

# NNLO QCD + NLO EW for diboson processes

Jonas M. Lindert



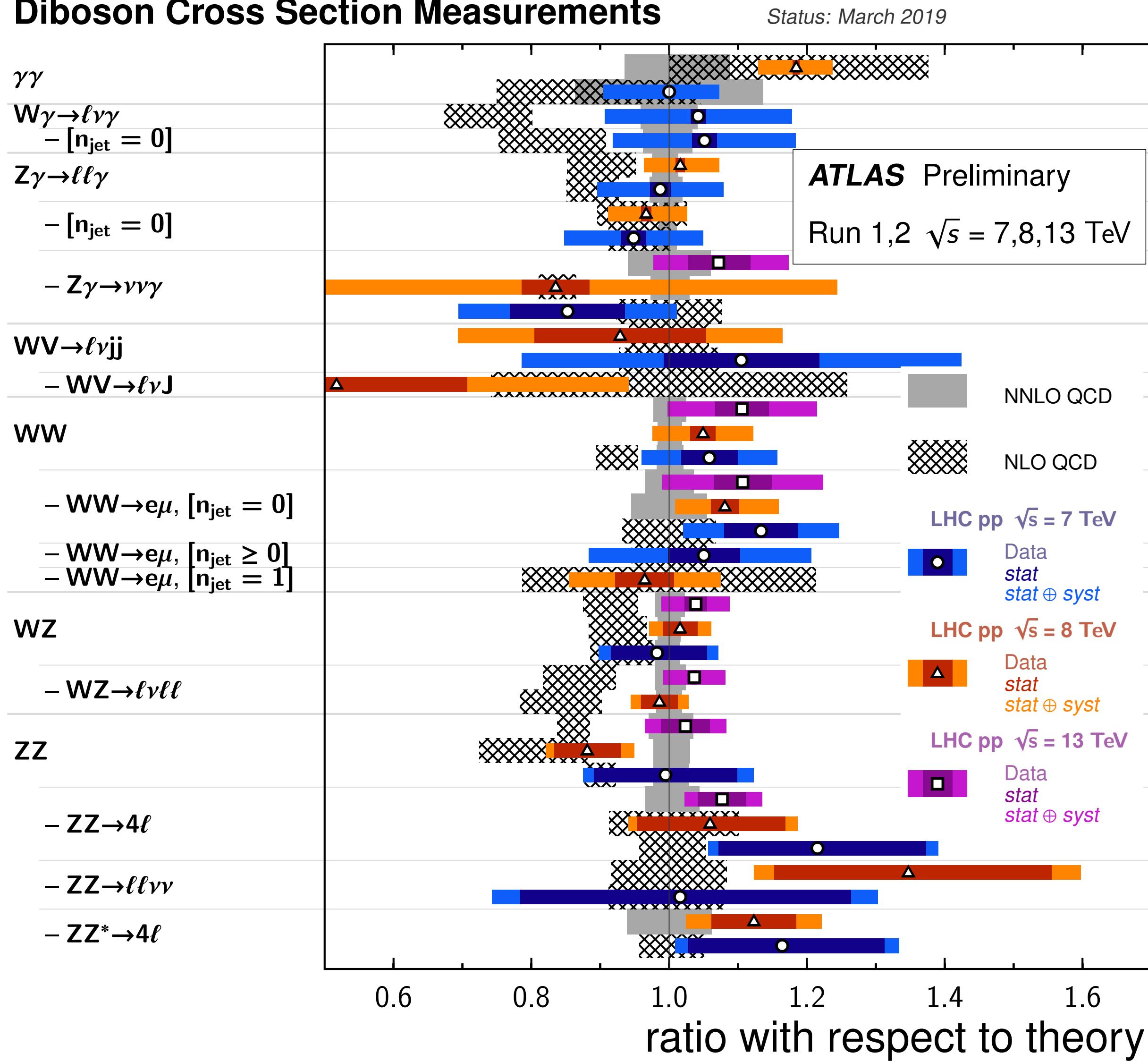
Durham  
University



Multi-Boson Interactions 2019  
Thessaloniki, 26. August 2019

# Status

## Diboson Cross Section Measurements

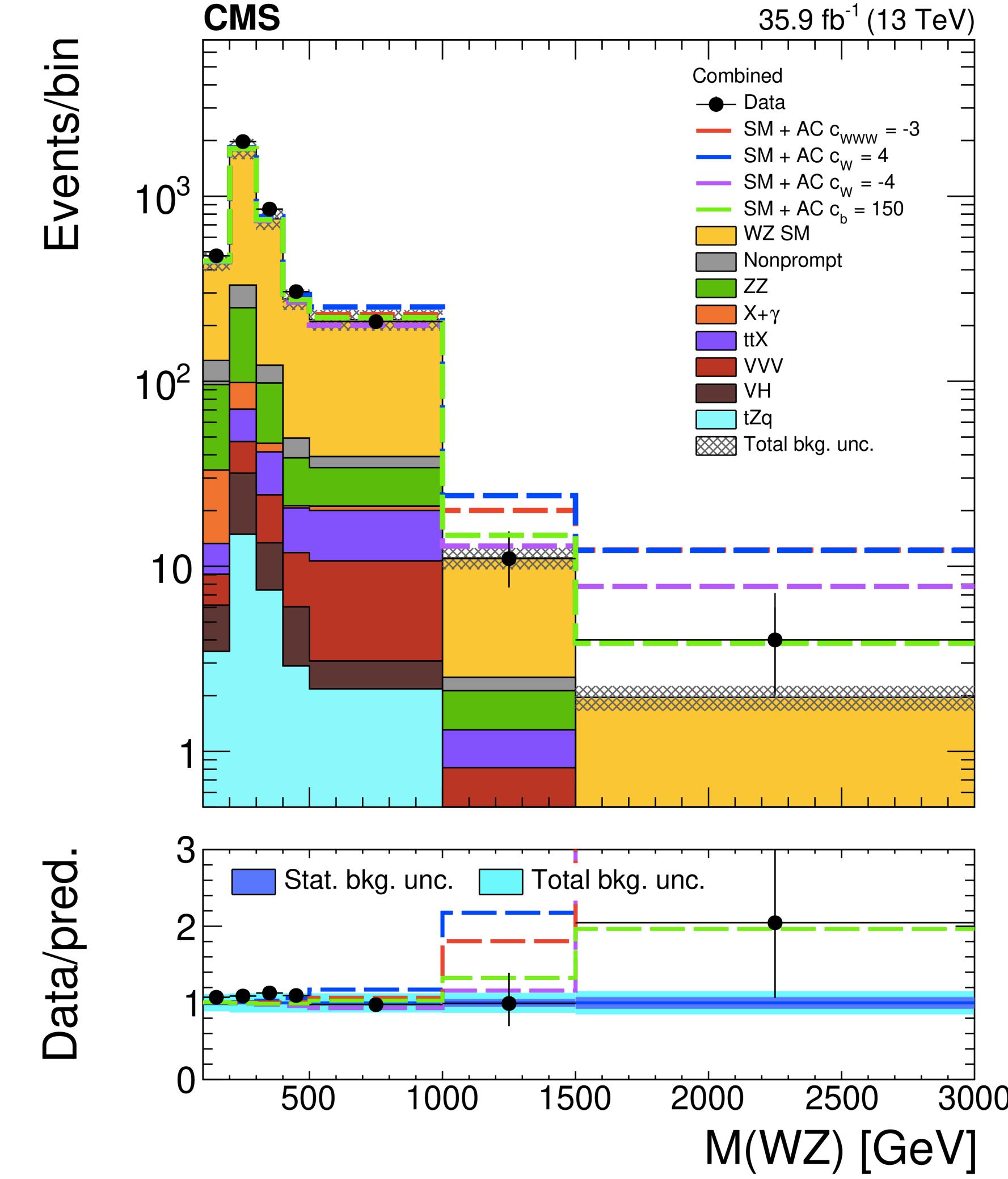
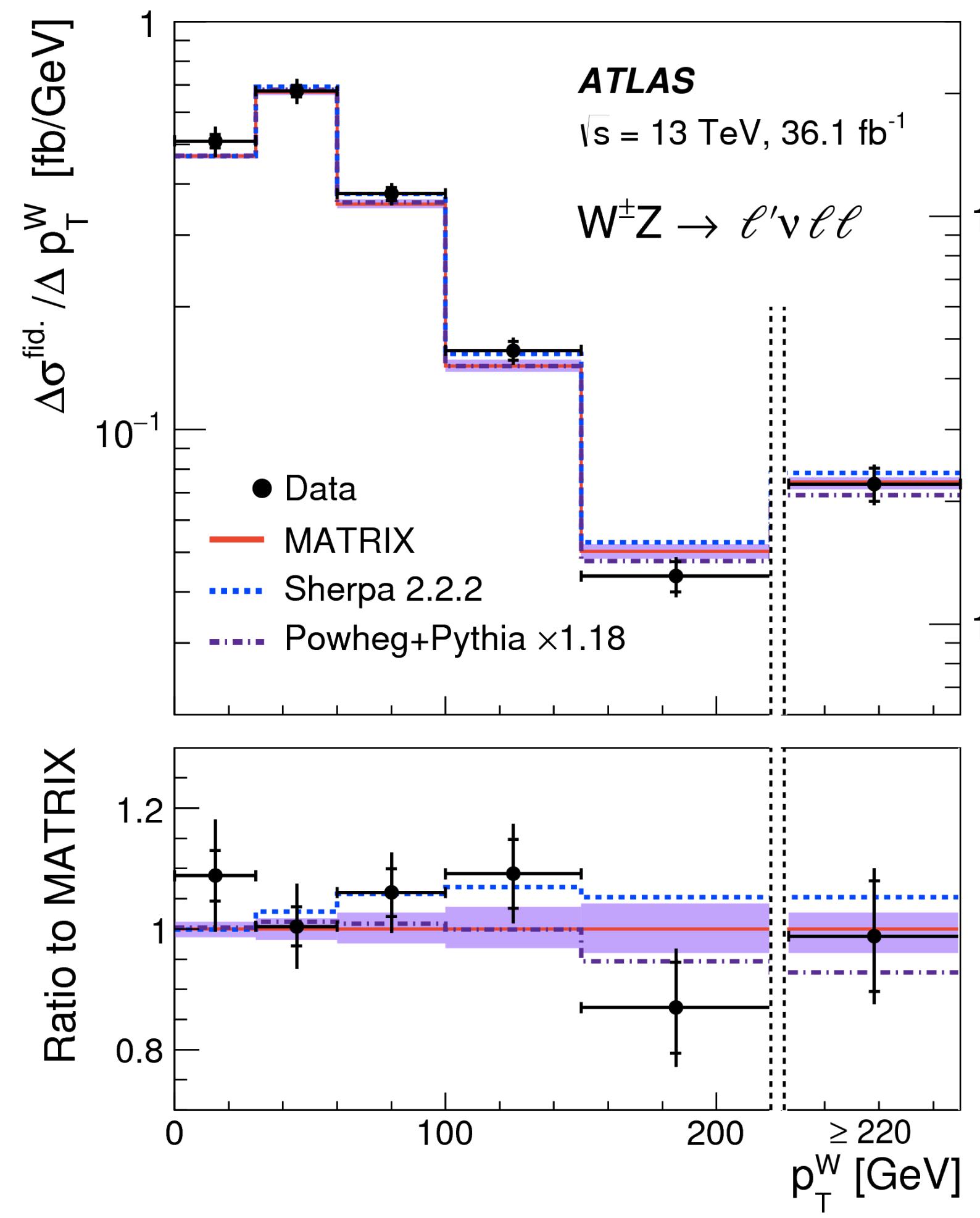


Remarkable agreement of inclusive diboson cross sections with NNLO QCD

Allows for stringent SM tests

Dibosons important background for Higgs and BSM searches

# Tails, tails, tails,....



# NNLO QCD corrections vor VV

**All VV processes known through NNLO QCD:**

[Talk by M. Wiesemann]

→ **inclusive/on-shell Z,W & differential/off-shell Z,W (leptonic)**

**YY** - **inclusive and differential** [Catani, Cieri, de Florian, Ferrera, Grazzini '12],  
[Campbell, Ellis, Li, Williams '16], [Grazzini, Kallweit, MW '17]

**Zγ** - **inclusive/on-shell and differential/off-shell**  
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]; see also: [Campbell et al. '17]

**Wγ** - **inclusive/on-shell and differential/off-shell**  
[Grazzini, Kallweit, Rathlev, Torre '13], [Grazzini, Kallweit, Rathlev '15]

**ZZ** - **inclusive/on-shell** [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer,  
von Manteuffel, Pozzorini, Rathlev, Tancredi, Weihs '14]; see also: [Heinrich et al. '17]  
- **differential/off-shell** [Grazzini, Kallweit, Rathlev '15], [Kallweit, MW '18]

**WW** - **inclusive/on-shell** [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, et al. '14]  
- **differential/off-shell** [Grazzini, Kallweit, Pozzorini, Rathlev, MW '15]

**WZ** - **inclusive/on-shell** [Grazzini, Kallweit, Rathlev, MW '16]  
- **differential/off-shell** [Grazzini, Kallweit, Rathlev, MW '17]

# Perturbative expansion

$$d\sigma = d\sigma_{\text{LO}} + \alpha_s d\sigma_{\text{NLO}} + \alpha_{\text{EW}} d\sigma_{\text{NLO EW}}$$

NLO QCD

NLO EW

$$+ \alpha_s^2 d\sigma_{\text{NNLO}} + \alpha_{\text{EW}}^2 d\sigma_{\text{NNLO EW}} + \alpha_s \alpha_{\text{EW}} d\sigma_{\text{NNLO QCDxEW}} + \dots$$

NNLO QCD

NNLO EW

NNLO QCD-EW

Numerically  $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$

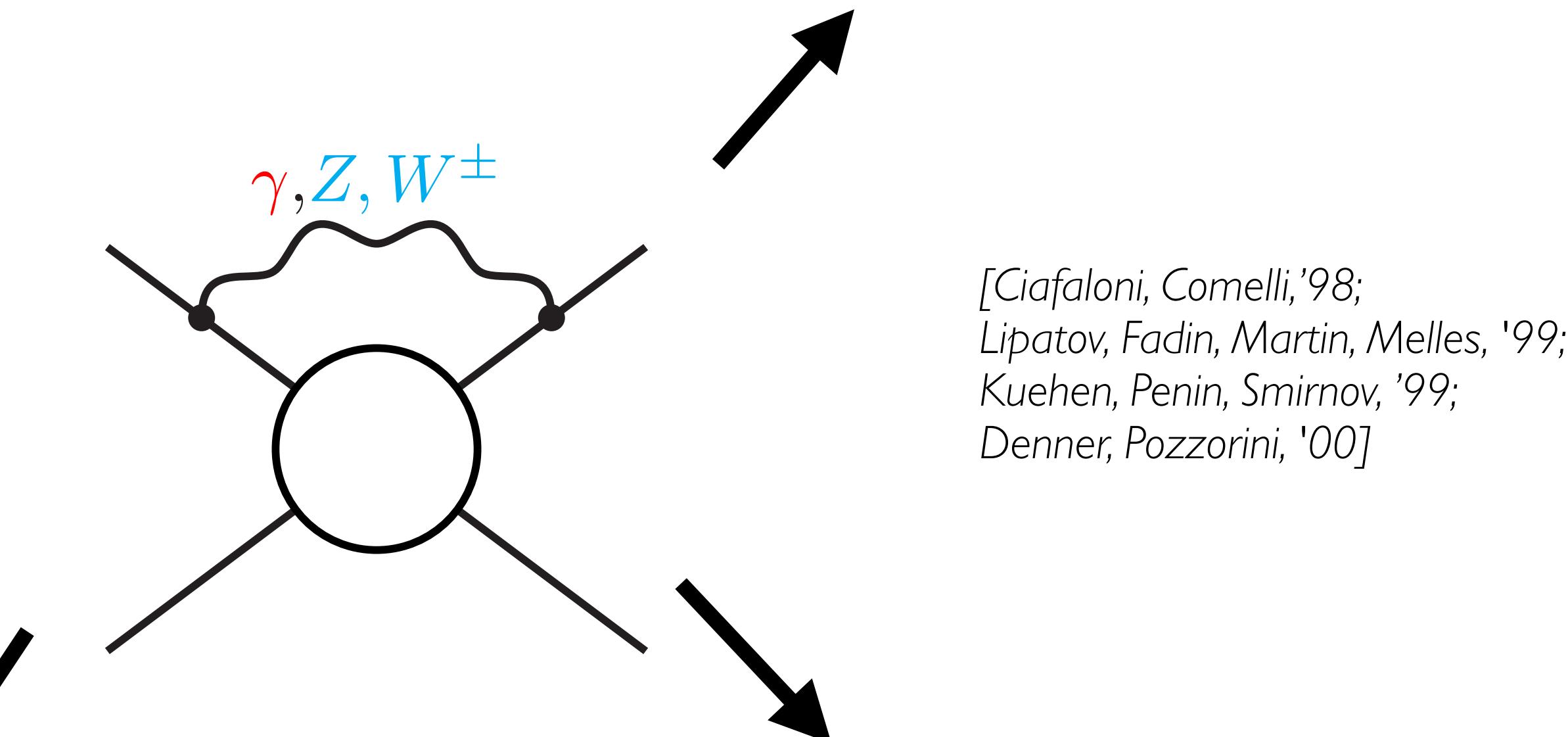
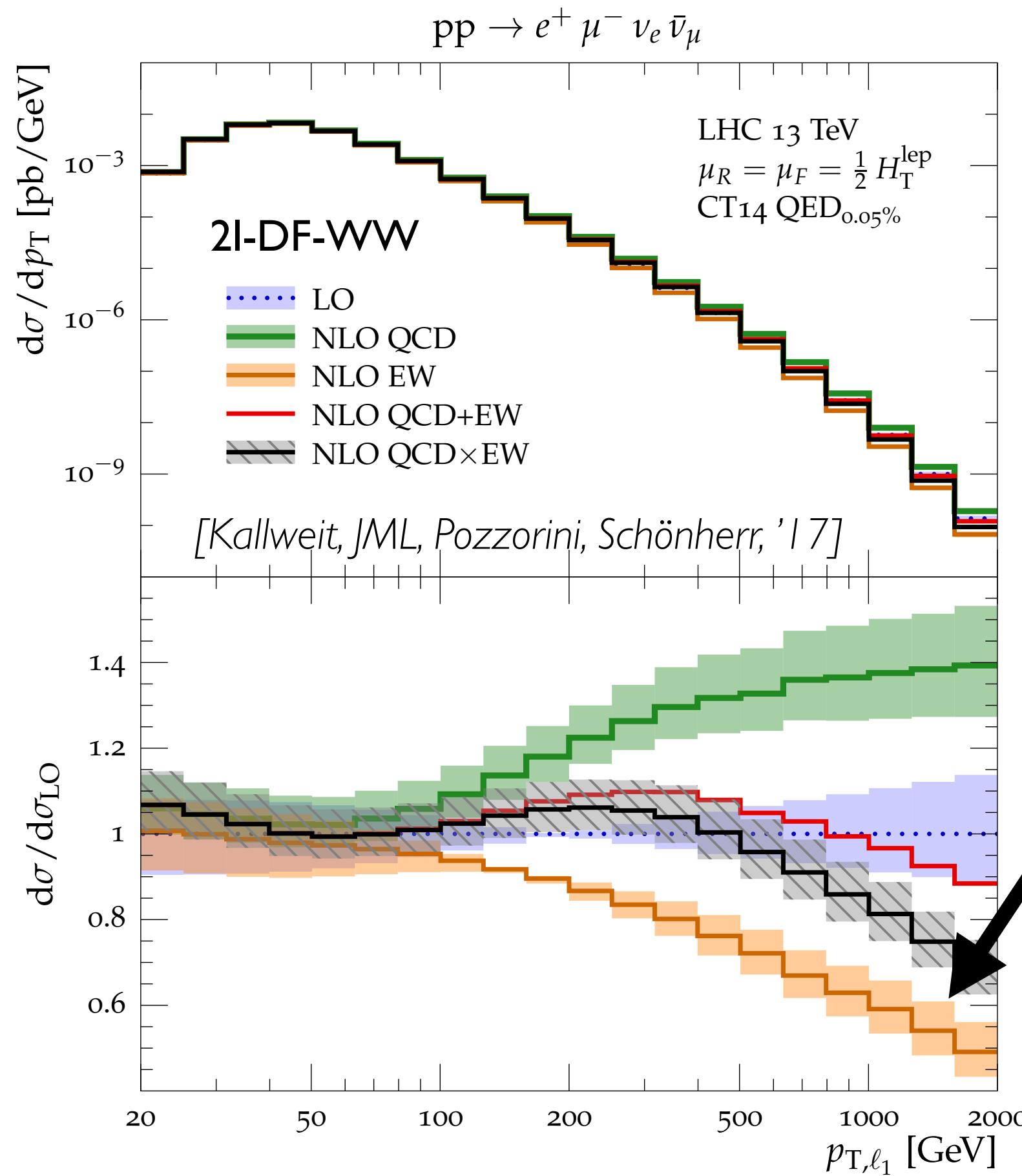
**NLO EW ~ NNLO QCD**

