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# Combining NNLO QCD and NLO EW corrections matched to parton showers for WZ production using MiNNLO$_{PS}$

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

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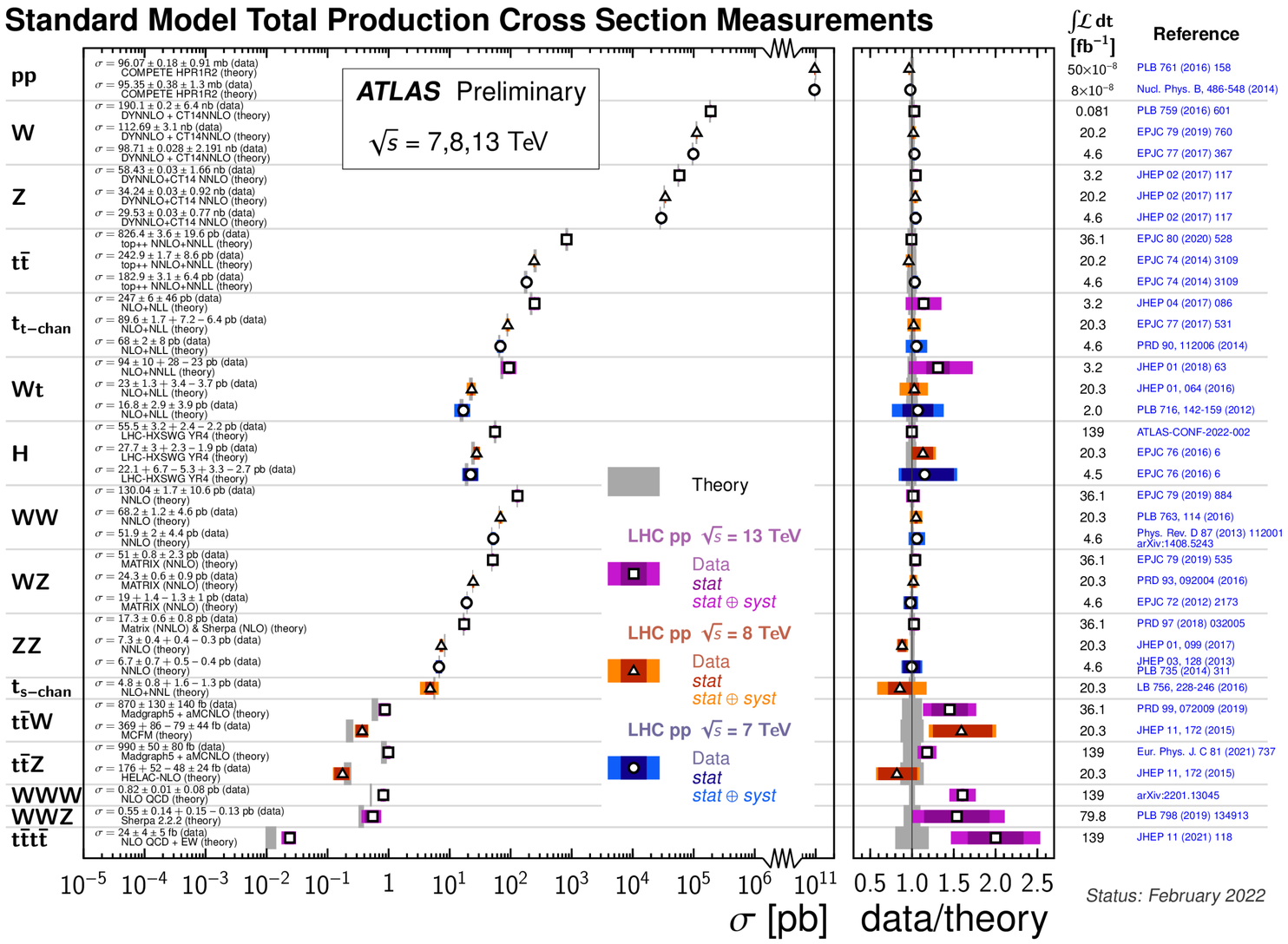
**Max Planck Institute for Physics**

# Multiboson production

- Fundamental for testing the **gauge structure** of the EW sector and its interplay with the scalar sector.
- **Access to triple/quartic gauge couplings**, which may be modified by new-physics effects.

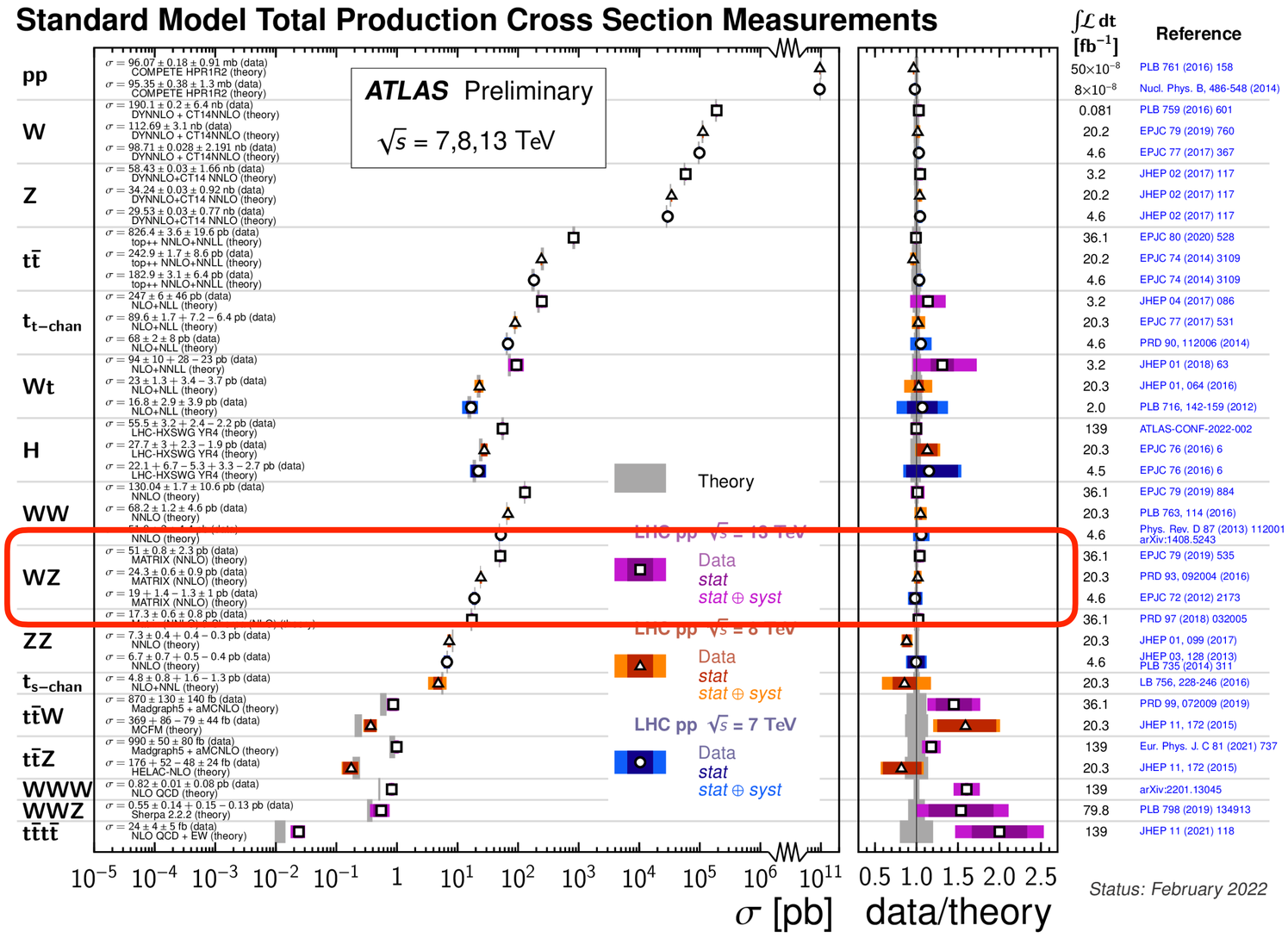


# WZ production

**WZ production is particularly interesting** both for the large cross section and the clean experimental signature (we consider the fully leptonic decay channel).

