V+jets pT-ratios at NLO QCD+EW

Universität Zürich[UZH]

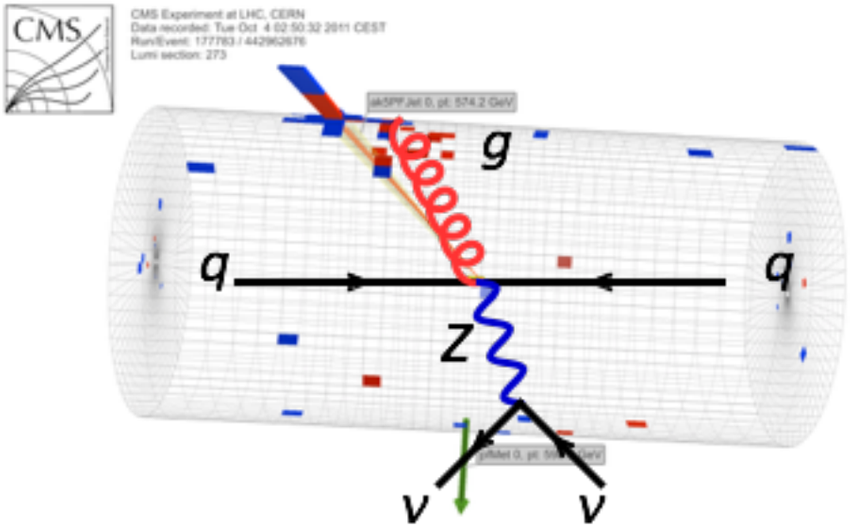
Jonas M. Lindert

work in collaboration with:

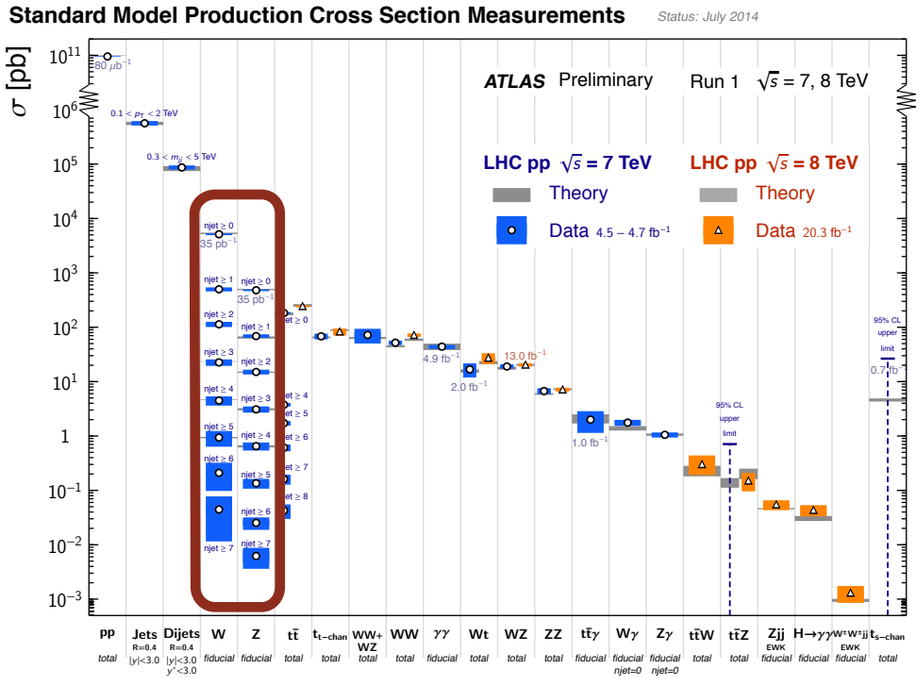
S. Kallweit, P. Maierhöfer, S. Pozzorini, M. Schönherr

Les Houches, 2015

Motivation: V + multijet production



- Z(→νν̄)+jets **irreducible background for monojet** Dark Matter searches
- can be determined from γ+jets and/or W+jets measurements together with *theoretical predictions* for Z+jets/γ+jets and Z+jets/W+jets ratios



