W-Boson Pair Production at the LHC

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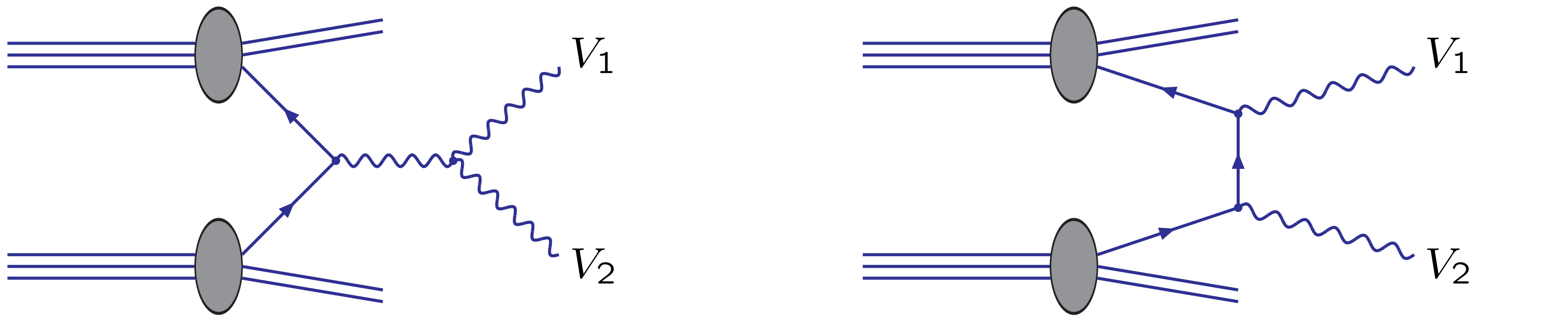
arXiv: 1208.3147

Durham 23-26. September 2012



- $\mathbf{WW/ZZ}$ is an important irreducible background to inclusive SM Higgs boson production.

- Gauge boson pair production provides an excellent opportunity to test the non-abelian structure of triple gauge boson couplings of the SM at high energies.
  $\hookrightarrow$ constraint on non-standard γWW and ZWW- couplings.

- Search for anomalous triple and quartic couplings.

- Backgrounds to new physics searches, i.e. leptons $+\not{E}_{\rm T}$ signatures.
  $\hookrightarrow$ Pair production of supersymmetric particles.

I. Motivation and Introduction

II. Theoretical Status of QCD and Electroweak Corrections

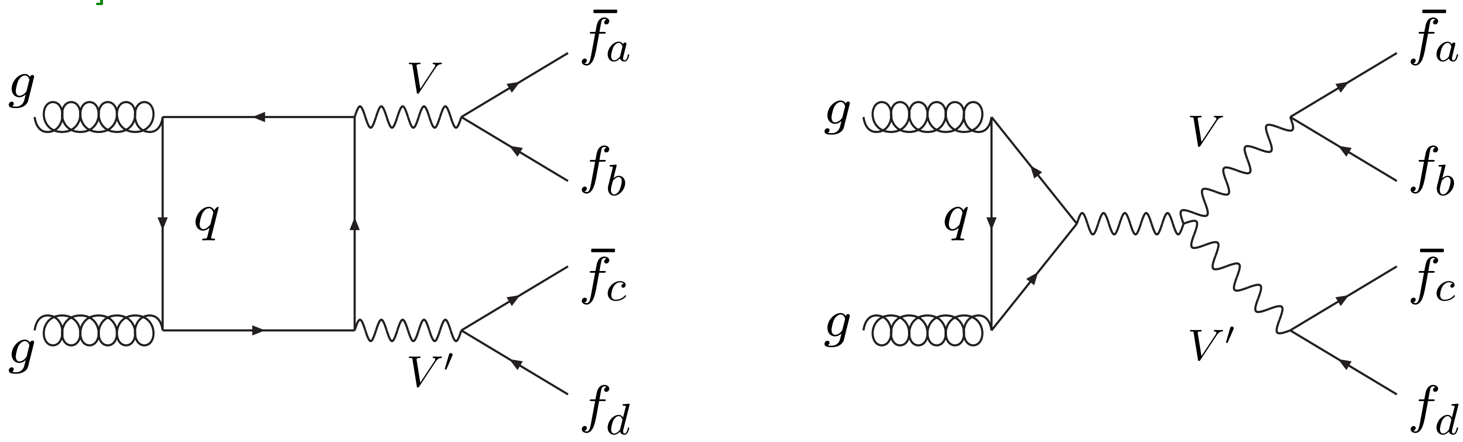
III. Theoretical issues . . .

