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Electroweak Precision at the LHC

Alexander Mück

Paul Scherrer Institut, Villigen

Particle Theory Seminar

PSI, February 28, 2008

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Outline

- LHC prospects
  - as a discovery machine
  - for high precision measurements
- Electroweak corrections for LHC processes:
  - W production
  - Higgs production in vector boson fusion
  - Higgs production in bottom quark fusion

(only a biased selection)

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LHC Prospects

New energy frontier:

- pp collision at $\sqrt{s} = 14$ TeV
- high luminosity: 10-100 fb^{-1}/year

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$\Rightarrow$ understand electroweak symmetry breaking

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- Higgs boson(s)
- strong dynamics
- supersymmetry
- extra dimensions
- little Higgs models ...

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Measure and predict as precisely as possible!

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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: $\alpha \to \alpha \log^2(Q/M_W)$)

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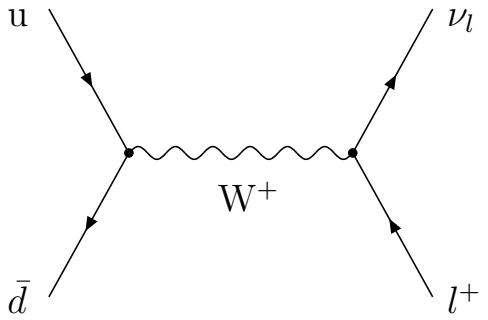
W Production at the LHC

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)

300-3000 Million W bosons per year!

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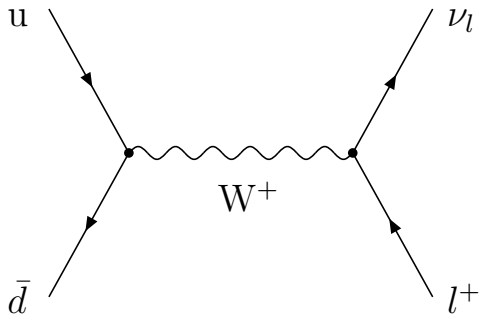

- clean signal: lepton + missing p_{T}
- huge cross section: $\sigma_W = 30$ nb (5 nb after basic cuts)
- goals: W mass M_W with $\Delta M_W = 15$ MeV (30 MeV at Tevatron)
  W width Γ_W with $\Delta\Gamma_W < 30$ MeV

  Tev4LHC report [arXiv:0705.3251]

  determine collider or parton-parton luminosity, PDFs

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

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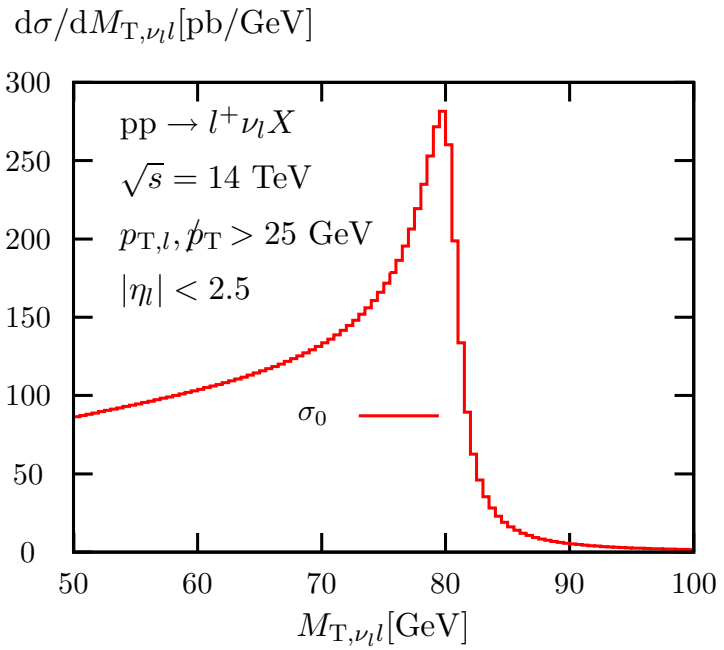
Precision Measurements

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)
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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]

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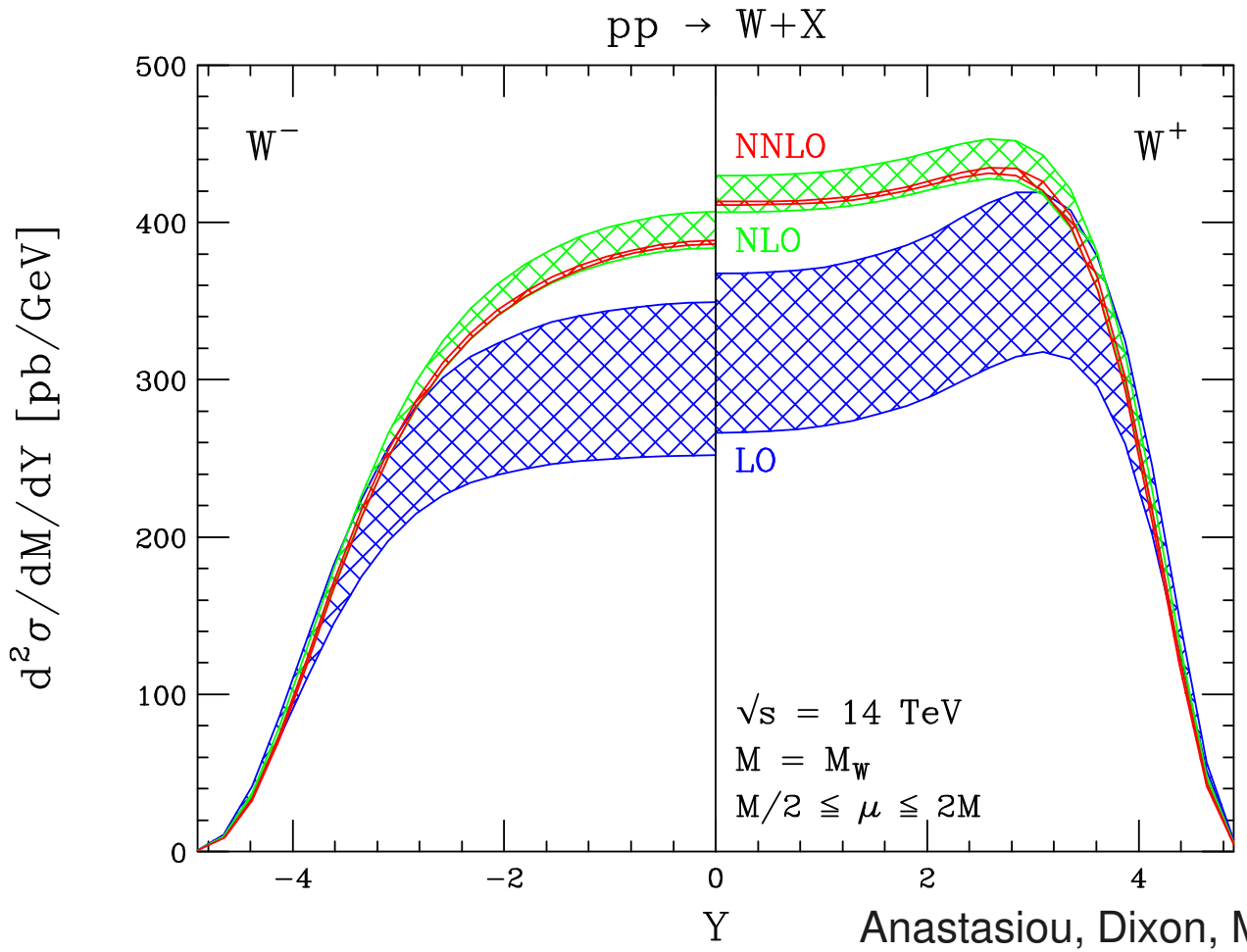
QCD Predictions

