Electroweak corrections to W/Z+jet production at the LHC

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in collaboration with

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HP^2.3rd

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Outline

- W/Z production at the LHC
- W/Z+jet production:

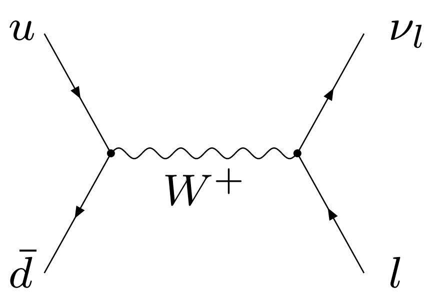
$$pp \to W/Z + \text{jet} \to l\nu_l/ll + \text{jet}$$

  - motivation and theoretical status
  - Electroweak and QCD corrections
  - Numerical results for the LHC
- Conclusions

W/Z Production at the LHC

Charged-current Drell-Yan:

$$pp \to W^{\pm} \to l^{\pm}\nu_l$$



- clean signal: lepton + missing p_{T}
- huge cross section: $\sigma_{W^+\to\mu^+\nu_\mu} = 3$ nb (Atlas cuts at 7 TeV)

  $\Rightarrow$ 2 events per minute at LHC right now

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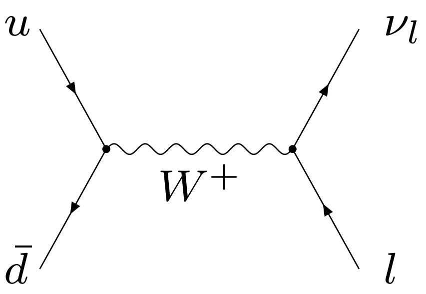

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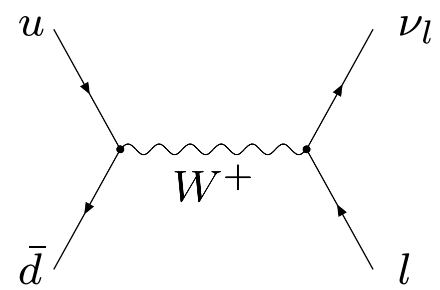

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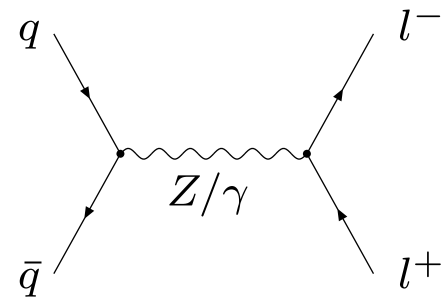
Neutral-current Drell-Yan:

$$pp \to Z/\gamma \to l^+ l^-$$



- clean signal: charged lepton pair
- huge cross section: $\sigma_{Z \to \mu^+ \mu^-} = 0.5$ nb (Atlas cuts at 7 TeV)
- very useful: calibration, luminosity, PDFs

W/Z Production at the LHC

Theory status:

- QCD: NNLO, resummation, parton shower matching
- EW: NLO, leading higher order contributions

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$$d\sigma = d\sigma_{\mathrm{MC@NLO}} + \left(d\sigma^{\mathrm{HORACE}}_{\mathrm{EW}} - d\sigma_{\mathrm{Born}}\right)_{\mathrm{HERWIG-PS}} \quad \text{etc.}$$

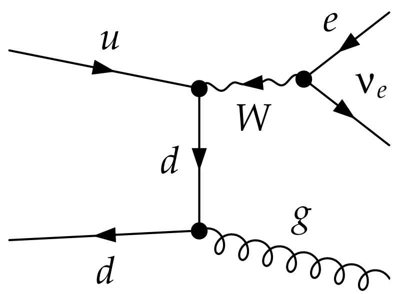
Balossini et al. [arXiv:0907.0276]

hard QCD radiation + EW corrections?

$\Rightarrow$ look at EW corrections for W/Z+jet production

W/Z+jet production

$pp \to l\nu_l/l^+l^- + \text{jet}$:



- large cross section (~ 10% of inclusive sample)
- dominant SM channel for high p_T leptons
- precision tests for jet dynamics
- W+jet(s) important background for many searches (high p_T lepton, missing energy, jet(s))

W/Z+jet production

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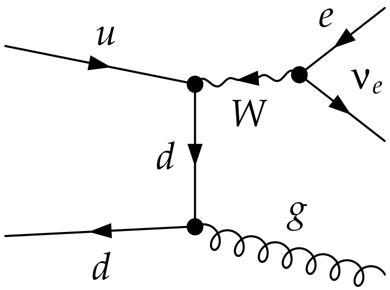

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Theoretical status:

- NLO QCD corrections known and available

DYRAD: Giele et al. [hep-ph/9302225]

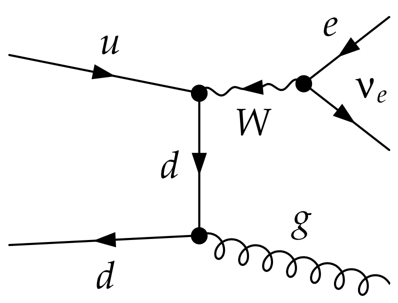
MCFM: Campbell, Ellis [hep-ph/0202176]

and as part of NNLO single W: Melnikov, Petriello [hep-ph/0609070]

Catani et al. [arXiv:0903.2120]

W/Z+jet production

$pp \to l\nu_l/l^+l^- + \text{jet}$:



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Theoretical status:

- NLO QCD corrections known and available
- EW corrections for stable (on-shell) W/Z bosons

Z+jet: Kühn, Kulesza, Pozzorini, Schulze [hep-ph/0408308], [hep-ph/0507178]

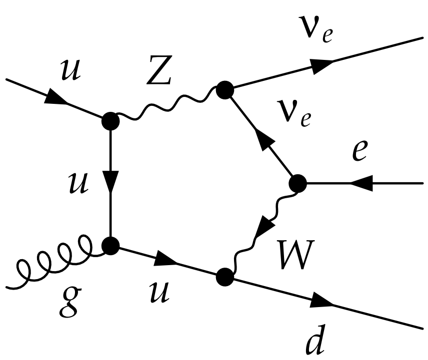
W+jet: Kühn, Kulesza, Pozzorini, Schulze [hep-ph/0703283], [arXiv:0708.0476]
Hollik, Kasprzik, Kniehl [arXiv:0707.2553]

EW corrections

Complete EW corrections calculated

W+jet: Denner, Dittmaier, Kasprzik, AM [arXiv:0906.1656]

Z+jet: internal comparison just finished



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$\mathcal{O}(100)$ diagrams for W,

$\mathcal{O}(200)$ diagrams for Z

per partonic channel

- physical final state
- all off-shell effects included
- part of the $\mathcal{O}(\alpha\alpha_s)$ corrections for incl. W production

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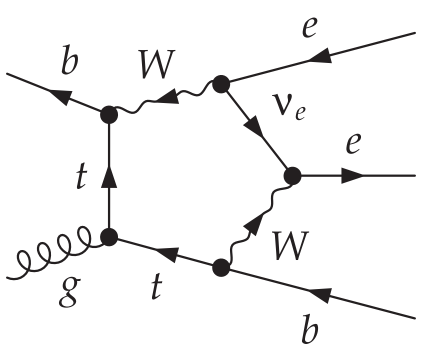

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tops in the loop for Z in bottom initiated processes

- W/Z+jet very similar in general
- more partonic channels, diagrams, helicities for Z+jet

EW corrections

Complete EW corrections calculated

- stable reduction scheme for tensor integrals

  Denner, Dittmaier [hep-ph/0509141]

  - avoid inverse Gram determinants for pentagon reduction
  - expand around vanishing determinants in critical phase-space regions

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- complex mass scheme for resonances

  Denner, Dittmaier, Roth, Wieders [hep-ph/0505042]

  - use complex W and Z masses everywhere by means of complex renormalization:

    $$M_{\mathrm{V},0}^2 = \mu_{\mathrm{V}}^2 + \delta\mu_V^2$$

    with: $M_{\mathrm{V},0}^2$ = bare mass $(\mathrm{V} = \mathrm{W}, \mathrm{Z})$
    μ_{V}^2 = ren. complex mass
    $\delta\mu_V^2$ = complex counterterm

  - $\Rightarrow$ complex $s_{\mathrm{W}}^2 = 1 - \mu_{\mathrm{W}}^2/\mu_{\mathrm{Z}}^2$
  - loop-integrals for complex masses needed

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- dipole subtraction for infrared divergencies

  Catani, Seymour [hep-ph/9605323]

  Dittmaier [hep-ph/9904440]

  - subtraction formalism also for non-collinear safe observables e.g. for bare muons (without lepton–photon recombination)

    $\Rightarrow$ muon-mass logarithms extracted analytically

    Dittmaier, Kabelschacht, Kasprzik [arXiv:0802.1405]

  - phase-space slicing used as a check

non collinear-safe subtract.

- usual subtraction procedure:

$$\int \mathrm{d}\Phi_{n+1}\, |\mathcal{M}|^2 = \int \mathrm{d}\Phi_{n+1} \left(|\mathcal{M}|^2 - |\mathcal{M}_{\mathrm{Sub}}|^2\right) + \int \mathrm{d}\Phi_n \int \mathrm{d}k_\gamma\, |\mathcal{M}_{\mathrm{Sub}}|^2$$

- clever choice of $|\mathcal{M}_{\mathrm{Sub}}|^2$

  $\Rightarrow \left(|\mathcal{M}|^2 - |\mathcal{M}_{\mathrm{Sub}}|^2\right)$ is integrable

  $\Rightarrow \int \mathrm{d}k_\gamma\, |\mathcal{M}_{\mathrm{Sub}}|^2$ can be done analytically

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  - $\mathcal{M}_{\mathrm{Sub}} = \sum_f \mathcal{M}_{\mathrm{Sub}}(p_{\mathrm{jet}}, z_f)$ where $z_f \to p_f^0/(p_f^0 + p_\gamma^0)$, $p_{\mathrm{jet}} \to p_f^0 + p_\gamma^0$ for collinear events
  - only cuts on p_{jet}, no cuts on p_f $\Rightarrow$ cuts independent of z_f

    $\Rightarrow z_f$ integration can be done analytically

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- non-collinear safe implementation:
  - no recombination: cuts on p_f allowed
  - cut on z_f in $\mathcal{M}_{\mathrm{Sub}}$ to ensure cancellation of singularities
  - integrate over z_f in $\mathrm{d}k_\gamma$ numerically

    (soft divergence treated via Plus-distribution
    in analogy to treatment of initial-state emitters/spectators)

photon–jet recombination

Treat photon like another parton?

