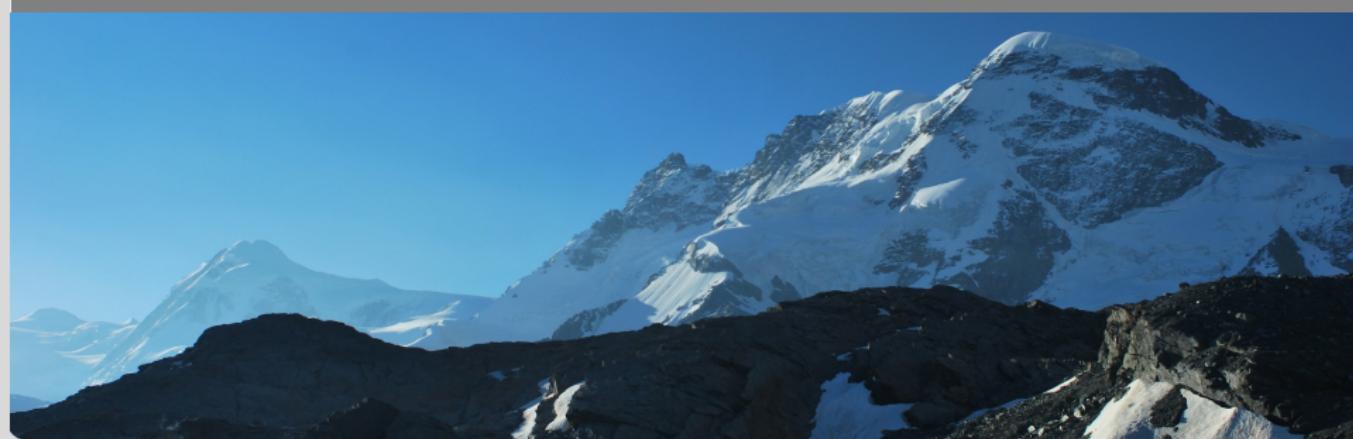


NLO massive gauge boson pair production at the LHC

LHC Run1 Aftermath, Where Theory meets Experiment, Bad Honnef, Germany

Julien Baglio (in collaboration with Le Duc Ninh and Marcus M. Weber, arXiv:1307.4331) | 02.10.2013

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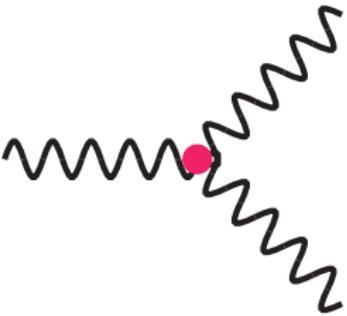


- 1 Introduction
- 2 Overview of the calculation
- 3 Differential distributions and radiative corrections hierarchy
- 4 Total cross sections and experimental data
- 5 Conclusion and outlook

Motivation of the calculation

$pp \rightarrow WW, ZZ, WZ$ are important processes at hadron colliders:

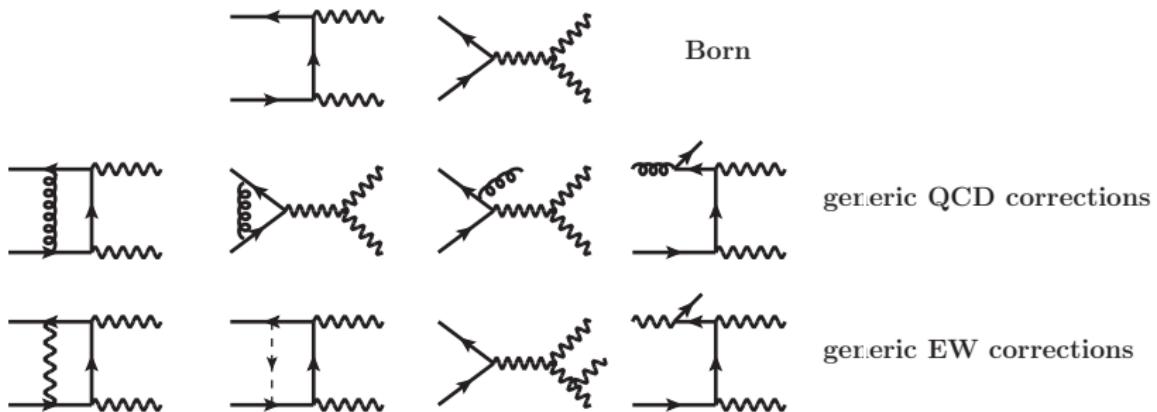
- Probe of the non abelian structure of the electroweak sector of the SM



- Important backgrounds for Higgs search
 - ⇒ measuring and predicting these processes with high precision is compulsory

Calculational setup

- QCD corrections: NLO corrections to $q\bar{q} \rightarrow VV$, $gg \rightarrow WW, ZZ$ included (formally a **NNLO contribution**) [see Ohnemus (1991); Frixion et al. (1992); Frixione (1993); Dixon et al. (1998); Campbell, Ellis (1999); ...]
- EW corrections: NLO virtual and real corrections to $q\bar{q} \rightarrow VV$ including γq and $\gamma\bar{q}$ subprocesses, $\gamma\gamma \rightarrow WW$ included at NLO (MRST2004QED PDF set used)



