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A NLO story of massive gauge boson pair production at the LHC

Windows on the Universe Conference, ICISE Quy Nhón, Vietnam

Julien Baglio (in collaboration with Le Duc Ninh and Marcus M. Weber, arXiv:1307.4331) | 14.08.2013

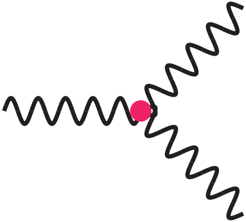
INSTITUT FÜR THEORETISCHE PHYSIK

Outline

Motivation of the calculation

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

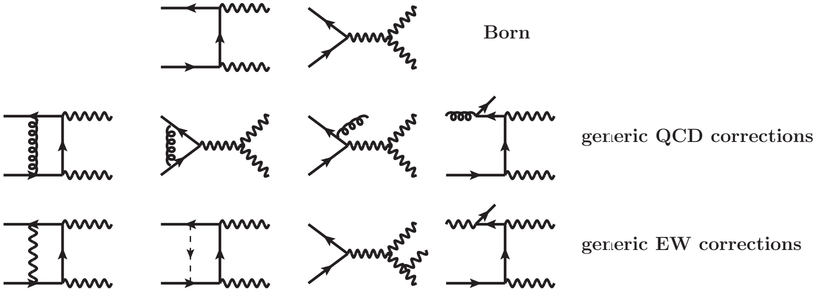
- Probe of the non abelian structure of the electroweak sector of the SM



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

Calculational setup

- QCD corrections: NLO corrections to $q\bar{q} \to VV$, $gg \to WW, ZZ$ 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 $q\bar{q} \to VV$ including γq and $\gamma\bar{q}$ subprocesses, $\gamma\gamma \to WW$ 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 substraction method

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

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

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

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

where $d\sigma^{\rm A}$ a substraction term with the following properties:

- $d\sigma^{\rm A}$ cancels soft & collinear divergences of $d\sigma^{\rm real}$
- $\int_{\phi_1} d\sigma^{\rm A}$ 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

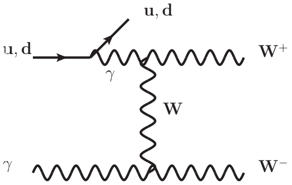
- What value for α in EW corrections? use G_μ scheme:

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

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

When physical photon in external state: $\alpha(0)$ has to be used!
$\Rightarrow$ rescale all contributions by $(\alpha(0)/\alpha)^i$ ($i = 3$ for $\gamma\gamma$, otherwise $i = 1$)

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



Parameter set and uncertainties

Parameter set:

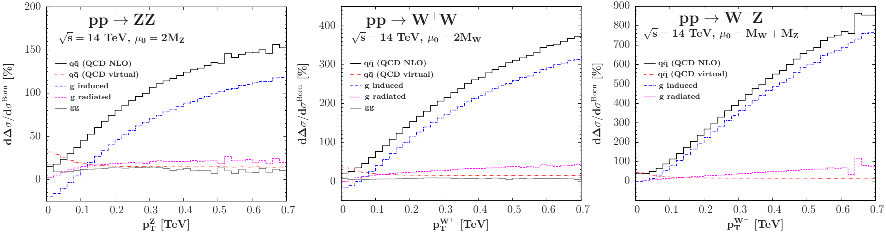
- α in the G_μ–scheme, $\alpha(0)^{-1} = 137.036$ for $\alpha/\alpha(0)$ rescaling
- $\alpha_s^{\rm NLO}(M_Z^2) = 0.12018^{+0.00317}_{-0.00386}$ (90% CL) (MSTW2008) or $\alpha_s(M_Z^2) = 0.1190$ (MRST2004QED)
- $\alpha_s^{\rm NNLO}(M_Z^2) = 0.11707^{+0.00340}_{-0.00340}$ (90% CL) used at NNLO for $gg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

Uncertainties on total cross sections:

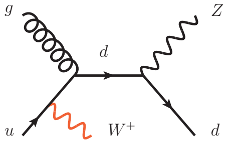
- **Scale uncertainty:** calculated with $\frac{1}{2}\mu_0 \leq \mu_R = \mu_F \leq 2\mu_0$, $\mu_0 = M_{V_1} + M_{V_2}$ as central scale
- **PDF+α_s uncertainty:** use MSTW2008 PDF set with correlated PDF+α_s 90%CL uncertainties
- **Parametric uncertainties:** impact of the experimental errors on M_W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