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

**NNLO(QCD)+PS and NLO(EW)+PS**



# 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

# NNLO+PS accuracy

- MiNLO'+ reweighting [Hamilton, Nason, Zanderighi '12]
- Geneva [Alioli, Bauer, Berggren, Tackmann,Walsh, Zuberi '13, + subsequent papers]
- UNNLOPS [Höche, Prestel '14]

## MiNNLO$_{PS}$

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

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

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

# POWHEG

[Nason '04]

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

FO calculation at NLO

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

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

$$\Delta(\Phi_n, p_T) = exp\left\{ - \int d\Phi'_r \frac{R(\Phi_n, \Phi'_r)}{B(\Phi_n)} \Theta(p'_T - p_T) \right\}$$

| | F | F+J | F+JJ |
|---|---|---|---|
| **F@POWHEG** | NLO | LO | LL |

**pt-veto** on subsequent emissions generated by the shower

# MiNLO'

[Hamilton, Nason, Oleari, Zanderighi '12]



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

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

- **Finite result** for F+J production when the **jet is unresolved**
- Prescription in the **choice of the scales** $\mu_R$ and $\mu_F$ ($\mu_R = \mu_F \sim p_{\mathrm{T}}$)
- **NLO** accuracy for observables inclusive in F and F+J

| | **F** | **F+J** | **F+JJ** |
|---|---|---|---|
| **FJ@MiNLO'** | NLO | NLO | LO |

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



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

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

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



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

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

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

# MiNNLO$_{PS}$

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



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

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

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

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Calculation embedded in POWHEG

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

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

Simplified notation!

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

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1. **EVENT GENERATION:**
    1. generation of $NNLO_{QCD}$+PS results using $MiNNLO_{PS}$
    2. generation of $NLO_{EW}$+PS results using POWHEG
2. **APPLICATION OF THE SHOWER:**

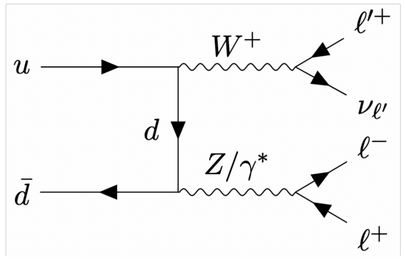
    non trivial treatment, dedicated veto procedure is needed
3. **A-POSTERIORI RECOMBINATION:**

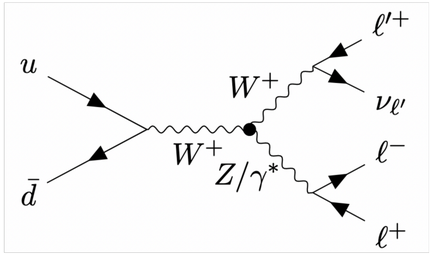
    different possible matching schemes for QCD and EW corrections

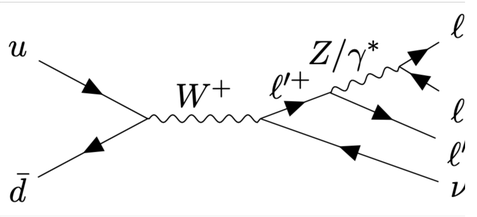
# NNLO$_{QCD}$+PS predictions



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




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

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

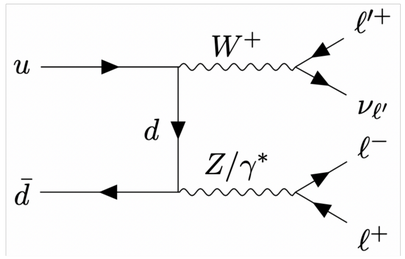
$$\bar{\mathrm{B}}^{\mathrm{MiNNLO_{PS}}} \sim \mathrm{e}^{-\mathrm{S}}\left\{ \mathrm{d}\sigma_{\mathrm{FJ}}^{(1)}\left(1+\mathrm{S}^{(1)}\right) + \mathrm{d}\sigma_{\mathrm{FJ}}^{(2)} + \left(\mathrm{D}-\mathrm{D}^{(1)}-\mathrm{D}^{(2)}\right) \right\}$$

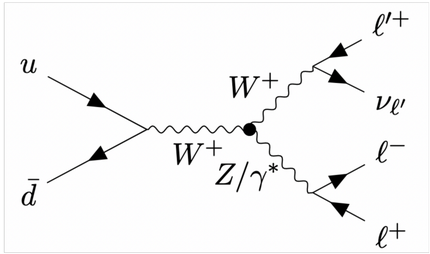
- Up to order $\mathcal{O}(\alpha^4\alpha_s^2)$.
- No loop-induced gluon-fusion contributions.
- Important NNLO corrections (10-15%), due to radiation zero effect at LO (= vanishing of the leading helicity amplitudes in some kinematic regions).

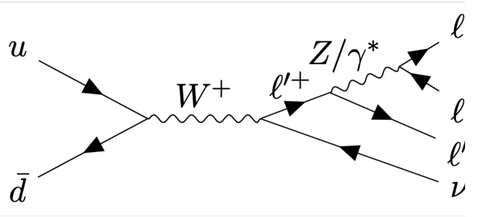
# NLO$_{EW}$+PS predictions



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




## 2) Generation of NLO$_{EW}$+PS results using POWHEG

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

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

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

# Matching with the shower PY8

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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).

# Combination of QCD&EW

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## 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.

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

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

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**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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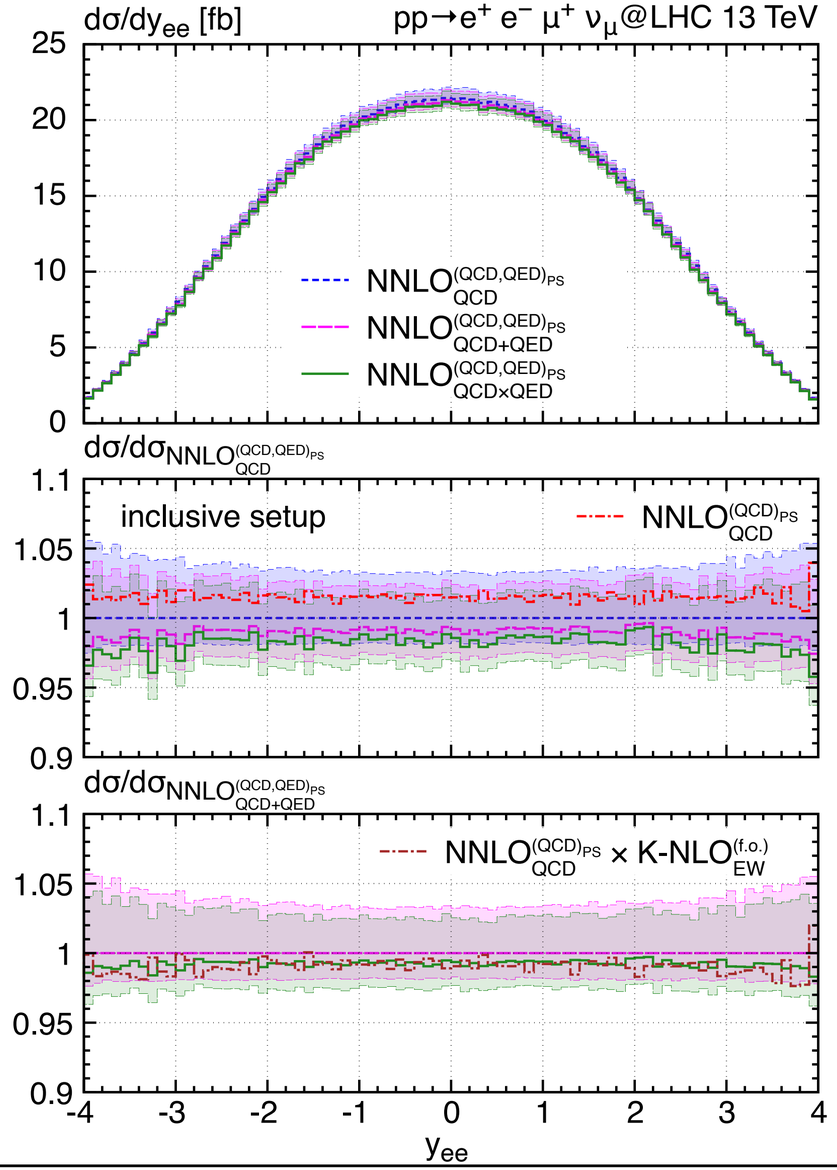
## Rapidity of the Z boson - inclusive setup




