Electroweak corrections for V+jets and Diboson production

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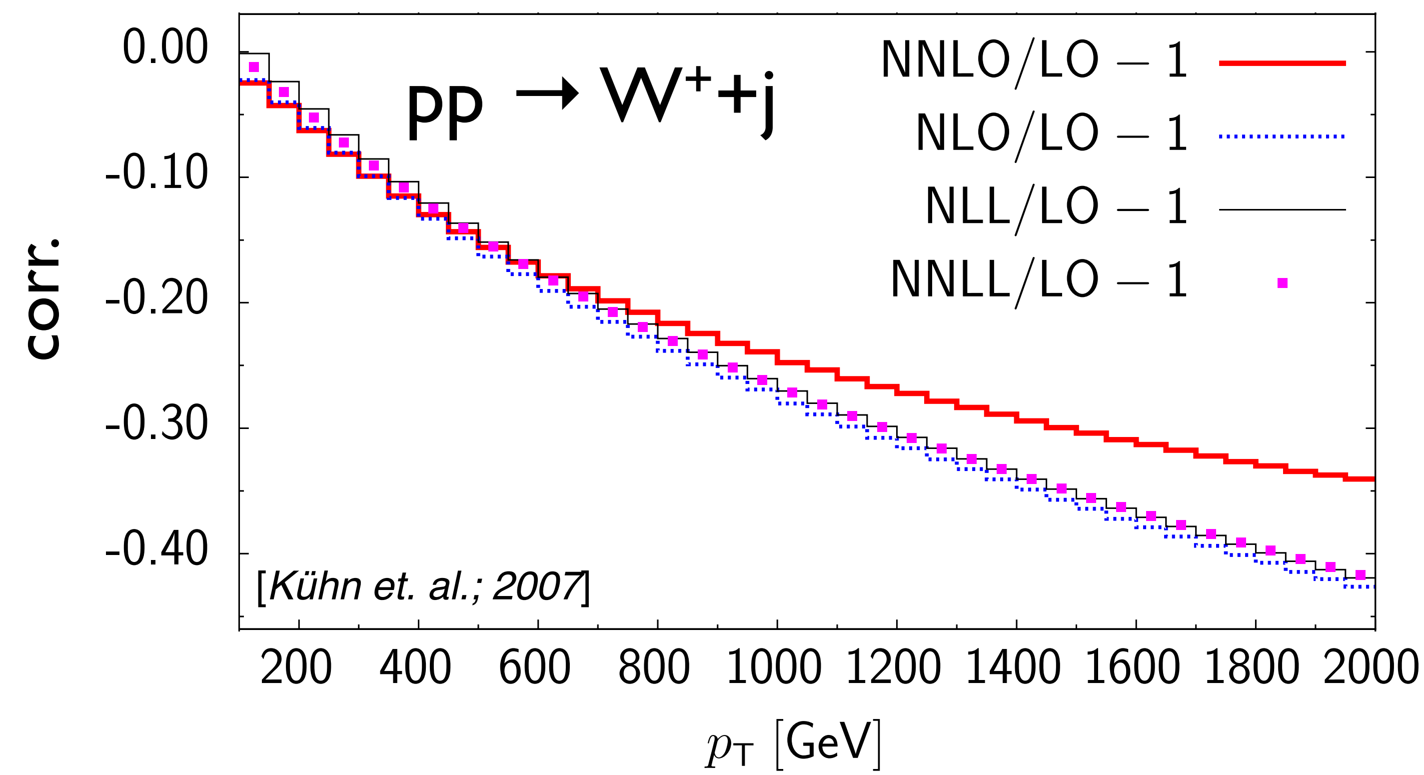
Relevance of NLO EW

- Numerically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$ **NLO EW ~ NNLO QCD**
- Possible large (negative) enhancement due to universal virtual Sudakov logs at high energies (i.e. in the tails of the distributions):
  $\text{NLO EW} \sim -\alpha \log^2\left(\frac{M_V^2}{\hat{s}}\right)$

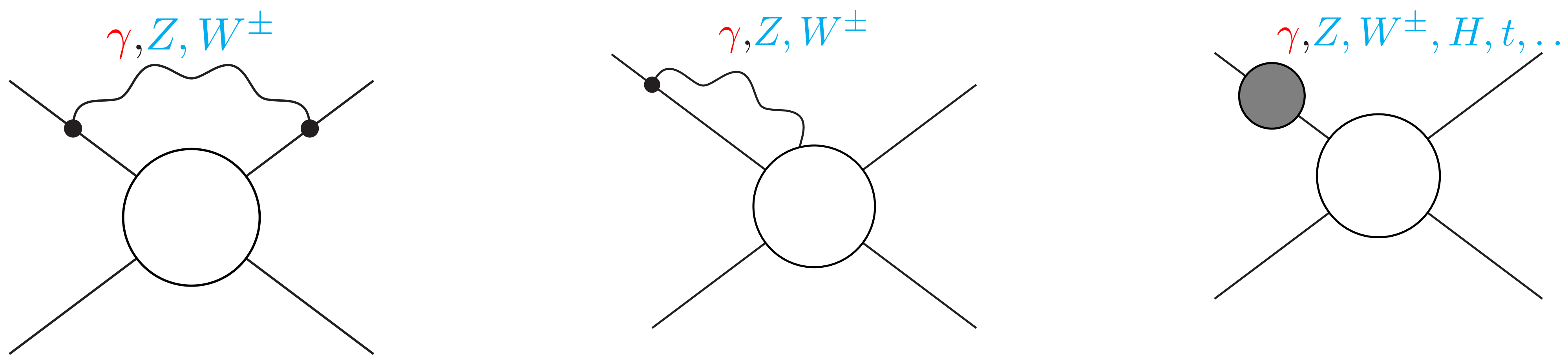
[Ciafaloni, Comelli,'98; Lipatov, Fadin, Martin, Melles, '99; Kuehen, Penin, Smirnov, '99; Denner, Pozzorini, '00]



- NLO EW known for most (some) 2→2(3) processes
- …missing for a multitude of 2→3(4) processes (and with decays and/or PS matching)

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

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

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

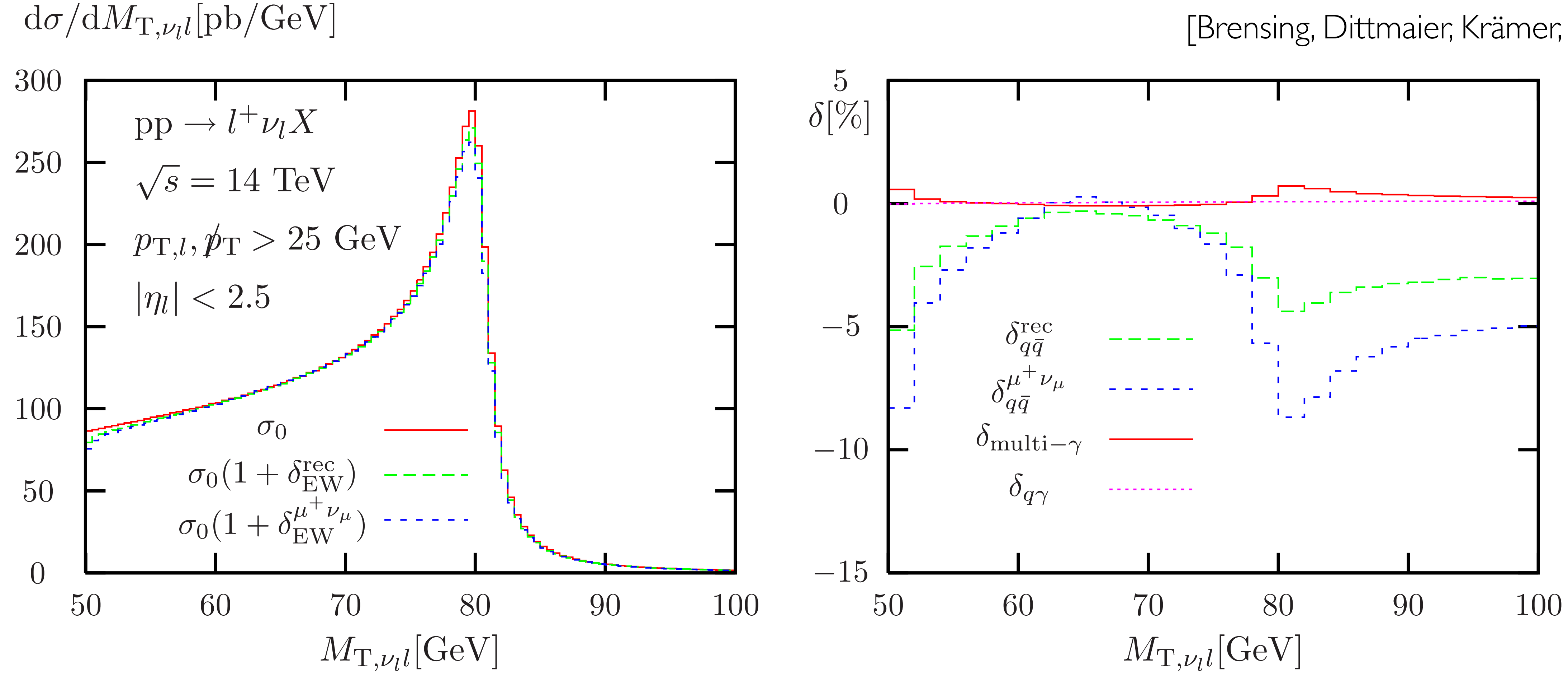
➡ overall very large effect in the tail of distributions (relevant for BSM searches)

➡ large cancellations possible

Real QED logarithms

- Photon bremsstrahlung known to be important for various precision observables, e.g. for determination of M_W.
- Origin: soft/collinear photon radiation $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$
- Possible important corrections in sufficiently exclusive observables.

[Brensing, Dittmaier, Krämer, Mück; '08]



Automation of NLO EW

Tool	Process	Reference
Recola	pp → ll + 2 jets	[1411.0916]
	pp → $e^+e^-\mu^+\mu^-$ / $\mu^+\mu^-\mu^+\mu^-$	[1601.07787][1611.05338
	pp → $e^+\nu_e\mu^-\nu_\mu$	[1605.03419]
	pp → $(t\bar{t})$ → $e^+\nu_e\mu^-\nu_\mu$ bb	[1607.05571]
	pp → $e^+\nu_e\mu^-\nu_\mu$ + 2 jets (VBS)	[1611.02951]
	pp → $(t\bar{t}H)$ → $e^+\nu_e\mu^-\nu_\mu$ $b\bar{b}H$	[1612.07138]
Sherpa/Munich +OpenLoops	pp → W+1,2,3 jets	[1412.5156]
	pp → ll/lν/νν + 0, 1, 2 jets	[1511.08692]
	pp → llνν	[1705.00598] (New today!)
MadGraph_aMC@NLO	pp → $t\bar{t}$+H/Z/W	[1504.03446]
	pp → $t\bar{t}$	[1606.01915]
	pp → 2 jets	[1612.06548]
GoSam+MadDipole	pp → W+2 jets	[1507.08579]

- many NLO QCD+EW calculations for multi-particle processes are becoming available
- NLO QCD+EW **matching and merging** with parton showers is under way (approximations available)

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V+jets

VV

- many NLO QCD+EW calculations for multi-particle processes are becoming available
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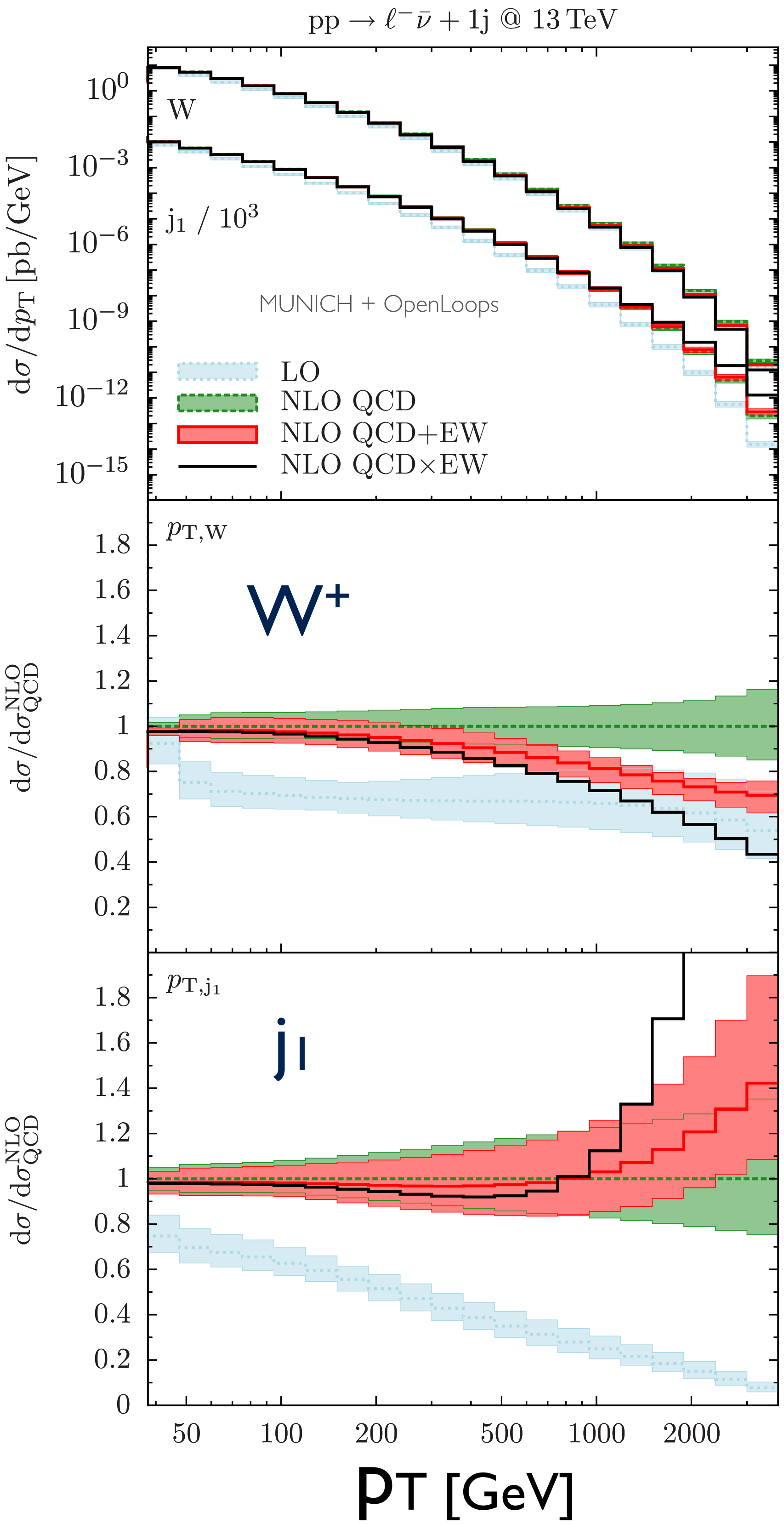
V + jets

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



Setup:

$\sqrt{S} = 13$ TeV

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

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

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

inclusive

$\lesssim$ 1% EW corrections

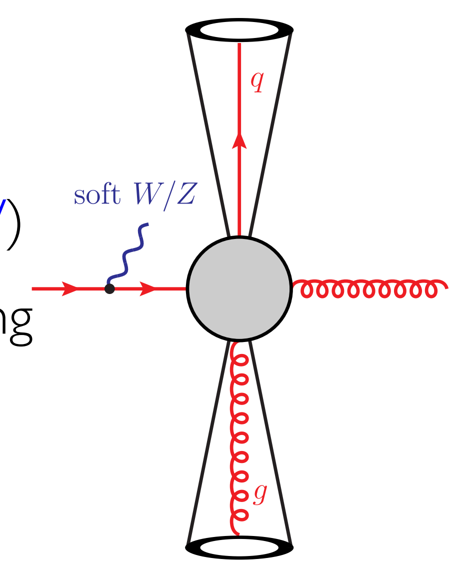
pT of W-boson

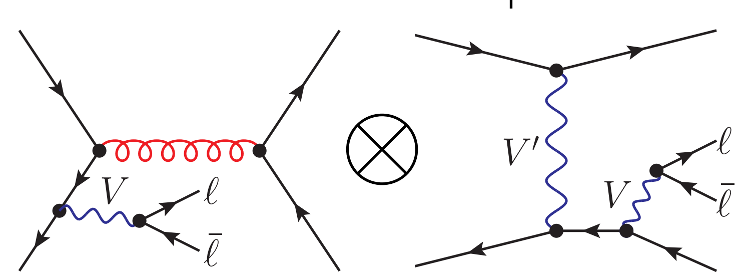
- +100 % QCD corrections in the tail
- large negative EW corrections due to **Sudakov behaviour:** -20–35% corrections at 1-4 TeV
- sizeable difference between QCD+EW and QCDxEW !

$$d\sigma_{\text{NLO QCD+EW}} = d\sigma_{\text{LO}}\left(1 + \delta_{\text{QCD}} + \delta_{\text{EW}}\right) \qquad d\sigma_{\text{NLO QCD}\times\text{EW}} = d\sigma_{\text{LO}}\left(1 + \delta_{\text{QCD}}\right)\left(1 + \delta_{\text{EW}}\right)$$

pT 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

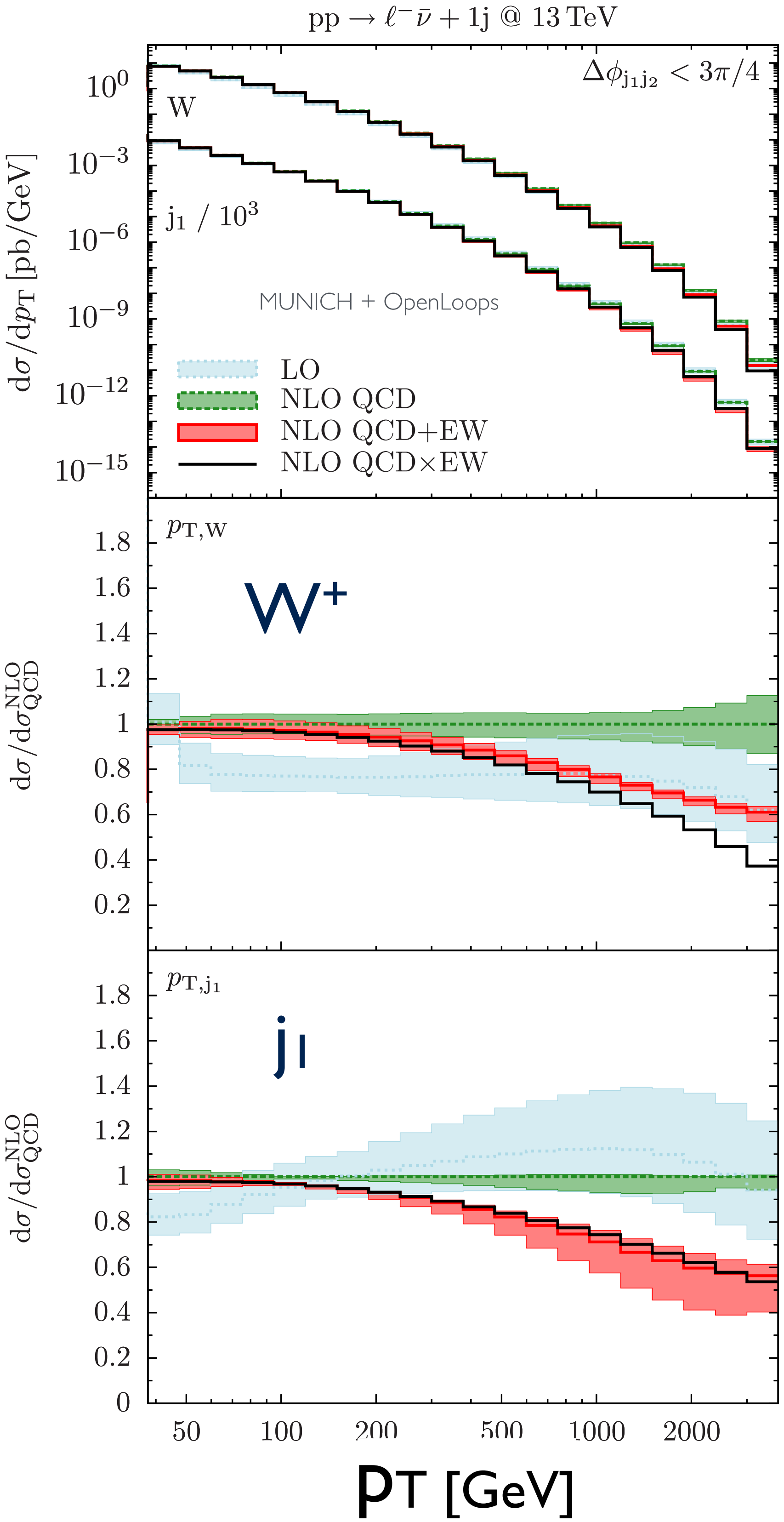




⟹ pathologic with large uncertainties!

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

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



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

(veto on dijet configurations)

QCD corrections

- mostly moderate and stable QCD corrections

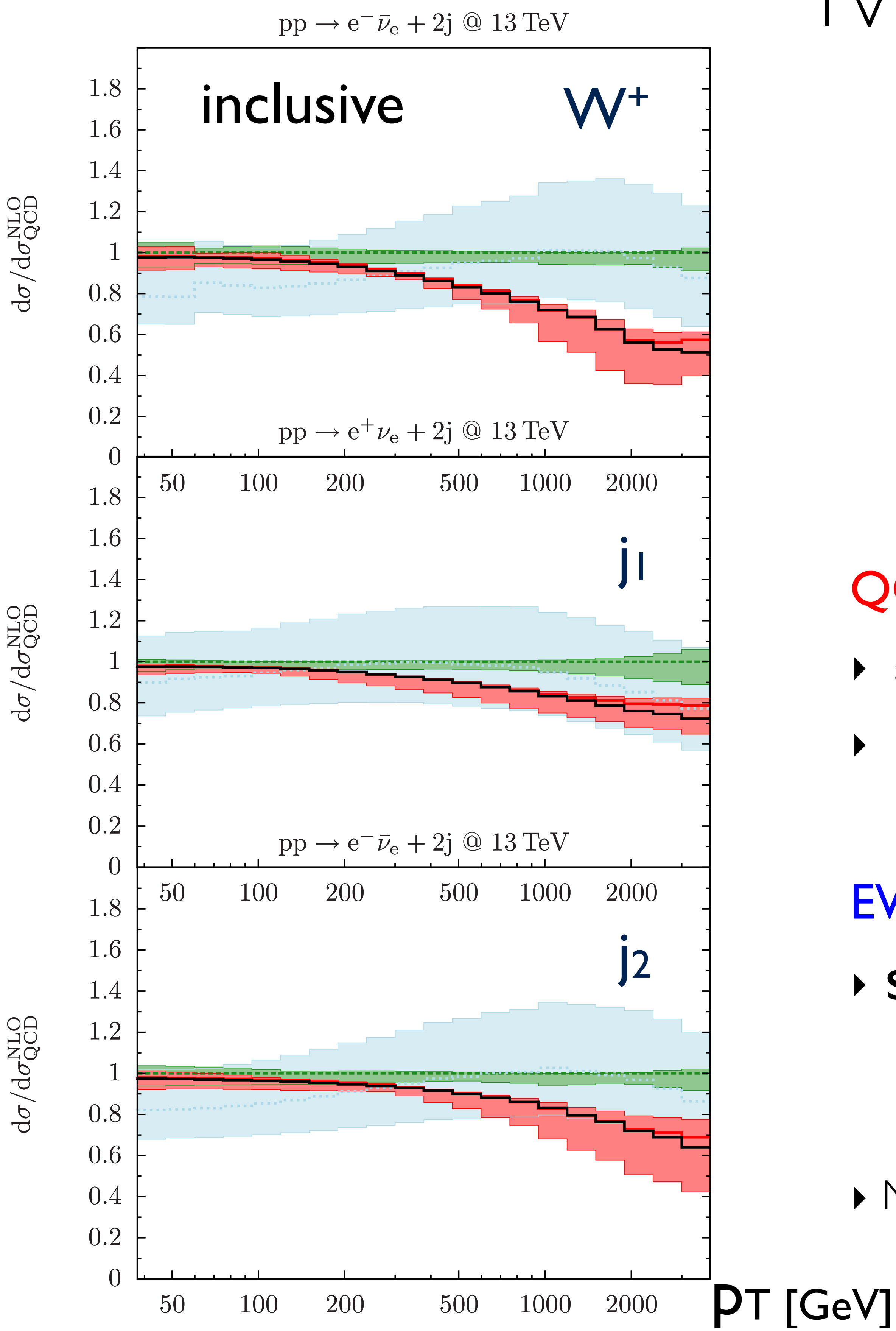
EW corrections

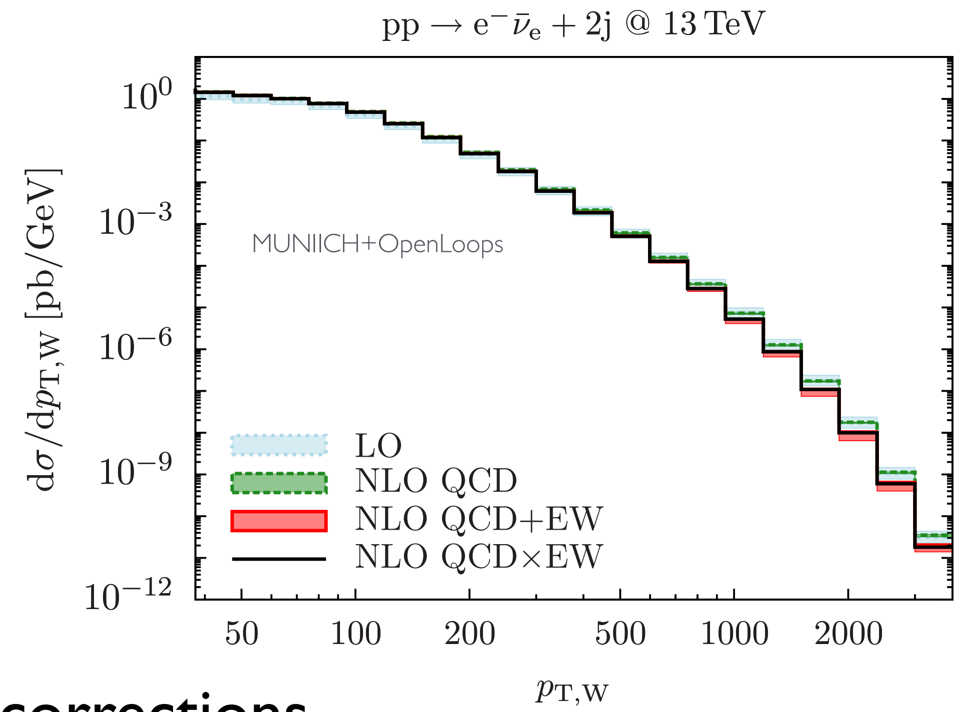
- **Sudakov behaviour** in both tails:
  -20–50% EW corrections at 1-4 TeV
- EW corrections larger than QCD uncertainties for $p_{T,W+}$ > 300 GeV

