The indispensable role of neutrinos in the global fit of SMEFT

Yong Du（杜勇）

WIN2023, Zhuhai SYSU, July 7, 2023

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

PRL 126 (2021) 13, 131801, with Ayres Freitas, Hiren Patel, Michael Ramsey-Musolf

On-going work,
with Justin Fagnoni, Leon Friedrich, Michael Ramsey-Musolf, Jia Zhou
with Michael Peskin, Junping Tian

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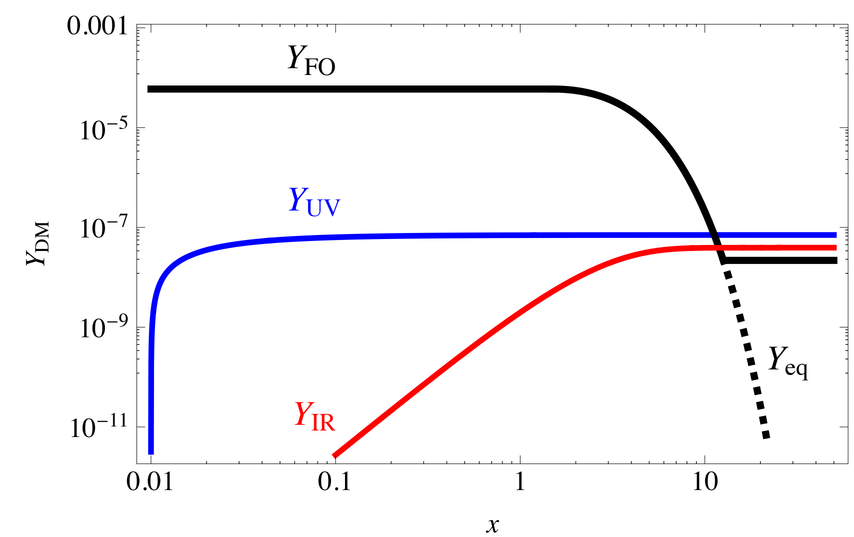
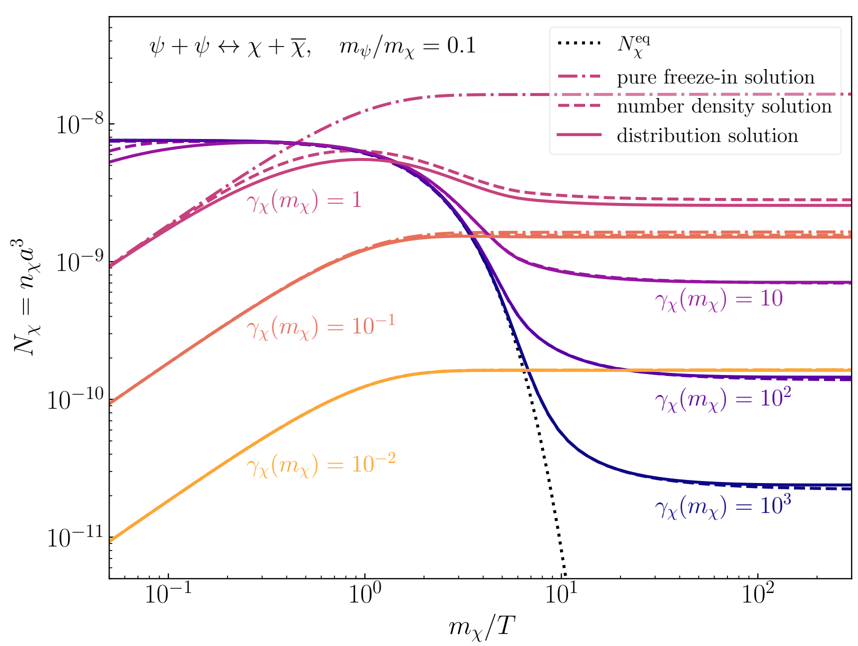
The SM, up to now, is very successful. But there are some flaws:

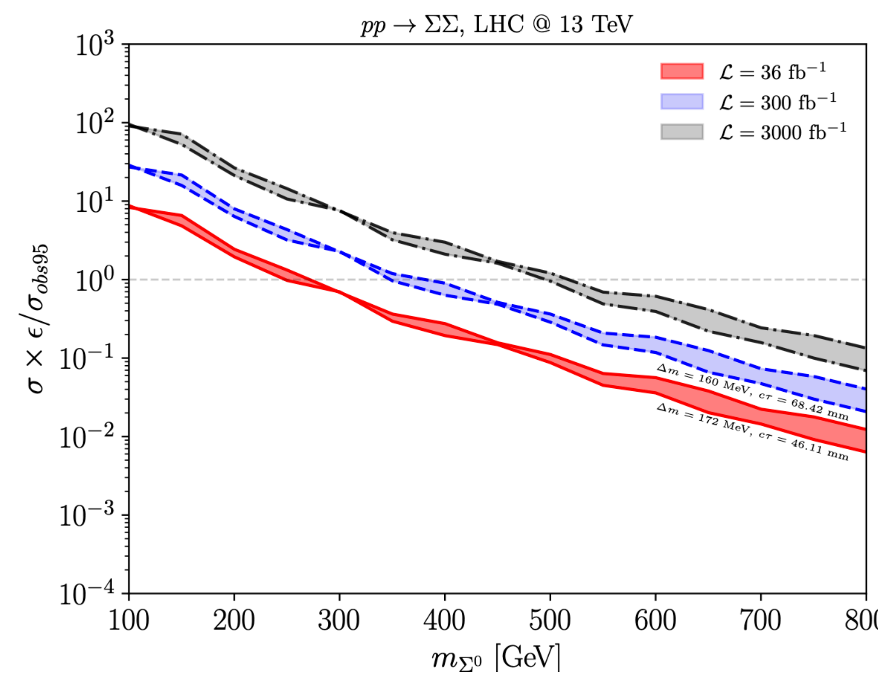
Elahi et al, 1410.6157





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

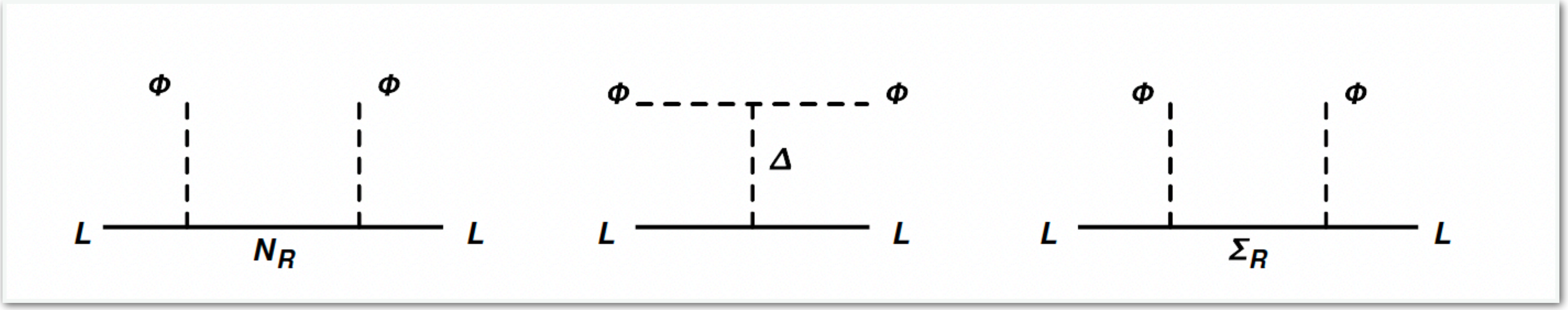
YD, Huang, Li, Li, Yu, 2111.01267 (JCAP)

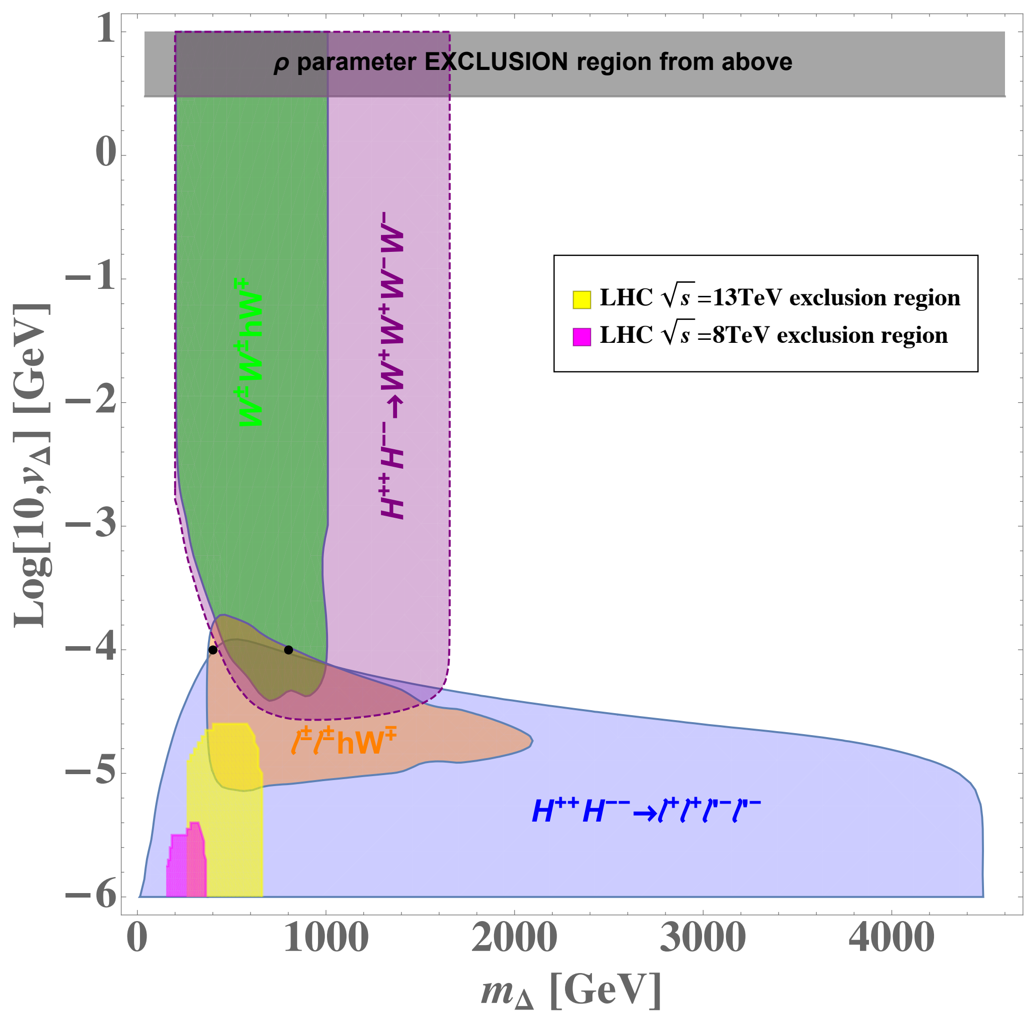


Chiang, Cottin, **YD**, Fuyuto, Ramsey-Musolf, 2003.07867(JHEP)

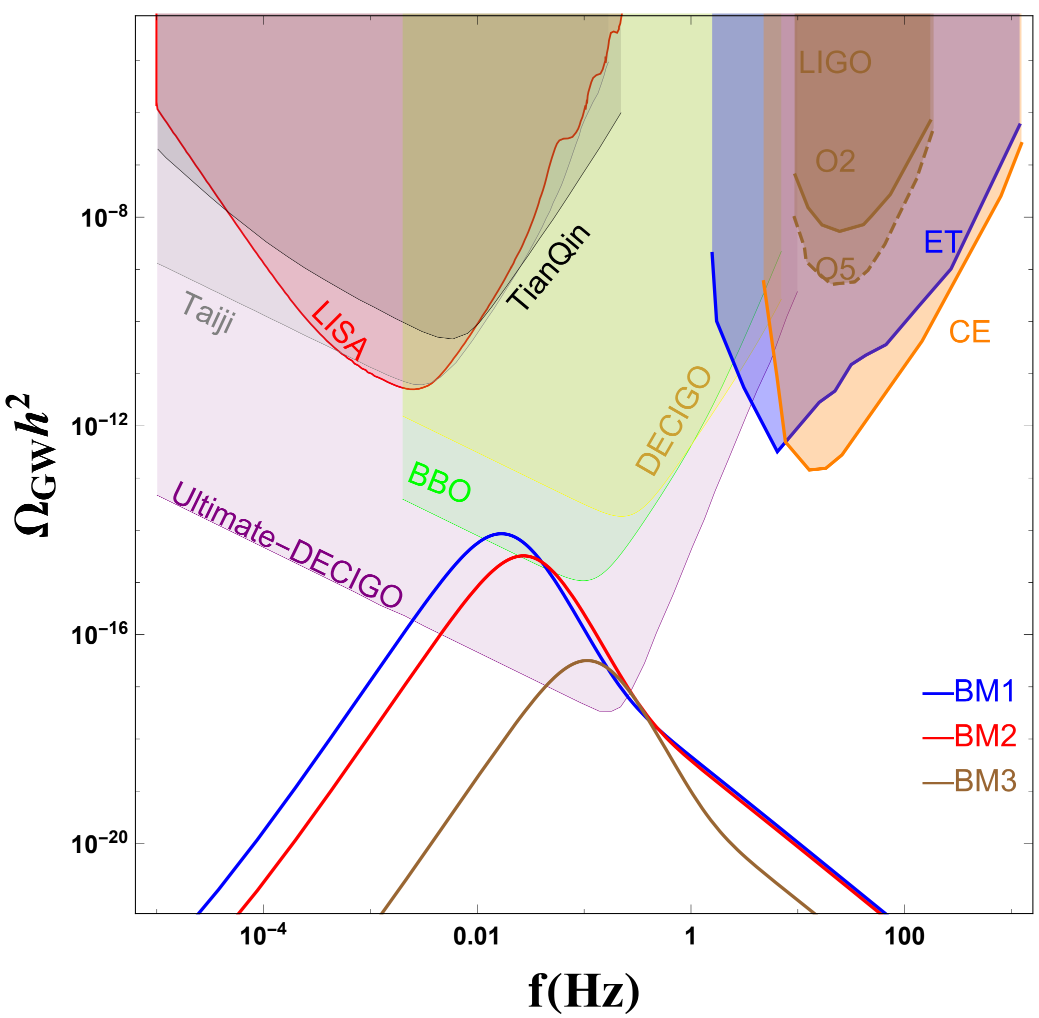
Introduction

On the other hand, neutrinos oscillate





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



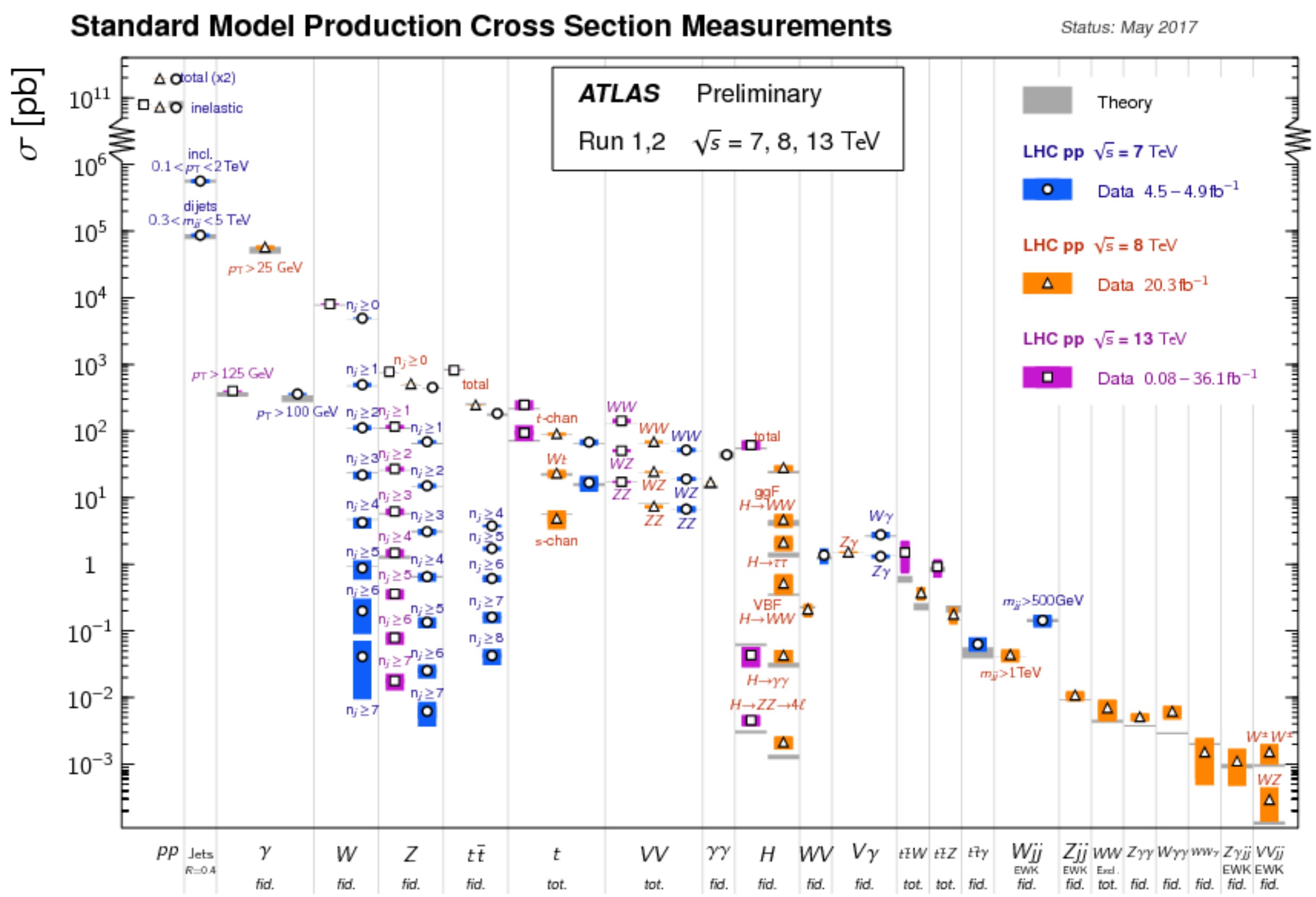
Zhou, Bian, YD, 2203.01561 (JHEP)

Introduction

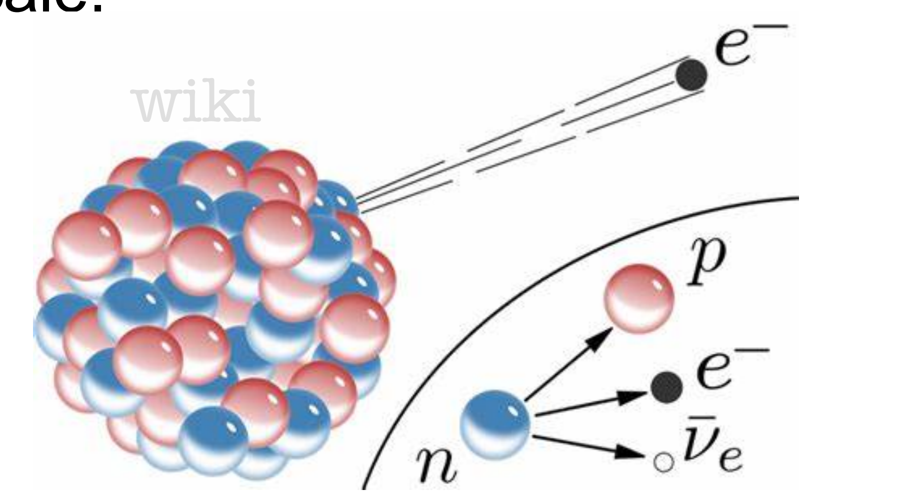
While there are many models for dark matter, neutrinos and other topics as you prefer, the direct experimental observation of any new particle is still null.

