Electroweak effects in vector-boson pair production at the LHC

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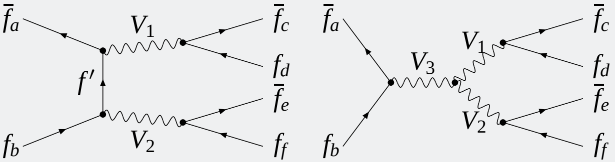
Outline

Introduction – Weak-Boson Pair Production at the LHC

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



- ZZ/WW/$\gamma\gamma$ 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
  $\longrightarrow$ SUSY-particle pair production

High-energy limit

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

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

- EW corrections at high energies dominated by universal large logarithms

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

  at the L-loop level
- Corrections of $\sim -40\%$ at $p_\mathrm{T} = 500$ GeV (Z-pair production)
- Change of sign going from LL to NLL (to NNLL . . .)
  $\rightarrow$ **substantial cancellations possible!**

NLO Electroweak Corrections – Our Strategy

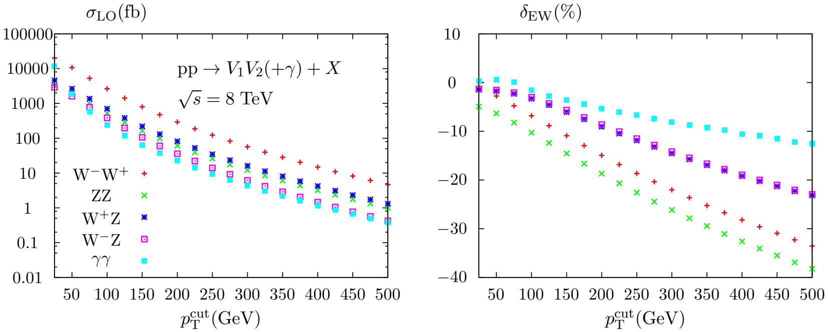
1. Only consider on-shell vector bosons $\oplus$ include all mass effects
2. Include leptonic decays $\rightarrow$ **physical final states phenomenologically accessible**

Setup

- **Renormalization:**
  On-shell scheme (G_μ, M_W, M_Z) to obtain UV finite
- **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 and factorization scheme small, in general sub-percent)

Numerical Results for WW/WZ/ZZ/$\gamma\gamma$ Production

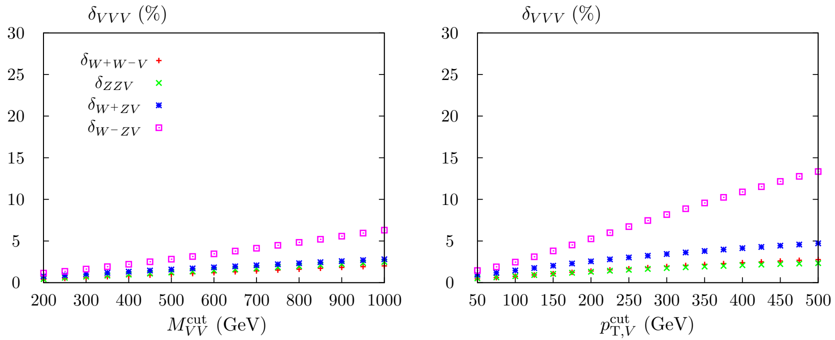
LHC at 8 TeV, default cuts: $p_{T,V} > 15$ GeV, $|y_V| < 2.5$



- **LO:** Drastically decreasing cross sections for large p_T
- **NLO:**
  - Full result, i.e. virtual, soft, hard, and collinear photons included
  - all mass effects included
  - corrections largest for ZZ, smallest for $\gamma\gamma$
- results published in arXiv:1208.3147, arXiv:1208.3404

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

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



- corrections below 5% even for large transverse momenta and invariant masses
- corrections to $\mathrm{W^-Z}$ production enhanced due to $\mathrm{W^-ZW^+}$ final states (PDFs!)
- could easily be implemented in MC studies

Leptonic Decays – ZZ Production

Purely weak corrections well defined in ZZ production
$\rightarrow$ contributions of QED in general below 1%

- compute purely weak corrections to pp $\rightarrow (Z/\gamma^*)(Z/\gamma^*) \rightarrow e^+e^-\mu^+\mu^-$
- **LO:** full calculation, non-resonant and off-shell effects included.
  - naive fixed-width scheme
  - Complex-Mass Scheme (CMS) [Denner, Dittmaier, Roth, Wieders 2005]
- **NLO:** Two different approaches, including full spin correlations
  - Double-Pole Approximation (DPA): only doubly resonant contributions included, finite width taken into account
    (On-shell projection, **caveat:** non-factorizable corrections neglected)
  - Narrow-Width Approximation (NWA): particles strictly on shell

$$\frac{1}{(Q^2-M^2)^2+M^2\Gamma^2} \rightarrow \frac{\pi}{M\Gamma}\delta(Q^2-M^2)\,,$$

valid if $\Gamma/M \rightarrow 0$.

