EW corrections for V+jets

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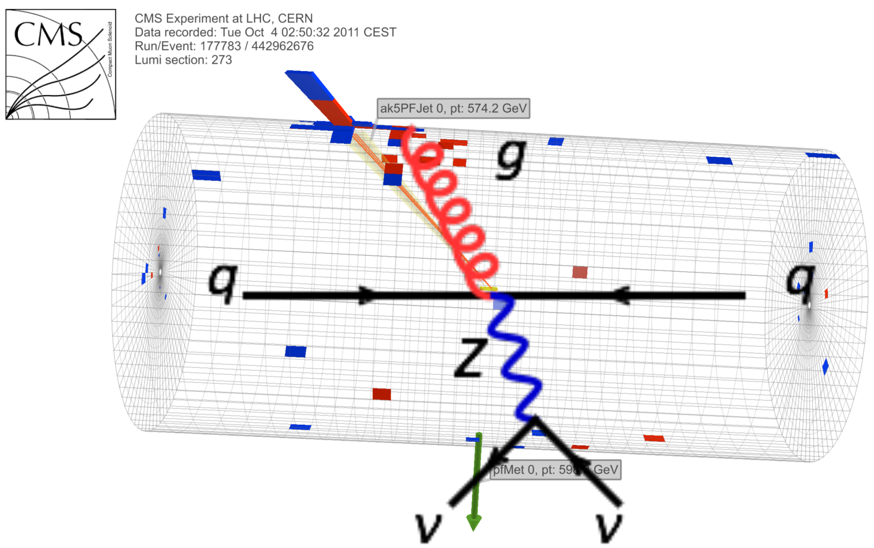
IP3

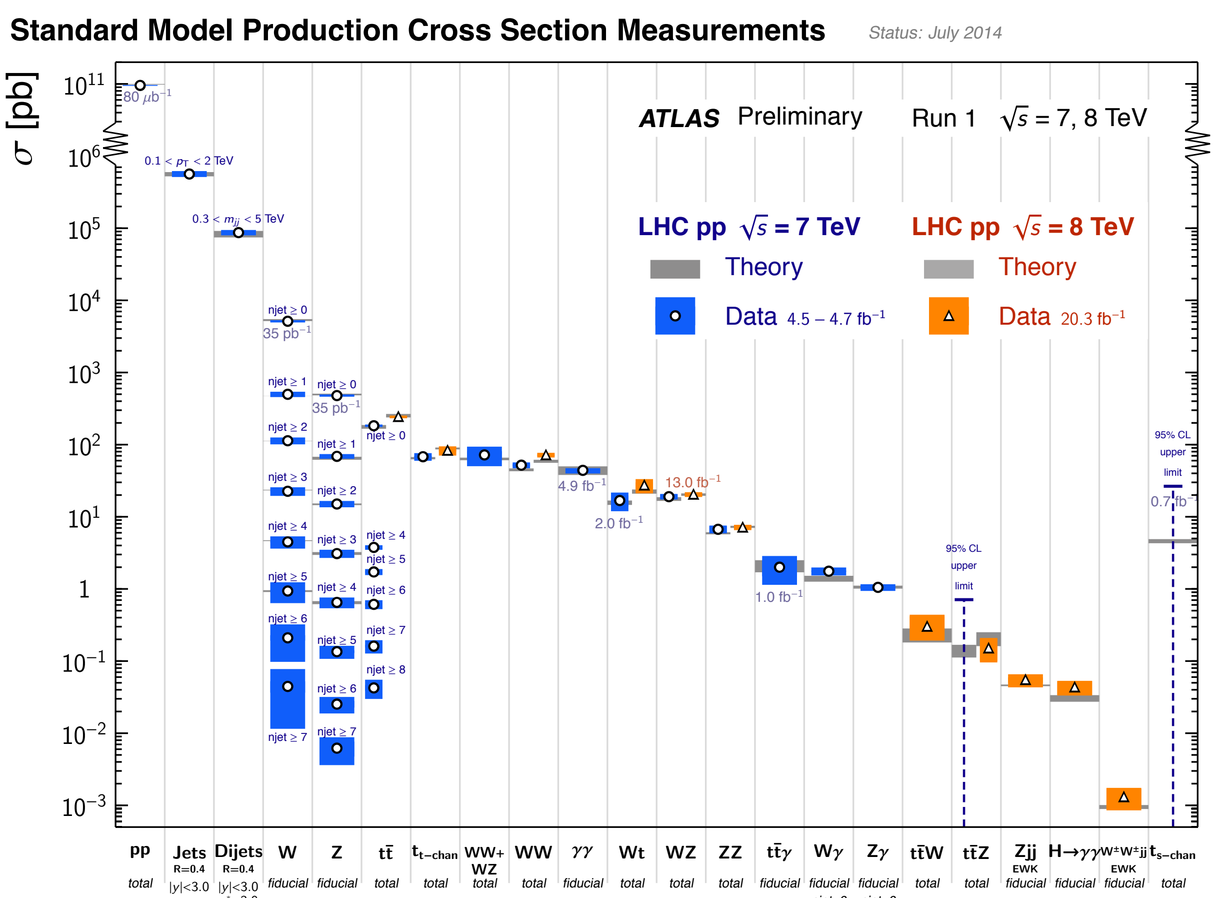
work in collaboration with:
R. Boughezal, A. Denner, S. Dittmaier, A. Huss, A. Gehrmann-De Ridder, T. Gehrmann, N. Glove, S. Kallweit, P. Maierhöfer, M. L. Mangano, T.A. Morgan, A. Mück, M. Schönherr, F. Petriello, S. Pozzorini, G. P. Salam

Illuminating standard candles at the LHC - V+jets
Imperial, London, 25.04.2017

V + multijet production



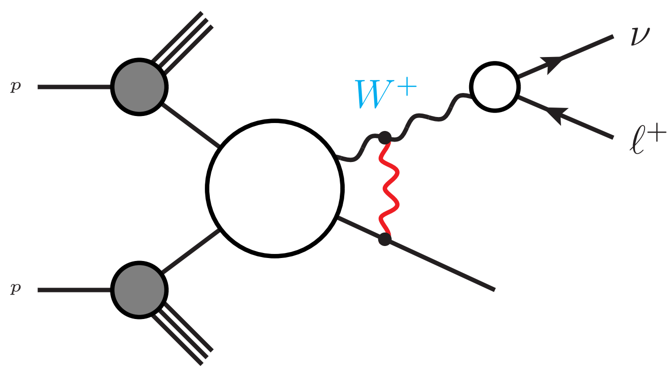
- Dominant backgrounds for monojet **DM searches**
- Important/dominant backgrounds for various **BSM searches** (lepton + missing E_T + ets)
- Dominant backgrounds for **top physics**
- Dominant backgrounds for **Higgs physics**, e.g. VH(→bb), H→WW

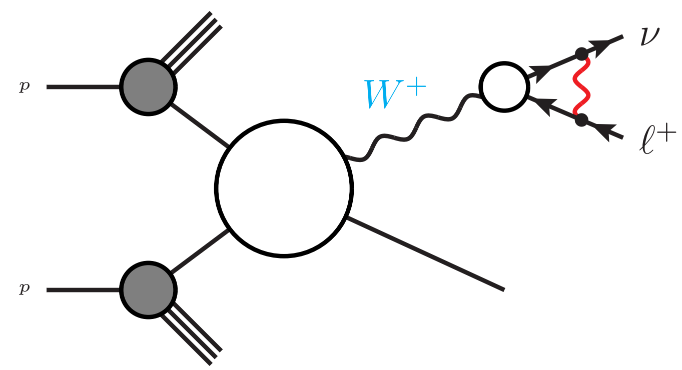


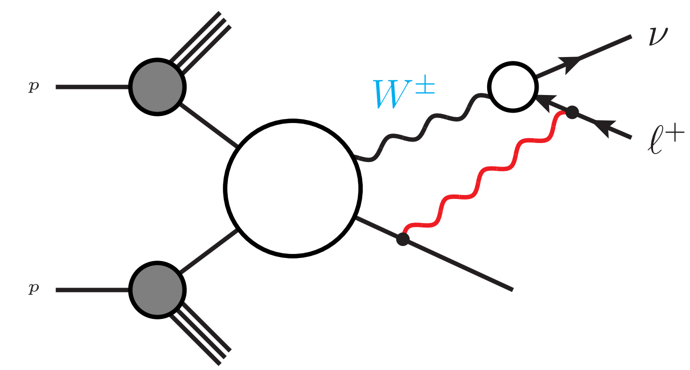
- Large cross-sections and clean leptonic signatures
- **V+jets**: Precision QCD at LHC
- Playground to probe different aspects of higher-order calculations (LO+PS, NLO+PS, NLO-Merging, NLO EW,…)
- Probe and constrain PDFs

Decays of heavy particles @ NLO EW

- Leptonic decays of gauge bosons are trivial at NLO QCD. At NLO EW corrections in production, decay and non-factorizable contributions have to be considered.







- Scheme of choice: complex-mass-scheme *[Denner, Dittmaier]*
  - gauge invariant and exact NLO
  - **computationally very expensive**: one extra leg per two-body decay

- Pragmatic choice: Narrow-width-approximation (NWA)
  - gauge invariant in strict on-shell limit of NWA
  - **allows to capture all Sudakov effects** (not present in decay)
  - **allows to go to higher jet multiplicities**
  - not applicable to all processes at all perturbative orders

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 EW-QCD corrections of $\mathcal{O}(\alpha\alpha_s)$

Relative corrections w.r.t. NLO QCD:

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

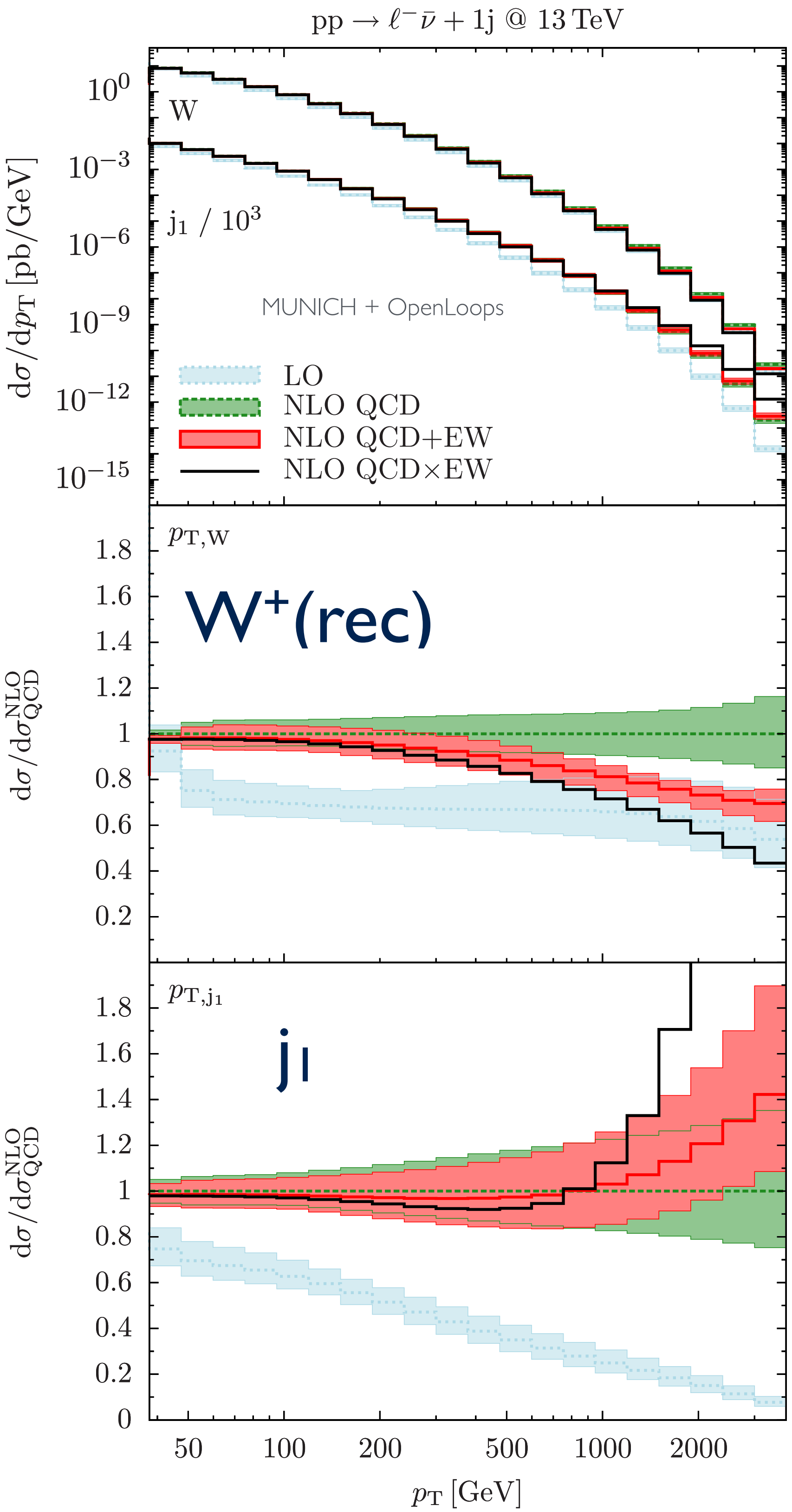
suppressed by large NLO QCD corrections

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

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

V + 1 jet

$l^-\nu$ + 1 jet: inclusive



[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

Setup:

$\sqrt{S} = 13$ TeV

$p_{\mathrm{T,j}} > 30$ GeV, $|\eta_{\mathrm{j}}| < 4.5$

$p_{\mathrm{T,l}} > 20$ GeV, $|\eta_{\mathrm{l}}| < 2.5$, $E_T^{\mathrm{miss}} > 25$

$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

inclusive

$\lesssim$ 1% EW corrections

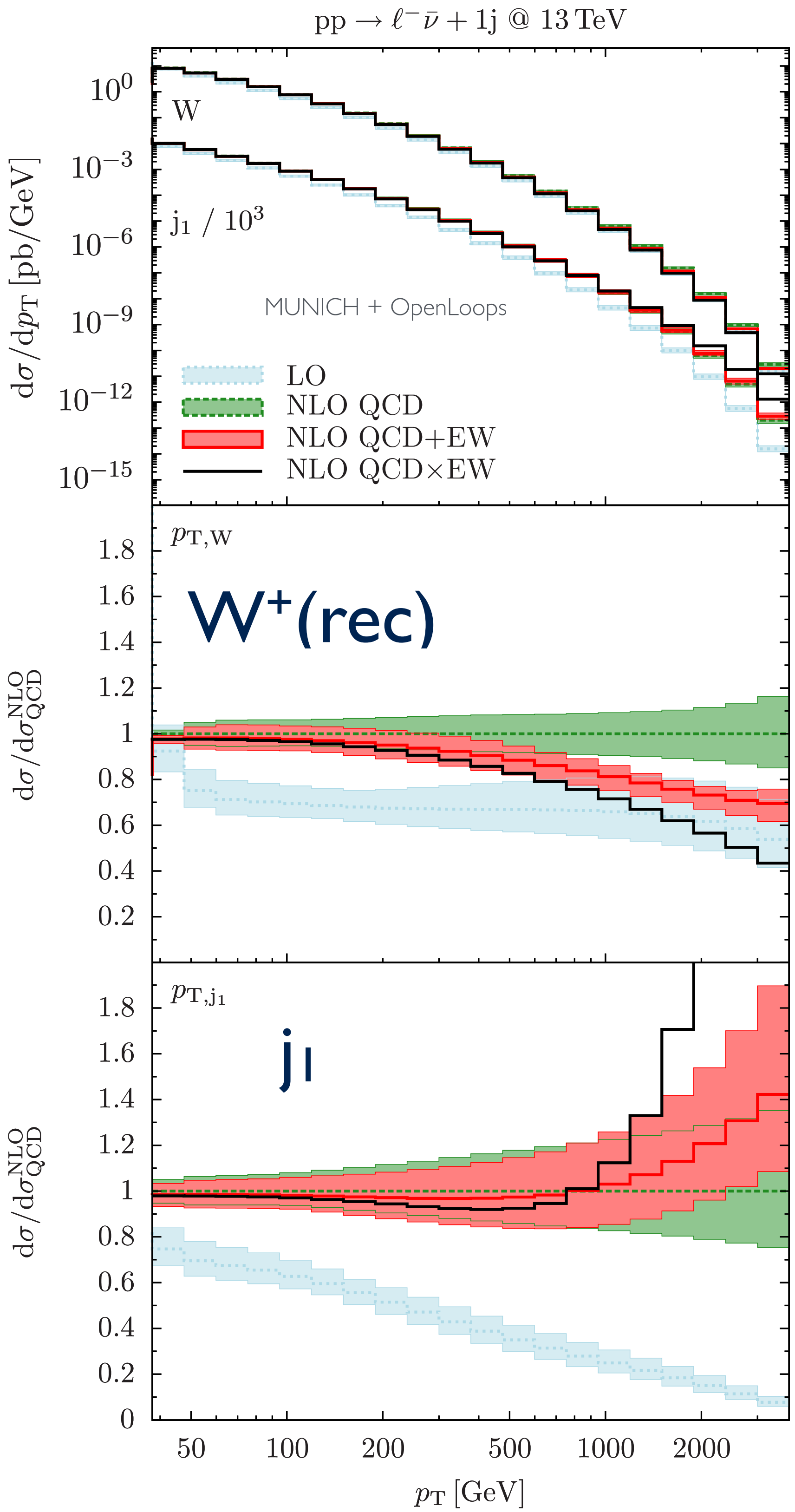
p_T of W-boson

- +100 % QCD corrections in the tail
- large negative EW corrections due to **Sudakov behaviour:** -20–35% corrections at 1-4 TeV
- sizeable difference between QCD+EW and QCDxEW !

p_T of jet

- "giant QCD K-factors" in the tail *[Rubin, Salam, Sapeta '10]*
- dominated by **dijet configurations** (effectively LO, no EW)
- positive 10-50% EW corrections from quark bremsstrahlung

$l^-\nu$ + 1 jet: inclusive



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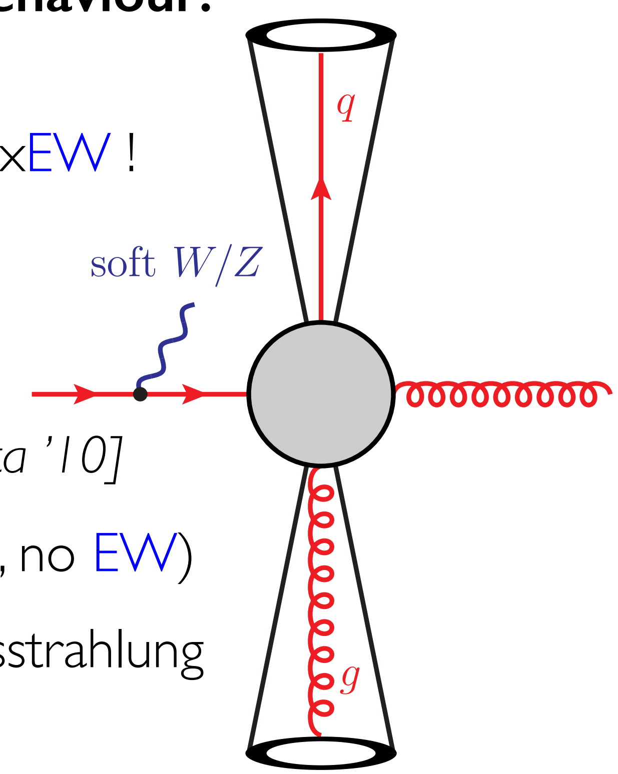

[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

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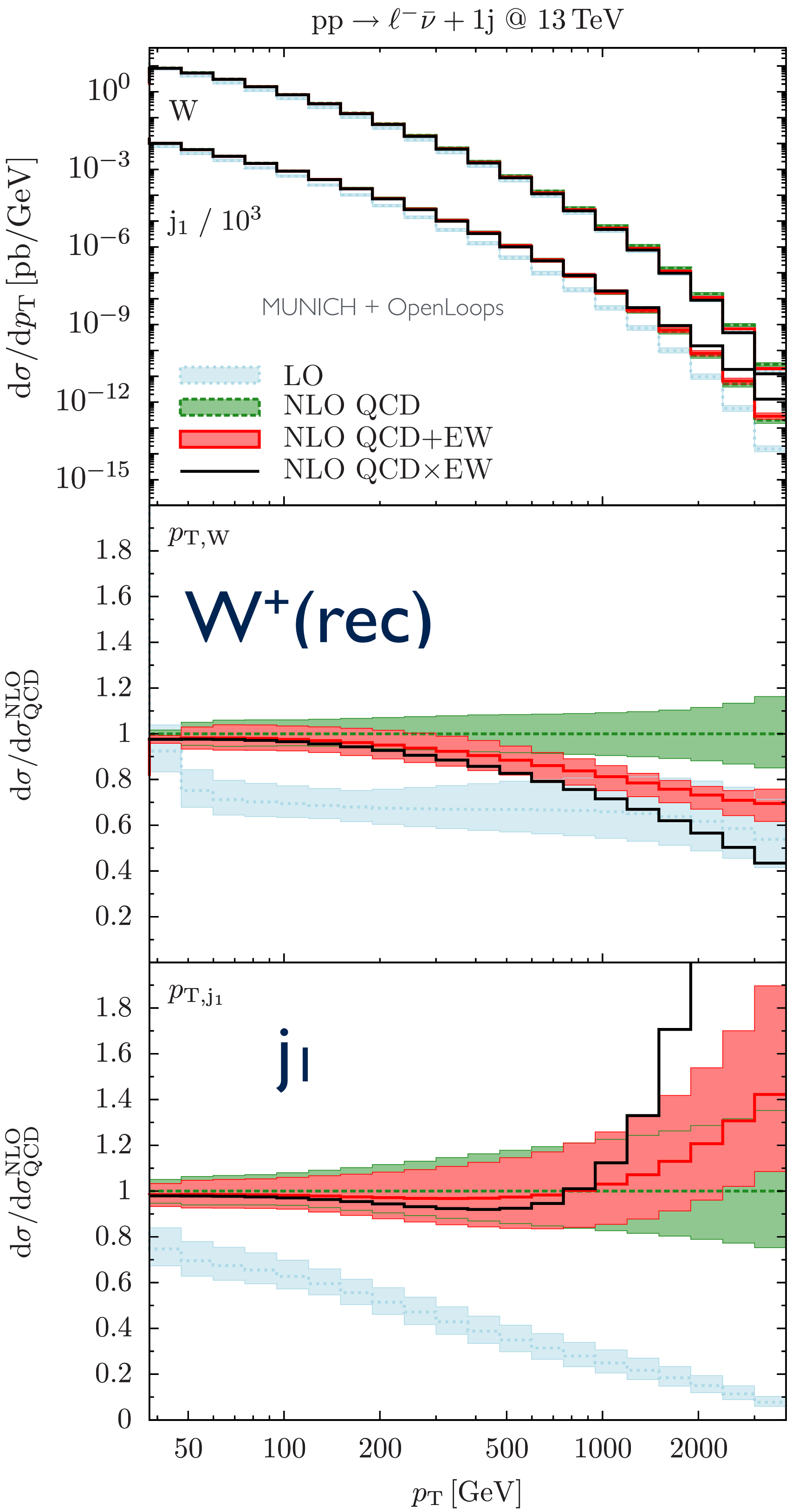

[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

inclusive

≲ 1% EW corrections

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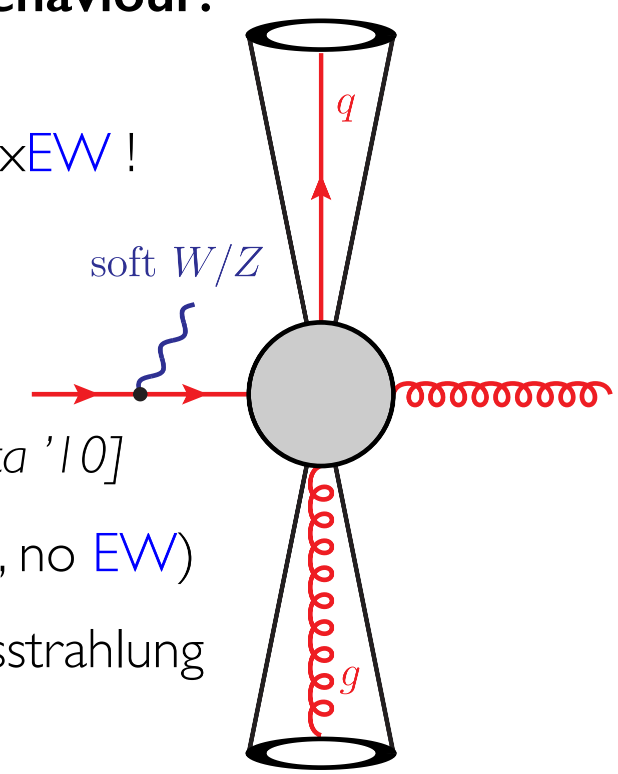

p_T of jet

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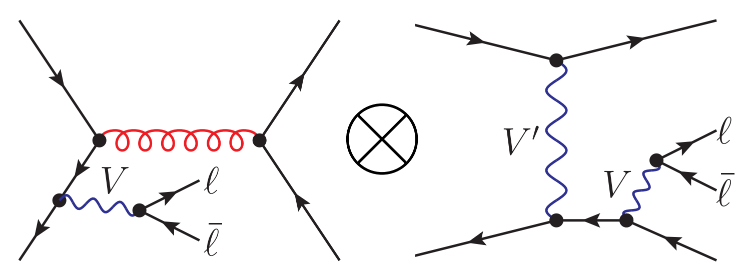
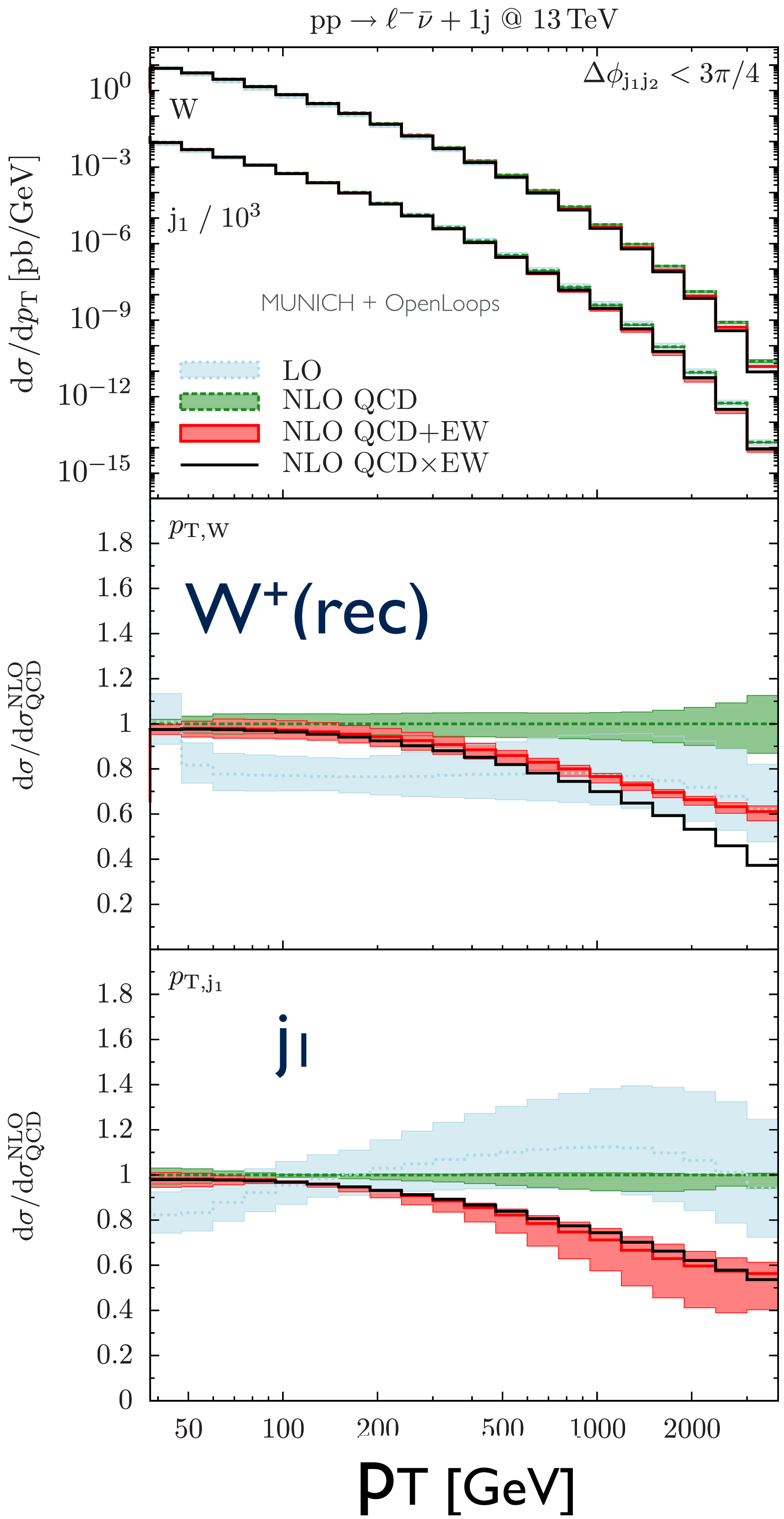


⟹ pathologic with large uncertainties!

