NLO QCD+EW for Dark Matter Backgrounds

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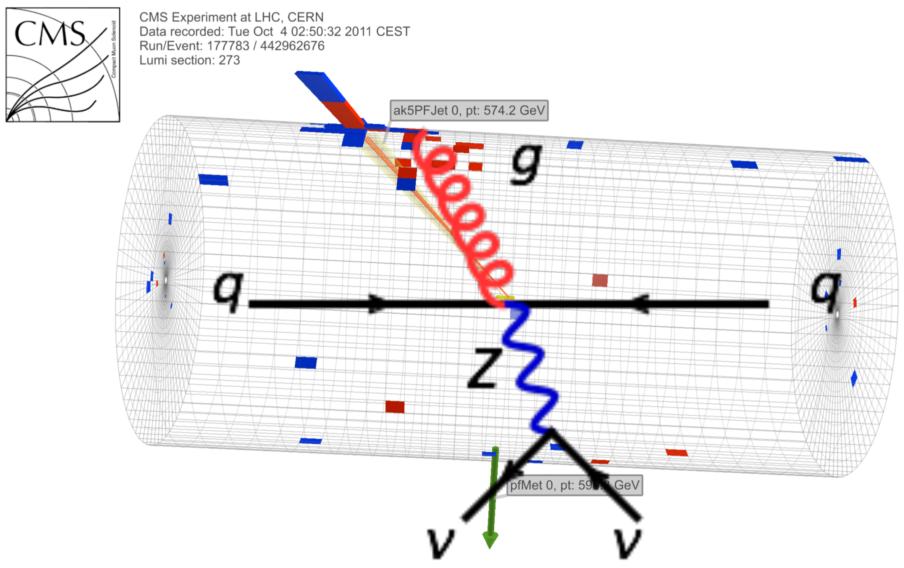
LHC Dark Matter WG, CERN, 20.09.2016

V+jets backgrounds in monojet/MET + jets searches



irreducible background:

pp→Z(→νν̄)+jets ⟹ MET + jets

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

- can be determined from Z(→ll̄)+jets, W(→lν̄)+jets or γ+jets measurements (combination!)

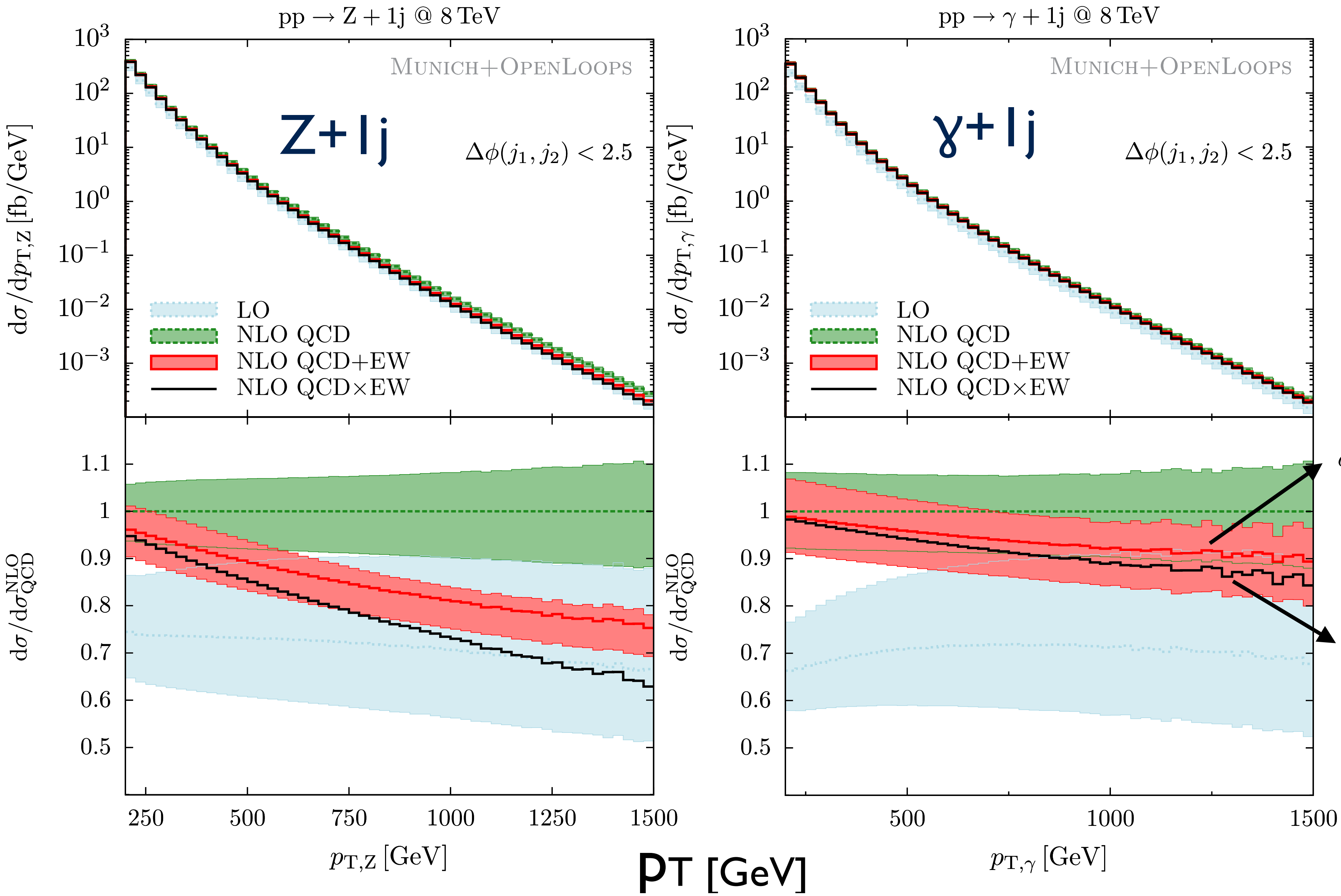
- hardly any systematics (just QED dressing)
- but: limited statistics at large pT

- fairly large data samples at large pT

- need theory input, i.e. predictions at (N)NLO QCD+NLO EW:

$$R_{ZZ}(\mathrm{d}p_\mathrm{T}) = \frac{\mathrm{d}\sigma(Z\to\nu\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}{\mathrm{d}\sigma(Z\to\ell\bar\ell+\mathrm{jets})/\mathrm{d}p_\mathrm{T}} \qquad R_{ZW}(\mathrm{d}p_\mathrm{T}) = \frac{\mathrm{d}\sigma(Z\to\nu\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}{\mathrm{d}\sigma(W\to\ell\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}} \qquad R_{Z\gamma}(\mathrm{d}p_\mathrm{T}) = \frac{\mathrm{d}\sigma(Z\to\nu\bar\nu+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}{\mathrm{d}\sigma(\gamma+\mathrm{jets})/\mathrm{d}p_\mathrm{T}}$$

