NLO EW+QCD corrections to W+jet production at hadron colliders for decaying (off-shell) W bosons

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Contents

1 Introduction

Importance of W+jet production: $\mathrm{pp} \to l\nu_l + \mathrm{jet} + X$

- large SM cross section (~ 1nb after basic cuts) $\to$ standard candle
- single-W production often shows additional jet activity
  $\hookrightarrow$ relevance for W-mass determination at the LHC
- offers precision test for jet dynamics in QCD
- dominant channel for high-p_T leptons
  $\hookrightarrow$ important background for various new-physics searches

Theoretical status:

- NLO QCD DYRAD [Giele et al. '93]; MCFM [Campbell/R.K.Ellis '02]; Melnikov/Petriello '06; Catani et al. '09
- NLO EW for stable W bosons
  Kühn, Kulesza, Pozzorini, Schulze '07; Hollik, Kasprzik, Kniehl '07

Motivation for this work:

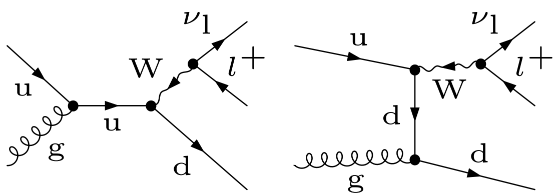
Inclusion of full off-shell effects in NLO QCD+EW predictions

$\hookrightarrow$ e.g. essential for W-mass determination

2 Calculation of NLO corrections

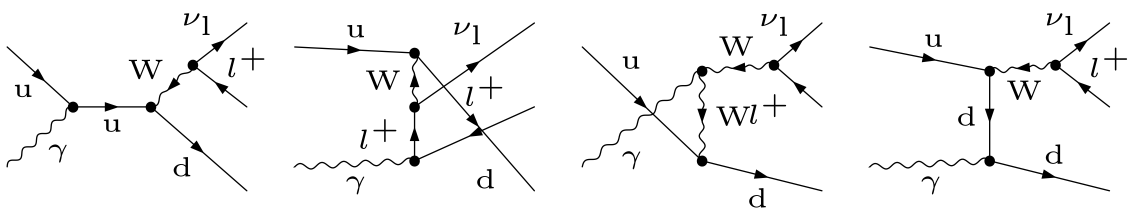
2.1 Lowest-order prediction

LO diagrams:



$+$ crossed graphs for $u\bar{d}$ and $g\bar{d}$ channels

Contributions from photon-induced processes



$+$ $\gamma\bar{d}$ channel

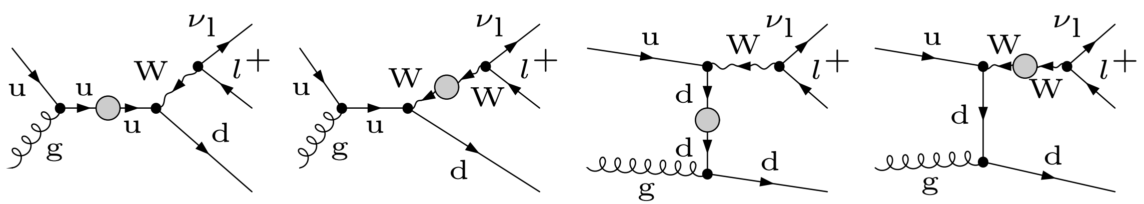
Features of the LO cross section:

- IR safety requires at least lower cut on $p_{\mathrm{T,jet}}$
  $\hookrightarrow$ apply jet algorithm for NLO cross section before cut on $p_{\mathrm{T,jet}}$
- contributions from photon-induced processes generically small ($\sim 1\%$)
  $\hookrightarrow$ inclusion of LO and NLO QCD as corrections

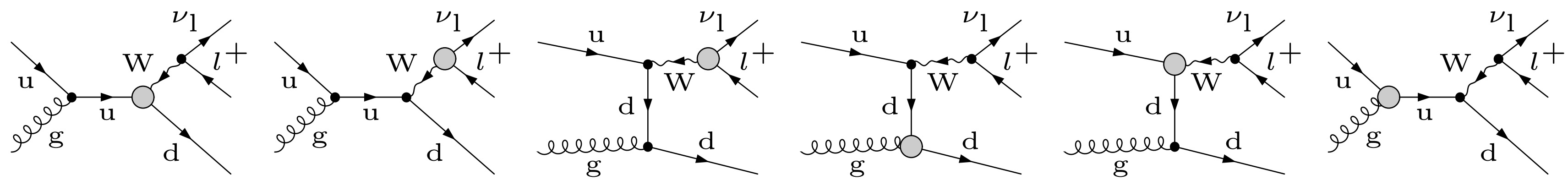
2.2 Survey of NLO EW+QCD corrections and technical details

1PI loop insertions in virtual corrections: $\mathcal{O}(100)$ EW loop diagrams per channel

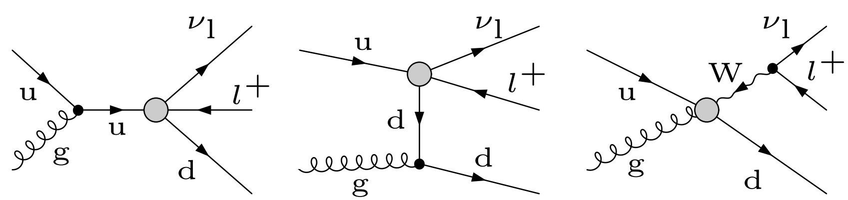
Self-energy insertions:



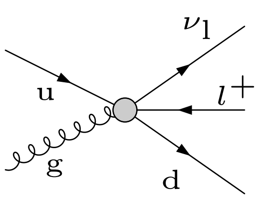
Vertex corrections:



Box corrections:

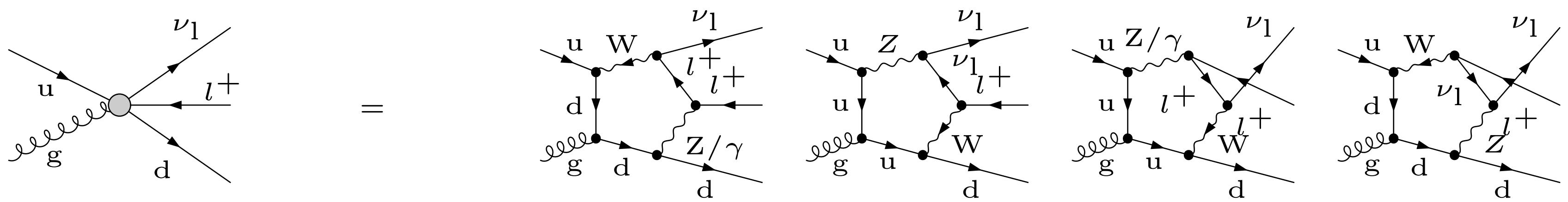


Pentagon graphs:



Most complicted parts of the loop calculation:

- pentagon graphs:



  $\hookrightarrow$ stable reduction to box integrals without inverse Gram determinants

  Denner, S.D. ’02,’05 (similar to Binoth et al. ’05)

- numerical instabilities in Passarino–Veltman reduction of tensor integrals

  $\hookrightarrow$ expansion about exceptional points

  Denner, S.D. ’05 (similar to Giele et al. ’04; R.K.Ellis et al. ’05)

- gauge-invariant treatment of W resonances

  $\hookrightarrow$ “complex-mass scheme” Denner, S.D., Roth, Wieders ’05

The complex-mass scheme at NLO Denner, S.D., Roth, Wieders '05

Basic idea: mass^2 = location of propagator pole in complex p^2 plane

$\hookrightarrow$ consistent use of complex masses everywhere !

Application to gauge-boson resonances:

- replace $M_\mathrm{W}^2 \to \mu_\mathrm{W}^2 = M_\mathrm{W}^2 - \mathrm{i}M_\mathrm{W}\Gamma_\mathrm{W}$, $M_\mathrm{Z}^2 \to \mu_\mathrm{Z}^2 = M_\mathrm{Z}^2 - \mathrm{i}M_\mathrm{Z}\Gamma_\mathrm{Z}$

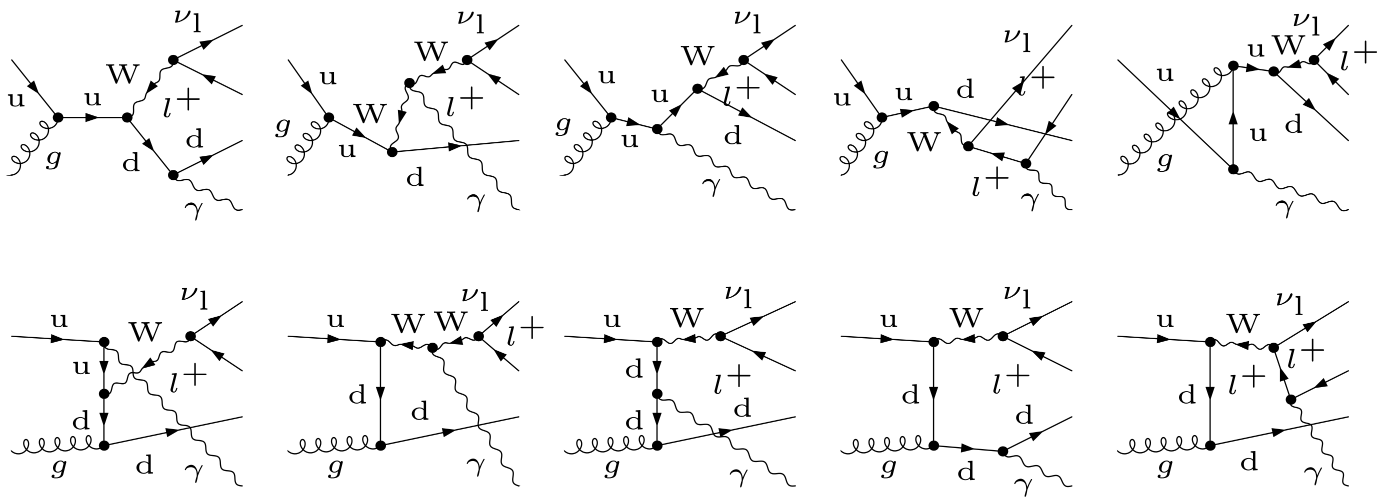
  and define (complex) weak mixing angle via $c_\mathrm{W}^2 = 1 - s_\mathrm{W}^2 = \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$

- virtues:
  - ◇ gauge-invariant result (Slavnov–Taylor identities, gauge-parameter independence)
    $\hookrightarrow$ unitarity cancellations respected !
  - ◇ perturbative calculations as usual (loops and counterterms)
  - ◇ no double counting of contributions (bare Lagrangian unchanged !)

- drawbacks:
  - ◇ unitarity-violating spurious terms of $\mathcal{O}(\alpha^2)$ $\to$ but beyond NLO accuracy !
    (from t-channel/off-shell propagators and complex mixing angle)
  - ◇ complex gauge-boson masses also in loop integrals

Real emission corrections

- NLO QCD:
  - ◇ gluon bremsstrahlung: $\mathrm{u\bar{d}} \to l^+\nu_l \mathrm{gg}$, $\mathrm{ug} \to l^+\nu_l \mathrm{dg}$, $\mathrm{\bar{d}g} \to l^+\nu_l \mathrm{\bar{u}g}$
  - ◇ gg fusion: $\mathrm{gg} \to l^+\nu_l \mathrm{\bar{u}d}$
  - ◇ gluon splitting $\mathrm{g}^* \to q\bar{q}$: $\mathrm{u\bar{d}} \to l^+\nu_l q\bar{q}$ $+$ crossed variants
- NLO EW:
  - ◇ photon bremsstrahlung: $\mathrm{u\bar{d}} \to l^+\nu_l \mathrm{g}\gamma$, $\mathrm{ug} \to l^+\nu_l \mathrm{d}\gamma$, $\mathrm{\bar{d}g} \to l^+\nu_l \mathrm{\bar{u}}\gamma$