**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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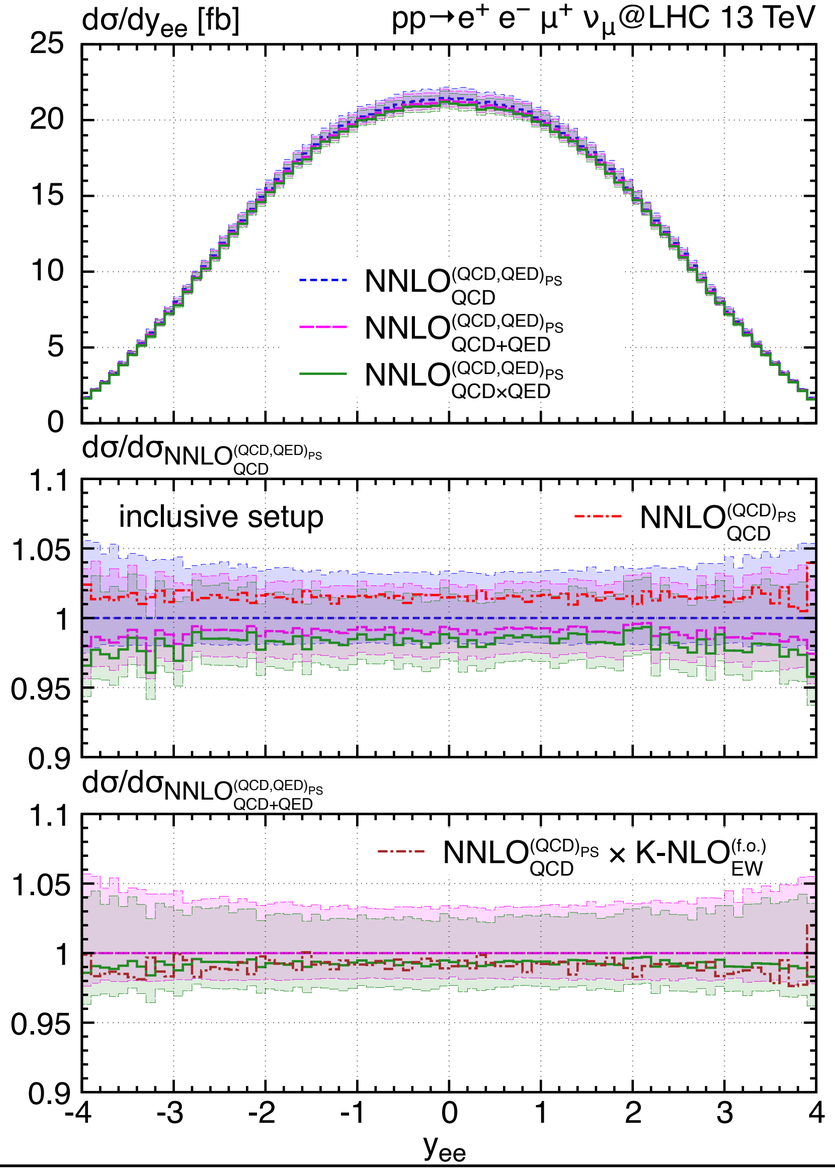
## Rapidity of the Z boson - inclusive setup

- Almost no shape effect
- EW corrections are -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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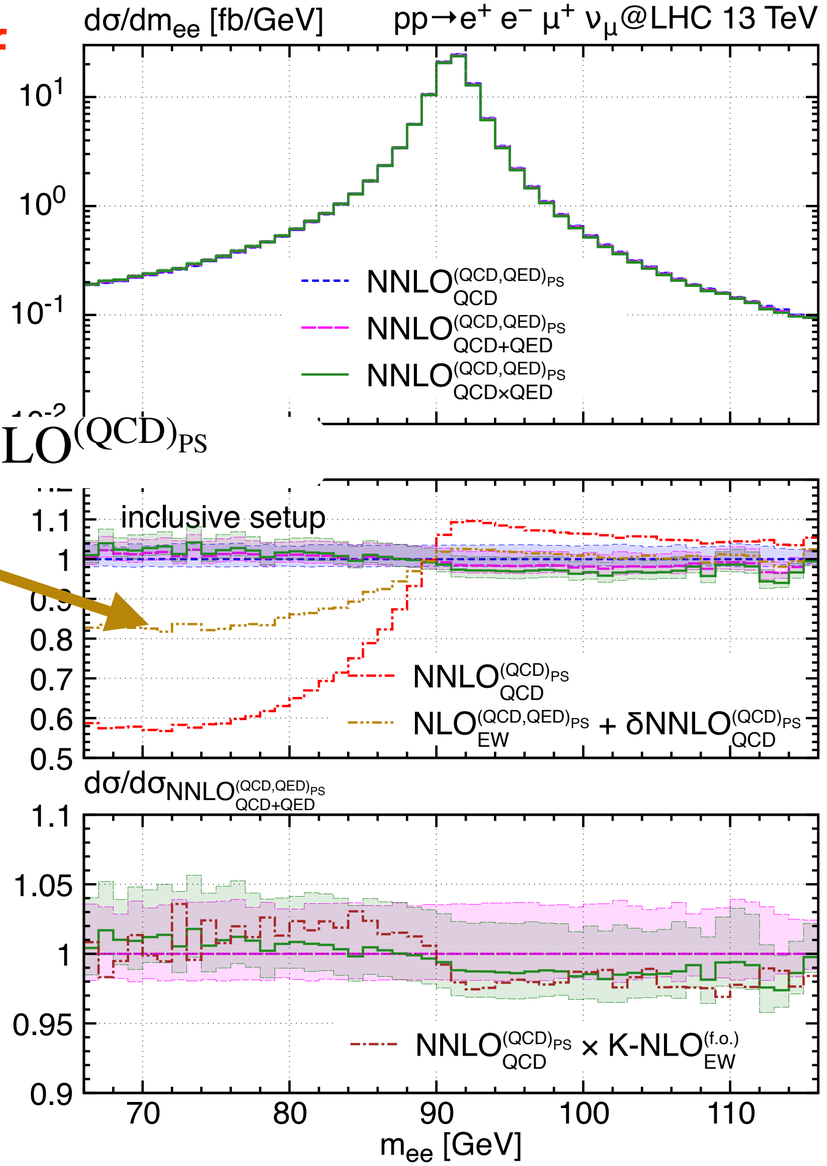
## Invariant mass of the Z boson - inclusive setup

