High-precision predictions for V+jet production

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IP3

work in collaboration with:
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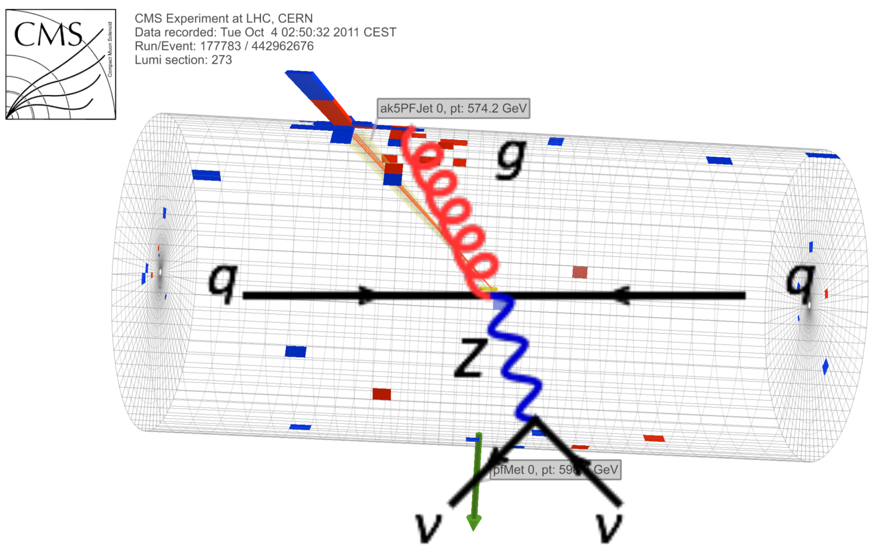
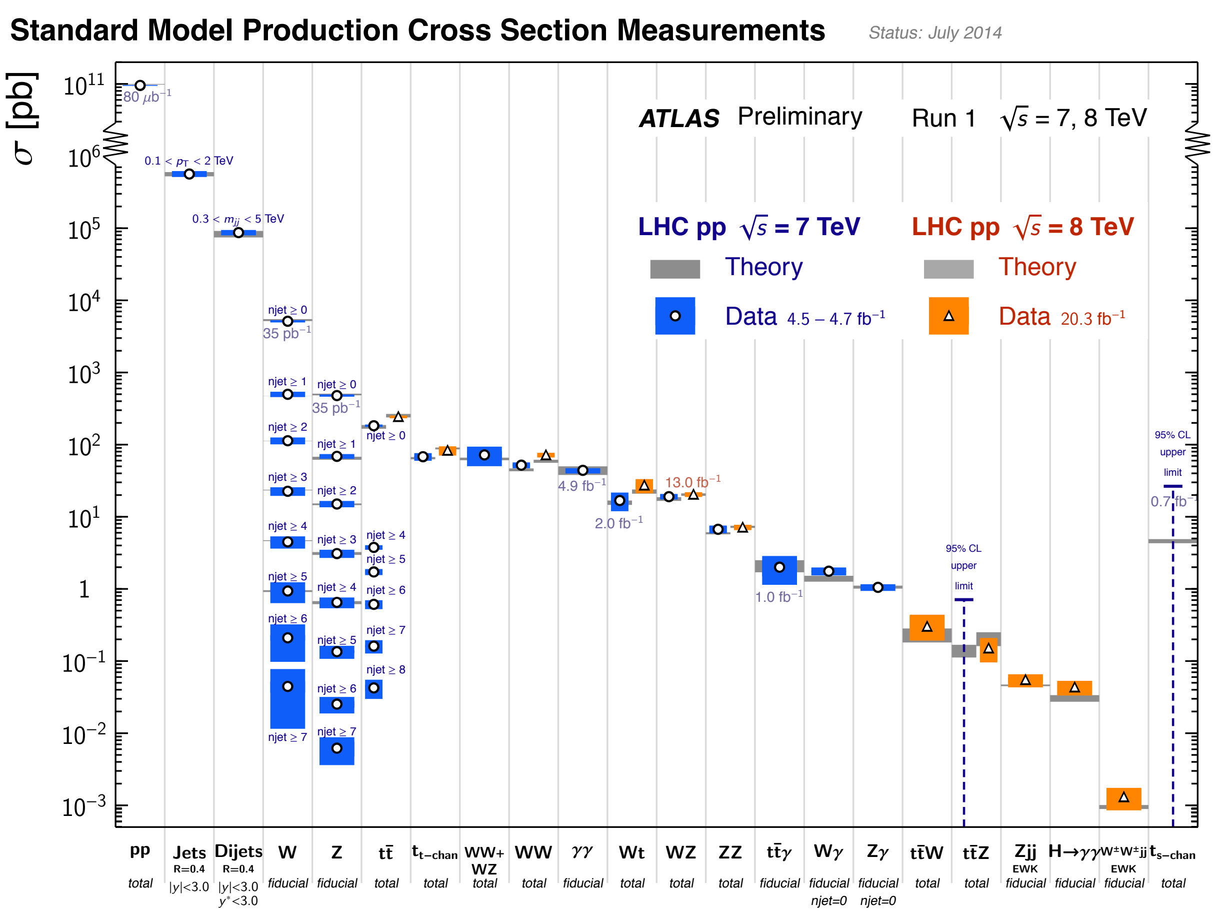
UCL HEP Seminars
UCL, London, 21.04.2017

V + multijet production

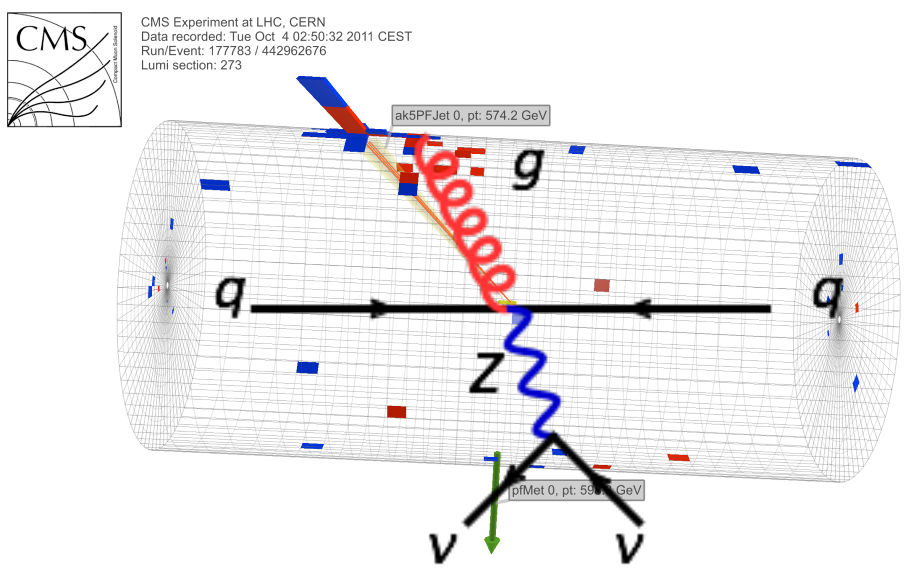


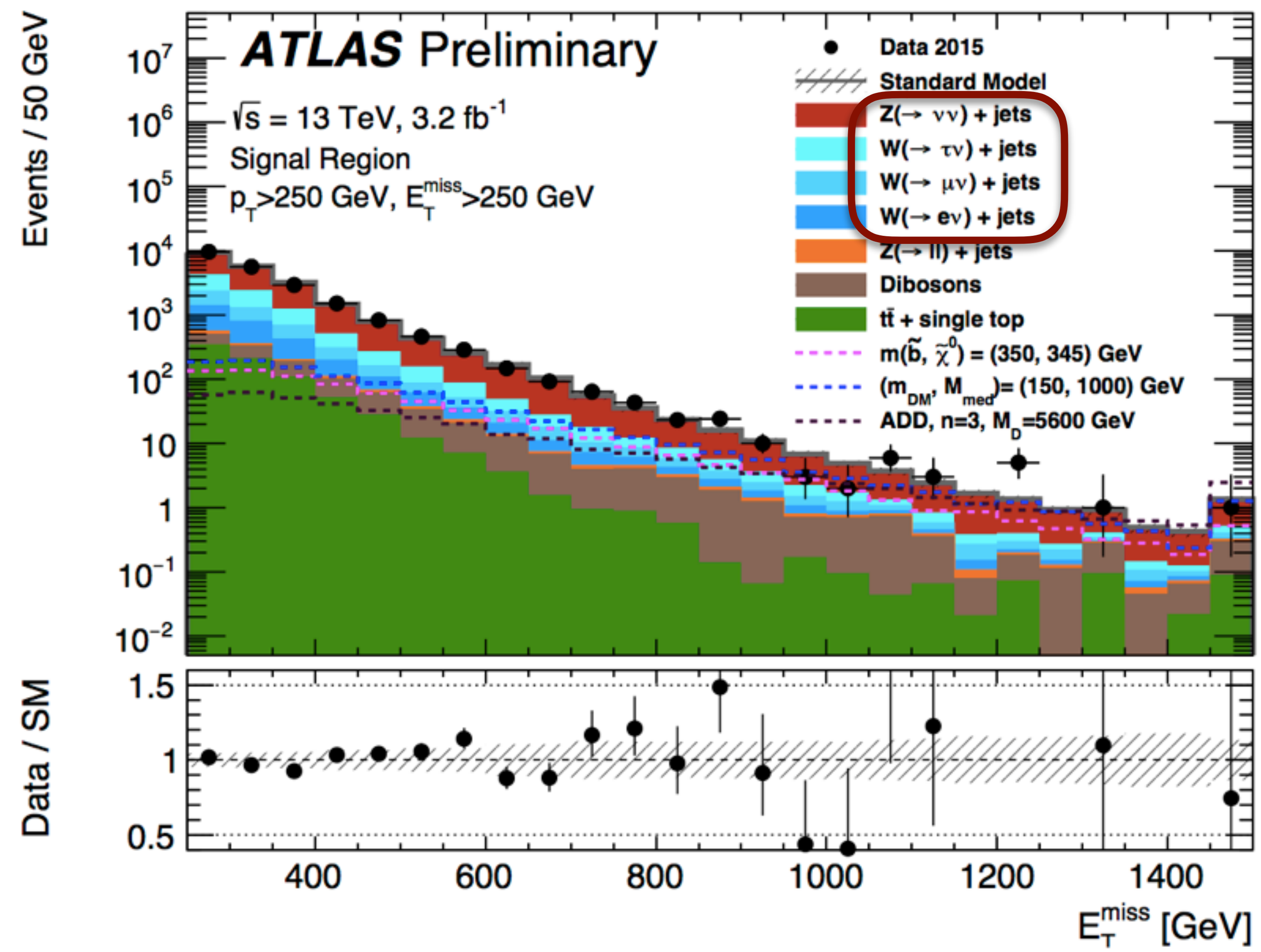
- Dominant backgrounds for monojet **DM searches**
- Important/dominant backgrounds for various **BSM searches** (lepton + missing E_T + ets)
- Dominant backgrounds for **top physics**
- Dominant backgrounds for **Higgs physics**, e.g. VH(→bb), H→WW



- Large cross-sections and clean leptonic signatures
- **V+jets**: Precision QCD at LHC
- Playground to probe different aspects of higher-order calculations (LO+PS, NLO+PS, NLO-Merging, NLO EW,…)
- Probe and constrain PDFs

V+jets backgrounds in monojet/MET + jets searches



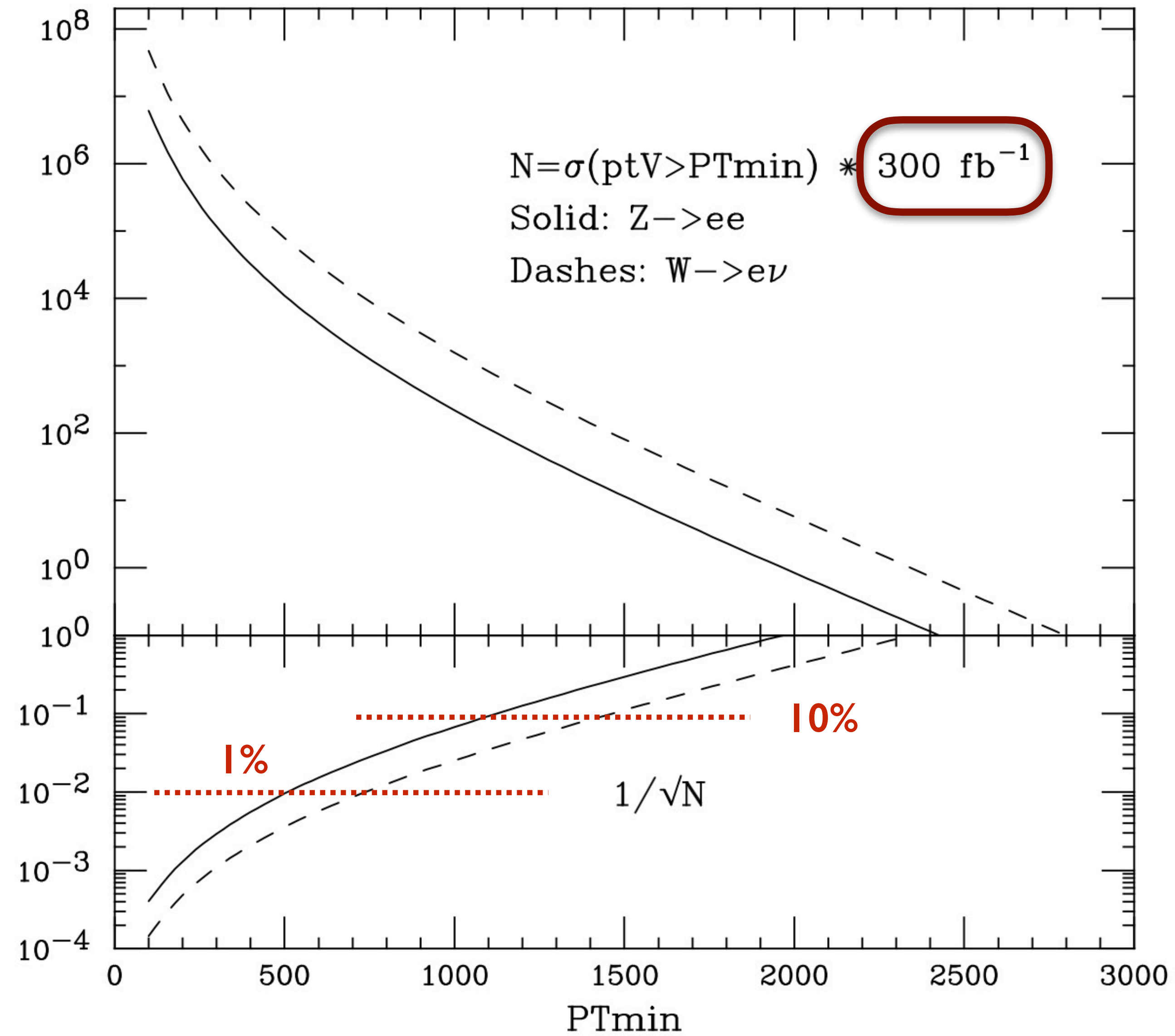


irreducible backgrounds:

pp→Z(→ν$\bar{\nu}$)+jets ⟹ MET + jets

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

Target precision

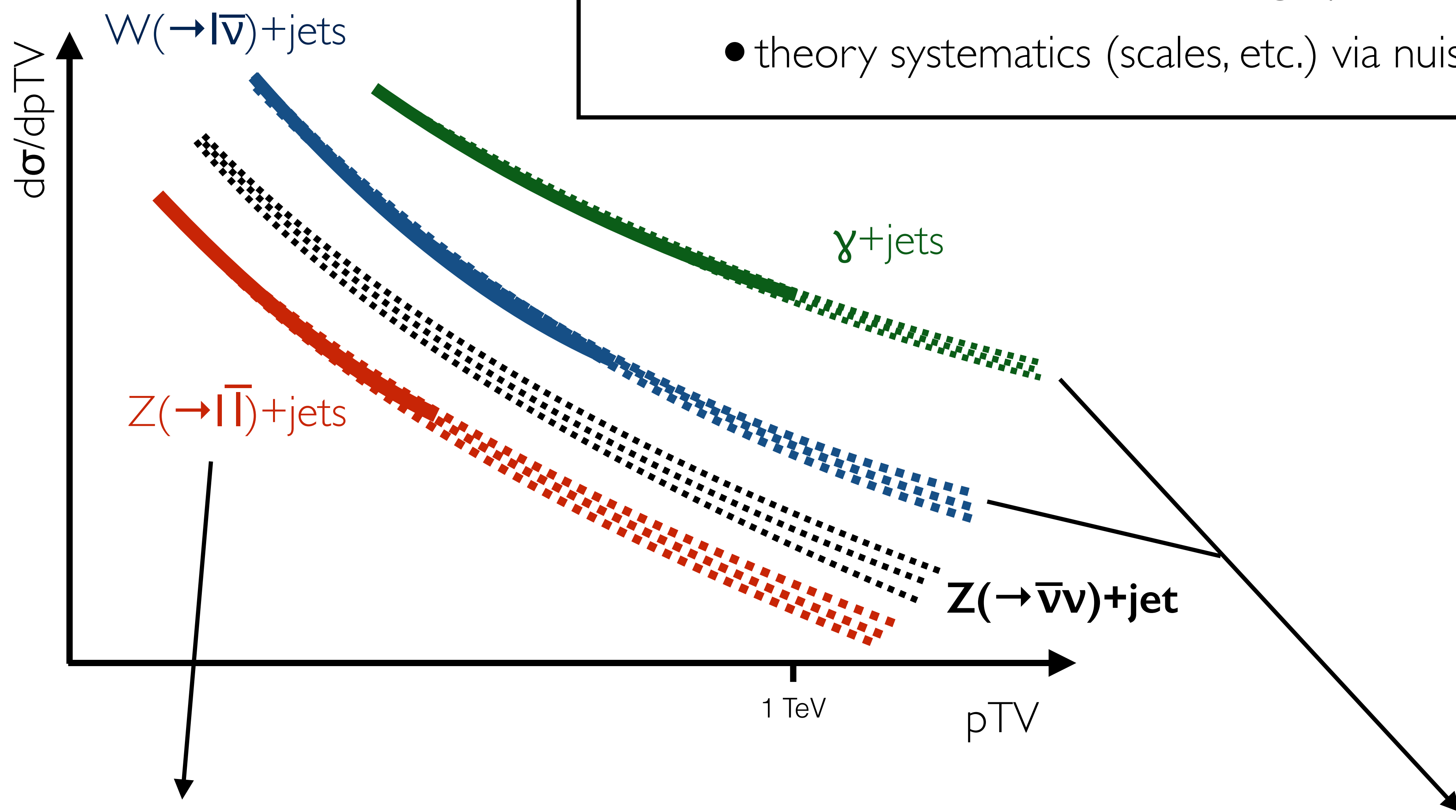


- for 500 GeV < pTV < 1000 GeV: background statistics will be at **1% level**
- understanding of V+jets backgrounds at this level increases sensitivity in DM searches
- this level of precision is theoretically possible @ NNLO QCD + NNLO EW
- requires solid understanding of **uncertainties**!

