SMEFT global fit for 4-fermion and CPV operators at future colliders

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Based on
2206.08326, with Jorge de Blas, Christophe Grojean, Jiayin Gu, Victor Miralles, Michael Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou

Ongoing work with Michael Peskin, Junping Tian

SMEFT global fit: ***Some remarks***

Big picture of the SMEFT global fit:

Fit 1 for Higgs + electroweak physics (**Jiayin Gu's talk on Monday**)

Fit 2 & 3 for four-fermion ($f \neq t$) and bosonic CP-violating operators (**This talk**)

Fit 4 for top physics (**My talk yesterday**)

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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*

- **4-fermion interactions**
- **Bosonic CPV operators**
- **Benchmark UV study (*time permitting*)**
  - ❖ Comparison with ESU results
  - ❖ The Y-Universal Z' model
  - ❖ The leptoquark model
- **Summary**

4-fermion interactions

4-fermion: SMEFT 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

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

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

4-fermion: SMEFT setup

We only consider flavor conserving 4-fermion operators

$2\ell 2q$ operators $(p, r = 1,2,3)$	4ℓ operators $(p < r = 1,2,3)$
Chirality conserving	Two flavors
$[\mathcal{O}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell\ell}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_r \bar{\sigma}^\mu \ell_r)$
$[O^{(3)}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \sigma^i \ell_p)(\bar{q}_r \bar{\sigma}^\mu \sigma^i q_r)$	$[\mathcal{O}_{\ell\ell}]_{prrp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_r)(\bar{\ell}_r \bar{\sigma}^\mu \ell_p)$
$[\mathcal{O}_{\ell u}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(u^c_r \sigma^\mu \bar{u}^c_r)$	$[\mathcal{O}_{\ell e}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e^c_r \sigma^\mu \bar{e}^c_r)$
$[\mathcal{O}_{\ell d}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(d^c_r \sigma^\mu \bar{d}^c_r)$	$[\mathcal{O}_{\ell e}]_{rrpp} = (\bar{\ell}_r \bar{\sigma}_\mu \ell_r)(e^c_p \sigma^\mu \bar{e}^c_p)$
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$[\mathcal{O}_{ed}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(d^c_r \sigma^\mu \bar{d}^c_r)$	
Chirality violating	One flavor
$[\mathcal{O}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{e}^c_p)\epsilon_{jk}(\bar{q}^k_r \bar{u}^c_r)$	$[\mathcal{O}_{\ell\ell}]_{pppp} = \frac{1}{2}(\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_p \bar{\sigma}^\mu \ell_p)$
$[O^{(3)}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{\sigma}_{\mu\nu} \bar{e}^c_p)\epsilon_{jk}(\bar{q}^k_r \bar{\sigma}_{\mu\nu} \bar{u}^c_r)$	$[\mathcal{O}_{\ell e}]_{pppp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e^c_p \sigma^\mu \bar{e}^c_p)$
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Left of chirality conserving rows: $\sum_i h_i = 0$; right of two-flavor rows: $\sum_i h_i = 0$

Left of chirality violating rows: $\sum_i h_i = \pm 2$; right of one-flavor rows: $\sum_i h_i = 0$

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)

4-fermion: ***Strategy***

- ☑ All observables are analytically re-derived, keeping also the (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.

4-fermion: *Strategy*

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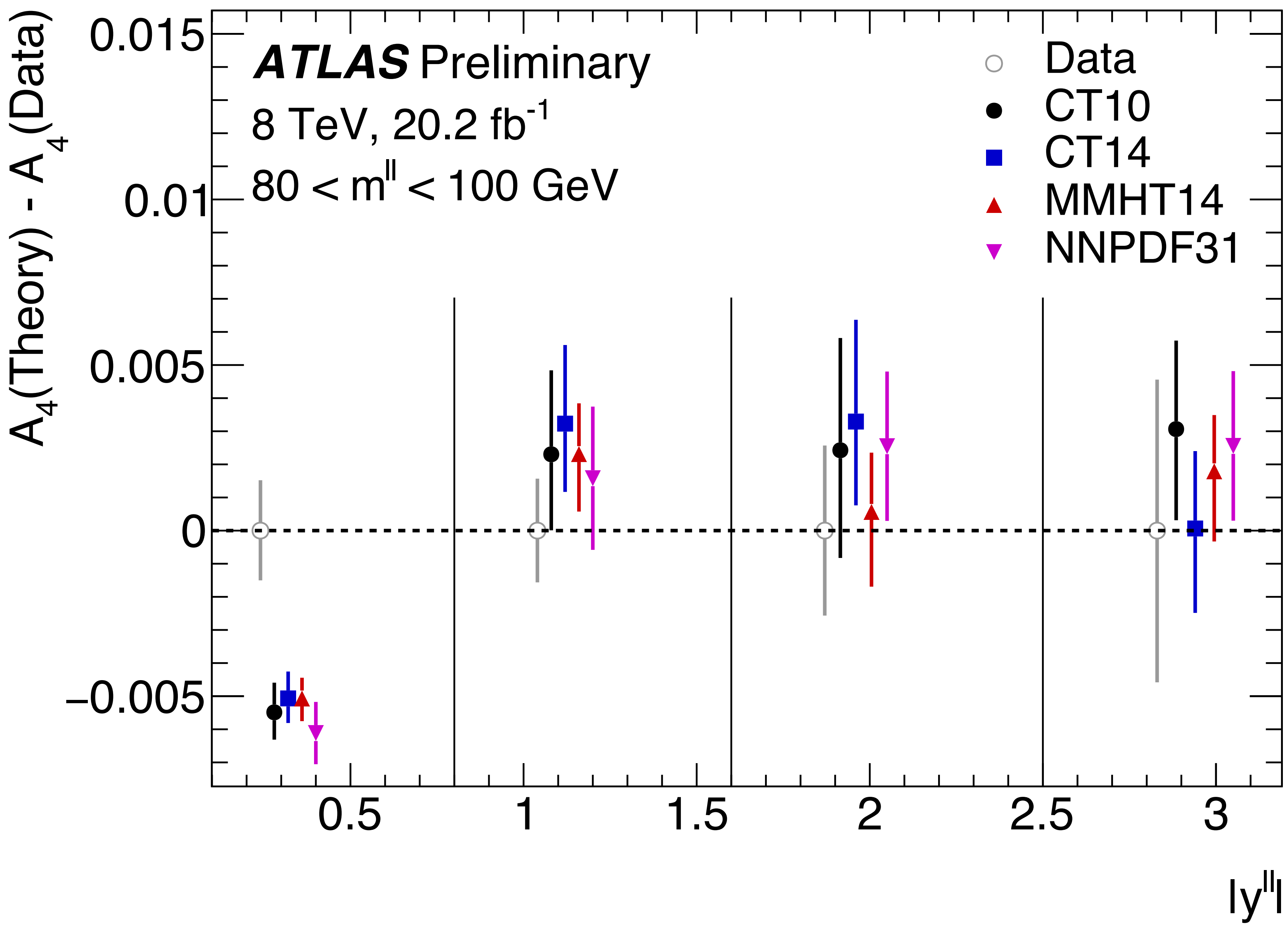
- ☑ For the global fit discussed below, only linear dim-6 corrections are included.
- ☑ For consistency, dim-8 operators are always ignored and left for future.

Alioli, Boughezal, Petriello, 2003.11615
Hays, Helset, Martin, Trott, 2007.00565
Ellis, He, Xiao, 2008.04298
Fuks, Liu, Zhang, Zhou, 2009.02212
Yamashita, Zhang, Zhou, 2009.04490
Jin, Ren, Yang, 2011.02494
Gu, Wang, Zhang, 2011.03055
Dedes, Kozow, Szleper, 2011.03367
Bonnefoy, Gendy, Grojean, 2011.12855
Murphy, 2012.13291
Kim, Martin, 2203.11976
Ardu, Davidson, 2103.07212
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
Ellis, He, Xiao, 2206.11676
Boughezal, Huang, Petriello, 2207.01703
Hamoudou, Kumar, London, 2207.08856
……

4-fermion: *Strategy*

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

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



ATLAS-CONF-2018-037

4-fermion: ***Strategy***

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

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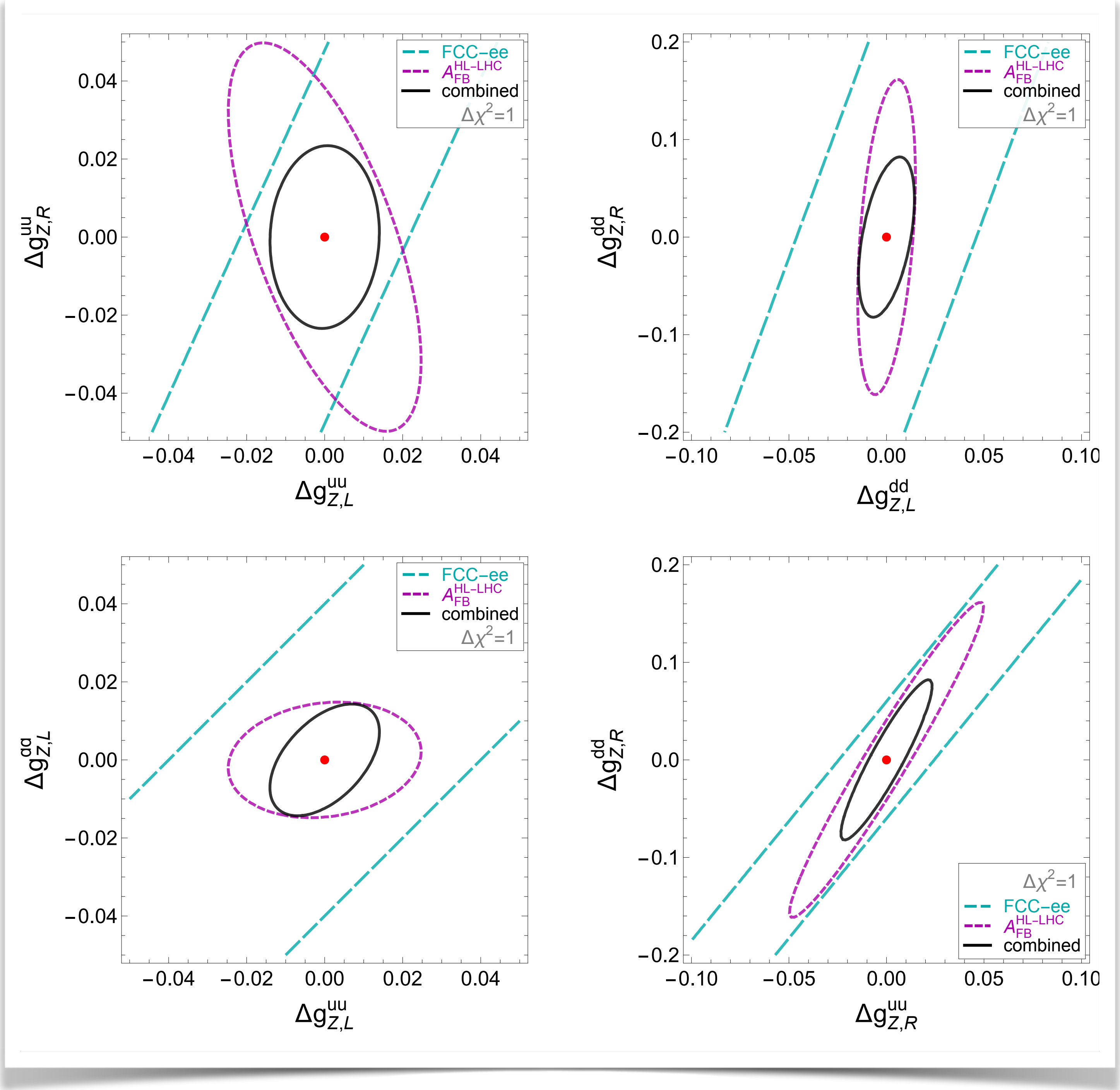

4-fermion: *Strategy*

Optimal observables (Please see my talk yesterday for its review) are used to improve sensitivity for $A_{\rm FB}^{ff}$ and σ_{ff} at future (polarized) lepton colliders:

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

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

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

* Thanks to Adrain Irles.

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
$\overset{(-)}{\nu}_\mu - e^-$ scattering	$g_{LV}^{\nu_\mu e}$	-0.035 ± 0.017	CHARM-II [47]	-0.0396 [48]
	$g_{LA}^{\nu_\mu e}$	-0.503 ± 0.017		-0.5064 [48]
τ decay	$\frac{G_{\tau e}^2}{G_F^2}$	1.0029 ± 0.0046	PDG2014 [49]	1
	$\frac{G_{\tau\mu}^2}{G_F^2}$	0.981 ± 0.018		
Neutrino scattering	R_{ν_μ}	0.3093 ± 0.0031	CHARM ($r = 0.456$) [50]	0.3156 [50]
	$R_{\bar{\nu}_\mu}$	0.390 ± 0.014		0.370 [50]
	R_{ν_μ}	0.3072 ± 0.0033	CDHS ($r = 0.393$) [51]	0.3091 [51]
	$R_{\bar{\nu}_\mu}$	0.382 ± 0.016		0.380 [51]
	κ	0.5820 ± 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 ± 0.0013	SLAC-E158 [55]	0.2381 ± 0.0006 [56]
	$Q_W^{\text{Cs}}(55, 78)$	-72.62 ± 0.43	PDG2016 [54]	-73.25 ± 0.02 [54]
	$Q_W^{\text{P}}(1, 0)$	0.064 ± 0.012	QWEAK [57]	0.0708 ± 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 ± 0.057	SAMPLE ($\sqrt{Q^2} = 200$ MeV) [59]	-0.0360 [54]
		-0.12 ± 0.074	SAMPLE ($\sqrt{Q^2} = 125$ MeV) [59]	0.0265 [54]
	b_{SPS}	$-(1.47 \pm 0.42) \times 10^{-4}\,\text{GeV}^{-2}$	SPS ($\lambda = 0.81$) [60]	$-1.56 \times 10^{-4}\,\text{GeV}^{-2}$ [60]
		$-(1.74 \pm 0.81) \times 10^{-4}\,\text{GeV}^{-2}$	SPS ($\lambda = 0.66$) [60]	$-1.57 \times 10^{-4}\,\text{GeV}^{-2}$ [60]
τ polarization	$\mathcal{P}_\tau$	0.012 ± 0.058	VENUS [61]	0.028 [61]
	$\mathcal{A}_\mathcal{P}$	0.029 ± 0.057		0.021 [61]
Neutrino trident production	$\frac{\sigma}{\sigma^{\text{SM}}}(\nu_\mu \gamma^* \to \nu_\mu \mu^+ \mu^-)$	0.82 ± 0.28	CCFR [62–64]	1
$d_I \to u_J \ell \bar{\nu}_\ell (\gamma)$	$\epsilon_{L,R,S,P,T}^{de_J}$	See text	[65]	0
$e^+e^- \to f\bar{f}$	δA_{LR}^e	2.0%	SuperKEKB [66]	0.00015
	δA_{LR}^μ	1.5%		-0.0006
	δA_{LR}^τ	2.4%		-0.0006
	δA_{LR}^c	0.5%		-0.005
	δA_{LR}^b	0.4%		-0.020

SMEFT global fit 2: Low-energy observables

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

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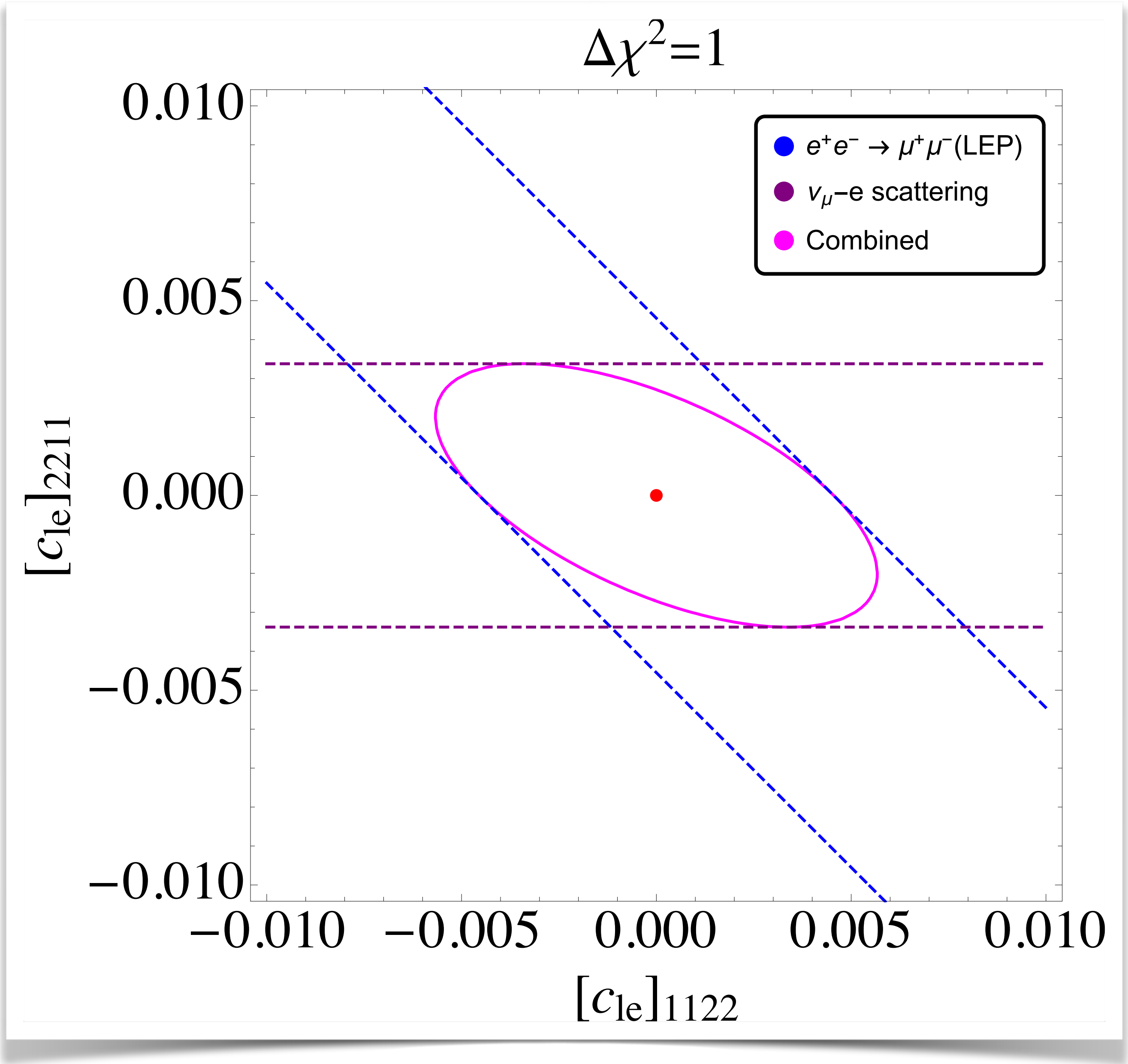
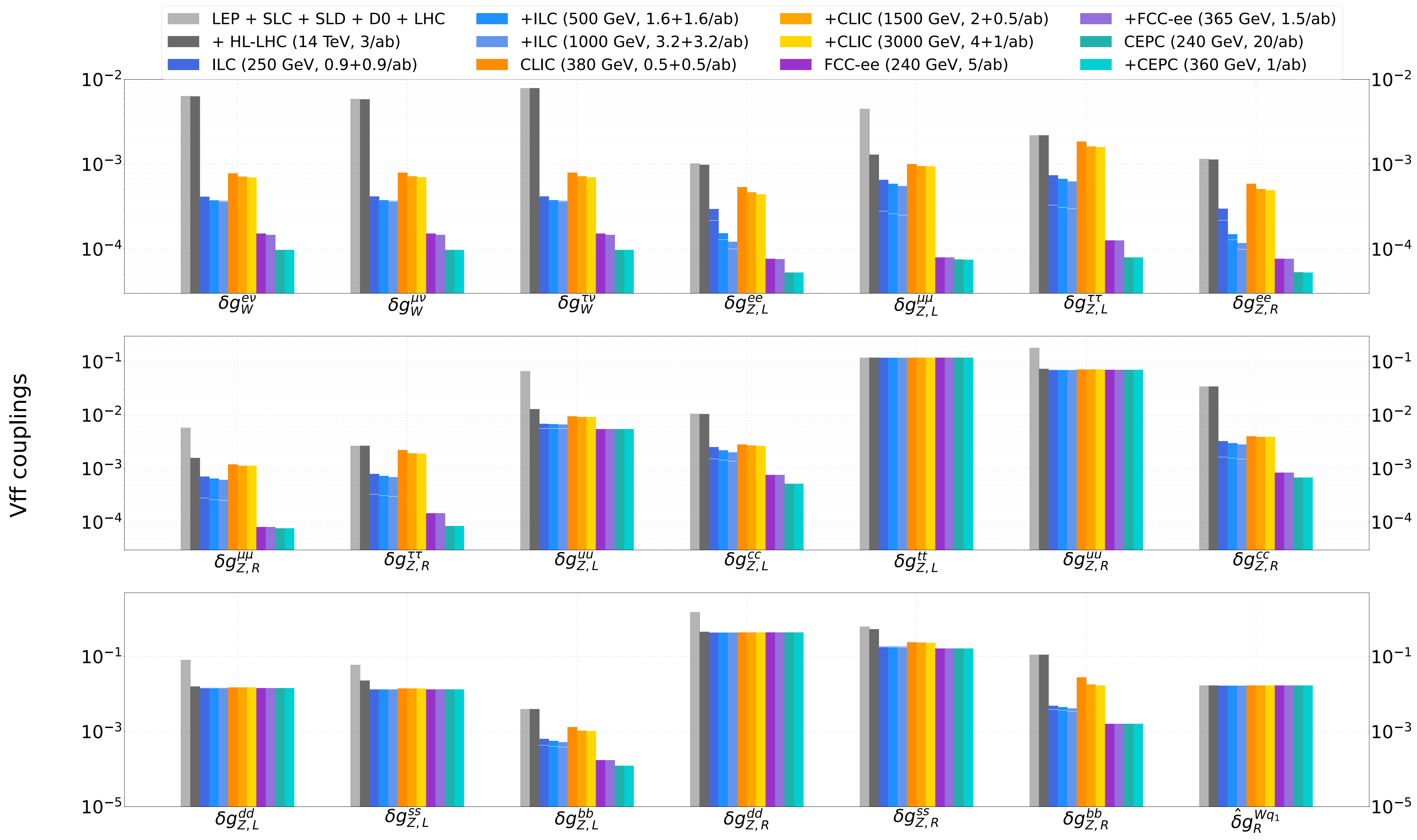
SMEFT global fit 2: *Low-energy observables*