<u>Q: How to approach new physics beyond the Standard Model?</u>

<u>A: ⋯</u>



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



SMEFT global fit

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

SMEFT global fit: *flavor*

Big picture of the SMEFT global fit:

Fit 1 for Higgs + electroweak physics (See Jiayin Gu's talk yesterday)

Fit 2 & 3 for four-fermion ($f \neq t$) and bosonic CPV operators

Fit 4 for top physics (not covered in this talk)

SMEFT global fit: ***flavor***

Big picture of the SMEFT global fit:

Fit 1 for Higgs + electroweak physics (See Jiayin Gu's talk yesterday)

Fit 2 & 3 for four-fermion ($f \neq t$) and bosonic CPV operators

Fit 4 for top physics (not covered in this talk)

Some words on the flavors:

U35, top specific, MFV, U23

No flavor assumptions are made.

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: ***Basis***

We choose to work in the Higgs basis

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

We choose to work in the Higgs basis

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

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

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

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

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

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

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

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]
	$R_{\bar{\nu}_\mu}$	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: *4f*

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

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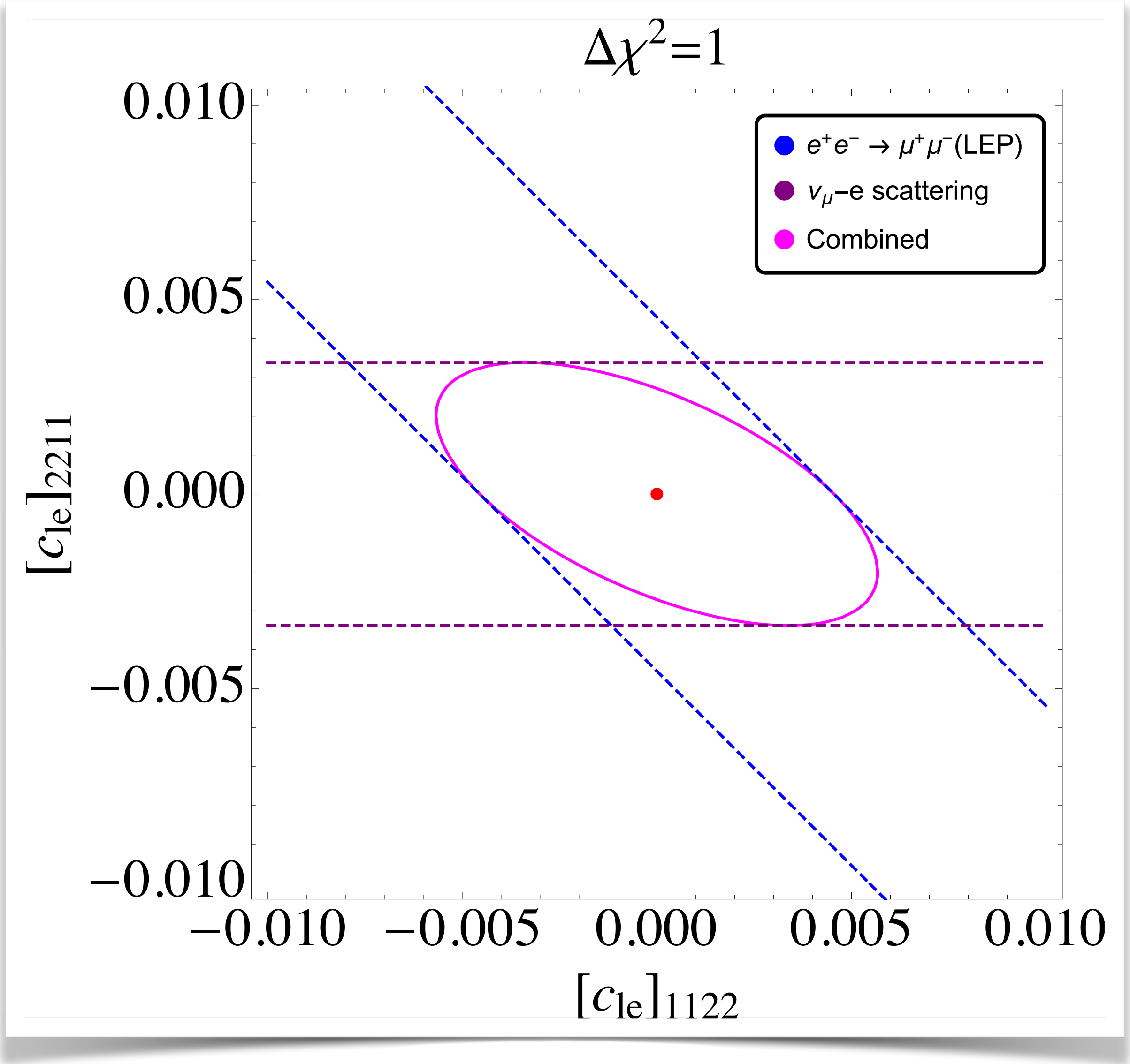
	$g_{LA}^{\nu_\mu e}$	-0.503 ± 0.017		-0.5064 [48]
τ decay	$\frac{G_{\tau e}^2}{G_F^2}$	1.0029 ± 0.0046	PDG2014 [49]	1
	$\frac{G_{\tau\mu}^2}{G_F^2}$	0.981 ± 0.018		
Neutrino scattering	R_{ν_μ}	0.3093 ± 0.0031	CHARM ($r = 0.456$) [50]	0.3156 [50]
	$R_{\bar{\nu}_\mu}$	0.390 ± 0.014		0.370 [50]
	R_{ν_μ}	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: *4f*

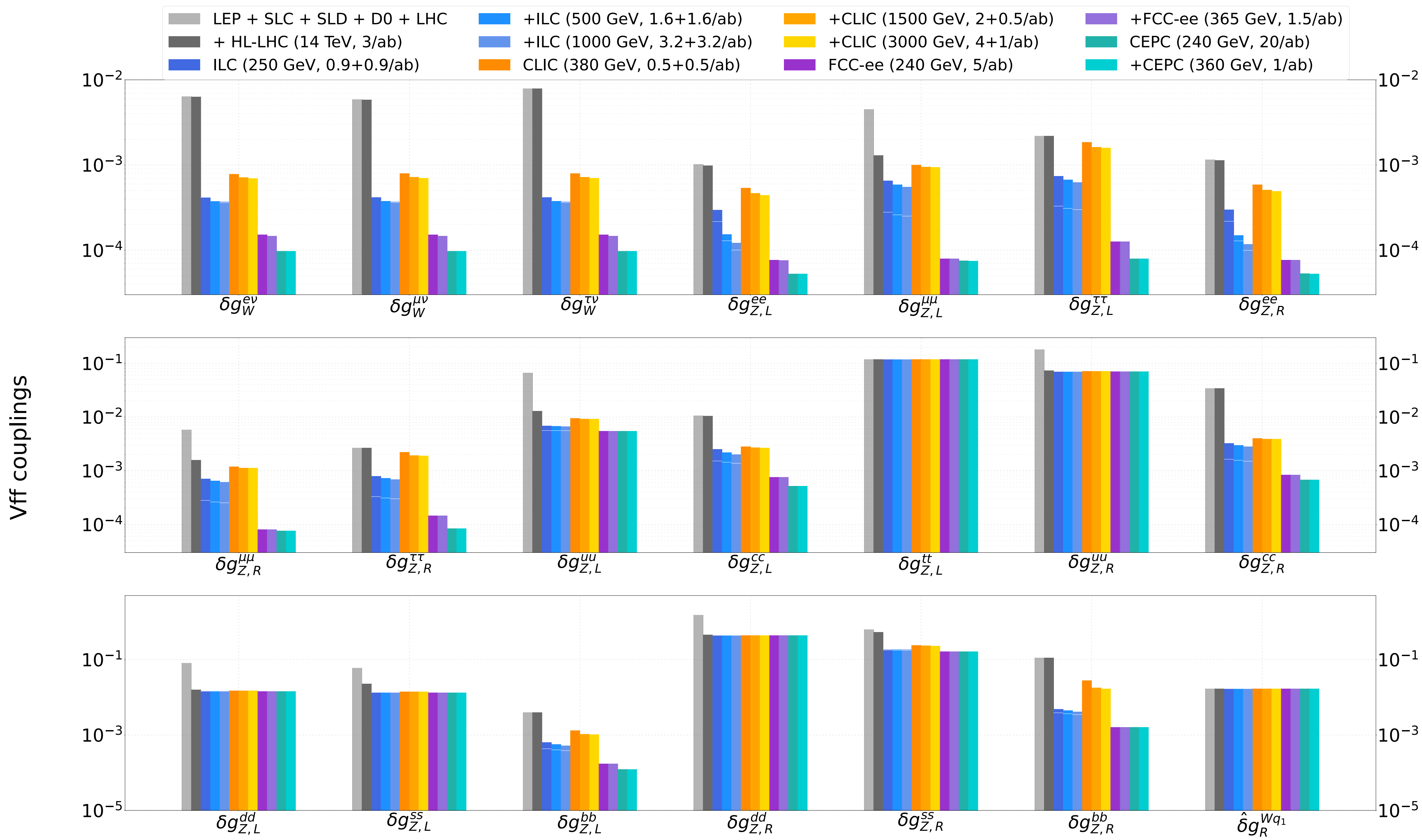
Flat direction lifted by low-energy experiments: One example



Correlations matter especially for UV studies where the Wilson coefficients are dependent.

SMEFT global fit: *4f*

Global fit results: Vff couplings

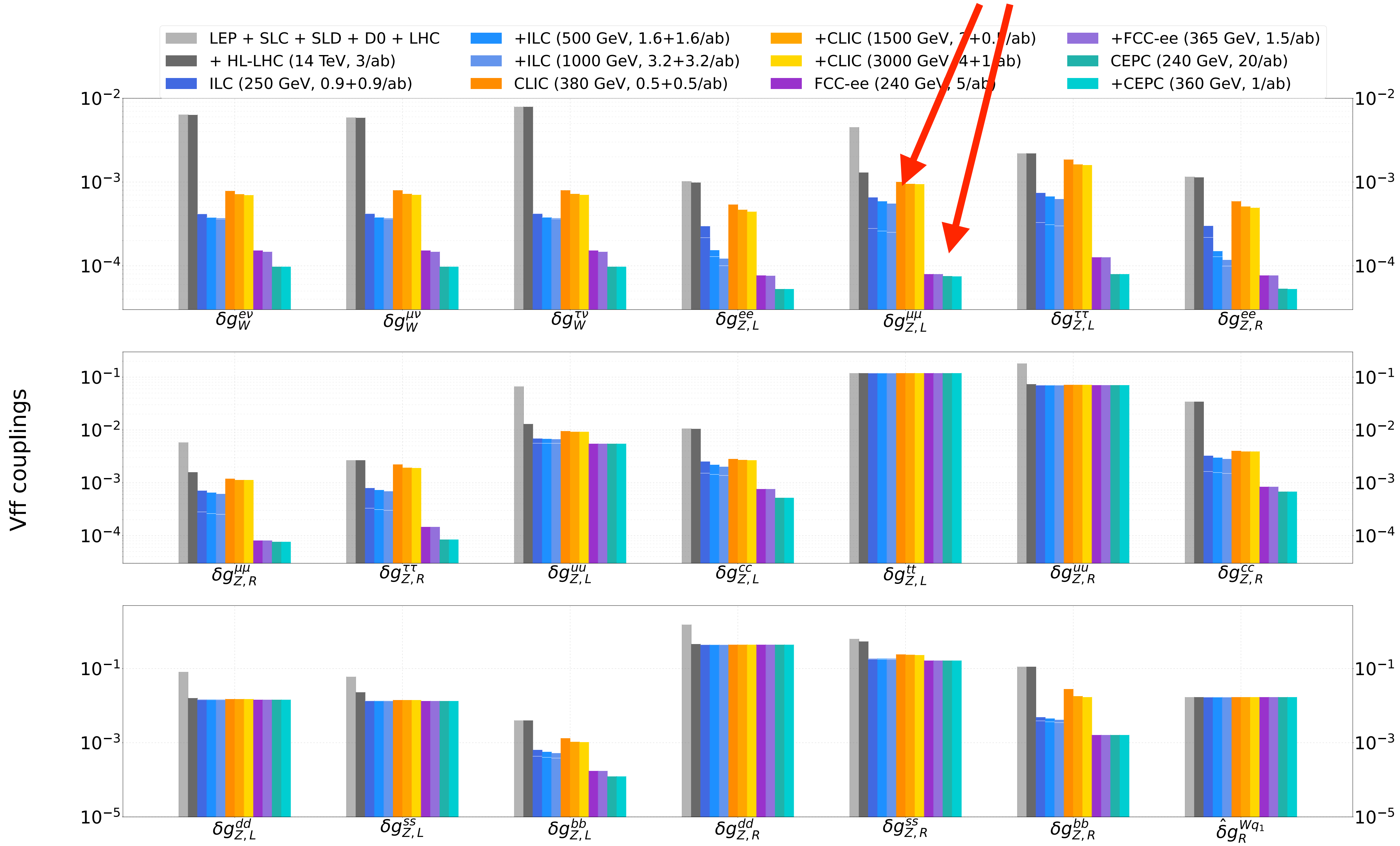


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

SMEFT global fit: *4f*

Global fit results: Vff couplings

Luminosity wins (through radiative return)

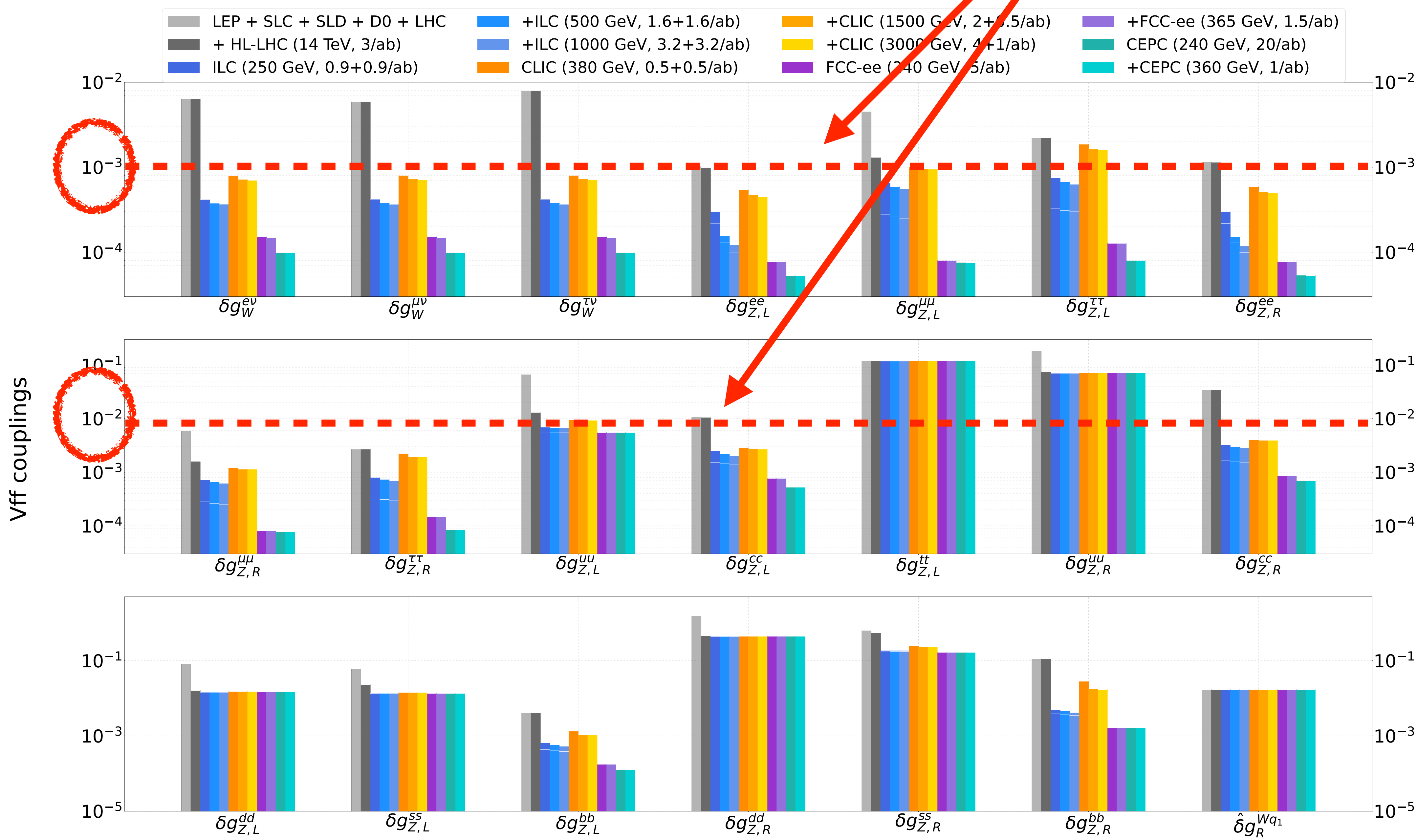


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

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

Global fit results: Vff couplings

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



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

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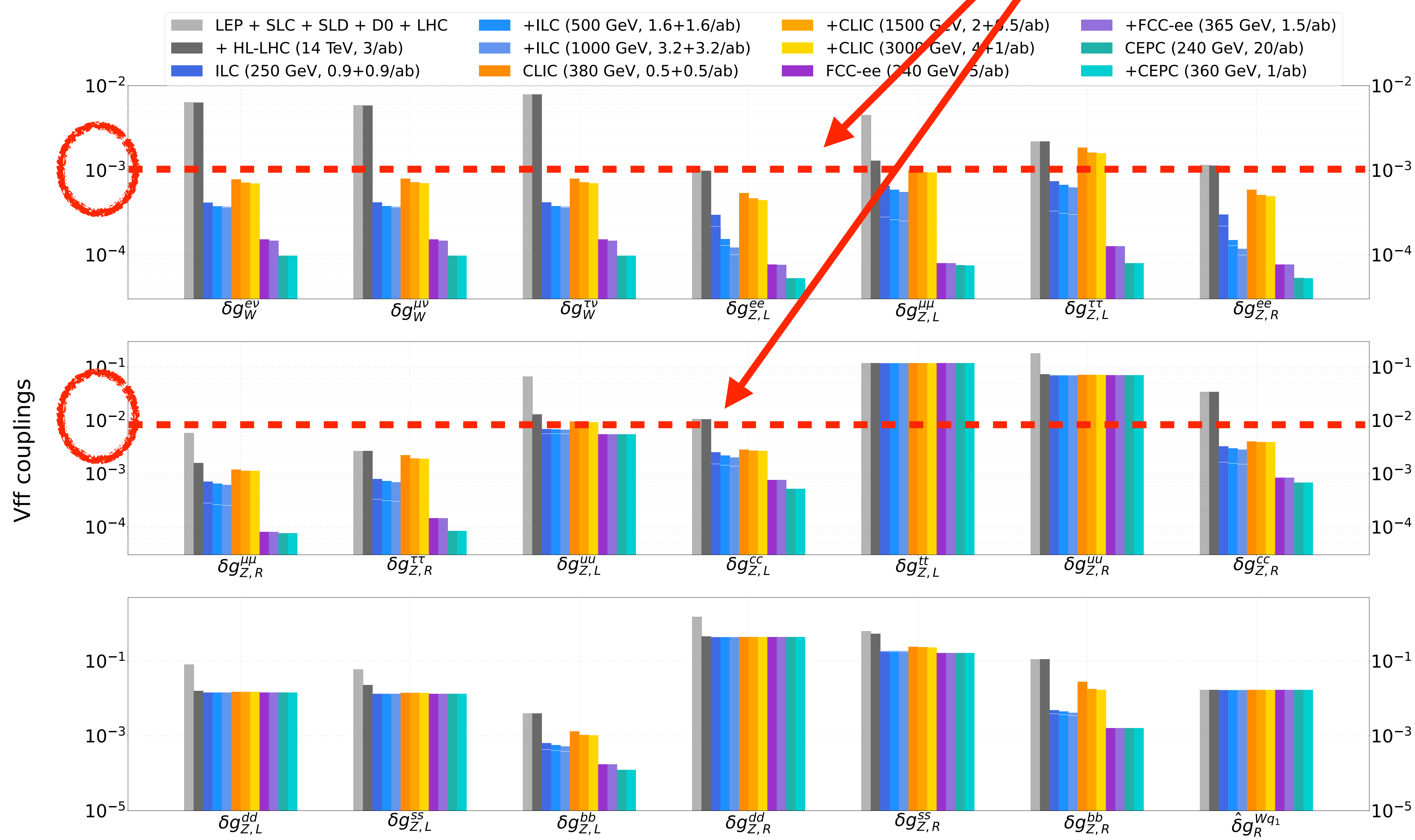


