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Electroweak Corrections to W hadroproduction

Alexander Mück

Paul Scherrer Institut, Villigen

in collaboration with

S. Brensing, S. Dittmaier, M. Krämer

(RWTH Aachen) (MPI München) (RWTH Aachen)

LHC-D workshop on QCD and EW Physics
Zürich, June 3, 2008

based on PRD 77 (2008) 073006
arXiv:0710.3309

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Outline

- W-boson production
  - precision physics at the LHC
  - measuring the W mass
  - electroweak corrections
- new results
  - multi-photon final-state radiation
  - photon-induced processes
  - corrections at large energies
  - corrections in the MSSM

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High precision at the LHC

LHC is a tool for precision physics: e.g. M_{W}, Γ_{W}, $\sin\theta_{\mathrm{eff}}^{\mathrm{lept}}$, ...

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- precise theoretical prediction

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problems (to solve):

- hadron collider environment (large backgrounds)
- understand QCD (in signal and background)
  - Leading order (LO) up to 100% uncertainty
  - Next-to-leading order (NLO) needed everywhere
  - NNLO needed for some processes

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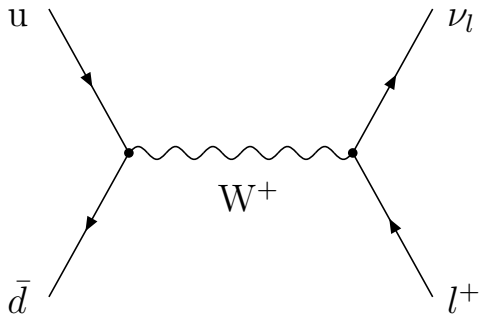
EW corrections:

- needed for specific (high precision) observables
  $(\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2))$
- needed if enhanced
  (e.g. at high energies: $\alpha \to \alpha \log^2(Q/M_W)$)

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)

300-3000 Million W bosons per year!

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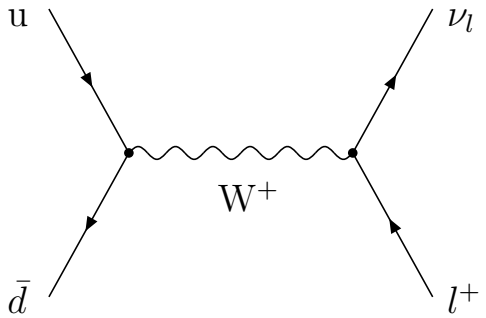


- clean signal: lepton + missing p_{T}
- huge cross section: $\sigma_W = 30$ nb (5 nb after basic cuts)
- goals: W mass M_W with $\Delta M_W = 15$ MeV (30 MeV at Tevatron)
  W width Γ_W with $\Delta\Gamma_W < 30$ MeV

  Tev4LHC report [arXiv:0705.3251]

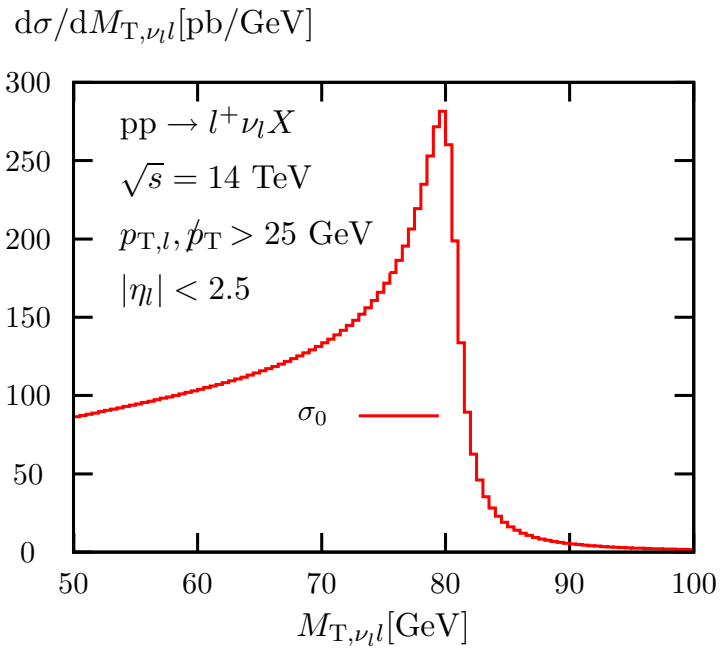
  determine collider or parton-parton luminosity, PDFs

  Dittmar, Pauss, Zürcher [hep-ex/9705004]

Precision Measurements

W boson mass:

- fit to distributions
  - transverse momentum: $p_{\mathrm{T},l}$
  - transverse mass: $M_{\mathrm{T}} = \sqrt{2\, p_{\mathrm{T},l}\, p_{\mathrm{T}}^{\mathrm{miss}}\, (1 - \cos\phi_{\nu_l l})}$



Jacobian peak at $M_{\mathrm{T}} = M_{\mathrm{W}}$

$\mathrm{d}\sigma/\mathrm{d}M_{\mathrm{T}}$ and $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T},l}$ equivalent at tree-level

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- challenges
  - excellent detector calibration

    (use data from $pp \to Z \to l^+ l^-$)
  - $p_{\mathrm{T},l}$: sensitive to $p_{\mathrm{T},W}$ (initial state QCD radiation)
  - M_{T}: reconstruction of $p_{\mathrm{T}}^{\mathrm{miss}}$

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  - excellent theoretical prediction: QCD and EW