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

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

l⁻ν + 2 jets





QCD corrections

- small and very stable
- ≲ 10% scale uncertainties

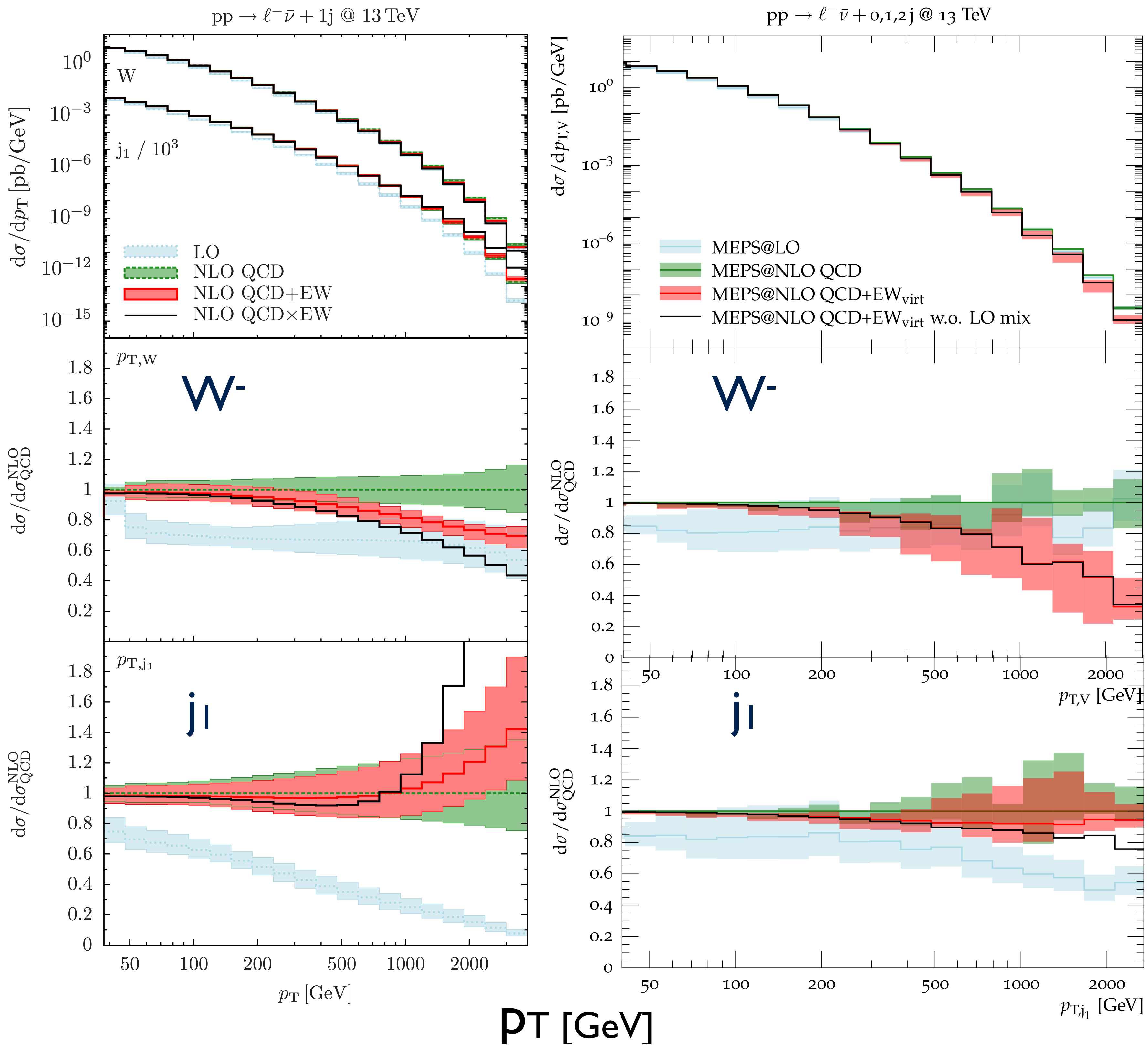
EW corrections

- **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

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

inclusive V+1 jet: MEPS@NLO QCD+EW_{virt}

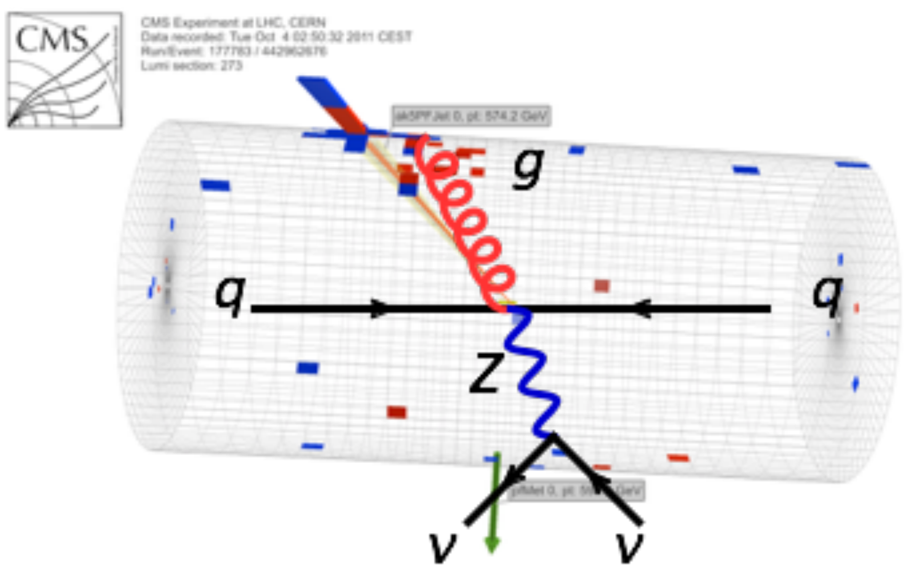


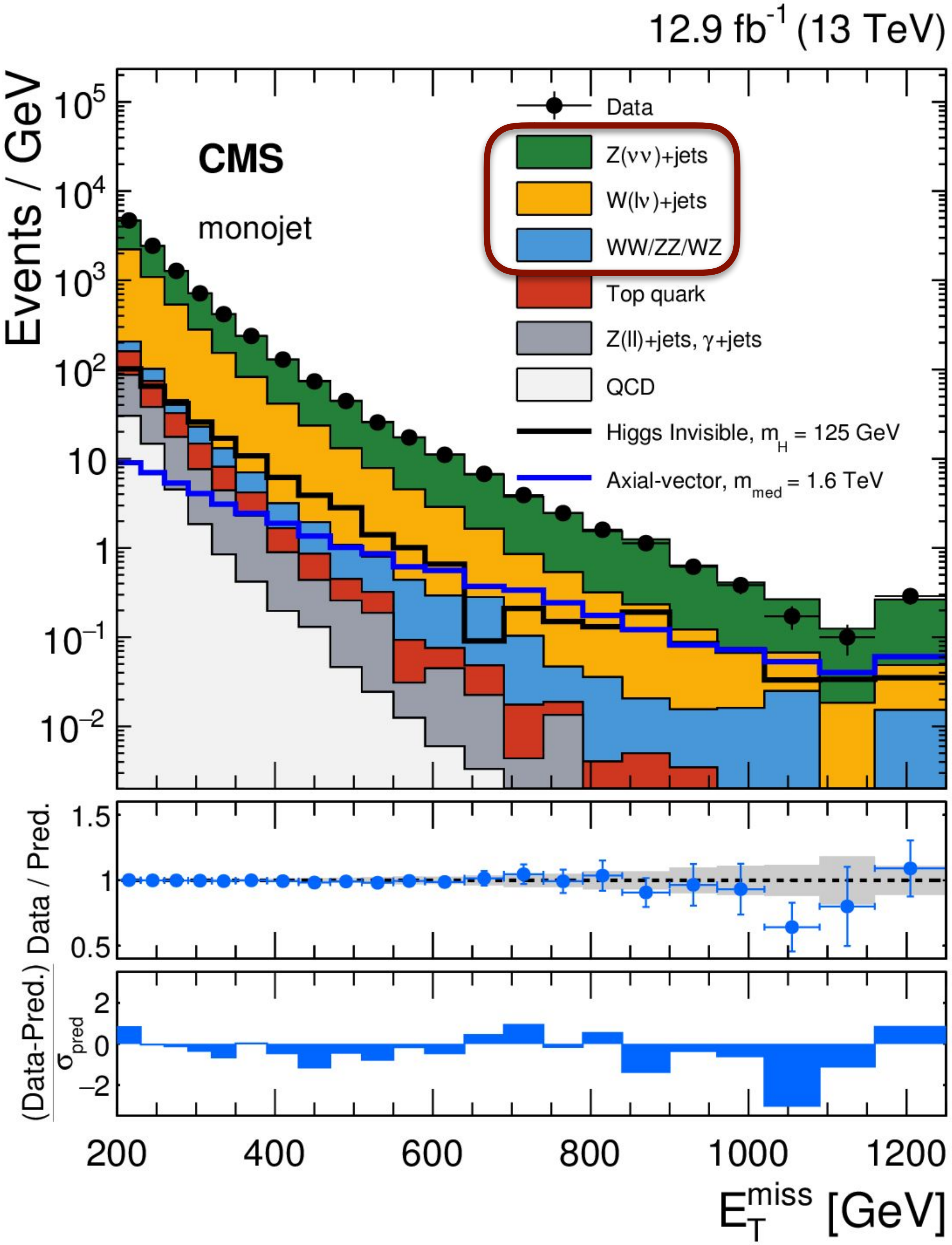
- Bases on Sherpa's standard MEPS@NLO
- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations

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

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

V+jets backgrounds in monojet/MET + jets searches



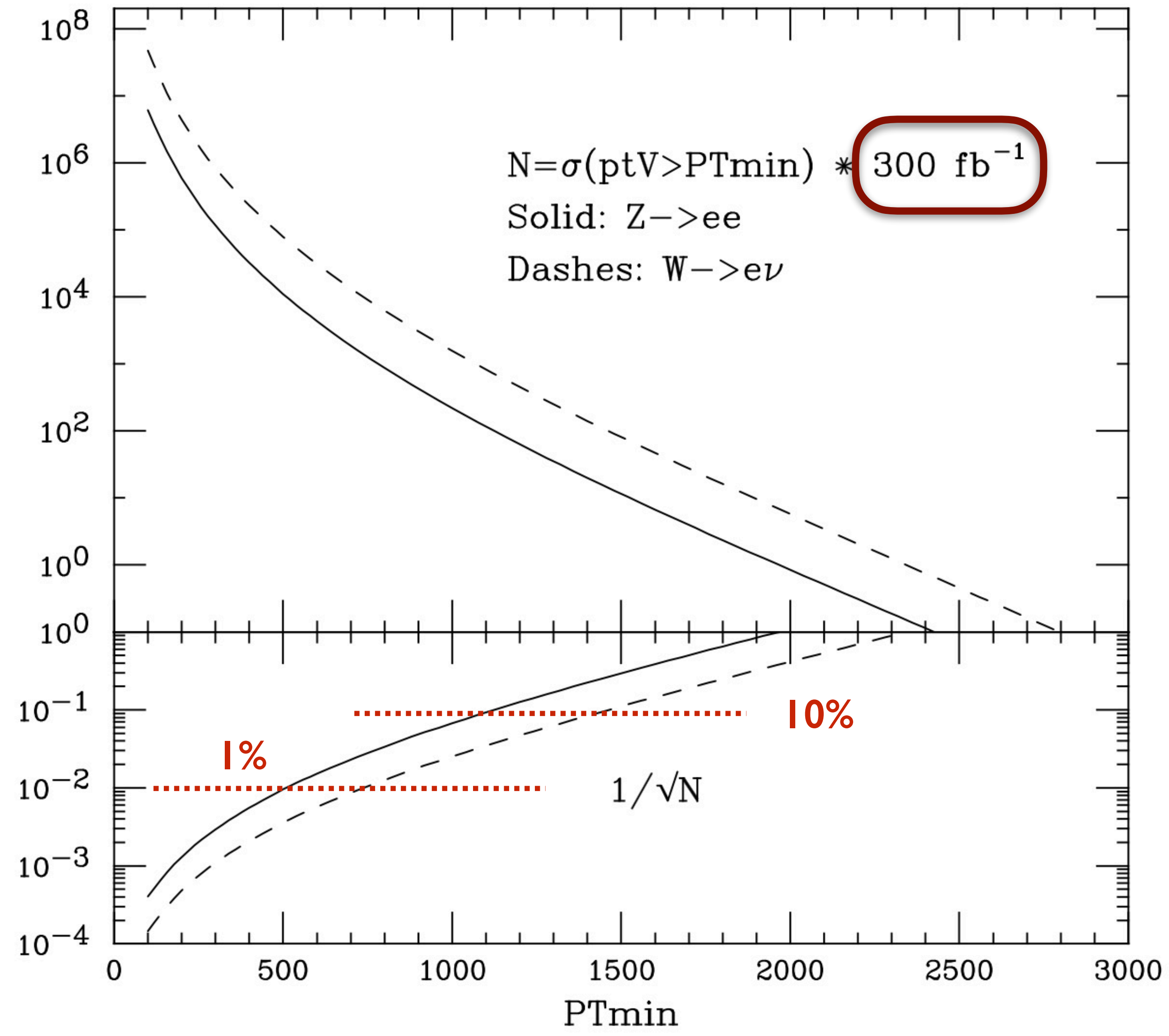


irreducible backgrounds:

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

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

Target precision

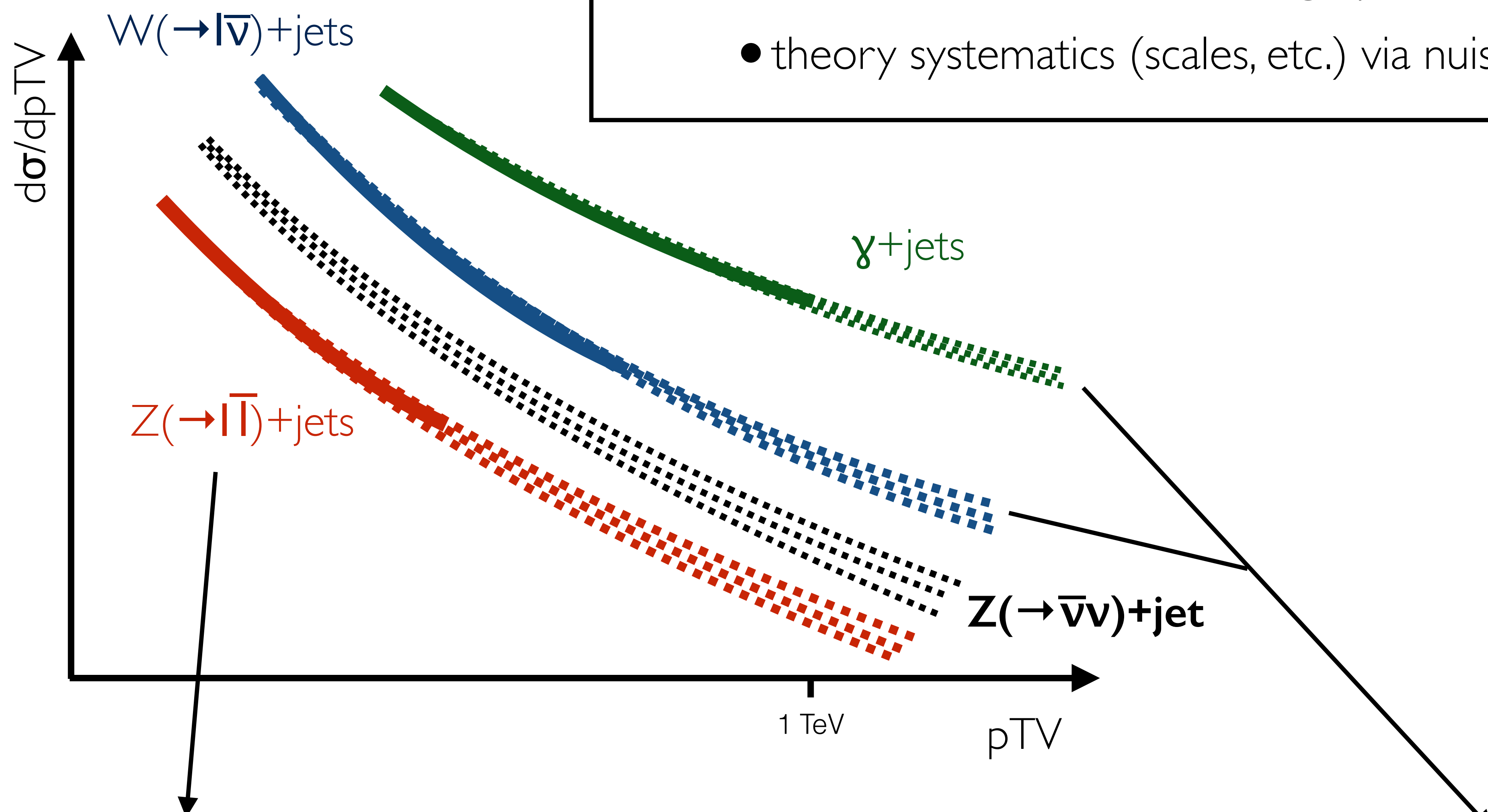


- for 500 GeV < pTV < 1000 GeV: background statistics will be at **1% level**
- understanding of V+jets backgrounds at this level increases sensitivity in DM searches
- this level of precision is theoretically possible @ NNLO QCD + NNLO EW
- requires solid understanding of **uncertanties**!

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

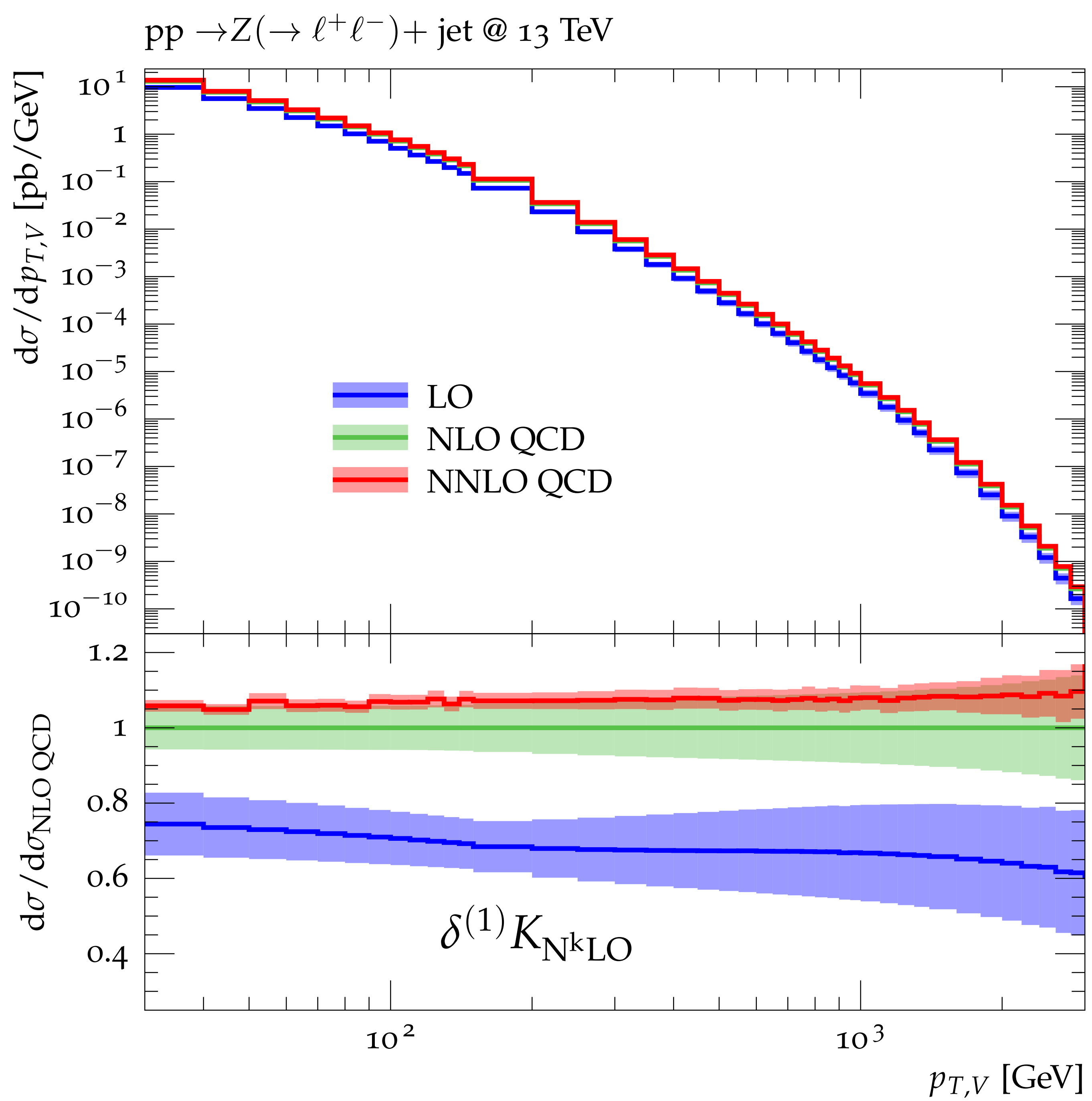
- Robust **uncertainty estimates** including
  1. Pure QCD uncertainties
  2. Pure EW uncertainties
  3. Mixed QCD-EW uncertainties
  4. PDF, γ-induced uncertainties ….

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

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

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

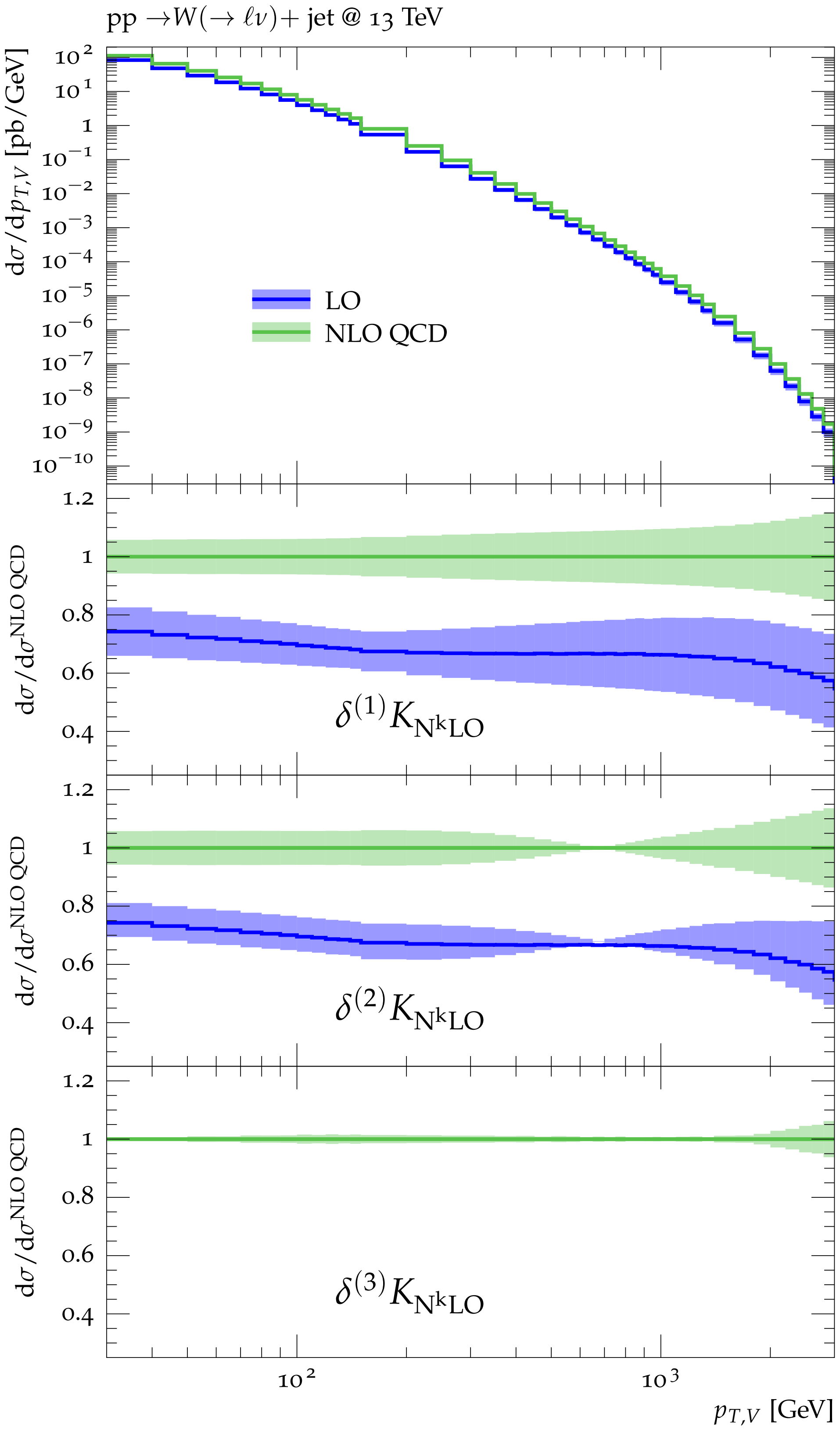
$$(\xi_\mathrm{R}, \xi_\mathrm{F}) = (2,2),\ (2,1),\ (1,2),\ (1,1),\ (1,0.5),\ (0.5,1), (0.5,0.5)$$

yields

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

with minor shape variations

QCD uncertainties



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

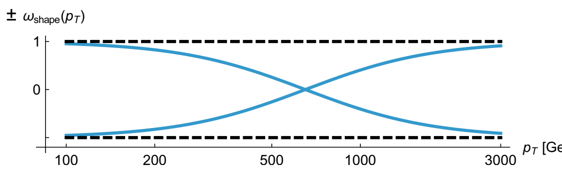
nuisance parameters: interpreted as 1σ Gaussian

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

- correlated across processes
- correlated across pT bins

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

  symmetrized **scale uncertainty**



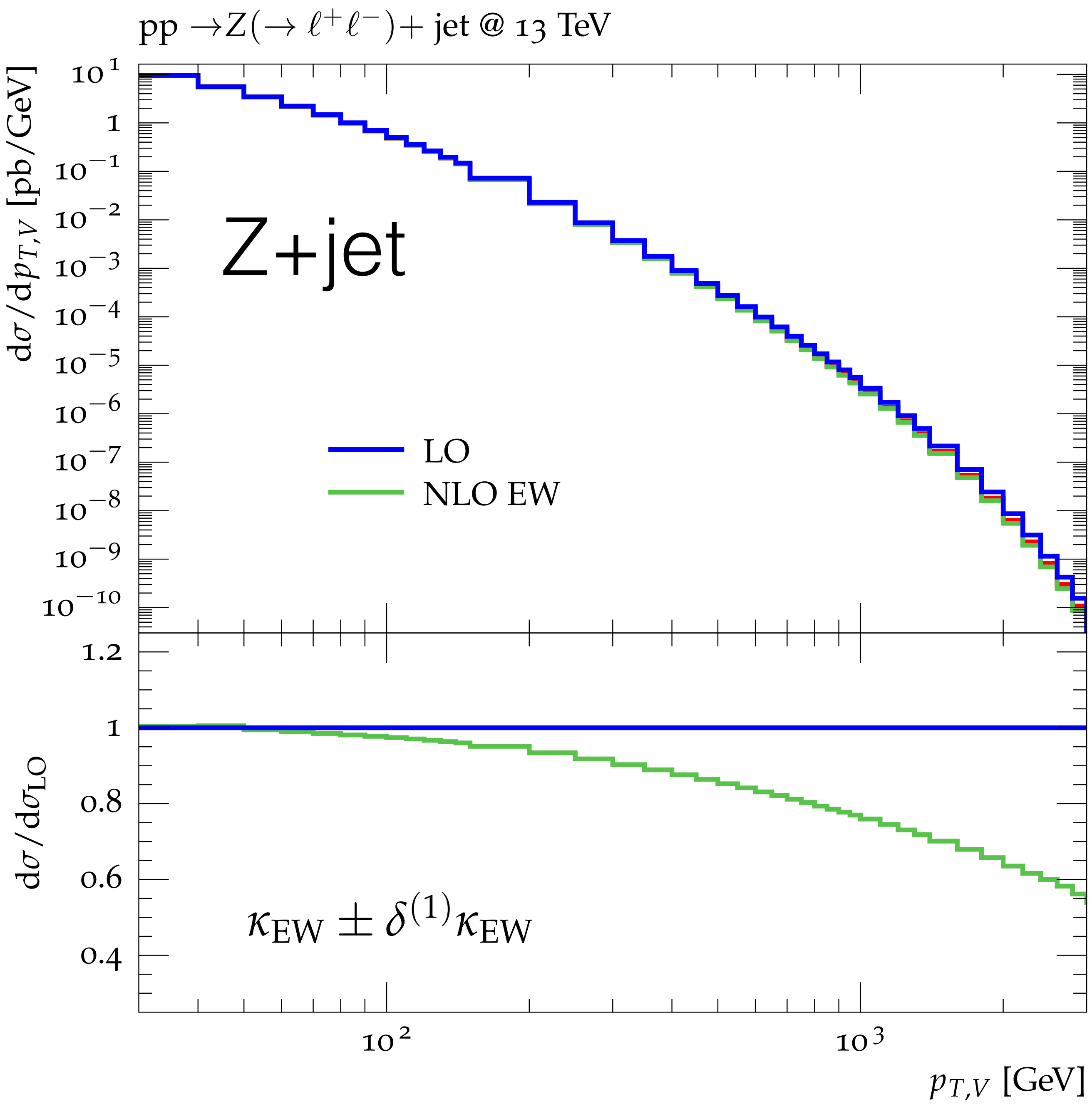
- $$\delta^{(2)}K^V_{\mathrm{N^kLO}} = \frac{p_T^2 - 650\ \mathrm{GeV}}{p_T^2 + 650\ \mathrm{GeV}}\delta^{(1)}K^V_{\mathrm{N^kLO}}$$

  yields max **shape distortion** within scale variation band *(correlated)*

- $$\delta^{(3)}K^V_{\mathrm{N^kLO}} = \frac{K^V_{\mathrm{N^kLO}}}{K^V_{\mathrm{N^{k-1}LO}}} - \frac{K^Z_{\mathrm{N^kLO}}}{K^Z_{\mathrm{N^{k-1}LO}}}$$ *(correlated)*

