

# SMEFT fit for 4-fermion and CP-violating interactions

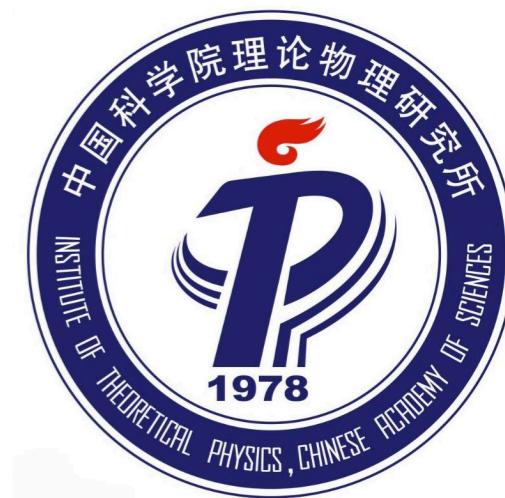
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Seattle Community Summer Study, July 21, 2022

Based on Snowmass white paper [2206.08326](#), with Jorge de Blas, Christophe Grojean, Jiayin Gu, Victor Miralles, Michael Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou

Disclaimer: Given the very specific topic chosen here, I apologize if your work is not mentioned.



# SMEFT global fit: Some remarks

Overall goal of our team: Fit 1 for Higgs+EW, fit 2 for 4-fermion operators, fit 3 for top, and fit 4 for CPV operators.

Higgs + EW fit at the (HL)LHC and muon colliders (See Jorge de Blas' talk)

Higgs + EW fit including helicity conserving 4-fermion operators (See Michael Peskin's talk)

Top fit (See Victor Miralles' talk)

Flavor diagonal 4-fermion and CPV fit (this talk)

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Flavor diagonal 4-fermion and CPV fit (this talk)

Some words on the flavors:

U35, top specific, MFV, U23...

No flavor assumptions are made for this study.

Han et al, PRD 71 075009 (2005)  
Falkowski et al, JHEP 02 (2015) 039  
Berthier et al, JHEP 02 (2016) 069 ,  
JHEP 09 (2016) 157  
Ellis et al, JHEP 04 (2021) 279, JHEP  
06 (2018) 146

Ellis et al, JHEP 03 (2015) 157  
Pomarol et al, JHEP 01 (2014) 151  
Grojean et al, JHEP 03 (2019) 020  
Hartland et al, JHEP 04 (2019) 100  
Aoude et al, JHEP 12 (2020) 113  
Brivio et al, JHEP 02 (2020) 131  
.....

# SMEFT global fit: Outline

- Fit 2: 4-fermion interactions
- Fit 4: Bosonic CPV operators
- Global fit on some benchmark models (*time permitting*)
  - ❖ Comparison with ESU results
  - ❖ The Y-Universal Z' model
  - ❖ The leptoquark model
- Summary and outlook

## **Fit 2: 4-fermion operators**

# SMEFT global fit 2: Setup

We work in the Higgs basis

Efrati et al, JHEP 07(2015) 018  
Falkowski et al, JHEP 02 (2016) 086  
Falkowski et al, JHEP 08 (2017) 123

$$\begin{aligned}\mathcal{L} \supset & e A^\mu \sum_{f=u,d,e} Q_f (\bar{f}_I \bar{\sigma}_\mu f_I + f_I^c \sigma_\mu \bar{f}_I^c) \\ & + \frac{g_L}{\sqrt{2}} \left[ W^{\mu+} \bar{\nu}_I \bar{\sigma}_\mu (\delta_{IJ} + [\delta g_L^{W\ell}]_{IJ}) e_J + W^{\mu+} \bar{u}_I \bar{\sigma}_\mu \left( V_{IJ} + [\delta g_L^{Wq}]_{IJ} \right) d_J + \text{h.c.} \right] \\ & + \frac{g_L}{\sqrt{2}} \left[ W^{\mu+} u_I^c \sigma_\mu \left[ \delta g_R^{Wq} \right]_{IJ} \bar{d}_J^c + \text{h.c.} \right] \\ & + \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{f=u,d,e,\nu} \bar{f}_I \bar{\sigma}_\mu \left( (T_3^f - s_w^2 Q_f) \delta_{IJ} + [\delta g_L^{Zf}]_{IJ} \right) f_J \\ & + \sqrt{g_L^2 + g_Y^2} Z^\mu \sum_{f=u,d,e} f_I^c \sigma_\mu \left( -s_w^2 Q_f \delta_{IJ} + [\delta g_R^{Zf}]_{IJ} \right) \bar{f}_J^c,\end{aligned}$$

W mass correction  $m_W(1 + \delta m)$  cannot be absorbed though field redefinition, but  $\delta m$  will be stringently constrained by LEP-W data at  $\mathcal{O}(10^{-4})$ .

# SMEFT global fit 2: Setup

We only consider flavor conserving 4-fermion operators

$2\ell 2q$ operators ( $p, r = 1, 2, 3$ )	$4\ell$ operators ( $p < r = 1, 2, 3$ )
Chirality conserving	Two flavors
$[\mathcal{O}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell\ell}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_r \bar{\sigma}^\mu \ell_r)$
$[\mathcal{O}_{\ell q}^{(3)}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \sigma^i \ell_p)(\bar{q}_r \bar{\sigma}^\mu \sigma^i q_r)$	$[\mathcal{O}_{\ell\ell}]_{prrp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_r)(\bar{\ell}_r \bar{\sigma}^\mu \ell_p)$
$[\mathcal{O}_{\ell u}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(u_r^c \sigma^\mu \bar{u}_r^c)$	$[\mathcal{O}_{\ell e}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e_r^c \sigma^\mu \bar{e}_r^c)$
$[\mathcal{O}_{\ell d}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(d_r^c \sigma^\mu \bar{d}_r^c)$	$[\mathcal{O}_{\ell e}]_{rrpp} = (\bar{\ell}_r \bar{\sigma}_\mu \ell_r)(e_p^c \sigma^\mu \bar{e}_p^c)$
$[\mathcal{O}_{eq}]_{pprr} = (e_p^c \sigma_\mu \bar{e}_p^c)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell e}]_{prrp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_r)(e_r^c \sigma^\mu \bar{e}_p^c)$
$[\mathcal{O}_{eu}]_{pprr} = (e_p^c \sigma_\mu \bar{e}_p^c)(u_r^c \sigma^\mu \bar{u}_r^c)$	$[\mathcal{O}_{ee}]_{pprr} = (e_p^c \sigma_\mu \bar{e}_p^c)(e_r^c \sigma^\mu \bar{e}_r^c)$
$[\mathcal{O}_{ed}]_{pprr} = (e_p^c \sigma_\mu \bar{e}_p^c)(d_r^c \sigma^\mu \bar{d}_r^c)$	
Chirality violating	One flavor
$[\mathcal{O}_{lequ}]_{pprr} = (\bar{\ell}_p^j \bar{e}_p^c) \epsilon_{jk} (\bar{q}_r^k \bar{u}_r^c)$	$[\mathcal{O}_{\ell\ell}]_{pppp} = \frac{1}{2} (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_p \bar{\sigma}^\mu \ell_p)$
$[\mathcal{O}_{lequ}^{(3)}]_{pprr} = (\bar{\ell}_p^j \bar{\sigma}_{\mu\nu} \bar{e}_p^c) \epsilon_{jk} (\bar{q}_r^k \bar{\sigma}_{\mu\nu} \bar{u}_r^c)$	$[\mathcal{O}_{\ell e}]_{pppp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e_p^c \sigma^\mu \bar{e}_p^c)$
$[\mathcal{O}_{ledq}]_{pprr} = (\bar{\ell}_p^j \bar{e}_p^c)(d_r^c q_r^j)$	$[\mathcal{O}_{ee}]_{pppp} = \frac{1}{2} (e_p^c \sigma_\mu \bar{e}_p^c)(e_p^c \sigma^\mu \bar{e}_p^c)$

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Chirality conserving		Two flavors	
$\sum_i h_i = 0$	$[\mathcal{O}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell\ell}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_r \bar{\sigma}^\mu \ell_r)$	$\sum_i h_i = 0$
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Chirality violating		One flavor	
$\sum_i h_i = \pm 2$	$[\mathcal{O}_{\ell equ}]_{pprr} = (\bar{\ell}_p^j \bar{e}_p^c) \epsilon_{jk} (\bar{q}_r^k \bar{u}_r^c)$	$[\mathcal{O}_{\ell\ell}]_{pppp} = \frac{1}{2} (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_p \bar{\sigma}^\mu \ell_p)$	$\sum_i h_i = 0$
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Interference with the SM can be easily seen from the helicity selection rules, but the chirality violating ones are needed to lift some flat directions.

Cheung et al, PRL 115 071601 (2015)  
Azatov et al, PRD 95 065014 (2017)  
Jiang et al, PRL 126 011601 (2021)

# SMEFT global fit 2: Setup

18 : $(\bar{L}L)(\bar{L}L)H^2$		$\sum_i h_i = 0$
$Q_{l^4 H^2}^{(1)}$		$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu l_t)(H^\dagger H)$
$Q_{l^4 H^2}^{(2)}$		$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma_\mu \tau^I l_t)(H^\dagger \tau^I H)$

One readily obtains the helicity amplitudes

$$M(1^-, 2^+, 3^-, 4^+, 5_l^0, 6_m^0) = -\frac{2c_{l^4 H^2}^{(1)} H_l^\dagger H_m \delta_{lm}}{\Lambda^4} \langle 14 \rangle [23]$$

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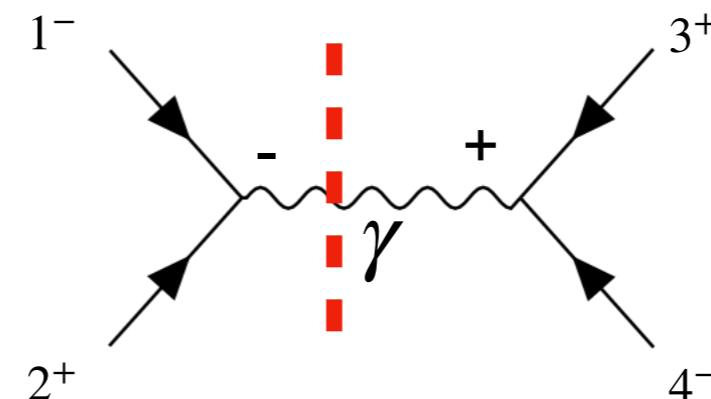
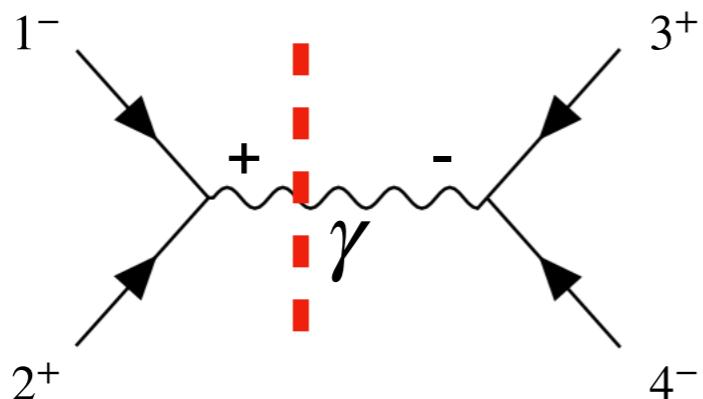
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$$M(1^-, 2^+, 3^-, 4^+)_{\gamma, \text{SM}} = -\frac{2e^2}{s} \langle 14 \rangle [23]$$



\* Drawn with qgraf

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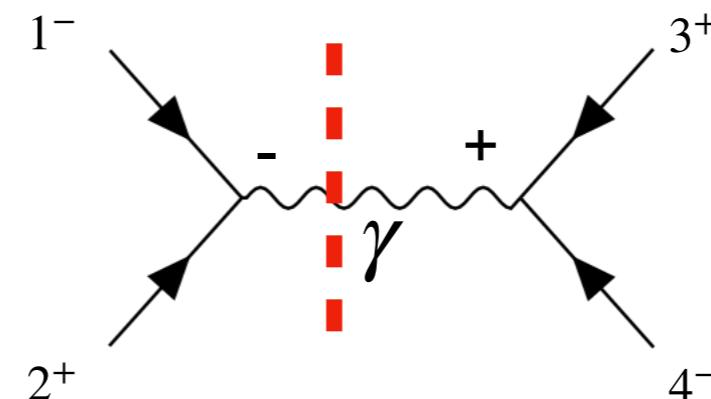
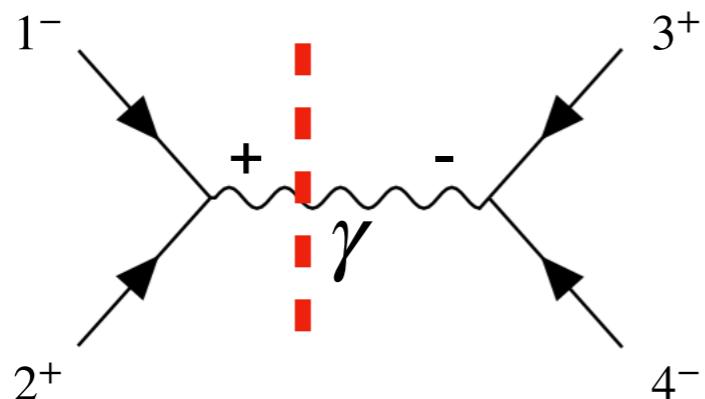
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$$M(1^-, 2^+, 3^-, 4^+)_{\gamma, \text{SM}} = -\frac{2e^2}{s} \langle 14 \rangle [23]$$

$$\begin{aligned} M_{\text{int}}^2 &= \frac{4e^2 c_{l^4 H^2}^{(1)} v^2}{s \Lambda^4} \langle 14 \rangle [23] (\langle 14 \rangle [23])^* \\ &= 4e^2 c_{l^4 H^2}^{(1)} \frac{v^2 u^2}{s \Lambda^4} \end{aligned}$$



\* Drawn with qgraf

## SMEFT global fit 2: *Strategy*

- All observables are analytically re-derived, keeping also the  $(\text{dim-6})^2$  terms.
- For the global fit discussed below, only linear dim-6 corrections are included.
- For consistency, dim-8 operators are always ignored and left for future.

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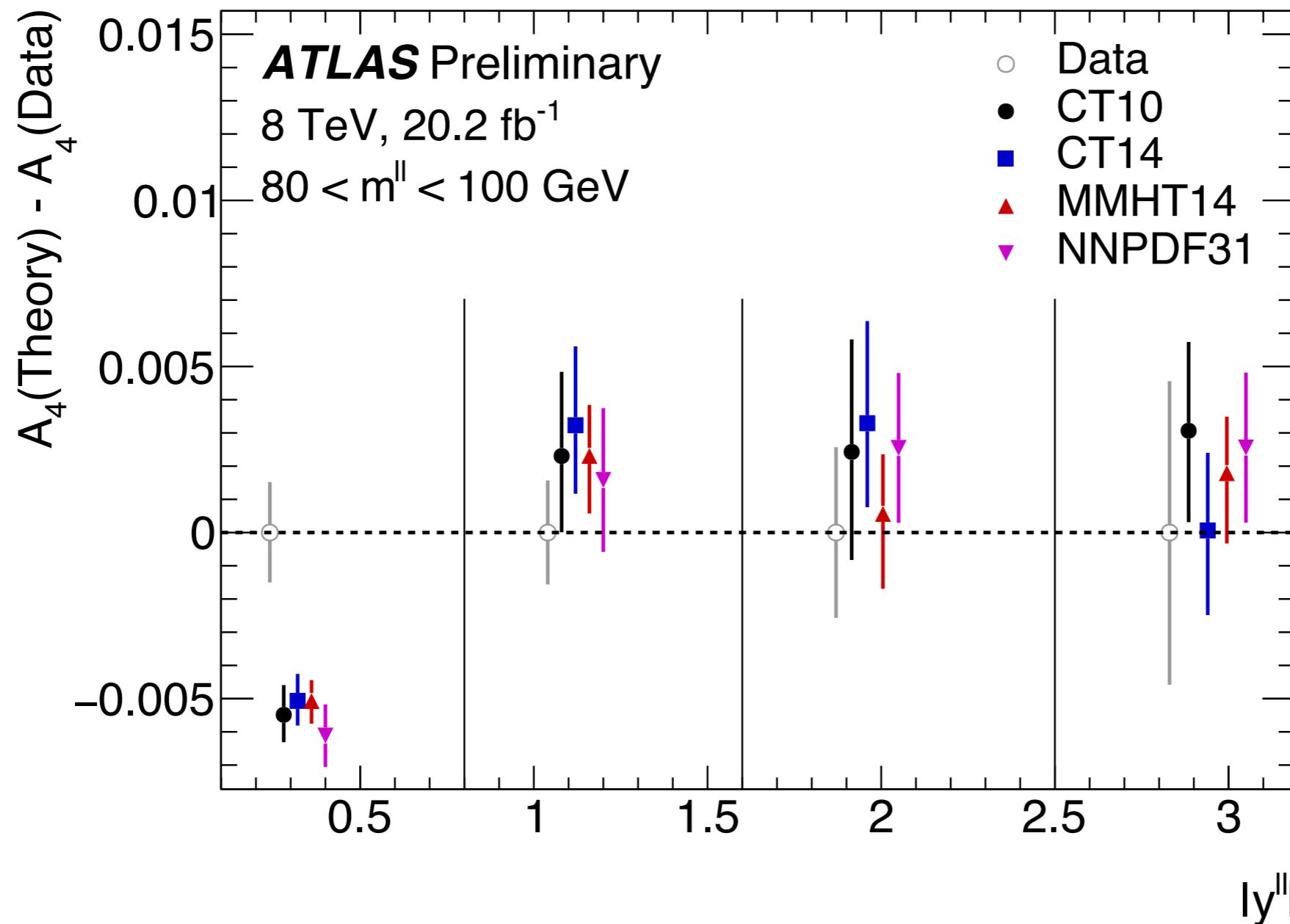
Alioli, Boughezal, Petriello, 2003.11615  
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Ellis, He, Xiao, 2008.04298  
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Jin, Ren, Yang, 2011.02494  
Gu, Wang, Zhang, 2011.03055  
Dedes, Kozow, Szleper, 2011.03367  
Bonnefoy, Gendy, Grojean, 2011.12855  
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Kim, Martin, 2203.11976  
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Boughezal, Petriello, Wiegand, 2104.03979  
Boughezal, Mereghetti, Petriello, 2106.05337  
Chala, Guedes, Ramos, Santiago, 2106.05291  
Chala, Santiago, 2110.01624

Dawson, Homiller, Sullivan, 2110.06929  
Chala, Diaz-Carmona, Guedes, 2112.12724  
Cen Zhang, 2112.11665  
Li, Mimasu, Yamashita, Yang et al, 2204.13121  
Dawson, Fontes, Homiller, Sullivan, 2205.01561  
Bakshi, Chala, Diaz-Carmona, Guedes, 2205.03301  
Boughezal, Huang, Petriello, 2207.01703  
Hamoudou, Kumar, London, 2207.08856  
.....

