QCD and EW corrections for DM searches

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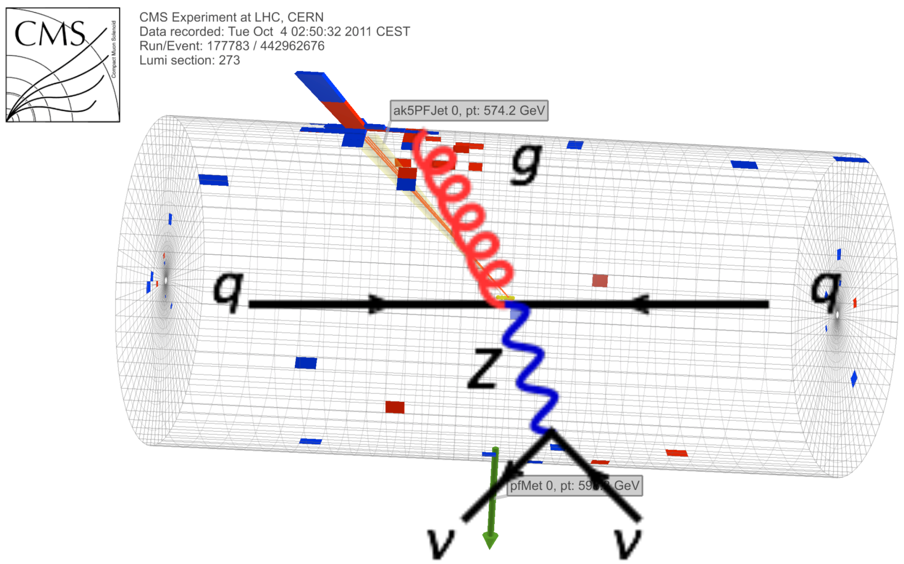
LHC Dark Matter WG, CERN, 15.12.2016

V+jets backgrounds in monojet/MET + jets searches



irreducible background:

pp→Z(→νν̄)+jets ⟹ MET + jets

pp→W(→lν)+jets ⟹ MET + jets (lepton lost)

▸ can be determined from Z(→ll̄)+jets, W(→lν̄)+jets or γ+jets measurements (combination!)

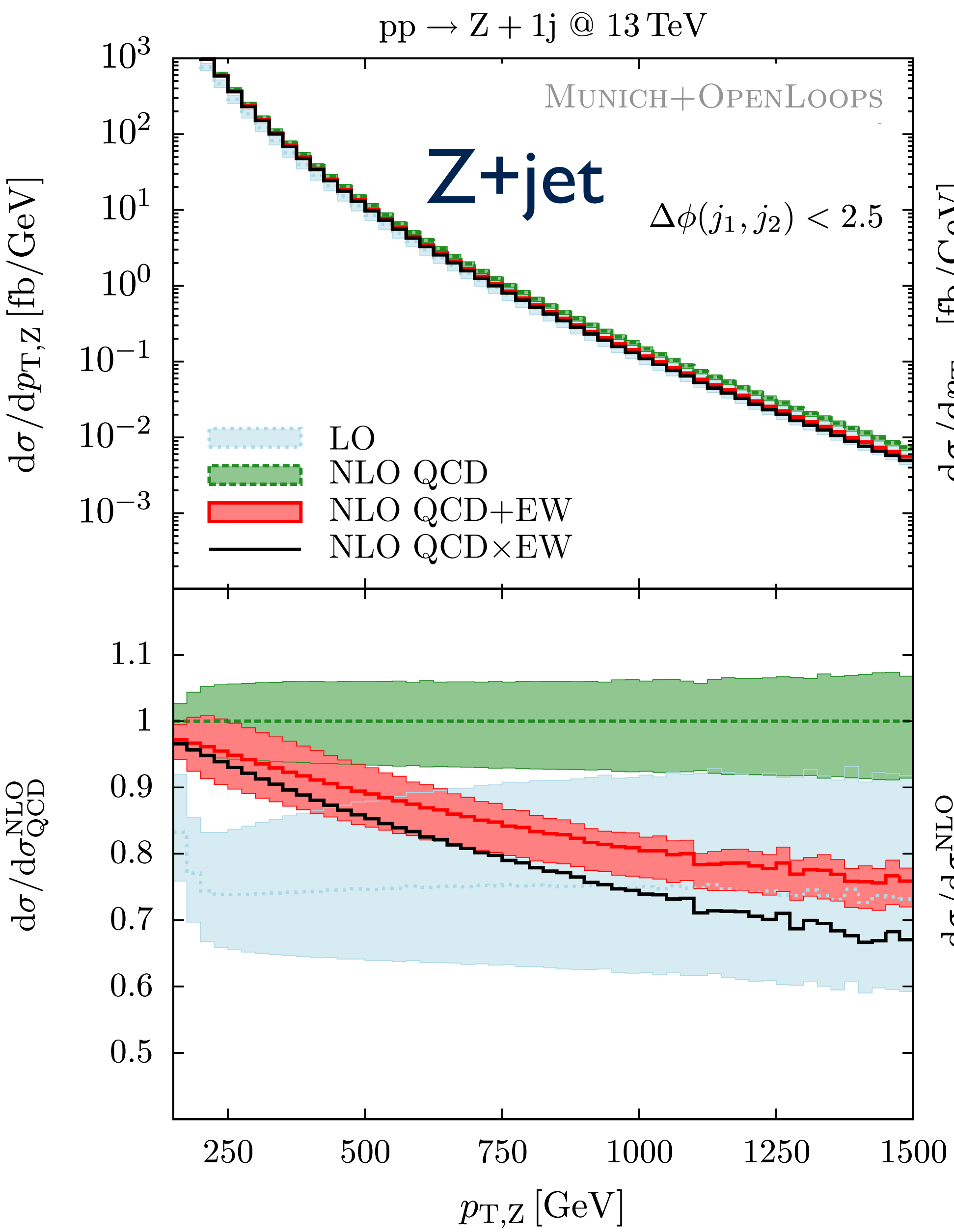
- hardly any systematics (just QED dressing)
- but: limited statistics at large pT

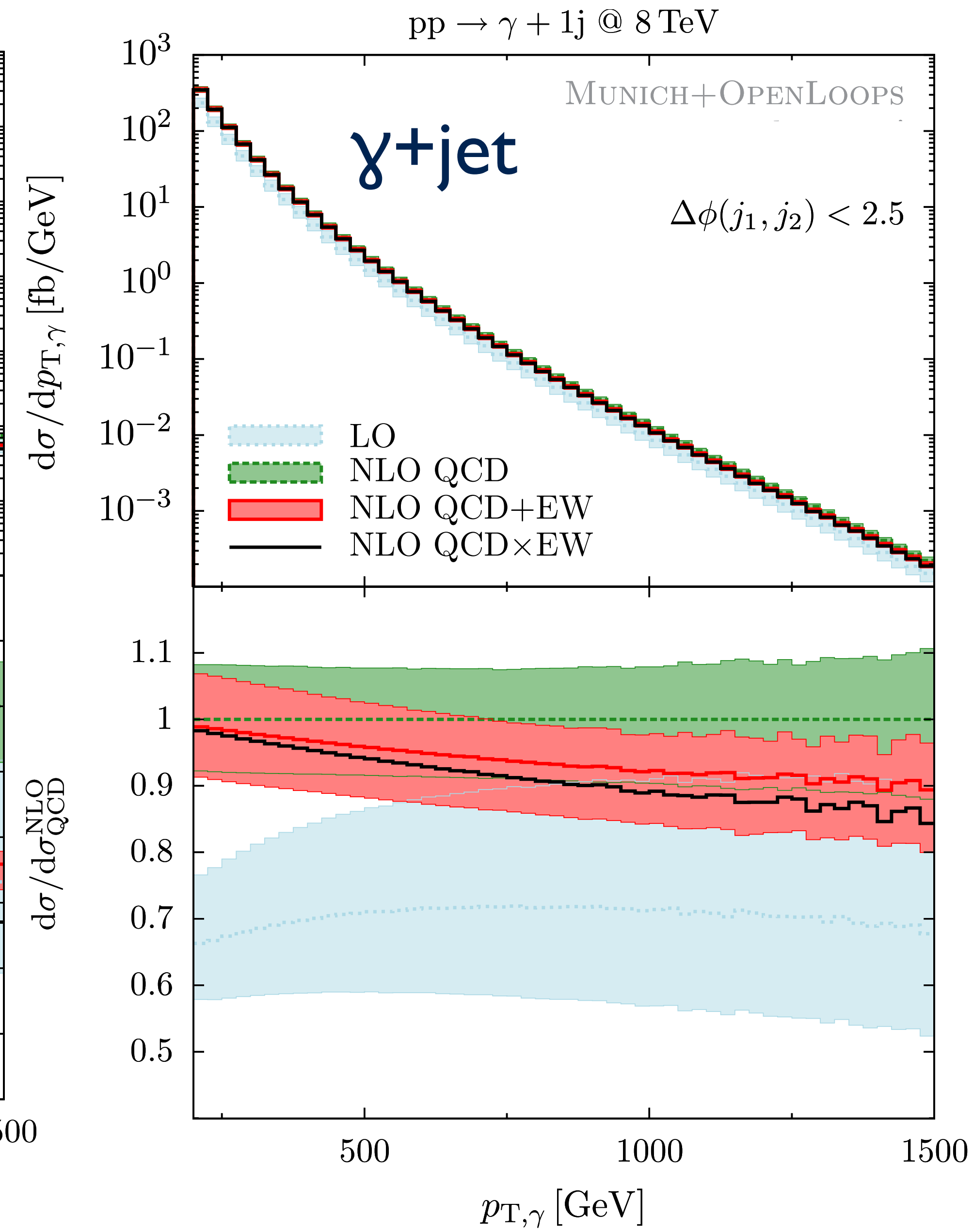
- fairly large data samples at large pT

▸ need theory input, i.e. predictions at (N)NLO QCD+NLO EW:

$$R_{ZZ}(\mathrm{d}p_\mathrm{T}) = \frac{\mathrm{d}\sigma(Z\to\nu\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}{\mathrm{d}\sigma(Z\to\ell\bar\ell+\mathrm{jets})/\mathrm{d}p_\mathrm{T}} \qquad R_{ZW}(\mathrm{d}p_\mathrm{T}) = \frac{\mathrm{d}\sigma(Z\to\nu\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}{\mathrm{d}\sigma(W\to\ell\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}} \qquad R_{Z\gamma}(\mathrm{d}p_\mathrm{T}) = \frac{\mathrm{d}\sigma(Z\to\nu\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}{\mathrm{d}\sigma(\gamma+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}$$

Z+jet vs. ɣ + 1 jet





QCD corrections

- mostly moderate and stable QCD corrections
- (almost) **identical QCD corrections in the tail**, sizeable differences for small pT (mass effects)

EW corrections

- **correction in pT(Z) > correction in pT(ɣ)**
- -20/-8% EW for Z/ɣ at 1 TeV
- EW corrections > QCD uncertainties for $p_{T,Z}$ > 350 GeV

Goal of the ongoing study

- Combination of state-of-the-art predictions including QCD and EW corrections in order to match future experimental sensitivities (1-10% accuracy in the multi-TeV range)

- Robust **uncertainty estimates** including
  - Pure QCD uncertainties
  - Pure EW uncertainties
  - Mixed QCD-EW uncertainties

- Study of **correlation** of these uncertainties
  - within a process (between low-pT and high-pT)
  - across processes

- First draft of a prescription to incorporate NNLO QCD + (N)NLO EW corrections and uncertainties in the MCs has already been circulated within ATLAS and CMS and will be made publicly available within the DM WG in the next few weeks.

Pure QCD uncertainties

Best handle we have for pure QCD uncertainties:
muR / muF scale variations

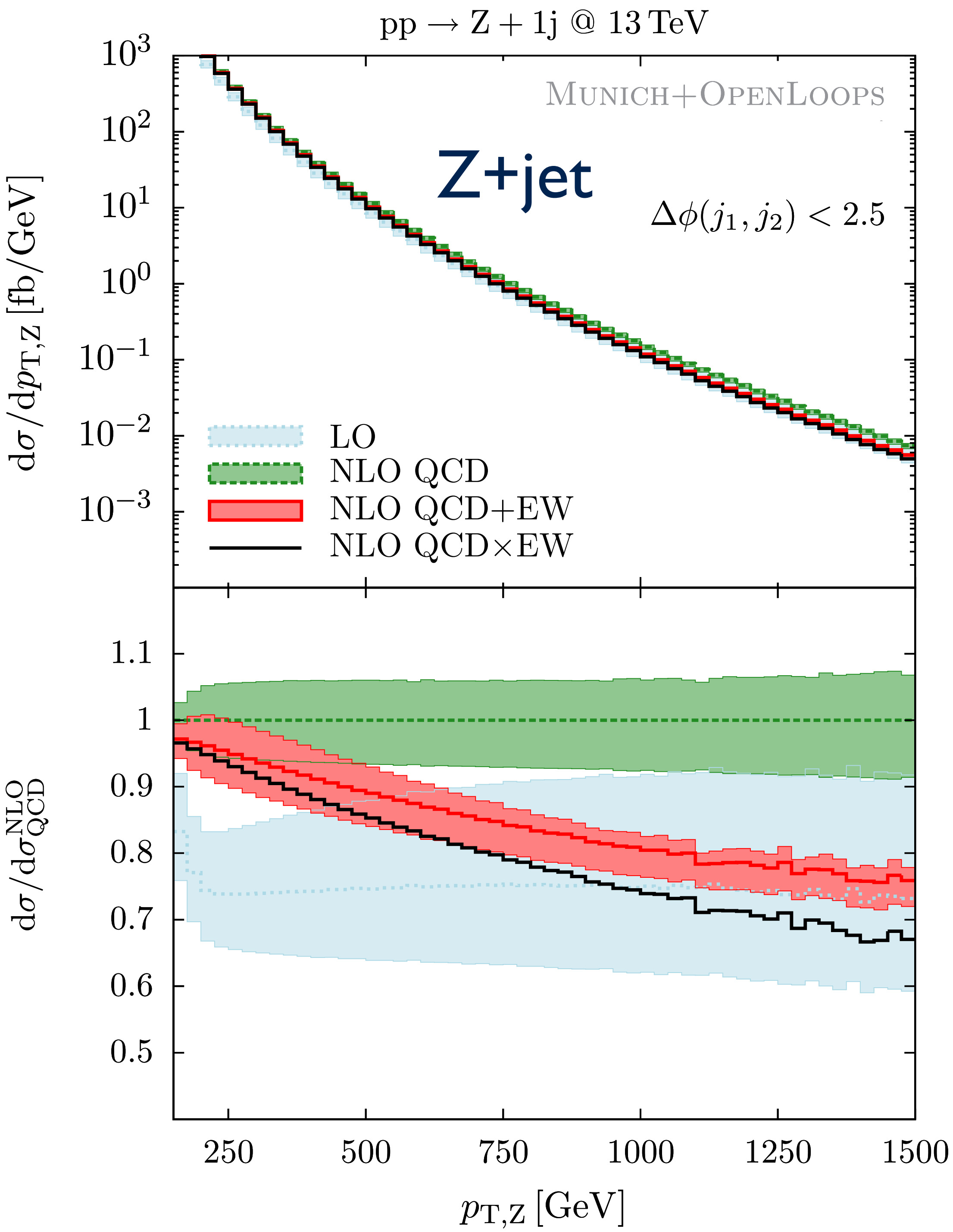
$$\mu_0 = \frac{H_T}{2} = \frac{1}{2}\left(\sqrt{M_V^2 + p_{T,V}^2} + \sum_{i \in \text{partons}} |p_{T,i}|\right)$$