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

Pure EW uncertainties



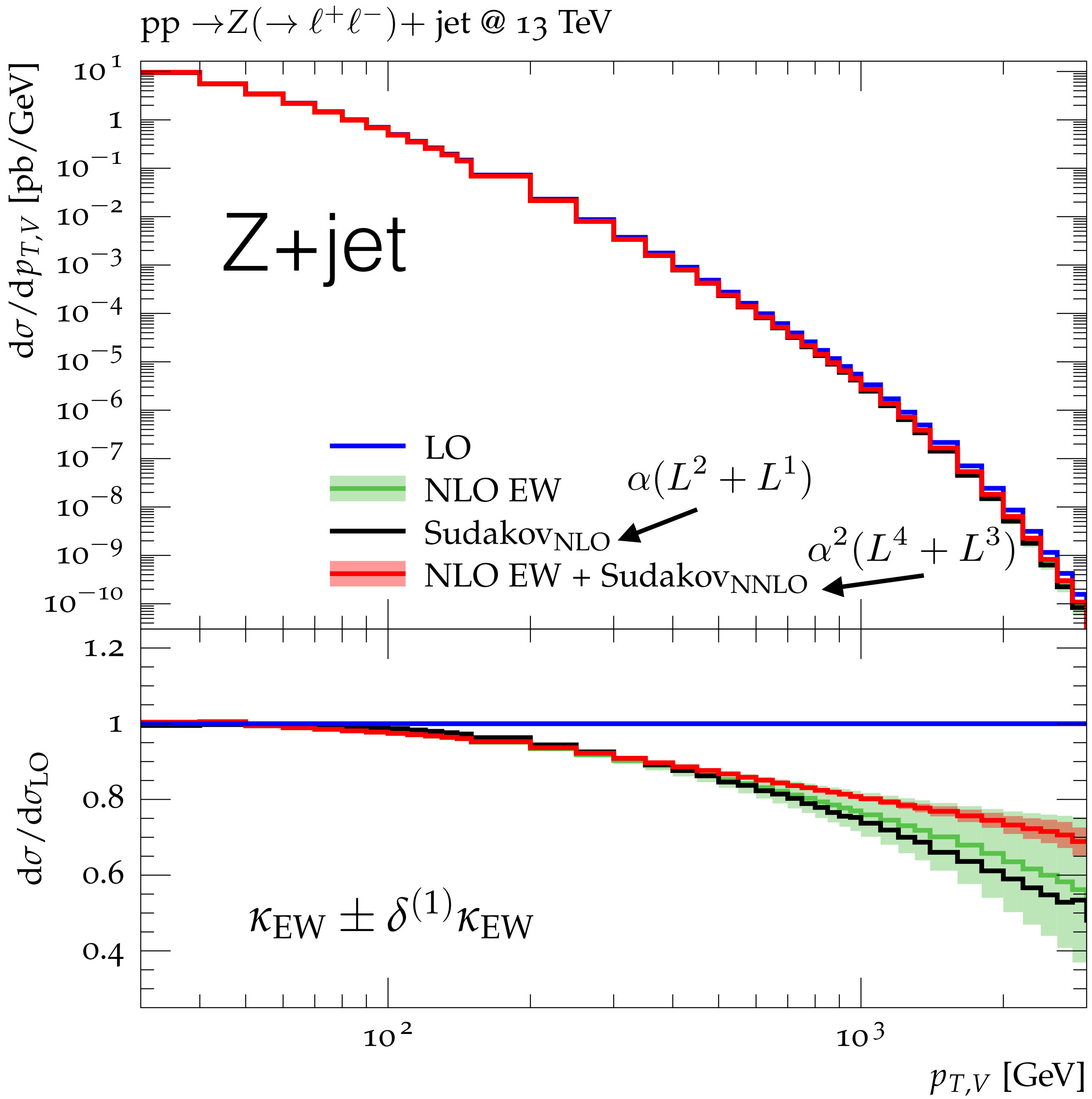
EW corrections become sizeable at large $p_{T,V}$

Origin: virtual EW Sudakov logarithms

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

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

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

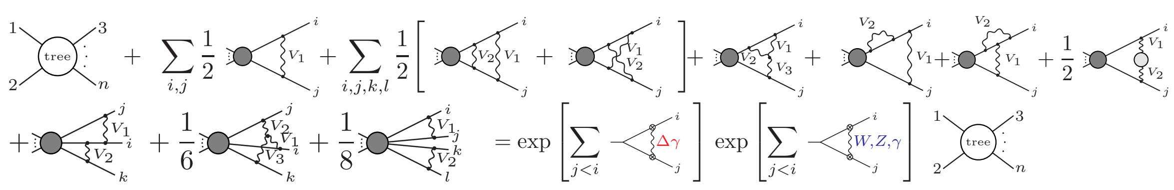
↓

Uncertainty estimate of (N)NLO EW from naive exponentiation x 2:

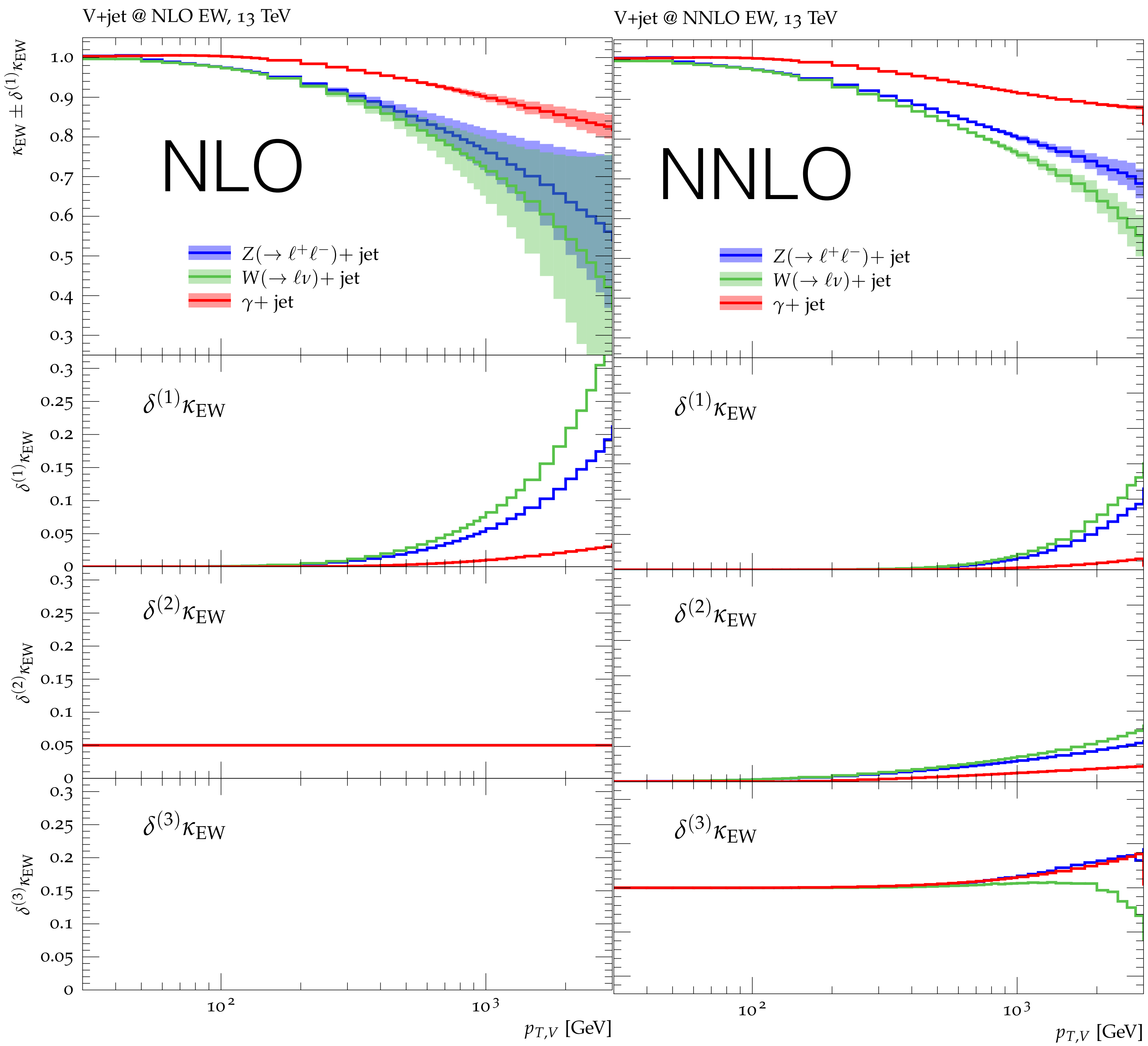
$$\delta^{(1)}\kappa_{\mathrm{EW}} \simeq \frac{2}{k!}\left(\kappa_{\mathrm{NLO,EW}}\right)^k$$

↓

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



Pure EW uncertainties



NNLO EW corrections at 1 TeV

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

- 'higher-order logs' *(correlated)*

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

- 'hard non-log NNLO effects I' *(uncorrelated)*

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

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

- 'hard non-log NNLO effects II' *(uncorrelated)*

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

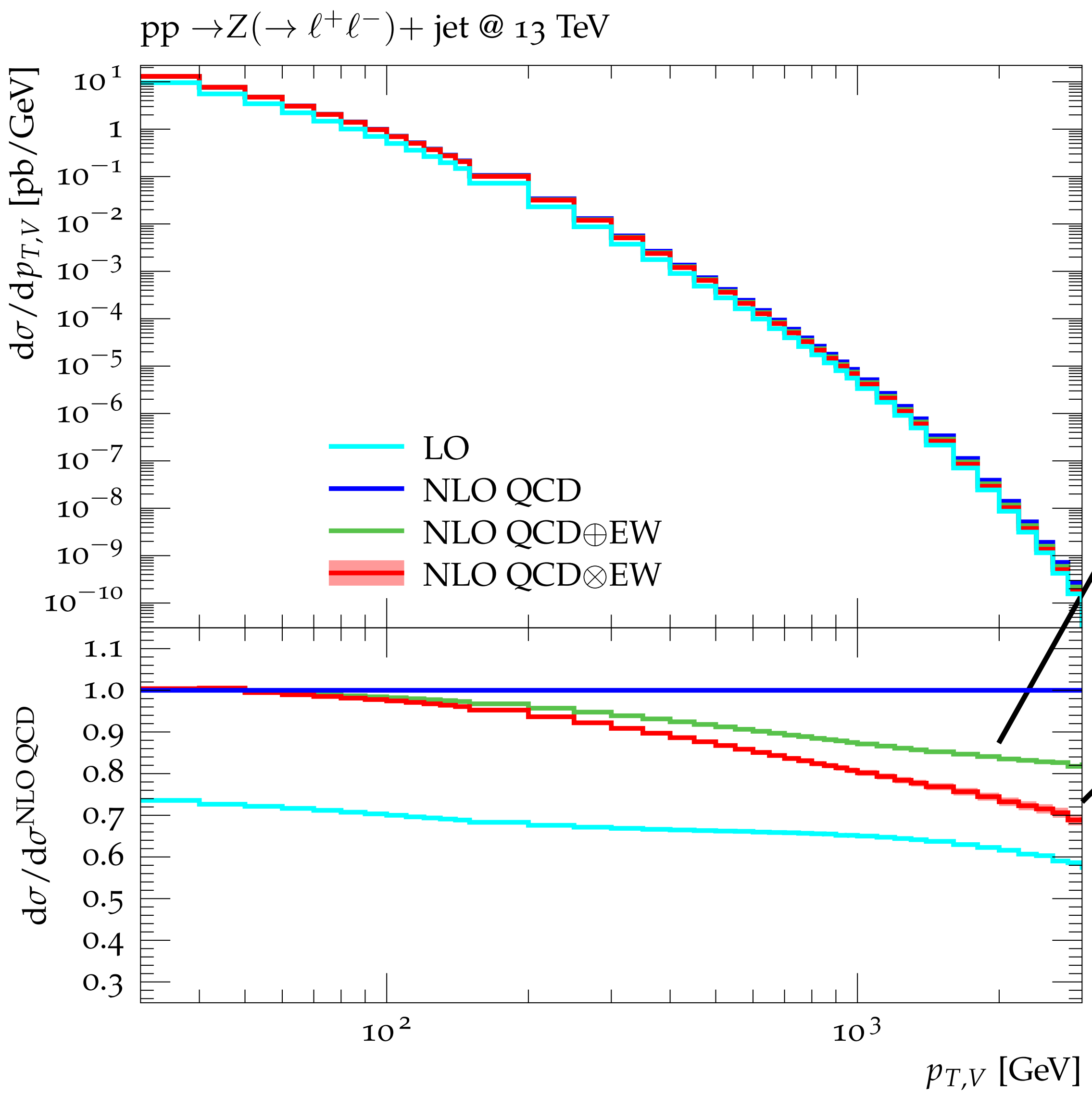
estimate of typical size of

$$\left[\delta^{(1)}_{\mathrm{hard}}\right]^2 \quad \text{or} \quad \delta^{(1)}_{\mathrm{hard}} \times \delta^{(1)}_{\mathrm{Sud}}.$$

Pure EW uncertainties

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

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)

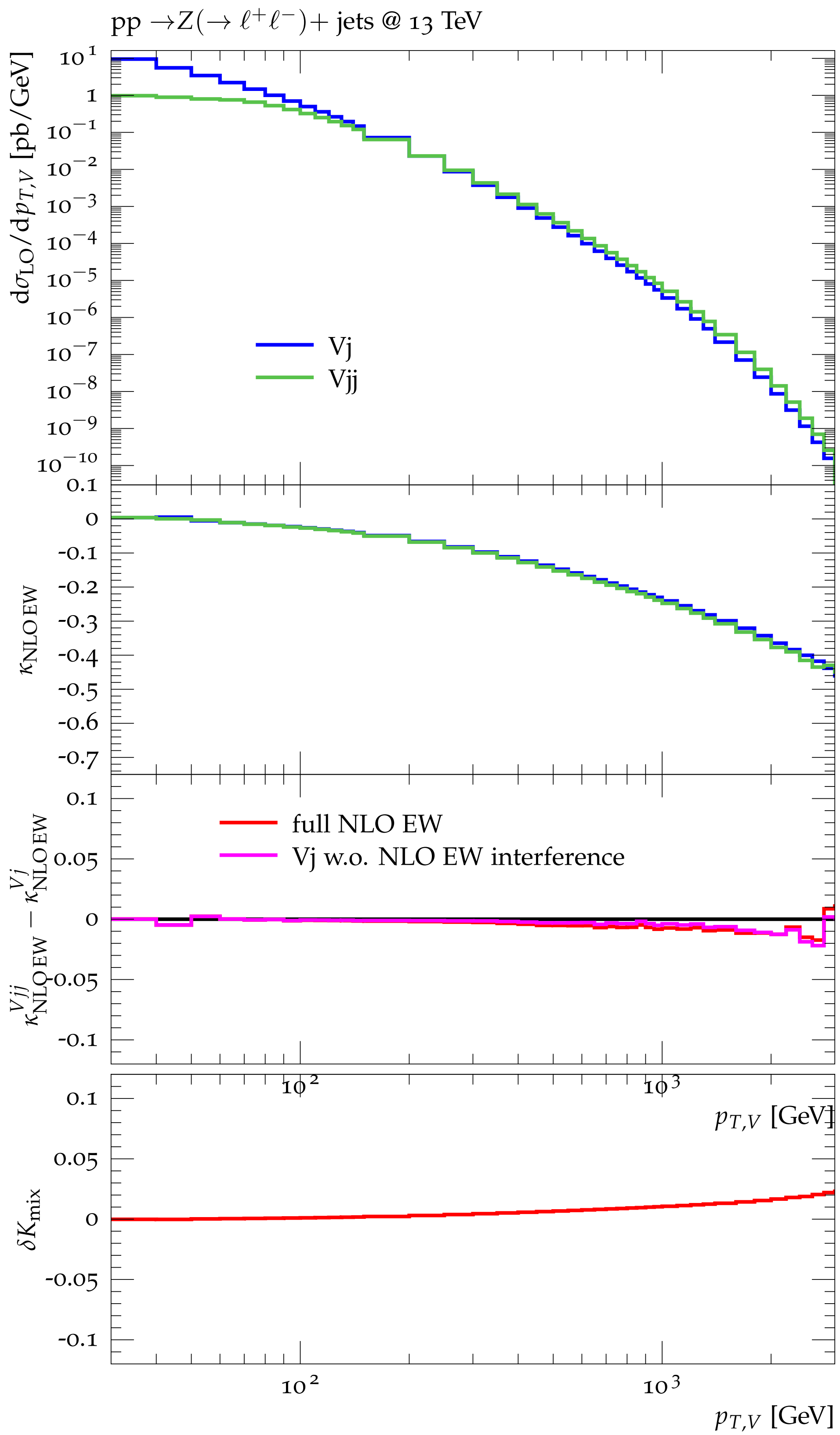
Difference between these two approaches indicates size of missing mixed EW-QCD corrections.

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

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

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

strong support for

- factorization
- multiplicative QCD x EW combination

Estimate of non-factorising contributions

(correlated)

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

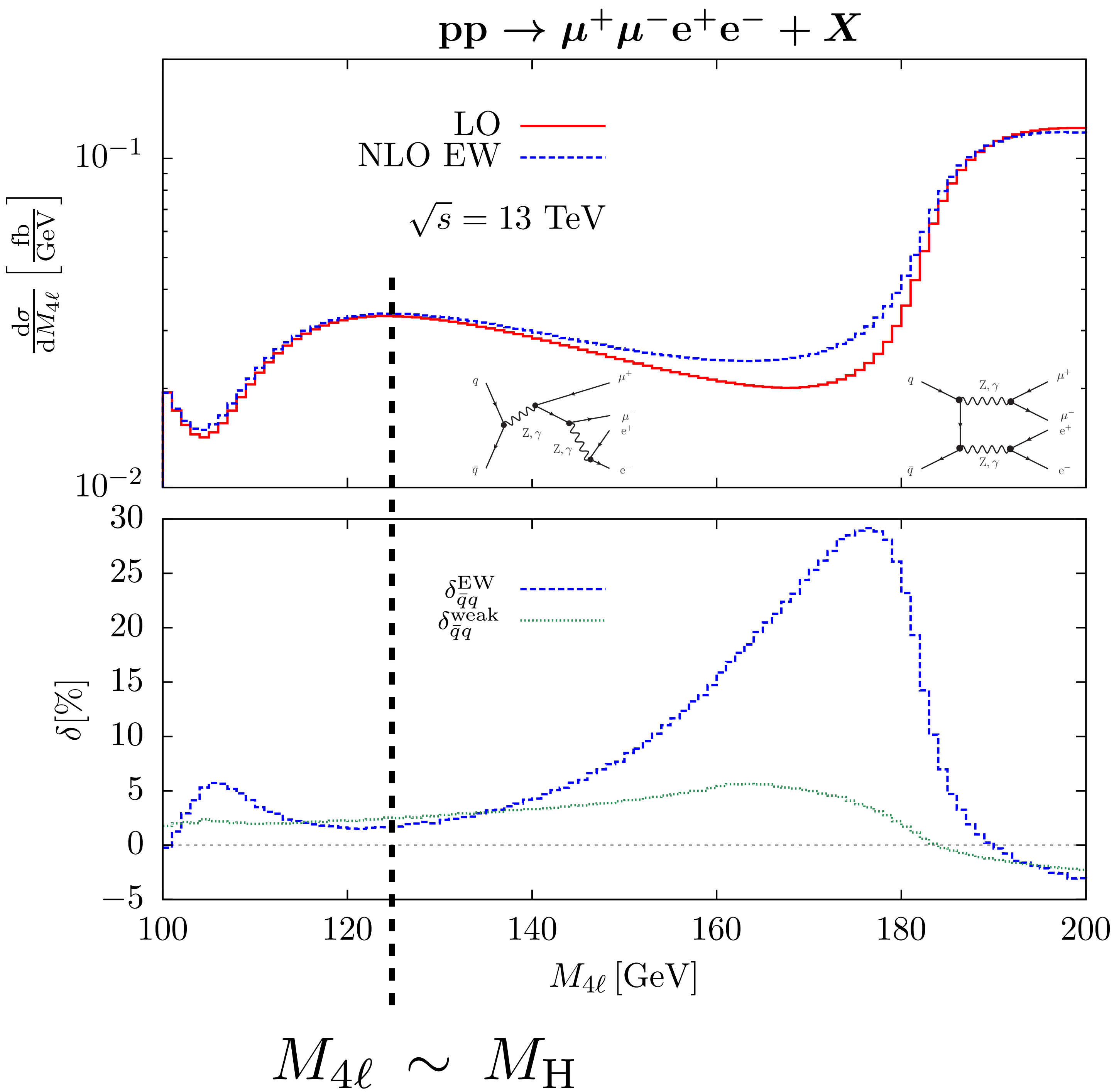
(tuned to cover above difference of EW K-factors)

VV

[see Lorenzo's talk]

ZZ→4l as H→ZZ*→4l background

$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{LO}}_{\bar{q}q}$ [fb]	$\delta^{\mathrm{EW}}_{\bar{q}q}$ [%]	$\delta^{\mathrm{weak}}_{\bar{q}q}$ [%]
8	8.4704(2)	−3.5	−3.4
13	13.8598(3)	−3.6	−3.6



- Inclusive: 3-4% (dominated by weak corrections)
- non-trivial phase-space dependence (distortion of distributions relevant for Higgs analyses)

- Weak: -5 … +5%
- QED: 10-30% (due to radiative tails of resonances / kinematic shoulders)

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

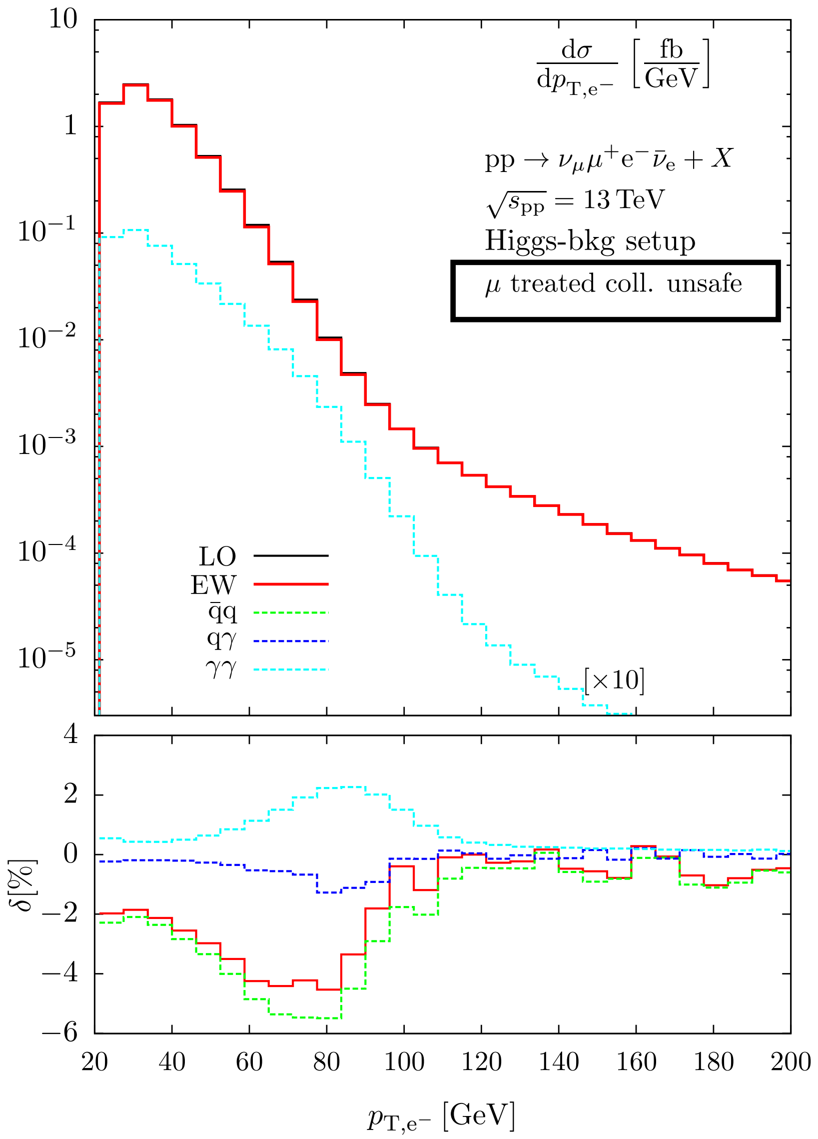
[see Lorenzo's talk]

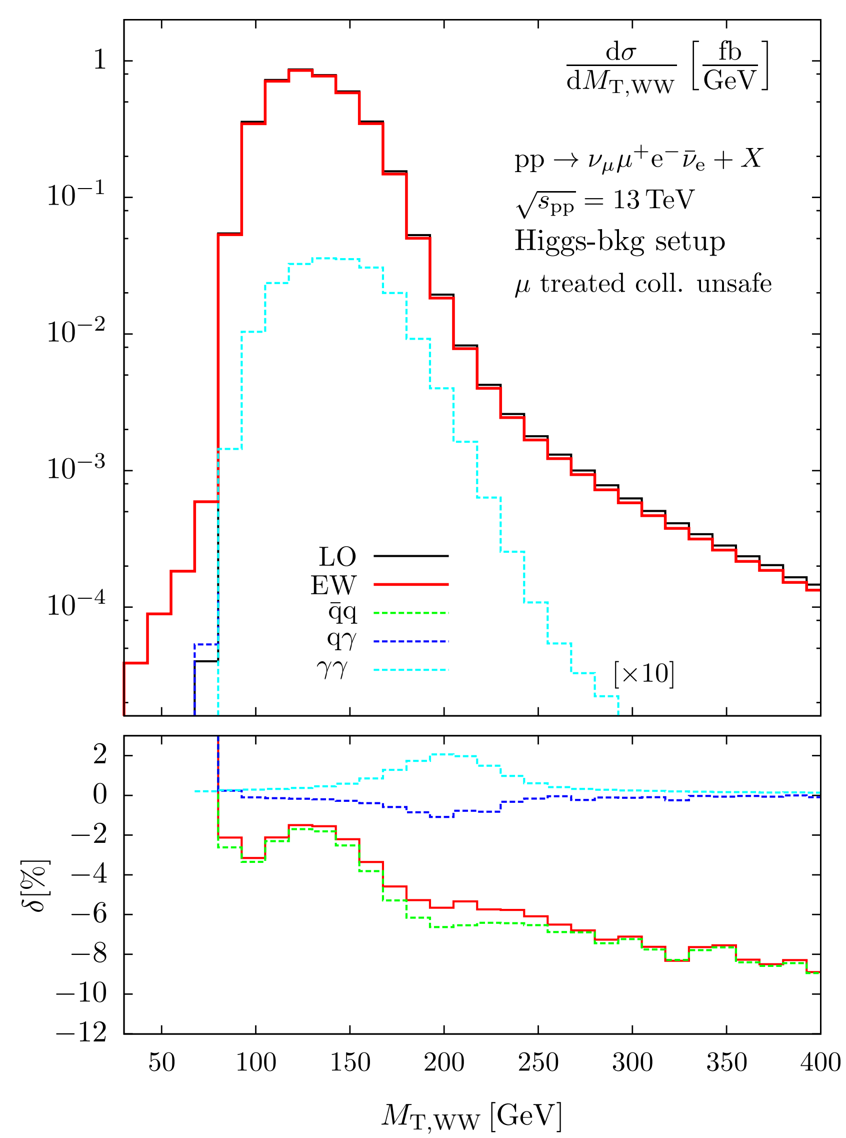
WW→2l2ν as H→WW*→2l2ν background

Higgs setup:

$10\,\mathrm{GeV} < M_{e^-\mu^+} < 55\,\mathrm{GeV}, \qquad \Delta\phi_{e^-\mu^+} < 1.8$

$$\mathrm{pp} \;\rightarrow\; \nu_\mu \mu^+ e^- \bar{\nu}_e + X$$



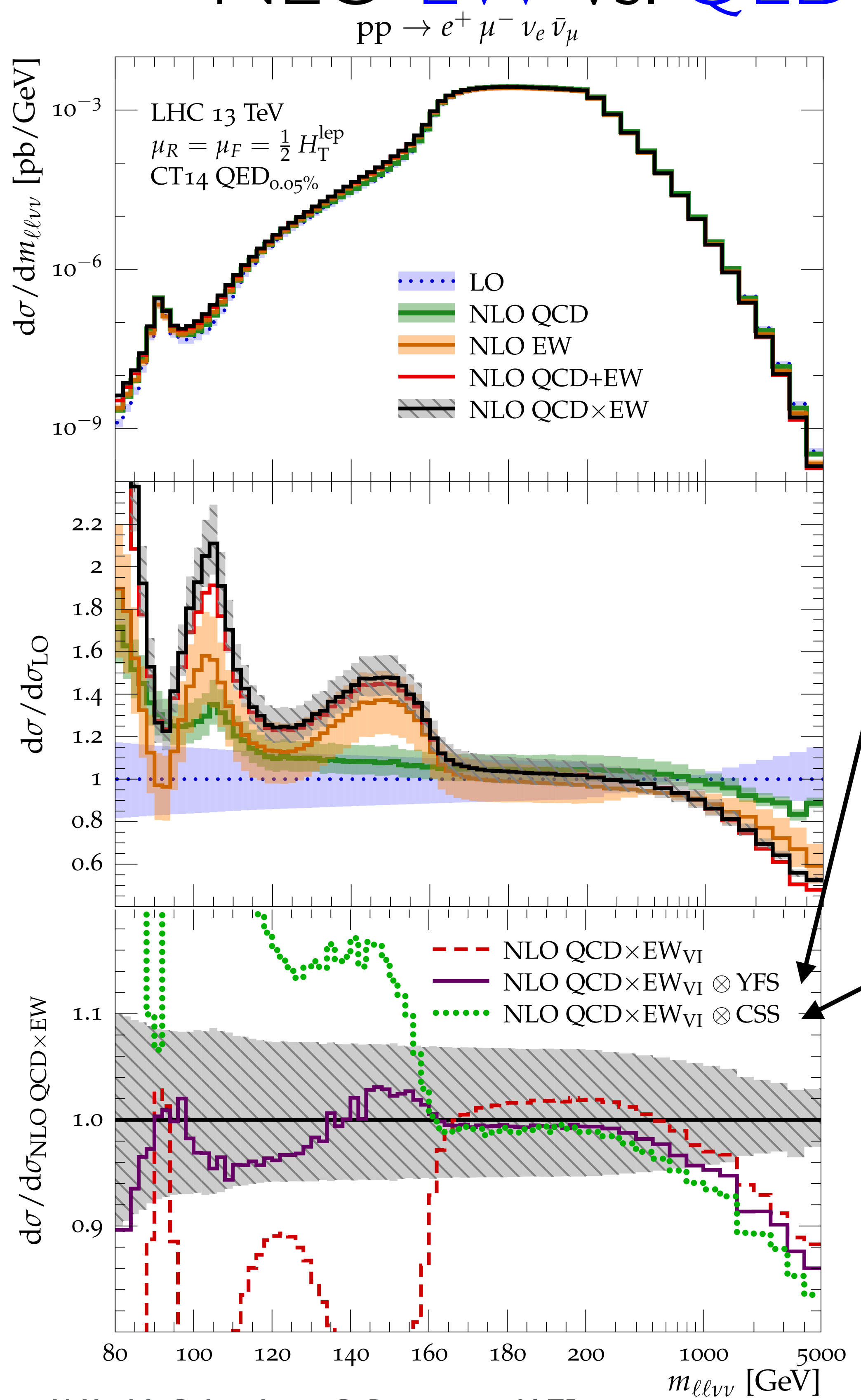


- non-trivial phase-space dependence (distortion of distributions relevant for Higgs analyses)

