Electroweak effects in vector-boson pair production at the LHC

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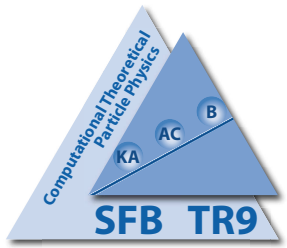
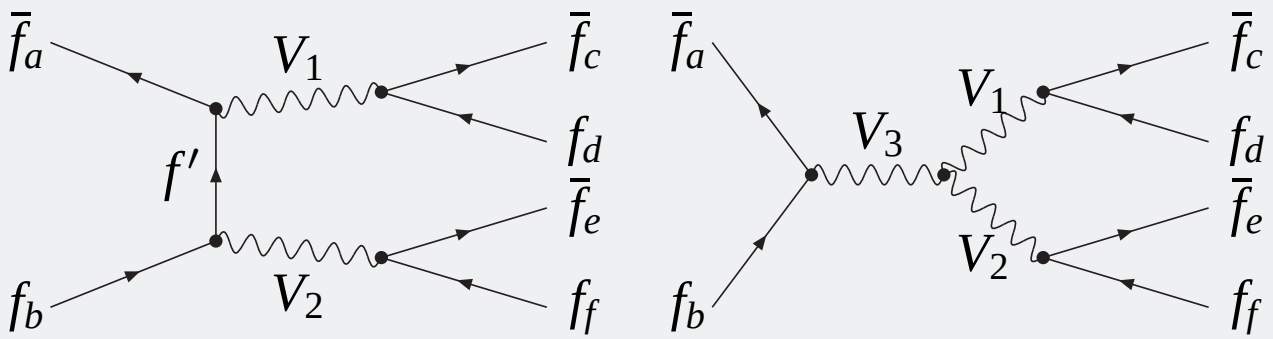
6th July 2012, 36th ICHEP, Melbourne



Outline

Introduction – Weak-Boson Pair Production at the LHC

Vector-boson pair production: pp $\rightarrow$ WW/ZZ/WZ $\rightarrow$ 4l

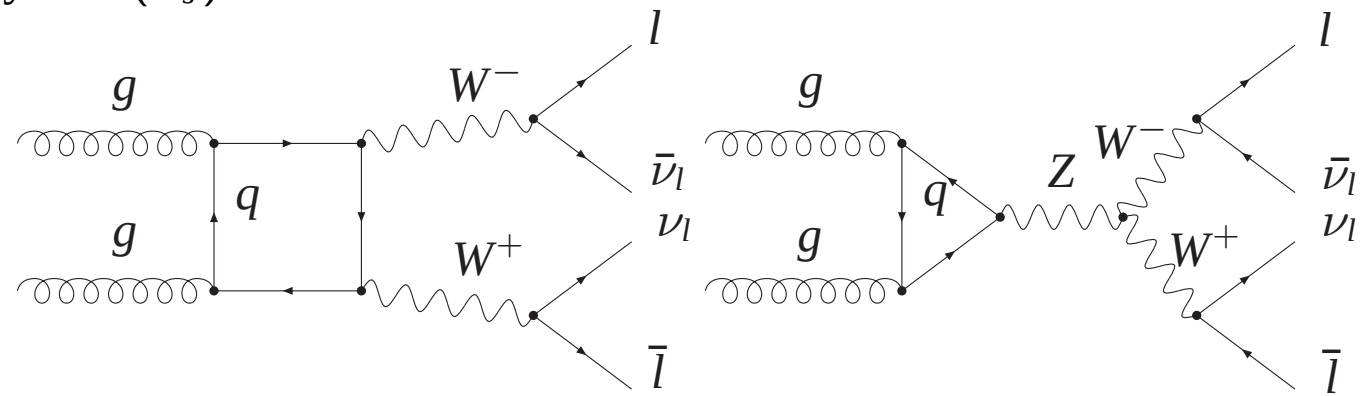


- ZZ/WW production important irreducible background to inclusive SM Higgs-boson production
- Probe non-abelian structure of the Standard Model (SM) at high energies
- Search for anomalous couplings
- Backgrounds to new-physics searches, i.e. leptons + $\not{E}_{\mathrm{T}}$ signatures
  $\rightarrow$ SUSY-particle pair production

Vector-Boson Pair Production – QCD Effects

Extensive study of production of WW, WZ, ZZ, Wγ, Zγ, $\gamma\gamma$ at NLO QCD [Campbell, Ellis, Williams 2005; Campbell, Ellis 1999,. . .]

- Results matched with parton showers $\oplus$ combined with soft gluon resummation [Nason, Ridolfi 2006; Frixione, Webber 2006]
- On-shell leptonic decays of the vector bosons taken into account (narrow-width approximation) retaining all spin information
- Corrections dominated by the $q\bar{q}$ channels
  - Significant contributions of the channels $gg \to V_1 V_2 \sim 10$ % to LO, although formally at $\mathcal{O}(\alpha_s^2)$ [Glover, van der Bij 1989; Kao, Dicus 1991; Duhrssen et al. 2005]



  - Even larger corrections of 30% if event selection for Higgs searches is applied [Binoth et al. 2006]

High-energy limit

$$s, |t|, |u| \gg M_V^2, \quad V = W, Z$$

→ **bosons have to be produced at large p_T**

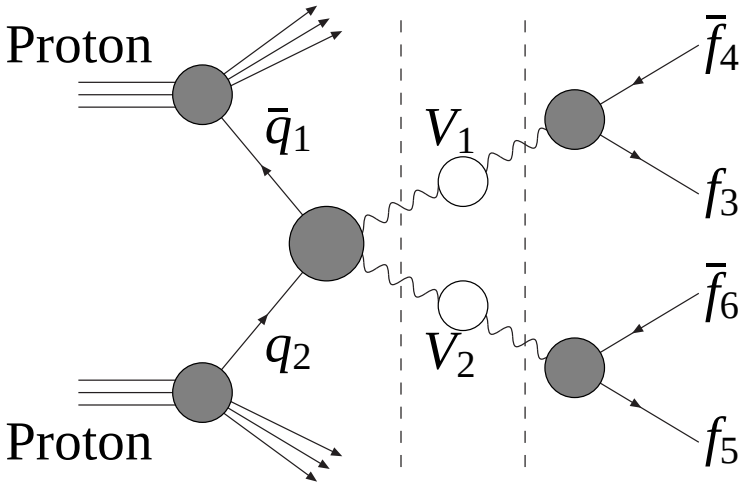
- EW corrections at high energies dominated by universal large logarithms

$$\begin{aligned} &\propto \alpha^L \ln^{2L}(M_V/\sqrt{s}) \quad \text{(LL)}, \\ &\propto \alpha^L \ln^{2L-1}(M_V/\sqrt{s}) \quad \text{(NLL)}, \ldots \end{aligned}$$

  at the L-loop level
- Corrections of $\sim -50\%$ at $p_T = 1$ TeV (W-pair production)
- Change of sign going from LL to NLL (to NNLL . . .)
  → **substantial cancellations possible!**

EW Corrections to V-Pair Production – Overview

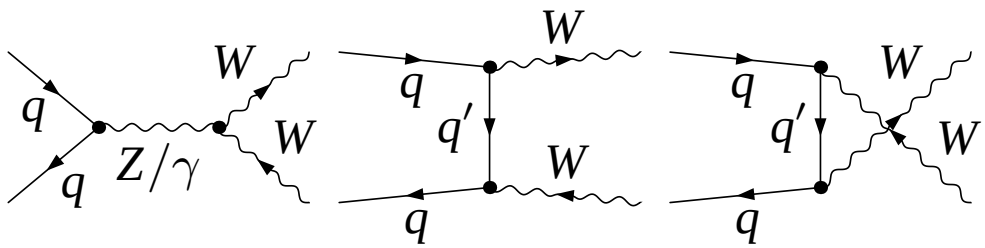
- $\mathcal{O}(\alpha)$ high-energy approximation known for WW/WZ/ZZ production, vector bosons treated in pole-approximation → final-state leptons phenomenologically accessible [Accomando et al. 2002–2006]



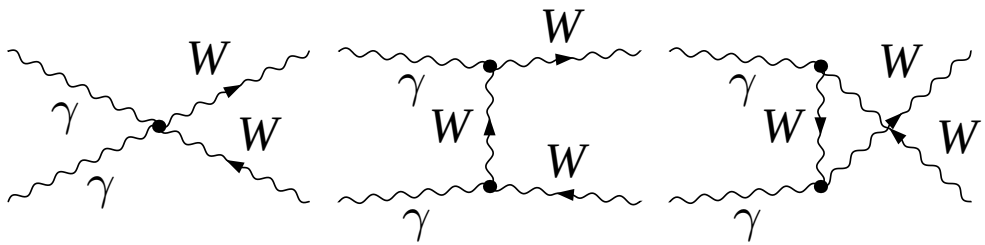
- NNLL effects at two loops published for the WW channel [Kühn, Metzler, Uccirati, Penin 2011]
- **We have calculated the full one-loop corrections to on-shell V-pair production at the LHC [Bierweiler, TK, Kühn, Uccirati, in prep.]**

Lowest-Order Contributions to $pp \to W^-W^+ + X$

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



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



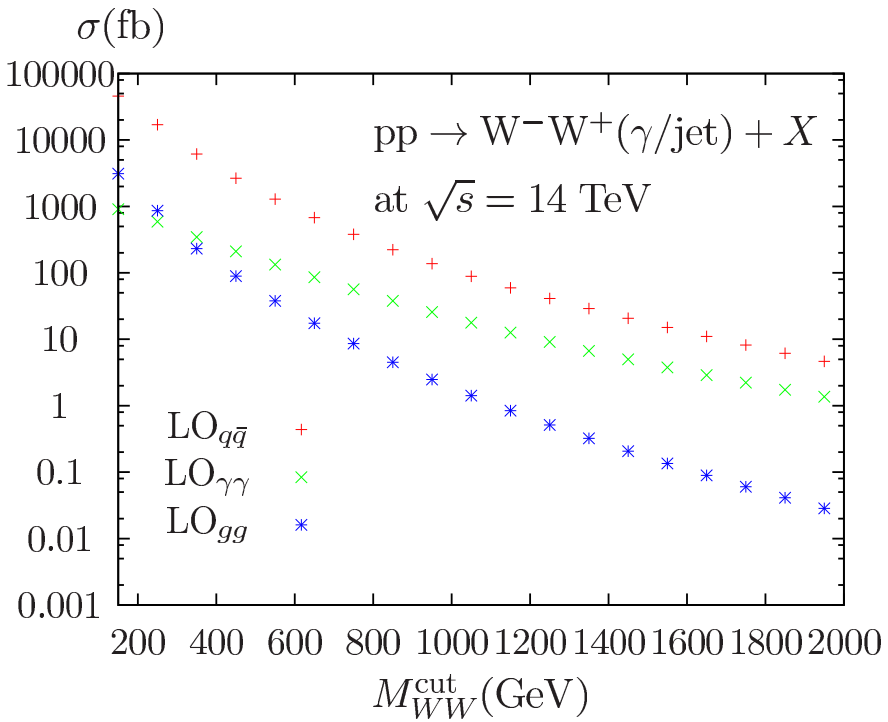
  - Adopt `MRST2004QED` PDF set [Martin et al. 2005]
  - Potentially large contribution at high invariant masses!