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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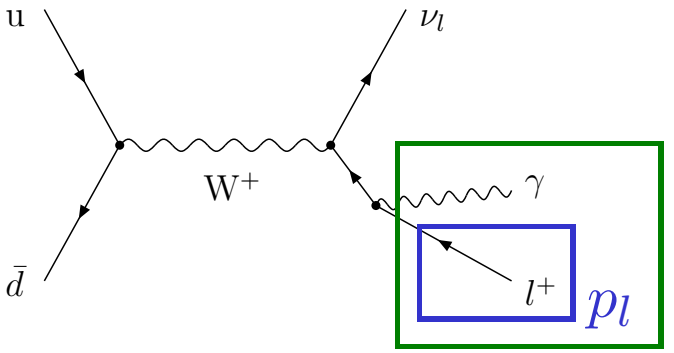

$p_l = p_l + p_\gamma$
(for collinear photons)

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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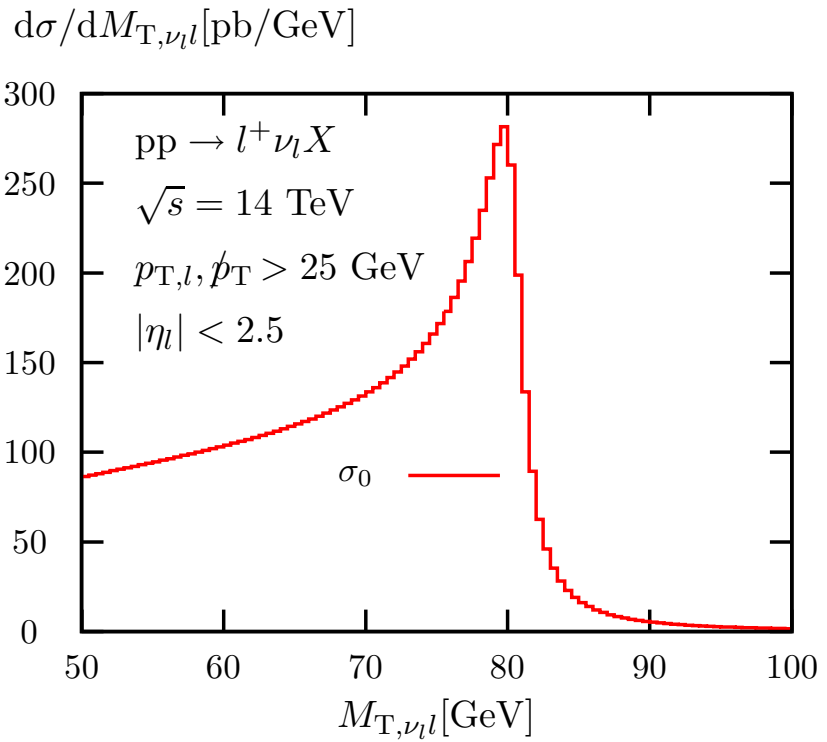
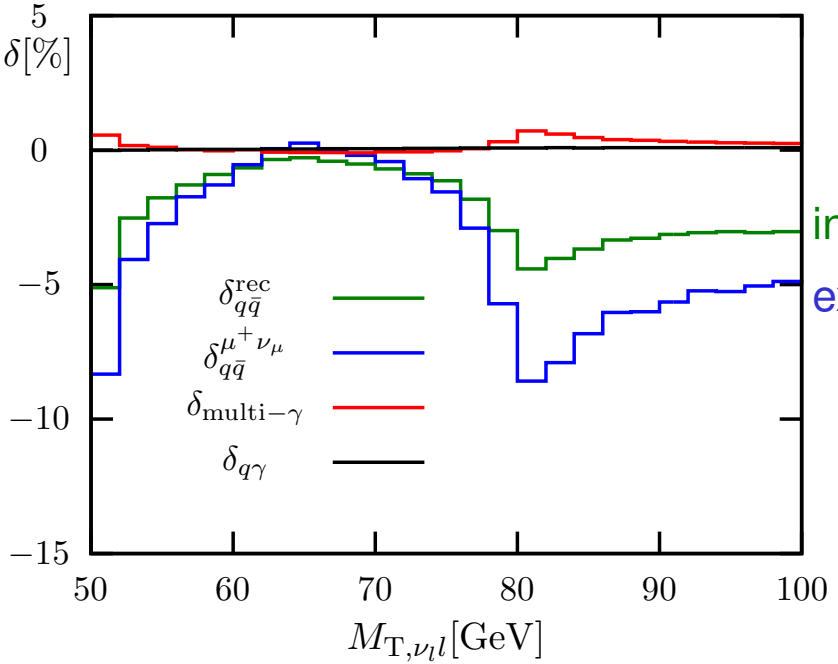


Brensing, Dittmaier, Krämer, AM [arXiv:0710.3309]



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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]
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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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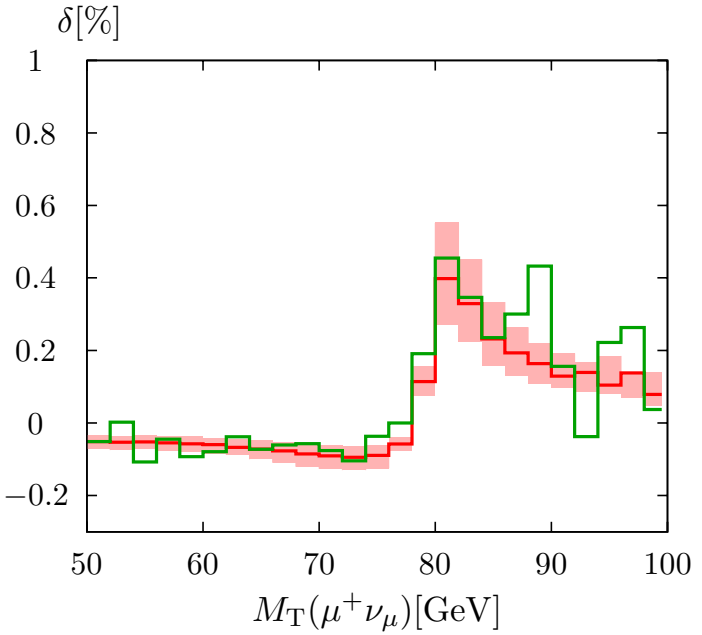

