Global fit of the SMEFT at future lepton colliders

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CEPC2023, Fudan University, August 17, 2023

Based on

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

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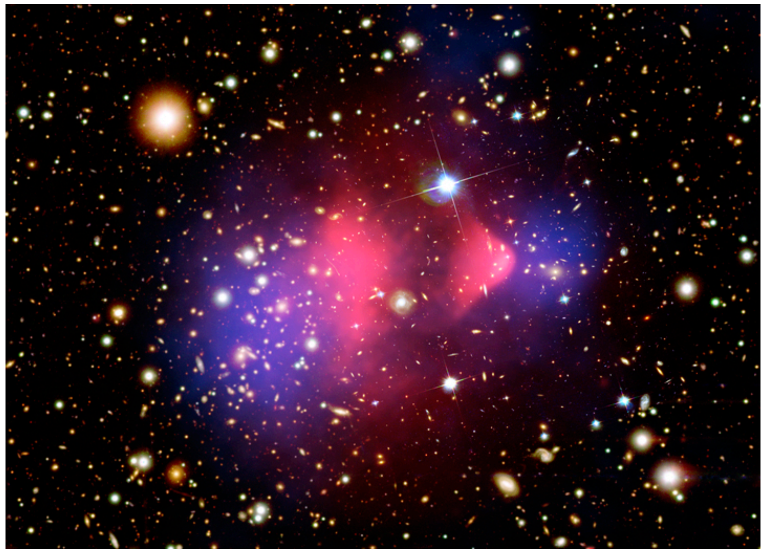
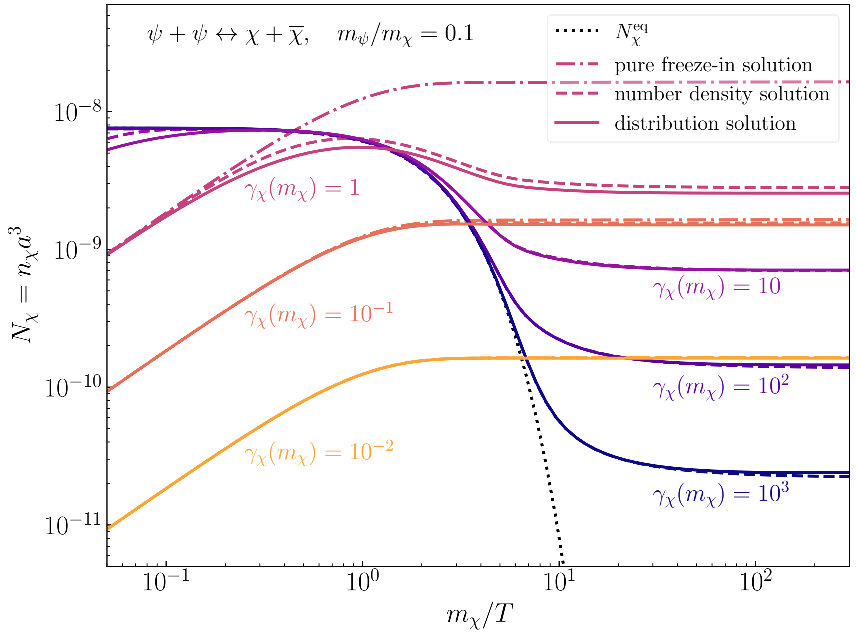
The SM, up to now, is very successful. But there are some flaws:

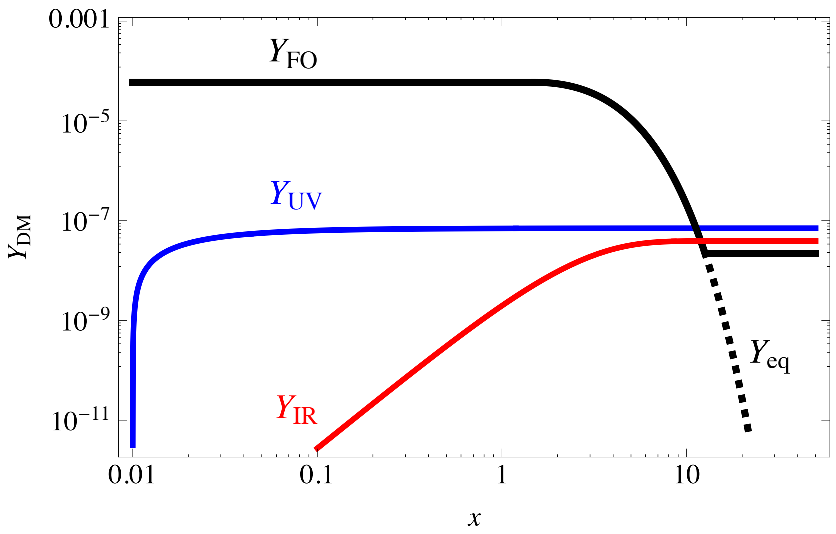


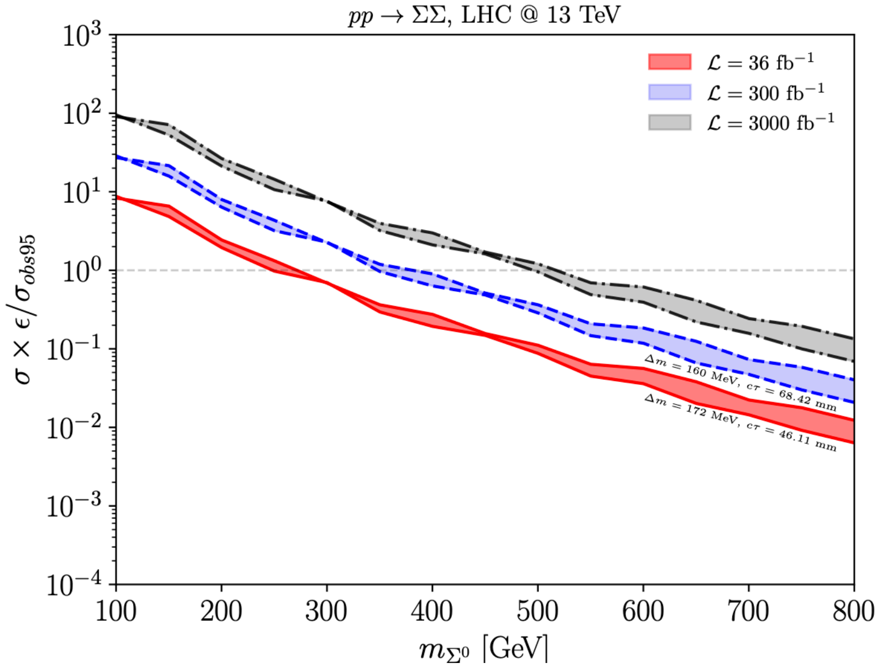


YD, Huang, Li, Yu, 2005.01717 (JHEP)

YD, Huang, Li, Li, Yu, 2111.01267 (JCAP)

Elahi et al, 1410.6157

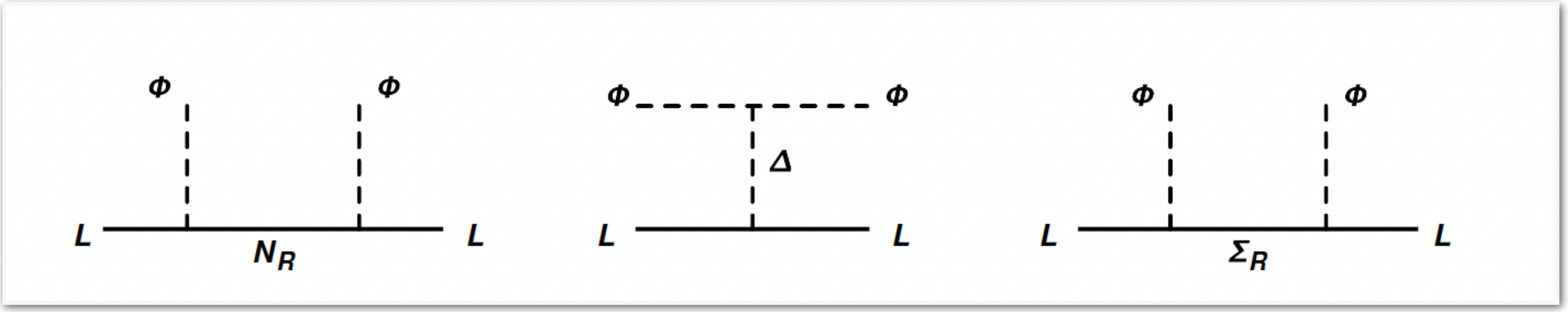


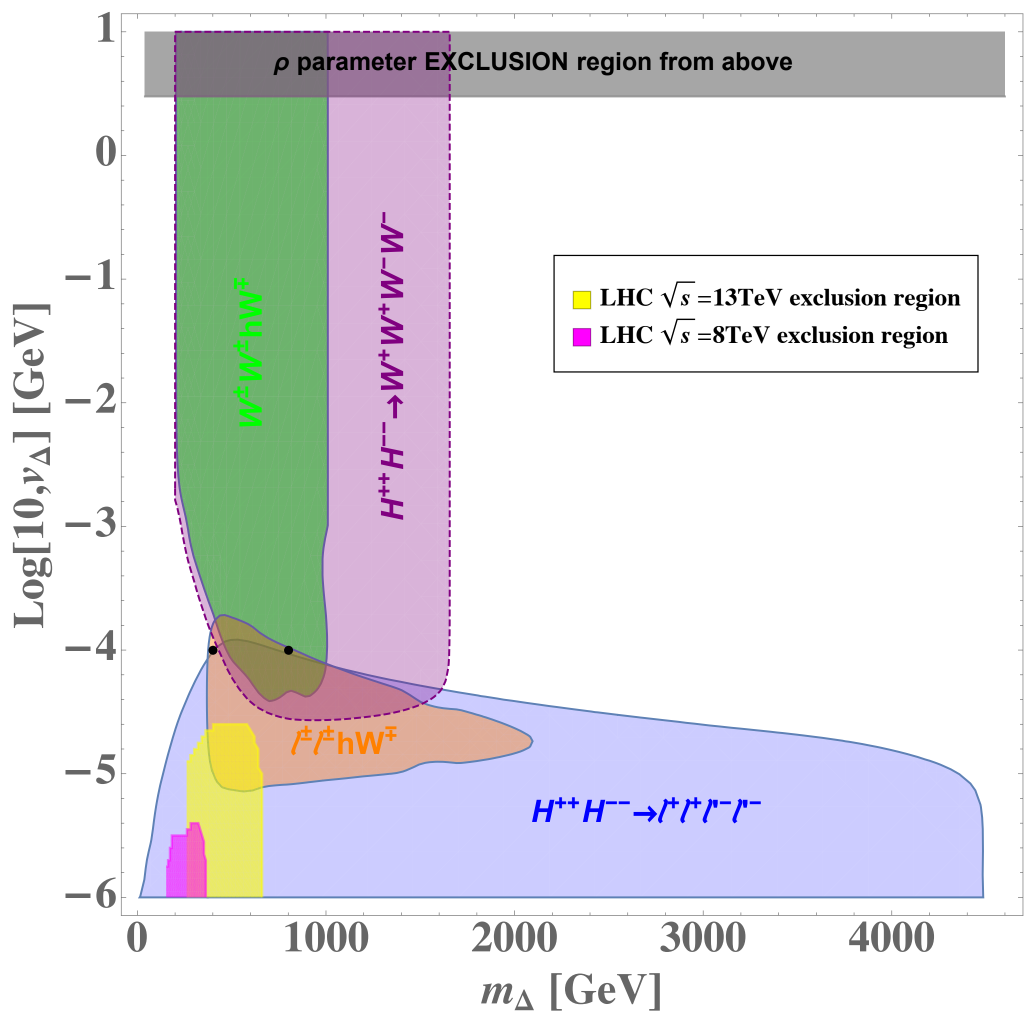


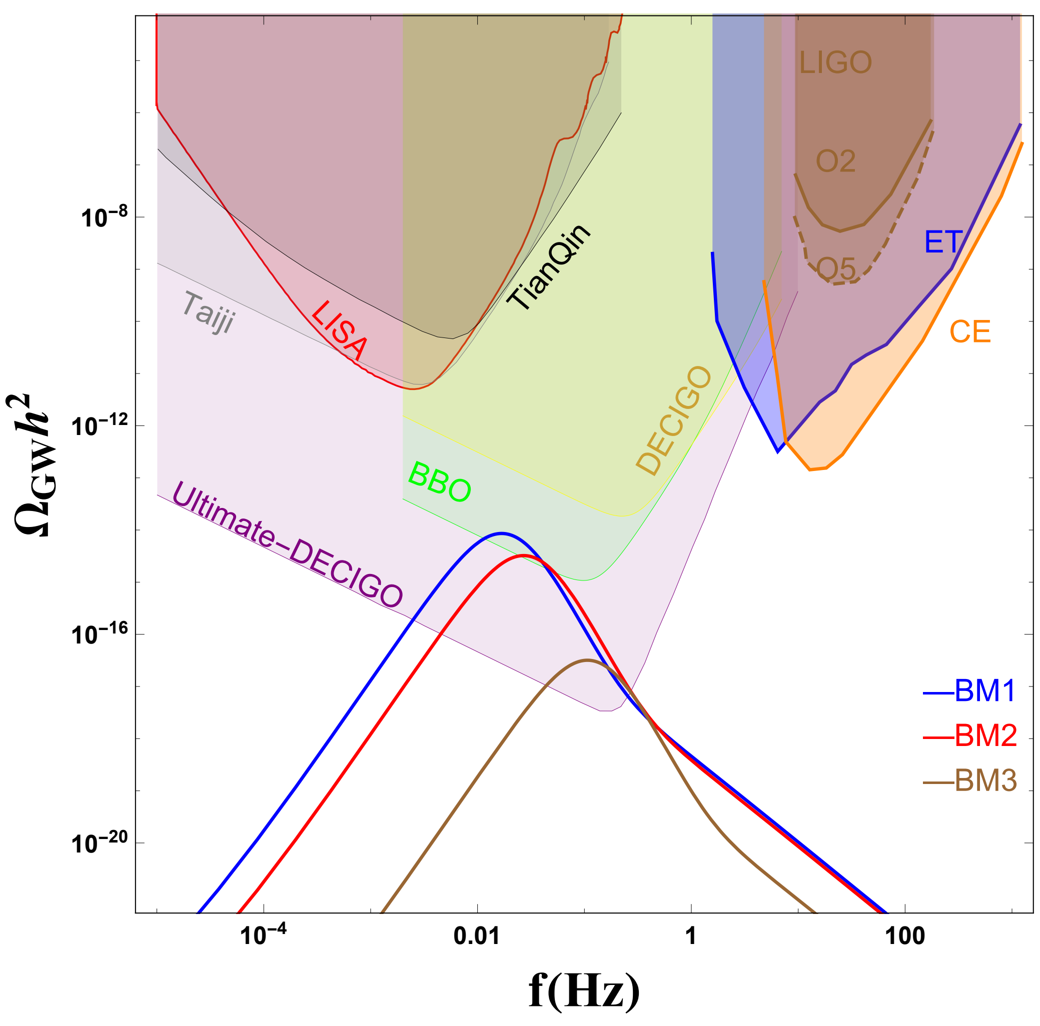
Chiang, Cottin, **YD**, Fuyuto, Ramsey-Musolf, 2003.07867(JHEP)

Introduction

On the other hand, neutrinos oscillate







YD, Dunbrack, Ramsey-Musolf, Yu, 1810.09450 (JHEP)