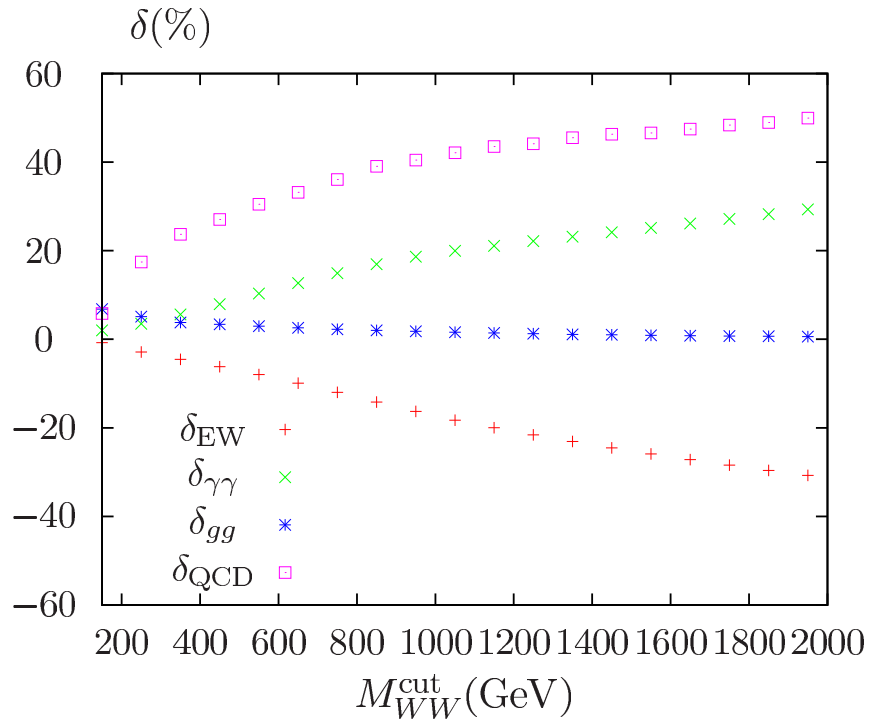
NLO Electroweak Corrections – Our Strategy

- **Renormalization:**
  On-shell scheme (G_μ, M_W, M_Z)
- **Virtual corrections:**
  IR divergent (regularized by m_γ, m_q), compensated by
- **Real radiation:**
  remaining collinear singularities to be absorbed in PDFs
- **Practical implementation:**
  use `MSTW2008LO` PDFs [Martin et al. 2009] (impact of QED small)
- for comparison also **NLO QCD corrections**:
  eliminate hard jets
  (Discard jets with $p_{\mathrm{T}}^{\mathrm{jet}} > \max(p_{\mathrm{T}}^{W^+}/2, p_{\mathrm{T}}^{W^-}/2)$ if $p_{\mathrm{T}}^{\mathrm{jet}} > 15$ GeV, $|y^{\mathrm{jet}}| < 2.5$)

Numerical Results (I): $pp \to W^-W^+(\gamma)$

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





- assume $\int \mathcal{L} dt = 200$ fb^{-1}
  $\Rightarrow$ 1000 WW events with
  $M_{WW} > 2$ TeV
- rapidly increasing admixture of $\gamma\gamma$

- **large admixture** of $\gamma\gamma$ (up to 30%)
- **sizable negative EW corrections** (-30%) at high energies,
  comparable to QCD corrections

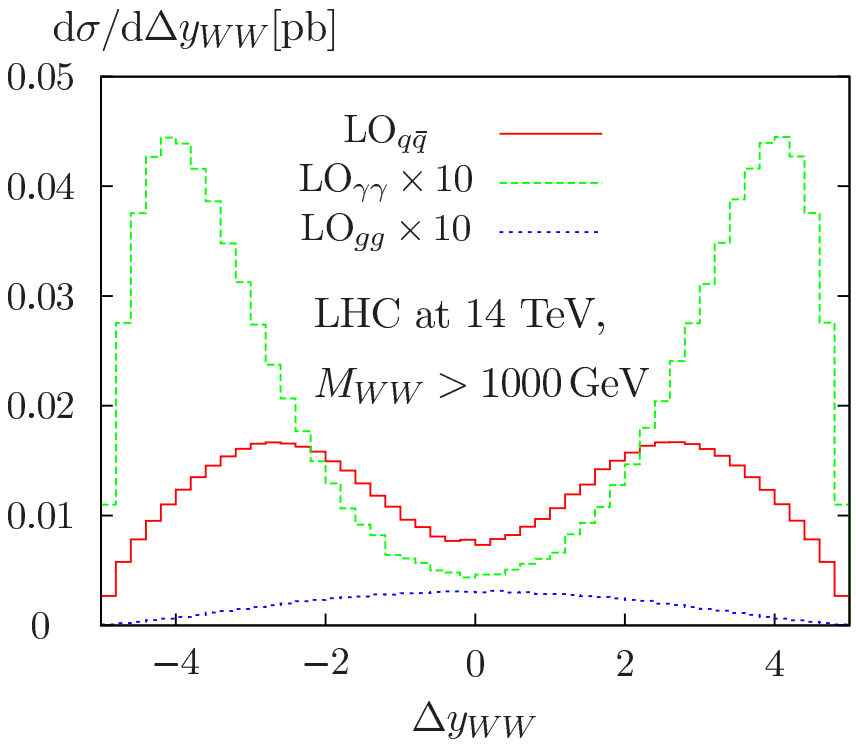
$\mathcal{O}(\alpha)$-Contributions to pp $\to$ W$^-$W$^+$

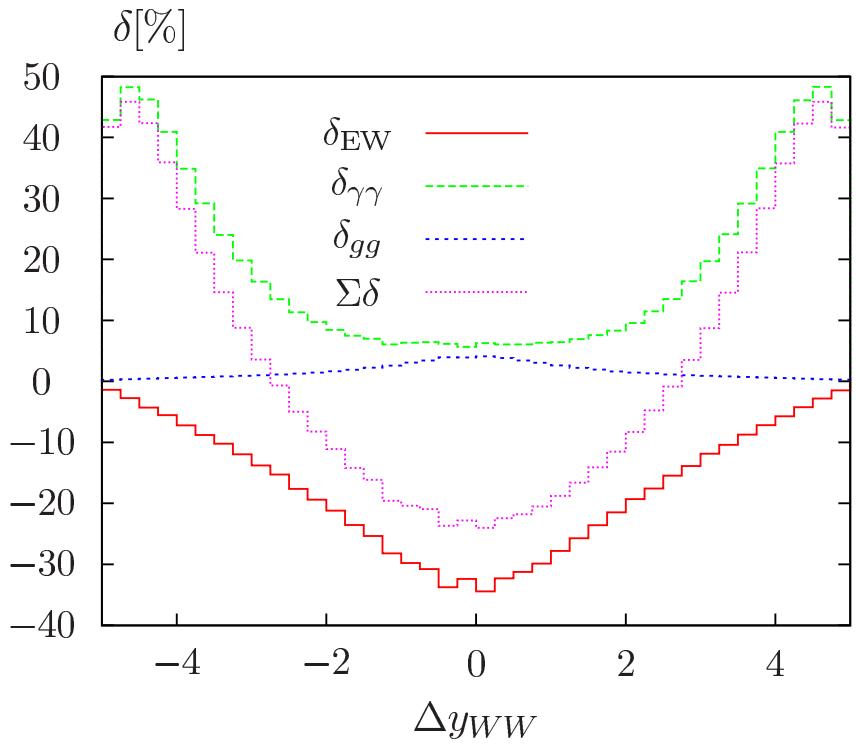
No compensation between $\gamma\gamma \to WW$ and weak corrections!
$\Longrightarrow$ Different angular distributions!

- $\sigma(\gamma\gamma \to WW) \to \frac{8\pi\alpha^2}{M_W^2}$ for large $\hat{s}$
  $\Rightarrow$ strong enhancement in forward & backward directions
- **weak corrections:**
  negative Sudakov logs for large $\hat{s}$ and $\hat{t}$
  $\Rightarrow$ negative corrections for large scattering angles
- gg small, isotropic
- implications for $\mathrm{d}\sigma/\mathrm{d}\Delta y_{WW}$ with $\Delta y_{WW} = y_{W^+} - y_{W^-}$
  (for fixed M_{WW} this corresponds to the angular distribution in the W-W rest frame!)

Numerical Results (II): $pp \to W^-W^+(\gamma)$

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





- 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!

”Real Radiation” of massive vector bosons

Low energies: Phase-space and perturbative suppression of $pp \to WW + (W/Z)$
$\Rightarrow$ contribution below 1%

High energies: Logarithmic enhancement of additional soft/collinear W- or Z-boson radiation
$\Rightarrow$ Investigation of $WW + W/Z$ production as background to W pairs at large p_T

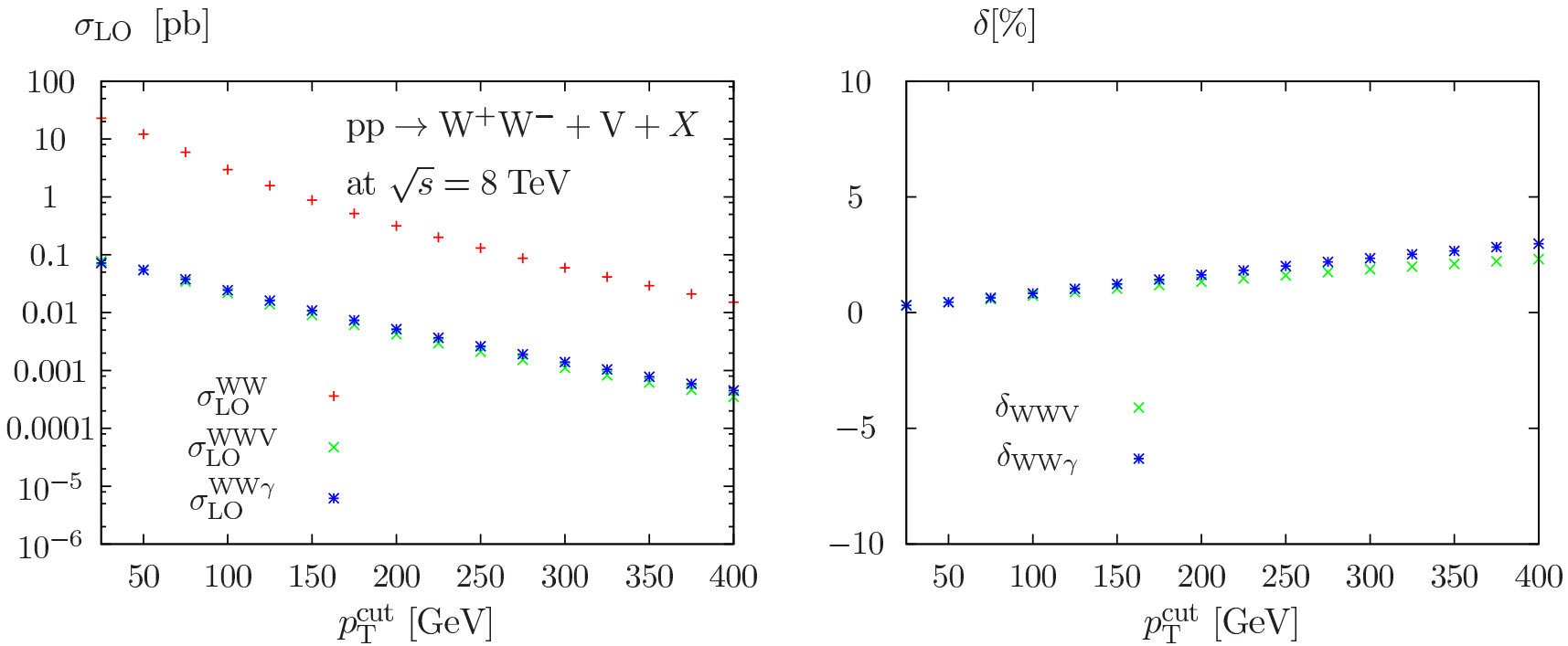
- invisible decay of $Z \to \nu\bar{\nu}$
- collinear emission
- ...