$l^-\nu$ + 1 jet: exclusive



[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

$\Delta\phi_{j1j2} < 3\pi/4$

(veto on dijet configurations)

QCD corrections

- mostly moderate and stable QCD corrections

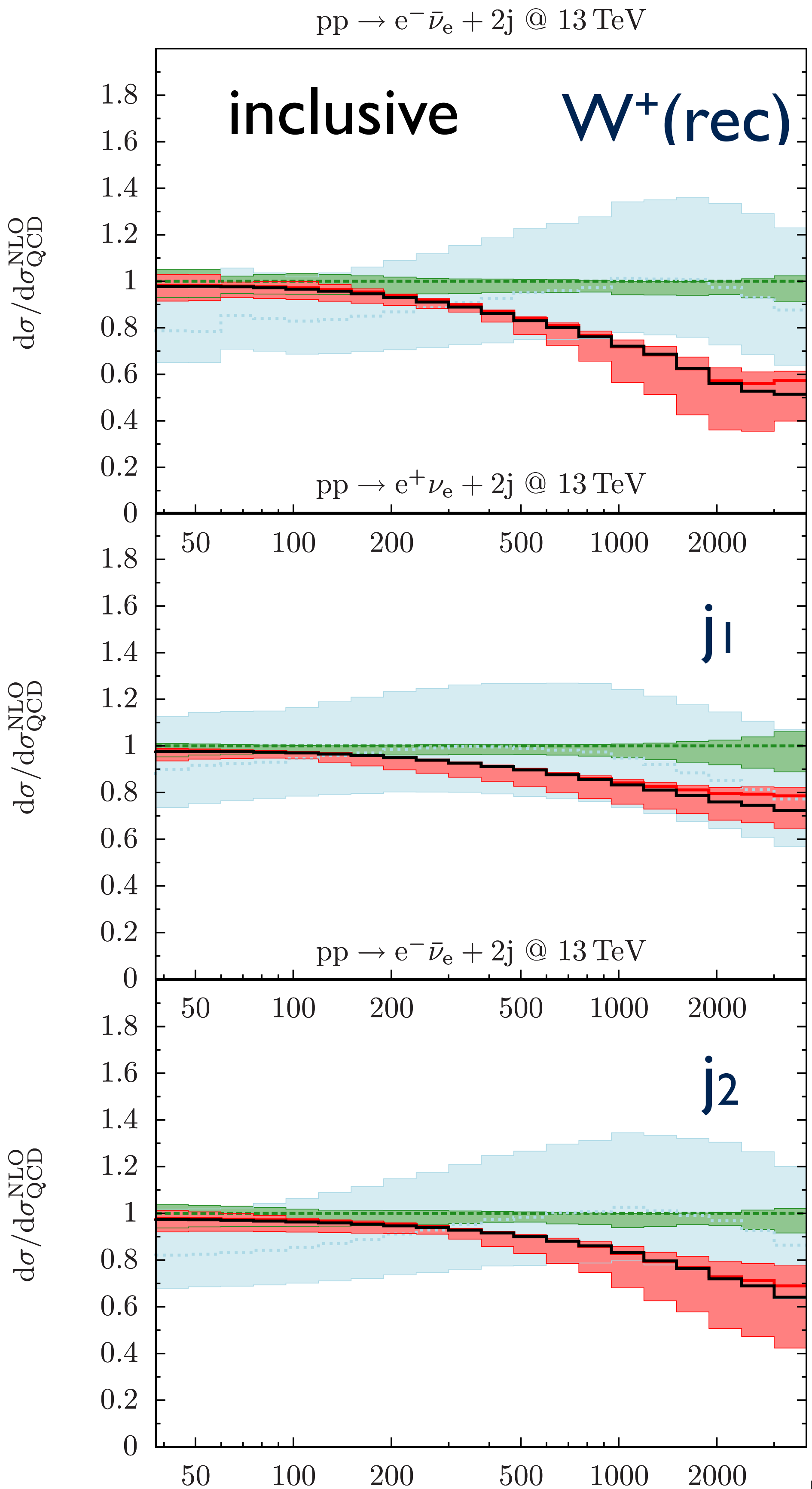
EW corrections

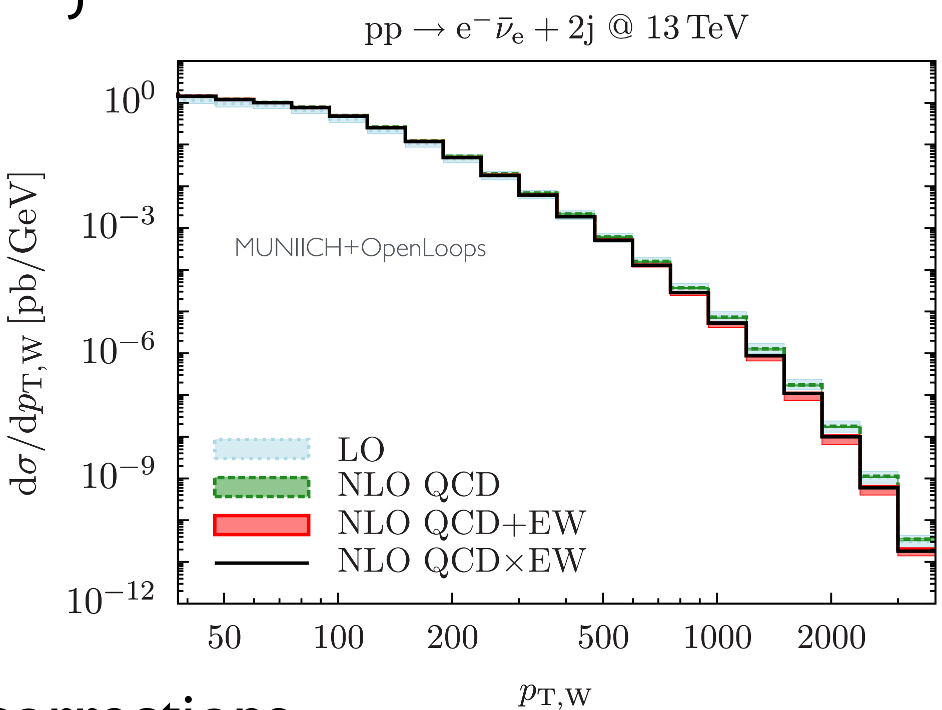
- **Sudakov behaviour** in both tails: -20–50% EW corrections at 1-4 TeV
- EW corrections larger than QCD uncertainties for $p_{T,W+}$ > 300 GeV

⟹ for jet-observables *inclusive* W+1jet requires merging with W+2 jets at NLO QCD+EW!

V + 2 jet

l⁻ν + 2 jets





[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

QCD corrections

- small and very stable
- ≲ 10% scale uncertainties

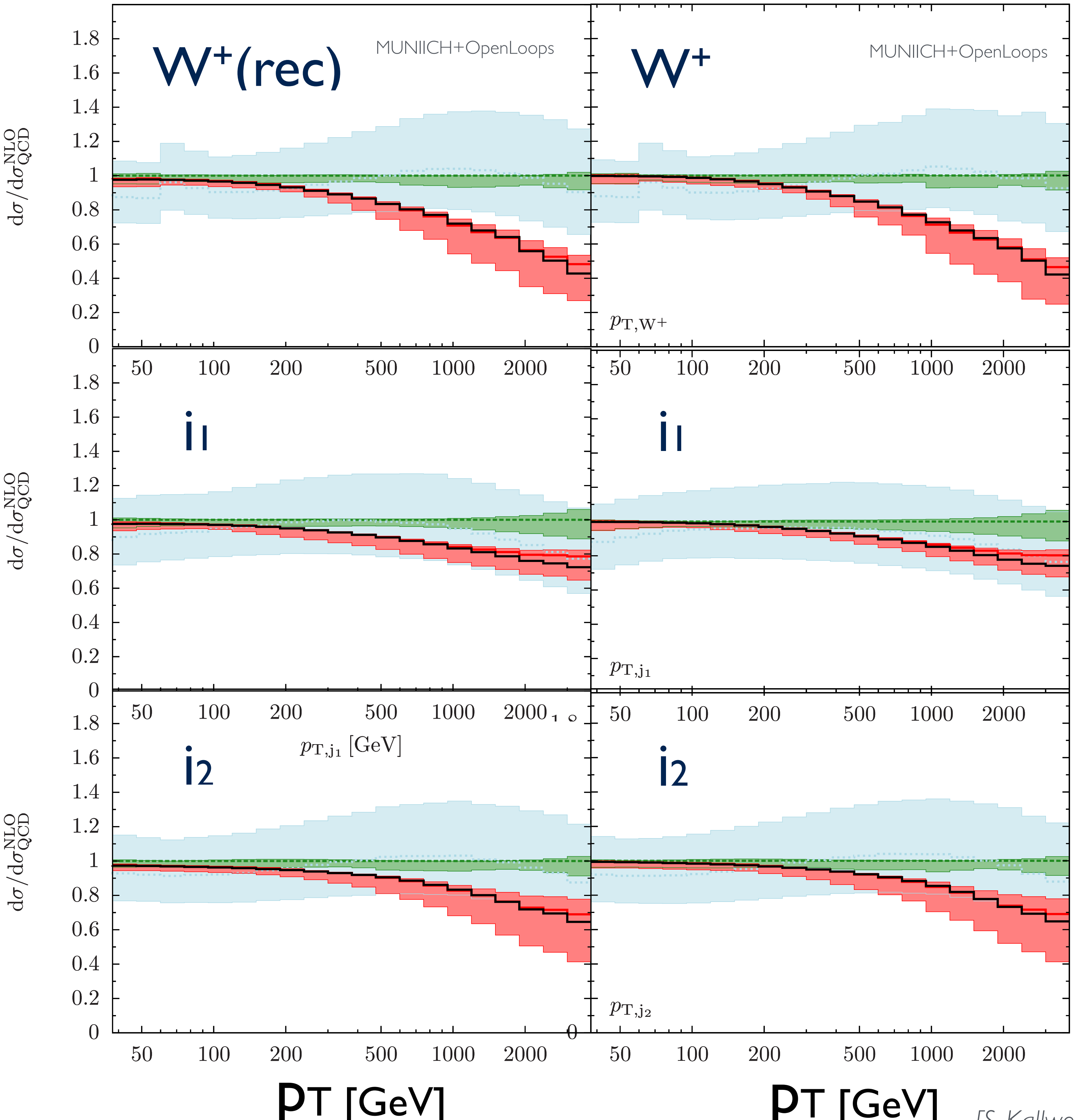
EW corrections

- **Sudakov behaviour** in all p_T tails:
  - -30–60% for W-boson at 1-4 TeV
  - -15–25% for 1st and 2nd jet at 1-4 TeV

  different!
- Might need resummation of leading EW Sudakov logs

off-shell vs. on-shell production

$l^+\nu$ + 2 jets vs. W^++2 jets

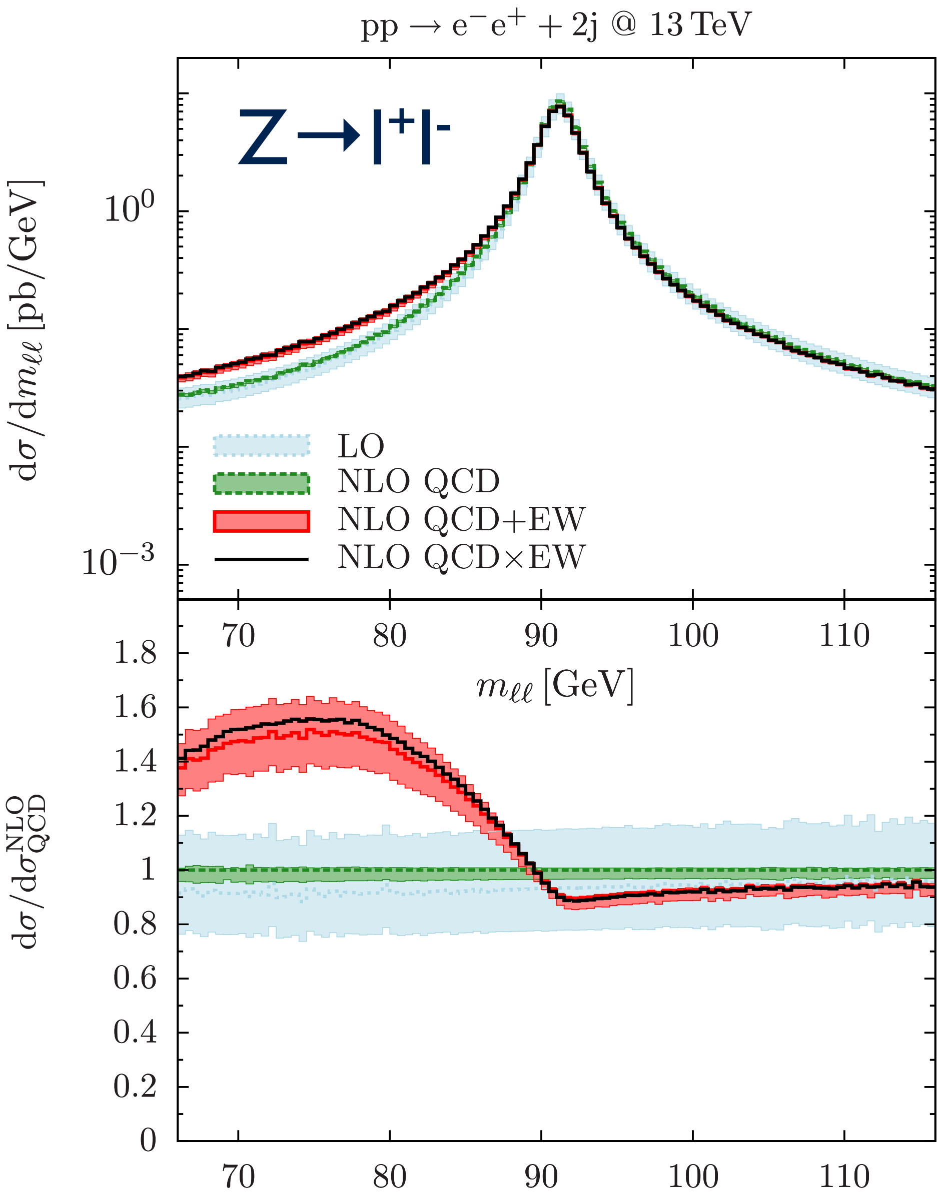


Effect of decays:

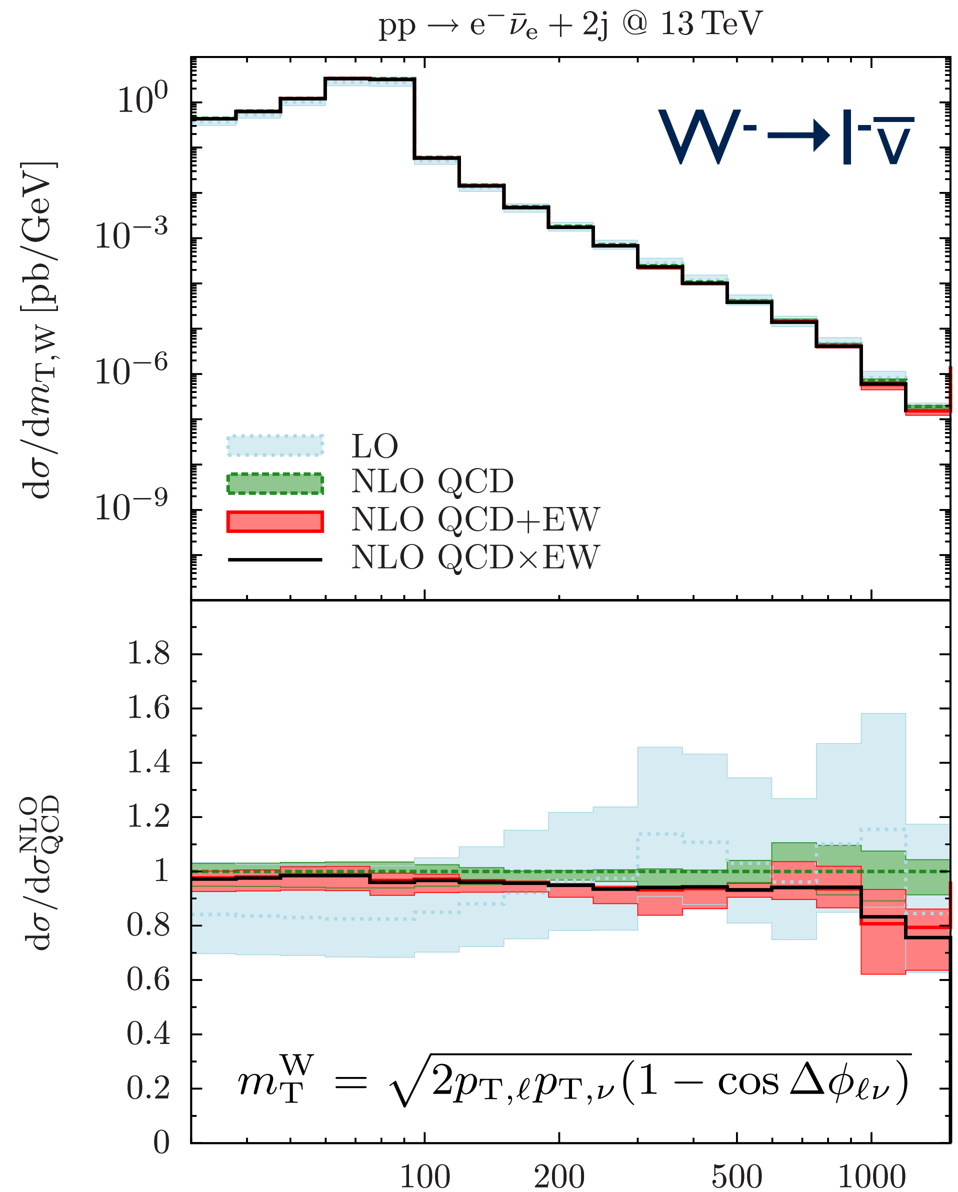
- **Large Sudakov corrections unaffected**
- However: needed for realistic experimental cuts

[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

Leptonic observables: only in off-shell calculation



m_{ll} [GeV]



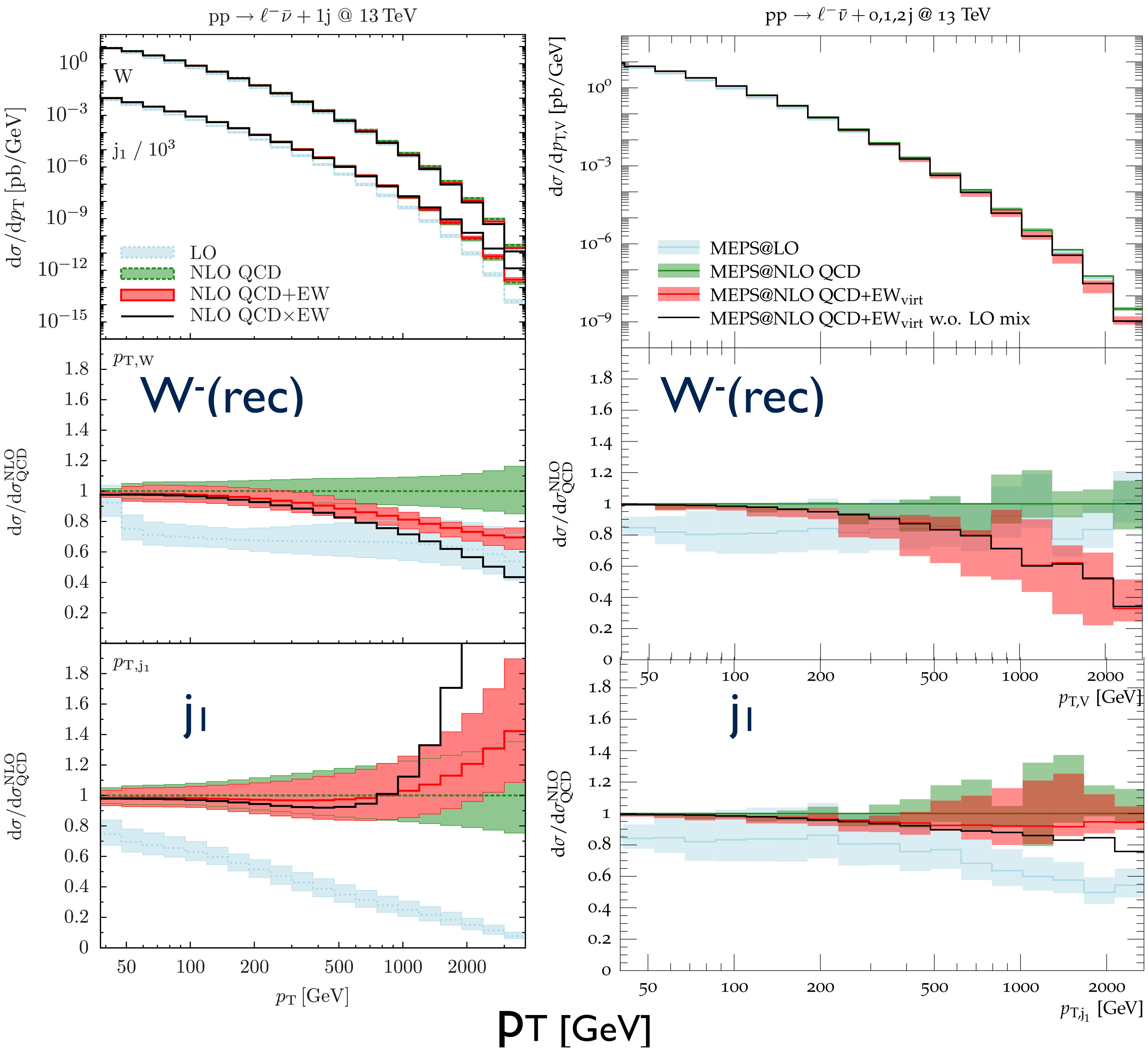
$m_{T,W}$ [GeV]

- up to 50% from QED Bremsstrahlung.
- Similar shape as for NC DY
- moderate EW corrections at large $m_{T,W}$
- no (strong) Sudakov enhancement

[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '14+'15]

$V + 1$ jet $\otimes$ $V + 2$ jets

inclusive V+1 jet: MEPS@NLO QCD+EW$_{virt}$



- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations

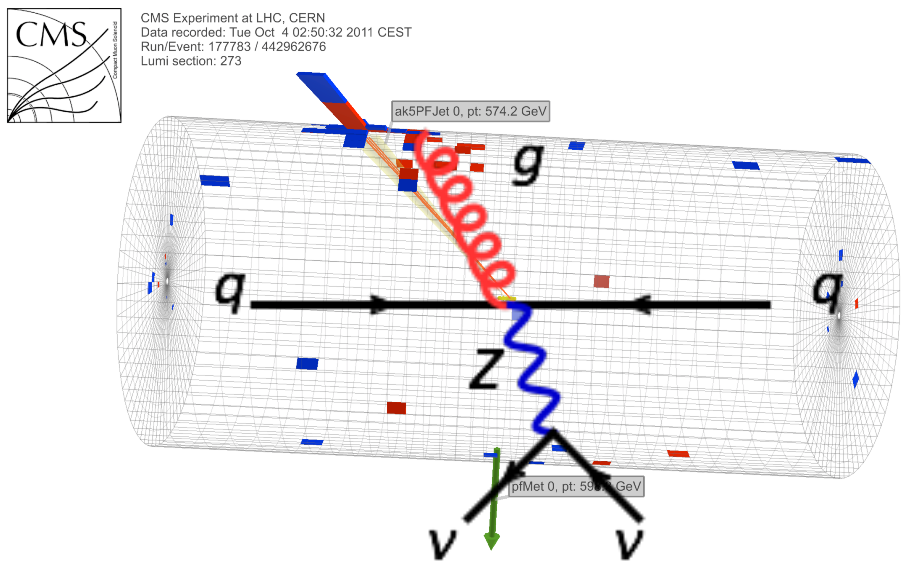
- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)
- $p_{T,j1}$: compensation between negative Sudakov and LO mix