$$\mu_{R,F} = \xi_{R,F}\,\mu_0$$

$$(\xi_R, \xi_F) = (2,2),\ (2,1),\ (1,2),\ (1,1),\ (1,0.5),\ (0.5,1), (0.5,0.5)$$

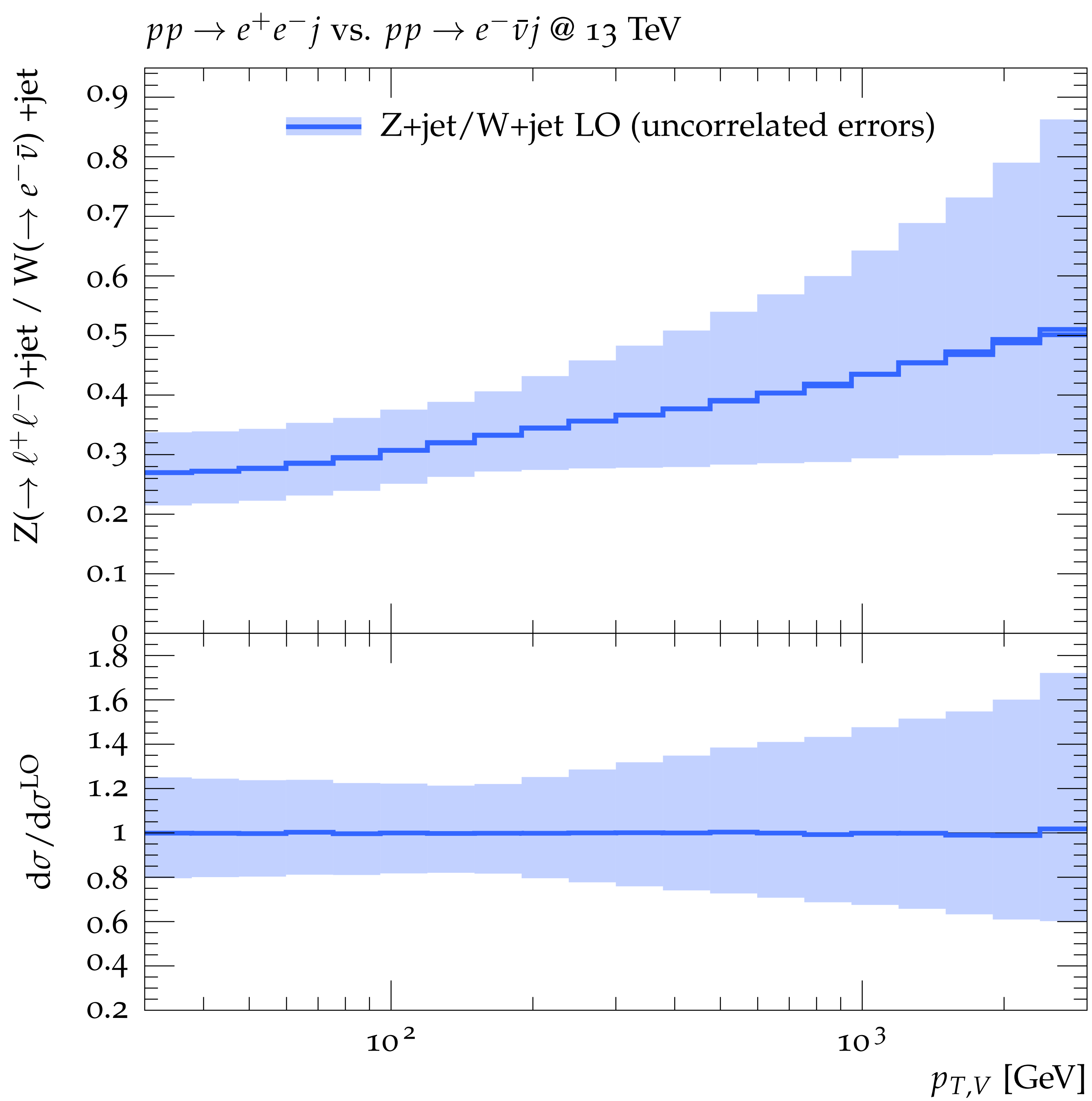
yields

- O(20%) uncertainties at LO
- O(10%) uncertainties at NLO
- O(5%) uncertainties at NNLO (see later)



What about correlations between different V+jets processes?

Pure QCD uncertainties

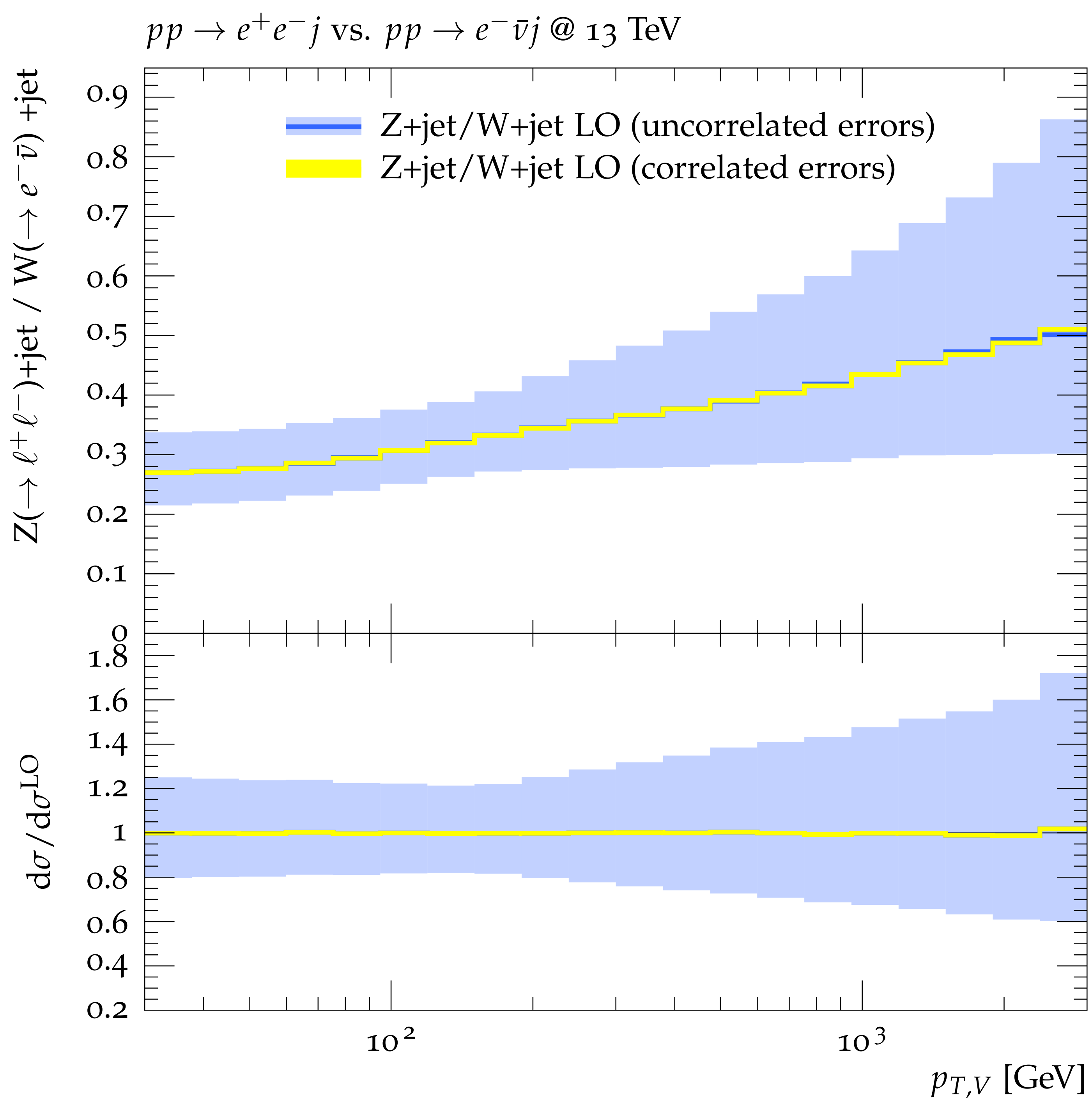


What about correlations between different V+jets processes?

consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

Pure QCD uncertainties



What about correlations between different V+jets processes?

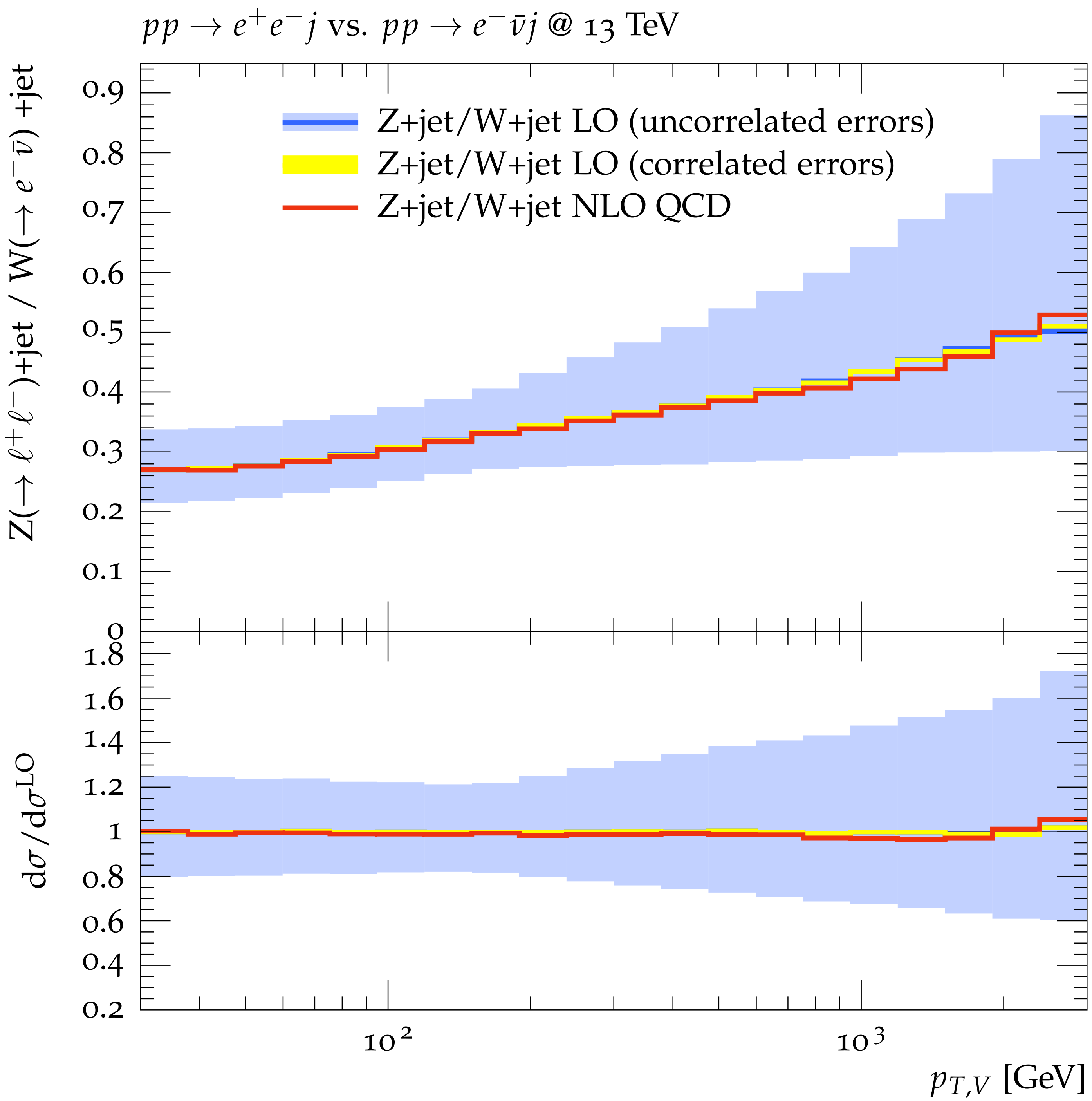
consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

correlated treatment yields tiny O(<~ 1%) uncertainties

check against NLO QCD!