Note: $\mathrm{u\bar{d}} \to l^+\nu_l \mathrm{g}\gamma$ contributes to both

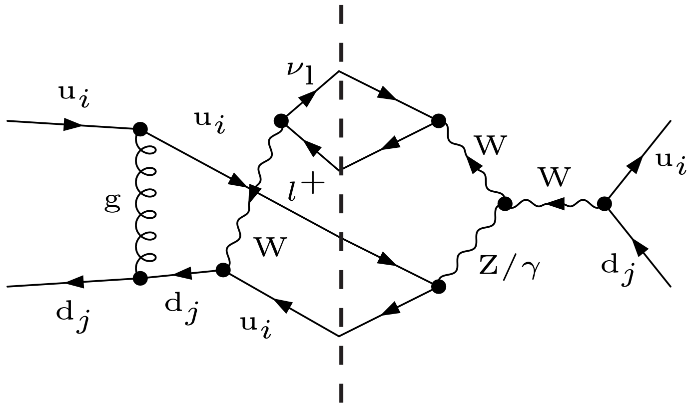
– NLO EW corrections to $\mathrm{u\bar{d}} \to l^+\nu_l \mathrm{g}$ and

– NLO QCD corrections to $\mathrm{u\bar{d}} \to l^+\nu_l \gamma$

Further technical details

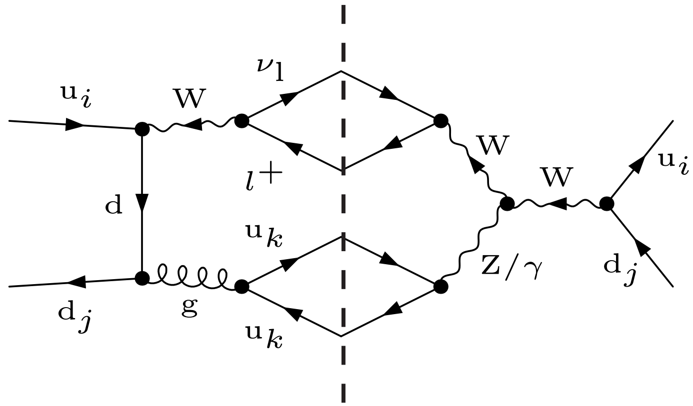
- Generic features
  - ◇ two completely independent calculations of all ingredients
    $\hookrightarrow$ results in mutual agreement
  - ◇ dipole subtraction for QCD and photonic IR (soft and collinear) singularities
    Catani, Seymour ’96; S.D. ’99; S.D., Kabelschacht, Kasprzik ’08
    $\hookrightarrow$ checked against phase-space slicing
- MPI/FR
  - ◇ loop amplitude generation with FEYNARTS 1 Böhm, Denner, Küblbeck ’90
    $\hookrightarrow$ algebraic reduction with inhouse MATHEMATICA routines
  - ◇ tree amplitudes evaluated analytically via spinor formalism
  - ◇ phase-space integration via VEGAS
- PSI
  - ◇ loop amplitude generation with FEYNARTS 3 Hahn ’00
    $\hookrightarrow$ algebraic reduction with FORMCALC Hahn ’98–’09 and POLE Meier ’05; Mück
  - ◇ real corrections generated with program POLE
    $\hookrightarrow$ automatic generation of tree amplitudes via spinor formalism,
    dipole subtraction terms, and multi-channel phase-space integration

Non-trivial interferences between real NLO QCD and EW corrections



$\mathcal{M}_{\mathrm{QCD}}(\mathcal{M}_{\mathrm{EW}})^* \propto \mathrm{Tr}[T^a T^a]$

$\rightarrow$ interference non zero



$\mathcal{M}_{\mathrm{QCD}}(\mathcal{M}_{\mathrm{EW}})^* \propto (\mathrm{Tr}[T^a])^2$

$\rightarrow$ interference vanishes

$\hookrightarrow$ Non-singular contributions of $\mathcal{O}(\alpha^3\alpha_{\mathrm{s}})$ = same order as NLO EW

Interferences included in our calculation

$\hookrightarrow$ effect phenomenologically negligible
(%-effects only for $p_{\mathrm{T,jet}} \gtrsim 1\,\mathrm{TeV}$, otherwise $\ll 1\%$)

3 Numerical results for the LHC

Setup and definition of observables

- PDF set MRST2004QED which includes NLO QCD+EW corrections
  - $\hookrightarrow$ initial-state collinear QCD and photonic singularities removed via factorization
  - $\hookrightarrow$ PDF set includes photon density
- two scale choices: $\mu = \mu_{\mathrm{ren}} = \mu_{\mathrm{fact}} = M_{\mathrm{W}}$ (fixed) or
  $\mu = \sqrt{M_{\mathrm{W}}^2 + (p_{\mathrm{T}}^{\mathrm{had}})^2}$ (variable)
- k_{T}-algorithm for jet definition
- basic cuts: $p_{\mathrm{T,\,jet1\,/\,}l\mathrm{\,/\,miss}} > 25\,\mathrm{GeV}$, $|y_{\mathrm{jet1\,/\,}l}| < 2.5$, $R_{\mathrm{l,jet}} > 0.5$
- jet veto optionally applied to 2nd hard jet if $p_{\mathrm{T,\,jet2}} > p_{\mathrm{T,\,jet1}}/2$
- two lepton identifications: "bare leptons" ($l = \mu^+$)
  - $\hookrightarrow$ large corrections $\propto \alpha \ln(m_l^2/Q^2)$

  or photon–lepton recombination if $R_{\gamma,l} < 0.1$ ($l = \mathrm{e}^+$)
  - $\hookrightarrow$ cancellation of all $\alpha \ln(m_l^2/Q^2)$ terms a la KLN
- photon fragmentation function for photon–jet separation Glover, Morgan '94

Photon–jet separation via photon fragmentation function $D_{q\to\gamma}$

Why?

- collinear quarks and photons have to be recombined $\to$ quasiparticle
  otherwise corrections $\propto \ln(m_q^2/Q^2)$ $\to$ perturbative “IR instability”
- quark and gluon jets cannot be distinguished event by event
  $\hookrightarrow$ common recombination required for quarks/gluons with photons

  $\Rightarrow$ $\underbrace{(\mathrm{g}_{\mathrm{hard}} + \gamma_{\mathrm{soft}})}_{\text{EW corr. to W+jet}}$ and $\underbrace{(\mathrm{g}_{\mathrm{soft}} + \gamma_{\mathrm{hard}})}_{\text{QCD corr. to W+}\gamma}$ both appear as 1 jet

Solution:

- exclude events with photon energy fraction $z_\gamma = \dfrac{E_\gamma}{E_{\mathrm{jet}} + E_\gamma} > z_0$
  for $(\mathrm{jet} + \gamma)$ quasiparticles (chosen value $z_0 = 0.7$)
- subtract convolution of LO cross section with