- EW: around -2 …-5%
- Sudakov behaviour at large $M_{T,WW}$

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

NLO EW vs. QED approximations for VV



[S. Kallweit, JML, M. Schönherr, S. Pozzorini, '17]

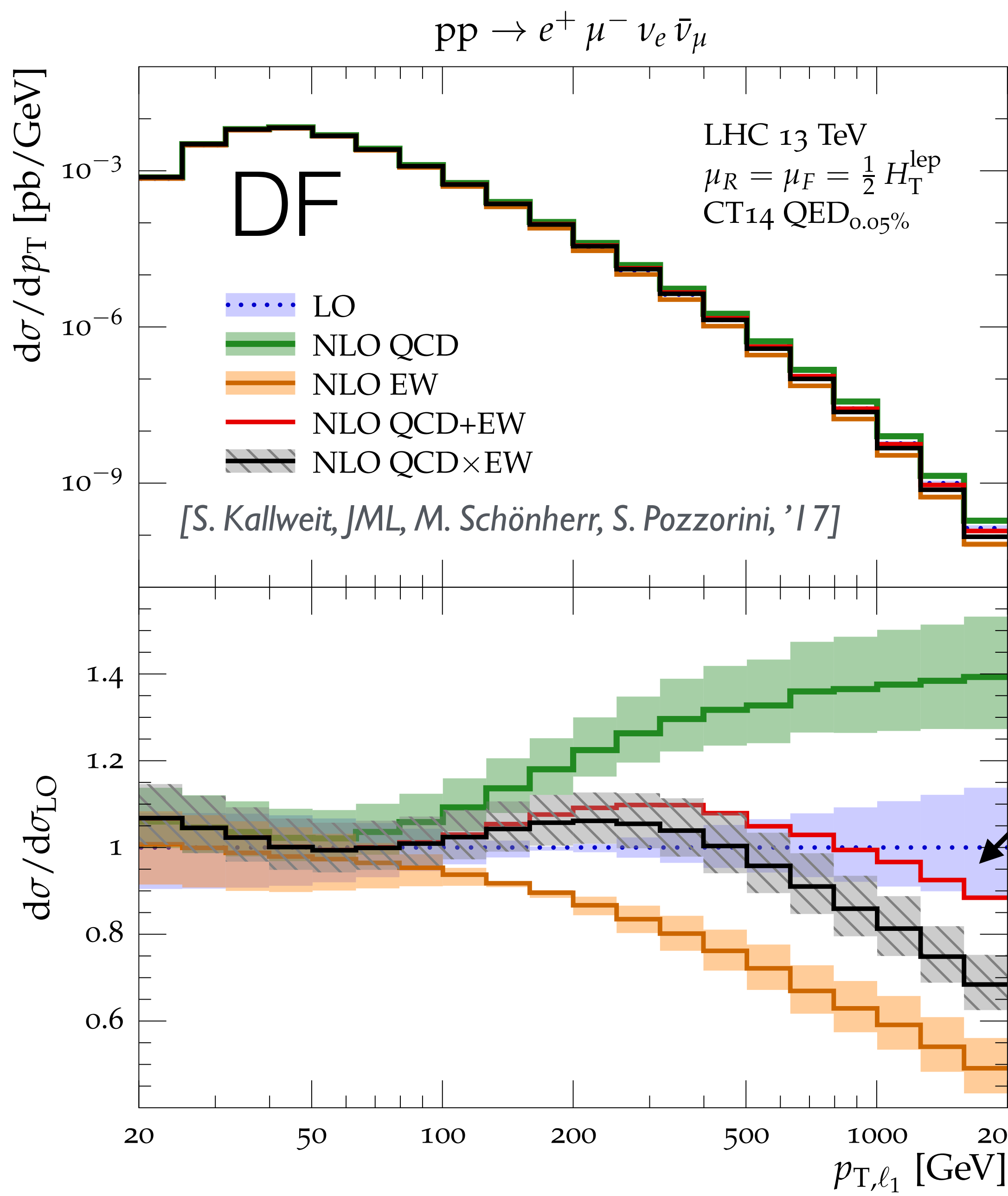
Question:
can the leading QED corrections be approximated by QED PS?

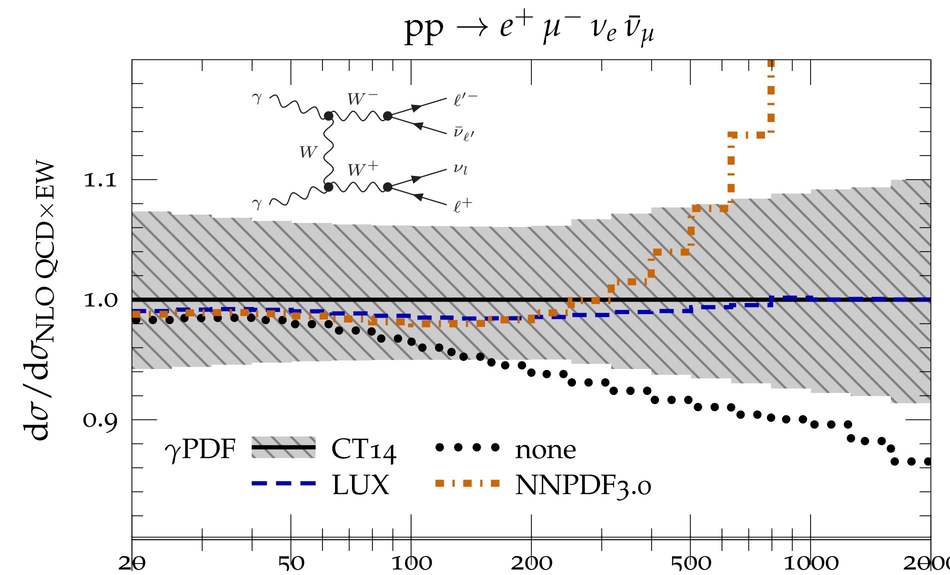
YFS (Multi-Photon-Resummation) preserves resonance structure → EW effects agree at the few percent level.
Source of differences:

- Multi-poton effects in YFS
- Resonance-assignment in YFS

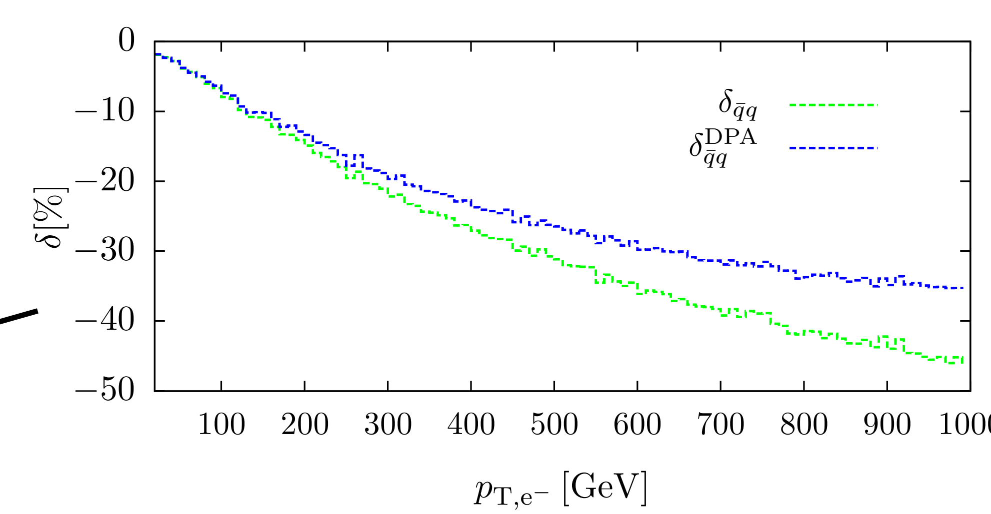
CSS (Catani-Seymour-Shower) unaware of resonance structure → QED effects largely overestimated

VV at high energies: $p_{T,l}$

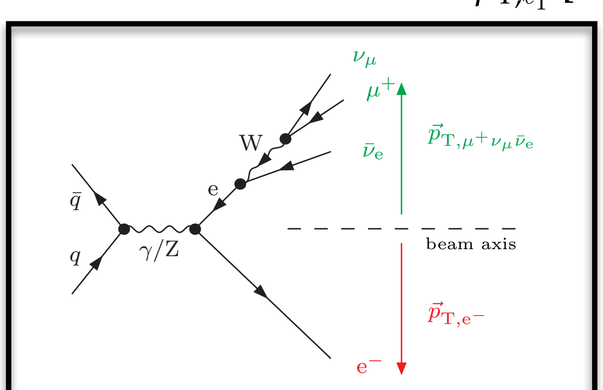




- large negative EW corrections: **-40% at 1 TeV** (larger then QCD corrections)
- sizeable impact of γPDF: **10% at 1 TeV**
- sizeable difference with respect to pp→WW→2l2v



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



Conclusions

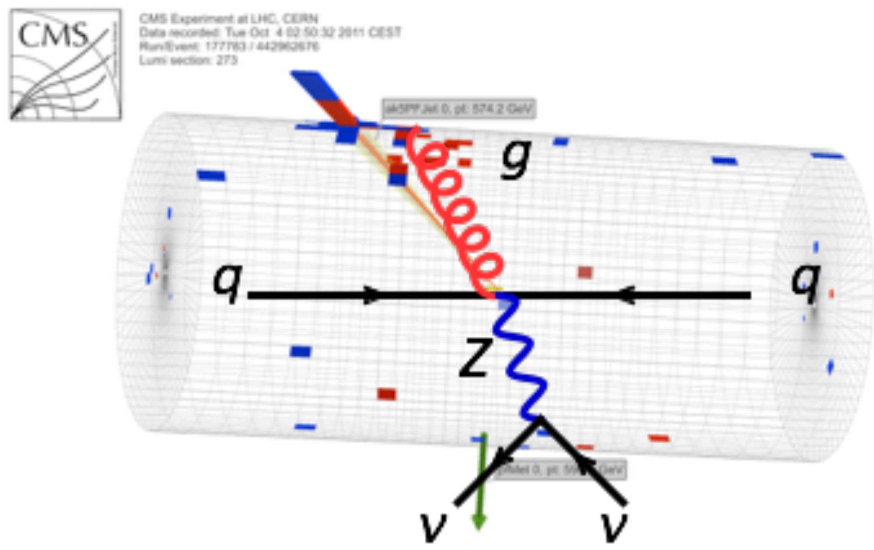
- NLO EW automation well under way
- V+jets:
  - inclusion of EW corrections *crucial* due to large Sudakov logs: **up to -35% at 1 TeV**
  - MC reweighting allows to promote V+jets to NNLO QCD + N(NLO) EW
  - Perturbative systematics in pTV under control at the level of 1-10% up to the TeV
  - Uncertainty estimates applicable for more exclusive V+jets observables?

    (…or other process classes?)
- VV:
  - QED effects crucial in H→VV backgrounds
  - huge EW Sudakov logs in the tails of important distributions: **up to -50% at 1 TeV**
  - Outlook: NNLO QCD + NLO EW for VV

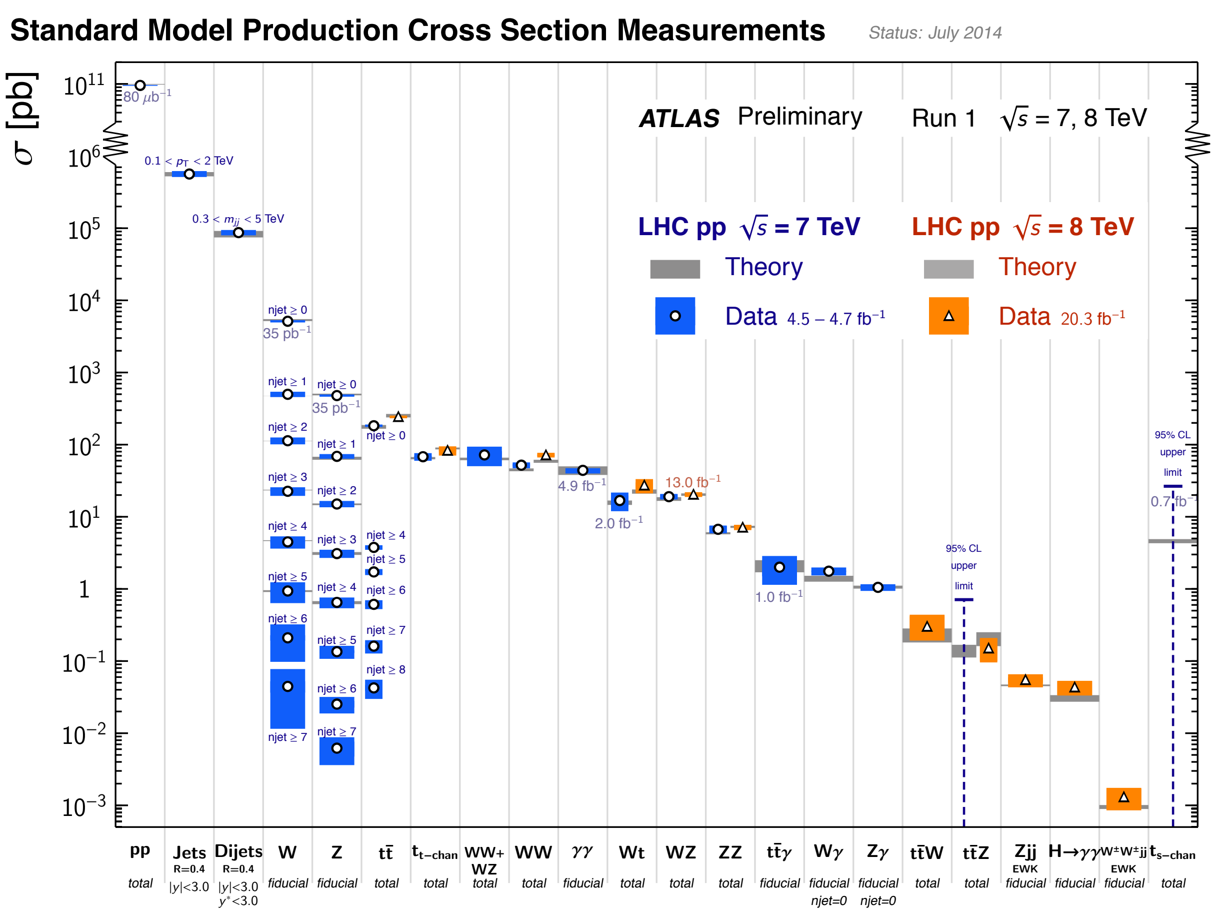
- automated NLO+PS QCD + EW for any process (including multi-jet merging)

BACKUP

V + multijet & VV + jets production



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



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

Combination of NLO QCD and EW

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:

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

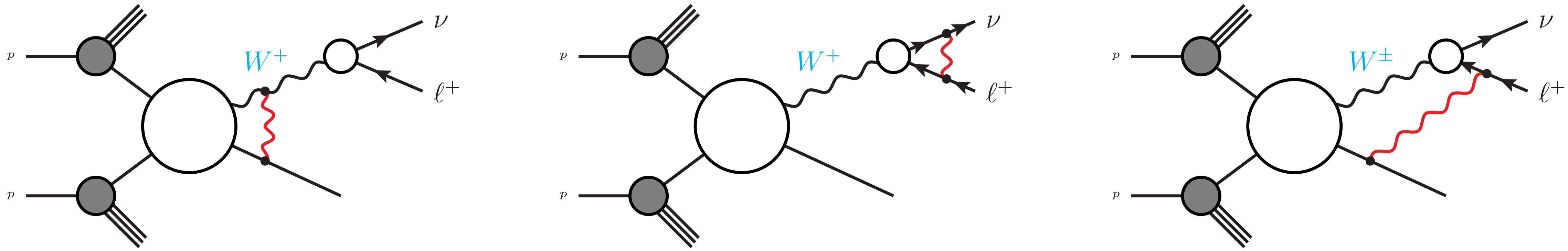
suppressed by large NLO QCD corrections

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

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

Decays of heavy particles @ NLO EW

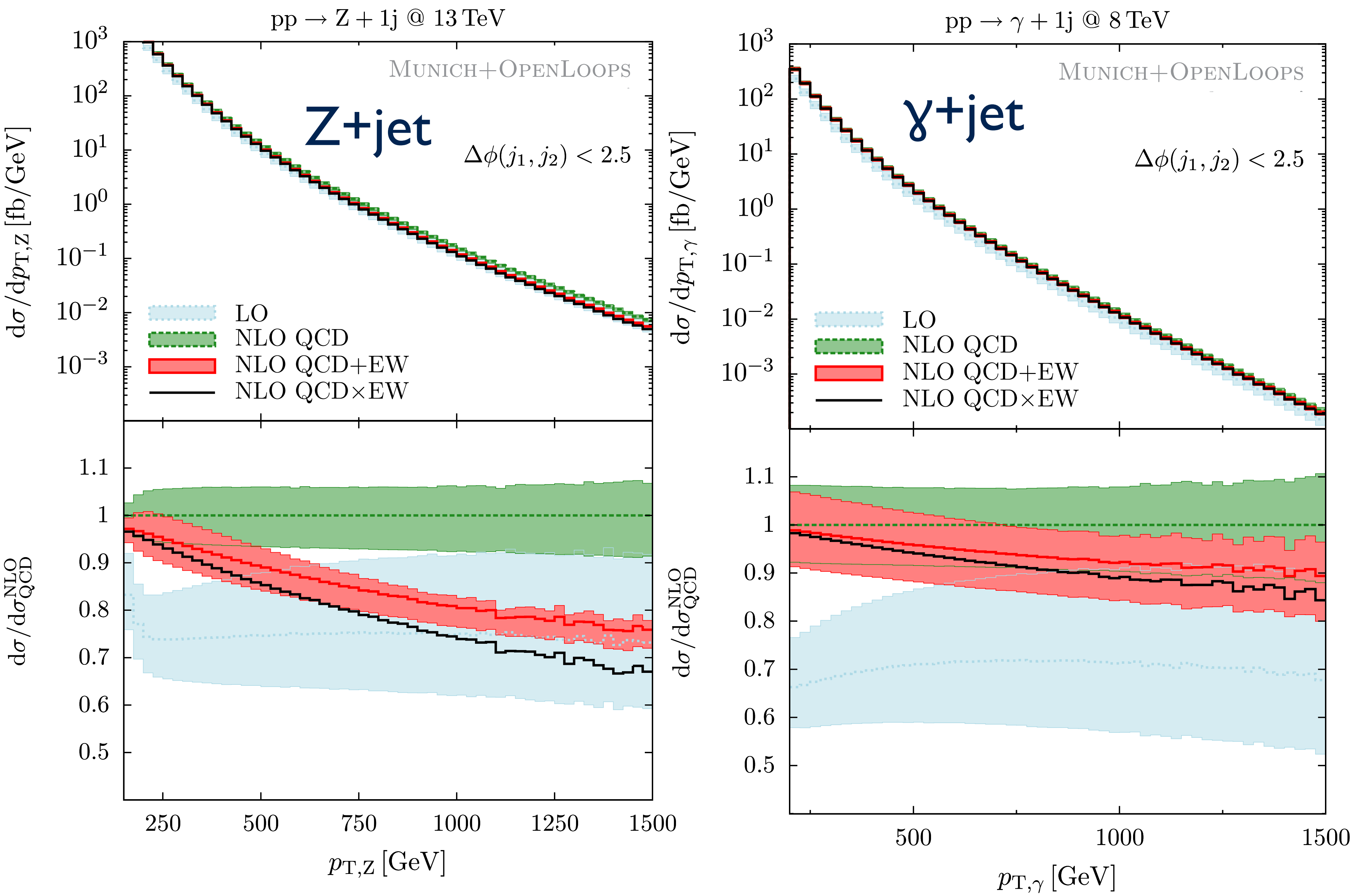
- Leptonic decays of gauge bosons are trivial at NLO QCD.
- At NLO EW corrections in production, decay and non-factorizable contributions have to be considered.



- 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**

Prelude: Z+jet vs. ɣ + 1 jet



QCD corrections

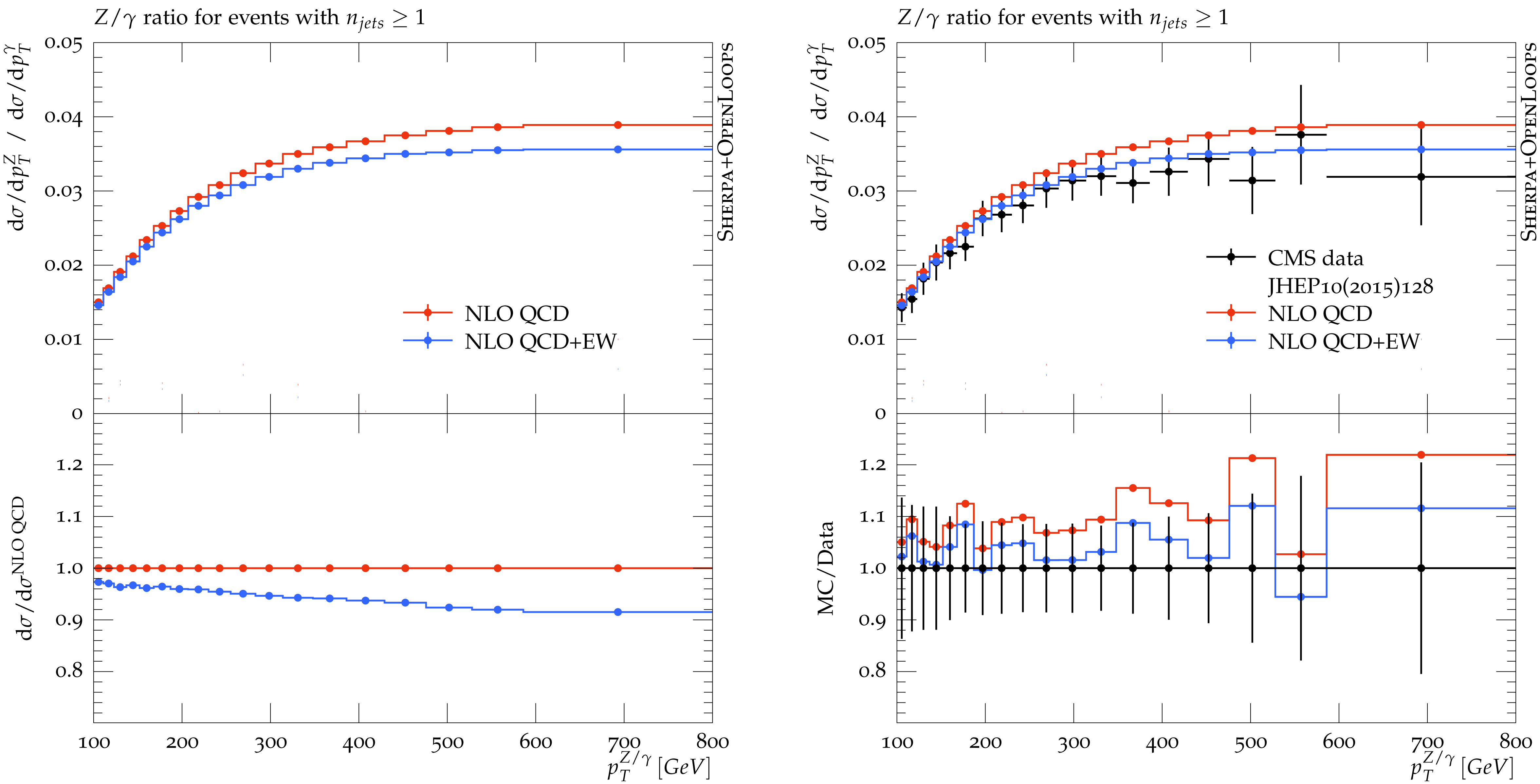
- mostly moderate and stable QCD corrections
- (almost) **identical QCD corrections in the tail**, sizeable differences for small pT

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: compare against Z/γ-data

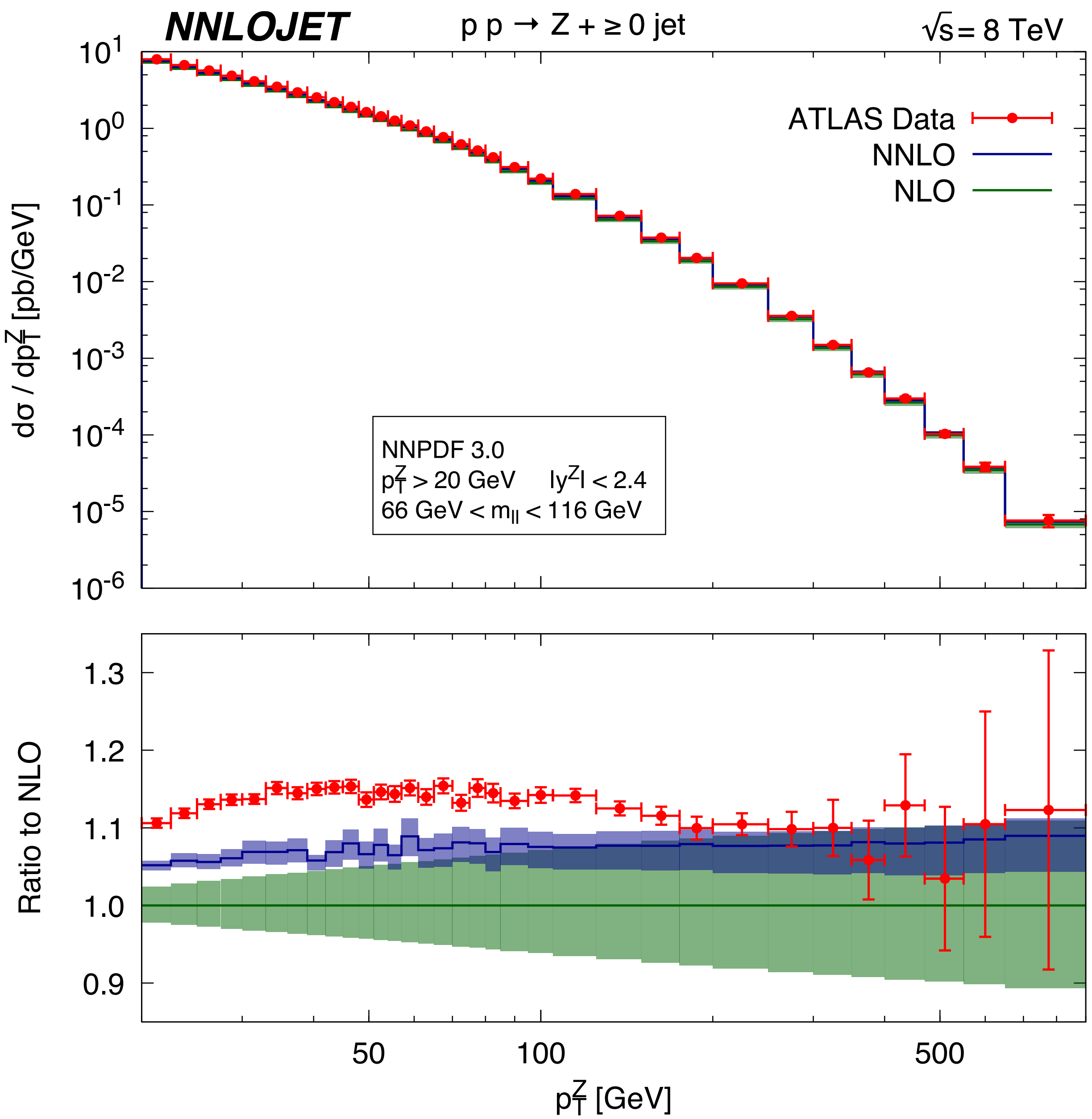
[JHEP10(2015)128]