# SMEFT global fit 2: Strategy

$R_{uc}, g_{Zu,Zd}^{D0}, A_{FB}^{pp \rightarrow \ell\bar{\ell}}$ : To eliminate the flat directions in the fit for EWPOs and allow for a precision determination of  $\delta g_{L,R}^{Zu,Zd}$

Breso-Pla, Falkowski, Gonzalez-Alonso, JHEP 08 (2021) 021

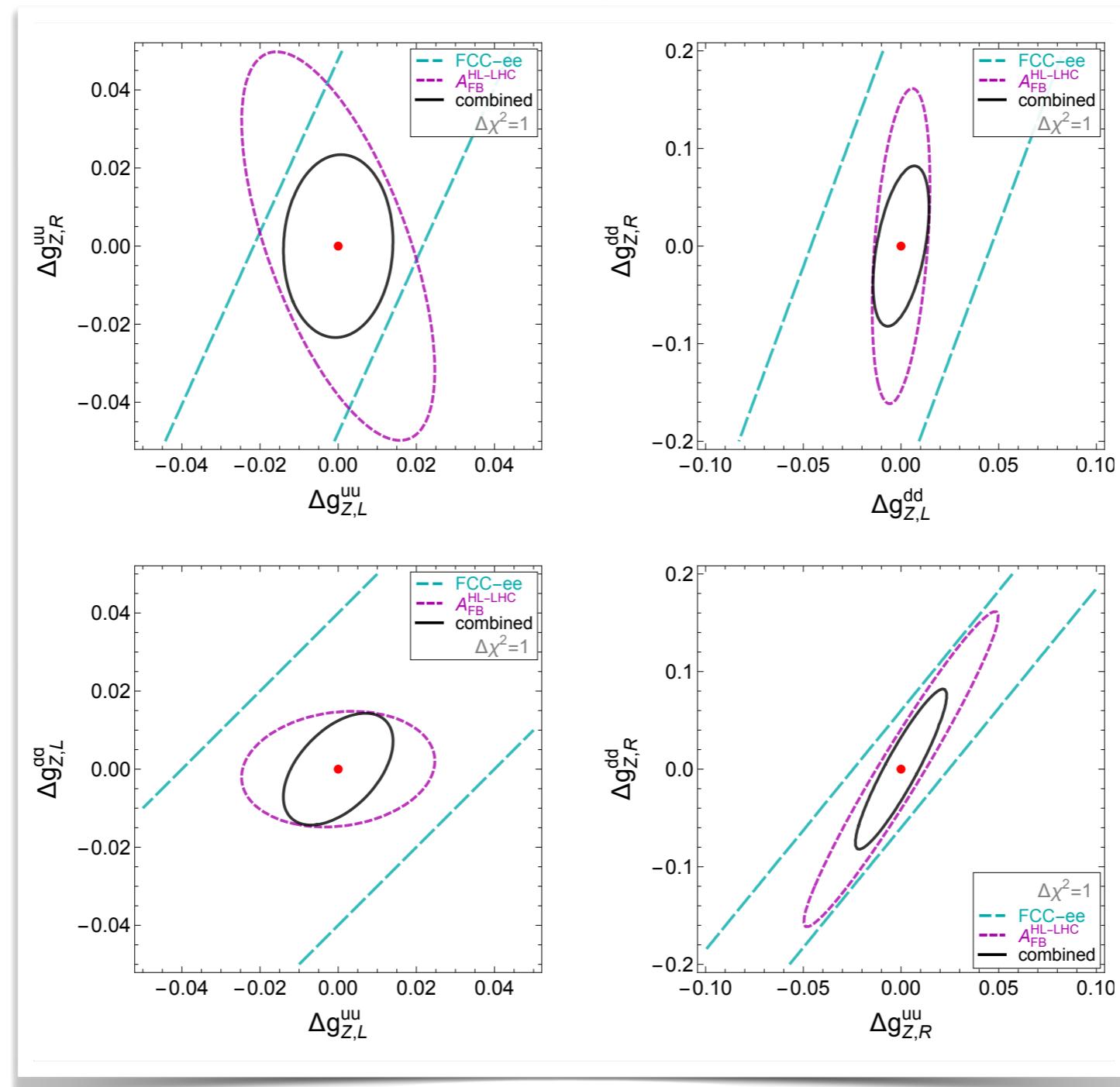


ATLAS-CONF-2018-037

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AFB input from:  
 SMP-16-007-pas  
 ATL-PHYS-PUB-2018-037  
 ATLAS-CONF-2018-037

## SMEFT global fit 2: Strategy

Optimal observables are used to improve sensitivity for  $A_{\text{FB}}^{ff}$  and  $\sigma_{ff}$  at future (polarized) lepton colliders:

$$\frac{d\sigma}{d\Omega} = S_0 + \sum_i S_{1,i} \delta g_i$$

$$c_{ij}^{-1} = \int d\Omega \frac{S_{1,i} S_{1,j}}{S_0} \cdot \mathcal{L} \cdot \epsilon$$

$f$	cos $\theta$ cutoff	total efficiency	efficiency incl. charge tagging
$e, \mu$	0.95	98%	98%
$\tau$	0.90	90%	90%
$c$	0.90	8.2%	3%
$b$	0.90	33%	15%

\* Thanks to Adrain Irles.

\* Systematical errors not implemented.

# SMEFT global fit 2: Low-energy observables

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Process	Observable	Experimental value	Ref.	SM prediction
$(-) \nu_\mu - e^-$ scattering	$g_{LV}^{\nu_\mu e}$ $g_{LA}^{\nu_\mu e}$	$-0.035 \pm 0.017$ $-0.503 \pm 0.017$	CHARM-II [47]	$-0.0396$ [48] $-0.5064$ [48]
$\tau$ decay	$\frac{G_{\tau e}^2}{G_F^2}$ $\frac{G_{\tau \mu}^2}{G_F^2}$	$1.0029 \pm 0.0046$ $0.981 \pm 0.018$	PDG2014 [49]	1
Neutrino scattering	$R_{\nu_\mu}$	$0.3093 \pm 0.0031$	CHARM ( $r = 0.456$ ) [50]	0.3156 [50]
	$R_{\bar{\nu}_\mu}$	$0.390 \pm 0.014$		0.370 [50]
	$R_{\nu_\mu}$	$0.3072 \pm 0.0033$	CDHS ( $r = 0.393$ ) [51]	0.3091 [51]
	$R_{\bar{\nu}_\mu}$	$0.382 \pm 0.016$		0.380 [51]
	$\kappa$	$0.5820 \pm 0.0041$	CCFR [52]	0.5830 [52]
	$R_{\nu_e \bar{\nu}_e}$	$0.406^{+0.145}_{-0.135}$	CHARM [53]	0.33 [54]
Parity-violating scattering	$(s_w^2)^{\text{Møller}}$	$0.2397 \pm 0.0013$	SLAC-E158 [55]	$0.2381 \pm 0.0006$ [56]
	$Q_W^{\text{Cs}}(55, 78)$	$-72.62 \pm 0.43$	PDG2016 [54]	$-73.25 \pm 0.02$ [54]
	$Q_W^{\text{P}}(1, 0)$	$0.064 \pm 0.012$	QWEAK [57]	$0.0708 \pm 0.0003$ [54]
	$A_1$	$(-91.1 \pm 4.3) \times 10^{-6}$	PVDIS [58]	$(-87.7 \pm 0.7) \times 10^{-6}$ [58]
	$A_2$	$(-160.8 \pm 7.1) \times 10^{-6}$		$(-158.9 \pm 1.0) \times 10^{-6}$ [58]
	$g_{VA}^{eu} - g_{VA}^{ed}$	$-0.042 \pm 0.057$ $-0.12 \pm 0.074$	SAMPLE ( $\sqrt{Q^2} = 200$ MeV) [59] SAMPLE ( $\sqrt{Q^2} = 125$ MeV) [59]	-0.0360 [54] 0.0265 [54]
	$b_{\text{SPS}}$	$-(1.47 \pm 0.42) \times 10^{-4} \text{ GeV}^{-2}$ $-(1.74 \pm 0.81) \times 10^{-4} \text{ GeV}^{-2}$	SPS ( $\lambda = 0.81$ ) [60] SPS ( $\lambda = 0.66$ ) [60]	$-1.56 \times 10^{-4} \text{ GeV}^{-2}$ [60] $-1.57 \times 10^{-4} \text{ GeV}^{-2}$ [60]
$\tau$ polarization	$\mathcal{P}_\tau$ $\mathcal{A}_\mathcal{P}$	$0.012 \pm 0.058$ $0.029 \pm 0.057$	VENUS [61]	0.028 [61] 0.021 [61]
Neutrino trident production	$\frac{\sigma}{\sigma^{\text{SM}}}(\nu_\mu \gamma^* \rightarrow \nu_\mu \mu^+ \mu^-)$	$0.82 \pm 0.28$	CCFR [62–64]	1
$d_I \rightarrow u_J \ell \bar{\nu}_\ell(\gamma)$	$\epsilon_{L,R,S,P,T}^{de_J}$	See text	[65]	0

Polarized asymmetry at KEK-B to be included (Thanks to Mike Roney.)

# SMEFT global fit 2: Low-energy observables

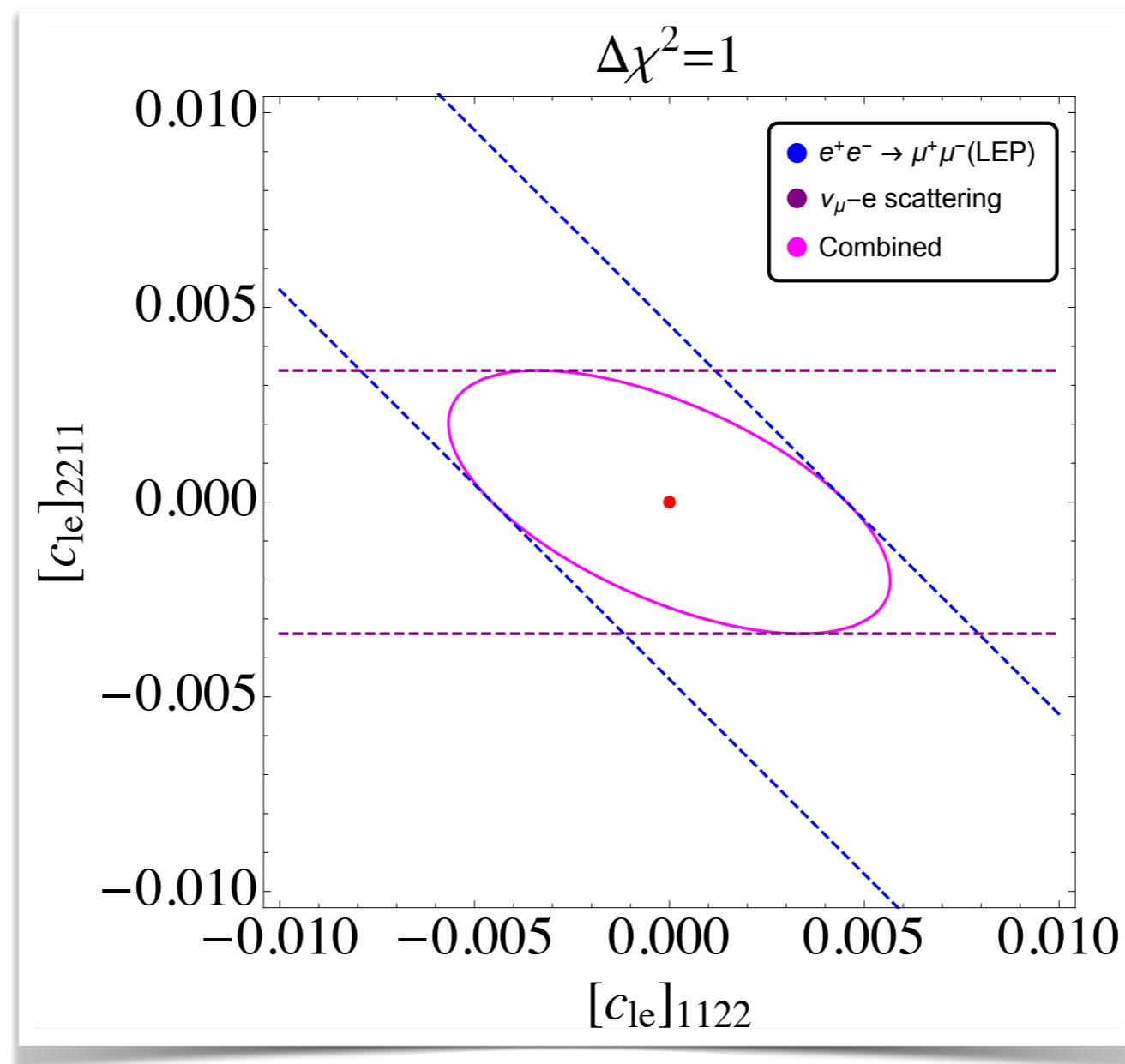
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	$(s_w^2)^{\text{Møller}}$	$0.2397 \pm 0.0013$	SLAC-E158 [55]	$0.2381 \pm 0.0006$ [56]
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	$Q_W^{\text{P}}(1, 0)$	$0.064 \pm 0.012$	QWEAK [57]	$0.0708 \pm 0.0003$ [54]
	$A_1$	$(-91.1 \pm 4.3) \times 10^{-6}$	PVDIS [58]	$(-87.7 \pm 0.7) \times 10^{-6}$ [58]
	$A_2$	$(-160.8 \pm 7.1) \times 10^{-6}$		$(-158.9 \pm 1.0) \times 10^{-6}$ [58]
	$g_{VA}^{eu} - g_{VA}^{ed}$	$-0.042 \pm 0.057$ $-0.12 \pm 0.074$	SAMPLE ( $\sqrt{Q^2} = 200$ MeV) [59] SAMPLE ( $\sqrt{Q^2} = 125$ MeV) [59]	-0.0360 [54] 0.0265 [54]
$\tau$ polarization	$b_{\text{SPS}}$	$-(1.47 \pm 0.42) \times 10^{-4} \text{ GeV}^{-2}$ $-(1.74 \pm 0.81) \times 10^{-4} \text{ GeV}^{-2}$	SPS ( $\lambda = 0.81$ ) [60] SPS ( $\lambda = 0.66$ ) [60]	$-1.56 \times 10^{-4} \text{ GeV}^{-2}$ [60] $-1.57 \times 10^{-4} \text{ GeV}^{-2}$ [60]
	$\mathcal{P}_\tau$ $\mathcal{A}_\mathcal{P}$	$0.012 \pm 0.058$ $0.029 \pm 0.057$	VENUS [61]	0.028 [61] 0.021 [61]
Neutrino trident production	$\frac{\sigma}{\sigma^{\text{SM}}}(\nu_\mu \gamma^* \rightarrow \nu_\mu \mu^+ \mu^-)$	$0.82 \pm 0.28$	CCFR [62–64]	1
$d_I \rightarrow u_J \ell \bar{\nu}_\ell(\gamma)$	$\epsilon_{L,R,S,P,T}^{de_J}$	See text	[65]	0

Polarized asymmetry at KEK-B to be included (Thanks to Mike Roney.)

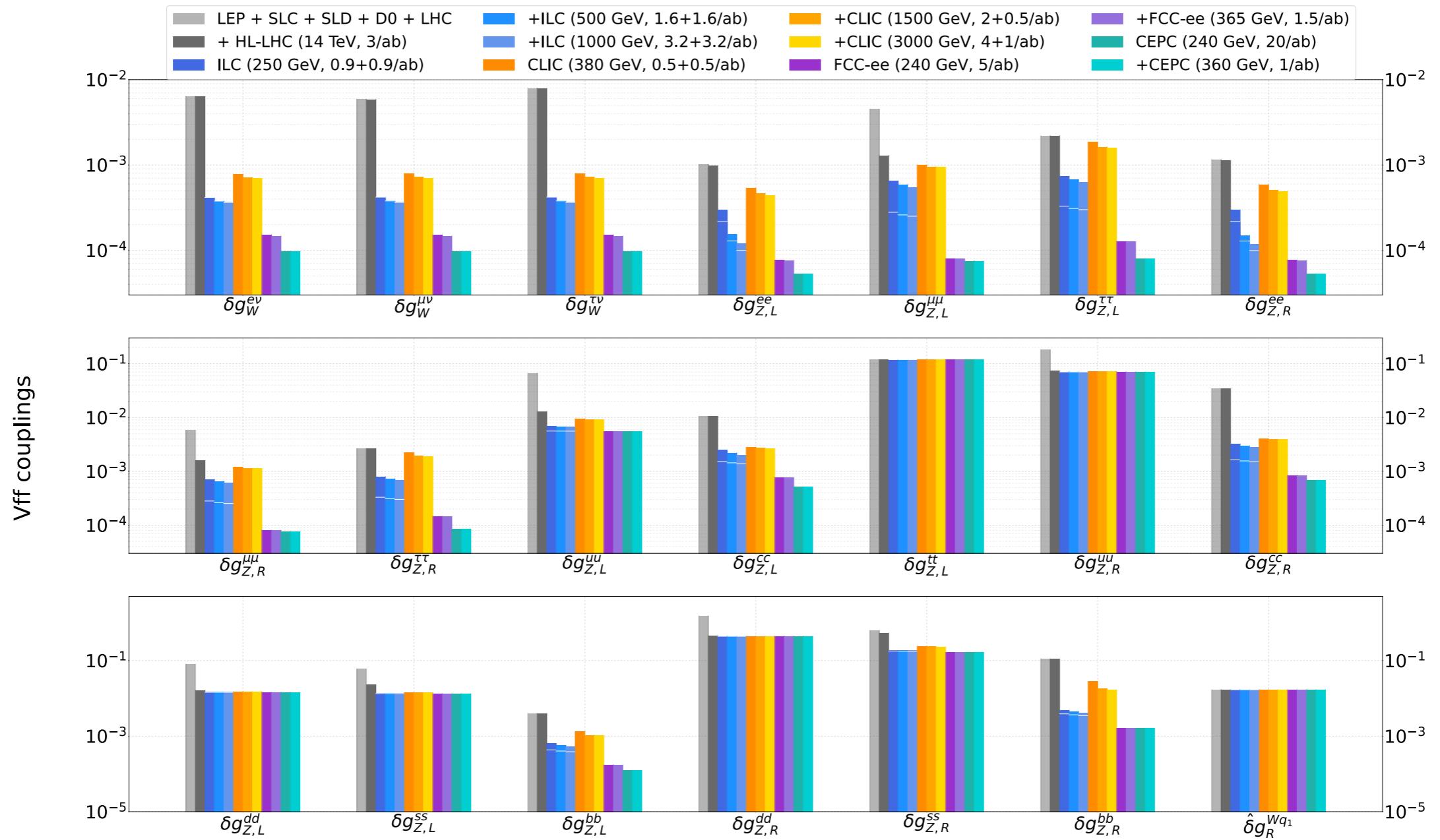
# SMEFT global fit 2: Low-energy observables

