MAX PLANCK INSTITUTE
FOR PHYSICS

Higher-order corrections in multiboson production

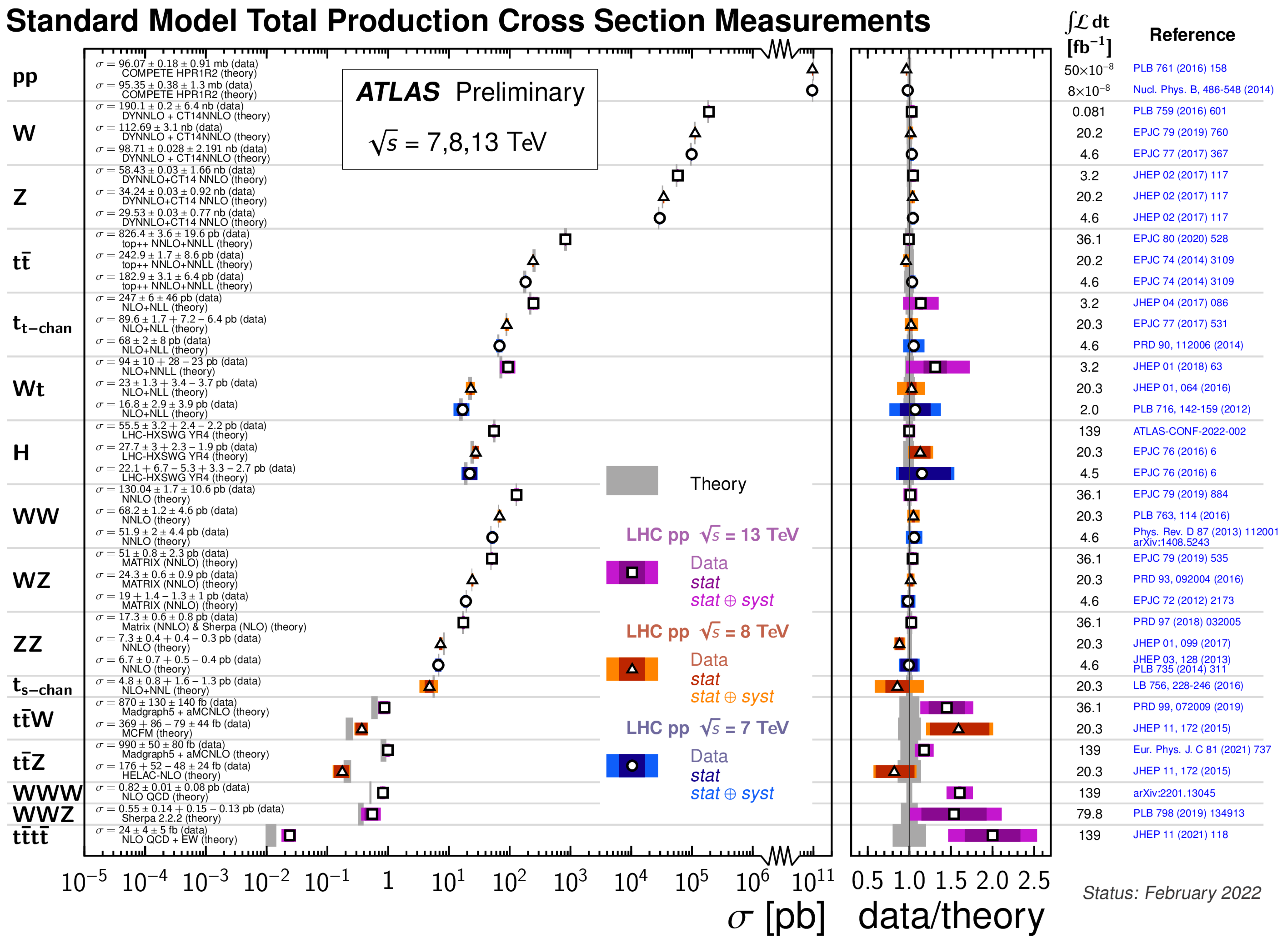
LHCP 2023 - Belgrade, 25.05.23

Silvia Zanoli

Motivation

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.
- Experimental measurements will improve significantly → theoretical predictions should account for **both NNLO QCD and NLO EW effects.**

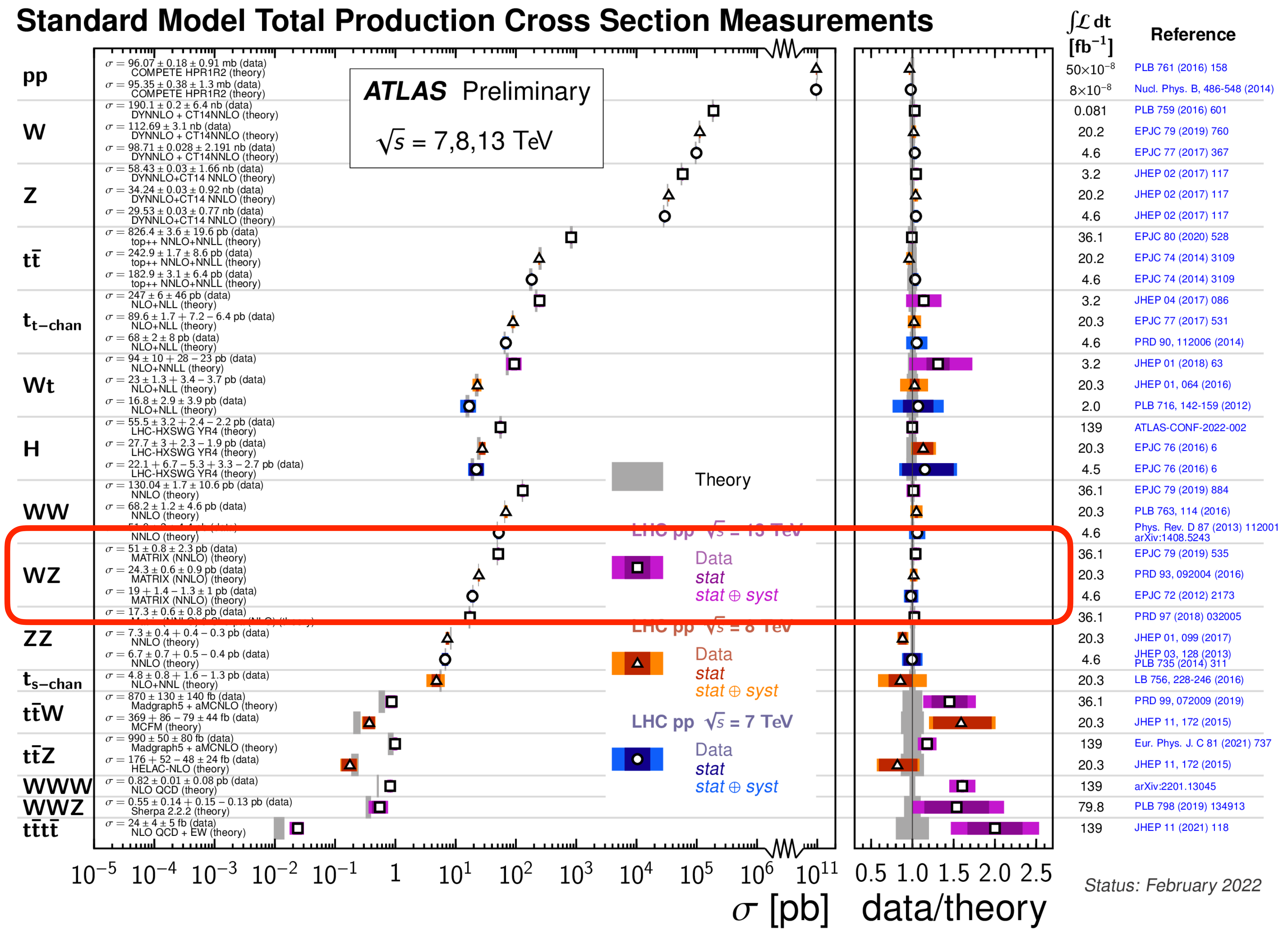


WZ production

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



The method

Strategy

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:**

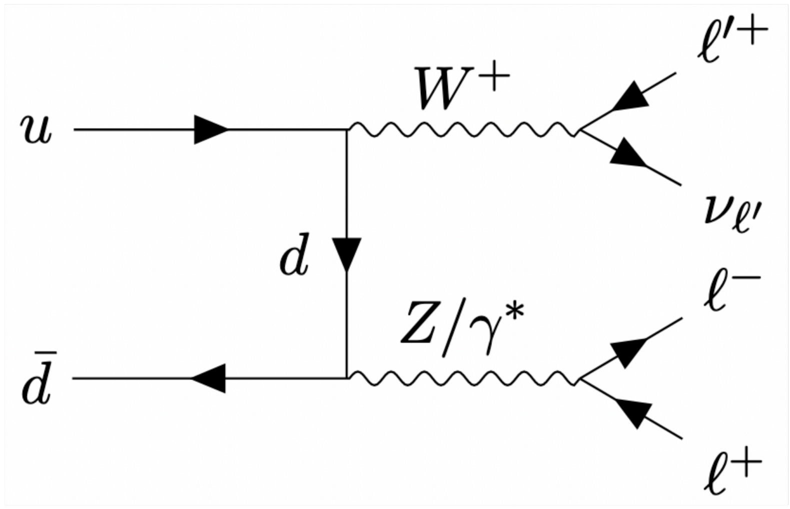
   non trivial treatment, dedicated veto procedure is needed

