Scales for DM searches: V+jet pT-ratios

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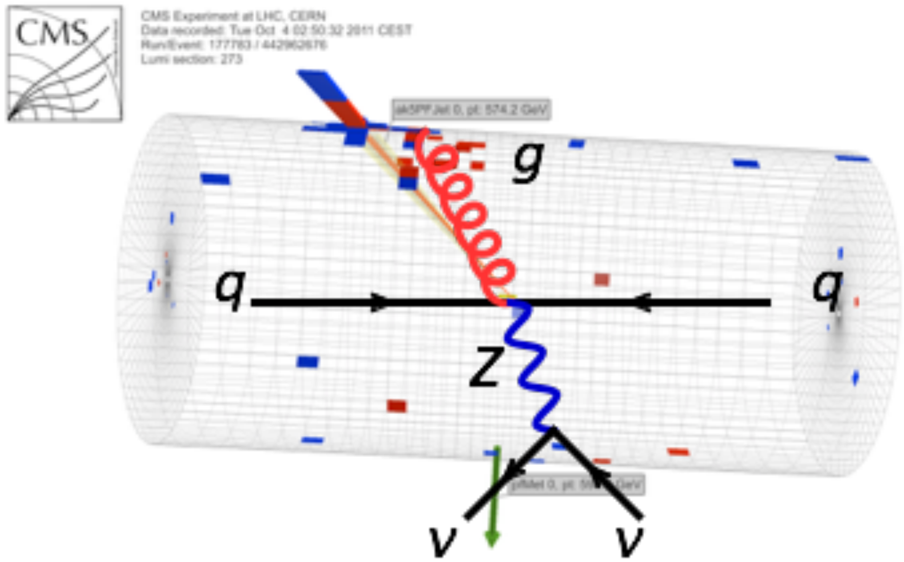
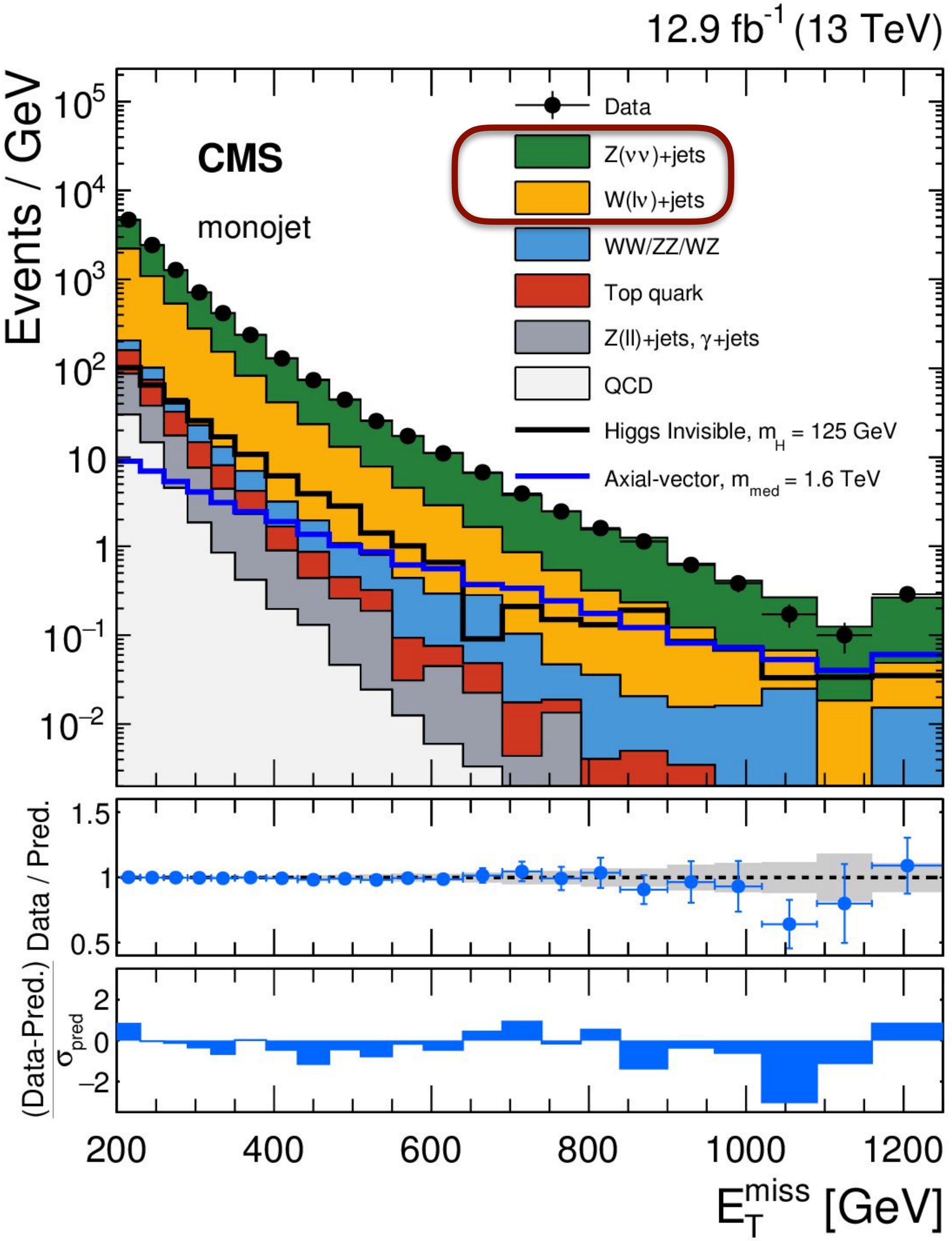
IP3

work in collaboration with:
R. Boughezal, A. Denner, S. Dittmaier, A. Huss, A. Gehrmann-De Ridder,
T. Gehrmann, N. Glove, S. Kallweit, M. L. Mangano,
T.A. Morgan, A. Mück, M. Schönherr, F. Petriello, S. Pozzorini, G. P. Salam

Taming Unphysical Scales for Physical Predictions,
Cambridge, 31.03.2016

V+jets backgrounds in monojet/MET/X + jets searches





irreducible backgrounds:

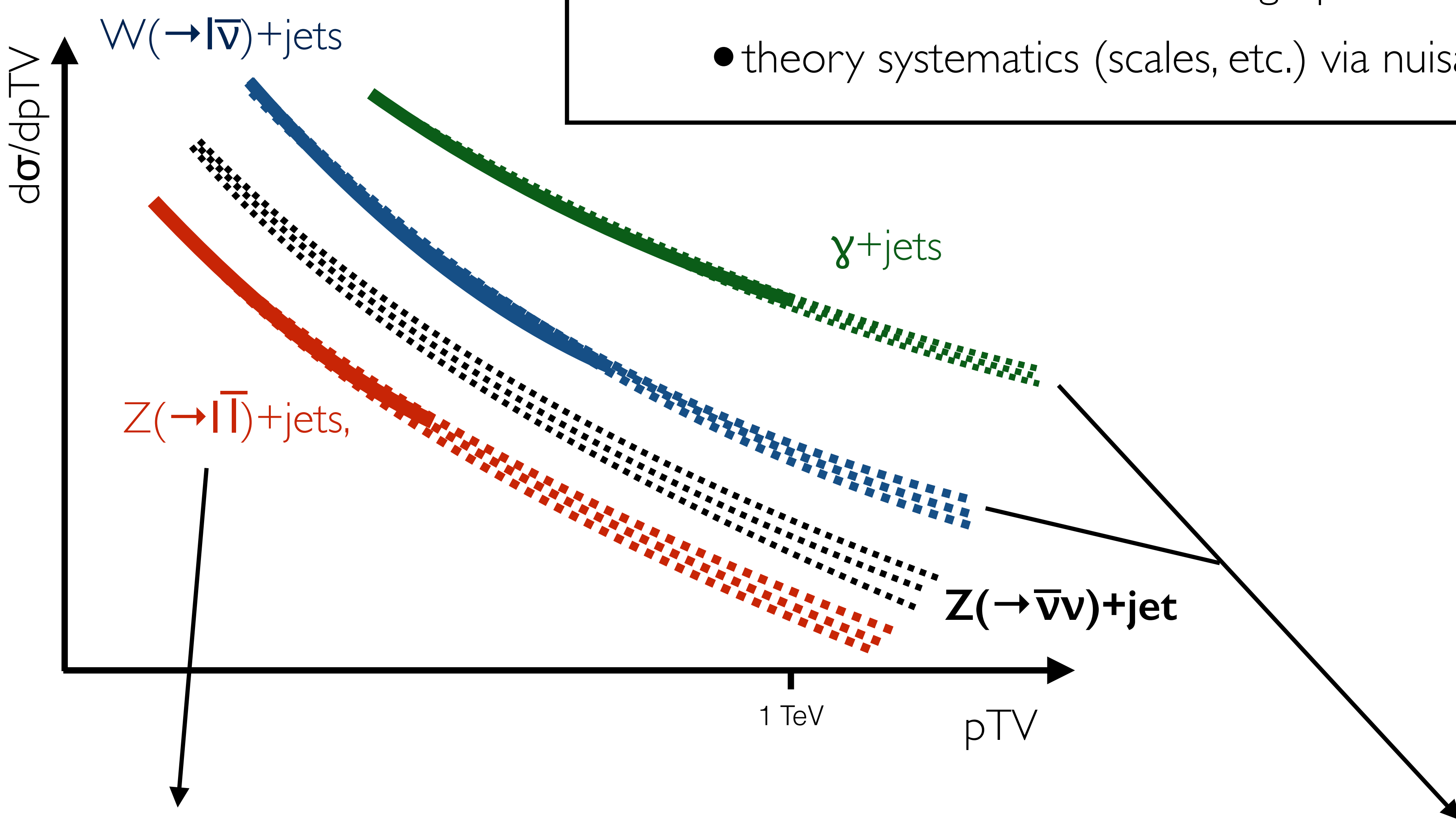
pp→Z(→$\nu\bar{\nu}$)+jets ⟹ MET + jets

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

Determine V+jets backgrounds

global fit of $Z(\rightarrow l\bar{l})$+jets, $W(\rightarrow l\bar{\nu})$+jets and γ+jets measurements

- to determine $Z(\rightarrow \bar{\nu}\nu)$+jet
- and the visible channels at high-pT
- theory systematics (scales, etc.) via nuisance parameters in fit



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

- fairly large data samples at large pT
- systematics from transfer factors

Goal of the ongoing study

- Combination of state-of-the-art predictions: (N)NLO QCD+(N)NLO EW in order to match (future) experimental sensitivities (1-10% accuracy in the few hundred GeV-TeV range)

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

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

with
$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{mix}} + \frac{\mathrm{d}}{\mathrm{d}x}\Delta\sigma^{(V)}_{\mathrm{EW}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\gamma-\mathrm{ind.}}$$

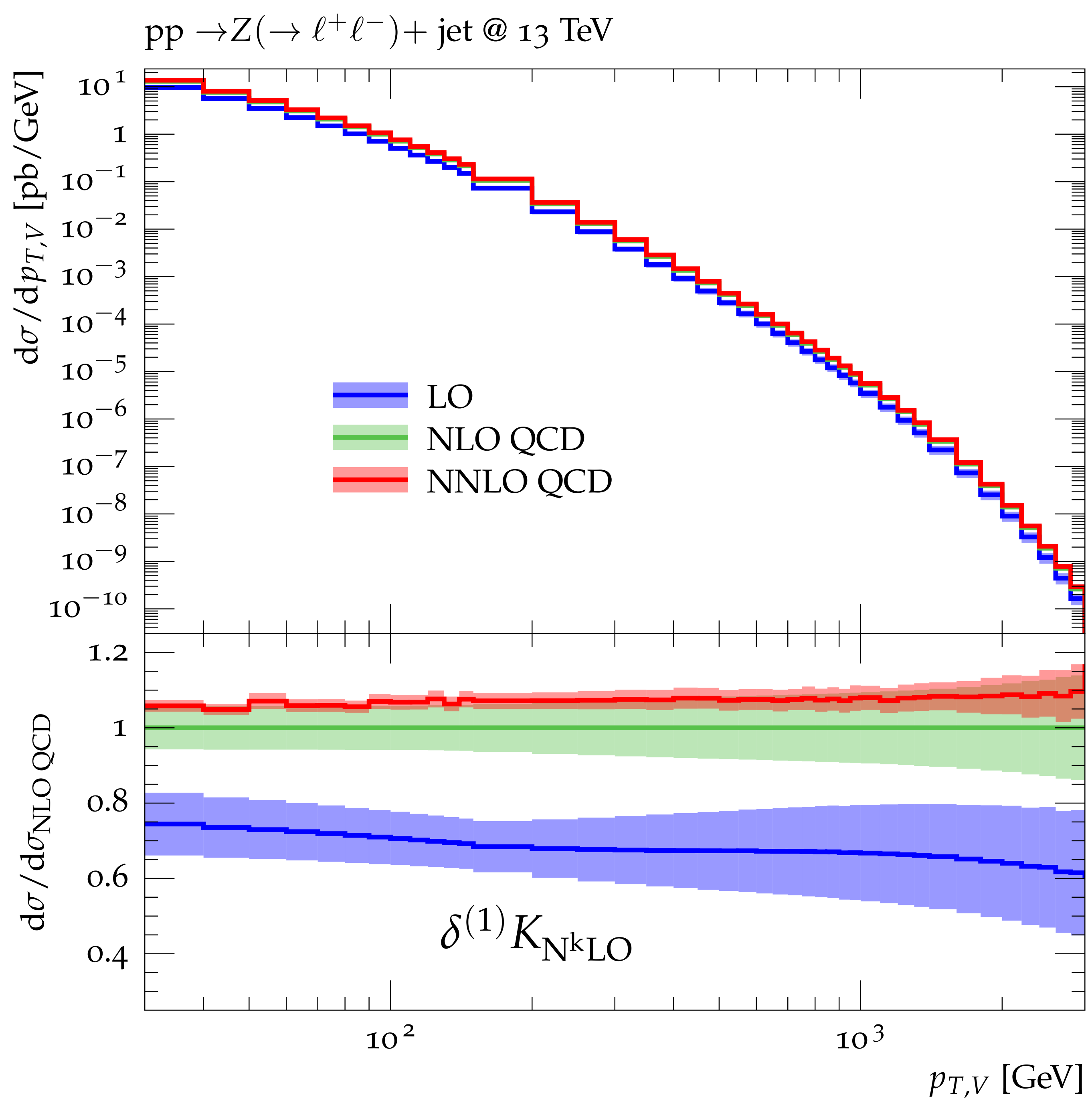
- Robust **uncertainty estimates** including
  - Pure QCD uncertainties
  - Pure EW uncertainties
  - Mixed QCD-EW uncertainties

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

QCD effects: scale issues

QCD effects: scale issues

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



NNLO from [A. Huss, A. Gehrmann-De Ridder, T. Gehrmann, N. Glove, T.A. Morgan]

$$\mu_0 = \frac{1}{2}\left(\sqrt{p^2_{\mathrm{T},\ell^+\ell^-} + m^2_{\ell^+\ell^-}} + \sum_{i\in\{q,g,\gamma\}} |p_{\mathrm{T,i}}|\right)$$

this is a 'good' scale for V+jets

- at large pTV: HT'/2 ≈ pTV
- modest higher-order corrections
- sufficient convergence

scale uncertainties due to 7-pt variations

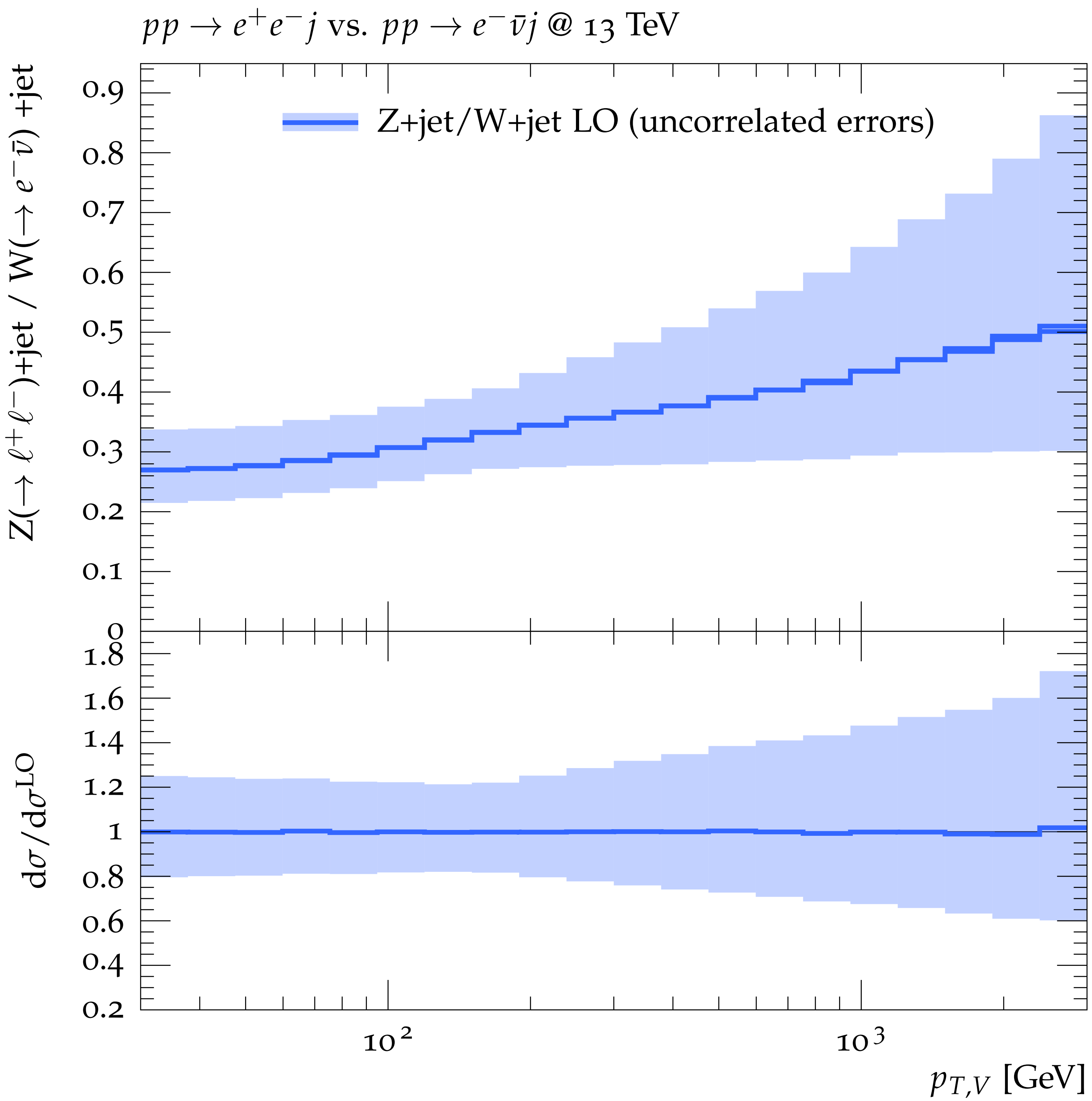
$$\mu_{\mathrm{R,F}} = \xi_{\mathrm{R,F}}\mu_0$$

