Workshop on High Precision for Hard Processes at the LHC (HP2 2022)
Newcastle - 21st September 2022

WZ production at NNLO QCD and NLO EW matched to parton showers with MiNNLO$_{PS}$

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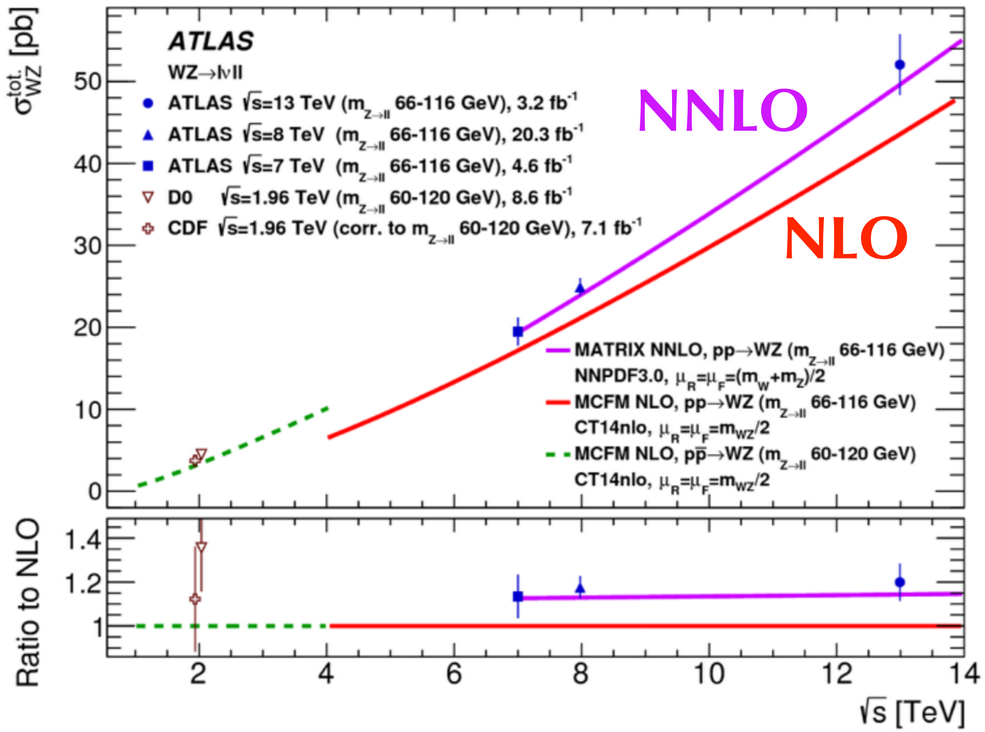
[2208.12660] in collaboration with J. Lindert, D. Lombardi, M. Wiesemann and G. Zanderighi

Introduction: NNLO+PS

- **No clear hints of new physics** at the LHC so far —> precision physics is a promising path for the observation of effects beyond the Standard Model.
- **NNLO computations are crucial** for an accurate description of data.



[ATLAS EPJC 79 (2019) 535]

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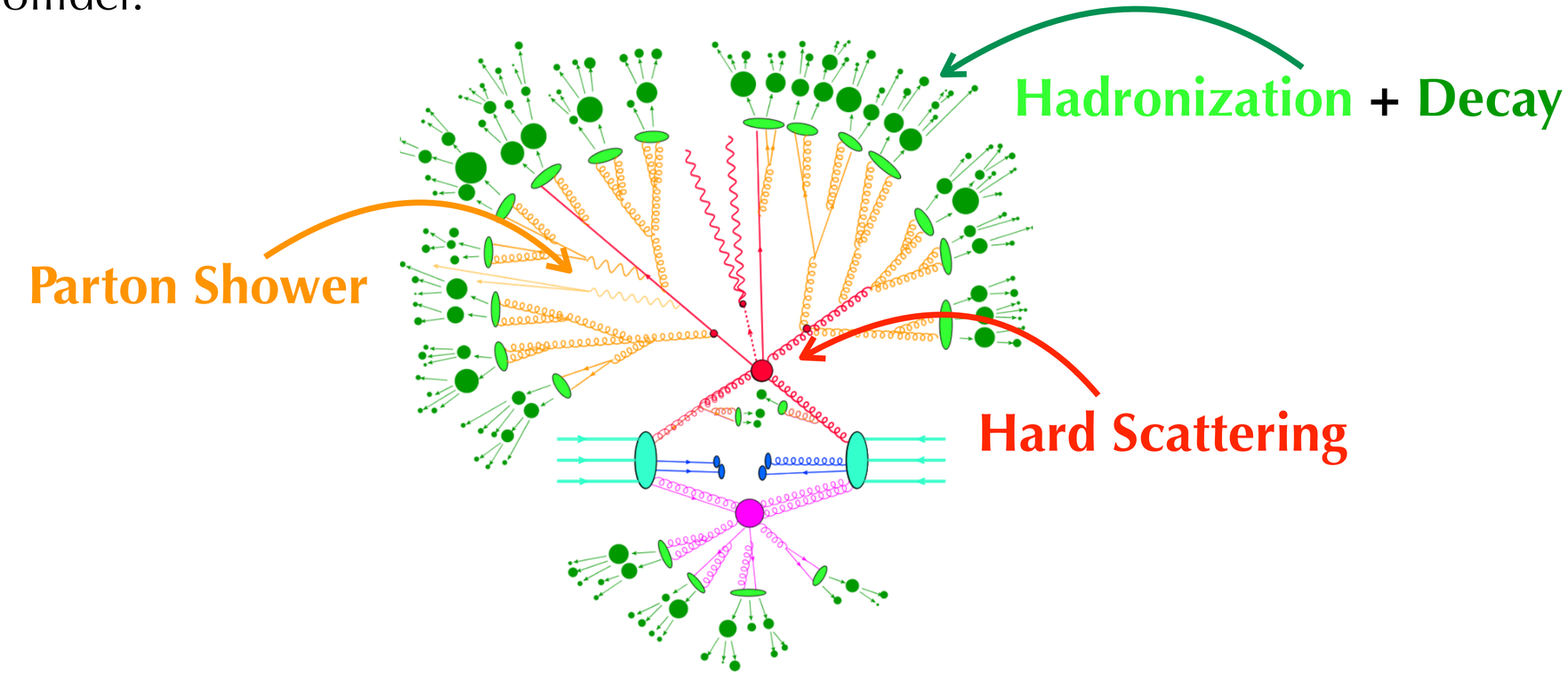

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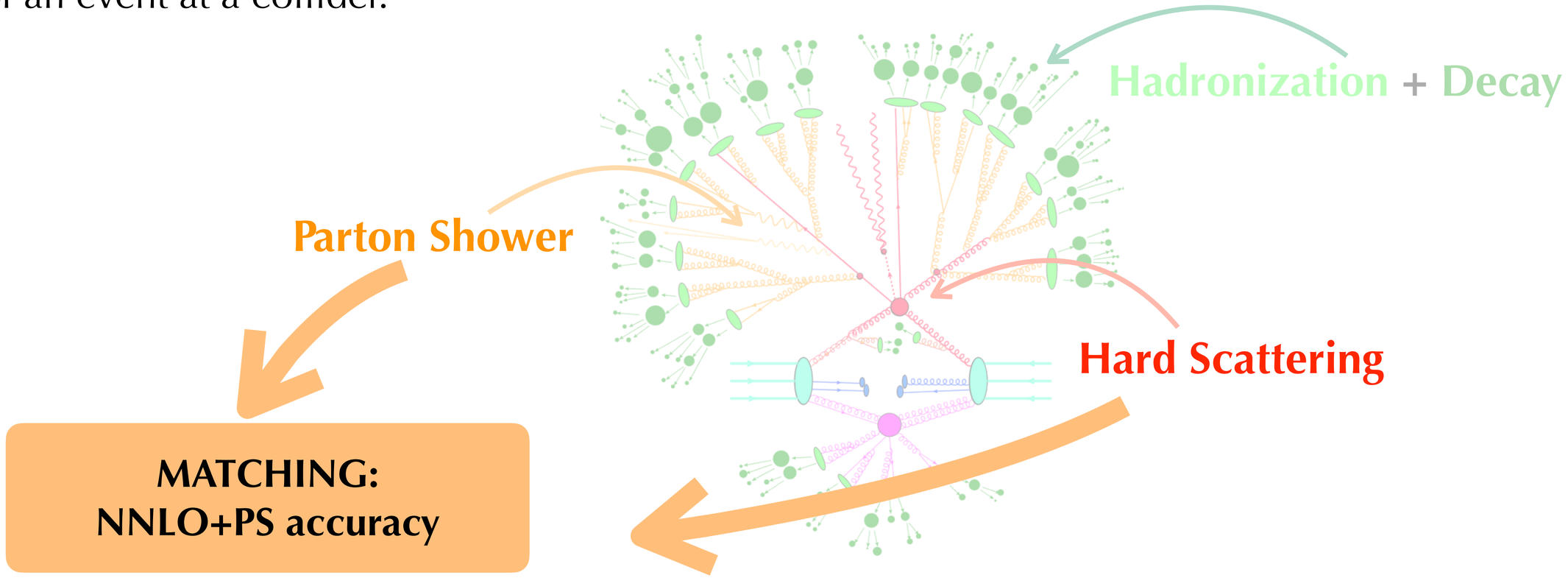

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WZ PRODUCTION : why?

- **The production of a pair of vector bosons is highly relevant**, as it provides access to trilinear gauge couplings and to the gauge symmetry structure of the EW sector.
- **WZ production is particularly interesting** both for the large cross section and the clean experimental signature (we consider the purely leptonic decay with one neutrino).