Flat direction lifted by low-energy experiments: One example



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

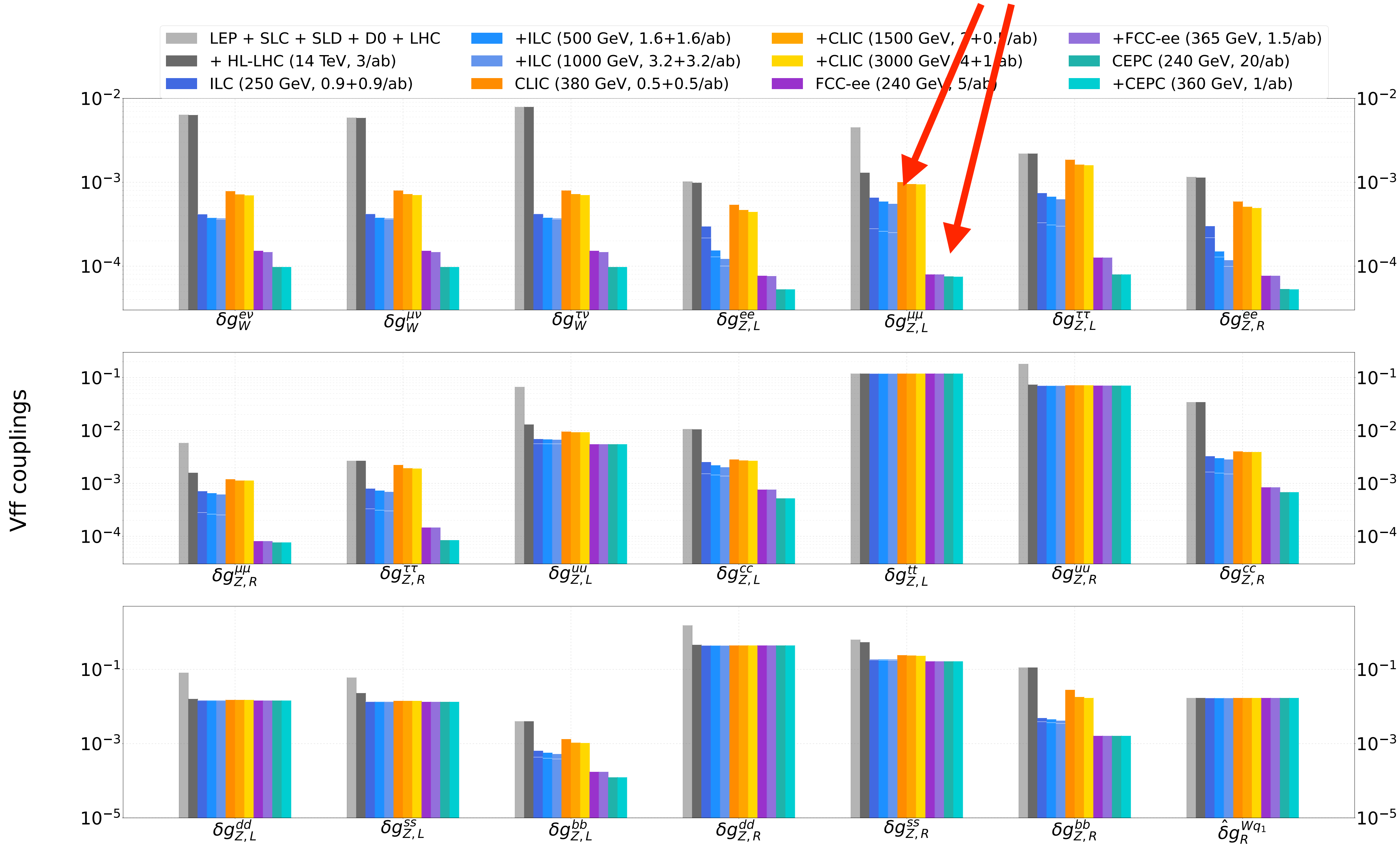
Global fit results: Vff couplings



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

Global fit results: Vff couplings

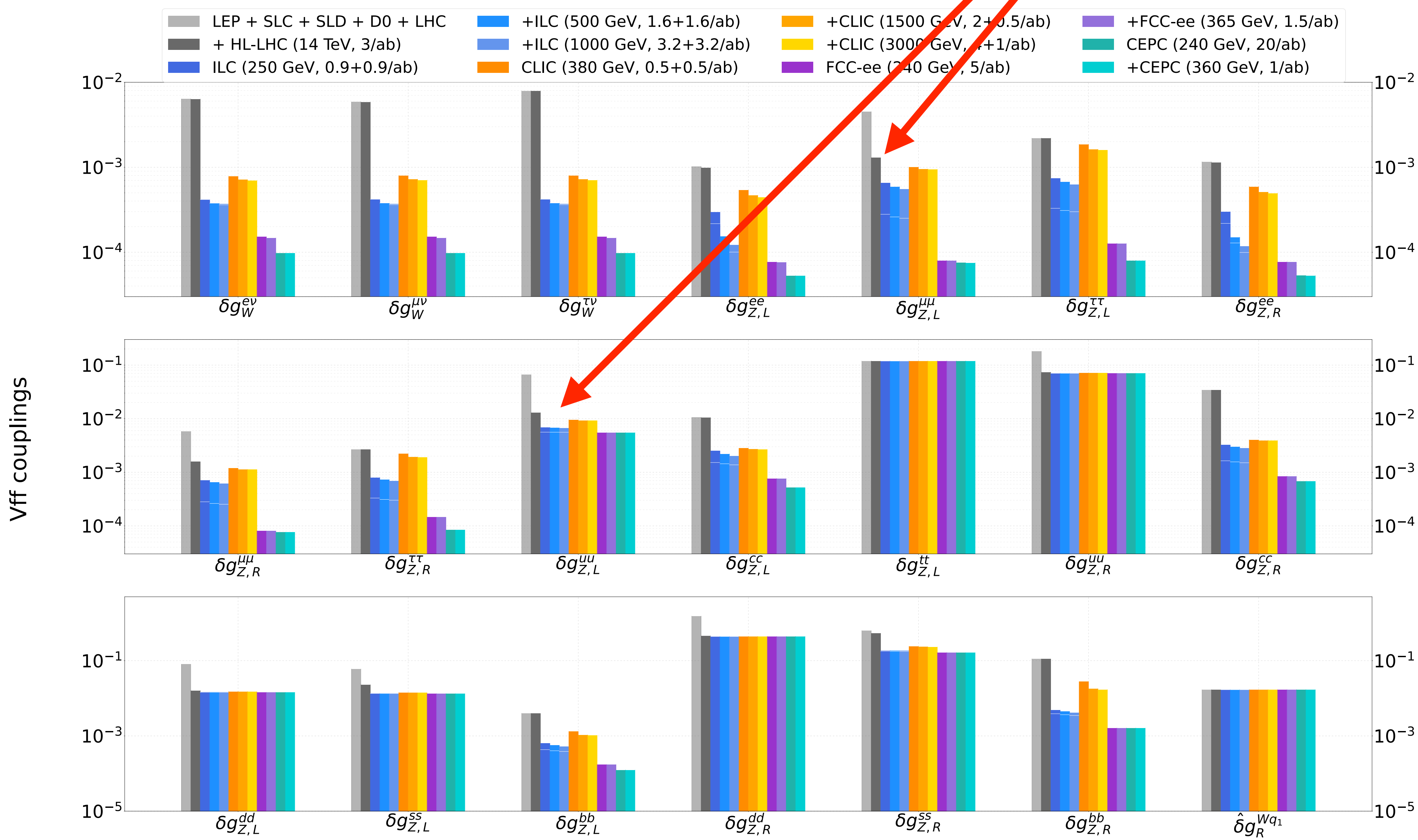
Luminosity wins (through radiative return)



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

Global fit results: Vff couplings

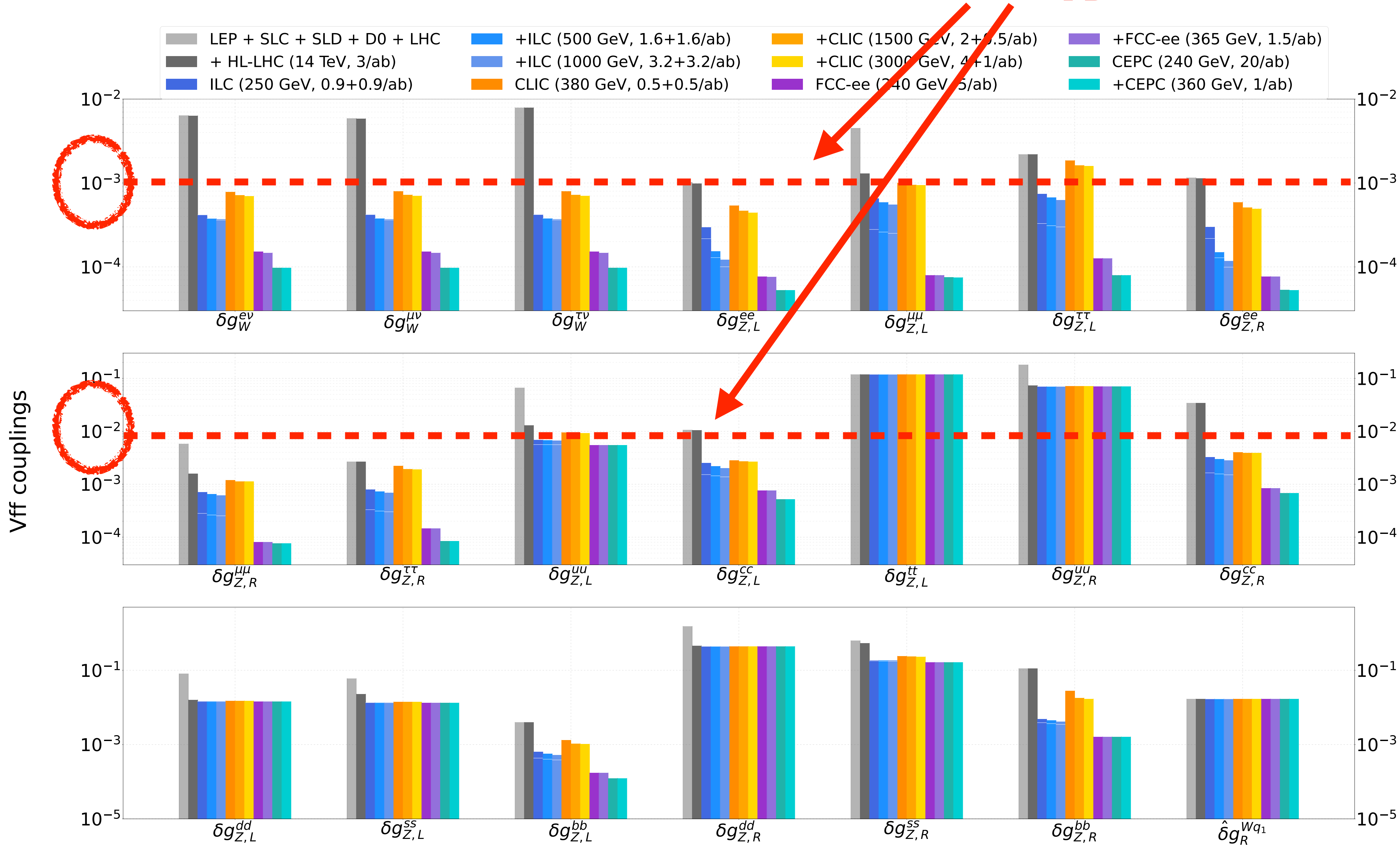
D0 + A_{FB} at the (HL-)LHC relaxes the U2 assumption & improve the fit.



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

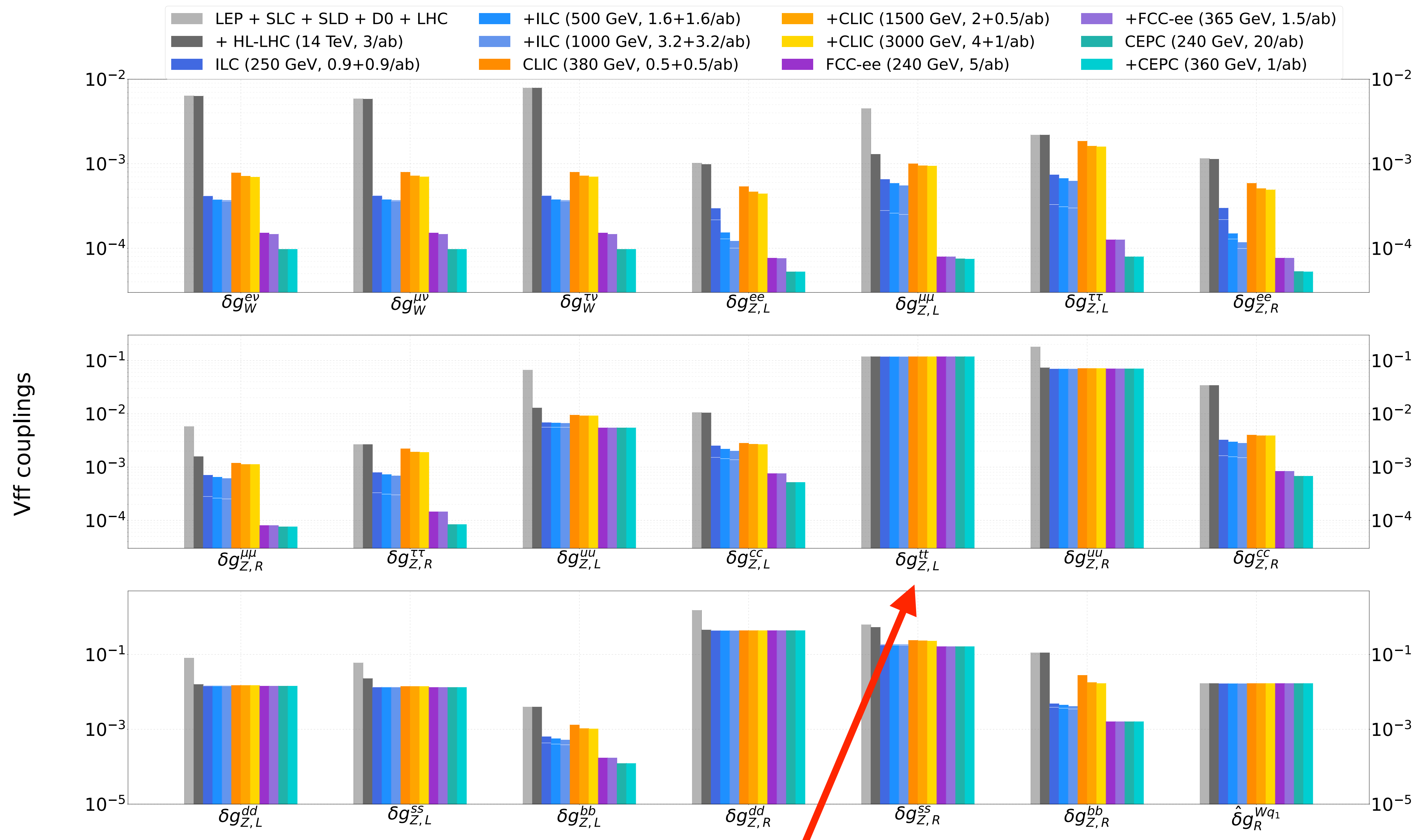
Global fit results: Vff couplings

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



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

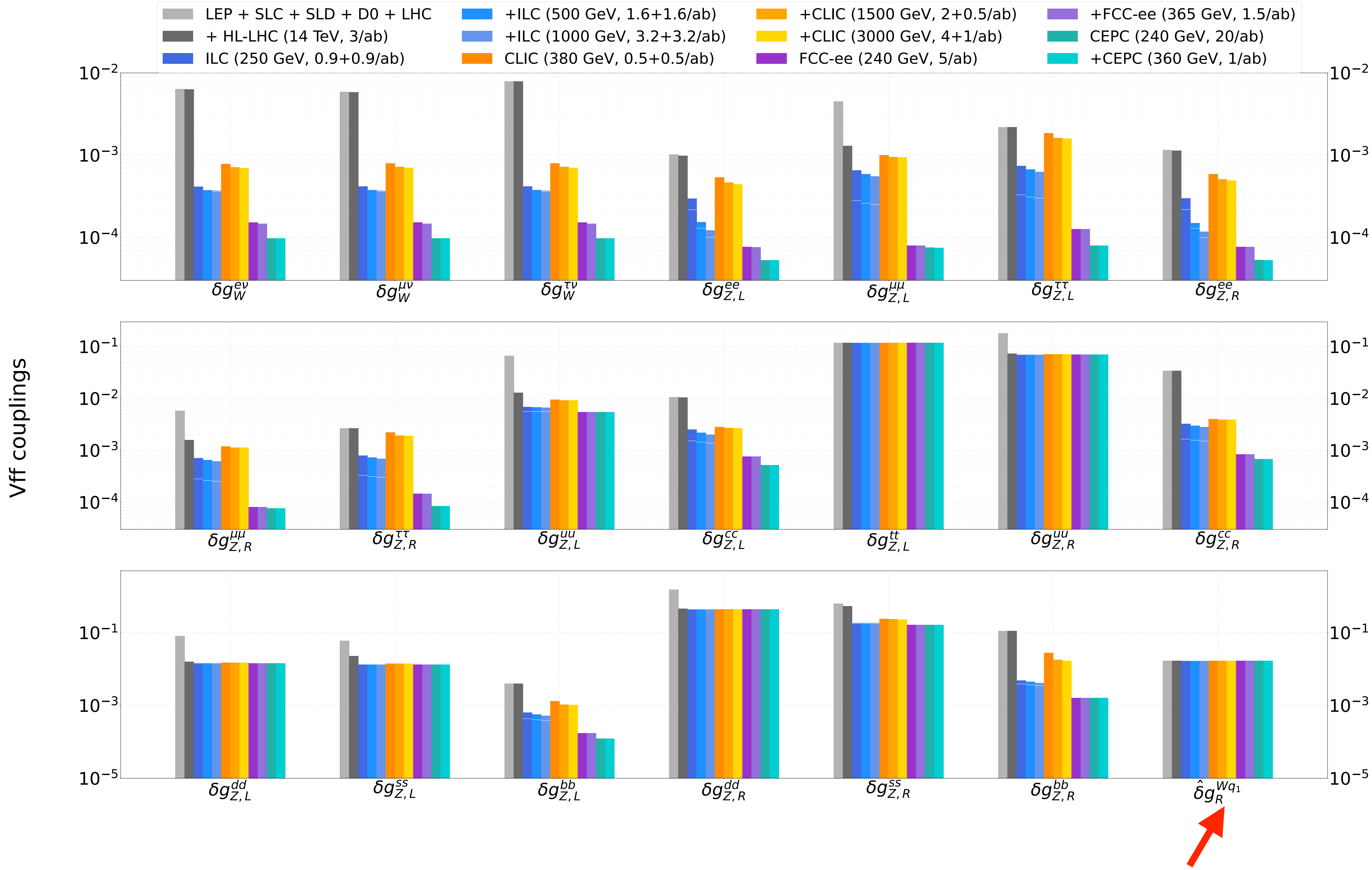
Global fit results: Vff couplings



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

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

Global fit results: Vff couplings



CKM unitarity test.

