Electroweak effects in vector-boson pair production at the LHC

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[arXiv:1208.3147], [arXiv:1208.3404]

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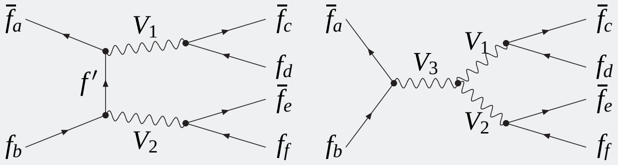
Outline

Introduction – Weak-Boson Pair Production at the LHC

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

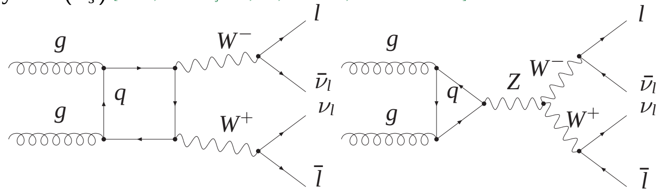


- ZZ/WW production important irreducible background to inclusive SM Higgs-boson production
- Probe non-abelian structure of the Standard Model (SM) at high energies
- Search for anomalous couplings
- Backgrounds to new-physics searches, i.e. leptons + $\not{E}_T$ signatures
  $\longrightarrow$ SUSY-particle 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
- anomalous couplings included
- Corrections dominated by the $q\bar{q}$ channels
  - Significant contributions of the channels $gg \to V_1V_2 \sim 10\,\%$ 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 (Sudakov) limit

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

$\rightarrow$ **bosons have to be produced at large p_T**

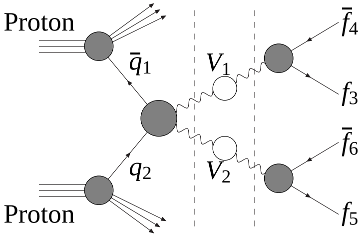
- EW corrections at high energies dominated by universal large logarithms

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

  at the L-loop level
- Corrections of $\sim -50\%$ at $\sqrt{s} = 2$ TeV (W-pair production)
- Change of sign going from LL to NLL (to NNLL . . .)
  $\rightarrow$ **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 [Accomando et al. 2002–2006]
  $\rightarrow$ **final-state leptons phenomenologically accessible**



- 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 2012]**

Motivation – Why the full Calculation?

- **First LHC results on total cross sections** for pp $\to$ WW/WZ/ZZ have been published
  - ATLAS: pp $\to$ W^+W^- at 7 TeV, 1.02 fb^{-1} [arXiv:1203.6232 [hep-ex]],
    pp $\to$ W^+W^- at 8 TeV, 5.8 fb^{-1} [ATLAS-CONF-2012-090]
  - CMS: pp $\to$ WW/WZ/ZZ at 7 TeV, 1.1 fb^{-1} [CMS PAS EWK-11-010],
    pp $\to$ WW(ZZ) at 8 TeV, 3.5(5.3) fb^{-1} [CMS PAS SMP-12-013, CMS PAS SMP-12-014]

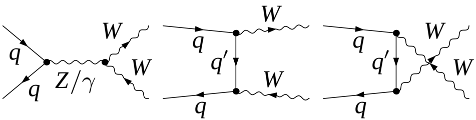
  experimental error at the level of 15%; WW dominated by systematics, ZZ dominated by statistics
  $\Longrightarrow$ **Quantify EW effects in this SM benchmark process**

- **Focus of LHC physics:** V-pair production at high energies, $\hat{s} \gg M_W^2$:
  - V-pair production dominated by **small scattering angles,** i.e. small $\hat{t}, \hat{u}$
  - Potentially sizable effects due to anomalous couplings
  - **Until now, no predictions for EW effects in this particular kinematic regime!**

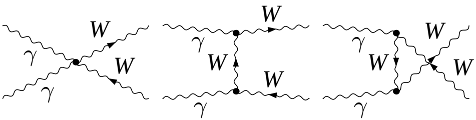
- Electroweak corrections potentially large