Flat direction lifted by low-energy experiments: One example



# SMEFT global fit 2: *Results*

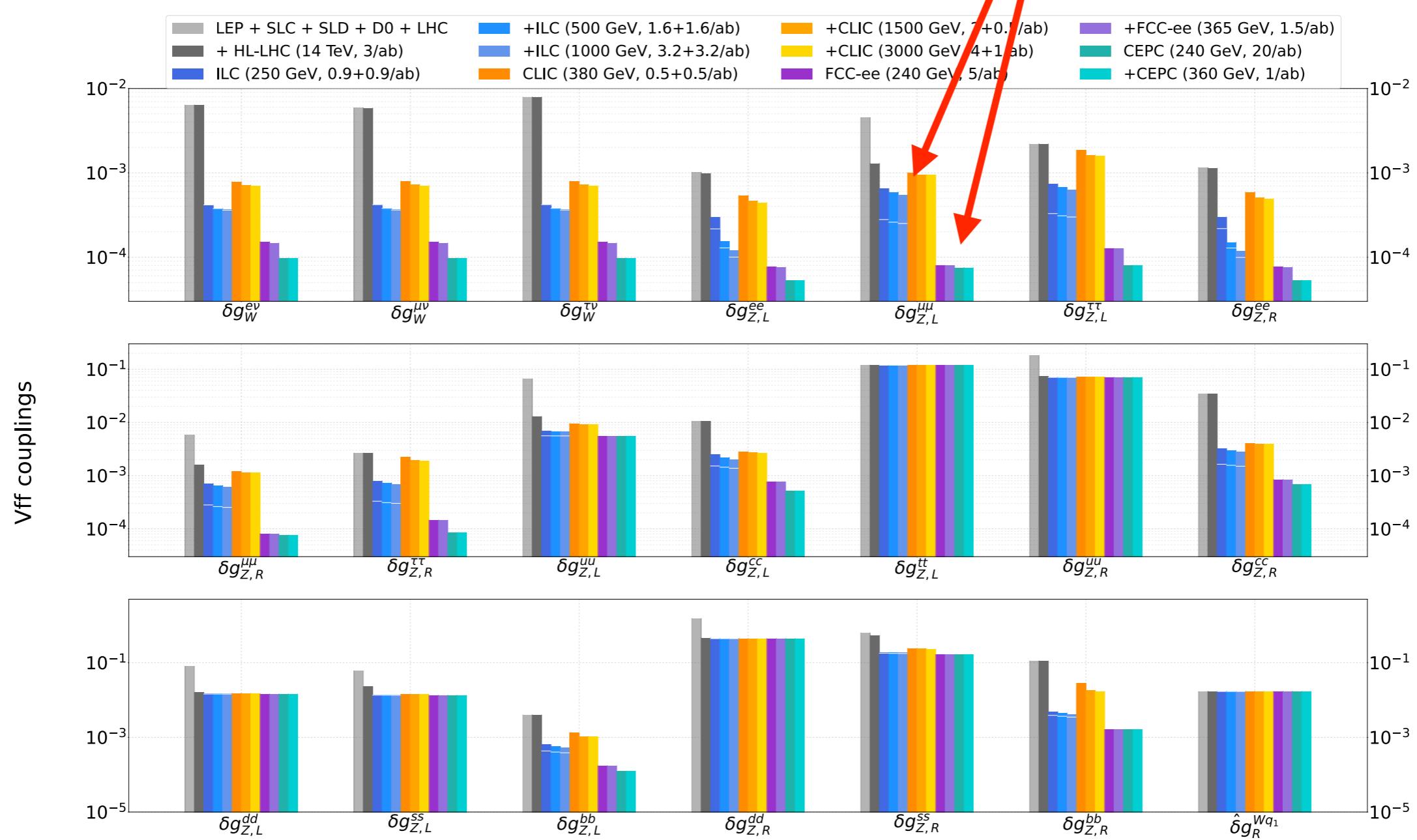
## Global fit results: Vff couplings



# SMEFT global fit 2: *Results*

Global fit results: Vff couplings

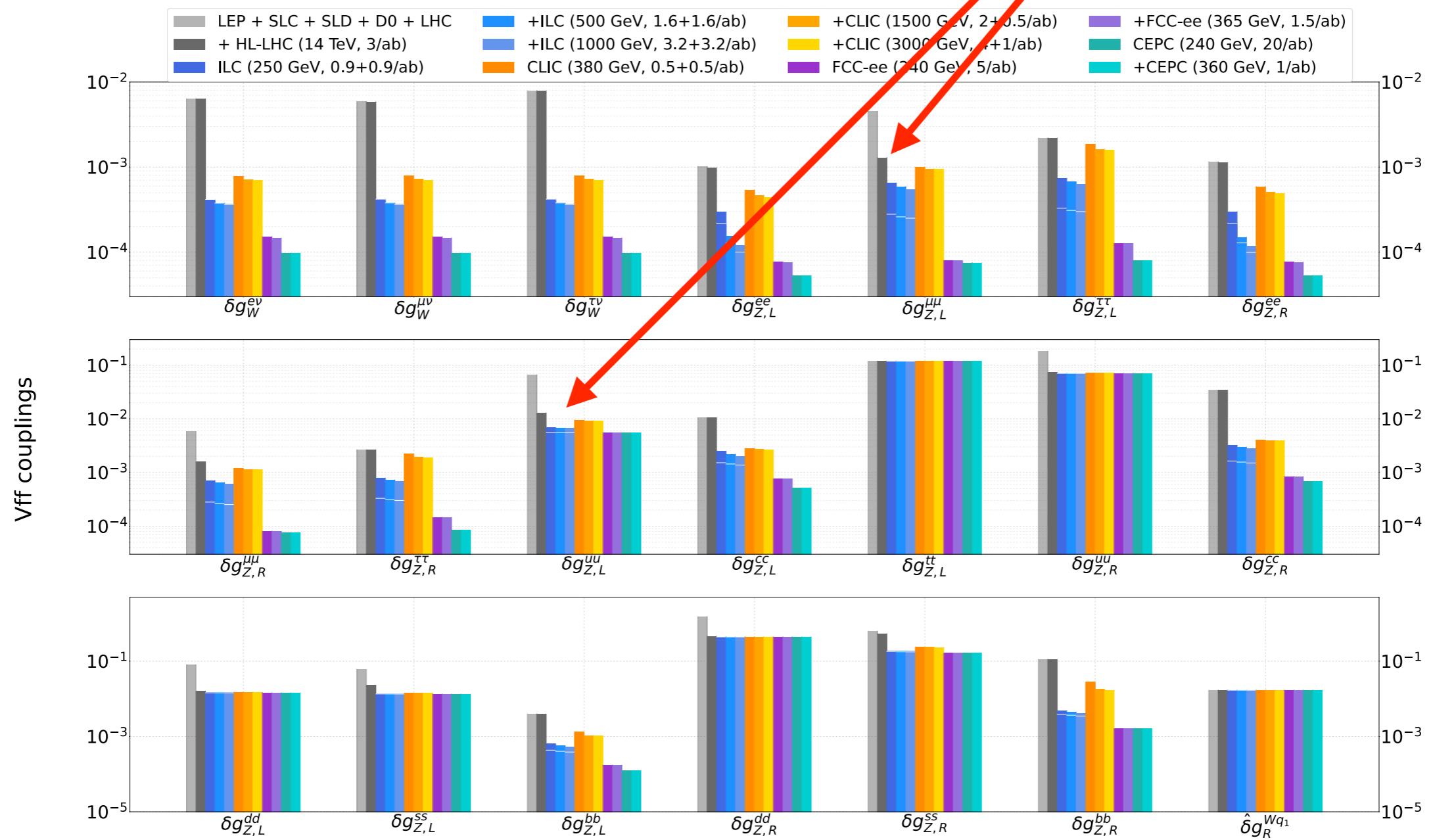
Luminosity wins (through radiative return)



# SMEFT global fit 2: *Results*

Global fit results: Vff couplings

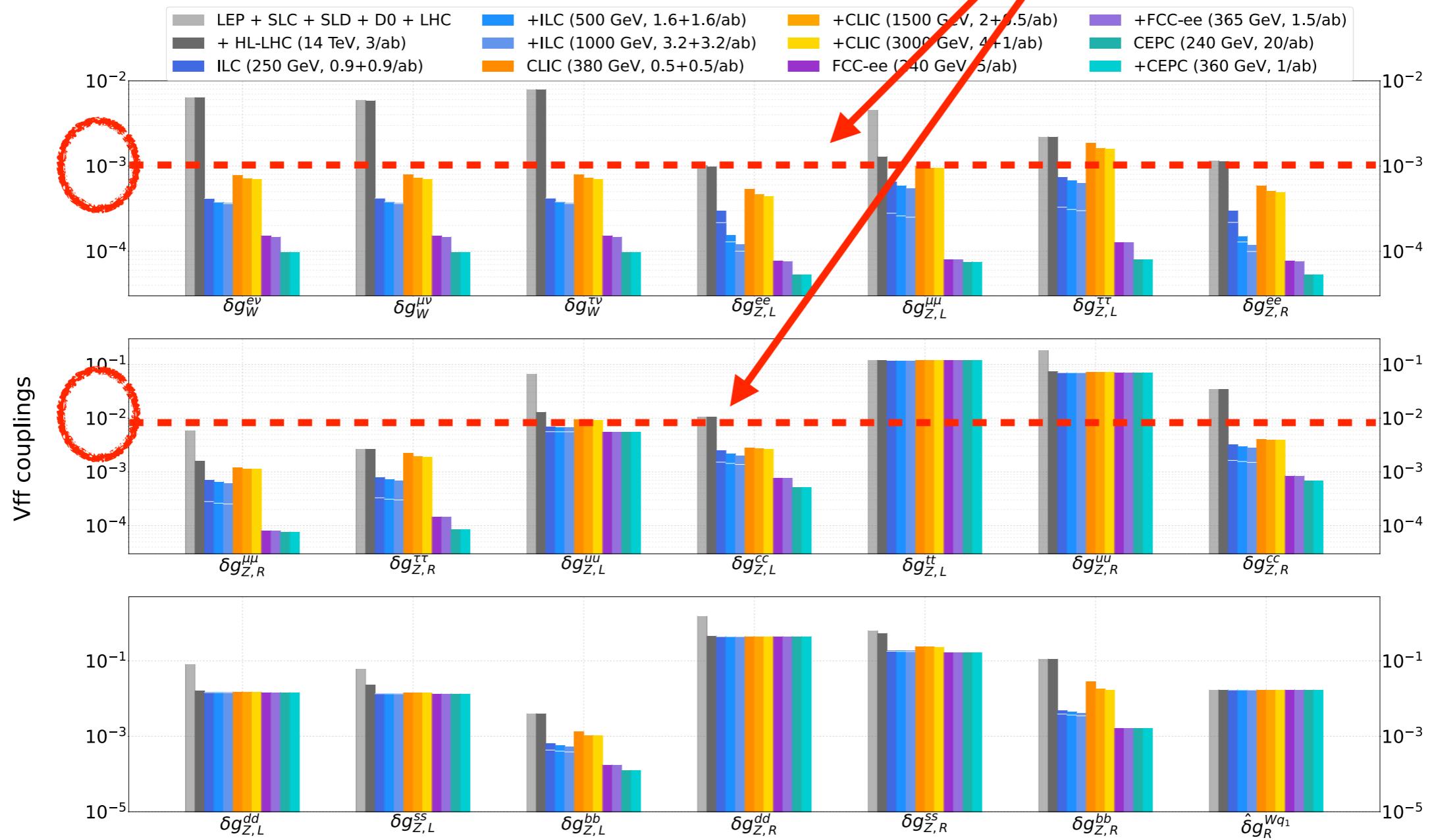
D0 +  $A_{FB}$  at the (HL-)LHC relaxes the U2 assumption & improve the fit.



# SMEFT global fit 2: *Results*

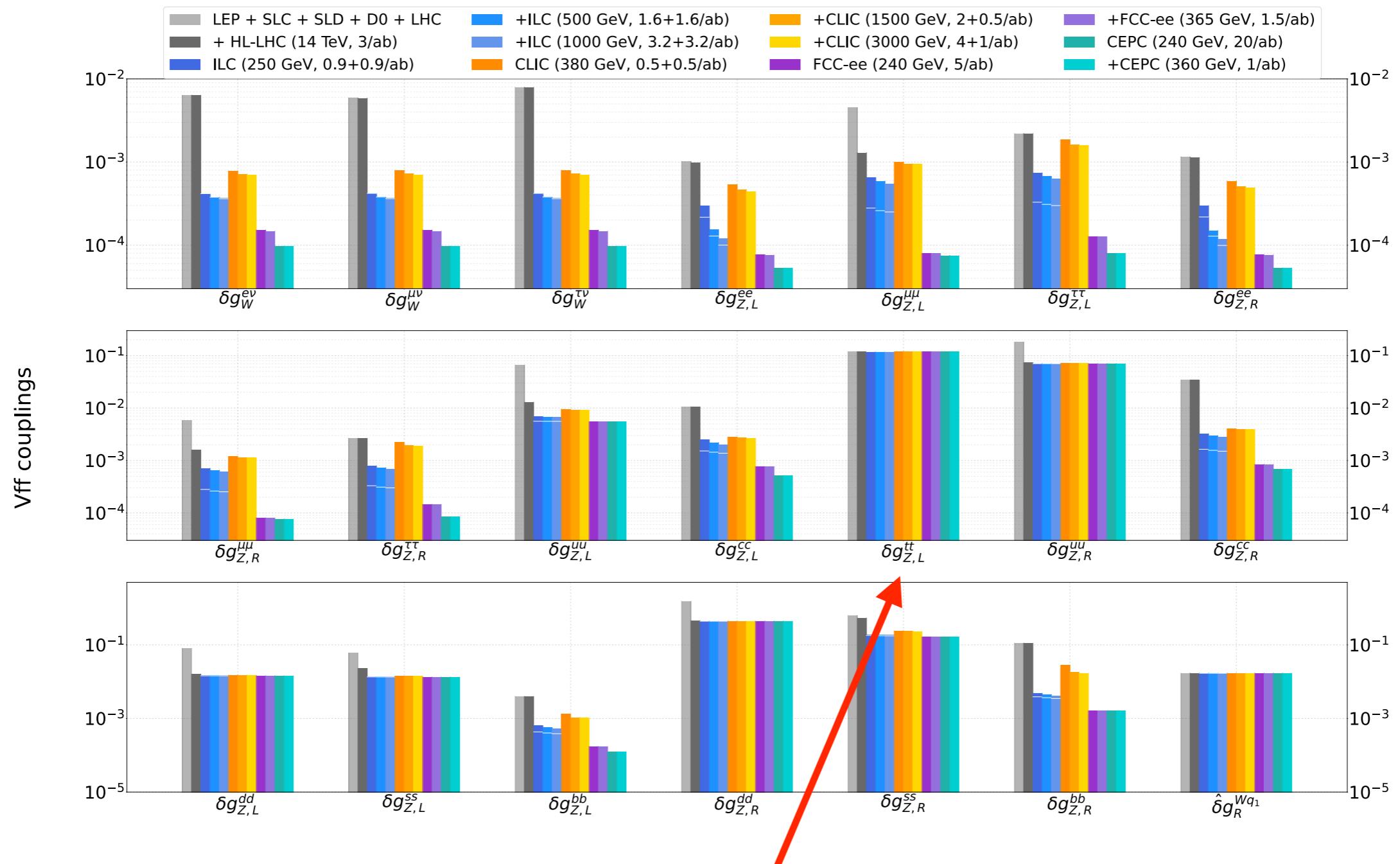
Global fit results: Vff couplings

$\mathcal{O}(10)$  weaker: Limited by the missing projections of  $R_{uc}$ ,  $A_{FB}^{ss}$ ,  $\sigma^{ss}$



# SMEFT global fit 2: *Results*

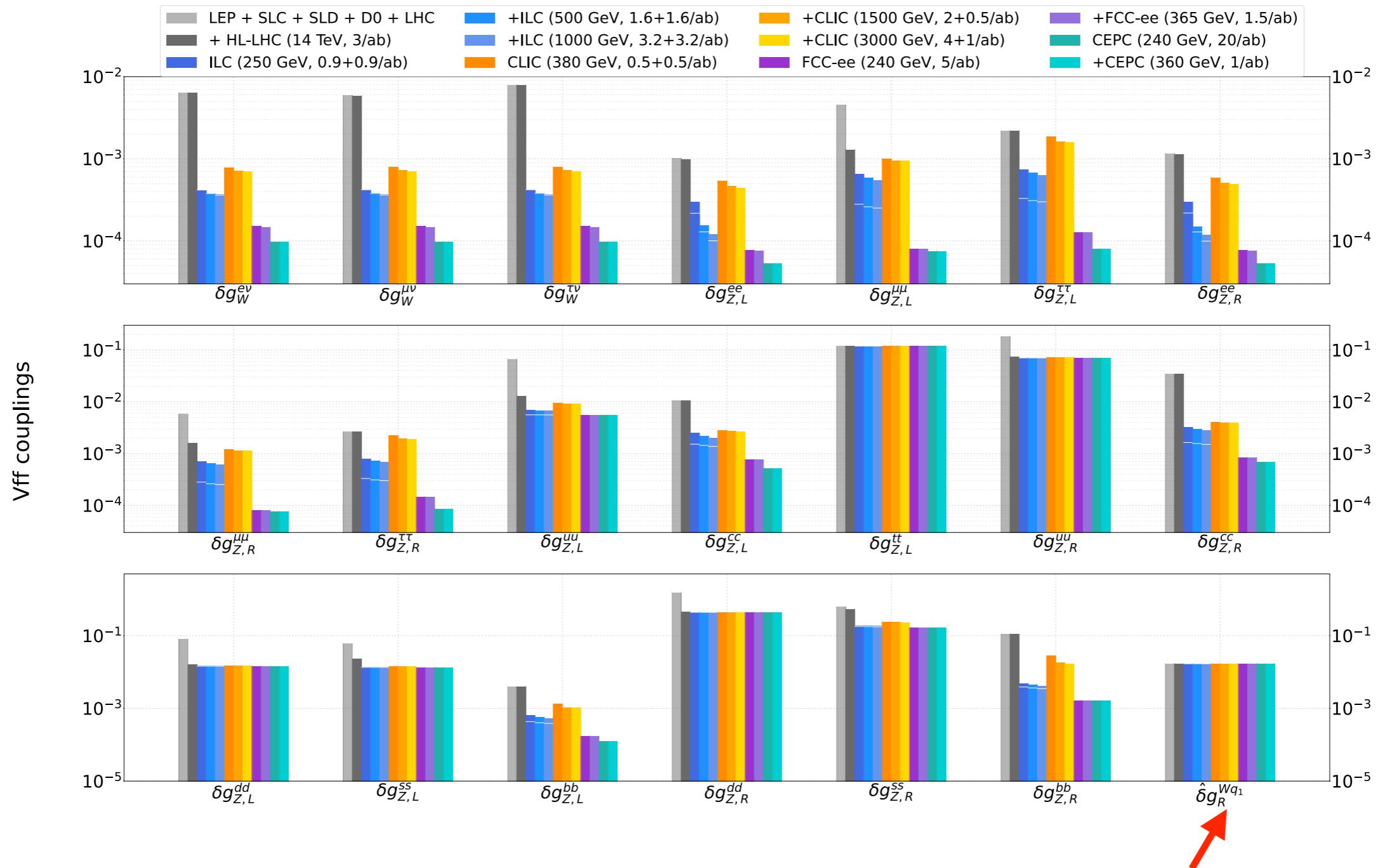
## Global fit results: Vff couplings



Limited by t-channel single-top production  
at the LHC

# SMEFT global fit 2: *Results*

## Global fit results: Vff couplings



CKM unitarity test.