Simplified approach: (details depend on experimental analysis)

1. Include $pp \to W^-W^+Z$ with totally inclusive Z
2. Include $pp \to W^-W^+W^\pm$; treat $W^\pm$ with lowest p_T totally inclusively

Numerical Results (III) – “Real Radiation” of W/Z

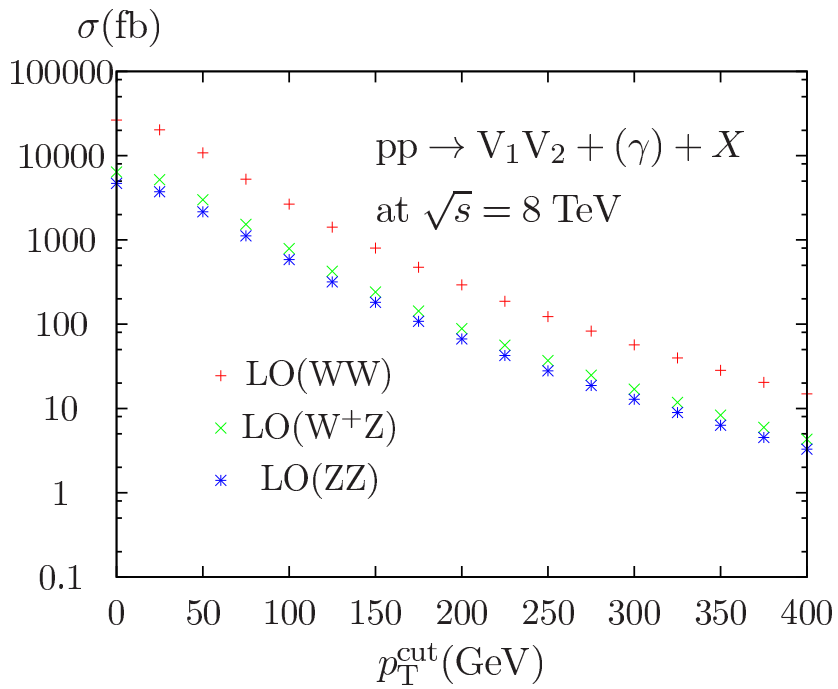
LHC at 8 TeV, default cuts: $p_{\mathrm{T},W^\pm} > 15$ GeV, $|y_{W^\pm}| < 2.5$

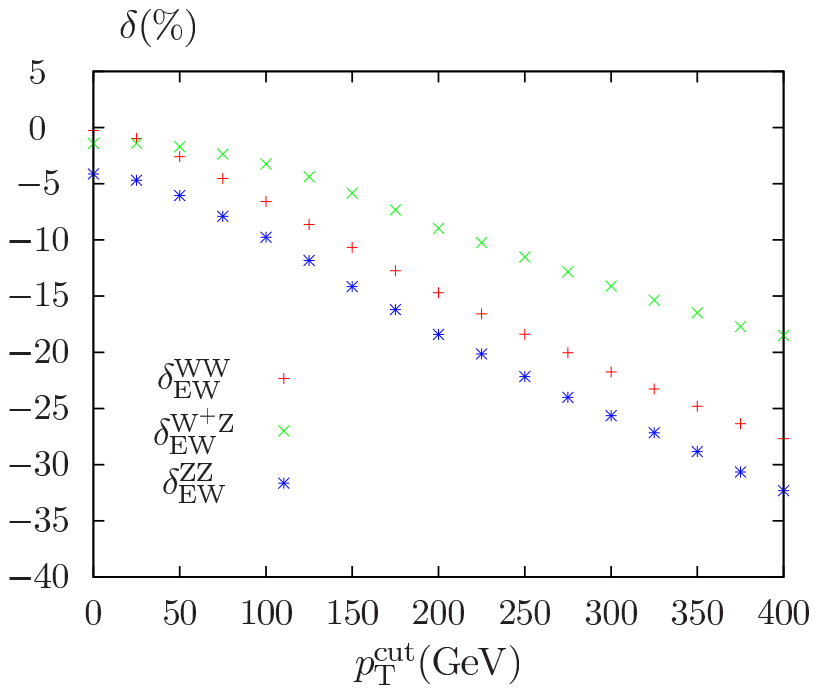


- Corrections due to hard photons ($p_{\mathrm{T},\gamma} > 15$ GeV, $|y_\gamma| < 2.5$) below 5 %
- Contributions of massive-boson radiation below 5 %

Numerical Results (IV) – WW, W^+Z and ZZ production

LHC at 8 TeV, default cuts: $p_{T,V} > 15$ GeV, $|y_V| < 2.5$





- **LO:** $\sigma_{WW}/\sigma_{W^+Z}/\sigma_{ZZ} \sim 5/1/0.7$
- moderate EW corrections to WZ production
- large EW corrections to ZZ production

Summary & Conclusions

- **Proper understanding of V-pair production processes crucial at the LHC:**
  - Understand SM at highest energies
  - Understand backgrounds to Higgs- and BSM-physics searches
- **We have computed the full EW corrections to V-pair production at the LHC**
  - Small corrections to the total cross section
  - **But:** Sizable negative corrections at large transverse momenta
  - **W-pair production:** significant contributions of photon-induced channels at large scattering angles
  - Real-radiation contributions of W/Z small; further investigation needed?
- **Future work:**
  - Leptonic decays of the vector bosons should be included.
  - Discuss interplay of EW and QCD effects

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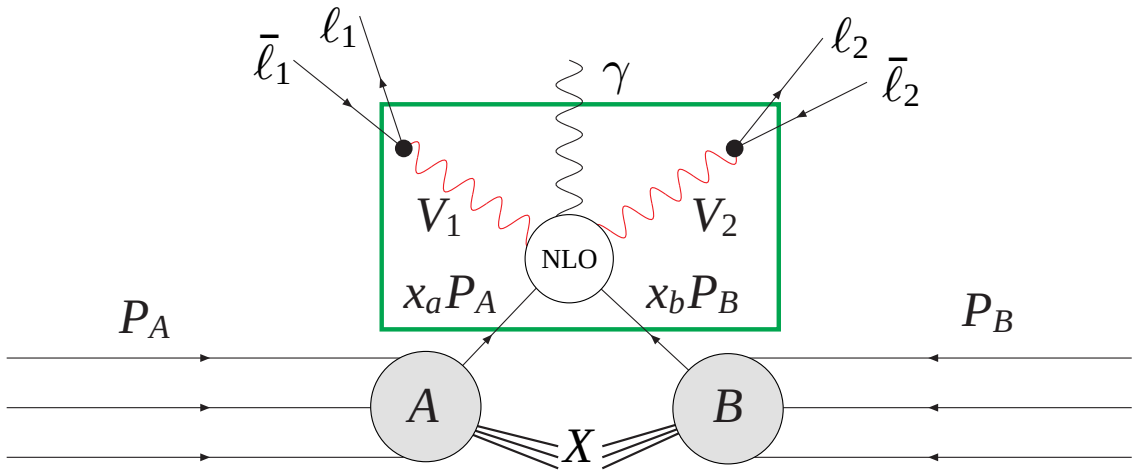
Thank You!

Reminder: Calculation of Hadronic Cross Sections

Schematic illustration for
$pp \to V_1 V_2 (+\gamma) + X$
$\to \ell_1 \ell_2 \bar{\ell}_1 \bar{\ell}_2 (+\gamma) + X$



Hadronic cross sections

$$\mathrm{d}\sigma_{AB}(p_A, p_B) = \sum_{a,b} \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \, f_{a/A}(x_a, \mu_\mathrm{F}) \, f_{b/B}(x_b, \mu_\mathrm{F}) \, \mathrm{d}\hat{\sigma}_{ab}^{\mathrm{NLO}}(p_a, p_b, \mu_\mathrm{F}, \mu_\mathrm{R})$$
$$\times \mathcal{F}^{(4\ell+\gamma)}(\{\mathcal{O}_\mathrm{FS}\}), \qquad p_{\{a,b\}}^\mu = x_{\{a,b\}} P_{\{A,B\}}^\mu$$

- Dependence on μ_R, μ_F reduced by inclusion of higher perturbative orders
- $\mathcal{F}^{(4\ell+\gamma)}$ incorporates definition of observables + phase-space cuts

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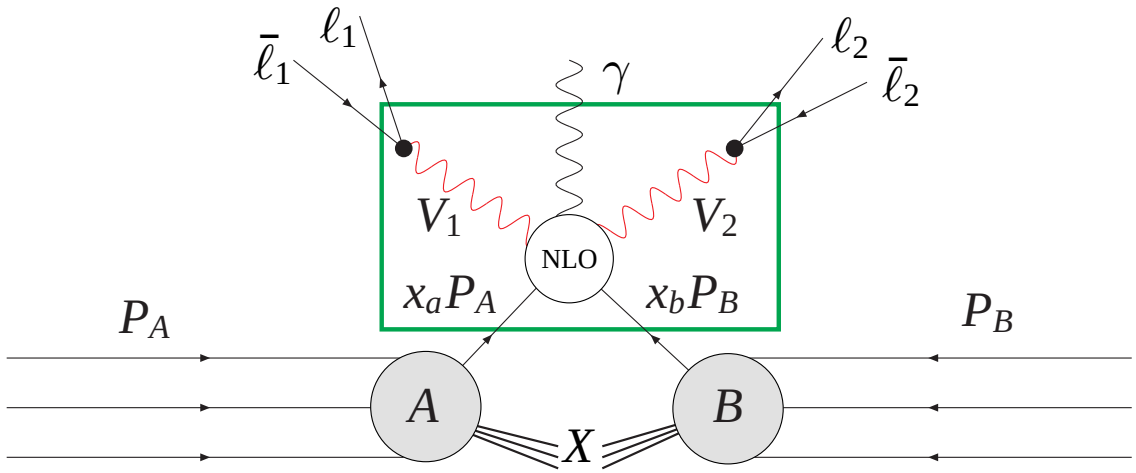

