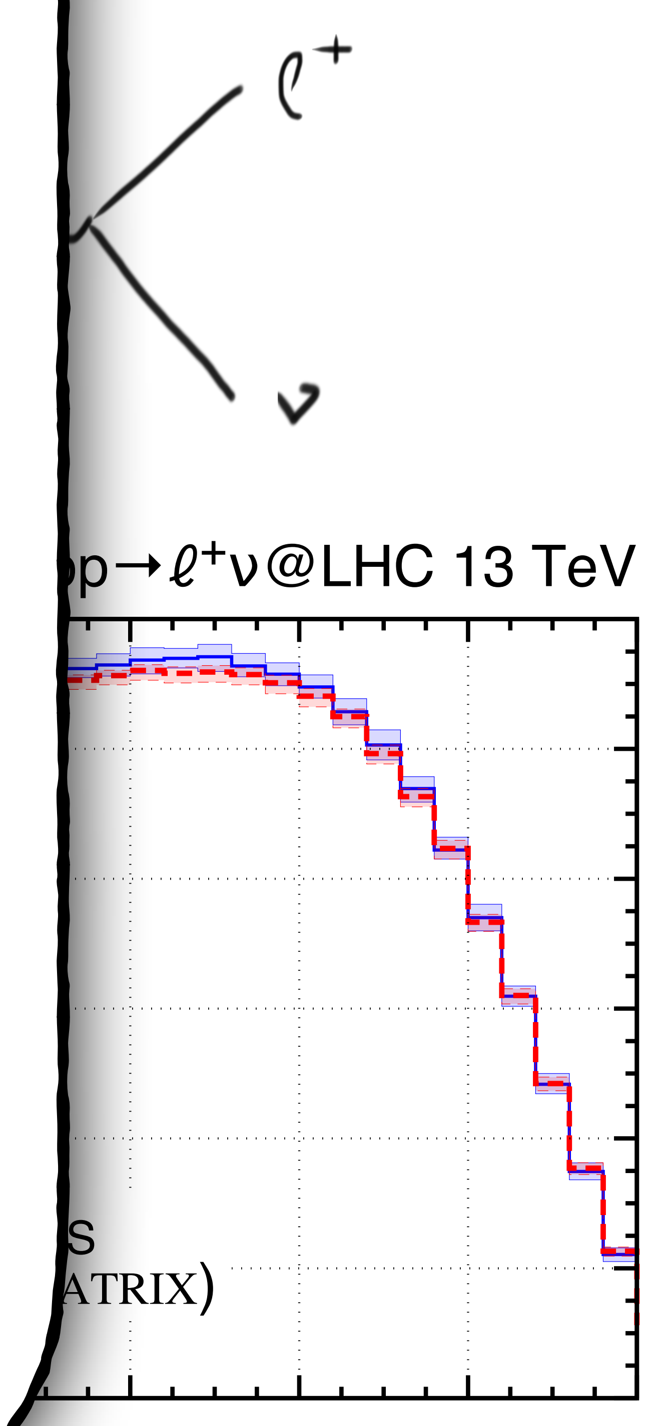
[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, Rotolli '21]

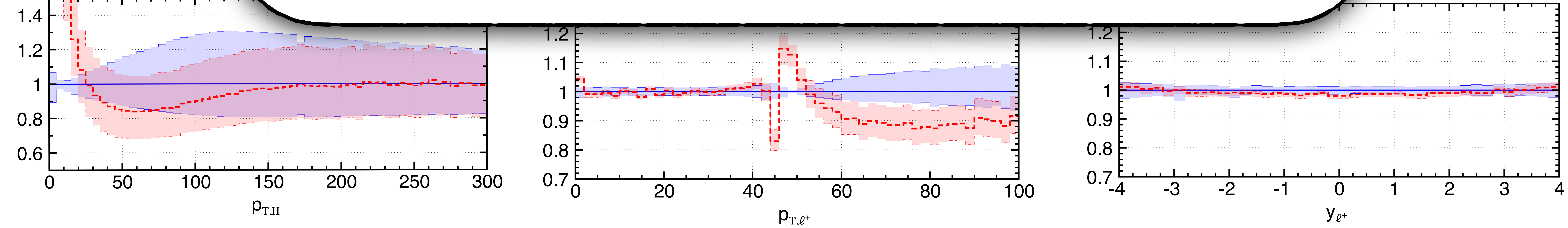




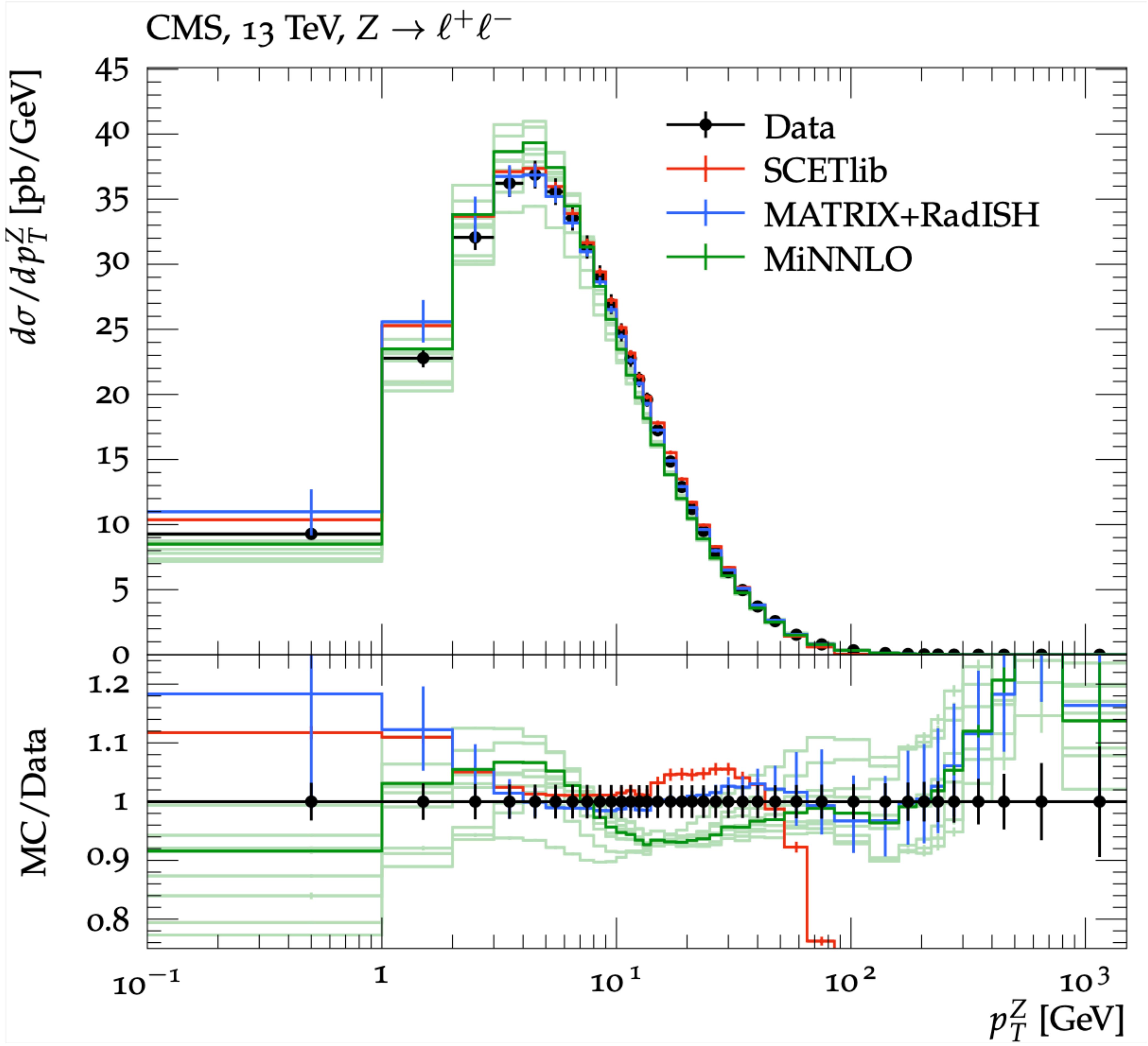








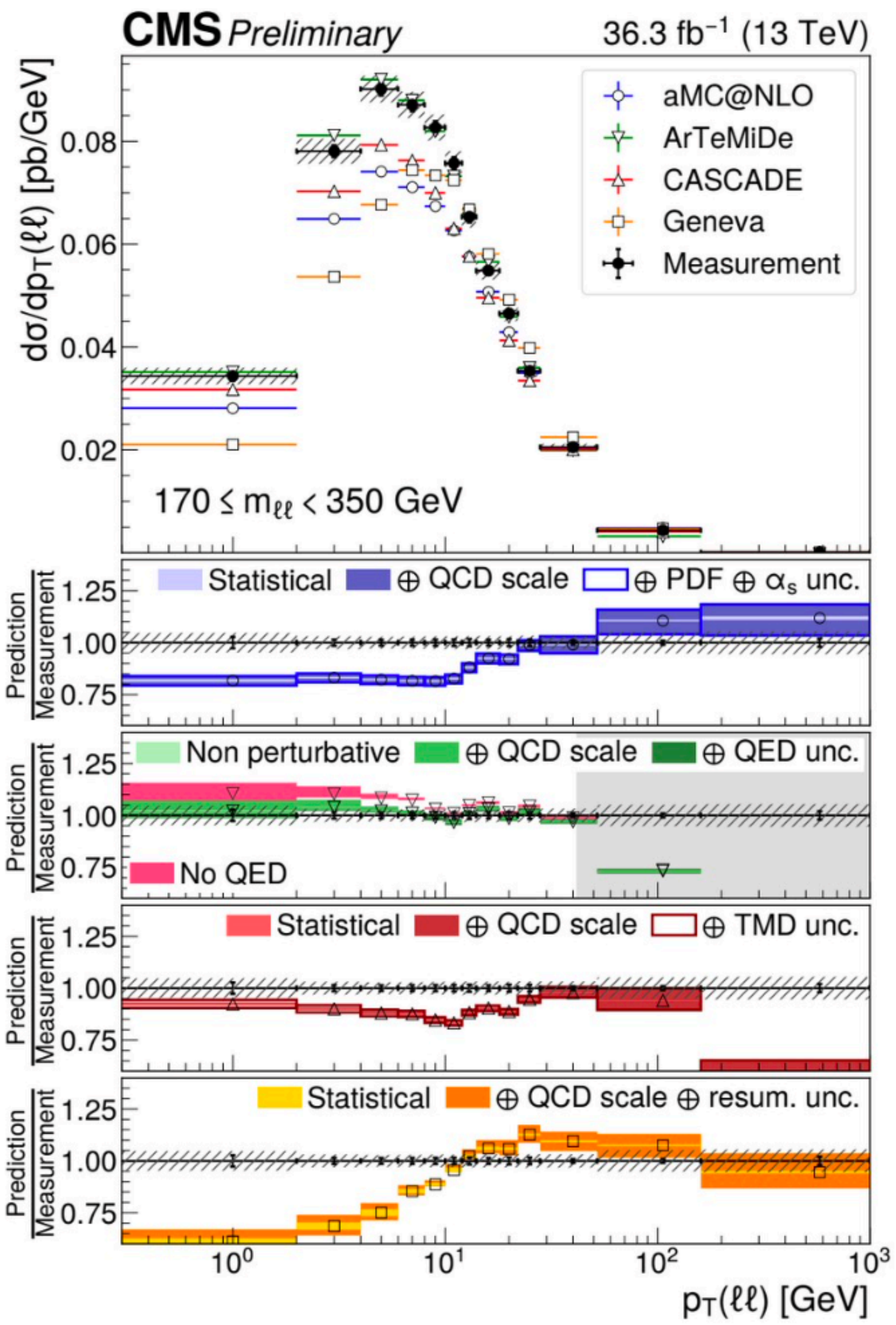
Comparison to high-precision Drell-Yan data



MATRIX+RadISH (NNLO+N³LL)

MiNNLO (NNLO+PS)

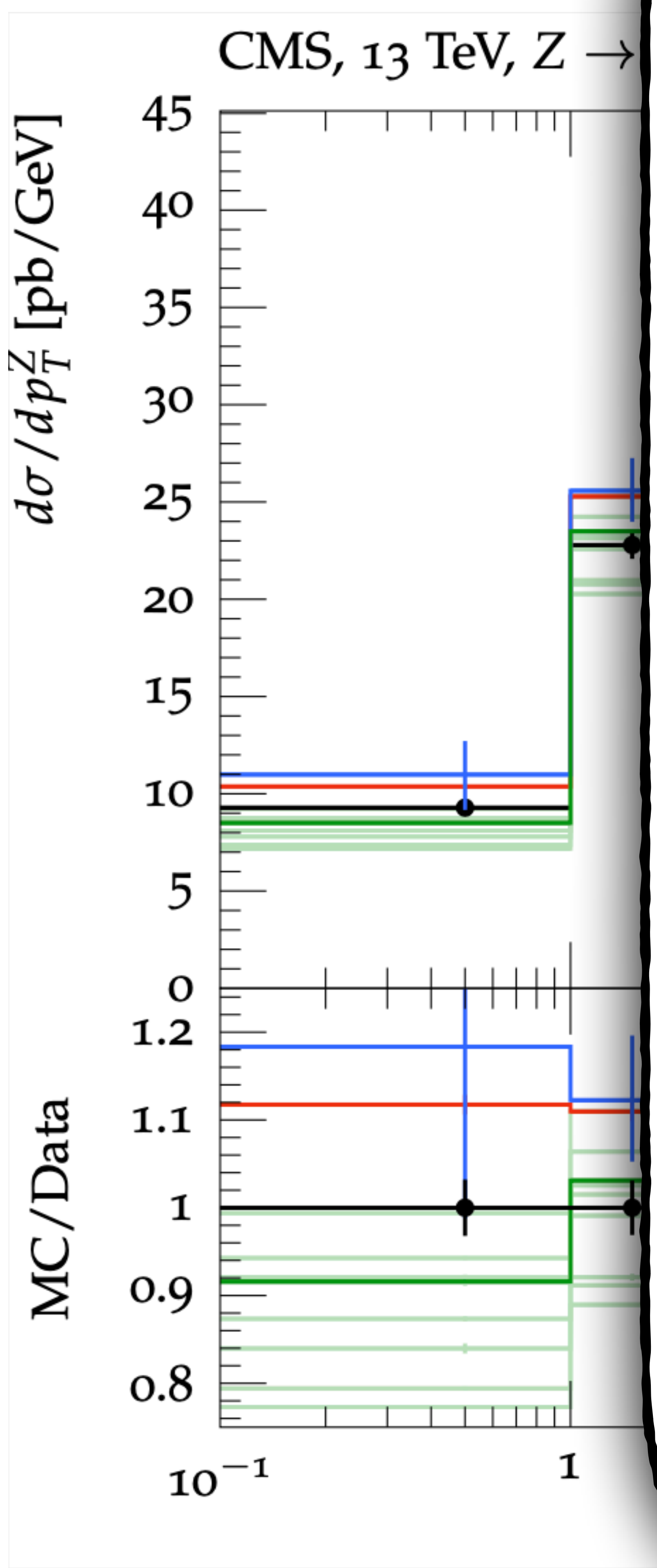
SCETlib (N³LL) (FO matching supported, but not included here)



- MG5_aMC@NLO ≤2j@NLO
- ArTeMIDe: Parton branching with NNLO TMD PDFs+QED FSR correction from Pythia
- CASCADE: parton branching with TMD PDF+Pythia6
- Geneva: τ_0 NNLO+Pythia8

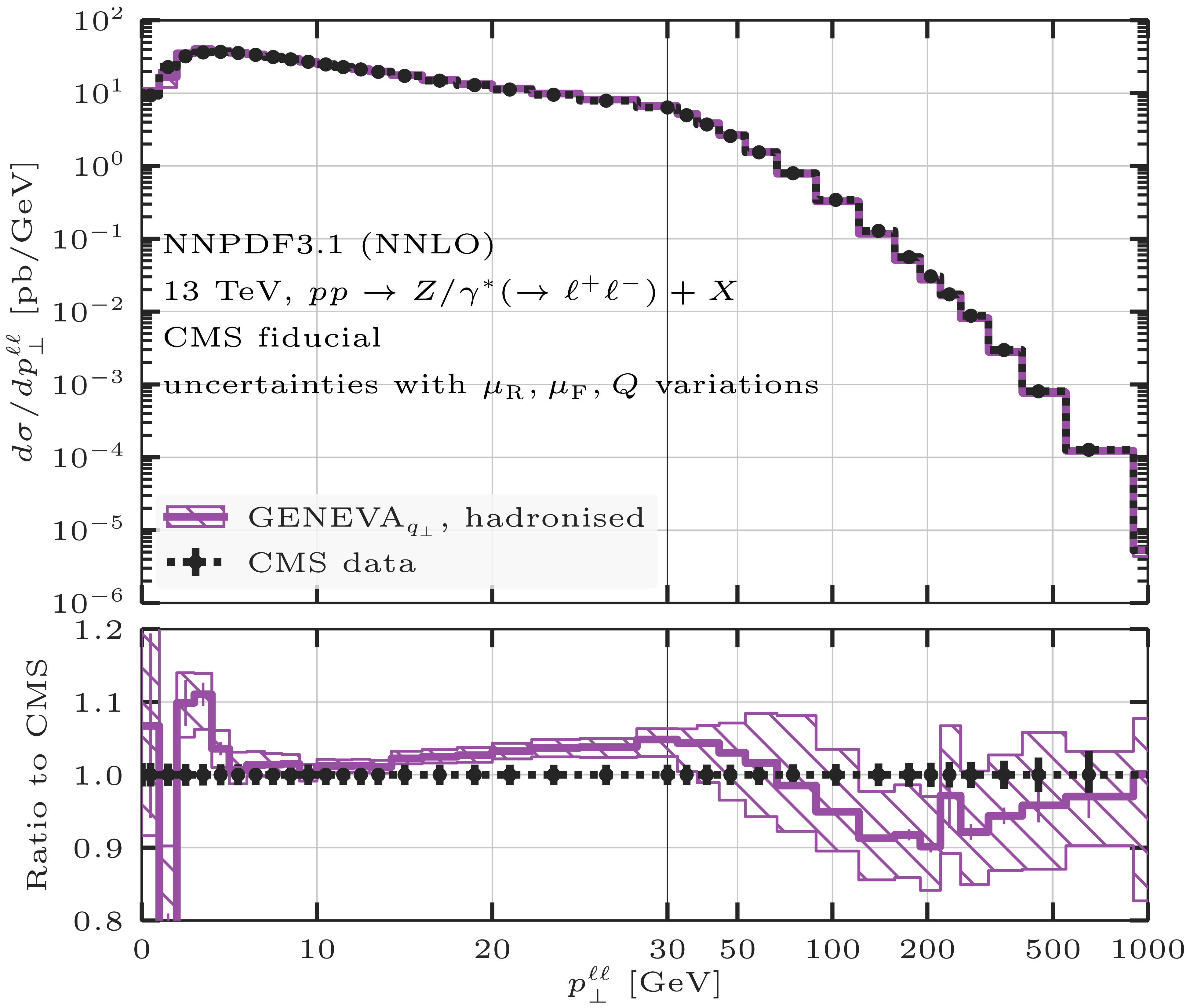
figures from Kenneth Long's talk @Blois2021

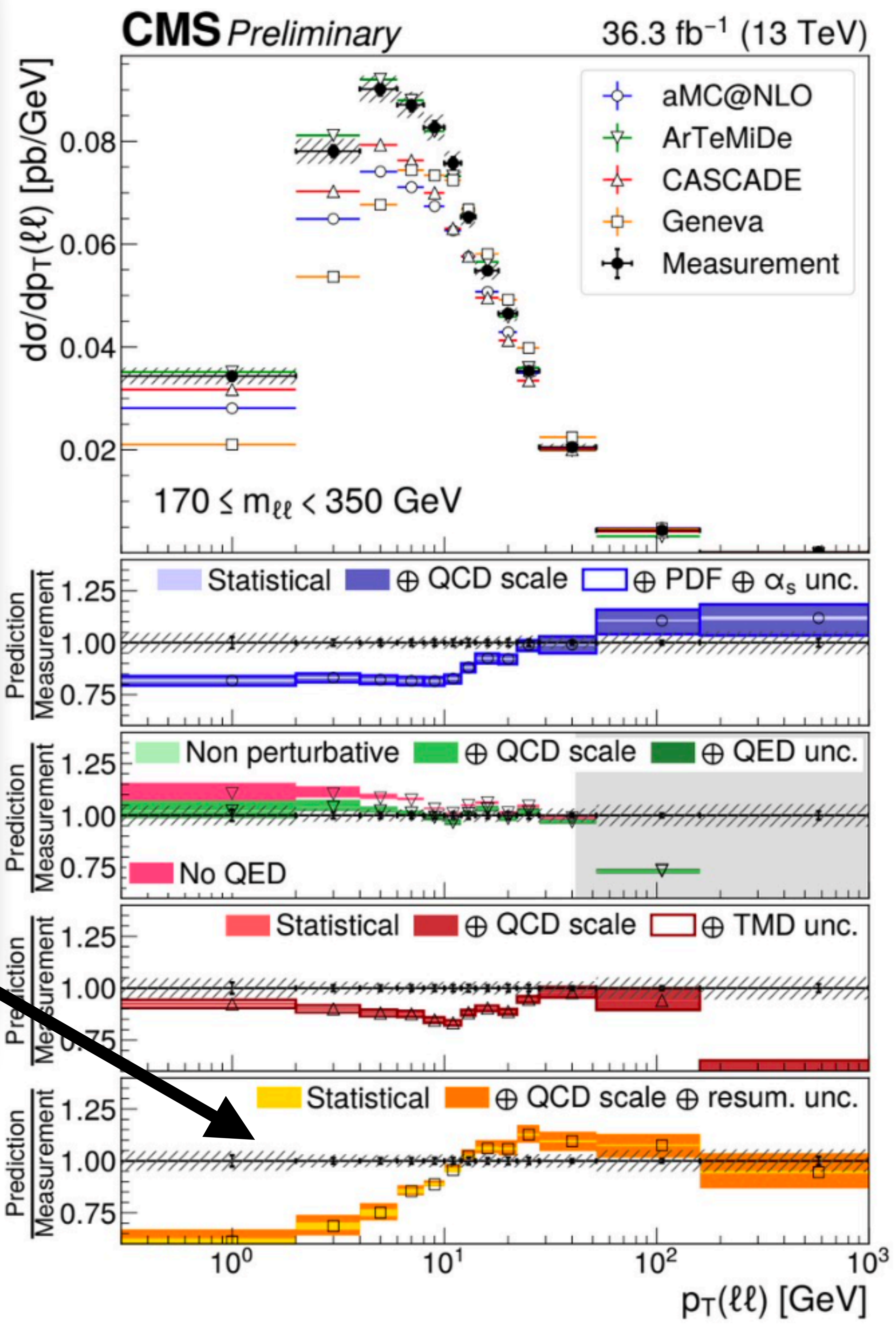
Con rell-Yan data



substantial improvement using p_T instead of τ_0 as resolution variable in ***Geneva***:

[Alioli, Bauer, Broggio, Gavardi, Kallweit, Lim, Nagar, Napoletano, Rotolli '21]





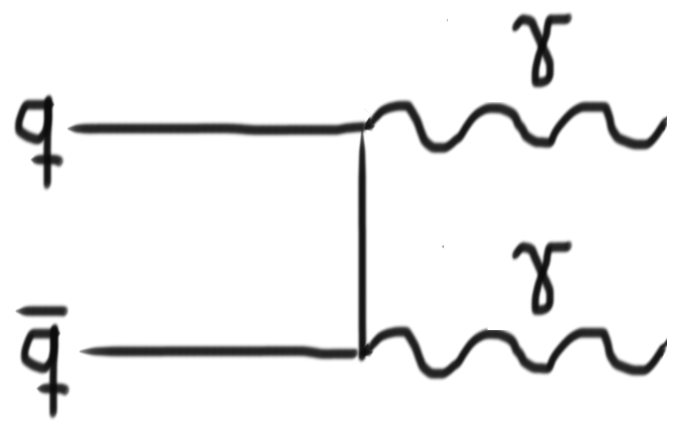
g with

TMD PDF+Pythia6

- Geneva: τ_0 NNLO+Pythia8

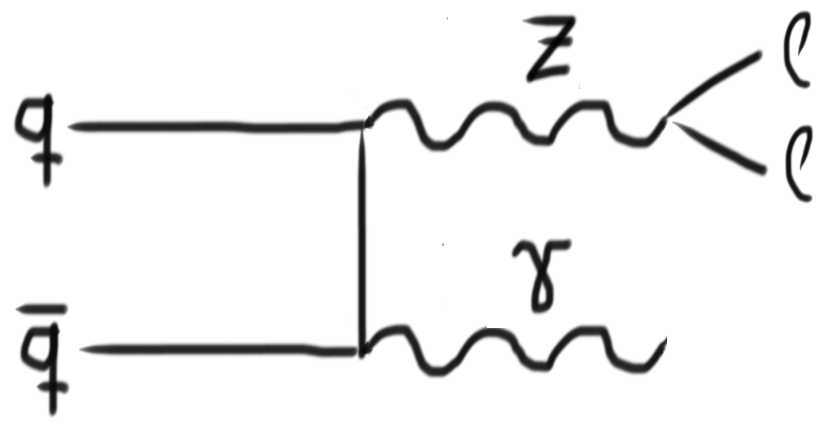
figures from Kenneth Long's talk @Blois2021

Isolated photon production at NNLO+PS



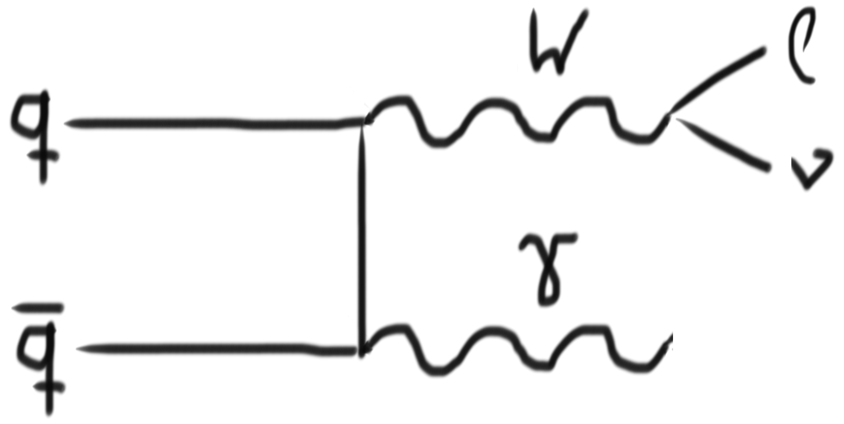
[Alioli et al. '20]

- ✦ large cross section, clean process, well measured
- ✦ power corrections need to be controlled well
- ✦ important background to Higgs and BSM



- ✦ relatively large cross section, clean in $Z \to \ell\ell$
- ✦ relevant BSM/DM background (especially $Z \to \nu\nu$)
- ✦ inclusion of anomalous triple gauge couplings

[Lombardi, MW, Zanderighi '20 '21]



- ✦ reasonably well measured
- ✦ important SM probe
- ✦ background to very specific BSM searches

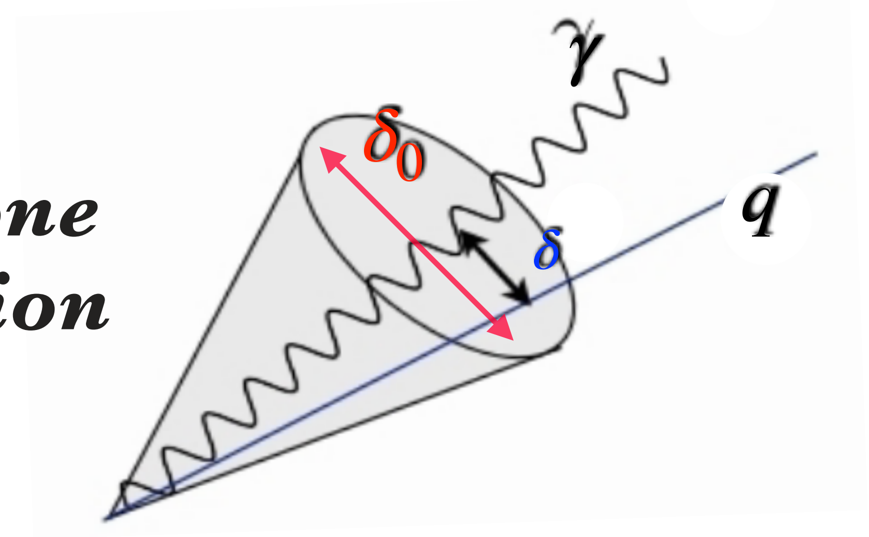
[Cridge, Lim, Nagar '21]

Photon isolation requirement:

- ✤ *Experimentally needed to identify isolated photons*
- ✤ *Theoretically delicate infrared-safe definition*

$$\sum_{had/part \in \delta} E_T^{had/part} \leq E_T^{max}(\delta) = E_T^{ref} \cdot \left(\frac{1 - \cos\delta}{1 - \cos\delta_0} \right)^n, \quad \forall \delta \leq \delta_0$$

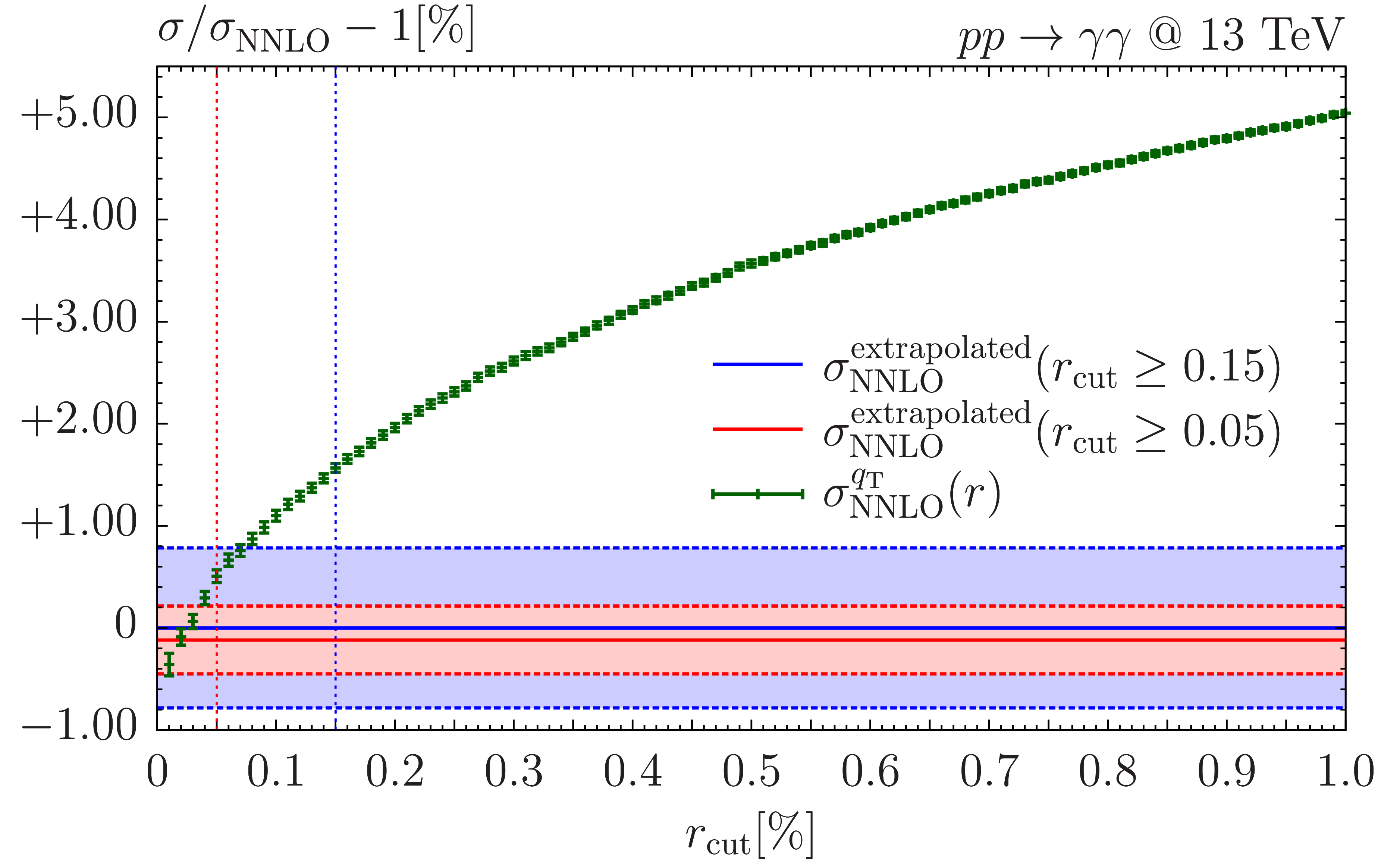
Frixione isolation



Geneva: $\gamma\gamma$ production

[Alioli et al. '20]

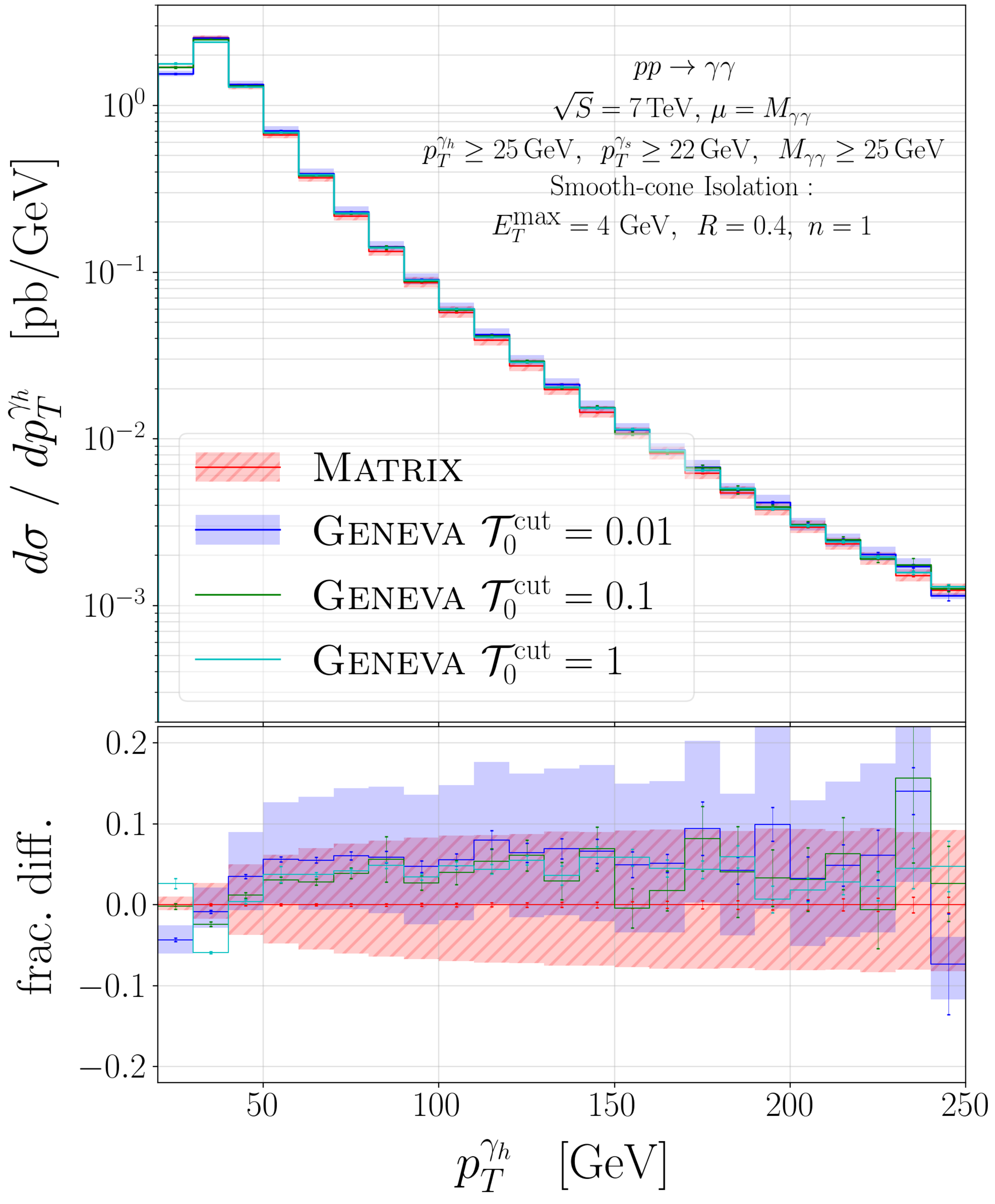
✦ photon processes feature large power corrections