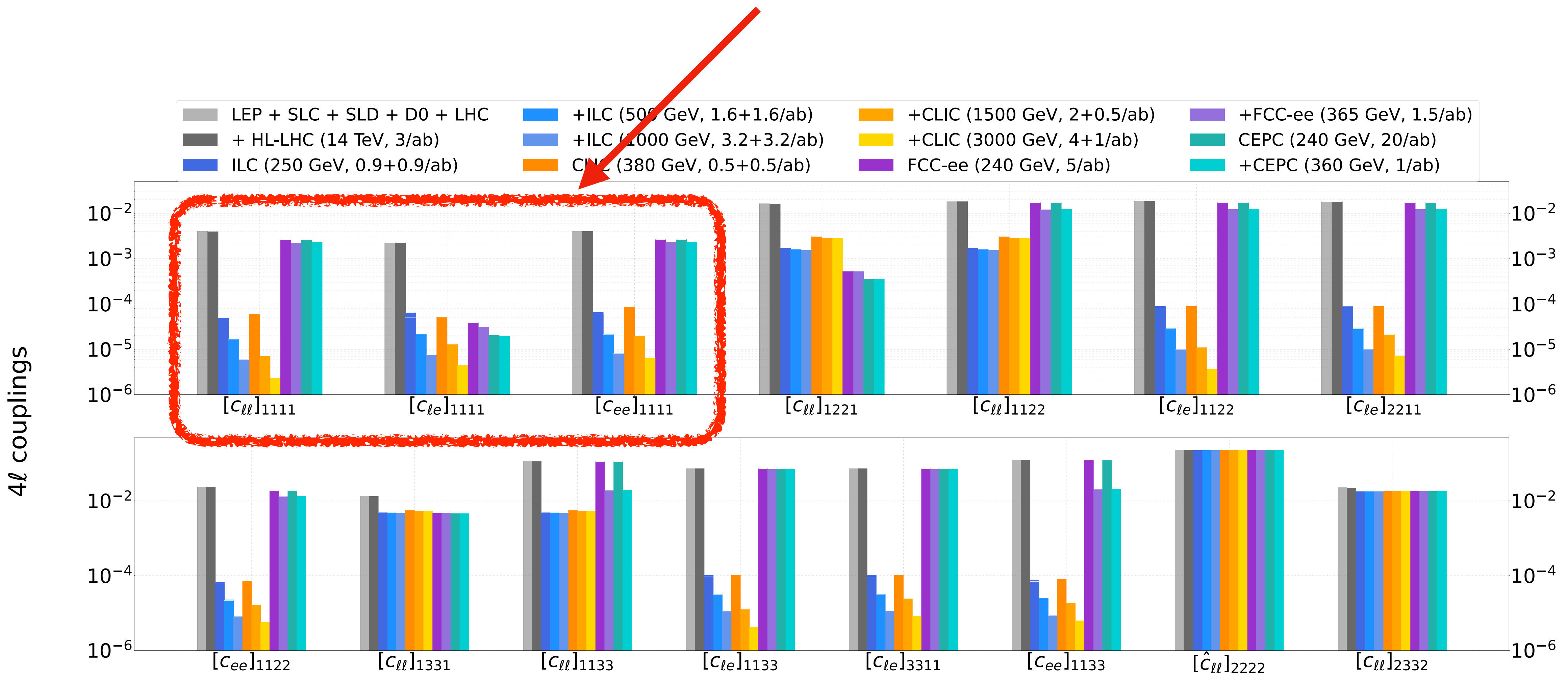
de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

* PhD thesis now under study.

SMEFT global fit: *4f*

Global fit results: 4ℓ couplings

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

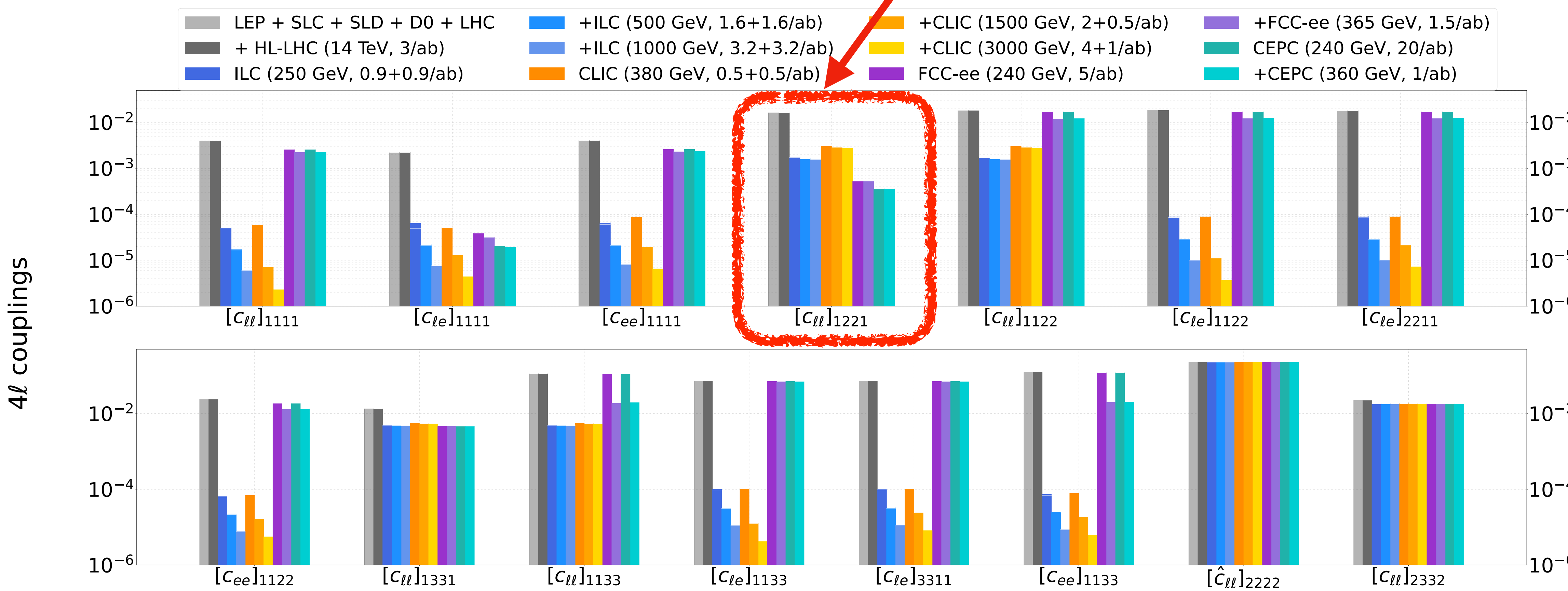


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

SMEFT global fit: *4f*

Global fit results: 4ℓ couplings

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



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

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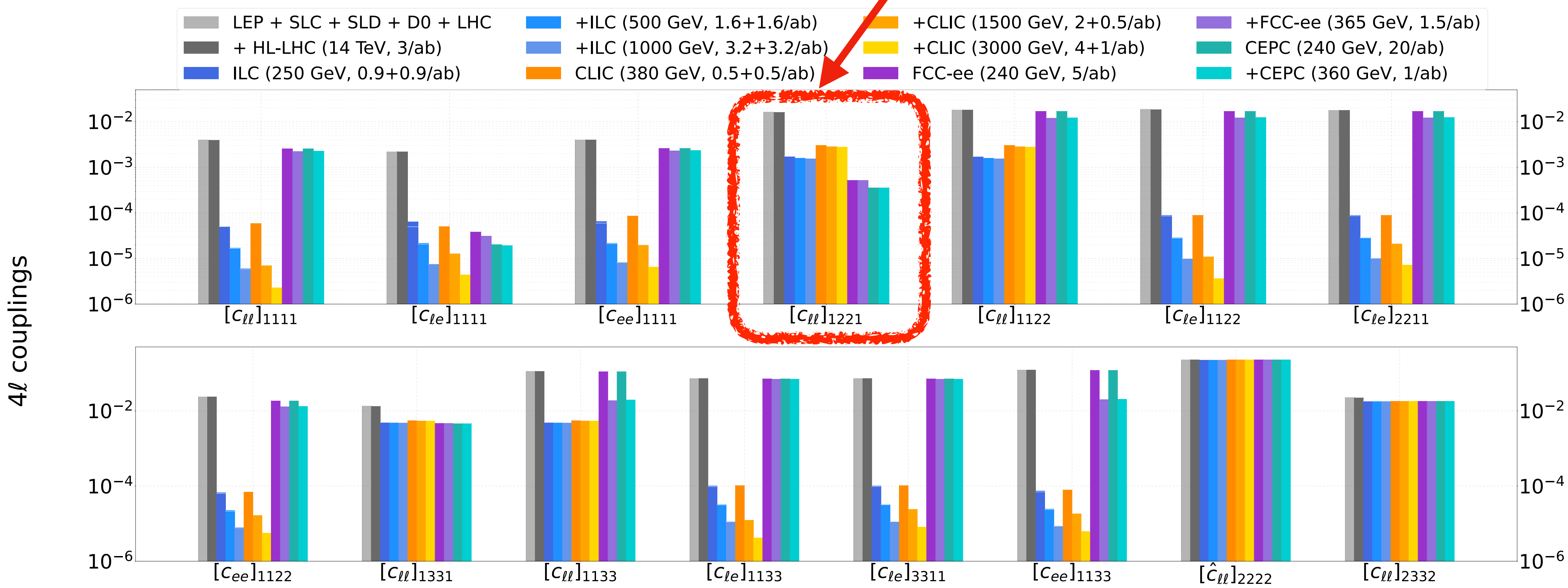
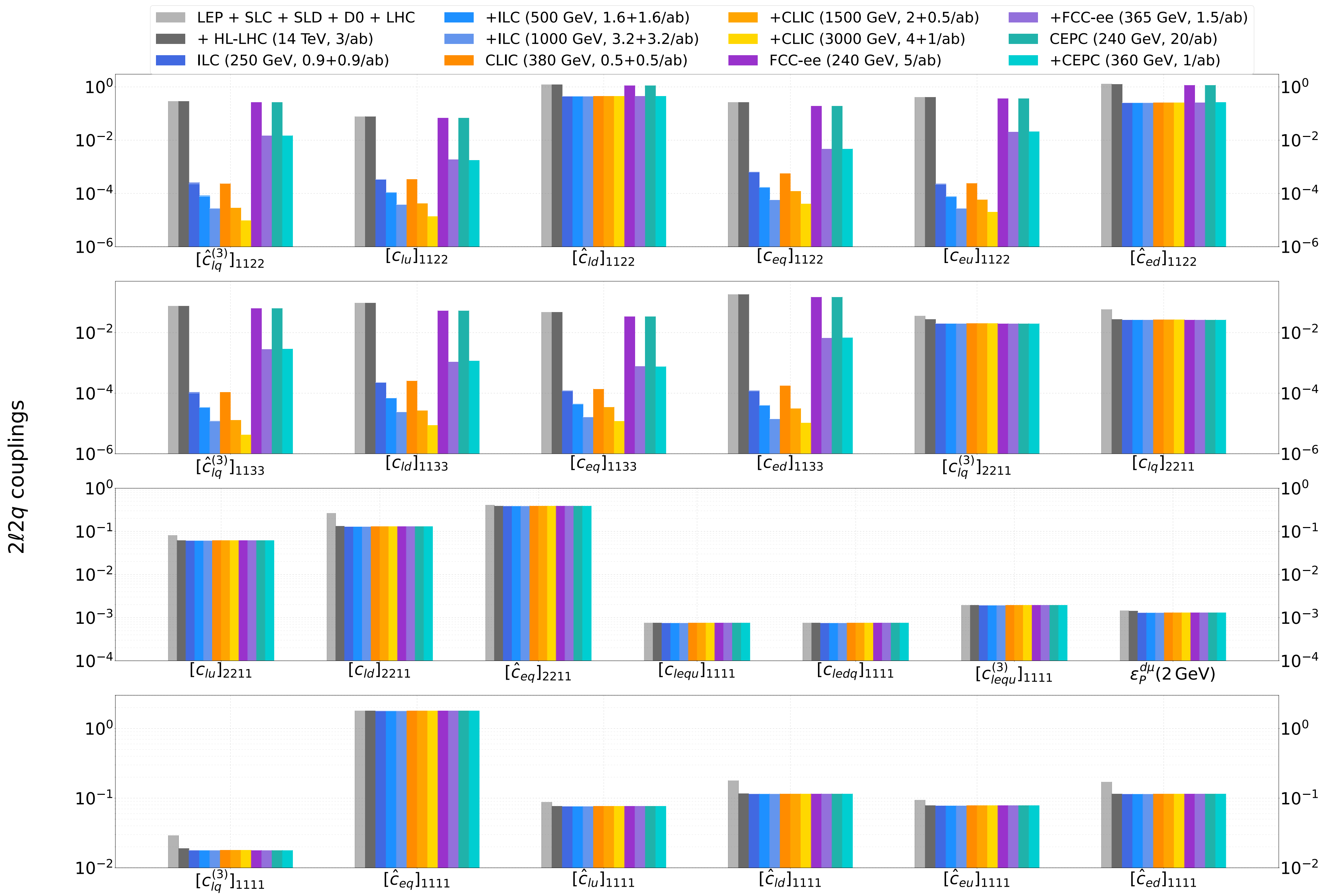


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

* Linear colliders are in general more powerful in exploring 4f operators — a fact largely not realized by the th. & exp. communities.

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

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



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

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

SMEFT global fit: ***CPV***

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

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

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

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

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

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

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

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

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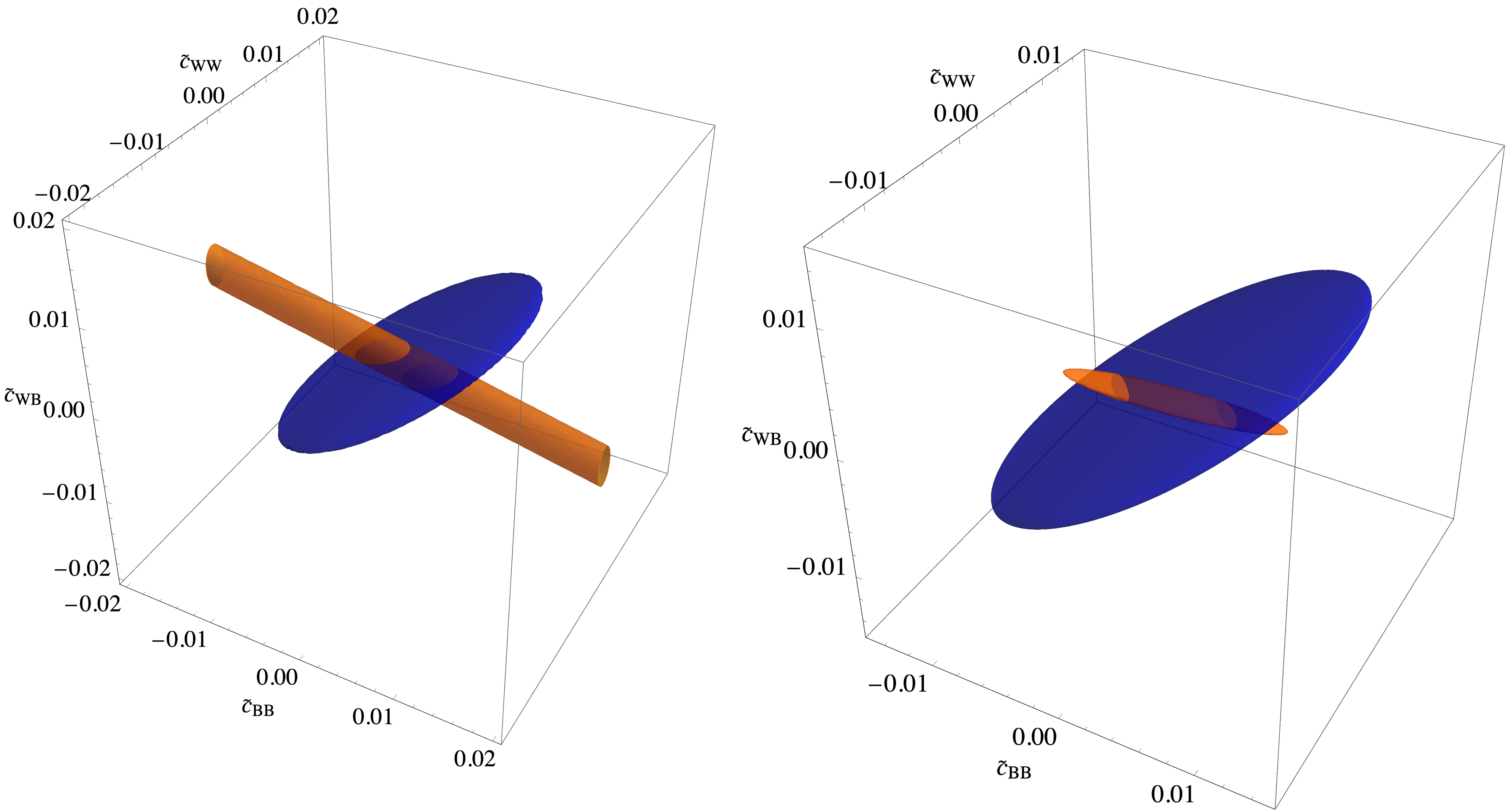
1. Determination of two anomalous triple gauge couplings (aTGC) from $e^+e^- \to W^+W^-$
2. Another two anomalous Higgs couplings (aHC) from $e^+e^- \to Zh$ (dominant production channel of ILC at low energies) using angular asymmetries.