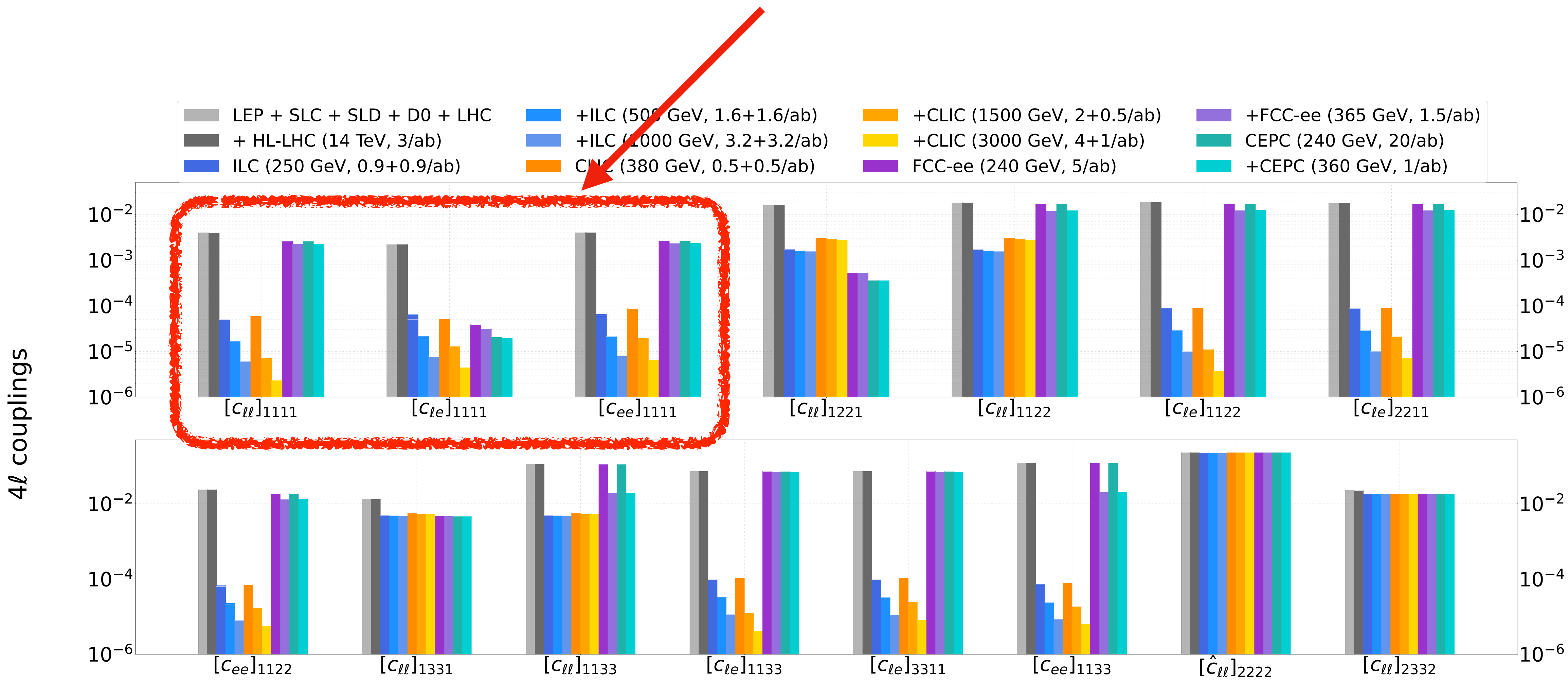
SMEFT global fit 2: ***Results***

Global fit results: 4ℓ couplings

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

Global fit results: 4ℓ couplings

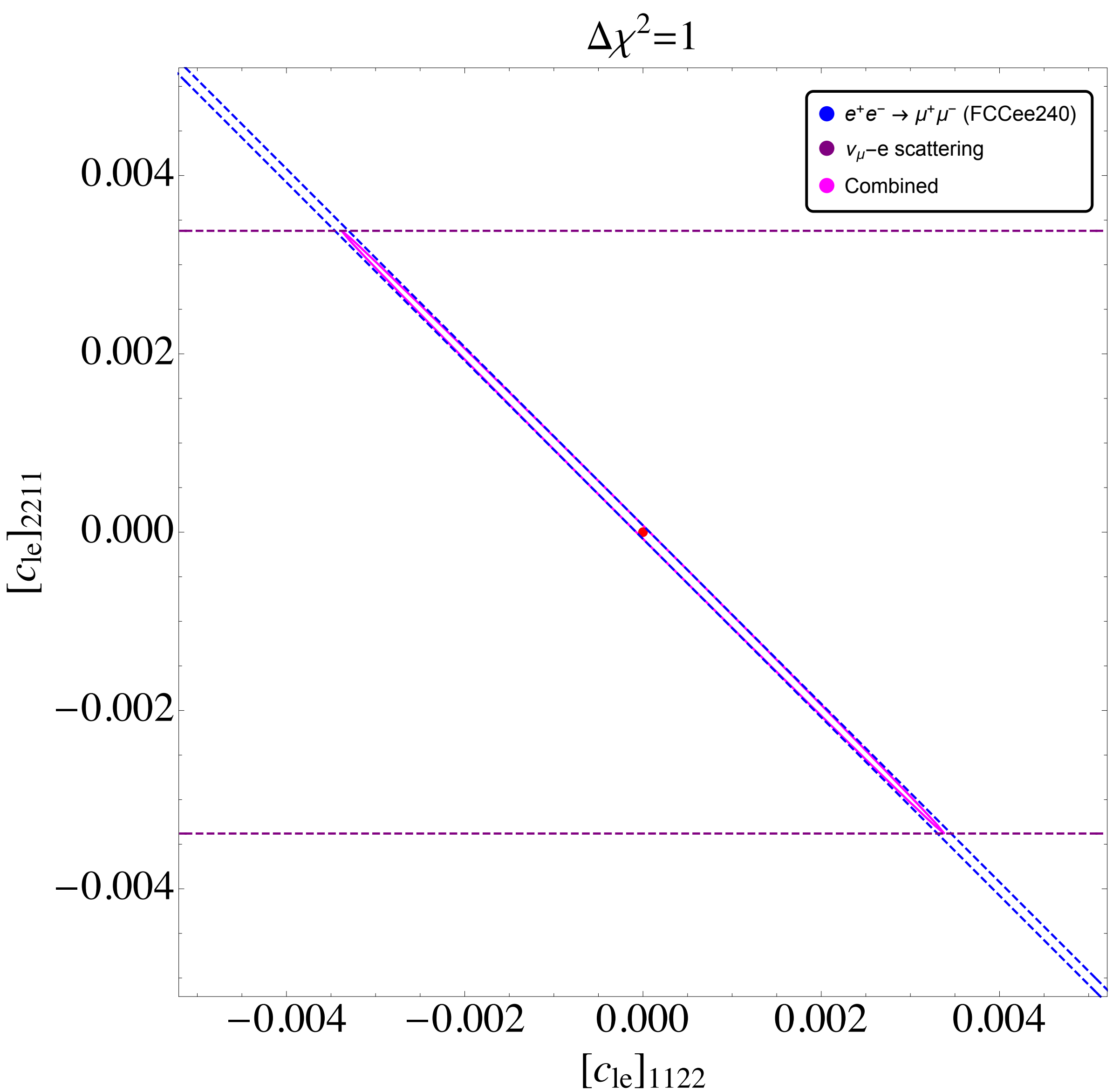
Beam polarization is the key in beating the (HL-)LHC and also circular colliders.

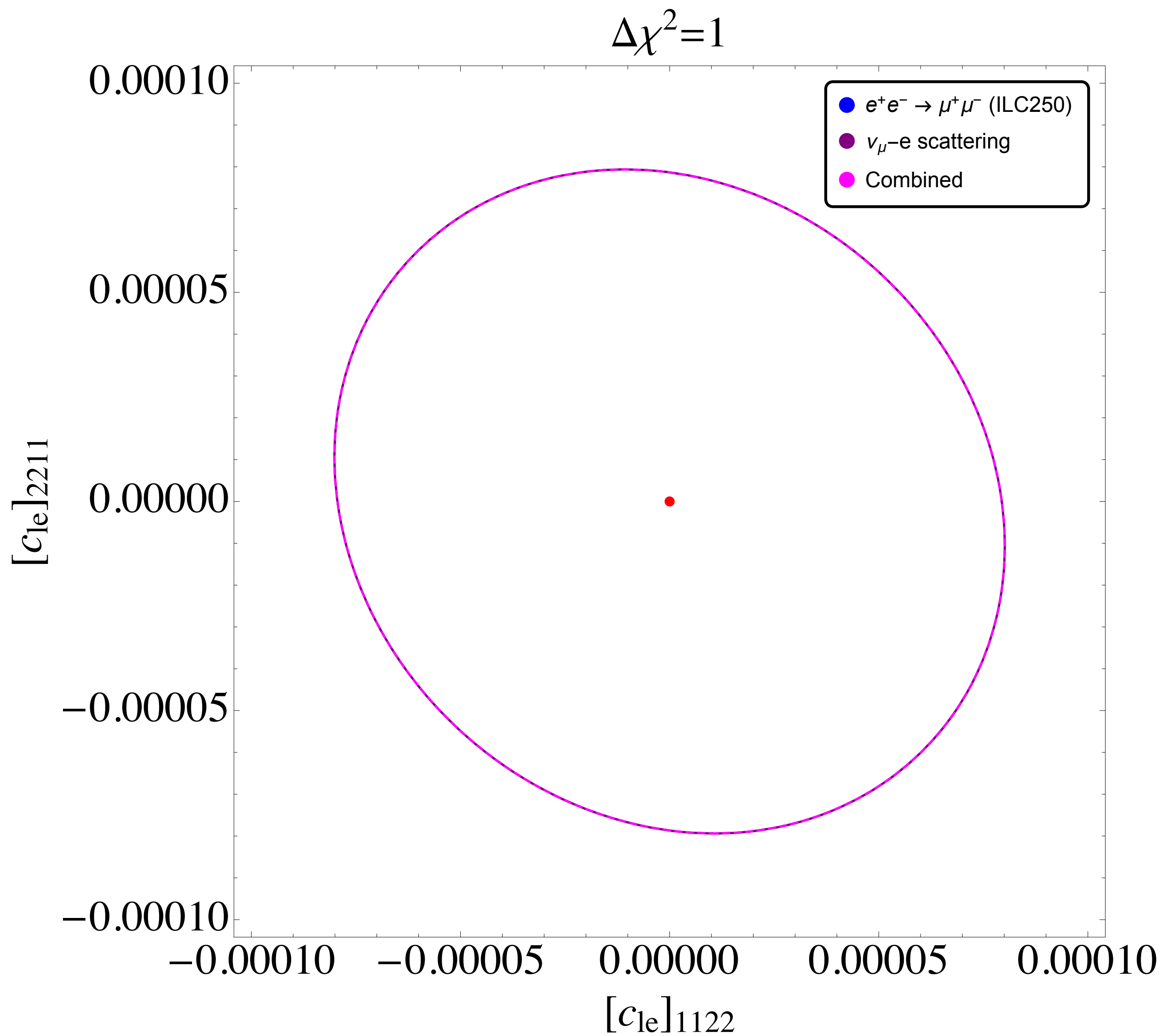


SMEFT global fit 2: ***Results***

Global fit results: 4ℓ couplings

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



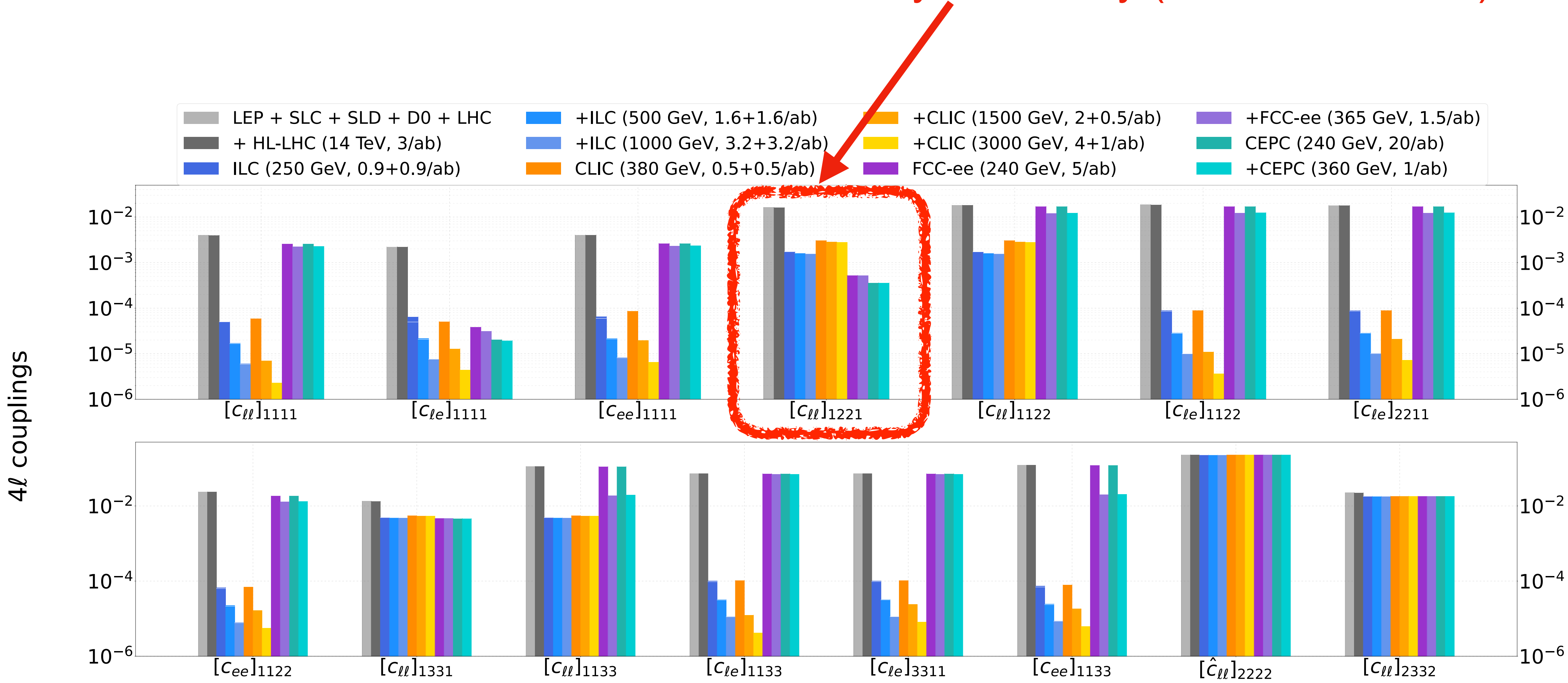


* Please note the scale difference.

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

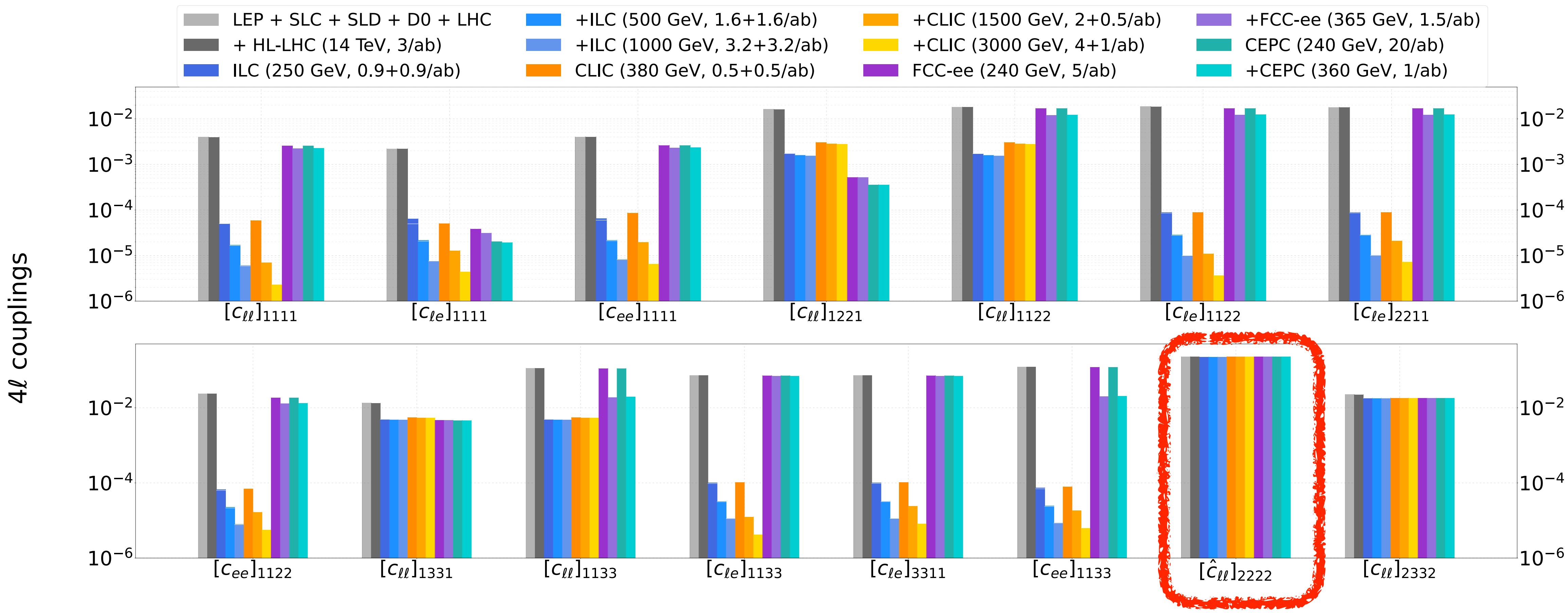
Global fit results: 4ℓ couplings

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



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

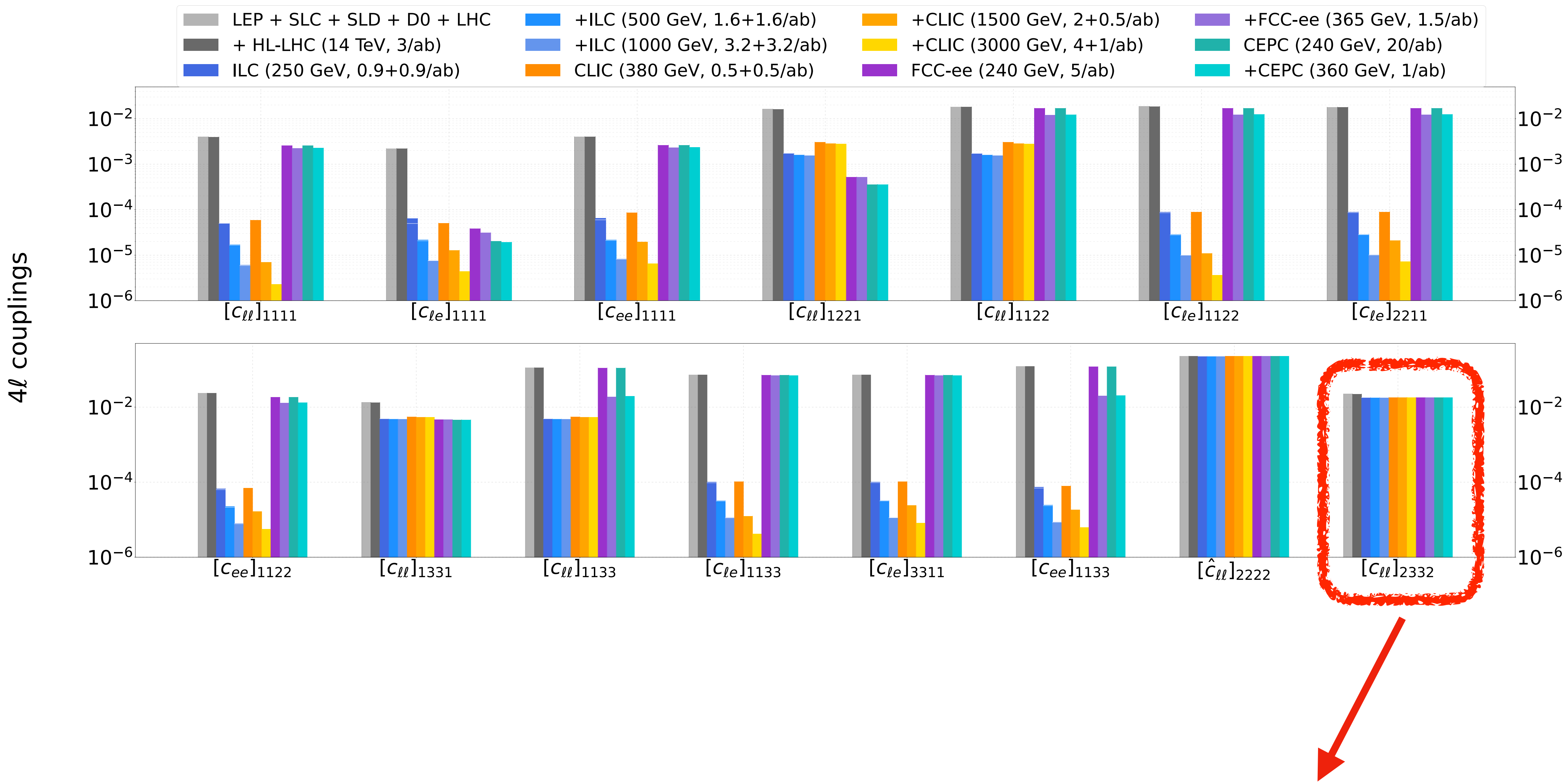
Global fit results: 4ℓ couplings



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

SMEFT global fit 2: *Results*

Global fit results: 4ℓ couplings



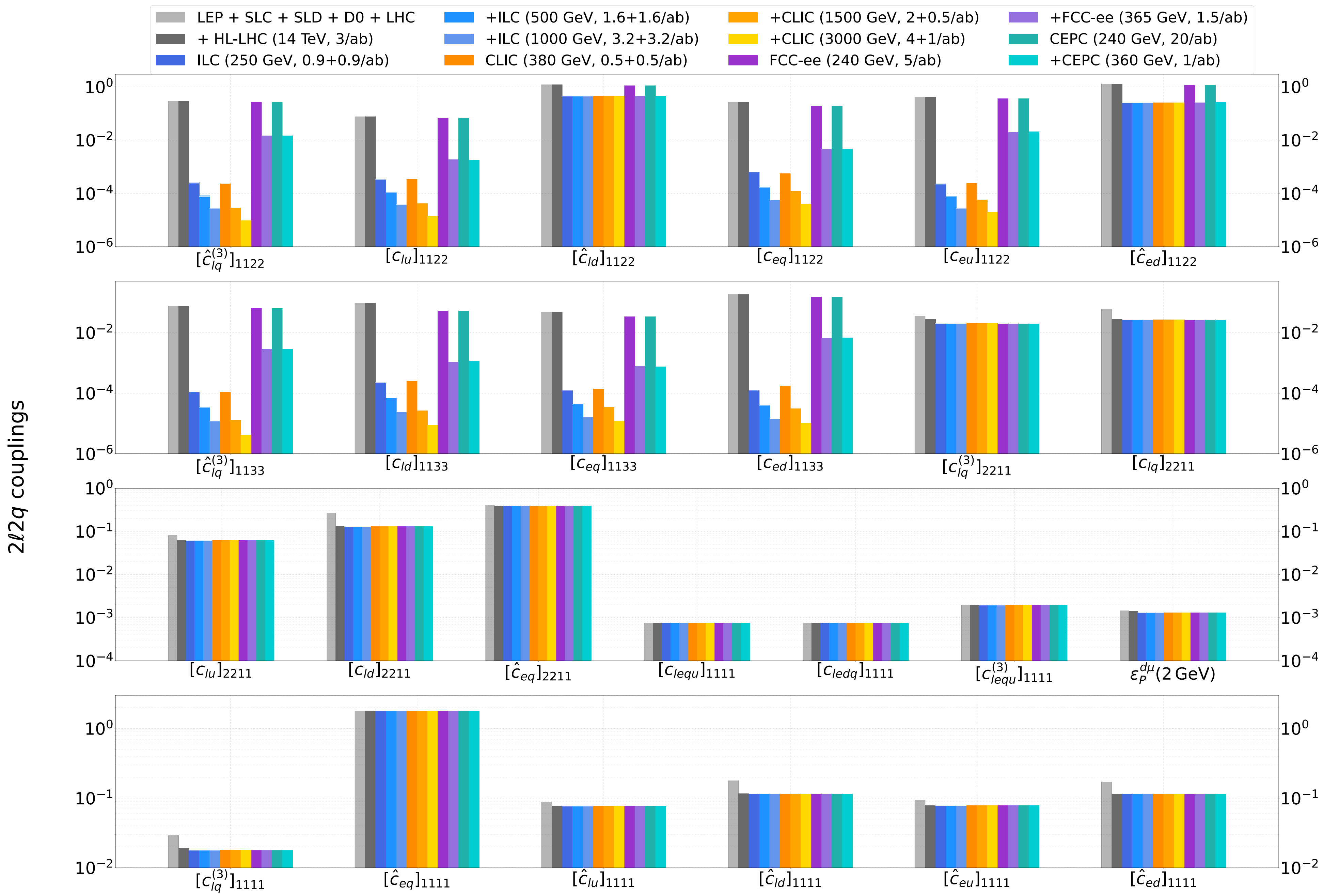
Limited by leptonic τ decay, but is the only one sensitive to this operator. A muon collider also helps.