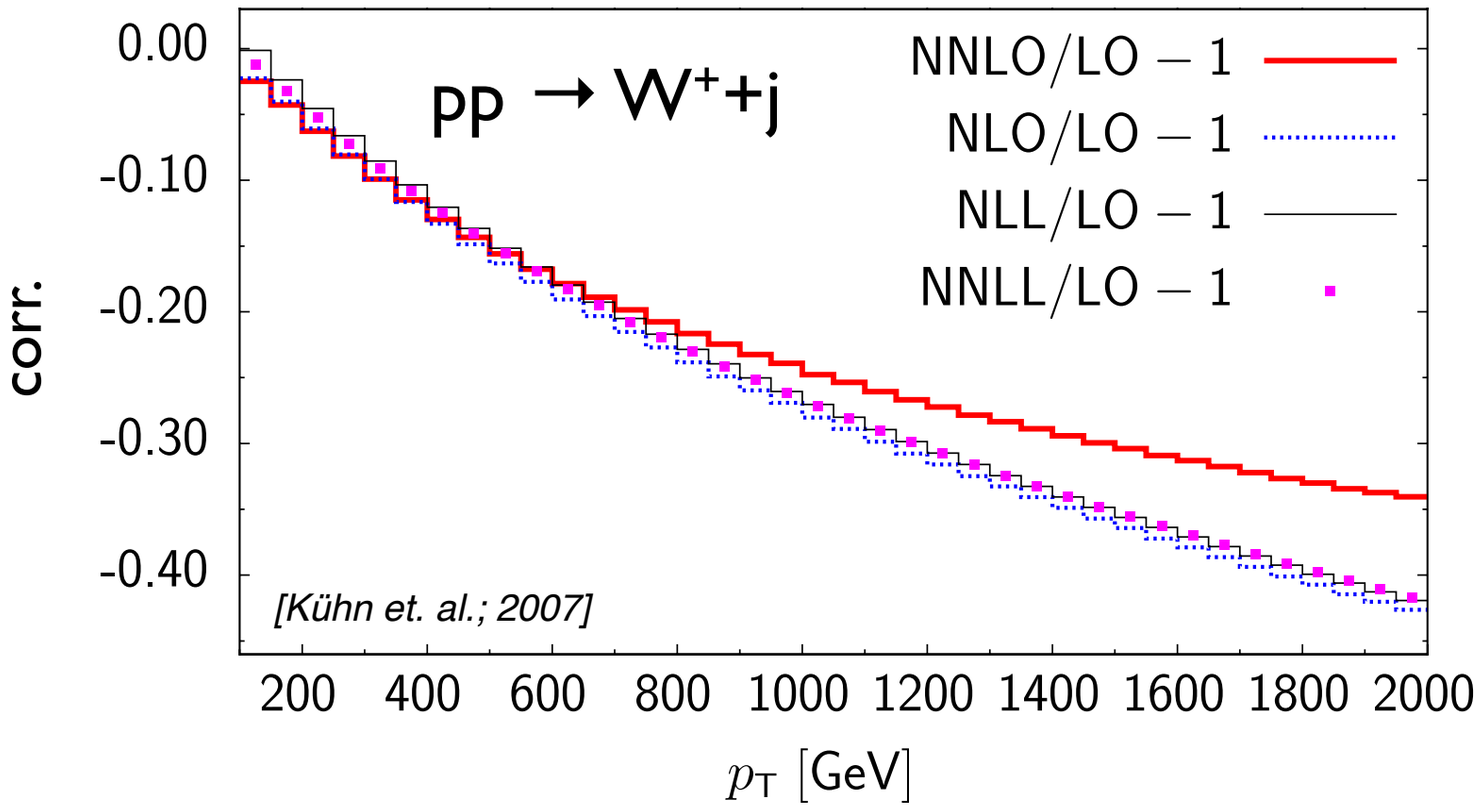
- Large cross-sections and clean leptonic signatures
- Precision QCD at LHC
- Playground to probe different aspects of higher-order calculations
(LO+PS, NLO+PS, NLO-Merging, NLO EW,…)

Why EW corrections?

- Formally suppressed by α/α_s with respect to QCD and 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):
  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]



Automation of NLO QCD

$$\sigma^{\mathrm{NLO}} = \int d\Phi_B \left(B + V + I\right) + \int d\Phi_R \left(R - S\right)$$

OpenLoops

[Cascioli, JML, Pozzorini]

Monte-Carlo-Framework:

Sherpa

[Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert, Winter et. al.]

MUNICH

[Kallweit]

POWHEG-BOX

[Alioli, Nason, Oleari, Re, et. al.]

Herwig++/Matchbox

[Bellm, Gieseke, Grellscheid, Papaefstathiou, Plätzer, Richardson, Seymour, Siodmok et al.]

OpenLoops with NLO QCD is publicly available at

`http://openloops.hepforge.org`

Automation of NLO QCD+EW

$$\sigma^{\mathrm{NLO}} = \int d\Phi_B \left(B + V + I\right) + \int d\Phi_R \left(R - S\right)$$

OpenLoops

[Cascioli, JML, Pozzorini]

Monte-Carlo-Framework:

Sherpa

[Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert, Winter et. al.]

MUNICH

[Kallweit]

POWHEG-BOX

[Alioli, Nason, Oleari, Re, et. al.]

Herwig++/Matchbox

[Bellm, Gieseke, Grellscheid, Papaefstathiou, Plätzer, Richardson, Seymour, Siodmok et al.]

- NLO corrections in the full SM (QCD & EW) are implemented in OpenLoops together with Sherpa and MUNICH (will be included in upcoming public releases)
- missing: PS matching & merging

Combination of NLO QCD and EW & Setup

Two alternatives:

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

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

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:

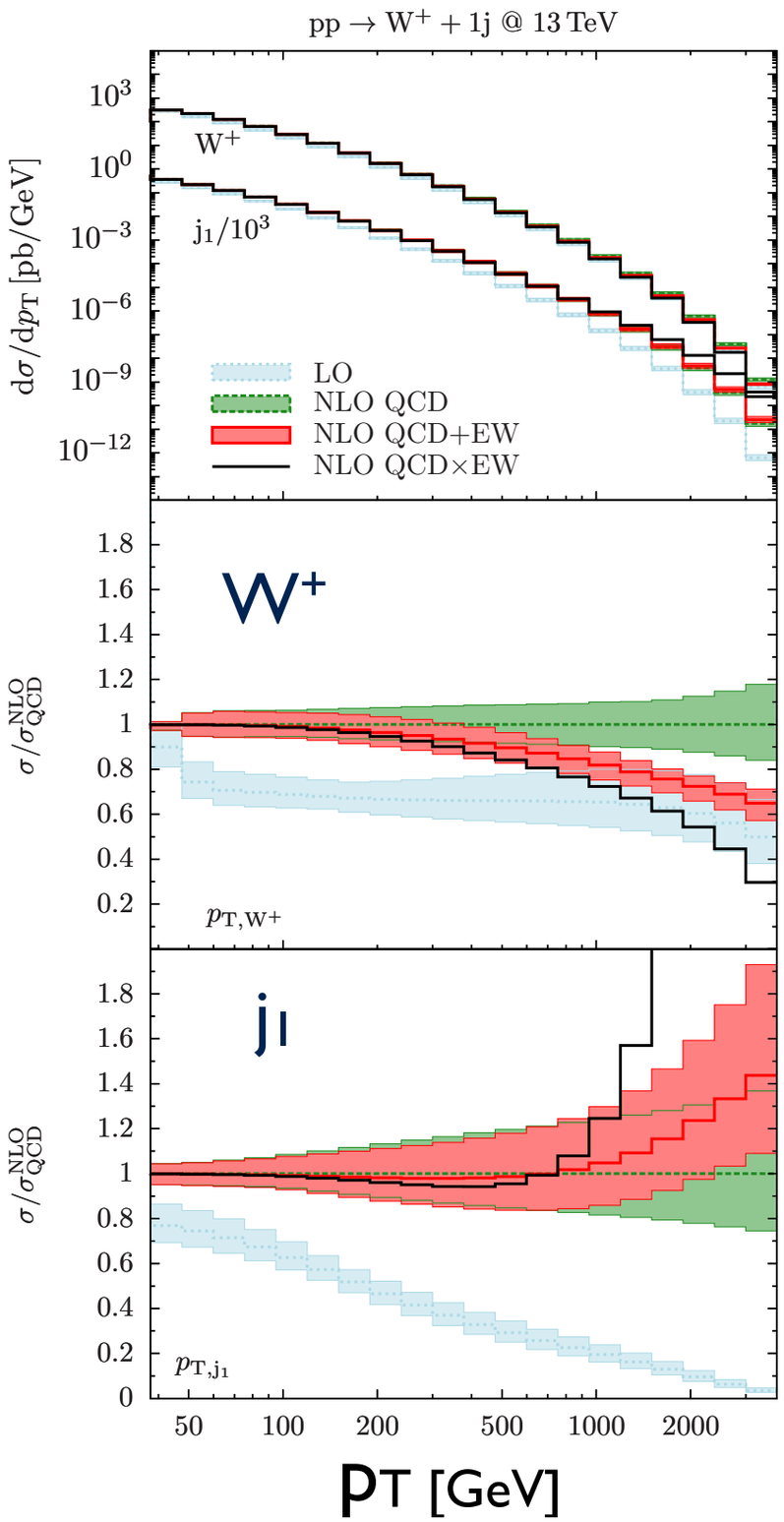
$$\frac{\sigma^{\mathrm{NLO}}_{\mathrm{QCD+EW}}}{\sigma^{\mathrm{NLO}}_{\mathrm{QCD}}} = \left(1 + \frac{\delta\sigma^{\mathrm{NLO}}_{\mathrm{EW}}}{\sigma^{\mathrm{NLO}}_{\mathrm{QCD}}}\right)$$ suppressed by large NLO QCD corrections

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

- $\alpha = \frac{\sqrt{2}}{\pi} G_\mu M^2_{\mathrm{W}} \left(1 - \frac{M^2_{\mathrm{W}}}{M^2_{\mathrm{Z}}}\right)$ in G_μ -scheme with $G_\mu = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$
- PDFs: NNPDF 2.3QED with $\alpha_{\mathrm{S}}(M_{\mathrm{Z}}) = 0.118$ for LO and NLO QCD/EW

V + 1 jet

$W^+ + 1$ jet: inclusive



Setup:

$\sqrt{S} = 13$ TeV

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

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

inclusive

≲ 1% EW corrections

p_T of W-boson

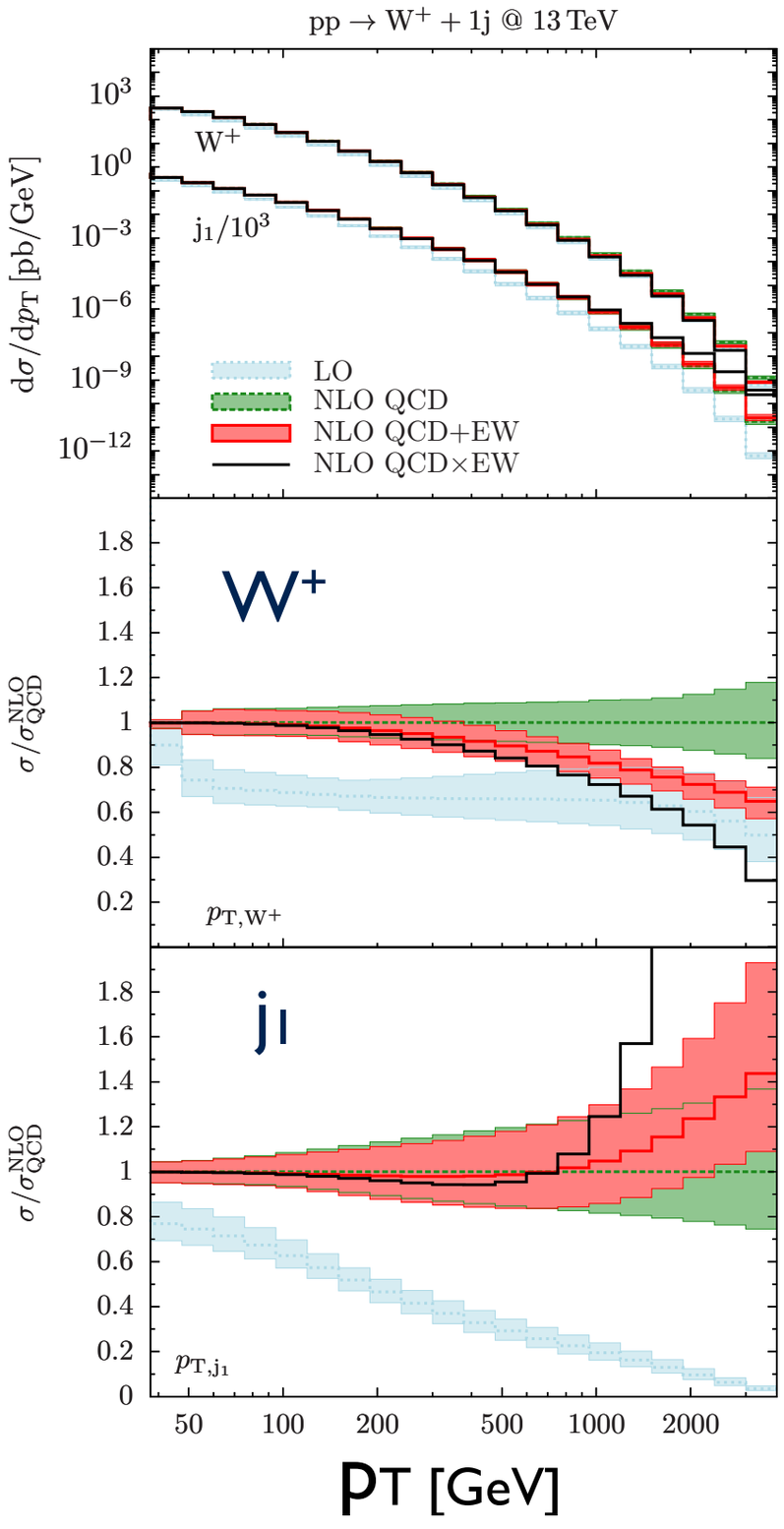
- +100 % QCD corrections in the tail
- large negative EW corrections due to **Sudakov behaviour:** -20–35% corrections at 1-4 TeV
- sizeable difference between QCD+EW and QCDxEW !