Determine V+jets backgrounds

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

- to determine $Z(\to \bar{\nu}\nu)$+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

[to be published soon, already available to ATLAS & CMS]

- 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)

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

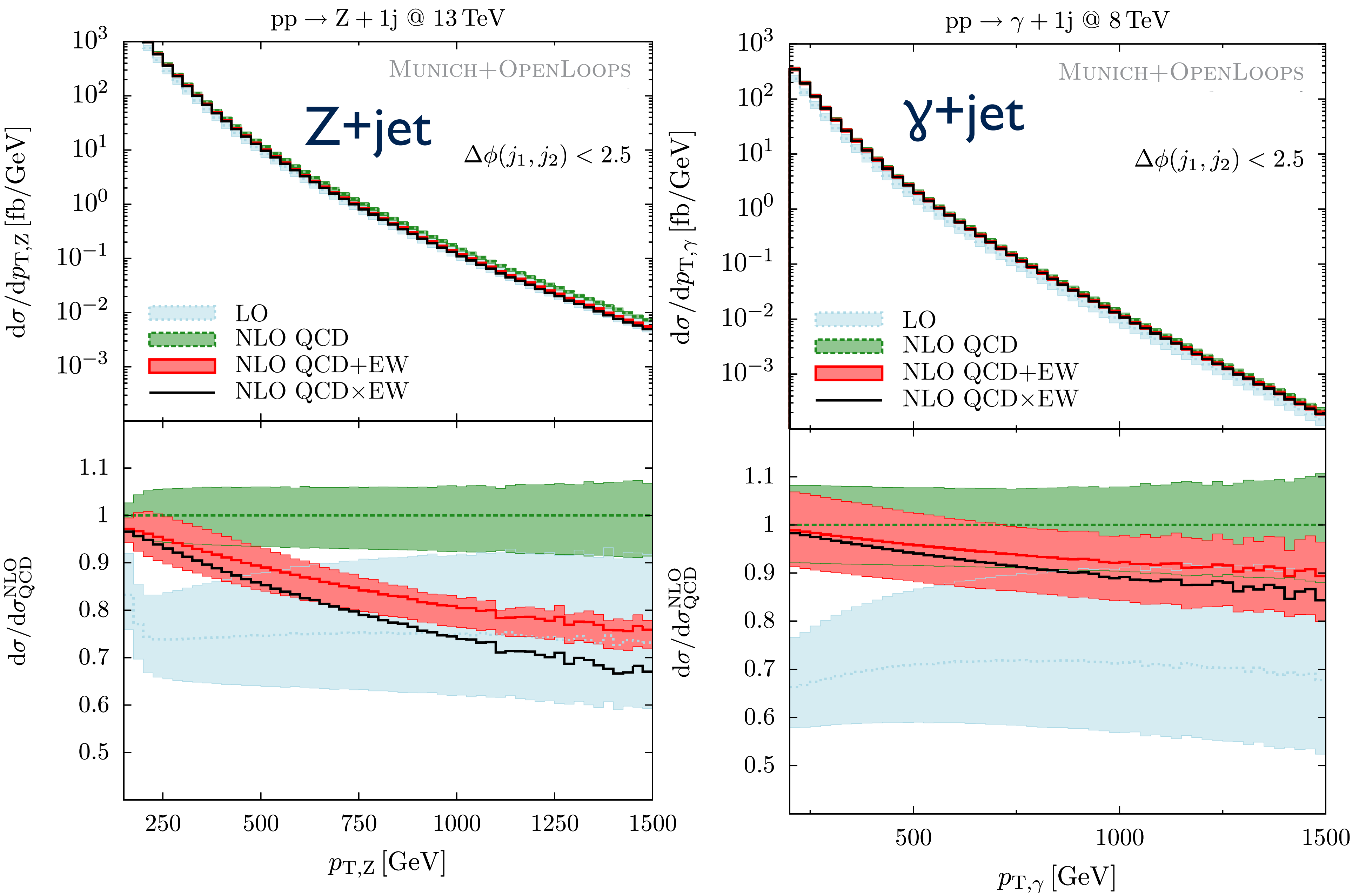
one-dimensional reweighting of MC samples in $x = p_{\mathrm{T}}^{(V)}$

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
  1. Pure QCD uncertainties
  2. Pure EW uncertainties
  3. Mixed QCD-EW uncertainties
  4. PDF, γ-induced uncertainties ….

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

Prelude: Z+jet vs. ɣ + 1 jet



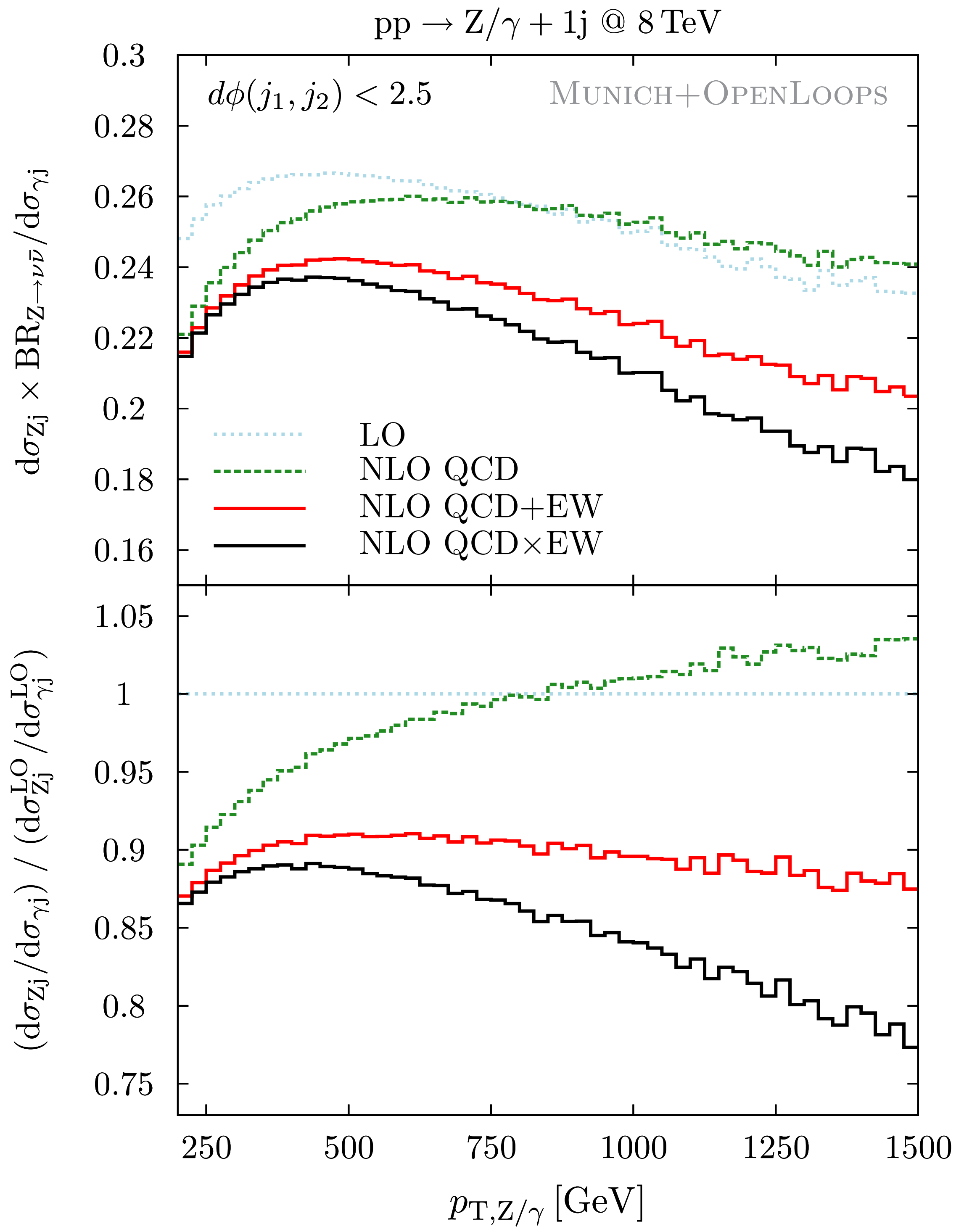
QCD corrections

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

EW corrections

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

Prelude: Z/γ pT-ratio



Overall

- mild dependence on the boson pT

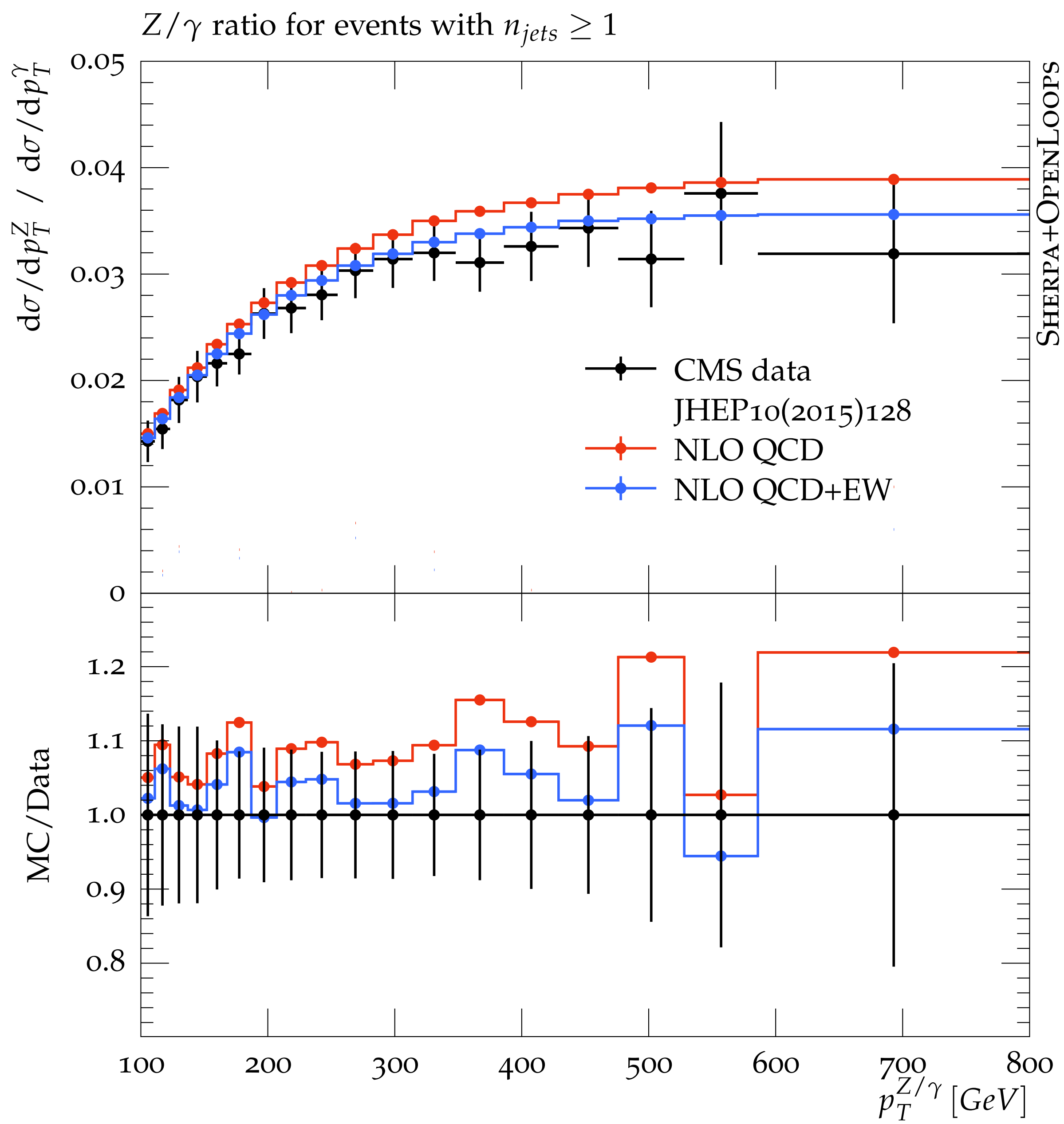
QCD corrections

- 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

Prelude: compare against Z/γ-data *[JHEP10(2015)128]*



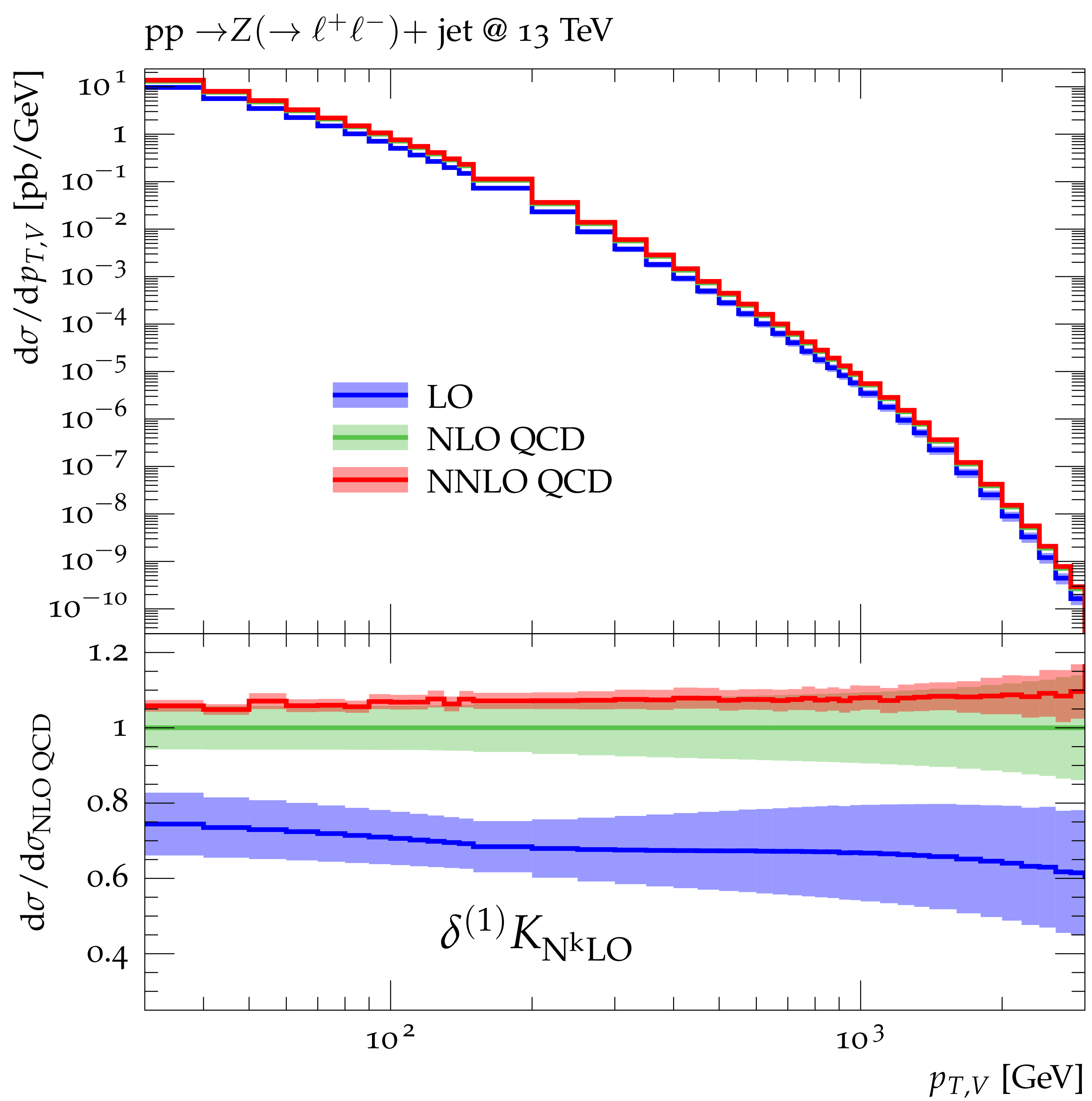
*[Ciulli, Kallweit, JML, Pozzorini, Schönherr for **LH'15**]*

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

1. pure QCD uncertainties

QCD effects

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



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

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

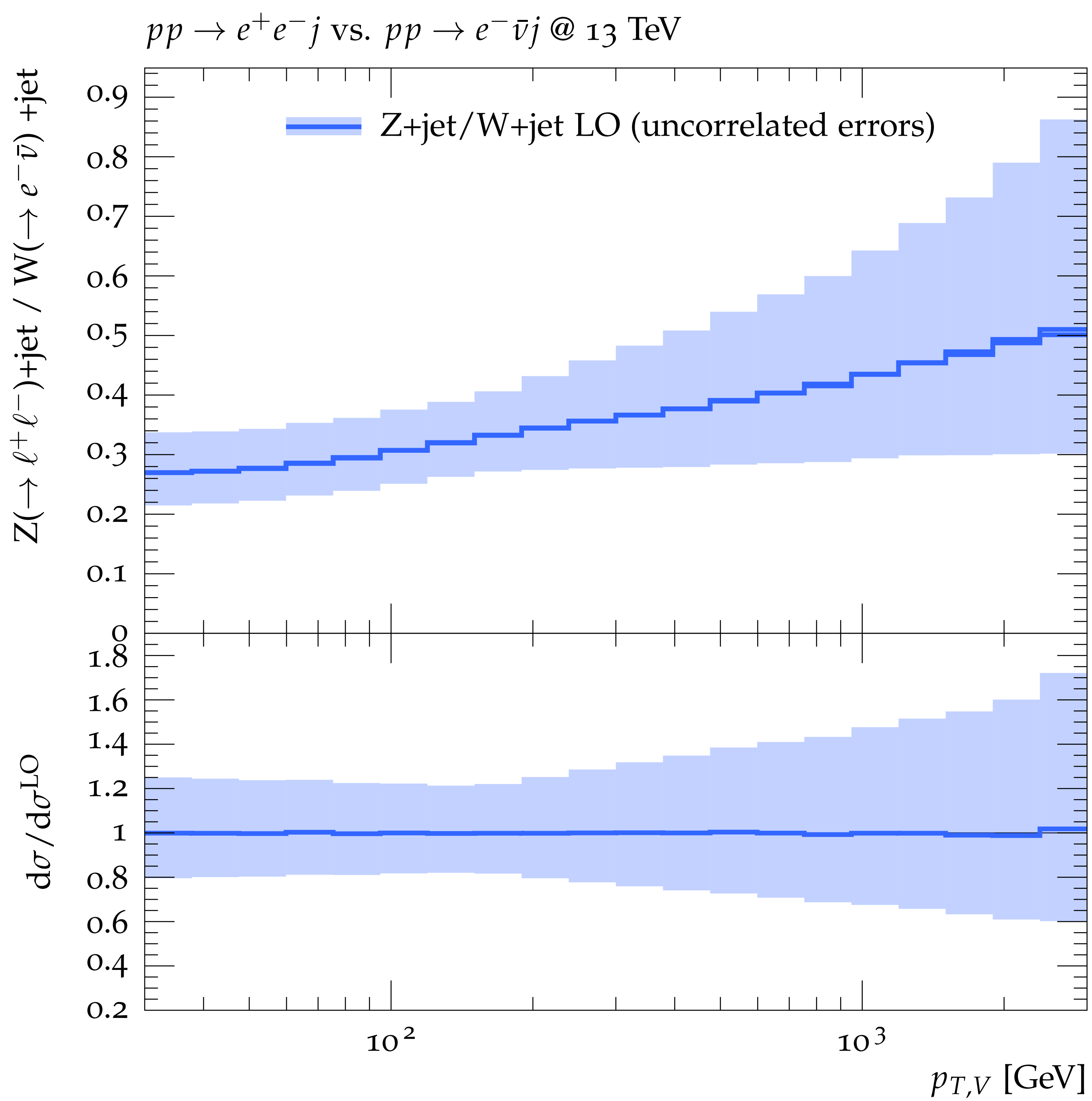
$$(\xi_{\mathrm{R}},\xi_{\mathrm{F}}) = (2,2),\ (2,1),\ (1,2),\ (1,1),\ (1,0.5),\ (0.5,1),(0.5,0.5)$$