IV. Numerical Results

V. Conclusions and Outlook

QCD Corrections to VV'-pair production:

- NLO QCD corrections are available for full process including leptonic decays. [Dixon, Kunszt, Signer '99; Campbell, Ellis '99; De Florian, Signer '00]
- Results matched with parton showers and combined with soft-gluon resummation.[S. Frixione, B.R. Weber '06; P. Nason, G. Redolfi '06]
- QCD corrections dominated by tree-level $q\bar{q}$ annihilation channels. Significant contributions of the channels $gg \to VV' \sim 10\%$ to LO, although formally at $\mathcal{O}(\alpha_s^2)$. [Dührssen et.al. '05; Glover, van der Bij '89; Kao, Dicus'91]



- By considering event selection for Higgs searches corrections of 30% can even be obtained. [Binoth et. al. '06]

EW corrections to gauge-boson pair production:

- Complete $\mathcal{O}(\alpha)$ corrections known to $pp \to W\gamma \to \ell\bar{\nu}\gamma + X$ in single pole approximation.[Accomando, Denner, Pozzorini '01; Accomando, Denner, Meier '05]
- Complete $\mathcal{O}(\alpha)$ corrections for on-shell Z bosons $pp \to Z\gamma$. [Hollik, Meier '04]
- Complete $\mathcal{O}(\alpha)$ corrections for $pp \to Z\gamma \to \ell\ell\gamma + X$ in a single pole approximation. [Accomando, Denner, Meier '05]
- Complete $\mathcal{O}(\alpha)$ corrections for $pp \to WW, ZZ, WZ \to 4\ell + X$ in high energy and pole-approximation.
  $\longrightarrow$ Large negative EW corrections at large transverse momentum.
  [Accomando, Denner, Pozzorini '01; Accomando, Denner, Kaiser '04]
- NNLL effects at two loops for WW channel.
  [Kühn, Metzler, Penin, Uccirati '11]

EW Corrections at High Energies:

High-energy limit:

$$\hat{s} \sim |\hat{t}| \sim |\hat{u}| \gg M^2 := M_\mathrm{W}^2 \simeq M_\mathrm{Z}^2 \sim M_\mathrm{H}^2 \sim M_\mathrm{t}^2 \gg m_f^2 \gg \underbrace{m_\gamma^2}_{\text{IR-regulator}}$$

$\hookrightarrow$ bosons are produced at large p_T

- EW corrections are enhanced by universal large logarithms that originate from mass singularities $\mathrm{Log}(s/M^2)$ and grow with energy:

$$\underbrace{\alpha^L \mathrm{Log}^{2L}(s/M^2)}_{\text{LL}}, \quad \underbrace{\alpha^L \mathrm{Log}^{2L-1}(s/M^2)}_{\text{NLL}}, \ \ldots$$

- Corrections are of $\sim -50\%$ at $p_\mathrm{T} = 1\mathrm{TeV}$ (WW production)

Note: Change of sign going from LL to NLL (to NNLL etc.)
$\hookrightarrow$ **substantial cancellations are possible!**

We have calculated the full one-loop corrections to the W-pair production at the LHC. [A. Bierweiler, T. Kasprzik, J.H. Kühn, S. Uccirati '12]