## NLO EW

- 4I-DF-ZZ Biedermann, Denner, Dittmaier, Hofer, Jäger; '16, '16
- 2I-DF-WW Biedermann, Billoni, Denner, Dittmaier, Hofer, Jäger, Salfelder; '16
- 2I-SF-ZZ & 2I-SF-ZZWW & 2I-DF-WW Kallweit, JML, Pozzorini, Schönherr, '17
- 3I-DF-WZ & 3I-DF-WZ Biedermann, Denner, Hofer, '17

# Relevance of EW higher-order corrections: Sudakov logs in the tails

I. Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:



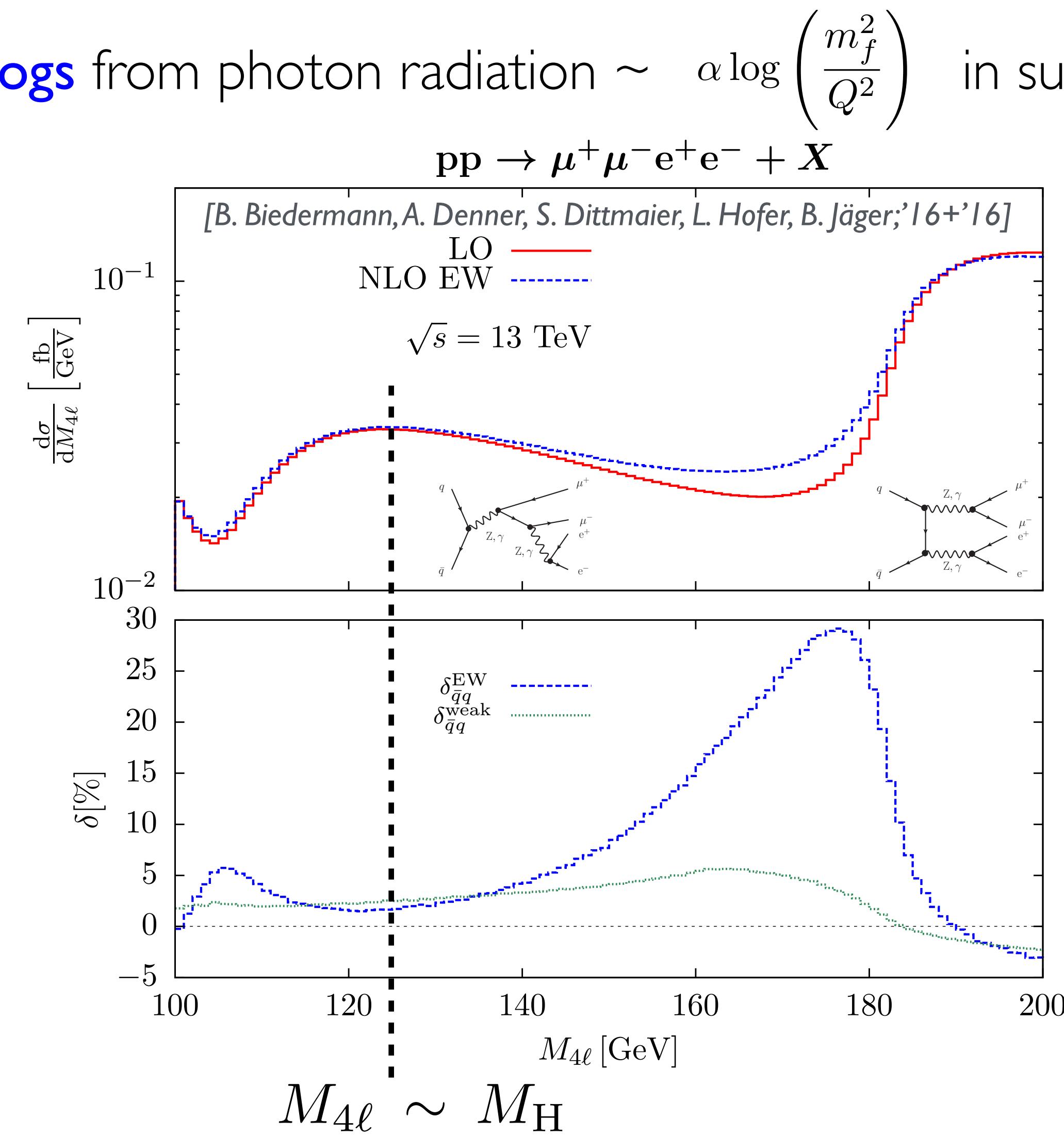
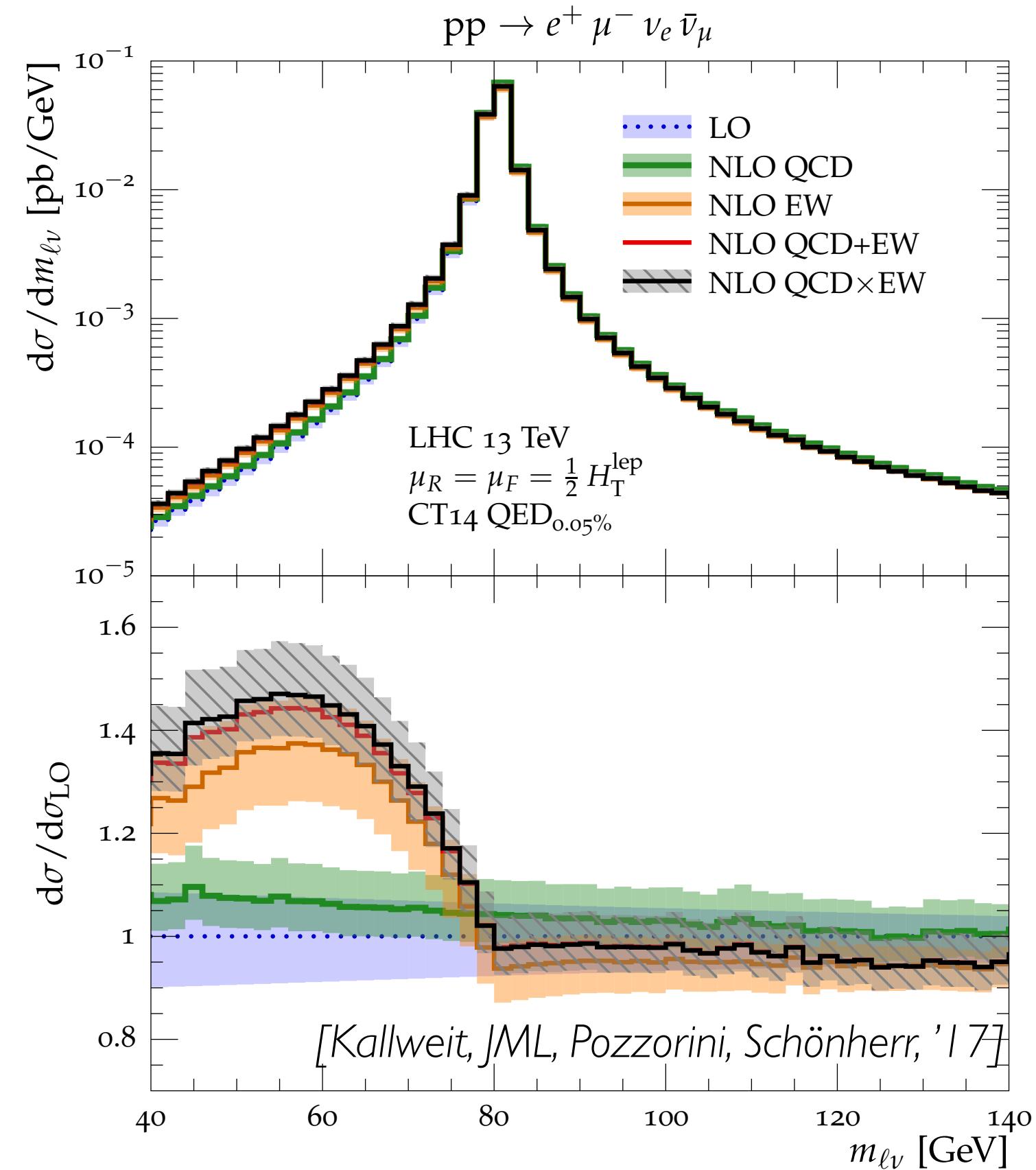
Universality and factorisation: [Denner, Pozzorini; '01]

$$\delta \mathcal{M}_{\text{LL+NLL}}^{1\text{-loop}} = \frac{\alpha}{4\pi} \sum_{k=1}^n \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma, Z, W^\pm} I^a(k) I^{\bar{a}}(l) \ln^2 \frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k) \ln \frac{\hat{s}}{M^2} \right\} \mathcal{M}_0$$

→ overall large (negative) effect in the tails of distributions:  
 $p_T, m_{\text{inv}}, H_T, \dots$  (relevant for BSM searches!)

# Relevance of EW higher-order corrections: collinear QED radiation

- II. Possible large enhancement due to soft/collinear **logs** from photon radiation  $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$  in sufficiently exclusive observables.



→ important for radiative tails, Higgs backgrounds etc.

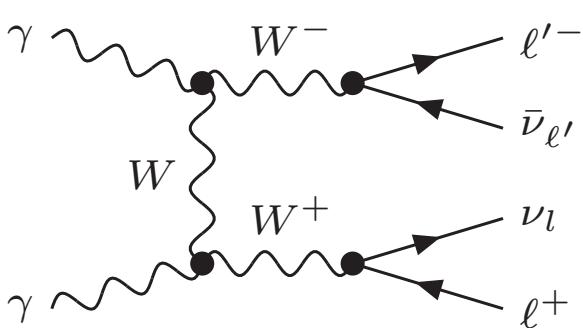
→ typically considered via QED PS (PHOTOS / YFS)

# Relevance of EW higher-order corrections: photon-induced channels

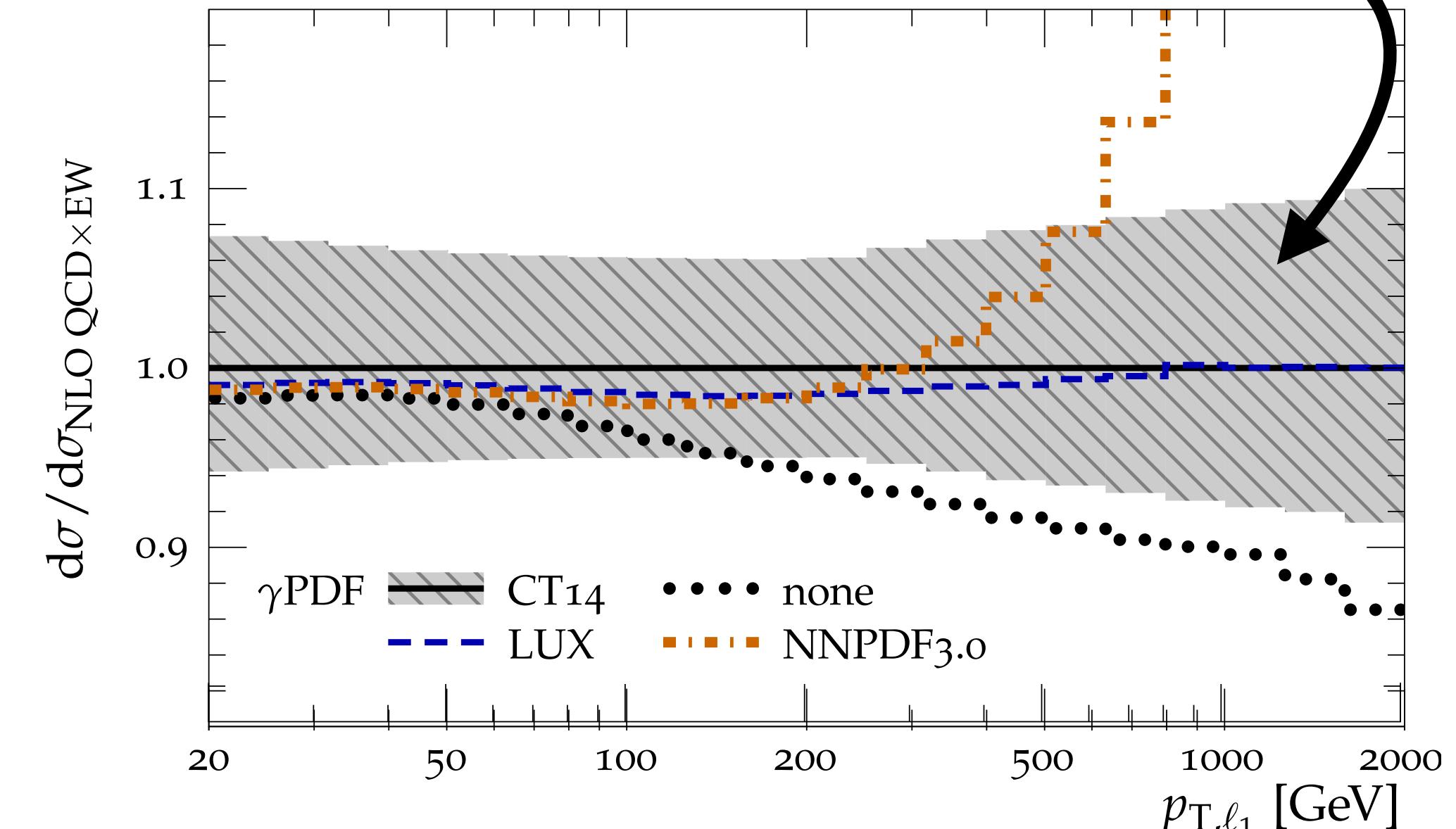
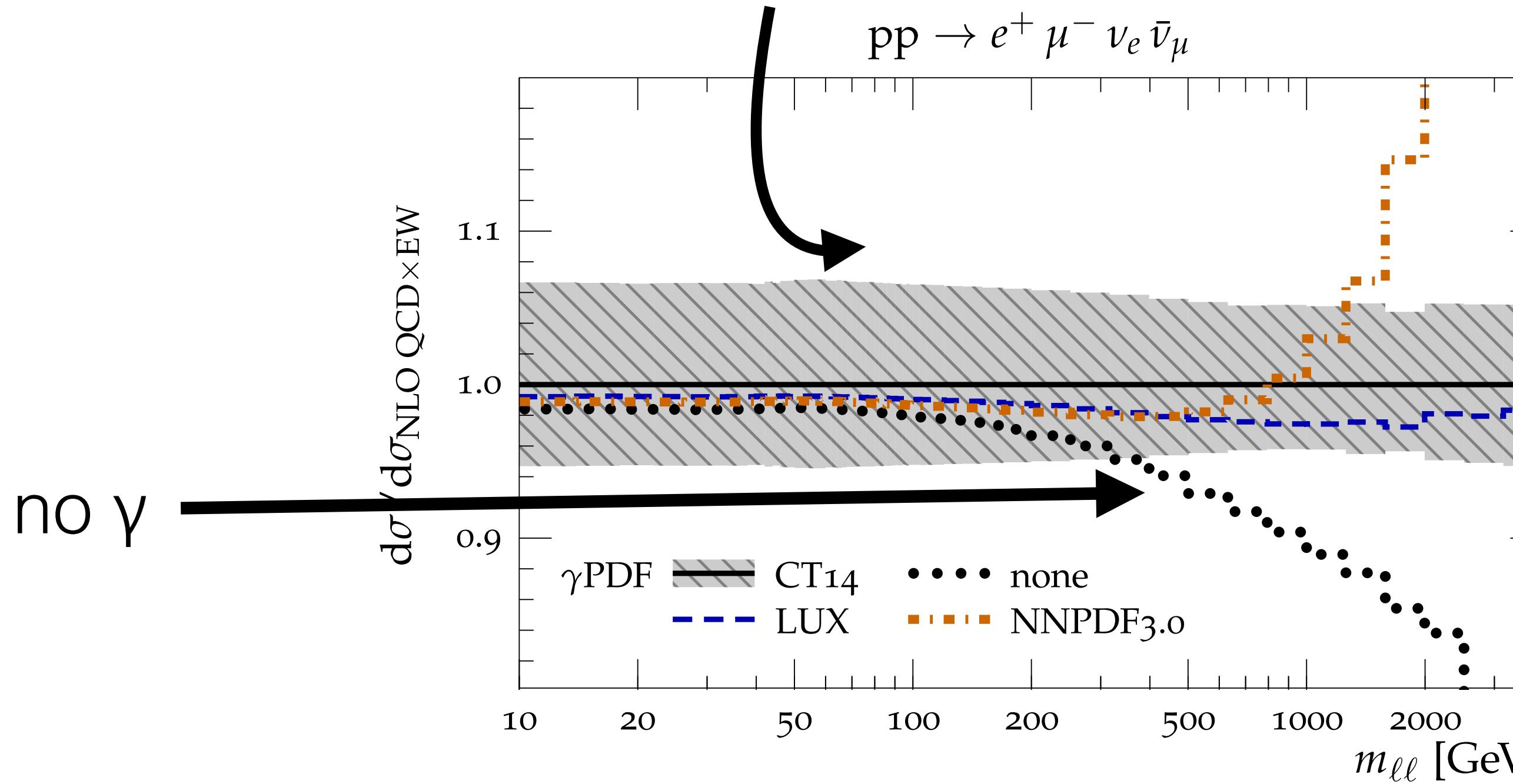
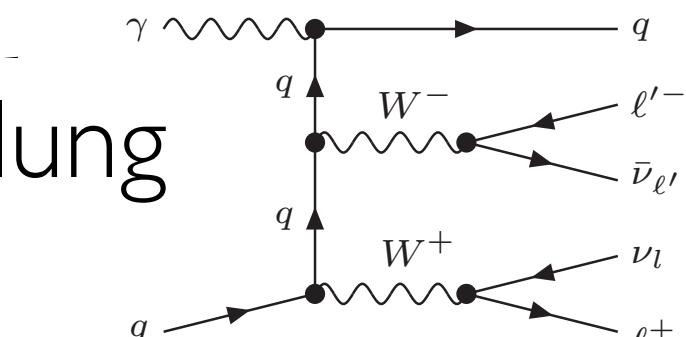
III. QED factorisation and thus photon luminosities needed to absorb IS photon singularities.