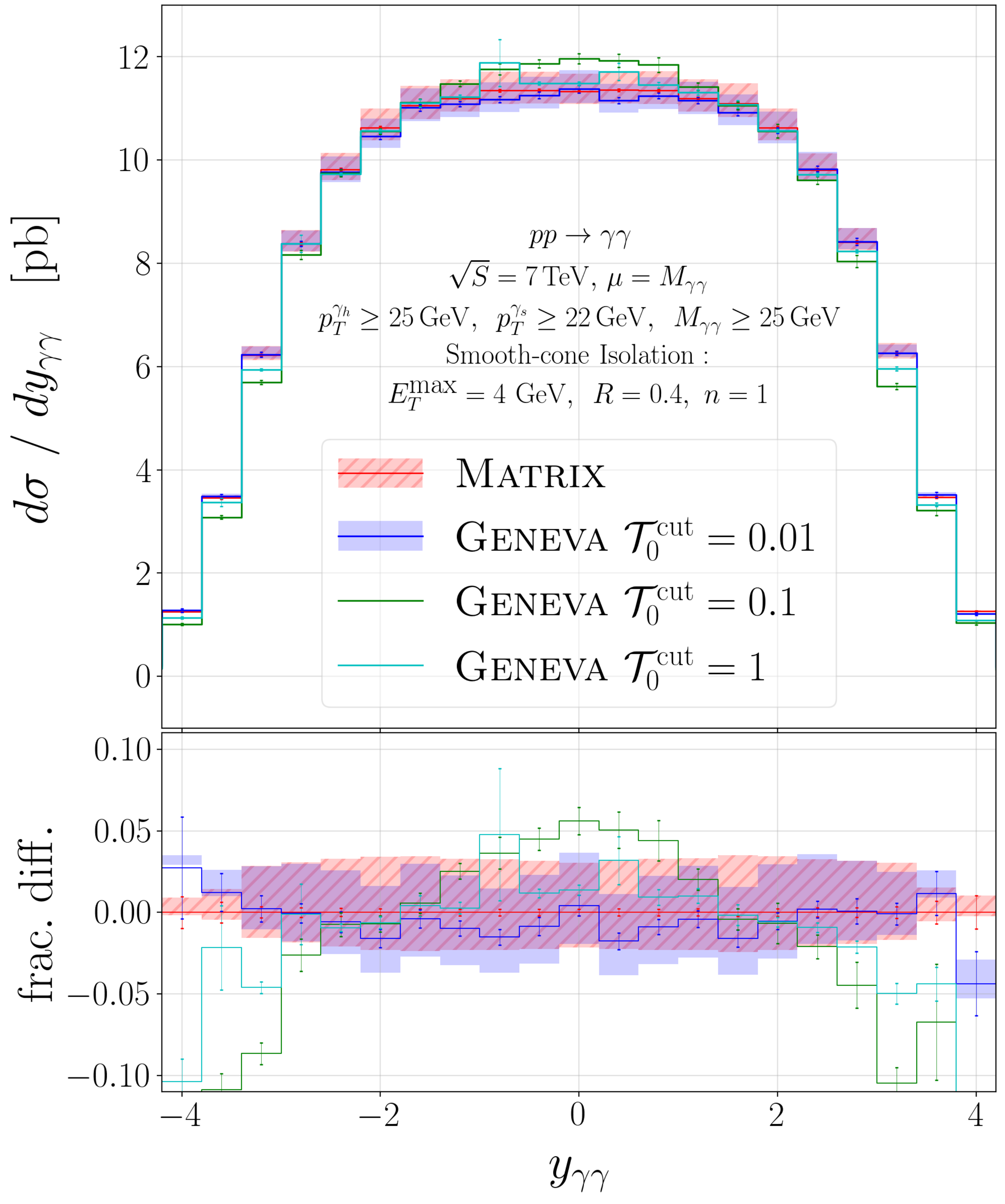


from MATRIX [Grazzini, Kallweit, MW '17]

see also: [Ebert Tackmann '19], [Becher, Neumann, '20]

✦ cutoff dependence of differential Geneva $\gamma\gamma$ results



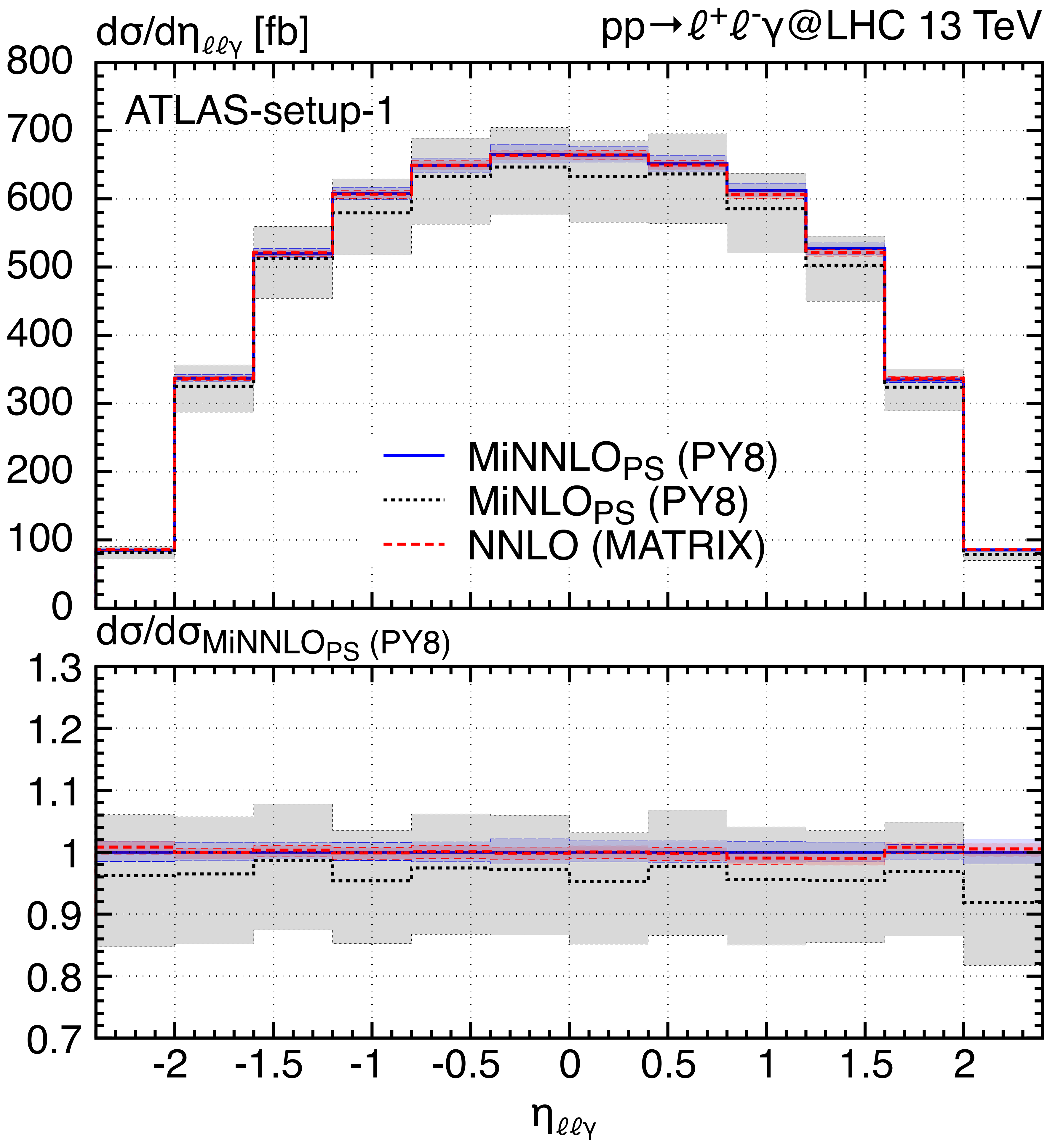


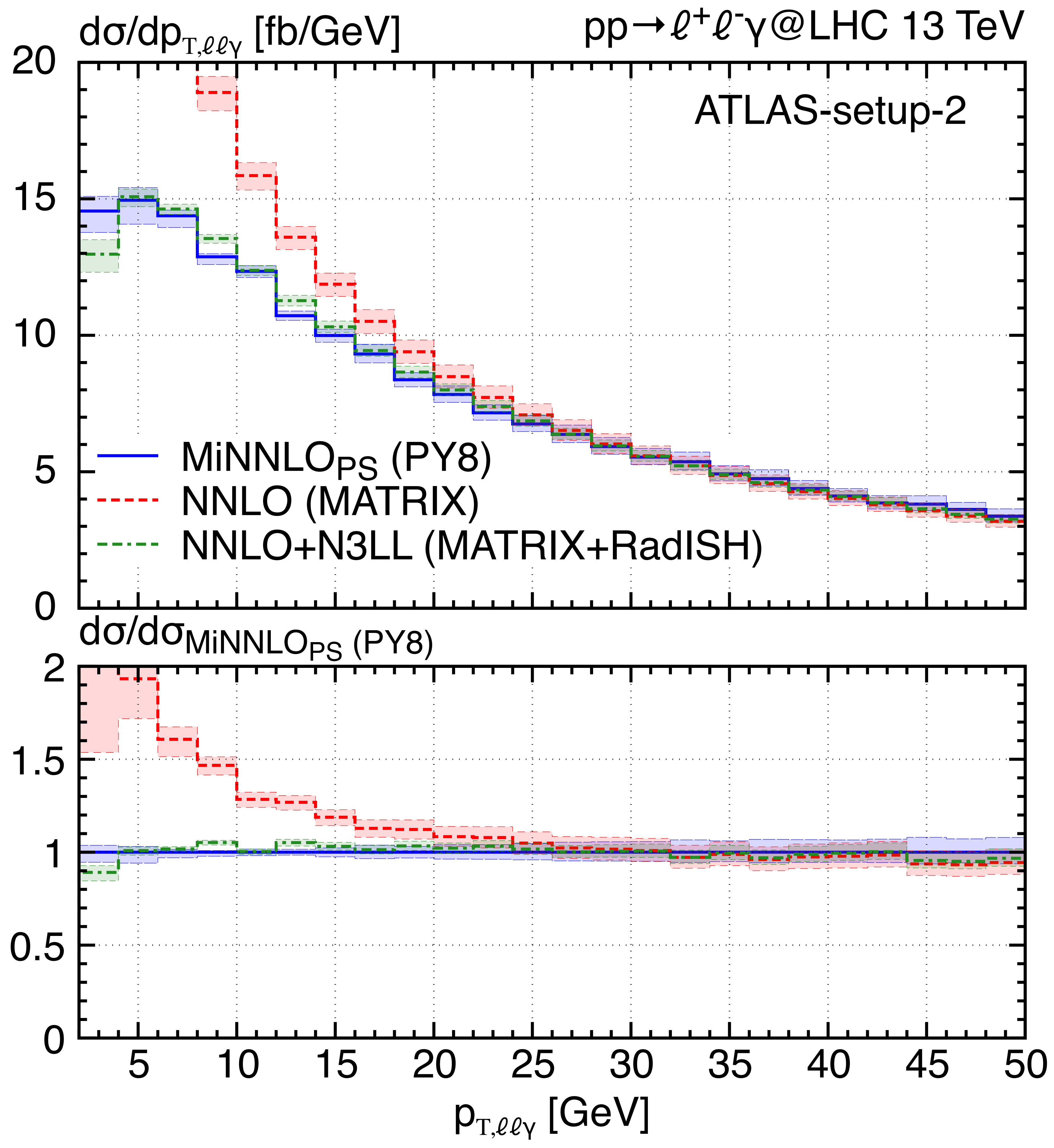
Geneva: $\gamma\gamma$ production

[Alioli et al. '20]

MiNNLO$_{PS}$: $Z\gamma\,(\ell\ell\gamma)$ production

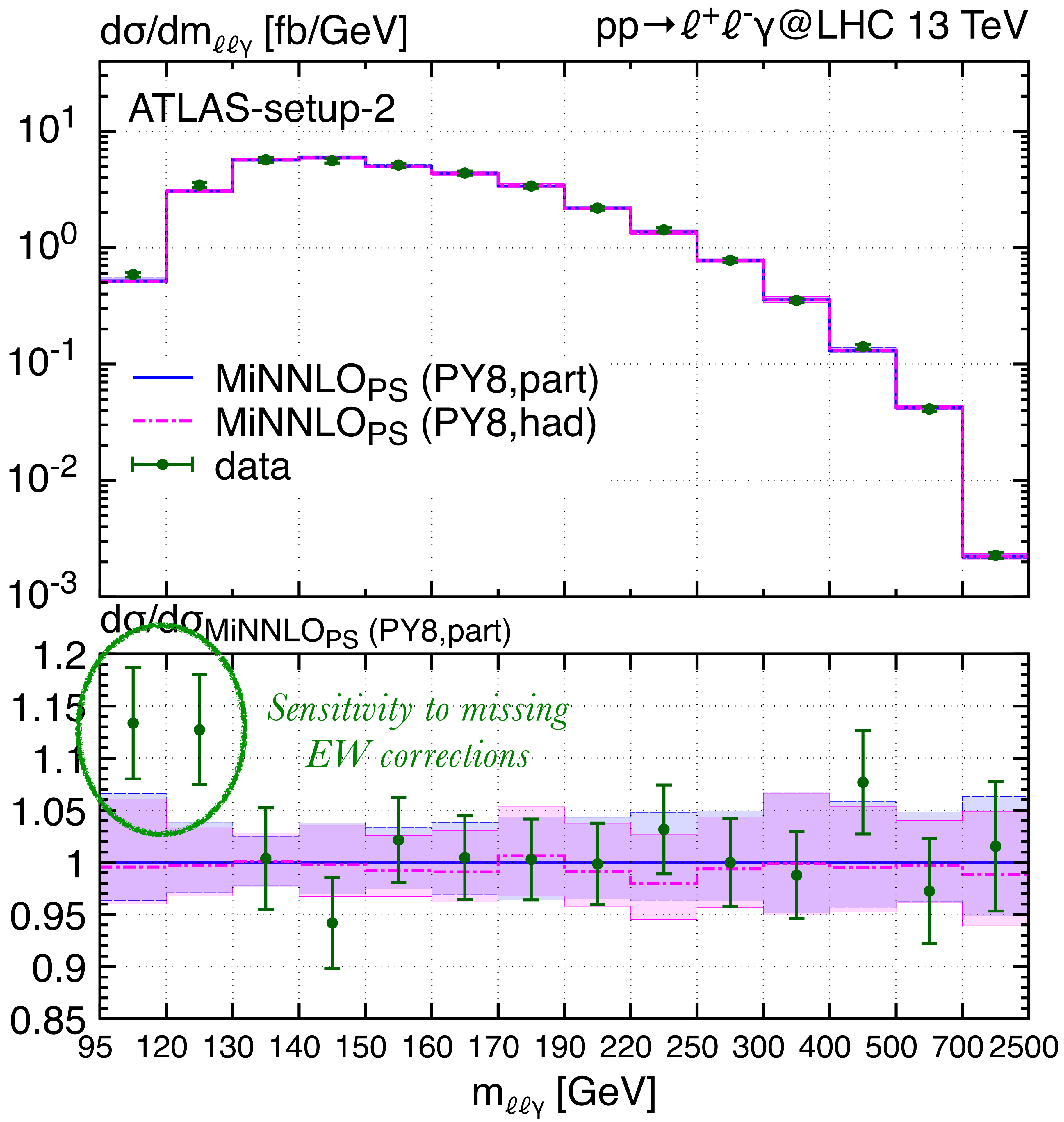
[Lombardi, MW, Zanderighi '20]

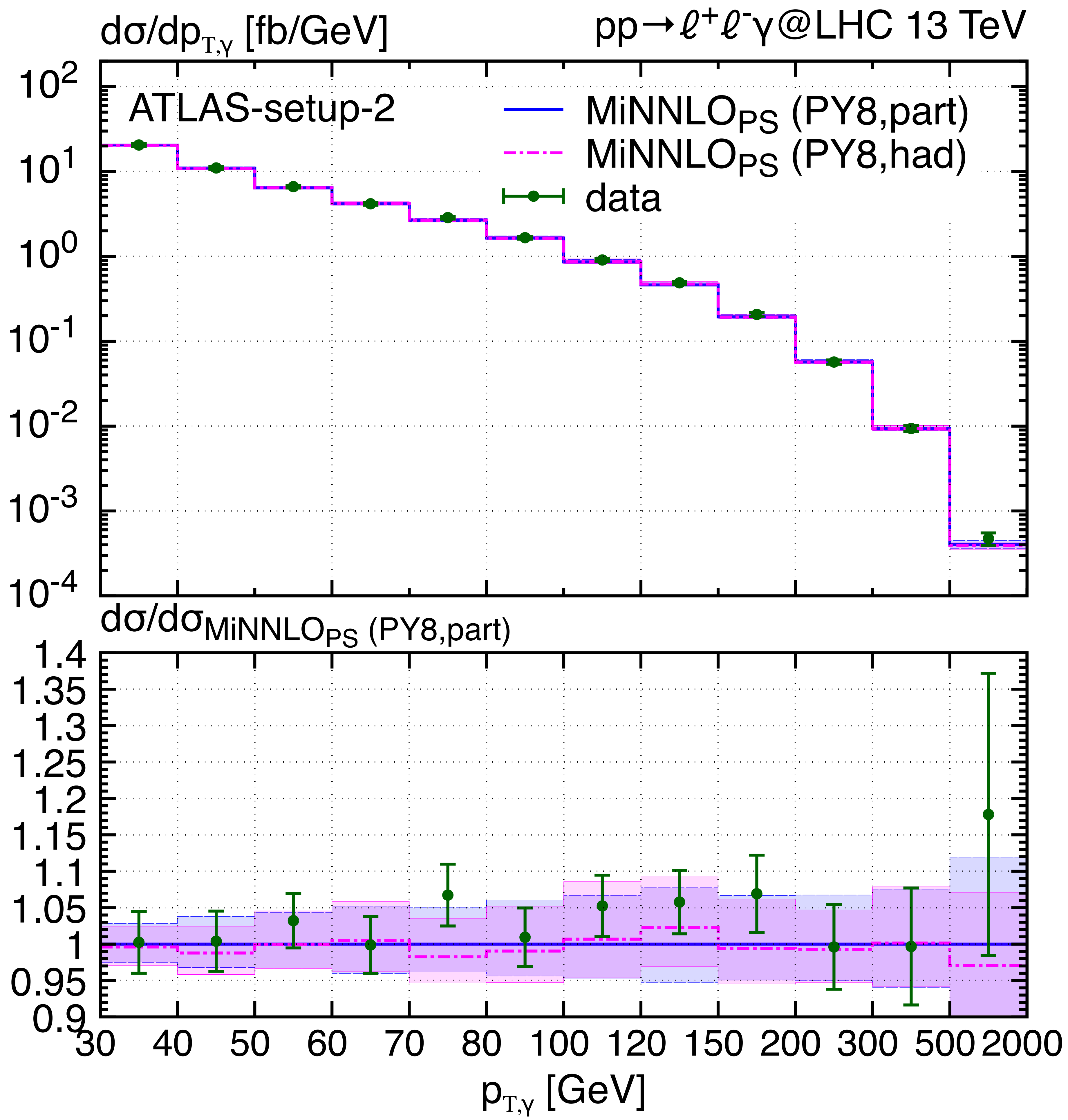




MiNNLO$_{PS}$: $Z\gamma\,(\ell\ell\gamma)$ production

[Lombardi, MW, Zanderighi '20]



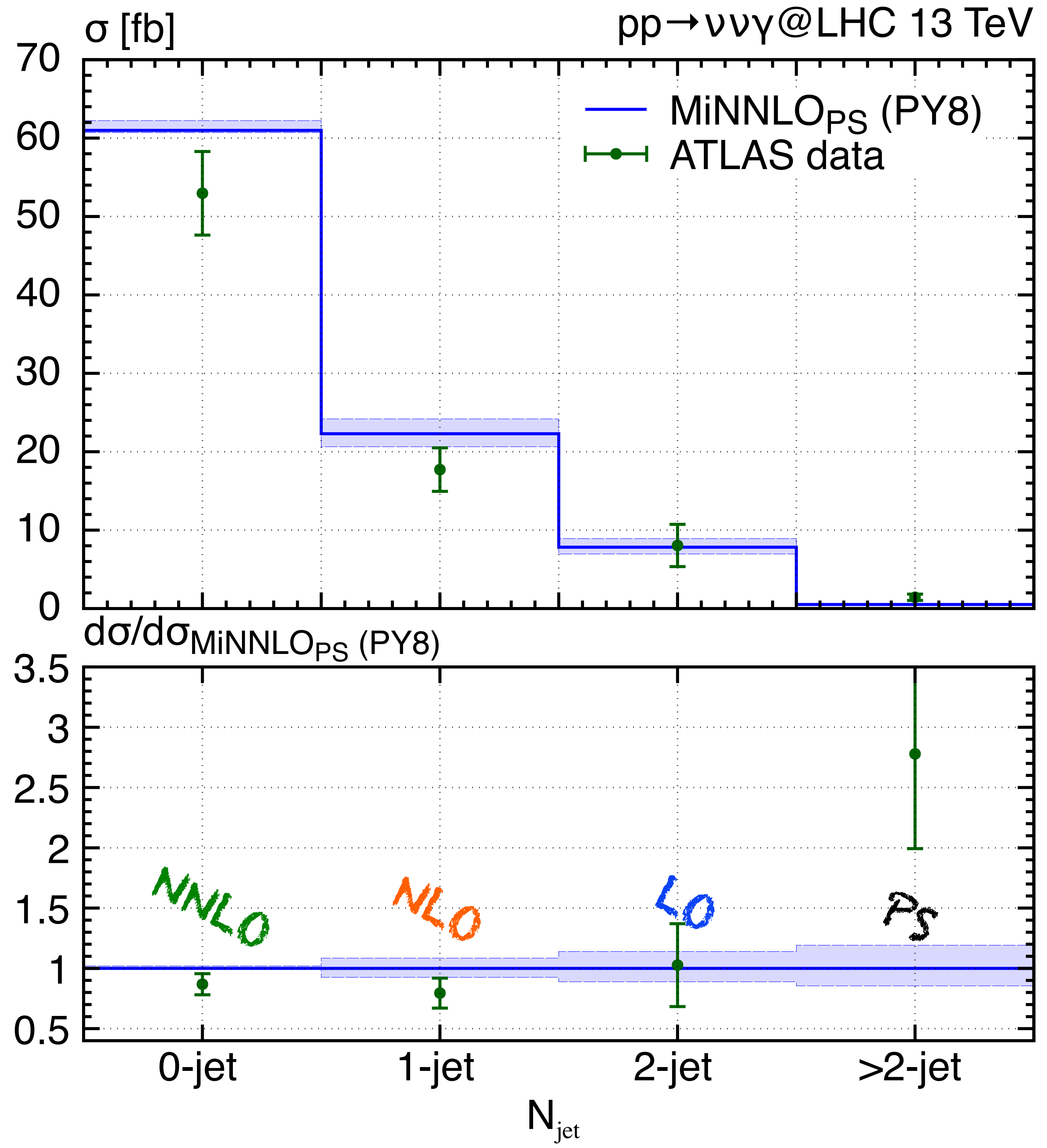


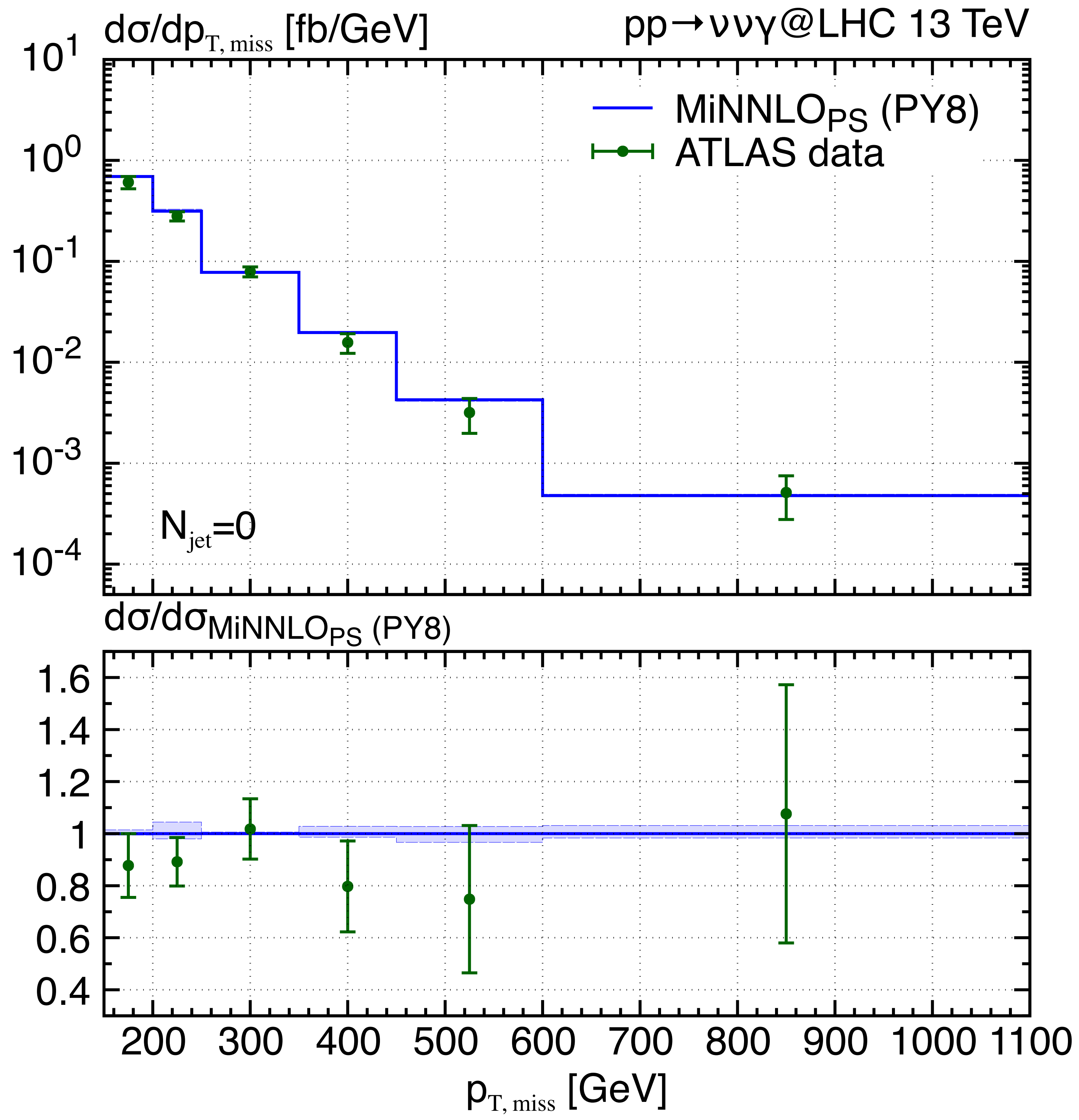
MiNNLO$_{PS}$: $Z\gamma\,(\nu\nu\gamma)$ production

[Lombardi, MW, Zanderighi '21]

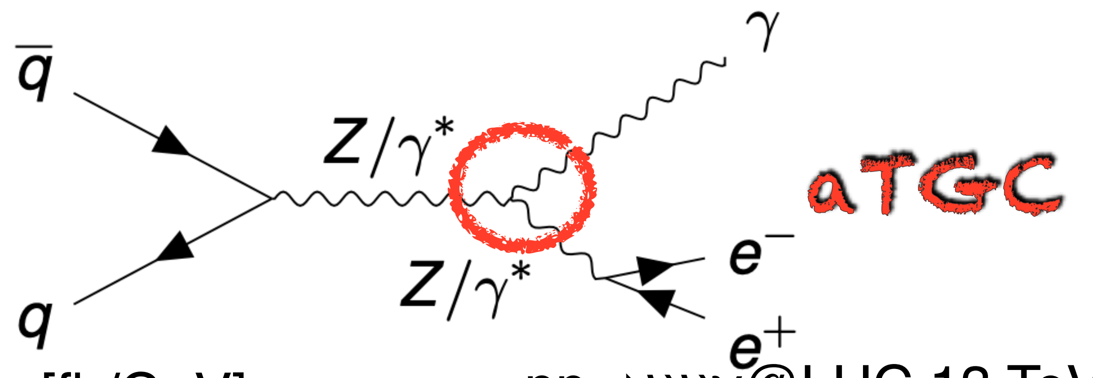
- *presence of isolated photon → theoretically challenging*
- *highly relevant as a **probe for BSM** (especially $Z \to \nu\bar{\nu}$)*

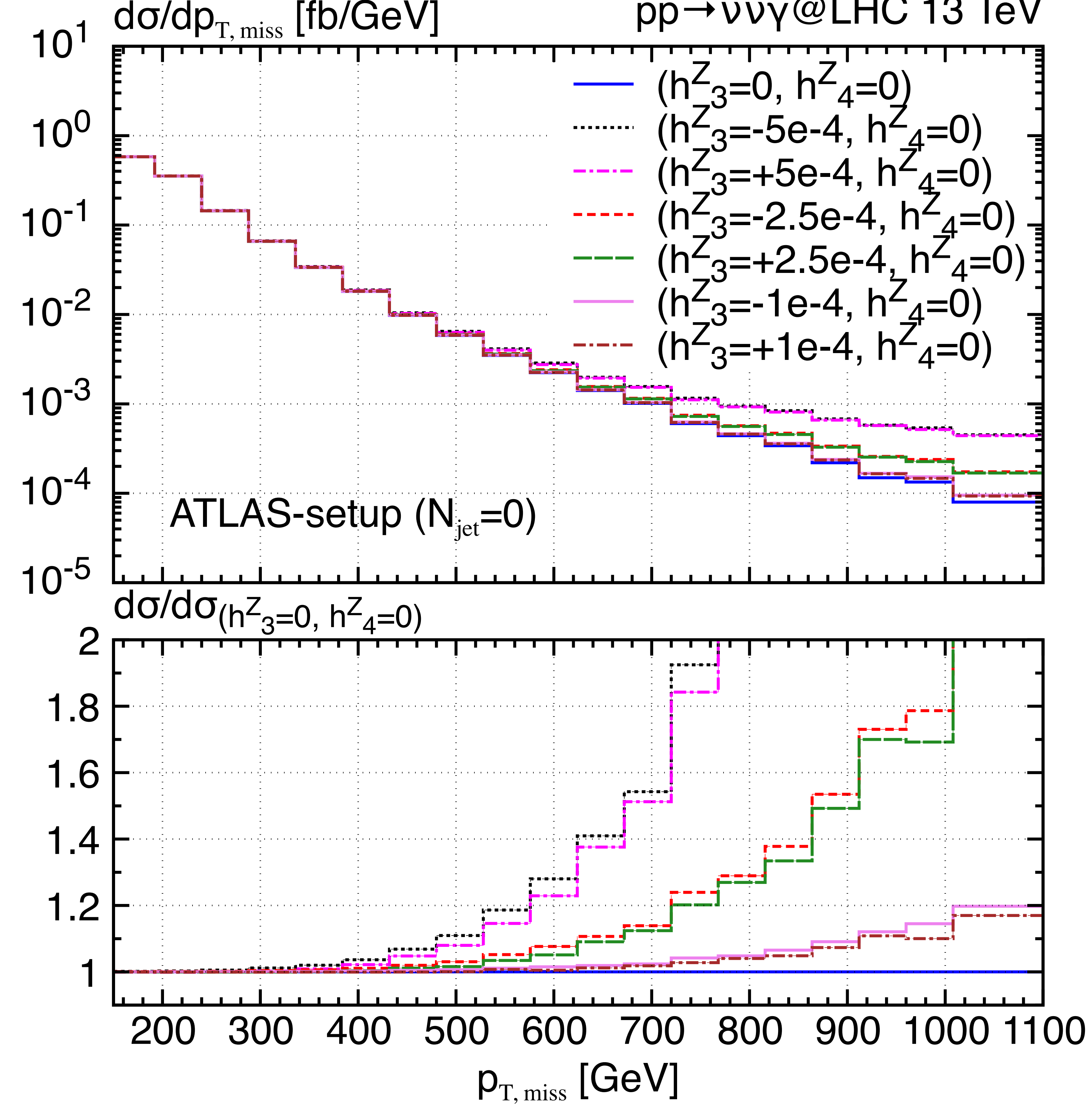
Good agreement with experimental data from ATLAS 36.1fb^{-1} analysis!



