LHC EW WG General Meeting - CERN

15-17 November 2022

WZ at NNLO QCD and NLO EW matched to parton showers

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

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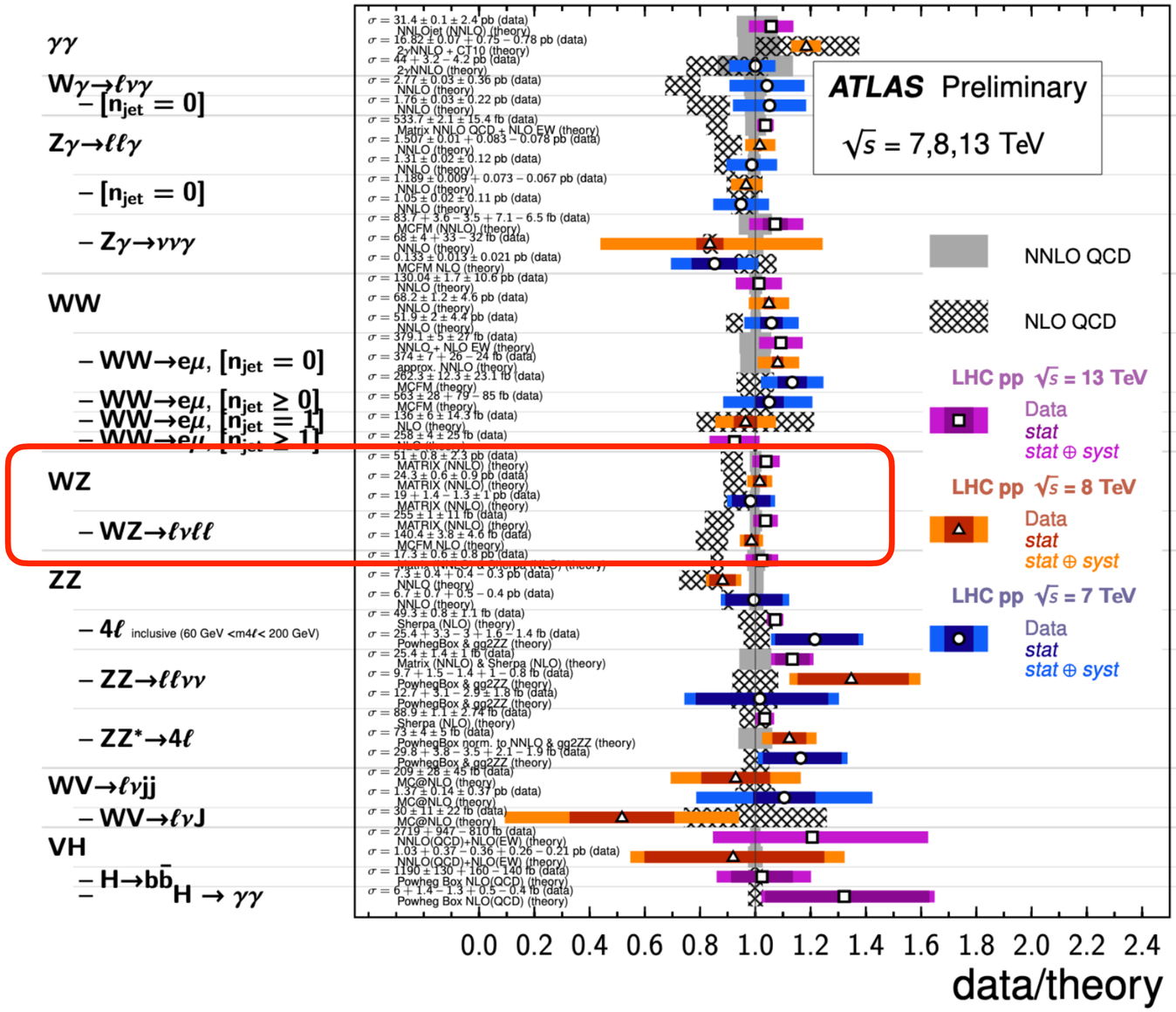
Silvia Zanoli

Max Planck Institute for Physics

WZ production



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)]

THIS TALK:

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

MiNNLO$_{PS}$

	F	F+J	F+JJ
F@MiNNLO$_{PS}$	**NNLO**	NLO	LO

[Monni, Nason, Re, Wisemann, Zanderighi '19]

- No computationally intense reweighting
- No unphysical merging scale
- LL accuracy of the shower preserved
- Numerically efficient

MiNNLOPS starting point : analytic all order formula

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

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

MiNNLOPS starting point : analytic all order formula

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

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

MiNNLOPS starting point : analytic all order formula

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

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Calculation embedded in the POWHEG formalism:

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

POWHEG Sudakov for the emission of the first (hardest) radiation

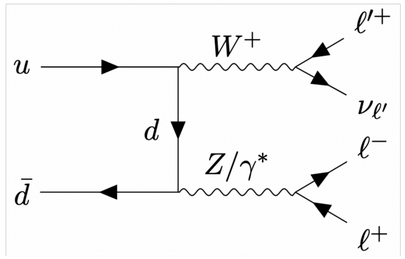
NNLO accurate in F

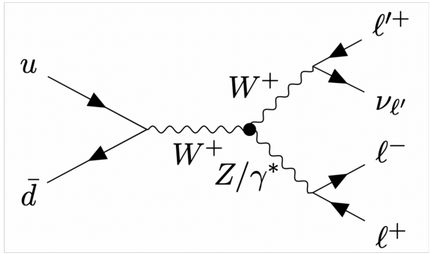
$$\bar{\mathrm{B}}^{\mathrm{MiNNLO_{PS}}} \sim \mathrm{e}^{-\mathrm{S}}\left\{ \mathrm{d}\sigma_{\mathrm{FJ}}^{(1)}\left(1 + \mathrm{S}^{(1)}\right) + \mathrm{d}\sigma_{\mathrm{FJ}}^{(2)} + \left(\mathrm{D} - \mathrm{D}^{(1)} - \mathrm{D}^{(2)}\right) \right\}$$

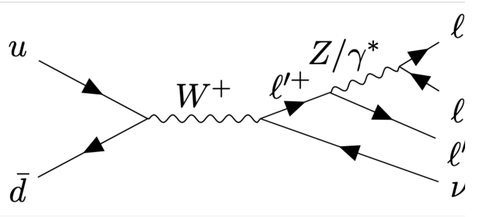
Simplified notation!