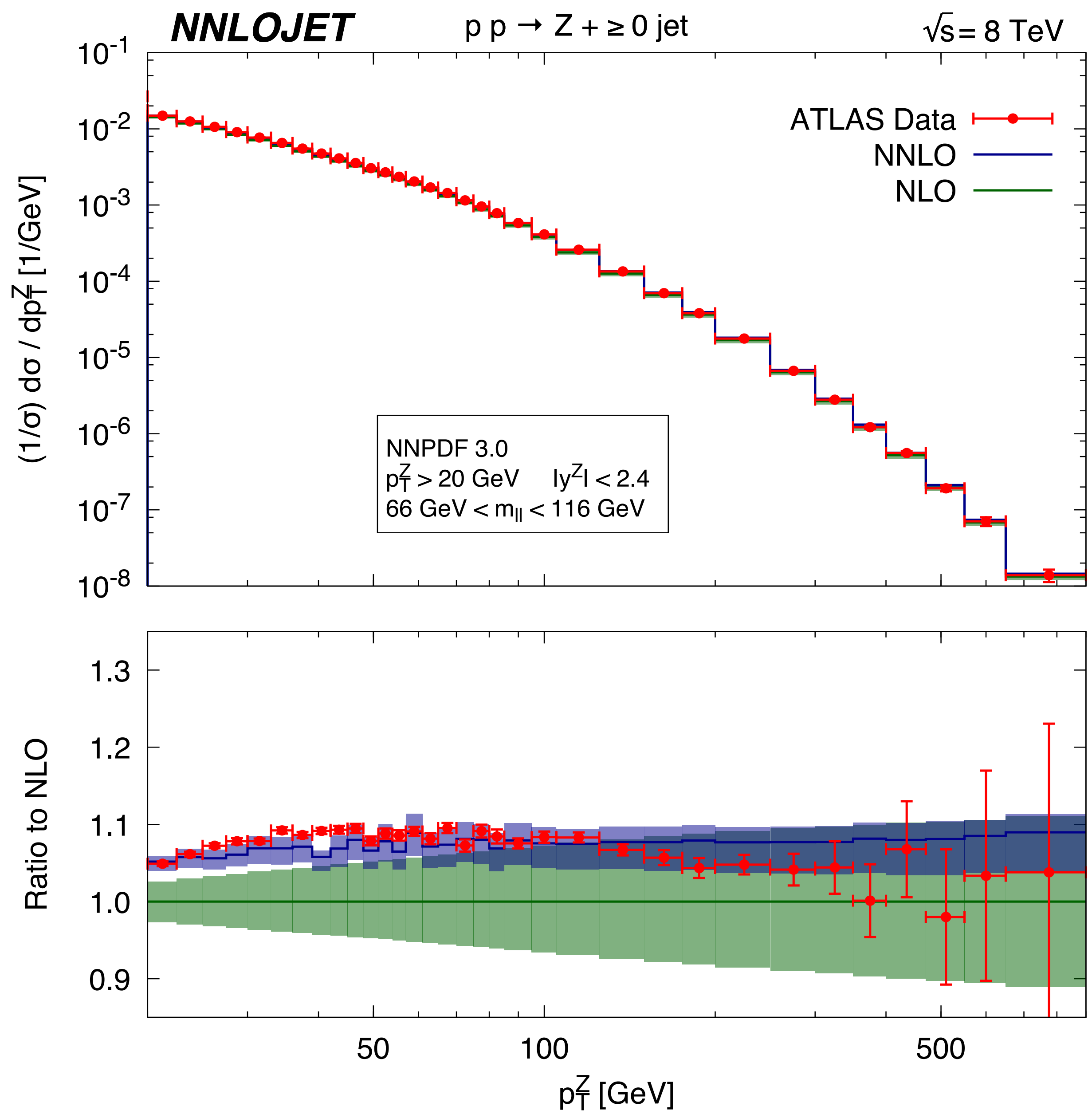


*[Ciulli, Kallweit, JML, Pozzorini, Schönherr for **LH'15**]*

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

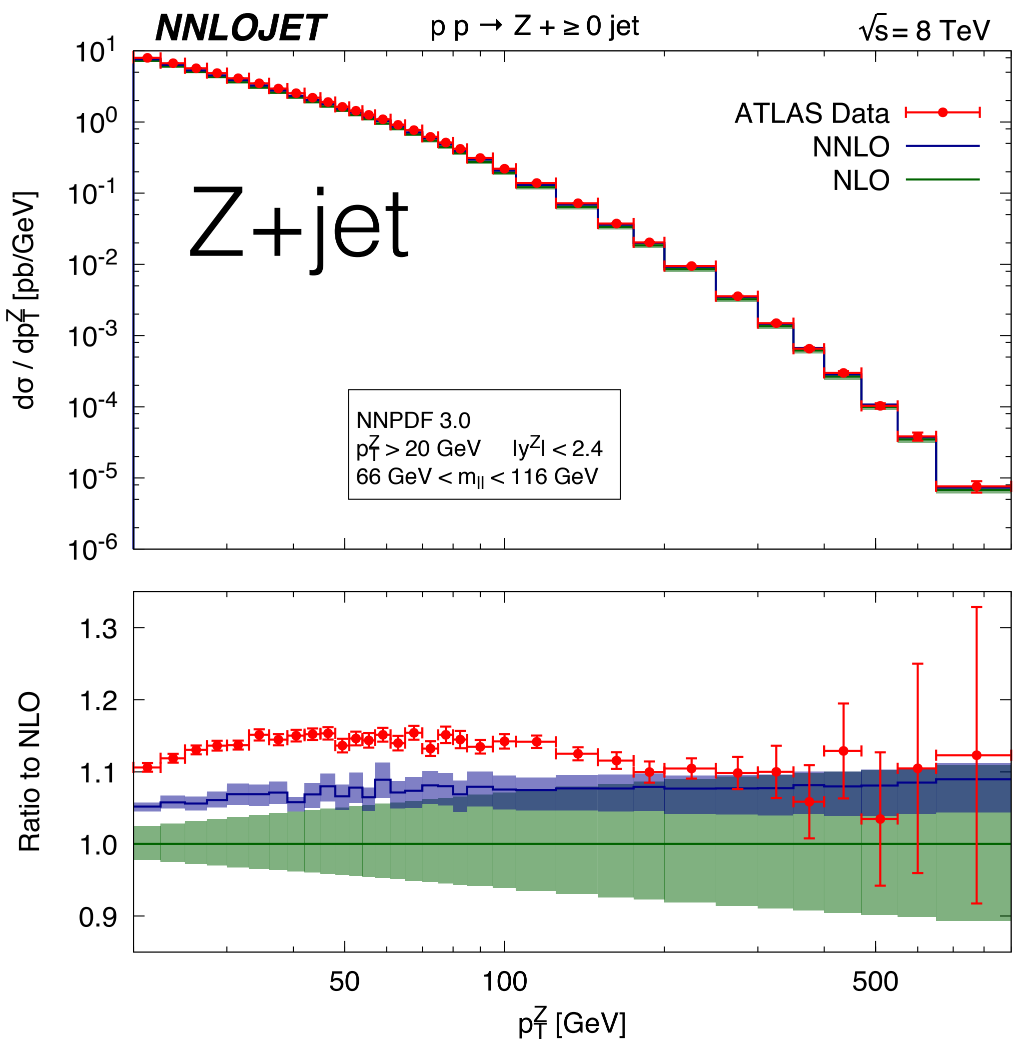
NNLO for Z+jet



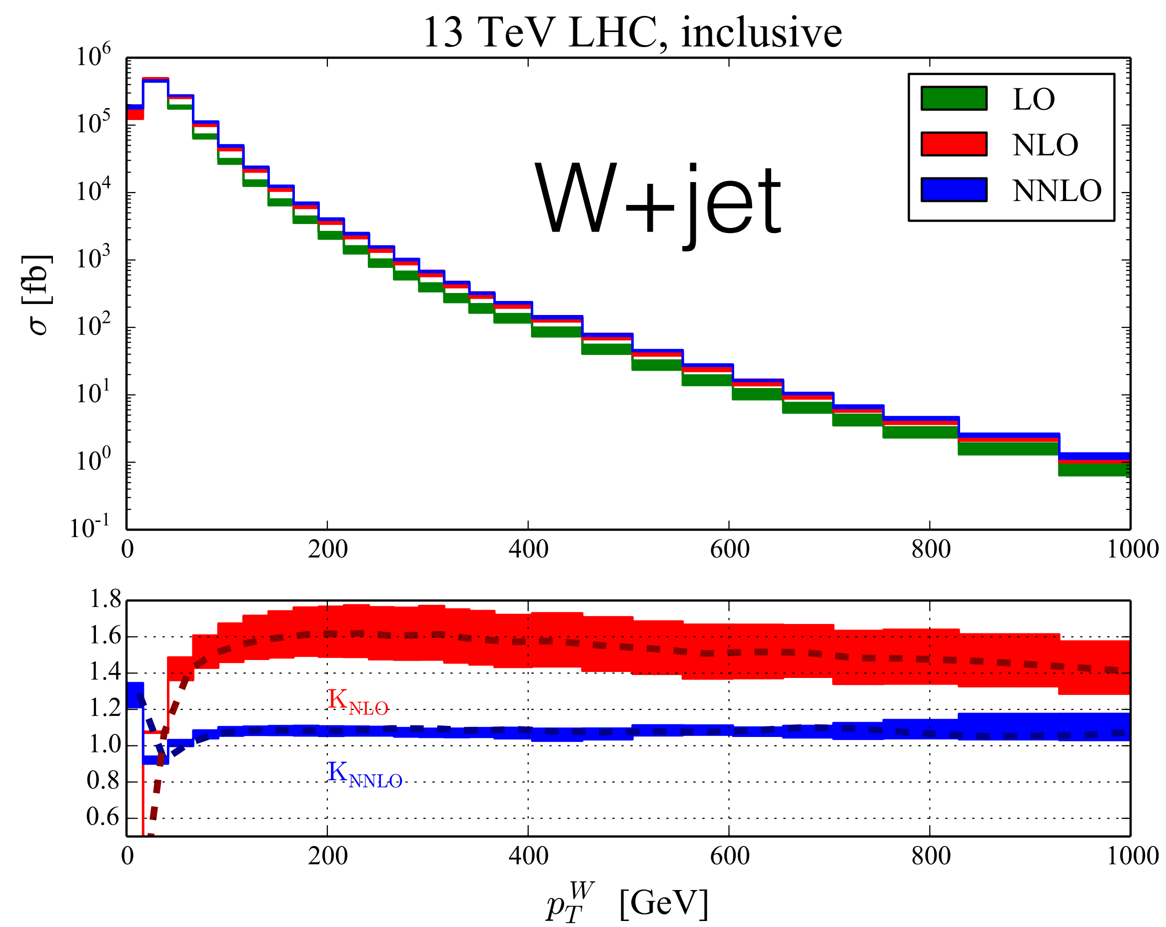


[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]

NNLO for W/Z+jet



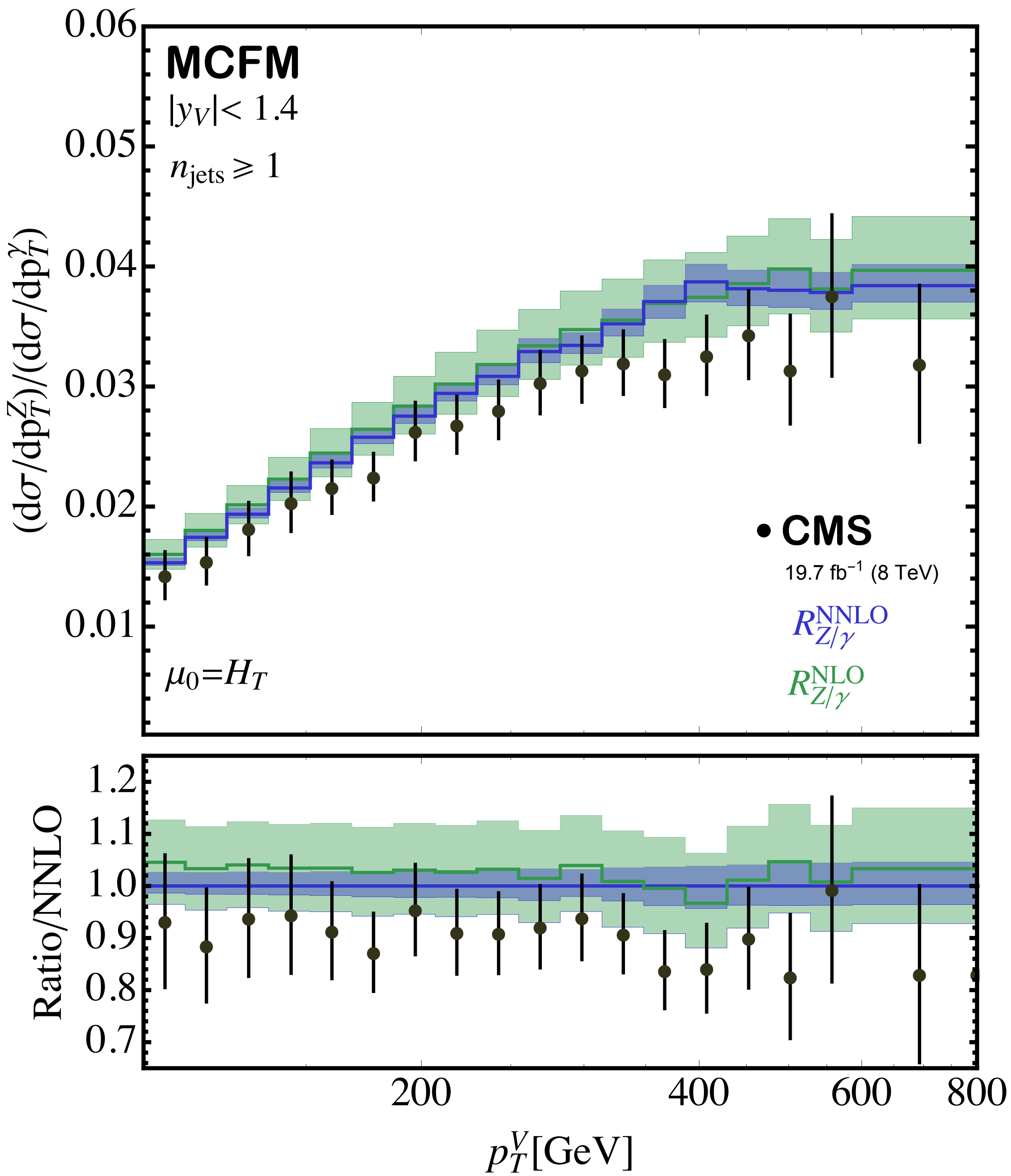
[Gehrmann-De Ridder, Gehrmann, Glover, A. Huss, Morgan; '16]



[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



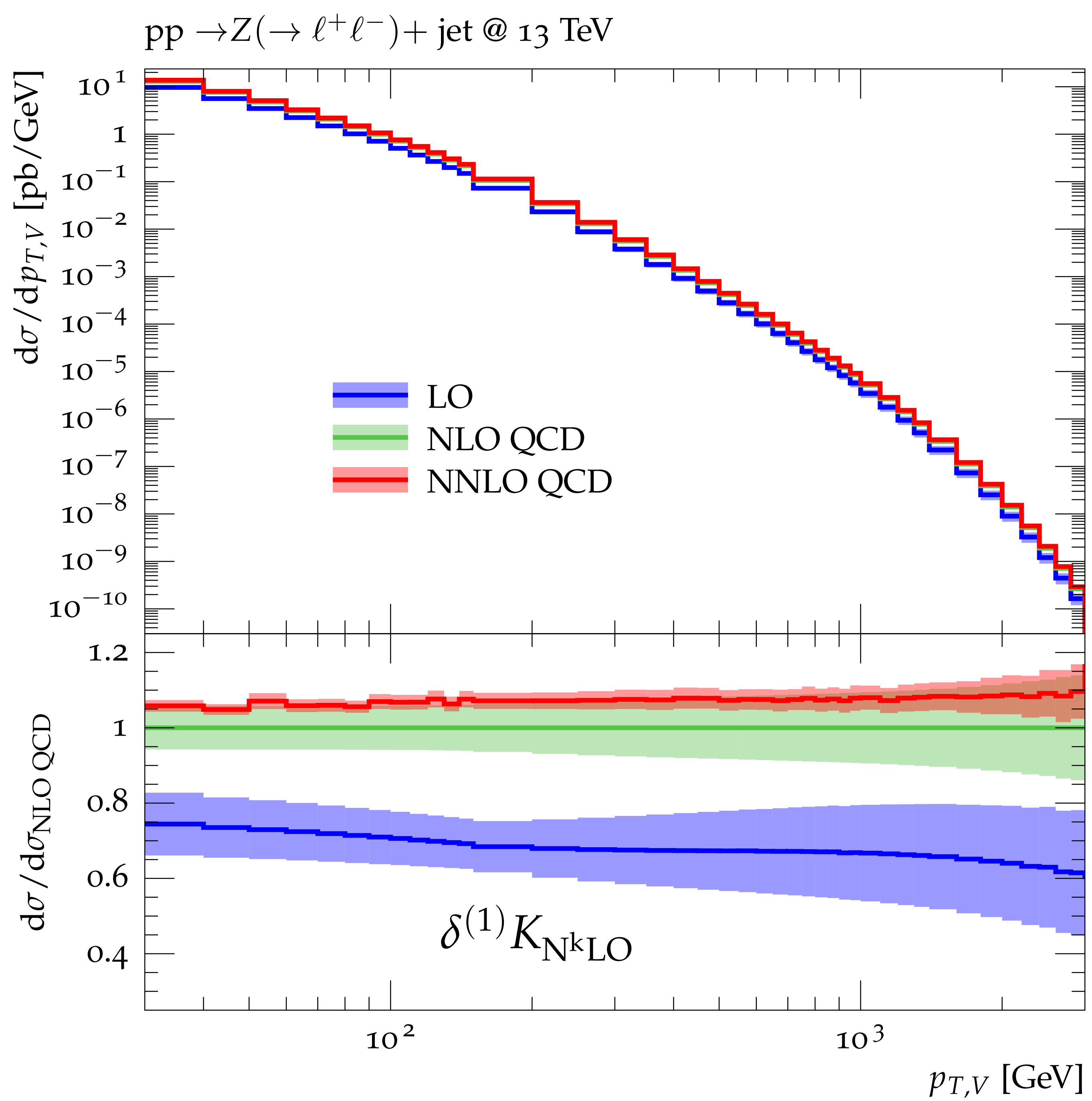
[Campbell, Ellis, Williams; '17]

NNLO/NLO ~ 1 for large pT!

QCD effects

[see Nigel's talk]

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



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

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

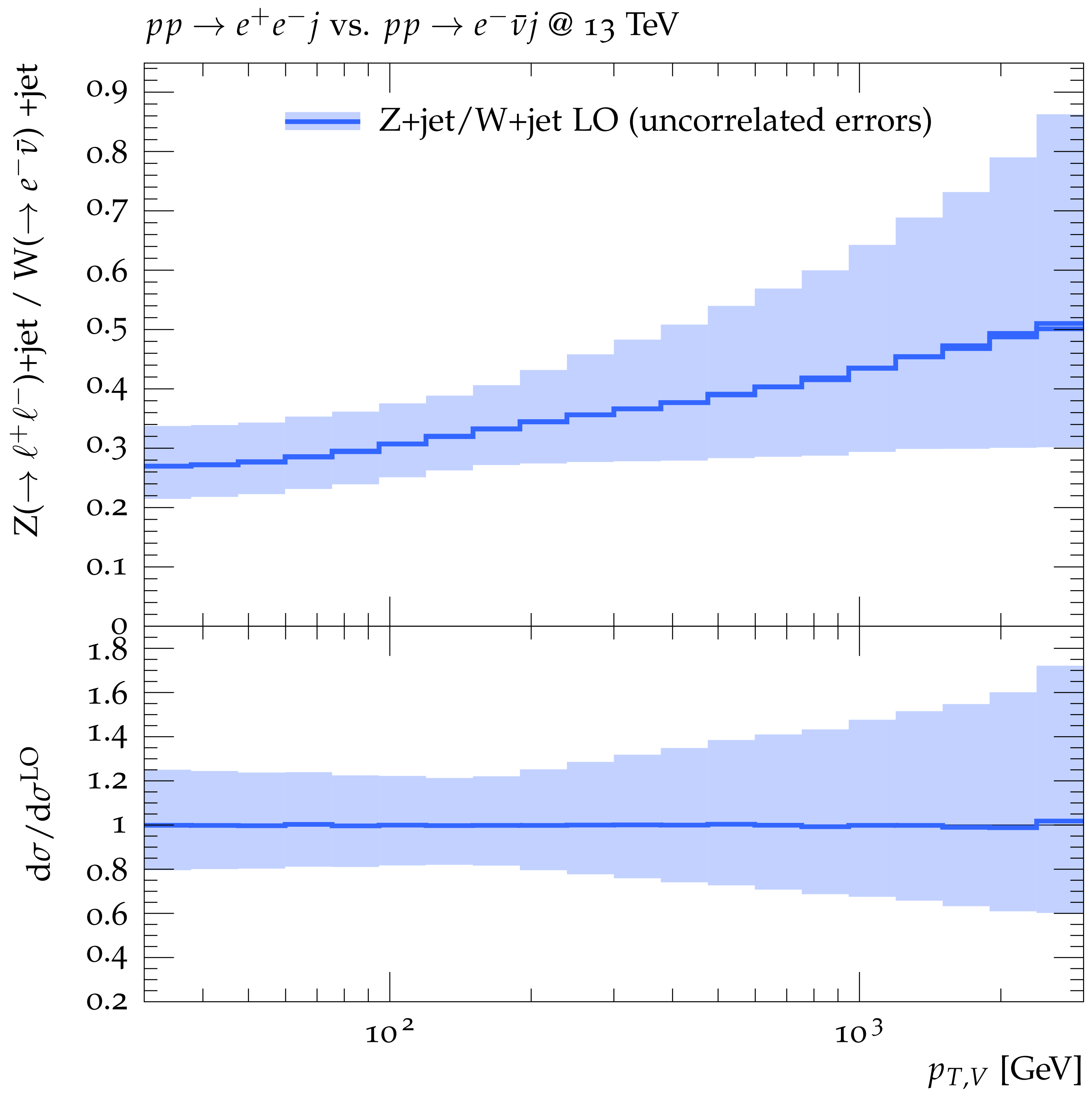
$$(\xi_{\mathrm{R}}, \xi_{\mathrm{F}}) = (2,2),\ (2,1),\ (1,2),\ (1,1),\ (1,0.5),\ (0.5,1),(0.5,0.5)$$

yields

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

with minor shape variations

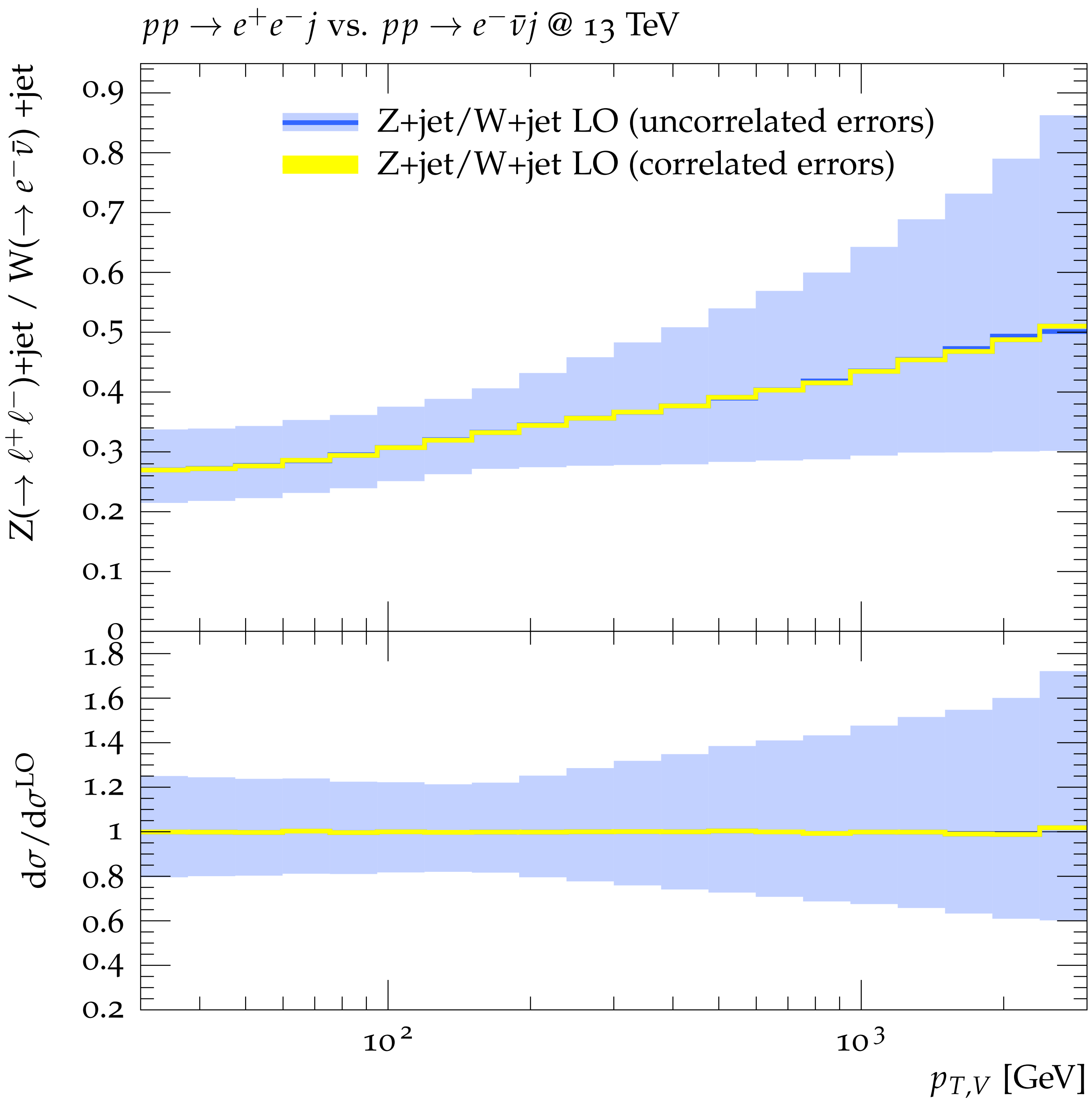
Correlation of scale variations



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

uncorrelated treatment yields O(40%) uncertainties

Correlation of scale variations



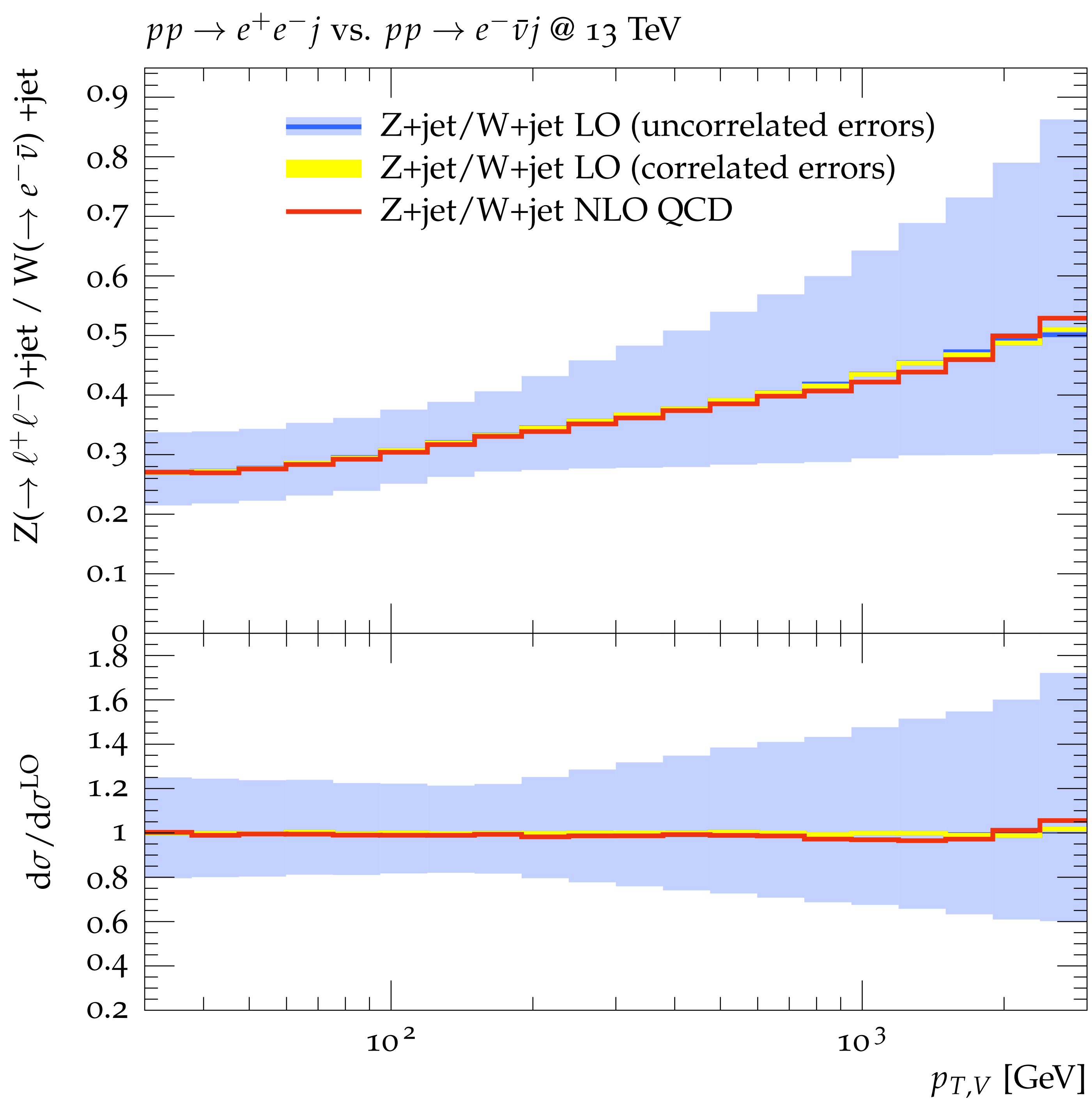
consider Z+jet / W+jet $p_{T,V}$-ratio @ LO

uncorrelated treatment yields O(40%) uncertainties

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

check against NLO QCD!

