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HEPTOOLS

Tools and Precision Calculations for Physics Discoveries at Colliders

Electroweak corrections to W+jet hadroproduction including leptonic W-boson decays

Alexander Mück

in collaboration with

A. Denner (PSI), S. Dittmaier (Freiburg),

T. Kasprzik (MPI Munich, Karlsruhe)

RADCOR 2009

Ascona, 29th October 2009

based on Denner, Dittmaier, Kasprzik, AM, JHEP 08 (2009) 075 [arXiv:0906.1656]

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Outline

- W production at the LHC
- W+jet production: $pp \to W + \text{jet} \to l\nu_l + \text{jet}$
  - motivation and theoretical status
  - Electroweak and QCD corrections
  - Numerical results for the LHC
  - towards $\mathcal{O}(\alpha\alpha_s)$ corrections for inclusive W prod.
- Conclusions

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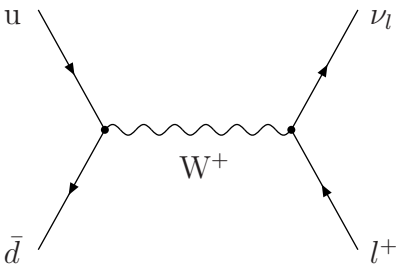
W Production at the LHC

Charged-current Drell-Yan:

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



- clean signal: lepton + missing p_{T}
- huge cross section: $\sigma_W = 30$ nb (5 nb after basic cuts)
- very useful: M_W, Γ_W, luminosity, PDFs, calibration

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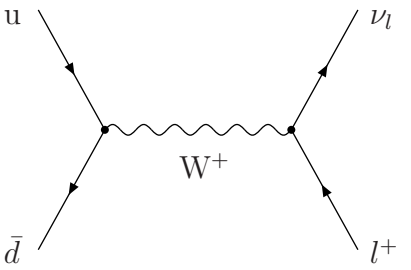

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- EW: NLO, leading higher order contributions

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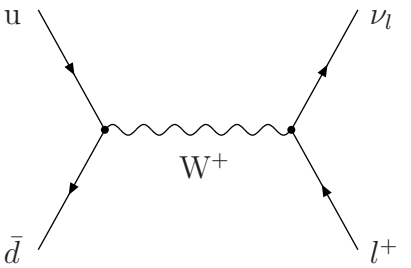

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- EW: NLO, leading higher order contributions
- combined EW and QCD corrections?

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

Balossini et al. [arXiv:0907.0276]

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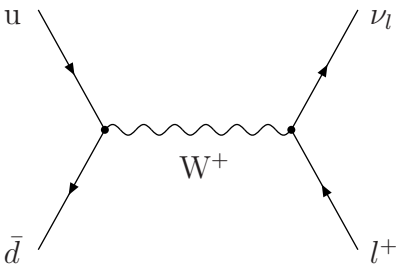

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- EW: NLO, leading higher order contributions
- combined EW and QCD corrections?

  hard QCD radiation + EW corrections?

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

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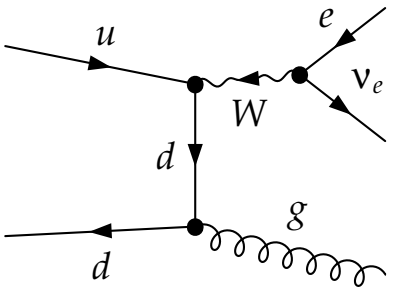
W+jet production

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



- large cross section
  ($\sim$ 1nb after basic cuts)
- 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))

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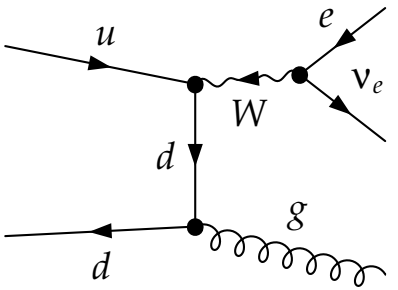

- large cross section
  (~ 1nb after basic cuts)
- dominant SM channel for high p_T leptons
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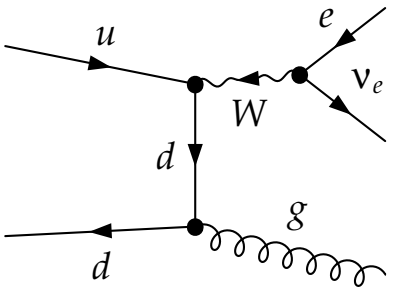
Theoretical status:

- 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+jet production

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



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Theoretical status:

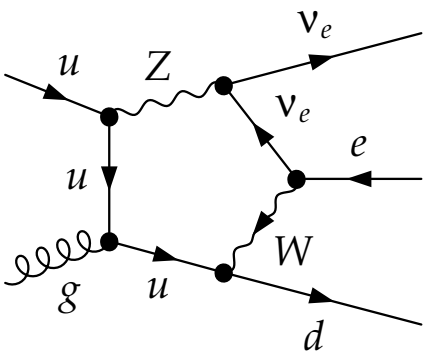
- NLO QCD corrections known and available
- EW corrections for stable (on-shell) W bosons

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

EW corrections

Complete EW corrections calculated

Denner, Dittmaier, Kasprzik, AM [arXiv:0906.1656]



+

$\mathcal{O}(100)$ diagrams

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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- 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:

    $$M^2_{\mathrm{W},0} = \mu^2_{\mathrm{W}} + \delta\mu^2_W$$

    with: $M^2_{\mathrm{W},0}$ = bare mass
    μ^2_{W} = ren. complex mass
    $\delta\mu^2_W$ = complex counterterm

  - $\Rightarrow$ complex $s^2_{\mathrm{W}} = 1 - \mu^2_{\mathrm{W}}/\mu^2_{\mathrm{Z}}$
  - 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

non collinear-safe subtract.

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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)

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photon–jet recombination

Treat photon like another parton?

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Treat photon like another parton?

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

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photon–jet recombination

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- No: a gluon in a gluon-photon jet can become soft (in accidentally collinear configurations) $\Rightarrow$ IR singularity

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

- do not distinguish (also calculate W+γ and its NLO QCD corr.)
- or cut on photon energy fraction z_γ inside a jet

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  $\Rightarrow$ this is what we want

  But: not infrared safe

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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 ($Z \to q\bar{q} \to q\bar{q}\gamma$)
  - 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 $\mathcal{O}(\alpha^3\alpha_s)$

- also full NLO QCD corrections
  - variable (phase-space dependent) scale supported

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

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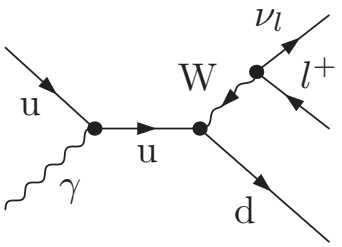
  - variable (phase-space dependent) scale supported
- photon-induced processes



at NLO QCD
(phenomenologically irrelevant)

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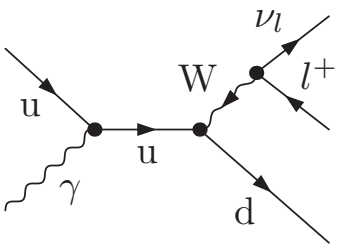
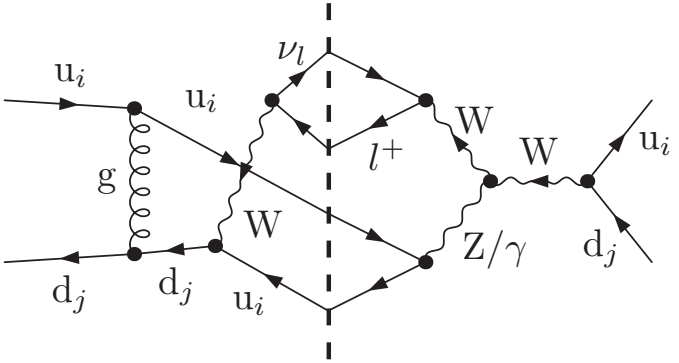


at NLO QCD
(phenomenologically irrelevant)

- QCD-EW interference terms in 4-quark processes



(phenomenologically irrelevant)