→ Possible large enhancement due to photon-induced channels in the tails of kinematic distributions,

in particular in WW:



(t-channel enhancement), but also in Bremsstrahlung

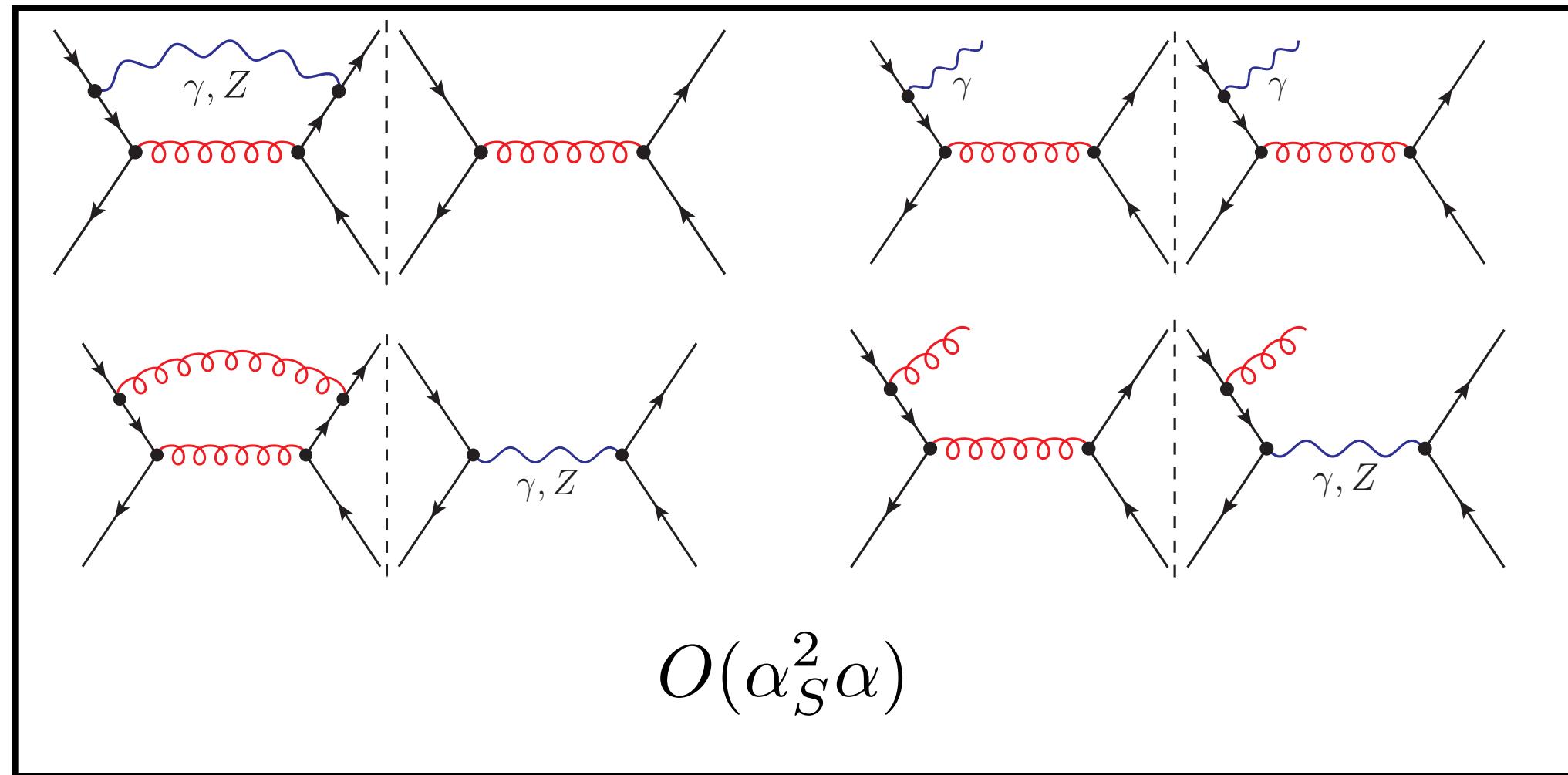


→ large differences between different photon descriptions. Now settled: LUXqed superior

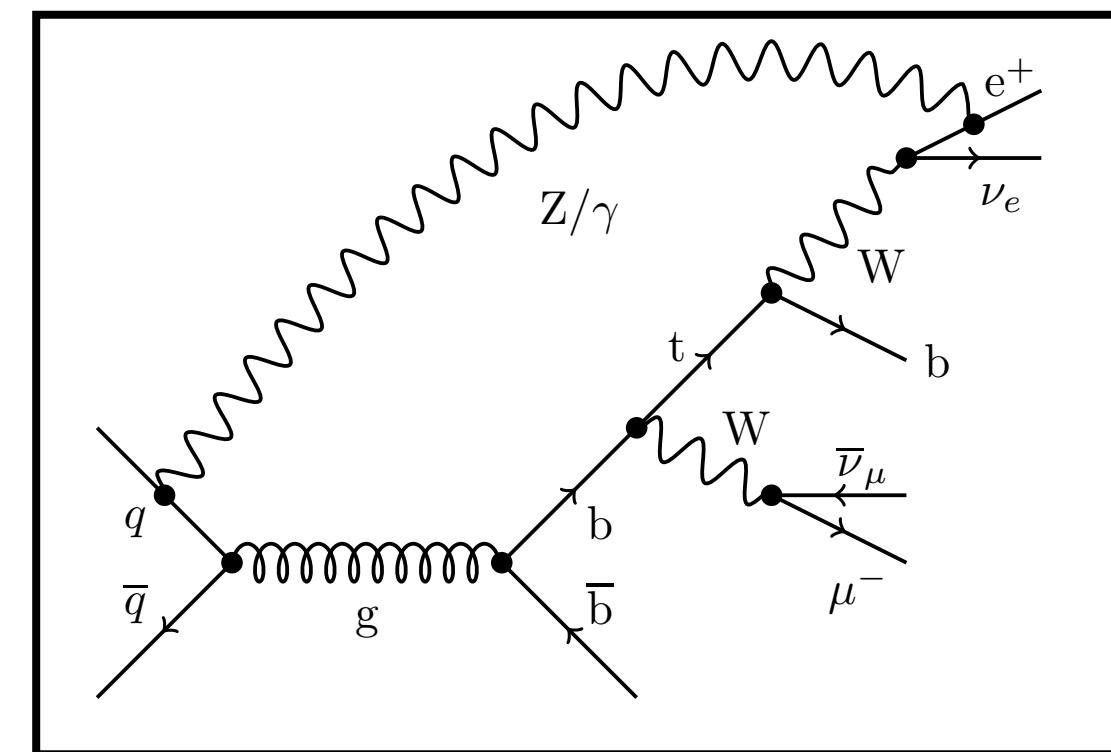
→ O(10%) contributions from photon-induced channels

# Nontrivial features in NLO QCD → NLO EW

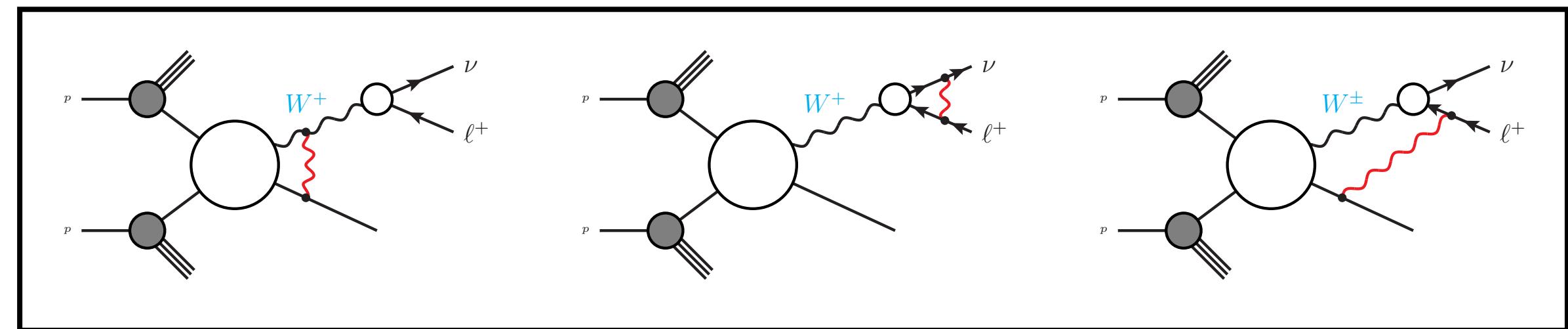
## I. QCD-EW interplay



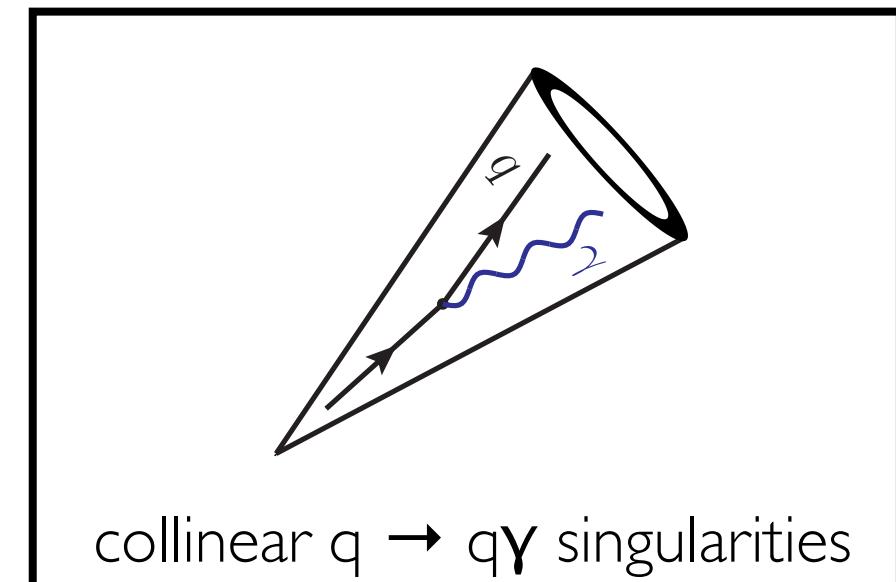
3. virtual **EW** corrections more involved than **QCD**  
(many internal masses)



2. At NLO **EW** corrections in production, decay and non-factorizable contributions for V decays  
→ **complex-mass-scheme**



4. photon contributions in jets and proton  
→ **photon-jet separation,  $\gamma$ PDF**



Automation of fixed-order NLO EW well advanced:  
MadGraph\_aMC@NLO, Sherpa+OpenLoops/Recola, MUNICH+OpenLoops, ...

# Validation between tools

- There are subtle differences in implementation of these schemes in particular in the context of CMS (complex mass scheme).  
→ Have been studied for ZZ in the context of [LHI7, 1803.07977]

$$u\bar{u} \rightarrow e^+e^-\mu^+\mu^-$$

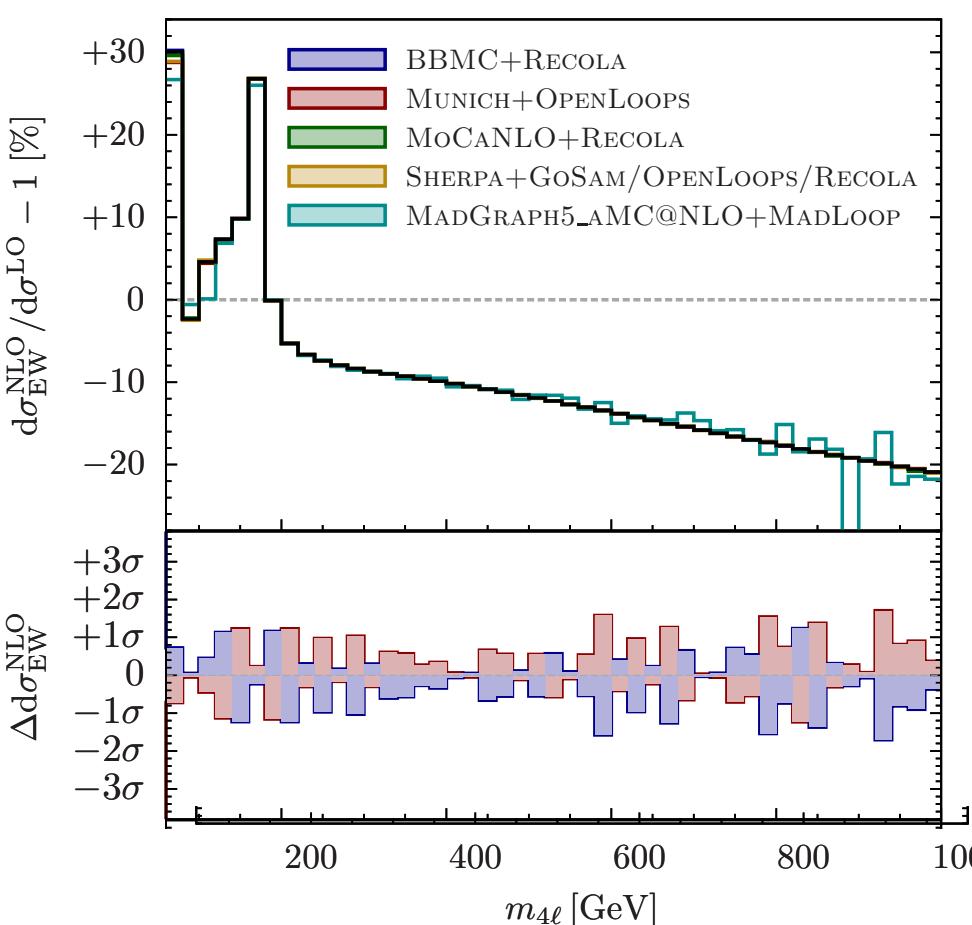
individual phase-space points:

a) PSP 1	$B/10^{-15}$	$V_{\text{finite}}/10^{-16}$	$V_1/10^{-17}$	$V_2/10^{-17}$
MADLOOP	5.26592465401088	6.60297993618509	2.63915540074976	-3.09566543908773
RECOLA	5.26592465401090	6.60088670209820	2.63915540075328	-3.09566543908732
OPENLOOPS	5.26592465401100	6.60088670210145	2.63915540078563	-3.09566543905505
GoSAM	5.26592465401086	6.60088670209788	2.63915540076095	-3.09566543909091
NLOX	5.26592465401084	6.60088670211436	2.63915540076702	-3.09566543908783

$$\gamma\gamma \rightarrow e^+e^-\mu^+\mu^-$$

c) PSP 1	$B/10^{-13}$	$V_{\text{finite}}/10^{-14}$	$V_1/10^{-15}$	$V_2/10^{-15}$
MADLOOP	4.63762790127829	6.79330655006349	4.07216839247769	-2.23061748556626
RECOLA	4.63762790127830	6.79163662486900	4.07216839245629	-2.23061748556050
OPENLOOPS	4.63762790127838	6.79163662486753	4.07216839246097	-2.23061748560388
GoSAM	4.63762790127830	6.79163662486761	4.07216839247955	-2.23061748556541