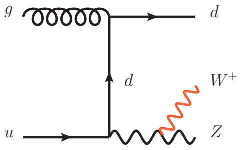
QCD distributions at 14 TeV

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)]





QCD distributions at 14 TeV

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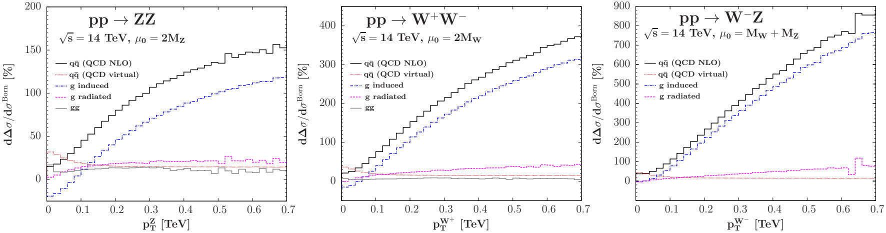
NLO QCD effects (no cuts):



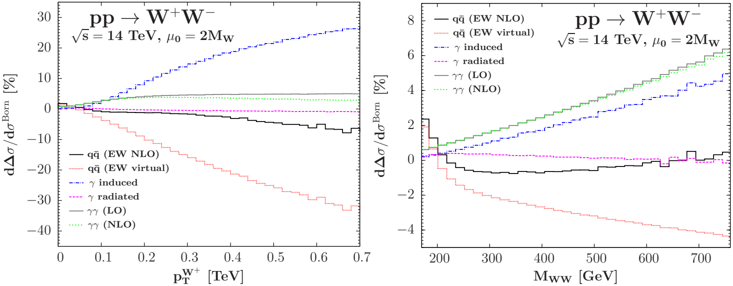
- Large QCD effect at high p_T driven by leading-logarithmic term $\alpha_s \log^2\left(\frac{M_W^2}{p_T^2}\right)$ in gluon–induced processes [see also Frixione et al., Nucl.Phys. B383, 3 (1992); Frixione, Nucl.Phys. B410, 280 (1993); Ohnemus, Phys.Rev. D50, 1931 (1994)]
- Radiative correction hierarchy: $WZ > WW > ZZ$ because of non-abelian structure, coupling strengths and PDFs (PDF(u)> PDF(d)):

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

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

EW distributions at 14 TeV

NLO EW effects (no cuts, illustrated here in *WW* channel):



- Sudakov factor in the $q\bar{q} \to VV'$ correction $\propto \alpha \log^2\left(\frac{p_T^2}{M_W^2}\right)$ [see also Bierweiler et al., 2012/2013]
- γ-induced processes compensate this Sudakov effect $\Leftarrow$ t–channel massive boson exchange diagram in WW and WZ channels $\Rightarrow$ big hierarchy in EW corrections

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

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

- $\gamma\gamma$ dominates in M_{WW} distribution

Experimental results summary

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

- $pp \to ZZ$:

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

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

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

- $pp \to WW$:

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)]

Experimental results summary

How to obtain the total cross section?

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

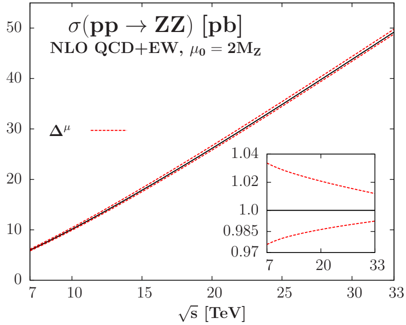
where X is the final state measured:

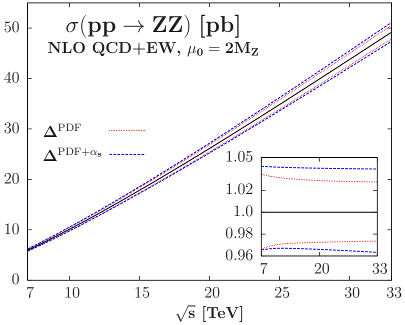
e.g. for ZZ it is $X = 4\ell$, for WW it is $X = \ell\ell'\nu\nu'$

