Workshop on Tools for High Precision LHC Simulations

Inclusion of NLO EW corrections in NNLO+PS event generation with MiNNLO$_{PS}$

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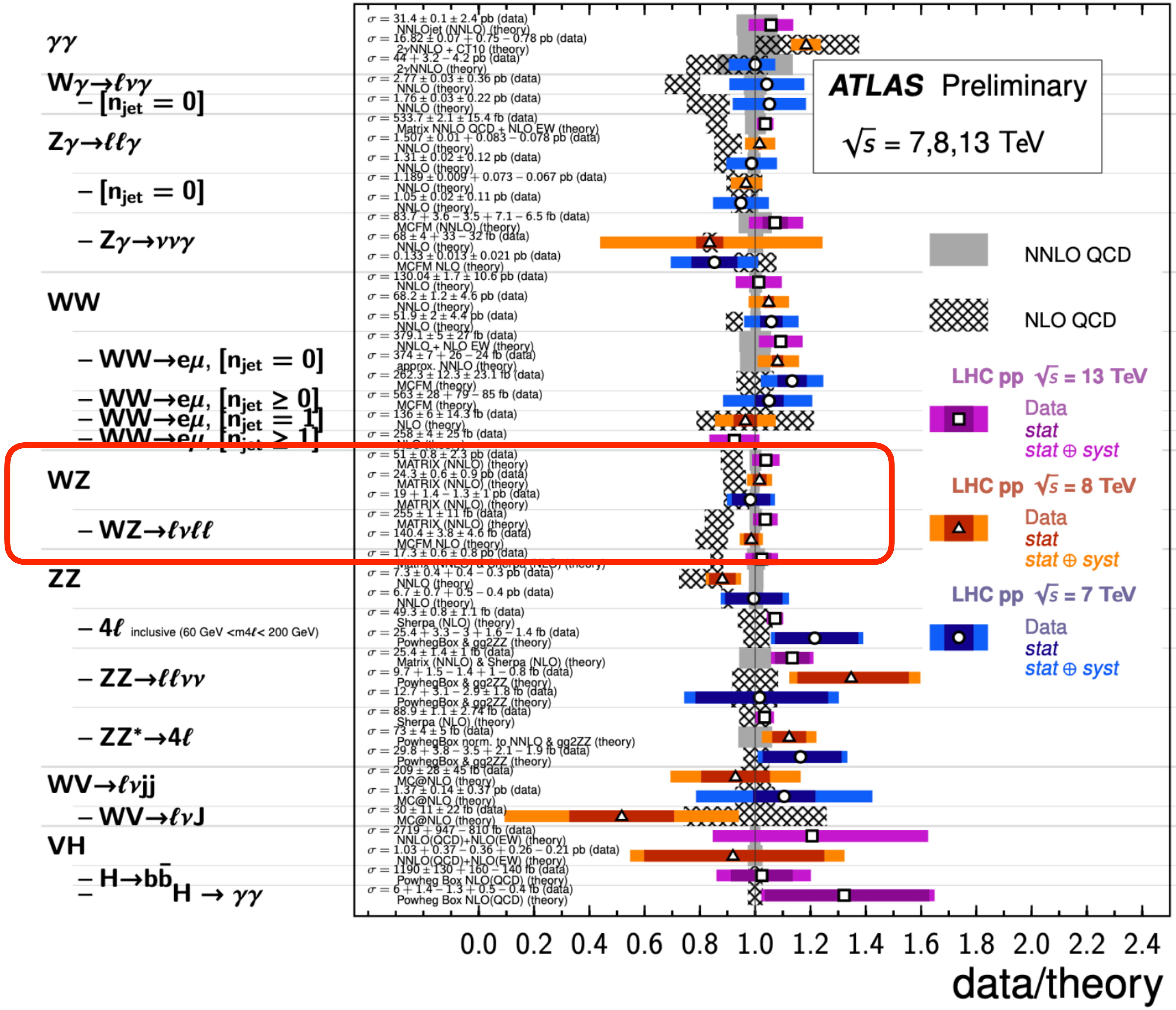
Silvia Zanoli
Max Planck Institute for Physics

Based on [2208.12660] J. Lindert, D. Lombardi, M. Wiesemann, G. Zanderighi, S.Z.

Introduction

- **Precision physics** is a promising path for the **observation of effects beyond the Standard Model**.
- **NNLO (QCD) computations are crucial** for an accurate description of data, but they need to be supplemented by **EW corrections** for reaching the required experimental accuracy.
- The **matching** of a fixed-order calculation **with parton showers** is required for a realistic description of an event at a collider.



WZ production

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WHY WZ PRODUCTION?

- **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).

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)]

Outline of the talk

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THIS TALK:

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

1) How to obtain NNLO+PS (QCD) and NLO+PS (EW) results for WZ production
    a. Generation of NNLO+PS (QCD) results using MiNNLO$_{PS}$
    b. Generation of NLO+PS (EW) results using POWHEG
    c. Combination of NNLO+PS (QCD) and NLO+PS (EW) results (different matching schemes)
    d. Treatment of the shower (PY8) and implementation of a veto procedure
2) Phenomenological analysis and comparison with data
3) Summary and outlooks

NNLO+PS (QCD) predictions

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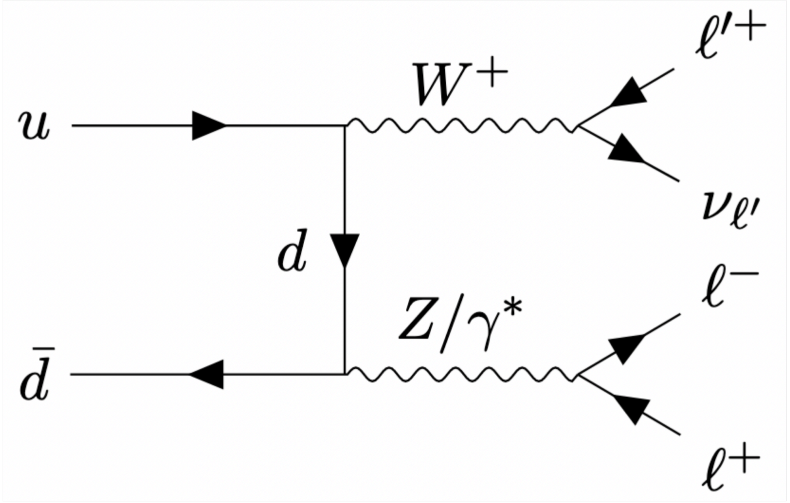
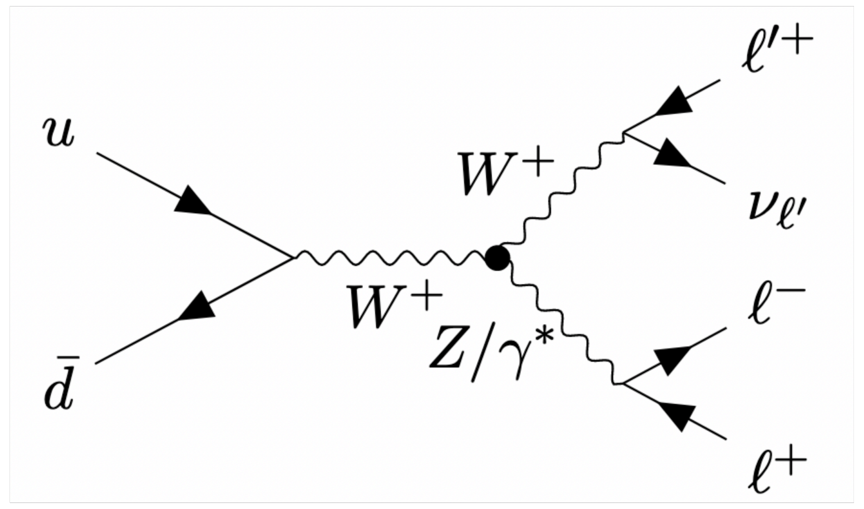
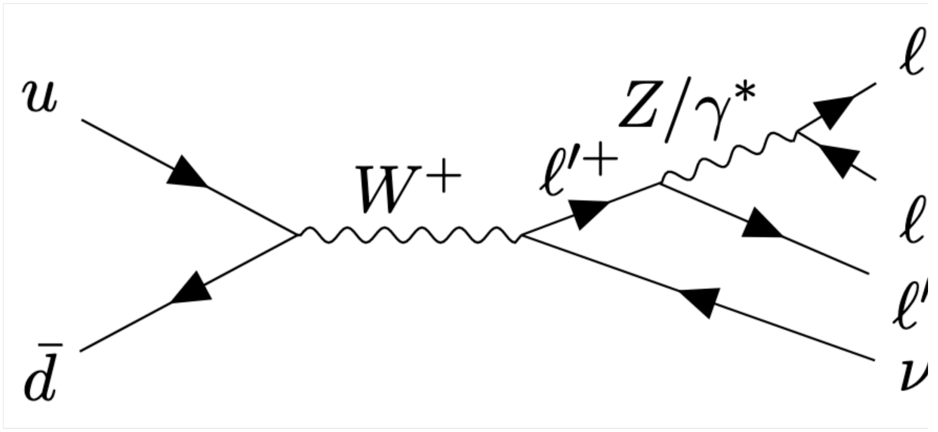
$$pp \to l'^{\pm}\nu_{l'}l^{+}l^{-} + X$$







