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HEPTOOLS

Tools and Precision Calculations for Physics Discoveries at Colliders

Electroweak corrections for W/Z(+jet) production

Alexander Mück

in collaboration with

A. Denner (PSI)

S. Dittmaier, M. Huber, T. Kasprzik (MPI Munich)

S. Brensing, M. Krämer (RWTH Aachen)

W mass workshop

Milano, March 17, 2009

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Outline

- single W production
  - NLO EW corrections
  - multiphoton emission
  - MSSM corrections
- single Z production
  - different schemes for treating the Z resonance
- W+jet production
  - complete NLO EW corrections for
    $pp \longrightarrow W + \text{jet} \longrightarrow l\nu_l + \text{jet}$

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single W production

Dittmaier, Krämer [hep-ph/0109062]
Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

EW 1-loop corrections:

- input: G_μ scheme

$$\alpha = \alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_{\rm W}^2 s_{\rm W}^2}{\pi} = \alpha(0)(1+\Delta r) \; + \; \mathcal{O}(\alpha^3)$$

and $\alpha = \alpha(0)$ for collinear photon emission

$\Rightarrow$ higher-order universal effects due to $\Delta\alpha$ and $\Delta\rho$ absorbed in the coupling via Δr

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- resonance prescription:
  - fixed width, correction factorizes from resonant Born
  - $\ln(\hat{s} - M_\mathrm{W}^2 + \mathrm{i}\epsilon) \to \ln(\hat{s} - M_\mathrm{W}^2 + \mathrm{i} M_\mathrm{W} \Gamma_\mathrm{W})$

    to cure on-shell divergences in the correction

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    to cure on-shell divergences in the correction

- lepton-photon recombination:
  - bare muons and electron–γ recombination supported
  - dipole subtraction also for non-collinear safe bare muons

Dittmaier,Kabelschacht,Kasprzik [arXiv:0802.1405]

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Extras

- NLO QCD corrections
- leading 2-loop Sudakov logs included
- photon-induced processes included
- MSSM corrections

and most important for the W-mass measurement:

- multi-photon emission

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MSSM corrections

W production is considered a SM candle:

- contamination from physics beyond the SM, e.g. SUSY?
- calculate $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha)$ corrections in the MSSM

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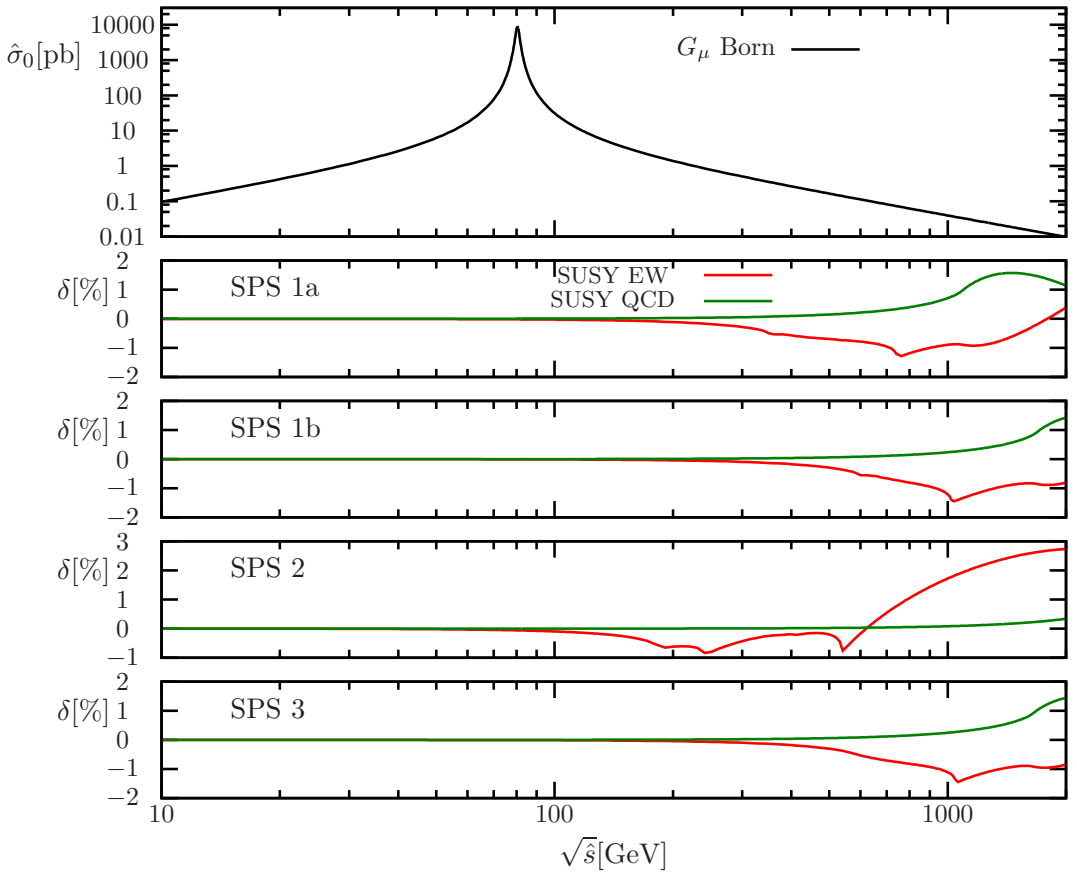

partonic cross section for SPS benchmark points

no impact for M_W measurement

percent-level corrections only at large $\sqrt{s}$, $p_{T,l}$, M_T

W production is SM candle!

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Multi-photon radiation

- important for exclusive leptons (no recombination)
- perturbative expansion in $\alpha^n \log^n(M_W^2/m_l^2)$

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Multi-photon radiation

- two approaches in leading logarithmic accuracy:
  - QED parton shower
  - structure function approach Kuraev, Fadin '85; ... Abruzov '99

$$\sigma_{\mathrm{LLFSR}} = \int \mathrm{d}\sigma_0(p_{\mathrm{u}}, p_{\mathrm{d}}; k_{\nu_l l}, k_l) \int_0^1 \mathrm{d}z\, \Gamma_{ll}^{\mathrm{LL}}(z, Q^2)\, \Theta_{\mathrm{cut}}(z k_l)$$

where

$$\Gamma_{ll}^{\mathrm{LL}}(z, Q^2) = \frac{\exp\left(-\frac{1}{2}\beta_l \gamma_{\mathrm{E}} + \frac{3}{8}\beta_l\right)}{\Gamma\left(1 + \frac{1}{2}\beta_l\right)} \frac{\beta_l}{2} (1-z)^{\frac{\beta_l}{2}-1} - \frac{\beta_l}{4}(1+z) + \mathcal{O}(\beta_l^2) + \mathcal{O}(\beta_l^3)$$

and

$$\beta_l = \frac{2\alpha(0)}{\pi}\left[\log\left(\frac{Q^2}{m_l^2}\right) - 1\right]$$

Q: scale of the process

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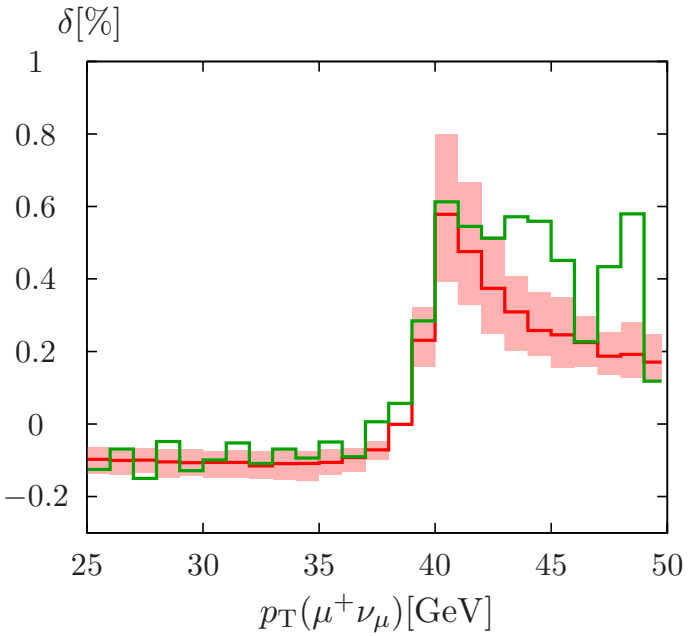

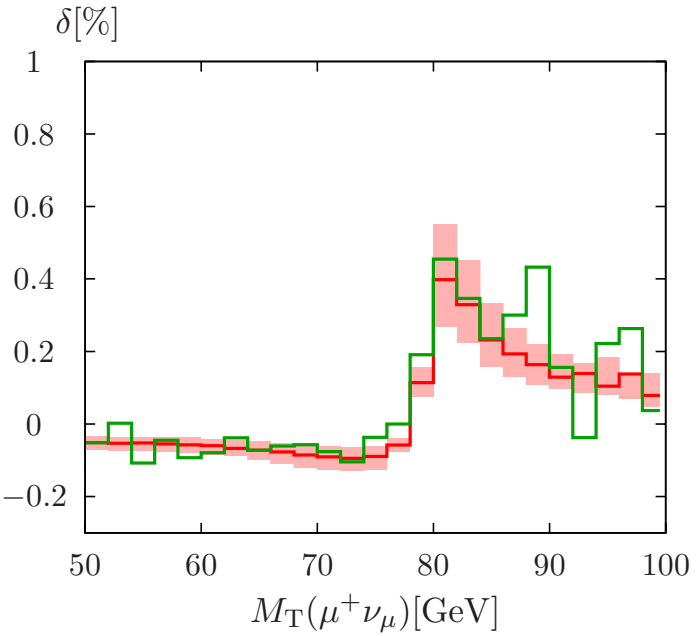

parton shower: from Horace (Carloni Calame et al.) in arXiv:0705.3251

structure function (with scale variation): Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