$\mathcal{A}_{\rm geometry}$ rescaling factor to extrapolate to the full phase space, estimated from MC predictions: $\mathcal{A}_{\rm geometry} = \dfrac{\sigma^{\rm fid,cut}}{\sigma^{\rm tot,cut}}$

ZZ total cross section

- **EW correction factor:** NLO EW corrections negative and sizeable, $\delta^{\rm EW} = 0.97$
- **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

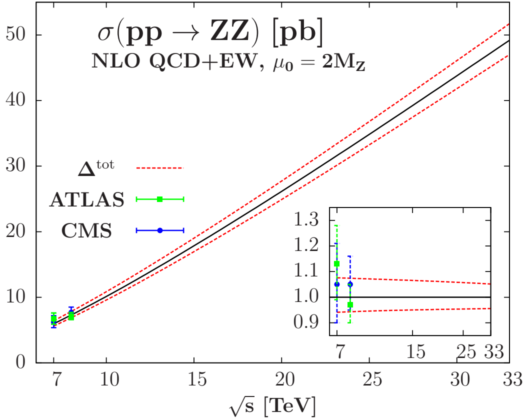




ZZ total cross section

Total uncertainty and comparison with experiment:

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



ATLAS @ 7 TeV: agree within 0.8σ

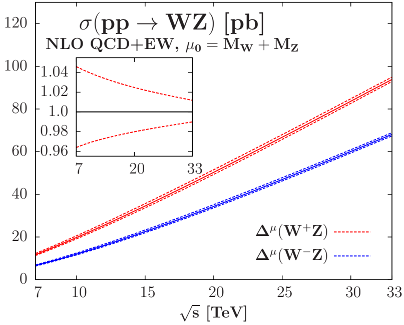
CMS @ 7 TeV: perfect agreement ($< 0.3\sigma$)

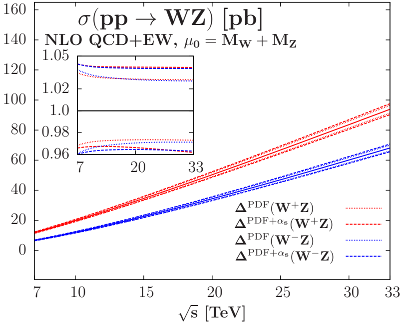
ATLAS @ 8 TeV: perfect agreement ($< 0.3\sigma$)

CMS @ 8 TeV: agree within 0.4σ

WZ total cross section

- **EW correction factor:** NLO EW corrections negligible, $\delta^{\rm EW} = 1.00$
- **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

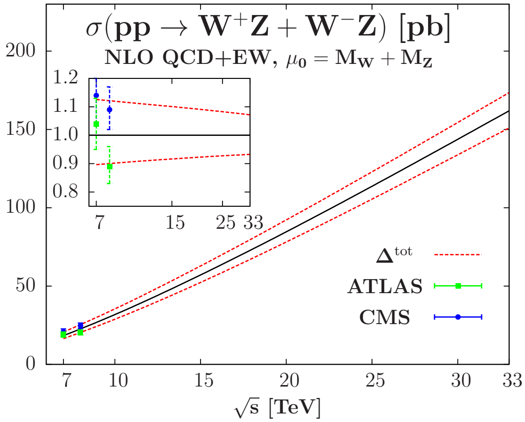




WZ total cross section

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

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

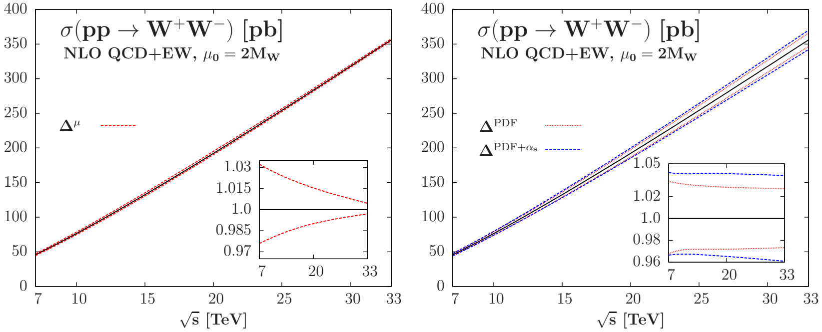


ATLAS @ 7 TeV: perfect agreement ($< 0.2\sigma$)
CMS @ 7 TeV: agreement within 0.85σ