p_T of jet

- factor-10 NLO QCD corrections in the tail!
- dominated by **dijet configurations** (effectively LO)
- positive 10-50% EW corrections from quark bremsstrahlung

NNLO QCD: *[Boughezal, Focke, Liu, Petriello '15]*

$W^+ + 1$ jet: inclusive



Setup:

$\sqrt{S} = 13$ TeV

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

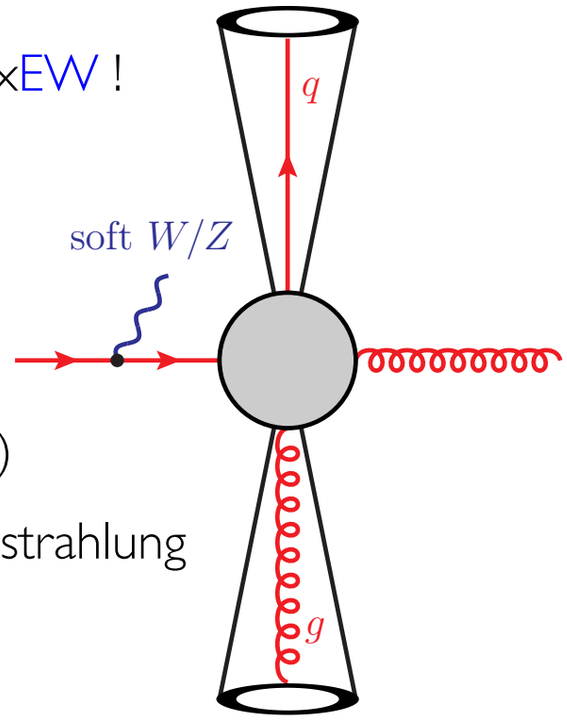
$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

inclusive

≲ 1% EW corrections

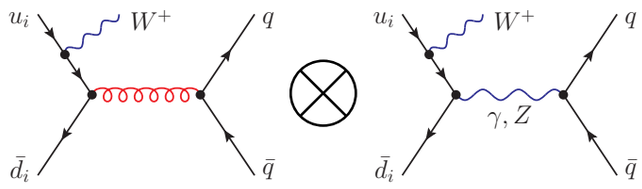
p_T of W-boson

- +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

- factor-10 NLO QCD corrections in the tail!
- dominated by **dijet configurations** (effectively LO)
- positive 10-50% EW corrections from quark bremsstrahlung