Z/γ + 1 jet: exclusive



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

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

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

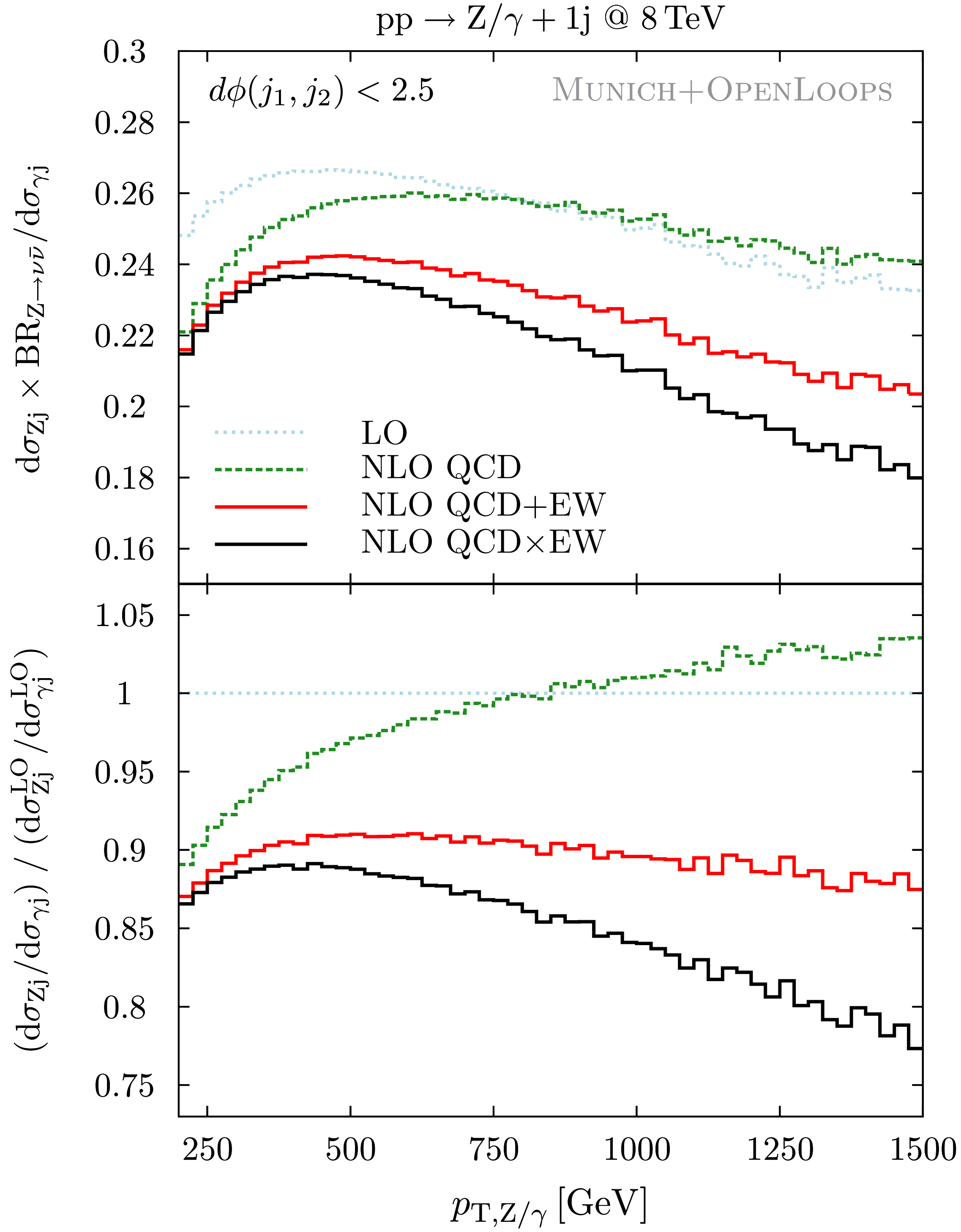
QCD corrections

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

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

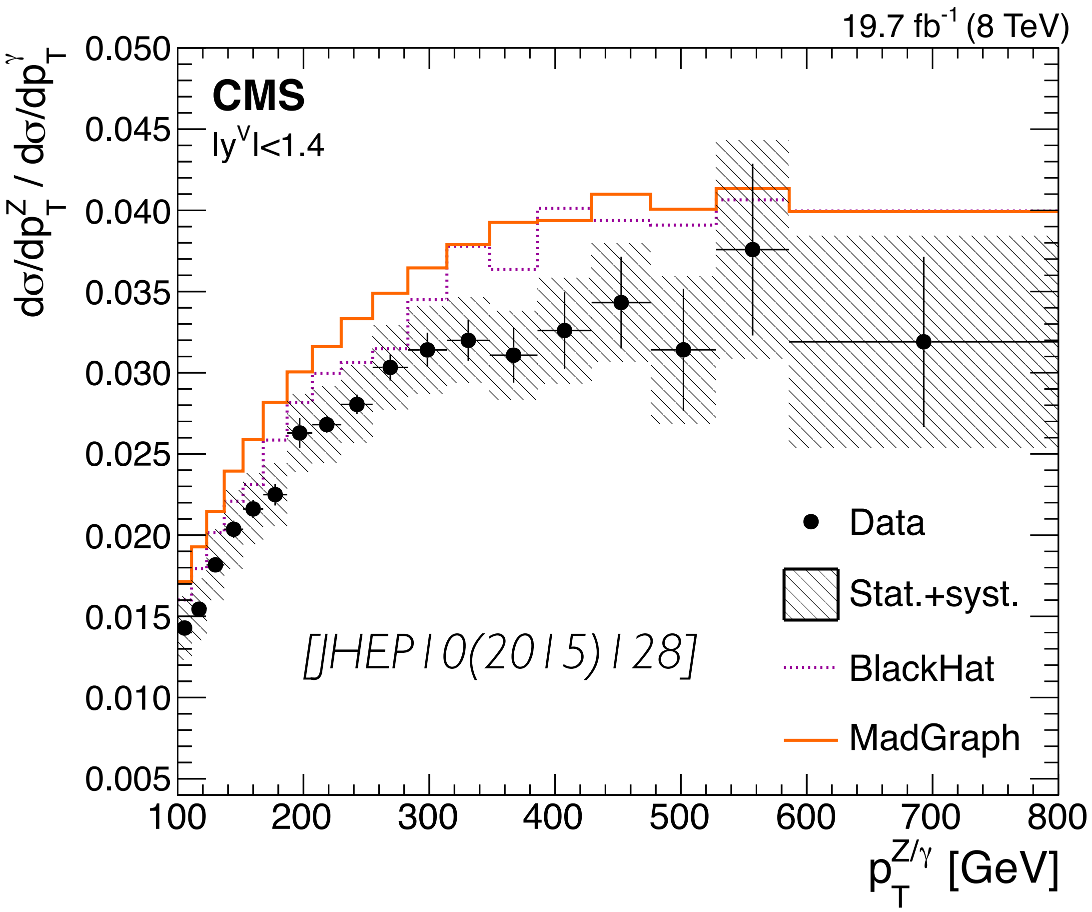
QCD corrections

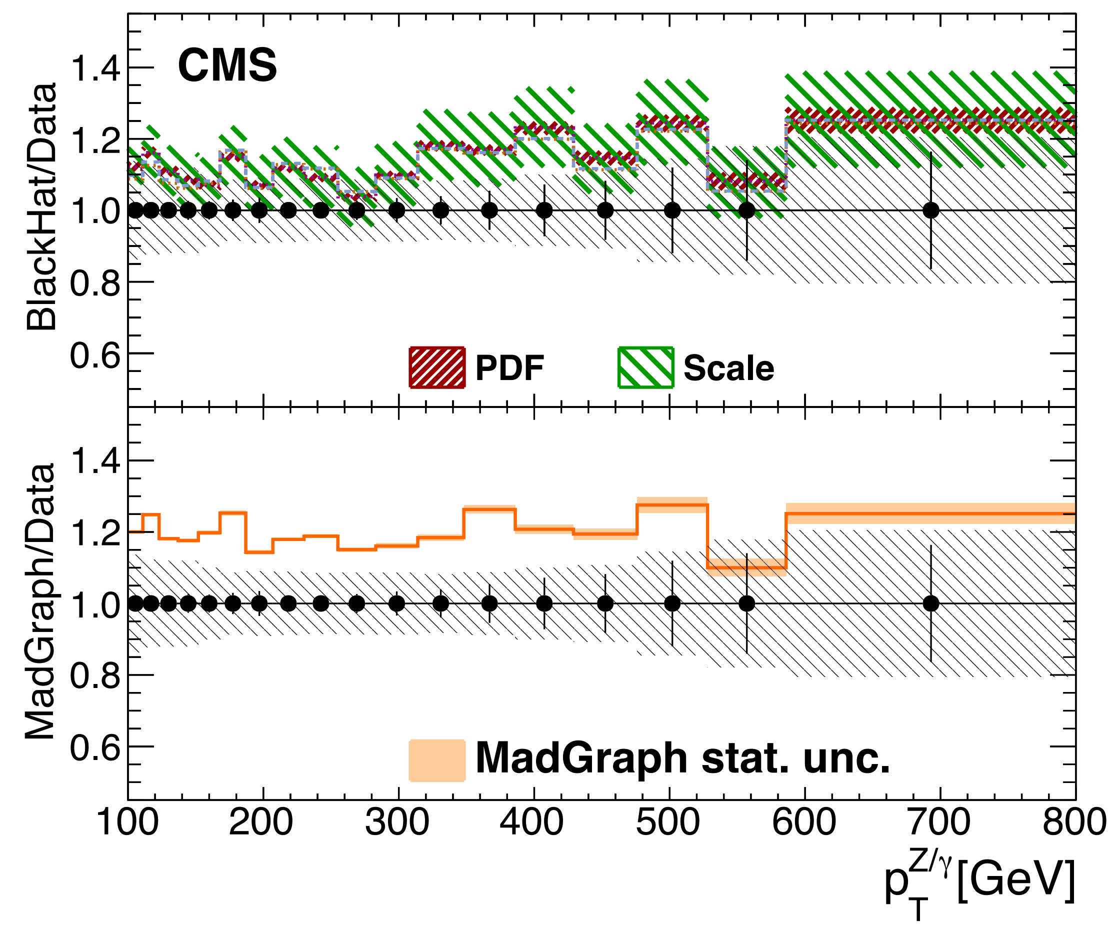
- 10-15% below 250 GeV
- ≲ 5% above 350 GeV

EW corrections

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

Compare against data



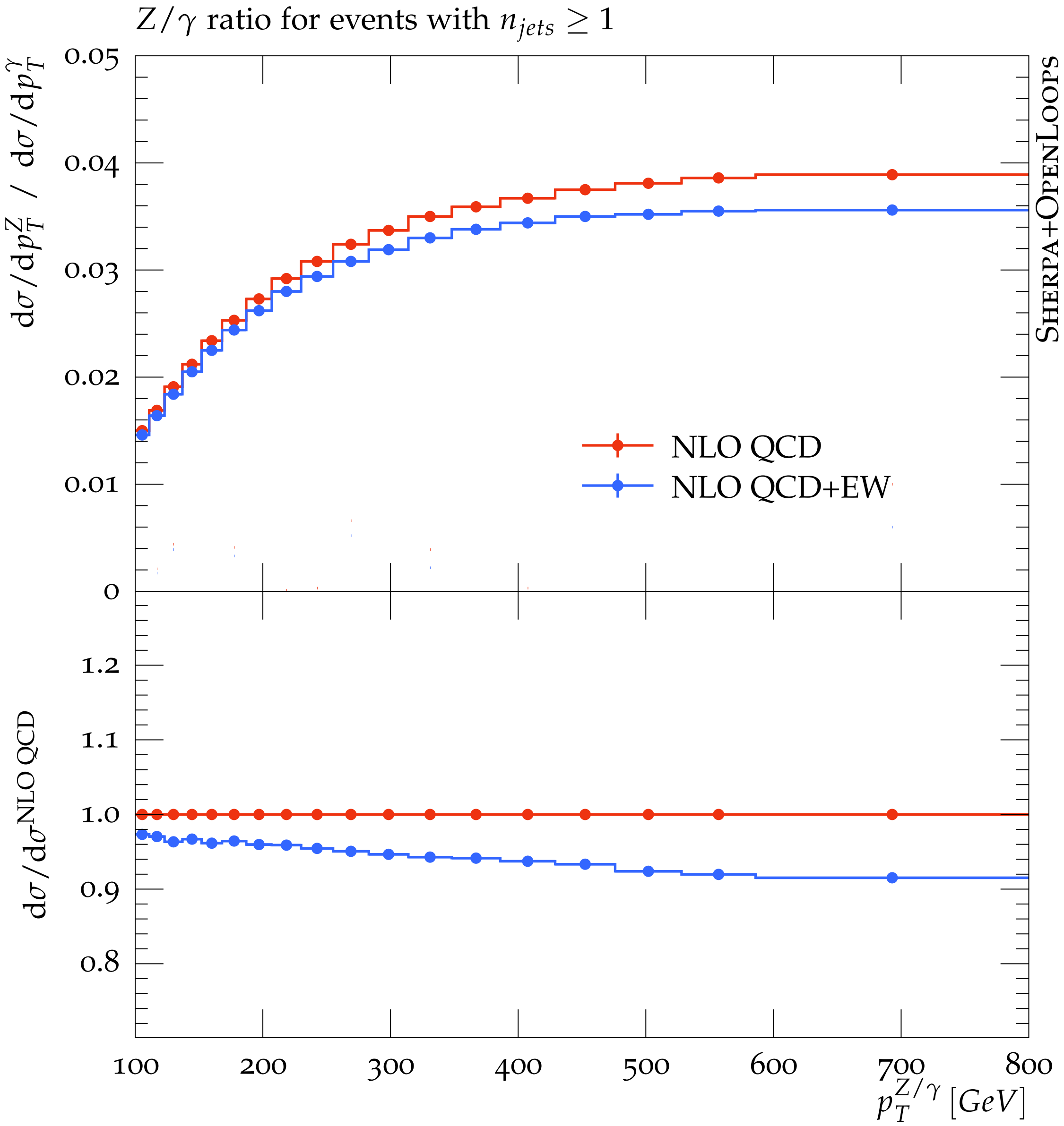


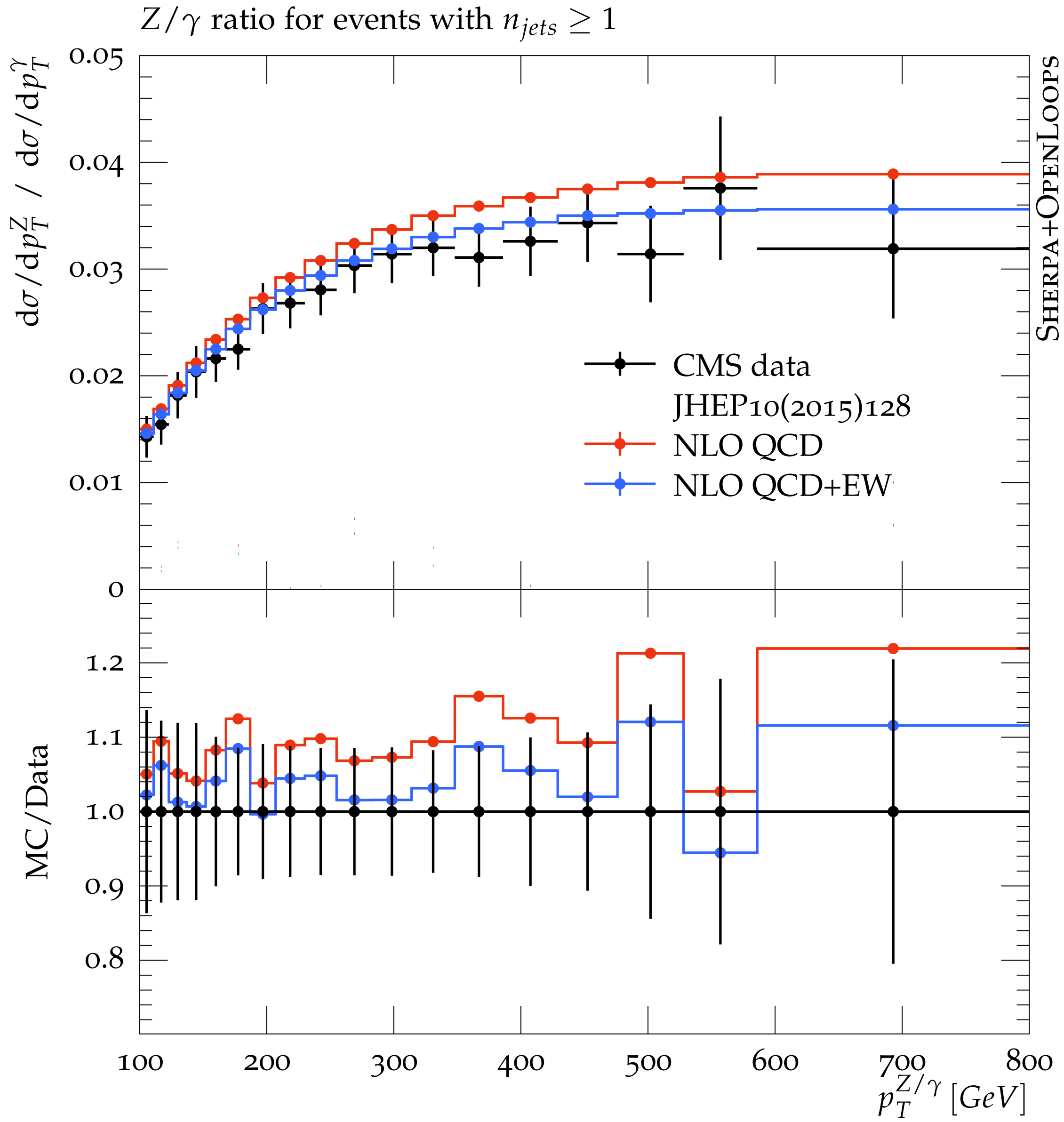
- constant off-set with respect to LO
- improved agreement at NLO QCD for small pT