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$$\times \mathcal{F}^{(4\ell+\gamma)}(\{\mathcal{O}_\mathrm{FS}\}), \qquad p_{\{a,b\}}^\mu = x_{\{a,b\}} P_{\{A,B\}}^\mu$$

NLO partonic cross section:

$$\hat{\sigma}_{ab}^{\mathrm{NLO}} = \hat{\sigma}_{ab}^{\mathrm{LO}} + \hat{\sigma}_{ab}^{\mathrm{virt}} + \hat{\sigma}_{ab}^{\mathrm{real}}$$

Double-Pole Approximation (DPA)

- **Lowest order:** Amplitude given as a product of
  on-shell (OS) production amplitude $\otimes$ on-shell decay amplitude $\otimes$ Breit–Wigner:

$$\mathcal{M}^{\bar{q}_1 q_2 \to V_1 V_2 \to 4f}_{\text{Born,DPA}} = \frac{1}{k_1^2 - M_1^2 + \mathrm{i} M_1 \Gamma_1} \frac{1}{k_2^2 - M_2^2 + \mathrm{i} M_2 \Gamma_2} \times \sum_{\lambda_1, \lambda_2} \mathcal{M}^{\bar{q}_1 q_2 \to V_1, \lambda_1 V_2, \lambda_2}_{\text{Born}} \mathcal{M}^{V_1, \lambda_1 \to f_3 \bar{f}_4}_{\text{Born}} \mathcal{M}^{V_2, \lambda_2 \to f_5 \bar{f}_6}_{\text{Born}}$$

- Use OS-projected momenta $\hat{k}$ [Denner, Dittmaier, Roth, Wackeroth 2000] in the OS matrix elements:

$$\hat{k}_{1,0} = \frac{1}{2}\sqrt{\hat{s}}\,, \quad \hat{\mathbf{k}}_1 = \frac{\mathbf{k}_1}{|\mathbf{k}_1|}\beta_{\mathrm{W}}\frac{\sqrt{\hat{s}}}{2}\,, \quad \ldots$$

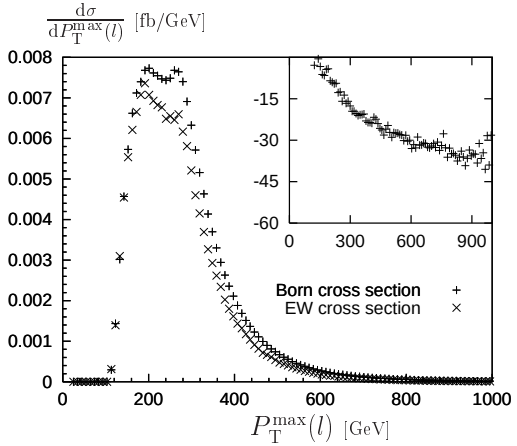
- **NLO:** EW corrections consist of factorizable and non-factorizable contributions, e.g.

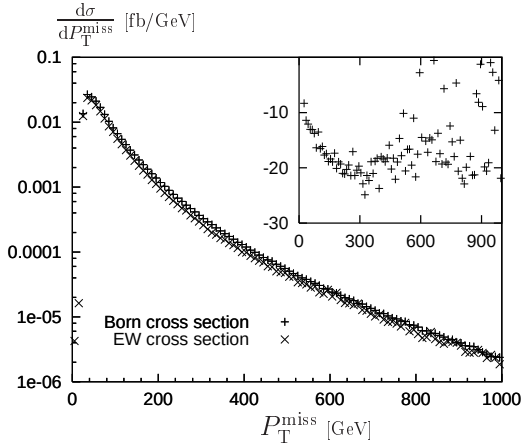
$$\mathcal{M}_{\text{fact}} = \frac{R(k_1, k_2, \theta)}{(k_1^2 - M_1^2 + \mathrm{i} M_1 \Gamma_1)\,(k_2^2 - M_2^2 + \mathrm{i} M_2 \Gamma_2)}$$

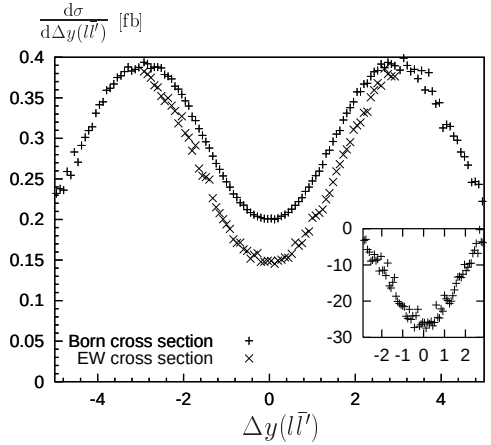
  Caution: Gauge invariance!

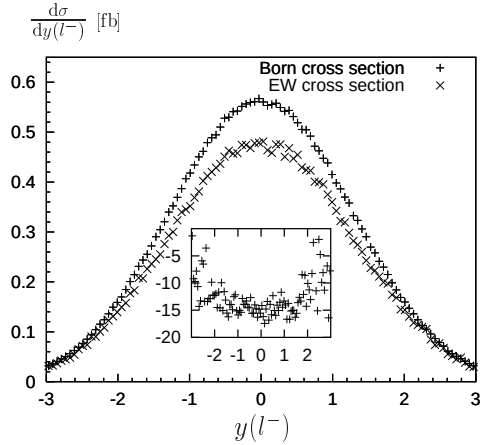
EW corrections to pp $\to$ $W^+W^- \to \nu_e e^+ \mu^- \bar{\nu}_\mu$ (DPA)

- Standard LHC event selection cuts applied to final-state leptons and missing transverse momentum; additionally $M_{e^+\mu^-} > 500$ GeV required
- Large negative corrections at large transverse momenta
- Substantial negative corrections to inclusive observables
- Error due to DPA about 10% in the relative corrections
- **EW corrections significantly larger than experimental error throughout the whole energy range (for $L \sim 30$ fb^{-1})**









[Accomando, Denner, Kaiser: arXiv:0409247 [hep-ph]]

Photon PDFs (MRST2004QED)

- Simple LL ansatz for $f_{\gamma/\mathrm{p}}(x, Q_0^2)$

$$f_{\gamma/\mathrm{p}}(x, Q_0^2) = \frac{\alpha}{2\pi}\left[\frac{4}{9}\ln\left(\frac{Q_0^2}{m_u^2}\right) f_{u/\mathrm{p,v}}(x, Q_0^2) + \frac{1}{9}\ln\left(\frac{Q_0^2}{m_d^2}\right) f_{d/\mathrm{p,v}}(x, Q_0^2)\right] \otimes \frac{1+(1-x)^2}{x}$$

- Running of $f_{q/\mathrm{p}}(x, Q^2)$ at $\mathcal{O}(\alpha)$ affected by photon PDFs!

$$\frac{\partial f_{q/\mathrm{p}}(x, \mu^2)}{\partial \ln \mu^2} = \frac{\alpha}{2\pi}\int_x^1 \frac{\mathrm{d}y}{y}\left[P_{qq}(y)\, Q_q^2\, f_{q/\mathrm{p}}(x/y, \mu^2) + P_{q\gamma}(y)\, Q_q^2\, f_{\gamma/\mathrm{p}}(x/y, \mu^2)\right]$$

- Momentum conservation

$$\int_0^1 \mathrm{d}x\, x\left[\sum_q f_{q/\mathrm{p}}(x, \mu^2) + f_{g/\mathrm{p}}(x, \mu^2) + f_{\gamma/\mathrm{p}}(x, \mu^2)\right] = 1$$

$\Rightarrow$ QED effects on $f_{q/\mathrm{p}}(x, \mu^2)$ small!

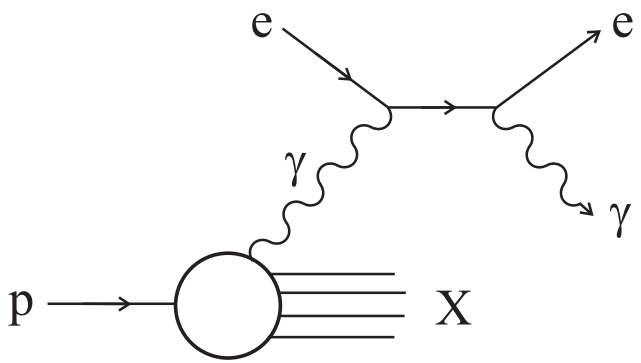
$\Rightarrow$ Still large conceptual uncertainties in $f_{\gamma,0}$

Measure Photon PDFs?

Consider the DIS process

$$e\mathrm{p} \to e\gamma + X$$

with high-p_T back-to-back e, γ in the final state



$$\sigma(e\mathrm{p} \to e\gamma + X) = \int \mathrm{d}x^\gamma f_{\gamma/\mathrm{p}}(x^\gamma, \mu^2)\hat{\sigma}(e\gamma \to e\gamma) \ ,$$

related to Compton scattering

- $x^\gamma = \frac{E_\mathrm{T}^\gamma E_e \exp(\eta^\gamma)}{2E_\mathrm{p}E_e - E_\mathrm{T}^\gamma E_e \exp(-\eta^\gamma)}$
- $f_{\gamma/\mathrm{p}}(x^\gamma, \mu^2)$ could be in principle extracted from HERA data!