Tools: FeynArt/FormCalc/LoopTools cross-checked with home-made implementation of 1 loop integrals (LoopInts), MadGraph HELAS routines

Renormalization and subtraction method

- Renormalization: on-shell scheme used for EW corrections, calculation cross-checked with dimensional and mass regularization schemes for the infrared singularities
- Infrared singularities: subtraction method

$$\sigma^{\text{NLO}} = \int_{\phi_n} d\sigma^{\text{Born}} + \int_{\phi_n} d\sigma^{\text{virt}} + \int_{\phi_{n+1}} d\sigma^{\text{real}}$$

with each contribution divergent \Rightarrow cancel soft & collinear singularities before Monte-Carlo integration:

$$\sigma^{\text{NLO}} = \int_{\phi_{n+1}} \left(d\sigma^{\text{real}}|_{\varepsilon=0} - d\sigma^A|_{\varepsilon=0} \right) + \int_{\phi_n} \left(d\sigma^{\text{Born}} + d\sigma^{\text{virt}} + \int_{\phi_1} d\sigma^A \right) |_{\varepsilon=0}$$

where $d\sigma^A$ a subtraction term with the following properties:

- $d\sigma^A$ cancels soft & collinear divergences of $d\sigma^{\text{real}}$
- $\int_{\phi_1} d\sigma^A$ done (partially) analytically in d dimensions $\Rightarrow I, P, K$ operators

The calculation has been done with Catani-Seymour dipoles, cross-checked with phase-space slicing method [Catani, Seymour, Nucl.Phys. B485 (1997); Baur, Keller, Wackeroth, Phys.Rev. D59, 013002 (1999)]

EW corrections and photons

- What value for α in EW corrections? use G_μ scheme:

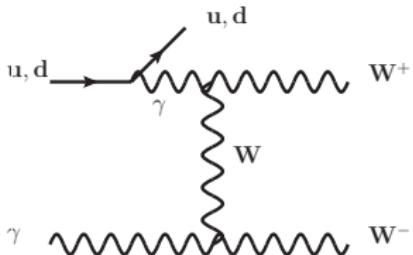
$$\alpha = \frac{\sqrt{2}G_F M_W^2}{\pi} \left(1 - \frac{M_W^2}{M_Z^2} \right)$$

Charge renormalization constant shifted: $\delta Z_e \rightarrow \delta Z_e|_{G_\mu} = \delta Z_e|_{\alpha(0)} - \frac{1}{2}\delta r$
⇒ EW corrections independant of light quark masses

When physical photon in external state: $\alpha(0)$ has to be used!

⇒ rescale all contributions by $(\alpha(0)/\alpha)^i$ ($i = 3$ for $\gamma\gamma$, otherwise $i = 1$)

- Spin correlation: in $q\gamma \rightarrow WWq$ real correction some diagrams include $\gamma\gamma$ contribution
⇒ spin correlation between the subprocess $\gamma\gamma \rightarrow WW$ and the initial quark/antiquark to be taken into account



Parameter set and uncertainties

Parameter set:

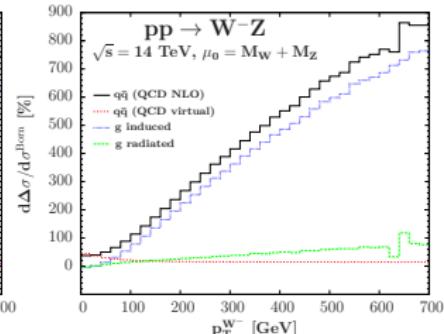
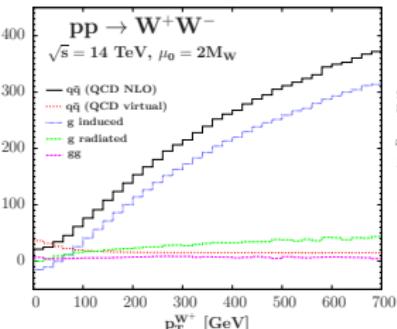
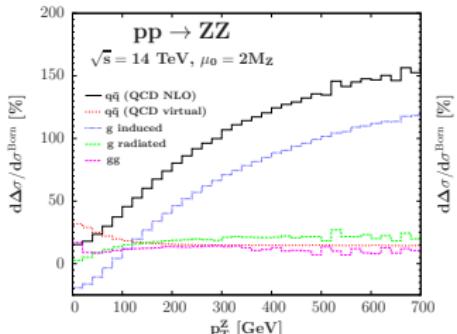
- α in the G_μ -scheme, $\alpha(0)^{-1} = 137.036$ for $\alpha/\alpha(0)$ rescaling
- $\alpha_s^{\text{NLO}}(M_Z^2) = 0.12018^{+0.00317}_{-0.00386}$ (90% CL) (MSTW2008) or $\alpha_s(M_Z^2) = 0.1190$ (MRST2004QED)
- $\alpha_s^{\text{NNLO}}(M_Z^2) = 0.11707^{+0.00340}_{-0.00340}$ (90% CL) used at NNLO for $gg \rightarrow WW, ZZ$ subprocesses (with MSTW2008)
- $M_t = 173.5 \text{ GeV}, M_W = 80.385 \pm 0.015 \text{ GeV}, M_Z = 91.1876 \pm 0.0021 \text{ GeV}, M_H = 125 \text{ GeV}$
- Full NLO QCD+EW total cross section: $\delta^{\text{EW}} = \sigma^{\text{NLO QCD+EW}} / \sigma^{\text{NLO QCD}}$ (calculated with MRST2004QED) and $\sigma^{\text{tot,MSTW}} = \delta^{\text{EW}} \times \sigma^{\text{NLO QCD,MSTW}}$