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

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



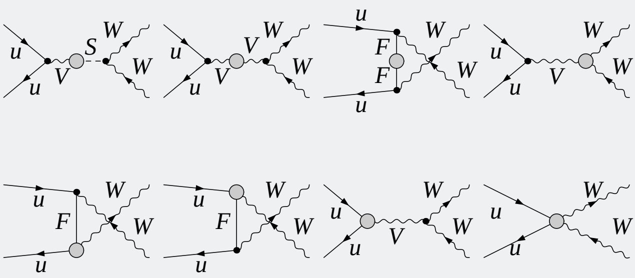
- **Photon-induced contributions at** $\mathcal{O}(\alpha^2)$



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

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

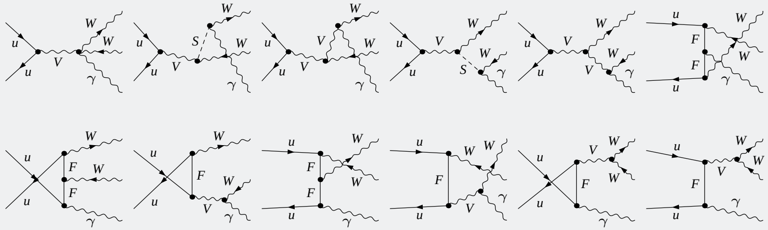
One-loop contributions at $\mathcal{O}(\alpha^3)$



- On-shell renormalization of SM parameters
- We use the Fermi scheme to calculate the loop corrections.
  $\rightarrow$ universal corrections to Δr absorbed in effective LO coupling
- $V_{ij}^{\mathrm{CKM}} = \delta_{ij}$ within the loops $\rightarrow$ 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 $\longrightarrow$ renormalization of PDFs
- Introduce small **quark mass** m_q and infinitesimal **photon mass** λ to regularize divergences $\longrightarrow$ results exhibit unphysical $\ln m_q$ and $\ln \lambda$ terms

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

Numerical Results (I) – Total Cross Sections

LHC at 8 TeV:

no cuts	$\sigma_{\mathrm{LO}}^{q\bar{q}'}$ (pbarn)	δ_{EW} (%)	$\delta_{\gamma\gamma}$(%)
$\mathrm{W^+W^-}$	35	-0.4	1.5
$\mathrm{W^+Z}$	9	-1.4	–
$\mathrm{W^-Z}$	5	-1.3	–
ZZ	6	-4.1	–

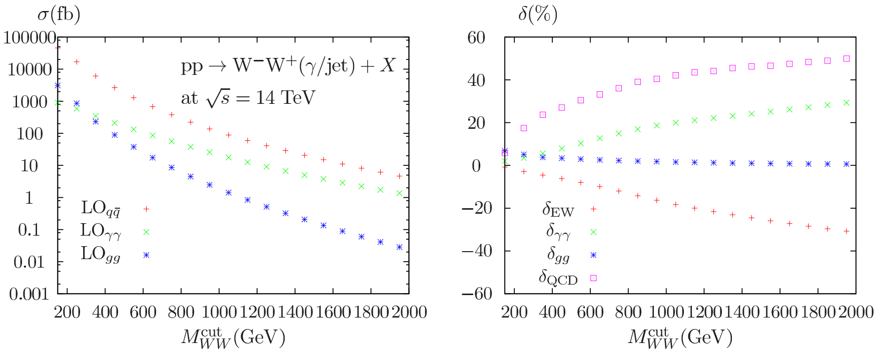
LHC at 14 TeV:

no cuts	$\sigma_{\mathrm{LO}}^{q\bar{q}'}$ (pbarn)	δ_{EW} (%)	$\delta_{\gamma\gamma}$(%)
$\mathrm{W^+W^-}$	75	-0.5	1.6
$\mathrm{W^+Z}$	19	-1.4	–
$\mathrm{W^-Z}$	12	-1.4	–
ZZ	12	-4.2	–

- $\sigma = \sigma_{\mathrm{LO}} \times (1+\delta)$
- **Setup:** `MSTW2008LO` PDFs [Martin et al. 2009], $\mu_R = \mu_F = (m_{T,1} + m_{T,2})/2$