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




**LEGEND:**

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

# Phenomenological results (2)

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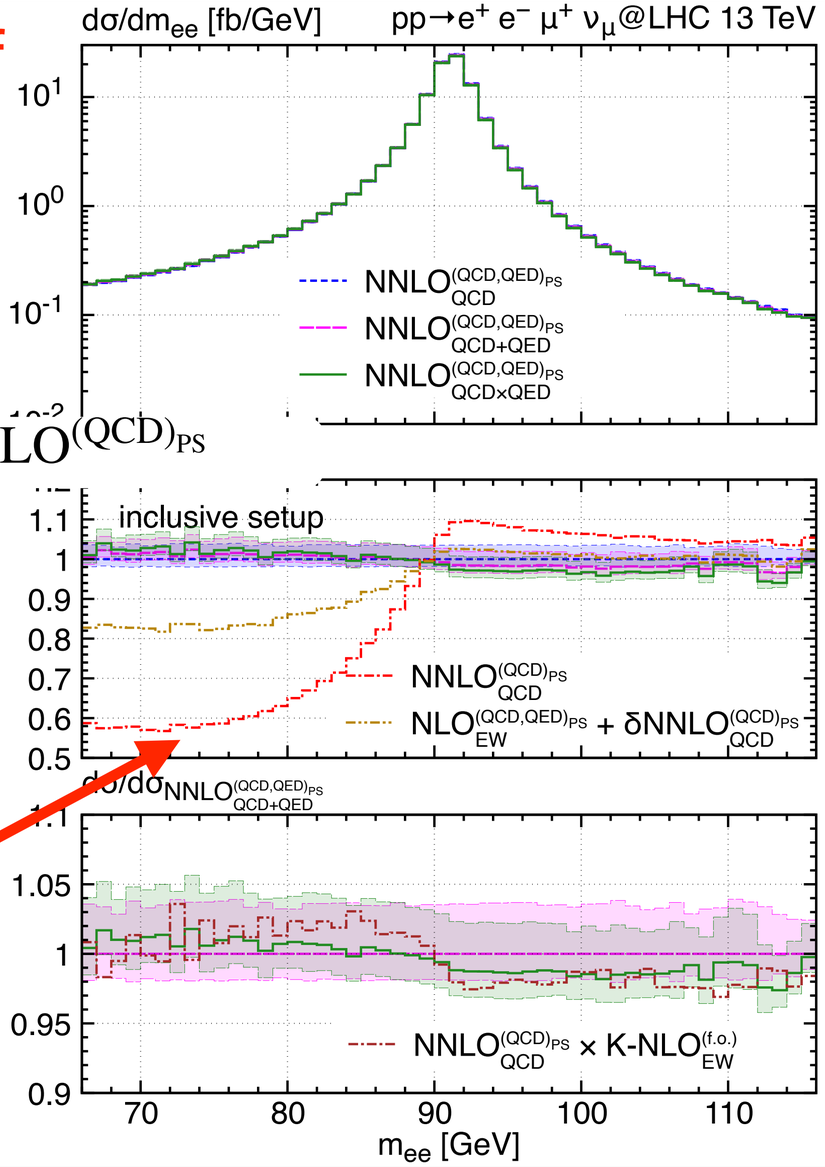
## Invariant mass of the Z boson - inclusive setup

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




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

**LEGEND:**

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

# Phenomenological results (2)

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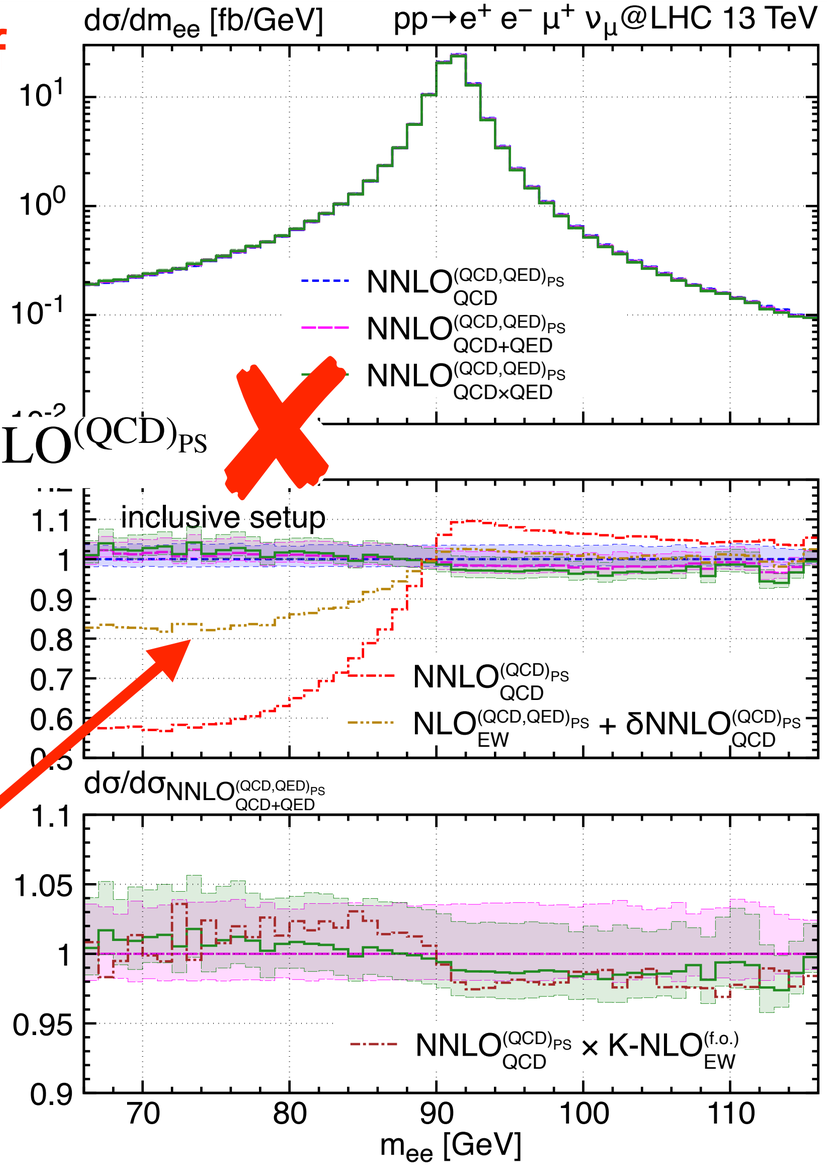
## Invariant mass of the Z boson - inclusive setup

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




- 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)