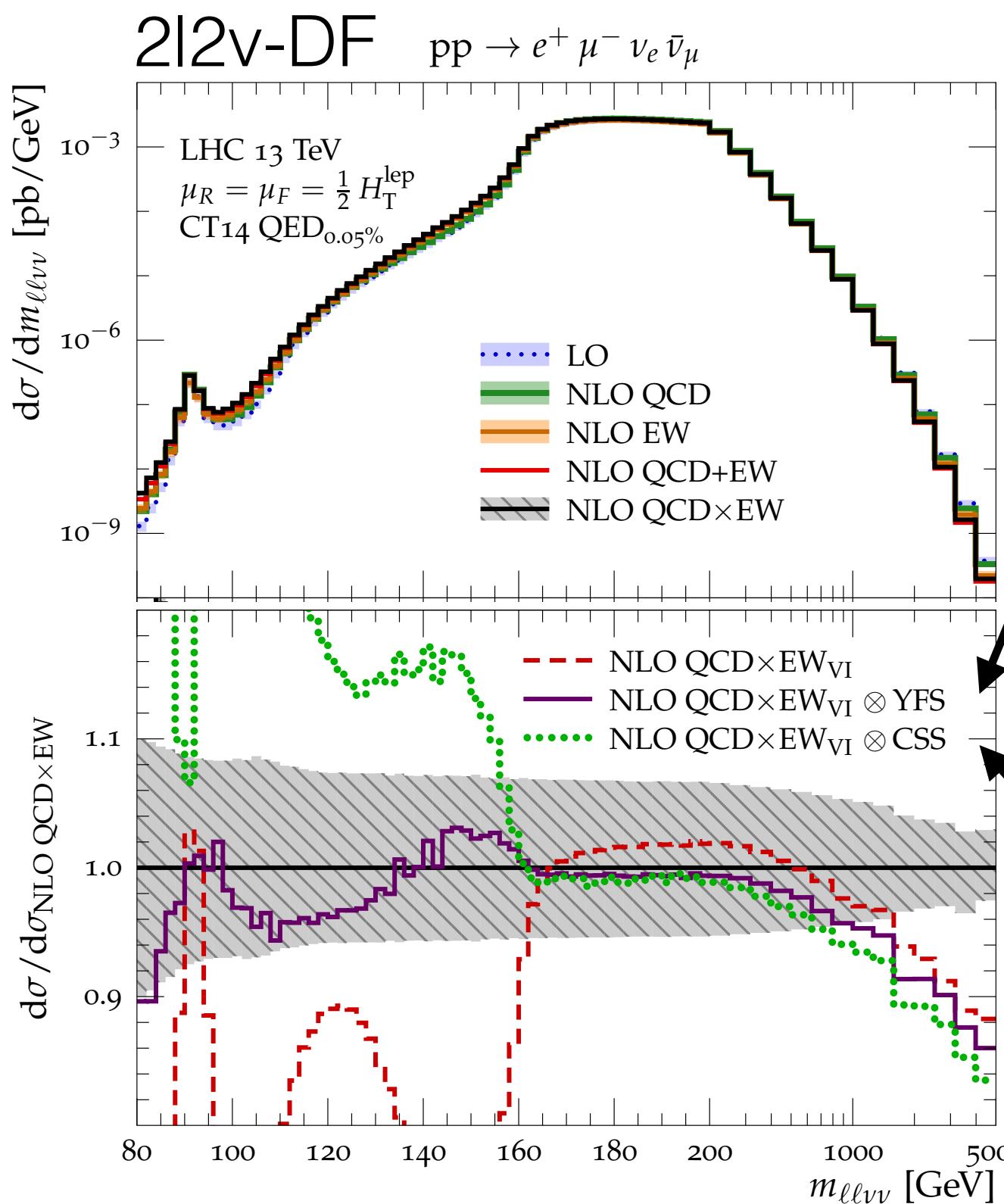
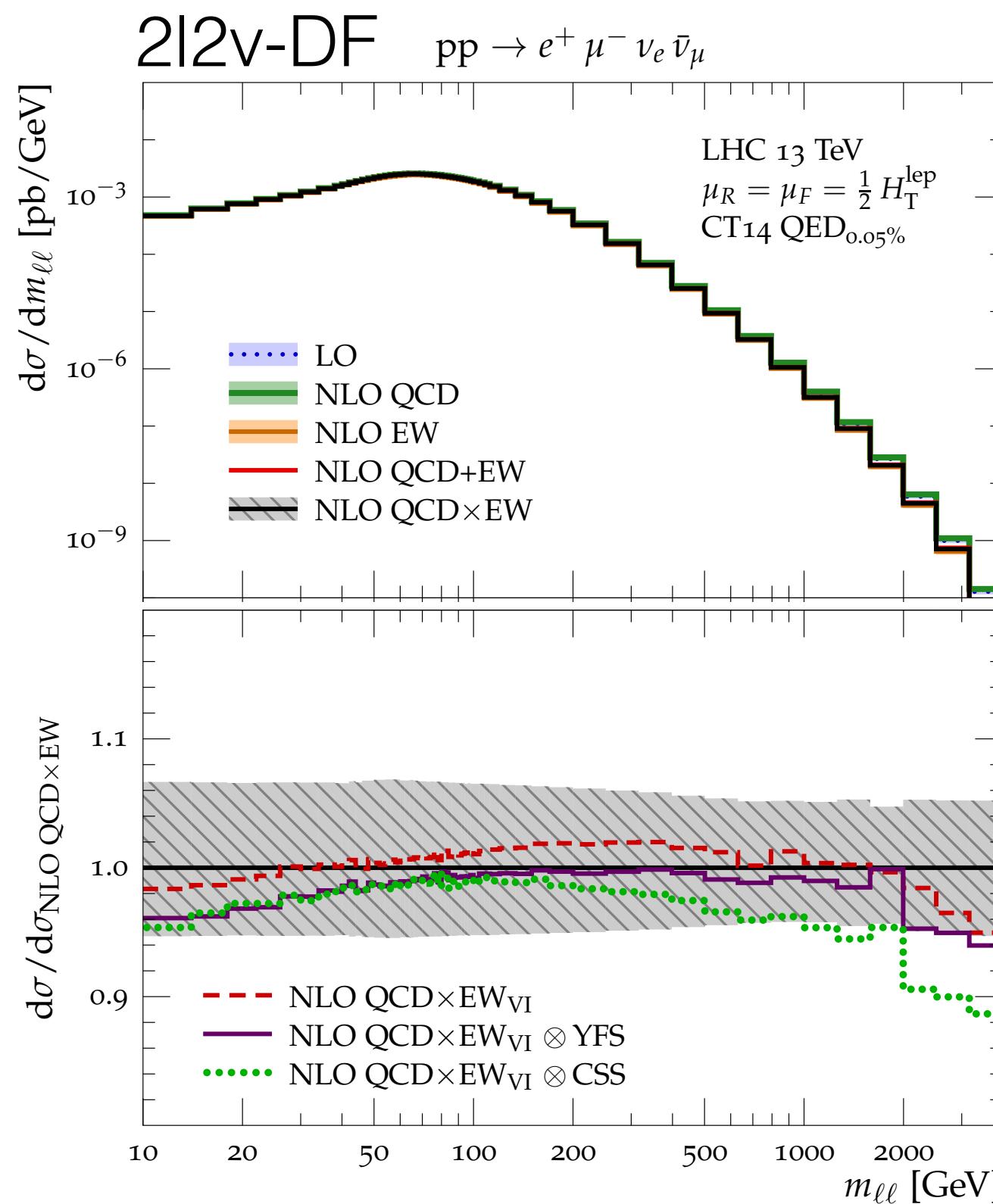
inclusive cross sections:



→ very convincing agreement  
between automated tools

# Diboson production at NLO QCD+EW: Collinear QED radiation

[Kallweit, JML, Pozzorini, Schönherr; '17]



**YFS (Multi-Photon-Resummation) preserves resonance structure**  
→ EW effects agree at the few percent level.

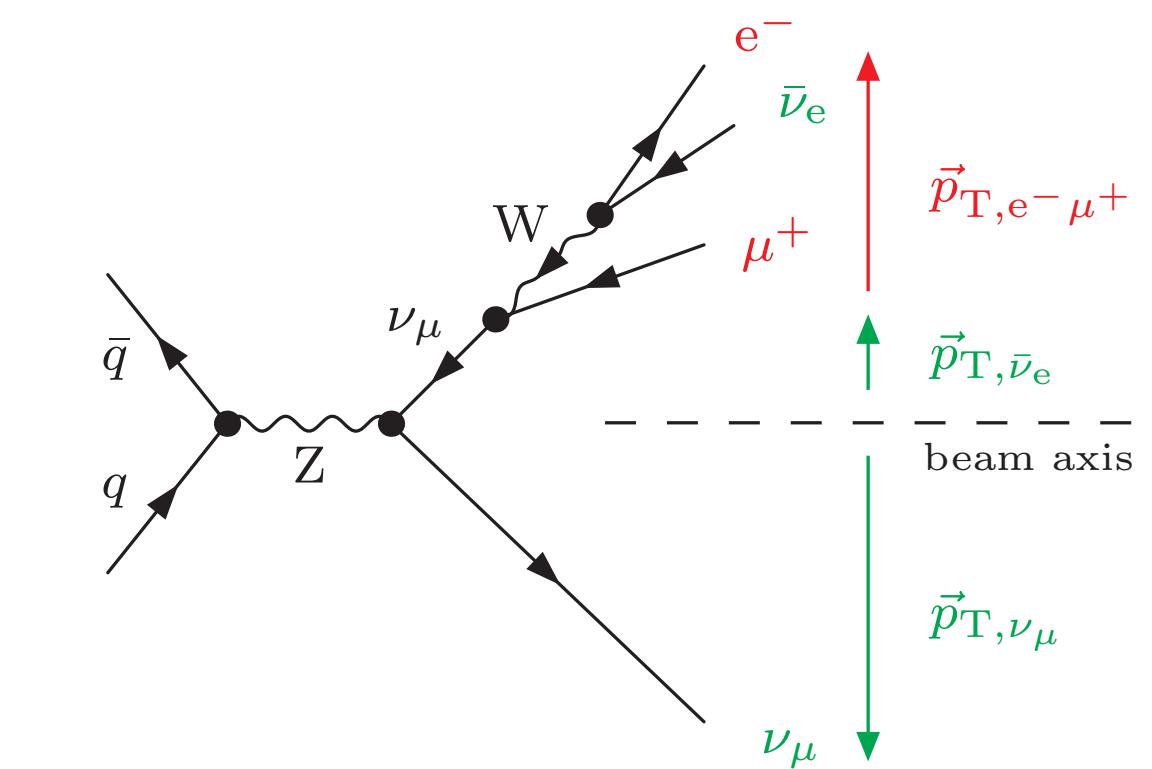
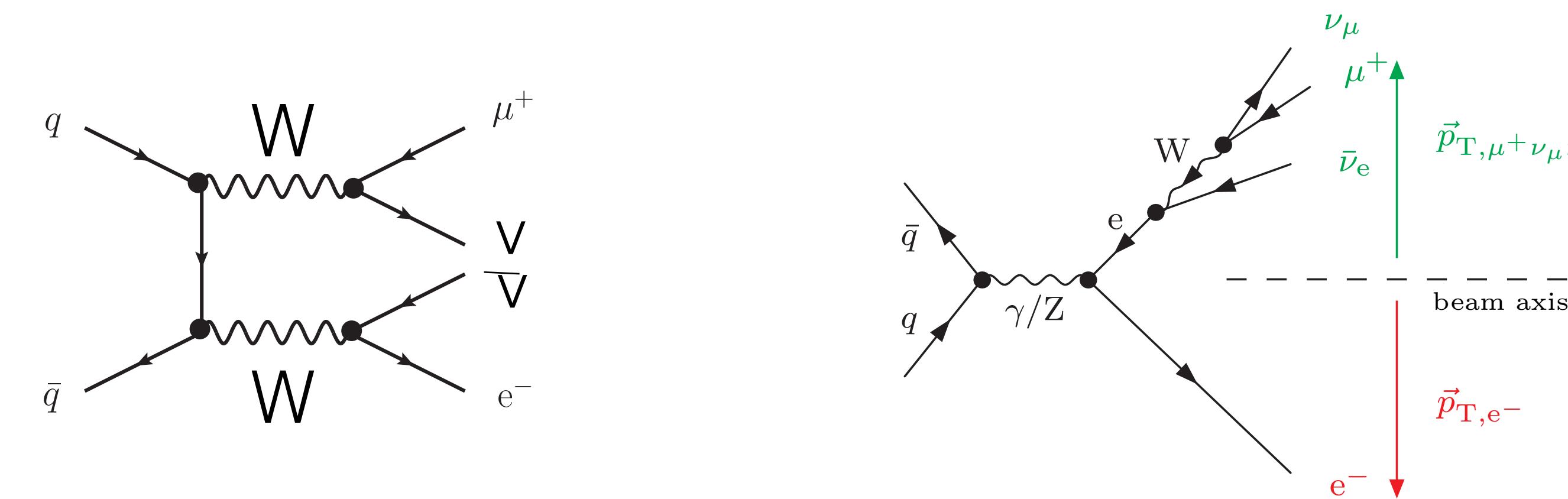
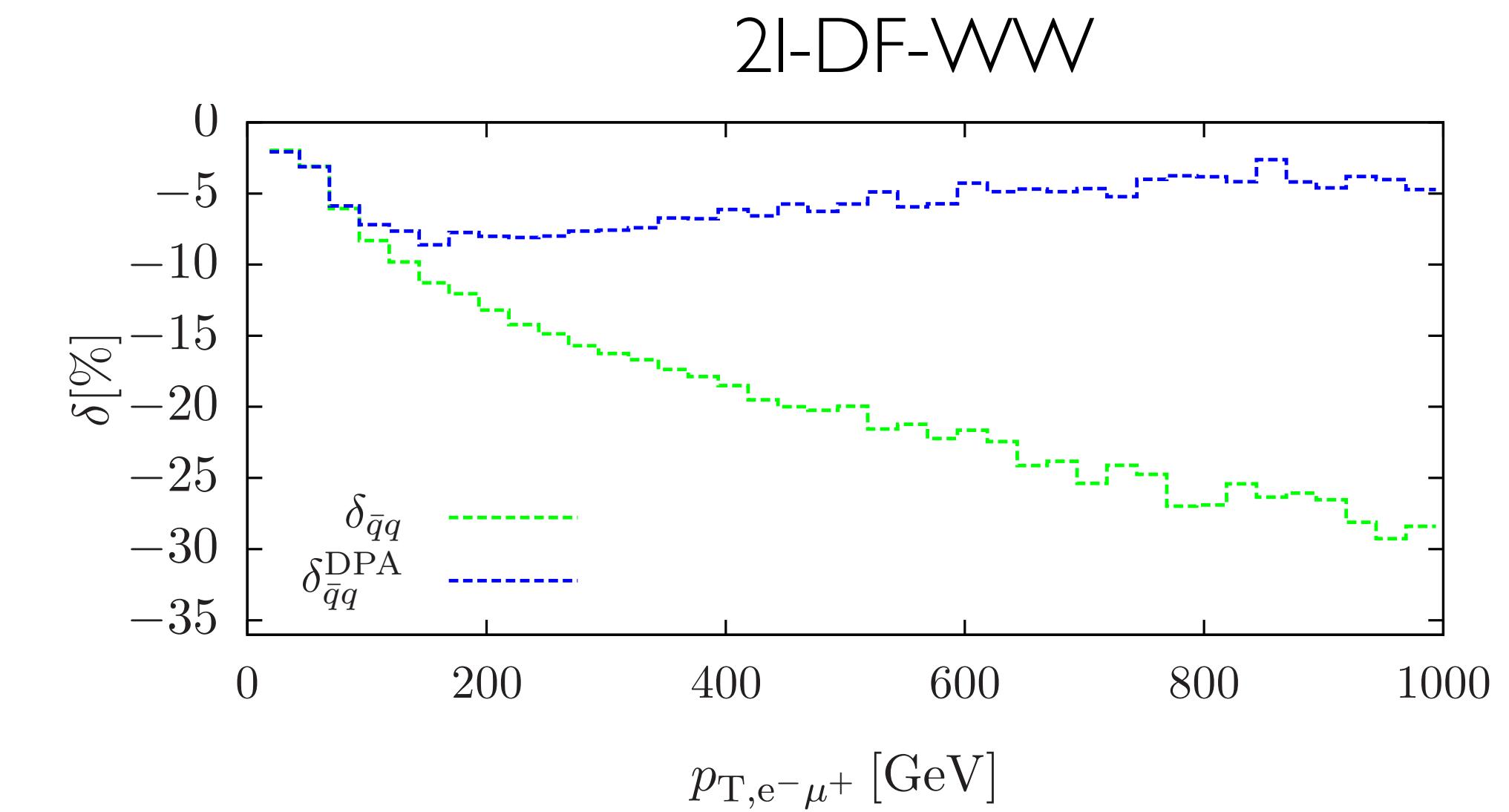
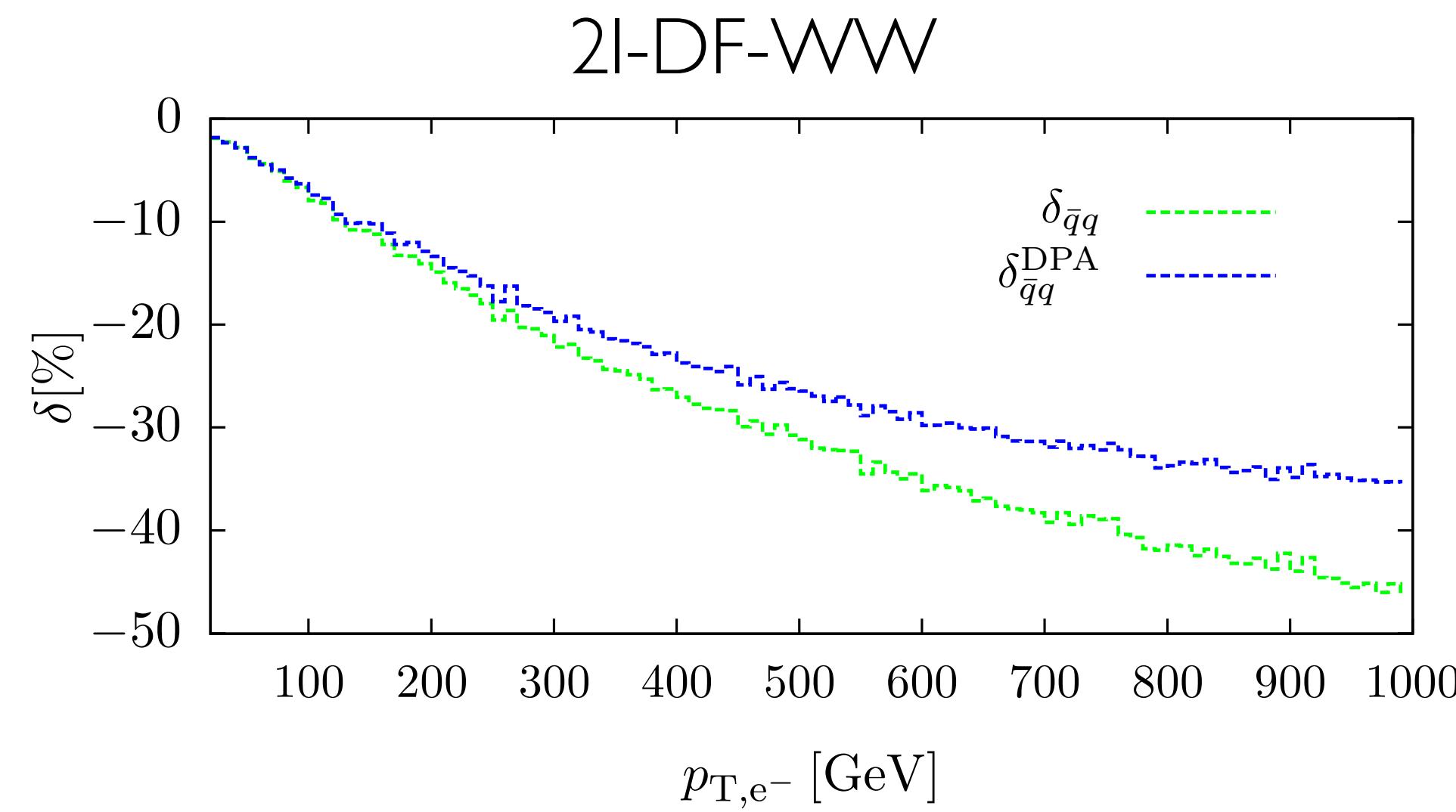
Source of differences:  
• Multi-poton effects in YFS  
• Resonance-assignment in YFS