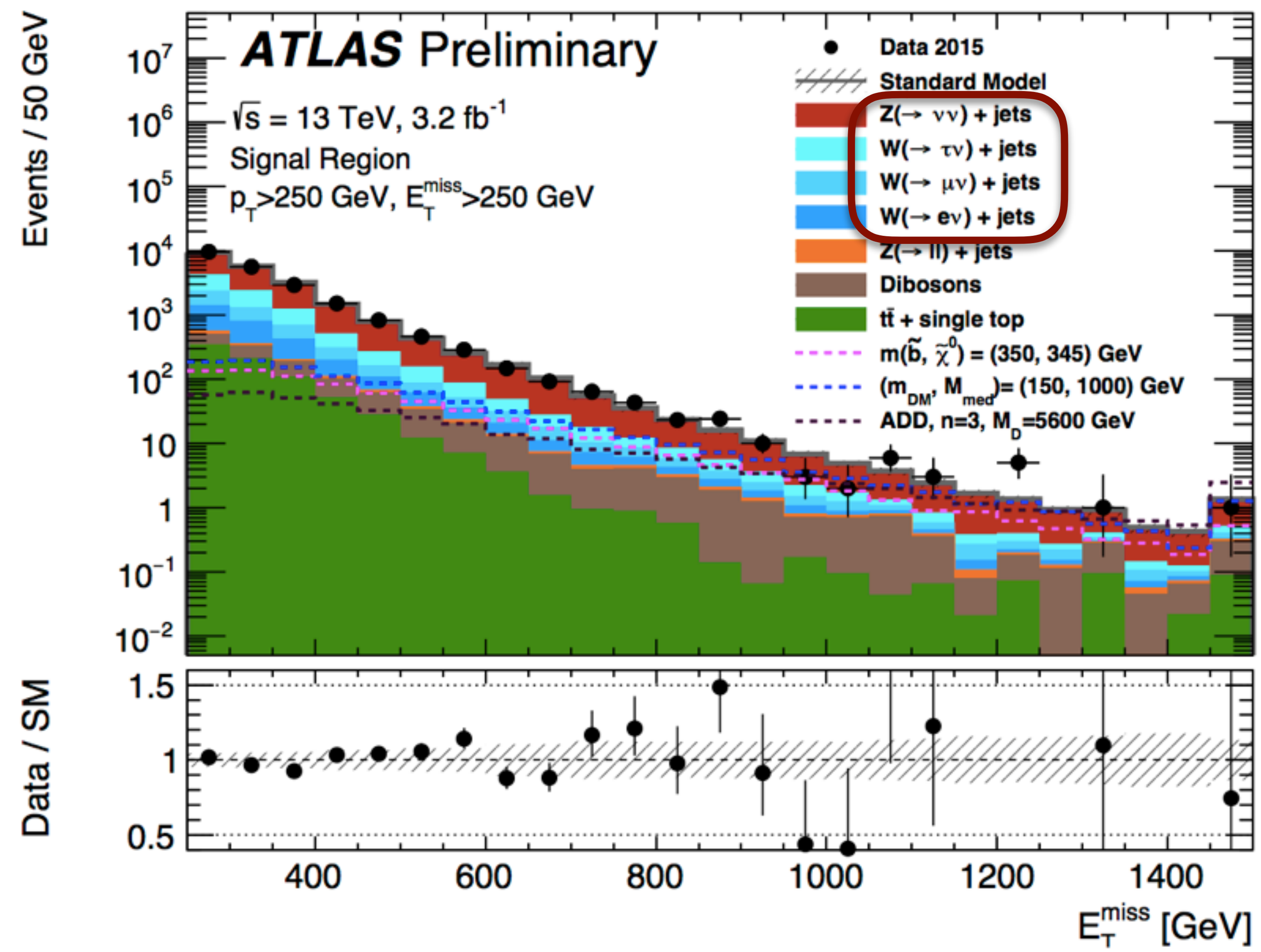
[see Marek's talk]

[S. Kallweit, JML, P. Maierhöfer, M. Schönherr, S. Pozzorini, '15]

Uncertainties

V+jets backgrounds in monojet/MET + jets searches



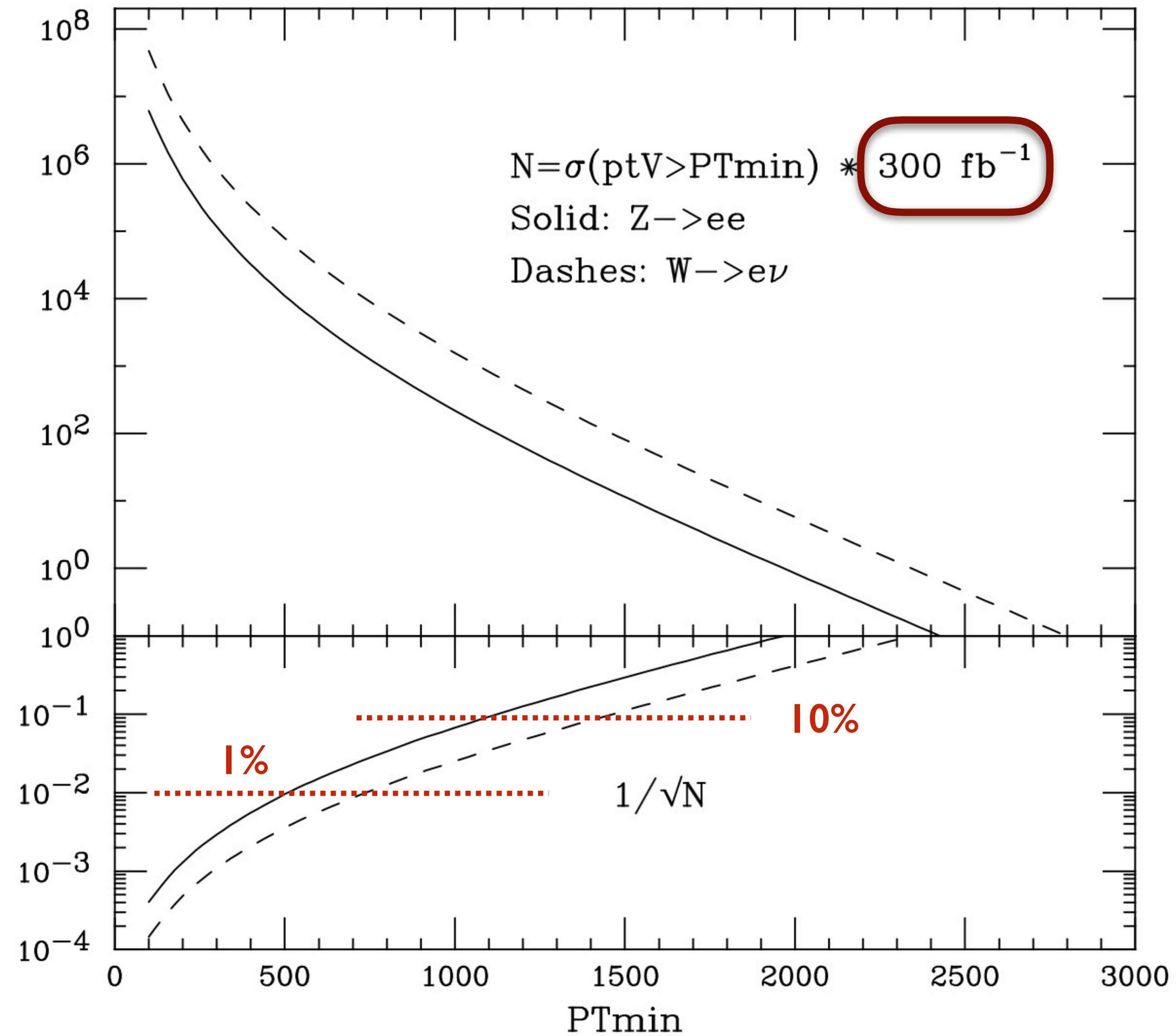


irreducible backgrounds:

$pp \to Z(\to \nu\bar{\nu})$+jets $\Longrightarrow$ MET + jets

$pp \to W(\to l\nu)$+jets $\Longrightarrow$ MET + jets (lepton lost)

Target precision

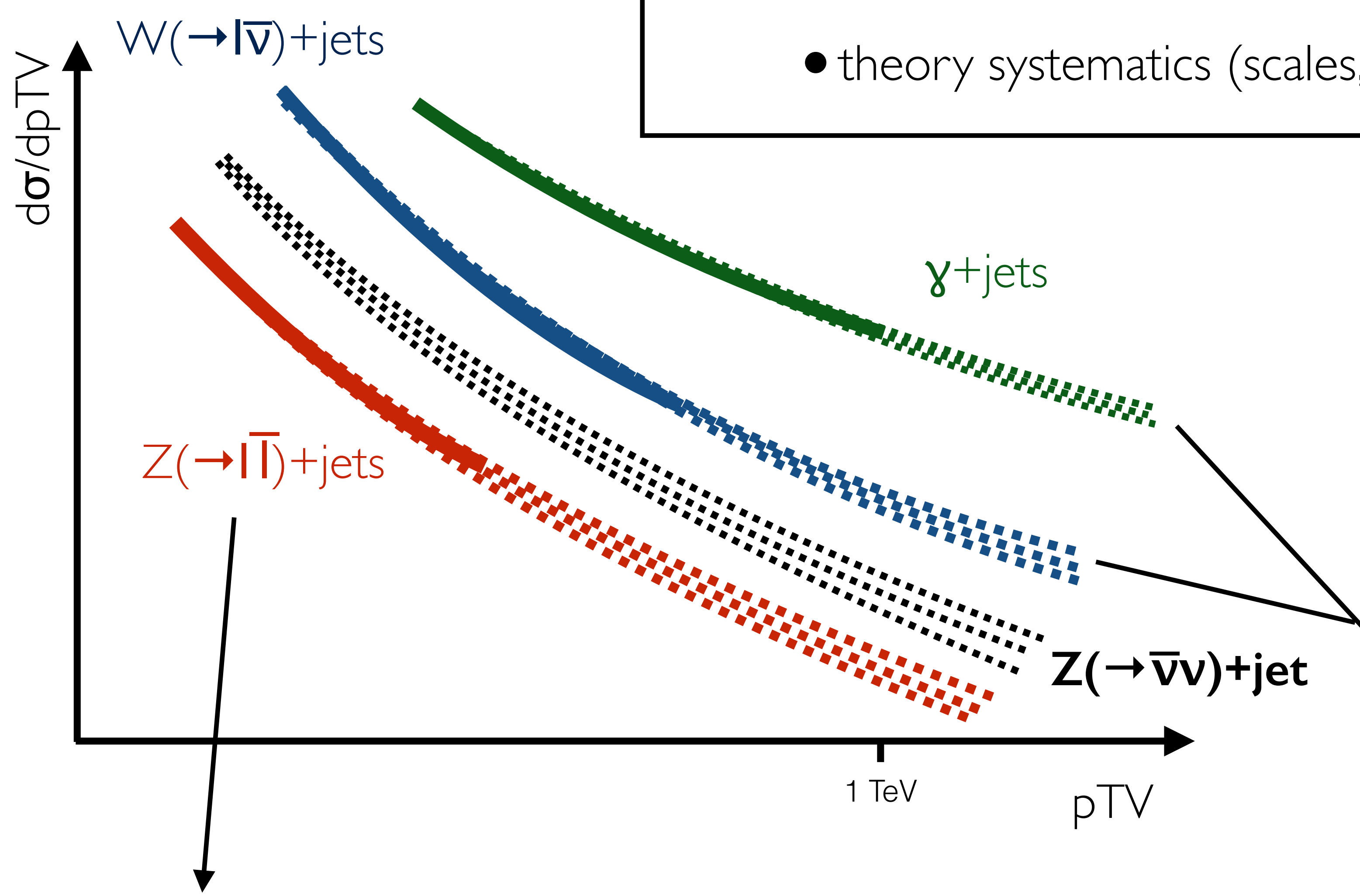


- for 500 GeV < pTV < 1000 GeV: background statistics will be at **1% level**
- understanding of V+jets backgrounds at this level increases sensitivity in DM searches
- this level of precision is theoretically possible @ **NNLO QCD + NNLO EW**
- requires solid understanding of **uncertanties**!

Determine V+jets backgrounds

global fit of Z(→l l̅)+jets, W(→lν̅)+jets and γ+jets measurements

- to determine Z(→ν̅ν)+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]

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

- 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)

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

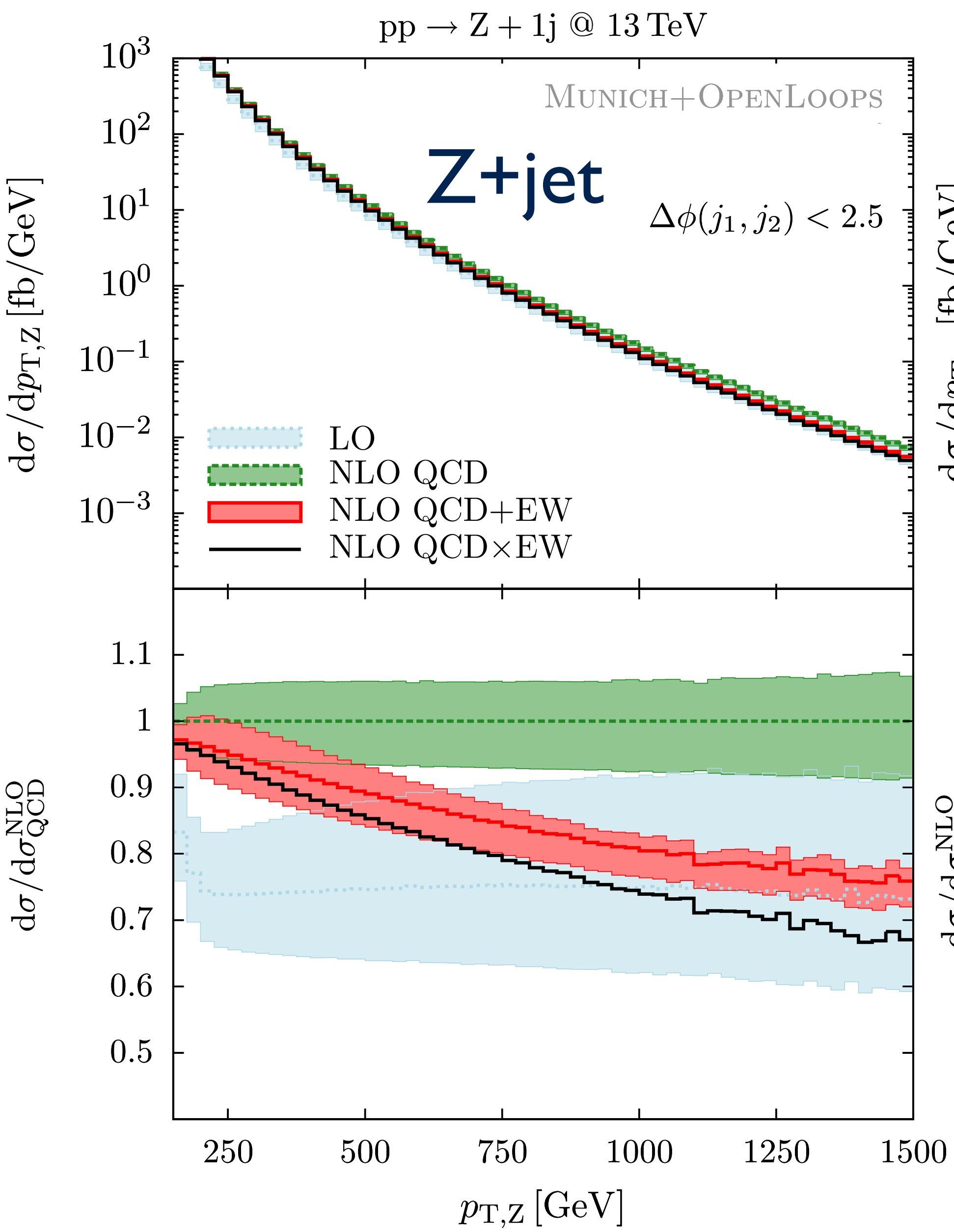
one-dimensional reweighting of MC samples in $x = p_{\mathrm{T}}^{(V)}$

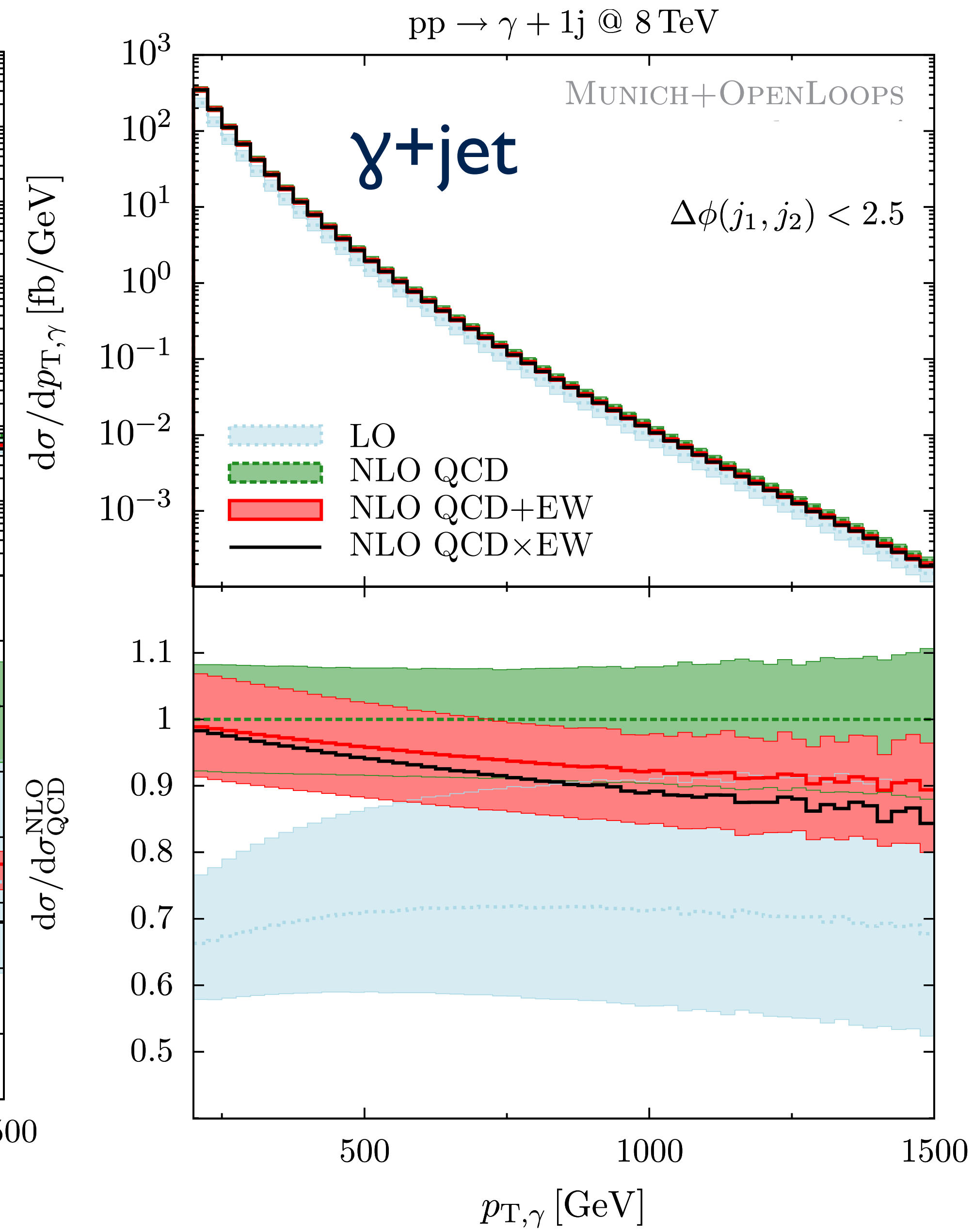
with
$$\frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{TH}} = \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{QCD}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\mathrm{mix}} + \frac{\mathrm{d}}{\mathrm{d}x}\Delta\sigma^{(V)}_{\mathrm{EW}} + \frac{\mathrm{d}}{\mathrm{d}x}\sigma^{(V)}_{\gamma-\mathrm{ind.}}$$

- 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





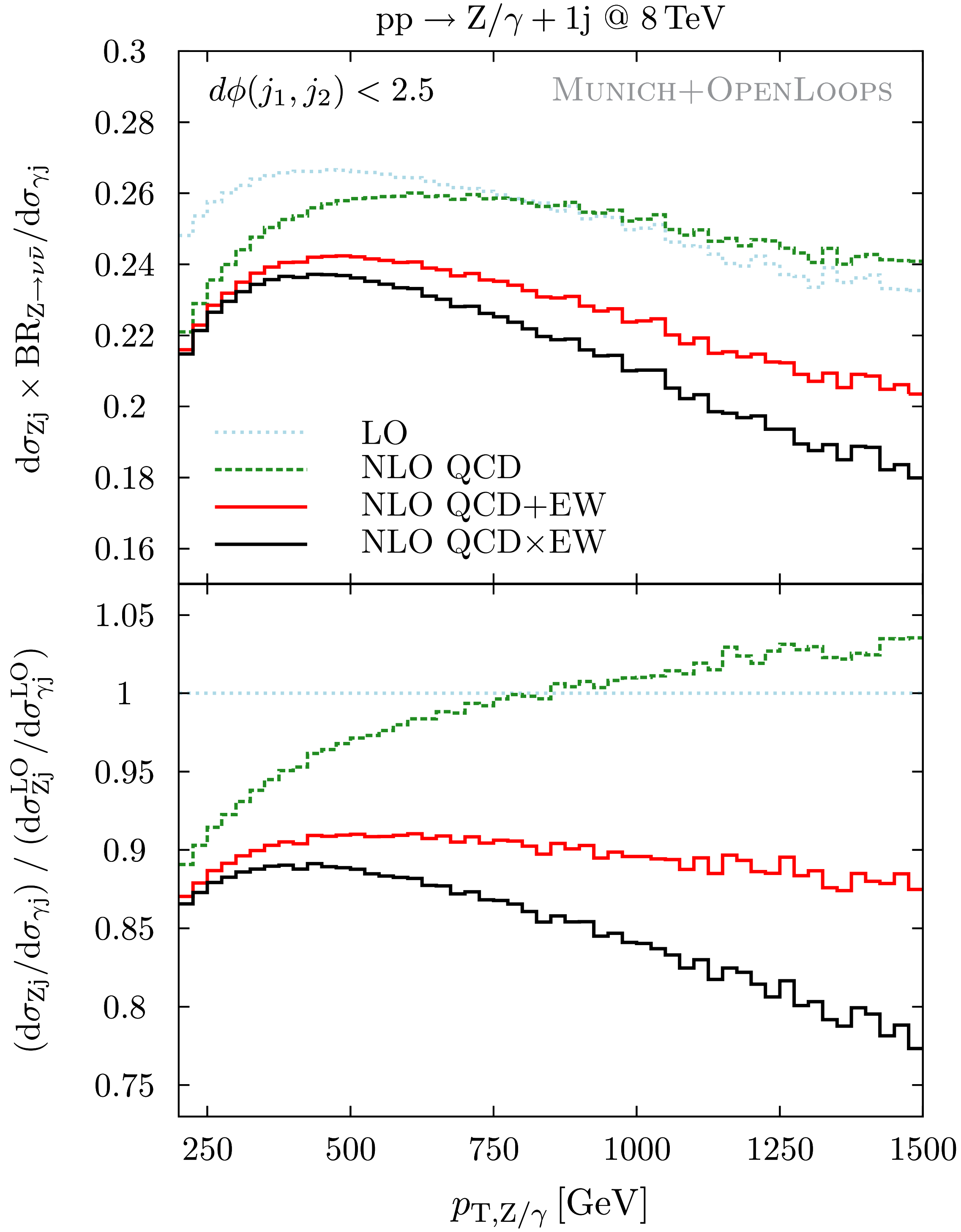
QCD corrections

- 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/ɣ pT-ratio



Overall

- mild dependence on the boson pT

QCD corrections

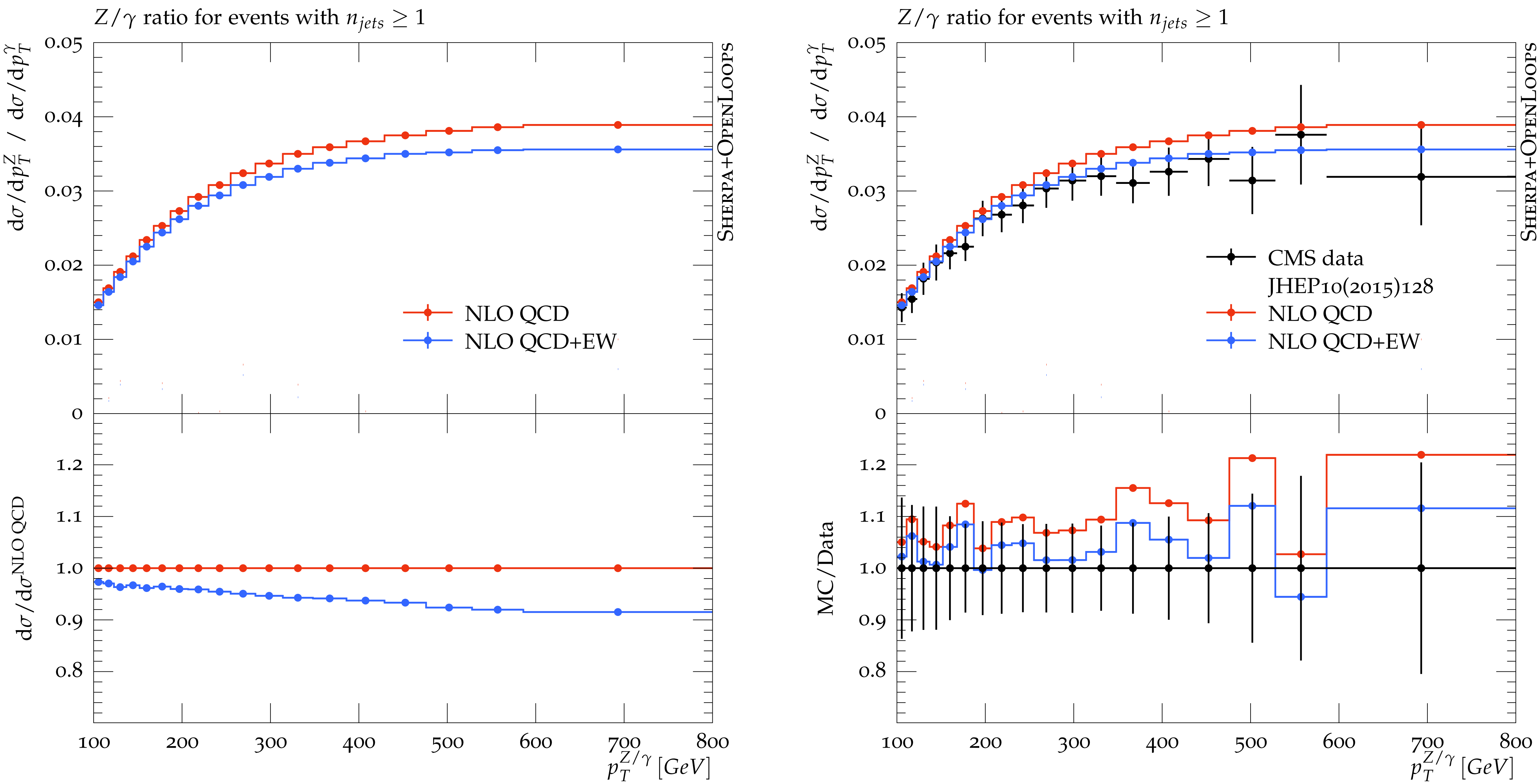
- 10-15% below 250 GeV
- ≲ 5% above 350 GeV

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]