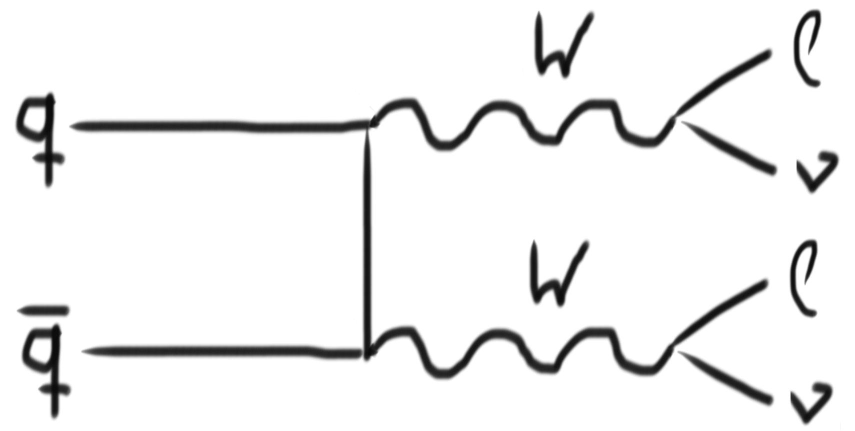


$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,q_2,p) = \frac{i(p^2-m_V^2)}{\Lambda^2}\Big(h_1^V\big(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\big) + \frac{h_2^V}{\Lambda^2} p^\alpha \Big(p\cdot q_2\ g^{\mu\beta} - q_2^\mu p^\beta\Big) - h_3^V \varepsilon^{\mu\alpha\beta\nu} q_{2\,\nu} - \frac{h_4^V}{\Lambda^2}\varepsilon^{\mu\beta\nu\sigma}p^\alpha p_\nu q_{2\,\sigma}\Big)$$



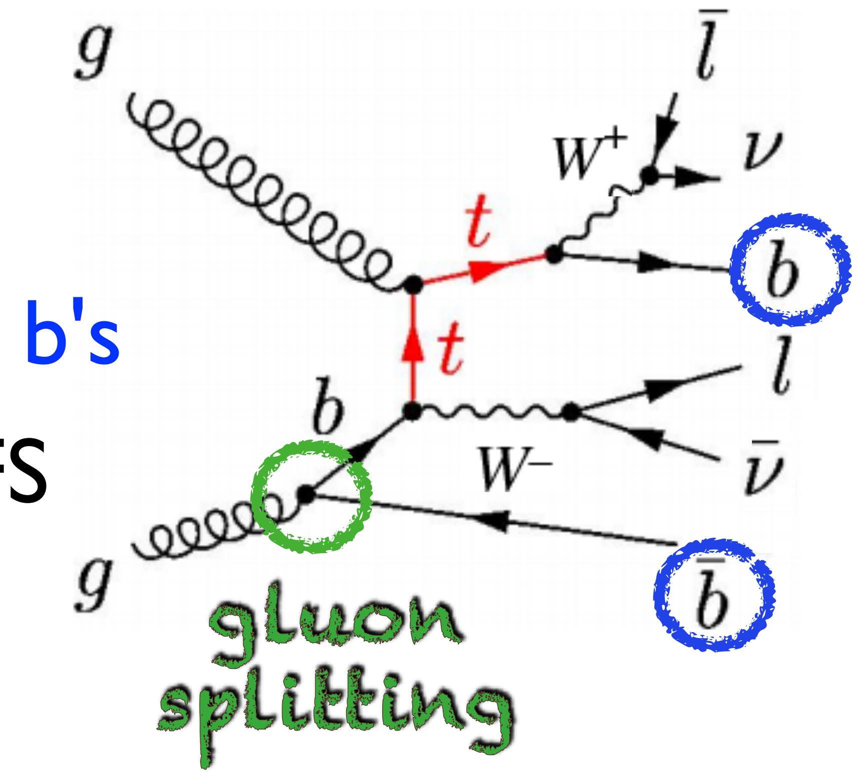


Massive VV production at (n)NNLO+PS

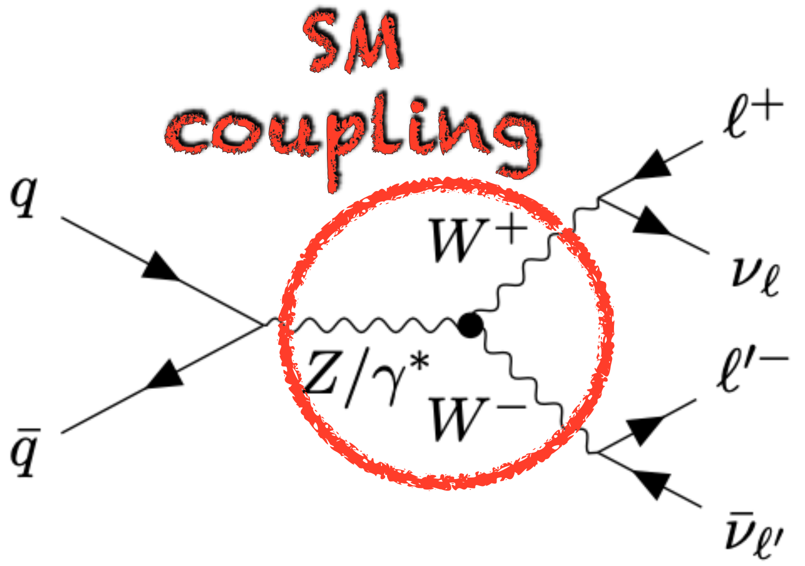


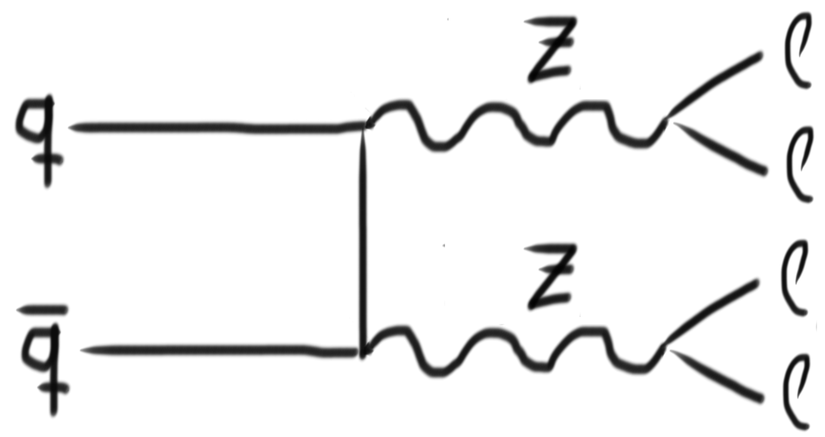
[Lombardi, MW, Zanderighi '21]

- largest cross section of massive VV processes
- no full event reconstruction due to neutrinos
- jet-veto requirement to suppress top backgrounds
  - remove diagrams with external b's
  - not finite for massless b's ➞ 4FS (top-free 5FS in good agreement) [Grazzini, Kallweit, Pozzorini, Rathlev, MW '17]



- important Higgs background
- direct access at LO to anomalous triple gauge couplings

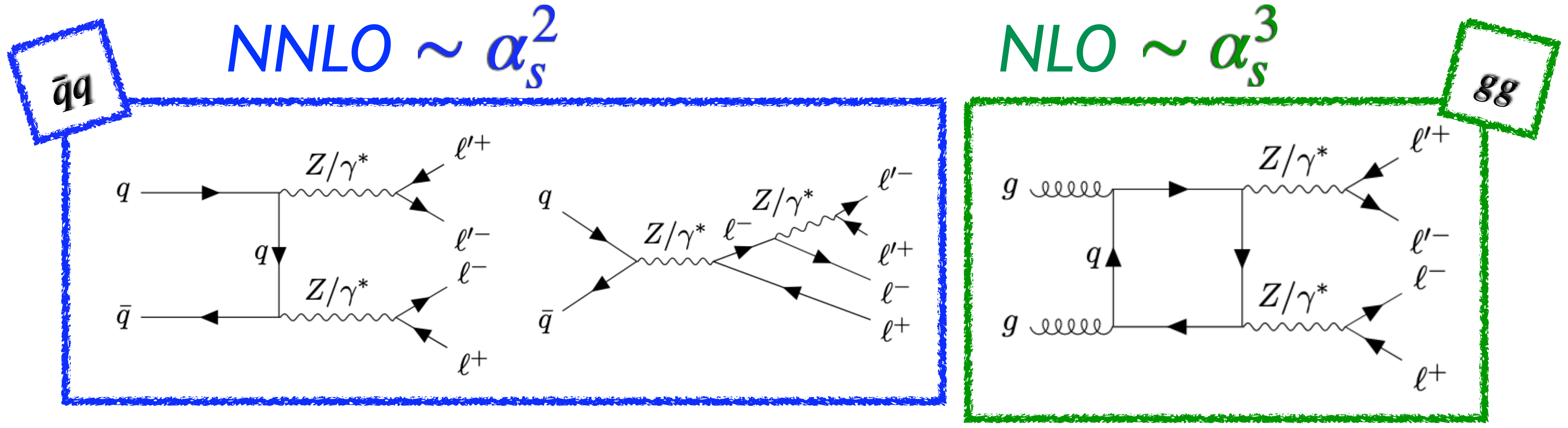




[Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]

- 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* *

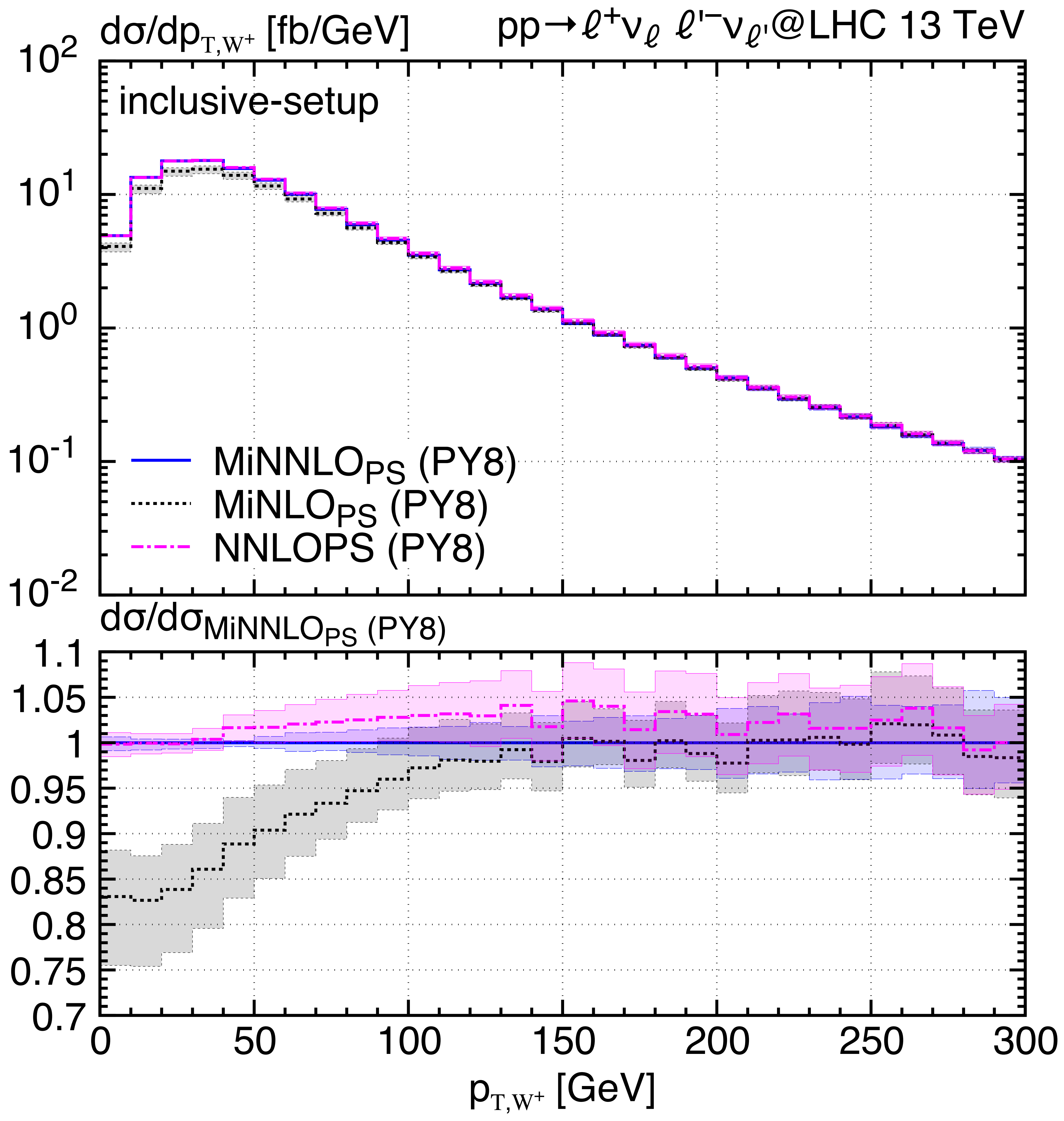
$$pp \to \ell^+\ell^-\ell^{(\prime)+}\ell^{(\prime)-}$$

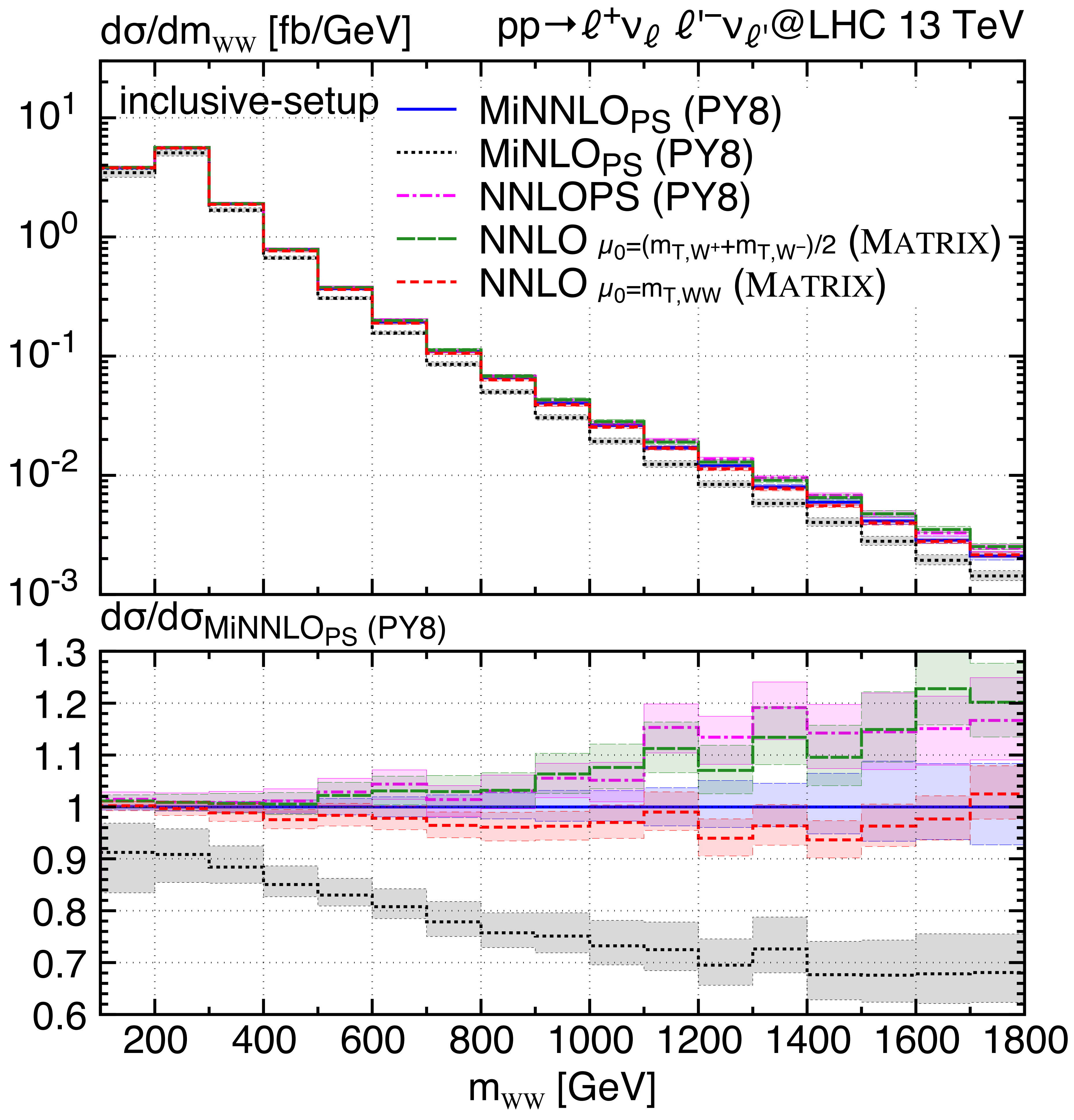
Incoherent combination ⟶ *nNNLO+PS*

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

MiNNLO$_{PS}$: $WW\,(\ell\nu\ell'\nu')$ production

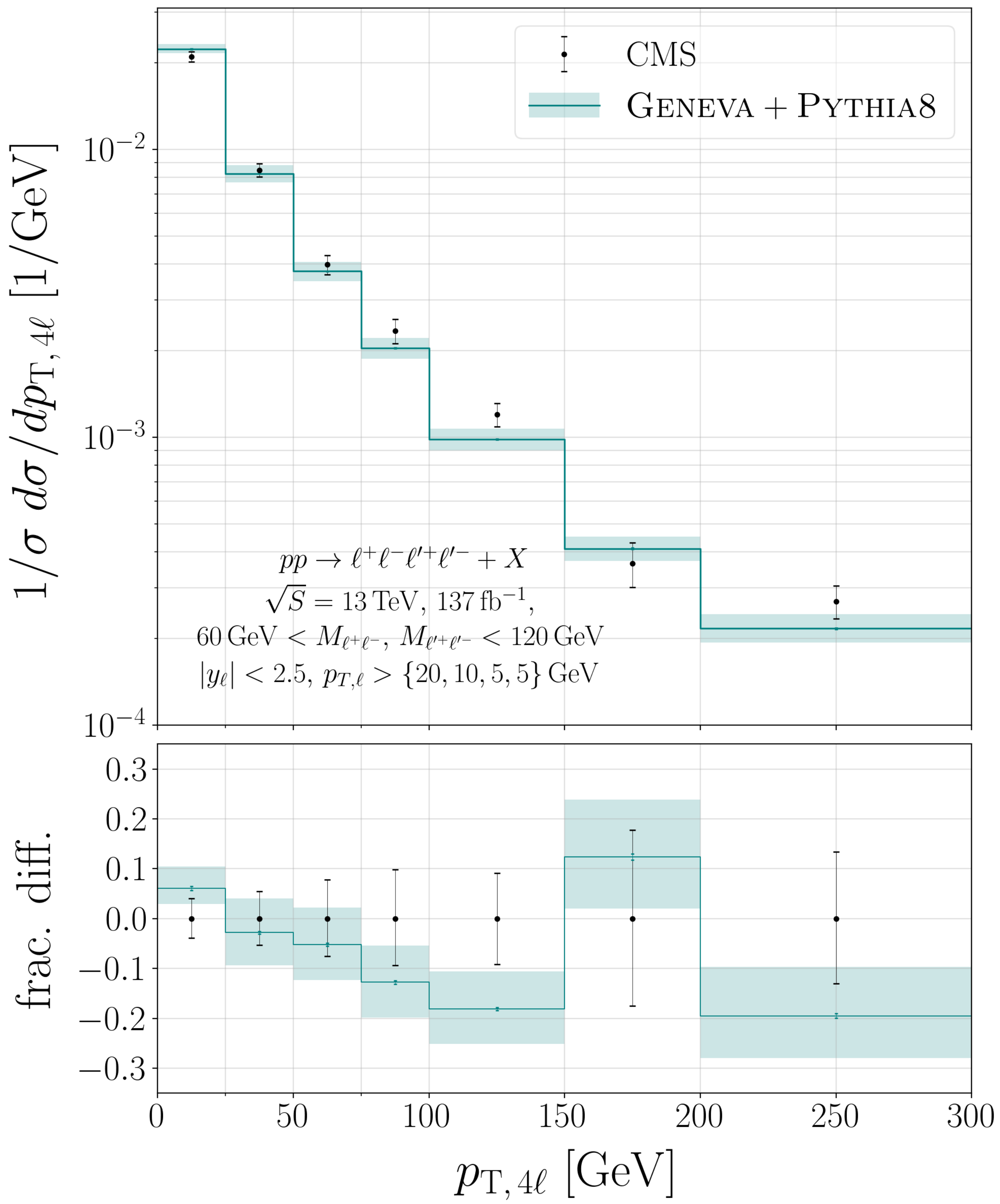
[Lombardi, MW, Zanderighi '21]



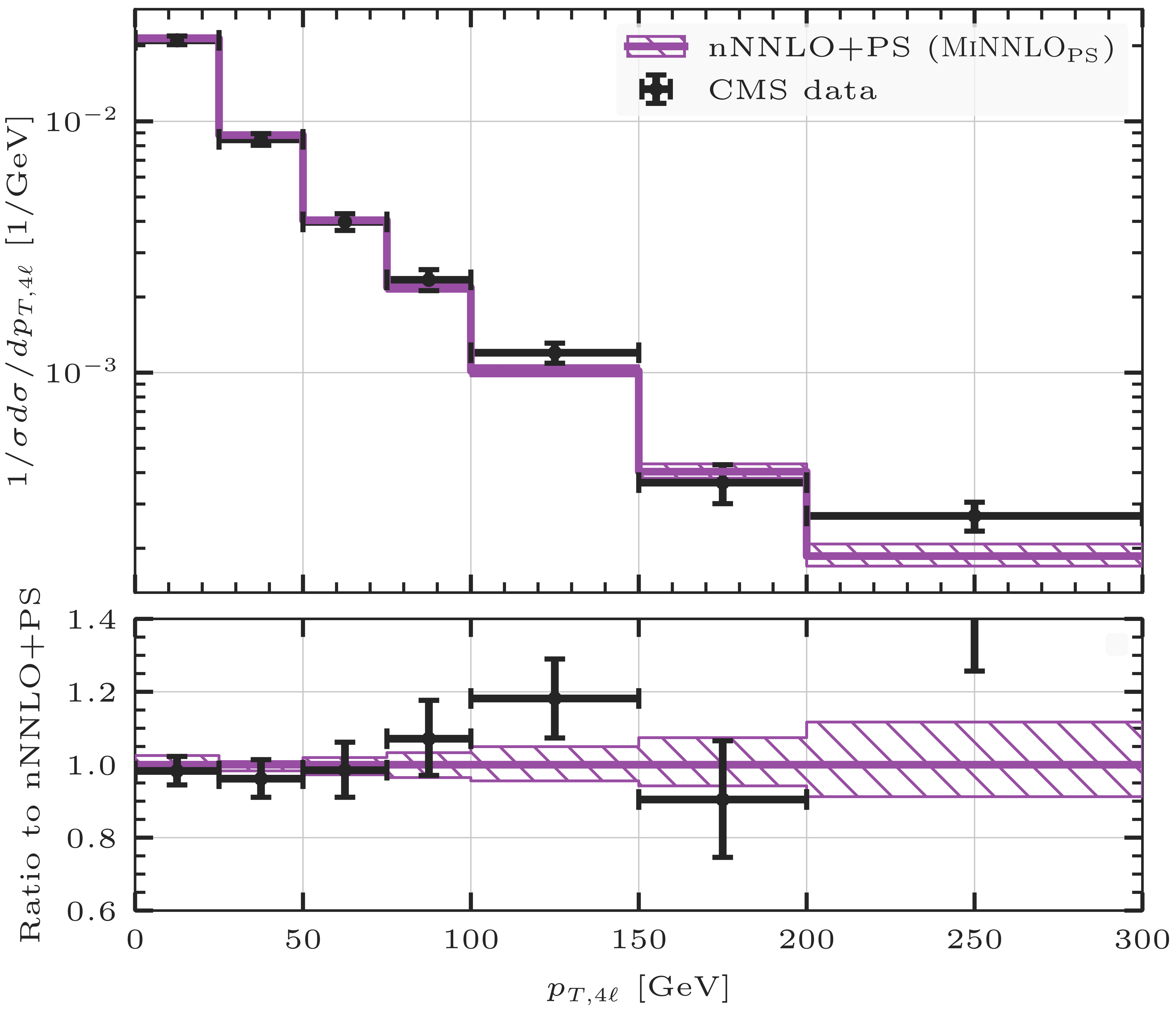


$ZZ(\ell\ell\ell'\ell')$ production

Geneva: NNLO+PS

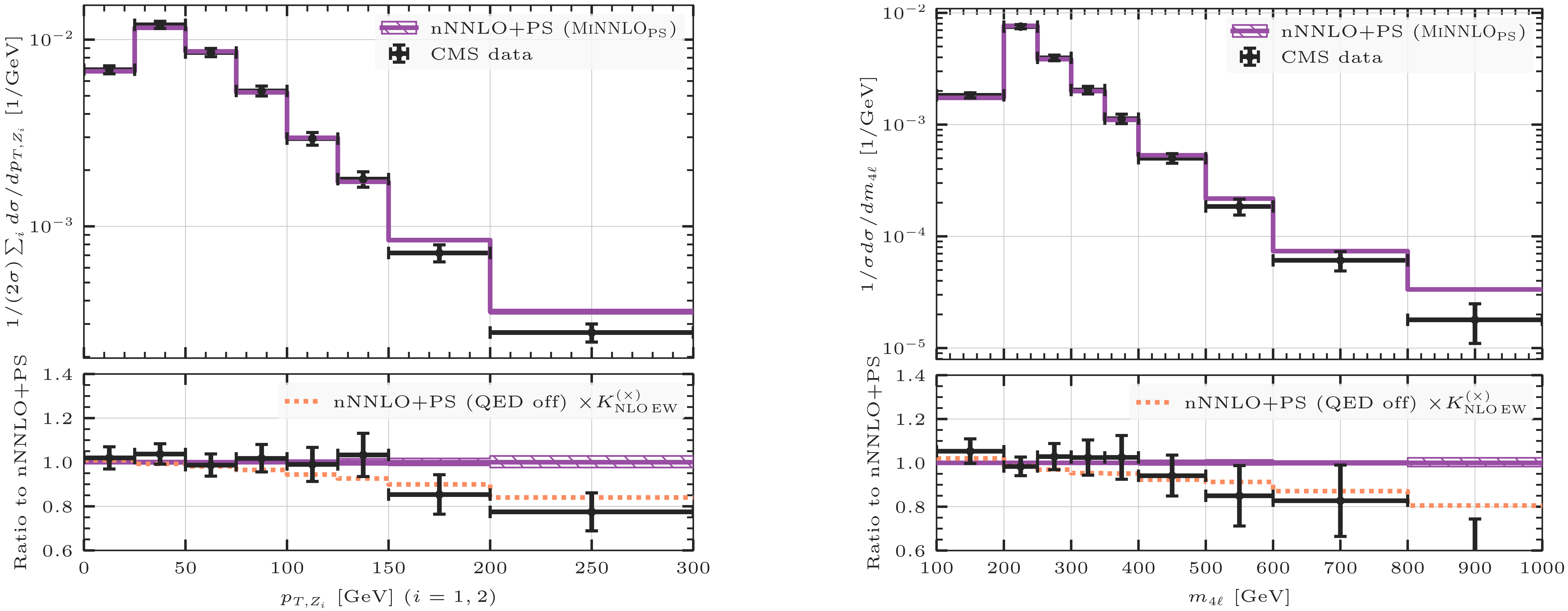


MiNNLO$_{PS}$: nNNLO+PS



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

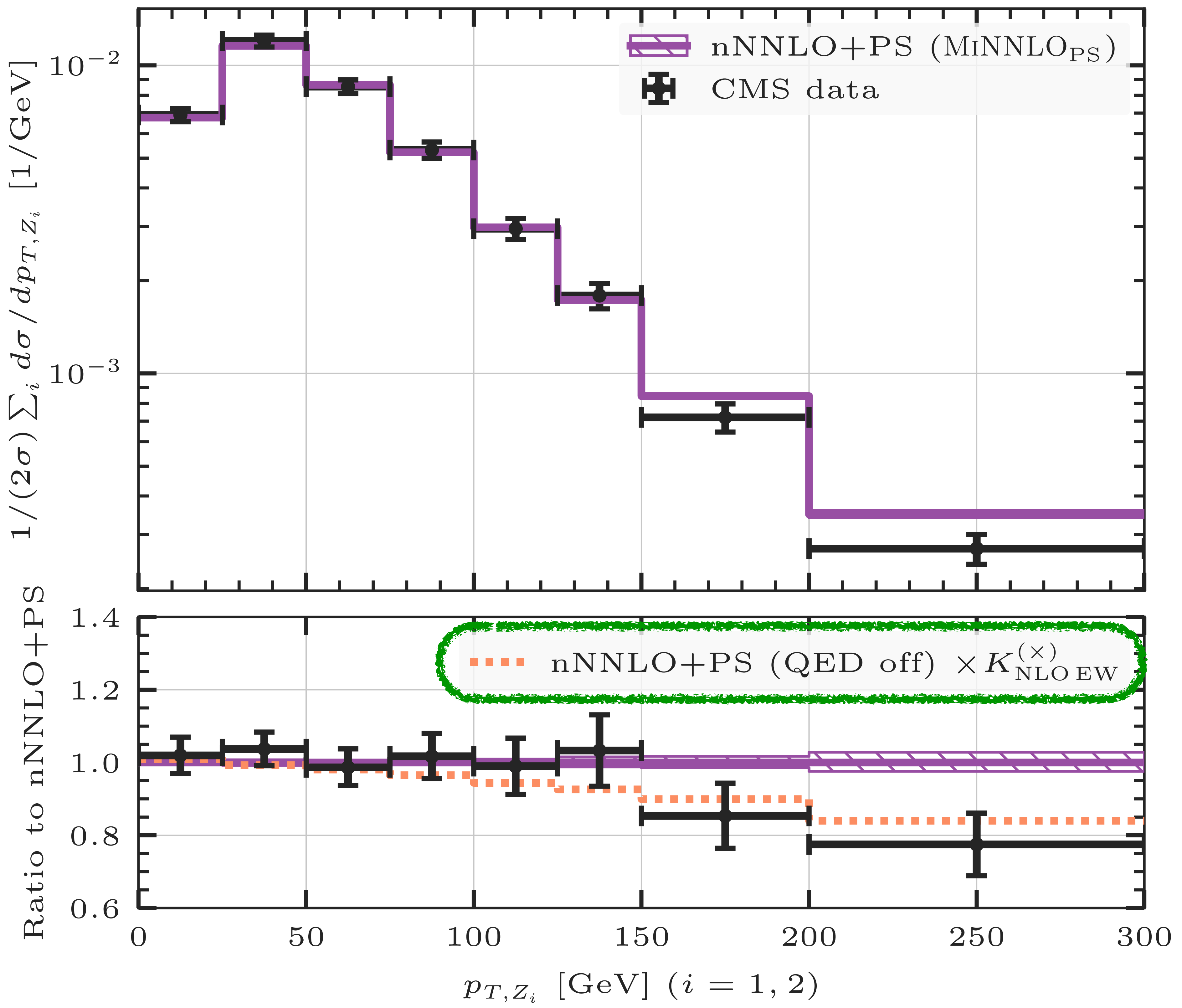
[Buonocore, Koole, Lombardi, Rottoli, MW, Zanderighi '21]

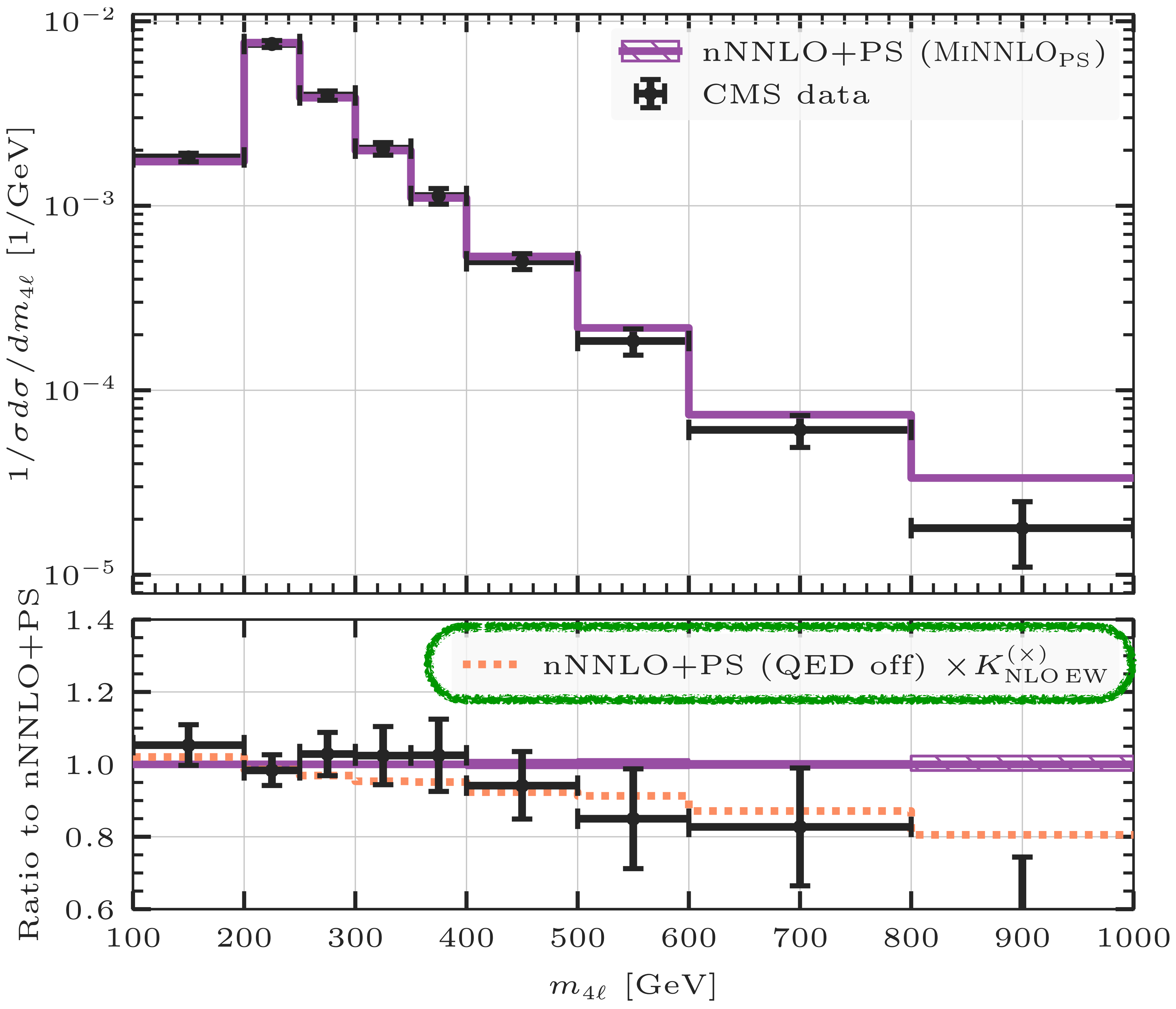


✓ *nNNLO+PS predictions in good agreement with CMS results, based on the a137fb^{-1} 13TeV analysis ([arXiv:2009.01186])!*

