QCD Corrections in SMEFT Fits to *WZ* and *WW* Production

VBSCan Working Group 1 meeting

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[in collaboration with Sally Dawson and Sam Homiller, arXiv:1909.11576]

CERN

EFT in a nutshell

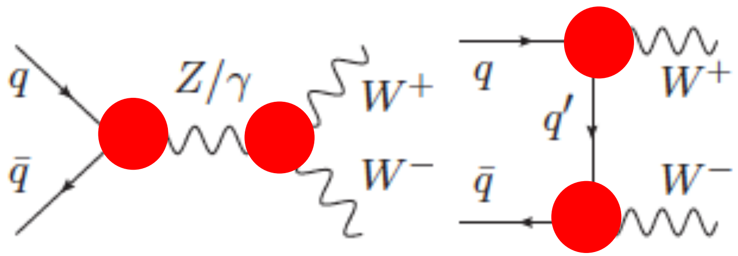
Goal: parametrize effects of high-scale new physics

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

- Gauge theory $SU(3)_c \times SU(2)_L \times U(1)_Y$ assumed
- **SMEFT**: Higgs field is an $SU(2)$ doublet
- New physics scale Λ, effective higher-dimensional operators $\mathcal{O}_i$ built with SM fields
- Dimension-5 operator violating lepton number not considered in this talk

Diboson process and fits

How large can the coefficients C_i/Λ^2 be?



- Use W^+W^- and $W^\pm Z$ channels to fit the Wilson coefficients
- Usual fits use lowest order cross section: Do NLO (QCD) corrections matter?

Mapping anomalous couplings and EFT: *VVV*

Can easily map any EFT basis[1] over the anomalous couplings
⇒ use now anomalous coupling language

For the triple gauge boson couplings:

$$\mathcal{L}_{WWZ} \propto \left[(1+\delta g_1^Z)\left(W^+_{\mu\nu}W^{-\mu}Z^\nu - W^-_{\mu\nu}W^{+\mu}Z^\nu\right) + (1+\delta\kappa^Z)\, W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda^Z}{M_W^2} W^+_{\rho\mu} W^{-\mu\nu} Z_\nu{}^\rho \right],$$

$$\mathcal{L}_{WW\gamma} \propto \left[\left(W^+_{\mu\nu}W^{-\mu}A^\nu - W^-_{\mu\nu}W^{+\mu}A^\nu\right) + (1+\delta\kappa^\gamma)\, W^+_\mu W^-_\nu A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W^+_{\rho\mu} W^{-\mu\nu} A_\nu{}^\rho \right]$$

- 5 new parameters
- With $SU(2)$ invariance: $\lambda^\gamma = \lambda^Z$, $\delta\kappa^\gamma = \dfrac{\cos^2\theta_W}{\sin^2\theta_W}\left(\delta g_1^Z - \delta\kappa^Z\right)$

  ⇒ 3 independent parameters in the gauge sector

[1] See e.g. [J.B., Dawson, Lewis, PRD 96 (2017) 073003, arXiv:1708.03332]

Mapping anomalous couplings and EFT: $q\bar{q}V$

Effective $Z - q - q$ and $W - q - q'$ couplings can be important!

[see e.g. Zhang, PRL 118 (2017) 011803, arXiv:1610.01618]

$$\mathcal{L}_{Zqq} \propto Z_\mu \Big[(g_L^{Zu} + \delta g_L^{Zu}) \bar{u}_L \gamma^\mu u_L + (g_R^{Zu} + \delta g_R^{Zu}) \bar{u}_R \gamma^\mu u_R + (g_L^{Zd} + \delta g_L^{Zd}) \bar{d}_L \gamma^\mu d_L + (g_R^{Zd} + \delta g_R^{Zd}) \bar{d}_R \gamma^\mu d_R \Big],$$

$$\mathcal{L}_{Wqq'} \propto W_\mu \Big[(1 + \delta g_L^{Wq}) \bar{u}_L \gamma^\mu d_L + h.c. \Big]$$

- With $SU(2)$ invariance: $\delta g_L^{Wq} = \delta g_L^{Zu} - \delta g_L^{Zd}$
  7 independent parameters in the gauge+fermion sector
- Right-handed W couplings not included

W^+W^- and $W^\pm Z$ calculation

Implementation of the leptonic processes $pp \to W^+W^- \to e^\pm\mu^\mp + 2\nu$ and $pp \to W^\pm Z \to e^\pm\nu\mu^+\mu^-$ at NLO QCD

- **Full $2 \to 4$** matrix elements with single resonant diagrams taken into account [Dixon, Kunszt, Signer, NPB 531 (1998) 3, hep-ph/9803250; PRD 60 (1999) 114037, hep-ph/9907305]
- Anomalous gauge couplings [Melia *et al*, JHEP 11 (2011) 078, arXiv:1107.5051; Nason, Zanderighi, EPJC 74 (2014) 2702, arXiv:1311.1365] and **fermionic coupling (new)**
- QCD corrections are straightforward: unaffected by anomalous EW couplings, just adapt the individual Born, virtual, real pieces to the anomalous couplings irrespective of QCD
- Fully differential calculation with arbitrary cuts