EW Input Schemes – Definition of α

- $\alpha(0)$: On-shell definition in the Thomson-limit (zero momentum transfer)

$$\bar{u}(p)\Gamma_{\mu}^{Ae\bar{e}}(p,p)u(p)\big|_{p^2=m_e^2} = e(0)\bar{u}(p)\gamma_{\mu}u(p)\,,\alpha(0) = e(0)^2/4\pi$$

- $\alpha(M_Z)$ obtained via renormalization-group running from 0 to weak scale M_Z

$$\alpha(M_Z) = \frac{\alpha(0)}{1-\Delta\alpha(M_Z)}\,, \qquad \Delta\alpha(M_Z) = \Pi_{f\neq t}^{AA}(0) - \mathrm{Re}\,\Pi_{f\neq t}^{AA}(M_Z^2)$$

- α_{G_μ} defined through the Fermi constant related to the muon lifetime

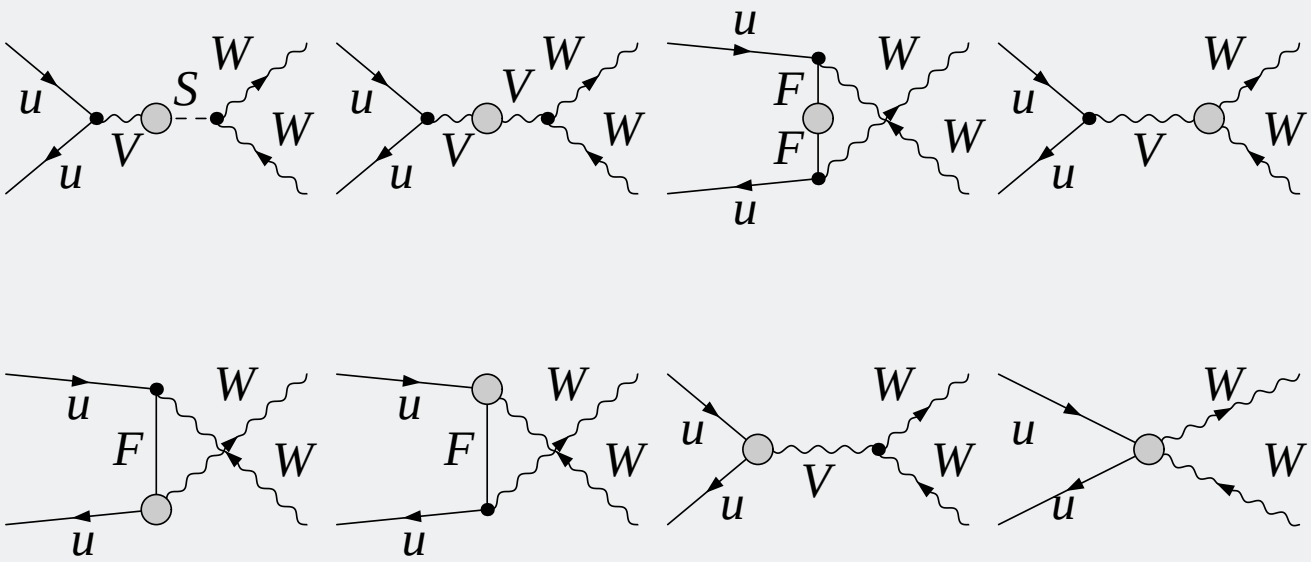
$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_W^2 s_w^2}{\pi} = \frac{\alpha(0)}{1-\Delta r}$$

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

- **light-fermion mass logs contained in $\Pi_{f\neq t}^{AA}(0)$ resummed in effective couplings $\alpha(M_Z)$ and α_{G_μ}**

Virtual EW Corrections to $pp \to W^-W^+ + X$

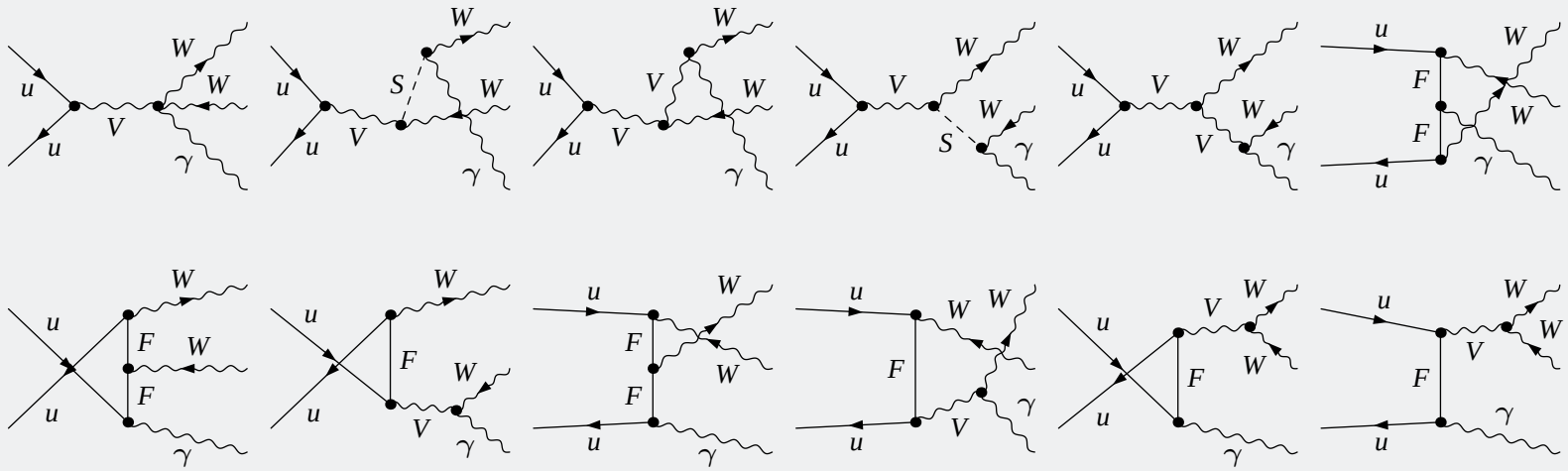
One-loop contributions at $\mathcal{O}(\alpha^3)$



- On-shell renormalization of SM parameters
- We use the Fermi scheme to calculate the loop corrections.
  $\to$ universal corrections to Δr absorbed in effective LO coupling
- $V_{ij}^{\mathrm{CKM}} = \delta_{ij}$ within the loops $\to$ no renormalization of V_{ij}^{CKM}

Real EW Corrections – Infrared Singularities

Real photon radiation at $\mathcal{O}(\alpha^3)$ (generic diagrams): $q\bar{q} \to \mathrm{W}^-\mathrm{W}^+ + \gamma$



- Soft singularities due to soft photons
- Initial-state collinear singularities due to collinear photon radiation off initial-state quarks $\to$ renormalization of PDFs
- Introduce small **quark mass** m_q and infinitesimal **photon mass** λ to regularize divergences $\to$ results exhibit unphysical $\ln m_q$ and $\ln \lambda$ terms

Apply phase-space slicing for numerically-stable evaluation of phase-space integral

Phase-Space Slicing

Two-cut-off phase-space slicing

- Definition of bremsstrahlung phase space:

$$\sigma_{\text{real}} = \int \text{dPS}(\text{W}^-\text{W}^+\gamma)|\mathcal{M}^\gamma|^2$$

- Phase-space decomposition:

$$\sigma_{\text{real}} = \sigma_{\text{hard}} + \sigma_{\text{soft}} + \sigma_{\text{coll}}$$

Phase-Space Slicing

- **Soft limit:** $E_\gamma < \Delta E \ll M_W$

$$\sigma_{\text{soft}}(\Delta E) = -\sigma_{\text{LO}} \left[\frac{e^2}{(2\pi)^3} \int_{|\mathbf{k}_\gamma|<\Delta E} \frac{\mathrm{d}^3\mathbf{k}_\gamma}{2\sqrt{\mathbf{k}_\gamma^2+\lambda^2}} \sum_{ij} \frac{\pm Q_i Q_j (p_i p_j)}{(p_i k_\gamma)(p_j k_\gamma)} \right]$$

- **Collinear limit:** $\theta_{q\gamma} < \Delta\theta \ll 1, \quad E_\gamma > \Delta E$

$$\sigma_{\text{coll},q}(\Delta E, \Delta\theta) = \frac{\alpha Q_q^2}{2\pi} \int_0^{1-2\Delta E/\sqrt{\hat{s}}} \mathrm{d}z \, \frac{(1+z^2)}{1-z} \left(\ln \frac{\hat{s}(\Delta\theta)^2}{4m_q^2} - \frac{2z}{1+z^2} \right) \sigma_{\text{LO}}(z\hat{s})$$

- **Hard bremsstrahlung:** $\theta_{q\gamma} > \Delta\theta, \quad E_\gamma > \Delta E$;
  numerical evaluation of $\sigma_{\text{hard}}(\Delta E, \Delta\theta)$ without regulators
- Numerical result independent of $\ln \Delta E$ and $\ln \Delta\theta$

$\ln m_q$ **and** $\ln \lambda$ **terms cancel in the sum** $\sigma_{\text{virt}} + \sigma_{\text{soft}} + \sigma_{\text{coll}}$ **in infrared-safe observables**

EW Corrections to pp $\to W^-W^+ + X$ – Technicalities

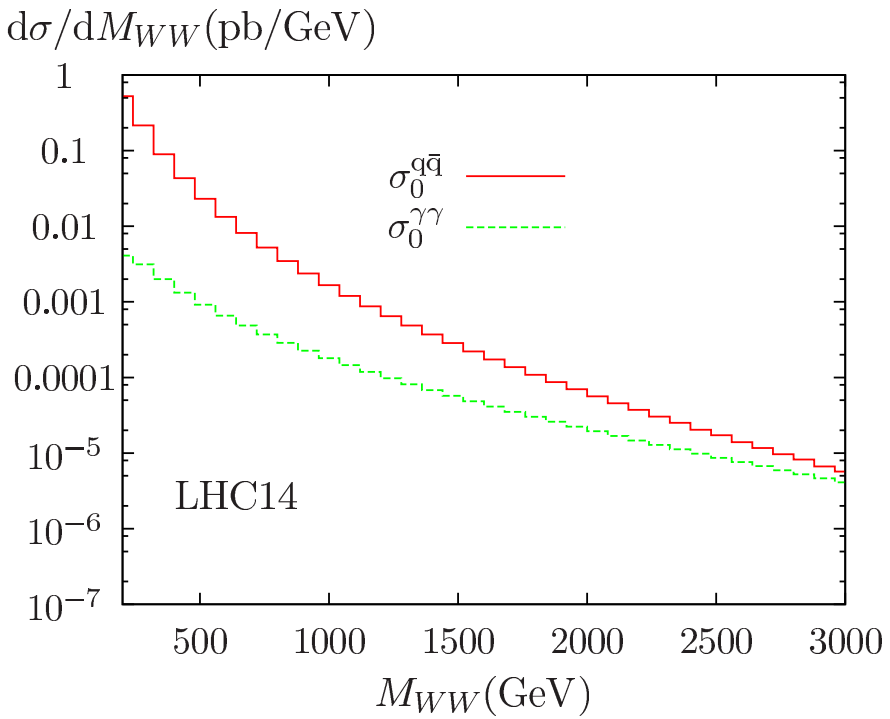
Virtual corrections computed in the FeynArts/FormCalc/LoopTools(FF) framework [(FA): Küblbeck, Böhm, Denner 1990; (FC,LT): Hahn, Pérez Victoria 1999; Hahn 2001; (FF): van Oldenborgh, Vermaseren 1990]