$$(\xi_{\mathrm{R}}, \xi_{\mathrm{F}}) = (2,2),\ (2,1),\ (1,2),\ (1,1),\ (1,0.5),\ (0.5,1), (0.5,0.5)$$

yields

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

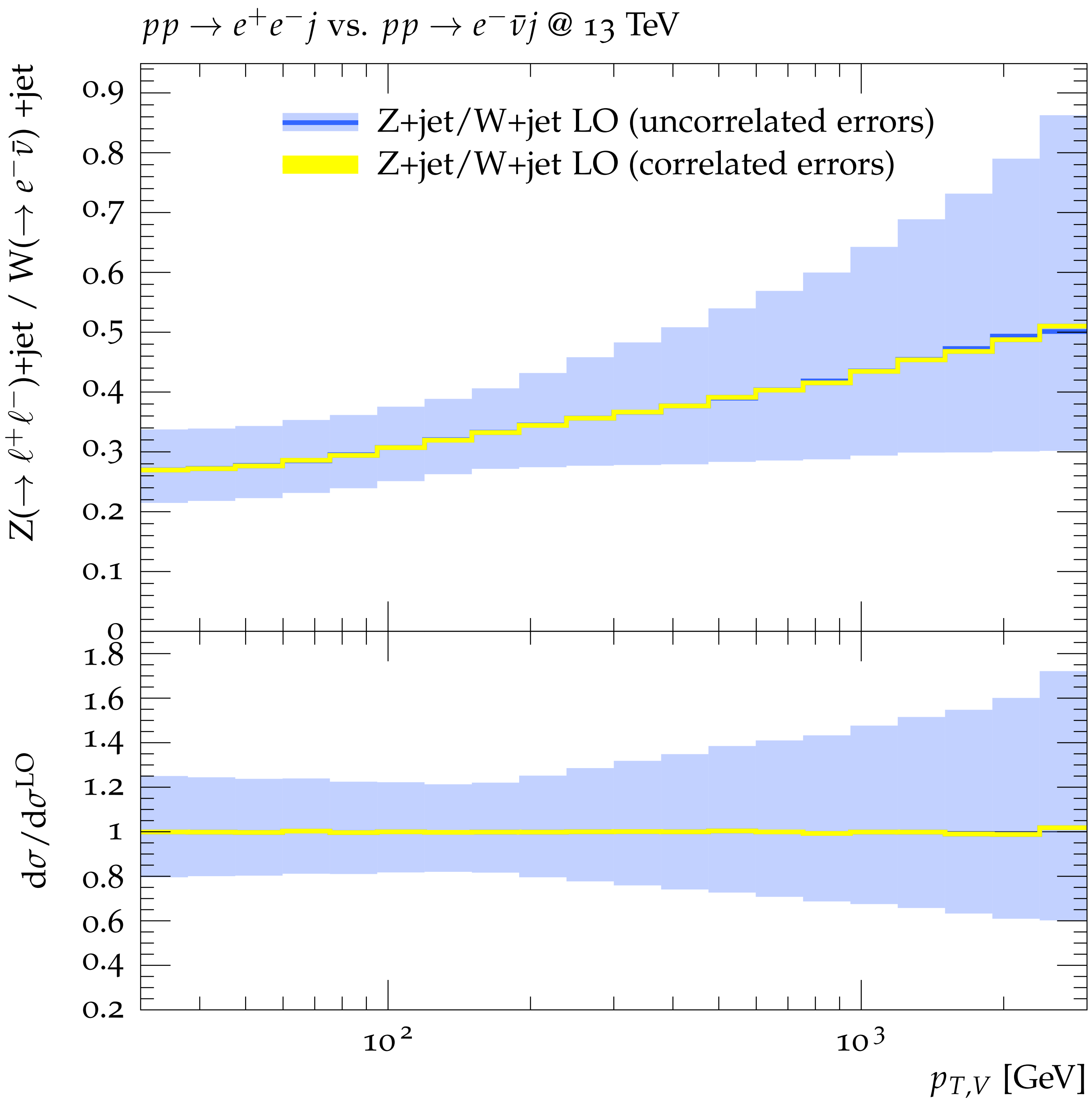
Correlation of scale variations



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

uncorrelated treatment yields
O(40%) uncertainties

Correlation of scale variations



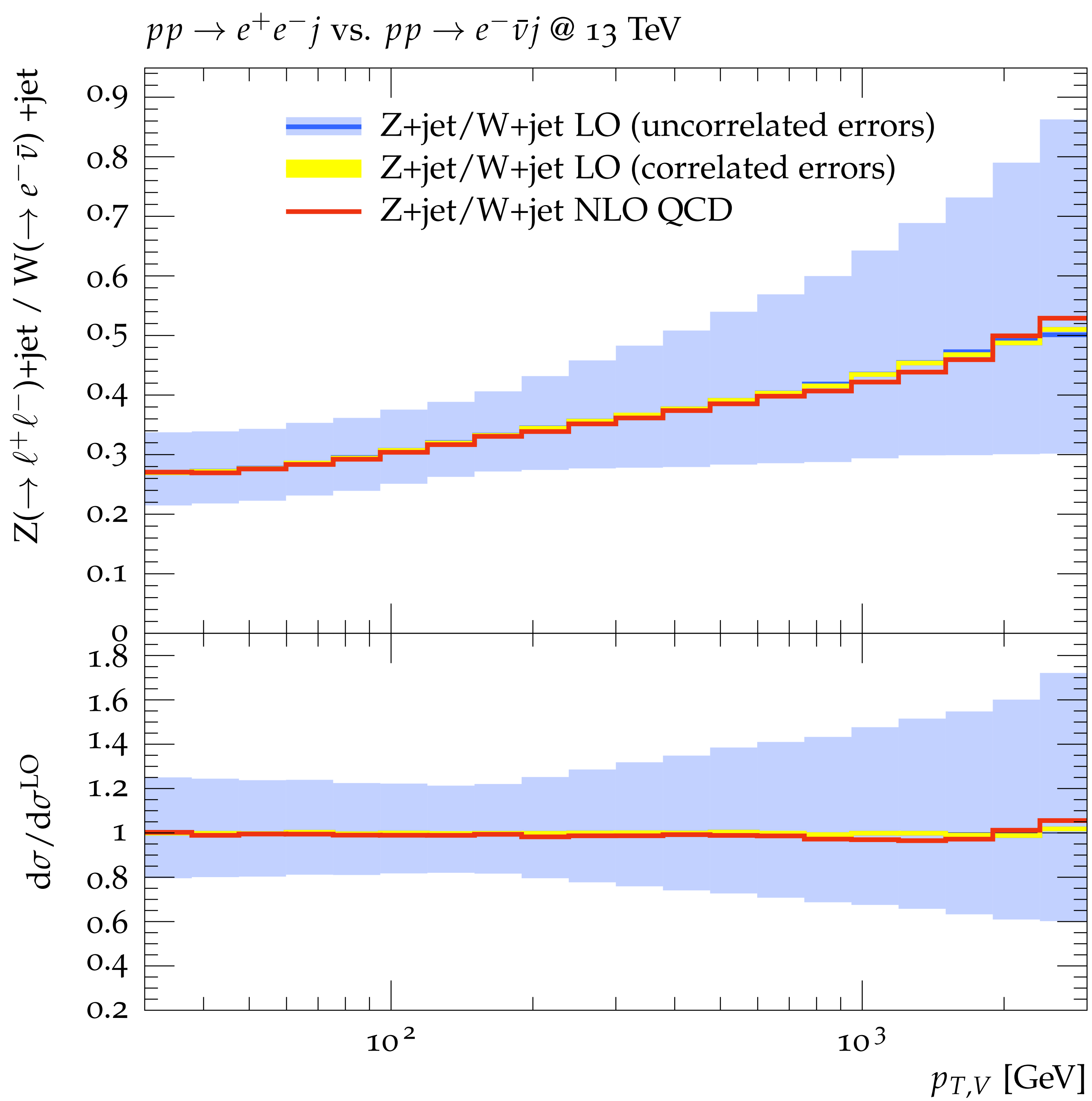
consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

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

check against NLO QCD!

Correlation of scale variations



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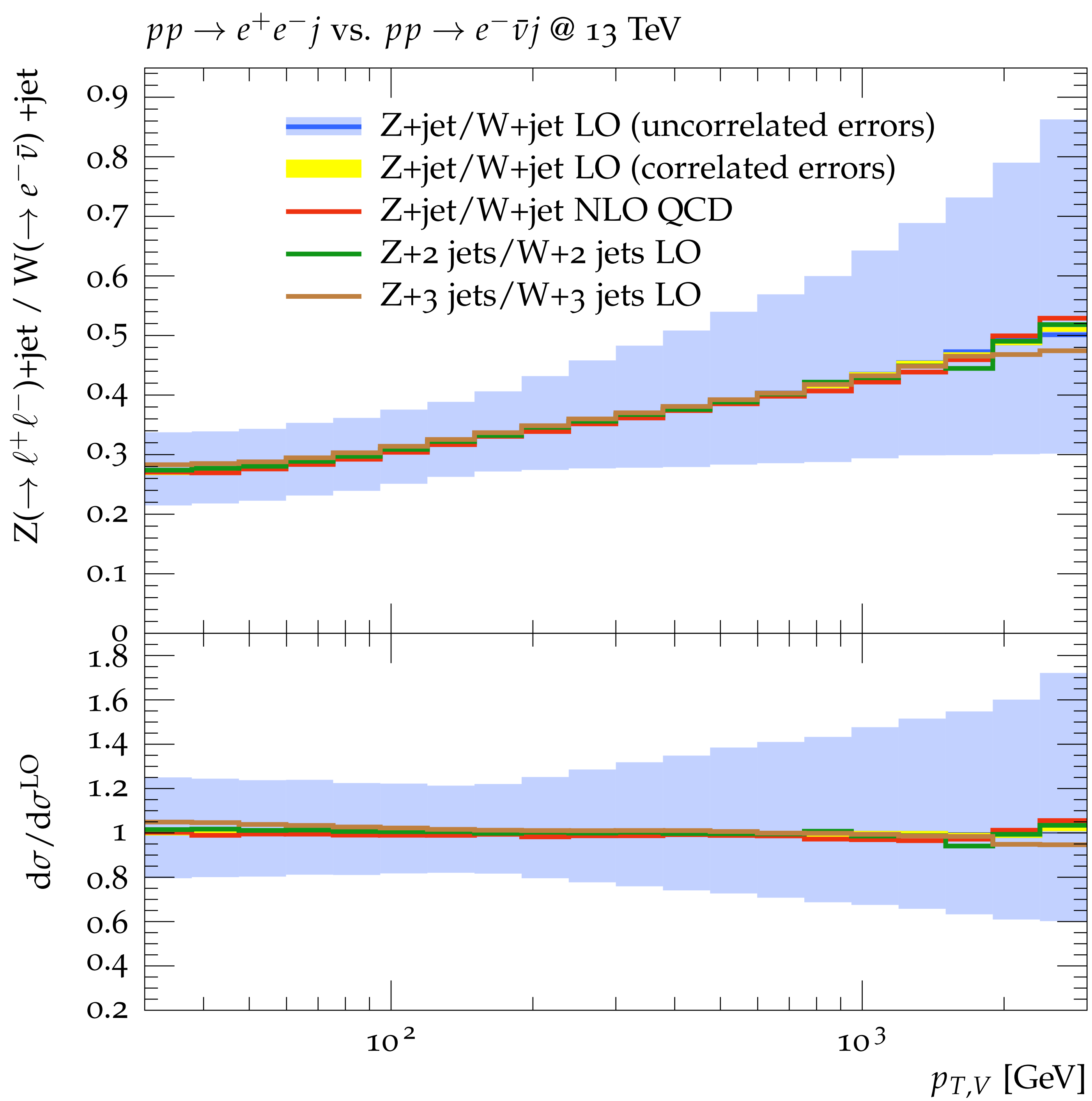
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

Correlation of scale variations



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uncorrelated treatment yields O(40%) uncertainties

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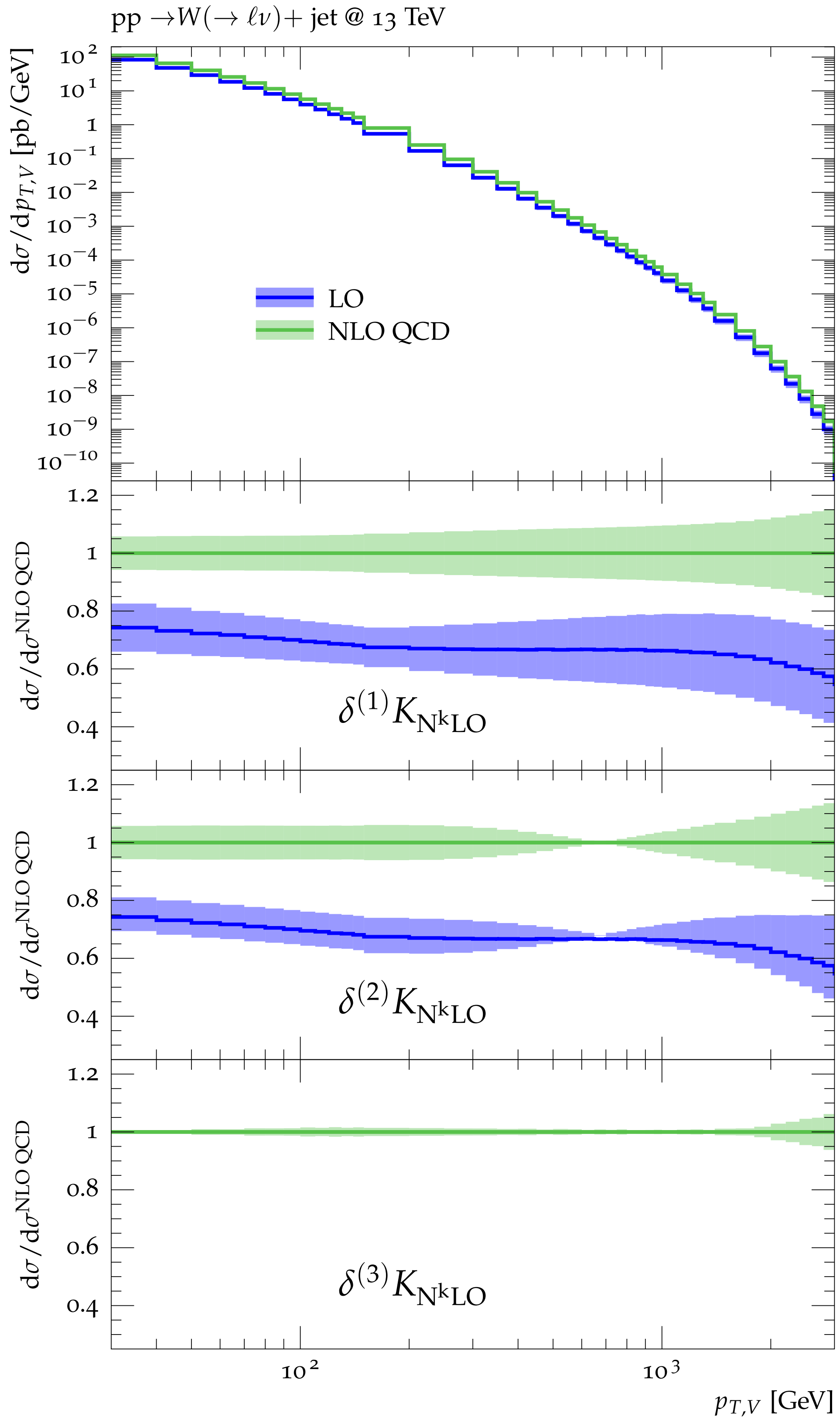
check against NLO QCD!

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

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

QCD uncertainties



$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{N}^k\mathrm{LO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}) = \left[K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) + \sum_{i=1}^{3}\varepsilon_{\mathrm{QCD},i}\,\delta^{(i)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)\right] \times \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0).$$

nuisance parameters:
interpreted as 1σ Gaussian

$$\epsilon^{(Z)}_{\mathrm{QCD,i}} = \epsilon^{(W^\pm)}_{\mathrm{QCD,i}} = \epsilon^{(\gamma)}_{\mathrm{QCD,i}} = \epsilon_{\mathrm{QCD,i}}$$

- fully correlated across processes
- correlated across pT bins

- $\delta^{(1)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \frac{1}{2}\left[K^{(V,\max)}_{\mathrm{N}^k\mathrm{LO}}(x) - K^{(V,\min)}_{\mathrm{N}^k\mathrm{LO}}(x)\right]$

- $\delta^{(2)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \omega_{\mathrm{shape}}(x)\,\delta^{(1)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)$

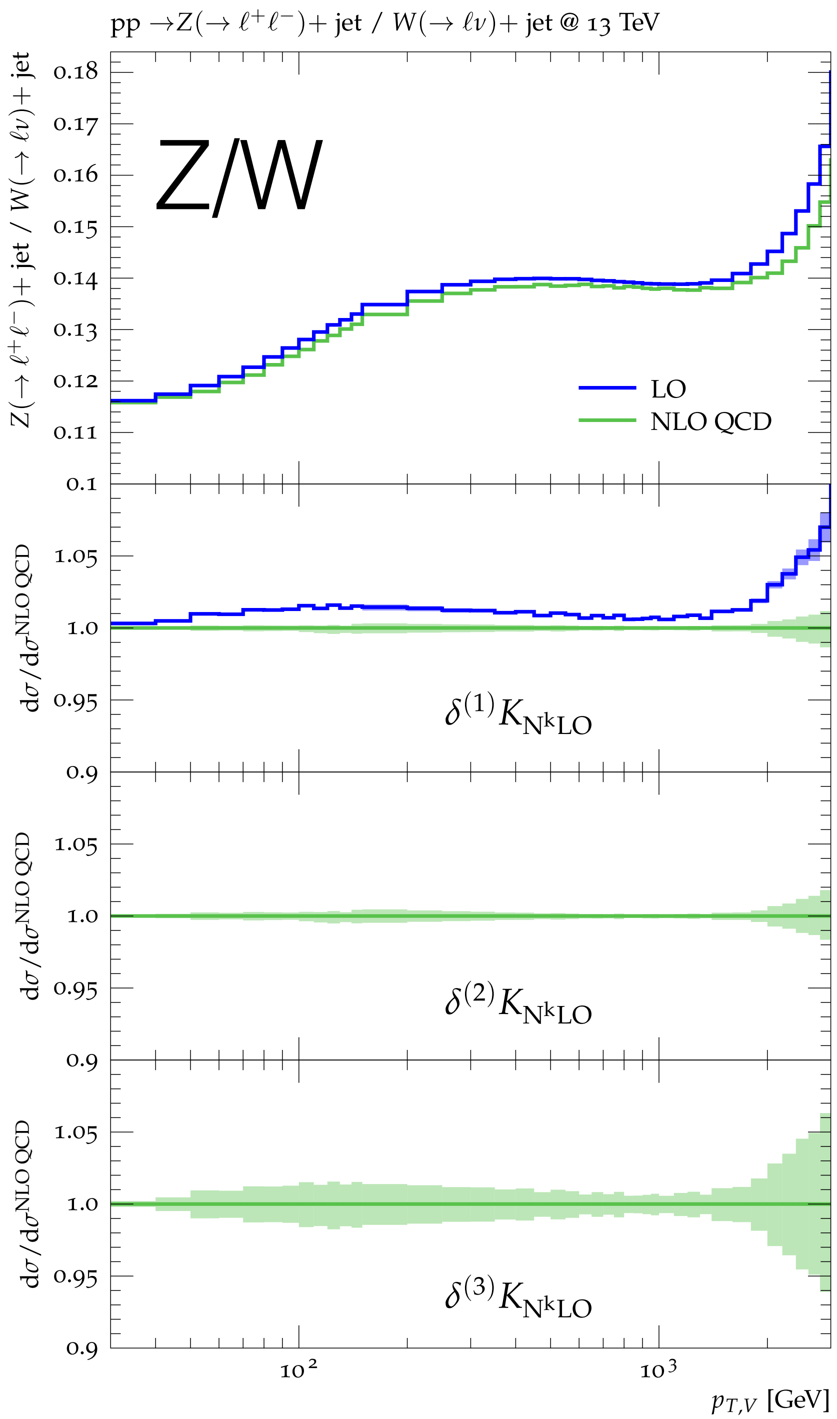
  with $\omega_{\mathrm{shape}}(x) = \frac{p_{\mathrm{T}}^2 - p_{\mathrm{T},0}^2}{p_{\mathrm{T}}^2 + p_{\mathrm{T},0}^2}$