Our implementation in the POWHEG-BOX

W^+W^- and $W^\pm Z$ implemented in the POWHEG-BOX

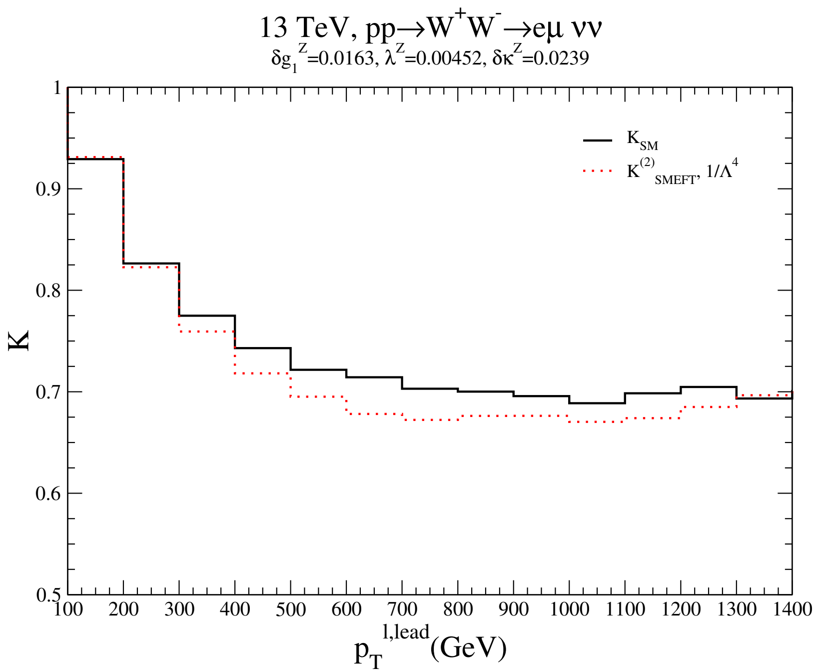
[Nason, JHEP 11 (2004) 040, hep-ph/0409146; Frixione, Nason, Oleari, JHEP 11 (2007) 070, arXiv:0709.2092; Alioli *et al*, JHEP 06 (2010) 043, arXiv:1002.2581]

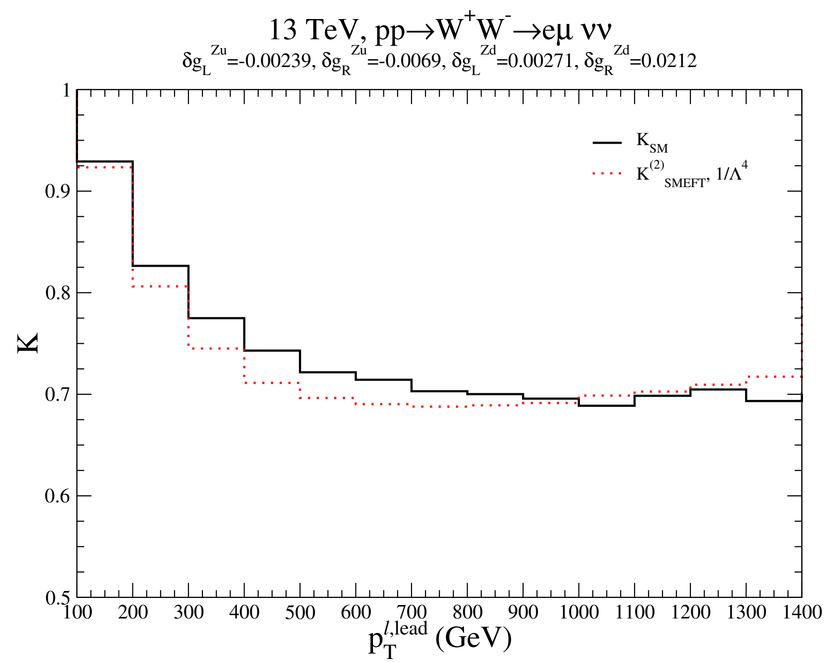
- Subtraction of IR divergences in the FKS scheme [Frixione, Kunszt, Signer, NPB 467 (1996) 399, hep-ph/9512328]
- Matching of the NLO QCD corrections to parton shower
- 6 $\neq$ EW input parameter schemes implemented
- Consistent $\mathcal{O}(1/\Lambda^{2n})$ expansion implemented
- Choice between anomalous couplings or dim-6 EFT Wilson coefficients in the Warsaw basis
- **Our implementation publically available in the `POWHEG-BOX-V2`, projects `WWanomal` and `WZanomal`**

Visit http://powhegbox.mib.infn.it/ to download the code!

QCD corrections: W^+W^-

Compare $K = \frac{d\sigma^{\mathrm{NLO}}}{d\sigma^{\mathrm{LO}}}$ in SM and in SMEFT for $pp \to W^+W^- \to e^\pm\mu^\mp + 2\nu$ [J.B., Dawson, Lewis, PRD 99 (2019) 035029, arXiv:1812.00214]