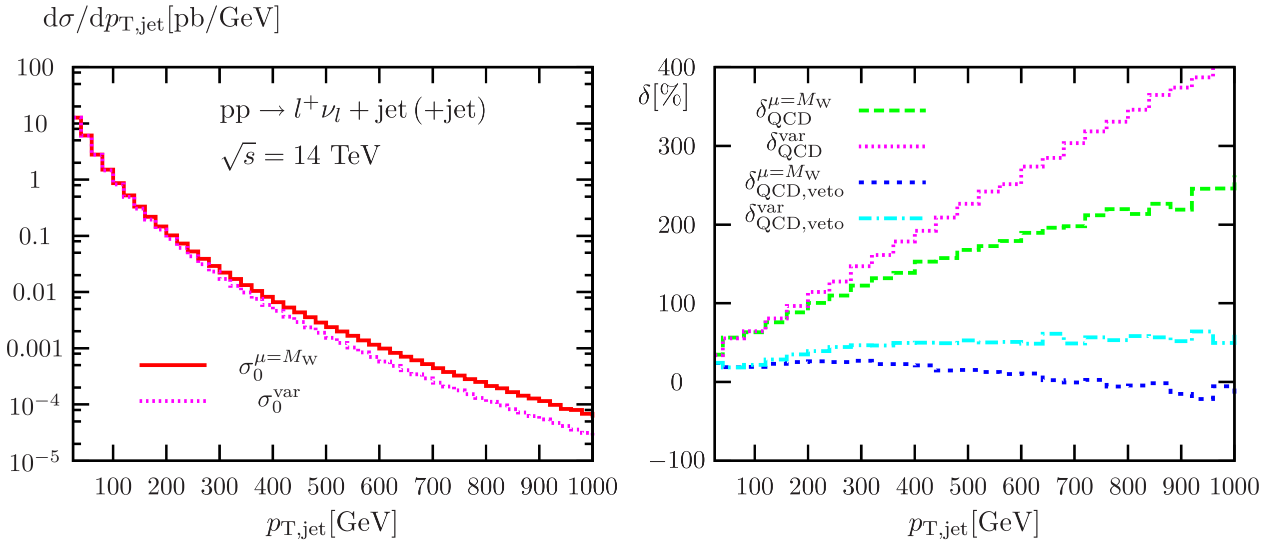
$$D_{q\to\gamma}^{\overline{\mathrm{MS}}}(z_\gamma, \mu_{\mathrm{fact}})\Big|_{\mathrm{mass.reg.}} = \frac{\alpha Q_q^2}{2\pi} P_{q\to\gamma}(z_\gamma)\left[\ln\frac{m_q^2}{\mu_{\mathrm{fact}}^2} + 2\ln z_\gamma + 1\right] \quad \leftarrow \text{cancels coll. singularities}$$

$$+ \; D_{q\to\gamma}^{\mathrm{ALEPH}}(z_\gamma, \mu_{\mathrm{fact}}) \quad \leftarrow \text{non-perturbative part fitted to ALEPH data}$$

where $P_{q\to\gamma}(z_\gamma) = \frac{1+(1-z_\gamma)^2}{z_\gamma}$ = quark-to-photon splitting function

Transverse-momentum distribution of the hardest jet

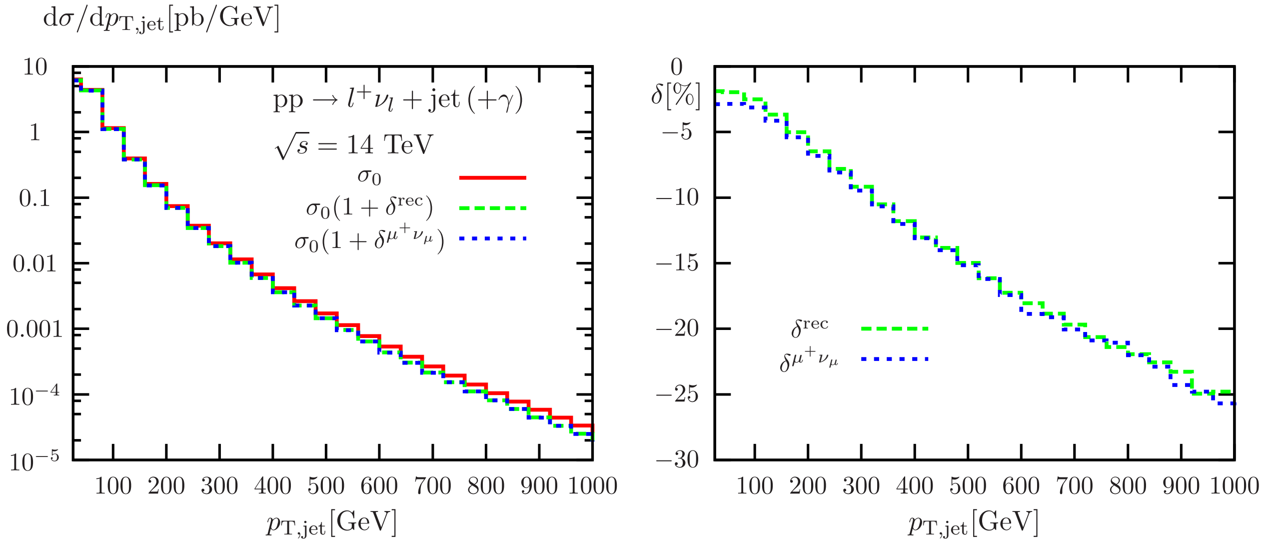
QCD corrections:



Large positive corrections from W+2jets (mainly back-to-back jets)

$\hookrightarrow$ significant reduction of corrections via jet veto

EW corrections:



Large neg. corrections due to EW Sudakov logs

$\hookrightarrow$ qualitative agreement with previous results for on-shell Ws Kühn et al. '07 Hollik et al. '07