NNLO+PS (QCD) predictions

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







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

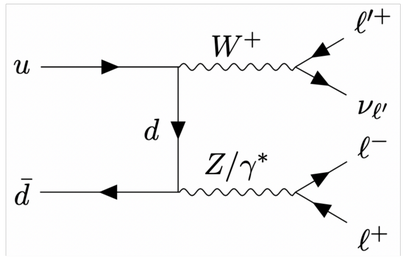
$$\mathrm{d}\sigma_{\mathrm{F}}^{\mathrm{MiNNLO_{PS}}} = \mathrm{d}\Phi_{\mathrm{FJ}}\bar{\mathrm{B}}^{\mathrm{MiNNLO_{PS}}} \times \left\{ \Delta_{\mathrm{pwg}}(\Lambda_{\mathrm{pwg}}) + \int \mathrm{d}\Phi_{\mathrm{rad}}\Delta_{\mathrm{pwg}}(\mathrm{p_{T,rad}})\frac{\mathrm{R_{FJ}}}{\mathrm{B_{FJ}}}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

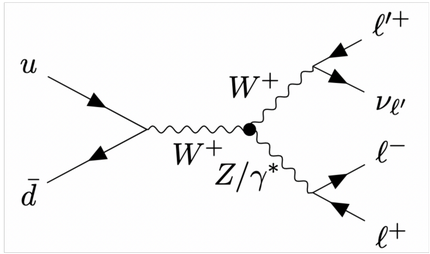
$$\bar{\mathrm{B}}^{\mathrm{MiNNLO_{PS}}} \sim \mathrm{e}^{-\mathrm{S}}\left\{ \mathrm{d}\sigma_{\mathrm{FJ}}^{(1)}\left(1+\mathrm{S}^{(1)}\right) + \mathrm{d}\sigma_{\mathrm{FJ}}^{(2)} + \left(\mathrm{D}-\mathrm{D}^{(1)}-\mathrm{D}^{(2)}\right) \right\}$$

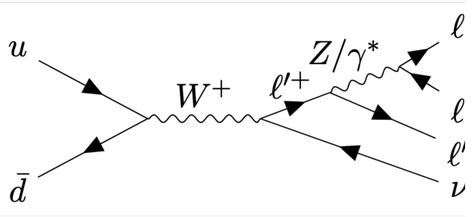
- Order $\mathcal{O}(\alpha^4\alpha_s^2)$.
- No loop-induced gluon-fusion contributions.
- Important NNLO corrections (10-15%), due to radiation zero effect at LO (= vanishing of the leading helicity amplitudes in some kinematic regions).

NLO+PS (EW) predictions

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







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

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

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

- 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 $\mathcal{O}(\alpha^6 L)$).

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

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

ADDITIVE SCHEME

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

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

MULTIPLICATIVE SCHEME

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

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

- 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.

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

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4) 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).

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

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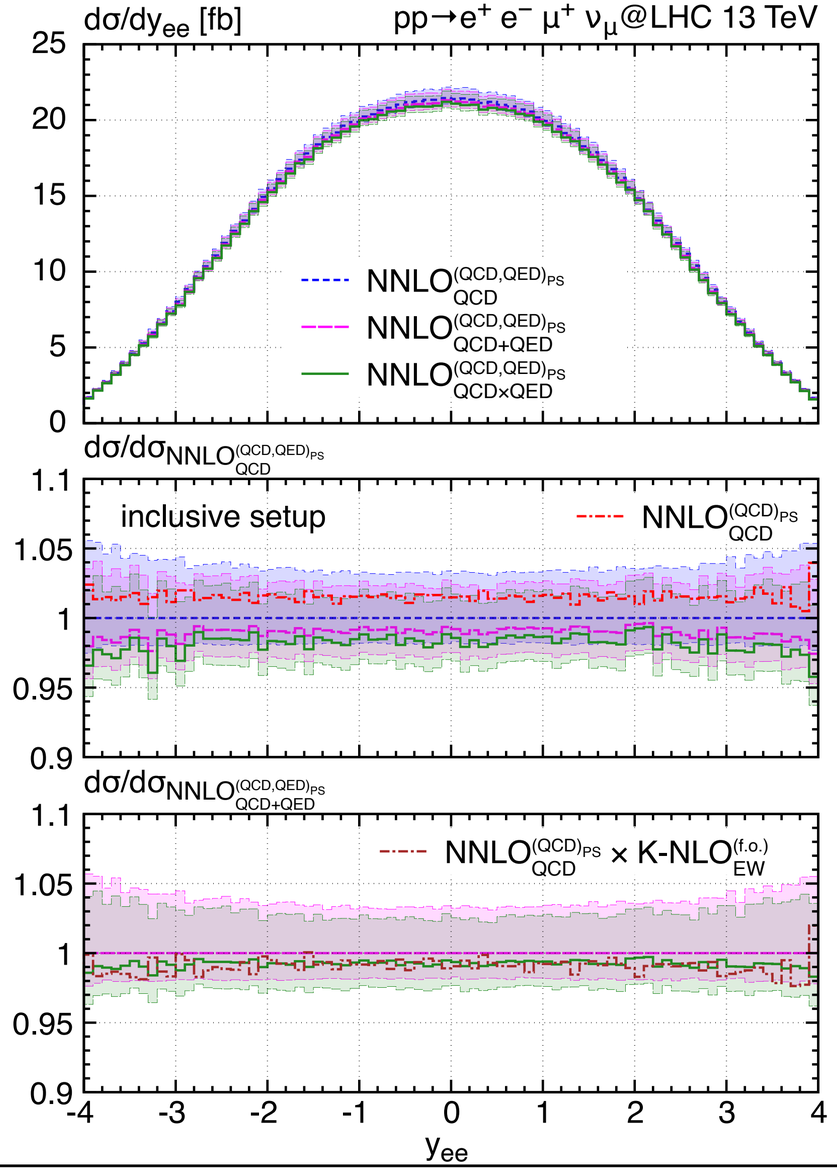
Rapidity of the Z boson - inclusive setup



LEGEND:

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

Phenomenological results (1)

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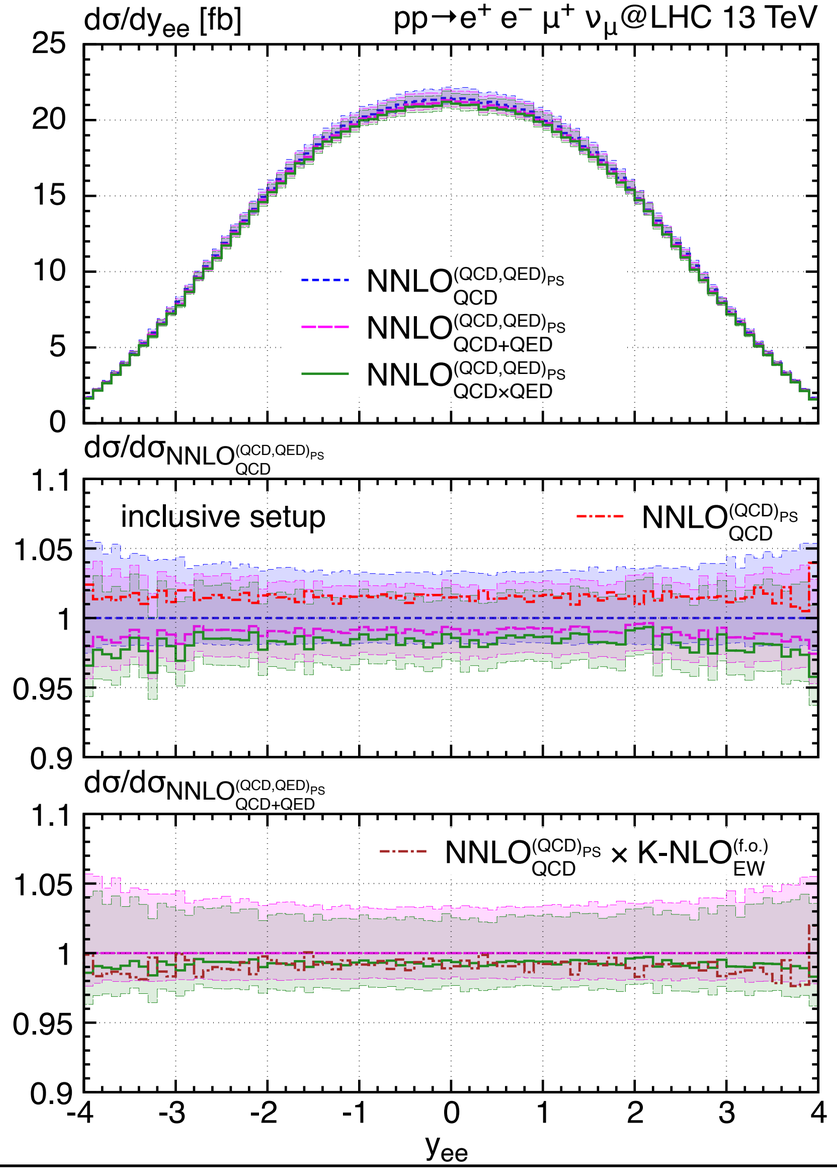
Rapidity of the Z boson - inclusive setup

