Interplay of future lepton colliders and precision cosmology in SMEFT global fit

Yong Du（杜勇）

CEPC2023, Nanjing University, Oct 27, 2023

Based on

2206.08326, Jorge de Blas, **YD**, Christophe Grojean, Jiayin Gu, Victor Miralles, Michael Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou for SNOWMASS 2021

2310.10034, **YD**

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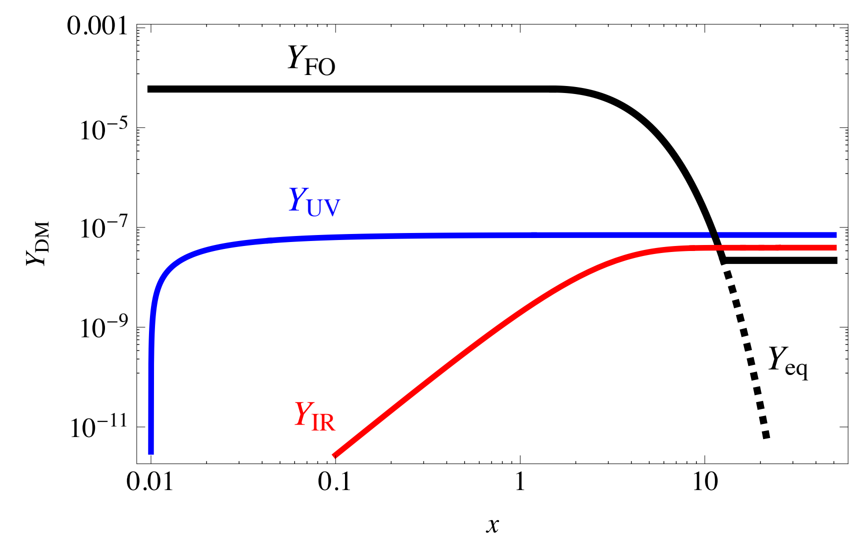
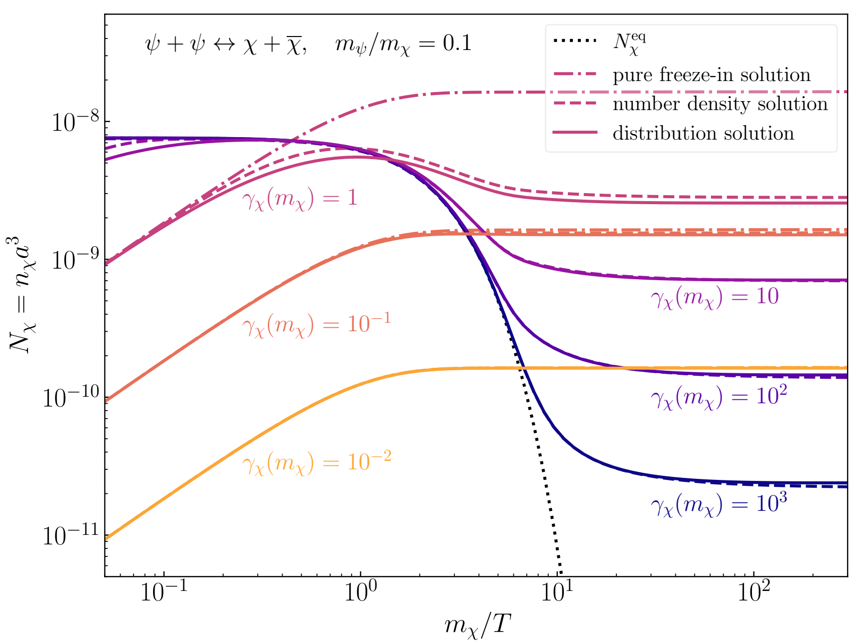
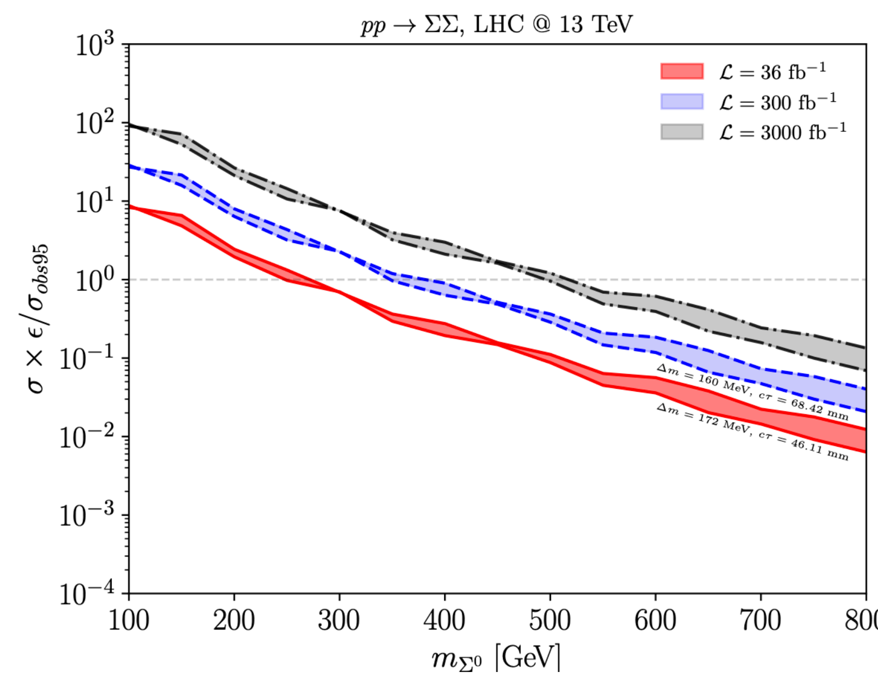
Introduction

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

Elahi et al, 1410.6157







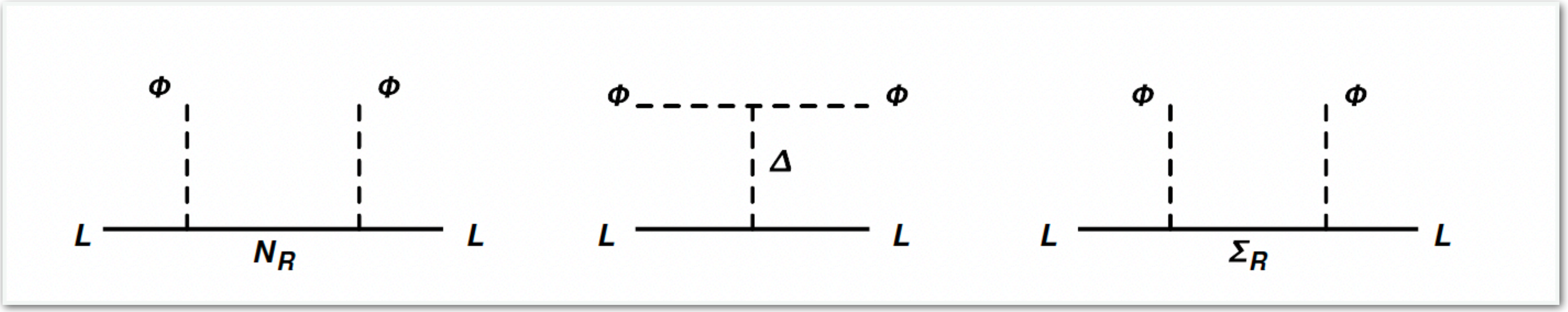
YD, Huang, Li, Yu, 2005.01717 (JHEP)

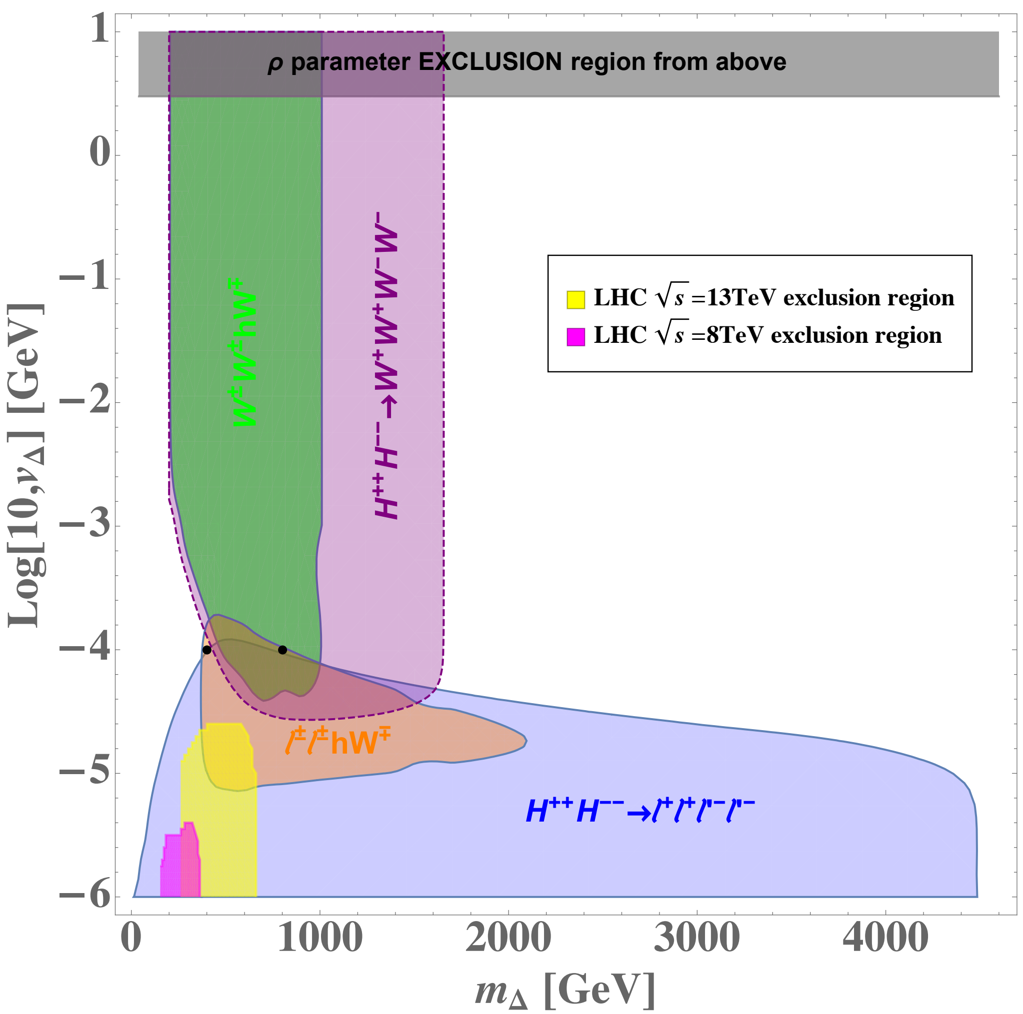
YD, Huang, Li, Li, Yu, 2111.01267 (JCAP)

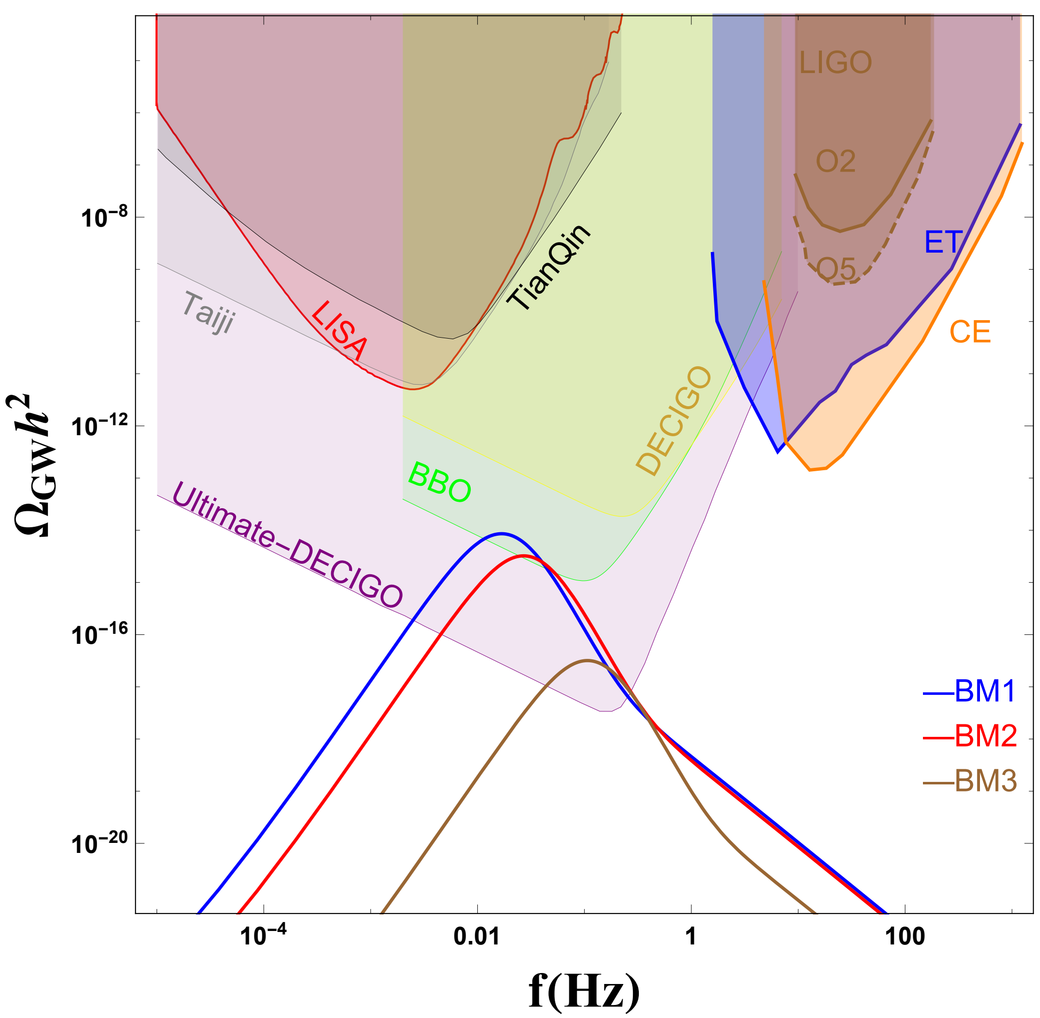
Chiang, Cottin, **YD**, Fuyuto, Ramsey-Musolf, 2003.07867(JHEP)