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

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

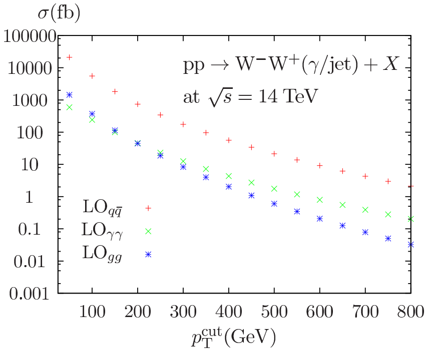


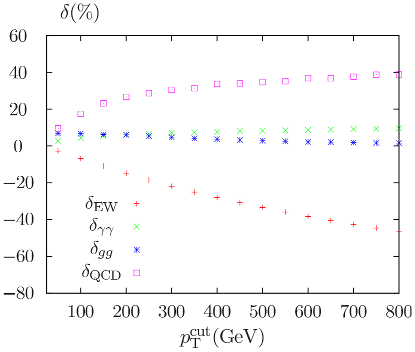
- assume $\int \mathcal{L}\text{d}t = 200\ \text{fb}^{-1}$
  $\Rightarrow$ 1000 WW events with
  $M_{\text{WW}} > 2$ TeV
- rapidly increasing admixture of $\gamma\gamma$

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

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

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





- assume $\int \mathcal{L}dt = 200\ \text{fb}^{-1}$
  $\Rightarrow$ 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

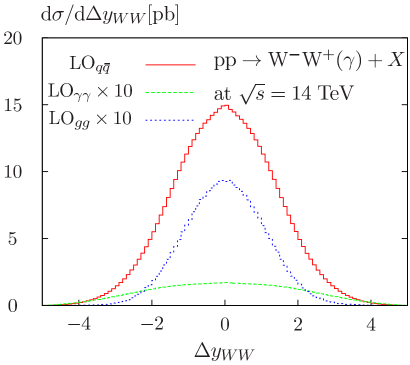
$\mathcal{O}(\alpha)$-Contributions to pp $\rightarrow$ W$^-$W$^+$

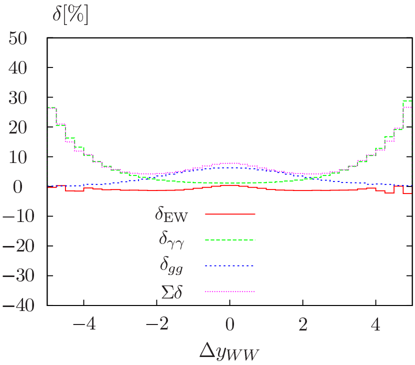
No compensation between $\gamma\gamma \rightarrow WW$ and weak corrections!
$\Longrightarrow$ **Different angular distributions!**

- $\sigma(\gamma\gamma \rightarrow WW) \rightarrow \frac{8\pi\alpha^2}{M_W^2}$ 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 $\rightarrow$ WW 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 (IV) – pp → W^-W^+

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

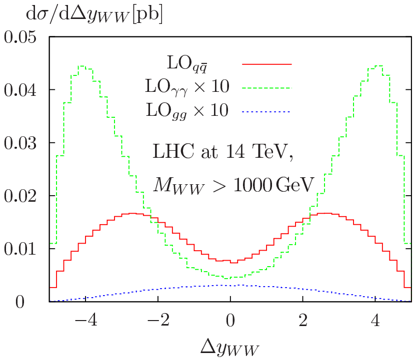


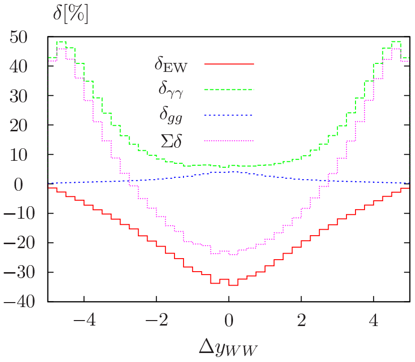


- WW production dominated by events near threshold, isotropic production at small Δy_{WW}
- 5% increase of cross section by gg channel
- EW corrections at the percent level
- Sizable contributions from $\gamma\gamma$ at large $|\Delta y_{WW}|$