SMEFT global fit: ***CPV***

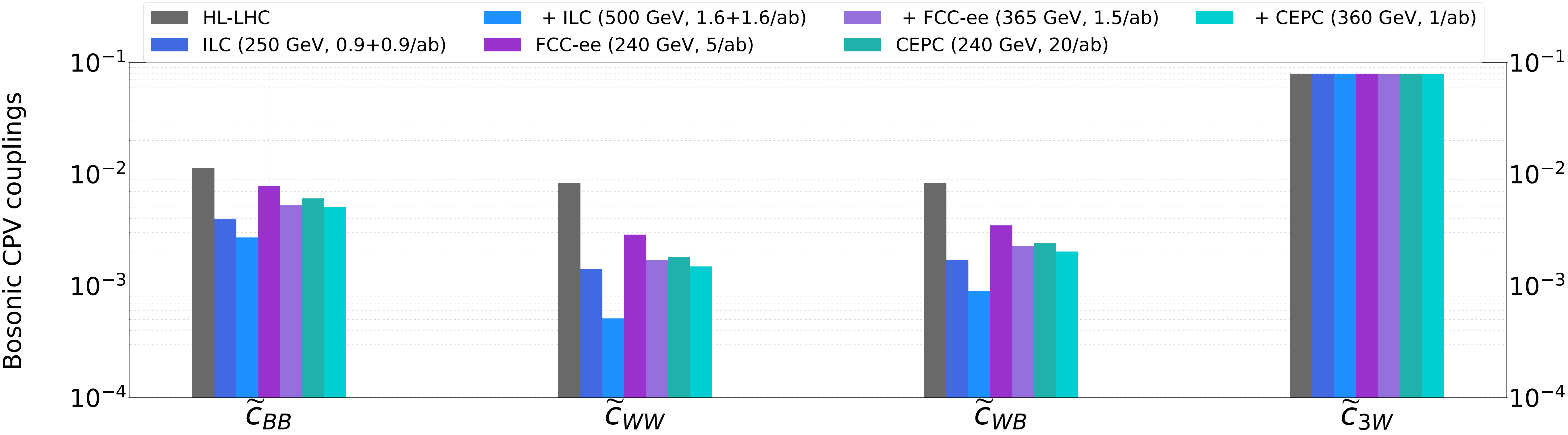
Complementarity of hadron and lepton colliders in probing CP violation



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

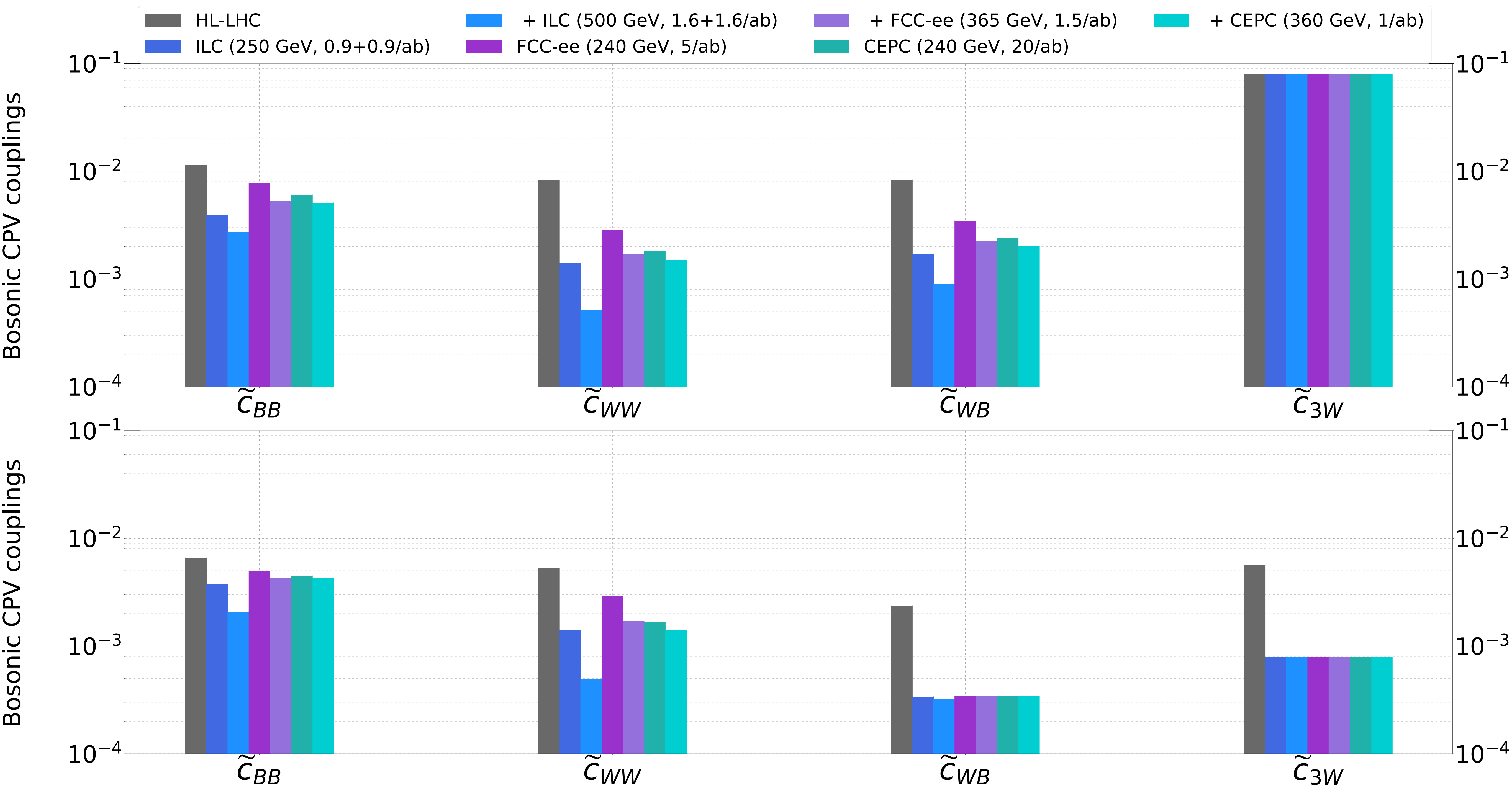
SMEFT global fit: *CPV*

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



SMEFT global fit: CPV

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



Benchmark: *Type-II seesaw model*

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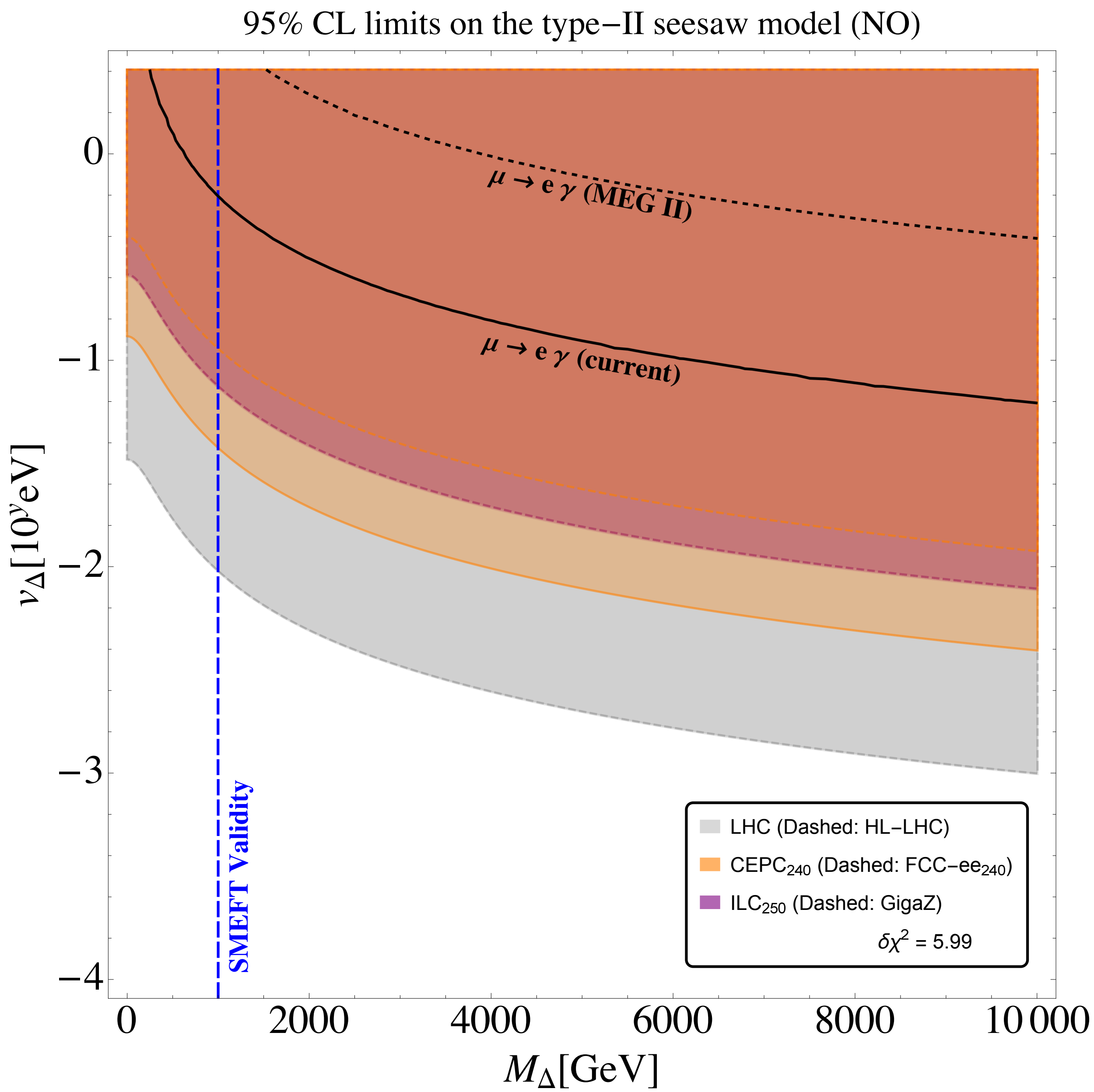
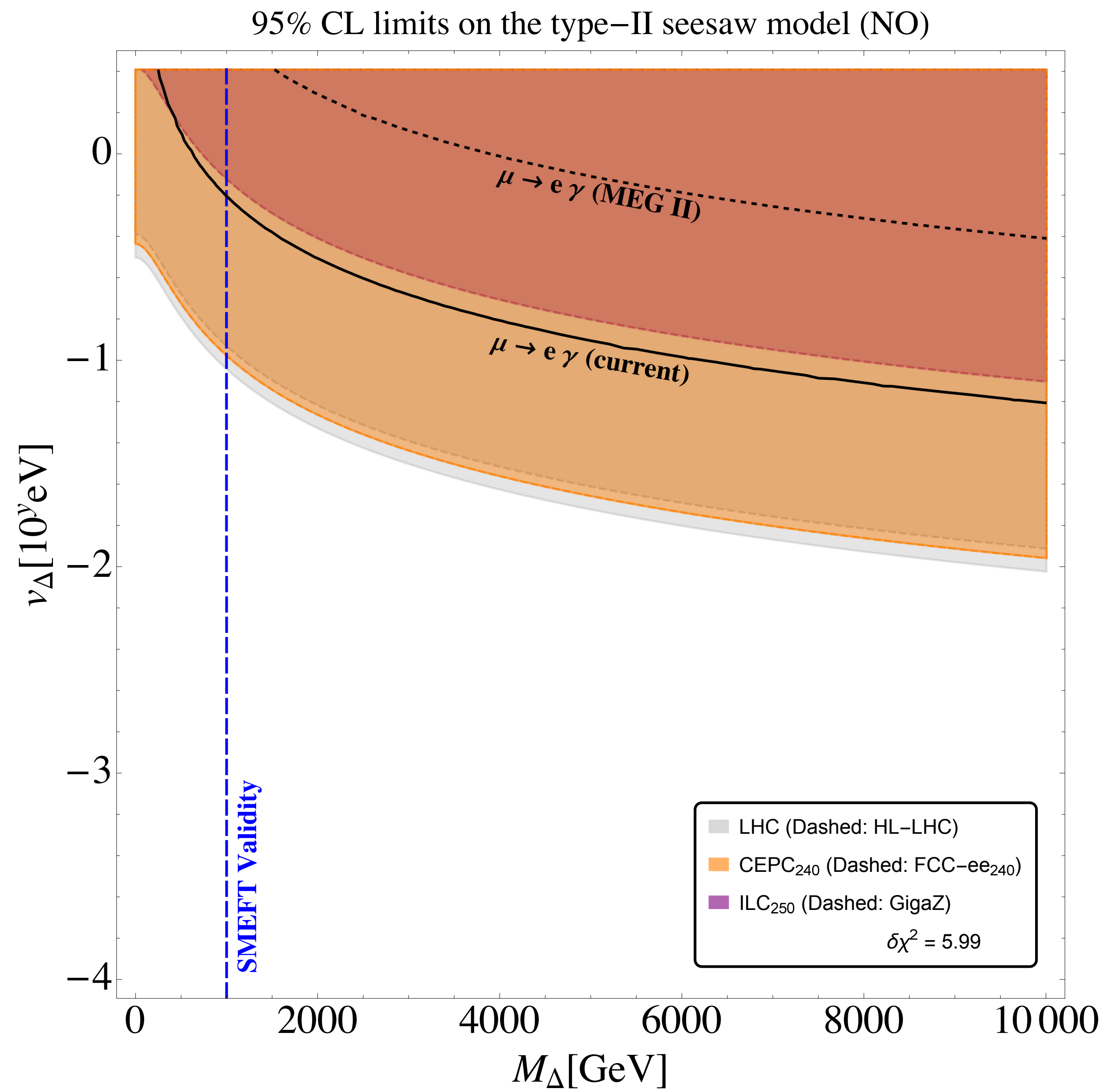
$$V(\Phi,\Delta) \supset \lambda_4(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5\Phi^\dagger\Delta\Delta^\dagger\Phi$$

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



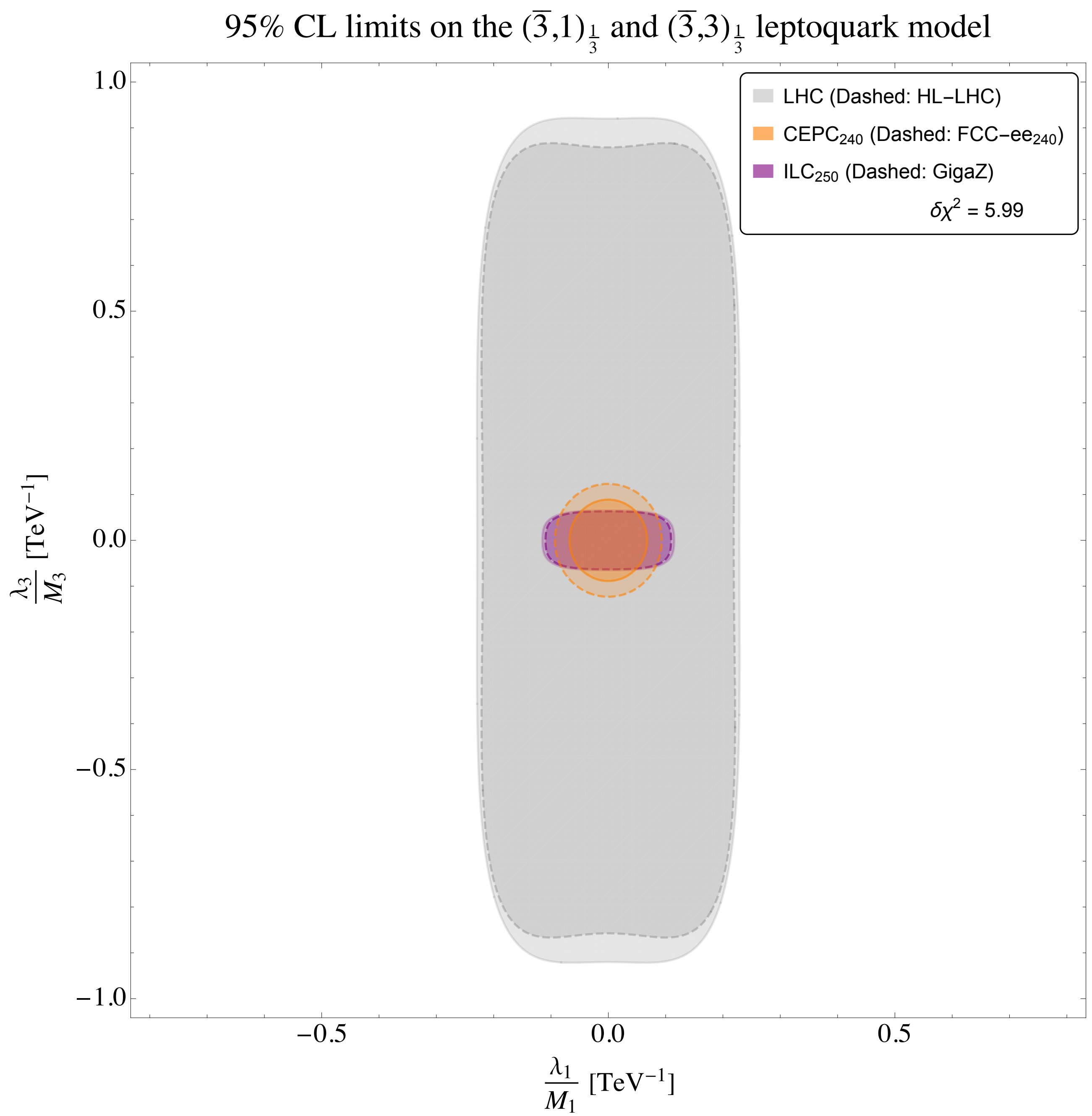


$m_{\text{light}} = 0$ vs $m_{\text{light}} = 0.1\,\text{eV}$

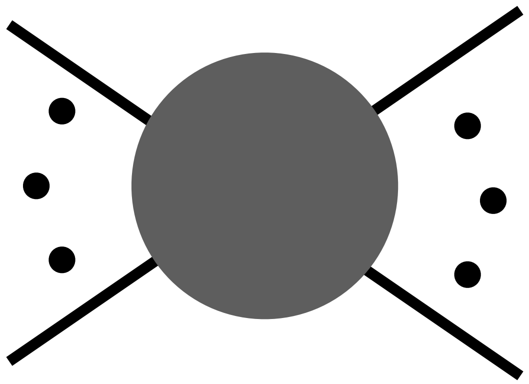
YD, 2303.16400
YD, Li, Yu, 2201.04646 (JHEP)
Li, Zhang, Zhou, 2201.05082 (JHEP)

