# SMEFT at Tera-Z

Yong Du（杜勇）

7th FCC Physics Workshop, LAPP, Annecy, Feb 1, 2024

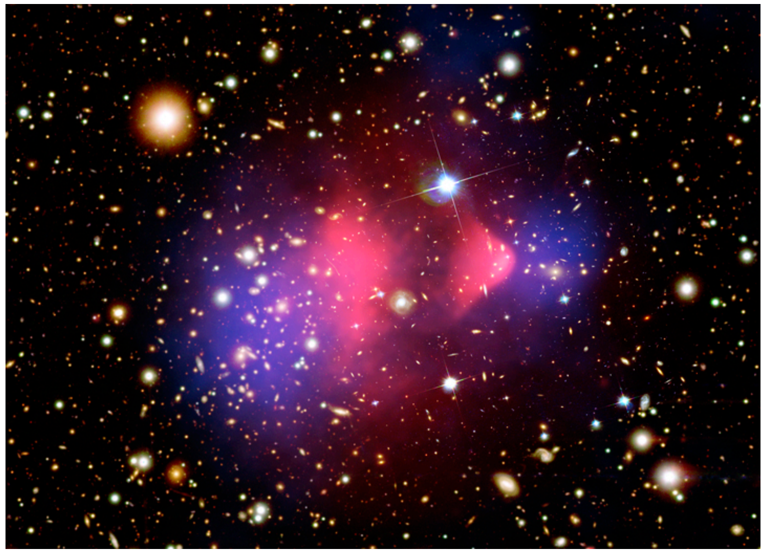
Based on

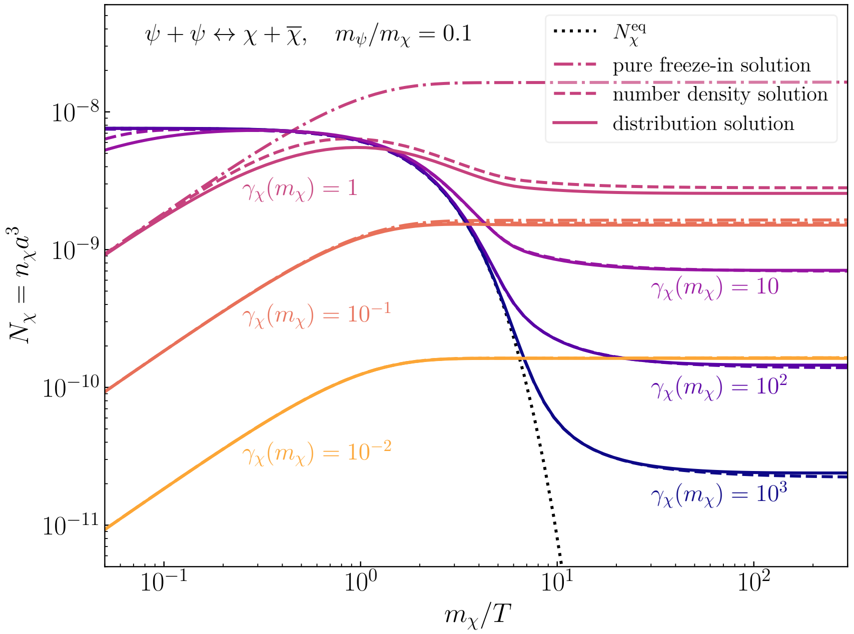
2206.08326, Jorge de Blas, **YD**, Christophe Grojean, Jiayin Gu, Victor Miralles, Michael Peskin, Junping Tian, Marcel Vos, Eleni Vryonidou for SNOWMASS 2021

李政道研究所
TSUNG-DAO LEE INSTITUTE

# Introduction

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

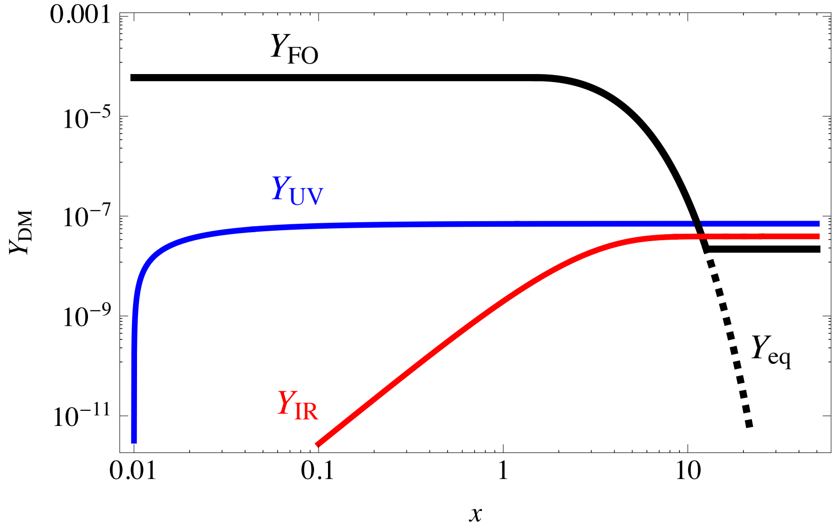


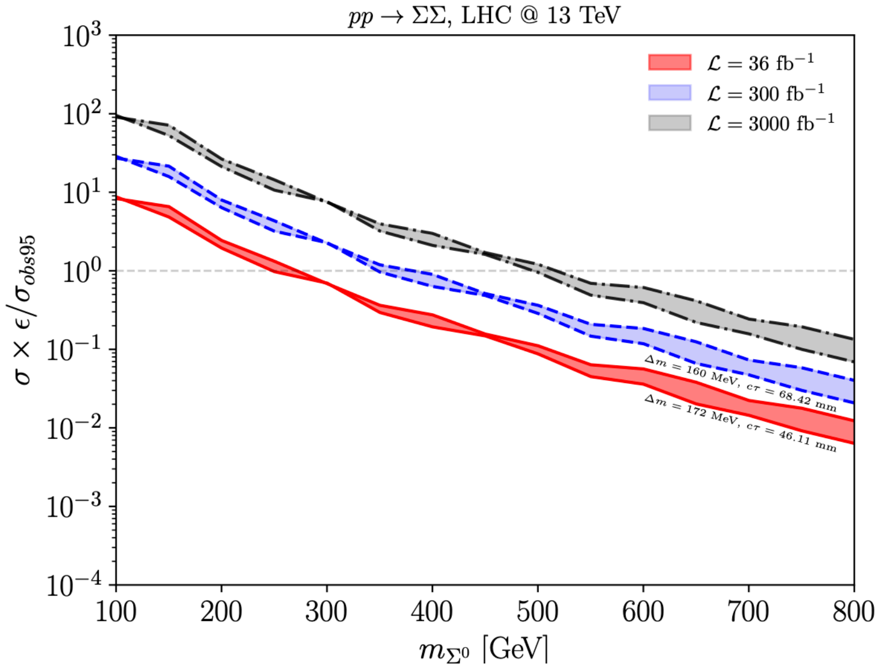


**YD**, Huang, Li, Yu, 2005.01717 (JHEP)

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

Elahi et al, 1410.6157

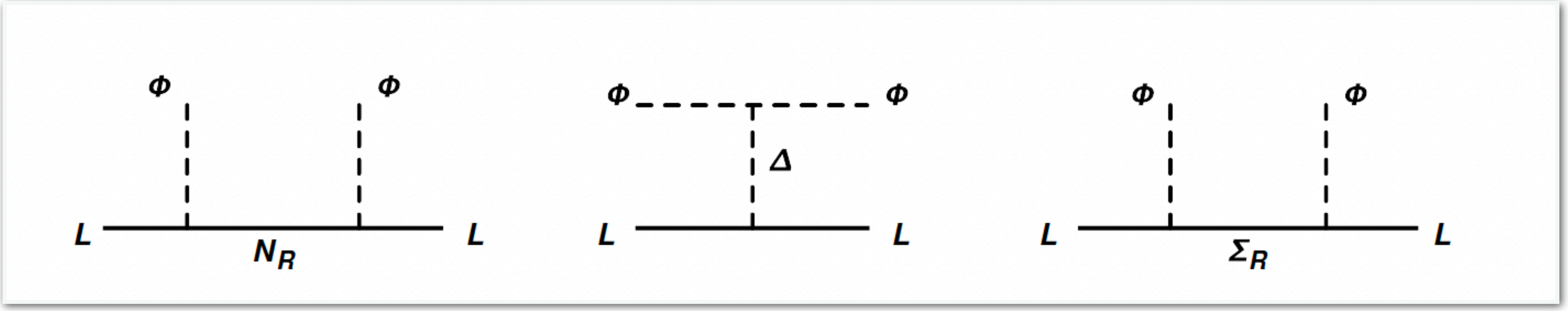


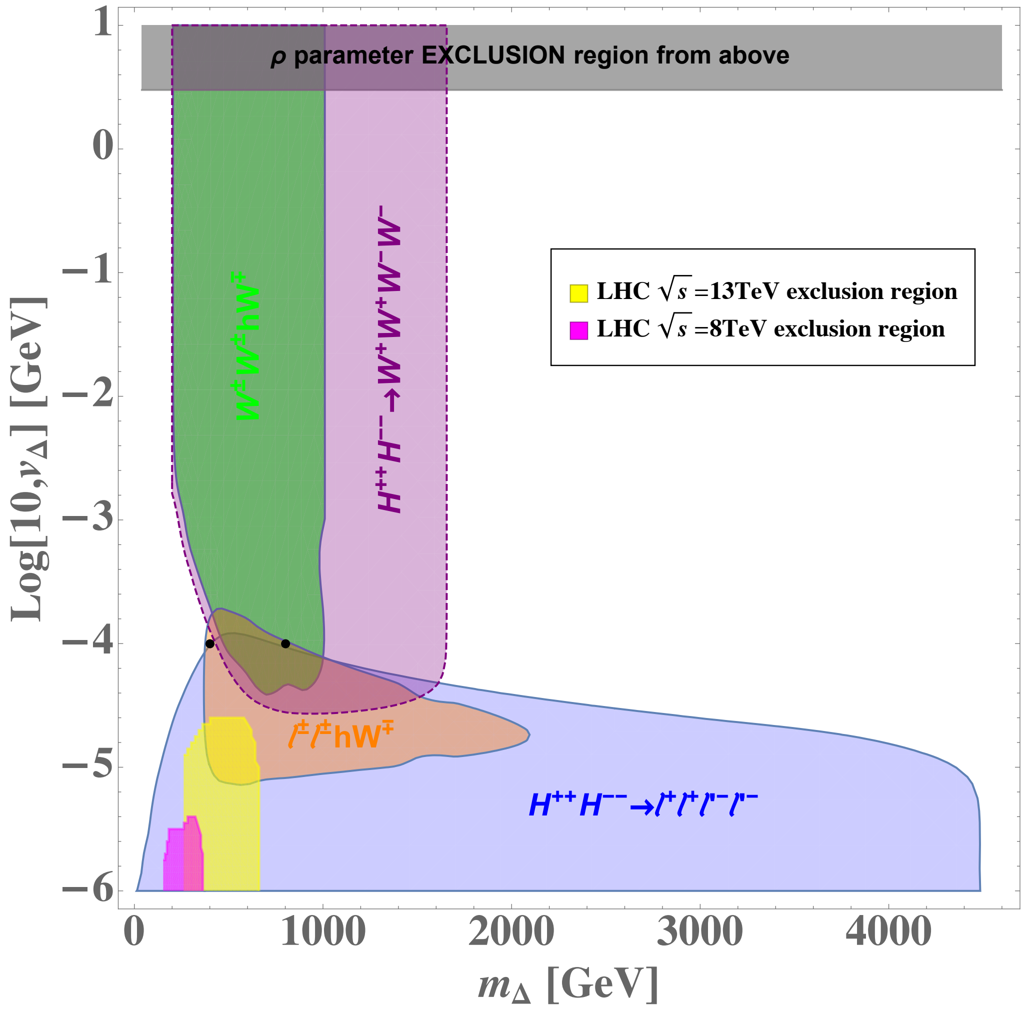


Chiang, Cottin, **YD**, Fuyuto, Ramsey-Musolf, 2003.07867(JHEP)

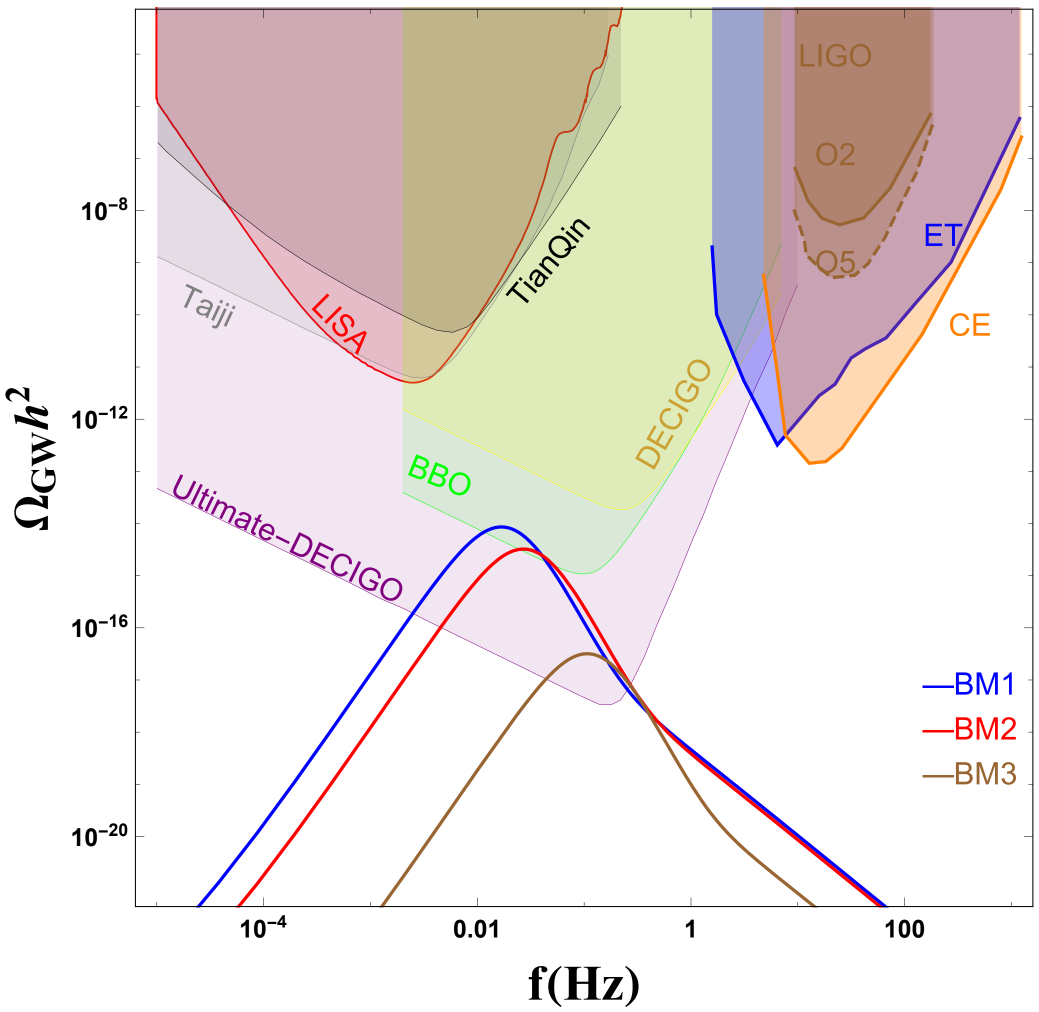
# Introduction

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: ⋯***

# 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.

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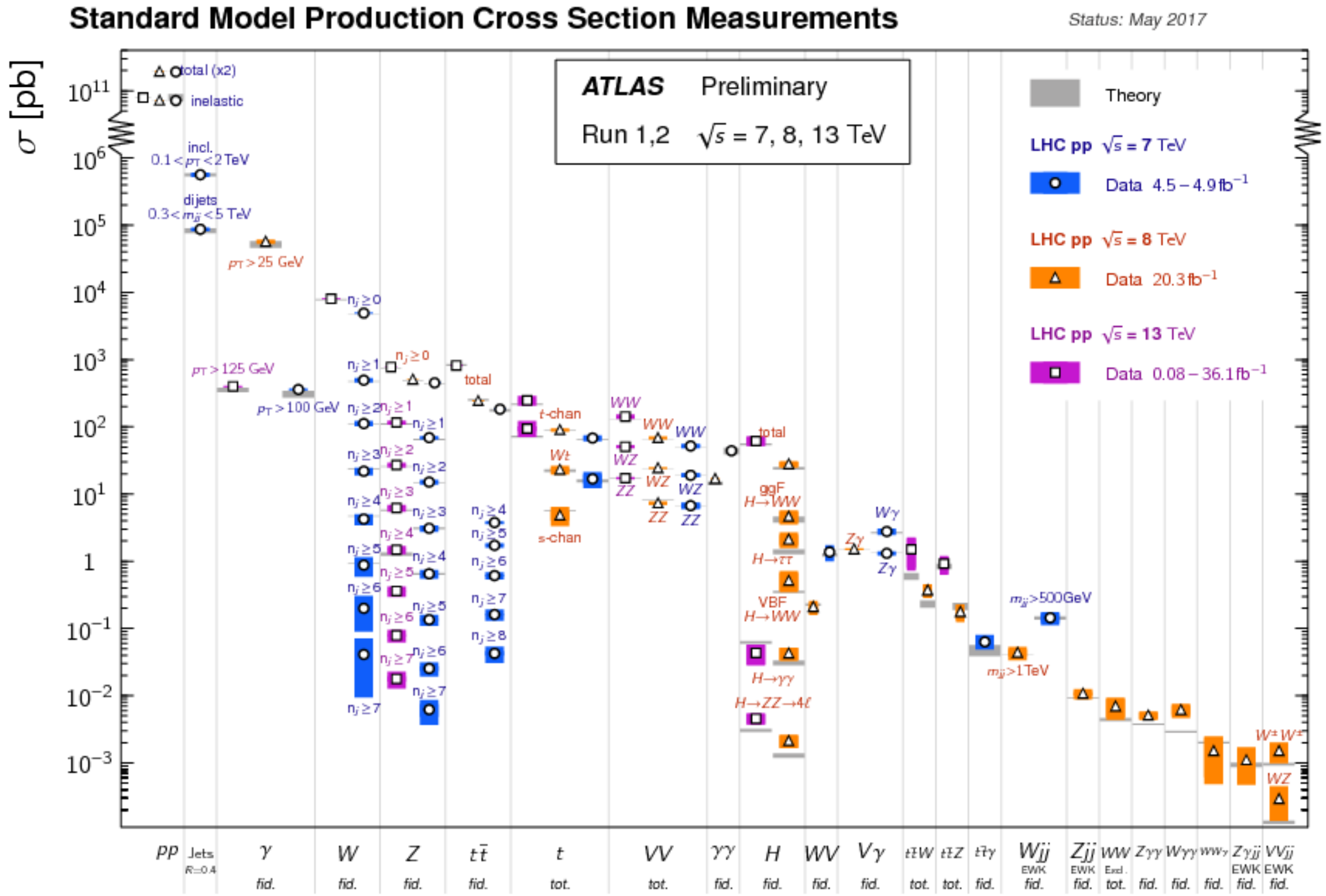
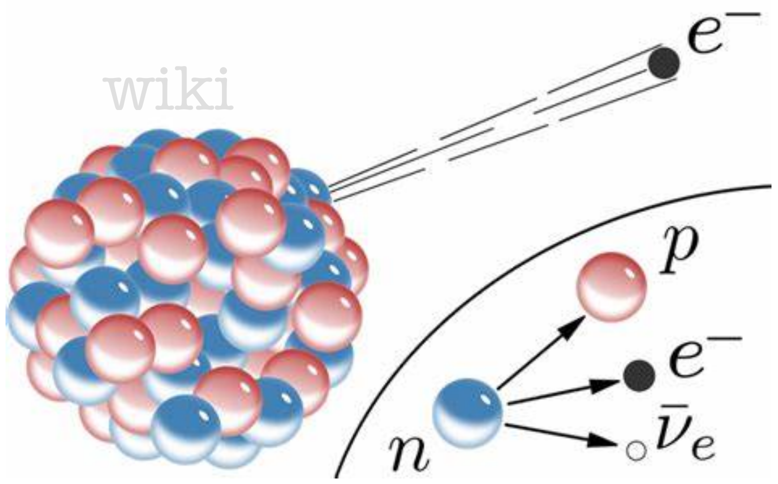
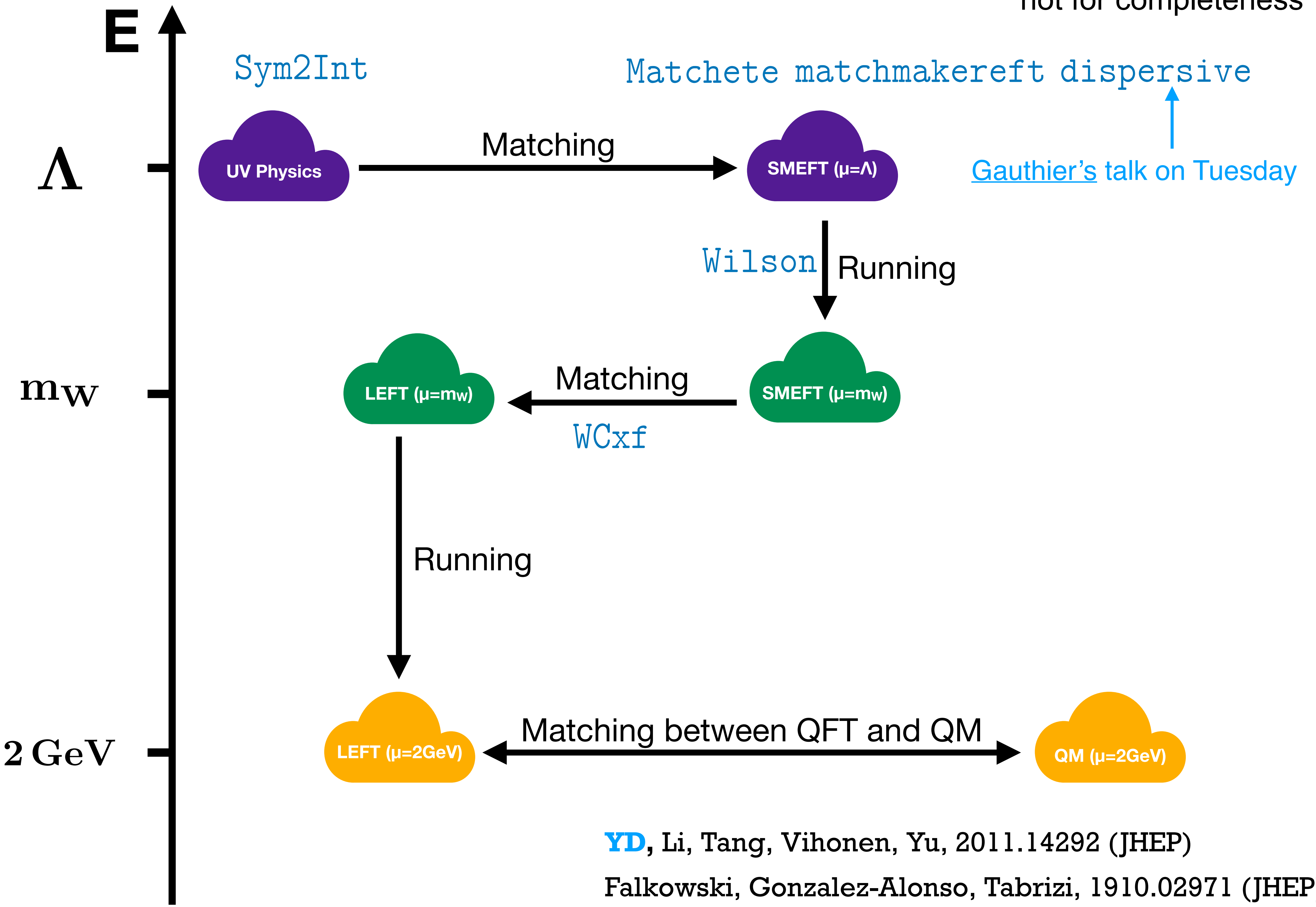