Numerical Results: pp $\to$ ZZ $\to e^+e^-\mu^+\mu^-$

$\text{pp} \to (\text{Z}/\gamma^*)(\text{Z}/\gamma^*) + X \to \text{e}^+\text{e}^-\mu^+\mu^- + X,\ \lvert\Delta y_{\text{ZZ}}\rvert < 3$					
$M_{\text{inv}}^{\text{cut}}(4l)/\text{GeV}$	$\sigma_{\text{LO}}^{\text{naive}}/\text{pb}$	$\sigma_{\text{LO}}^{\text{CMS}}/\text{pb}$	$\sigma_{\text{LO}}^{\text{DPA}}/\text{pb}$	$\sigma_{\text{LO}}^{\text{NWA}}/\text{pb}$	$\delta_{\text{weak}}^{\text{DPA}}/\%$
LHC14					
500	0.326×10^{-3}	0.326×10^{-3}	0.319×10^{-3}	0.343×10^{-3}	-15.9
600	0.168×10^{-3}	0.168×10^{-3}	0.164×10^{-3}	0.177×10^{-3}	-19.3
700	0.962×10^{-4}	0.962×10^{-4}	0.941×10^{-4}	1.017×10^{-4}	-22.3
800	0.587×10^{-4}	0.587×10^{-4}	0.575×10^{-4}	0.621×10^{-4}	-24.9
900	0.374×10^{-4}	0.374×10^{-4}	0.367×10^{-4}	0.397×10^{-4}	-27.4
1000	0.247×10^{-4}	0.247×10^{-4}	0.242×10^{-4}	0.262×10^{-4}	-29.7

LHC14, standard leptonic cuts

- **LO:** DPA works well, NWA: discrepancy of 5–10%
- **NLO:** Good agreement ($\sim 1\%$) with K-factors obtained in Sudakov approximation [Accomando, Denner, Kaiser 2004]

$\to$ QED contributions (real-photon radiation, photon-loops, non-factorizable contributions, corrections to Z-boson decay) only at the 1% level

Conclusion: weak K-factors of hard process sufficient to describe resonant 4-lepton production at reasonable accuracy

Monte Carlo Implementation in HERWIG++

Our strategy

Factorization of EW and QCD corrections:

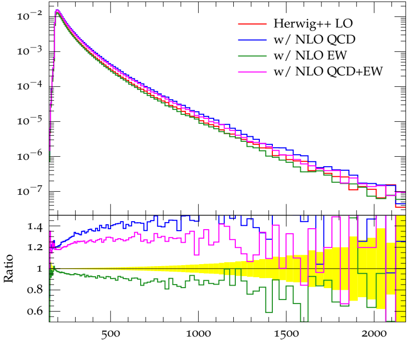
$$d\sigma_{\text{QCD}\times\text{EW}} = K_{\text{weak}}(\hat{s},\hat{t}) \times d\sigma_{\text{QCD}}$$

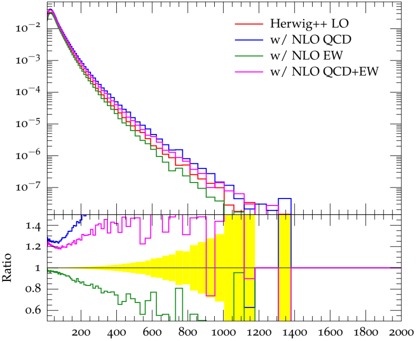
σ_{QCD}: best prediction available for QCD-corrected cross section

- Assumption: bulk of EW effects properly described by weak corrections to $2 \to 2$ process $K_{\text{weak}}(\hat{s},\hat{t})$.
- FSR included in YFS formalism (SOPHTY) [Hamilton, Richardson 2006] (only dressed leptons)
- $K_{\text{weak}}(\hat{s},\hat{t})$ computed once and for all, data provided as grid files.
- **Some caveats:**
  - factorization assumption only sensible without additional hard jets; $\rightarrow$ EW corrections to ZZ+jet have to be included.
  - Ansatz does not include corrections to non-resonant or off-shell contributions

HERWIG++ Analysis for ZZ Production – Preliminary!

Simulation for pp $\longrightarrow ZZ \longrightarrow e^+e^-\mu^+\mu^- + X$ at 8 TeV, M_{ZZ} and $p_{T,Z}$ distributions





- Standard `Herwig++` setup used
  (v2.6.2, with simple add-on for EW corrections, 10M events), ZZ at NLO QCD matched with parton showers, hadronization included, underlying event switched off
- huge QCD corrections at large $p_{T,Z}$, factorized ansatz not justified
  $\longrightarrow$ jet veto, restriction on $p_{T,ZZ}$

The QED Issue

Problem:

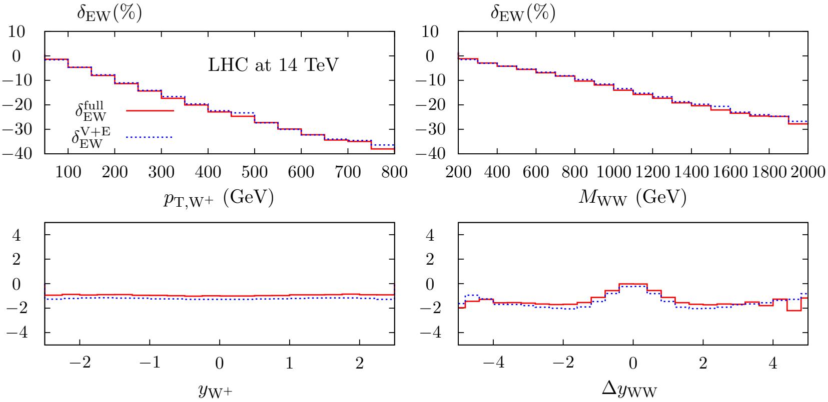
- In WW and WZ production no gauge-invariant separation of dominant weak corrections and QED possible
- QED contributions inevitably lead to IR singularities
- Real radiation has to be included:
  numerical integration has to deal with singular integrands, check cancellation of divergences, check that slicing cuts drop out, ...
- Finally, QED effects at the level of 1% (α/π).