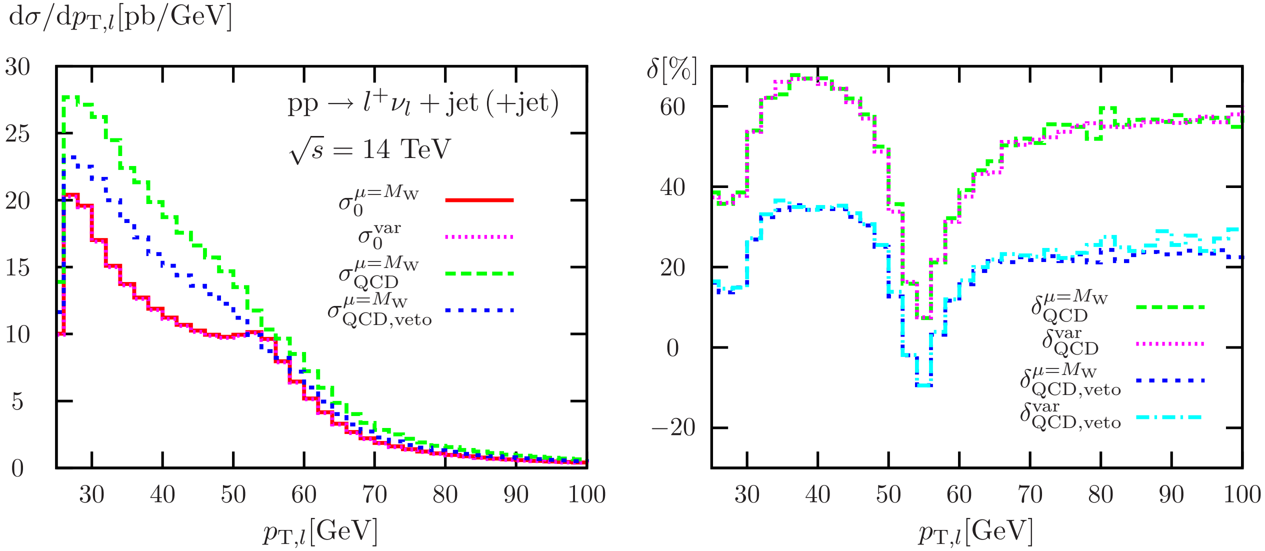
Integrated cross section for various cuts on $p_{\mathrm{T,\,jet}}$

$$\mathrm{pp} \to l^+\nu_l\ \mathrm{jet} + X \text{ at } \sqrt{s} = 14\,\mathrm{TeV}$$

$p_{\mathrm{T,jet}}/\,\mathrm{GeV}$	$25-\infty$	$50-\infty$	$100-\infty$	$200-\infty$	$500-\infty$	$1000-\infty$	
$\sigma_{\mathrm{Born}}^{\mu=M_\mathrm{W}}/\,\mathrm{pb}$	509.45(5)	182.74(2)	49.777(5)	8.1086(9)	0.3156(1)	0.0117(1)	
$\sigma_{\mathrm{Born}}^{\mathrm{var}}/\,\mathrm{pb}$	502.66(5)	176.39(1)	45.382(4)	6.4990(6)	0.1850(1)	0.0048(1)	
$\delta_{\mathrm{EW}}^{\mu^+\nu_\mu,\mathrm{var}}/\%$	−3.07(6)	−3.35(1)	−4.64(1)	−8.50(1)	−18.0(1)	−28.0(1)	EW Sudakov
$\delta_{\mathrm{EW}}^{\mathrm{rec},\mathrm{var}}/\%$	−2.07(1)	−2.55(2)	−4.18(1)	−8.37(3)	−17.8(1)	−27.9(1)	logs
$\delta_{\mathrm{QCD}}^{\mu=M_\mathrm{W}}/\%$	48.0(1)	64.8(1)	80.7(1)	115	188	270(1)	
$\delta_{\mathrm{QCD}}^{\mathrm{var}}/\%$	47.9(2)	65.4(1)	85.8(1)	135	270	494(1)	
$\delta_{\mathrm{QCD,veto}}^{\mu=M_\mathrm{W}}/\%$	21.5(1)	18.2(1)	22.5(2)	24.6(1)	5.3(1)	−26.4(2)	jet veto
$\delta_{\mathrm{QCD,veto}}^{\mathrm{var}}/\%$	22.3(1)	20.8(1)	29.8(2)	43.3(2)	52.4(1)	58.7(1)	
$\delta_{\gamma,\mathrm{NLO}}^{\mathrm{var}}/\%$	0.38	0.70	1.18	1.86	3.26	5.18(1)	γ-induced
$\delta_{\gamma,\mathrm{NLO,veto}}^{\mathrm{var}}/\%$	0.35	0.64	1.10	1.76	3.03	4.73(1)	processes
$\delta_{\mathrm{IF}}^{\mathrm{var}}/\%$	0.05	0.13	0.51	1.88	11.50	49.95	QCD–EW
$\delta_{\mathrm{IF,veto}}^{\mathrm{var}}/\%$	0.01(1)	0.03	0.12	0.40	1.63	4.72	interferences

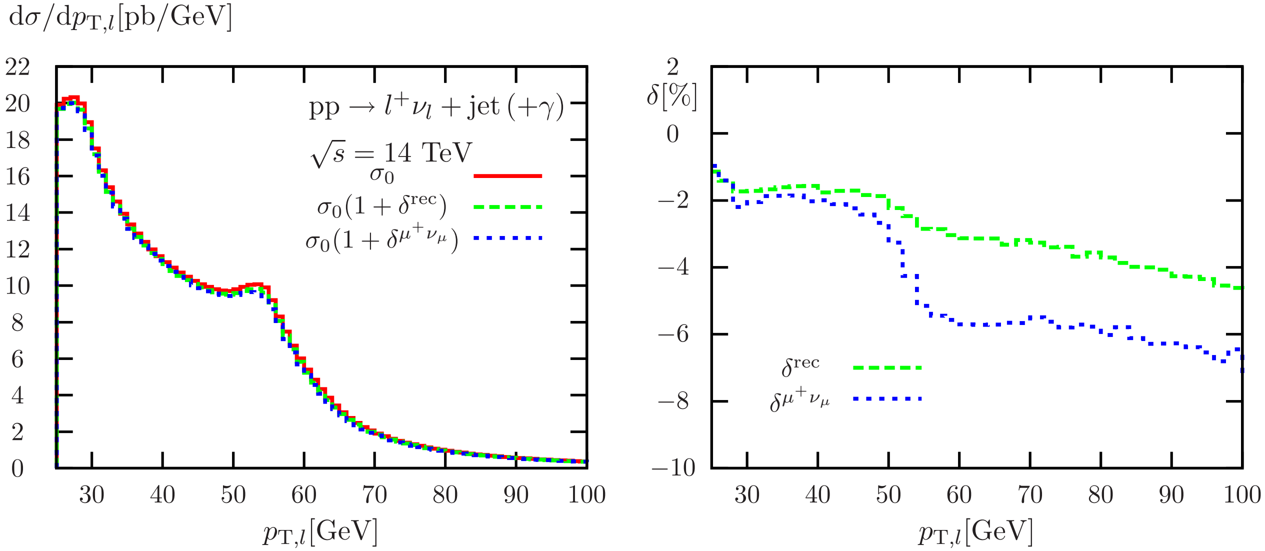
Transverse-momentum distribution of the charged lepton