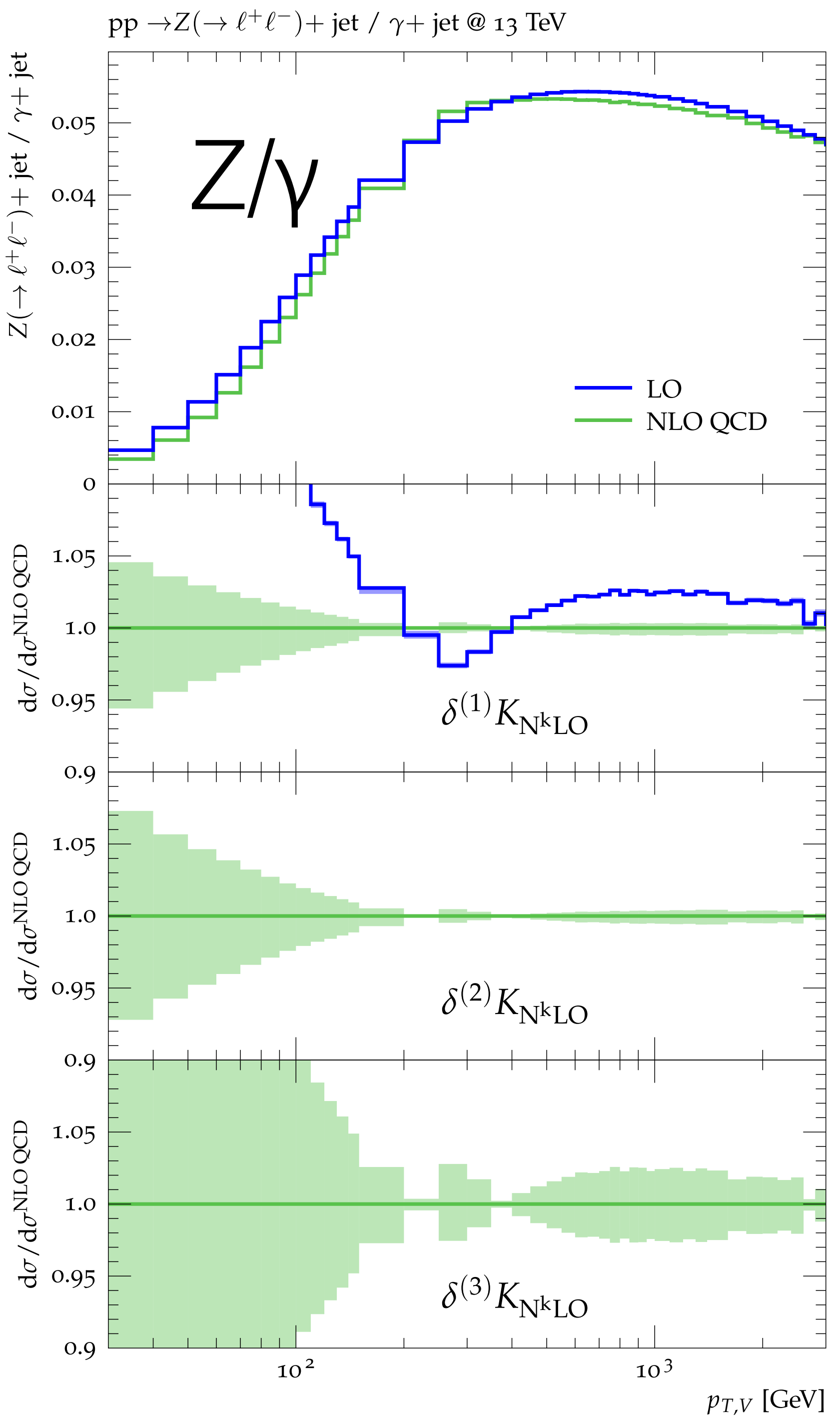
- $\delta^{(3)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \Delta K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) - \Delta K^{(Z)}_{\mathrm{N}^k\mathrm{LO}}(x)$

  $\Delta K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)/K^{(V)}_{\mathrm{N}^{k-1}\mathrm{LO}}(x) - 1$

this modelling of process correlations assumes a close similarity of QCD effects between different V+jets processes

QCD uncertainties in pT-ratios



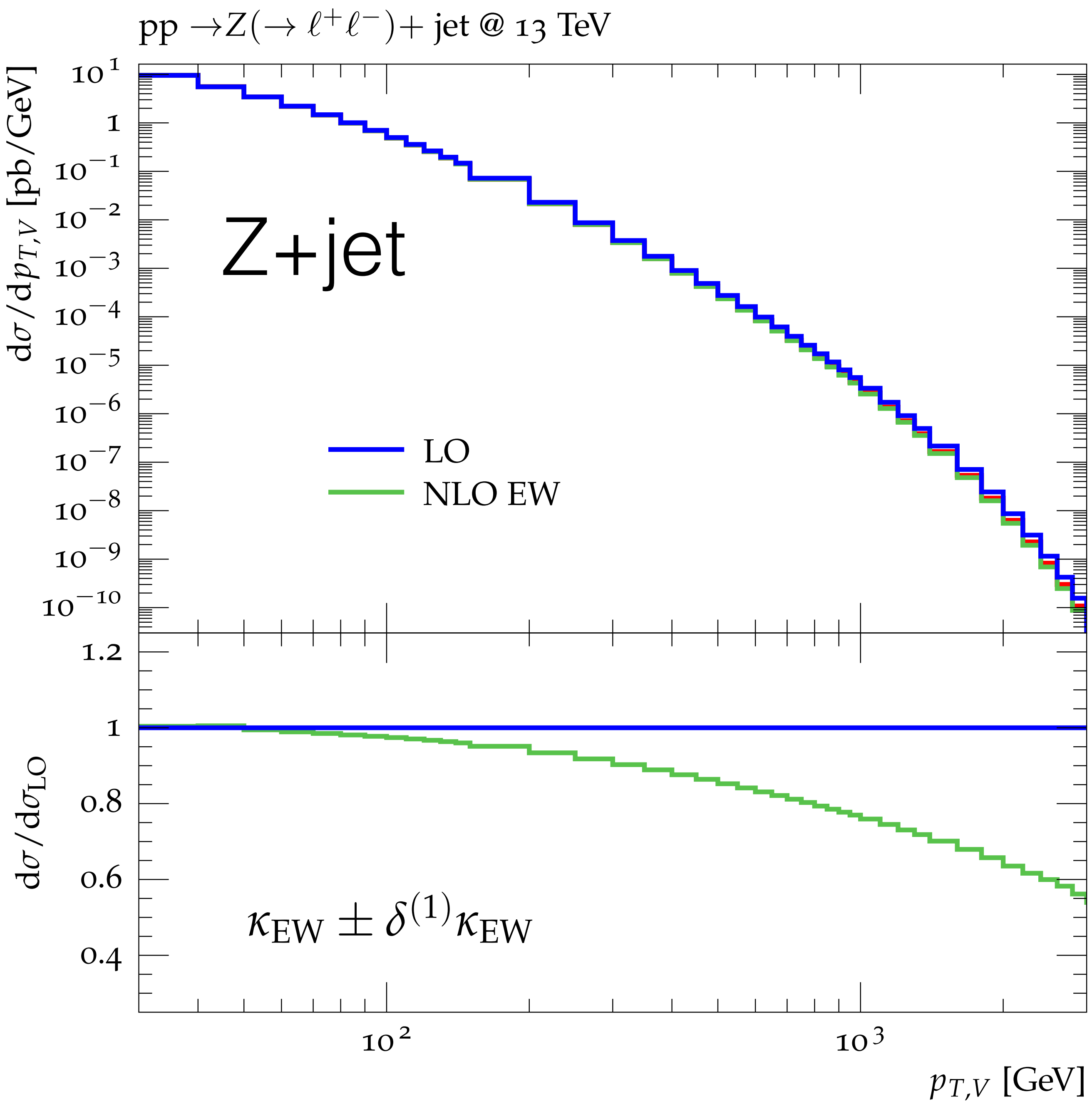


this modelling of process correlations assumes a close similarity of QCD effects between all V+jets processes

- apart from PDF effects it is the case for W+jets vs. Z+jets
- at large pT is is also the case for **γ**+jets vs. Z+jets. In particular with dynamical cone $R_{\rm dyn}(E_{{\rm T},\gamma},\varepsilon_0) = \frac{M_Z}{E_{{\rm T},\gamma}\sqrt{\varepsilon_0}}$

EW effects

Pure EW uncertainties



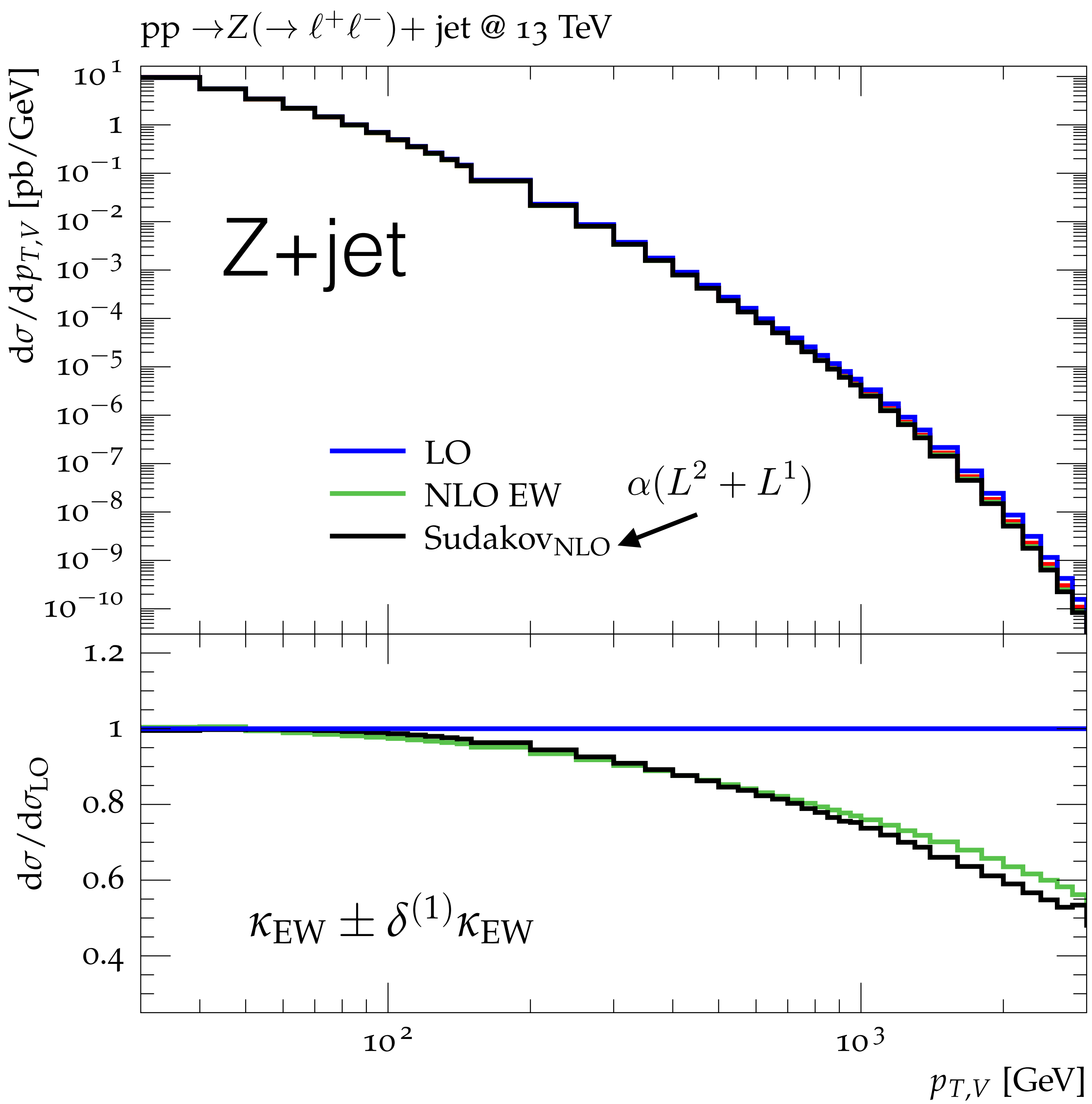
EW corrections become sizeable at large $p_{T,V}$

Origin: virtual EW Sudakov logarithms

Note: real EW Sudakov logarithms included as separate VV(+jets) backgrounds

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

Pure EW uncertainties



$$\kappa_{\mathrm{NLO\,EW}}(\hat{s},\hat{t}) \quad = \quad \frac{\alpha}{\pi}\left[\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{Sud}}\right]$$

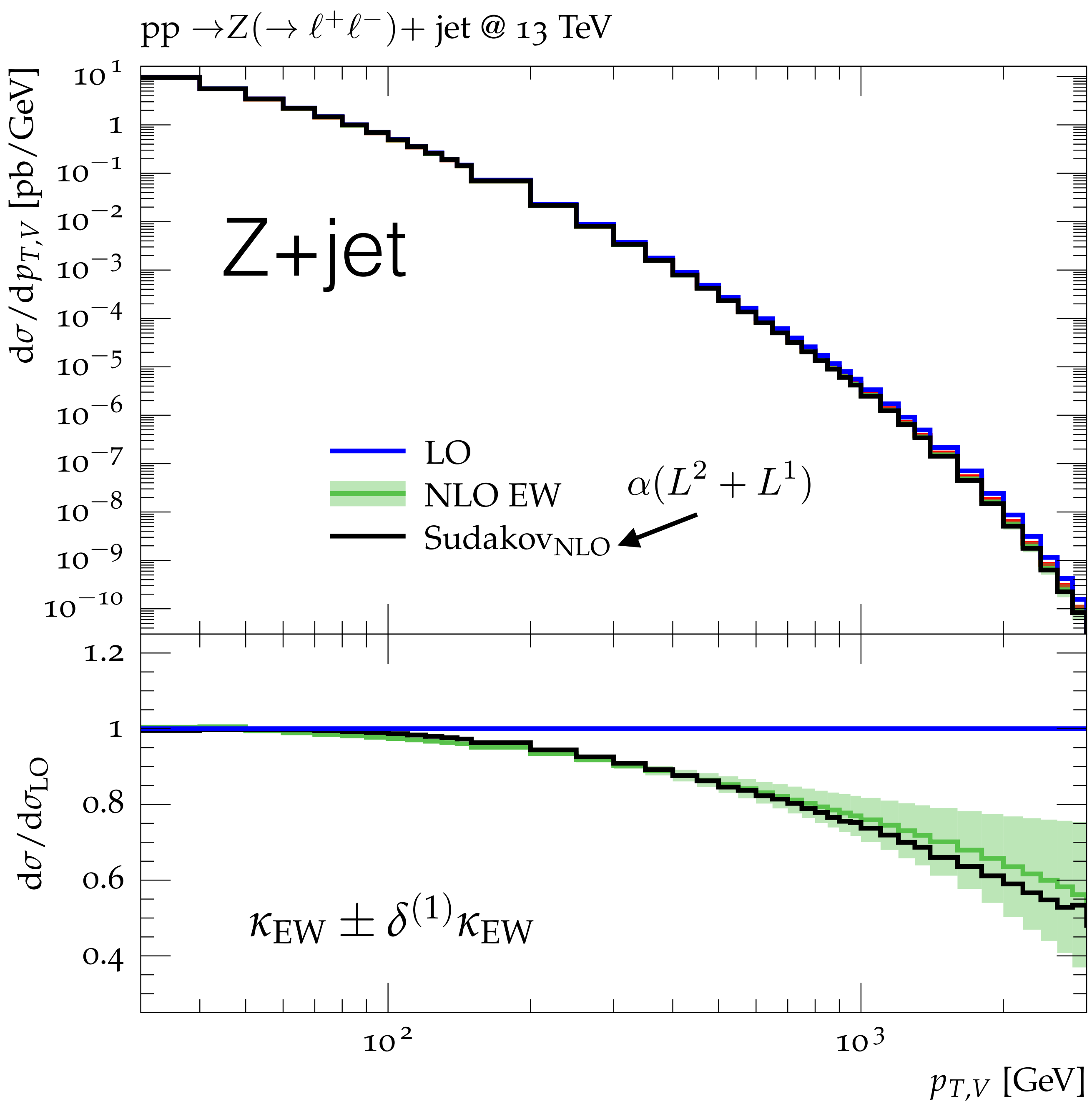
Large EW corrections dominated by Sudakov logs

↓

Uncertainty estimate of NLO EW from naive exponentiation × 2:

$$\delta^{(1)}\kappa^{(V)}_{\mathrm{EW}}(x) \quad = \quad \delta\kappa^{(V)}_{\mathrm{NLO\,EW}}(x) = \frac{2}{2}\left[\kappa^{(V)}_{\mathrm{NLO\,EW}}(x)\right]^2$$