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

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



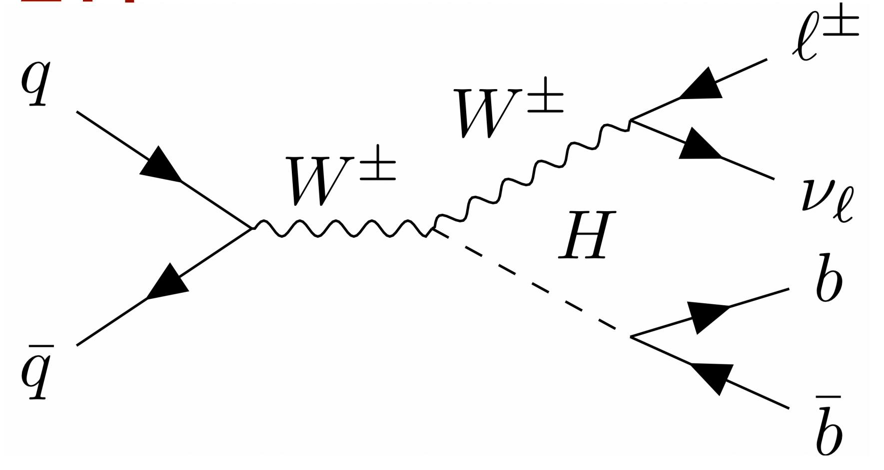


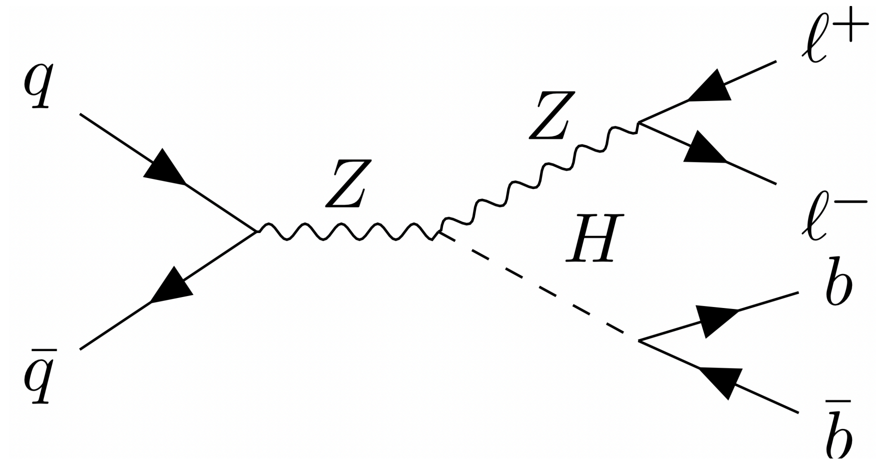
- ✓ *nNNLO+PS predictions in good agreement with CMS results, based on the a137fb^{-1} 13TeV analysis ([arXiv:2009.01186])!*
- ✓ *inclusion of EW corrections (through fixed order NLO K factor) to describe tails of distributions*

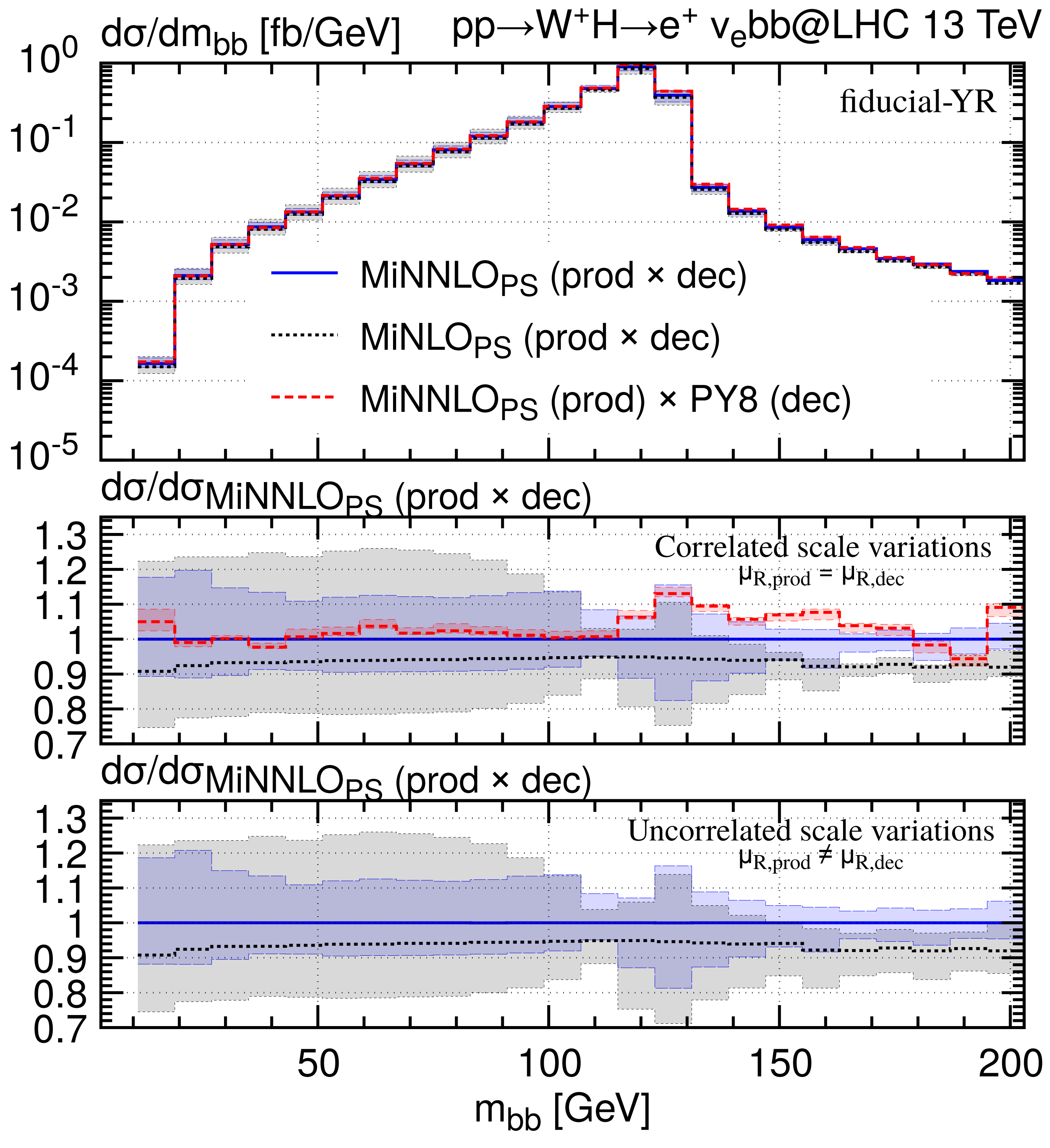
MiNNLO$_{PS}$: Higgsstrahlung with $H \to b\bar{b}$ decay

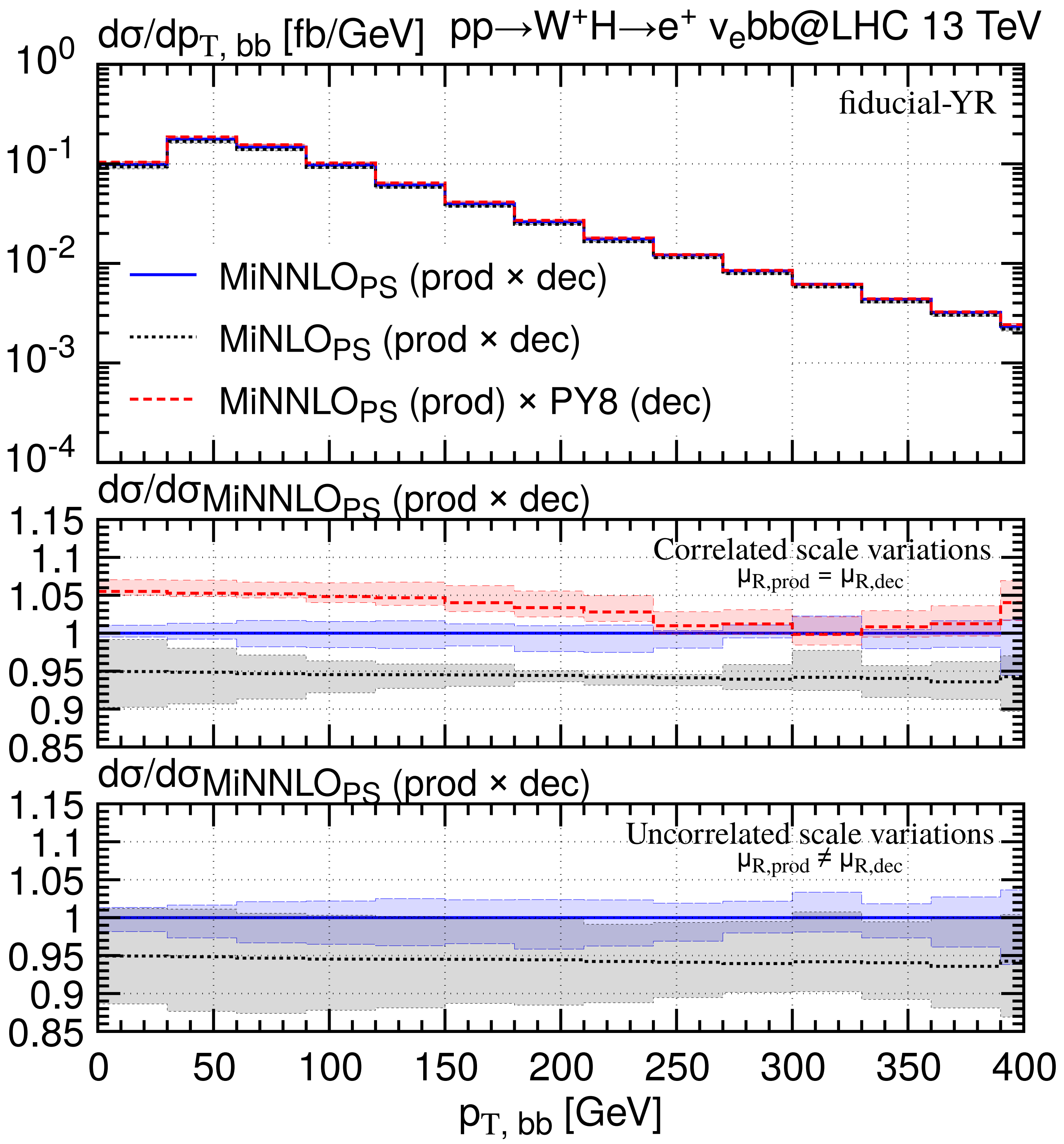
[Zanoli, Chiesa, Re, MW, Zanderighi '21]

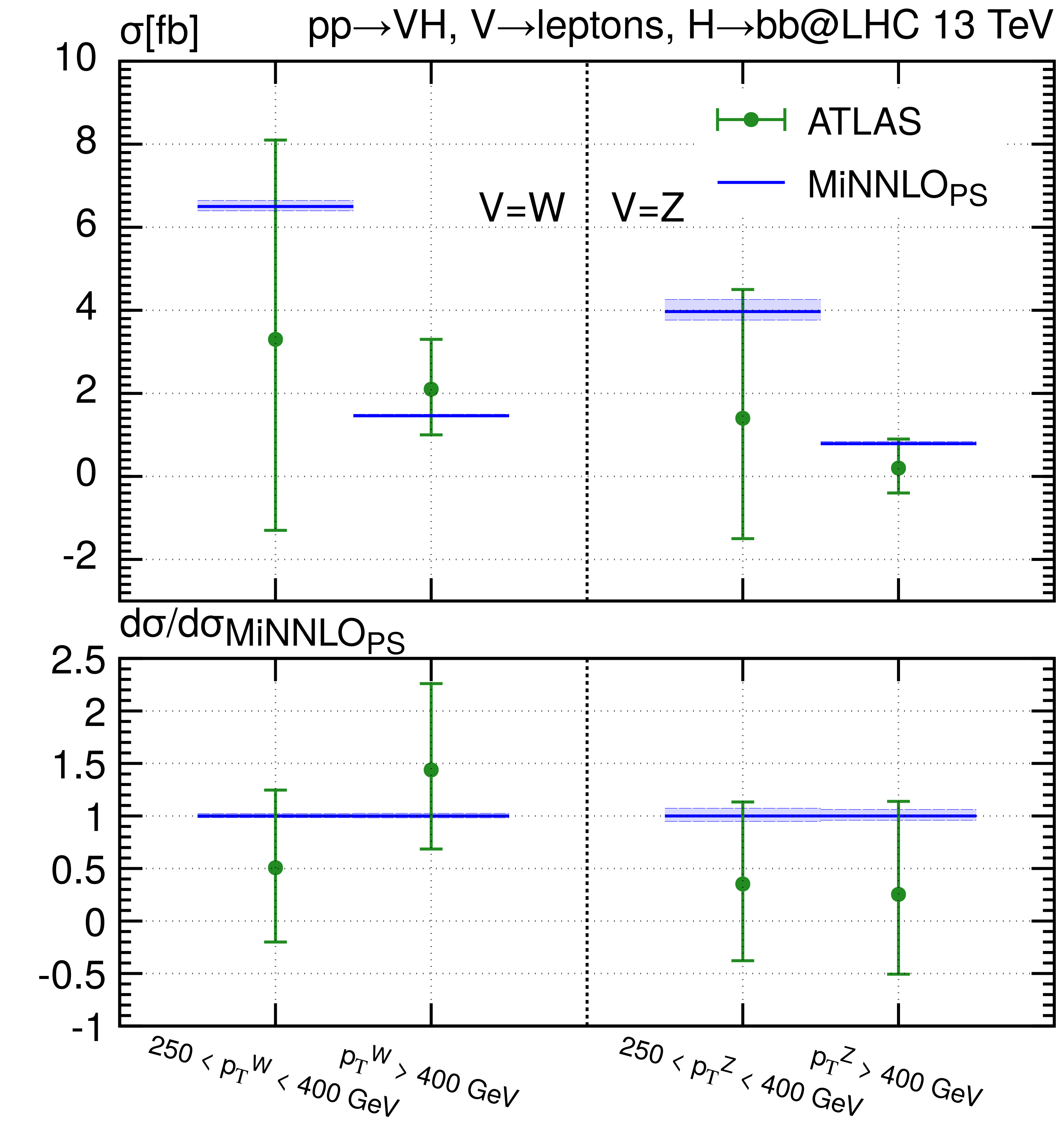
- ***NNLO+PS** accuracy in both **production** and **decay***
  see also [Alioli et al. '19]   see also [Alioli et al. '20]
- *needed for **precision measurement** in the Higgs sector*
- *main production channel to observe $H \to b\bar{b}$ (largest branching fraction)*





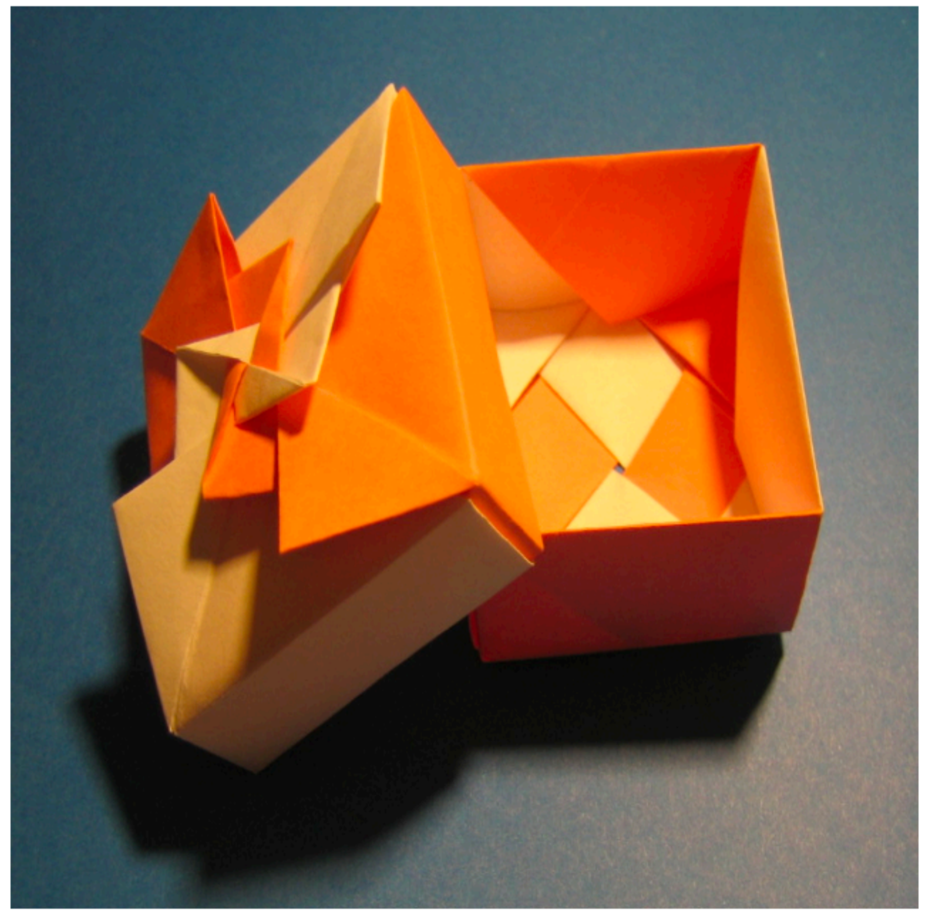






MiNNLO$_{PS}$ generators public in POWHEG BOX

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

MiNNLO$_{PS}$ for $2 \to 1$ processes (H, Z, W) 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).

NEW *First implementation of* $\boldsymbol{Z\gamma}$ *generator (both $Z \to \ell^+\ell^-$ and $Z \to \bar{\nu}\nu$ + aTGC @NNLO) [Lombardi, MW, Zanderighi '20, '21]*

NEW *New approach to the existing* **WW** *generator [Lombardi, MW, Zanderighi '21]*

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

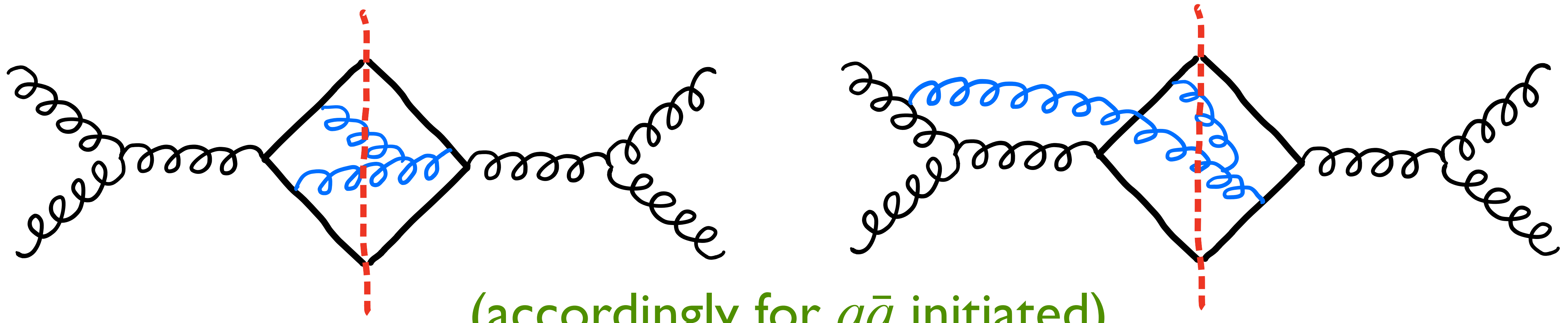
NEW **VH** *generator interfaced with* **H→bb** *decay (t.b.a.) [Zanoli, Chiesa, Re, MW, Zanderighi 'ongoing]*

NEW *More to come …*

MiNNLO$_{PS}$: heavy quark production

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

✦ substantial complication due to final-state radiation and interferences



(accordingly for $q\bar{q}$ initiated)

✦ compare resummation formulas (very schematic):

colour singlet: $$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S} \quad H \quad (C\otimes f)(C\otimes f)\right\}$$

heavy quark pair: $$d\sigma^F_{\rm res} \sim \frac{d}{dp_T}\left\{e^{-S}\,{\rm Tr}(\mathbf{H}\boldsymbol{\Delta})\,(C\otimes f)(C\otimes f)\right\}$$

[Catani, Grazzini, Torre '14]

$\boldsymbol{\Delta}$: operator/matrix in colour space that encodes soft emissions of $t\bar{t}$ and interferences

MiNNLO$_{PS}$: $t\bar{t}$ production

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

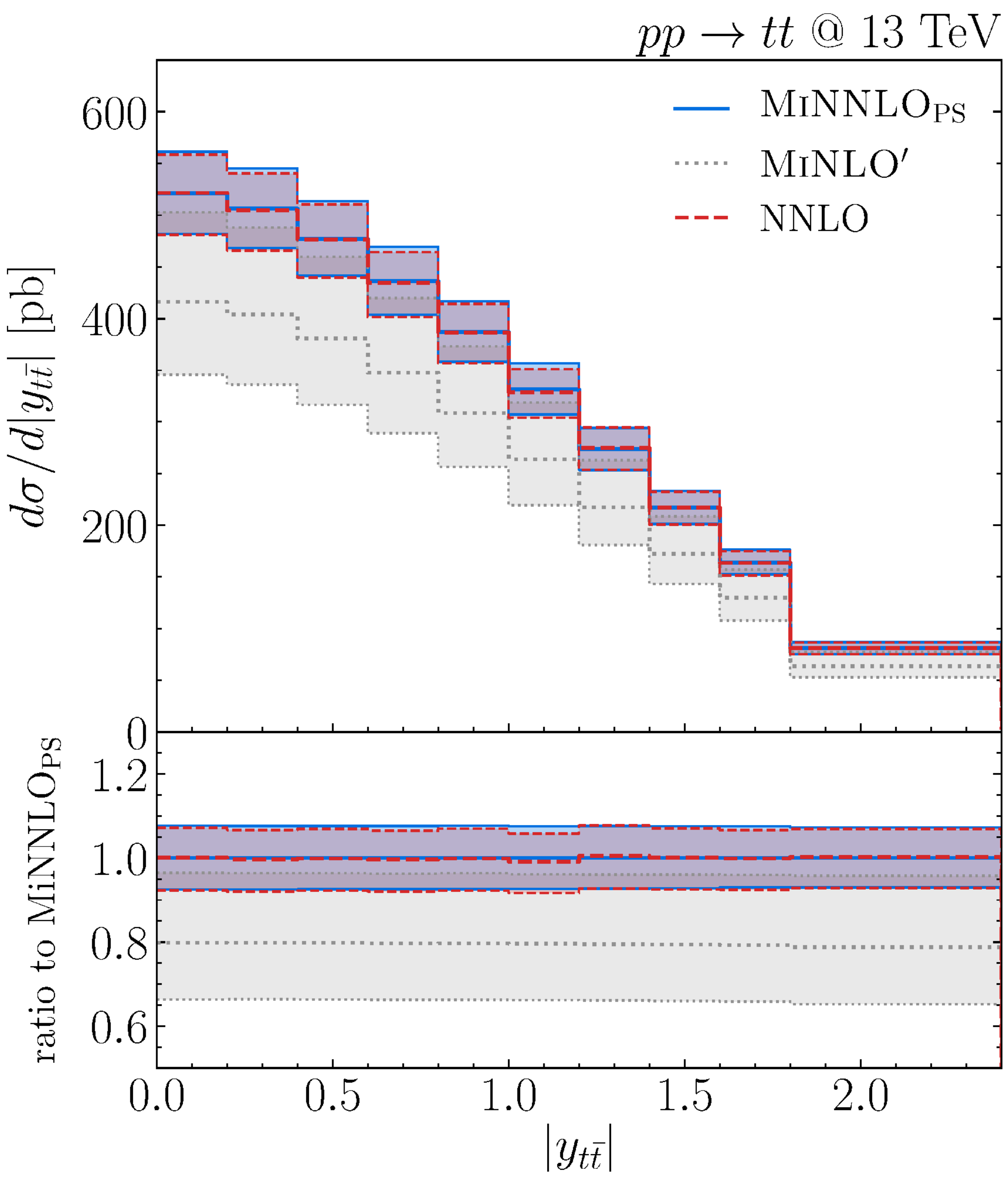
- total cross section:

MiNLO′	NNLO	MiNNLO$_{PS}$
$572.9(2)^{+21\%}_{-17\%}$ pb	$719.1(8)^{+7.0\%}_{-7.6\%}$ pb	$719.8(2)^{+7.6\%}_{-7.4\%}$ pb

MiNNLO$_{PS}$ and NNLO agree at permille level
(note: different scale settings)

- excellent agreement of MiNNLO$_{PS}$ with NNLO for $t\bar{t}$ rapidity

- substantial reduction of scale uncertainties w.r.t. MiNLO′



MiNNLO$_{PS}$: $t\bar{t}$ production with decay

[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '21]

Summary

★ NNLO+PS for 2 ➞ 2 becoming available for colour singlets

★ Combination with other relevant corrections in ZZ (NLO gg, NLO EW)

★ First coloured process at NNLO+PS: Top-quark pair production

★ MiNNLO$_{PS}$ generators publicly available in POWHEG BOX

Outlook

★ NNLO+PS becoming available for "all" colour-singlet processes

★ SMEFT effects at NNLO+PS

★ Sophisticated treatment of top-quark decays at NNLO+PS (spin correllations, higher orders)

★ NNLO+PS for other process classes (heavy quarks + colour singlet, final-state jets, ...)

Summary

★ NNLO+PS for 2 → 2 becoming available for colour singlets

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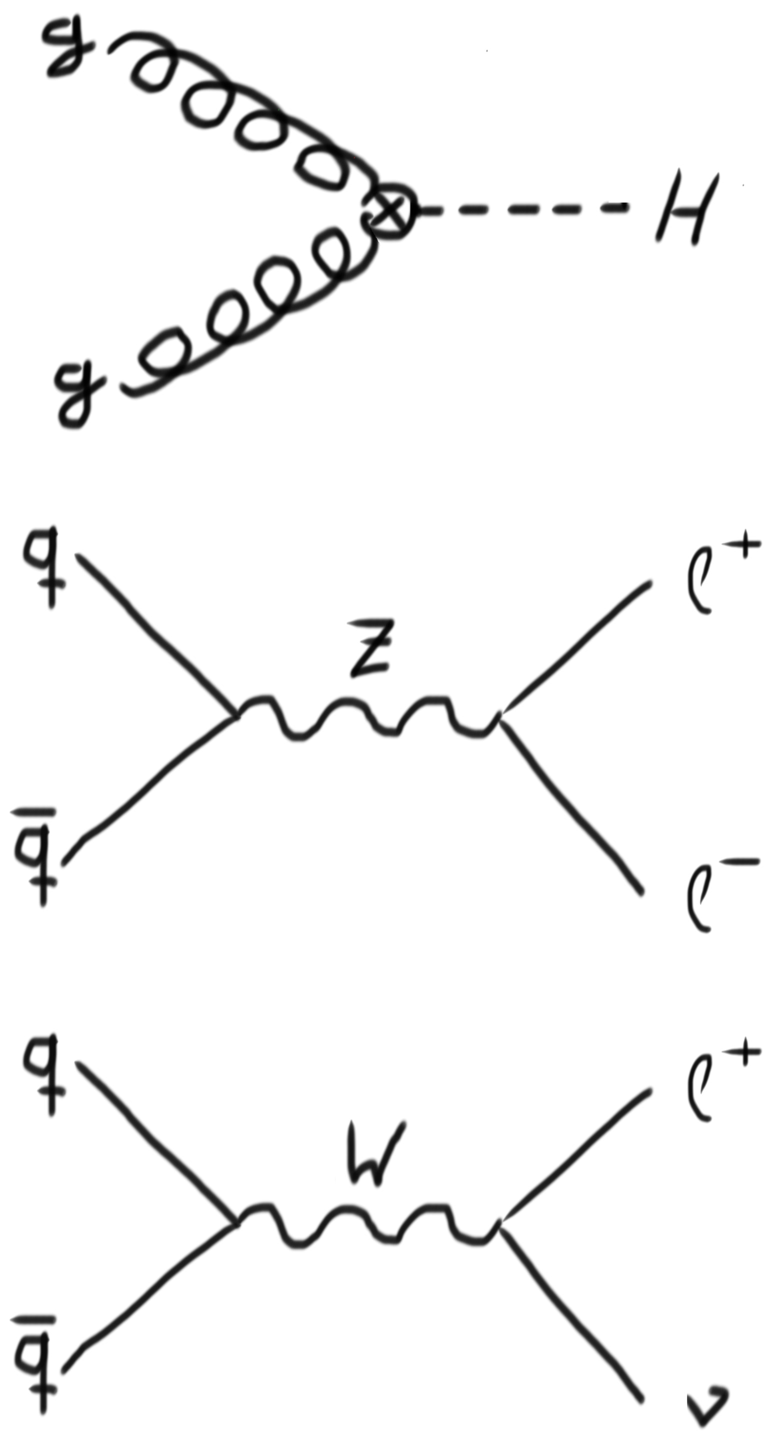
Stay tuned !

Back Up

MiNNLOPS for 2→1 colour singlets

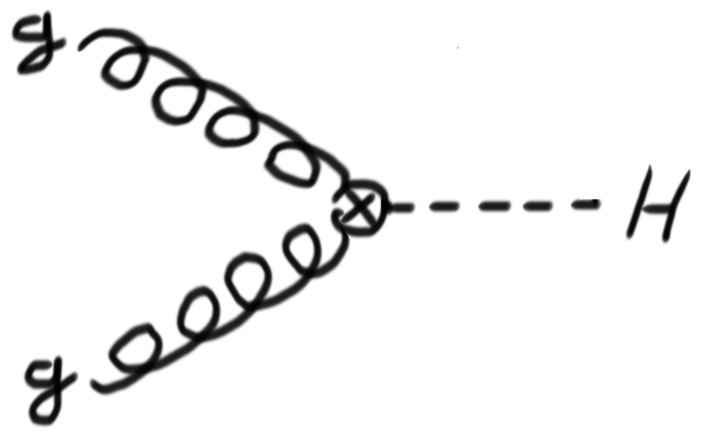
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

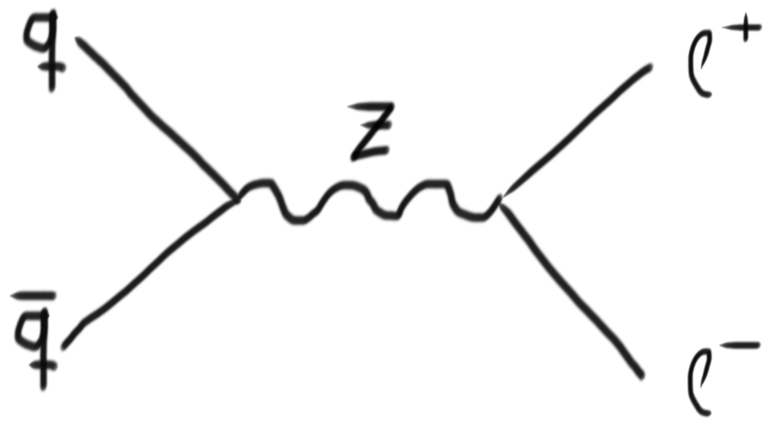


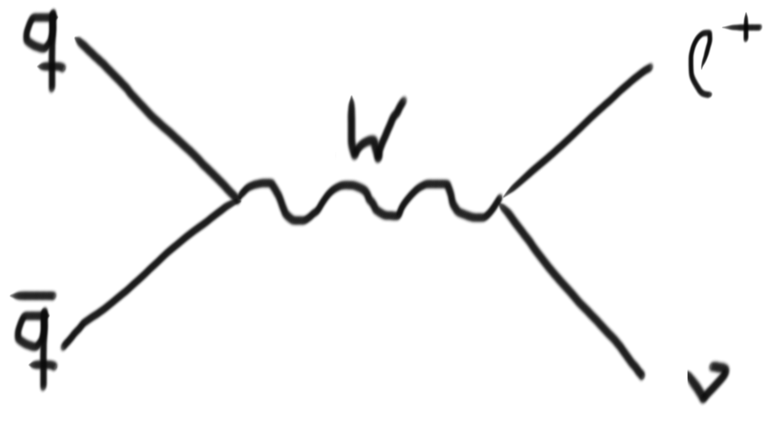
Process	NNLO (MATRIX)	MINNLOPS	Ratio
$pp \to H$	$39.64(1)^{+10.7\%}_{-10.4\%}$ pb	$39.1(5)^{+10.2\%}_{-9.0\%}$ pb	0.987
$pp \to \ell^+\ell^-$	$1919(1)^{+0.8\%}_{-1.1\%}$ pb	$1917(1)^{+1.4\%}_{-1.1\%}$ pb	0.999
$pp \to \ell^-\bar{\nu}_\ell$	$8626(4)^{+1.0\%}_{-1.2\%}$ pb	$8643(4)^{+1.7\%}_{-1.5\%}$ pb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