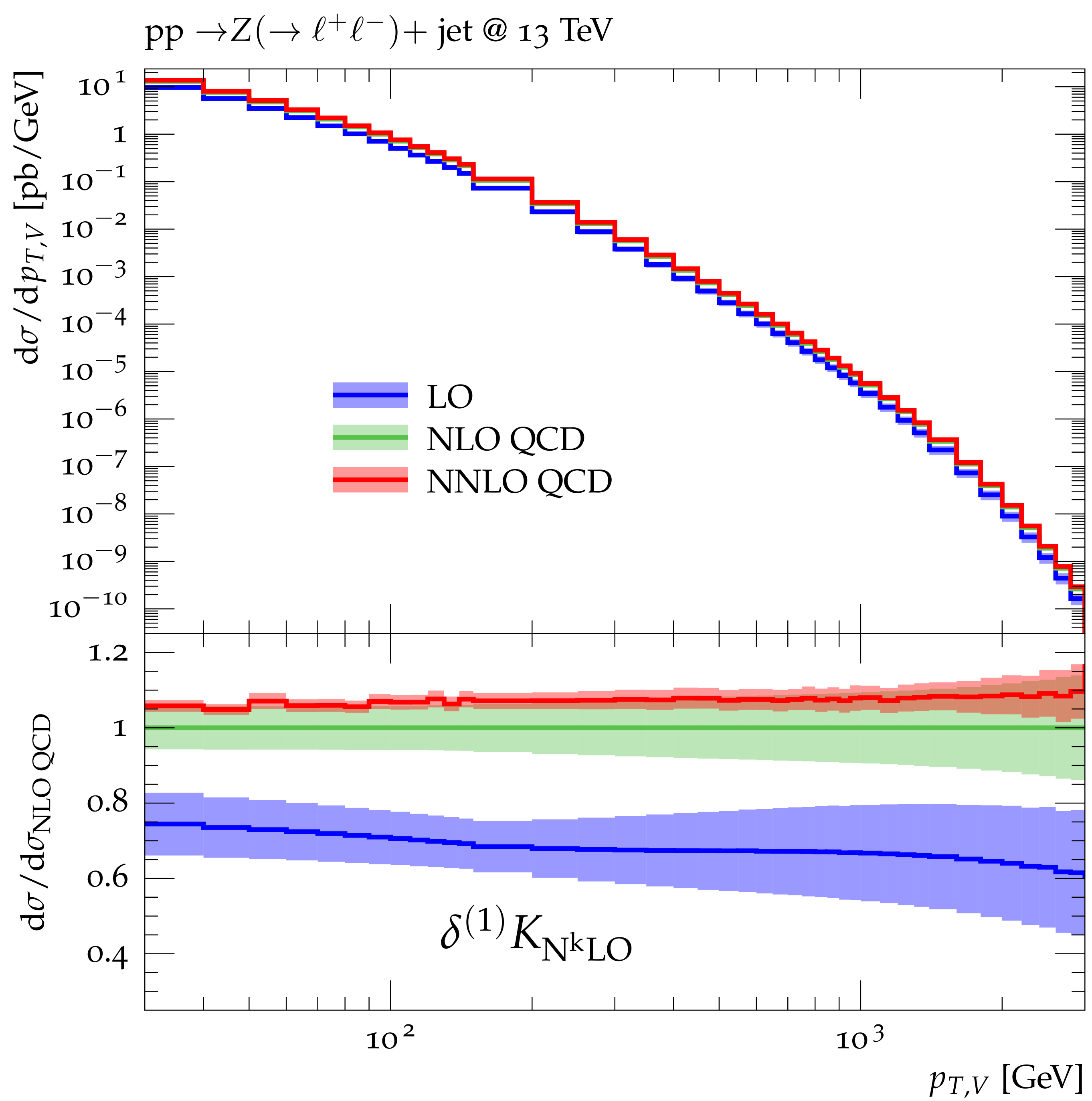
*[Ciulli, Kallweit, JML, Pozzorini, Schönherr for **LH'15**]*

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

1. pure QCD uncertainties

QCD effects [see Nigel's talk]

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



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

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

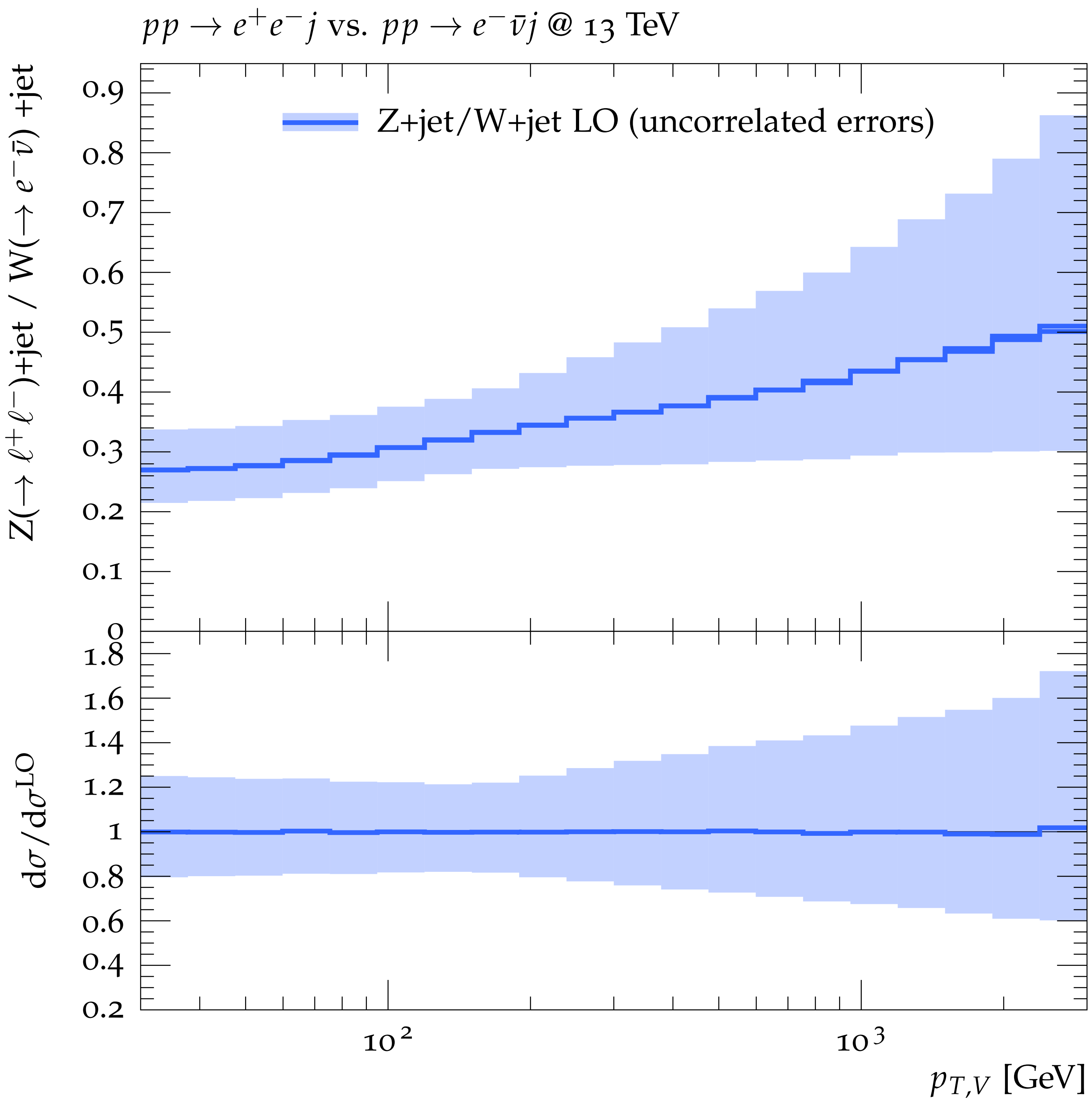
$$(\xi_{\mathrm{R}}, \xi_{\mathrm{F}}) = (2,2),\ (2,1),\ (1,2),\ (1,1),\ (1,0.5),\ (0.5,1), (0.5,0.5)$$

yields

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

with minor shape variations

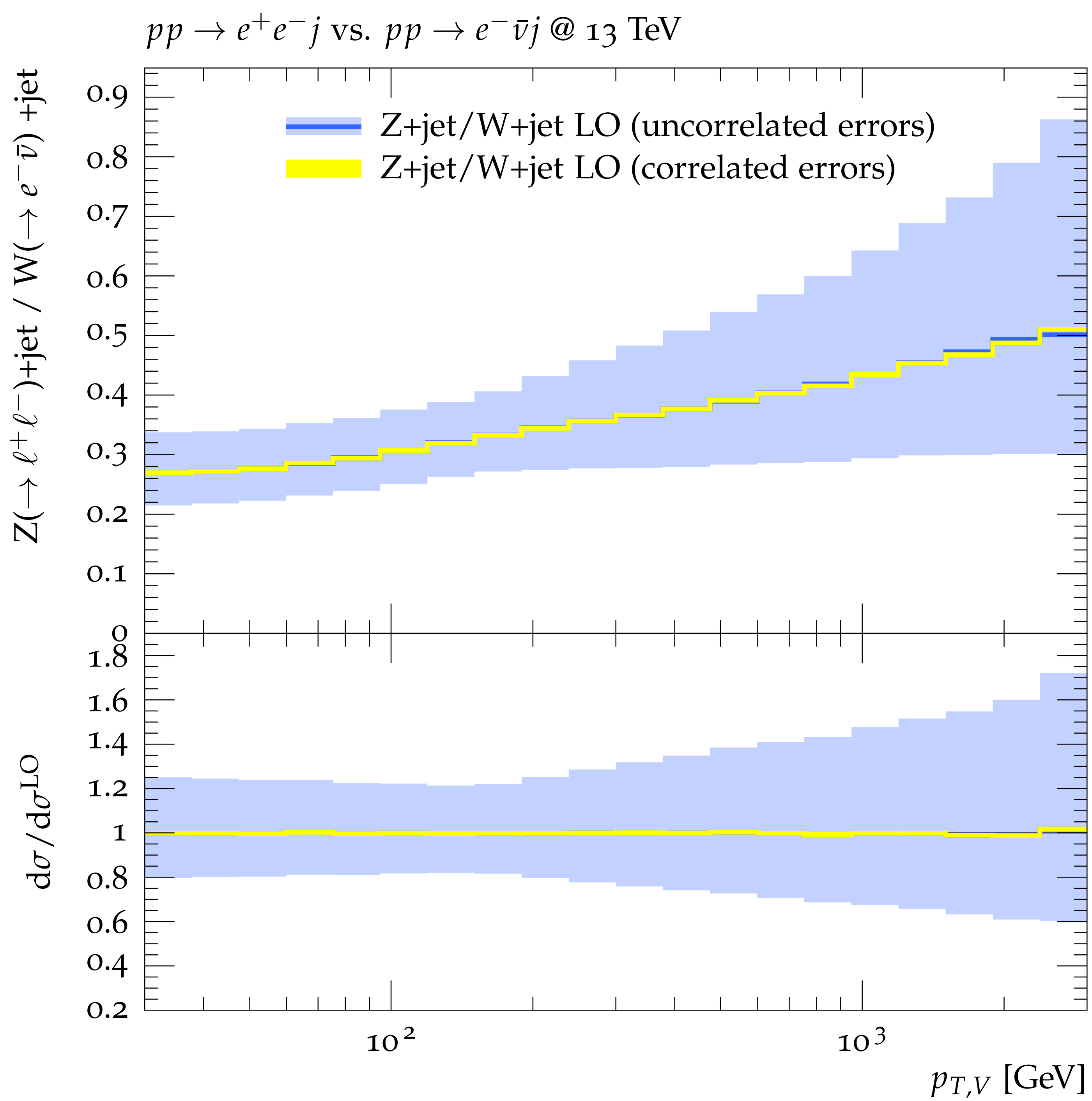
Correlation of scale variations



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

uncorrelated treatment yields O(40%) uncertainties

Correlation of scale variations



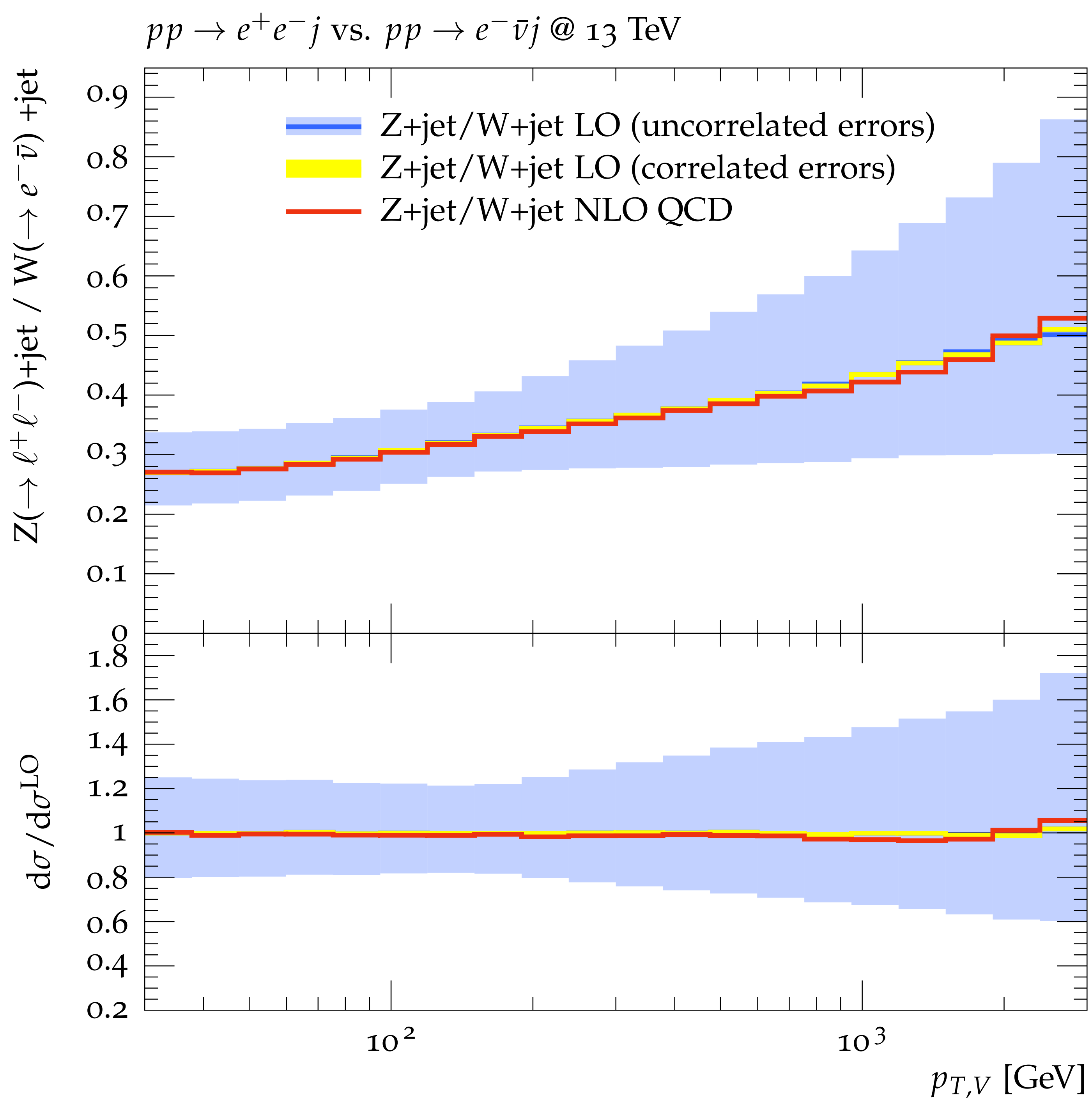
consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

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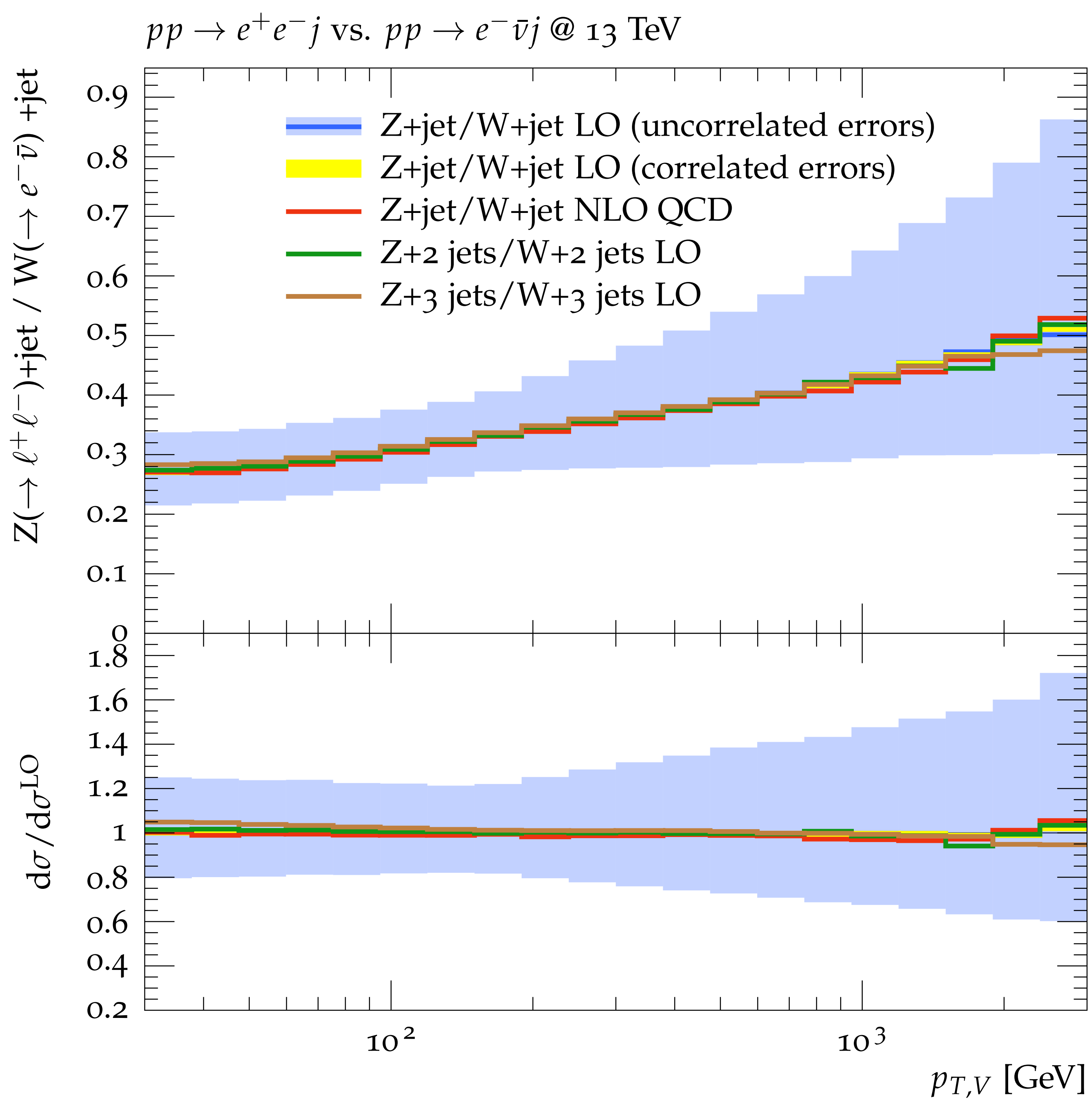
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

Correlation of scale variations



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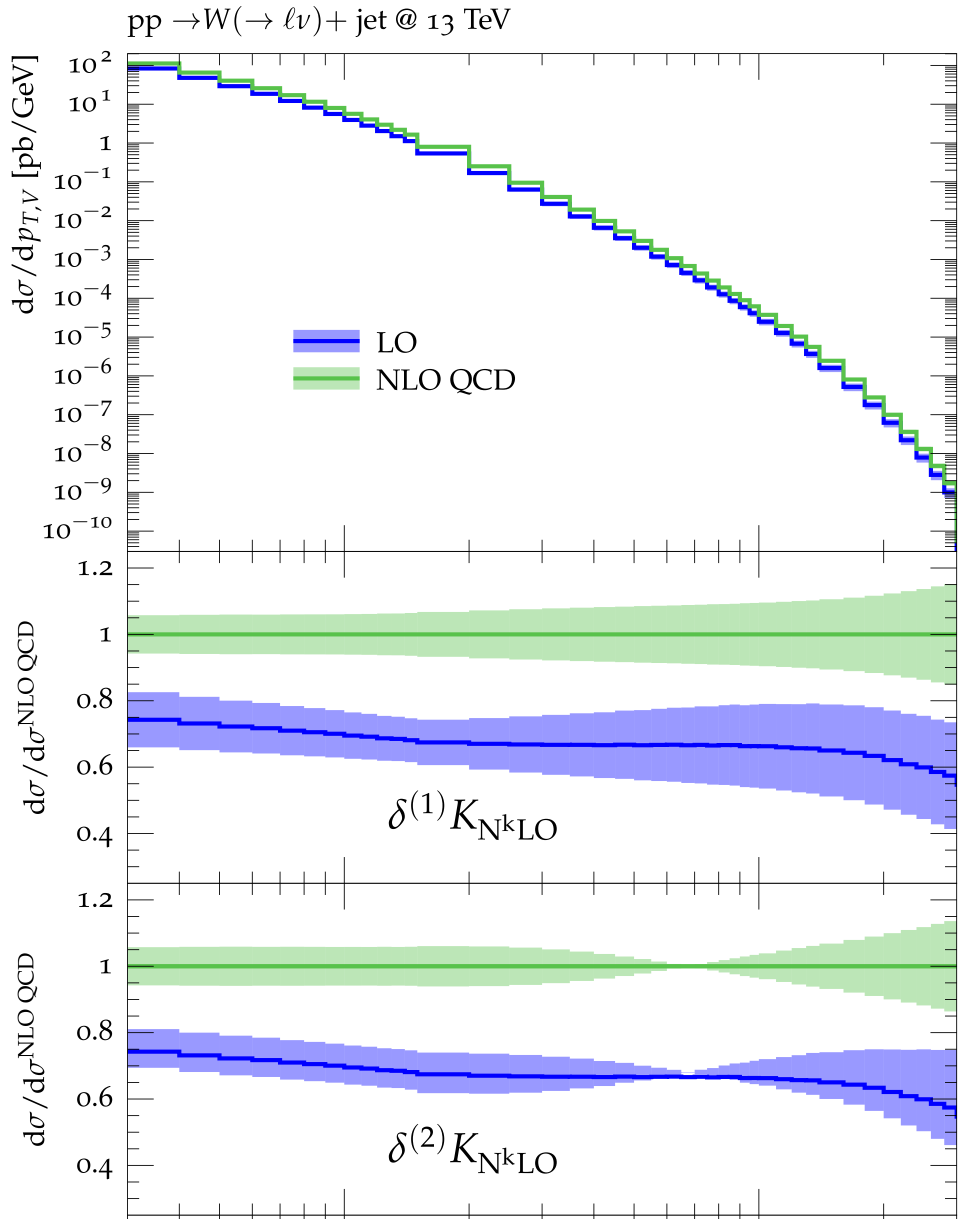
correlated treatment yields tiny O(<~ 1%) uncertainties

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

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

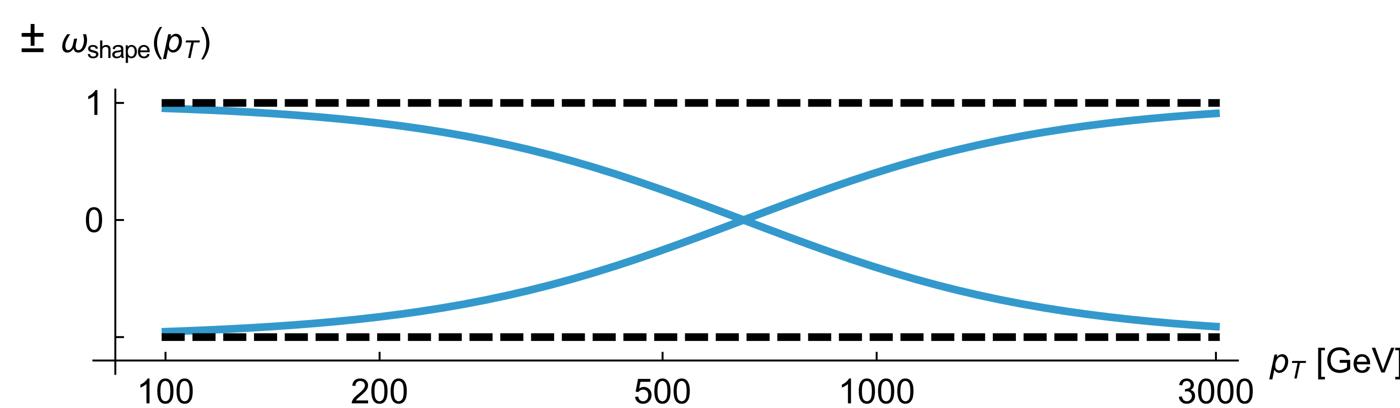
- correlated across processes
- correlated across pT bins