Introduction: WZ production

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CURRENT STATE OF THE ART:

- ☑ NLO EW calculation [Bierweiler, Kasprzik, Kühn (2013), Baglio, Ninh, Weber (2013)] [Biedermann, Denner, Hofer (2017)]
- ☑ NNLO QCD calculation [Grazzini, Kallweit, Rathlev, Wiesemann (2016), (2017)]
- ☑ NLO QCD + NLO EW matched to Parton Showers [Chiesa, Oleari, Re (2020)]
- ☑ NNLO QCD + NLO EW combination [Grazzini, Kallweit, Lindert, Pozzorini, Wiesemann (2020)]

Introduction: WZ production

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THIS TALK:

- ☐ NNLO+PS (QCD) calculation using MiNNLO$_{PS}$
- ☐ Combination of NNLO+PS (QCD) with NLO+PS (EW) computations

The MiNNLO$_{PS}$ method

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POWHEG:

[Nason (2004)]

$$d\sigma^{POW} = \bar{B}(\Phi_n) d\Phi_n \left\{ \Delta(\Phi_n, \Lambda) + \Delta(\Phi_n, p_T) \frac{R(\Phi_n, \Phi_r)}{B(\Phi_n)} d\Phi_r \right\}$$

$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_r \left[R(\Phi_{n+1}) - C(\Phi_{n+1}) \right] \qquad \Delta(\Phi_n, p_T) = exp\left\{ -\int d\Phi'_r \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \Theta(p'_T - p_T) \right\}$$

MiNLO':

[Hamilton, Nason, Oleari, Zanderighi (2012)]

$$\bar{B}(\Phi_n) = e^{-\tilde{S}(p_T)} \left(B(\Phi_n)(1 + \alpha_s(p_T)[\tilde{S}]^{(1)}) + V(\Phi_n) + \int d\Phi_r \left[R(\Phi_{n+1}) - C(\Phi_{n+1}) \right] \right)$$

$$\tilde{S}(p_T) = \int_{p_t^2}^{Q^2} \frac{dq^2}{q^2} \left[A(\alpha_s(q^2)) \log \frac{Q^2}{q^2} + B(\alpha_s(q^2)) \right] \qquad A = \sum_{k=1}^{2} \left(\frac{\alpha_s}{2\pi} \right)^k A^{(k)}, \quad B = \sum_{k=1}^{2} \left(\frac{\alpha_s}{2\pi} \right)^k B^{(k)}$$

- **Finite result** for F+J production when the **jet is unresolved**.
- Prescription for the **choice of the scales** μ_R and μ_F ($\mu_R = \mu_F \sim p_T$).

	F (inclusive)	F+J (inclusive)	F+JJ (inclusive)
FJ@MiNLO'	NLO	NLO	LO

The MiNNLO$_{PS}$ method

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MiNNLO$_{PS}$:

[Monni, Nason, Re, Wiesemann, Zanderighi (2019)]

	F (inclusive)	F+J (inclusive)	F+JJ (inclusive)
FJ@MiNNLOPS	**NNLO**	NLO	LO

The MiNNLO$_{PS}$ method

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MiNNLO$_{PS}$:

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	F (inclusive)	F+J (inclusive)	F+JJ (inclusive)
FJ@MiNNLOPS	**NNLO**	NLO	LO

$$D(p_T) \equiv -\frac{d\tilde{S}(p_T)}{dp_T}\mathscr{L}(p_T) + \frac{d\mathscr{L}(p_T)}{dp_T}$$

$$\frac{d\sigma}{d\Phi_F dp_T} = \frac{d}{dp_T}\left\{ e^{-\tilde{S}(p_T)}\mathscr{L}(p_T)\right\} + R_f(p_T) = e^{-\tilde{S}(p_T)}\left[D(p_T) + \frac{R_f(p_T)}{e^{-\tilde{S}(p_T)}}\right] = \ldots =$$

$$\int \frac{dp_T}{p_T}\alpha_s^m(p_T)\ln^n\frac{p_T}{Q}e^{-\tilde{S}(p_T)} \approx \mathcal{O}\left(\alpha_s^{m-\frac{n+1}{2}}\right)$$

$$= e^{-\tilde{S}(p_T)}\left\{ \frac{\alpha_s(p_T)}{2\pi}\left[\frac{d\sigma_{FJ}}{d\Phi_{FJ}dp_T}\right]^{(1)}\left(1 + \frac{\alpha_s(p_T)}{2\pi}[\tilde{S}]^{(1)}\right) + \left(\frac{\alpha_s(p_T)}{2\pi}\right)^2\left[\frac{d\sigma_{FJ}}{d\Phi_{FJ}dp_T}\right]^{(2)} + D(p_T) - D(p_T)^{(1)} - D(p_T)^{(2)} + reg\right\}$$

The MiNNLOPS method

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MiNNLOPS:

[Monni, Nason, Re, Wiesemann, Zanderighi (2019)]

	F (inclusive)	F+J (inclusive)	F+JJ (inclusive)
FJ@MiNNLOPS	**NNLO**	NLO	LO

$$D(p_T) \equiv -\frac{d\tilde{S}(p_T)}{dp_T}\mathscr{L}(p_T) + \frac{d\mathscr{L}(p_T)}{dp_T}$$

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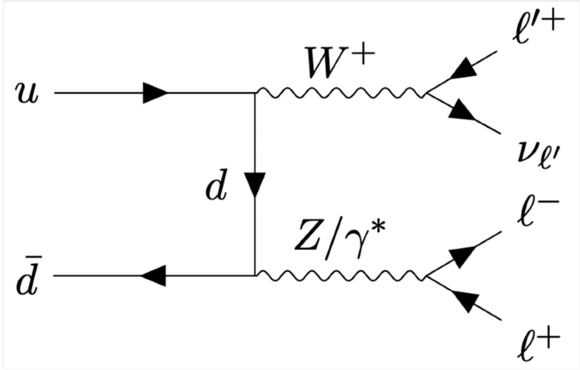
MiNLO' **MiNNLOPS**

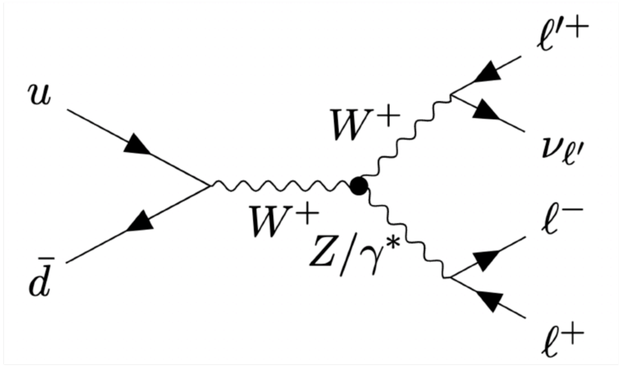
WZ production

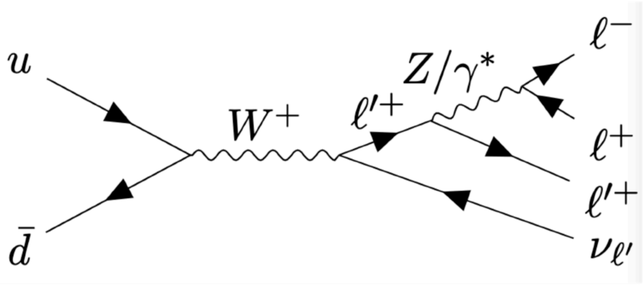
$$pp \to l'^{\pm}\nu_{l'}l^{+}l^{-} + X$$

NNLO+PS (QCD) calculation using MiNNLO$_{\mathrm{PS}}$ ($\mathcal{O}(\alpha^4\alpha_s^2)$)

- No loop-induced gluon-fusion contributions.
- Important NNLO corrections (10-15%), due to radiation zero effect at LO (= vanishing of the leading helicity amplitudes in some kinematic regions).







WZ production

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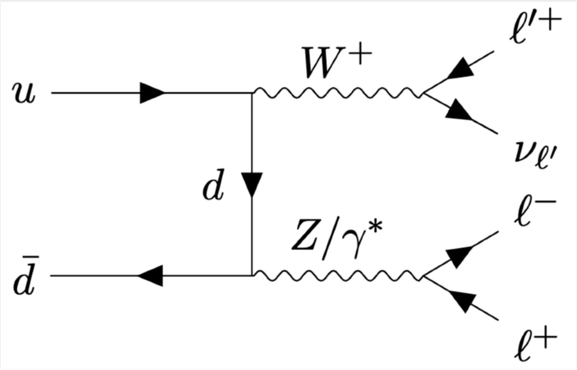

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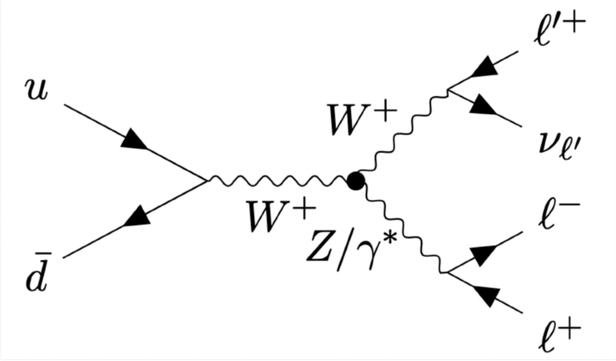
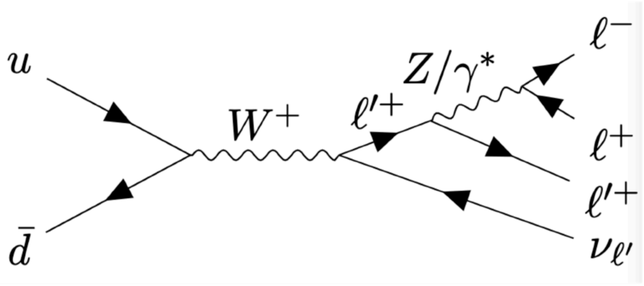


NLO+PS (EW) calculation using POWHEG ($\mathcal{O}(\alpha^5)$)

- Real radiation corresponds to photon radiation.
- No photon-photon contribution at this order.
- Photon-quark contributions are not considered (formally, they are $\mathcal{O}(\alpha^6 L)$).



