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New Physics in Yukawa Couplings with Flavour Symmetries

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Based on:

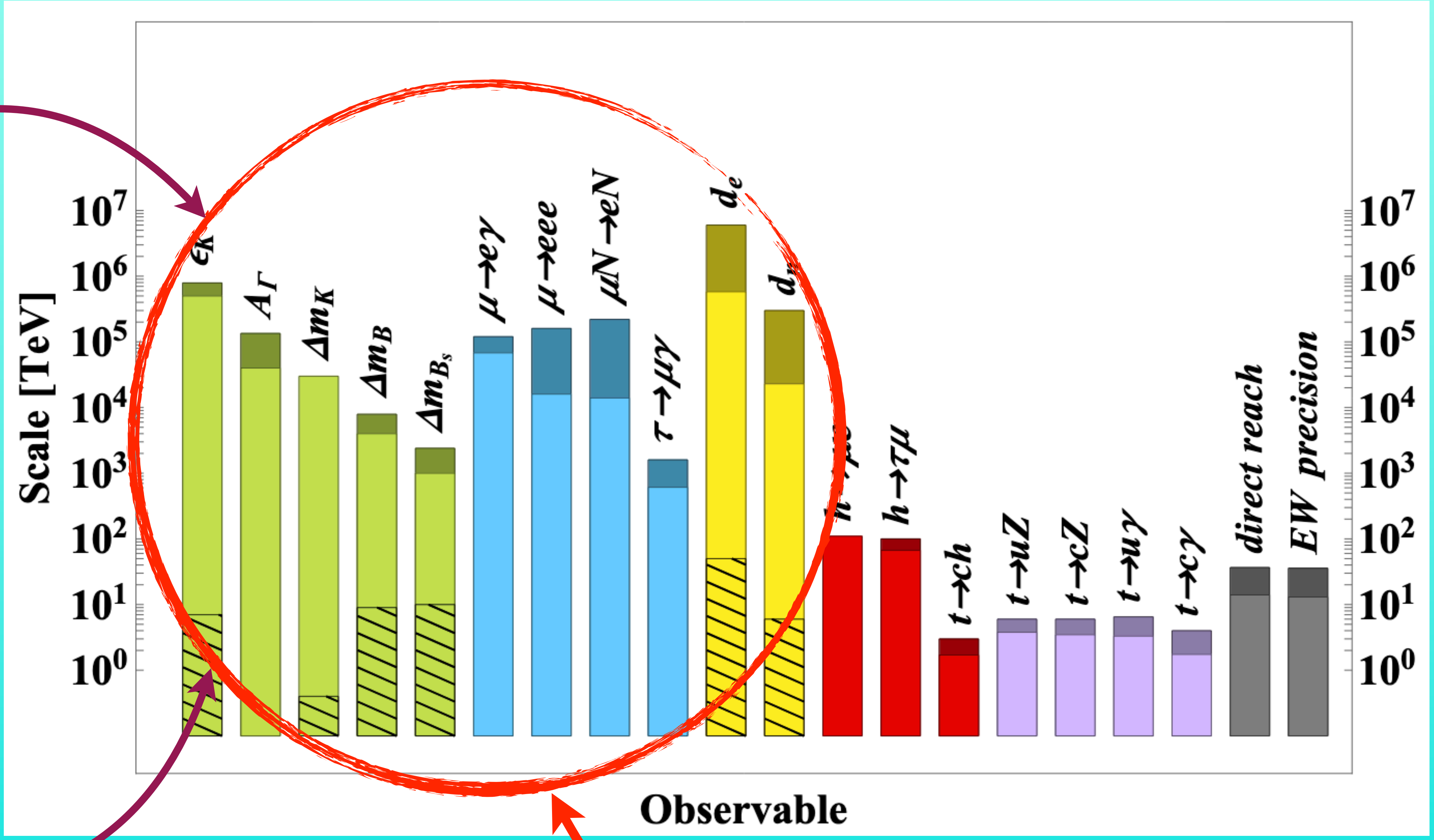
Alonso-González, LM, Pokorski, JHEP06 (2021) 166

Alonso-González, de Giorgi, LM, Pokorski, JHEP05 (2022) 041

Motivations

SMEFT with generic d=6 operators: $c\frac{\mathcal{O}}{\Lambda^2}$

$\mathcal{O}(1)$ factors



MFV

European Strategy for Particle Physics Update 2020, 1910.11775 by Aloni, Dery, Gavela, Nir

Flavour Models builder's main intest!

Flavour Symmetries

$\mathcal{G}_F$ rules the fermion interactions:

→ Allows to describe masses and mixings

→ Rules Yukawa interactions $\overline{f_L} H f_R$

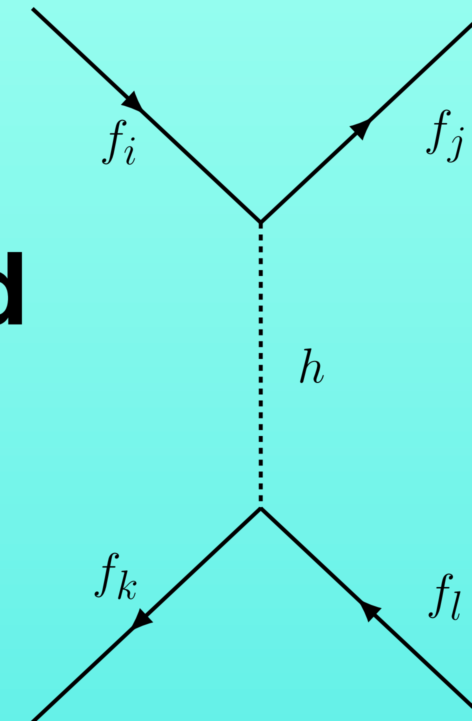
→ Rules the fermion interactions in any d>4 ops.

When $\mathcal{G}_F$ is present, the synergy within different experiments/observables can be MUCH STRONGER