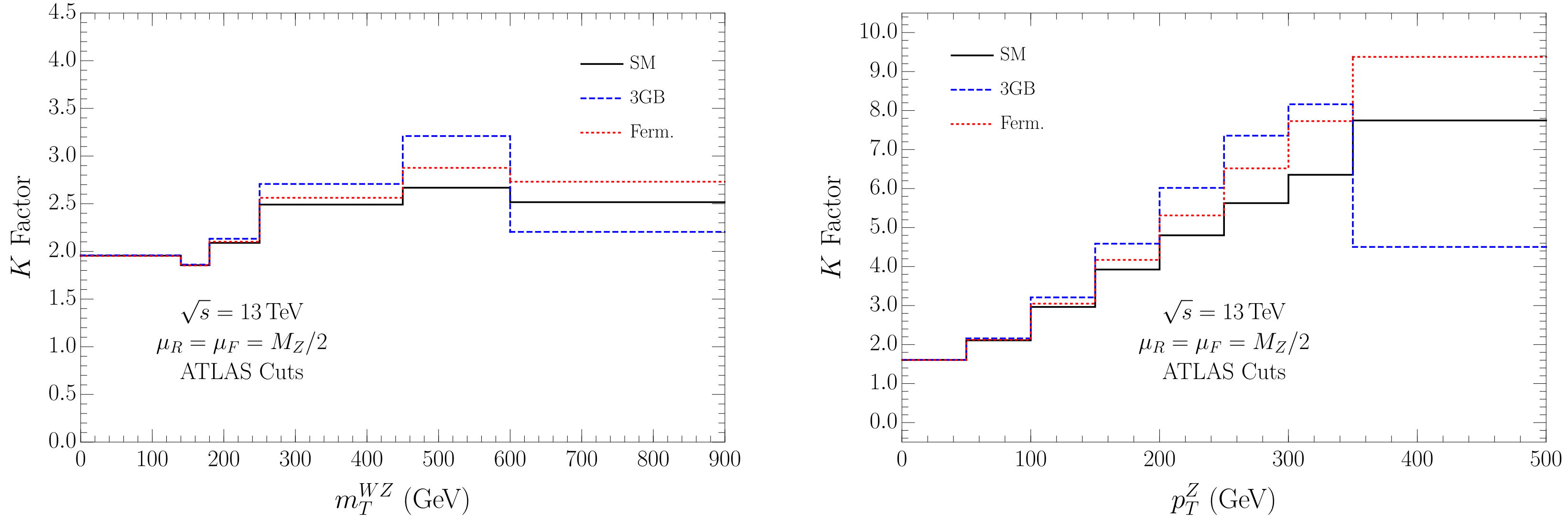




QCD corrections quite similar in SM and SMEFT

QCD corrections: $W^{\pm}Z$

Same for $pp \to W^{\pm}Z \to e^{\pm}\nu\mu^{+}\mu-$:



- Benchmark scenarios 3GB = only gauge operators; Ferm = only fermion operators
- **QCD corrections very different in the high-energy bins!** $\Rightarrow$ can't approximate SMEFT QCD effects with SM K-factors anymore

Set of data for the fits

χ^2 fit with the following sets of data:

Channel	Distribution	# bins	Data set	Int. Lum.
$WW \to \ell^+\ell'^- + \not{E}_T$ (0j)	$p_T^{\text{leading}\,\ell}$	1	ATLAS 8 TeV[2]	20.3 fb^{-1}
$WW \to e^\pm\mu^\mp + \not{E}_T$ (0j)	$p_T^{\text{leading}\,\ell}$	5	ATLAS 13 TeV[3]	36.1 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	2	ATLAS 8 TeV[4]	20.3 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	Z candidate $p_T^{\ell\ell}$	9	CMS 8 TeV[5]	19.6 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm}$	m_T^{WZ}	6	ATLAS 13 TeV[6]	36.1 fb^{-1}
$WZ \to \ell^+\ell^-\ell^{(\prime)\pm} + \not{E}_T$	m^{WZ}	3	CMS 13 TeV[7]	35.9 fb^{-1}

[2] [ATLAS, JHEP 09 (2016) 029, arXiv:1603.01702]
[3] [ATLAS, EPJC 79 (2019) 884, arXiv:1905.04242]
[4] [ATLAS, PRD 93 (2016) 092004, arXiv:1603.02151]
[5] [CMS, EPJC 77 (2017) 236, arXiv:1609.05721]
[6] [ATLAS, EPJC 79 (2019) 535, arXiv:1902.05759]
[7] [CMS, JHEP 04 (2019) 122, arXiv:1901.03428]

Primitive bins

Calculation of a set of 35 **primitive differential xs** for W^+W^- and 15 differential xs for $W^\pm Z$, at a given QCD order