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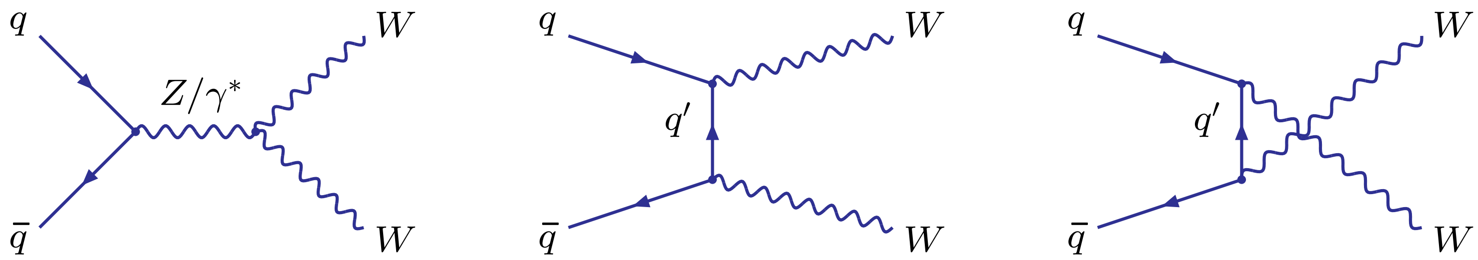
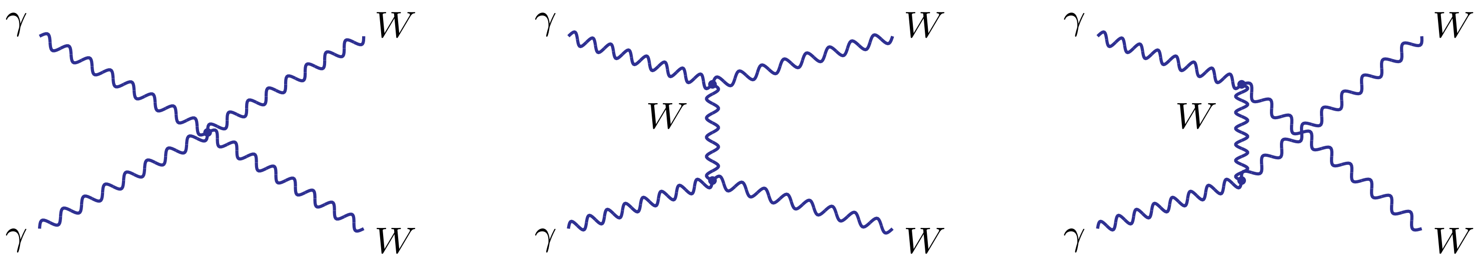
- **Partonic leading order contributions at $\mathcal{O}(\alpha^2)$:**



- **Photon-induced contributions at $\mathcal{O}(\alpha^2)$:**



→ MSTW2004qed PDF set is adopted [Martin et al. 2005]

→ Potentially large contribution at large invariant masses

NLO electroweak corrections:

- **Renormalization:**
  - masses and fields renormalized in the on-shell scheme
  - $\alpha(0)$ is defined in the Thomson-limit:

$$\alpha(0) = \frac{e(0)^2}{4\pi}$$

We work in G_μ scheme: renormalization of α_{G_μ} is defined through the Fermi constant related to the muon life time

$$\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_W^2 s_w^2}{\pi} = \frac{\alpha(0)}{1 - \Delta r}$$

Δr includes the corrections to muon lifetime not contained in QED-improved Fermi model

$\Rightarrow$ The EW corrections are independent of logarithms of the light quark masses.

IR Singularities:

- **Real Radiation:**
  - Soft singularities arise due to soft photons
  - Initial-state collinear singularities arise due to collinear photon radiation off initial-state quarks
  - introduce small **quark mass** m_f and **photon mass** m_γ to regularize divergences
    $\longrightarrow$ results contain unphysical $\log(m_f)$ and $\log(m_\gamma)$

- **Virtual corrections:**

  IR divergent (also regularized by m_γ and m_f), compensated partially by real radiation. Remaining collinear singularities have to be absorbed in PDFs.
  $\longrightarrow$ renormalization of PDFs is required

$\Rightarrow$ **Apply phase-space slicing for numerically stable evaluation of phase-space integral**

Technicalities:

Two different approaches to calculate **virtual corrections** and **bremsstrahlung amplitudes** to $pp \to W^+W^-$:

First approach: **Virtual corrections** and **bremsstrahlung amplitudes** computed in the QGRAF and FORM framework:

- QGRAF: [Nogueira]
  generation of Feynman diagrams
- FORM: [Vermaseren]
  calculation of amplitudes: implementation of Feynman rules, reconstruction of Dirac structures, introduction of tensor coefficients and their algebraical reduction to scalar integrals, ...

  analytical calculation of squared amplitudes
  generation of FORTRAN code

Numerical phase-space integration done within Fortran using the Vegas algorithm.