Uncertainties on total cross sections:

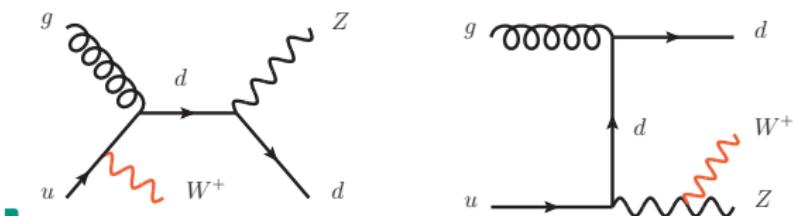
- **Scale uncertainty:** calculated with $\frac{1}{2}\mu_0 \leq \mu_R = \mu_F \leq 2\mu_0, \mu_0 = M_{V_1} + M_{V_2}$ as central scale
- **PDF+ α_s uncertainty:** use MSTW2008 PDF set with correlated PDF+ α_s 90%CL uncertainties
- **Parametric uncertainties:** impact of the experimental errors on M_W and M_Z

QCD distributions at 14 TeV

NLO QCD effects (no cuts):

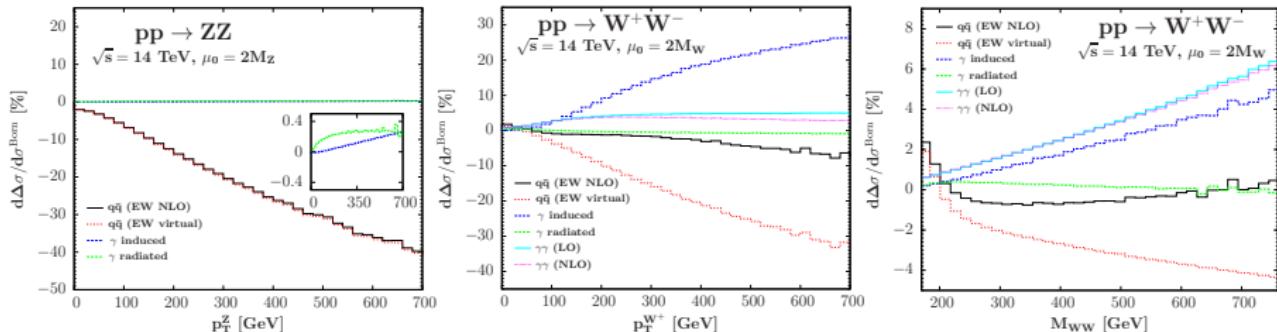


- Large QCD effect at high p_T driven by leading-logarithmic term $\alpha_s \log^2 \left(\frac{M_W^2}{p_T^2} \right)$ in gluon-induced processes [see also Frixione et al., Nucl.Phys. B383, 3 (1992); Frixione, Nucl.Phys. B410, 280 (1993); Ohnemus, Phys.Rev. D50, 1931 (1994)]



EW distributions at 14 TeV

NLO EW effects (no cuts):



- Virtual Sudakov factor in the $q\bar{q} \rightarrow VV'$ correction $\propto \alpha \log^2 \left(\frac{p_T^2}{M_W^2} \right)$

[see also Bierweiler, Kasprzik, Kühn, Uccirati, JHEP 1211 (2013) 093; Bierweiler, Kasprzik, Kühn, arXiv:1305.5402 (2013)]

- γ -induced processes compensate this Sudakov effect in WW and WZ channels, not in ZZ channel
- $\gamma\gamma$ dominates in M_{WW} distribution

The hierarchy of the radiative corrections

There is a radiative correction hierarchy in the p_T distributions

- QCD corrections: $WZ > WW > ZZ$ because of non-abelian structure, coupling strengths and PDFs ($\text{PDF}(u) > \text{PDF}(d)$):

$$\frac{d\Delta^{\text{QCD NLO}}}{\text{LO}} : 120\% \simeq \delta_{ZZ}^{\text{QCD}} \simeq \frac{1}{3} \delta_{WW}^{\text{QCD}} \simeq \frac{1}{6} \delta_{W-Z}^{\text{QCD}} \text{ (full)}$$

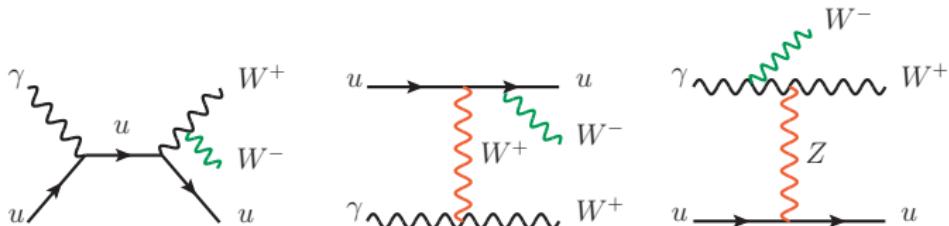
$$\delta_{ZZ}^{\text{QCD}} \simeq \frac{1}{4} \delta_{WW}^{\text{QCD}} \simeq \frac{1}{12} \delta_{W-Z}^{\text{QCD}} \text{ (leading-log)}$$