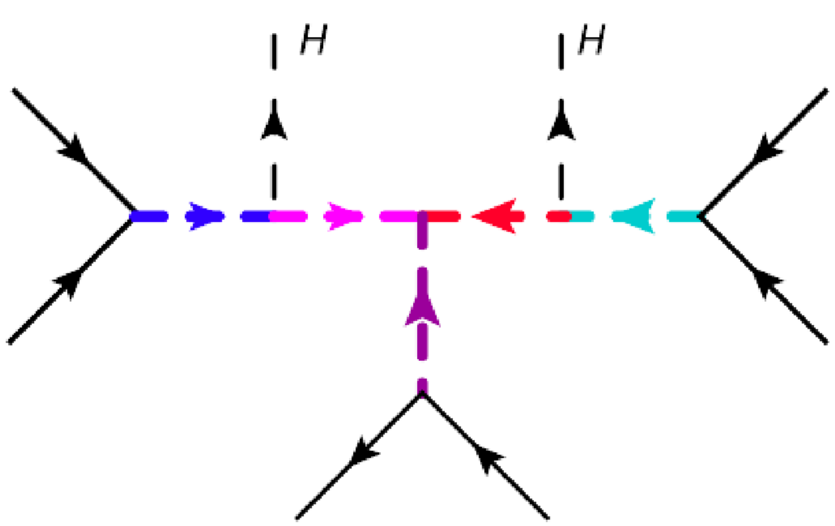
Benchmark: *Leptoquark model*

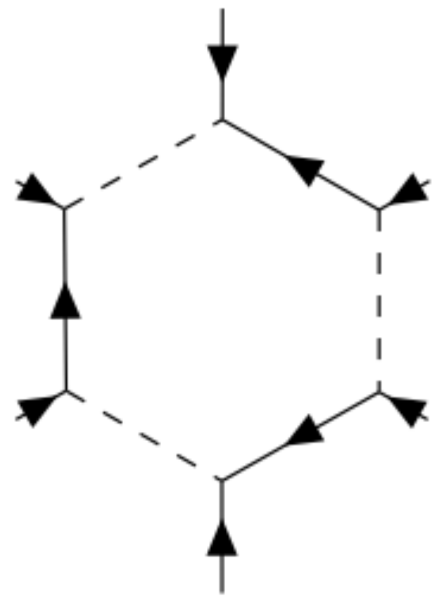
$$\mathcal{L}_{\rm LQ} \supset \left(\lambda^{1L}_{i\alpha}\bar{q}^c_i\epsilon\ell_\alpha + \lambda^{1R}_{i\alpha}\bar{u}^c_i e_\alpha\right) S_1 + \lambda^{3L}_{i\alpha}\bar{q}^c_i\epsilon\sigma^I\ell_\alpha S^I_3 + \textbf{h.c.}$$



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

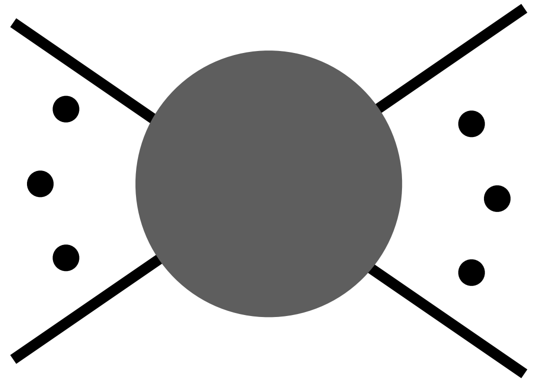


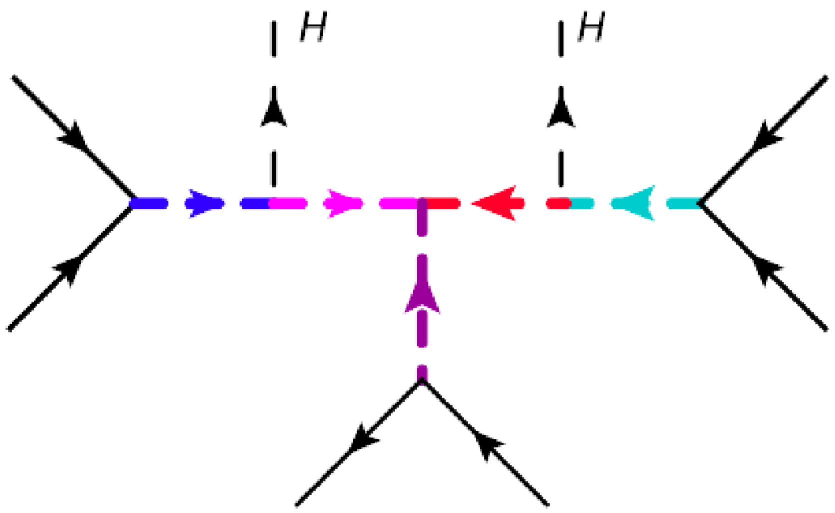


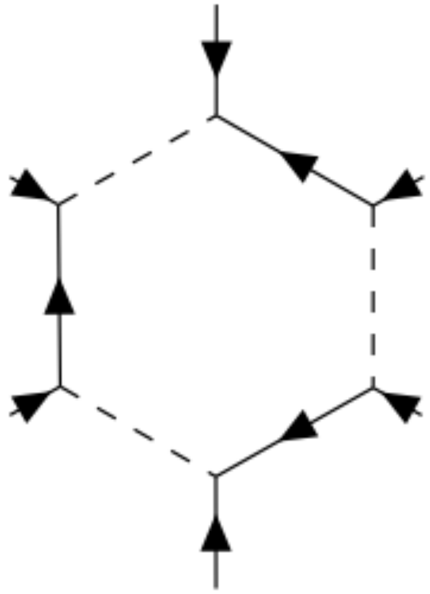


Find the UV models for any operator and any topology (`UVBuilder`).

Benchmark: *The inverse problem*







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

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

YD, Ma, Liao, 2307.XXXXX

SMEFT global fit: ***What is next?***

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Q: What if no future colliders or if the data taking process starts only after I retire?

A: We have many possibilities in neutrino, nuclear, cosmology etc.

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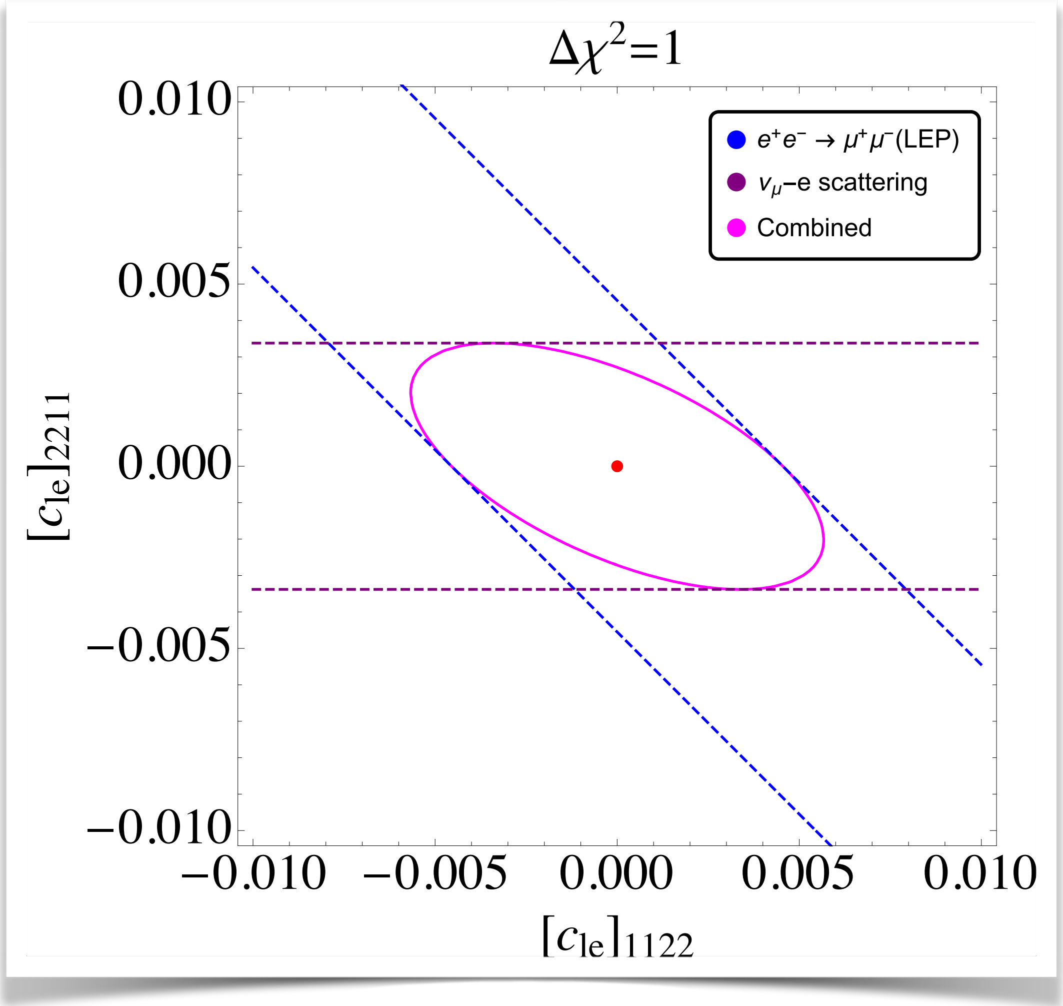

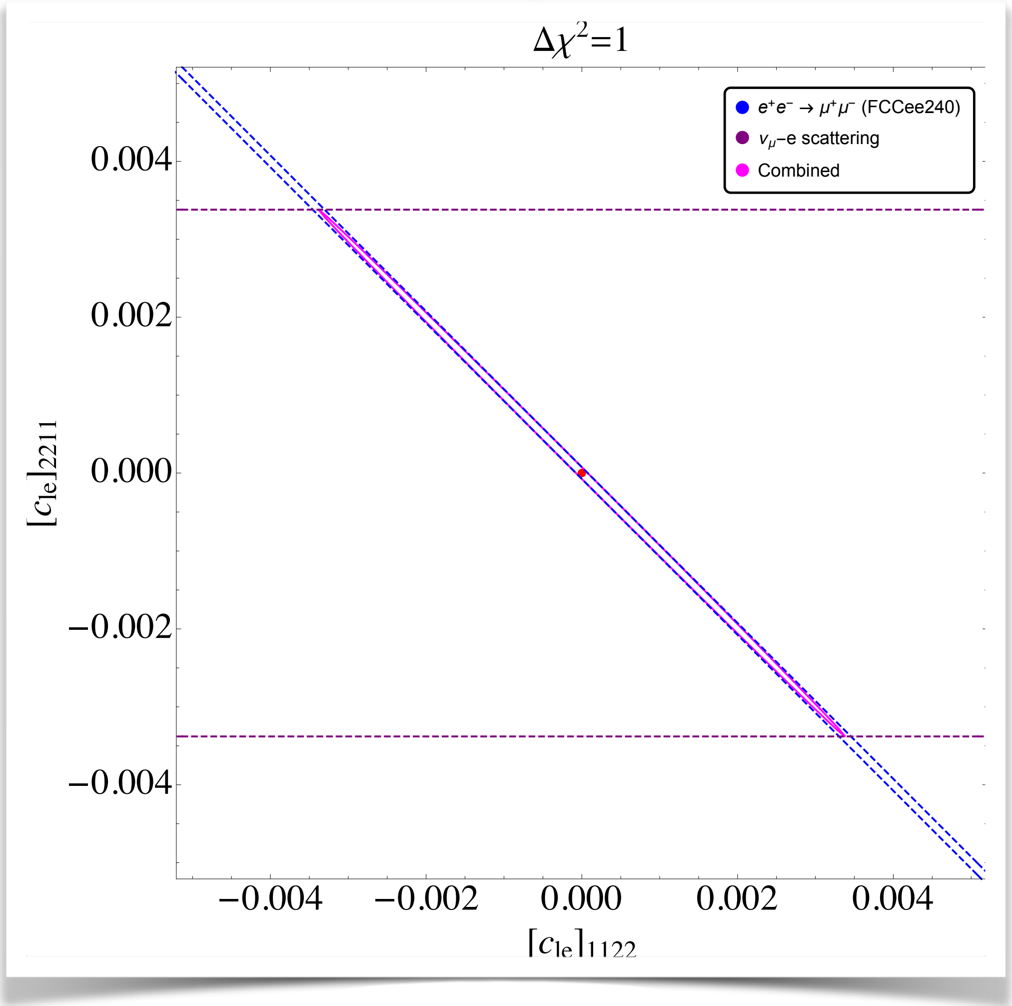

Neutrinos will play a similar role as linear colliders with 100% beam polarization (except for the right-handed sector). Neutrinos always help! This includes N_{eff} from precision cosmology.

SMEFT global fit: Cosmology

The state-of-the-art: the density matrix method

$$\left(\partial_t - Hp\partial_p\right)\rho_p(t) = -i\left[\left(\frac{1}{2p}\mathbb{M}_\mathrm{F} - \frac{8\sqrt{2}G_\mathrm{F}p}{3m_\mathrm{W}^2}\mathbb{E}\right), \rho_p(t)\right] + C\left[\rho_p(t)\right]$$

Usual out-of-equilibrium PSD

$$\rho_p(t) = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} \end{pmatrix}$$

Mixing from the oscillation (important 0.0007 shift of N_{eff})

Yvonne Wong's talk on Monday

C the usual collision term integral — sources of the most challenging part (too many coupled stiff integro-differential ODEs)

Calculations were made way easier with equilibrium distribution approximation with evolving temperature and chemical potential due to the expansion of the Universe.

Escudero, 2001.04466 (JCAP)

C can be obtained analytically then. Once this is done, accurate N_{eff} can be obtained in a few secs/mins.

SMEFT global fit: Cosmology

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Escudero, 2001.04466 (JCAP)

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Even for $2 \to 2$ processes, these are 12-fold integrals, very time consuming, and better that we have a dictionary for quick lookup.

SMEFT global fit: Cosmology

YD, Yu, 2101.10475 (JHEP)

$$C^{(j)}(p_{12}^2\cdot p_{14})=\begin{cases}-\frac{9}{2\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ -\frac{15}{2\pi^5}\left[3e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(2T_3+T_4)\right], & j=1\end{cases},\quad (4.22)$$

$$C^{(j)}(p_{12}\cdot p_{13}^2)=\begin{cases}-\frac{3}{\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ -\frac{15}{4\pi^5}\left[4e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(T_3+3T_4)\right], & j=1\end{cases},\quad (4.23)$$

$$C^{(j)}(p_{12}\cdot p_{13}\cdot p_{14})=\begin{cases}\frac{3}{2\pi^5}\left[-e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5+e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ \frac{15}{4\pi^5}\left[-2e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5+e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(T_3+T_4)\right], & j=1\end{cases},\quad (4.24)$$

$$C^{(j)}(p_{12}\cdot p_{14}^2)=\begin{cases}-\frac{3}{\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ -\frac{15}{4\pi^5}\left[4e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(3T_3+T_4)\right], & j=1\end{cases},\quad (4.25)$$

$$C^{(j)}(p_{13}^3)=\begin{cases}\frac{9}{4\pi^5}\left[-e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5+e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ \frac{9}{4\pi^5}\left[-5e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5+e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(T_3+4T_4)\right], & j=1\end{cases},\quad (4.26)$$

$$C^{(j)}(p_{13}^2\cdot p_{14})=\begin{cases}-\frac{3}{4\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ -\frac{3}{4\pi^5}\left[5e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(2T_3+3T_4)\right], & j=1\end{cases},\quad (4.27)$$

$$C^{(j)}(p_{13}\cdot p_{14}^2)=\begin{cases}-\frac{3}{4\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ -\frac{3}{4\pi^5}\left[5e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(3T_3+2T_4)\right], & j=1\end{cases},\quad (4.28)$$

$$C^{(j)}(p_{14}^3)=\begin{cases}-\frac{9}{4\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0\\ -\frac{9}{4\pi^5}\left[5e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5-e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(4T_3+T_4)\right], & j=1\end{cases},\quad (4.29)$$

JHEP05(2021)058

(1) For *any* related SM processes.

(2) For *any* UV theories (above m_μ).

(3) For *any* EFTs up to dim-7.

The stiff integro-differential equations then become trivial ODEs (`EFT2Neff`).