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 4ℓ case. Again, A_{FB}^{ss}, σ^{ss} and muon colliders will play a key role.

Bosonic CPV operators

CPV: Setup

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

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

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

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

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

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

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

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

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

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We need 4 independent observables to close the fit for the remaining 4 CPV operators.

CPV: *Setup*

Unbroken phase

Broken phase

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

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CPV: *Setup*

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Broken phase

hZZ

$h\gamma Z$

(aHC)

CPV: Setup

Unbroken phase

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

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Broken phase

hZZ, $h\gamma Z$ (aHC)

γW^+W^-, ZW^+W^- (aTGC)

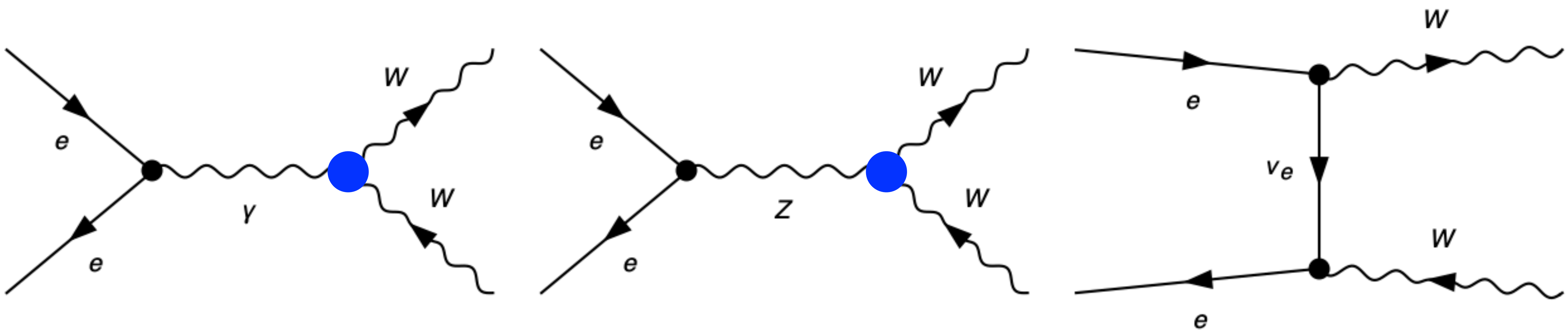
CPV: ***Setup***

Unbroken phase	Broken phase
$\mathcal{O}_{\varphi\tilde{W}} = \varphi^\dagger \varphi \tilde{W}^I_{\mu\nu} W^{I\mu\nu}$	hZZ, $h\gamma Z$ (aHC)
$\mathcal{O}_{\varphi\tilde{B}} = \varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	hZZ, $h\gamma Z$ (aHC)
$\mathcal{O}_{\varphi\tilde{W}B} = \varphi^\dagger \tau^I \varphi \tilde{W}^I_{\mu\nu} B^{\mu\nu}$	hZZ, $h\gamma Z$ (aHC); γW^+W^-, ZW^+W^- (aTGC)
$\mathcal{O}_{\tilde{W}} = \epsilon^{IJK} \tilde{W}^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$	γW^+W^-, ZW^+W^- (aTGC)

1. Determination of two anomalous triple gauge couplings (aTGC) from $e^+e^- \to W^+W^-$
2. Another two anomalous Higgs couplings (aHC) from $e^+e^- \to Zh$ using angular asymmetries.

CPV: aTGC from $e^+e^- \to W^+W^-$

aTGC modify the following vertices in **blue** of the CC03 diagrams:



Please note that both CP-even and -odd operators modify these vertices.

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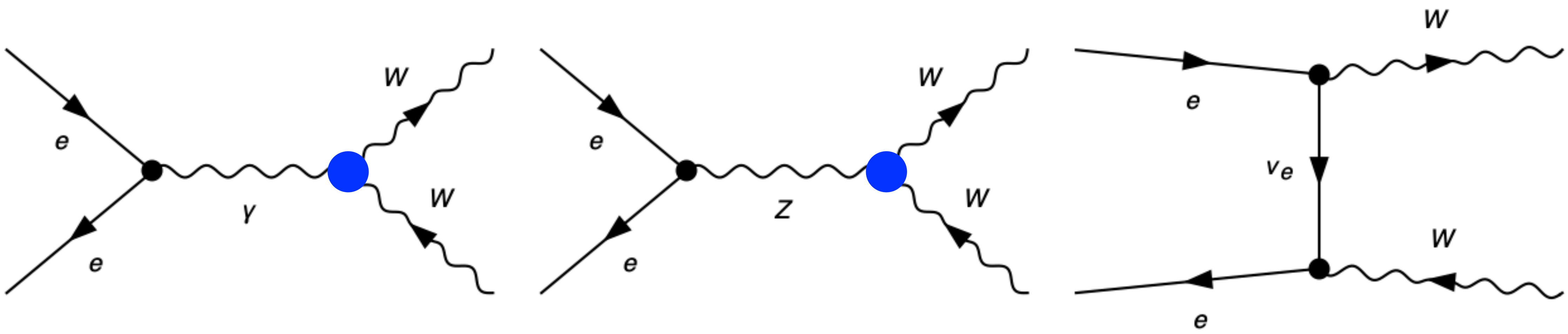

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Q: How to separate the CP-even corrections from the CP-odd ones?

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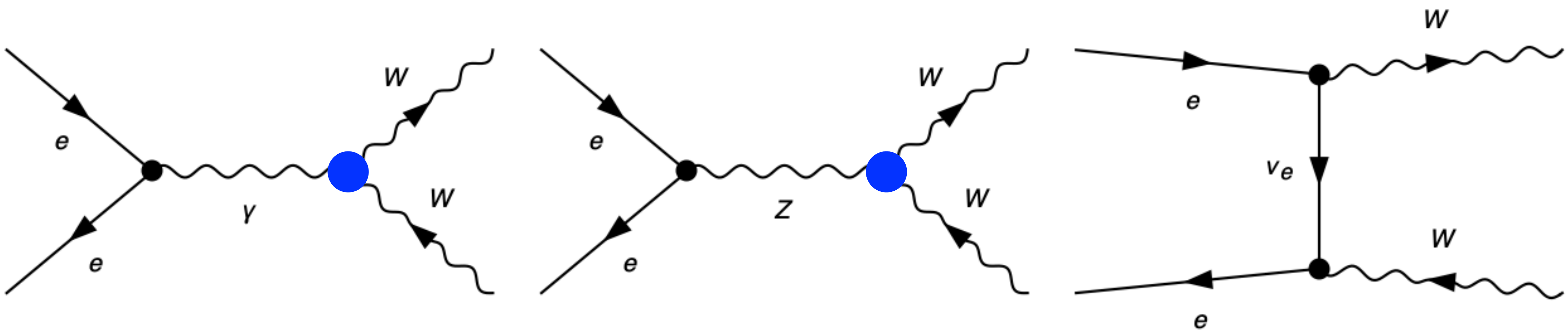


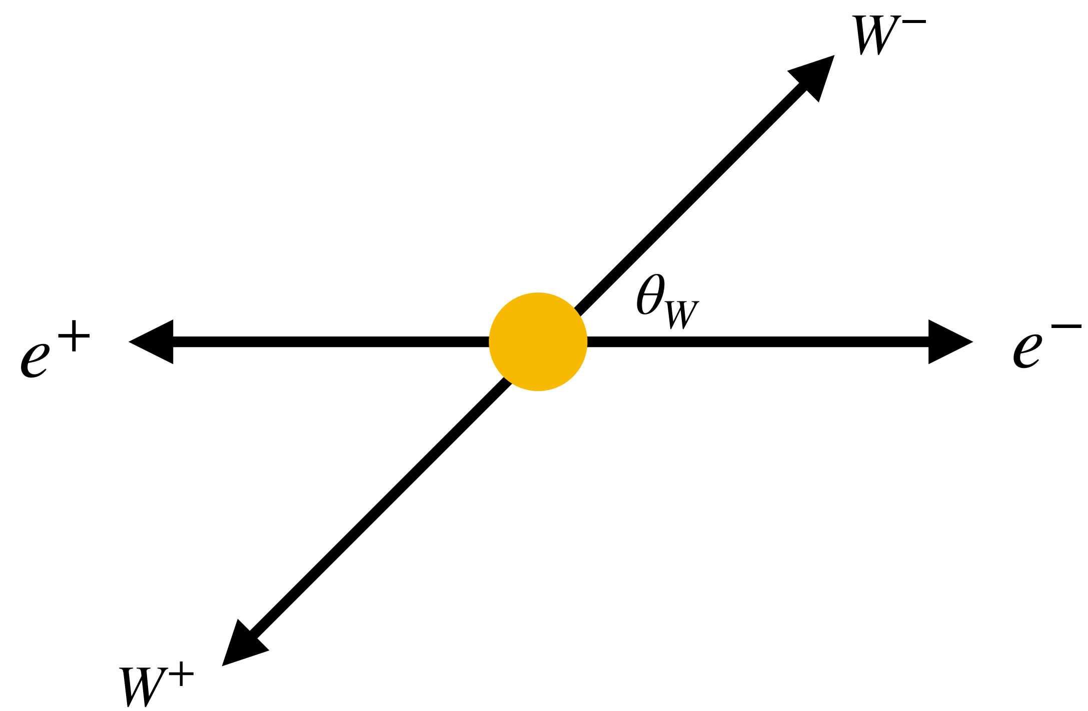
Please note that both CP-even and -odd operators modify these vertices.

Q: How to separate the CP-even corrections from the CP-odd ones?

A: The spin density matrix.

CPV: *aTGC from $e^+e^- \to W^+W^-$*

The Hermitian spin density matrix (SDM) constructed from helicity amplitudes provides genuine test of CPV



$$\rho_{\tau_-\tau'_-\tau_+\tau'_+}\left(s, \cos\theta_{\rm W}\right) = \frac{\sum_{\lambda} \mathscr{M}^{(\lambda)}_{\tau_-\tau_+}\left(\mathscr{M}^{(\lambda)}_{\tau'_-\tau'_+}\right)^\dagger}{\sum_{\lambda,\tau_+,\tau_-}\left|\mathscr{M}^{(\lambda)}_{\tau_-\tau_+}\right|^2}$$

Helicity of e^- (the index λ)

Helicity of W^+/W^- (the indices τ_+, τ_-)

CPV: *aTGC from $e^+e^- \to W^+W^-$*

To separate the CPV part, one can investigate the single SDM constructed from the two-particle joint one (especially when the sample size is limited)

$$\rho_{\tau_-\tau'_-}\left(s, \cos\theta_{\mathrm{W}}\right) = \sum_{\tau_+} \rho_{\tau_-\tau'_-\tau_+\tau_+}\left(s, \cos\theta_{\mathrm{W}}\right)$$

CPV: aTGC from $e^+e^- \to W^+W^-$

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CPT invariance

$$\mathrm{Re}\left(\rho^{W^-}_{\tau_1\tau_2}\right) - \mathrm{Re}\left(\rho^{W^+}_{-\tau_1-\tau_2}\right) = 0$$

$$\mathrm{Im}\left(\rho^{W^-}_{\tau_1\tau_2}\right) + \mathrm{Im}\left(\rho^{W^+}_{-\tau_1-\tau_2}\right) = 0$$

CP invariance

$$\mathrm{Im}\left(\rho^{W^-}_{\tau_1\tau_2}\right) - \mathrm{Im}\left(\rho^{W^+}_{-\tau_1-\tau_2}\right) = 0$$

Non-vanishing imaginary parts of the off-diagonal matrix element will thus be a direct signal of new CPV sources.

CPV: *aTGC from $e^+e^- \to W^+W^-$*

Theoretically, the SDM elements can be extracted with the projectors $P_{\tau\tau'}$

$$\frac{\mathrm{d}\sigma\left(\mathrm{e}^+\mathrm{e}^- \to \mathrm{W}^+\mathrm{W}^-\right)}{\mathrm{d}\cos\theta_{\mathrm{W}}}\rho_{\tau\tau'}^{W^-} = \frac{1}{\mathrm{Br}\left(\mathrm{W}^- \to \ell^-\bar{\nu}\right)}\int \frac{\mathrm{d}\sigma\left(\mathrm{e}^+\mathrm{e}^- \to W^+\ell^-\bar{\nu}\right)}{\mathrm{d}\cos\theta_{\mathrm{W}}\mathrm{d}\cos\theta^*\ \mathrm{d}\phi^*} P_{\tau\tau'}\left(\cos\theta^*, \phi^*\right)\mathrm{d}\cos\theta^*\ \mathrm{d}\phi^*$$

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Experimentally, it is related to the projector evaluated in the k-th bin of the W decay angle θ^*, normalized by the corresponding number of events N_k

$$\rho_{\tau_1\tau_2}^k\left(\cos\theta_W^k\right) = \frac{1}{N_k}\sum_{i=1}^{N_k} P_{\tau_1\tau_2}\left(\cos\theta_i^*, \phi_i^*\right)$$

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Evaluation of the cross section taking detector acceptance/resolution into account? Please see backup slides.

CPV: *aTGC from* $e^+e^- \to W^+W^-$

The OPAL collaboration obtained, dominated by statistical errors.

$$\tilde{\kappa}_Z = -0.20^{+0.10}_{-0.07}$$
$$\tilde{\lambda}_z = -0.18^{+0.24}_{-0.16}$$

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

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

This will certainly be improved at future colliders, especially with the utilization of optimal observables:

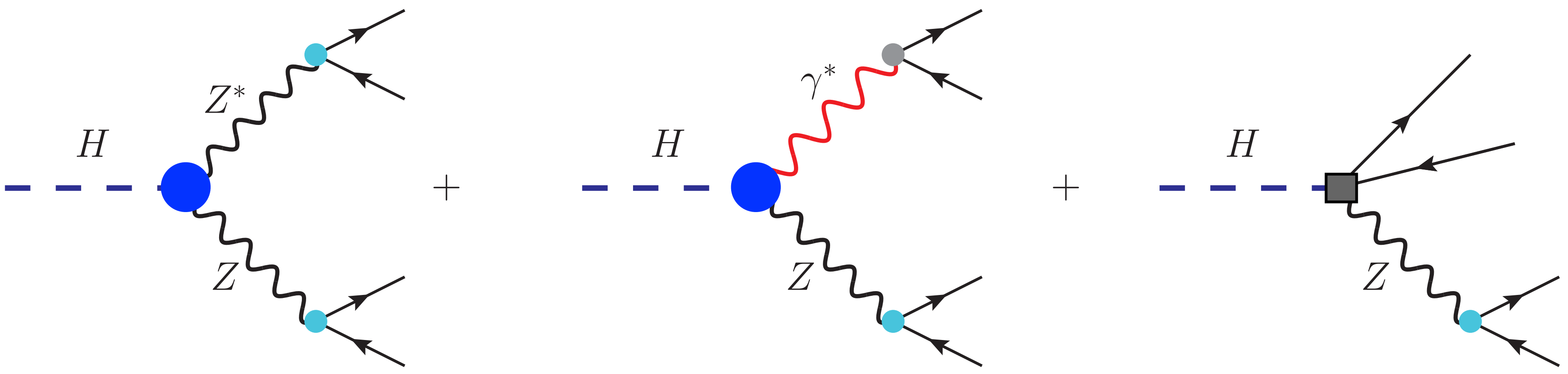
$$\frac{d\sigma(c)}{d\Pi} = \frac{d\sigma_0}{d\Pi} + \sum_j \frac{d\bar{\sigma}_j}{d\Pi} c_j + \cdots$$

$$(\mathrm{Cov})^{-1}_{jk} = \int d\Pi \frac{(d\bar{\sigma}_j/d\Pi)(d\bar{\sigma}_k/d\Pi)}{d\sigma_0/d\Pi} \cdot \int \mathscr{L}$$

The optimal observable analysis is still ongoing, we expect a factor of 10/100 improvement for HL-LHC and future e^+e^- colliders

CPV: aHC from $e^+e^- \to Zh$

The heuristic: $h \to Z(\to \ell^+\ell^-)\ell^+\ell^-$



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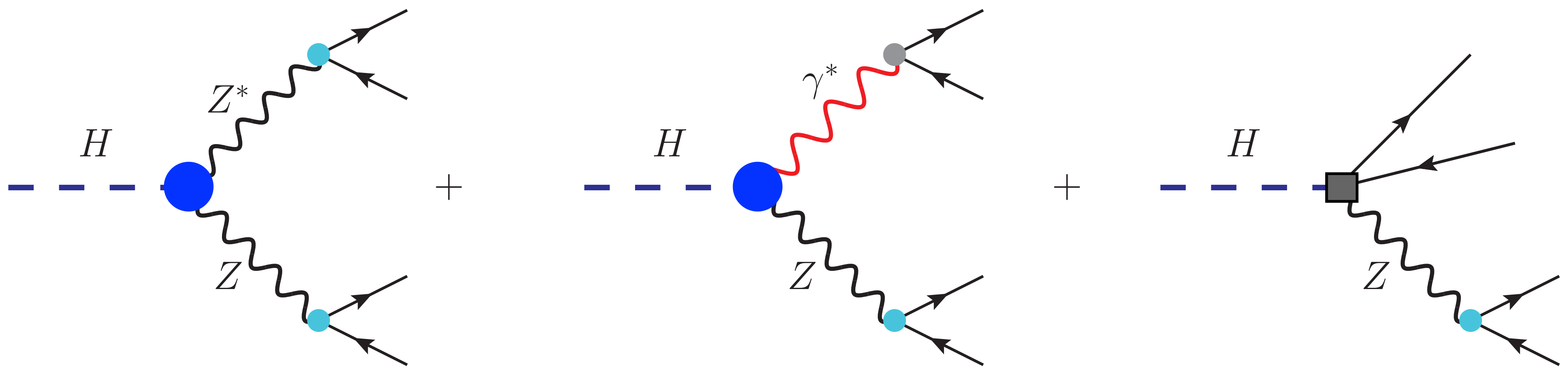

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Q: *How to disentangle?*

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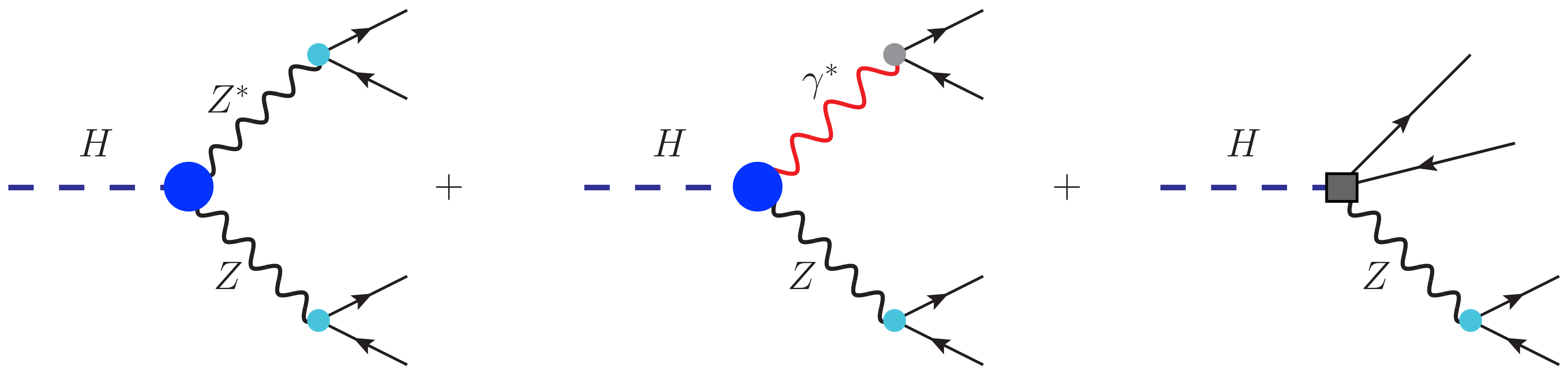

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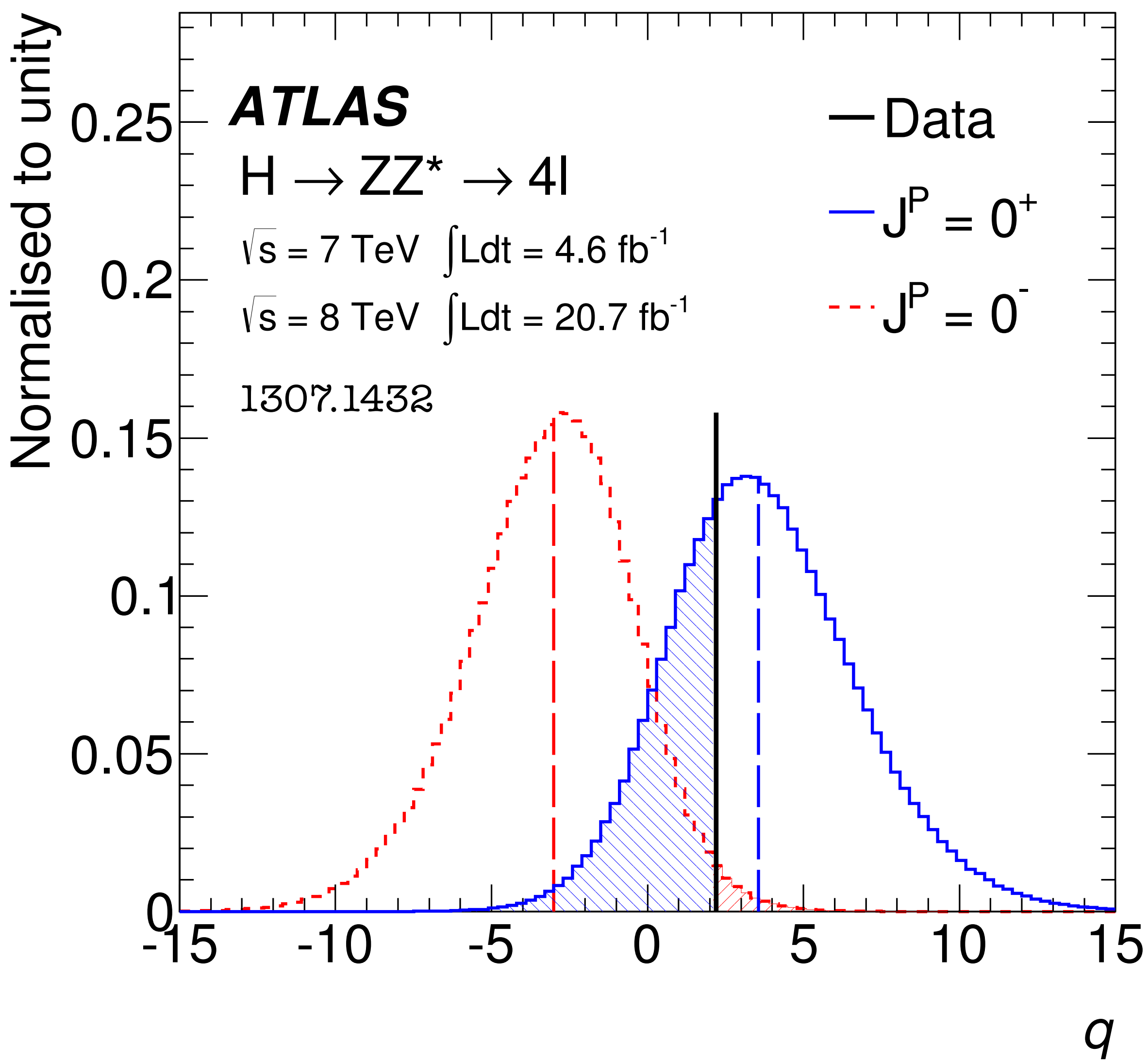
Q: *How to disentangle?*