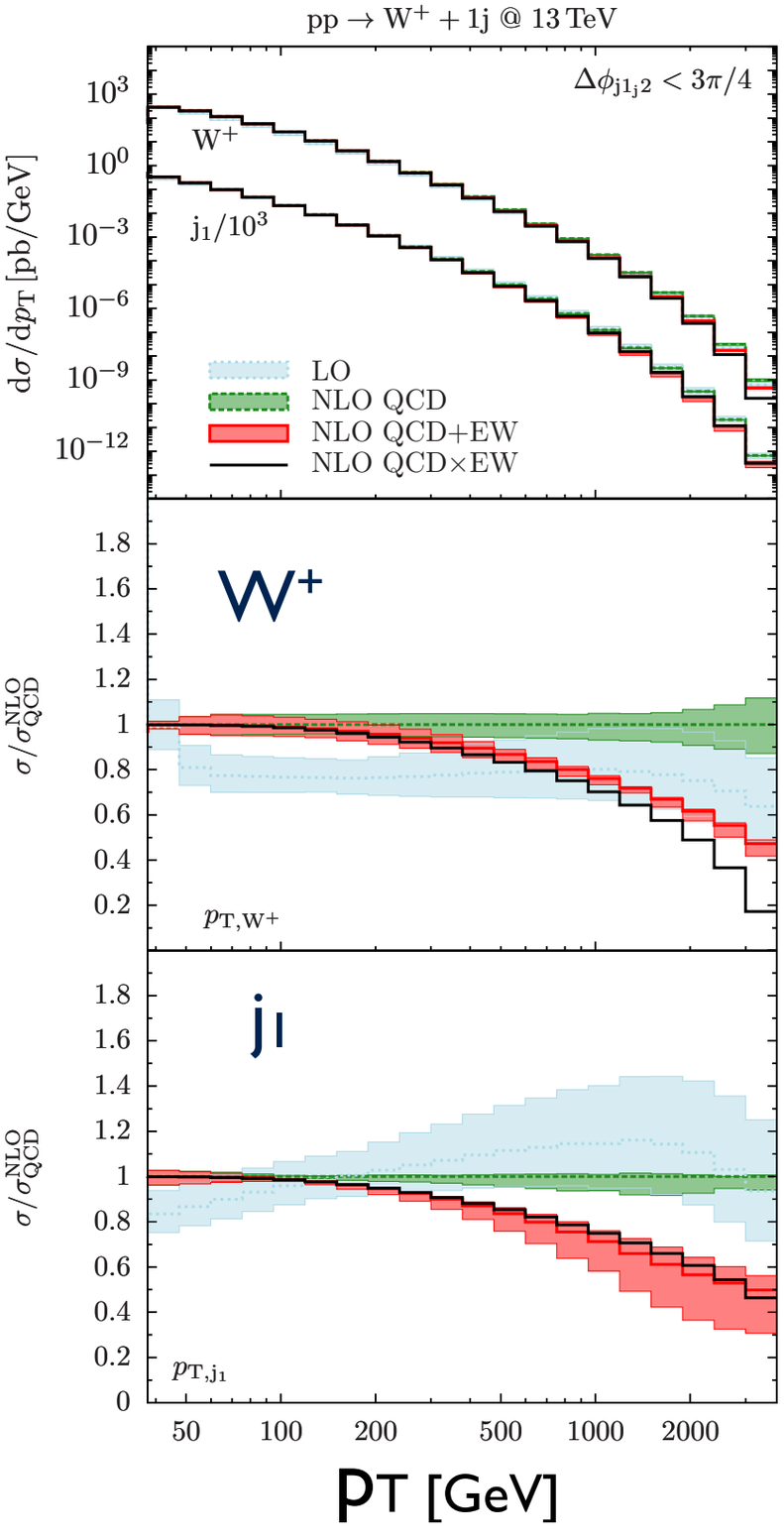


⟹ pathologic with large uncertainties!

W^+ + 1 jet: exclusive

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

(veto on dijet configurations)



Setup:

$\sqrt{S} = 13$ TeV

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

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

QCD corrections

- mostly moderate and stable QCD corrections

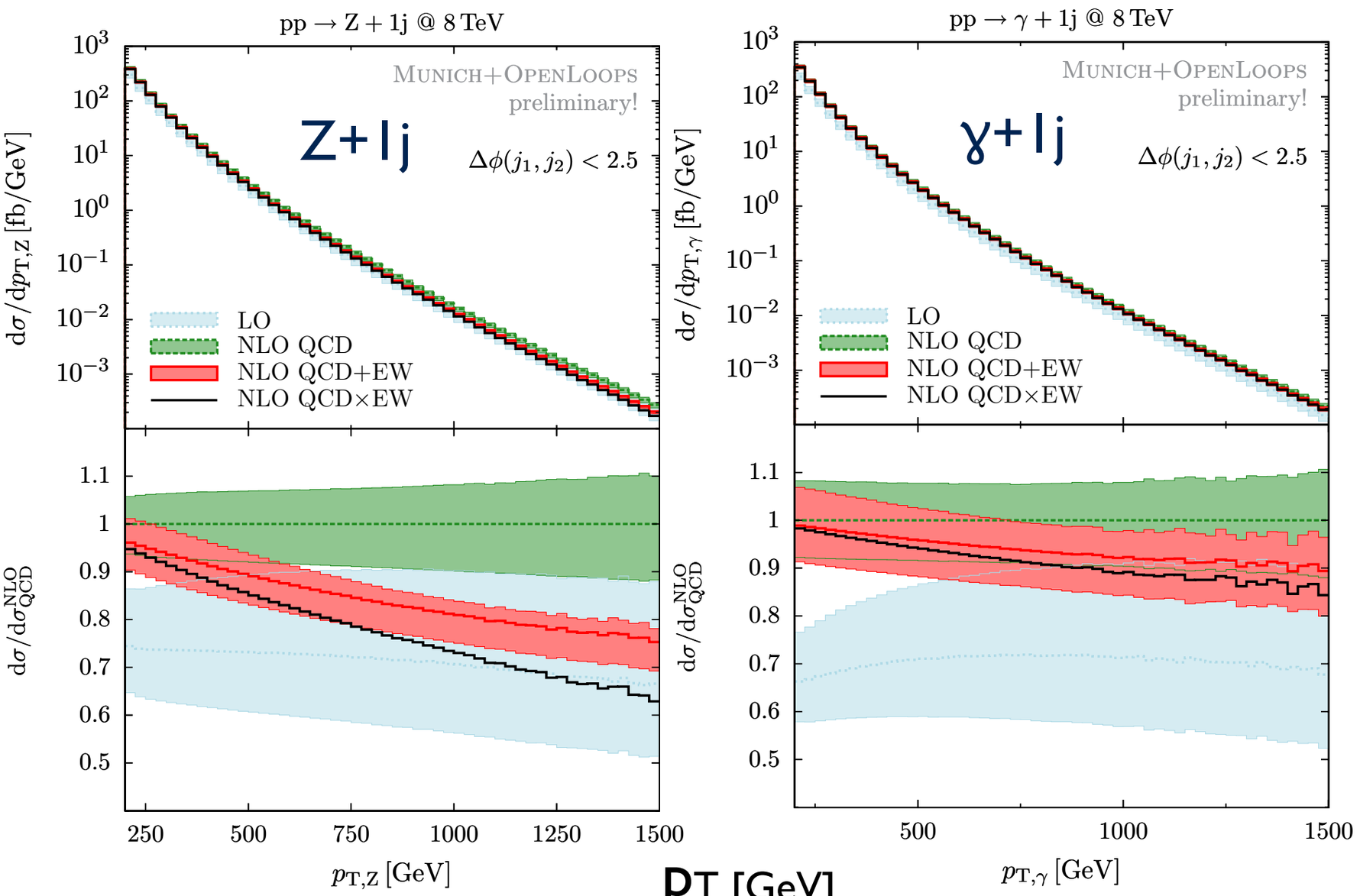
EW corrections

- **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

⟹ *exclusive* W+1jet ok!

⟹ *inclusive* W+1jet requires W+2 jets at NLO QCD+EW!