- EW corrections: same order as for QCD corrections but with larger ratios,

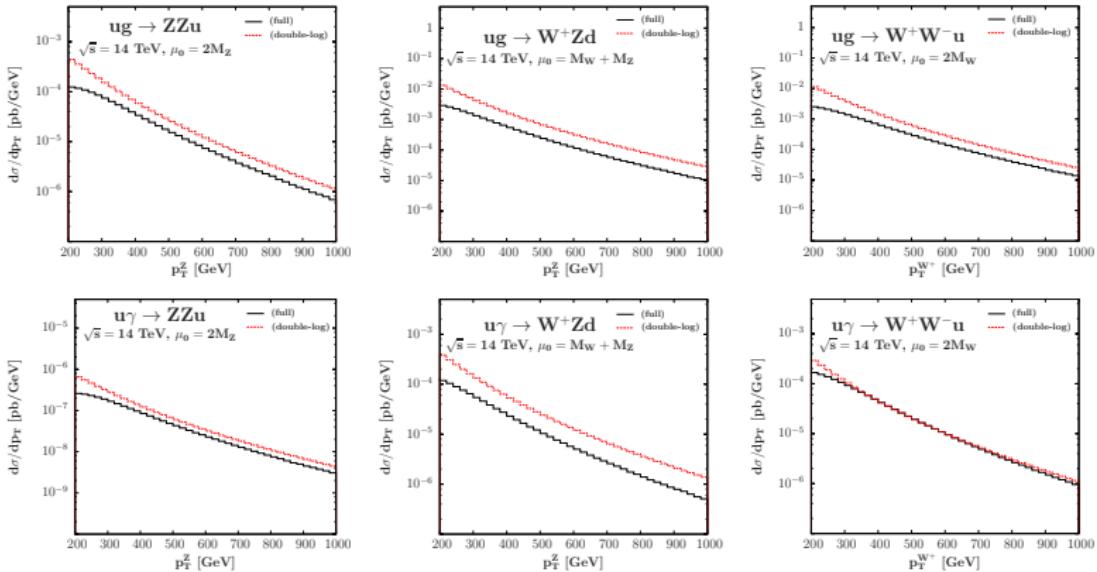
$$\frac{d\Delta^{\text{EW NLO}}}{\text{LO}} : 0.3\% \simeq \delta_{ZZ}^{\text{EW}} \simeq \frac{1}{90} \delta_{WW}^{\text{EW}} \simeq \frac{1}{190} \delta_{W-Z}^{\text{EW}}$$

The explanation for larger ratios in the EW corrections: t -channel massive boson exchange diagram in WW and WZ channels, not in ZZ channel

$$d\sigma^{u\gamma \rightarrow W^+ W^- u} \simeq \left(\frac{a_W^4}{4c_{L,u}^2} d\sigma_L^{u\gamma \rightarrow Z u} + \frac{a_W^2}{4} d\sigma_L^{u\gamma \rightarrow W^+ d} + \frac{1}{4} d\sigma_{LT}^{uW\gamma \rightarrow W^+ u} \right) \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^{W^+})^2}{M_W^2} \right]$$



Leading-logarithmic approximation vs full result



- **Leading-logarithmic approximation:** off by up to a factor of two at $p_T \simeq 700$ GeV (WW QCD case)
- **But still converges at very high p_T** (checked numerically at a super LHC)
- Approximation works better in the EW case than in the QCD case,
almost perfect for EW WW distribution

Experimental results summary

Up-to-date results since HEP-EPS 2013:

- $pp \rightarrow ZZ$:

Experiment	7 TeV	8 TeV
ATLAS	$6.7^{+0.9}_{-0.8}$ pb	$7.1^{+0.6}_{-0.5}$ pb
CMS	$6.24^{+0.96}_{-0.87}$ pb	7.7 ± 0.8 pb

- $pp \rightarrow W^+Z + W^-Z$:

Experiment	7 TeV	8 TeV
ATLAS	$19.0^{+1.7}_{-1.6}$ pb	$20.3^{+1.6}_{-1.4}$ pb
CMS	20.8 ± 1.8 pb	24.7 ± 1.7 pb

- $pp \rightarrow WW$:

Experiment	7 TeV	8 TeV
ATLAS	51.9 ± 4.8 pb	/
CMS	52.4 ± 5.1 pb	69.9 ± 7.0 pb

[ATLAS Collaboration, Eur.Phys.J. C72, 2173 (2012); arXiv:1210.2979; JHEP 1303 (2013) 128; ATLAS-CONF-2013-020; ATLAS-CONF-2013-021]

[CMS Collaboration, CMS-PAS-SMP-12-005; Phys.Lett. B721, 190 (2013); JHEP 1301, 063 (2013)]

How to obtain the total cross section?