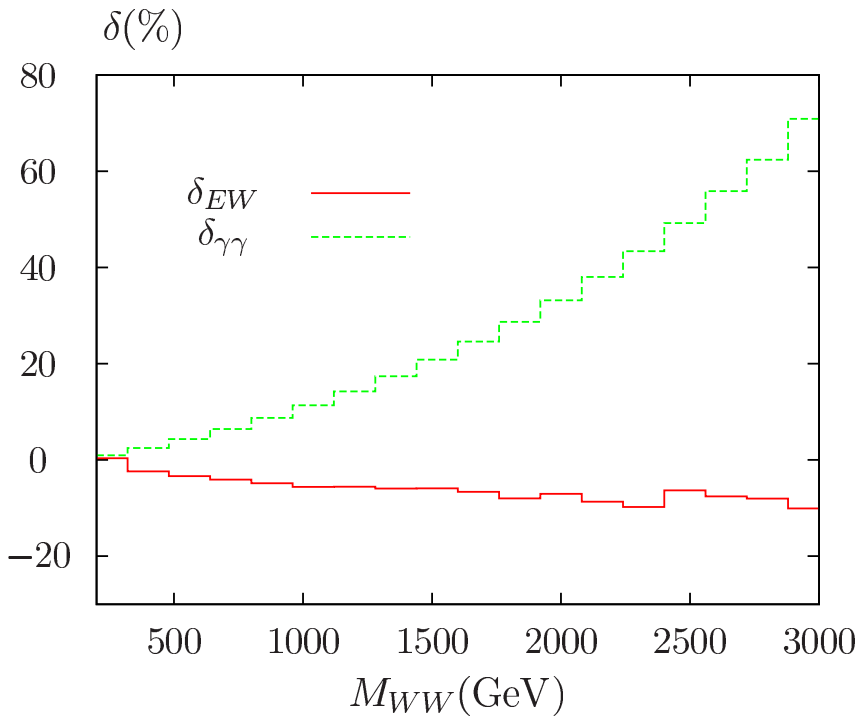
1. FeynArts-3.5:
   - Automatic generation of diagrams
   - Calculation of amplitudes
2. FormCalc-6.1:
   - Algebraical simplification of amplitudes, introduction of tensor coefficients
   - Analytical calculation of squared amplitudes
   - Spin-, colour- and polarization sums
   - Generation of `Fortran` code
3. LoopTools-2.5:
   - Numerical Passarino–Veltman reduction within Fortran
   - Numerically-stable evaluation of scalar integrals

Bremsstrahlung amplitudes computed with FeynArts/FeynCalc $\oplus$ Madgraph [Alwall et al.], numerical phase-space integration within `Fortran` using the `Vegas` algorithm

$pp \to W^-W^+(\gamma)$ – Numerical Results

No cuts





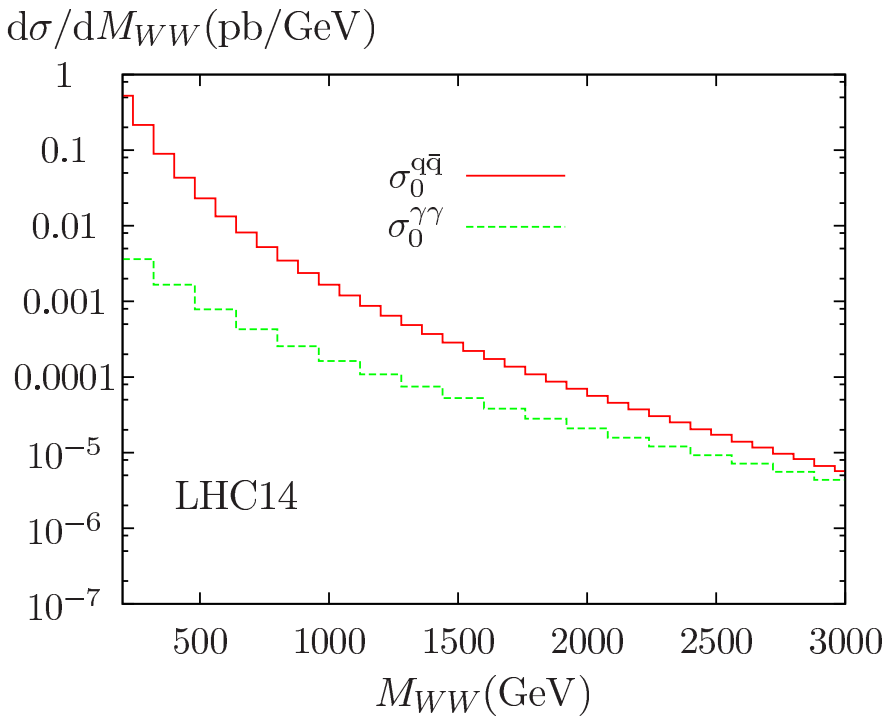
- LO cross section dominated by $q\bar{q}$ contributions
- Rapid decrease of cross section for increasing invariant masses

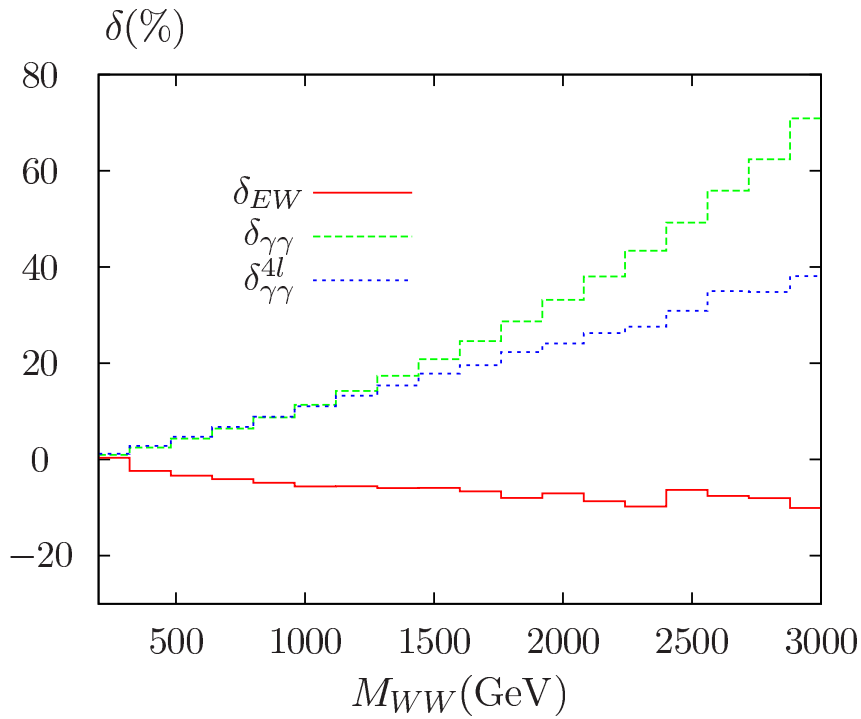
- EW corrections small even for large values of M_{WW}
- Large contributions (+80%!) from $\gamma\gamma \to WW$ at high invariant masses

$\Rightarrow$ Leptonic decays?

$pp \to W^-W^+(\gamma)$ – Numerical Results

LHC acceptance cuts





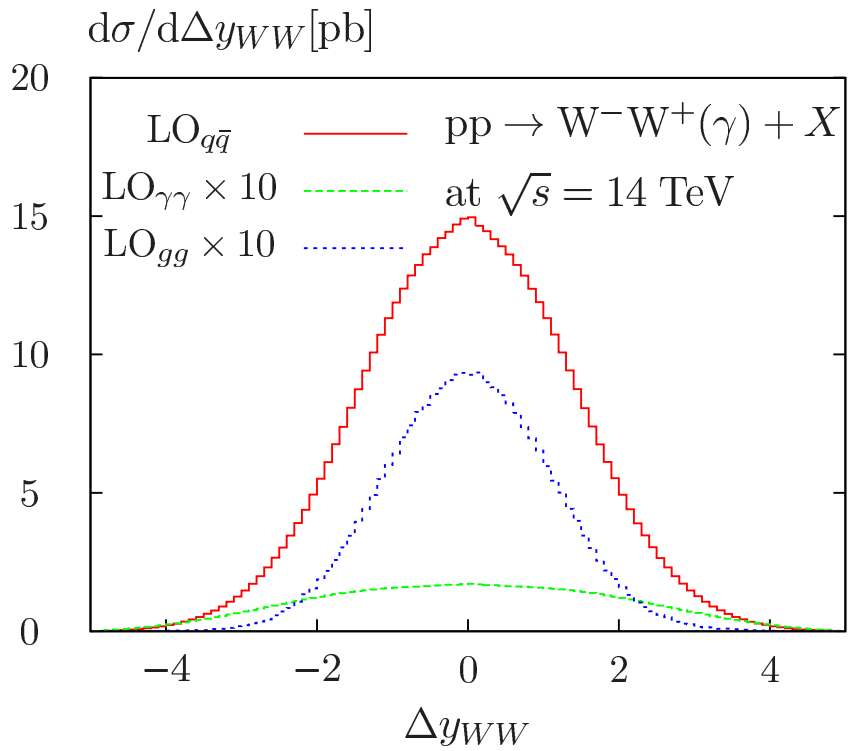
- LO cross section dominated by $q\bar{q}$ contributions
- Rapid decrease of cross section for increasing invariant masses

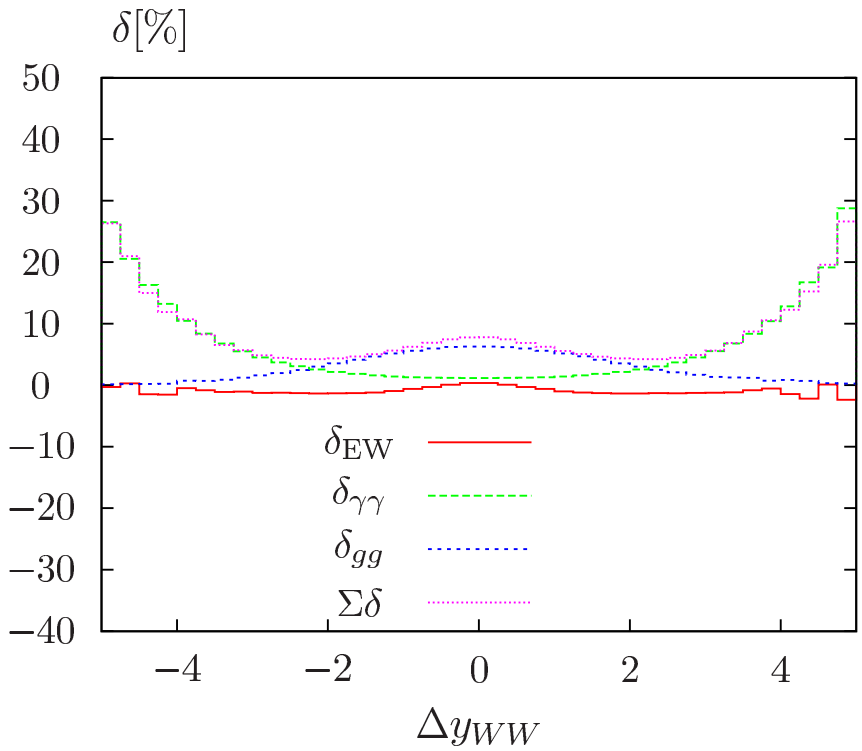
- Employ LHC cuts on decay products: $p_{\mathrm{T},l} > 20$ GeV, $|y_l| < 3$, $p_{\mathrm{T,miss}} > 25$ GeV