SMEFT global fit: Cosmology

YD, Yu, 2101.10475 (JHEP)

$$C^{(j)}(p_{12}^2\cdot p_{14}) = \begin{cases} -\frac{9}{2\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5 - e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0 \\ -\frac{15}{2\pi^5}\left[3e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5 - e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(2T_3+T_4)\right], & j=1 \end{cases}, \quad (4.22)$$

$$C^{(j)}(p_{12}\cdot p_{13}^2) = \begin{cases} -\frac{3}{\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5 - e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0 \\ -\frac{15}{4\pi^5}\left[4e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5 - e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(T_3+3T_4)\right], & j=1 \end{cases}, \quad (4.23)$$

$$C^{(j)}(p_{12}\cdot p_{13}\cdot p_{14}) = \begin{cases} \frac{3}{2\pi^5}\left[-e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5 + e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0 \\ \frac{15}{4\pi^5}\left[-2e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5 + e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(T_3+T_4)\right], & j=1 \end{cases}, \quad (4.24)$$

$$C^{(j)}(p_{12}\cdot p_{14}^2) = \begin{cases} -\frac{3}{\pi^5}\left[e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^5T_2^5 - e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5\right], & j=0 \\ -\frac{15}{4\pi^5}\left[4e^{\frac{\mu_1}{T_1}+\frac{\mu_2}{T_2}}T_1^6T_2^5 - e^{\frac{\mu_3}{T_3}+\frac{\mu_4}{T_4}}T_3^5T_4^5(3T_3+T_4)\right], & j=1 \end{cases}, \quad (4.25)$$

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JHEP05(2021)058

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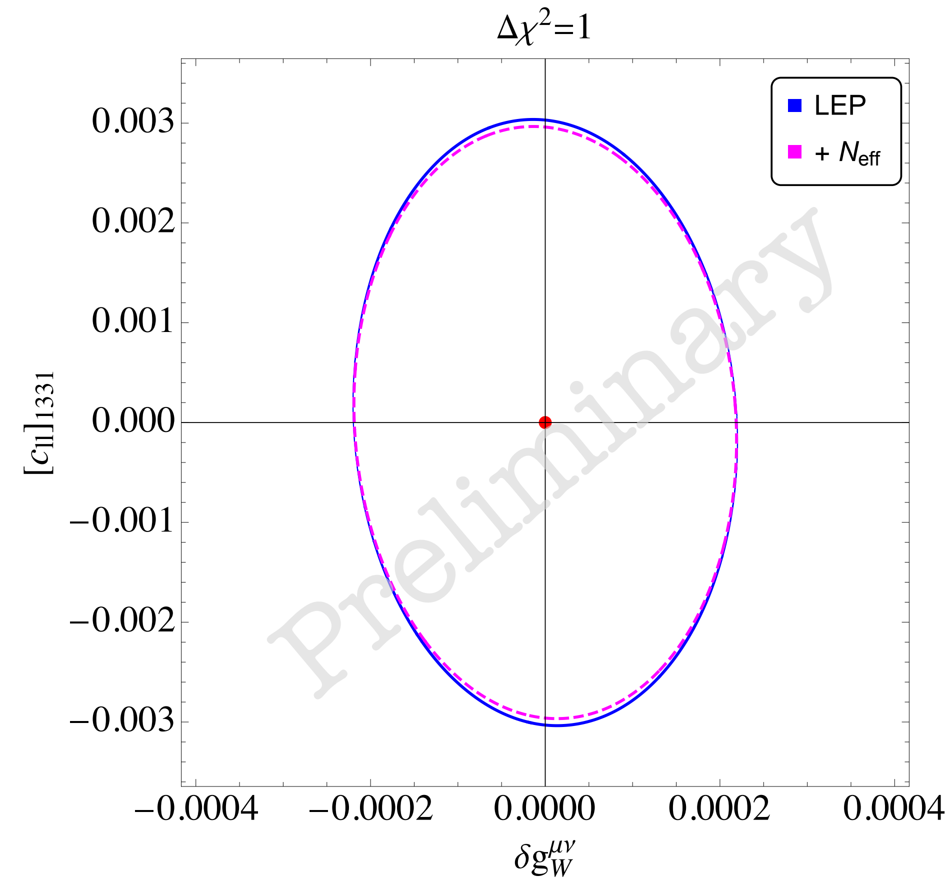
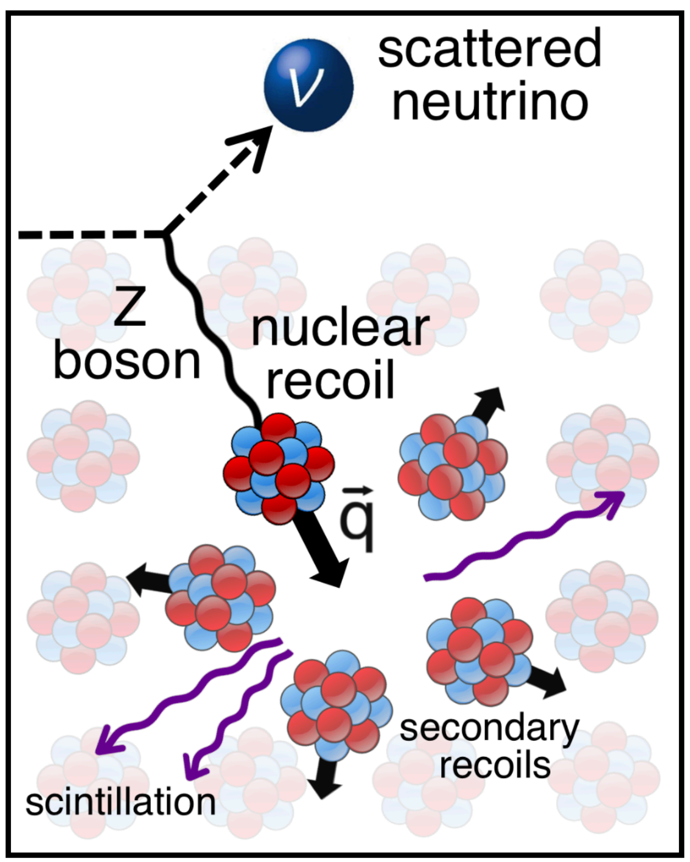


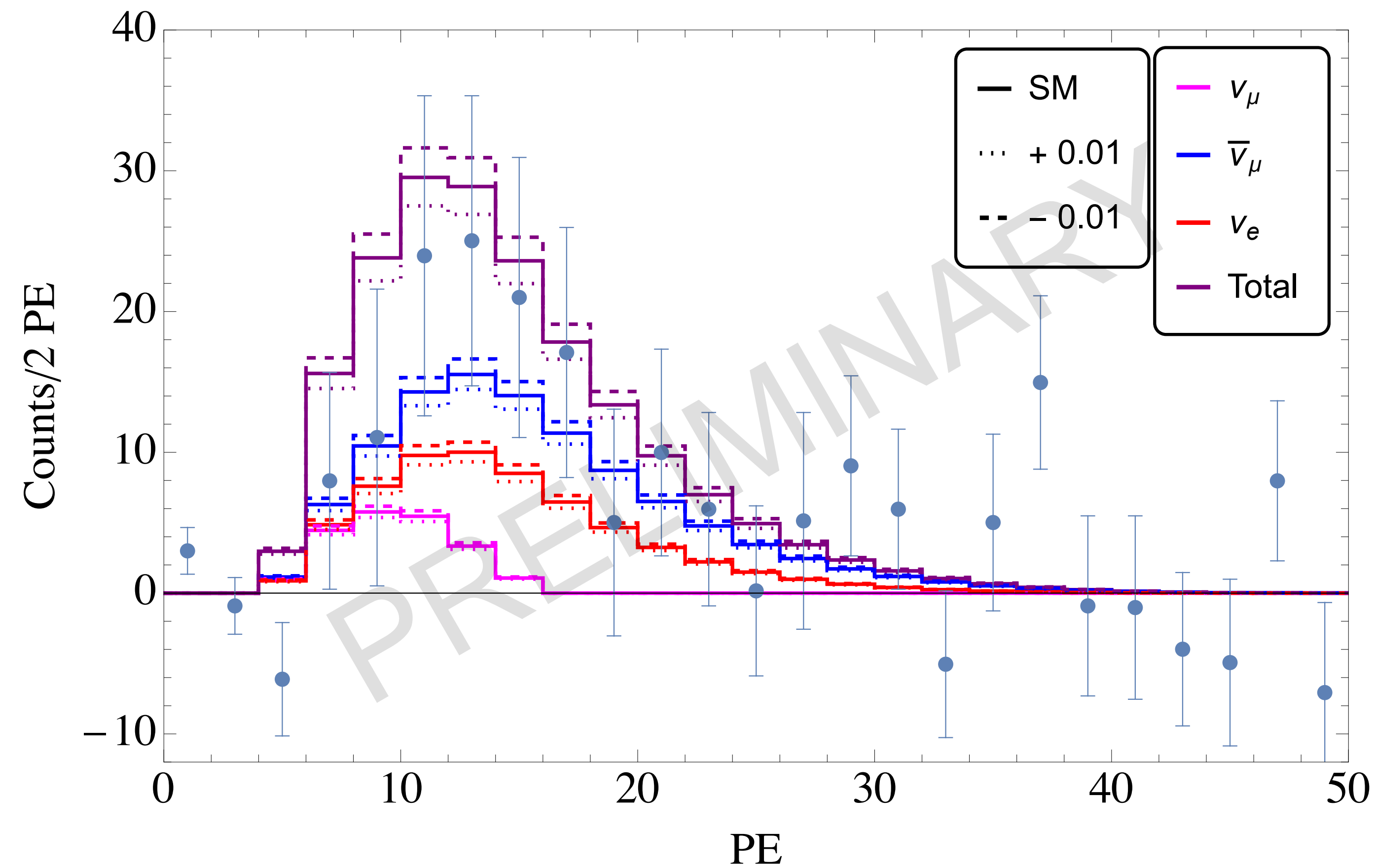
SMEFT global fit: CEvNS

$2\ell 2q$ 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
$[\mathcal{O}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{e}^c_p)\epsilon_{jk}(\bar{q}^k_r \bar{u}^c_r)$	$[\mathcal{O}_{\ell\ell}]_{pppp} = \frac{1}{2}(\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(\bar{\ell}_p \bar{\sigma}^\mu \ell_p)$
$[O^{(3)}_{\ell equ}]_{pprr} = (\bar{\ell}^j_p \bar{\sigma}_{\mu\nu} \bar{e}^c_p)\epsilon_{jk}(\bar{q}^k_r \bar{\sigma}_{\mu\nu} \bar{u}^c_r)$	$[\mathcal{O}_{\ell e}]_{pppp} = (\bar{\ell}_p \bar{\sigma}_\mu \ell_p)(e^c_p \sigma^\mu \bar{e}^c_p)$
$[\mathcal{O}_{\ell edq}]_{pprr} = (\bar{\ell}^j_p \bar{e}^c_p)(d^c_r q^j_r)$	$[\mathcal{O}_{ee}]_{pppp} = \frac{1}{2}(e^c_p \sigma_\mu \bar{e}^c_p)(e^c_p \sigma^\mu \bar{e}^c_p)$

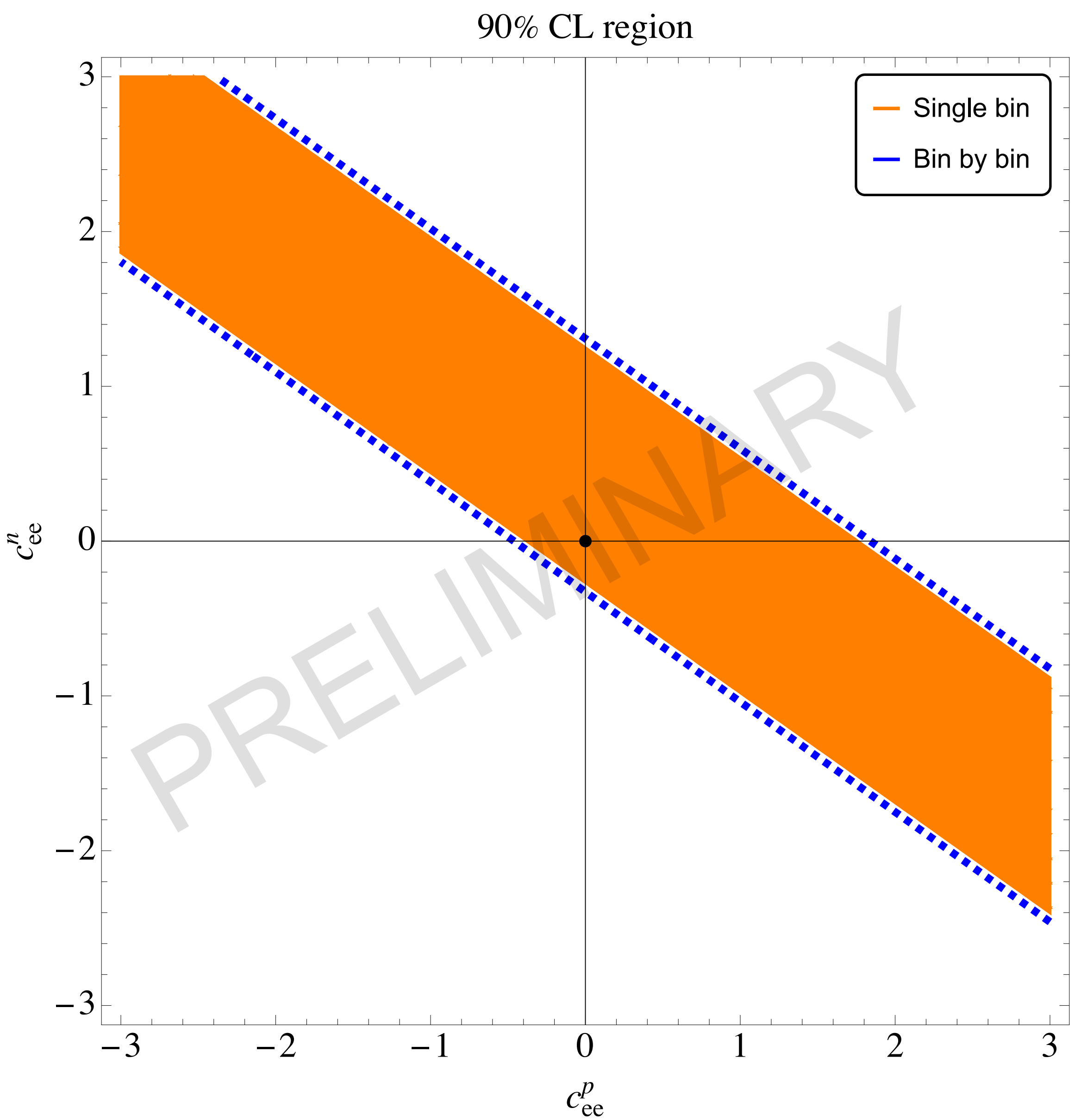
$$g_p^V = g_p^{V,\mathrm{SM}} + 3[c_{\ell q}] + [c^{(3)}_{\ell q}] + 2[c_{\ell u}] + [c_{\ell d}]$$

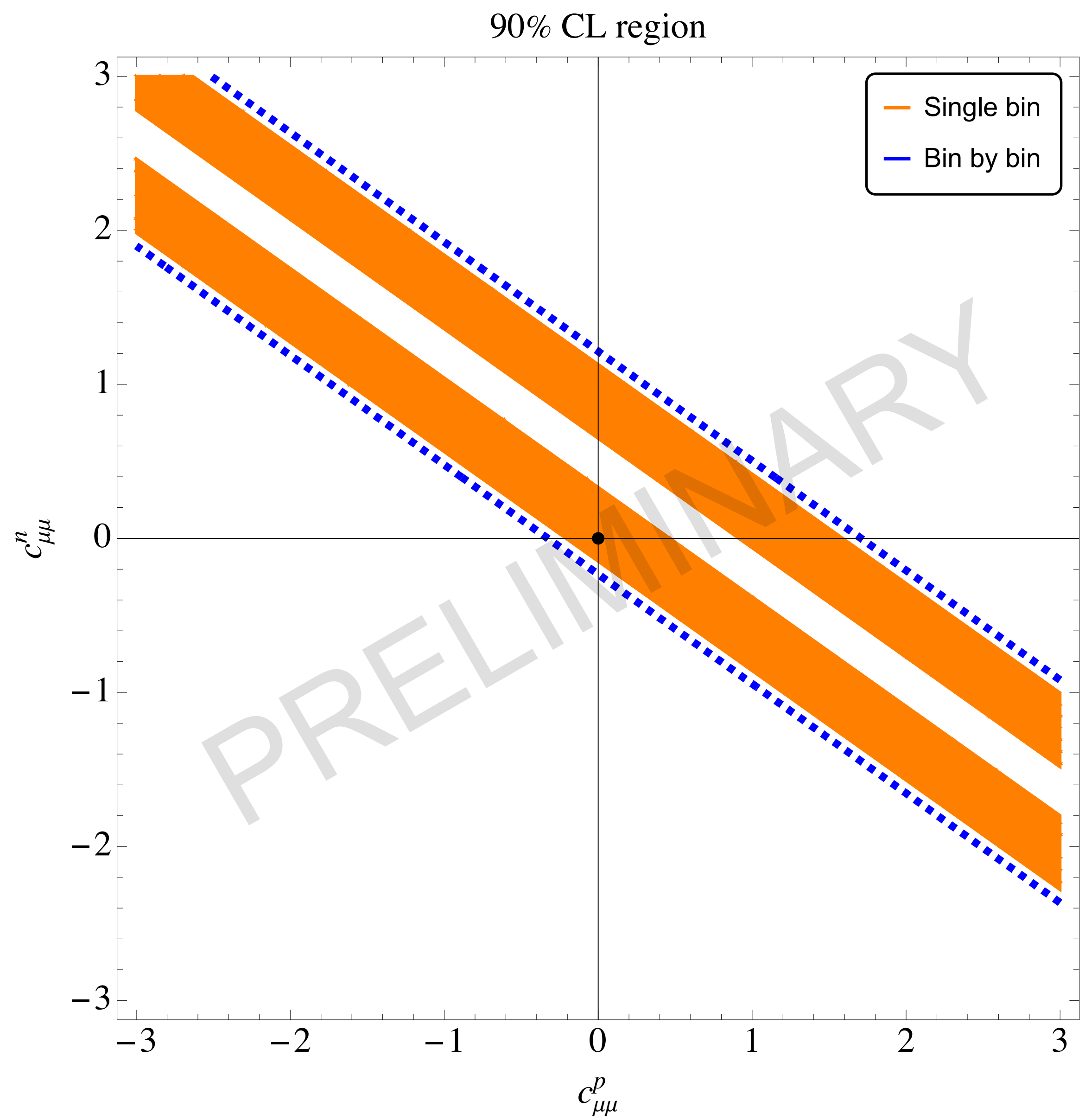
$$g_n^V = g_n^{V,\mathrm{SM}} + 3[c_{\ell q}] - [c^{(3)}_{\ell q}] + [c_{\ell u}] + 2[c_{\ell d}]$$