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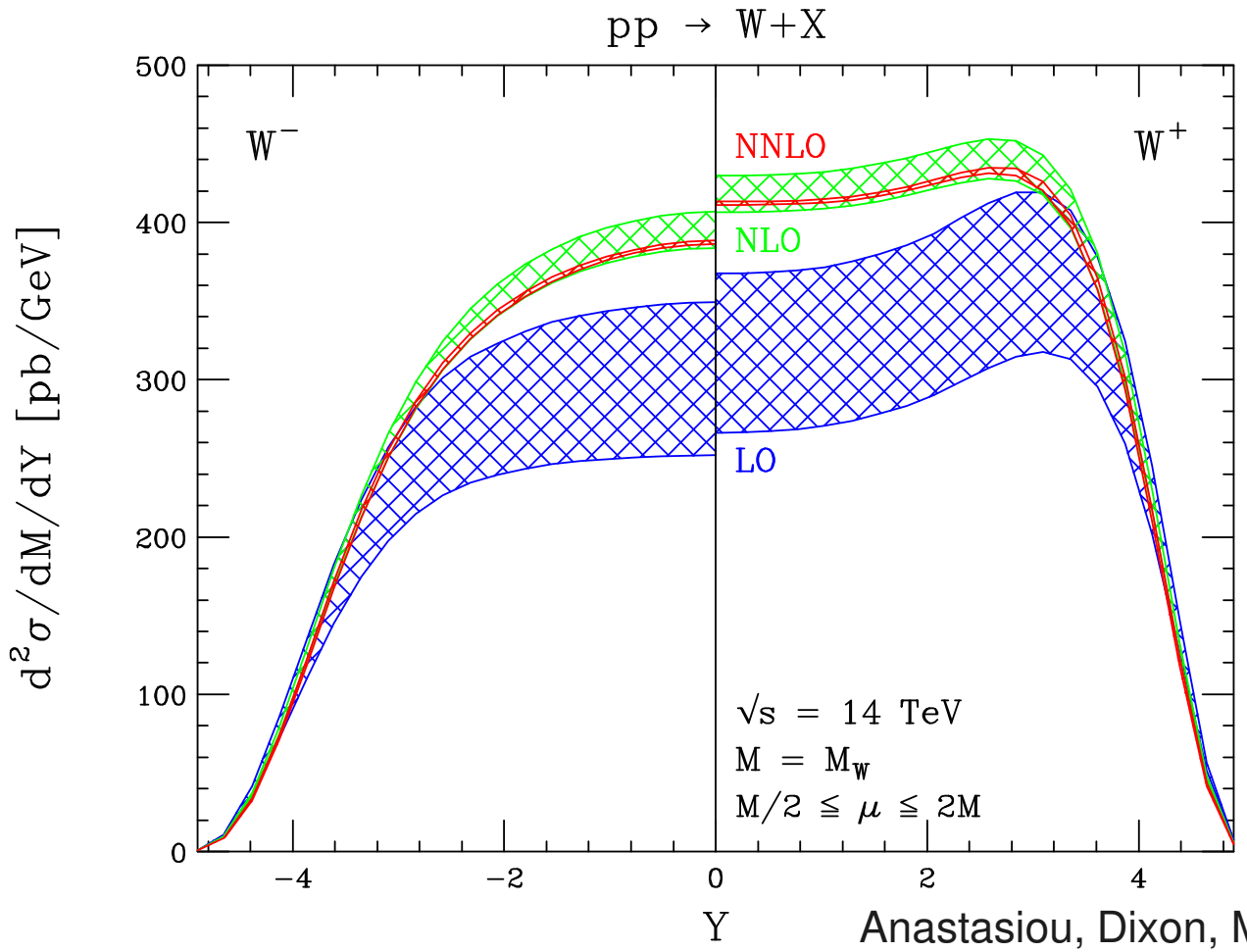
QCD Predictions

NNLO QCD:

- total cross section — v.Neerven, Zijlstra [NPB **382** (1992) 11]; Harlander, Kilgore [hep-ph/0201206]
- rapidity distributions — Anastasiou et al. [hep-ph/0312266]
- fully differential cross sections — Melnikov, Petriello [hep-ph/0609070]

QCD Predictions

Rapidity distribution: 1% uncertainty at NNLO



Anastasiou, Dixon, Melnikov, Petriello
[hep-ph/0312266]

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further QCD improvements:

- NNNLO in soft + virtual approximation Moch, Vogt [hep-ph/0508265]
- soft gluon resummation for $p_{\mathrm{T},W}$ distribution

  Balasz, Yuan [hep-ph/9704258]; Ellis, Veseli [hep-ph/9706526]; Cao,Yuan [hep-ph/0401026]
- NLO plus parton shower (MC@NLO)

  Frixione, Nason, Webber [hep-ph/0305252]

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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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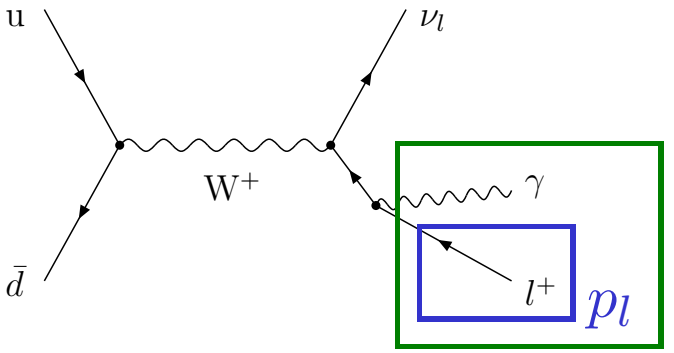

$p_l = p_l + p_\gamma$
(for collinear photons)

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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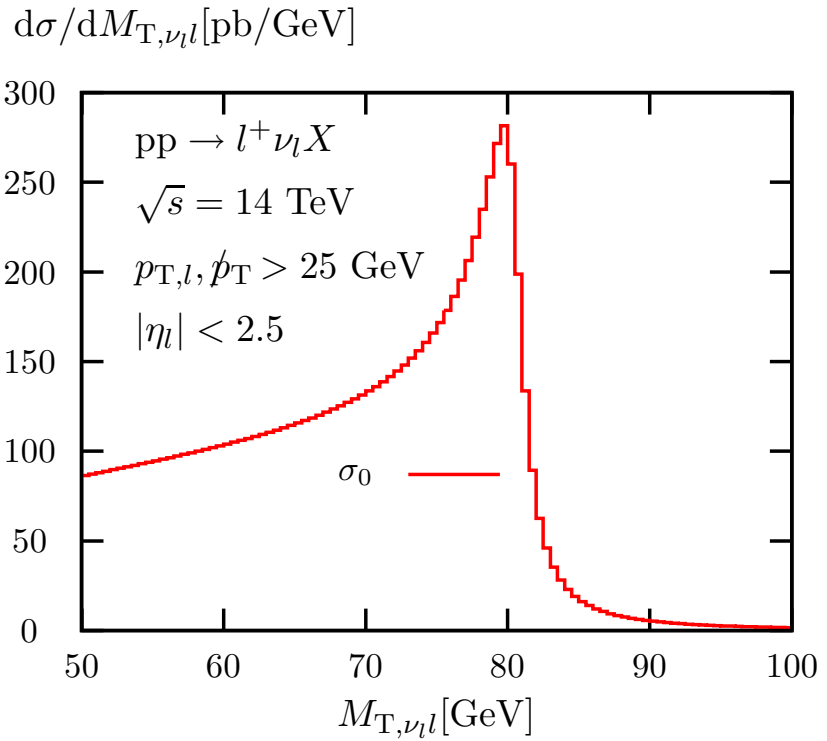
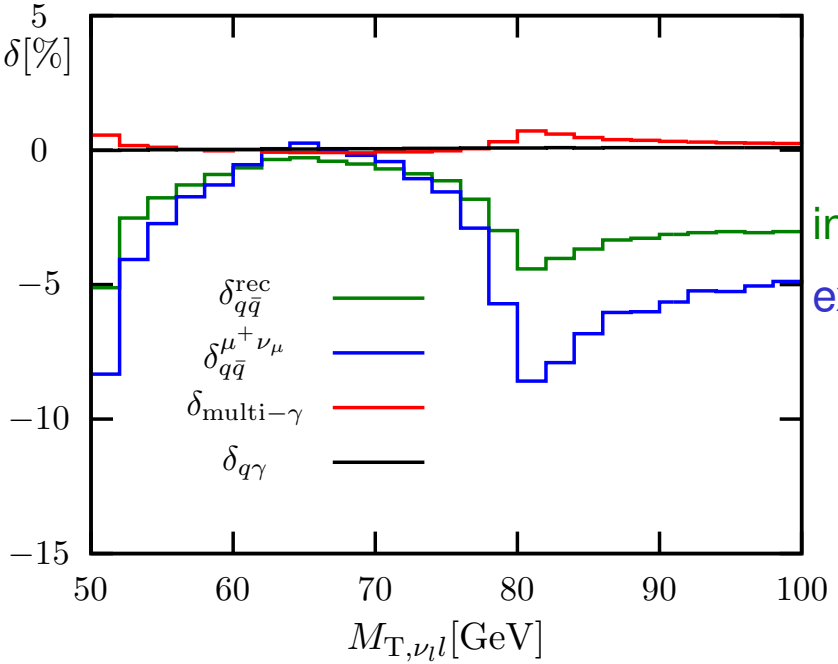


Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]



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EW corrections

available 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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  $\Rightarrow \sim$ 170 (65) MeV shift for M_W for $\mu^{\pm}$ ($e^{\pm}$) channel from final state radiation

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

CDF [hep-ex/0007044]

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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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more details in the following

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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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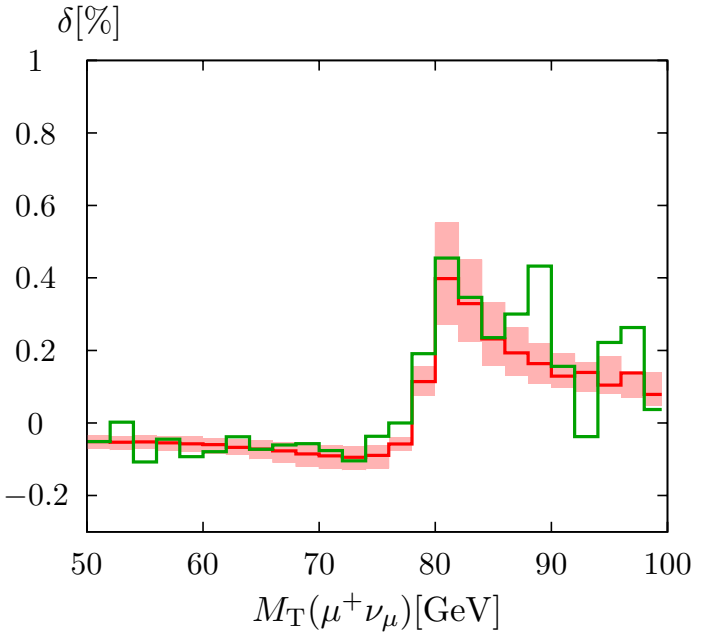

parton shower: from Horace (Carloni Calame et al.) in arXiv:0705.3251
structure function (with scale variation): Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]

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Photon-induced processes

There are photons inside the proton: γ as a parton

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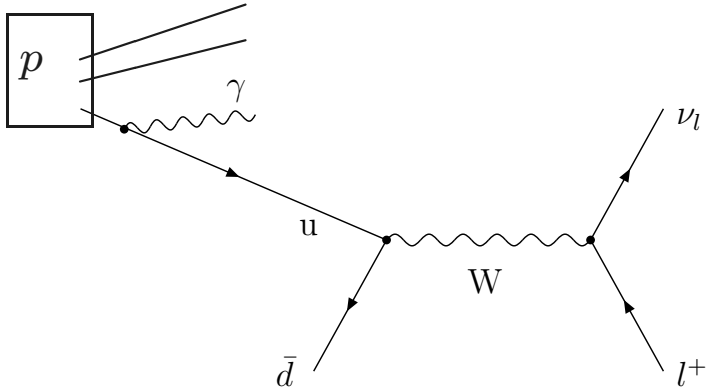

- initial state photon emission $\Rightarrow$ collinear singularity

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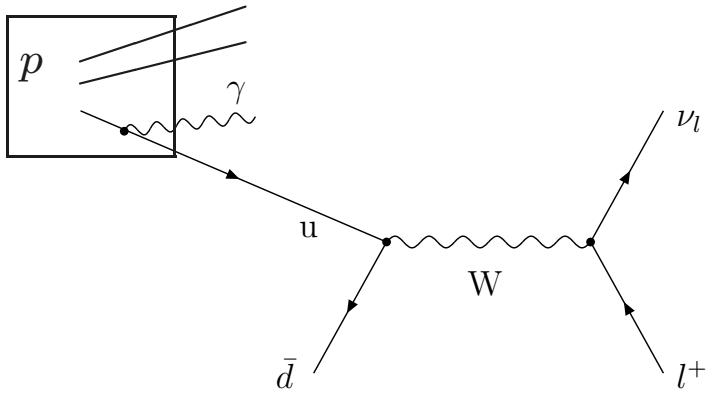

- initial state photon emission $\Rightarrow$ collinear singularity
- absorb singularity into PDF:

$$f_q(x) \to f_q(x,\mu_F) - \int_x^1 \frac{dz}{z}\, f_q\left(\frac{x}{z},\mu_F\right) Q_q^2\, \frac{\alpha}{2\pi}$$
$$\times\left\{\ln\left(\frac{\mu_F^2}{m_q^2}\right)\left[P_{qq}(z)\right]_+ - \left[P_{qq}(z)\left(2\ln(1-z)+1\right)\right]_+ + C_{qq}(z)\right\}$$

with $C_{qq} = 0$ in $\overline{\rm MS}$

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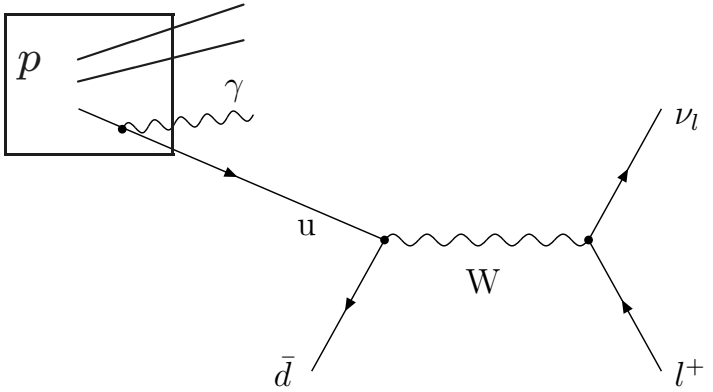