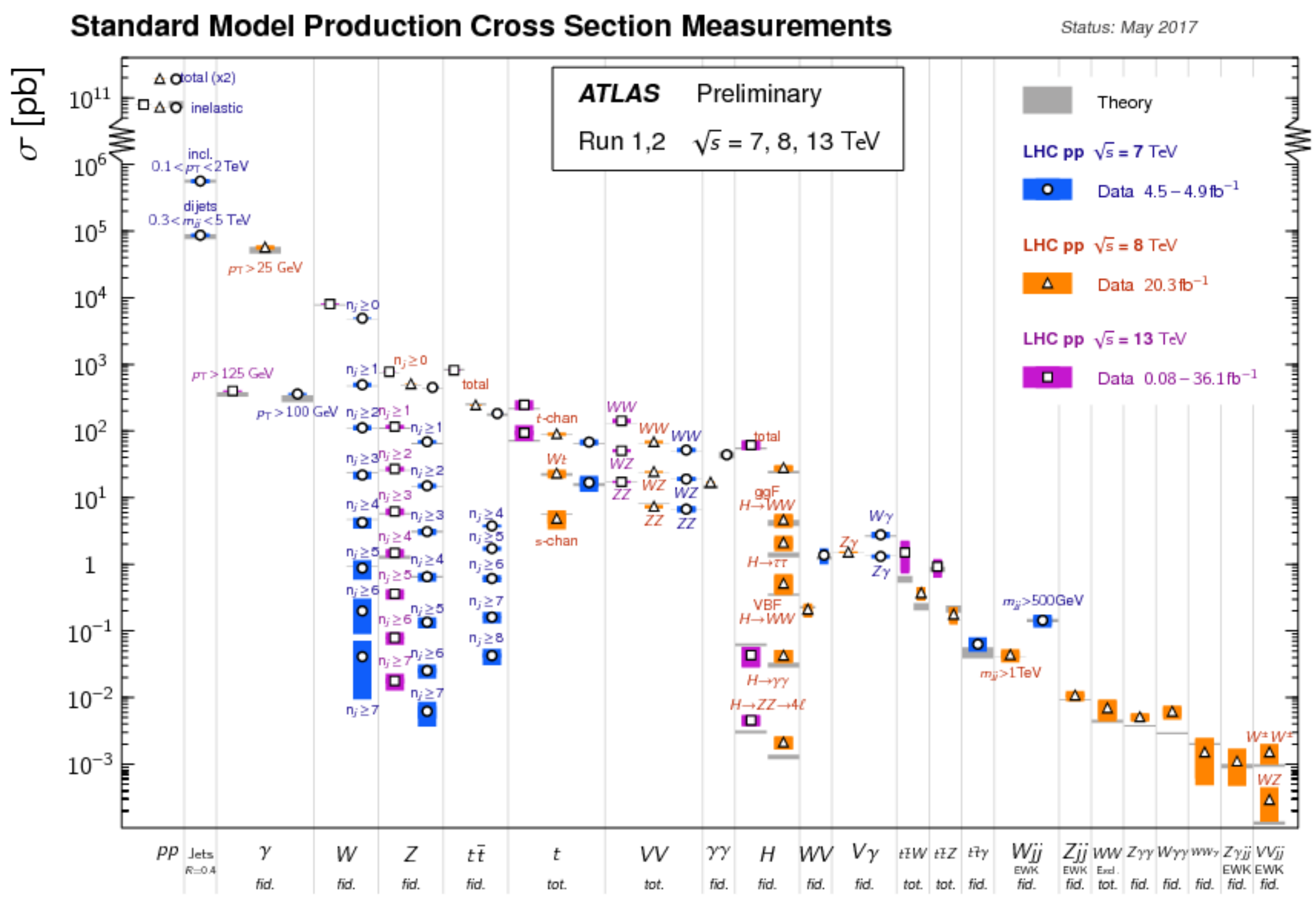
Zhou, Bian, **YD**, 2203.01561 (JHEP)

Introduction

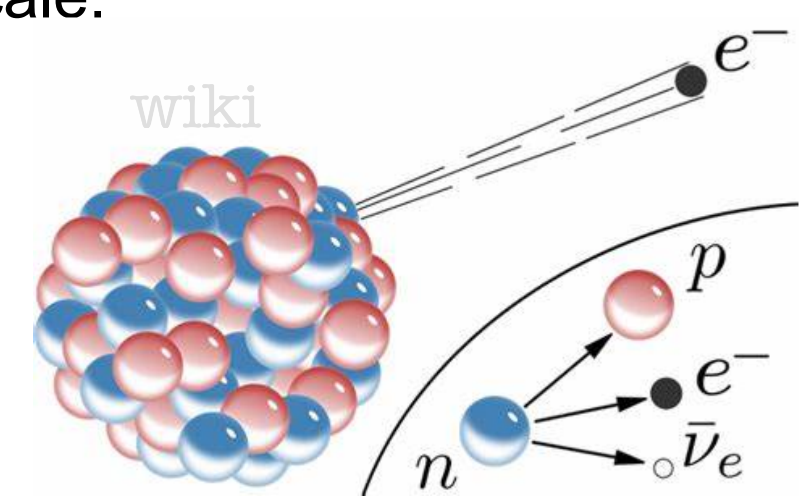
While there are many models for dark matter, neutrinos and other topics as you prefer, the direct experimental observation of any new particle is still null.

Q: How to approach new physics beyond the Standard Model?

A: ⋯

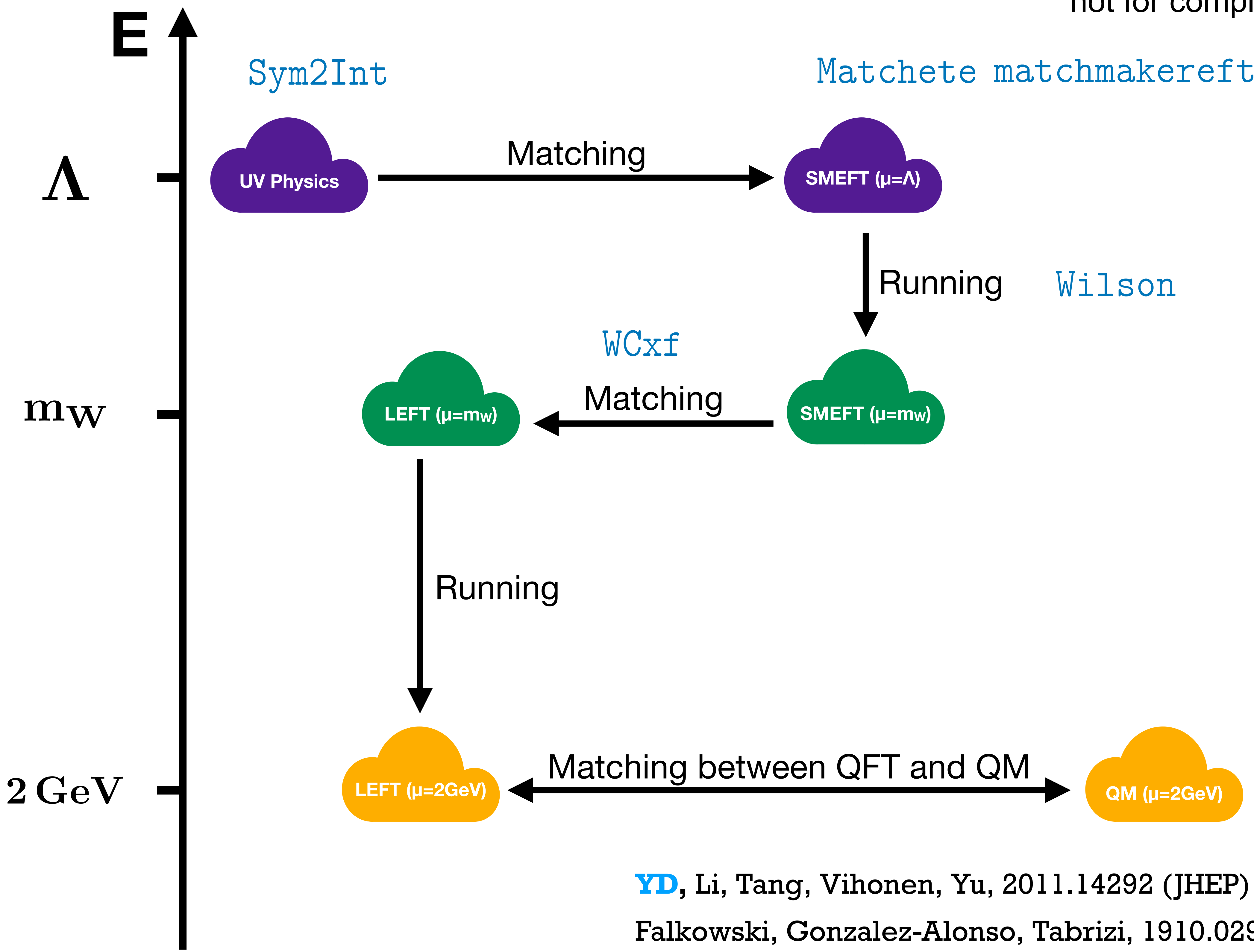


The experimental data are suggesting that the SM is an effective low-energy theory of some UV model above the weak scale.



Introduction

* not for completeness



YD, Li, Tang, Vihonen, Yu, 2011.14292 (JHEP)

Falkowski, Gonzalez-Alonso, Tabrizi, 1910.02971 (JHEP)

Operators in the Warsaw basis:

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				
$X^2\varphi^2$		**$\psi^2 X\varphi$**		**$\psi^2\varphi^2 D$**	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		**B-violating**			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$				

59 operators (+ 4 B-violating ones)

2499 operators: 1350 (CP-even) + 1149 (CP-odd)

No flavor assumptions are made.

We choose to work in the Higgs basis

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

SMEFT global fit: *Basis*

We choose to work in the Higgs basis

$$\delta gLWe \to \text{cHl3⌘Warsaw}\, v^2 - \frac{\text{cHD⌘Warsaw}\, gL^2 v^2}{4\left(gL^2 - gY^2\right)} - \frac{\text{cHWB⌘Warsaw}\, gL\, gY\, v^2}{gL^2 - gY^2} - \frac{gL^2 v^2 \Delta GF}{2\left(gL^2 - gY^2\right)}$$

$$\delta gLZe \to -\frac{\text{cHl1⌘Warsaw}\, v^2}{2} - \frac{\text{cHl3⌘Warsaw}\, v^2}{2} + \frac{\text{cHWB⌘Warsaw}\, gL\, gY\, v^2}{gL^2 - gY^2} + \frac{\text{cHD⌘Warsaw}\left(gL^2 + gY^2\right) v^2}{8\left(gL^2 - gY^2\right)} + \frac{\left(gL^2 + gY^2\right) v^2 \Delta GF}{4\left(gL^2 - gY^2\right)}$$

$$\delta gRZe \to -\frac{\text{cHe1⌘Warsaw}\, v^2}{2} + \frac{\text{cHD⌘Warsaw}\, gY^2 v^2}{4\, gL^2 - 4\, gY^2} + \frac{\text{cHWB⌘Warsaw}\, gL\, gY\, v^2}{gL^2 - gY^2} + \frac{gY^2 v^2 \Delta GF}{2\, gL^2 - 2\, gY^2}$$

$$\delta gLZu \to -\frac{\text{cHq1⌘Warsaw}\, v^2}{2} + \frac{\text{cHq3⌘Warsaw}\, v^2}{2} - \frac{2\, \text{cHWB⌘Warsaw}\, gL\, gY\, v^2}{3\left(gL^2 - gY^2\right)} - \frac{\text{cHD⌘Warsaw}\left(3\, gL^2 + gY^2\right) v^2}{24\left(gL^2 - gY^2\right)} - \frac{\left(3\, gL^2 + gY^2\right) v^2 \Delta GF}{12\left(gL^2 - gY^2\right)}$$

$$\delta gLZd \to -\frac{\text{cHq1⌘Warsaw}\, v^2}{2} - \frac{\text{cHq3⌘Warsaw}\, v^2}{2} + \frac{\text{cHWB⌘Warsaw}\, gL\, gY\, v^2}{3\, gL^2 - 3\, gY^2} + \frac{\text{cHD⌘Warsaw}\left(3\, gL^2 - gY^2\right) v^2}{24\left(gL^2 - gY^2\right)} + \frac{\left(3\, gL^2 - gY^2\right) v^2 \Delta GF}{12\left(gL^2 - gY^2\right)}$$

$$\delta gRZu \to -\frac{\text{cHu⌘Warsaw}\, v^2}{2} - \frac{2\, \text{cHWB⌘Warsaw}\, gL\, gY\, v^2}{3\left(gL^2 - gY^2\right)} + \frac{\text{cHD⌘Warsaw}\, gY^2 v^2}{6\left(-gL^2 + gY^2\right)} + \frac{gY^2 v^2 \Delta GF}{3\left(-gL^2 + gY^2\right)}$$

$$\delta gRZd \to -\frac{\text{cHd⌘Warsaw}\, v^2}{2} + \frac{\text{cHWB⌘Warsaw}\, gL\, gY\, v^2}{3\, gL^2 - 3\, gY^2} + \frac{\text{cHD⌘Warsaw}\, gY^2 v^2}{12\left(gL^2 - gY^2\right)} + \frac{gY^2 v^2 \Delta GF}{6\, gL^2 - 6\, gY^2}$$

SMEFT global fit: *4f*

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
$[\mathcal{O}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell\ell}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_r \bar{\sigma}^\mu \ell_r)$
$[O^{(3)}_{\ell q}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \sigma^i \ell_p)(\bar{q}_r \bar{\sigma}^\mu \sigma^i q_r)$	$[\mathcal{O}_{\ell\ell}]_{prrp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_r)(\bar{\ell}_r \bar{\sigma}^\mu \ell_p)$
$[\mathcal{O}_{\ell u}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(u^c_r \sigma^\mu \bar{u}^c_r)$	$[\mathcal{O}_{\ell e}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e^c_r \sigma^\mu \bar{e}^c_r)$
$[\mathcal{O}_{\ell d}]_{pprr} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(d^c_r \sigma^\mu \bar{d}^c_r)$	$[\mathcal{O}_{\ell e}]_{rrpp} = (\bar{\ell}_r \bar{\sigma}_\mu \ell_r)(e^c_p \sigma^\mu \bar{e}^c_p)$
$[\mathcal{O}_{eq}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(\bar{q}_r \bar{\sigma}^\mu q_r)$	$[\mathcal{O}_{\ell e}]_{prrp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_r)(e^c_r \sigma^\mu \bar{e}^c_p)$
$[\mathcal{O}_{eu}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(u^c_r \sigma^\mu \bar{u}^c_r)$	$[\mathcal{O}_{ee}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(e^c_r \sigma^\mu \bar{e}^c_r)$
$[\mathcal{O}_{ed}]_{pprr} = (e^c_p \sigma_\mu \bar{e}^c_p)(d^c_r \sigma^\mu \bar{d}^c_r)$	
Chirality violating	One flavor
$[\mathcal{O}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{e}^c_p)\epsilon_{jk}(\bar{q}^k_r \bar{u}^c_r)$	$[\mathcal{O}_{\ell\ell}]_{pppp} = \frac{1}{2}(\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_p \bar{\sigma}^\mu \ell_p)$
$[O^{(3)}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{\sigma}_{\mu\nu} \bar{e}^c_p)\epsilon_{jk}(\bar{q}^k_r \bar{\sigma}_{\mu\nu} \bar{u}^c_r)$	$[\mathcal{O}_{\ell e}]_{pppp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e^c_p \sigma^\mu \bar{e}^c_p)$
$[\mathcal{O}_{\ell edq}]_{pprr} = (\bar{\ell}^j_p \bar{e}^c_p)(d^c_r q^j_r)$	$[\mathcal{O}_{ee}]_{pppp} = \frac{1}{2}(e^c_p \sigma_\mu \bar{e}^c_p)(e^c_p \sigma^\mu \bar{e}^c_p)$

Full list of observables and different collider options are summarized in great detail in our snowmass paper 2206.08326