Possible solution:

- V + E approximation: Endpoint from subtraction contributions $\oplus$ virtual corrections gives IR finite result [Dittmaier 1999]
- completely avoid computation of real photon radiation

V + E Approximation

On-shell W-Pair production at LHC14, default cuts

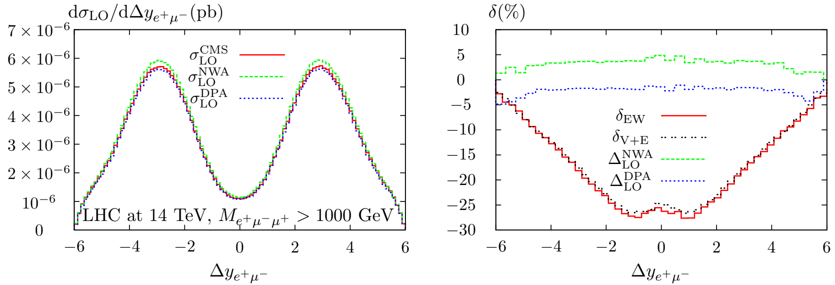


- fantastic approximation of full result (better than 1% in WW, WZ production)
- Approximation works well at high $p_{\rm T}$, high invariant masses and near threshold.
- NNLO EW corrections at the level of 5–10% at high $p_{\rm T}$ [Kühn, Metzler, Penin, Uccirati 2011]

Conclusion: Corresponding K-factor should be used for MC implementation.

4-Lepton Production – Test of our Approach

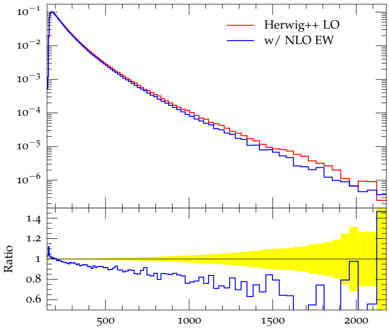
$pp \to (W^+ \to) e^+ \nu_e \; (Z \to) \mu^- \mu^+$ at LHC14, standard event-selection cuts (Preliminary results!)

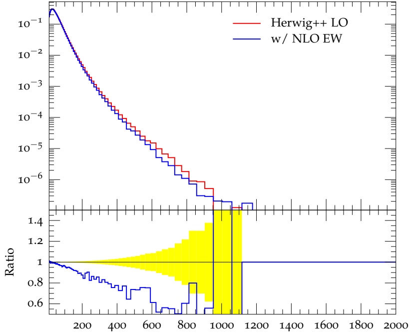


- **LO:** NWA and DPA work at the level of $\pm 5\%$
- **NLO:**
  - $\boldsymbol{\delta_{EW}}$: Full NLO EW corrections to production process in NWA, spin correlations for decay process included
  - $\boldsymbol{\delta_{V+E}}$: LO in NWA multiplied with $K_{EW}(\hat{s}, \hat{t})$ (unpolarized K-factor used!)
  - $\to$ Good agreement at the 1% level for relative corrections
  - $\to$ Spin correlations well reproduced!

HERWIG++ Analysis for WW Production – Preliminary!

Simulation for pp $\rightarrow$ ($W^+ \rightarrow$)$e^+\nu_e$ ($W^- \rightarrow$)$\mu^-\bar{\nu}_\mu + X$ at 8 TeV, M_{WW} and $p_{T,W}$ distributions





- Standard `Herwig++` setup used
  (v2.6.2, with simple add-on for EW corrections, 10M events), ZZ at LO QCD $\oplus$ parton shower, hadronization included, underlying event switched off
- V+E approximate results consistent with arXiv:1208.3147

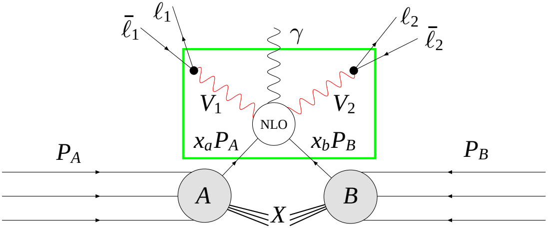
Summary & Outlook

- We have computed the full NLO EW corrections to vector-boson pair production at the LHC, including all mass effects [arXiv:1208.3147, arXiv:1208.3404]
- Leptonic decays have been implemented for ZZ, WZ production, including spin correlations
- effect of real W/Z radiation in general below 5%
- We have proposed a straight-forward MC implementation in the `HERWIG++` setup, relying on $2 \to 2$ K-factors.
  - Claim: predictions match the "true" NLO EW result at the level of a few %.
  - QCD uncertainties (PDFs, hadronization, missing higher orders, . . .) presumably much larger
  - Approach could easily be applied to V+jet, $t\bar{t}$ production in the future.