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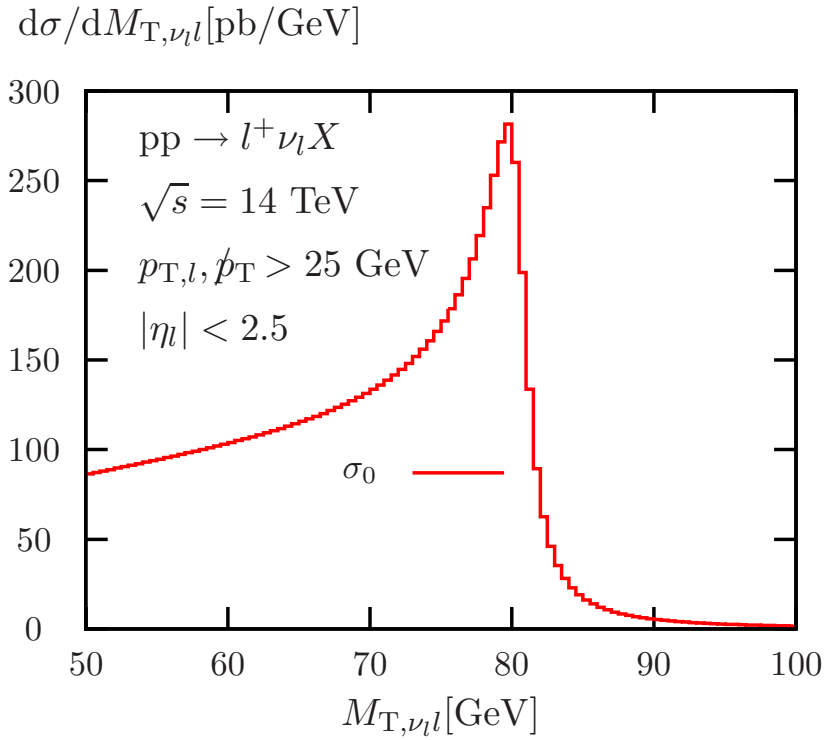
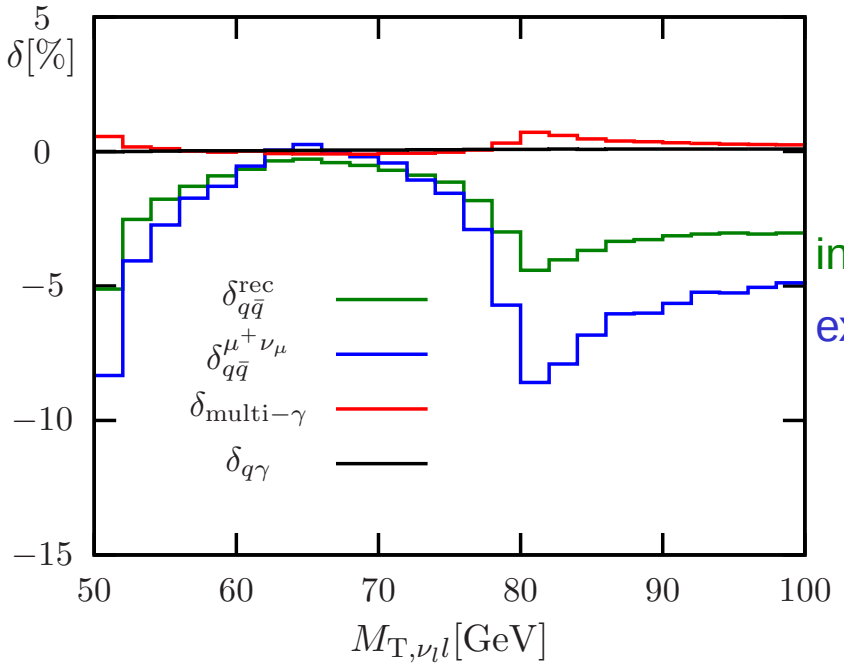
Results

M_{T} distribution for the LHC:





inclusive

exclusive

single Z production

Dittmaier, Huber [in preparation]

features of the calculation:

- full NLO EW+QCD corrections in the SM
  - using complex mass scheme Denner et al.'05

    $\Rightarrow$ use complex W and Z masses everywhere by means of complex renormalization ($\Rightarrow$ complex weak mixing angle)

    $\Rightarrow$ loop-integrals for complex masses needed

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  - $\gamma q / \gamma \bar{q}$ collisions included

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- improvements beyond NLO
  - G_μ scheme: absorb higher-order universal effects ($\Delta\alpha$, $\Delta\rho$)
  - two-loop Sudakov logarithms
  - multi-photon emission via structure functions

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  - two-loop Sudakov logarithms
  - multi-photon emission via structure functions
- NLO EW+QCD corrections in the MSSM (preliminary)
  - corrections as small as for single W production

$\Rightarrow$ effects negligible near Z resonance for relevant SUSY scales

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single Z production

- status of the calculation
  - two independent calculations for partonic results
  - results on hadronic observables in progress

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Z boson resonance: compare different gauge invariant implementations of the Z-boson width for the weak corrections

- complex mass scheme (CMS) Denner et al.'05

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Z boson resonance: compare different gauge invariant implementations of the Z-boson width for the weak corrections

- complex mass scheme (CMS) Denner et al.'05
- pole scheme (PS) Stuart '91; Aeppli et al.'93

  $\Rightarrow$ Laurent expand amplitude around the pole

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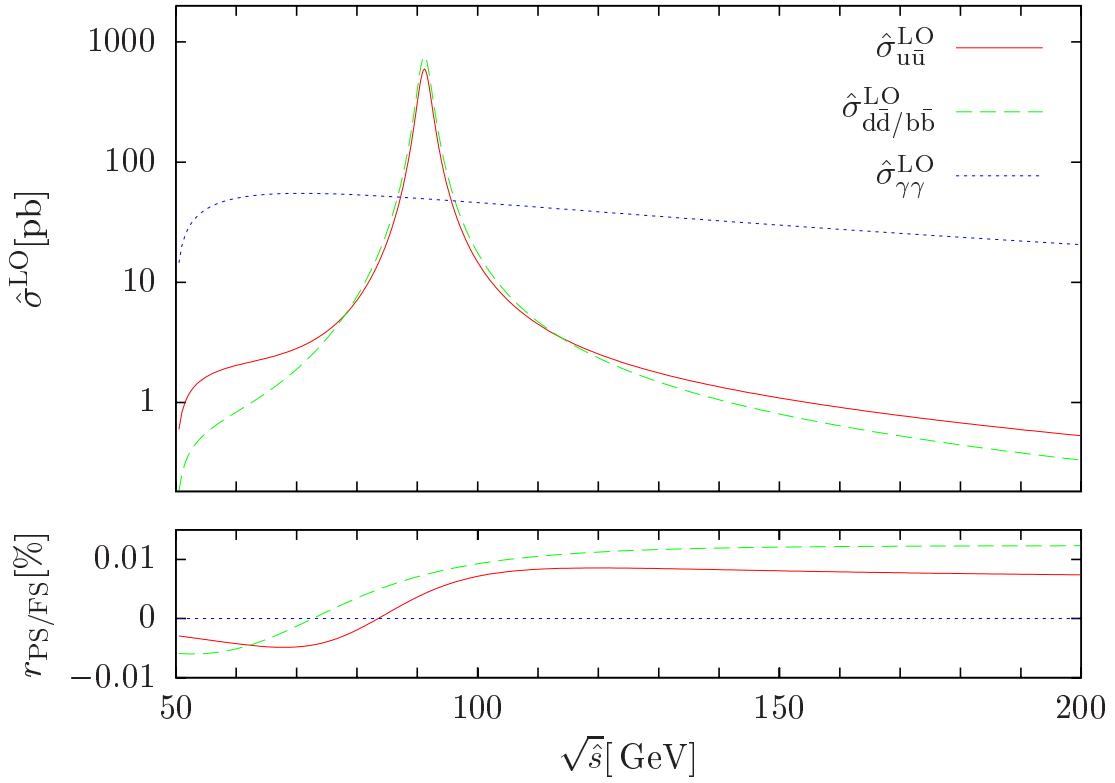
Z boson resonance: compare different gauge invariant implementations of the Z-boson width for the weak corrections

- complex mass scheme (CMS) — Denner et al.'05
- pole scheme (PS) — Stuart '91; Aeppli et al.'93
- factorization scheme (FS) — Dittmaier,Krämer '01

$$\Rightarrow \quad \sigma^{\mathrm{NLO}} = \left(1 + \delta^{\mathrm{weak}}|_{\Gamma_Z=0}\right) \sigma^{\mathrm{LO}}|_{\Gamma_Z\neq 0}$$