Proof of Concept: Yukawas

Higgs Production
Higgs Decays

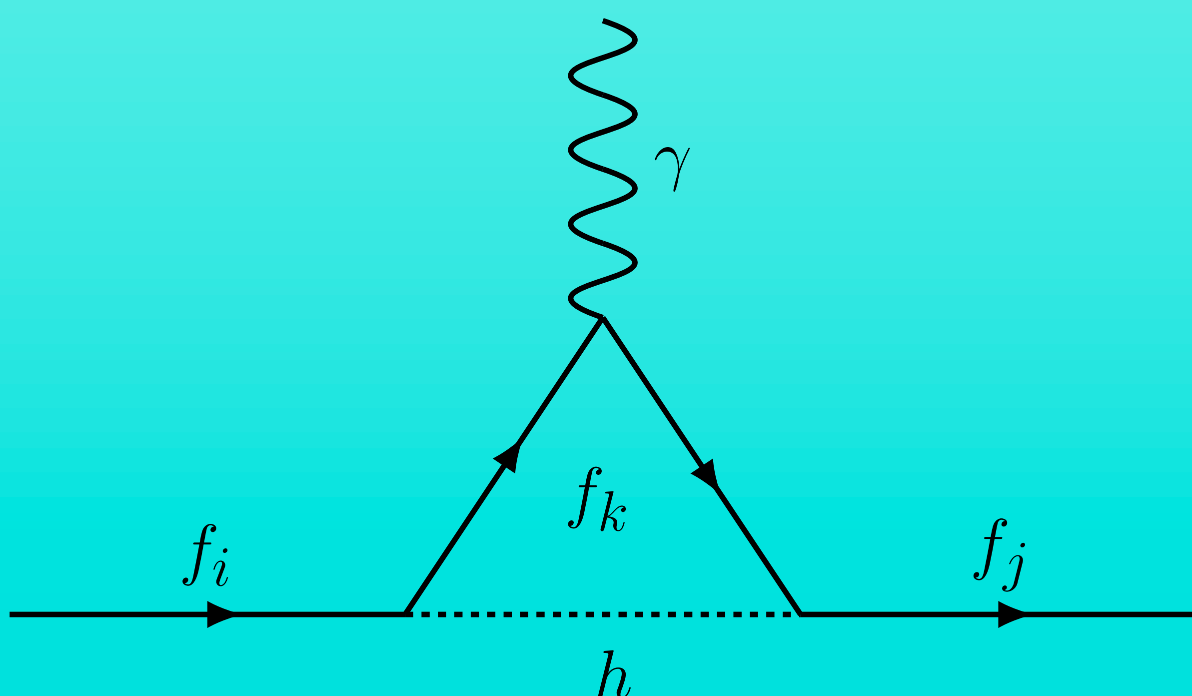
Tree-level Higgs-mediated

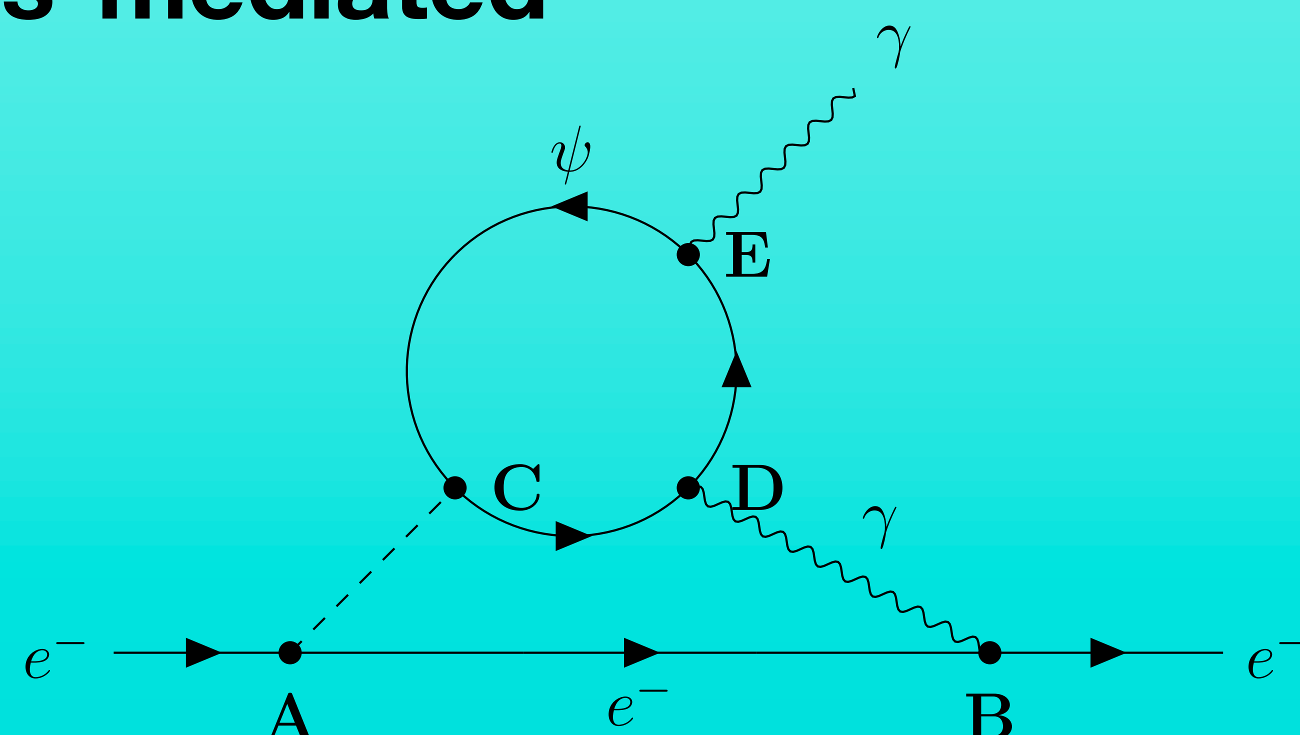


$$\overline{f_L} H f_R$$

Baryogenesis

Loop-level Higgs-mediated

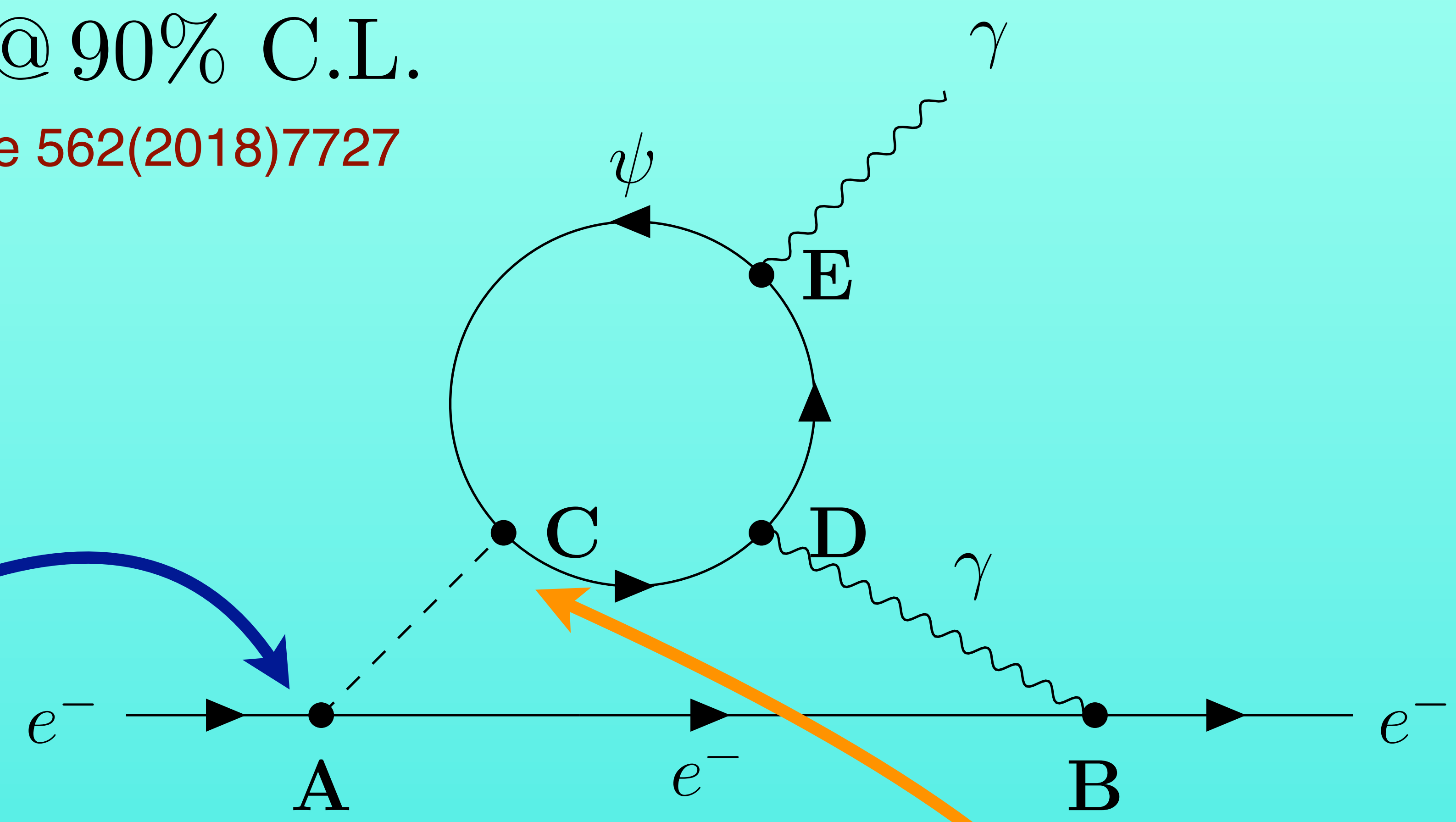




An Example: eEDM

$$|d_e| < 1.1 \times 10^{-29}\ \text{e cm} \ @\, 90\%\ \text{C.L.}$$

ACME II, Nature 562(2018)7727



[Brod *et al.*, JHEP 11 (2013) 180]

$$\mathcal{L}_{\text{eff}} = -\frac{y_\psi}{\sqrt{2}} \left(\kappa_\psi \overline{\psi}\psi + i\tilde{\kappa}_\psi \overline{\psi}\gamma_5\psi \right) h$$

$|\tilde{\kappa}_e| \lesssim 0.0017$

$|\tilde{\kappa}_\mu| \lesssim 31$ $|\tilde{\kappa}_c| \lesssim 0.37$

$|\tilde{\kappa}_\tau| \lesssim 0.29$ $|\tilde{\kappa}_t| \lesssim 0.0012$ $|\tilde{\kappa}_b| \lesssim 0.24$

[See also: Fuchs *et al.*, JHEP 05 (2020) 056; Brod & Stamou, JHEP 07 (2021) 080]

An Example: eEDM

Assuming the presence of $\mathcal{G}_F$:

$\tilde{\kappa}_e \approx \tilde{\kappa}_\mu \approx \tilde{\kappa}_\tau$ $\tilde{\kappa}_u \approx \tilde{\kappa}_c \approx \tilde{\kappa}_t$ $\tilde{\kappa}_d \approx \tilde{\kappa}_s \approx \tilde{\kappa}_b$

Direct bounds:		Indirect bounds:
$\lvert\tilde{\kappa}_e\rvert \lesssim 0.0017$		
$\lvert\tilde{\kappa}_\mu\rvert \lesssim 31$	⟶	$\tilde{\kappa}_{e,\mu,\tau} \lesssim 0.0017$
$\lvert\tilde{\kappa}_\tau\rvert \lesssim 0.29$		
$\lvert\tilde{\kappa}_c\rvert \lesssim 0.37$	⟶	$\tilde{\kappa}_{u,c,t} \lesssim 0.0012$
$\lvert\tilde{\kappa}_t\rvert \lesssim 0.0012$		
$\lvert\tilde{\kappa}_b\rvert \lesssim 0.24$	⟶	$\tilde{\kappa}_{d,s,b} \lesssim 0.24$

Impact on Baryogenesis

Fuchs *et al.*, JHEP 05 (2020) 056

In the SMEFT case, with d=6 ops. modifying the Yukawas, have concluded the following:

→ Strong sphalerons wash out baryon asymmetry generated by both $\tilde{\kappa}_t$ and $\tilde{\kappa}_b$

→ A valid possibility is with $\tilde{\kappa}_\tau$ if

$$\tilde{\kappa}_\tau \gtrsim 0.08$$

(Analysis done with only one $\tilde{\kappa}_i$ at a time, but similar results with more than one $\tilde{\kappa}_i$ contemporary)

<u>If there is $\mathcal{G}_F$, then $\tilde{\kappa}_{e,\mu,\tau} \lesssim 0.0017$ and therefore, baryogenesis cannot be explained even with $\tilde{\kappa}_\tau$!</u>

How General is this?

$$\tilde{\kappa}_e \approx \tilde{\kappa}_\mu \approx \tilde{\kappa}_\tau$$

$$\tilde{\kappa}_u \approx \tilde{\kappa}_c \approx \tilde{\kappa}_t$$

$$\tilde{\kappa}_d \approx \tilde{\kappa}_s \approx \tilde{\kappa}_b$$

We verified this is the case for two extreme cases:

→ Minimal Flavour Violation (MFV)

Effective approach where any source of flavour and CP violation is controlled by the Yukawas!

→ Froggatt-Nielsen (FN)

Simplest flavour model, but low predictivity power!

The Formalism

SMEFT with d=6 operators affecting the Yukawas:

$$\mathcal{L} = -\overline{Q'_L}\tilde{H}Y'_u u'_R - \overline{Q'_L}HY'_d d'_R - \overline{L'_L}HY'_e e'_R +$$

$$-\left(\overline{Q'_L}\tilde{H}C'_u u'_R + \overline{Q'_L}HC'_d d'_R\right)\frac{H^\dagger H}{\Lambda_q^2} - \overline{L'_L}HC'_e e'_R\frac{H^\dagger H}{\Lambda_\ell^2} + \text{h.c.}$$

primed fields in the flavour basis!

After EWSB:

$$\mathcal{L} = -\overline{u'_L}\left(Y'_u + \frac{v^2}{2\Lambda_q^2}C'_u\right)u'_R\,\frac{v}{\sqrt{2}} - \overline{u'_L}\left(Y'_u + \frac{3v^2}{2\Lambda_q^2}C'_u\right)u'_R\,\frac{h}{\sqrt{2}} + \text{h.c.} + \ldots$$

$+$ d-quarks $+$ charged-leptons

masses ≠ Higgs couplings!

going to the mass basis:

$$Y'_f + \frac{v^2}{2\Lambda^2} C'_f = V_f Y_f U_f^\dagger$$

$$\mathcal{L} = -\,\overline{u_L} Y_u u_R \frac{v}{\sqrt{2}} - \left[\overline{u_L} \left(Y_u + \frac{v^2}{\Lambda_q^2} C_u \right) u_R \right] \frac{h}{\sqrt{2}} +$$

$+$ d-quarks $+$ charged-leptons

where $C_f = V_f^\dagger C'_f U_f$.

The matching with the κ formalism is:

$$\mathcal{L}_{\rm eff} = -\frac{y_\psi}{\sqrt{2}} \left(\kappa_\psi \overline{\psi} \psi + i \tilde{\kappa}_\psi \overline{\psi} \gamma_5 \psi \right) h \qquad \begin{cases} Y_f K_f = Y_f + \dfrac{v^2}{\Lambda^2} \texttt{diag}(\texttt{Re} C_f) \\ Y_f \tilde{K}_f = \dfrac{v^2}{\Lambda^2} \texttt{diag}(\texttt{Im} C_f) \end{cases}$$

Useful: $r_\psi^2 \equiv \dfrac{v^2 |\hat{y}_{\psi\psi}|^2}{2 m_\psi^2} = \kappa_\psi^2 + \tilde{\kappa}_\psi^2$

MFV case

Chivukula & Georgi, Phys. Lett. B188 (1987) 99
D'Ambrosio *et al.*, Nucl. Phys. B645 (2002) 155
Cirigliano *et al.*, Nucl. Phys. B728 (2005) 121
Davidson & Parolini, Phys. Lett. B642 (2006) 72
Alonso *et al.*, JHEP06 (2011) 037

$$G_f = \underbrace{U(3)_{\ell_L} \times U(3)_{e_R}} \times \underbrace{U(3)_{Q_L} \times U(3)_{u_R} \times U(3)_{d_R}}$$

Spurions: $Y_e \sim (3, \bar{3})$ $\quad Y_u \sim (3, \bar{3}, 1)$ $\quad Y_d \sim (3, 1, \bar{3})$

$$C'_f = c'_f Y'_f \longrightarrow \begin{cases} \kappa_t = \kappa_c = \kappa_u \simeq 1 + \dfrac{v^2}{\Lambda_q^2} \mathtt{Re}\, c'_u \\ \tilde{\kappa}_t = \tilde{\kappa}_c = \tilde{\kappa}_u \simeq \dfrac{v^2}{\Lambda_q^2} \mathtt{Im}\, c'_u \\ r_t^2 = r_c^2 = r_u^2 \simeq 1 + \dfrac{v^4}{\Lambda_q^4} |c'_u|^2 + 2 \dfrac{v^2}{\Lambda_q^2} \mathtt{Re}\, c'_u \end{cases}$$

and similarly for the down quarks and the charged leptons.