**CSS (Catani-Seymour-Shower)**  
unaware of resonance structure  
→ QED effects largely overestimated

- Fully consistent PS matching at NLO EW under development
- Naive NLO EW+PS matching available in Sherpa+OpenLoops (applicable at particle level)
  - CSS dipole shower (not resonance aware) ⇒ significant mismodelling
  - YFS resummation (resonance aware) ⇒ valid approximation

# The need for off-shell calculations

[Biedermann, M. Billoni, A. Denner, S. Dittmaier, L. Hofer, B. Jäger, L. Salfelder ;'16]



→ sizeable differences in fully off-shell vs. double-pole approximation in tails

# Combination of NNLO QCD and NLO EW

- In Matrix+OpenLoops all (massive) diboson processes are available at NNLO QCD + NLO EW (parton-level) [M. Grazzini, S. Kallweit, JML, S. Pozzorini, M. Wiesemann; very soon]

4l-SF-ZZ	$pp \rightarrow \ell^+ \ell^- \ell^+ \ell^-$	(ZZ)	
4l-DF-ZZ	$pp \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$	(ZZ)	
2l-SF-ZZ	$pp \rightarrow \ell^+ \ell^- \nu_{\ell'} \bar{\nu}_{\ell'}$	(ZZ)	
2l-SF-ZZWW	$pp \rightarrow \ell^+ \ell^- \nu_{\ell} \bar{\nu}_{\ell}$	(ZZ/WW)	(soon to be made public)
2l-DF-WW	$pp \rightarrow \ell^+ \ell'^- \nu_{\ell} \bar{\nu}_{\ell'}$	(WW)	
3l-SF-WZ	$pp \rightarrow \ell^+ \ell^- \ell \nu_{\ell}$	(WZ)	
3l-DF-WZ	$pp \rightarrow \ell^+ \ell^- \ell' \nu_{\ell'}$	(WZ)	

- Combination of QCD and EW

additive:  $\text{d}\sigma_{\text{QCD+EW}}^{(\text{N})\text{NLO}} = \text{d}\sigma^{\text{LO}}(1 + \delta_{\text{QCD}}^{(\text{N})\text{NLO}} + \delta_{\text{EW}}) + \text{d}\sigma^{\text{ggLO}}$

multiplicative:  $\text{d}\sigma_{\text{QCD} \times \text{EW}}^{(\text{N})\text{NLO}} = \text{d}\sigma^{\text{LO}}(1 + \delta_{\text{QCD}}^{(\text{N})\text{NLO}})(1 + \delta_{\text{EW}}) + \text{d}\sigma^{\text{ggLO}}$

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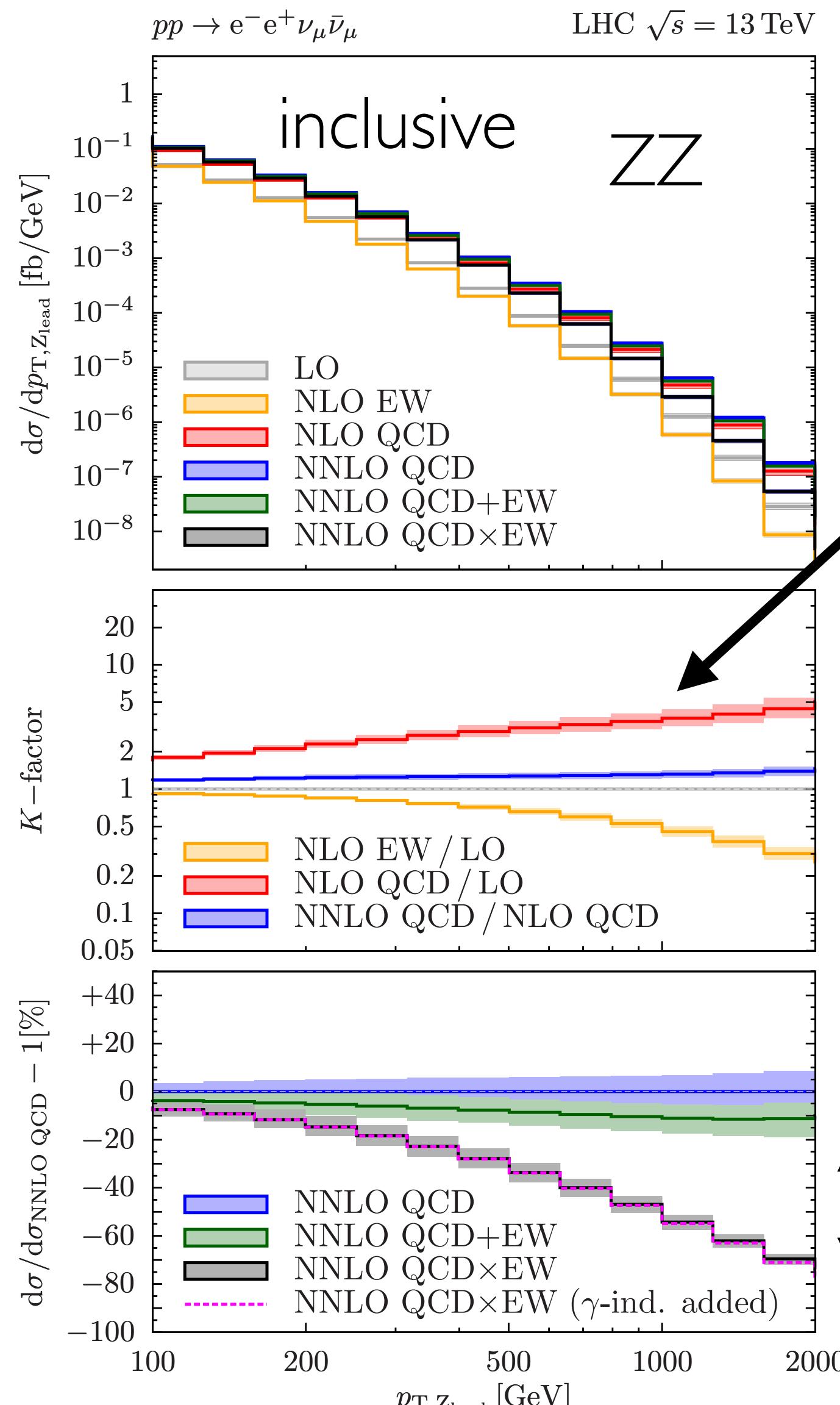
4l-SF-ZZ	$pp \rightarrow \ell^+ \ell^- \ell^+ \ell^-$	(ZZ)	
4l-DF-ZZ	$pp \rightarrow \ell^+ \ell^- \ell'^+ \ell'^-$	(ZZ)	
2l-SF-ZZ	$pp \rightarrow \ell^+ \ell^- \nu_{\ell'} \bar{\nu}_{\ell'}$	(ZZ)	
2l-SF-ZZWW	$pp \rightarrow \ell^+ \ell^- \nu_{\ell} \bar{\nu}_{\ell}$	(ZZ/WW)	(soon to be made public)
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3l-SF-WZ	$pp \rightarrow \ell^+ \ell^- \ell \nu_{\ell}$	(WZ)	
3l-DF-WZ	$pp \rightarrow \ell^+ \ell^- \ell' \nu_{\ell'}$	(WZ)	

- Combination of QCD and EW

additive:  $\text{d}\sigma_{\text{QCD}+\text{EW}}^{(\text{N})\text{NLO}} = \text{d}\sigma^{\text{LO}}(1 + \delta_{\text{QCD}}^{(\text{N})\text{NLO}} + \delta_{\text{EW}}) + \text{d}\sigma^{\text{ggLO}}$

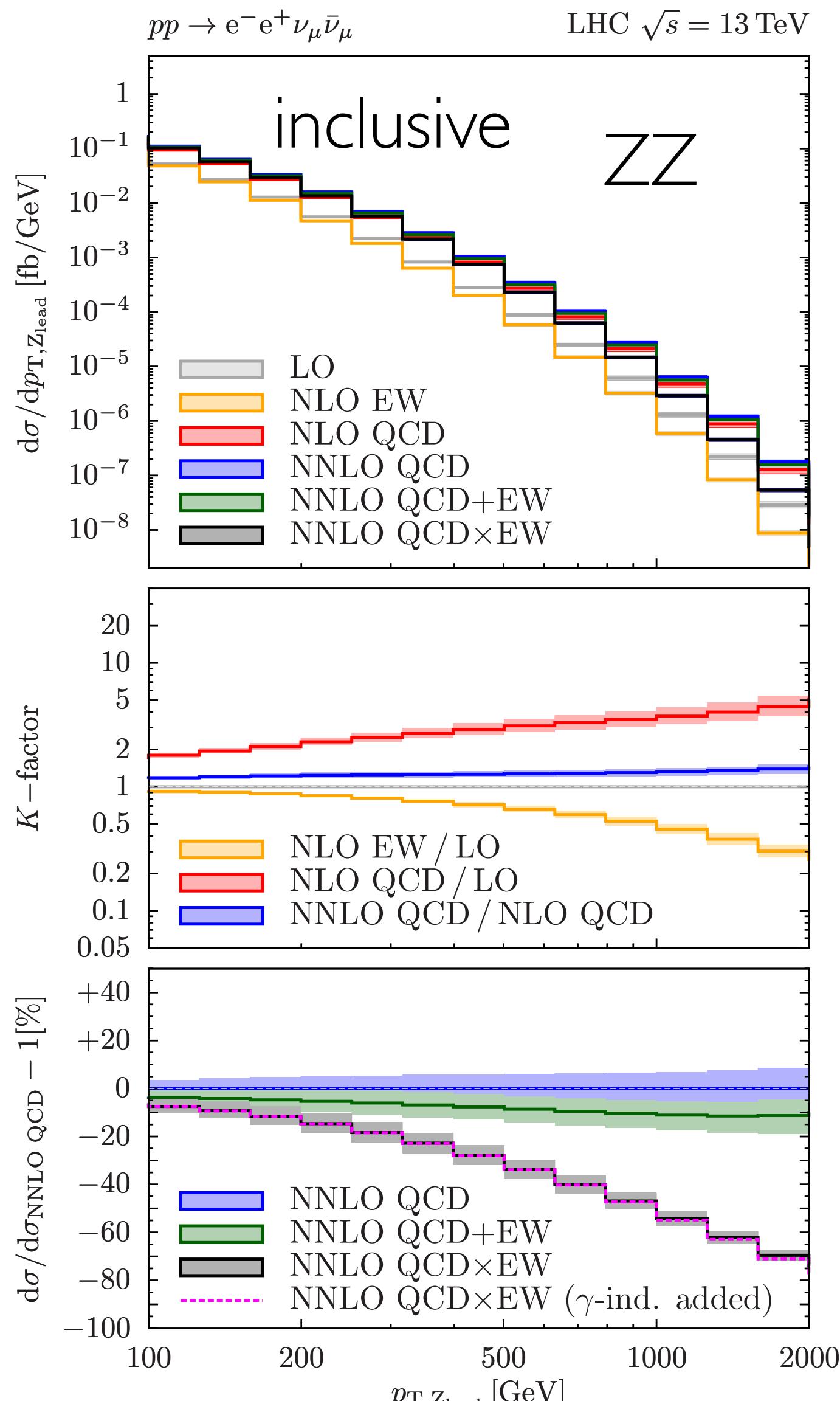
multiplicative:  $\text{d}\sigma_{\text{QCD} \times \text{EW}}^{(\text{N})\text{NLO}} = \text{d}\sigma^{\text{LO}}(1 + \delta_{\text{QCD}}^{(\text{N})\text{NLO}})(1 + \delta_{\text{EW}}) + \text{d}\sigma^{\text{ggLO}}$

# Giant K-factors and EW corrections

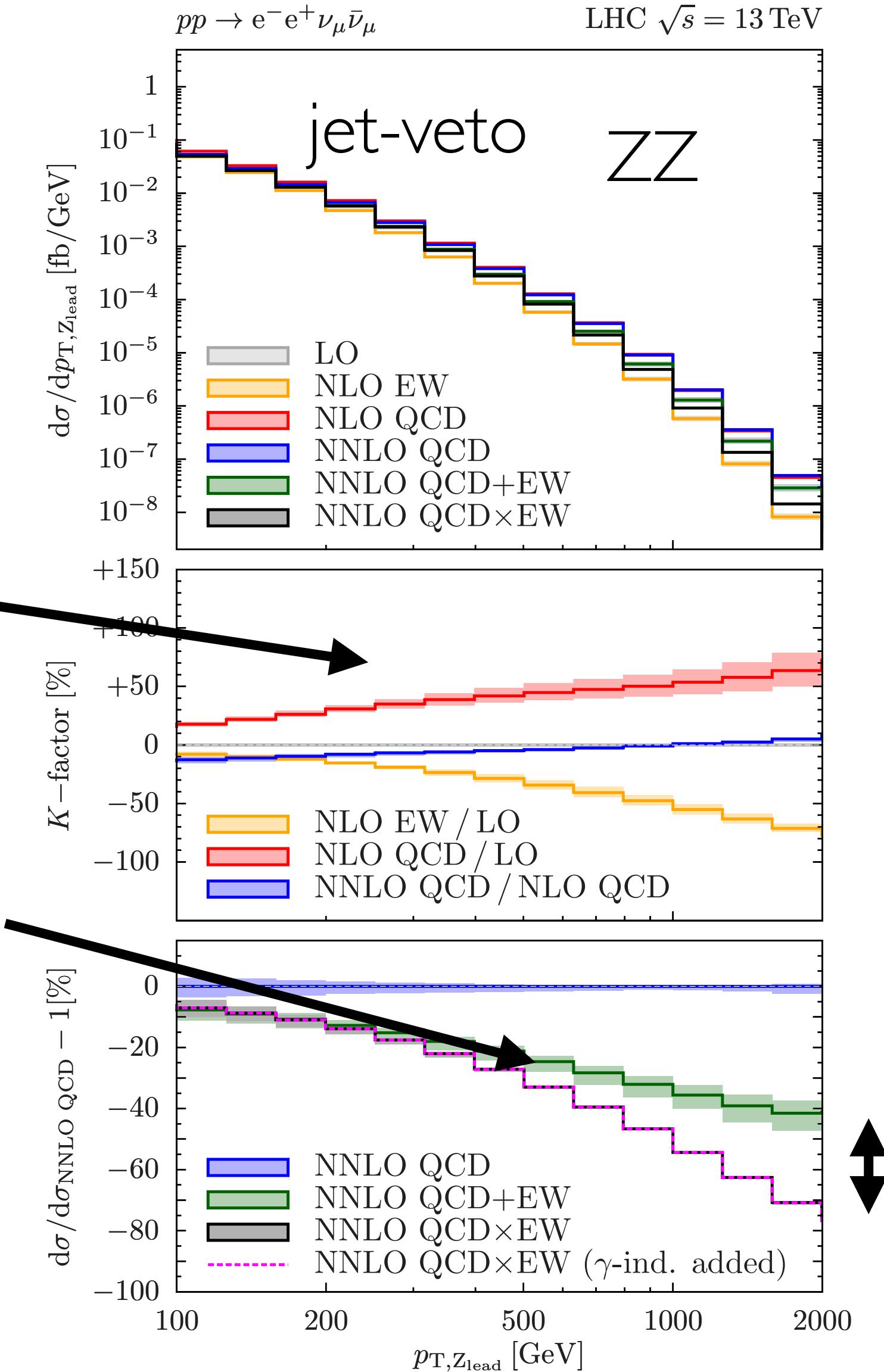


- NLO QCD/LO=2-5! (“giant K-factor”)
- at large  $p_{T,V1}$ : VV is dominated by V+jets (w/ soft V radiation)
- NNLO QCD uncertainty: 5-10%
- NLO EW/LO=-40-50%
- O(1) difference in  
 $d\sigma_{\text{QCD+EW}}^{(\text{N})\text{NLO}}$  vs.  $d\sigma_{\text{QCD}\times\text{EW}}^{(\text{N})\text{NLO}}$