$\Rightarrow$ relative effect of $\gamma\gamma \to WW$ reduced by factor 2 at large M_{WW}

EW Corrections to pp → W^-W^+ – Numerical Results

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



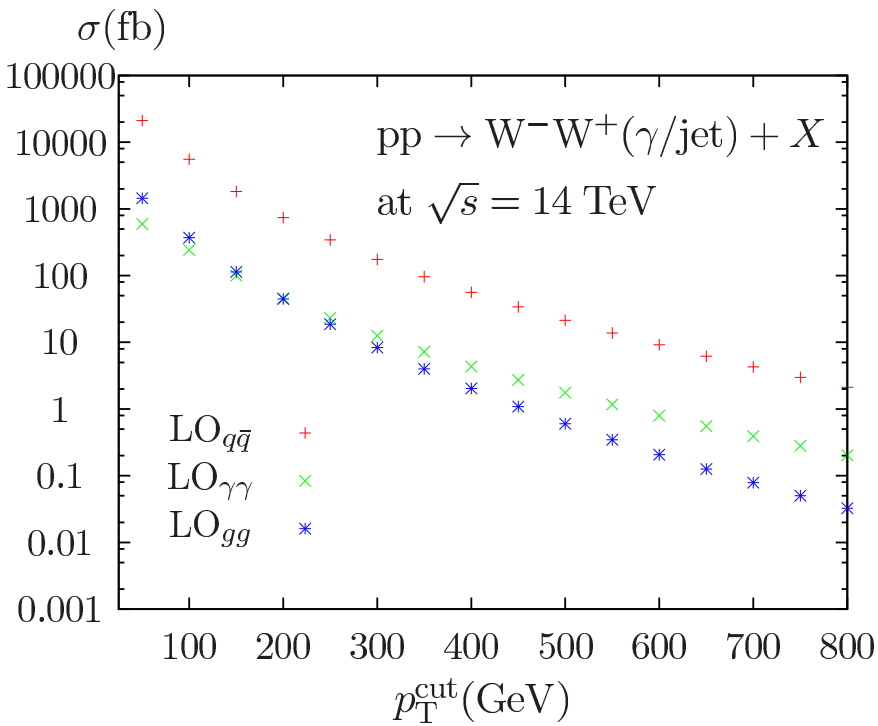


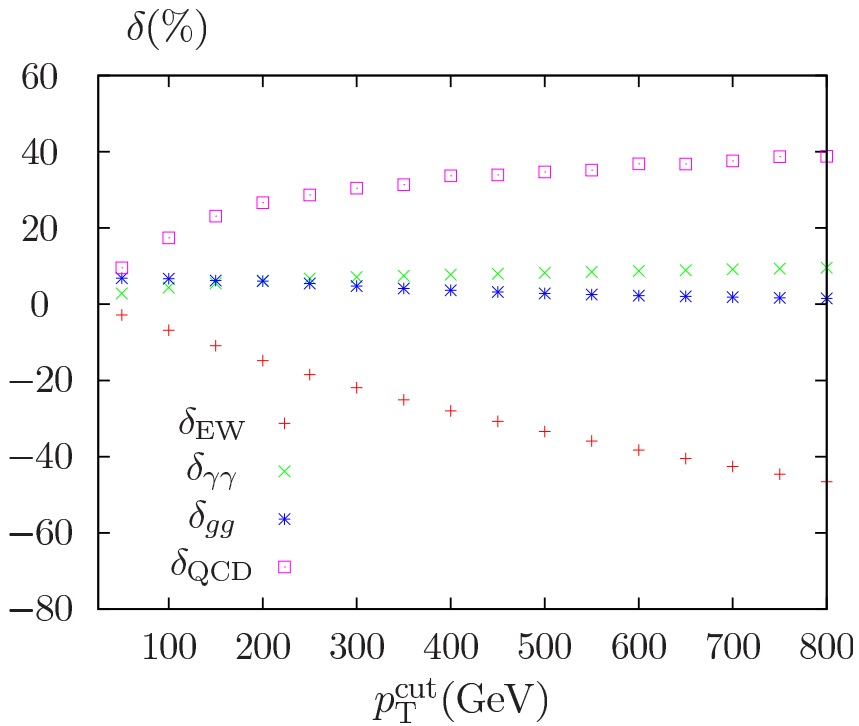
- WW production dominated by events near threshold, isotropic production at small Δy_{WW}
- 5% increase of cross section by gg channel

- EW corrections at the percent level
- Sizable contributions from $\gamma\gamma$ at large $|\Delta y_{WW}|$

$pp \to W^-W^+(\gamma)$ – Numerical Results

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

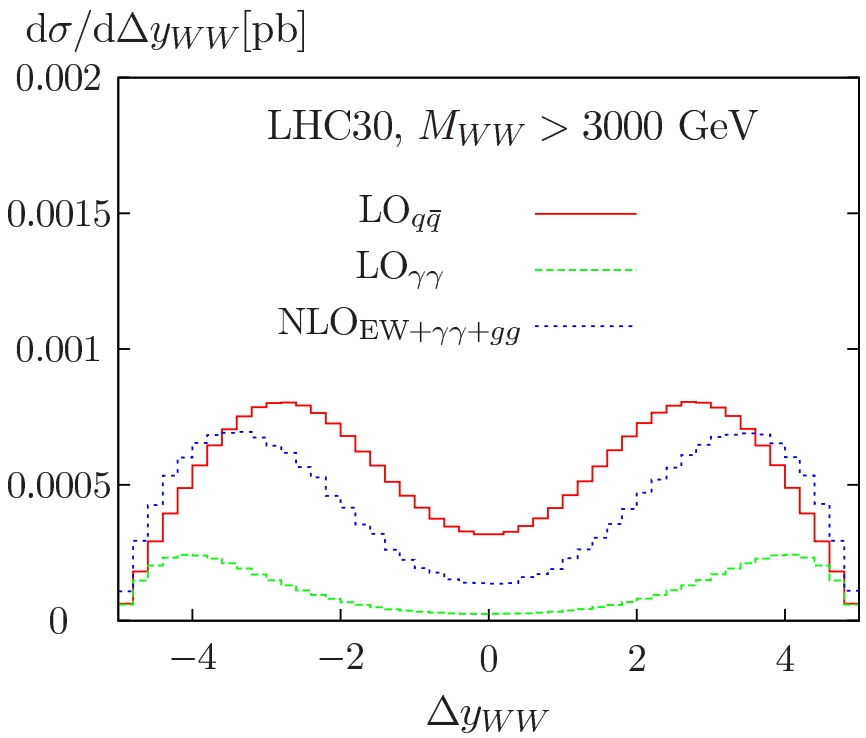


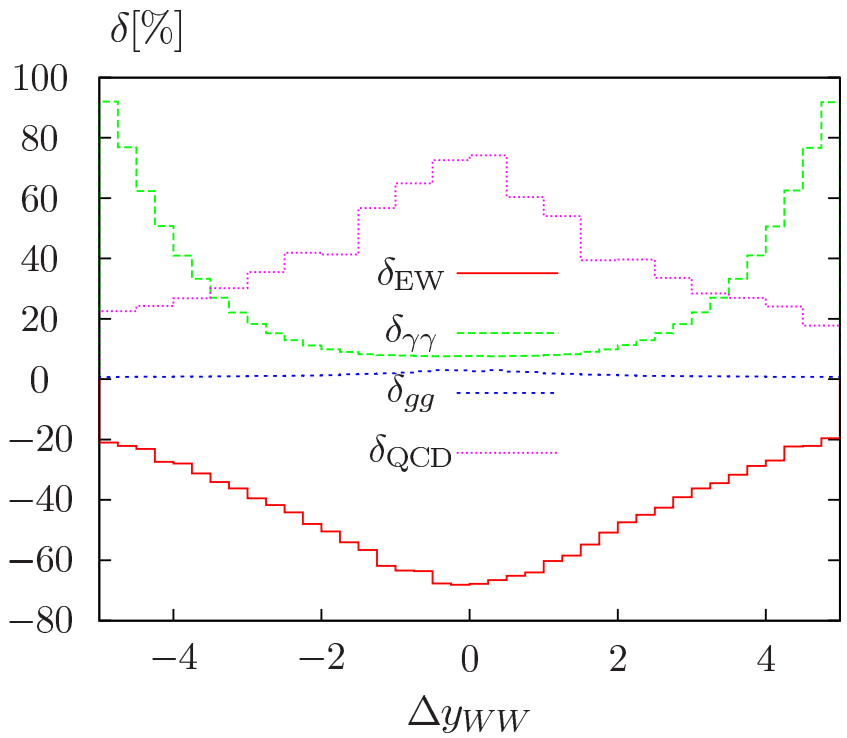


- assume $\int \mathcal{L} dt = 200$ fb^{-1}
  $\Rightarrow$ 1000 WW events with $p_T > 500$ GeV
- decreasing admixture of gg, increasing admixture of $\gamma\gamma$
- large admixture of $\gamma\gamma$ (10%!)
- large negative EW corrections (-45%), comparable to QCD corrections

EW Corrections to pp → W^-W^+ – Numerical Results

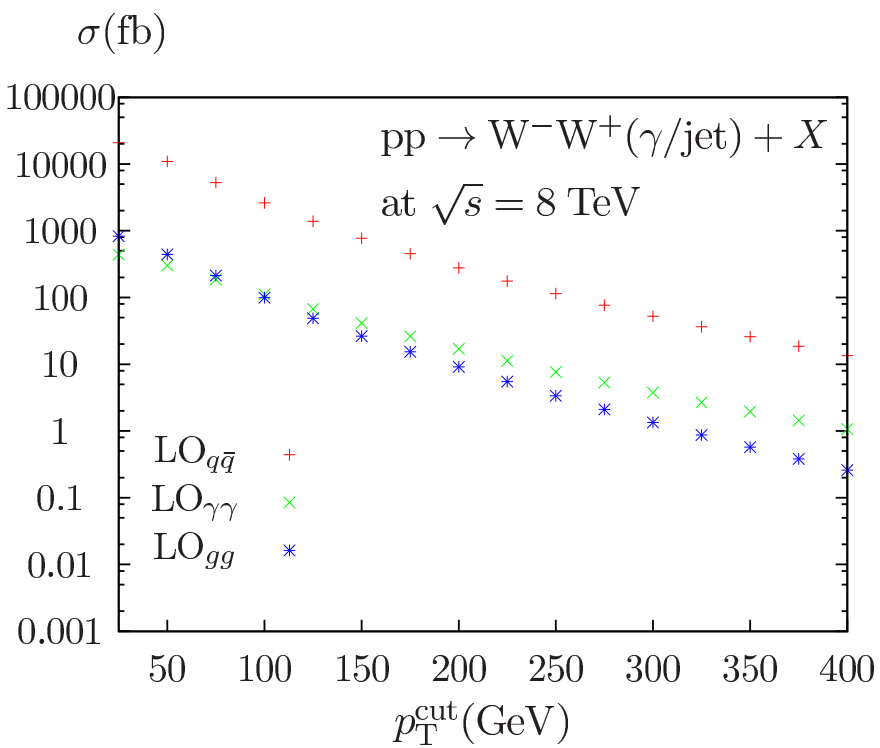
Very-high-energy cuts: $p_{T,W^\pm} > 15$ GeV, $y_{W^\pm} < 2.5$, $M_{WW} > 3$ TeV