Z/γ + 1 jet: exclusive



PT [GeV]

Setup:

$\sqrt{S} = 8$ TeV

$p_{T,j} > 110$ GeV, $|\eta_j| < 2.4$

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

$\Delta\phi_{j1j2} < 2.5$

Frixione-Isolation with dR=0.3

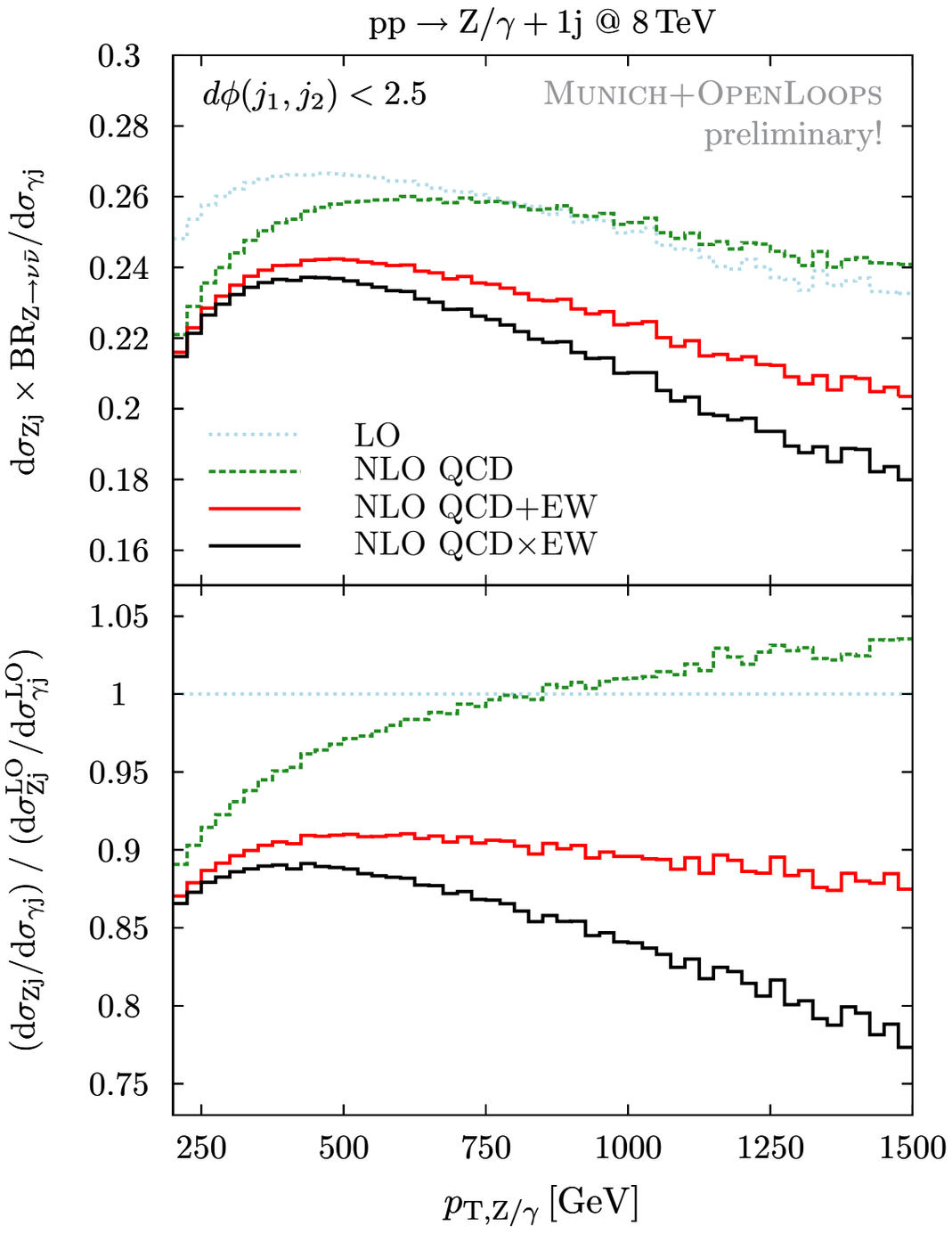
QCD corrections

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

Z/γ + 1 jet: pT-ratio