# Giant K-factors and EW corrections



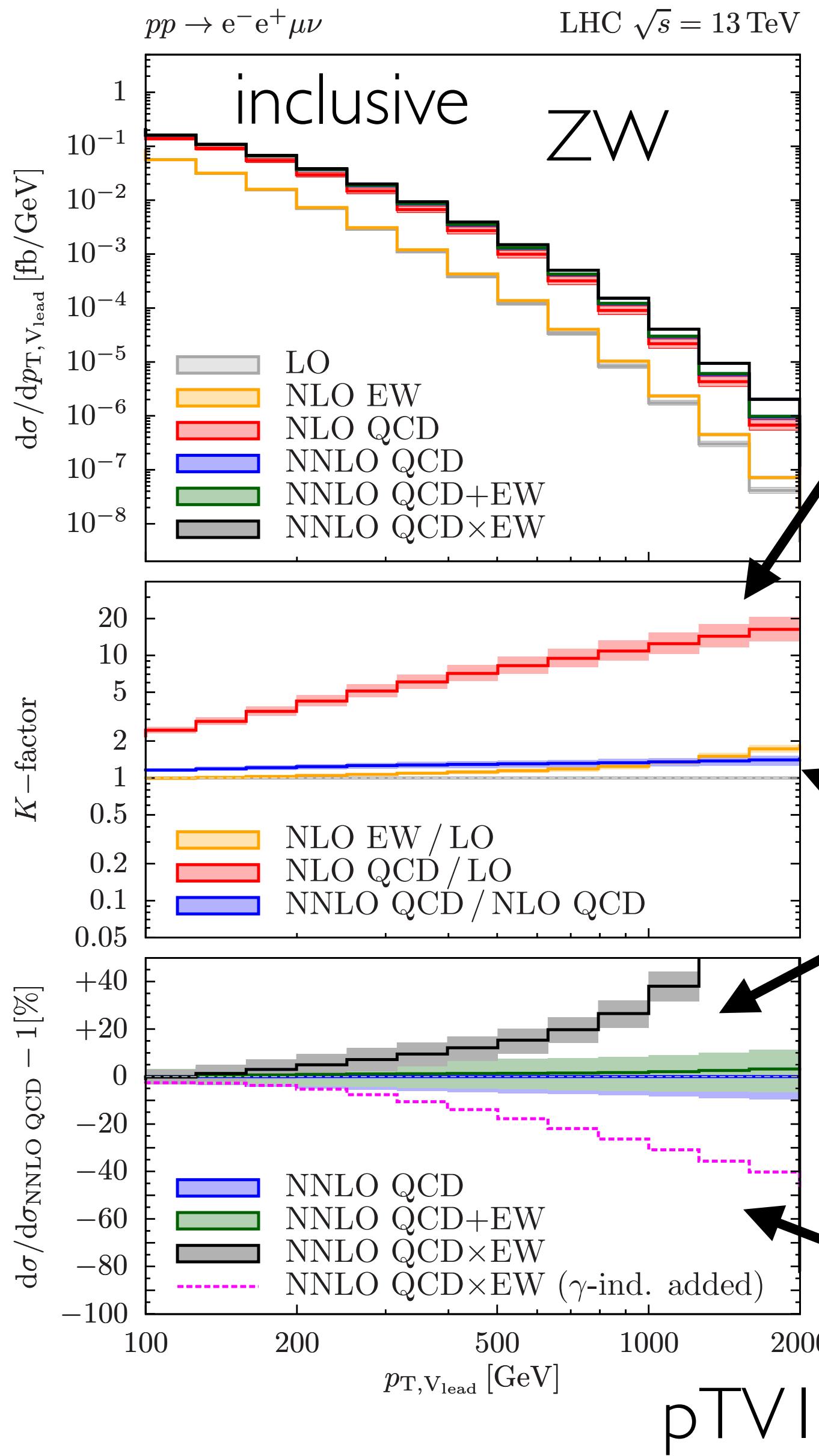
- jet veto  
 $H_T^{\text{jet}} < 0.2 H_T^{\text{lep}}$
- NLO QCD/LO =  $\sim < 1.5$  ("normal K-factor")
  - Reliable estimate of  $\mathcal{O}(\alpha_s)$  from  $d\sigma_{\text{QCD+EW}}^{(N)\text{NLO}}$  vs.  $d\sigma_{\text{QCD}\times\text{EW}}^{(N)\text{NLO}}$
  - Here: 10-20% in TeV range
  - However:  
 additional uncertainty due to efficiency of jet veto



pTVI

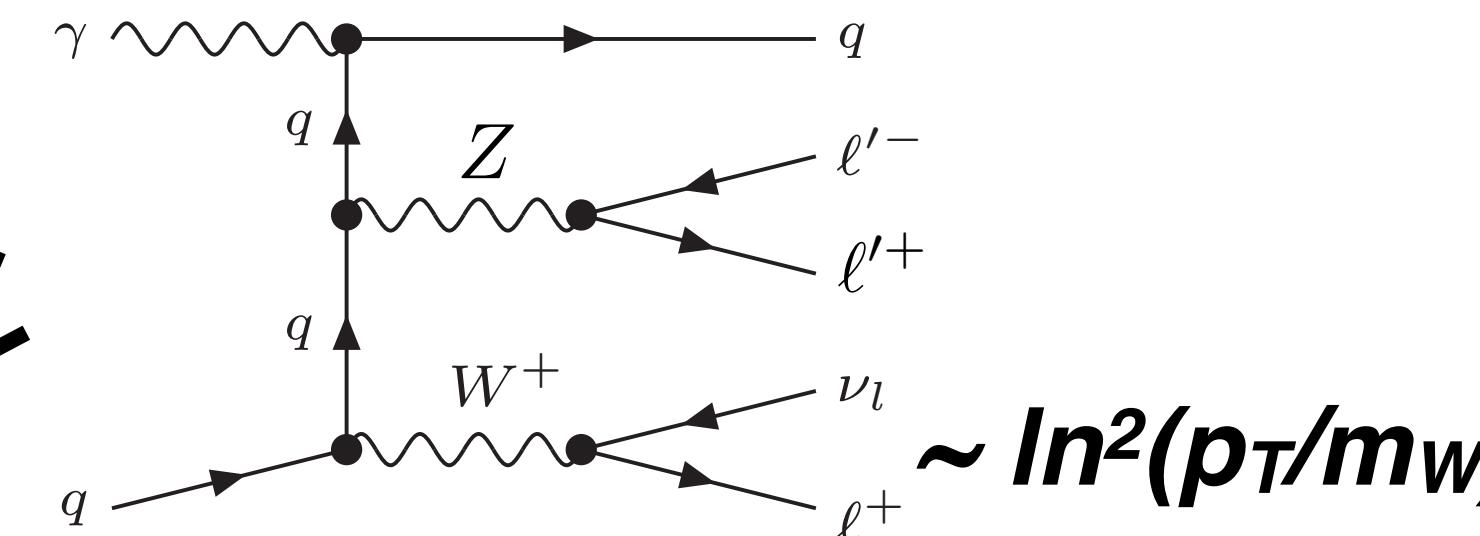
pTVI

# Photon-induced contributions



- NLO QCD/LO=5-10! (“giant K-factor”)

- Similar mechanism also in gamma-induced:

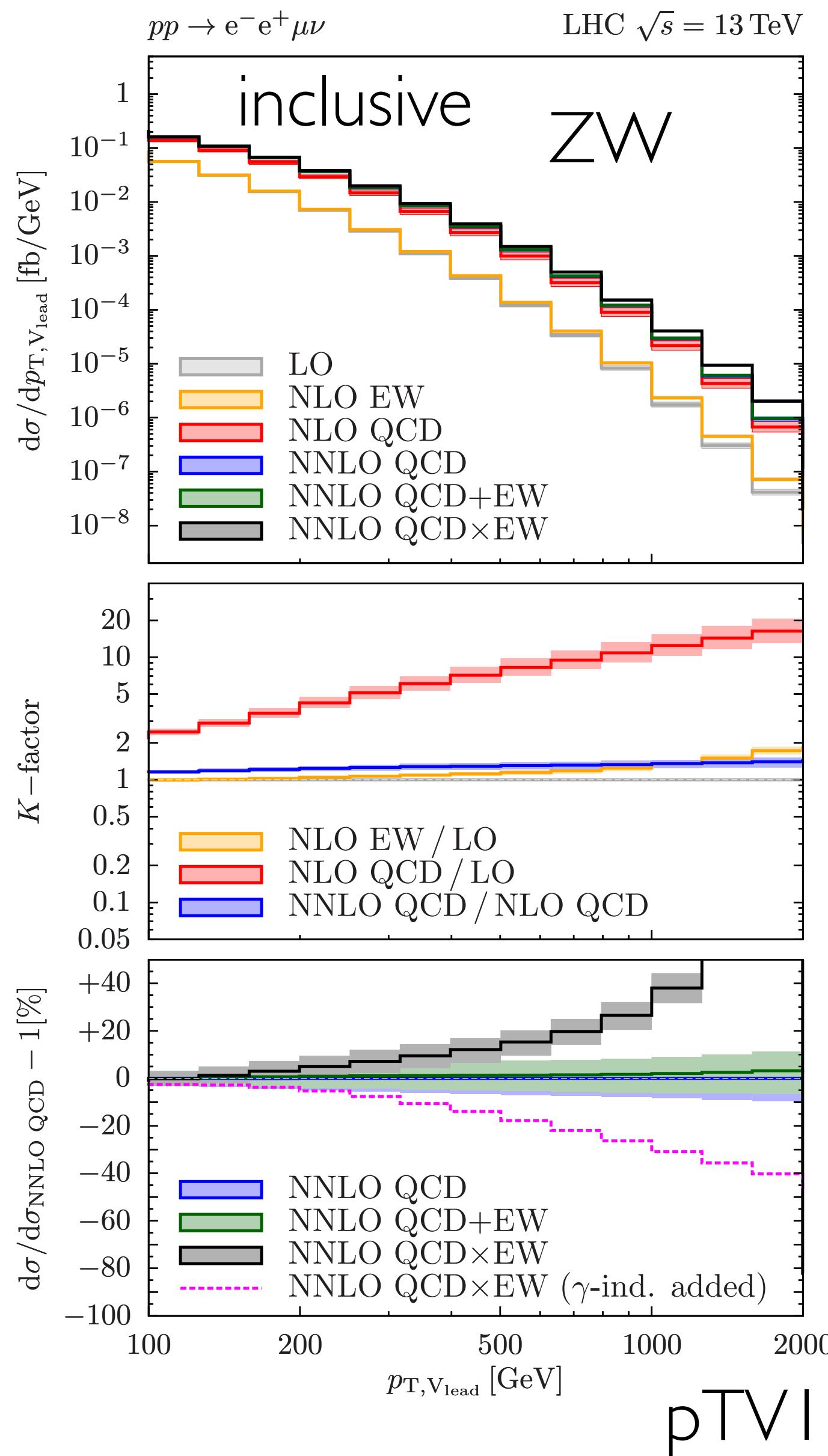


- Exclude photon-induced contri. from factorisation:

$$\sigma_{q\bar{q}}^{\text{NNLO QCD}\times\text{EW}} + \sigma_{\gamma\text{-ind.}}^{\text{NLO EW}} = \sigma_{q\bar{q}}^{\text{NNLO QCD}} \left( 1 + \frac{\delta\sigma_{q\bar{q}}^{\text{NLO EW}}}{\sigma_{q\bar{q}}^{\text{LO}}} \right) + \sigma_{gg}^{\text{LO}} + \sigma_{\gamma\text{-ind.}}^{\text{NLO EW}}$$

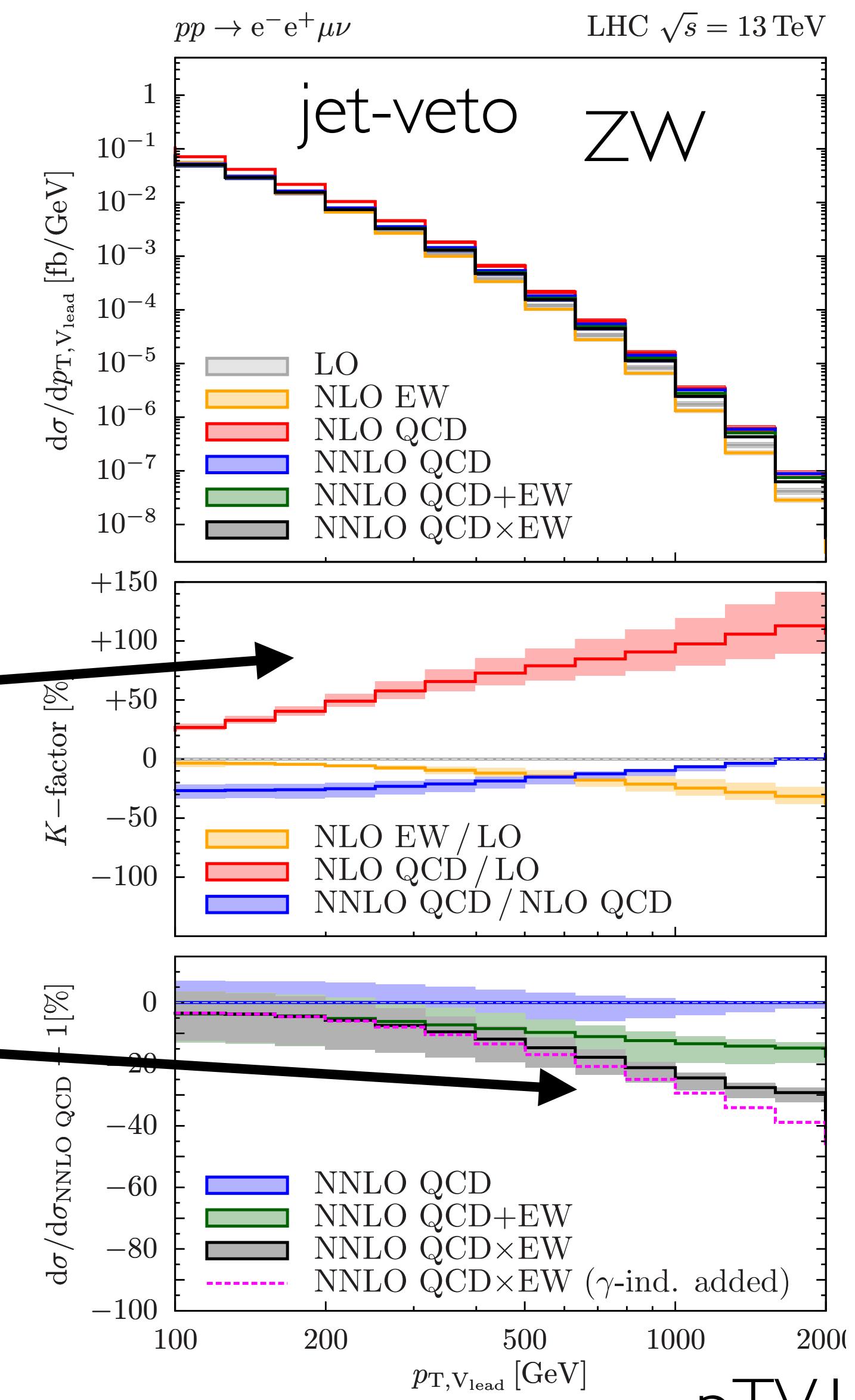
- PDF: NNPDF31\_LUXqed

# Photon-induced contributions

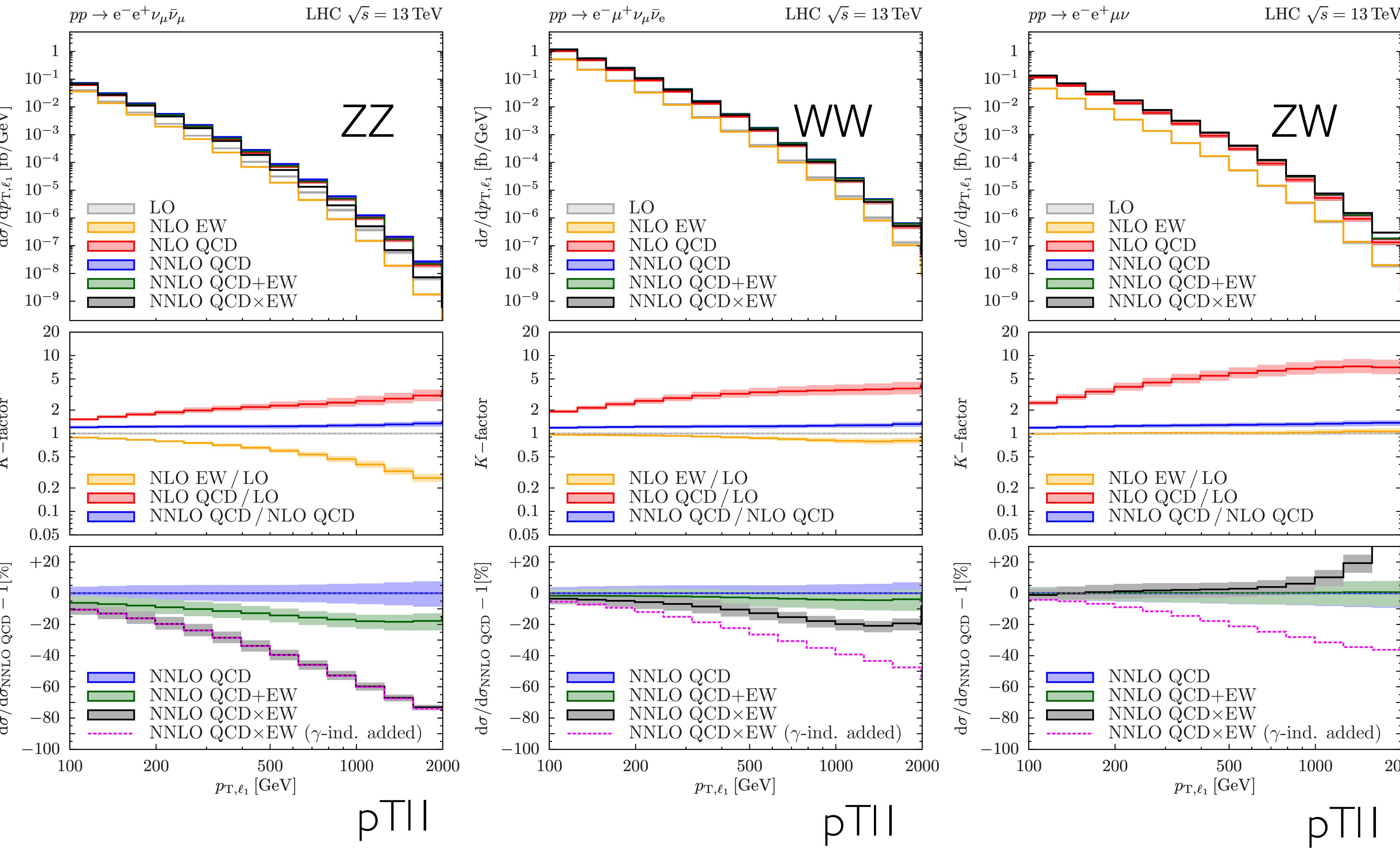


jet veto  
 $H_T^{\text{jet}} < 0.2 H_T^{\text{lep}}$

- NLO QCD/LO =  $\sim < 1.5$  (“normal K-factor”)
- Reliable estimate of  $\mathcal{O}(\alpha s)$  from  $d\sigma_{\text{QCD+EW}}^{(N)\text{NLO}}$  vs.  $d\sigma_{\text{QCD}\times\text{EW}}^{(N)\text{NLO}}$   
 Here: 5–10% in TeV range
- Small difference in treatment of photon induced contributions.