Pure QCD uncertainties



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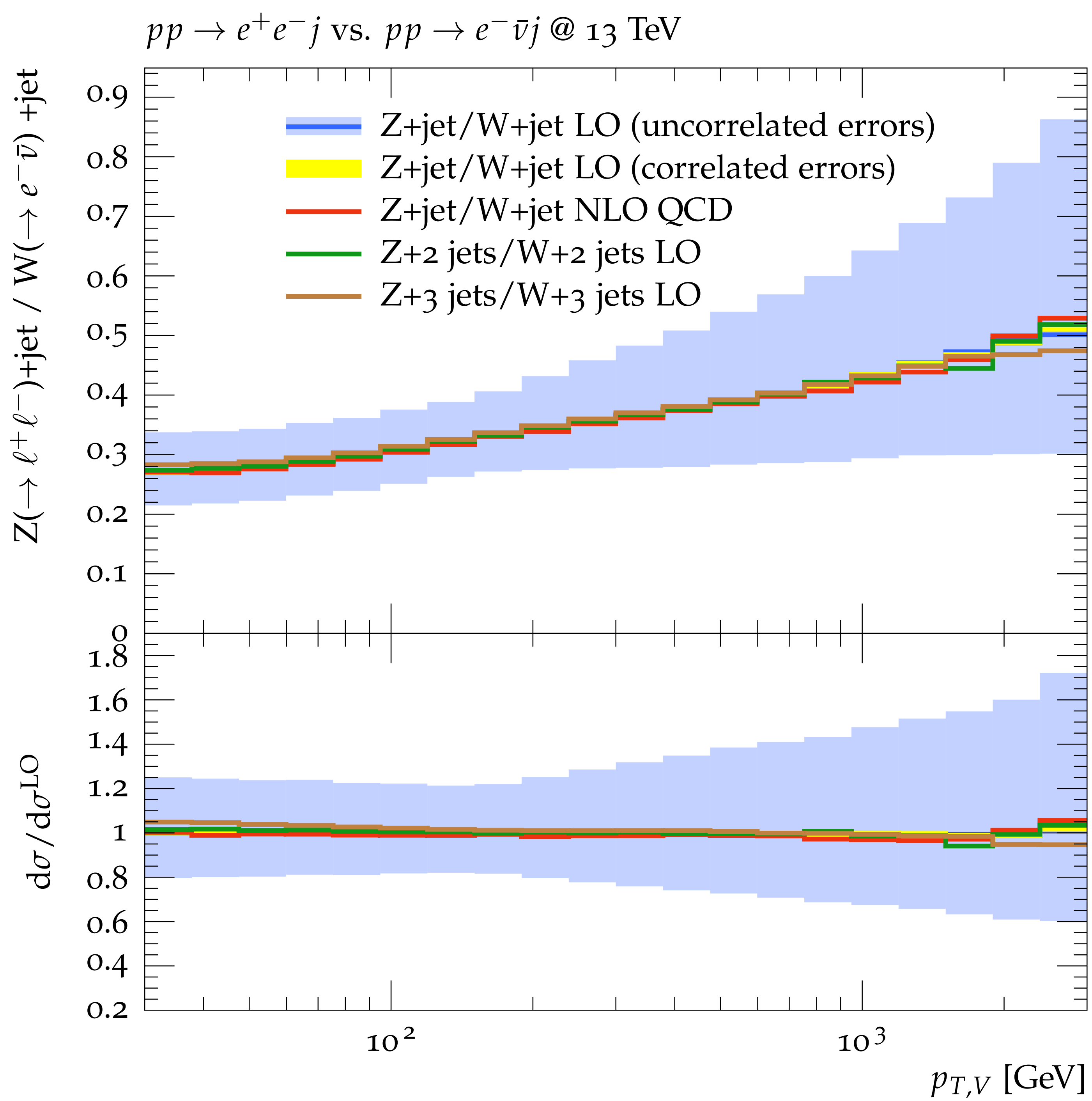
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ NLO predictions support correlated treatment of uncertainties!

Pure QCD uncertainties



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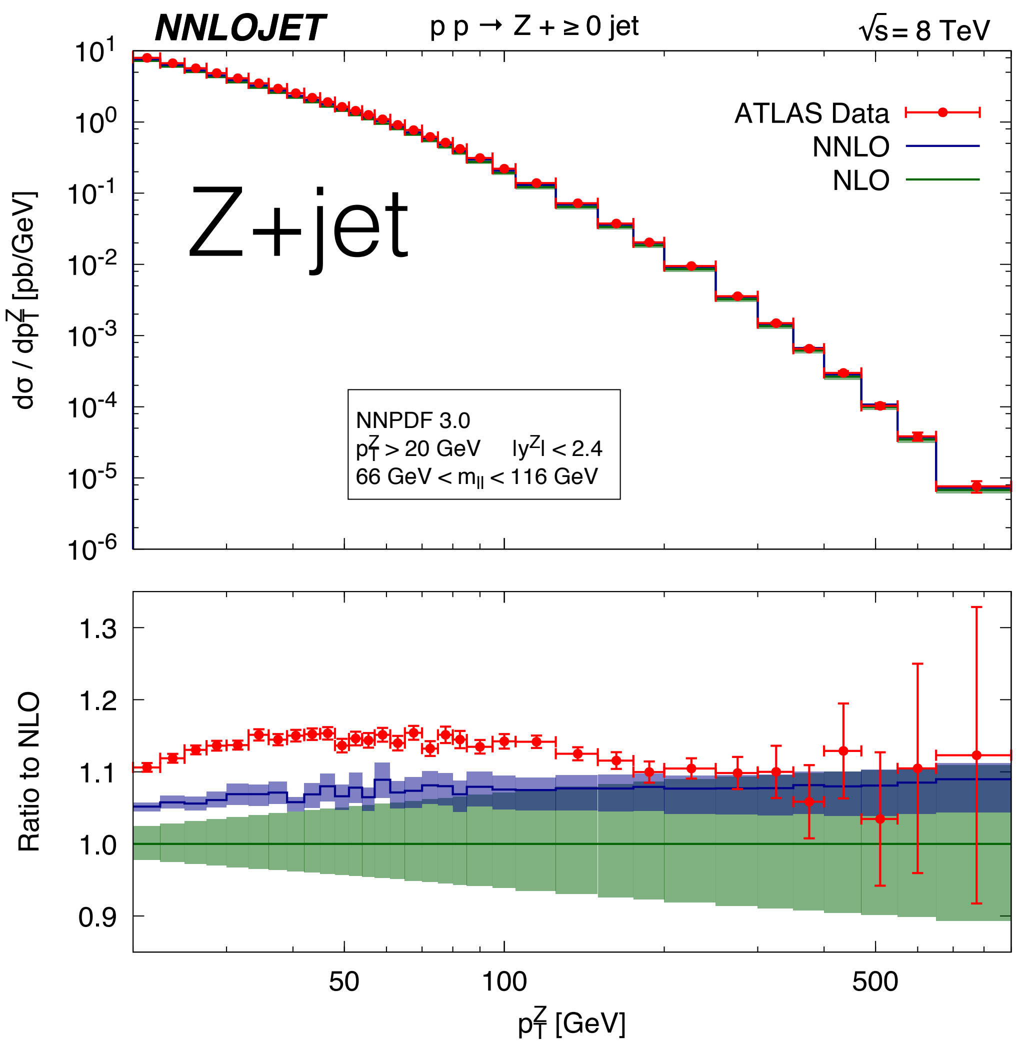
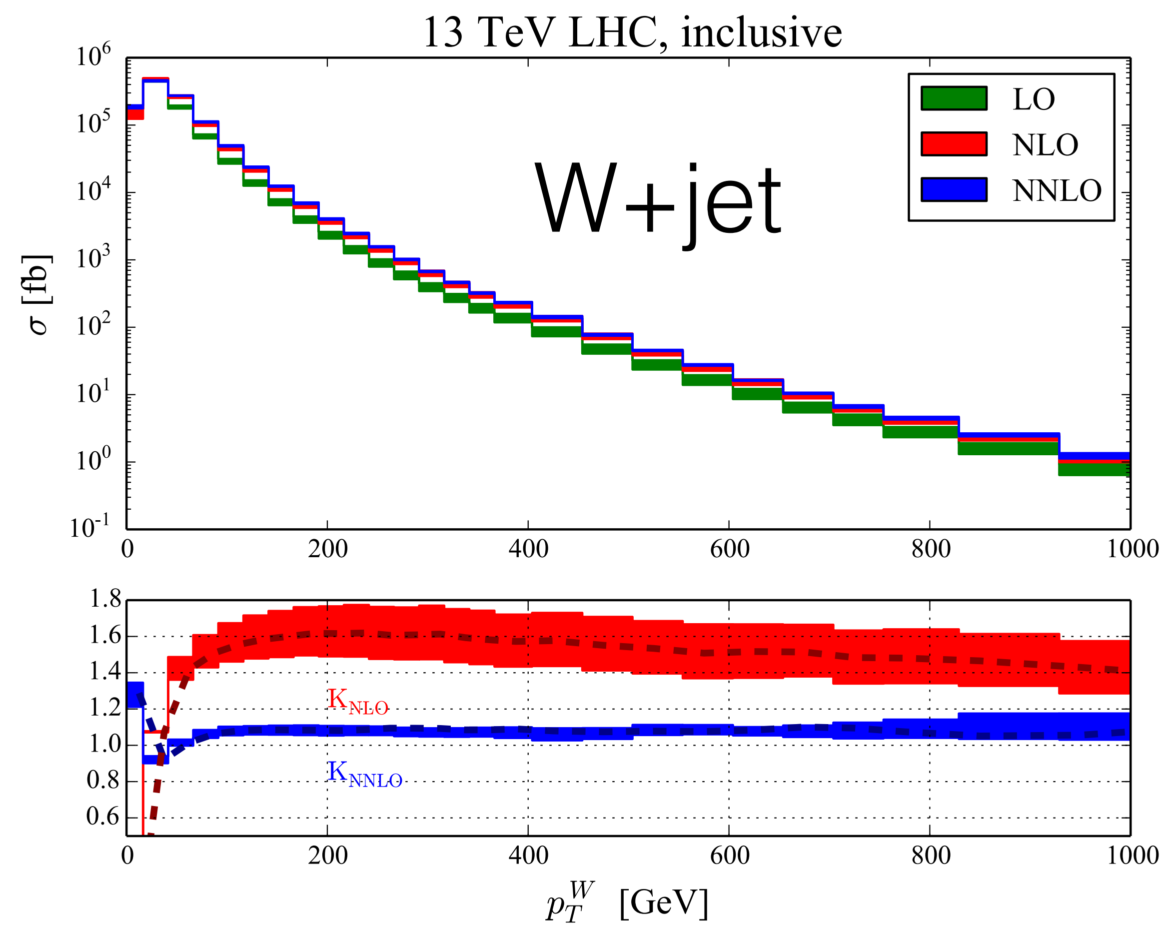
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ NLO predictions support correlated treatment of uncertainties!

Also holds for higher jet-multiplicities
→ indication of correlation also in higher-order corrections beyond NLO!

NNLO for W/Z+jet



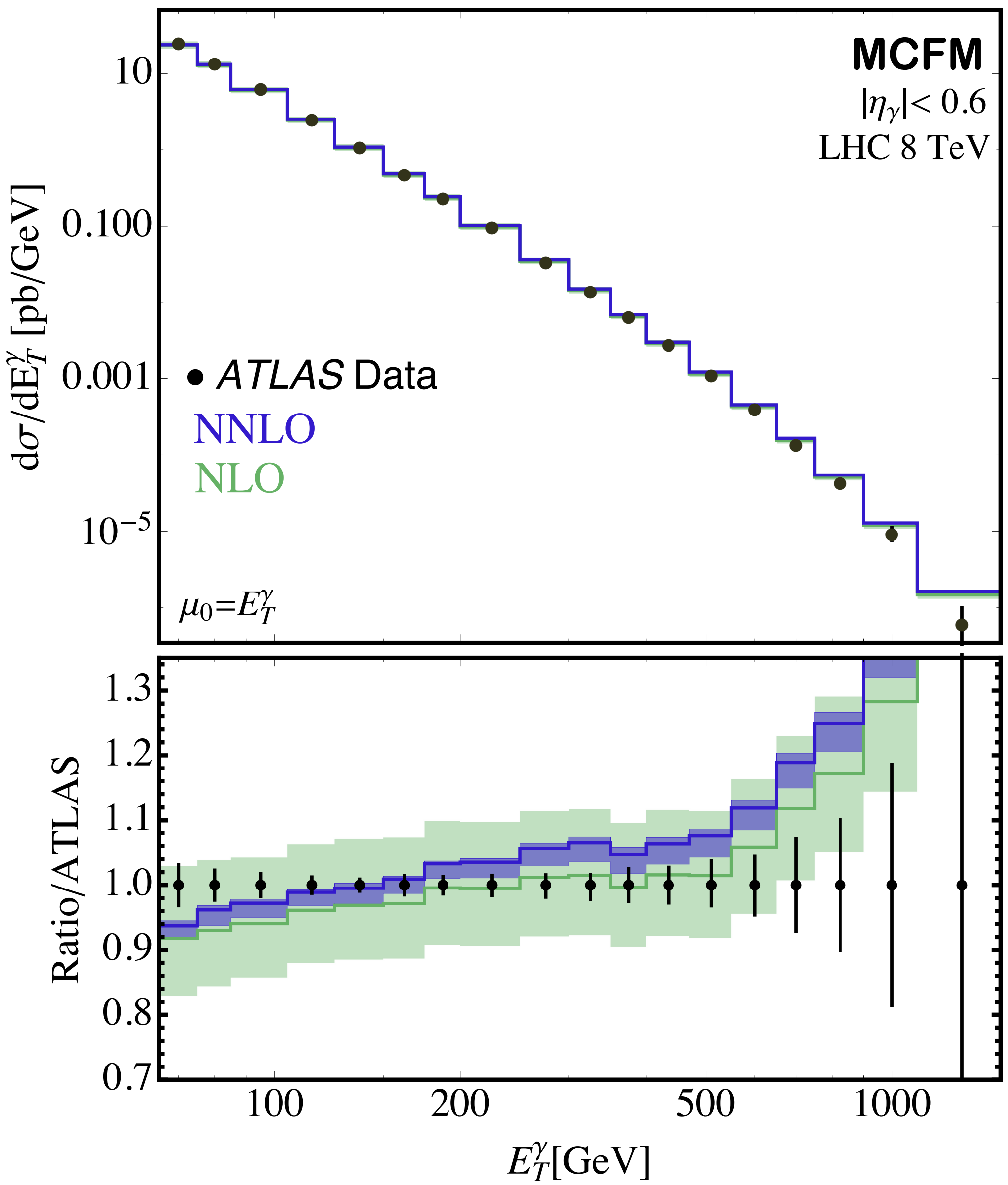
[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]