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

High-energy cuts: $p_{\mathrm{T,W^\pm}} > 15$ GeV, $y_{\mathrm{W^\pm}} < 2.5$, $M_{WW} > 1$ 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 $\mathrm{pp} \to \mathrm{WW} + (\mathrm{W}/\mathrm{Z})$
$\Rightarrow$ contribution below 1%

High energies: Logarithmic enhancement of additional soft/collinear W- or Z-boson radiation
$\Rightarrow$ Investigation of $\mathrm{WW} + \mathrm{W}/\mathrm{Z}$ production as background to W pairs at large p_{T}, M_{WW}

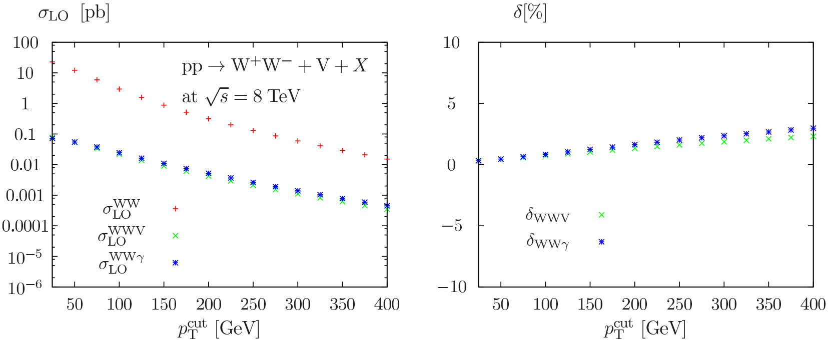
- invisible decay of $Z \to \nu\bar{\nu}$
- collinear emission
- ...

Simplified approach: (details depend on experimental analysis)

1. Include $\mathrm{pp} \to \mathrm{W}^-\mathrm{W}^+\mathrm{Z}$ with totally inclusive Z
2. Include $\mathrm{pp} \to \mathrm{W}^-\mathrm{W}^+\mathrm{W}^\pm$; treat $W^\pm$ with lowest p_{T} totally inclusively

Numerical Results (VI) – "Real Radiation" of W/Z

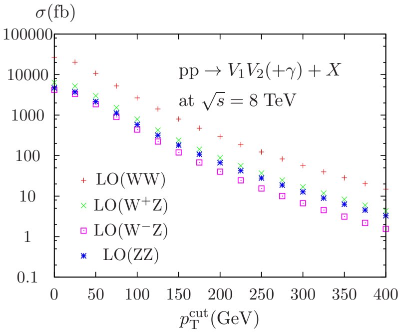
LHC at 8 TeV, default cuts: $p_{T,W^\pm} > 15$ GeV, $|y_{W^\pm}| < 2.5$

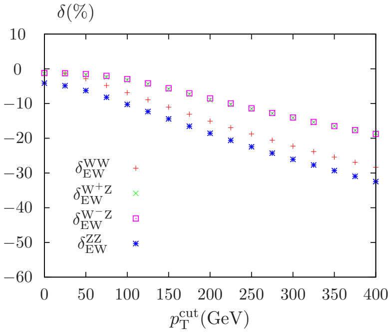


- Corrections due to hard photons ($p_{T,\gamma} > 15$ GeV, $|y_\gamma| < 2.5$) below 5 %
- Contributions of massive-boson radiation below 5 %

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

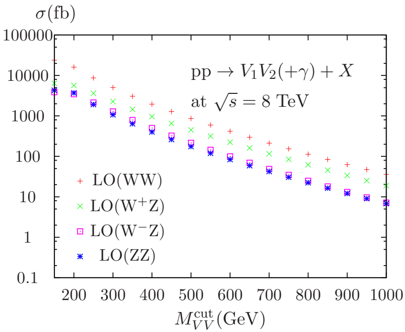
LHC at 8 TeV, default cuts: $p_{T,V} > 15$ GeV, $|y_V| < 2.5$, large scattering angles