<u>There are NO flavour violating couplings!</u>

FN case

[Froggatt & Nielsen, NPB 147 (1979)]

$$
\begin{aligned}
\mathscr{L}_{\rm FN} = & - y'_{u,ij}\,\overline{Q'_{Li}}\tilde{H}u'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{Q_i}+n_{u_j})} - y'_{d,ij}\,\overline{Q'_{Li}}Hd'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{Q_i}+n_{d_j})} + \\
& - y'_{e,ij}\,\overline{L'_{Li}}He'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{L_i}+n_{e_j})} + \\
& - \left[c'_{u,ij}\,\overline{Q'_{Li}}\tilde{H}u'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{Q_i}+n_{u_j})} + c'_{d,ij}\,\overline{Q'_{Li}}Hd'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{Q_i}+n_{d_j})}\right]\frac{H^\dagger H}{\Lambda_q^2} + \\
& - c'_{e,ij}\,\overline{L'_{Li}}He'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{L_i}+n_{e_j})}\frac{H^\dagger H}{\Lambda_\ell^2} + \text{h.c.}\,,
\end{aligned}
$$

Quarks	Q'_L	u'_R	d'_R
	$(2,1,0)$	$(5,2,0)$	$(5,4,2)$

Leptons	L'_L	e'_R
Anarchy (A)	$(0,0,0)$	$(10,5,3)$
$\mu\tau$-Anarchy $(A_{\mu\tau})$	$(1,0,0)$	$(9,5,3)$
Hierarchy (H)	$(2,1,0)$	$(8,4,3)$

[Altarelli, Feruglio, Masina & LM, JHEP **1211** (2012) 139
Bergstrom, Meloni and LM, Phys.Rev. **D89** (2014) 093021]

Diagonal:

$$C_{f,ii} \approx \mathcal{O}(Y_{f,i}) e^{i\theta_{f,ii}}$$

$$K_f = 1 + \frac{v^2}{\Lambda^2} \texttt{diag}\left(\mathcal{O}(1)\cos\theta_{f,11},\ \mathcal{O}(1)\cos\theta_{f,22},\ \mathcal{O}(1)\cos\theta_{f,33}\right)$$

$$\tilde{K}_f = \frac{v^2}{\Lambda^2} \texttt{diag}\left(\mathcal{O}(1)\sin\theta_{f,11},\ \mathcal{O}(1)\sin\theta_{f,22},\ \mathcal{O}(1)\sin\theta_{f,33}\right)$$

$$r_\psi^2 \simeq 1 + \mathcal{O}(1)^2 \frac{v^4}{\Lambda^4} + 2\mathcal{O}(1)\frac{v^2}{\Lambda^2}\cos\theta_{f,\psi}$$

Off-diagonal:

$$\begin{cases} C_{u,ij} \approx \mathcal{O}(1)\epsilon^{n_{Q_i}+n_{u_j}} e^{i\theta_{u,ij}} \\ C_{d,ij} \approx \mathcal{O}(1)\epsilon^{n_{Q_i}+n_{d_j}} e^{i\theta_{d,ij}} \\ C_{e,ij} \approx \mathcal{O}(1)\epsilon^{n_{L_i}+n_{e_j}} e^{i\theta_{e,ij}} \end{cases}$$

$$\langle \frac{\phi}{\Lambda_F} \rangle \equiv \epsilon$$

Back to the eEDM

The complete expression for the bound on $\tilde{\kappa}_\tau$ reads:

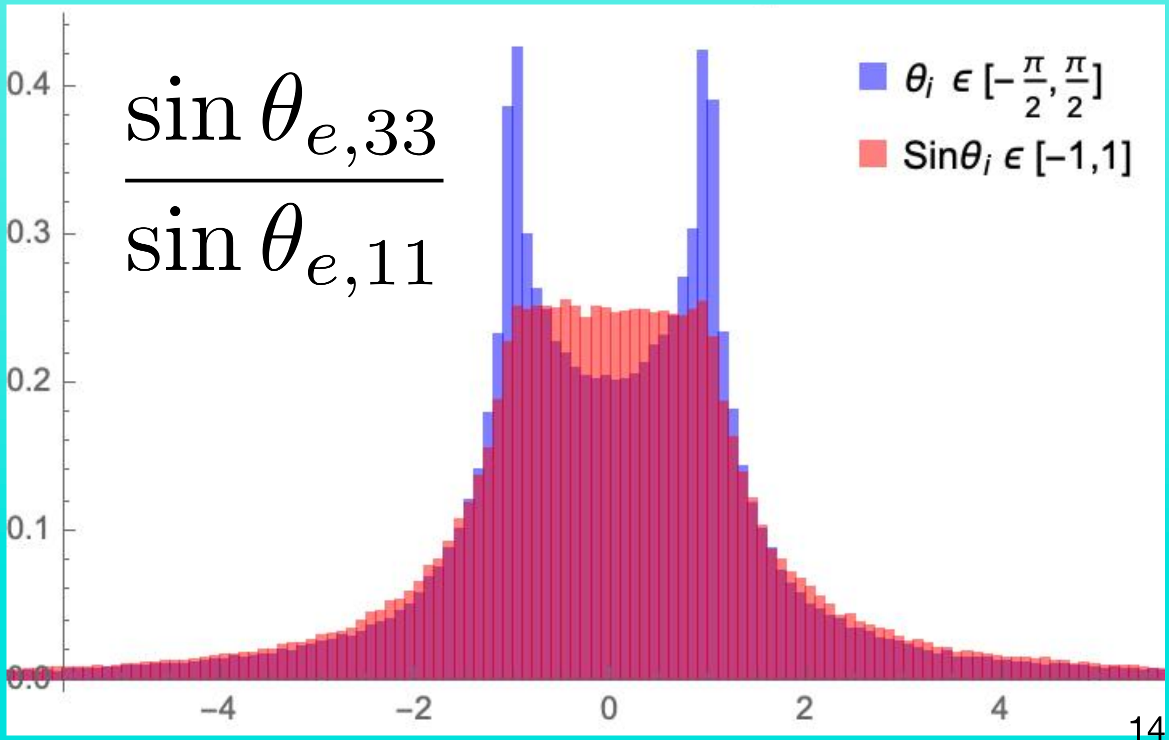
$$|\tilde{\kappa}_\tau| \lesssim 0.0017 \frac{m_e}{m_\tau} \frac{\texttt{Im}\ C_{e,33}}{\texttt{Im}\ C_{e,11}}$$

MFV: $C'_f = c'_f Y'_f \rightarrow \frac{\texttt{Im}\ C_{e,33}}{\texttt{Im}\ C_{e,11}} = \frac{m_\tau}{m_e} \rightarrow |\tilde{\kappa}_\tau| \lesssim 0.0017$

FN: $C_{f,ii} \approx \mathcal{O}(Y_{f,i}) e^{i\theta_{f,ii}} \rightarrow \frac{\texttt{Im}\ C_{e,33}}{\texttt{Im}\ C_{e,11}} = \mathcal{O}(1) \frac{m_\tau}{m_e} \frac{\sin\theta_{e,33}}{\sin\theta_{e,11}}$

$\rightarrow |\tilde{\kappa}_\tau| \lesssim \mathcal{O}(1)\, 0.0017 \frac{\sin\theta_{e,33}}{\sin\theta_{e,11}}$

$\rightarrow |\tilde{\kappa}_\tau| \lesssim \mathcal{O}(1)\, 0.0017$



Collider Bounds

The signal strength: $$\mu_P^F = \frac{\sigma_P}{\sigma_P^{\rm SM}} \frac{\Gamma\left(h \to F\right)}{\Gamma^{\rm SM}\left(h \to F\right)} \left(\frac{\Gamma_{h,{\rm tot}}}{\Gamma^{\rm SM}_{h,{\rm tot}}}\right)^{-1}$$

$$\frac{\sigma_P}{\sigma_P^{\rm SM}} = \begin{cases} 1 & \text{for } P = {\rm VBF}, {\rm VH} \\ r_t^2 & \text{for } P = {\rm ggF}, {\rm ttH} + {\rm tH} \end{cases}$$

$$r_\psi^2 = \kappa_\psi^2 + \tilde{\kappa}_\psi^2$$

$$\frac{\Gamma\left(h \to F\right)}{\Gamma^{\rm SM}\left(h \to F\right)} = \begin{cases} 1, & \text{for } F = VV^* \\ 1.639 - 0.718\, r_t, & \text{for } F = \gamma\gamma\,, \\ r_b^2, & \text{for } F = b\bar{b}\,, \\ r_\tau^2, & \text{for } F = \tau\bar{\tau}\,, \\ r_\mu^2, & \text{for } F = \mu\bar{\mu}\,. \end{cases}$$

for the relevant processes

$$\frac{\Gamma_{h,{\rm tot.}}}{\Gamma^{\rm SM}_{h,{\rm tot.}}} = 1 + {\rm BR}^{\rm SM}_{bb}\left(r_b^2 - 1\right) + \left({\rm BR}^{\rm SM}_{gg} + {\rm BR}^{\rm SM}_{cc}\right)\left(r_t^2 - 1\right) + {\rm BR}^{\rm SM}_{\gamma\gamma}\left(0.639 - 0.718\, r_t\right) + {\rm BR}^{\rm SM}_{\tau\tau}\left(r_\tau^2 - 1\right)$$

ATLAS $\sqrt{s} = 13$ TeV $24.5 - 79.8$ fb^{-1}

Production mech. P	Final state F	$\sigma \times BR$ normalised to SM
ggF	$\gamma\gamma$	0.96 ± 0.14
	ZZ^*	$1.04^{+0.16}_{-0.15}$
	WW^*	1.08 ± 0.19
	$\tau\bar{\tau}$	$0.96^{+0.59}_{-0.52}$
VBF	$\gamma\gamma$	$1.39^{+0.40}_{-0.35}$
	ZZ^*	$2.68^{+0.98}_{-0.83}$
	WW^*	$0.59^{+0.36}_{-0.35}$
	$\tau\bar{\tau}$	$1.16^{+0.58}_{-0.53}$
	$b\bar{b}$	$3.01^{+1.67}_{-1.61}$
VH	$\gamma\gamma$	$1.09^{+0.58}_{-0.54}$
	ZZ^*	$0.68^{+1.20}_{-0.78}$
	$b\bar{b}$	$1.19^{+0.27}_{-0.25}$
$t\bar{t}H + tH$	$\gamma\gamma$	$1.10^{+0.41}_{-0.35}$
	VV^*	$1.50^{+0.59}_{-0.57}$
	$\tau\bar{\tau}$	$1.38^{+1.13}_{-0.96}$
	$b\bar{b}$	$0.79^{+0.60}_{-0.59}$

CMS $\sqrt{s} = 13$ TeV 35.9 fb^{-1}

Production mech. P	Final state F	$\sigma \times BR$ normalised to SM
ggF	bb	$2.51^{+2.43}_{-2.01}$
	$\tau\tau$	$1.05^{+0.53}_{-0.47}$
	WW	$1.35^{+0.21}_{-0.19}$
	ZZ	$1.22^{+0.23}_{-0.21}$
	$\gamma\gamma$	$1.16^{+0.21}_{-0.18}$
	$\mu\mu$	$0.31^{+1.80}_{-1.79}$
VBF	$\tau\tau$	$1.12^{+0.45}_{-0.43}$
	WW	$0.28^{+0.64}_{-0.60}$
	ZZ	$-0.09^{+1.02}_{-0.76}$
	$\gamma\gamma$	$0.67^{+0.59}_{-0.46}$
	$\mu\mu$	$2.72^{+7.12}_{-7.03}$
WH	bb	$1.73^{+0.70}_{-0.68}$
	WW	$3.91^{+2.26}_{-2.01}$
	ZZ	$0.00^{+2.33}_{-0.00}$
	$\gamma\gamma$	$3.76^{+1.48}_{-1.35}$
ZH	bb	$0.99^{+0.47}_{-0.45}$
	WW	$0.96^{+1.81}_{-1.46}$
	ZZ	$0.00^{+4.26}_{-0.00}$
	$\gamma\gamma$	$0.00^{+1.14}_{-0.00}$
$t\bar{t}H$	bb	$0.91^{+0.45}_{-0.43}$
	$\tau\tau$	$0.23^{+1.03}_{-0.88}$
	WW	$1.60^{+0.65}_{-0.59}$
	ZZ	$0.00^{+1.50}_{-0.00}$
	$\gamma\gamma$	$2.18^{+0.88}_{-0.75}$

ATLAS $h \to \mu\bar{\mu}$ $\sqrt{s} = 13$ TeV 139 fb^{-1}

Production mech. P	Category	$\sigma \times$ BR normalised to SM
ggF	0-jet	-0.4 ± 1.6
	1-jet	2.4 ± 1.2
	2-jet	-0.6 ± 1.2
VBF		1.8 ± 1.0
VH+$t\bar{t}H$		5.0 ± 3.5

[ATLAS: PRD 101 (2020), PLB 812 (2021)]