parton shower: from Horace (Carloni Calame et al.) in arXiv:0705.3251

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

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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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- 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?
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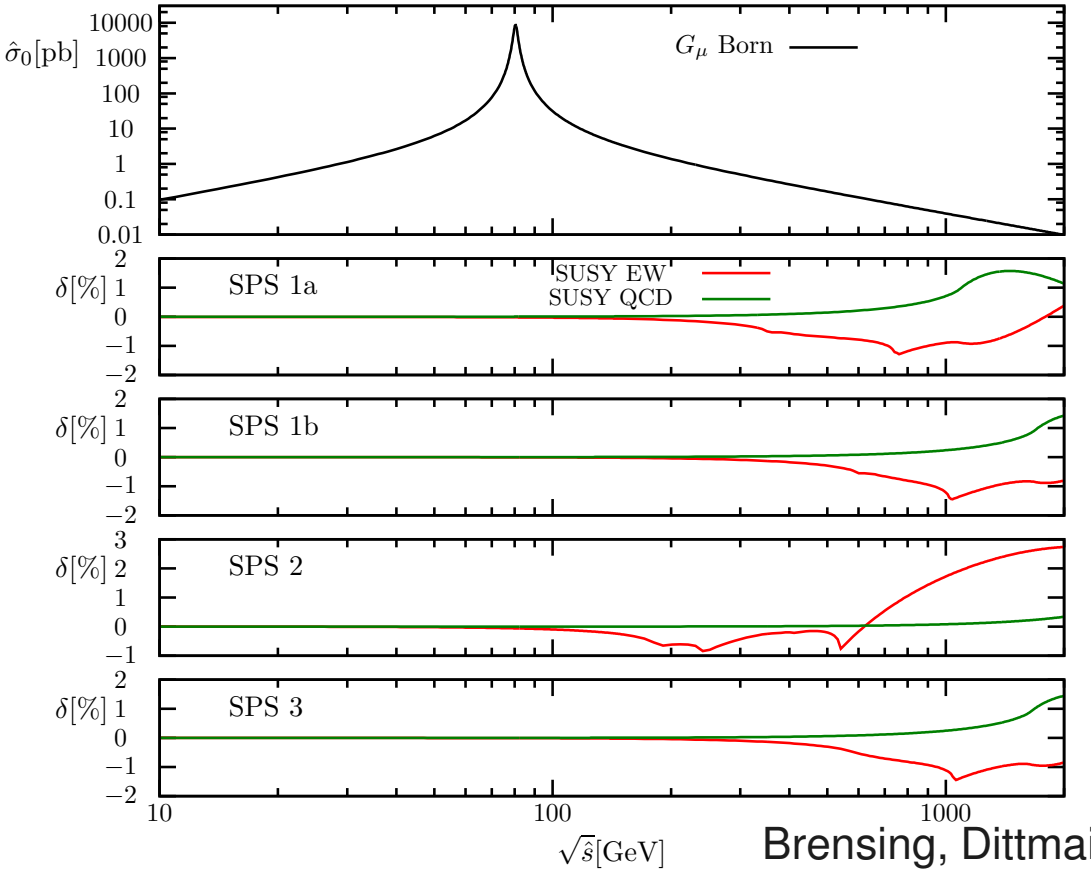

partonic cross section for SPS benchmark points

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

  Cao,Yuan [hep-ph/0401026]

- first attempt for QCD + full EW :

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

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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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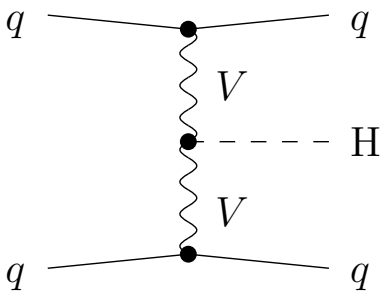
Higgs production in VBF

Vector-boson fusion (VBF): $pp \to H + 2\text{jets} + X$

- important Higgs discovery channel
  (over broad M_{H} range)
- measurement of HVV couplings
- powerful cuts for background suppression



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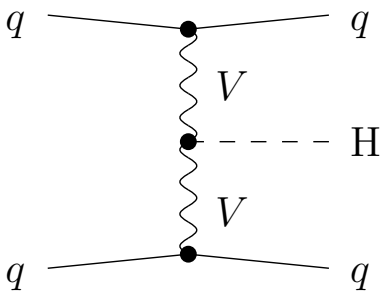

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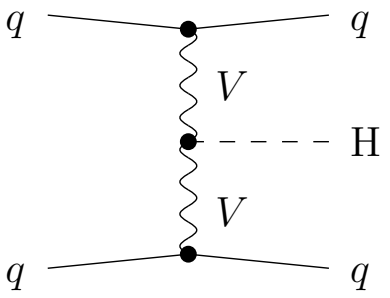

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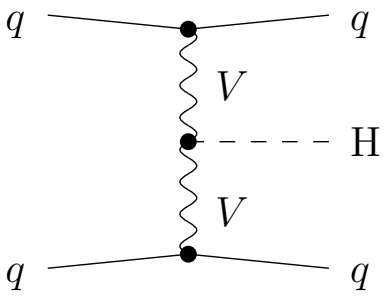
- measurement of HVV couplings
- powerful cuts for background suppression
- small uncertainties
  - statistical: 5-10%
  - small NLO QCD corrections (approx. only vertex corr. as in DIS)
    total cross section: 5-10%



Han, Valencia, Willenbrock [hep-ph/9206246]
Spira [hep-ph/9705337]

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Higgs production in VBF

Vector-boson fusion (VBF): $pp \to H + 2\text{jets} + X$

- important Higgs discovery channel
  (over broad M_{H} range)
- measurement of HVV couplings
- powerful cuts for background suppression
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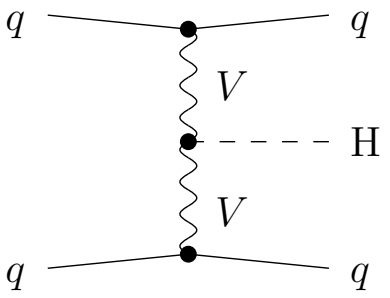

Figi, Oleari, Zeppenfeld [hep-ph/0306109]
Berger, Campbell [hep-ph/0403194]

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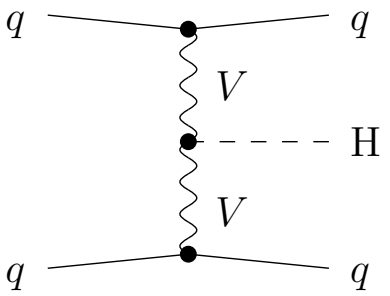

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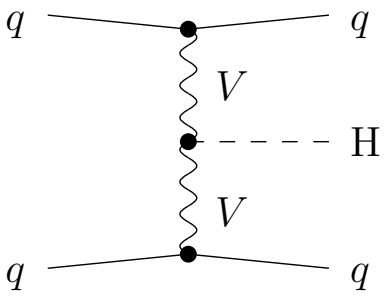
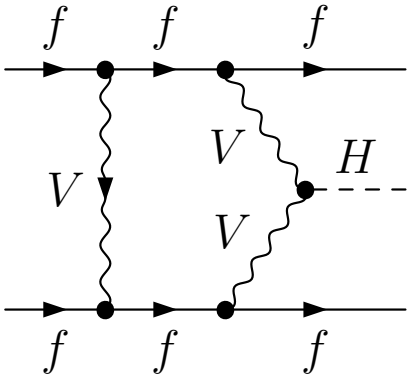


What about EW corrections?

