Precision Z physics at the LHC in the flavorful SMEFT

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In collaboration with

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arXiv:[2103.12074]

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1. Introduction

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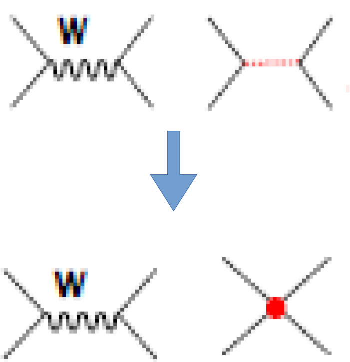
General framework: SMEFT



NP ~ 10 TeV

SM ~ 1 TeV

$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

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

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Precise measurements: LEP + LHC

- 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

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- **Could it be that LHC can also compete with or complement LEP by means of the measurements it can provide for the Z observables?**

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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 are sensitive to the Zff couplings

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

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

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

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Flavor-general corrections!!

[Efrati, Falkowski & Soreq '15; Falkowski & Mimouni '15; Falkowski, González-Alonso & Mimouni '17; Aebischer et al. '18; …]

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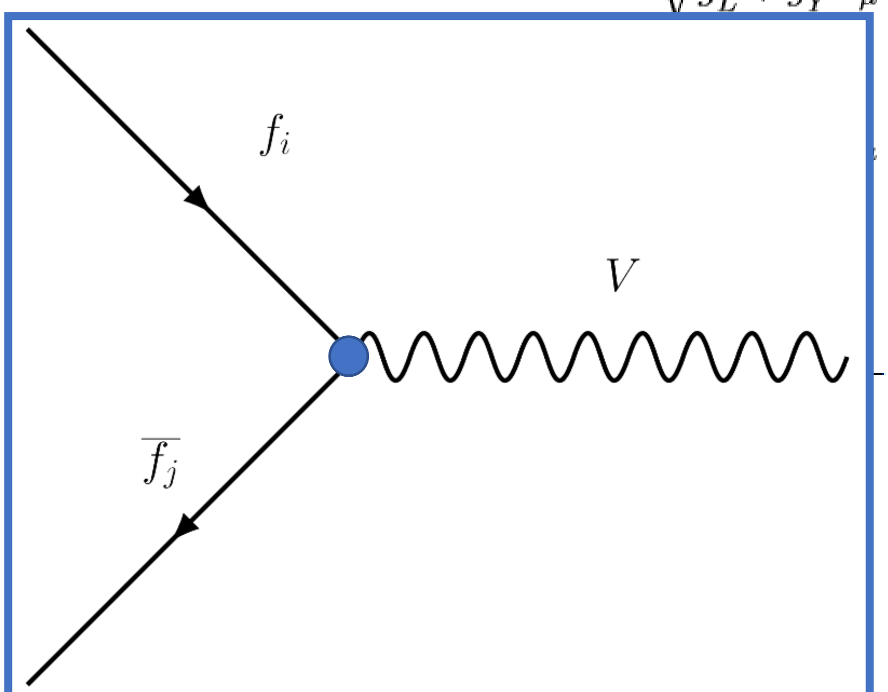

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\mathcal{L}_{\rm SMEFT} \supset \frac{g_L^2 v^2}{4}(1+\delta m_w)^2 W_\mu^+ W_\mu^- + \ldots
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We end up with only 20 independent parameters

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

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:

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

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

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

[Update of Efrati, Falkowski & Soreq '15]

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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: $|t| < 0.2$