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Monte-Carlo programs

two completely independent calculations

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

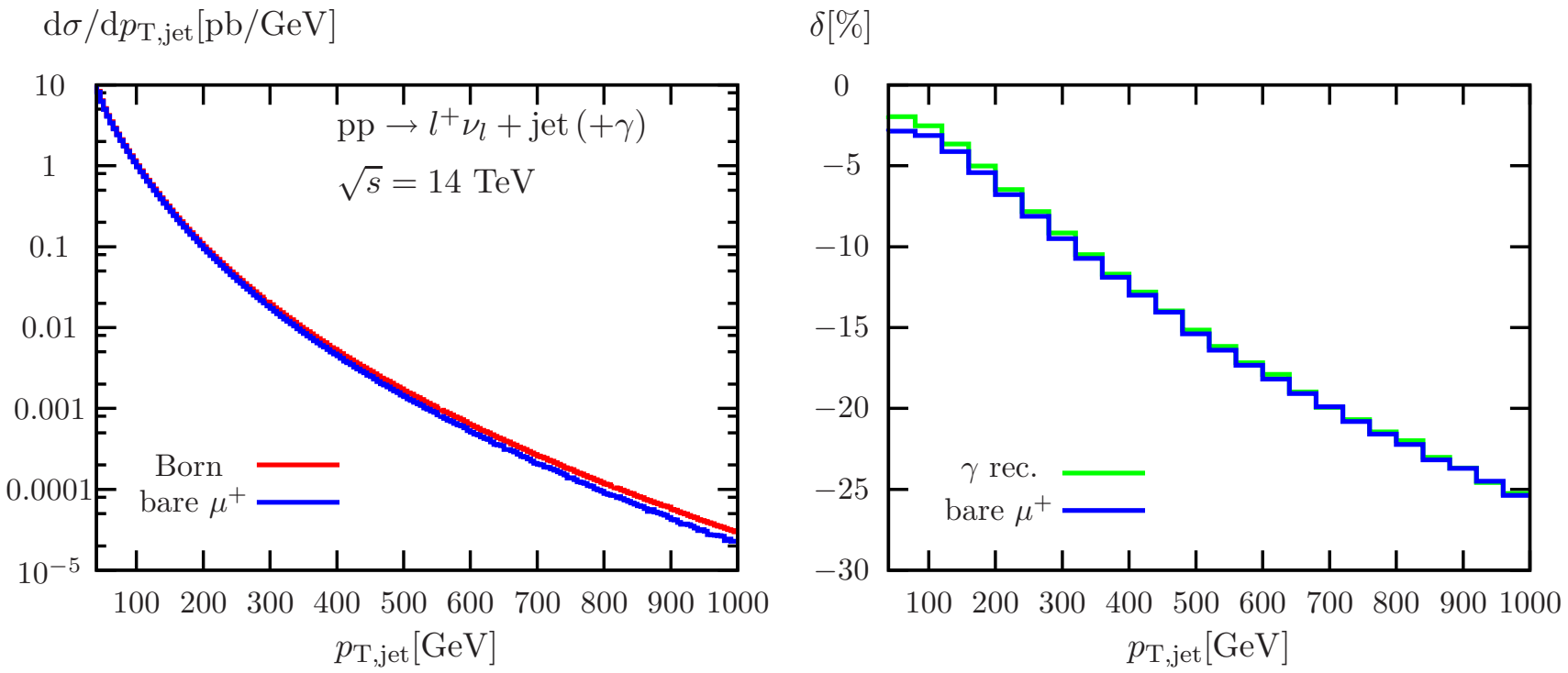
- do not recombine photons and muons (bare μ^+)
- photons and electrons: $R_{\gamma,l} < 0.1$ (γ rec.)
- photons and partons: $R_{\gamma,\mathrm{jet}} < 0.5$

renormalization and factorization scale

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

EW corrections

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



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

QCD corrections

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

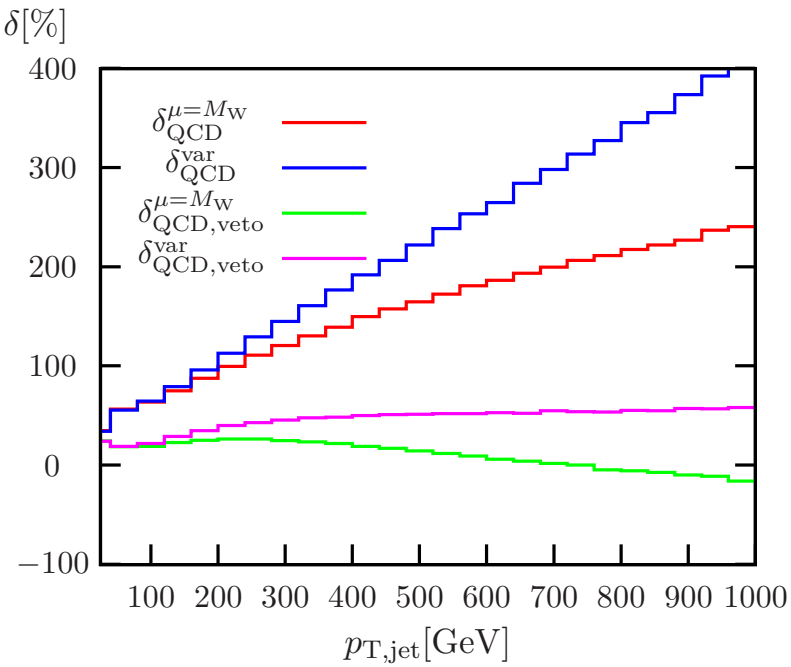
huge NLO QCD corrections:

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



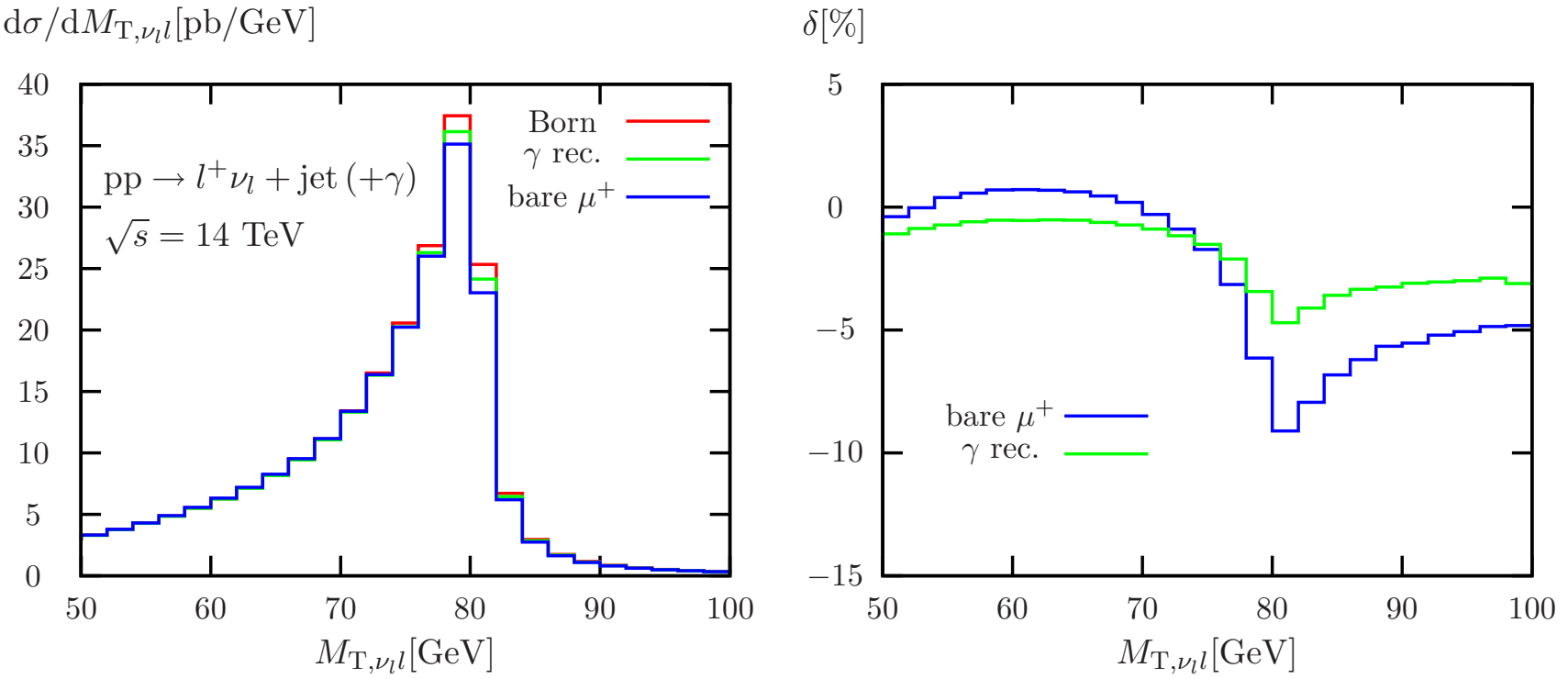
use simple jet veto:

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)