The experimental data are suggesting that the SM is an effective low-energy theory of some UV model above the weak scale.



# Introduction

* not for completeness



E

$\Lambda$

$m_W$

2 GeV

`Sym2Int`

`Matchete matchmakereft dispersive`

Gauthier's talk on Tuesday

UV Physics

Matching

SMEFT (μ=Λ)

`Wilson` Running

SMEFT (μ=mw)

Matching

`WCxf`

LEFT (μ=mw)

Running

LEFT (μ=2GeV)

Matching between QFT and QM

QM (μ=2GeV)

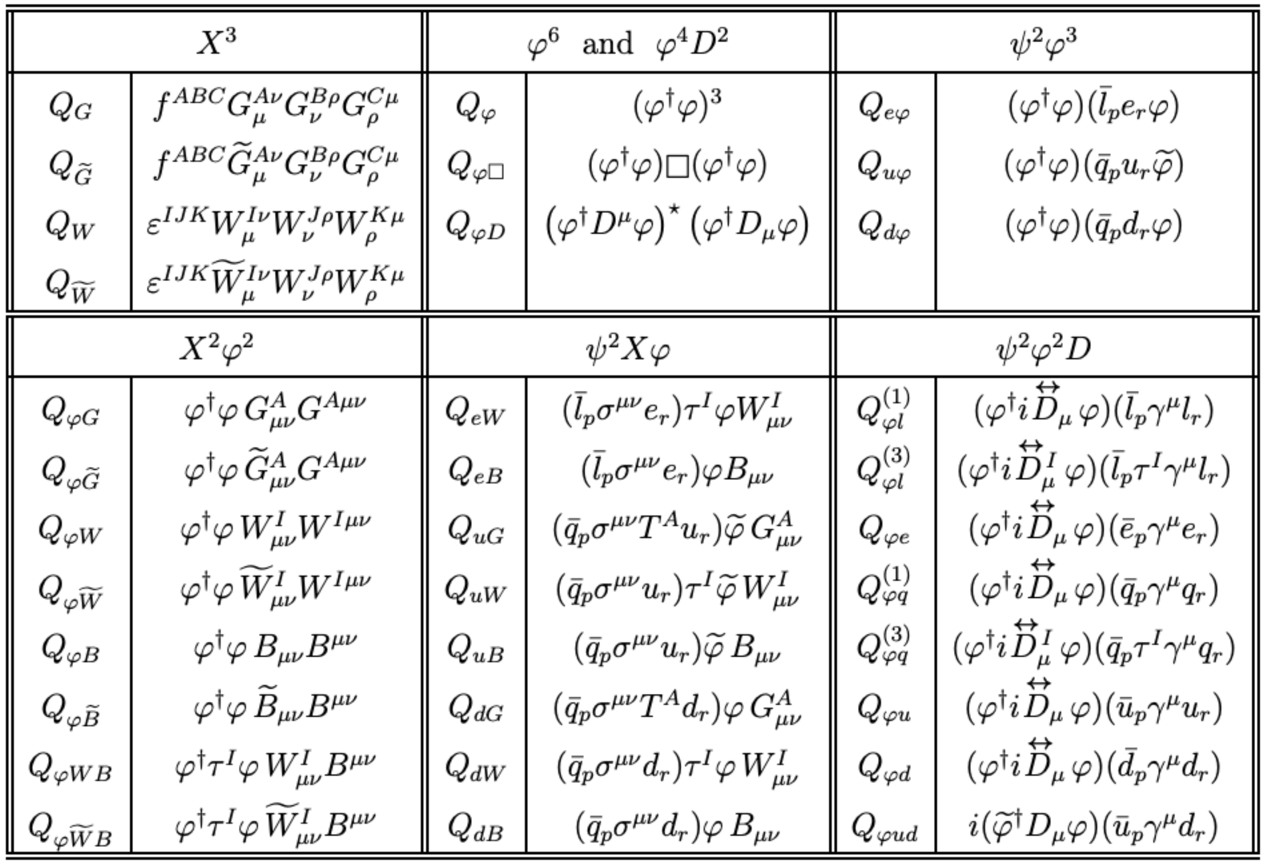
**YD**, Li, Tang, Vihonen, Yu, 2011.14292 (JHEP)

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

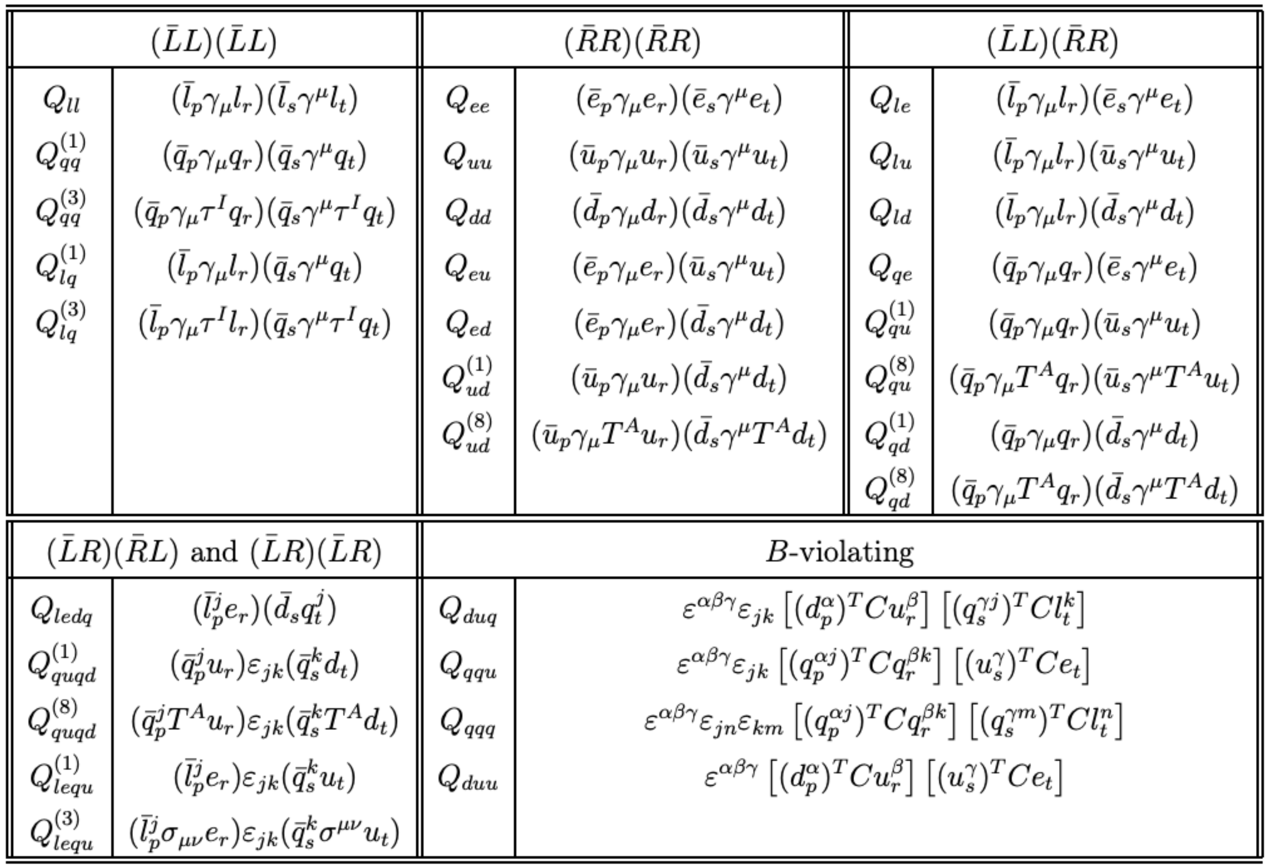
# SMEFT global fit

Operators in the Warsaw basis:

Buchmuller and Wyler, Nucl.Phys.B 268 (1986) 621
Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP 10 (2010) 085



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



| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$ |
| $(\bar LR)(\bar RL)$ 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.

Sophie's and Ben's talks on Tuesday

# SMEFT global fit

The SMEFT is then simply constructed by adding these operators on top of the SM:

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^d$$

with each of the term a SM singlet and respecting the SM local gauge symmetry.

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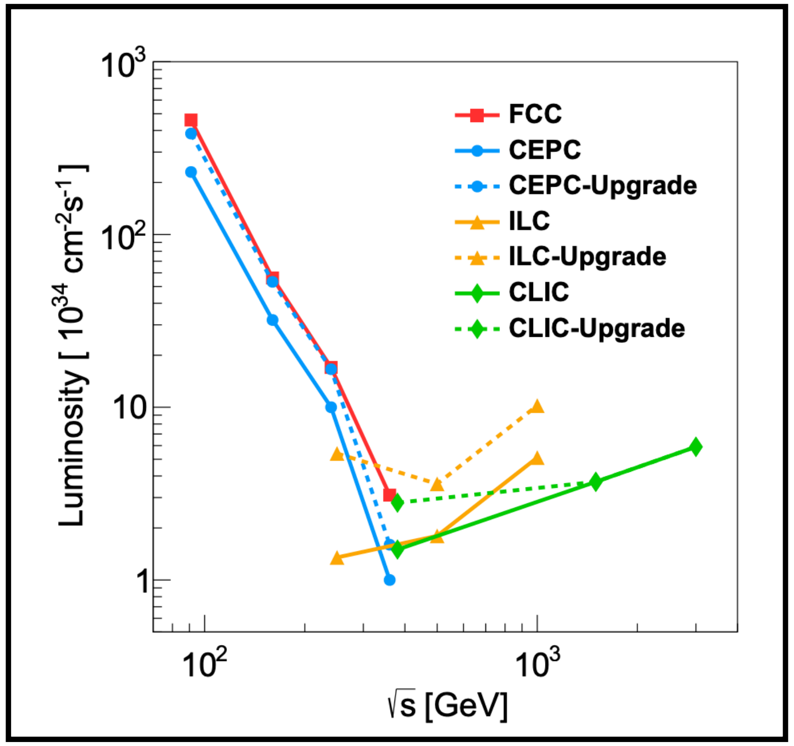
with each of the term a SM singlet and respecting the SM local gauge symmetry.

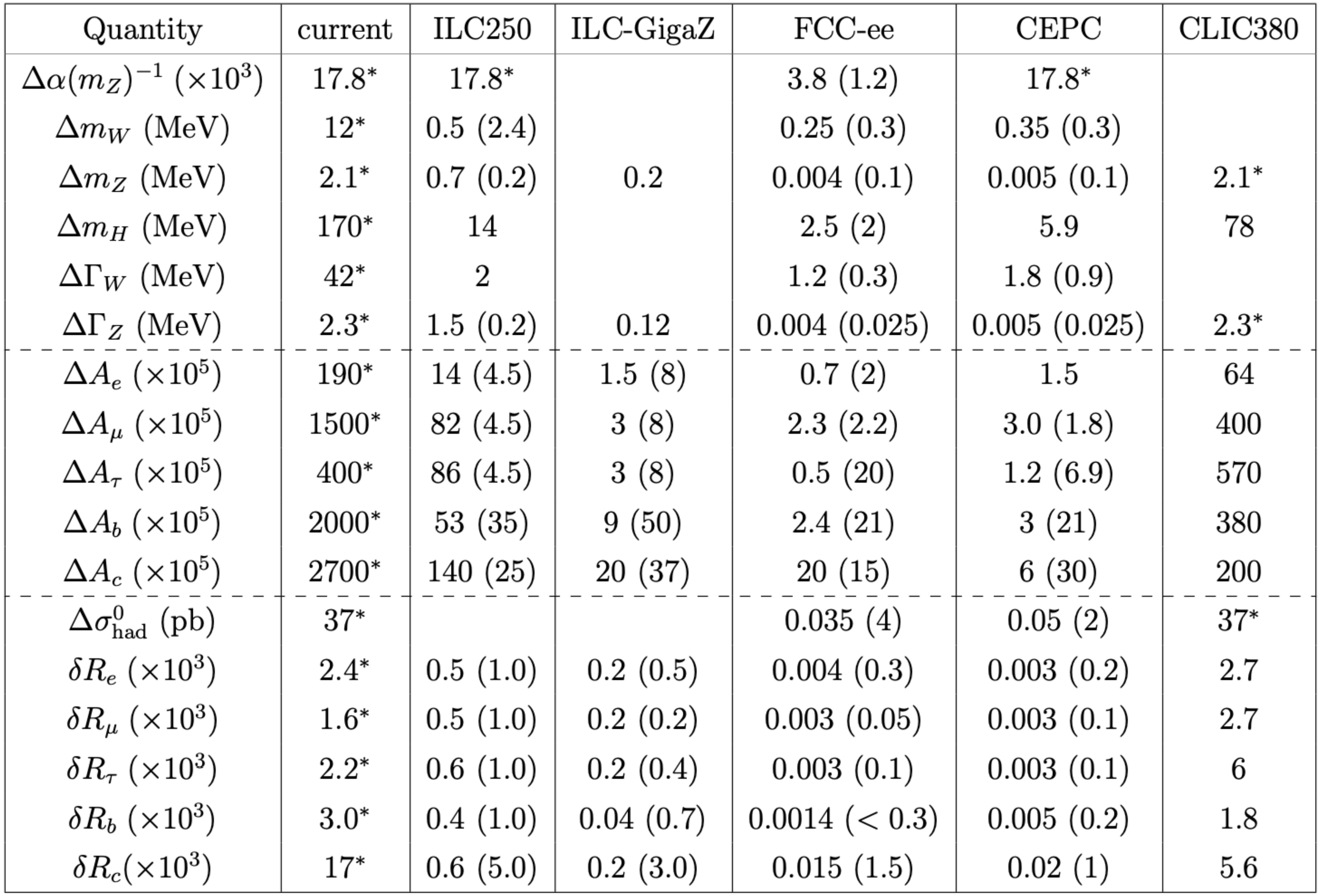
FCC-ee is an ideal precision machine for new physics studies in the SMEFT since $s \ll \Lambda^2$ with $\Lambda \gtrsim 1\,\text{TeV}$ from the LHC data.



CEPC Physics Study Group, 2205.08553

# SMEFT global fit: $\delta_{\mathrm{ex}}$

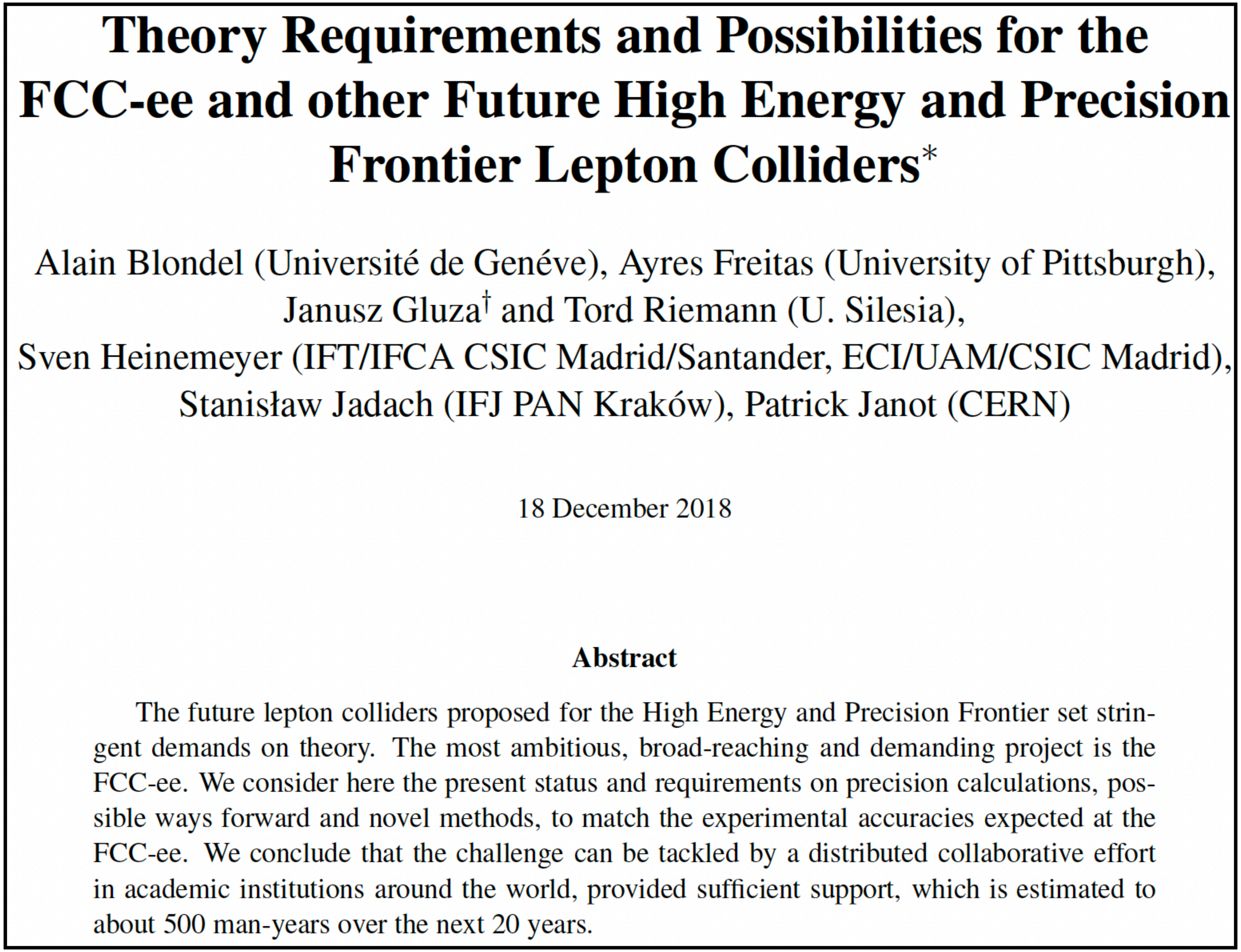
de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326



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

We thank our experimental colleagues for doing excellent. Recent improvement not implemented ($R_b$ from inclusive (Michele's talk)/exclusive (Lars's talk) studies for example)

# SMEFT global fit: ~~$\delta_{\text{th}}$~~



## Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders*

Alain Blondel (Université de Genéve), Ayres Freitas (University of Pittsburgh),
Janusz Gluza† and Tord Riemann (U. Silesia),
Sven Heinemeyer (IFT/IFCA CSIC Madrid/Santander, ECI/UAM/CSIC Madrid),
Stanisław Jadach (IFJ PAN Kraków), Patrick Janot (CERN)

18 December 2018

**Abstract**

The future lepton colliders proposed for the High Energy and Precision Frontier set stringent demands on theory. The most ambitious, broad-reaching and demanding project is the FCC-ee. We consider here the present status and requirements on precision calculations, possible ways forward and novel methods, to match the experimental accuracies expected at the FCC-ee. We conclude that the challenge can be tackled by a distributed collaborative effort in academic institutions around the world, provided sufficient support, which is estimated to about 500 man-years over the next 20 years.