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- Yes: Photon–jet recombination mandatory for infrared safe observables (poles in q $\to$ qγ splitting)

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The problem: V+jet $\Leftrightarrow$ V+photon

- do not distinguish (also calculate V+γ and its NLO QCD corr.)
- or use a sophisticated isolation Frixione [hep-ph:9801442]
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$\Rightarrow$ this is what we want; But: not infrared safe

photon–jet recombination

What does z_γ cut imply?

- sensitivity to $q \to q\gamma$ splitting
- non-perturbative corrections to be included

photon–jet recombination

What does z_γ cut imply?

- sensitivity to $q \to q\gamma$ splitting
- non-perturbative corrections to be included
- introduce quark-to-photon fragmentation function $D_{q\to\gamma}(z_\gamma, \mu_F)$
  - measured in hadronic Z decays at LEP ($\mathrm{Z} \to \mathrm{q\bar{q}} \to \mathrm{q\bar{q}}\gamma$)
  - using ALEPH fit:

$$D_{q\to\gamma}(z_\gamma, \mu_F) = \frac{\alpha Q_q^2}{2\pi} P_{q\to\gamma}(z_\gamma) \left(\ln \frac{m_q^2}{\mu_F^2} + 2 \ln z_\gamma + 1 \right) + D_{q\to\gamma}^{\mathrm{ALEPH}}(z_\gamma, \mu_F),$$

where
$$D_{q\to\gamma}^{\mathrm{ALEPH}}(z_\gamma, \mu_F) = \frac{\alpha Q_q^2}{2\pi} \left(P_{q\to\gamma}(z_\gamma) \ln \frac{\mu_F^2}{(1-z_\gamma)^2 \mu_0^2} + C \right)$$

$$P_{q\to\gamma}(z_\gamma) = \frac{1 + (1-z_\gamma)^2}{z_\gamma}$$

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up to $\mathcal{O}(\alpha^3\alpha_s)$

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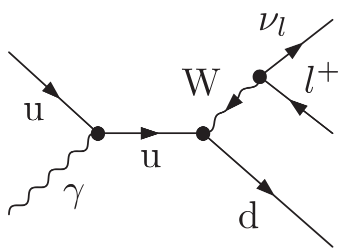
- photon-induced processes



at NLO QCD
(phenomenologically irrelevant)

up to $\mathcal{O}(\alpha^3\alpha_s)$

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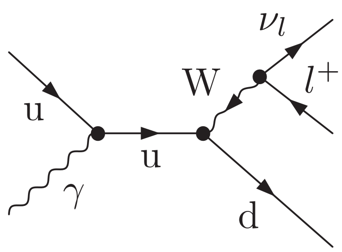
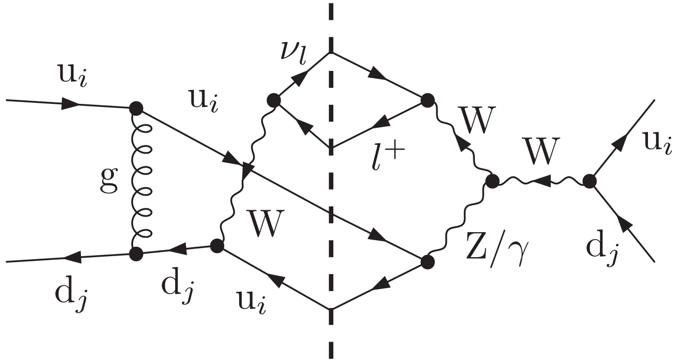


at NLO QCD
(phenomenologically irrelevant)

- QCD-EW interference terms in 4-quark processes



(phenomenologically irrelevant, dropped for Z+jet)

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Monte-Carlo programs

two completely independent calculations

- in mutual agreement

- FeynArts 1.0 [Böhm, Denner, Küblbeck]
  in-house Mathematica Routines
  loop integral library: DD [Dittmaier]
  Vegas integration

- FeynArts 3.2,FormCalc 3.1 [Hahn]
  loop integral library: Coli [Denner]
  Pole [Meier, AM]
  - using Weyl-van der Waerden formalism
    Dittmaier [hep-ph/9805445]
  - automatic generation of subtraction/slicing terms
  - automatic multi-channeling using Lusifer
    Dittmaier, Roth [hep-ph/0206070]

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Setup

basic cuts

- $p_{\mathrm{T},l/\mathrm{miss/jet}} >$ 25 GeV
- $|y_{l/\mathrm{jet}}| <$ 2.5
- lepton isolation: $R_{l,\mathrm{jet}} > 0.5$
- photon-energy fraction inside jets: $z_\gamma < 0.7$

recombination

- do not recombine photons and muons (bare μ^+)
- photons and electrons: $R_{\gamma,l} < 0.1$ (γ rec.)
- photons and partons: $R_{\gamma,\mathrm{jet}} < 0.5$

renormalization and factorization scale

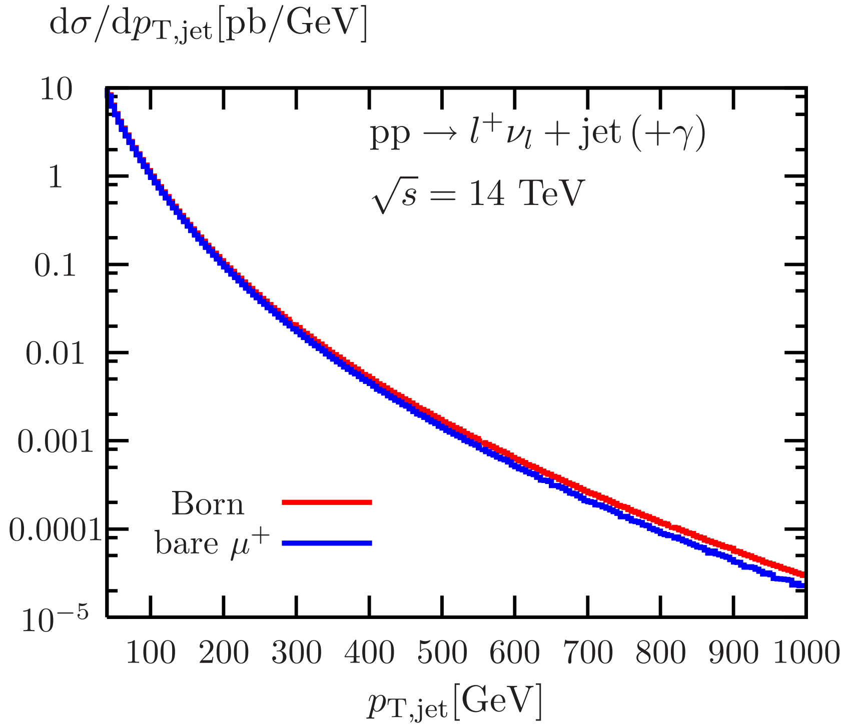
- fixed scale ($\mu = M_{\mathrm{W/Z}}$)
- variable scale: $\mu = \sqrt{M_{\mathrm{W/Z}}^2 + p_{\mathrm{T}}^{\mathrm{had}}}$ (our default choice)

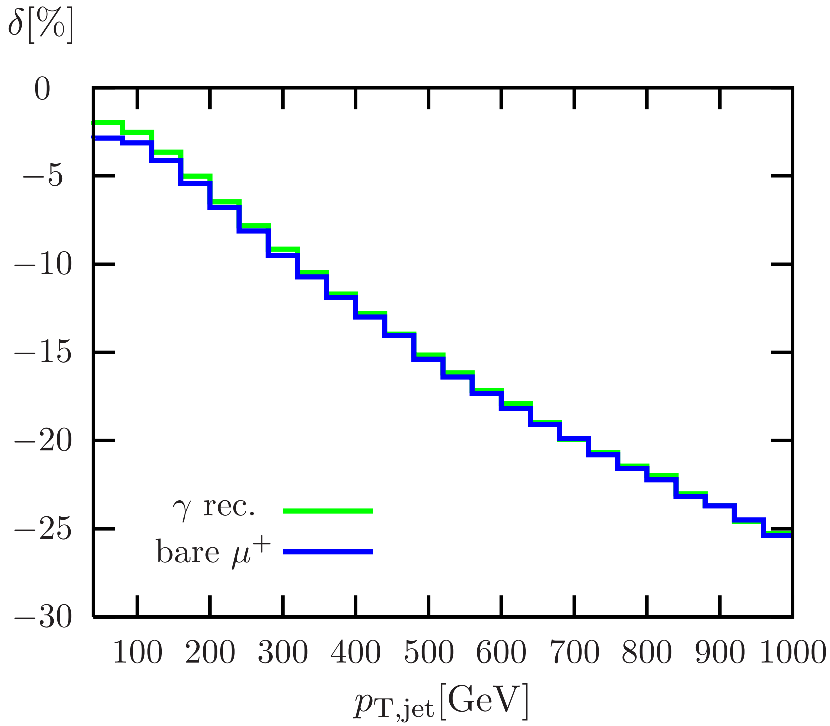
General Remarks

- PDF choice:
  - MRST2004QED $\Rightarrow$ modern PDFs
  - almost no dependence of EW corrections on PDFs
- LHC energy
  - almost no dependence of EW corrections on energy
  - also Tevatron results very similar

EW corrections

$p_{\mathrm{T,jet}}$ distribution for W+jet at the LHC:





large corrections at large energies (Sudakov logs)
(on-shell W/Z good approximation)