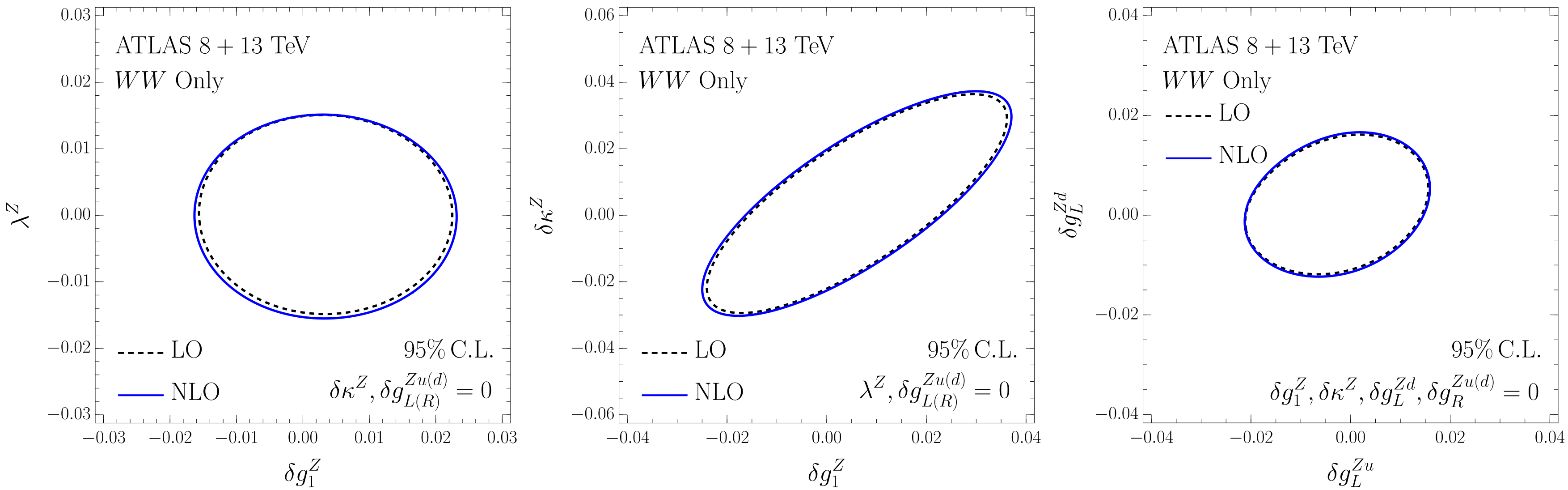
[see J.B., Dawson, Lewis, PRD 99 (2019) 035039, arXiv:1812.00214]

$$d\sigma(\vec{C}) = d\sigma_{SM}\left(1 - \sum_{i=1}^{m} C_i\right) + \sum_{i=1}^{m} C_i\, d\sigma(1;\vec{R}_i) + \sum_{i=1}^{m} C_i^2\left(d\sigma(2;\vec{R}_i) - d\sigma(1;\vec{R}_i)\right)$$
$$+ \sum_{i>j=1}^{m} C_i C_j \left(d\sigma(2;\vec{M}_{ij}) - d\sigma(2;\vec{R}_i) - d\sigma(2;\vec{R}_j) + d\sigma_{SM}\right)$$

- Formula at order $\mathcal{O}(1/\Lambda^4)$ for a set of m Wilson coefficients $\vec{C} = (C_i)_{i=1\ldots m}$
- Primitive $d\sigma(n;\vec{R}_i)$ is $d\sigma$ at order $\mathcal{O}(1/\Lambda^{2n})$ with $C_i = 1, C_j = 0\,(j \neq i)$
- Primitive $d\sigma(2;\vec{M}_{ij})$ is $d\sigma$ at order $\mathcal{O}(1/\Lambda^4)$ with $C_i = 1, C_j = 1, C_k = 0\,(k \neq i, k \neq j)$

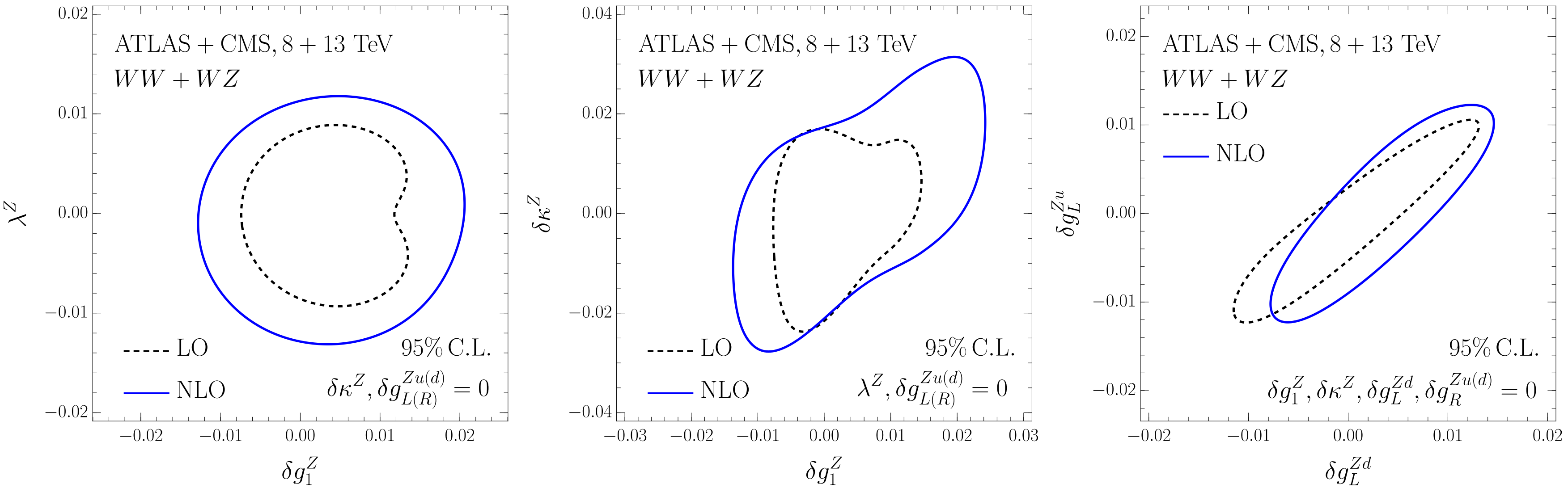
Can compute in a fast way any bin with arbitrary anomalous couplings

Fits to W^+W^- alone



- **NLO QCD effects very mild** $\Leftarrow$ QCD radiation dominate, not spoiled by anomalous couplings
- $\delta\kappa^Z$ constrained at the same level as the other anomalous couplings