Partonic results

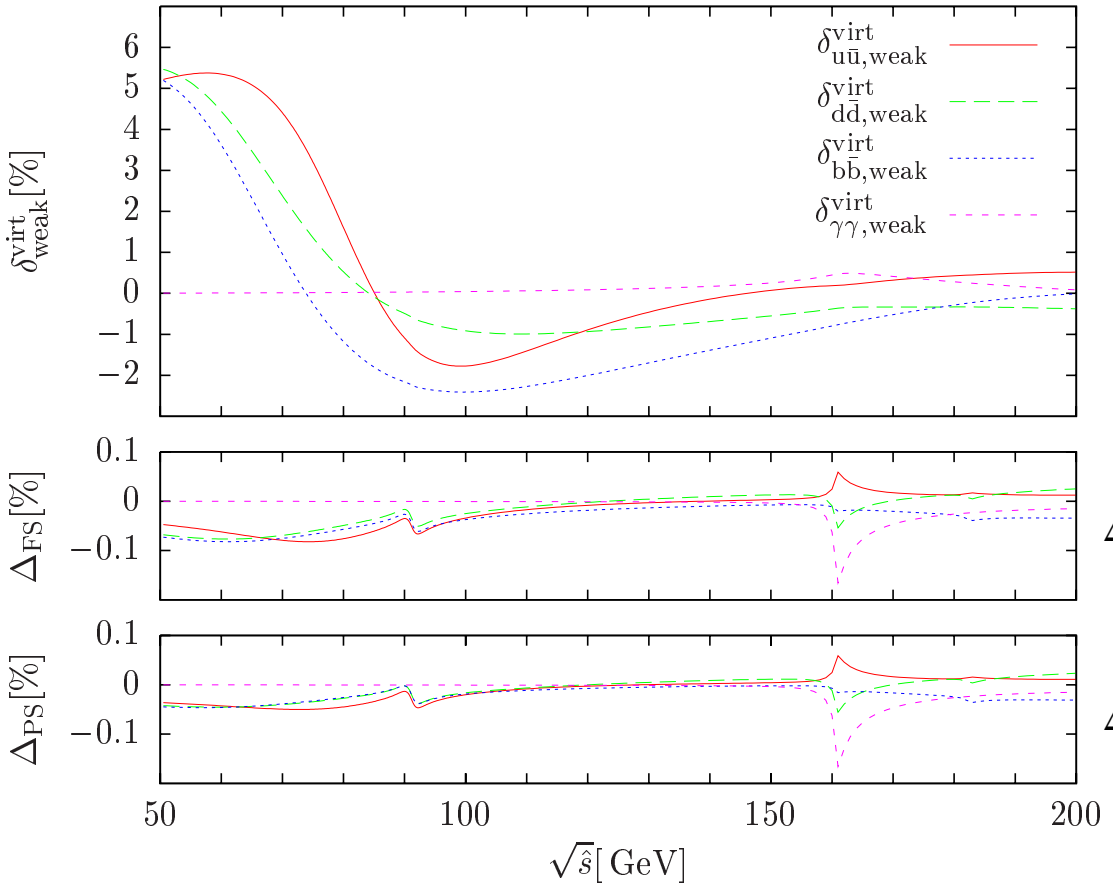
leading order:



where $r_{\mathrm{PS/FS}} = 1 - \hat{\sigma}^{\mathrm{LO}}|_{\mathrm{PS/FS}} \;/\; \hat{\sigma}^{\mathrm{LO}}|_{\mathrm{CMS}}$

Partonic results

weak corrections:



$$\Delta_{\rm FS} = \delta^{\rm virt}_{\rm q\bar{q},weak}\Big|_{\rm FS} - \delta^{\rm virt}_{\rm q\bar{q},weak}\Big|_{\rm CMS}$$

$$\Delta_{\rm PS} = \delta^{\rm virt}_{\rm q\bar{q},weak}\Big|_{\rm PS} - \delta^{\rm virt}_{\rm q\bar{q},weak}\Big|_{\rm CMS}$$

$\Rightarrow$ relative corrections differ by about 0.1% wrt LO

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QCD + EW

How to combine QCD and EW corrections?

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QCD + EW

How to combine QCD and EW corrections?

- soft-gluon resum. + final-state photon radiation (ResBos-A)

Cao,Yuan [hep-ph/0401026]

- first attempt for QCD + full EW :

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

Balossini et al. '07

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hard QCD radiation + EW corrections?

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  hard QCD radiation + EW corrections?

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

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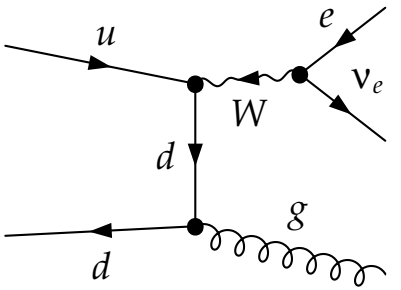
W+jet production

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



- large cross section
  (~ 1nb after basic cuts)
- dominant channel for high p_T leptons
- W+jet(s) important background for many (new physics) searches

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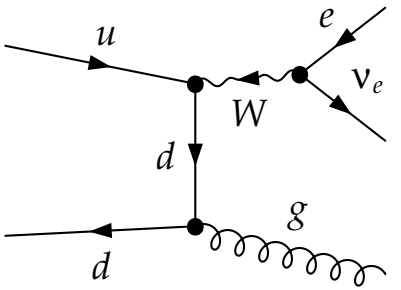

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Theoretical status:

- 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]

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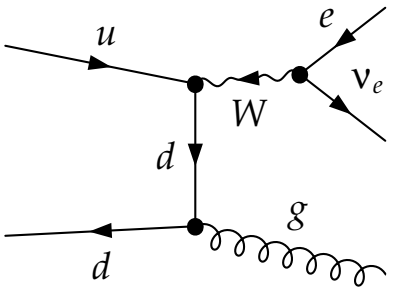

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Theoretical status:

- NLO QCD corrections known and available
- EW corrections for stable W bosons

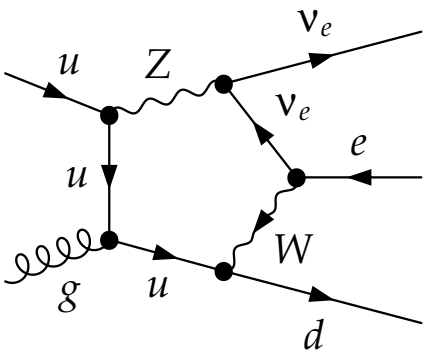
Kühn, Kulesza,Pozzorini,Schulze [hep-ph/0703283], [arXiv:0708.0476]

Hollik,Kasprzik,Kniehl [arXiv:0707.2553]

EW corrections

Complete EW corrections for off-shell W bosons calculated

Denner, Dittmaier, Kasprzik, AM [in preparation]



+

95 diagrams

per partonic channel

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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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- dipole subtraction for infrared divergences

  Catani, Seymour [hep-ph/9605323]

  Dittmaier [hep-ph/9904440]

  Dittmaier,Kabelschacht,Kasprzik [arXiv:0802.1405]

  - subtraction formalism also for non-collinear safe observables
  - slicing used as a check

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EW corrections

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- multi-channel phase space integration

  Berends, Kleiss, Pittau [hep-ph/9904440]

  - adaptive realization using Vegas (e.g. like in Whizard, Sherpa)

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some details

- consistent photon–jet recombination
  - W+jet and W+γ production separated by means of photon fragmentation function

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some details

- consistent photon–jet recombination
- also full NLO QCD corrections
  - variable (phase-space dependent) scale choice supported
  - for photon induced processes

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- also full NLO QCD corrections
- two completely independent calculations
  - in mutual agreement

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- consistent photon–jet recombination
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- two completely independent calculations
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  - 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]

Results for W+jet

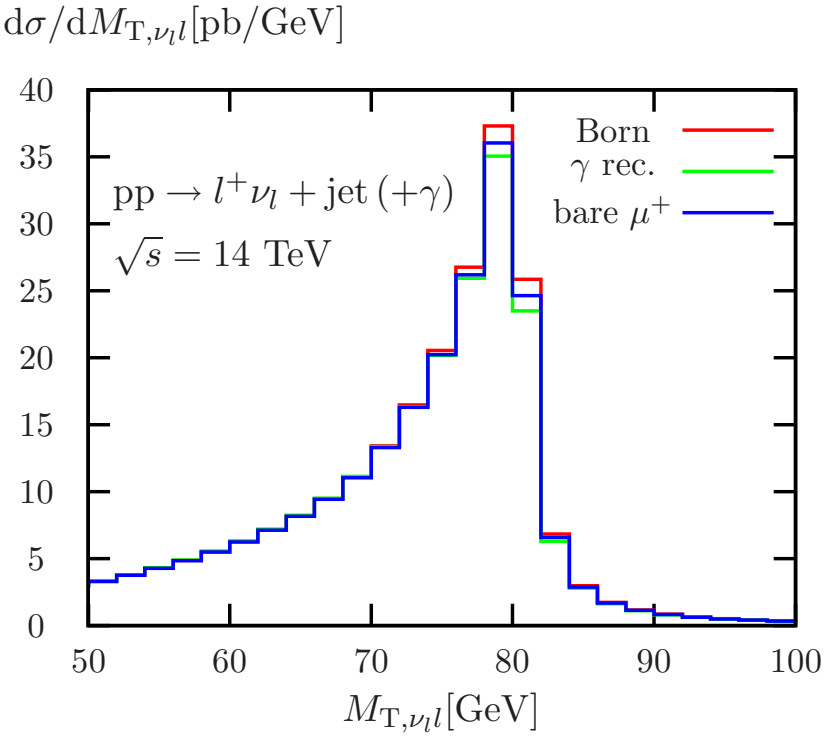
M_{T} distribution for the LHC:

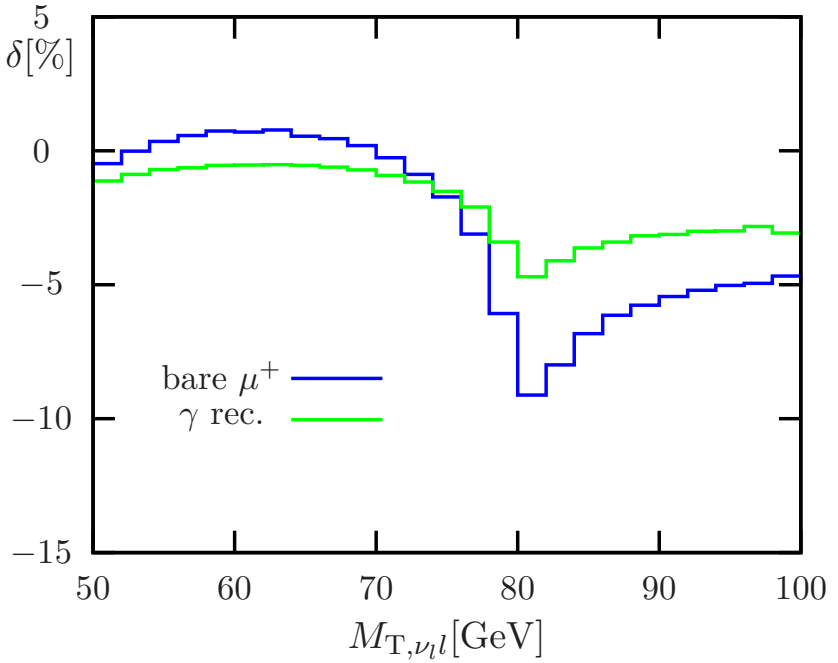
basic cuts:

$p_{\mathrm{T},l/\mathrm{miss/jet}} > 25$ GeV, $|y_{l/\mathrm{jet}}| < 2.5$

lepton isolation: $R_{l,\mathrm{jet}} > 0.5$

recomb. for $R_{\gamma,l} < 0.1$, $R_{\gamma,\mathrm{jet}} < 0.5$





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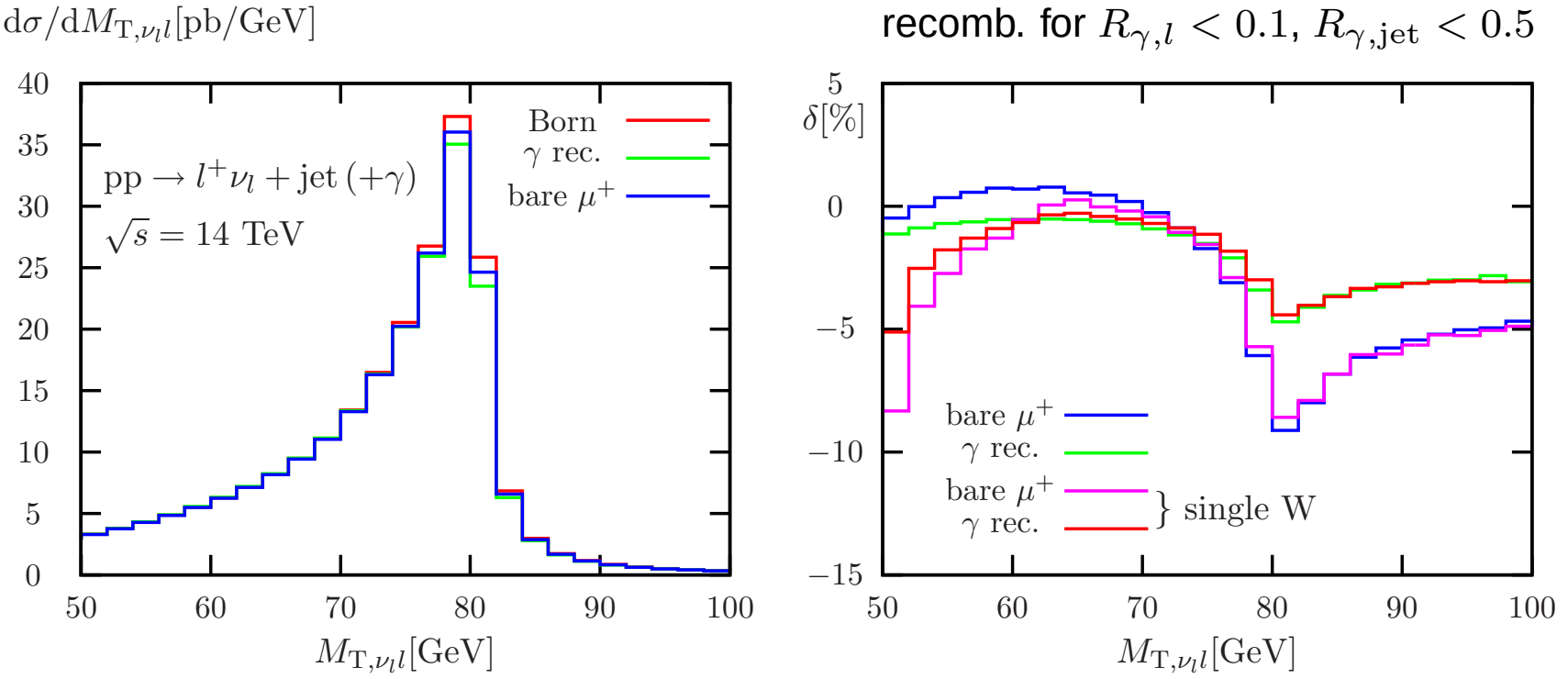

corrections very similar to single W production

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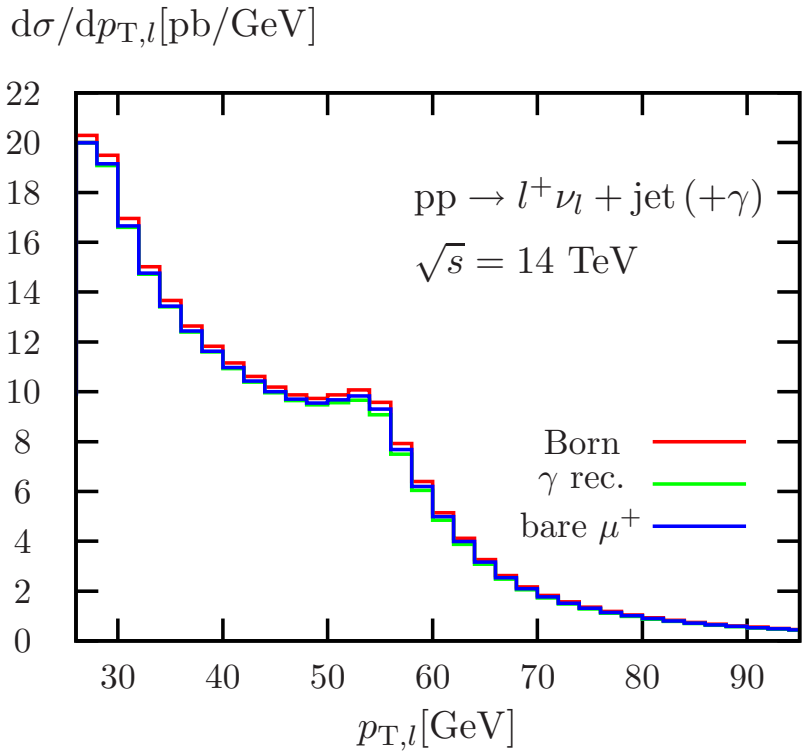