EW corrections

Complete EW corrections calculated

Ciccolini, Denner, Dittmaier [arXiv:0710.4749]



+ hundreds of diagrams

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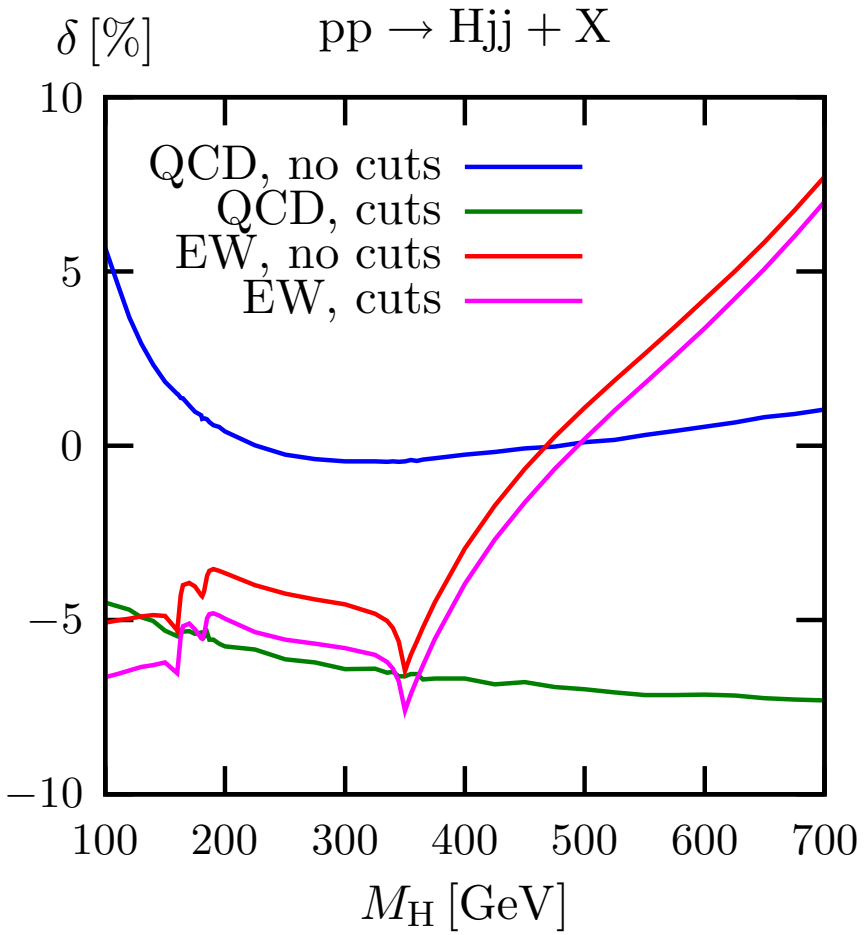
  Dittmaier [hep-ph/9904440]
- multi-channel phase space integration

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

QCD + EW corrections

total cross section:



Ciccolini, Denner, Dittmaier [arXiv:0710.4749]

VBF cuts:

- at least 2 tagging jets
- $p_{T_j} > 20$ GeV, $|y_j| < 4.5$
- large rapidity gap

$$|y_{j_1} - y_{j_2}| < 4.5, \quad y_{j_1} \cdot y_{j_2} < 0$$

with $p_{T_{j_1}} > p_{T_{j_2}} > \dots$

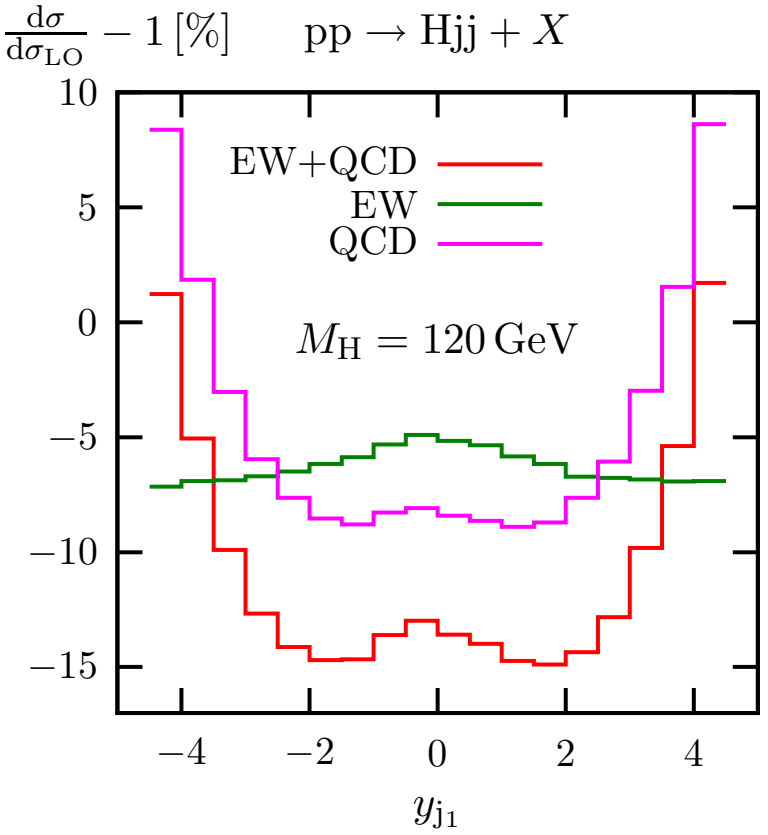
EW corrections sizable

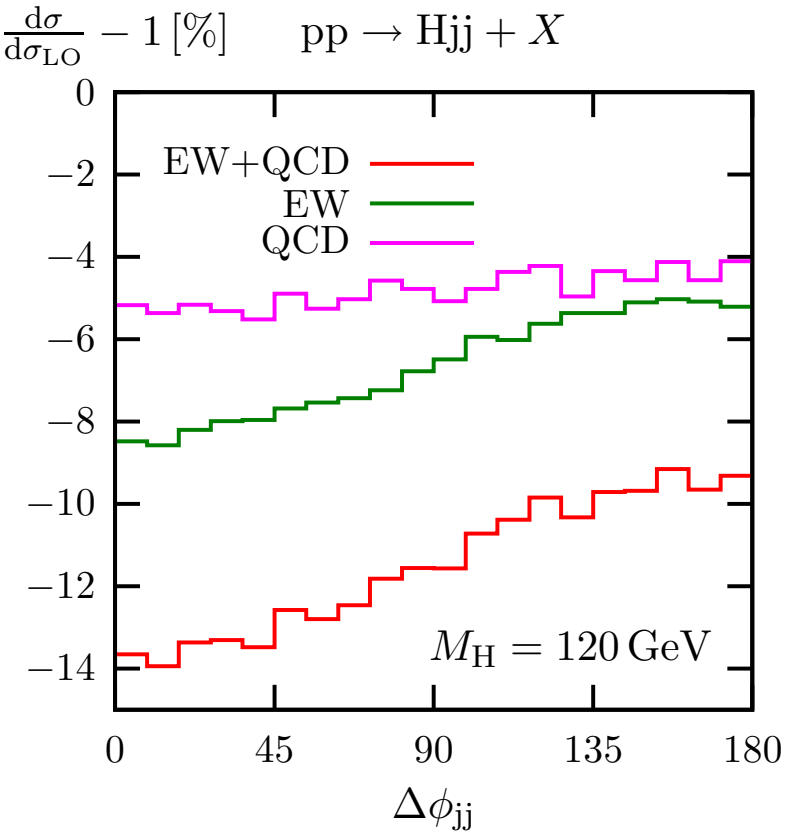
(γ-induced process: $\sim +1\%$)

QCD + EW corrections

distributions:

Ciccolini, Denner, Dittmaier [arXiv:0710.4749]