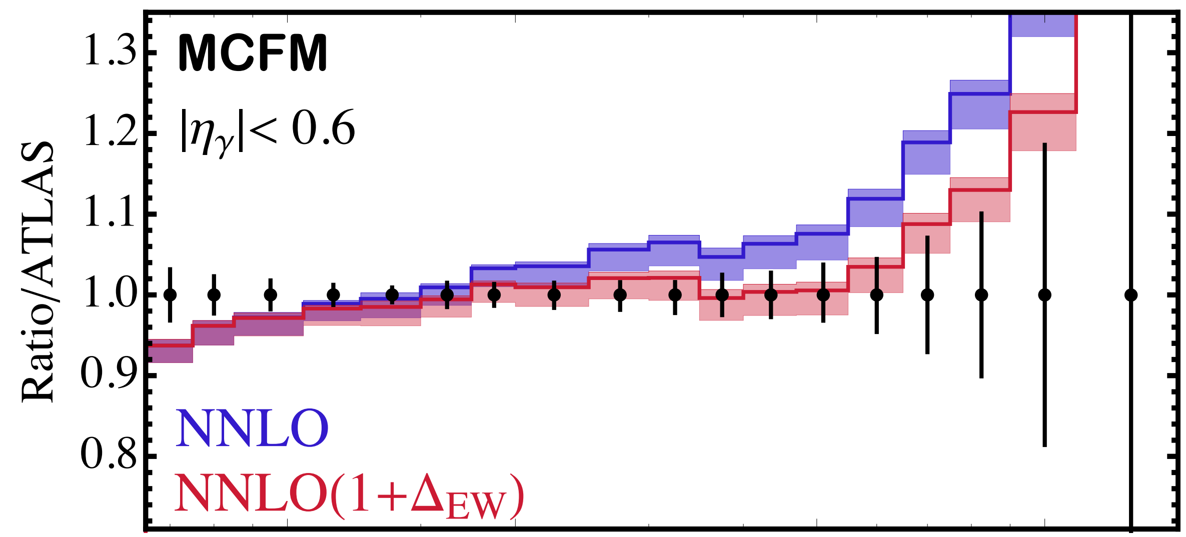


[Boughezal, Liu, Petriello; '16]

- unprecedented reduction of scale uncertainties at NNLO: O(~ 5%)
- we can now check the correlation of the uncertainties going from NLO to NNLO
- both groups joined our collaborative effort and will provide dedicated NNLO samples for Z+jet and W+jet including conservative factor-4 scale variations

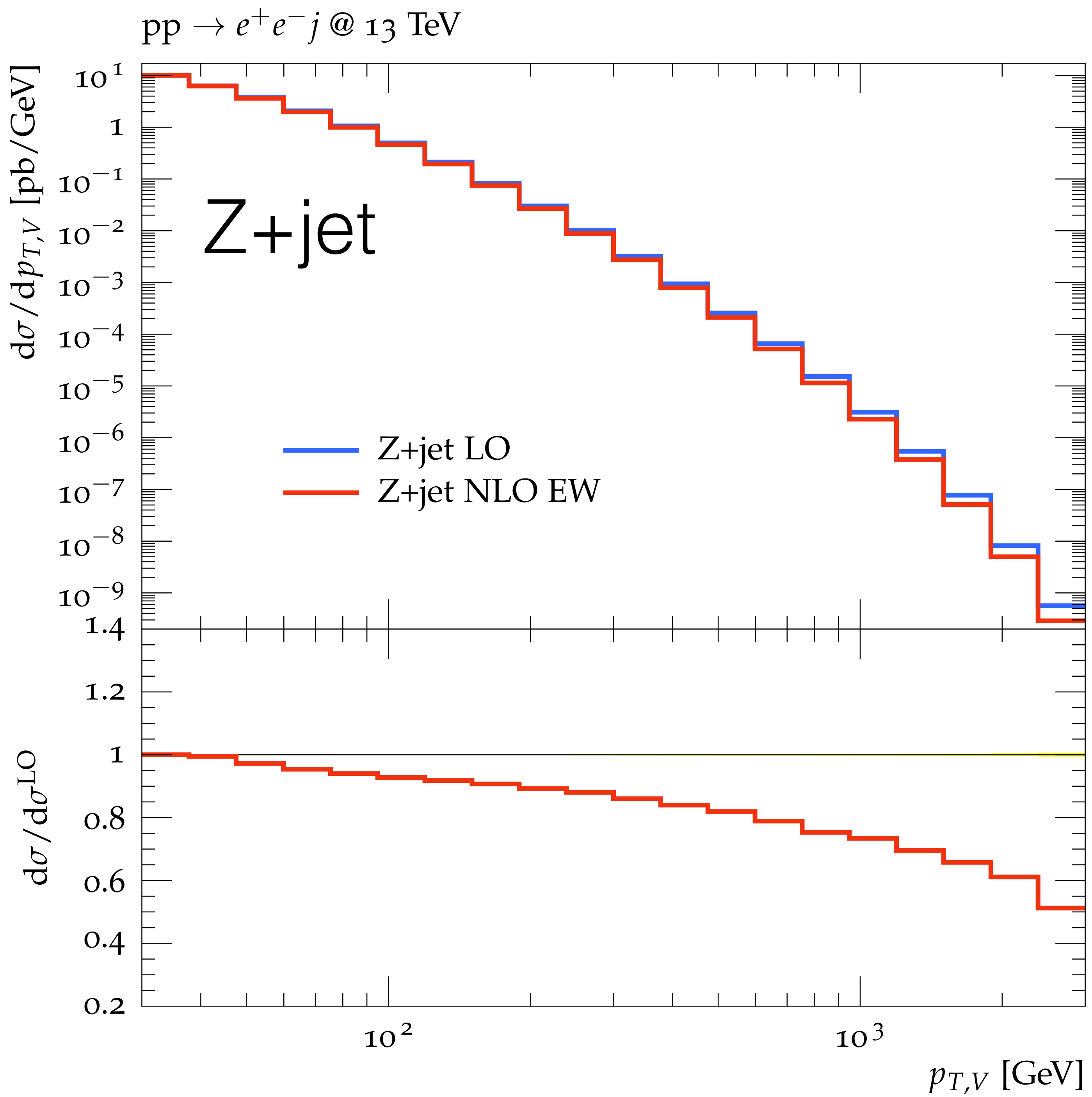
NNLO for γ+jet





[Campbell, Ellis, Williams; arXiv:1612.04333]

Pure EW uncertainties



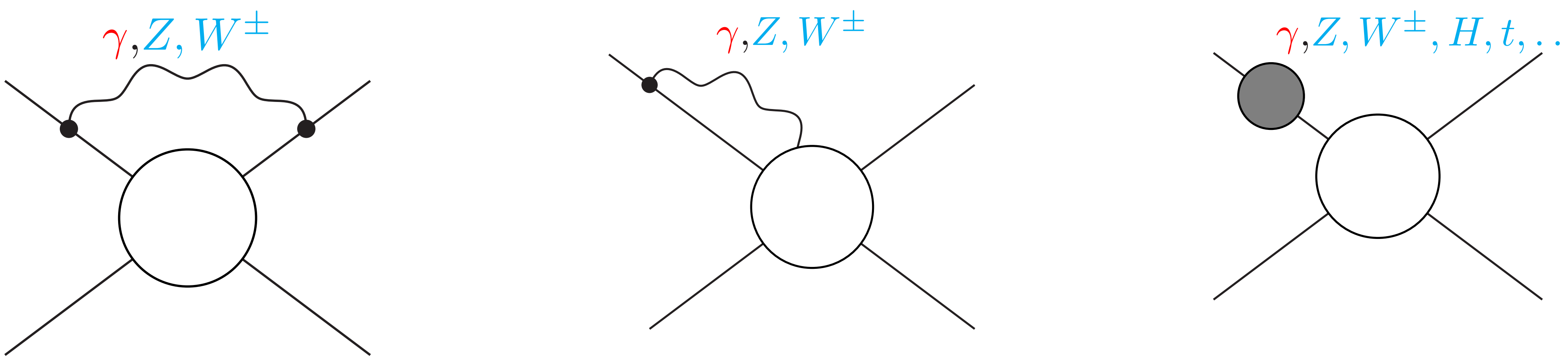
EW corrections become sizeable at large $p_{T,V}$

Origin: EW Sudakov logarithms

How to estimate corresponding pure EW uncertainties of relative $\mathcal{O}(\alpha^2)$?

Virtual EW Sudakov logarithms

Originate from soft/collinear virtual EW bosons coupling to on-shell legs



Universality and factorisation similar as in QCD *[Denner, Pozzorini; '01]*

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

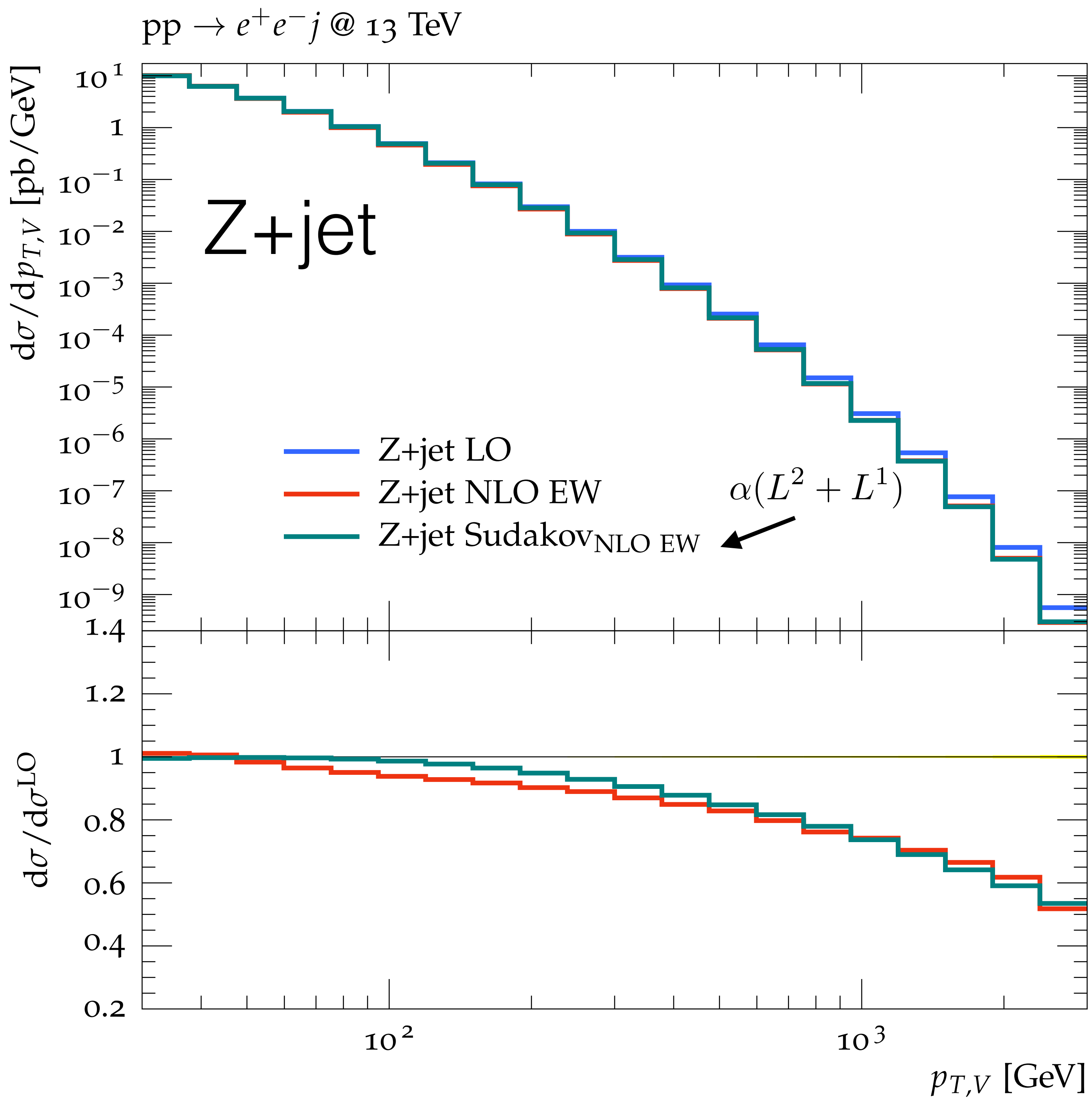
- process-independent, simple structure
- 2-loop extension and resummation partially available
- typical size at $\sqrt{\hat{s}} = 1, 5, 10$ TeV:

$$\delta_{\mathrm{LL}} \sim -\frac{\alpha}{\pi s_W^2} \log^2 \frac{\hat{s}}{M_W^2} \simeq -28, -76, -104\%,$$

$$\delta_{\mathrm{NLL}} \sim +\frac{3\alpha}{\pi s_W^4} \log \frac{\hat{s}}{M_W^2} \simeq +16, +28, +32\%$$