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: …

Introduction

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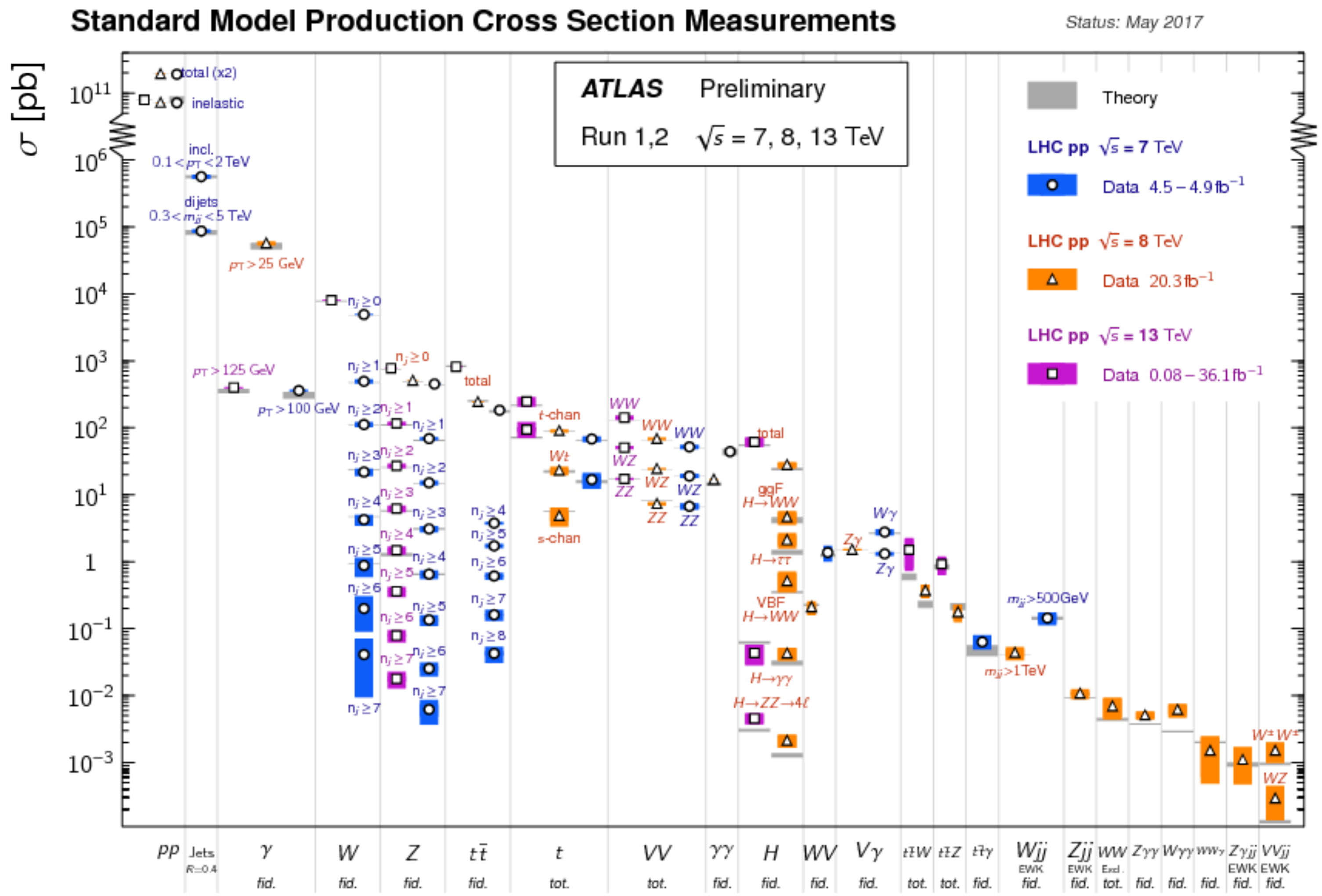
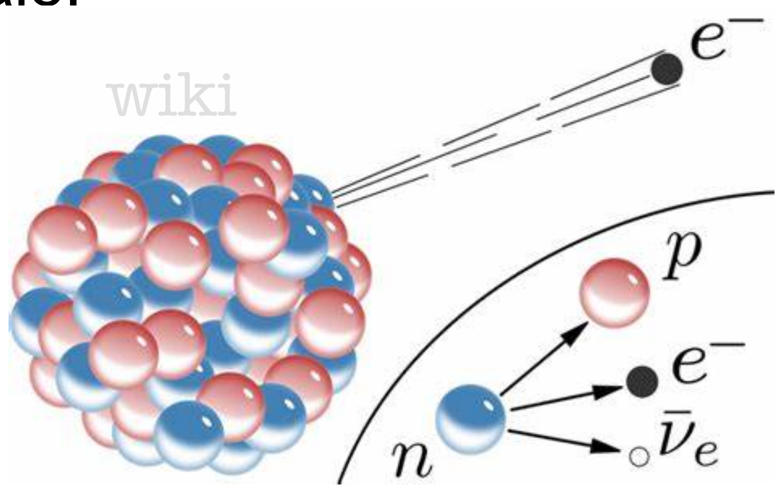
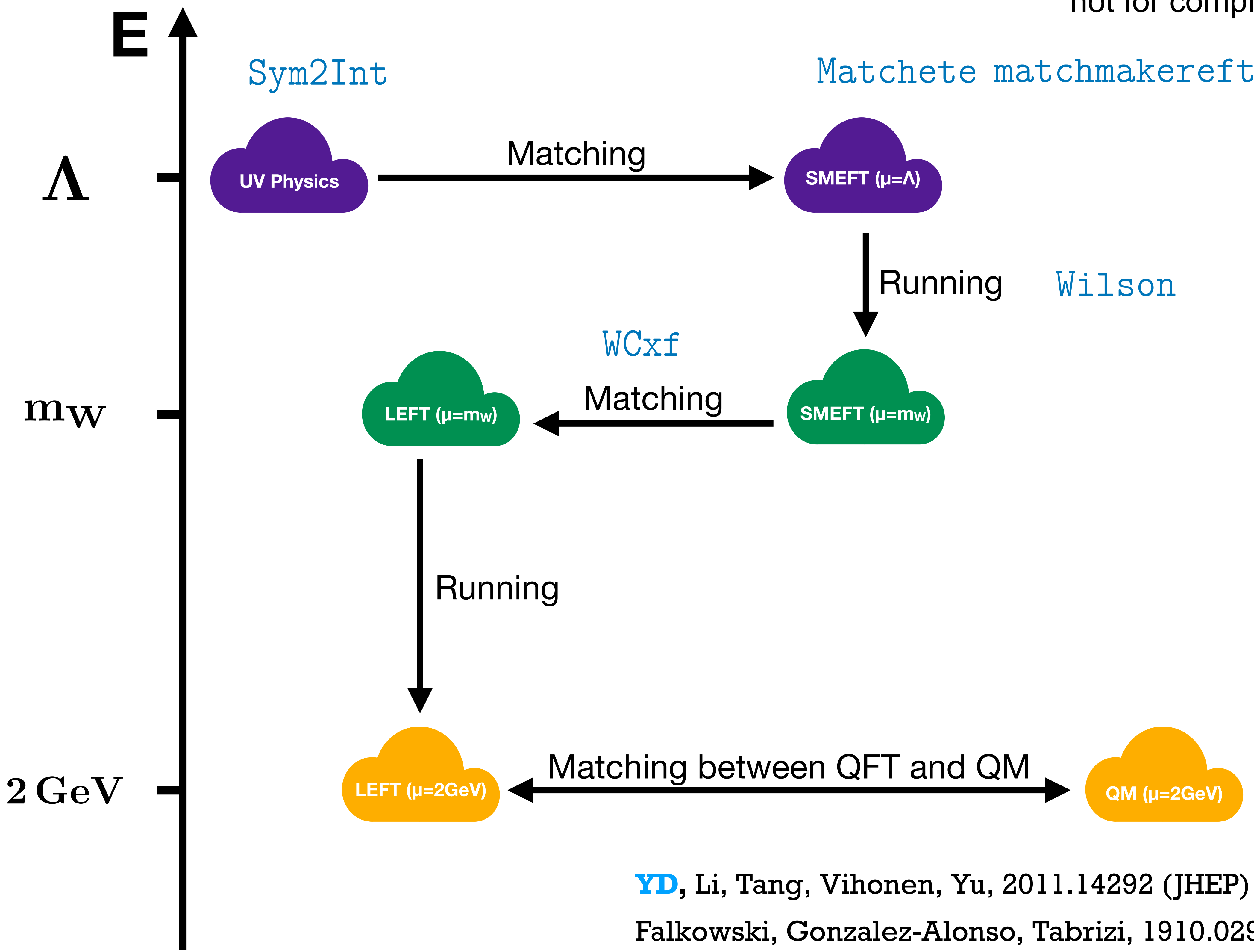


The experimental data are suggesting that the SM is an effective low-energy theory of some UV model above the weak scale.



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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	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.

SMEFT global fit: ***Basis***

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

Higgs physics in the context of SMEFT global fit? Jiayin Gu's talk on Monday

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

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

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

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

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

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

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

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

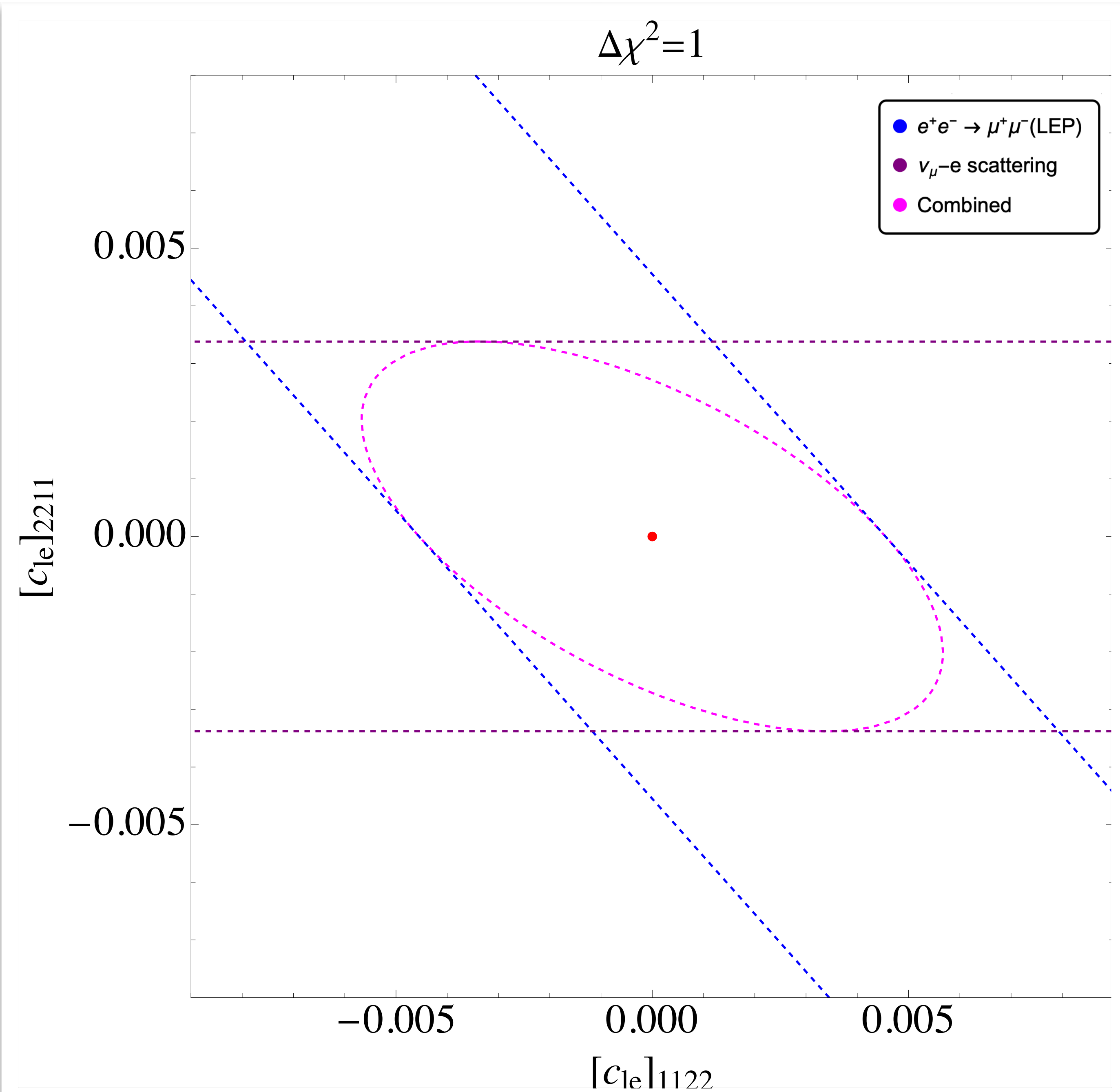
SMEFT global fit: *4f*

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

Process	Observable	Experimental value	Ref.	SM prediction
$\overset{(-)}{\nu}_\mu - e^-$ scattering	$g_{LV}^{\nu_\mu e}$	-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]
	$R_{\overline{\nu}_\mu}$	0.390 ± 0.014		0.370 [50]
	R_{ν_μ}	0.3072 ± 0.0033	CDHS ($r = 0.393$) [51]	0.3091 [51]
	$R_{\overline{\nu}_\mu}$	0.382 ± 0.016		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	$(-91.1 \pm 4.3) \times 10^{-6}$	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
$d_I \to u_J \ell \overline{\nu}_\ell(\gamma)$	$\epsilon_{L,R,S,P,T}^{de_J}$	See text	[65]	0
$e^+e^- \to f\bar{f}$	δA_{LR}^e	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: ***4f***