Overall

- mild dependence on the boson pT

QCD corrections

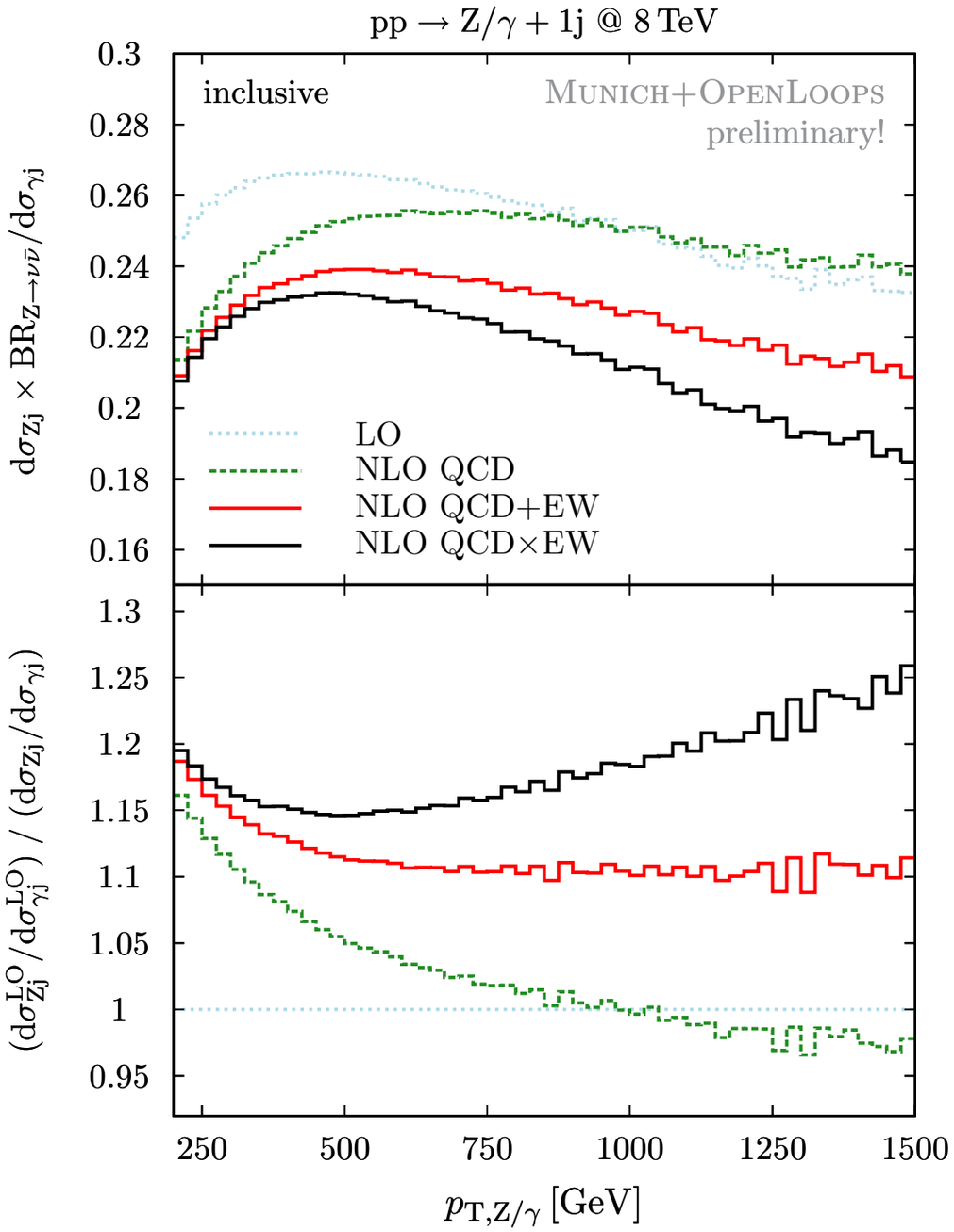
- ≲ 5% above 350 GeV

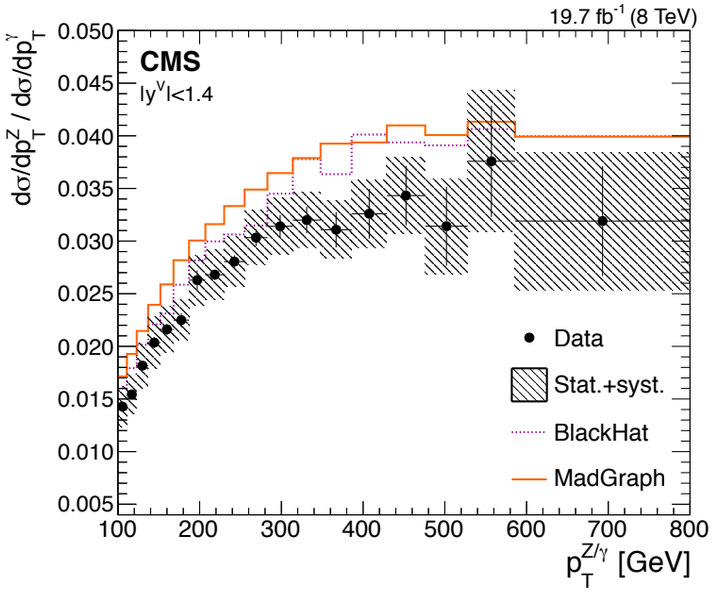
EW corrections

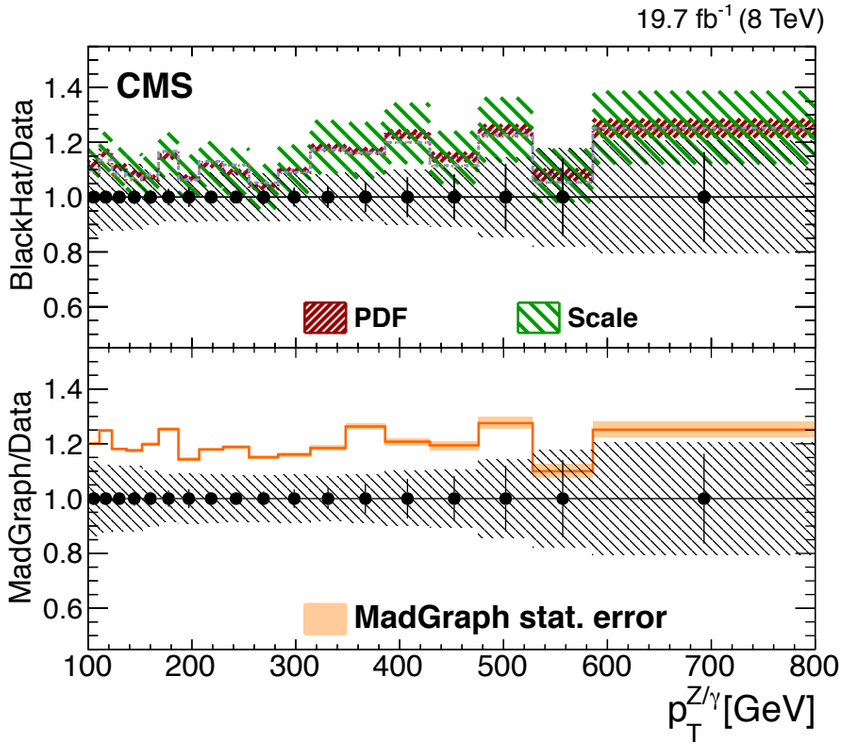
- result in an almost constant shift between LO and NLO QCD+EW of ~10-15%

Z/γ + 1 jet: pT-ratio

[CERN-PH-EP-2015-089]