- ▶ Measure the cross section in the detector fiducial region, $\sigma^{\text{fid}} = \frac{N_{\text{signal}}}{\mathcal{L}}$
- ▶ Extrapolate to the full phase space, $\sigma^{\text{tot}} = \frac{\sigma^{\text{fid}}}{BR(VV' \rightarrow X) \times \mathcal{A}_{\text{geometry}}}$

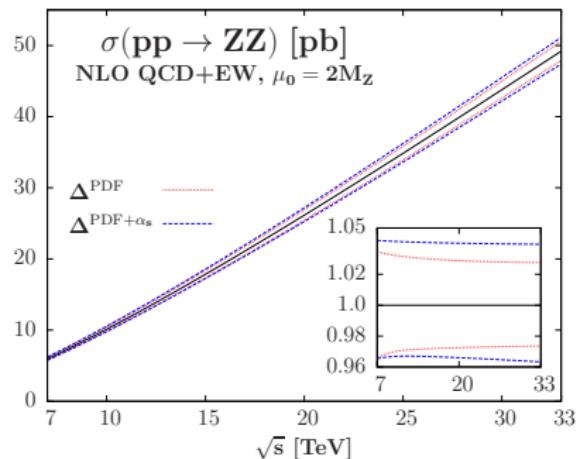
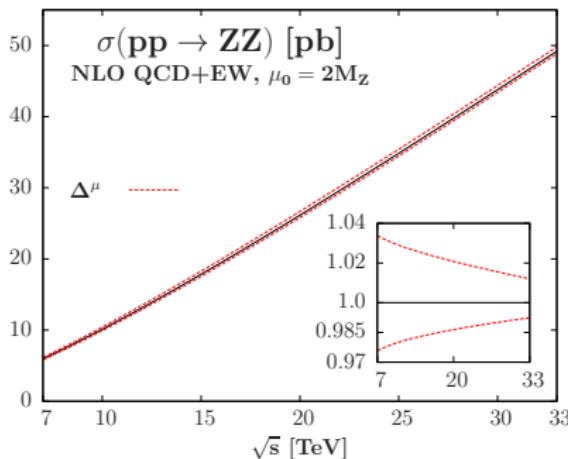
where X is the final state measured:

e.g. for ZZ it is $X = 4\ell$, for WW it is $X = \ell\ell'\nu\nu'$

$\mathcal{A}_{\text{geometry}}$ rescaling factor to extrapolate to the full phase space, estimated from MC predictions: $\mathcal{A}_{\text{geometry}} = \frac{\sigma^{\text{fid,cut}}}{\sigma^{\text{tot,cut}}} \Rightarrow$ we only compare to the extrapolated total cross section, fiducial cross section yet too difficult to calculate including EW corrections

ZZ total cross section

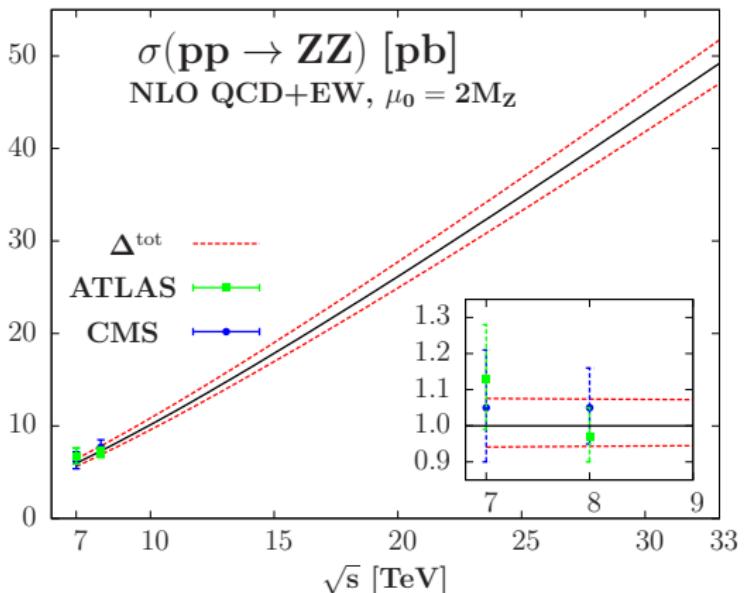
- **EW correction factor:** NLO EW corrections negative and sizeable, $\delta^{\text{EW}} = 0.97$
- **Parametric uncertainties negligible (< 0.1%)**
- **Scale uncertainty:** $\Delta^\mu = +3.2\% / -2.4\%$ @ 7 TeV down to $+1.2\% / -0.8\%$ @ 33 TeV
- **PDF+ α_s uncertainty:** use 90% CL MSTW2008 PDF set, $+4.2\% / -3.5\%$ @ 7 TeV down to $\pm 3.9\%$ @ 33 TeV



ZZ total cross section

Total uncertainty and comparison with experiment:

$$\sigma_{ZZ} = 5.95^{+0.45}_{-0.35} \text{ pb @ 7 TeV} \quad \sigma_{ZZ} = 7.3^{+0.5}_{-0.4} \text{ pb @ 8 TeV}$$