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



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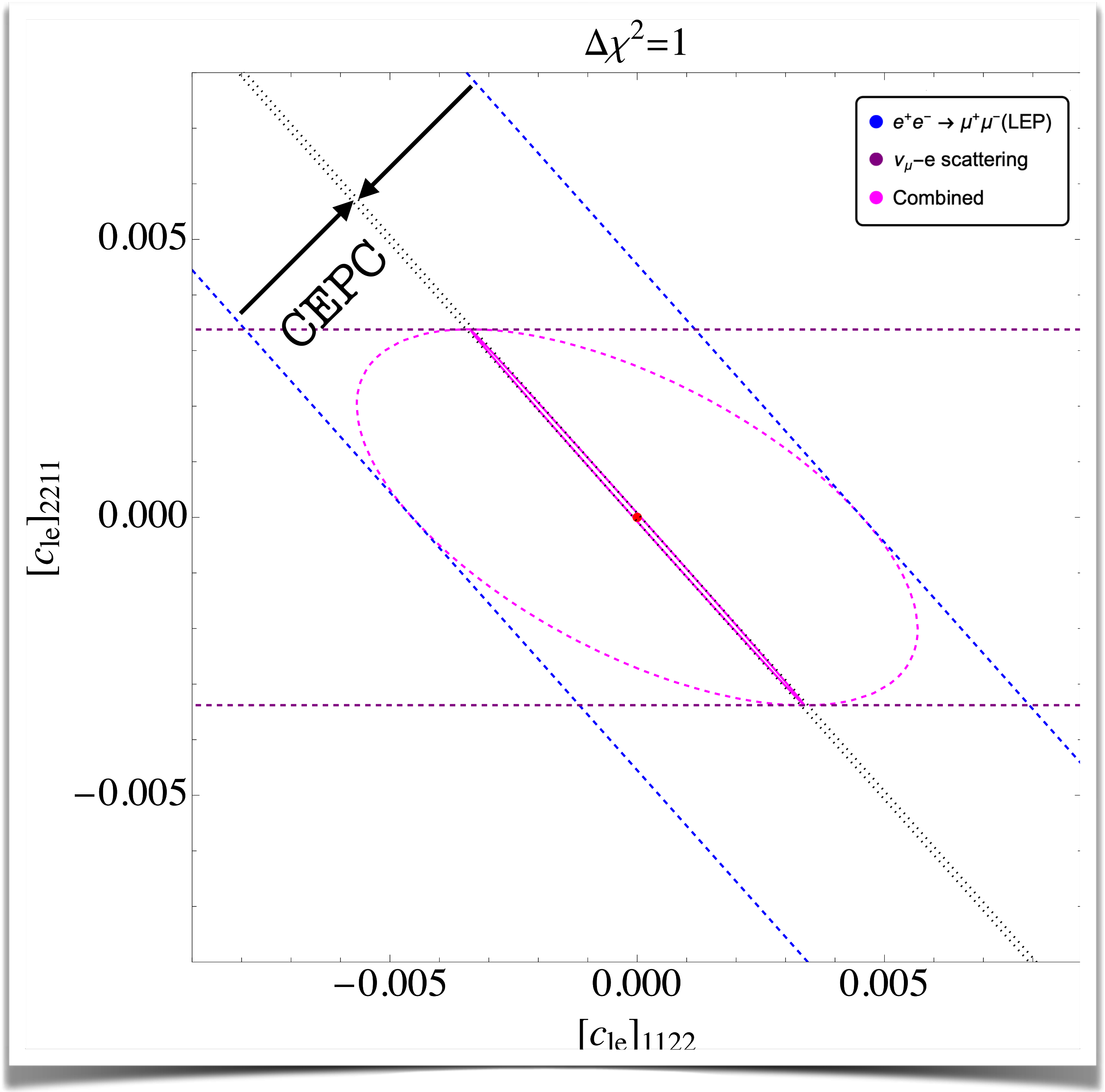

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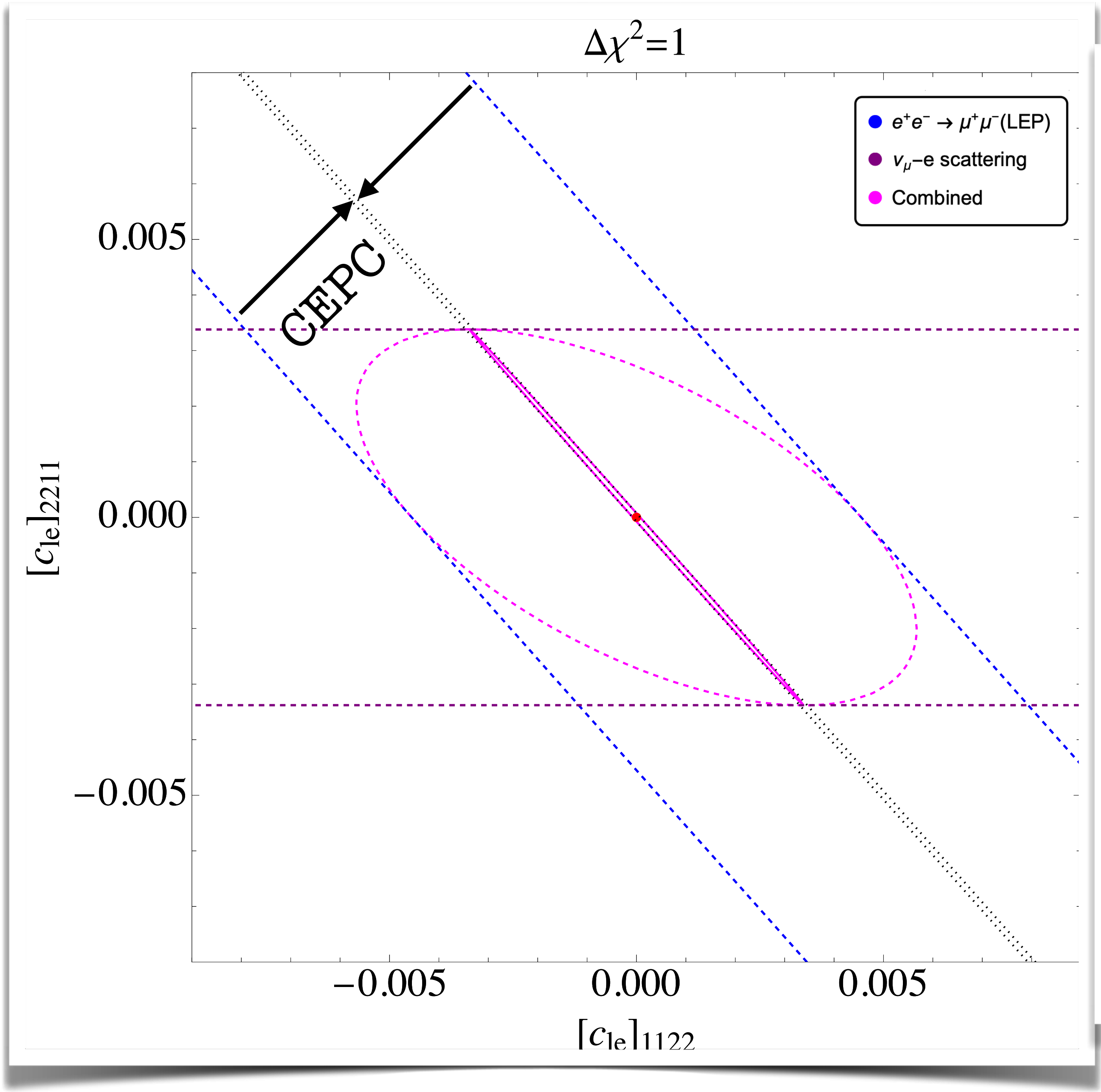
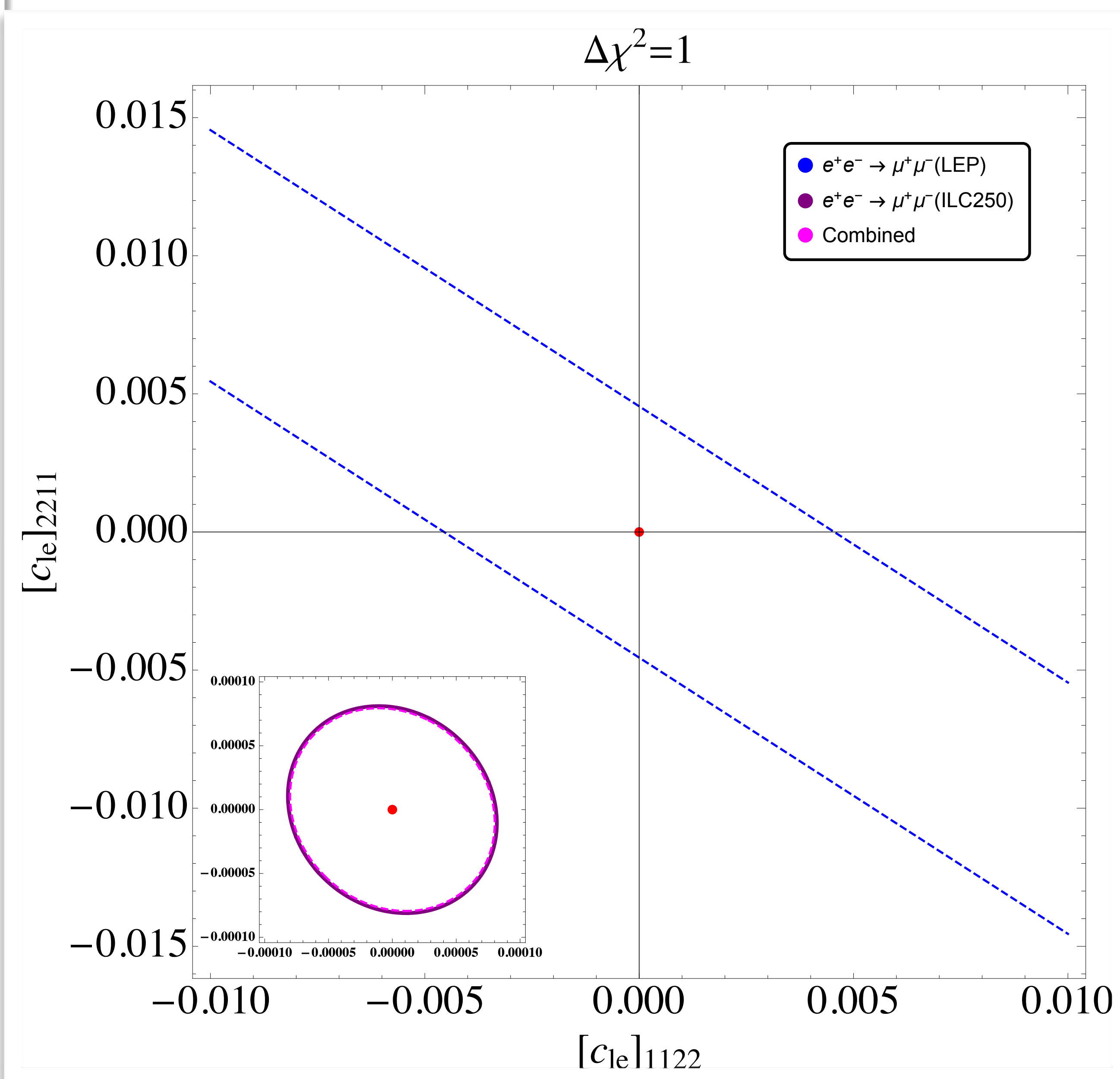
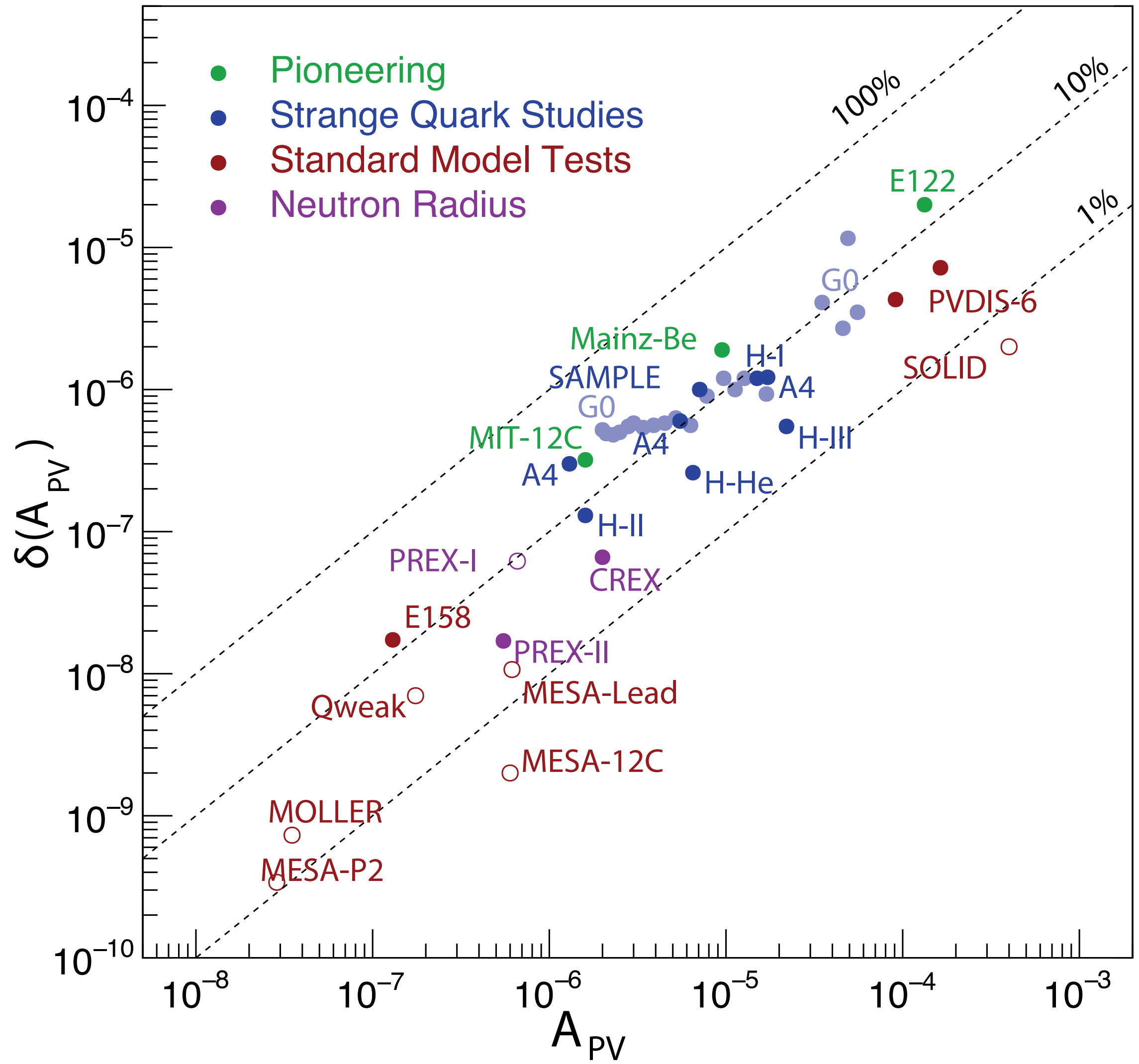