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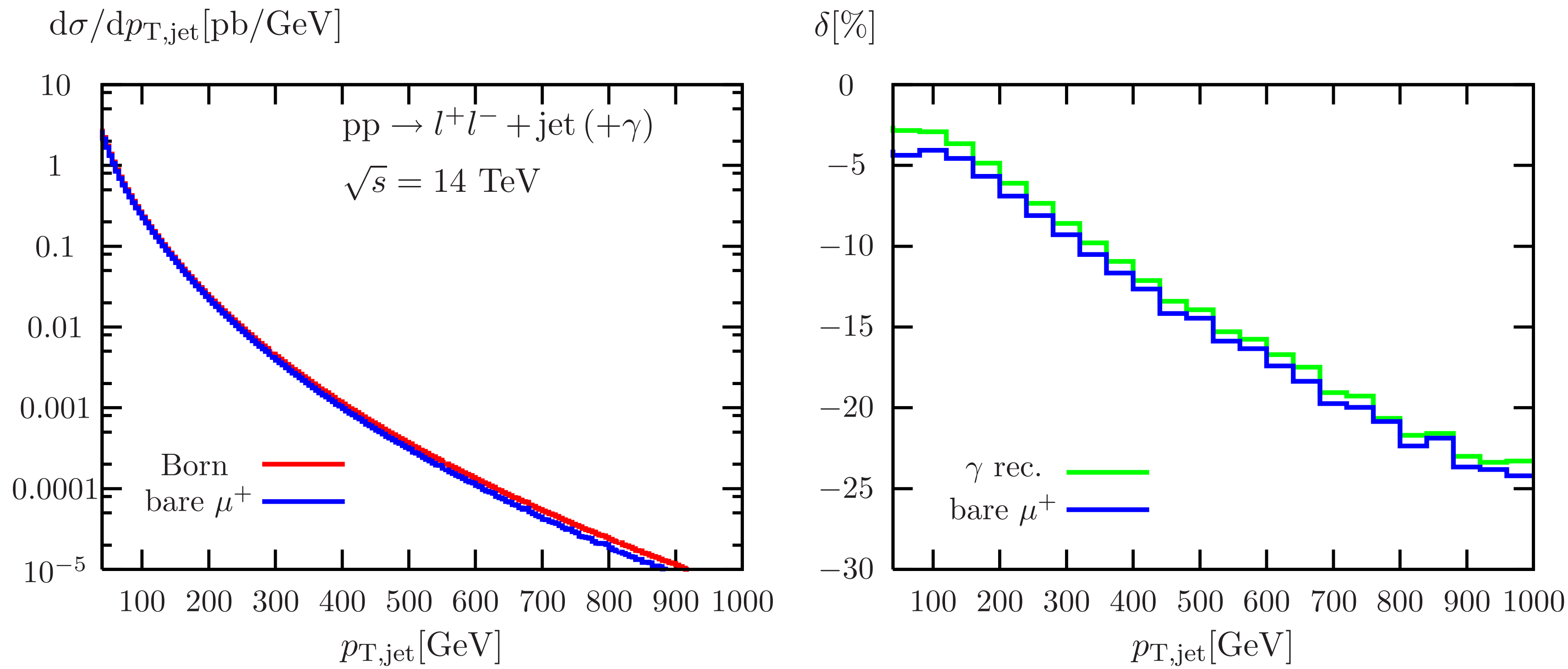

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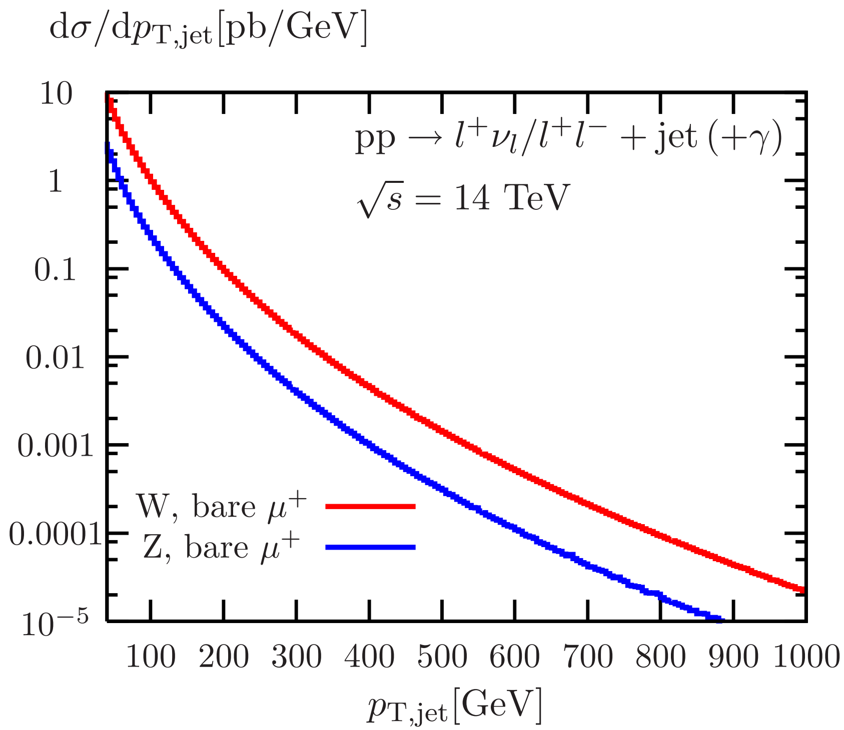

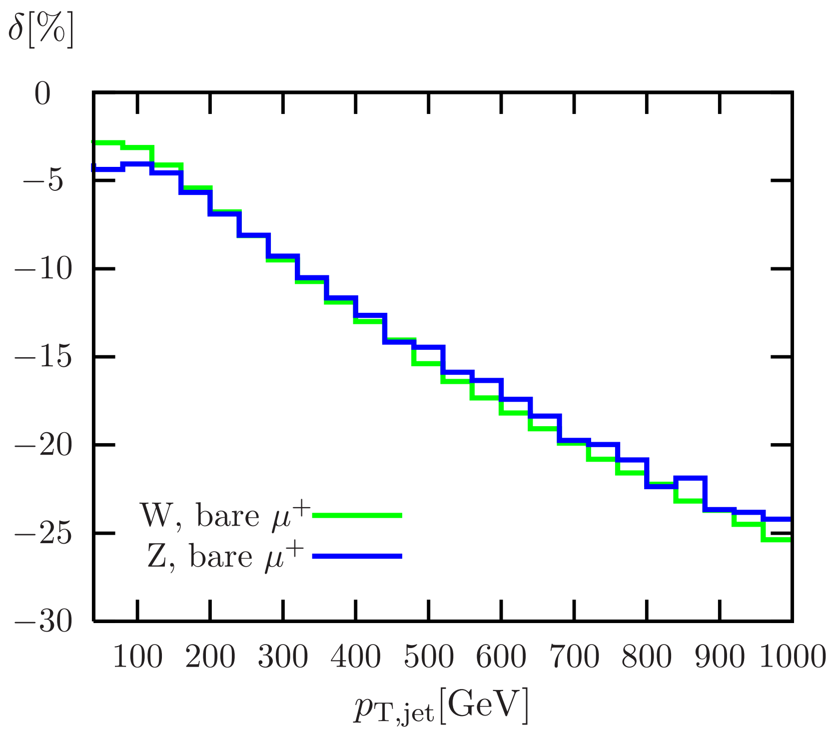

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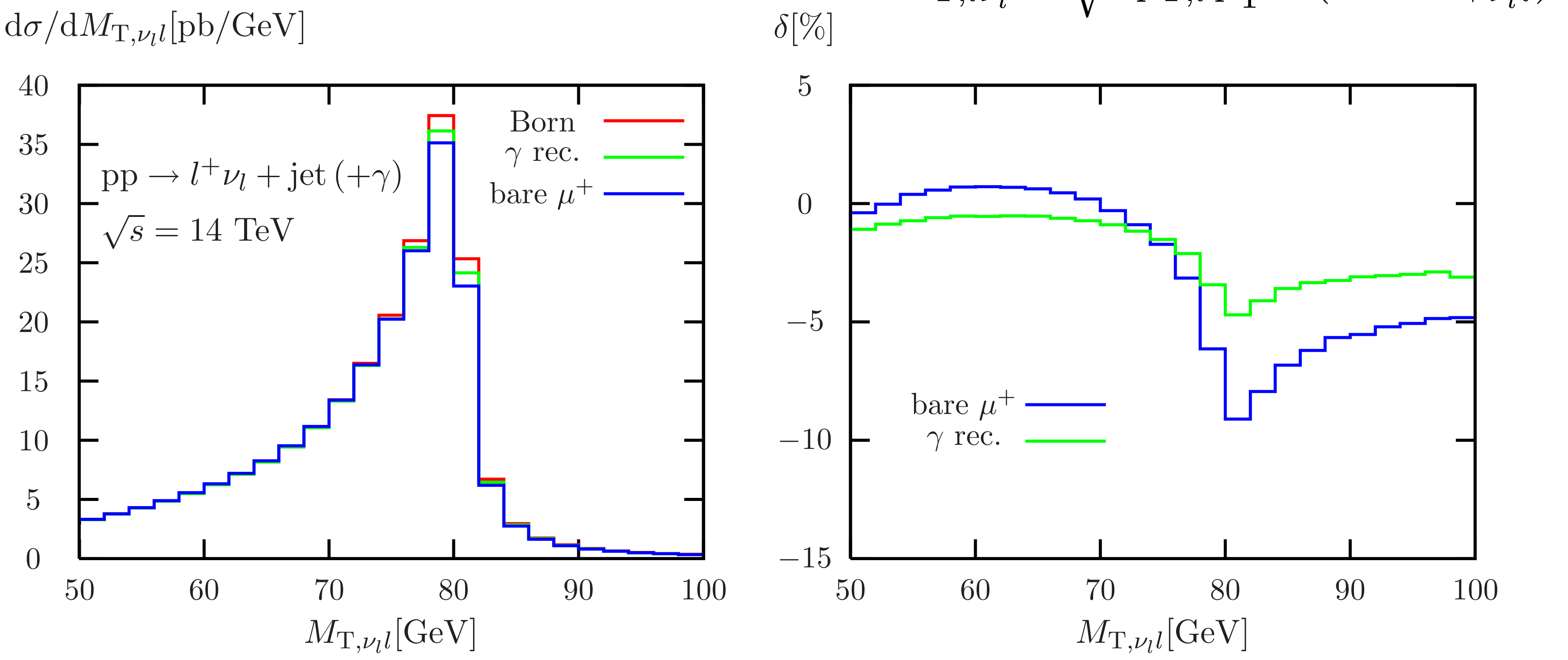
EW corrections