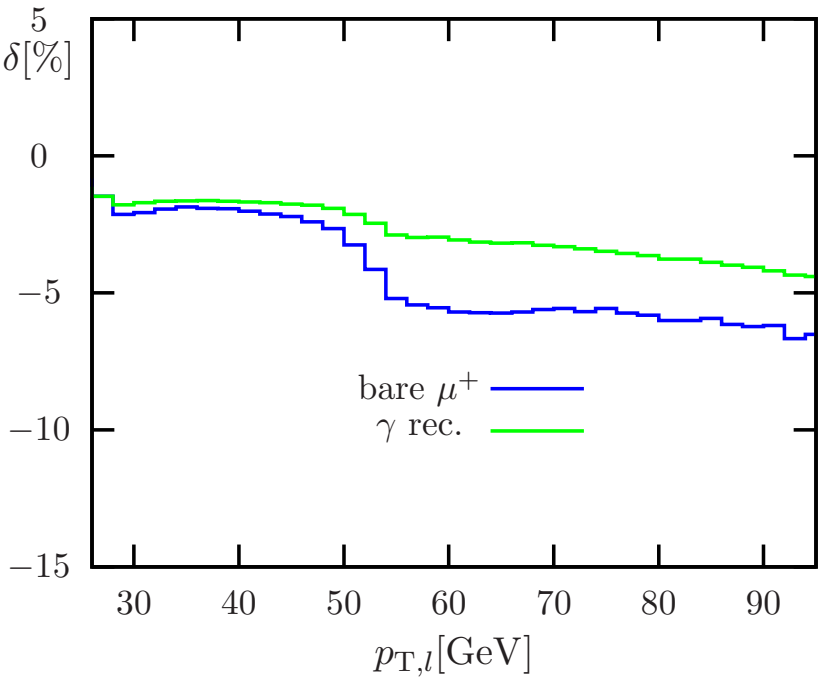

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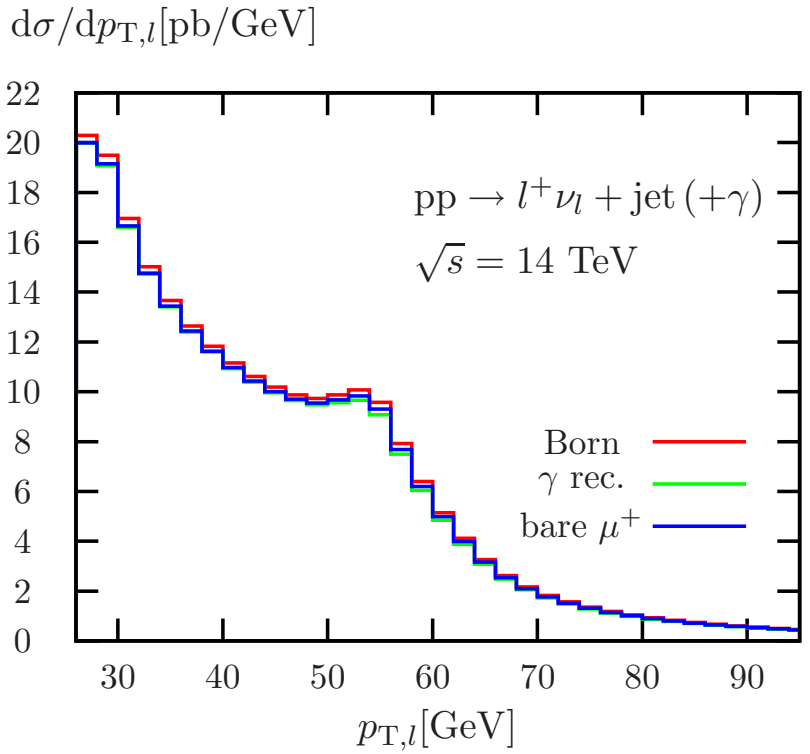

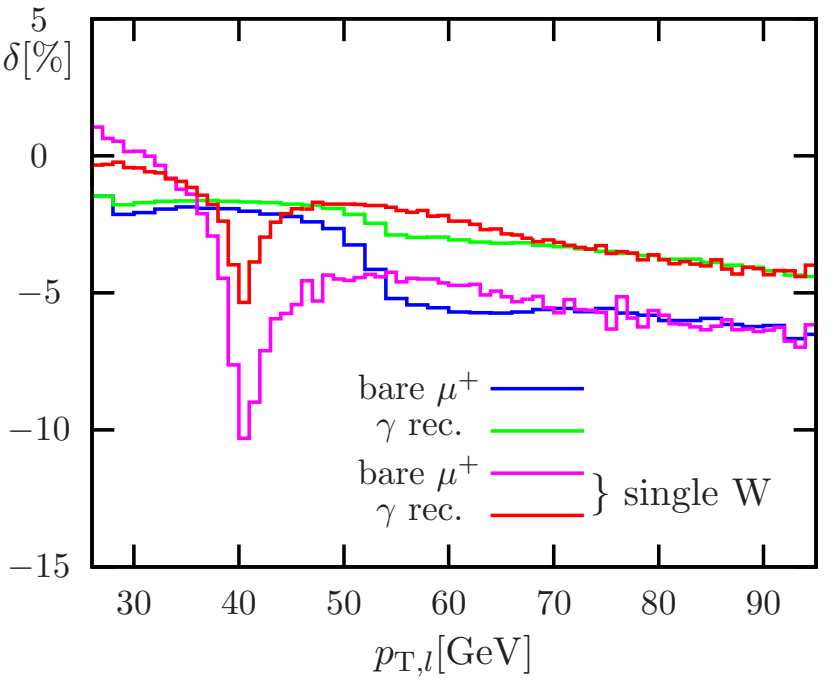

no similarity to single W production

Results for W+jet

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

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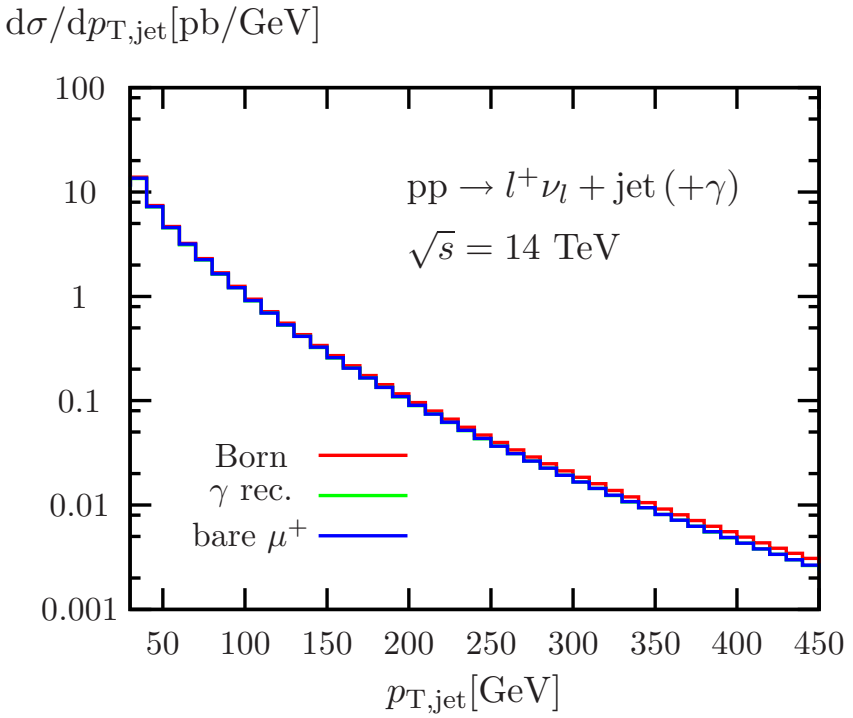

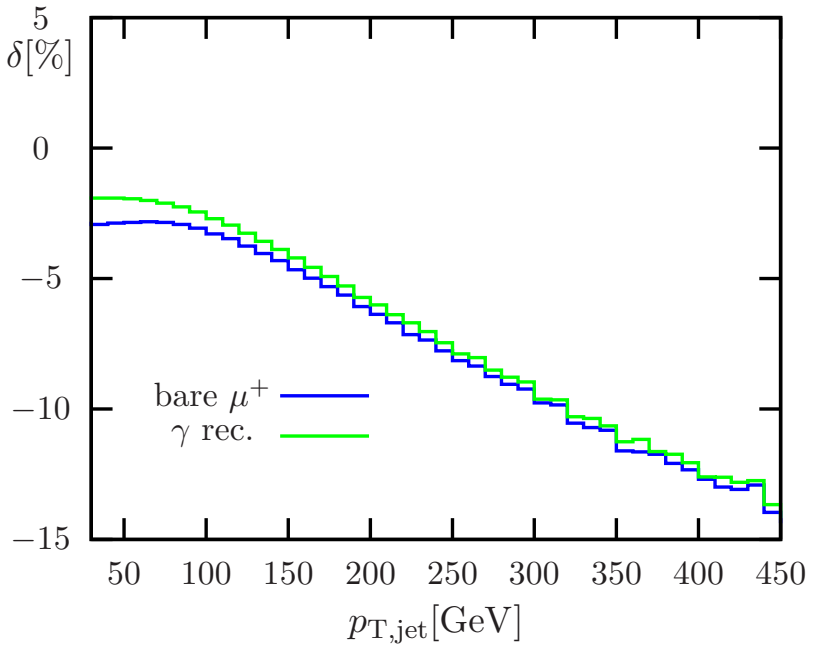

large corrections at large energies

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Summary

- single W production
  - complete NLO EW+QCD corrections
  - plus higher-order improvements
- single Z production
  - complete NLO EW+QCD corrections
  - plus higher-order improvements
  - finalizing checks for hadronic observables
- W+jet production
  - complete NLO EW+QCD corrections
- What comes next?
  - Z+jet production
  - improved QCD predictions: resummation

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Back-up slides

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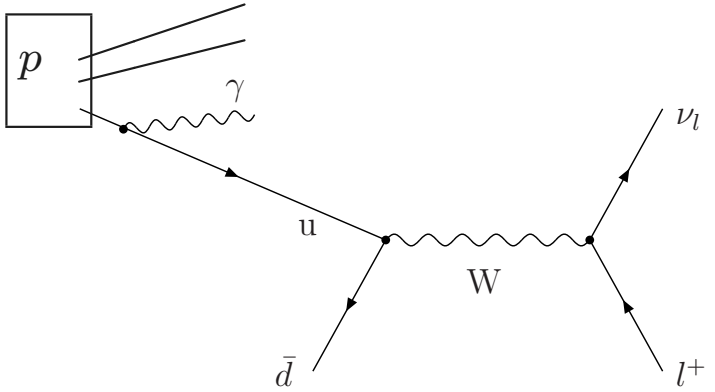
Photon-induced processes