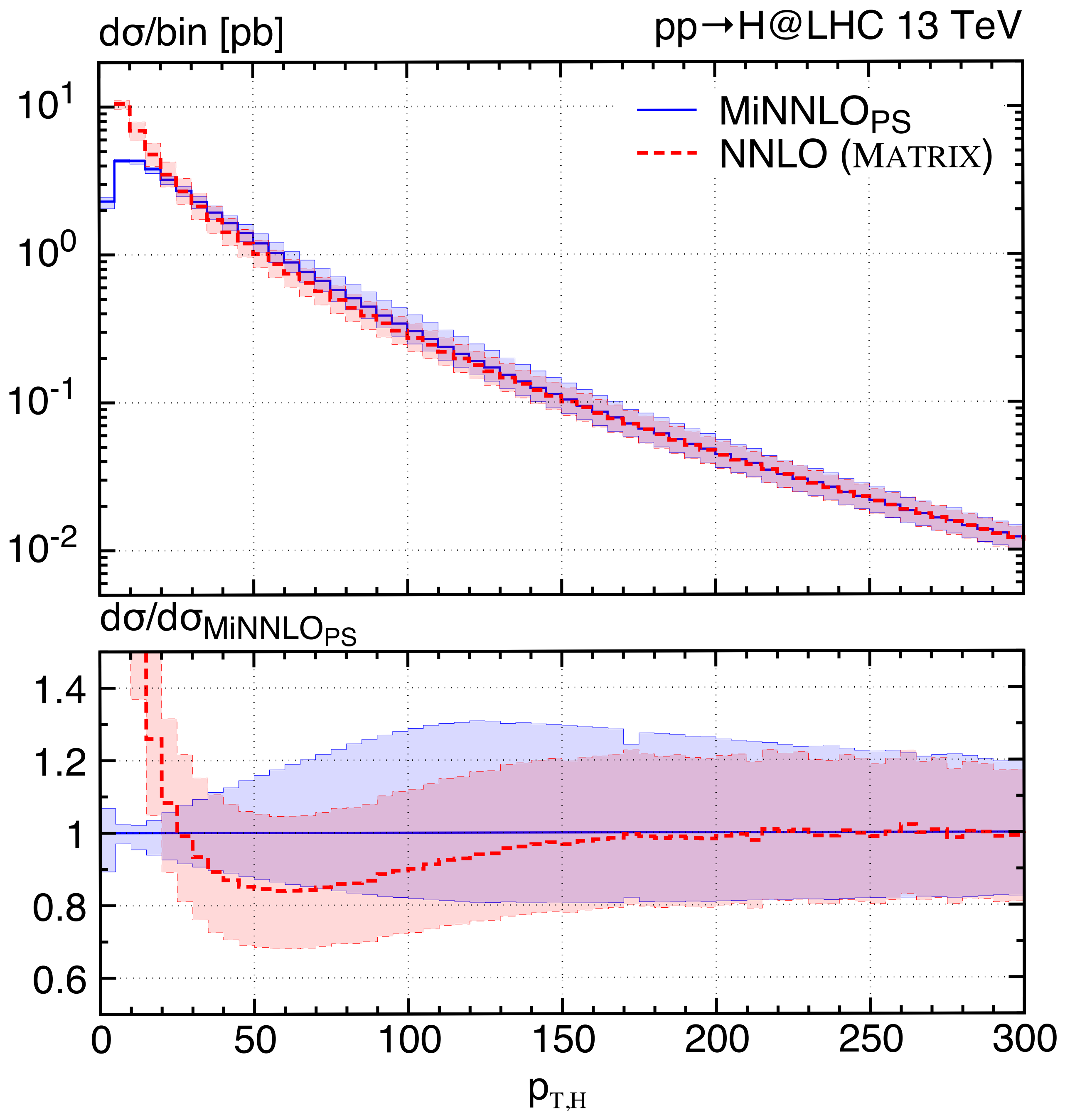
MiNNLOPS for 2→1 colour singlets

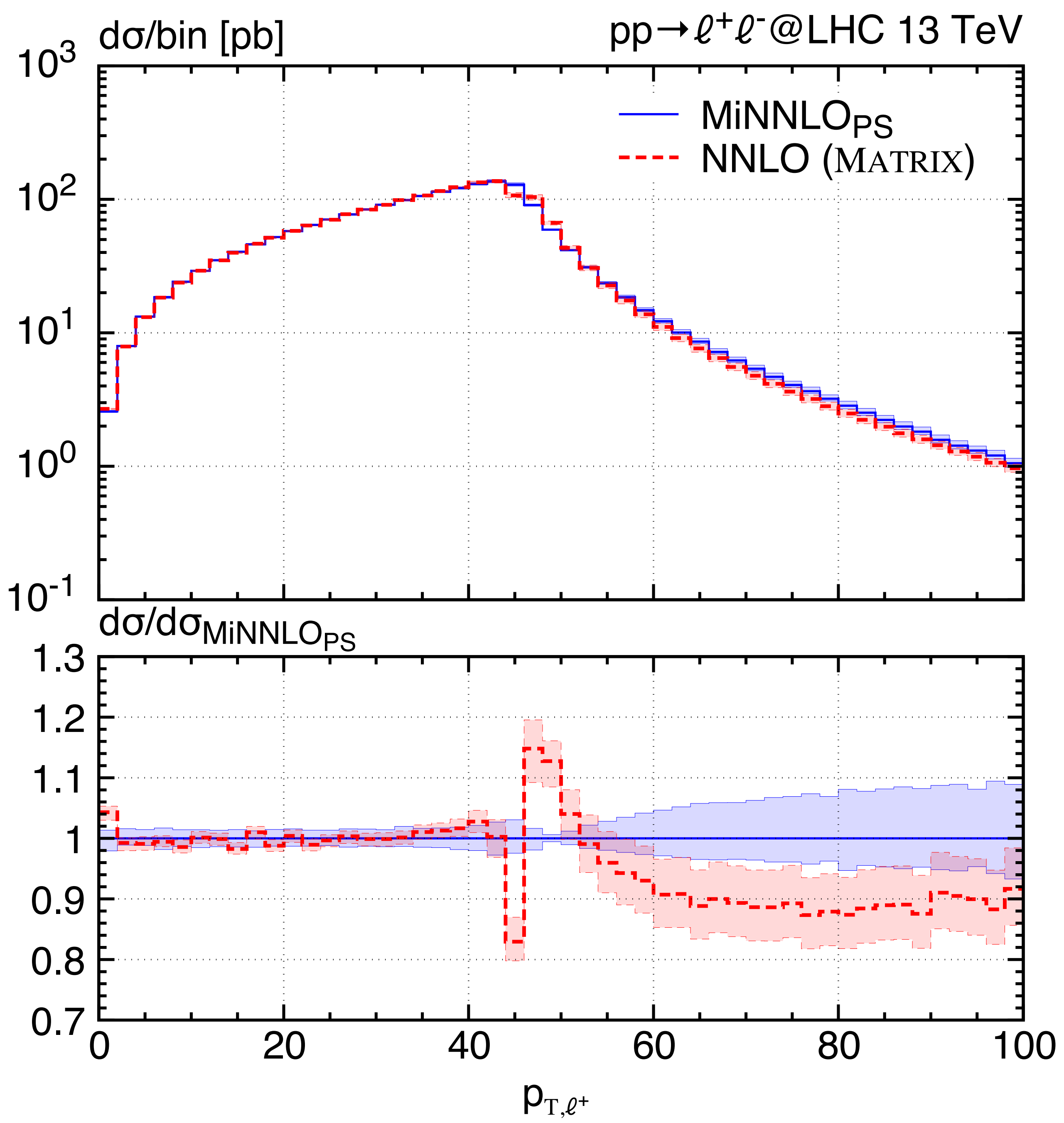
[Monni, Nason, Re, MW, Zanderighi '19], [Monni, Re, MW '20]

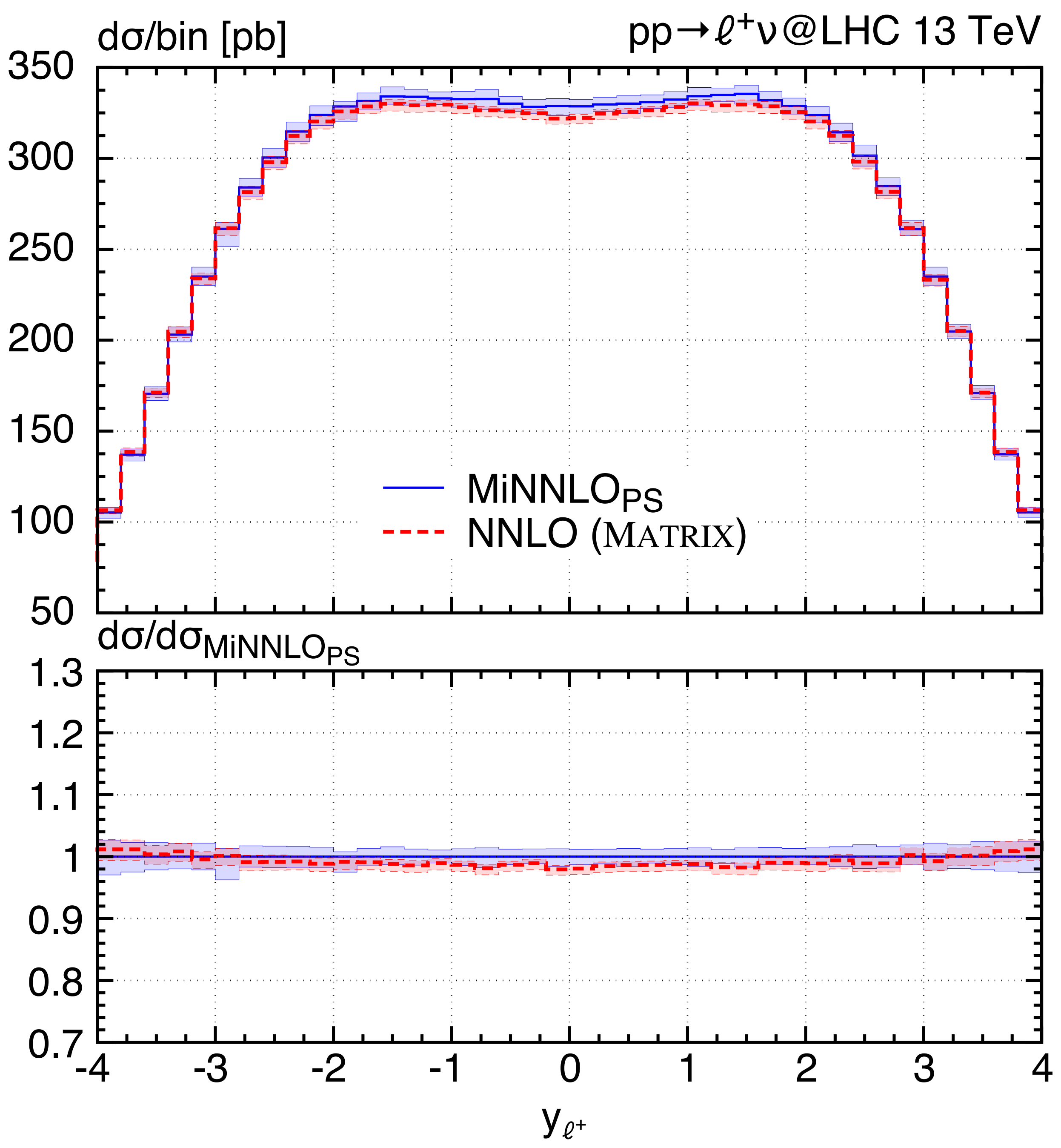






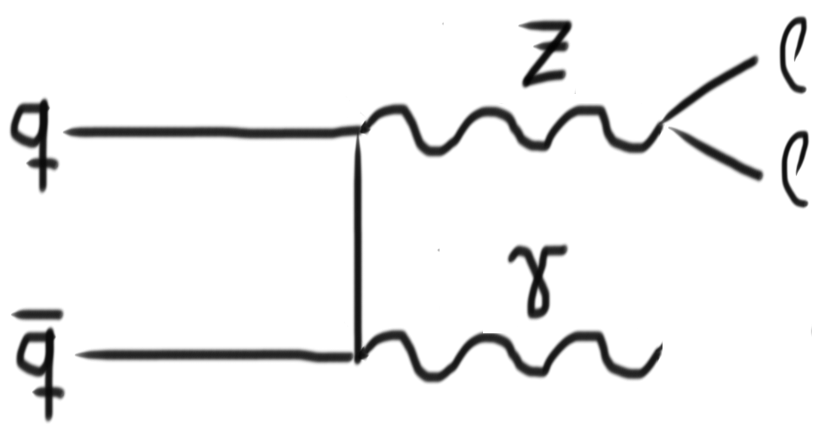


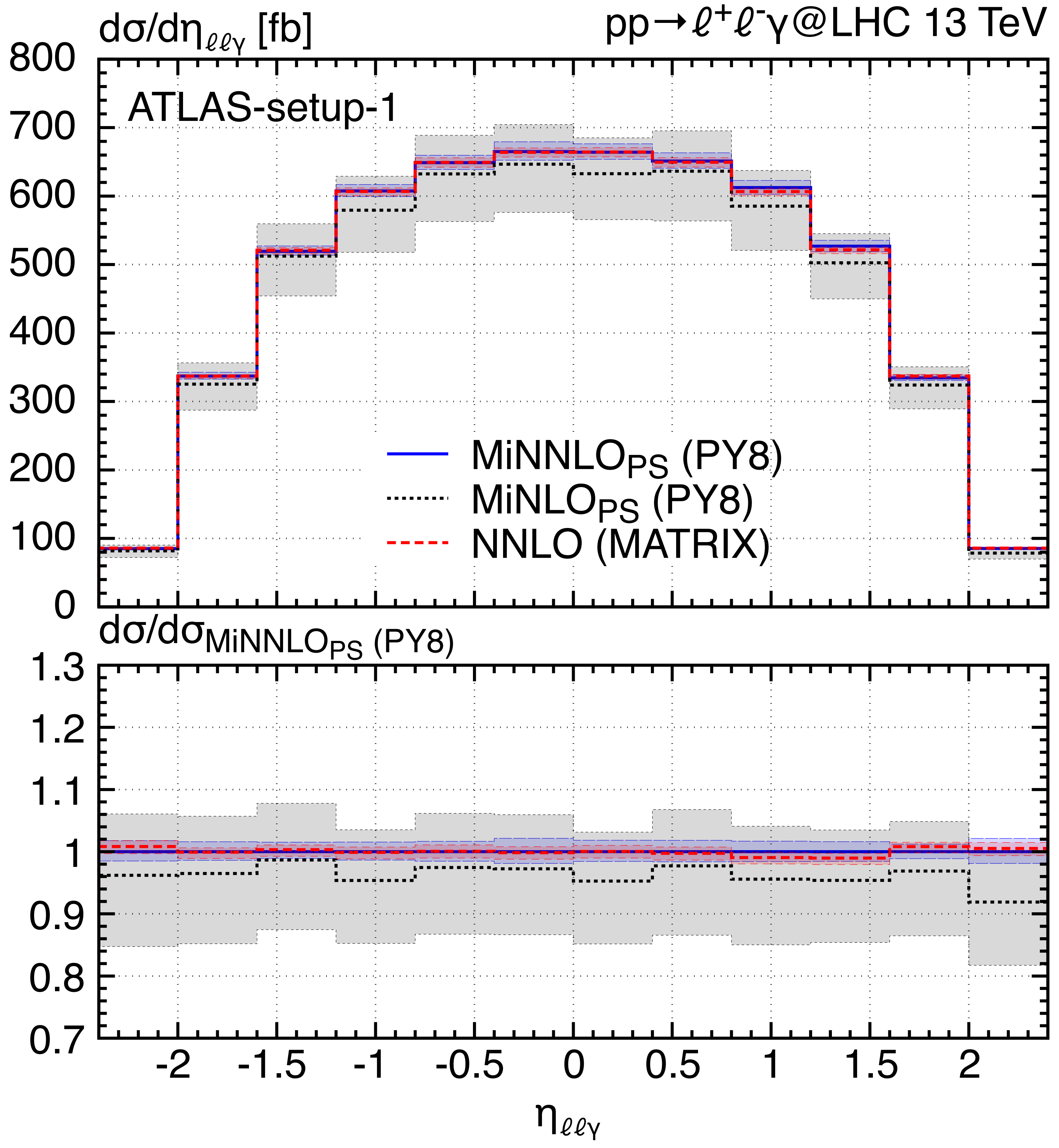


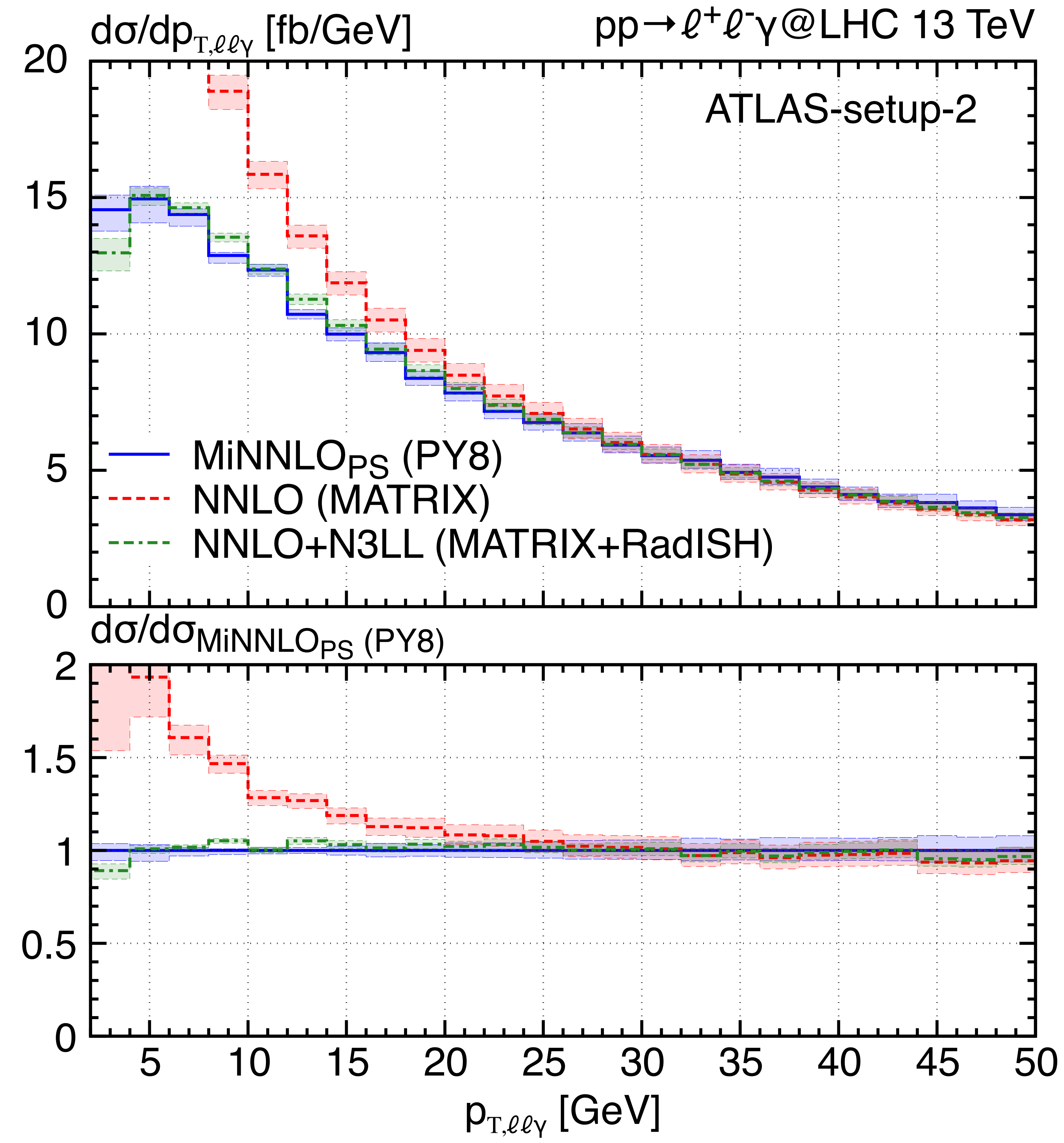


MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]







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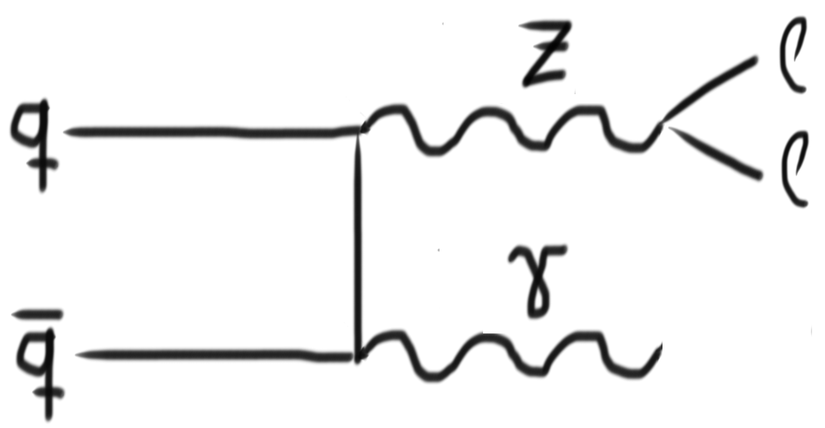

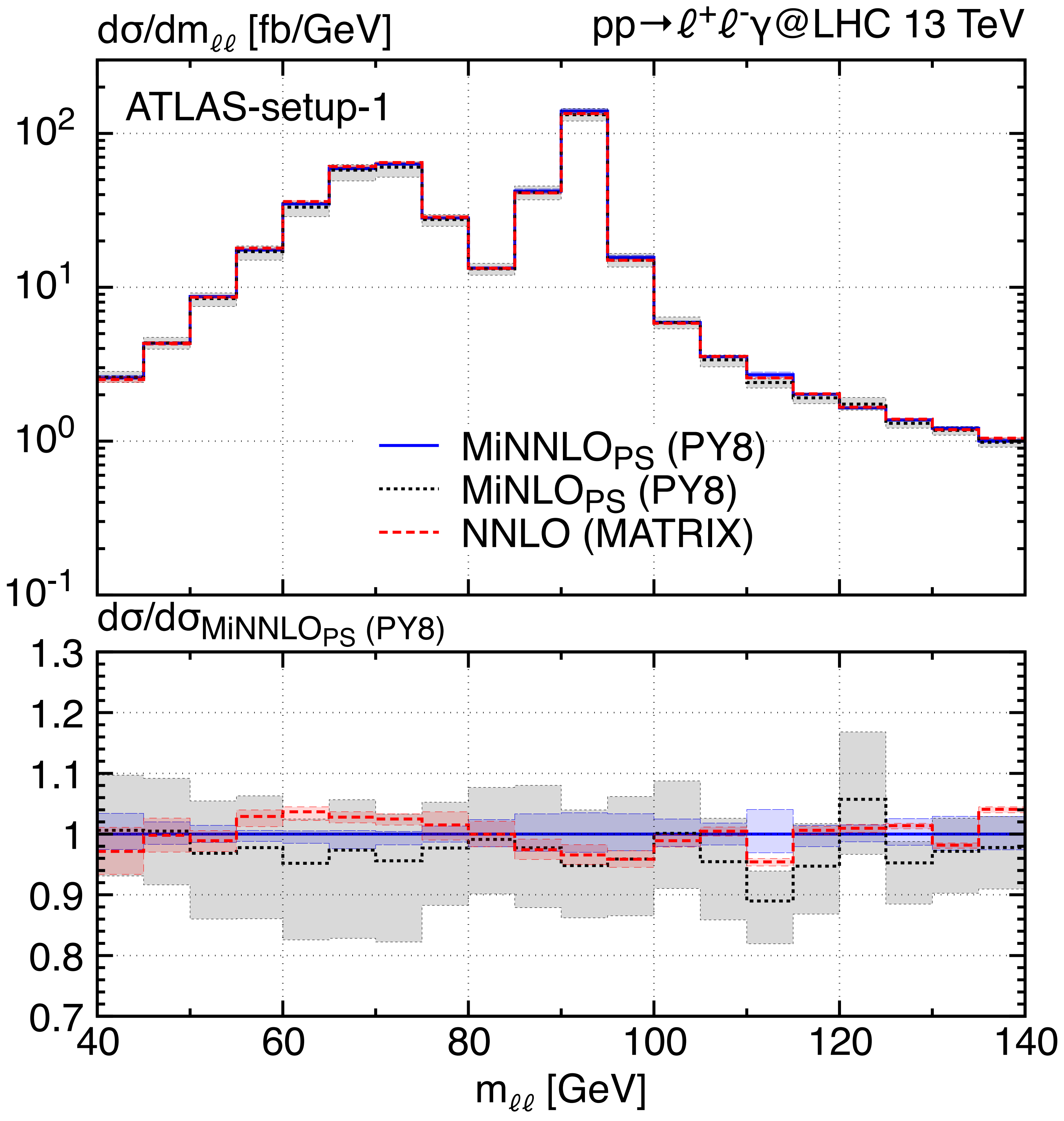

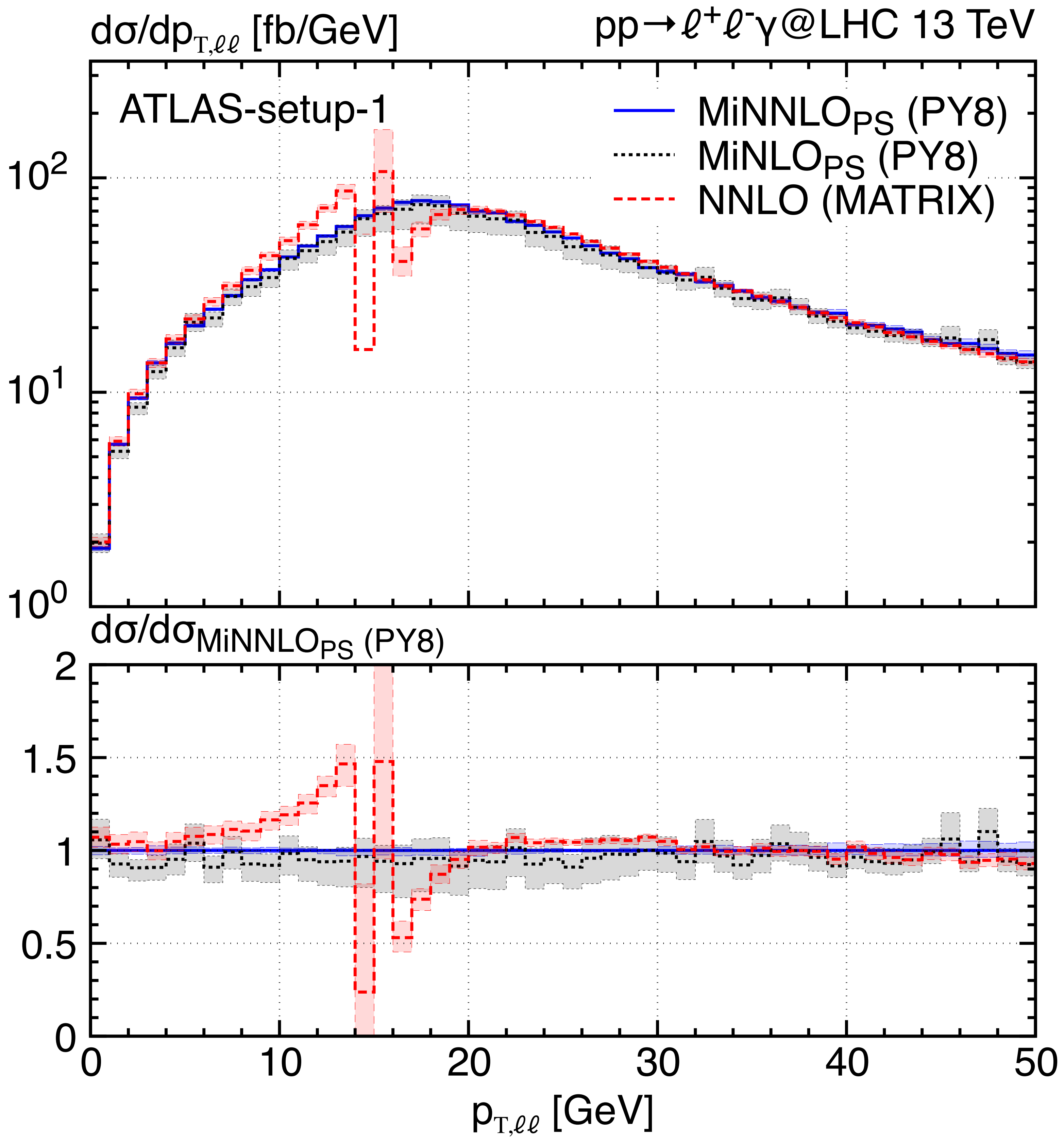

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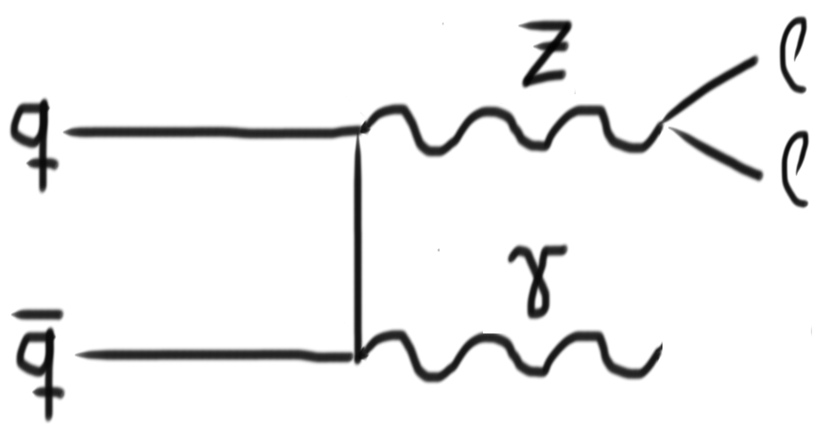
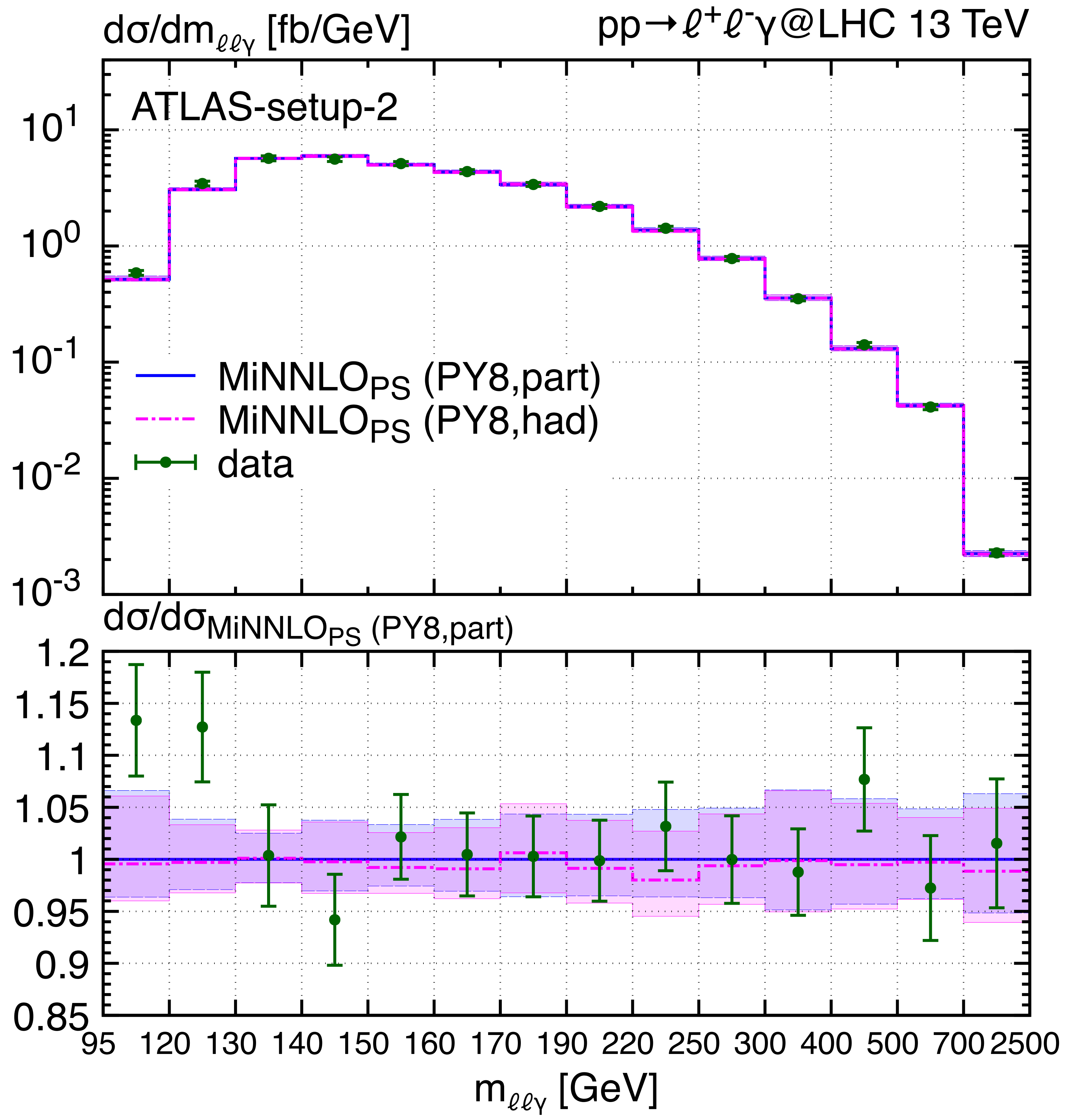
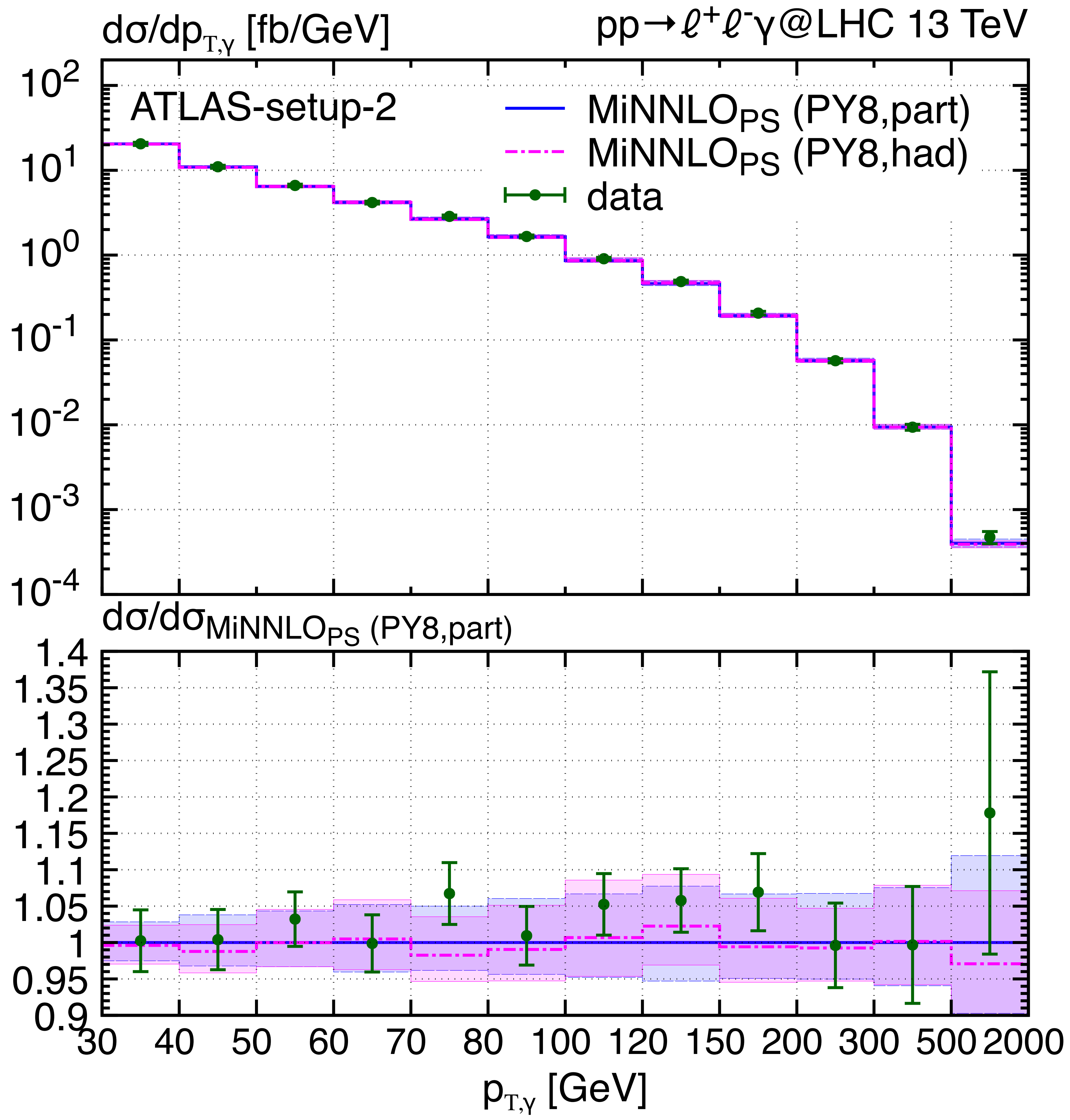
[Lombardi, MW, Zanderighi '20]