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



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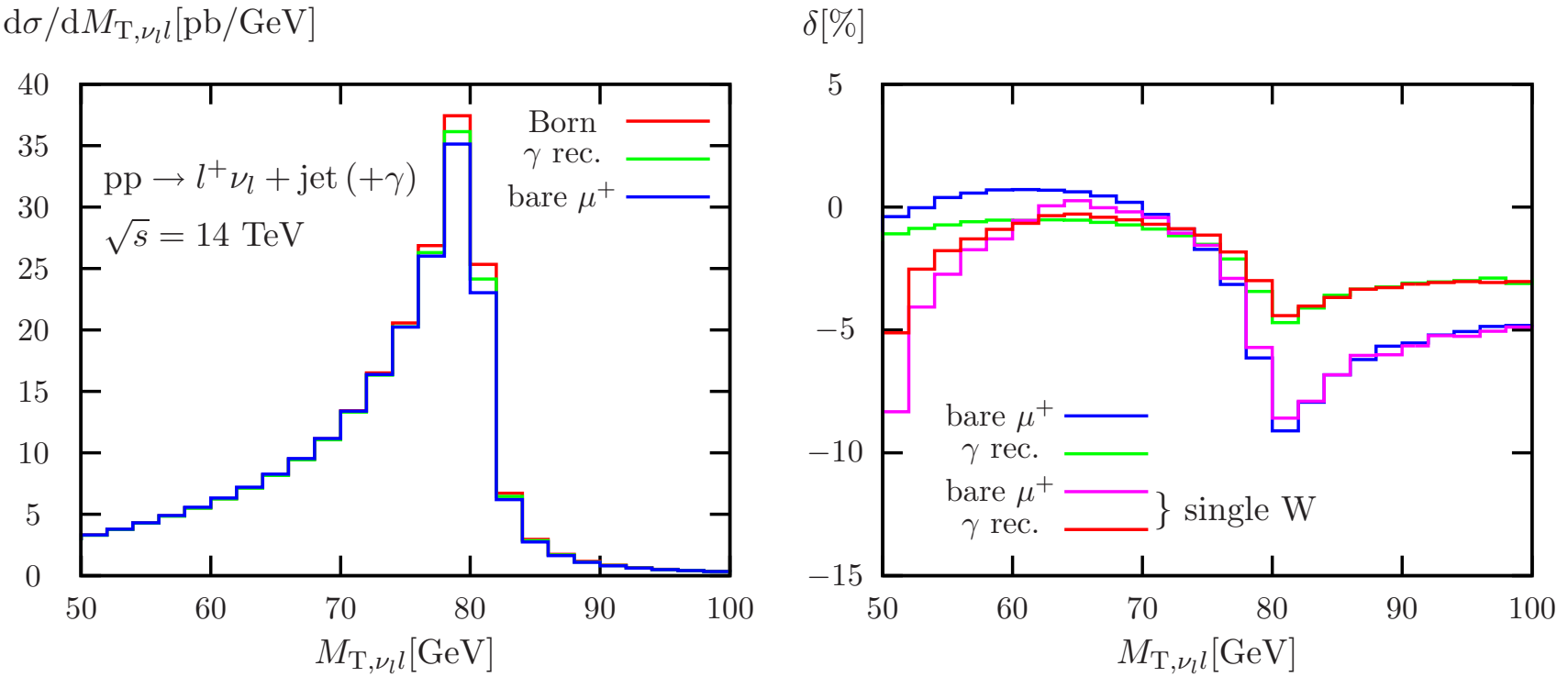

corrections very similar to single W production

EW corrections

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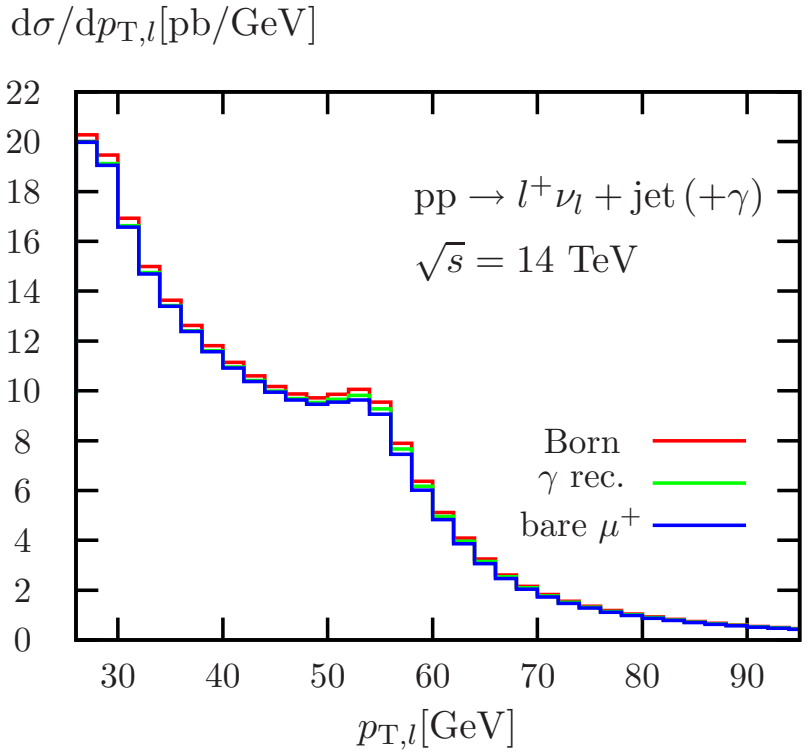