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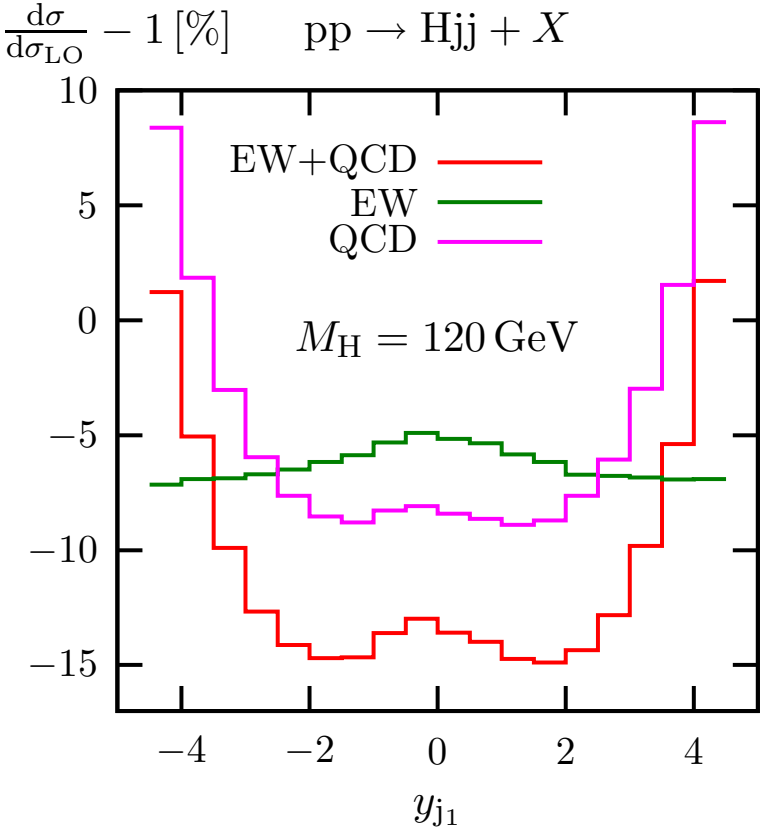

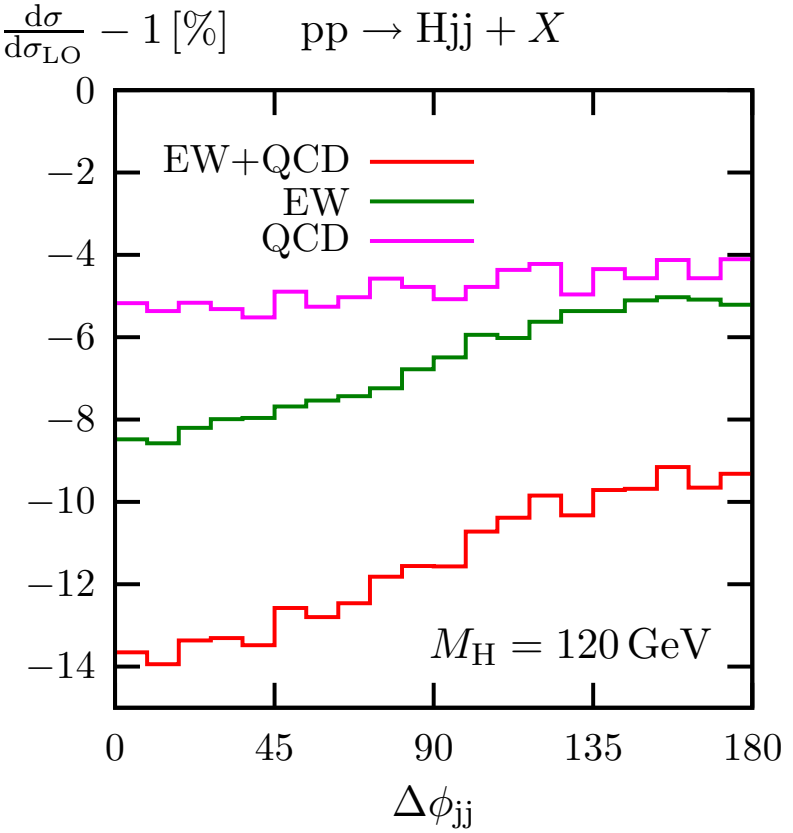

What about SUSY corrections?

S-QCD for σ^{tot}: Djouadi, Spira [hep-ph/9912476]

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Higgs from b quarks

Higgs production in association with b quarks:

- small Yukawa coupling in the SM: $\lambda_{\mathrm{b}} \propto m_{\mathrm{b}}$

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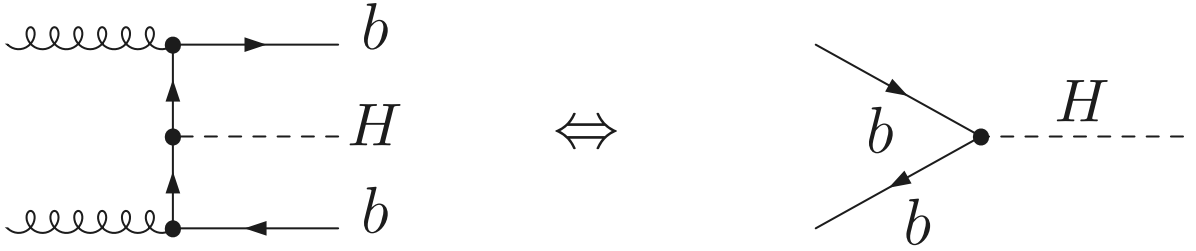
- two calculational schemes:



4 flavors in proton (4FNS)

NLO-QCD:

Dittmaier et al. [hep-ph/0309204]

Dawson et al. [hep-ph/0508293]

5 flavors in proton (5FNS)

NNLO-QCD:

Harlander et al. [hep-ph/0304035]

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EW corrections

- schemes agree reasonably well
- remaining QCD uncertainty: $\sim$ 20%

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EW corrections relevant?

- t_β enhanced SUSY corrections
  (from loop-induced coupling of bottom quarks to up-type Higgs)
- can be resummed
  Carena et al. [hep-ph/9912516]
  e.g. SPS 4: S-QCD: $-$ 41%
  S-QCD + S-EW: $-$ 22% (for $\sigma^{\rm tot}$ in 5FNS)
- remaining EW corrections at the percent level
  Dittmaier, Krämer, AM, Schlüter [hep-ph/0611353]
  AM [arXiv:0710.2409]

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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 at the LHC:

- important for any precision measurement (5-10% level)
  e.g. for W production, Higgs production in VBF
- enhancements in specific cases
  - collinear photon radiation
    e.g. for M_{w} measurement
  - Sudakov Logs at high energies
    e.g. for W production
  - model dependent enhancements
    e.g. for Higgs production from b quarks in the MSSM

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PSI

Back-up slides

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Photon-induced processes

There are photons inside the proton: γ as a parton

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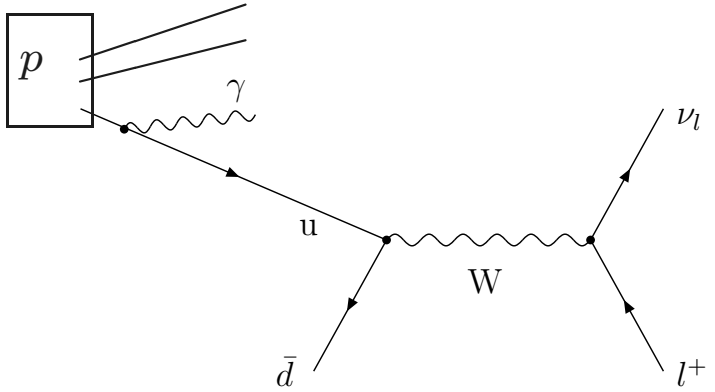
There are photons inside the proton: γ as a parton