- initial state photon emission $\Rightarrow$ collinear singularity
- absorb singularity into PDF:
- include QED in DGLAP evolution

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

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

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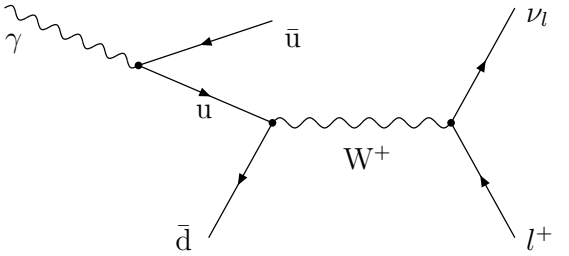
Photon-induced processes

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



collinear singularity again absorbed into PDF:

$$f_q(x) \to f_q(x,\mu_F) - \int_x^1 \frac{dz}{z}\, f_\gamma\left(\frac{x}{z},\mu_F\right)\, 3\,Q_q^2\,\frac{\alpha}{2\pi}\,\left\{\ln\left(\frac{\mu_F^2}{m_q^2}\right) P_{q\gamma}(z) + C_{q\gamma}(z)\right\}$$

with: $C_{q\gamma}^{\mathrm{DIS}}(z) = P_{q\gamma}(z)\ln\frac{1-z}{z} - 8z^2 + 8z - 1$

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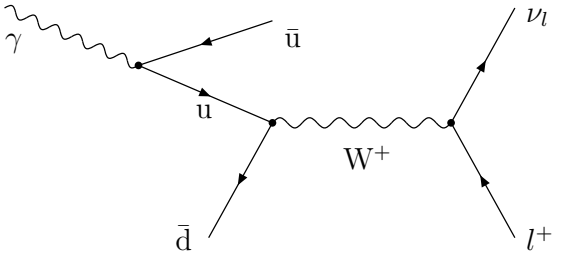
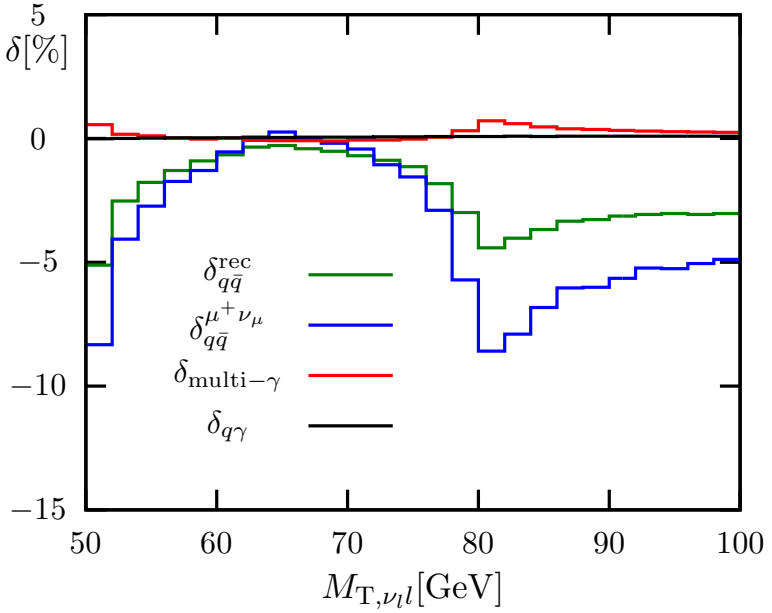
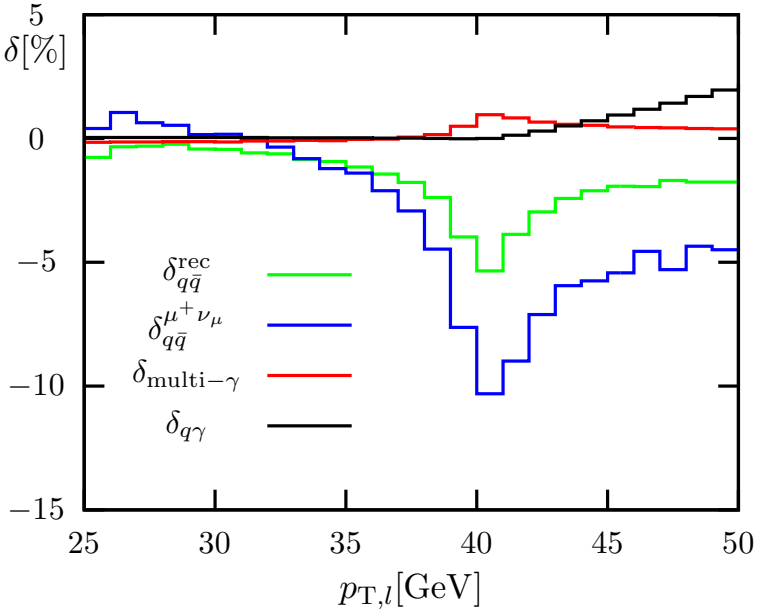


- usually percent level correction
- not relevant for M_{W} measurement in M_{T}





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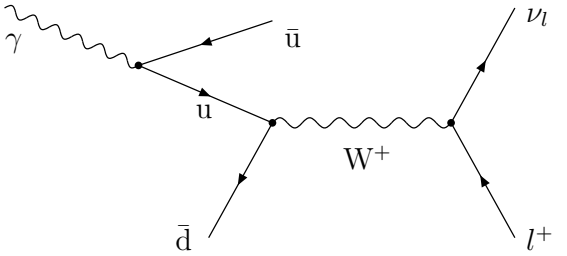

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- enhanced up to $\sim$15% at large $p_{\mathrm{T},l} \sim$ 500 GeV

$p_{\mathrm{T},l}/\mathrm{GeV}$	25–∞	50–∞	100–∞	200–∞	500–∞	1000–∞
$\delta_{q\gamma}/\%$	0.065(1)	4.7(1)	12.3(1)	17.1(1)	16.7(1)	13.5(1)

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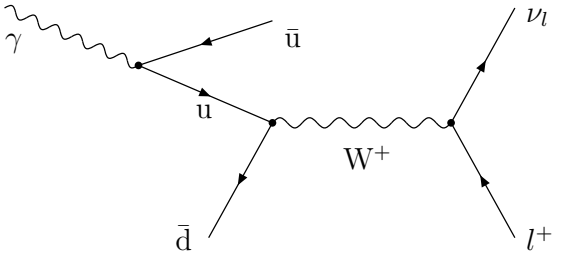

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$\delta_{\mathrm{QCD}}^{\mu=M_{\mathrm{T,W}}}/\%$	$-2.8(1)$	793(1)	685(1)	607(1)	323(1)	127(1)