Thank you!

Reminder: Calculation of Hadronic Cross Sections

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



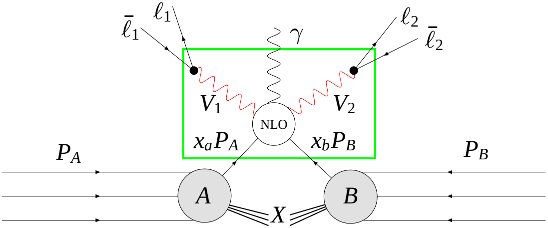
Hadronic cross sections

$$\mathrm{d}\sigma_{AB}(p_A, p_B) = \sum_{a,b} lslsls \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b\, f_{a/A}(x_a, \mu_\mathrm{F})\, f_{b/B}(x_b, \mu_\mathrm{F})\, \mathrm{d}\hat{\sigma}_{ab}^{\mathrm{NLO}}(p_a, p_b, \mu_\mathrm{F}, \mu$$

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

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

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

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

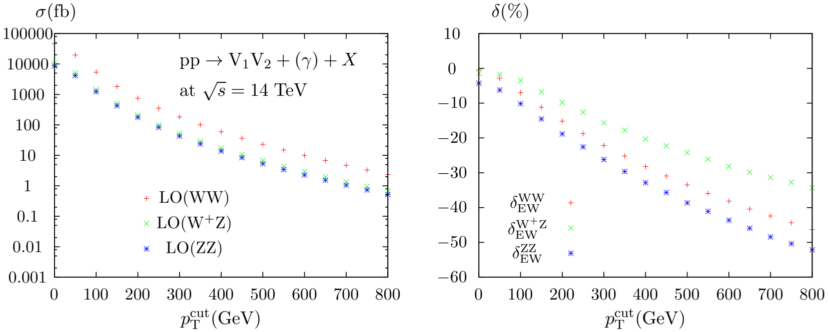
$$\times \mathcal{F}^{(4\ell+\gamma)}(\{\mathcal{O}_{\mathrm{FS}}\}), \qquad p^\mu_{\{a,b\}} = x_{\{a,b\}} P^\mu_{\{A,B\}}$$

NLO partonic cross section:

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

Numerical Results for WW/WZ/ZZ/$\gamma\gamma$ Production

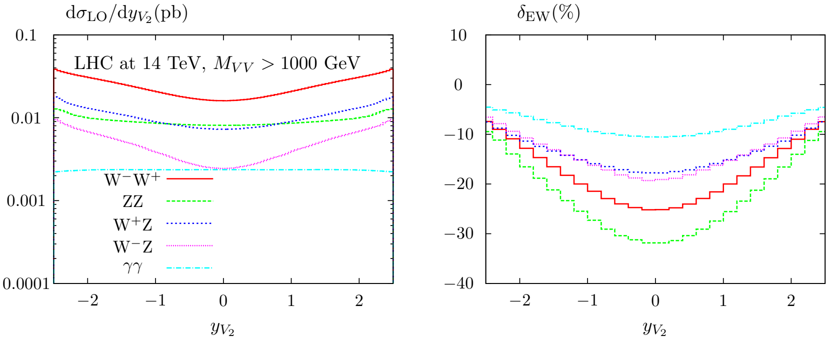
LHC at 14 TeV, default cuts: $p_{\mathrm{T},V} > 15$ GeV, $|y_V| < 2.5$



- **LO:** Drastically decreasing cross sections for large p_{T}
- **NLO:**
  - Full result, i.e. virtual, soft, hard, and collinear photons included
  - corrections largest for ZZ, smallest for $\gamma\gamma$

Numerical Results (II) for WW/WZ/ZZ/$\gamma\gamma$ Production

LHC at 14 TeV, high-energy cuts: $p_{\mathrm{T},V} > 15$ GeV, $|y_V| < 2.5$, $M_{VV} > 1000$ GeV



- significant distortion of rapidity distributions at large invariant masses
- Corrections could be misinterpreted as signal of anomalous couplings.

Double-Pole Approximation (DPA)

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

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

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

$$\hat{k}_{1,0} = \frac{1}{2}\sqrt{\hat{s}}, \quad \hat{\mathbf{k}}_1 = \frac{\mathbf{k}_1}{|\mathbf{k}_1|} \beta_W \frac{\sqrt{\hat{s}}}{2}, \quad \dots$$

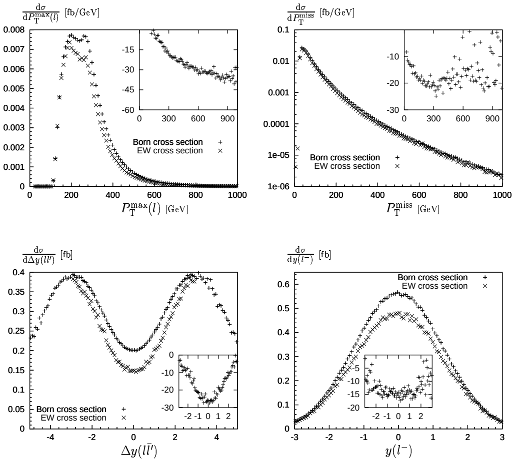
- **NLO:** EW corrections consist of factorizable and non-factorizable contributions, e.g.