- 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 emissions are negligible for this observable



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 (2)

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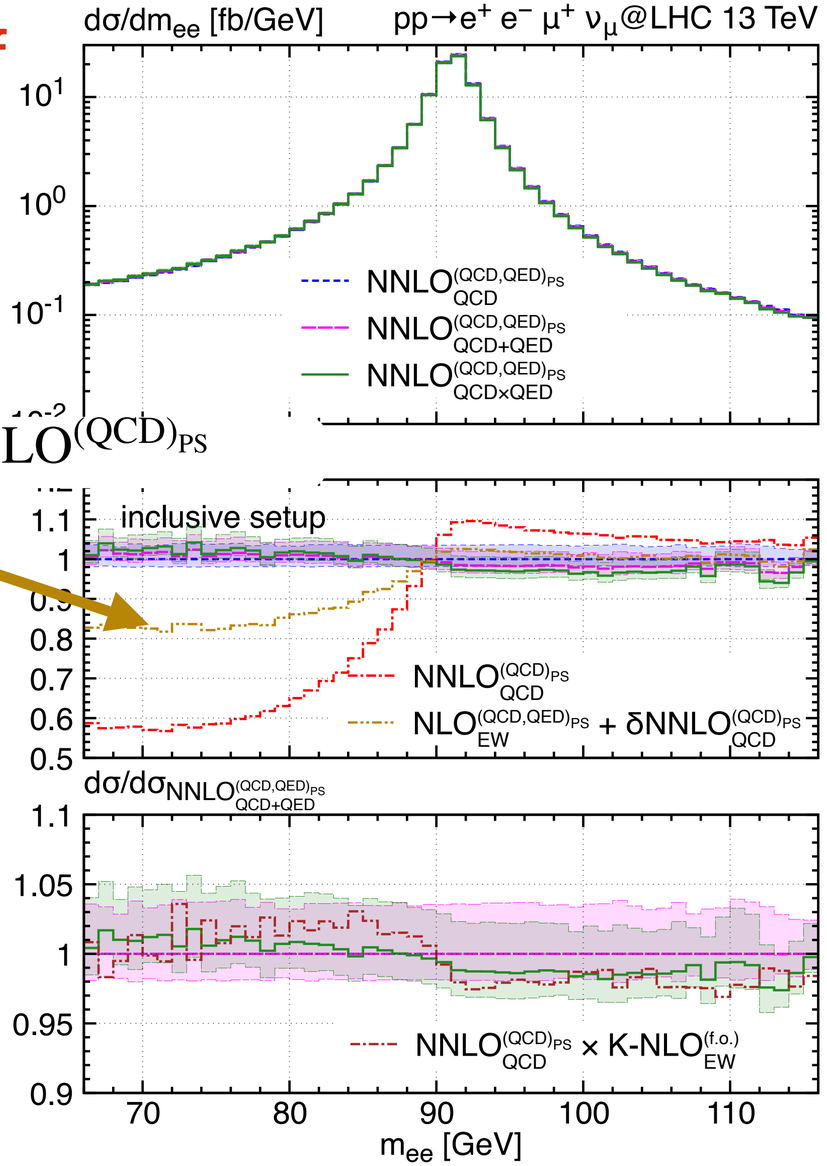
Invariant mass of the Z boson - inclusive setup

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



LEGEND:

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

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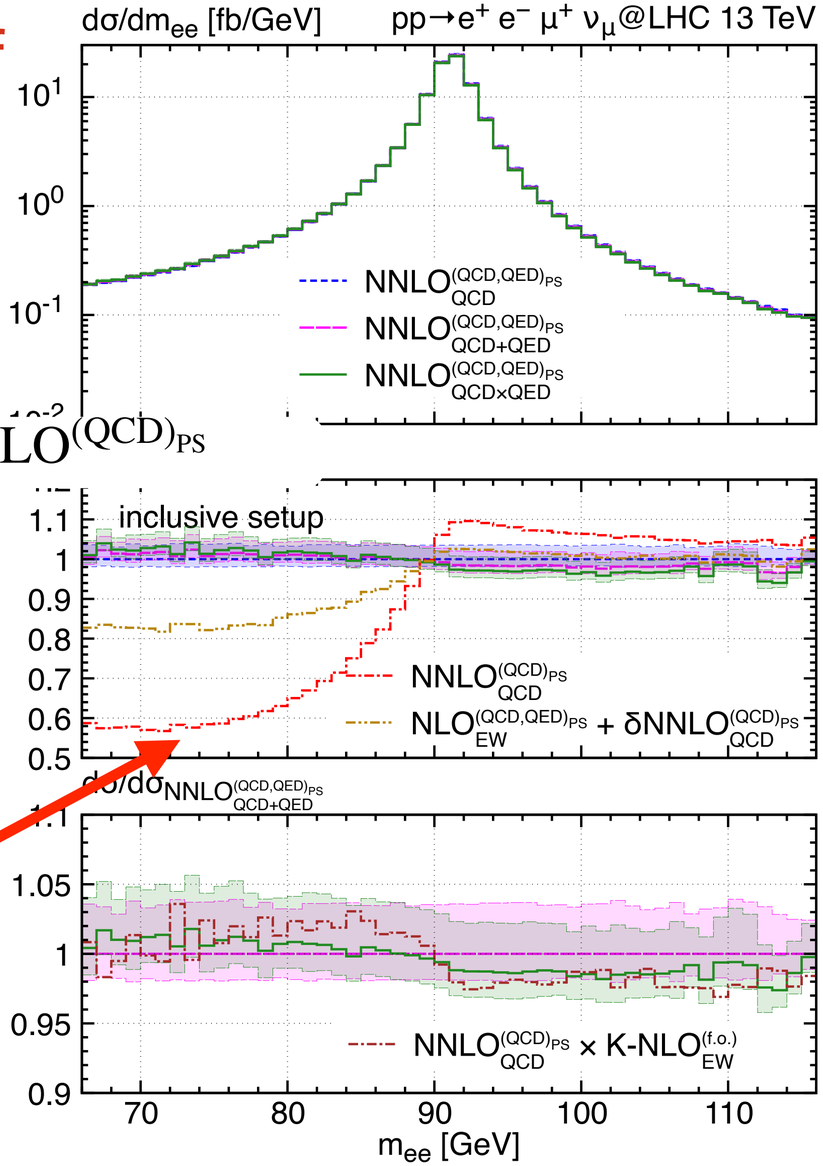
Invariant mass of the Z boson - inclusive setup