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

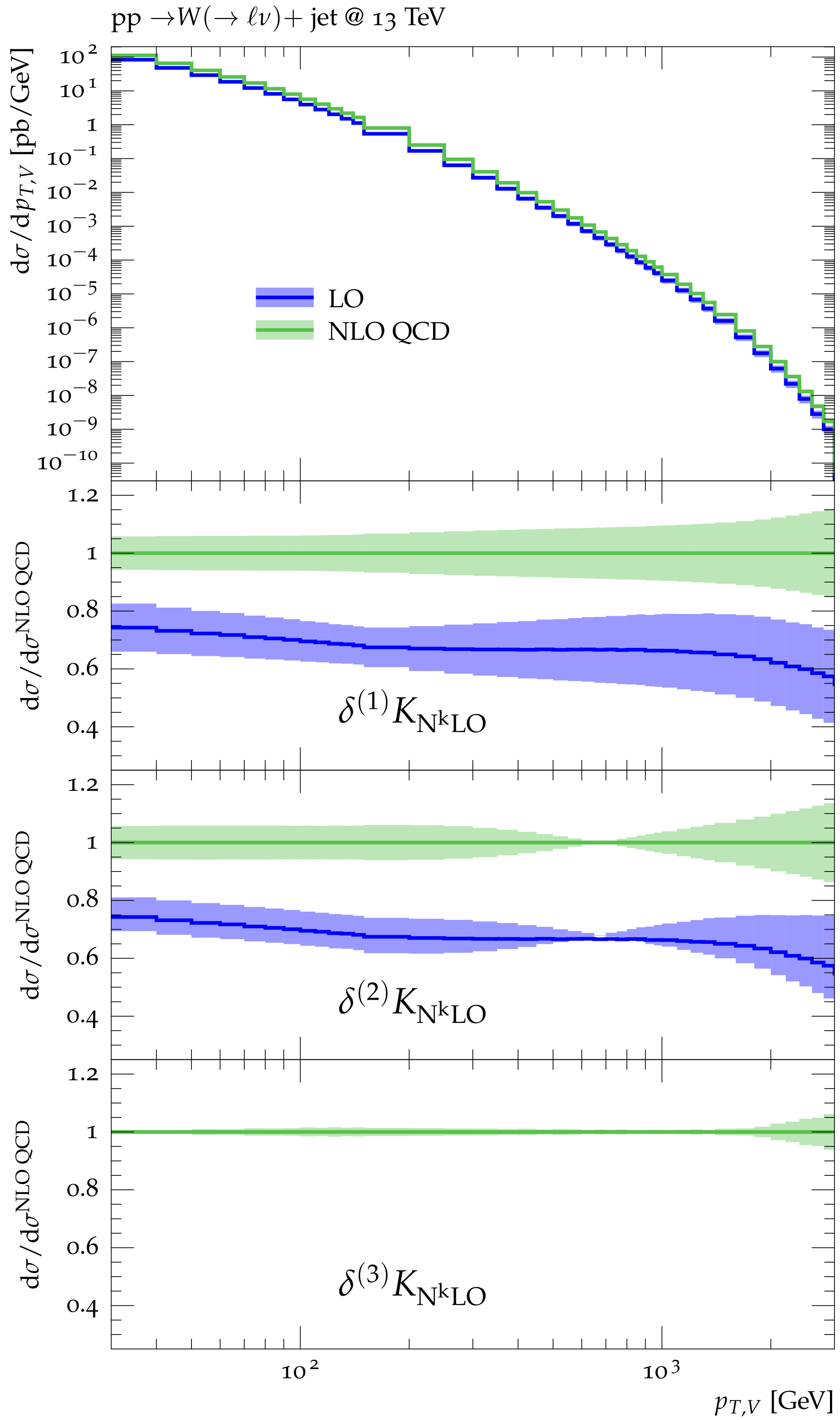
  symmetrized **scale uncertainty**

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

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



QCD uncertainties



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

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**

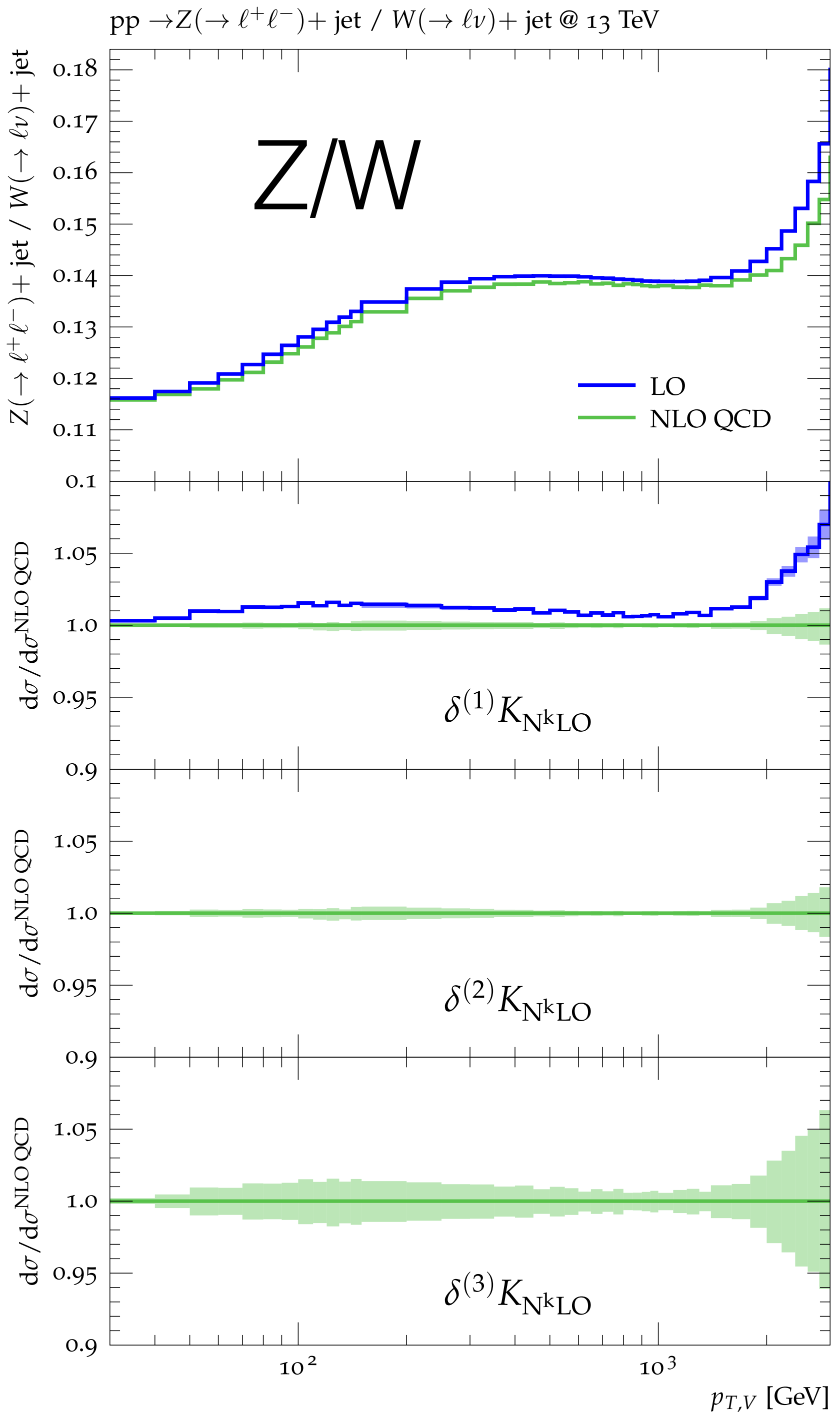
- $$\delta^{(2)}K^{V}_{\mathrm{N^kLO}} = \frac{p_{\mathrm{T}}^2 - 650\ \mathrm{GeV}}{p_{\mathrm{T}}^2 + 650\ \mathrm{GeV}}\delta^{(1)}K^{V}_{\mathrm{N^kLO}}$$

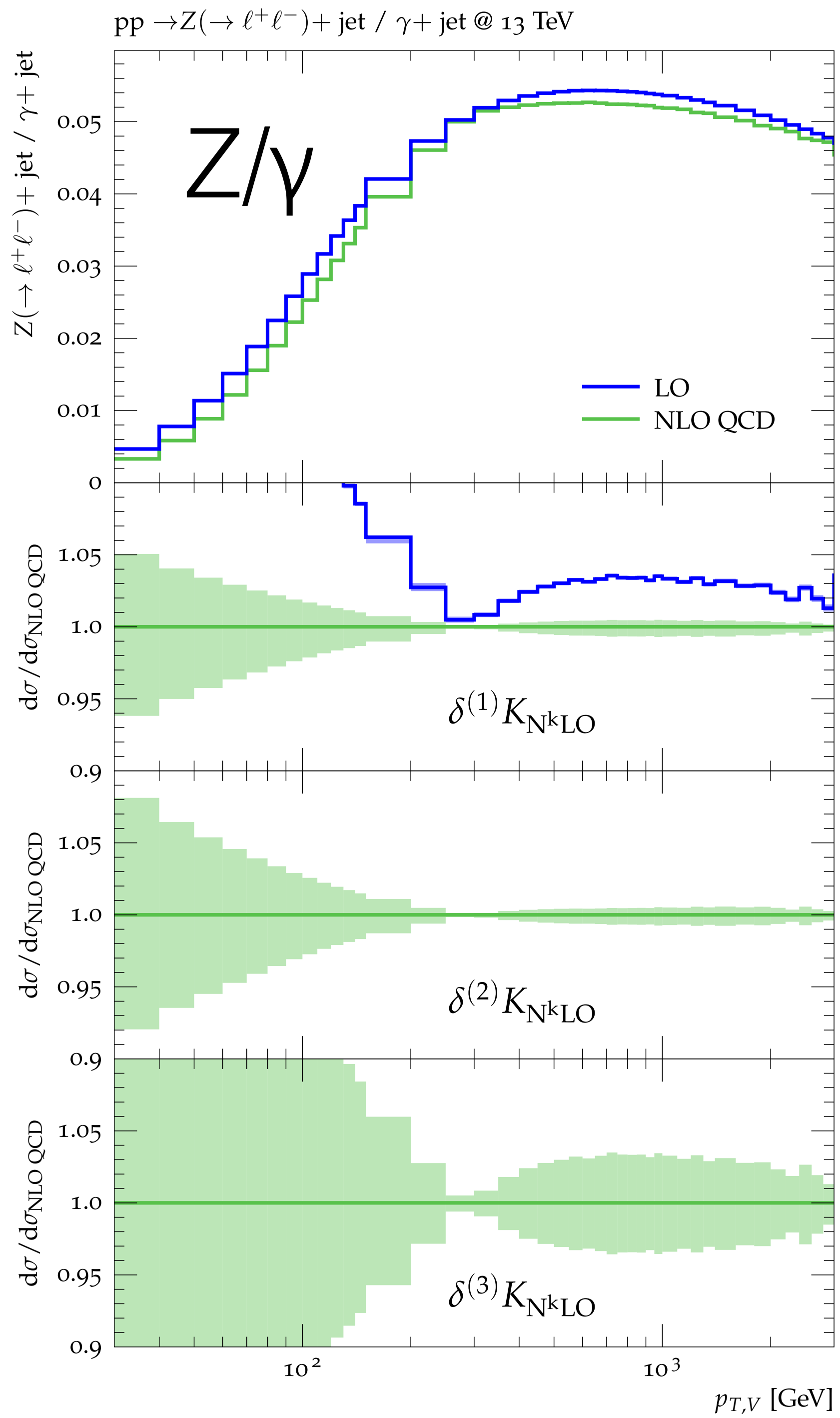
yields max **shape distortion** within scale variation band

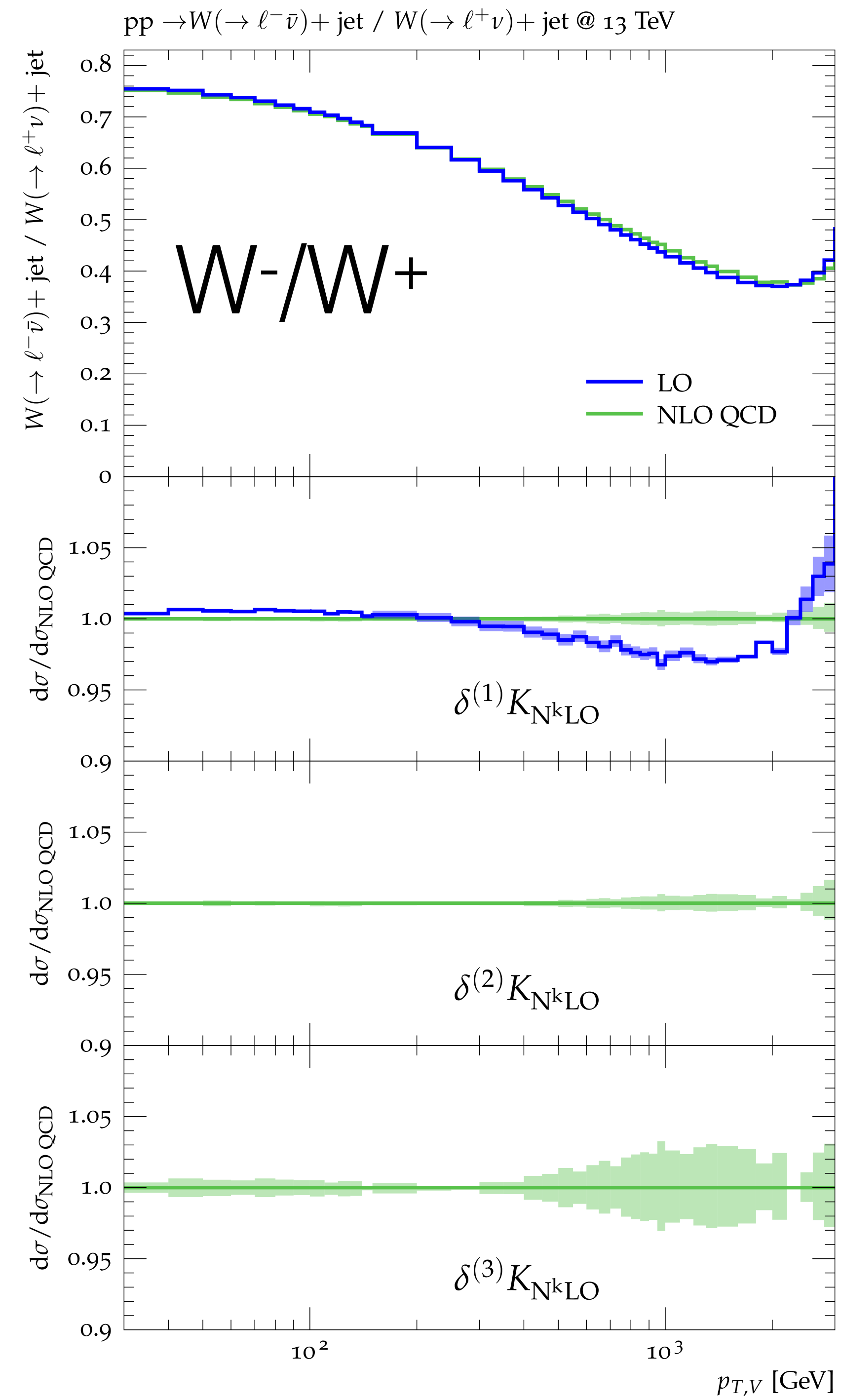
- $$\delta^{(3)}K^{V}_{\mathrm{N^kLO}} = \frac{K^{V}_{\mathrm{N^kLO}}}{K^{V}_{\mathrm{N^{k-1}LO}}} - \frac{K^{Z}_{\mathrm{N^kLO}}}{K^{Z}_{\mathrm{N^{k-1}LO}}}$$

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

QCD uncertainties in pT-ratios







$Z/W^{\pm} \simeq 1\%$

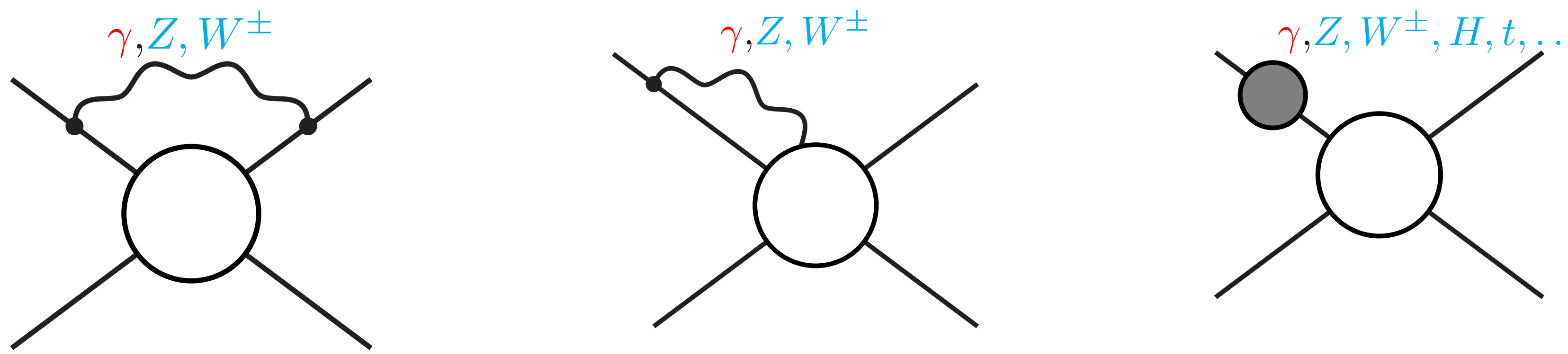
$Z/\gamma \simeq 3\%$

$W^+/W^- \simeq 1$–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]*

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

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

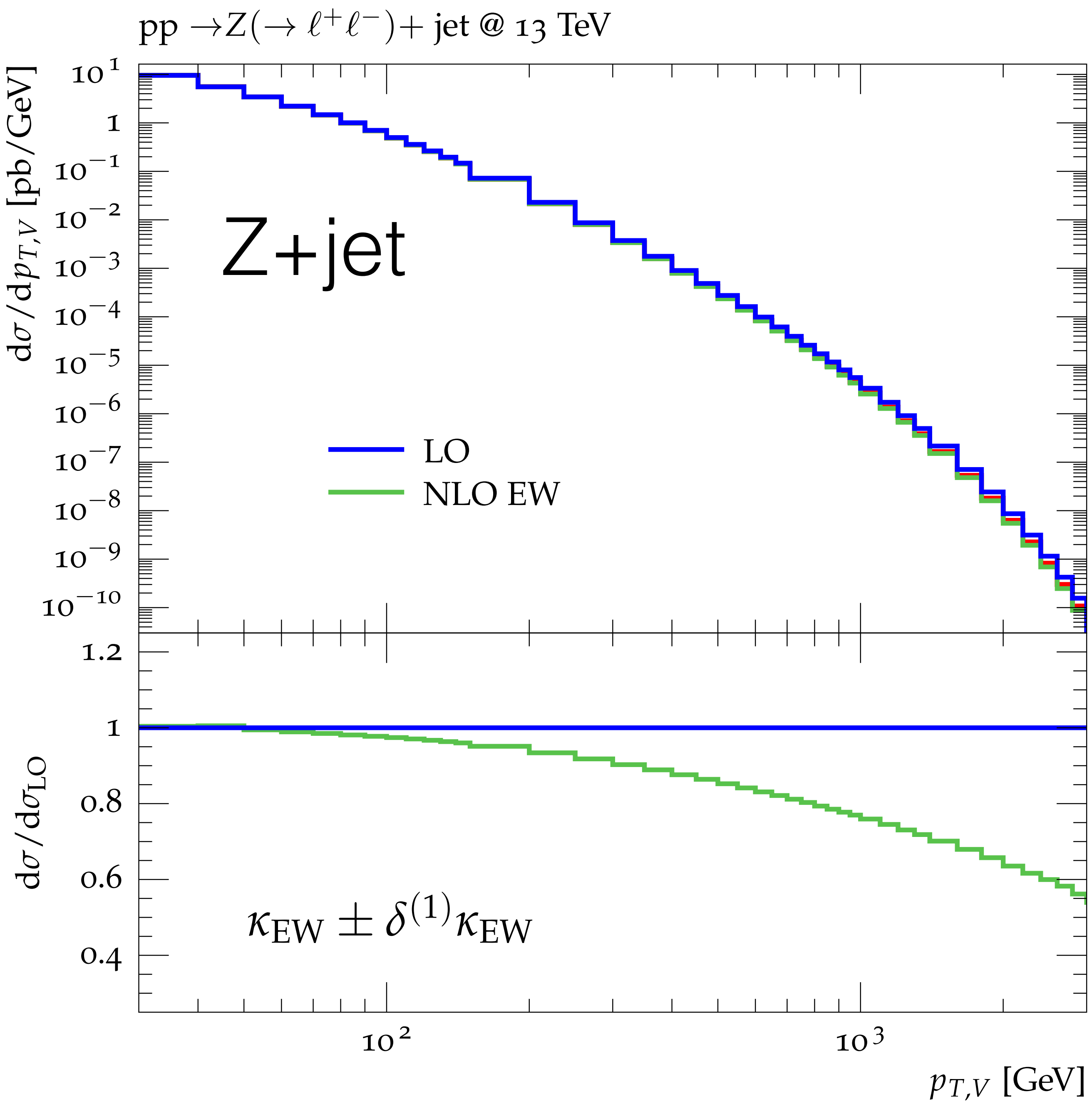
$$\delta_{\text{LL}} \sim -\frac{\alpha}{\pi s_W^2}\log^2\frac{\hat{s}}{M_W^2} \simeq -28, -76, -104\%,$$

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

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

➡ sizeable cancellations between leading and subleading terms possible

Pure EW uncertainties



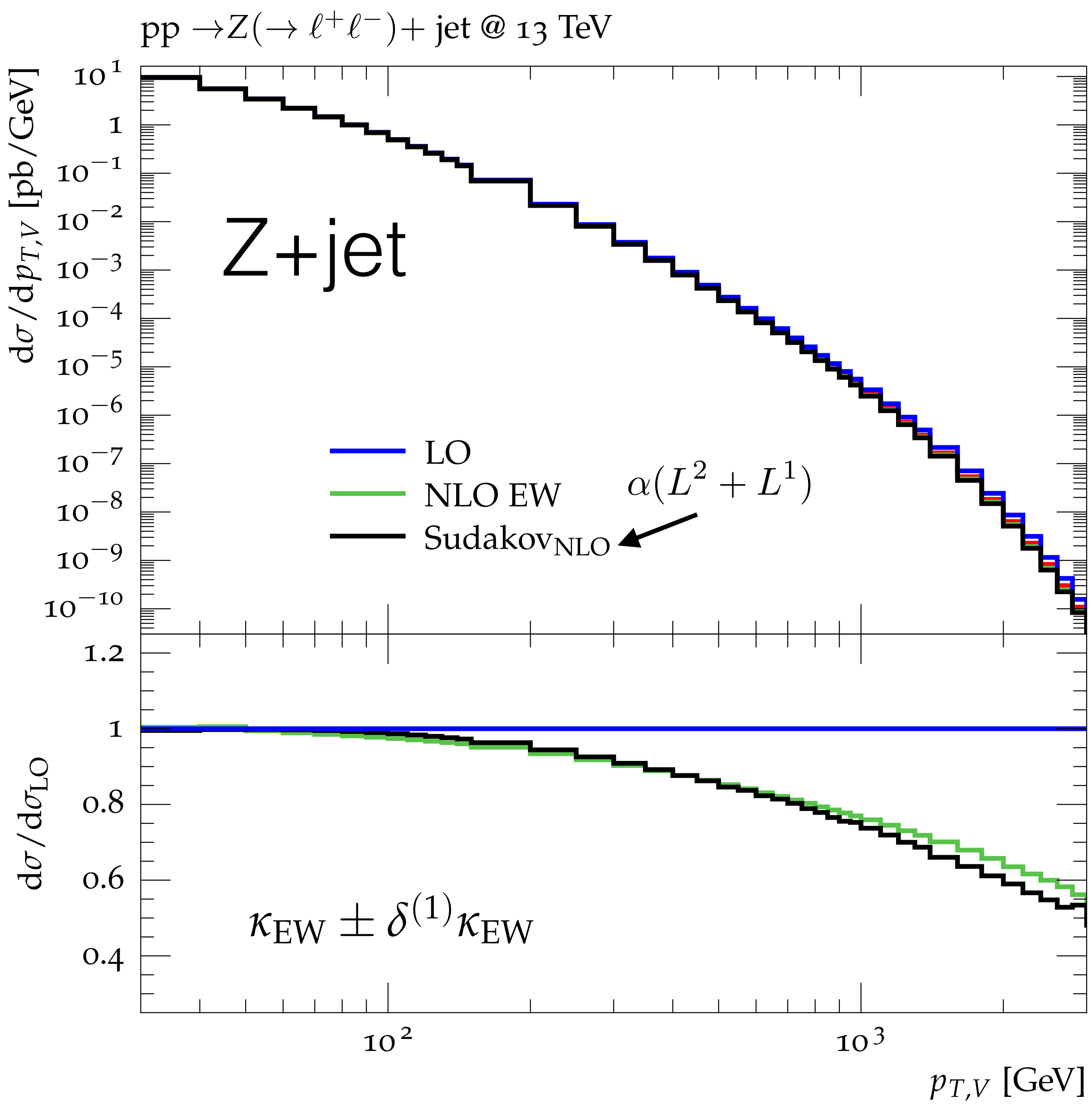
EW corrections become sizeable at large $p_{T,V}$

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



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

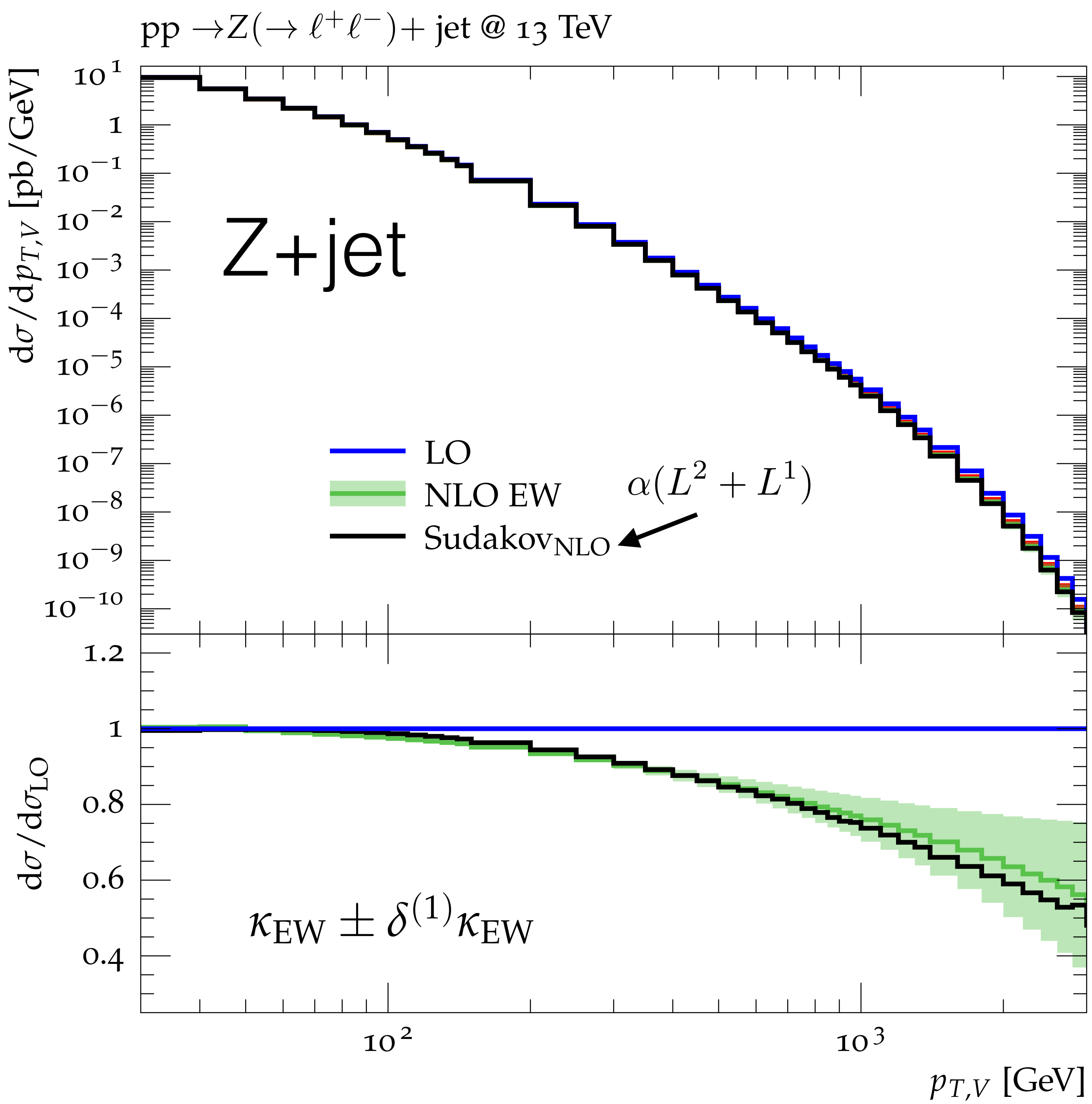
Large EW corrections dominated by Sudakov logs