M_{T} distribution for W+jet at the LHC:
(similar results for the Tevatron)

$$M_{\mathrm{T},l\nu_l} = \sqrt{2\, p_{\mathrm{T},l}\, p_{\mathrm{T}}^{\mathrm{miss}}\,(1 - \cos\phi_{\nu_l l})}$$

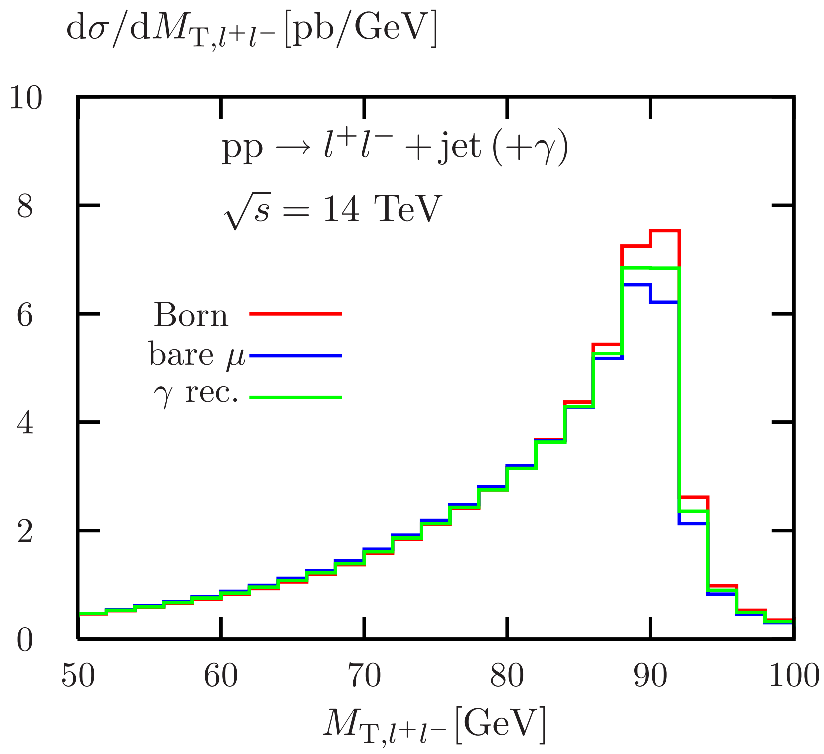


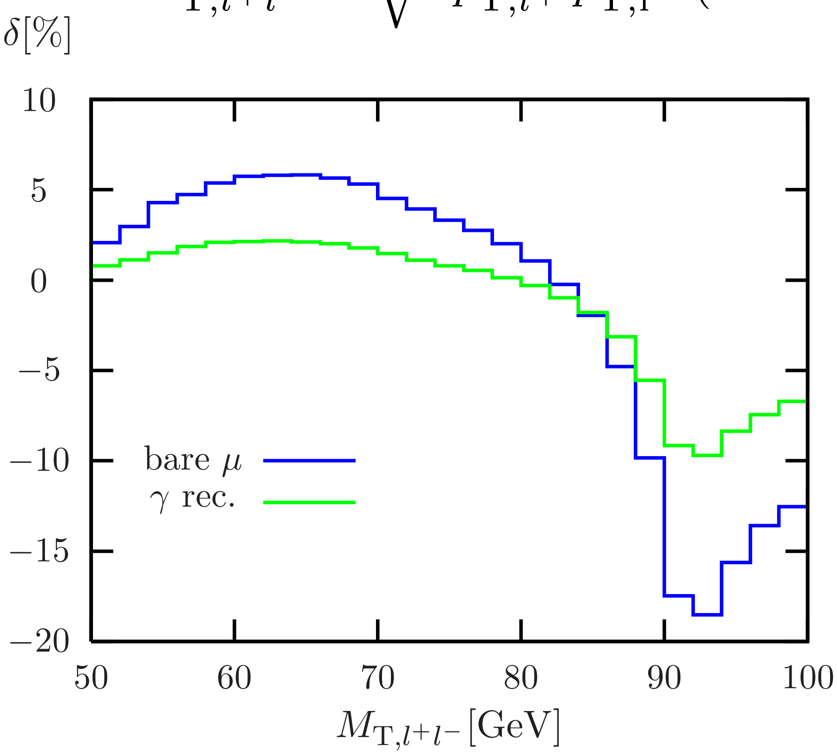
corrections dominated by (collinear) final state radiation

EW corrections

M_T distribution for Z+jet at the LHC:
(similar results for the Tevatron)

$$M_{T,l^+l^-} = \sqrt{2\, p_{T,l^+}\, p_{T,l^-}\, (1 - \cos\phi_{l^+l^-})}$$





larger correction due to second charged lepton

EW corrections

p_{T} distribution for W+jet at the LHC:
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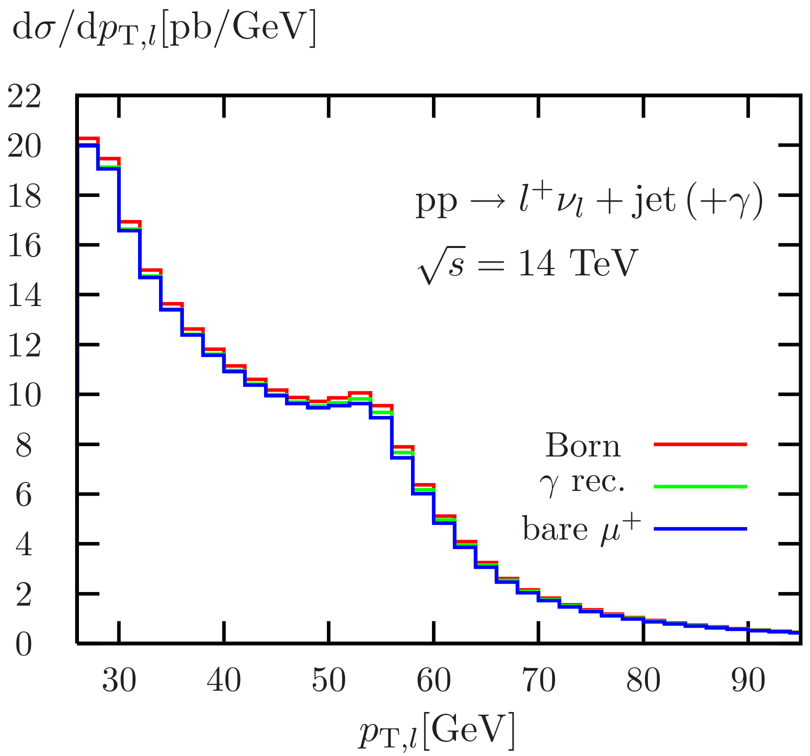
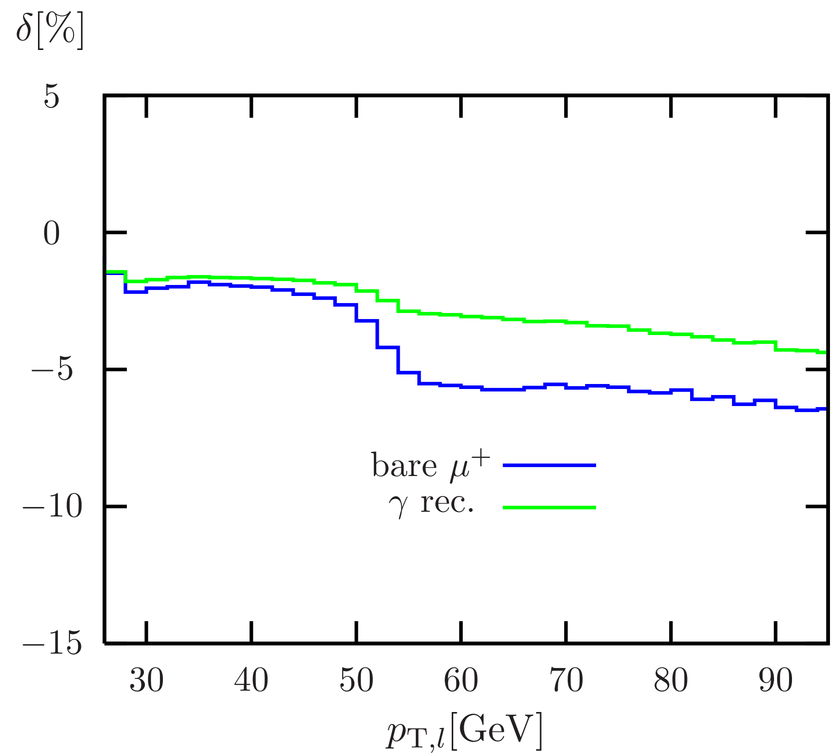
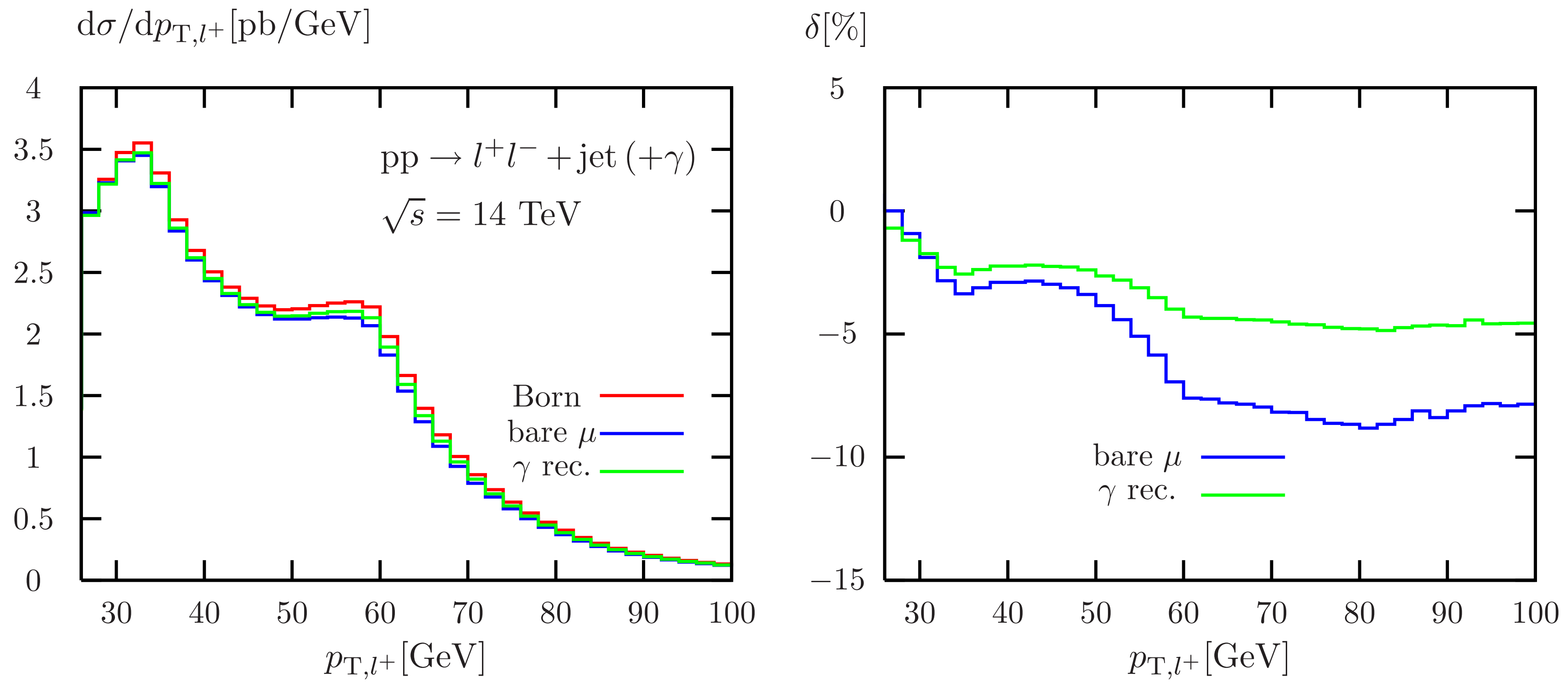