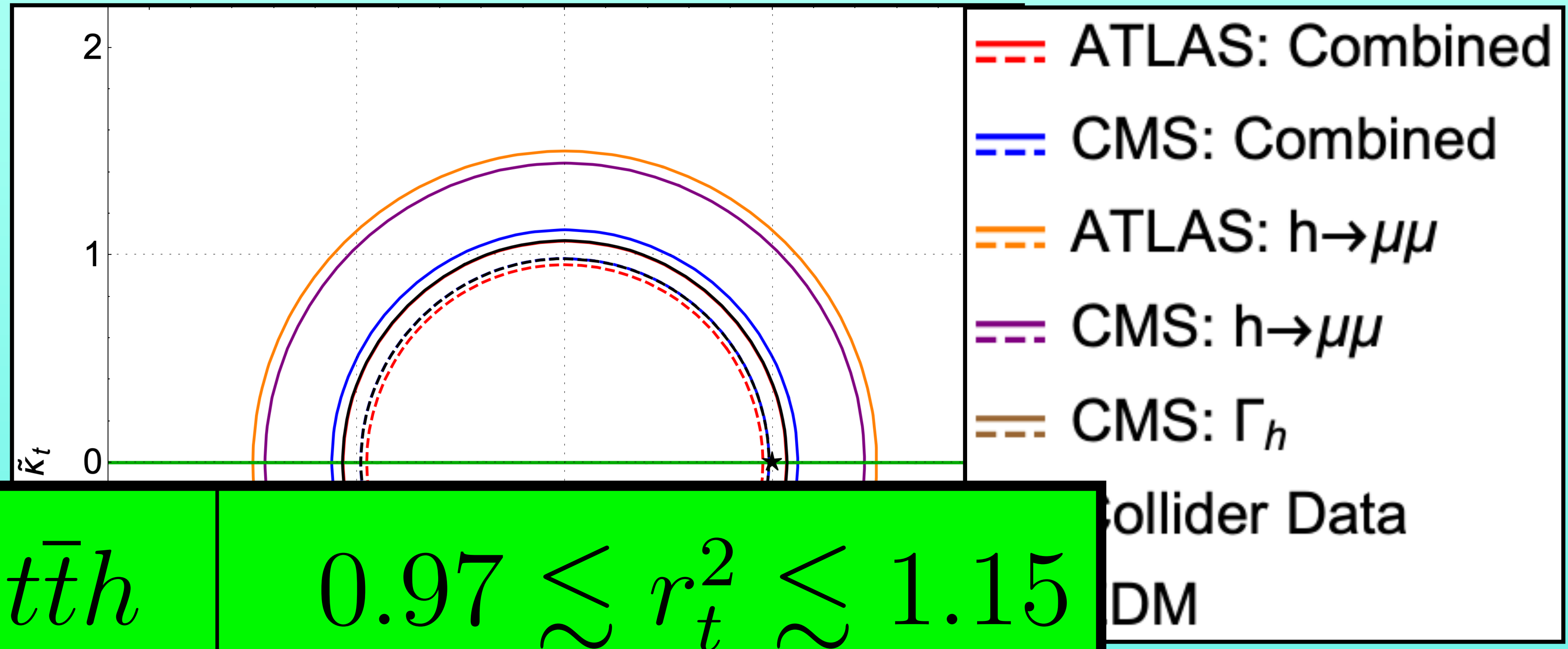
CMS $h \to \mu\bar{\mu}$ $\sqrt{s} = 13$ TeV 137 fb^{-1}

Production mech. P	$\sigma \times$ BR normalised to SM
ggH+$t\bar{t}H$	$0.66^{+0.67}_{-0.66}$
VBF+VH	$1.84^{+0.89}_{-0.77}$

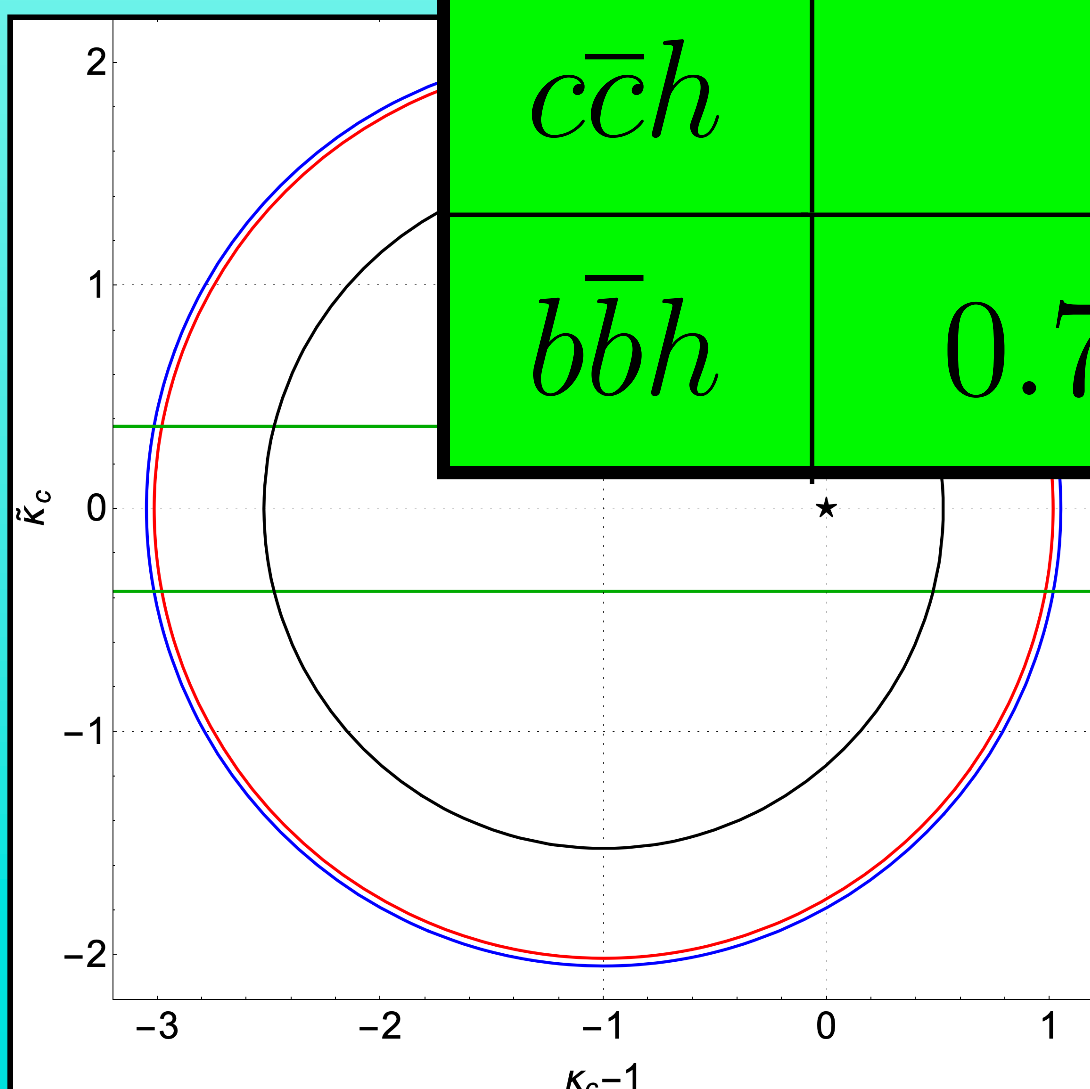
$$\Gamma^{\rm CMS}_{h,\rm tot} = 3.2^{+2.8}_{-2.2}\ \text{MeV}$$

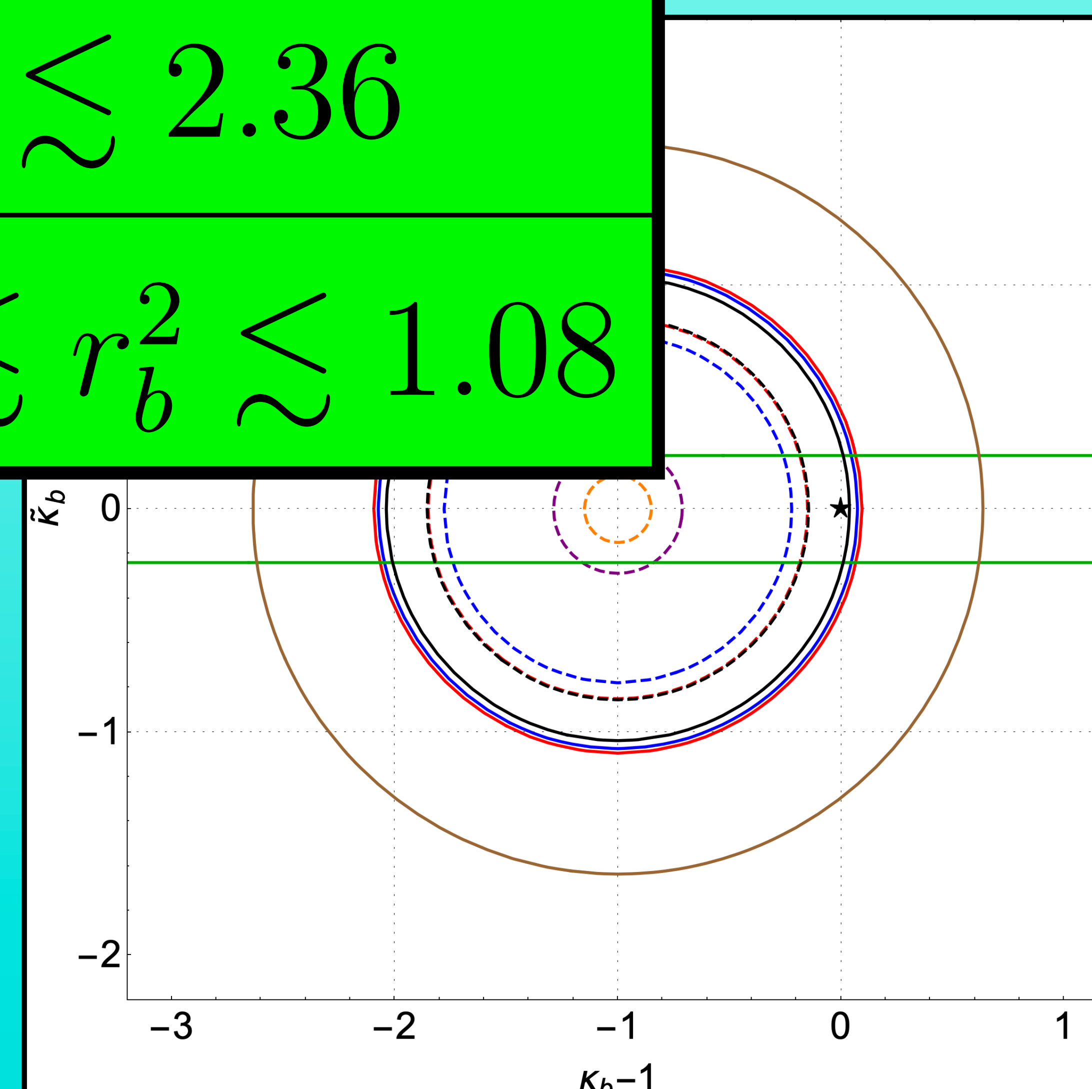
[CMS: PRD 99 (2019)]