↓

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



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

Large EW corrections dominated by Sudakov logs

↓

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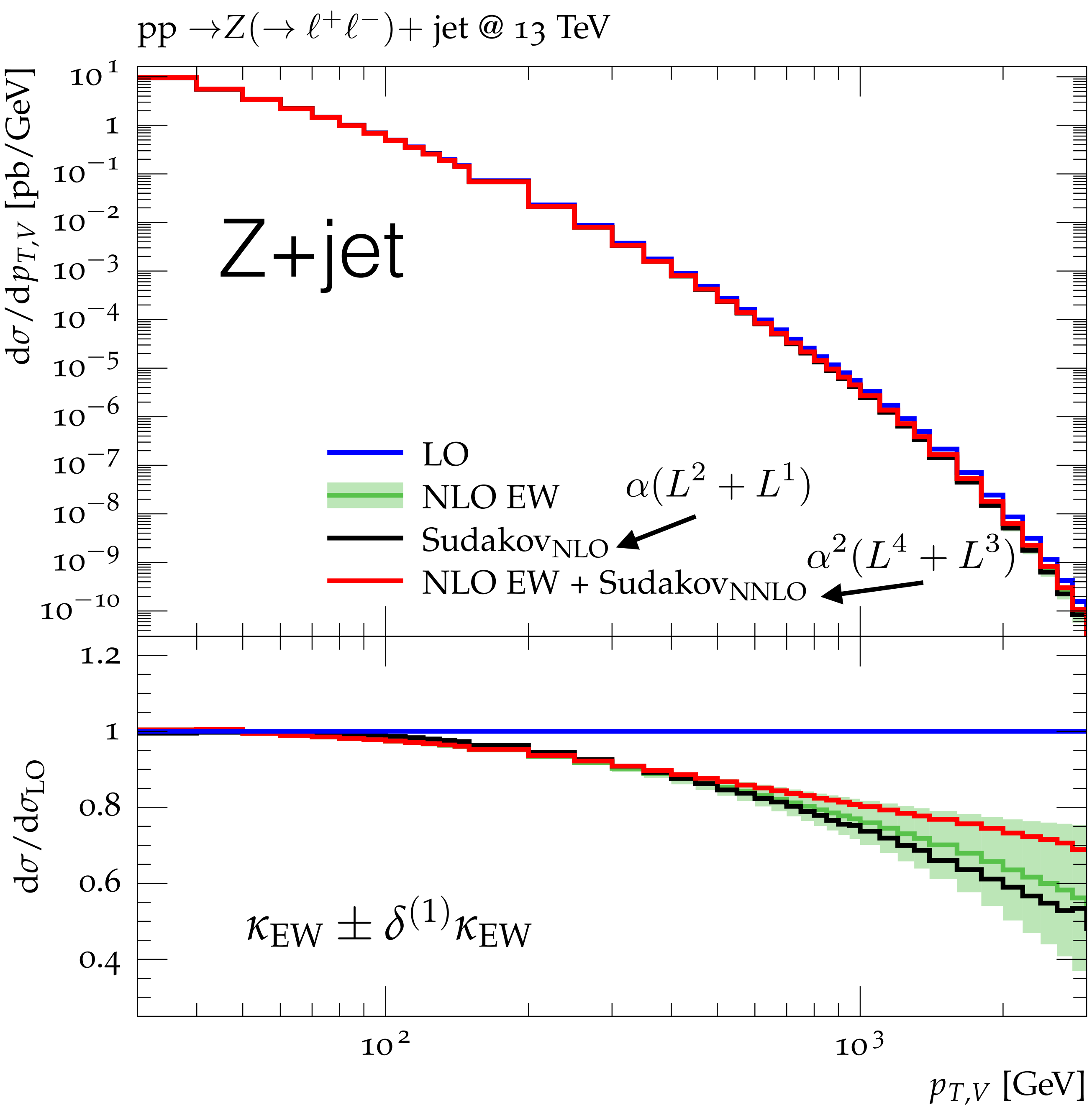
Pure EW uncertainties



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

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

Large EW corrections dominated by Sudakov logs

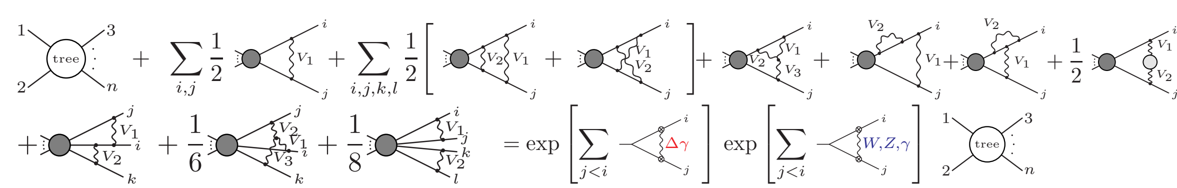
↓

Uncertainty estimate of NLO EW from naive exponentiation × 2:

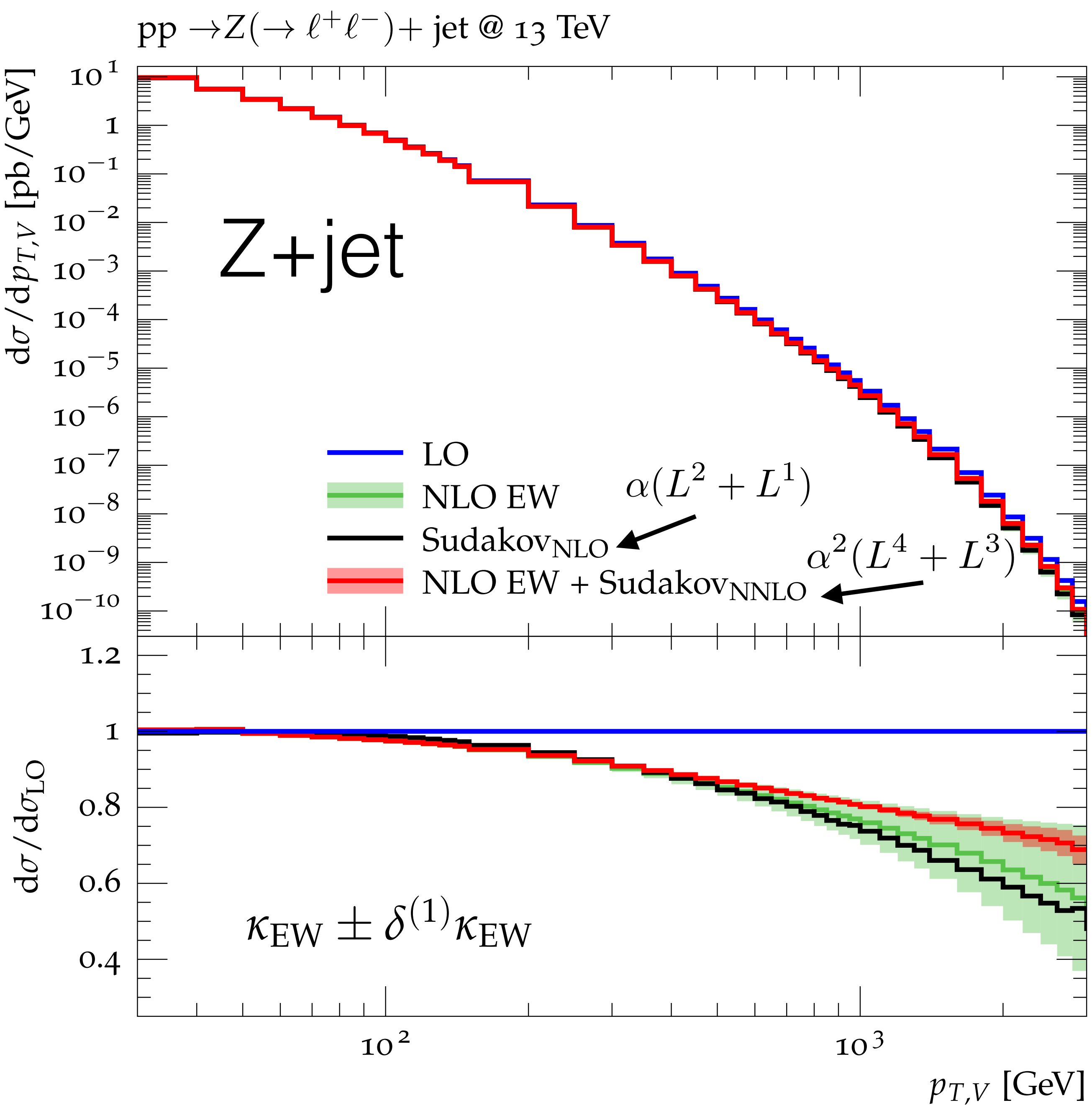
$$\delta^{(1)}\kappa_{\mathrm{EW}} \simeq \frac{2}{k!}\left(\kappa_{\mathrm{NLO,EW}}\right)^k$$

↓

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



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 x 2:

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

↓

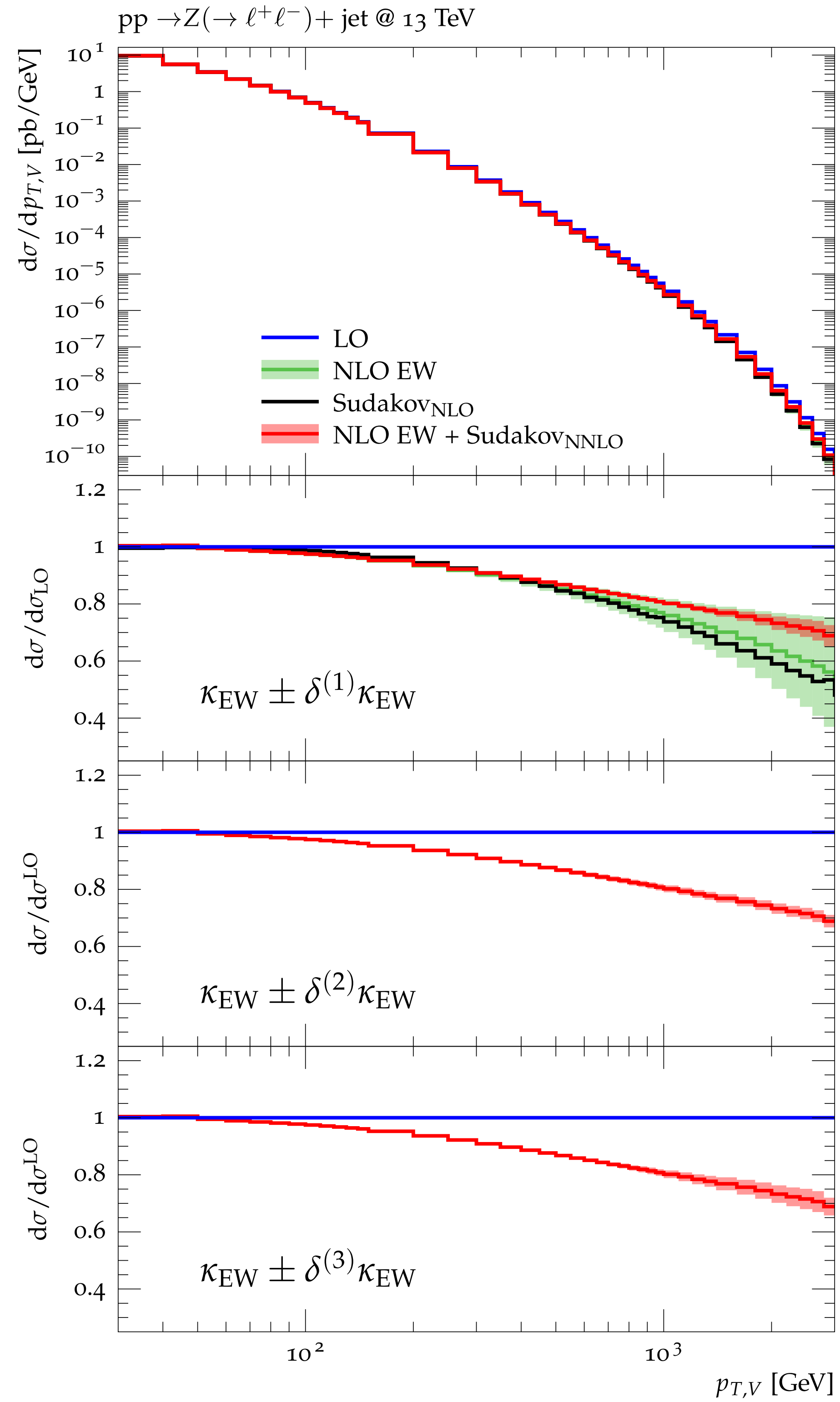
check against two-loop Sudakov logs
[Kühn, Kulesza, Pozzorini, Schulze; 05-07]

↓

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'

(correlated)

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

Additional uncorrelated uncertainties:

- 'hard non-log NNLO effects I'

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

(uncorrelated)

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

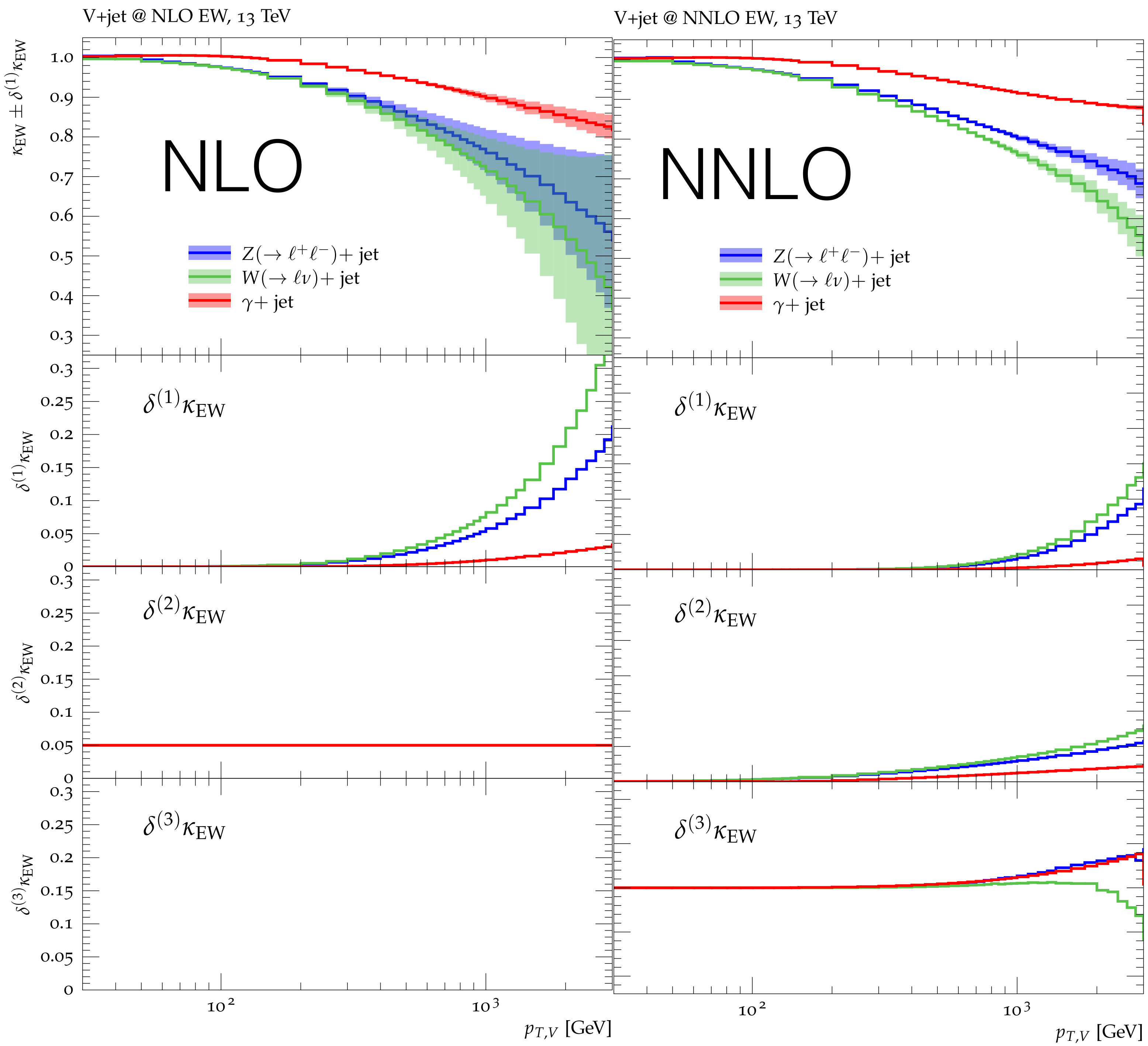
- 'hard non-log NNLO effects II'

(uncorrelated)

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

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

Pure EW uncertainties



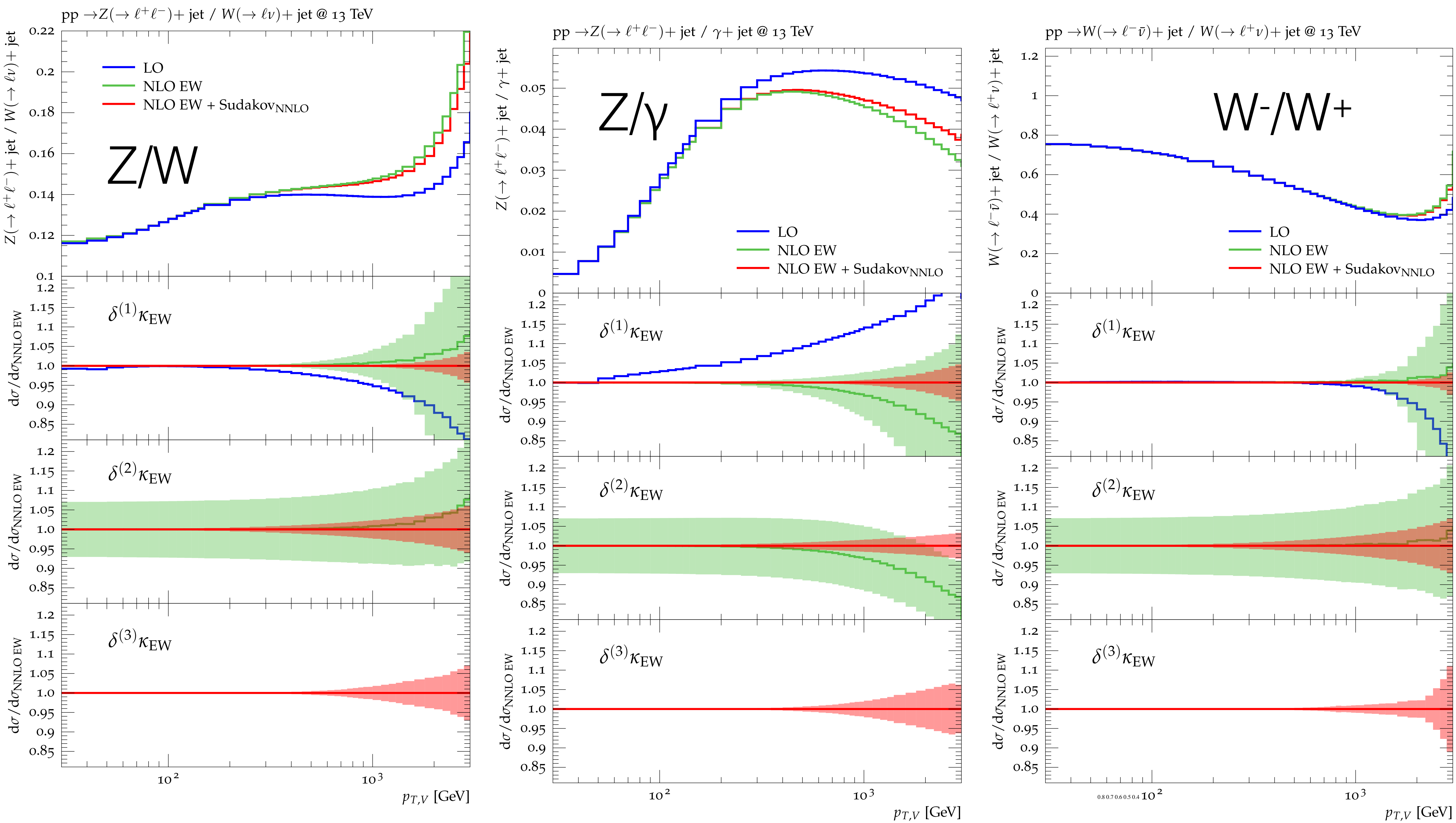
NNLO EW corrections at 1 TeV

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

Pure EW uncertainties

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

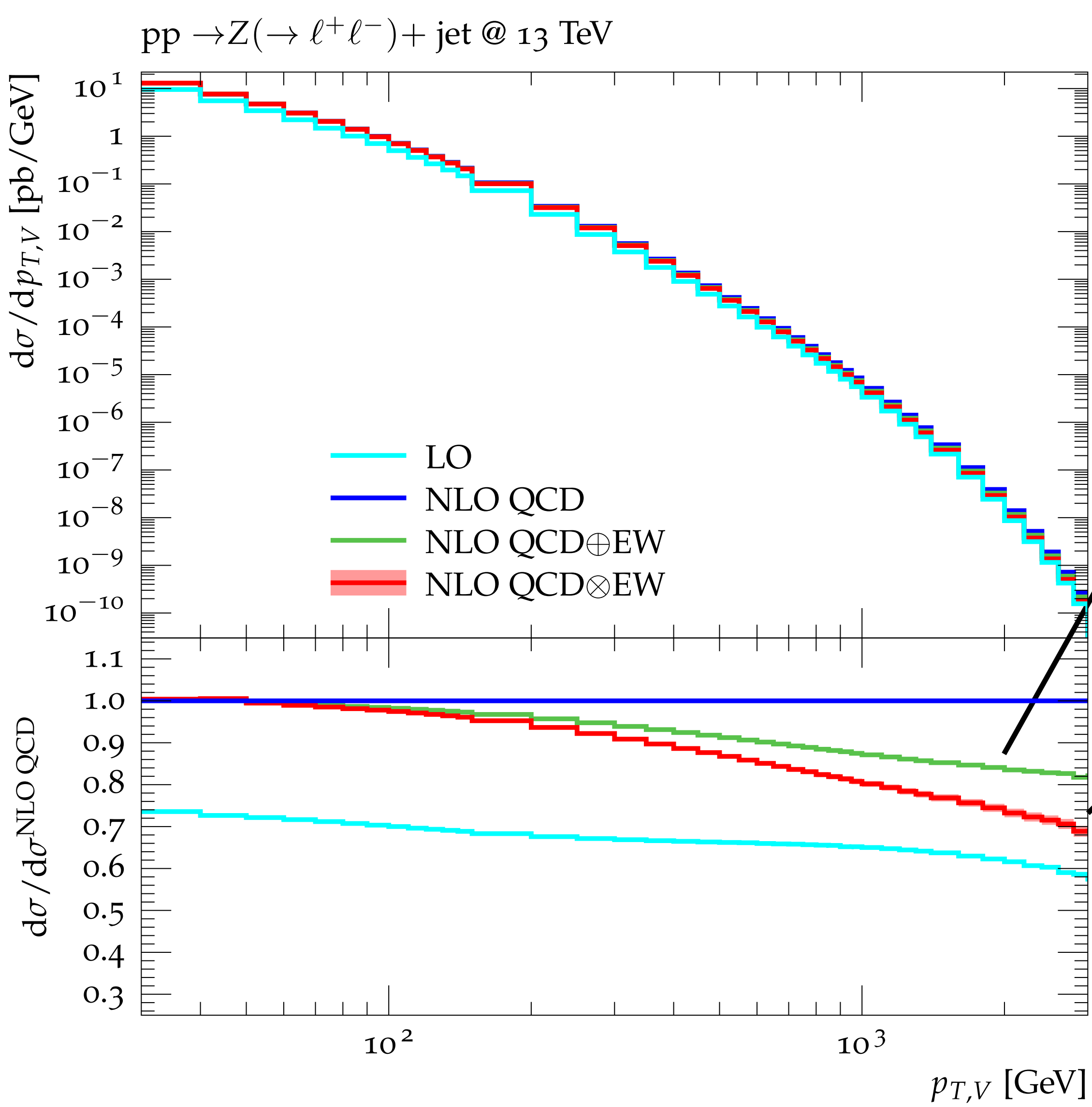
EW uncertainties in pT-ratios



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

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

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

Multiplicative combination

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

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

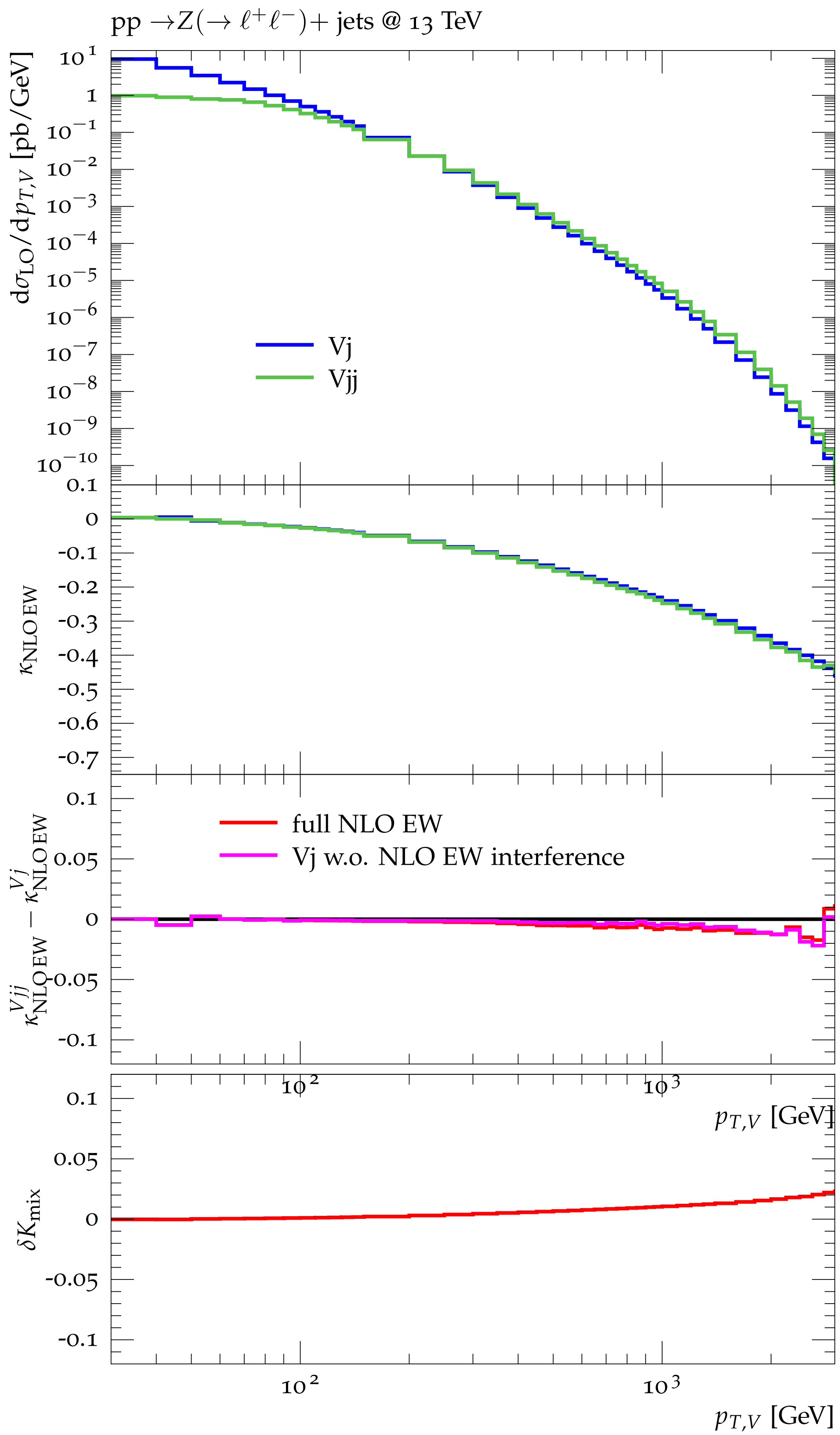
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