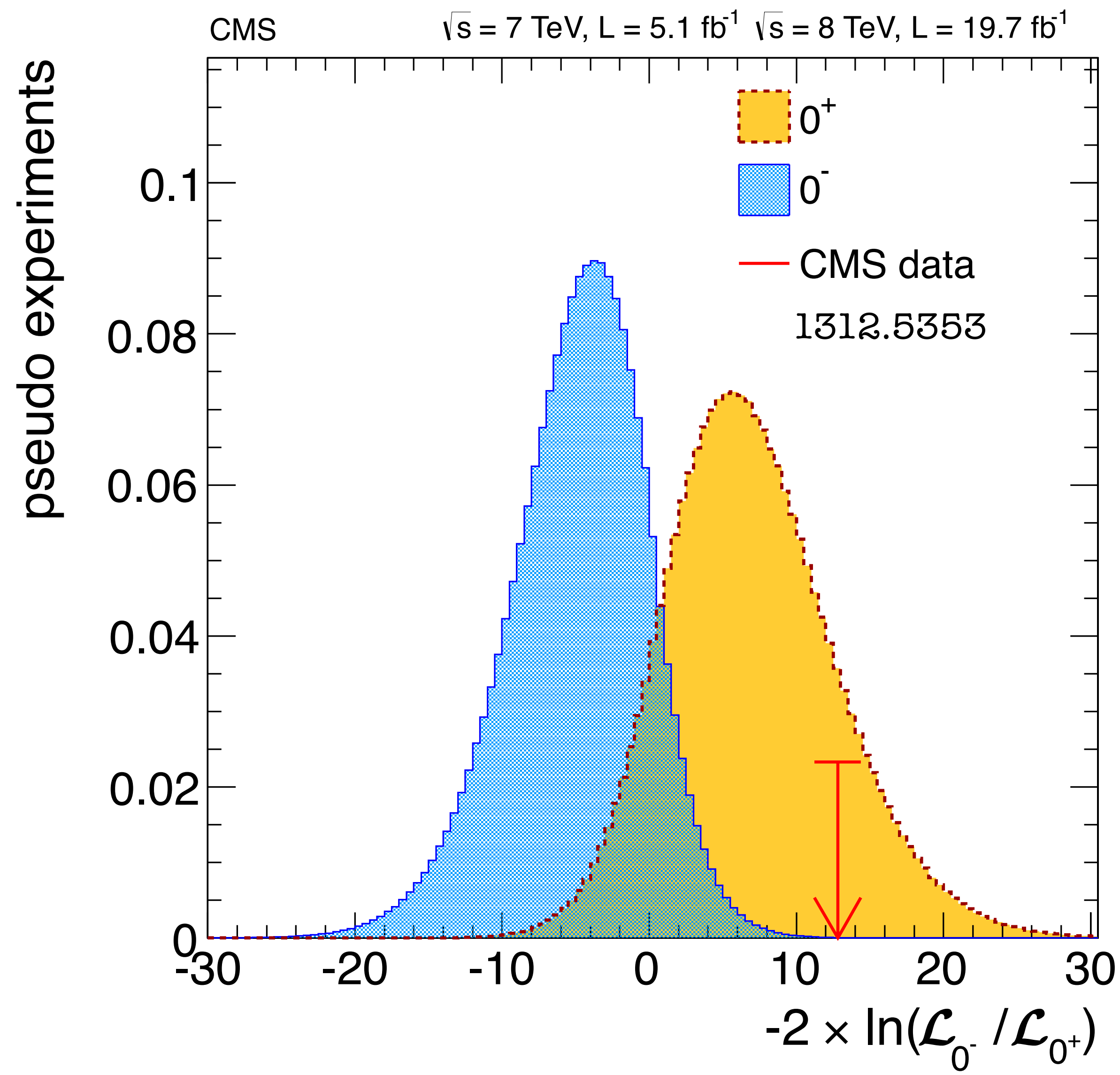
A: *Angular asymmetries.*

CPV: *aHC from $e^+e^- \to Zh$*

The heuristic: $h \to Z(\to \ell^+\ell^-)\ell^+\ell^-$

Angular distribution of the 4 leptons for the determination of Higgs spin & parity.





CPV: *aHC from $e^+e^- \to Zh$*

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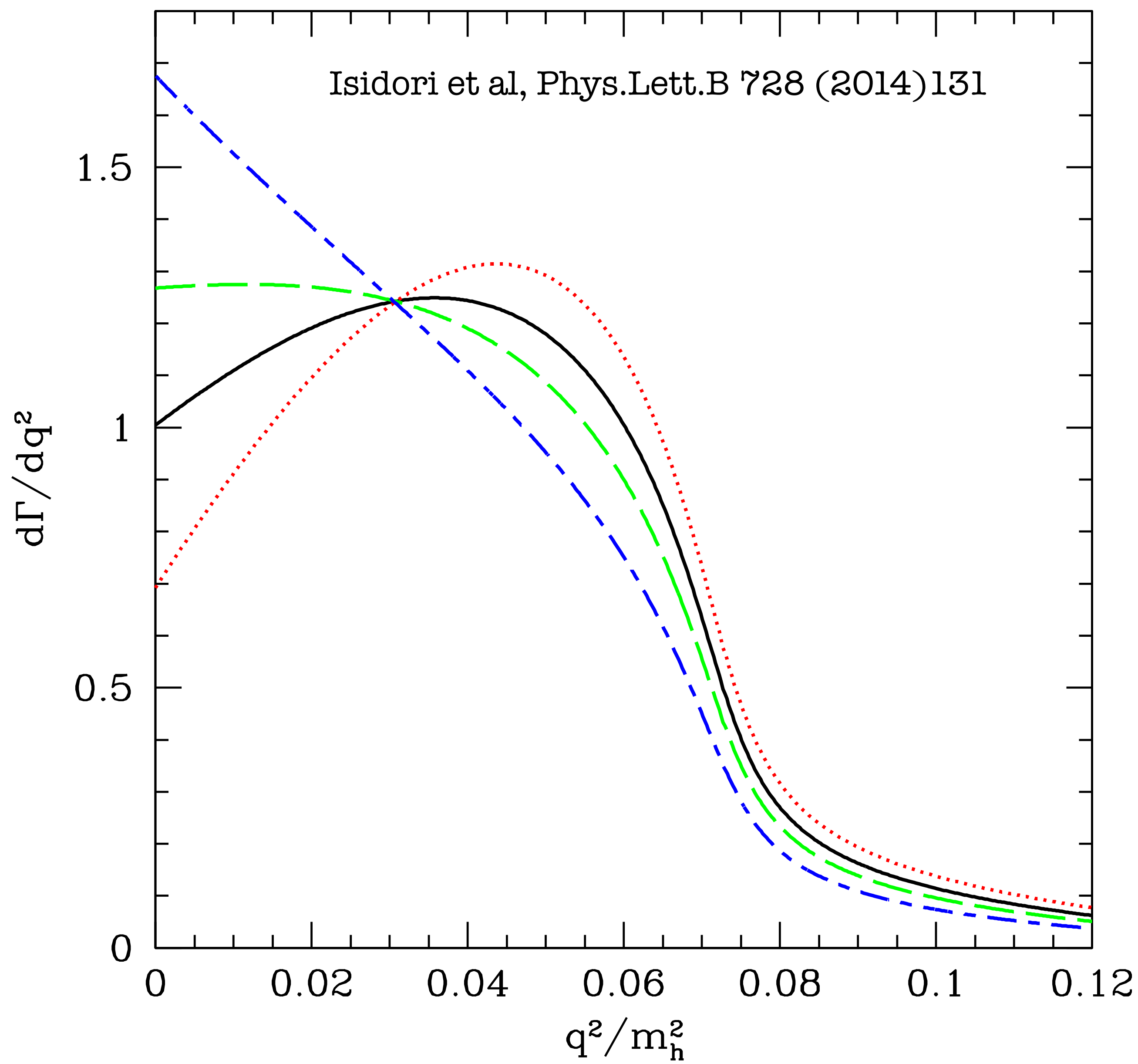
Revealing new effects hidden in the total rate form the invariant mass distribution of the di-lepton system



CPV: aHC from $e^+e^- \to Zh$

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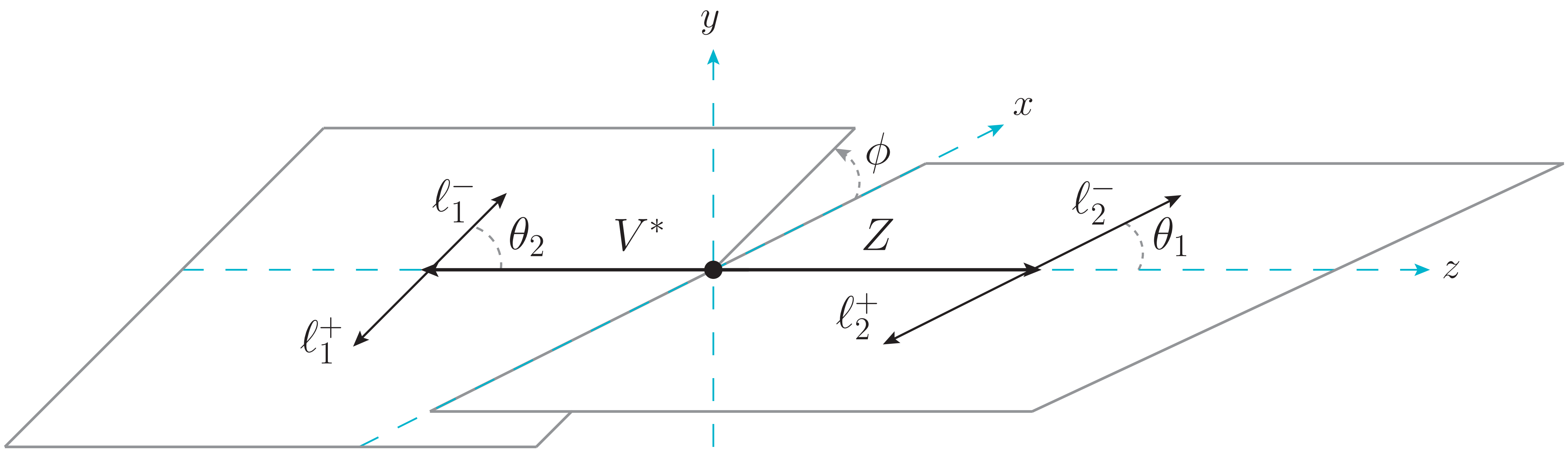
Beneke et al, JHEP 11 (2014) 028

The angular asymmetries are then realized to be powerful for aHC determination.



$$\frac{d^4\Gamma}{dq^2 d\cos\theta_1 d\cos\theta_2 d\phi} = \frac{1}{2^{10}(2\pi)^5}\frac{1}{m_H^3}\frac{1}{m_Z\Gamma_Z}\lambda^{1/2}\left(m_H^2, m_Z^2, q^2\right)\sum_{\text{spins}}\left|\mathcal{M}^\mu_{HZ\ell\ell}\mathcal{M}_{Z\ell\ell,\mu}\right|^2$$

$$= \sum_{i=1}^{9} k_i(q^2)\, J_i\left(q^2, \theta_1, \theta_2, \phi, c_i\right)$$

CPV: aHC from $e^+e^- \to Zh$

The heuristic: $h \to Z(\to \ell^+\ell^-)\ell^+\ell^-$

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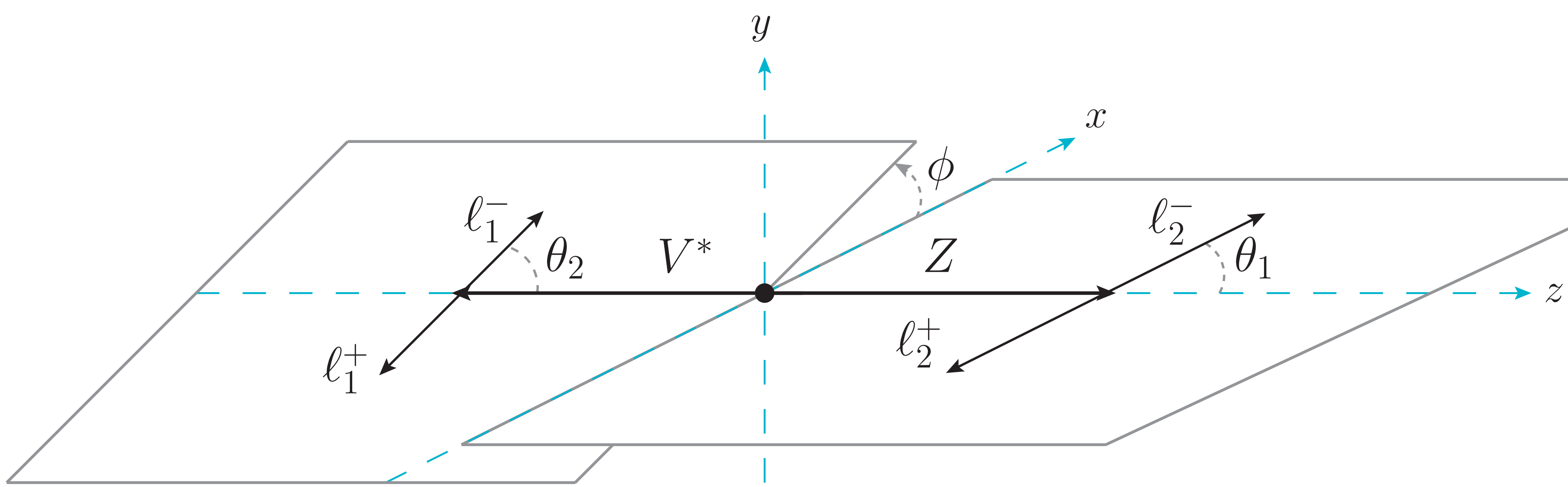


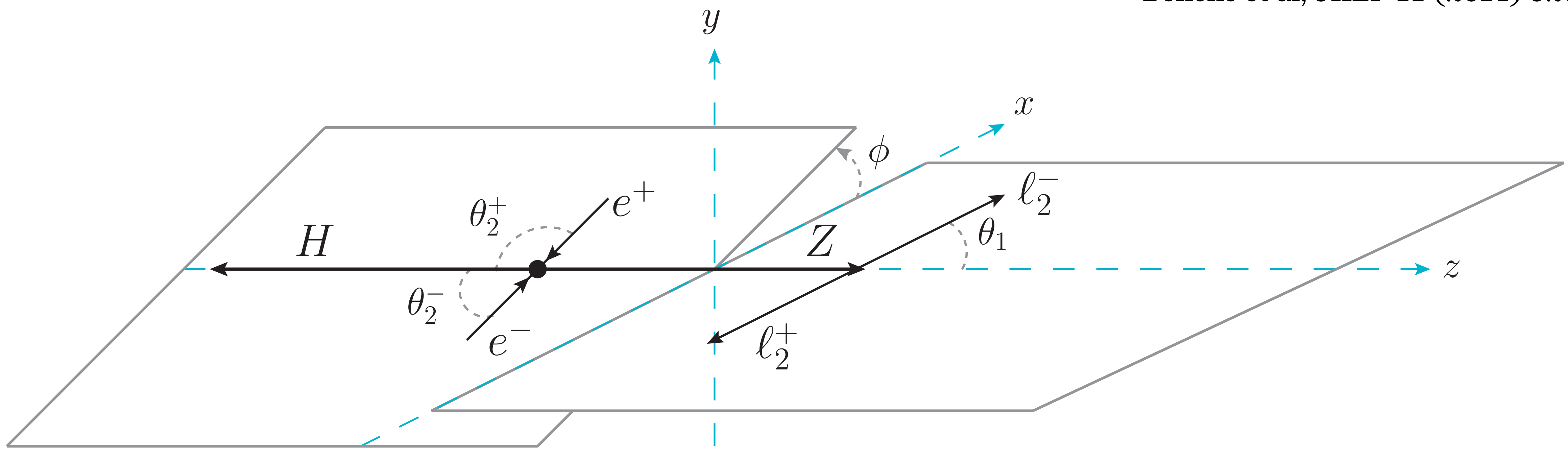
$$\mathscr{A}_\phi^{(1)} = \frac{1}{d\Gamma/dq^2}\int_0^{2\pi} d\phi\, \mathrm{sgn}(\sin\phi)\frac{d^2\Gamma}{dq^2 d\phi} \longrightarrow J_4$$

$$\mathscr{A}_\phi^{(2)} = \frac{1}{d\Gamma/dq^2}\int_0^{2\pi} d\phi\, \mathrm{sgn}(\sin(2\phi))\frac{d^2\Gamma}{dq^2 d\phi} \longrightarrow J_8$$

CPV: aHC from $e^+e^- \to Zh$

$e^+e^- \to Zh$ is just the crossed version of $h \to Z(\to \ell^+\ell^-)\ell^+\ell^-$ but at a much different energy scale

Beneke et al, JHEP 11 (2014) 028



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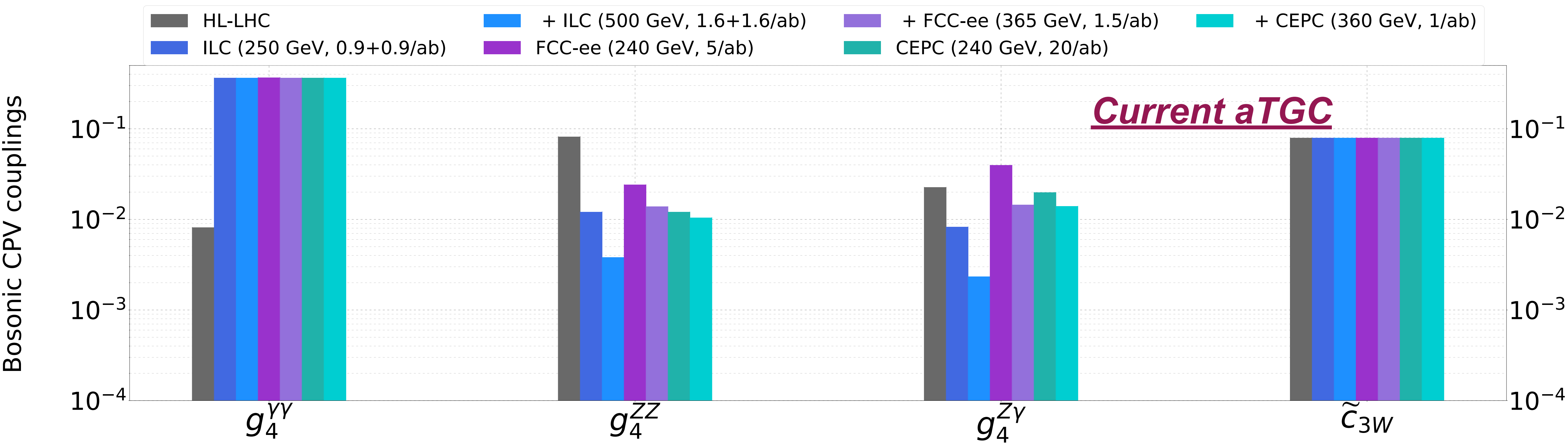
CPV: *Results*