yields

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

with minor shape variations

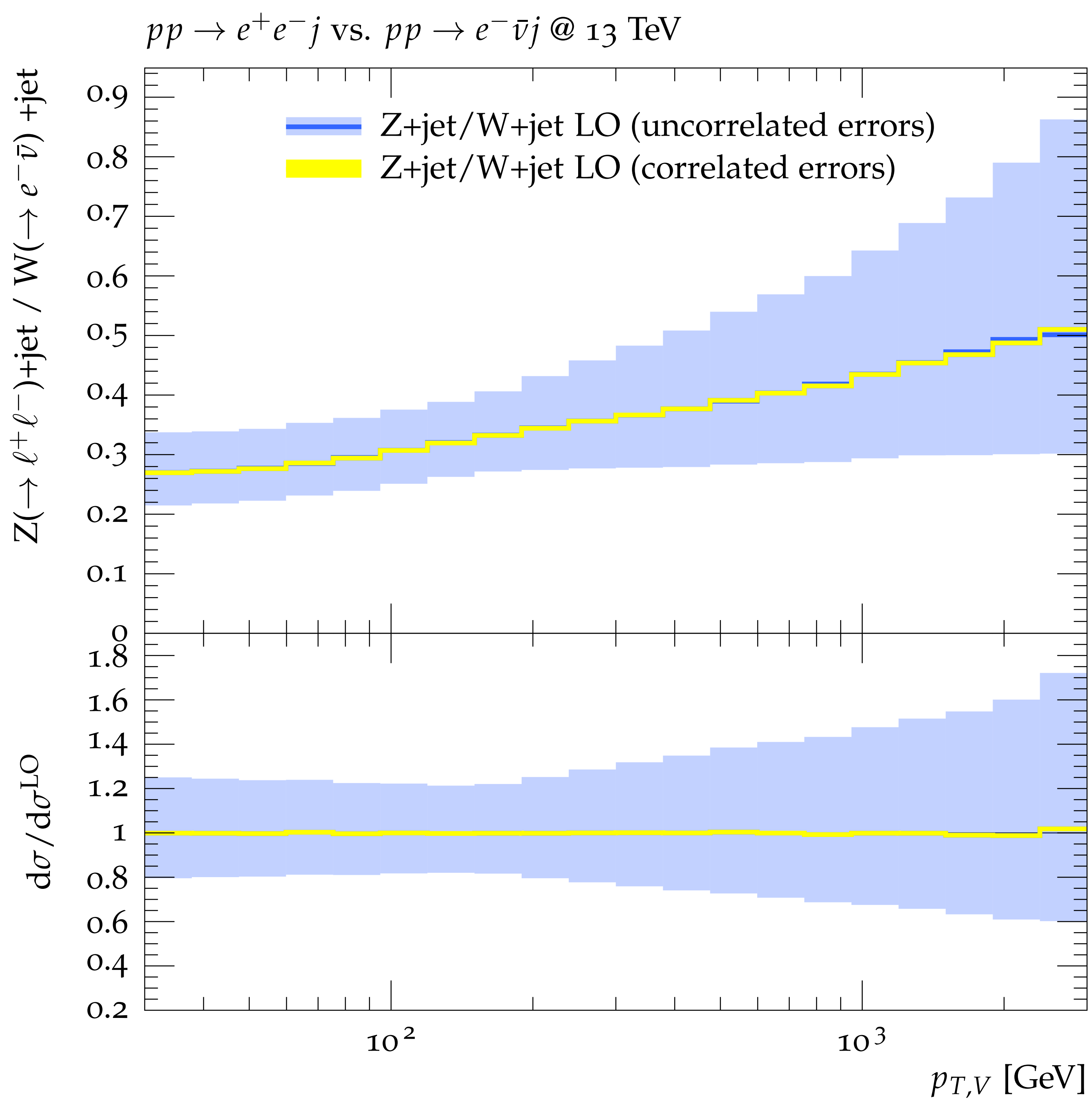
Correlation of scale variations



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

uncorrelated treatment yields O(40%) uncertainties

Correlation of scale variations



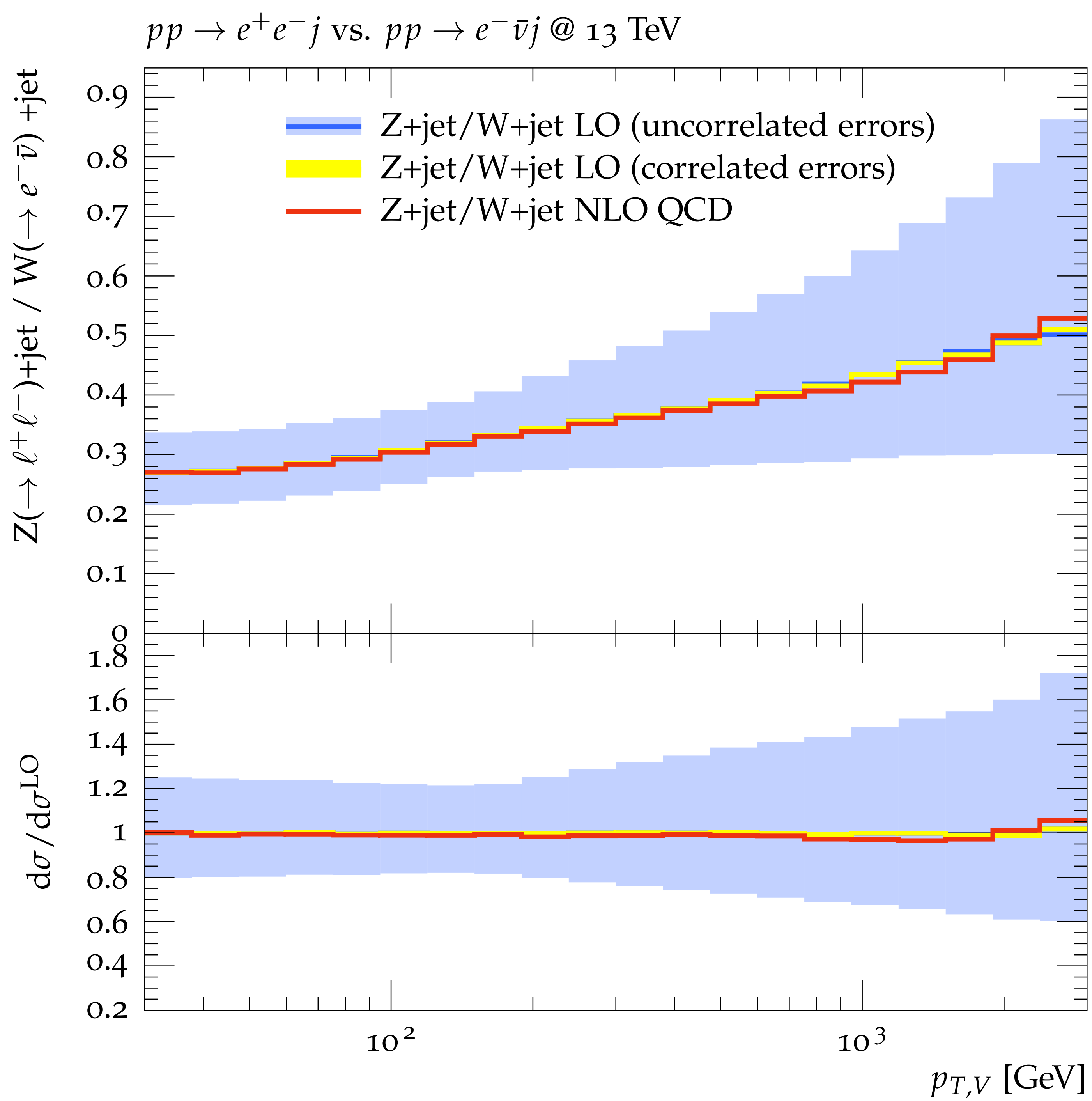
consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

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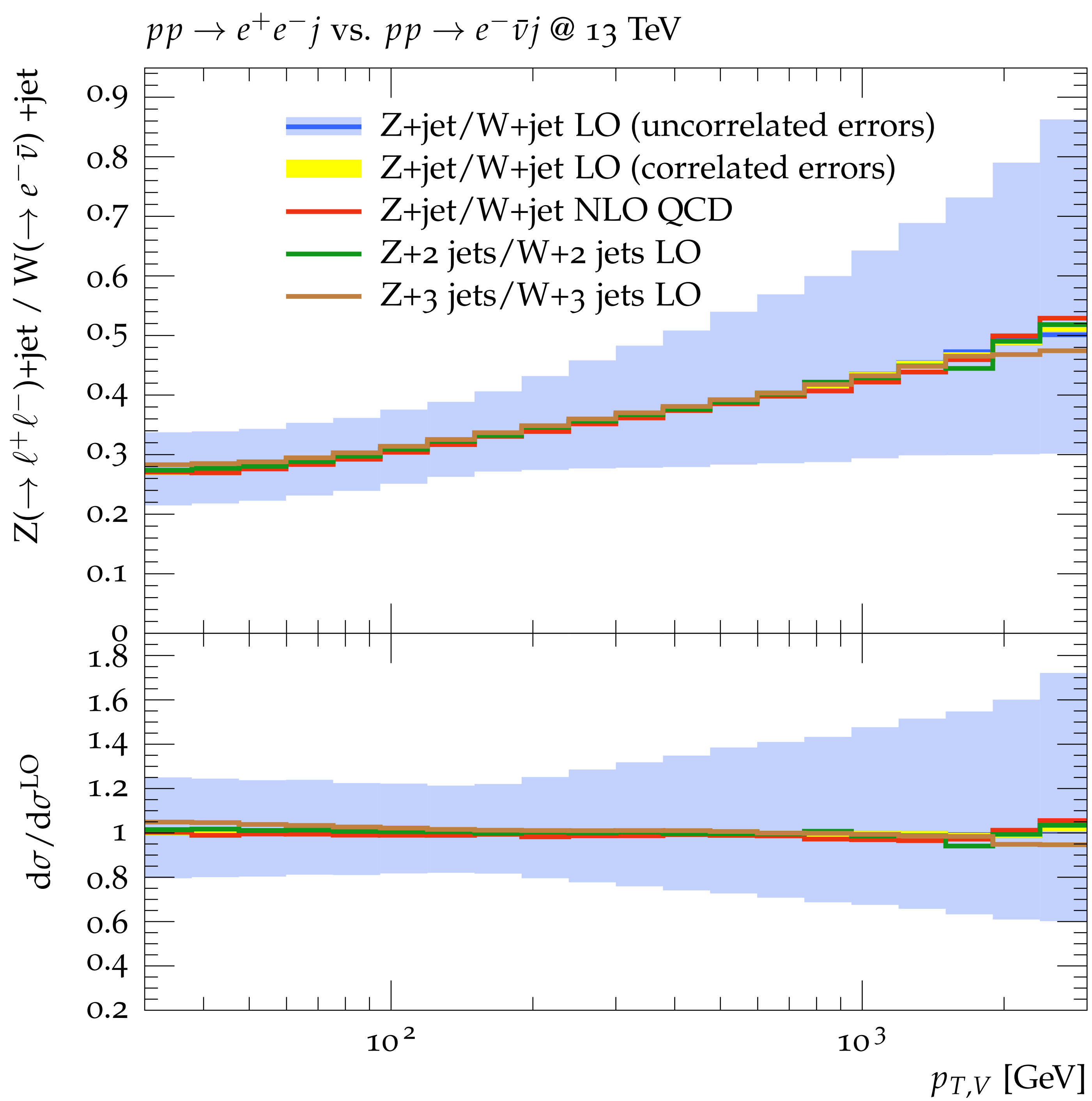
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

Correlation of scale variations



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uncorrelated treatment yields O(40%) uncertainties

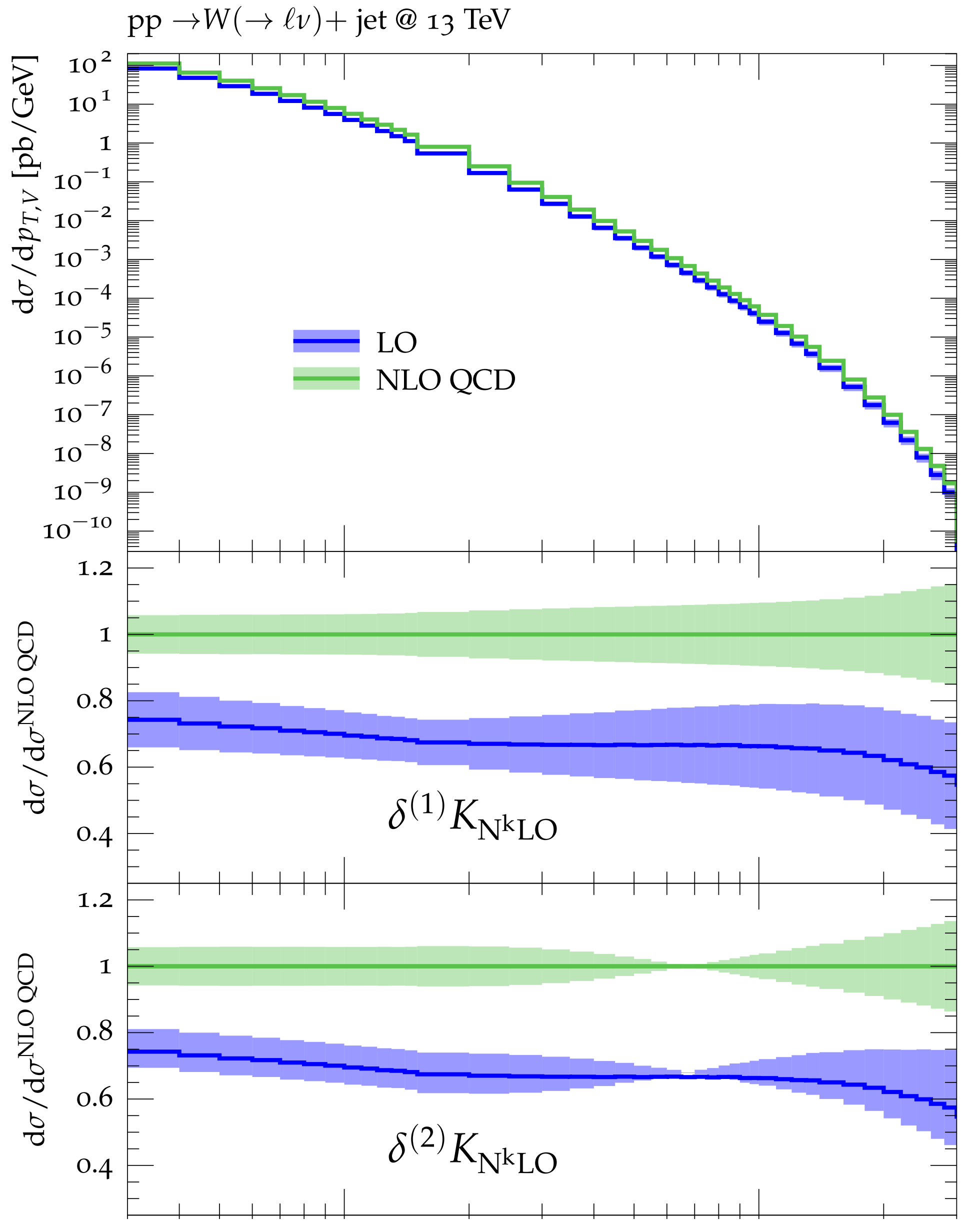
correlated treatment yields tiny O(<~ 1%) uncertainties

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

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

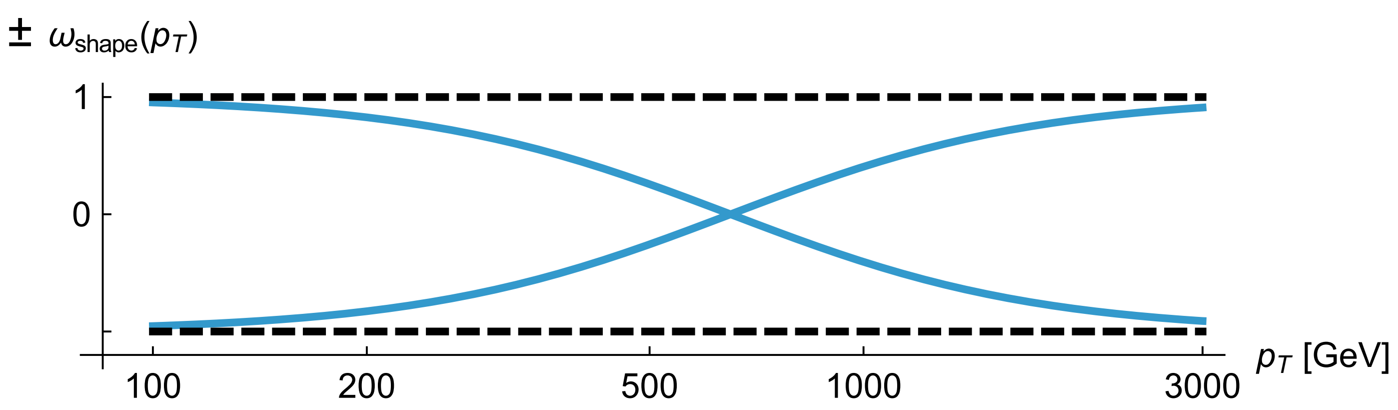
- correlated across processes
- correlated across pT bins

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

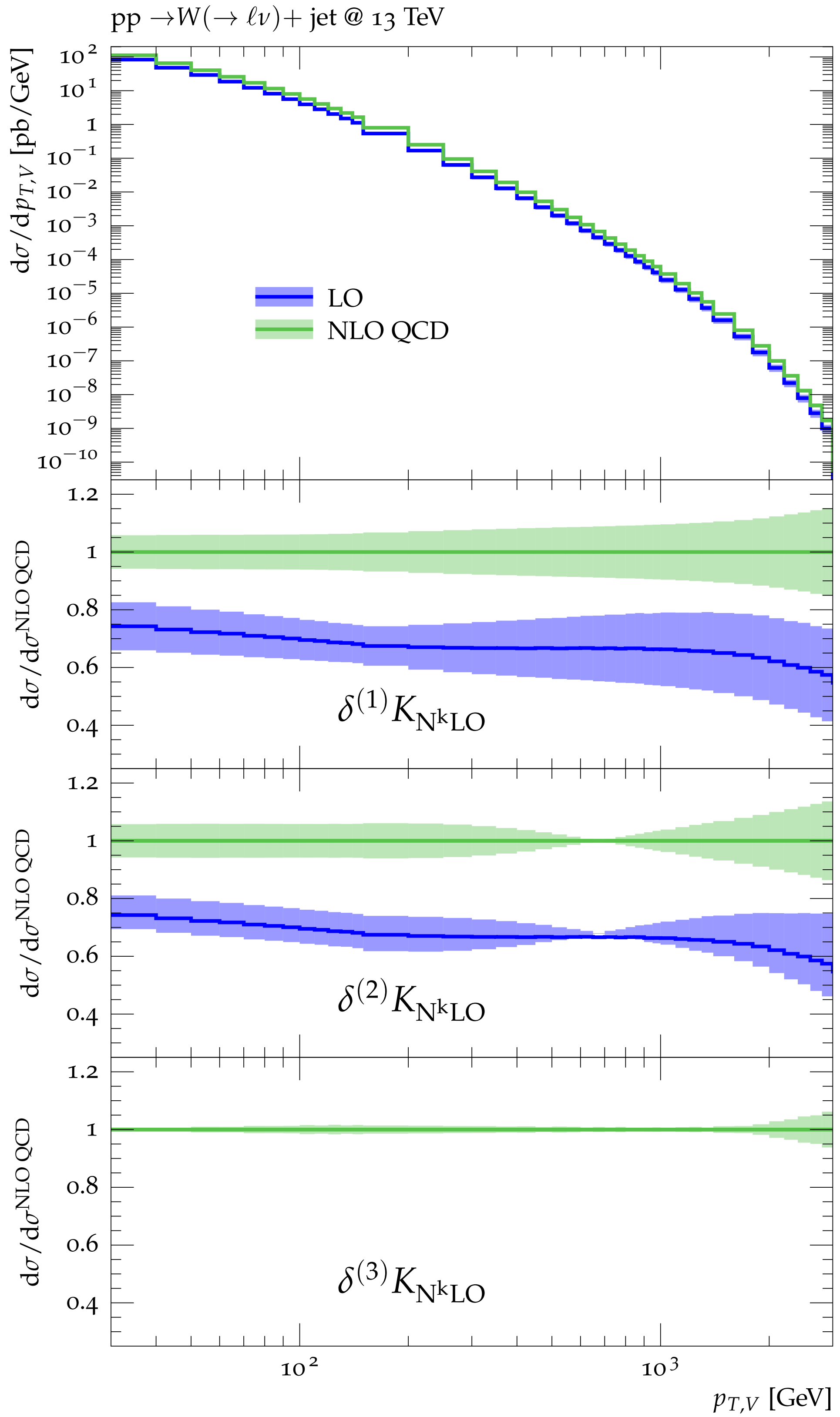
symmetrized **scale uncertainty**

- $\delta^{(2)}K^{V}_{\mathrm{N^kLO}} = \frac{p_{\mathrm{T}}^2 - 650\ \mathrm{GeV}}{p_{\mathrm{T}}^2 + 650\ \mathrm{GeV}}\delta^{(1)}K^{V}_{\mathrm{N^kLO}}$

yields max **shape distortion** within scale variation band



QCD uncertainties



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

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yields max **shape distortion** within scale variation band

- $$\delta^{(3)}K^{V}_{\mathrm{N^kLO}} = \frac{K^{V}_{\mathrm{N^kLO}}}{K^{V}_{\mathrm{N^{k-1}LO}}} - \frac{K^{Z}_{\mathrm{N^kLO}}}{K^{Z}_{\mathrm{N^{k-1}LO}}}$$

Difference of (N)NLO corrections as **process correlation uncertainty**

Caveat: γ+jet

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

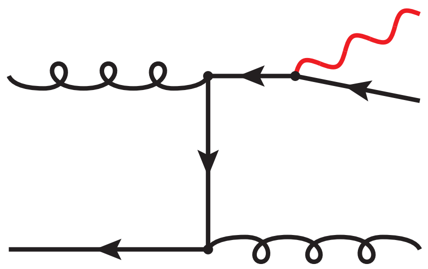
$$\left|\frac{\sigma^{(V)}_{\mathrm{NLO}}}{\sigma^{(V)}_{\mathrm{LO}}} - \frac{\sigma^{(Z)}_{\mathrm{NLO}}}{\sigma^{(Z)}_{\mathrm{LO}}}\right| \ll \left|\frac{\sigma^{(Z)}_{\mathrm{NLO}}}{\sigma^{(Z)}_{\mathrm{LO}}}\right|$$

- apart from PDF effects it is the case for W+jets vs. Z+jets
- at pT > 200 GeV it is also the case for **γ**+jets vs. Z+jets.