EW corrections

$p_{\rm T}$ distribution for Z+jet at the LHC:
(similar results for the Tevatron)



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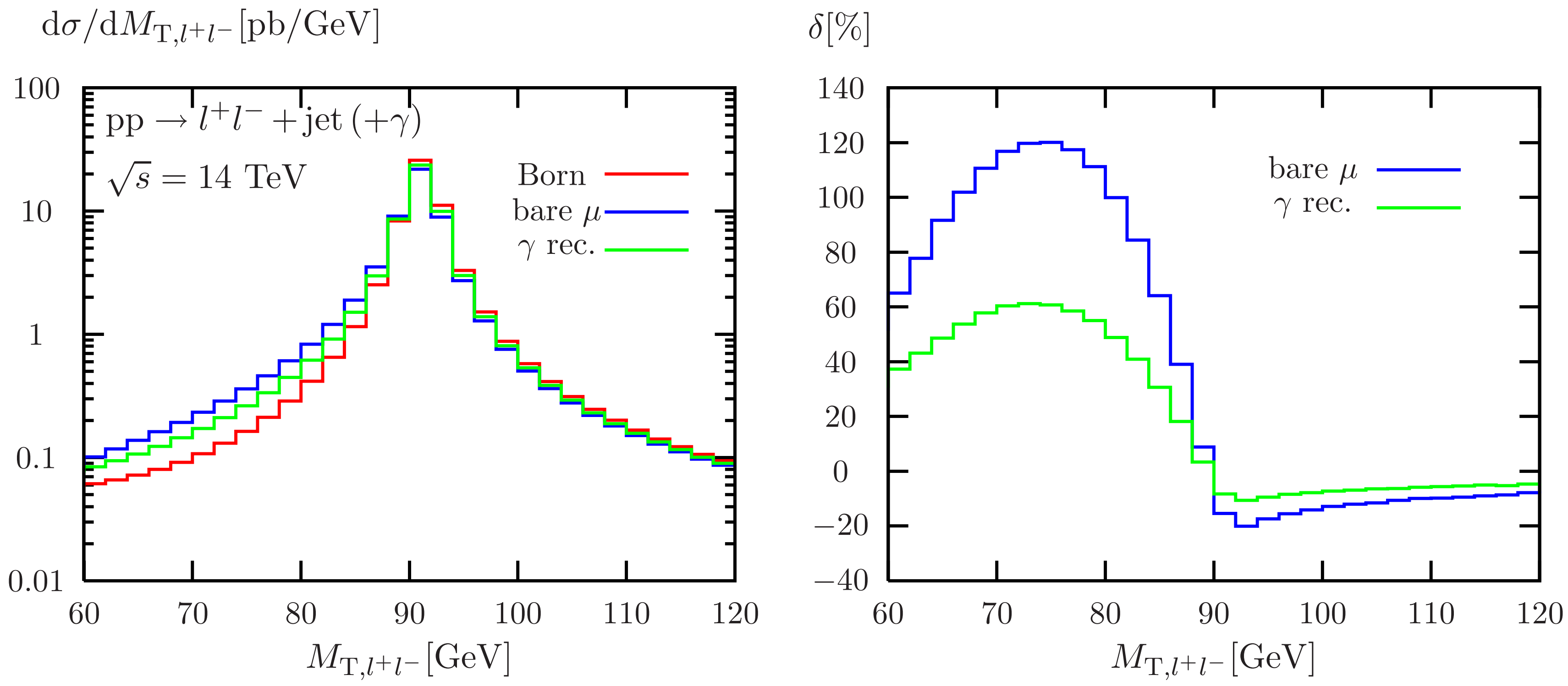
Z lineshape in Z+jet events at the LHC:



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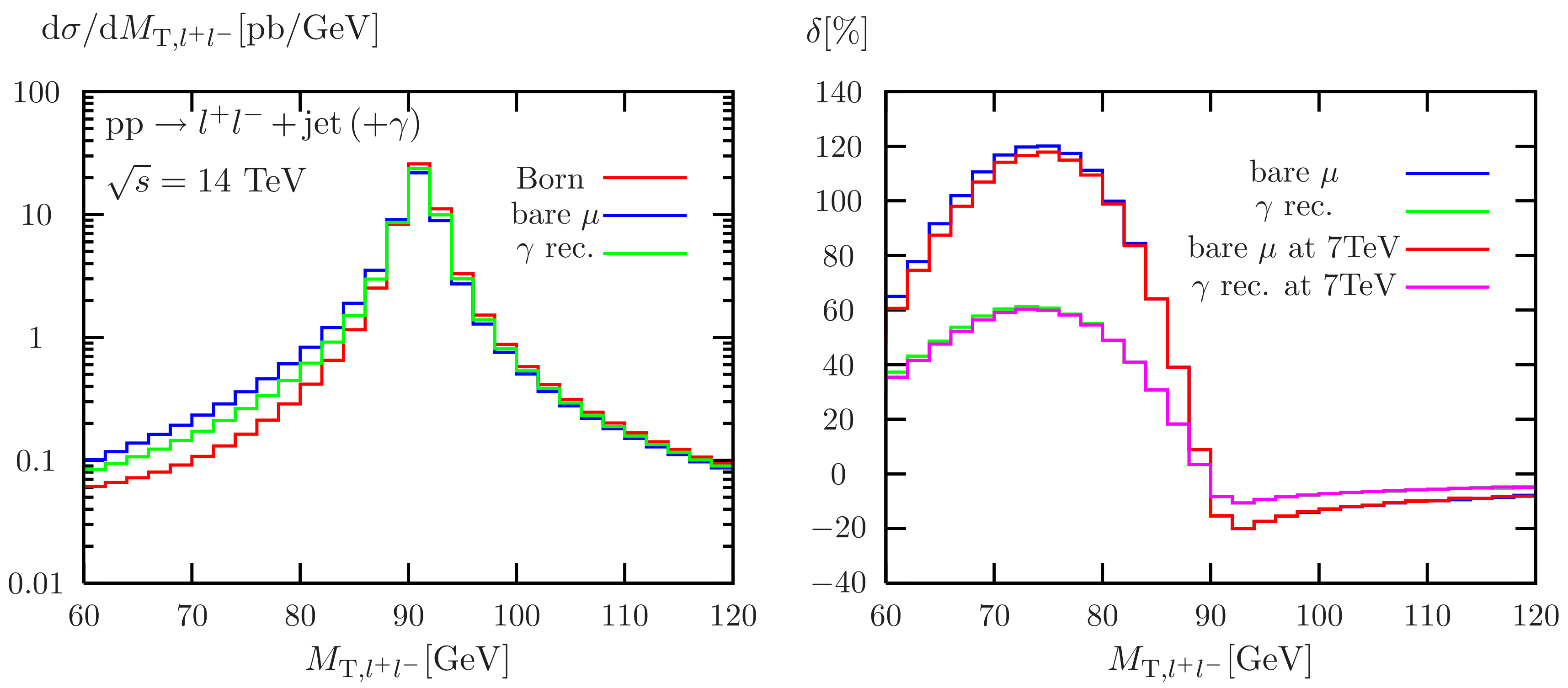
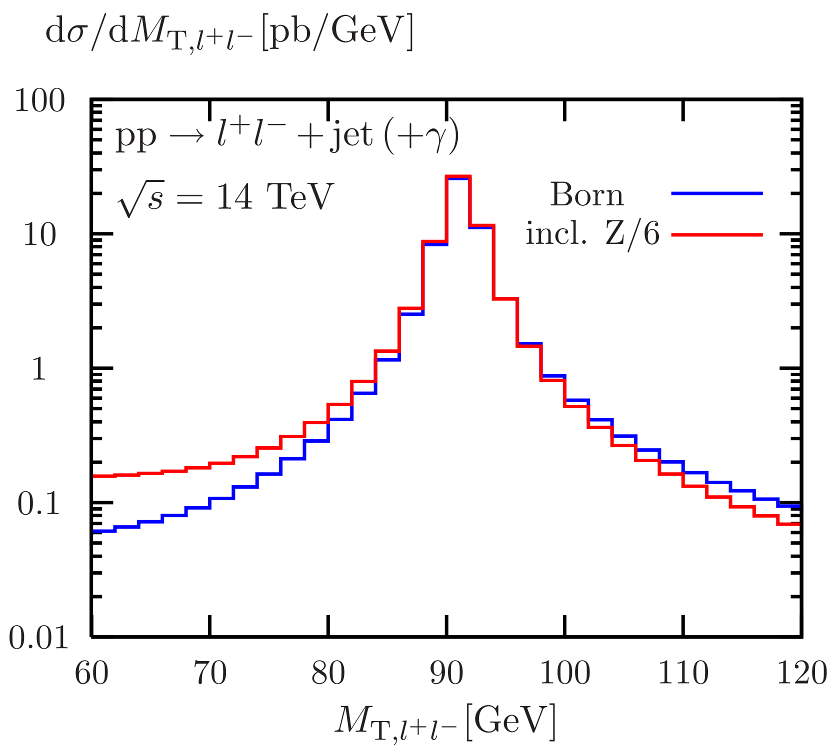
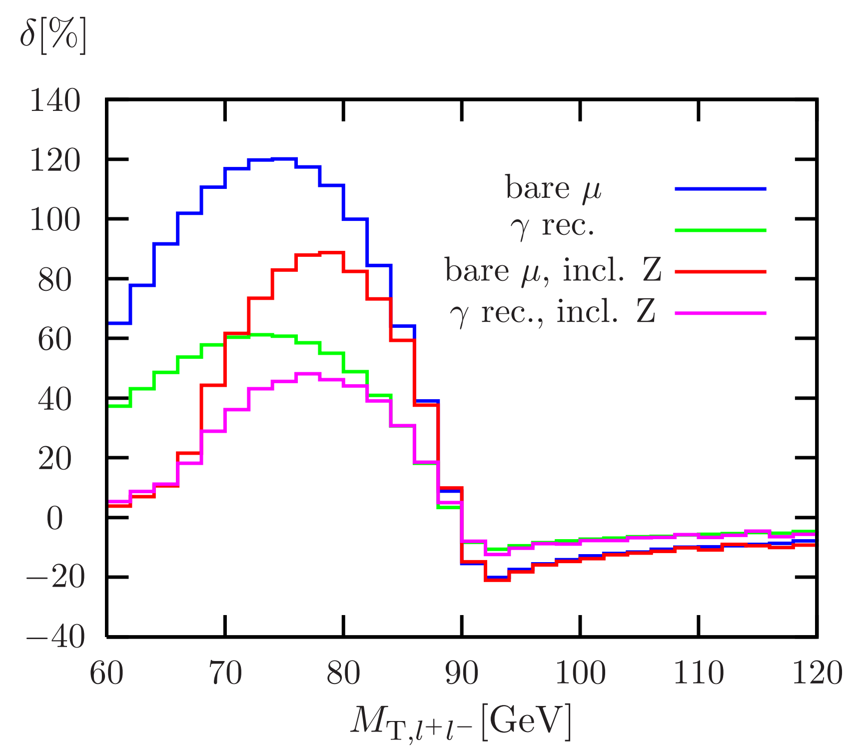


corrections hardly differ at 7 TeV

EW corrections

comparison with inclusive Z production:
(incl. Z production: Dittmaier, Huber [arXiv:0911.2329])





lineshape (and corrections) depends on $p_{\mathrm{T,Z}}$ in the tails

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Summary

- W/Z+jet are SM benchmark process
- our calculation
  - flexible Monte Carlo programs for NLO EW+QCD
  - physical final state (all off-shell effects included)
  - for single W, single Z, W+jet, Z+jet
- EW corrections
  - typically at the percent level
  - larger corrections in some distributions
  - growing with energy ($\sim -25\%$ at $p_{\mathrm{T,jet}} = 1$ TeV)
- outlook
  - more pheno, e.g. W+jet $\leftrightarrow$ Z+jet, incl. V $\leftrightarrow$ V+jet
  - Z/W+γ, Z/W+Higgs production

Back-up slides

QCD corrections

$p_{\mathrm{T,jet}}$ distribution for the LHC:

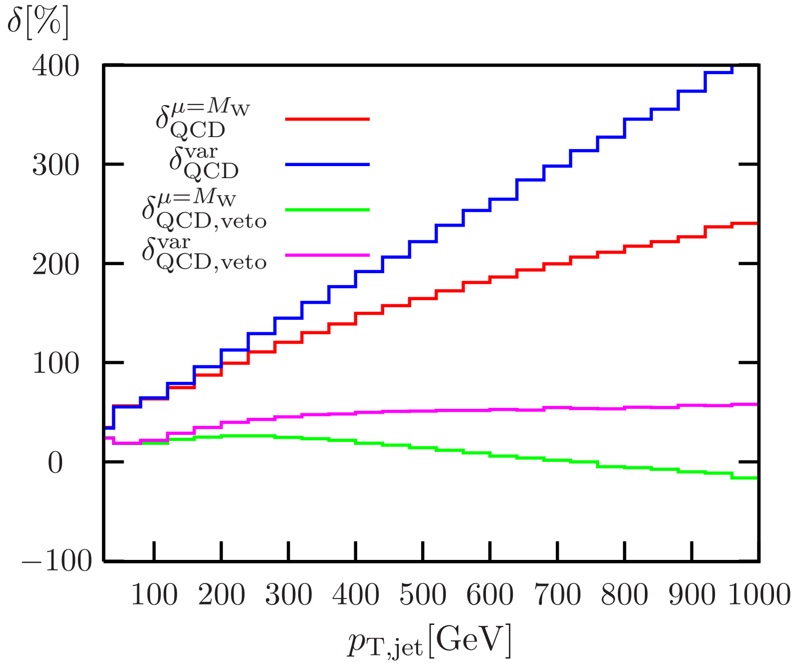
huge NLO QCD corrections:

new kinematical configuration:

back-to-back jets balance p_{T}

$\Rightarrow$ 2 jet events with W emission

$\Rightarrow$ no genuine QCD correction for W+jet



use simple jet veto:

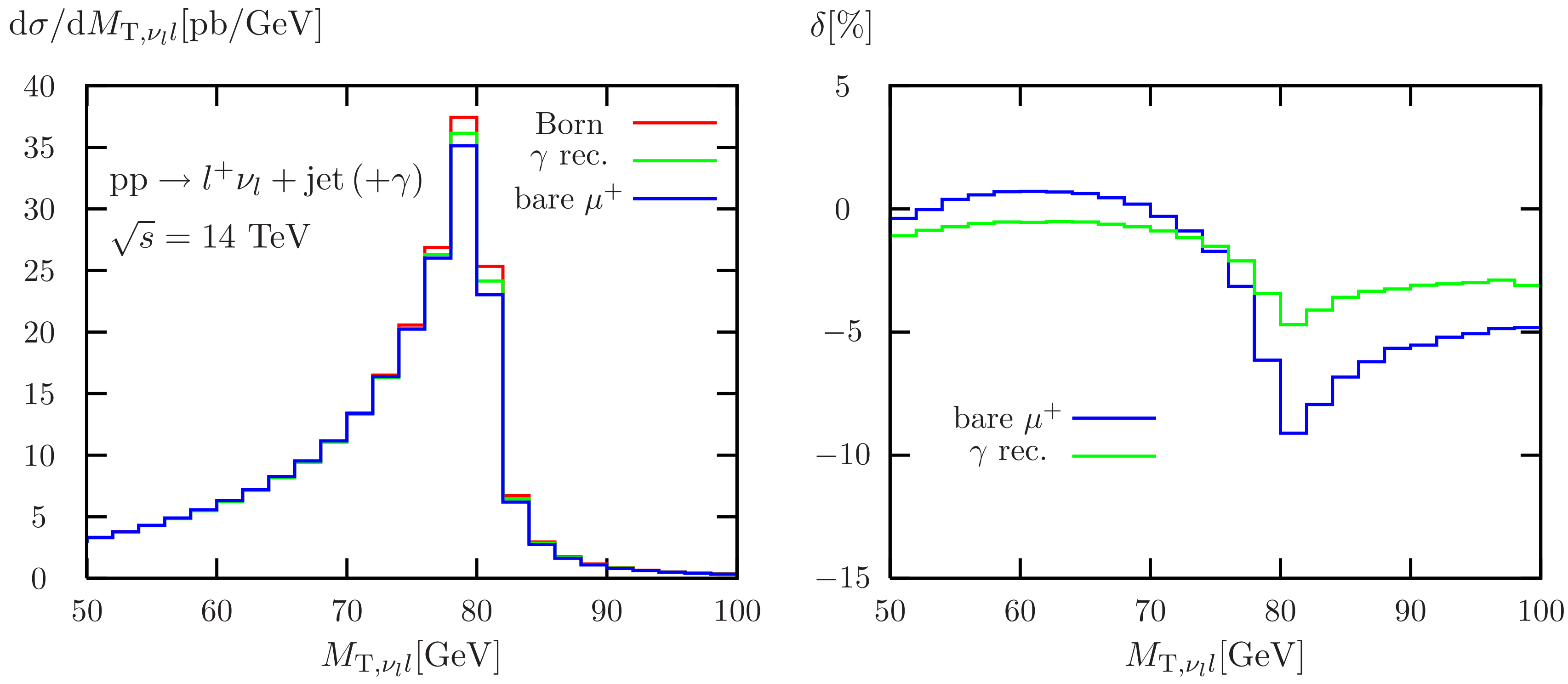
veto second jet with $p_{\mathrm{T}} > \frac{1}{2}\, p_{\mathrm{T}}^{\mathrm{lead.}}$