1) Generation of NNLO+PS (QCD) results using MiNNLO$_{PS}$

Very simplified notation!

$$d\sigma_{F}^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ}\bar{B}^{\mathrm{MiNNLO_{PS}}} \times \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad}\Delta_{pwg}(p_{T,rad})\frac{R_{FJ}}{B_{FJ}} \right\}$$

$$\bar{B}^{\mathrm{MiNNLO_{PS}}} \sim e^{-S}\left\{ d\sigma_{FJ}^{(1)}\left(1 + S^{(1)}\right) + d\sigma_{FJ}^{(2)} + \left(D - D^{(1)} - D^{(2)}\right) \right\}$$

- Order $\mathcal{O}(\alpha^4\alpha_s^2)$.
- 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).

NLO+PS (EW) predictions

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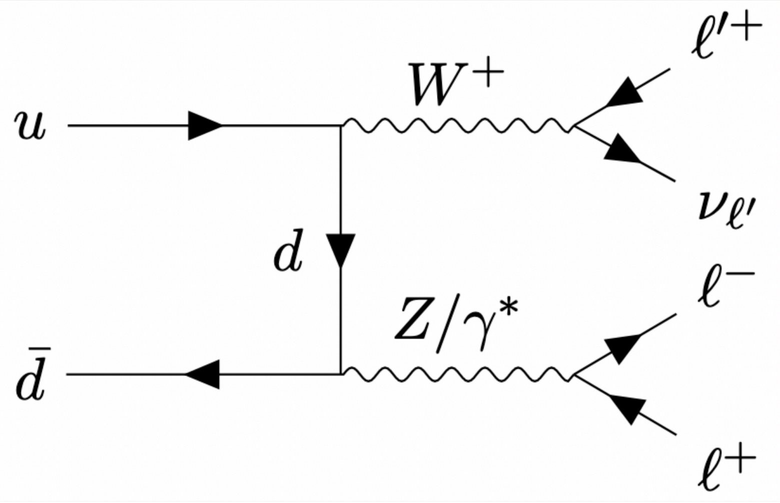
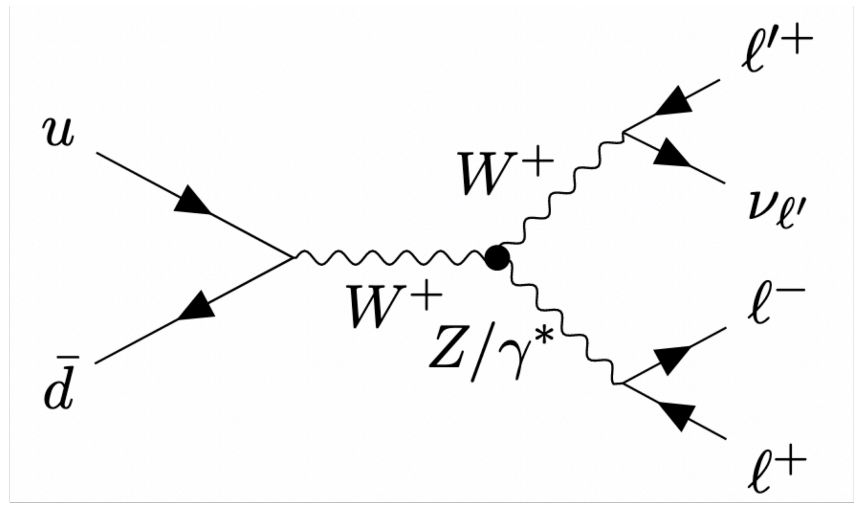
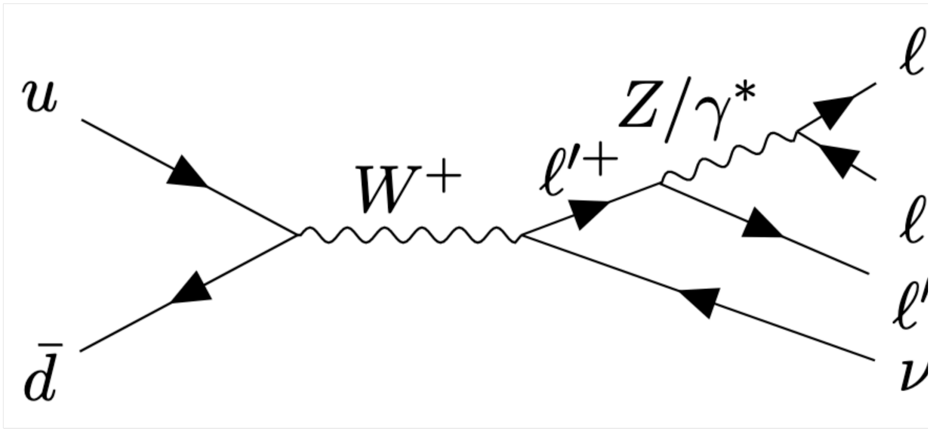
$$pp \to l'^{\pm}\nu_{l'}l^{+}l^{-} + X$$







2) Generation of NLO+PS (EW) results using POWHEG

Very simplified notation!

$$\mathrm{d}\sigma_{\mathrm{F}}^{\mathrm{pwg}} = \mathrm{d}\Phi_{\mathrm{F}}\bar{\mathrm{B}}^{\mathrm{pwg}} \times \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \int \mathrm{d}\Phi_{\mathrm{rad}}\Delta_{\mathrm{pwg}}(\mathrm{p}_{\mathrm{T,rad}})\frac{\mathrm{R}_{\mathrm{F}}}{\mathrm{B}_{\mathrm{F}}} \right\}$$

$$\bar{\mathrm{B}}^{\mathrm{pwg}} = \mathrm{d}\sigma_{\mathrm{F}}^{(1)} + \mathrm{d}\sigma_{\mathrm{F}}^{(2)}$$

- Order $\mathcal{O}(\alpha^5)$.
- Real radiation corresponds to photon radiation.
- No photon-photon contribution at this order.
- Photon-quark contributions are not considered (formally, they are $\mathcal{O}(\alpha^6 L)$).

Combinations of QCD(+PS) and EW(+PS) results

3) Combination of $NNLO_{QCD}$+PS and NLO_{EW}+PS: MATCHING SCHEMES

ADDITIVE SCHEME

$$\mathrm{NNLO}_{\mathrm{QCD}} + \mathrm{NLO}_{\mathrm{EW}} - \mathrm{LO}$$

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

MULTIPLICATIVE SCHEME

$$\mathrm{NNLO}_{\mathrm{QCD}} \times \mathrm{NLO}_{\mathrm{EW}}/\mathrm{LO}$$

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

- 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.

Combinations of QCD(+PS) and EW(+PS) results

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3) Combination of $NNLO_{QCD}$+PS and NLO_{EW}+PS: TREATMENT OF THE SHOWER

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 (POWHEG multiple-radiation scheme —> **three different starting scales** for ISR, FSR from W decay, FSR from Z decay).