Pure EW uncertainties



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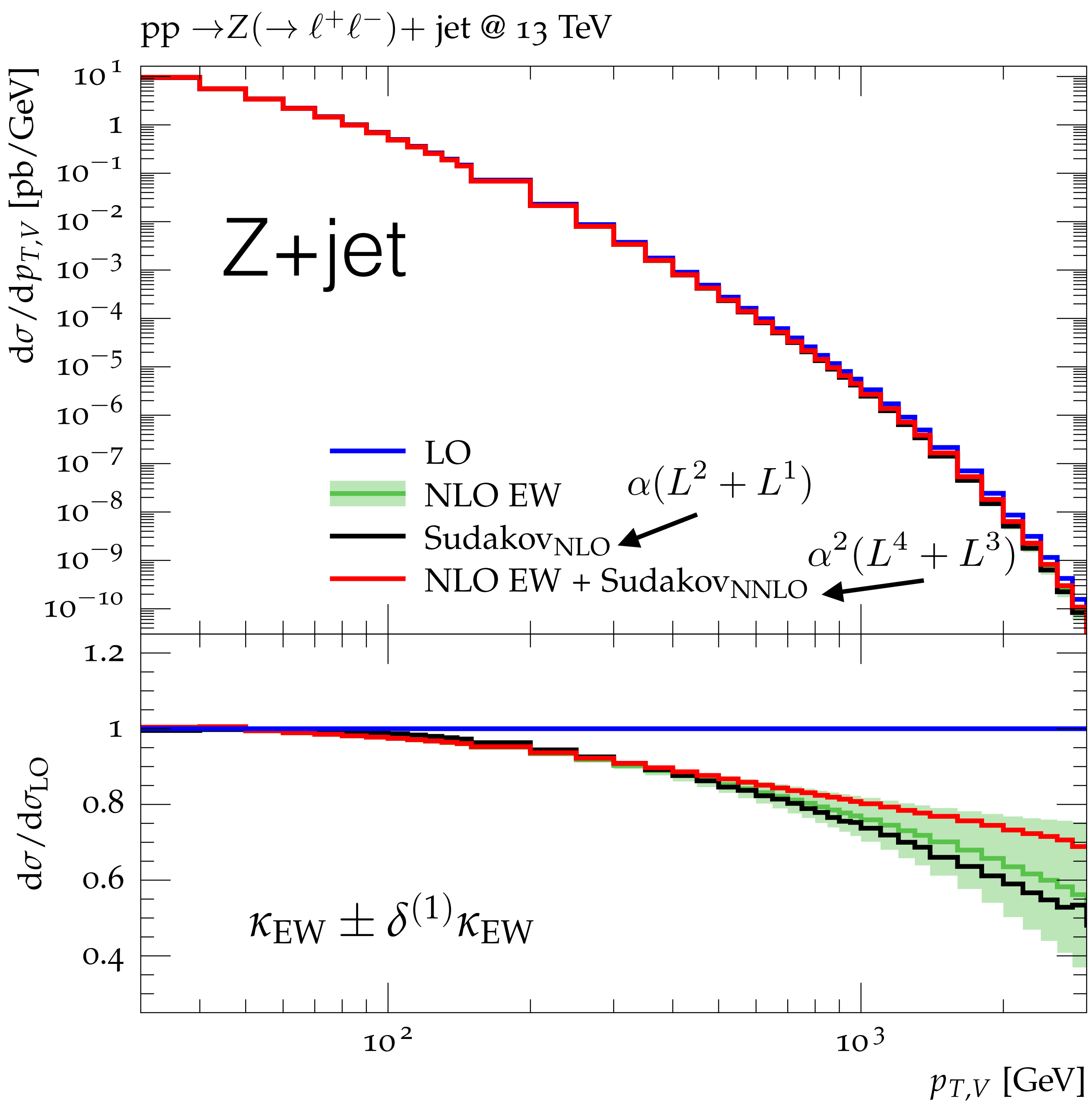
Pure EW uncertainties



$$\kappa_{\text{NLO EW}}(\hat{s},\hat{t}) = \frac{\alpha}{\pi}\left[\delta^{(1)}_{\text{hard}} + \delta^{(1)}_{\text{Sud}}\right]$$

$$\kappa_{\text{NNLO Sud}}(\hat{s},\hat{t}) = \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\text{Sud}}$$

Large EW corrections dominated by Sudakov logs

↓

Uncertainty estimate of NLO EW from naive exponentiation × 2:

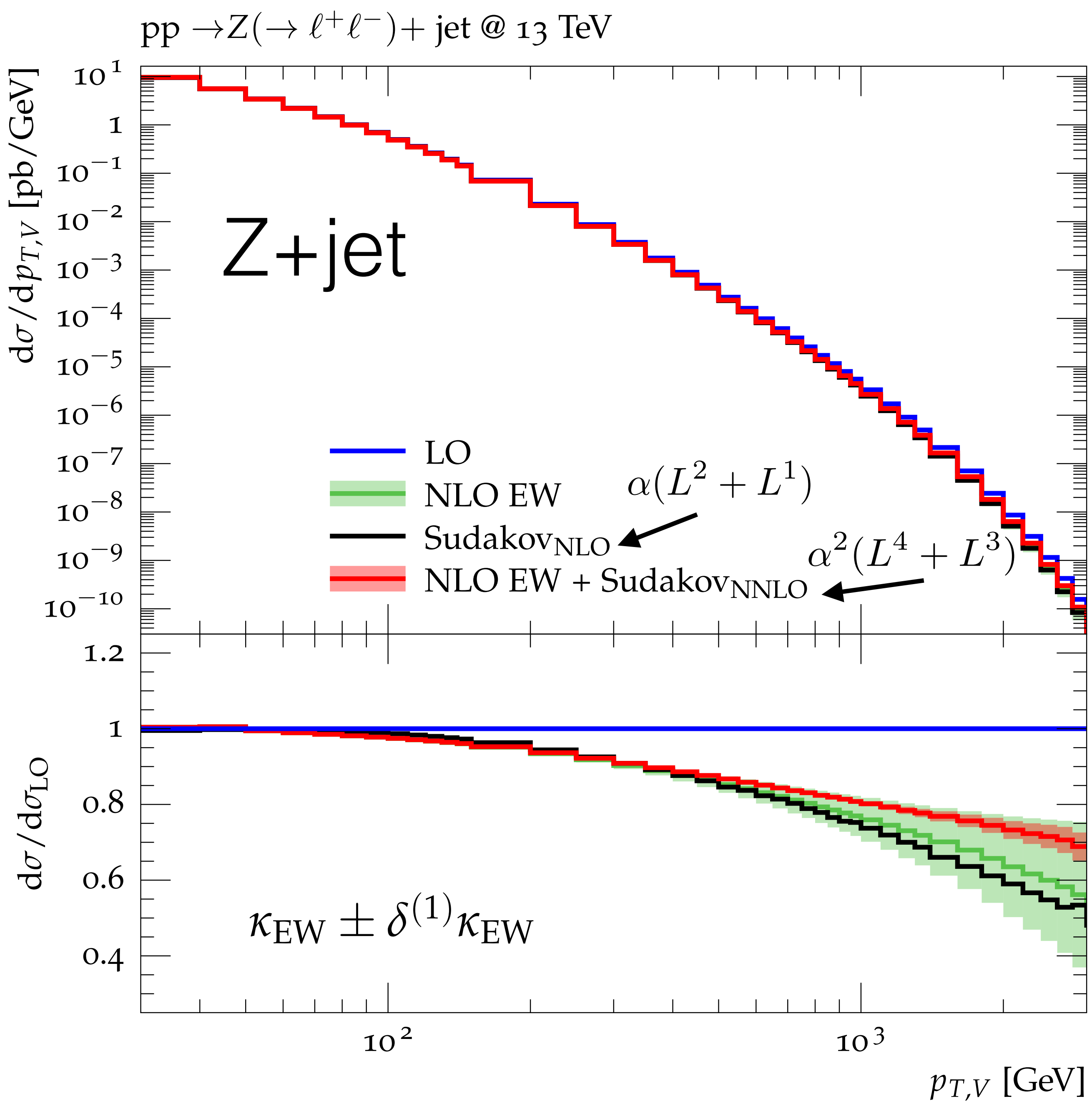
$$\delta^{(1)}\kappa^{(V)}_{\text{EW}}(x) = \delta\kappa^{(V)}_{\text{NLO EW}}(x) = \frac{2}{2}\left[\kappa^{(V)}_{\text{NLO EW}}(x)\right]^2$$

↓

check against two-loop Sudakov logs

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

Pure EW uncertainties



$$\kappa_{\rm NLO\,EW}(\hat{s},\hat{t}) = \frac{\alpha}{\pi}\left[\delta^{(1)}_{\rm hard} + \delta^{(1)}_{\rm Sud}\right]$$

$$\kappa_{\rm NNLO\,Sud}(\hat{s},\hat{t}) = \left(\frac{\alpha}{\pi}\right)^2 \delta^{(2)}_{\rm Sud}$$

Large EW corrections dominated by Sudakov logs

↓

Uncertainty estimate of NLO EW from naive exponentiation x 2:

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↓

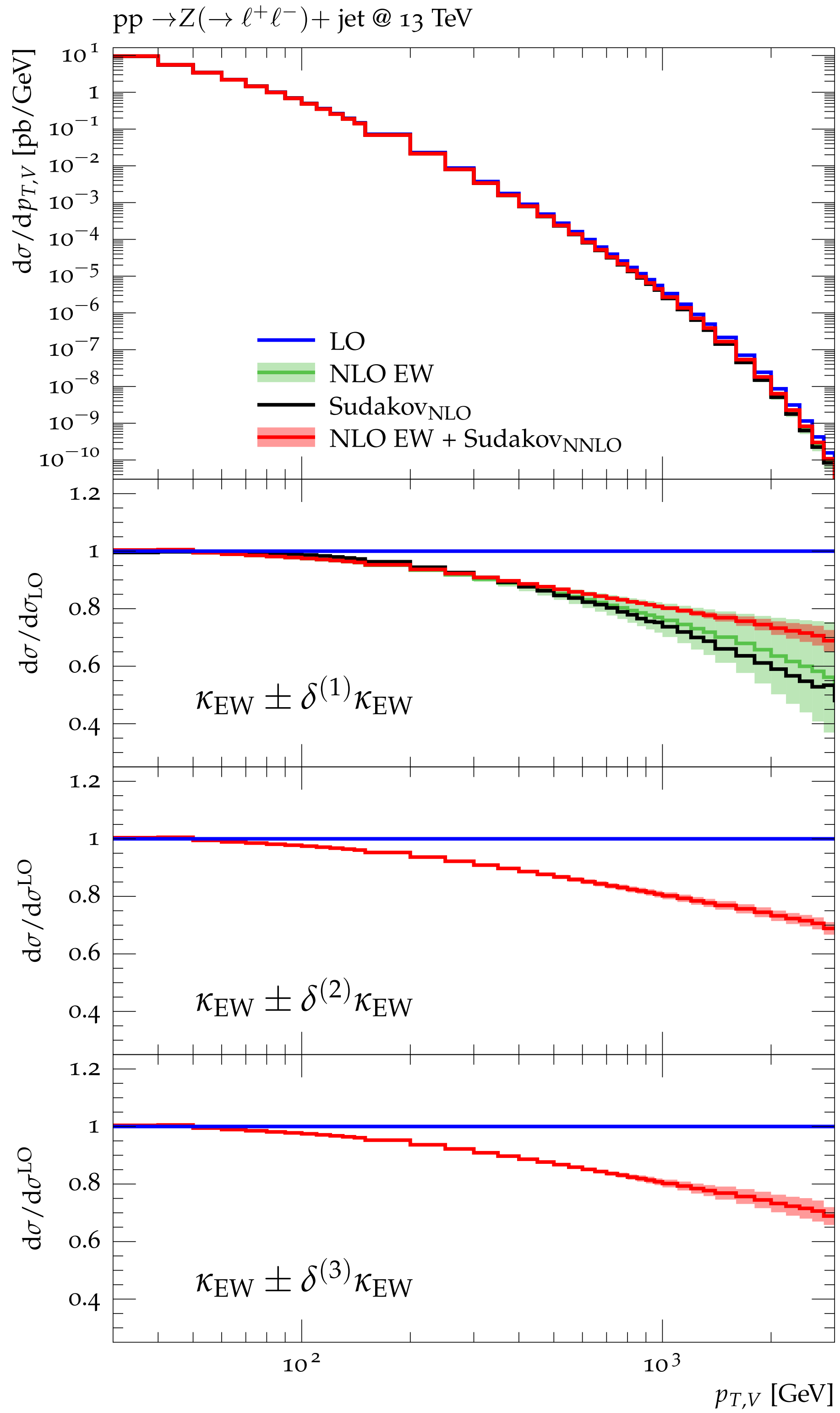
check against two-loop Sudakov logs
[Kühn, Kulesza, Pozzorini, Schulze; 05-07]

↓

Uncertainty estimate of NNLO EW:

$$\delta^{(1)}\kappa^{(V)}_{\rm EW}(x) = \frac{2}{3}\kappa^{(V)}_{\rm NLO\,EW}(x)\,\kappa^{(V)}_{\rm NNLO\,Sud}(x)$$

Pure EW uncertainties



- 'higher-order logs'

(correlated)

$$\delta^{(1)}\kappa_{\mathrm{EW}}^{(V)}(x) \quad =: \frac{2}{3}\kappa_{\mathrm{NLO\,EW}}^{(V)}(x)\,\kappa_{\mathrm{NNLO\,Sud}}^{(V)}(x)$$

Additional uncorrelated uncertainties:

- 'hard non-log NNLO effects I'

$$\delta^{(2)}\kappa_{\mathrm{EW}}^{(V)}(x) = 0.05\,\kappa_{\mathrm{NLO\,EW}}^{(V)}(x)$$

(uncorrelated)

$$\Leftrightarrow \quad \delta_{\mathrm{hard}}^{(2)} \leq \frac{0.05\pi}{\alpha}\delta_{\mathrm{hard}}^{(1)} \simeq 20\,\delta_{\mathrm{hard}}^{(1)}$$

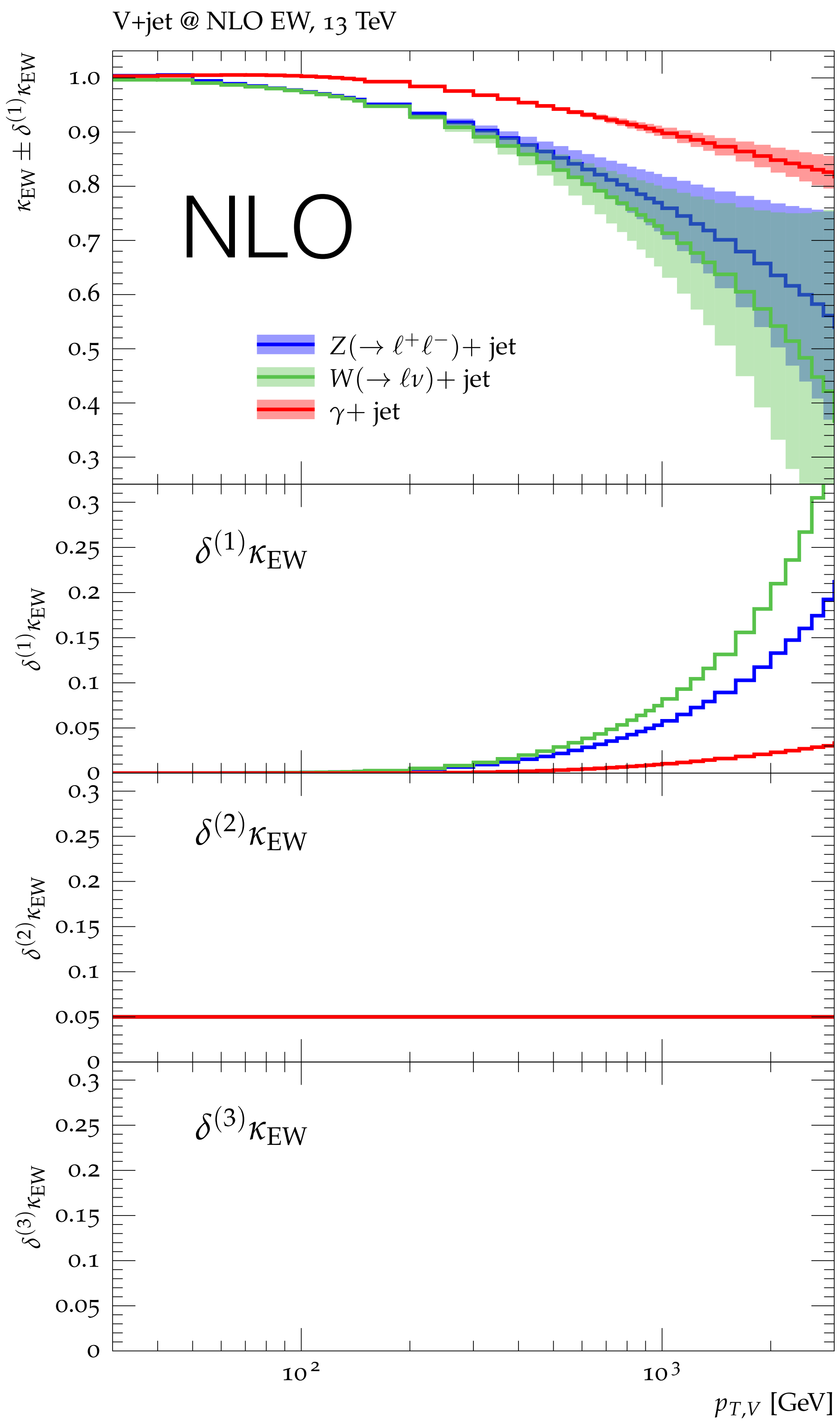
- 'hard non-log NNLO effects II'