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



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

LEGEND:

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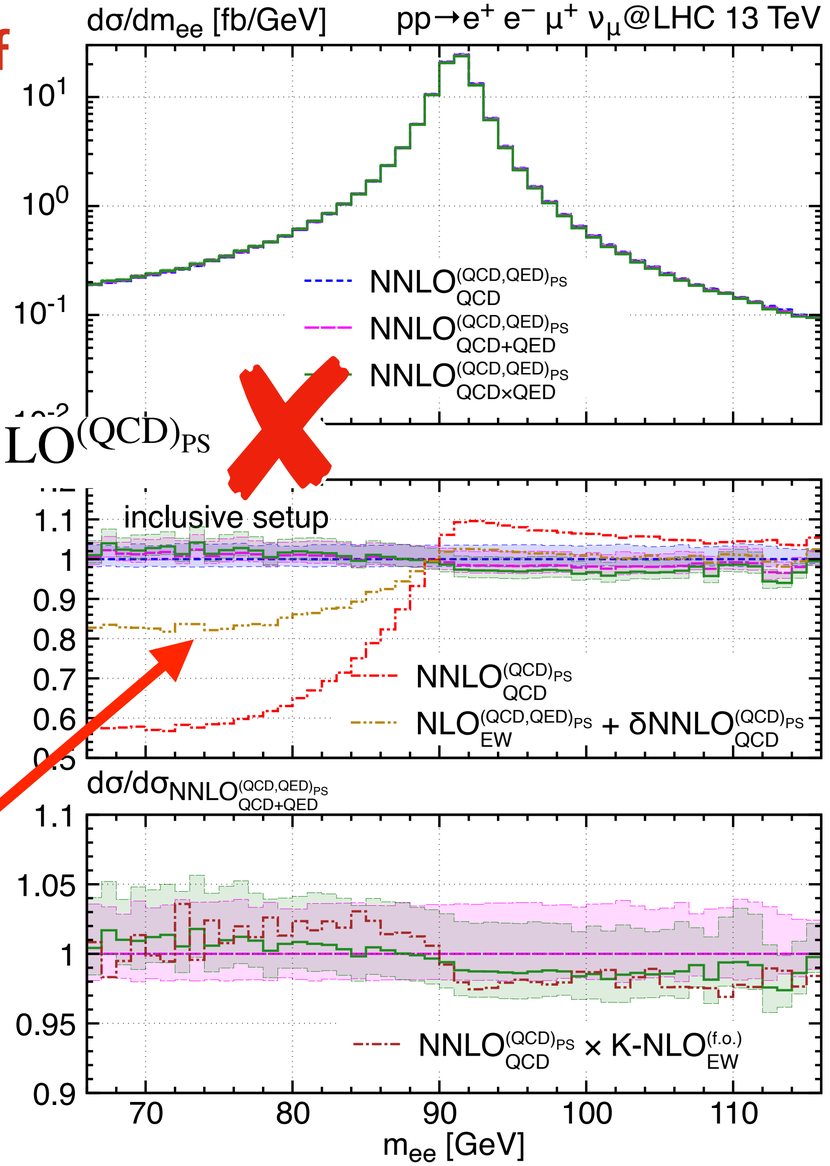
Phenomenological results (2)

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:

- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD+EW}}$
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Phenomenological results (3)

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LEGEND:

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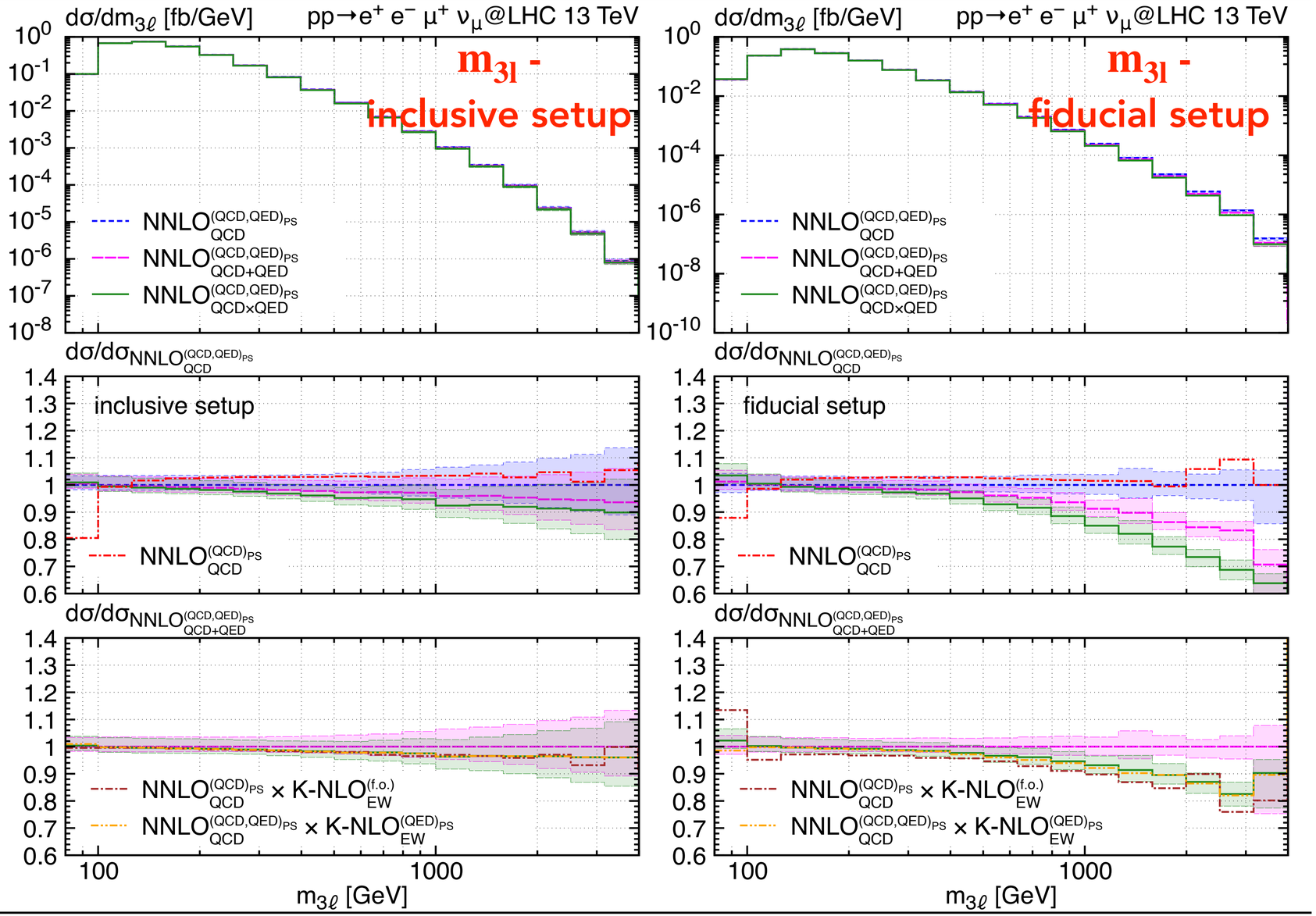