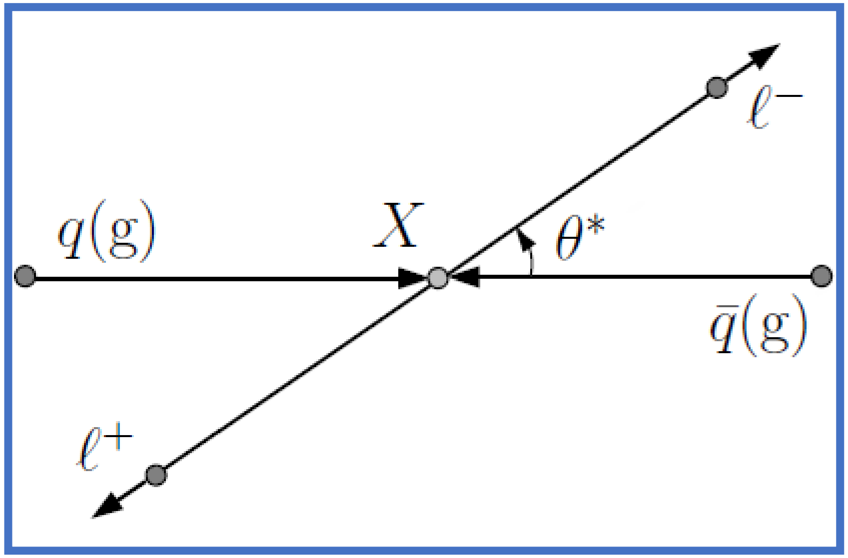
- ***t* unconstrained. Can we use LHC data to restrict it?**

4. The A_{FB} asymmetry at the LHC

- We find that the cleanest observable for the task at hand is the Drell-Yan forward-backward asymmetry (A_{FB})

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

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



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$f(Zqq)$

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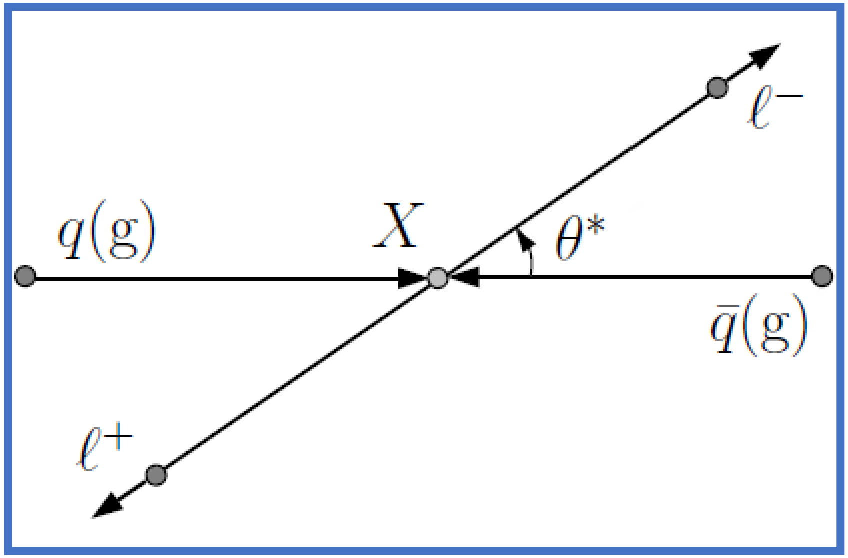

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$$A_{FB}\left(Y,\hat{s}\right) = \frac{\sigma_F\left(Y,\hat{s}\right) - \sigma_B\left(Y,\hat{s}\right)}{\sigma_F\left(Y,\hat{s}\right) + \sigma_B\left(Y,\hat{s}\right)} = SM(1 + \#\delta g_i + \cdots)$$

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$\|Y\|$	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

Exp. value: [ATLAS-CONF-2018-037 (2018)]
NNLO in QCD SM prediction:
[Bozzi et al., 1007.2351;
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- **Restrictions from each bin:**

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

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

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

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We are capable of obtaining per mille level constraints

- **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 in t', since $t \cdot t' = 0.16$