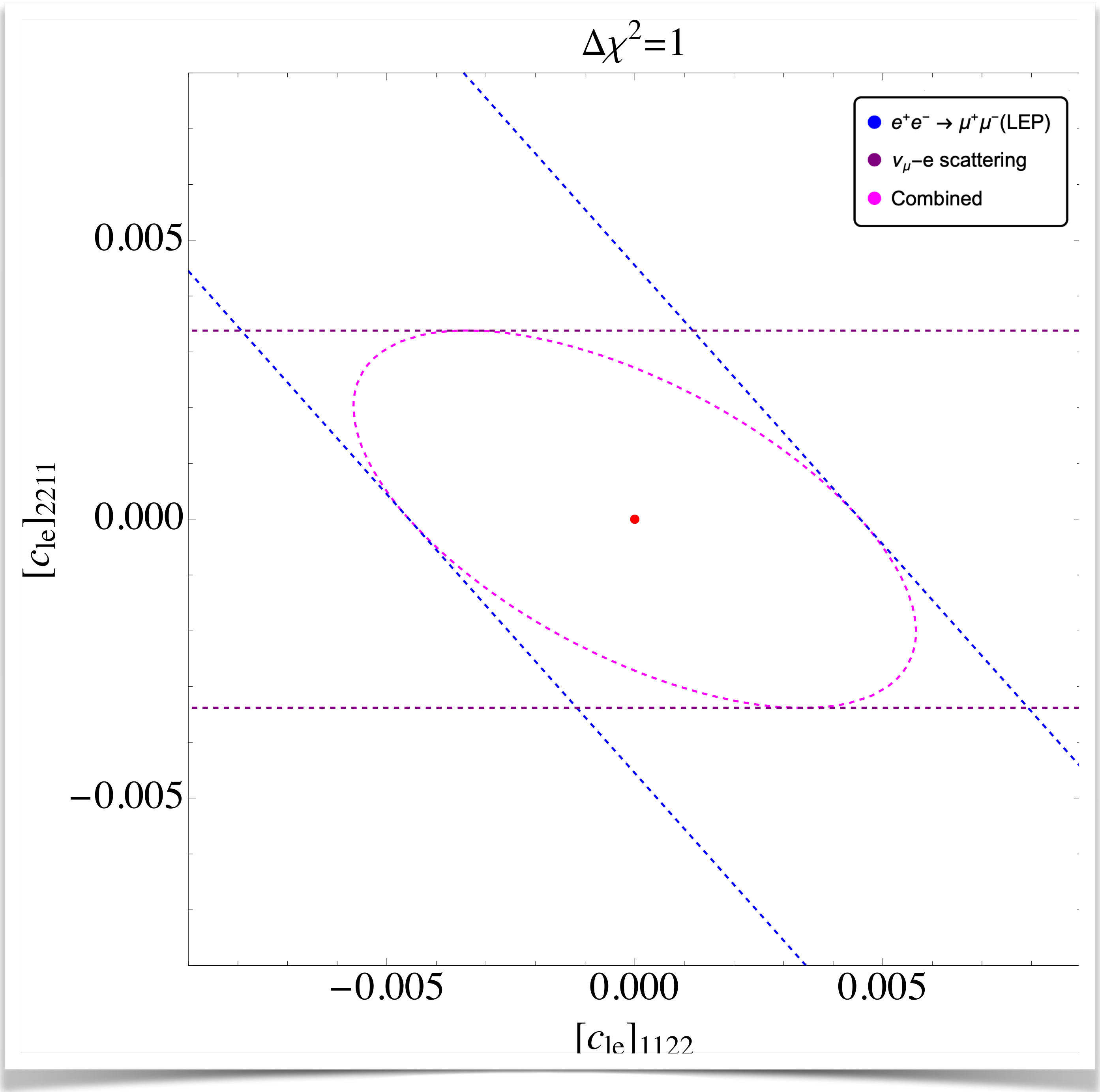
SMEFT global fit: *4f*

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

Process	Observable	Experimental value	Ref.	SM prediction
$\overset{(-)}{\nu}_\mu - e^-$ scattering	$g_{LV}^{\nu_\mu e}$ $g_{LA}^{\nu_\mu e}$	-0.035 ± 0.017 -0.503 ± 0.017	CHARM-II [47]	-0.0396 [48] -0.5064 [48]
τ decay	$\frac{G_{\tau e}^2}{G_F^2}$ $\frac{G_{\tau\mu}^2}{G_F^2}$	1.0029 ± 0.0046 0.981 ± 0.018	PDG2014 [49]	1
Neutrino scattering	R_{ν_μ} $R_{\overline{\nu}_\mu}$	0.3093 ± 0.0031 0.390 ± 0.014	CHARM ($r = 0.456$) [50]	0.3156 [50] 0.370 [50]
	R_{ν_μ} $R_{\overline{\nu}_\mu}$	0.3072 ± 0.0033 0.382 ± 0.016	CDHS ($r = 0.393$) [51]	0.3091 [51] 0.380 [51]
	κ	0.5820 ± 0.0041	CCFR [52]	0.5830 [52]
	$R_{\nu_e \overline{\nu}_e}$	$0.406^{+0.145}_{-0.135}$	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 A_2	$(-91.1 \pm 4.3) \times 10^{-6}$ $(-160.8 \pm 7.1) \times 10^{-6}$	PVDIS [58]	$(-87.7 \pm 0.7) \times 10^{-6}$ [58] $(-158.9 \pm 1.0) \times 10^{-6}$ [58]
	$g_{VA}^{eu} - g_{VA}^{ed}$	-0.042 ± 0.057 -0.12 ± 0.074	SAMPLE ($\sqrt{Q^2} = 200$ MeV) [59] SAMPLE ($\sqrt{Q^2} = 125$ MeV) [59]	-0.0360 [54] 0.0265 [54]
	b_{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]
τ polarization	$\mathcal{P}_\tau$ $\mathcal{A}_\mathcal{P}$	0.012 ± 0.058 0.029 ± 0.057	VENUS [61]	0.028 [61] 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
$d_I \to u_J \ell \overline{\nu}_\ell(\gamma)$	$\epsilon_{L,R,S,P,T}^{de_J}$	See text	[65]	0
$e^+e^- \to f\bar{f}$	δA_{LR}^e δA_{LR}^μ δA_{LR}^τ δA_{LR}^c δA_{LR}^b	2.0% 1.5% 2.4% 0.5% 0.4%	SuperKEKB [66]	0.00015 -0.0006 -0.0006 -0.005 -0.020

SMEFT global fit: *4f*

Flat direction lifted by low-energy experiments: **muon sector example**



SMEFT global fit: *4f*

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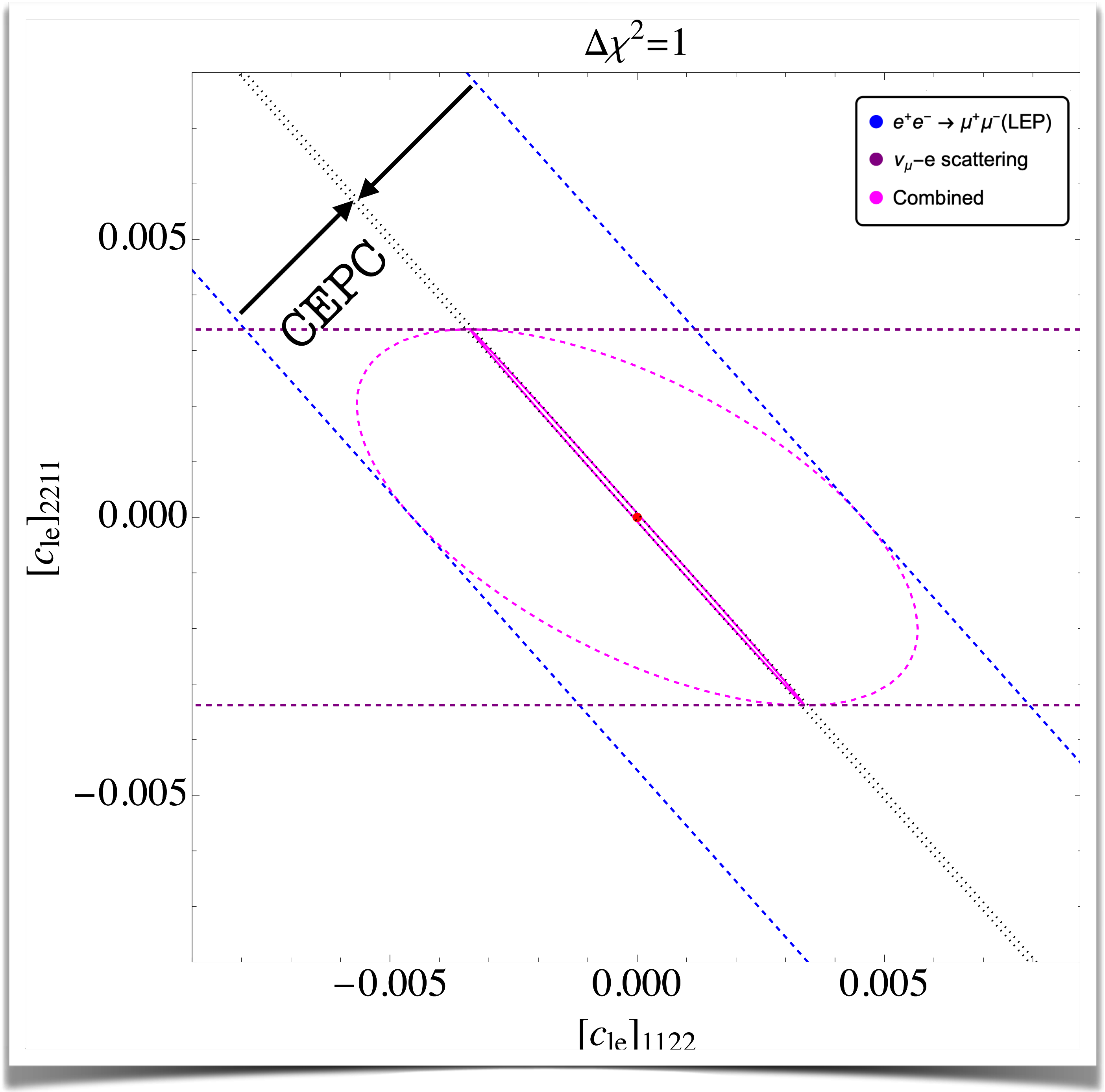
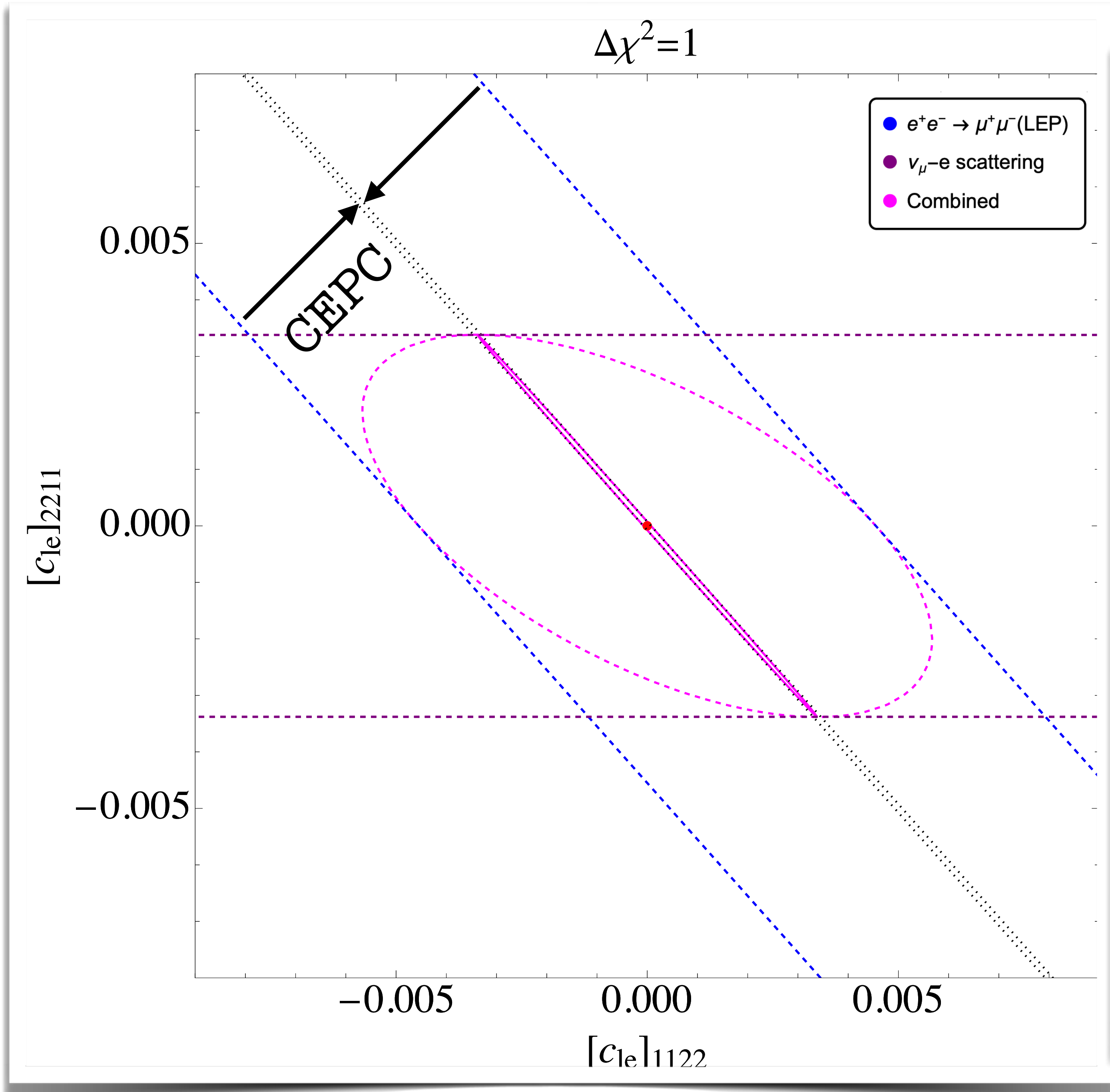
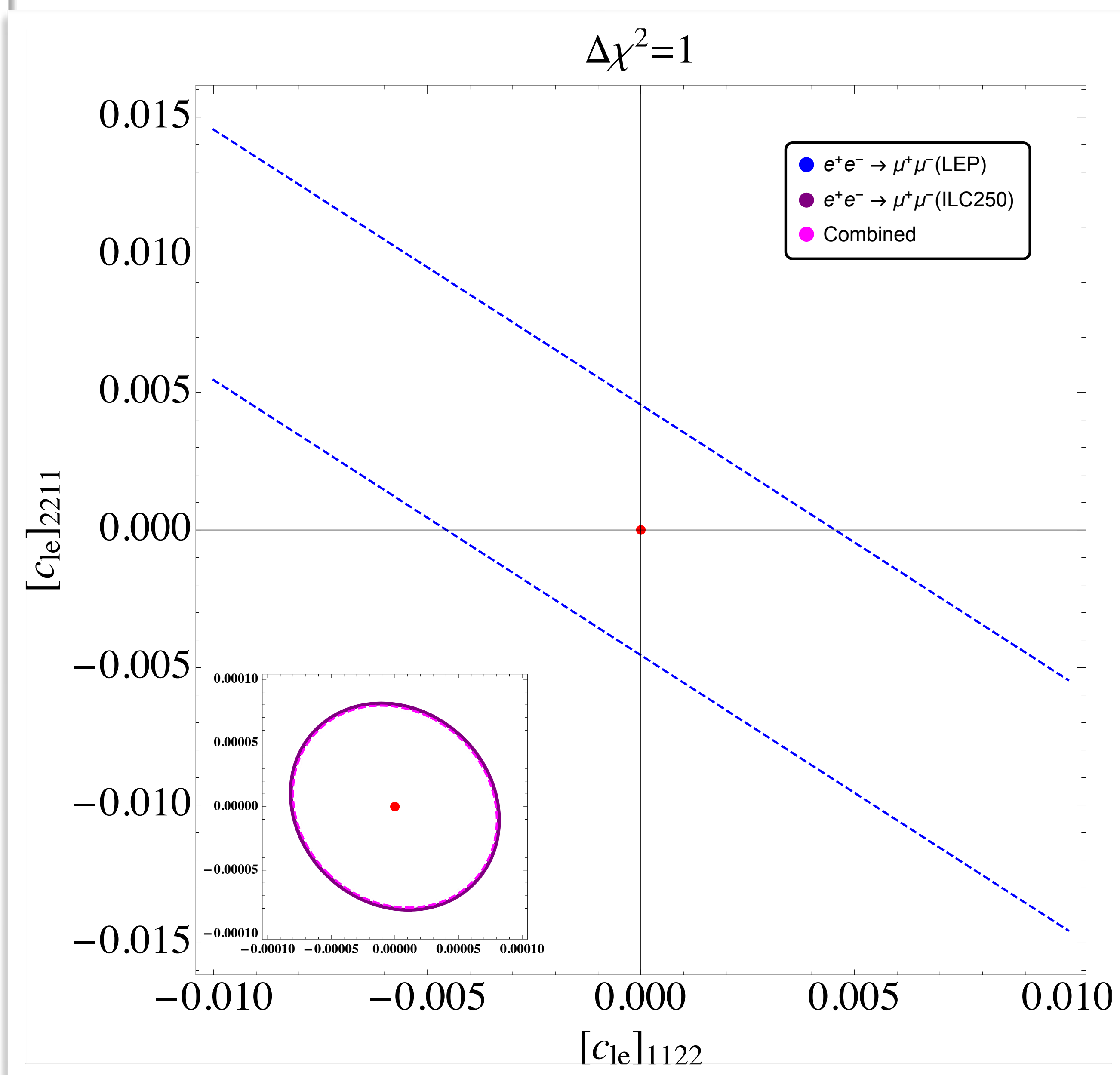


