A_{FB} in the SMEFT: the LHC as a Z physics laboratory

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In collaboration with

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1. Introduction

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General framework: SMEFT

- The only requirement is to assume a large gap between the electroweak (EW) scale and the new physics (NP) scale
- It allows us to take advantage of the EFT machinery, in order to test many NP models
- Especially useful if we look at low energy observables, since the indirect effect of heavy NP is guaranteed

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- LEP provides very precise measurements which leave little room for NP at the EW scale. LHC and Tevatron have also contributed to this thanks to some of their measurements for observables in the W, top and Higgs sectors
- **Could it be that LHC can also compete with or complement LEP by means of the measurements it can provide for the Z observables?**
- We will explore this possibility by looking at Drell-Yan dilepton production, which at the EW scale could be used to improve our knowledge of the Zff couplings

2. Theory framework

- SMEFT: Organized in an expansion in $1/\Lambda^2$, truncated at order Λ^{-2}:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i\, O_i^{D=6}$$

We focus only on **Z and W pole observables**, which are mainly sensitive to non-derivative interactions between EW bosons and fermions:

$$\begin{aligned}\mathcal{L}_{\rm SMEFT} \supset & -\frac{g_L}{\sqrt{2}}\left(W_\mu^+ \bar{u}_L\gamma_\mu(V+\delta g_L^{Wq})d_L + W_\mu^+\bar{u}_R\gamma_\mu\delta g_R^{Wq} d_R + \text{h.c.}\right)\\ & -\frac{g_L}{\sqrt{2}}\left(W_\mu^+\bar{\nu}_L\gamma_\mu(\mathbf{I}+\delta g_L^{We})e_L + \text{h.c.}\right)\\ & -\sqrt{g_L^2+g_Y^2}\,Z_\mu\left[\sum_{f\in u,d,e,\nu}\bar{f}_L\gamma_\mu((T_f^3 - s_\theta^2 Q_f)\,\mathbf{I}+\delta g_L^{Zf})f_L\right]\\ & -\sqrt{g_L^2+g_Y^2}\,Z_\mu\left[\sum_{f\in u,d,e}\bar{f}_R\gamma_\mu(-s_\theta^2 Q_f\,\mathbf{I}+\delta g_R^{Zf})f_R\right]\end{aligned}$$

$$\mathcal{L}_{\rm SMEFT} \supset \frac{g_L^2 v^2}{4}(1+\delta m_w)^2 W_\mu^+ W_\mu^- + \frac{(g_L^2+g_Y^2)v^2}{8}Z_\mu Z_\mu$$

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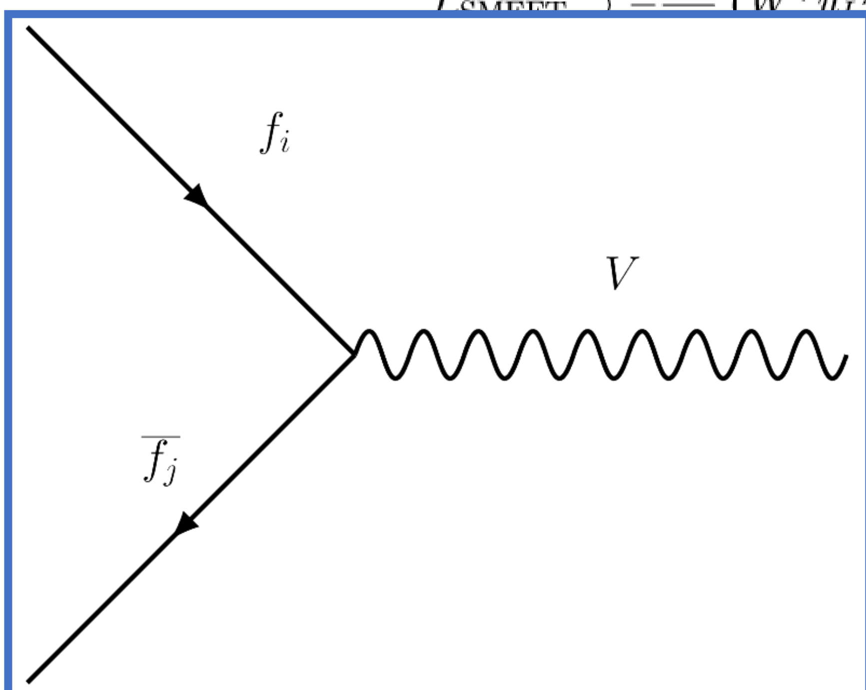

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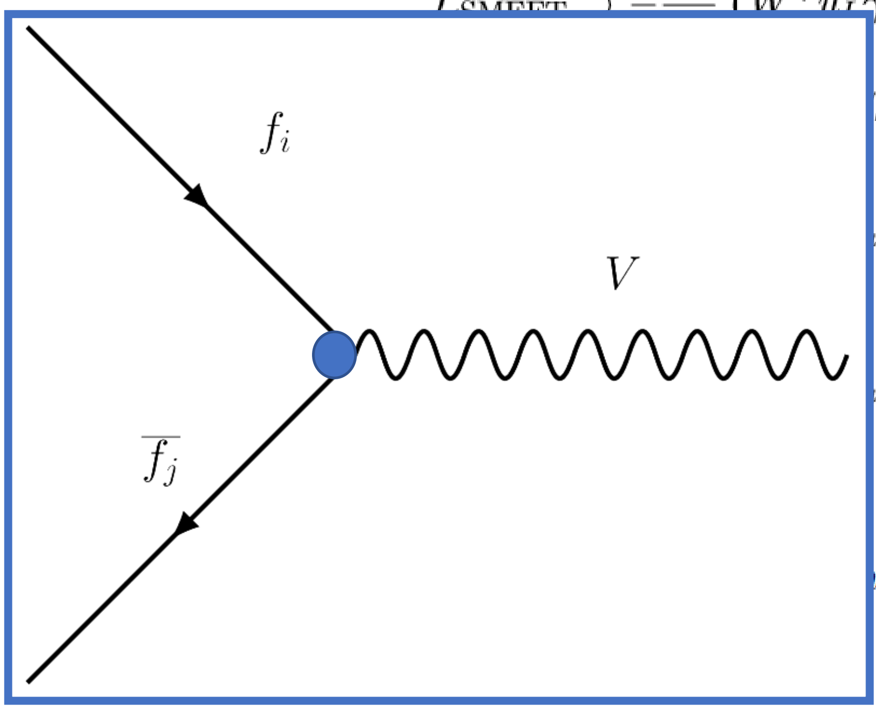