Correlation of scale variations



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

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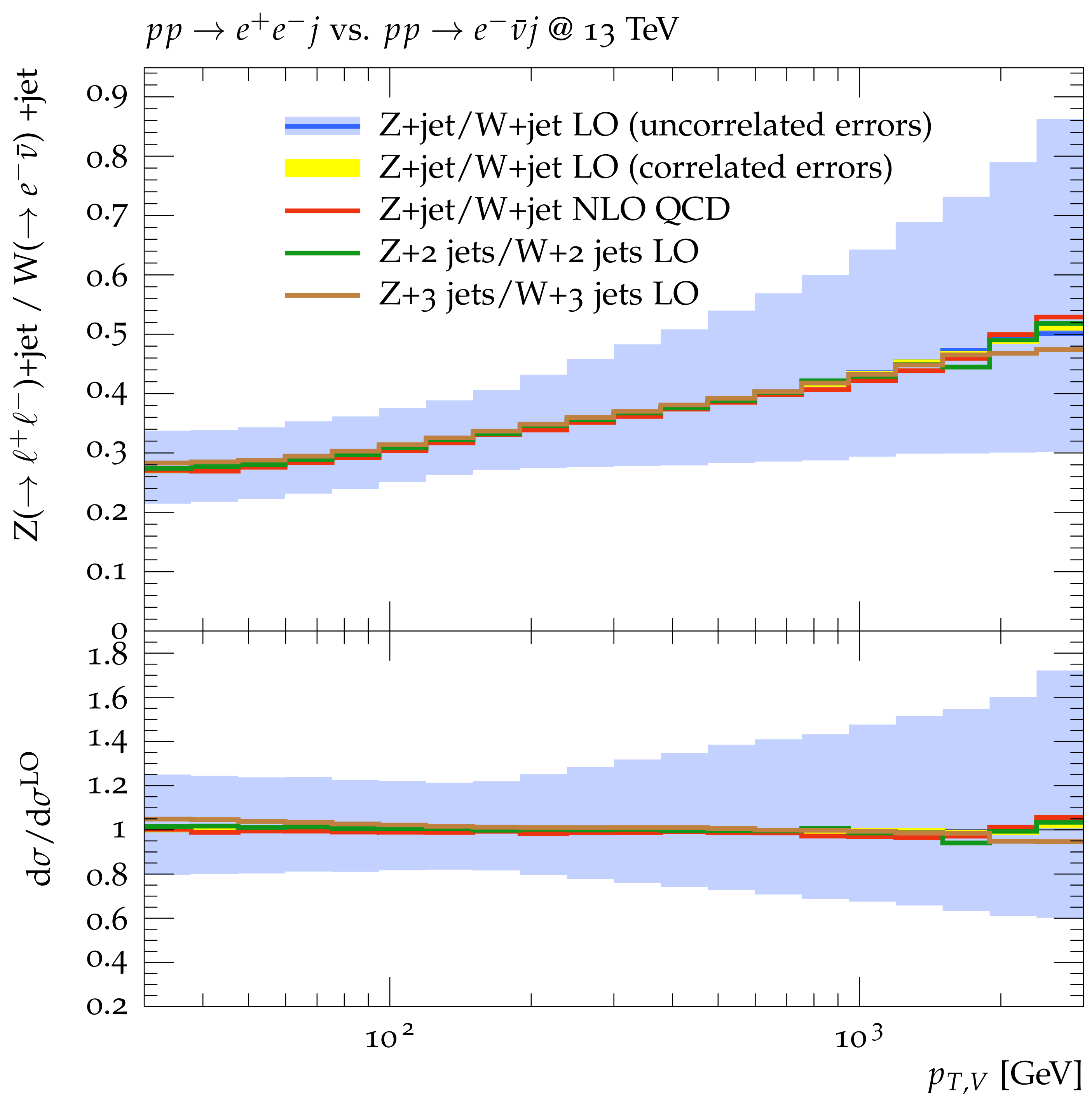
check against NLO QCD!

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

Correlation of scale variations



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

uncorrelated treatment yields O(40%) uncertainties

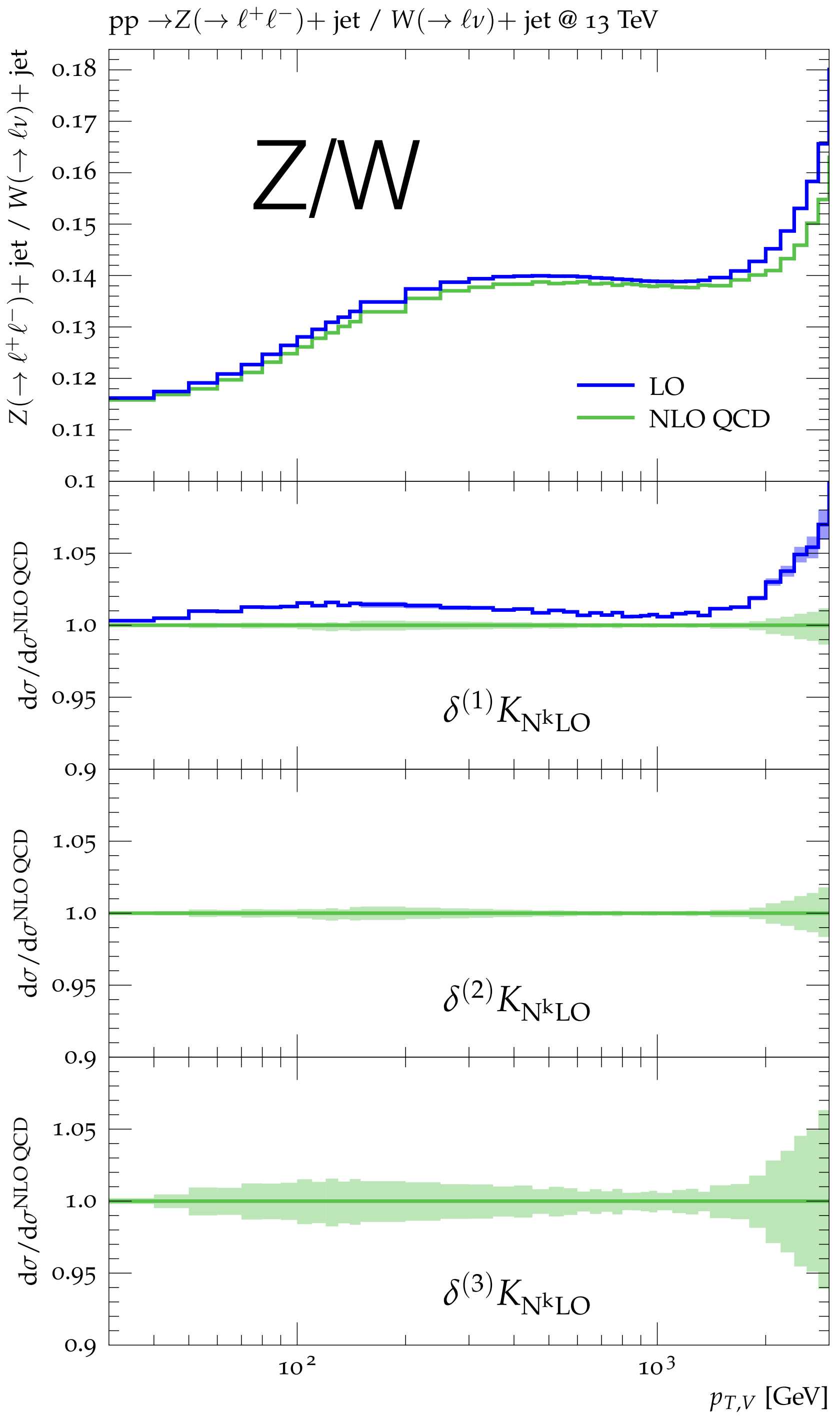
correlated treatment yields tiny O(<~ 1%) uncertainties

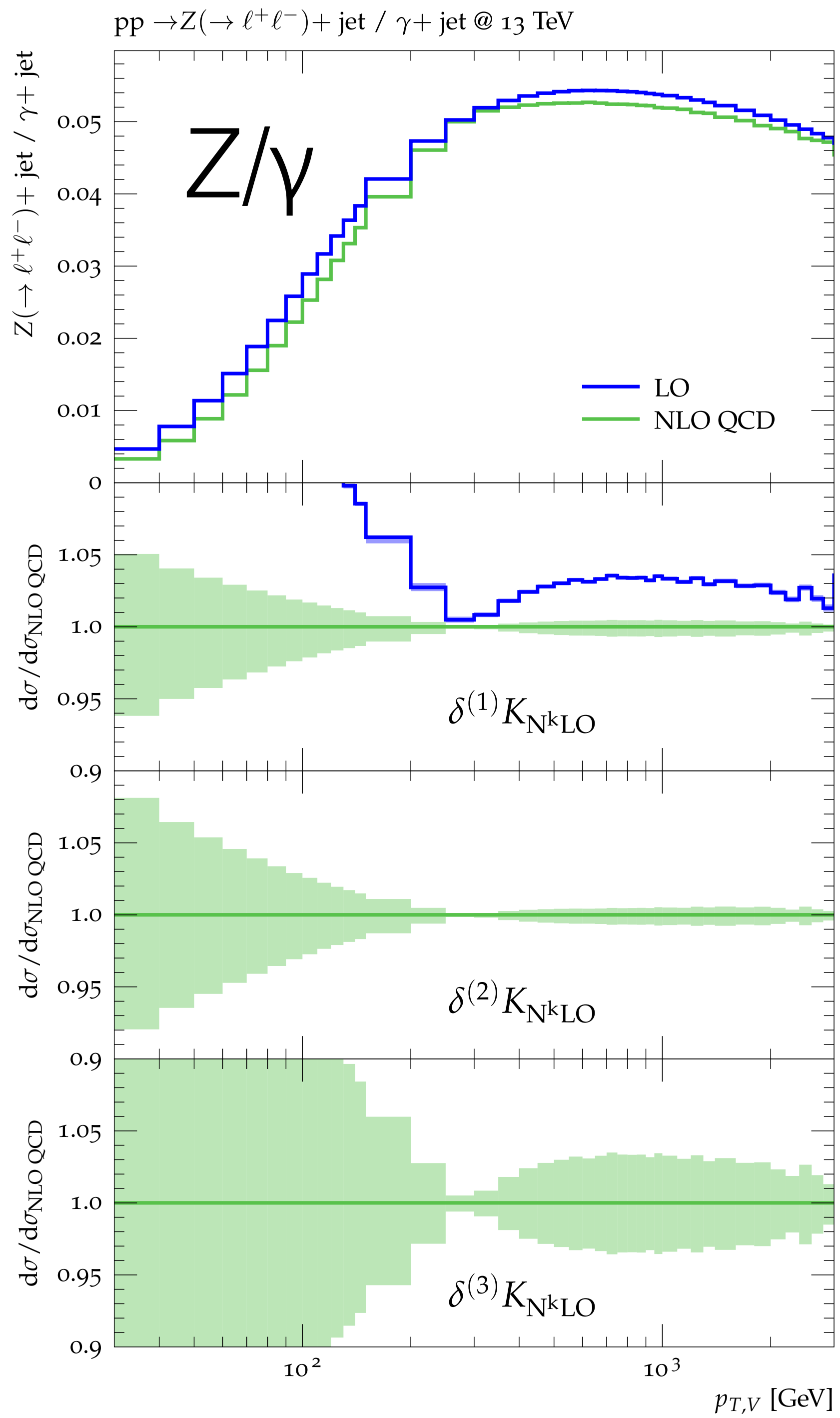
check against NLO QCD!

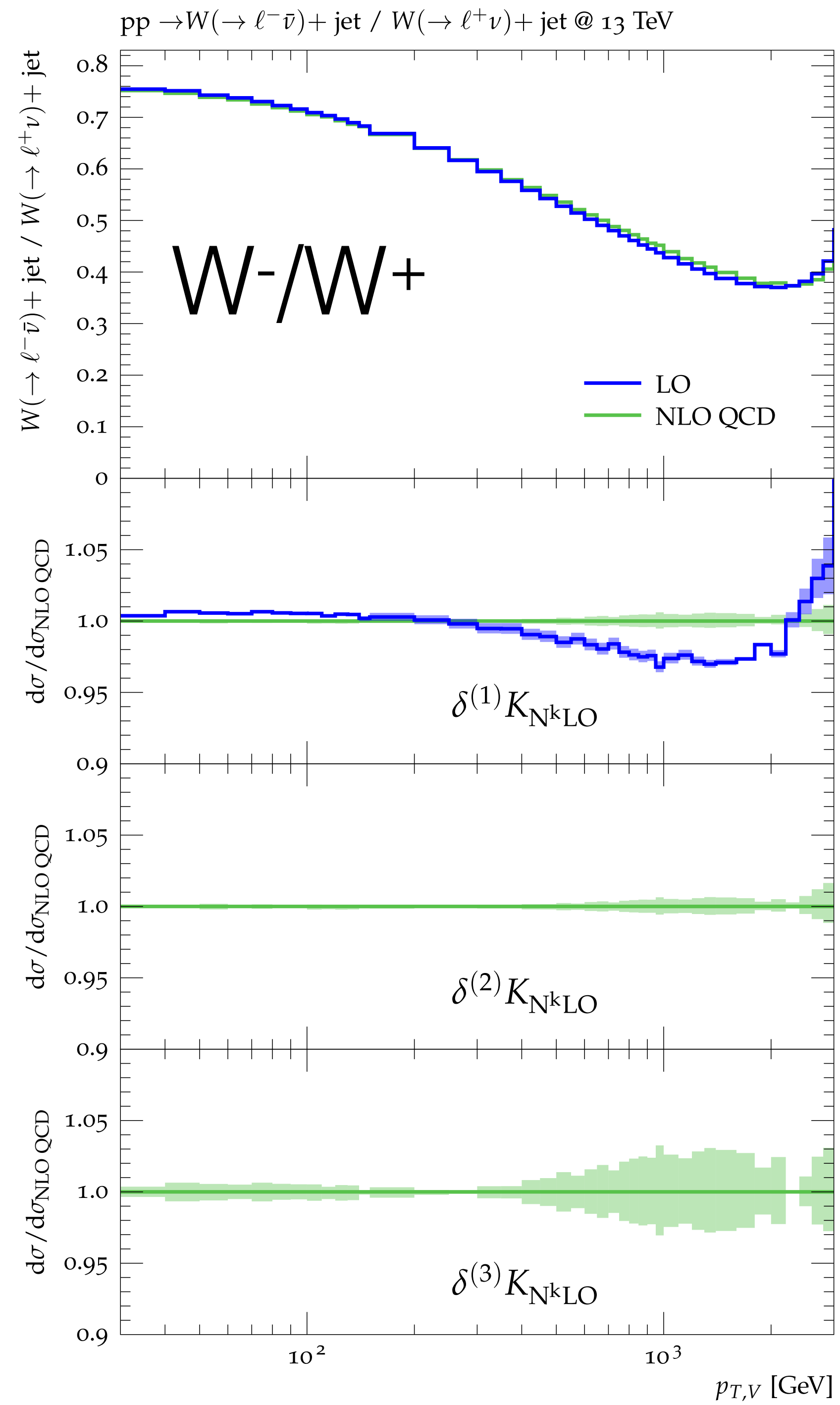
NLO QCD corrections remarkably flat in Z+jet / W+jet ratio!
→ supports correlated treatment of uncertainties!

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

QCD uncertainties in pT-ratios





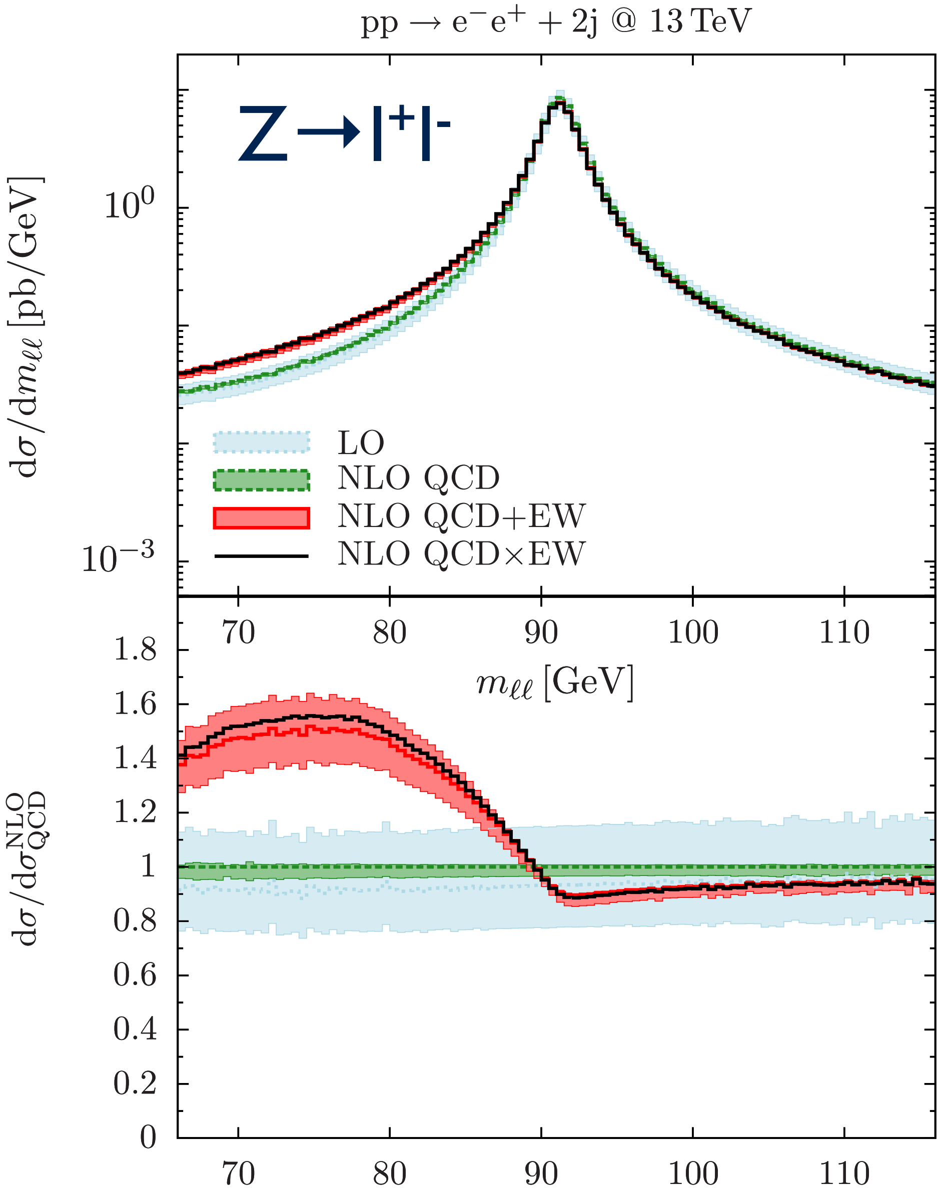


$Z/W^{\pm} \simeq 1\%$

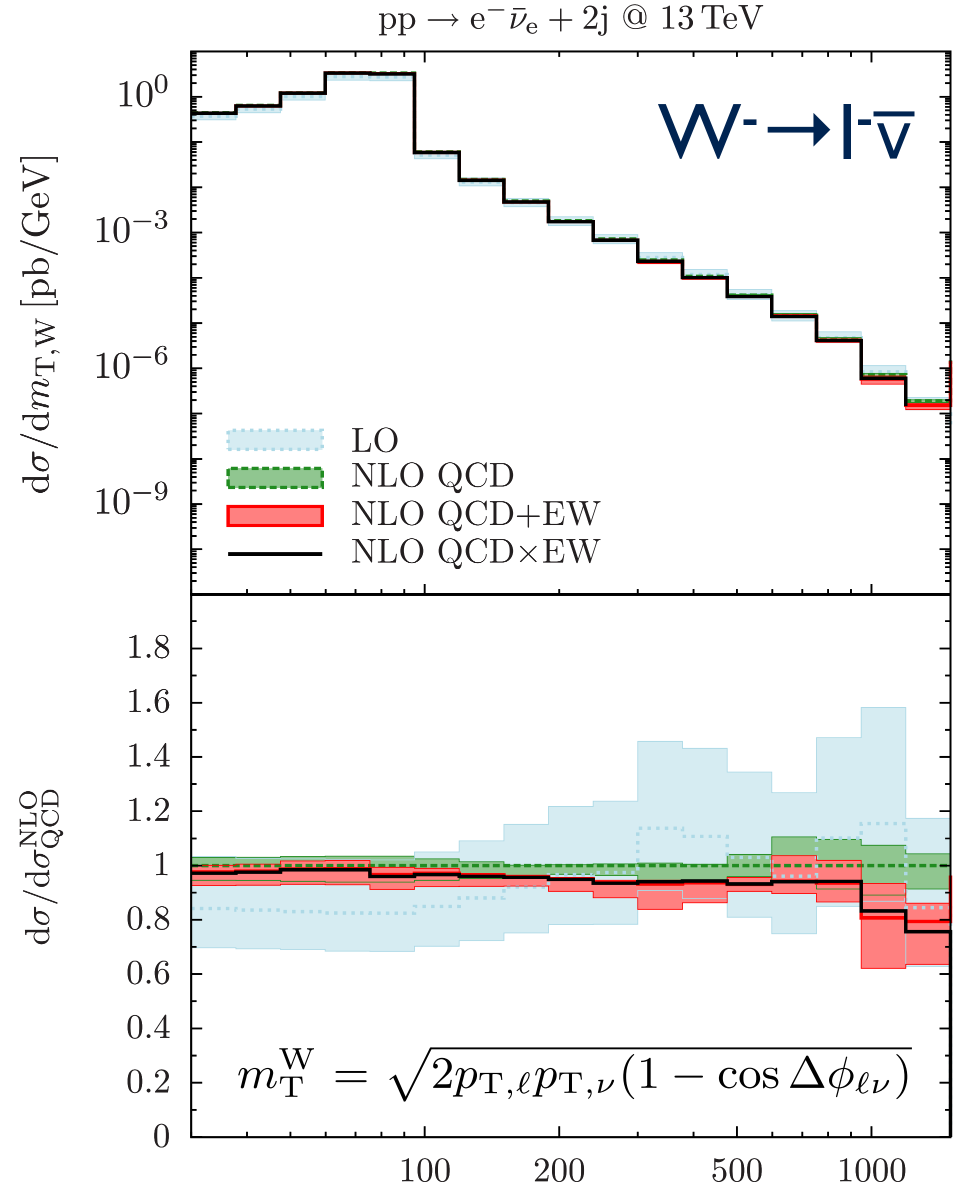
$Z/\gamma \simeq 3\%$

$W^{+}/W^{-} \simeq 1\text{–}3\%$

Leptonic observables: only in off-shell calculation



m_{ll} [GeV]



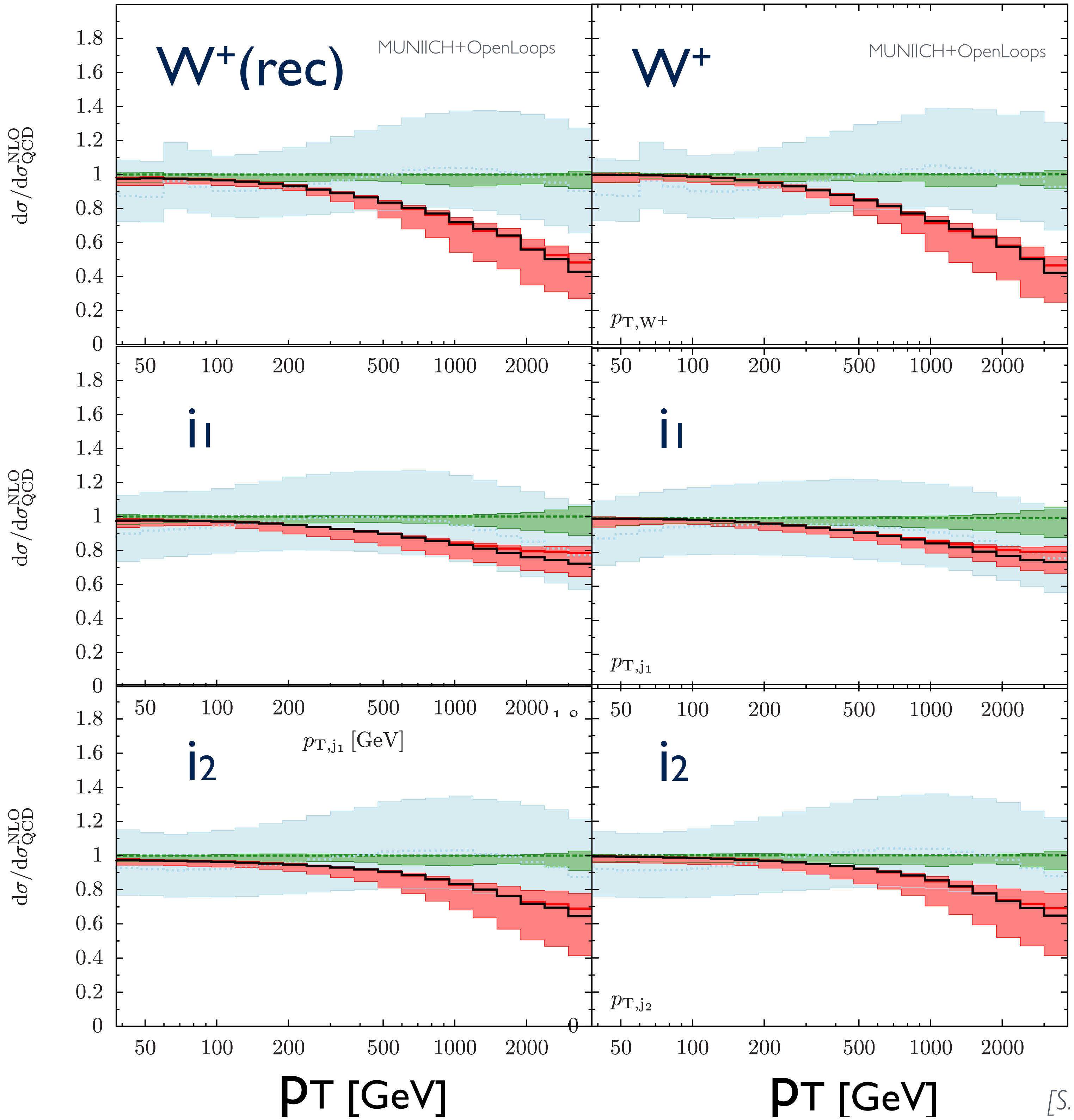
$m_{T,W}$ [GeV]