$\mathrm{NNLO_{QCD}}$+PS and $\mathrm{NLO_{EW}}$+PS combinations

ADDITIVE vs MULTIPLICATIVE SCHEMES

$$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}} - \mathrm{LO}$$

$$\mathcal{O}(\alpha^4), \mathcal{O}(\alpha^4\alpha_s), \mathcal{O}(\alpha^4\alpha_s^2), \mathcal{O}(\alpha^5)$$

$$\mathrm{NNLO_{QCD}} \times \mathrm{NLO_{EW}}/\mathrm{LO}$$

$$\mathcal{O}(\alpha^4), \mathcal{O}(\alpha^4\alpha_s), \mathcal{O}(\alpha^4\alpha_s^2), \mathcal{O}(\alpha^5), \mathcal{O}(\alpha^5\alpha_s), \mathcal{O}(\alpha^5\alpha_s^2)$$

- The **multiplicative scheme is preferable** in the high energy limit, where EW Sudakov-logs are dominant and dominant QCD effects arise at scales below the hard scale. —> **QCD factorizes**.
- This assumption is **violated when giant K-factors are present** (= hard vector-boson+jet topologies, with a soft second vector boson).
- The **average** of the two schemes can give a **pragmatic estimate** in these regions.

$NNLO_{QCD}$+PS and NLO_{EW}+PS combinations

QCD vs QED SHOWERS

1. The **formal accuracy** of the calculation **must not be spoilt**.
2. We must **avoid double counting**.

We let the QCD and/or QED showers radiate in whole the phase space and then we apply the following **veto procedure**:

$NNLO_{QCD}$+PS :
- **QCD** shower is **restricted** by the transverse momentum of the hardest QCD emission generated at Les Houches level (as commonly done in POWHEG).
- **QED** shower is **unconstrained**.

NLO_{EW}+PS :
- **QCD** shower is **unconstrained**.
- **QED** shower is **restricted** by the transverse momentum of the hardest QED emission generated at Les Houches level. We use the multiple-radiation scheme in POWHEG, which allows us to define **three different starting scales** for the shower in the three different singular regions (ISR, FSR form W decay, FSR from Z decay).

$\mathrm{NNLO_{QCD}}$+PS and $\mathrm{NLO_{EW}}$+PS combinations

ADDITIVE:

1. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}}$
2. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
3. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$

MULTIPLICATIVE:

4. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}}$
5. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QED})_{\mathrm{PS}}}$
6. $\mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD},\,\mathrm{QED})_{\mathrm{PS}}} \times \mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$
7. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{\mathrm{f.o.}} / \mathrm{LO}^{\mathrm{f.o.}}$

NOTATION:

$$(\mathrm{N})\mathrm{NLO}_{\mathrm{X}}^{(\mathrm{Y})_{\mathrm{PS}}}$$

X = QCD,EW calculation
Y = QCD,QED showers (PY8)

Phenomenological results 1

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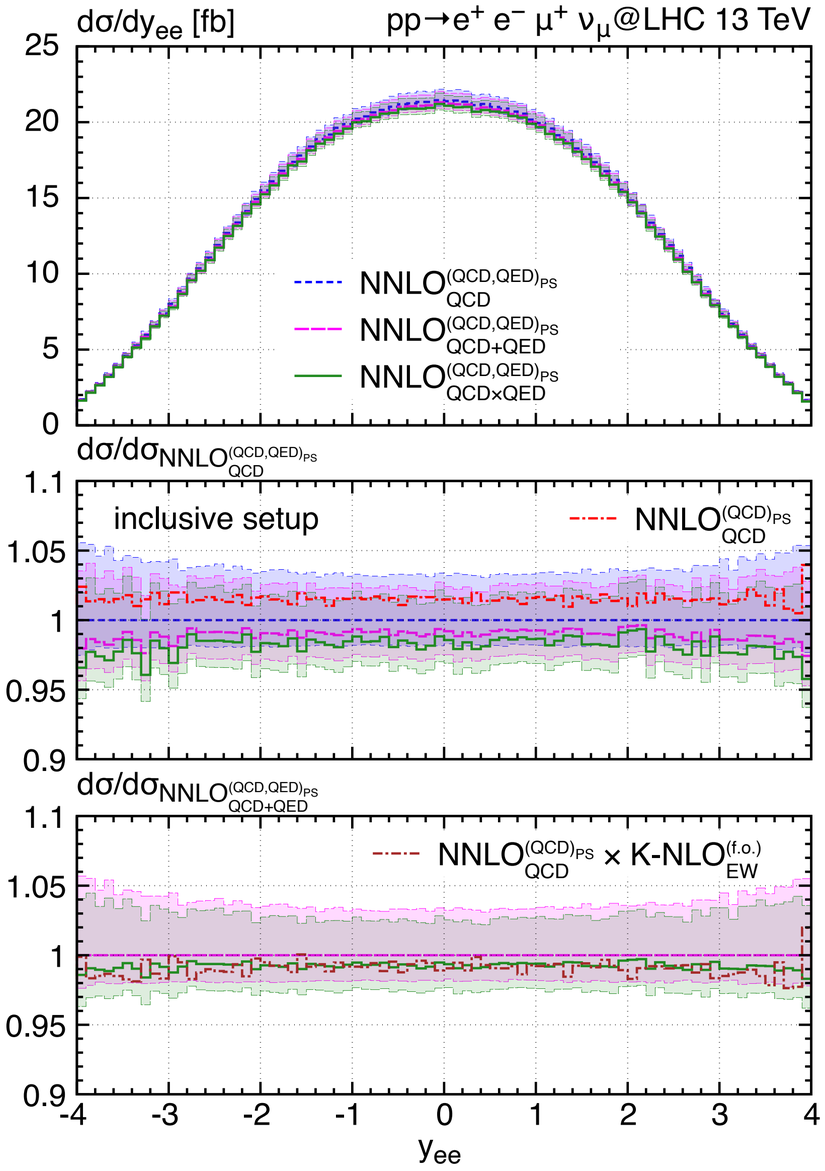
[2208.12660]

Rapidity of the Z boson - inclusive setup



LEGEND:

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- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD+QED}}$
- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD\times QED}}$
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}} \times \mathrm{K}^{\mathrm{f.o.}}_{\mathrm{EW}}$

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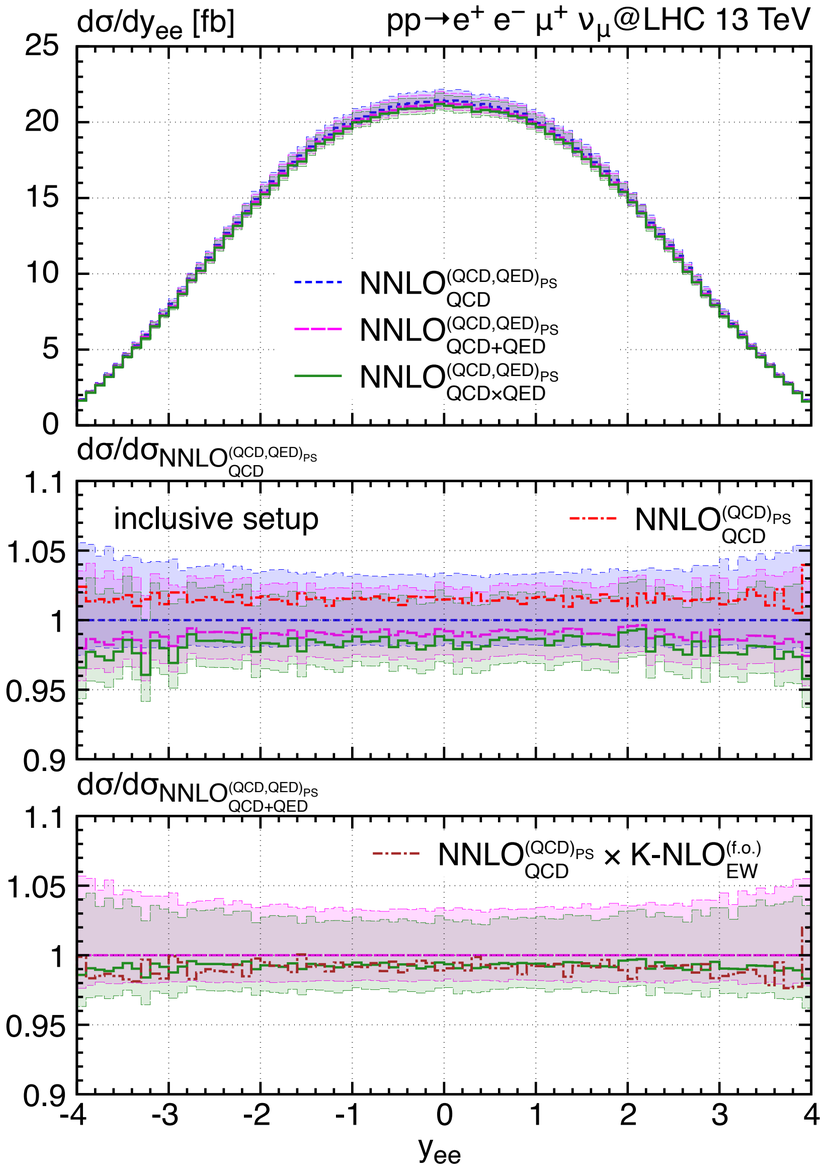