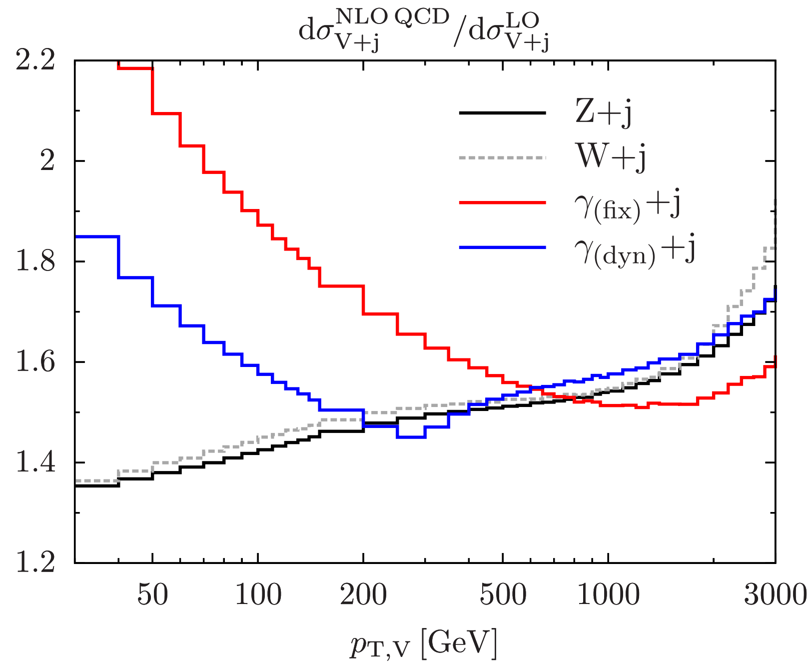
Different logarithmic effects from fragmentation

W/Z+jet: masscut-off MVj ≥MV

γ+ jet: Frixione-isolation cone of radius R_0



Consider dynamic **γ**-isolation with $R_{dyn}(pT,\gamma)$ = min{1.0, M_Z/pT_γ}

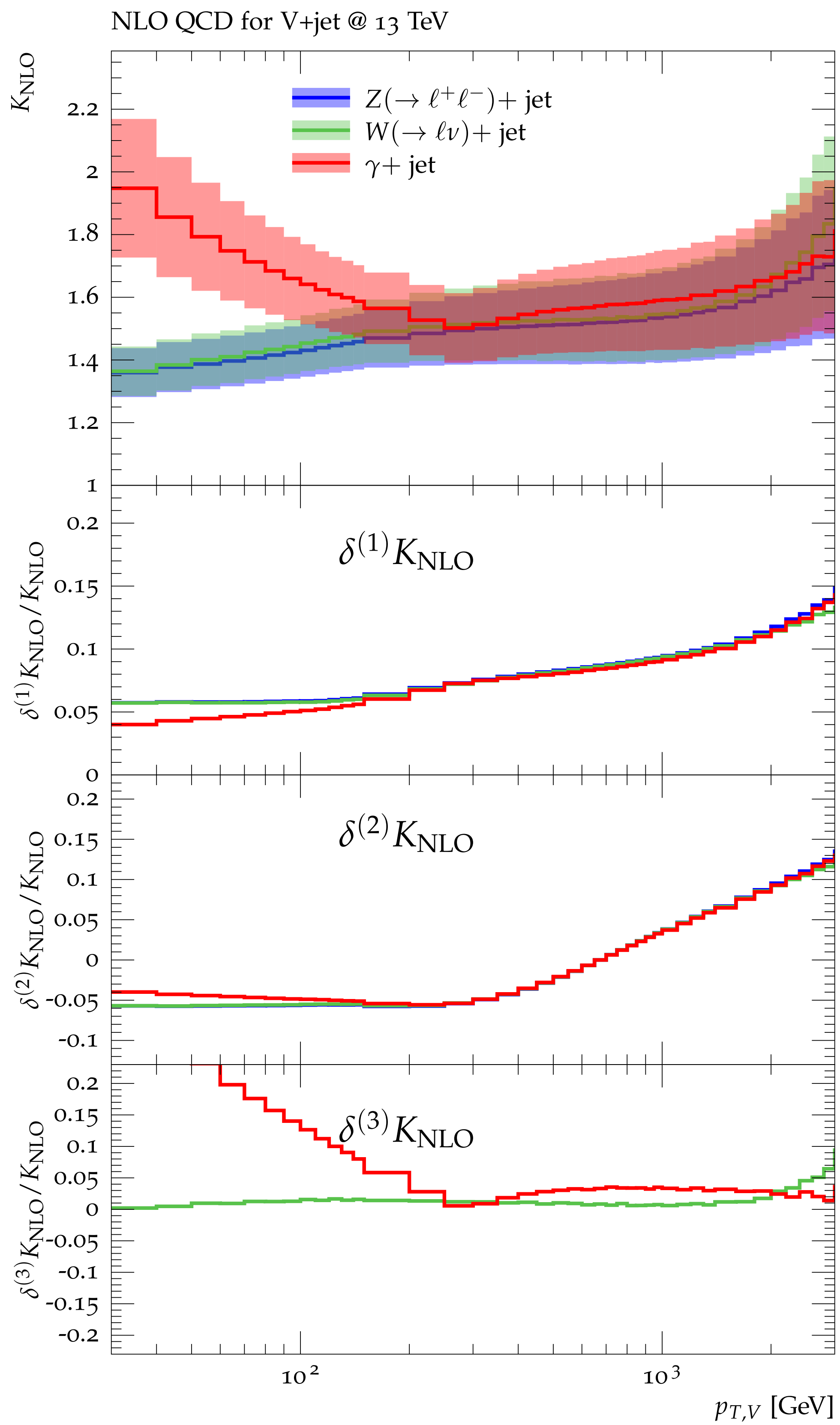


- **γ**$_{dyn}$ behaves like W/Z at pT > MZ

  ⇒justifies process-correlation estimate

- remnant part **γ**$_{fix}$ − **γ**$_{dyn}$ uncorrelated (uncertainty through extra reweighting and MC)

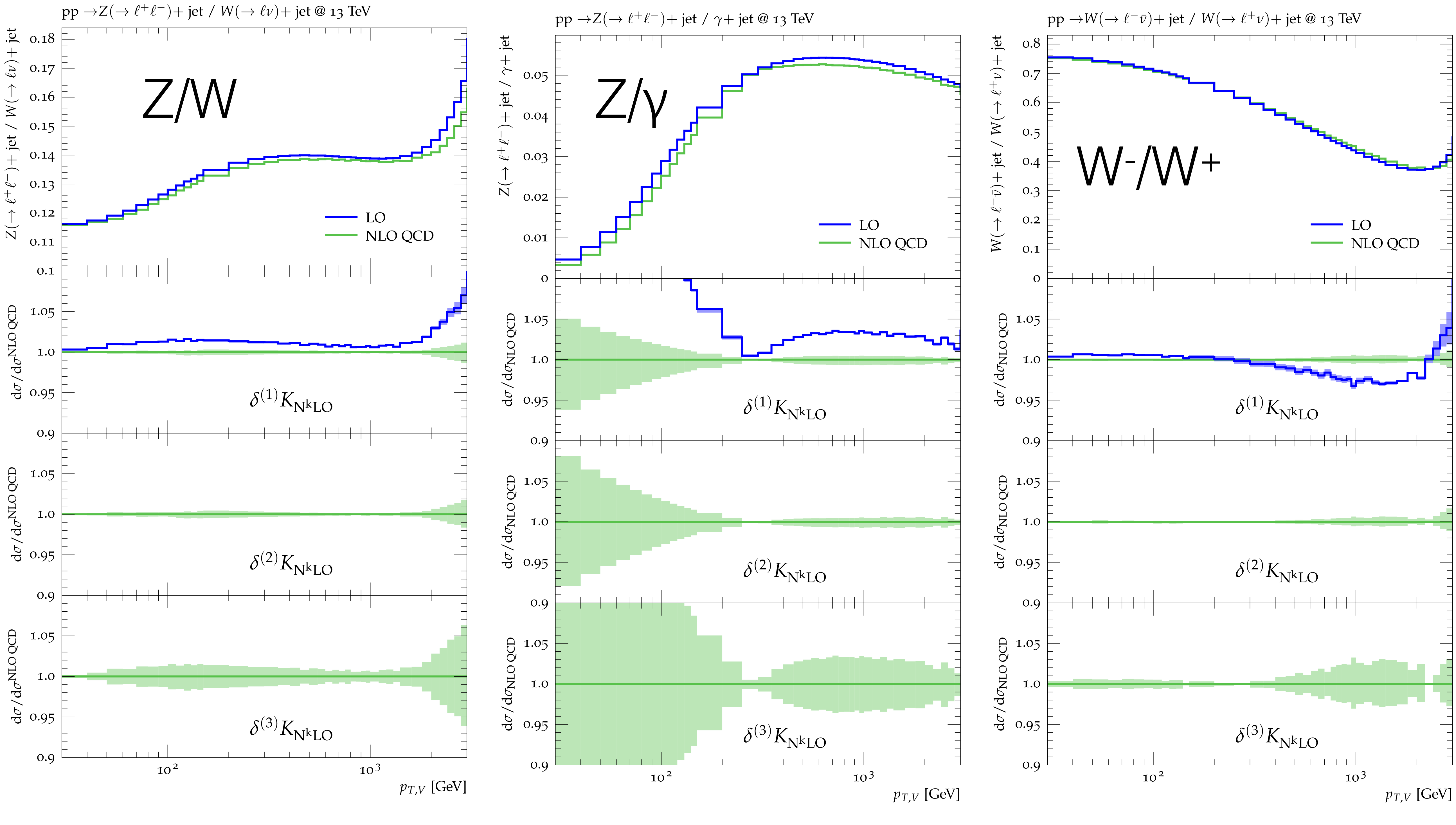
QCD uncertainties



NLO QCD corrections and uncertainties

- almost identical for W/Z/γ for pTV > 200 GeV
- sizeable γ+jet fragmentation for pTV > 200 GeV

QCD uncertainties in pT-ratios



Z/W± ≃1%

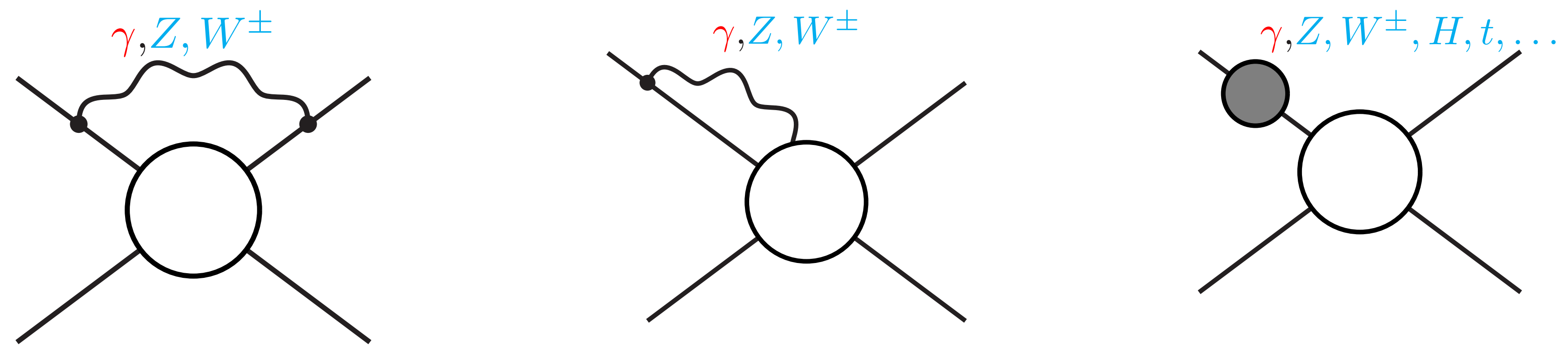
Z/γ ≃3%

W⁺/W⁻ ≃1–3%

2. pure EW effects uncertainties

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]*

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

- process-independent, simple structure
- typical size at $\sqrt{\hat{s}} = 1, 5, 10$ TeV:

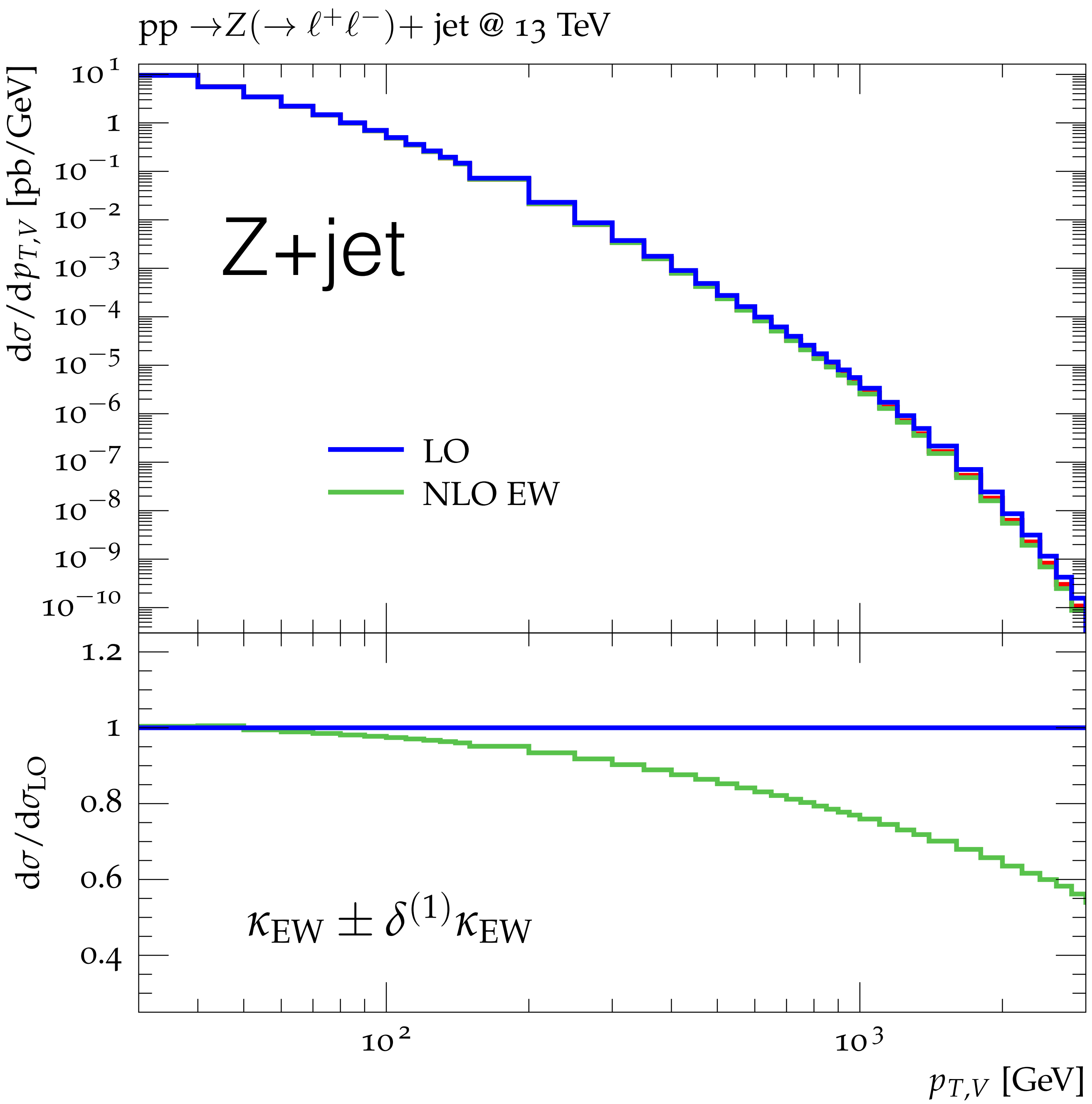
$$\delta_{\mathrm{LL}} \sim -\frac{\alpha}{\pi s_W^2}\log^2\frac{\hat{s}}{M_W^2} \simeq -28, -76, -104\%,$$

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

➡ large (negative) corrections at high energies (pT, MET, HT, Minv)

➡ sizeable cancellations between leading and subleading terms possible

Pure EW uncertainties



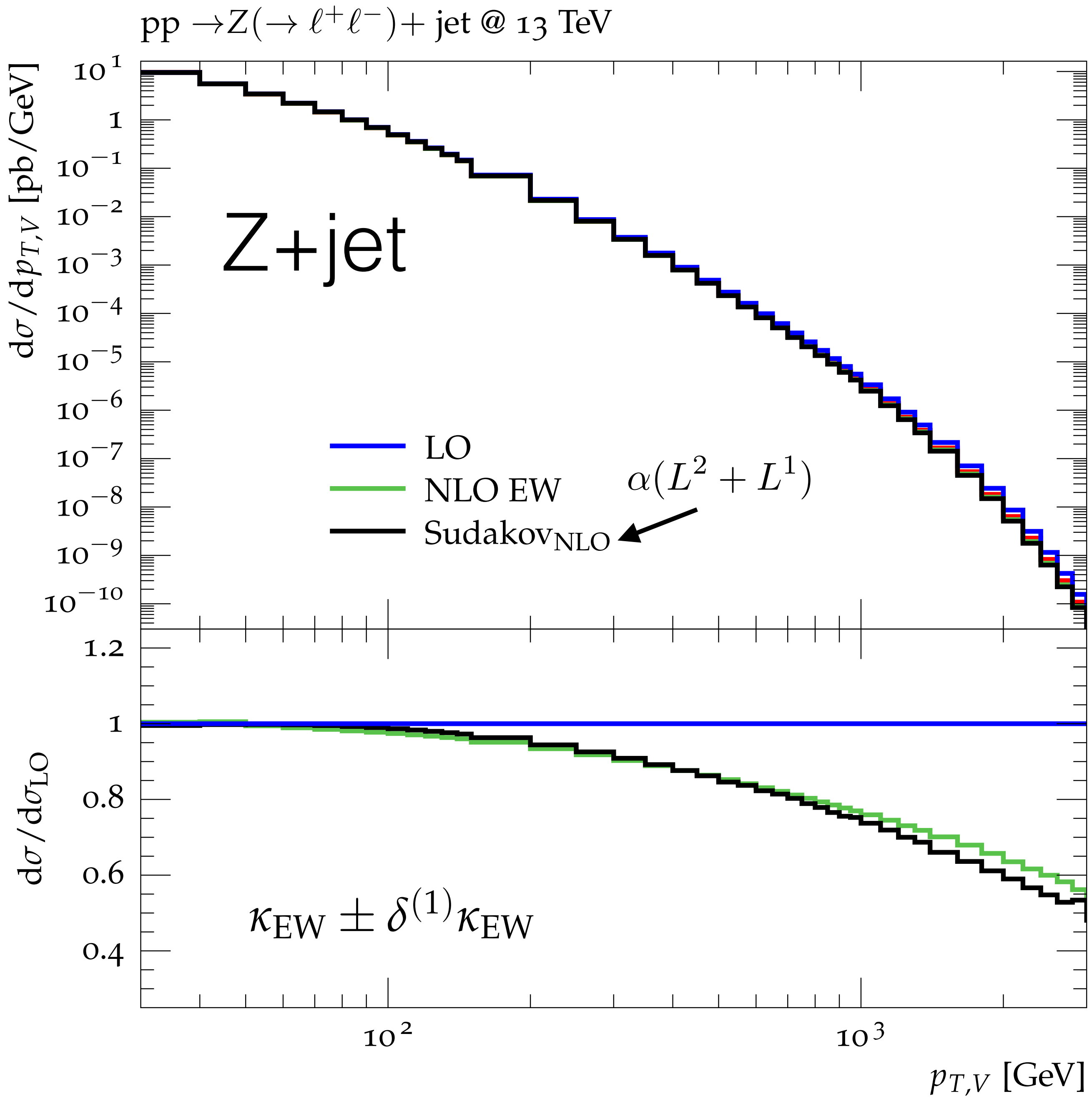
EW corrections become sizeable at large $p_{T,V}$

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



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

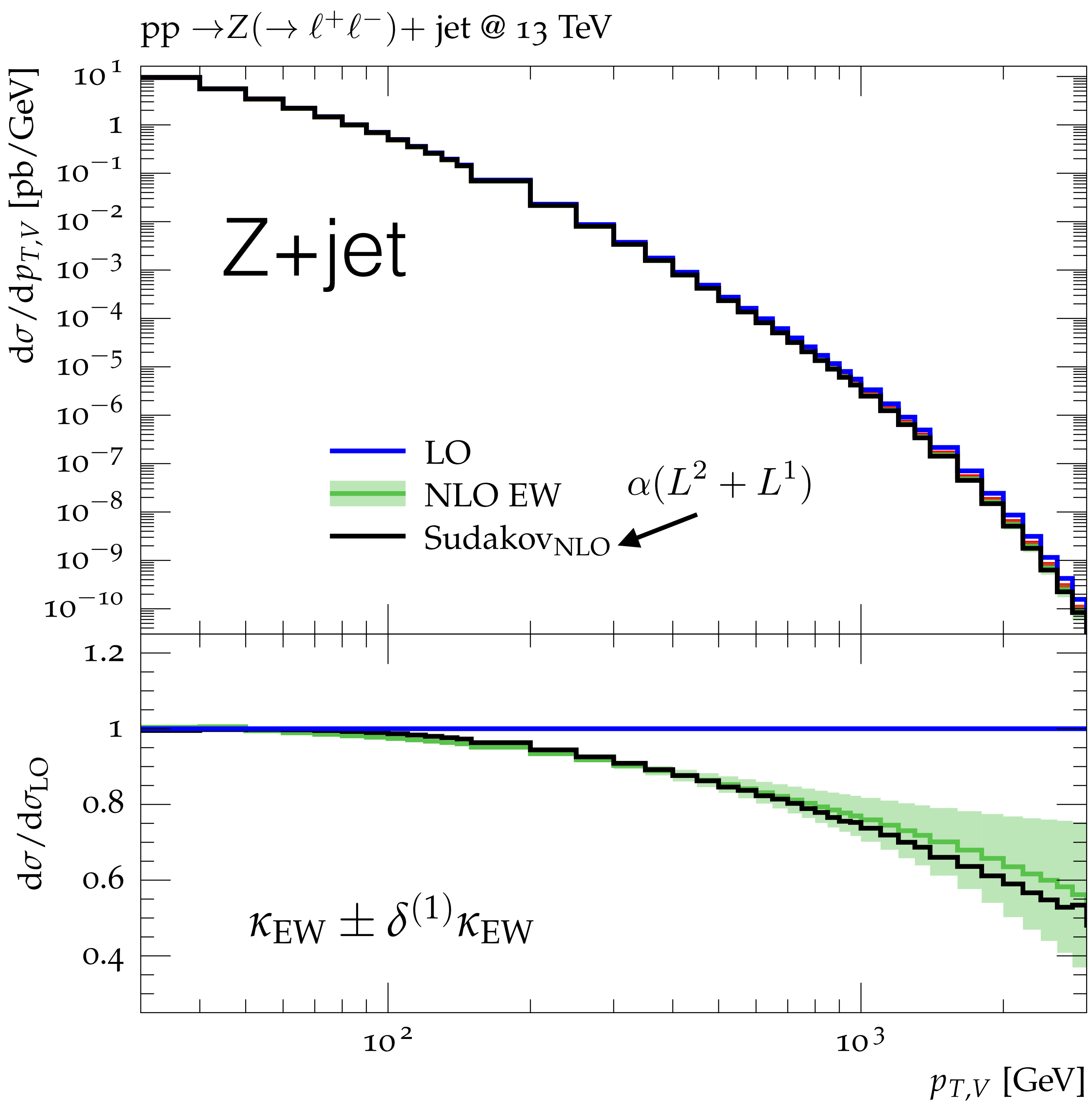
Large EW corrections dominated by Sudakov logs