Second approach: **Virtual corrections** computed in the FeynArts/ FormCalc/LoopTools(FF) framework

- FeynArts - 3.5: [Küblbeck, Böhm, Denner 1990]
  → automatic generation of diagrams, calculation of amplitudes
- FormCalc - 6.1: [Hahn, Perez, Victoria 1999]
  → algebraical simplification of amplitudes,
  → introduction of tensor coefficients
  → analytical calculation of squared amplitides
  → spin-, colour- and polarization sums
  → generation of FORTRAN code
- LoopTools - 2.5: [van Oldenborgh,Vermaseren 1990]
  → numerical Passarino-Veltman reduction within Fortran
  → numerically-stable evaluation of scalar-integrals

Bremsstrahlung amplitudes computed with FeynArts/FeynCalc [Mertig, Böhm, Denner 1991] ⊕Madgraph [Alwall et al.], numerical phase-space integration within Fortran using the Vegas algorithm.

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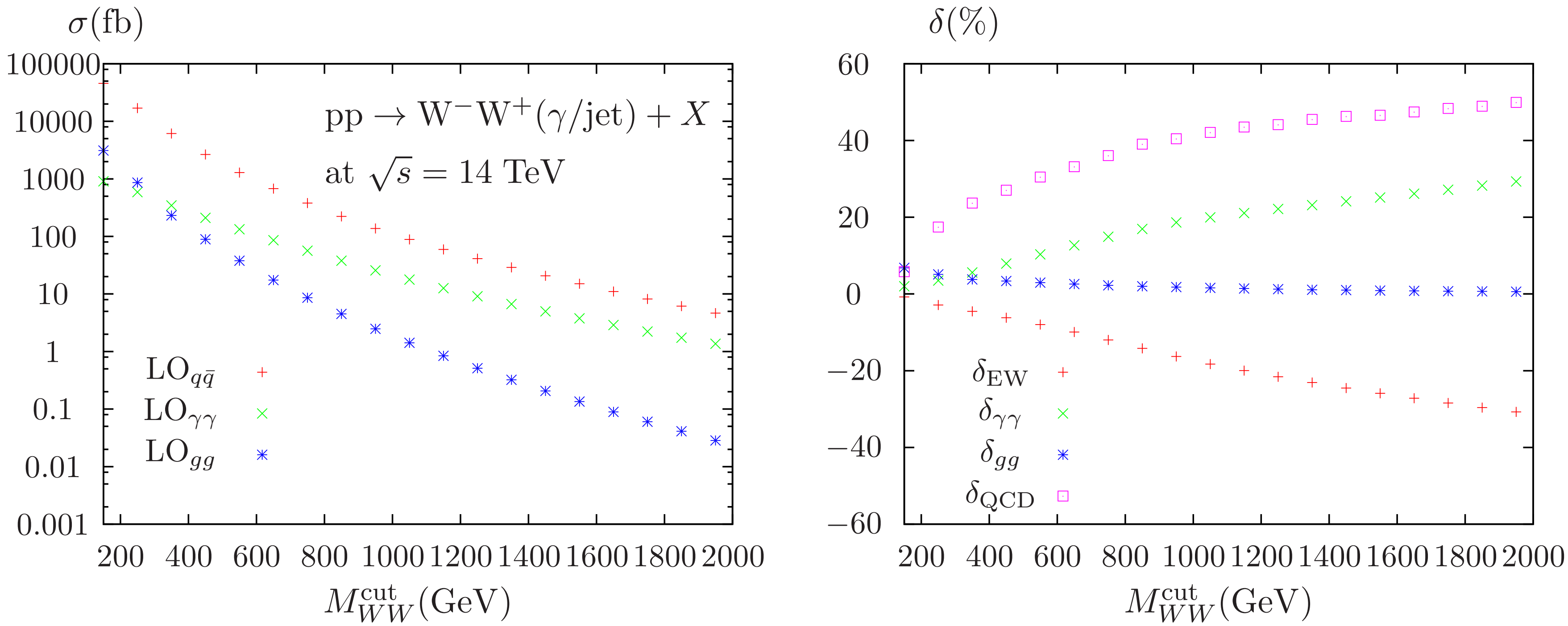
Default cuts: $p_{\mathrm{T,W^\pm}} > 15$ GeV, $|y_{\mathrm{W^\pm}}| < 2.5$ GeV