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

WW total cross section

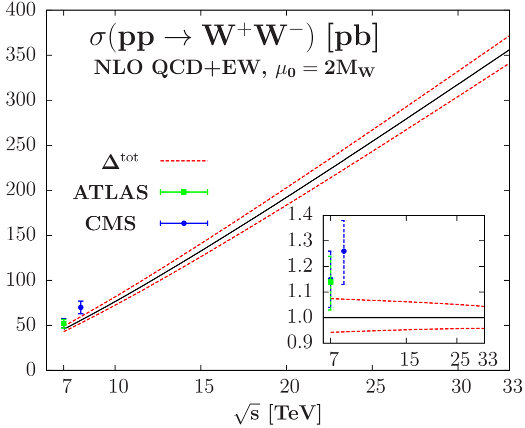
- **EW correction factor:** NLO EW corrections positive and small, $\delta^{EW} = 1.01 - 1.02$ (same when calculated with the newest NNPDF 2.3 QED set [NNPDF Collaboration, arXiv:1308.0598])
- **Parametric uncertainties negligible**
- **Scale uncertainty:** $\Delta^{\mu} = +3.2\%/-2.4\%$ @ 7 TeV down 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 $\pm3.9\%$ @ 33 TeV



WW total cross section

Total uncertainty and comparison with experiment:

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



ATLAS & CMS @ 7 TeV: 1.1σ excess

CMS @ 8 TeV: 1.8σ excess

Summary and outlook

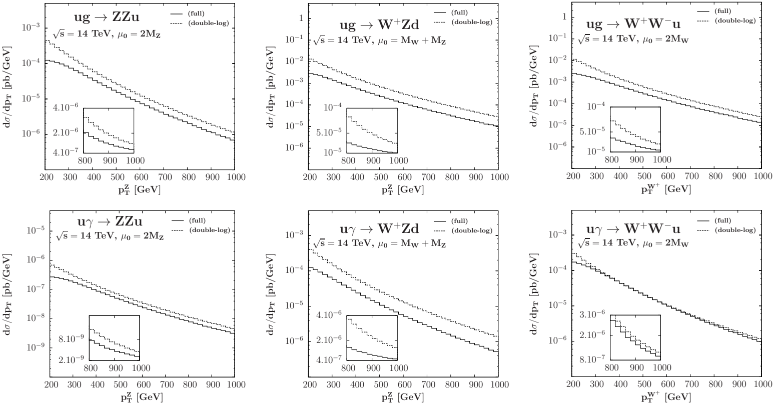
Diboson production at the LHC:

- **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**
  $\Rightarrow$ 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)

Thank you!

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
- Approximation works better in the EW case than in the QCD case, almost perfect for EW WW distribution

EW leading-log equations for ZZ, WW and WZ

- *ZZ* p_T distribution

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

- *WW* p_T distribution

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

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

- *WZ* p_T distribution

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

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

with $a_W = \dfrac{1}{\sqrt{2}\sin\theta_W}$, $c_{L,f} = (I_3^f - \sin^2\theta_W Q_f)/(\sin\theta_W\cos\theta_W)$, $c_{R,f} = -Q_f \sin\theta_W/\cos\theta_W$,
$c_{ZZ}^u = (c_{L,u}^4 + c_{R,u}^4)/(4c_{L,u}^2) = 0.18$, $c_{ZZ}^d = (c_{L,d}^4 + c_{R,d}^4)/(4c_{L,u}^2) = 0.26$,
$c_{WZ}^d = \dfrac{1}{2}a_W^2 \dfrac{c_{L,u}}{c_{L,d}}\left(1 + \dfrac{\cot\theta_W}{c_{L,d}} - \dfrac{\cot\theta_W}{c_{L,u}}\right) = 2.81$, $c_{WZ}^u = \dfrac{1}{2}a_W^2 \dfrac{c_{L,d}}{c_{L,u}}\left(1 + \dfrac{\cot\theta_W}{c_{L,d}} - \dfrac{\cot\theta_W}{c_{L,u}}\right) = 4.13$