Flat direction lifted by low-energy experiments: **muon sector example**

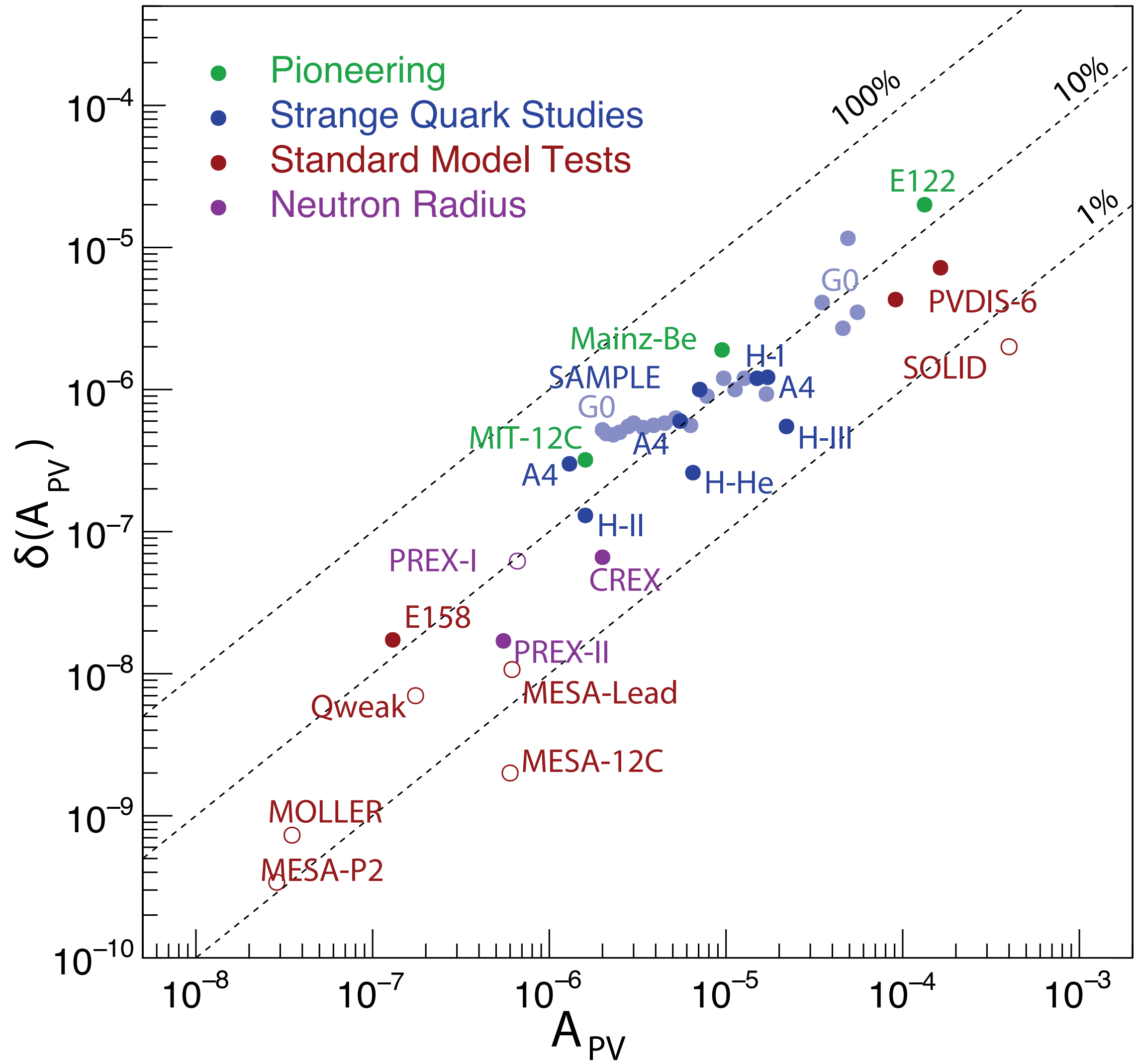




SMEFT global fit: *4f*

Flat direction lifted by low-energy experiments: **electron sector example**

Bhabha alone is not enough to close the fit, $A_{\rm PV}$ from PVES is the key



P2 collaboration, 1802.04759 (EPJA)

Dev, Ramsey-Musolf, Zhang, 1806.08499 (PRD)

YD, Freitas, Patel, Ramsey-Musolf, 1912.08220 (PRL)

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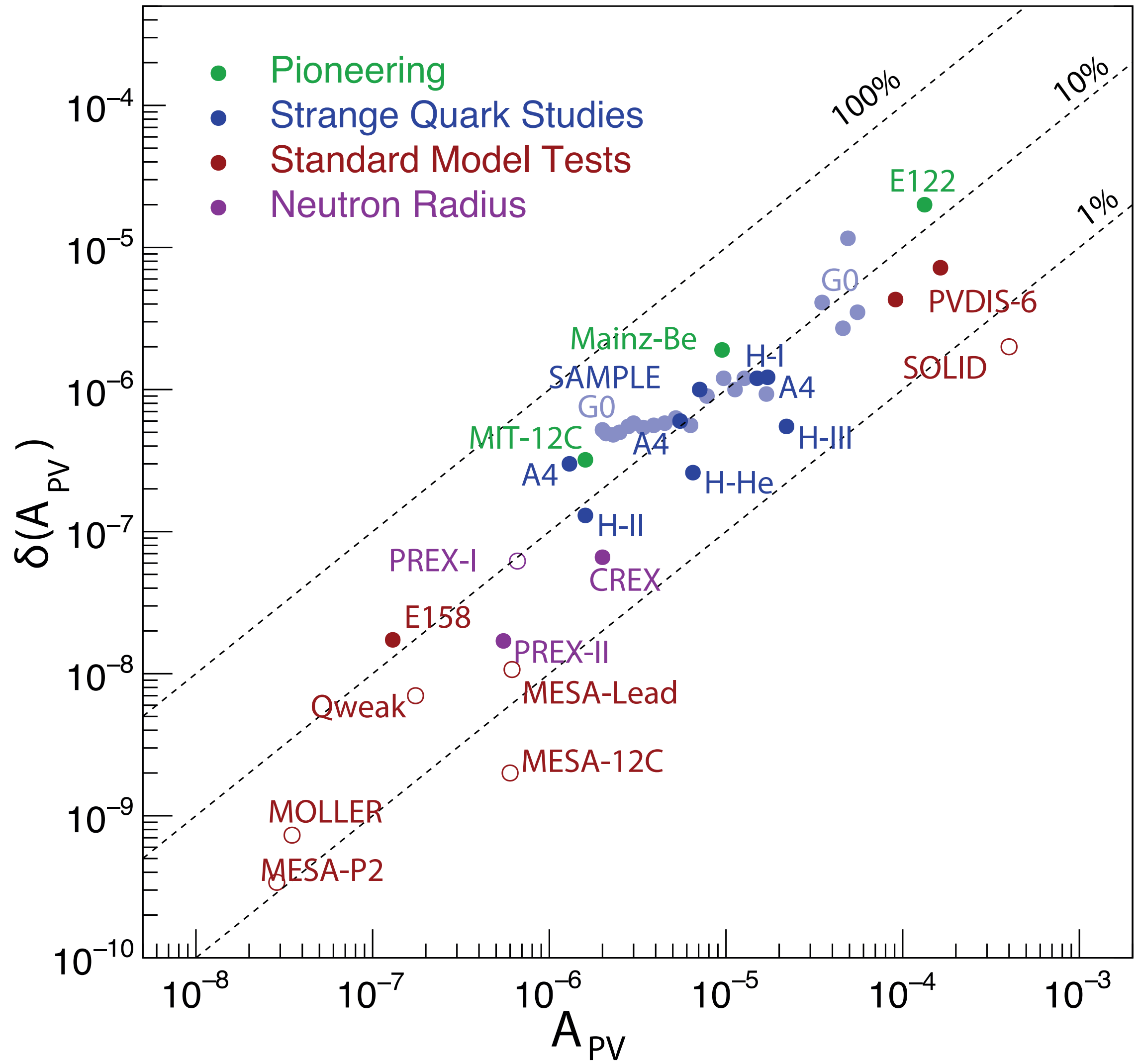

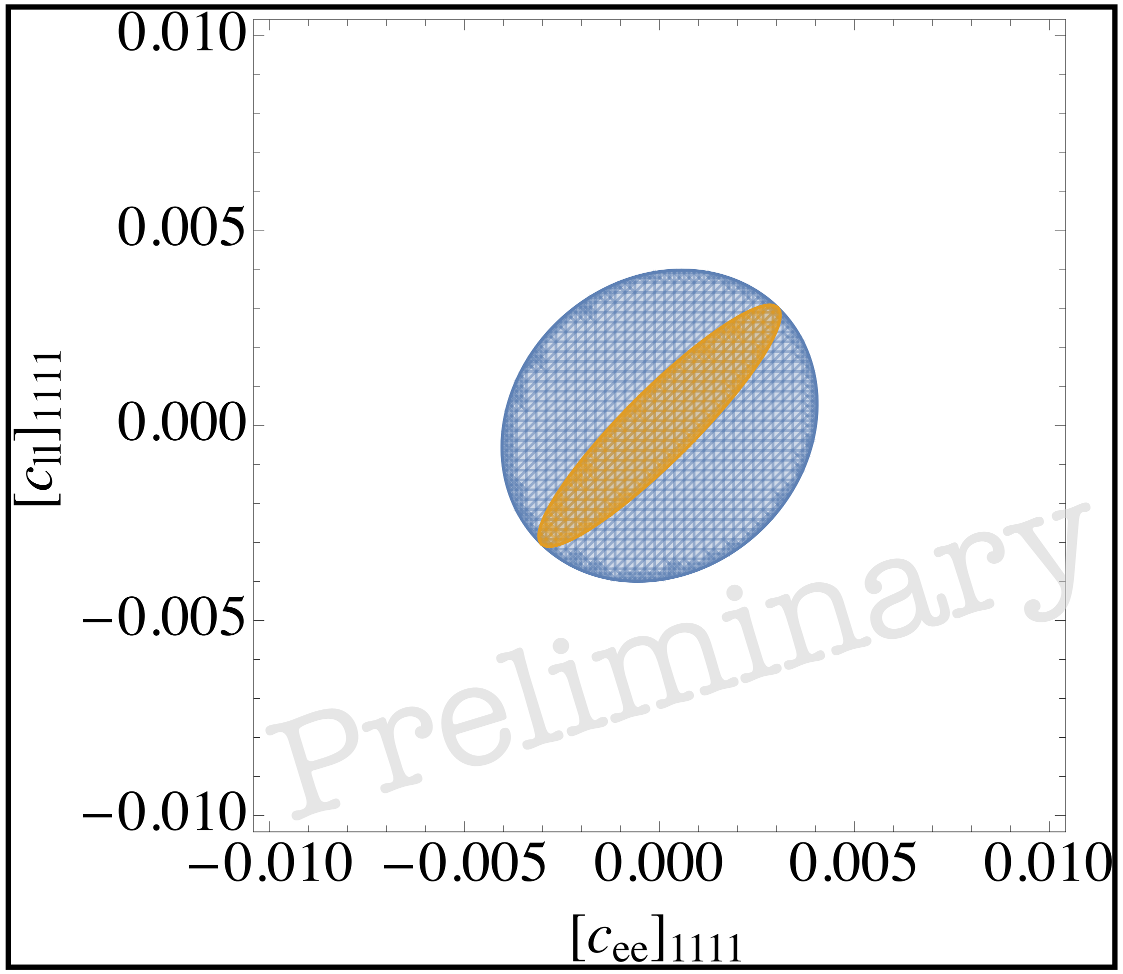

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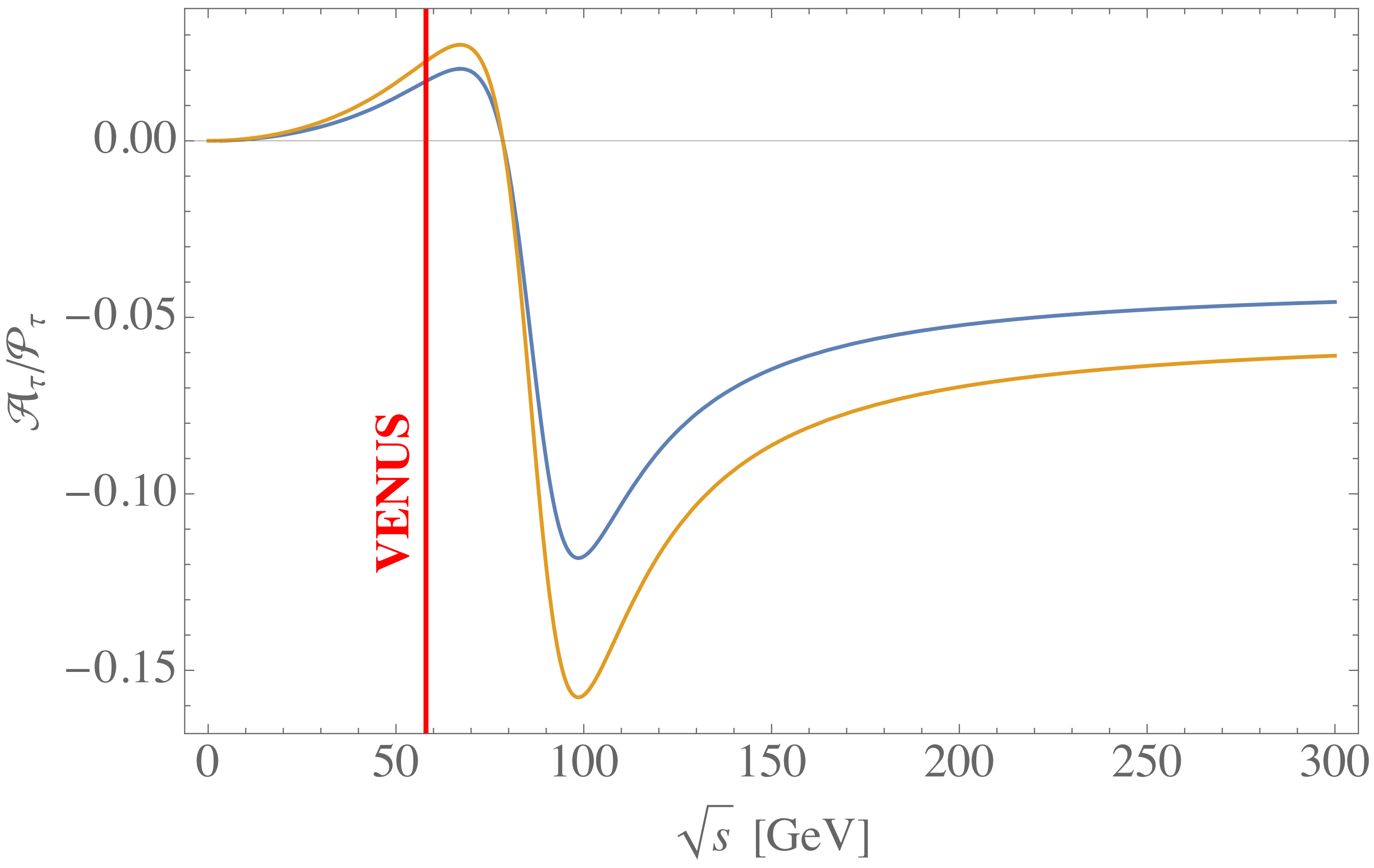
Flat direction lifted by low-energy experiments: **tau sector example**

τ polarization measurement at VENUS is limited by statistics ($\mathscr{L} = 271\,\mathrm{pb}^{-1}$). CEPC at 240GeV will have better sensitivity with much more statistics (let alone STCF).