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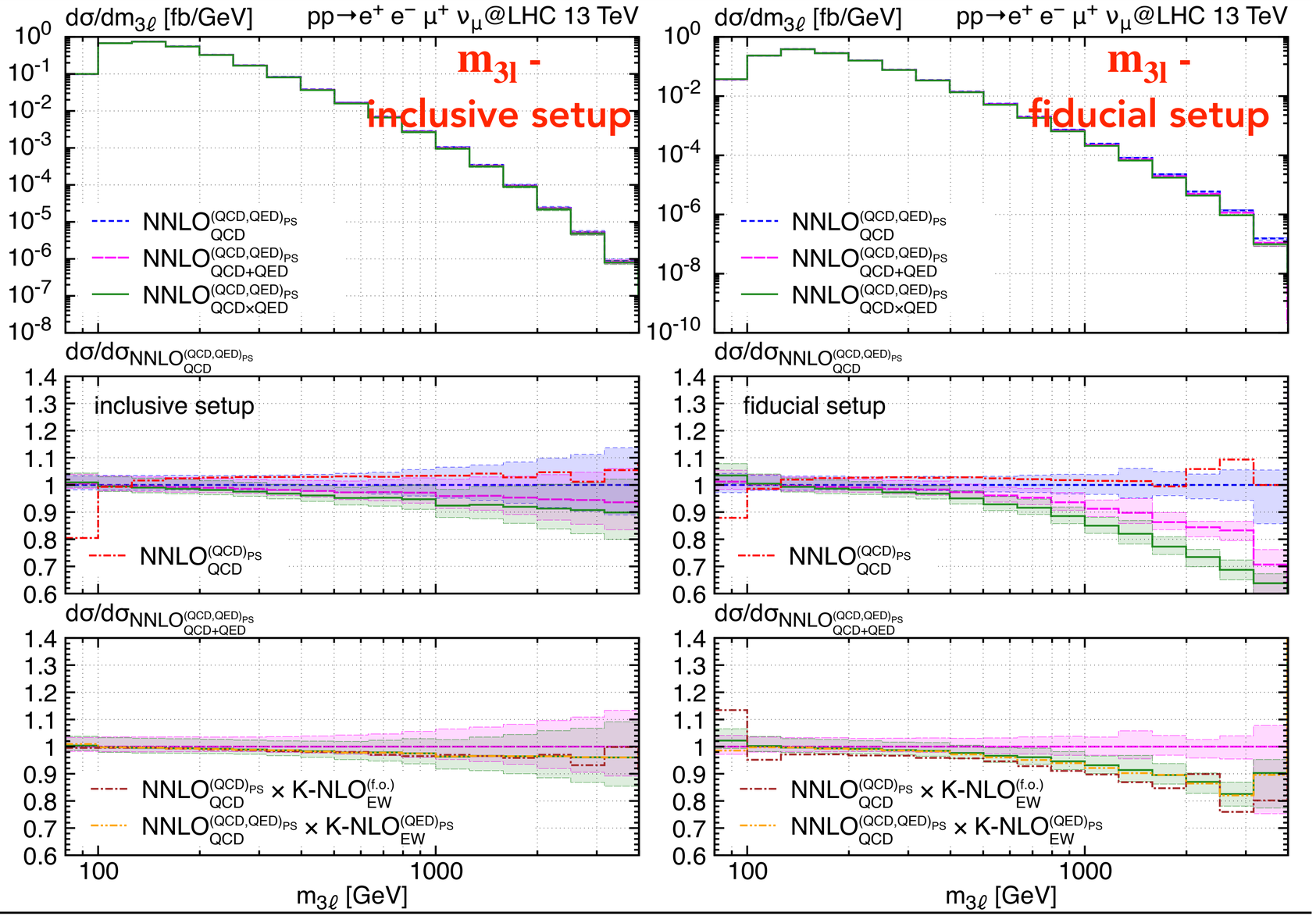
**LEGEND:**

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



# Phenomenological results (3)

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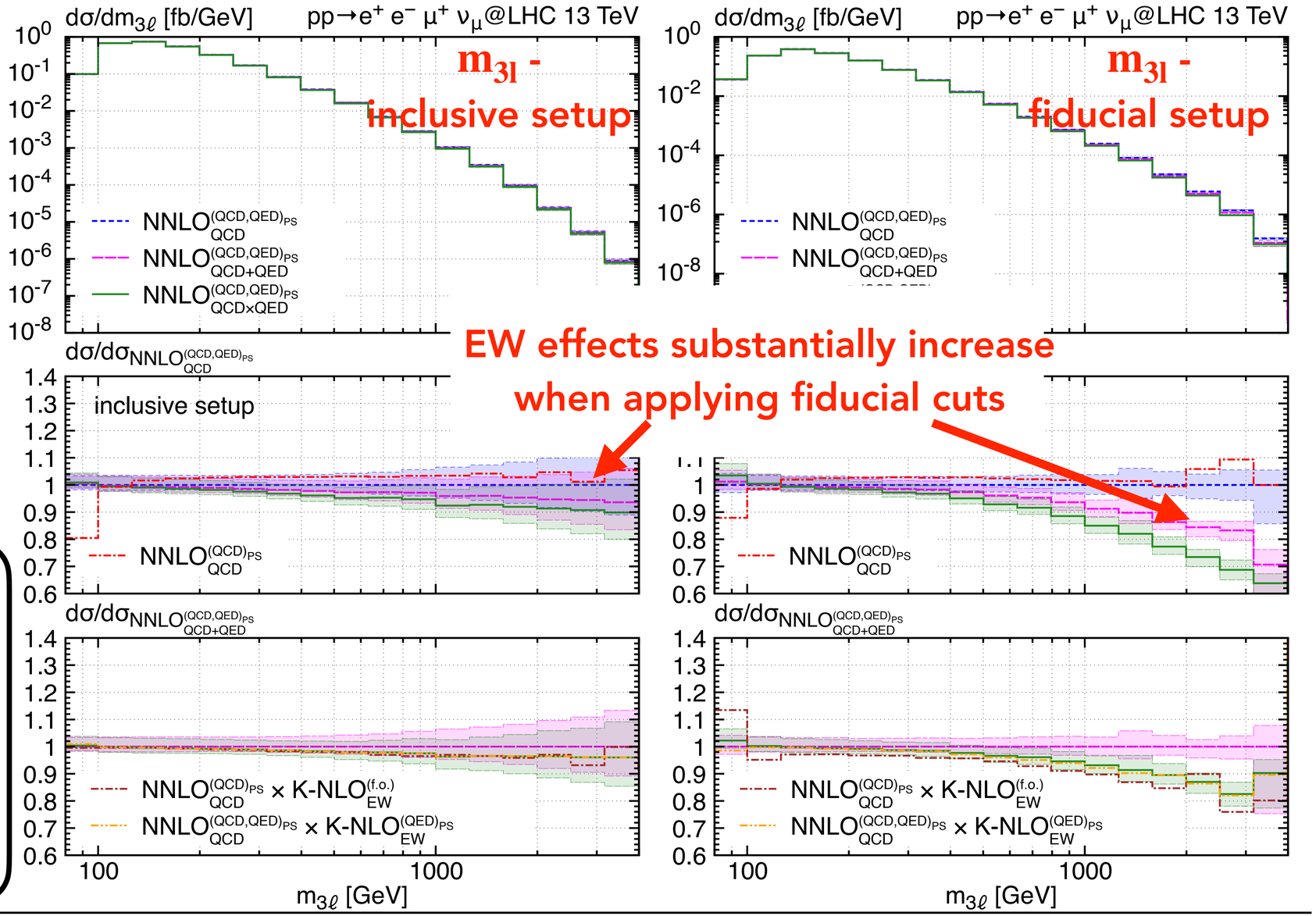
**LEGEND:**

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

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.