Collider by collider for comparison



CPV: ***Results***

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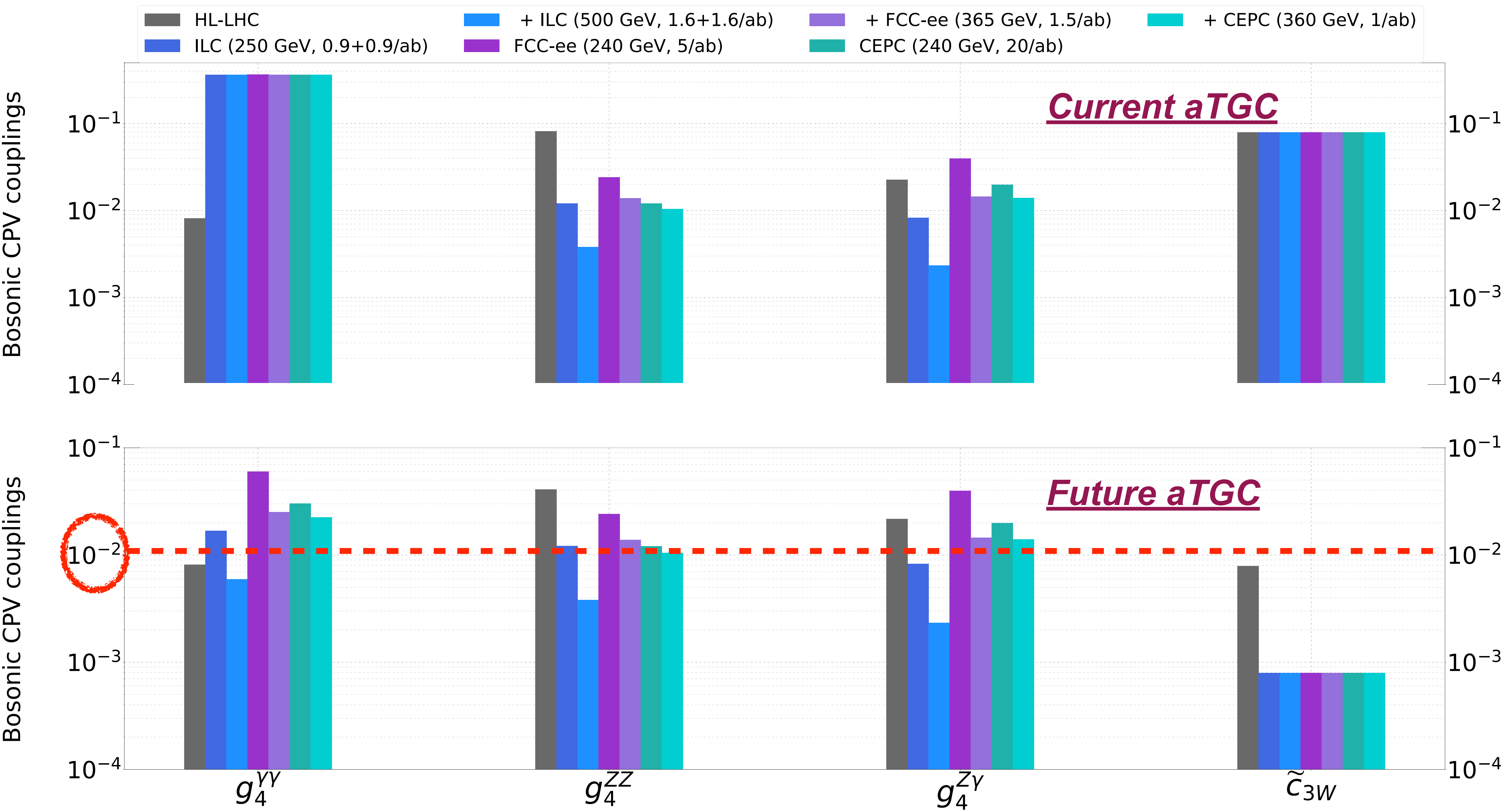
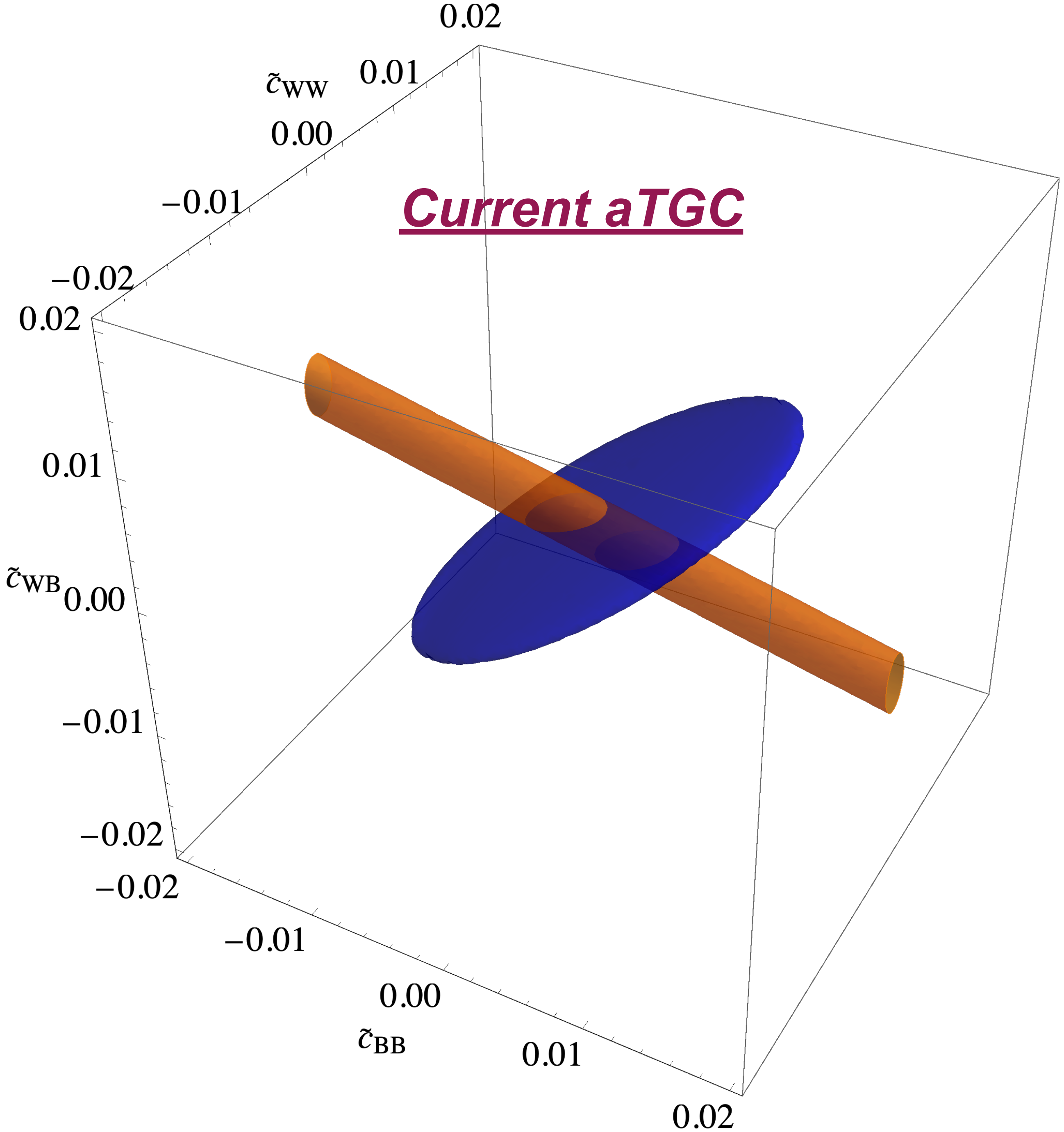
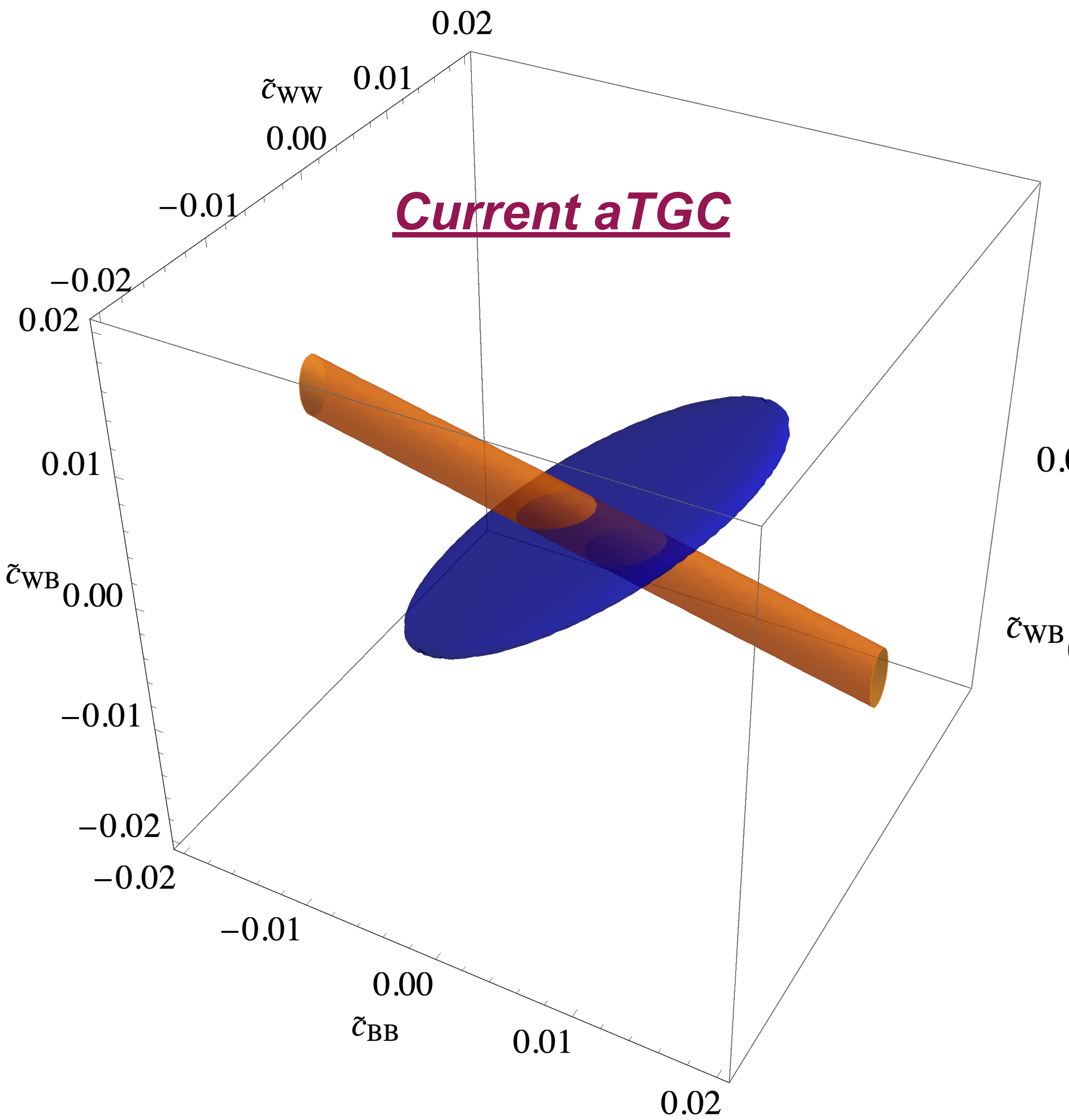


CPV: *Results*

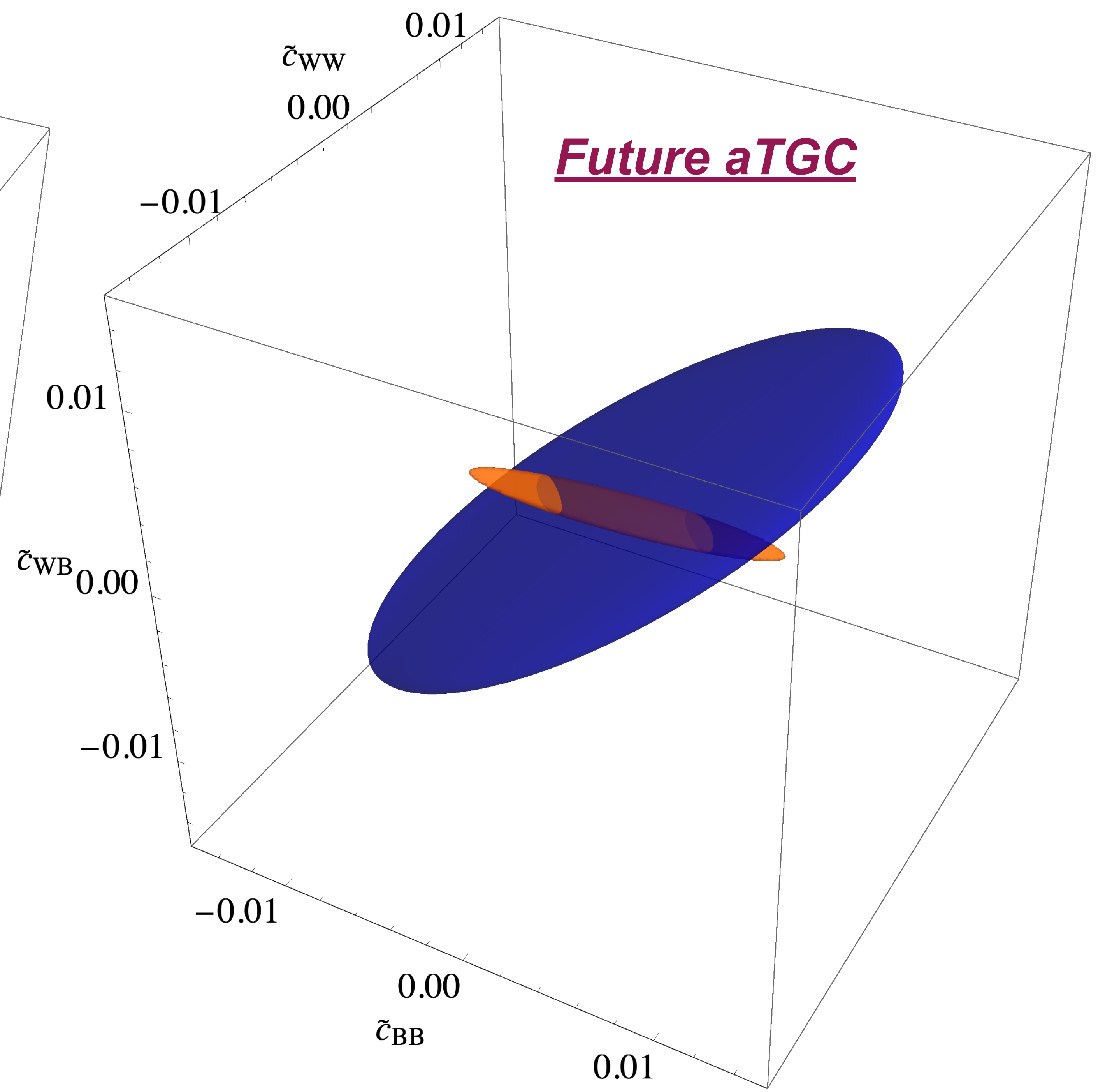


Current aTGC
$\tilde{c}_{WW}$
0.02
0.01
0.00
−0.01
−0.02
$\tilde{c}_{WB}$
0.02
0.01
0.00
−0.01
−0.02
$\tilde{c}_{BB}$
−0.02
−0.01
0.00
0.01
0.02

CPV: *Results*

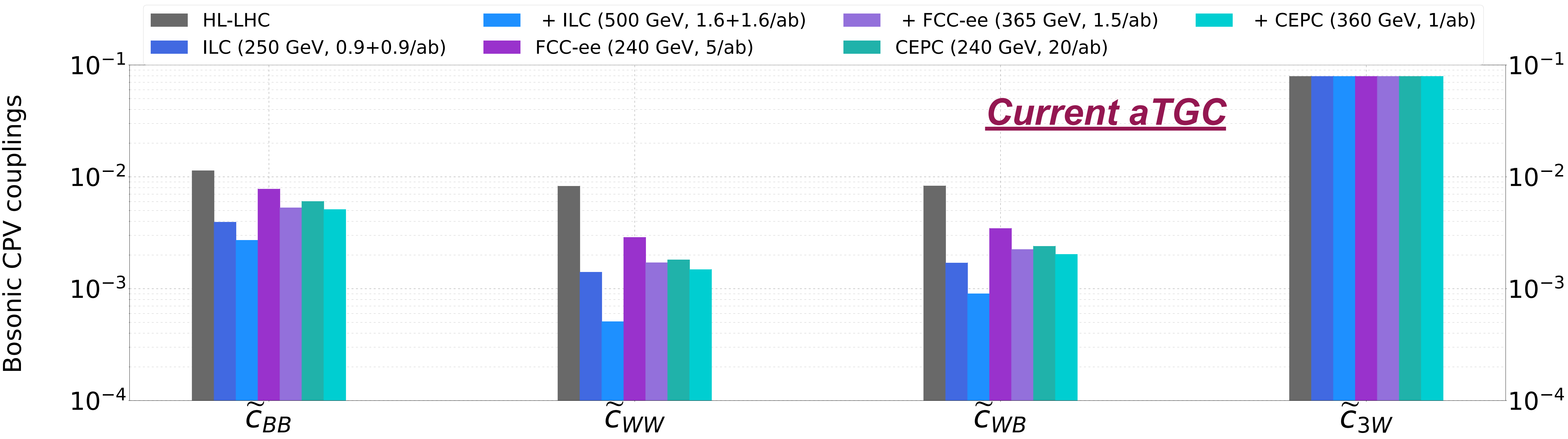


Current aTGC
0.02
0.01
0.00
−0.01
−0.02
$\tilde{c}_{WW}$
0.02
0.01
$\tilde{c}_{WB}$ 0.00
−0.01
−0.02
−0.02
−0.01
0.00
$\tilde{c}_{BB}$
0.01
0.02

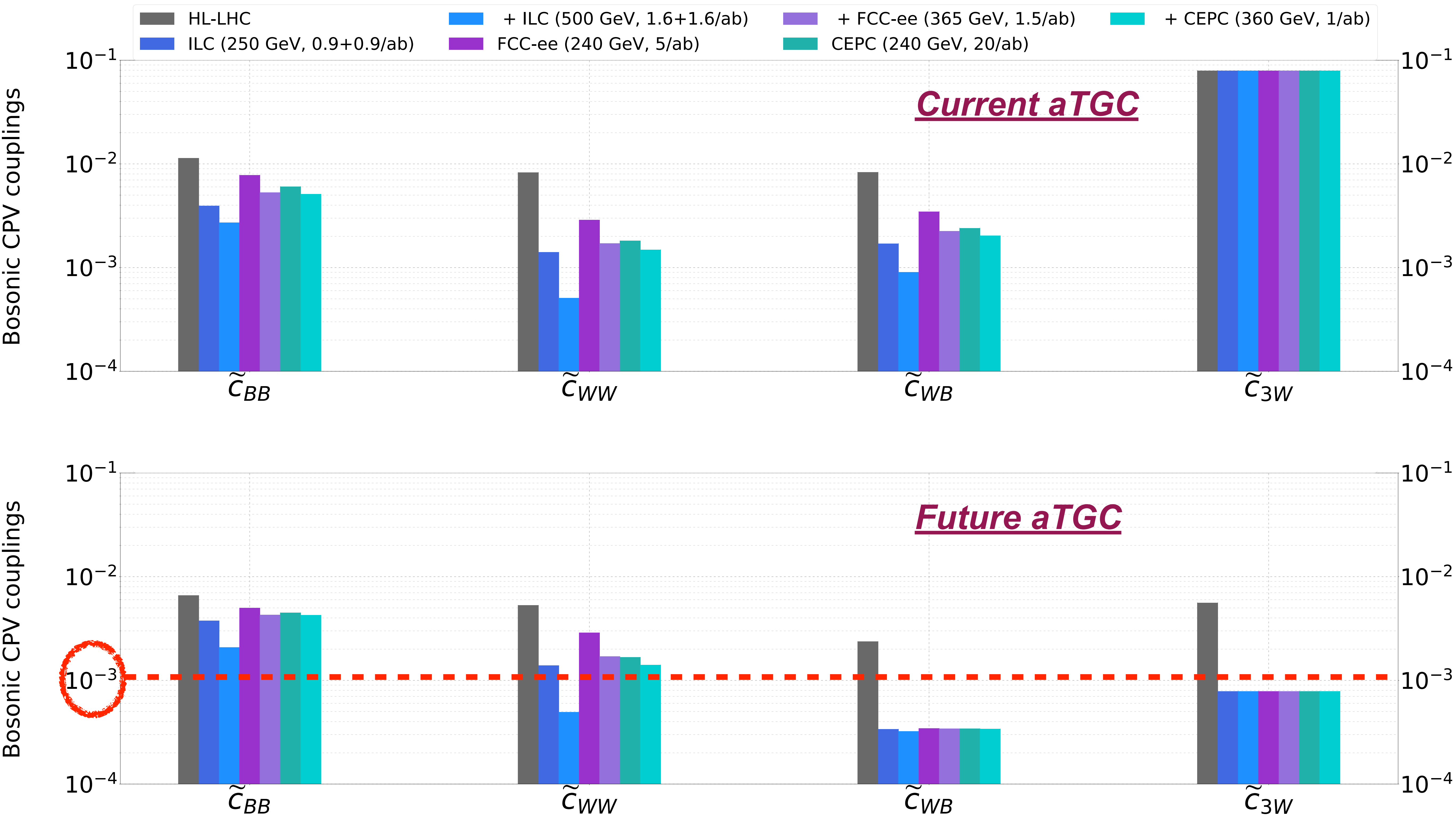


Future aTGC
0.01
$\tilde{c}_{WW}$
0.00
−0.01
0.01
$\tilde{c}_{WB}$ 0.00
−0.01
−0.01
0.00
$\tilde{c}_{BB}$
0.01

CPV: *Results*

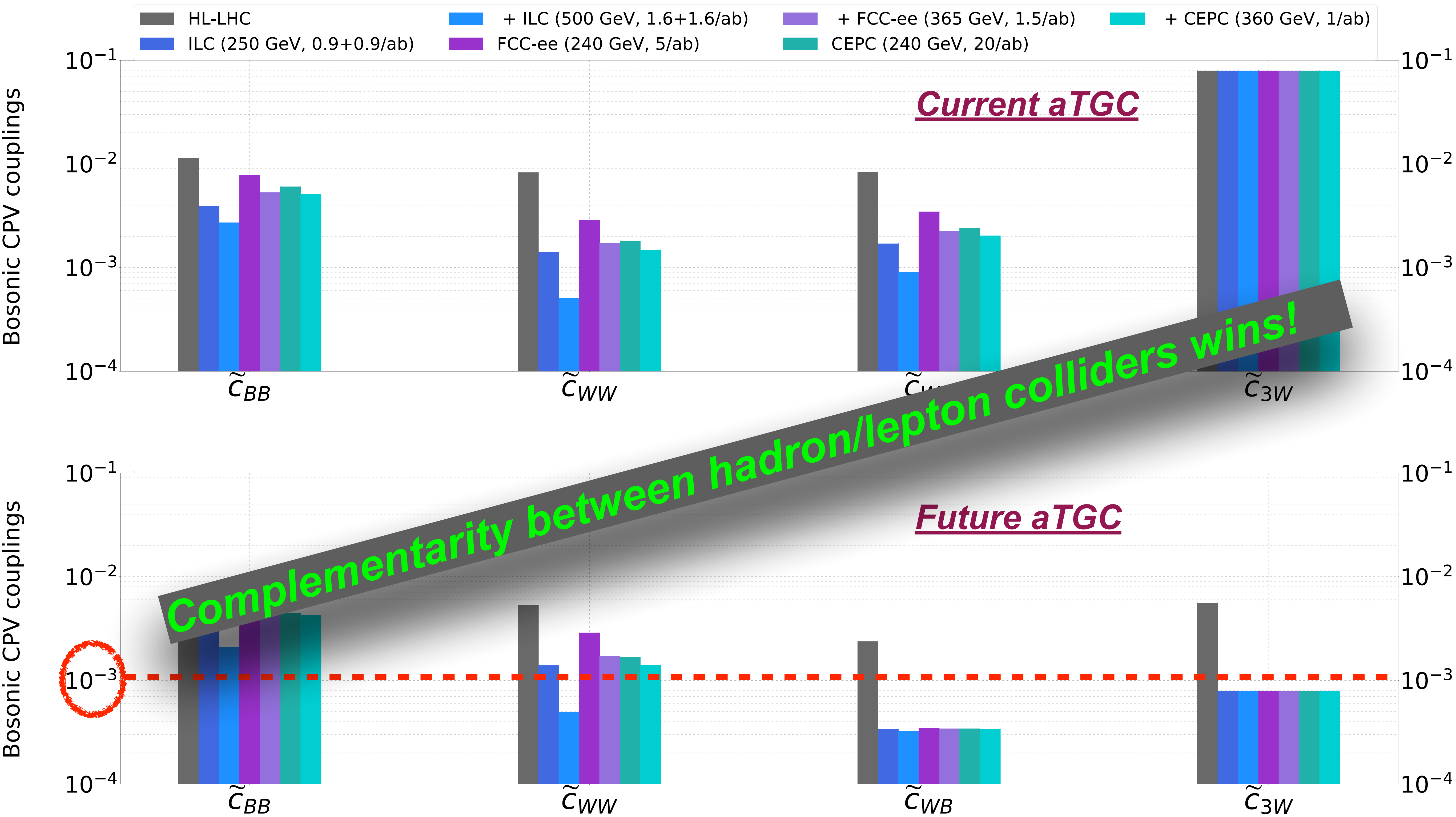

HL-LHC
ILC (250 GeV, 0.9+0.9/ab)
+ ILC (500 GeV, 1.6+1.6/ab)
FCC-ee (240 GeV, 5/ab)
+ FCC-ee (365 GeV, 1.5/ab)
CEPC (240 GeV, 20/ab)
+ CEPC (360 GeV, 1/ab)
Bosonic CPV couplings
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Current aTGC
$\tilde{c}_{BB}$
$\tilde{c}_{WW}$
$\tilde{c}_{WB}$
$\tilde{c}_{3W}$