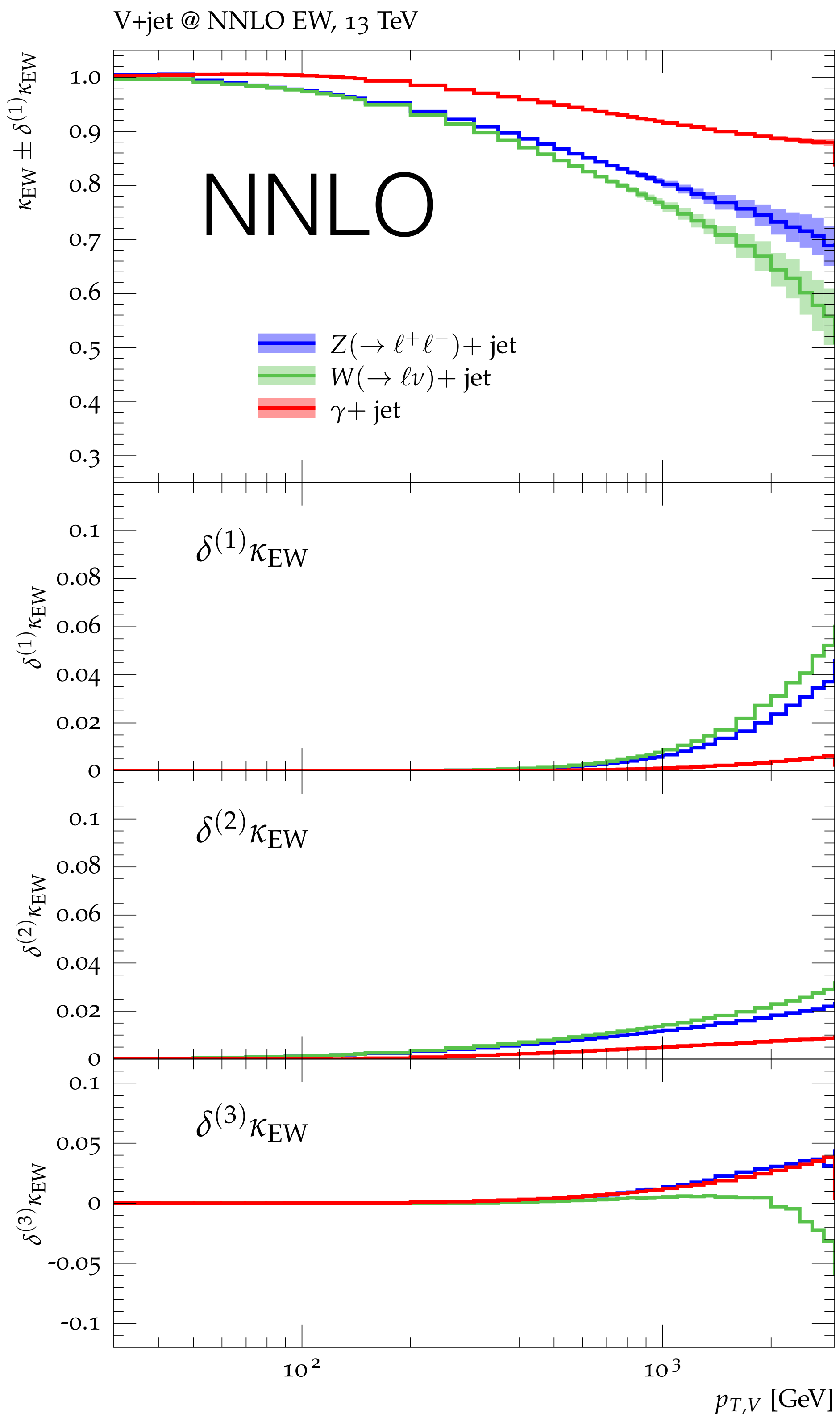
(uncorrelated)

$$\delta^{(3)}\kappa_{\mathrm{EW}}^{(V)}(x) \quad = \quad \kappa_{\mathrm{NNLO\,Sud}}^{(V)}(x) - \frac{1}{2}[\kappa_{\mathrm{NLO\,EW}}^{(V)}(x)]^2$$

estimate of typical size of $\left[\delta_{\mathrm{hard}}^{(1)}\right]^2$ or $\delta_{\mathrm{hard}}^{(1)} \times \delta_{\mathrm{Sud}}^{(1)}$.

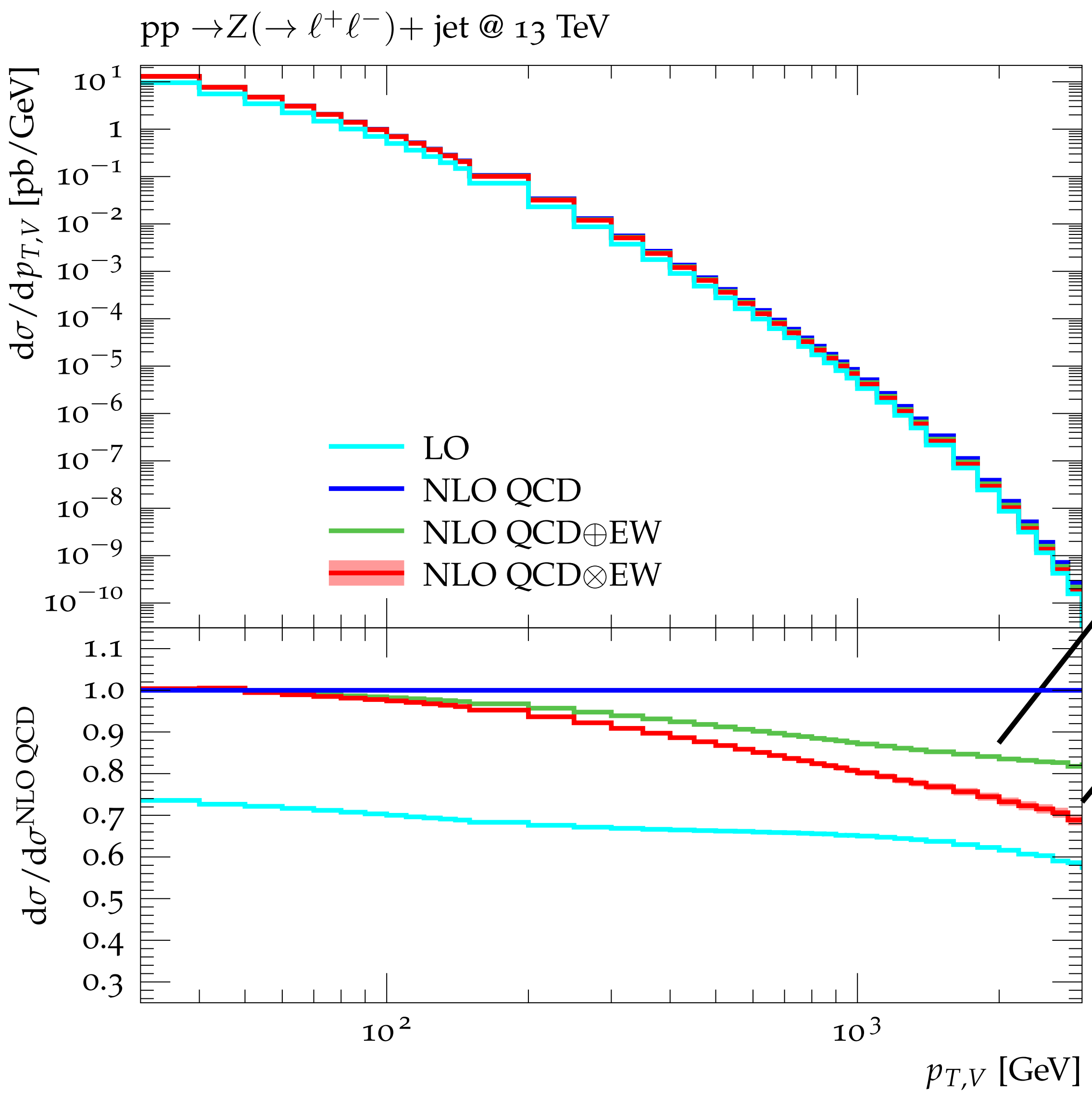
Pure EW uncertainties





mixed QCD-EW effects

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.

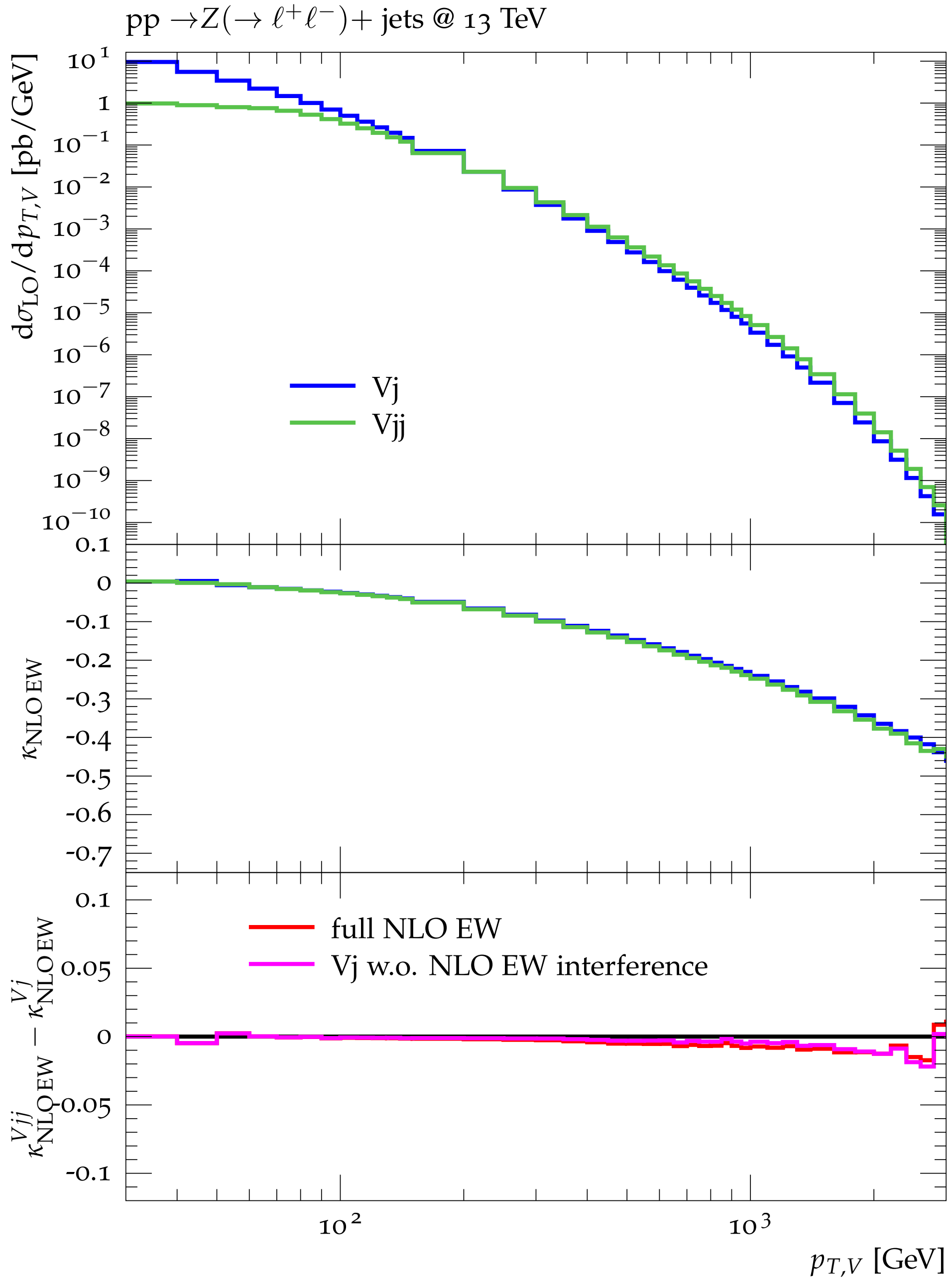
$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}} = \sigma^{\mathrm{LO}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{QCD}} + \delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$$

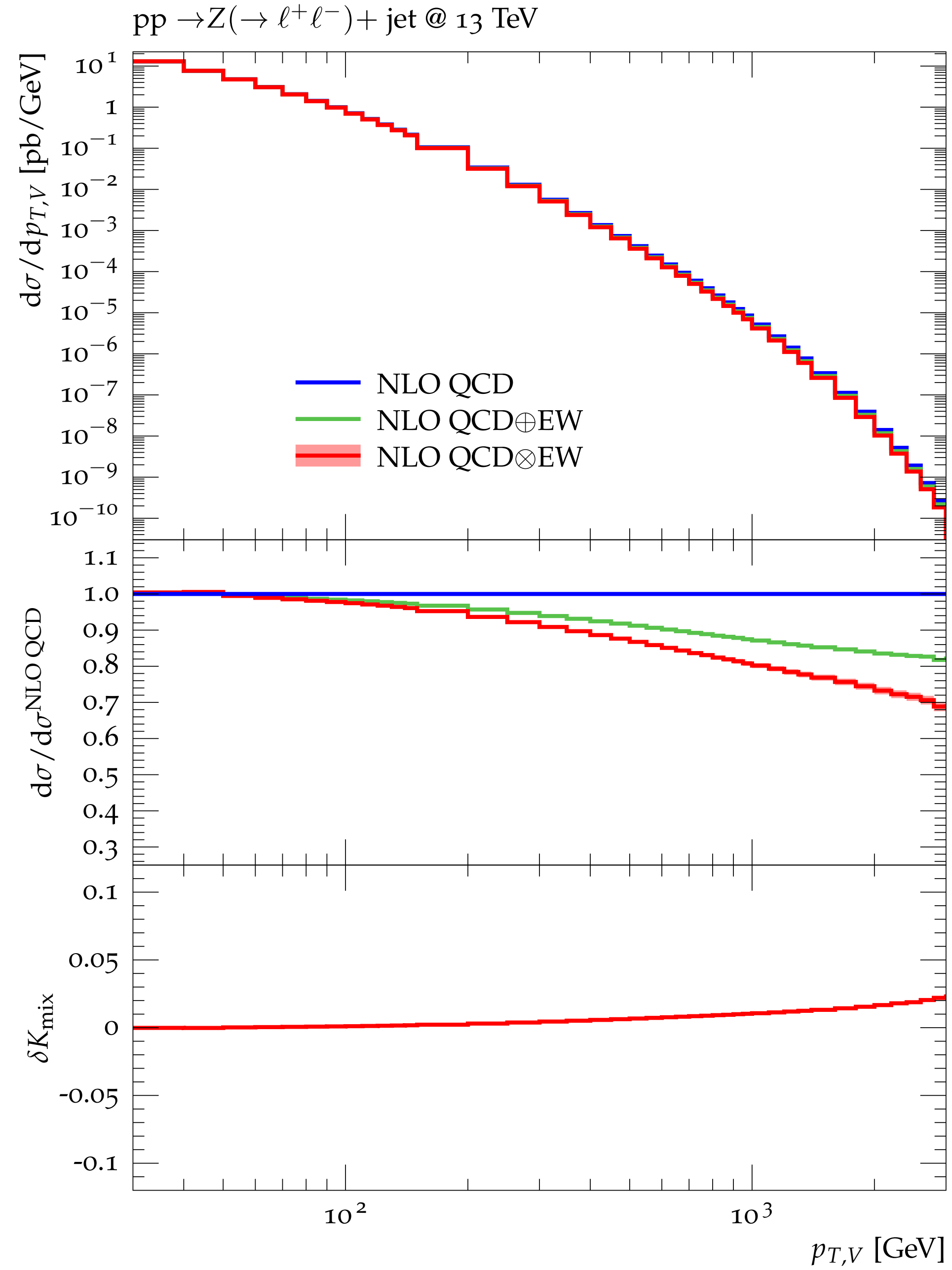
$$\sigma^{\mathrm{NLO}}_{\mathrm{QCD\times EW}} = \sigma^{\mathrm{NLO}}_{\mathrm{QCD}} \left(1 + \frac{\delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{LO}}}\right)$$

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

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

Mixed QCD-EW uncertainties





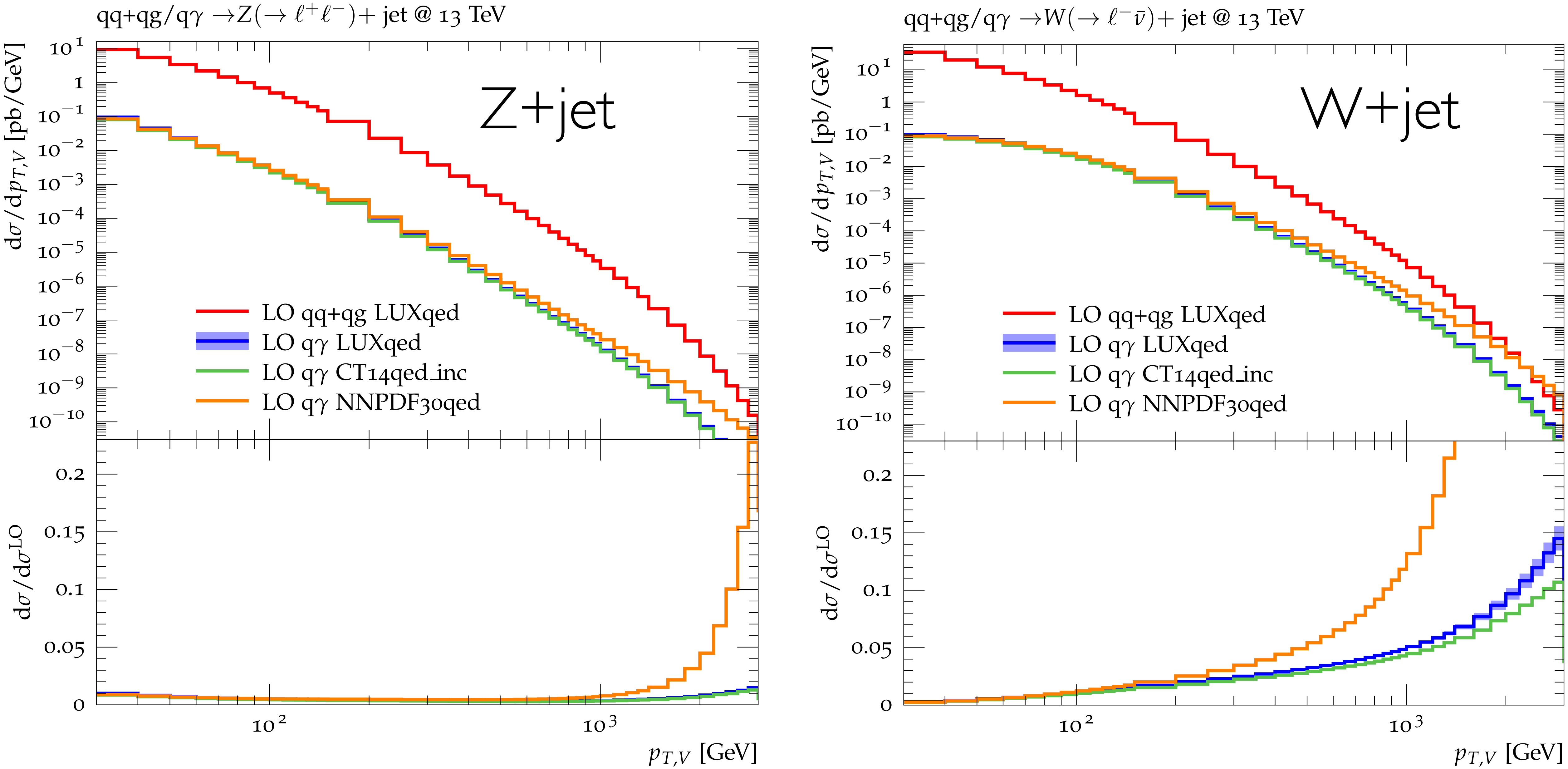
- V+j and V+2j NLO EW corrections (almost) identical
- supports factorization

$$\delta K^{(V)}_{\mathrm{mix}}(x) \;=\; 0.1\left[K^{(V)}_{\mathrm{TH},\oplus}(x,\vec{\mu}_0) - K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\mu}_0)\right]$$