4. The A_{FB} asymmetry at the LHC

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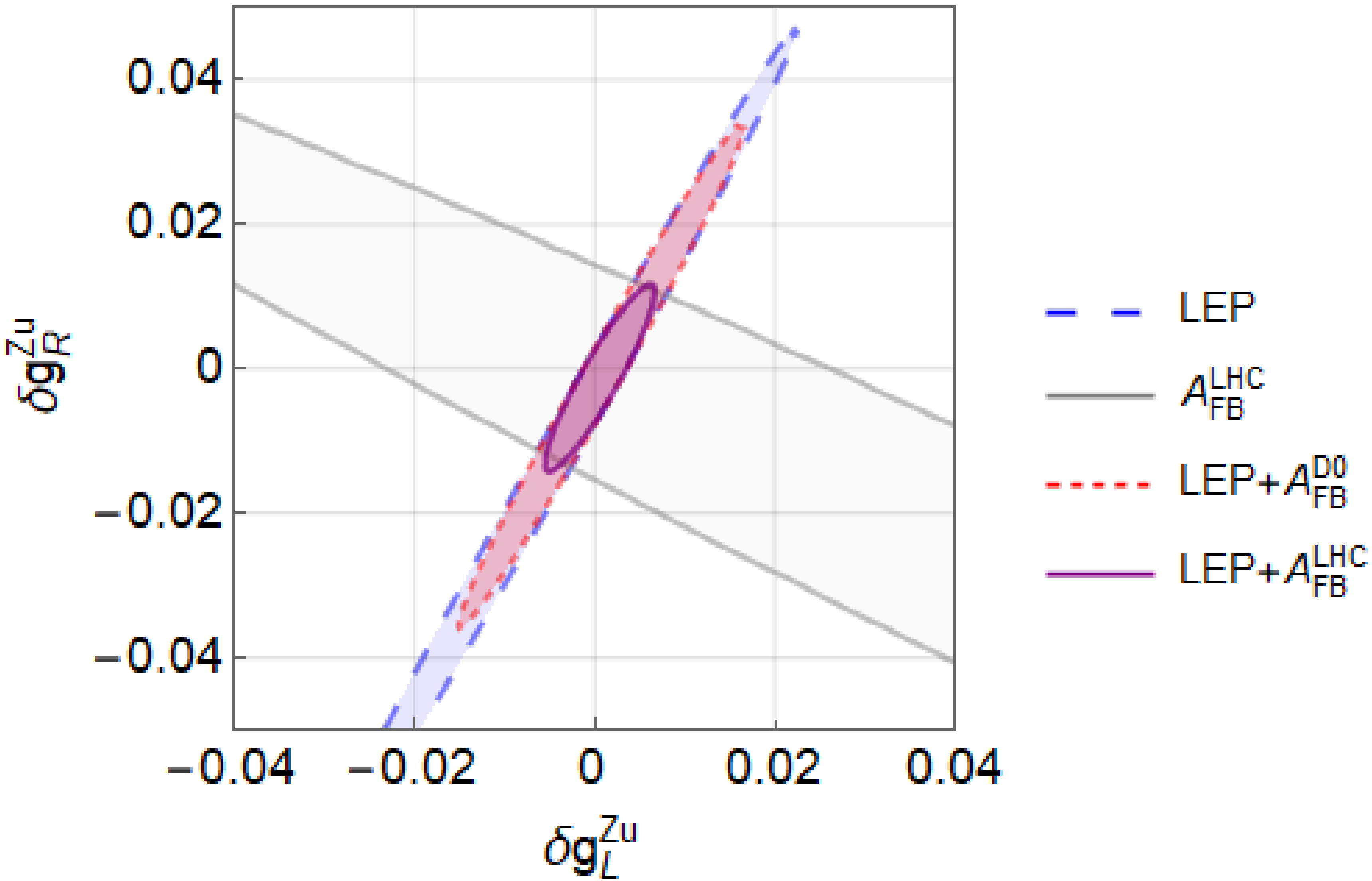
- LHC constrains a specific direction much strongly than D0. Both hadron measurements are important for the global fit, although for simple scenarios LHC has a larger effect. All in all, **"traditional pole" observables + ATLAS + D0** give:

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

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

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



5. Conclusions

- LHC A_{FB} provides ~0.5% bounds on Zqq corrections

$$0.51\delta g_L^{Zu} + 0.82\delta g_R^{Zu} - 0.17\delta g_L^{Zd} - 0.22\delta g_R^{Zd} = -0.001 \pm 0.005$$

- **The t variable is 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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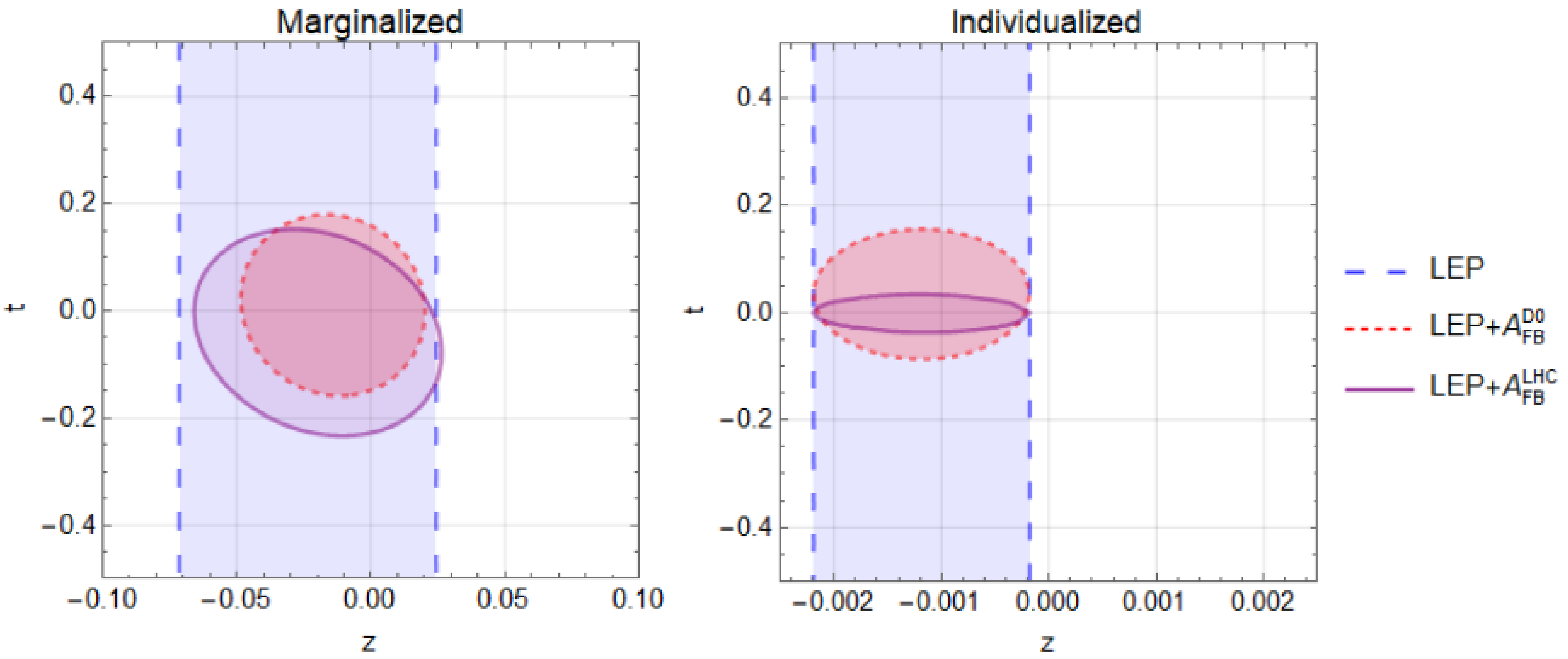