Phenomenological results (3)

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LEGEND:

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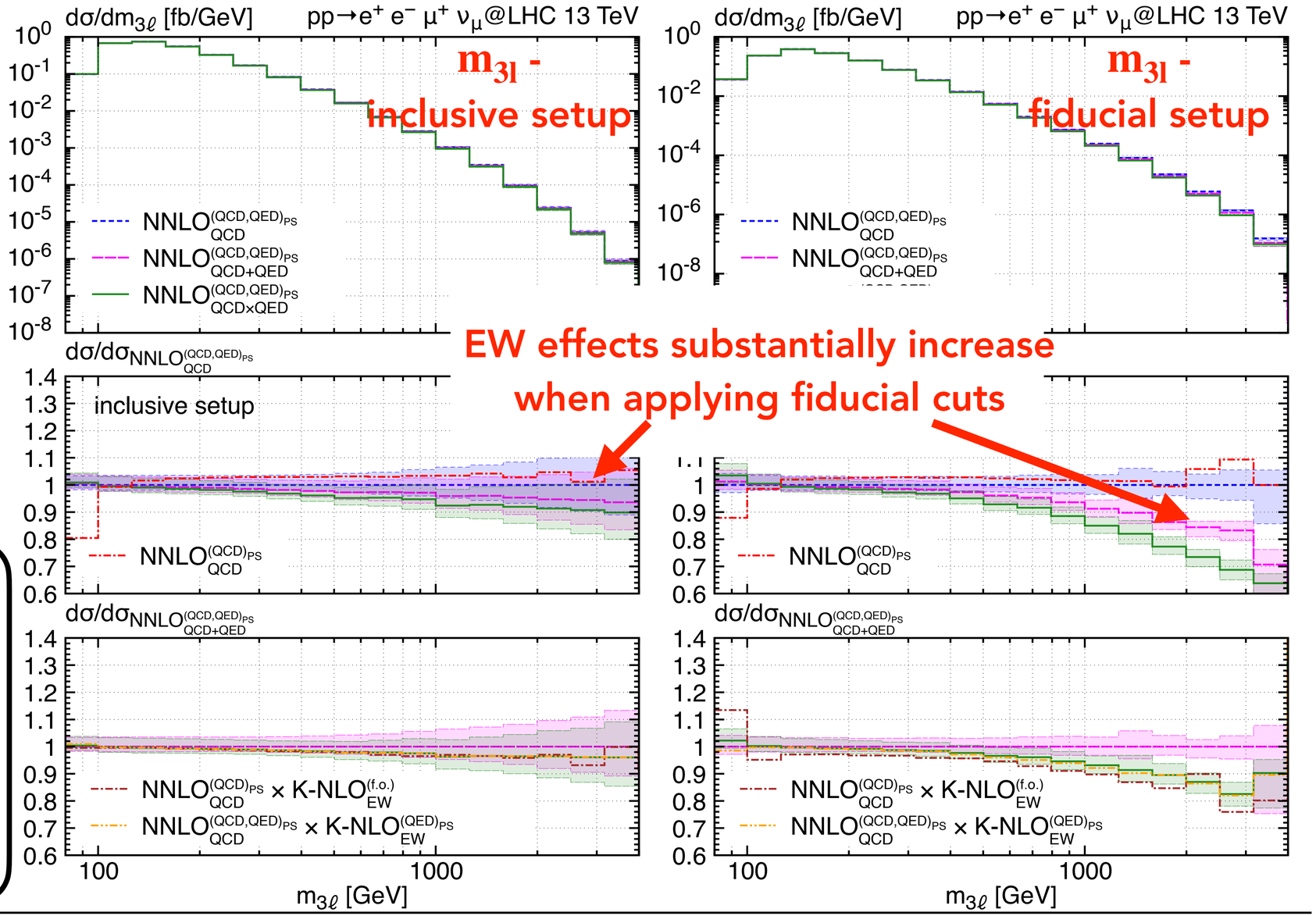
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}} \times \mathrm{K}^{\mathrm{f.o.}}_{\mathrm{EW}}$