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

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



[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

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

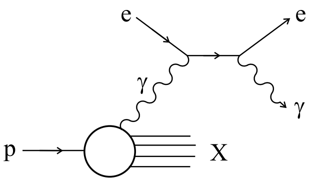
$\Rightarrow$ QED effects on $f_{q/\mathrm{p}}(x,\mu^2)$ small!
$\Rightarrow$ Still large conceptual uncertainties in $f_{\gamma,0}$

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



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

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

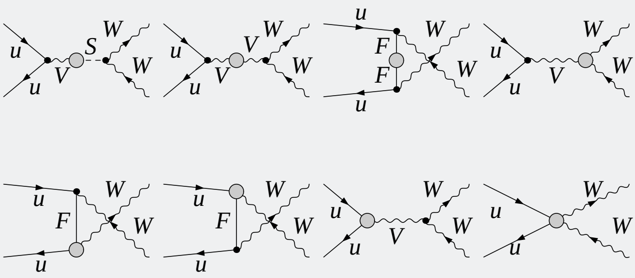
$$\alpha_{G_\mu} = \frac{\sqrt{2}G_\mu M_W^2 s_w^2}{\pi} = \frac{\alpha(0)}{1-\Delta r}$$

  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}**

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

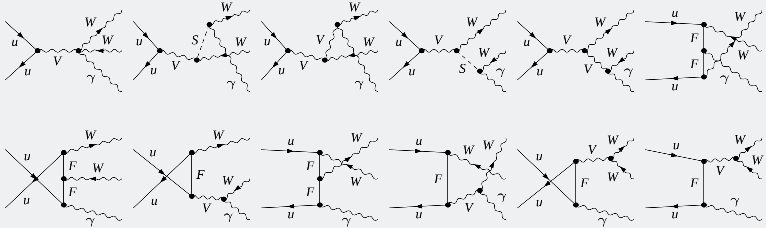
One-loop contributions at $\mathcal{O}(\alpha^3)$



- 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
- $V_{ij}^{\text{CKM}} = \delta_{ij}$ 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:

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

- Phase-space decomposition:

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

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**

The Complex-Mass Scheme (CMS) for Unstable Particles

[Denner, Dittmaier, Roth, Wieders 2005]

A problem with unstable particles

Naive implementation of finite width in gauge-boson propagator:

$$\frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}\epsilon} \rightarrow \frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}M_\mathrm{W}\Gamma_\mathrm{W}}$$

Γ_W includes Dyson summation of self energies, mixing of perturbative orders
$\rightarrow$ **might destroy gauge invariance (even at leading order!)**

The Complex-Mass Scheme (CMS) for Unstable Particles

[Denner, Dittmaier, Roth, Wieders 2005]

A problem with unstable particles

Naive implementation of finite width in gauge-boson propagator:

$$\frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}\epsilon} \to \frac{-\mathrm{i}g^{\mu\nu}}{q^2 - M_\mathrm{W}^2 + \mathrm{i}M_\mathrm{W}\Gamma_\mathrm{W}}$$

Γ_W includes Dyson summation of self energies, mixing of perturbative orders
$\rightarrow$ **might destroy gauge invariance (even at leading order!)**

$\rightarrow$ **CMS universal solution that**

- respects gauge invariance
- is valid in all phase-space regions

Straightforward implementation:

- **LO:** $M_\mathrm{V}^2 \rightarrow \mu_\mathrm{V}^2 = M_\mathrm{V}^2 - \mathrm{i}M_\mathrm{V}\Gamma_\mathrm{V}, \quad \cos^2\Theta_\mathrm{W} = \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}, \quad \mathrm{V} = \mathrm{W}, \mathrm{Z}$
- **NLO:**
  - Complex renormalization: $\mathcal{L}_0 \rightarrow \mathcal{L} + \delta\mathcal{L}$, **bare (real) Lagrangian unchanged!**
  - Evaluate loop integrals with complex masses

"Real Radiation" of Massive Vector Bosons

Low energies: Phase-space and perturbative suppression of $\mathrm{pp} \to V_1 V_2 + (\mathrm{W/Z})$
$\Rightarrow$ contribution below 1%

High energies: Logarithmic enhancement of additional soft/collinear W- or Z-boson radiation
$\Rightarrow$ Investigation of $V_1 V_2 + \mathrm{W/Z}$ production as background to V pairs at large p_T, M_{VV}

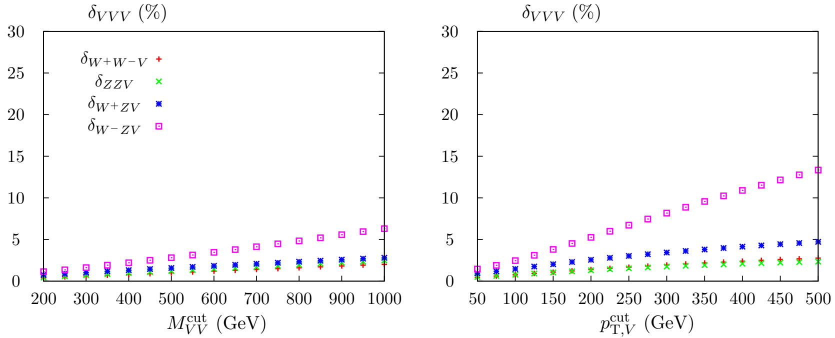
- invisible decay of $Z \to \nu\bar{\nu}$
- collinear emission
- ...