SMEFT global fit: ***4f***

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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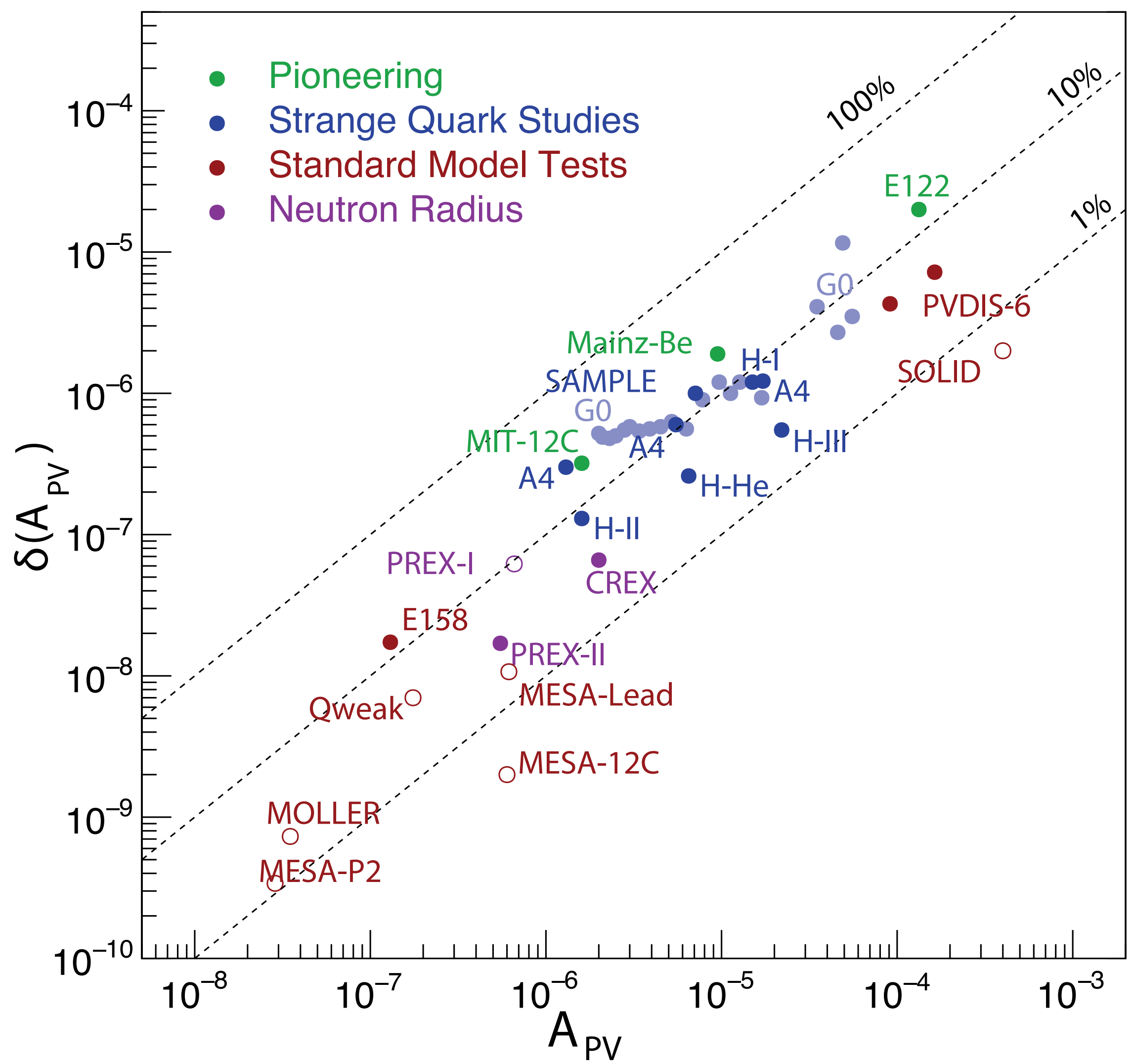

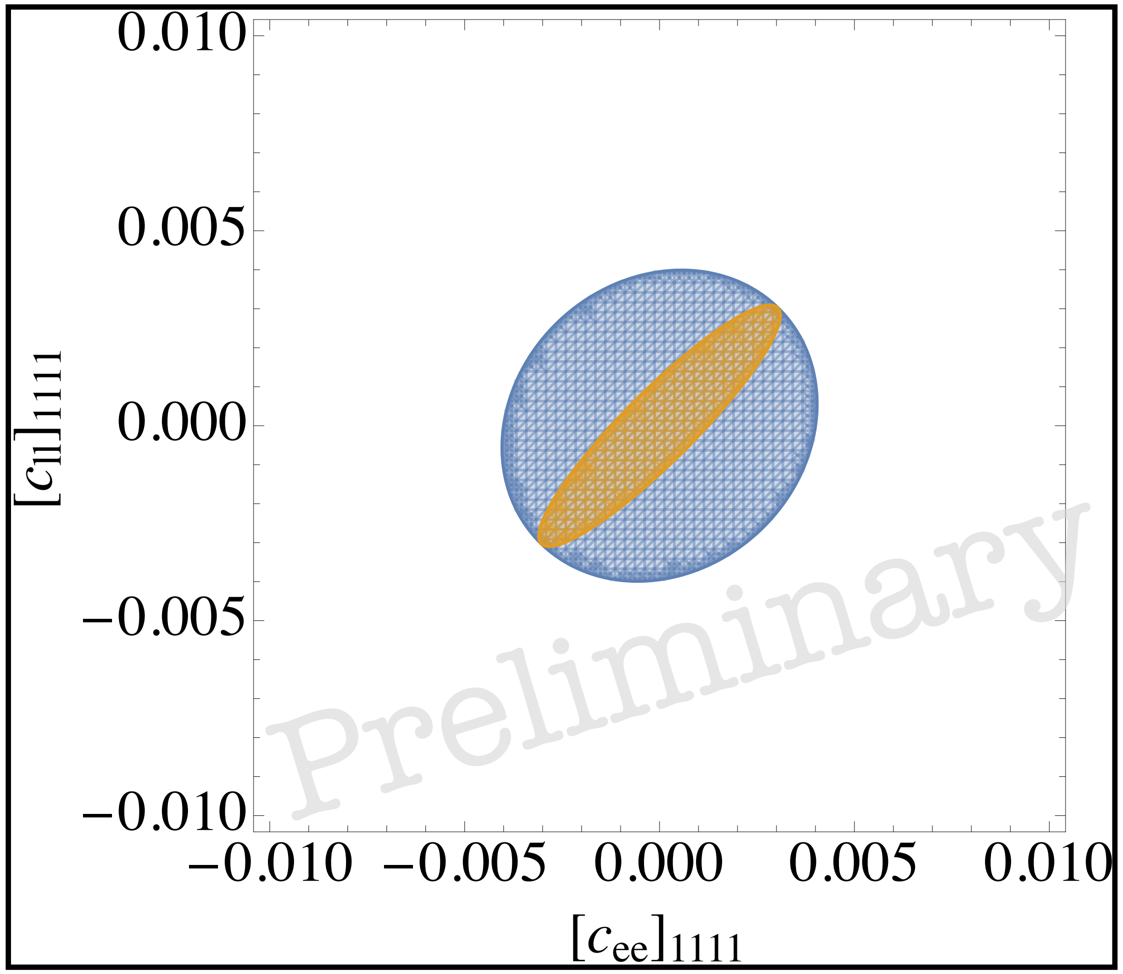

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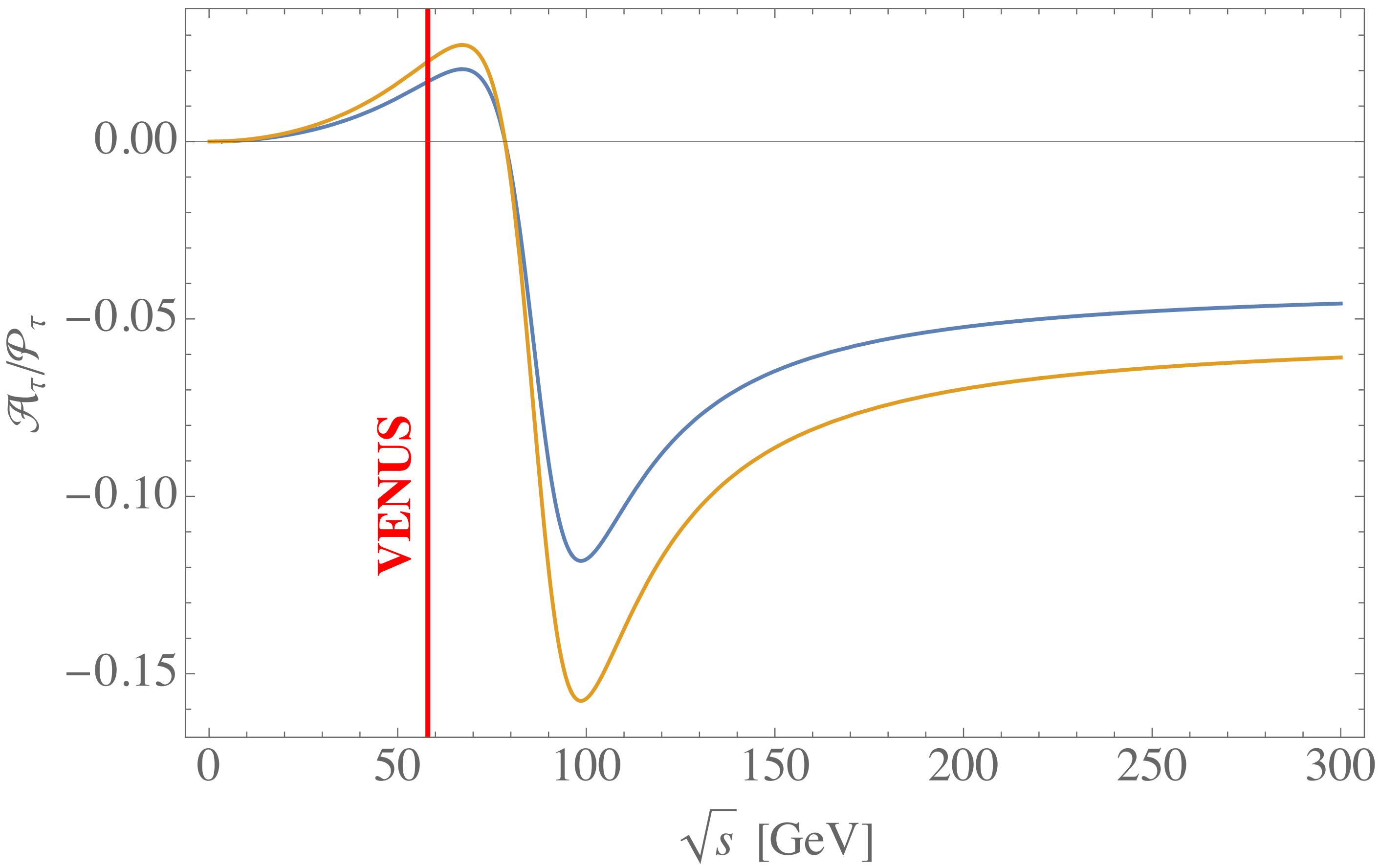
τ polarization measurement at VENUS is limited by statistics ($\mathscr{L} = 271\,\mathrm{pb}^{-1}$). CEPC at 240GeV will have better sensitivity with much more statistics (let alone STCF).