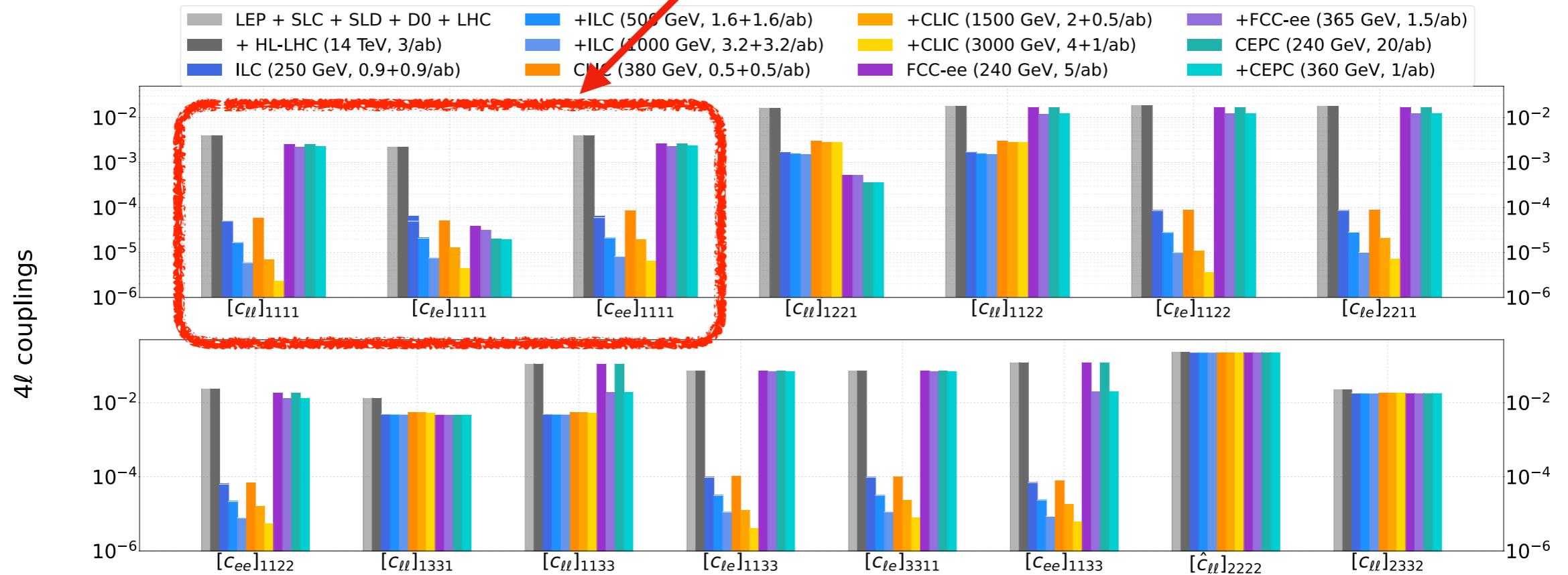
# SMEFT global fit 2: ***Results***

*Global fit results:*  $4\ell$  couplings

# SMEFT global fit 2: *Results*

Global fit results:  $4\ell$  couplings

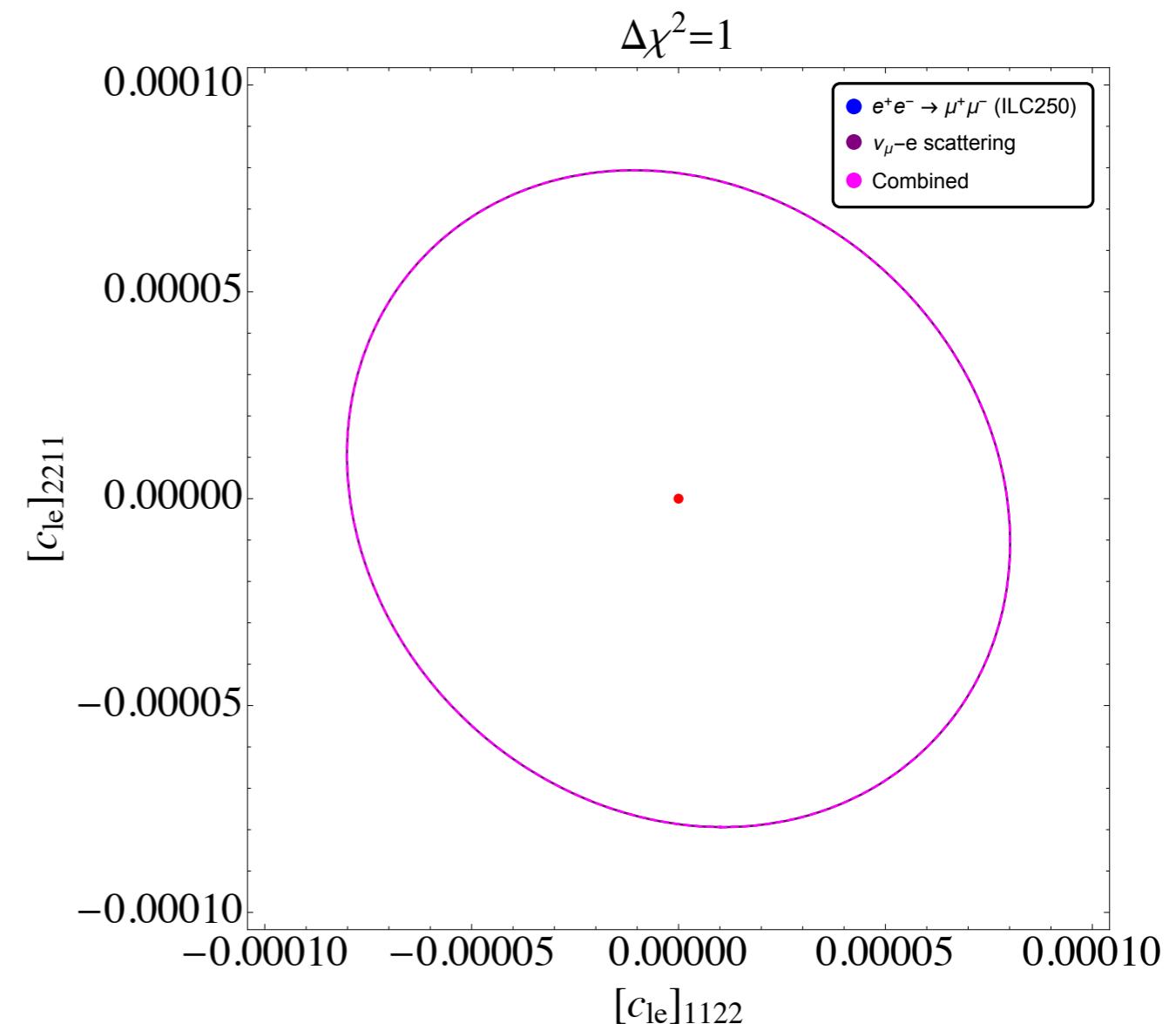
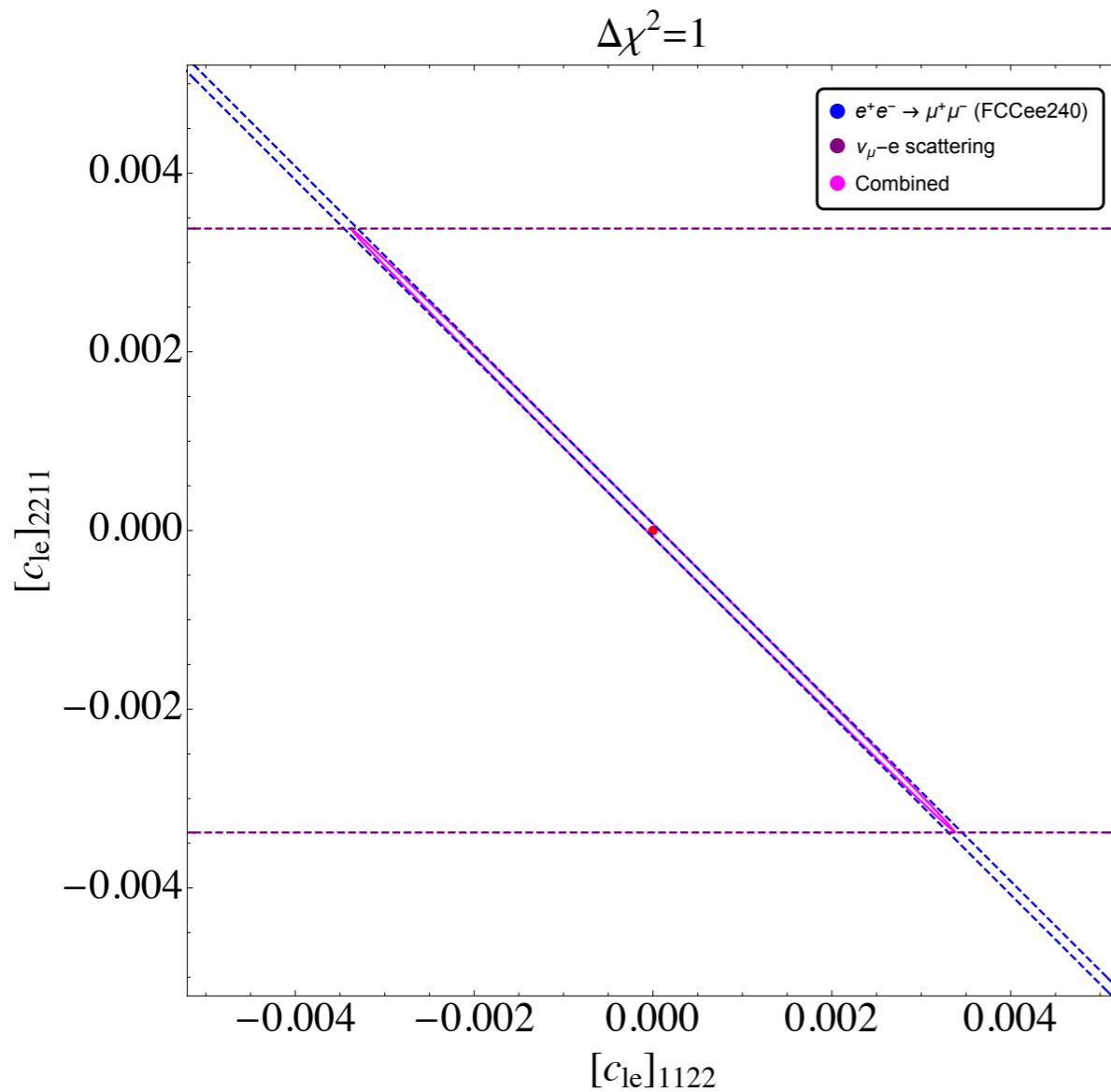
Beam polarization is the key in beating the (HL-)LHC and also circular colliders.



# SMEFT global fit 2: *Results*

Global fit results:  $4\ell$  couplings

Beam polarization is the key in beating the (HL-)LHC and also circular colliders.

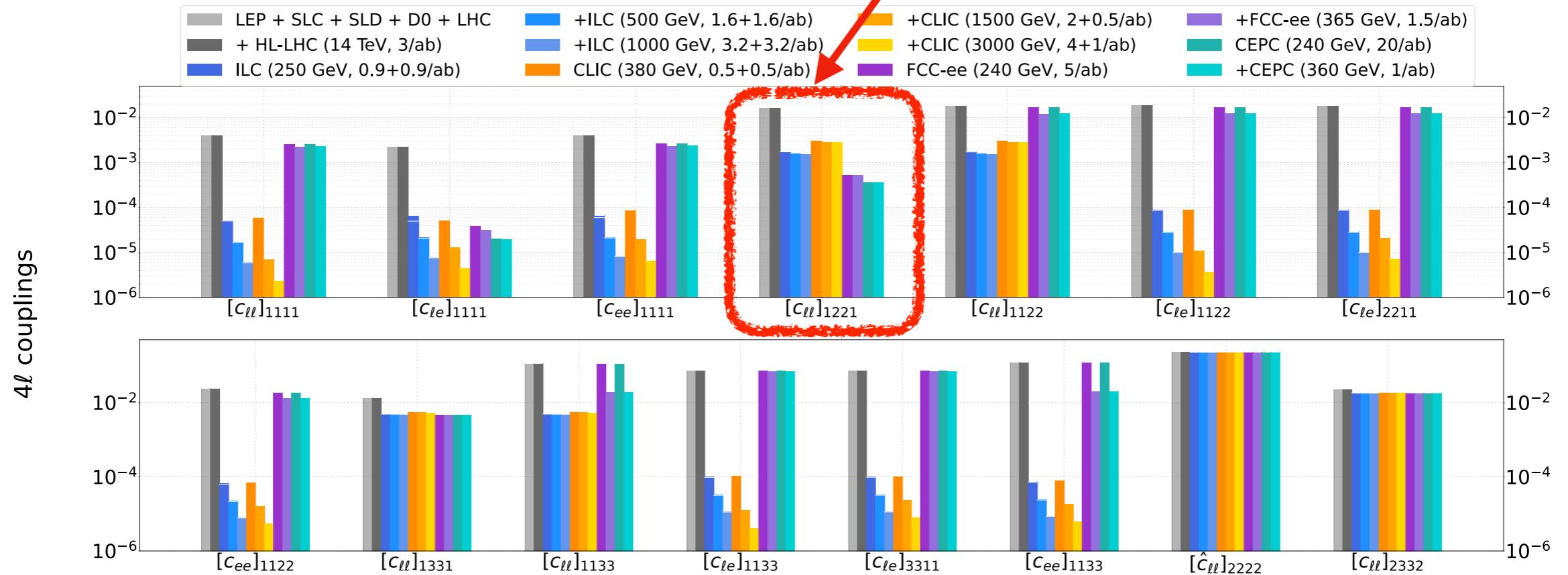


\* Please note the scale difference.

# SMEFT global fit 2: *Results*

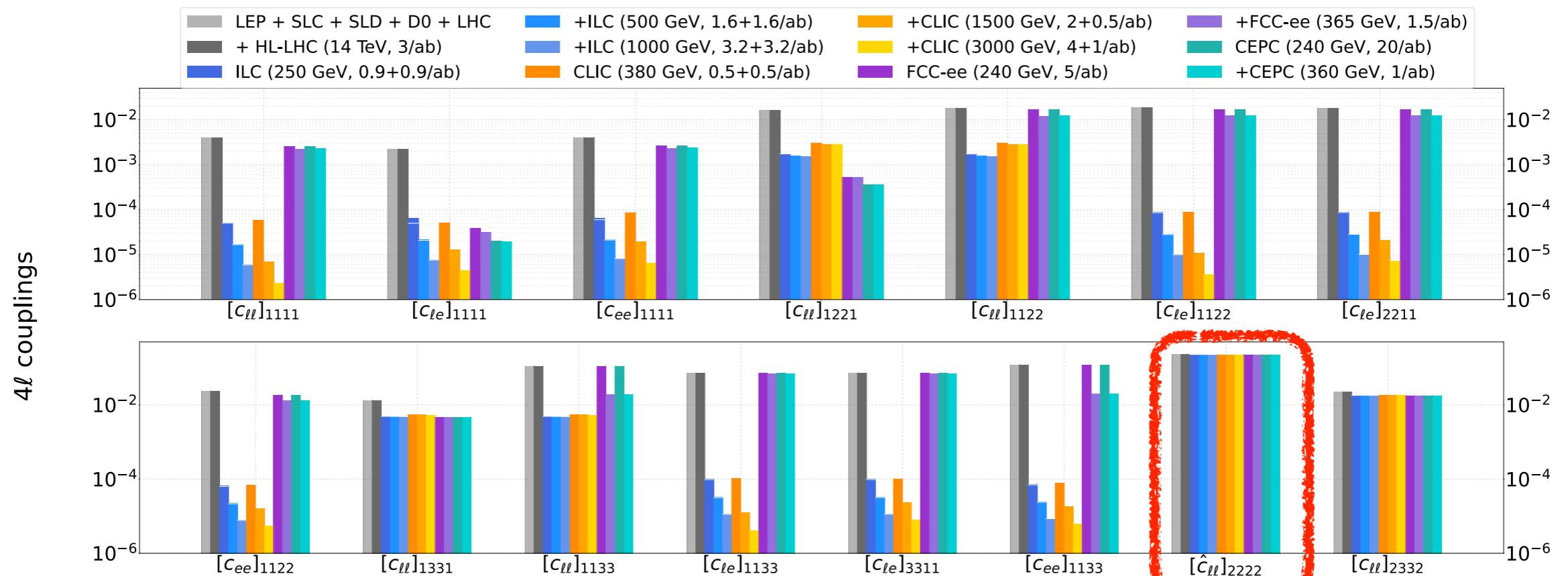
Global fit results:  $4\ell$  couplings

Strongly correlated with  $\delta g_W^{\nu\ell}$  through  $G_F$ ,  
dominated by luminosity (circular colliders)



# SMEFT global fit 2: *Results*

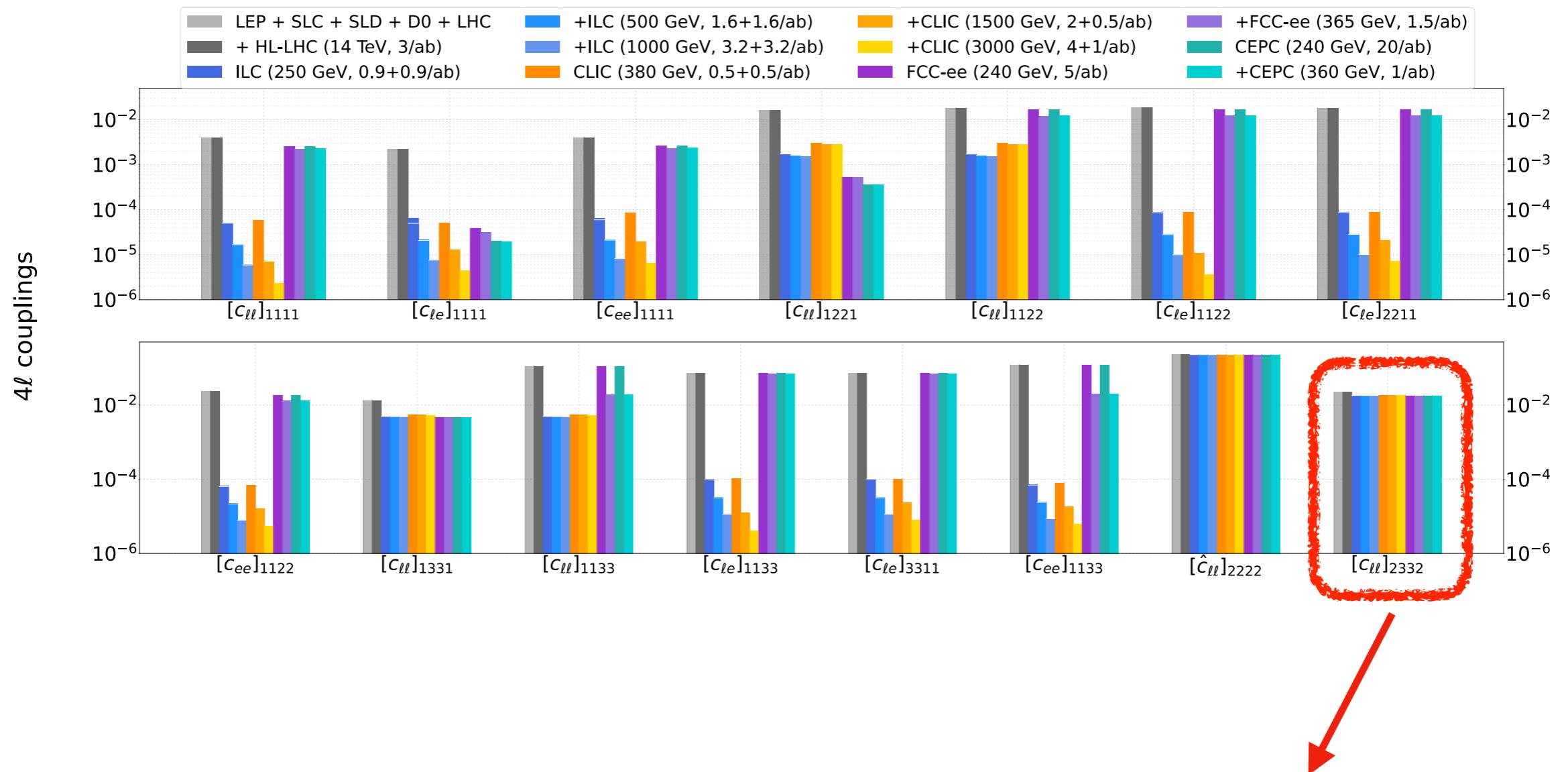
Global fit results:  $4\ell$  couplings



One input from neutrino trident production at CCFR. Muon colliders/FASER $\nu$  could play the role of lifting this flat direction.

# SMEFT global fit 2: *Results*

Global fit results:  $4\ell$  couplings



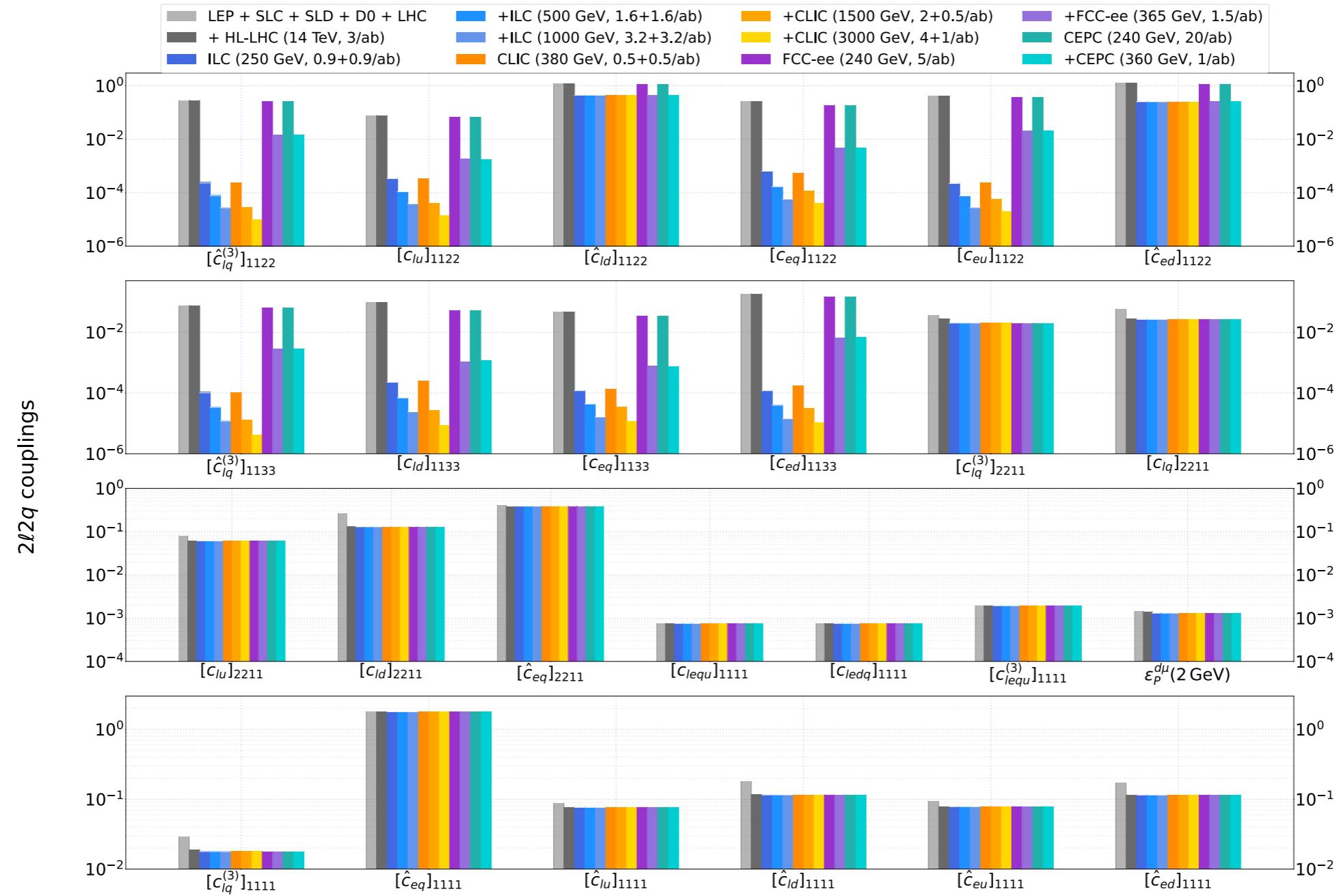
Limited by leptonic  $\tau$  decay, but is the only one sensitive to this operator. A muon collider also helps.

# SMEFT global fit 2: *Results*

[Global fit results:  \$2\ell 2q\$  couplings](#)

# SMEFT global fit 2: *Results*

## Global fit results: $2\ell 2q$ couplings



Same as the  $4\ell$  case. Again,  $A_{FB}^{ss}$ ,  $\sigma^{ss}$  and muon colliders will play a key role.