Considered as well under control by the operation time.
See also Johann's talk on Tuesday and Alain's talk this morning.

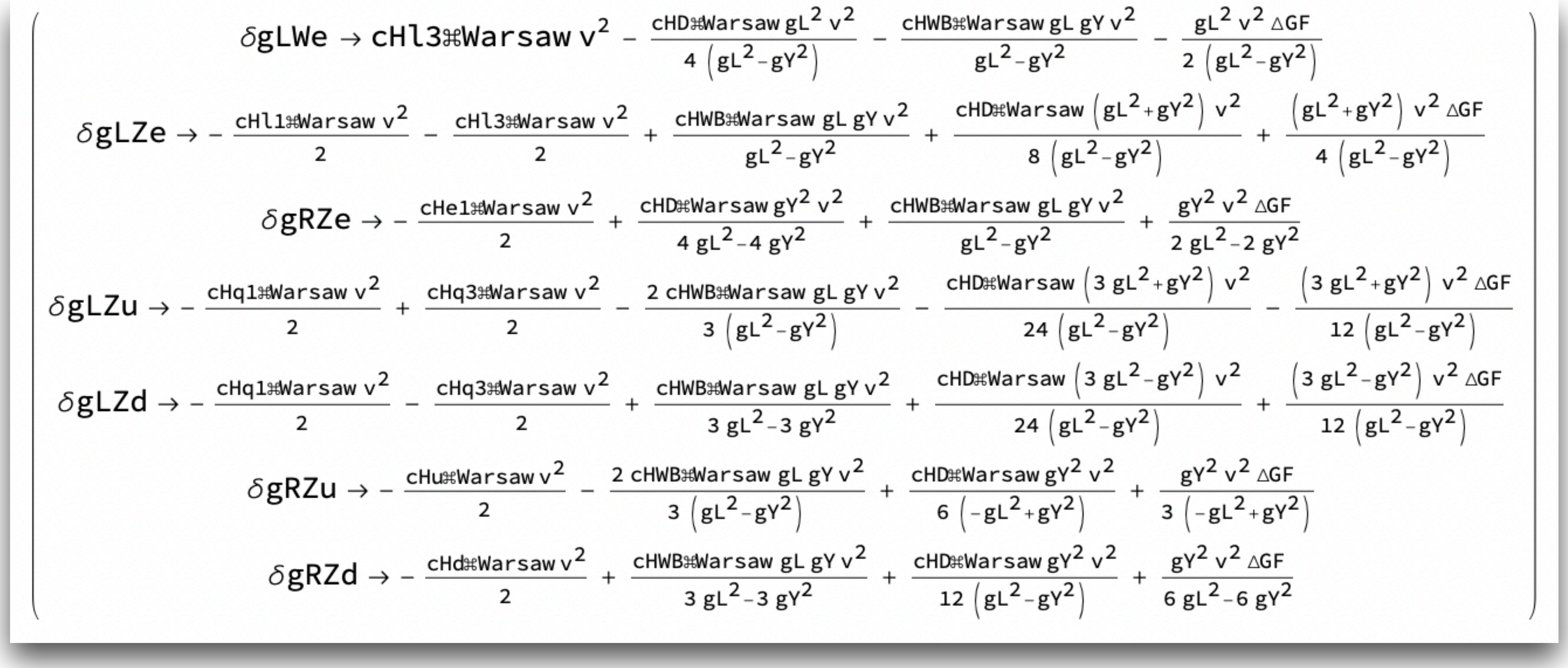
# SMEFT global fit: ***Basis***

Presenting the results will be basis dependent. We choose to work in the Higgs basis to disentangle physics in different sectors

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

# SMEFT global fit: ***Basis***

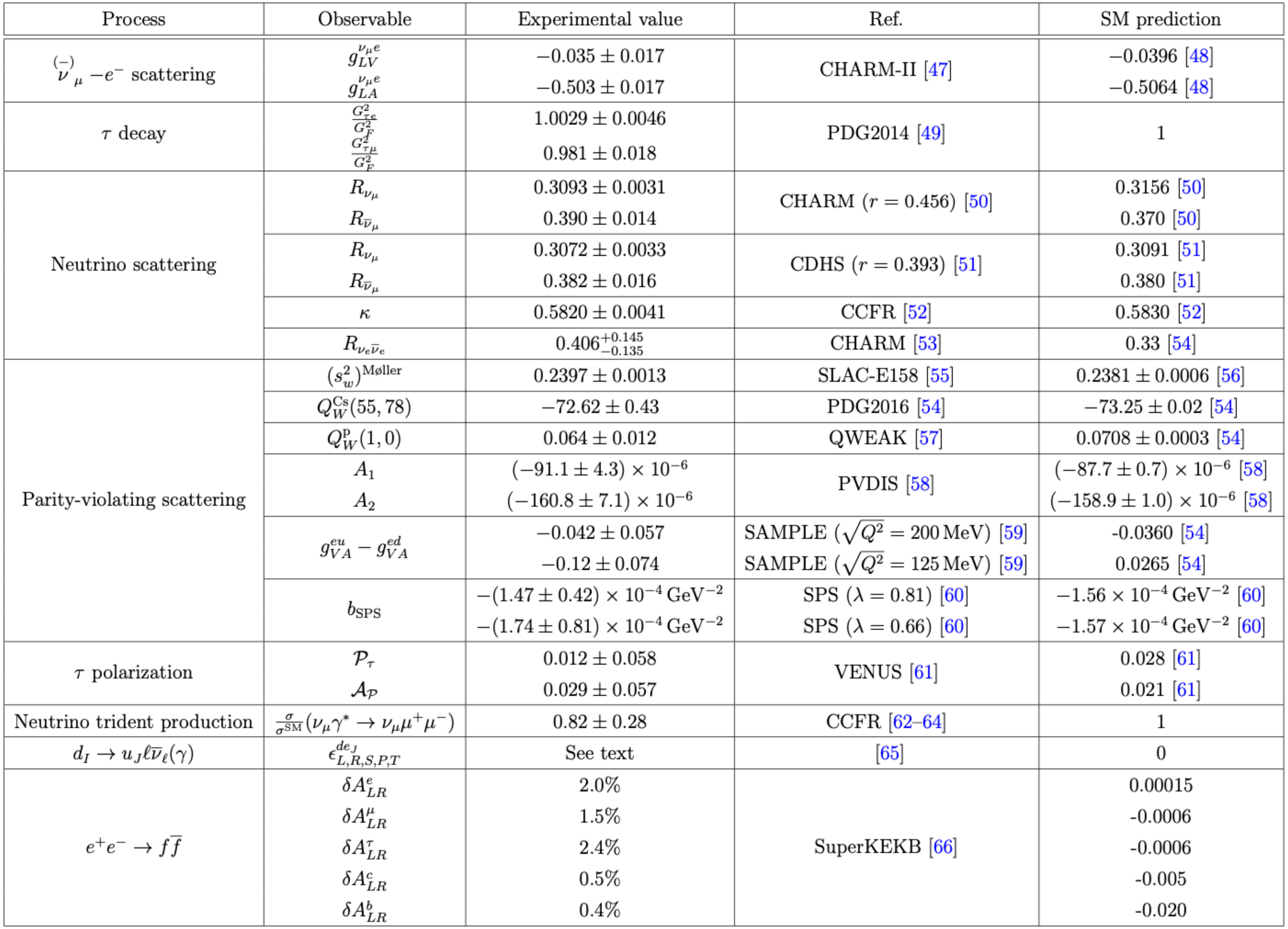
Presenting the results will be basis dependent. We choose to work in the Higgs basis to disentangle physics in different sectors



$$\begin{pmatrix}
\delta\text{gLWe} \to \text{cHl3⌘Warsaw}\, v^2 - \frac{\text{cHD⌘Warsaw}\, \text{gL}^2 v^2}{4\left(\text{gL}^2-\text{gY}^2\right)} - \frac{\text{cHWB⌘Warsaw}\, \text{gL}\, \text{gY}\, v^2}{\text{gL}^2-\text{gY}^2} - \frac{\text{gL}^2 v^2\, \Delta\text{GF}}{2\left(\text{gL}^2-\text{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}\, \text{gL}\, \text{gY}\, v^2}{\text{gL}^2-\text{gY}^2} + \frac{\text{cHD⌘Warsaw}\left(\text{gL}^2+\text{gY}^2\right) v^2}{8\left(\text{gL}^2-\text{gY}^2\right)} + \frac{\left(\text{gL}^2+\text{gY}^2\right) v^2\, \Delta\text{GF}}{4\left(\text{gL}^2-\text{gY}^2\right)} \\
\delta\text{gRZe} \to -\frac{\text{cHe1⌘Warsaw}\, v^2}{2} + \frac{\text{cHD⌘Warsaw}\, \text{gY}^2 v^2}{4\,\text{gL}^2-4\,\text{gY}^2} + \frac{\text{cHWB⌘Warsaw}\, \text{gL}\, \text{gY}\, v^2}{\text{gL}^2-\text{gY}^2} + \frac{\text{gY}^2 v^2\, \Delta\text{GF}}{2\,\text{gL}^2-2\,\text{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}\, \text{gL}\, \text{gY}\, v^2}{3\left(\text{gL}^2-\text{gY}^2\right)} - \frac{\text{cHD⌘Warsaw}\left(3\,\text{gL}^2+\text{gY}^2\right) v^2}{24\left(\text{gL}^2-\text{gY}^2\right)} - \frac{\left(3\,\text{gL}^2+\text{gY}^2\right) v^2\, \Delta\text{GF}}{12\left(\text{gL}^2-\text{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}\, \text{gL}\, \text{gY}\, v^2}{3\,\text{gL}^2-3\,\text{gY}^2} + \frac{\text{cHD⌘Warsaw}\left(3\,\text{gL}^2-\text{gY}^2\right) v^2}{24\left(\text{gL}^2-\text{gY}^2\right)} + \frac{\left(3\,\text{gL}^2-\text{gY}^2\right) v^2\, \Delta\text{GF}}{12\left(\text{gL}^2-\text{gY}^2\right)} \\
\delta\text{gRZu} \to -\frac{\text{cHu⌘Warsaw}\, v^2}{2} - \frac{2\,\text{cHWB⌘Warsaw}\, \text{gL}\, \text{gY}\, v^2}{3\left(\text{gL}^2-\text{gY}^2\right)} + \frac{\text{cHD⌘Warsaw}\, \text{gY}^2 v^2}{6\left(-\text{gL}^2+\text{gY}^2\right)} + \frac{\text{gY}^2 v^2\, \Delta\text{GF}}{3\left(-\text{gL}^2+\text{gY}^2\right)} \\
\delta\text{gRZd} \to -\frac{\text{cHd⌘Warsaw}\, v^2}{2} + \frac{\text{cHWB⌘Warsaw}\, \text{gL}\, \text{gY}\, v^2}{3\,\text{gL}^2-3\,\text{gY}^2} + \frac{\text{cHD⌘Warsaw}\, \text{gY}^2 v^2}{12\left(\text{gL}^2-\text{gY}^2\right)} + \frac{\text{gY}^2 v^2\, \Delta\text{GF}}{6\,\text{gL}^2-6\,\text{gY}^2}
\end{pmatrix}$$

# SMEFT global fit: *4f*

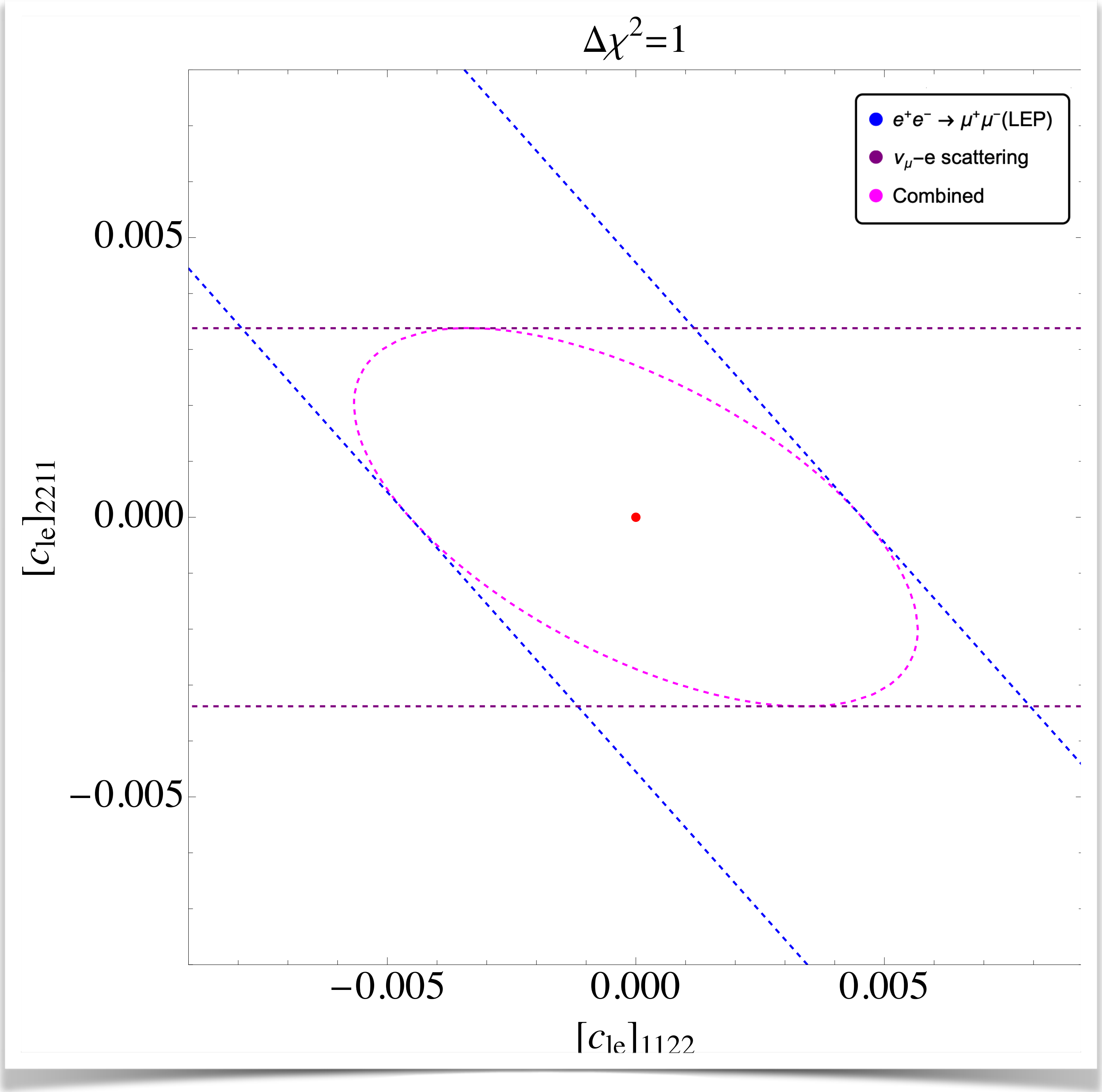
de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326



| Process | Observable | Experimental value | Ref. | SM prediction |
|---|---|---|---|---|
| $\overset{(-)}{\nu}_{\mu} - e^-$ scattering | $g_{LV}^{\nu_\mu e}$ | $-0.035 \pm 0.017$ | CHARM-II [47] | $-0.0396$ [48] |
| | $g_{LA}^{\nu_\mu e}$ | $-0.503 \pm 0.017$ | | $-0.5064$ [48] |
| $\tau$ decay | $\frac{G_{\tau e}^2}{G_F^2}$ | $1.0029 \pm 0.0046$ | PDG2014 [49] | 1 |
| | $\frac{G_{\tau\mu}^2}{G_F^2}$ | $0.981 \pm 0.018$ | | |
| Neutrino scattering | $R_{\nu_\mu}$ | $0.3093 \pm 0.0031$ | CHARM ($r = 0.456$) [50] | 0.3156 [50] |
| | $R_{\overline{\nu}_\mu}$ | $0.390 \pm 0.014$ | | 0.370 [50] |
| | $R_{\nu_\mu}$ | $0.3072 \pm 0.0033$ | CDHS ($r = 0.393$) [51] | 0.3091 [51] |
| | $R_{\overline{\nu}_\mu}$ | $0.382 \pm 0.016$ | | 0.380 [51] |
| | $\kappa$ | $0.5820 \pm 0.0041$ | 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 | $(s_w^2)^{\text{Møller}}$ | $0.2397 \pm 0.0013$ | SLAC-E158 [55] | $0.2381 \pm 0.0006$ [56] |
| | $Q_W^{\text{Cs}}(55, 78)$ | $-72.62 \pm 0.43$ | PDG2016 [54] | $-73.25 \pm 0.02$ [54] |
| | $Q_W^{\text{p}}(1, 0)$ | $0.064 \pm 0.012$ | QWEAK [57] | $0.0708 \pm 0.0003$ [54] |
| | $A_1$ | $(-91.1 \pm 4.3) \times 10^{-6}$ | PVDIS [58] | $(-87.7 \pm 0.7) \times 10^{-6}$ [58] |
| | $A_2$ | $(-160.8 \pm 7.1) \times 10^{-6}$ | | $(-158.9 \pm 1.0) \times 10^{-6}$ [58] |
| | $g_{VA}^{eu} - g_{VA}^{ed}$ | $-0.042 \pm 0.057$ | SAMPLE ($\sqrt{Q^2} = 200\,\text{MeV}$) [59] | -0.0360 [54] |
| | | $-0.12 \pm 0.074$ | SAMPLE ($\sqrt{Q^2} = 125\,\text{MeV}$) [59] | 0.0265 [54] |
| | $b_{\text{SPS}}$ | $-(1.47 \pm 0.42) \times 10^{-4}\,\text{GeV}^{-2}$ | 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] |
| $\tau$ polarization | $\mathcal{P}_\tau$ | $0.012 \pm 0.058$ | VENUS [61] | 0.028 [61] |
| | $\mathcal{A}_\mathcal{P}$ | $0.029 \pm 0.057$ | | 0.021 [61] |
| Neutrino trident production | $\frac{\sigma}{\sigma^{\text{SM}}}(\nu_\mu \gamma^* \to \nu_\mu \mu^+ \mu^-)$ | $0.82 \pm 0.28$ | 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 |
| $e^+e^- \to f\overline{f}$ | $\delta A_{LR}^e$ | 2.0% | SuperKEKB [66] | 0.00015 |
| | $\delta A_{LR}^\mu$ | 1.5% | | -0.0006 |
| | $\delta A_{LR}^\tau$ | 2.4% | | -0.0006 |
| | $\delta A_{LR}^c$ | 0.5% | | -0.005 |
| | $\delta A_{LR}^b$ | 0.4% | | -0.020 |