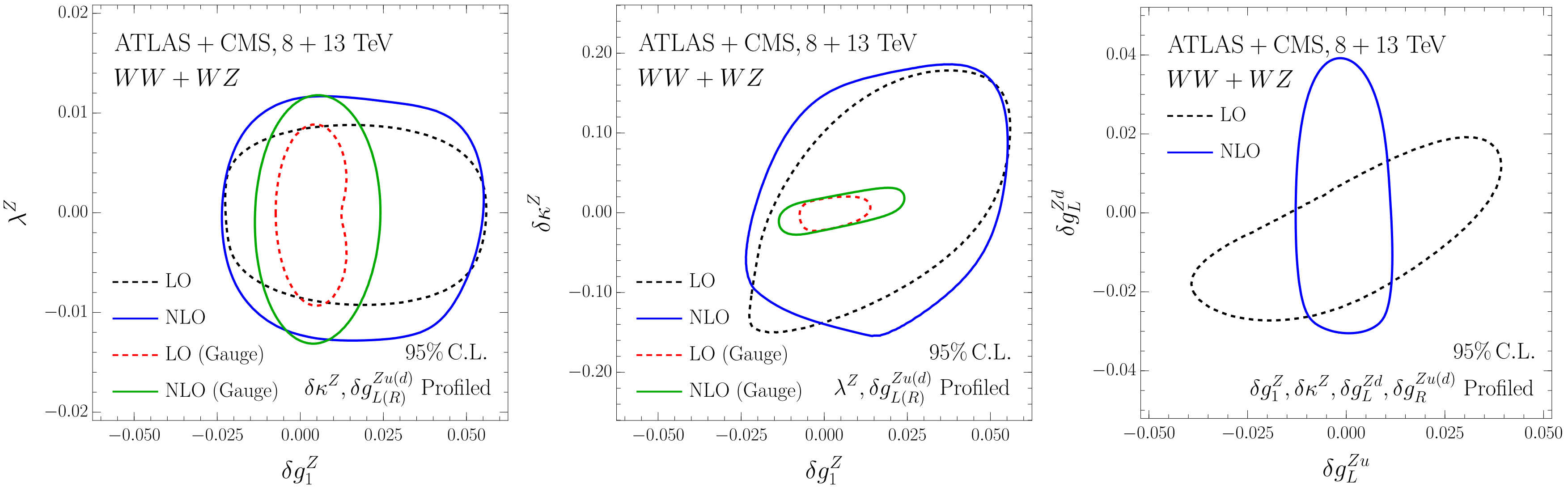
Fits to W^+W^- + $W^\pm Z$ data



- **NLO QCD effects visible** (amplitude 0 spoiled)
- Subleading dependence of $W^\pm Z$ on $\delta\kappa^Z$ at high energies $\Rightarrow$ fit dominated by W^+W^- data $\Rightarrow$ LO and NLO results similar

Fits to W^+W^- + $W^{\pm}Z$ data

Same NLO QCD effects in profiled fits:



- Correlation between δg_L^{Zu} and δg_L^{Zd} removed at NLO
- **Limits much weaker when fermion operators taken into account!** [see also Zhang, PRL 118 (2017) 011803, arXiv:1610.01618; J.B., Dawson, Lewis, PRD 99 (2019) 035029, arXiv:1812.00214 ; Butter *et al*, JHEP 07 (2016) 152, arXiv:1604.03105]

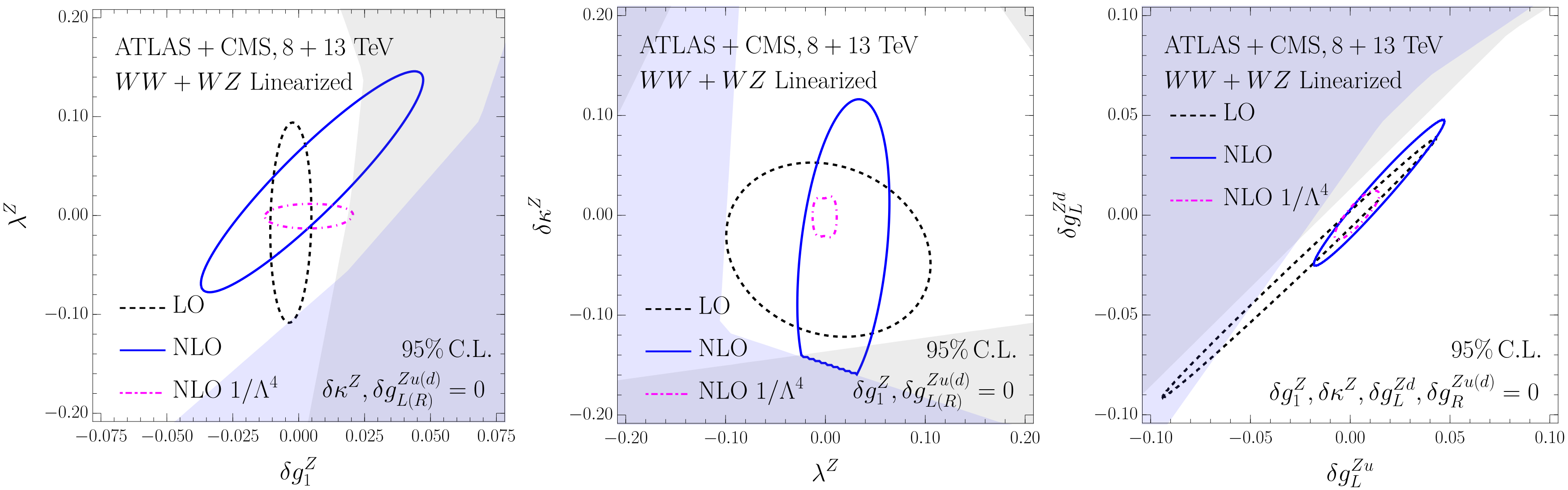
Linearized fits vs quadratic fits

EFT Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{C_i^6}{\Lambda^2}\mathcal{O}_i^6 + \sum_i \frac{C_i^8}{\Lambda^4}\mathcal{O}_i^8 + \dots$