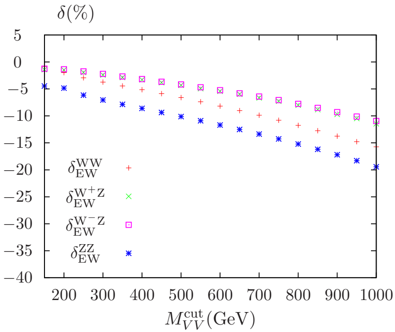




- moderate EW corrections to WZ production
- large EW corrections to ZZ production

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





- moderate EW corrections to WZ production
- large EW corrections to ZZ production
- **EW corrections important at high energies and small scattering angles**

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 high energies
  - **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 combination of EW and QCD effects
  - Discuss interplay of anomalous couplings and EW effects

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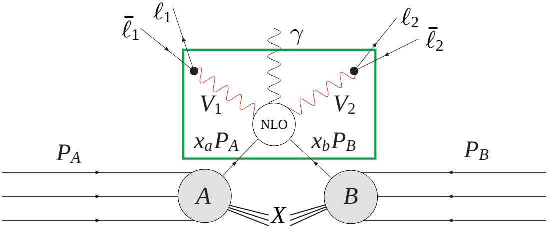
Thank You!

Reminder: Calculation of Hadronic Cross Sections

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



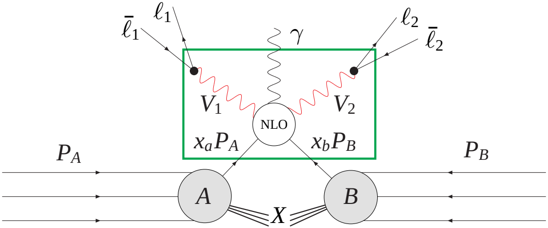
Hadronic cross sections

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

- 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

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

$$d\sigma_{AB}(p_A, p_B) = \sum_{a,b} \int_0^1 dx_a \int_0^1 dx_b\, f_{a/A}(x_a, \mu_F)\, f_{b/B}(x_b, \mu_F)\, d\hat{\sigma}^{NLO}_{ab}(p_a, p_b, \mu_F, \mu_R)$$

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

NLO partonic cross section:

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

Double-Pole Approximation (DPA)

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

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

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

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

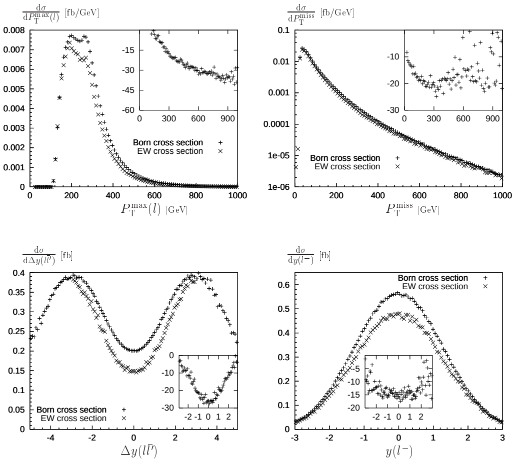
- **NLO:** EW corrections consist of factorizable and non-factorizable contributions, e.g.

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

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 $L \sim 30\ \mathrm{fb}^{-1}$)**



[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

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

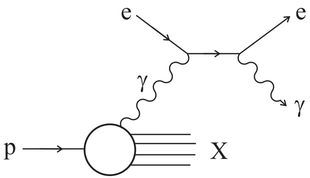
$\Rightarrow$ QED effects on $f_{q/\mathrm{p}}(x, \mu^2)$ small!
$\Rightarrow$ Still large conceptual uncertainties in $f_{\gamma,0}$

Measure Photon PDFs?