MSTW2008LO PDFs [Martin et al. 2009]



- assume $\int \mathcal{L}\mathrm{d}t = 200\ \mathrm{fb}^{-1}$ $\Rightarrow$ 1000 WW events with $M_{WW} > 2$ TeV
- rapidly increasing admixture of $\gamma\gamma \to WW$ due to the behaviour: $\sigma(\gamma\gamma \longrightarrow WW) \stackrel{\hat{s}\to\infty}{\longrightarrow} 8\,\pi\,\alpha^2/M_{\mathrm{W}}^2$
- **sizable** (up to -30%) **negative EW corrections**, **comparable to QCD corrections**

No compensation between $\gamma\gamma \longrightarrow W^+W^-$ and weak corrections!

$\Rightarrow$ **Different angular distributions**

- $\gamma\gamma \longrightarrow \mathbf{W^+W^-}$:
  strong enhancement in forward and backward directions
- **weak corrections:**
  negative Sudakov Logarithms for large $\hat{s}$ and $\hat{t}$
  $\Rightarrow$ negative corrections for large scattering angles

$\Rightarrow$ Implications for dσ/dΔy_{WW} with $\Delta y_{WW} = y_{W^+} - y_{W^-}$:
for fixed M_{WW} this corresponds to the angular distribution in the WW-rest frame

High energy cuts: $p_{T,W^\pm} > 15$ GeV, $|y_{W^\pm}| < 2.5$ GeV, $M_{WW} > 1$ TeV

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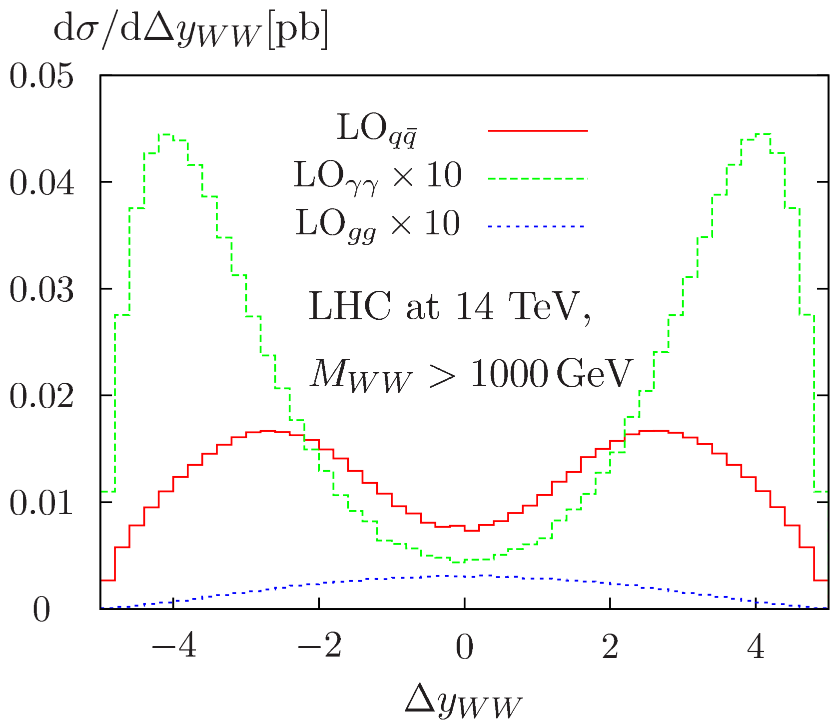