ATLAS @ 7 TeV: agree within 0.8σ

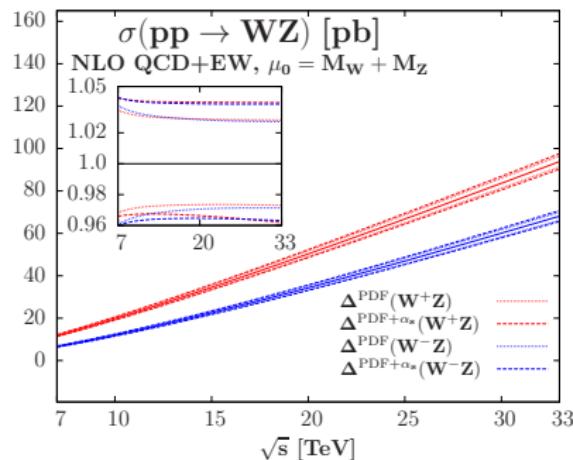
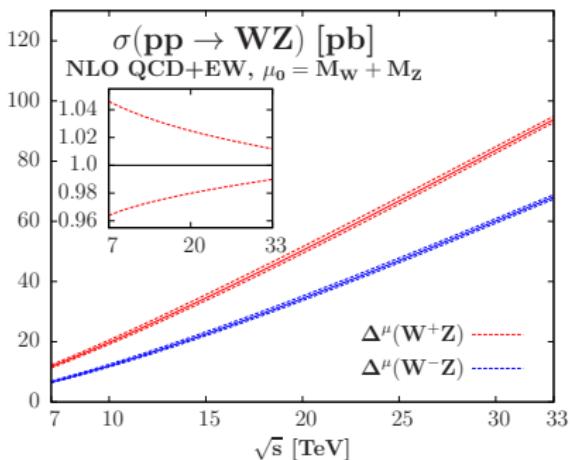
CMS @ 7 TeV: perfect agreement ($< 0.3\sigma$)

ATLAS @ 8 TeV: perfect agreement ($< 0.3\sigma$)

CMS @ 8 TeV: agree within 0.4σ

WZ total cross section

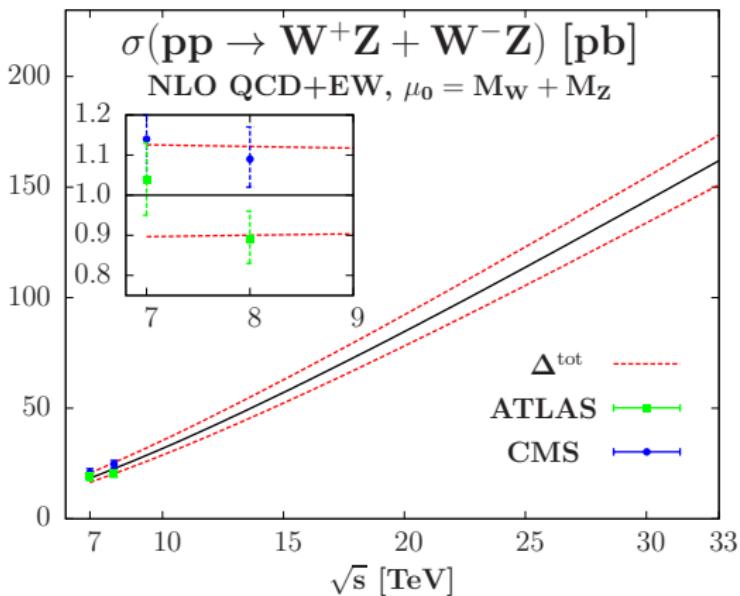
- **EW correction factor:** NLO EW corrections negligible, $\delta^{\text{EW}} = 1.00$
- **Parametric uncertainties negligible (< 0.1%)**
- **Scale uncertainty ($W^+ / W^- Z$):** $\Delta^\mu = +4.6\% / -3.6\%$ @ 7 TeV down to $+1.2\% / -1.0\%$ @ 33 TeV
- **PDF+ α_s uncertainty ($W^+ / W^- Z$):** use 90% CL MSTW2008 PDF set, $+4.3\% / -4.0\%$ @ 7 TeV down to $+3.9\% / -3.7\%$ @ 33 TeV



WZ total cross section

Total uncertainty on $W^+Z + W^-Z$ production cross section
and comparison with experiment:

$$\sigma_{W^-Z+W^+Z} = 18.3^{+2.3}_{-1.9} \text{ pb @ 7 TeV} \quad \sigma_{W^-Z+W^+Z} = 22.7^{+2.7}_{-2.3} \text{ pb @ 8 TeV}$$

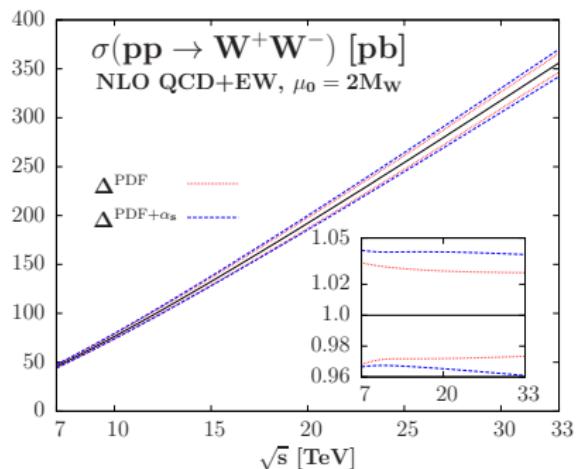
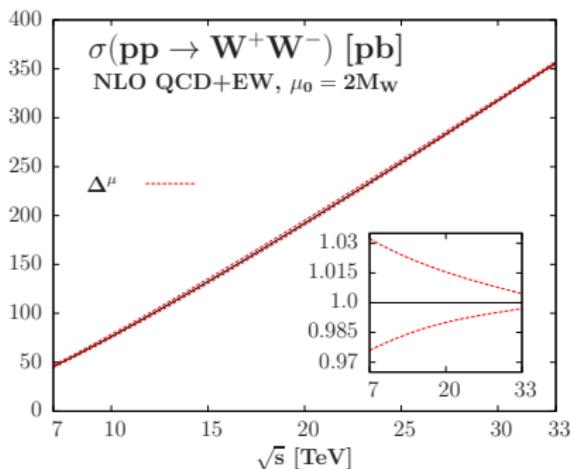