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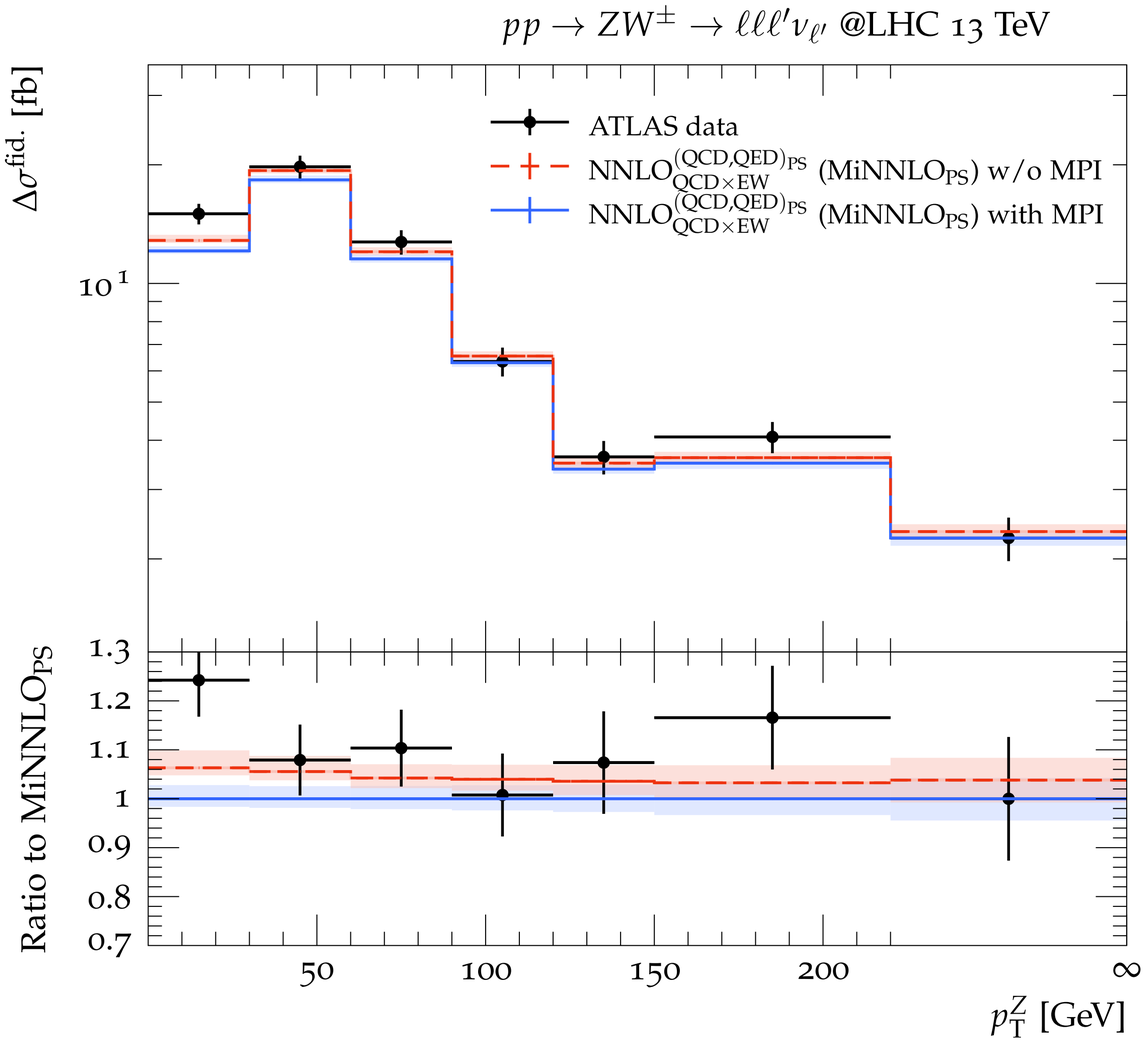
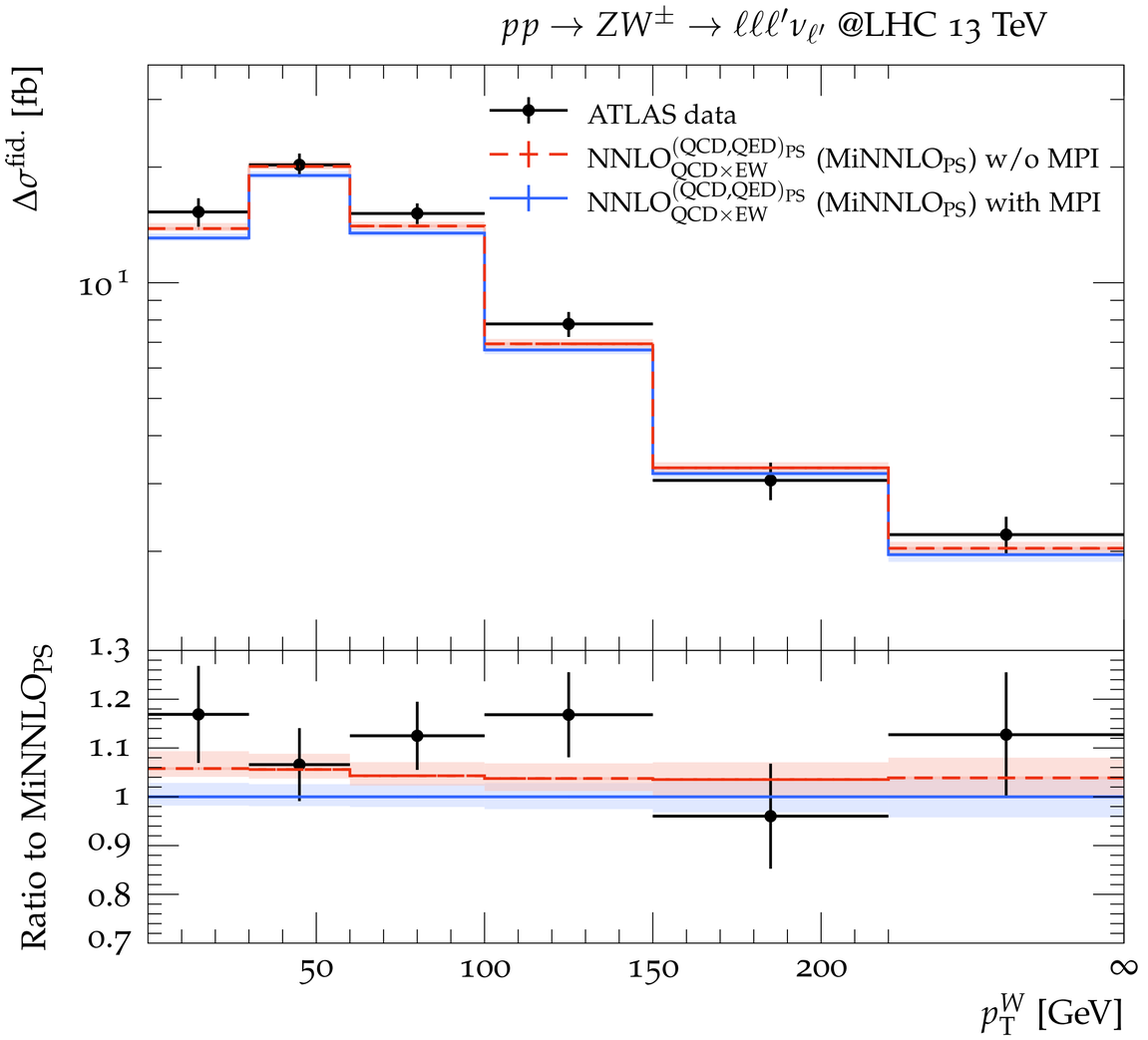
ATLAS data from Eur. Phys. J. C 79 (2019)