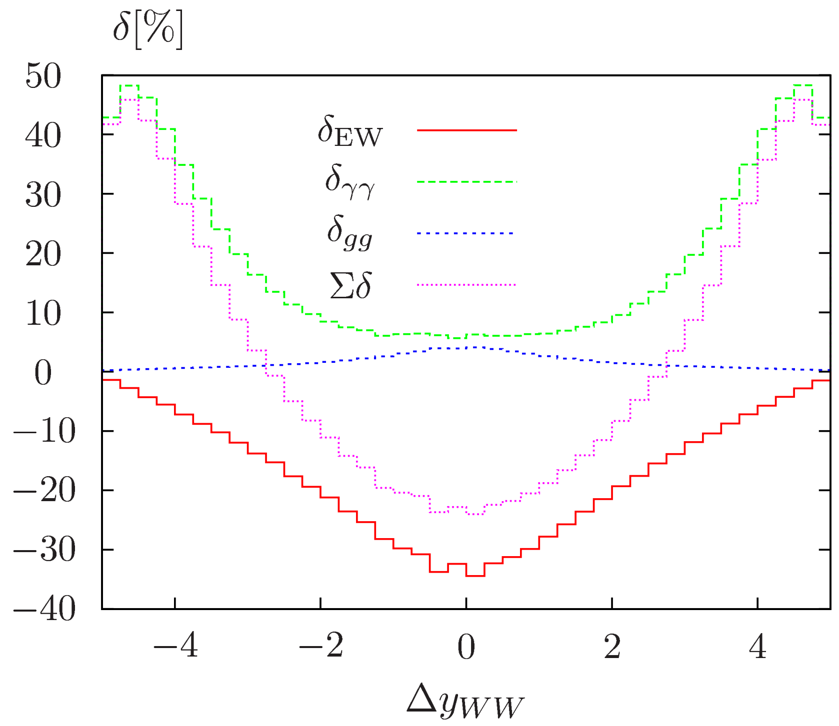

- WW production dominated by small scattering angles
- drastic forward-backward peaking of $\gamma\gamma \to WW$
- drastic distortion of angular distribution
- $\Sigma\delta$ varies from -30% and $+45\%$ for $M_{WW} > 1$ TeV

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- **Understanding of gauge boson pair production processes crucial at the LHC:**
  - → Understand SM at high energies
  - → Understand background to Higgs- and BSM physic searches
- **We have computed the full EW corrections to the W-pair production at the LHC:**
  - → Small corrections to the total cross section
  - → **But:** Sizable negative corrections at large transverse momenta
  - → W-pair production: significant contribution of photon-induced channel at large scattering angles
- **Future work:**
  - → Leptonic decays of the vector bosons should be included
  - → Consider WZ and ZZ production

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Thank you!

Backup

Thomson-limit: (zero momentum transfer)

$$\delta Z_e\Big|_{\alpha(0)} = \frac{1}{2}\frac{\partial\Sigma_{\mathrm{T}}^{\gamma\gamma}(k^2)}{\partial k^2}\Bigg|_{k^2=0} - \frac{s_w}{c_w}\frac{\partial\Sigma_{\mathrm{T}}^{\gamma\gamma}(0)}{M_{\mathrm{Z}}^2}$$

$\Sigma_{\mathrm{T}}^{\gamma\gamma}(k^2)$ is transverse part of $\gamma\gamma$ self-energy with momentum transfer k.