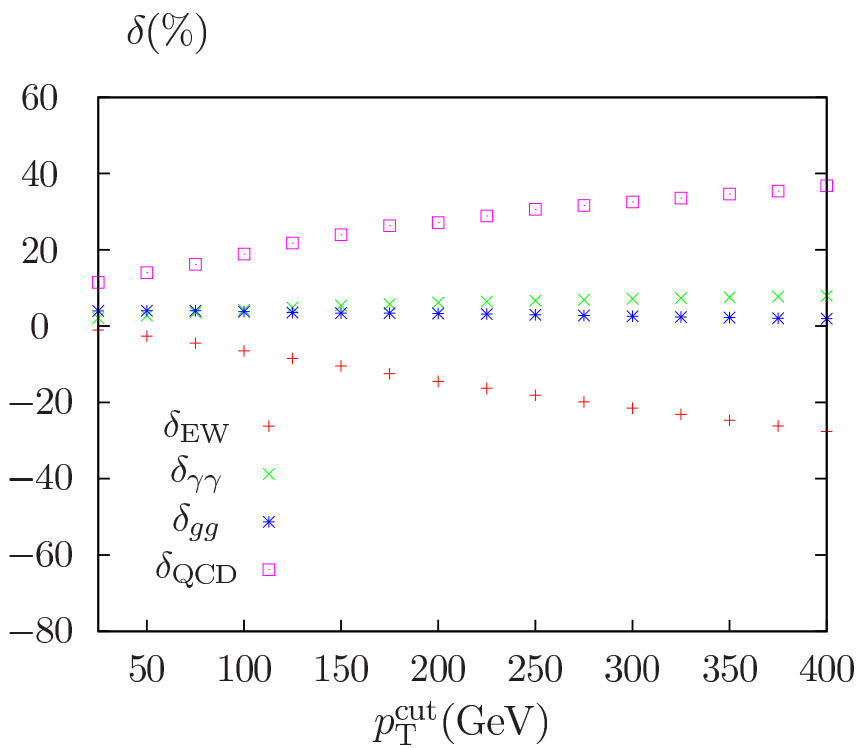




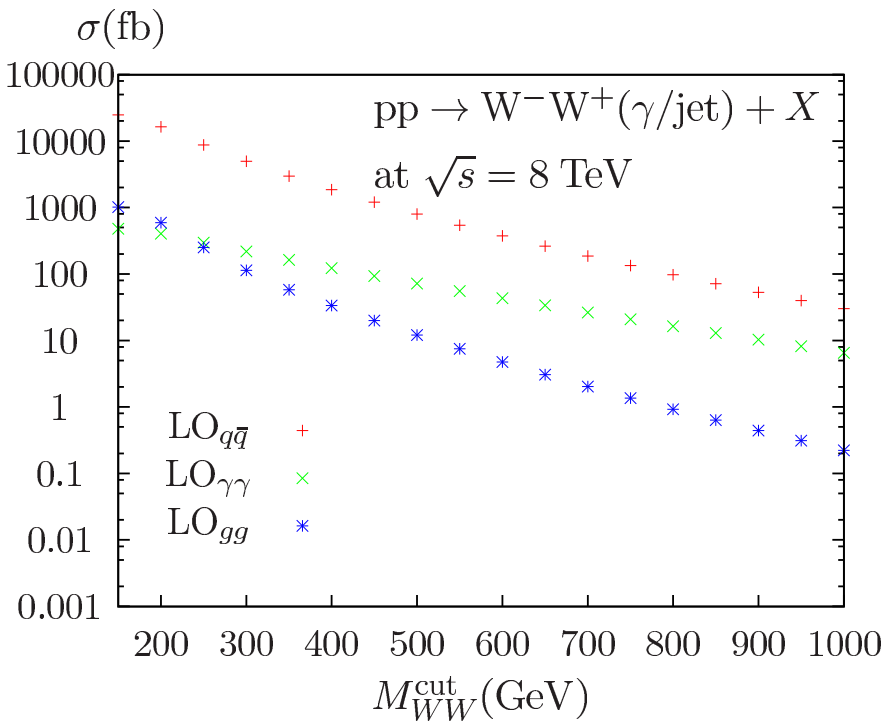
- NLO EW as important as QCD
- extreme distortion due to $\gamma\gamma$ (**caveat:** high uncertainty in photon PDFs)

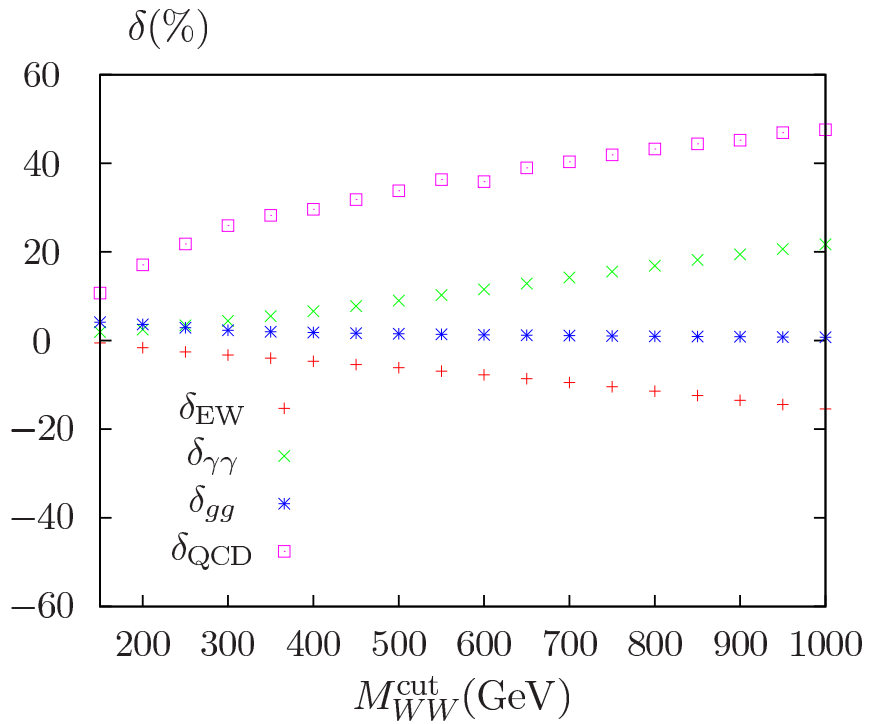
Transverse-momentum distribution at the LHC8



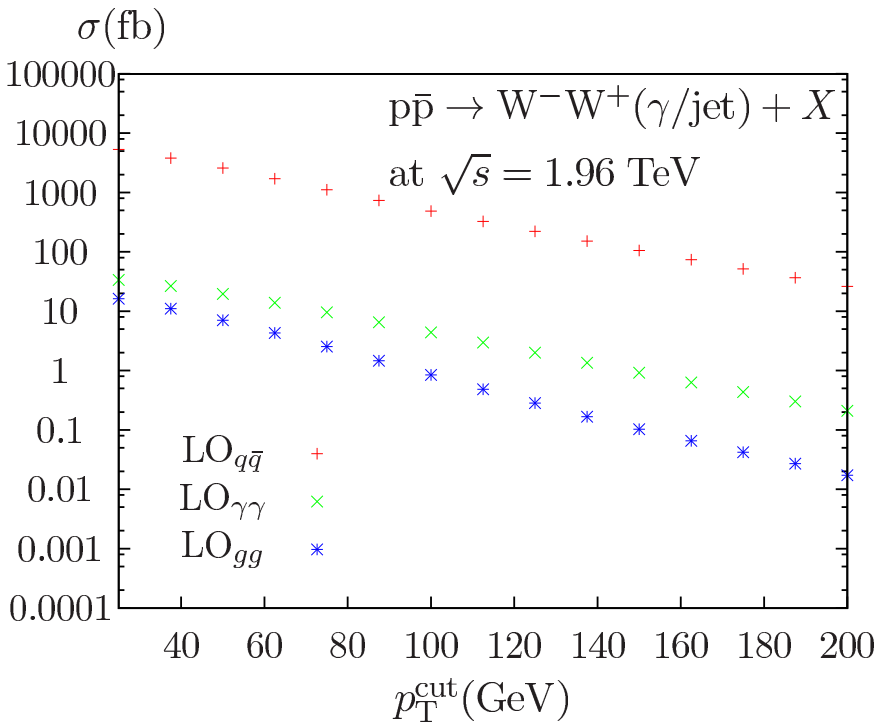


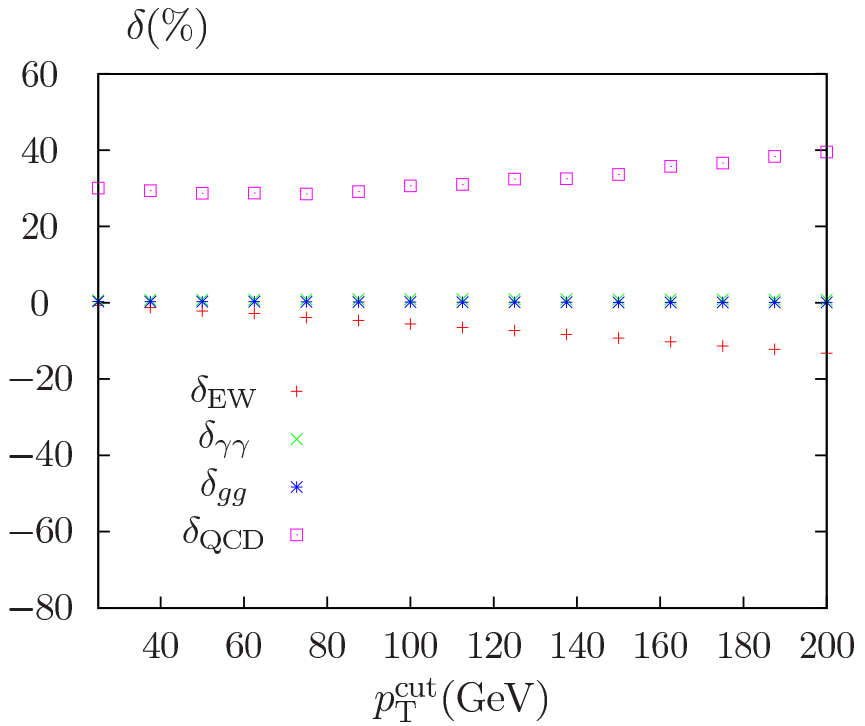
Invariant-mass distribution at the LHC8





Transverse-momentum distribution at the Tevatron





Invariant-mass distribution at the Tevatron