Compare against data

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

"a Frixione cone with these choices mimics the selections in the true on-shell photon definition at particle level" *[JHEP10(2015)128]*





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

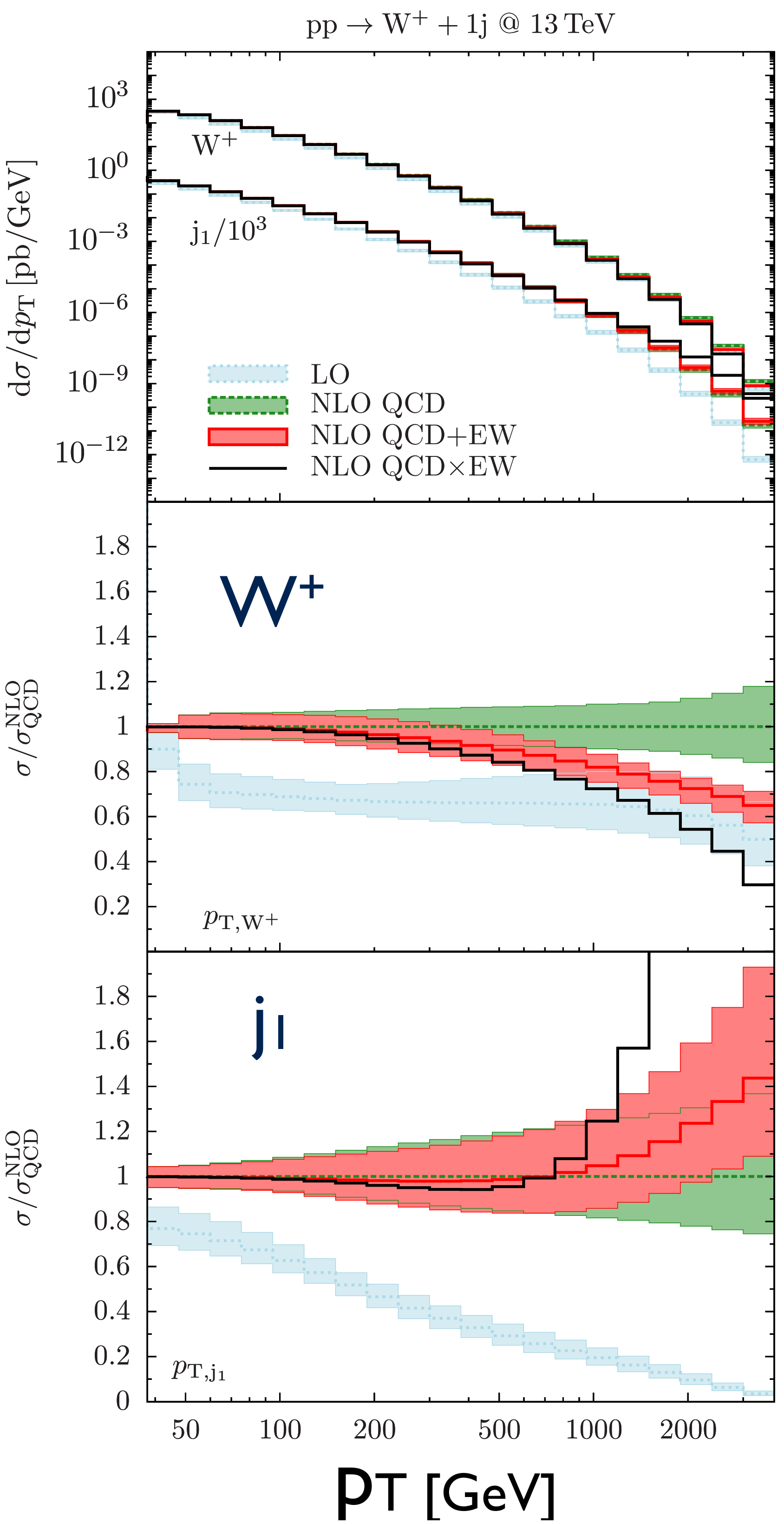
- remarkable agreement with data at @ NLO QCD+EW!

Open Questions

- Uncertainty of such a ratio?
  (QCD uncertainties should be *fairly* correlated)
- Dependence on jet multiplicity?
- Impact of jet cuts?

… let's first discuss V+jets @ NLO QCD+EW on more general grounds!

W^+ + 1 jet: inclusive



Setup:

$\sqrt{S} = 13$ TeV

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

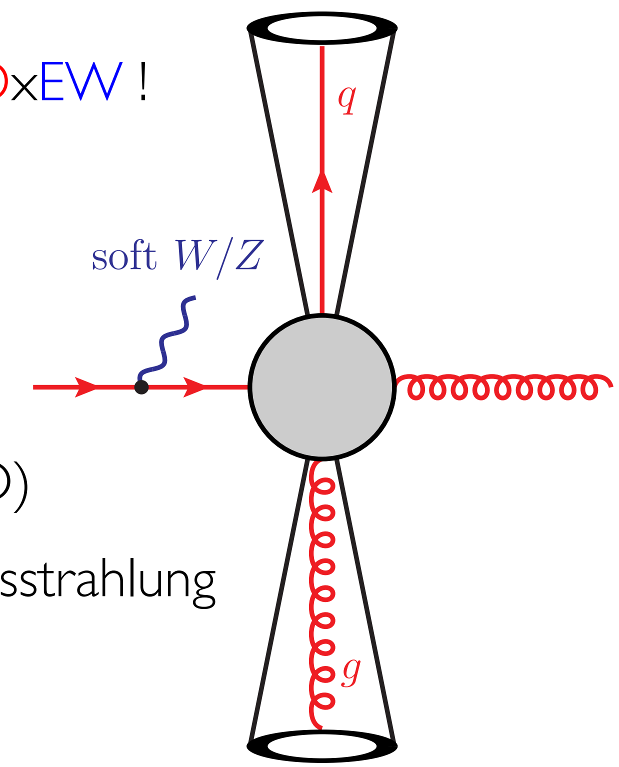
$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

inclusive

$\lesssim$ 1% EW corrections

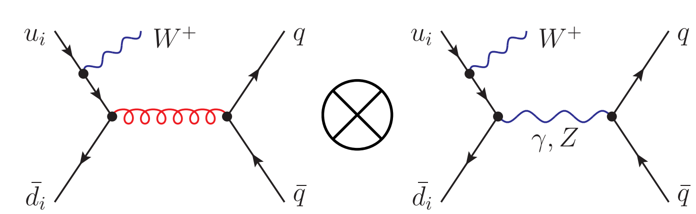
p_T of W-boson

- +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

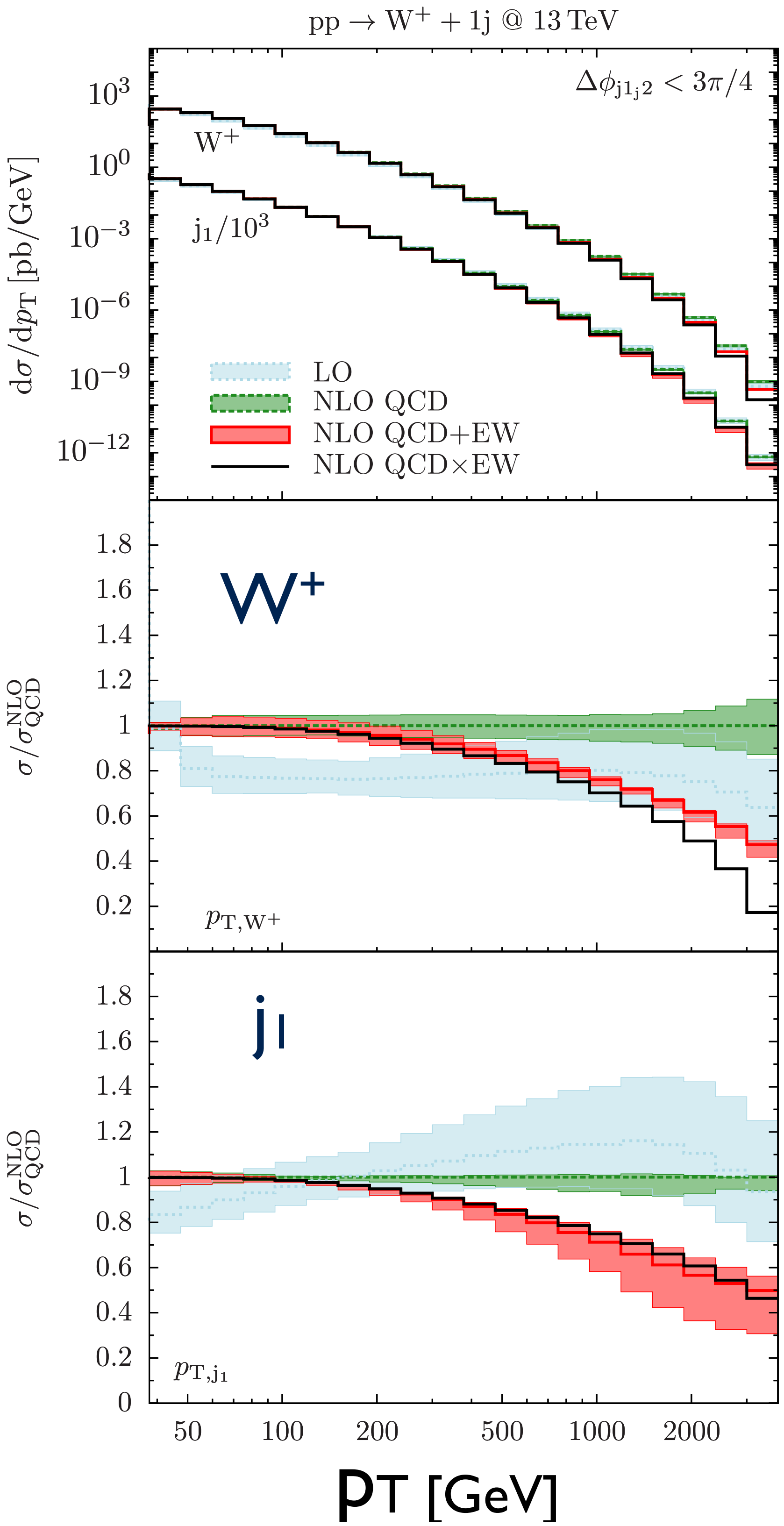
- factor-10 NLO QCD corrections in the tail!
- dominated by **dijet configurations** (effectively LO)
- positive 10-50% EW corrections from quark bremsstrahlung



$\Longrightarrow$ pathologic with large uncertainties!