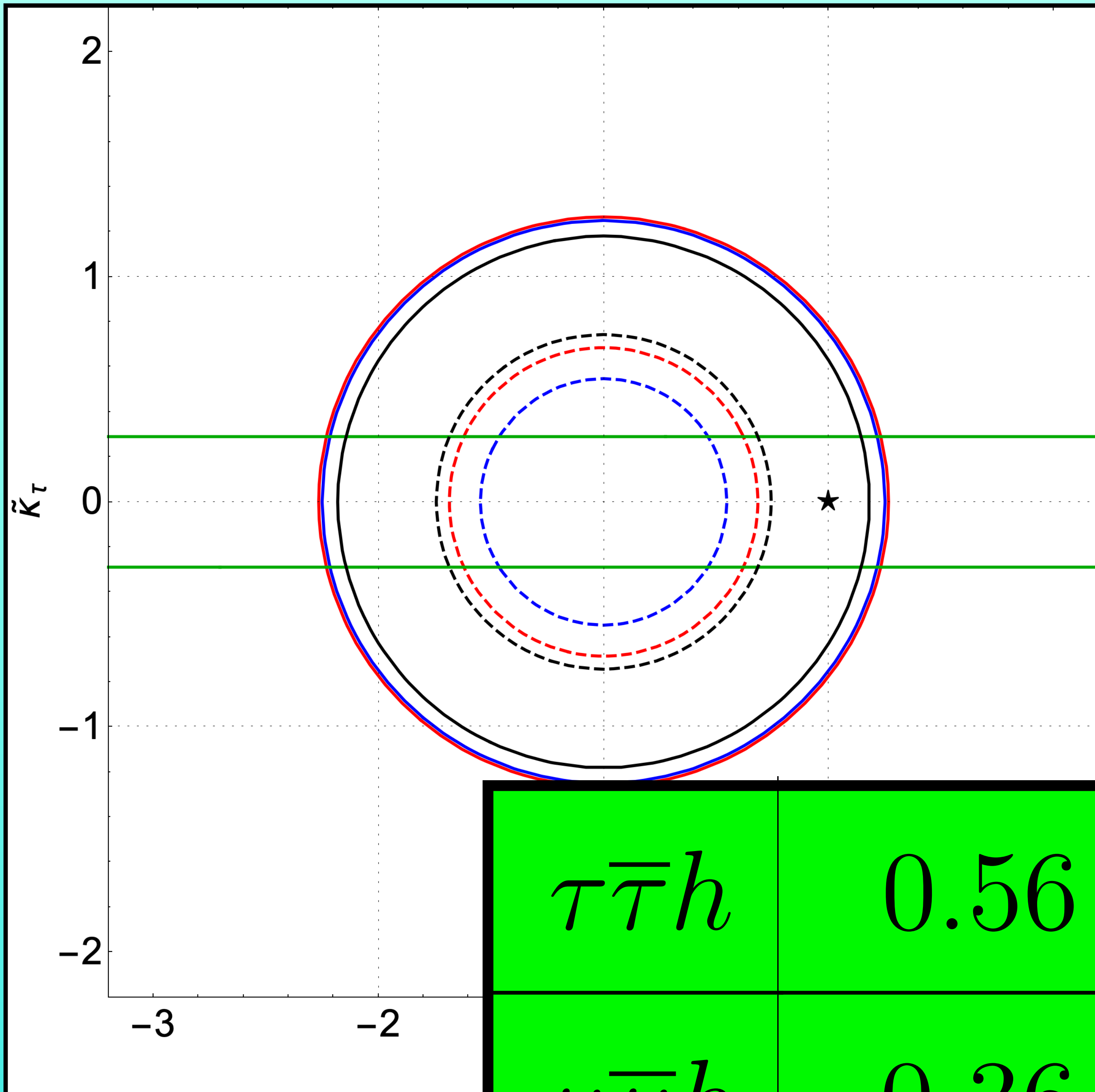
[CMS: EPJC 79 (2019), JHEP 01 (2021)]

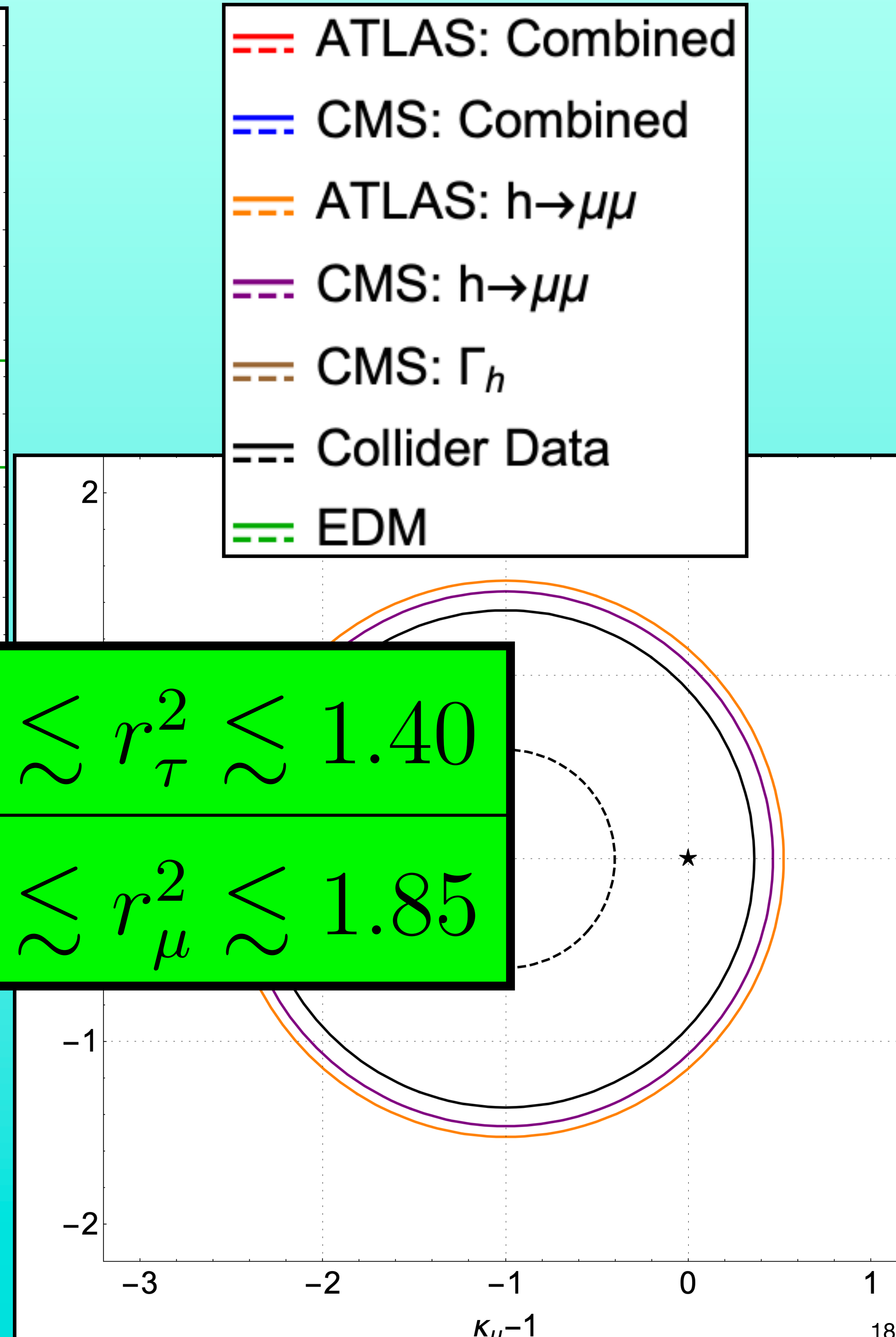


$t\bar{t}h$	$0.97 \lesssim r_t^2 \lesssim 1.15$
$c\bar{c}h$	$r_c^2 \lesssim 2.36$
$b\bar{b}h$	$0.73 \lesssim r_b^2 \lesssim 1.08$



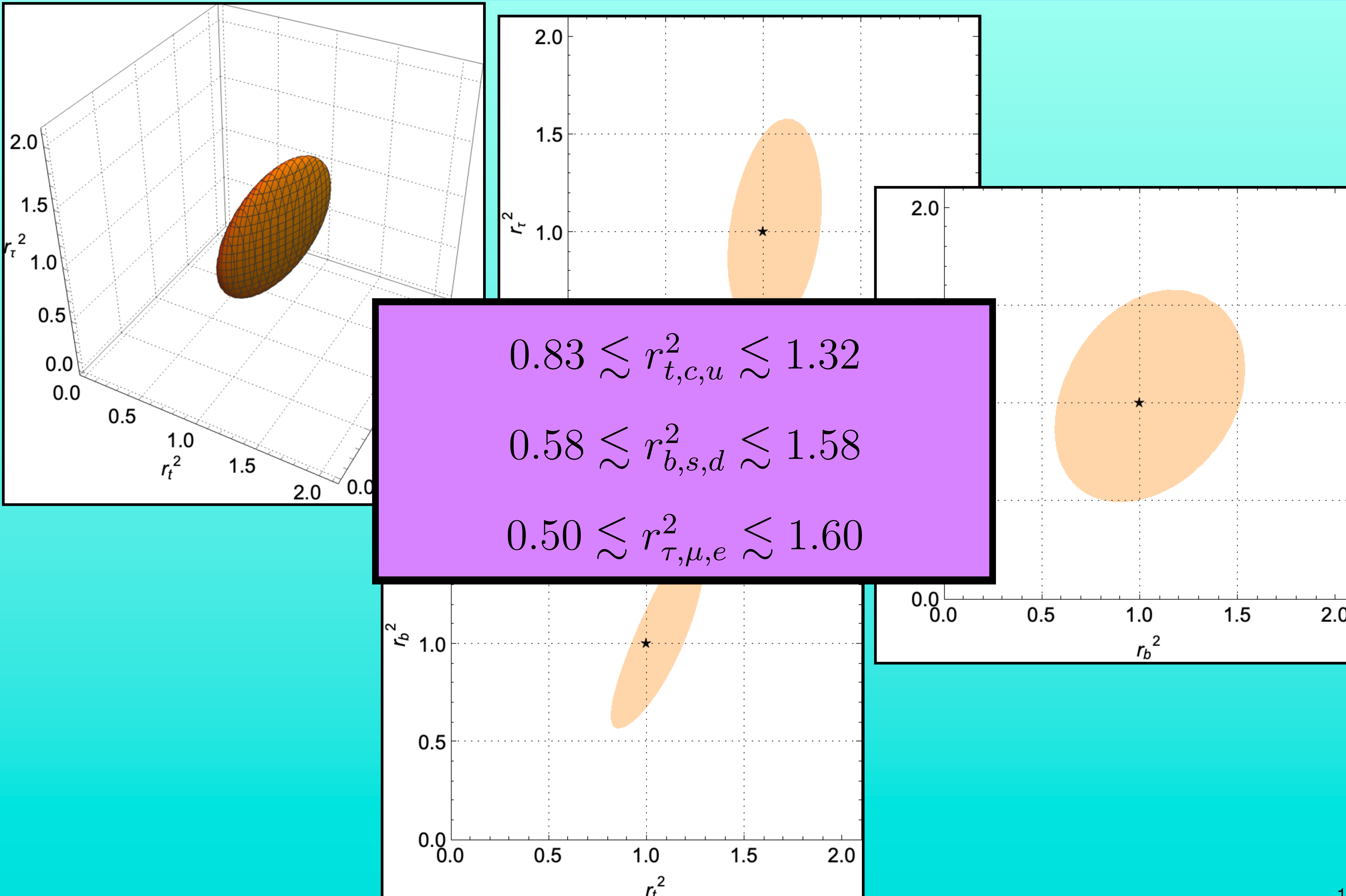






$\tau\bar{\tau}h$	$0.56 \lesssim r_\tau^2 \lesssim 1.40$
$\mu\bar{\mu}h$	$0.36 \lesssim r_\mu^2 \lesssim 1.85$