$\Rightarrow$ charge renormalization constant contains logarithms of light fermion masses including large corrections proportional to $\sim \alpha \log(m_f^2/\hat{s})$

G_μ scheme: The transition from $\alpha(0)$ to G_μ is ruled by the weak corrections to muon decay Δr:

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

$$\Rightarrow \delta Z_e\Big|_{\alpha(G_\mu)} = \delta Z_e\Big|_{\alpha(0)} - \frac{\Delta r}{2}$$

$\Rightarrow$ large fermion mass logs are resummed in G_μ scheme

$\Rightarrow$ the lowest order cross section in G_μ parametrization absorbes large universal corrections to SU(2) gauge coupling introduced by ρ parameter

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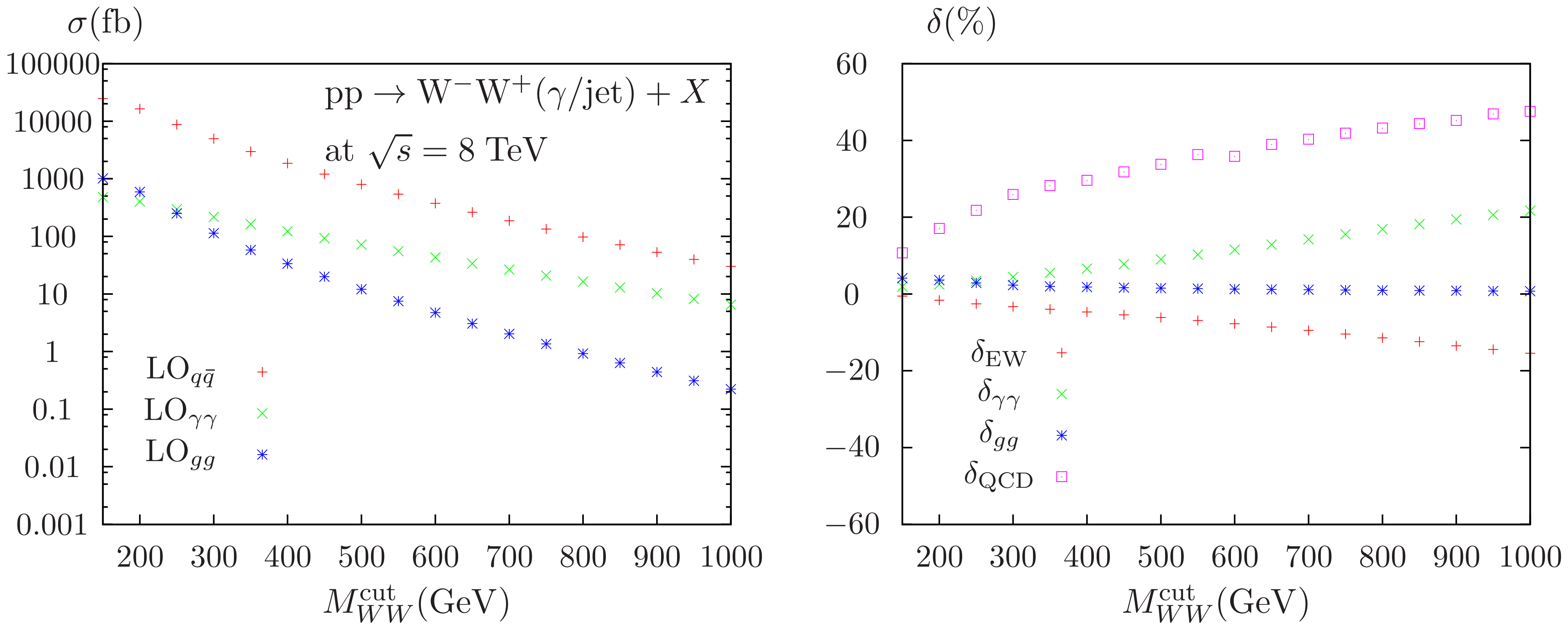
MSTW2008LO PDFs [Martin et al. 2009]