- up to 50% from QED Bremsstrahlung.
- Similar shape as for NC DY

- moderate EW corrections at large $m_{T,W}$
- no (strong) Sudakov enhancement

off-shell vs. on-shell production

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

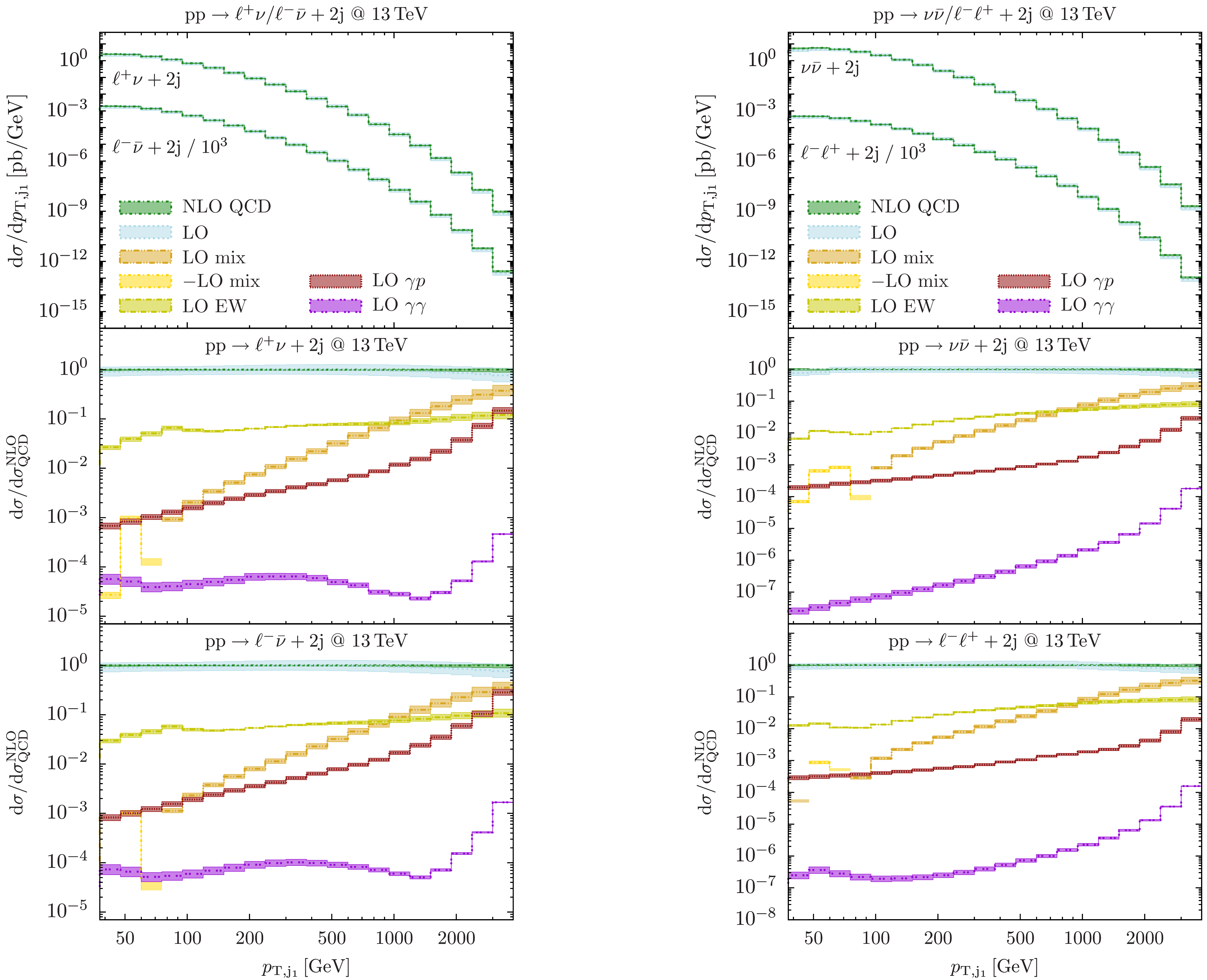


Effect of decays:

- **Large Sudakov corrections driven by hard process**
- However: needed for realistic experimental cuts

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

Subleading Born: $p_{T,j1}$



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

Caveat: γ+jet

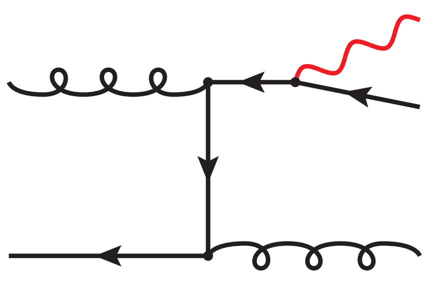
Note: this modelling of process correlations assumes close similarity of QCD effects between different V+jets processes

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

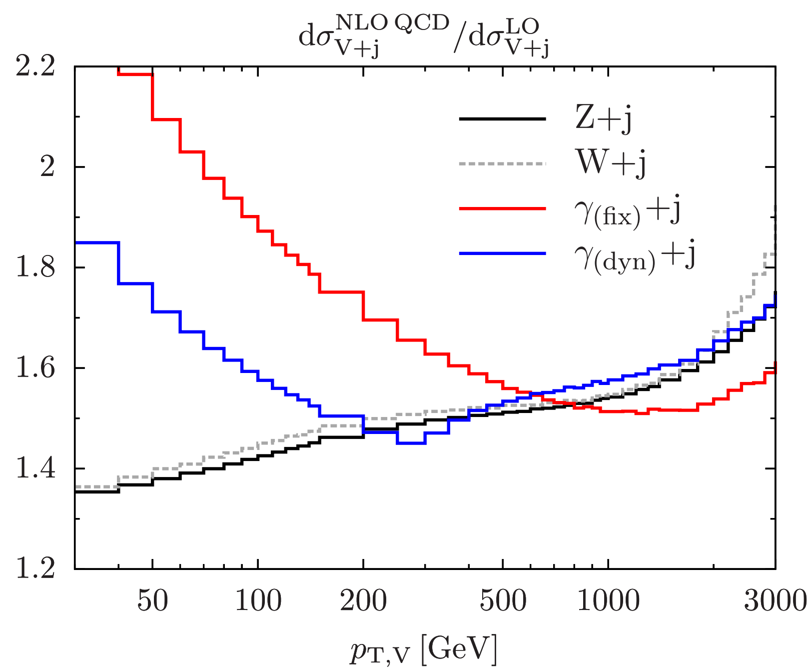
- apart from PDF effects it is the case for W+jets vs. Z+jets
- at pT > 200 GeV it is also the case for γ+jets vs. Z+jets.

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 $R_{dyn}(pT,\gamma) = \min\{1.0, M_Z/pT_\gamma\}$

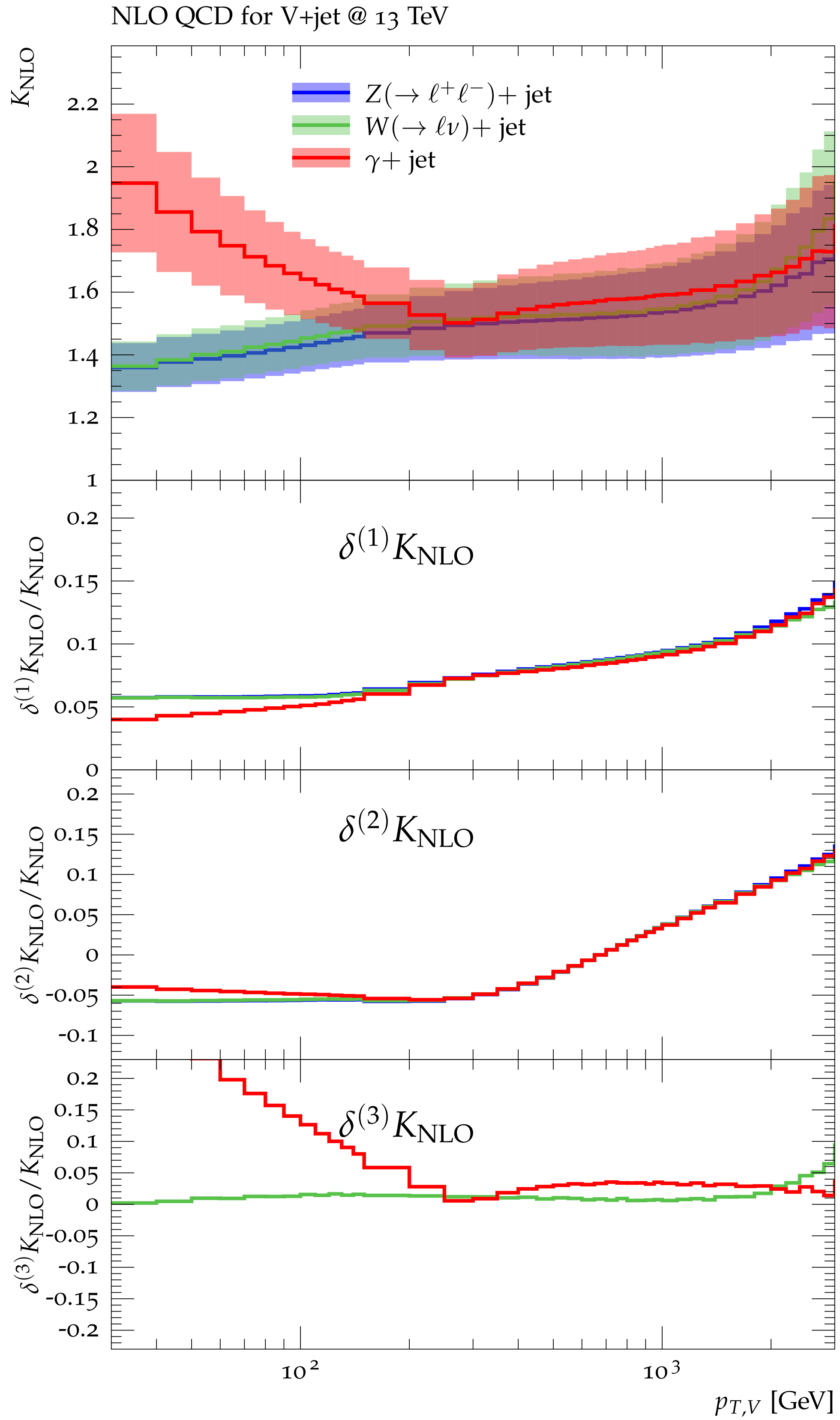


- γ_{dyn} behaves like W/Z at pT > MZ

  ⇒justifies process-correlation estimate

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

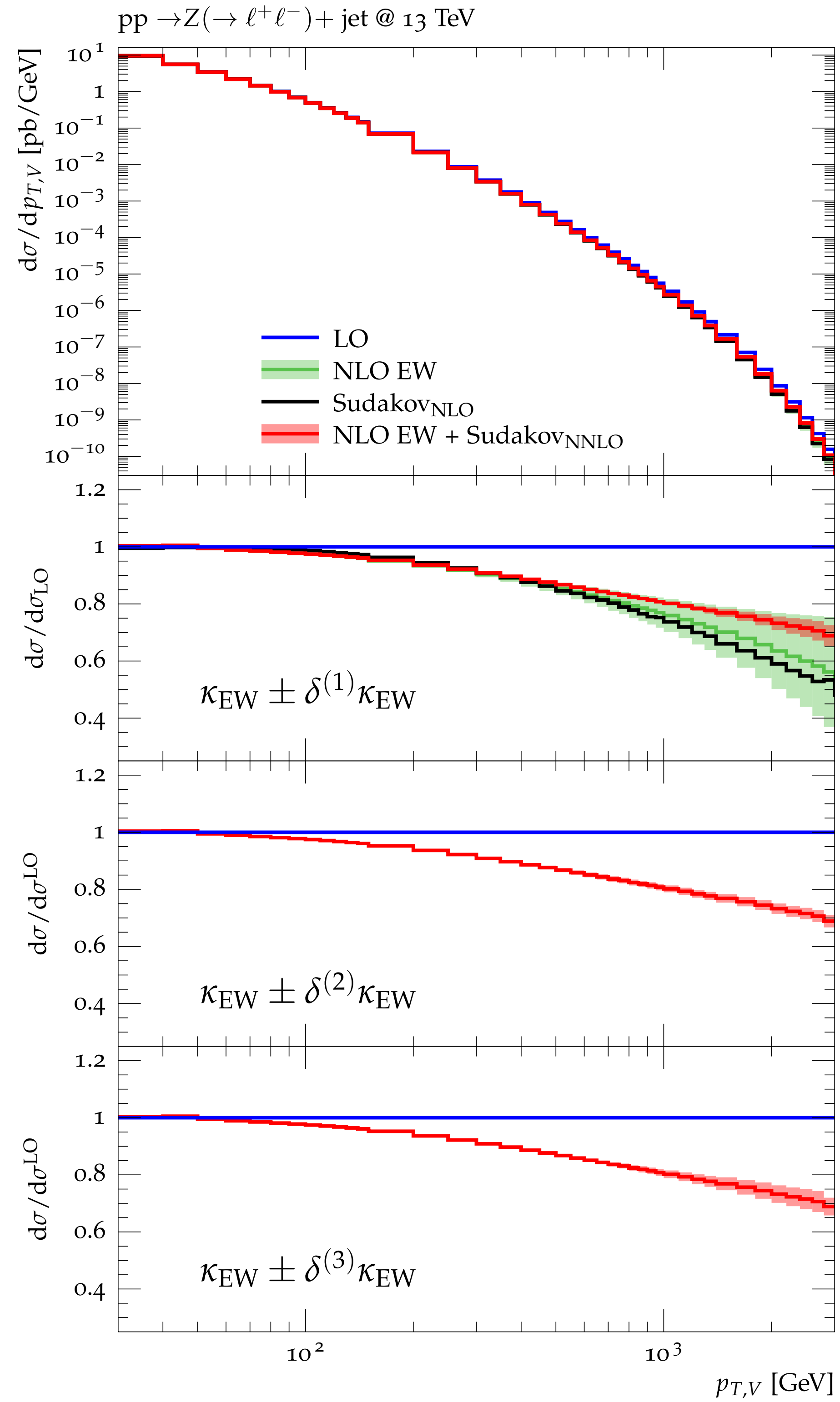
QCD uncertainties



NLO QCD corrections and uncertainties

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

Pure EW uncertainties



- 'higher-order logs'

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

(correlated)

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)

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

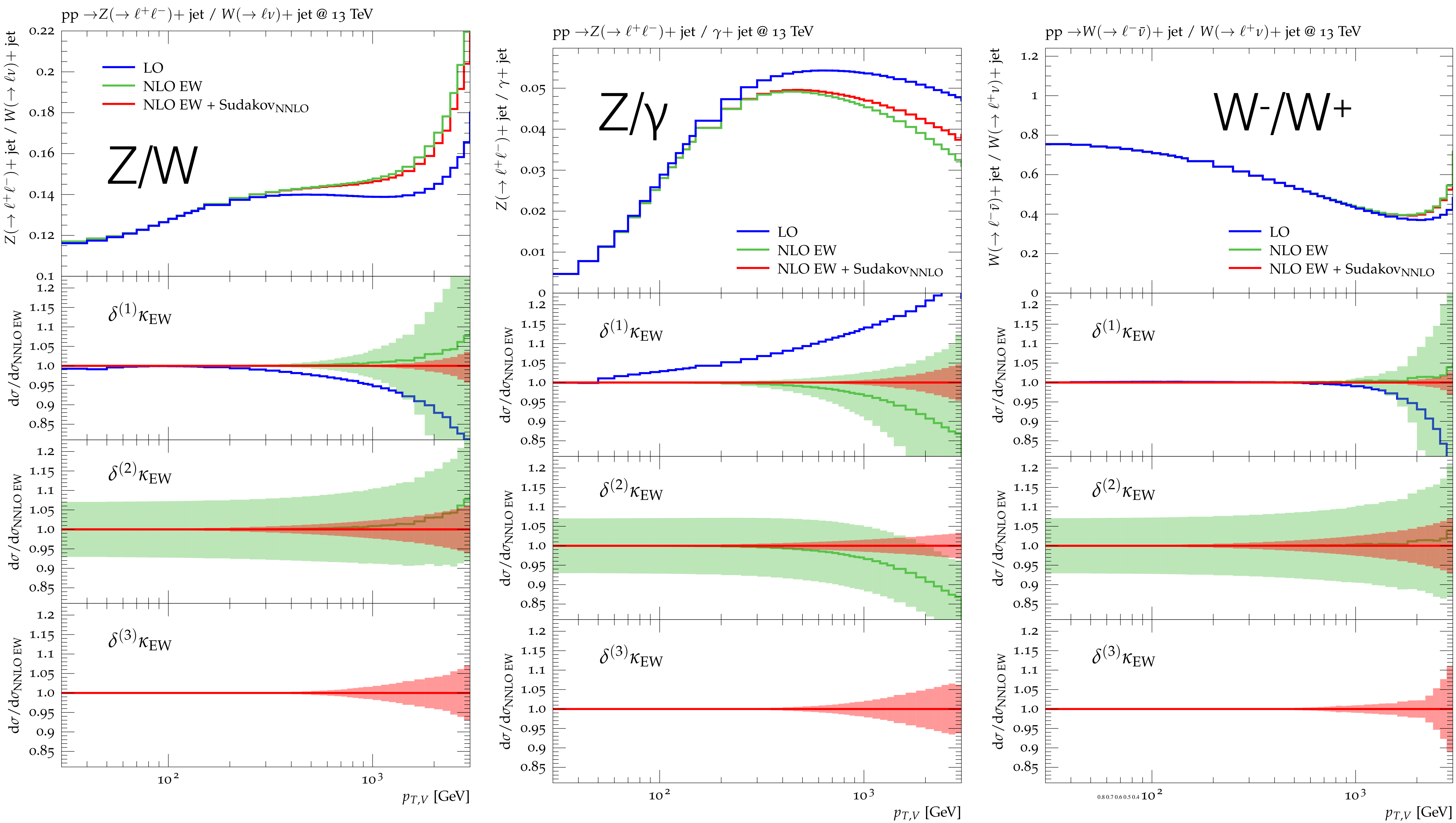
- 'hard non-log NNLO effects II'

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

(uncorrelated)

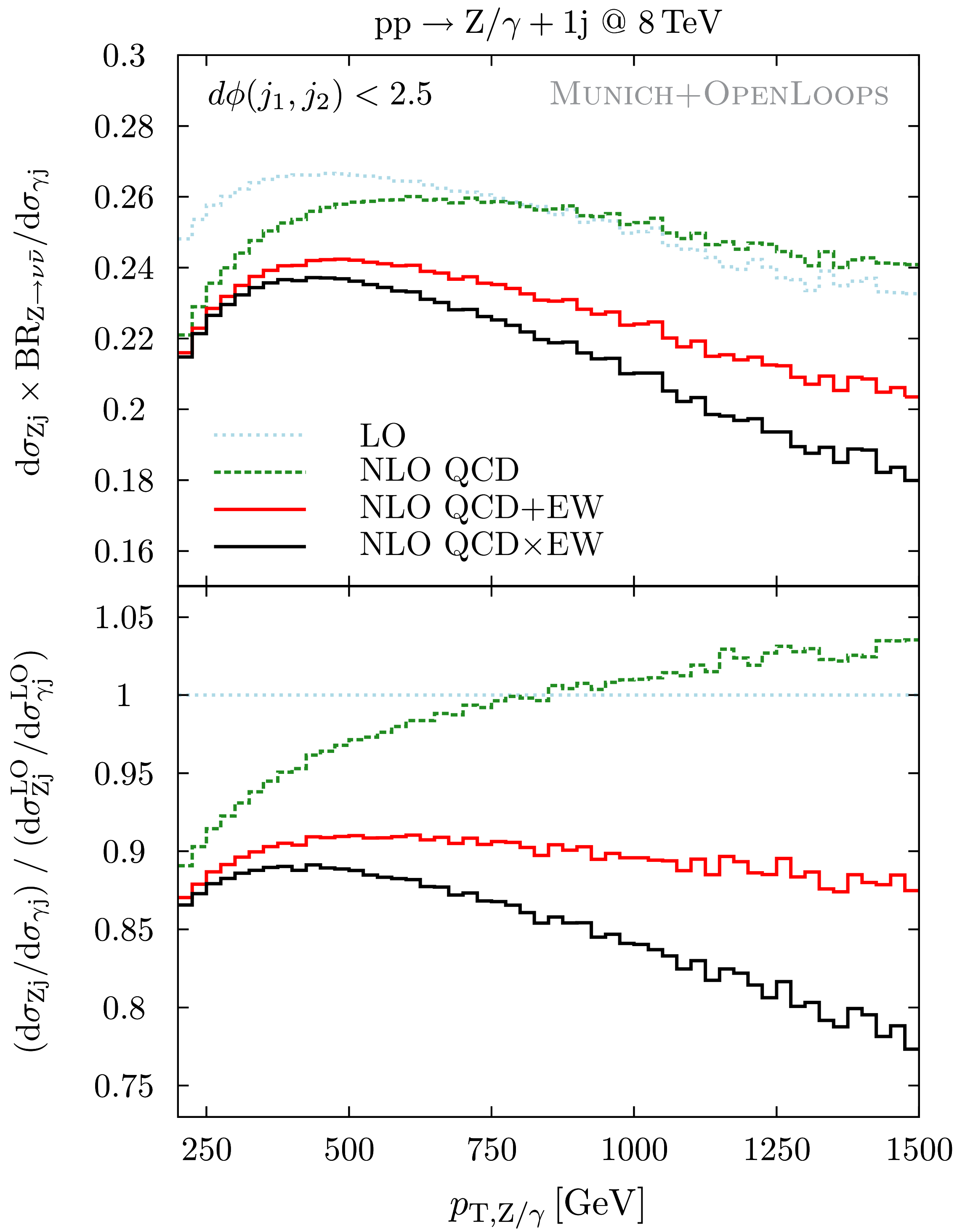
estimate of typical size of $\left[\delta^{(1)}_{\mathrm{hard}}\right]^2$ or $\delta^{(1)}_{\mathrm{hard}} \times \delta^{(1)}_{\mathrm{Sud}}$.

EW uncertainties in pT-ratios



Z/W± ≃2-3%   Z/**γ** ≃2-3%   W+/W− ≃2–3%

Z/γ + 1 jet: pT-ratio



Overall

- mild dependence on the boson pT

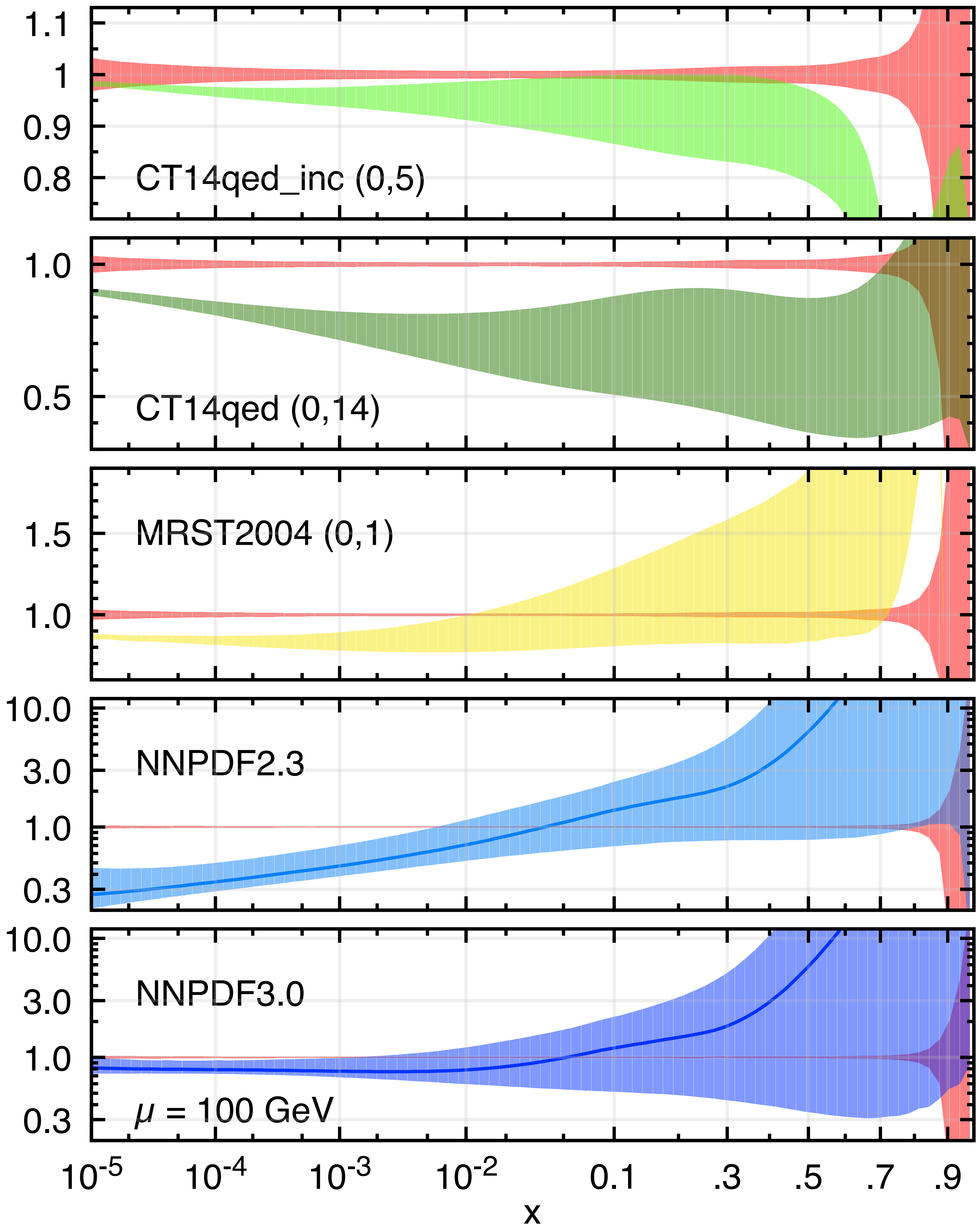
QCD corrections

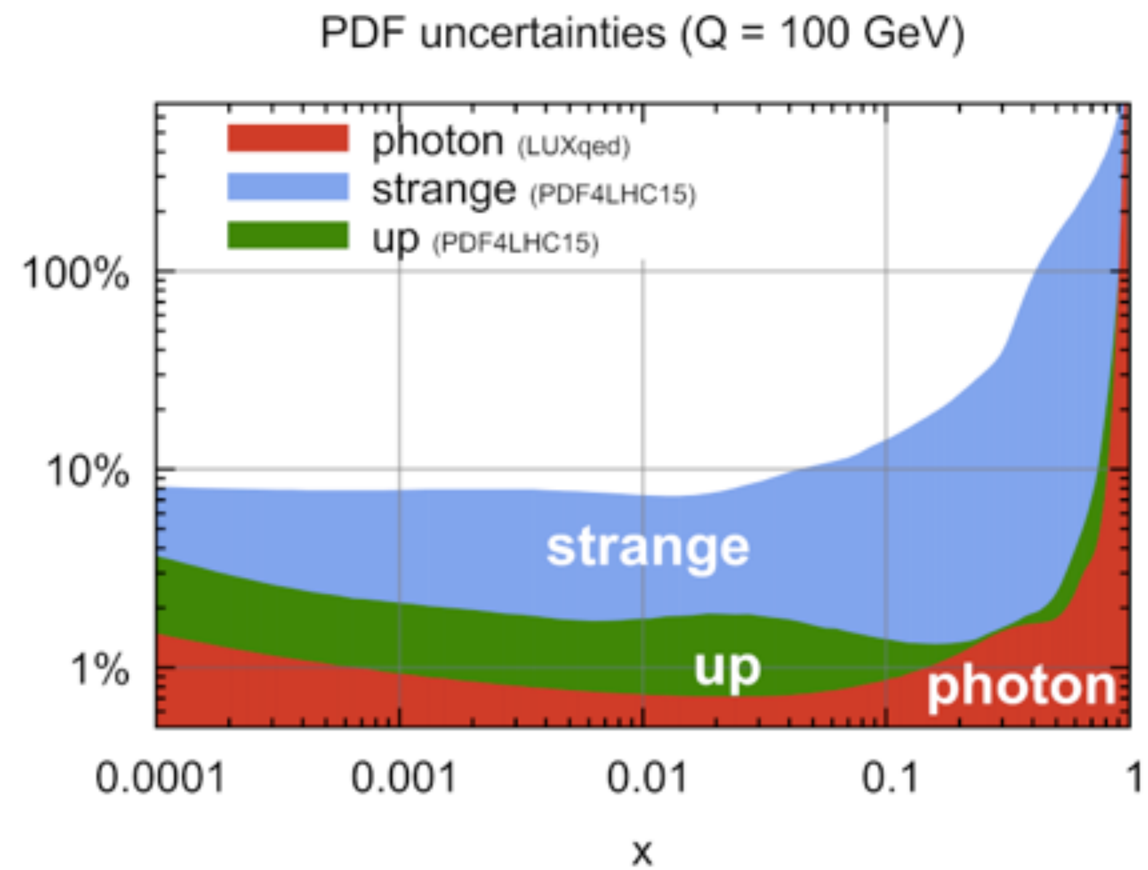
- 10-15% below 250 GeV
- ≲ 5% above 350 GeV