There are photons inside the proton: γ as a parton

Photon-induced processes

There are photons inside the proton: γ as a parton



- initial state photon emission $\Rightarrow$ collinear singularity

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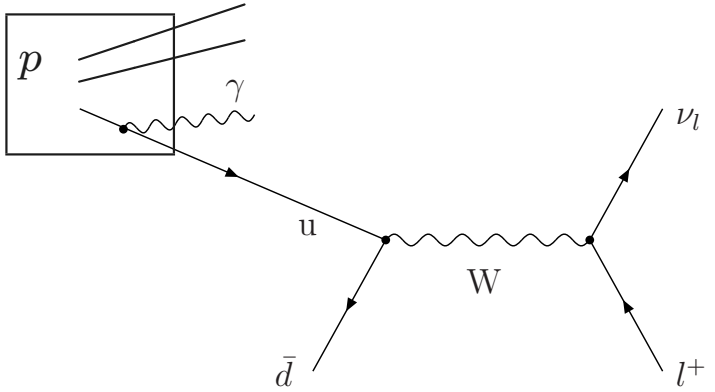


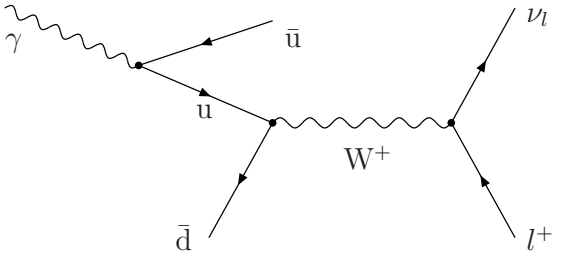
- initial state photon emission $\Rightarrow$ collinear singularity
- absorb singularity into PDF
- include QED in DGLAP evolution

  $\Rightarrow$ photon density inside the proton: MRSTQED2004 PDF

  Martin, Roberts, Stirling, Thorne [hep-ph/0411040]

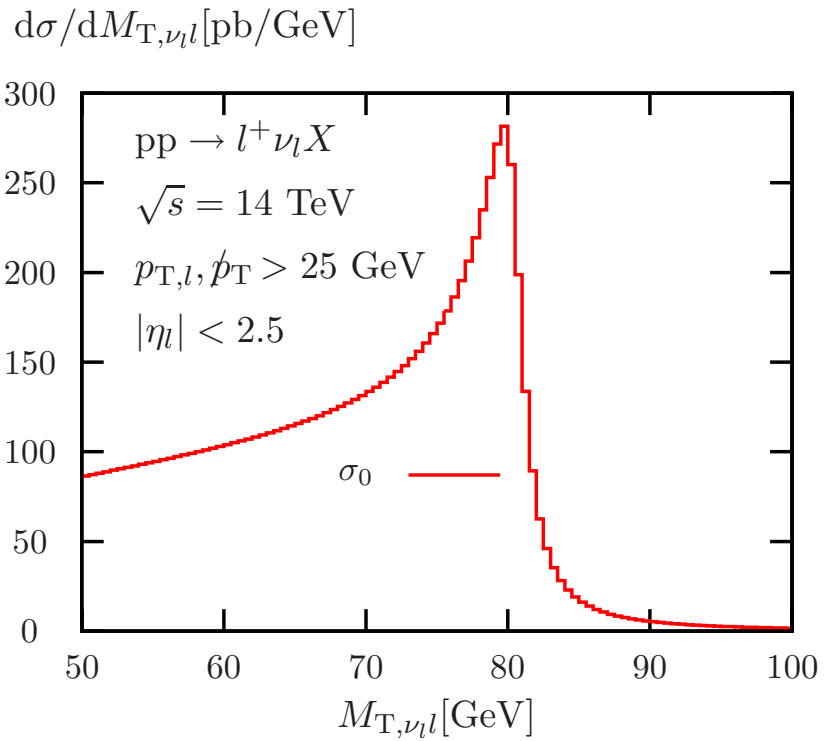
Photon-induced processes

- genuine contribution at $\mathcal{O}(\alpha)$:

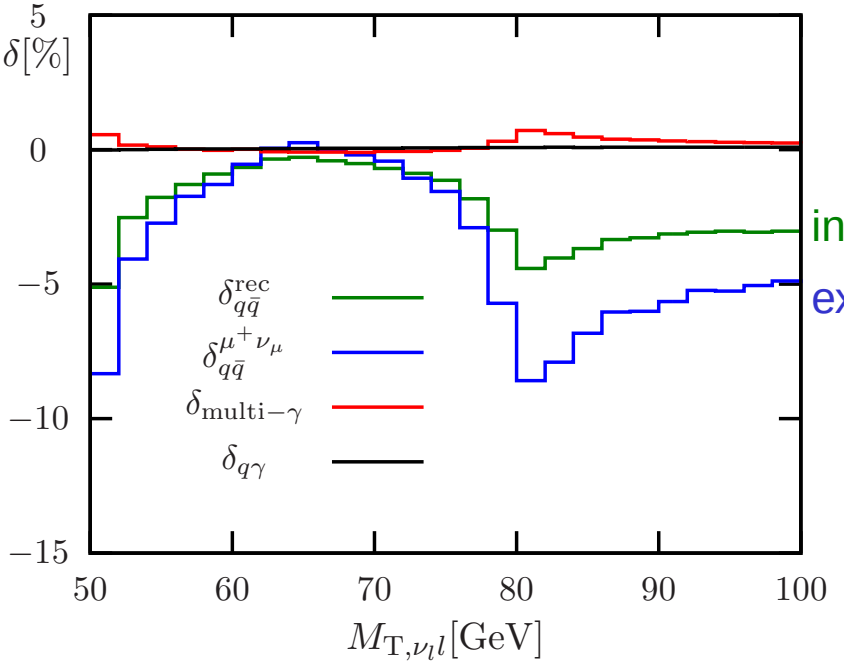


- usually percent level correction
- not relevant for M_{W} measurement in M_{T}
- can be enhanced:
  - up to $\sim$15% at large $p_{\mathrm{T},l} \sim 500$ GeV
  - but overwhelmed by QCD uncertainties
  - below 1% in M_{T}

EW corr.: M_{T} @ LHC



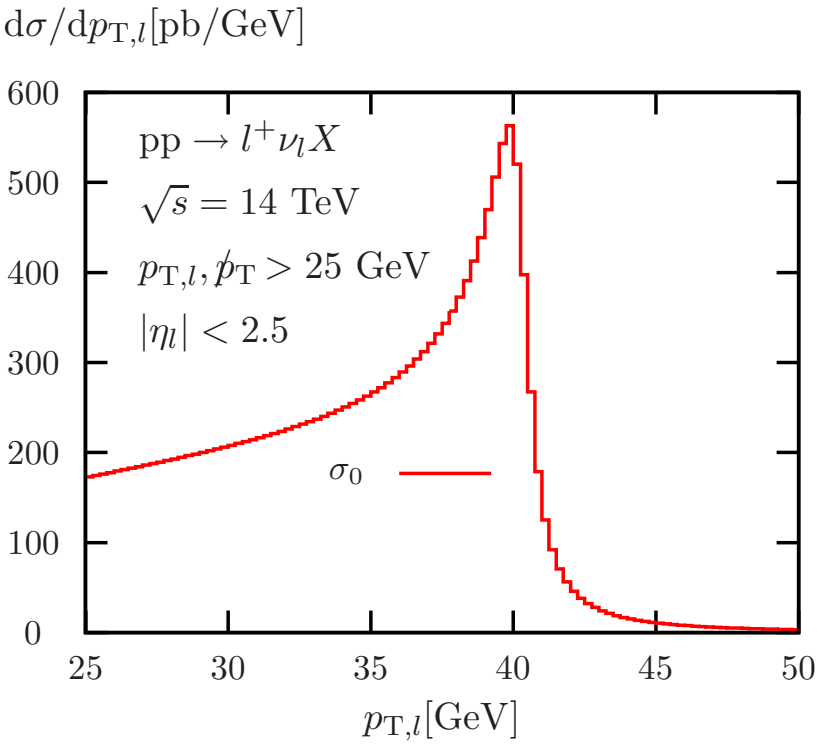
Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]