Simplified approach (details depend on experimental analysis), e.g. W-Pair production:

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

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

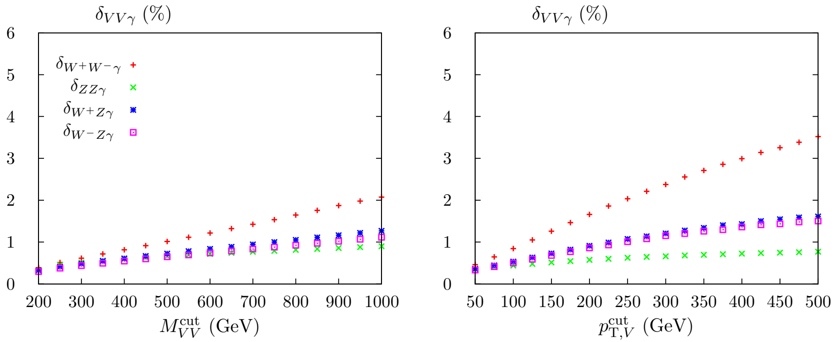
LHC at 8 TeV, default cuts: $p_{\mathrm{T},V} > 15$ GeV, $|y_V| < 2.5$



- corrections below 5% even for large transverse momenta and invariant masses
- corrections to $\mathrm{W^-Z}$ production enhanced due to $\mathrm{W^-ZW^+}$ final states (PDFs!)

Numerical Results (II) – Real Radiation of Hard Photons

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



- real radiation of hard photons marginal ($< 2\%$)
  $\longrightarrow$ neglect in MC implementation
- corrections largest for WW production

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

ZZ Production: Polarizations

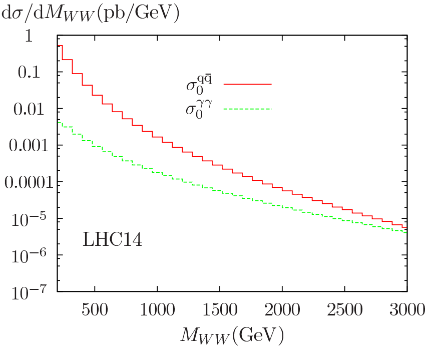
$pp \to ZZ + X$					
ZZ polarizations	summed	LL	L+	++	+−
LHC8					
σ_{LO}/pb $\delta\sigma_{weak}/pb$	3.810 $-0.179(-0.155)$	0.223 $-0.009(-0.008)$	0.396 $-0.016(-0.014)$	$10^{-1} \times [0.559$ $-0.002(-0.002)]$	2.676 $-0.134(-0.117)$
$p_{T,Z} > 500$ GeV σ_{LO}/pb $\delta\sigma_{weak}/pb$	$10^{-2} \times [0.101$ $-0.039(-0.030)]$	$10^{-7} \times [0.202$ $-0.975(+0.748)]$	$10^{-5} \times [0.779$ $-0.204(-0.157)]$	$10^{-8} \times [0.504$ $-0.895(-0.425)]$	$10^{-3} \times [0.996$ $-0.383(-0.293)]$
$p_{T,Z} > 1000$ GeV σ_{LO}/pb $\delta\sigma_{weak}/pb$	$10^{-5} \times [0.919$ $-0.557(-0.387)]$	$10^{-10} \times [0.121$ $-2.599(+14.909)]$	$10^{-7} \times [0.231$ $-0.098(-0.070)]$	$10^{-11} \times [0.303$ $-1.742(+1.043)]$	$10^{-5} \times [0.915$ $-0.555(-0.387)]$

- small transverse momenta: 70% from $(+-)$, similar K-factors for all polarizations.
- large transverse momenta: 99% from $(+-)$, other contributions negligible.
- **Note:** One-loop squared term (given in brackets) contributes at $\sim 10\%$
  $\rightarrow$ large uncertainties due to missing EW higher orders.

Conclusion: One *K*-factor sufficient to describe polarized ZZ production

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

No cuts



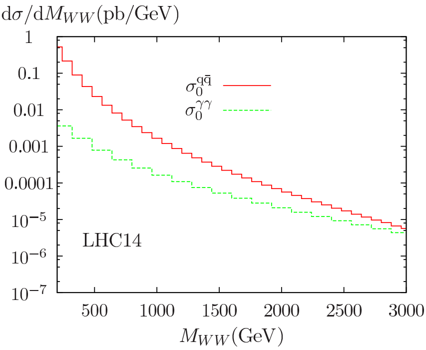
- LO cross section dominated by $q\bar{q}$ contributions
- Rapid decrease of cross section for increasing invariant masses

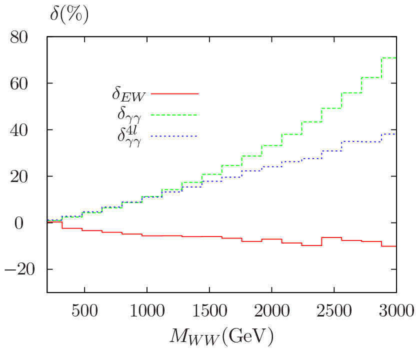
- EW corrections small even for large values of M_{WW}
- Large contributions (+80%!) from $\gamma\gamma \to WW$ at high invariant masses

⇒ Leptonic decays?