$\mathrm{NNLO}_{\mathrm{QCD}}$+PS and $\mathrm{NLO}_{\mathrm{EW}}$+PS combinations

ADDITIVE:

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

MULTIPLICATIVE:

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

[2208.12660]

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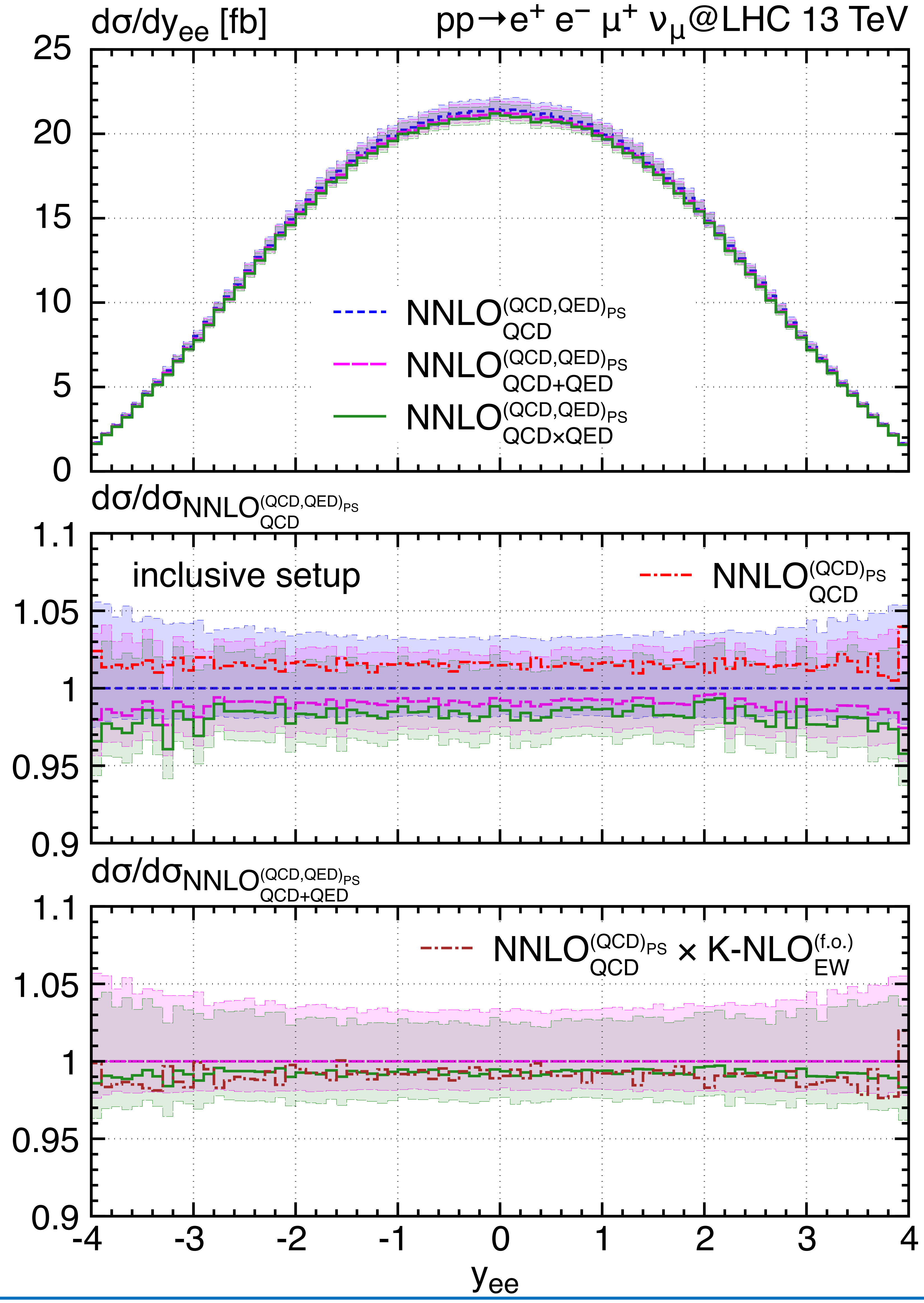
Rapidity of the Z boson - inclusive setup



LEGEND:

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

Phenomenological results (1)

[2208.12660]

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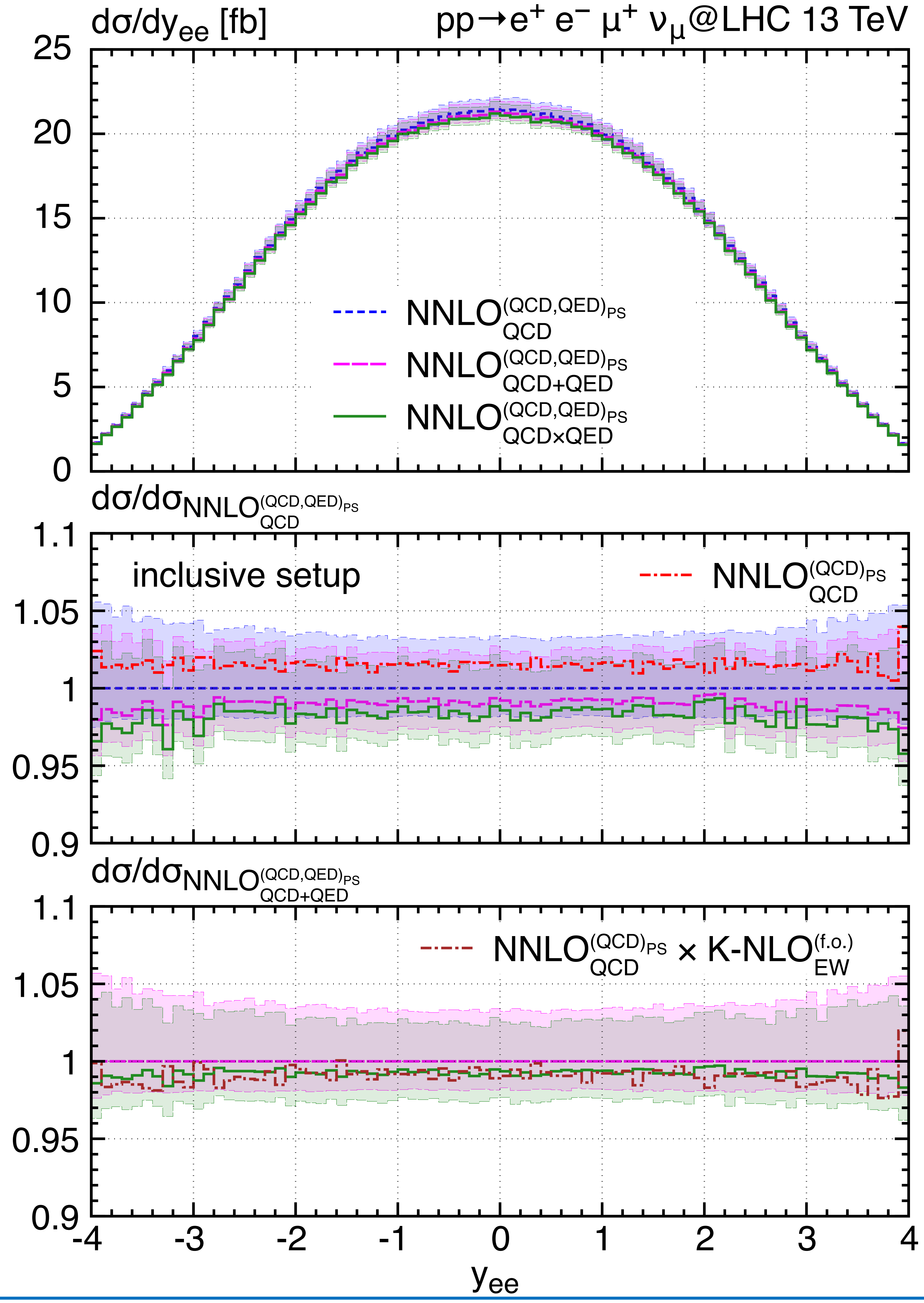
Rapidity of the Z boson - inclusive setup