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- We only need to consider a subset of all involved operators since many of them can be ignored when looking at Z and W pole observables:

  -$\delta g_L^{Z\nu}$ and δg_L^{Wq} can be expressed by the vertex corrections:

$$\delta g_L^{Z\nu} = \delta g_L^{We} + \delta g_L^{Ze}, \qquad \delta g_L^{Wq} = \delta g_L^{Zu} V - V \delta g_L^{Zd}$$

  -The contributions from 4-fermion operators are suppressed by Γ_V / M_V or by a loop factor relatively to those of δg and are neglected

  -As for the dipole interactions, their interference with the SM amplitudes is suppressed by the small fermion masses

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$$\delta g_L^{We},\ \delta g_L^{W\mu},\ \delta g_L^{W\tau},\ \delta g_{L/R}^{Ze},\ \delta g_{L/R}^{Z\mu},\ \delta g_{L/R}^{Z\tau},\ \delta g_{L/R}^{Zd},\ \delta g_{L/R}^{Zs},\ \delta g_{L/R}^{Zb},\ \delta g_{L/R}^{Zu},\ \delta g_{L/R}^{Zc},\ \delta m_w$$

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We end up with only 20 independent parameters

$$\delta g_L^{We},\ \delta g_L^{W\mu},\ \delta g_L^{W\tau},\ \delta g_{L/R}^{Ze},\ \delta g_{L/R}^{Z\mu},\ \delta g_{L/R}^{Z\tau},\ \delta g_{L/R}^{Zd},\ \delta g_{L/R}^{Zs},\ \delta g_{L/R}^{Zb},\ \delta g_{L/R}^{Zu},\ \delta g_{L/R}^{Zc},\ \delta m_w$$

3. Traditional pole observables

- Z pole observables:

Observable	Experimental value	SM prediction	Definition
Γ_Z [GeV]	2.4955 ± 0.0023 [4, 28]	2.4941	$\sum_f \Gamma(Z \to f\bar{f})$
σ_{had} [nb]	41.4802 ± 0.0325 [4, 28]	41.4842	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050 [4]	20.734	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033 [4]	20.734	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045 [4]	20.781	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\text{FB}}^{0,e}$	0.0145 ± 0.0025 [4]	0.0162	$\frac{3}{4}A_e^2$
$A_{\text{FB}}^{0,\mu}$	0.0169 ± 0.0013 [4]	0.0162	$\frac{3}{4}A_e A_\mu$
$A_{\text{FB}}^{0,\tau}$	0.0188 ± 0.0017 [4]	0.0162	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066 [4]	0.21581	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030 [4]	0.17222	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
A_b^{FB}	0.0996 ± 0.0016 [4, 29]	0.1032	$\frac{3}{4}A_e A_b$
A_c^{FB}	0.0707 ± 0.0035 [4]	0.0736	$\frac{3}{4}A_e A_c$
A_e	0.1516 ± 0.0021 [4]	0.1470	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015 [4]	0.1470	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015 [4]	0.1470	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_e	0.1498 ± 0.0049 [4]	0.1470	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_τ	0.1439 ± 0.0043 [4]	0.1470	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020 [4]	0.935	$\frac{\Gamma(Z\to b_L\bar{b}_L)-\Gamma(Z\to b_R\bar{b}_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027 [4]	0.668	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091 [30]	0.936	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 0.009 [9]	0.1722	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$

- W pole observables:

Observable	Experimental value	SM prediction
m_W [GeV]	80.379 ± 0.012 [9]	80.356
Γ_W [GeV]	2.085 ± 0.042 [9]	2.088
$\text{Br}(W \to e\nu)$	0.1071 ± 0.0016 [5]	0.1082
$\text{Br}(W \to \mu\nu)$	0.1063 ± 0.0015 [5]	0.1082
$\text{Br}(W \to \tau\nu)$	0.1138 ± 0.0021 [5]	0.1081
$\text{Br}(W \to \mu\nu)/\text{Br}(W \to e\nu)$	0.982 ± 0.024 [32]	1.000
$\text{Br}(W \to \mu\nu)/\text{Br}(W \to e\nu)$	1.020 ± 0.019 [12]	1.000
$\text{Br}(W \to \mu\nu)/\text{Br}(W \to e\nu)$	1.003 ± 0.010 [13]	1.000
$\text{Br}(W \to \tau\nu)/\text{Br}(W \to e\nu)$	0.961 ± 0.061 [9, 31]	0.999
$\text{Br}(W \to \tau\nu)/\text{Br}(W \to \mu\nu)$	0.992 ± 0.013 [14]	0.999
$R_{Wc} \equiv \frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$	0.49 ± 0.04 [9]	0.50