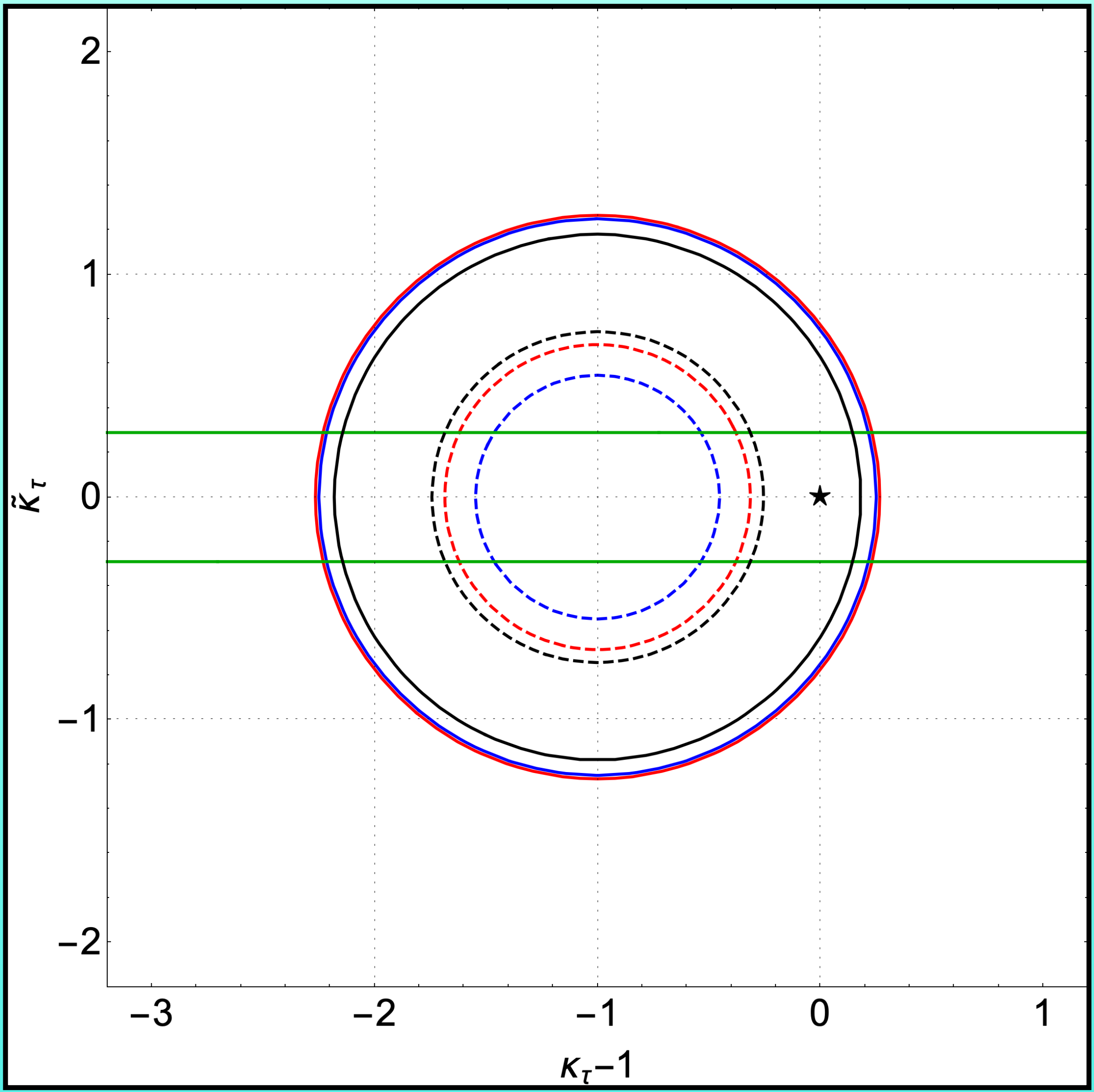
Assuming $\mathcal{G}_F$

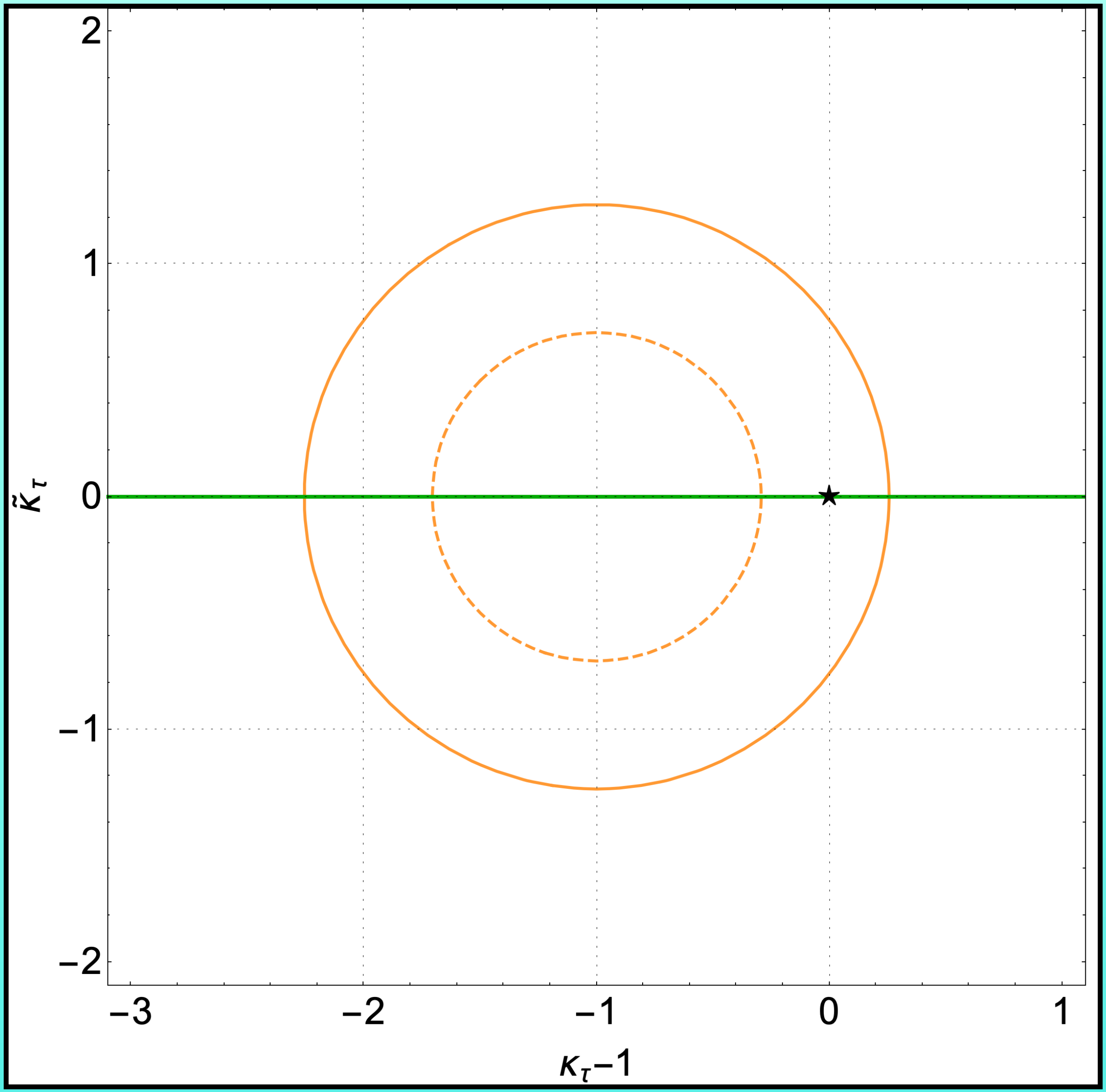


$$0.83 \lesssim r^2_{t,c,u} \lesssim 1.32$$

$$0.58 \lesssim r^2_{b,s,d} \lesssim 1.58$$

$$0.50 \lesssim r^2_{\tau,\mu,e} \lesssim 1.60$$





$t\bar{t}h$	$0.97 \lesssim r_t^2 \lesssim 1.15$
$c\bar{c}h$	$r_c^2 \lesssim 2.36$
$b\bar{b}h$	$0.73 \lesssim r_b^2 \lesssim 1.08$
$\tau\bar{\tau}h$	$0.56 \lesssim r_\tau^2 \lesssim 1.40$
$\mu\bar{\mu}h$	$0.36 \lesssim r_\mu^2 \lesssim 1.85$

$$0.83 \lesssim r_{t,c,u}^2 \lesssim 1.32$$

$$0.58 \lesssim r_{b,s,d}^2 \lesssim 1.58$$

$$0.50 \lesssim r_{\tau,\mu,e}^2 \lesssim 1.60$$

Bounds on Λ assuming $\mathcal{G}_F$

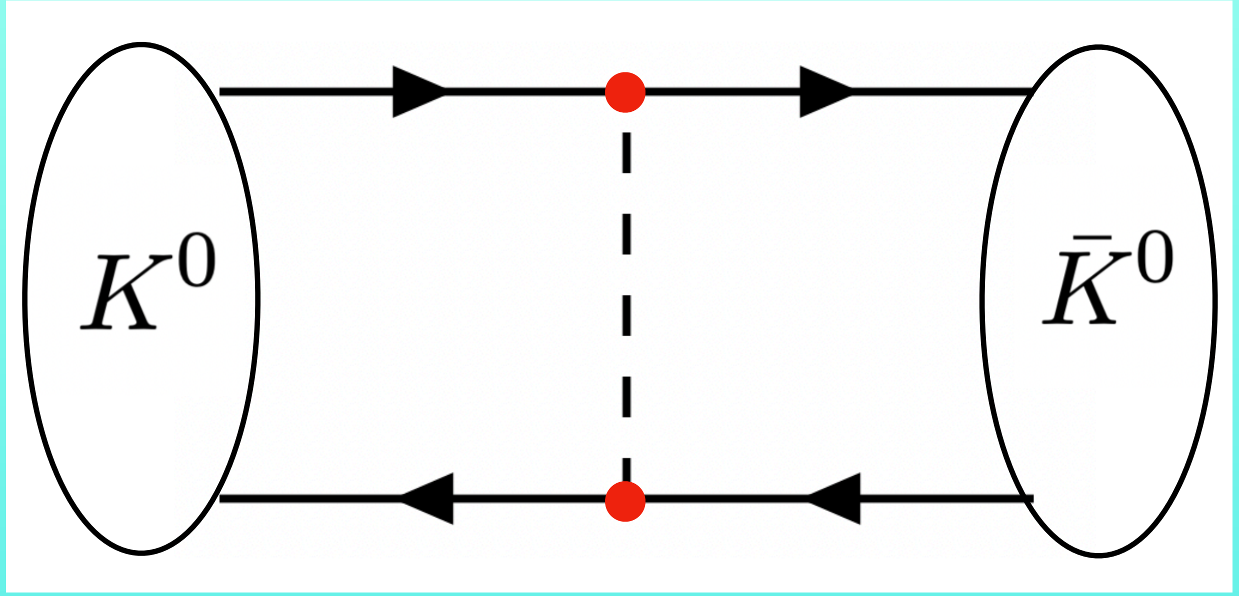
	Conditions on $\theta_{f,ii}$	Bound
EDM	$\sin\theta_{u,33} = 1$	$\Lambda_q \gtrsim 7.4$ TeV
	$\sin\theta_{e,11} = 1 = \sin\theta_{e,33}$	$\Lambda_\ell \gtrsim 6.0$ TeV
Collider (diag couplings)	$\sin\theta_{u,33} = 0$	$\Lambda_q \gtrsim 0.8$ TeV
	$\sin\theta_{e,11} = 0 = \sin\theta_{e,33}$	$\Lambda_\ell \gtrsim 0.5$ TeV

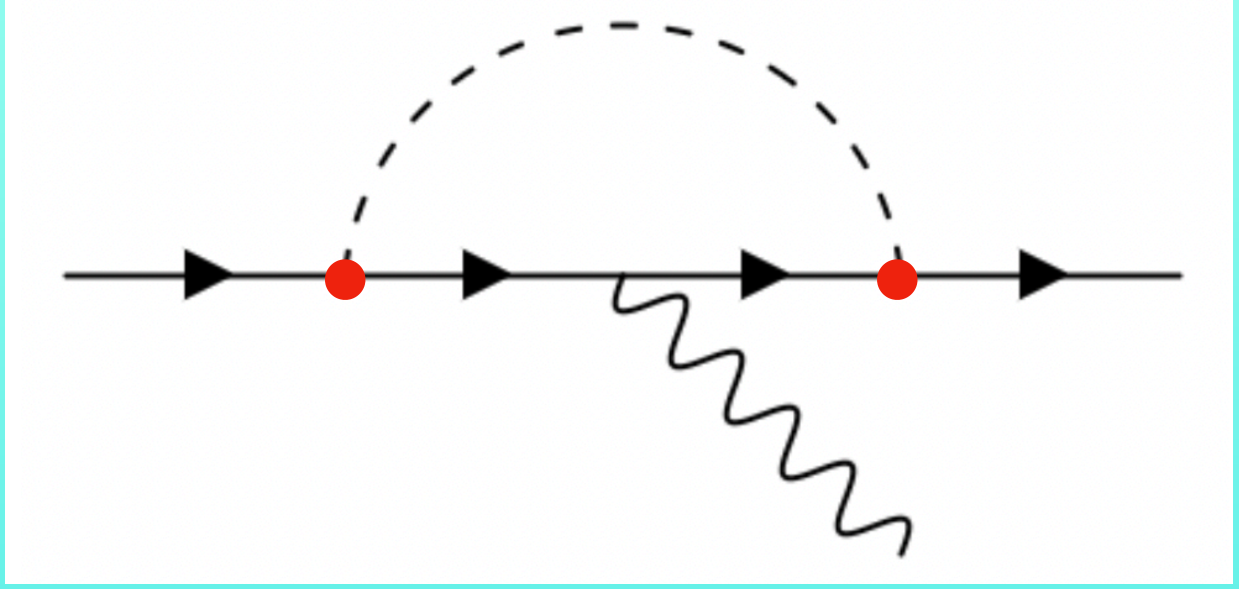
Pretty model independent: exact for MFV and $\mathcal{O}(1)$ for FN

[See later papers on similar topic, but without flavour symmetries, with consistent results from EDMs and colliders: Bahl *et al.*, 2202.11753; Brod *et al.*, 2203.03736]