EW corrections

M_{T} distribution for the LHC:

(similar results for the Tevatron)

$$M_{\mathrm{T},l\nu_l} = \sqrt{2\, p_{\mathrm{T},l}\, p_{\mathrm{T}}^{\mathrm{miss}}\, (1 - \cos\phi_{\nu_l l})}$$



EW corrections

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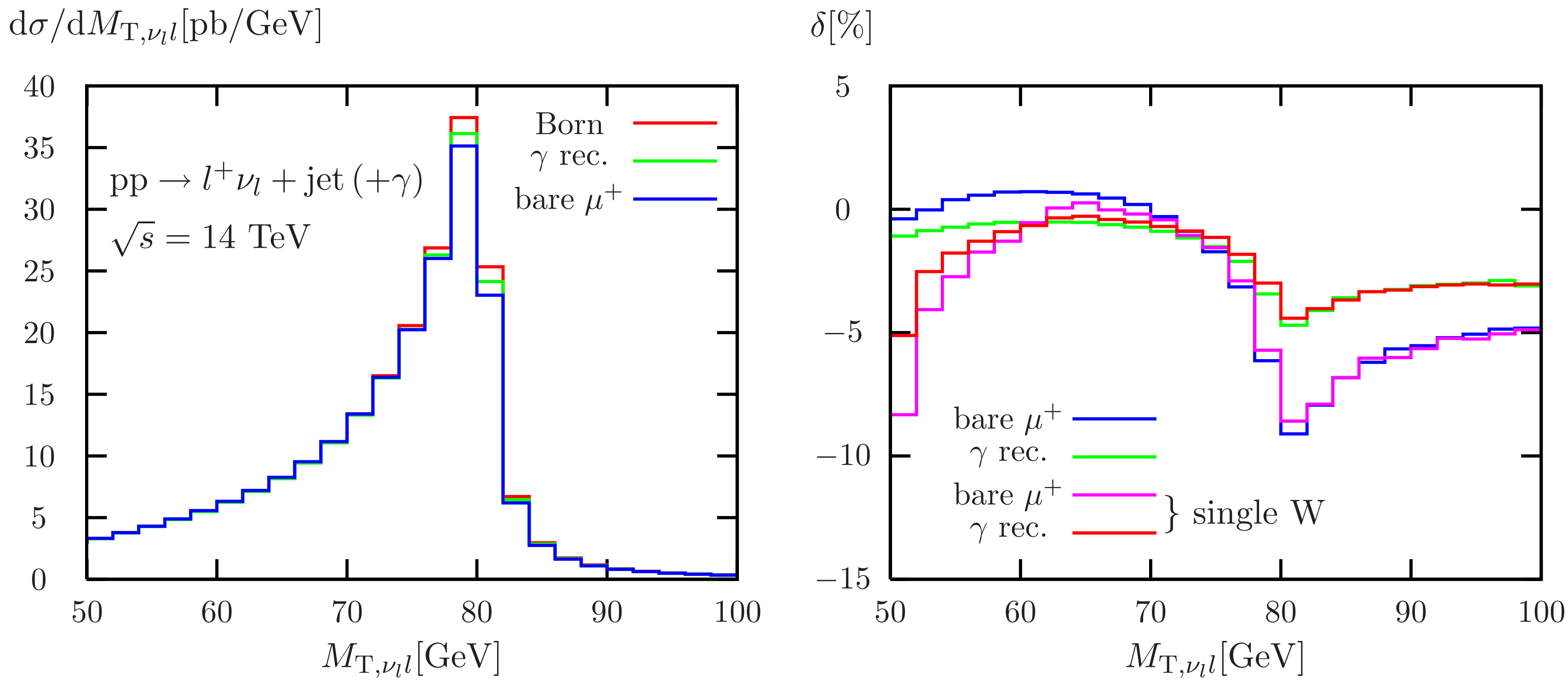
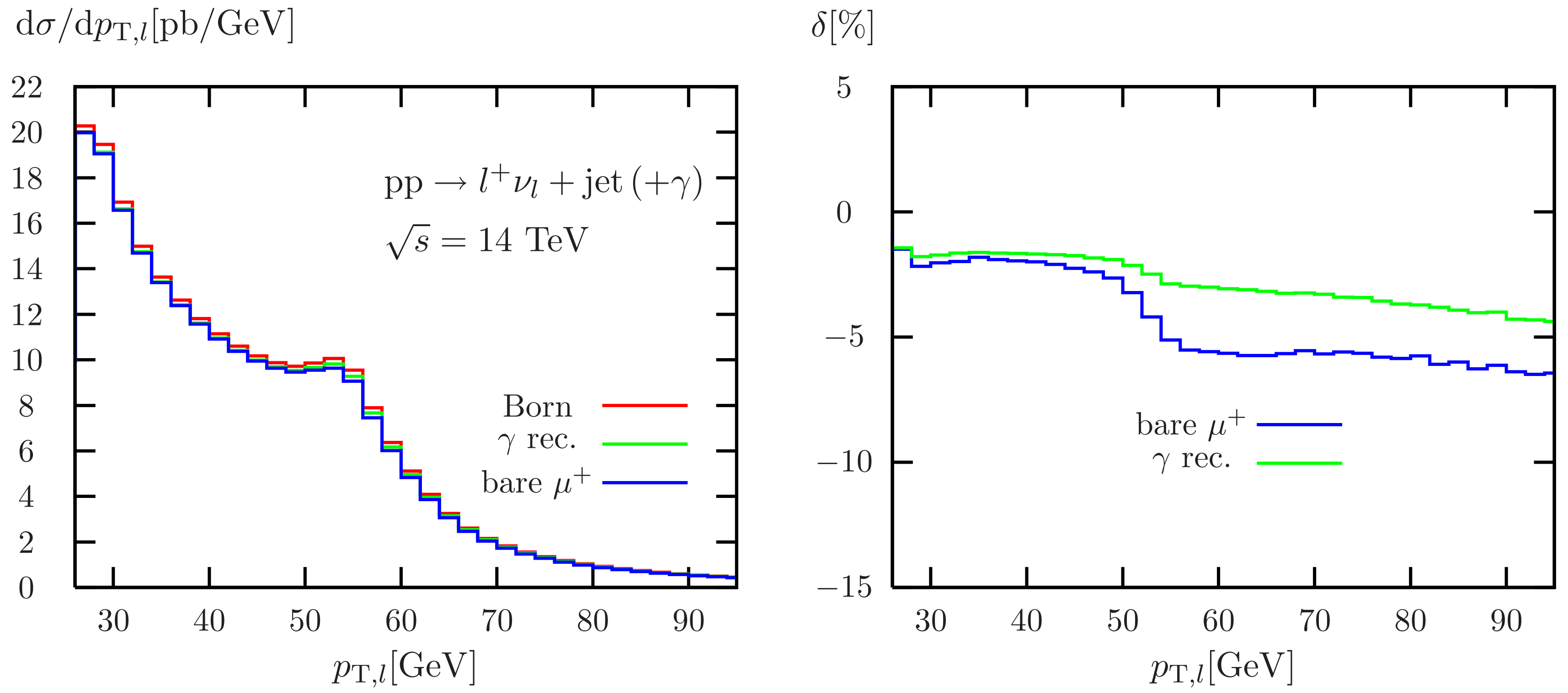