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

LHC acceptance cuts





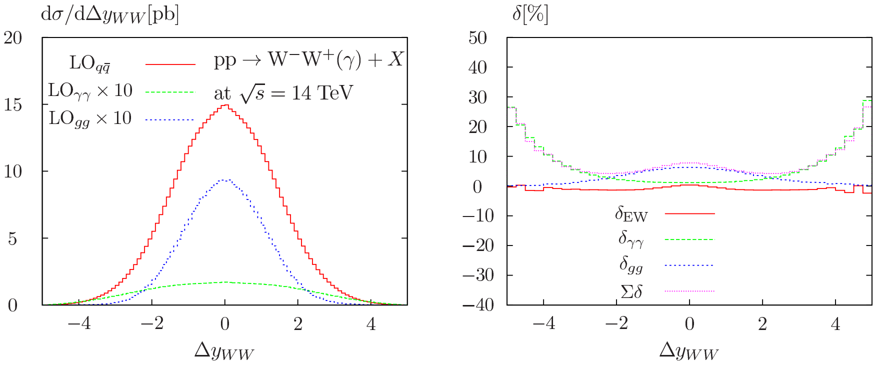
- LO cross section dominated by $q\bar{q}$ contributions
- Rapid decrease of cross section for increasing invariant masses

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

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

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

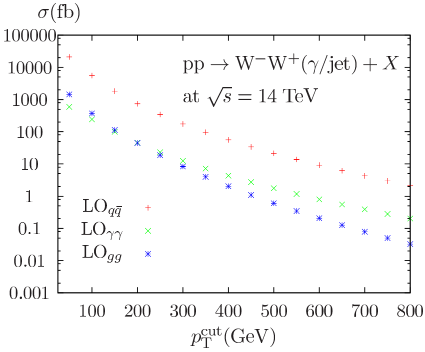
Default cuts: $p_{T,W^\pm} > 15$ GeV, $y_{W^\pm} < 2.5$

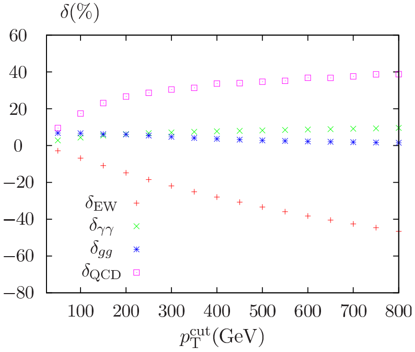


- WW production dominated by events near threshold, isotropic production at small Δy_{WW}
- 5% increase of cross section by gg channel
- EW corrections at the percent level
- Sizable contributions from $\gamma\gamma$ at large $|\Delta y_{WW}|$

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

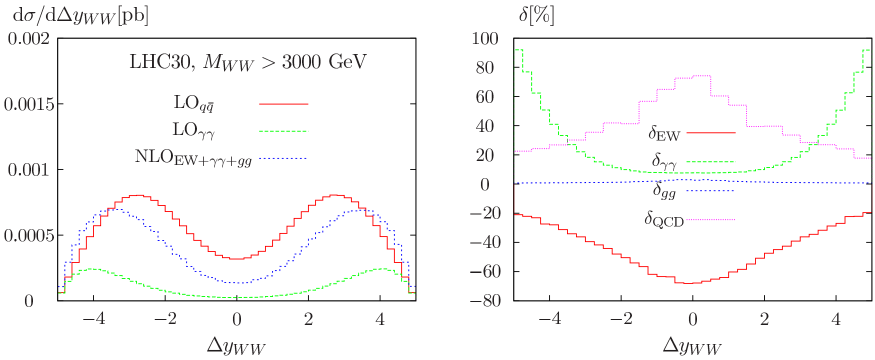
Default cuts: $p_{T,W^\pm} > 15$ GeV, $|y_{W^\pm}| < 2.5$





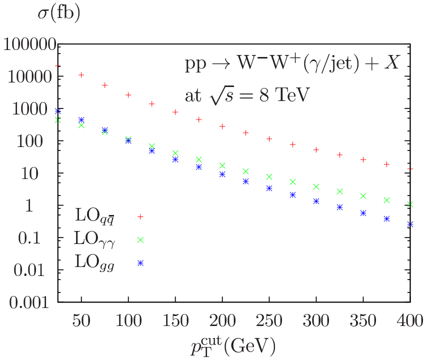
- assume $\int \mathcal{L}dt = 200\ \text{fb}^{-1}$
  $\Rightarrow$ 1000 WW events with $p_T > 500$ GeV
- decreasing admixture of gg, increasing admixture of $\gamma\gamma$
- large admixture of $\gamma\gamma$ (10%!)
- large negative EW corrections (-45%), comparable to QCD corrections