↓

Uncertainty estimate of NLO EW from naive exponentiation × 2:

$$\delta^{(1)}\kappa_{\mathrm{EW}} \simeq \frac{2}{k!}\Big(\kappa_{\mathrm{NLO,EW}}\Big)^{k}$$

Pure EW uncertainties



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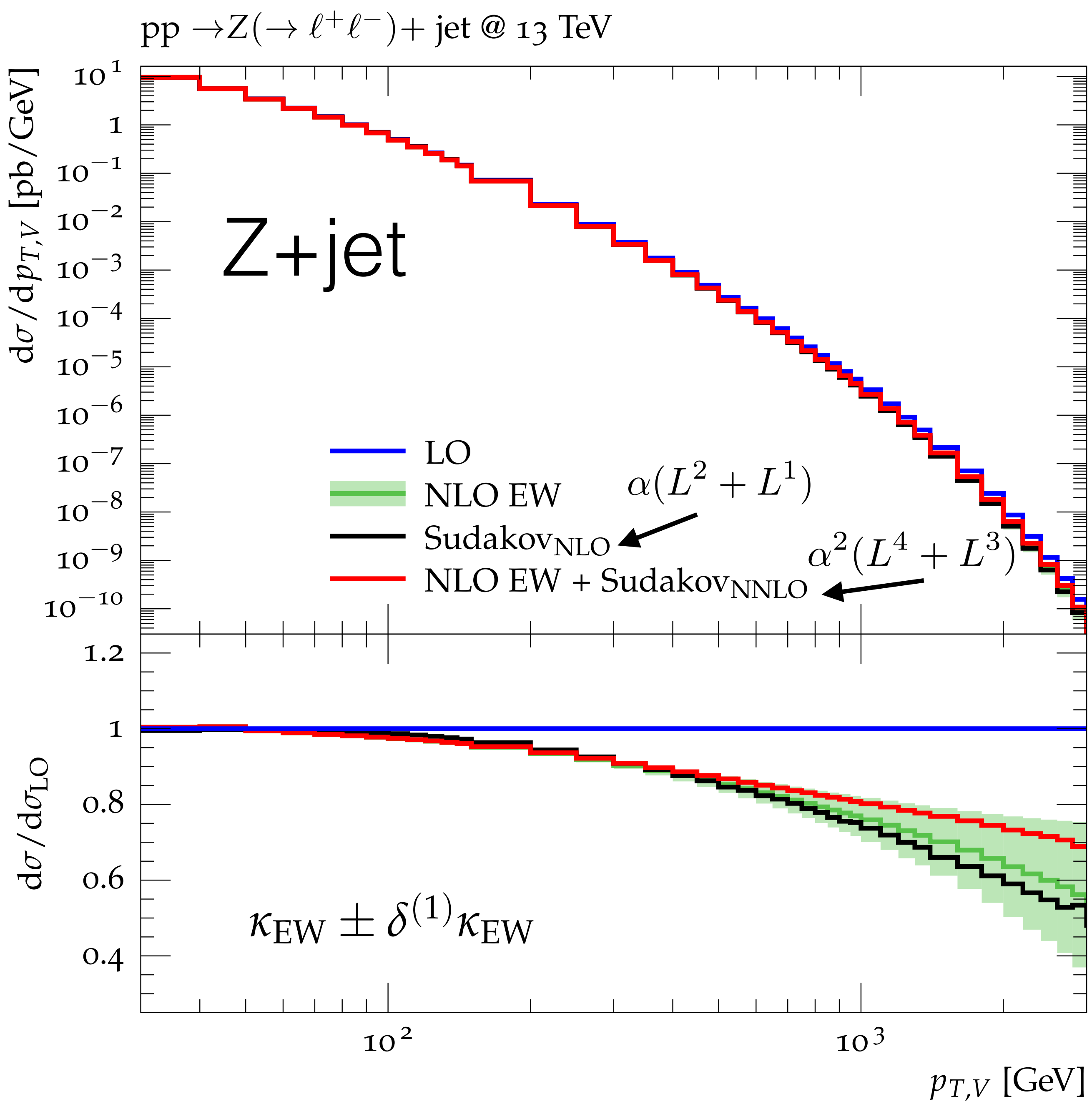


$$\kappa_{\mathrm{NLO\,EW}}(\hat{s},\hat{t}) = \frac{\alpha}{\pi}\left[\delta^{(1)}_{\mathrm{hard}} + \delta^{(1)}_{\mathrm{Sud}}\right]$$

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

Large EW corrections dominated by Sudakov logs

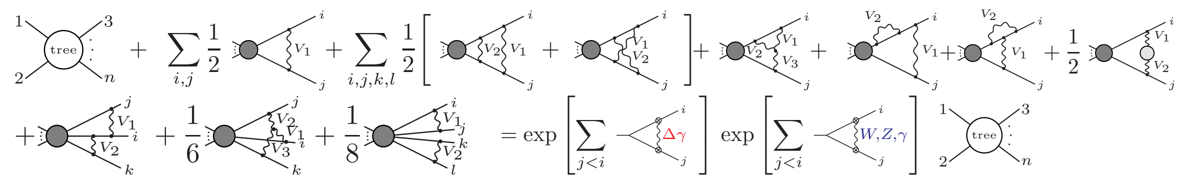
↓

Uncertainty estimate of NLO EW from naive exponentiation × 2:

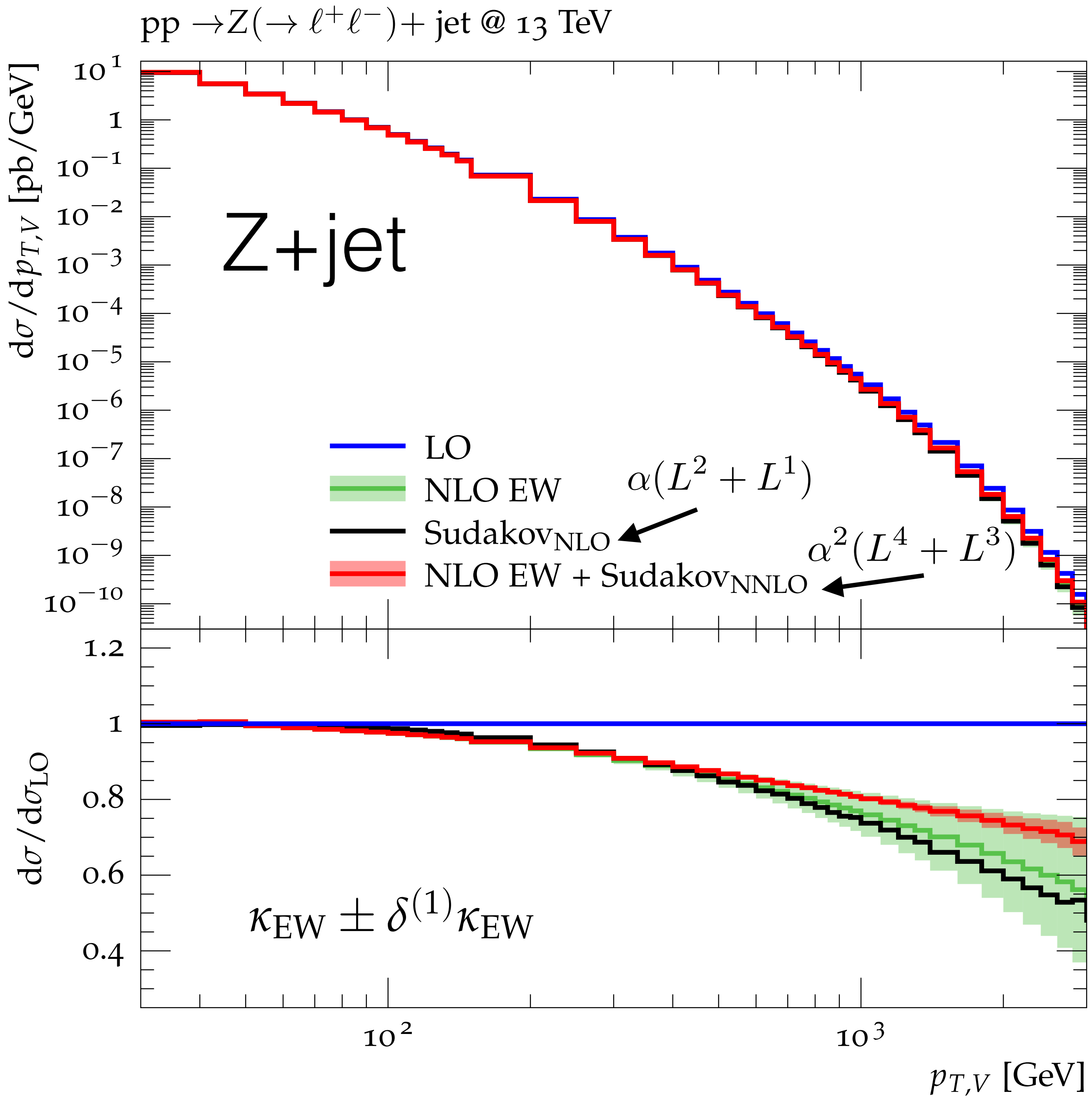
$$\delta^{(1)}\kappa_{\mathrm{EW}} \simeq \frac{2}{k!}\left(\kappa_{\mathrm{NLO,EW}}\right)^k$$

↓

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



Pure EW uncertainties



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

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

Large EW corrections dominated by Sudakov logs

↓

Uncertainty estimate of NLO EW from naive exponentiation × 2:

$$\delta^{(1)}\kappa_{\mathrm{EW}} \simeq \frac{2}{k!}\left(\kappa_{\mathrm{NLO,EW}}\right)^k$$

↓

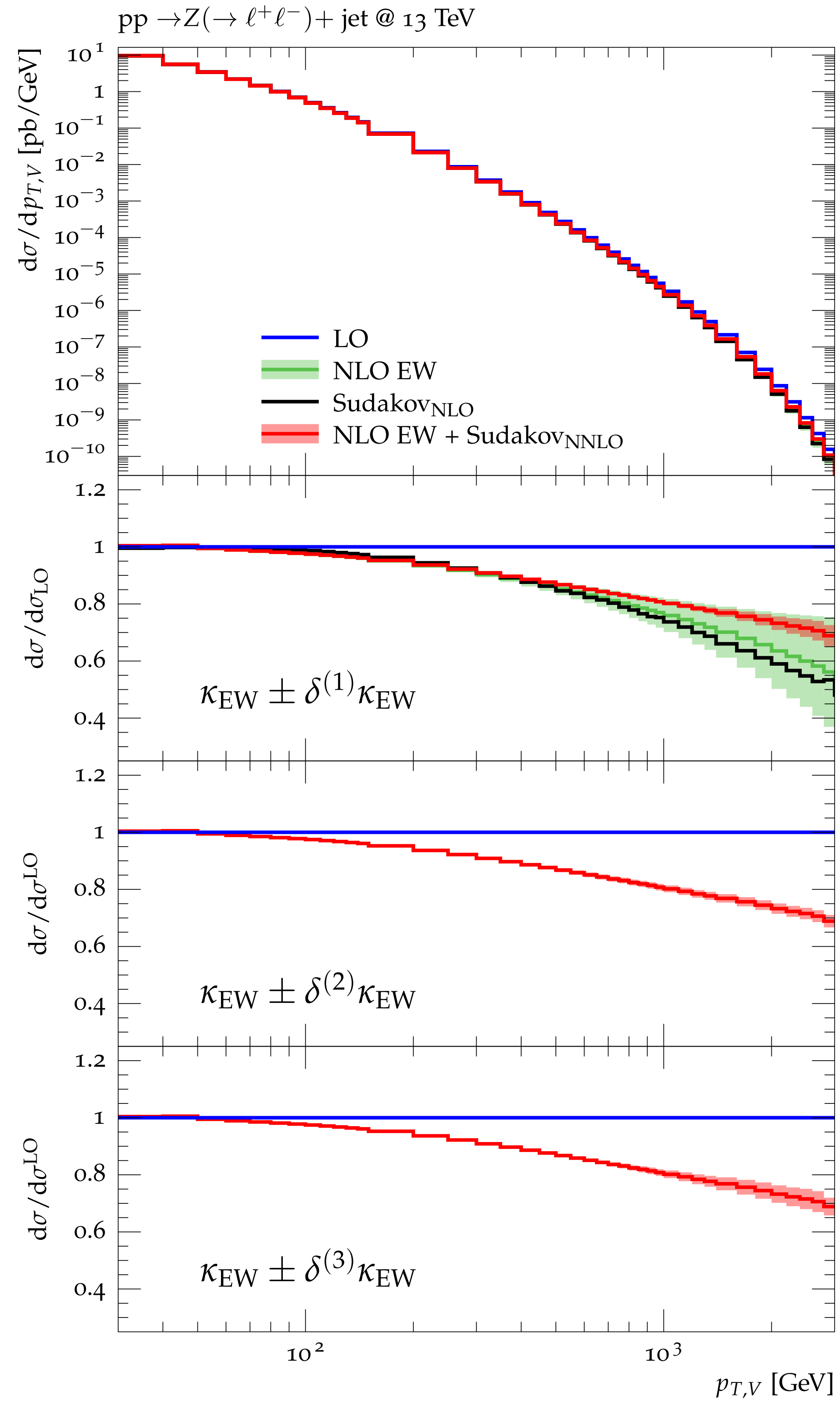
check against two-loop Sudakov logs
[Kühn, Kulesza, Pozzorini, Schulze; 05-07]

↓

Uncertainty estimate of NNLO EW:

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

Pure EW uncertainties



- 'higher-order logs'

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

(correlated)

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)

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

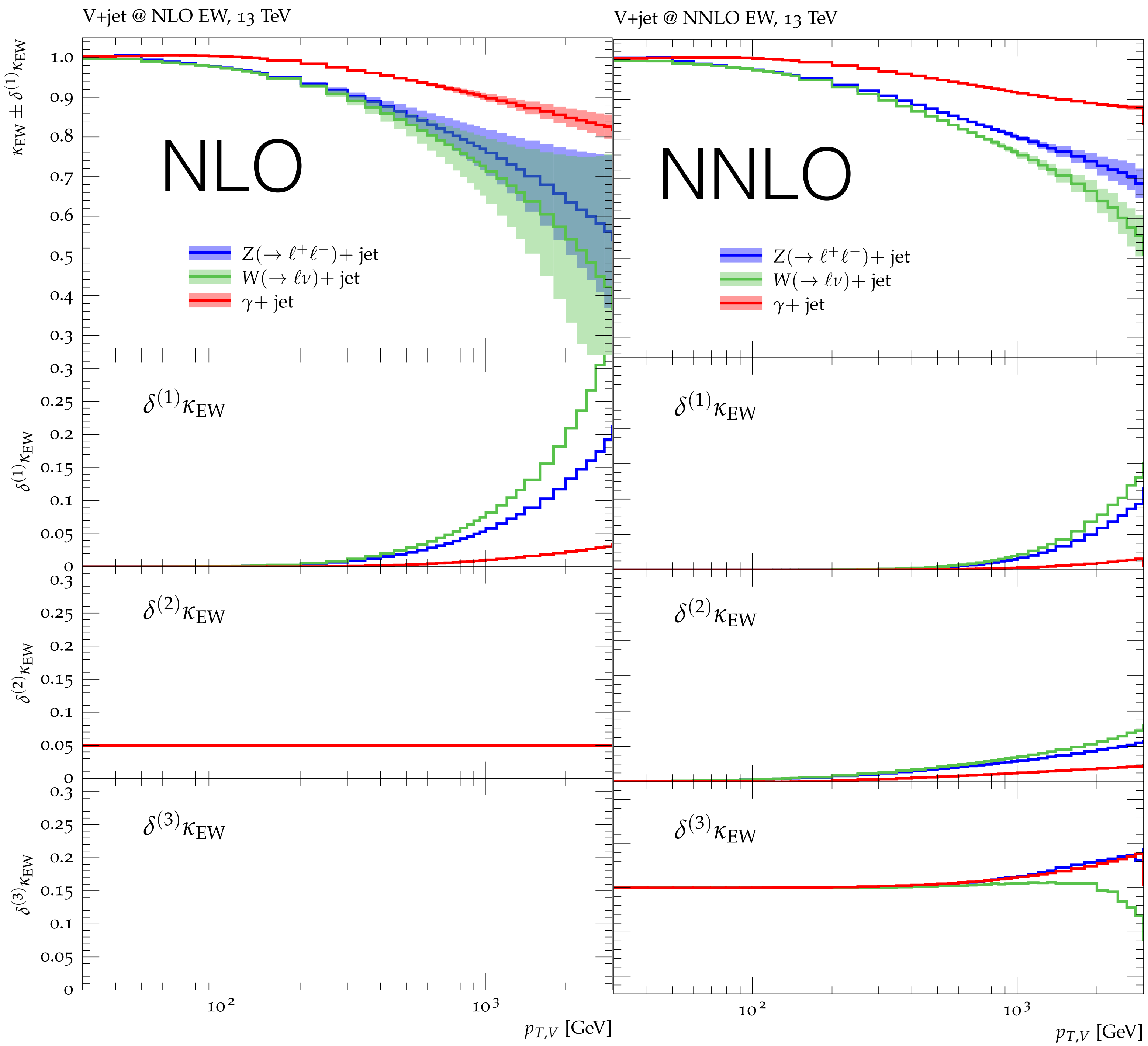
- 'hard non-log NNLO effects II'

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

(uncorrelated)

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



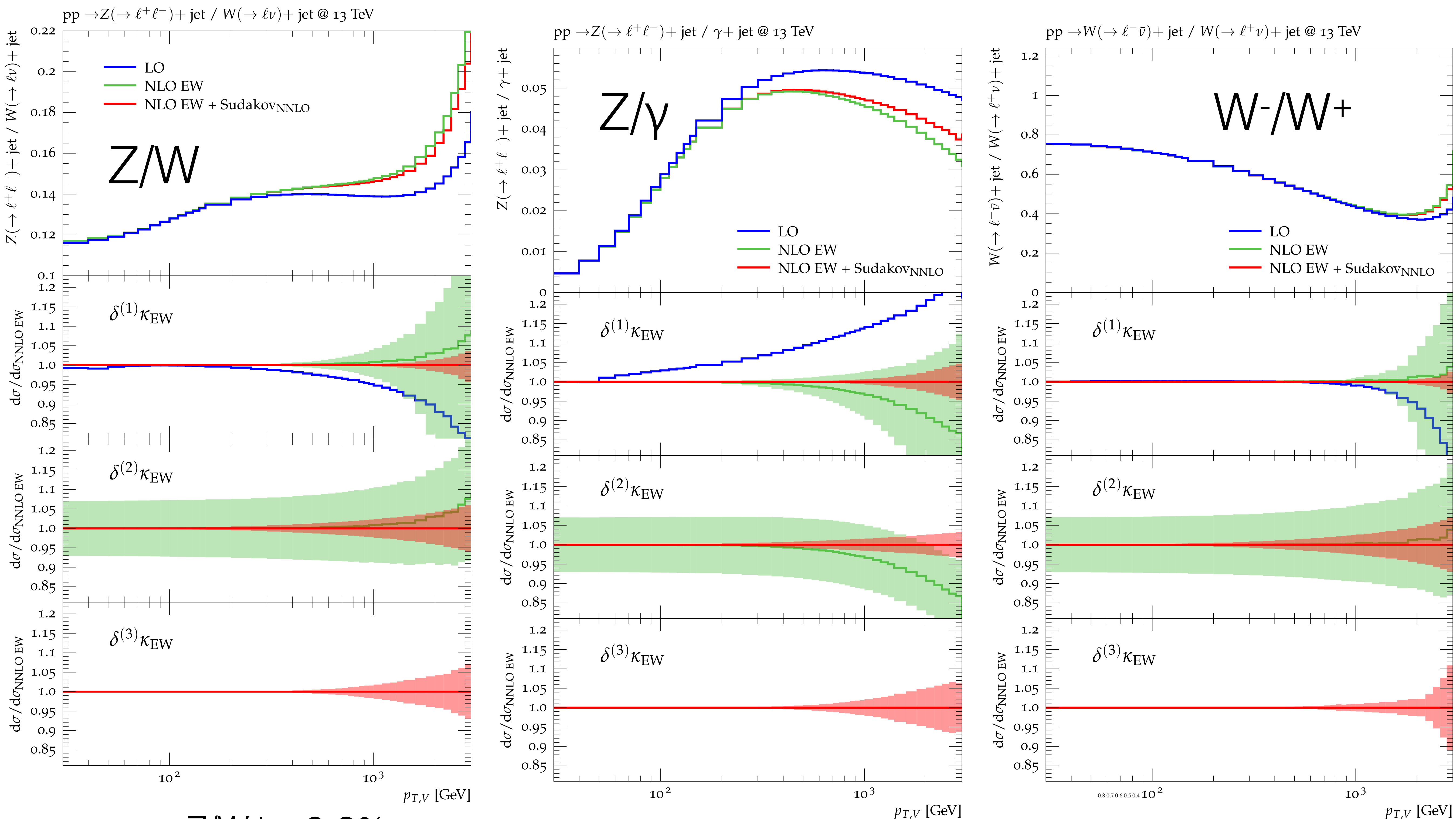
NNLO EW corrections at 1 TeV

- -10% for γ+jets
- -20% for Z+jet
- -25% for W+jet

Pure EW uncertainties

- tiny at low pT and only 1-2% at 1 TeV
- thanks to NNLO Sudakov logs (up to ~ 5%)