- Almost no shape effect
- EW corrections are 2-3%
- Additive and multiplicative schemes are almost identical
- Fixed-order K-factor is in excellent agreement —> effects of secondary photon emission are negligible for this observable

LEGEND:

- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD+QED}}$
- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD\times QED}}$
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- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}} \times \mathrm{K}^{\mathrm{f.o.}}_{\mathrm{EW}}$

Phenomenological results 2

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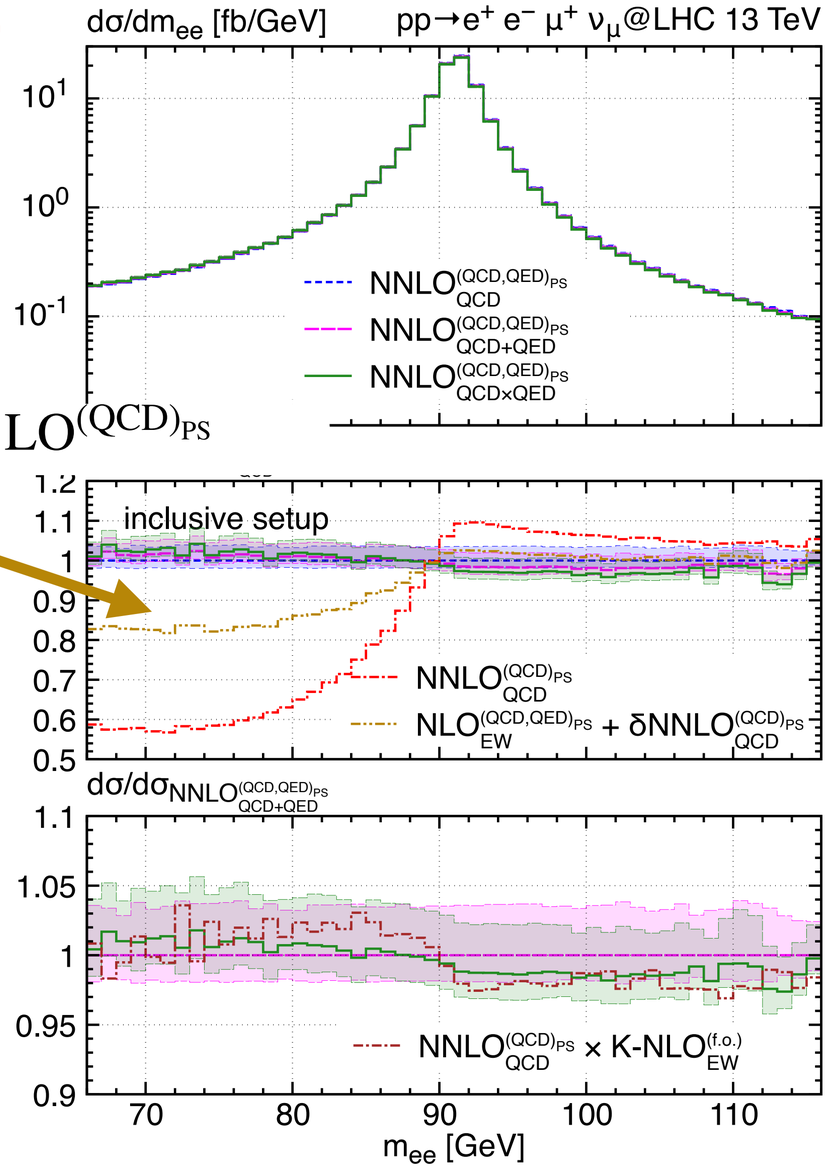
[2208.12660]

Invariant mass of the Z boson - inclusive setup

$\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$



LEGEND:

- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD+QED}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD\times QED}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{K}_{\mathrm{EW}}^{\mathrm{f.o.}}$

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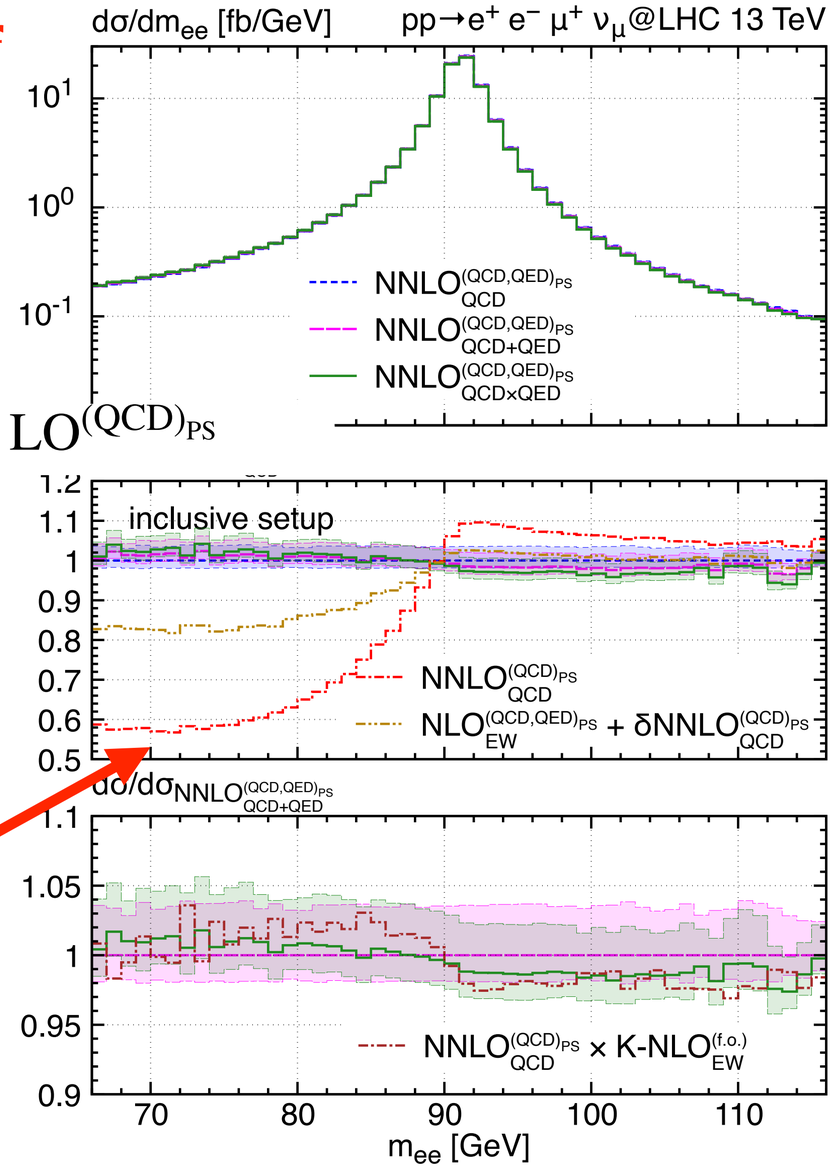

● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$

Large effects from collinear QED radiations (~40%), which are absent in ●

LEGEND:

- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD+QED}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
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Phenomenological results 2

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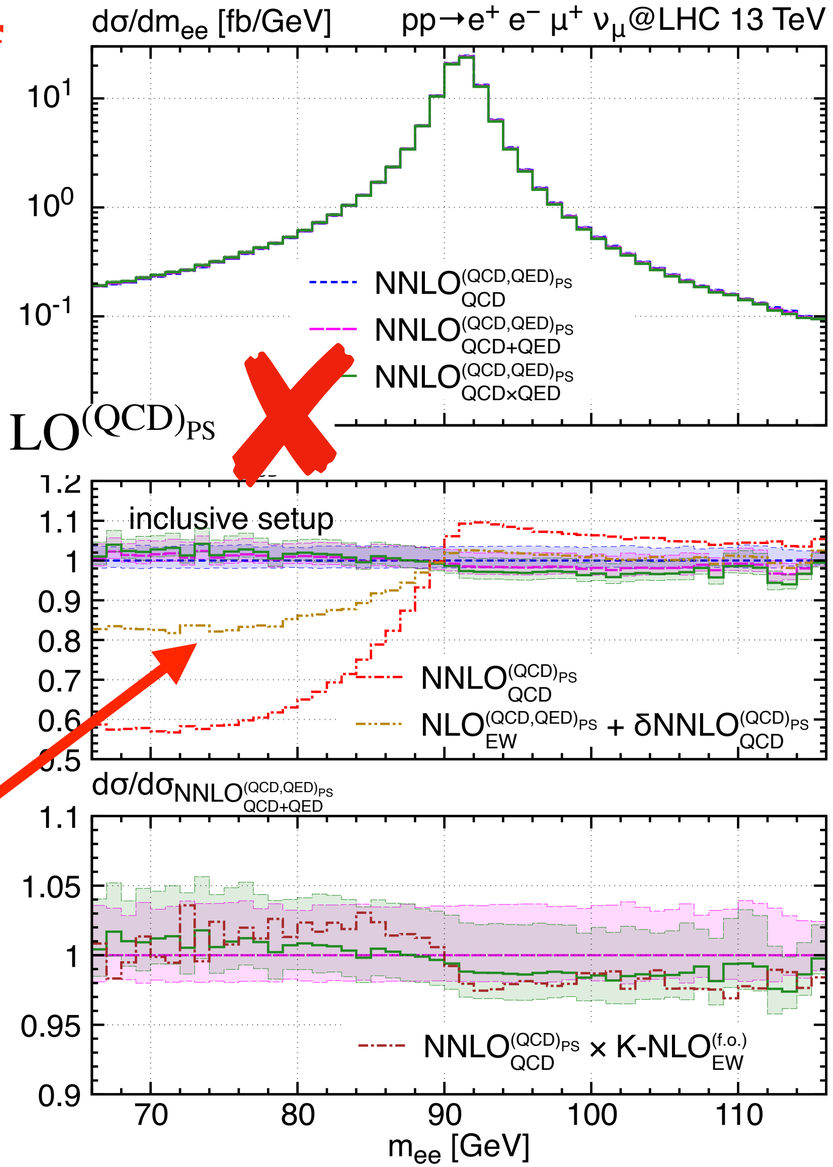

- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} + \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} - \mathrm{LO}^{(\mathrm{QCD})_{\mathrm{PS}}}$

- misses important QED-QCD effects originating from QED emissions on top of the NNLO calculation —> **DISCARDED**

LEGEND:

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- $\mathrm{NNLO}_{\mathrm{QCD+QED}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD\times QED}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{K}_{\mathrm{EW}}^{\mathrm{f.o.}}$

Phenomenological results 3

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[2208.12660]

LEGEND:

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- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD+QED}}$
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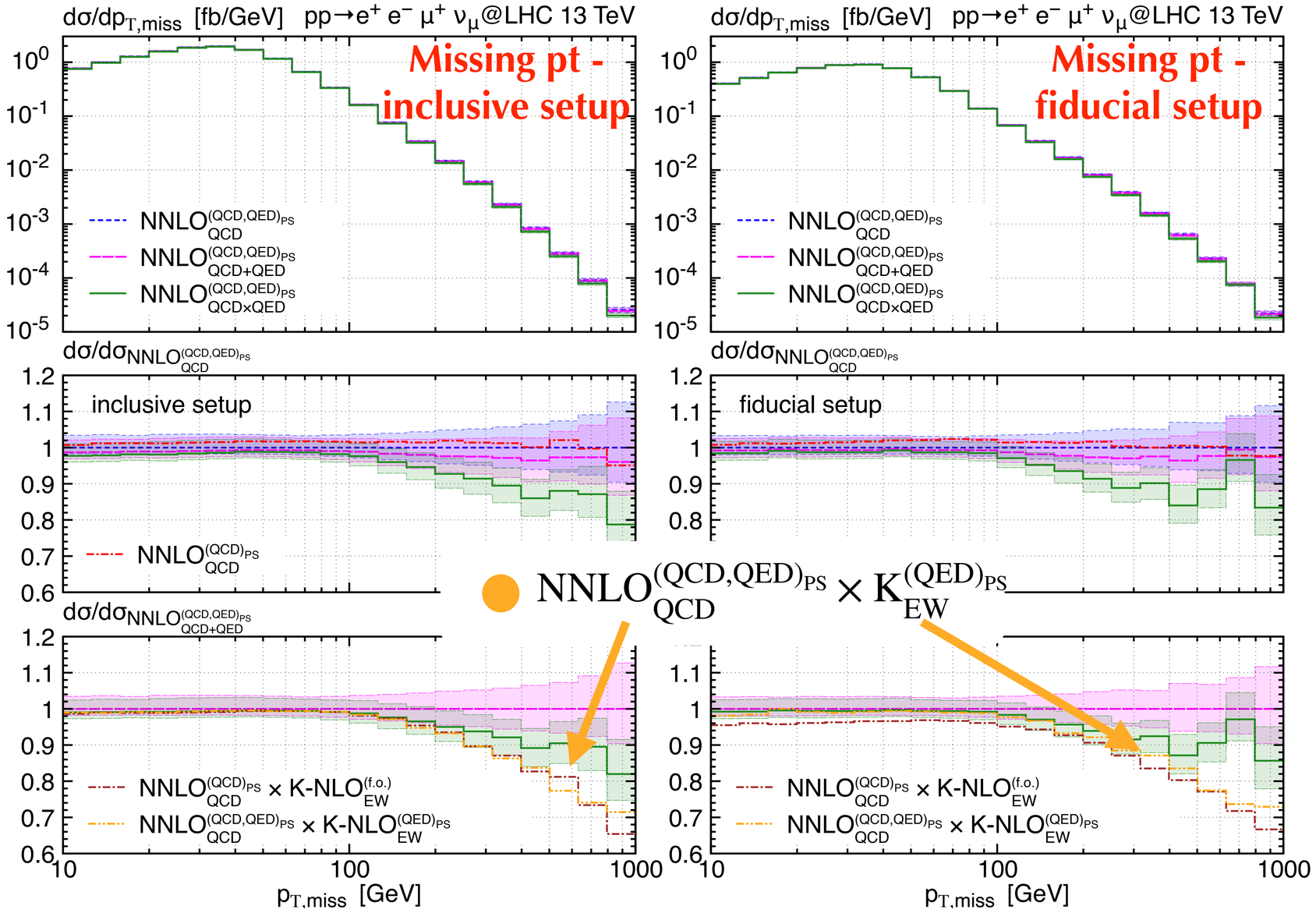

Phenomenological results 3

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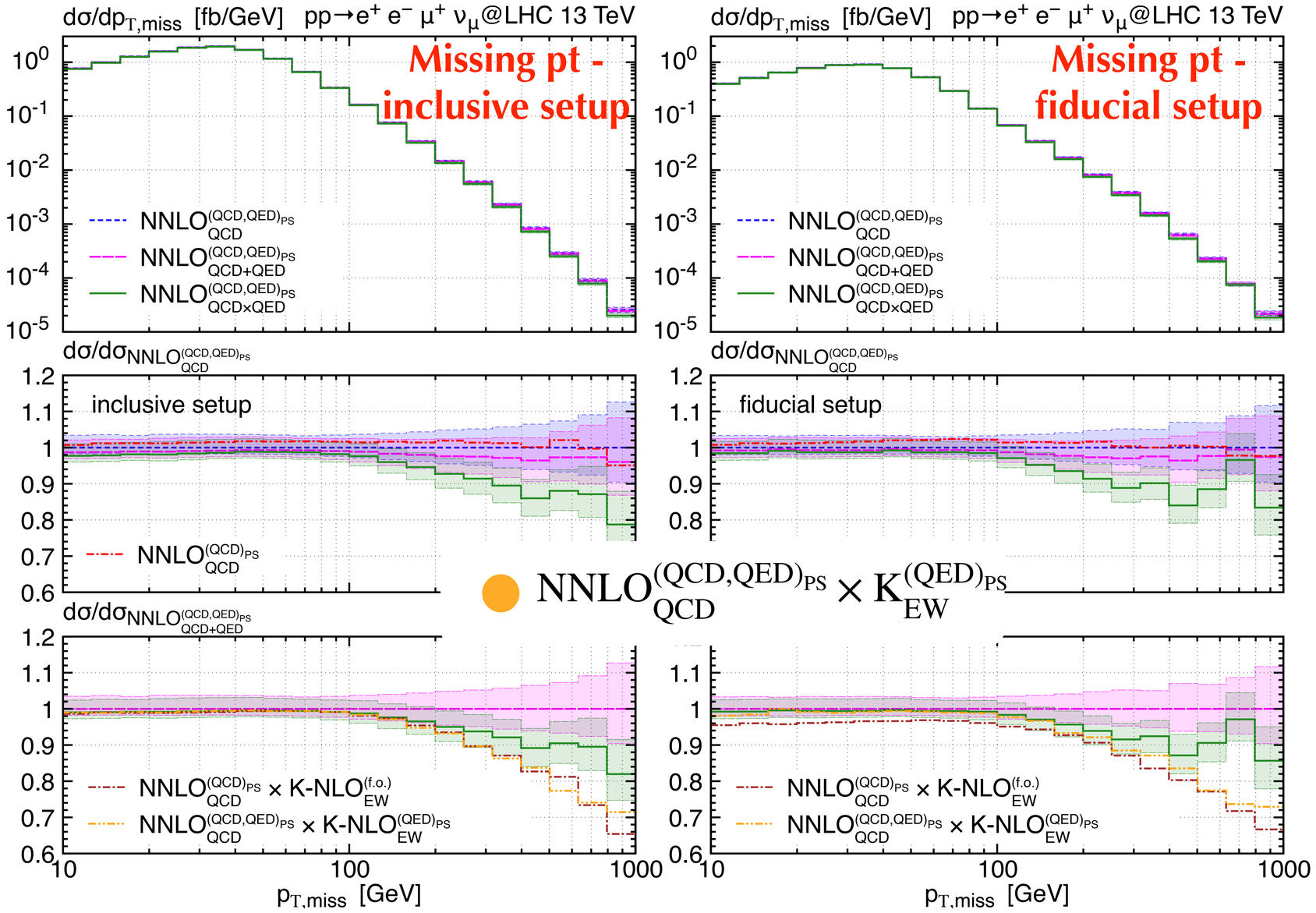

- is affected by giant K-factors

Phenomenological results 4

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[2208.12660]

LEGEND:

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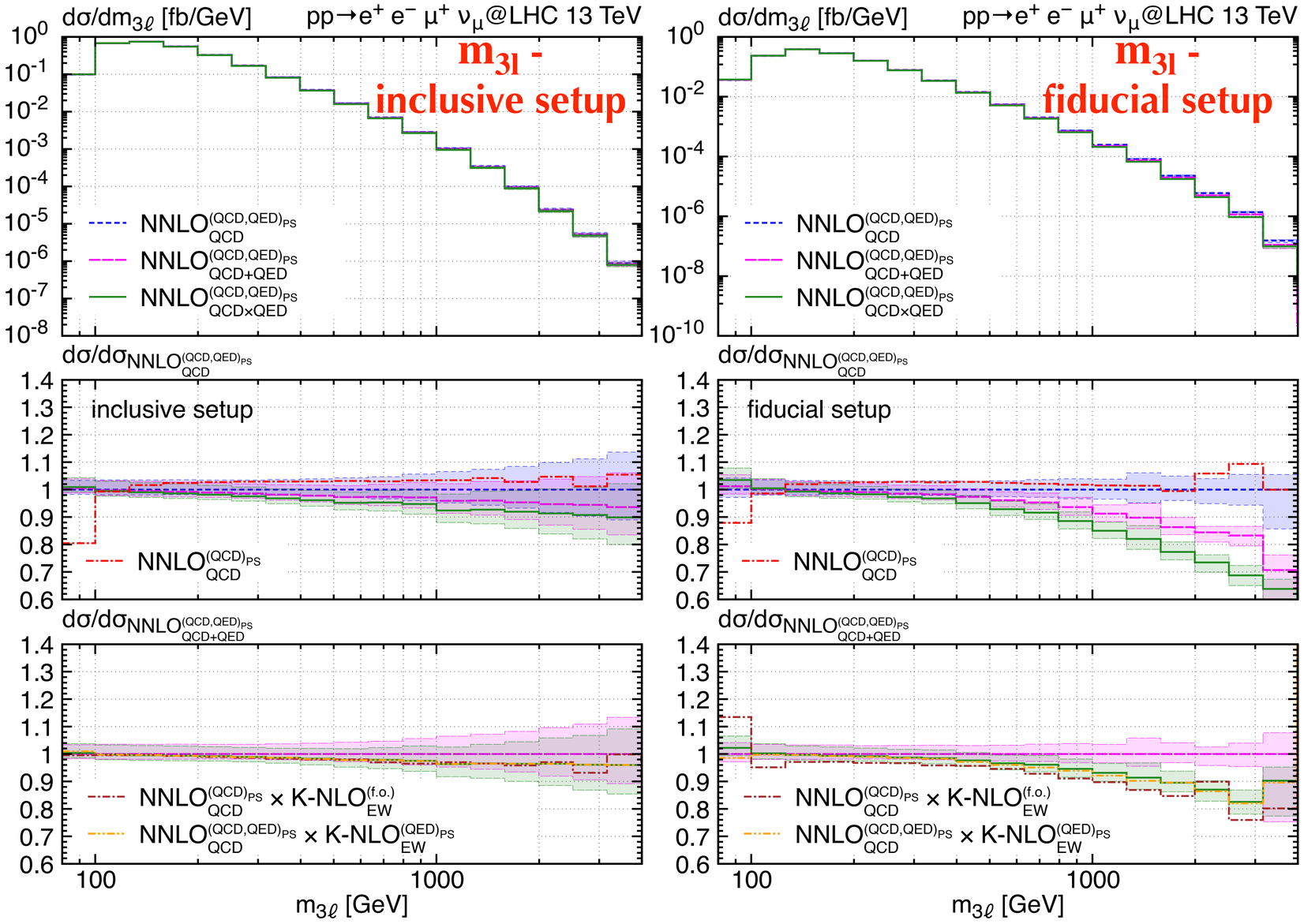
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}} \times \mathrm{K}^{\mathrm{f.o.}}_{\mathrm{EW}}$



Phenomenological results 4

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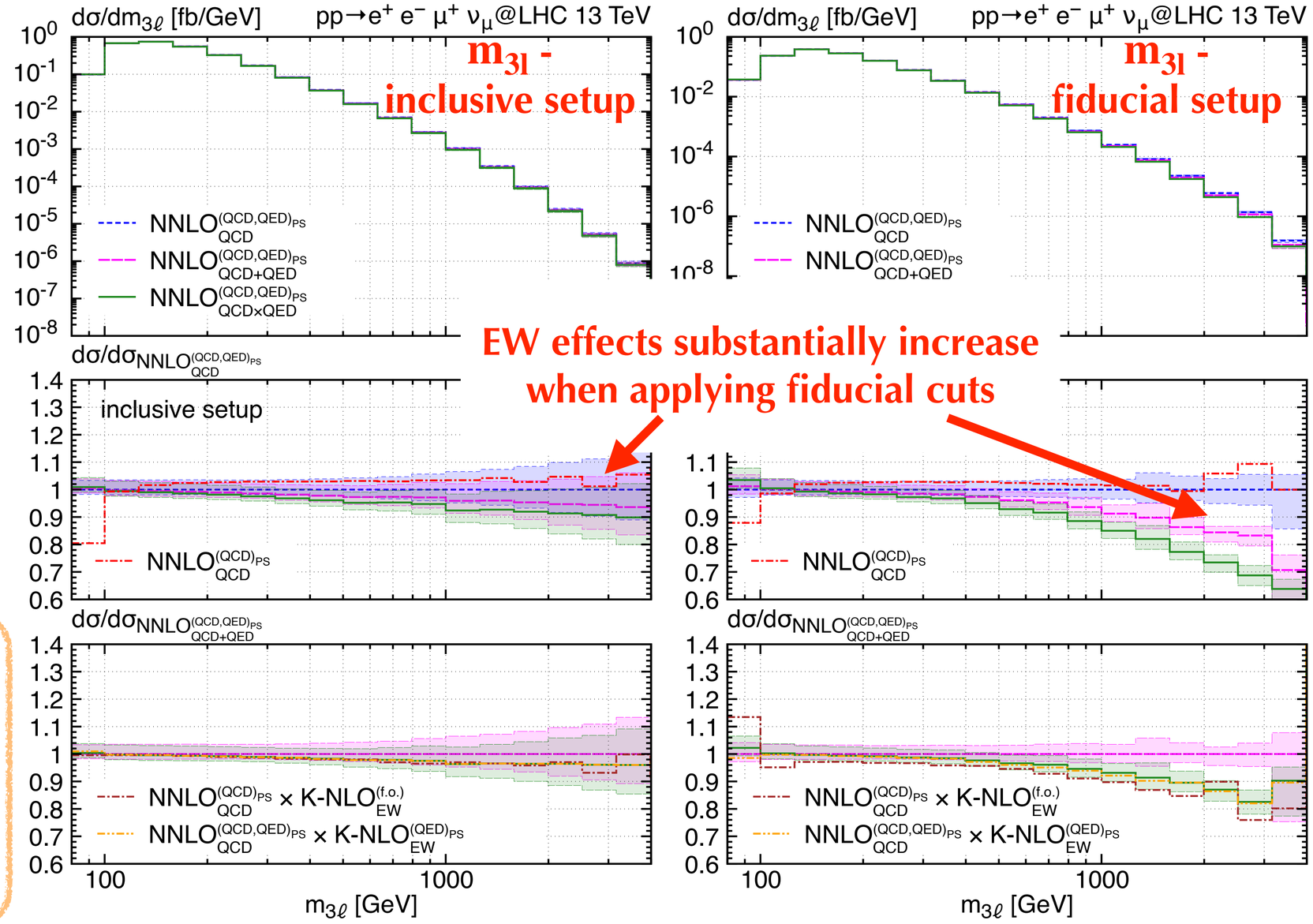
LEGEND:

- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD+QED}}$
- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD\times QED}}$
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}} \times \mathrm{K}^{\mathrm{f.o.}}_{\mathrm{EW}}$

In the inclusive case, Sudakov-logs are suppressed because not all the Mandelstam invariants are large in the very forward regime. These regions are removed when applying fiducial cuts.