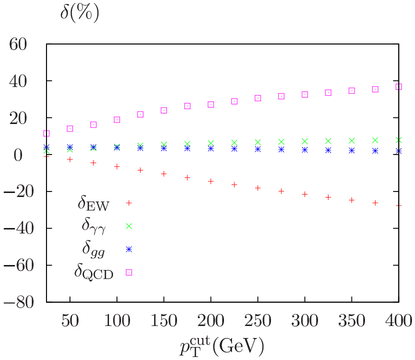
Very-high-energy cuts: $p_{T,W^\pm} > 15$ GeV, $y_{W^\pm} < 2.5$, $M_{WW} > 3$ TeV



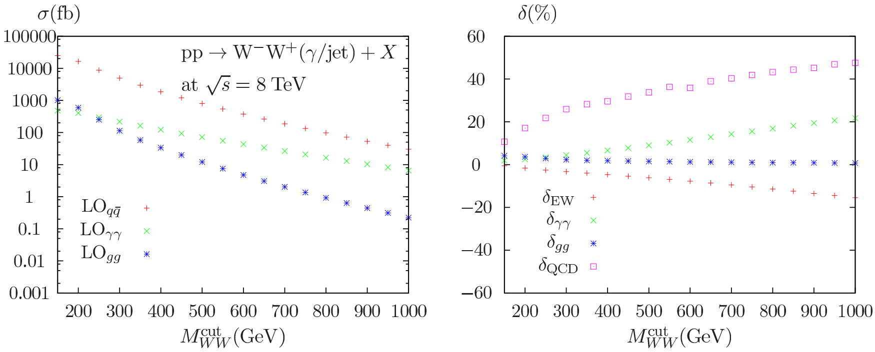
- NLO EW as important as QCD
- extreme distortion due to $\gamma\gamma$ (**caveat:** high uncertainty in photon PDFs)

Transverse-momentum distribution at the LHC8

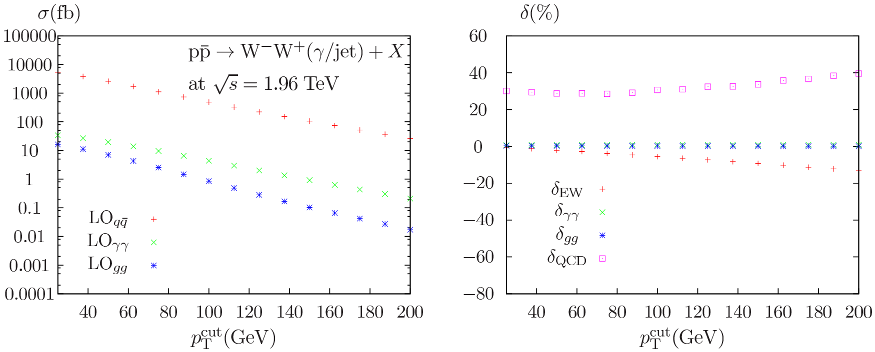




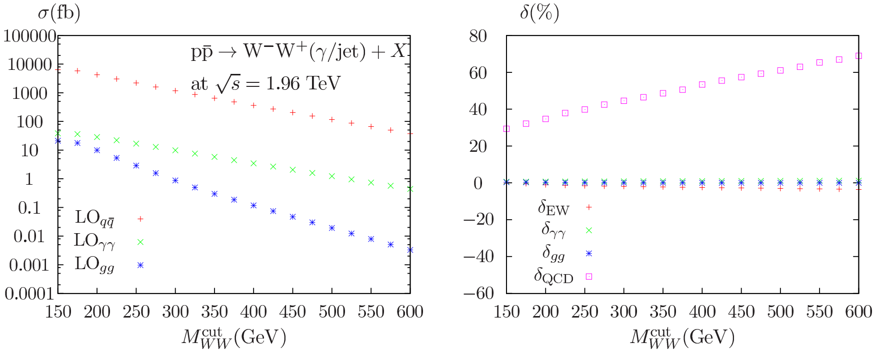
Invariant-mass distribution at the LHC8



Transverse-momentum distribution at the Tevatron

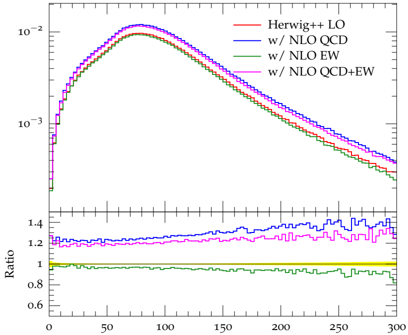


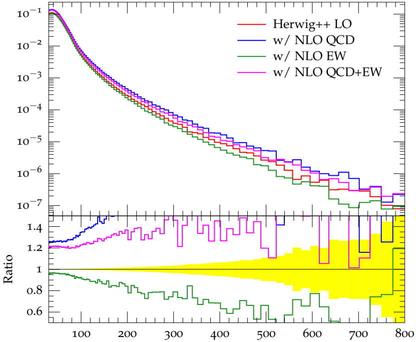
Invariant-mass distribution at the Tevatron



HERWIG++ Analysis for ZZ Production (II) – Preliminary!

Simulation for pp $\rightarrow ZZ \rightarrow e^+e^-\mu^+\mu^- + X$ at 8 TeV, $M_{e^+\mu^-}$ and $p_{\mathrm{T},l}$ distributions





- Standard Herwig++ setup used (v2.6.2, with simple add-on for EW corrections, 10M events), ZZ at NLO QCD matched with parton showers, hadronization included, underlying event switched off
- Implementation seems to work fine