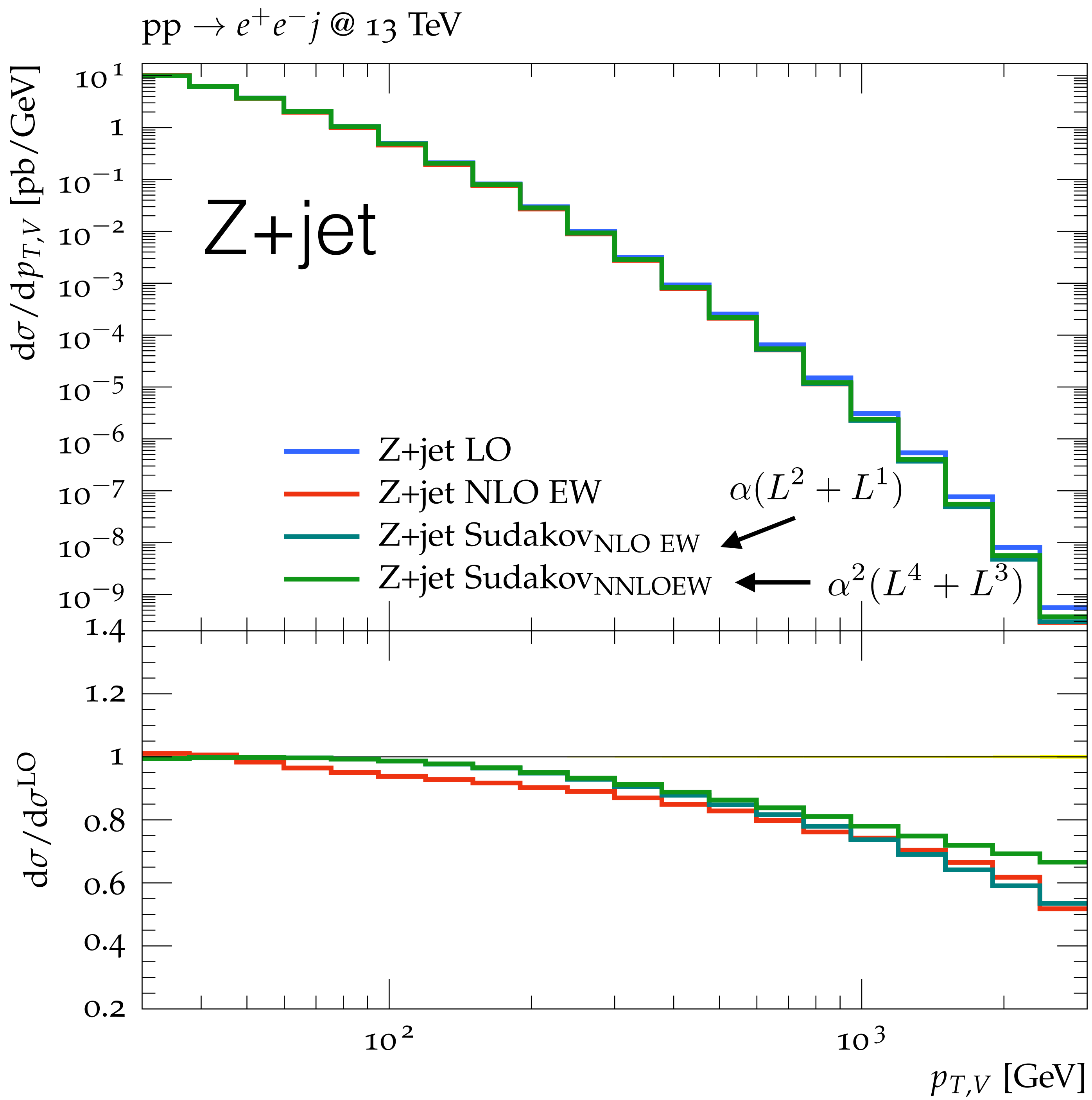
➡ large cancellations possible

Pure EW uncertainties



Large EW corrections dominated by Sudakov logs

Pure EW uncertainties

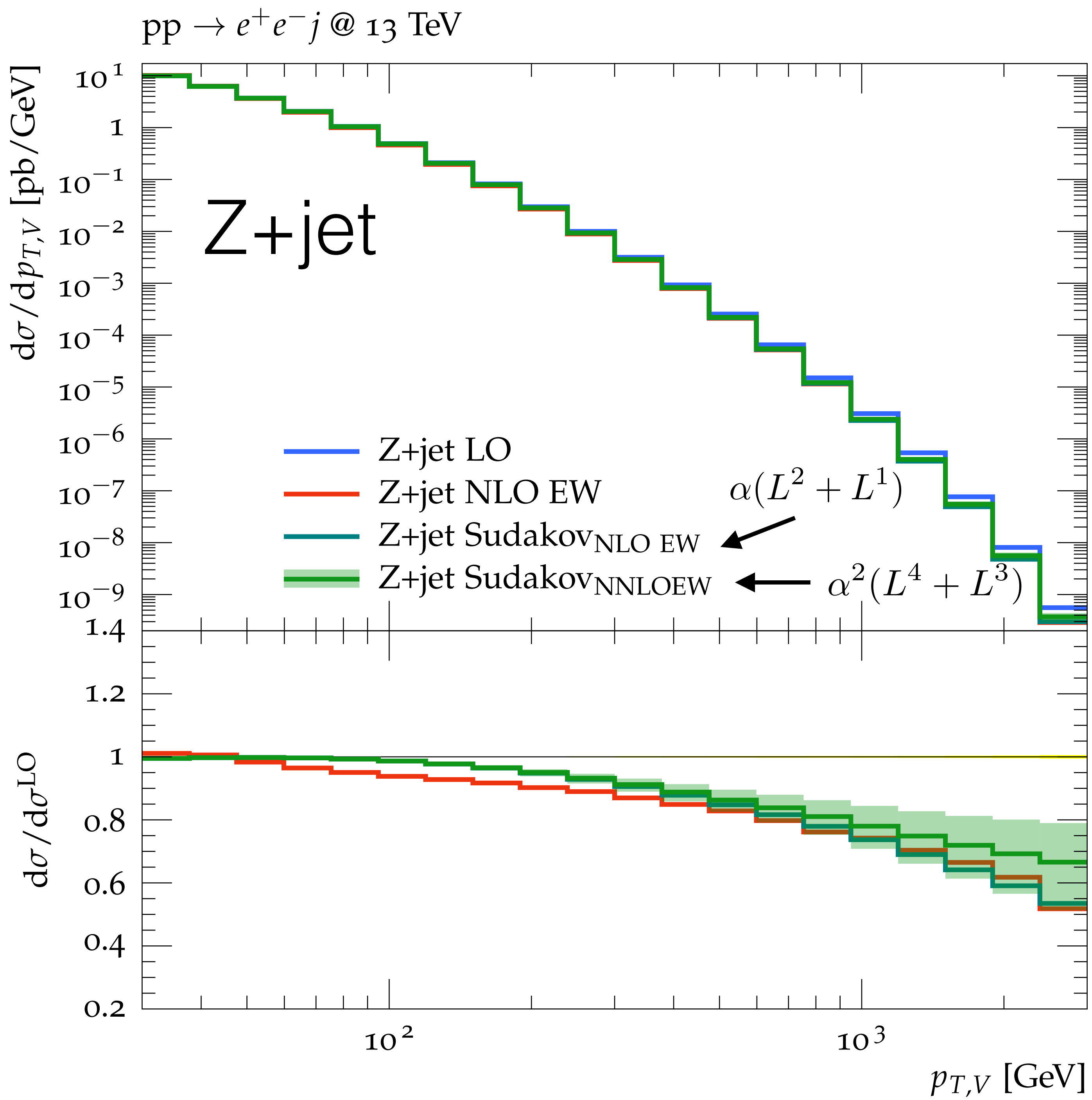


Large EW corrections dominated by Sudakov logs

Include (positive) two-loop Sudakov logs

[Kühn, Kulesza, Pozzorini, Schulze; 05-07]

Pure EW uncertainties



Large EW corrections dominated by Sudakov logs

Include (positive) two-loop Sudakov logs
[Kühn, Kulesza, Pozzorini, Schulze; 05-07]

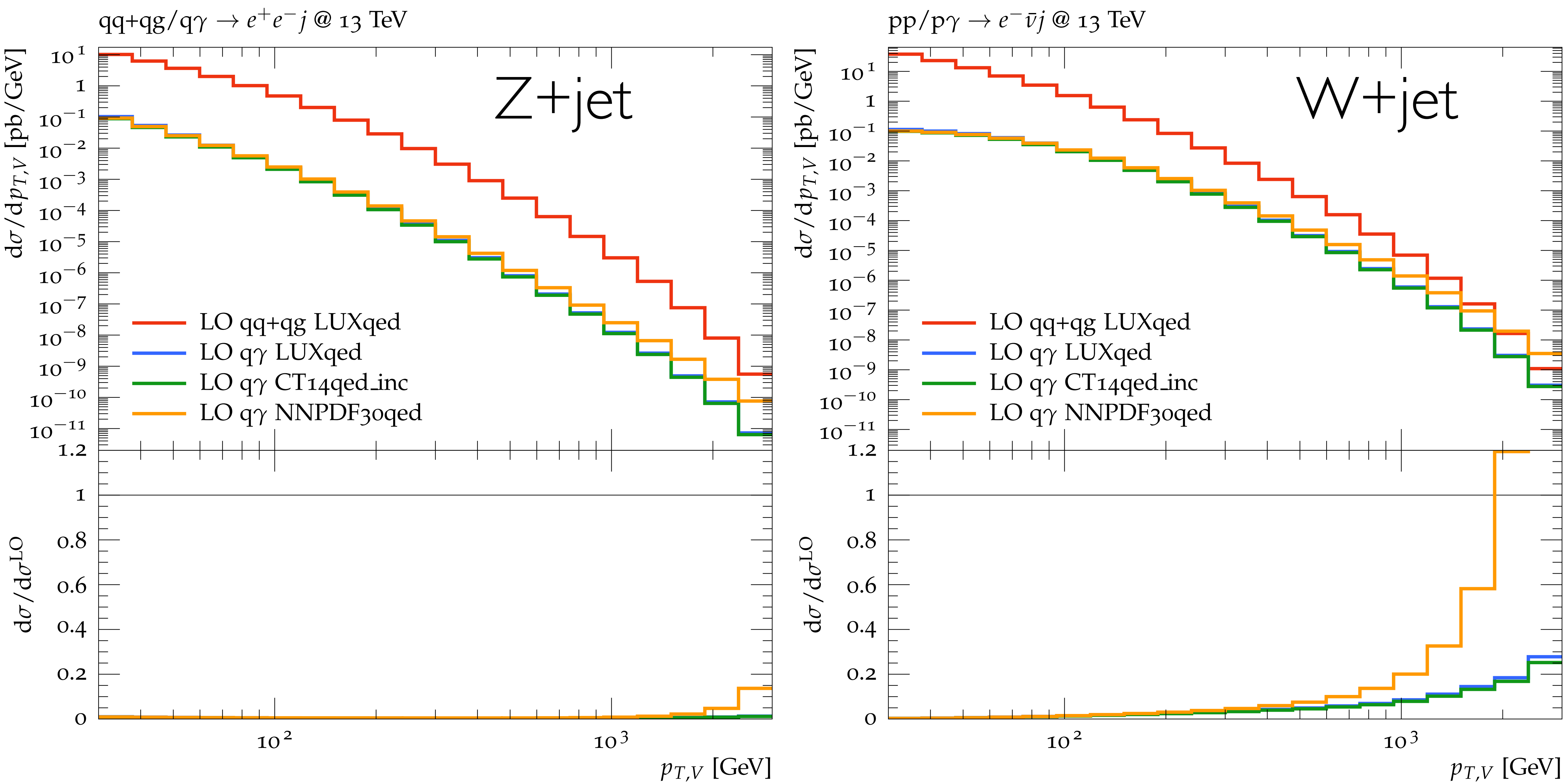
Estimate missing higher-order log-enhanced corrections via factor-2 variation in the two-loop NLL: $\log(s/(\xi M_W)^2)\ ,\ \ \xi=(0.5,2)$

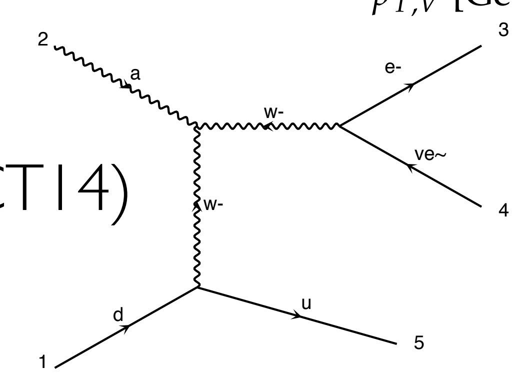
Can be considered as correlated between V+jets processes

Add additional uncorrelated 10% x NLO EW uncertainty to account for non-log enhanced higher-order corrections: $\delta^{(2)}_{\text{hard}} \to \frac{0.1\pi}{\alpha}\delta^{(1)}_{\text{hard}} \approx 40\times\delta^{(1)}_{\text{hard}}$

Under discussion!