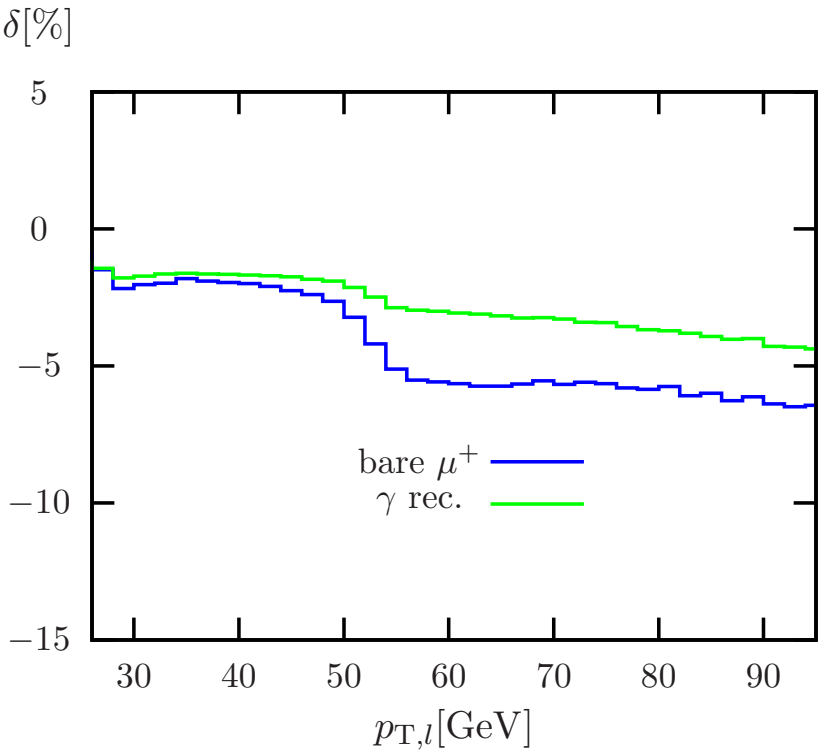

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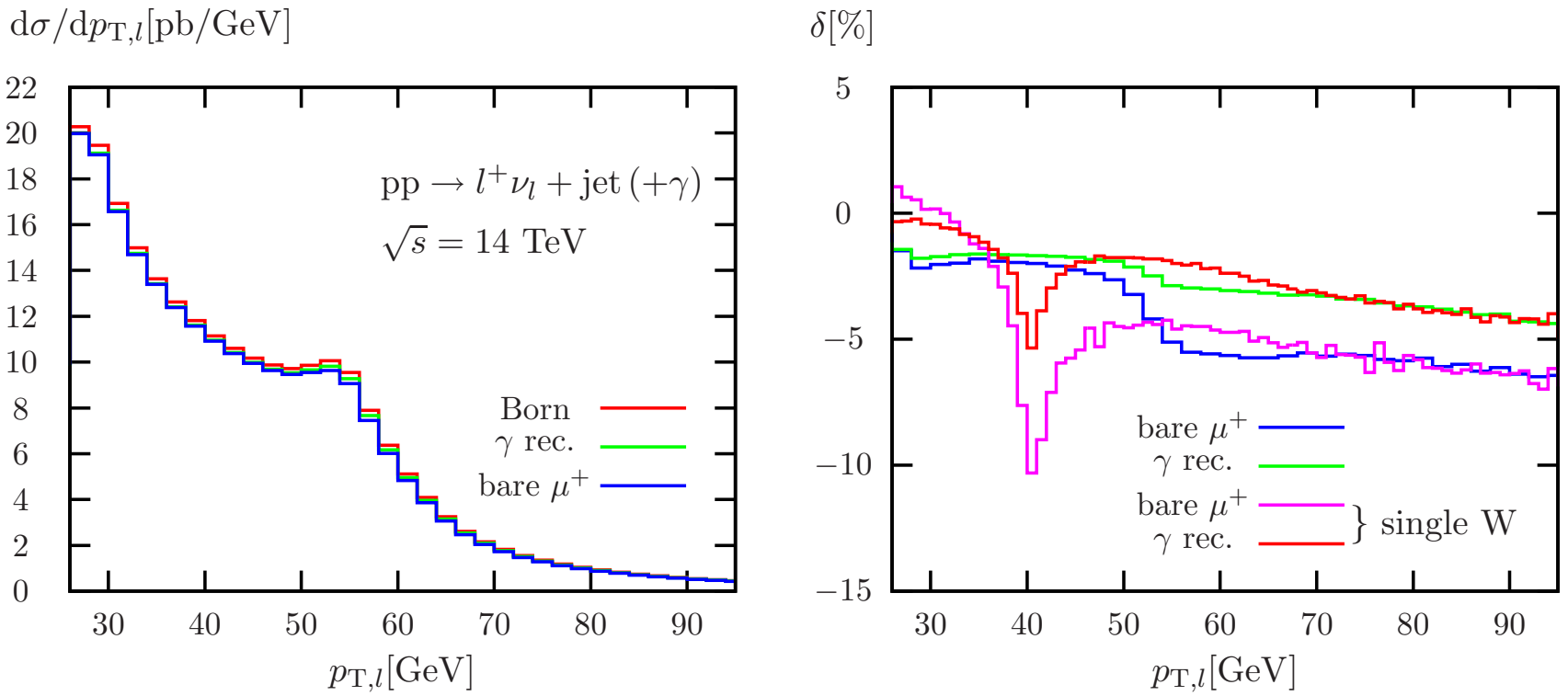