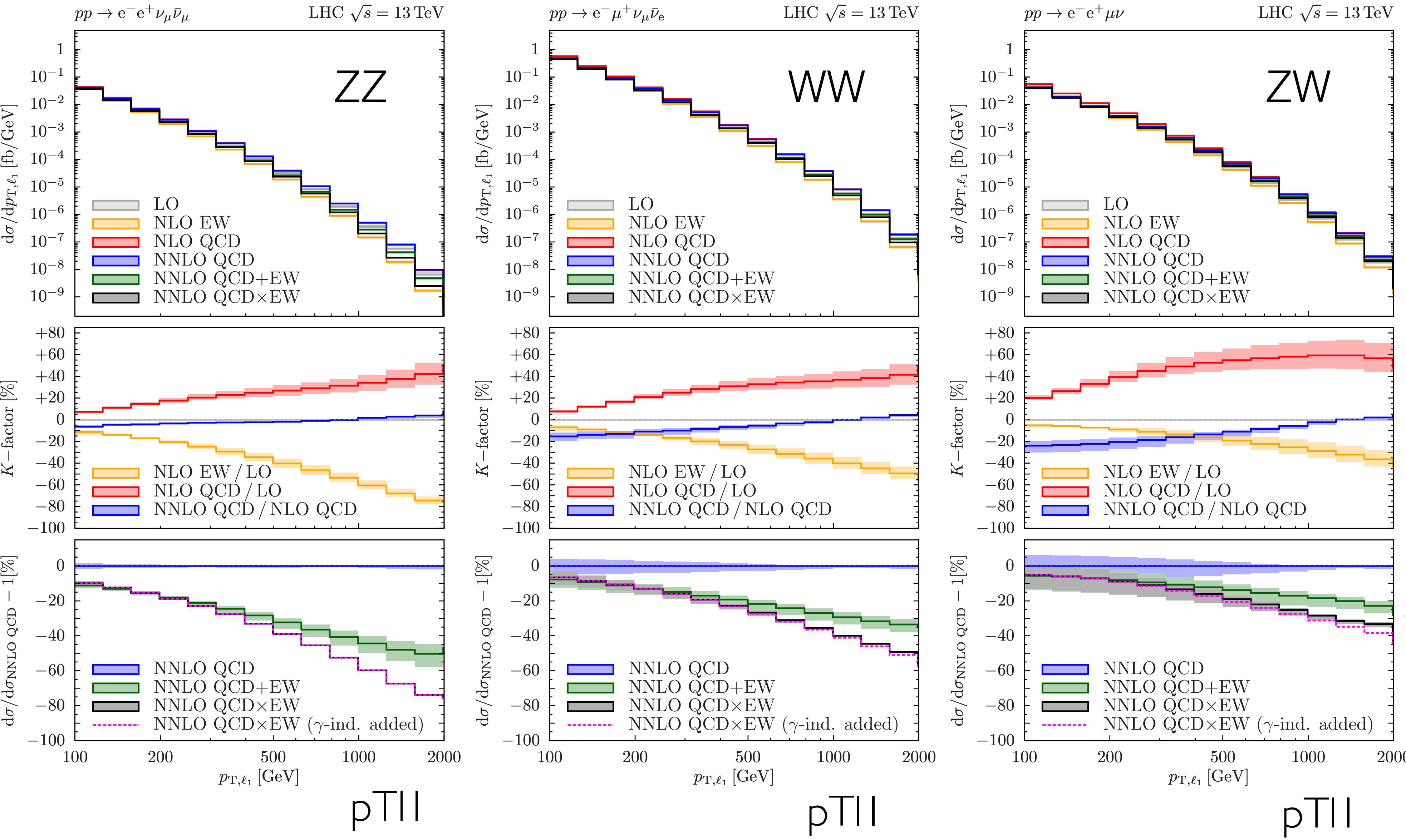
# Giant K-factors and EW corrections: pTII



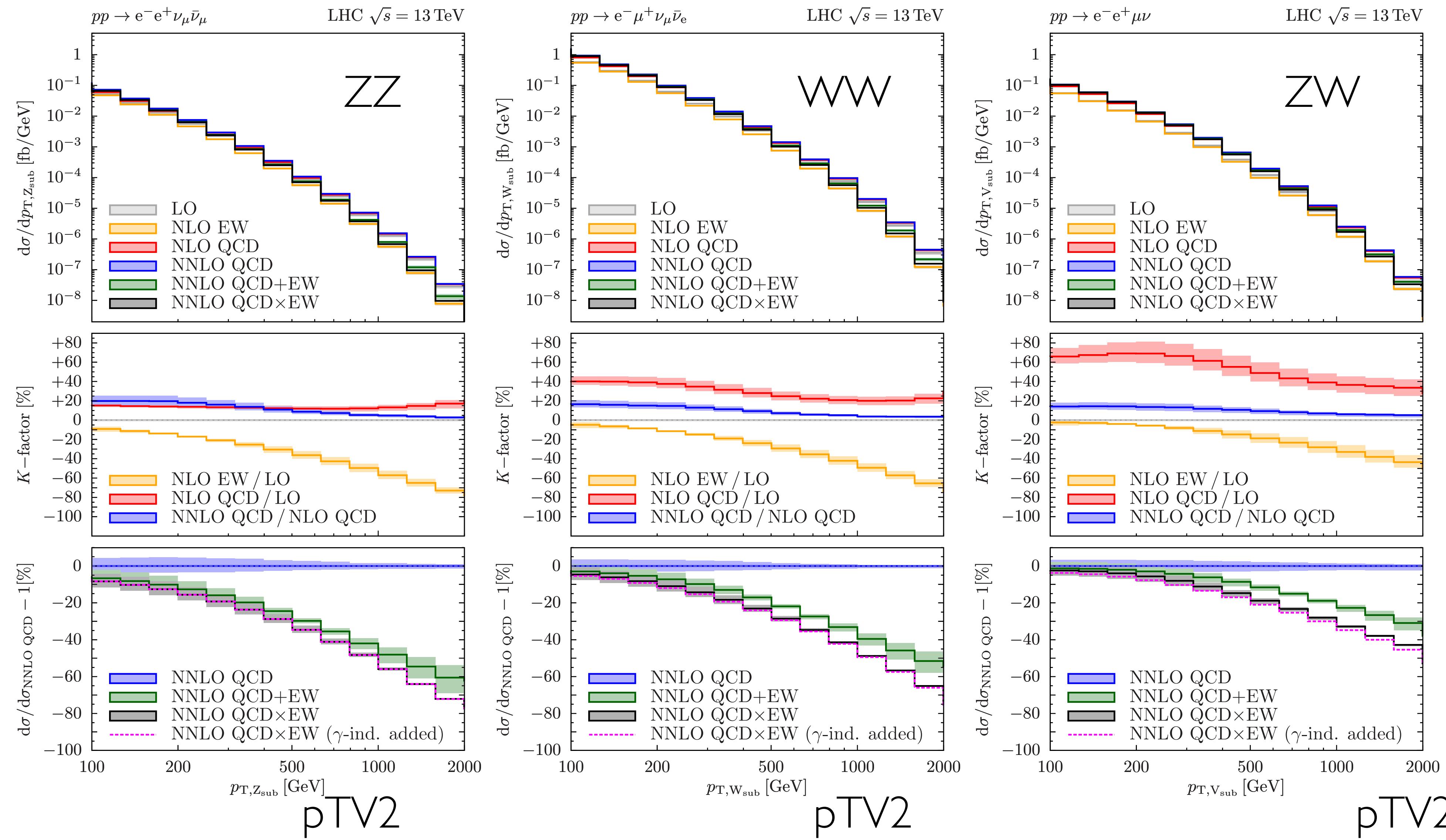
inclusive

- Same features as pTVI

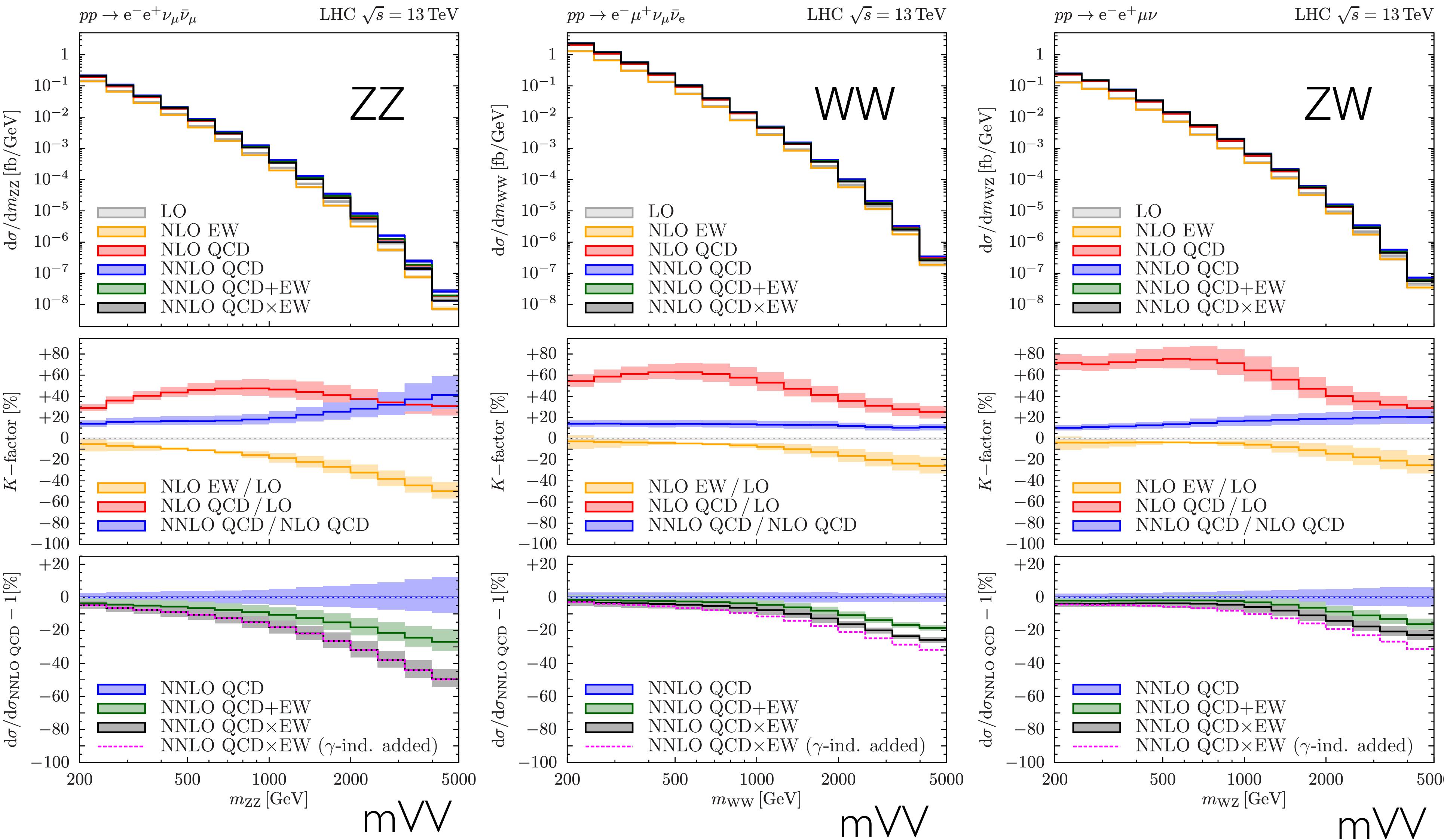
# Giant K-factors and EW corrections: pTII



# Without giant K-factors: stable predictions for pTV2



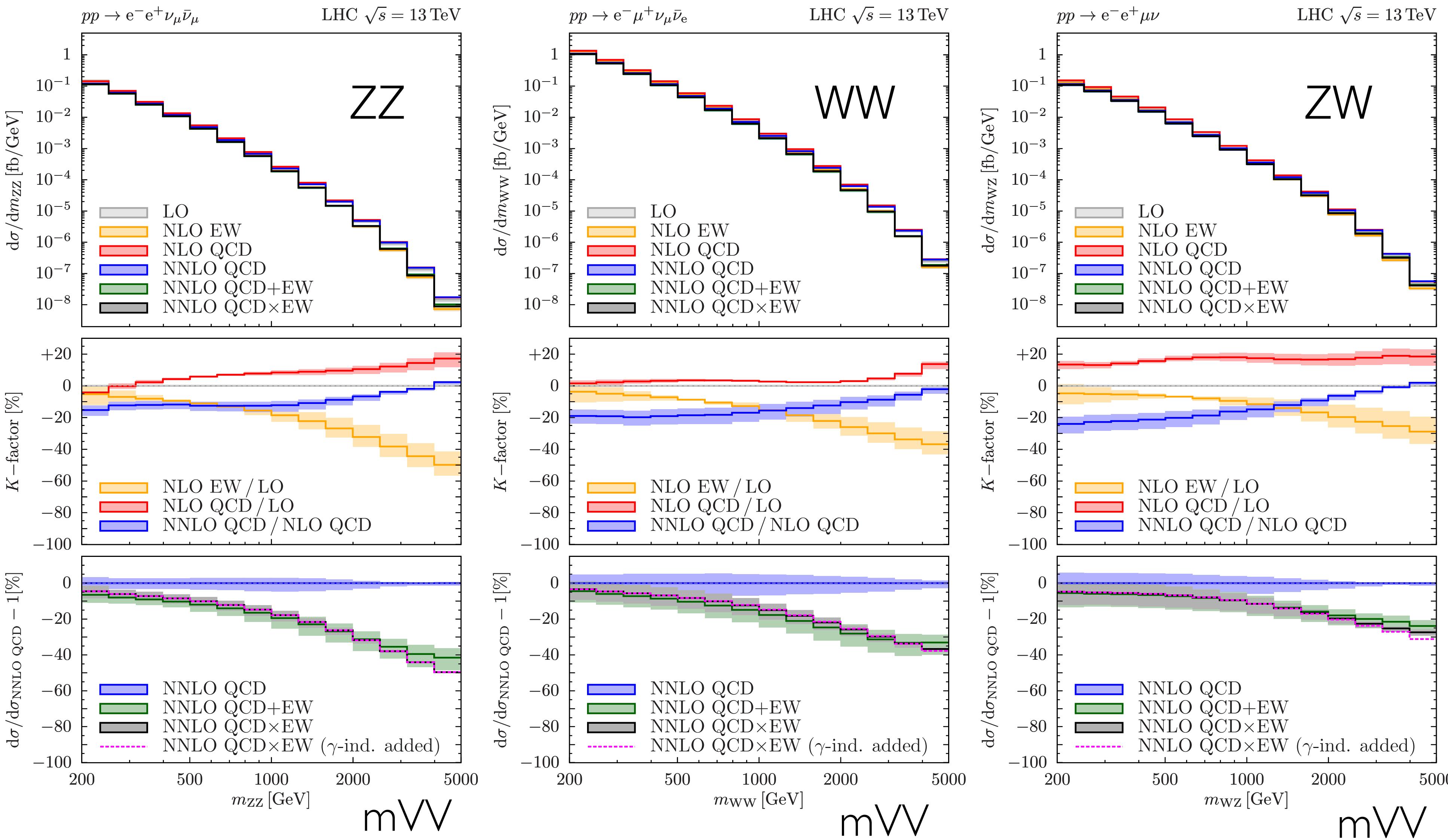
# Without giant K-factors: stable predictions for mVV



inclusive

Reliable estimate of  
 $O(\alpha_s)$  from  
 $d\sigma_{\text{QCD+EW}}^{(N)\text{NLO}}$   
 vs.  
 $d\sigma_{\text{QCD}\times\text{EW}}^{(N)\text{NLO}}$