## **Fit 4: Bosonic CPV operators**

## SMEFT global fit 4: Operators and observables

Purely bosonic CPV operators: 6 in total, in Warsaw basis

$$\mathcal{O}_{\tilde{G}} = f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$$

$$\mathcal{O}_{\varphi \tilde{G}} = \varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$$

$$\mathcal{O}_{\varphi \tilde{W}} = \varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$$

$$\mathcal{O}_{\varphi \tilde{B}} = \varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{\varphi \tilde{W}B} = \varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$$

$$\mathcal{O}_{\tilde{W}} = \epsilon^{IJK} \tilde{W}_{\mu}^{I\nu} W_{\nu}^{J\rho} W_{\rho}^{K\mu}$$

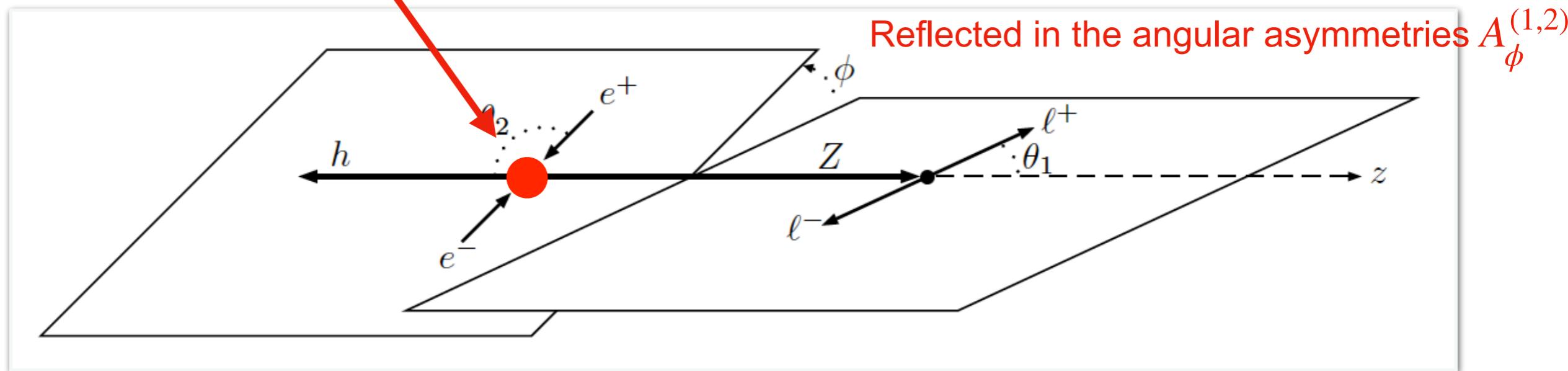
Not included (gluon free) — strong constraints from neutron/chromo-EDMs

Cirigliano et al, Phys.Rev.D 94 (2016) 3, 034031

# SMEFT global fit 4: Operators and observables

Purely bosonic CPV operators: 6 in total, in Warsaw basis

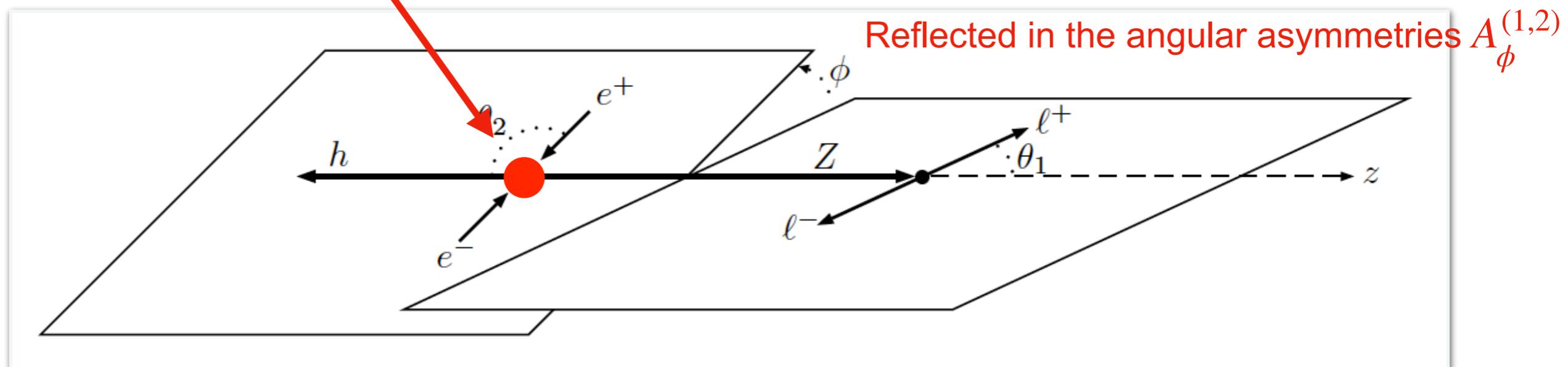
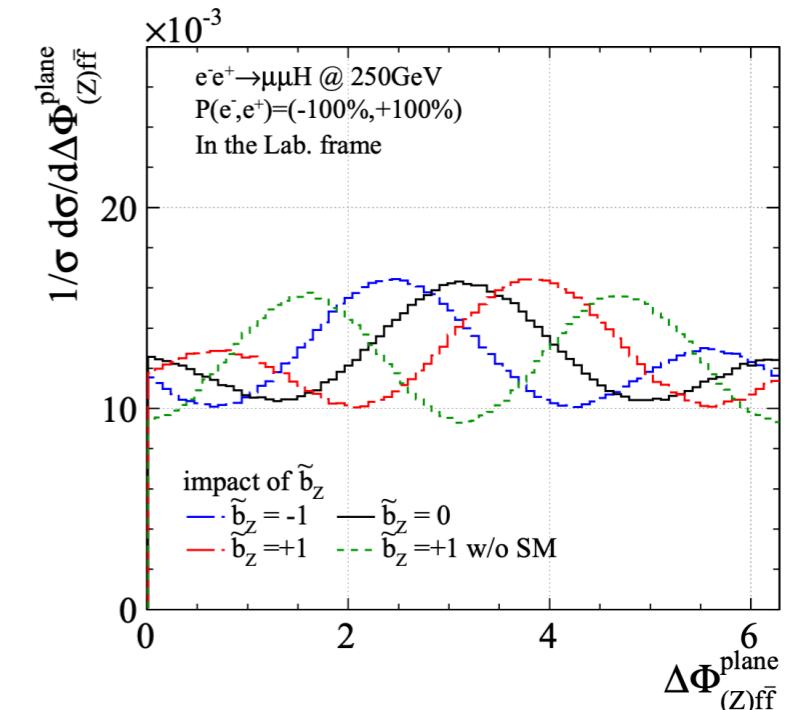
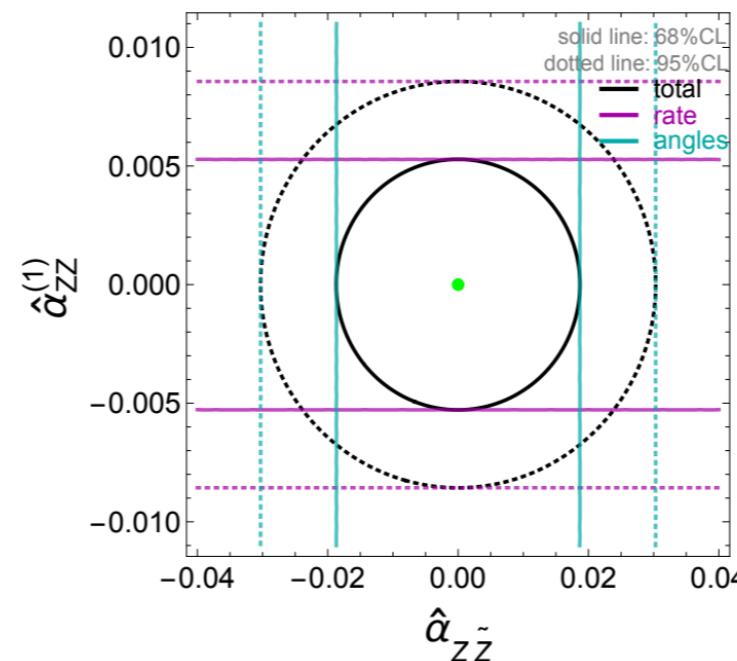
$$\begin{aligned}\mathcal{O}_{\varphi \tilde{W}} &= \varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu} \\ \mathcal{O}_{\varphi \tilde{B}} &= \varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu} \\ \mathcal{O}_{\varphi \tilde{W}B} &= \varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu} \\ \mathcal{O}_{\tilde{W}} &= \epsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}\end{aligned}$$



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# SMEFT global fit 4: Operators and observables

Anomalous triple gauge couplings (aTGCs) from  $e^+e^- \rightarrow W^+W^-$  at OPAL

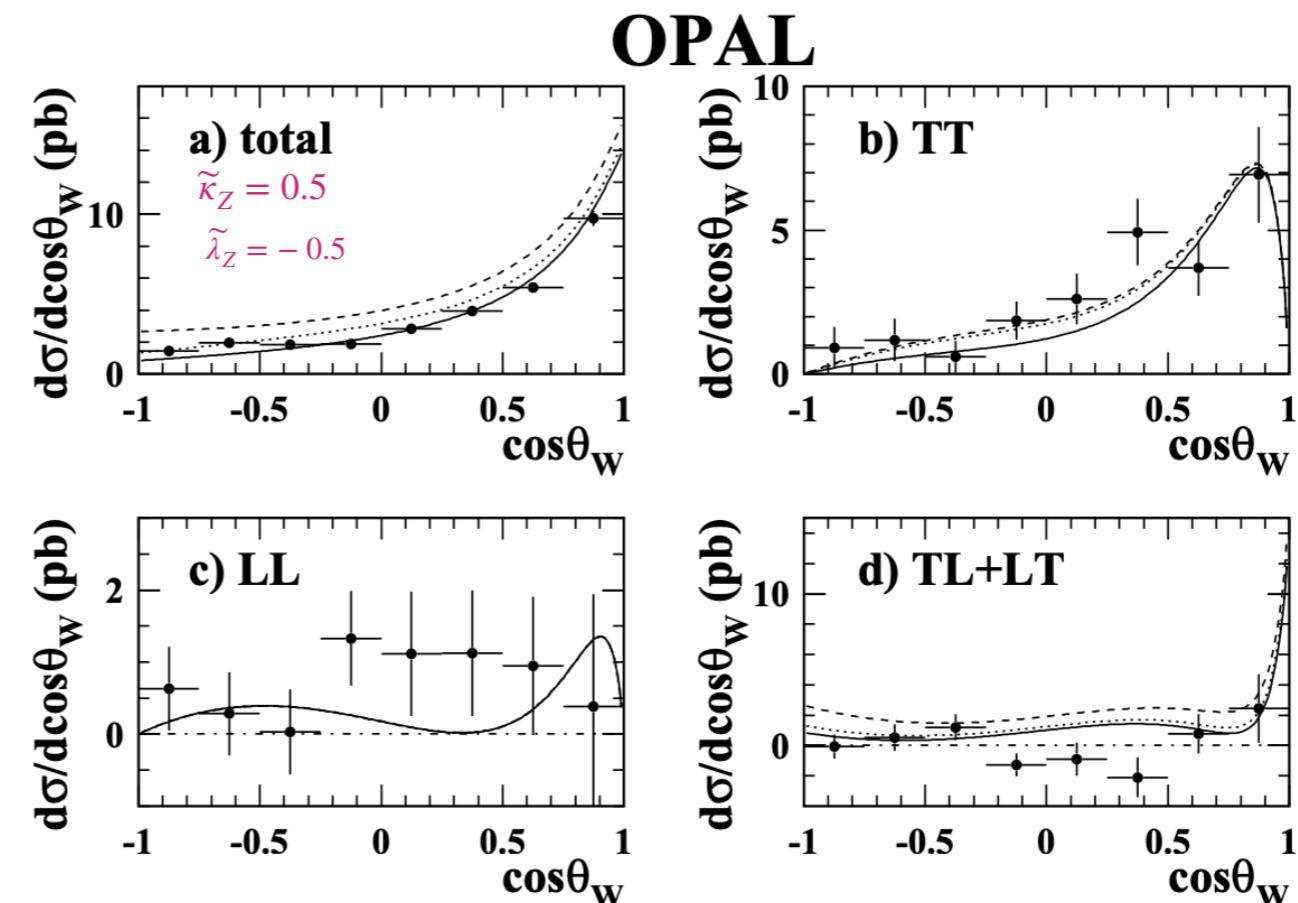
$$\mathcal{O}_{\varphi\tilde{W}} = \varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$$

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$$\mathcal{L}_{CPV} \supset ie \left( \tilde{\kappa}_\gamma \tilde{F}_{\mu\nu} W^{+\mu} W^{-\nu} + \frac{\lambda_\gamma}{M_W^2} \tilde{F}^{\nu\lambda} W_{\lambda\mu}^+ W_{\nu}^{-\mu} + \cot \theta_w \tilde{\kappa}_Z \tilde{Z}_{\mu\nu} W^{+\mu} W^{-\nu} + \cot \theta_w \frac{\lambda_Z}{M_W^2} \tilde{Z}^{\nu\lambda} W_{\lambda\mu}^+ W_{\nu}^{-\mu} \right)$$



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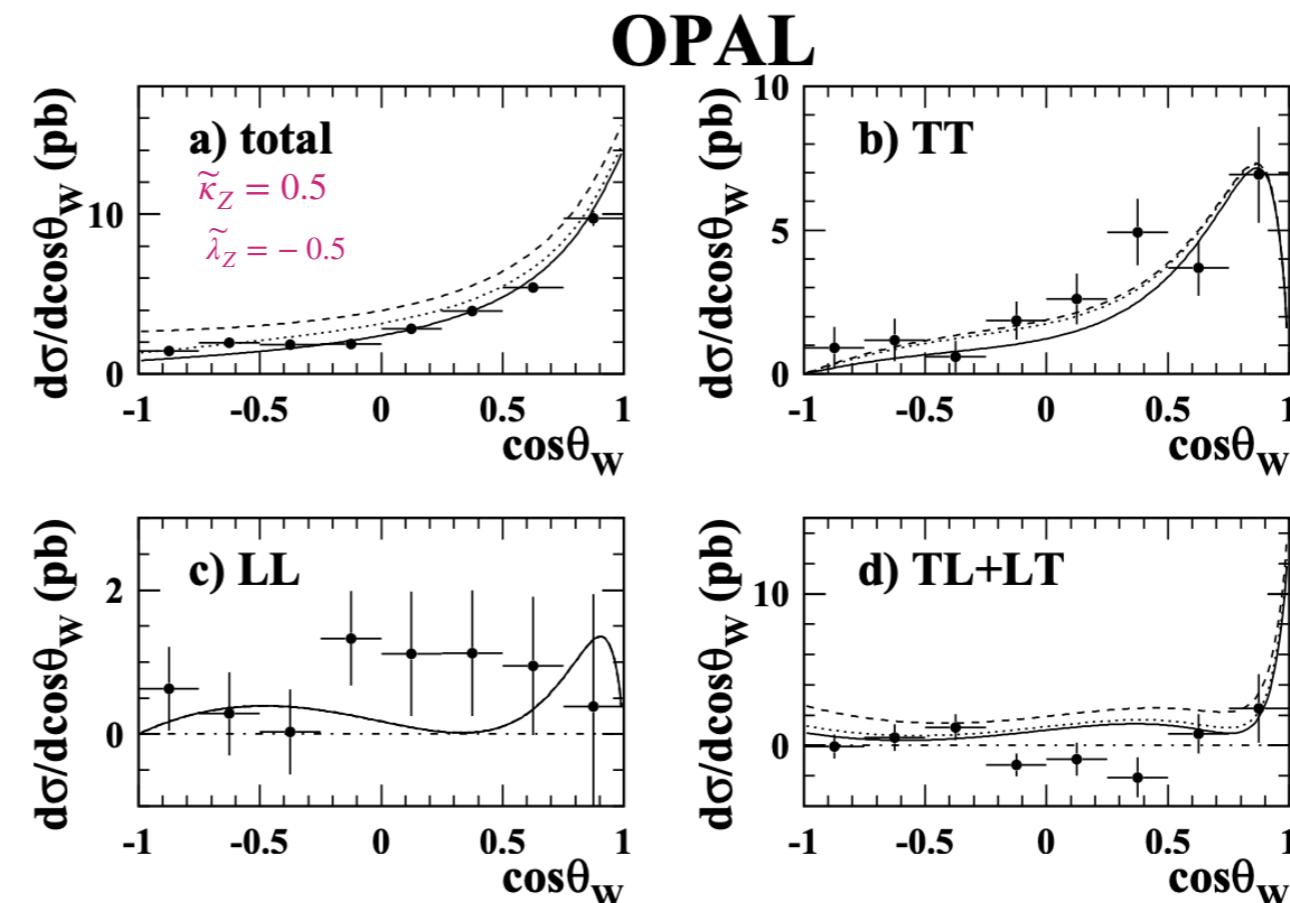
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$$\tilde{\kappa}_Z = -0.20^{+0.10}_{-0.07}$$

$$\tilde{\lambda}_Z = -0.18^{+0.24}_{-0.16}$$

OPAL, aTGCs, Eur.Phys.J.C 19 (2001) 229

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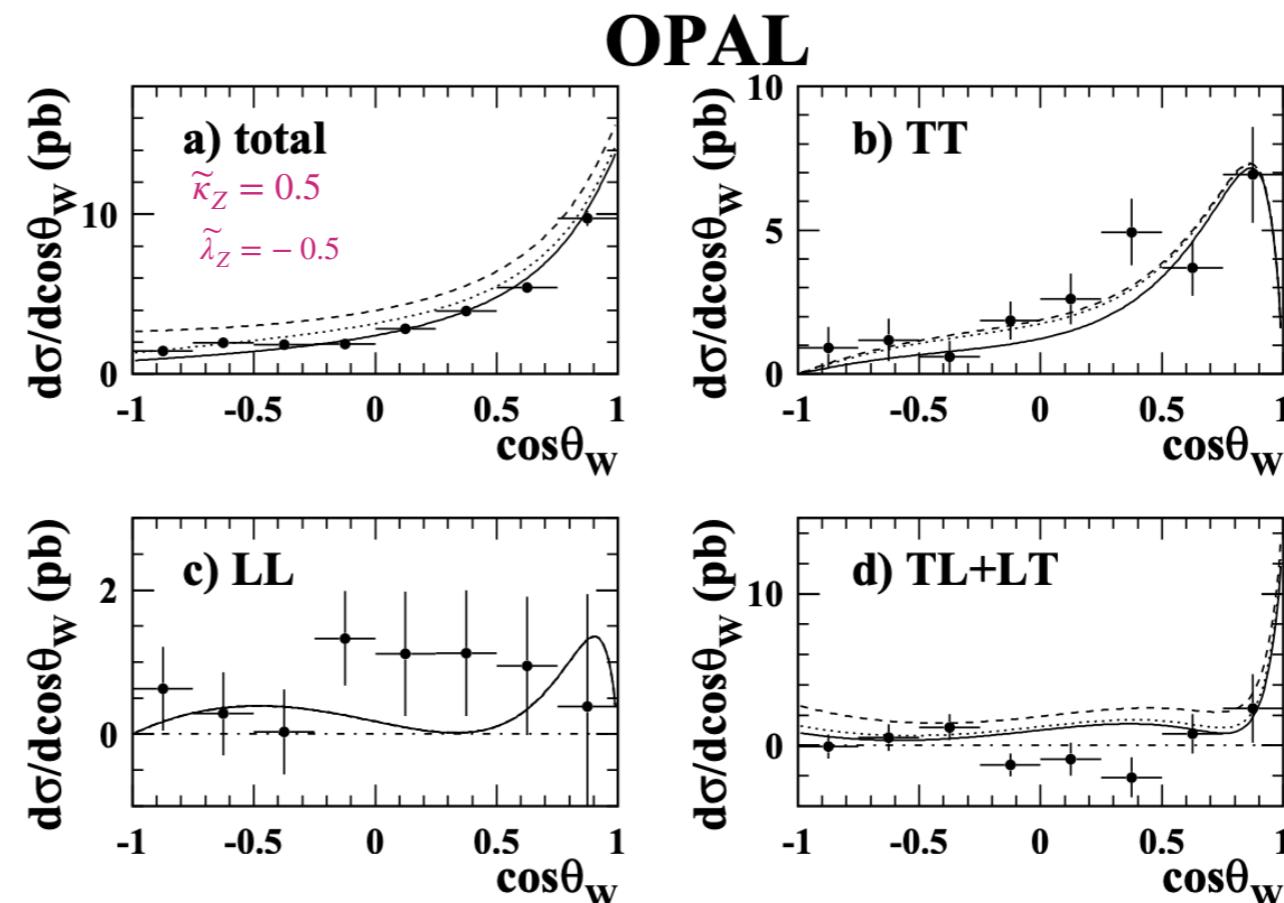
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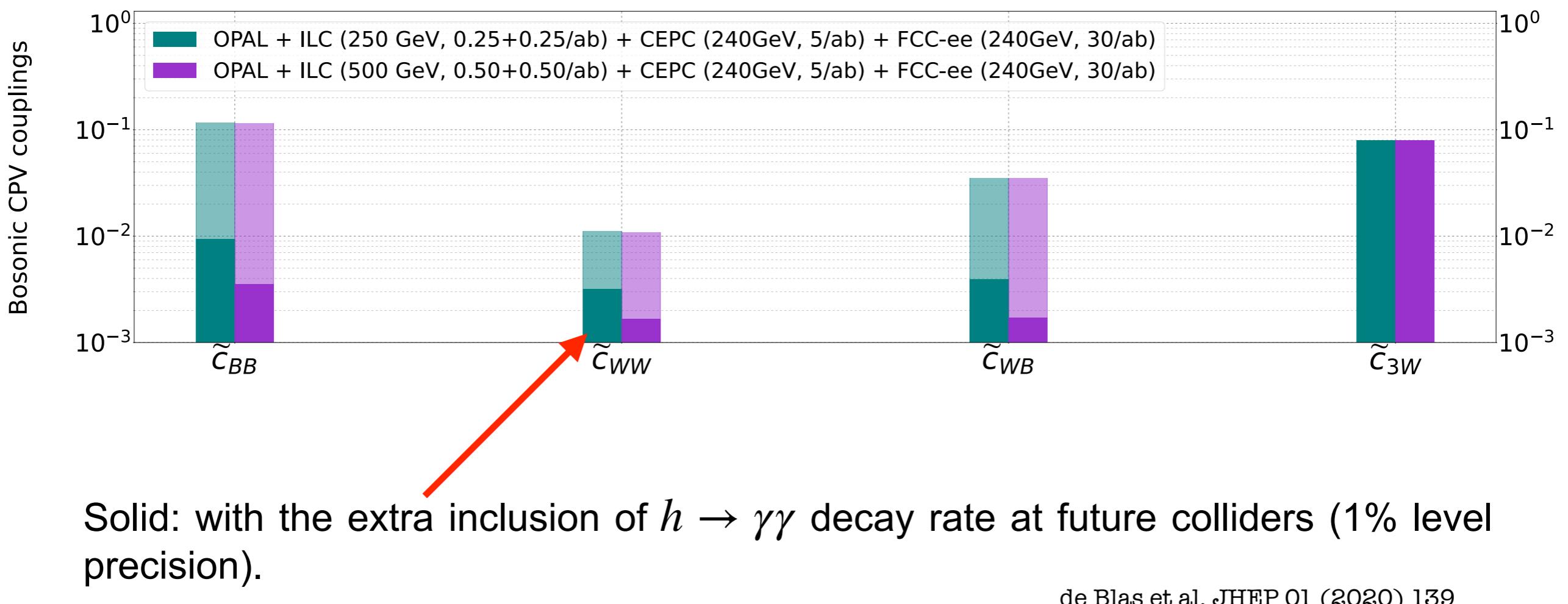
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OPAL, aTGCs, Eur.Phys.J.C 19 (2001) 229

\* OPAL results to be overtaken by  $e^+e^- \rightarrow W^+W^-$  at future lepton colliders.