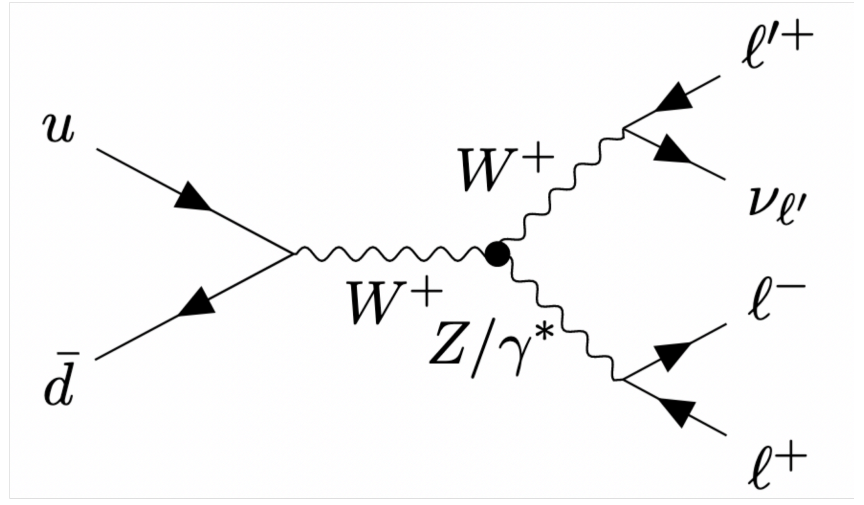
3. **A-POSTERIORI RECOMBINATION:**

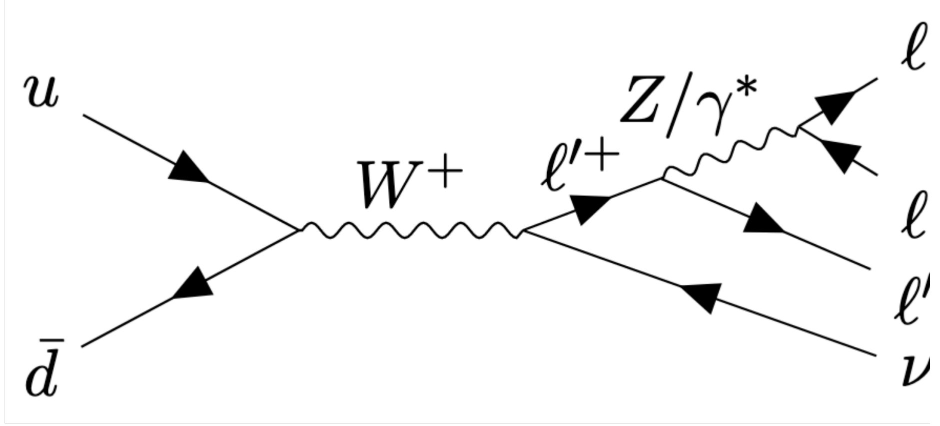
   different possible matching schemes for QCD and EW corrections

NNLO$_{QCD}$+PS events

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







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

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

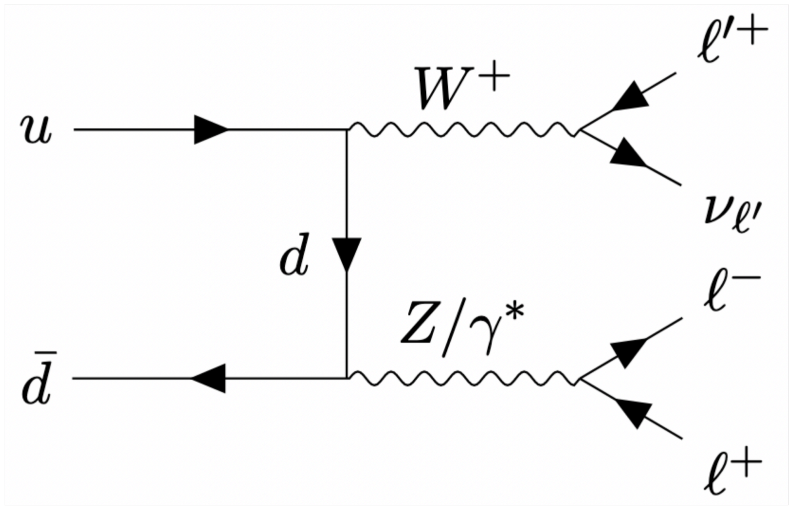
$$d\sigma_F^{\mathrm{MiNNLO_{PS}}} = d\Phi_{FJ}\bar{B}^{\mathrm{MiNNLO_{PS}}} \times \left\{ \Delta_{pwg}(\Lambda_{pwg}) + \int d\Phi_{rad}\Delta_{pwg}(p_{T,rad})\frac{R_{FJ}}{B_{FJ}} \right\}$$

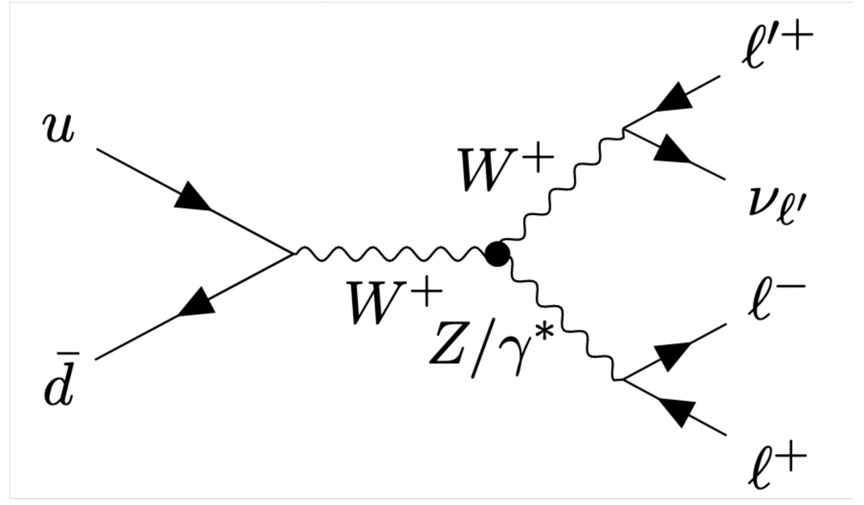
$$\bar{B}^{\mathrm{MiNNLO_{PS}}} \sim e^{-S}\left\{ d\sigma_{FJ}^{(1)}\left(1 + S^{(1)}\right) + d\sigma_{FJ}^{(2)} + \left(D - D^{(1)} - D^{(2)}\right) \right\}$$

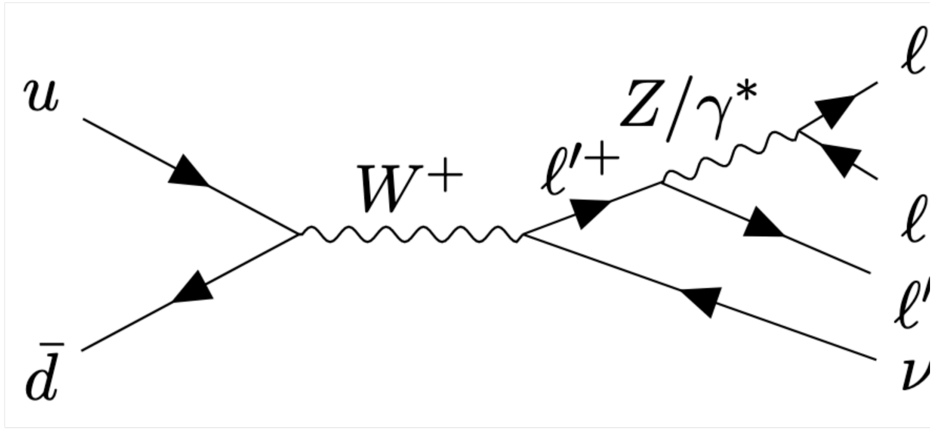
- Up to order $\mathcal{O}(\alpha^4\alpha_s^2)$.
- No loop-induced gluon-fusion contributions.
- Important NNLO corrections (10-15%), due to radiation zero effect at LO (= vanishing of the leading helicity amplitudes in some kinematic regions).