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

LEGEND:

- (blue) $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- (magenta) $\mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- (green) $\mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- (red) $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
- (brown) $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times K_{\mathrm{EW}}^{\mathrm{f.o.}}$

Phenomenological results (2)

[2208.12660]

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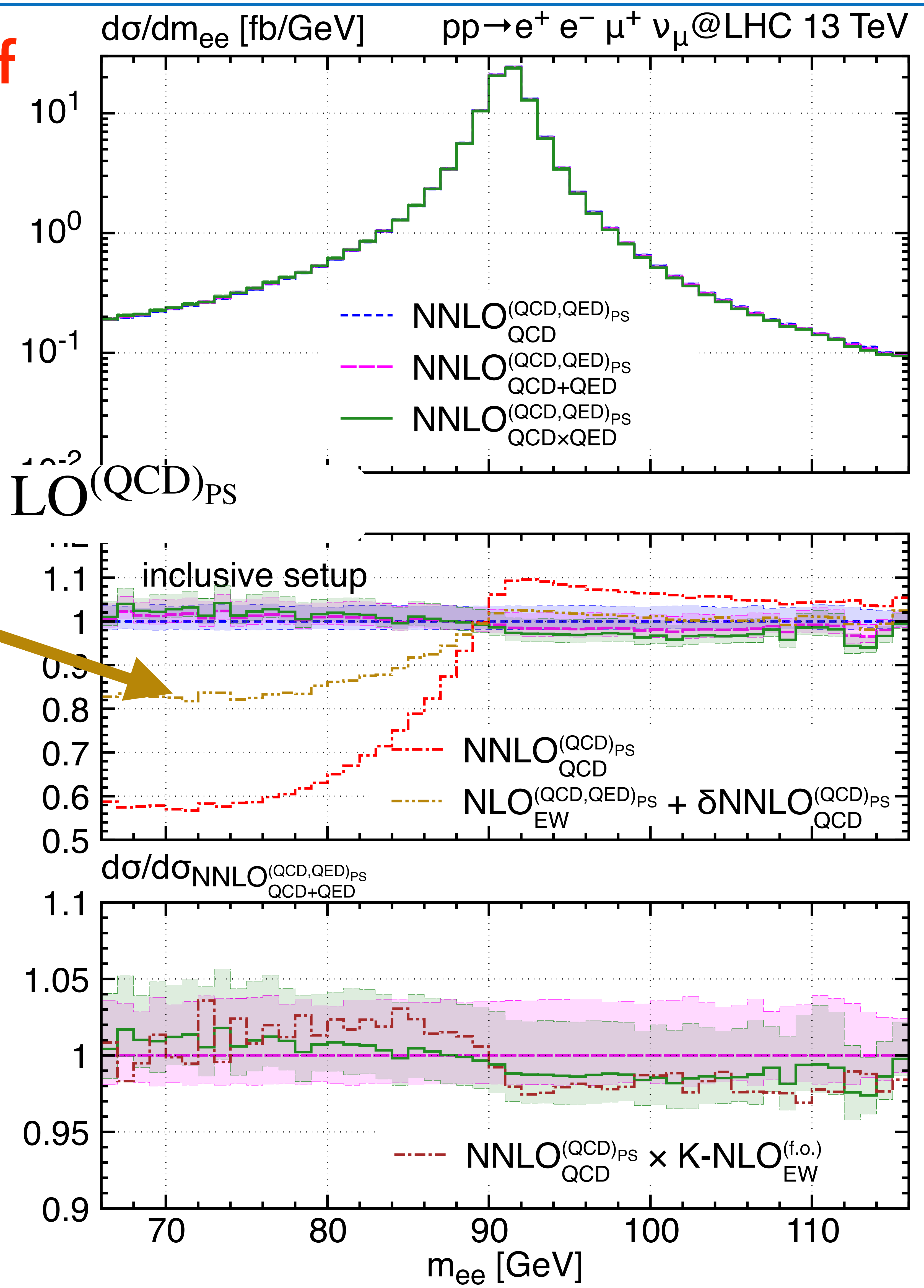
Invariant mass of the Z boson - inclusive setup

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



LEGEND:

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

Phenomenological results (2)

[2208.12660]

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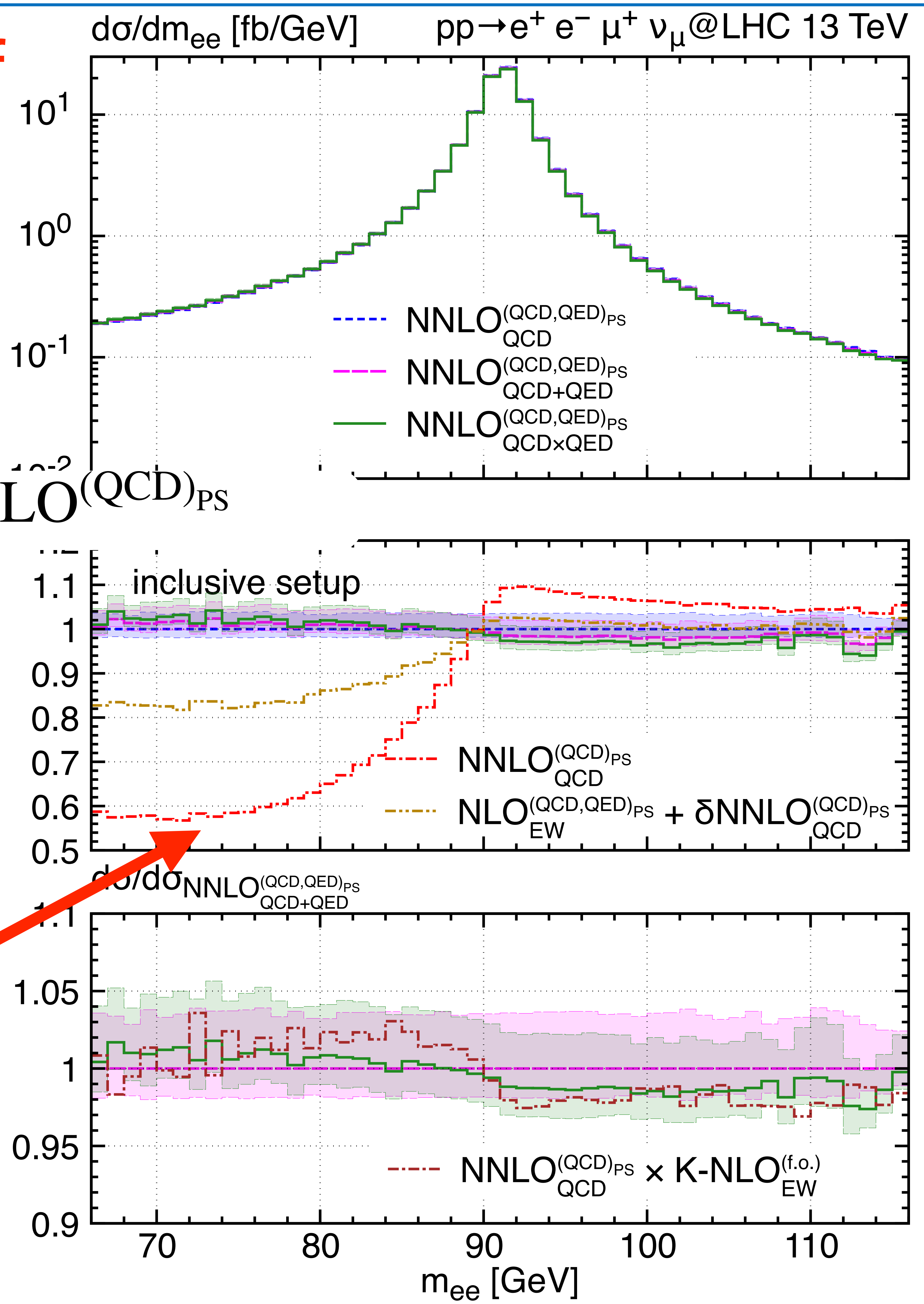
Invariant mass of the Z boson - inclusive setup

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



LEGEND:

- (blue) $\text{NNLO}^{(\text{QCD,QED})_{\text{PS}}}_{\text{QCD}}$
- (magenta) $\text{NNLO}^{(\text{QCD,QED})_{\text{PS}}}_{\text{QCD+EW}}$
- (green) $\text{NNLO}^{(\text{QCD,QED})_{\text{PS}}}_{\text{QCD}\times\text{EW}}$
- (red) $\text{NNLO}^{(\text{QCD})_{\text{PS}}}_{\text{QCD}}$
- (brown) $\text{NNLO}^{(\text{QCD})_{\text{PS}}}_{\text{QCD}} \times K^{\text{f.o.}}_{\text{EW}}$

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

Phenomenological results (2)

[2208.12660]

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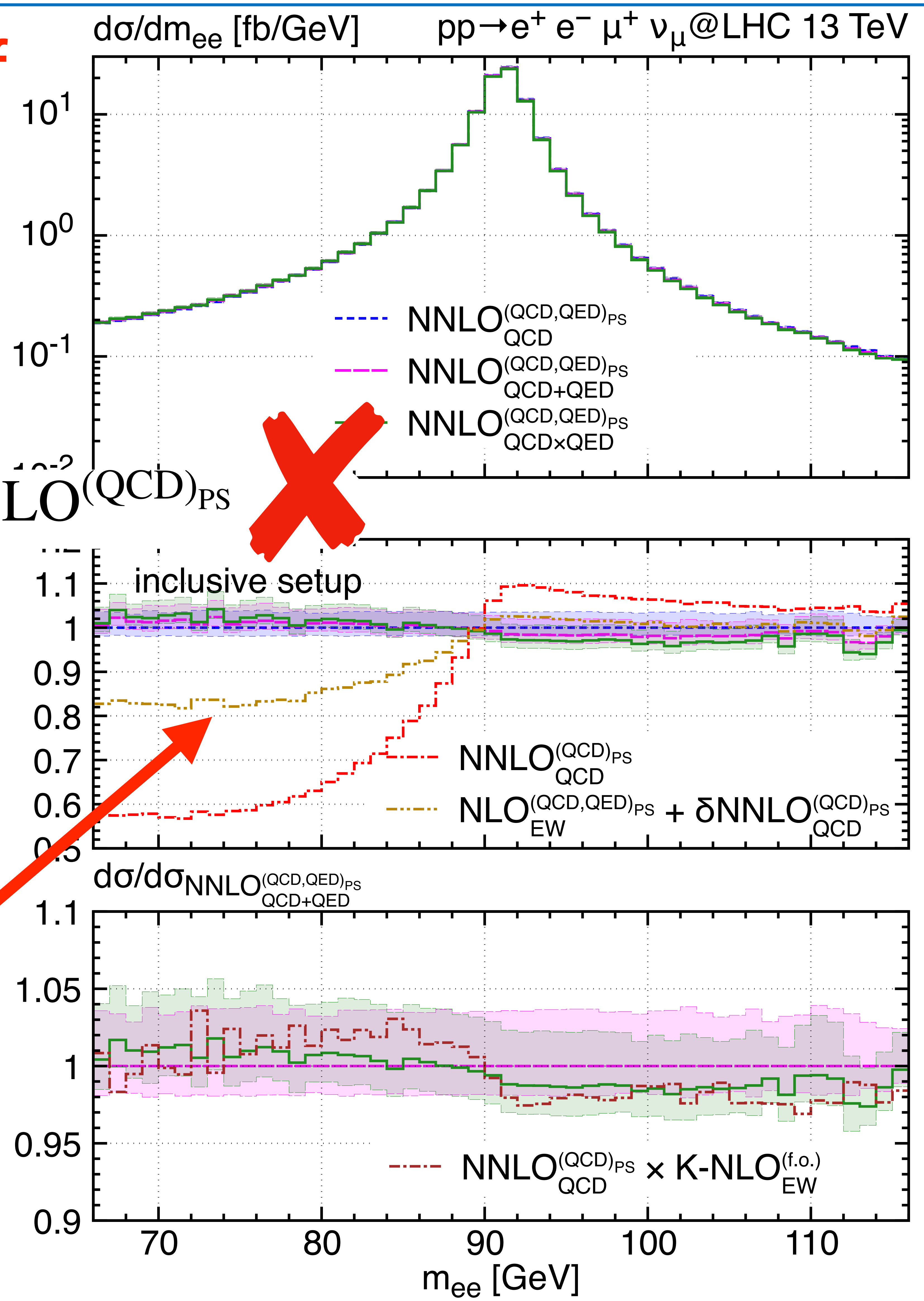
Invariant mass of the Z boson - inclusive setup



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

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

LEGEND:

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

Phenomenological results (3)

[2208.12660]

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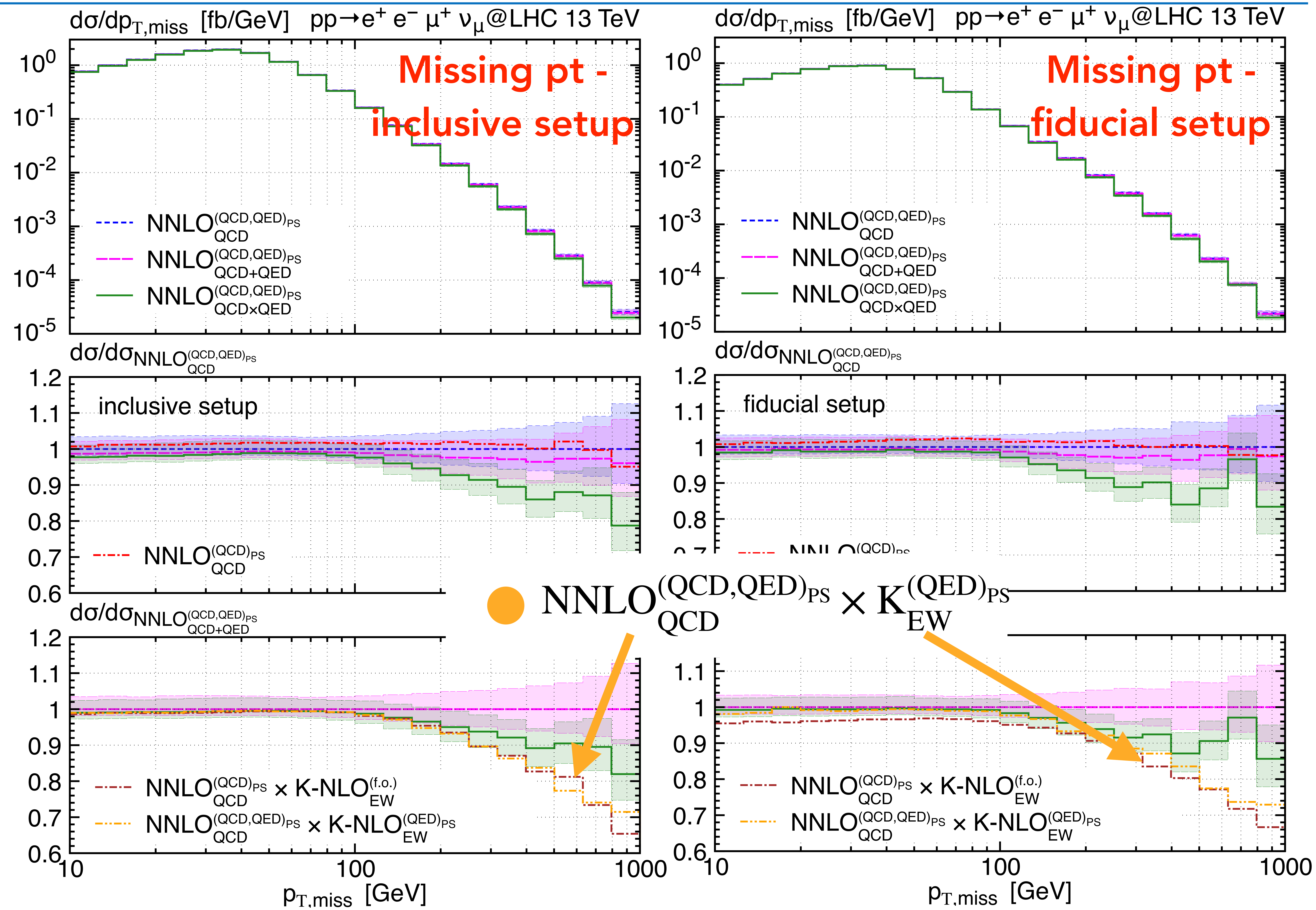
LEGEND:

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



Phenomenological results (3)

[2208.12660]

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LEGEND:

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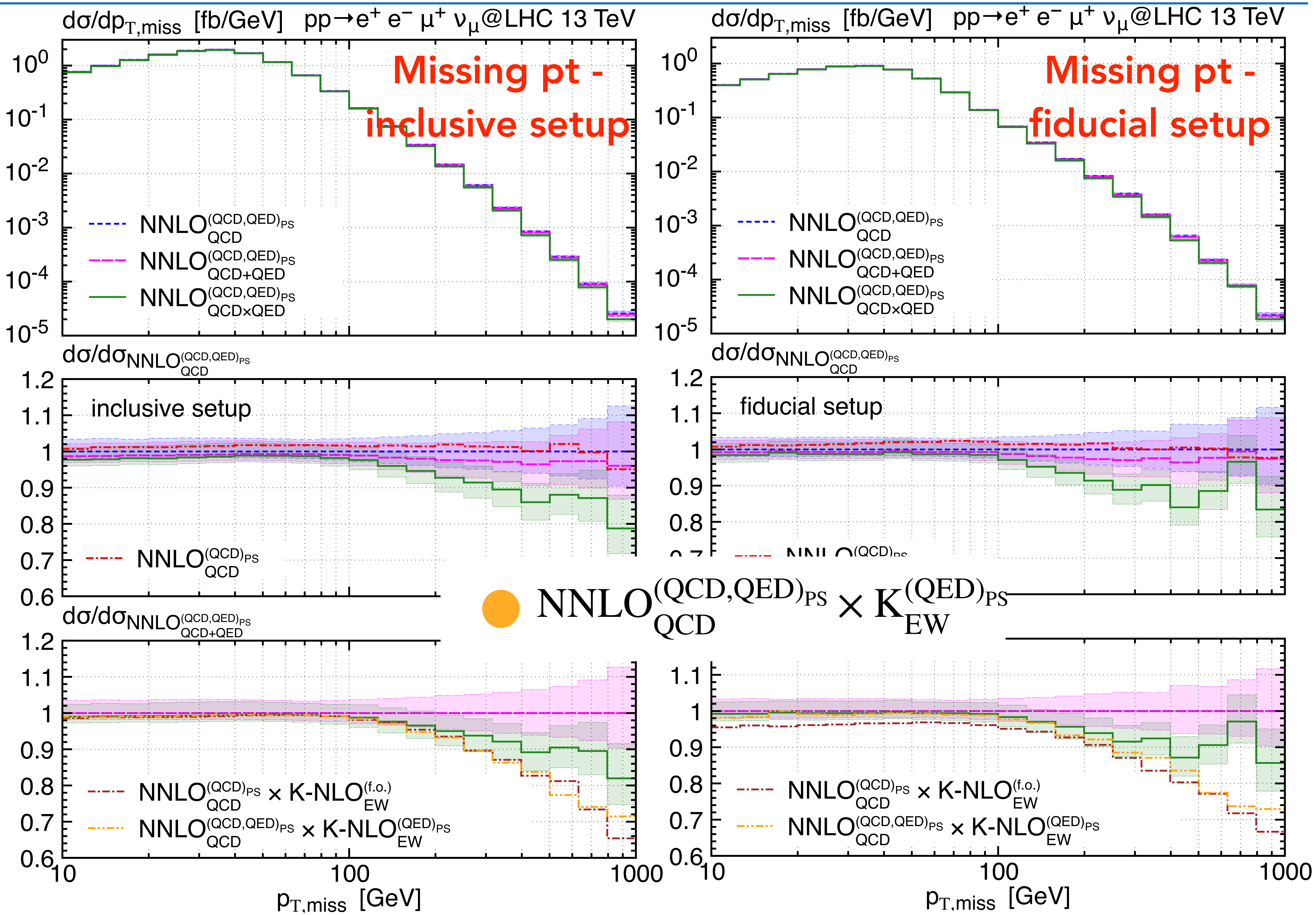
- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
- $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}} \times \mathrm{K}_{\mathrm{EW}}^{\mathrm{f.o.}}$



$\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}} \times \mathrm{K}_{\mathrm{EW}}^{(\mathrm{QED})_{\mathrm{PS}}}$

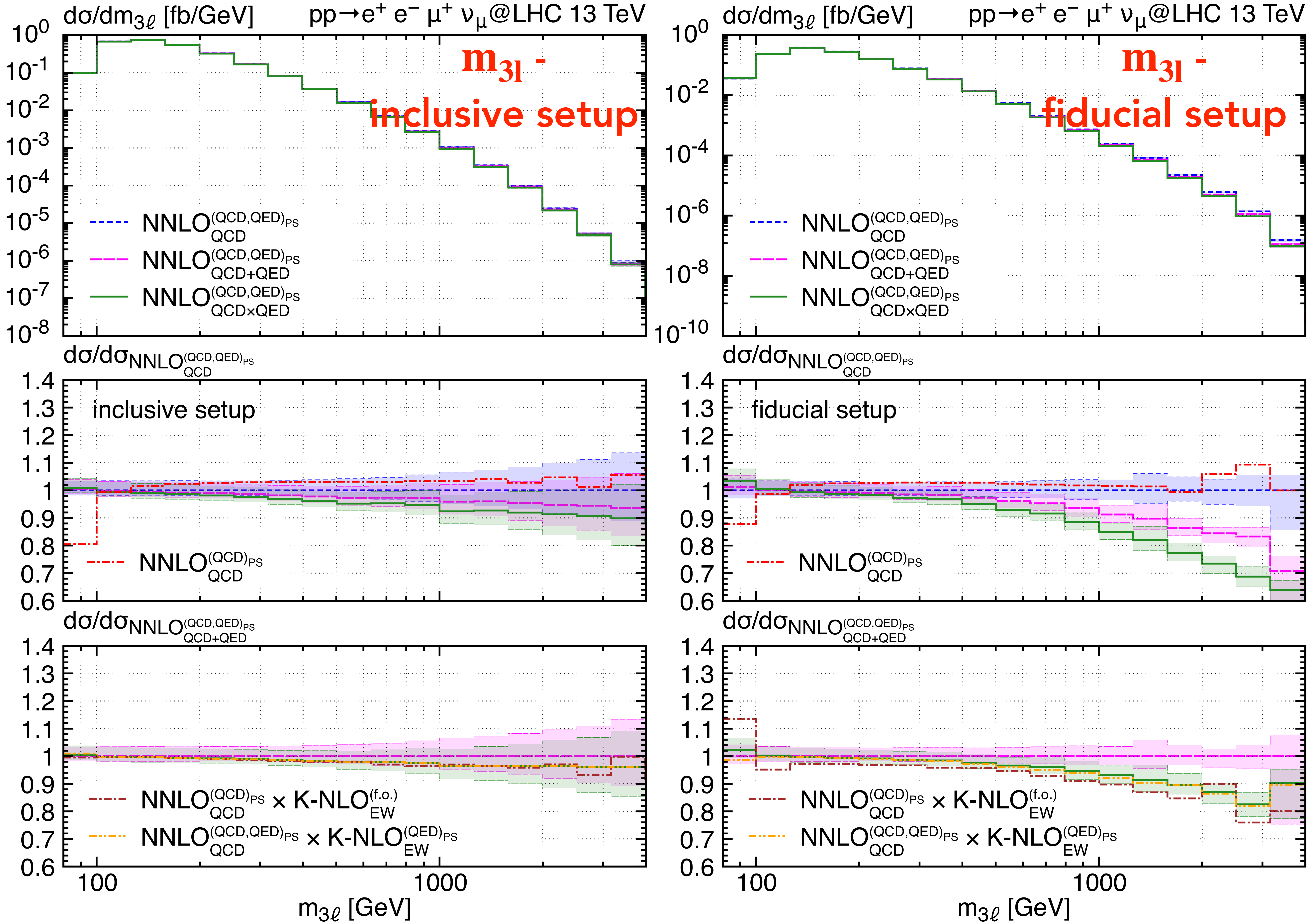
is affected by giant K-factors

Phenomenological results (4)