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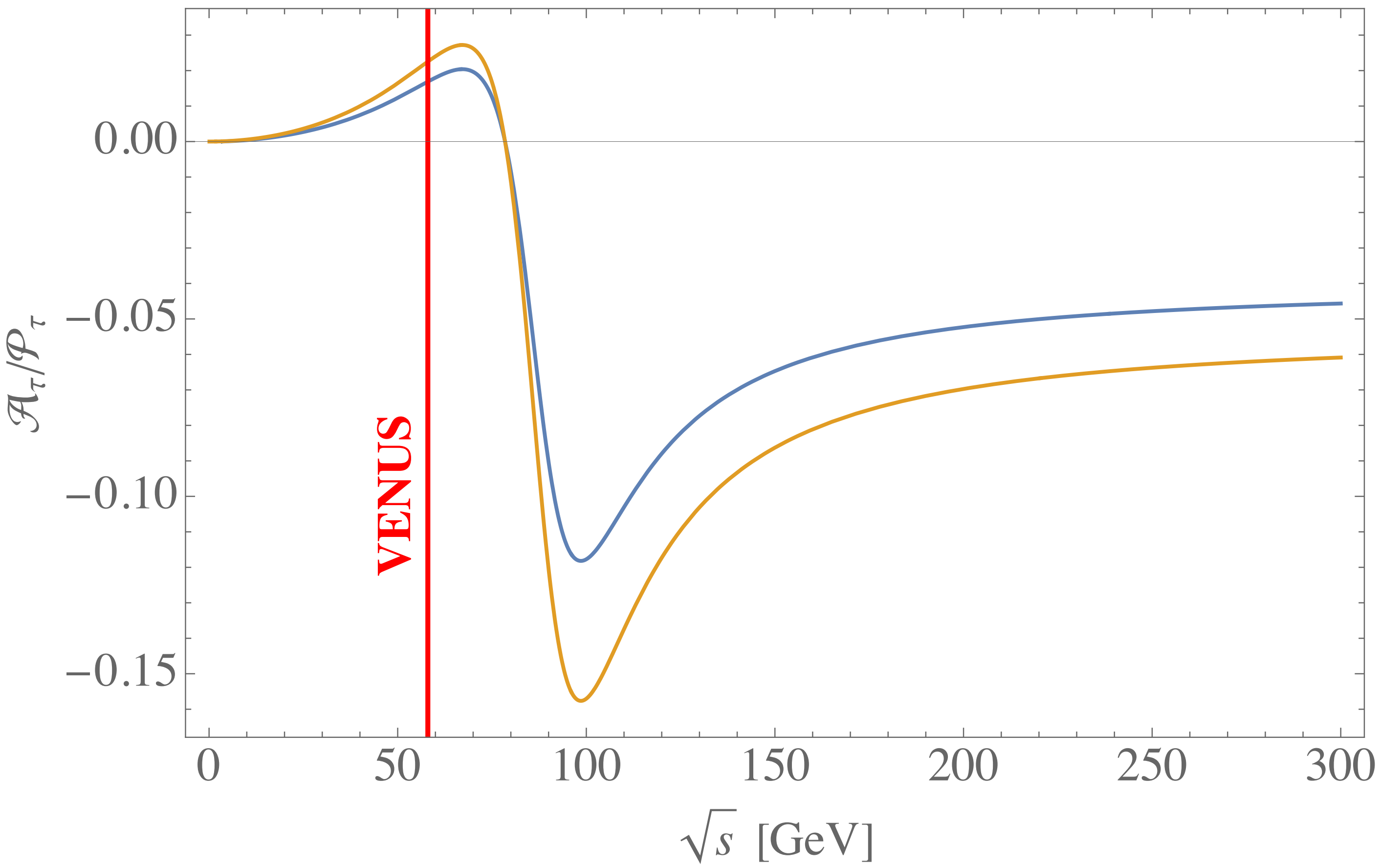
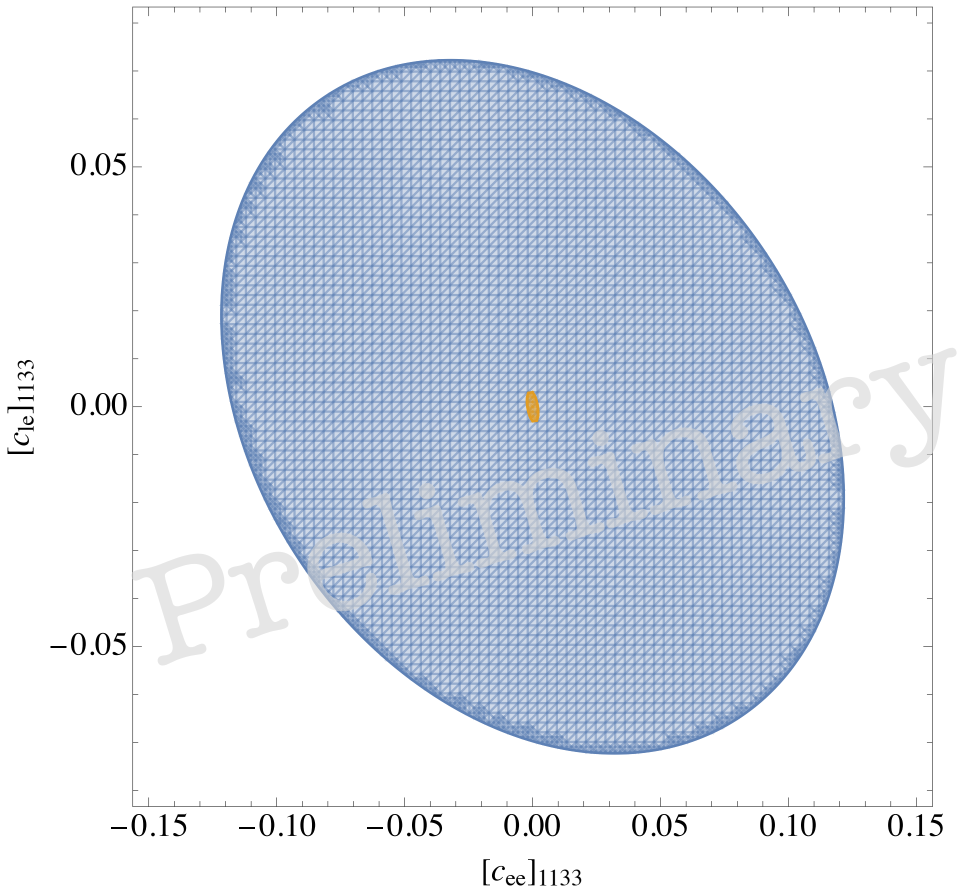
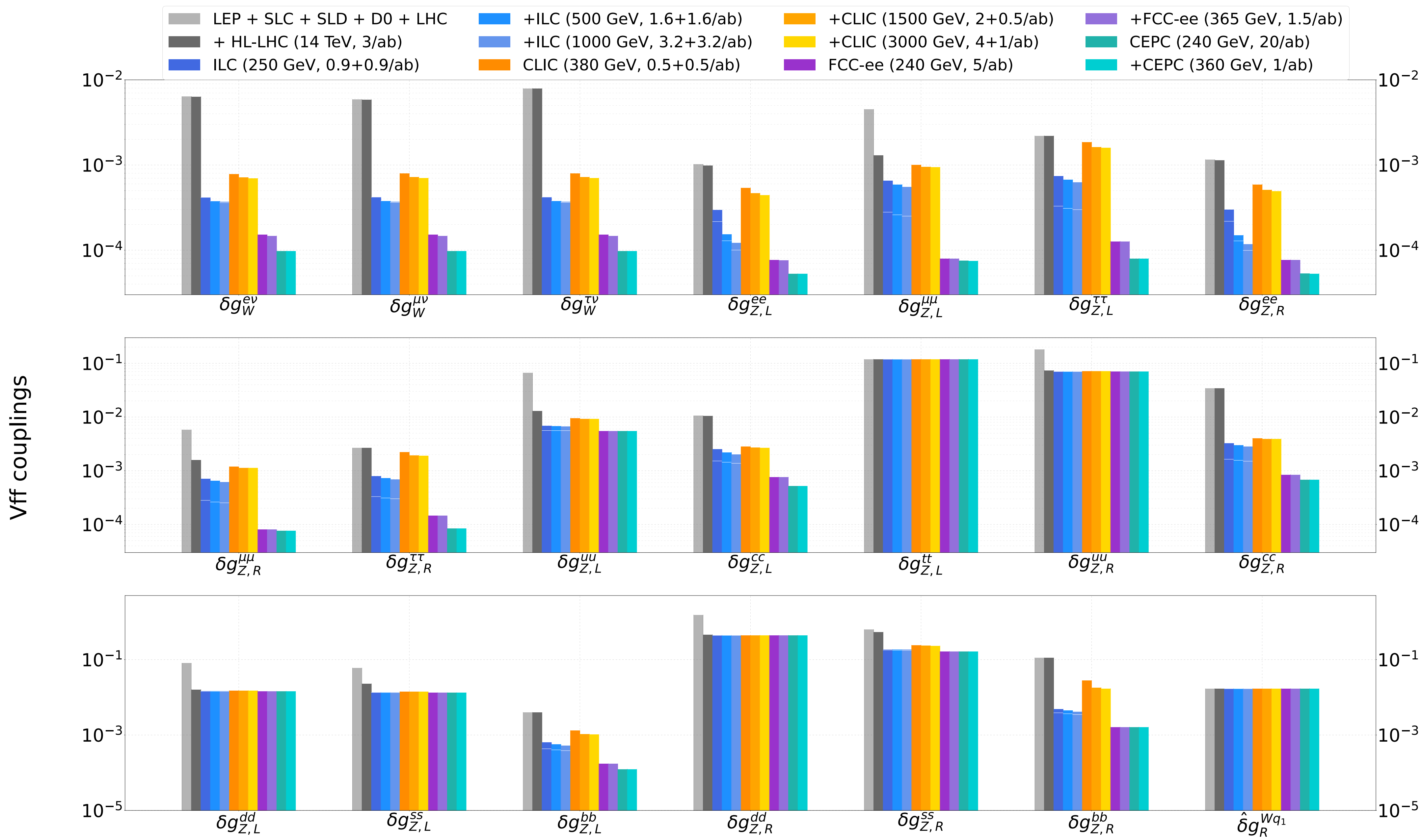




SMEFT global fit: *4f*

Global fit results: Vff couplings

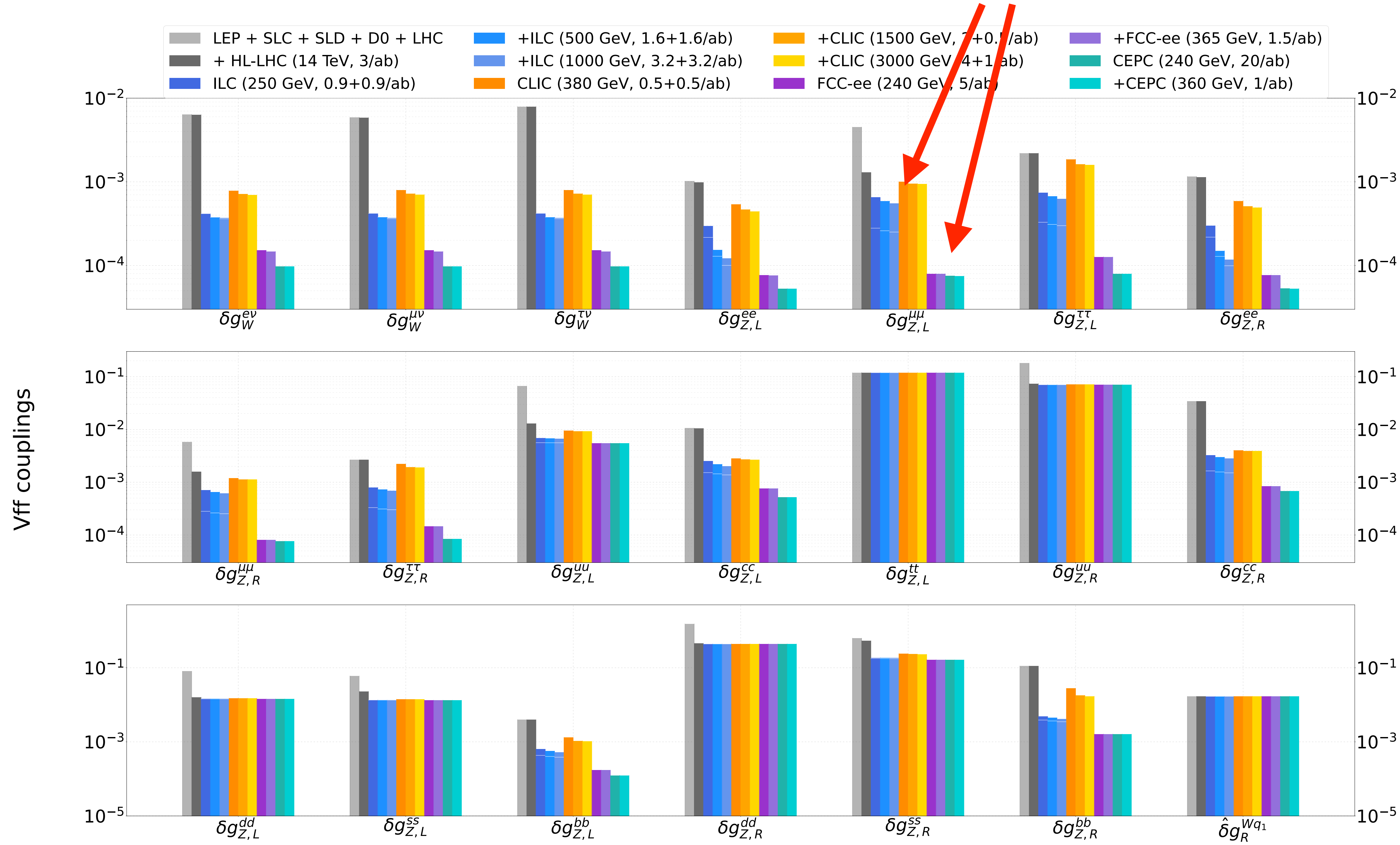


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

SMEFT global fit: *4f*

Global fit results: Vff couplings

Luminosity wins (through radiative return)