NLO$_{EW}$+PS events

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







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

[Nason, '04] [Frixione, Nason, Oleari, '07]

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

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

- 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 PY8

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

NNLO$_{QCD}$+PS :

- **QCD** shower is **restricted** by the transverse momentum of the hardest QCD emission generated at Les Houches level (default 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

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&EW

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

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

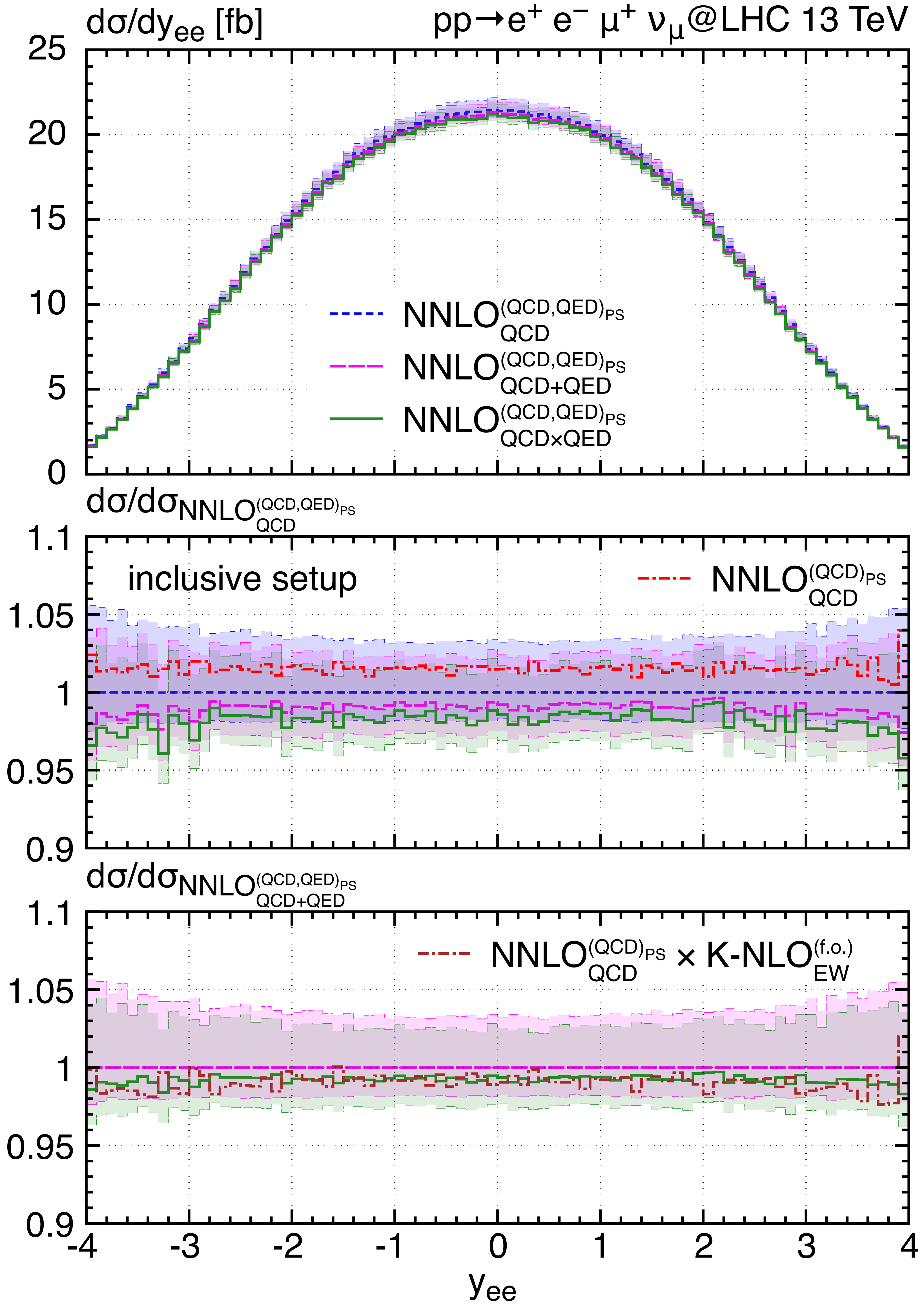
X = QCD,EW calculation
Y = QCD,QED showers (PY8)

Phenomenological results

WZ: results (1)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]

Rapidity of the Z boson - inclusive setup



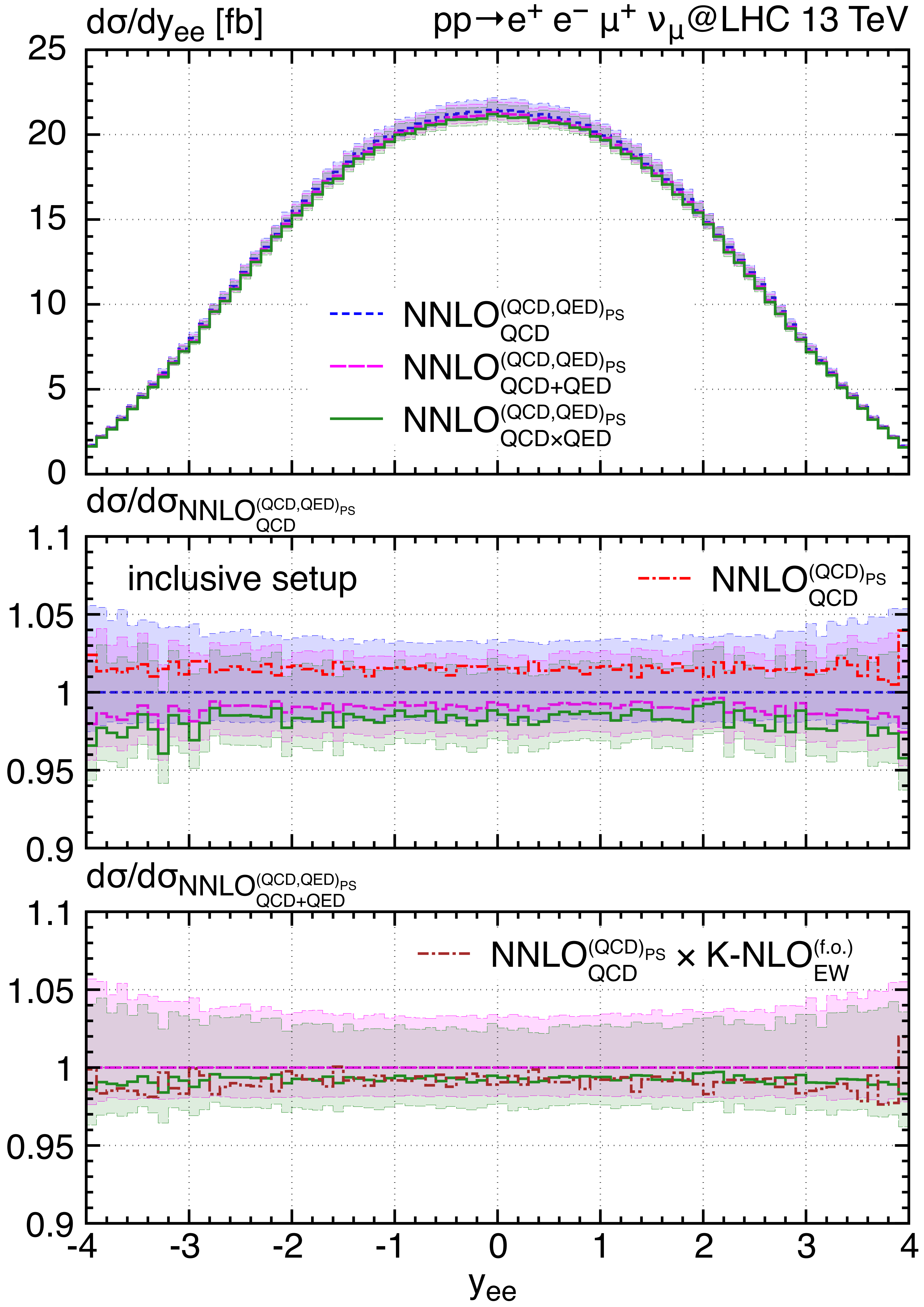
LEGEND:

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

WZ: results (1)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., ’22]

Rapidity of the Z boson - inclusive setup



- Almost no shape effect
- EW corrections are -3%
- Additive (magenta) and multiplicative (green) schemes are almost identical
- Fixed-order K-factor (brown) is in excellent agreement → effects of secondary photon emissions are negligible in this case

LEGEND:

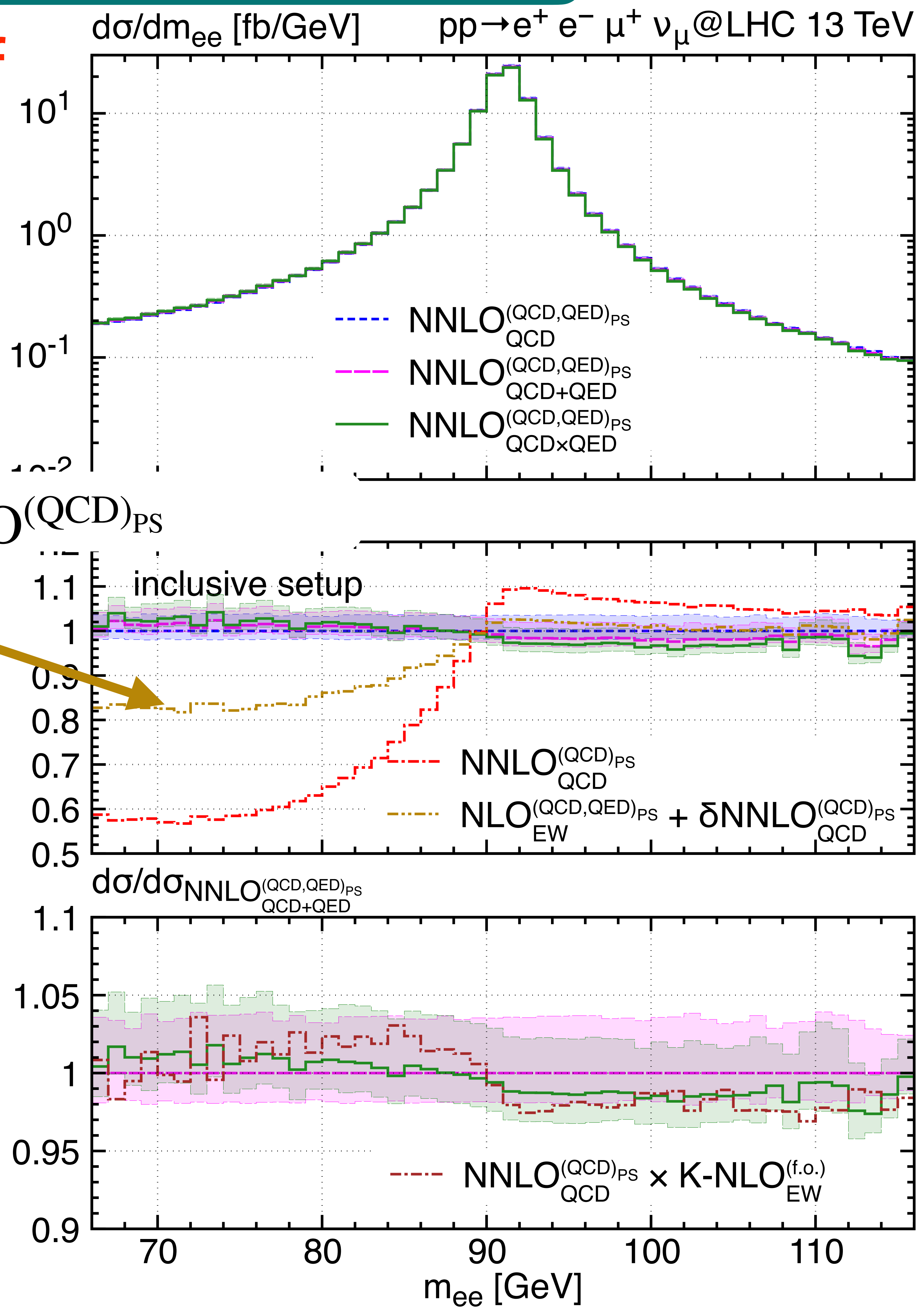
- (blue) $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- (magenta) $\mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- (green) $\mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- (red) $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$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

WZ: results (2)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]

Invariant mass of the Z boson - inclusive setup

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



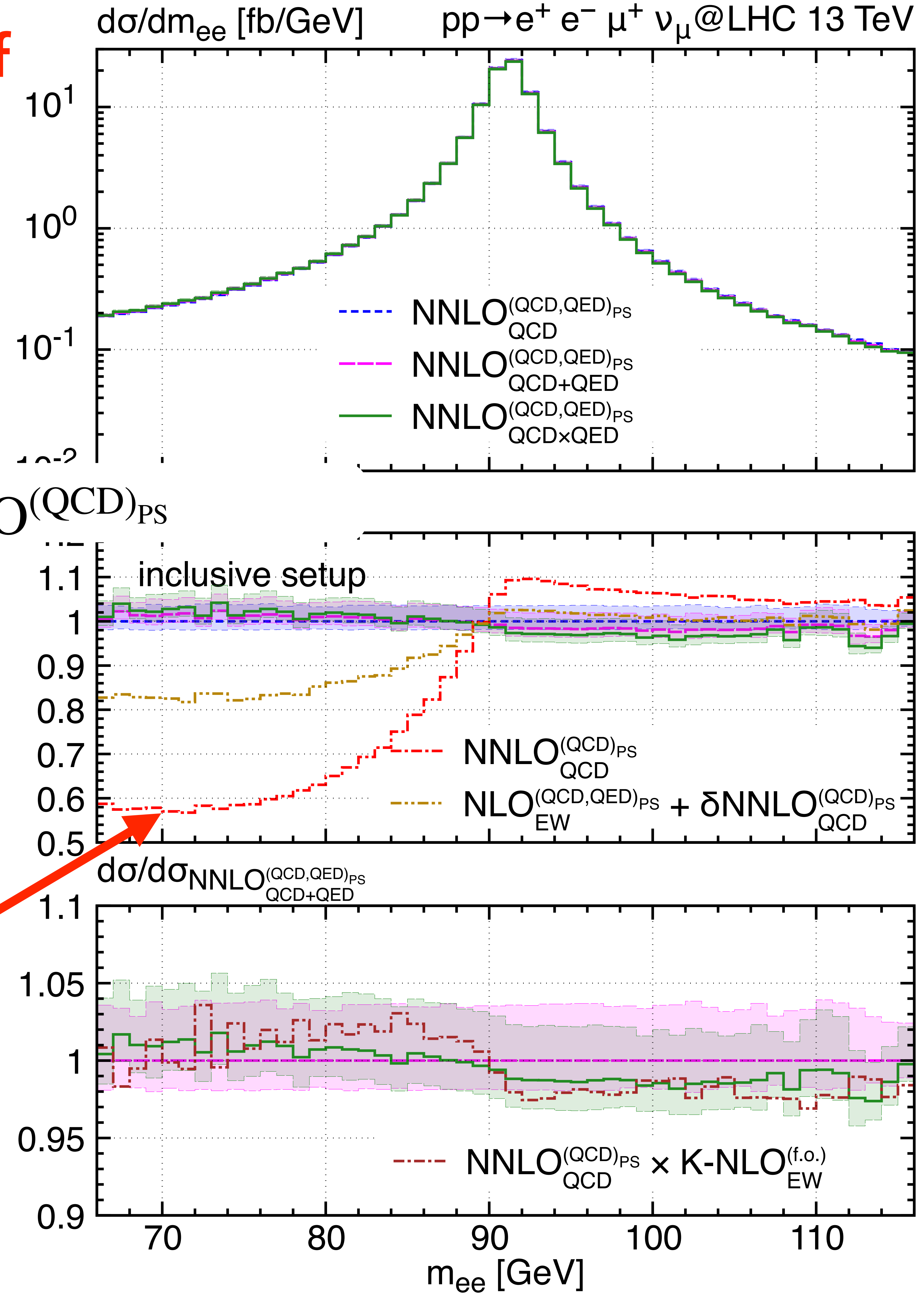
LEGEND:

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

WZ: results (2)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]

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:

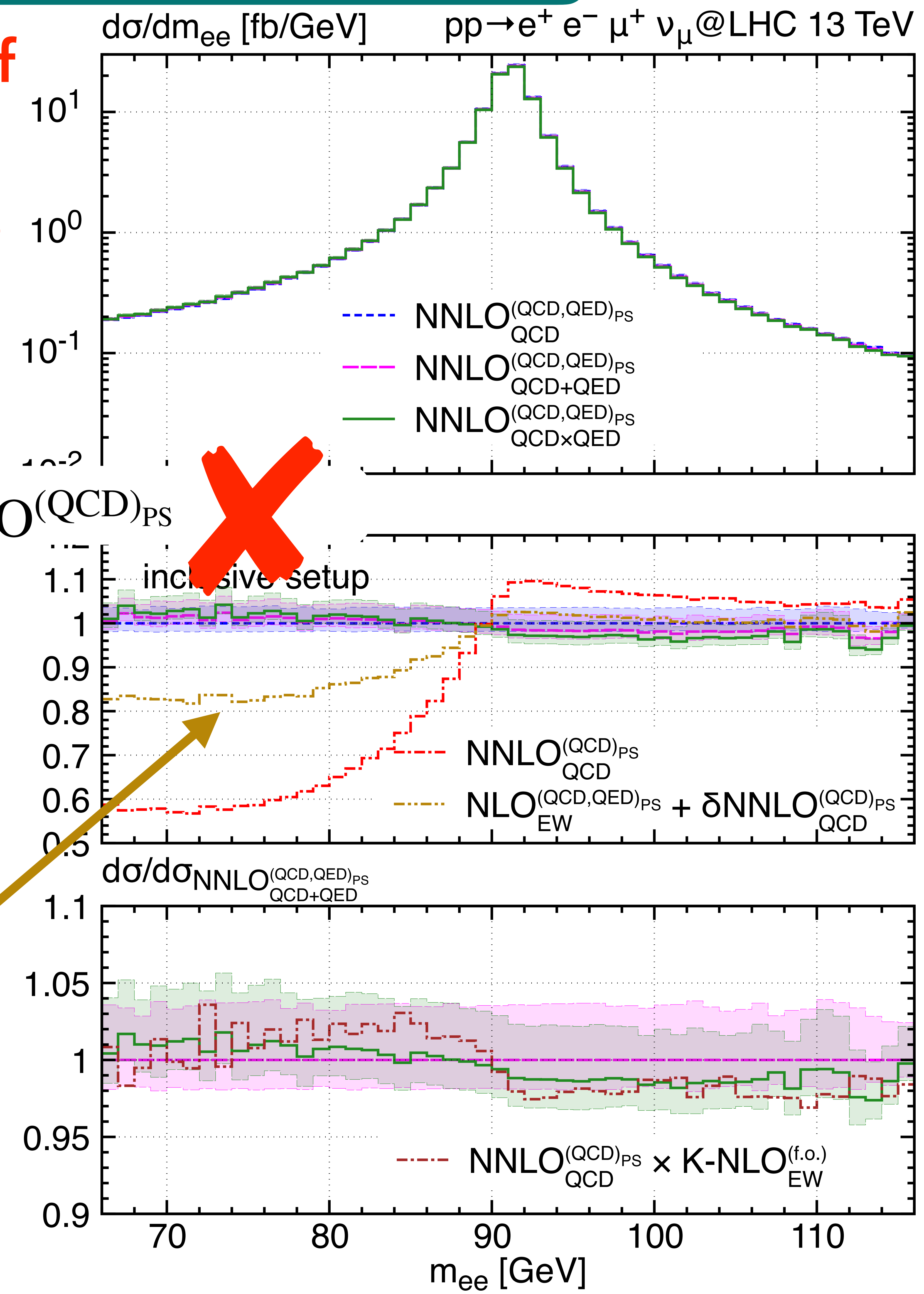
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD+EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD\times EW}}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}$
- ● $\mathrm{NNLO}_{\mathrm{QCD}}^{(\mathrm{QCD})_{\mathrm{PS}}}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

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

WZ: results (2)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]

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:

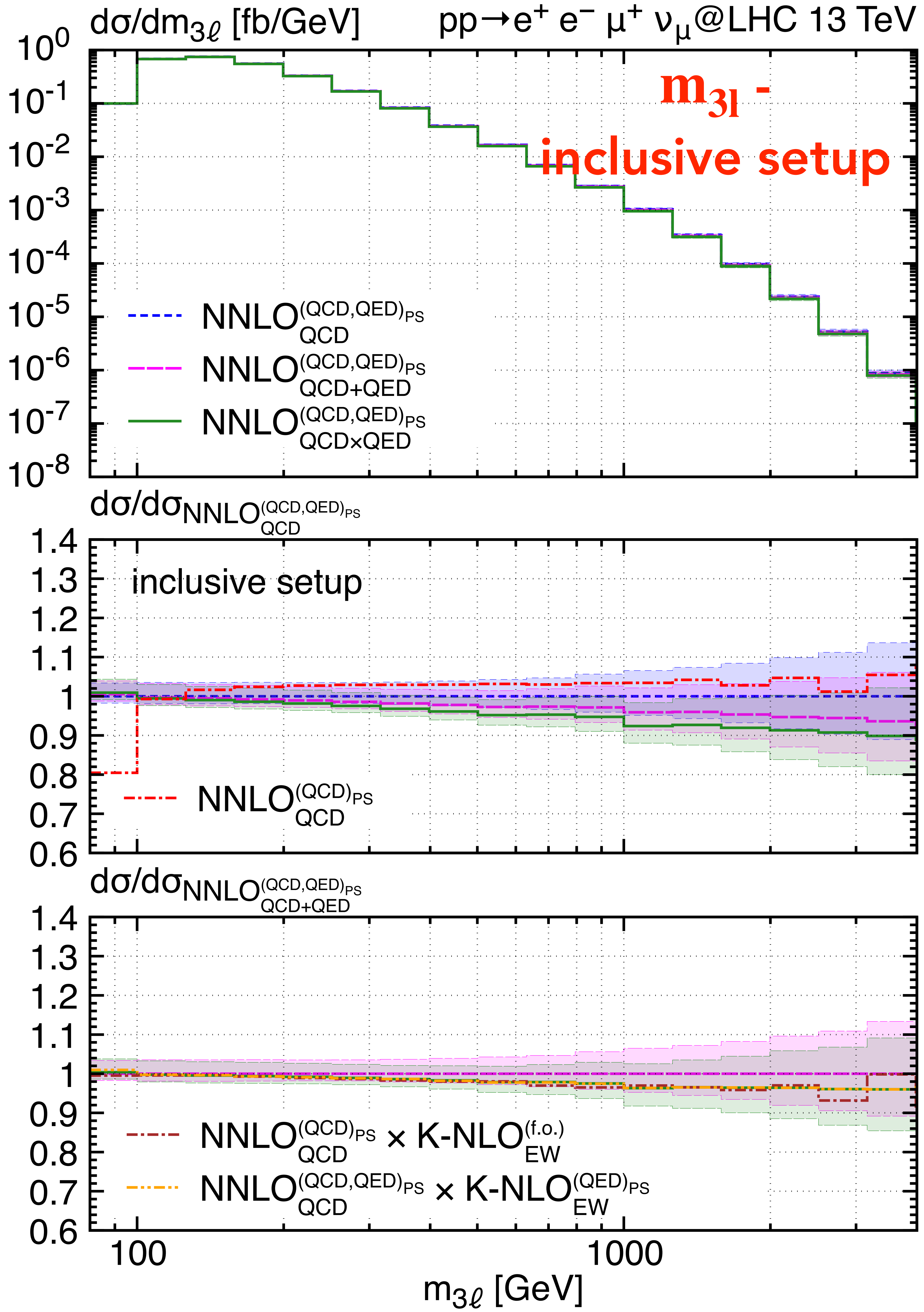
- ● (blue) $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD}}$
- ● (magenta) $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD+EW}}$
- ● (green) $\mathrm{NNLO}^{(\mathrm{QCD,QED})_{\mathrm{PS}}}_{\mathrm{QCD\times EW}}$
- ● (red) $\mathrm{NNLO}^{(\mathrm{QCD})_{\mathrm{PS}}}_{\mathrm{QCD}}$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