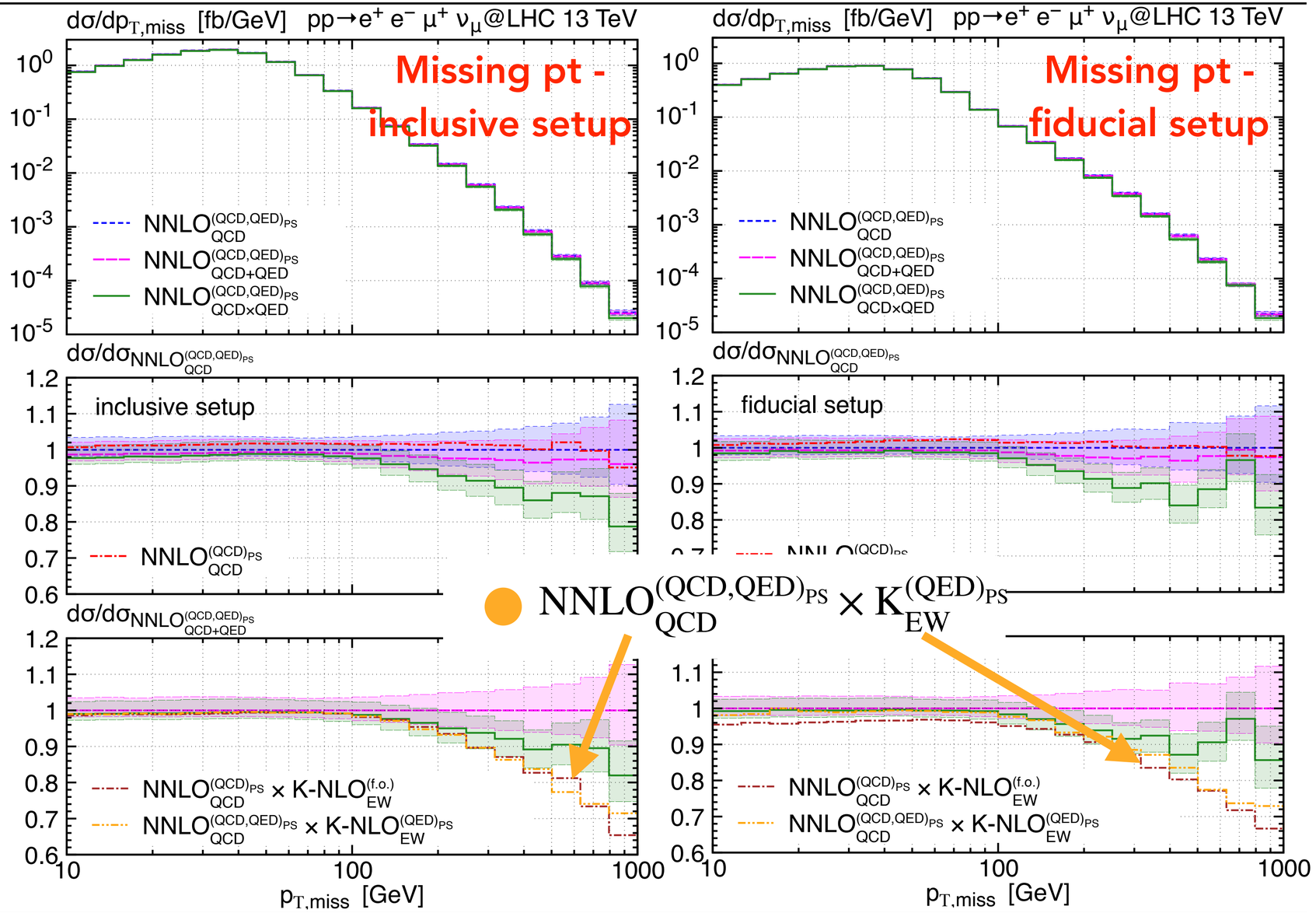


# Phenomenological results (4)

MAX PLANCK INSTITUTE FOR PHYSICS

**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 (4)

MAX PLANCK INSTITUTE FOR PHYSICS

**LEGEND:**

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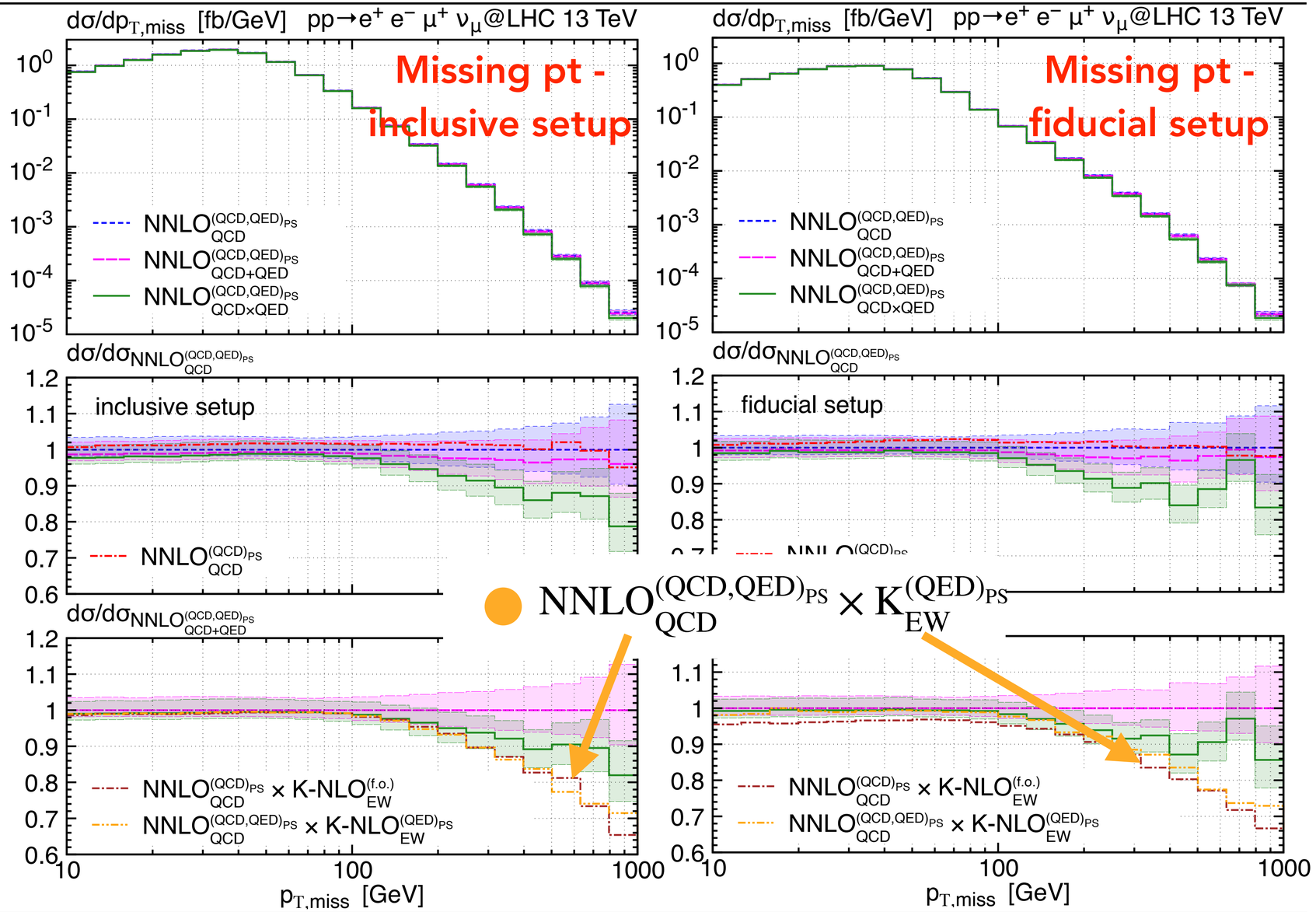
● is affected by giant K-factors




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

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

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

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**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)**

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

MAX PLANCK INSTITUTE FOR PHYSICS

ADDITIVE:

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

**OUR DEFAULT PREDICTION:**

MULTIPLICATIVE:

4. $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} \times \mathrm{NLO}_{\mathrm{EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} / \mathrm{LO}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}} = \mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,\,QED})_{\mathrm{PS}}}$
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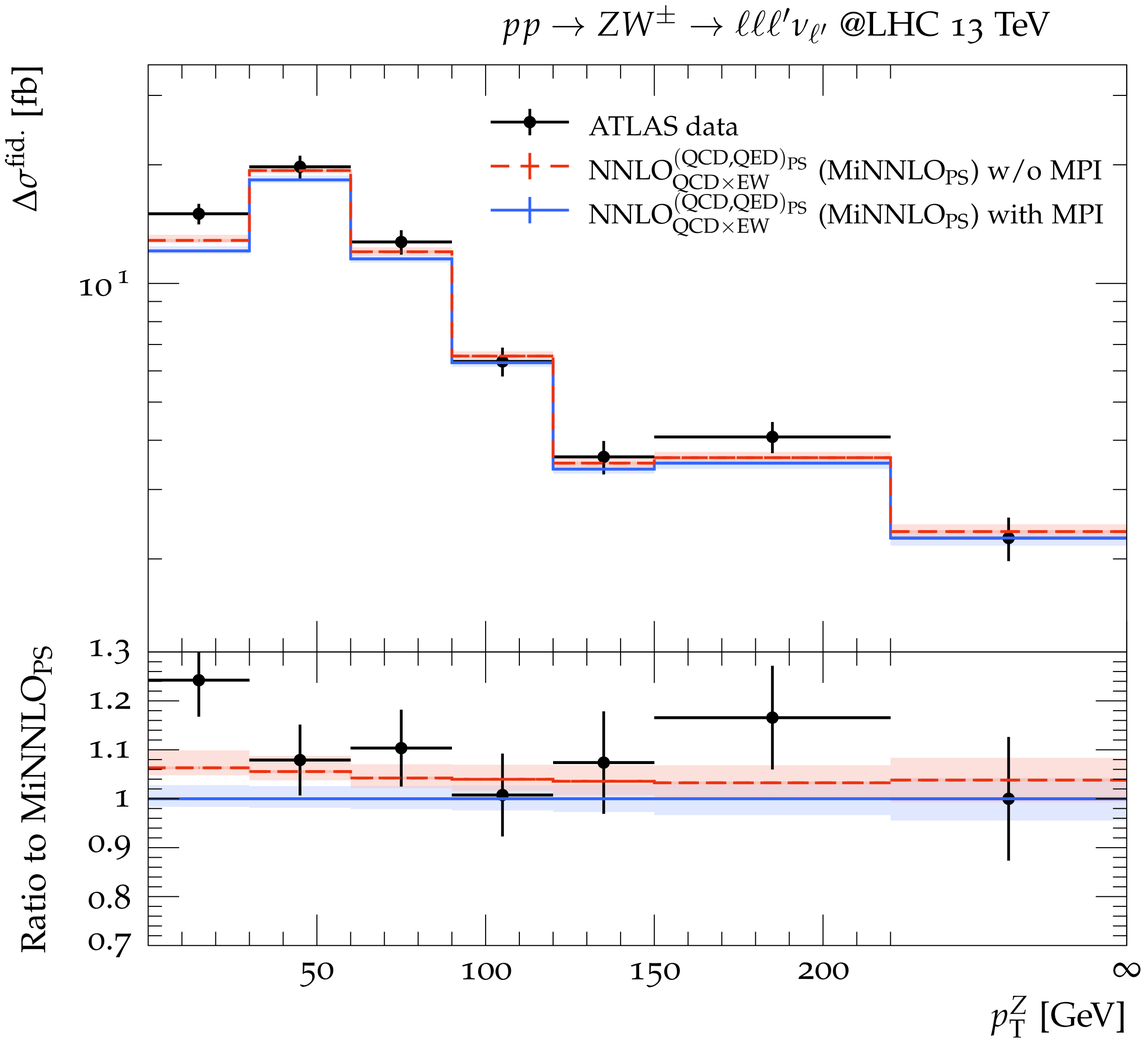
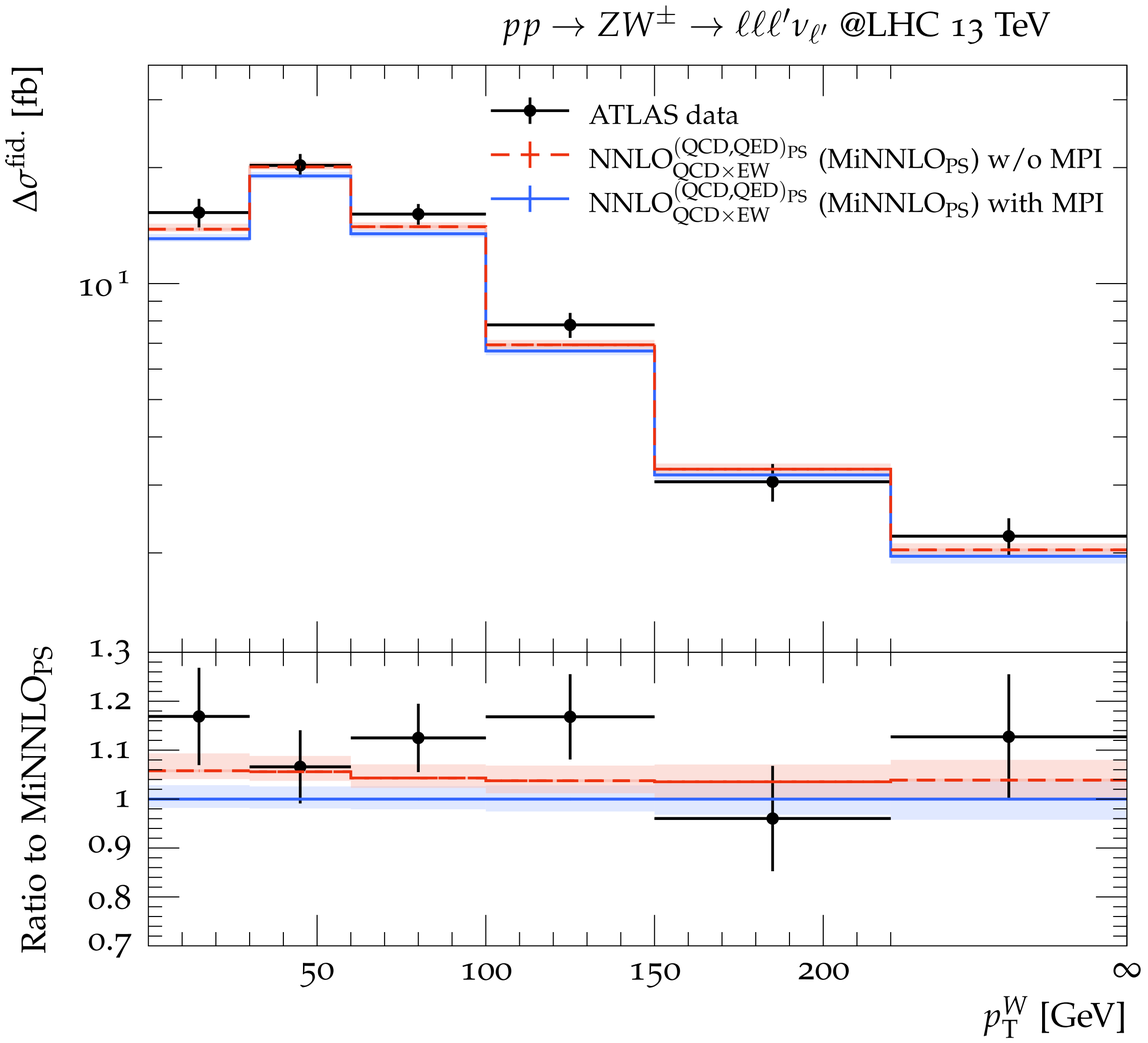
X = QCD,EW calculation
Y = QCD,QED showers (PY8)