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

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

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

strong support for
- factorization
- multiplicative QCD x EW combination

Estimate of non-factorising contributions

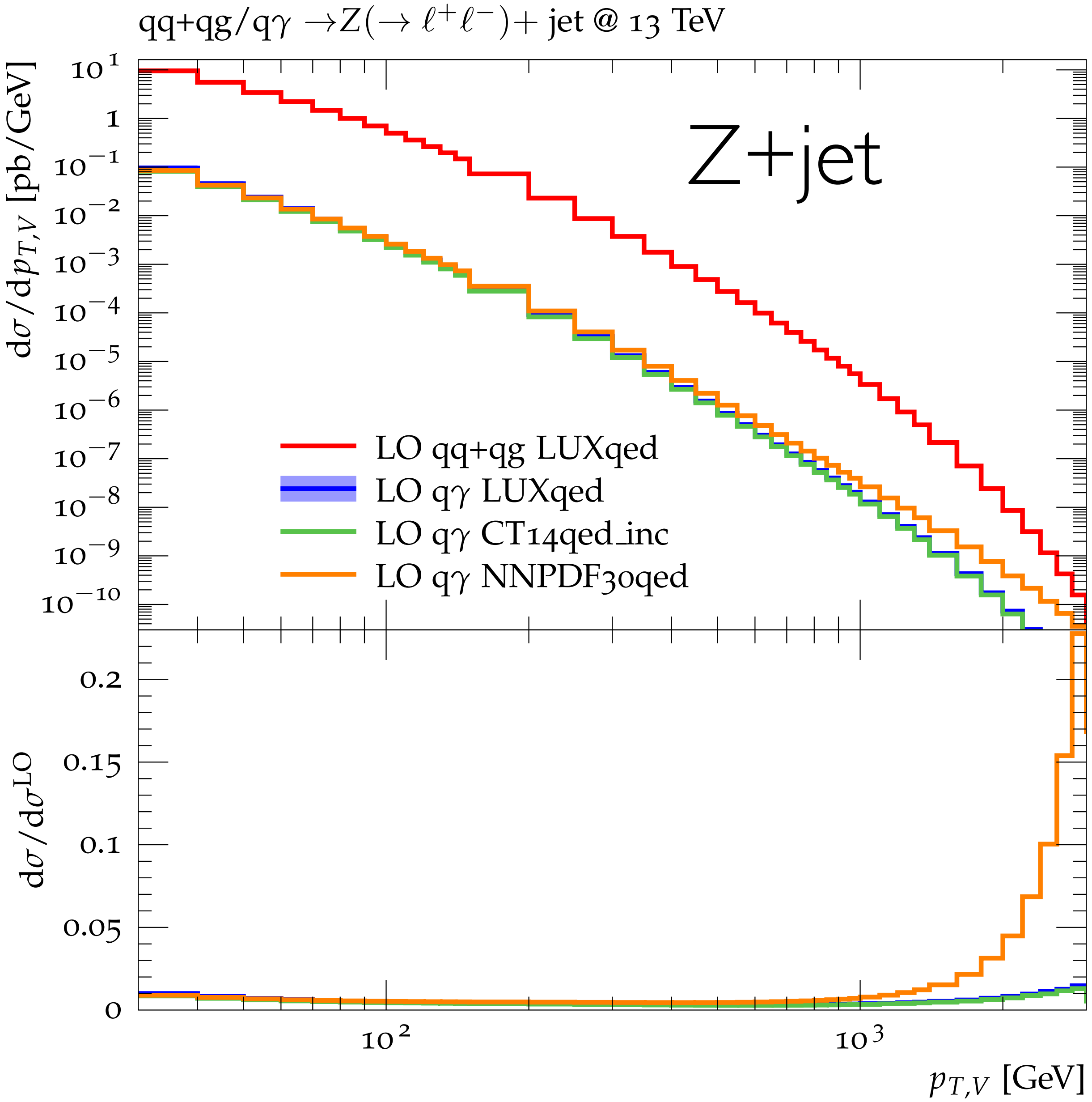
(correlated)

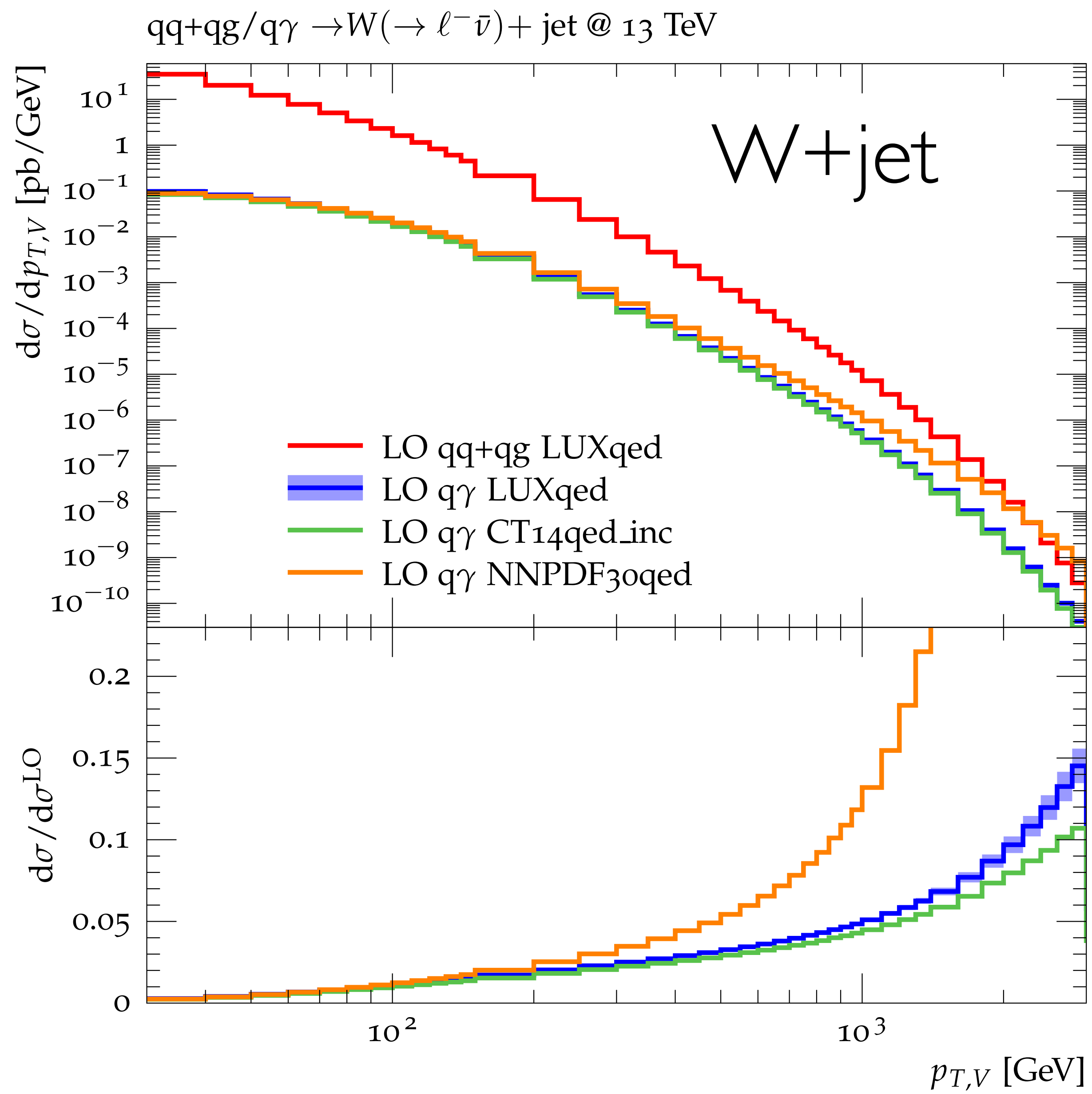
$$\delta K^{(V)}_{\mathrm{mix}}(x) \;=\; 0.1\left[K^{(V)}_{\mathrm{TH},\oplus}(x,\vec{\mu}_0) - K^{(V)}_{\mathrm{TH},\otimes}(x,\vec{\mu}_0)\right]$$

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

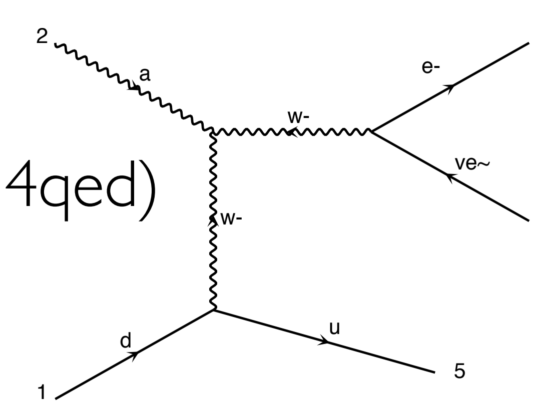
4. Other issues (PDFs, γ-induced)

Photon-induced production

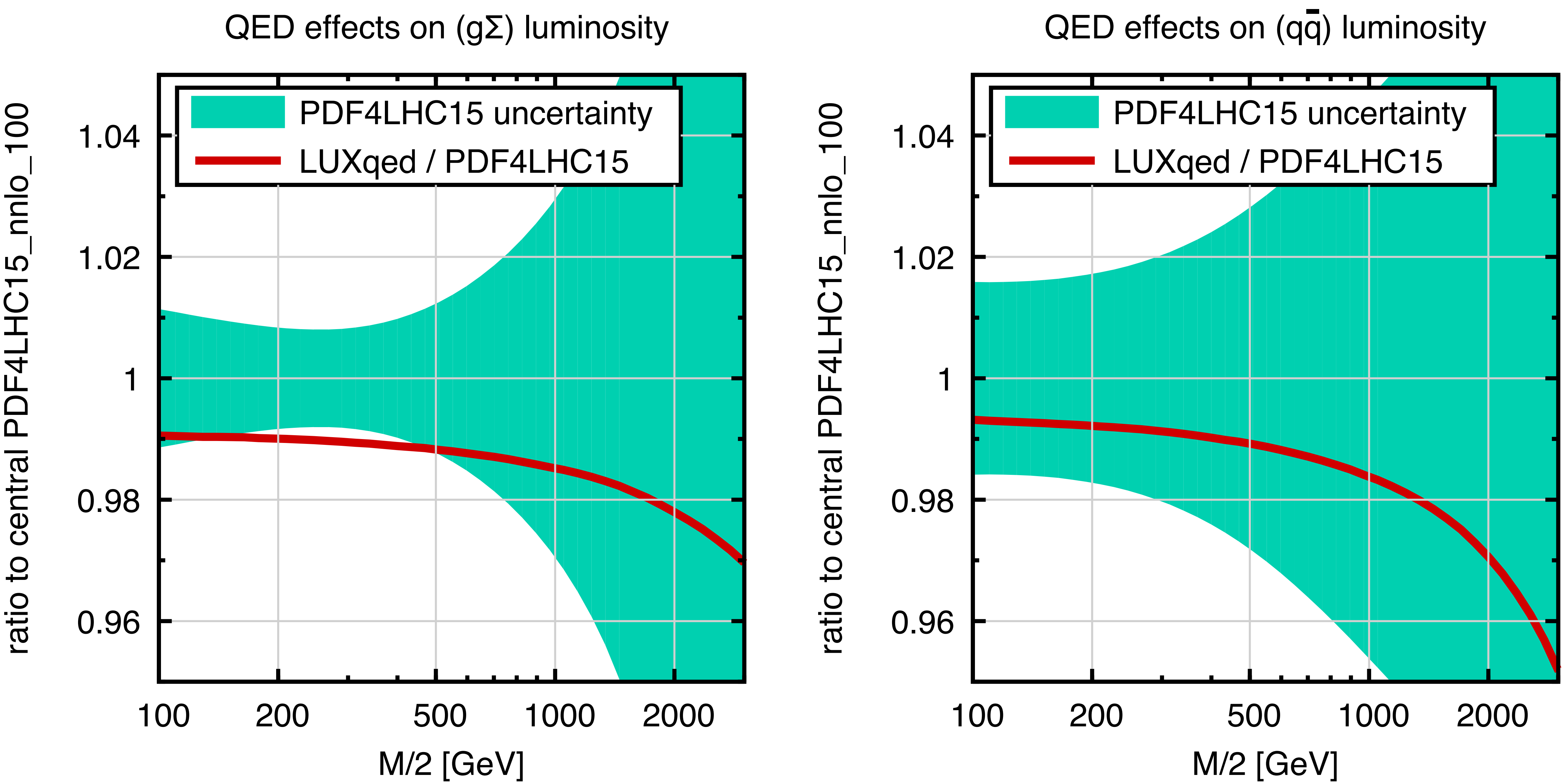




- photon-induced production irrelevant for Z+jet (and γ+jet)
- in W+jet O(5%) contribution with LUXqed (consistent with CT14qed) (due to t-channel enhancement)
- ~1% uncertainties in photon PDFs due to LUXqed



PDFs



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

Conclusions

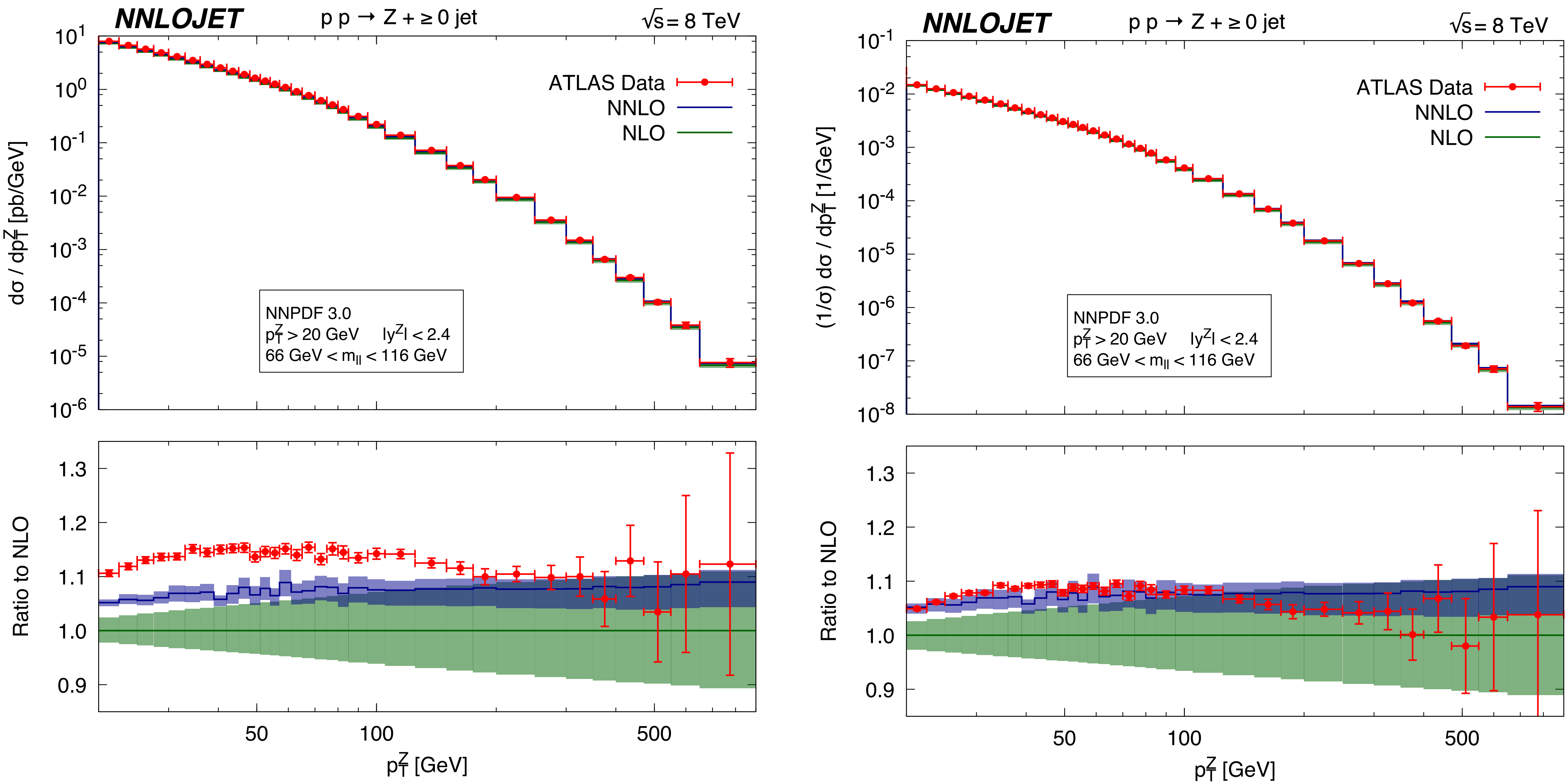
- monojet / MET+jets searches *soon* limited by V+jets background systematics
- MC reweighting allows to promote V + jet to NNLO QCD+(N)NLO EW:
    - inclusion of EW corrections *crucial* due to large Sudakov logs
- Perturbative systematics in pTV under control at the level of 1-10% up to the TeV

Outlook / Questions

- percent precision requires scrutiny of many subtleties and close TH/EXP interplay
- Experimental closure tests in control regions
- Uncertainty estimates applicable to other more exclusive observables?
- Framework applicable to other process classes?
- Utilisation in PDF fits?

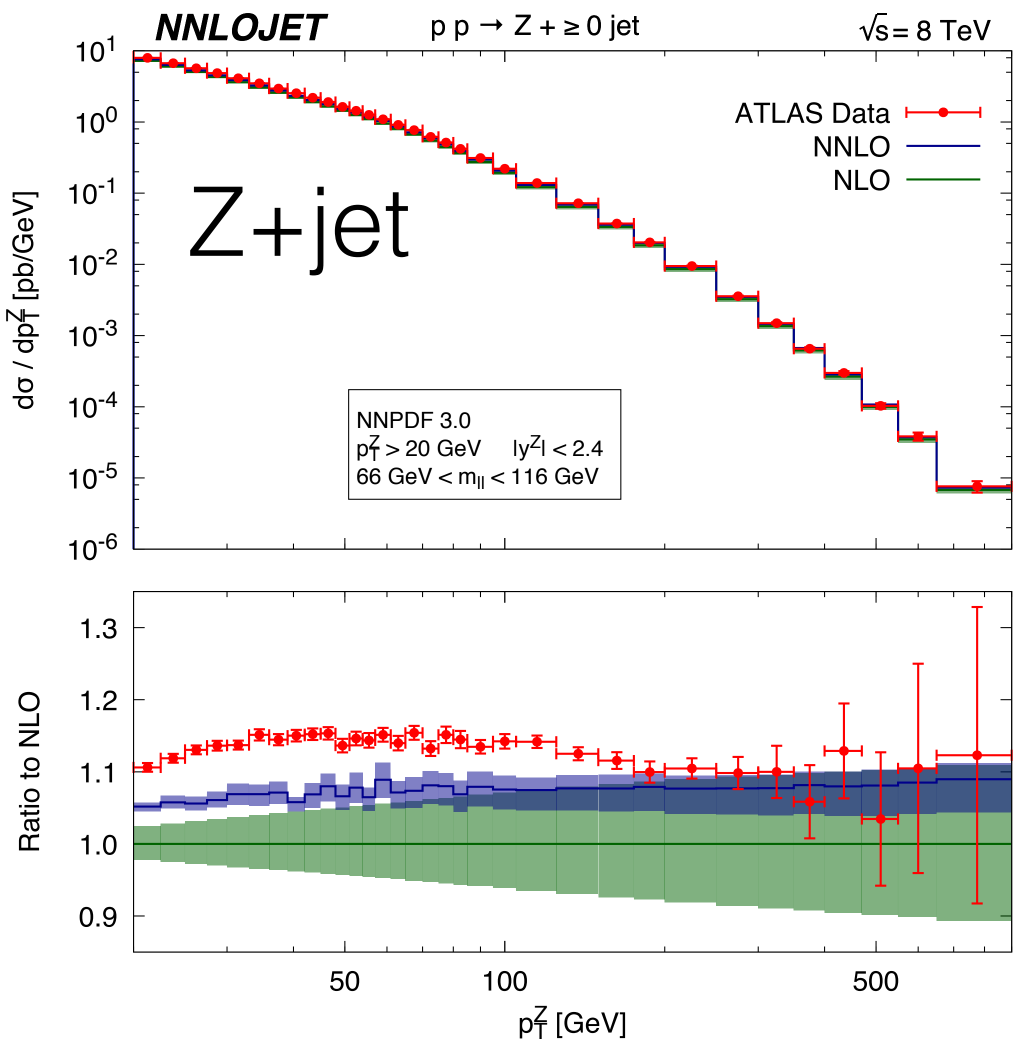
BACKUP

NNLO for Z+jet

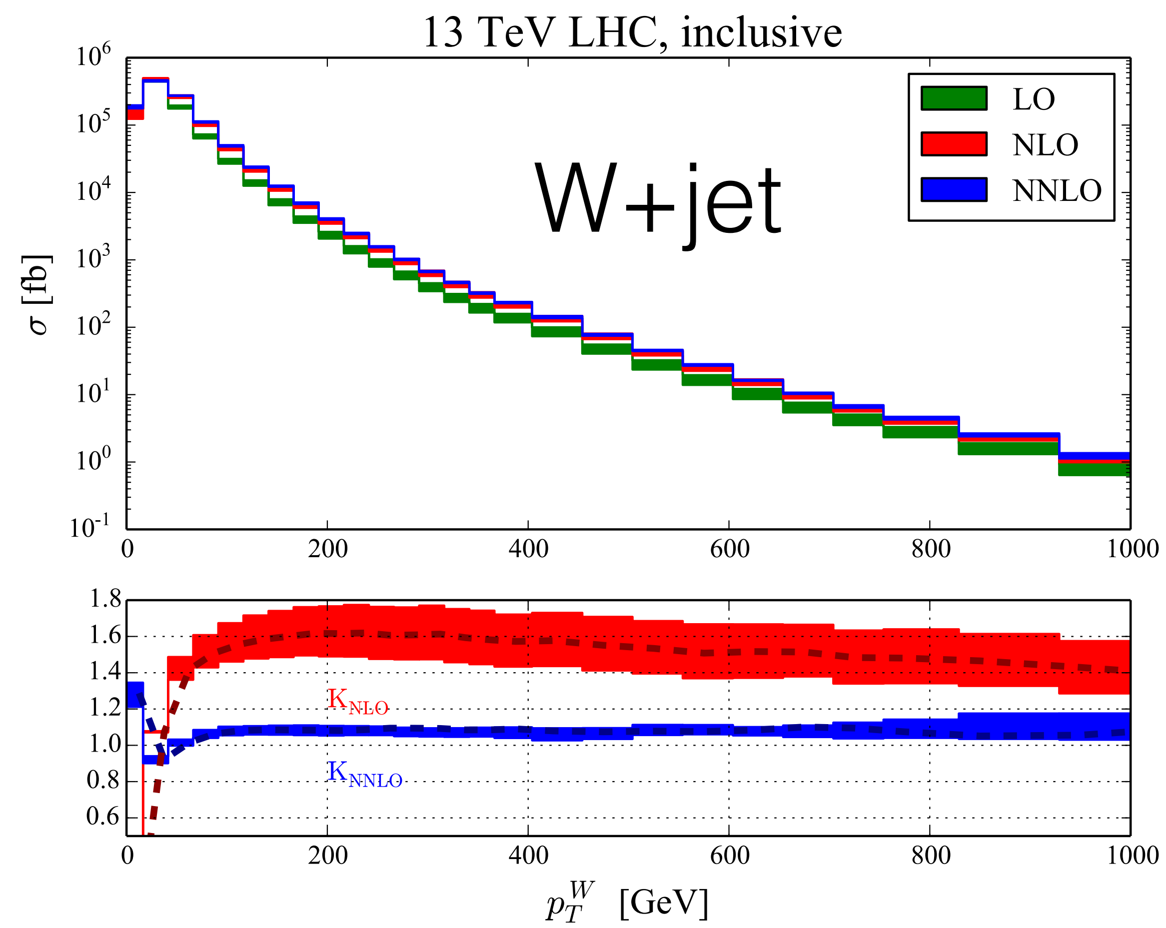


[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]

NNLO for W/Z+jet



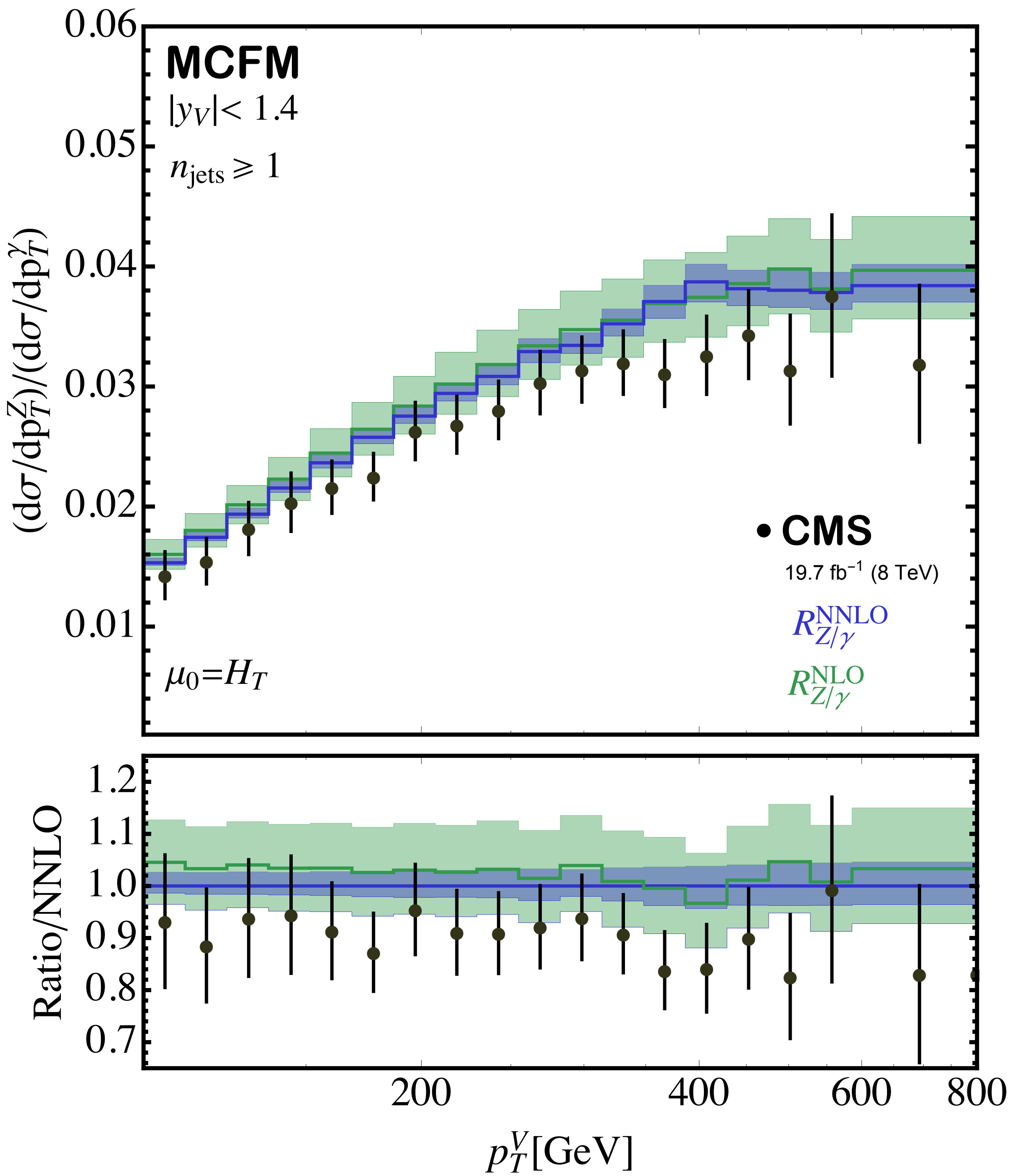
[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]