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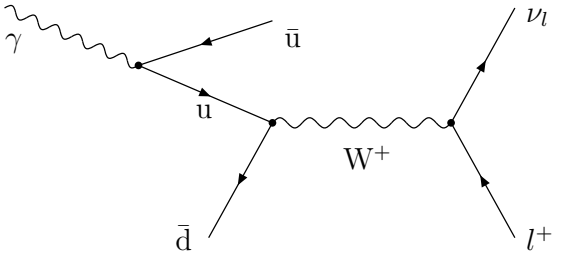

- usually percent level correction
- not relevant for M_{W} measurement in M_{T}
- enhanced up to $\sim$15% at large $p_{\mathrm{T},l} \sim$ 500 GeV
  - but overwhelmed by QCD uncertainties
  - below 1% in M_{T}

$M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$	50–∞	100–∞	200–∞	500–∞	1000–∞	2000–∞
$\delta_{q\gamma}/\%$	0.052(1)	0.12(1)	0.25(1)	0.37(1)	0.39(1)	0.36(1)
$\delta_{\mathrm{QCD}}^{\mu=M_{\mathrm{T,W}}}/\%$	−4.4(1)	22.5(1)	24.0(1)	12.6(1)	−6.2(1)	−34.6(1)

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Corrections at high energies

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

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- new physical scale: expect log enhanced corr.

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  $\Rightarrow$ 1-loop corrections: $\alpha \log^2(s/M_W^2)$ (Sudakov logs)

  (also subleading and angular dependent logs)

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  (also subleading and angular dependent logs)
- W production at LHC: -30% correction for $\sqrt{s} = 2$ TeV

$M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$	50–∞	100–∞	200–∞	500–∞	1000–∞	2000–∞
$\delta_{q\bar{q}}^{\mu^+\nu_\mu}/\%$	$-2.9(1)$	$-5.2(1)$	$-8.1(1)$	$-14.8(1)$	$-22.6(1)$	$-33.2(1)$
$\delta_{q\bar{q}}^{\mathrm{rec}}/\%$	$-1.8(1)$	$-3.5(1)$	$-6.5(1)$	$-12.7(1)$	$-20.0(1)$	$-29.6(1)$

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  (also subleading and angular dependent logs)
- W production at LHC: -30% correction for $\sqrt{s} = 2$ TeV
- 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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Corrections at high energies

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

- new physical scale: expect log enhanced corr.
- soft exchange of virtual massive vector bosons

  $\Rightarrow$ 1-loop corrections: $\alpha \log^2(s/M_W^2)$ (Sudakov logs)

  (also subleading and angular dependent logs)
- W production at LHC: -30% correction for $\sqrt{s} = 2$ TeV
- leading two-loop corrections important
  - W production at LHC: +4% correction for $\sqrt{s} = 2$ TeV

    (from leading logs)

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

$M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$	50–∞	100–∞	200–∞	500–∞	1000–∞	2000–∞
$\delta^{(2)}_{\mathrm{Sudakov}}/\%$	-0.0002	-0.023	-0.082	0.21	1.3	3.8

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- partial compensation from real W and Z emission

Ciafaloni, Cornelli [hep-ph/0604070]

Baur [hep-ph/0611241]

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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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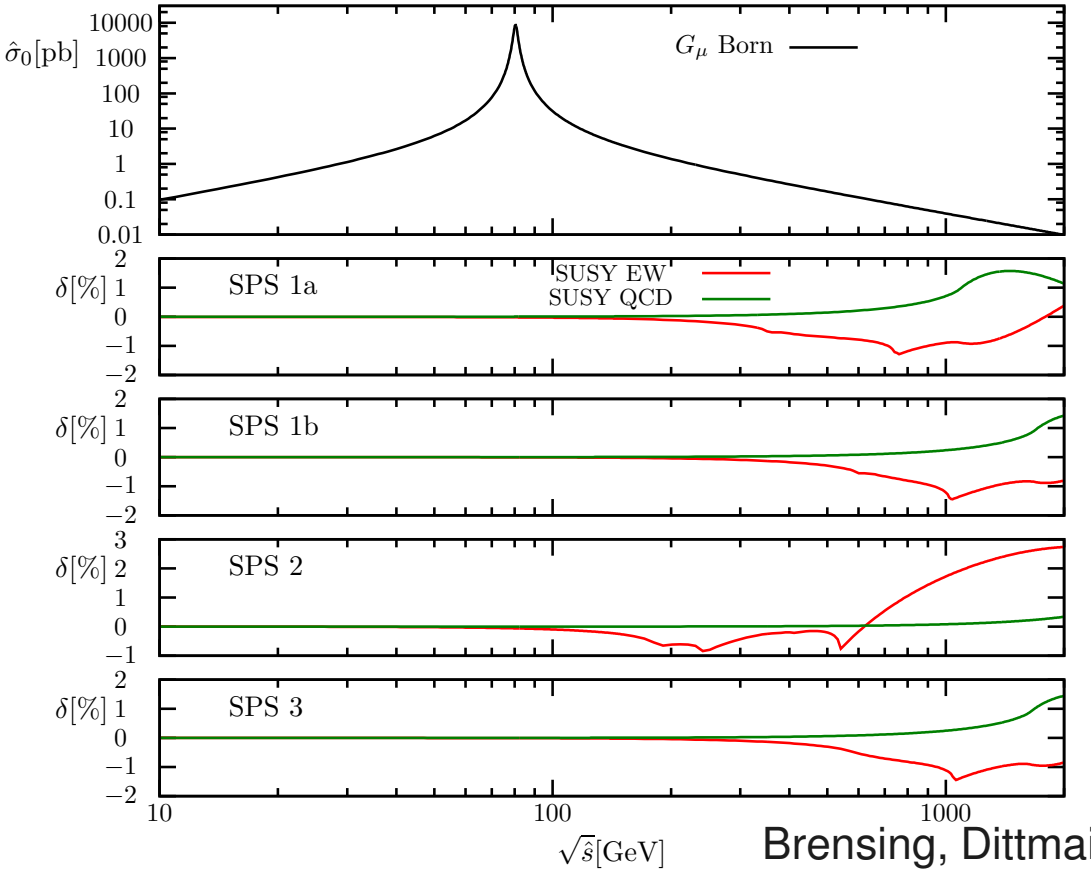

partonic cross section for SPS benchmark points

no impact for M_W measurement

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

W production is SM candle!

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

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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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  $\Rightarrow$ no hard QCD radiation + EW corrections

- full $\mathcal{O}(\alpha\alpha_{\mathrm{s}})$ desirable, but very hard
  - important part: EW corrections to $pp \to l^{\pm}\nu_l + \mathrm{jet}$
  - so far: $pp \to \mathrm{W} + \mathrm{jet}$ Kühn et al. [hep-ph/0703283], [arXiv:0708.0476]
    Hollik et al. [arXiv:0707.2553]

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Summary

LHC is a tool for precision physics

e.g. M_{W}, Γ_{W}, $\sin\theta_{\mathrm{eff}}^{\mathrm{lept}}$, ...