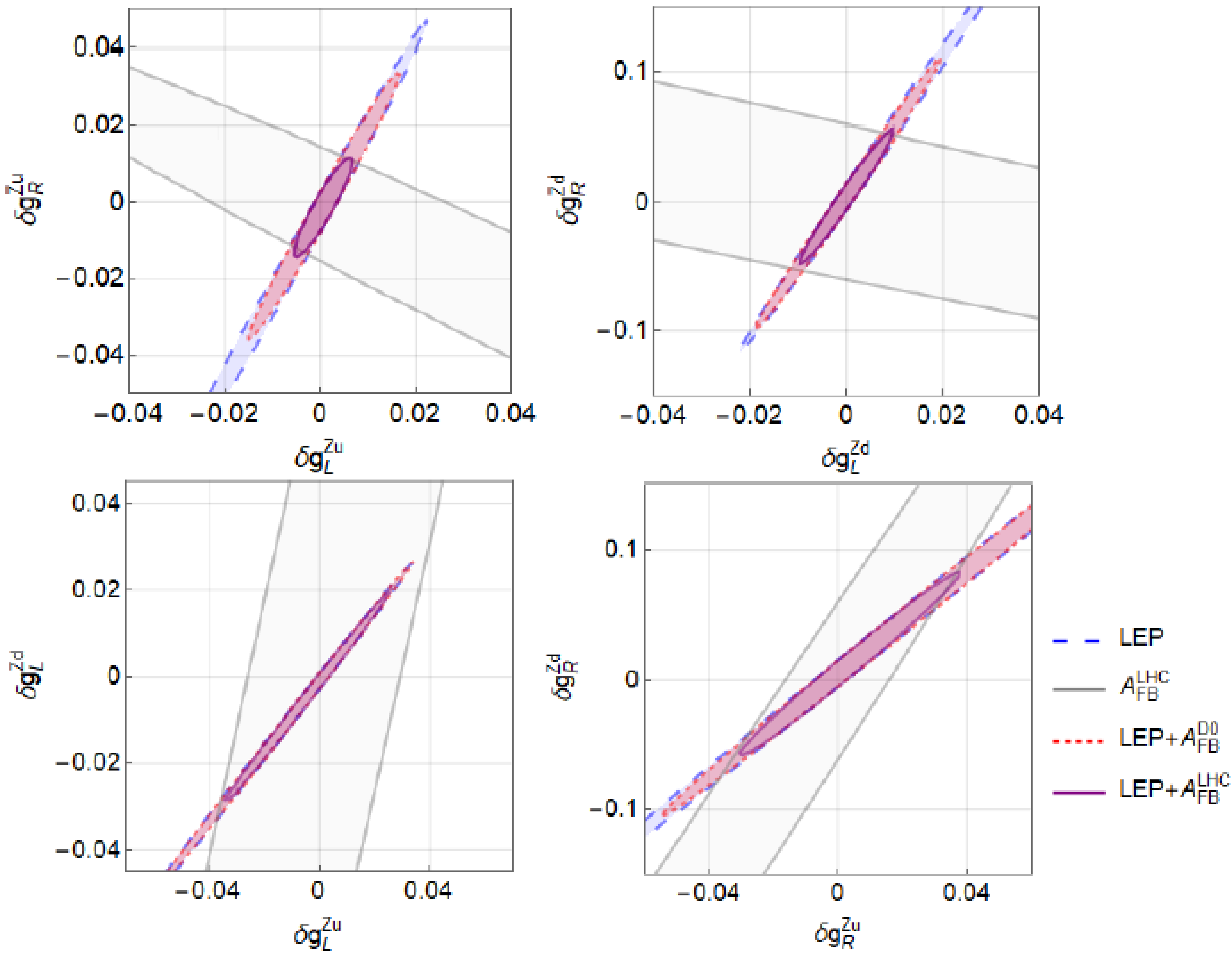
- **Outlook 1:** Current and future measurements of Drell-Yan dilepton production by LHC could be analyzed following a similar procedure to ours in order to extend the impact of hadron colliders on the electroweak precision program
- **Outlook 2:** Information from Drell-Yan cross sections could be added, and off-pole data could be analyzed too ($\longrightarrow$ LLQQ operators enter)