[Kallweit, Maierhöfer, JML, Pozzorini, Schönherr, '14]

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

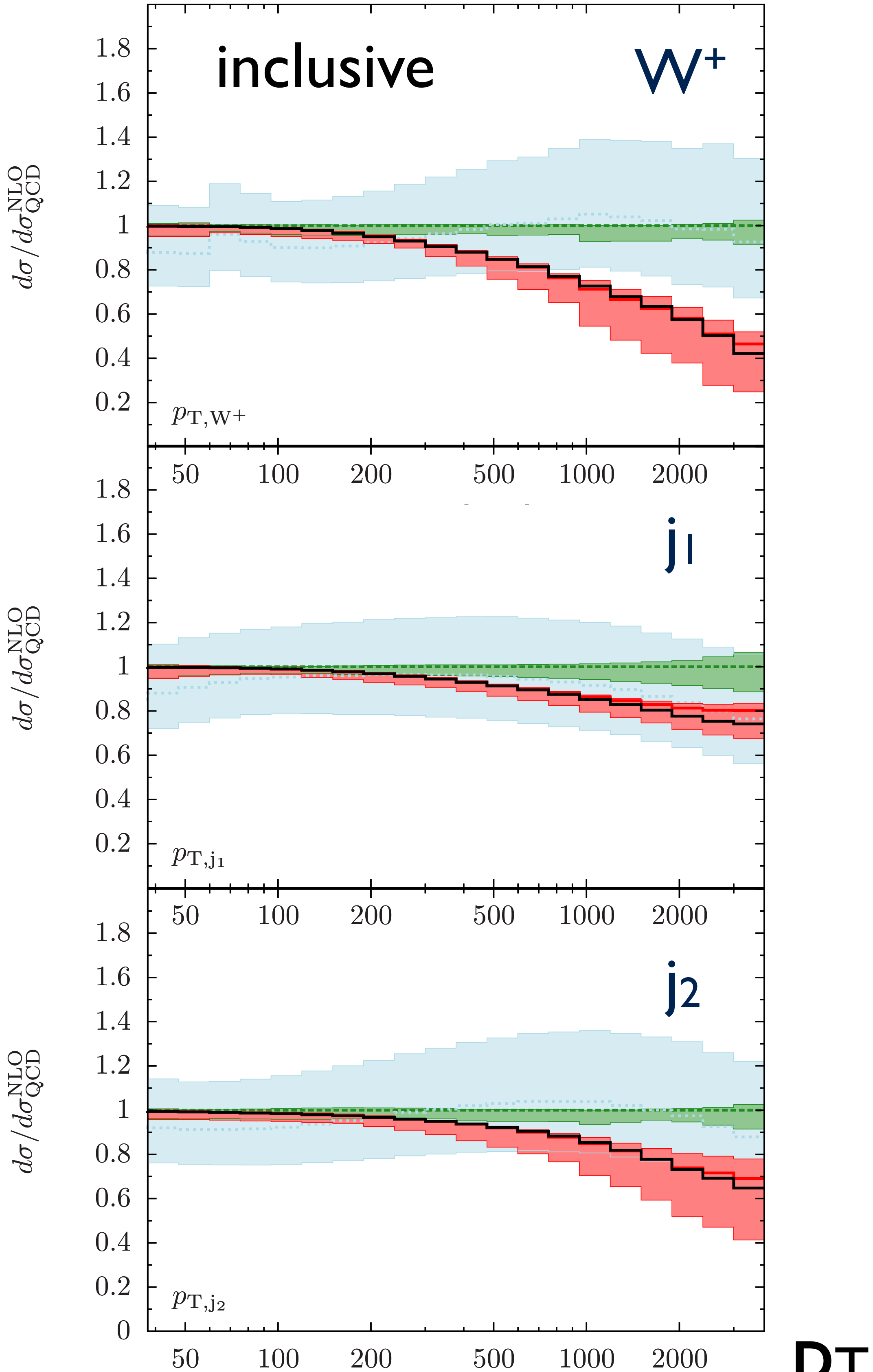
- **Sudakov behaviour** in both tails:
  -20–50% EW corrections at 1-4 TeV
- EW corrections larger than QCD uncertainties for $p_{T,W+} > 300$ GeV

⟹ *exclusive* W+1jet ok!

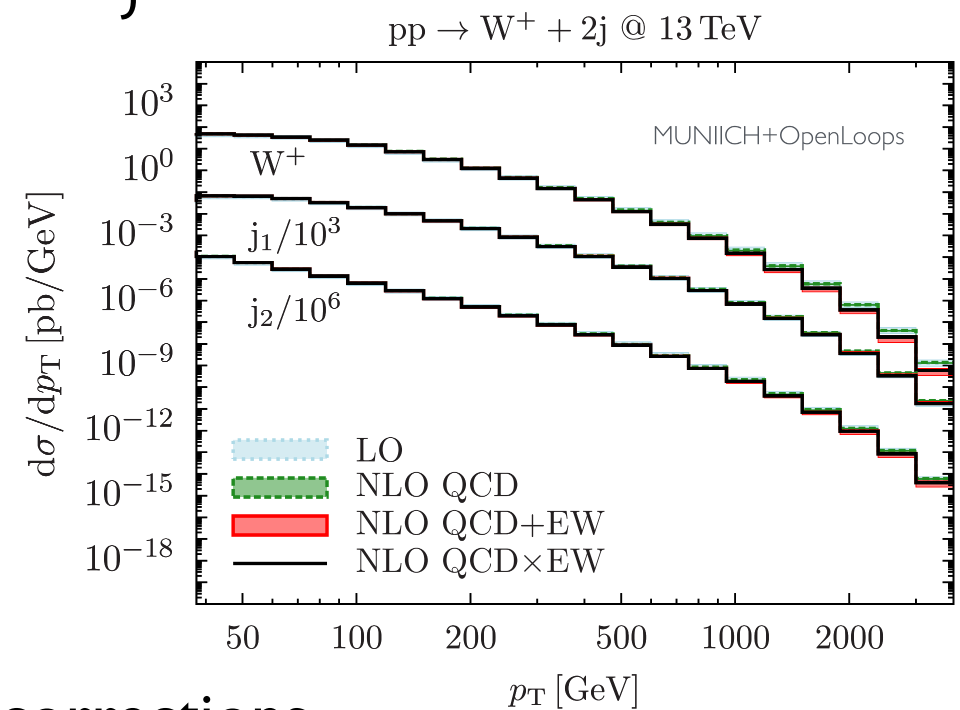
⟹ *inclusive* W+1jet requires W+2 jets at NLO QCD+EW!

[Kallweit, Maierhöfer, JML, Pozzorini, Schönherr, '14]

W^+ + 2 jets



[Kallweit, Maierhöfer, JML, Pozzorini, Schönherr, '14]



QCD corrections

- small and very stable
- ≲ 10% scale uncertainties

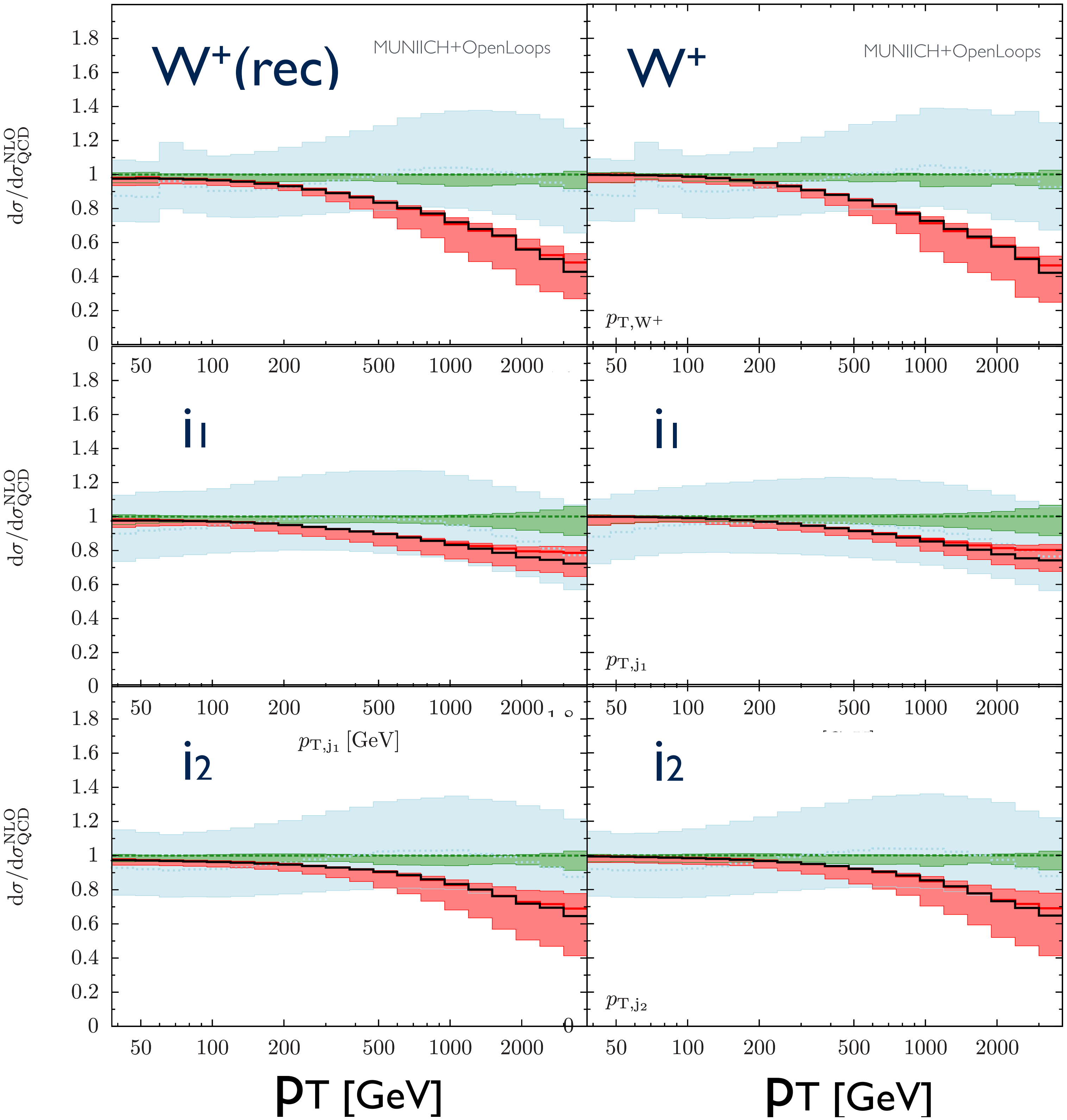
EW corrections

- **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

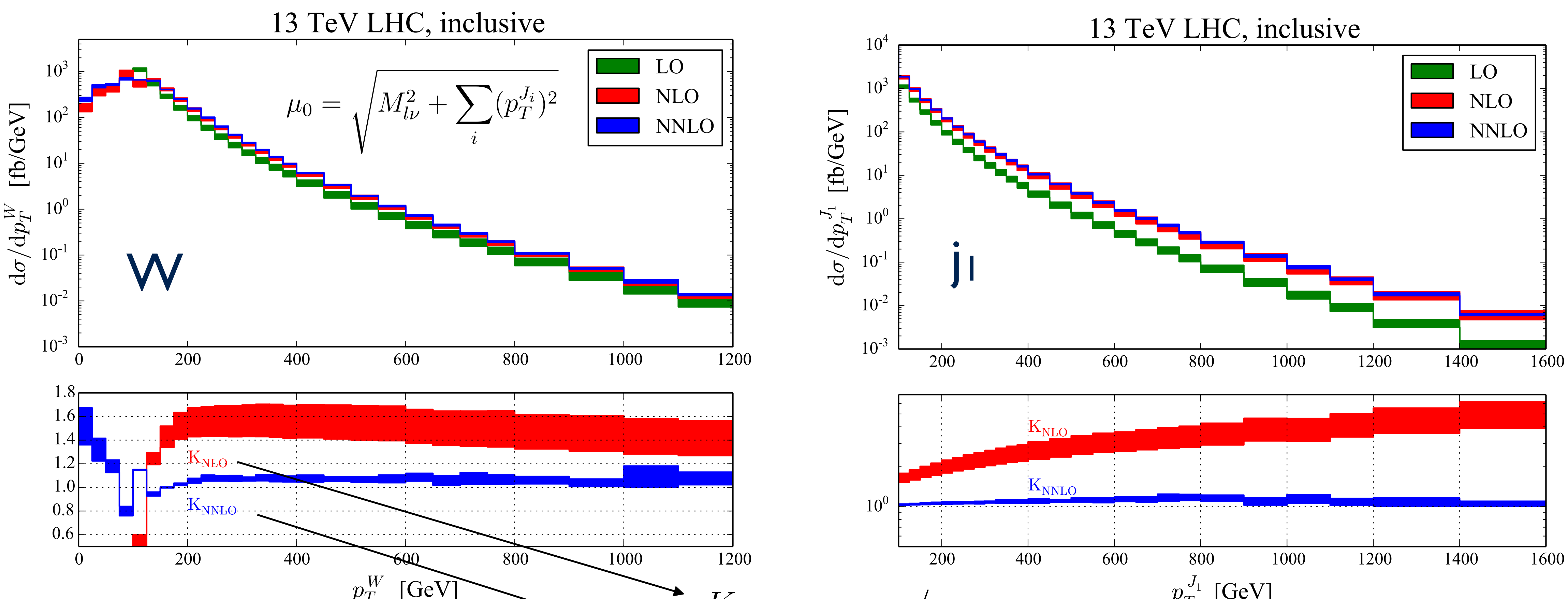


Effect of decays:

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

inclusive W + 1 jet @ NNLO QCD

[Boughezal, Liu, Petriello, '15,'16]



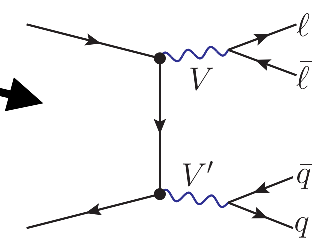
$$K_{\rm NLO} = \sigma_{\rm NLO}/\sigma_{\rm LO}$$
$$K_{\rm NNLO} = \sigma_{\rm NNLO}/\sigma_{\rm NLO}$$

- NNLO QCD: tiny remaining scale uncertainties (at the few % level)
- very small NNLO/NLO corrections in the tails

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

- Incorporate approximate EW corrections into MEPS@NLO framework *[Höche, Krauss, Schönherr, Siegert; '13]*
- **Idea**: integrate out real photon corrections (typical at the percent level for high-energy observables)

$$\tilde{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) \longrightarrow \tilde{\mathrm{B}}_{n,\mathrm{QCD+EW}}(\Phi_n) = \tilde{\mathrm{B}}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$



$$d\sigma = d\sigma(\alpha_S^2\alpha) + d\sigma(\alpha_S\alpha^2) + d\sigma(\alpha^3)$$

QCD EW QCD EW QCD EW

$$+\, d\sigma(\alpha_S^3\alpha) + d\sigma(\alpha_S^2\alpha^2) + d\sigma(\alpha_S\alpha^3) + d\sigma(\alpha^4)$$

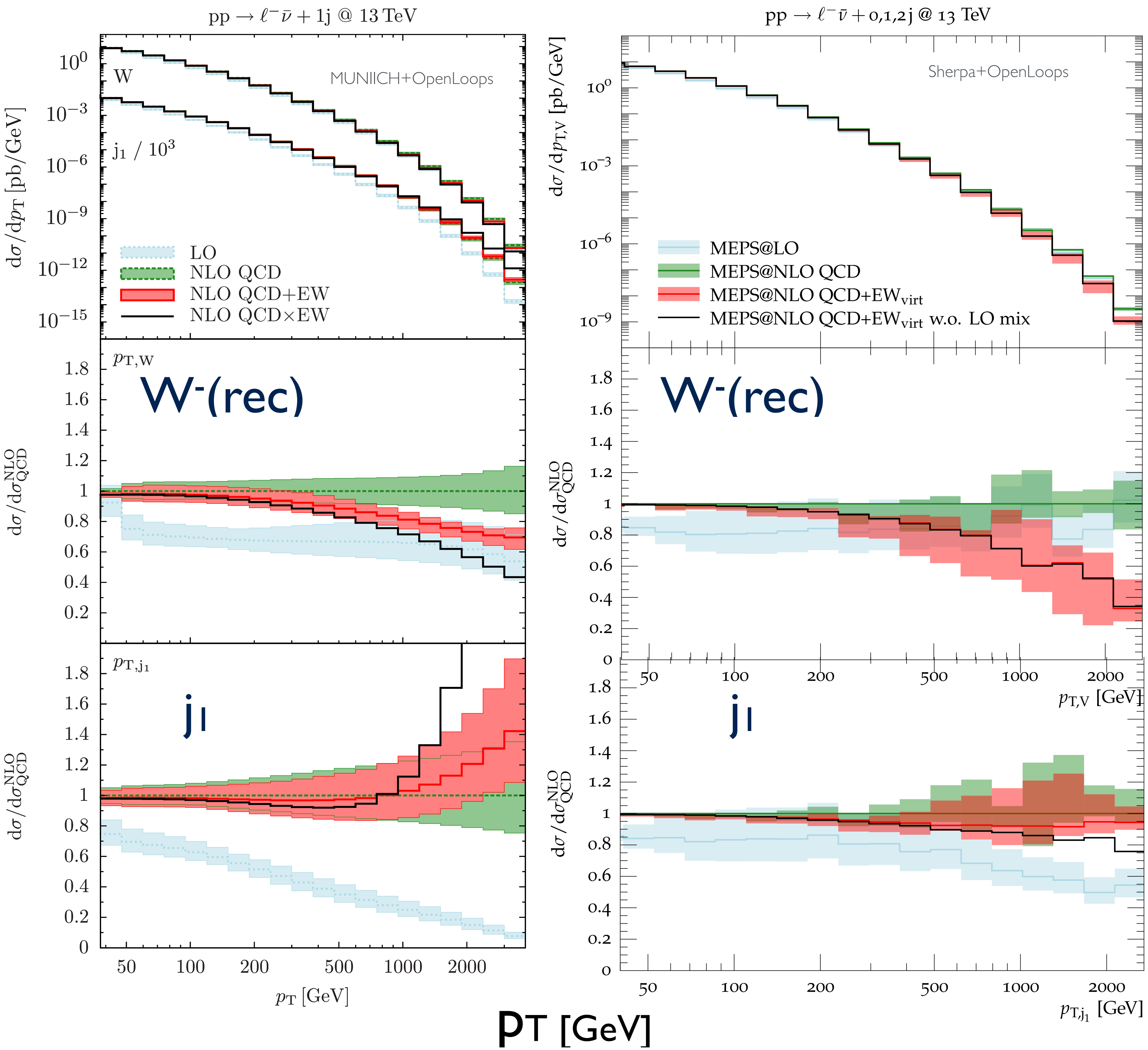
- Validated at fixed-order level (using exclusive sums for merging):

  → found to be reliable at the percent level

- exlusive QED corrections could be readded via QED parton shower
- use CKKW scale setting $\alpha_S^N(\mu_{\mathrm{CKKW}}^2) = \alpha_S^{N-M}(\mu_{\mathrm{core}}^2)\,\alpha_S(t_1)\ldots\alpha_S(t_M)$ with EW clustering and

$$\mu_{\mathrm{core},\ell\ell} = m_{\ell\ell}, \qquad \mu_{\mathrm{core},Vj} = \frac{1}{2}E_{T,V} = \frac{1}{2}\sqrt{M_V^2 + p_{T,V}^2}, \qquad \mu_{\mathrm{core},jj} = \frac{1}{2}\left(\frac{1}{\hat{s}} - \frac{1}{\hat{t}} - \frac{1}{\hat{u}}\right)^{-\frac{1}{2}}$$

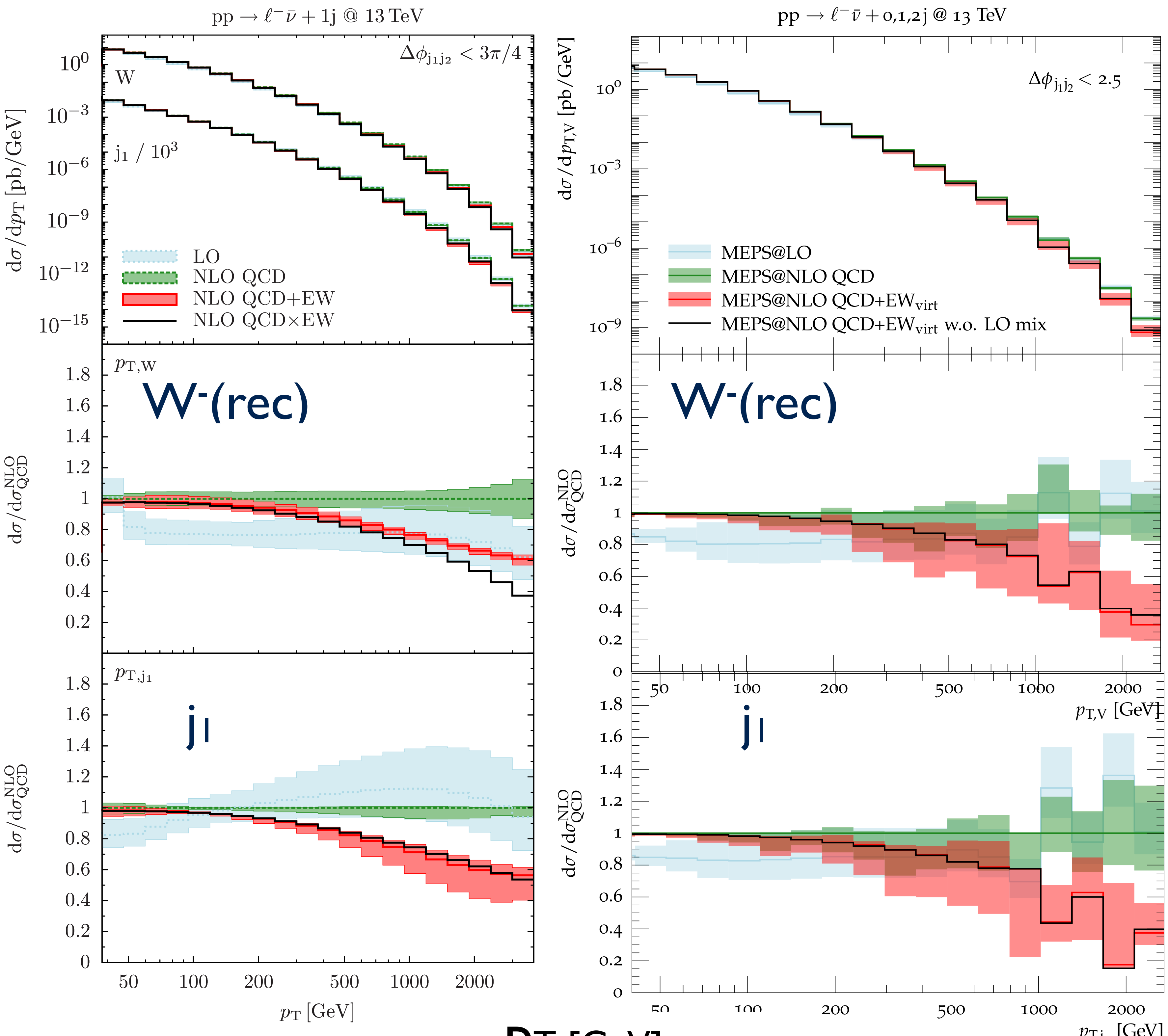
inclusive V+jets: MEPS@NLO QCD+EW$_{\text{virt}}$