- initial state photon emission $\Rightarrow$ collinear singularity

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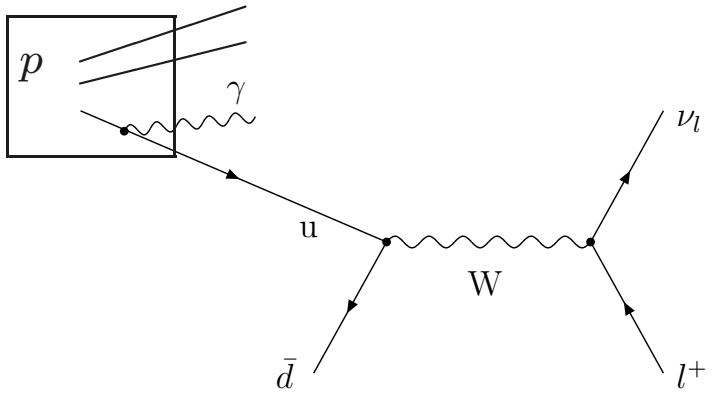
Photon-induced processes

There are photons inside the proton: γ as a parton



- 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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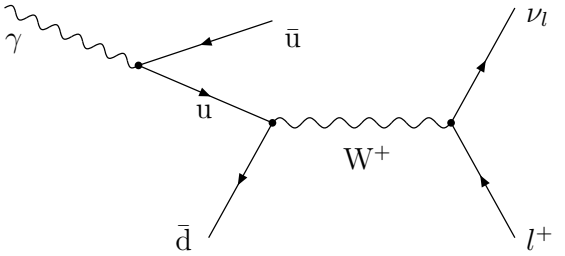
Photon-induced processes

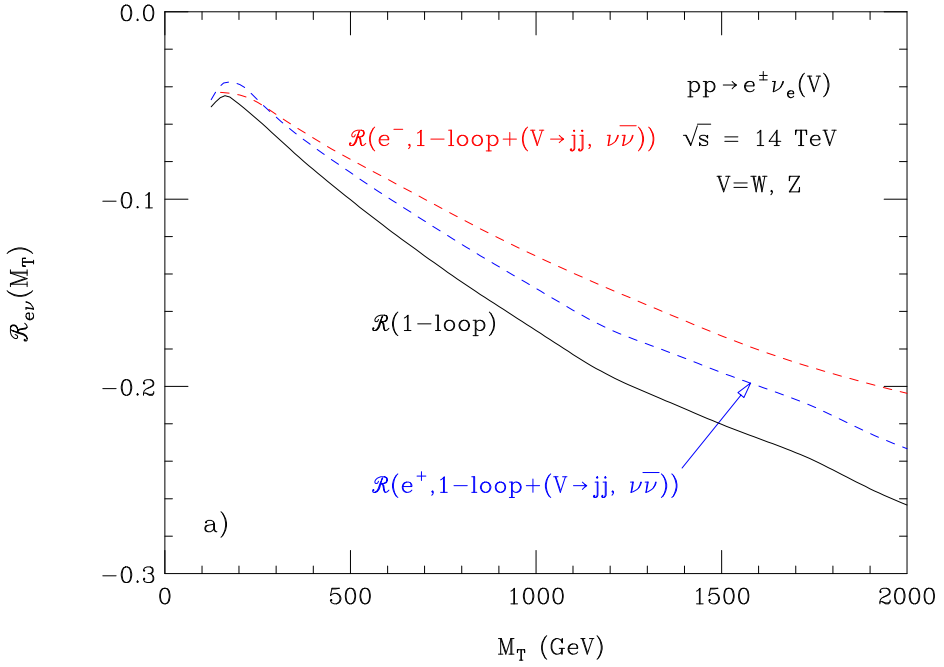
- genuine contribution at $\mathcal{O}(\alpha)$:

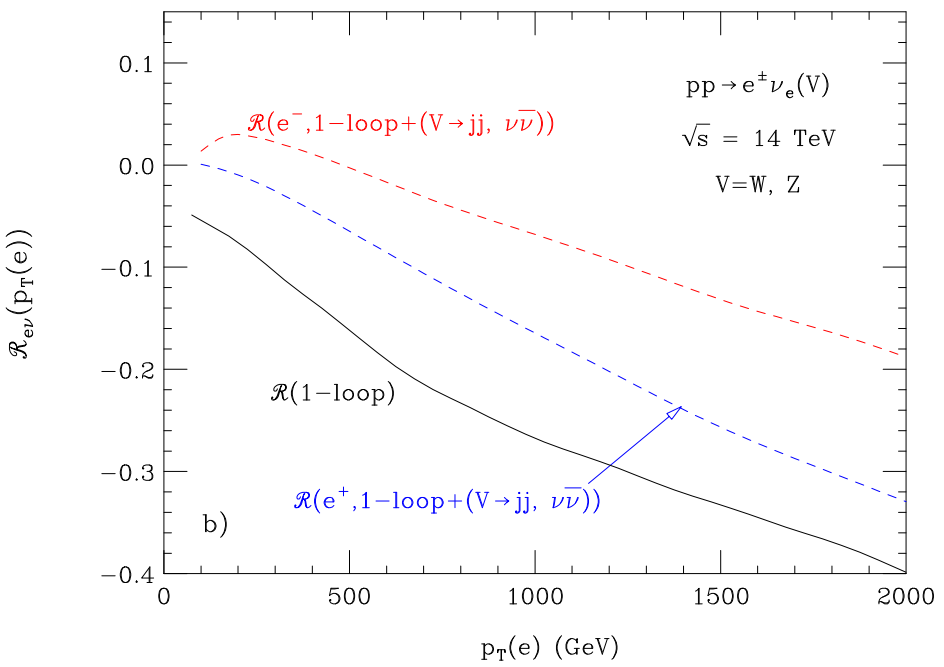


- usually percent level correction
- not relevant for M_{W} measurement in M_{T}
- can be enhanced:
  - up to $\sim$15% at large $p_{\mathrm{T},l} \sim 500$ GeV
  - but overwhelmed by QCD uncertainties
  - below 1% in M_{T}