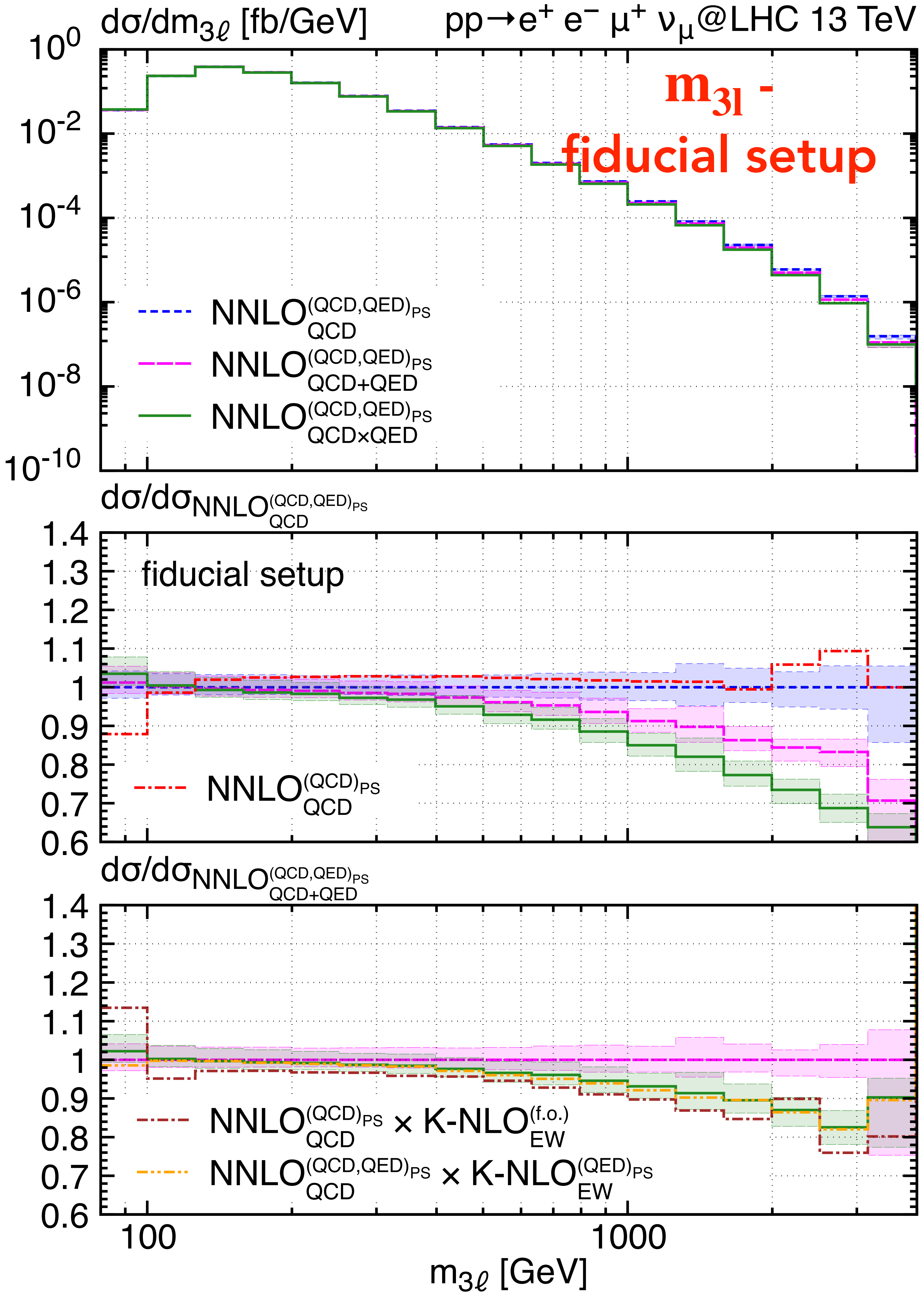
WZ: results (3)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., ’22]

LEGEND:

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



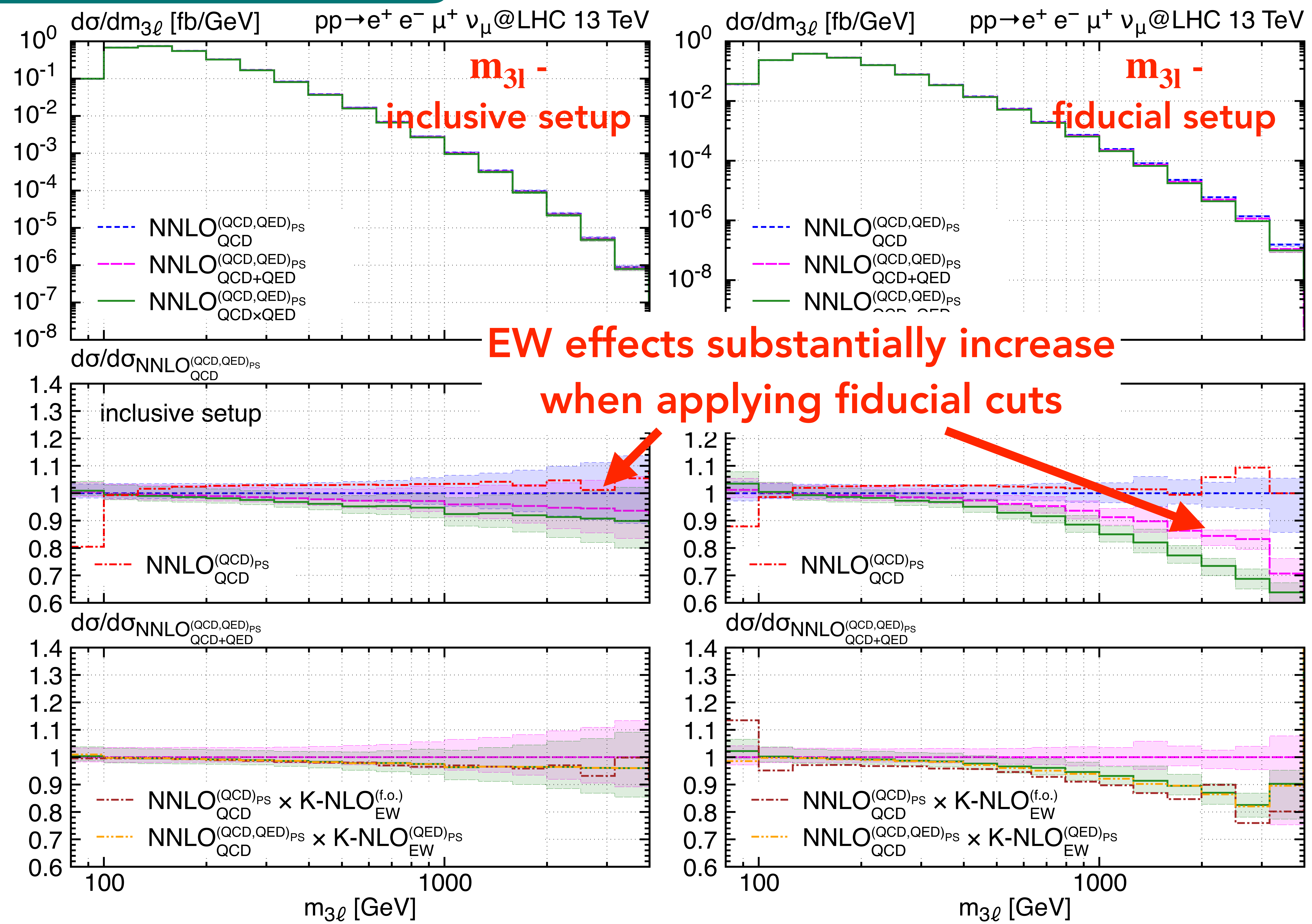


WZ: results (3)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]

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



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

Combination of QCD&EW

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:

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

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

Combination of QCD&EW

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

OUR DEFAULT PREDICTION:

MULTIPLICATIVE:

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

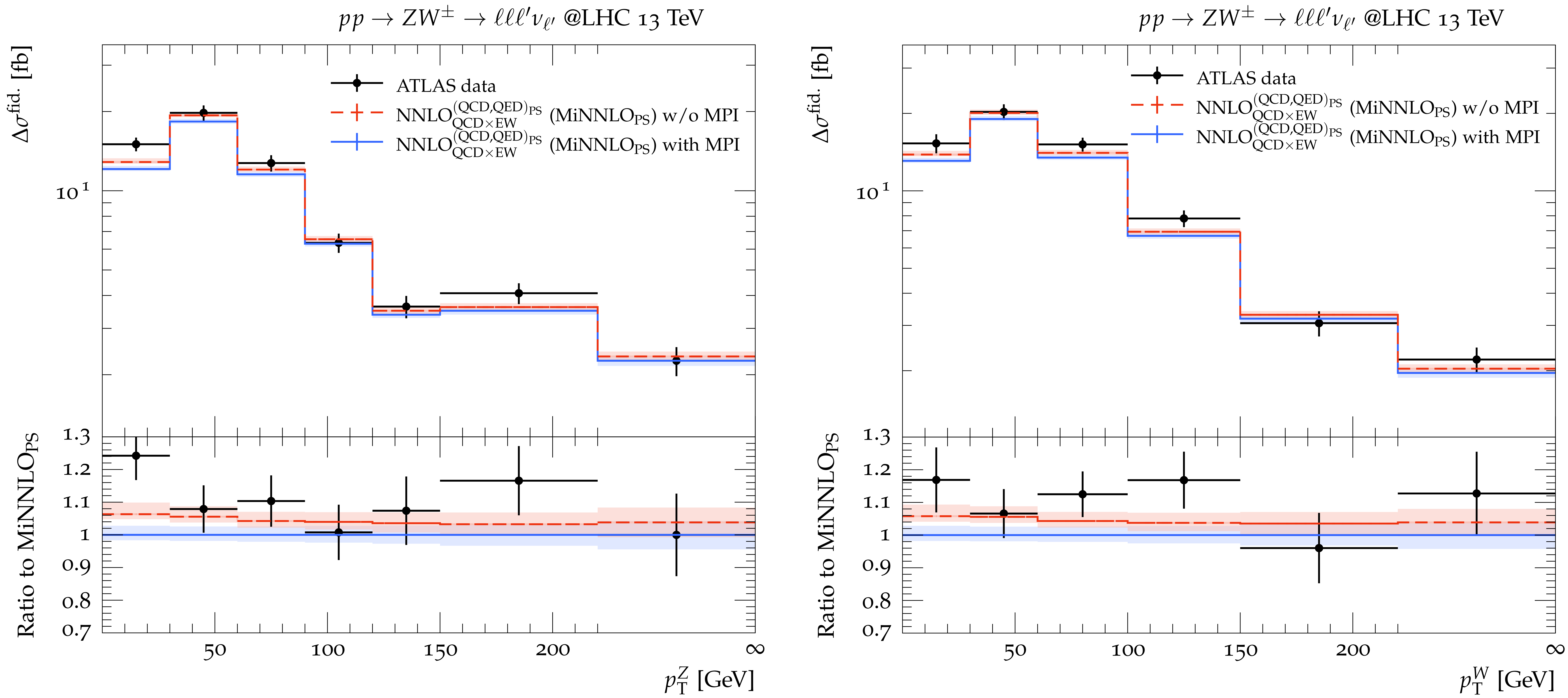
NOTATION:

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

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

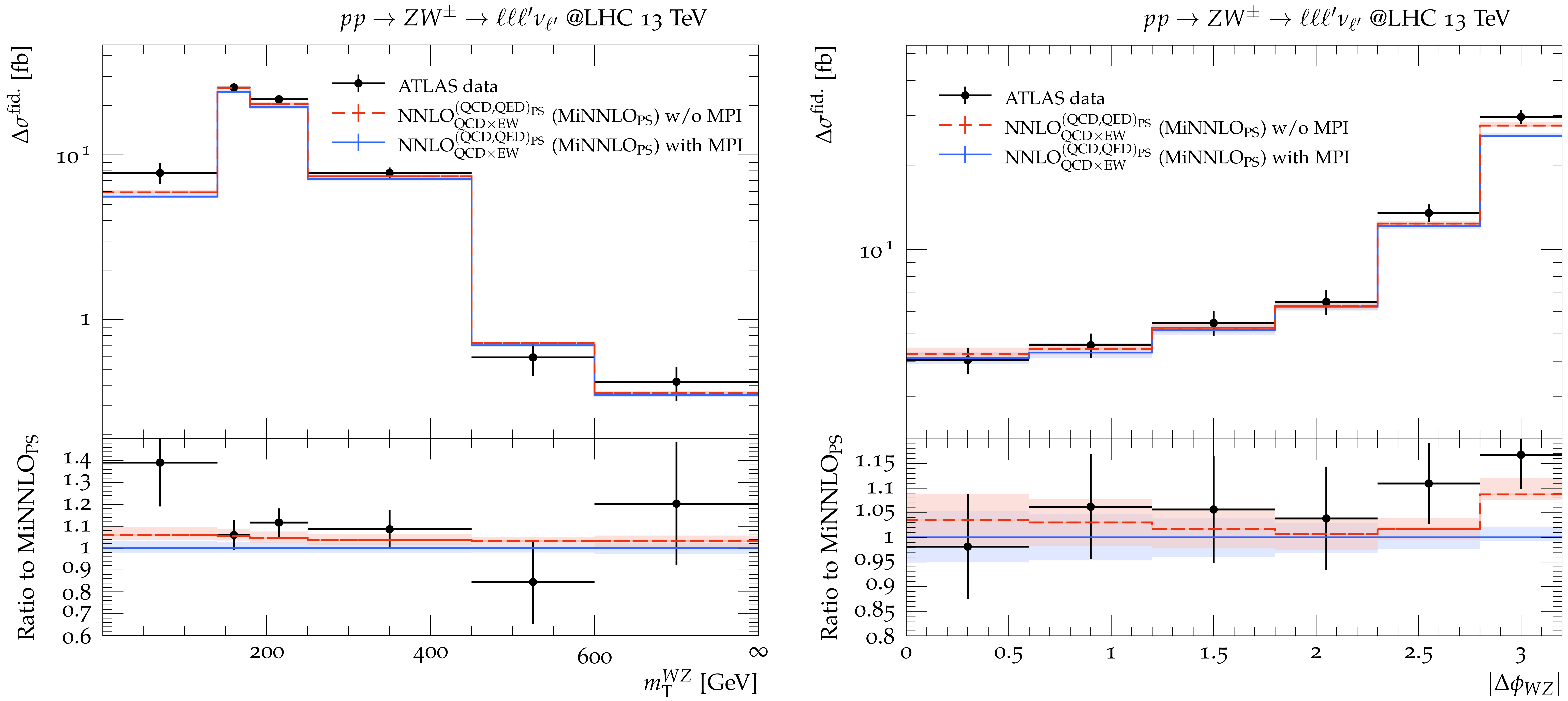
WZ: results (4)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]
[ATLAS data from Eur. Phys. J. C 79 (2019)]



WZ: results (4)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]
[ATLAS data from Eur. Phys. J. C 79 (2019)]



Conclusions

Conclusions & Outlooks

- **NNLO+PS** accuracy is **state of the art** for theory computations
- Supplementing NNLO QCD calculations with **EW effects is the new frontier for precision physics**
- I discussed how to reach $\mathrm{NNLO_{QCD}}$+PS and $\mathrm{NLO_{EW}}$+PS accuracy with an a-posteriori reweighting
- I showed phenomenological results for WZ production in the fully leptonic decay for a 13 TeV LHC analysis, showing the impact of EW effects for different combination schemes. **The multiplicative scheme with both QCD/QED showers switched on is our best prediction.**
- Outlook: combined generation of NNLO(QCD) and NLO(EW) results matched to parton showers without an a-posteriori reweighting.

Thank you!