SMEFT global fit: ***CEvNS***



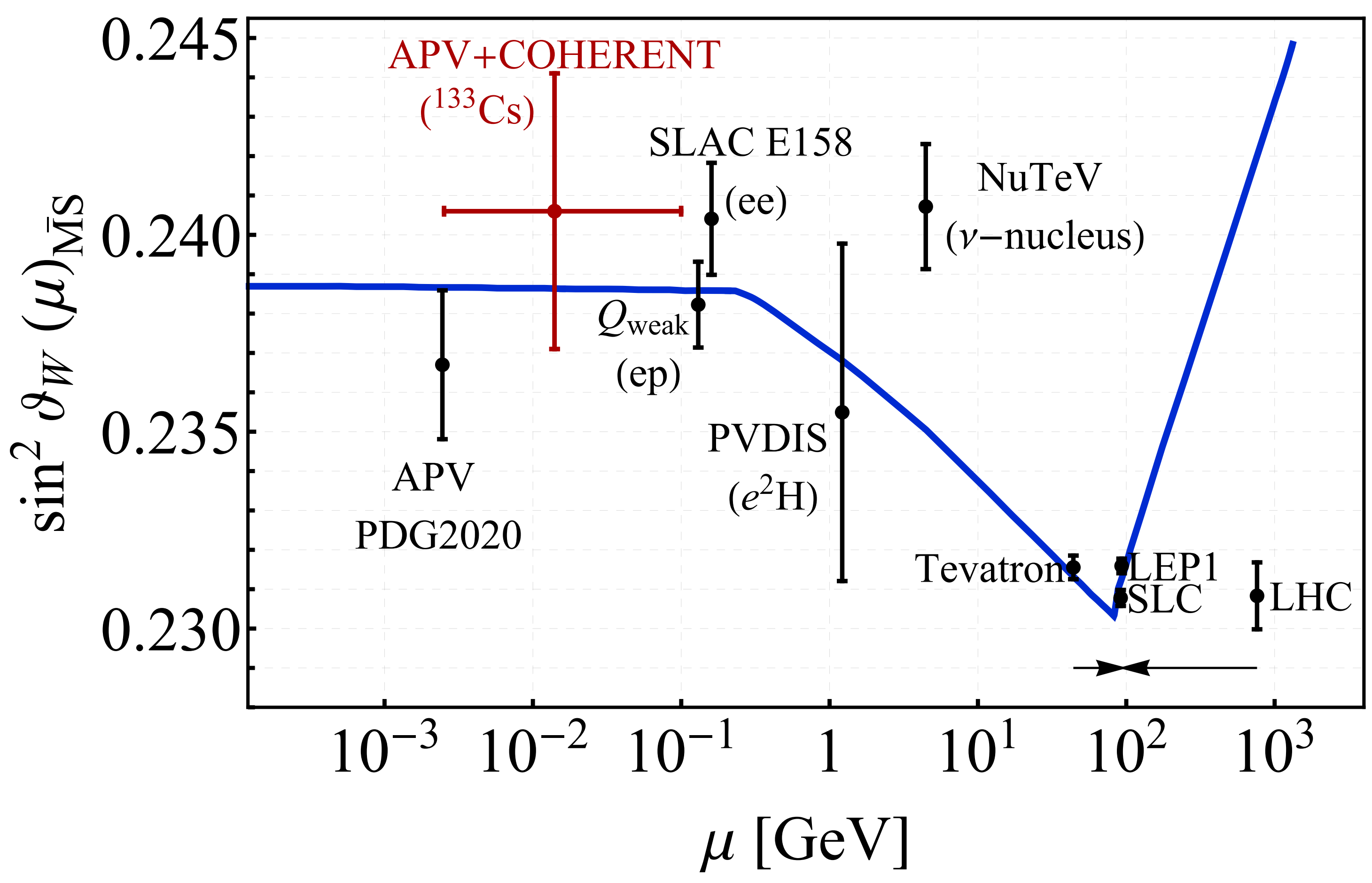


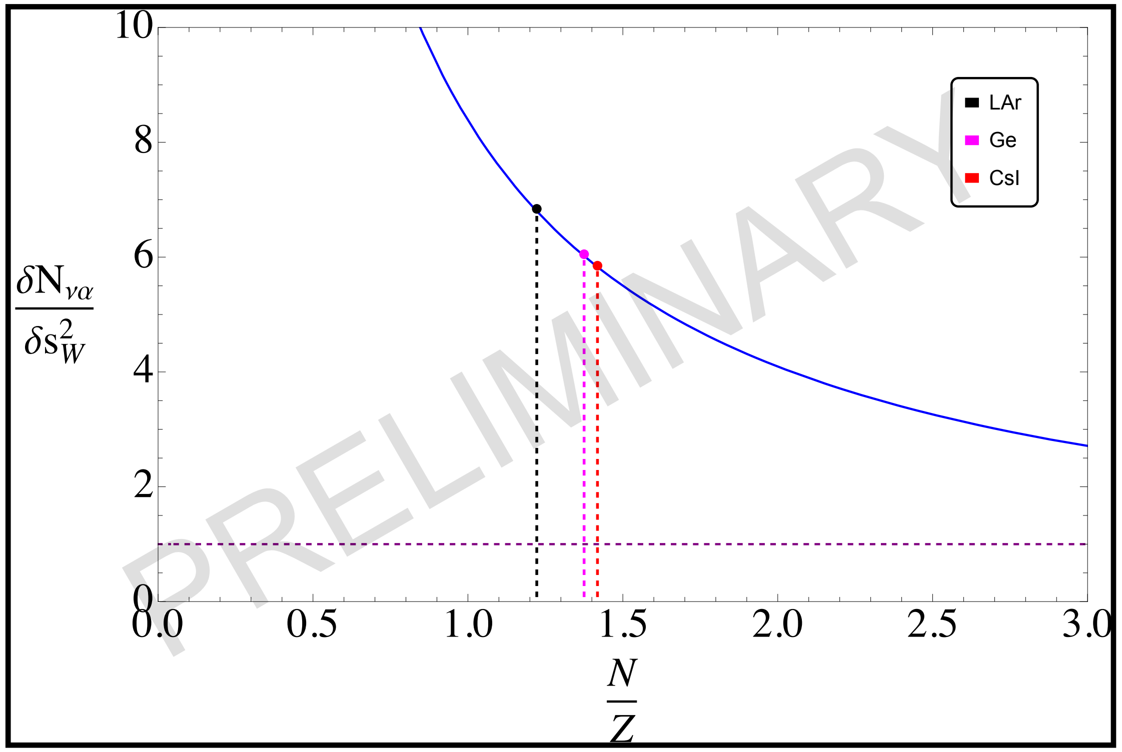
Martin Gonzalez-Alonso's talk next

SMEFT global fit: CEvNS

Weak mixing angle measurement

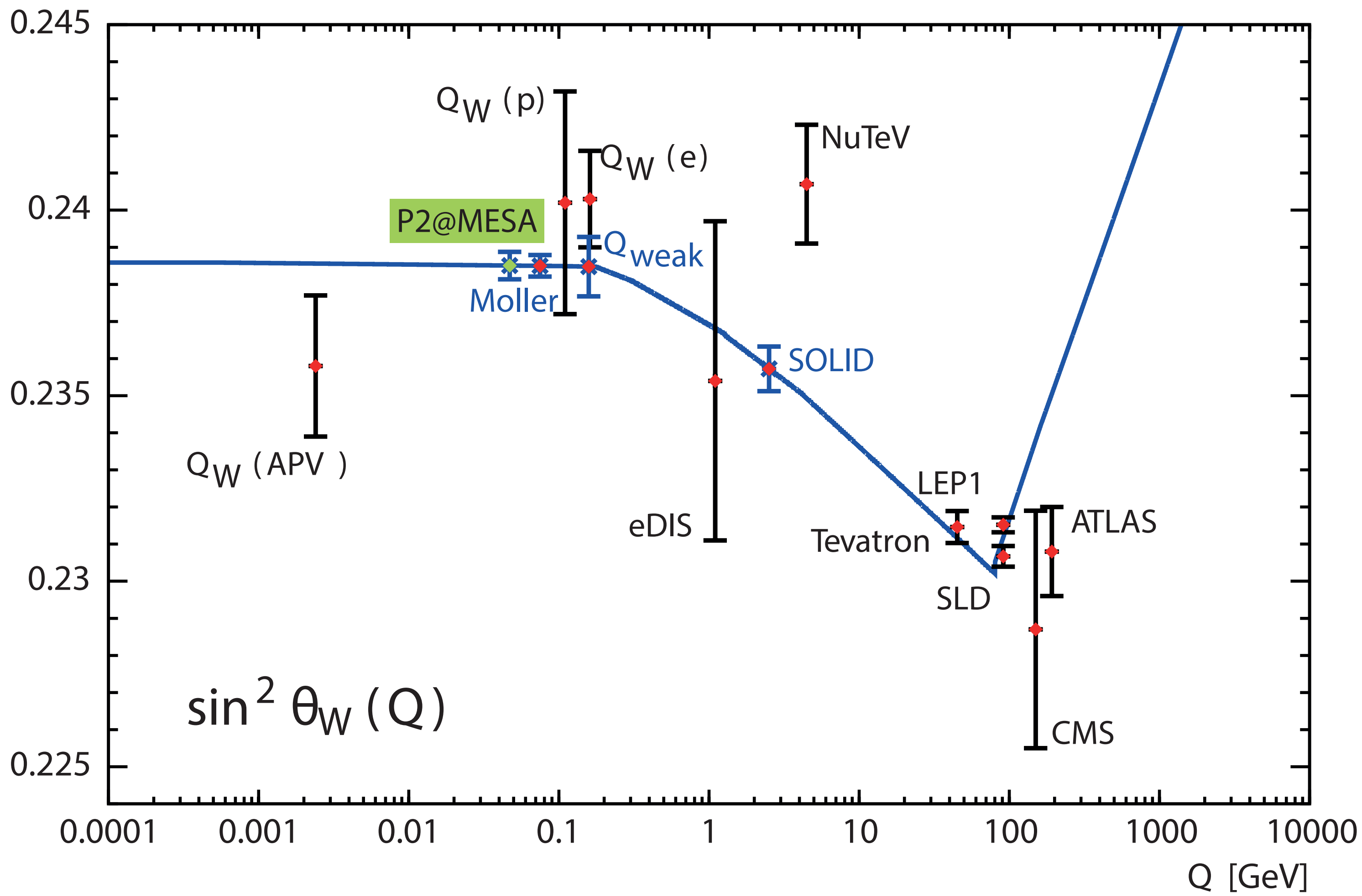
$$\frac{dN_\alpha}{dE_R} = n_N \int dE_\nu \phi_\alpha(E_\nu) \frac{d\sigma_\alpha}{dE_r} \propto (A - 2Z + 4s_w^2 Z)^2$$





M. Cadeddu, Y.F. Li et al, PRC 2021

SMEFT global fit: *PVES*

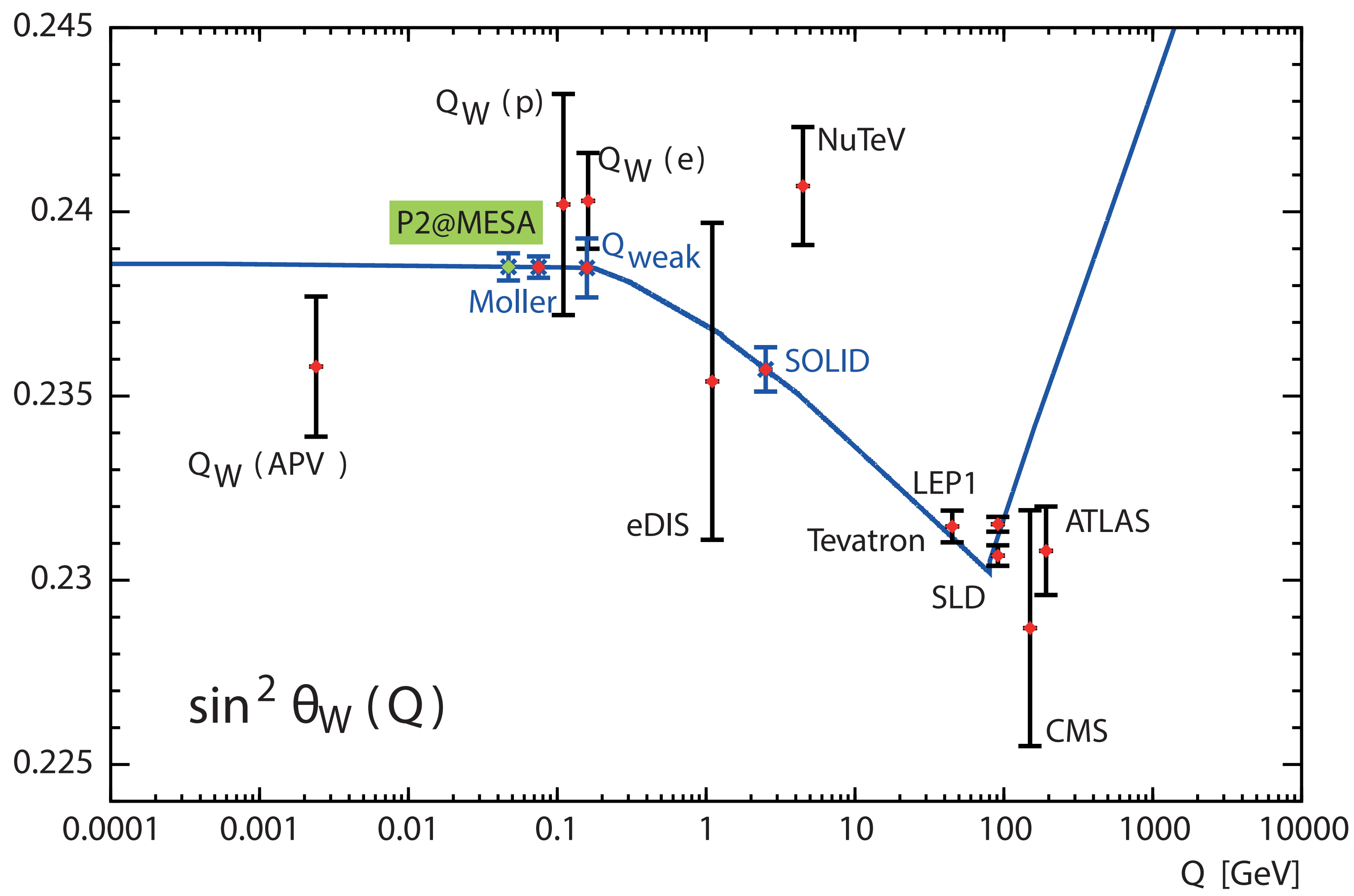


LO: Derman and Marciano, 1979

NLO: Czarnecki and Marciano, 1996; Denner and Pozzorini, 1998; Petriello, 2003; Zykunov, 2004; Kolomensky et al, 2005; Zykunov et al, 2005; Zykunov, 2009; Aleksejevs et al, 2010, 2011, 2012

NNLO: Aleksejevs et al, 2011, 2012, 2015 (partial estimation)

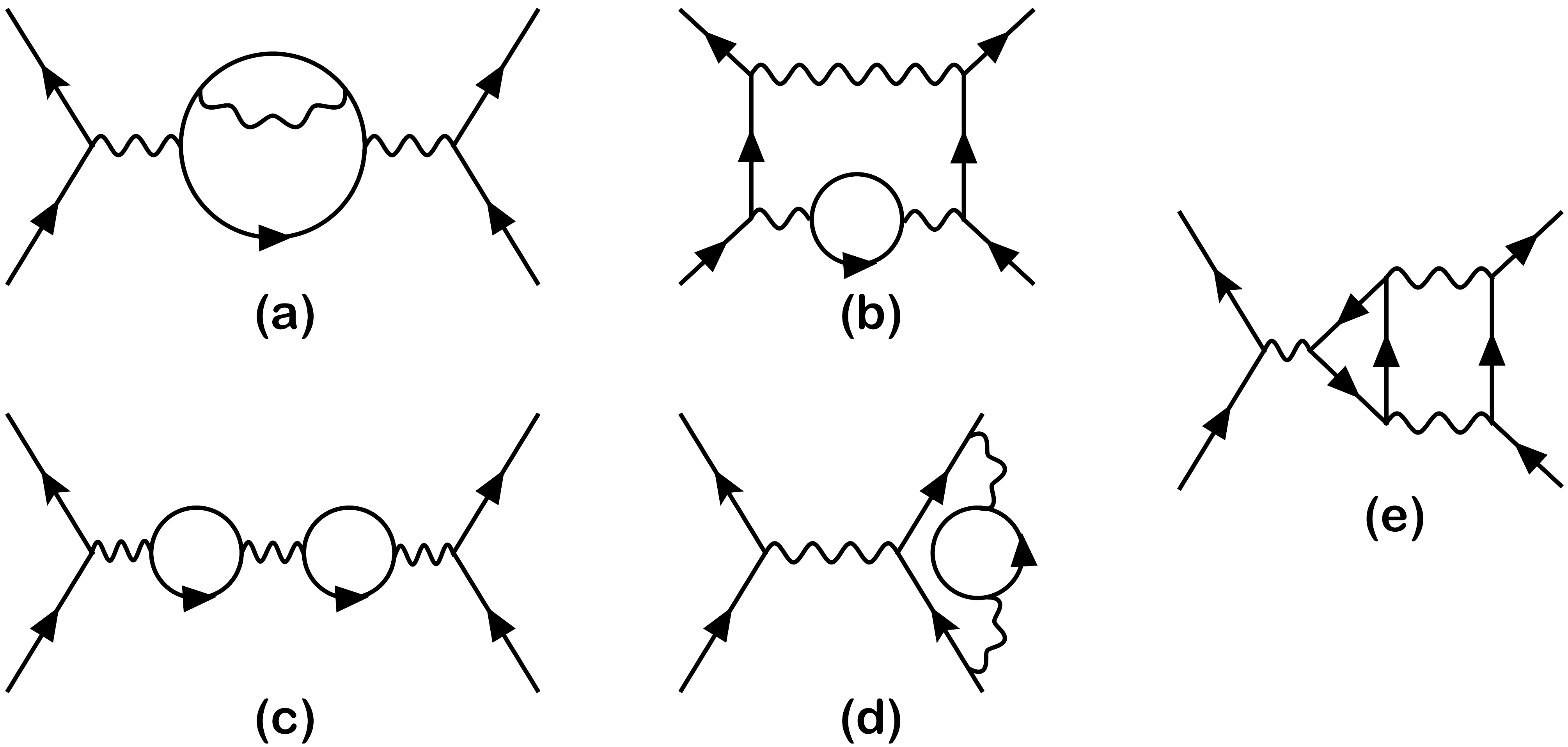
SMEFT global fit: ***PVES***



The MOLLER collaboration released their proposal in 2014, but US DOE will NOT support this experiment unless the theoretical error is reduced below the experimental one, which means we at least need to obtain the full 2-loop corrections.

SMEFT global fit: *PVES*

Topologies included with at least one closed fermion loop



All UV divergences are absorbed by the SM counter-terms. IR divergence are regularized by m_e and also by introducing a spurious non-vanishing m_γ.