# SMEFT global fit 4: *Results*

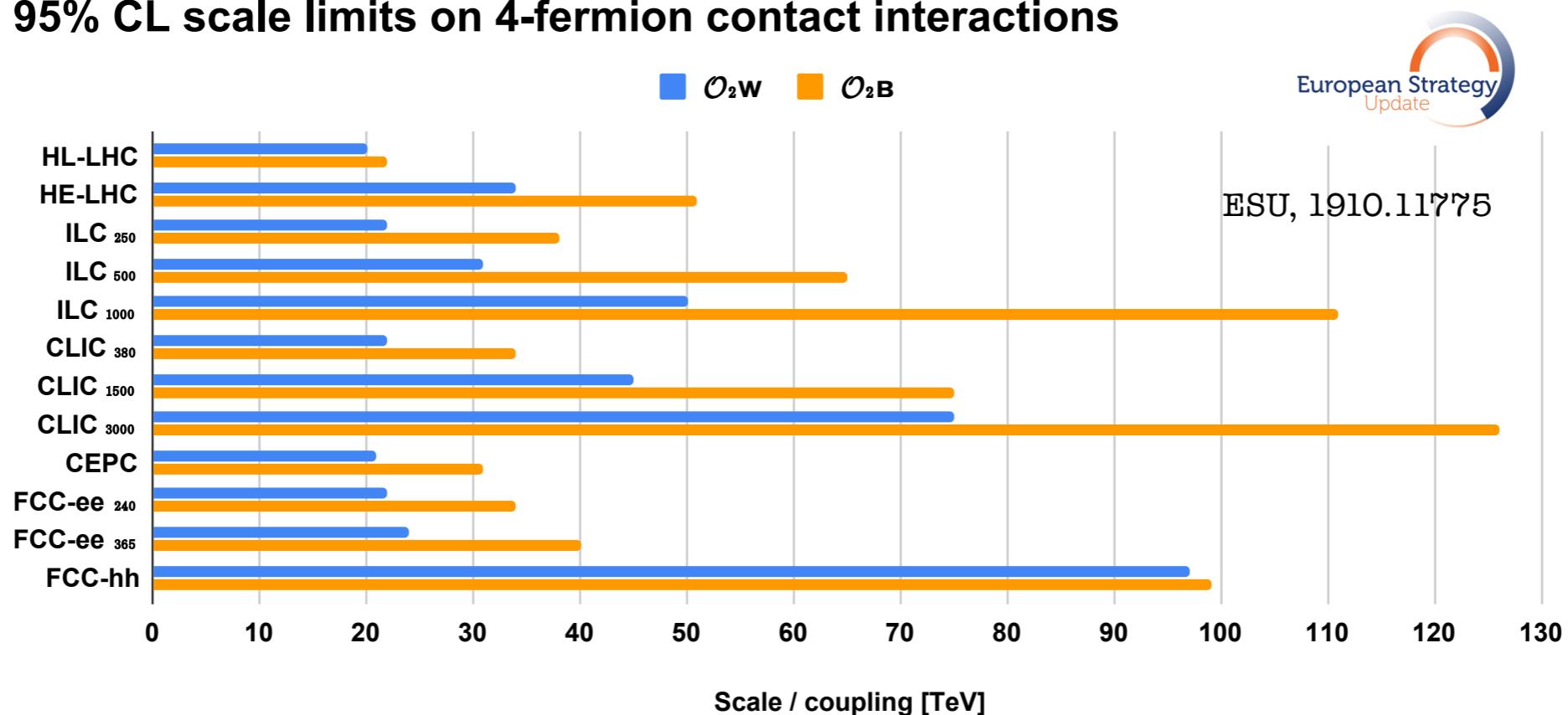


# **Global fit on some benchmark models**

(Preliminary results)

# Snowmass vs ESU: $\mathcal{O}_{2W,2B}$ update

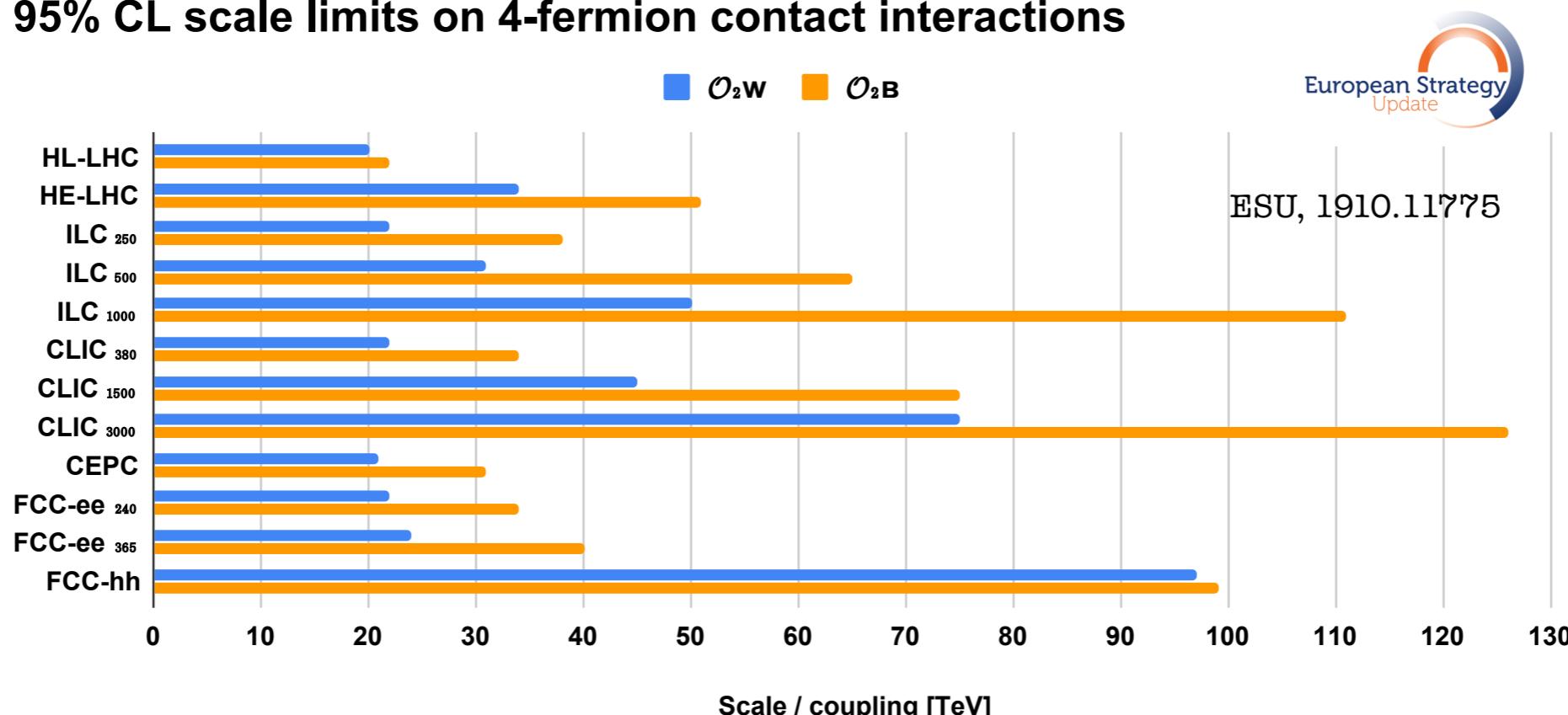
95% CL scale limits on 4-fermion contact interactions



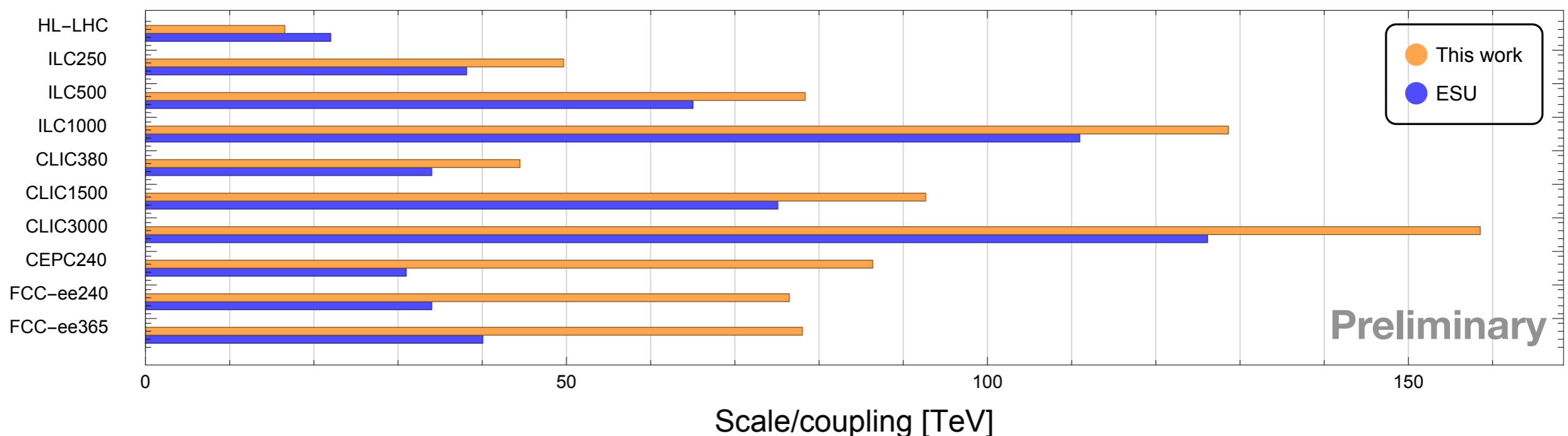
$$\{Y, W\} \leftrightarrow \{\delta g_{L,R}^{Zf}, c_{ll}, c_{le}, c_{ee}, c_{ed}, c_{eq}, c_{eu}, c_{ld}, c_{lq}, c_{lu}\}$$

# Snowmass vs ESU: $\mathcal{O}_{2W,2B}$ update

95% CL scale limits on 4-fermion contact interactions



95% CL scale limits on 4-fermion contact interactions from  $\mathcal{O}_{2B}$



## Benchmark models: *Y-Universal Z' model*

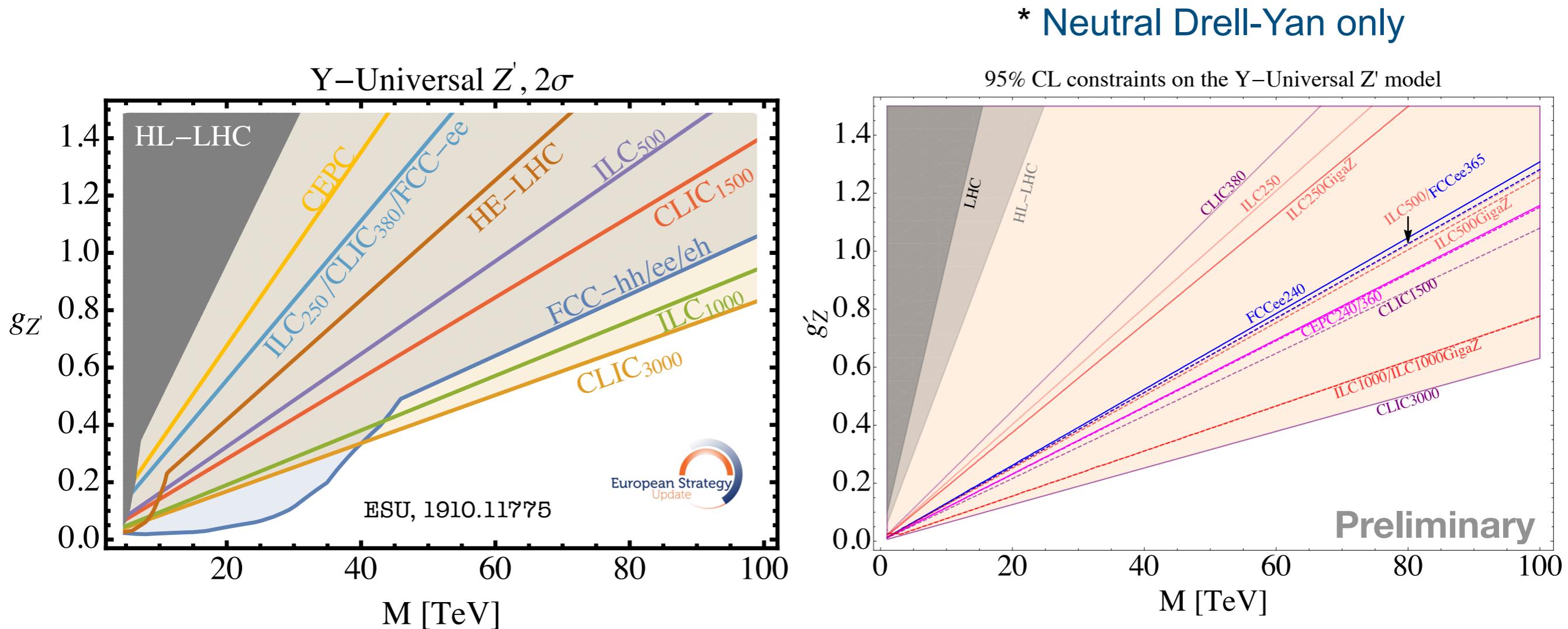
Extend the SM by  $U(1)_z$  but without introducing kinetic mixing and off-diagonal gauge couplings

$$\frac{c_{2B}}{\Lambda^2} = \frac{g_{Z'}^2}{g_1^4 M^2}$$

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## Benchmark models: Leptoquark model

$$\mathcal{L}_{\text{LQ}} \supset (\lambda_{i\alpha}^{1L} \bar{q}_i^c \epsilon \ell_\alpha + \lambda_{i\alpha}^{1R} \bar{u}_i^c e_\alpha) S_1 + \lambda_{i\alpha}^{3L} \bar{q}_i^c \epsilon \sigma^I \ell_\alpha S_3^I + \text{h.c.}$$

Gherardi et al, 2003.12525

Aebischer et al, 2102.08954

**YD** et al, JHEP 03 (2021) 019, Phys.Rev.D 105 (2022) 7, 075022

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$$[C_{lq}^{(1)}]_{\alpha\beta ij}^{(0)} = \frac{\lambda_{i\alpha}^{1L*} \lambda_{j\beta}^{1L}}{4M_1^2} + \frac{3\lambda_{i\alpha}^{3L*} \lambda_{j\beta}^{3L}}{4M_3^2},$$

$$[C_{lq}^{(3)}]_{\alpha\beta ij}^{(0)} = -\frac{\lambda_{i\alpha}^{1L*} \lambda_{j\beta}^{1L}}{4M_1^2} + \frac{\lambda_{i\alpha}^{3L*} \lambda_{j\beta}^{3L}}{4M_3^2},$$

$$[C_{lequ}^{(1)}]_{\alpha\beta ij}^{(0)} = \frac{\lambda_{j\beta}^{1R} \lambda_{i\alpha}^{1L*}}{2M_1^2},$$

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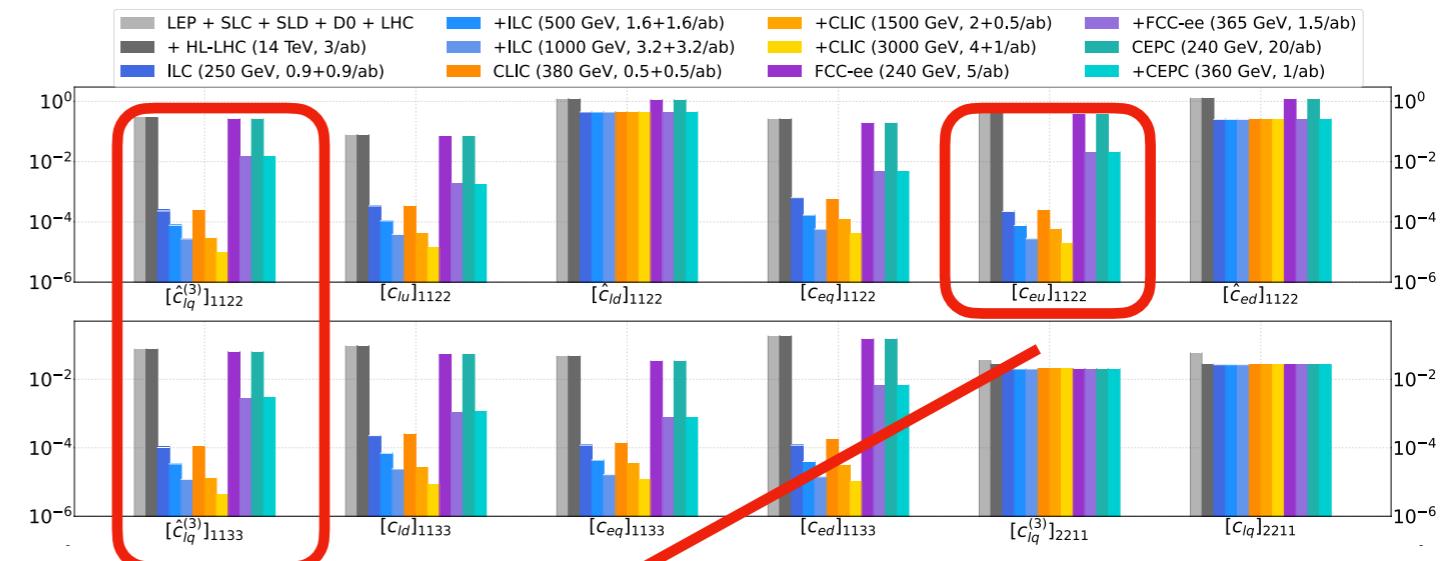
$$[C_{lq}]_{\alpha\beta ij}^{(1)} = \frac{\lambda_{i\alpha}^{1L*} \lambda_{j\beta}^{1L}}{4M_1^2} + \frac{3\lambda_{i\alpha}^{3L*} \lambda_{j\beta}^{3L}}{4M_3^2},$$

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$$[C_{lequ}]_{\alpha\beta ij}^{(1)} = \frac{\lambda_{j\beta}^{1R} \lambda_{i\alpha}^{1L*}}{2M_1^2},$$

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Leading constraints from the global fit:  $[c_{eu}]_{1122}$  and  $[\hat{c}_{lq}]_{1133,1122}$ .