Consider the DIS process

$$ep \to e\gamma + X$$

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

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

- 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}**

Phase-Space Slicing

Two-cut-off phase-space slicing

- Definition of bremsstrahlung phase space:

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

- Phase-space decomposition:

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

Phase-Space Slicing

- **Soft limit:** $E_\gamma < \Delta E \ll M_\mathrm{W}$

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

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

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

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

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

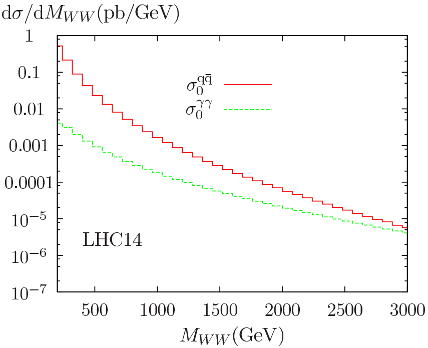
Virtual corrections computed in the FeynArts/FormCalc/LoopTools(FF) framework [(FA): Küblbeck, Böhm, Denner 1990; (FC,LT): Hahn, Pérez Victoria 1999; Hahn 2001; (FF): van Oldenborgh, Vermaseren 1990]

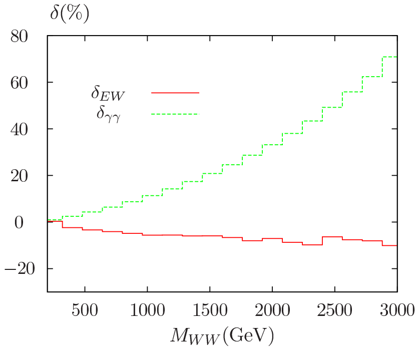
1. FeynArts-3.5:
   - Automatic generation of diagrams
   - Calculation of amplitudes
2. FormCalc-6.1:
   - Algebraical simplification of amplitudes, introduction of tensor coefficients
   - Analytical calculation of squared amplitudes
   - Spin-, colour- and polarization sums
   - Generation of Fortran 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





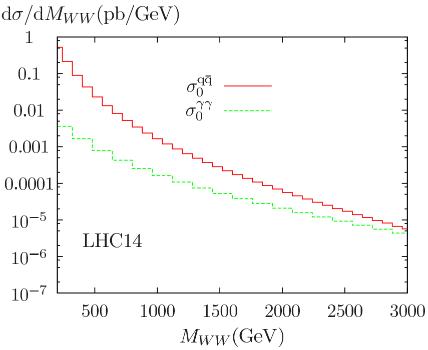
- LO cross section dominated by $q\bar{q}$ contributions
- Rapid decrease of cross section for increasing invariant masses

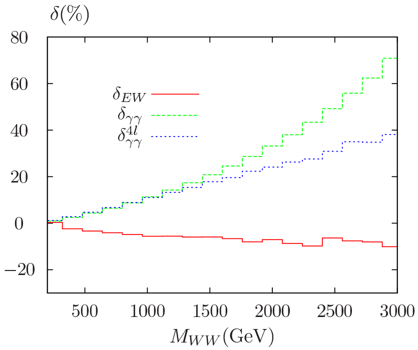
- EW corrections small even for large values of M_{WW}
- Large contributions (+80%!) from $\gamma\gamma \to WW$ at high invariant masses

$\Rightarrow$ Leptonic decays?

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

LHC acceptance cuts





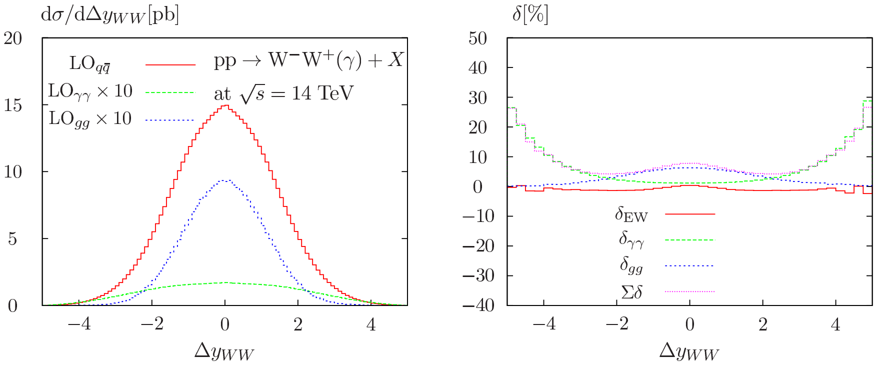
- LO cross section dominated by $q\bar{q}$ contributions
- Rapid decrease of cross section for increasing invariant masses