Comparison against data

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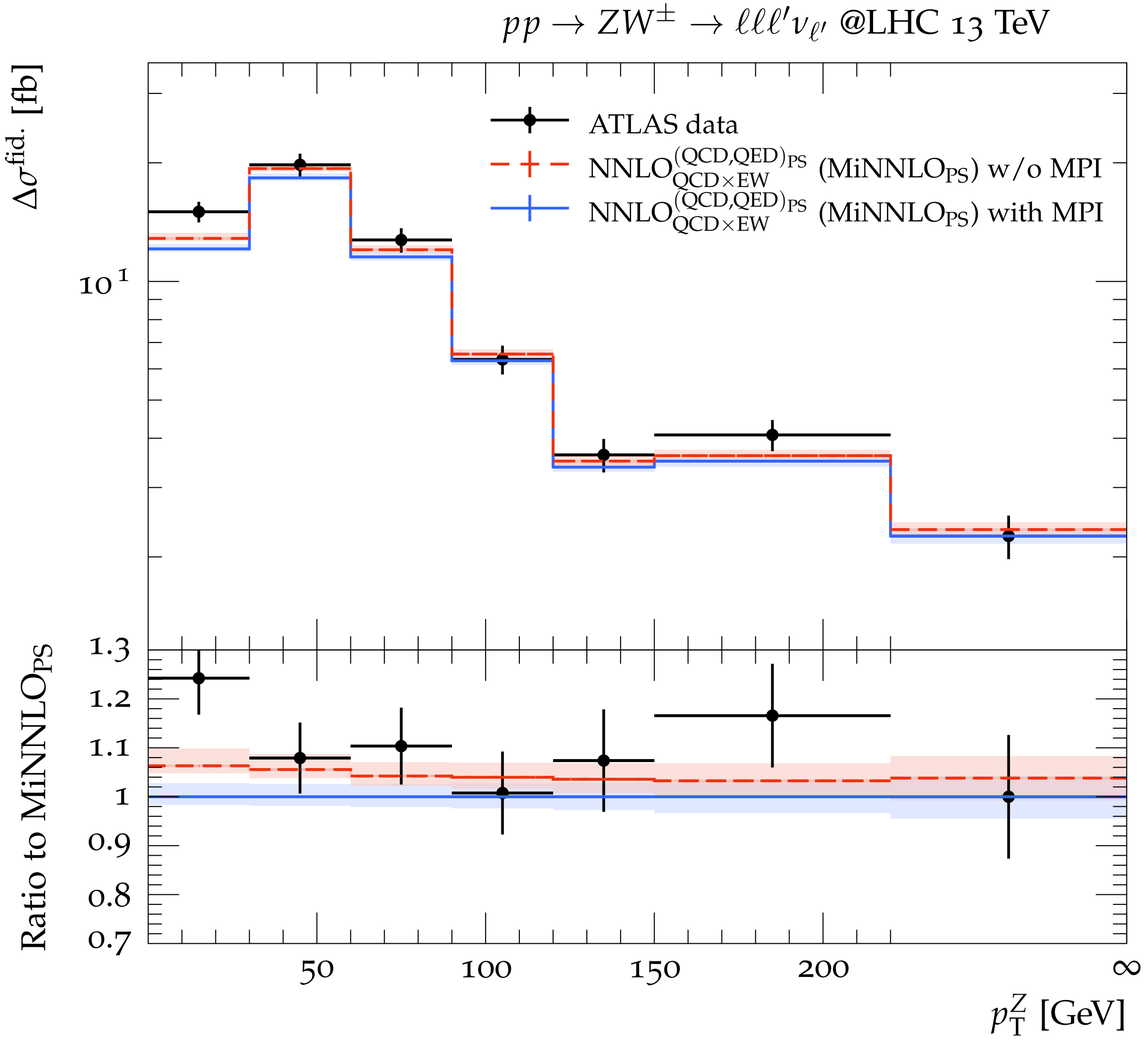
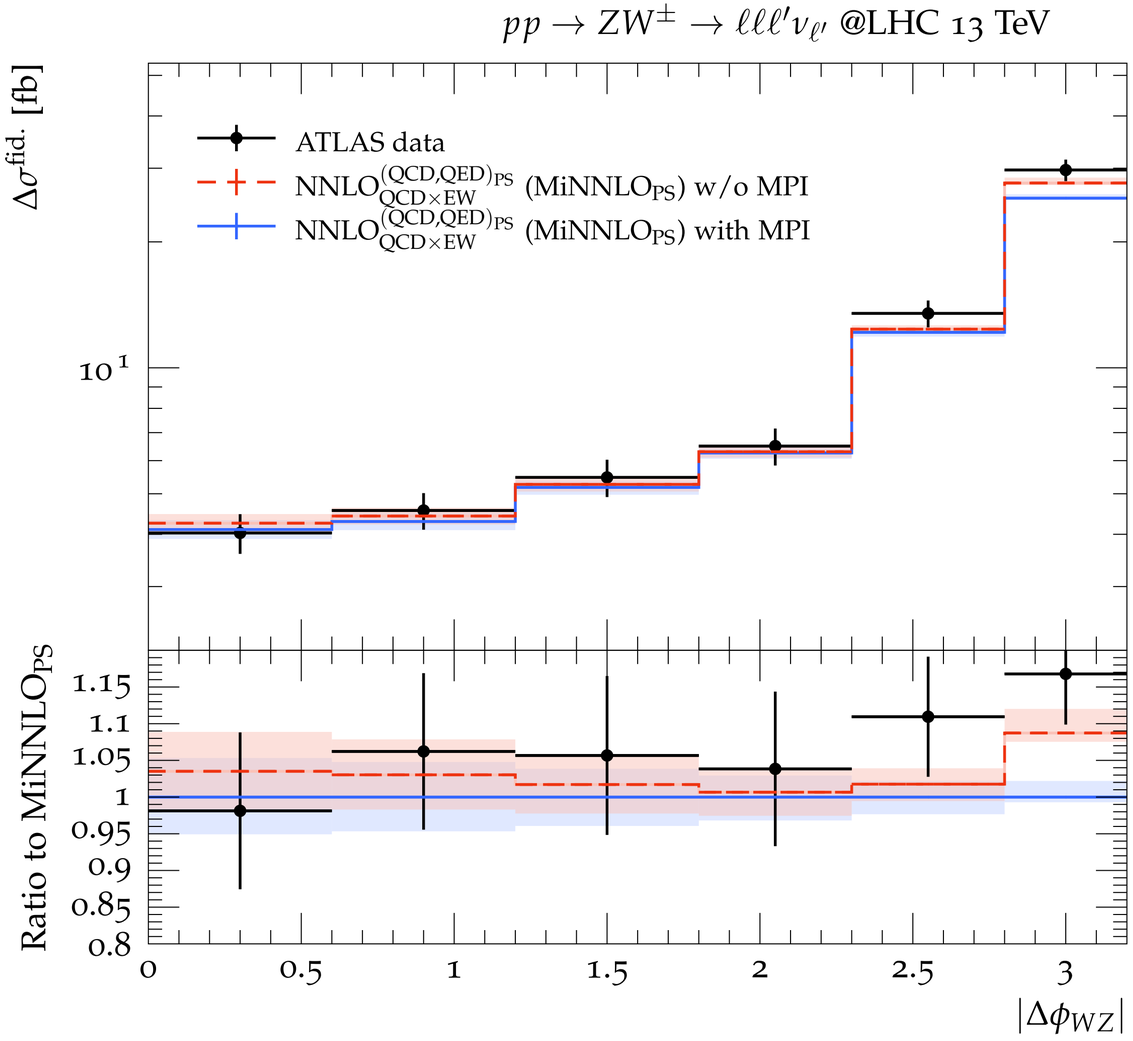
ATLAS data from Eur. Phys. J. C 79 (2019)





Conclusions and Outlooks

- **NNLO+PS** predictions are strongly needed for a realistic description of LHC events.
- The **MiNNLO$_{PS}$ method** is a powerful tool for reaching this accuracy.
- In the context of precision physics, the inclusion of **NLO EW corrections** on top of the NNLO calculations is particularly important.
- I showed and discuss results for **WZ production** at NNLO (QCD) and NLO (EW) accuracy matched to parton shower for 13TeV LHC collisions.
- The next step is the implementation of the combined generation of NNLO QCD and NLO EW accurate events, rather than an a posteriori recombination.

Thank you for your attention!

Conclusions and Outlooks

BACK UP

Validation QCD

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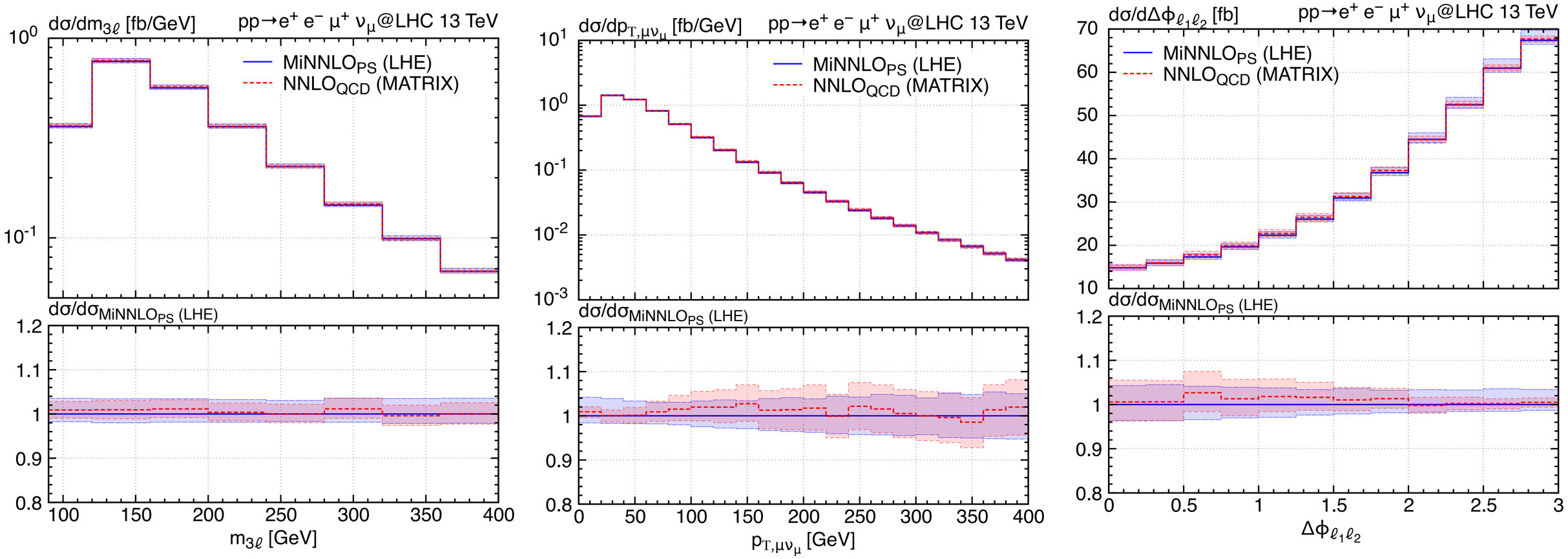