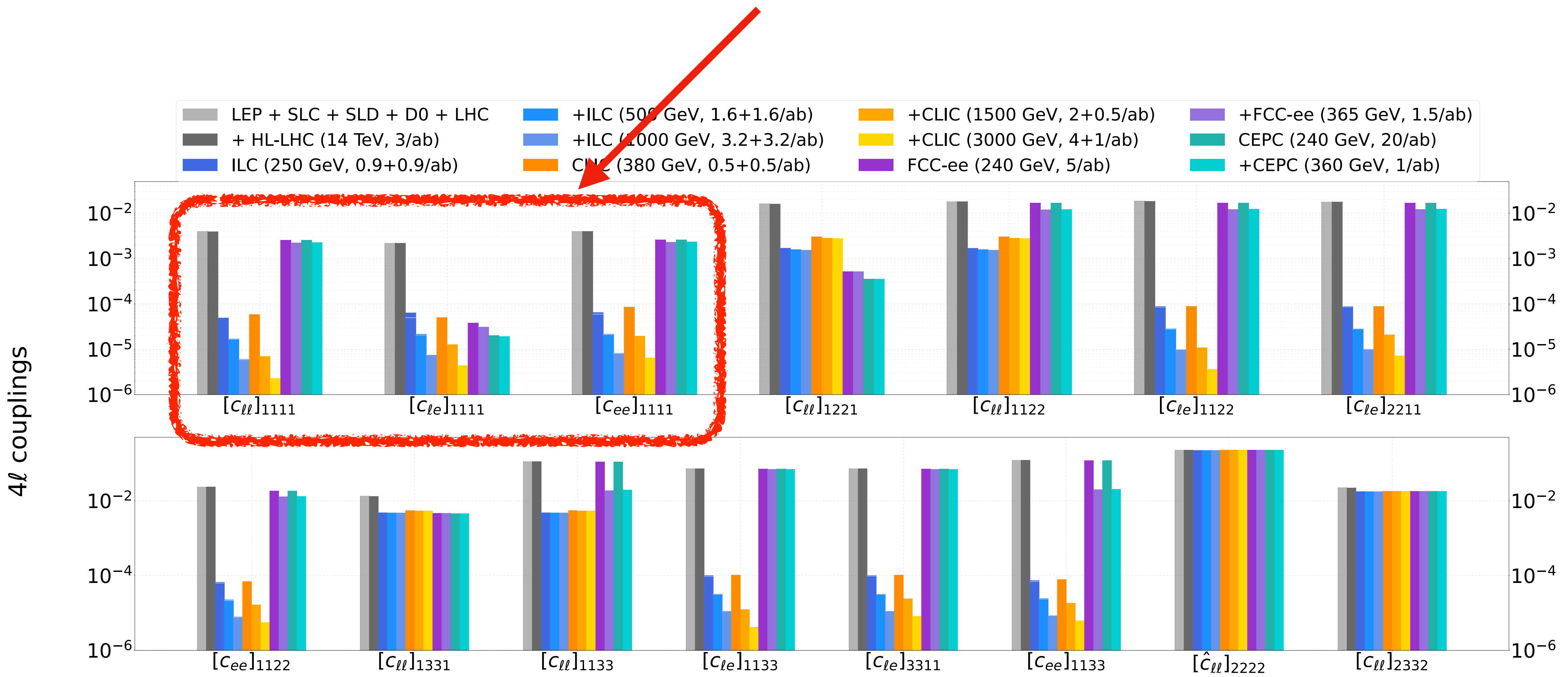


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

SMEFT global fit: *4f*

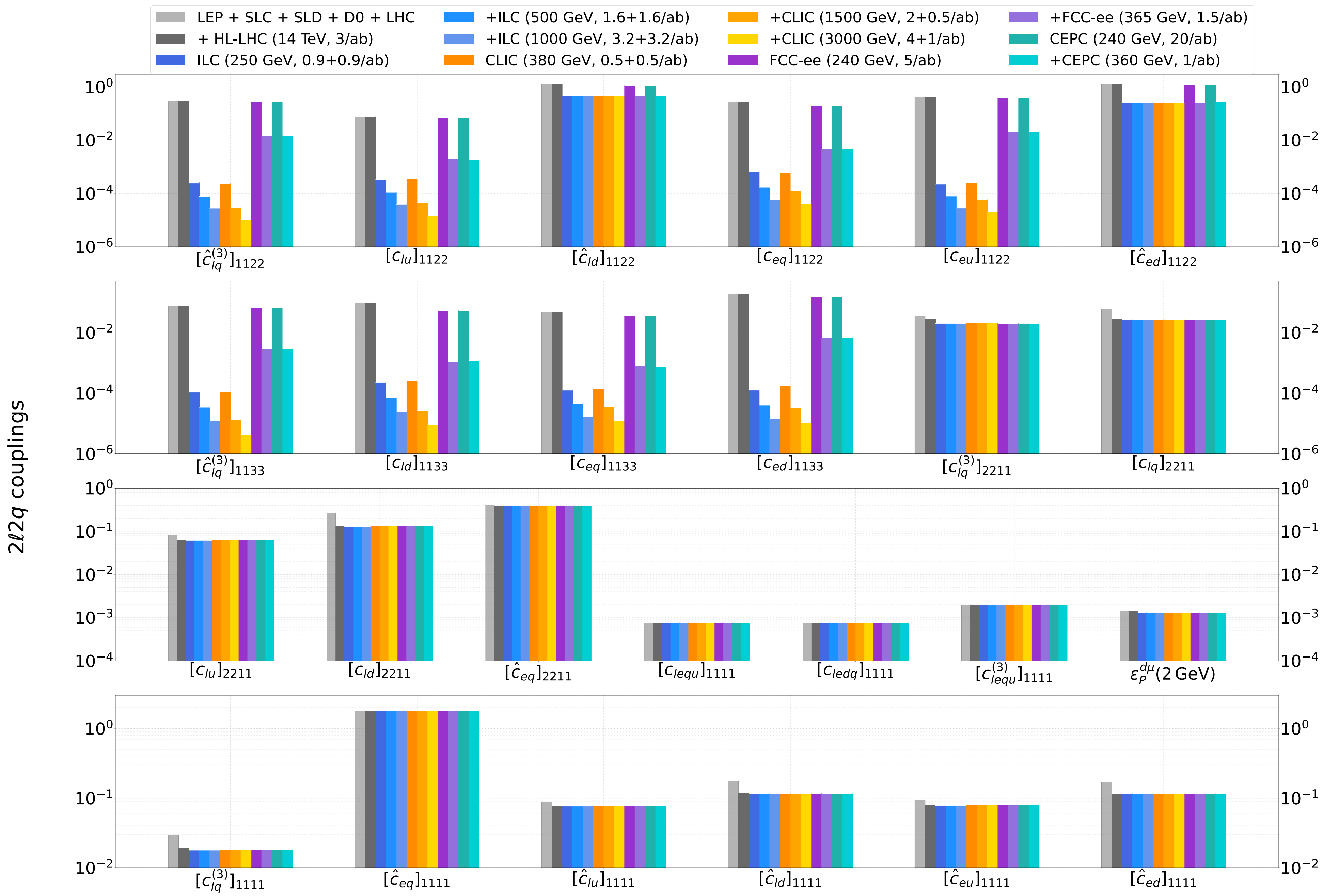
Global fit results: 4ℓ couplings

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



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

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



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

SMEFT global fit: ***CPV***

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

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

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

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

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

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

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

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

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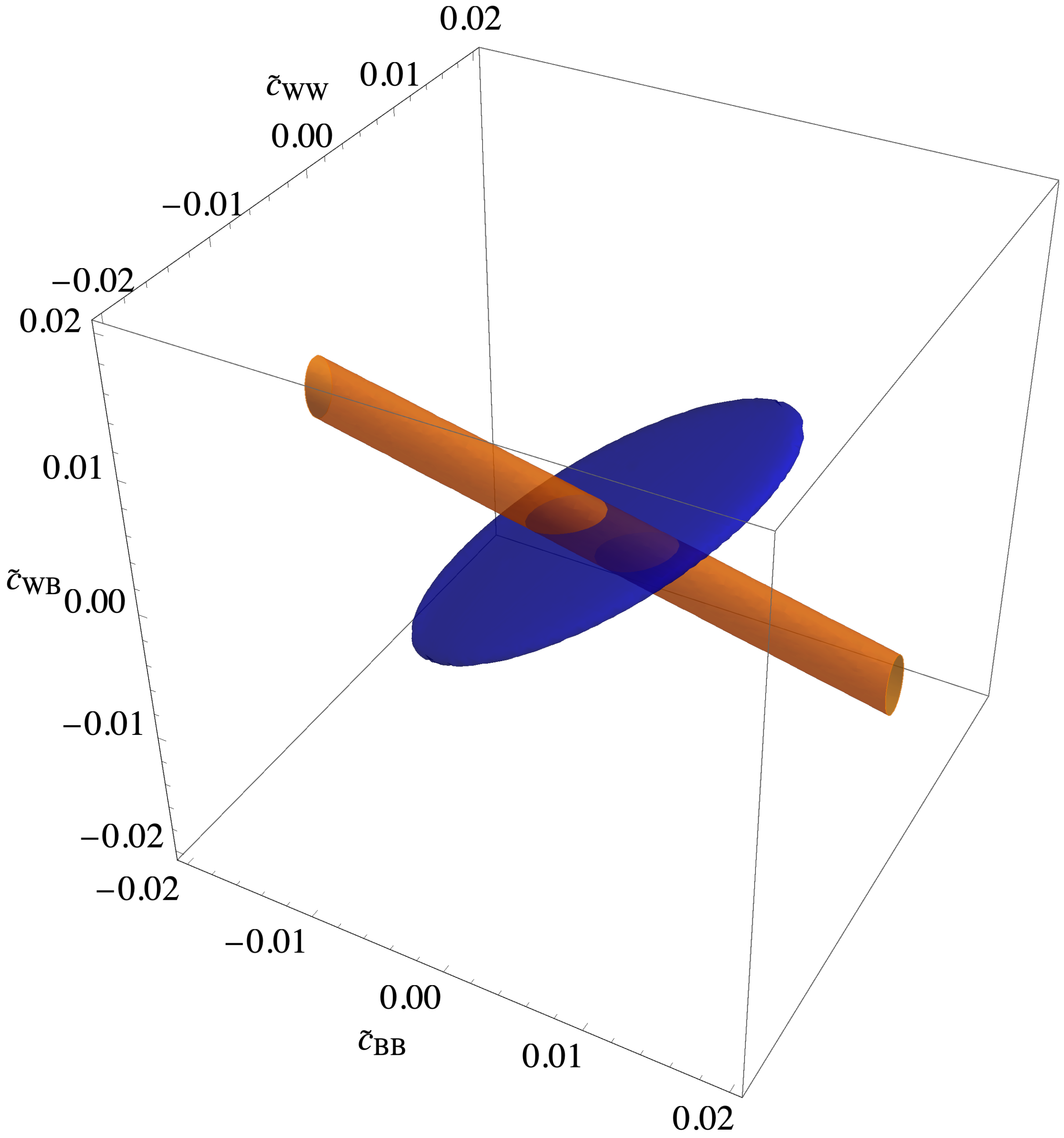
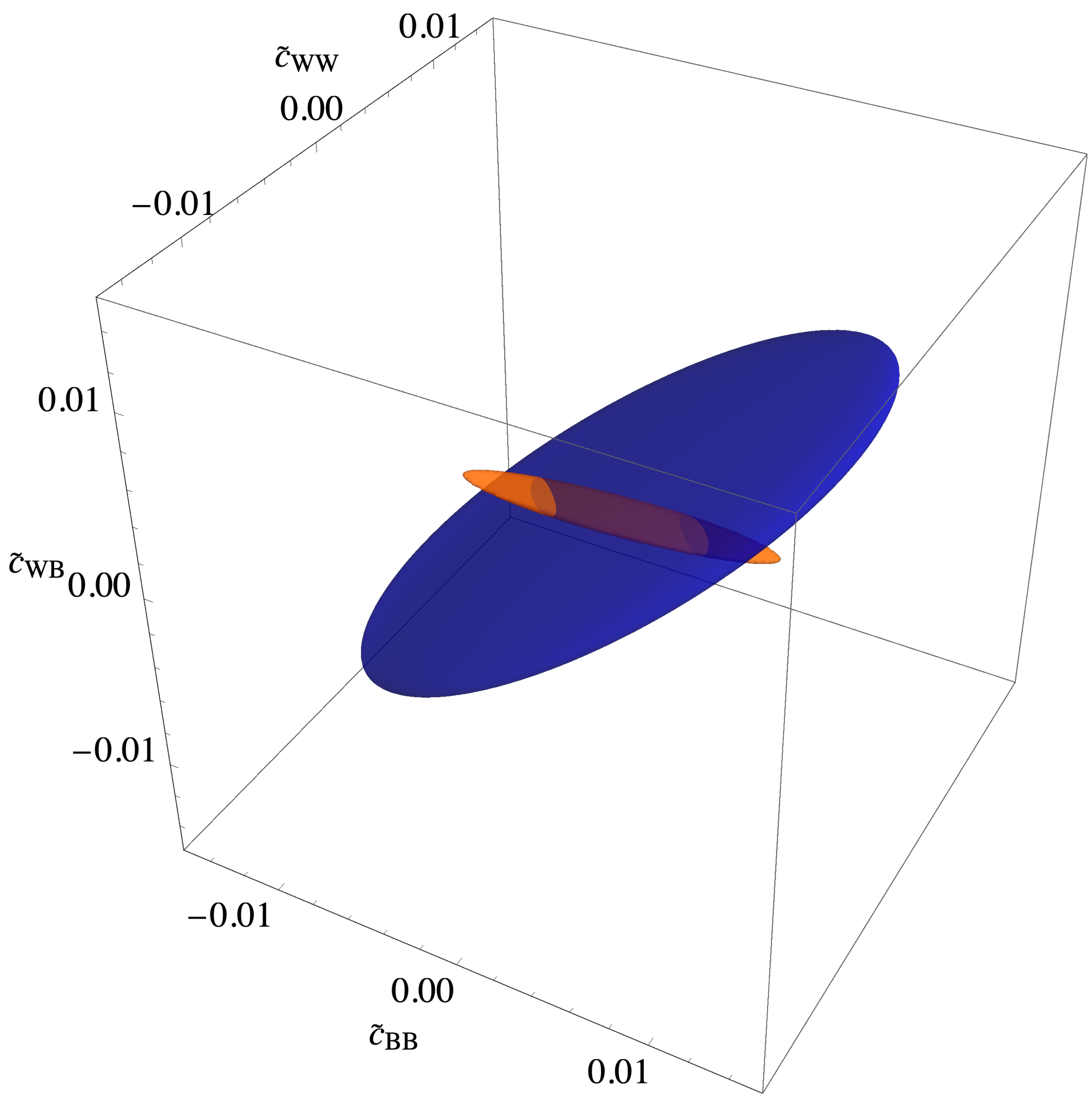
1. Determination of two anomalous triple gauge couplings (aTGC) from $e^+e^- \to W^+W^-$
2. Another two anomalous Higgs couplings (aHC) from $e^+e^- \to Zh$ (dominant production channel of ILC at low energies) using angular asymmetries.