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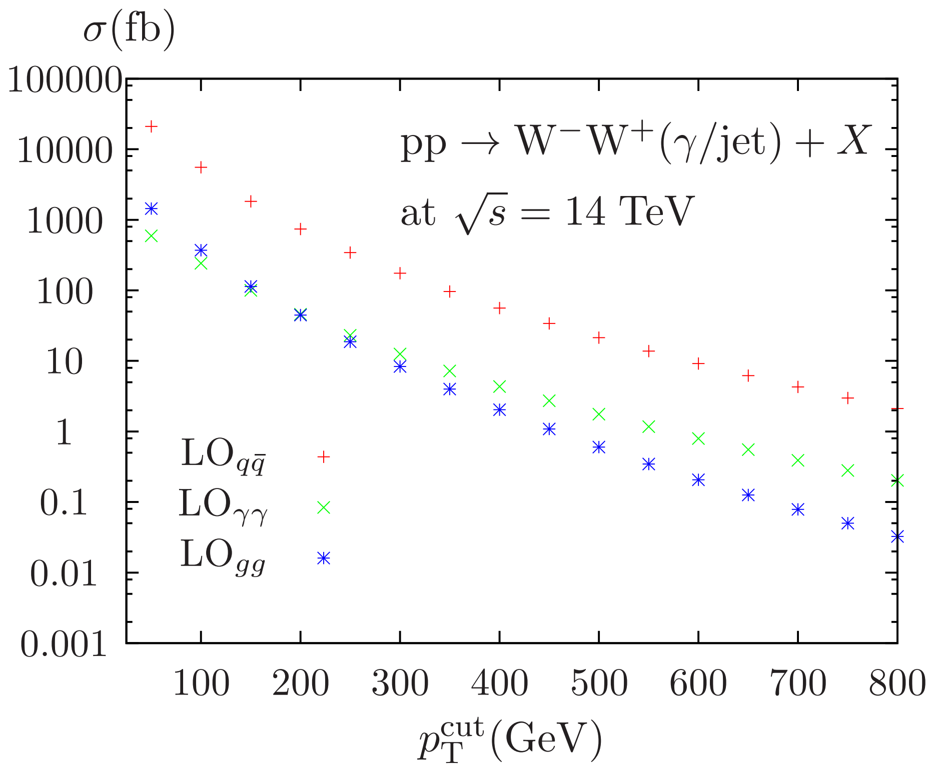

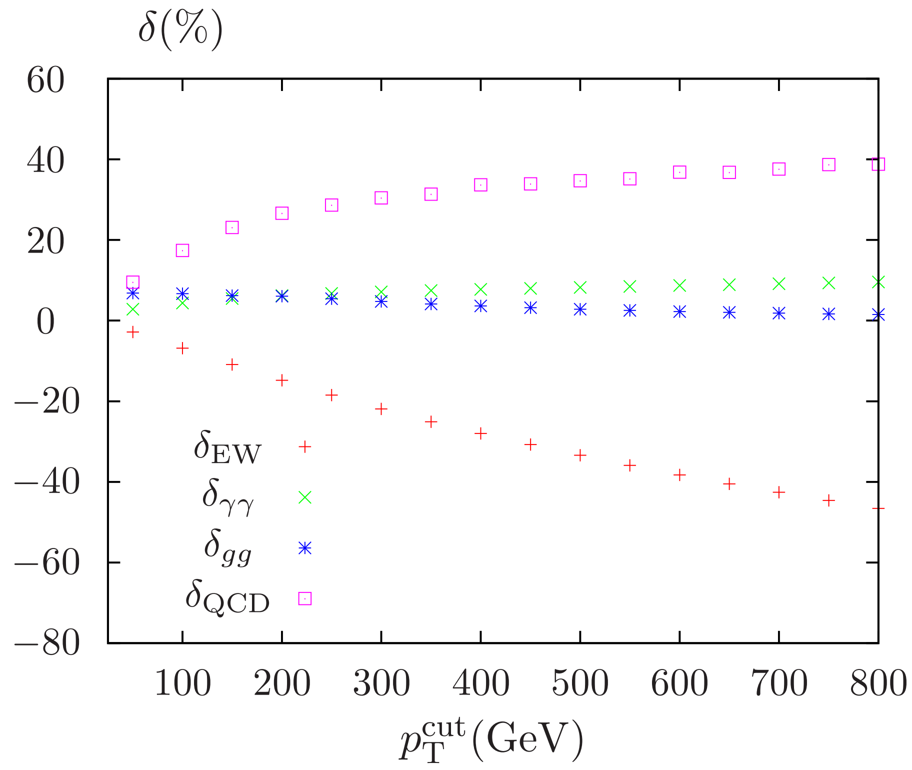

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