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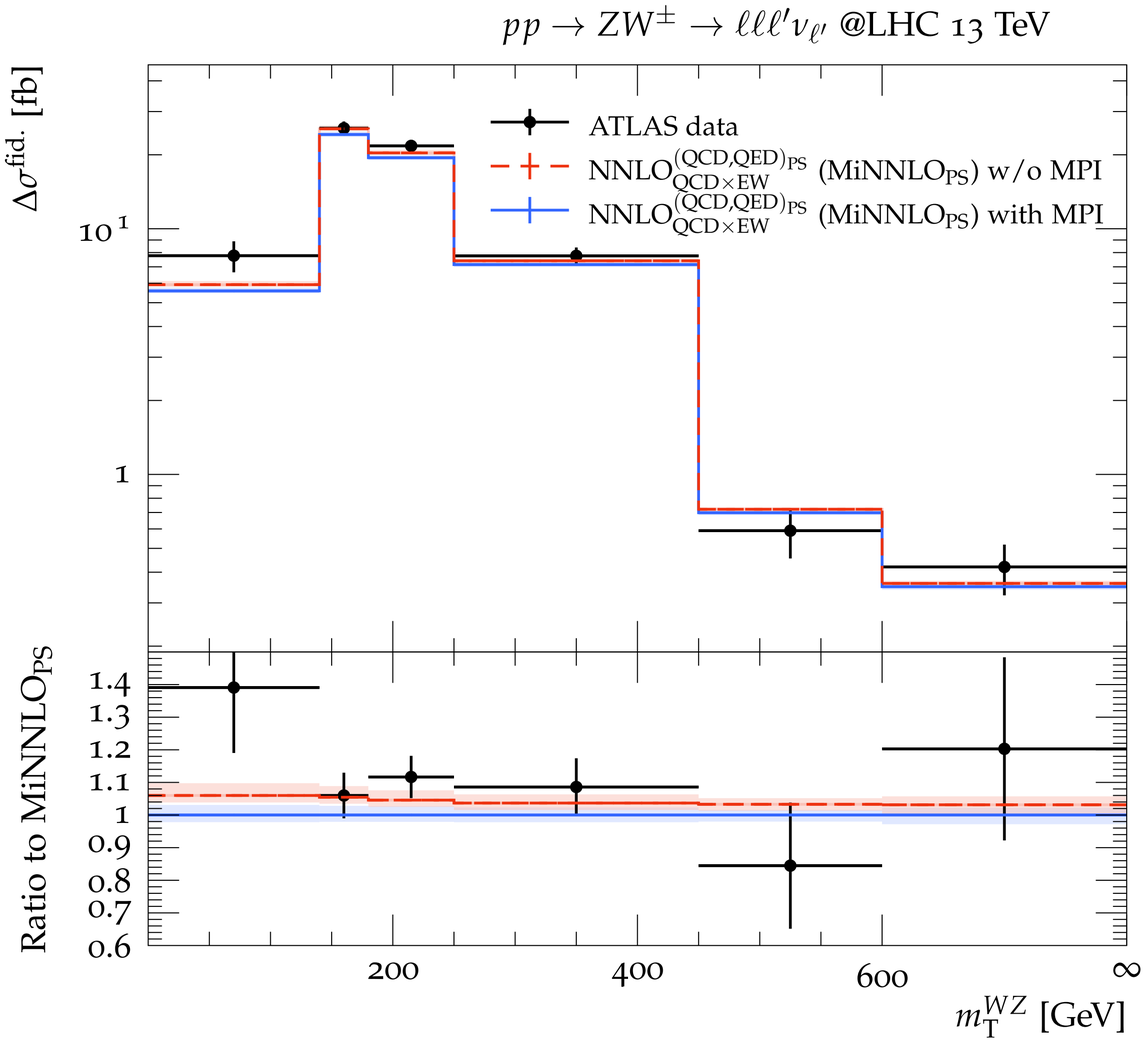

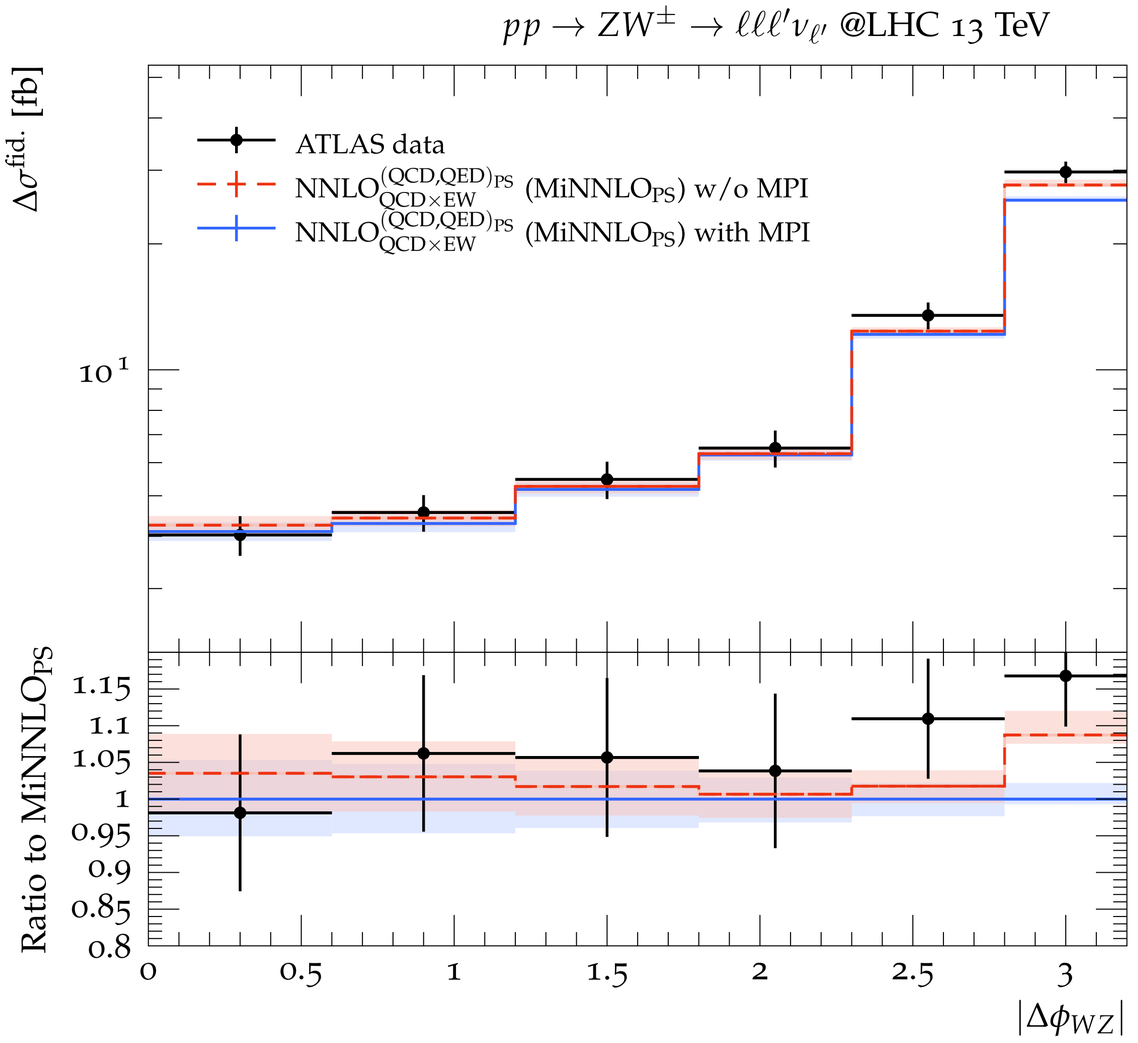

Conclusions and Outlooks

- **NNLO+PS (QCD)** predictions are strongly needed for a realistic description of LHC events and 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 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.

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Thank you!

BACKUP

MiNNLO$_{PS}$

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	F	F+J	F+JJ
F@POWHEG [Nason '04]	NLO	LO	LL
F@MiNLO' [Hamilton, Nason, Oleari, Zanderighi '12]	NLO	NLO	LO
F@MiNNLO$_{PS}$ [Monni, Nason, Re, Wisemann, Zanderighi '19]	**NNLO**	NLO	LO

- No computationally intense reweighting
- No unphysical merging scale
- LL accuracy of the shower preserved
- Numerically efficient

Phenomenological results (3)