SMEFT global fit: PVES

Quantity	Contribution ($\times 10^{-3}$)
$1\text{–}4\sin^2\theta_W$	$+74.4$
$\Delta Q^e_{W(1,1)}$	-29.0
$\Delta Q^e_{W(1,0)}$	$+3.1$
$\Delta Q^e_{W(2,2)}$	$-0.18^{+0.0024}_{-0.0040}$
$\Delta Q^e_{W(2,1)}$	$+1.18^{+0.015}_{-0.010}$
$\Delta Q^e_{W(2,0)}$	± 0.13 (estimate)

From our full analytical results

$$\Delta Q^e_{W(2,2)} + \Delta Q^e_{W(2,1)} = 1.00^{+0.012}_{-0.008} \times 10^{-3}$$

$$\Delta_{\text{exp}} Q^e_W = 1.1 \times 10^{-3}$$

SMEFT global fit: PVES

Quantity	Contribution ($\times 10^{-3}$)
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From our full analytical results

PHYSICAL REVIEW LETTERS **126,** 131801 (2021)

Parity-Violating Møller Scattering at Next-to-Next-to-Leading Order: Closed Fermion Loops

Yong Du,[1,*] Ayres Freitas,[2,†] Hiren H. Patel,[3,‡] and Michael J. Ramsey-Musolf[4,1,5,§]

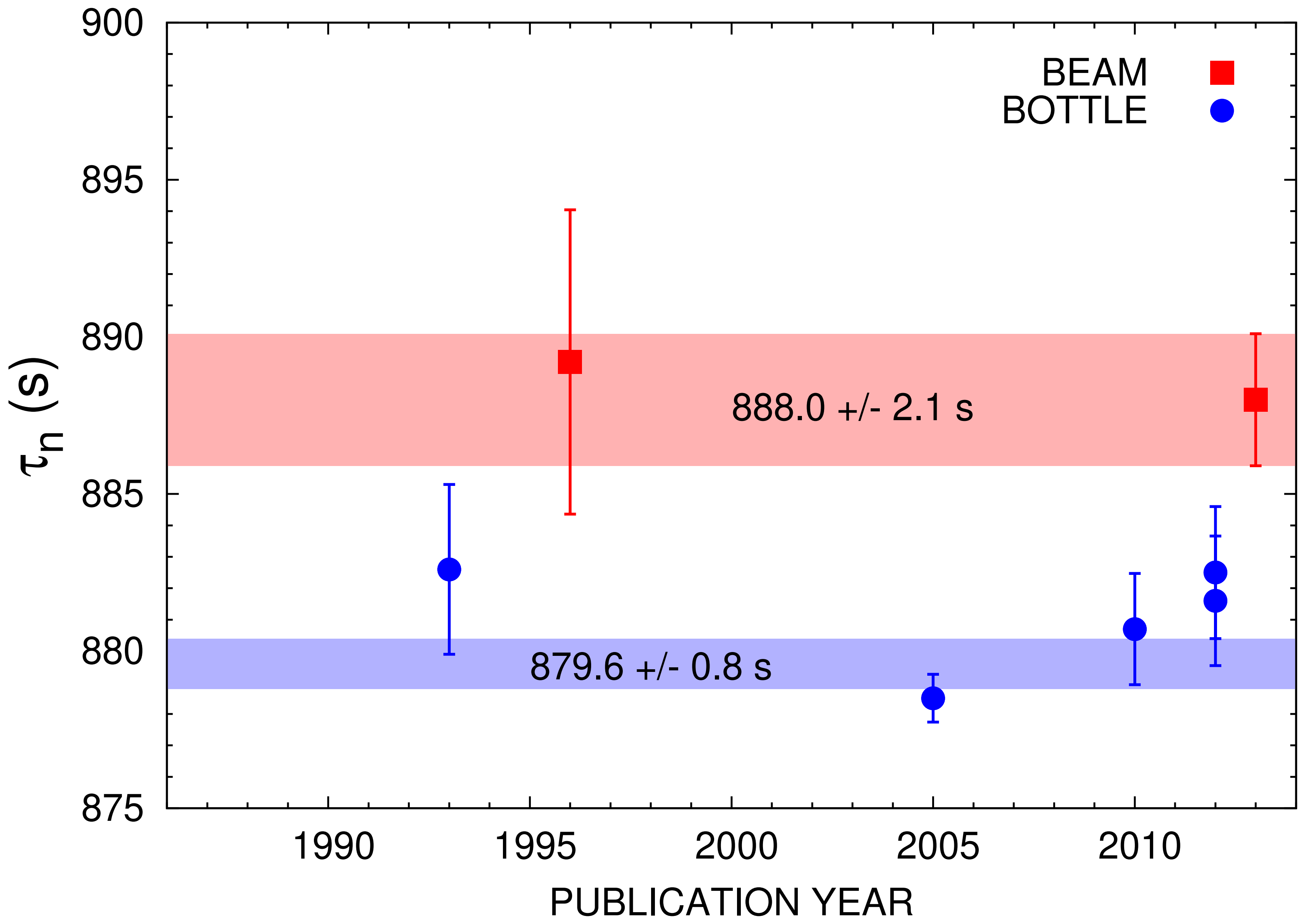
MOLLER project funded

Publication date: Tue, Nov 22, 2022 - 11:30pm

The MOLLER project which has been in planning and development stages for some years, has now been allocated $31M in Department of Energy funding to construct and install the experiment by 2025 and start data collection in early 2026.. The leader of the UMass team, Prof. Krishna Kumar, is the principal spokesperson for the project. The experiment, to be located at Jefferson National Lab, will study parity violation in electron-electron scattering.

Source: https://www.physics.umass.edu/news/2022-11-22-moller-project-funded

SMEFT global fit: β decay



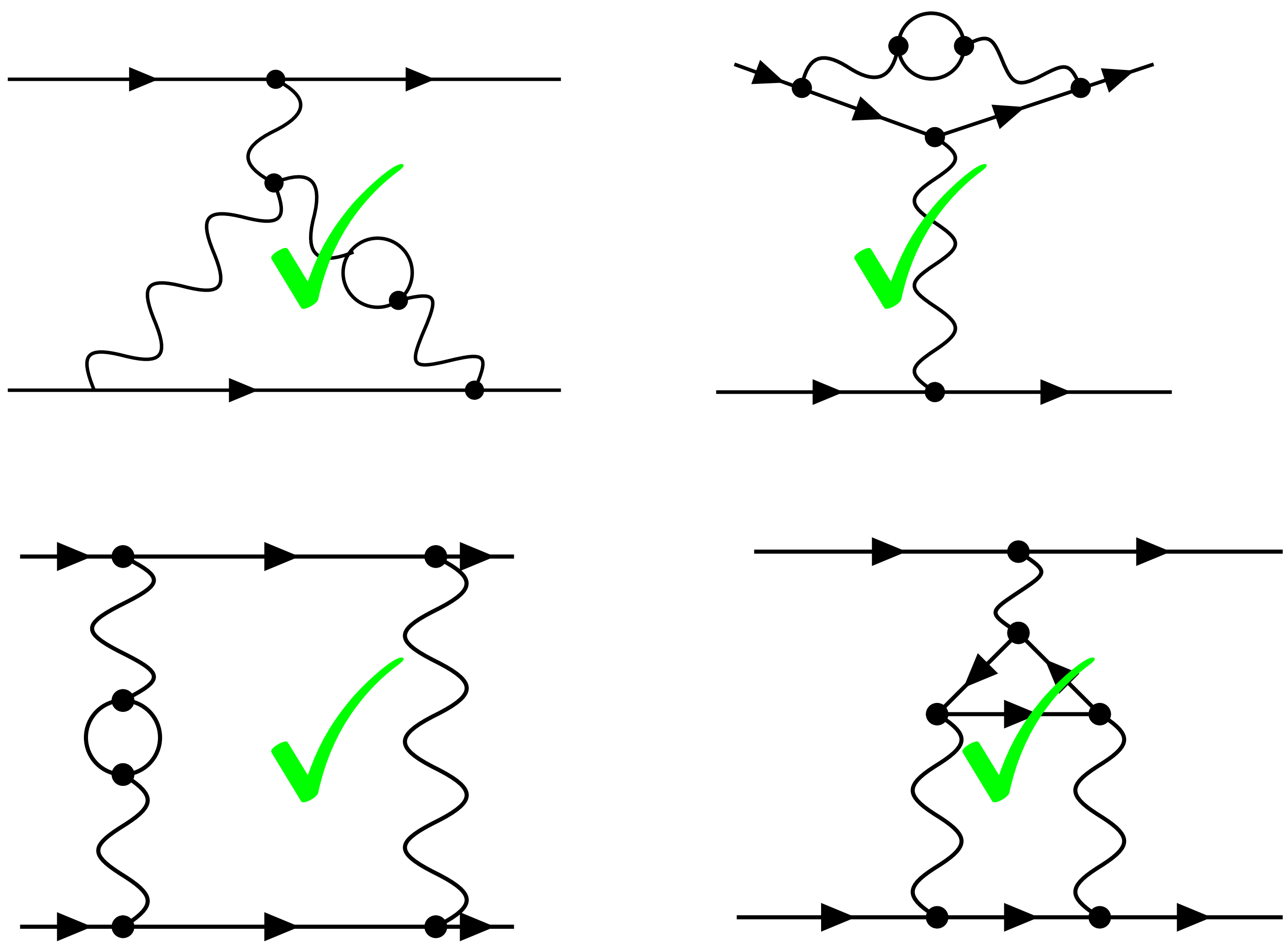
4σ disagreement!

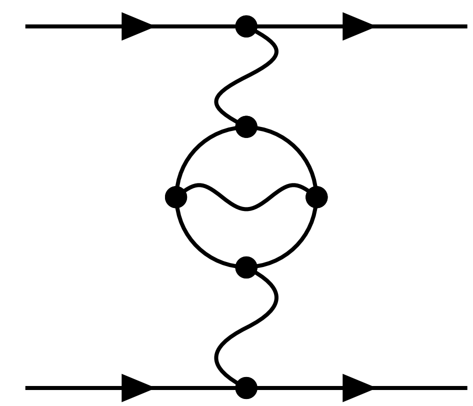
Bowman et al, 1410.5311

$$Y_p \approx \frac{2n}{n+p}$$

Neff shift and light element abundance of BBN

SMEFT global fit: β *decay*





Trivial and not necessary.

Remaining: Non-perturbative QCD corrections using DRs.

YD, Fagnoni, Friedrich, Ramsey-Musolf, Zhou, ongoing

SMEFT global fit: ν oscillations

$$|\nu_\alpha^s\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N_\alpha^s}|\nu_\gamma\rangle \qquad \langle\nu_\beta^d| = \langle\nu_\gamma|\frac{(1+\epsilon^d)_{\gamma\beta}}{N_\beta^d}$$

QM framework

$$\begin{aligned}\mathcal{L}_{CC} \supset -\frac{2V_{ud}}{v^2}\Big\{&[\mathbf{1}+\epsilon_L]^{ij}_{\alpha\beta}(\bar{u}_i\gamma^\mu P_L d_j)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R]^{ij}_{\alpha\beta}(\bar{u}_i\gamma^\mu P_R d_j)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\\ &+\frac{1}{2}[\epsilon_S]^{ij}_{\alpha\beta}(\bar{u}_i d_j)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]^{ij}_{\alpha\beta}(\bar{u}_i\gamma_5 d_j)(\bar{\ell}_\alpha P_L\nu_\beta)\\ &+\frac{1}{4}[\epsilon_T]^{ij}_{\alpha\beta}(\bar{u}_i\sigma^{\mu\nu}P_L d_j)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\},\end{aligned}$$

QFT framework

SMEFT global fit: ν oscillations

$$|\nu_\alpha^s\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N_\alpha^s}|\nu_\gamma\rangle \qquad \langle\nu_\beta^d| = \langle\nu_\gamma|\frac{(1+\epsilon^d)_{\gamma\beta}}{N_\beta^d}$$

QM framework

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QFT framework

Q: How to connect ν oscillation data with Lagrangian parameters?

A: Matching at the observable level for consistency

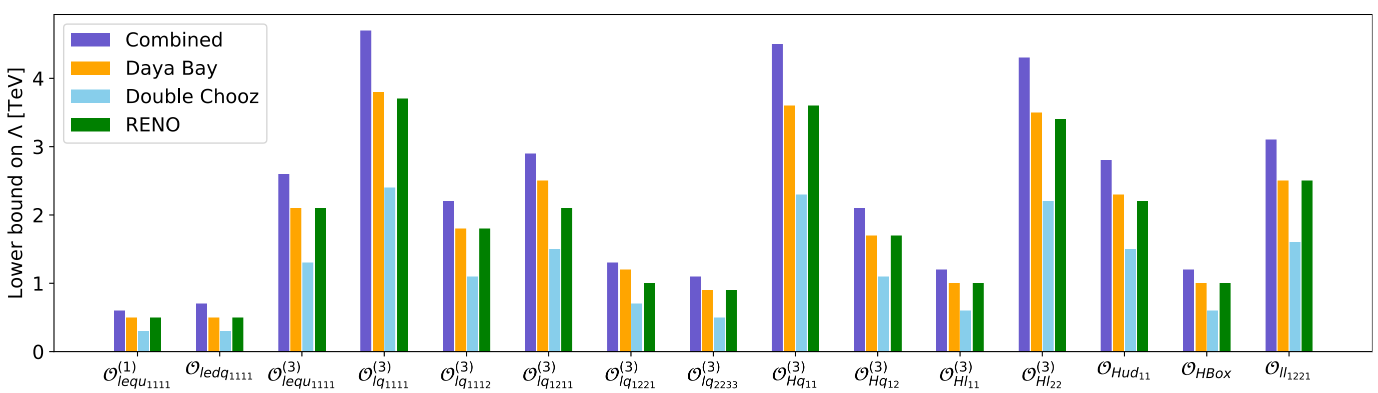
$$\epsilon^s_{\alpha\beta} = \sum_X p_{XL}\,[\epsilon_X]^*_{\alpha\beta}\,, \quad \epsilon^d_{\beta\alpha} = \sum_X d_{XL}\,[\epsilon_X]_{\alpha\beta} \qquad p_{XY} \equiv \frac{\int d\Pi_{P'} A_X^P \bar A_Y^P}{\int d\Pi_{P'} \left|A_L^P\right|^2}, \quad d_{XY} \equiv \frac{\int d\Pi_D A_X^D \bar A_Y^D}{\int d\Pi_D \left|A_L^D\right|^2}$$

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

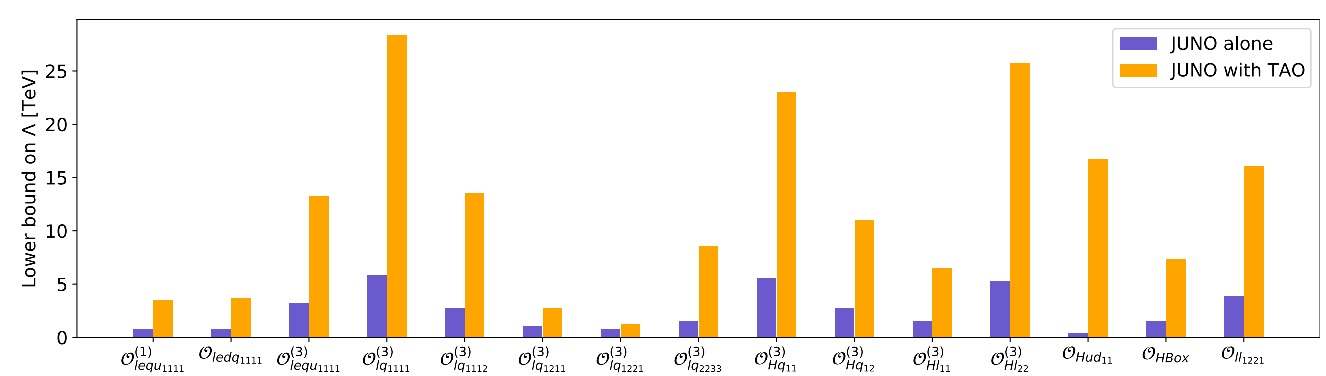
SMEFT global fit: ν oscillations

Table 1. Matching between QM and QFT NSI parameters

QM NSIs	Relations to QFT NSIs
$\epsilon^s_{e\beta}$ (β decay)	$\left[\epsilon_L - \epsilon_R - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}\epsilon_T\right]^*_{e\beta}$
$\epsilon^d_{\beta e}$ (inverse β decay)	$\left[\epsilon_L + \frac{1-3g_A^2}{1+3g_A^2}\epsilon_R - \frac{m_e}{E_\nu-\Delta}\left(\frac{g_S}{1+3g_A^2}\epsilon_S - \frac{3g_A g_T}{1+3g_A^2}\epsilon_T\right)\right]_{e\beta}$
$\epsilon^s_{\mu\beta}$ (pion decay)	$\left[\epsilon_L - \epsilon_R - \frac{m_\pi^2}{m_\mu(m_u+m_d)}\epsilon_P\right]^*_{\mu\beta}$
$\epsilon^s_{\mu\beta}$(muon decay)	$\left[g_{22} + \frac{3m_e m_\mu(m_\mu-2E_\nu)}{16m_\mu E_\nu^2+6m_\mu(m_\mu^2+m_e^2)-4E_\nu(5m_\mu^2+m_e^2)}h_{21}\right]^*_{\mu\beta}$
$\epsilon^s_{e\beta}$ (muon decay)	$\left[g_{22} + \frac{m_e}{4(m_\mu-2E_{\bar\nu})}h_{21}\right]^*_{e\beta}$



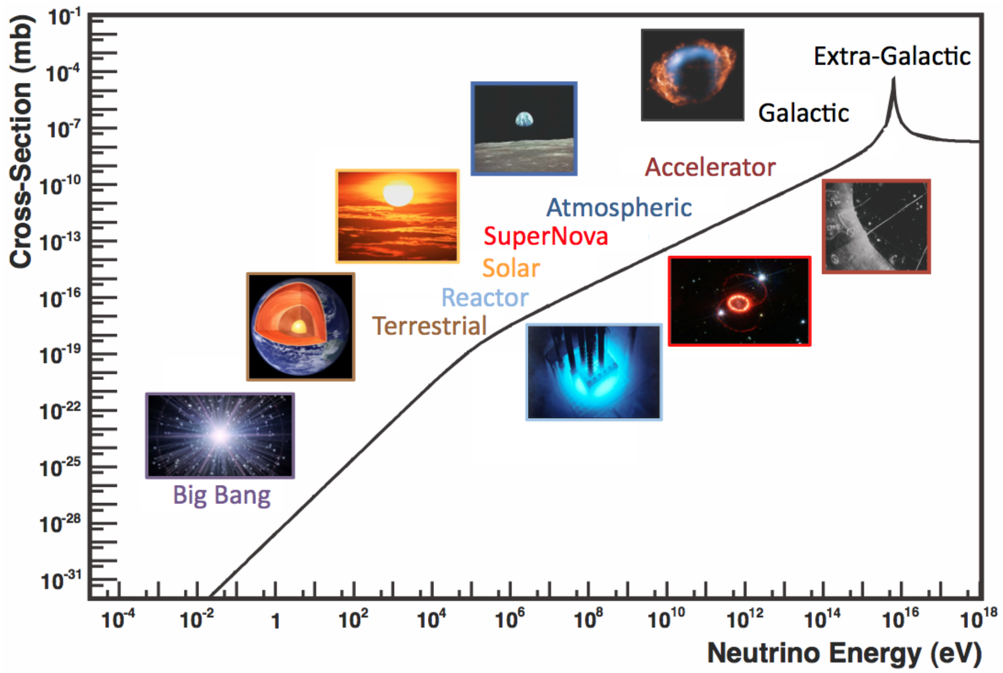
YD, Li, Tang, Vihonen, Yu, 2011.14292 (JHEP)

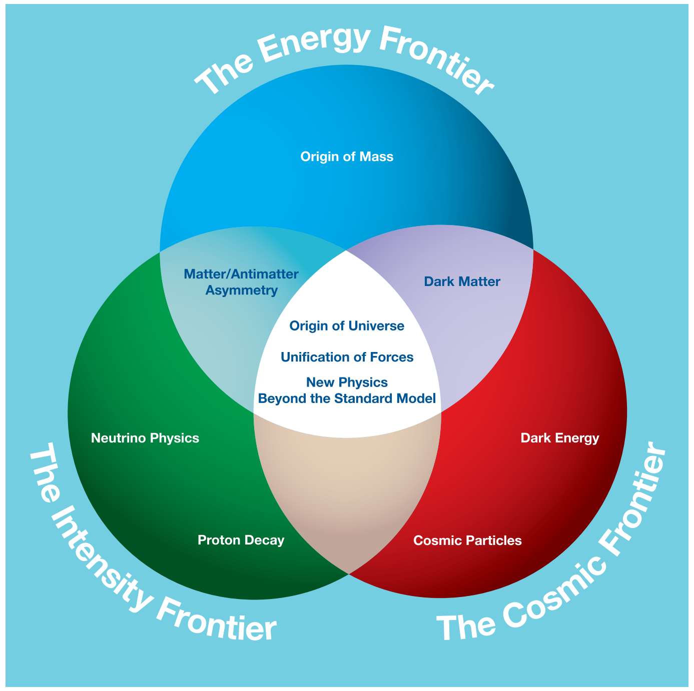


YD, Li, Tang, Vihonen, Yu, 2106.15800 (PRD)

Summary

- I discussed the global fit of 4f and CPV SMEFT operators:
  - 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.
- The indispensable role of neutrinos in the global fit was addressed, and future directions in this respect is discussed:
  - The rich physics from CEvNS experiments
  - Very important PVES experiments
  - Neutrino oscillation experiments





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