inclusive

exclusive

EW corr.: p_{T} @ LHC



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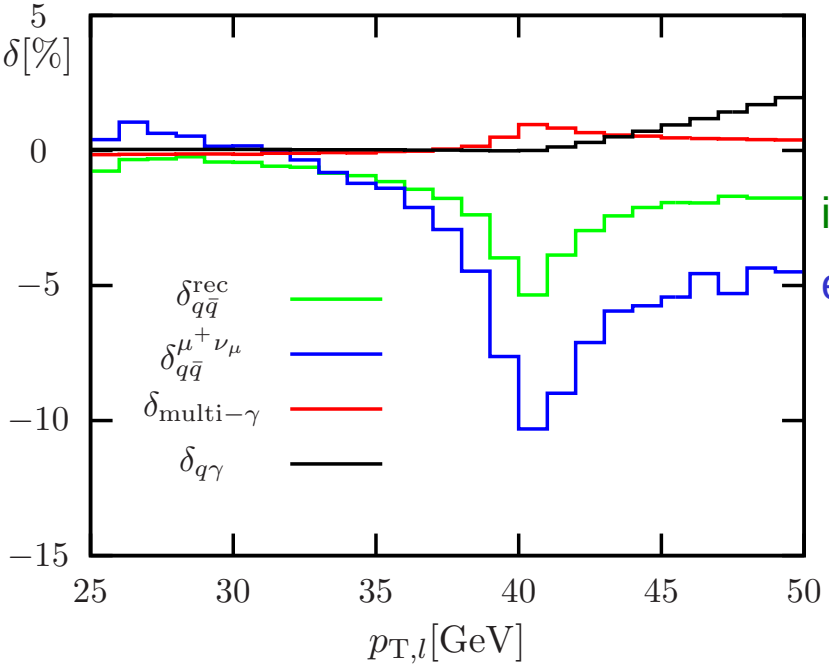
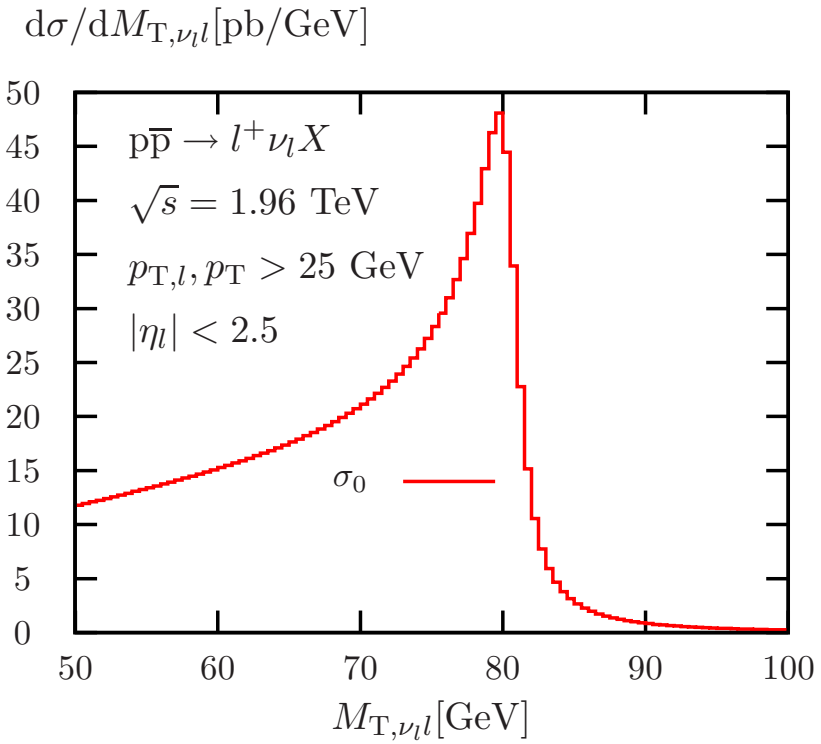


inclusive

exclusive

EW corr.: M_{T} @ Tevatron



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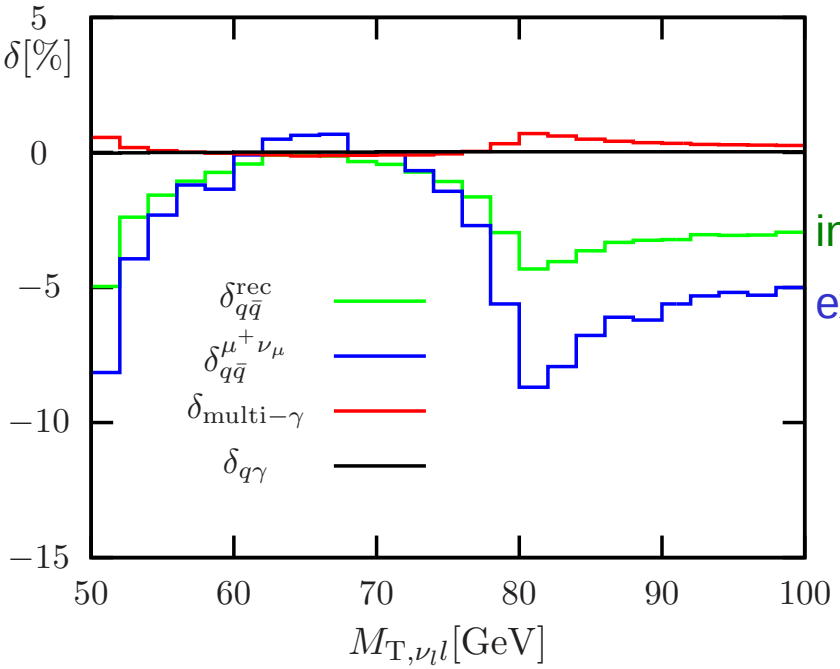
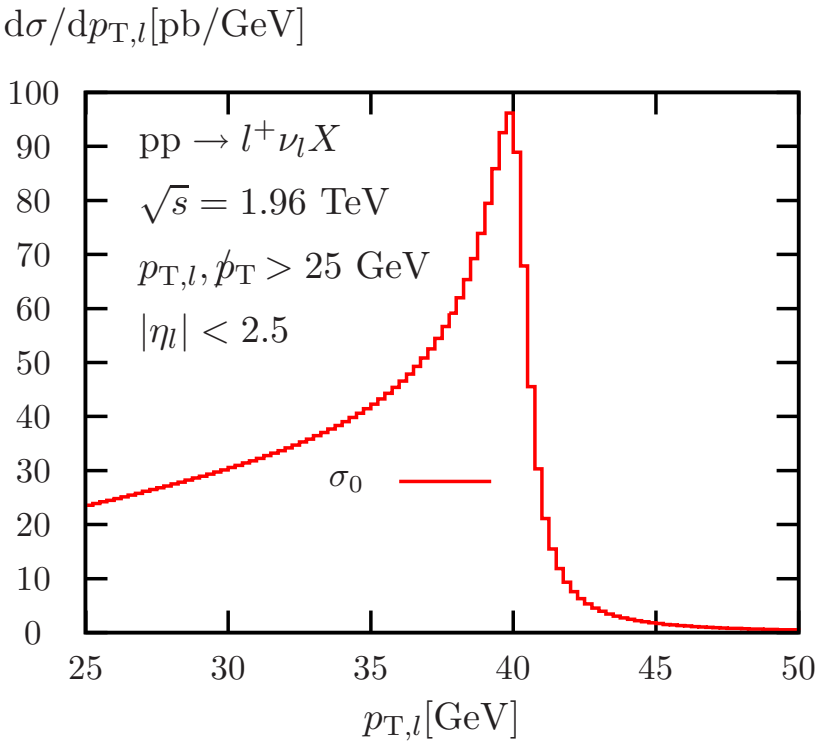


inclusive

exclusive

EW corr.: p_T @ Tevatron



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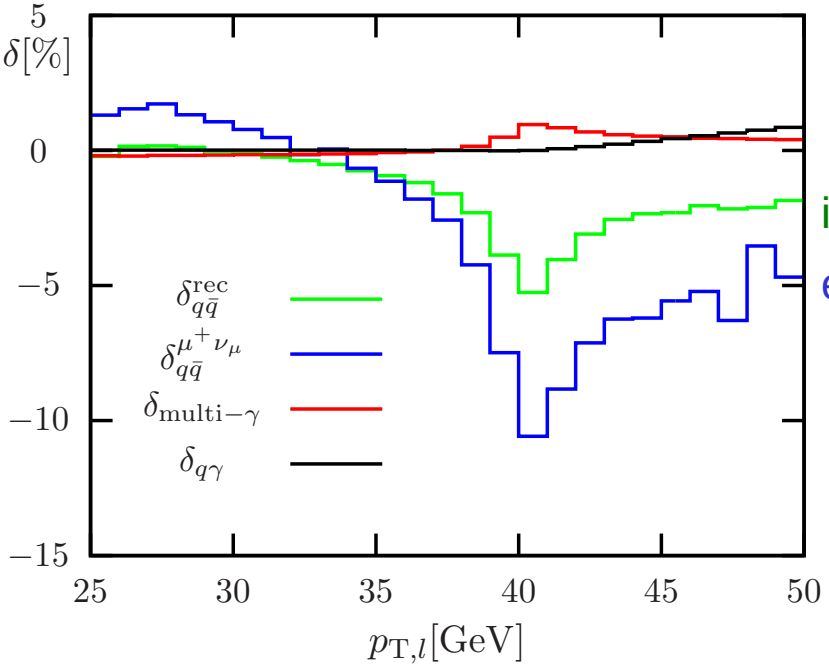

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EW corrections

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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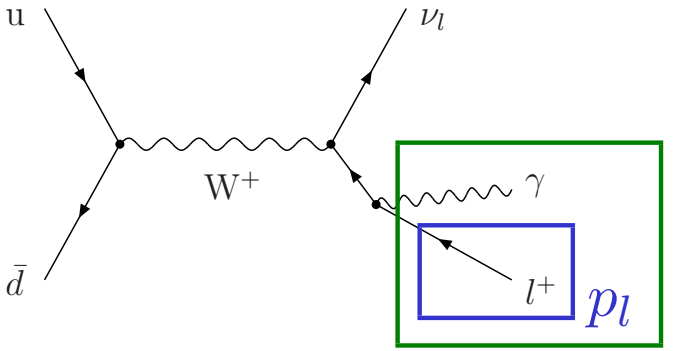

$p_l = p_l + p_\gamma$
(for collinear photons)