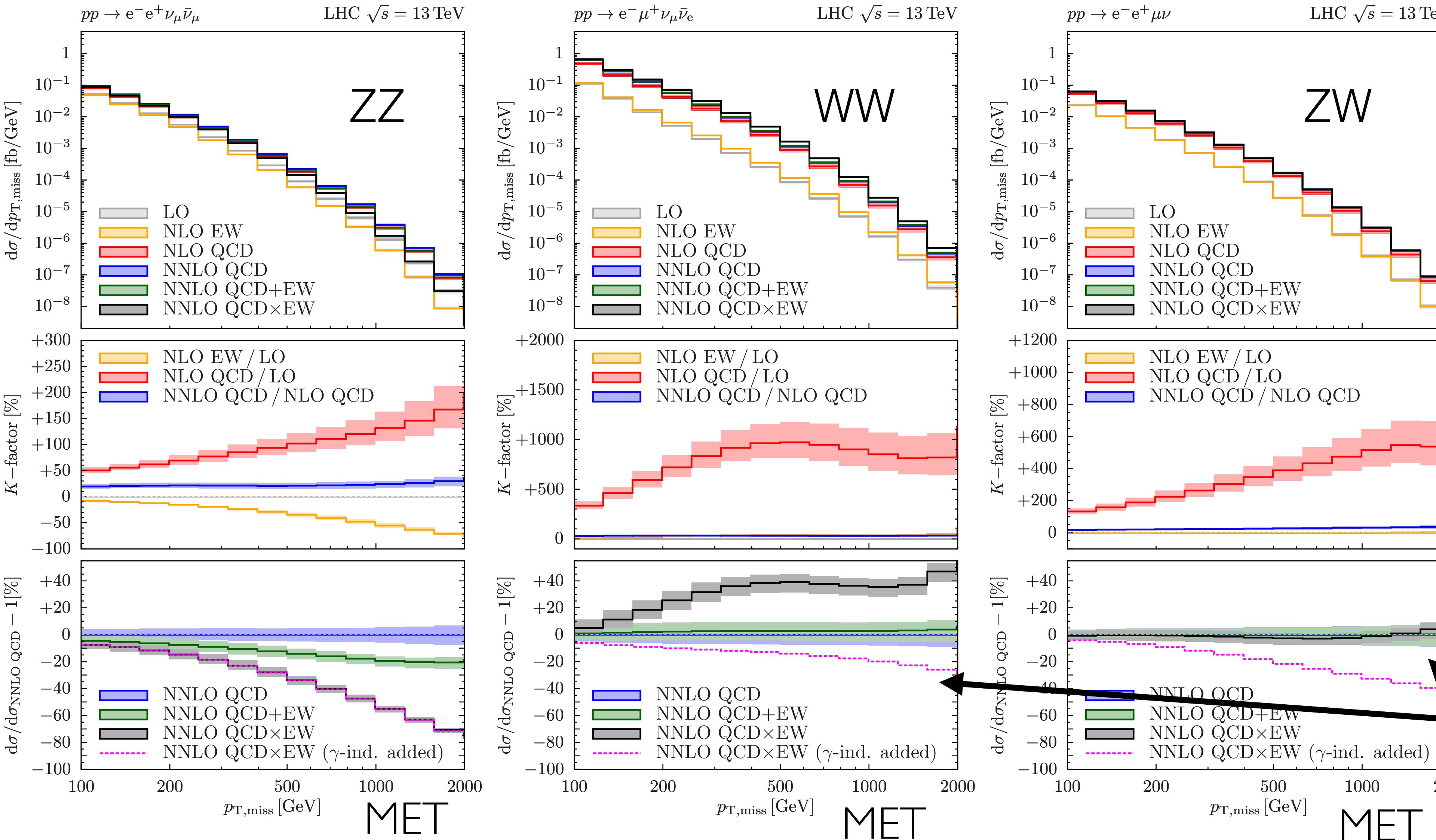
# Without giant K-factors: stable predictions for mVV



jet-veto

jet veto yields reduced  
uncertainties due to  
 $O(\alpha_s)$  uncertainties at  
large mVV

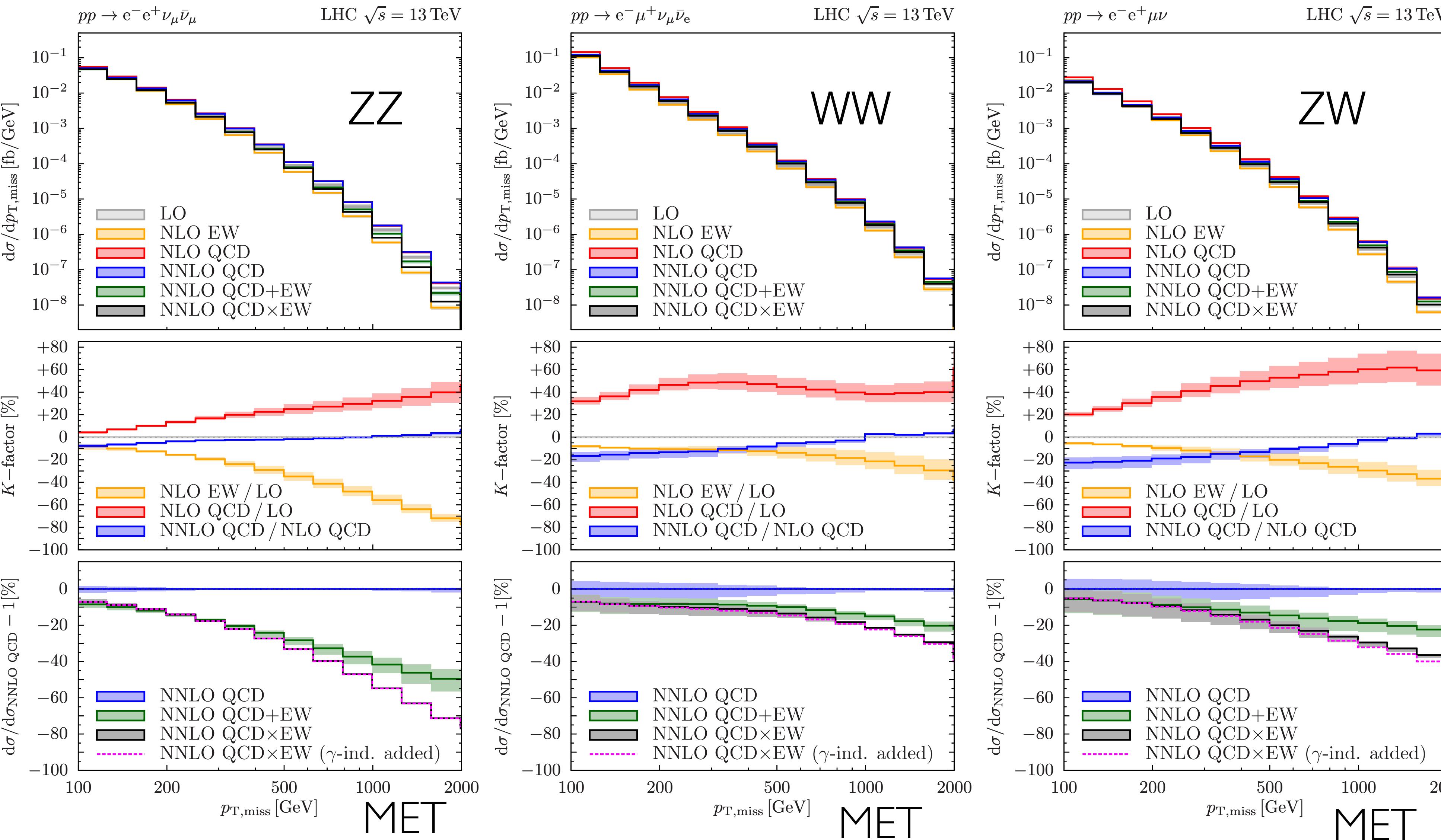
# Giant K-factors and EW corrections: MET



**inclusive**

- in WW at large MET>MW:  
W's are forced off-shell
- very large NLO QCD corrections (back-to-back opens up)
- large gamma-induced (also here Bremsstrahlung opens up back-to-back)

# Giant K-factors and EW corrections: MET



jet veto yields reduced uncertainties due to O(as a) uncertainties at large MET

# Conclusions

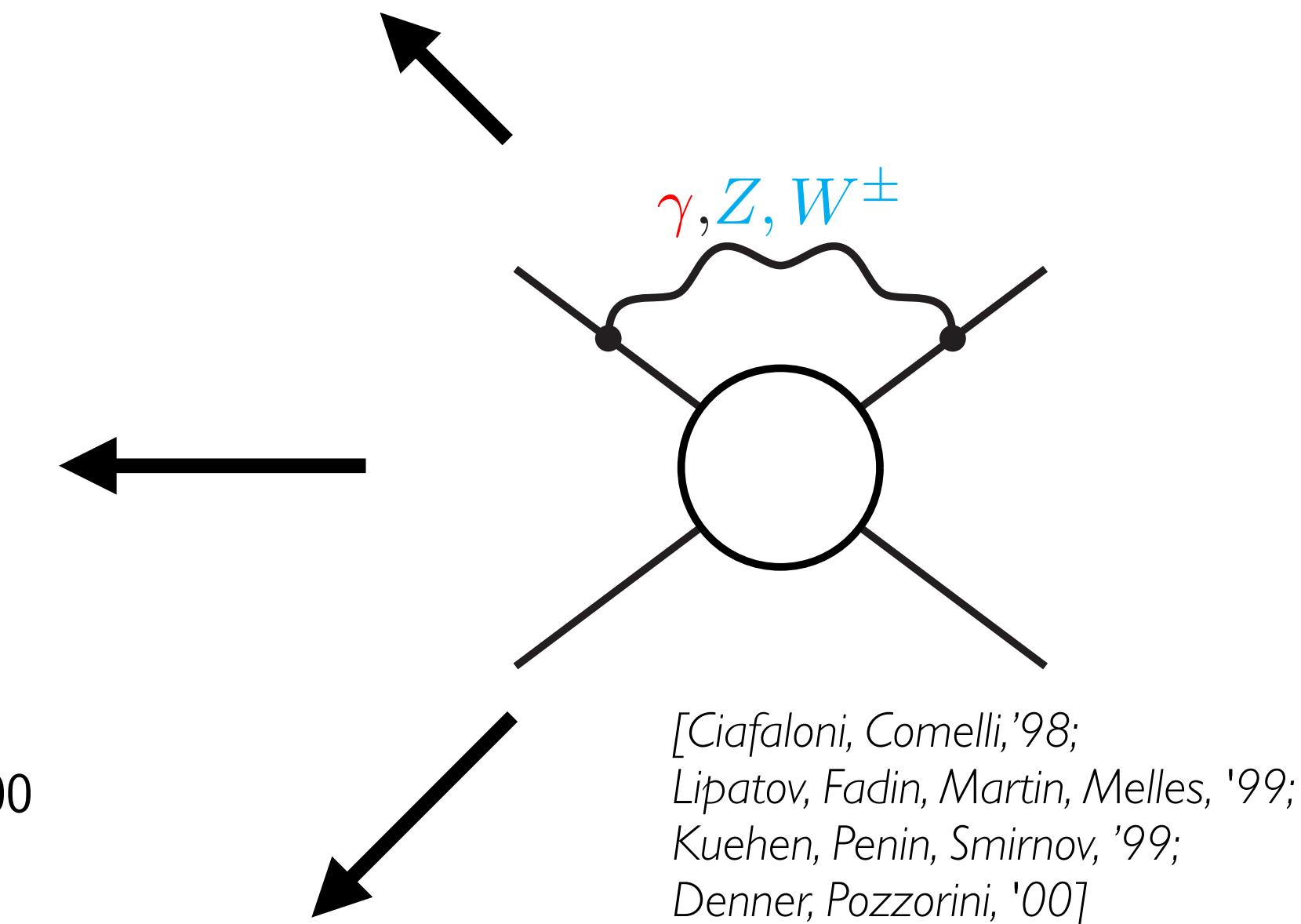
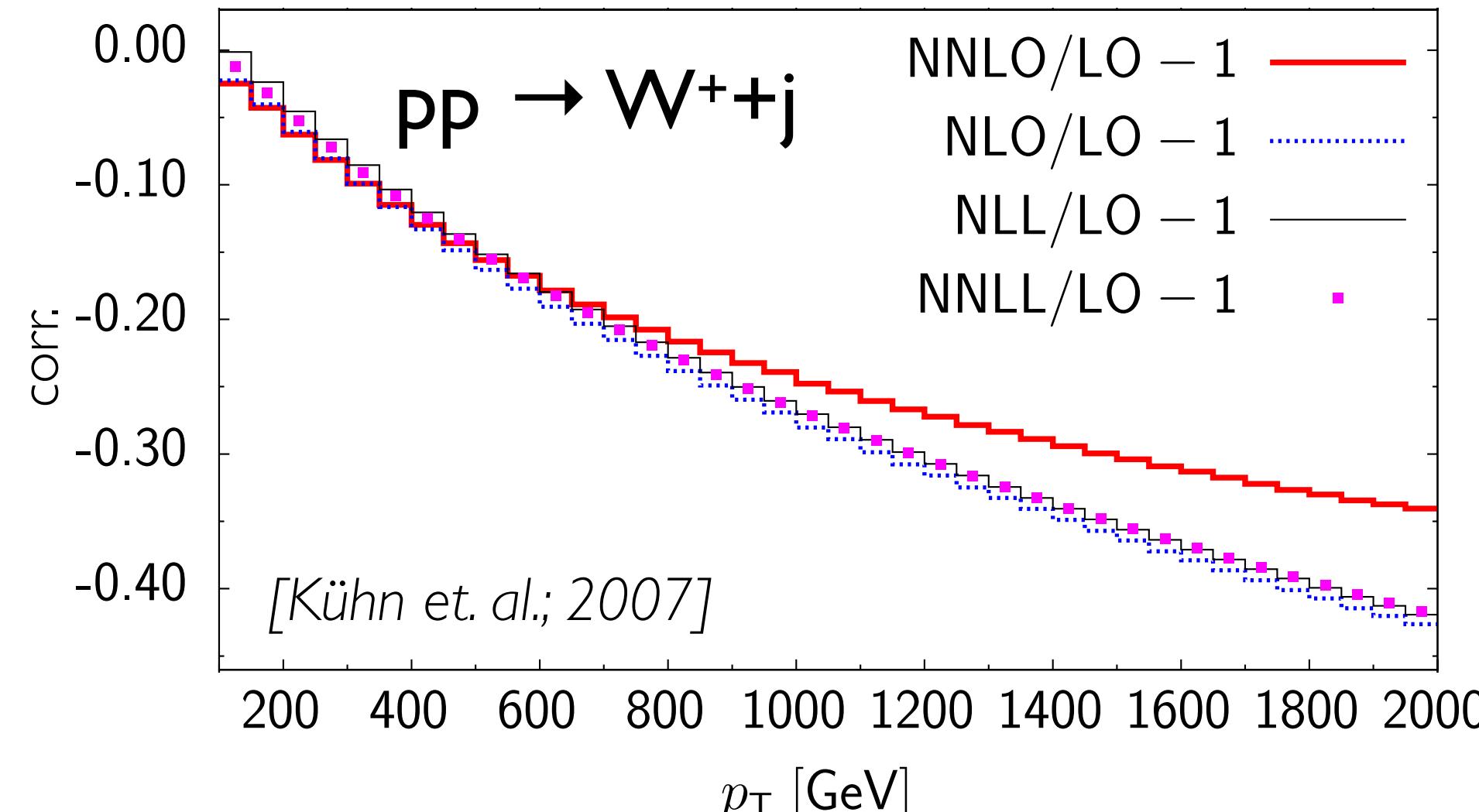
- NNLO QCD + NLO EW available in **MATRIX+OpenLoops** for all (massive) diboson processes
  - soon public
  - V+gamma in the making
  - QCD uncertainties at NNLO often reach few percent level.
  - EW corrections enhanced at high energies reaching several tens of percent.
  - In observables subject to ‘giant K-factors’: QCD+EW vs. QCDxEW introduces  $\mathcal{O}(1)$  uncert.
  - Can be cured via jet-veto.
  - Relevant contribution of photon-induced processes
- Open issues:
- When measuring diboson processes at large  $pT V/\text{MET}/m_{VV}$   
should always a jet veto be considered? Increased sensitivity to aTGCs?
  - How to obtain reliable inclusive predictions? In particular relevant for background simulations.
    - MEPS@NLO multi-jet merging including EW corrections (see V+jets, 1511.08692)
    - how to retain NNLO QCD precision?
  - How to estimate NNLO EW -  $\mathcal{O}(\alpha^2)$ ?

# BACKUP

# Relevance of EW higher-order corrections I

Numerically  $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$  **NLO EW ~ NNLO QCD**

Possible large (negative) enhancement due to soft/collinear **logs** from virtual EW gauge bosons:



Universality and factorisation: [Denner, Pozzorini; '01]

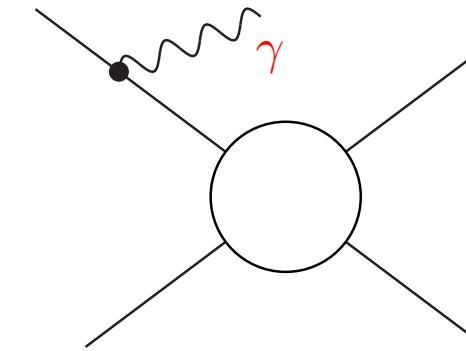
$$\delta\mathcal{M}_{\text{LL+NLL}}^{1\text{-loop}} = \frac{\alpha}{4\pi} \sum_{k=1}^n \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma, Z, W^\pm} I^a(k) I^{\bar{a}}(l) \ln^2 \frac{\hat{s}_{kl}}{M^2} + \gamma^{\text{ew}}(k) \ln \frac{\hat{s}}{M^2} \right\} \mathcal{M}_0$$

→ overall large effect in the tails of distributions:  $p_T, m_{\text{inv}}, H_T, \dots$

# Relevance of EW higher-order corrections II

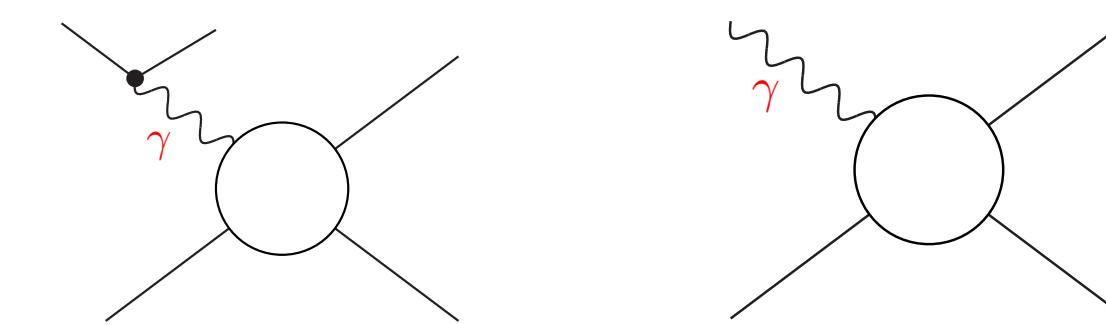
## Real photon radiation

- soft/coll. photon unresolved
- needed to cancel QED singularities



## Photon initial states

- QED factorisation needed to absorb IS photon singularities
- possible strong enhancement, e.g. for VV



## Real W,Z,h radiation (HBR)

- partial cancellation with virtual Sudakov logs (KLN theorem not applicable)  
(strongly dependent on experimental selection)
- free from singularities  $\Rightarrow$  separate processes
- themselves receive large virtual EW corrections  
& inclusion requires care (double-counting issues)