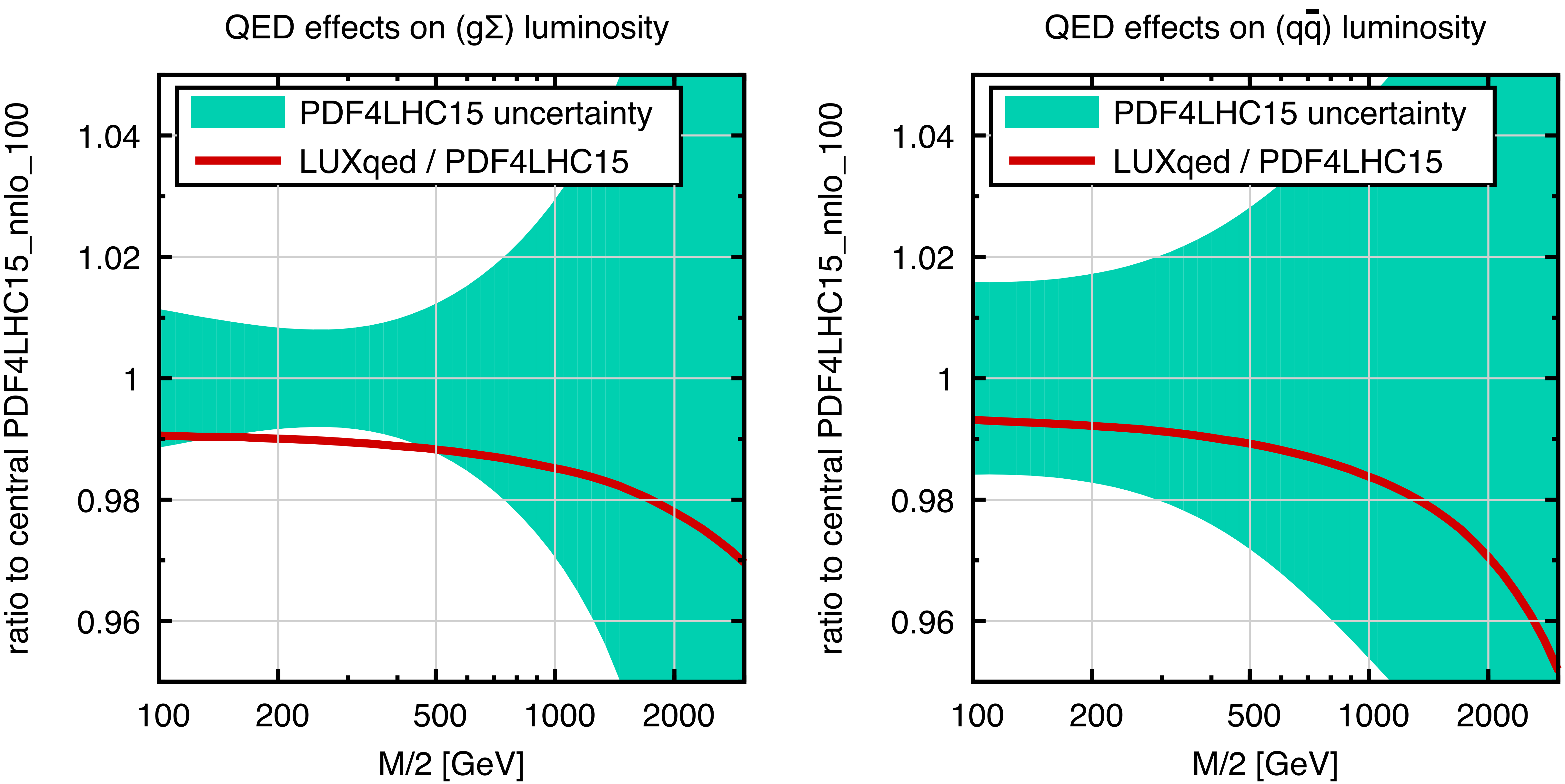
Photon-induced production





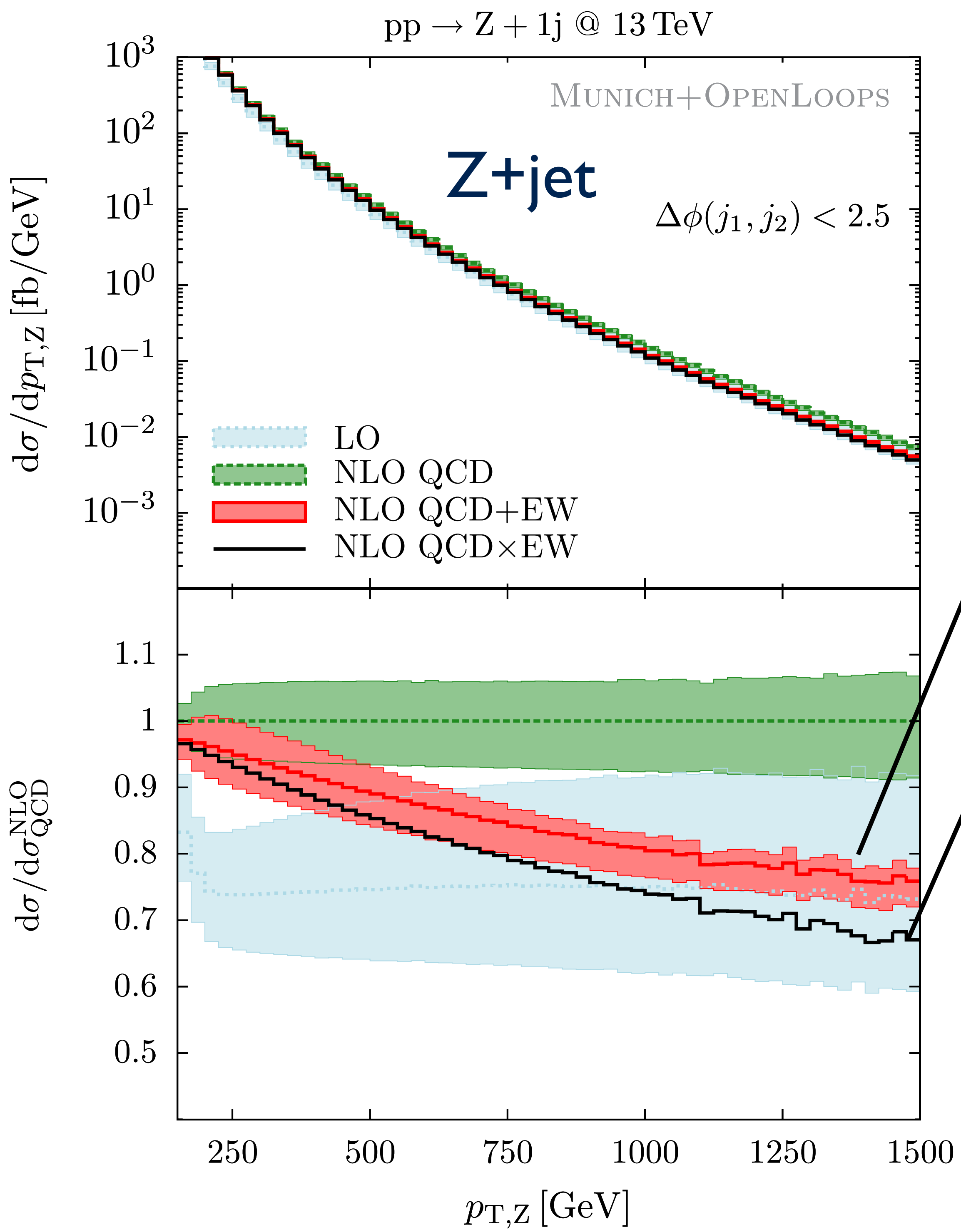
- photon-induced production irrelevant for Z+jet (and γ+jet)
- in W+jet O(10%) contribution with LUXqed (consistent with CT14) (due to t-channel enhancement)
- ~1% uncertainties in photon PDFs due to LUXqed

QED corrections to quark PDFs



- small percent-level QED effects on qg/qq luminosities (included via LUXqed)
- 1.5-5% PDF uncertainties

Mixed QCD-EW uncertainties



Given QCD and EW corrections are sizeable, also mixed QCD-EW uncertainties of relative $\mathcal{O}(\alpha\alpha_s)$ have to be considered.

$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \sigma^{\mathrm{LO}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$$

$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD\times EW}} = \sigma^{\mathrm{NLO}}_{\mathrm{QCD}}\left(1 + \frac{\delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}}\right)$$

Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

However, for dominant Sudakov EW logarithms factorization should be exact!

Under discussion!

Include theory predictions via MC reweighting

$$\boxed{\frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^{(V)}(\vec{\varepsilon}_{\mathrm{MC}},\vec{\varepsilon}_{\mathrm{TH}}) := \frac{\mathrm{d}}{\mathrm{d}x}\frac{\mathrm{d}}{\mathrm{d}\vec{y}}\sigma^{(V)}_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}})\left[\frac{\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}}(\vec{\varepsilon}_{\mathrm{TH}})}{\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{MC}}(\vec{\varepsilon}_{\mathrm{MC}})}\right]}$$

one-dimensional reweighting of MC samples in $x = p_{\mathrm{T}}^{(V)}$

Factorization!

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}}(\vec{\varepsilon}_{\mathrm{TH}}) = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}}(\vec{\varepsilon}_{\mathrm{QCD}})\left[1+\frac{\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{EW}}(\vec{\varepsilon}_{\mathrm{EW}},\vec{\varepsilon}_{\mathrm{QCD}})}{\frac{\mathrm{d}}{\mathrm{d}x}\hat{\sigma}^{(V)}_{\mathrm{QCD}}(\hat{\varepsilon},\vec{\varepsilon}_{\mathrm{QCD}})}\right]+\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\gamma-\mathrm{ind.}}(\varepsilon_{\gamma},\vec{\varepsilon}_{\mathrm{QCD}})$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NLO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NNLO\,QCD}}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{EW}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NLO\,EW}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{Sudakov\,NNLO\,EW}}$$

with nuisance parameters $\vec{\varepsilon}_{\mathrm{TH}} = (\vec{\varepsilon}_{\mathrm{QCD}},\hat{\varepsilon},\vec{\varepsilon}_{\mathrm{EW}},\varepsilon_{\gamma})$

Conclusions & Outlook

- monojet / MET+jets searches *soon* limited by V+jets background systematics

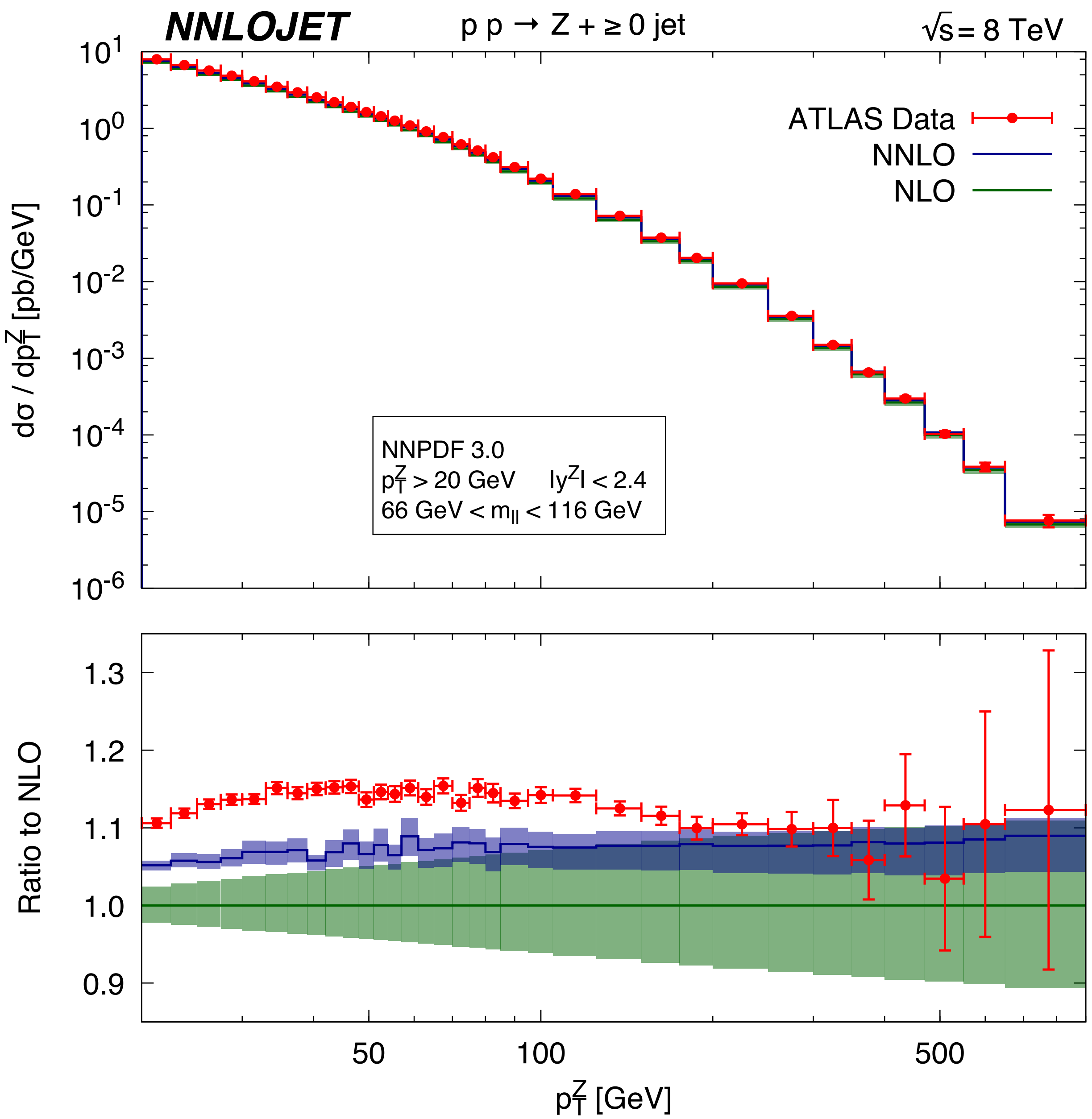
- MC reweighting allows to promote V + jet to NNLO QCD+(N)NLO EW:
    - inclusion of EW corrections *crucial* due to large Sudakov logs
    - NNLO QCD *crucial* due to remarkable reduction of scale variations