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

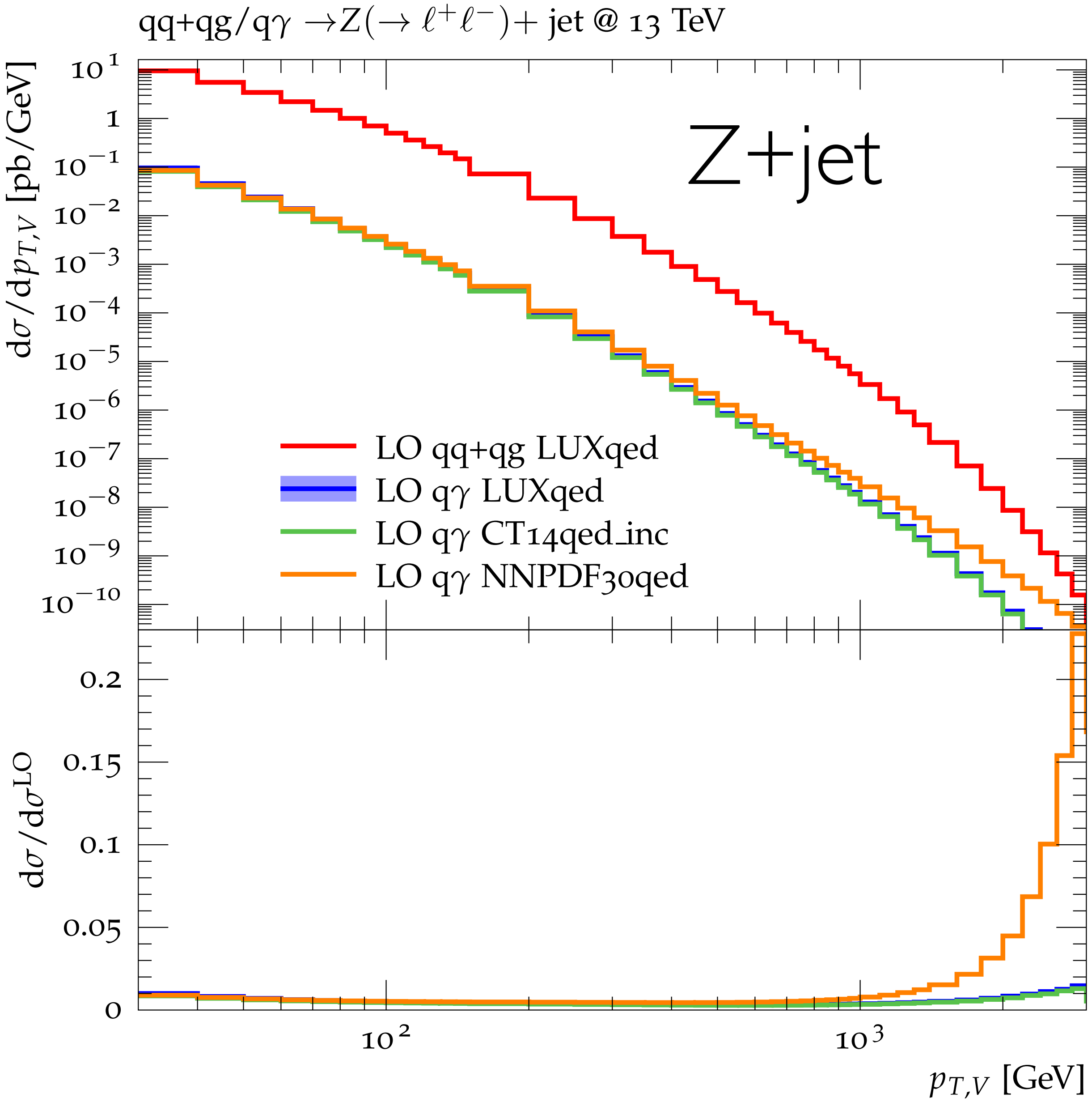
LUXqed

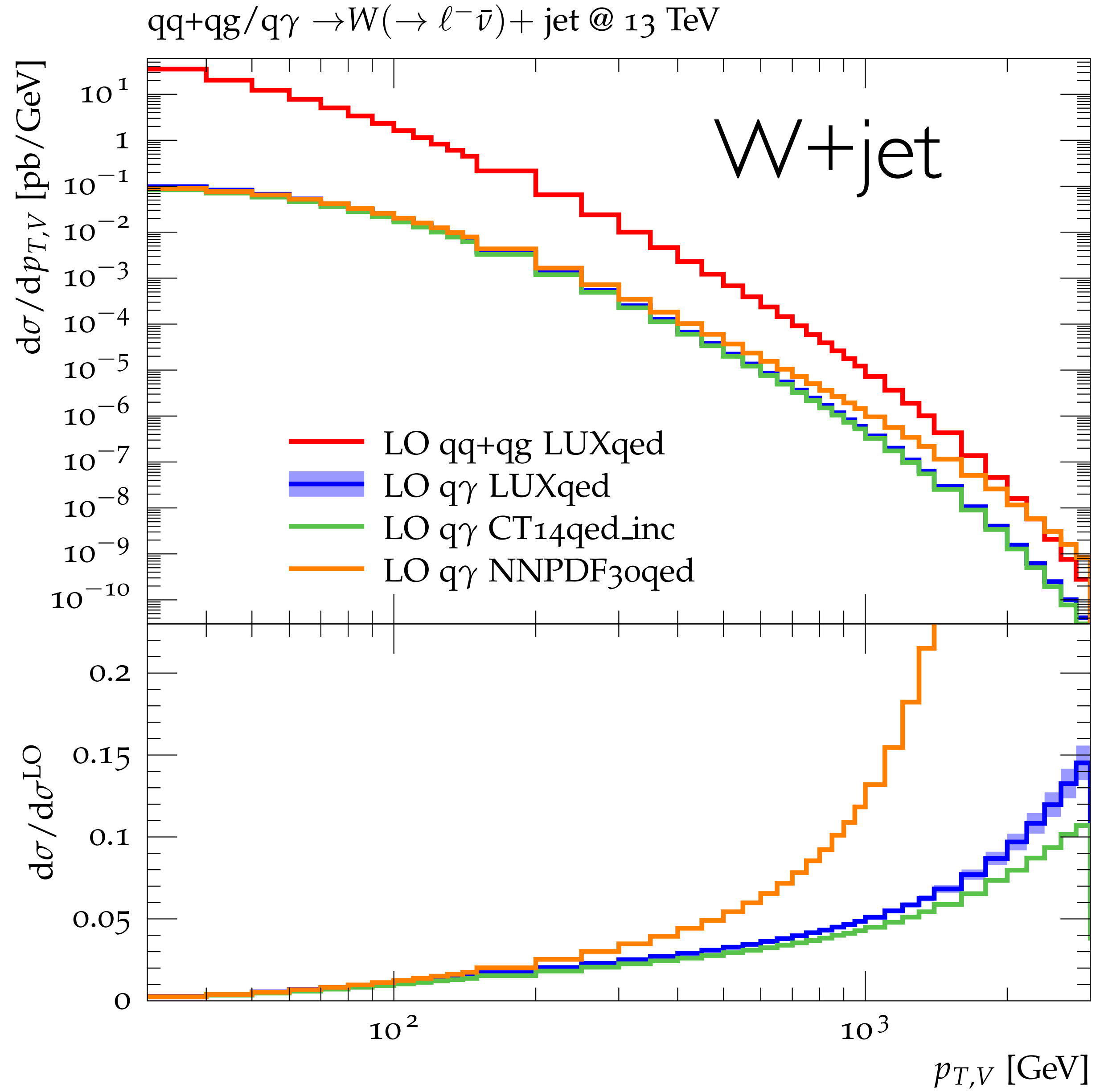




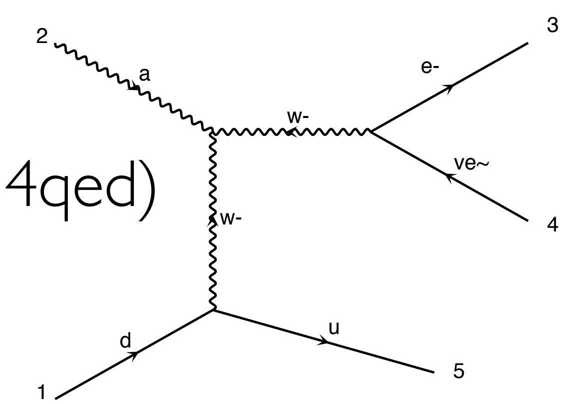
[Manohar, Nason, Salam, Zanderighi, '16]

Photon-induced production

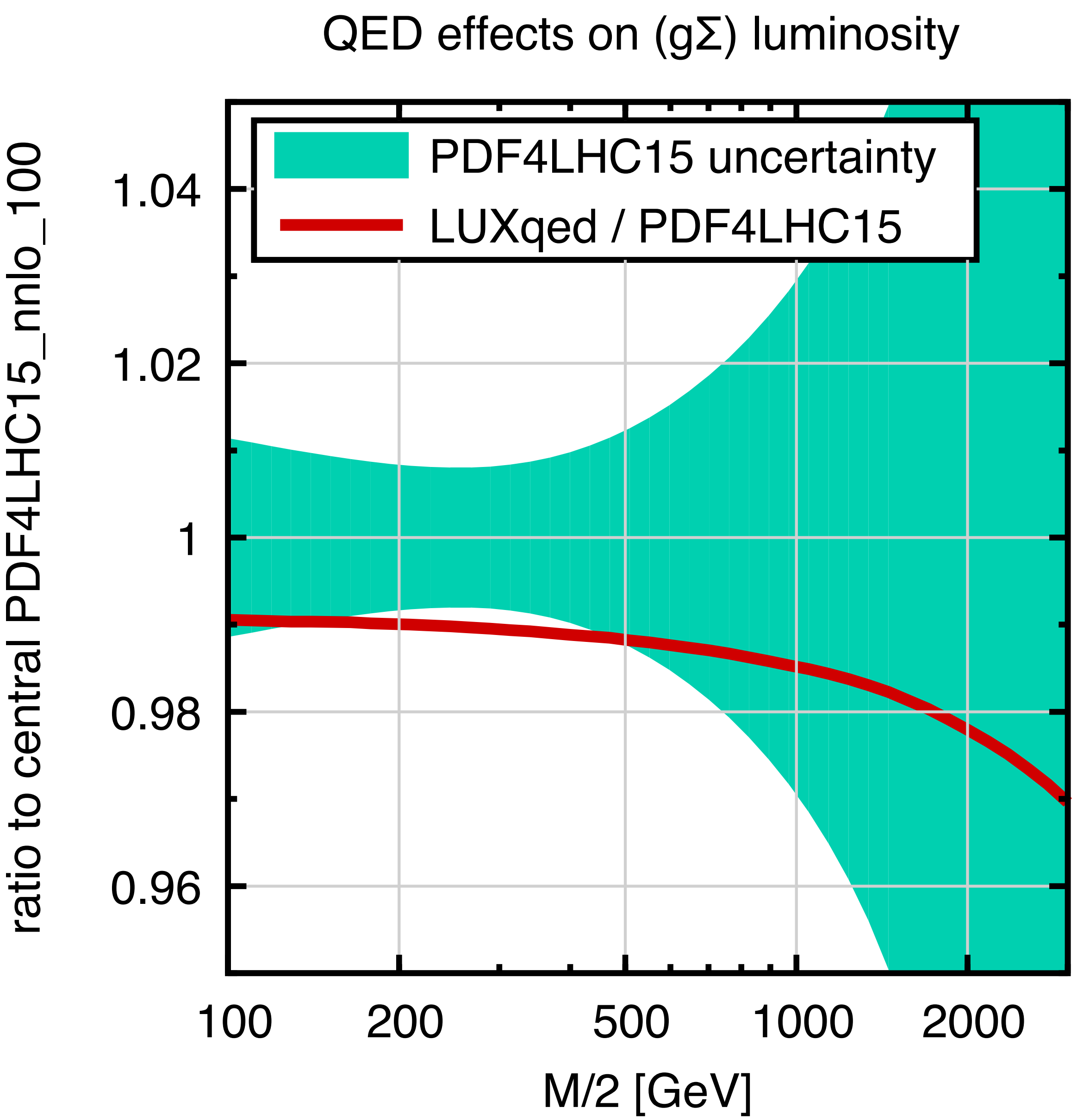


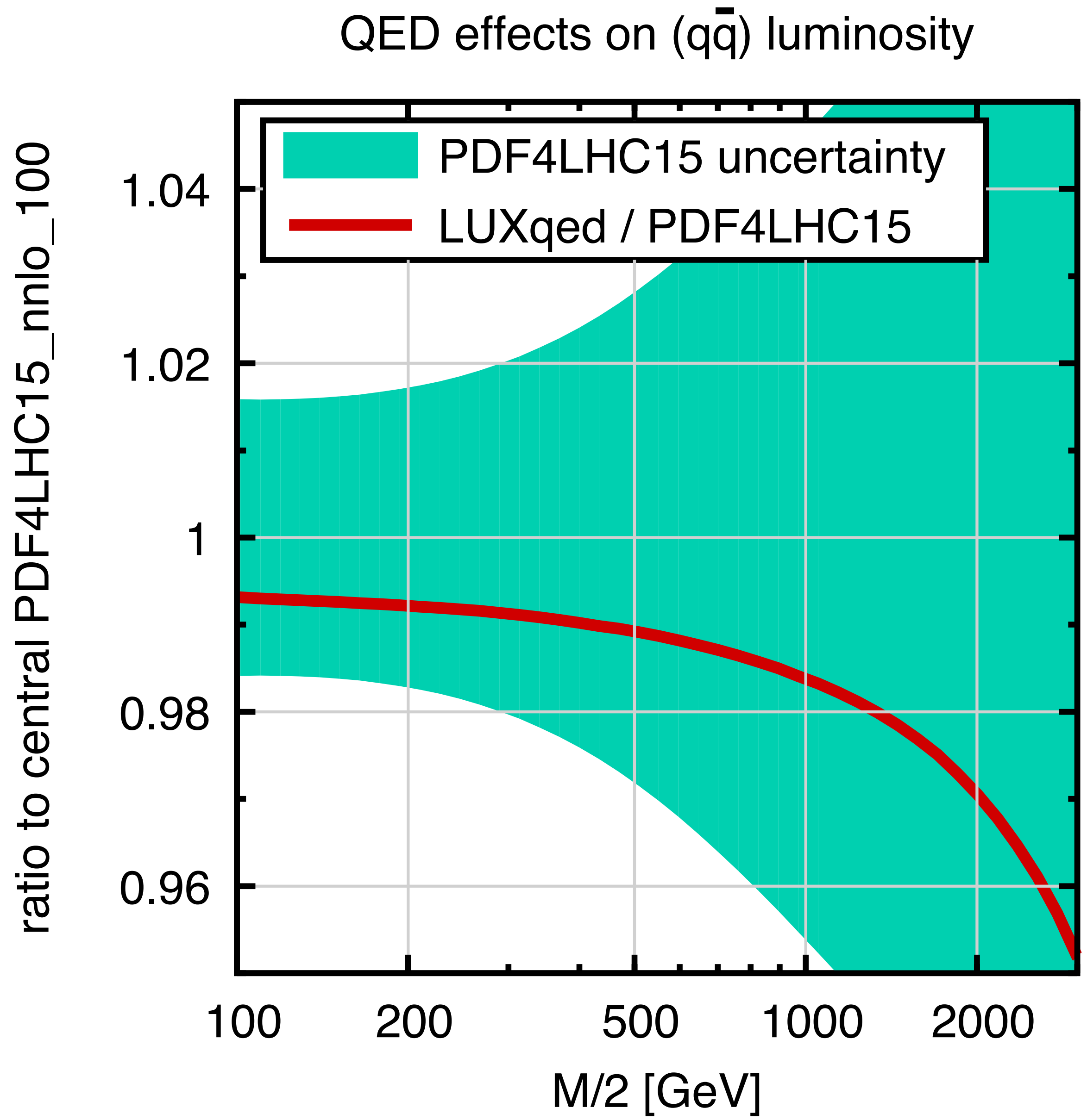


- photon-induced production irrelevant for Z+jet (and γ+jet)
- in W+jet O(5%) contribution with LUXqed (consistent with CT14qed) (due to t-channel enhancement)
- ~1% uncertainties in photon PDFs due to LUXqed



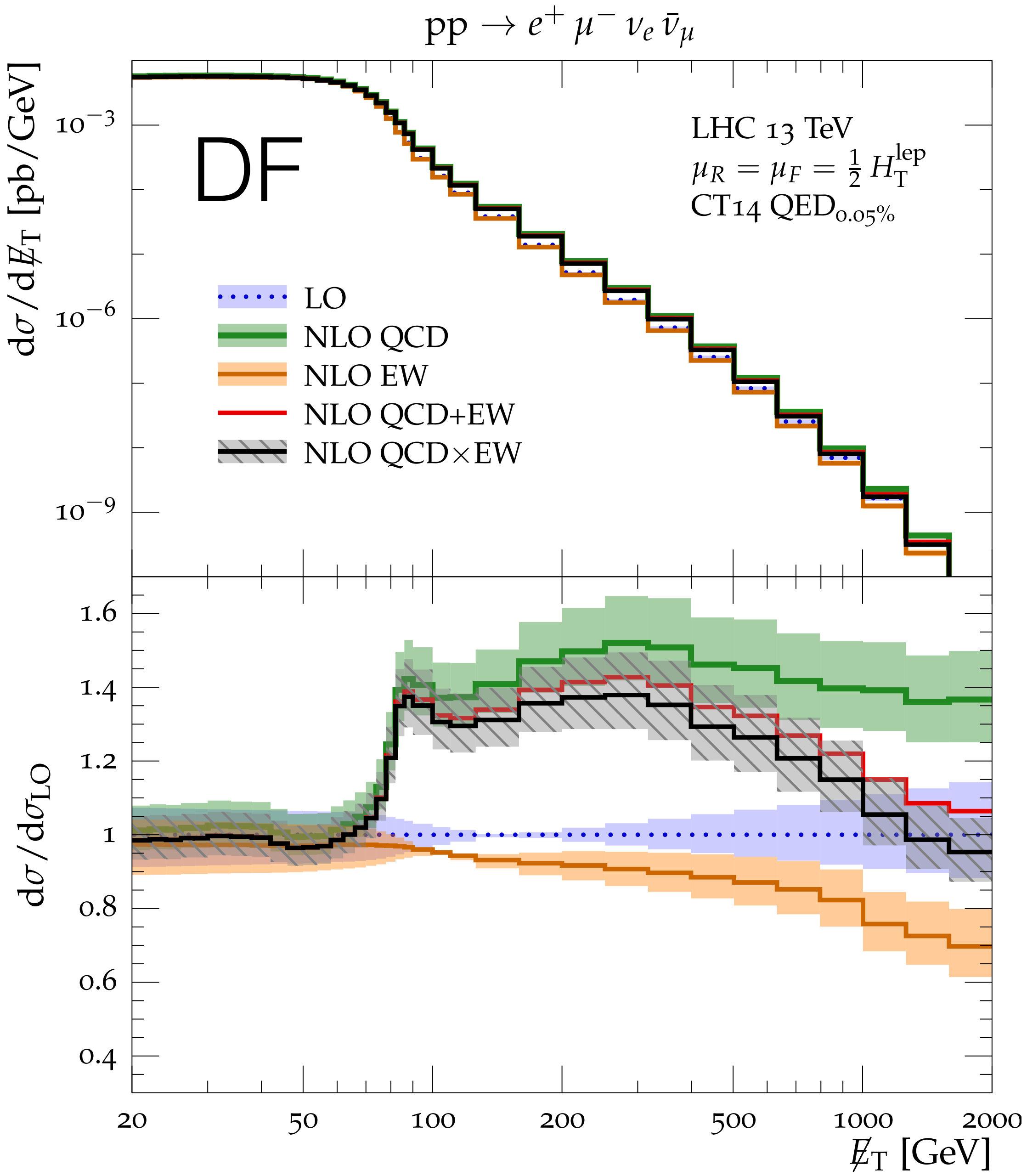
PDFs

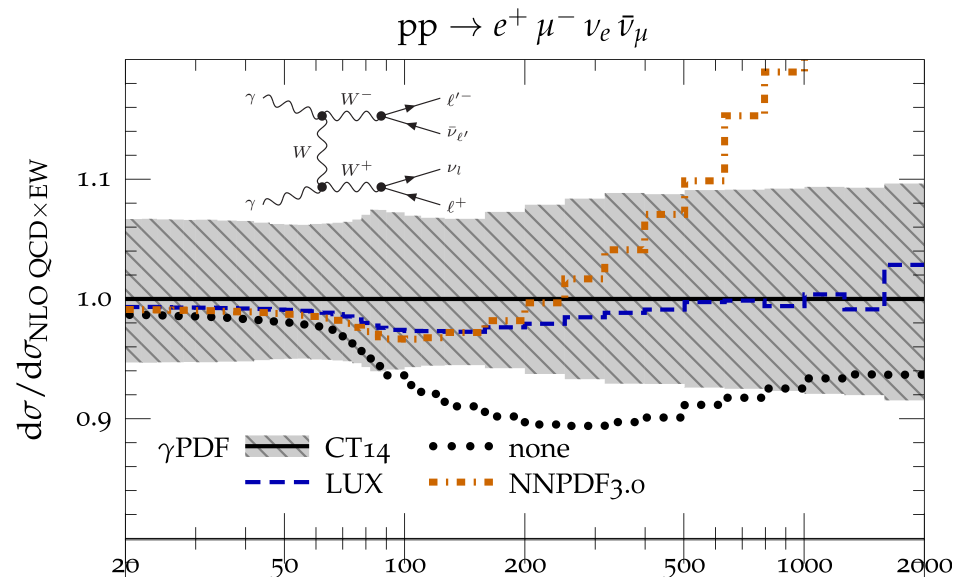


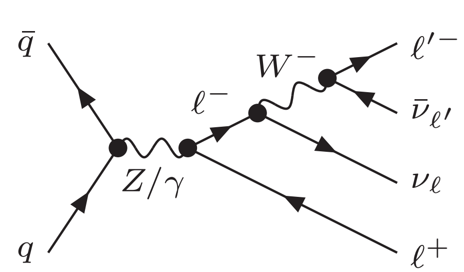


- small percent-level QED effects on qg/qq luminosities (included via LUXqed)
- 1.5-5% PDF uncertainties

VV at high energies: MET







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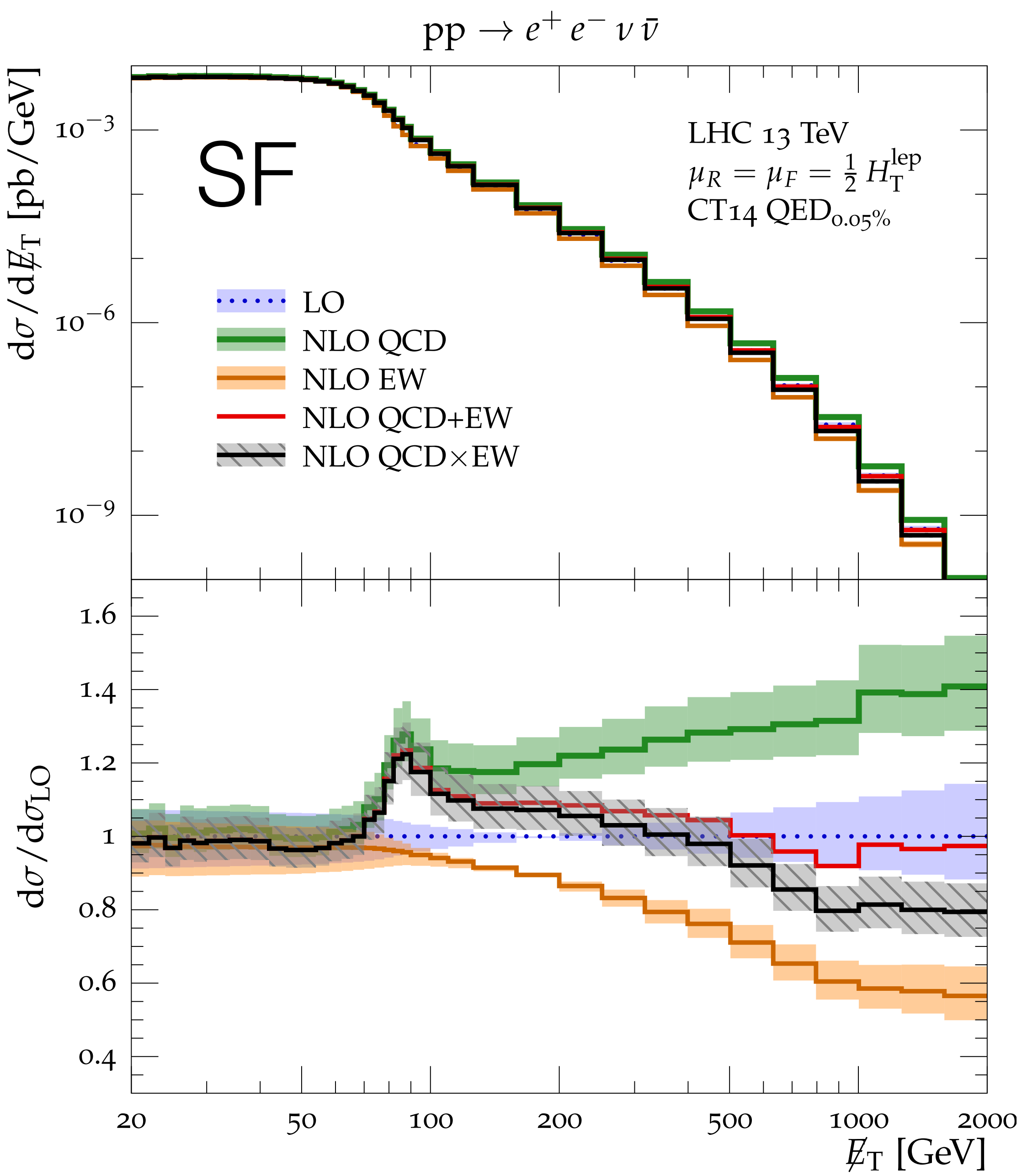
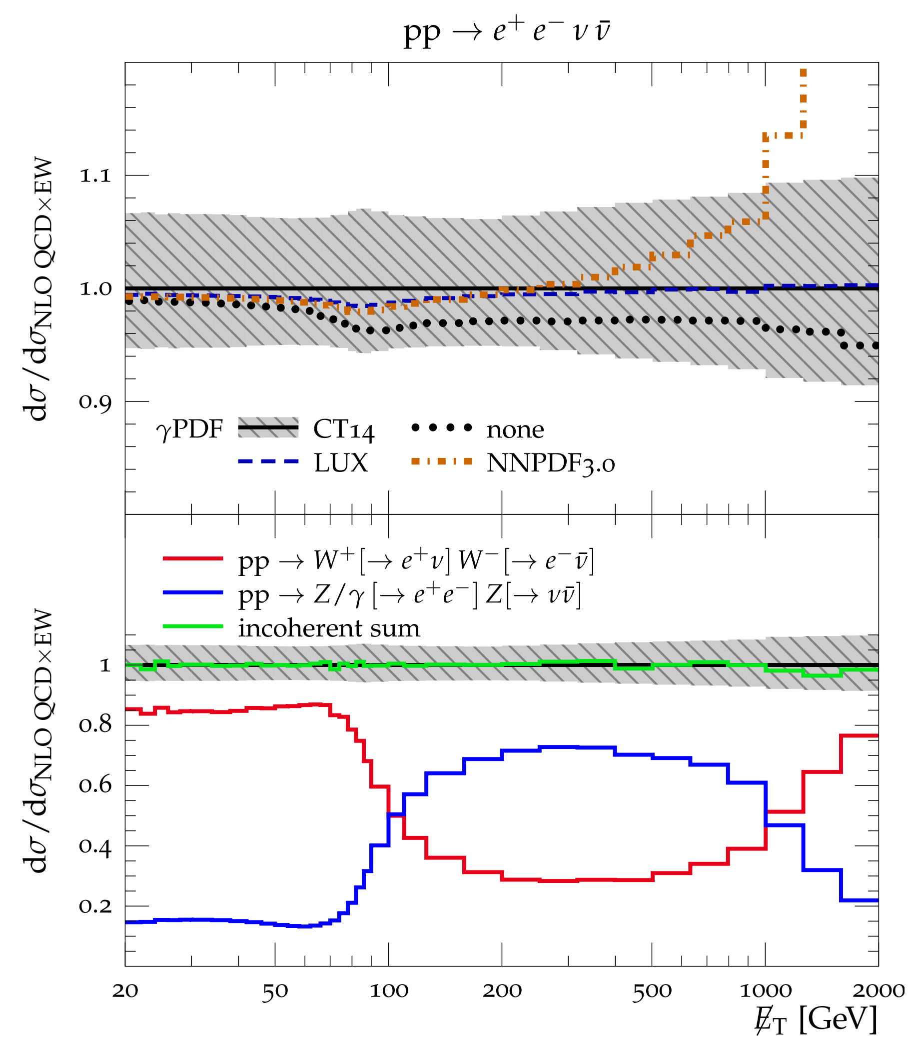
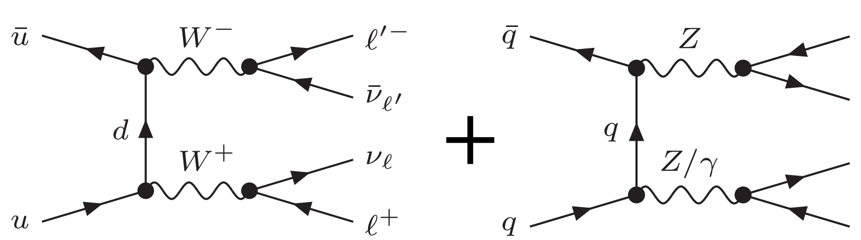
VV at high energies: MET







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