# Benchmark models: Leptoquark model

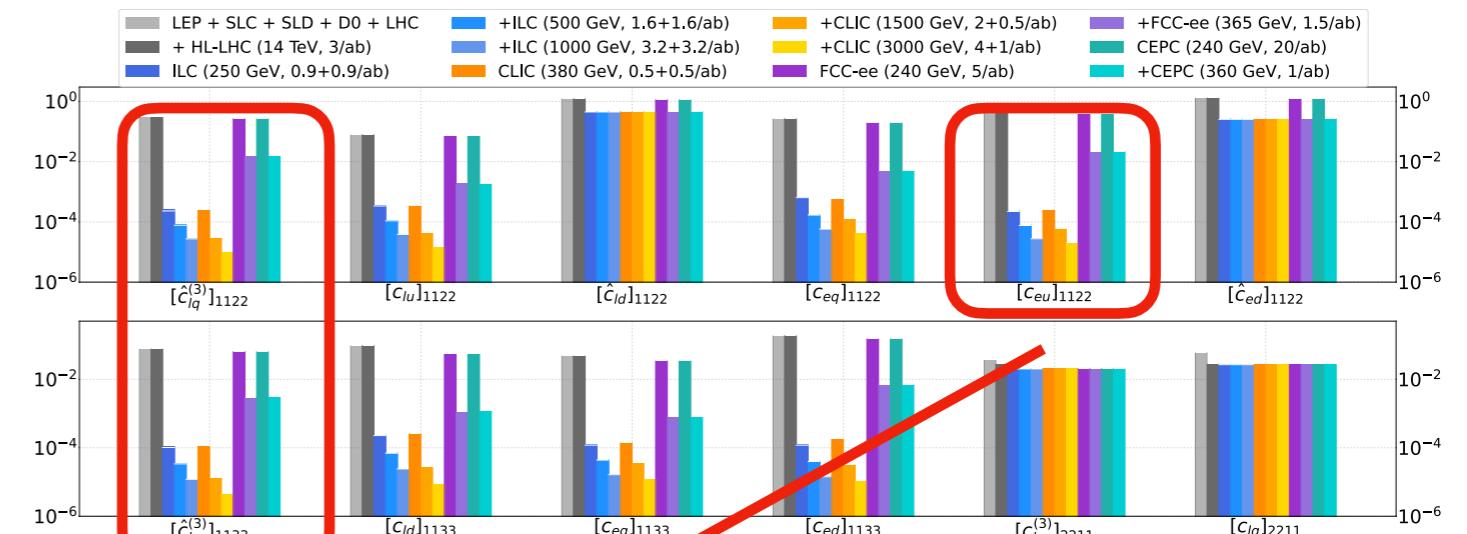
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Aebischer et al, 2102.08954

**YD** et al, JHEP 03 (2021) 019, Phys.Rev.D 105 (2022) 7, 075022

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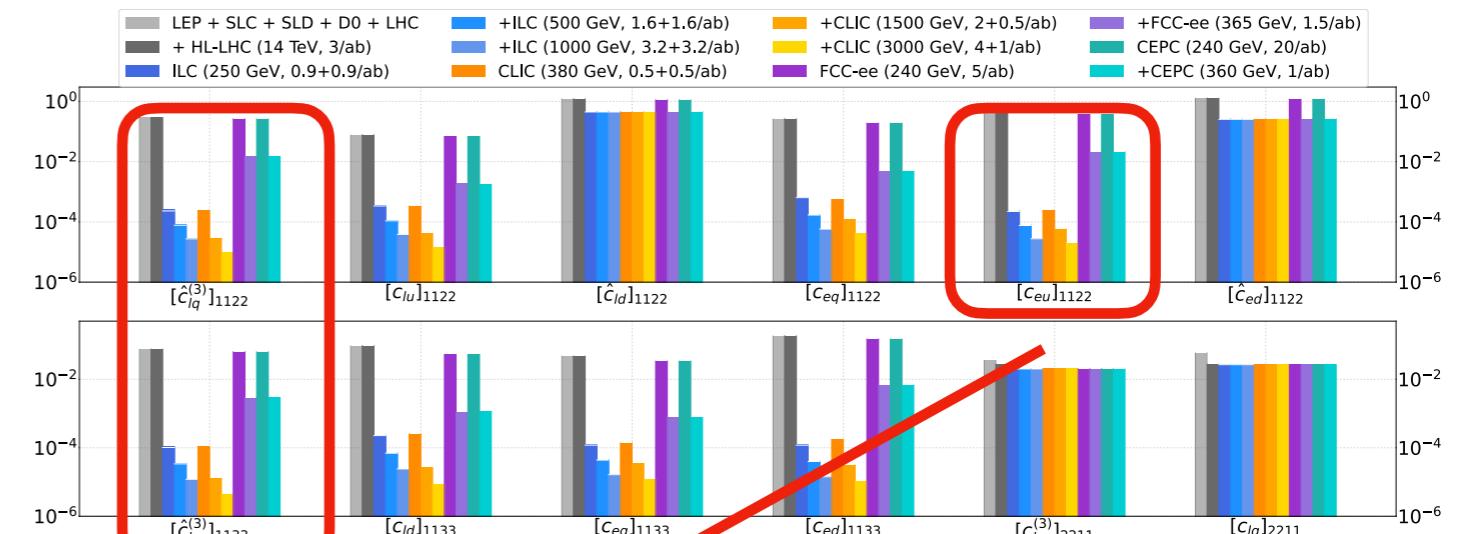
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Aebischer et al, 2102.08954

**YD** et al, JHEP 03 (2021) 019, Phys.Rev.D 105 (2022) 7, 075022

$$\begin{aligned} [C_{lq}^{(1)}]_{\alpha\beta ij}^{(0)} &= \frac{\lambda_{i\alpha}^{1L*} \lambda_{j\beta}^{1L}}{4M_1^2} + \frac{3\lambda_{i\alpha}^{3L*} \lambda_{j\beta}^{3L}}{4M_3^2}, \\ [C_{lq}^{(3)}]_{\alpha\beta ij}^{(0)} &= -\frac{\lambda_{i\alpha}^{1L*} \lambda_{j\beta}^{1L}}{4M_1^2} + \frac{\lambda_{i\alpha}^{3L*} \lambda_{j\beta}^{3L}}{4M_3^2}, \\ [C_{lequ}^{(1)}]_{\alpha\beta ij}^{(0)} &= \frac{\lambda_{j\beta}^{1R} \lambda_{i\alpha}^{1L*}}{2M_1^2}, \\ [C_{lequ}^{(3)}]_{\alpha\beta ij}^{(0)} &= -\frac{\lambda_{j\beta}^{1R} \lambda_{i\alpha}^{1L*}}{8M_1^2}, \\ [C_{eu}]_{\alpha\beta ij}^{(0)} &= \frac{\lambda_{i\alpha}^{1R*} \lambda_{j\beta}^{1R}}{2M_1^2}. \end{aligned}$$

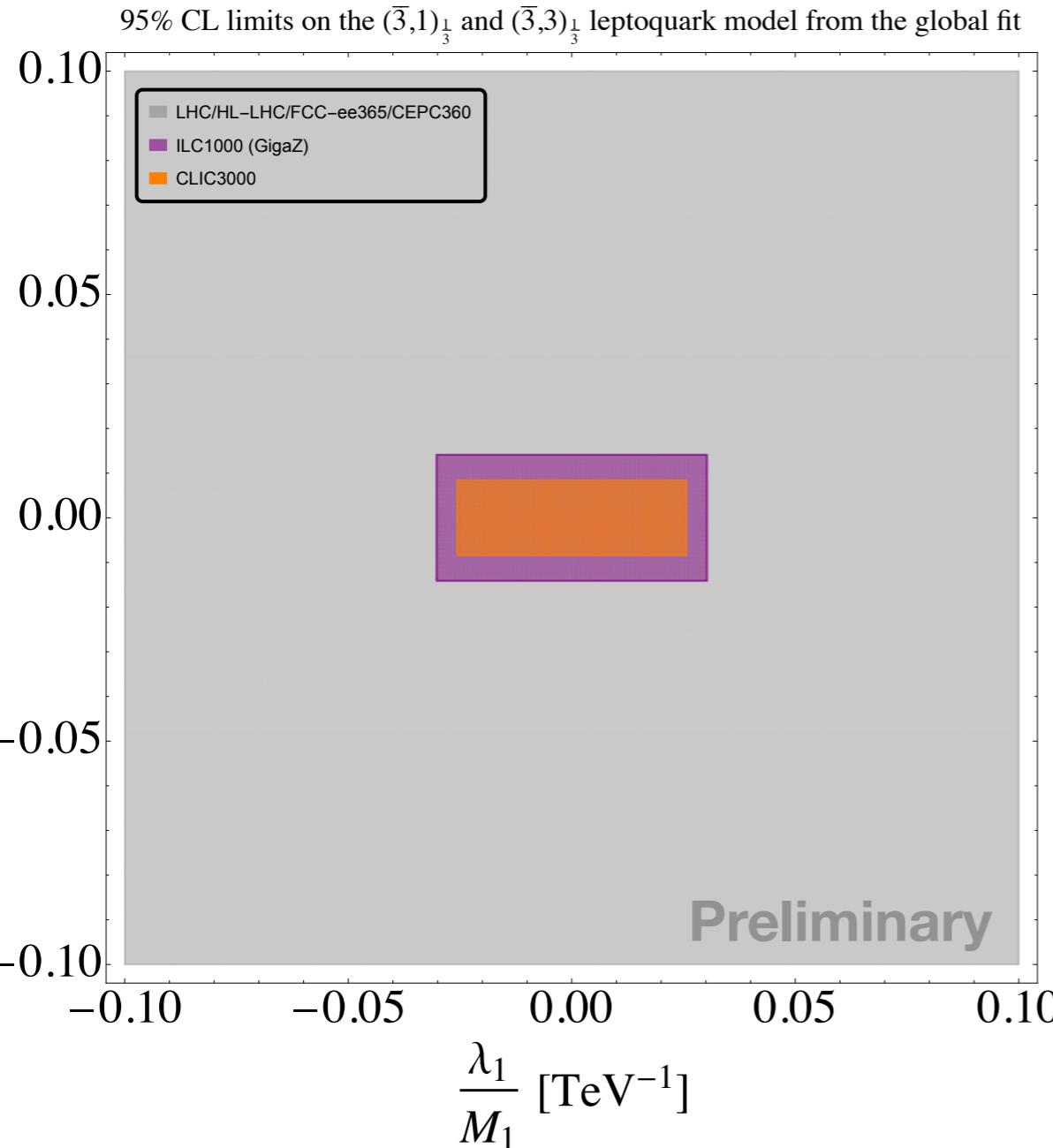


Leading constraints from the global fit:  $[c_{eu}]_{1122}$  and  $[\hat{c}_{lq}^{(3)}]_{1133,1122}$ .

\* Assuming universal Yukawa couplings for the following discussion.

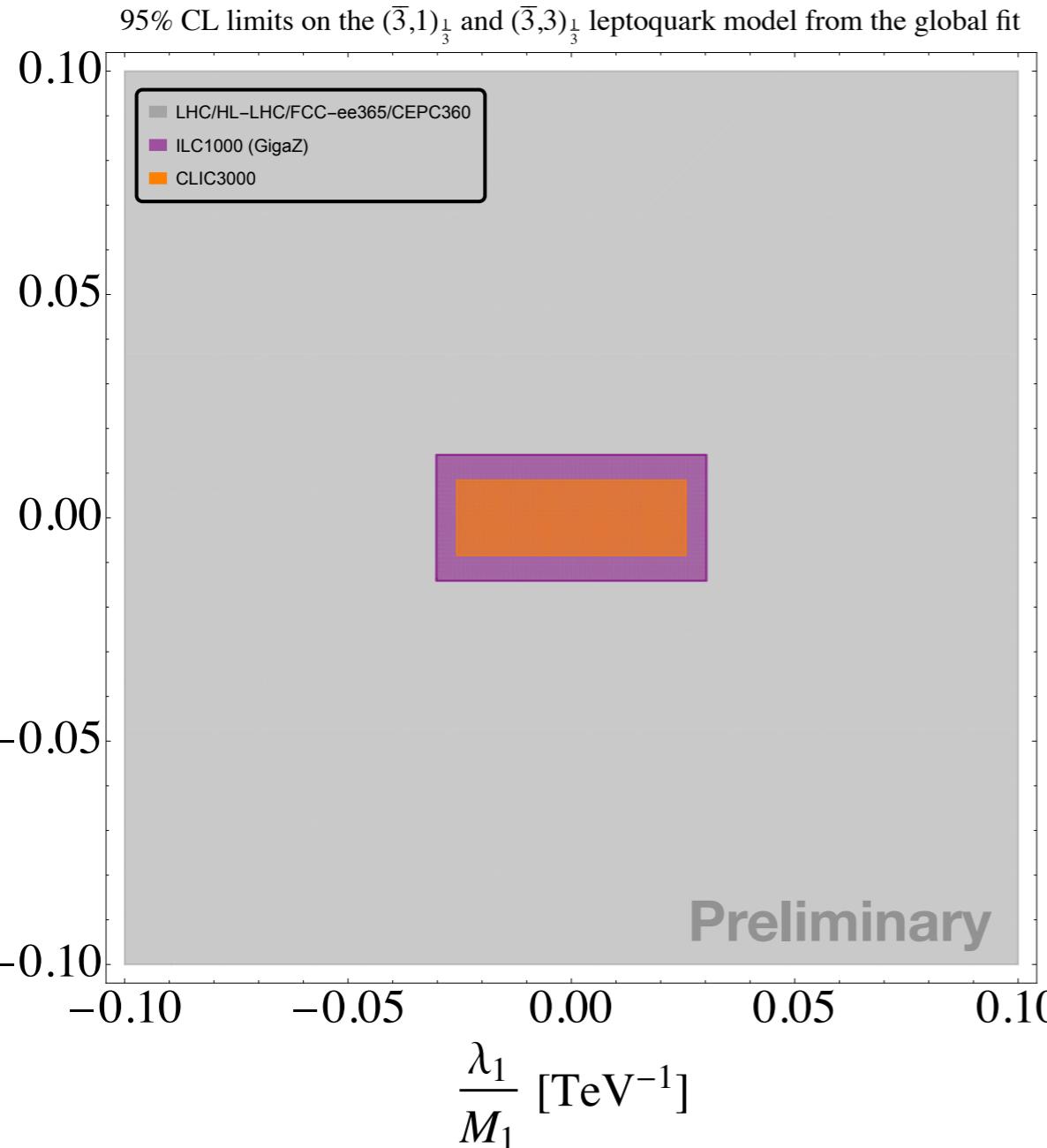
# Benchmark models: Leptoquark model

$$\mathcal{L}_{\text{LQ}} \supset (\lambda_{i\alpha}^{1L} \bar{q}_i^c \epsilon \ell_\alpha + \lambda_{i\alpha}^{1R} \bar{u}_i^c e_\alpha) S_1 + \lambda_{i\alpha}^{3L} \bar{q}_i^c \epsilon \sigma^I \ell_\alpha S_3^I + \text{h.c.}$$



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- \* Very stringent constraints on the parameter space from the global fit
- \* Can only constrain the ratios  $\lambda_{1(3)}/M_{1(3)}$

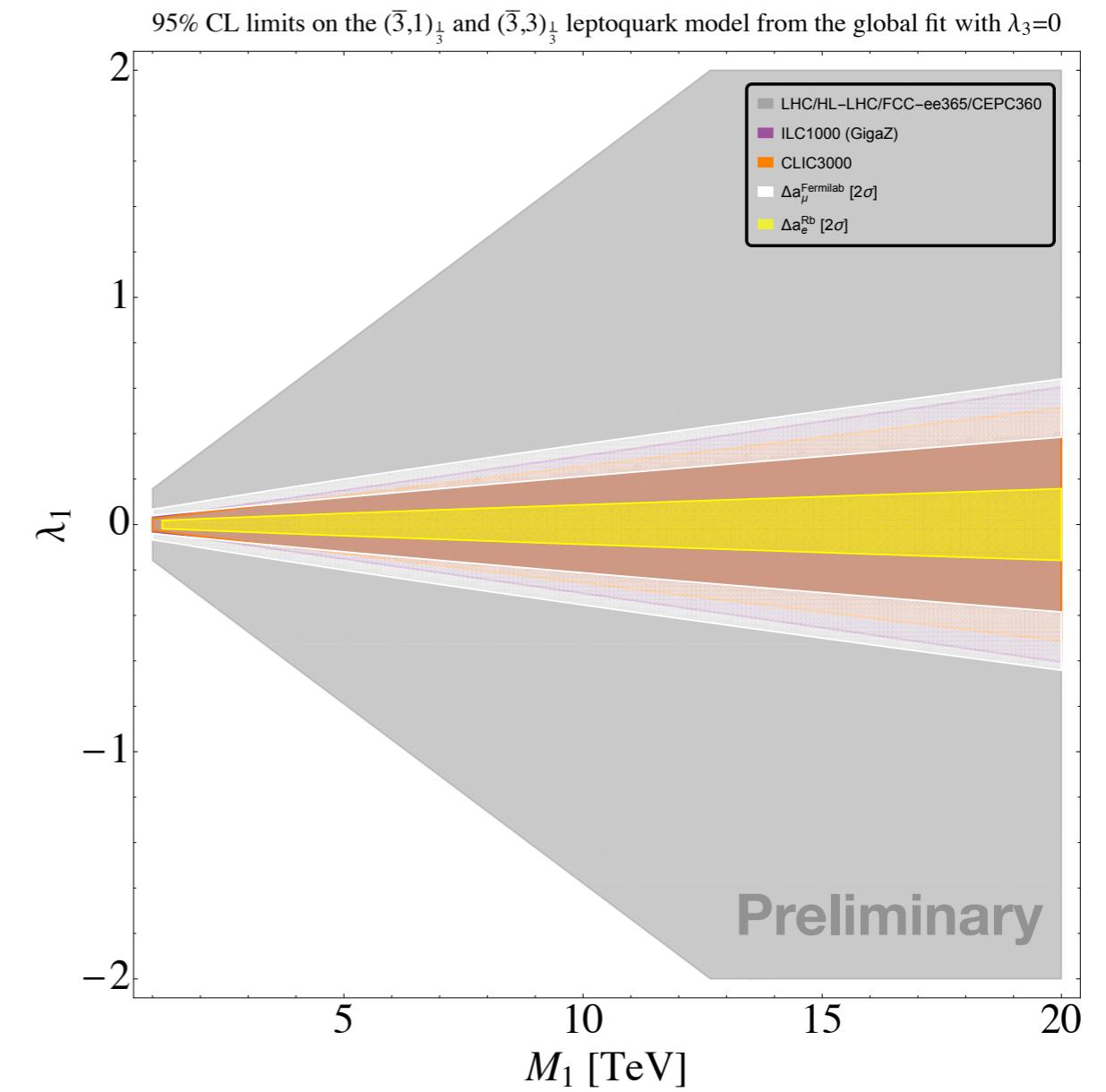
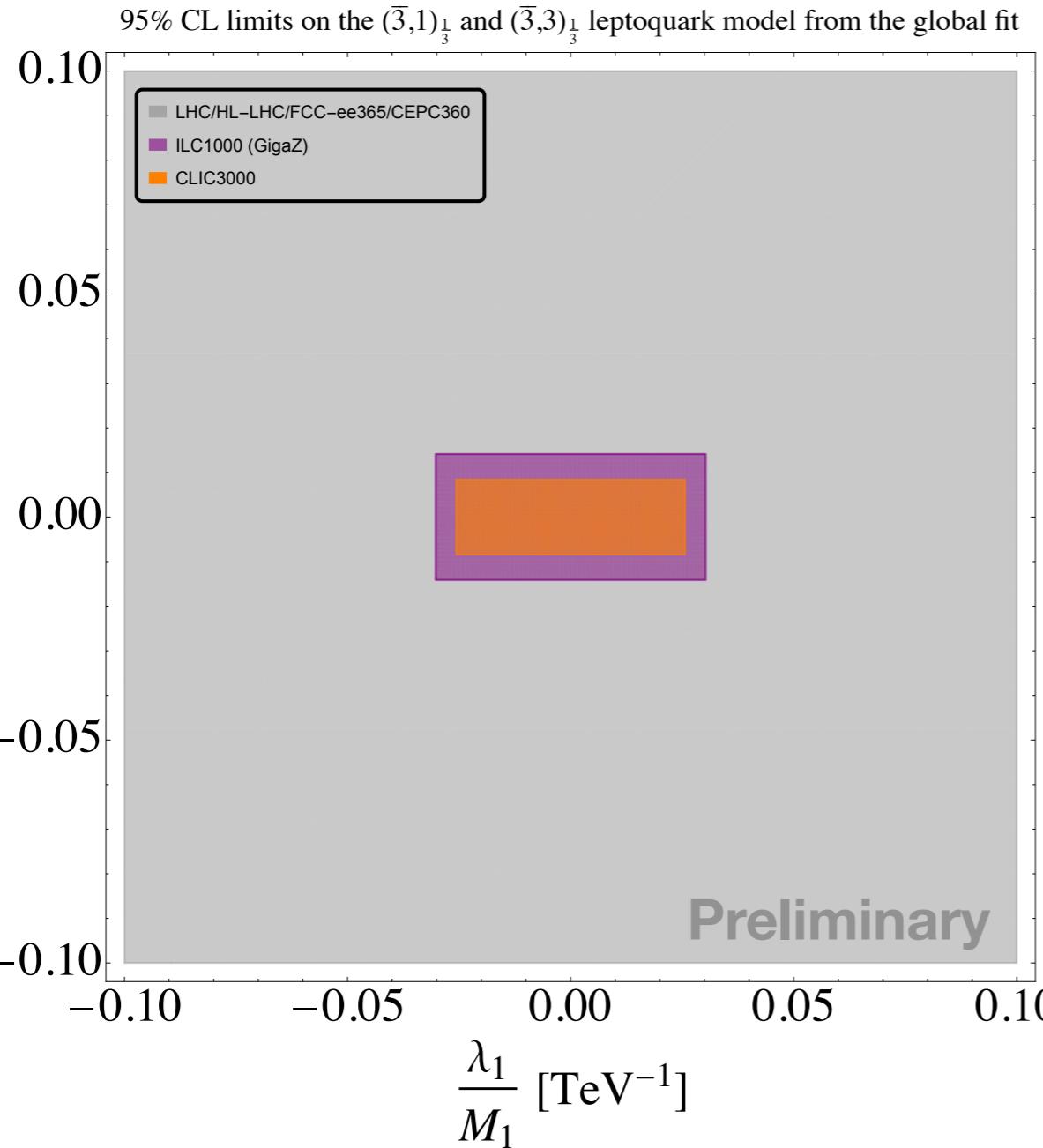
Extra observables? Lepton magnetic moments, for example.

$$\Delta a_\ell = -\frac{3}{8\pi^2} \frac{m_l m_t}{M_1^2} \lambda_1^2 \left( \frac{7}{6} + \frac{2}{3} \log \frac{m_t^2}{M_1^2} \right)$$

Aebischer et al, 2102.08954

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$$\mathcal{L}_{\text{LQ}} \supset (\lambda_{i\alpha}^{1L} \bar{q}_i^c \epsilon \ell_\alpha + \lambda_{i\alpha}^{1R} \bar{u}_i^c e_\alpha) S_1 + \lambda_{i\alpha}^{3L} \bar{q}_i^c \epsilon \sigma^I \ell_\alpha S_3^I + \text{h.c.}$$



## Summary and outlook

- ❖ We discuss the global fit results for 4-fermion and bosonic CPV operators without any flavor assumption, and its impact on some benchmark models ( $Z'$  and leptoquark).
- ❖ The sensitivity to new physics is significantly enhanced ( $\mathcal{O}(10^{-5})$ ) precision can be reached for both vertex and 4-fermion couplings) thanks to the high energy/luminosity/beam polarization of future lepton colliders, and also the use of optimal observables.
- ❖ Several flat directions remain due to missing projections for  $R_{uc}$ ,  $A_{FB}^{ss}$ , and  $\sigma_{ss}$  etc at future colliders. Muon colliders will also help improve the fit and eliminate further flat directions.
- ❖ Our global fit results for bosonic CPV operators could be further improved with  $e^+e^- \rightarrow W^+W^-$  data at future colliders.