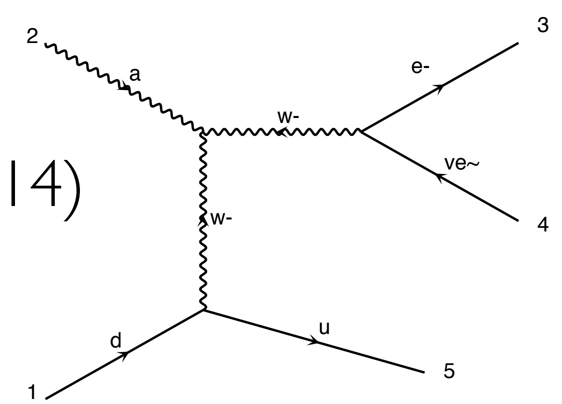
(correlated)

Other issues

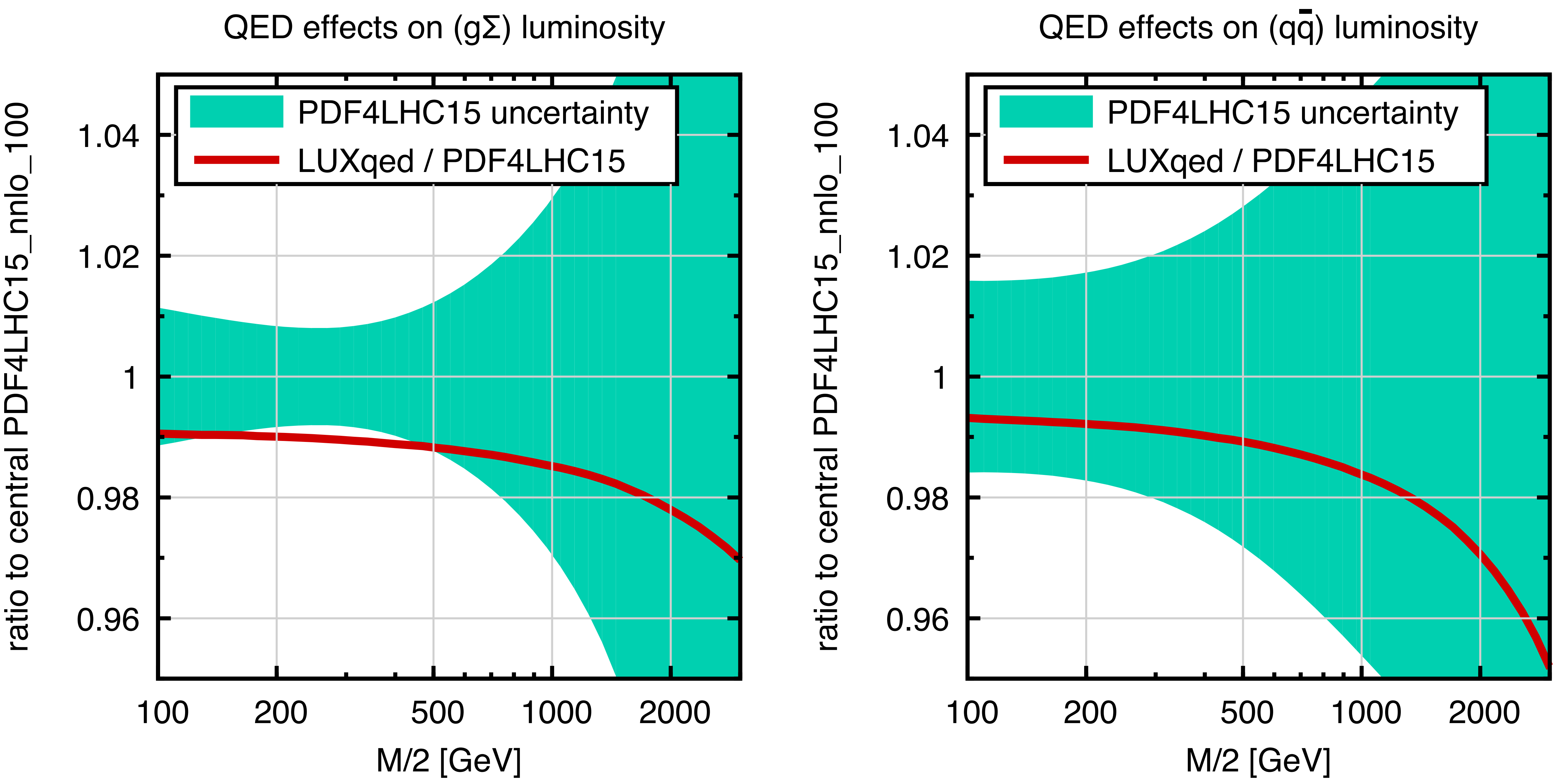
Photon-induced production



- photon-induced production irrelevant for Z+jet (and **γ**+jet)
- in W+jet O(5%) contribution with LUXqed (consistent with CT14) (due to t-channel enhancement)
- ~1% uncertainties in photon PDFs due to LUXqed



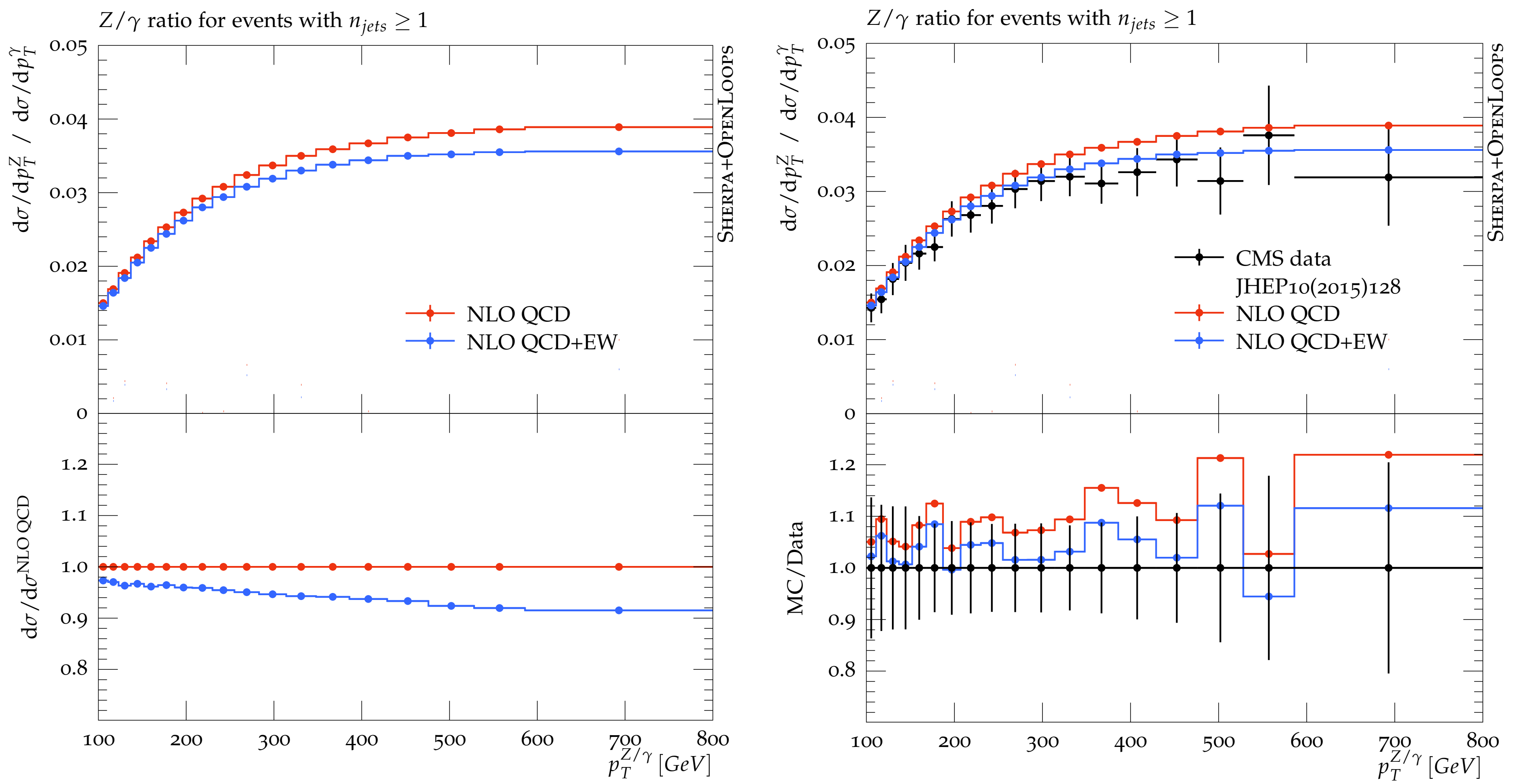
QED corrections to quark PDFs



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

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
- Perturbative systematics in pTV under control at the level of 1-10% up to the TeV
- Outlook: investigate/interpret post-fit nominal predictions and ratios



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

- remarkable agreement of Z/γ ratio with data at @ NLO QCD+EW!

Illuminating standard candles at the LHC - V+jets

25-26 April 2017
Imperial College London
Europe/London timezone

Search...

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- Timetable
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This informal, brainstorming workshop held in conjunction with the IPPP (Institute for Particle Physics Phenomenology at Durham) will focus on the Standard Model measurements of vector boson + jets processes that we can perform in Run 2 of the LHC to enhance our understanding of the high transverse momentum phase space and constrain higher order QCD and electroweak corrections.

Starts 25 Apr 2017 10:00
Ends 26 Apr 2017 14:00
Europe/London

Imperial College London
Blackett building, room 539
https://workspace.imperial.ac.uk/campusinfo/p

Sarah Malik
Bjoern Penning
Jonas Lindert

Materials

There are no materials yet.

Info on booking accommodation around the South Kensington area:
http://www.imperial.ac.uk/visitors-accommodation/local-hotels/

How to get to the South Kensington Campus: https://www.imperial.ac.uk/visit/campuses/south-kensington/

Registration
You have registered for this event.

See details >

https://indico.cern.ch/event/624982

BACKUP

Putting everything together

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}}(\vec{\mu}) \quad = \quad K^{(V)}_{\mathrm{TH}}(x,\vec{\mu})\,\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0) + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\gamma-\mathrm{ind.}}(x,\vec{\mu})$$

$$\begin{aligned}
&K^{(V)}_{\mathrm{TH}}(x,\vec{\varepsilon}_{\mathrm{QCD}},\vec{\varepsilon}_{\mathrm{EW}},\varepsilon_{\mathrm{mix}}) = K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\varepsilon}_{\mathrm{QCD}},\vec{\varepsilon}_{\mathrm{EW}}) + \varepsilon_{\mathrm{mix}}\,\delta K^{(V)}_{\mathrm{mix}}(x),\\
&= \left[K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) + \sum_{i=1}^{3}\varepsilon_{\mathrm{QCD},i}\,\delta^{(i)}K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)\right]\\
&\;\times\left[1+\kappa^{(V)}_{\mathrm{EW}}(x) + \sum_{i=1}^{3}\varepsilon^{(V)}_{\mathrm{EW},i}\,\delta^{(i)}\kappa^{(V)}_{\mathrm{EW}}(x)\right] + \varepsilon_{\mathrm{mix}}\,\delta K^{(V)}_{\mathrm{mix}}(x),
\end{aligned}$$

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

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

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

Correlation of scale variations: prescription

$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{N}^k\mathrm{LO\,QCD}}(\vec{\varepsilon}_{\mathrm{QCD}}) = \left[K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) + \sum_{i=1}^{3} \varepsilon_{\mathrm{QCD},i}\,\delta^{(i)} K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)\right] \times \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}}(\vec{\mu}_0).$$

nuisance parameters

$$K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \frac{1}{2}\left[K^{(V,\max)}_{\mathrm{N}^k\mathrm{LO}}(x) + K^{(V,\min)}_{\mathrm{N}^k\mathrm{LO}}(x)\right]$$

$$\delta^{(1)} K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \frac{1}{2}\left[K^{(V,\max)}_{\mathrm{N}^k\mathrm{LO}}(x) - K^{(V,\min)}_{\mathrm{N}^k\mathrm{LO}}(x)\right]$$

$$\epsilon^{(Z)}_{\mathrm{QCD},1} = \epsilon^{(W^\pm)}_{\mathrm{QCD},1} = \epsilon^{(\gamma)}_{\mathrm{QCD},1} = \epsilon_{\mathrm{QCD},1}$$

- fully correlated across processes
- correlated across pT bins

- include additional uncertainty based on differences in QCD corrections of the last calculated order:

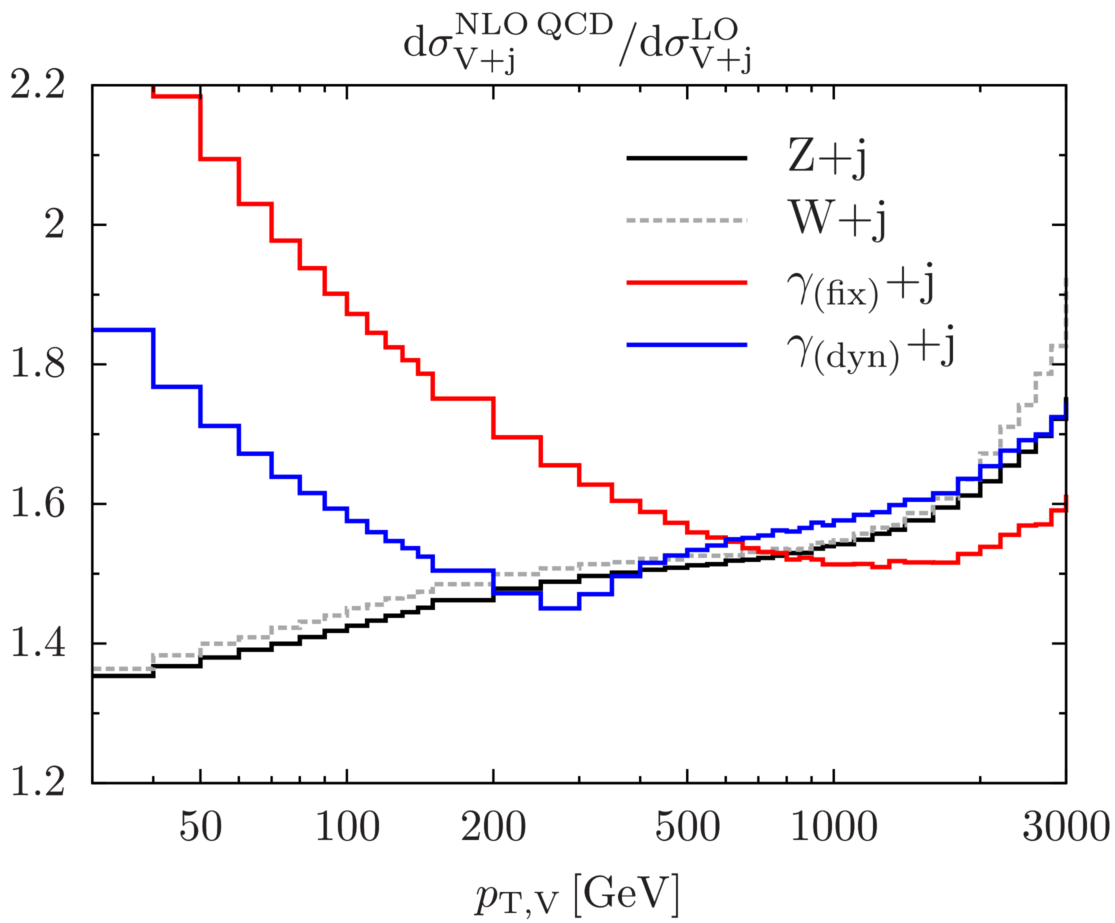
$$\Delta K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x)/K^{(V)}_{\mathrm{N}^{k-1}\mathrm{LO}}(x) - 1$$

$$\delta^{(3)} K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) = \Delta K^{(V)}_{\mathrm{N}^k\mathrm{LO}}(x) - \Delta K^{(Z)}_{\mathrm{N}^k\mathrm{LO}}(x)$$

$$\epsilon^{(Z)}_{\mathrm{QCD},3} = \epsilon^{(W^\pm)}_{\mathrm{QCD},3} = \epsilon^{(\gamma)}_{\mathrm{QCD},3} = \epsilon_{\mathrm{QCD},3}$$

- this modelling of process correlations assumes a close similarity of QCD effects between all V+jets processes
  - certainly the case for $Z(\to\nu\bar{\nu})$+jets vs. $Z(\to l\bar{l})$+jets
  - apart from PDF effects it is the case for W+jets vs. Z+jets
  - at large pT is is also the case for γ+jets vs. Z+jets

γ+jet: Isolation



dynamic cone:

$$\varepsilon_{0,\mathrm{dyn}} = 0.1, \qquad n_{\mathrm{dyn}} = 1, \qquad R_{0,\mathrm{dyn}} = \min\{1.0, R_{\mathrm{dyn}}(E_{\mathrm{T},\gamma}, \varepsilon_{\mathrm{dyn},0})\}$$

$$R_{\mathrm{dyn}}(E_{\mathrm{T},\gamma}, \varepsilon_0) = \frac{M_Z}{E_{\mathrm{T},\gamma}\sqrt{\varepsilon_0}}$$