[Kallweit, Maierhöfer, JML, Pozzorini, Schönherr, '15]

- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects!
- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)
- $p_{T,j1}$: compensation between negative Sudakov and quark-Bremsstrahlung (subleading Born for V+2 jet topology)

exclusive V+1jet: MEPS@NLO QCD+EW



pT [GeV]

[Kallweit, Maierhöfer, JML, Pozzorini, Schönherr, '15]

- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- $p_{T,j1}$: recover large EW corrections (as in fixed-order)

Conclusions

- monojet / MET+jets searches limited by systematics in transfer factors

- V + multijets @ NLO QCD+EW:
  - inclusion of EW corrections *crucial*
  - non-trivial interplay between QCD and EW
  - multi-jet final states genuinely different from V+1jet
  - merging essential for inclusive V+1 jet

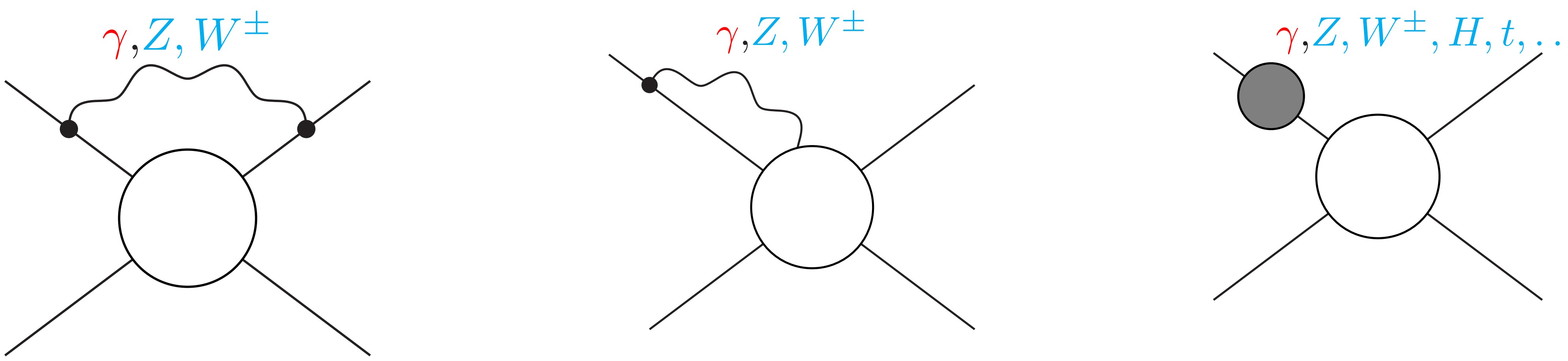
- Outlook:
  - R_{ZZ}, R_{ZW} & $R_{Z\gamma}$ @ MEPS@NLO QCD+EW_{virt}
  - Goal: (MEPS@NLO QCD+EW_{virt}/MEPS@NLO QCD) x NNLO QCD

    → few % accuracy for R-factors
  - Solid investigation of resulting theory uncertainty
  - MET + HF / V + HF

BACKUP

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]*

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

- 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:

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

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

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

➡ large cancellations possible

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:

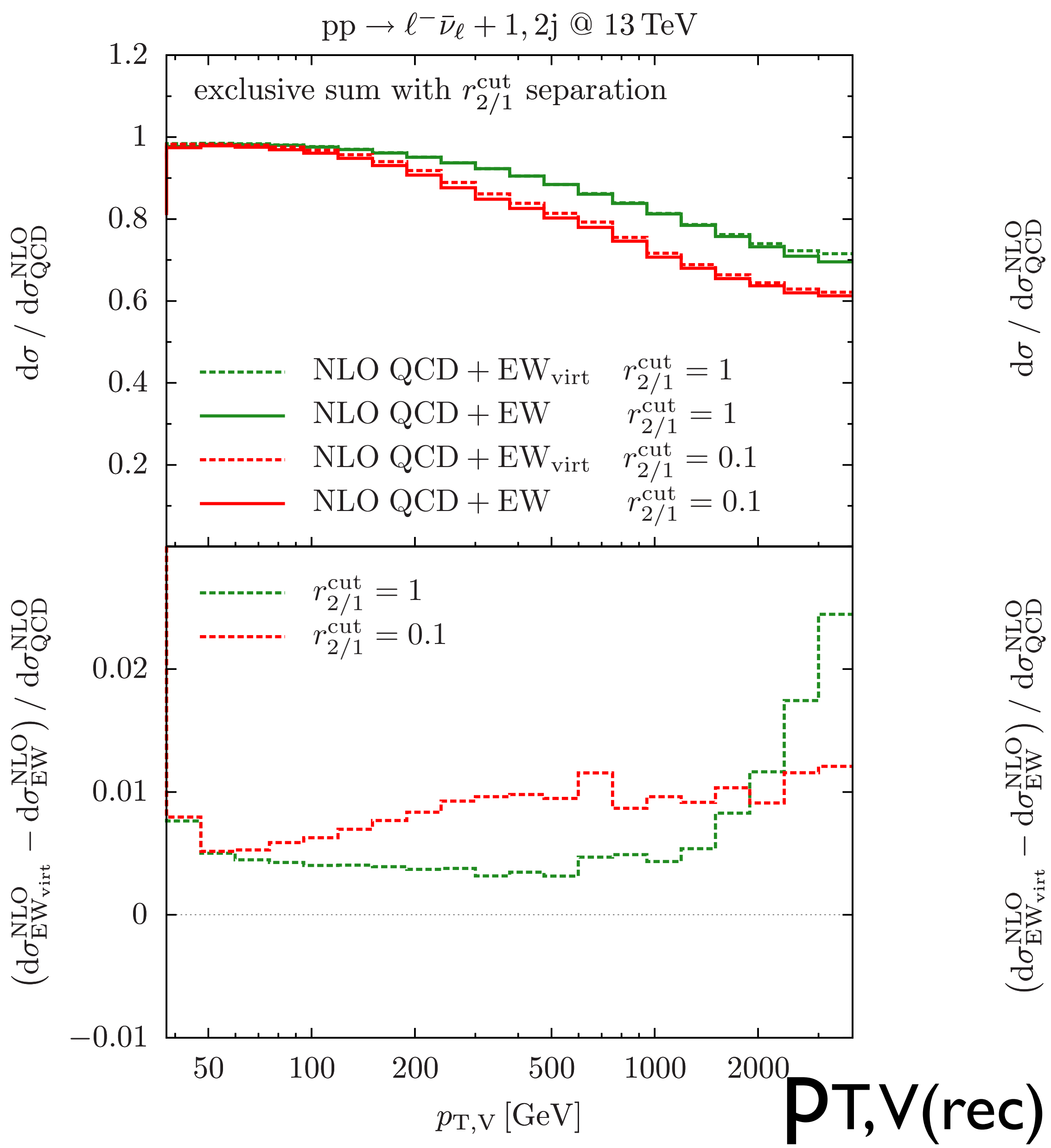
$$\frac{\sigma^{\rm NLO}_{\rm QCD+EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1 + \frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm NLO}_{\rm QCD}}\right)$$ suppressed by large NLO QCD corrections

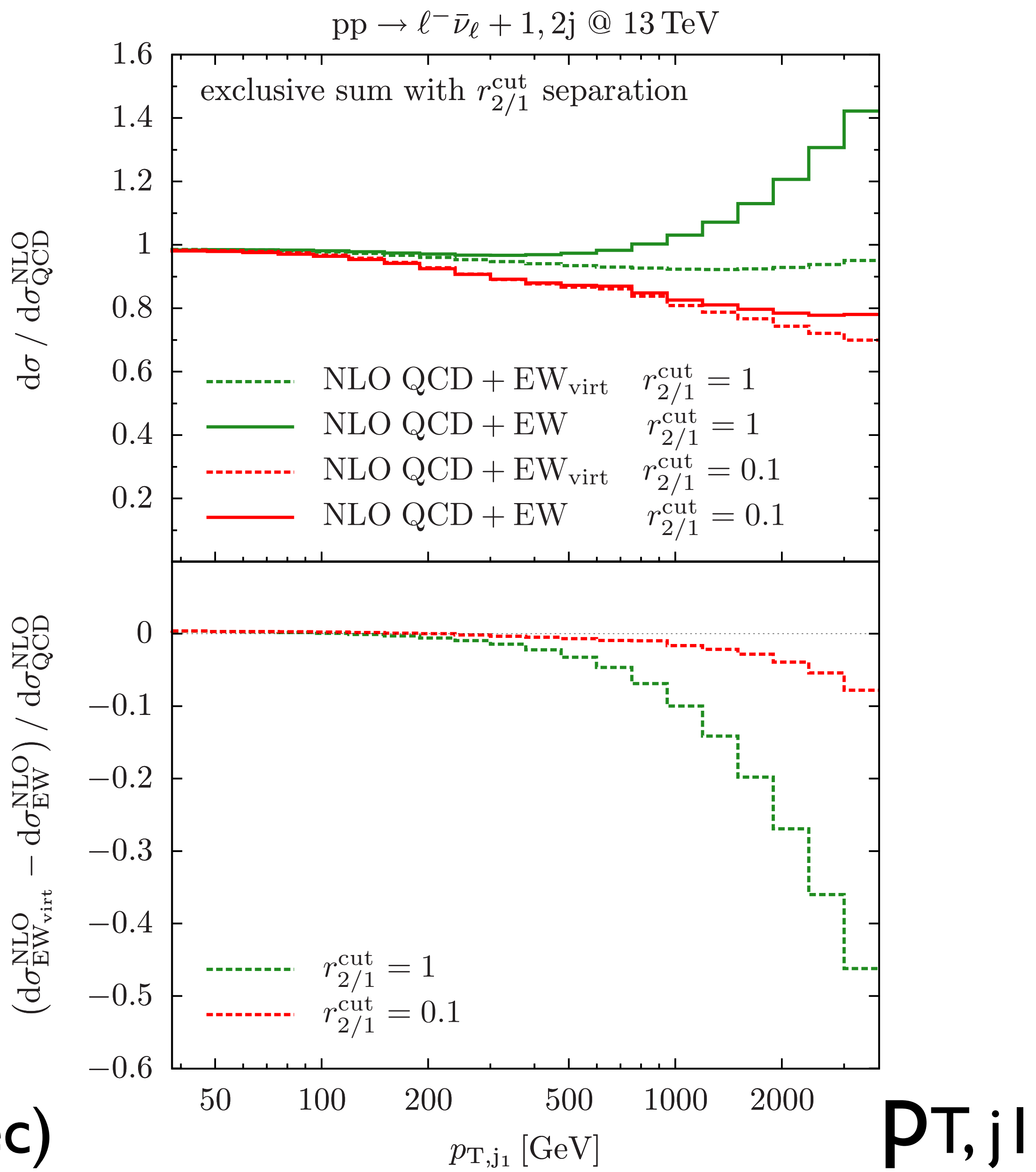
$$\frac{\sigma^{\rm NLO}_{\rm QCD\times EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1 + \frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right)$$ "usual" NLO EW w.r.t. LO