Electroweak corrections for single W production:

- important for W mass measurement ($\rightarrow \mathcal{O}(100$ MeV) shift)
- important at high-energies (Sudakov regime)
- including:
  - full $\mathcal{O}(\alpha)$ corrections $\rightarrow \mathcal{O}(-30\%)$ at $\sqrt{s} = 2$ TeV
  - leading two-loop Sudakov logs $\rightarrow \mathcal{O}(+4\%)$ at $\sqrt{s} = 2$ TeV
  - multi-photon final-state radiation $\rightarrow \mathcal{O}(10$ MeV) shift in M_{W}
  - photon-induced processes $\rightarrow$ visible?
  - MSSM corrections $\rightarrow$ standard candle

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Back-up slides

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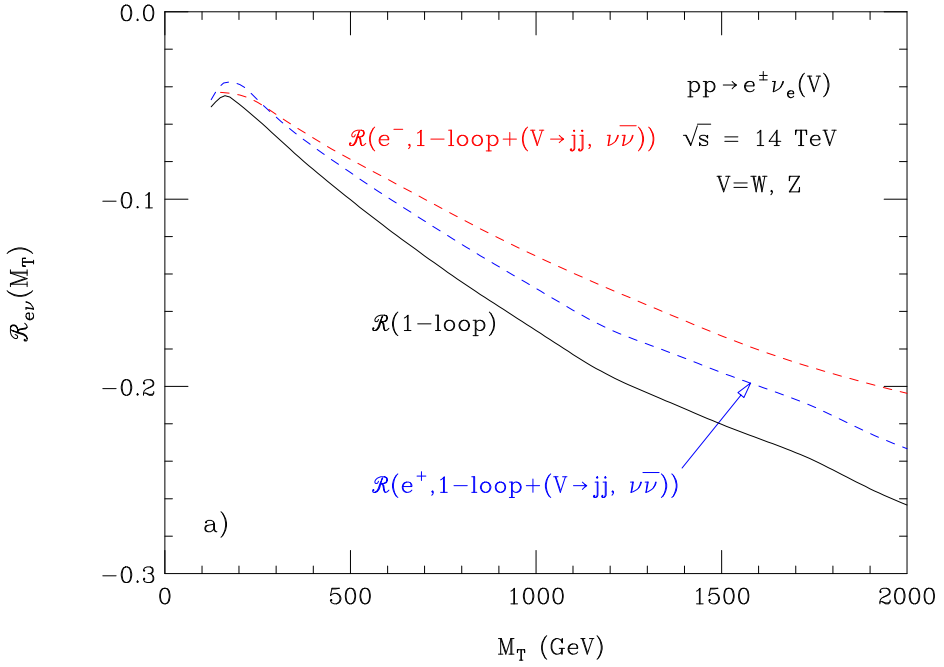
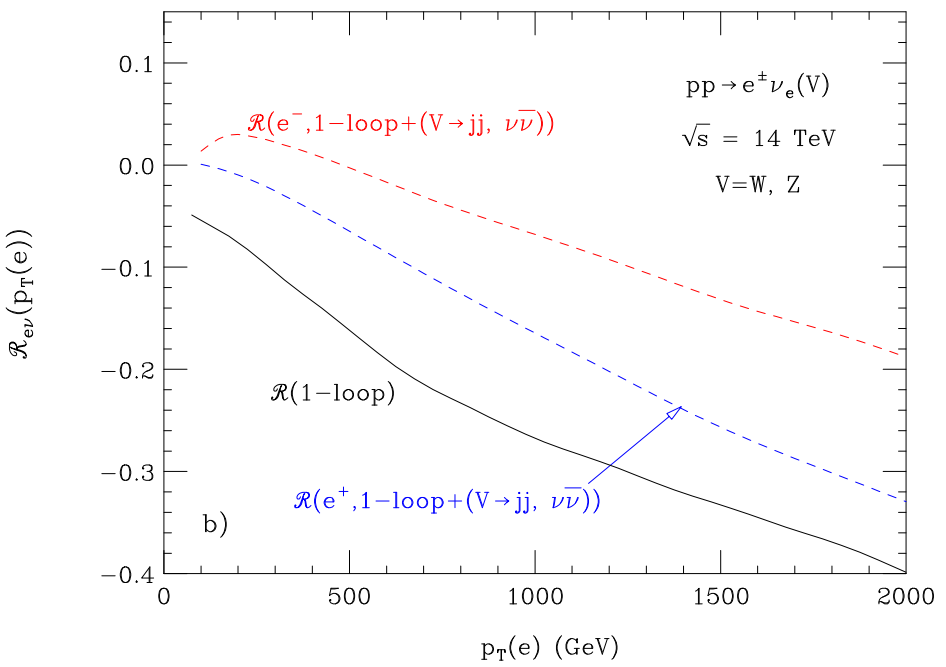
Corrections at high energies

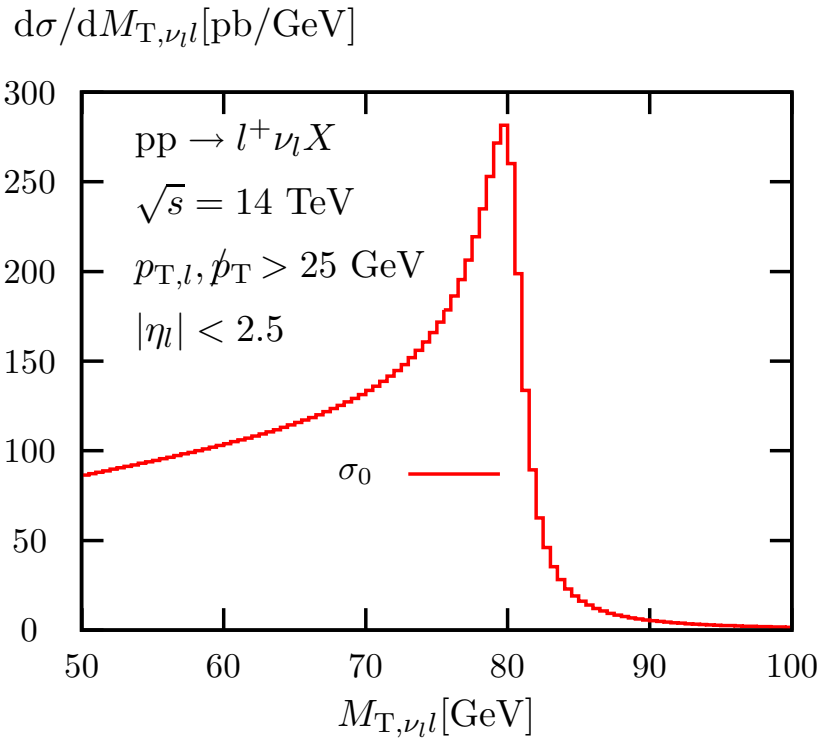
effect of real massive vector boson emission:



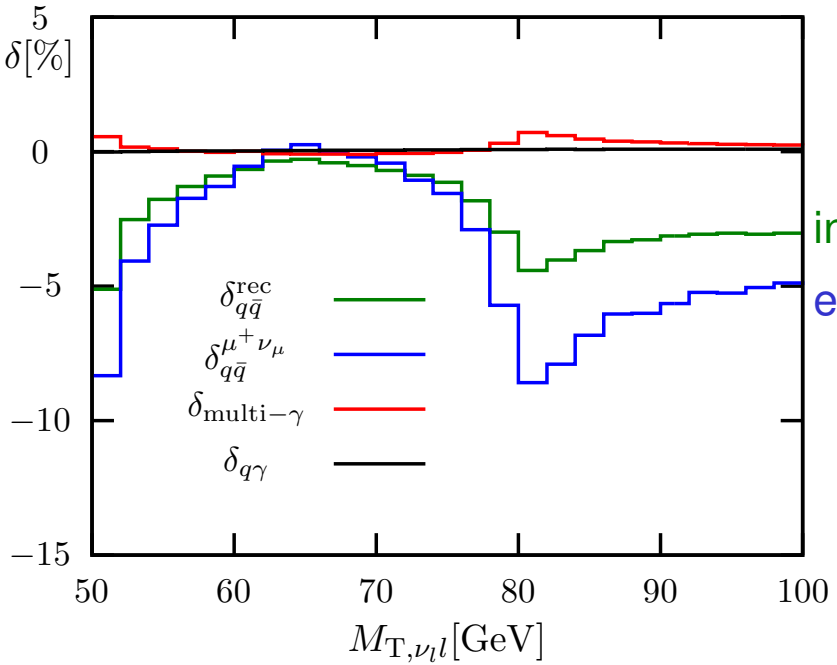


Baur [hep-ph/0611241]

EW corr.: M_{T} @ LHC



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



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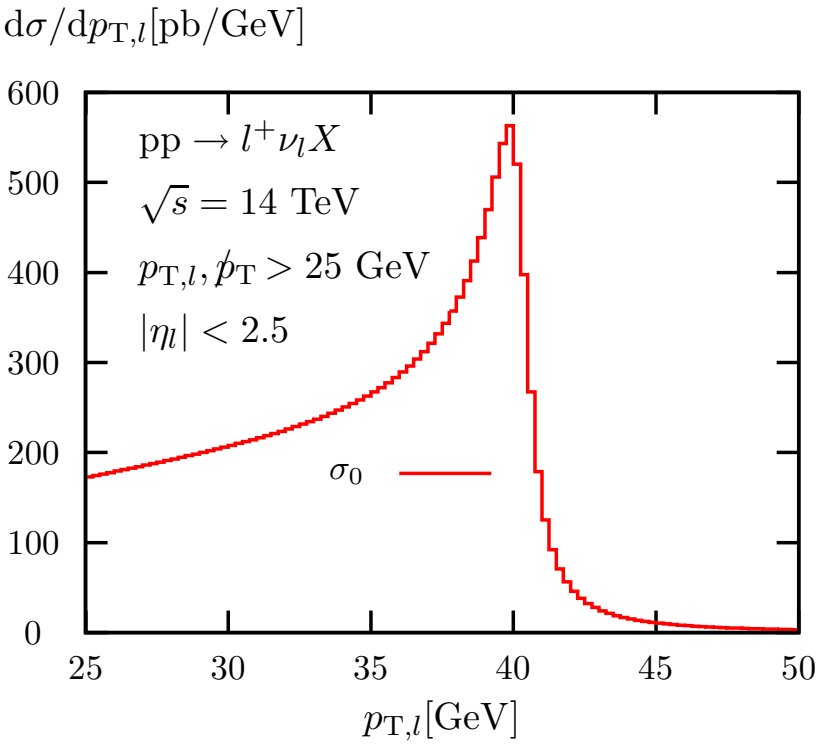
EW corr.: p_{T} @ LHC



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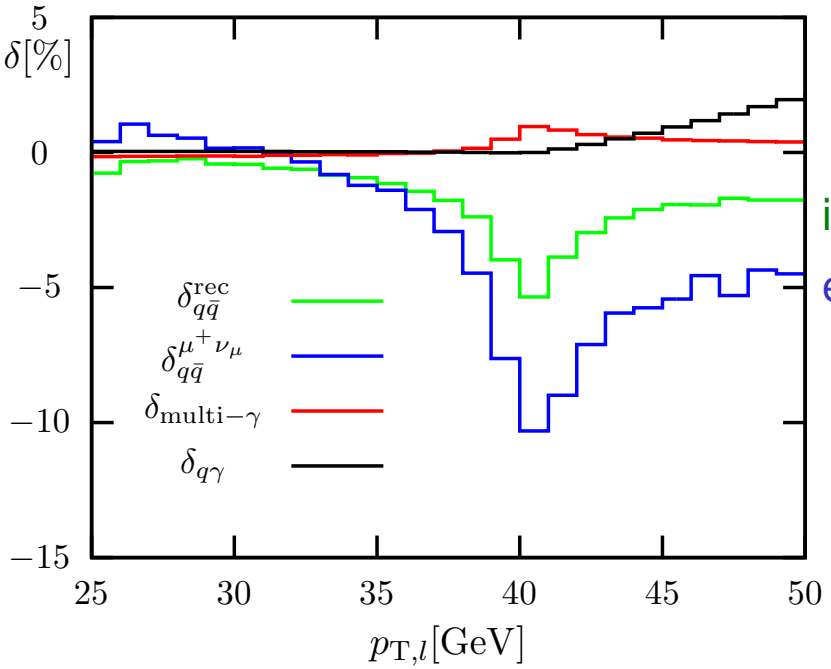