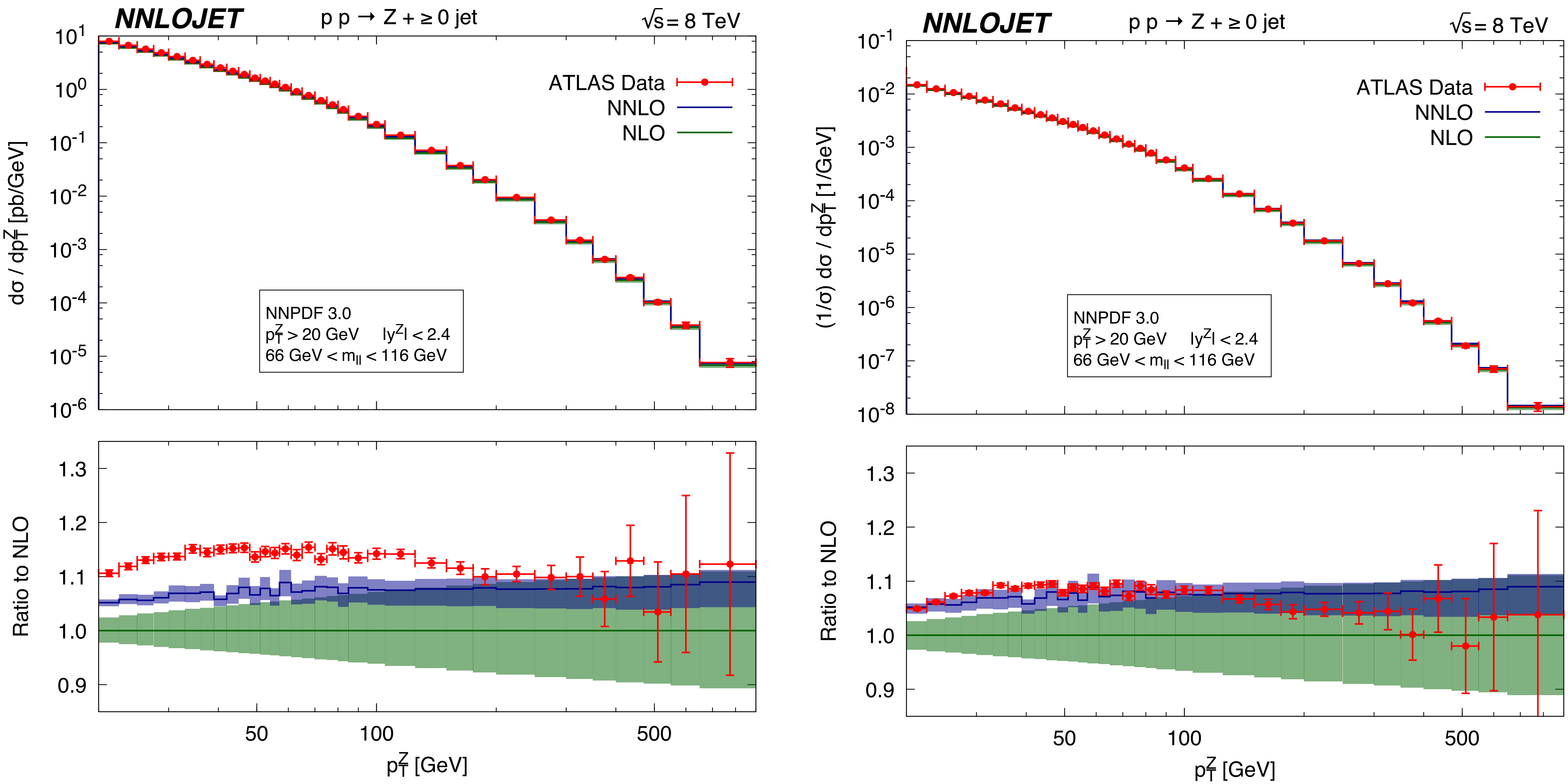
fixed cone:

$$\varepsilon_{0,\mathrm{fix}} = 0.025, \qquad n_{\mathrm{fix}} = 2, \qquad R_{0,\mathrm{fix}} = 0.4$$

$$\Longrightarrow \quad M^2_{\gamma j} \simeq E_{\mathrm{T},\gamma} E_{\mathrm{T},j} R^2_{\gamma j} = \varepsilon_0 E^2_{\mathrm{T},\gamma} R^2_{\mathrm{dyn}} = M^2_Z$$

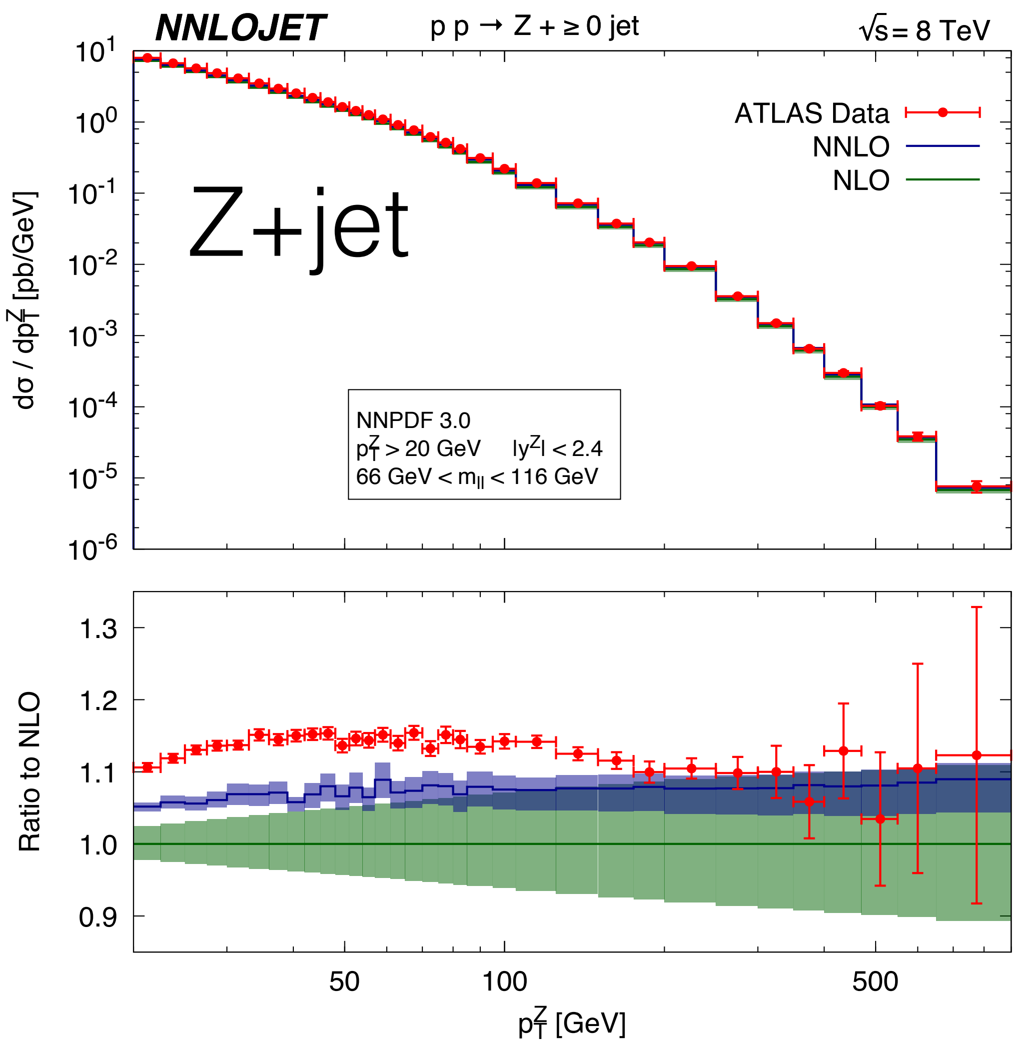
- Using this dynamic smooth isolation mimics the role of the Z- and W -boson masses as regulators of collinear singularities in Z/W +jet production at high pT.

NNLO for Z+jet

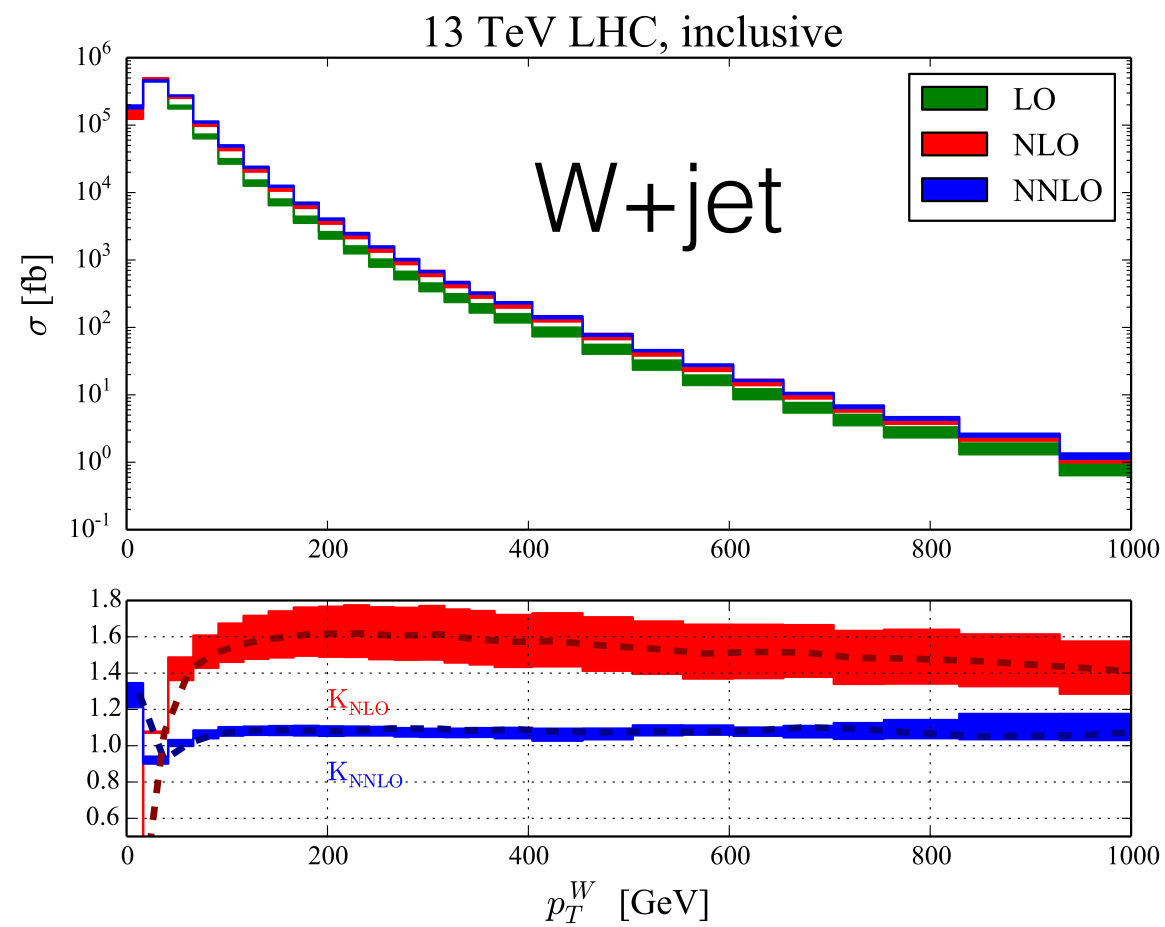


[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]

NNLO for W/Z+jet



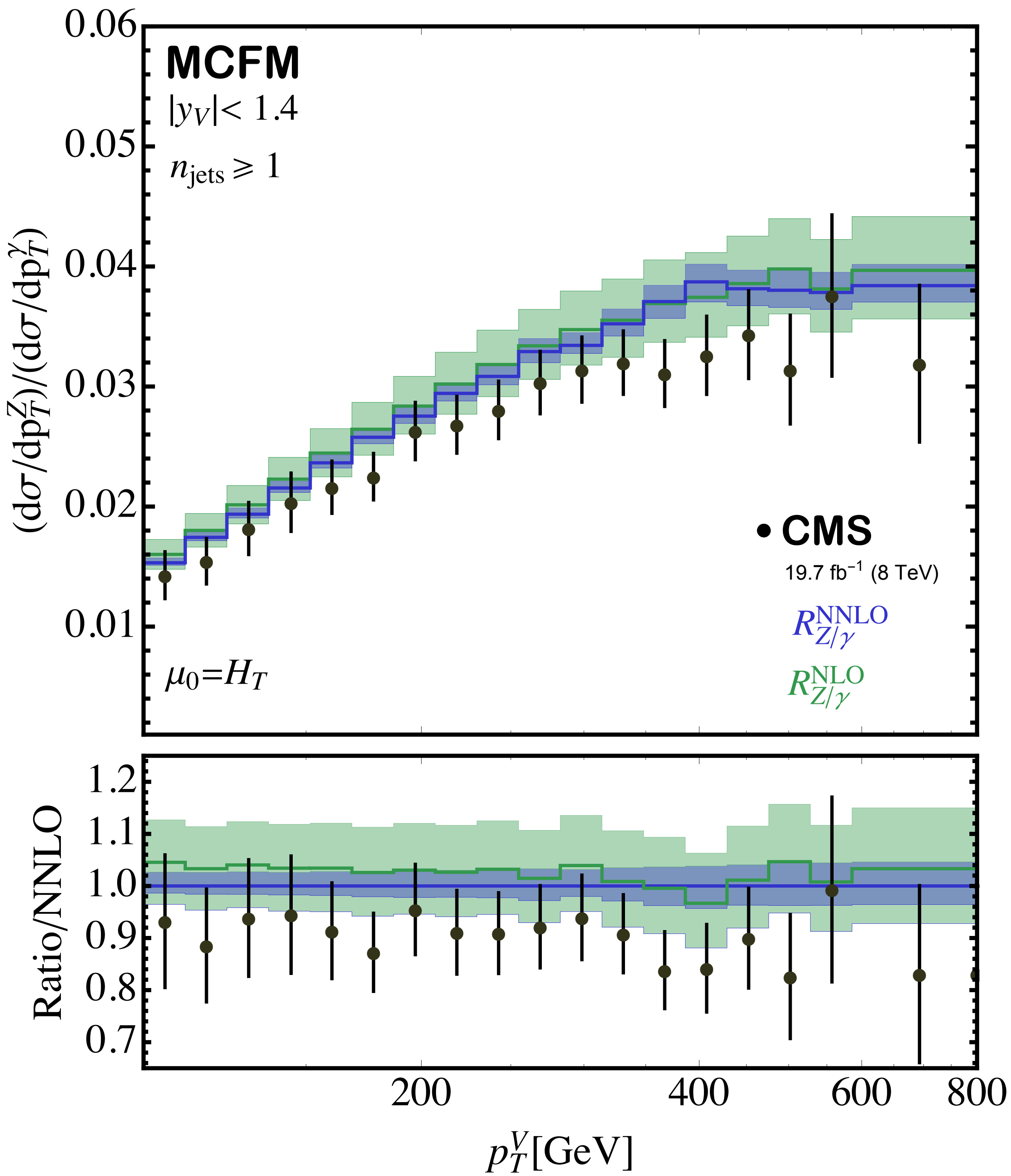
[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]



[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

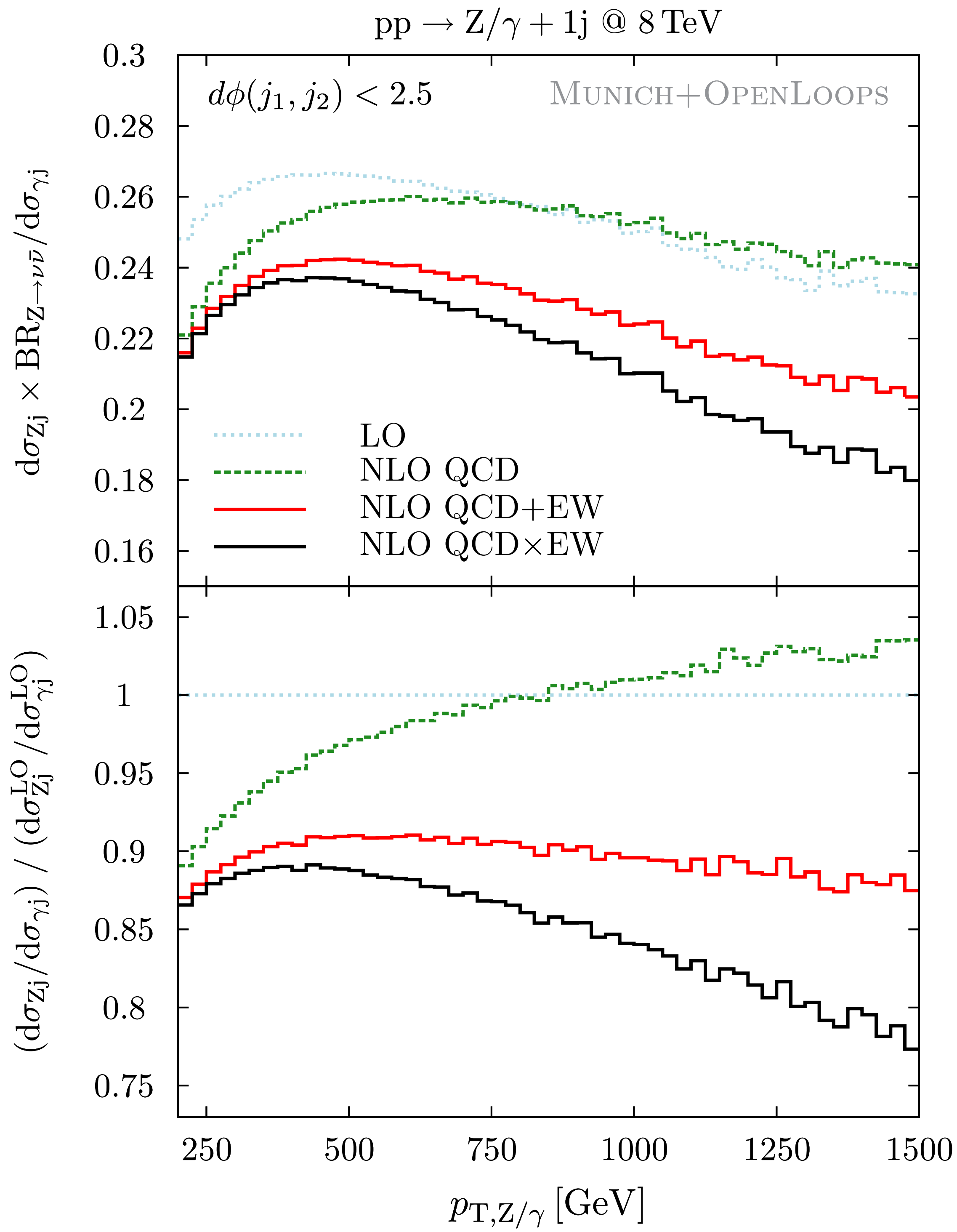
NNLO for Z/γ+jet



[Campbell, Ellis, Williams; '17]

NNLO/NLO ~ 1 for large pT!