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

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

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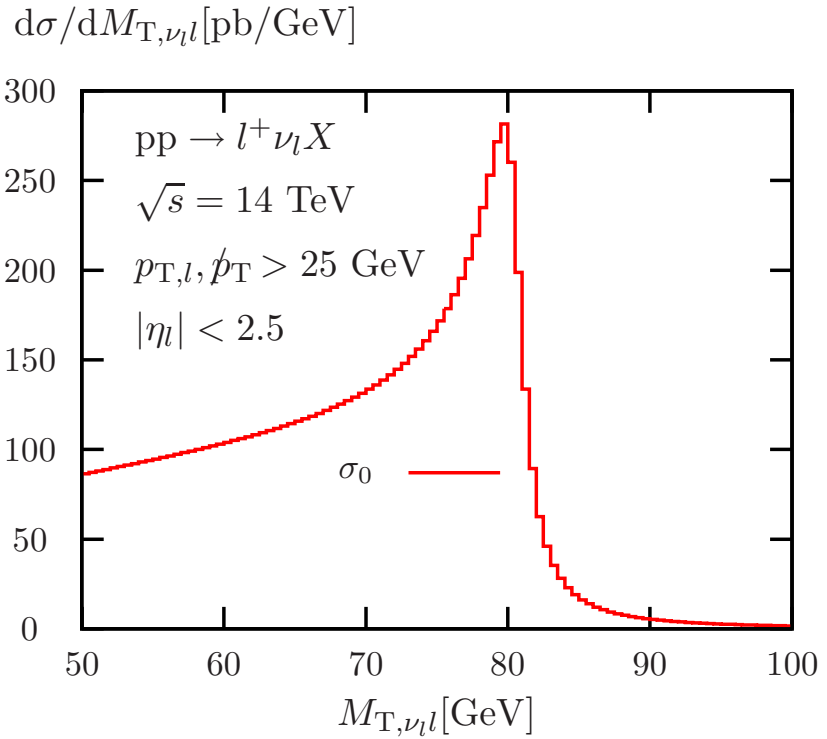

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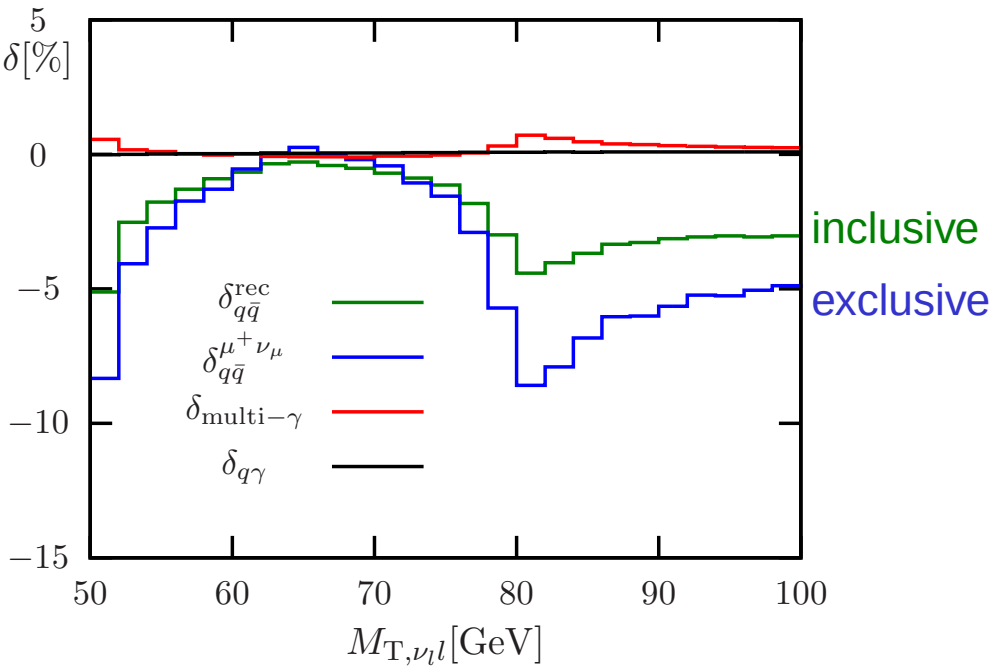

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EW corrections

- $\mathcal{O}(\alpha)$ corrections to resonant W production

  Hollik, Wackeroth [hep-ph/9606398]

  Baur, Keller, Wackeroth [hep-ph/9807417]

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  $\Rightarrow \sim$ 10 MeV shift for M_W beyond final state radiation

CDF [hep-ex/0007044]

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- multi-photon final-state radiation

  Baur, Stelzer [hep-ph/9910206]
  Placzek, Jadach [hep-ph/0302065]
  Carloni Calame et al. [hep-ph/0303102]
  Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

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Carloni Calame et al. [hep-ph/0303102]

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- complete $\mathcal{O}(\alpha)$ corrections

Dittmaier, Krämer [hep-ph/0109062]
Zykunov [hep-ph/0107059]
Baur, Wackeroth [hep-ph/0405191]
Arbuzov et. al [hep-ph/0506110]
Carloni Calame et. al [hep-ph/0609170]

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Dittmaier, Krämer [hep-ph/0604120]
Arbuzov, Sadykov [arXiv:0707.0423]
Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

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  - important at high $p_{\mathrm{T},l}$, M_{T}

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at LHC: $\sqrt{s} \gg M_W$ available: W' searches

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- leading two-loop corrections important Fadin et al. [hep-ph/9910338]
  Ciafaloni, Cornelli [hep-ph/0001142]
  Hori et al. [hep-ph/0007329]
  Melles [hep-ph/0108221]
  Beenakker, Werthenbach [hep-ph/0112030]
  Denner, Melles, Pozzorini [hep-ph/0301241]
  Jantzen, Kühn, Penin, Smirnov [hep-ph/0504111]
  [hep-ph/0509157]
  Denner, Jantzen, Pozzorini [hep-ph/0608326]

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

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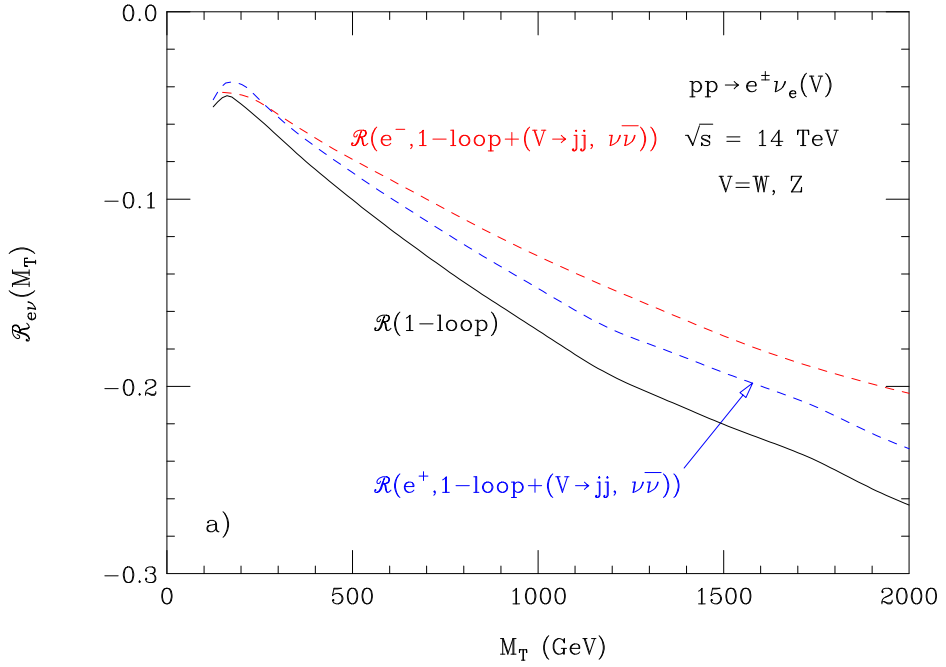
  - cancellations with subleading logs expected
- partial compensation from real W and Z emission

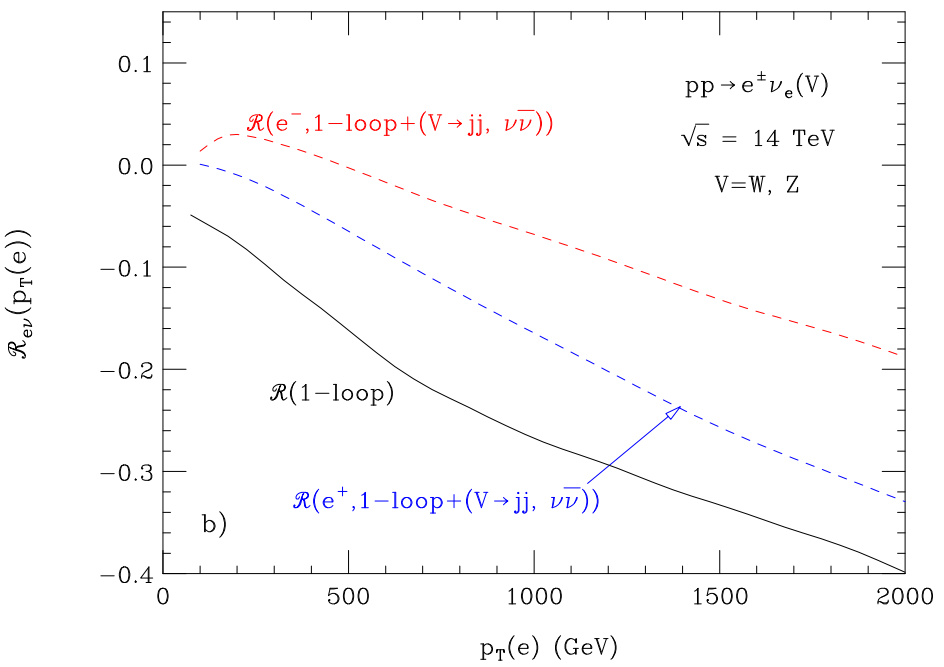
Ciafaloni, Cornelli [hep-ph/0604070]

Baur [hep-ph/0611241]

Corrections at high energies

effect of real massive vector boson emission:





Baur [hep-ph/0611241]