SMEFT global fit: CPV

Complementarity of hadron and lepton colliders in probing CP violation

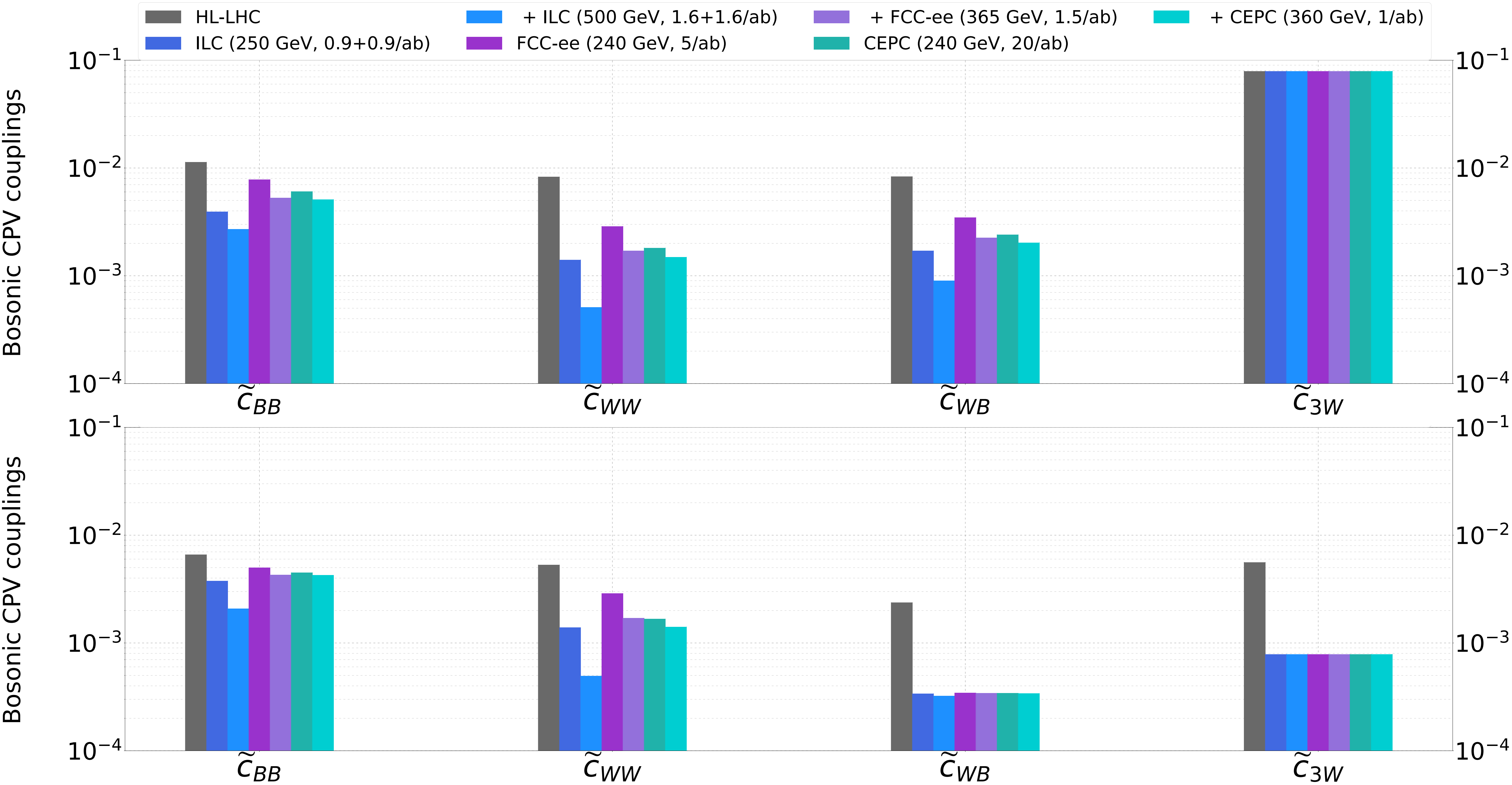




de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

SMEFT global fit: *CPV*

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

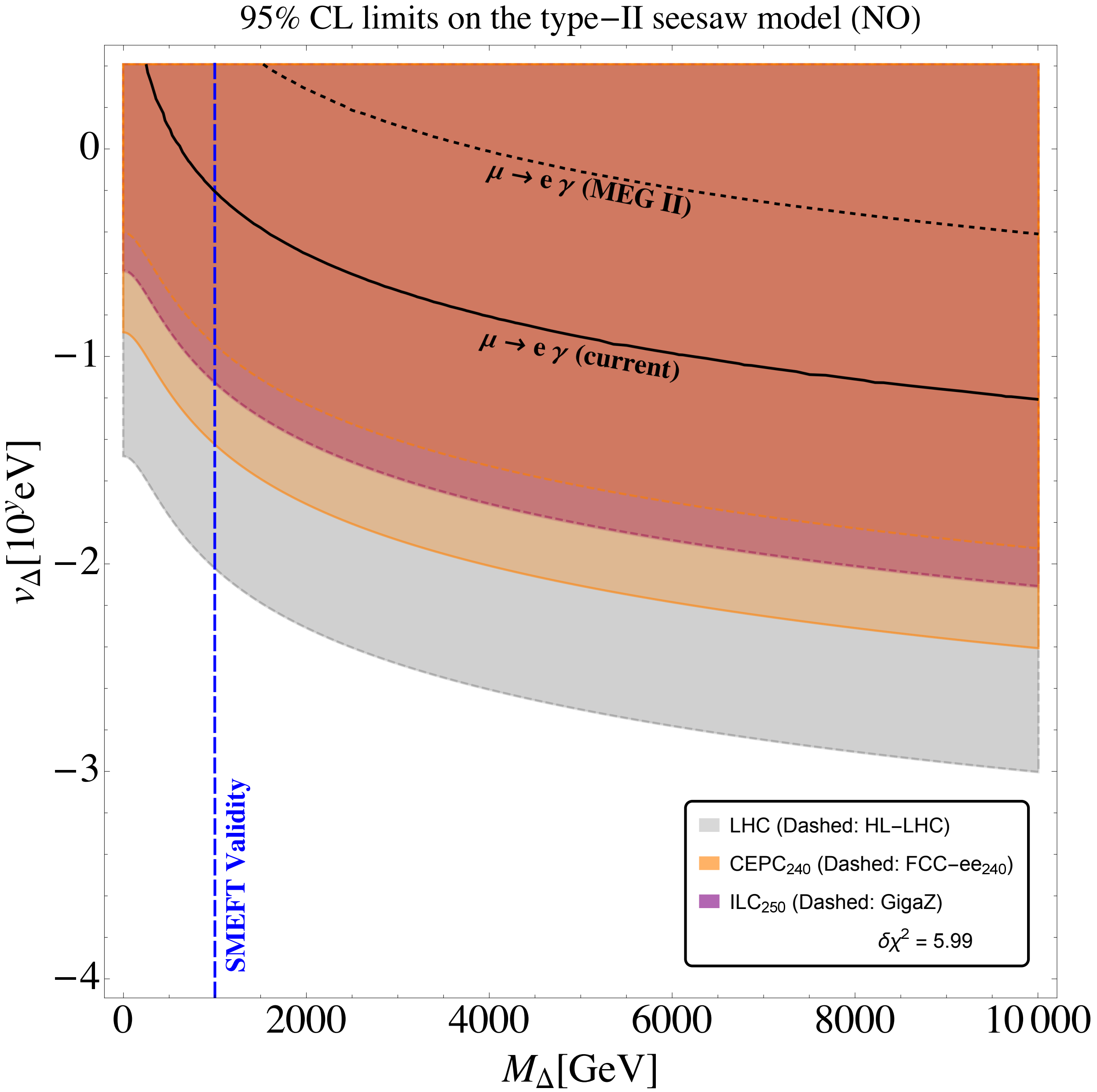


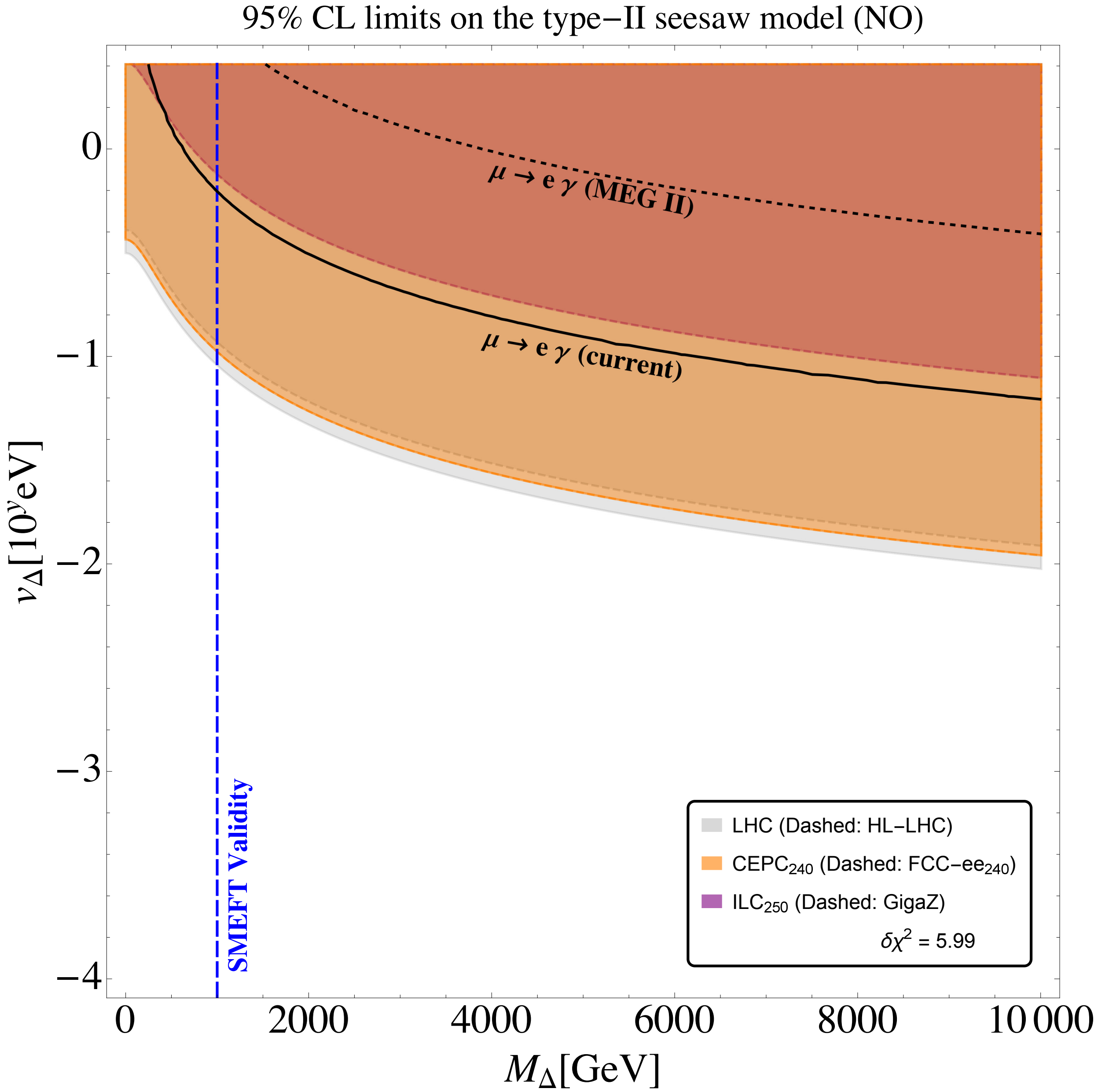
Benchmark: ***Type-II seesaw model***

Benchmark: *Type-II seesaw model*

$$V(\Phi, \Delta) \supset \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

$$\mathscr{L}_Y = (y_\nu)_{\alpha\beta}\overline{L^c_\alpha}i\tau_2\Delta L_\beta \mathrm{h.c.}$$





$m_{\mathrm{light}} = 0$ vs $m_{\mathrm{light}} = 0.1\,\mathrm{eV}$

YD, 2303.16400

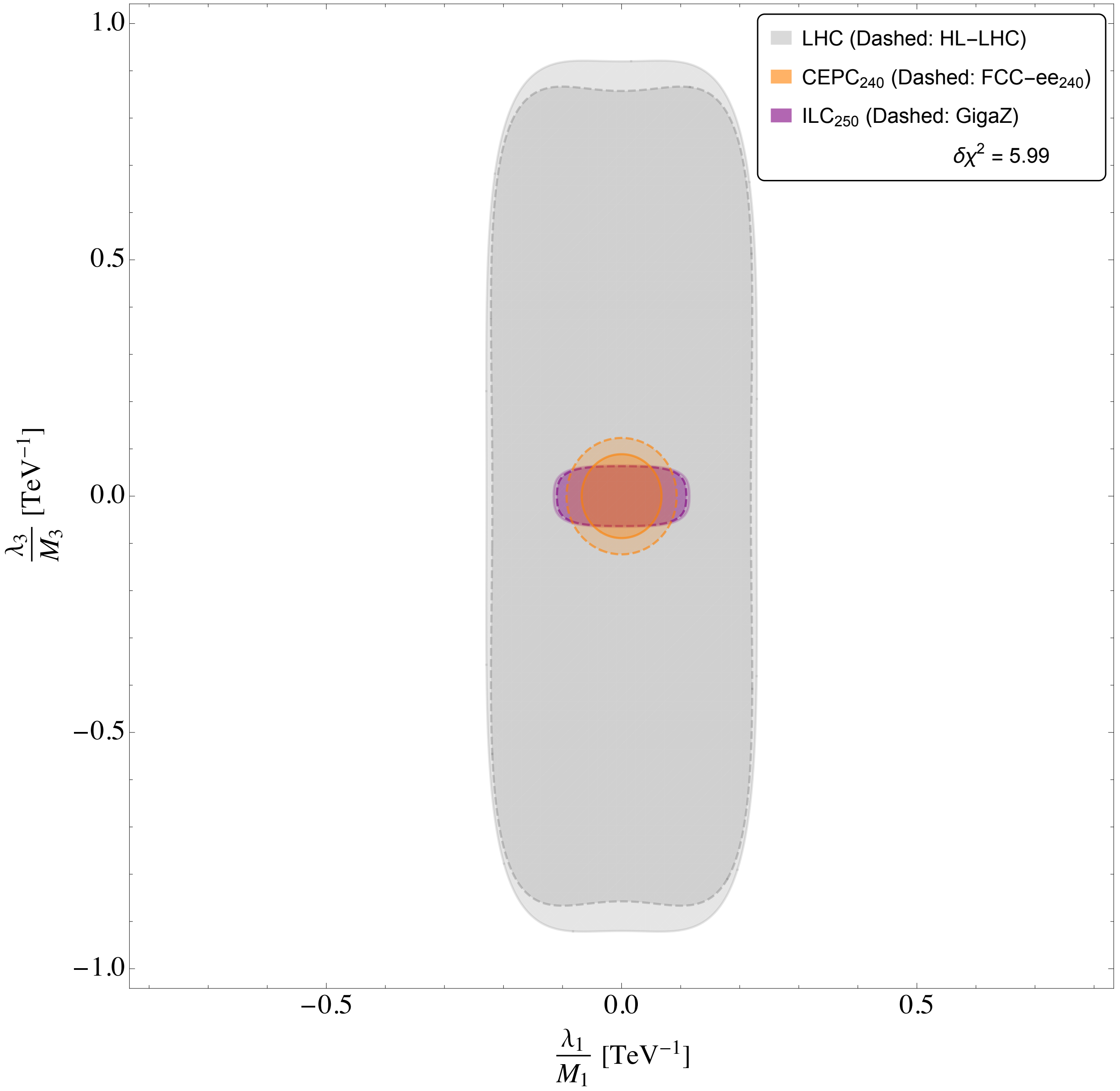
YD, Li, Yu, 2201.04646 (JHEP)

Li, Zhang, Zhou, 2201.05082 (JHEP)

Benchmark: *Leptoquark model*

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

95% CL limits on the $(\bar{3},1)_{\frac{1}{3}}$ and $(\bar{3},3)_{\frac{1}{3}}$ leptoquark model

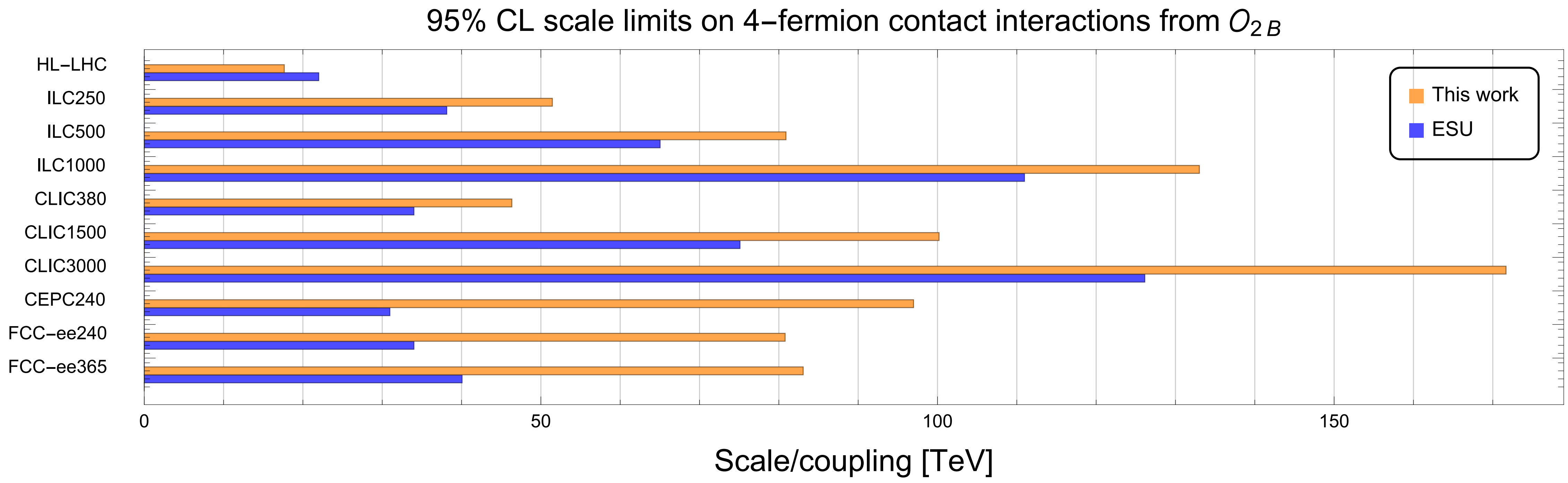


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Benchmark: *Y-Universal Z' model*