CPV: Results



HL-LHC
ILC (250 GeV, 0.9+0.9/ab)
+ ILC (500 GeV, 1.6+1.6/ab)
FCC-ee (240 GeV, 5/ab)
+ FCC-ee (365 GeV, 1.5/ab)
CEPC (240 GeV, 20/ab)
+ CEPC (360 GeV, 1/ab)
Bosonic CPV couplings
Current aTGC
Future aTGC
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\tilde{c}_{BB}$
$\tilde{c}_{WW}$
$\tilde{c}_{WB}$
$\tilde{c}_{3W}$

CPV: Results


HL-LHC
ILC (250 GeV, 0.9+0.9/ab)
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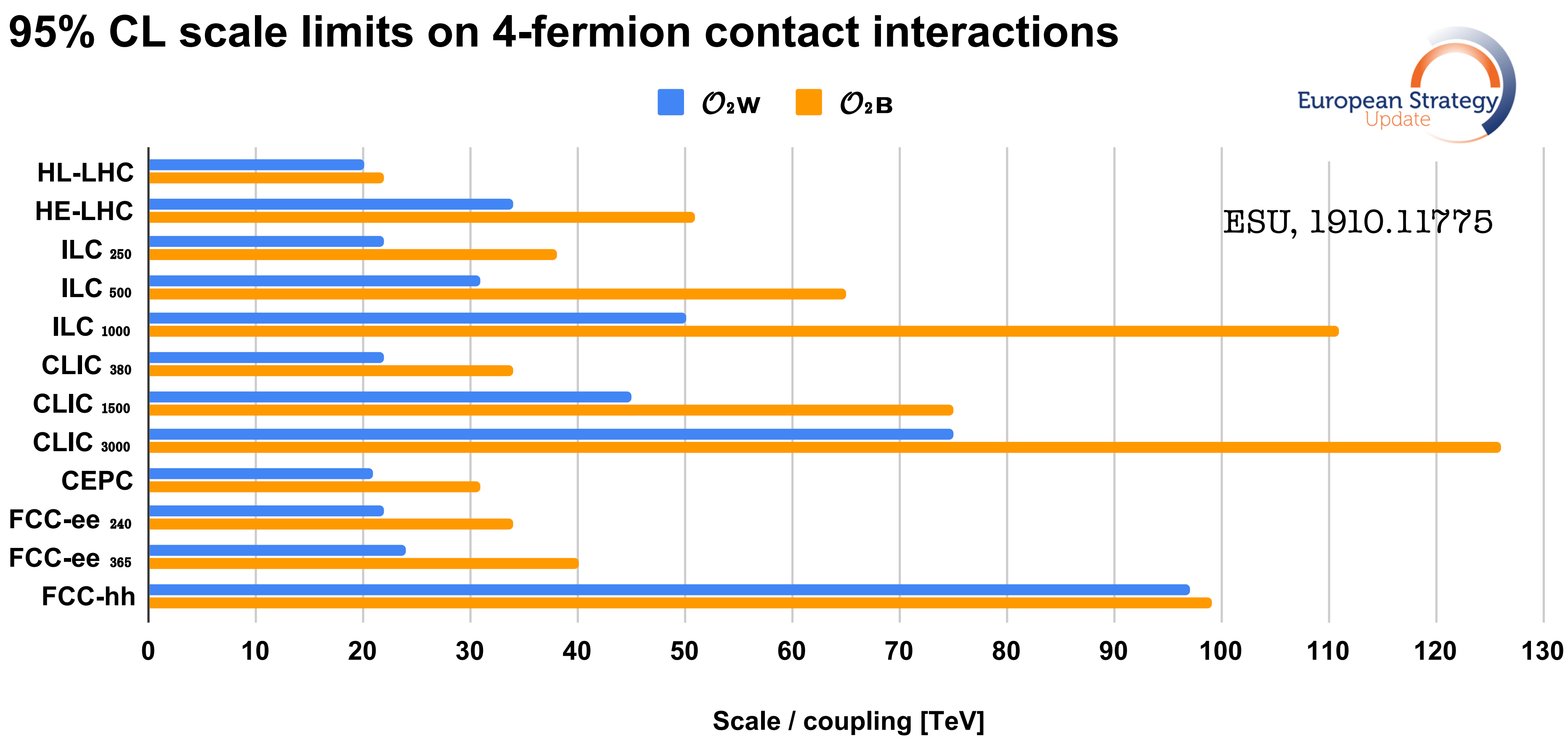
Bosonic CPV couplings
Current aTGC
Future aTGC
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\tilde{c}_{BB}$
$\tilde{c}_{WW}$
$\tilde{c}_{WB}$
$\tilde{c}_{3W}$
Complementarity between hadron/lepton colliders wins!

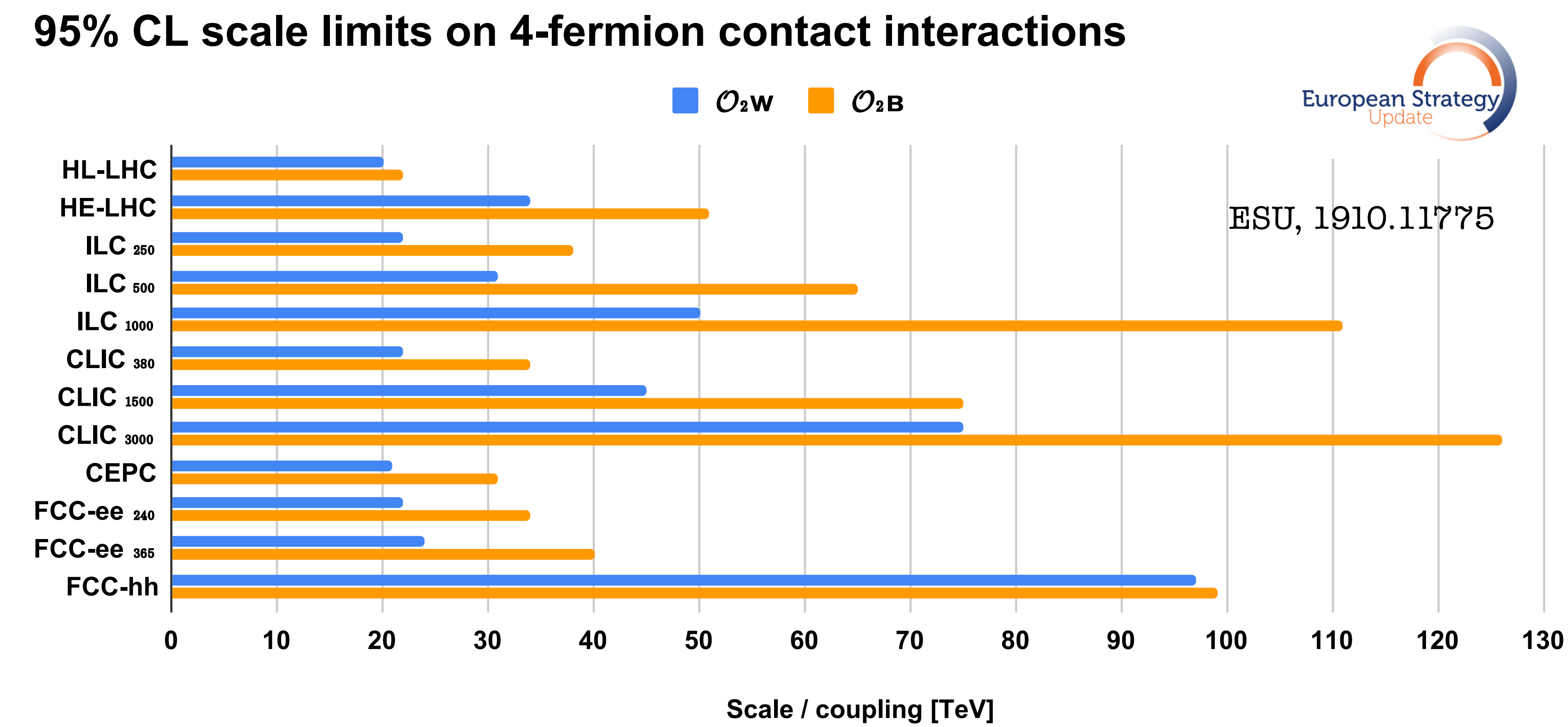
Benchmark UV Study

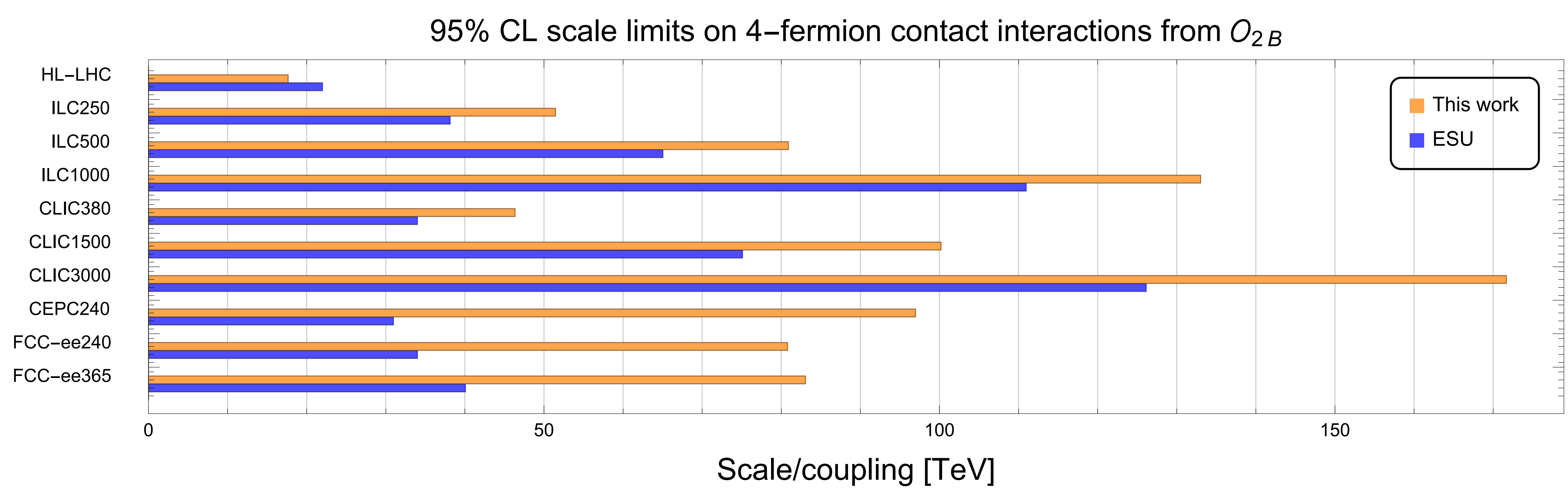
Benchmark UV Study: $\mathcal{O}_{2W,2B}$ update



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

Benchmark UV Study: $\mathcal{O}_{2W,2B}$ update



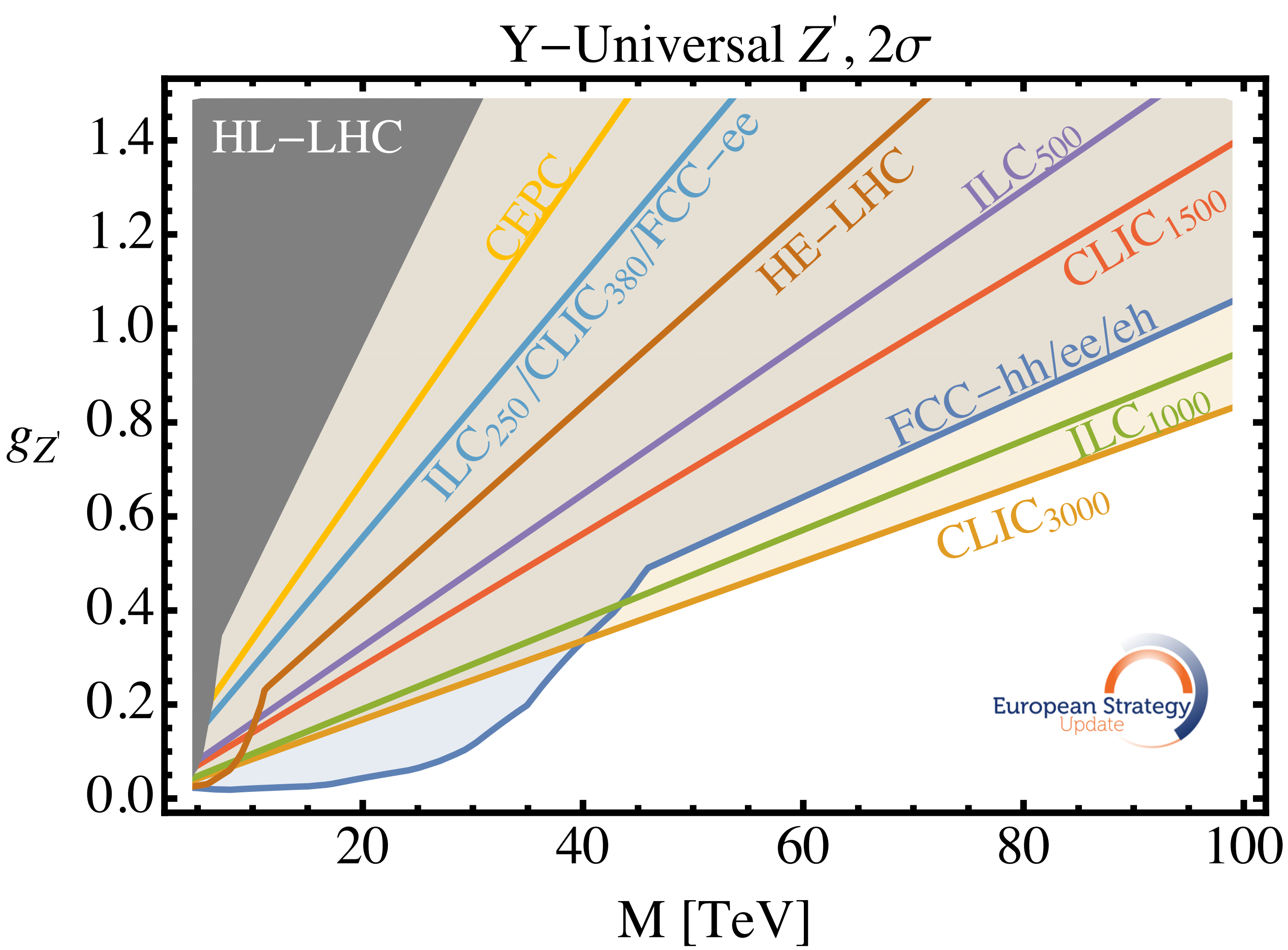


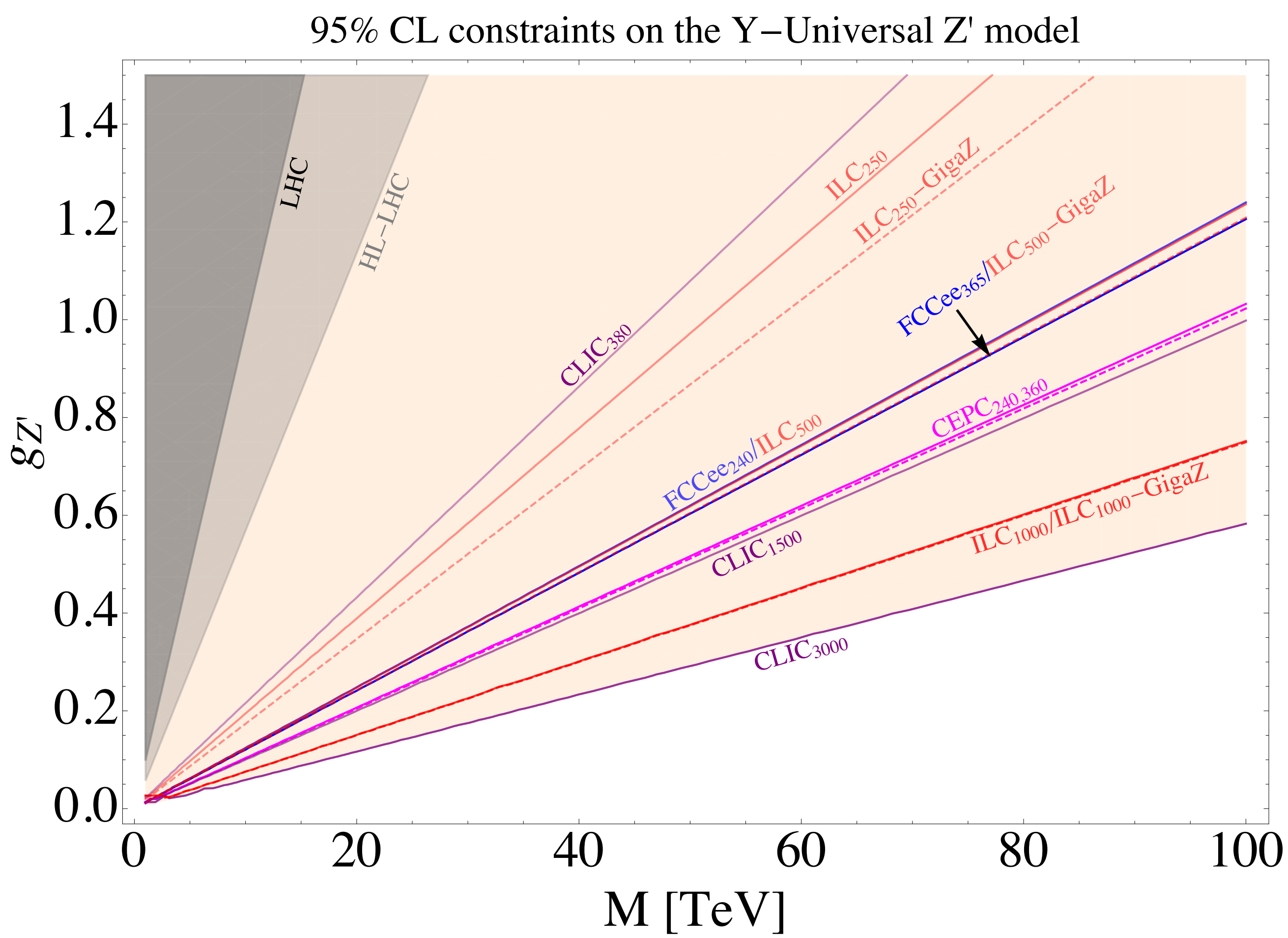
Benchmark UV Study: ***Y-Universal Z' model***

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

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

* Neutral Drell-Yan only





Benchmark UV Study: ***Leptoquark model***

$$\mathscr{L}_{\rm LQ} \supset \left(\lambda^{1L}_{i\alpha}\bar{q}^c_i\epsilon\ell_\alpha + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha\right) S_1 + \lambda^{3L}_{i\alpha}\bar{q}^c_i\epsilon\sigma^I\ell_\alpha S^I_3 + \textbf{ h.c.}$$

Gherardi et al, 2003.12525
Aebischer et al, 2102.08954

Benchmark UV Study: *Leptoquark model*

$$\mathscr{L}_{\rm LQ} \supset \left(\lambda^{1L}_{i\alpha}\bar{q}^c_i\epsilon\ell_\alpha + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha\right) S_1 + \lambda^{3L}_{i\alpha}\bar{q}^c_i\epsilon\sigma^I\ell_\alpha S_3^I + \text{ h.c.}$$

Gherardi et al, 2003.12525
Aebischer et al, 2102.08954

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

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

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

$$[C^{(3)}_{lequ}]^{(0)}_{\alpha\beta ij} = -\frac{\lambda^{1R}_{j\beta}\lambda^{1L*}_{i\alpha}}{8M_1^2} ,$$

$$[C_{eu}]^{(0)}_{\alpha\beta ij} = \frac{\lambda^{1R*}_{i\alpha}\lambda^{1R}_{j\beta}}{2M_1^2} .$$