MiNNLO$_{PS}$ for 2→2 colour singlets

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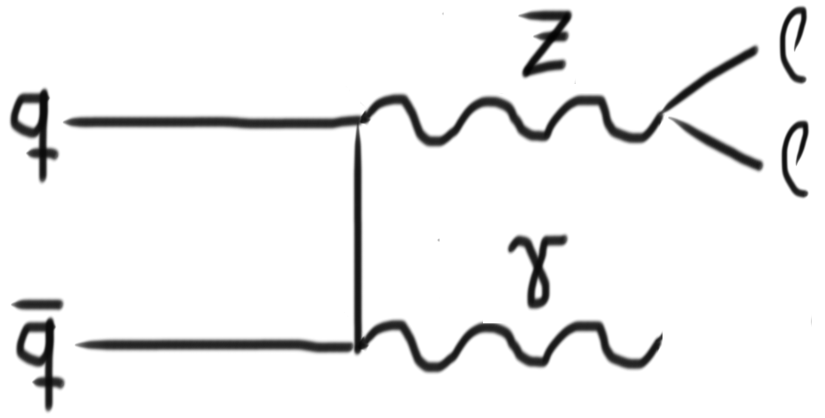
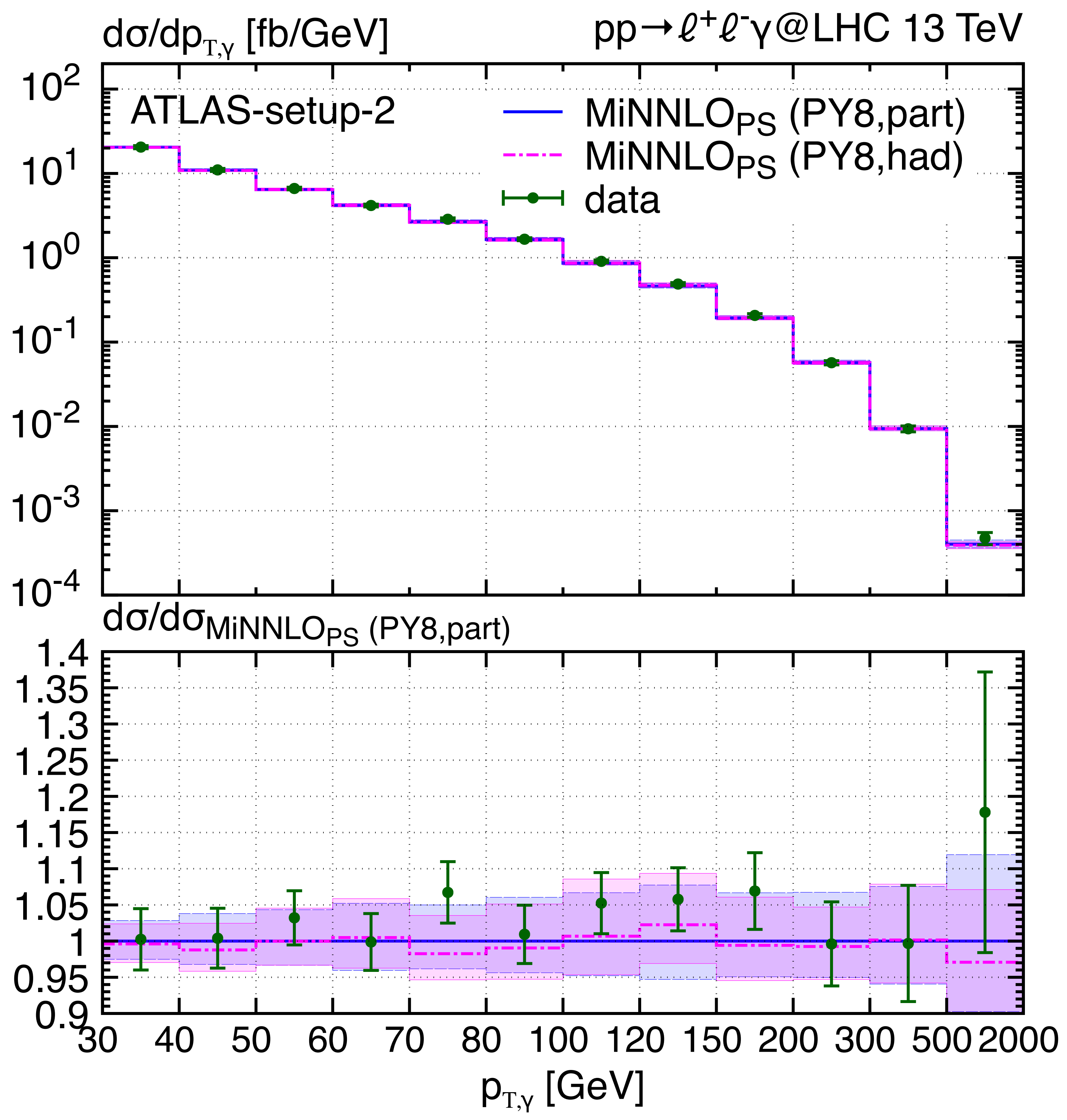
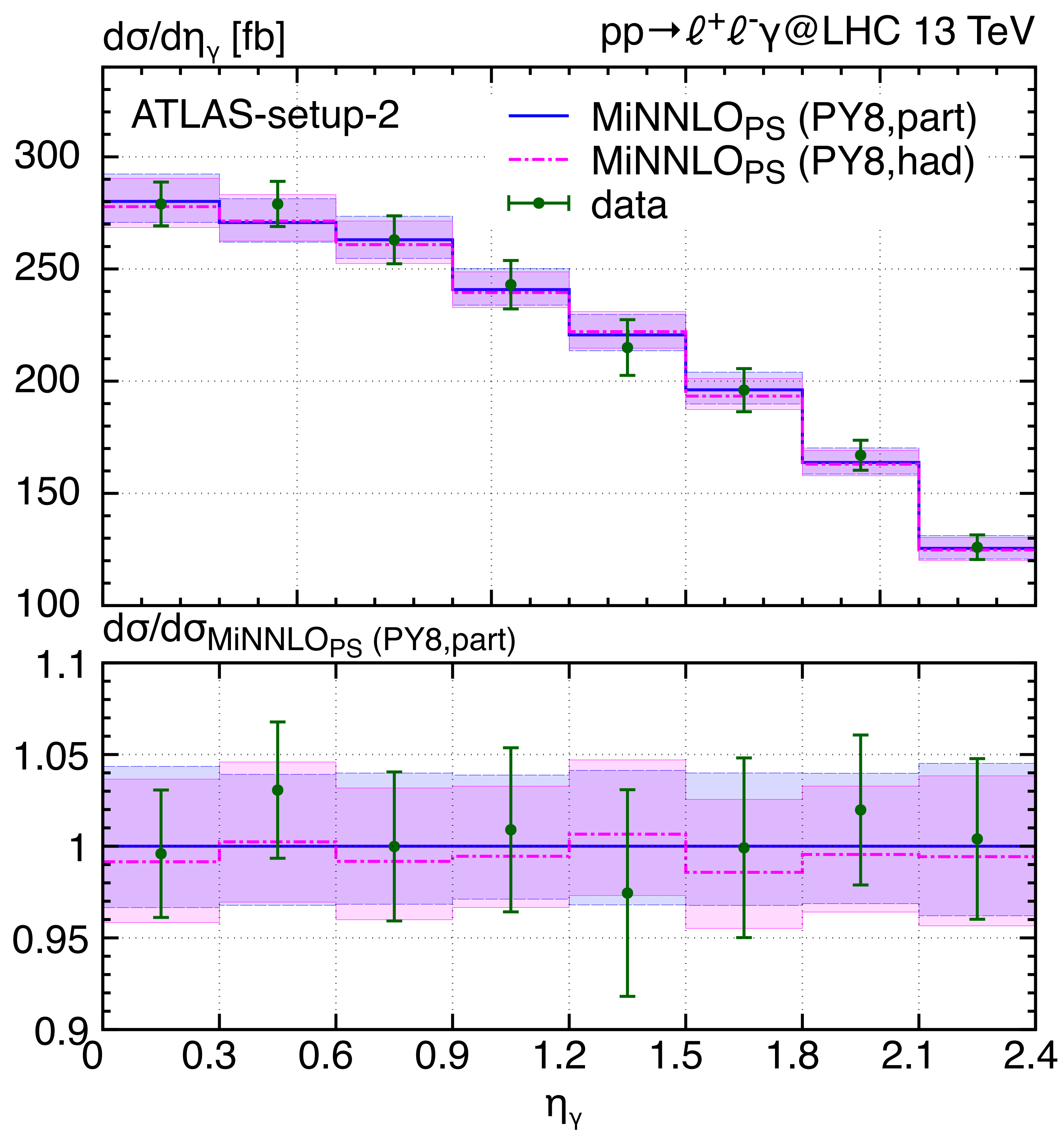
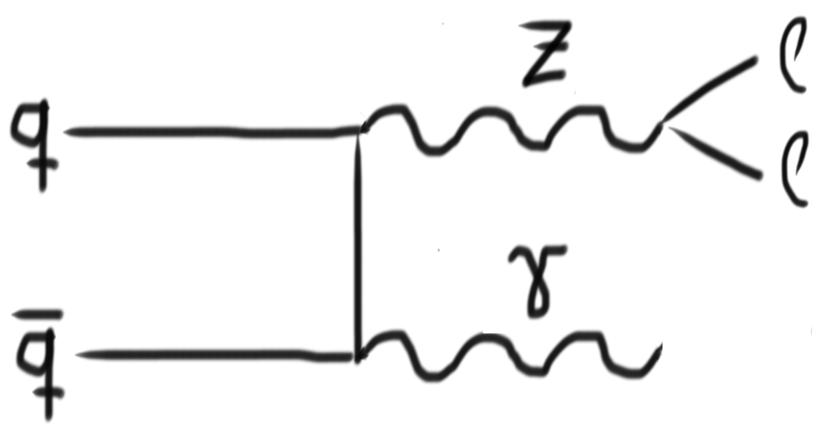


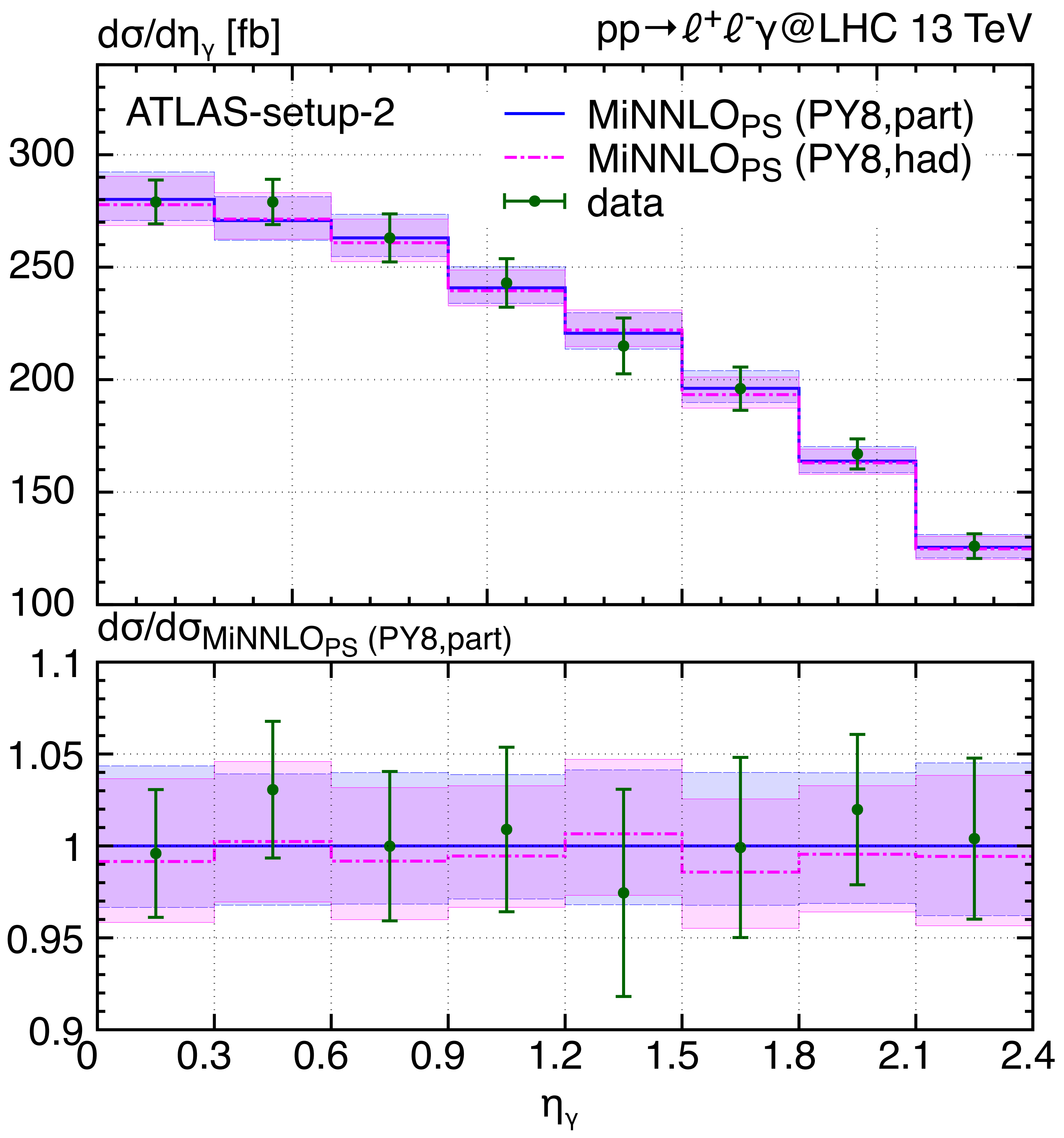


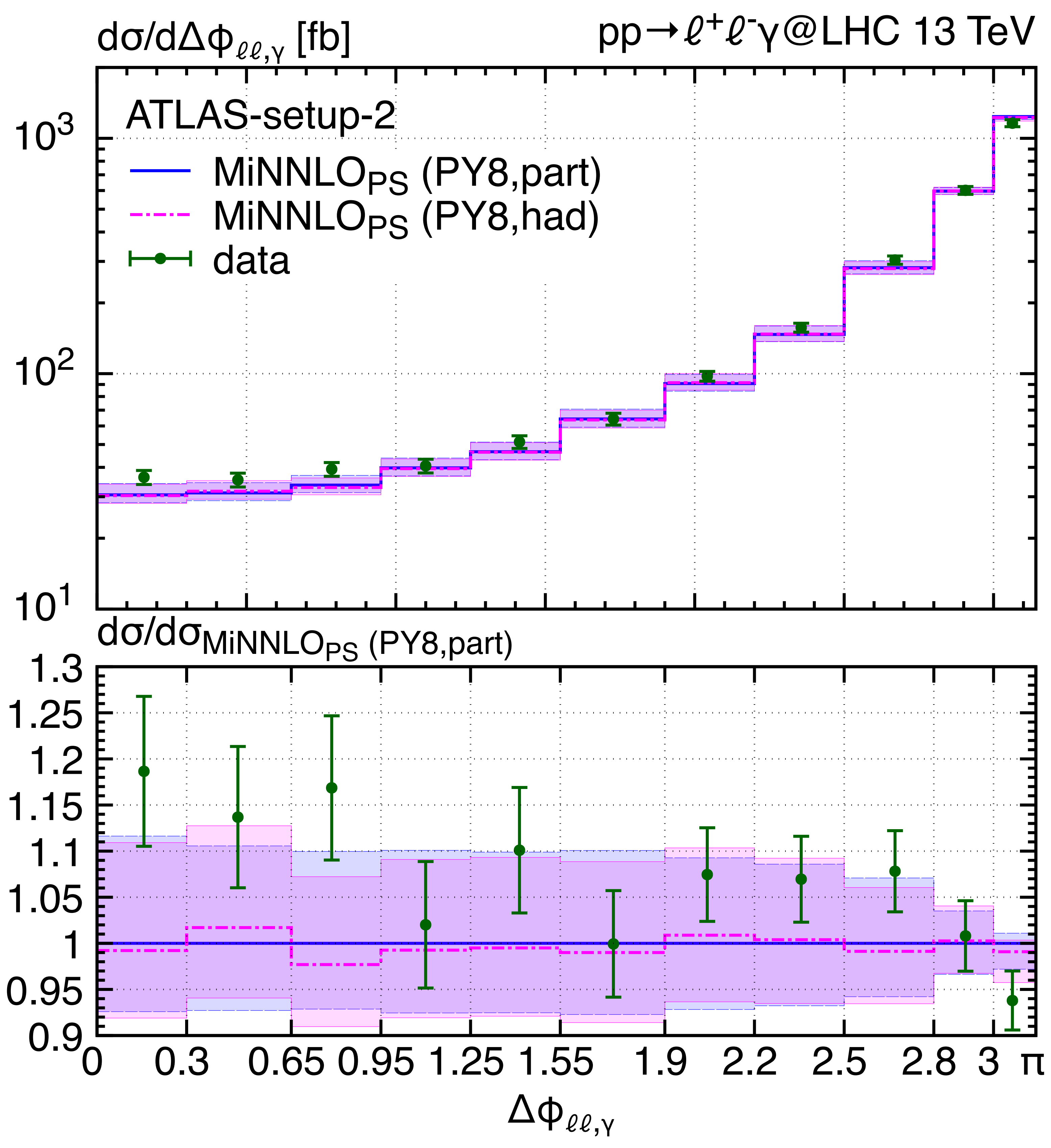


MiNNLOPS for 2→2 colour singlets

[Lombardi, MW, Zanderighi '20]







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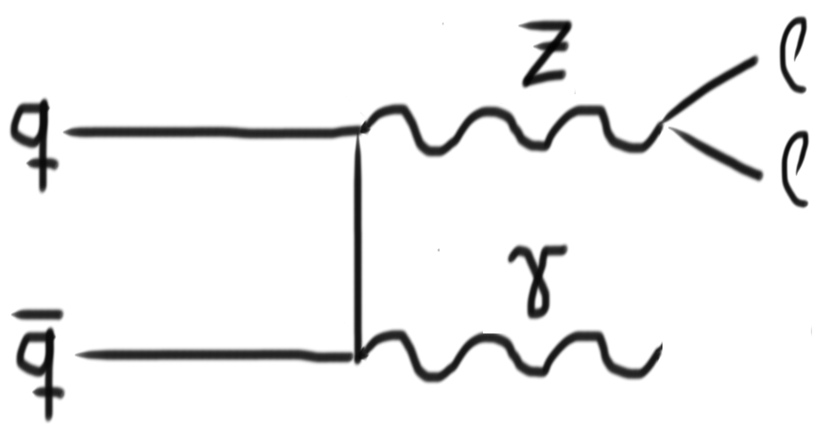
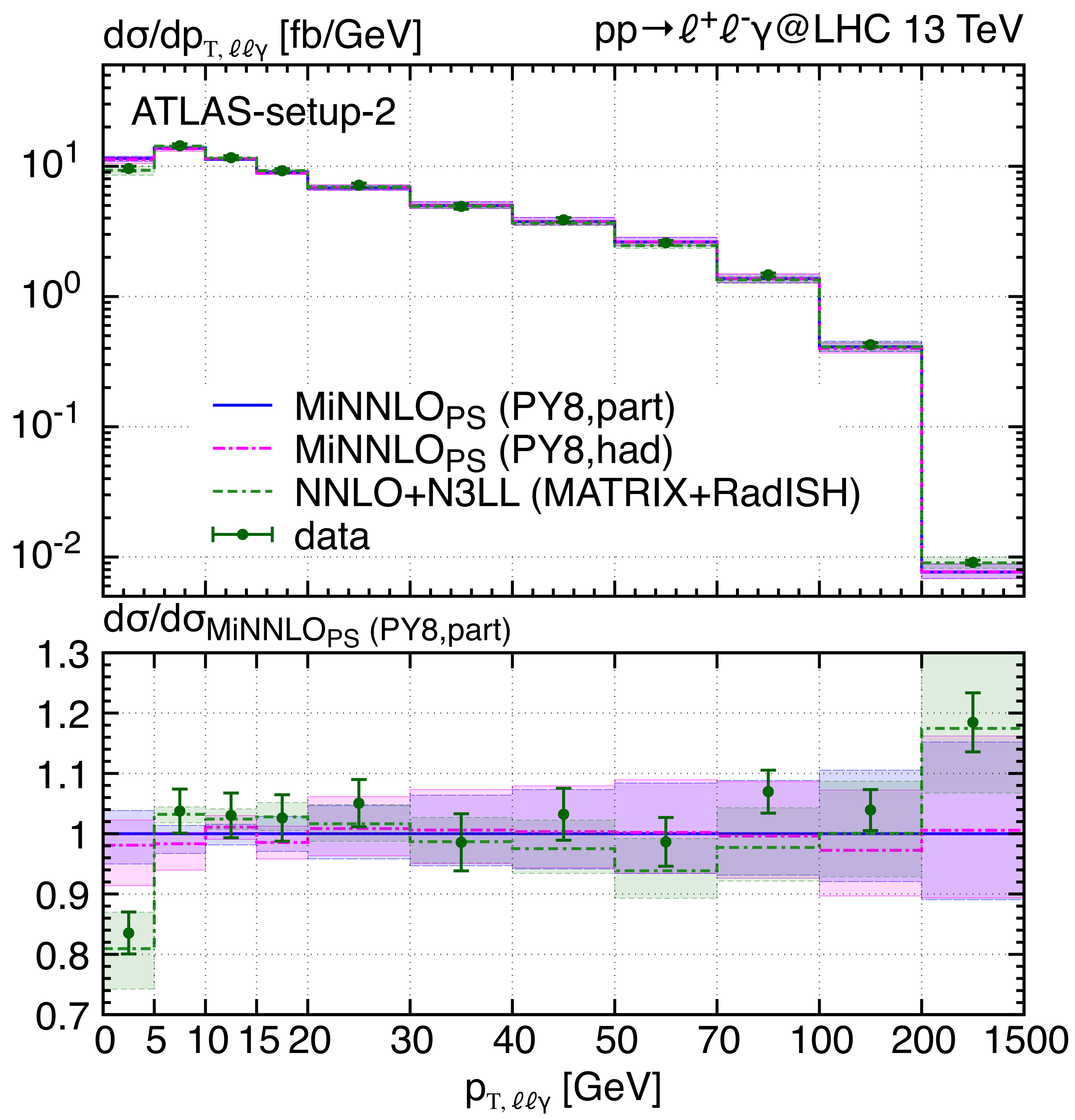
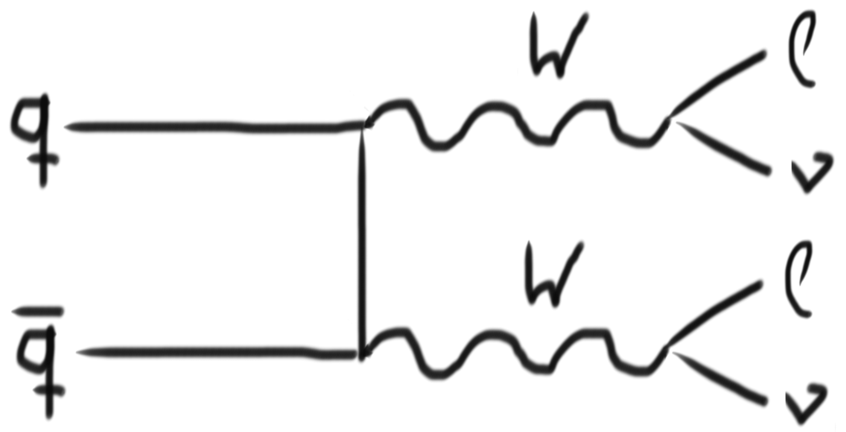




MiNNLOPS for 2→2 colour singlets

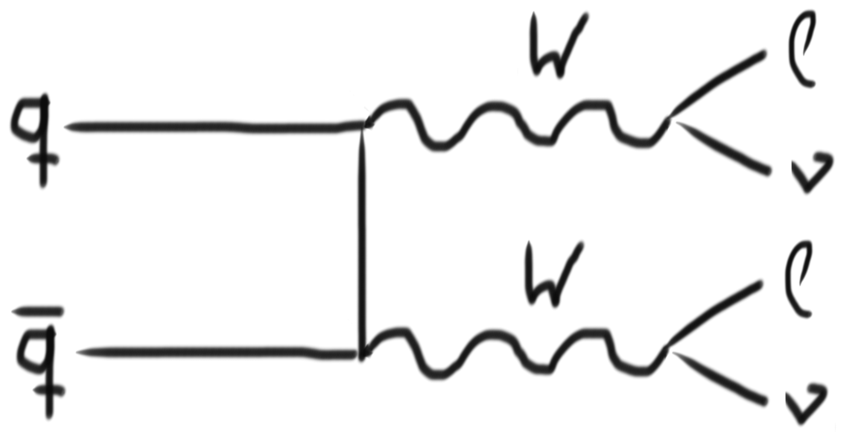
[Lombardi, MW, Zanderighi '21]



$\sigma(pp \to \ell^+\nu_\ell\,\ell'^-\nu_{\ell'})$ [fb]	`setup-inclusive`	`fiducial-1-JV`	`fiducial-2-JV`
MiNLO′	$1156.6(4)^{+5.4\%}_{-5.7\%}$	$185.0(2)^{+8.8\%}_{-6.5\%}$	$143.2(2)^{+4.9\%}_{-8.1\%}$
MiNNLOPS	$1292.2(7)^{+0.6\%}_{-0.7\%}$	$207.7(2)^{+1.6\%}_{-1.7\%}$	$159.2(4)^{+1.0\%}_{-1.4\%}$
NNLOPS *[arXiv:1805.09857]*	$1308.9(3)^{+1.7\%}_{-1.6\%}$	$206.4(1)^{+2.2\%}_{-2.3\%}$	$159.0(1)^{+1.7\%}_{-1.8\%}$
NNLO $\mu_0 = (m_{\mathrm{T},W^+} + m_{\mathrm{T},W^-})/2$	$1306.5(5)^{+1.6\%}_{-1.6\%}$	$206.5(1)^{+1.0\%}_{-0.7\%}$	$158.9(5)^{+0.8\%}_{-0.6\%}$
NNLO $\mu_0 = m_{\mathrm{T},WW}$	$1284.9(10)^{+1.4\%}_{-1.3\%}$	—	$160.8(3)^{+1.0\%}_{-0.8\%}$
ATLAS$-gg$ *[arXiv:1702.04519]*	$1481 \pm 59_{(\mathrm{stat})} \pm 154_{(\mathrm{syst})} \pm 108_{(\mathrm{lumi})}$	$236.5 \pm 10_{(\mathrm{stat})} \pm 25_{(\mathrm{syst})} \pm 5.5_{(\mathrm{lumi})}$	—
ATLAS$-gg$ *[arXiv:1905.04242]*	—	—	$178.5 \pm 2.5_{(\mathrm{stat})} \pm 12.7_{(\mathrm{syst})} \pm 4_{(\mathrm{lumi})}$
CMS$-gg$ *[CMS-PAS-SMP-16-006]*	$1289 \pm 68_{(\mathrm{stat})}{}^{\pm 67(\mathrm{exp.\ syst})}_{\pm 76(\mathrm{th.\ syst})} \pm 42_{(\mathrm{lumi})}$	—	—
CMS$-gg$ *[arXiv:2009.00119]*	$1316 \pm 65_{(\mathrm{stat})} \pm 23_{(\mathrm{syst})} \pm 38_{(\mathrm{lumi})}$	—	—

MiNNLOPS for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]



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MiNNLOPS	$1292.2(7)^{+0.6\%}_{-0.7\%}$ 10 %	$207.7(2)^{+1.6\%}_{-1.7\%}$ 10 %	$159.2(4)^{+1.0\%}_{-1.4\%}$ 10 %
NNLOPS *[arXiv:1805.09857]*	$1308.9(3)^{+1.7\%}_{-1.6\%}$	$206.4(1)^{+2.2\%}_{-2.3\%}$	$159.0(1)^{+1.7\%}_{-1.8\%}$
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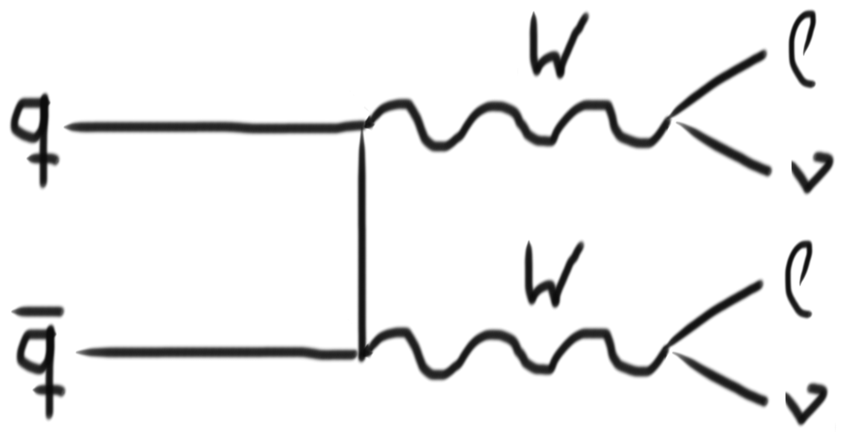
- *sizeable NNLO corrections + improved accuracy*

MiNNLOPS for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]



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NNLOPS *[arXiv:1805.09857]*	$1308.9(3)^{+1.7\%}_{-1.6\%}$ 1.3 %	$206.4(1)^{+2.2\%}_{-2.3\%}$	$159.0(1)^{+1.7\%}_{-1.8\%}$ 0.1 %
NNLO $\mu_0 = (m_{\mathrm{T},W^+} + m_{\mathrm{T},W^-})/2$	$1306.5(5)^{+1.6\%}_{-1.6\%}$	$206.5(1)^{+1.0\%}_{-0.7\%}$	$158.9(5)^{+0.8\%}_{-0.6\%}$
NNLO $\mu_0 = m_{\mathrm{T},WW}$	$1284.9(10)^{+1.4\%}_{-1.3\%}$ 1.7 %	—	$160.8(3)^{+1.0\%}_{-0.8\%}$ 1.2 %
ATLAS−gg *[arXiv:1702.04519]*	$1481 \pm 59_{\text{(stat)}} \pm 154_{\text{(syst)}} \pm 108_{\text{(lumi)}}$	$236.5 \pm 10_{\text{(stat)}} \pm 25_{\text{(syst)}} \pm 5.5_{\text{(lumi)}}$	—
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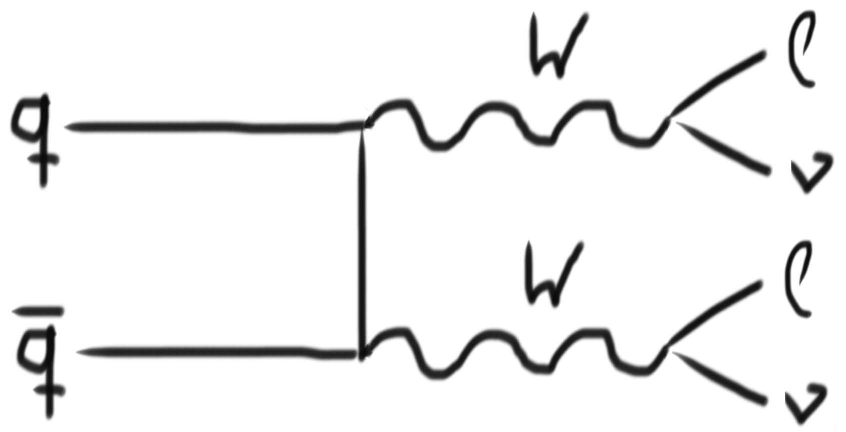
CMS−gg *[arXiv:2009.00119]*	$1316 \pm 65_{\text{(stat)}} \pm 23_{\text{(syst)}} \pm 38_{\text{(lumi)}}$	—	—

- *sizeable NNLO corrections + improved accuracy*
- *good agreement among NNLO predictions (differences induced by scale settings)*

MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]



$\sigma(pp \to \ell^+\nu_\ell\,\ell'^-\nu_{\ell'})$ [fb]	setup-inclusive	fiducial-1-JV	fiducial-2-JV
MINLO′	$1156.6(4)^{+5.4\%}_{-5.7\%}$	$185.0(2)^{+8.8\%}_{-6.5\%}$	$143.2(2)^{+4.9\%}_{-8.1\%}$
MINNLO$_{\rm PS}$	$1292.2(7)^{+0.6\%}_{-0.7\%}$	$207.7(2)^{+1.6\%}_{-1.7\%}$	$159.2(4)^{+1.0\%}_{-1.4\%}$
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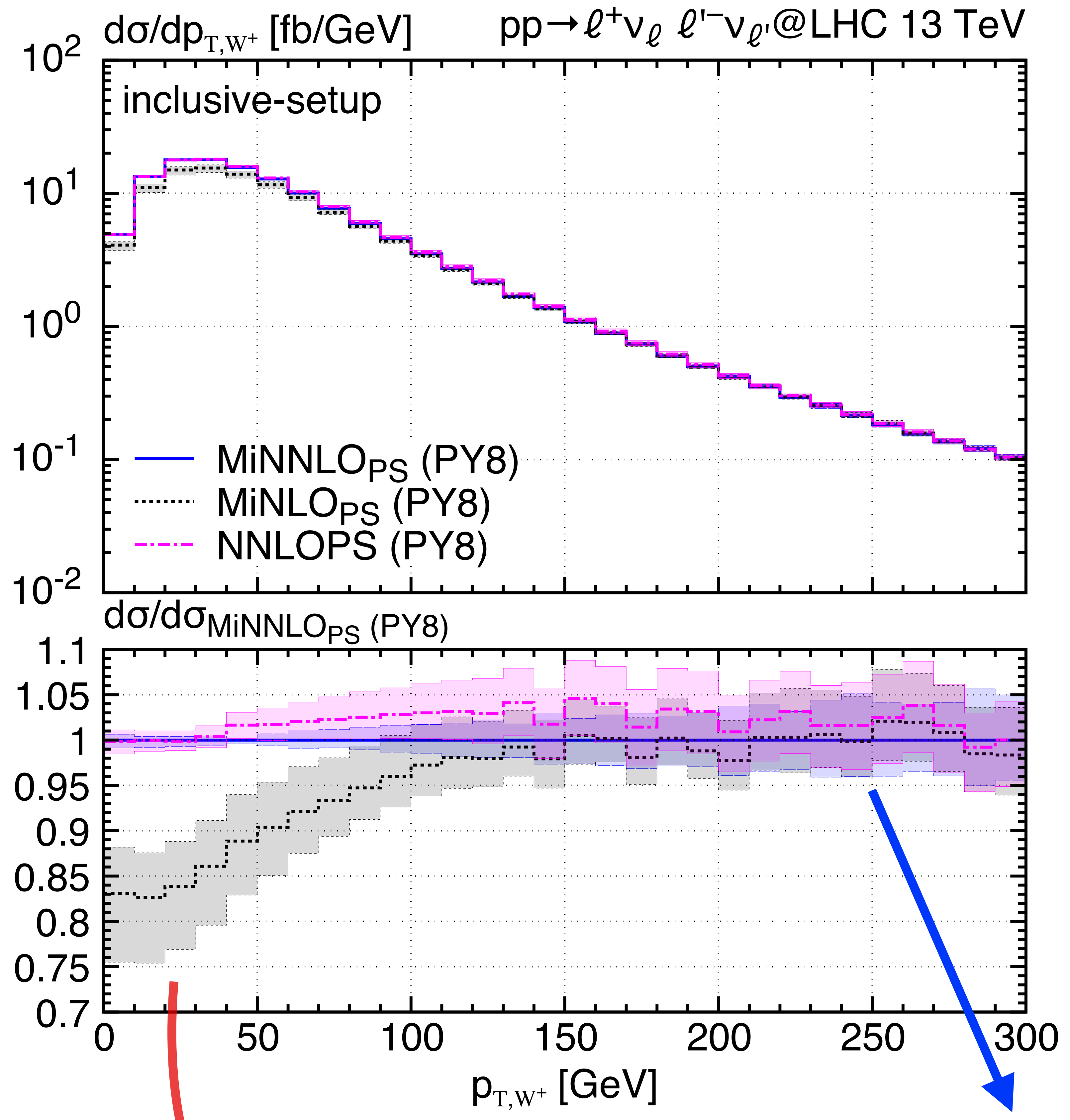
NNLO $\mu_0 = m_{\rm T,WW}$	$1284.9(10)^{+1.4\%}_{-1.3\%}$	—	$160.8(3)^{+1.0\%}_{-0.8\%}$
ATLAS$-gg$ *[arXiv:1702.04519]*	$1481 \pm 59_{\rm (stat)} \pm 154_{\rm (syst)} \pm 108_{\rm (lumi)}$	$236.5 \pm 10_{\rm (stat)} \pm 25_{\rm (syst)} \pm 5.5_{\rm (lumi)}$	—
ATLAS$-gg$ *[arXiv:1905.04242]*	—	—	$178.5 \pm 2.5_{\rm (stat)} \pm 12.7_{\rm (syst)} \pm 4_{\rm (lumi)}$
CMS$-gg$ *[CMS-PAS-SMP-16-006]*	$1289 \pm 68_{\rm (stat)}{}^{\pm 67 {\rm (exp.\,syst)}}_{\pm 76 {\rm (th.\,syst)}} \pm 42_{\rm (lumi)}$	—	—
CMS$-gg$ *[arXiv:2009.00119]*	$1316 \pm 65_{\rm (stat)} \pm 23_{\rm (syst)} \pm 38_{\rm (lumi)}$	—	—