3. Traditional pole observables

- Leptonic couplings:

$$[\delta g_L^{We}]_{ii} = \begin{pmatrix} -1.3 \pm 3.2 \\ -2.8 \pm 2.6 \\ 1.5 \pm 4.0 \end{pmatrix} \times 10^{-3}$$

$$[\delta g_R^{Ze}]_{ii} = \begin{pmatrix} -0.43 \pm 0.27 \\ 0.0 \pm 1.4 \\ 0.62 \pm 0.62 \end{pmatrix} \times 10^{-3}$$

$$[\delta g_L^{Ze}]_{ii} = \begin{pmatrix} -0.19 \pm 0.28 \\ 0.1 \pm 1.2 \\ -0.09 \pm 0.59 \end{pmatrix} \times 10^{-3}$$

- W mass correction:

$$\delta m_w = (2.9 \pm 1.6) \times 10^{-4}$$

- s, c, b couplings:

$$\delta g_L^{Zs} = (1.3 \pm 4.1) \times 10^{-2} \qquad \delta g_R^{Zs} = (2.2 \pm 5.6) \times 10^{-2}$$

$$\delta g_L^{Zc} = (-1.3 \pm 3.7) \times 10^{-3} \qquad \delta g_R^{Zc} = (-3.2 \pm 5.4) \times 10^{-3}$$

$$\delta g_L^{Zb} = (3.1 \pm 1.7) \times 10^{-3} \qquad \delta g_R^{Zb} = (21.8 \pm 8.8) \times 10^{-3}$$

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What about Zuu and Zdd corrections?

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- One linear combination of up and down quark vertex corrections is unconstrained:

$$\delta g_L^{Zu} + \delta g_L^{Zd} + \frac{3g_L^2 - g_Y^2}{4g_Y^2}\delta g_R^{Zu} + \frac{3g_L^2 + g_Y^2}{2g_Y^2}\delta g_R^{Zd}$$

- It is useful to rearrange these 4 couplings so that we can separate the blind direction from the rest of the parameter space:

$$\begin{pmatrix} x \\ y \\ z \\ t \end{pmatrix} = R \begin{pmatrix} \delta g_L^{Zu} \\ \delta g_R^{Zu} \\ \delta g_L^{Zd} \\ \delta g_R^{Zd} \end{pmatrix} = \begin{pmatrix} 0.93 & -0.29 & -0.23 & -0.01 \\ 0.18 & 0.87 & -0.33 & -0.33 \\ 0.27 & 0.18 & 0.90 & -0.29 \\ 0.17 & 0.37 & 0.17 & 0.90 \end{pmatrix} \begin{pmatrix} \delta g_L^{Zu} \\ \delta g_R^{Zu} \\ \delta g_L^{Zd} \\ \delta g_R^{Zd} \end{pmatrix}$$

$$\Downarrow$$

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This can be achieved using D0 data [Efrati, Falkowski, Soreq, ‘15] but with very modest precision: $|t| < 0.2$

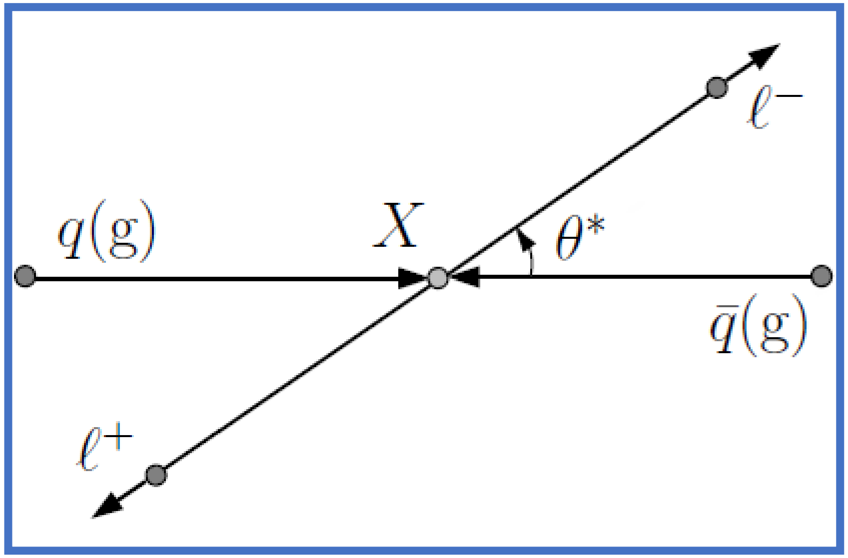
- ***t* unconstrained. Can we use LHC data to restrict it?**

4. Hadron colliders as probes of Zqq couplings

- We find that the cleanest observable for the task at hand is the Drell-Yan forward-backward asymmetry (A_{FB})
- This asymmetry arises in the SM due to parity-violating Z couplings to fermions:

$$\frac{d\hat{\sigma}_{q\bar{q}}\left(\hat{s}, cos\theta^*\right)}{d\cos\theta^*} \propto H^{even}_{q\bar{q}}\left(\hat{s}\right)\left(1+\cos^2\theta^*\right) + H^{odd}_{q\bar{q}}\left(\hat{s}\right)\cos\theta^*$$