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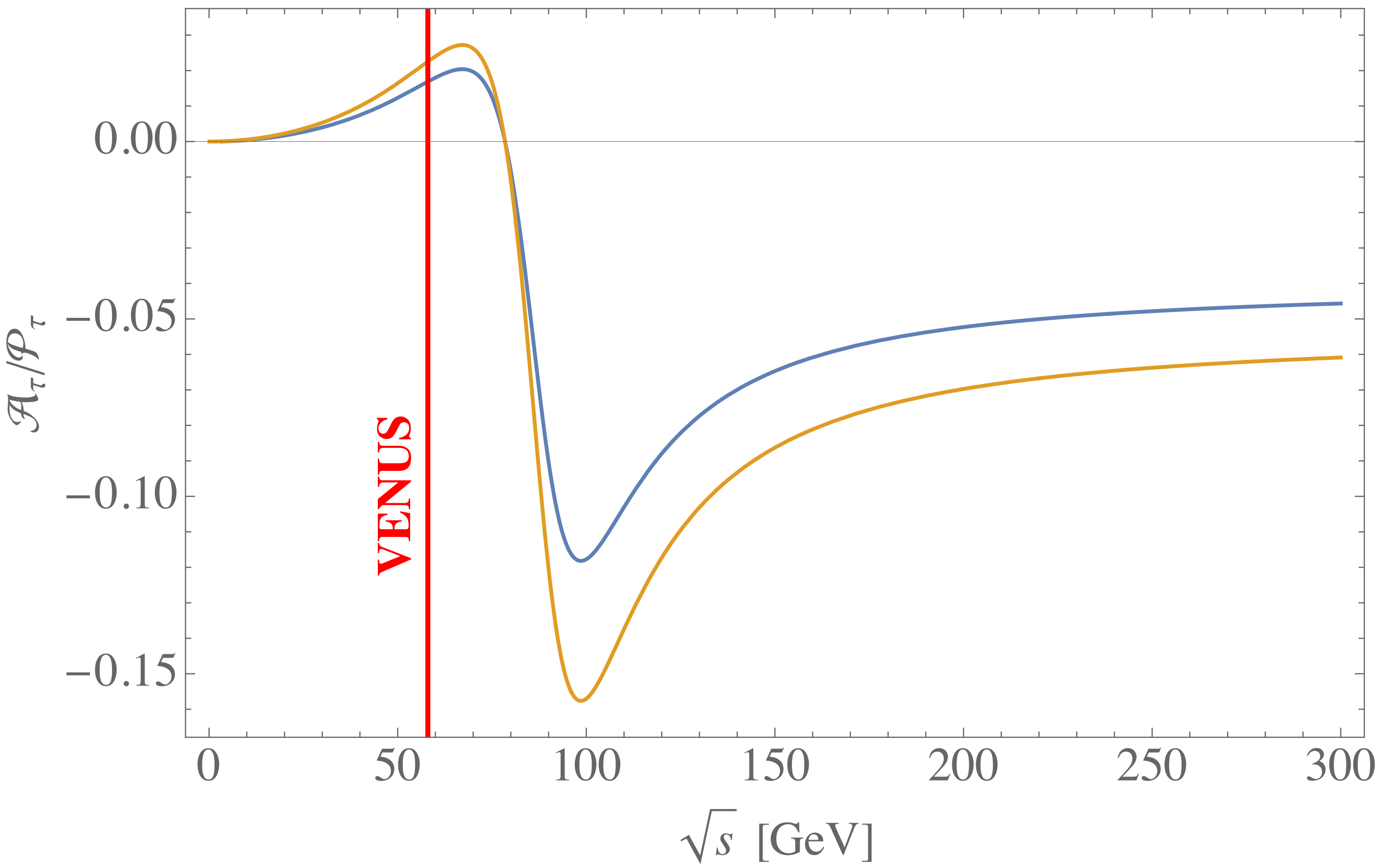

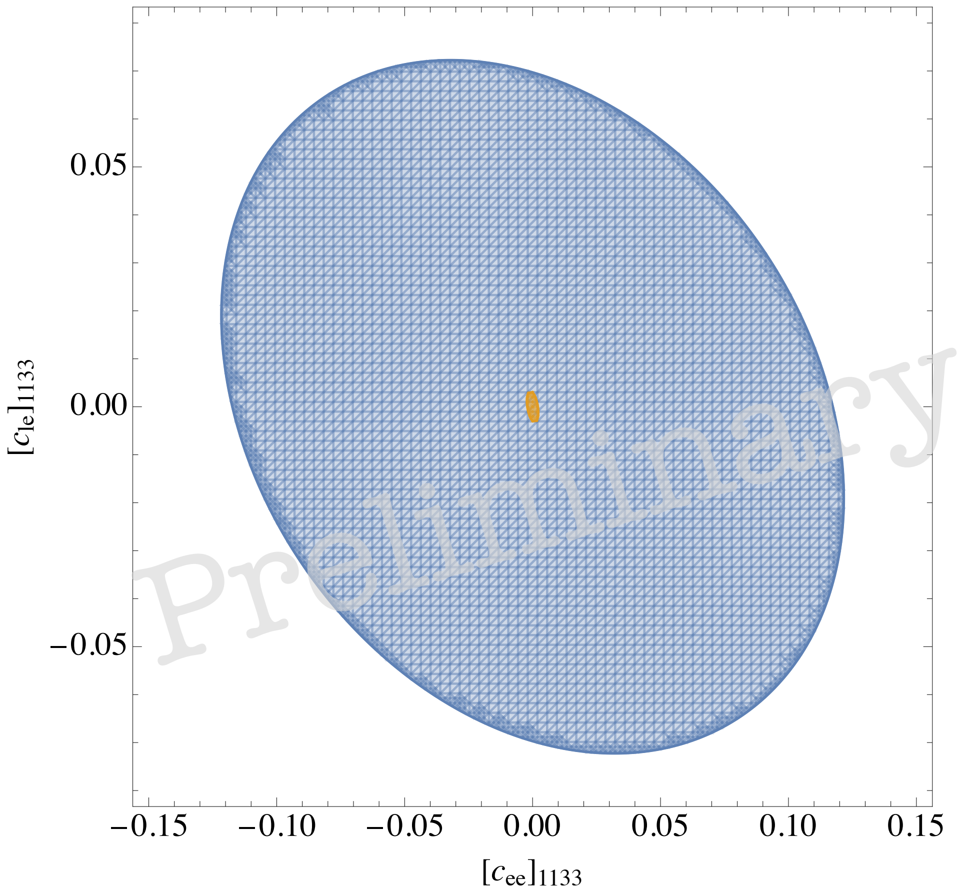

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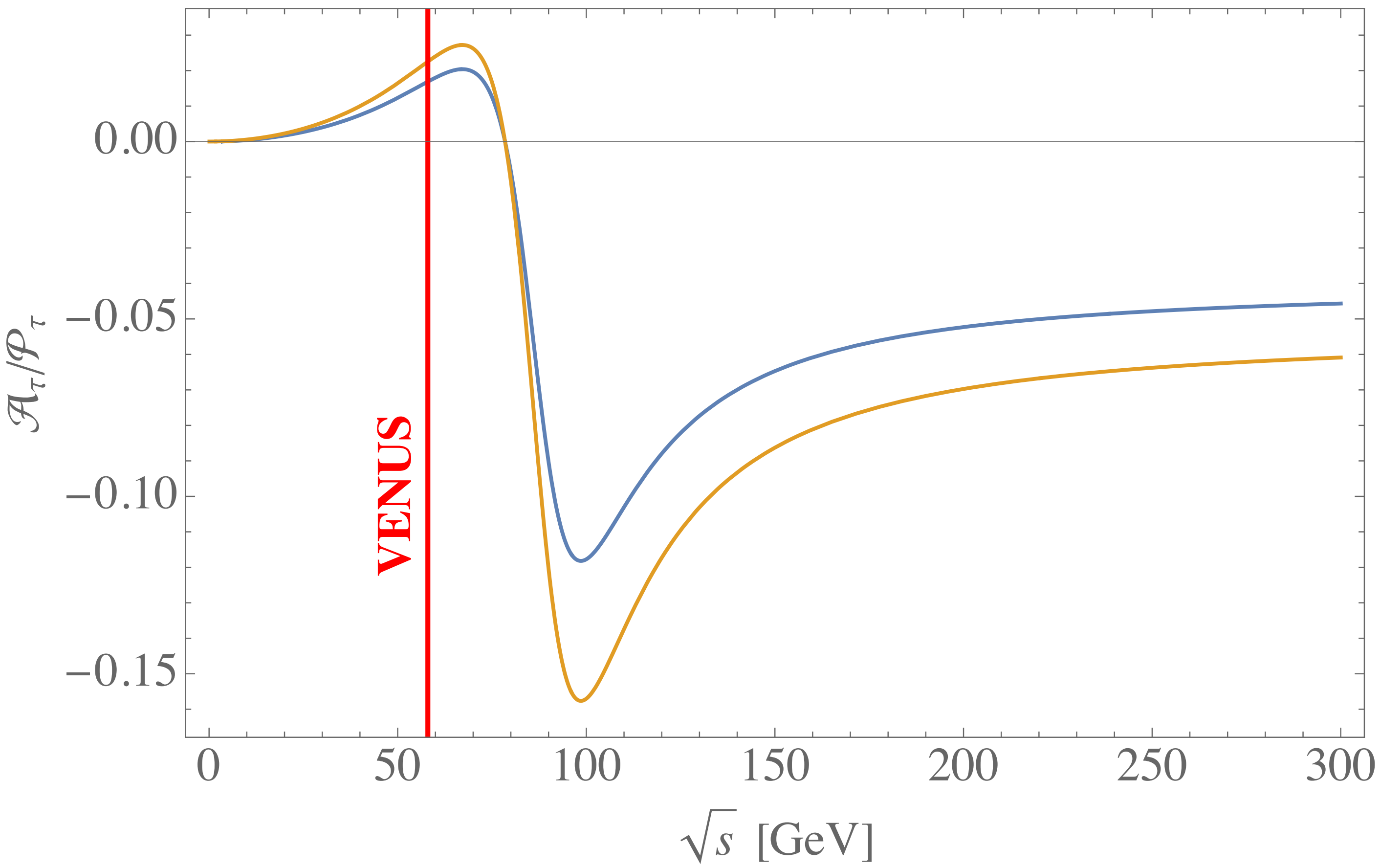
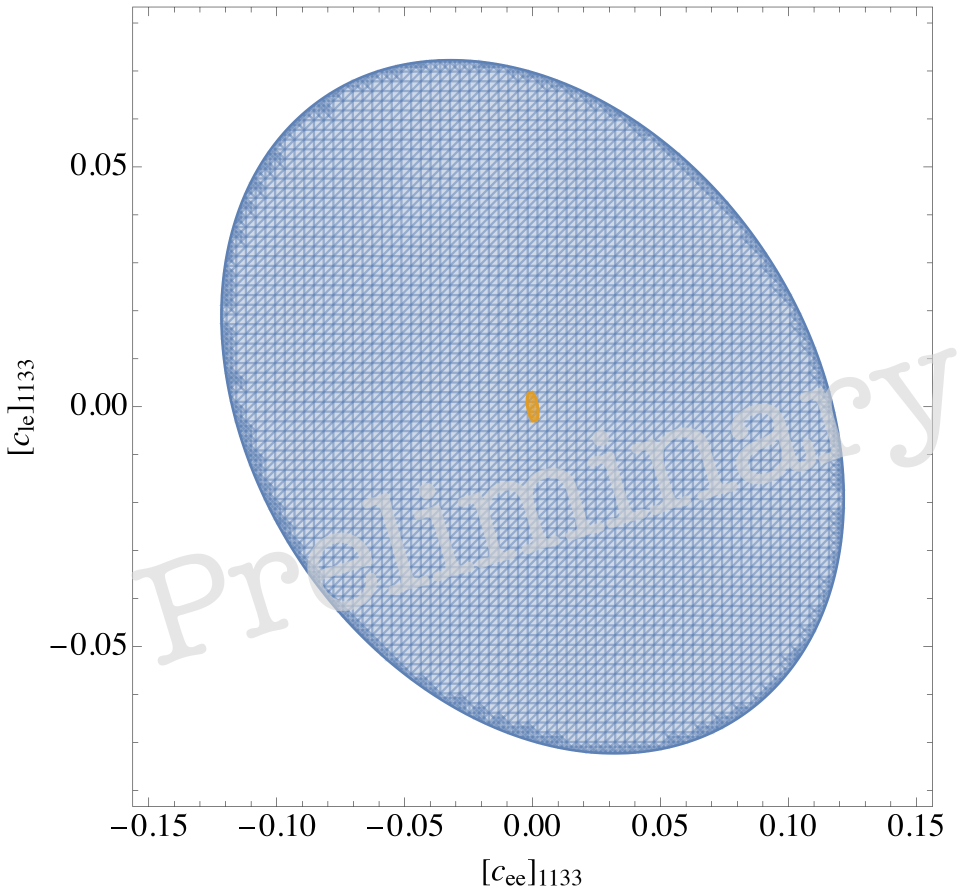
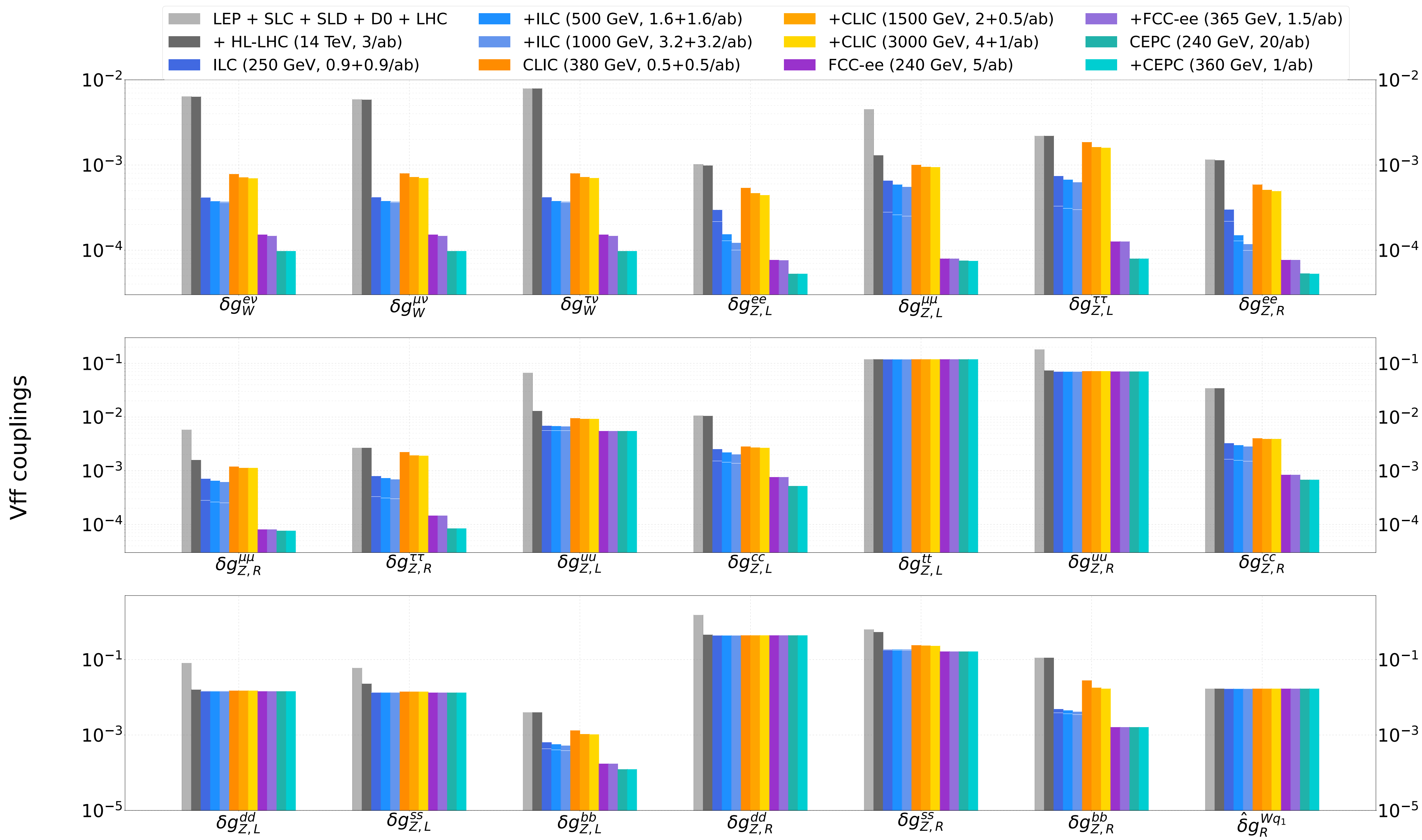