ATLAS @ 7 TeV: perfect agreement ($< 0.2\sigma$)
CMS @ 7 TeV: agreement within 0.85σ

ATLAS @ 8 TeV: agree within 0.85σ
CMS @ 8 TeV: agreement within 0.6σ

WW total cross section

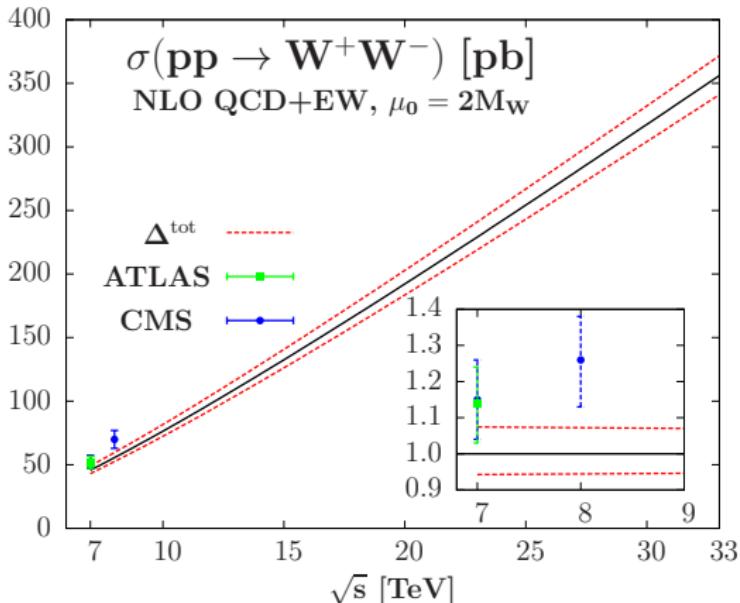
- **EW correction factor:** NLO EW corrections positive and small, $\delta^{\text{EW}} = 1.01 - 1.02$ (same when calculated with the newest NNPDF 2.3 QED set [NNPDF Collaboration, arXiv:1308.0598])
- **Parametric uncertainties negligible**
- **Scale uncertainty:** $\Delta^\mu = +3.2\% / -2.4\%$ @ 7 TeV down to $+0.5\% / -0.3\%$ @ 33 TeV
- **PDF+ α_s uncertainty:** use 90% CL MSTW2008 PDF set, $+4.2\% / -3.3\%$ @ 7 TeV down to $\pm 3.9\%$ @ 33 TeV



WW total cross section

Total uncertainty and comparison with experiment:

$$\sigma_{WW} = 45.7^{+3.4}_{-2.6} \text{ pb @ 7 TeV} \quad \sigma_{WW} = 55.6^{+4.0}_{-3.1} \text{ pb @ 8 TeV}$$



ATLAS & CMS @ 7 TeV: 1.1σ excess

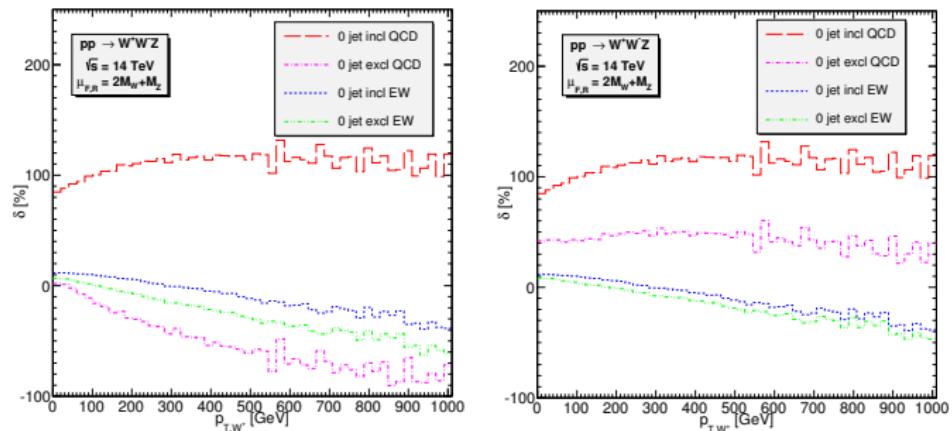
CMS @ 8 TeV: 1.8σ excess

Time to conclude... But before, jet veto issue

Fixed jet veto against dynamic jet veto, an example with WWZ production:

[D.T. Nhung, L.D. Ninh and M.M. Weber, arXiv:1307.7403]

- ★ **Fixed jet veto:** veto events with $p_{T,j} > 25 \text{ GeV}$ and $\eta_j < 4.5$
- ★ **Dynamic jet veto:** veto events with $p_{T,j} > \frac{1}{2} \max(M_{T,W^+}, M_{T,W^-}, M_{T,Z}) \text{ GeV}$