Corrections at high energies

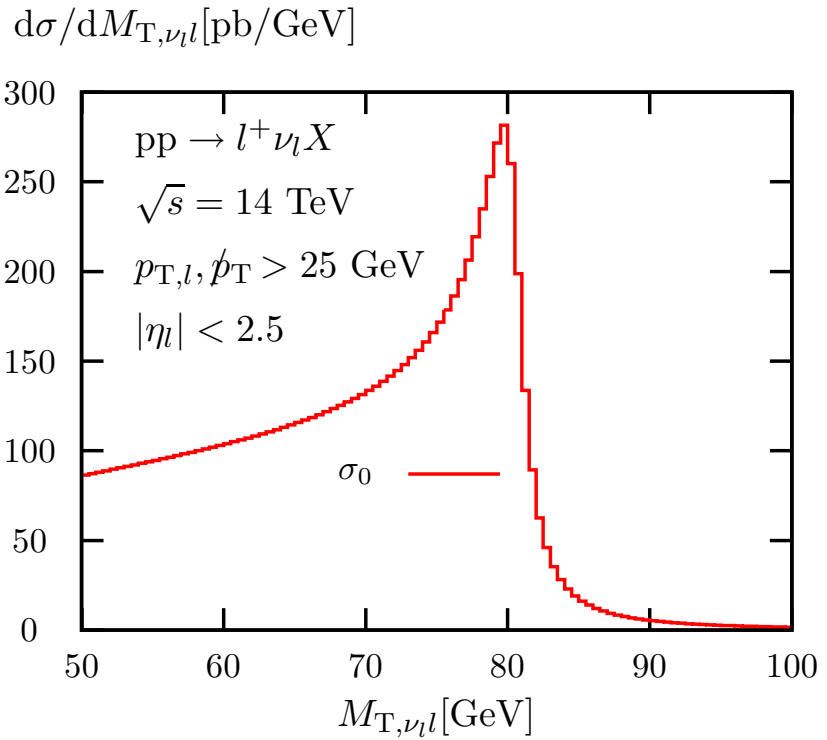
effect of real massive vector boson emission:





Baur [hep-ph/0611241]

EW corr.: M_{T} @ LHC



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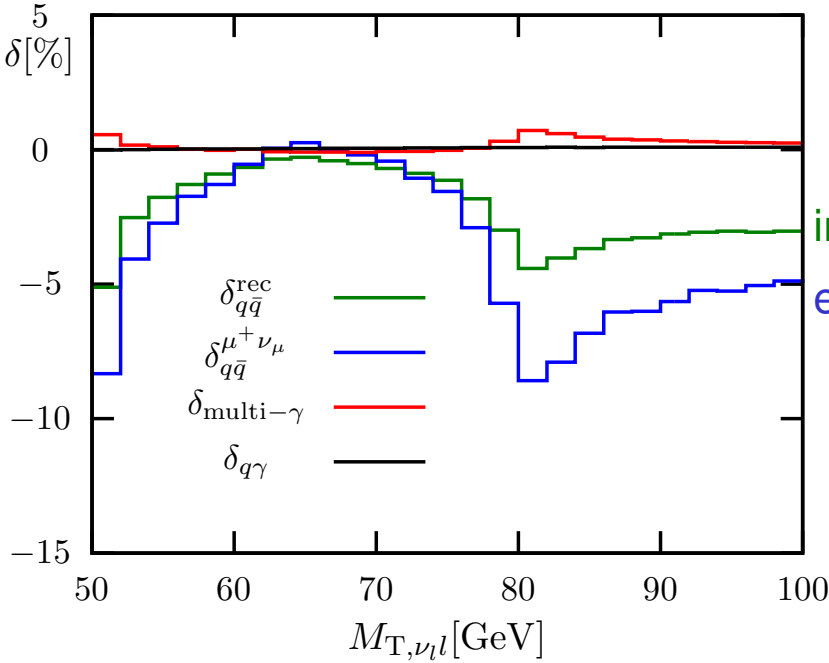

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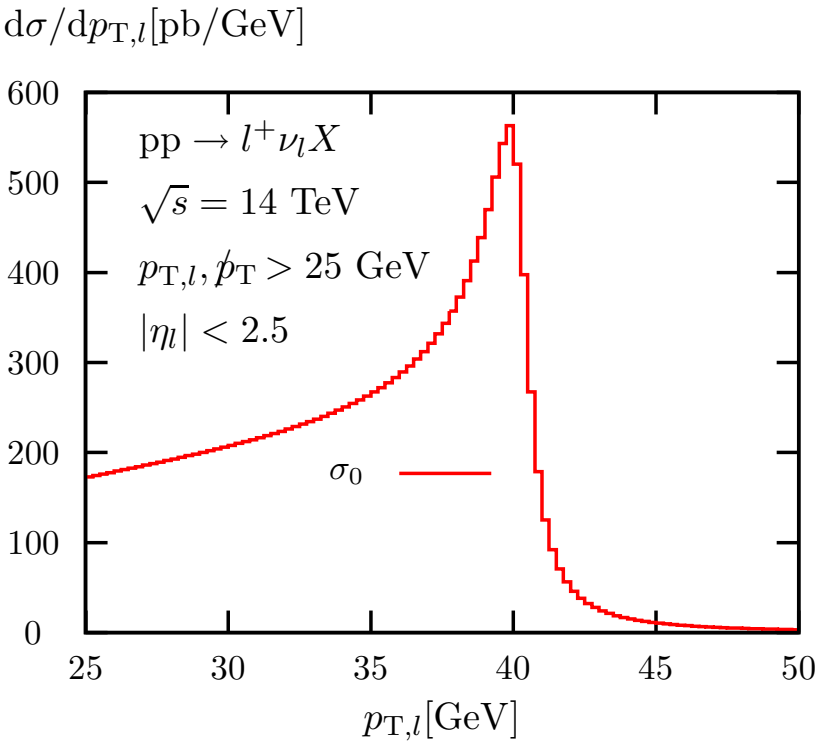
EW corr.: p_T @ LHC



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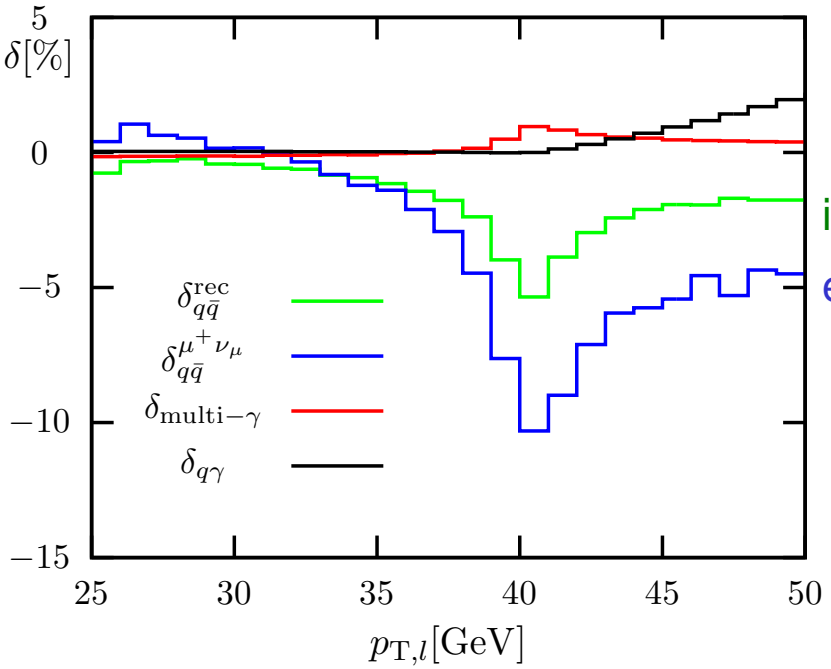