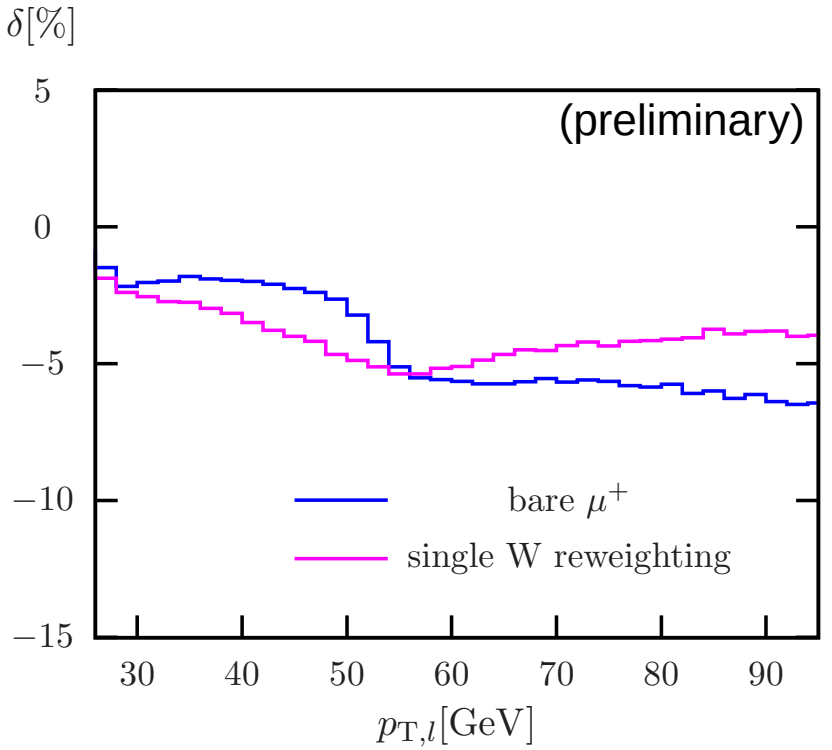
no similarity to single W production

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

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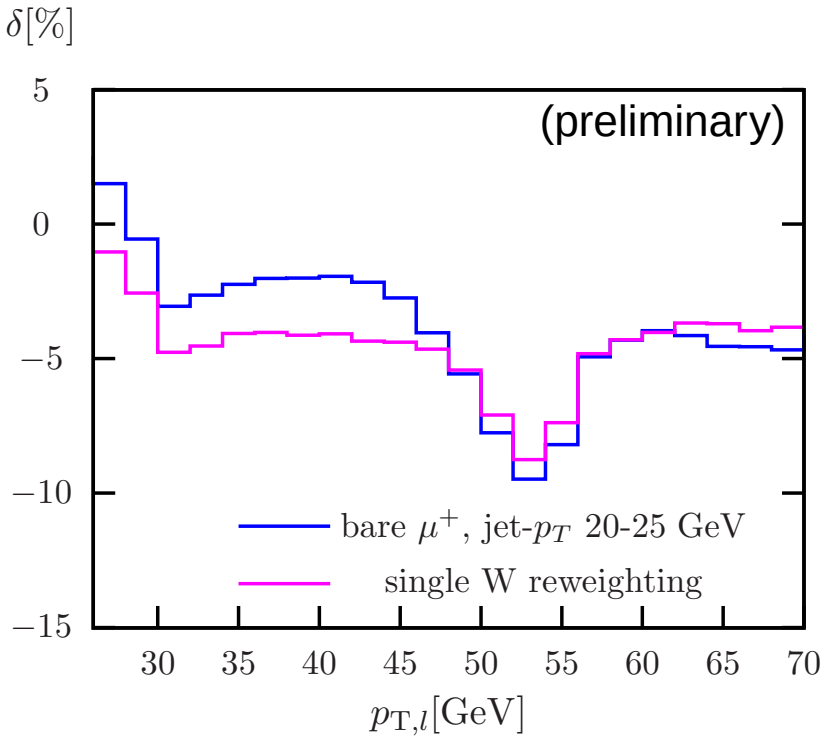
single W vs. W+jet

p_{T} distribution for the LHC:

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

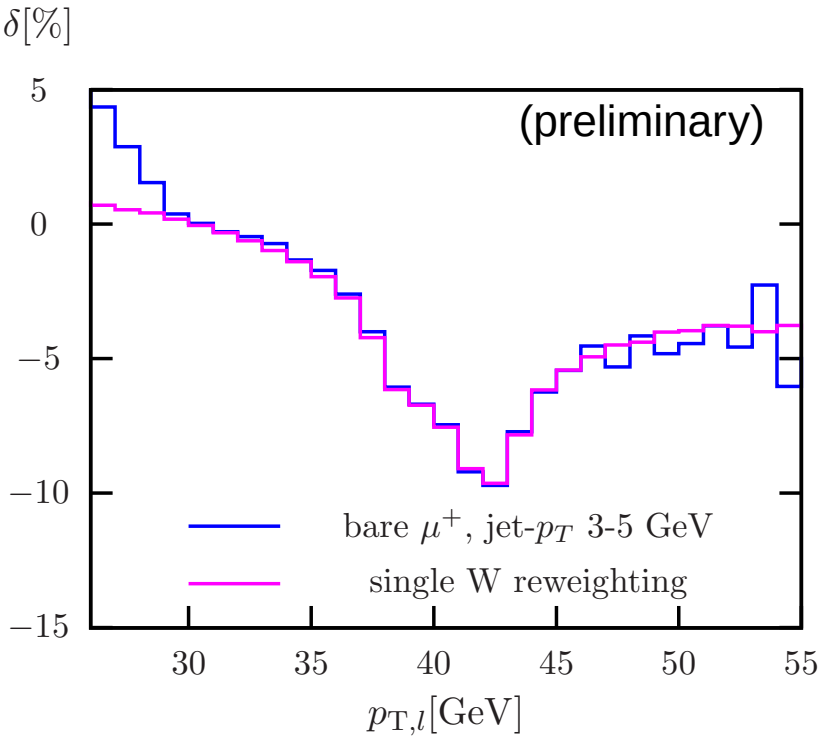


good but not perfect agreement

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

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RWTH

Summary

- W+jet is a SM benchmark process
- our calculation
  - flexible Monte Carlo program
  - recalculation of NLO QCD corrections
  - complete EW corrections
  - physical final state (all off-shell effects included)
- EW corrections
  - typically at the percent level
  - larger corrections in some distributions
  - growing with energy ($\sim -25\%$ at $p_{\mathrm{T,jet}} = 1$ TeV)
  - a step towards $\mathcal{O}(\alpha\alpha_s)$ for inclusive W production
- outlook
  - more on W+jet vs. inclusive W production
  - Z+jet production

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Back-up slides

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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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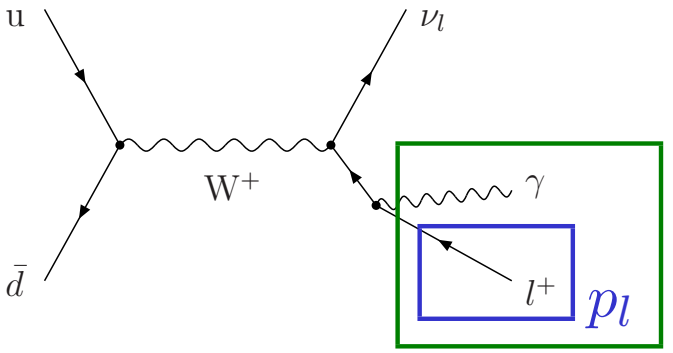

$p_l = p_l + p_\gamma$
(for collinear photons)

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

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

EW corrections: single W

EW corrections distort shapes:

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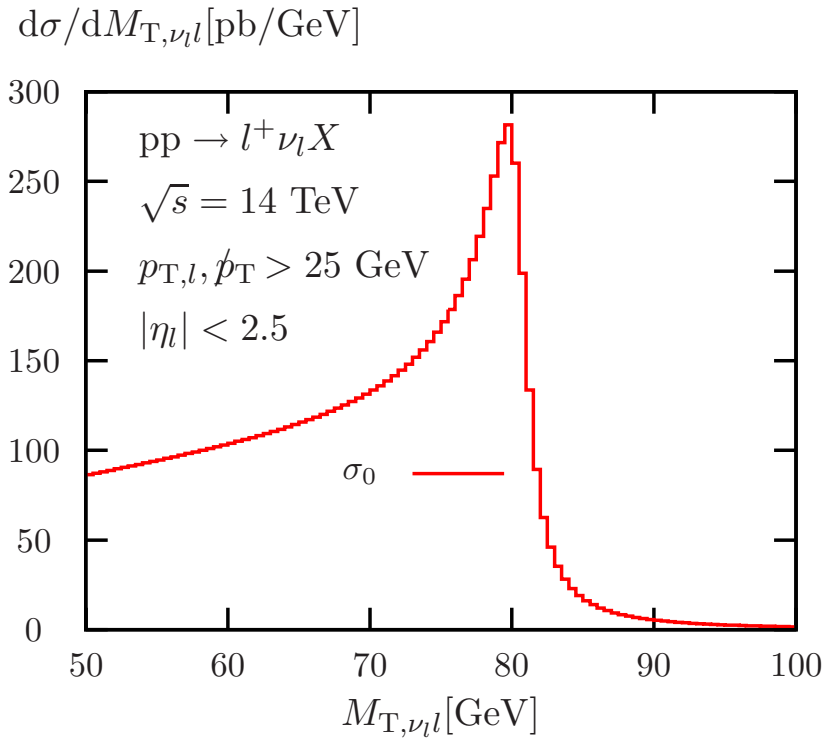

Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]