Back Up

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		$p_{T,e^\pm} > 15\,\text{GeV}, \quad p_{\text{T},\mu} > 20\,\text{GeV},$ $\lvert\eta_\ell\rvert < 2.5, \quad m_{\text{T,W}} > 30\,\text{GeV},$ $\Delta R_{e^+e^-} > 0.2, \quad \Delta R_{e^\pm\mu} > 0.3$

WZ production

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:

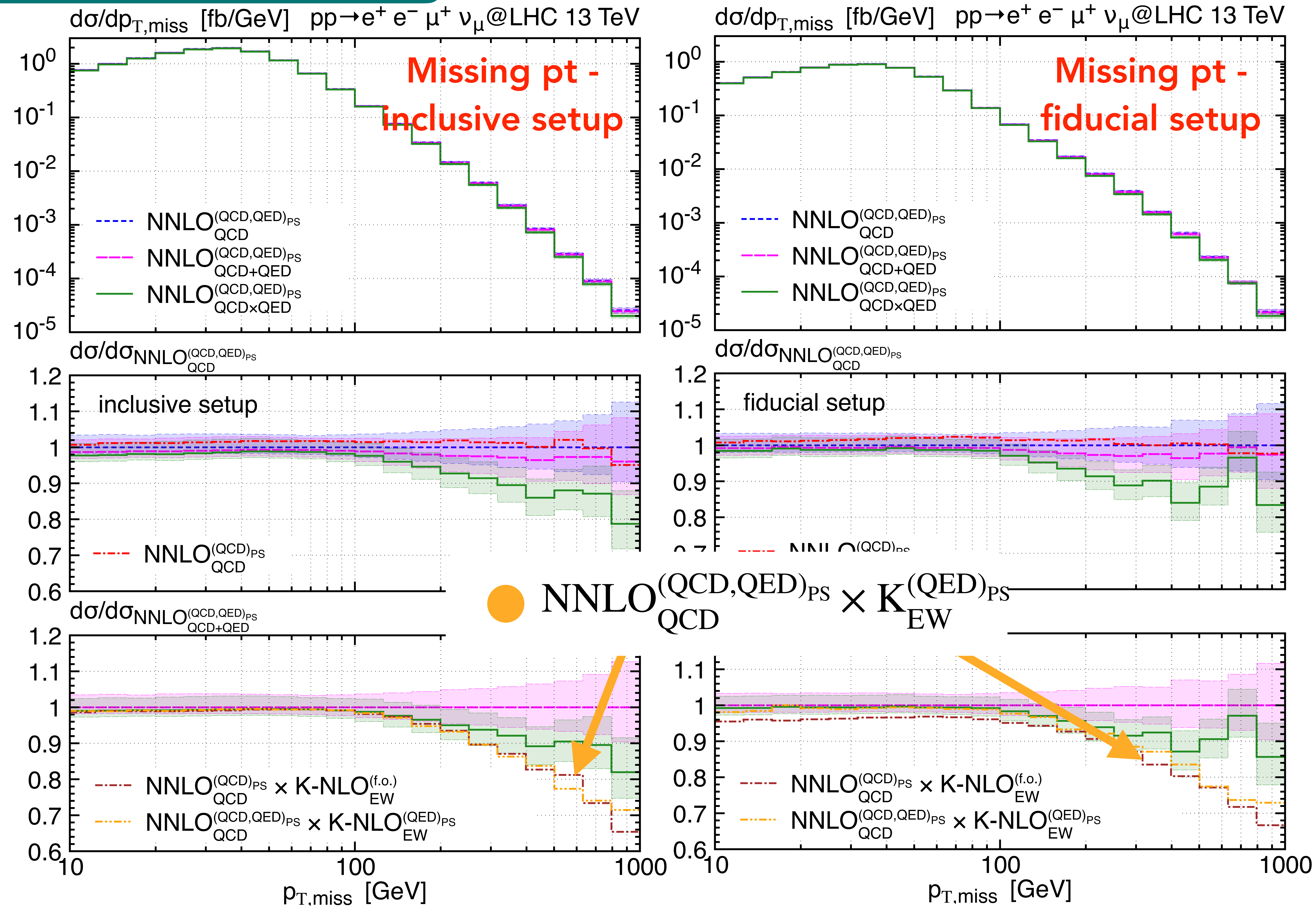
- ☐ Combination of NNLO+PS (QCD) with NLO+PS (EW) computations

WZ: results (4)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., '22]

LEGEND:

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

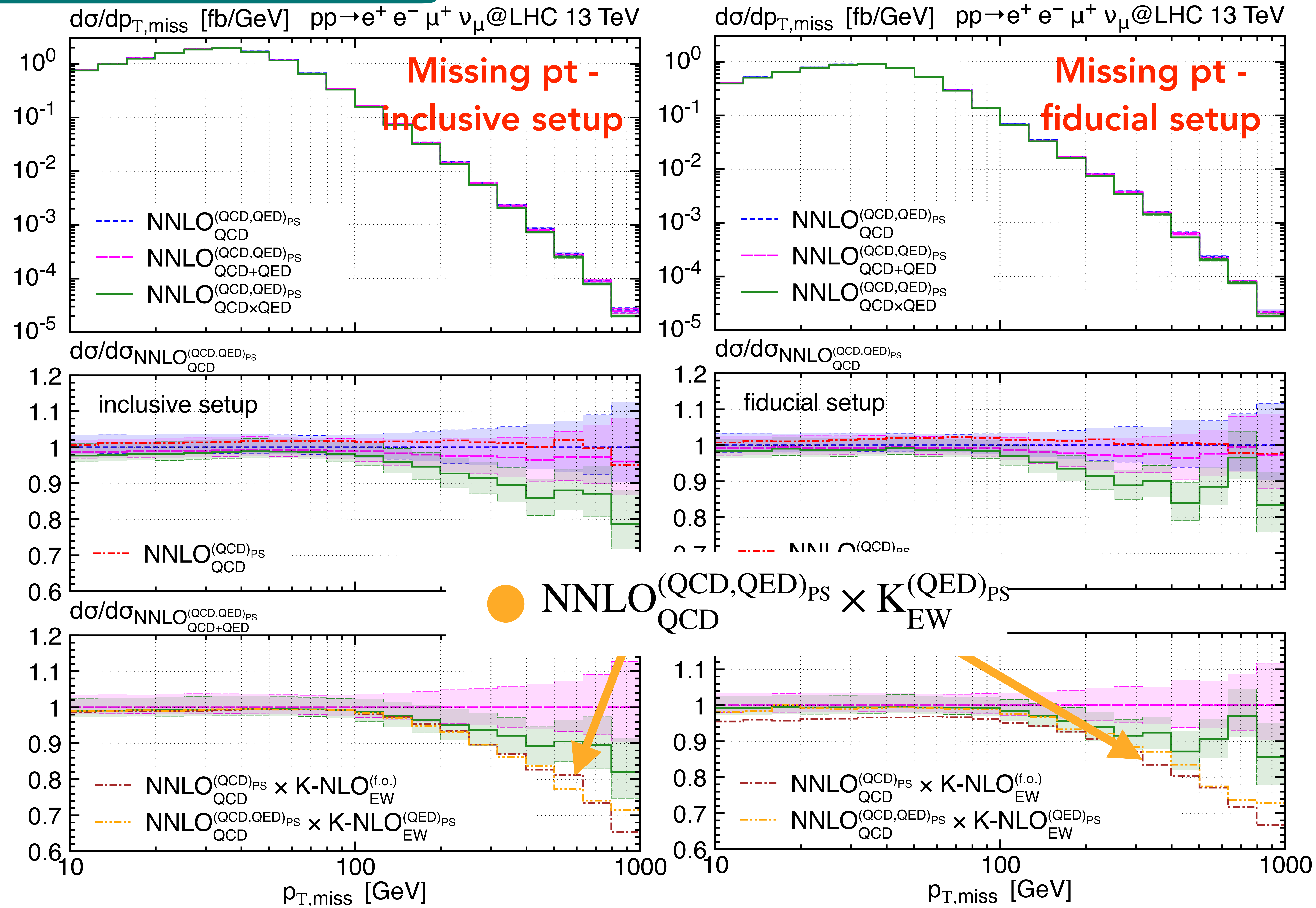


WZ: results (4)

[Lindert, Lombardi, Wiesemann, Zanderighi, S.Z., ’22]

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



● is affected by giant K-factors

MiNNLOPS

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

MiNNLOPS starting point : analytic all order formula

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

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

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

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

Calculation embedded in the POWHEG formalism:

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

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

NNLO accurate in F

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

Simplified notation!