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

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



# SMEFT global fit: *4f*

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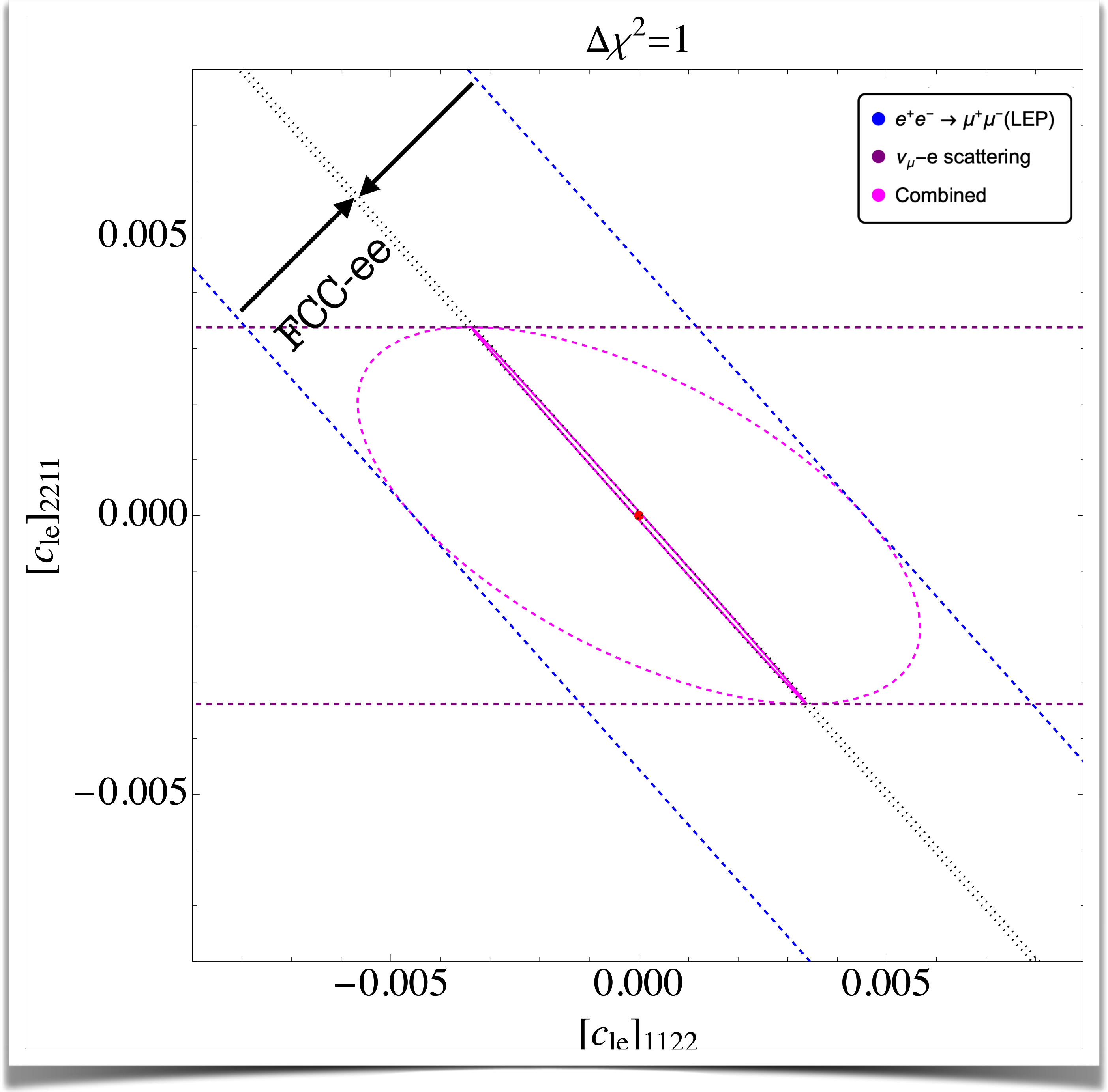
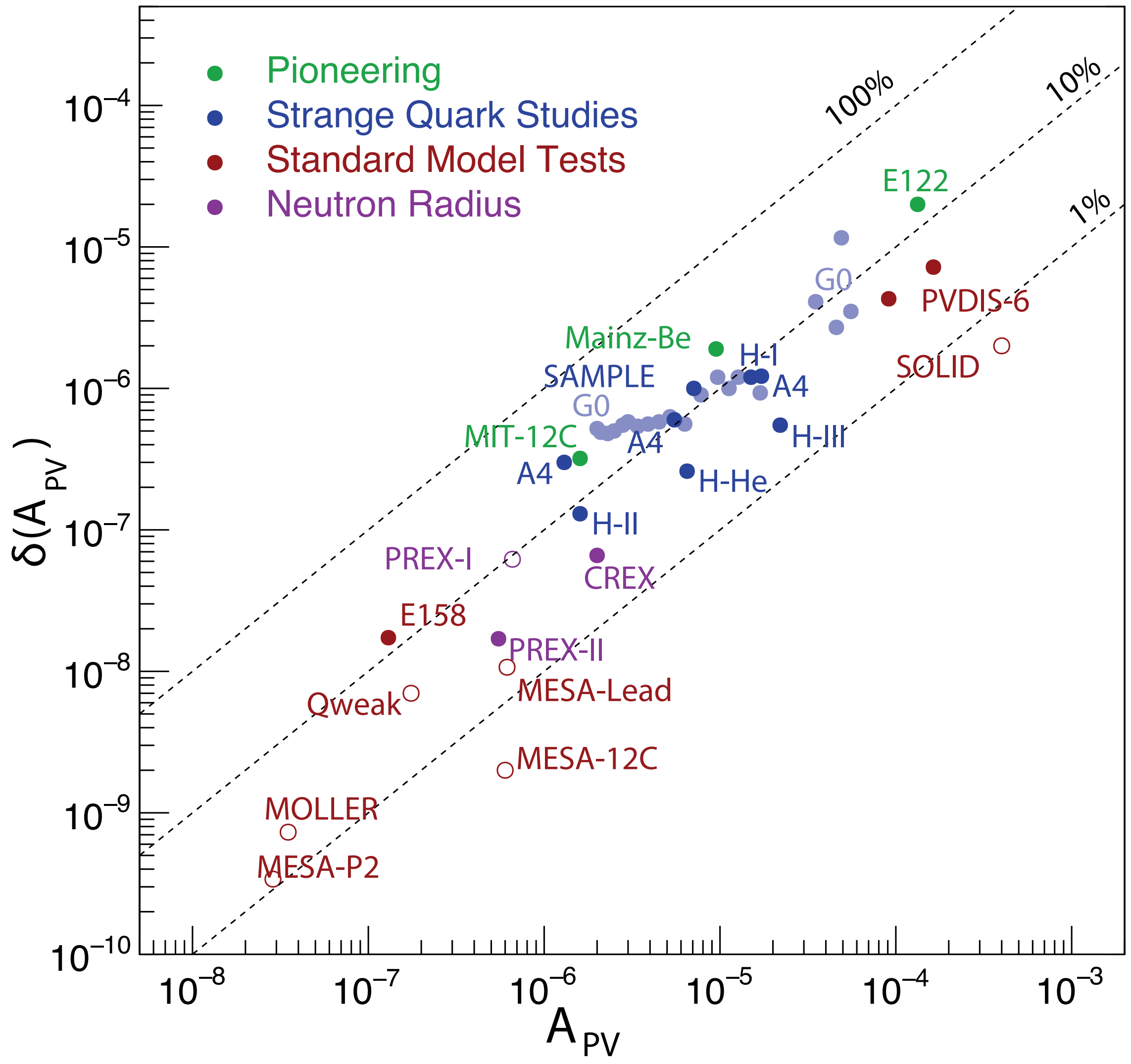


# SMEFT global fit: ***4f***

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

Bhabha alone is not enough to close the fit, $A_{\mathrm{PV}}$ 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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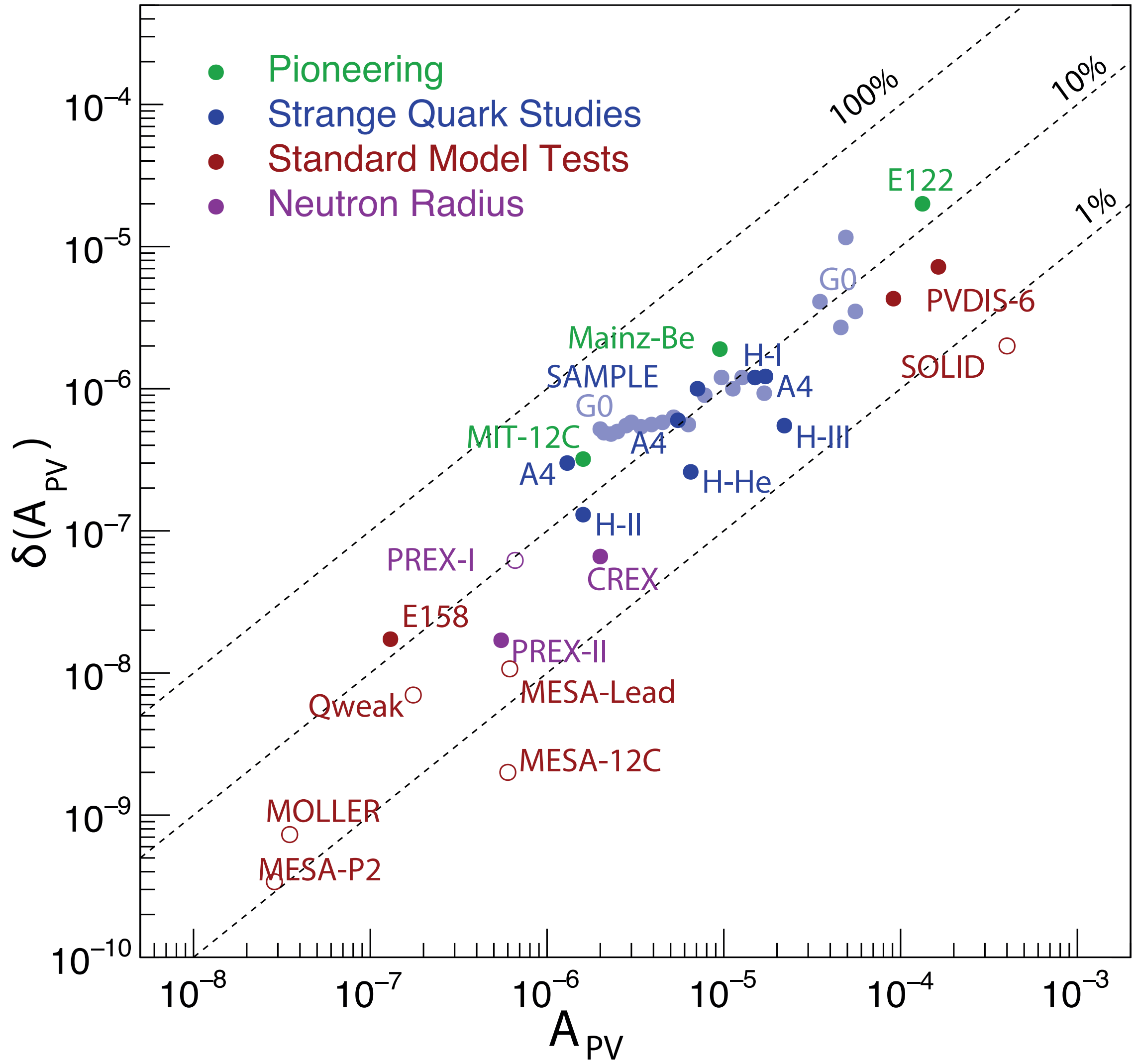

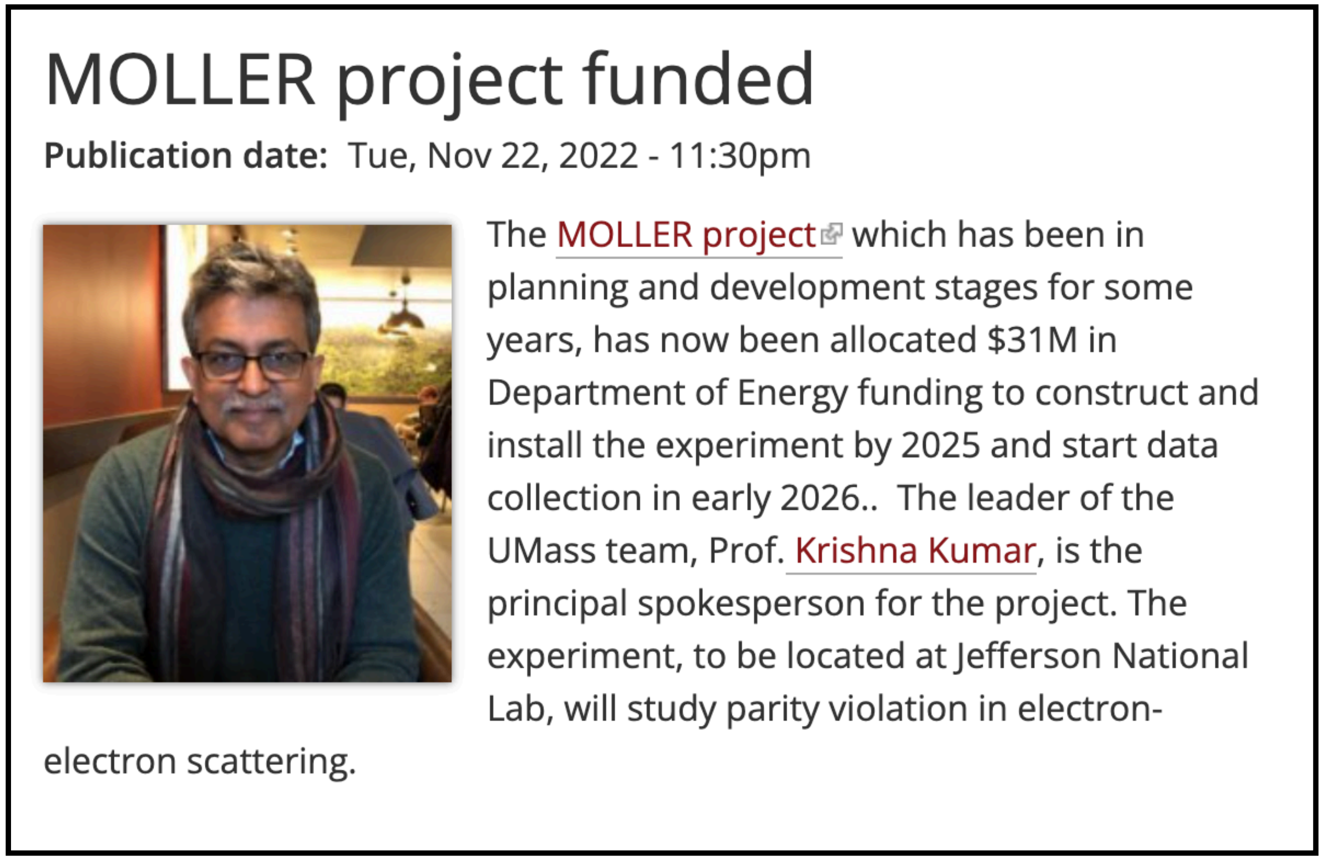

## MOLLER project funded

**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.

P2 collaboration, 1802.04759 (EPJA)

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

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

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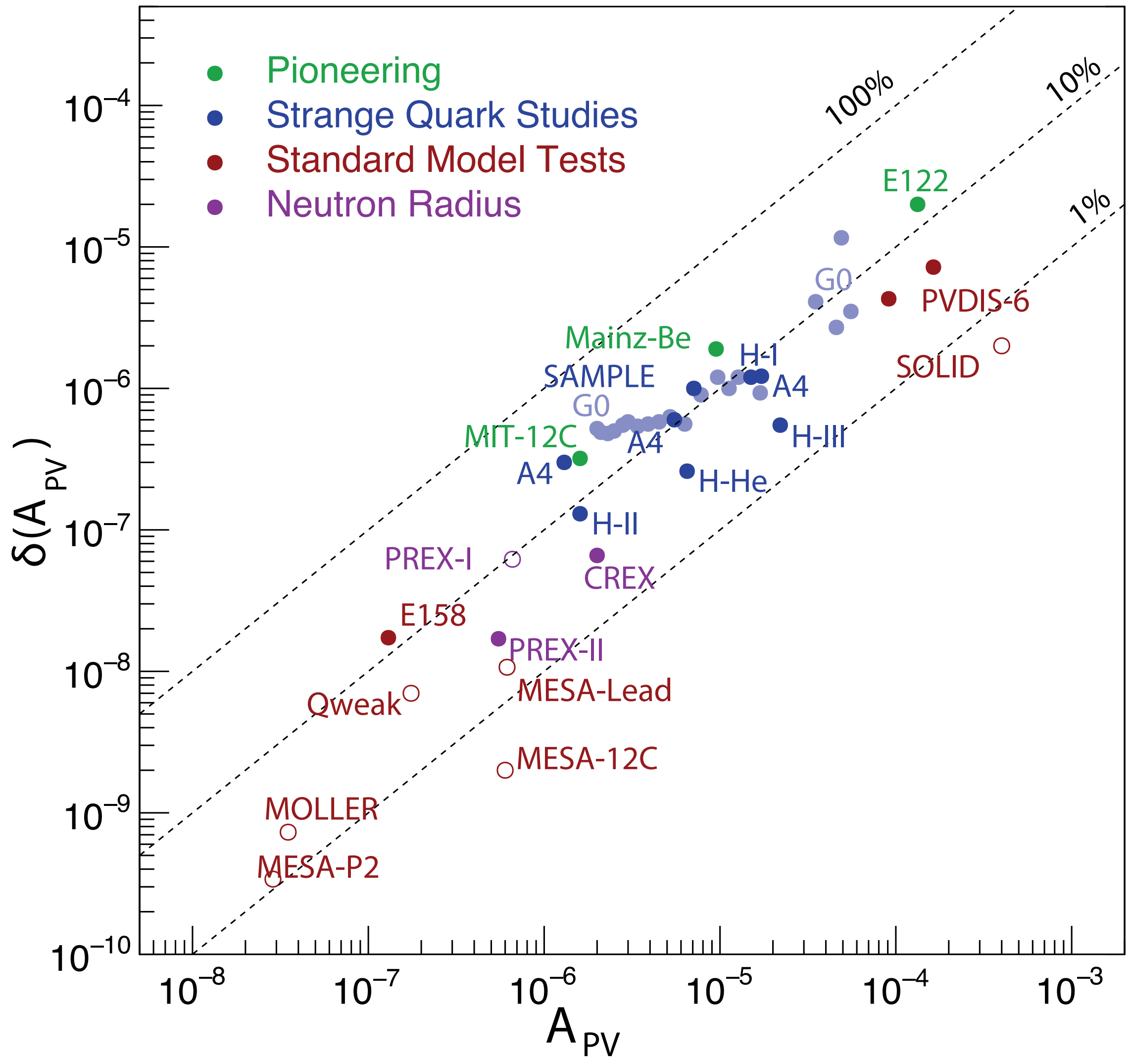

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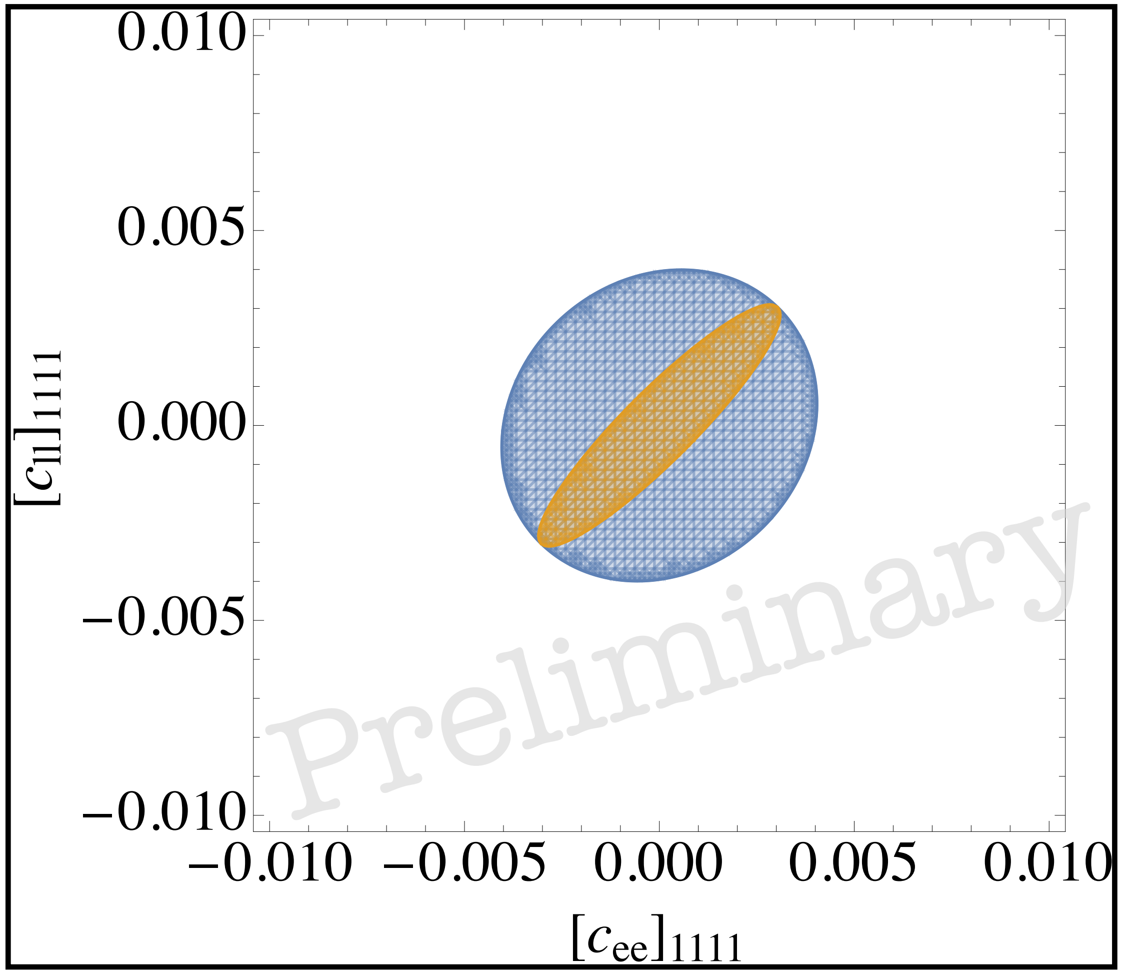