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

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

EW Corrections to pp $\to$ W^-W^+ – Numerical Results

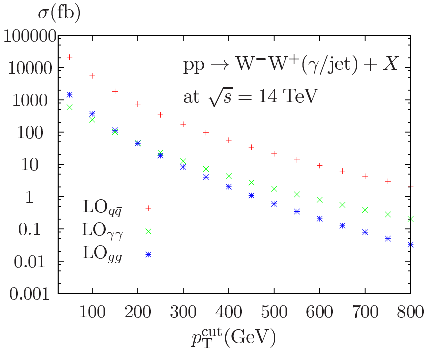
Default cuts: $p_{T,W^\pm} > 15$ GeV, $y_{W^\pm} < 2.5$

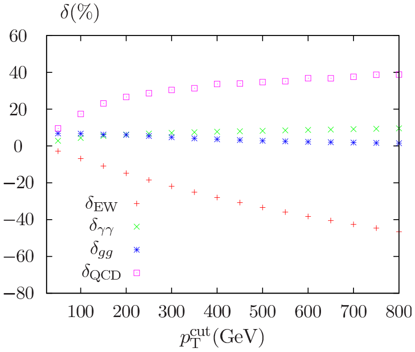


- WW production dominated by events near threshold, isotropic production at small Δy_{WW}
- 5% increase of cross section by gg channel
- EW corrections at the percent level
- Sizable contributions from $\gamma\gamma$ at large $|\Delta y_{WW}|$

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

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

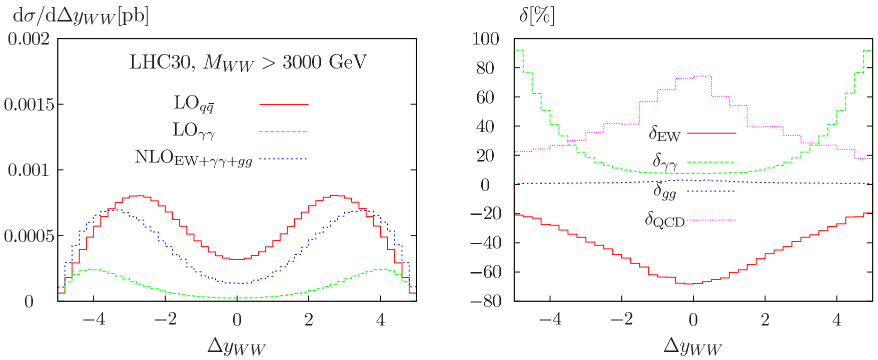




- assume $\int \mathcal{L}dt = 200$ fb^{-1}
  $\Rightarrow$ 1000 WW events with $p_T > 500$ GeV
- decreasing admixture of gg, increasing admixture of $\gamma\gamma$
- large admixture of $\gamma\gamma$ (10%!)
- large negative EW corrections (-45%), comparable to QCD corrections

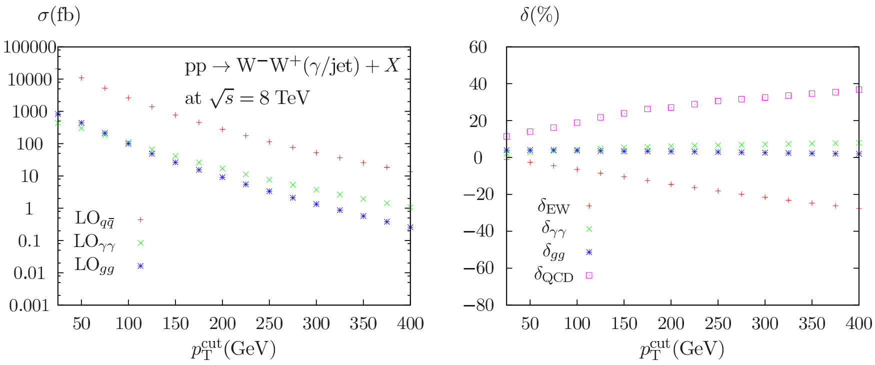
EW Corrections to pp → W^-W^+ – Numerical Results