Q: Projections for CEPC before it is too late? (Already too late?)

SMEFT global fit: *4f*

Global fit results: Vff couplings



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

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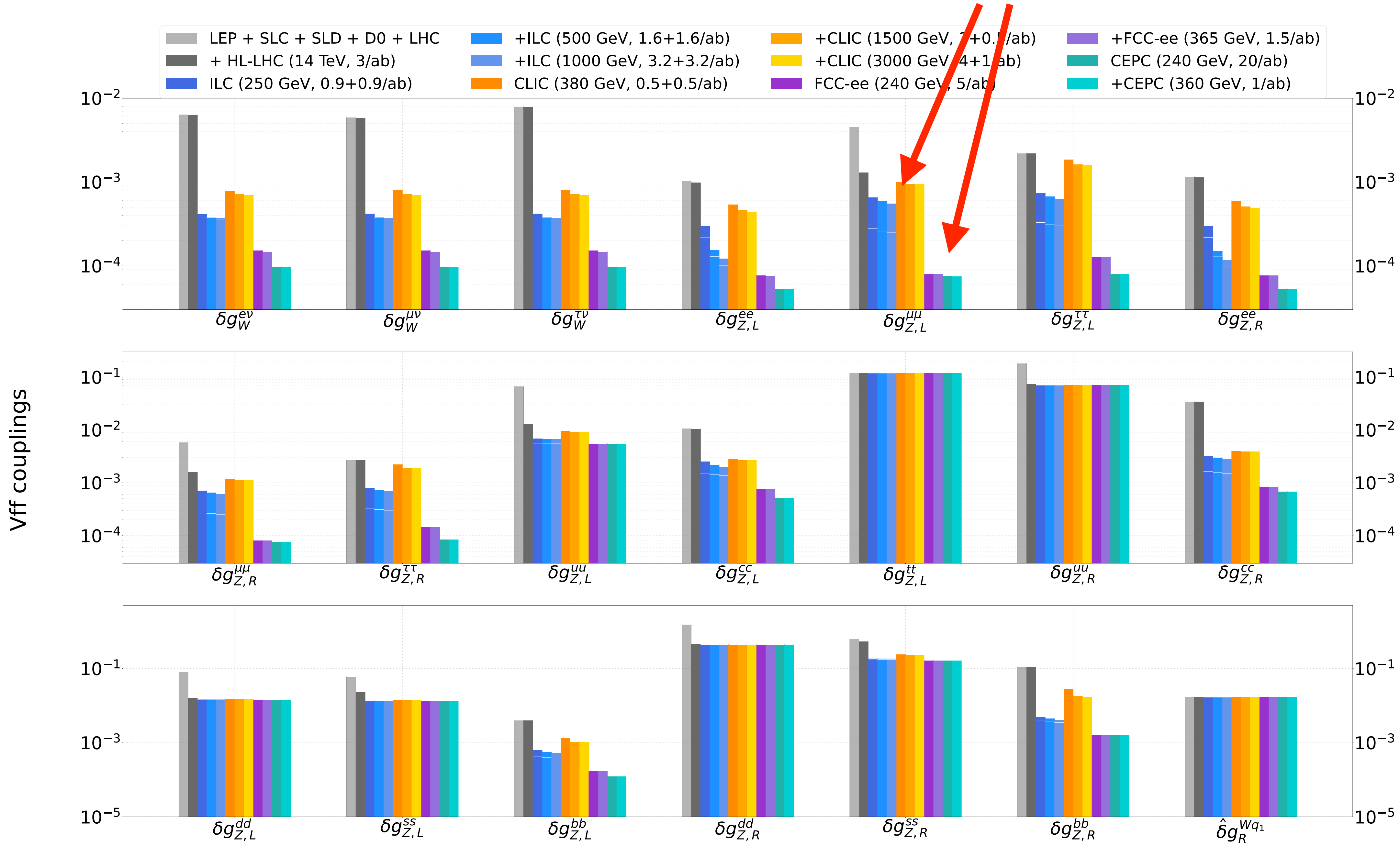
Luminosity wins (through radiative return)



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

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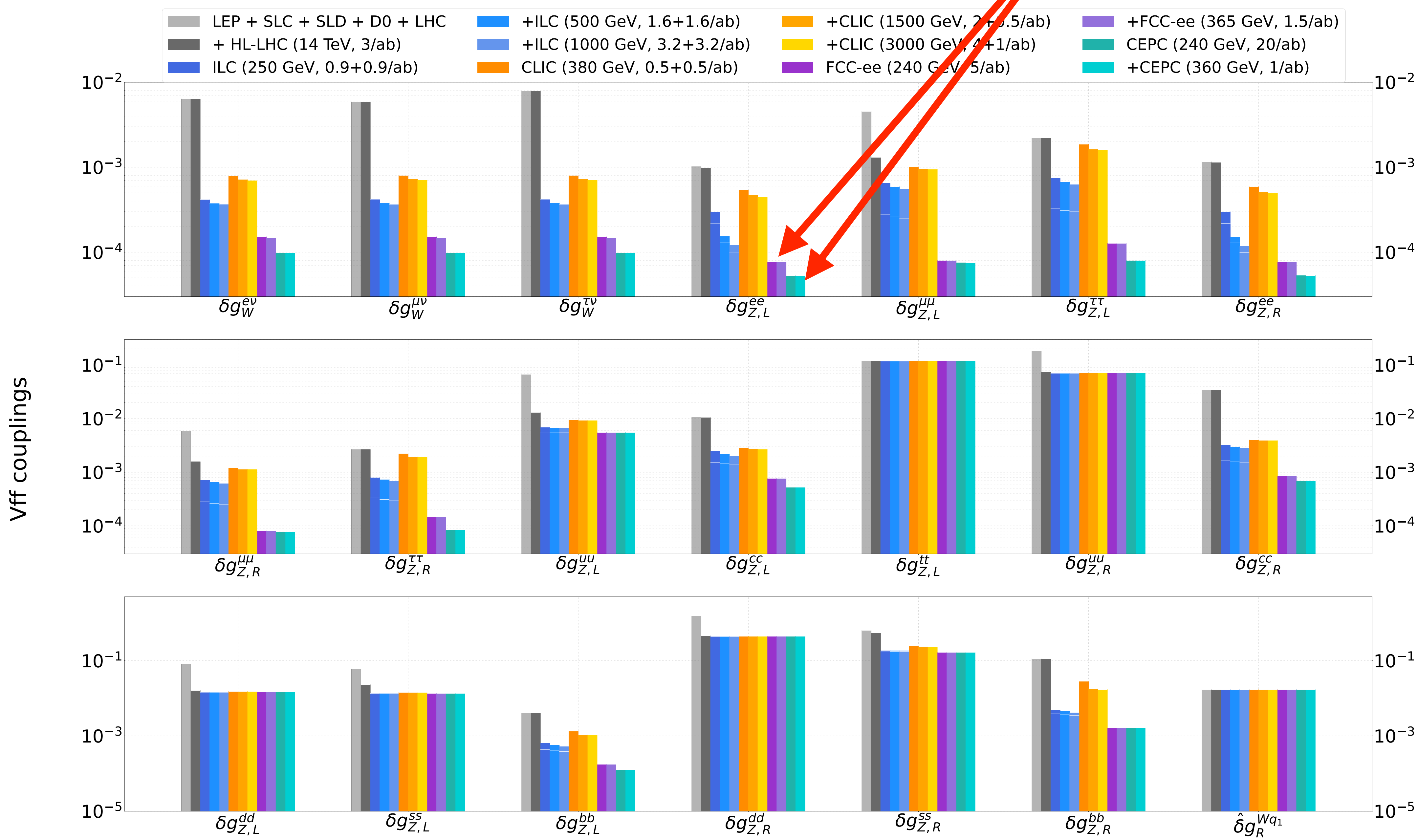
CEPC wins due to larger luminosity



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

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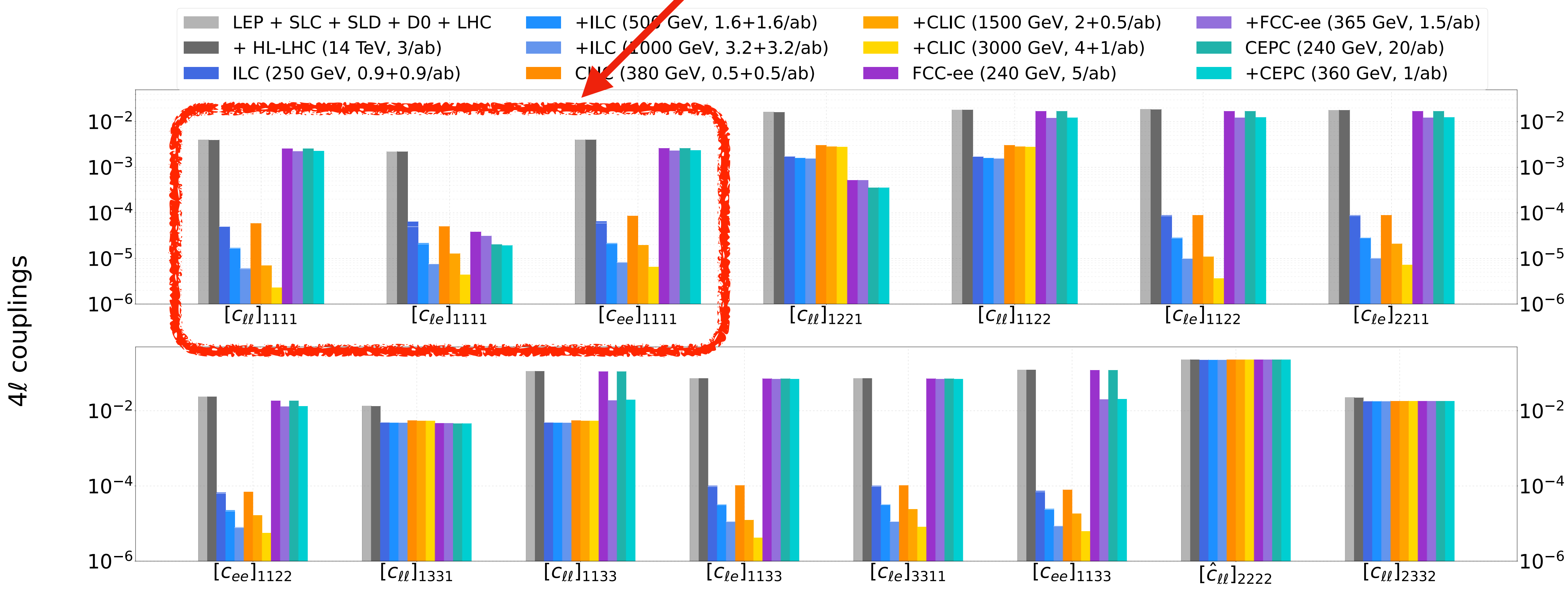
[*Global fit results:*]() 4ℓ couplings