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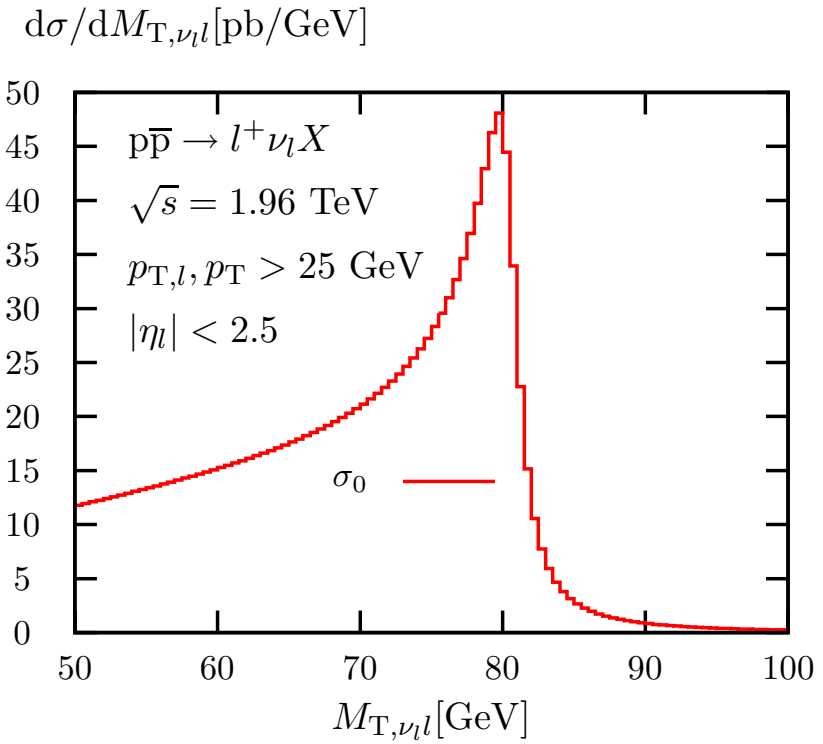
EW corr.: M_{T} @ Tevatron



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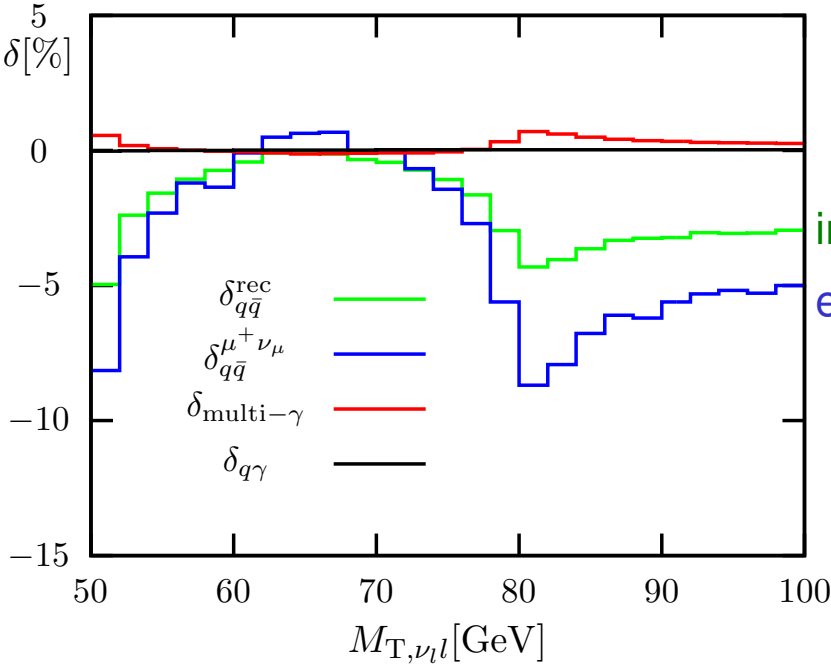

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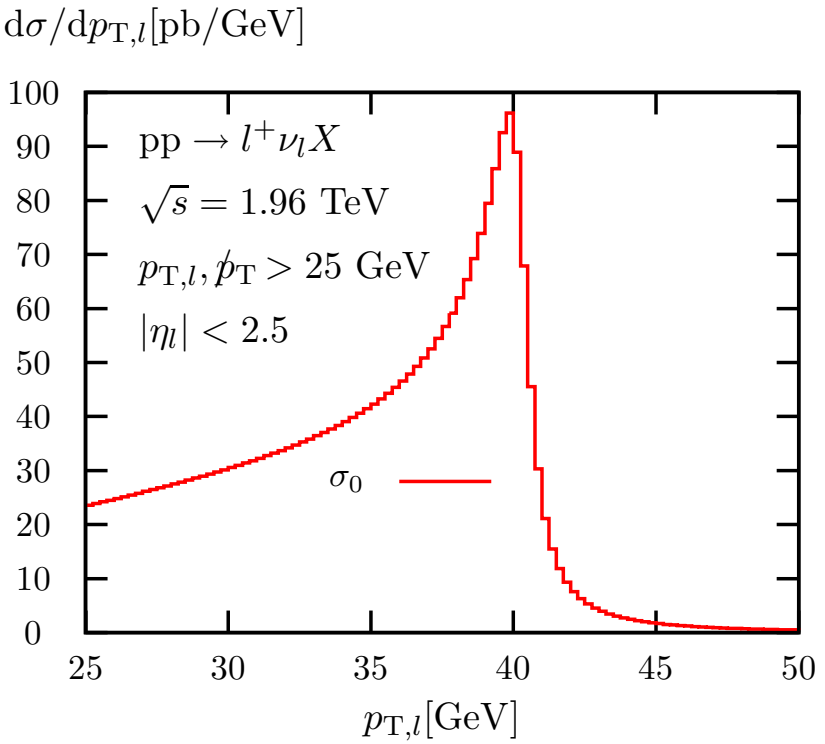

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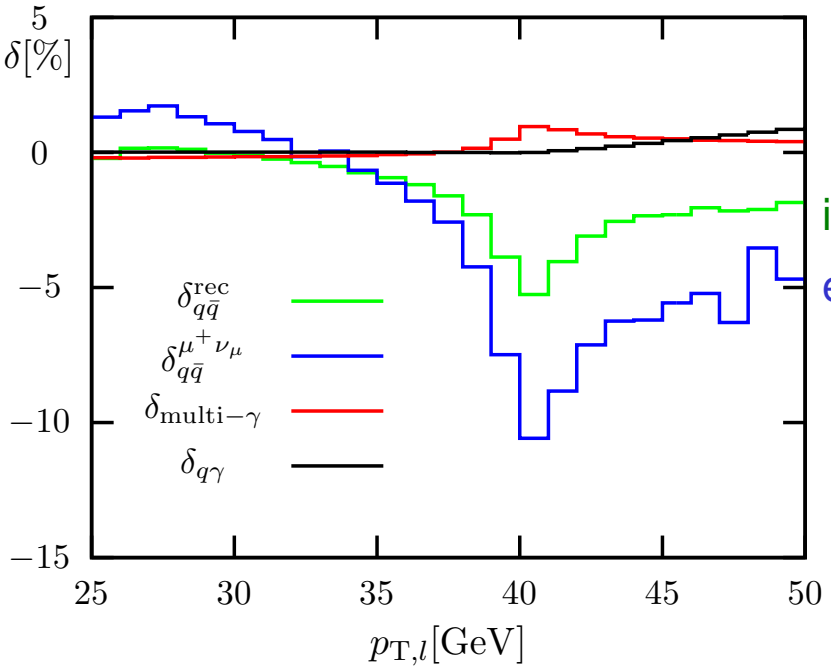

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