$$\Rightarrow \sigma \propto \frac{1}{s}\left\{ |\mathcal{A}_{SM}|^2 + \frac{2}{\Lambda^2}\mathrm{Re}\left(\mathcal{A}_{SM}^*\delta\mathcal{A}_{EFT}^{(6)}\right) + \frac{|\delta\mathcal{A}_{EFT}^{(6)}|^2}{\Lambda^4} + \frac{2}{\Lambda^4}\mathrm{Re}\left(\mathcal{A}_{SM}^*\delta\mathcal{A}_{EFT}^{(8)}\right) + \dots \right\}$$

- Assume dim-8 operators subleading $\Rightarrow$ safely include $|\delta\mathcal{A}_{EFT}^{(6)}|^2/\Lambda^4$
- **What impact of the dim-6 squared terms?** Truncation at the linear term in the EFT expansion
- Cross section not positive definite anymore $\Rightarrow$ throw away points in the fits where cross section negative

Linearized fits vs quadratic fits



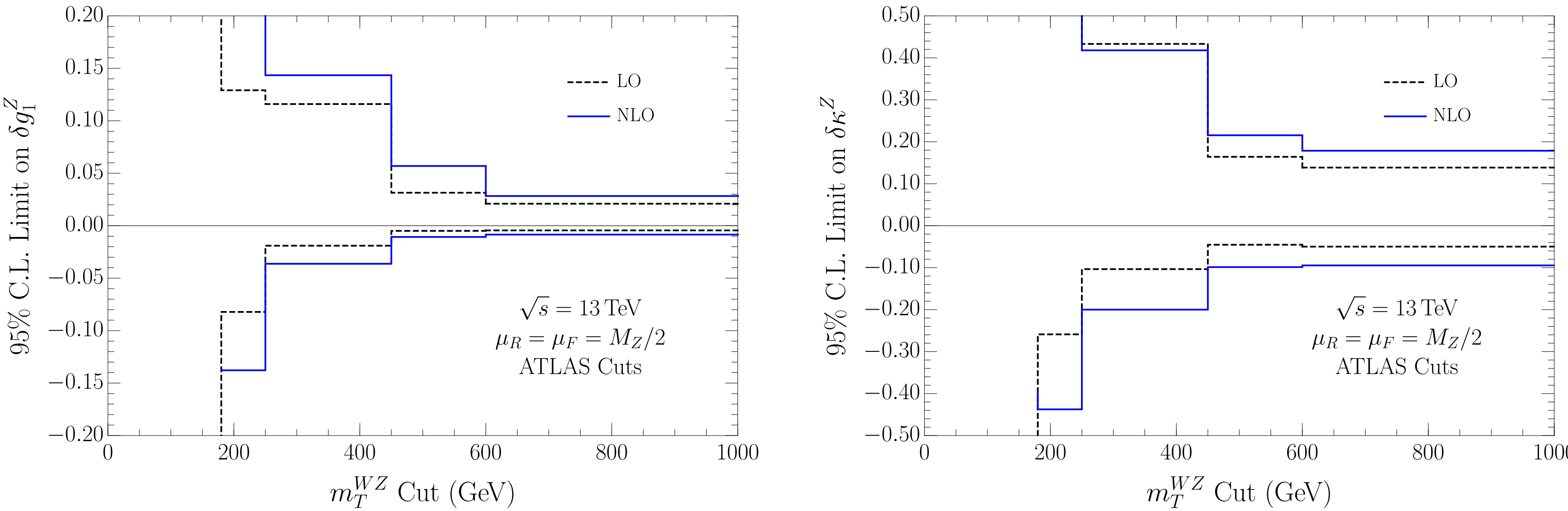
- Excluded at LO, Excluded at NLO, Excluded at LO+NLO
- **Huge impact of $1/\Lambda^4$ terms $\Rightarrow$ not (yet) sensitive to weak anomalous couplings**

Sensibility of the fit vs last bins

Important point: EFT valid only for $E \ll \Lambda$

[see e.g. Contino *et al*, JHEP 07 (2016) 144, arXiv:1604.06444; Farina *et al*, PLB 772 (2017) 210, arXiv:1609.08157]

What happens when last bin in data removed?
($m_T^{WZ} > 600$ GeV $\Rightarrow$ all points satisfy $m_T^{WZ} < \Lambda = 1$ TeV)



- Fit still the same within $\sim$ 10%
- Would be great to have the overflow bin explicitely singled out $\Rightarrow$ max energy in the last bin clearer!