- *sizeable NNLO corrections + improved accuracy*
- *good agreement among NNLO predictions (differences induced by scale settings)*
- *1-2 σ agreement with data in all setups*

MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]

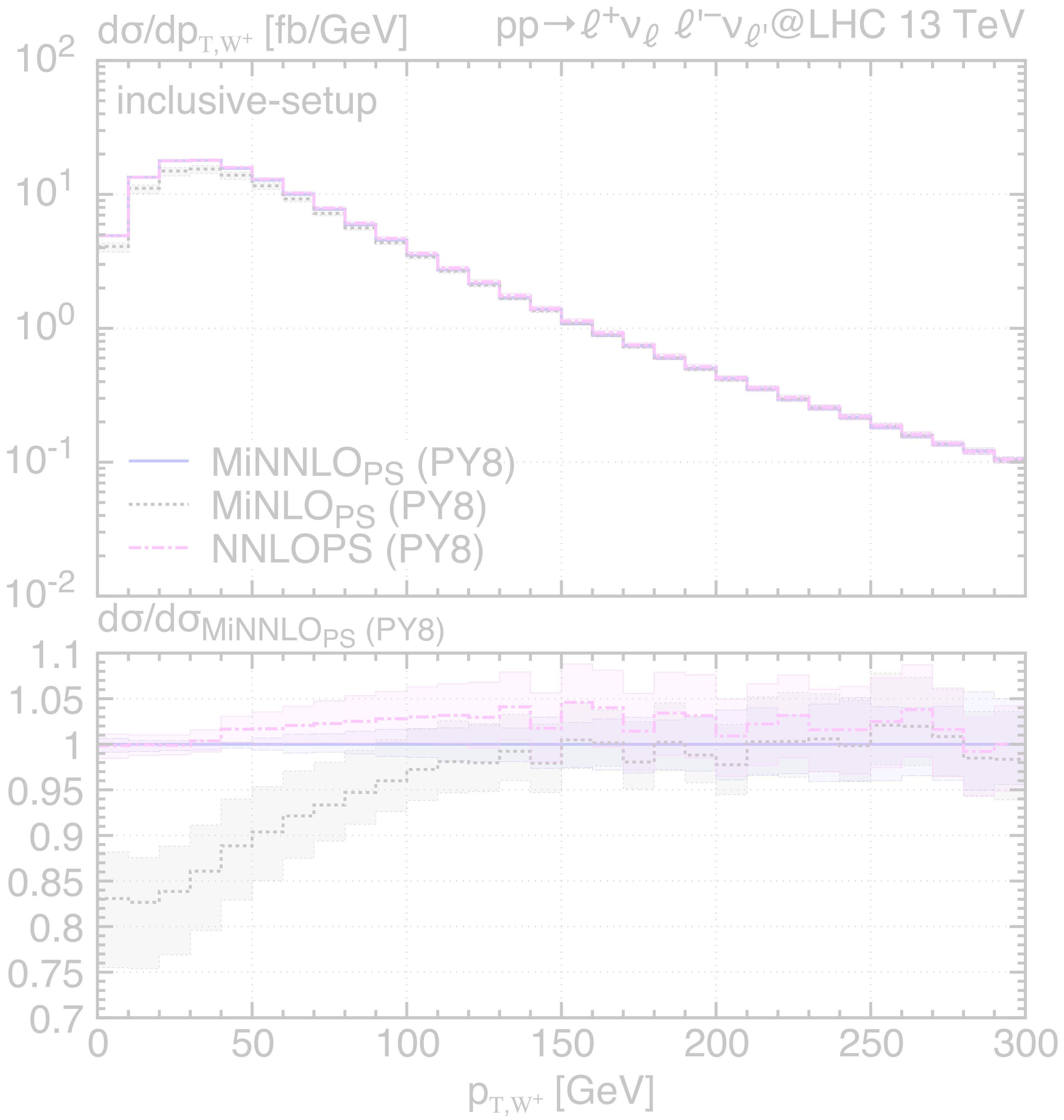


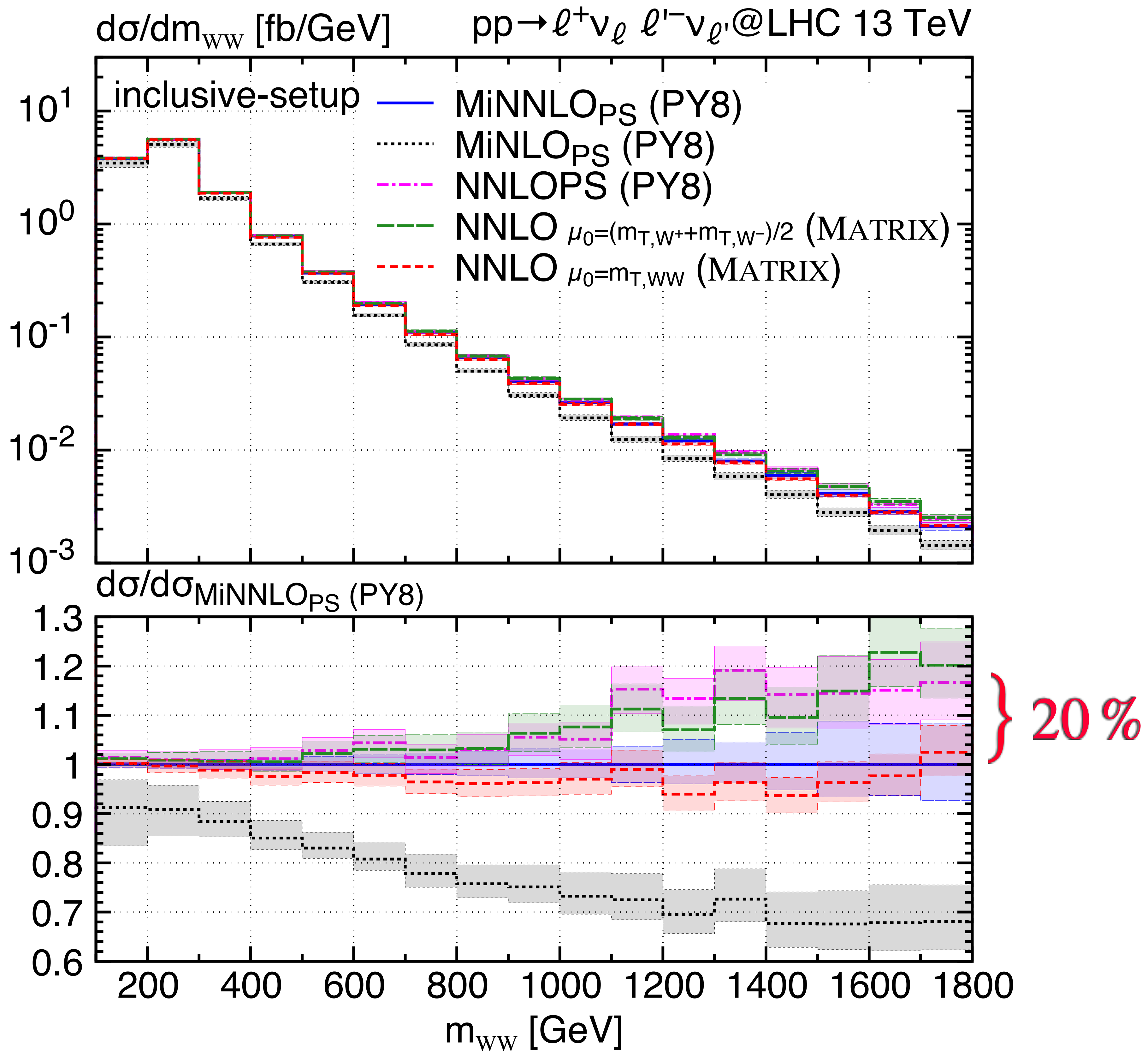
✓ *At high $p_{T,W+}$ NNLO+PS and MiNLO' predictions agree*

✓ *Improved description in the low $p_{T,W+}$ region (both normalisation and accuracy)*

MiNNLO$_{PS}$ for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]

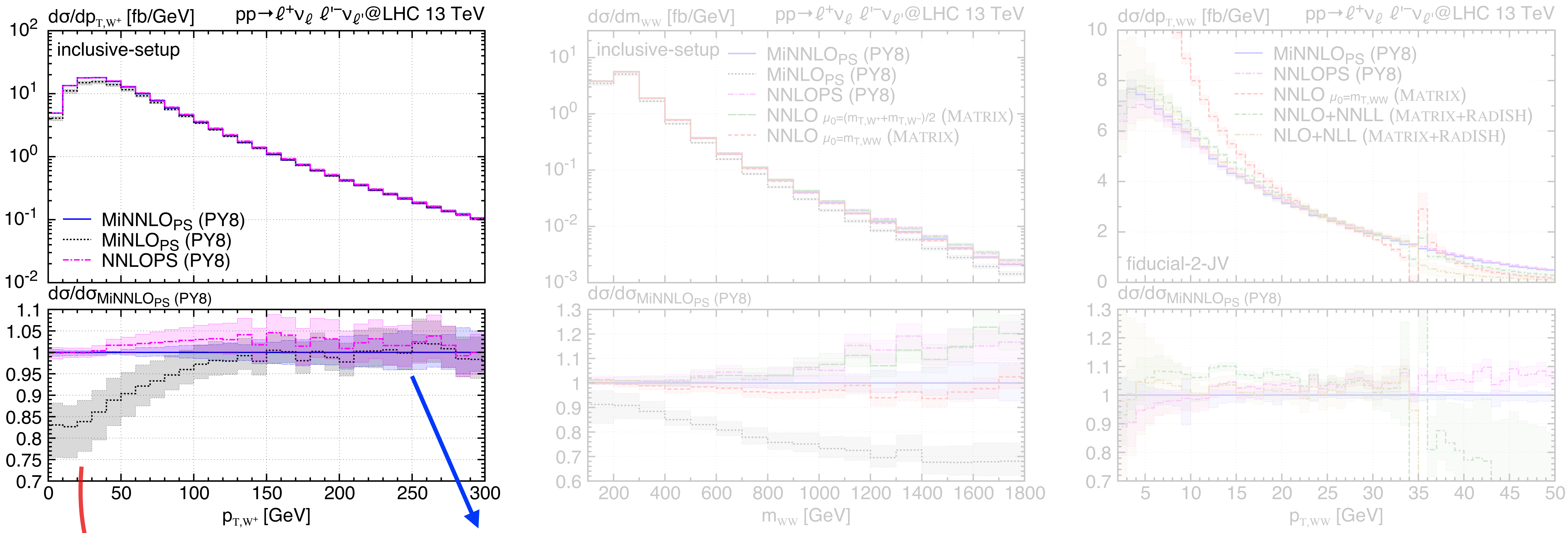




✓ *Different predictions between NNLOPS and MiNNLO$_{PS}$ at large m_{WW} due to scale settings*

MiNNLO$_{PS}$: $WW(\ell\nu\ell'\nu')$ production

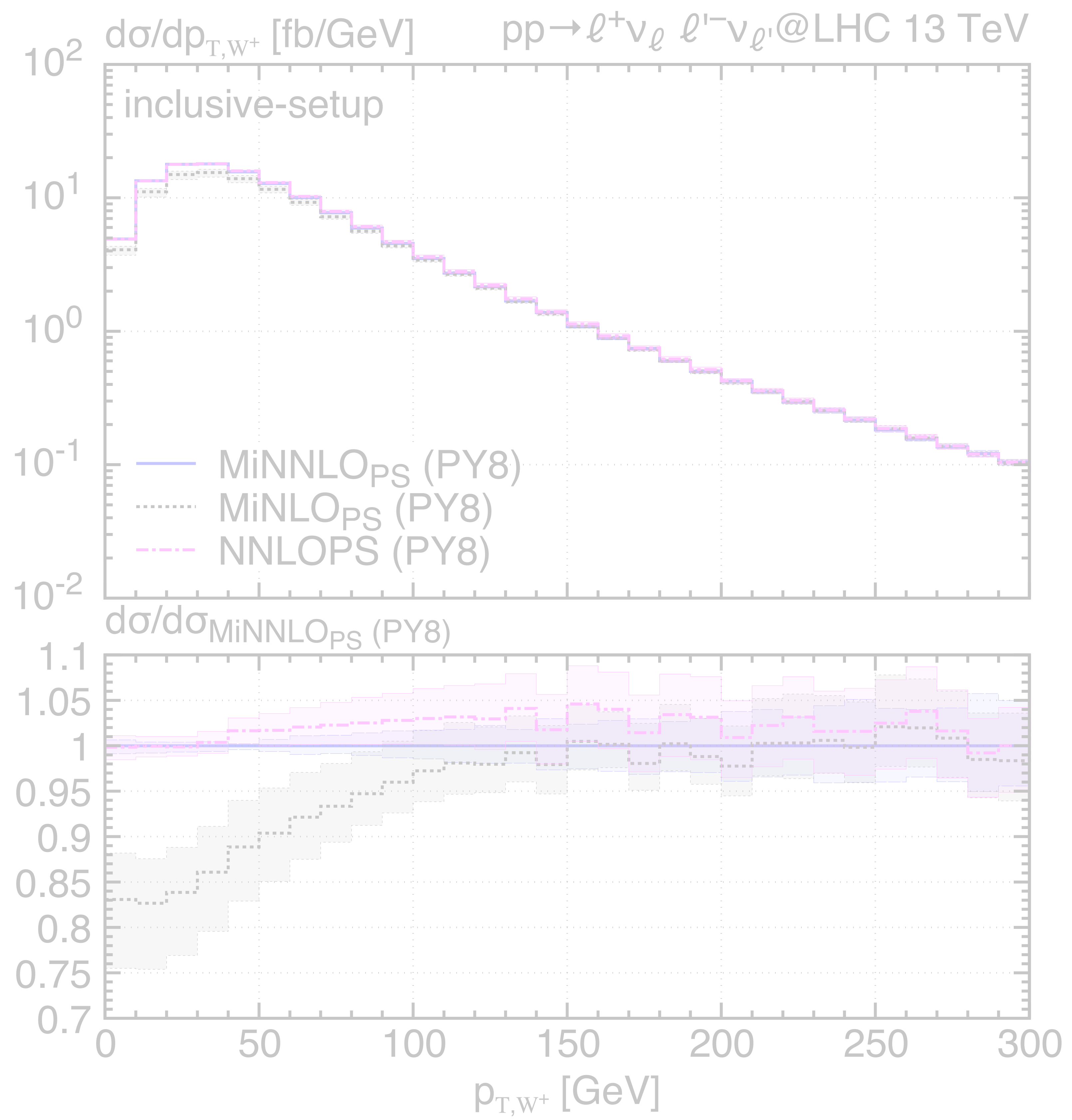
[Lombardi, MW, Zanderighi '21]

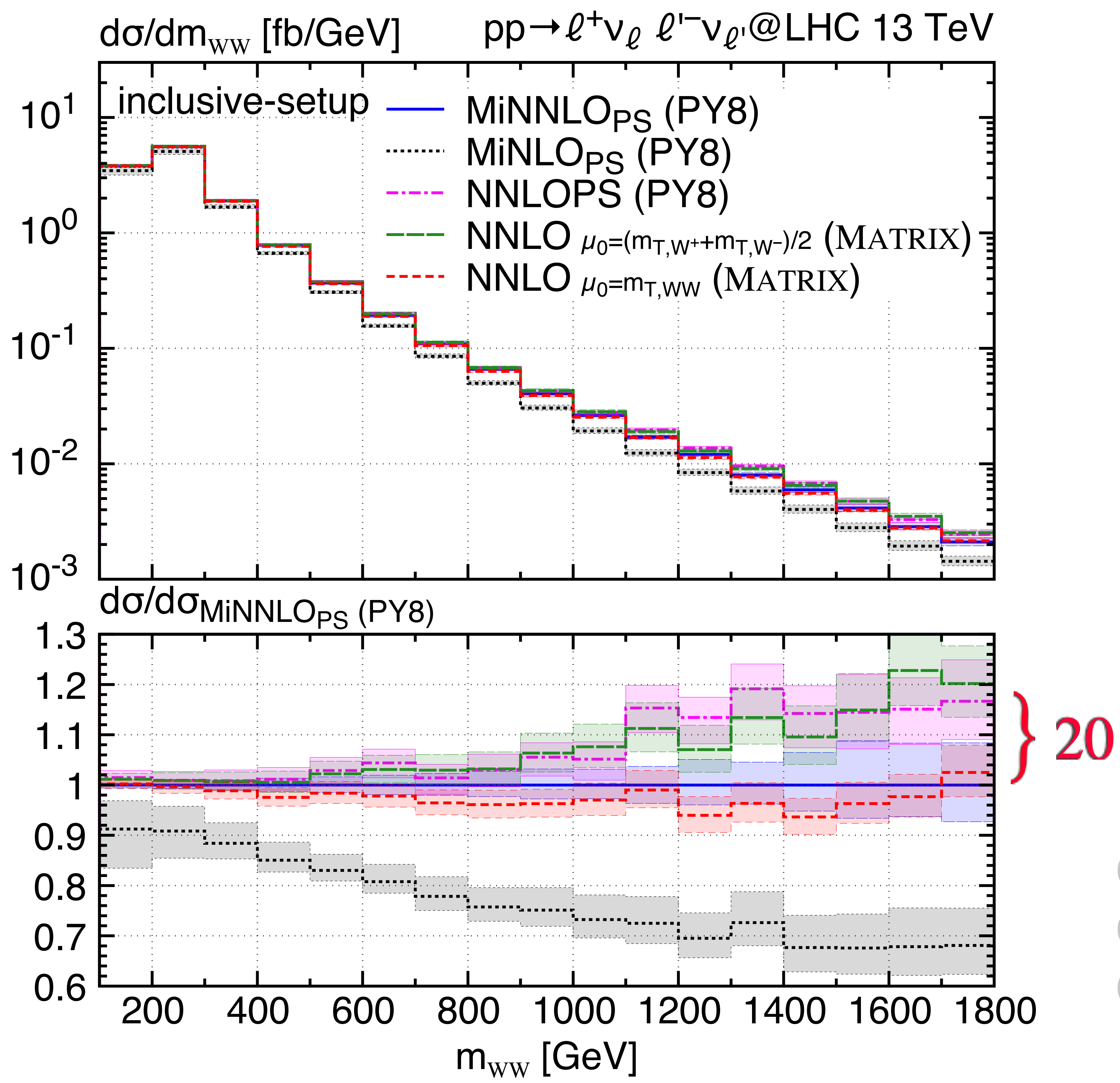


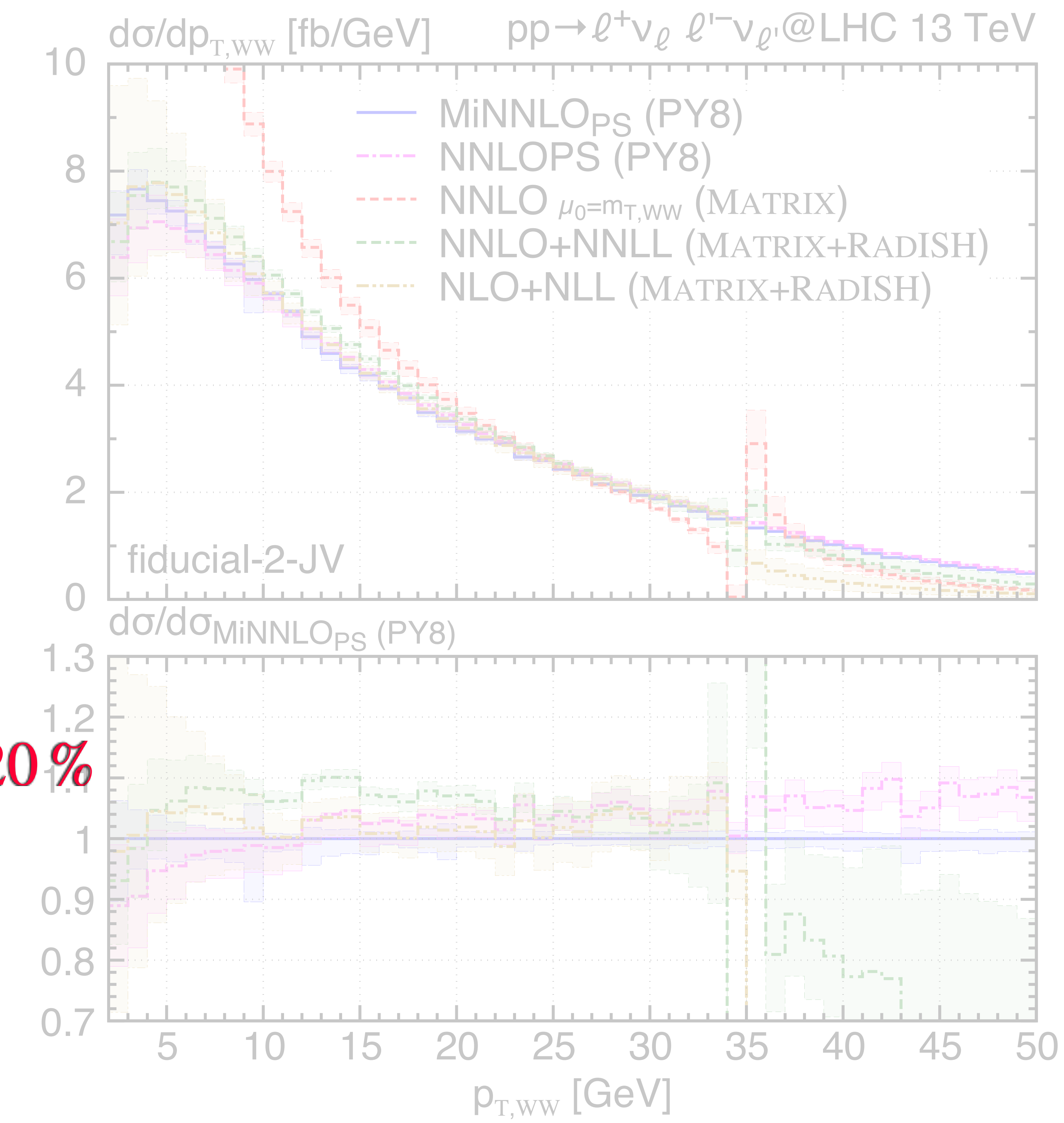
- ✓ *At high p_{T,W^+} NNLO+PS and MiNLO' predictions agree*
- ✓ *Improved description in the low p_{T,W^+} region (both normalisation and accuracy)*

$\textit{MiNNLO}_{PS}$: $WW\,(\ell\nu\ell'\nu')$ production

[Lombardi, MW, Zanderighi '21]



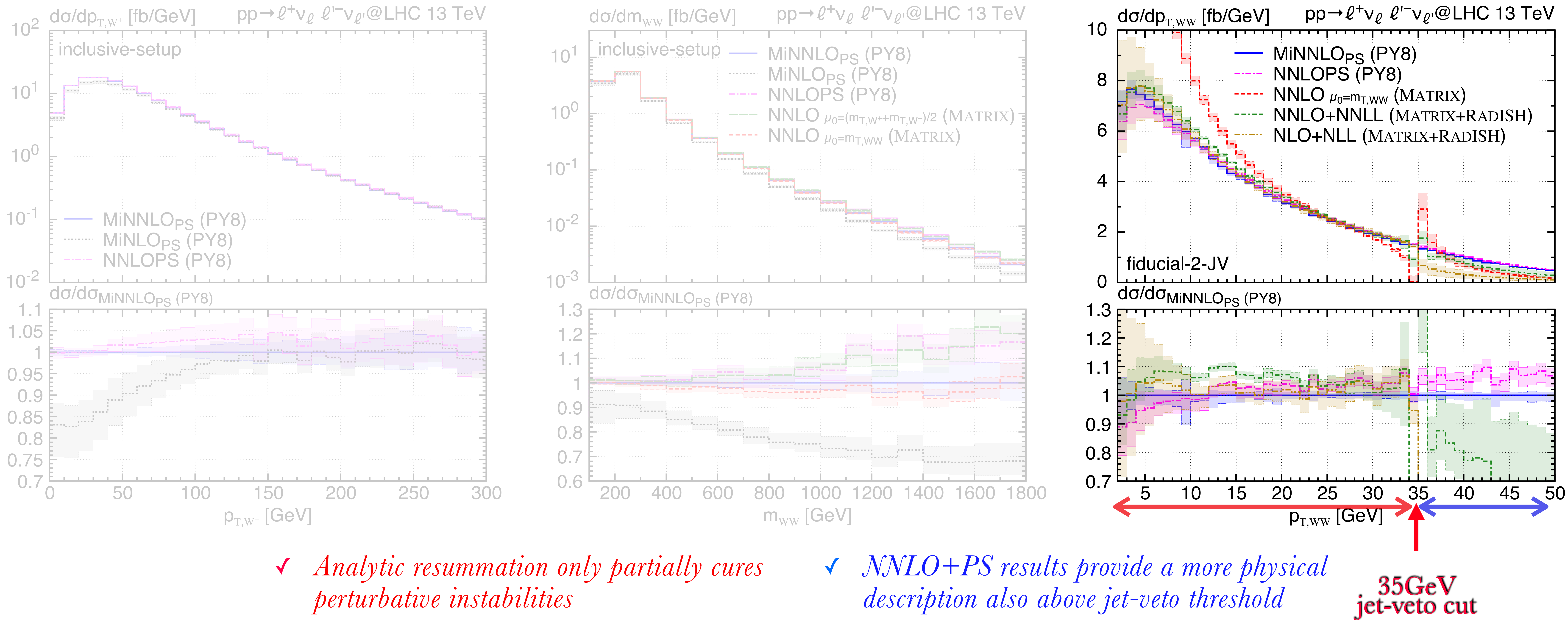




✓ *Different predictions between NNLOPS and $\textit{MiNNLO}_{PS}$ at large m_{WW} due to scale settings*

MiNNLO$_{PS}$: $WW\,(\ell\nu\ell'\nu')$ production

[Lombardi, MW, Zanderighi '21]

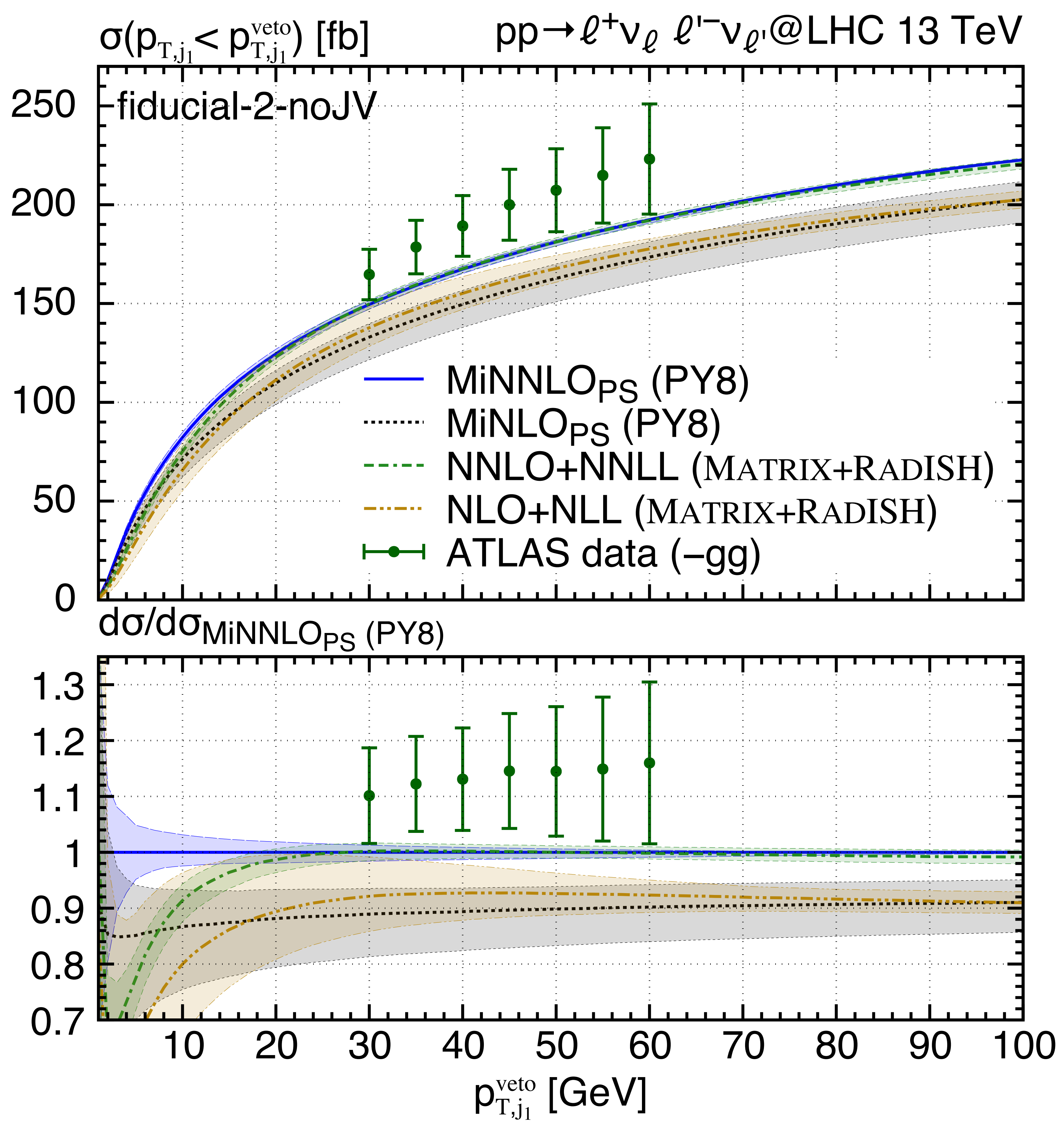


✓ *Analytic resummation only partially cures perturbative instabilities*

✓ *NNLO+PS results provide a more physical description also above jet-veto threshold*

MiNNLO$_{PS}$: $WW\,(\ell\nu\ell'\nu')$ production

[Lombardi, MW, Zanderighi '21]



$$\sigma(p_{\mathrm{T},j_1} < p_{\mathrm{T},j_1}^{\mathrm{veto}}) = \int_0^{p_{\mathrm{T},j_1}^{\mathrm{veto}}} \mathrm{d}p_{\mathrm{T},j_1} \, \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T},j_1}}$$

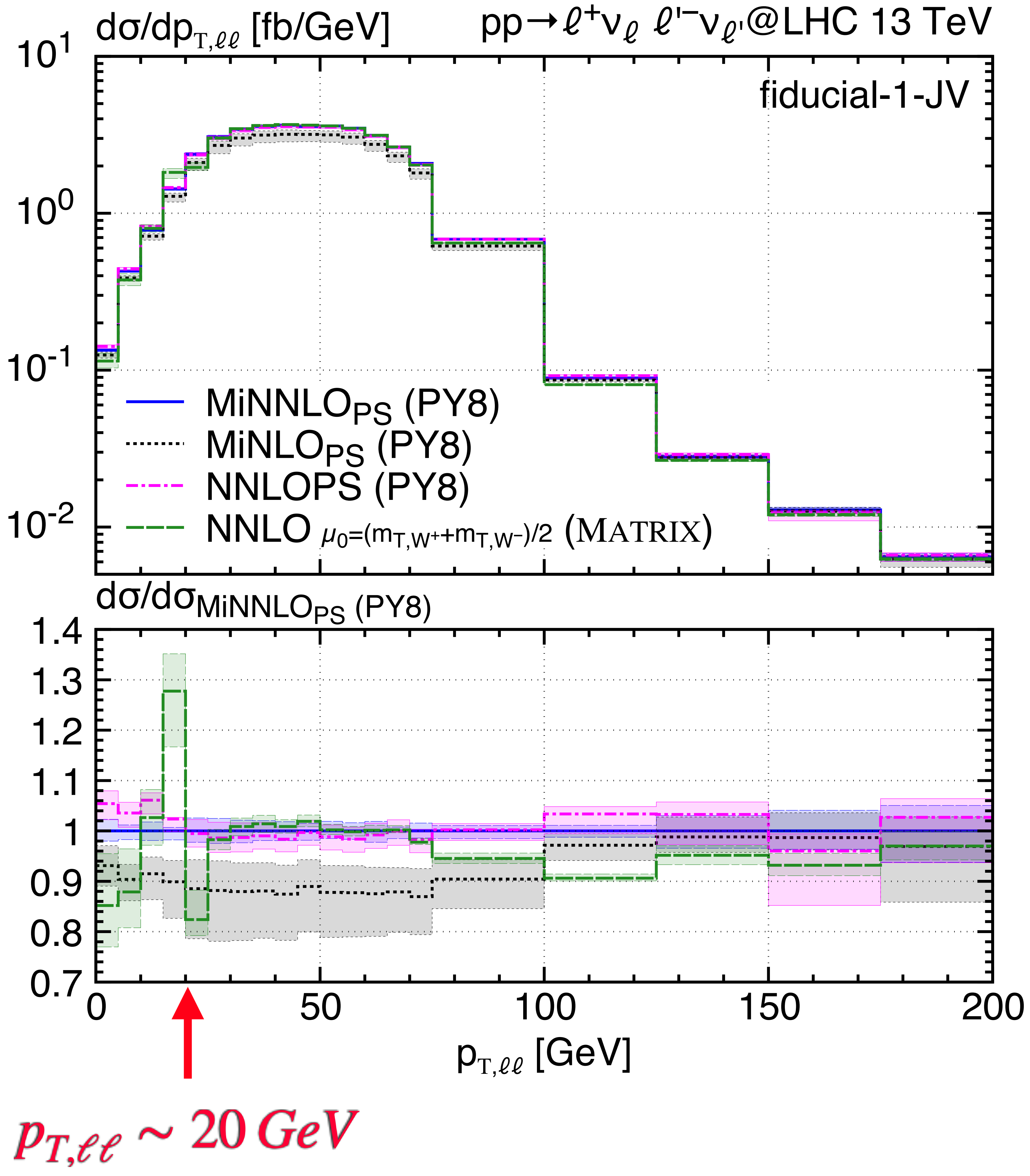
✓ *Excellent agreement between NNLOPS and resumed results down to typical veto-cuts*