EW uncertainties in pT-ratios



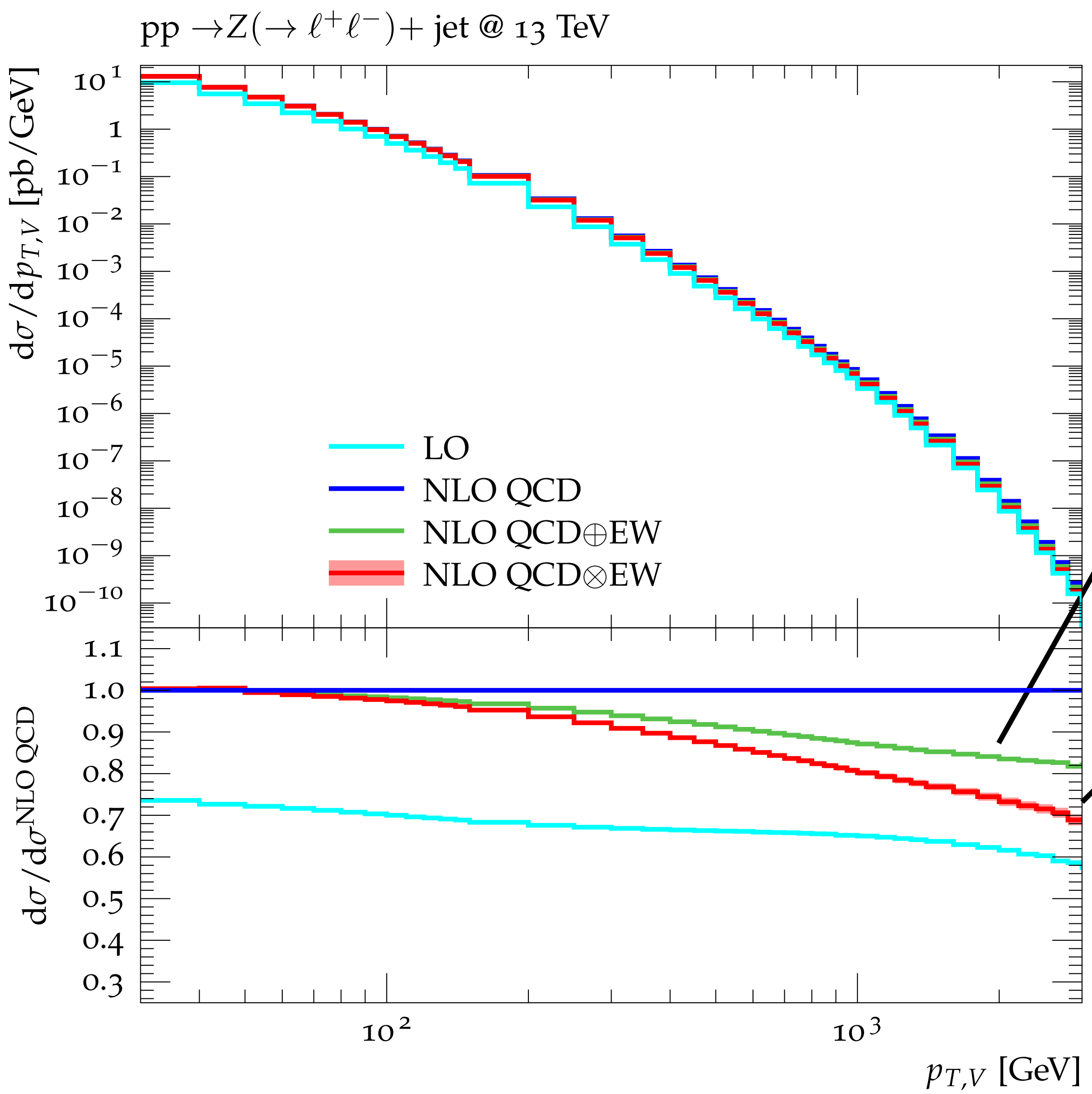
Z/W± ≃2-3%

Z/**γ** ≃2-3%

W+/W− ≃2–3%

3. mixed QCD-EW 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.

Additive combination

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

(no $\mathcal{O}(\alpha\alpha_s)$ contributions)

Multiplicative combination

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

(some dominant $\mathcal{O}(\alpha\alpha_s)$ contributions, e.g. EW Sudakov logs × soft QCD)

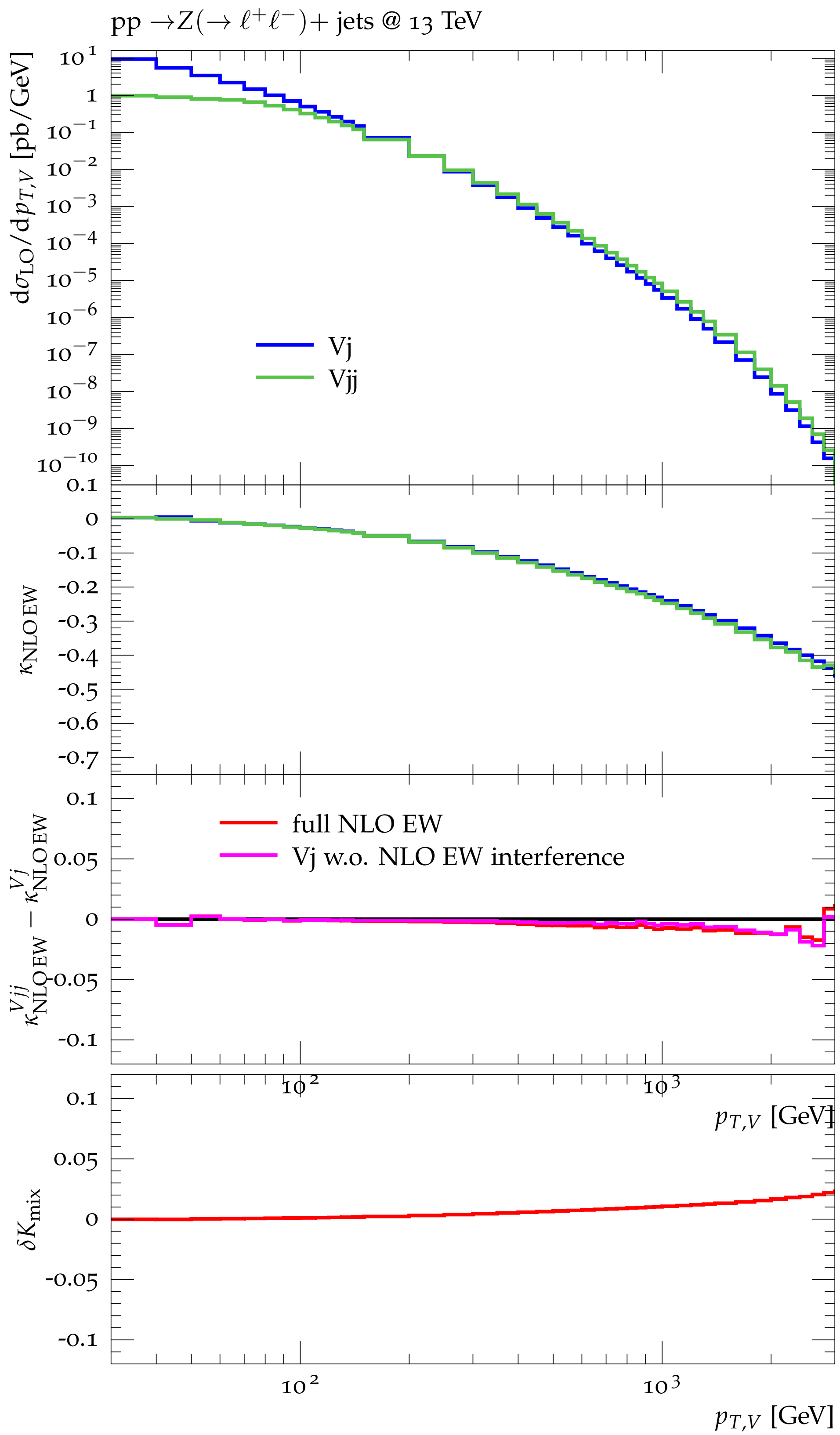
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

$$K_{\mathrm{QCD}\otimes\mathrm{EW}} - K_{\mathrm{QCD}\oplus\mathrm{EW}} \sim 10\% \quad \text{at 1 TeV}$$

Too conservative!?

For dominant Sudakov EW logarithms factorization should be exact!

Mixed QCD-EW uncertainties



Bold estimate:

Consider real $\mathcal{O}(\alpha\alpha_s)$ correction to V+jet

$\simeq$ NLO EW to V+2jets

and we observe

$$\left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{V+2\mathrm{jet}} - \left.\frac{d\sigma_{\mathrm{NLO\,EW}}}{d\sigma_{\mathrm{LO}}}\right|_{V+1\mathrm{jet}} \lesssim 1\%$$

strong support for

- factorization
- multiplicative QCD x EW combination

Estimate of non-factorising contributions

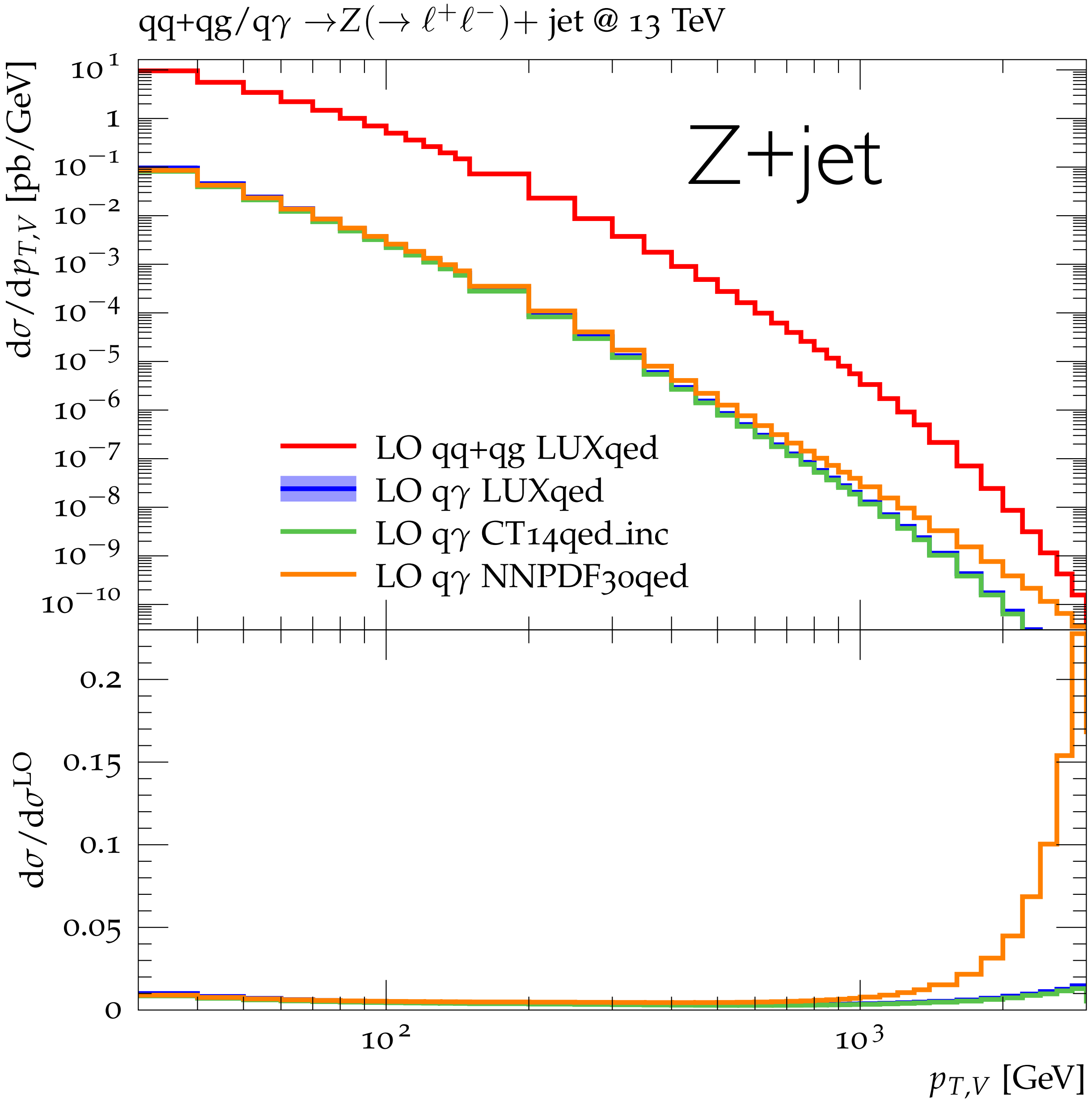
(correlated)

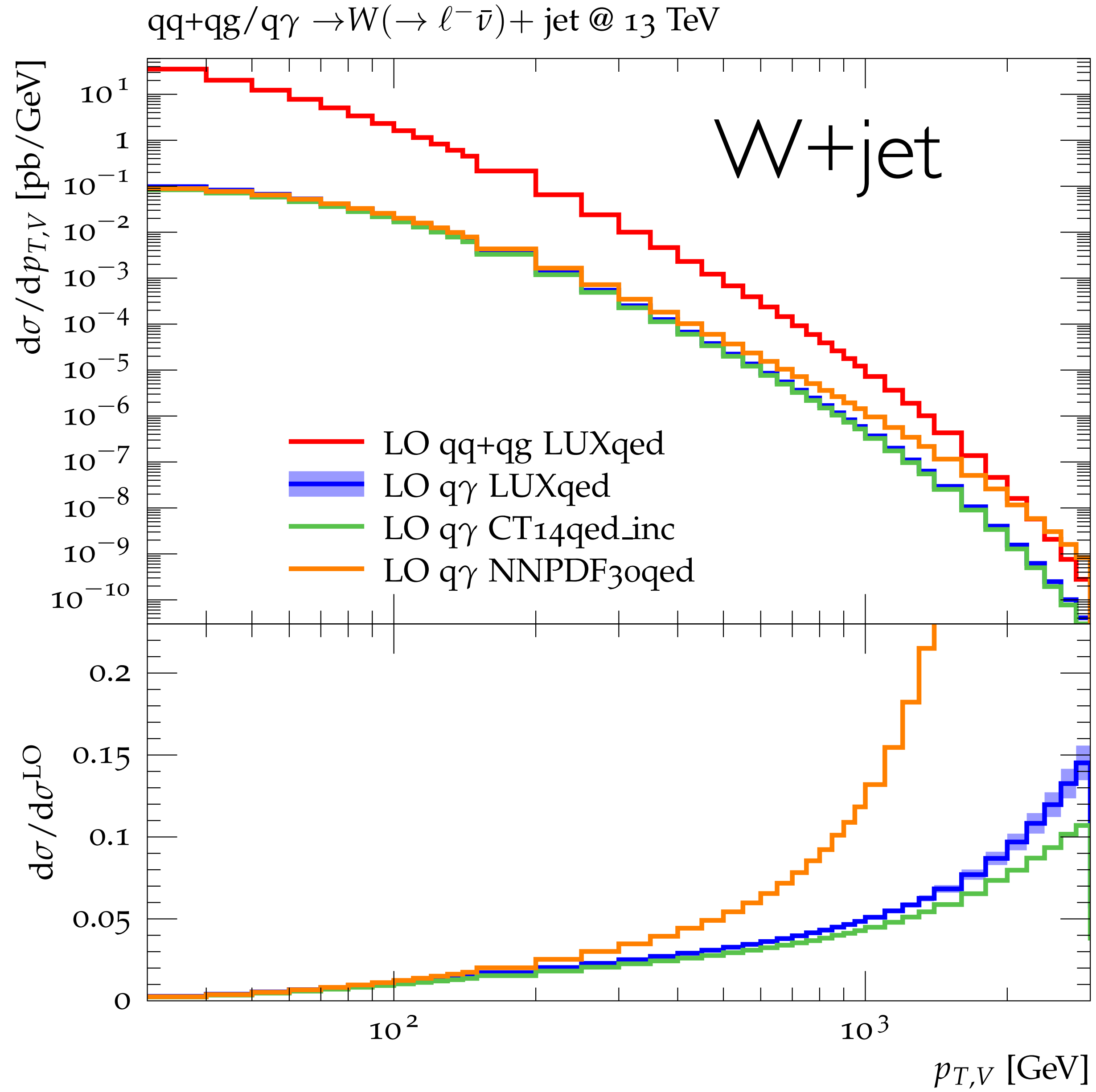
$$\delta K^{(V)}_{\mathrm{mix}}(x) \quad = \quad 0.1\left[K^{(V)}_{\mathrm{TH},\oplus}(x,\vec{\mu}_0) - K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\mu}_0)\right]$$

(tuned to cover above difference of EW K-factors)

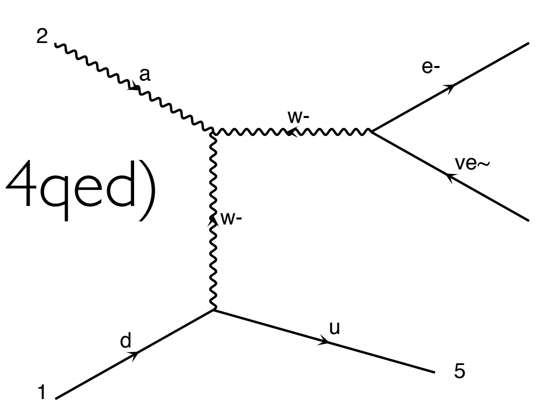
4. Other issues (PDFs, γ-induced)