Conclusions

- SMEFT at NLO QCD in W^+W^- and $W^\pm Z$ leptonic channels available, including quarks and gauge operators
- χ^2 fit clearly impacted by $W^\pm Z$ data $\Rightarrow$ NLO QCD corrections are significant in the fit!
- Results dominated by $1/\Lambda^4$ terms $\Rightarrow$ not yet sensitive to weak coupling regime
- Not including last bin gives good results $\Rightarrow$ Would be great to know the max energy in the data
- **Code released publically in the** `POWHEG-BOX`

  $\Rightarrow$ **anyone can use it!**

List of relevant operators in Warsaw basis

$\mathcal{O}_{\ell\ell}$	$(\bar{\ell}_L\gamma^\mu\ell_L)(\bar{\ell}_L\gamma_\mu\ell_L)$	$\mathcal{O}_{HWB}$	$(\Phi^\dagger\sigma^a\Phi)W^a_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{HD}$	$\left\|\Phi^\dagger(D_\mu\Phi)\right\|^2$
$\mathcal{O}_{3W}$	$\epsilon^{abc}W^{a\nu}_\mu W^{b\rho}_\nu W^{c\mu}_\rho$	$\mathcal{O}^{(3)}_{HF}$	$i\left(\Phi^\dagger\overleftrightarrow{D}^a_\mu\Phi\right)\bar{f}_L\gamma^\mu\sigma^a f_L$	$\mathcal{O}^{(1)}_{HF}$	$i\left(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right)\bar{f}_L\gamma^\mu f_L$
$\mathcal{O}_{Hu}$	$i\left(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right)\bar{u}_R\gamma^\mu u_R$	$\mathcal{O}_{Hd}$	$i\left(\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right)\bar{d}_R\gamma^\mu d_R$		

Warsaw basis $\Leftrightarrow$ anomalous couplings

With [Falkowski, arXiv:1505.00046; Brivio, Trott, JHEP 07 (2017) 148, arXiv:1701.06424]

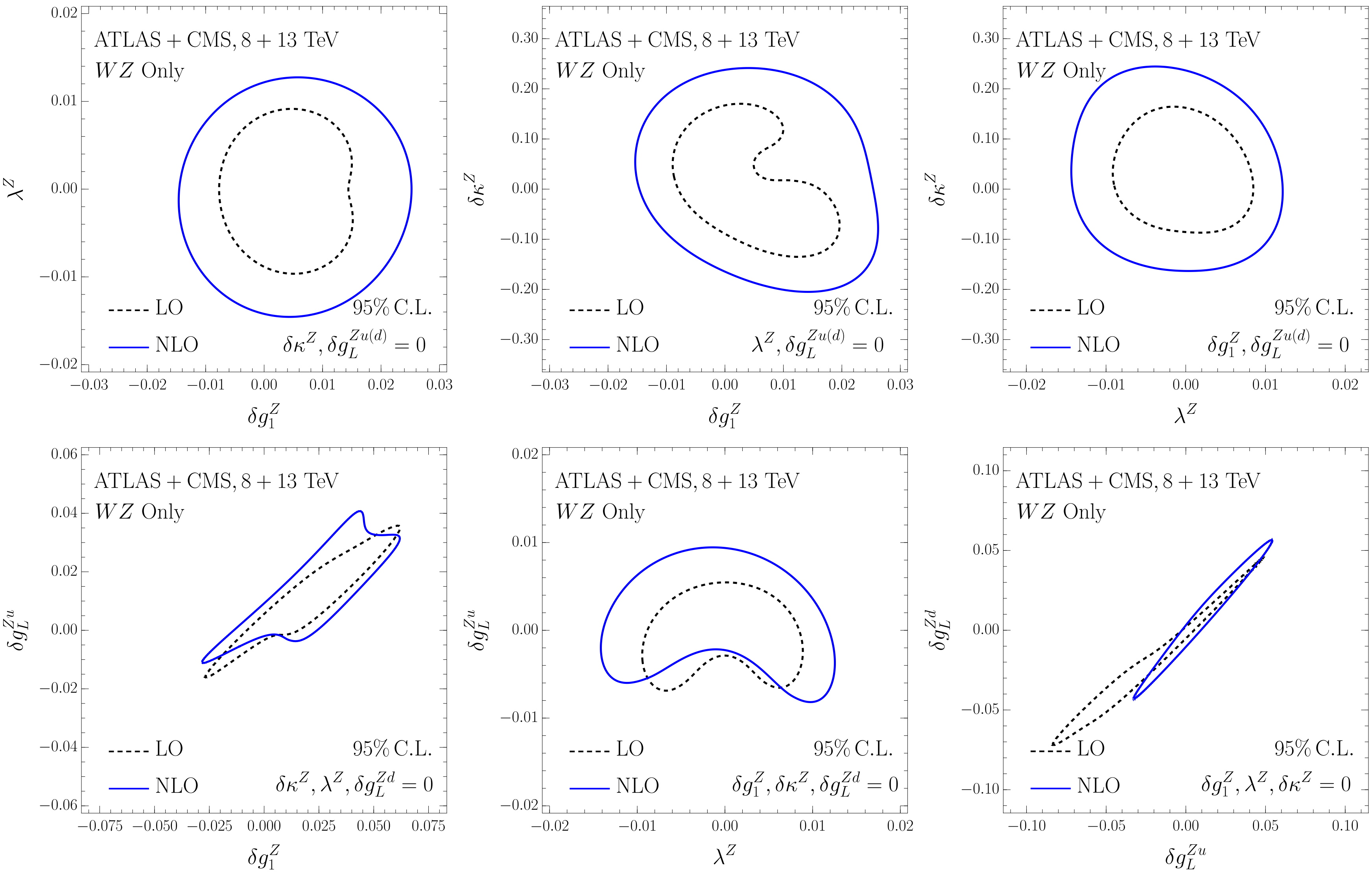
$$\delta v = C_{Hl}^{(3)} - \frac{1}{2}C_{ll}, \quad \delta g_Z = -\frac{v^2}{\Lambda^2}\left(\delta v + \frac{1}{4}C_{HD}\right), \quad \delta s_W^2 = -\frac{v^2}{\Lambda^2}\frac{s_W c_W}{c_W^2 - s_W^2}\left[2 s_W c_W\left(\delta v + \frac{1}{4}C_{HD}\right) + C_{HWB}\right],$$