[2208.12660]

LEGEND:

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



Phenomenological results (4)

[2208.12660]

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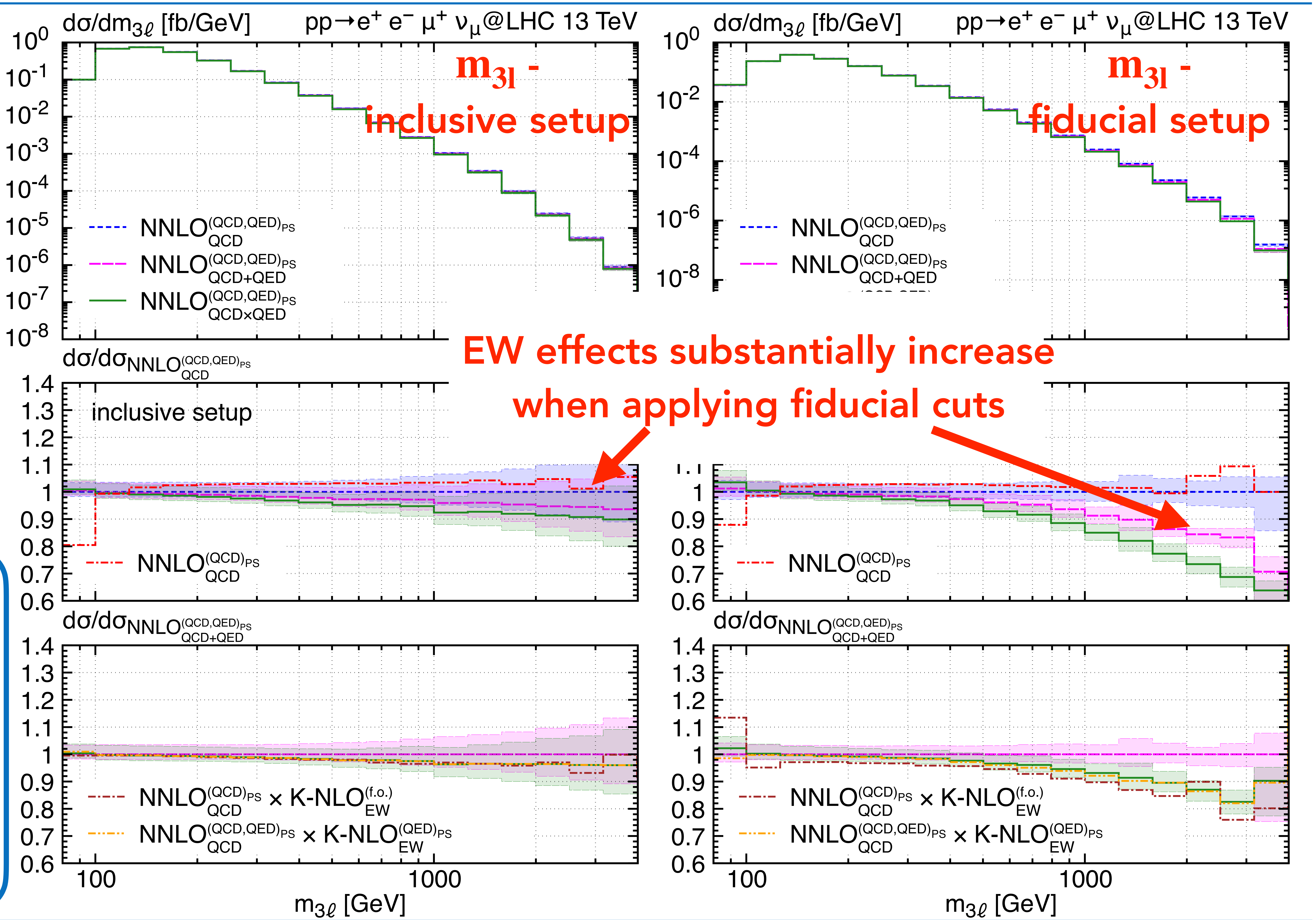
LEGEND:

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

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 (1)

[2208.12660]

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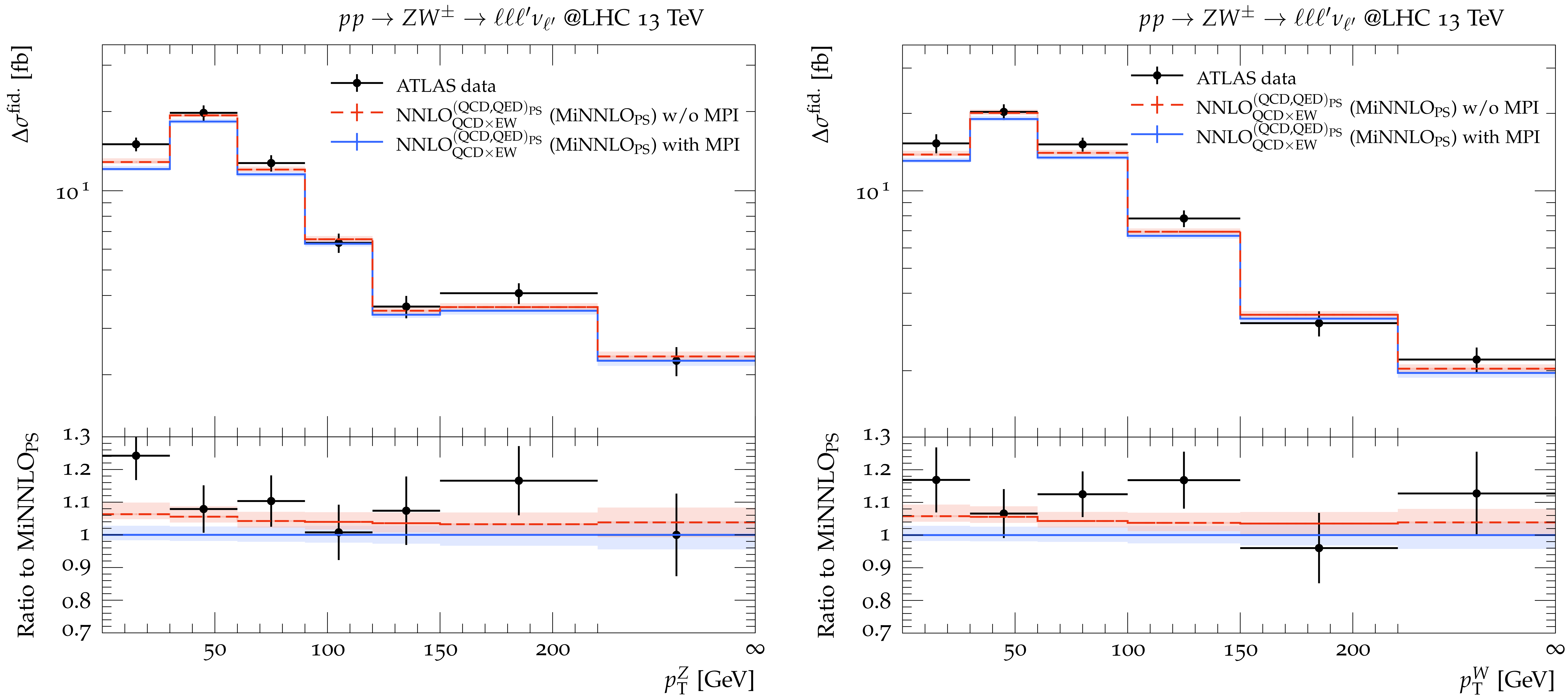
ATLAS data from Eur. Phys. J. C 79 (2019)



Comparison against data (2)

[2208.12660]