QCD corrections:



- large corrections distorting the shape
- corrections reduced by jet veto

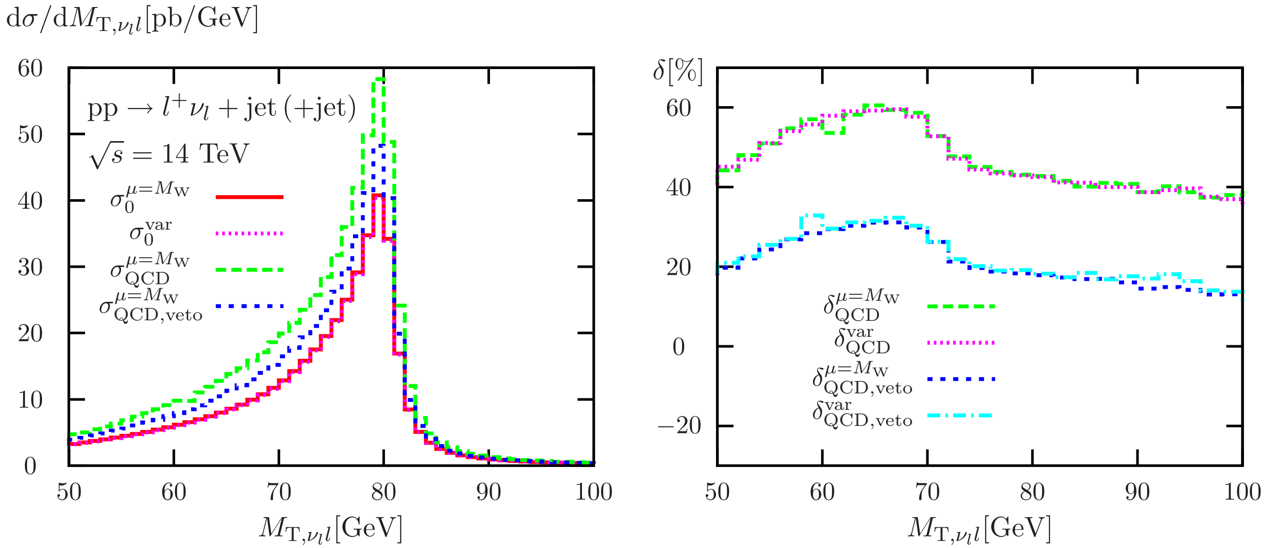
EW corrections:



- moderate corrections of $\mathcal{O}(5\%)$
- Jacobian peaks slightly distorted

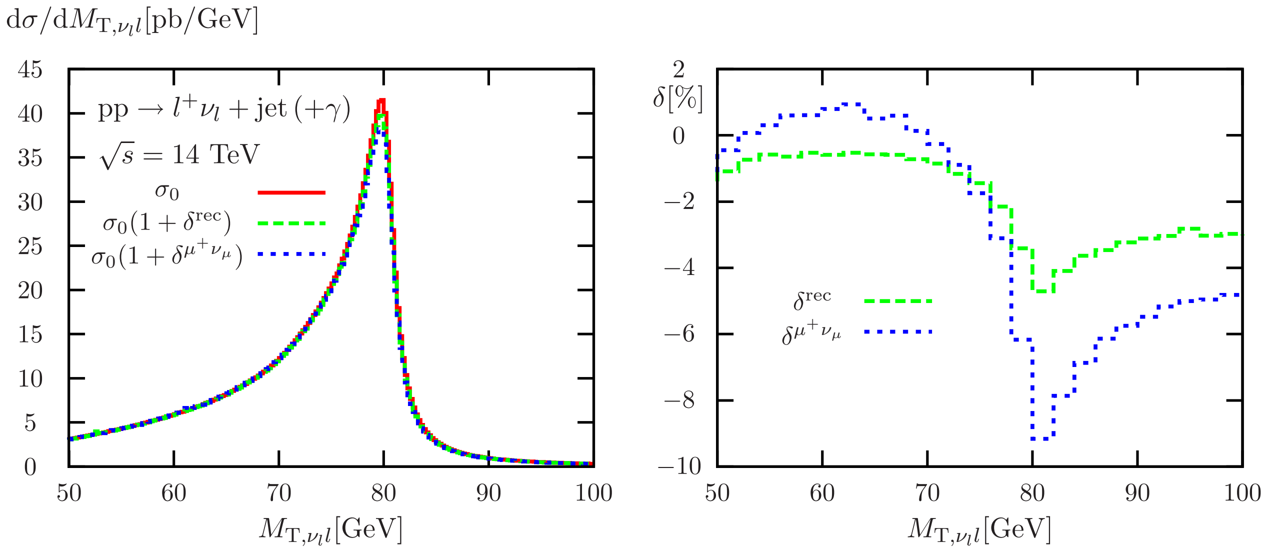
Transverse-mass distribution of the W boson

QCD corrections:



- corrections smooth near Jacobian peak
- corrections reduced by jet veto

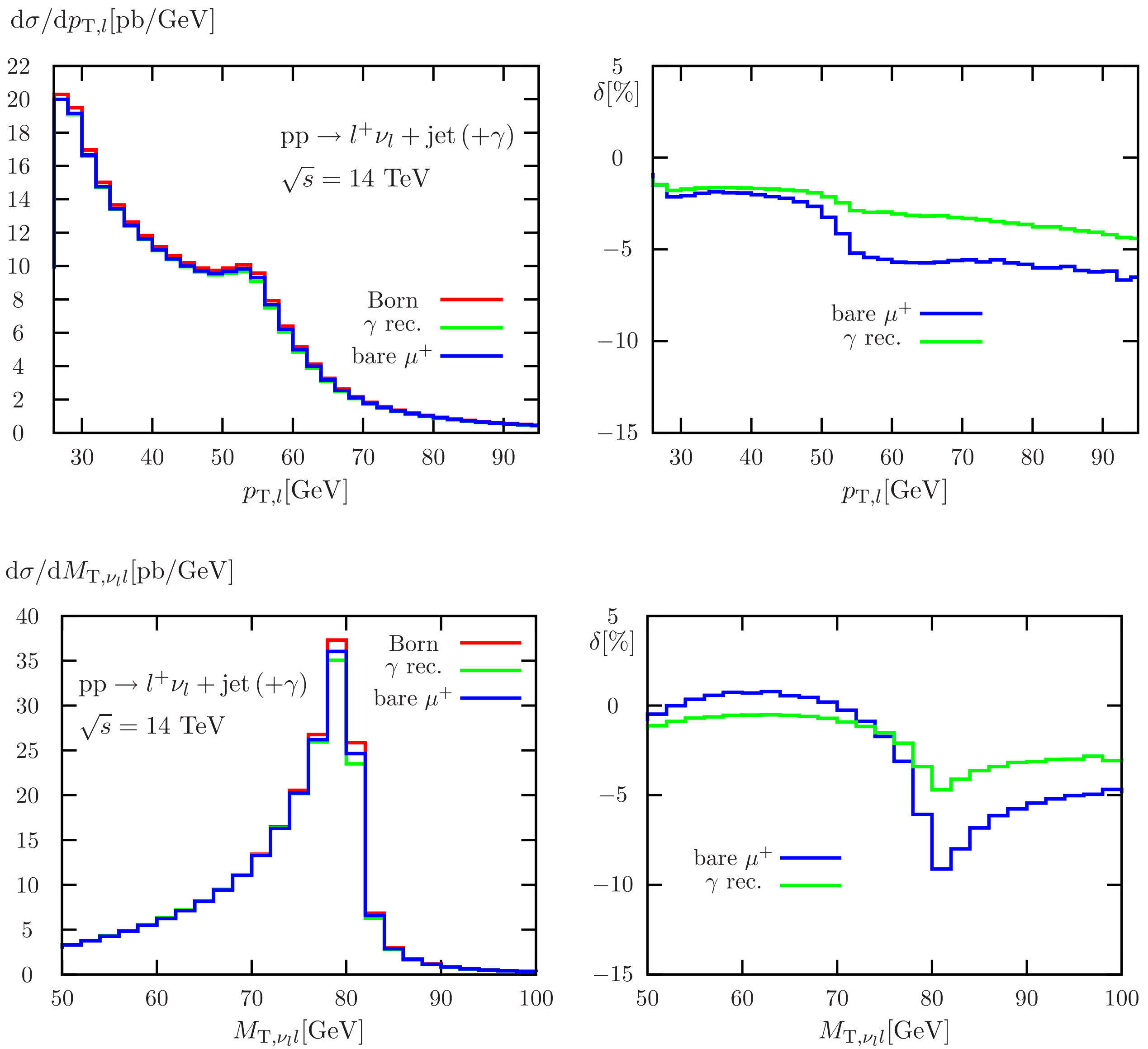
EW corrections:



- corrections of $\mathcal{O}(5\text{–}10\%)$
- Jacobian peak significantly distorted

Comparison of EW corrections to W+jet and single (jet-inclusive) W production

$\hookrightarrow$ interesting for W-mass determination via single-W production



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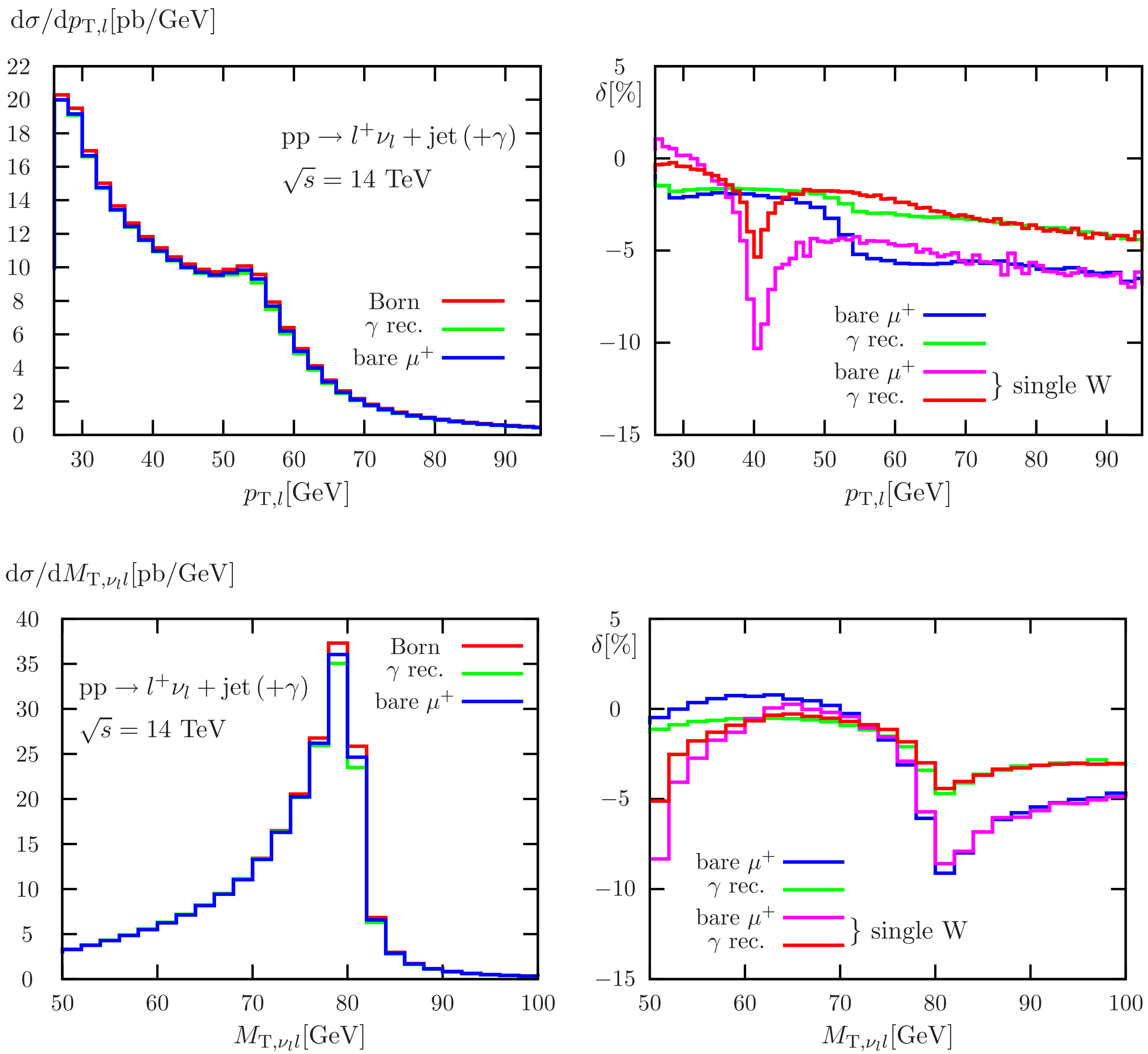