Forward events: $\cos\theta^* > 0$
Backward events: $\cos\theta^* < 0$



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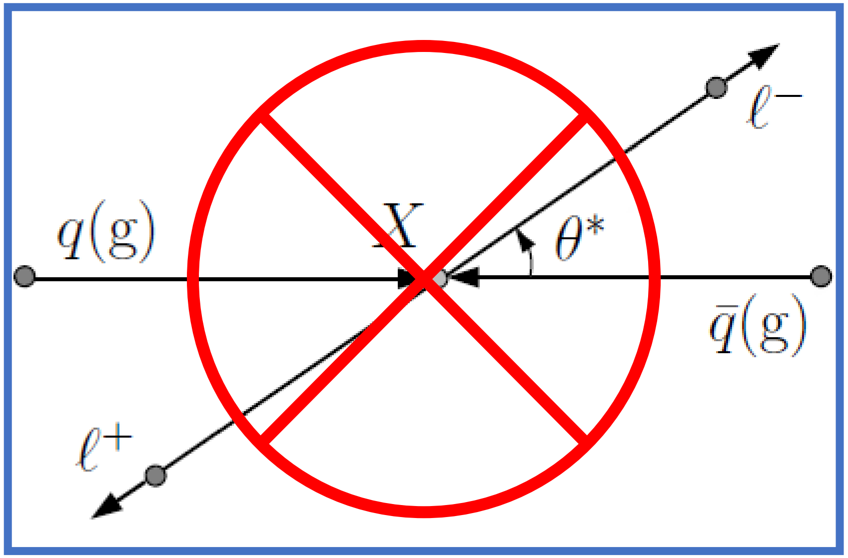

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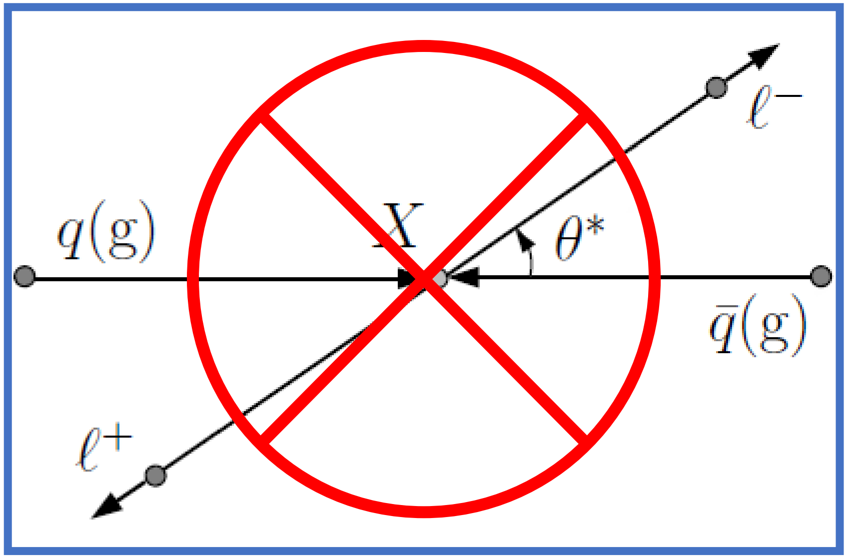

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$$\frac{d\sigma_{pp}\left(Y,\hat{s},\cos\theta^{*}\right)}{dY\,d\hat{s}\,d\cos\theta^{*}} \propto \sum_{q=u,d,s,c,b}\left[\hat{\sigma}_{q\overline{q}}^{even}\left(\hat{s},\cos\theta^{*}\right)+D_{q\overline{q}}\left(Y,\hat{s}\right)\hat{\sigma}_{q\overline{q}}^{odd}\left(\hat{s},\cos\theta^{*}\right)\right]F_{q\overline{q}}\left(Y,\hat{s}\right)$$

↓

$$A_{FB}\left(Y,\hat{s}\right)=\frac{\sigma_{F}\left(Y,\hat{s}\right)-\sigma_{B}\left(Y,\hat{s}\right)}{\sigma_{F}\left(Y,\hat{s}\right)+\sigma_{B}\left(Y,\hat{s}\right)}$$

4. Hadron colliders as probes of Zqq couplings

- The functional dependence on Y and $\hat{s}$ increases the number of independent observables at our disposal
- The measurement we will use is one of the angular coefficient A_4 ($A_{FB} = 3/8\, A_4$) coming from ATLAS:

|Y|	Experimental value	SM prediction
0.0 - 0.8	0.0195 ± 0.0015	0.0144 ± 0.0007
0.8 - 1.6	0.0448 ± 0.0016	0.0471 ± 0.0017
1.6 - 2.5	0.0923 ± 0.0026	0.0928 ± 0.0021
2.5 - 3.6	0.1445 ± 0.0046	0.1464 ± 0.0021

[ATLAS-CONF-2018-037 (2018)]

- This choice is motivated by the availability of a fully developed SM prediction [S. Catani, D. de Florian, G. Ferrera, and M. Grazzini ‘15]

4. Hadron colliders as probes of Zqq couplings

- **Restrictions from each bin:**

$$0.0 < |Y| < 0.8 : \quad 0.63\,\delta g_L^{Zu} + 0.71\,\delta g_R^{Zu} - 0.20\,\delta g_L^{Zd} - 0.22\,\delta g_R^{Zd} = 0.088(29)$$

$$0.8 < |Y| < 1.6 : \quad 0.60\,\delta g_L^{Zu} + 0.74\,\delta g_R^{Zu} - 0.18\,\delta g_L^{Zd} - 0.22\,\delta g_R^{Zd} = -0.012(12)$$

$$1.6 < |Y| < 2.5 : \quad 0.53\,\delta g_L^{Zu} + 0.80\,\delta g_R^{Zu} - 0.16\,\delta g_L^{Zd} - 0.23\,\delta g_R^{Zd} = -0.0014(92)$$

$$2.5 < |Y| < 3.6 : \quad 0.43\,\delta g_L^{Zu} + 0.86\,\delta g_R^{Zu} - 0.18\,\delta g_L^{Zd} - 0.21\,\delta g_R^{Zd} = -0.0030(81)$$