Validation EW

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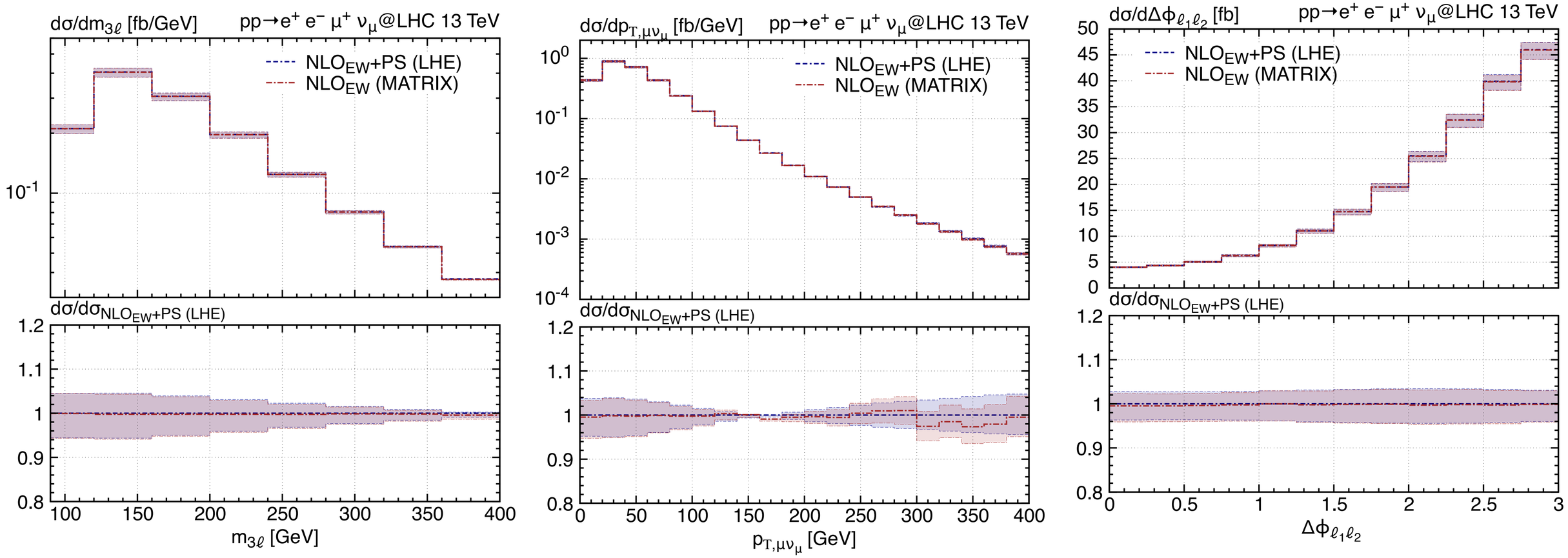

Comparison against data

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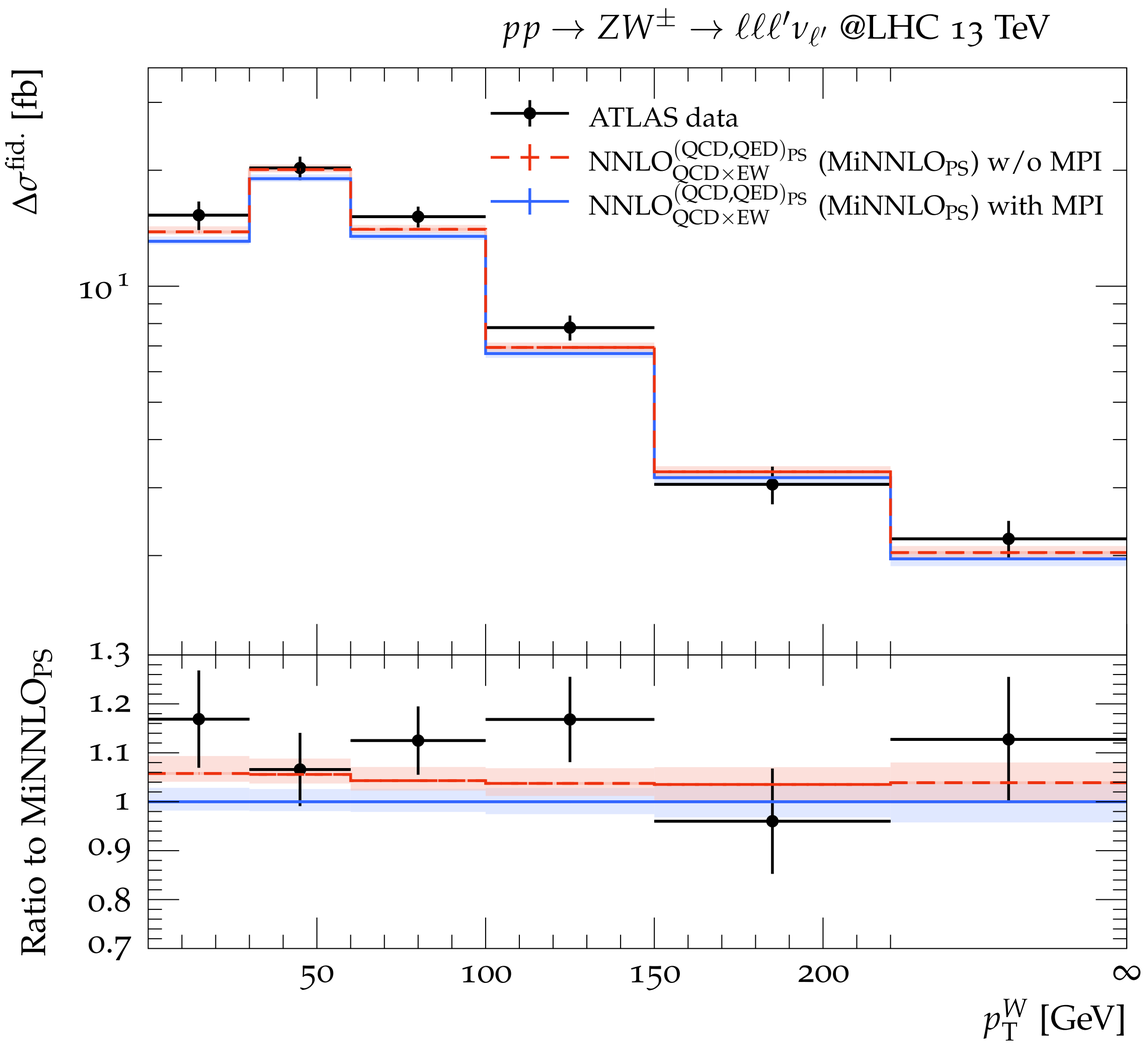
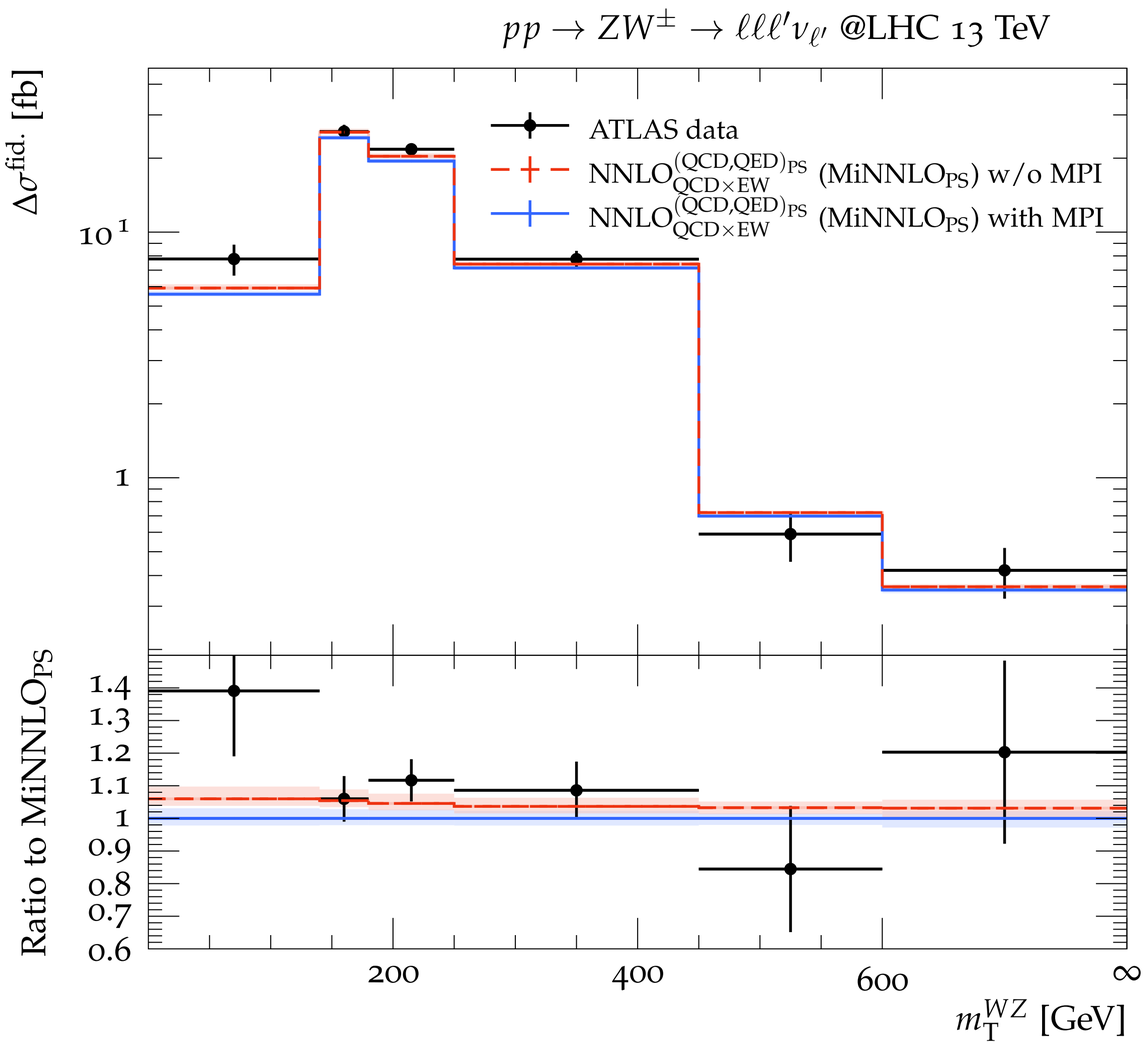
ATLAS data from Eur. Phys. J. C 79 (2019)





Comparison against data

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ATLAS data from Eur. Phys. J. C 79 (2019)