✓ *Reasonable agreement to data (almost within one sigma) → relatively large dependence on choice of PDF set (not included in the uncertainty bands)*

MiNNLO$_{PS}$ for 2→2 colour singlets

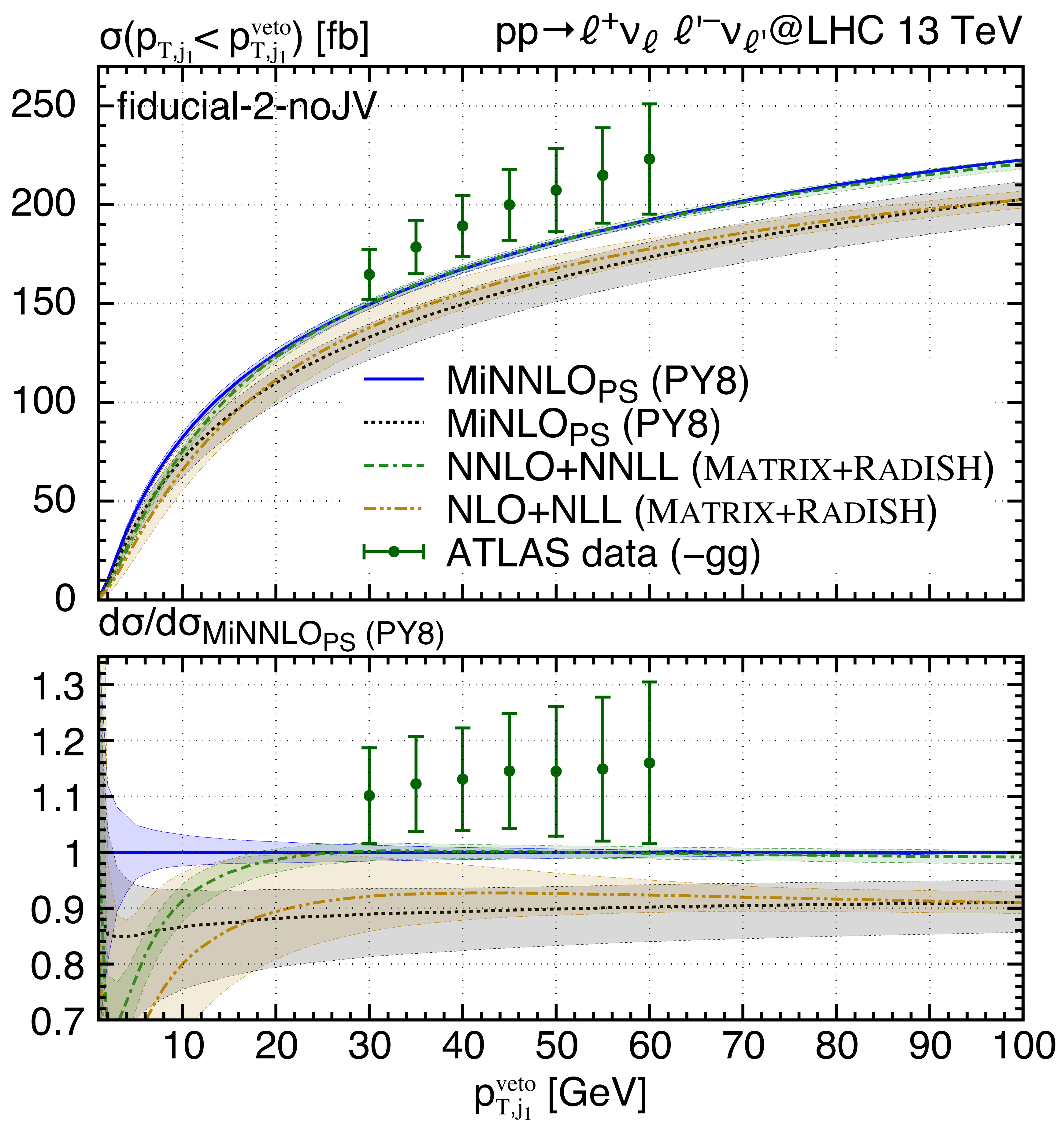
[Lombardi, MW, Zanderighi '21]

- ✓ *Normalization and accuracy improvement by including NNLO corrections*
- ✓ *Parton shower cures perturbative instabilities due to a fiducial $p_{T,miss}$ cut of 20GeV*



MiNNLOPS for 2→2 colour singlets

[Lombardi, MW, Zanderighi '21]



$$\sigma(p_{\mathrm{T},j_1} < p_{\mathrm{T},j_1}^{\mathrm{veto}}) = \int_0^{p_{\mathrm{T},j_1}^{\mathrm{veto}}} \mathrm{d}p_{\mathrm{T},j_1} \frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T},j_1}}$$

✓ *Excellent agreement between NNLOPS and resumed results down to typical veto-cuts*

✓ *Reasonable agreement to data (almost within one sigma) → relatively large dependence on choice of PDF set (not included in the uncertainty bands)*

Geneva: $ZZ\,(\ell\ell\ell'\ell')$ NNLO+PS

[Alioli et al. '21]

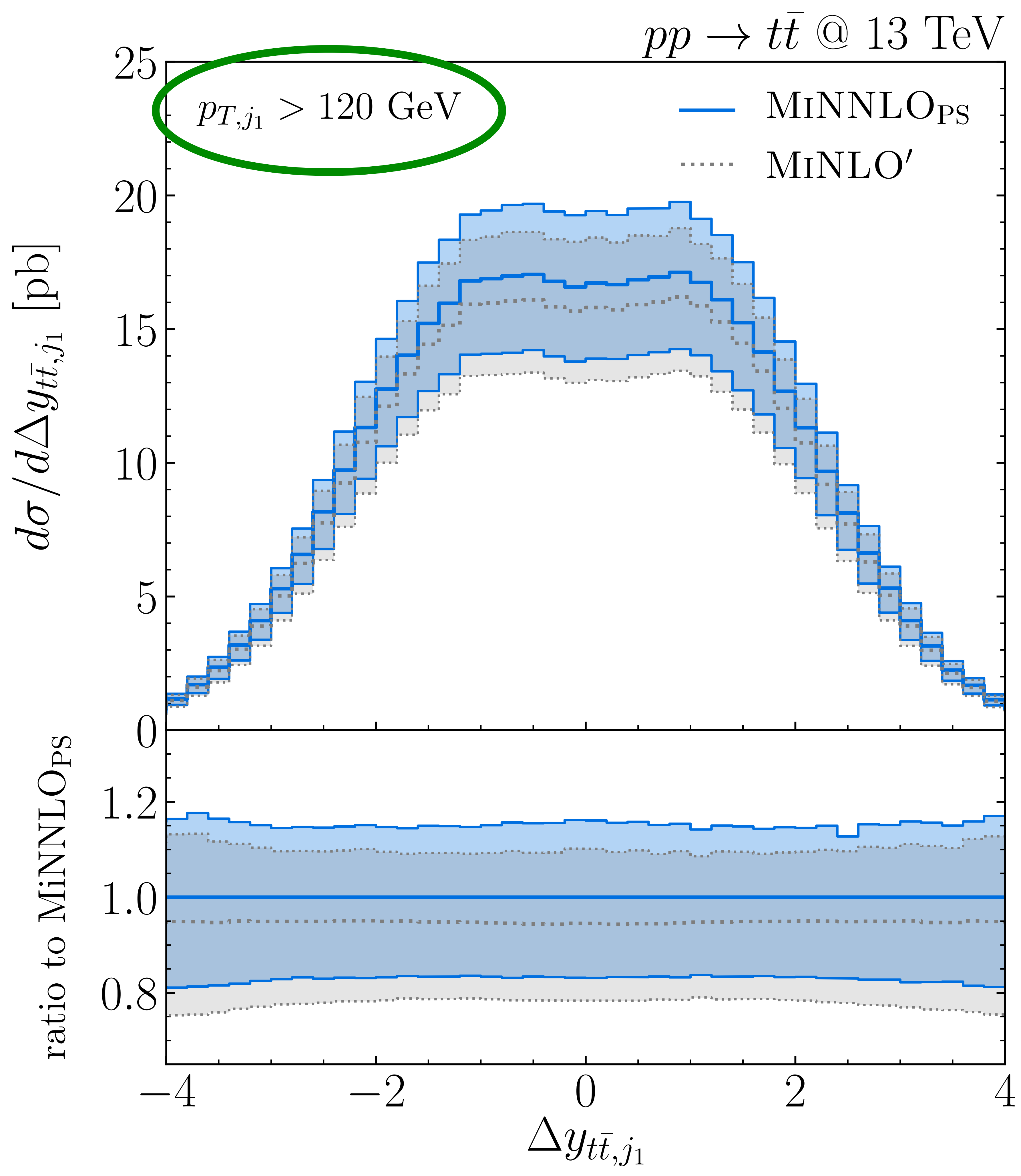
MiNNLO$_{PS}$: nNNLO+PS (x EW) for $ZZ\,(\ell\ell\ell'\ell')$

[Lombardi, MW, Zanderighi '21]

✓ *nNNLO+PS predictions in good agreement with CMS results, based on the a137fb^{-1} 13TeV analysis ([arXiv:2009.01186])!*

MiNNLO$_{\text{PS}}$ for $t\bar{t}$ production

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



- ✦ NLO accurate observable
- ✦ MiNNLO$_{\text{PS}}$ agrees well with MiNLO′
- ✦ shows that the way NNLO corrections included does not alter 1-jet observables (especially not in terms of shape)
- ✦ note: relatively large jet p_T threshold (not to become sensitive to NNLO effects)

MiNNLO$_{PS}$ for $t\bar{t}$ production

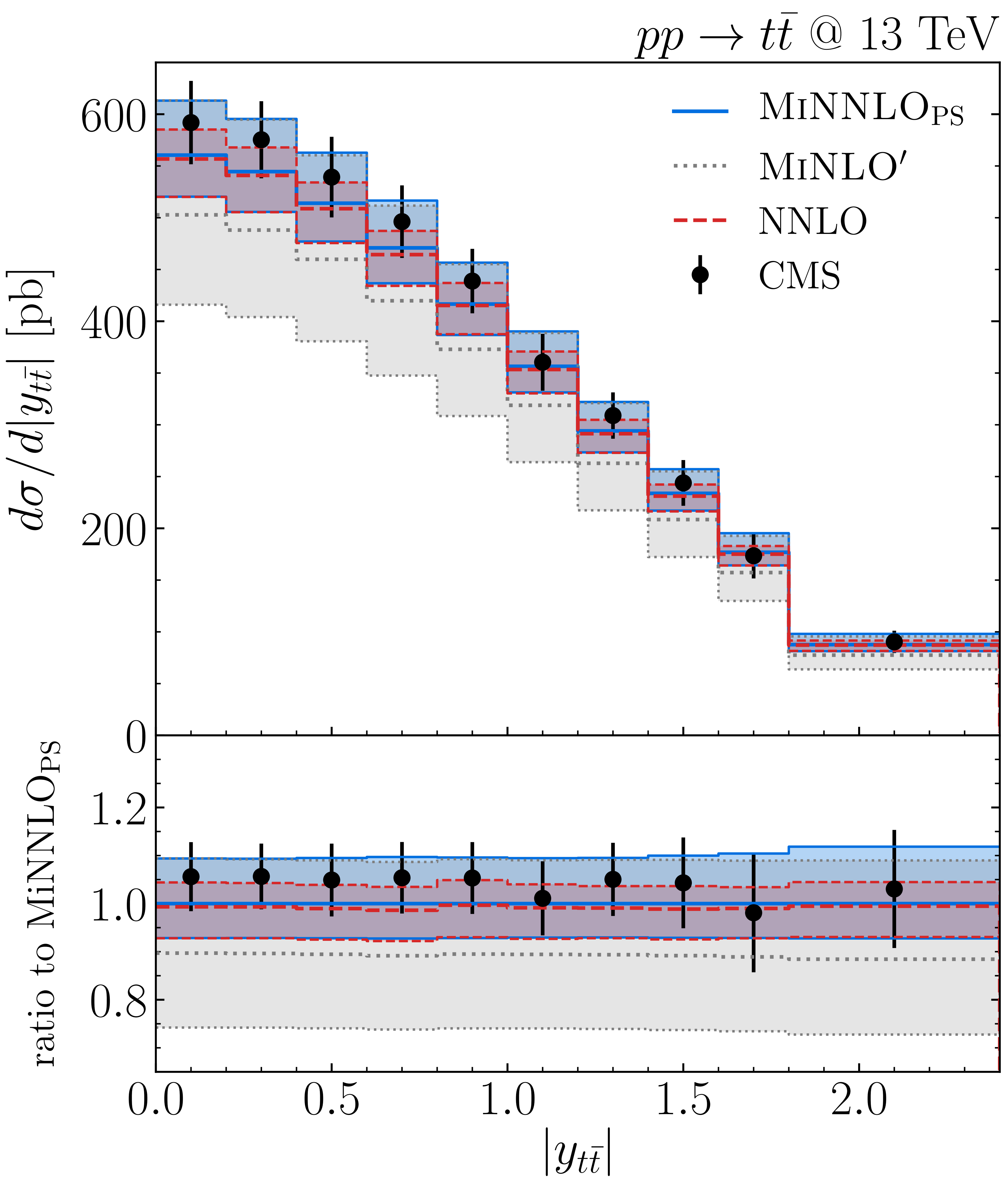
[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]

- total cross section:

MiNLO$'$	NNLO	MiNNLO$_{PS}$
$695.6(3)^{+22\%}_{-17\%}$ pb	$769.8(9)^{+5.0\%}_{-6.5\%}$ pb	$775.5(2)^{+9.8\%}_{-7.2\%}$ pb

MiNNLO$_{PS}$ and NNLO agree at permille level (note: different scale settings)

- excellent agreement of MiNNLO$_{PS}$ with NNLO for $t\bar{t}$ rapidity (especially in terms of shape)
- upper MiNNLO$_{PS}$ band slightly larger (reflects additional sources of scale variations)
- substantial reduction of scale uncertainties w.r.t. MiNLO$'$
- perfect agreement with CMS data



MiNNLOPS for t

[Mazzitelli, Monni, Nason, Re,

✦ total cross section:

MiNLO′	NNLO	MiNNLOPS
$695.6(3)^{+22\%}_{-17\%}$ pb	$769.8(9)^{+5.0\%}_{-6.5\%}$ pb	$775.5(2)^{+9.8\%}_{-7.2\%}$ pb

MiNLO′	NNLO	MiNNLOPS
$572.9(2)^{+21\%}_{-17\%}$ pb	$719.1(8)^{+7.0\%}_{-7.6\%}$ pb	$719.8(2)^{+7.6\%}_{-7.4\%}$ pb

✦ excellent agreement of MiNNLOPS with

N lly

in

overall factor in Born: $\alpha_s^2(m_{t\bar{t}})$

MiNNLOPS scales:

$\mu_R = \mu_F = m_{t\bar{t}}\, e^{-L}, Q = \dfrac{m_{t\bar{t}}}{2}$

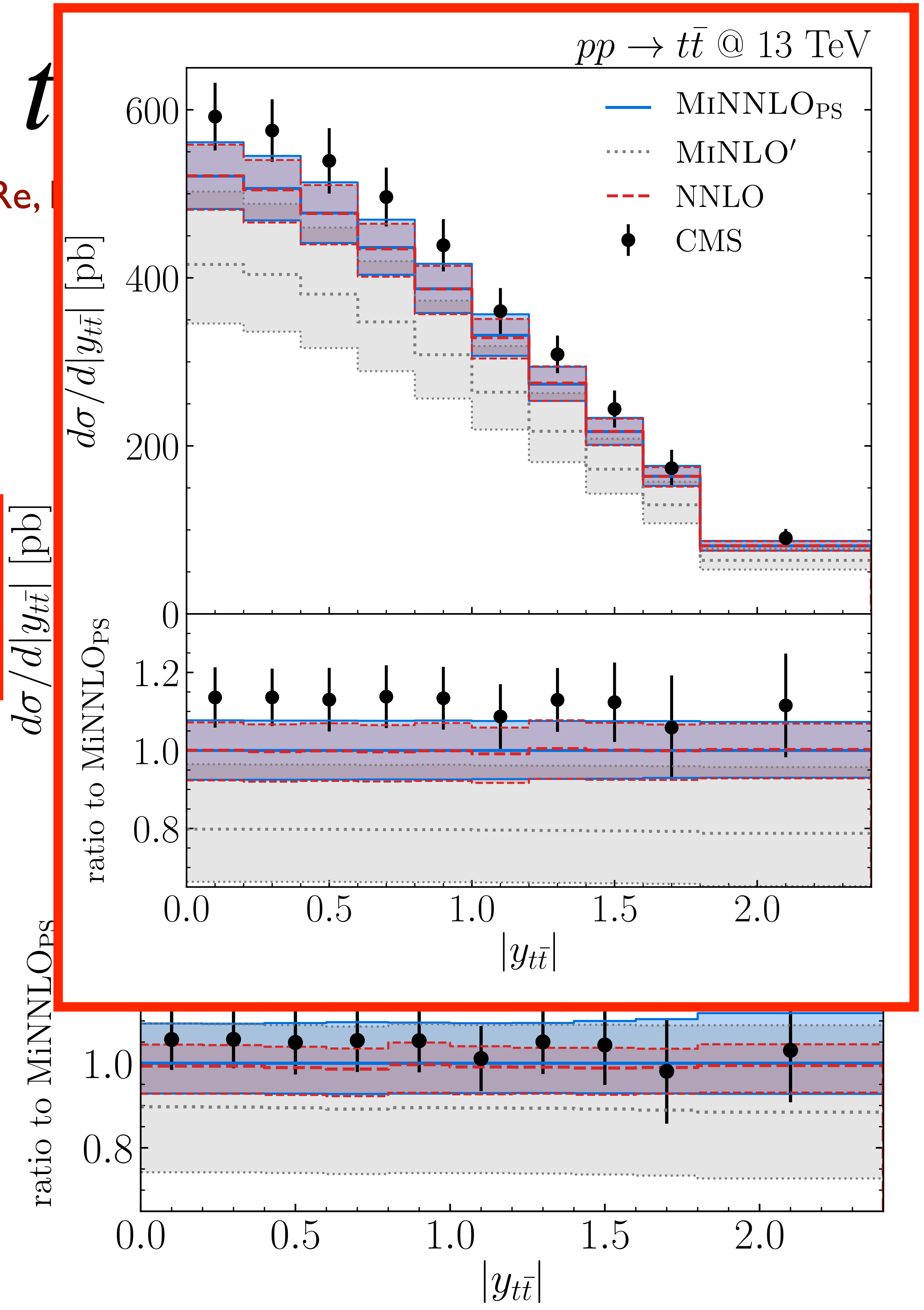
✦ up

(re)

✦ su es

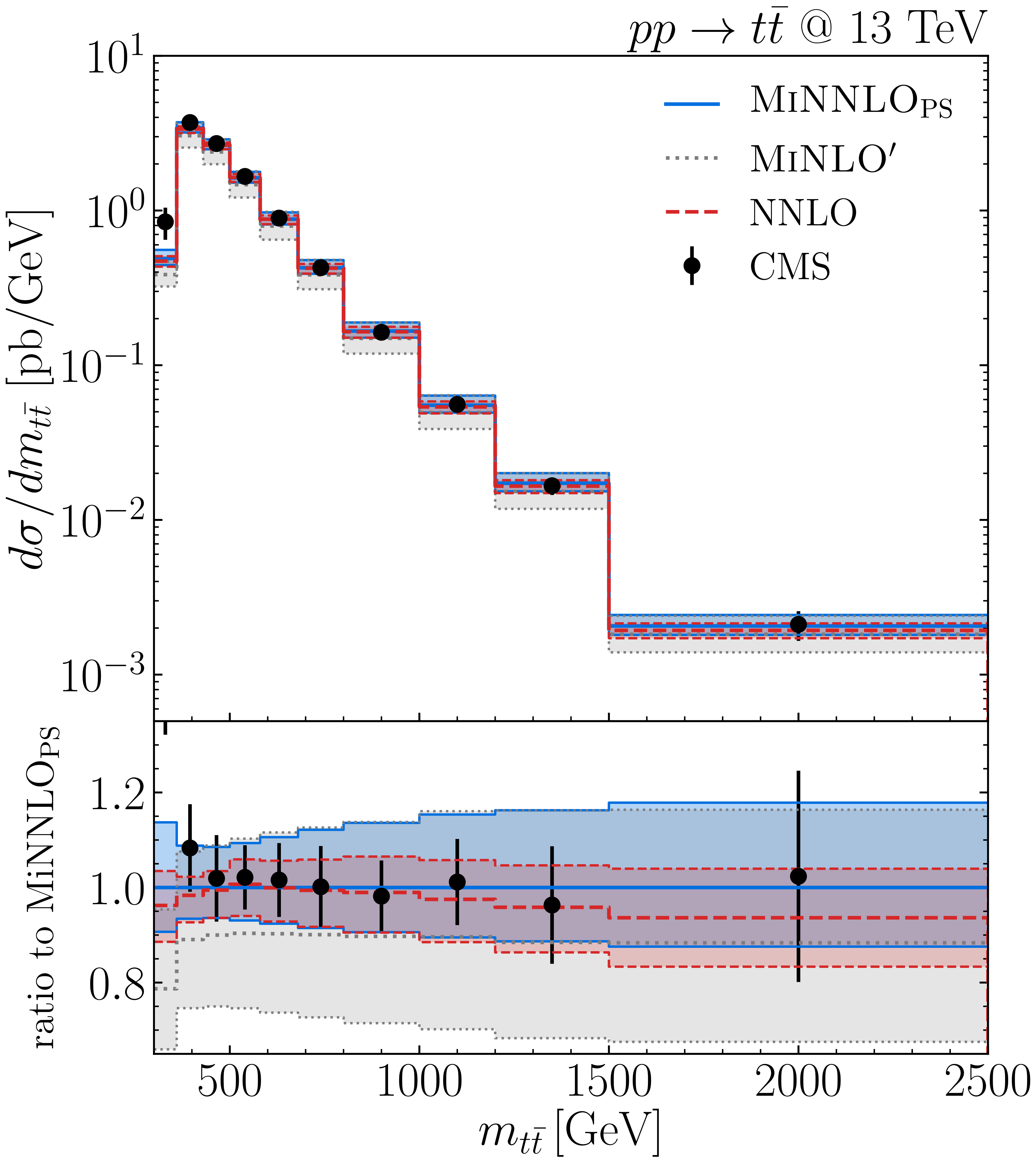
w.r.t. MiNLO

✦ perfect agreement with CMS data



MiNNLO$_{PS}$ for $t\bar{t}$ production

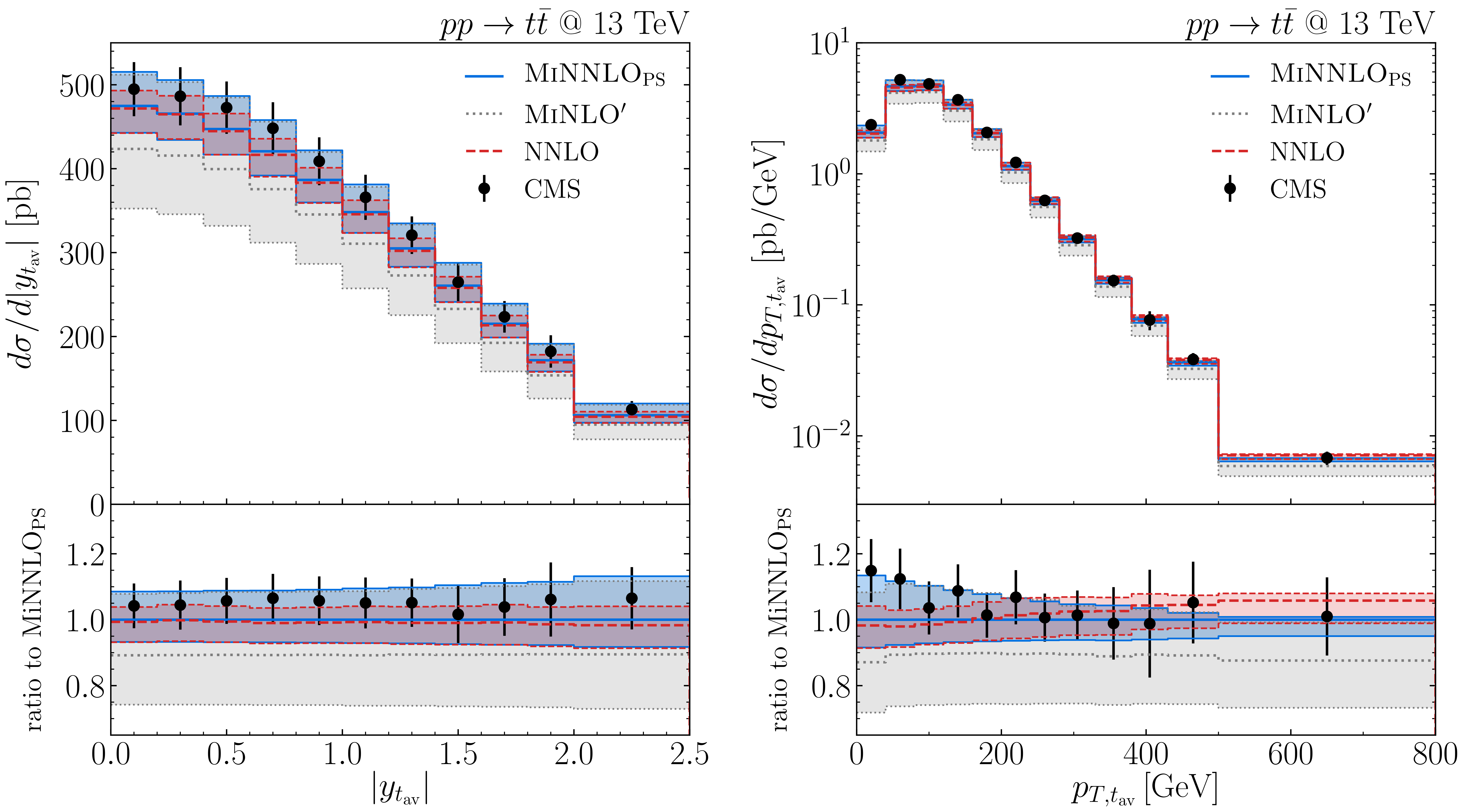
[Mazzitelli, Monni, Nason, Re, MW, Zanderighi '20]



- ✦ good description of measured $t\bar{t}$ invariant-mass spectrum
- ✦ except for first bin at $t\bar{t}$ threshold (finite width & non-relativistic effects)
- ✦ MiNNLO$_{PS}$ and NNLO compatible within uncertainties
- ✦ slightly different shape (different treatment of higher-order terms)
- ✦ slightly larger uncertainties in tail (reflects additional sources of scale variations)

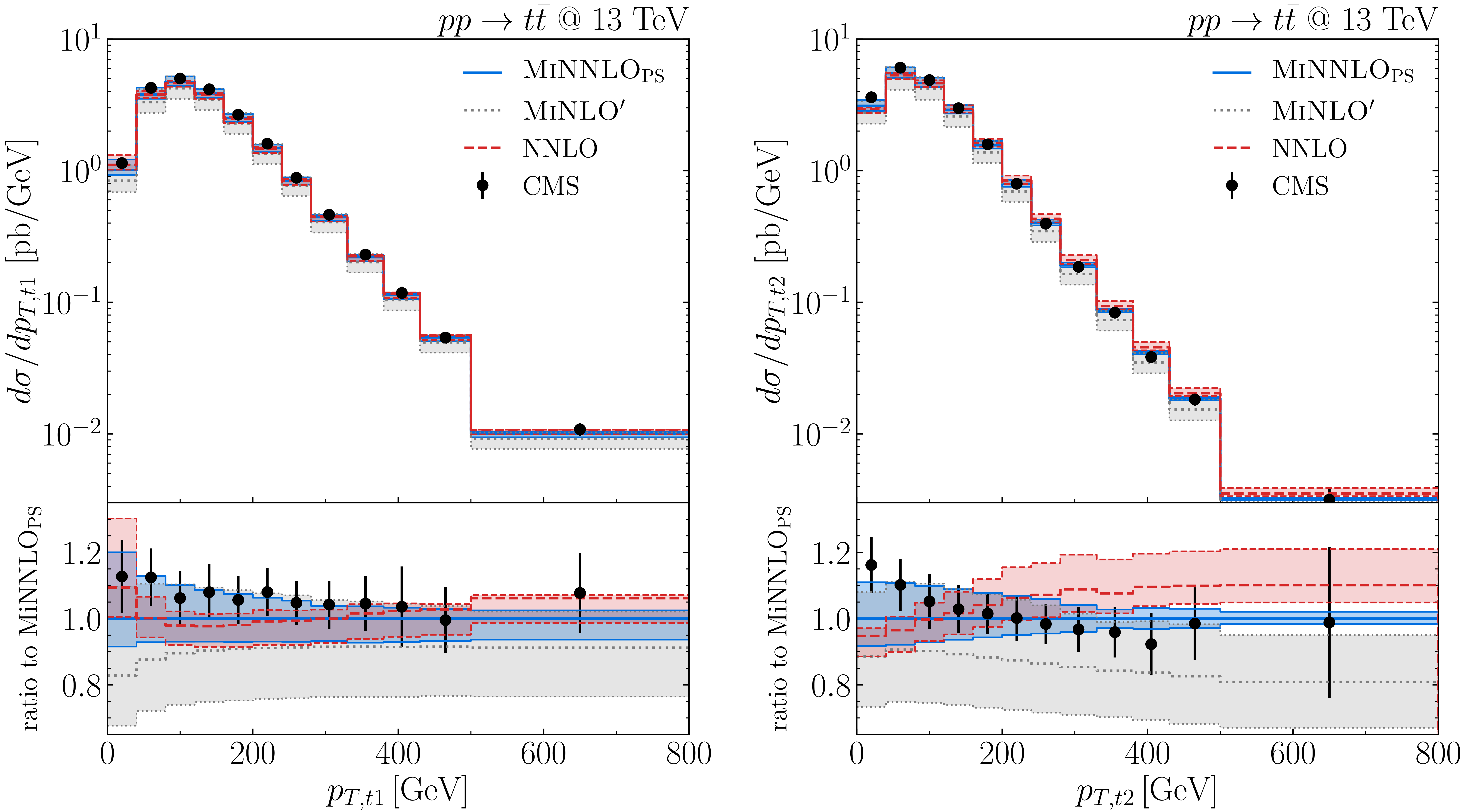
MiNNLO$_{PS}$ for $t\bar{t}$ production

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



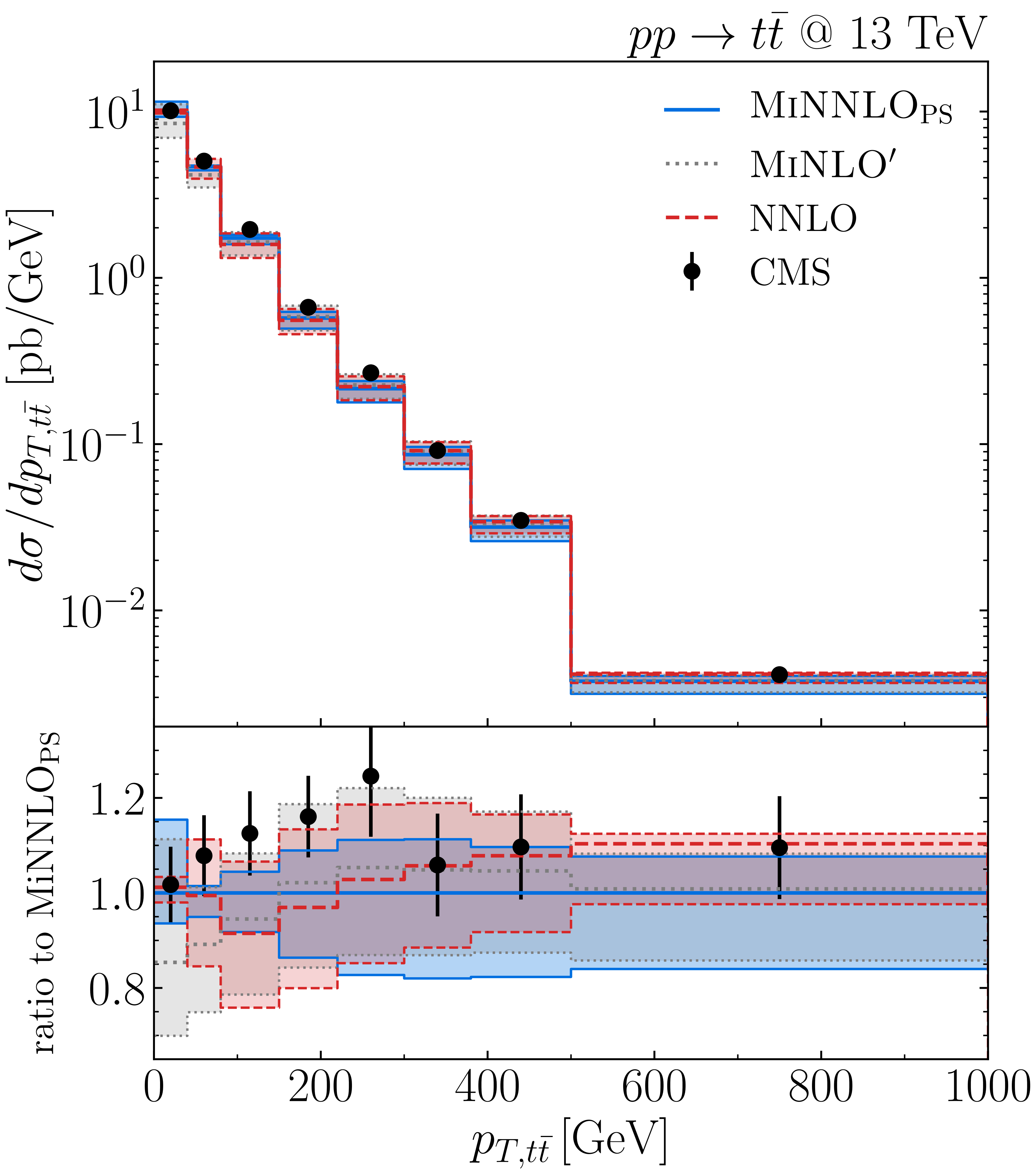
MiNNLO$_{\text{PS}}$ for $t\bar{t}$ production

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



MiNNLO$_{PS}$ for $t\bar{t}$ production

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



- ✦ NLO accurate at large p_T and full agreement of MiNNLO$_{PS}$ with MiNLO′
- ✦ also here: larger uncertainties in tail reflect additional sources of scale variations
- ✦ fixed-order unphysical at small p_T
- ✦ MiNNLO$_{PS}$ improves shape w.r.t. NNLO
- ✦ good description of data (especially in terms of shape!)