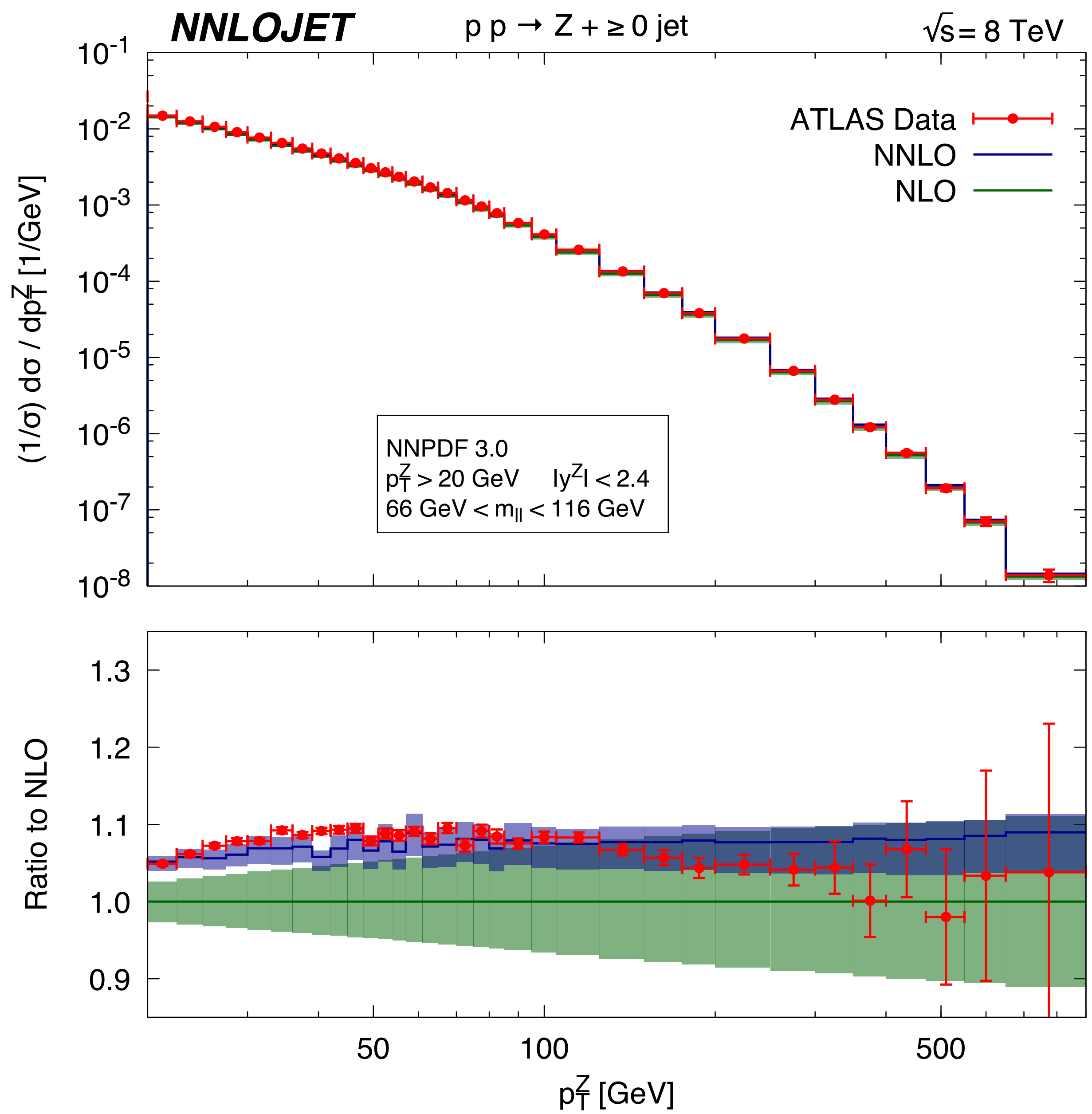
- High statistics MC runs are under way
- Ongoing technical studies:
    - refine treatment of uncertainties (incl. correlations and shape uncertainties)
    - impact of isolation in γ+jet
    - …

- Public document available very soon

BACKUP

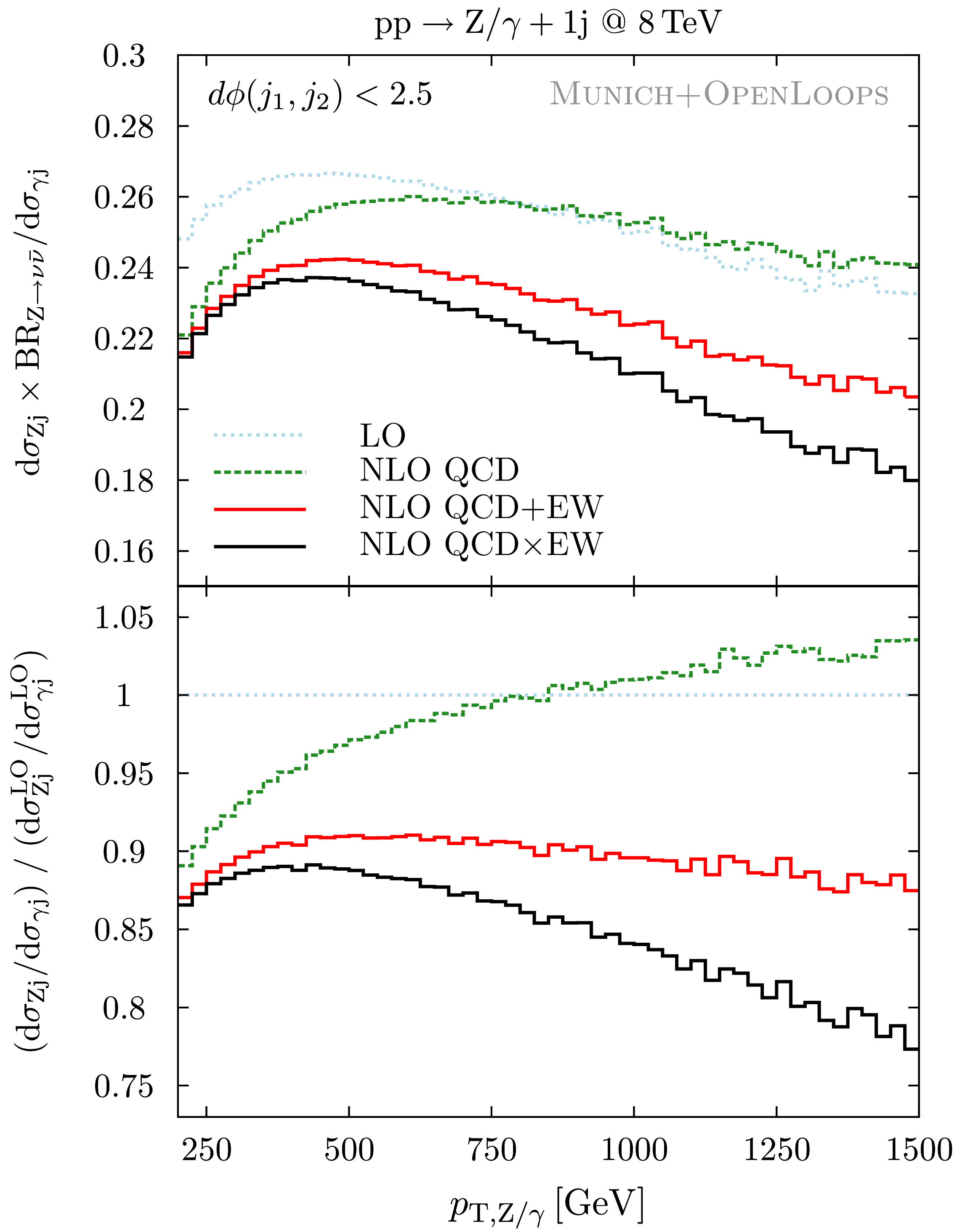
NNLO to the rescue





[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]

Z/γ + 1 jet: pT-ratio



Overall

- mild dependence on the boson pT

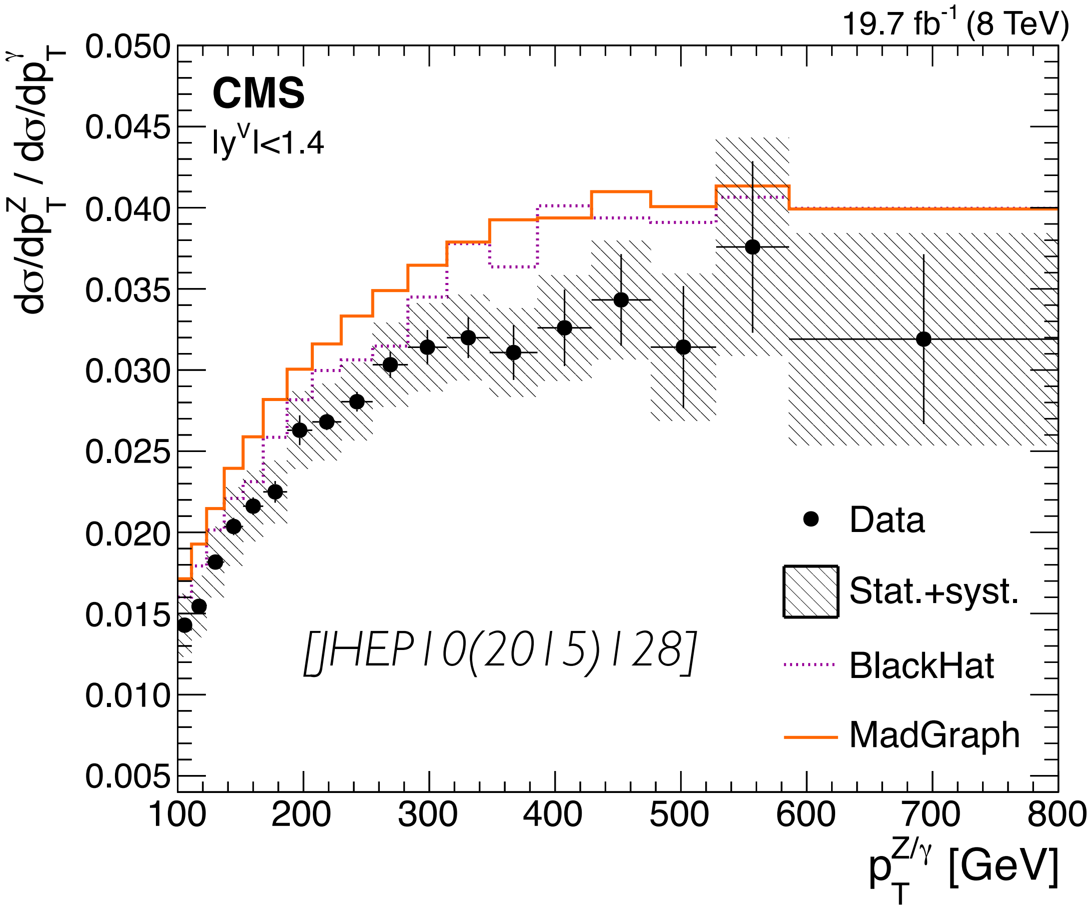
QCD corrections

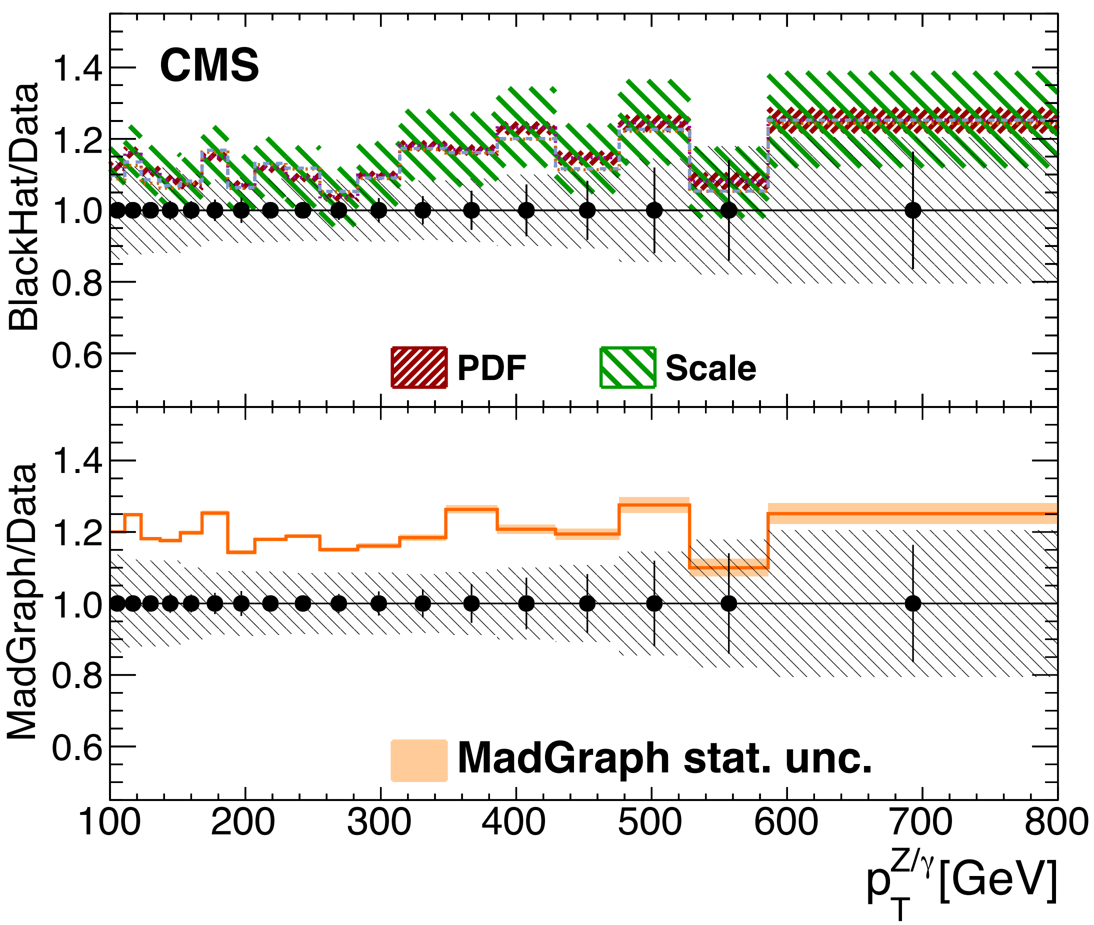
- 10-15% below 250 GeV
- ≲ 5% above 350 GeV