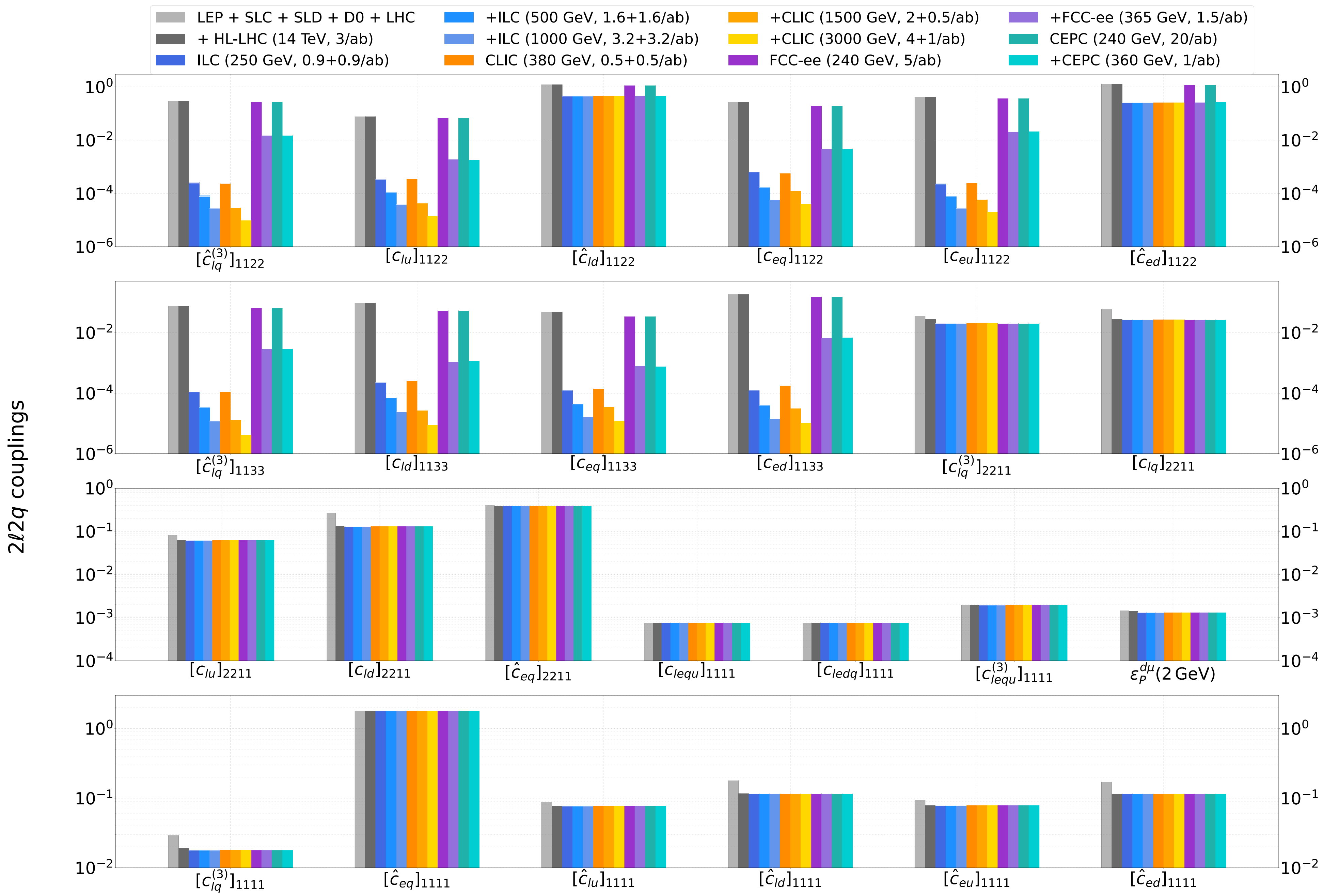
Beam polarization is the key in beating the (HL-)LHC and also circular colliders.



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

SMEFT global fit: *4f*

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



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

SMEFT global fit: ***4f***

Low-energy observables are helpful and even powerful in some cases (say the Moller scattering).

Q: Any other low-energy precision observables?

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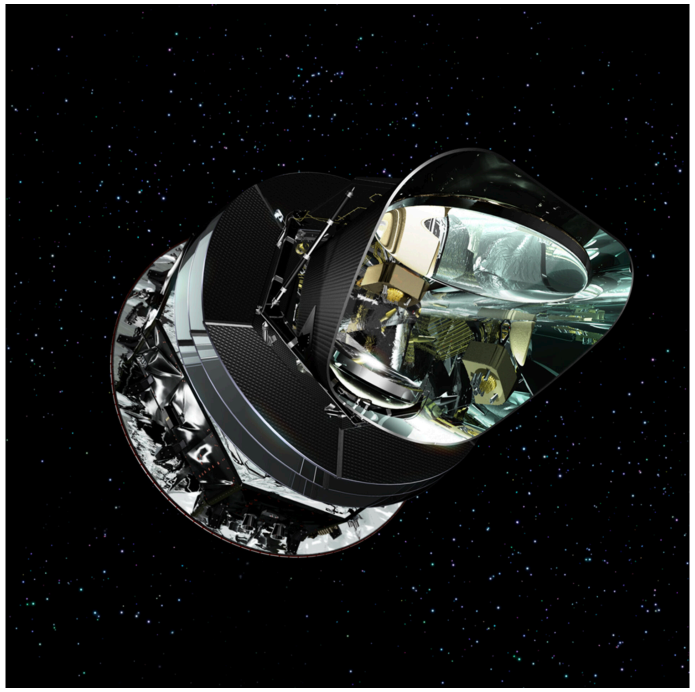
$N_{\rm eff}^{\rm Planck} = 2.99 \pm 0.34$

$\Delta N_{\rm eff}^{\rm CMB-S4} = 0.03$

$\delta N_{\rm eff}^{\rm future} \leq 1\,\%$



CMB-HD, PICO, CORE

We are entering the precision cosmology era.

SMEFT global fit: ***4f***

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2310.10034, **YD**

$$N_{\rm eff} = 3.04385 + 3.03784[c_{le}]_{1111} + 3.01675[c_{ll}]_{1111} + 3.03606[c_{le}]_{2211} + 3.03539[c_{le}]_{3311} + 3.07371\delta g_W^{e\nu} + 3.03917\delta g_{Z,L}^{ee} + 3.02654\delta g_{Z,R}^{ee} + 3.01006\,\hat{c}_{\rm cosmo}$$

$$\hat{c}_{\rm cosmo} \equiv [c_{ll}]_{1122} + [c_{ll}]_{1221} + [c_{ll}]_{1133} + [c_{ll}]_{1331} + [c_{ll}]_{2332} + [c_{ll}]_{2332} + [c_{ll}]_{2222} + [c_{ll}]_{2233} + [c_{ll}]_{3333} + \delta g_W^{\mu\nu} + \delta g_W^{\tau\nu} + \delta g_{Z,L}^{\mu\mu} + \delta g_{Z,L}^{\tau\tau}$$

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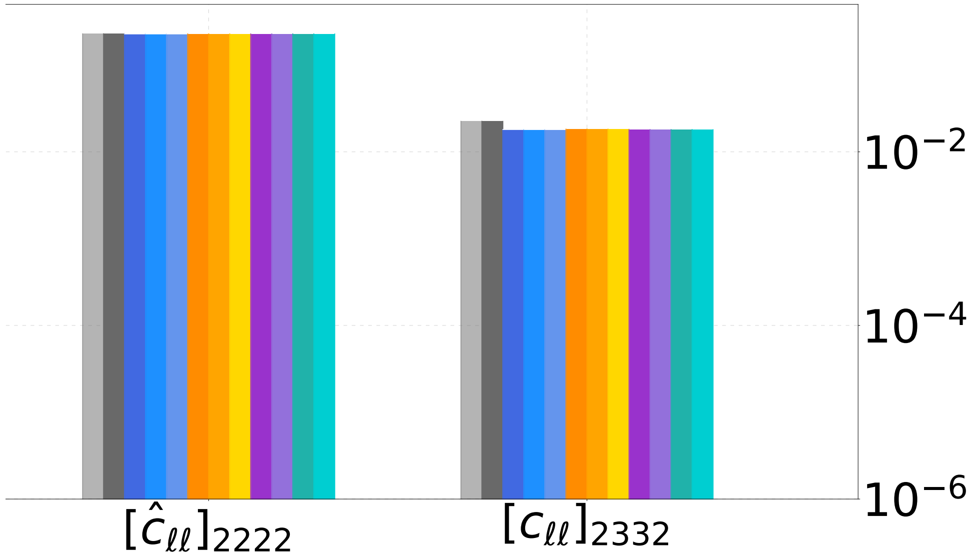
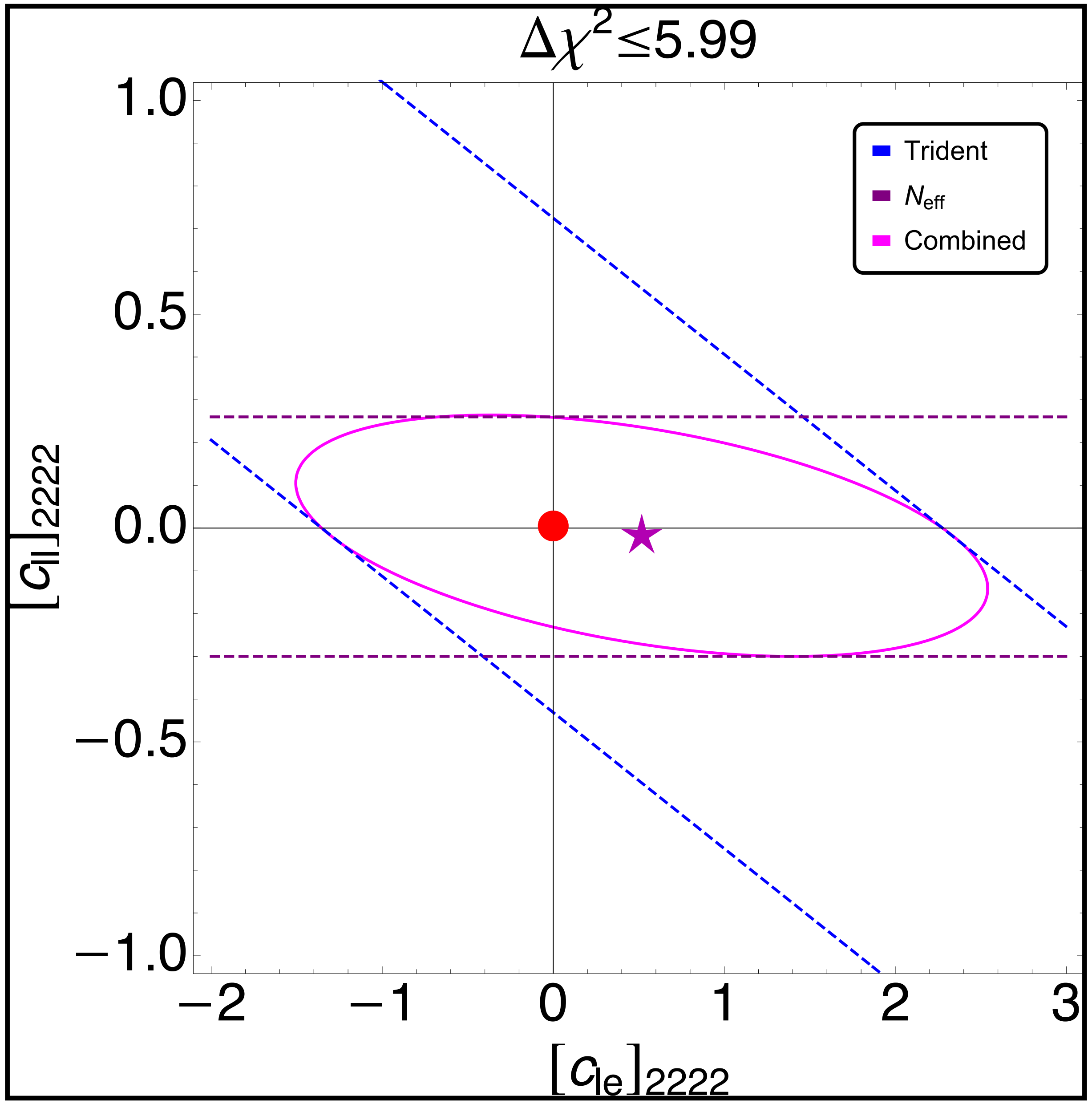


$$[\hat{c}_{\ell\ell}]_{2222} = [c_{\ell\ell}]_{2222} + \frac{2g_Y^2}{g_L^2 + 3g_Y^2}[c_{\ell e}]_{2222}$$