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

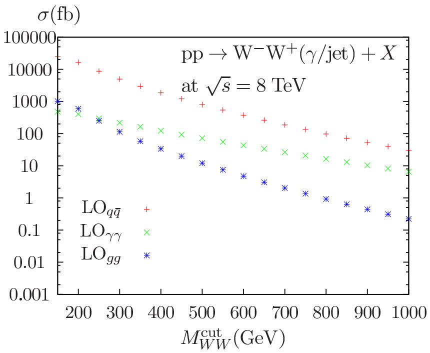


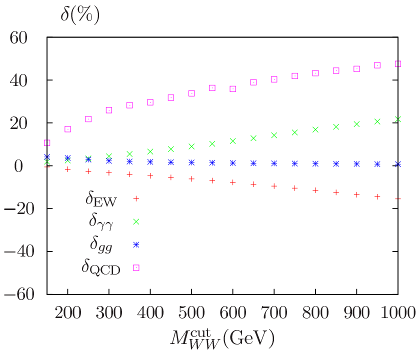
- NLO EW as important as QCD
- extreme distortion due to $\gamma\gamma$ (**caveat:** high uncertainty in photon PDFs)

Transverse-momentum distribution at the LHC8

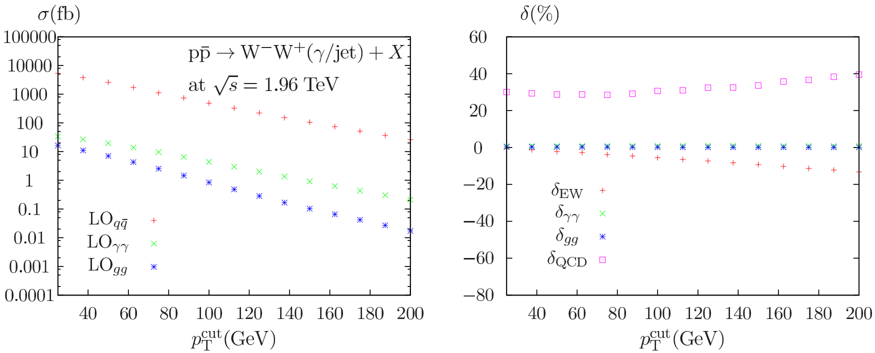


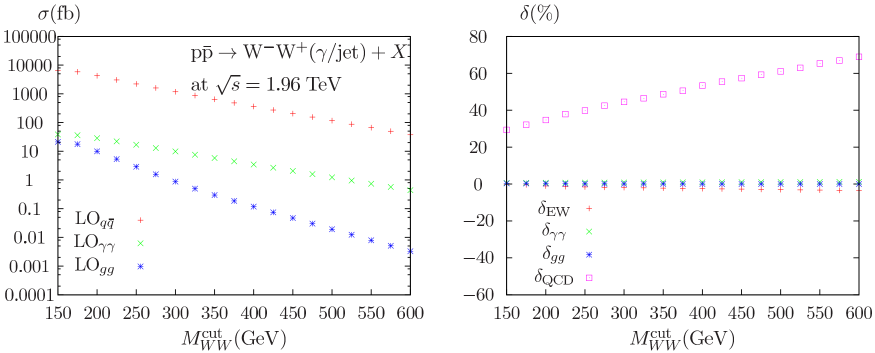
Invariant-mass distribution at the LHC8





Transverse-momentum distribution at the Tevatron





σ(fb)
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
$p\bar{p} \to W^-W^+(\gamma/\text{jet}) + X$
at $\sqrt{s} = 1.96$ TeV
$LO_{q\bar{q}}$
$LO_{\gamma\gamma}$
LO_{gg}
150 200 250 300 350 400 450 500 550 600
$M_{WW}^{cut}(\text{GeV})$
δ(%)
80
60
40
20
0
−20
−40
−60
δ_{EW}
$\delta_{\gamma\gamma}$
δ_{gg}
δ_{QCD}
150 200 250 300 350 400 450 500 550 600
$M_{WW}^{cut}(\text{GeV})$