# Comparison against data

MAX PLANCK INSTITUTE FOR PHYSICS

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



# Comparison against data

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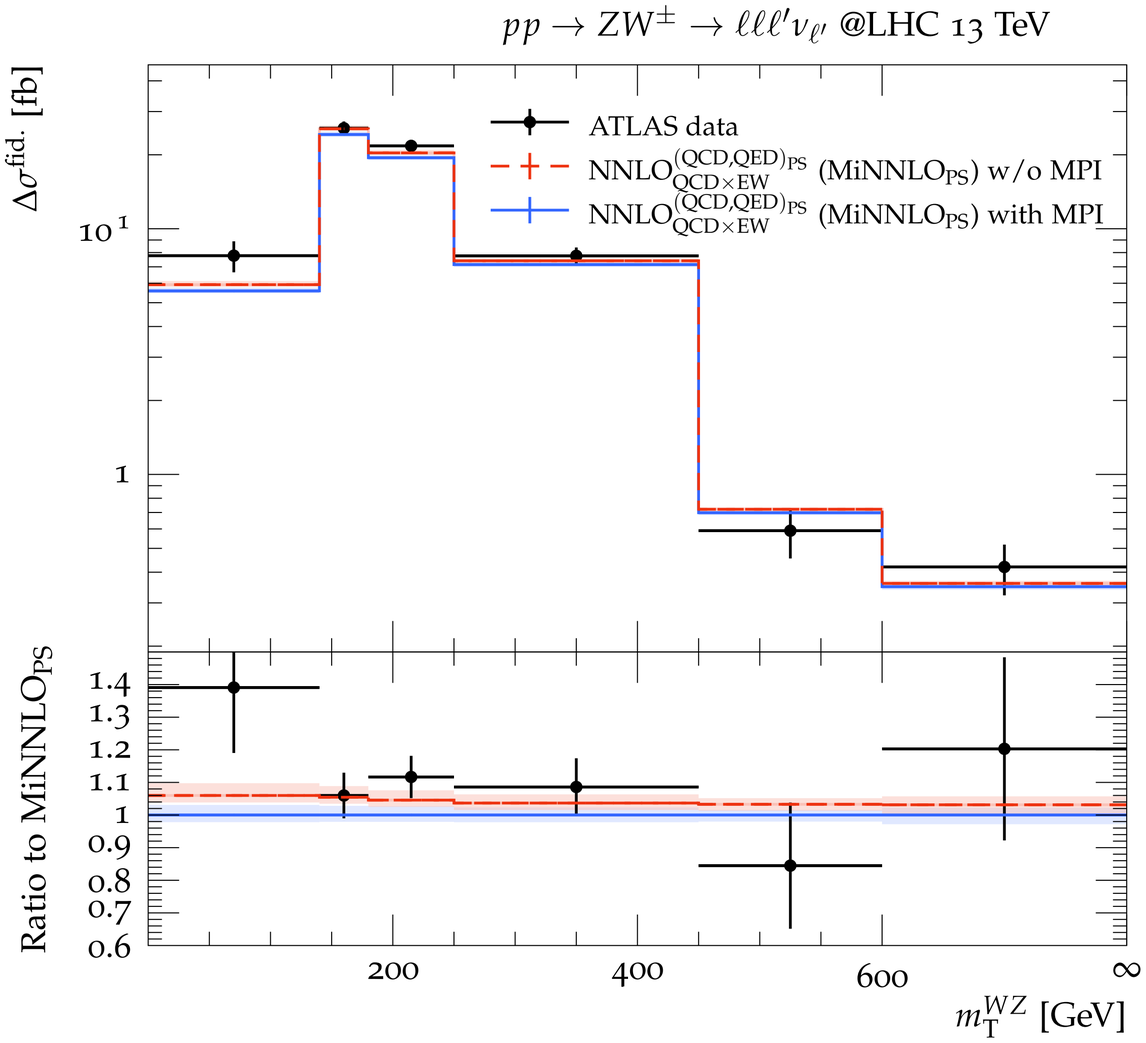


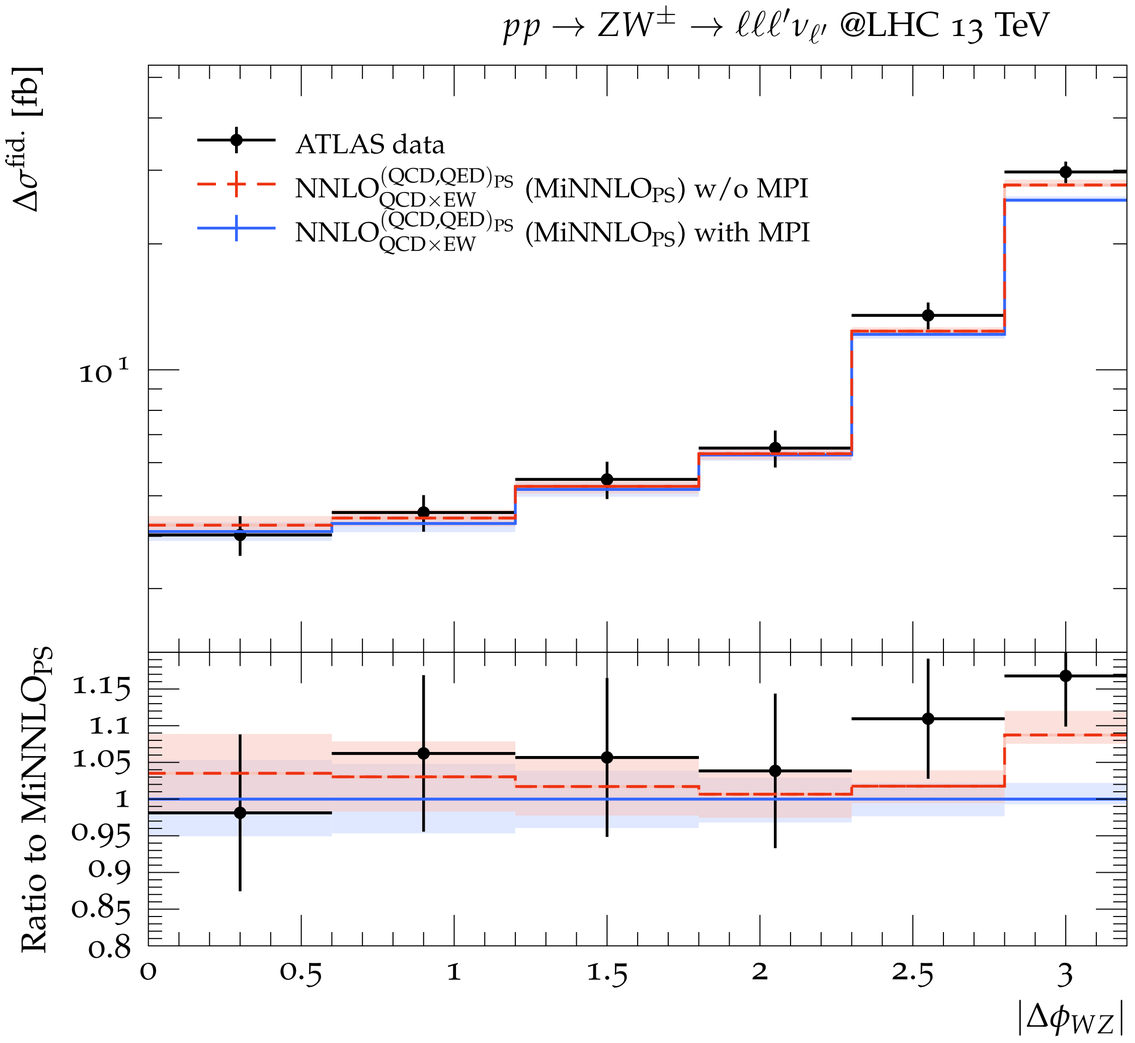

# Conclusions and Outlooks



- **NNLO+PS (QCD)** predictions are **strongly needed** for a realistic description of LHC events.
- **MiNNLO$_{PS}$** is a **powerful tool** for reaching this accuracy.
- The inclusion of **NLO EW corrections** on top of the NNLO calculations is crucial.
- 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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- 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.

Thank you!

# BACKUP

# Setup

| | inclusive setup | fiducial setup |
|---|---|---|
| $Z$-mass window | $66\,\text{GeV} < m_{e^+e^-} < 116\,\text{GeV}$ | $\lvert m_{e^+e^-} - m_\text{Z}\rvert < 10\,\text{GeV}$ |
| lepton cuts | | $p_{T,e^\pm} > 15\,\text{GeV}, \quad p_{\text{T},\mu} > 20\,\text{GeV},$ $\lvert\eta_\ell\rvert < 2.5, \quad m_{\text{T,W}} > 30\,\text{GeV},$ $\Delta R_{e^+e^-} > 0.2, \quad \Delta R_{e^\pm\mu} > 0.3$ |