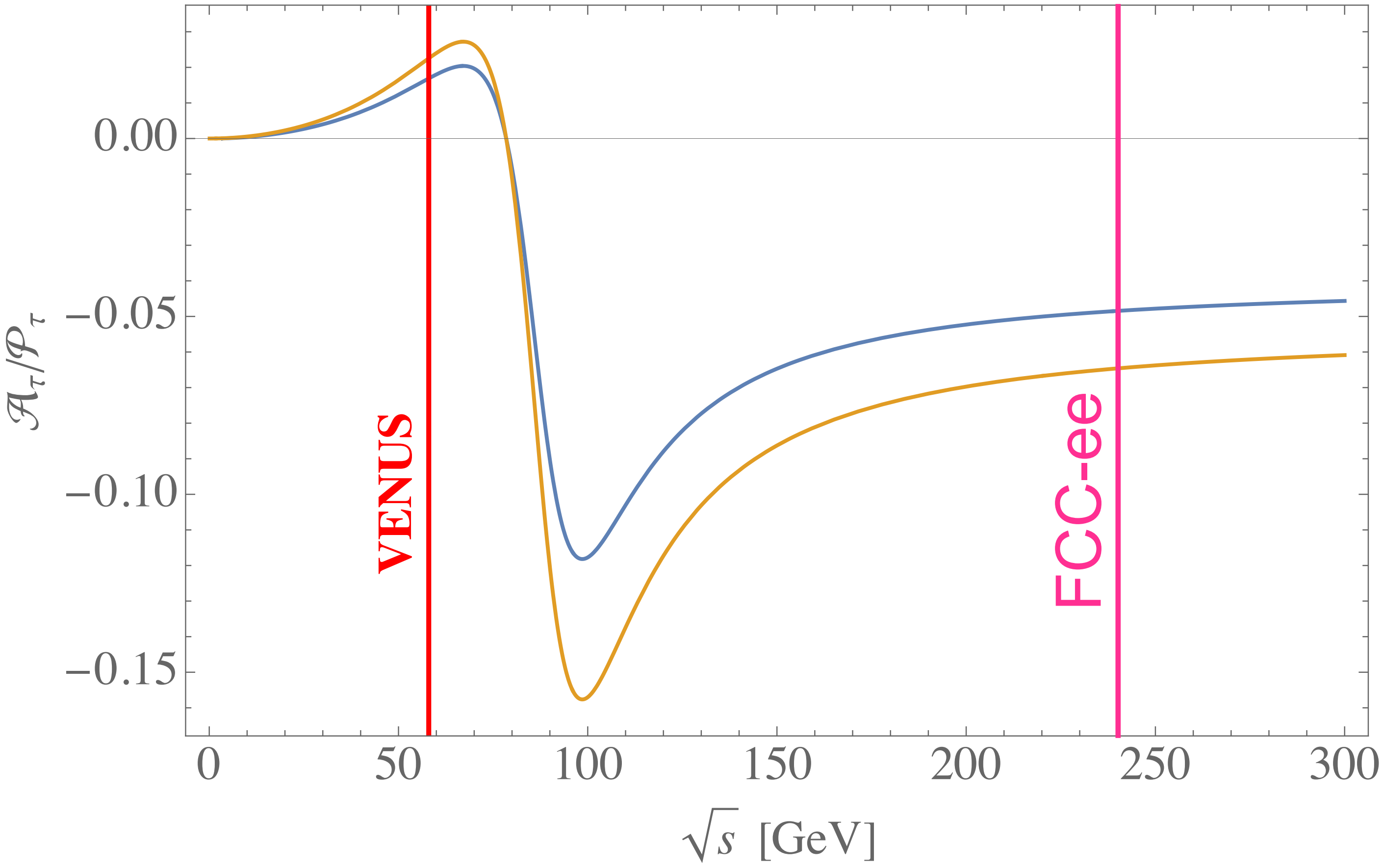
(Bhabha from FCC-ee not included here)

Fulvio's talk yesterday

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

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

$\tau$ polarization measurement at VENUS is limited by statistics ($\mathscr{L} = 271\,\mathrm{pb}^{-1}$). FCC-ee at 240GeV will have better sensitivity with much more statistics, how well can we control the systematical?



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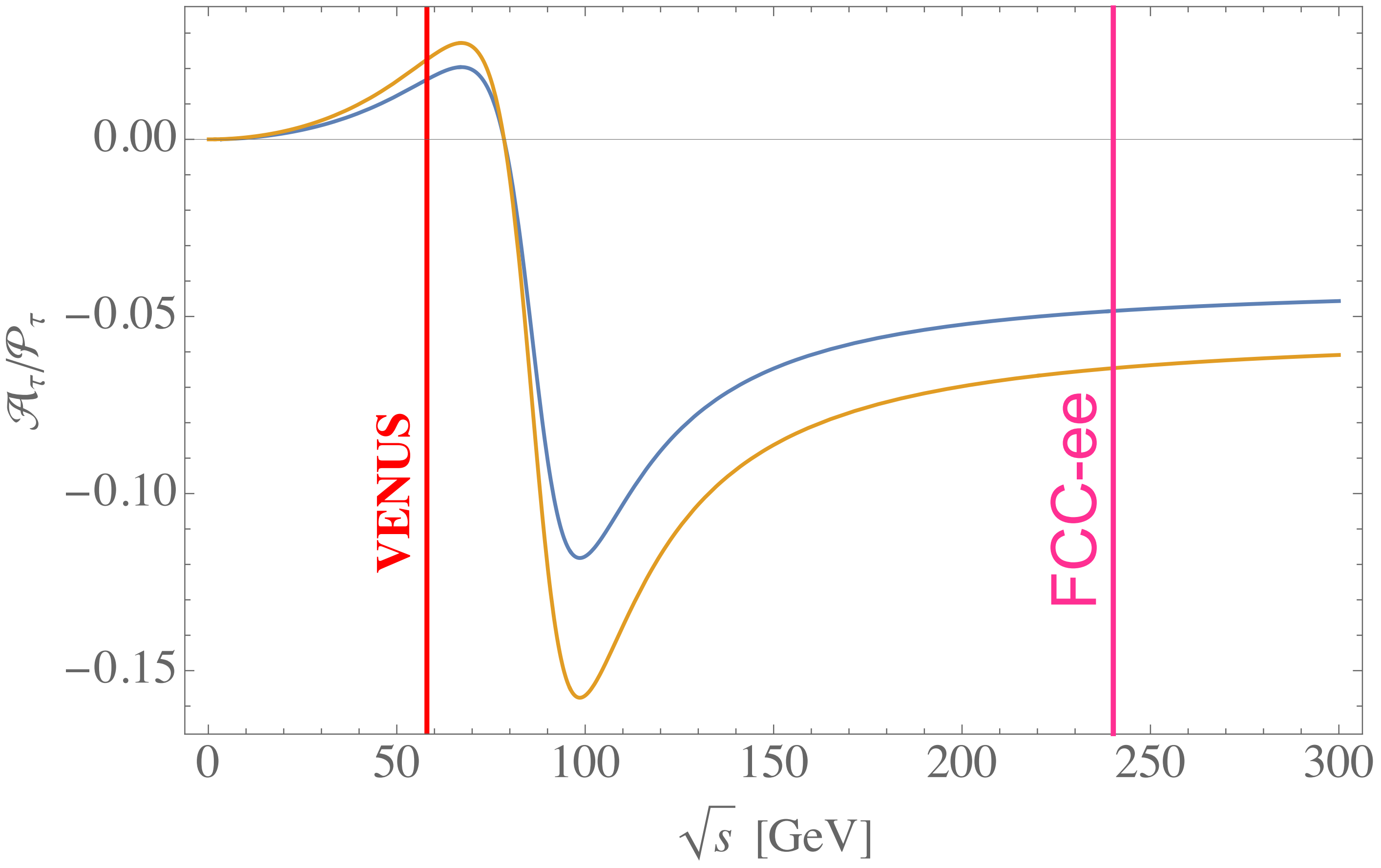

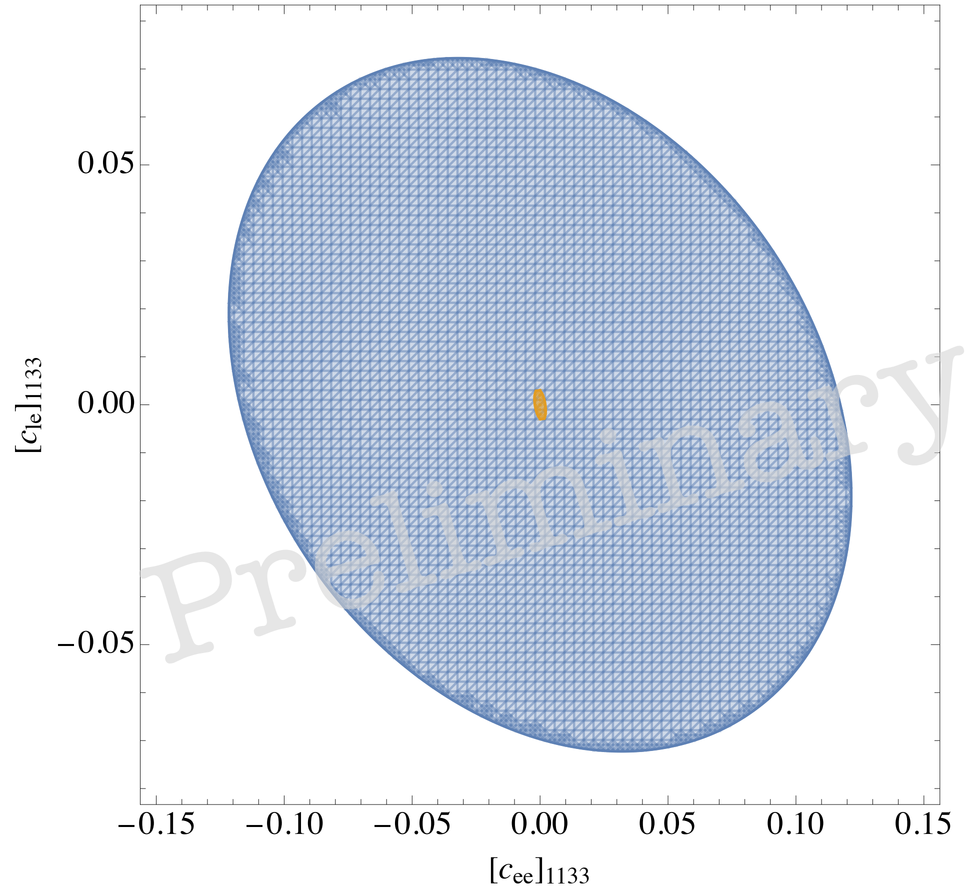

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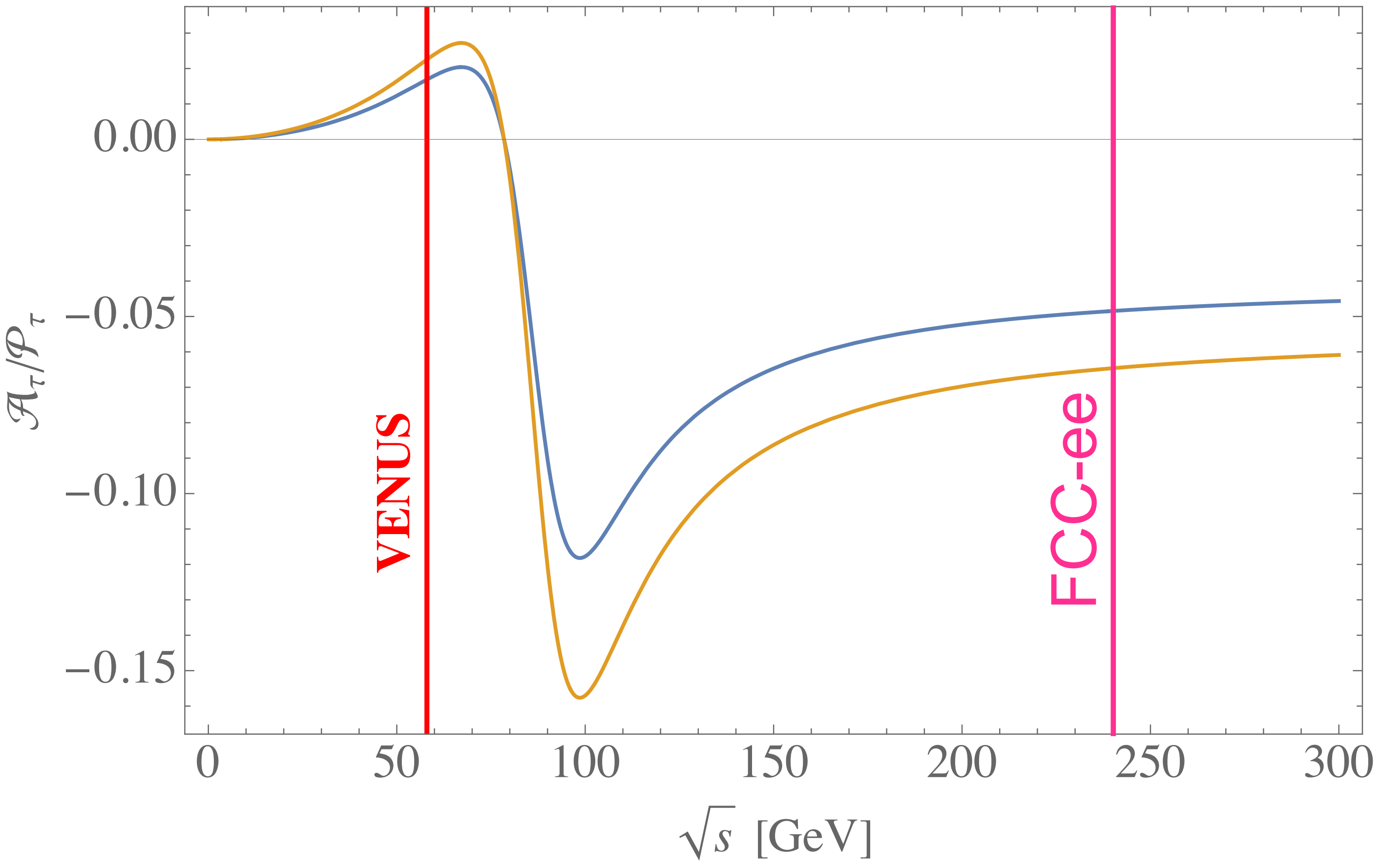

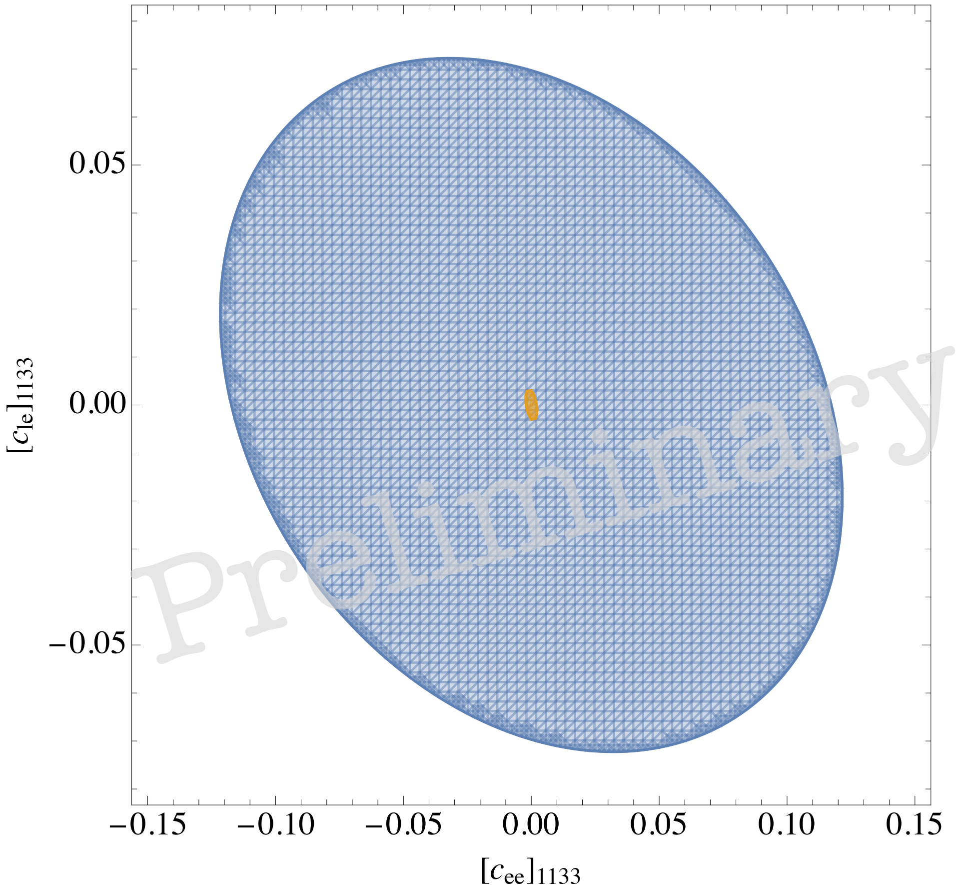

***Q: Projections for FCC-ee?***

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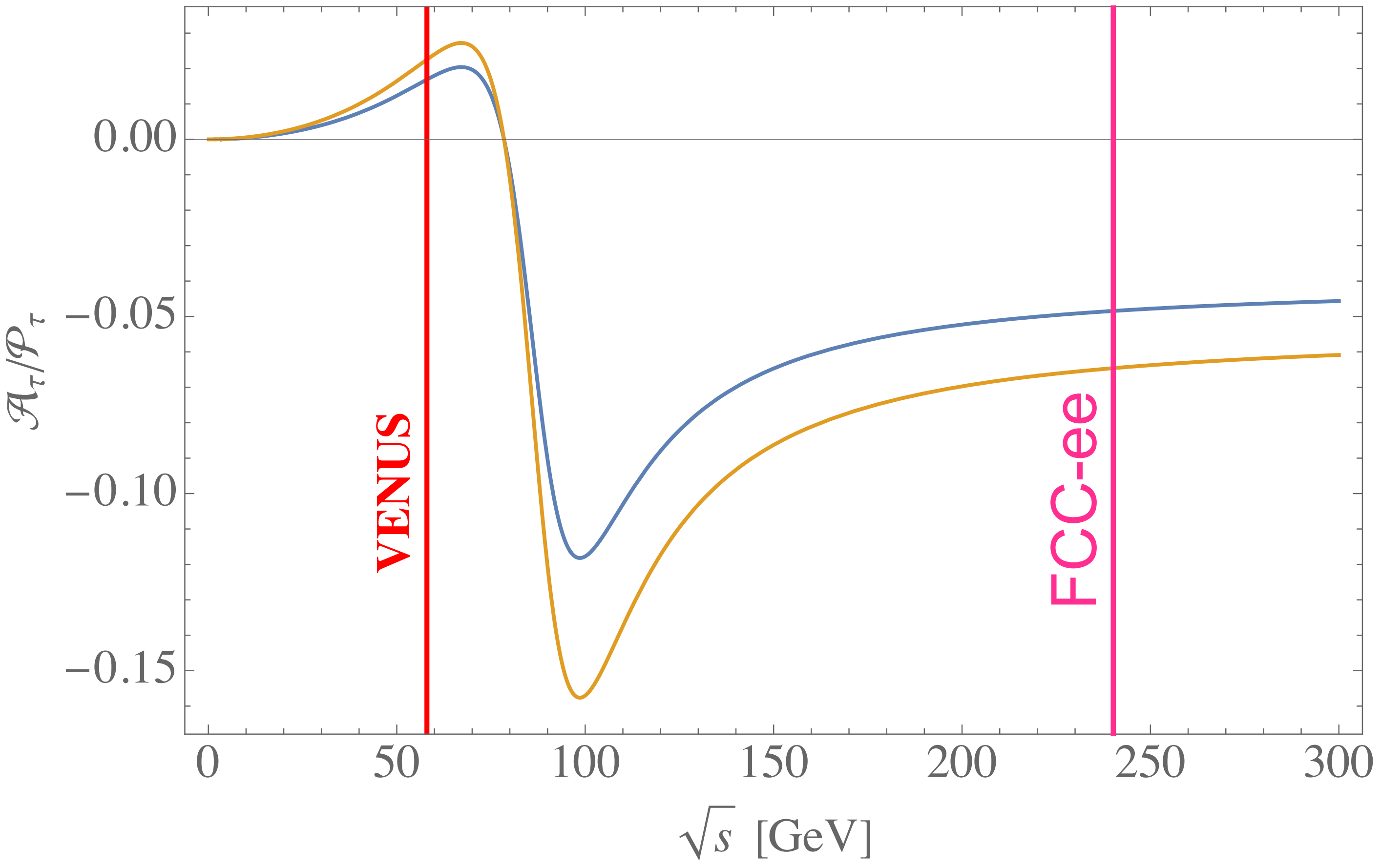
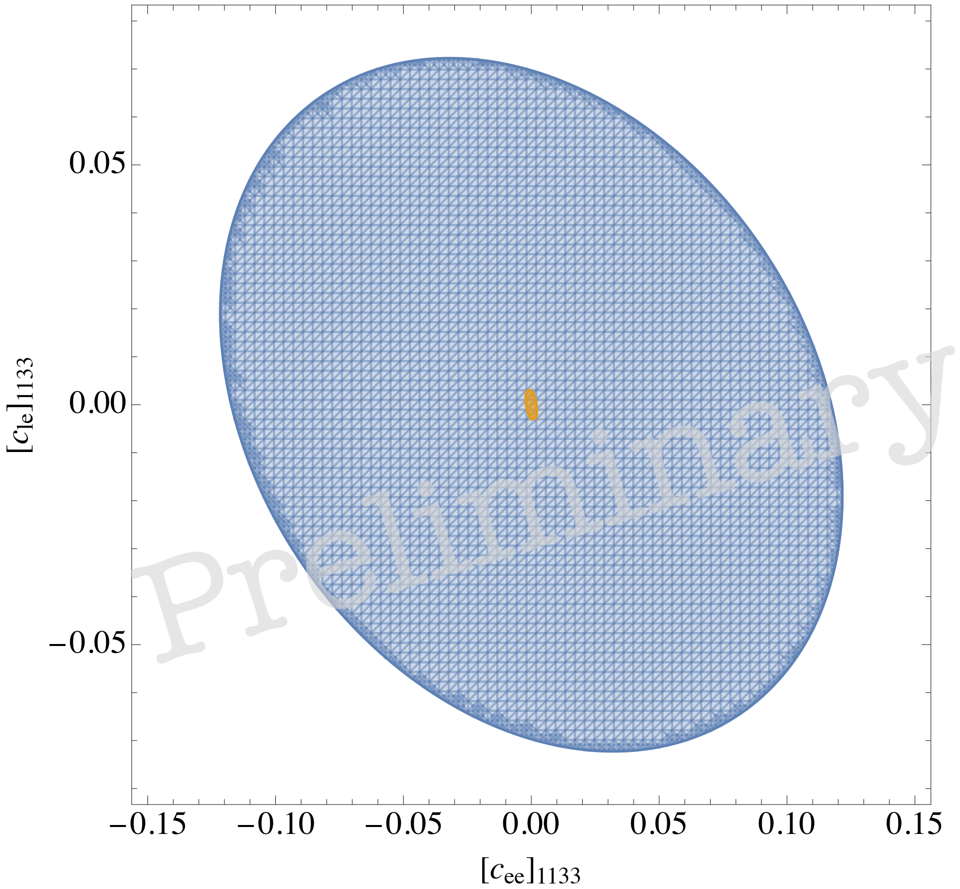