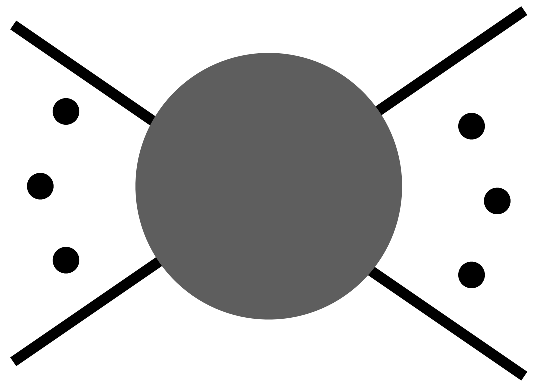
Extend the SM by $\mathrm{U}(1)_z$ but without introducing kinetic mixing and off-diagonal gauge couplings

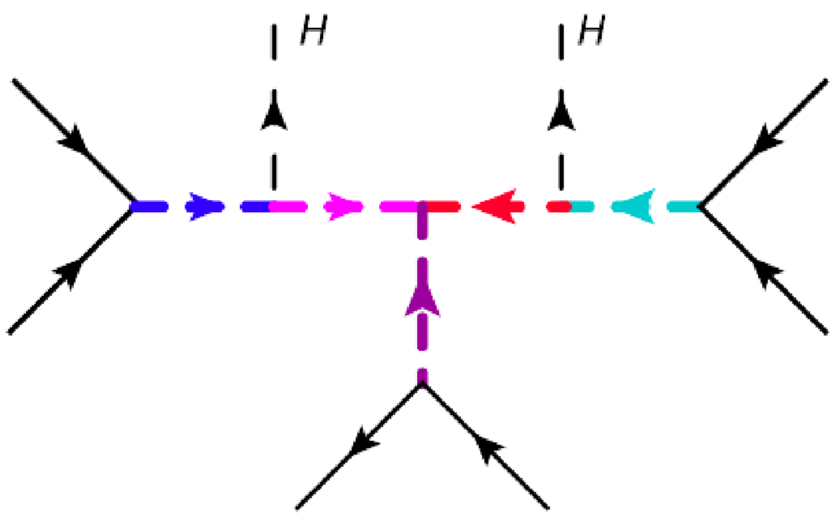
$$\frac{c_{2B}}{\Lambda^2} = \frac{g_{Z'}^2}{g_1^4 M^2}$$

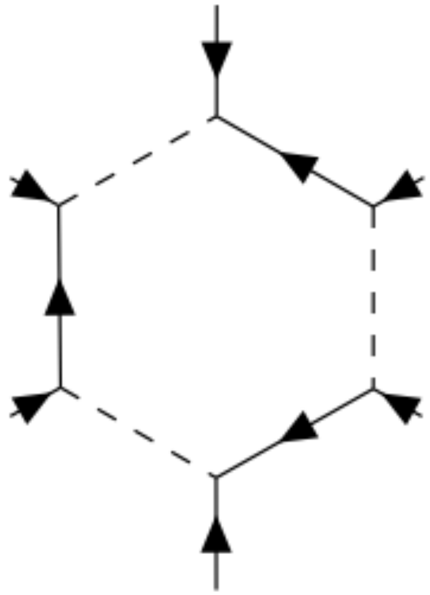


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

Benchmark: *Unfolding*

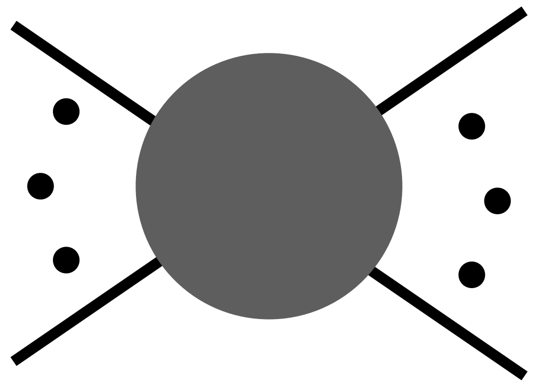


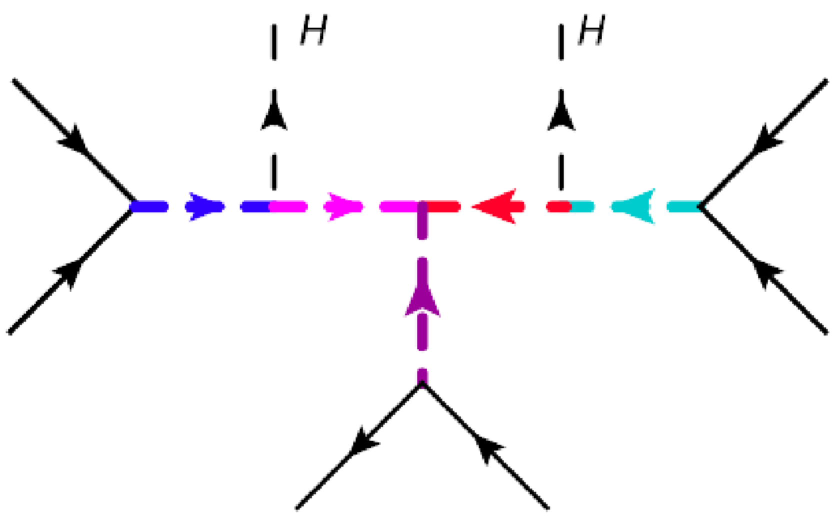


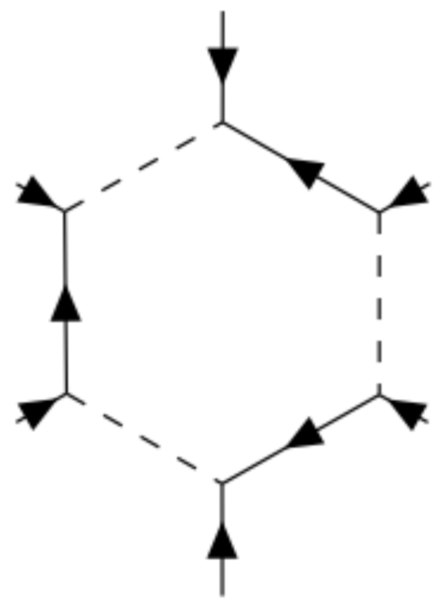


Find the UV models for any operator and any topology (`UVBuilder`).

Benchmark: *Unfolding*







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Internal fields				
I1	I2	I3	I4	I5
HyperCharges				
$-\frac{2}{3}$	$-\frac{5}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$
Gauge information {SU3, SU2}				
{3, 1}	{3, 2}	{3, 2}	{3, 1}	{3, 1}
{3, 1}	{3, 2}	{3, 2}	{3, 1}	{6, 1}
{3, 1}	{3, 2}	{3, 2}	{6, 1}	{3, 1}
{3, 1}	{3, 2}	{3, 2}	{6, 1}	{6, 1}
{3, 1}	{3, 2}	{6, 2}	{3, 1}	{3, 1}
{3, 1}	{3, 2}	{6, 2}	{6, 1}	{3, 1}
{3, 1}	{6, 2}	{3, 2}	{3, 1}	{3, 1}
{3, 1}	{6, 2}	{3, 2}	{6, 1}	{3, 1}
{3, 1}	{6, 2}	{6, 2}	{3, 1}	{6, 1}
{3, 1}	{6, 2}	{6, 2}	{6, 1}	{6, 1}
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{6, 1}	{6, 2}	{3, 2}	{6, 1}	{3, 1}
{6, 1}	{6, 2}	{6, 2}	{3, 1}	{6, 1}
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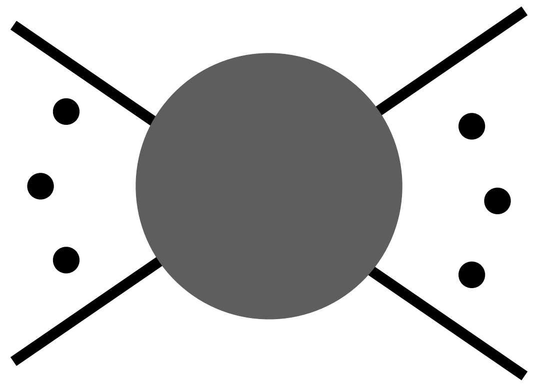
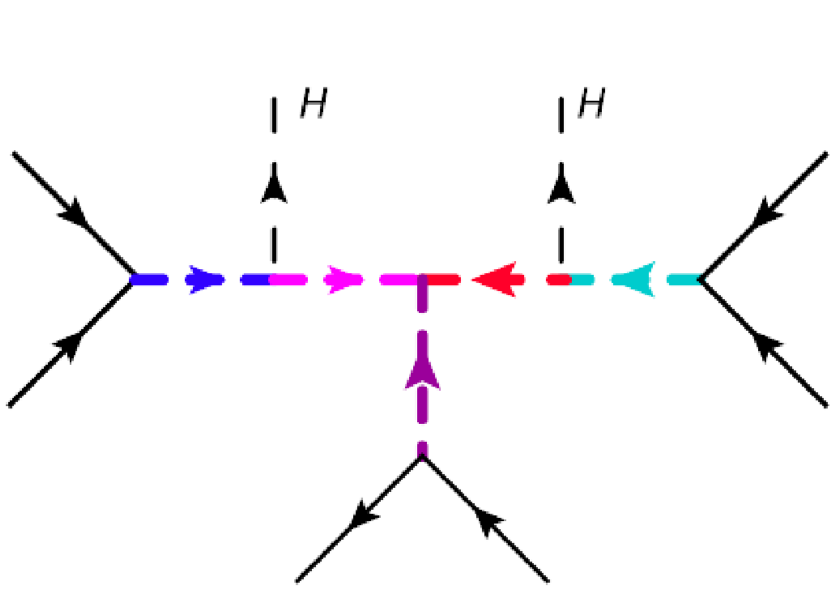
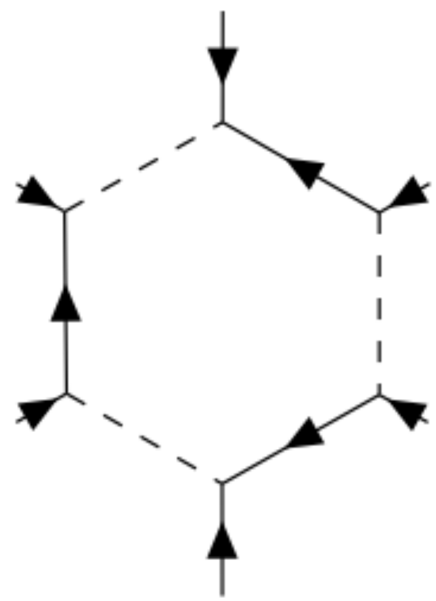
YD, Ma, Liao, 2308.XXXXX

Benchmark: Unfolding







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{6, 1}	{6, 2}	{6, 2}	{6, 1}	{6, 1}

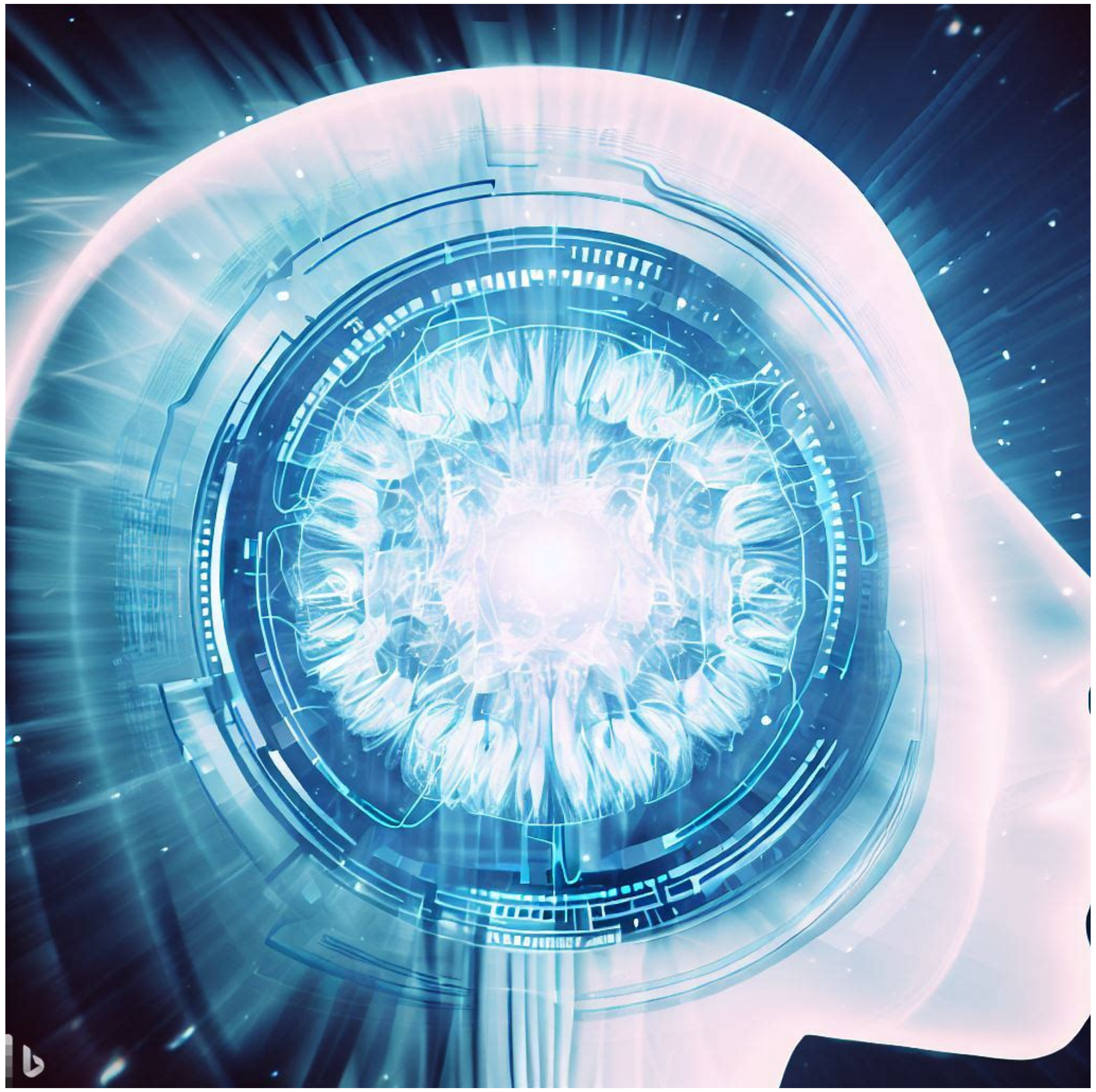
Find the UV models for any operator and any topology (`UVBuilder`).

Q: Which benchmark model for CEPC?

YD, Ma, Liao, 2308.XXXXX

Summary

- I discussed the global fit of 4f and CPV SMEFT operators at future colliders:
  - Beam polarization is the key to surpass circular colliders in studying 4f ints.
  - Luminosity largely wins otherwise for circular colliders;
  - aTGCs will be the key to improve the sensitivity of the bosonic CPV operators.
  - Several benchmark models are discussed (type-II seesaw, leptoquark models, etc)



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