Photon-induced production

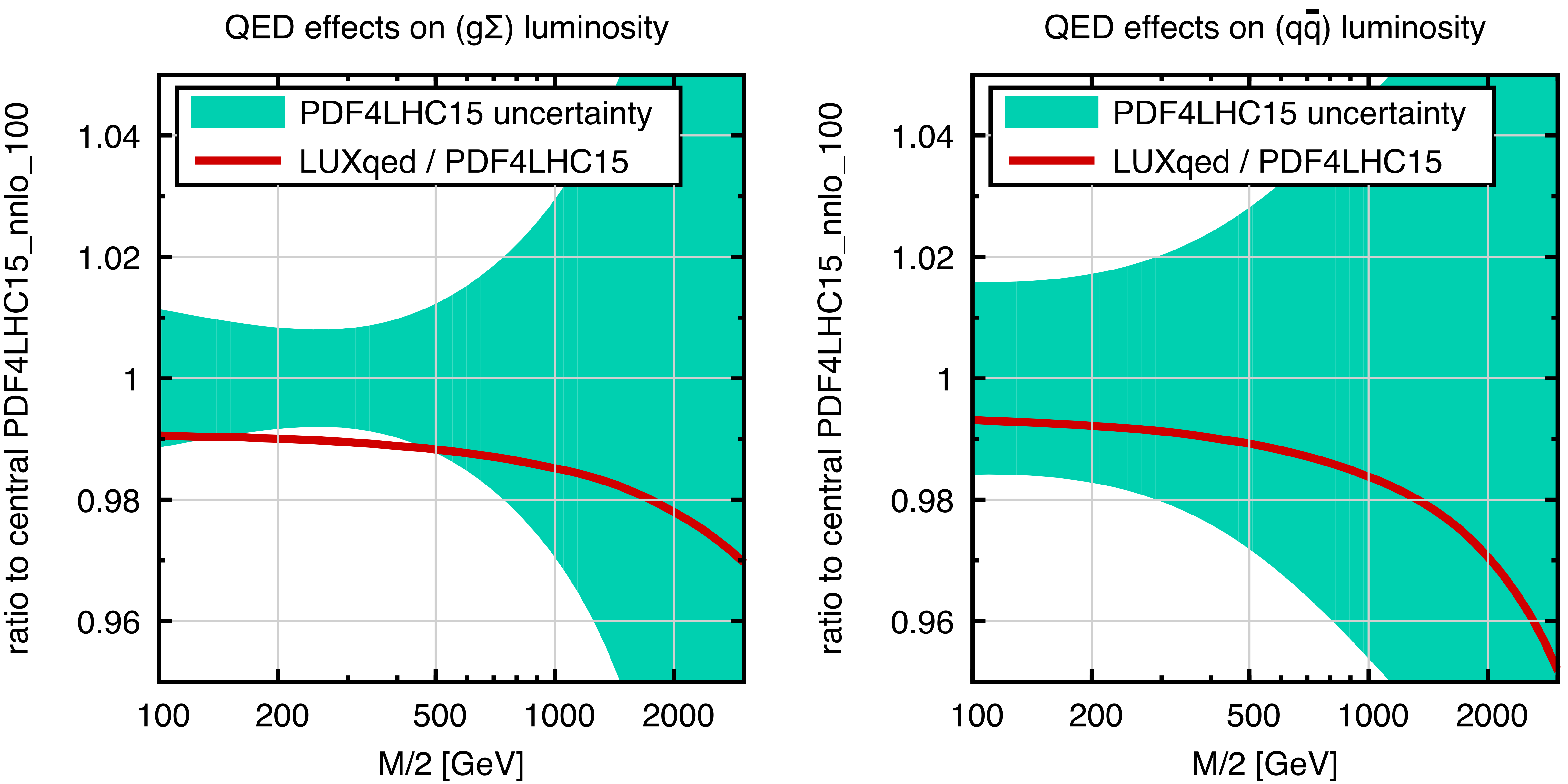




- photon-induced production irrelevant for Z+jet (and **γ**+jet)
- in W+jet O(5%) contribution with LUXqed (consistent with CT14qed) (due to t-channel enhancement)
- ~1% uncertainties in photon PDFs due to LUXqed



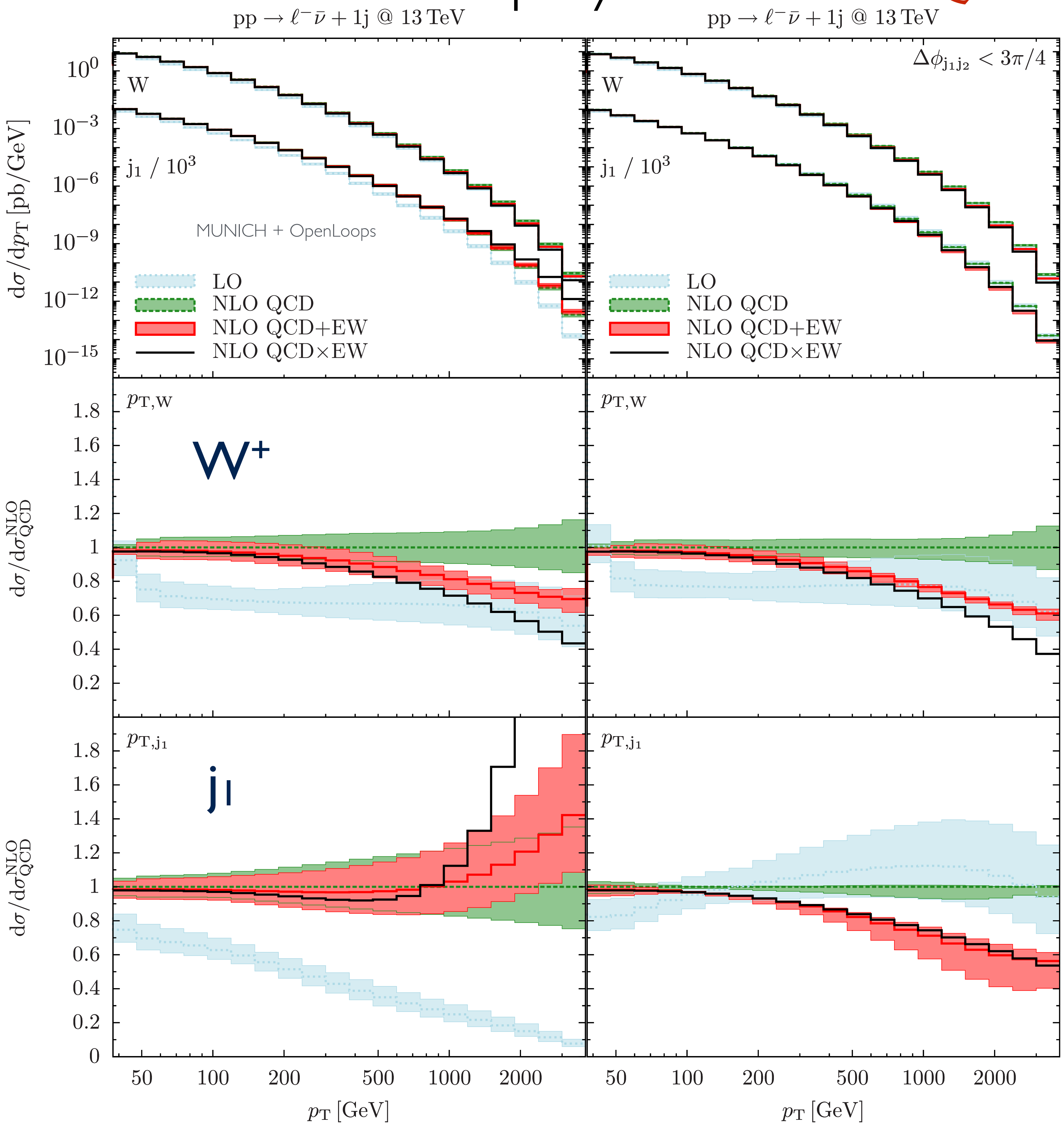
PDFs

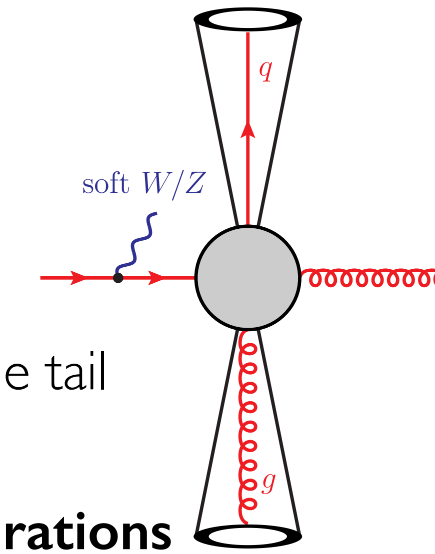


- small percent-level QED effects on qg/qq luminosities (included via LUXqed)
- 1.5-5% PDF uncertainties

Exclusive V+jets

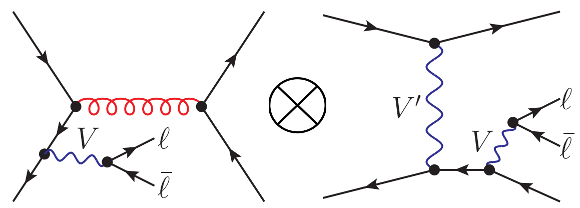
Interplay between QCD and EW





p_T of jet

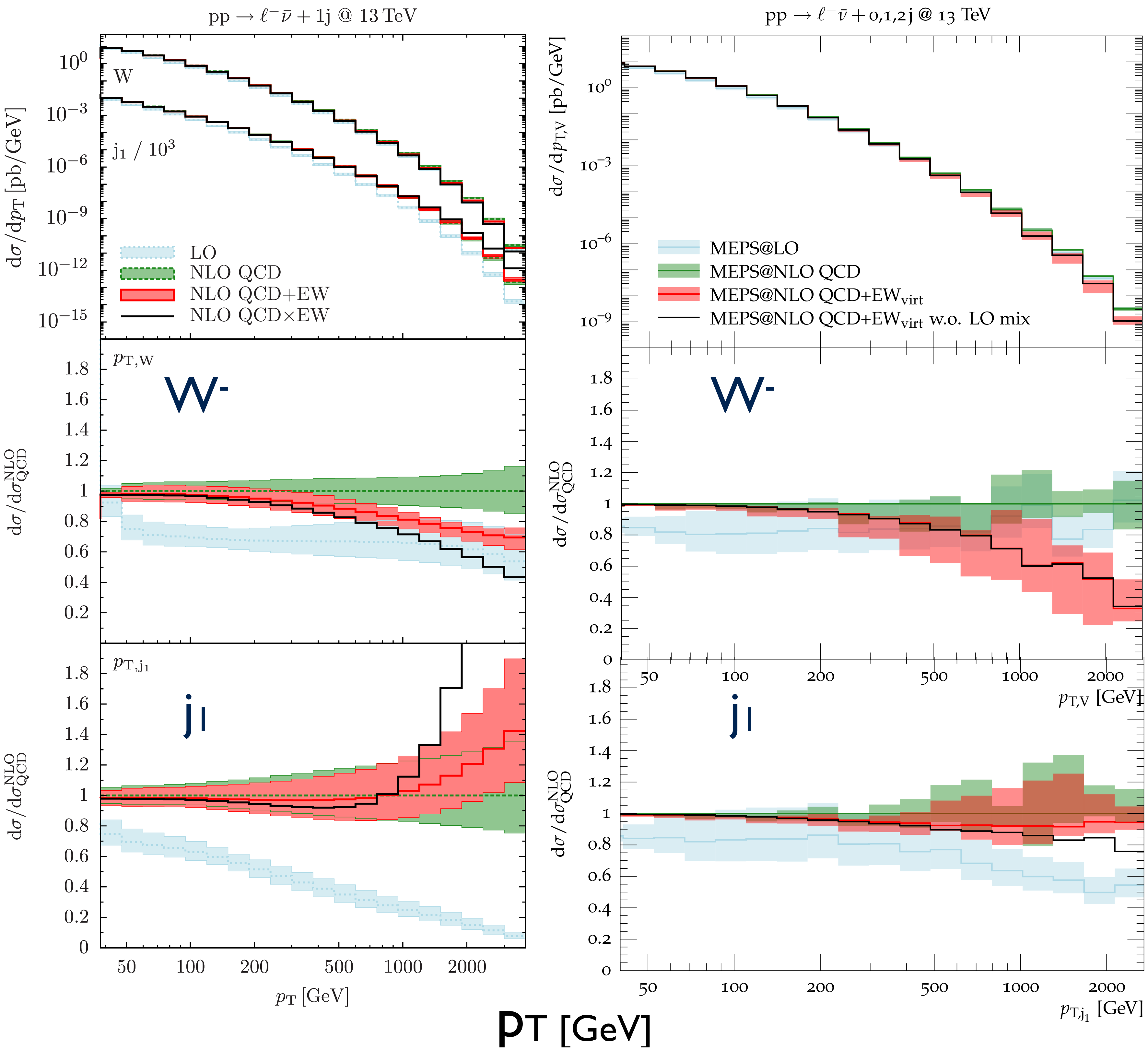
- "giant QCD K-factors" in the tail *[Rubin, Salam, Sapeta '10]*
- dominated by **dijet configurations**
- positive 10-50% EW corrections from quark bremsstrahlung



⟹ pathologic with large uncertainties!

⟹ exclusive jet observables require merging W+1jet with W+2 jets at NLO QCD+EW!

MEPS@NLO QCD+EW$_{\mathrm{virt}}$



- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations
- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)

  ★again: support for factorization!!
- $p_{T,j1}$: compensation between negative Sudakov and LO mix

Conclusions

- 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

- percent precision requires scrutiny of many subtleties and close TH/EXP interplay
- Experimental closure tests in control regions
- Applicability to other more exclusive observables / process classes

Illuminating standard candles at the LHC - V+jets

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

Search...

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- Registration
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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

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

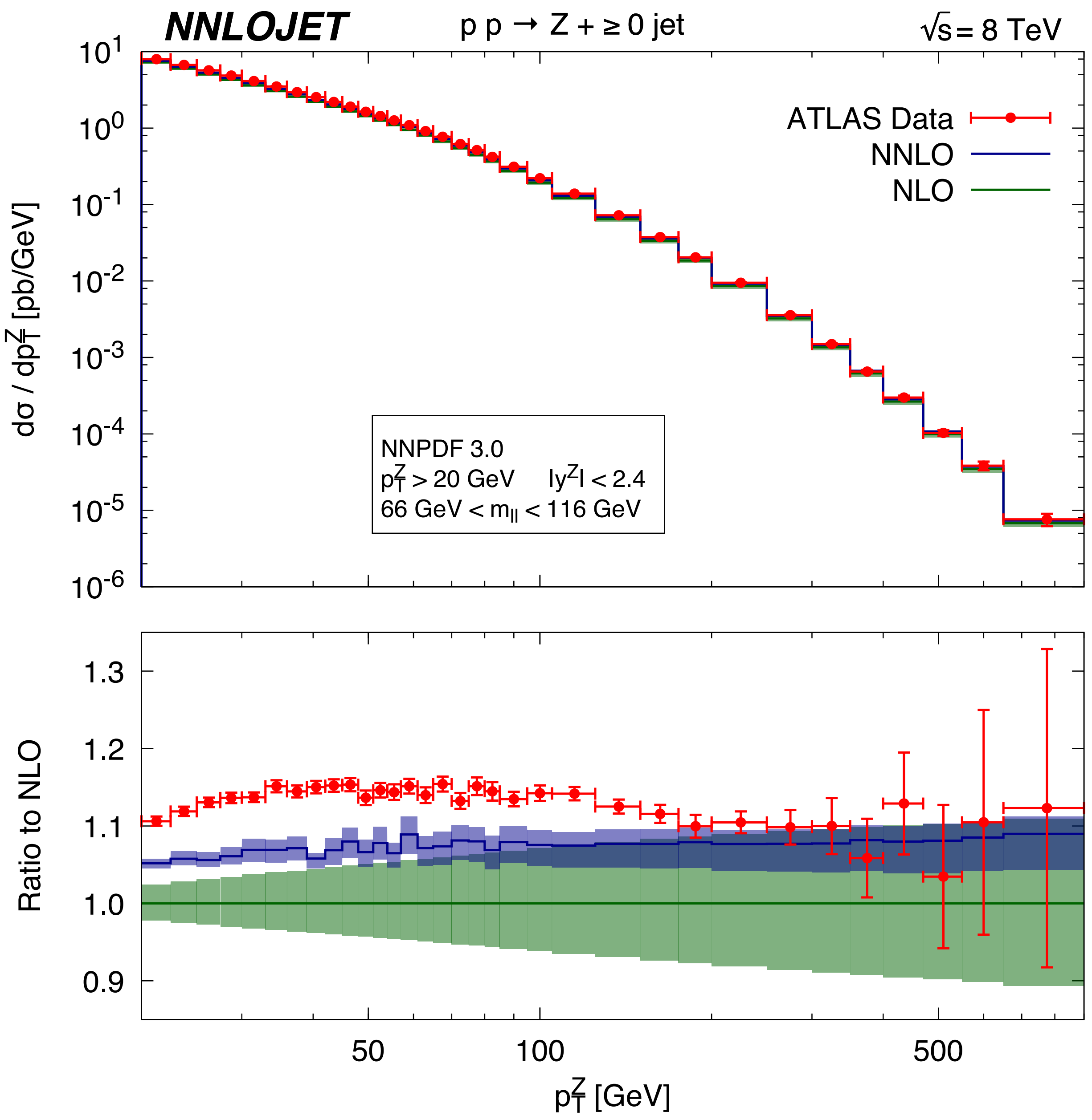
$$\begin{aligned} K^{(V)}_{\mathrm{TH}}(x,\vec{\varepsilon}_{\mathrm{QCD}},\vec{\varepsilon}_{\mathrm{EW}},\varepsilon_{\mathrm{mix}}) &= K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\varepsilon}_{\mathrm{QCD}},\vec{\varepsilon}_{\mathrm{EW}}) + \varepsilon_{\mathrm{mix}}\,\delta K^{(V)}_{\mathrm{mix}}(x), \\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

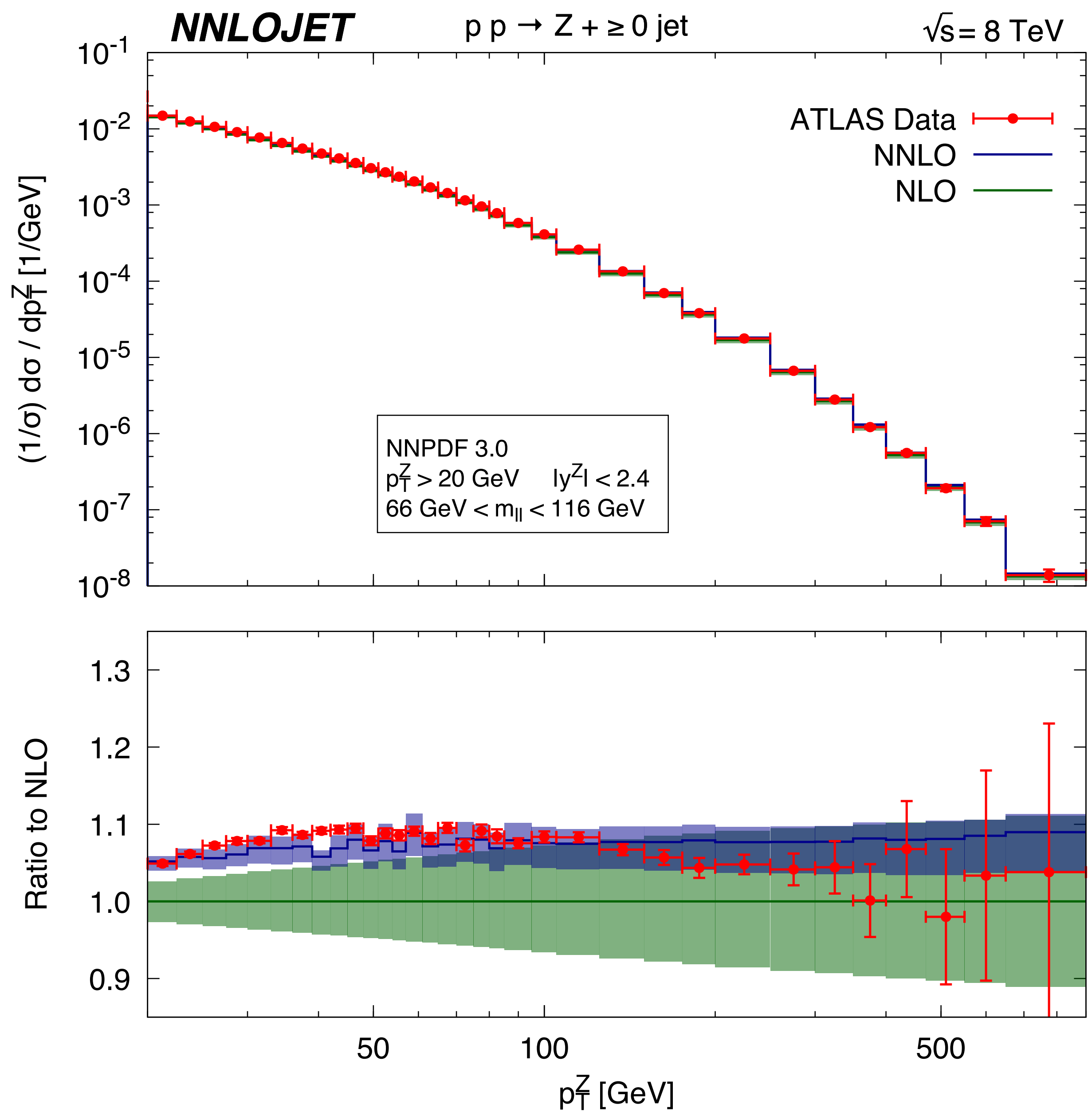
$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{LO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NLO\,QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{NNLO\,QCD}}$$