EXTRA SLIDES

Backup 1: A_{FB} impact on the global SMEFT fit



Backup 2: Allowed regions for some simple NP settings



4. The A_{FB} asymmetry at the LHC

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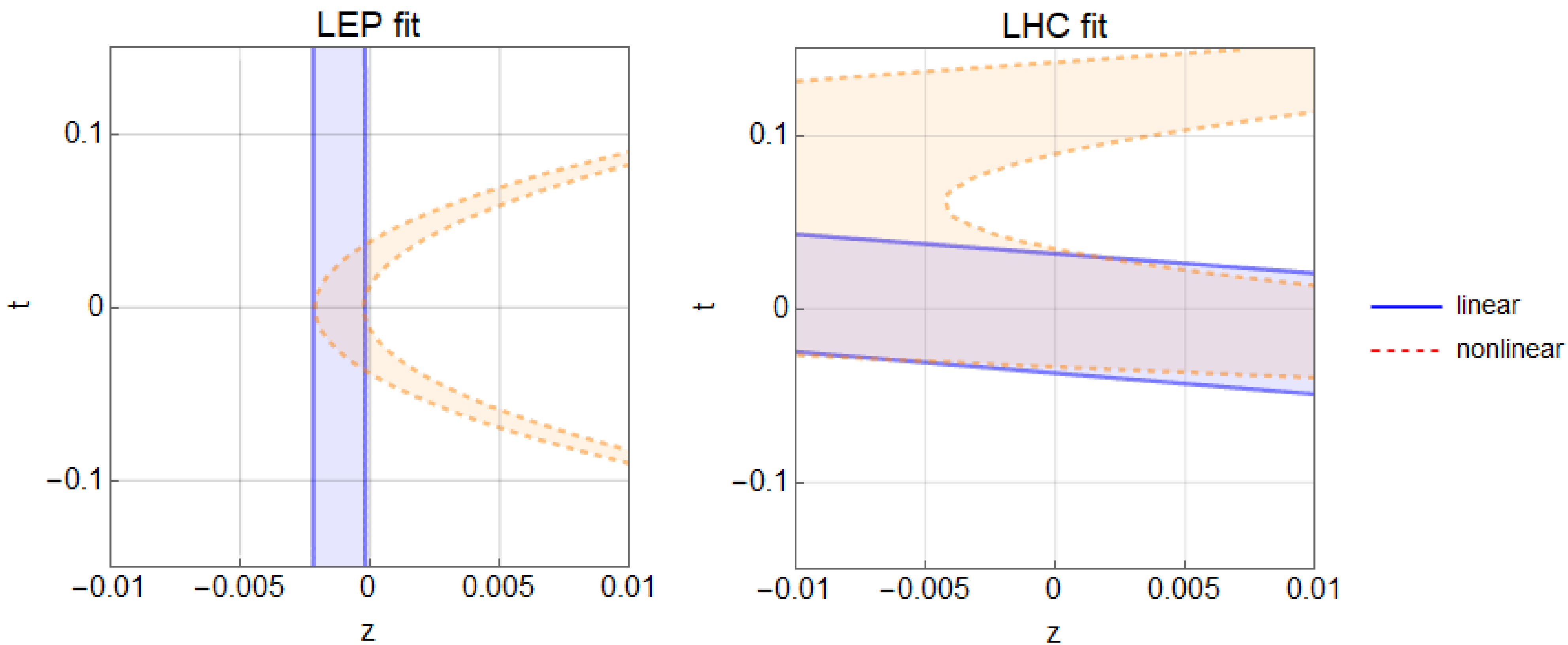

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