corrections very similar to single W production

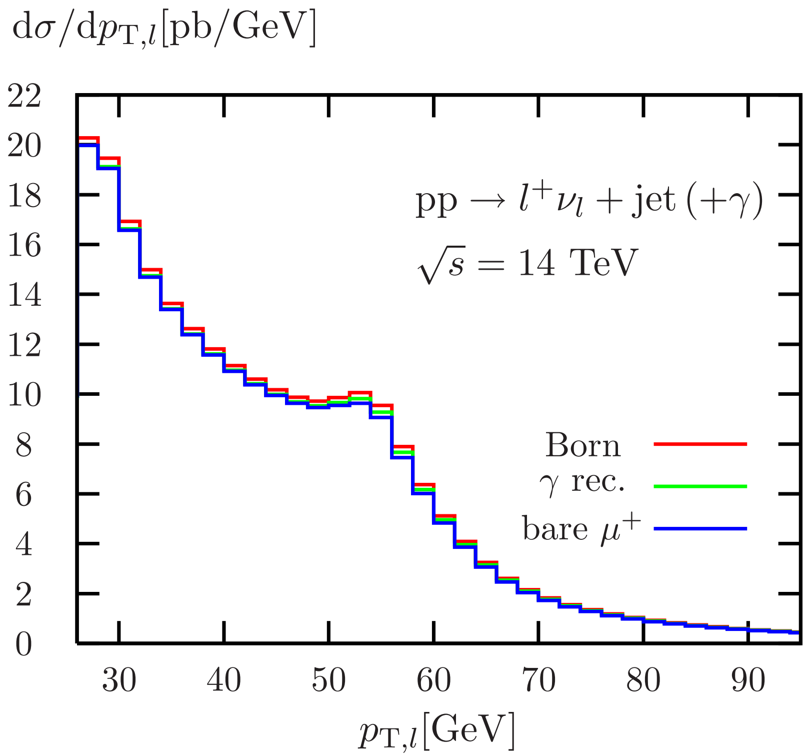
EW corrections

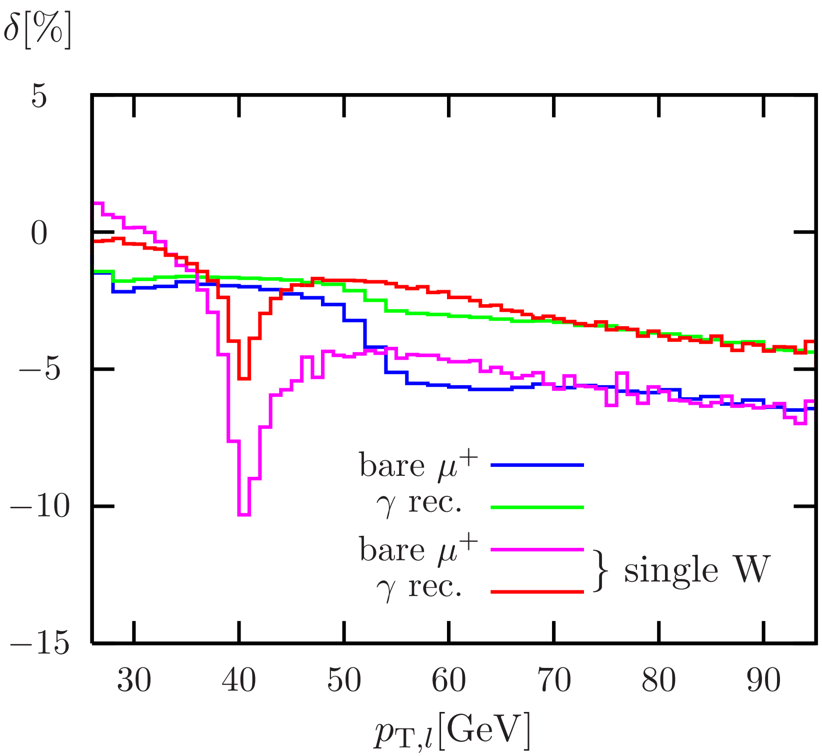
p_{T} distribution for the LHC:
(similar results for the Tevatron)



EW corrections

$p_{\rm T}$ distribution for the LHC:
(similar results for the Tevatron)





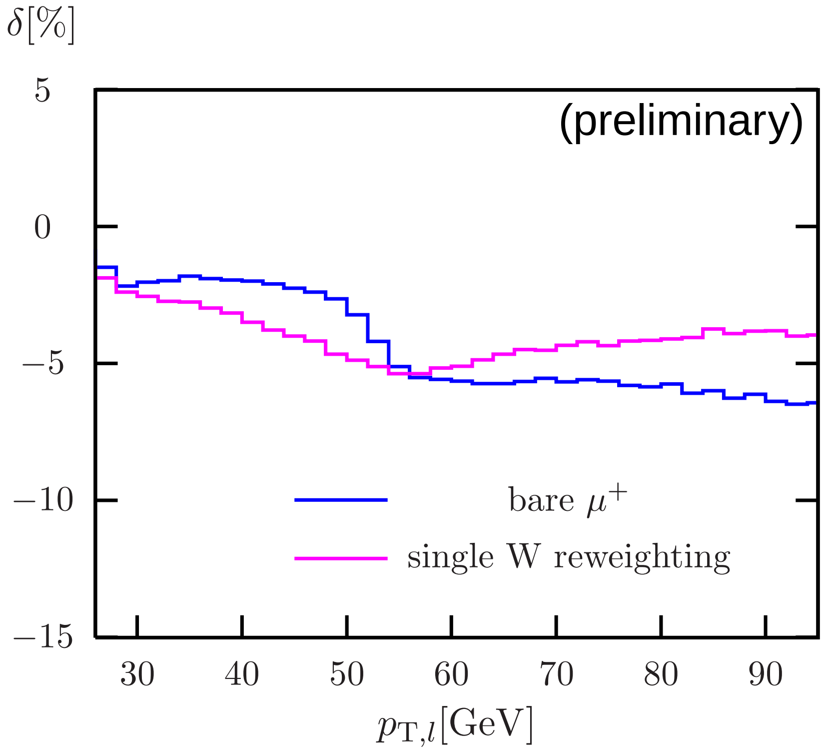
no similarity to single W production

single W vs. W+jet

p_{T} distribution for the LHC:

single W reweighting:

- boost W+jet event to W-boson rest frame
- reweight event with EW correction for single W in rest-frame $p_{T,l}$ bin

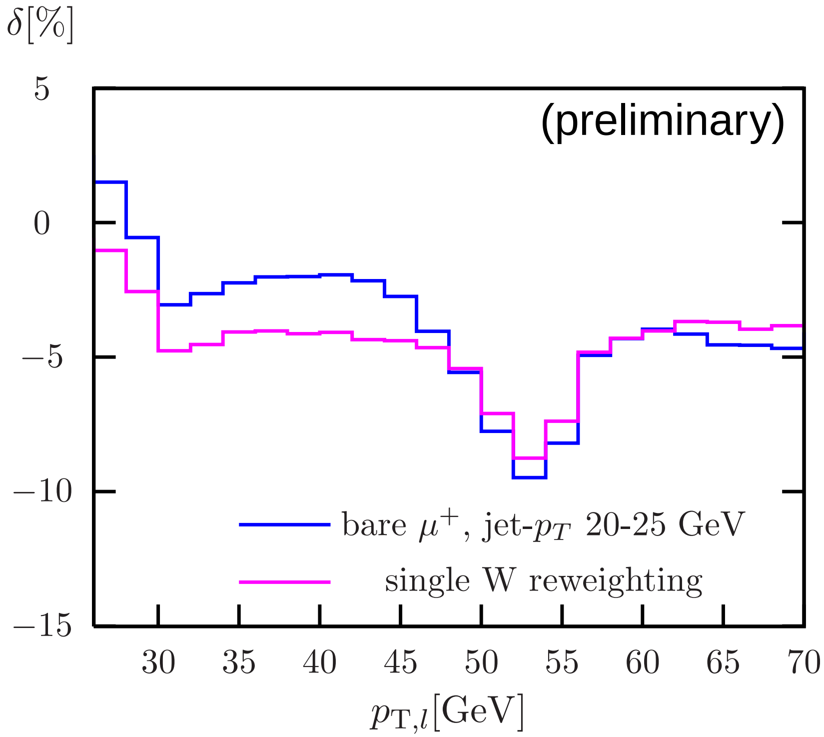


still big differences due to high-p_T jets

single W vs. W+jet

p_{T} distribution for the LHC:

- only look at jets with $p_{T,\mathrm{jet}} = 20 - 25$ GeV

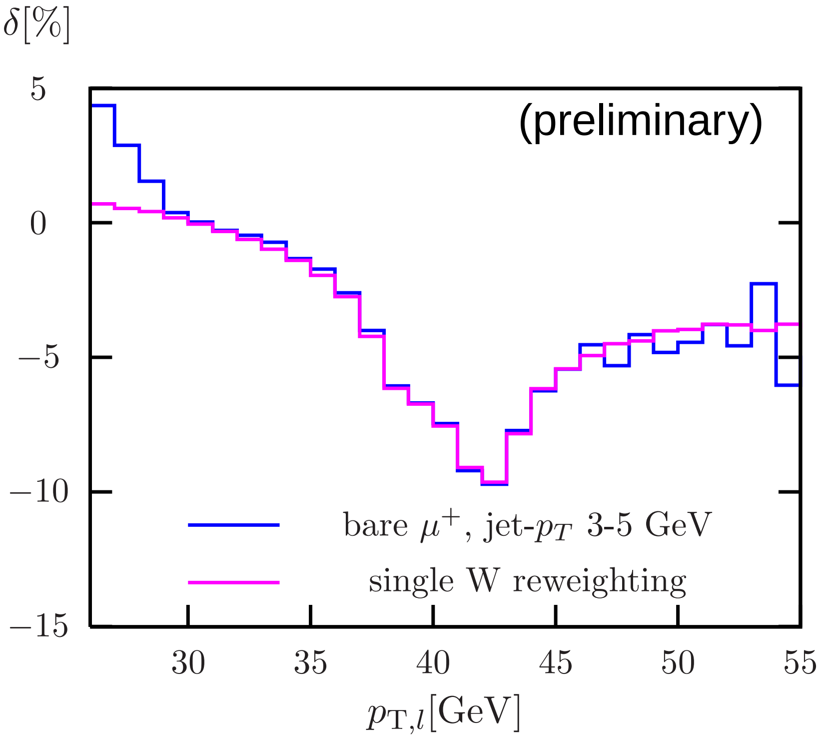


good but not perfect agreement

single W vs. W+jet

p_{T} distribution for the LHC:

- only look at jets with $p_{T,\mathrm{jet}} = 3 - 5$ GeV
- cross-section not reliably predicted in this region
- one can still estimate the EW corrections for the limited kinematical region



very good agreement

EW corrections: single W

EW corrections distort shapes:

- in particular due to final state photon radiation
- also for M_{T} distribution
- strong dependence on lepton-photon recombination

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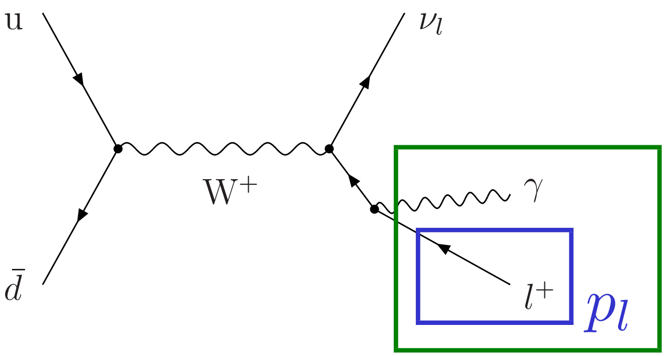

$p_l = p_l + p_\gamma$
(for collinear photons)

exclusive (bare) leptons (muons): $\alpha \log(M_W^2/M_l^2)$ corrections

inclusive leptons (electrons): no large logs (KLN theorem)

RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

EW corrections: single W

EW corrections distort shapes:

- in particular due to final state photon radiation
- also for M_T distribution
- strong dependence on lepton-photon recombination

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]