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

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

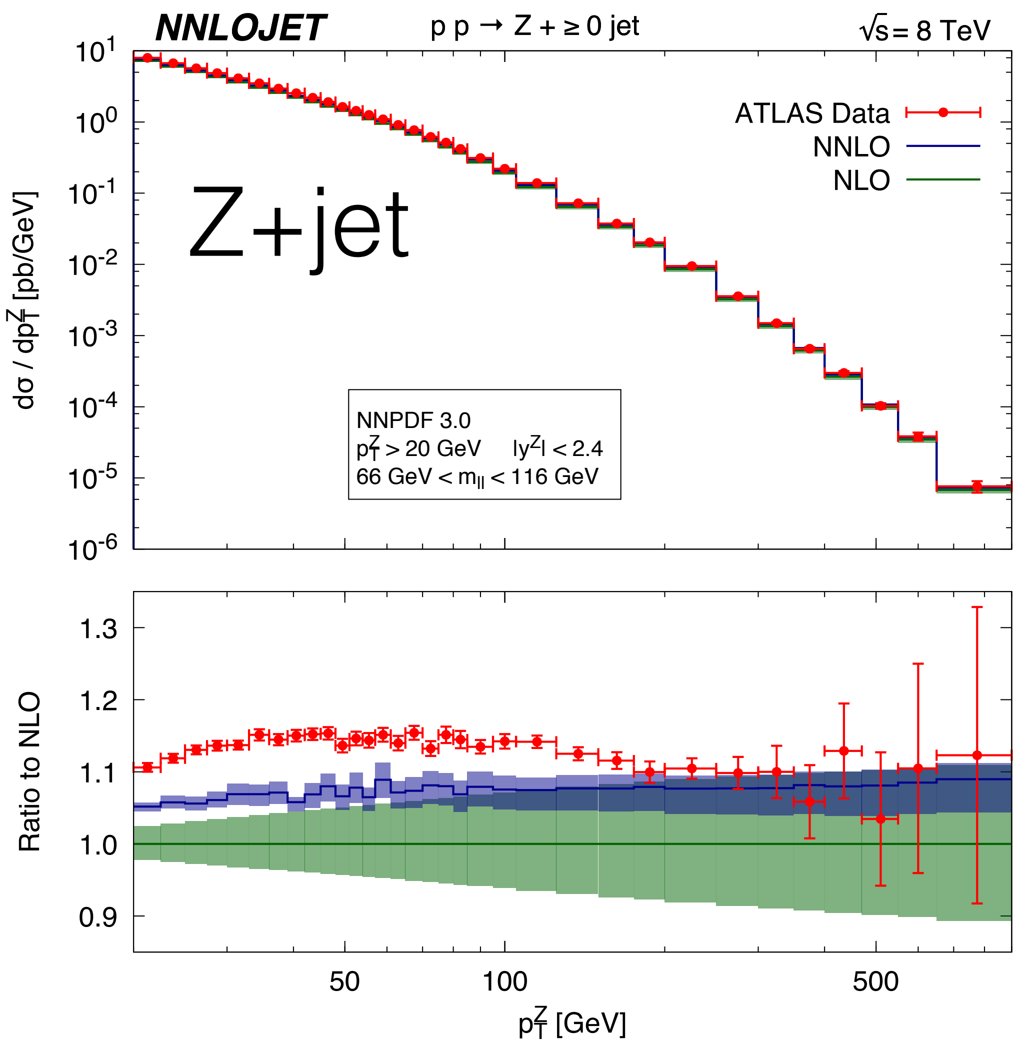
NNLO for Z+jet



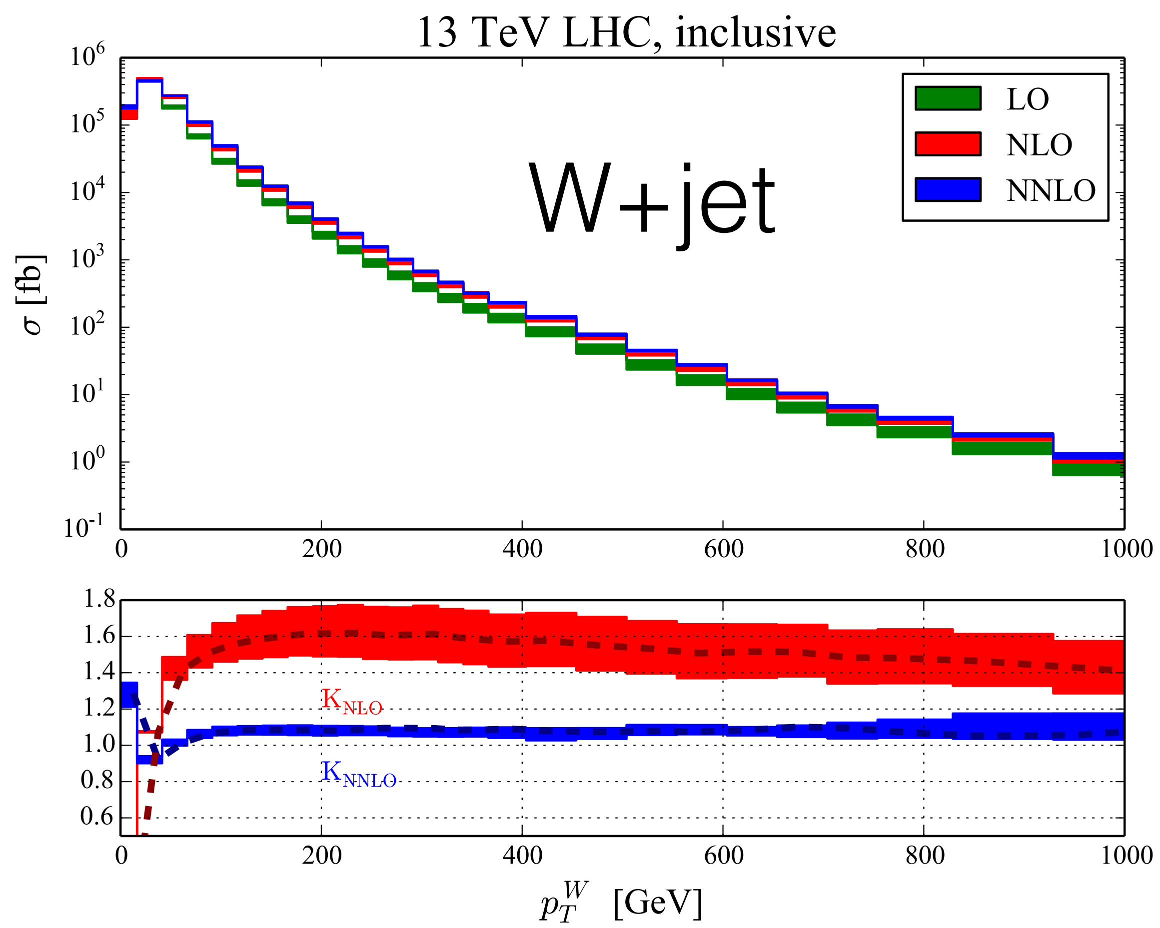


[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]

NNLO for W/Z+jet



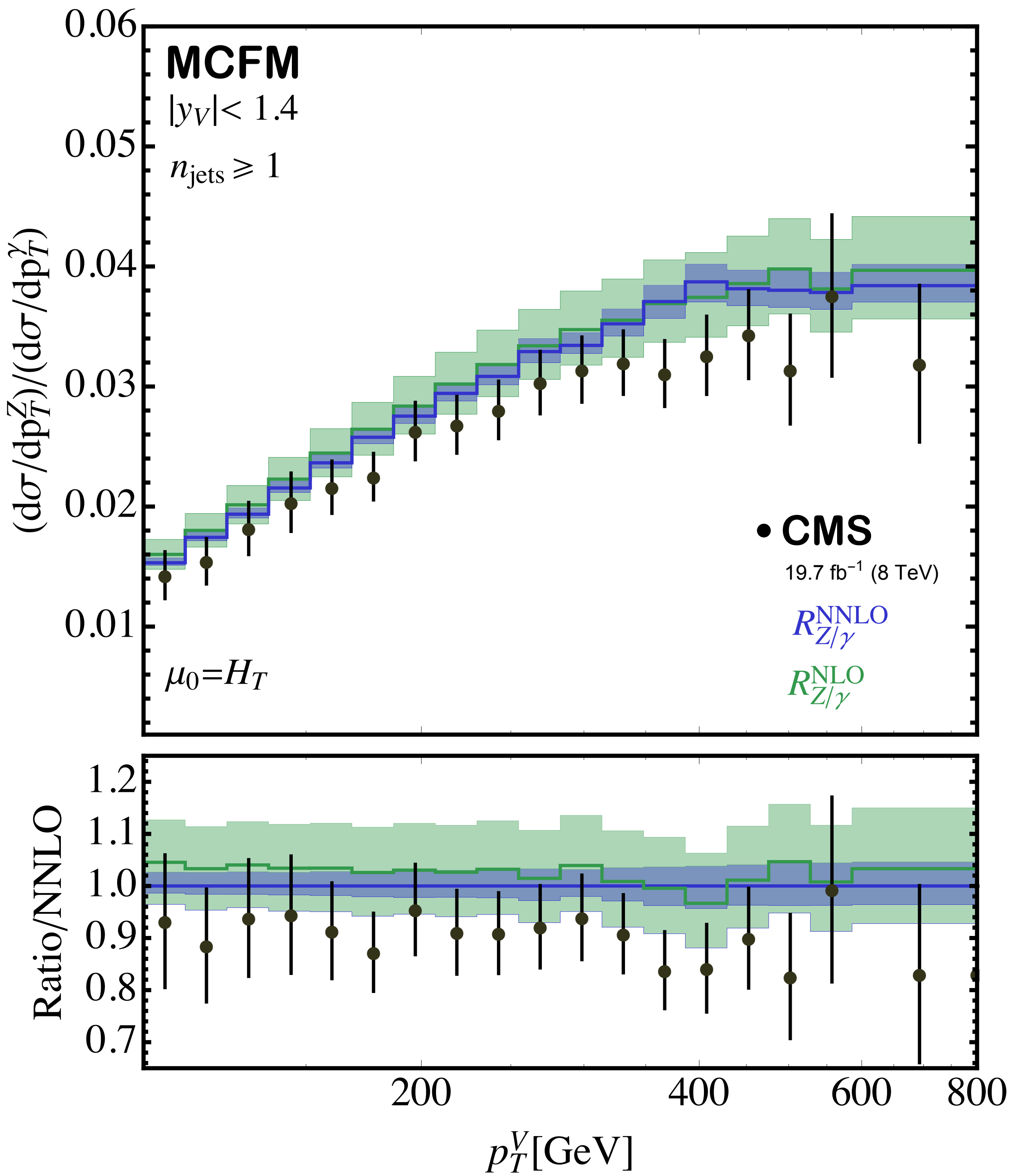
[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]



[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!

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:

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

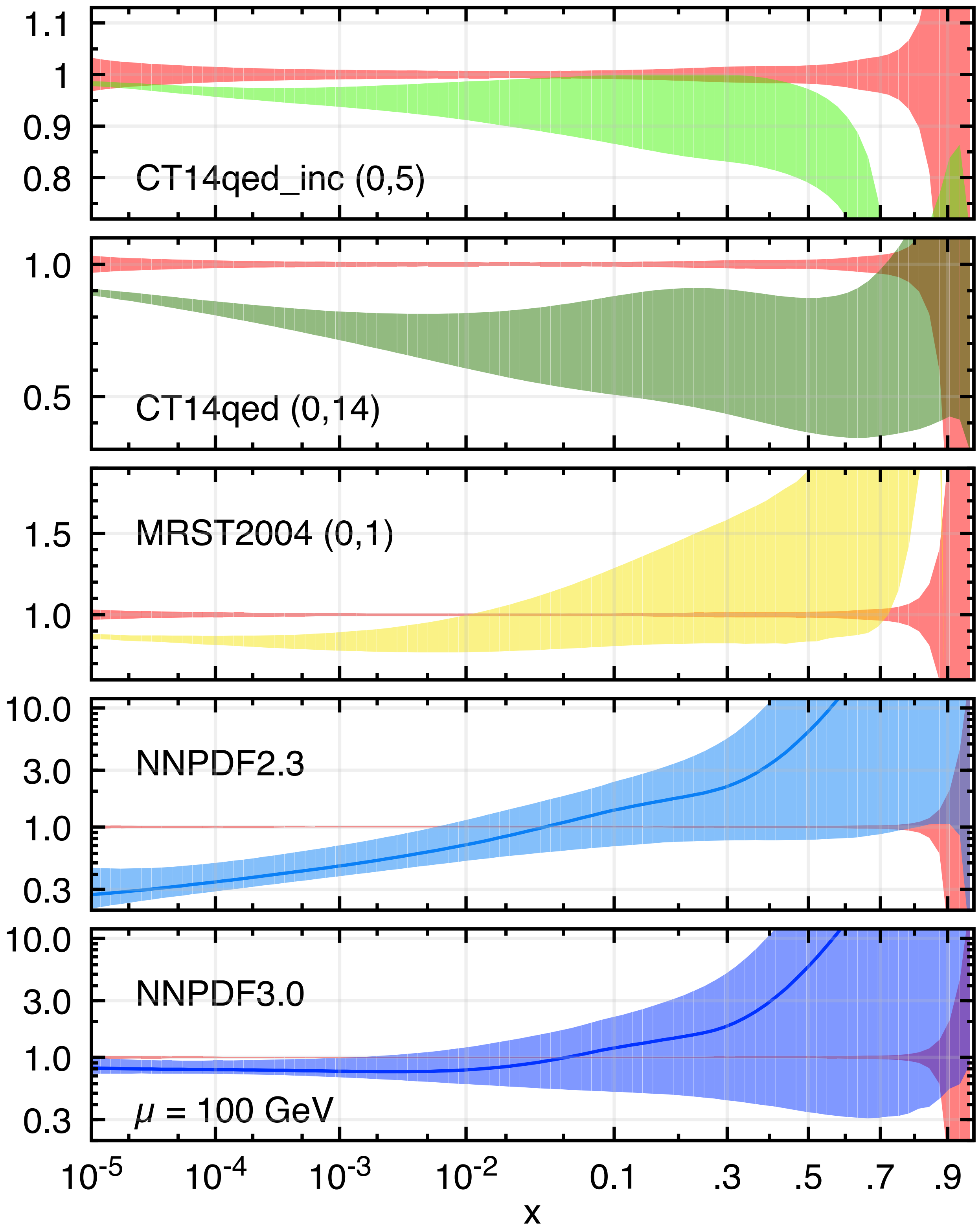
suppressed by large NLO QCD corrections

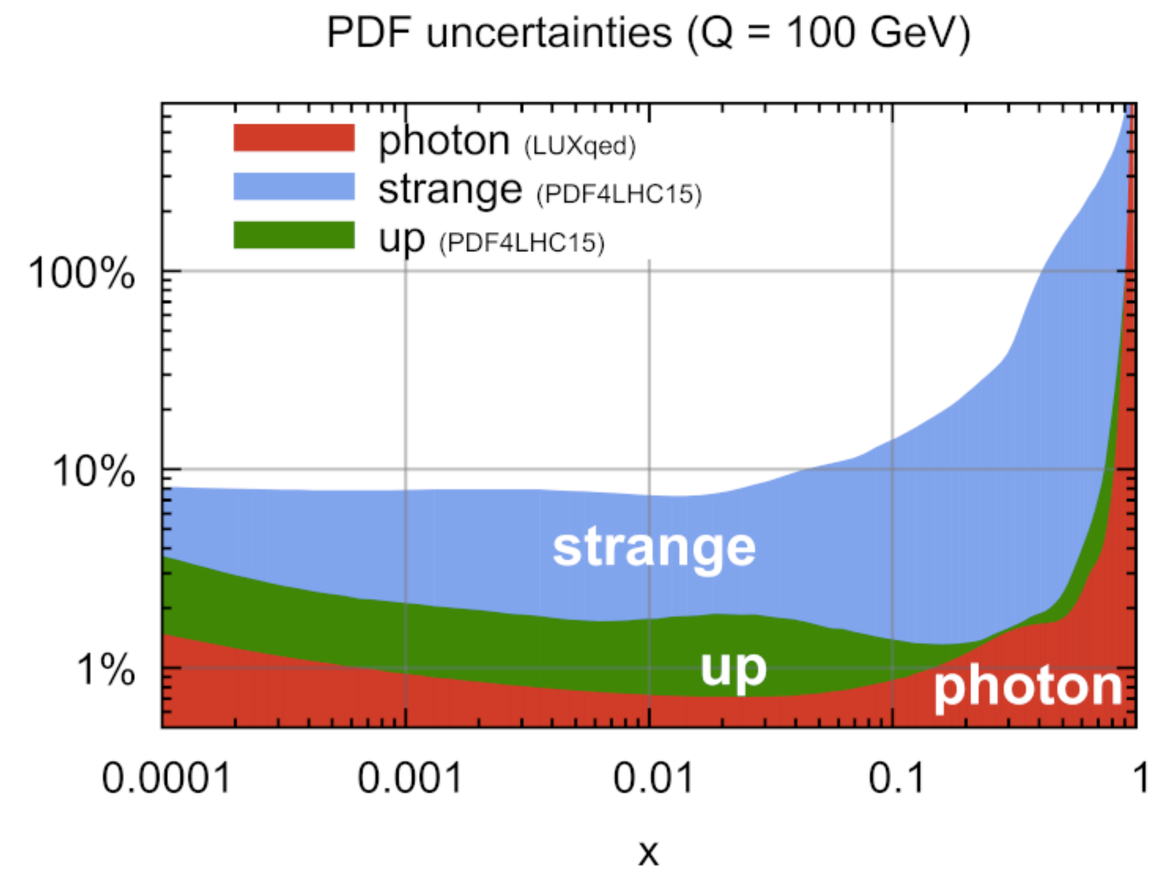
$$\frac{\sigma^{\rm NLO}_{\rm QCD\times EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right)$$

"usual" NLO EW w.r.t. LO

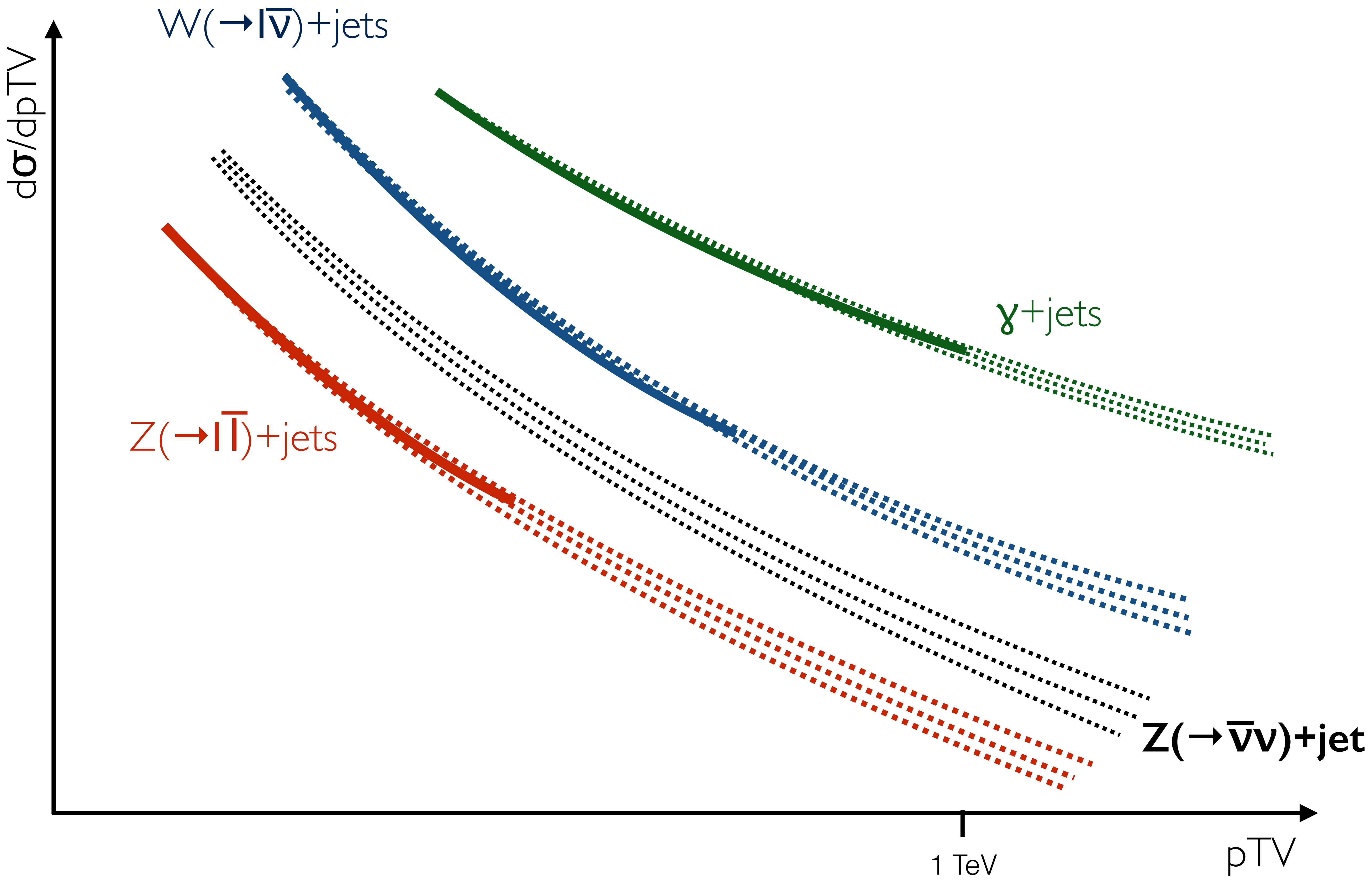
- $\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_{\rm W}^2 \left(1-\frac{M_{\rm W}^2}{M_{\rm Z}^2}\right)$ in G_μ -scheme with $G_\mu = 1.16637\times 10^{-5}\ {\rm GeV}^{-2}$

LUXqed





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



W(→l$\bar{\nu}$)+jets
dσ/dpTV
γ+jets
Z(→l$\bar{l}$)+jets
Z(→$\bar{\nu}\nu$)+jet
1 TeV
pTV