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- **Restrictions on the four uncorrelated and orthonormal linear combinations:**

$$\begin{pmatrix} x' = 0.21\delta g_L^{Zu} + 0.19\delta g_R^{Zu} + 0.46\delta g_L^{Zd} + 0.84\delta g_R^{Zd} \\ y' = 0.03\delta g_L^{Zu} - 0.07\delta g_R^{Zu} - 0.87\delta g_L^{Zd} + 0.49\delta g_R^{Zd} \\ z' = 0.83\delta g_L^{Zu} - 0.54\delta g_R^{Zu} + 0.02\delta g_L^{Zd} - 0.10\delta g_R^{Zd} \\ t' = 0.51\delta g_L^{Zu} + 0.82\delta g_R^{Zu} - 0.17\delta g_L^{Zd} - 0.22\delta g_R^{Zd} \end{pmatrix} = \begin{pmatrix} -10 \pm 4 \\ 0.5 \pm 0.4 \\ 0.04 \pm 0.06 \\ -0.001 \pm 0.005 \end{pmatrix}$$

4. Hadron colliders as probes of Zqq couplings

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\end{pmatrix}
=
\begin{pmatrix}
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\end{pmatrix}
$$

We are capable of obtaining per mille level constraints

4. Hadron colliders as probes of Zqq couplings

- **Impact on the global fit:**

$$\begin{pmatrix} x \\ y \\ z \\ t \end{pmatrix} = \begin{pmatrix} 0.004 \pm 0.017 \\ 0.010 \pm 0.032 \\ 0.021 \pm 0.046 \\ -0.03 \pm 0.19 \end{pmatrix}, \quad \rho = \begin{pmatrix} 1. & -0.09 & -0.08 & -0.04 \\ -0.09 & 1. & -0.09 & -0.93 \\ -0.08 & -0.09 & 1. & -0.19 \\ -0.04 & -0.93 & -0.19 & 1. \end{pmatrix}$$

→ The combination of LEP+LHC is good enough to lift the blind direction, but we are not as restrictive as we were in t', since $t \cdot t' = 0.16$

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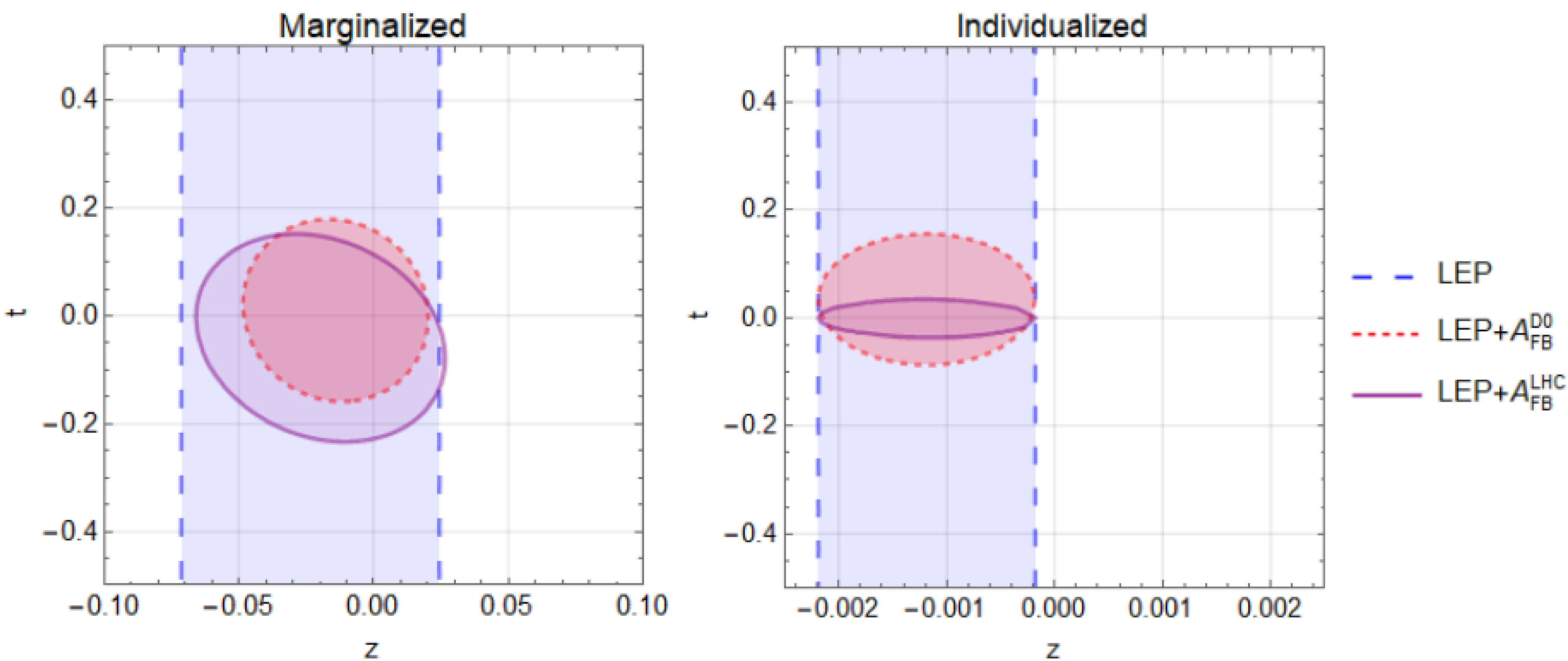

4. Hadron colliders as probes of Zqq couplings

- LHC constrains a specific direction much strongly than D0. Both hadron measurements are important for the global fit, although for simple scenarios LHC typically has a larger effect:

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$$\begin{pmatrix} \delta g_L^{Zu} \\ \delta g_R^{Zu} \\ \delta g_L^{Zd} \\ \delta g_R^{Zd} \end{pmatrix} = \begin{pmatrix} -0.012 \pm 0.024 \\ -0.005 \pm 0.032 \\ -0.020 \pm 0.037 \\ -0.03 \pm 0.13 \end{pmatrix}, \quad \rho = \begin{pmatrix} 1 & 0.51 & 0.68 & 0.69 \\ 0.51 & 1 & 0.56 & 0.94 \\ 0.68 & 0.56 & 1 & 0.54 \\ 0.69 & 0.94 & 0.54 & 1 \end{pmatrix}$$

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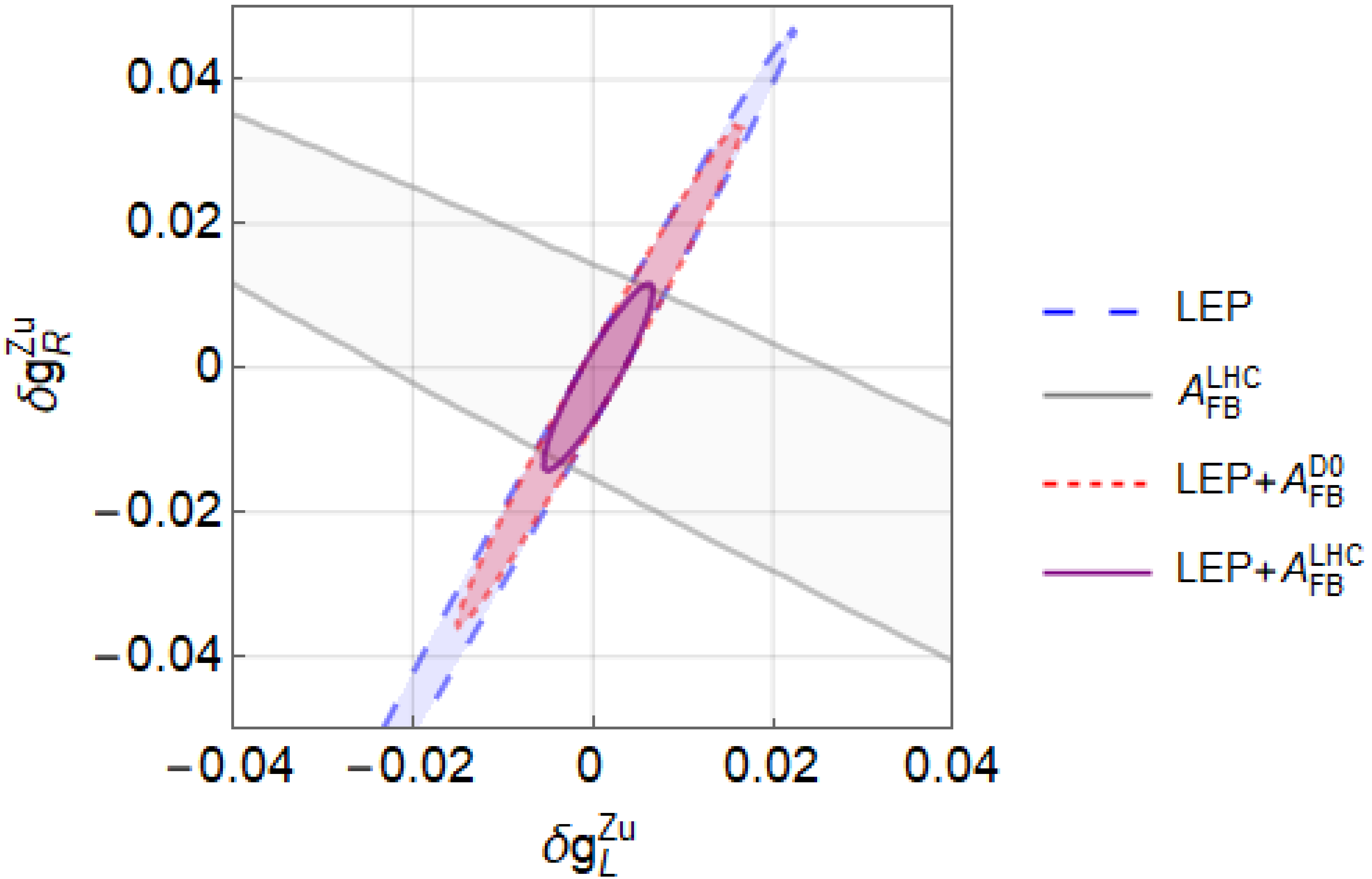
The other 16 parameters are also being fitted here, to almost no changes in their limits