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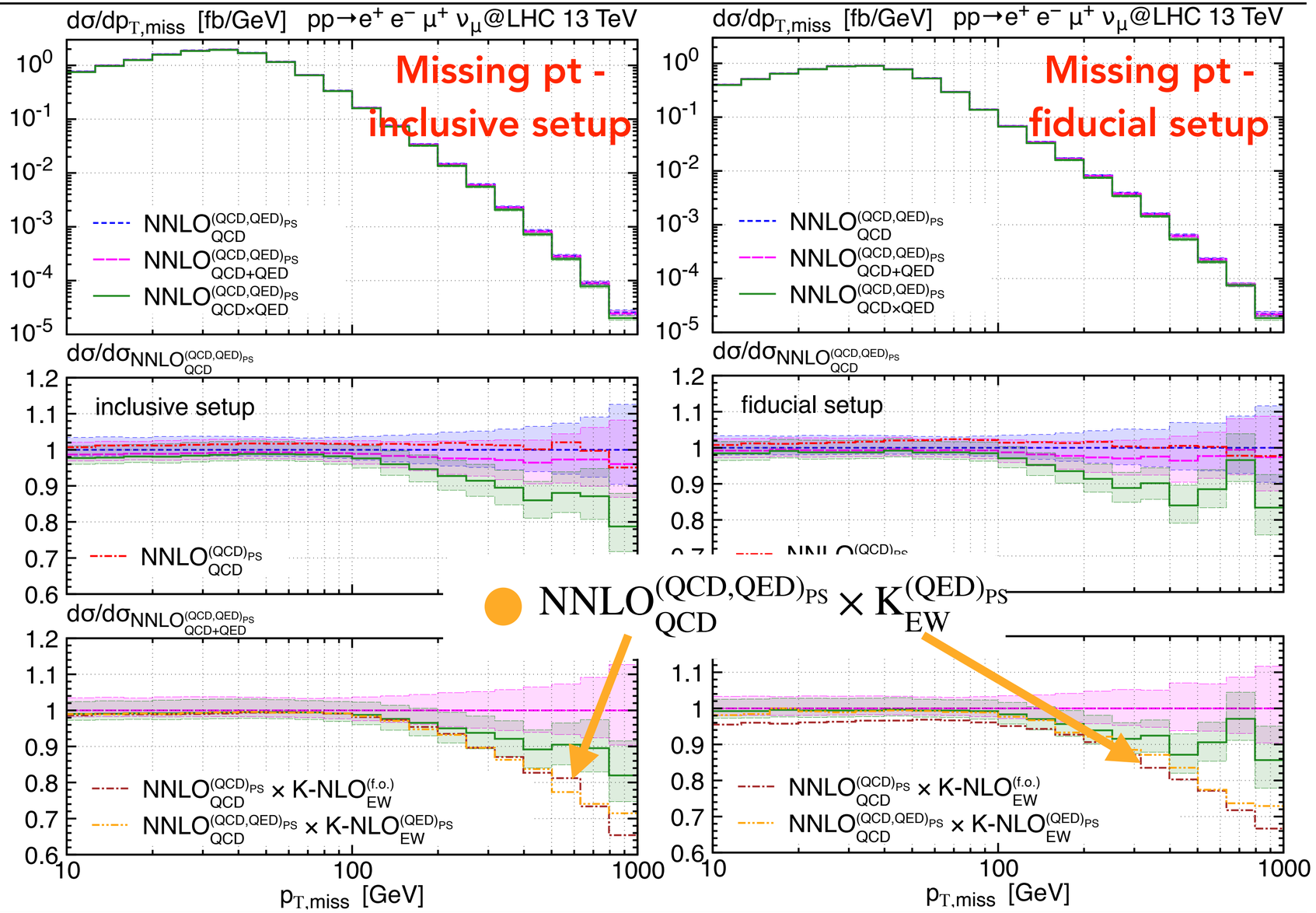
LEGEND:

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



Phenomenological results (3)

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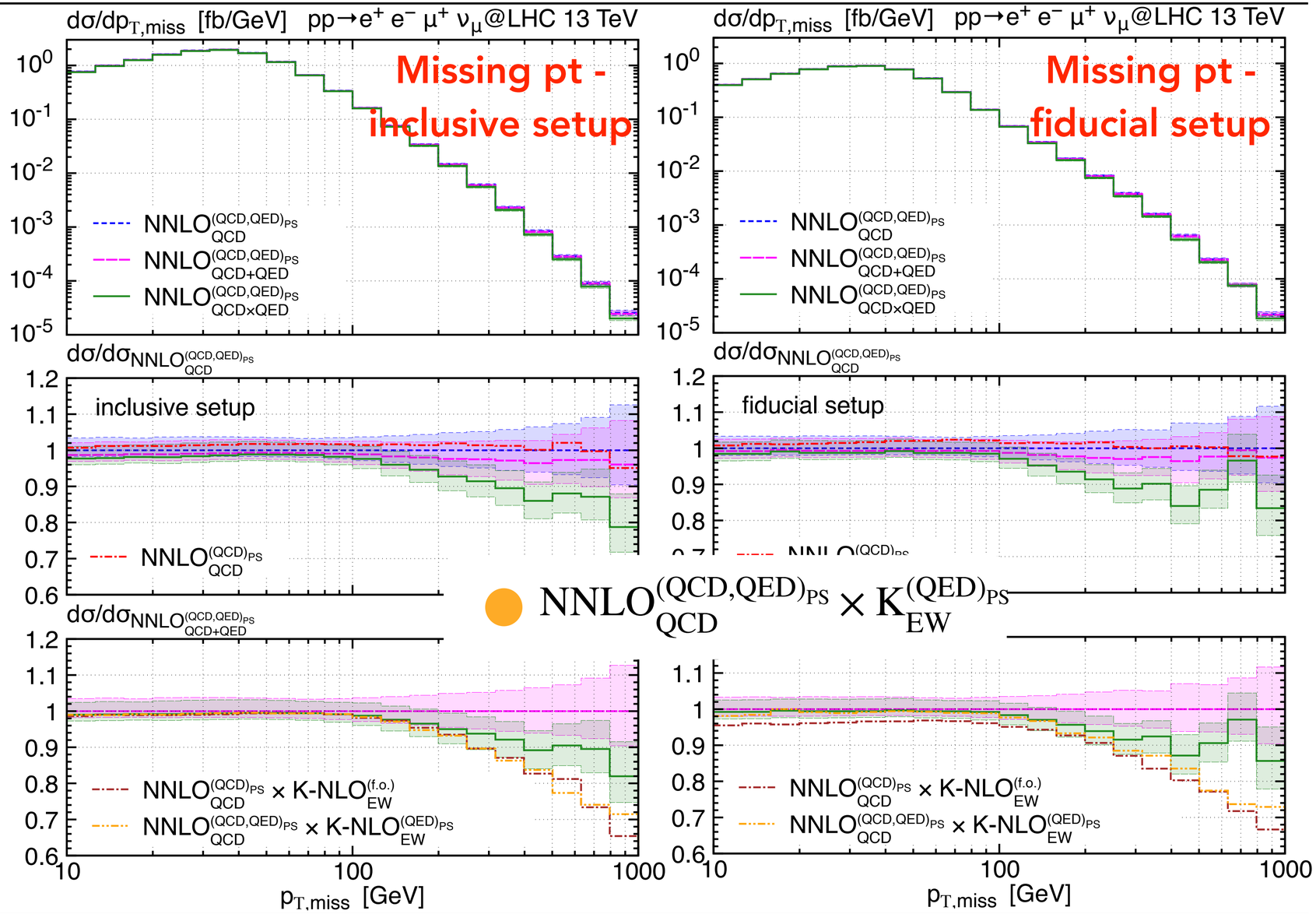
LEGEND:

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

● is affected by giant K-factors



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