Benchmark UV Study: ***Leptoquark model***

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

Gherardi et al, 2003.12525
Aebischer et al, 2102.08954

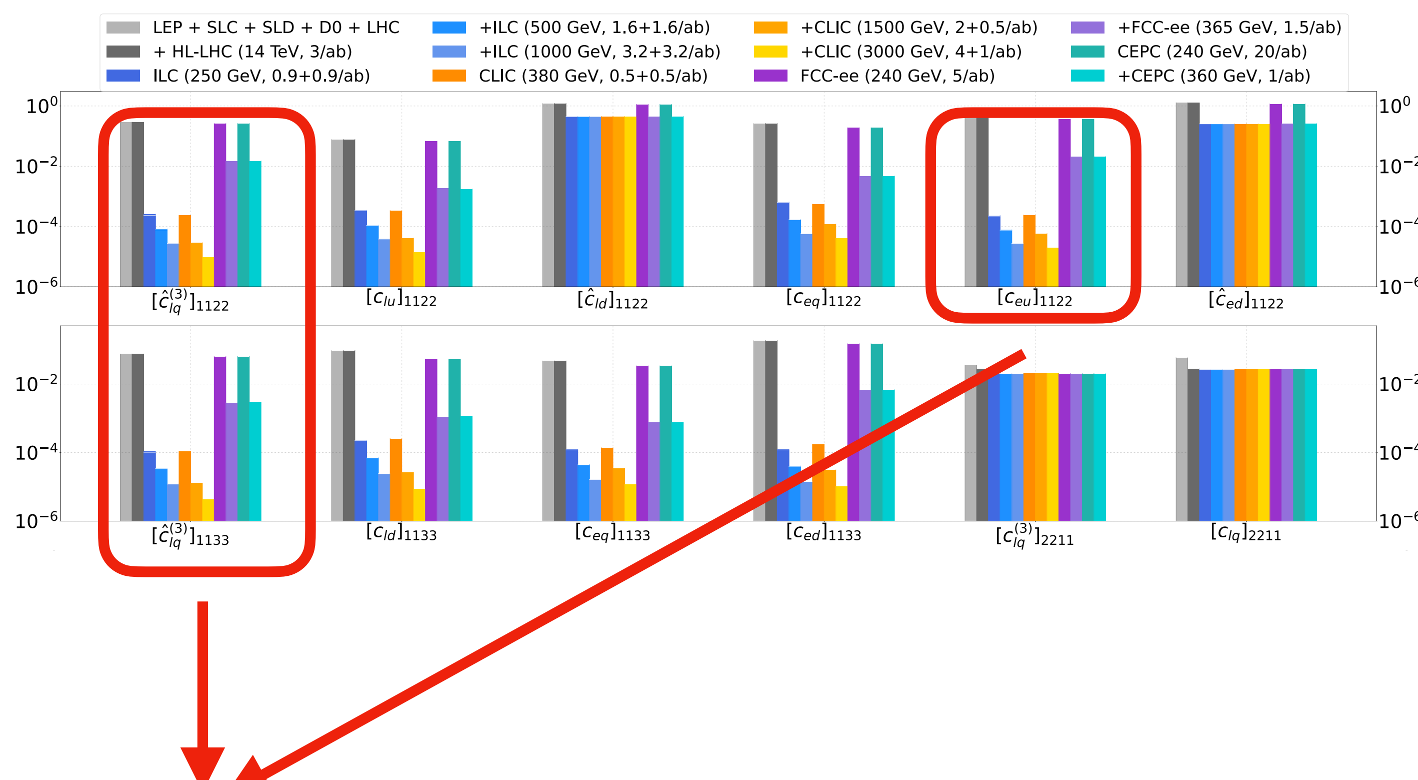
$$[C_{lq}^{(1)}]^{(0)}_{\alpha\beta ij} = \frac{\lambda_{i\alpha}^{1L*}\lambda_{j\beta}^{1L}}{4M_1^2} + \frac{3\lambda_{i\alpha}^{3L*}\lambda_{j\beta}^{3L}}{4M_3^2},$$

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

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

$$[C_{lequ}^{(3)}]^{(0)}_{\alpha\beta ij} = -\frac{\lambda_{j\beta}^{1R}\lambda_{i\alpha}^{1L*}}{8M_1^2},$$

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



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

Benchmark UV Study: ***Leptoquark model***

$$\mathscr{L}_{\rm LQ} \supset \left(\lambda^{1L}_{i\alpha}\bar{q}^c_i\epsilon\ell_\alpha + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha\right) S_1 + \lambda^{3L}_{i\alpha}\bar{q}^c_i\epsilon\sigma^I\ell_\alpha S^I_3 + \textbf{ h.c.}$$

Gherardi et al, 2003.12525
Aebischer et al, 2102.08954

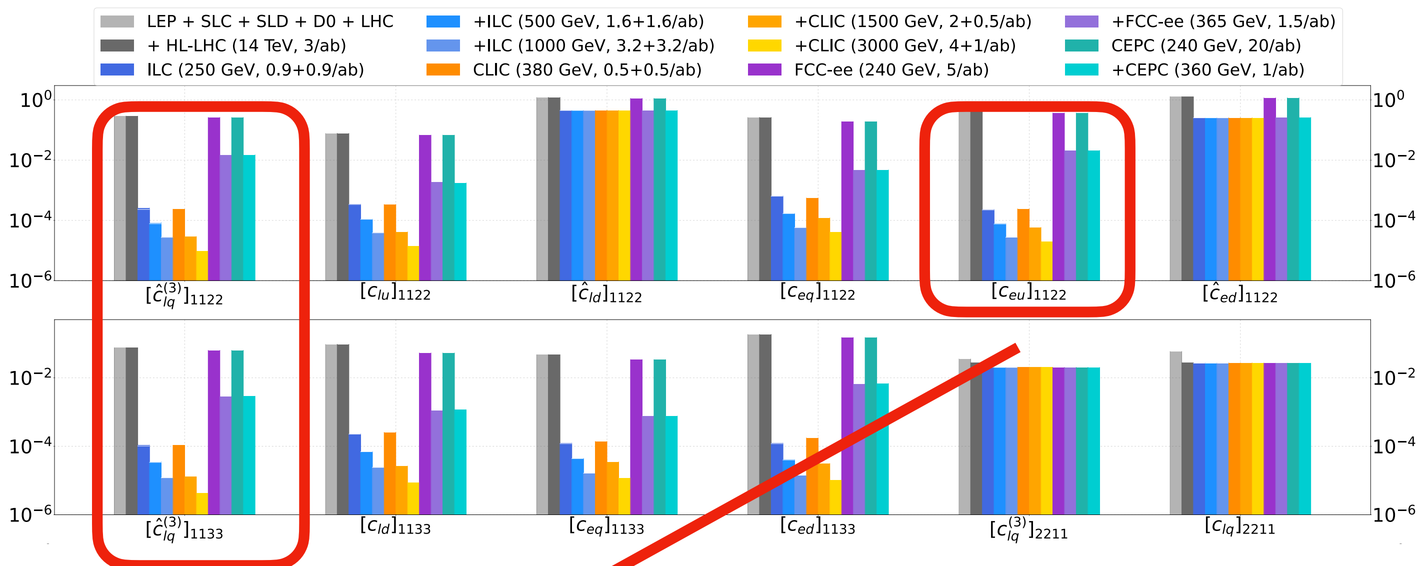
$$[C^{(1)}_{lq}]^{(0)}_{\alpha\beta ij} = \frac{\lambda^{1L*}_{i\alpha}\lambda^{1L}_{j\beta}}{4M_1^2} + \frac{3\lambda^{3L*}_{i\alpha}\lambda^{3L}_{j\beta}}{4M_3^2},$$

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

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

$$[C^{(3)}_{lequ}]^{(0)}_{\alpha\beta ij} = -\frac{\lambda^{1R}_{j\beta}\lambda^{1L*}_{i\alpha}}{8M_1^2},$$

$$[C_{eu}]^{(0)}_{\alpha\beta ij} = \frac{\lambda^{1R*}_{i\alpha}\lambda^{1R}_{j\beta}}{2M_1^2}.$$



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

Benchmark UV Study: ***Leptoquark model***

$$\mathscr{L}_{\rm LQ} \supset \left(\lambda^{1L}_{i\alpha}\bar{q}^c_i\epsilon\ell_\alpha + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha\right) S_1 + \lambda^{3L}_{i\alpha}\bar{q}^c_i\epsilon\sigma^I\ell_\alpha S^I_3 + \textbf{ h.c.}$$

Gherardi et al, 2003.12525
Aebischer et al, 2102.08954

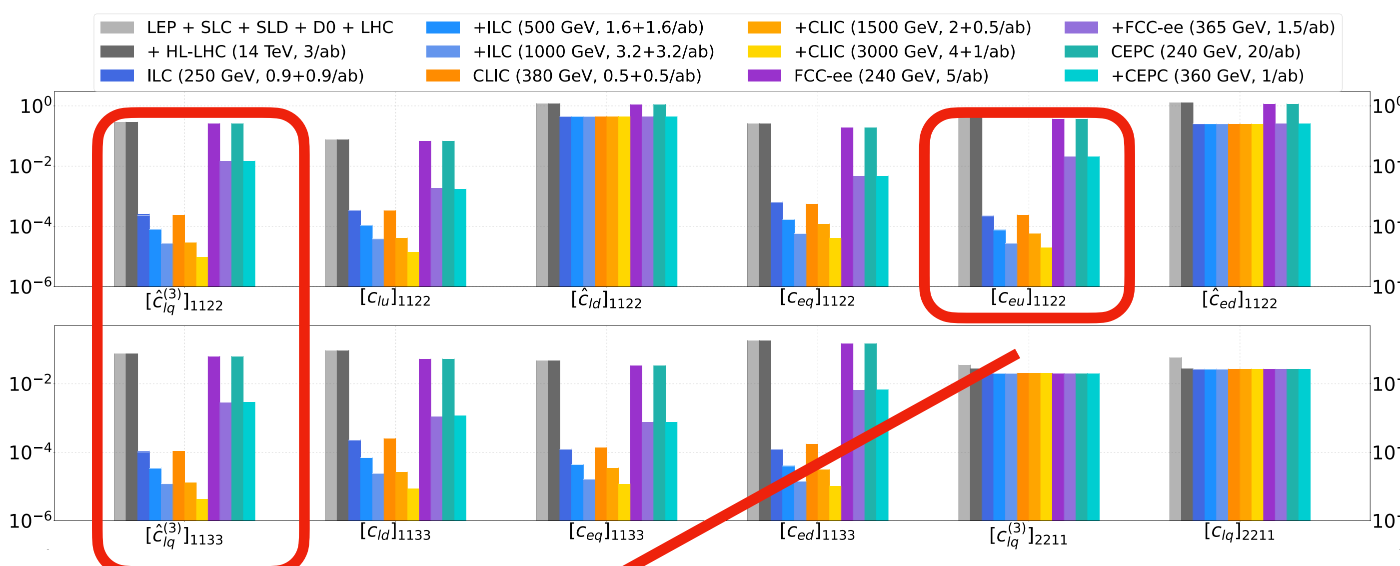
$$[C^{(1)}_{lq}]^{(0)}_{\alpha\beta ij} = \frac{\lambda^{1L*}_{i\alpha}\lambda^{1L}_{j\beta}}{4M_1^2} + \frac{3\lambda^{3L*}_{i\alpha}\lambda^{3L}_{j\beta}}{4M_3^2}\,,$$

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

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

$$[C^{(3)}_{lequ}]^{(0)}_{\alpha\beta ij} = -\frac{\lambda^{1R}_{j\beta}\lambda^{1L*}_{i\alpha}}{8M_1^2}\,,$$

$$[C_{eu}]^{(0)}_{\alpha\beta ij} = \frac{\lambda^{1R*}_{i\alpha}\lambda^{1R}_{j\beta}}{2M_1^2}.$$

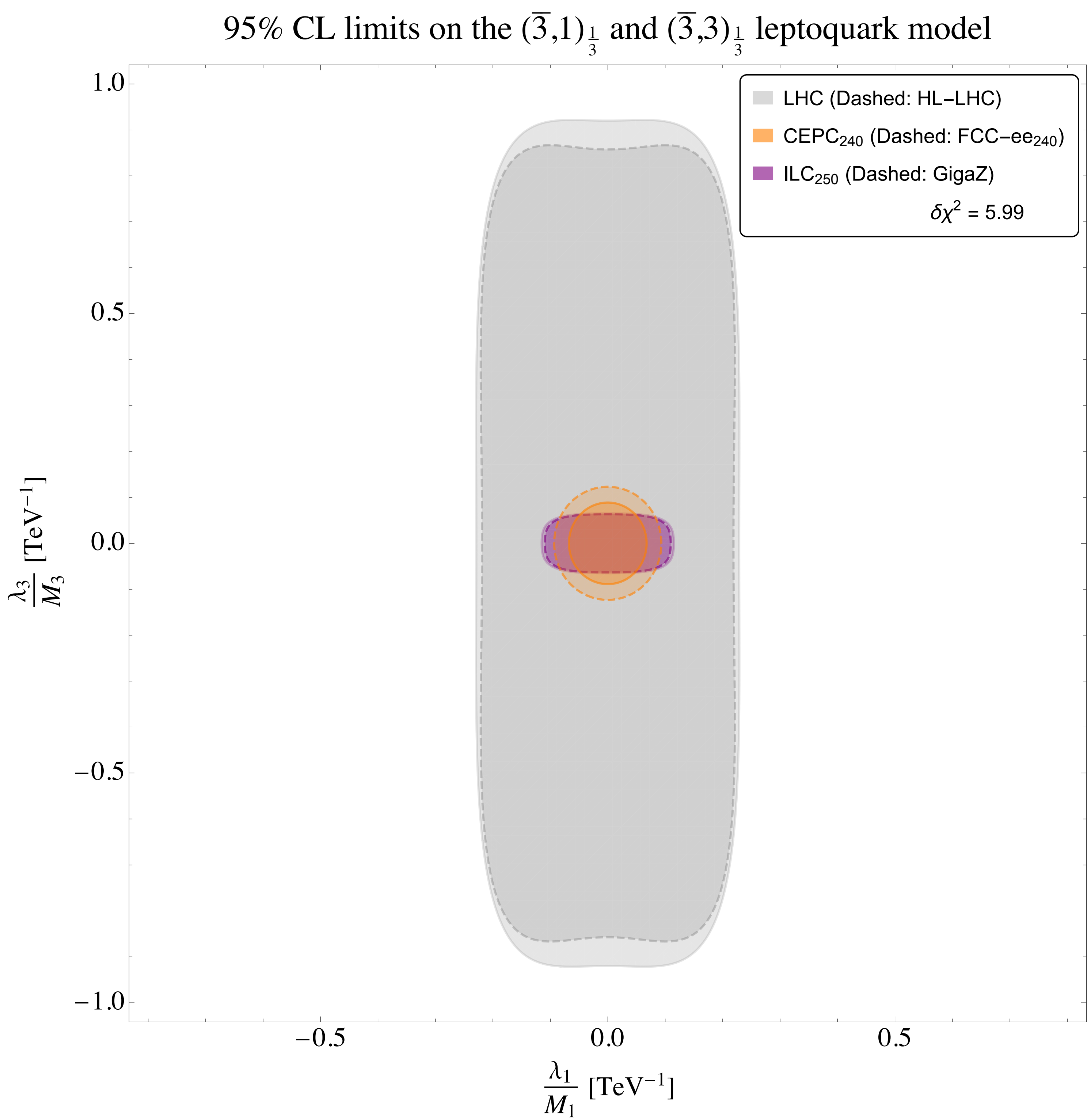


Leading constraints from the global fit: $[c_{eu}]_{1122}$ and $[\hat{c}^{(3)}_{lq}]_{1133,1122}$.

* Assuming universal Yukawa couplings for the following discussion.

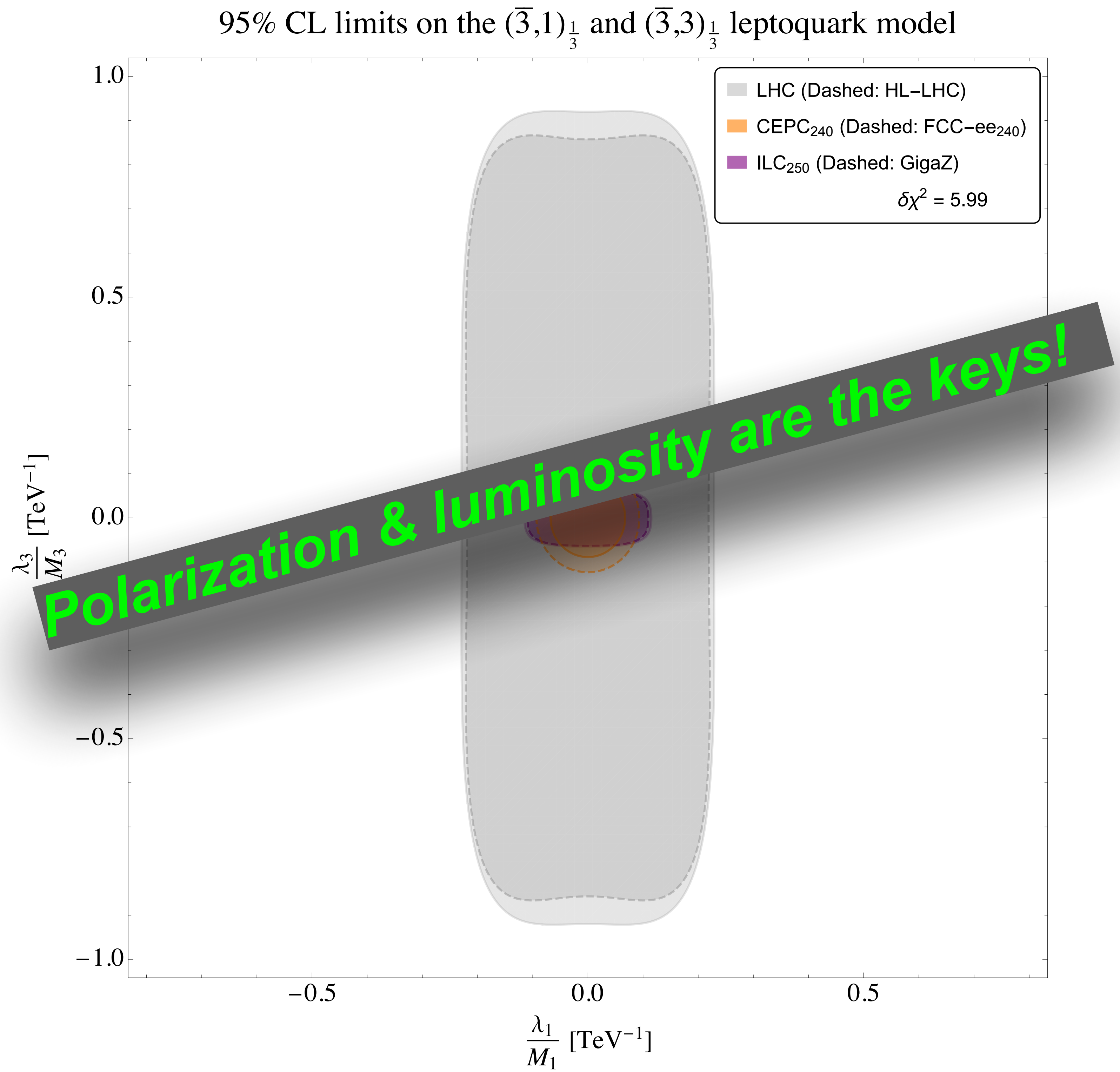
Benchmark UV Study: Leptoquark model

$$\mathcal{L}_{\rm LQ} \supset \left(\lambda^{1L}_{i\alpha}\bar{q}^c_i \epsilon \ell_\alpha + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha\right) S_1 + \lambda^{3L}_{i\alpha}\bar{q}^c_i \epsilon \sigma^I \ell_\alpha S^I_3 + \textbf{ h.c.}$$



Benchmark UV Study: Leptoquark model

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



Summary

- 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 σ_{ss} etc at future colliders. Muon colliders could help in this regard.

- Global fit of bosonic CPV operators could be further improved with $e^+e^- \to W^+W^-$ data at future colliders.

Backup

aTGC from $e^+e^- \to W^+W^-$

Explicit expressions for the projectors

$$P^{W^+}_{\mp\mp}(\theta_l, \phi_l) = P^{W^-}_{\pm\pm}(\theta_l, \phi_l) = \frac{1}{2}\left(5\cos^2\theta_l \mp 2\cos\theta_l - 1\right)$$

$$P^{W^+}_{00}(\theta_l, \phi_l) = P^{W^-}_{00}(\theta_l, \phi_l) = 2 - 5\cos^2\theta_l$$

$$P^{W^+}_{+-}(\theta_l, \phi_l) = P^{W^-}_{+-}(\theta_l, \phi_l) = 2\exp\left[-2i\phi_l\right]$$

$$\left(P^{W^+}_{\mp 0}\right)^*(\theta_l, \phi_l) = -P^{W^-}_{\pm 0}(\theta_l, \phi_l) = \frac{8}{3\pi\sqrt{2}}\left(1 \mp 4\cos\theta_l\right)\exp\left[\mp i\phi_l\right]$$

aTGC from $e^+e^- \to W^+W^-$

$$\frac{\mathrm{d}\sigma\left(\mathrm{e^+e^-} \to \mathrm{W^+W^-}\right)}{\mathrm{d}\cos\theta_{\mathrm{W}}}\rho_{\tau\tau'}^{W^-} = \frac{1}{\mathrm{Br}\left(\mathrm{W^-} \to \ell^-\bar{\nu}\right)}\int \frac{\mathrm{d}\sigma\left(\mathrm{e^+e^-} \to W^+\ell^-\bar{\nu}\right)}{\mathrm{d}\cos\theta_{\mathrm{W}}\mathrm{d}\cos\theta^*\ \mathrm{d}\phi^*} P_{\tau\tau'}\left(\cos\theta^*, \phi^*\right)\mathrm{d}\cos\theta^*\ \mathrm{d}\phi^*$$

$$\rho_{00}^{k} = \frac{1}{N_k^{\mathrm{cor}}}\sum_{i=1}^{N_k}\frac{1}{f_k\left(\cos\theta_i^*\right)}P_{00}\left(\cos\theta_i^*\right)$$

$$\rho_{++}^{k} + \rho_{--}^{k} = \frac{1}{N_k^{\mathrm{cor}}}\sum_{i=1}^{N_k}\frac{1}{f_k\left(\cos\theta_i^*\right)}\left[P_{++}\left(\cos\theta_i^*\right) + P_{--}\left(\cos\theta_i^*\right)\right]$$

$$N_k^{\mathrm{cor}} = \sum_{i=1}^{N_k}\frac{1}{f_k(\theta_i^*)}$$