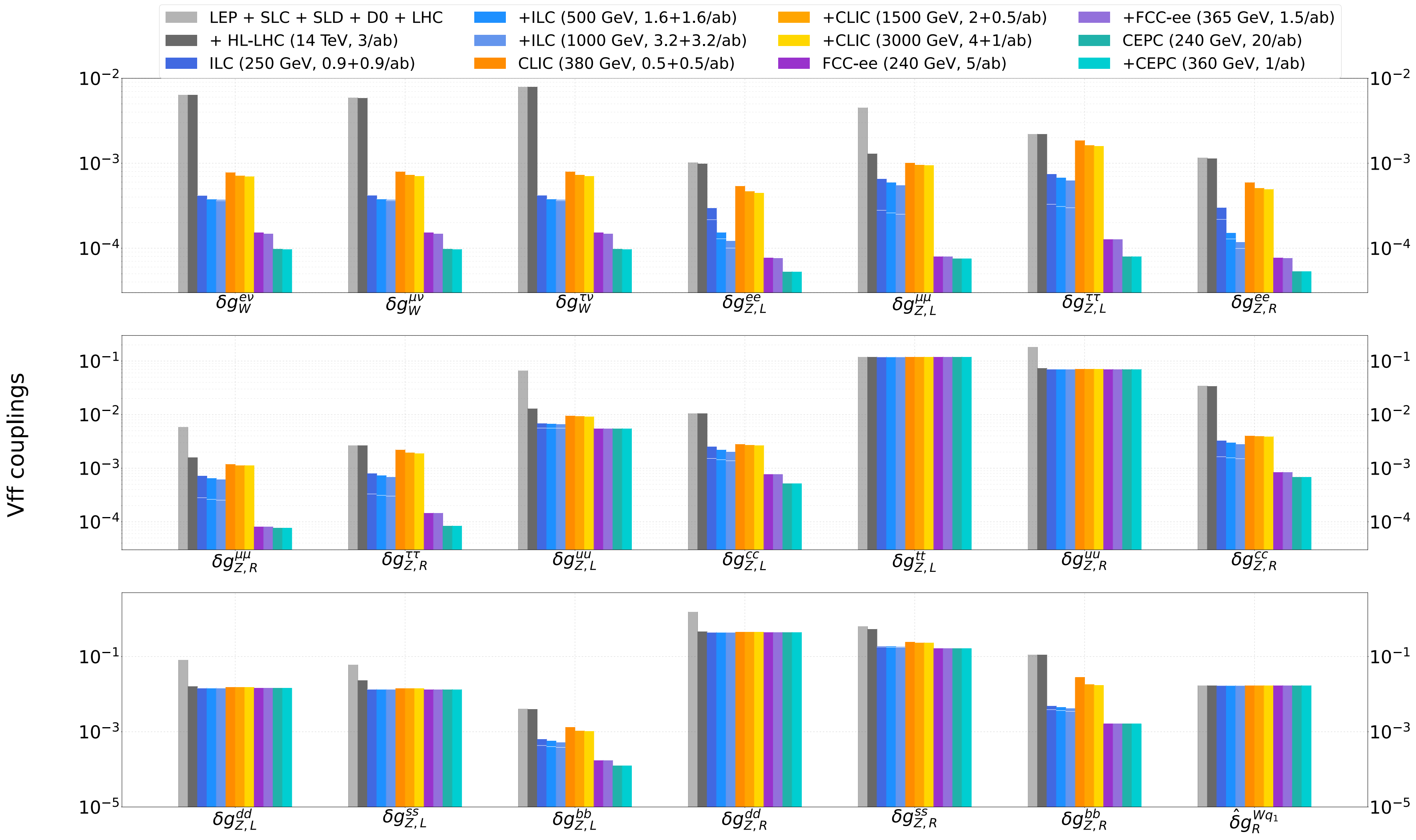


***Q: Projections for FCC-ee?***

Also very interesting $\tau$ physics at TeraZ
see for example Pich 2012.07099 (EPJP)

# SMEFT global fit: *4f*

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

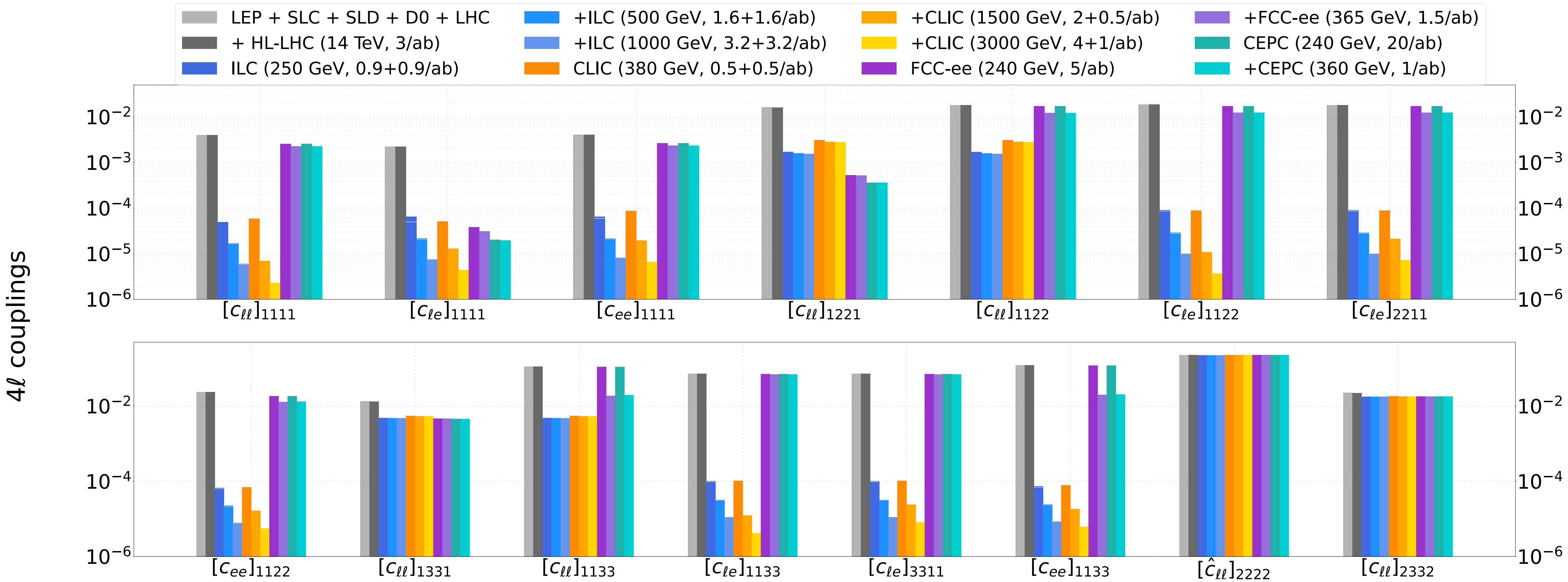


Unprecedented precision reached at the FCCee machine (same for Higgs couplings, see backup)

Still much room left for new physics generating large 1st and 2nd (could be improved with $\sigma_s$ and $A_{\mathrm{FB}}^{s}$) generation $Zq\bar{q}$ couplings (possible tagging improvement? The help with AI (Chai, Gu, Li, 2401.02427 for example)?)

# SMEFT global fit: *4f*

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



Also much room left for 4-fermion operators at FCC-ee or CEPC (same for top, see backup), mainly due to the difficulty in telling the right from the left.

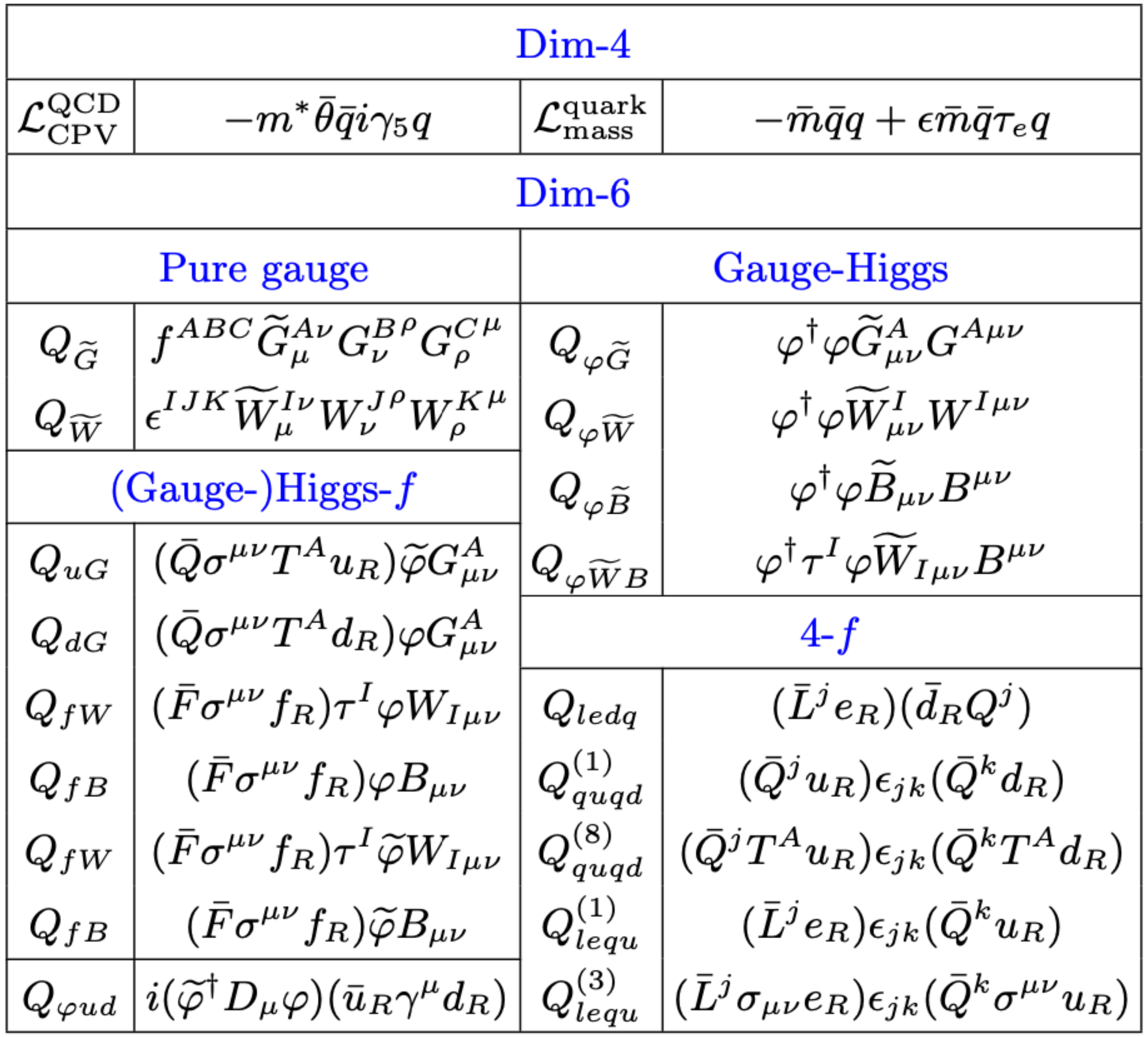
Merging current/future neutrino (e.g. CEvNS) and/or polarized experimental (EIC/EicC for example) data to make a difference?

Polarized future circular colliders? (See Zhe Duan's talk on Tuesday for a possible study)

# SMEFT global fit: ***CPV***

# SMEFT global fit: ***CPV***

This precision FCC-ee machine could also help in understanding our existence by closely investigating the CPV operators



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<tr><td colspan="4">Dim-4</td></tr>
<tr><td>$\mathcal{L}_{\rm CPV}^{\rm QCD}$</td><td>$-m^*\bar{\theta}\bar{q}i\gamma_5 q$</td><td>$\mathcal{L}_{\rm mass}^{\rm quark}$</td><td>$-\bar{m}\bar{q}q+\epsilon\bar{m}\bar{q}\tau_e q$</td></tr>
<tr><td colspan="4">Dim-6</td></tr>
<tr><td colspan="2">Pure gauge</td><td colspan="2">Gauge-Higgs</td></tr>
<tr><td>$Q_{\widetilde{G}}$</td><td>$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$</td><td>$Q_{\varphi\widetilde{G}}$</td><td>$\varphi^\dagger\varphi\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$</td></tr>
<tr><td>$Q_{\widetilde{W}}$</td><td>$\epsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$</td><td>$Q_{\varphi\widetilde{W}}$</td><td>$\varphi^\dagger\varphi\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$</td></tr>
<tr><td colspan="2">(Gauge-)Higgs-$f$</td><td>$Q_{\varphi\widetilde{B}}$</td><td>$\varphi^\dagger\varphi\widetilde{B}_{\mu\nu}B^{\mu\nu}$</td></tr>
<tr><td>$Q_{uG}$</td><td>$(\bar{Q}\sigma^{\mu\nu}T^A u_R)\widetilde{\varphi}G_{\mu\nu}^A$</td><td>$Q_{\varphi\widetilde{W}B}$</td><td>$\varphi^\dagger\tau^I\varphi\widetilde{W}_{I\mu\nu}B^{\mu\nu}$</td></tr>
<tr><td>$Q_{dG}$</td><td>$(\bar{Q}\sigma^{\mu\nu}T^A d_R)\varphi G_{\mu\nu}^A$</td><td colspan="2">4-$f$</td></tr>
<tr><td>$Q_{fW}$</td><td>$(\bar{F}\sigma^{\mu\nu}f_R)\tau^I\varphi W_{I\mu\nu}$</td><td>$Q_{ledq}$</td><td>$(\bar{L}^j e_R)(\bar{d}_R Q^j)$</td></tr>
<tr><td>$Q_{fB}$</td><td>$(\bar{F}\sigma^{\mu\nu}f_R)\varphi B_{\mu\nu}$</td><td>$Q_{quqd}^{(1)}$</td><td>$(\bar{Q}^j u_R)\epsilon_{jk}(\bar{Q}^k d_R)$</td></tr>
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<tr><td>$Q_{fB}$</td><td>$(\bar{F}\sigma^{\mu\nu}f_R)\widetilde{\varphi}B_{\mu\nu}$</td><td>$Q_{lequ}^{(1)}$</td><td>$(\bar{L}^j e_R)\epsilon_{jk}(\bar{Q}^k u_R)$</td></tr>
<tr><td>$Q_{\varphi ud}$</td><td>$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_R\gamma^\mu d_R)$</td><td>$Q_{lequ}^{(3)}$</td><td>$(\bar{L}^j\sigma_{\mu\nu}e_R)\epsilon_{jk}(\bar{Q}^k\sigma^{\mu\nu}u_R)$</td></tr>
</table>

Engel, Ramsey-Musolf, van Kolck, 1303.2371 (Prog.Part.Nucl.Phys.)

Chupp, Ramsey-Musolf, van Kolck, 1407.1064 (PRC)

# SMEFT global fit: ***CPV***

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

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

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

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

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

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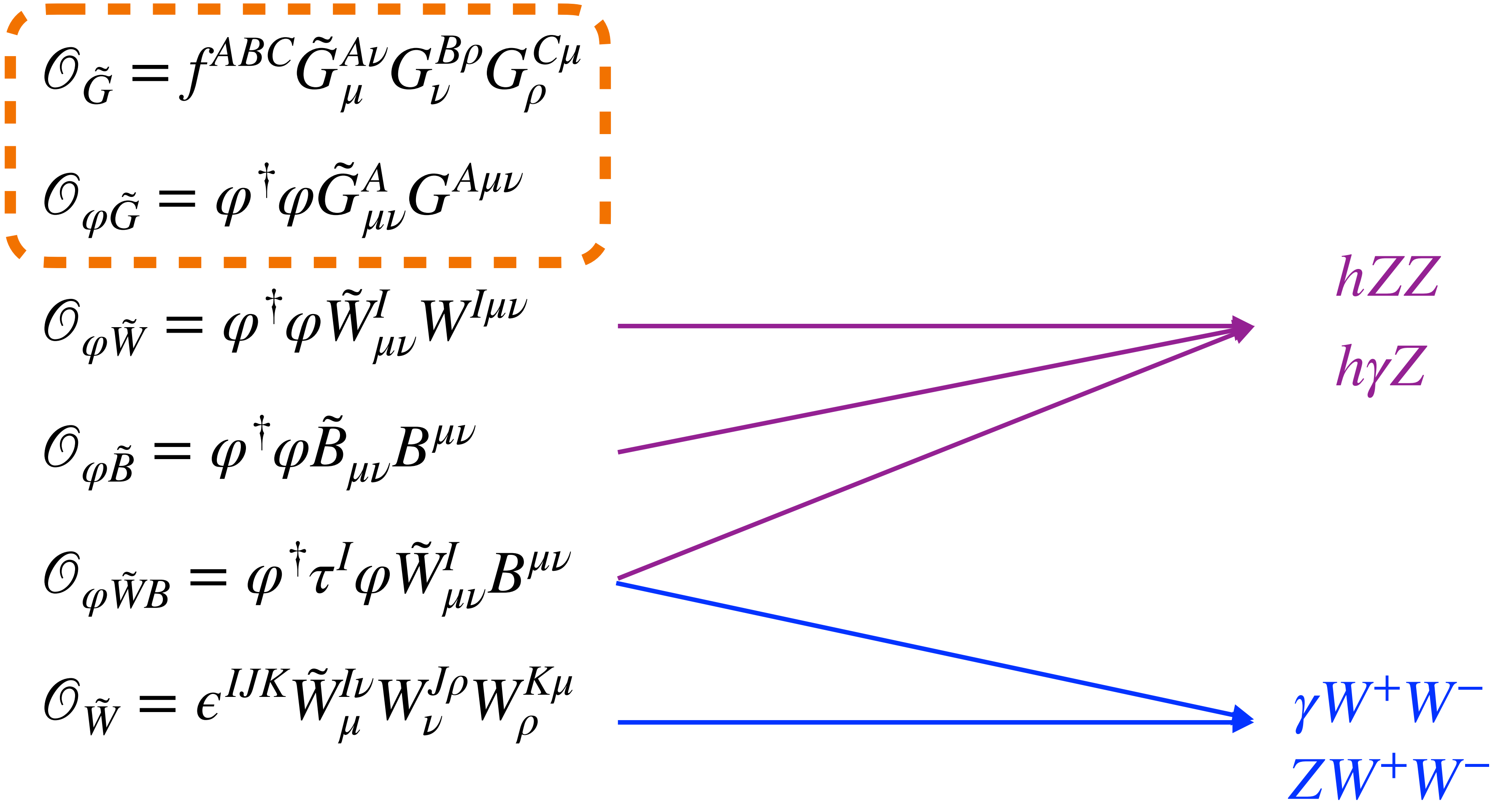
# SMEFT global fit: ***CPV***



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

$hZZ$

$h\gamma Z$

$\gamma W^+W^-$

$ZW^+W^-$

(Statistically limited at OPAL)

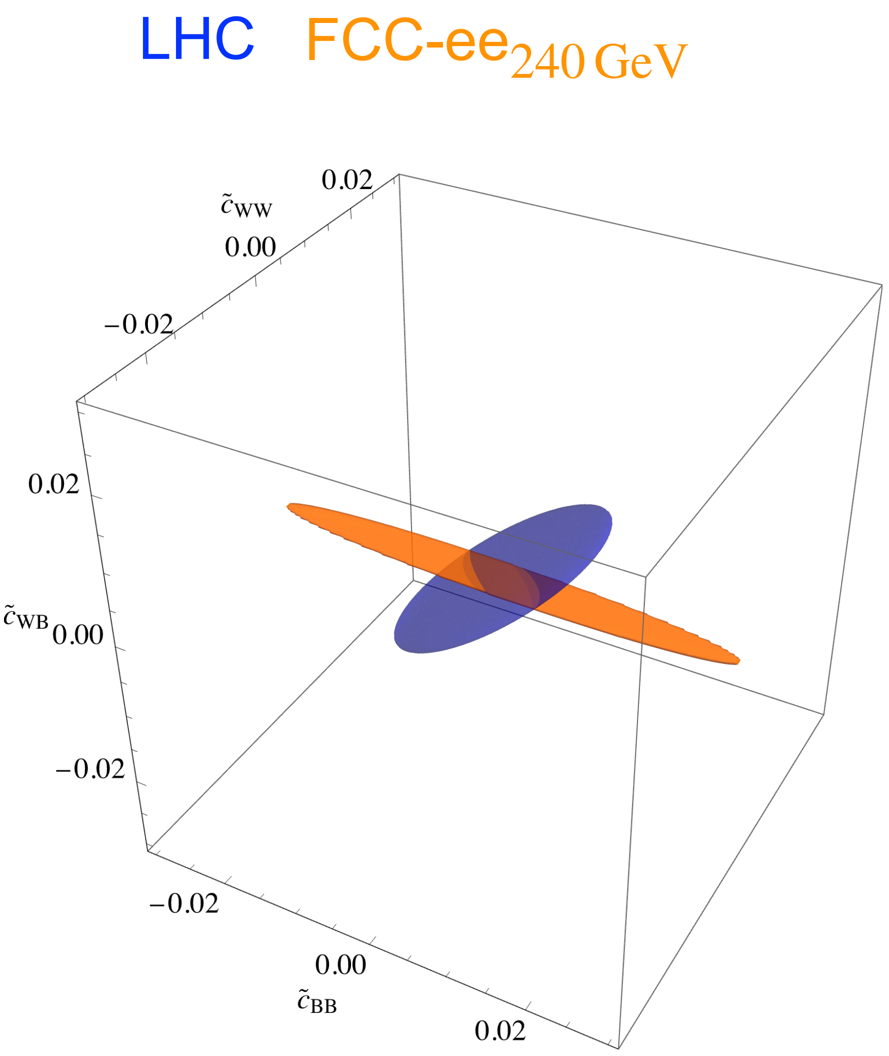
FCC-ee is well suited for both $Zh$ and $W^+W^-$ studies!