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

NLO EW$_{\text{virt}}$ Approximation

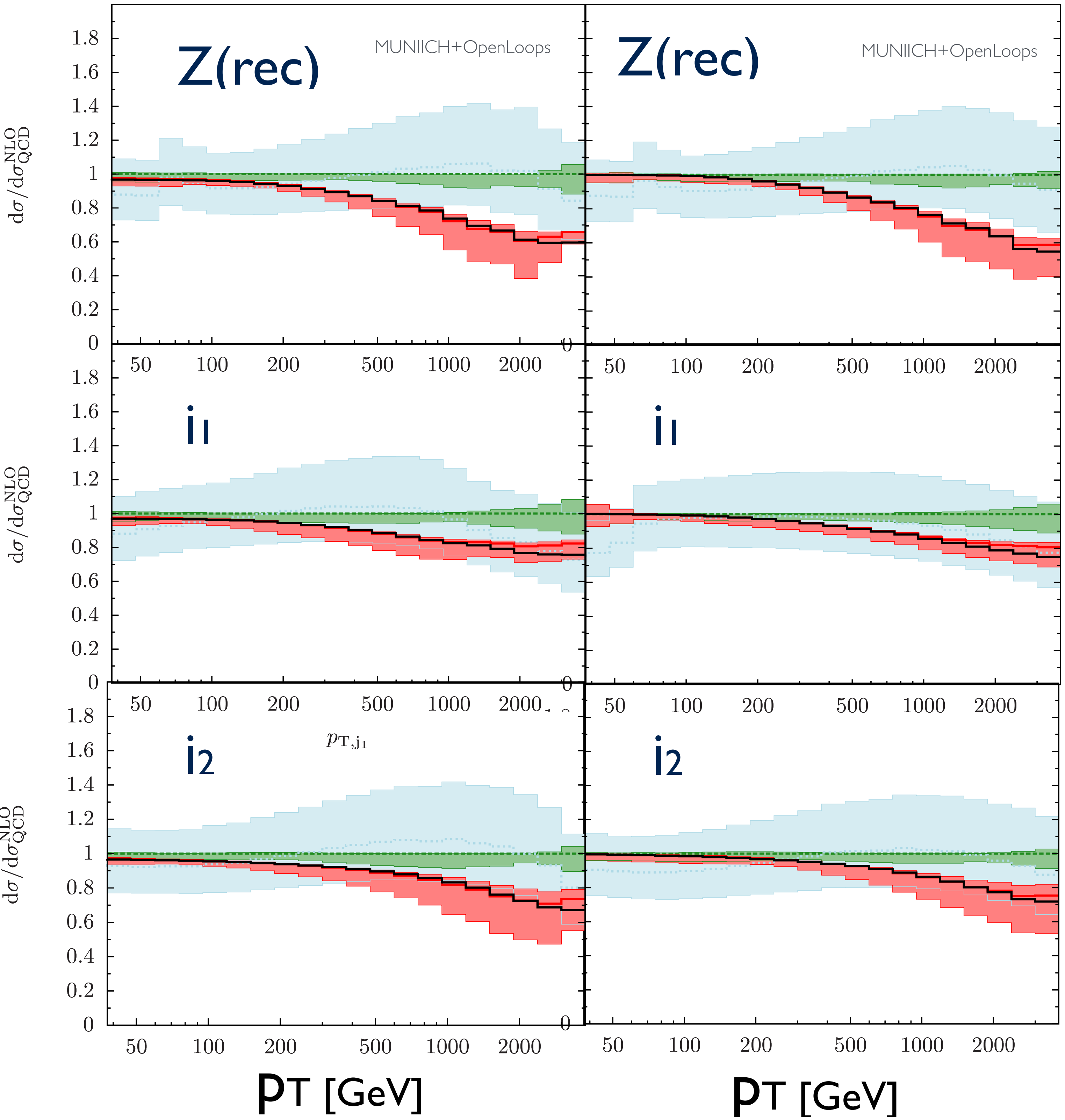
- Goal: include dominant (Sudakov) corrections into PS Monte-Carlo & apply multi-jet merging (MEPS@NLO)
- Idea: $\mathrm{d}\sigma_{n,\mathrm{NLO\,EW_{virt}}} = \left[\mathrm{B}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n)\right] \mathrm{d}\Phi_n.$
- Check: agreement within few percent (with $r_{2/1}^{\mathrm{cut}} = 0.1$):





Dependence on decay mode

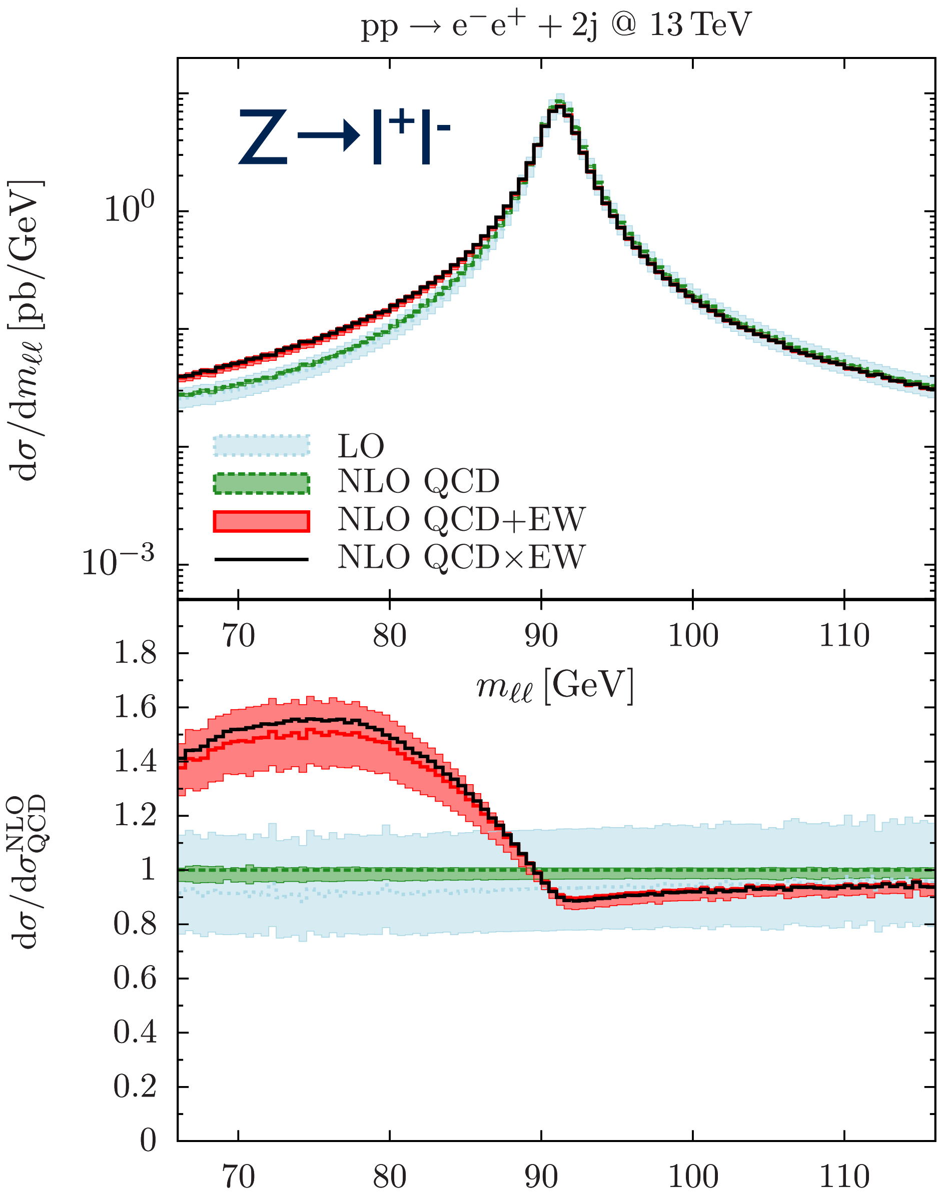
l^+l^-+ 2 jets vs. $\nu\bar{\nu}$+2 jets



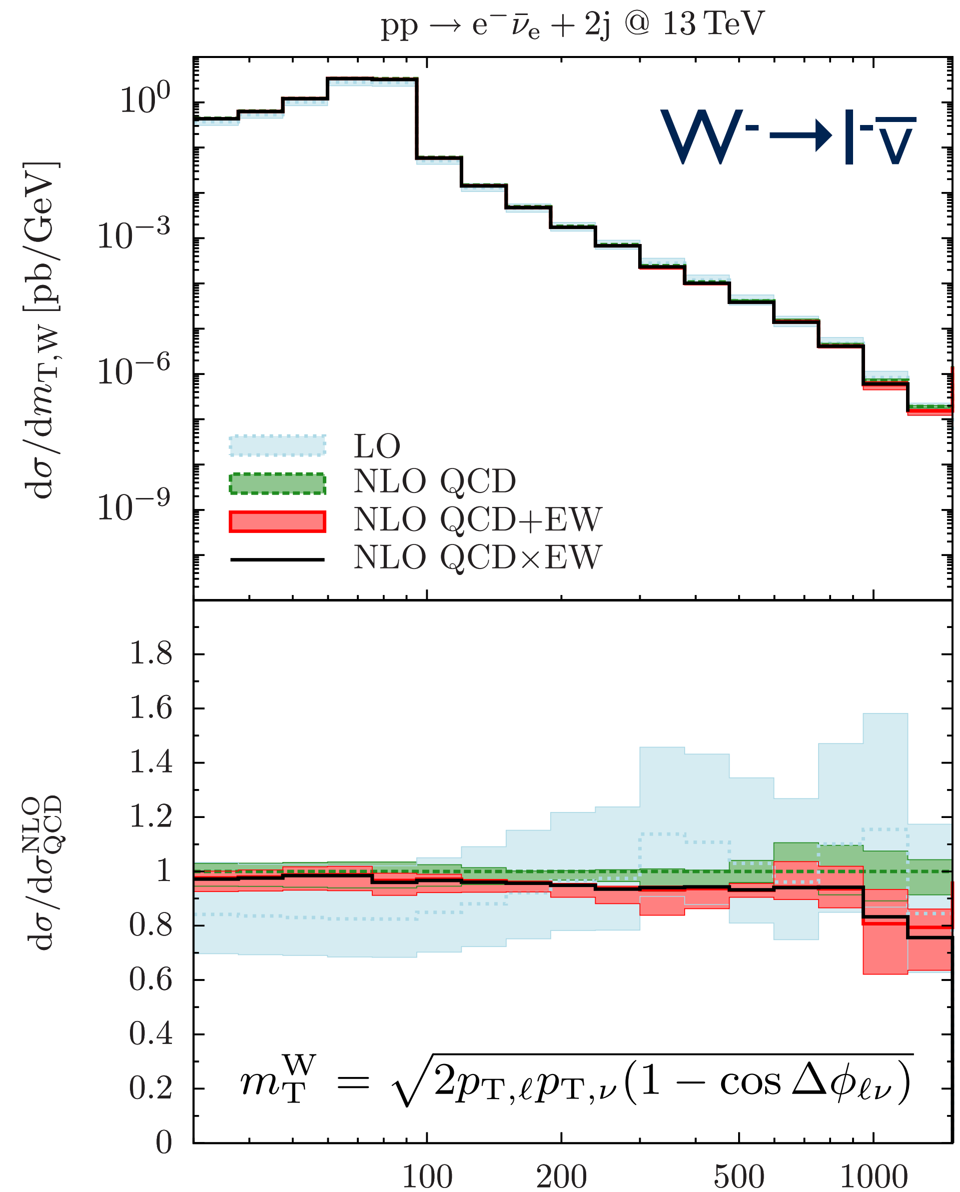
- Large EW Sudakov corrections independent of the decay mode (with inclusive lepton selections)

			$Z \to \ell^+\ell^-$	$Z \to \nu_\ell\bar{\nu}_\ell$
ℓ		$\in$	e, μ	e, μ, τ
$p_{T,\ell^\pm}$	[GeV]	$>$	25	
$\not{E}_T$	[GeV]	$>$		25
m_T^W	[GeV]	$>$		
$m_{\ell^+\ell^-}$	[GeV]	$\in$	[66, 116]	
$\lvert\eta_{\ell^\pm}\rvert$		$<$	2.5	
$\Delta R_{\ell^\pm j}$		$>$	0.5	
$\Delta R_{\ell^+\ell^-}$		$>$	0.2	

Leptonic observables



m_{ll} [GeV]