SMEFT global fit: *4f*

On the 2d plane,

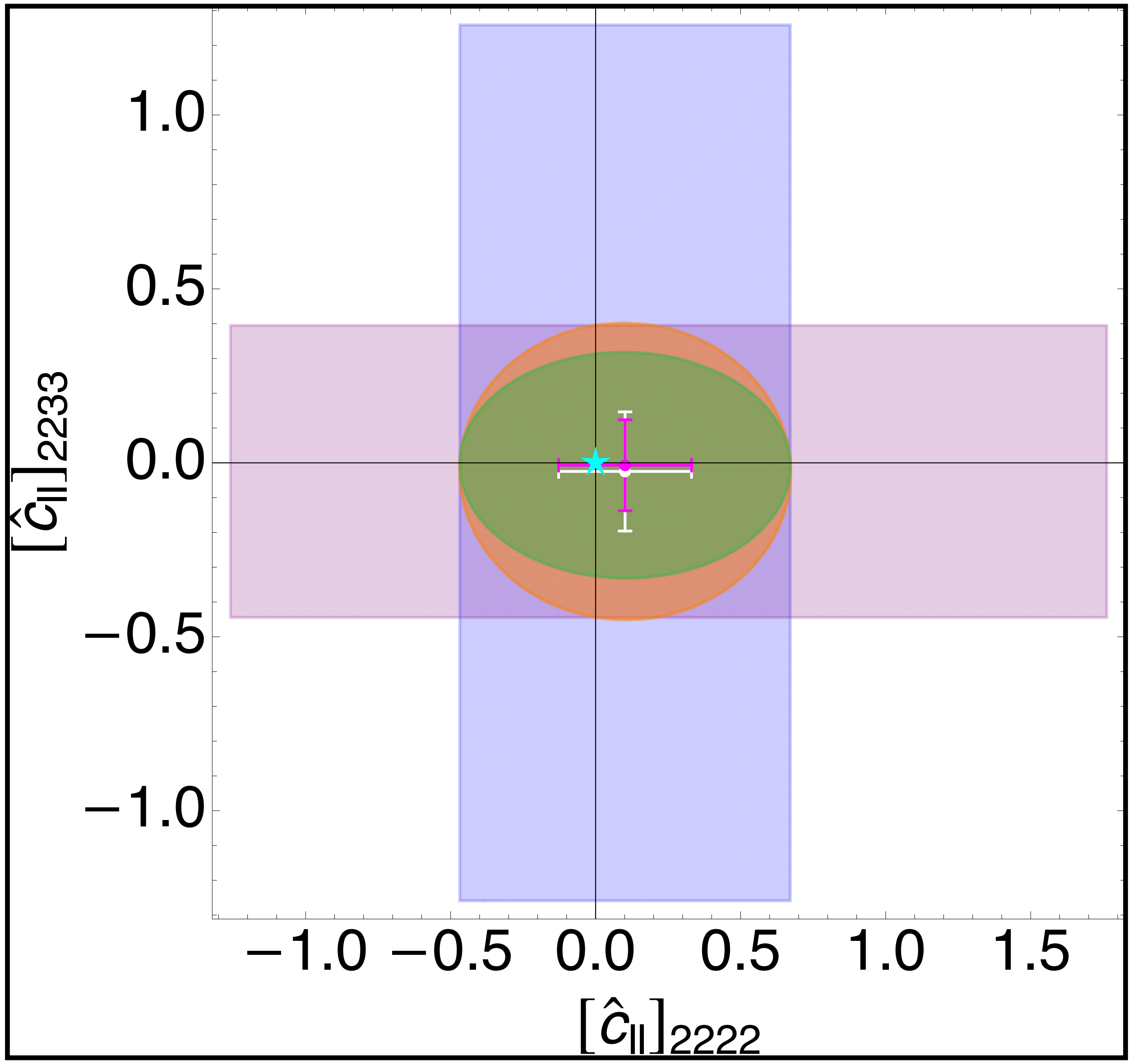
2310.10034, **YD**



Sensitivity to new operators in the tau sector:

2310.10034, **YD**

$$\hat{c}_{\text{cosmo}} \equiv [c_{ll}]_{1122} + [c_{ll}]_{1221} + [c_{ll}]_{1133} + [c_{ll}]_{1331} + [c_{ll}]_{2332} + [c_{ll}]_{2332} + [c_{ll}]_{2222} + [c_{ll}]_{2233} + [c_{ll}]_{3333} + \delta g_W^{\mu\nu} + \delta g_W^{\tau\nu} + \delta g_{Z,L}^{\mu\mu} + \delta g_{Z,L}^{\tau\tau}$$



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

$$\left[\hat{c}_{\ell\ell}\right]_{2233} = \left[c_{\ell\ell}\right]_{2222} + \left[c_{\ell\ell}\right]_{2233} + \left[c_{\ell\ell}\right]_{3333}$$

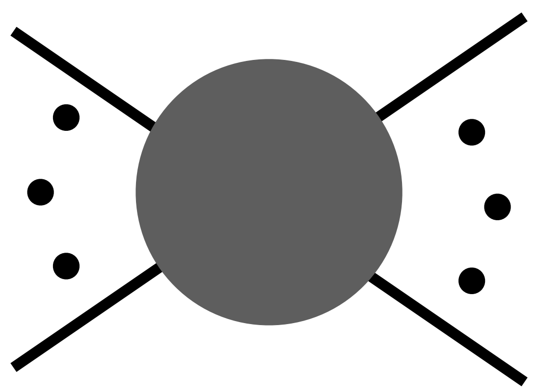
Summary

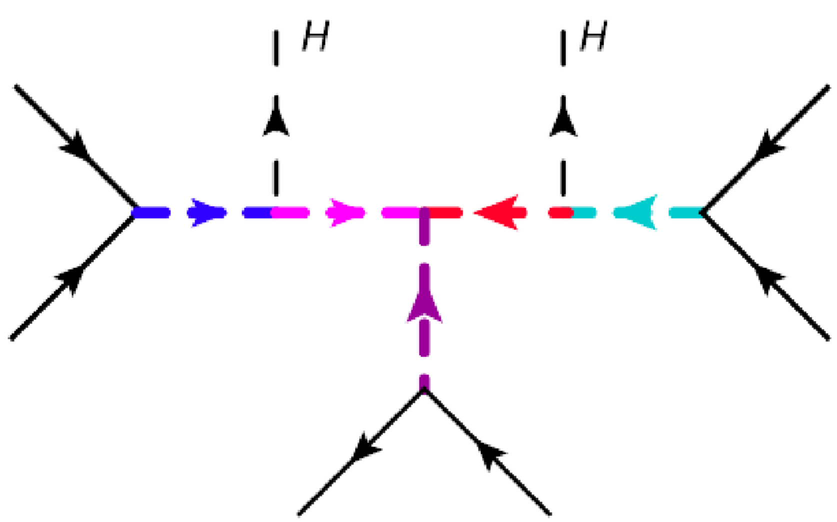
- I discussed the global fit of 4f SMEFT operators at future colliders:
  - Beam polarization is the key to surpass circular colliders in studying 4f interactions;
  - Luminosity largely wins otherwise for circular colliders;
  - Tau polarization projections at CECP will be very interesting (already too late?)

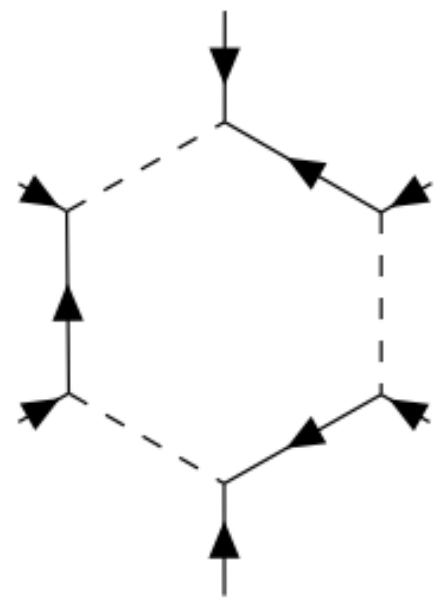
- Input from precision cosmology enlarges the parameter space in the tau sector:
  - It improves the fit by a factor of a few in the flavor universal case
  - It also has the chance to lift the well-known flat direction in the 4μ sector
  - 10% sensitivity to the new tau operators can be reached with the inclusion of Neff

Backup

Benchmark: ***Unfolding***







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}
{6, 1}	{3, 2}	{3, 2}	{3, 1}	{3, 1}
{6, 1}	{3, 2}	{3, 2}	{3, 1}	{6, 1}
{6, 1}	{3, 2}	{3, 2}	{6, 1}	{3, 1}
{6, 1}	{3, 2}	{3, 2}	{6, 1}	{6, 1}
{6, 1}	{3, 2}	{6, 2}	{3, 1}	{3, 1}
{6, 1}	{3, 2}	{6, 2}	{6, 1}	{3, 1}
{6, 1}	{6, 2}	{3, 2}	{3, 1}	{3, 1}
{6, 1}	{6, 2}	{3, 2}	{6, 1}	{3, 1}
{6, 1}	{6, 2}	{6, 2}	{3, 1}	{6, 1}
{6, 1}	{6, 2}	{6, 2}	{6, 1}	{6, 1}

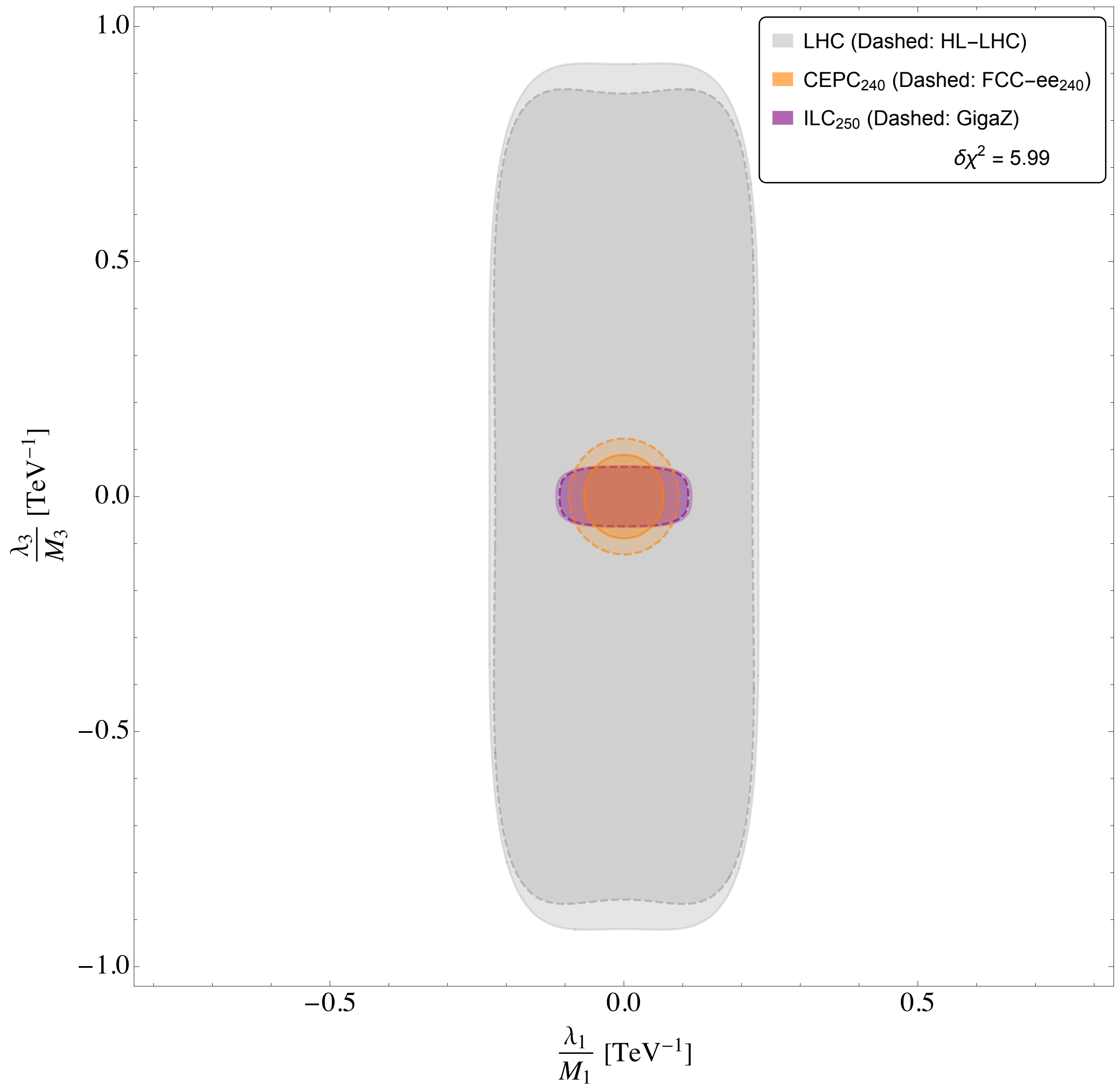
Find the UV models for any operator and any topology (`UVBuilder`).

Q: Which benchmark model for CEPC?

Benchmark: *Leptoquark model*

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

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



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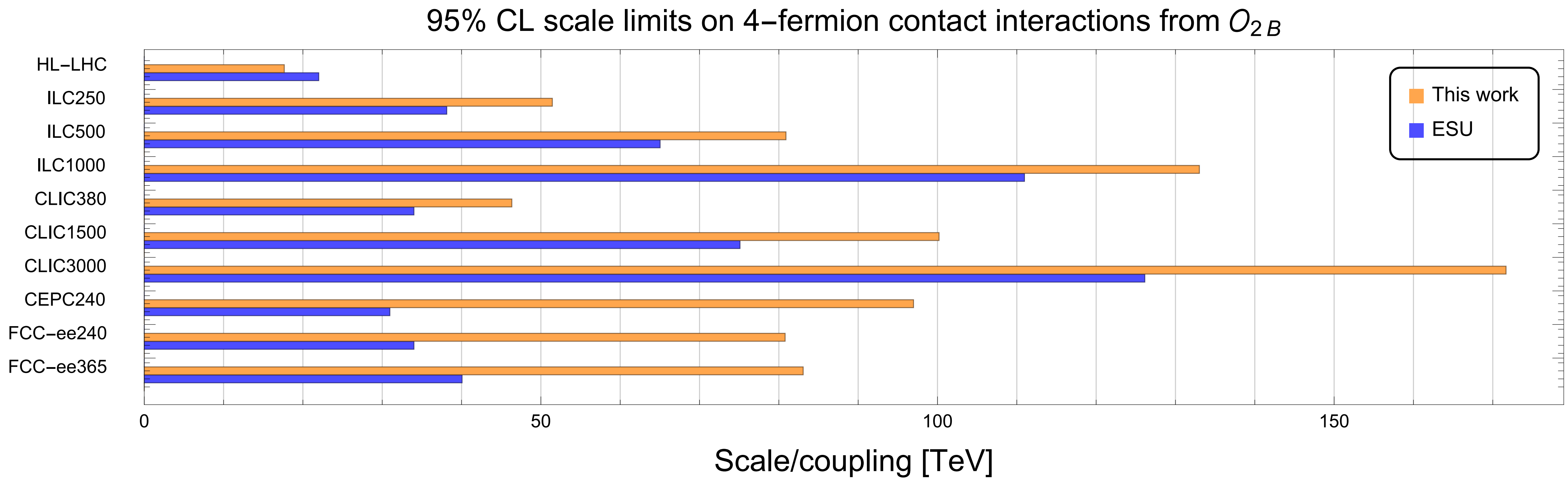
Benchmark: Y-Universal Z' model

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

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



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