We get [8]

$$\begin{aligned}
\delta g_1^Z &= \frac{v^2}{\Lambda^2}\frac{1}{c_W^2 - s_W^2}\left(\frac{s_W}{c_W}C_{HWB} + \frac{1}{4}C_{HD} + \delta v\right), \quad \delta\kappa^Z = \frac{v^2}{\Lambda^2}\frac{1}{c_W^2 - s_W^2}\left(2 s_W c_W C_{HWB} + \frac{1}{4}C_{HD} + \delta v\right),\\
\delta\kappa^\gamma &= -\frac{v^2}{\Lambda^2}\frac{c_W}{s_W}C_{HWB}, \quad \lambda^\gamma = \frac{v}{\Lambda^2}3M_W C_{3W}, \quad \lambda^Z = \frac{v}{\Lambda^2}3M_W C_{3W},\\
\delta g_L^W &= \frac{v^2}{\Lambda^2}C_{Hq}^{(3)} + c_W^2\delta g_Z + \delta s_W^2,\\
\delta g_L^{Zu} &= -\frac{v^2}{2\Lambda^2}\left(C_{Hq}^{(1)} - C_{Hq}^{(3)}\right) + \frac{1}{2}\delta g_Z + \frac{2}{3}\left(\delta s_W^2 - s_W^2\delta g_Z\right),\\
\delta g_L^{Zd} &= -\frac{v^2}{2\Lambda^2}\left(C_{Hq}^{(1)} + C_{Hq}^{(3)}\right) - \frac{1}{2}\delta g_Z - \frac{1}{3}\left(\delta s_W^2 - s_W^2\delta g_Z\right),\\
\delta g_R^{Zu} &= -\frac{v^2}{2\Lambda^2}C_{Hu} + \frac{2}{3}\left(\delta s_W^2 - s_W^2\delta g_Z\right), \quad \delta g_R^{Zd} = -\frac{v^2}{2\Lambda^2}C_{Hd} - \frac{1}{3}\left(\delta s_W^2 - s_W^2\delta g_Z\right)
\end{aligned}$$

[8] [Berthier, Trott, JHEP 05 (2015) 024, arXiv:1502.02570; Zhang, PRL 118 (2017) 011803, arXiv:1610.01618; J.B., Dawson, Lewis, PRD 96 (2017) 073003, arXiv:1708.03332]

Fits to $W^{\pm}Z$ alone



Amplitudes for W^+W^- in the high-energy limit

With $\overline{q}_s q_{s'} \to W^+_\lambda W^-_{\lambda'}$, θ between beam axis and gauge boson direction in the cms system:

$$\delta\mathcal{A}_{+-00} \;\to\; \frac{g^2}{2}\sin\theta\left(\frac{s}{M_W^2}\right)\left\{\delta\kappa^Z\left(s_W^2 Q_q - T_3^q\right) - s_W^2 Q_q \delta\kappa^\gamma - \delta g_L^{Zq} + 2T_3^q \delta g_L^W\right\},$$

$$\delta\mathcal{A}_{-+00} \;\to\; \frac{g^2}{2}\sin\theta\left(\frac{s}{M_W^2}\right)\left\{s_W^2 Q_q\left(\delta\kappa^\gamma - \delta\kappa^Z\right) + \delta g_R^{Zq}\right\},$$

$$\delta\mathcal{A}_{+-\pm\pm} \;\to\; -\frac{g^2}{2}\sin\theta\left(\frac{s}{M_W^2}\right)\lambda^Z T_3^q$$

Amplitudes for $W^{\pm}Z$ in the high-energy limit

With $\overline{q}_+ q_- \to W^+_\lambda Z_{\lambda'}$, θ between beam axis and gauge boson direction in the cms system:

$$\delta\mathcal{A}_{00} \;\to\; \frac{g^2}{2\sqrt{2}}\sin\theta\left(\frac{s}{M_Z^2}\right)\left\{\delta g_1^Z + \frac{(\delta g_L^{Zd} - \delta g_L^{Zu})}{c_W^2}\right\},$$

$$\delta\mathcal{A}_{\pm\pm} \;\to\; \frac{g^2}{2\sqrt{2}c_W}\sin\theta\left(\frac{s}{M_Z^2}\right)\lambda_Z,$$

$$\delta\mathcal{A}_{\pm,\mp} \;\to\; -\frac{g^2}{\sqrt{2}c_W}\sin\theta\left\{\delta g_L^{Zu}\tan^2\left(\frac{\theta}{2}\right) + \delta g_L^{Zd}\right\}$$