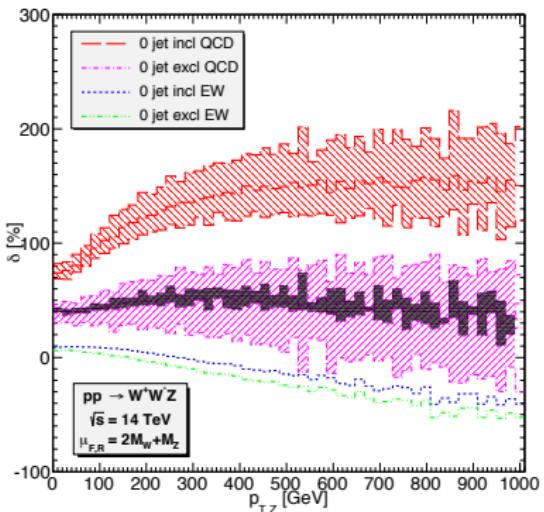
- Fixed jet veto: over-reduction of QCD corrections, driven to negative K -factors
- **Dynamic jet veto:** more reasonable reduction of QCD corrections, EW corrections marginally affected \Rightarrow better choice to study the p_T observable with jet veto

Time to conclude... But before, jet veto issue

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Dynamic jet veto increases scale uncertainty \Rightarrow issue here to be discussed?

(see also I. Stewart, F. Tackmann, Phys.Rev. D85 (2012) 034011)

Diboson production at the LHC:

- **Status of the calculation:**

On-shell WW/WZ/ZZ production cross sections known fully at NLO (EW+QCD)

- **Radiative corrections hierarchy:** gluon/photon-induced processes driven by double-logarithmic terms

⇒ first comprehensive explanation why $WZ > WW > ZZ$ thanks to non-abelian gauge structure, coupling strengths and PDF effects

γ -induced processes further enhanced by t -channel massive gauge boson exchange

- **EW effects:** γ -induced processes compensate or even overcompensate the virtual Sudakov effect in WW and WZ p_T distributions

- **Uncertainty on total cross sections:** +7% / - 6% @ 7–8 TeV, +5% / - 4% @ 33 TeV

- **Comparison with experimental results:**

WZ and ZZ total cross sections predictions agree very well with experiment

WW total cross section at 1σ @ 7 TeV and 1.8σ @ 8 TeV

(as a side-point: single-top interference is negligible in WW production)

- **Jet veto issue:** dynamic jet veto seems better than fixed jet veto, what is actually used in experiment? Scale uncertainty larger also...

Thank you!



EW leading-log equations for ZZ, WW and WZ

- ZZ p_T distribution

$$d\sigma^{q\gamma \rightarrow ZZq} = c_{ZZ}^q d\sigma_L^{q\gamma \rightarrow Zq} \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^Z)^2}{M_Z^2} \right]$$

- WW p_T distribution

$$d\sigma^{u\gamma \rightarrow W^+W^- u} = \left(\frac{a_W^4}{4c_{L,u}^2} d\sigma_L^{u\gamma \rightarrow Zu} + \frac{a_W^2}{4} d\sigma_L^{u\gamma \rightarrow W^+d} + \frac{1}{4} d\sigma_{LT}^{uW^+ \rightarrow W^+u} \right) \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^{W^+})^2}{M_W^2} \right]$$

$$d\sigma^{d\gamma \rightarrow W^+W^- d} = \left(\frac{a_W^4}{4c_{L,d}^2} d\sigma_L^{d\gamma \rightarrow Zd} + \frac{a_W^2}{4} d\sigma_L^{ud\gamma \rightarrow W^+d} + \frac{1}{4} d\sigma_{LT}^{dW^+ \rightarrow W^+d} \right) \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^{W^+})^2}{M_W^2} \right]$$

- WZ p_T distribution

$$d\sigma^{u\gamma \rightarrow W^+Zd} = \frac{c_{L,u}^2 c_{WZ}^u}{a_W^2} d\sigma_L^{u\gamma \rightarrow W^+d} \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^{W^+})^2}{M_Z^2} \right]$$

$$d\sigma^{d\gamma \rightarrow W^-Zu} = \frac{c_{L,d}^2 c_{WZ}^d}{a_W^2} d\sigma_L^{d\gamma \rightarrow W^-u} \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^{W^-})^2}{M_Z^2} \right]$$

with $a_W = \frac{1}{\sqrt{2} \sin \theta_W}$, $c_{L,f} = (I_3 - \sin^2 \theta_W Q_f) / (\sin \theta_W \cos \theta_W)$, $c_{R,f} = -Q_f \sin \theta_W / \cos \theta_W$,

$$c_{ZZ}^u = (c_{L,u}^4 + c_{R,u}^4) / (4c_{L,u}^2) = 0.18, c_{ZZ}^d = (c_{L,d}^4 + c_{R,d}^4) / (4c_{L,d}^2) = 0.26,$$

$$c_{WZ}^d = \frac{1}{2} a_W^2 \frac{c_{L,u}}{c_{L,d}} \left(1 + \frac{\cot \theta_W}{c_{L,d}} - \frac{\cot \theta_W}{c_{L,u}} \right) = 2.81, c_{WZ}^u = \frac{1}{2} a_W^2 \frac{c_{L,d}}{c_{L,u}} \left(1 + \frac{\cot \theta_W}{c_{L,d}} - \frac{\cot \theta_W}{c_{L,u}} \right) = 4.13$$