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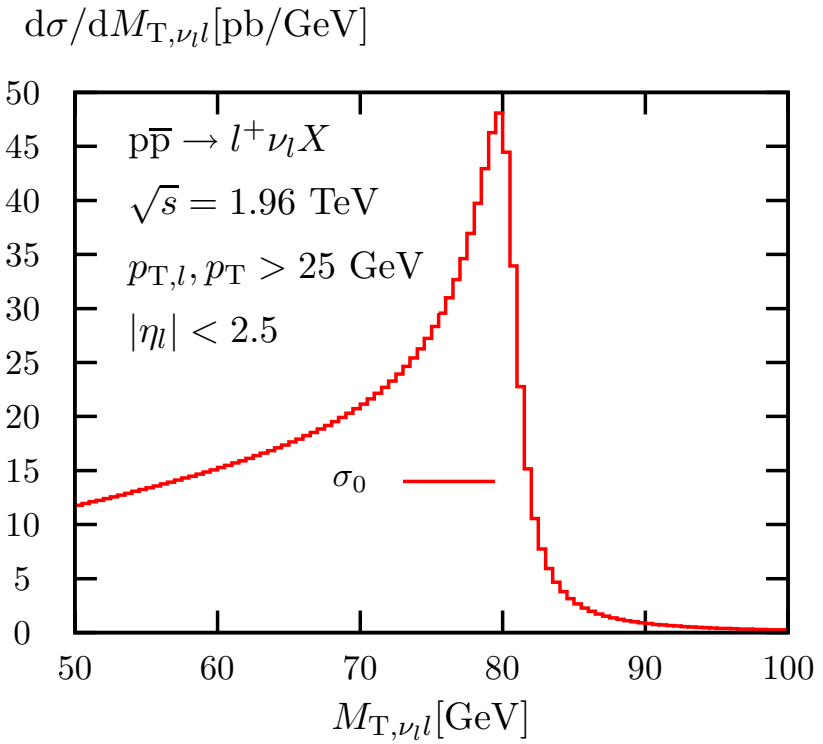
EW corr.: M_{T} @ Tevatron



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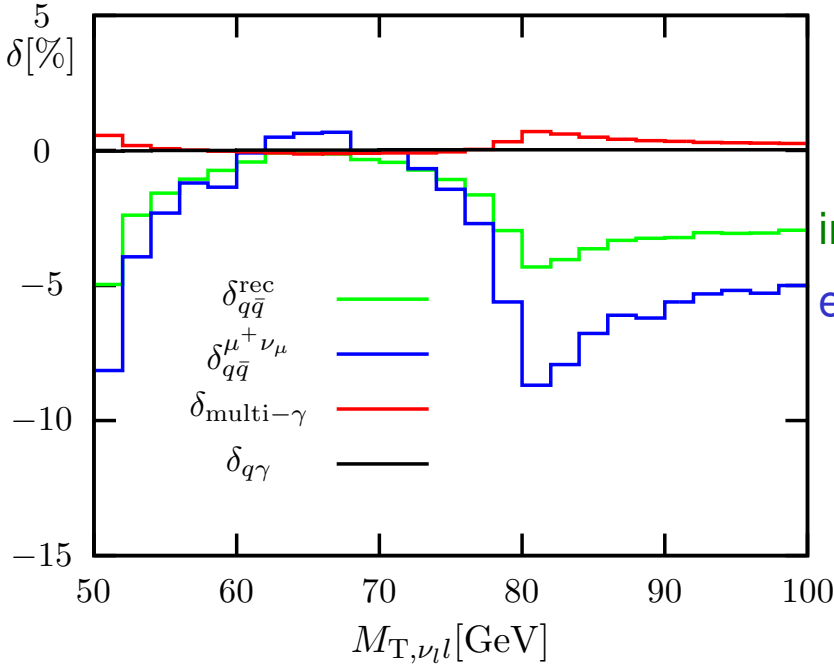

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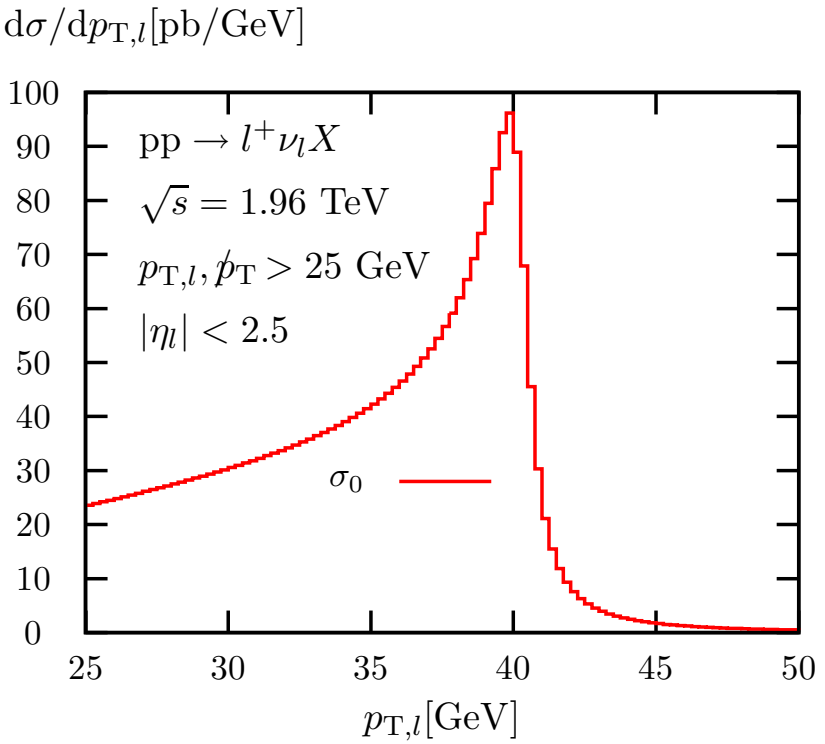

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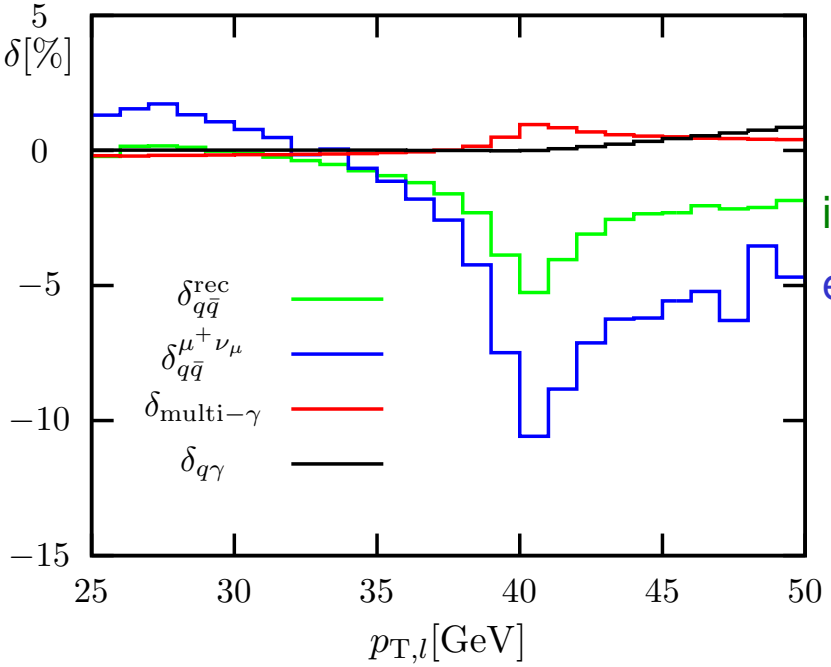

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