Also helps $V_{cb}$ extraction

See [Stephane's talk](#) yesterday

# SMEFT global fit: ***CPV***

Using angular asymmetries of $Zh$ and aTGC measurements for $W^+W^-$, the CPV parameters can be extracted, for which we use the optimal observable approach to improve the sensitivity



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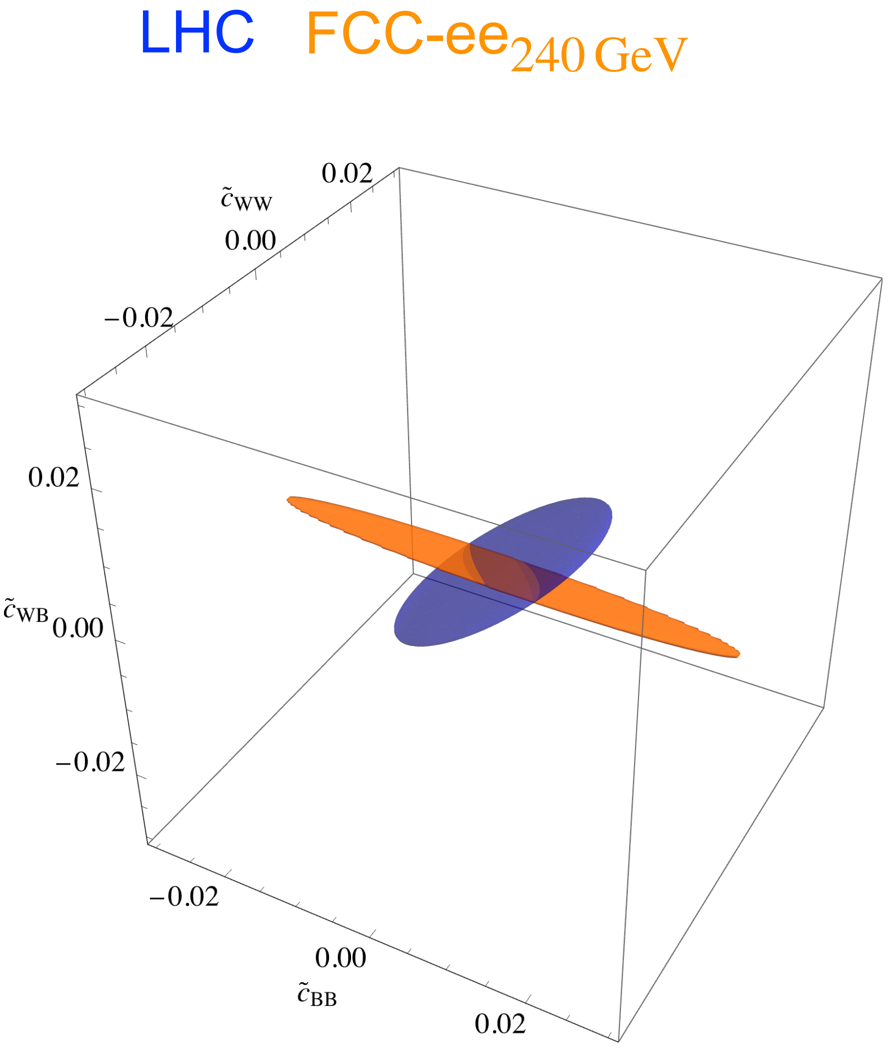
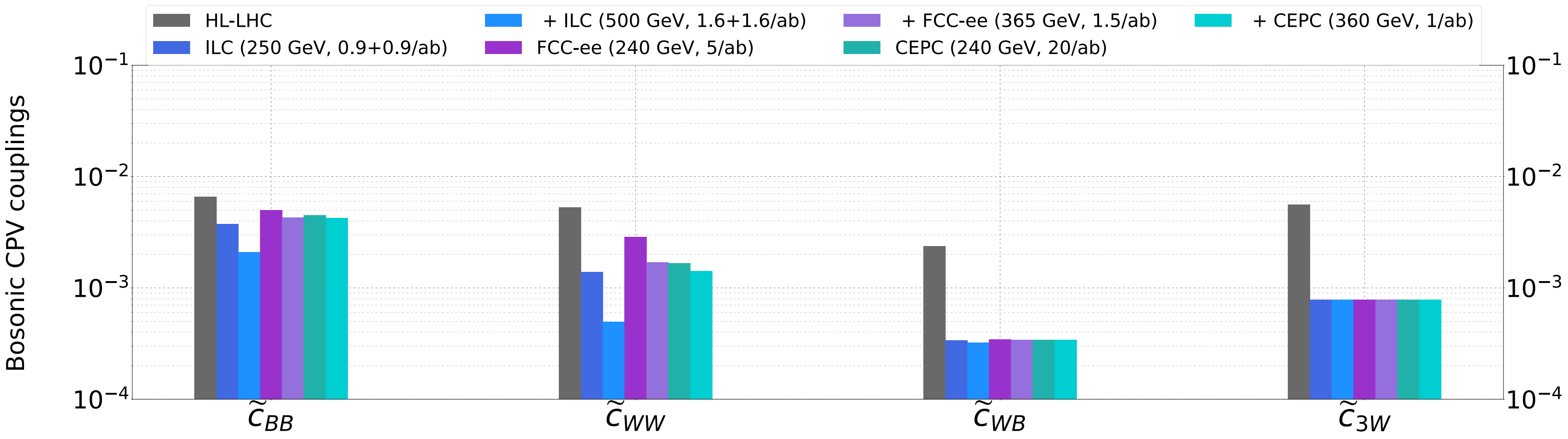




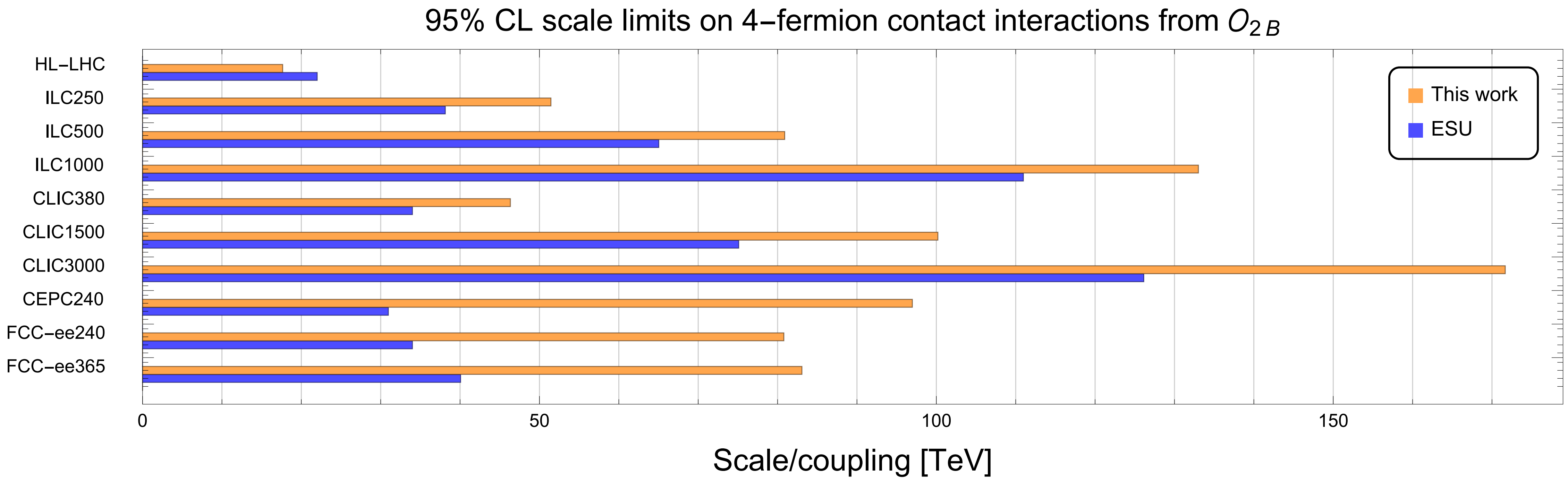
Per-mille level precision reach

# Benchmark

# Benchmark: *Y-Universal Z' model*

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

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

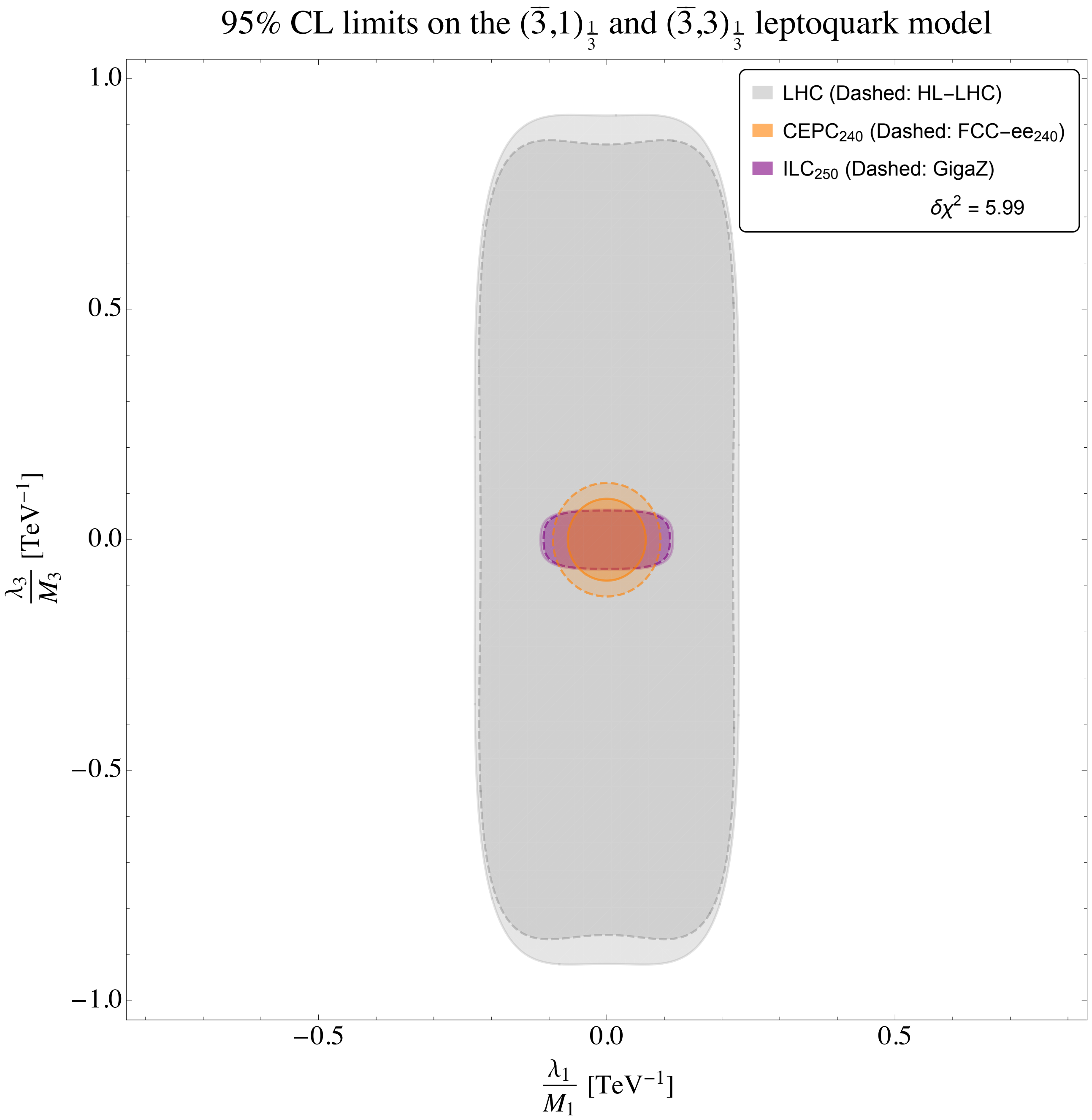


de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

FCC-hh? See Matthew's talk yesterday

# Benchmark: *Leptoquark model*

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

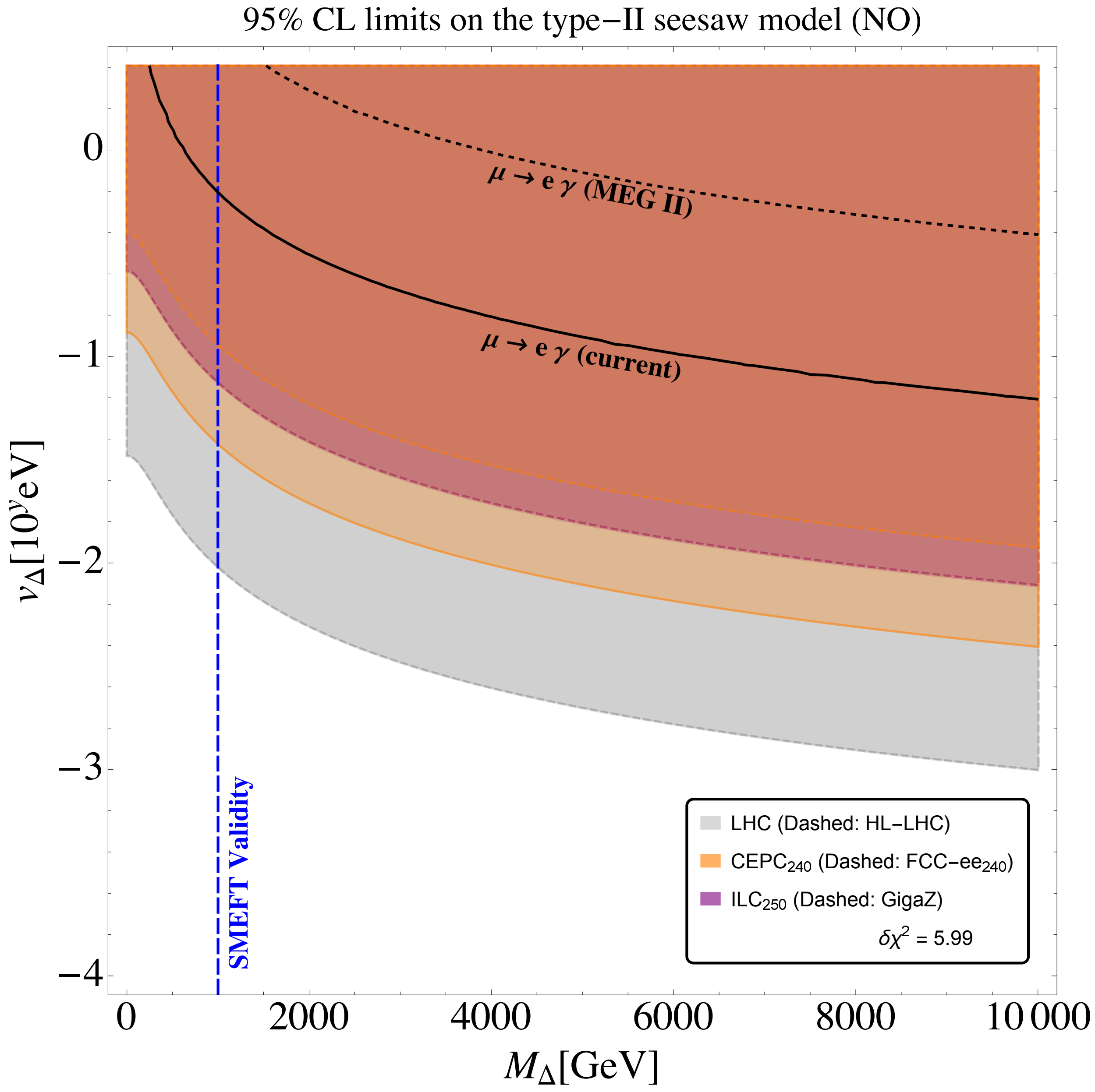


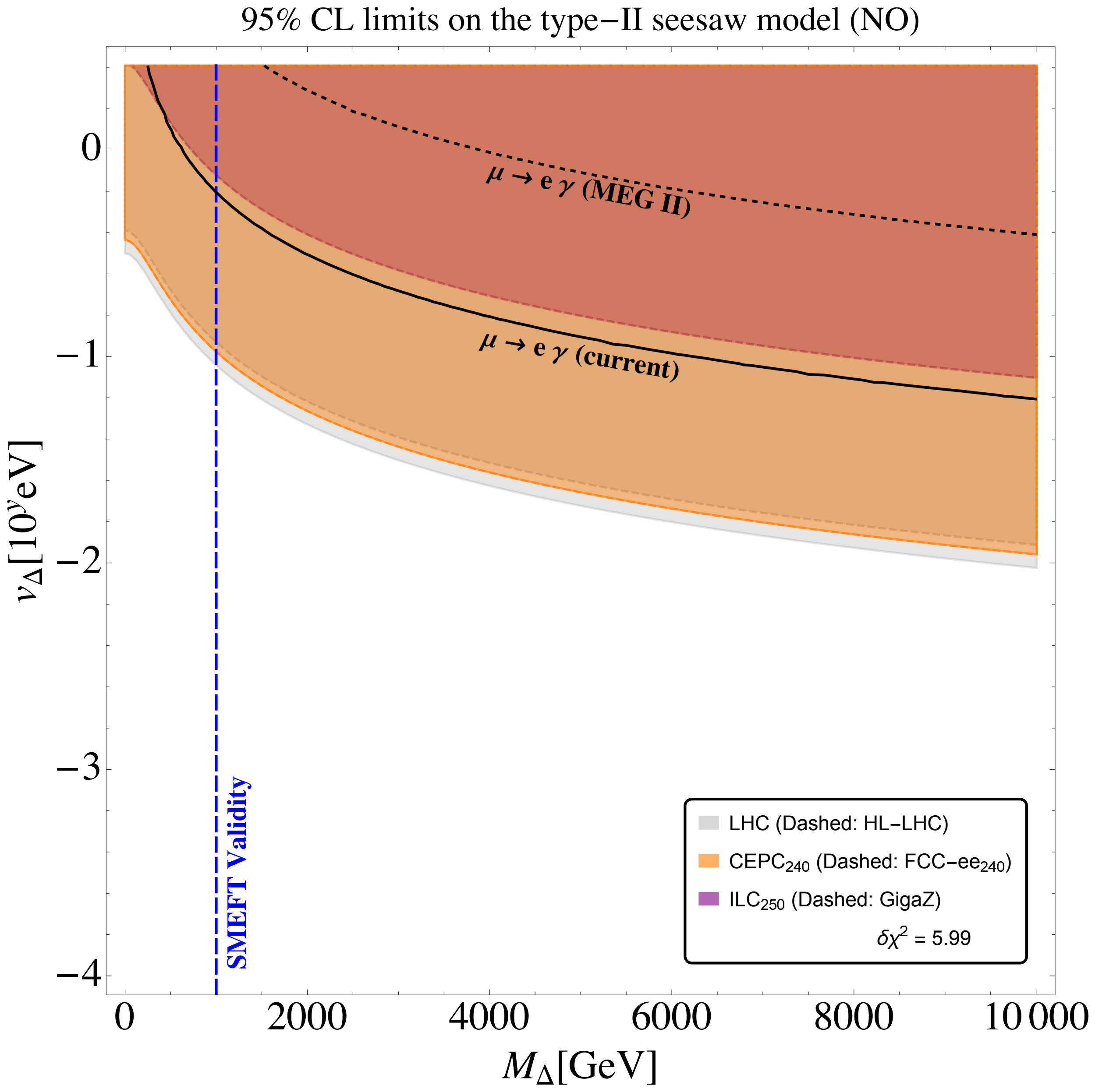
de Blas, **YD**, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou, 2206.08326