Z/γ + 1 jet: pT-ratio



Overall

- mild dependence on the boson pT

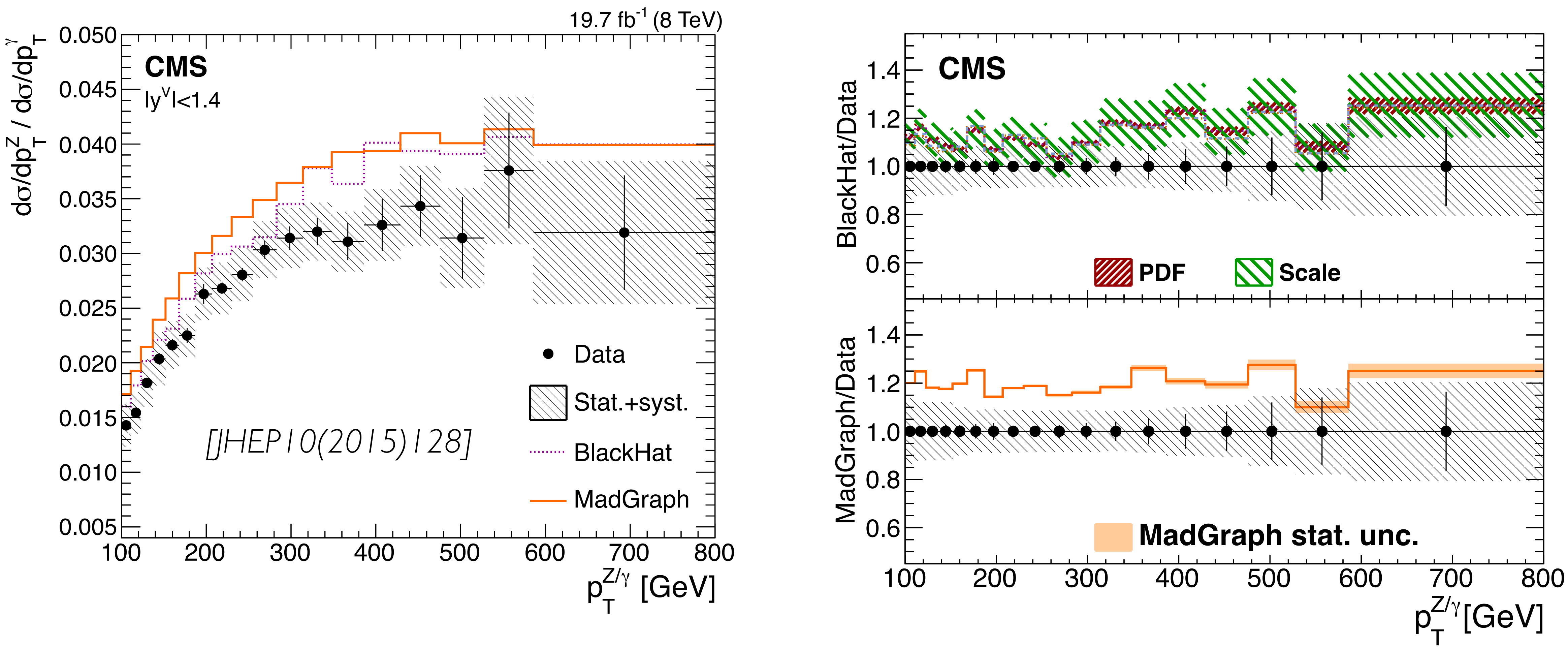
QCD corrections

- 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

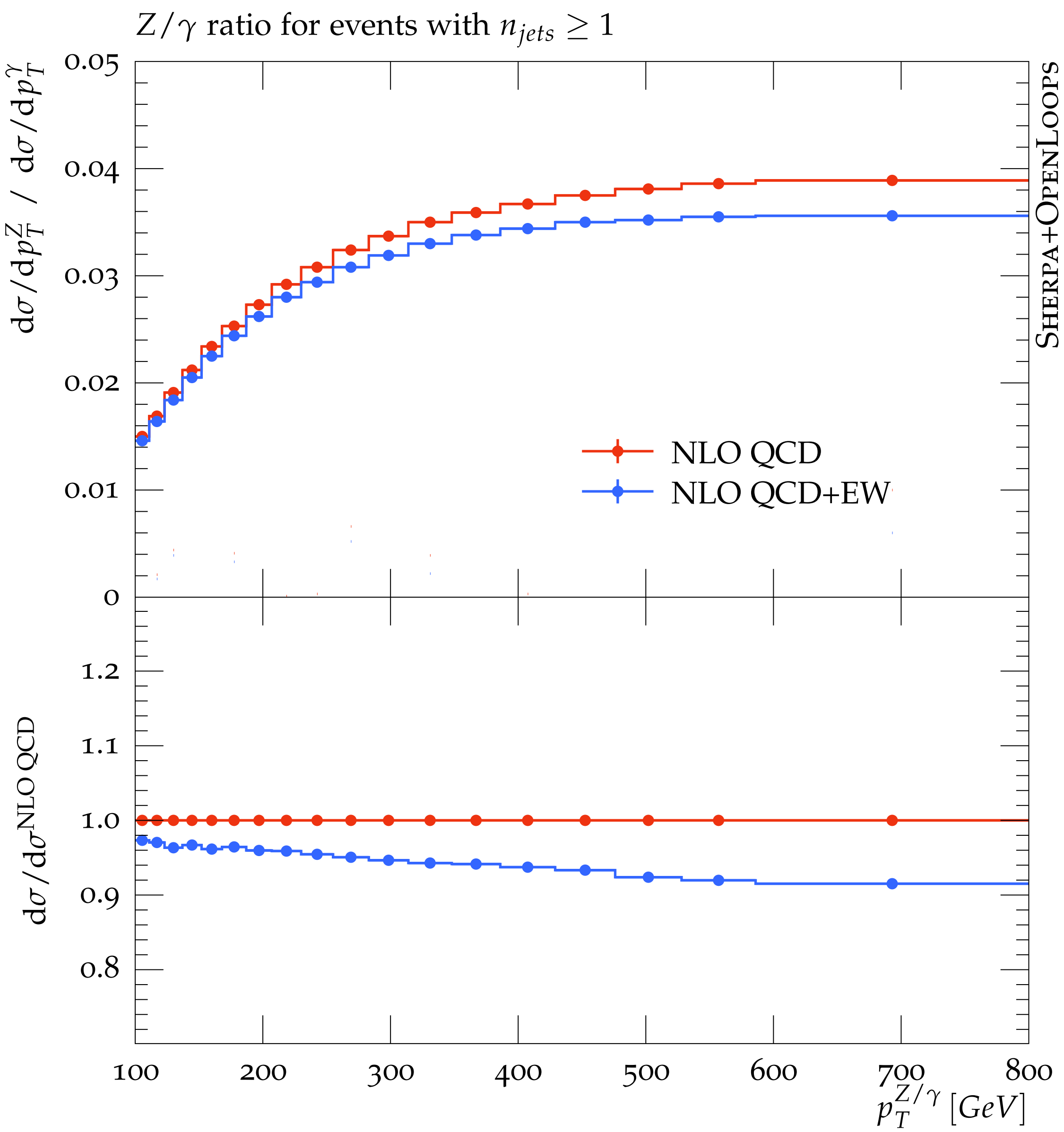


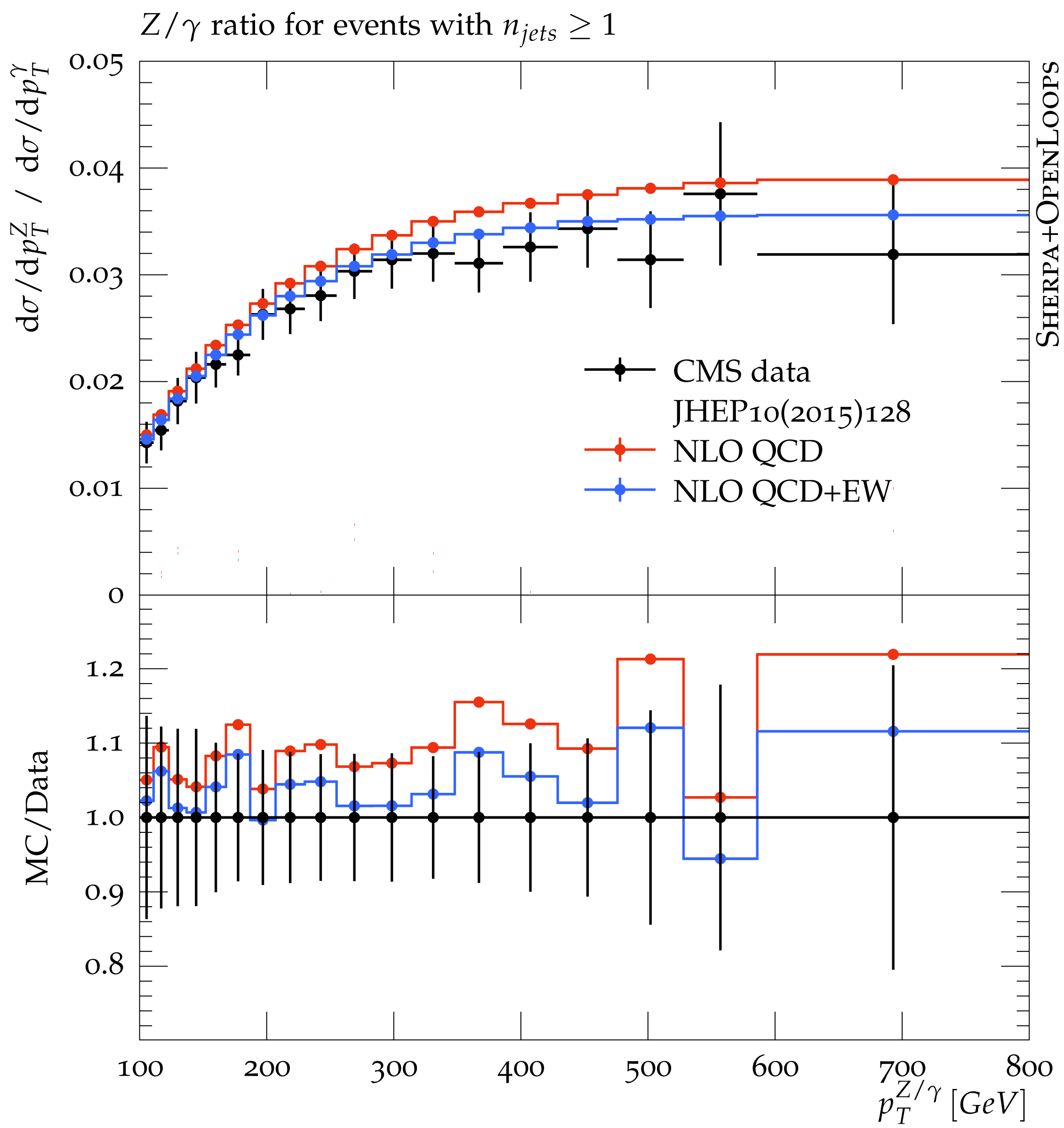
- constant off-set with respect to LO
- improved agreement at NLO QCD for small pT

Compare against data: Z/γ

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

[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:

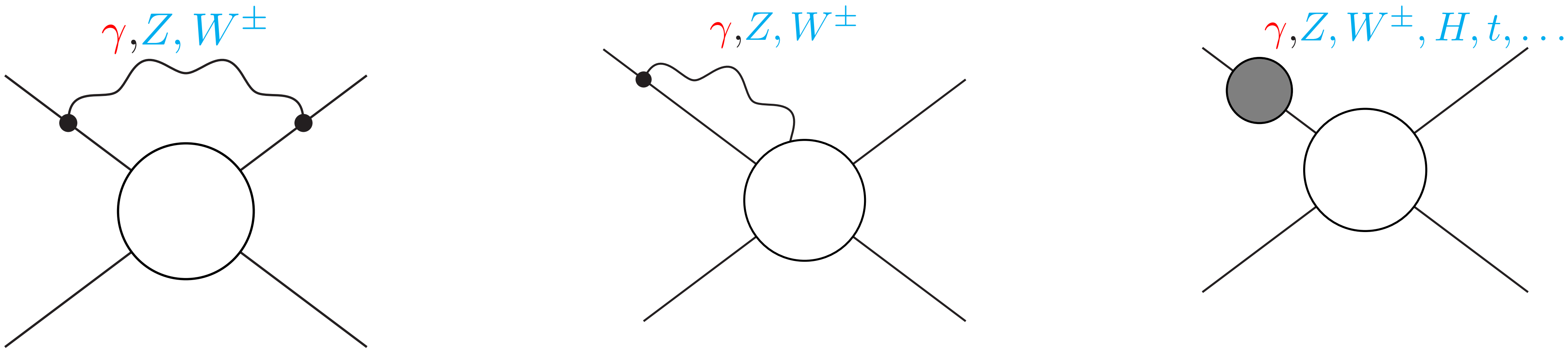
$$\frac{\sigma^{\rm NLO}_{\rm QCD+EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm NLO}_{\rm QCD}}\right)$$ suppressed by large NLO QCD corrections

$$\frac{\sigma^{\rm NLO}_{\rm QCD\times EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right)$$ "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 $G_\mu = 1.16637\times 10^{-5}\ {\rm GeV}^{-2}$

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]*

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

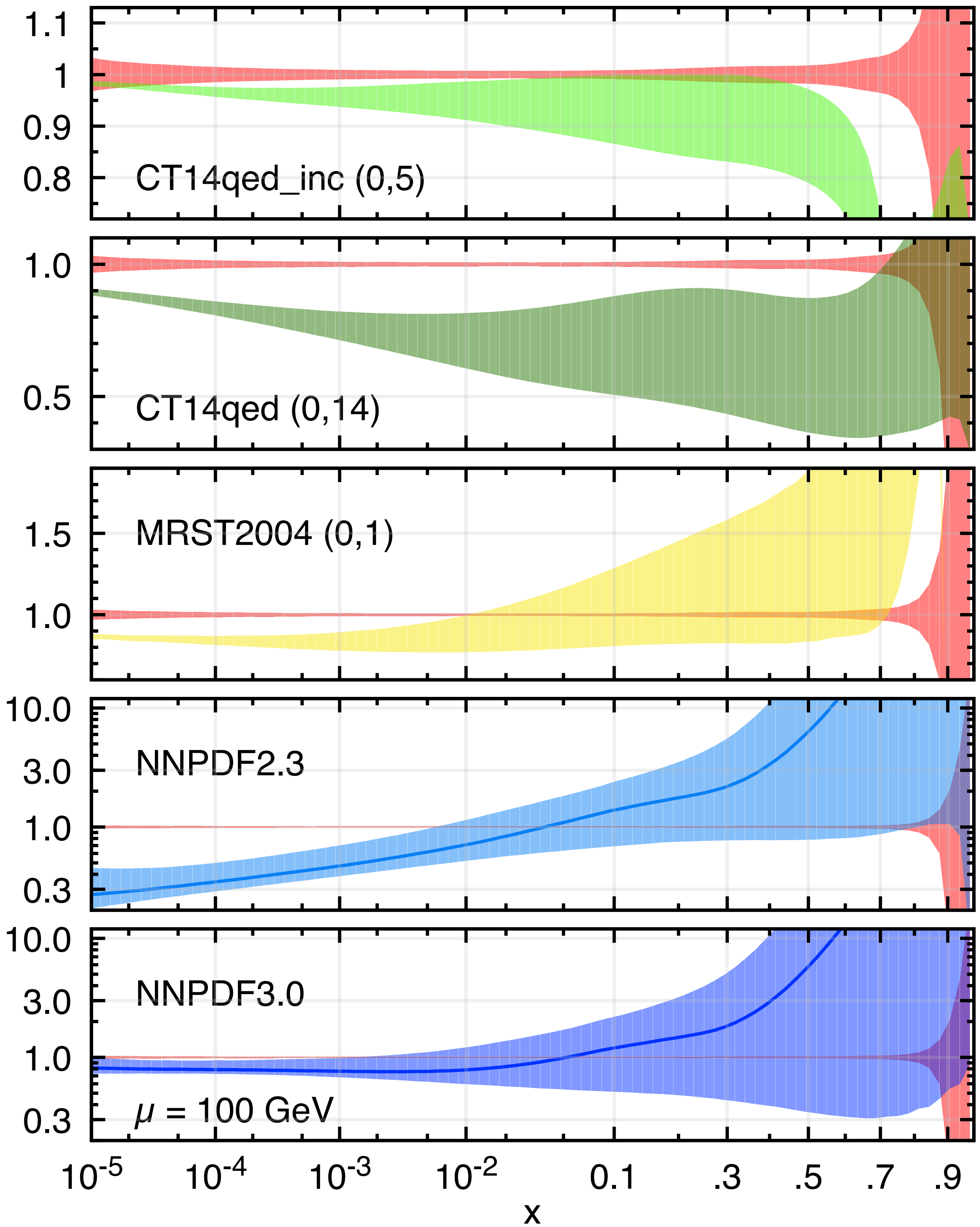
- process-independent, simple structure
- 2-loop extension and resummation partially available
- typical size at $\sqrt{\hat{s}} = 1, 5, 10$ TeV:

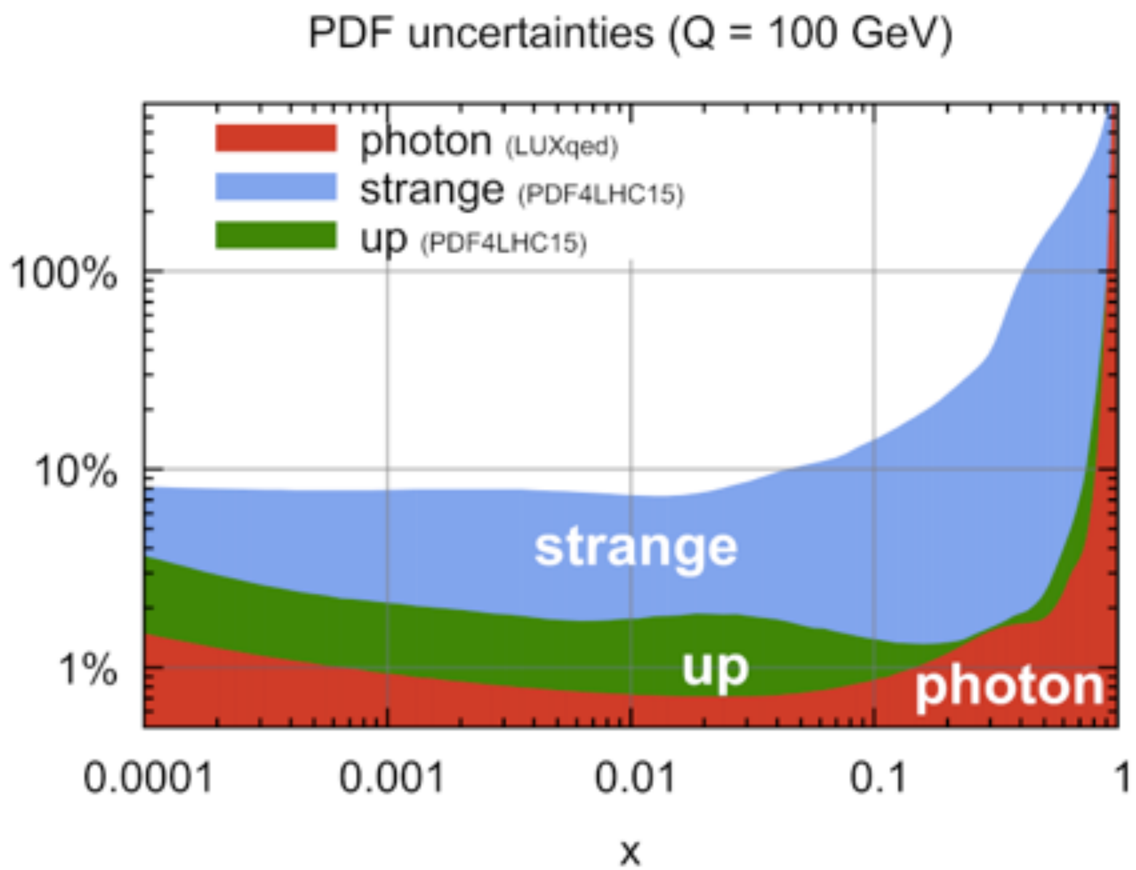
$$\delta_{\mathrm{LL}} \sim -\frac{\alpha}{\pi s_W^2} \log^2 \frac{\hat{s}}{M_W^2} \simeq -28, -76, -104\%,$$

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

➡ large cancellations possible

LUXqed





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