EW corrections

- sizeable difference in EW corrections results in 10-15% corrections at several hundred GeV
- ~5% difference between NLO QCD+EW and NLO QCD×EW

Compare against data



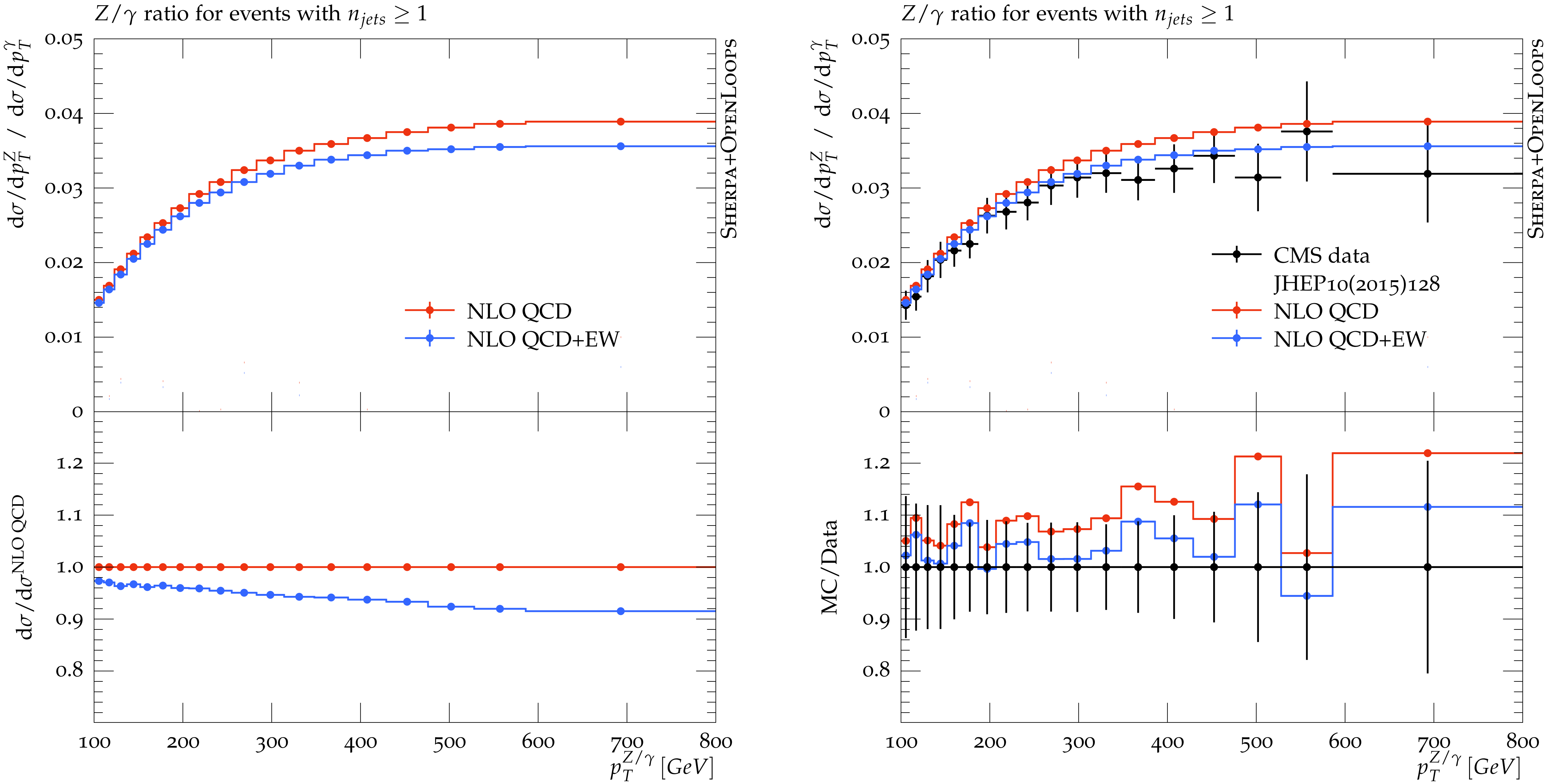


- constant off-set with respect to LO
- improved agreement at NLO QCD for small pT

Compare against data

Frixione-Isolation with $\epsilon = 0.025$, $\delta_0 = 0.4$

"a Frixione cone with these choices mimics the selections in the true on-shell photon definition at particle level" *[JHEP10(2015)128]*



[Ciulli, Kallweit, JML, Pozzorini, Schönherr for ***LH'15****]*

- remarkable agreement with data at @ NLO QCD+EW!

Combination of NLO QCD and EW & Setup

Two alternatives:

$$\sigma^{\rm NLO}_{\rm QCD+EW} = \sigma^{\rm LO} + \delta\sigma^{\rm NLO}_{\rm QCD} + \delta\sigma^{\rm NLO}_{\rm EW}$$

$$\sigma^{\rm NLO}_{\rm QCD\times EW} = \sigma^{\rm NLO}_{\rm QCD}\left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right) = \sigma^{\rm NLO}_{\rm EW}\left(1+\frac{\delta\sigma^{\rm NLO}_{\rm QCD}}{\sigma^{\rm LO}}\right)$$

Difference between the two approaches indicates uncertainties due to missing two-loop EW-QCD corrections of $\mathcal{O}(\alpha\alpha_s)$

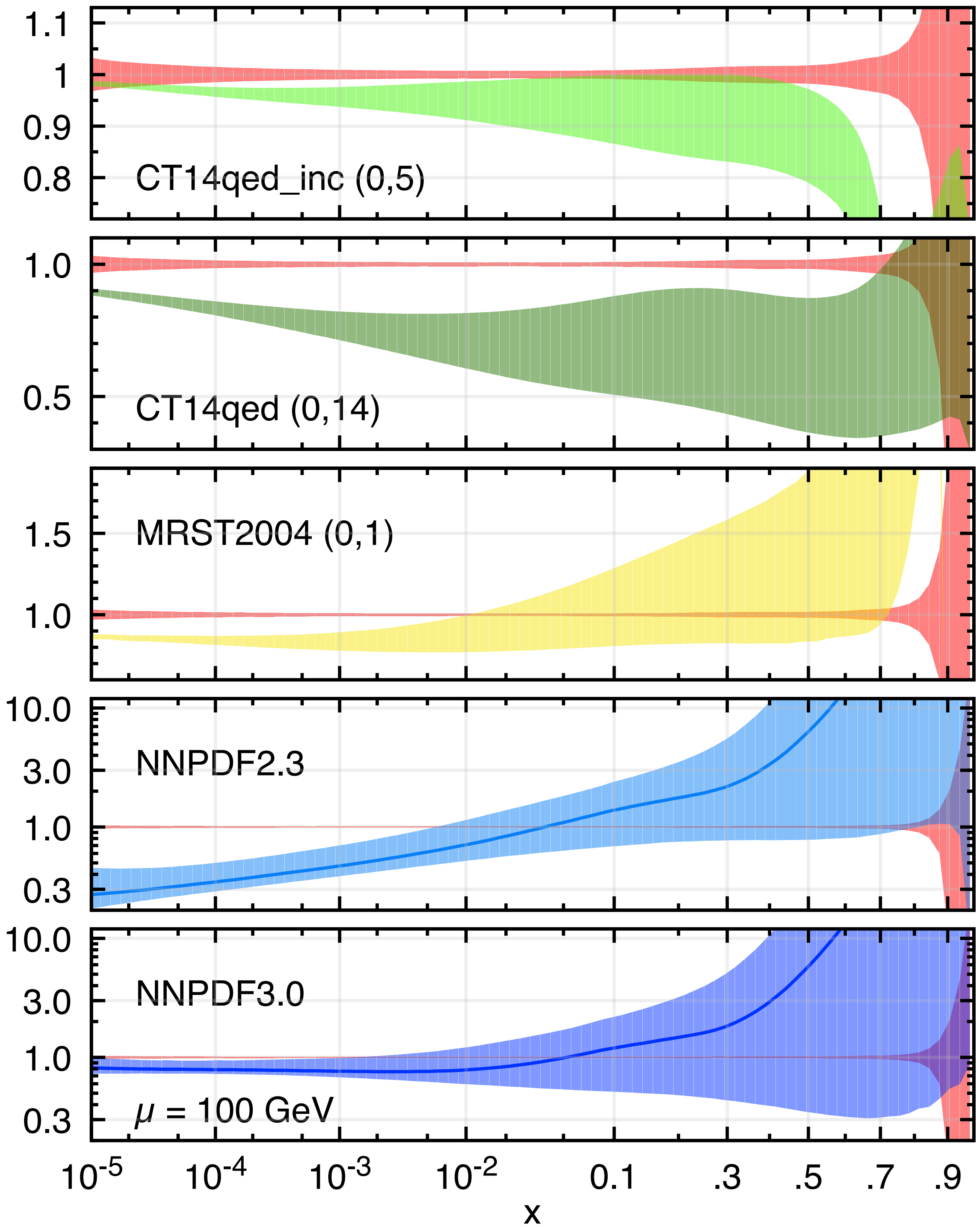
Relative corrections w.r.t. NLO QCD:

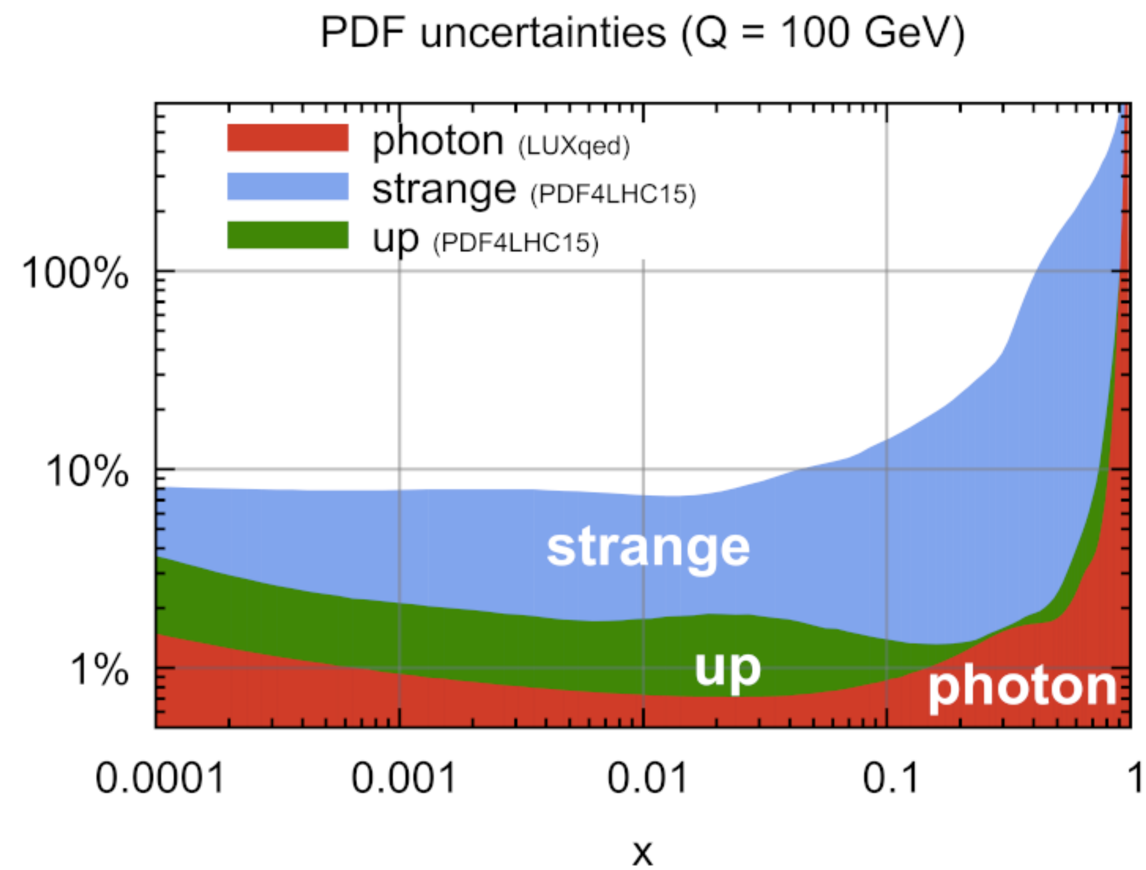
$$\frac{\sigma^{\rm NLO}_{\rm QCD+EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm NLO}_{\rm QCD}}\right)$$ suppressed by large NLO QCD corrections

$$\frac{\sigma^{\rm NLO}_{\rm QCD\times EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right)$$ “usual” NLO EW w.r.t. LO

- $\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_{\rm W}^2 \left(1-\frac{M_{\rm W}^2}{M_{\rm Z}^2}\right)$ in G_μ-scheme with $G_\mu = 1.16637\times 10^{-5}\ {\rm GeV}^{-2}$

LUXqed





[Manohar, Nason, Salam, Zanderighi, '16]