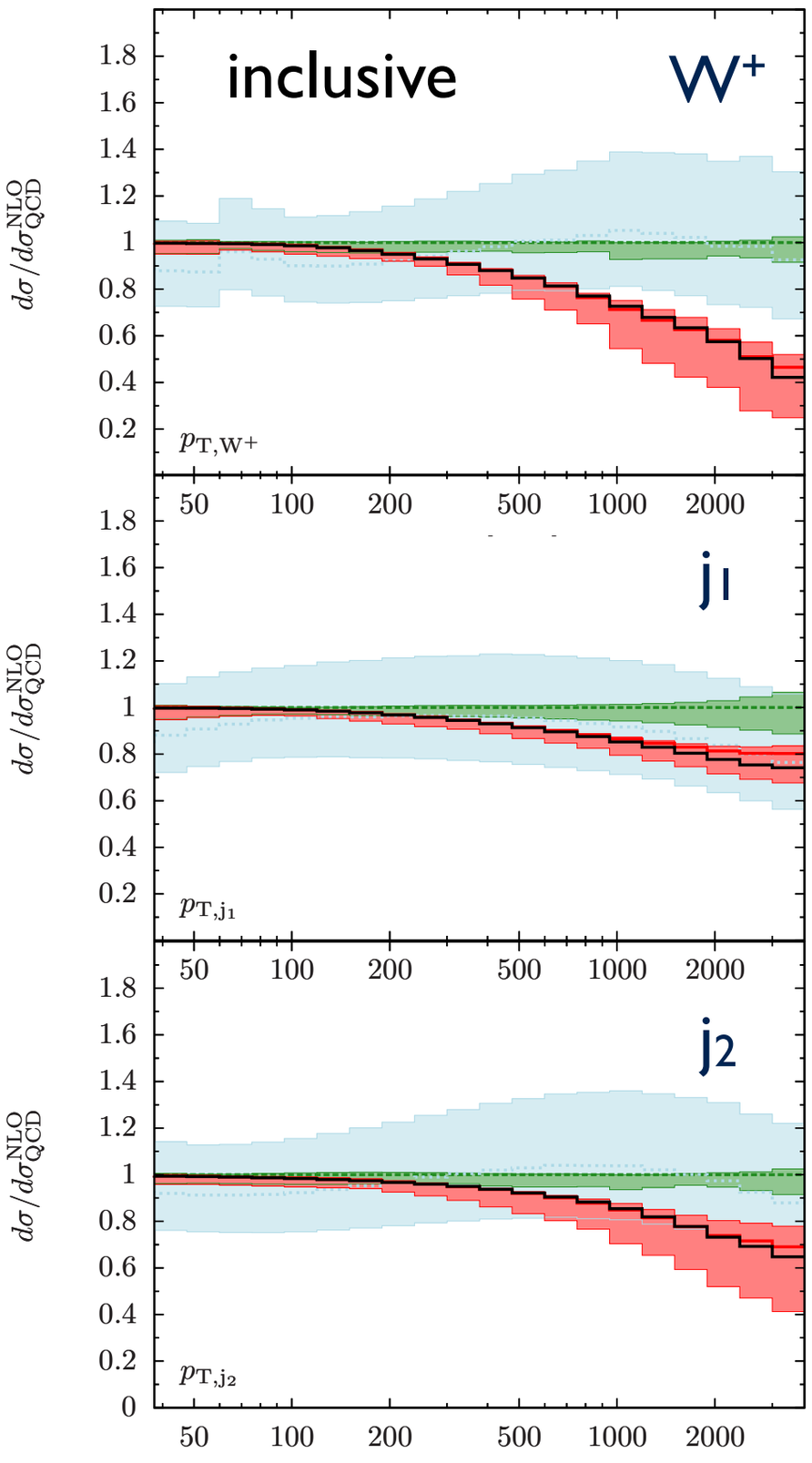


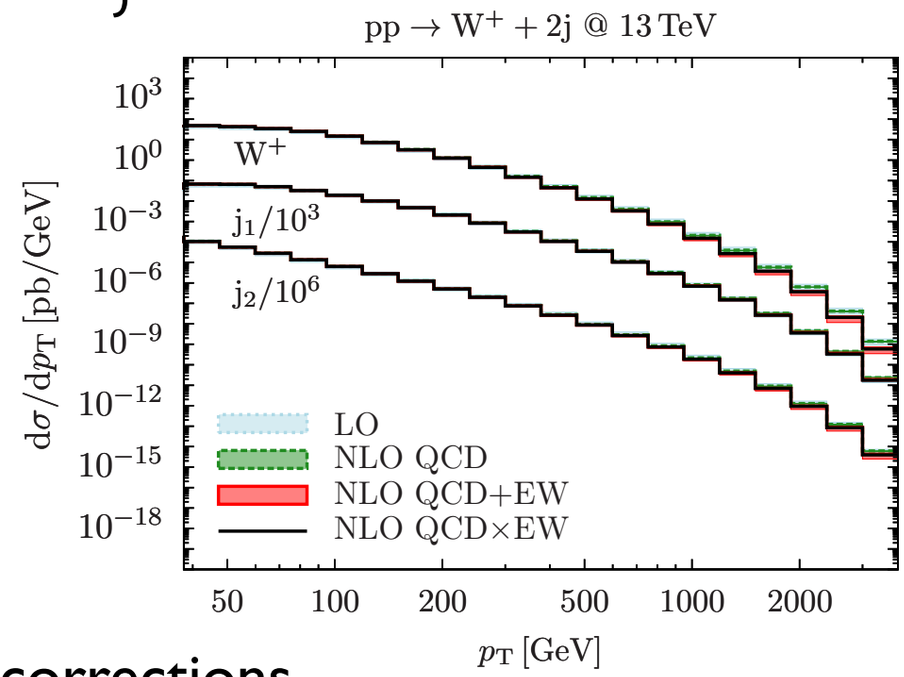


Note: fiducial regions not identical!

V + 2 jet

W^+ + 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