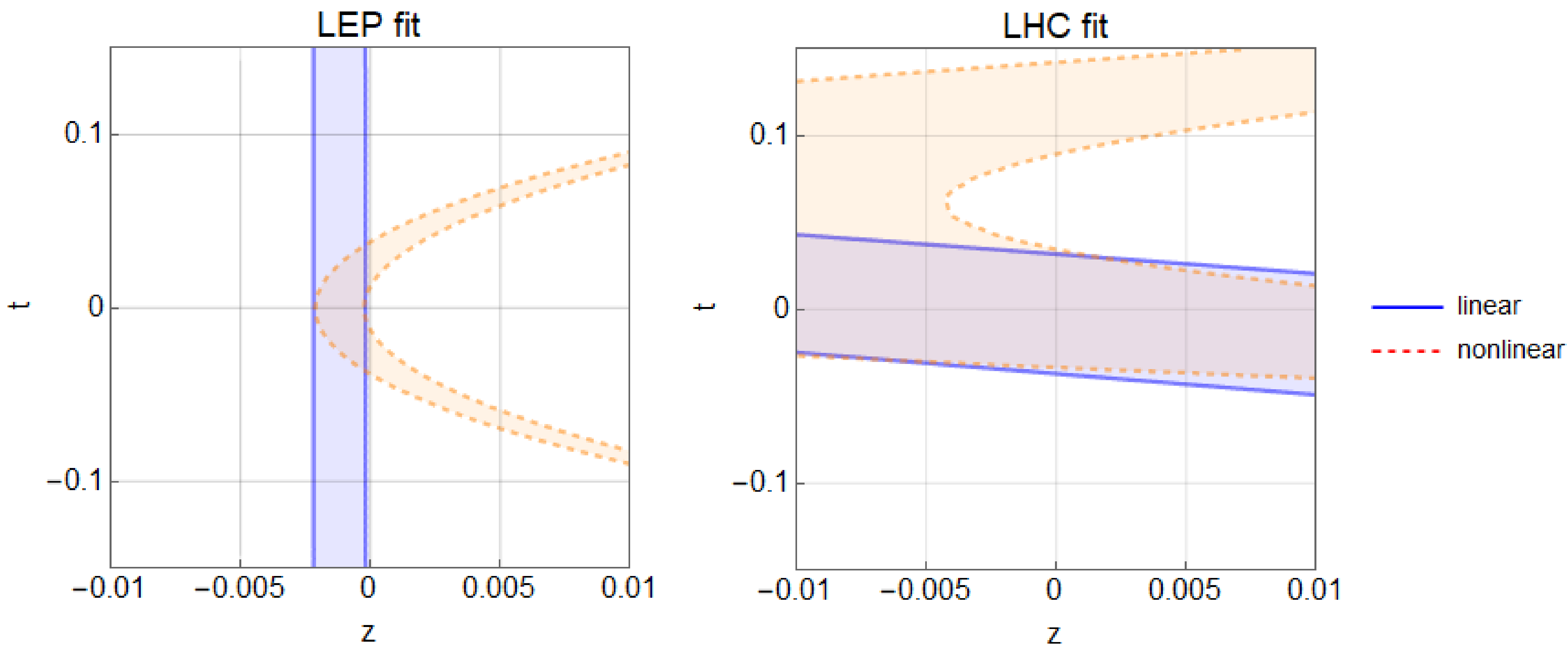
4. Hadron colliders as probes of Zqq couplings

- A_{FB}^{LHC} provides crucial information in simple NP scenarios:



4. Hadron colliders as probes of Zqq couplings

- The use of these two inputs leaves much less room for the inclusion of nonlinear contributions:



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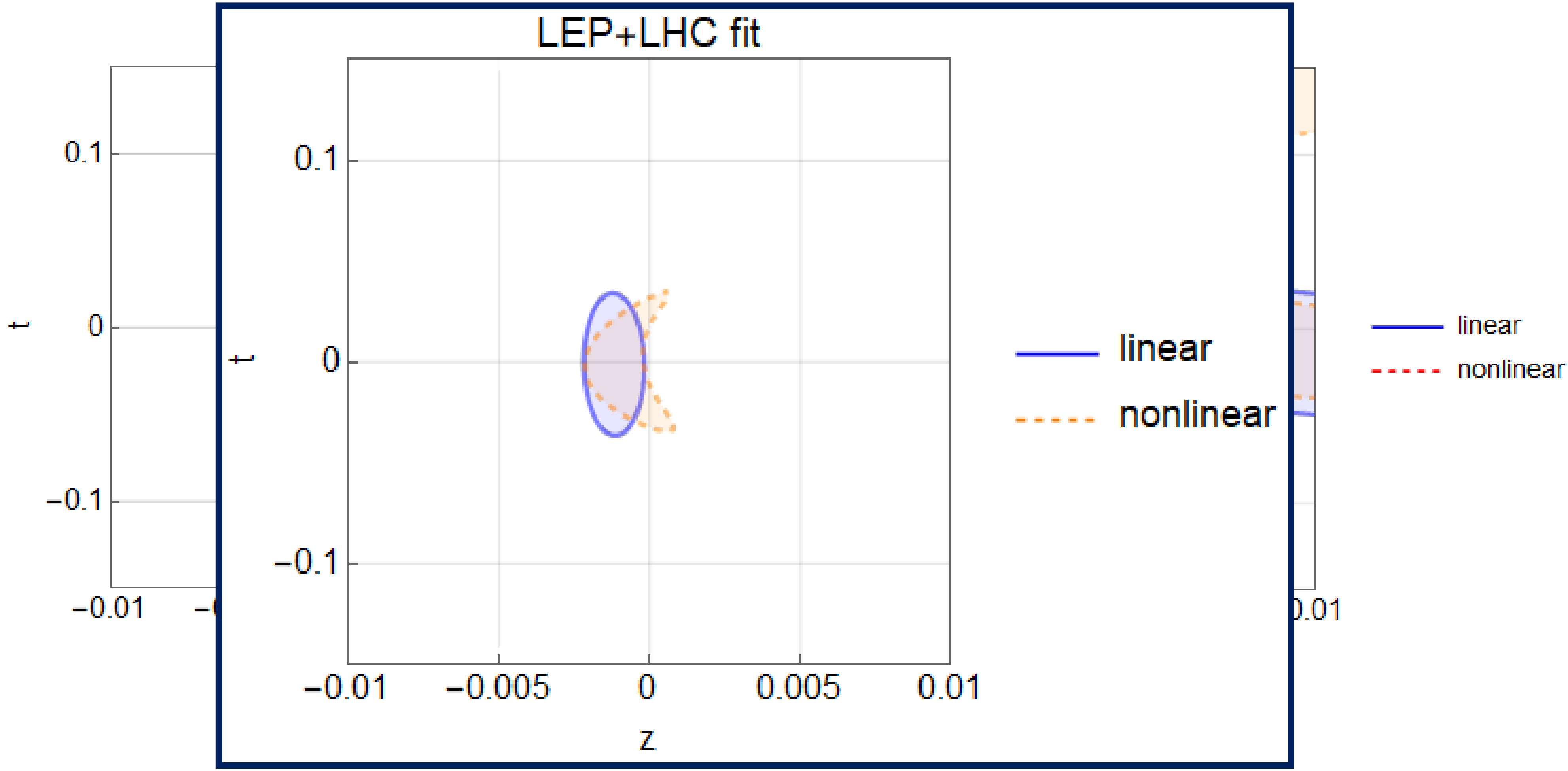
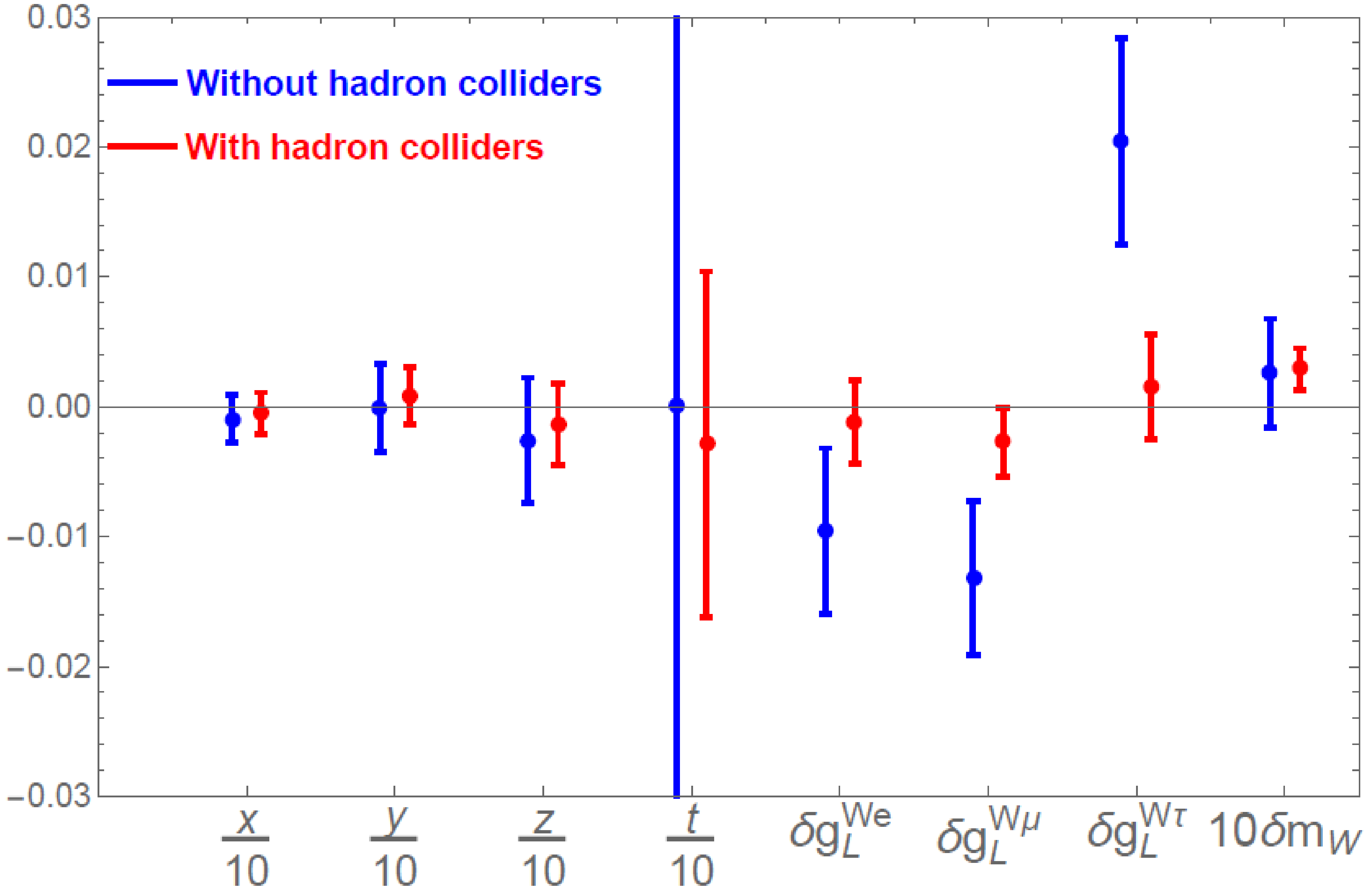


Side note: importance of hadron colliders for the EW fit



5. Conclusions

- We have discussed the impact of LHC Z-pole measurements on constraining the Wilson coefficients of dimension-6 operators in the SMEFT (mainly vertex corrections)

- Our main result is that the flat direction along the t variable is indeed lifted with the inclusion of the A_{FB} ATLAS input

- We find that the ATLAS A_{FB} information provides a significant improvement on LEP-only bounds on the Zqq vertex corrections even in simple scenarios with few free parameters

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- We have discussed the impact of LHC Z-pole measurements on constraining the Wilson coefficients of dimension-6 operators in the SMEFT (mainly vertex corrections)
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- We find that the ATLAS A_{FB} information provides a significant improvement on LEP-only bounds on the Zqq vertex corrections even in simple scenarios with few free parameters

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- **Outlook 1:** Current and future measurements of Drell-Yan dilepton production by LHC could be analyzed following a similar procedure to ours in order to extend the impact of hadron colliders on the electroweak precision program
- **Outlook 2:** Information from Drell-Yan cross sections (in addition to asymmetries) could be added, and the off-pole data could be analyzed at the same time in the context of a more general fit to both vertex corrections and 4-fermion operators

EXTRA SLIDES

Backup 1: Allowed regions for some simple NP settings