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Finally, as an early career physicist, I have been enjoying the collaboration with such an excellent group over three different continents (Asia, Europe, and North America). I thank all of them and also the EF04 conveners for the introduction.

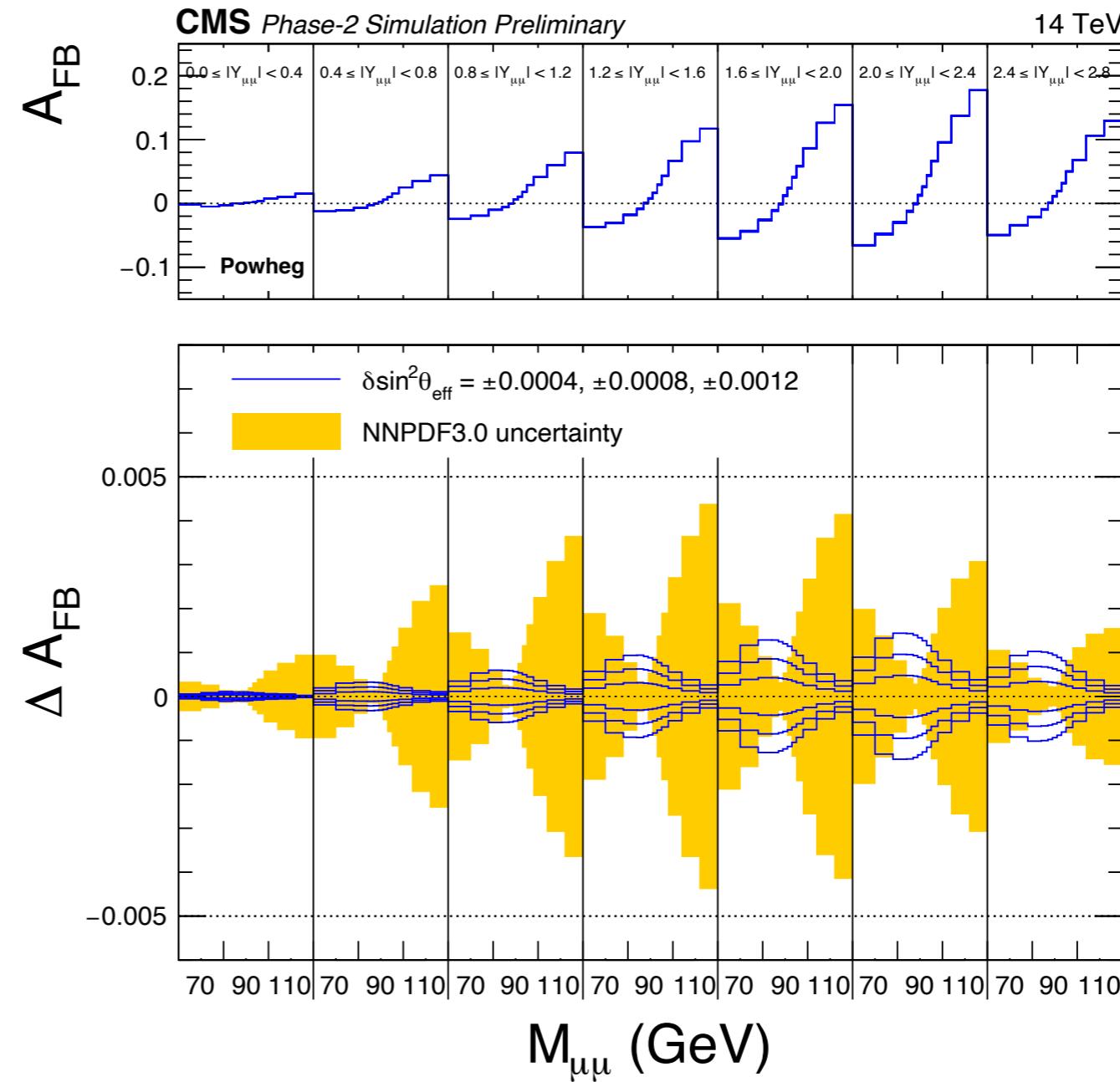
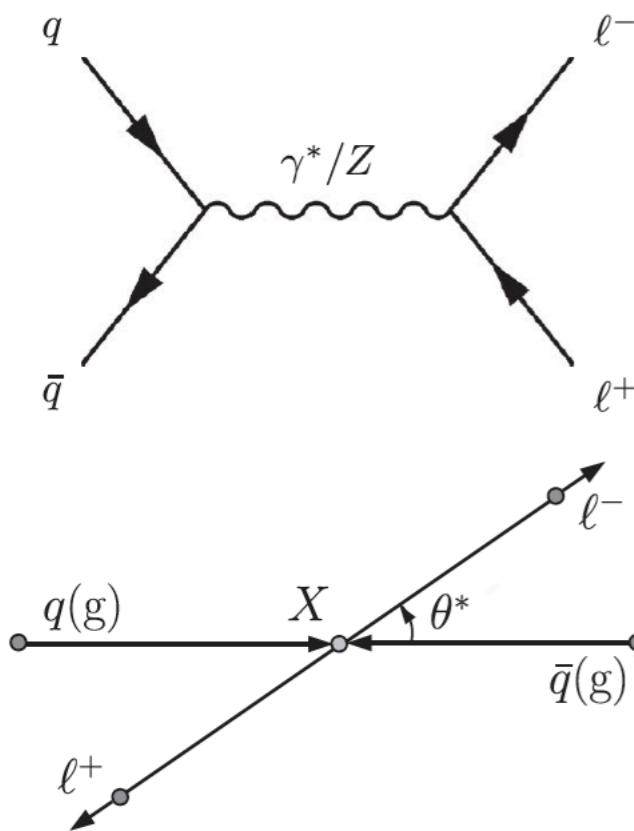
I will be on the market this fall, you are more than welcomed to contact me if you have any opening positions. More importantly, it will also be my honor to work with you on the exciting physics.

# Backup

# AFB at the HL-LHC: $\mu\mu$ channel

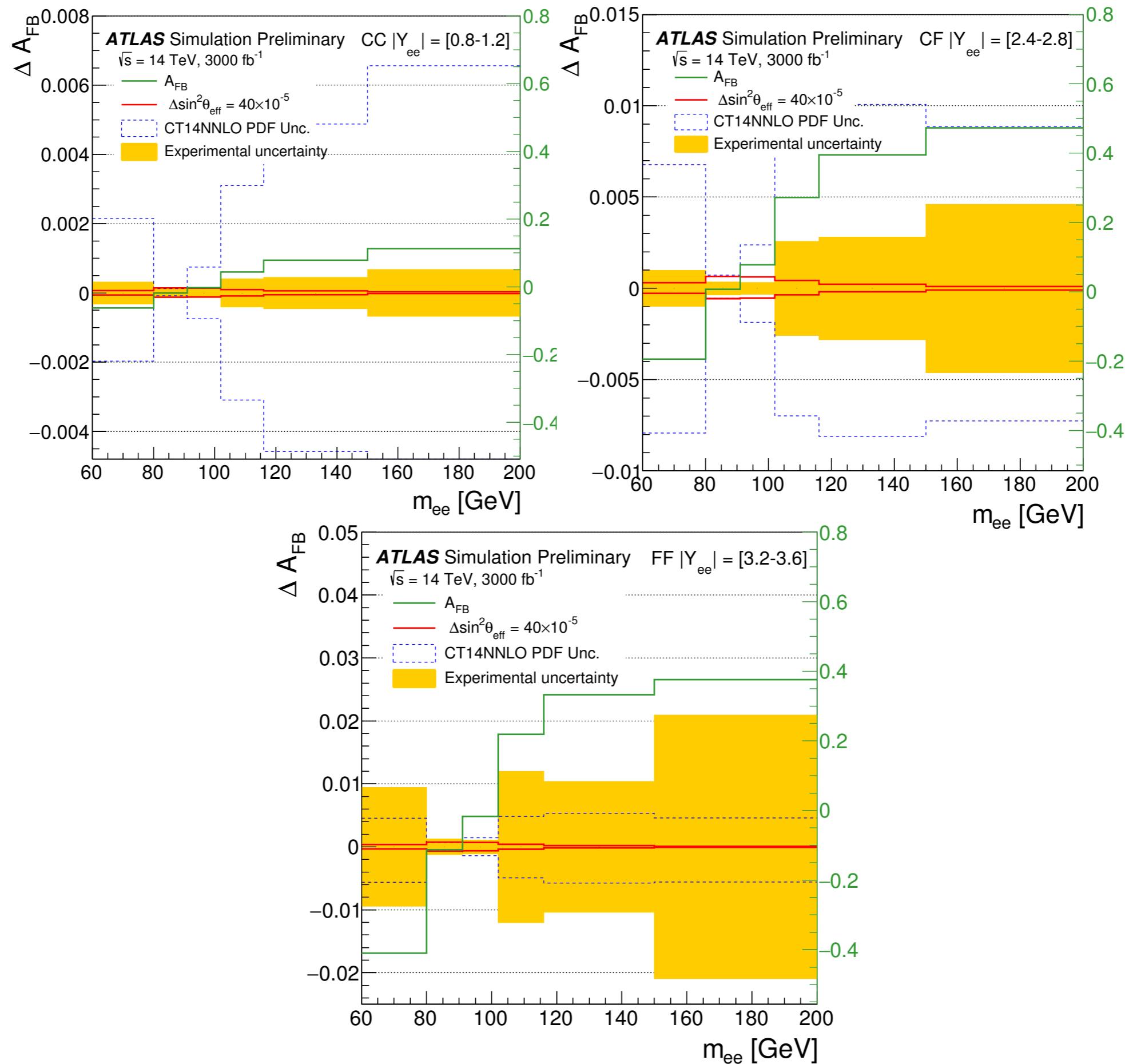
SMP-16-007-pas

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



# AFB at the HL-LHC: *ee channel*

ATL-PHYS-PUB-2018-037



# SMEFT global fit 2: *Remaining flat directions*

12 remaining flat directions: Falkowski et al, JHEP 08 (2017) 123

$$[\hat{c}_{eq}]_{1111} = [c_{eq}]_{1111} + [c_{\ell q}]_{1111}$$

$R_{\nu_e, \bar{\nu}_e}$  (CHARM), FASER $\nu$

$$[\hat{c}_{eq}]_{2211} = [c_{eq}]_{2211} + [c_{ed}]_{2211} - 2 [c_{eu}]_{2211}$$

CERN SPS, FASER $\nu$ , Muon collider

$$[\hat{c}_{\ell\ell}]_{2222} = [c_{\ell\ell}]_{2222} + \frac{2g_Y^2}{g_L^2 + 3g_Y^2} [c_{\ell e}]_{2222}$$

CCFR, FASER $\nu$ , Muon collider

$$\epsilon_P^{d\mu}(2\text{GeV}) = 0.86 [c_{ledq}]_{2211} - 0.86 [c_{lequ}]_{2211} + 0.012 [c_{ledq}^{(3)}]_{2211}$$

RGE, FASER $\nu$ ,  $\mu/\nu_\mu$ -N scattering, Muon collider

$\mu$ C: 2203.07256, 2203.07261

FASER $\nu$ : 2109.10905, 2203.05090

$$[\hat{c}_{ed}]_{1111} = [c_{ed}]_{1111} - [c_{\ell q}]_{1111}$$

$$[\hat{c}_{\ell d}]_{1122} = [c_{\ell d}]_{1122} + \left(5 - \frac{3g_L^2}{g_Y^2}\right) [c_{\ell q}]_{1122} - [\hat{c}_{eq}]_{1111}$$

$$[\hat{c}_{eu}]_{1111} = [c_{eu}]_{1111} - [c_{\ell q}]_{1111}$$

$$[\hat{c}_{ed}]_{1122} = [c_{ed}]_{1122} - \left(3 - \frac{3g_L^2}{g_Y^2}\right) [c_{\ell q}]_{1122} - [\hat{c}_{eq}]_{1111}$$

$$[\hat{c}_{\ell d}]_{1111} = [c_{\ell d}]_{1111} + [c_{\ell q}]_{1111} - [\hat{c}_{eq}]_{1111}$$

$$[\hat{c}_{\ell q}^{(3)}]_{1122} = [c_{\ell q}^{(3)}]_{1122} - [c_{\ell q}]_{1122}$$

$$[\hat{c}_{\ell u}]_{1111} = [c_{\ell u}]_{1111} + [c_{\ell q}]_{1111} - [\hat{c}_{eq}]_{1111}$$

$$[\hat{c}_{\ell q}^{(3)}]_{1133} = [c_{\ell q}^{(3)}]_{1133} + [c_{\ell q}]_{1133}$$

$A_{\text{PV}}$ , P2@MESA

$\sigma_q, \sigma_{b,c}, A_{\text{FB}}^{bb,cc}, R_{bb,cc}$   
e/ve-N scattering, FASER $\nu$

# SMEFT global fit 2: Observable summary (future)

## Pole observables (negligible correlation)

de Blas, YD, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380	
$\Delta\alpha(m_Z)^{-1} (\times 10^3)$	17.8*	17.8*		3.8 (1.2)	17.8*		
$\Delta m_W$ (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)		
$\Delta m_Z$ (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*	
$\Delta m_H$ (MeV)	170*	14		2.5 (2)	5.9	78	
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)		
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*	
$\Delta A_e (\times 10^5)$	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5	64	1905.03764
$\Delta A_\mu (\times 10^5)$	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400	1907.04311
$\Delta A_\tau (\times 10^5)$	400*	86 (4.5)	3 (8)	0.5 ( <b>20</b> )	1.2 ( <b>6.9</b> )	570	1908.11299
$\Delta A_b (\times 10^5)$	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	380	2106.13885
$\Delta A_c (\times 10^5)$	2700*	140 (25)	20 (37)	20 (15)	6 ( <b>30</b> )	200	
$\Delta\sigma_{\text{had}}^0$ (pb)	37*			0.035 (4)	0.05 (2)	37*	
$\delta R_e (\times 10^3)$	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7	
$\delta R_\mu (\times 10^3)$	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7	
$\delta R_\tau (\times 10^3)$	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6	
$\delta R_b (\times 10^3)$	3.0*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8	
$\delta R_c (\times 10^3)$	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6	

We **do not** have any projections yet for  $R_{uc}$ .

# SMEFT global fit: ***CPV in $Zh$ production at circular colliders***

$$\mathcal{A}_\phi^{(1)} \approx 0.040 \hat{\alpha}_{Z\tilde{Z}} + 0.20 \hat{\alpha}_{A\tilde{Z}},$$

$$\mathcal{A}_\phi^{(2)} \approx 0.57 \hat{\alpha}_{Z\tilde{Z}} + 0.031 \hat{\alpha}_{A\tilde{Z}},$$

	$\hat{\alpha}_{ZZ}$	$\hat{\alpha}_{ZZ}^{(1)}$	$\hat{\alpha}_{\Phi\ell}^V$	$\hat{\alpha}_{\Phi\ell}^A$	$\hat{\alpha}_{AZ}$	$\delta g_V$	$\delta g_A$	$\hat{\alpha}_{Z\tilde{Z}}$	$\hat{\alpha}_{A\tilde{Z}}$
rate	0.00064	0.0035	0.0079	0.00059	0.012	0.023	0.0018	$\infty$	$\infty$
angles	0.016	$\infty$	0.0058	0.078	0.0087	0.017	0.23	0.012	0.036
total	0.00064	0.0035	0.0047	0.00059	0.0070	0.014	0.0018	0.012	0.036

**Table 5.**  $1\sigma$  uncertainties for individual Wilson coefficients, with the assumption that all other coefficients are zero. The second row shows the constraints from the rate measurements only, the third row shows the constraints from measurements of angular observables (combined) only, and the last row shows the total combined constraints from both rate and angular measurements. If no constraint could be derived within our procedure, a  $\infty$  is shown.

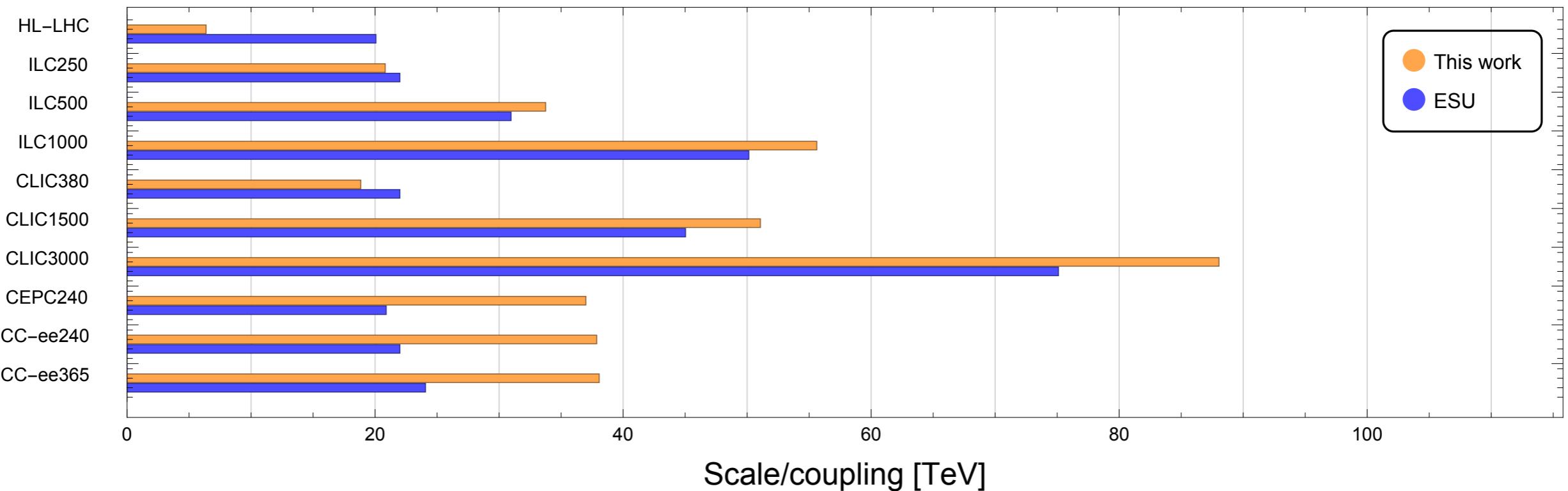
# SMEFT global fit: *CPV in Zh production at linear colliders*

$$\begin{aligned}
 ZH \text{ at } 250 \text{ GeV with } e_L^- e_R^+ : & \quad \left\{ \begin{array}{l} a_Z = \pm 0.409 \\ b_Z = \pm 0.147 \\ \tilde{b}_Z = \pm 0.066 \end{array} \right. , \quad \rho = \begin{pmatrix} 1 & -0.999 & 0.006 \\ - & 1 & -0.006 \\ - & - & 1 \end{pmatrix} \\
 ZH \text{ at } 250 \text{ GeV with } e_R^- e_L^+ : & \quad \left\{ \begin{array}{l} a_Z = \pm 0.441 \\ b_Z = \pm 0.159 \\ \tilde{b}_Z = \pm 0.074 \end{array} \right. , \quad \rho = \begin{pmatrix} 1 & -0.999 & -0.006 \\ - & 1 & 0.006 \\ - & - & 1 \end{pmatrix} \\
 ZH \text{ at } 500 \text{ GeV with } e_L^- e_R^+ : & \quad \left\{ \begin{array}{l} a_Z = \pm 0.123 \\ b_Z = \pm 0.029 \\ \tilde{b}_Z = \pm 0.023 \end{array} \right. , \quad \rho = \begin{pmatrix} 1 & -0.992 & 0.006 \\ - & 1 & -0.009 \\ - & - & 1 \end{pmatrix} \\
 ZH \text{ at } 500 \text{ GeV with } e_R^- e_L^+ : & \quad \left\{ \begin{array}{l} a_Z = \pm 0.132 \\ b_Z = \pm 0.031 \\ \tilde{b}_Z = \pm 0.023 \end{array} \right. , \quad \rho = \begin{pmatrix} 1 & -0.993 & -0.002 \\ - & 1 & 0.001 \\ - & - & 1 \end{pmatrix}
 \end{aligned}$$

Tian et al, 1712.09772

# Snowmass vs ESU: $\mathcal{O}_{2W,2B}$ *update*

95% CL scale limits on 4-fermion contact interactions from  $\mathcal{O}_{2W}$



# Benchmark models: Leptoquark model

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*Impact on the leptoquark model from the individual fit*