# Benchmark: *Type-II seesaw model*

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

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





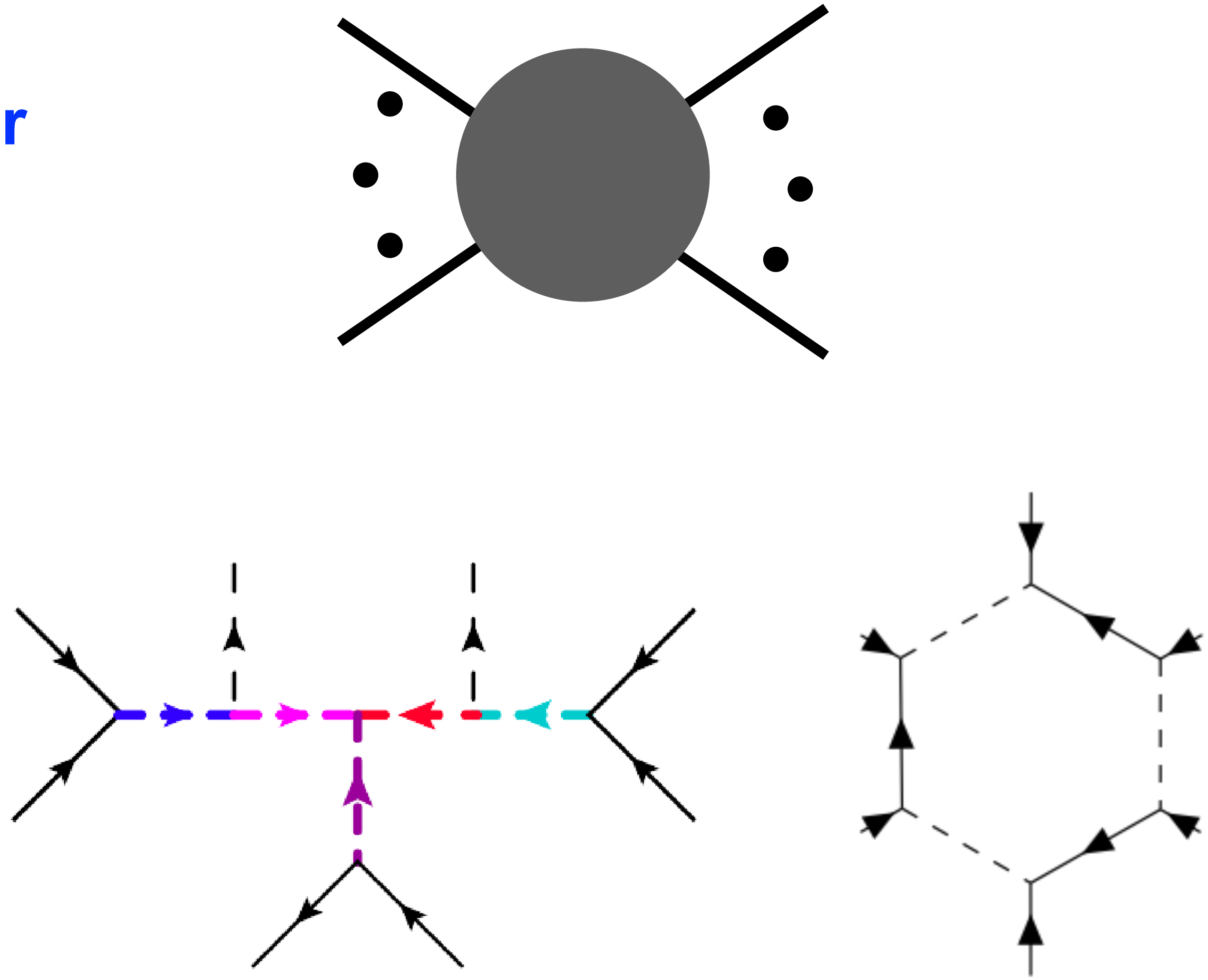
$$m_{\mathrm{light}} = 0 \text{ vs } m_{\mathrm{light}} = 0.1\,\mathrm{eV}$$

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

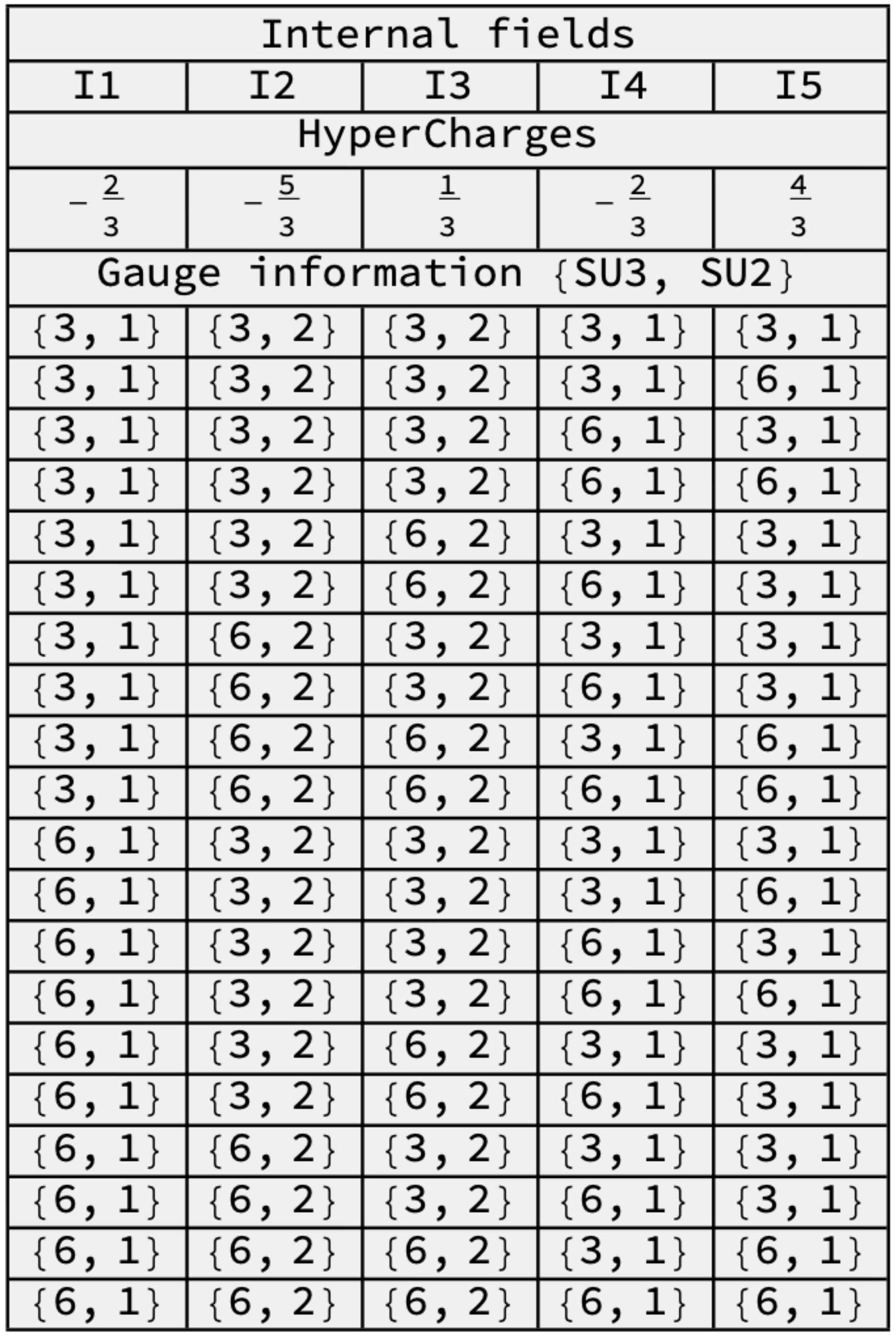
# Benchmark: *Unfolding*

**Operator**

**UV**



Find the UV 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} |

***Q: Which benchmark model for FCC-ee?***

# Summary

- FCC-ee is an ideal precision machine for new physics study within SMEFT:
  - Unprecedented precision reach for Higgs and EW physics (except 1st gen quarks)
  - Increase sensitivity reach of 4-fermion operator with beam polarization at FCC-ee?
  - Otherwise, merging low-energy data (neutrino for example) may make a difference
  - A new direction can be probed for CPV operators, complementary to the LHC

- FCC-ee also a perfect machine for specific new physics model studies
  - the Z’ model
  - the leptoquark model
  - …
  - operator unfolding upon anomaly observation?

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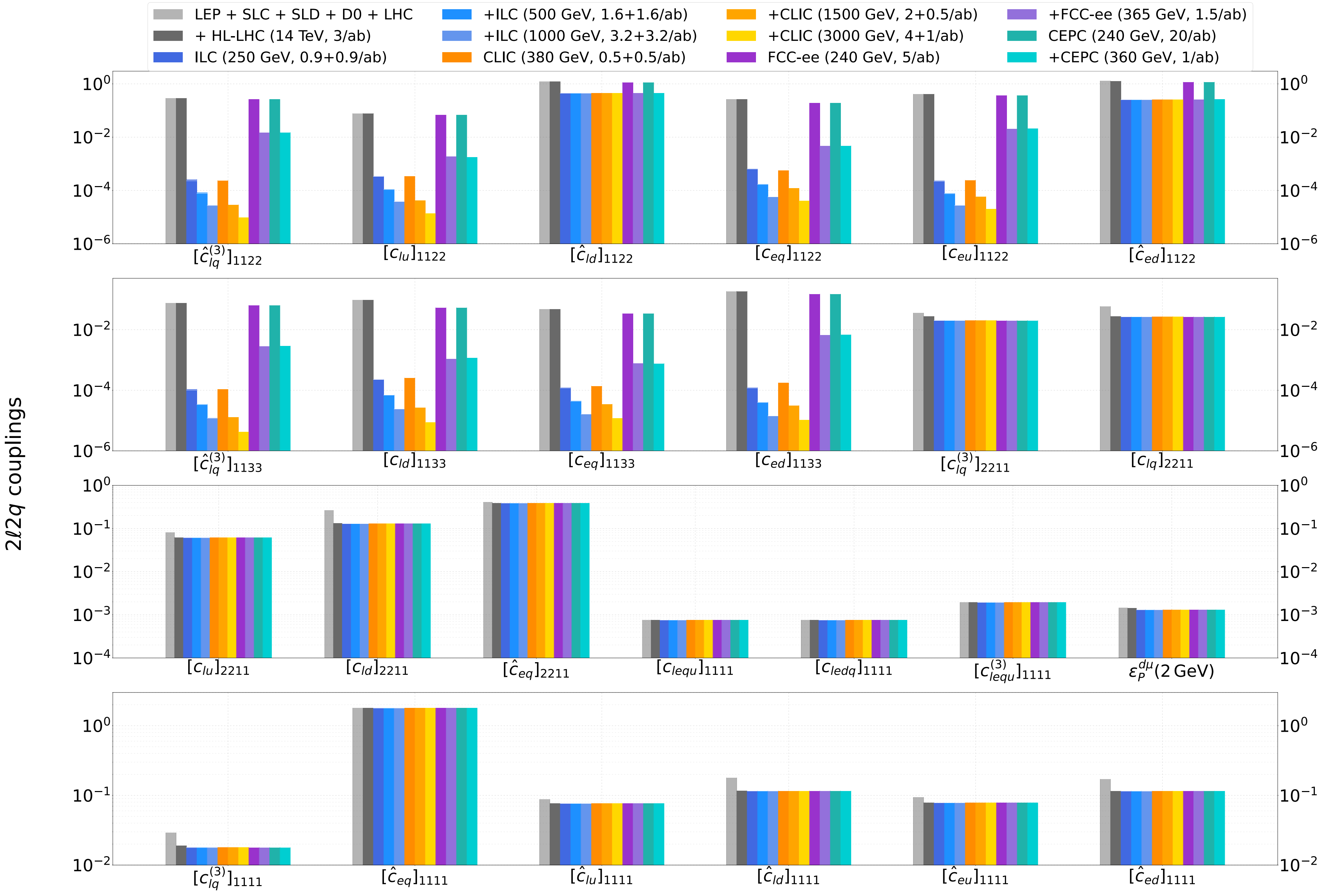
**While do not know when to expect**
**let’s witness the birth of FCC-ee solidly together**

# Backup

# SMEFT global fit: *4f*

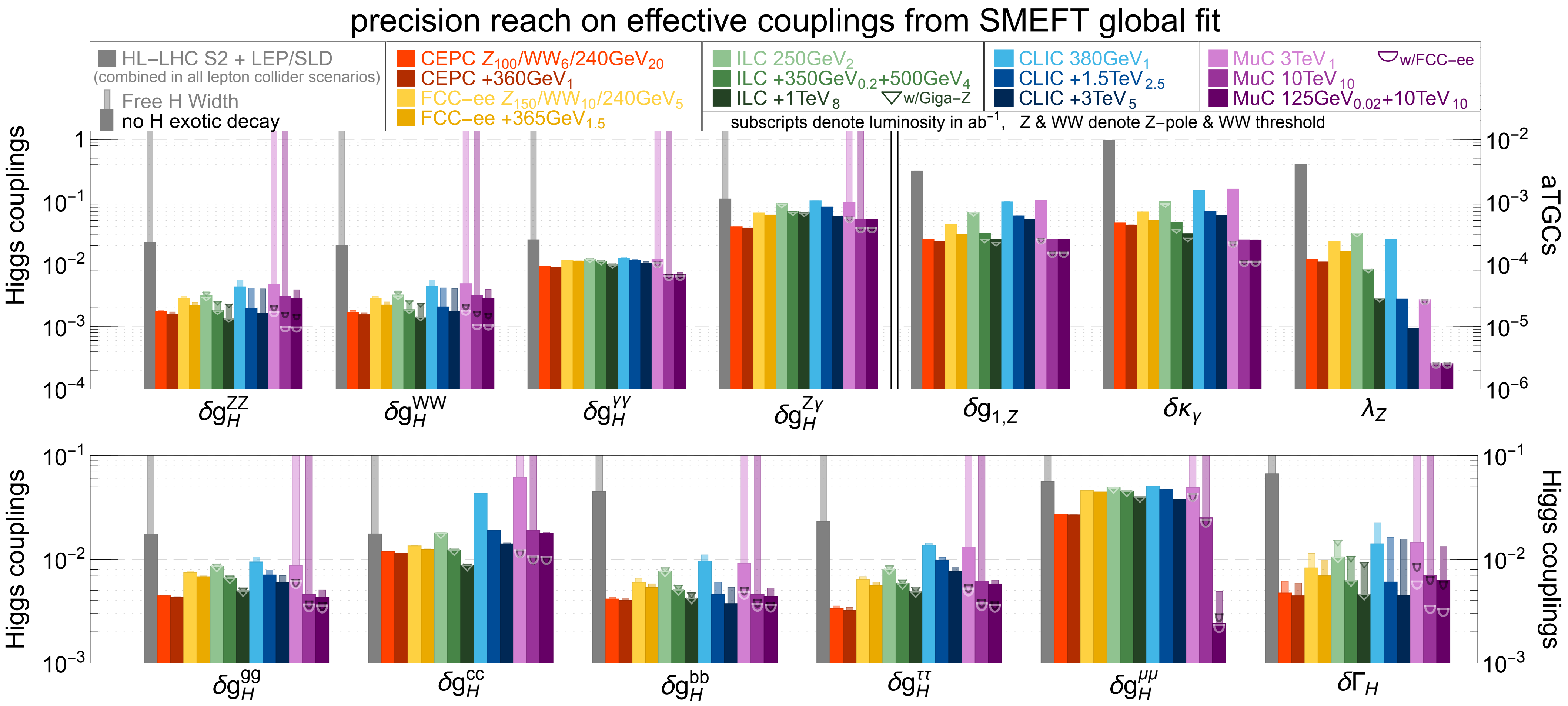
$2\ell 2q$ global fit results



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

# SMEFT global fit: ***Higgs***

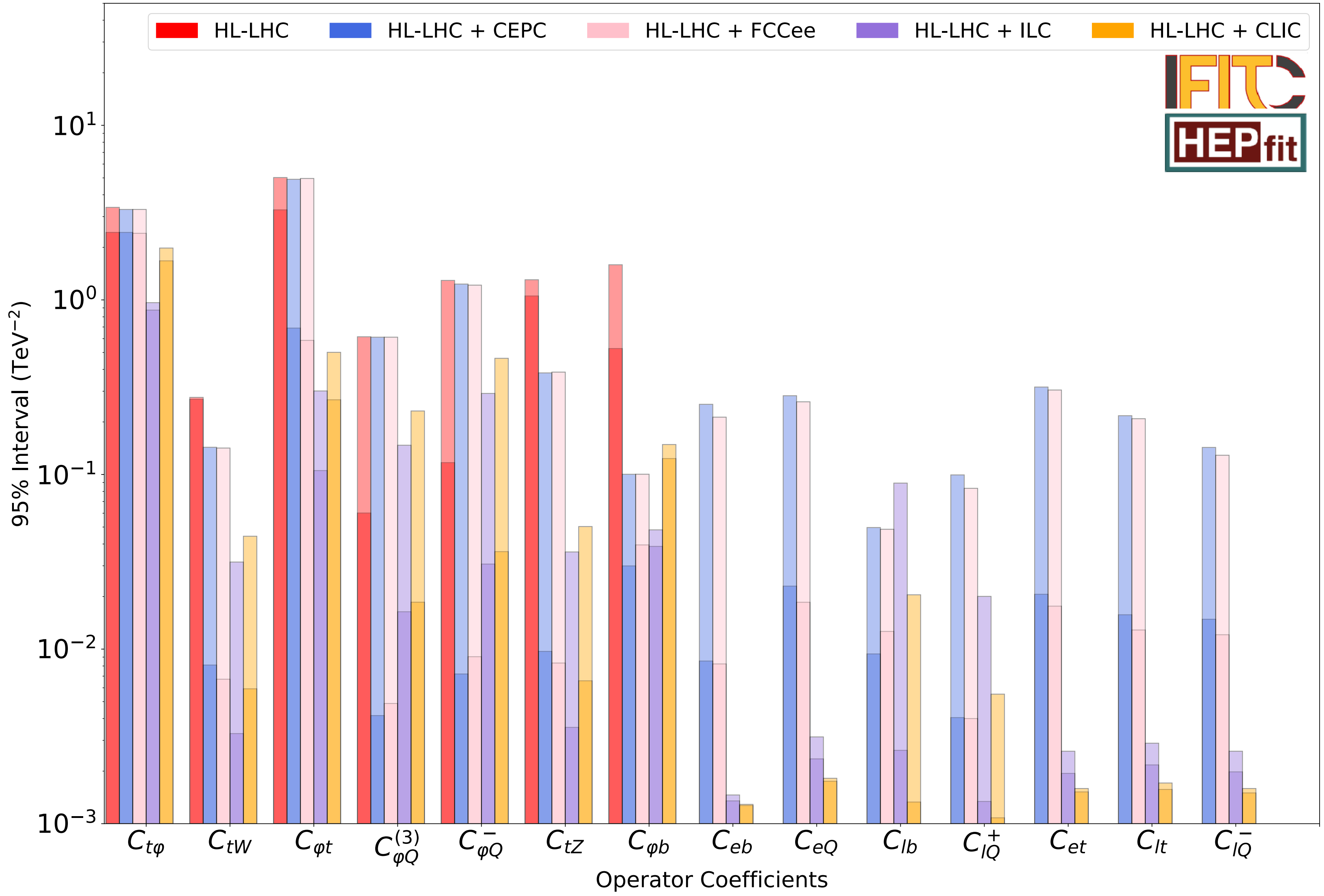
Higgs global fit



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

# SMEFT global fit: *top*

top global fit



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

# Optimal observables

# Optimal observables

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

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

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

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