[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

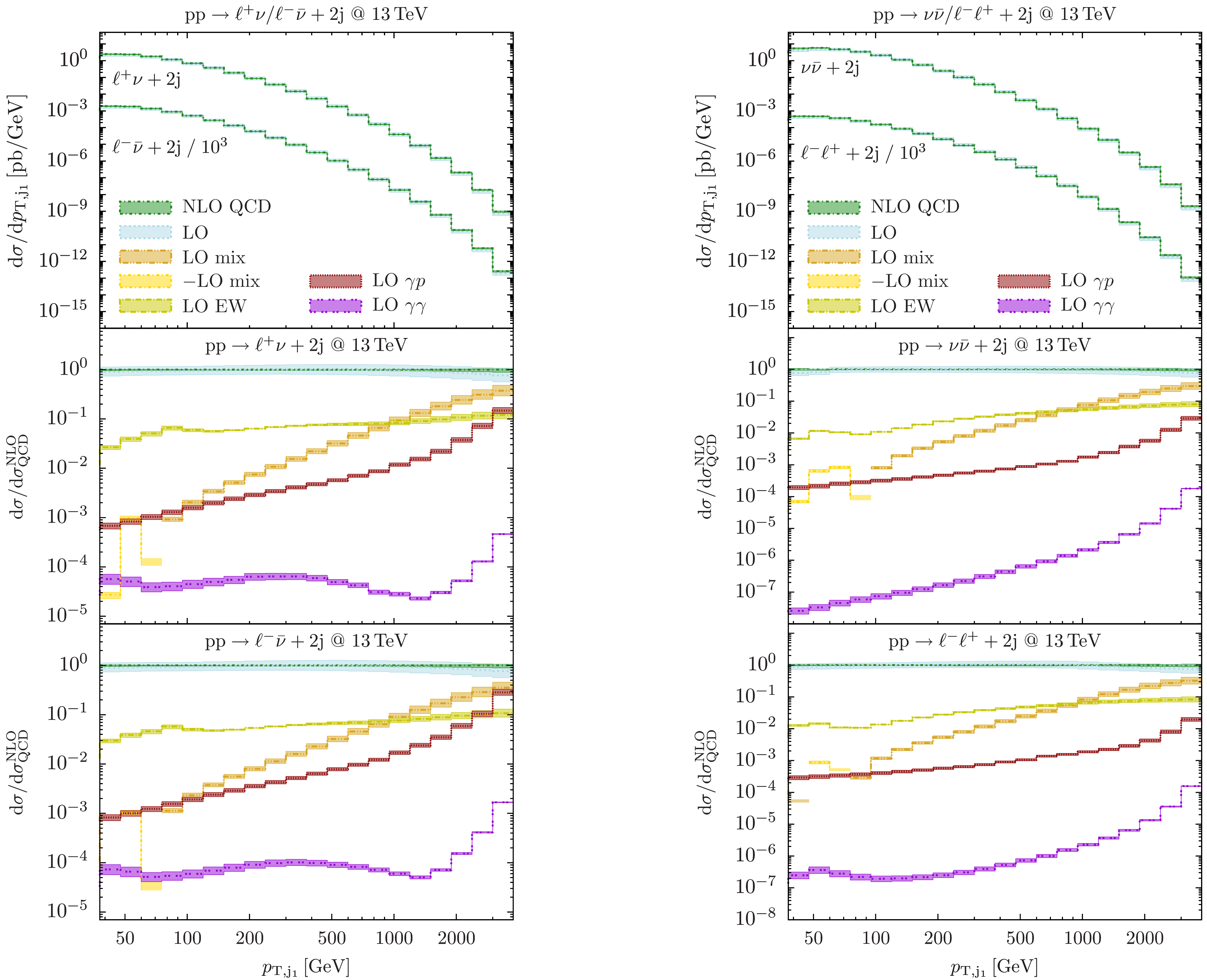
NNLO for Z/γ+jet



[Campbell, Ellis, Williams; '17]

NNLO/NLO ~ 1 for large pT!

Subleading Born: $p_{T,j1}$



Caveat: γ+jet

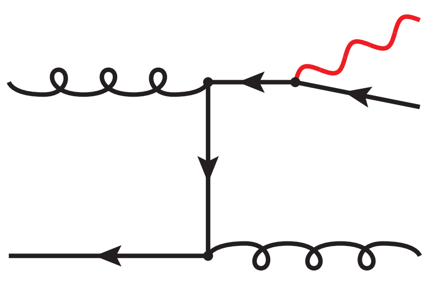
Note: this modelling of process correlations assumes close similarity of QCD effects between different V+jets processes

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

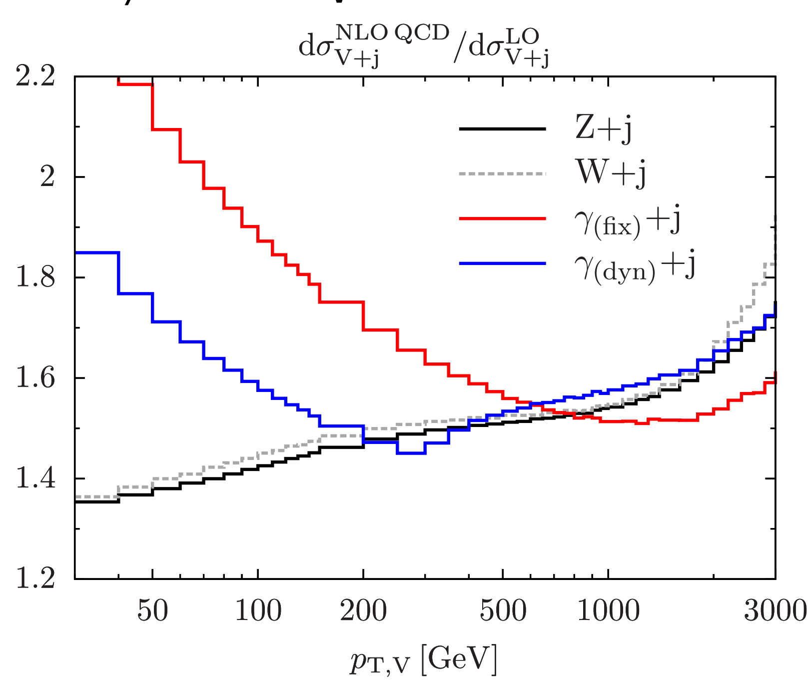
- apart from PDF effects it is the case for W+jets vs. Z+jets
- at pT > 200 GeV it is also the case for γ+jets vs. Z+jets.

Different logarithmic effects from fragmentation

- W/Z+jet: masscut-off $M_{Vj} \geq M_V$
- γ+ jet: Frixione-isolation cone of radius R_0



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

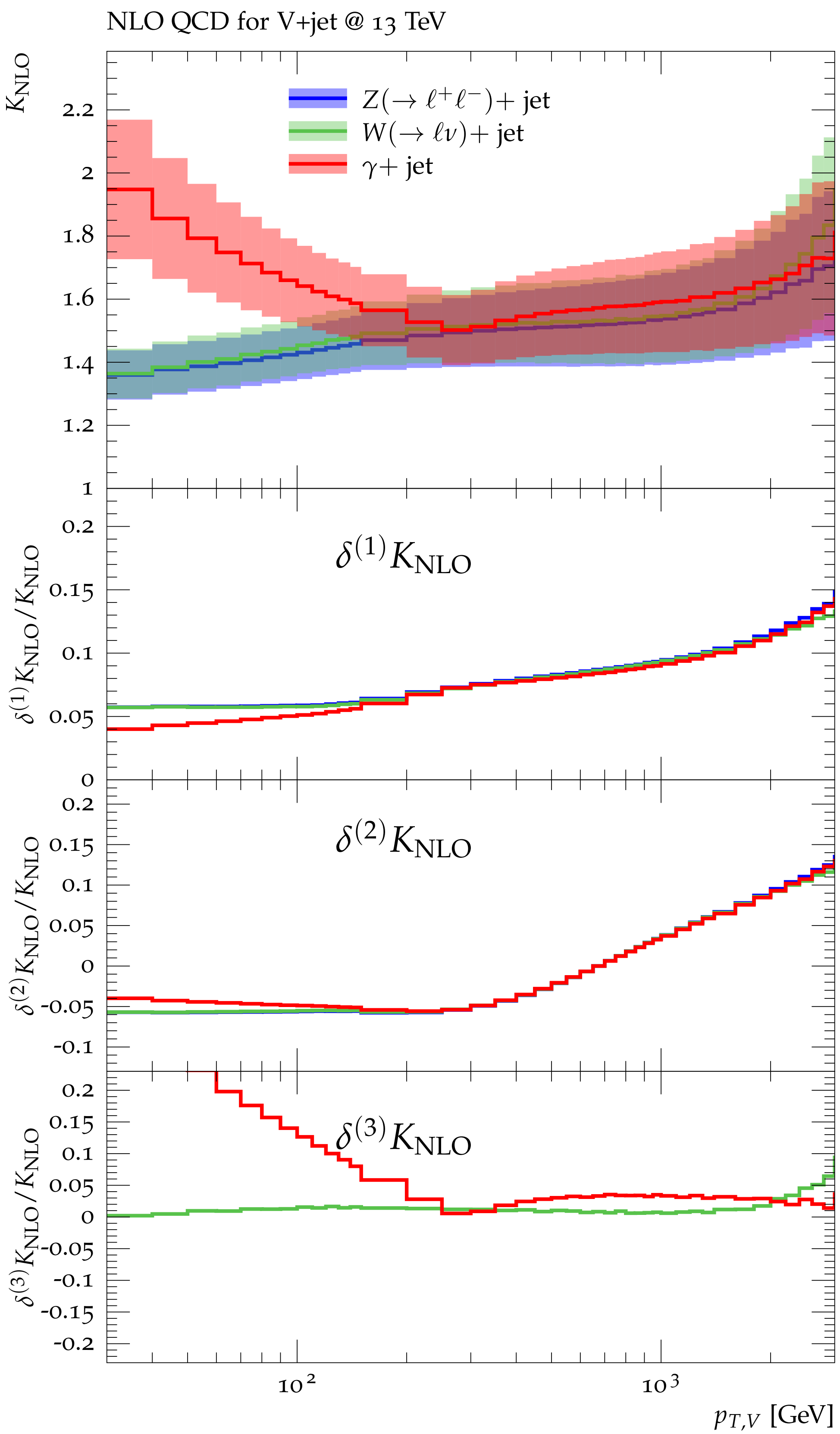


- γ_{dyn} behaves like W/Z at pT > MZ

  ⇒justifies process-correlation estimate

- remnant part $\gamma_{fix} - \gamma_{dyn}$ uncorrelated (uncertainty through extra reweighting and MC)

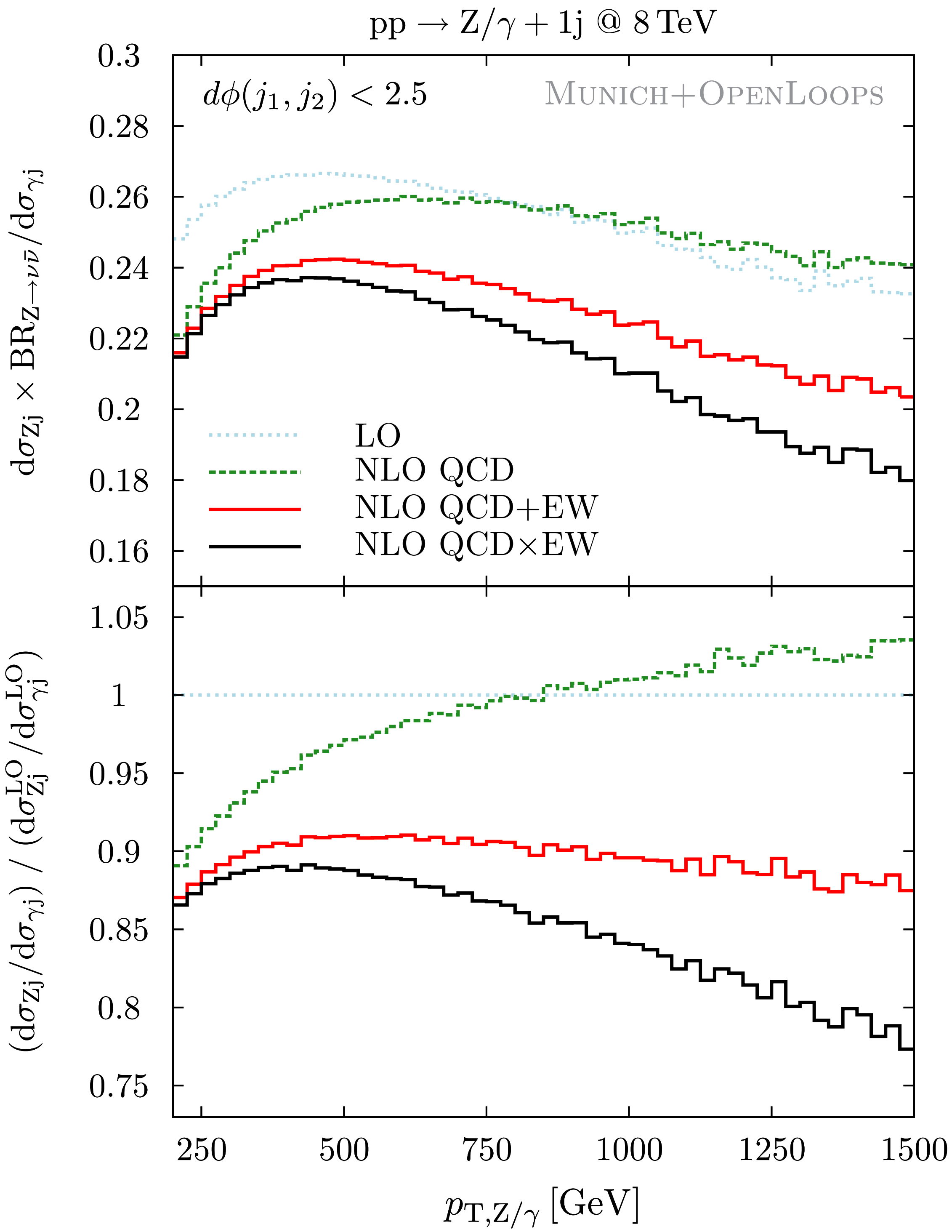
QCD uncertainties



NLO QCD corrections and uncertainties

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

Z/γ + 1 jet: pT-ratio



Overall

- mild dependence on the boson pT

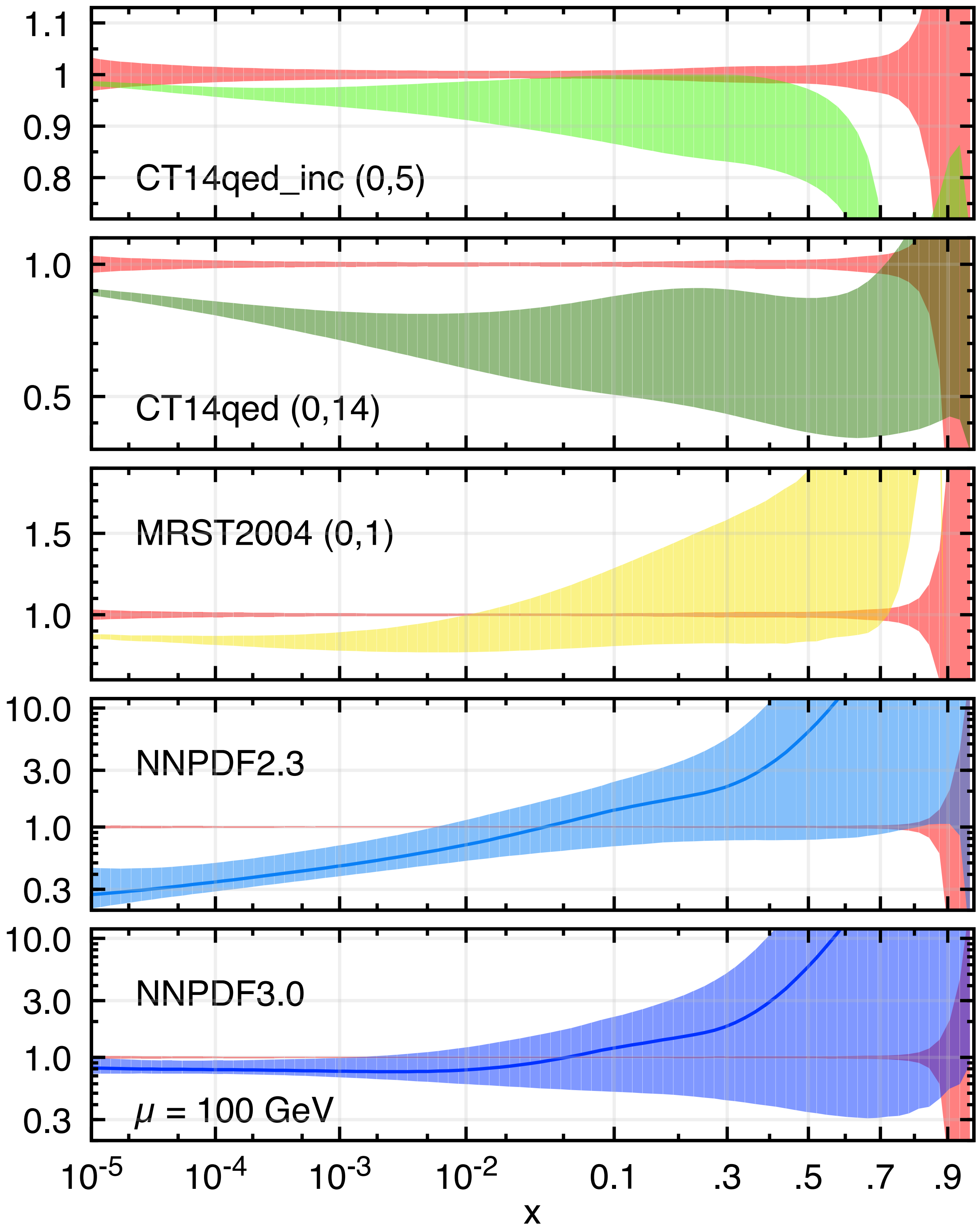
QCD corrections

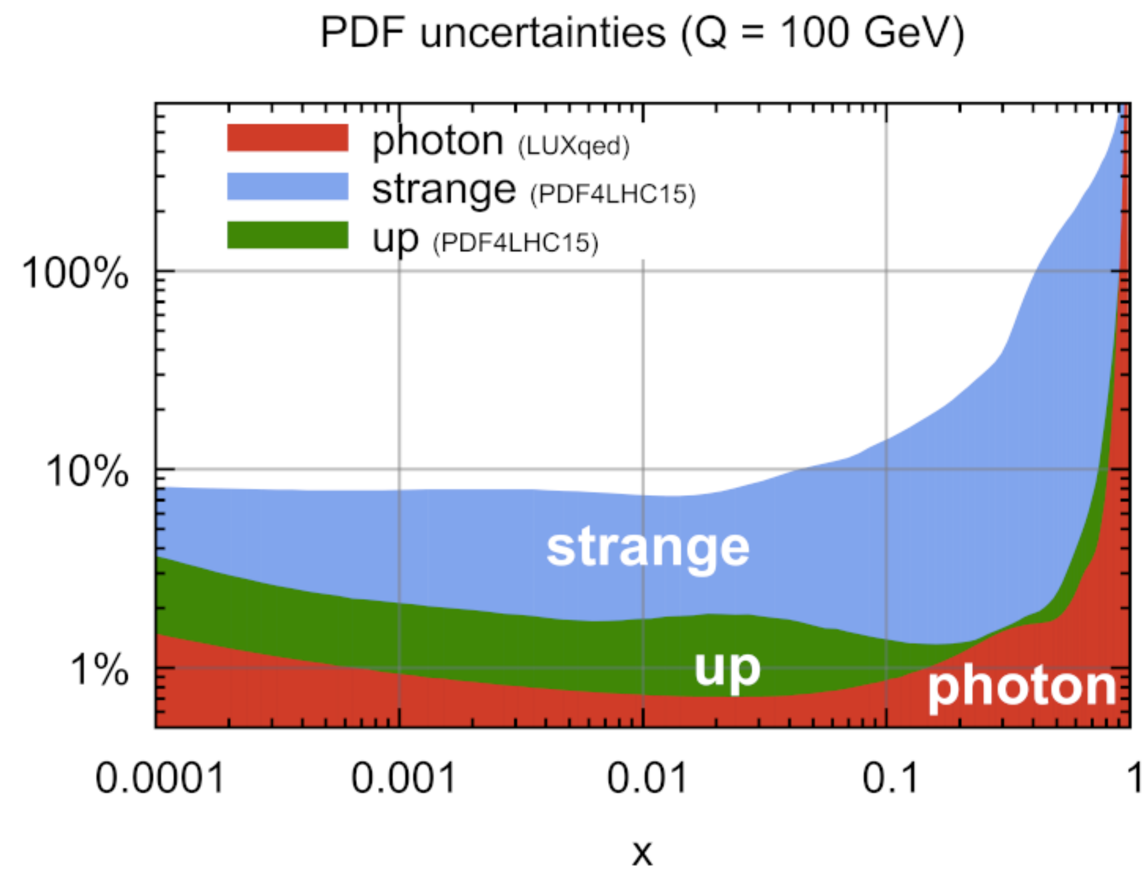
- 10-15% below 250 GeV
- ≲ 5% above 350 GeV

EW corrections

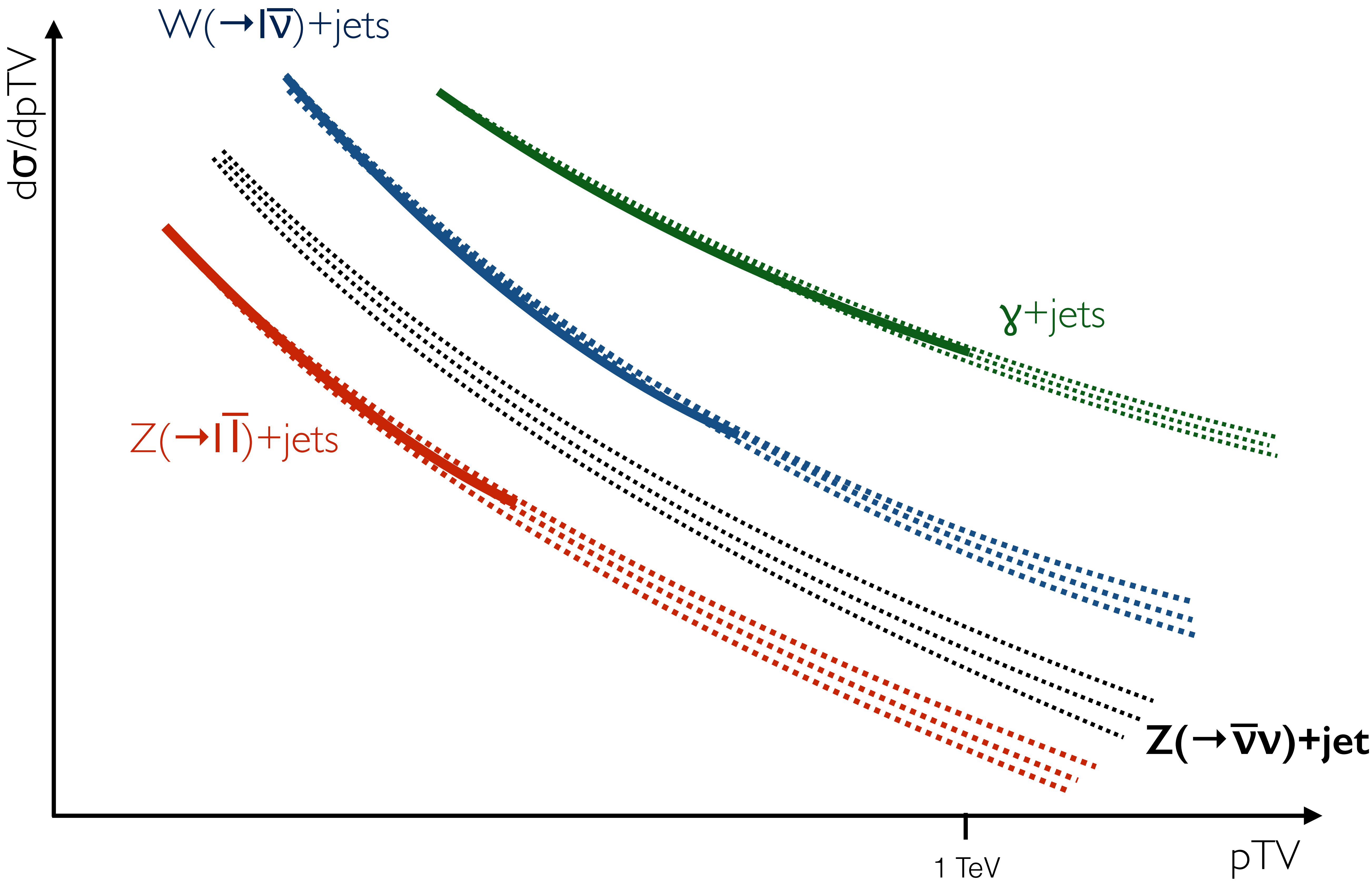
- sizeable difference in EW corrections results in 10-15% corrections at several hundred GeV
- ~5% difference between NLO QCD+EW and NLO QCD×EW

LUXqed





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



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