relative EW corrections
completely different

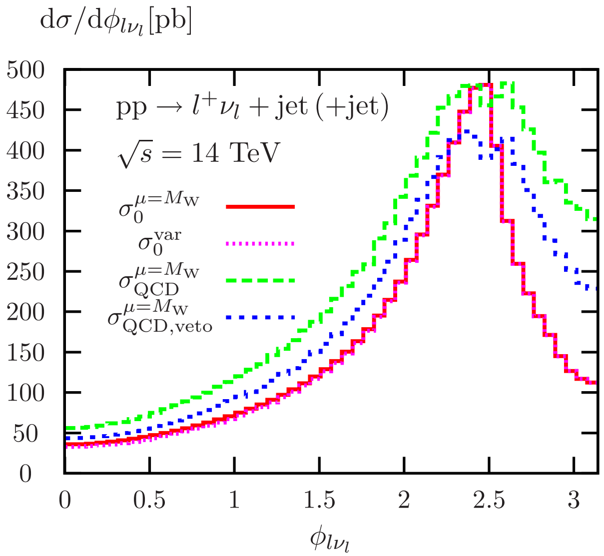
For single-W in NLO EW, see

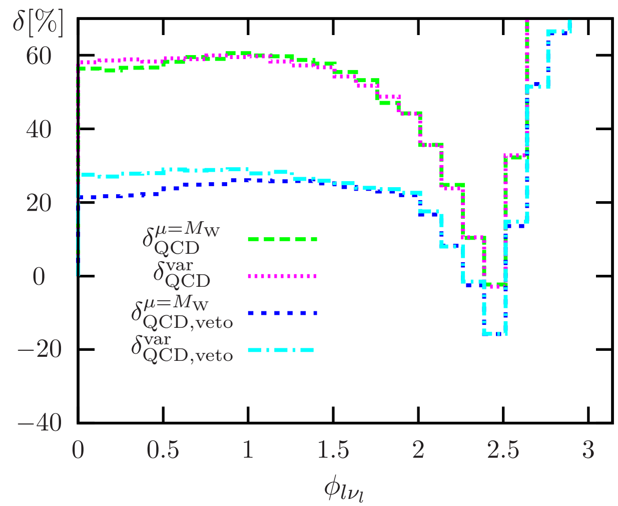
- Baur et al. '98/'04
- S.D./Krämer '01
- Arbuzov et al. '06
- Carloni Calame et al. '06

relative EW corrections
practically identical
near Jacobian peak

Distribution in the lepton–neutrino ($\not{p}_{\mathrm{T}}$) azimuthal angle in the transverse plane

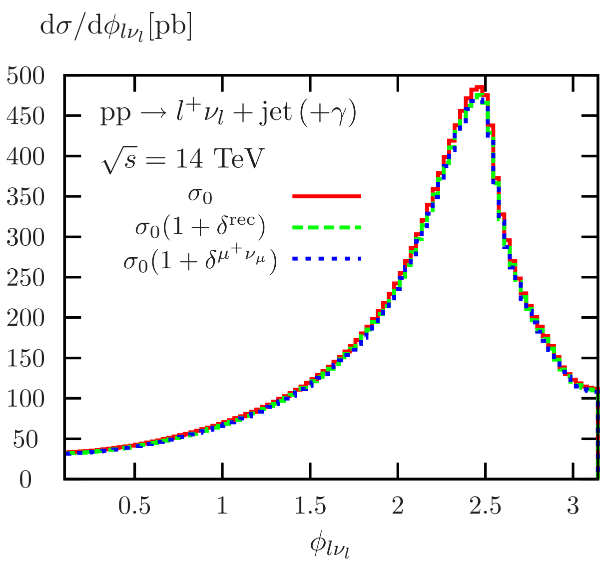
QCD corrections:

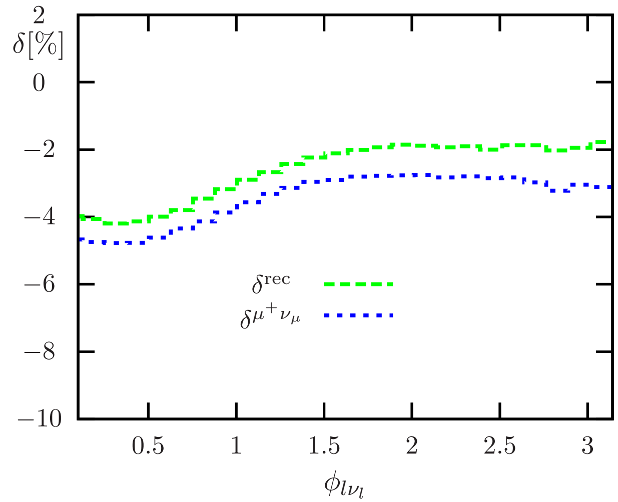




- significant distortion of shape
- corrections reduced by jet veto

EW corrections:





corrections small and relatively smooth

4 Conclusions

W+jet production is a very important process at Tevatron and LHC.
(standard candle, W mass, background, etc.)

Our calculation provides

- recalculation of NLO QCD corrections
- first calculation of NLO EW corrections including full off-shell effects
  (e.g. relevant for W-mass determination)
  $\hookrightarrow$ building block for NNLO corrections of $\mathcal{O}(\alpha\alpha_\mathrm{s})$ for single-W production

Size of corrections:

- EW corrections particularly large at high p_T of leptons and jets
- photon-induced processes and EW–QCD interferences phenomenologically unimportant

Outlook:

- low-p_T range should be further improved by soft-gluon resummation or by merging with parton showers
- off-shell Z+jet production straightforward with the same approach