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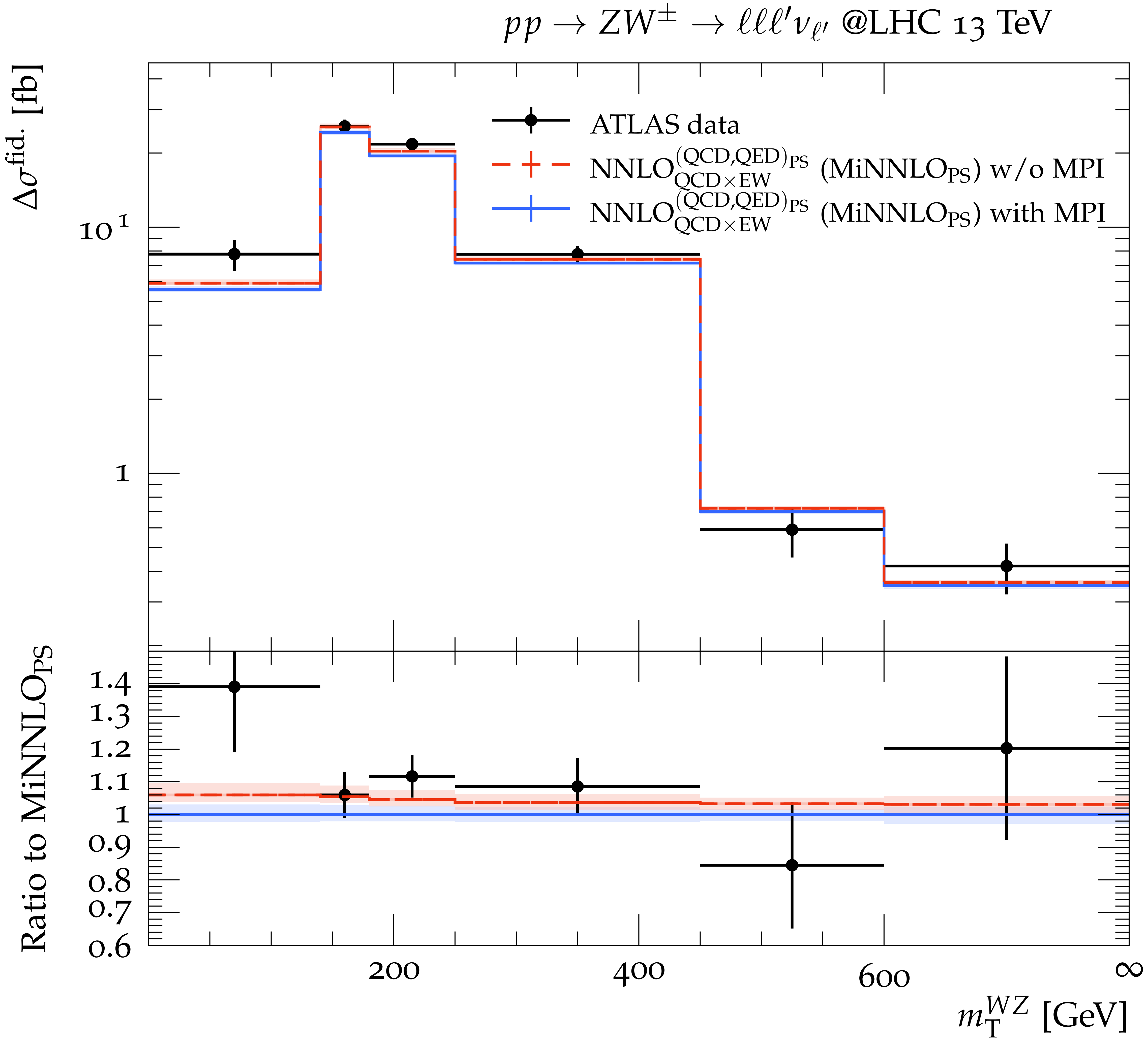
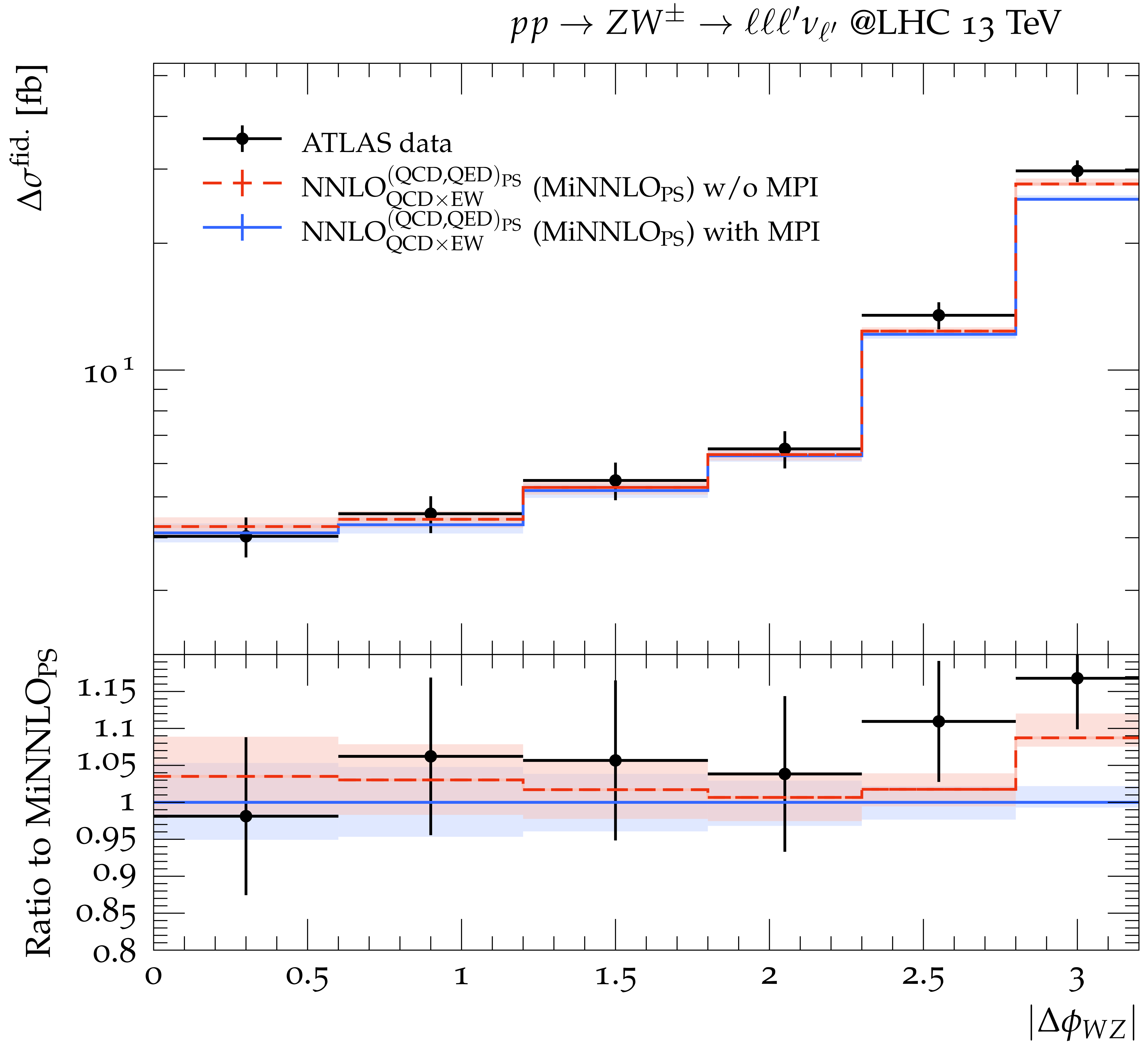
ATLAS data from Eur. Phys. J. C 79 (2019)





Conclusions and Outlooks

- **NNLO+PS (QCD)** predictions are strongly needed for a realistic description of LHC events.
- The **MiNNLO$_{\mathbf{PS}}$ 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 showers for 13 TeV LHC collisions.
- The natural next step is the implementation of the combined generation of NNLO QCD and NLO EW accurate events, rather than an a posteriori recombination.

Conclusions and Outlooks

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Thank you!