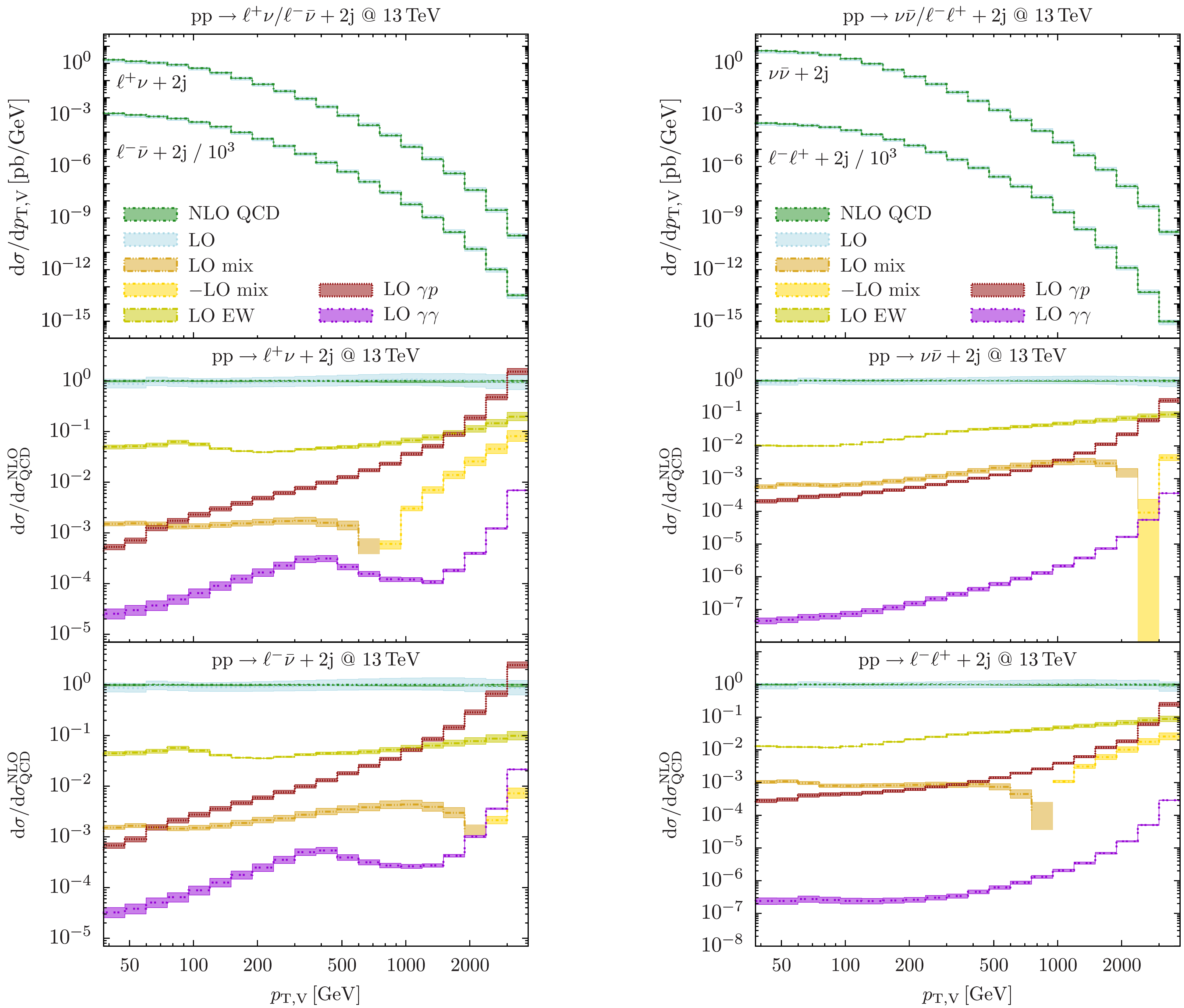
$$m_T^W = \sqrt{2 p_{T,\ell} p_{T,\nu} (1 - \cos \Delta\phi_{\ell\nu})}$$

$m_{T,W}$ [GeV]

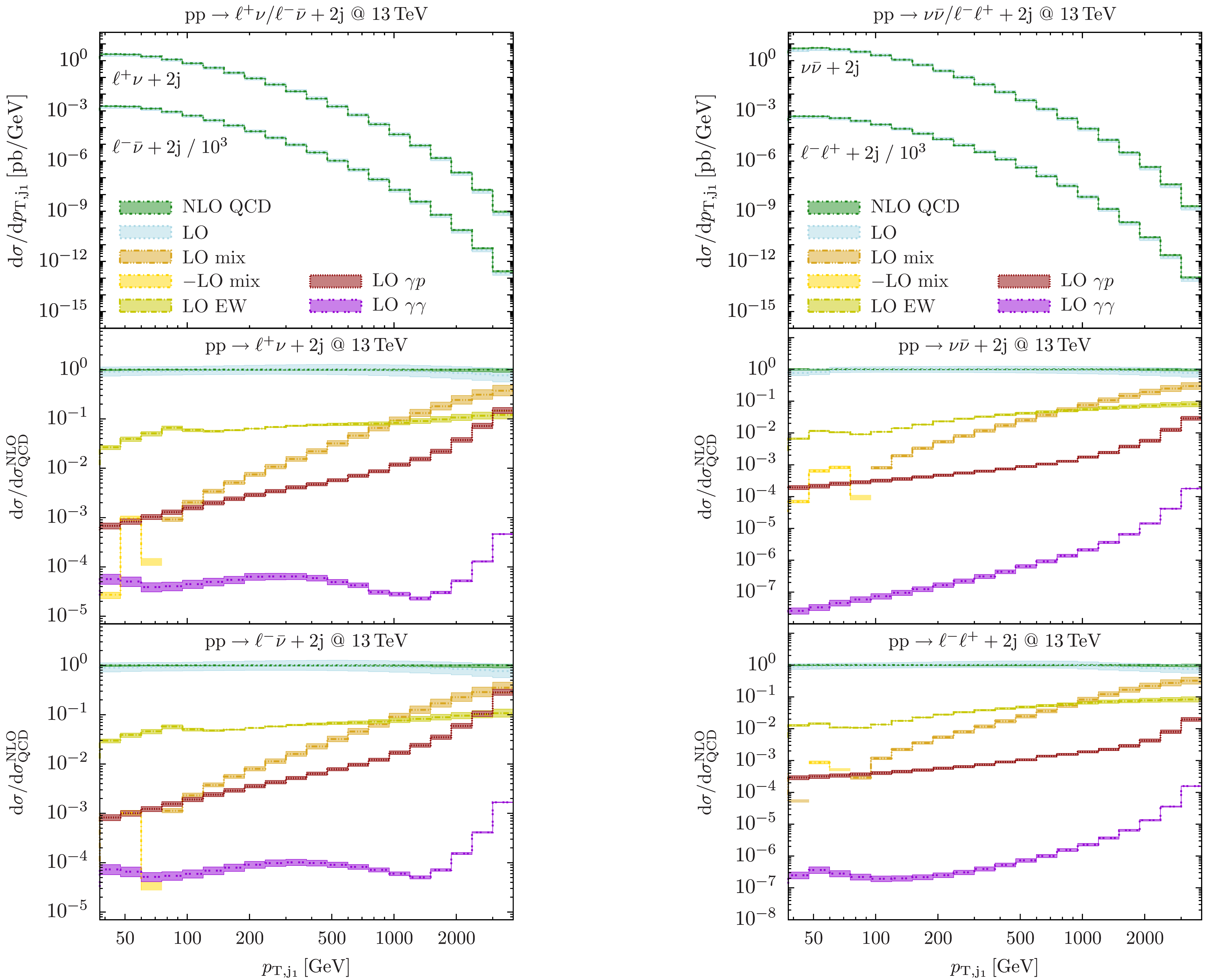
- up to 50% from QED Bremsstrahlung.
- Similar shape as for NC DY

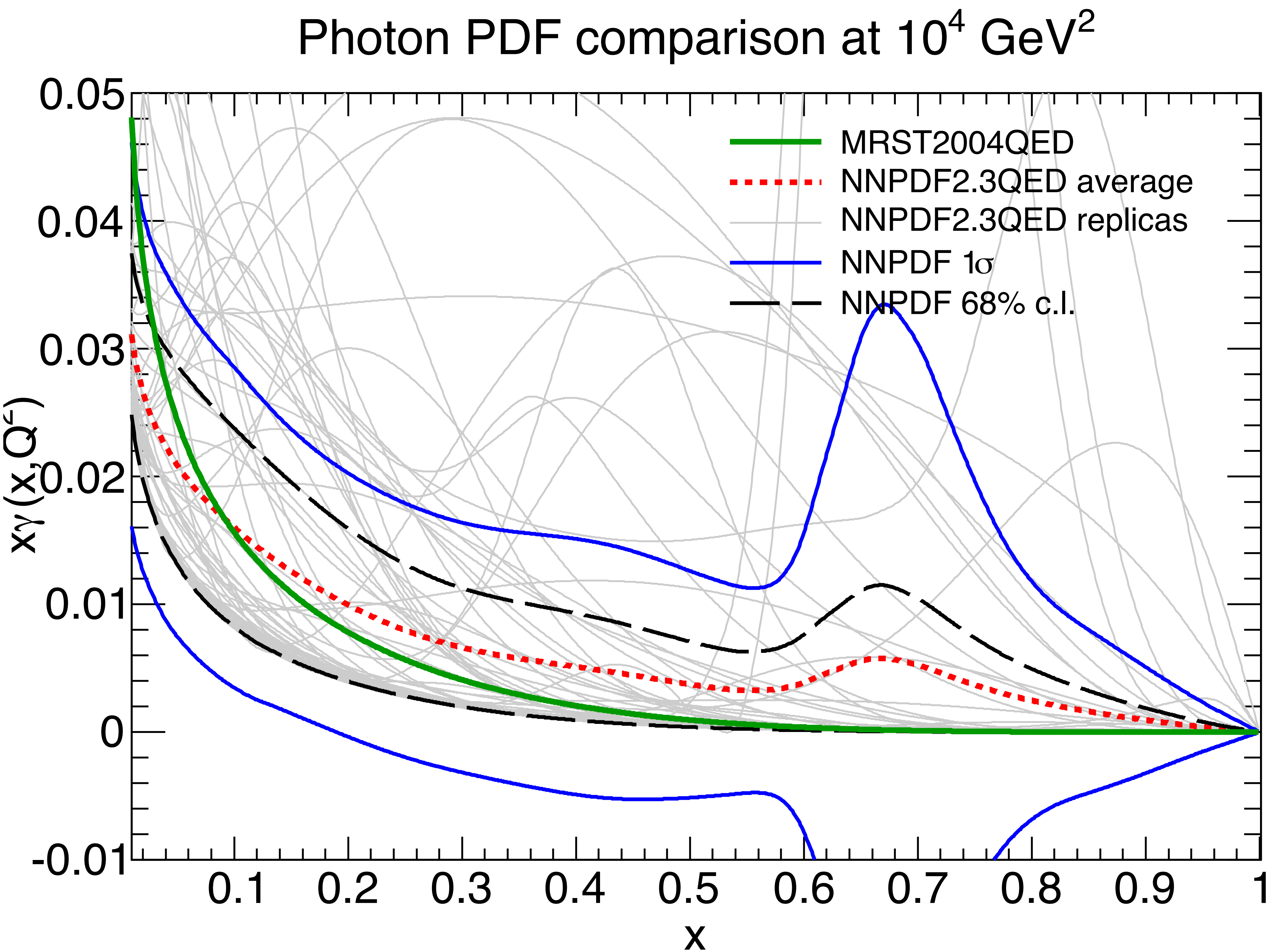
- moderate EW corrections at large $m_{T,W}$
- no (strong) Sudakov enhancement

Subleading Born: $p_{T,V}$



Subleading Born: $p_{T,j1}$




Photon PDF comparison at 10^4 GeV^2
MRST2004QED
NNPDF2.3QED average
NNPDF2.3QED replicas
NNPDF 1σ
NNPDF 68% c.l.
xγ(x,Q²)
x
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1