Flavour Bounds on Λ

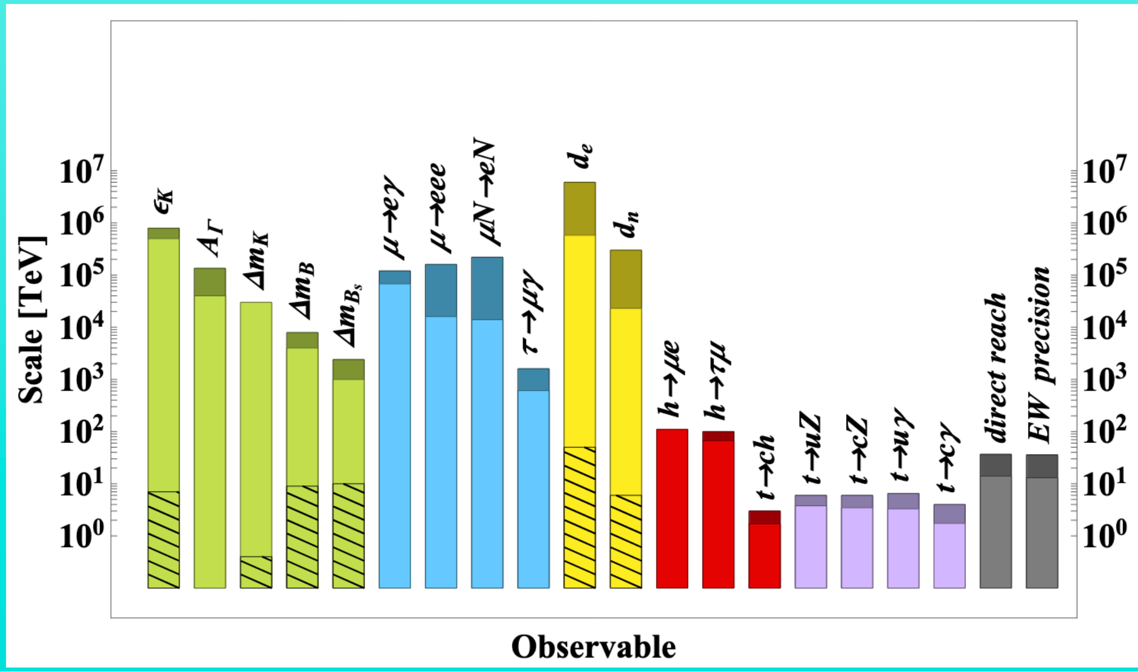
Tree and Loop-level Higgs-mediated processes





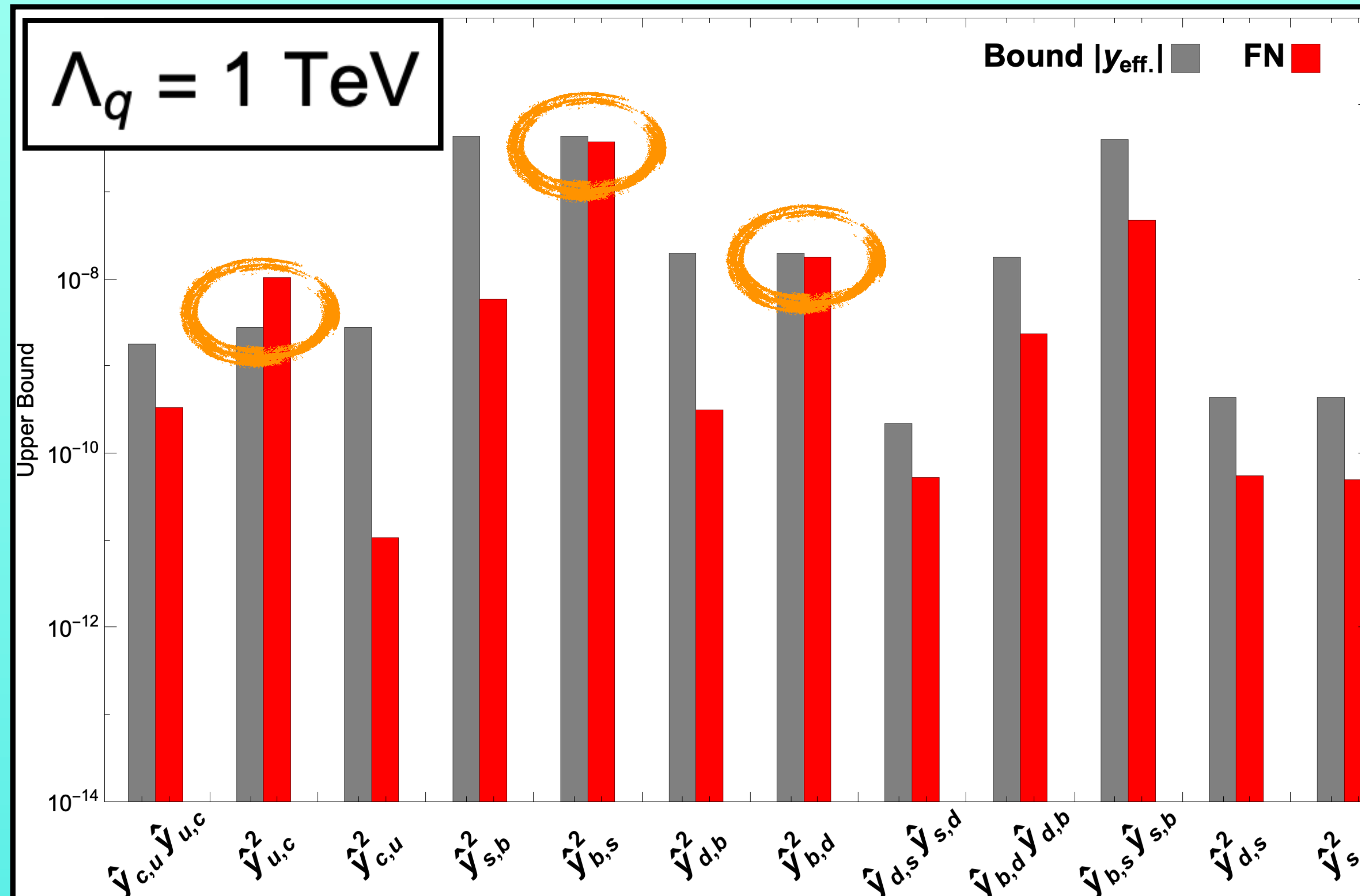
$$\bullet\ \widehat{Y}_{ij} \equiv (Y + \frac{v^2}{\Lambda^2} C)_{ij} \propto \frac{v^2}{\Lambda^2} C_{ij}$$

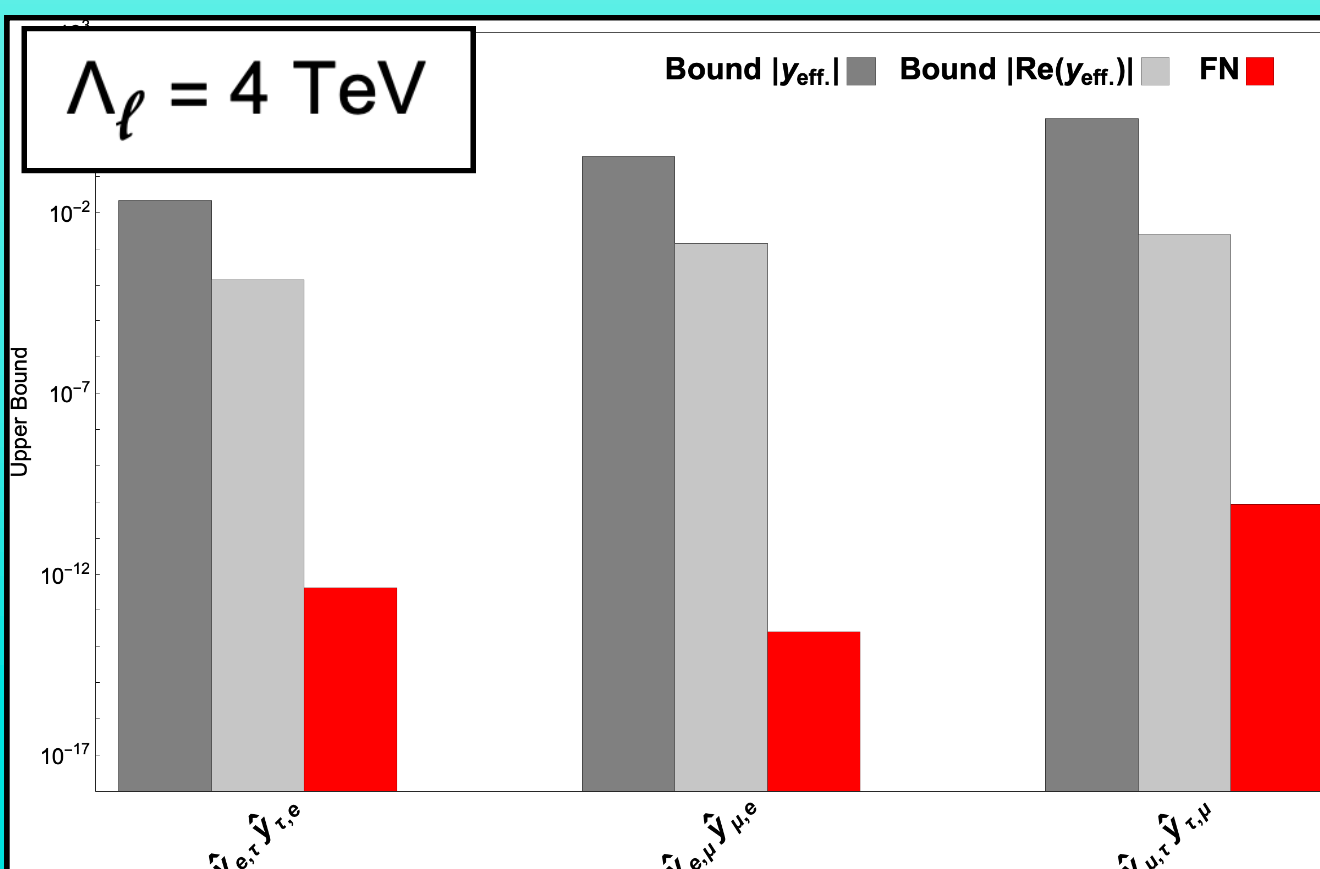
Without any flavour symmetry input:

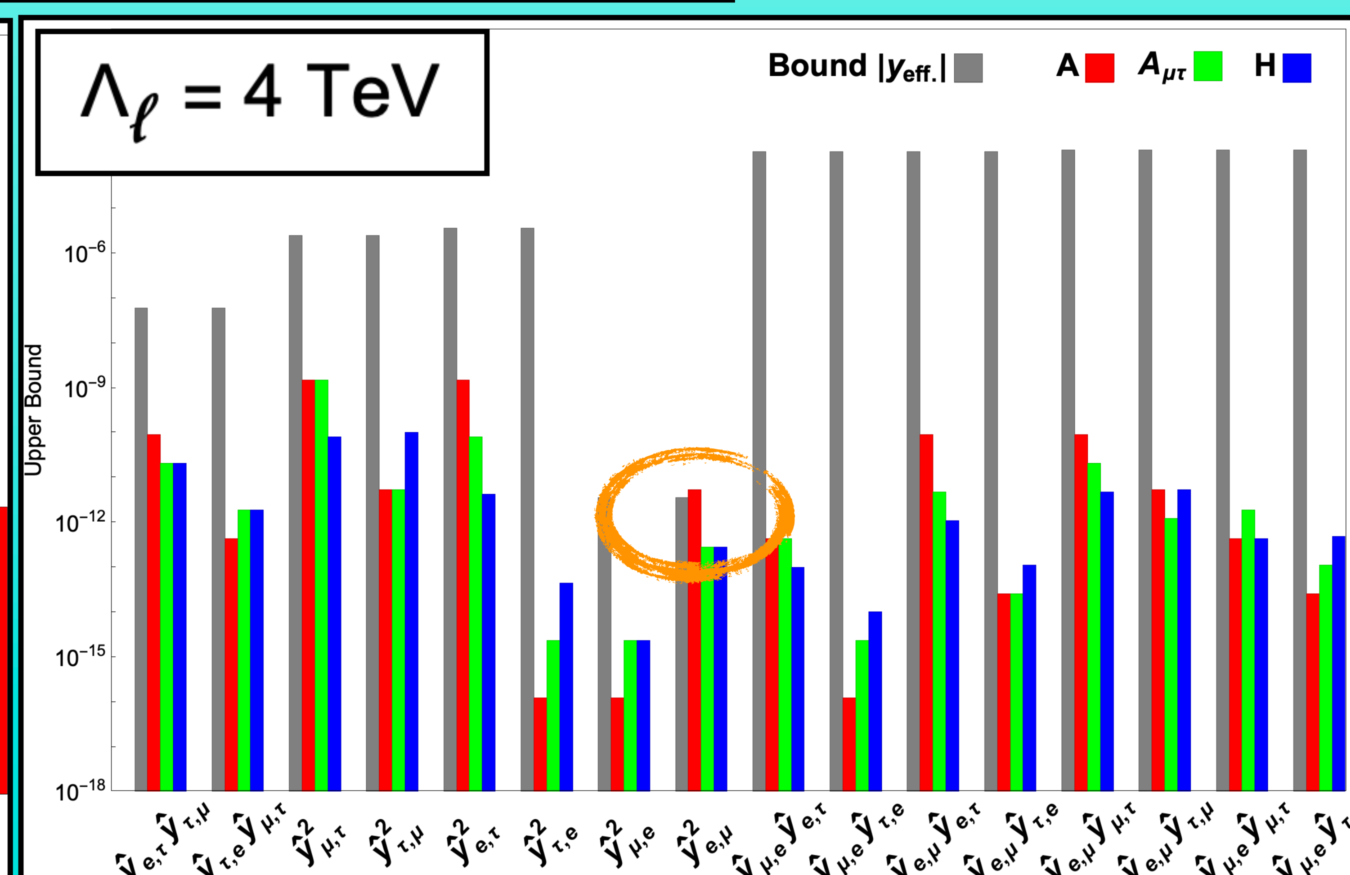


$$\Lambda \sim (60 - 300)\ \text{TeV}$$

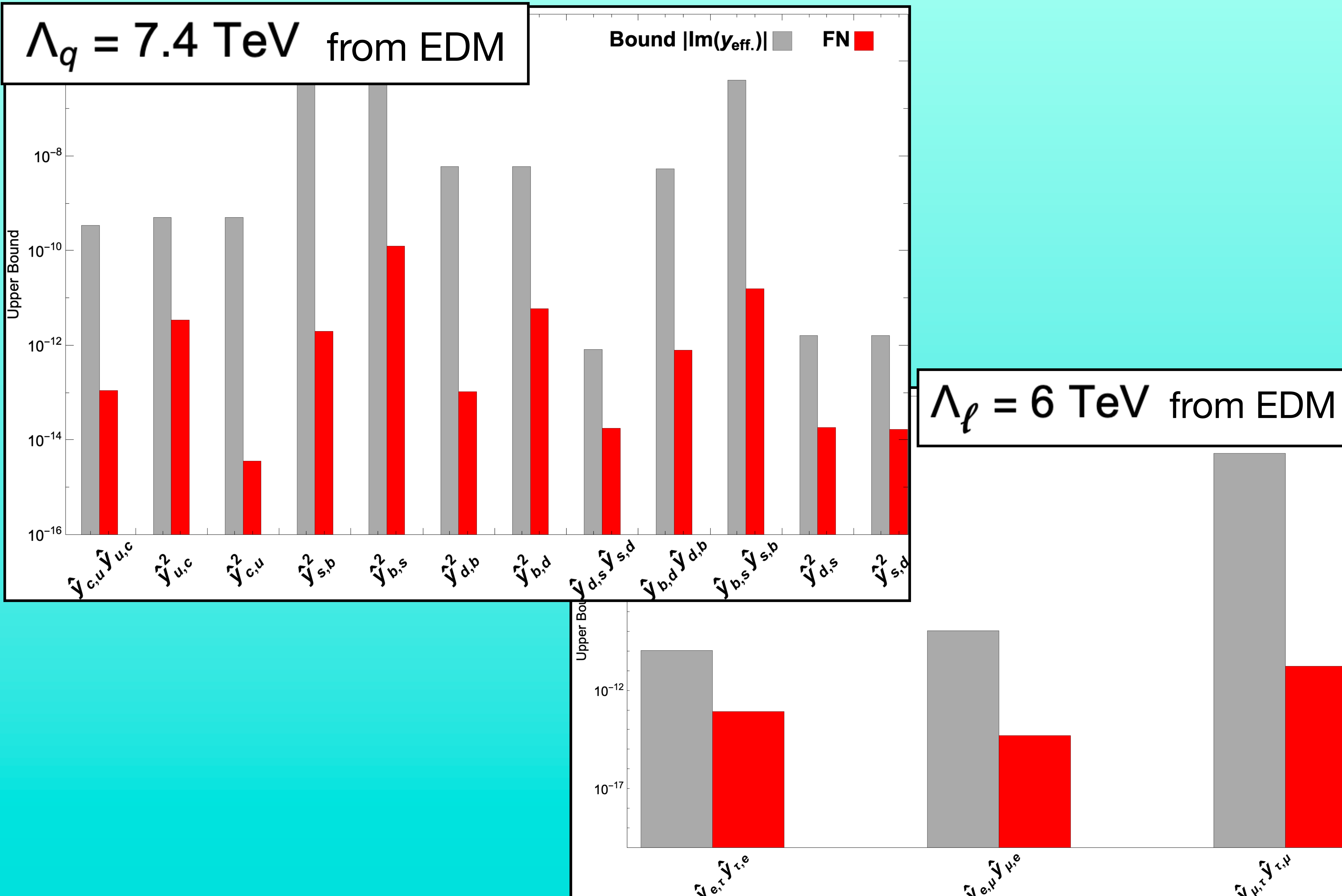
CP Conservation





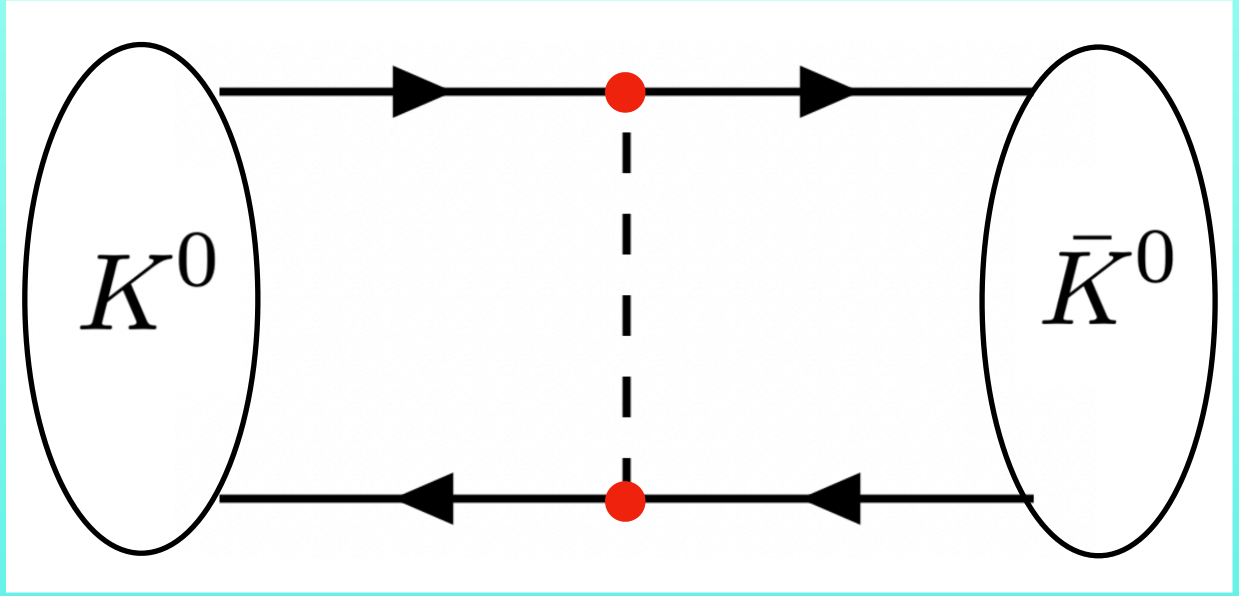


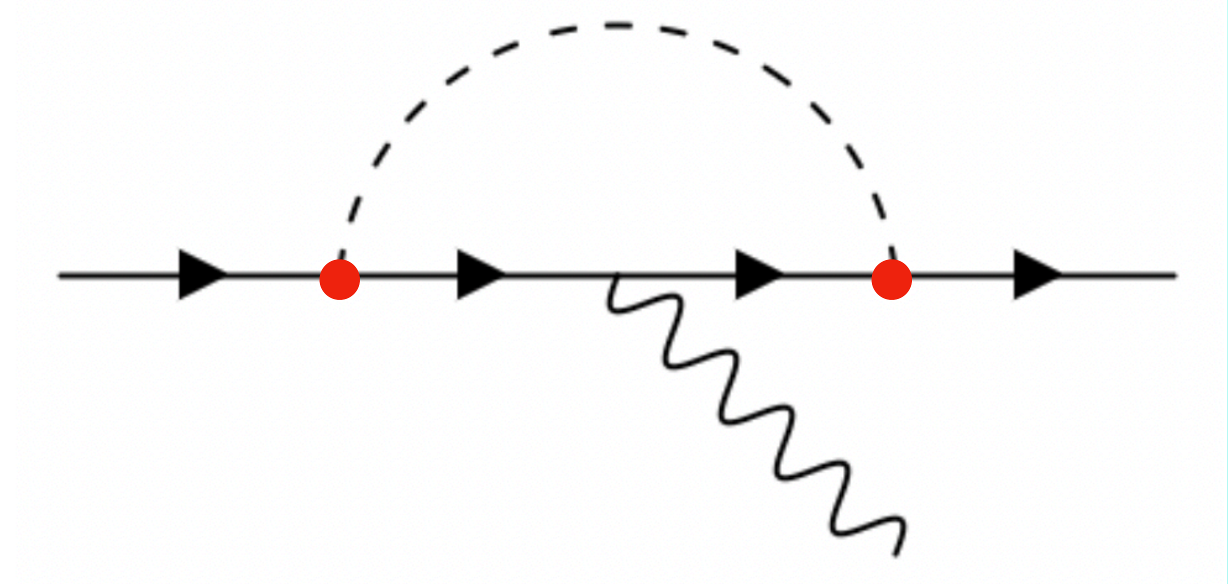
Maximal CPV


Λq = 7.4 TeV from EDM
Bound |Im(yeff.)|
FN
Upper Bound
10−8
10−10
10−12
10−14
10−16
Λℓ = 6 TeV from EDM
10−12
10−17

Flavour Bounds on Λ

Tree and Loop-level Higgs-mediated processes





CP conservation:

Meson oscillations $\longrightarrow$ $\Lambda_q \gtrsim 1$ TeV

Muon radiative decay $\longrightarrow$ $\Lambda_\ell \gtrsim 2 - 4$ TeV

Additional NP contributions may be present: cancellations?

Flavour Bounds on r_ψ^2

From Colliders:

$$0.83 \lesssim r^2_{t,c,u} \lesssim 1.32$$

$$0.58 \lesssim r^2_{b,s,d} \lesssim 1.58$$

$$0.50 \lesssim r^2_{\tau,\mu,e} \lesssim 1.60$$

From Flavour:

$$\Lambda_q \gtrsim 1 \text{ TeV} \qquad \Lambda_\ell \gtrsim 4 \text{ TeV}$$

$$\Rightarrow \quad 0.88 \lesssim r^2_q \lesssim 1.12 \qquad 0.99 \lesssim r^2_\ell \lesssim 1.01$$

Flavour data imply bounds on r_ψ^2 only a few % better than colliders

(good news for future Higgs collider measurements)

Higgs and Top Decays

$\Lambda_q = 1$ TeV

BR	Experimental Bound 95%C.L.		FN Prediction
$t \to hu$	4.5×10^{-3}		2×10^{-6}
$t \to hc$	4.6×10^{-3}	5.6×10^{-3}	4×10^{-5}

BR	Experimental Bound 95%C.L.	FN Prediction
$h \to uc$	–	6×10^{-8}
$h \to ds$	–	6×10^{-10}
$h \to db$	–	4×10^{-8}
$h \to sb$	–	8×10^{-7}

$\Lambda_\ell = 4$ TeV

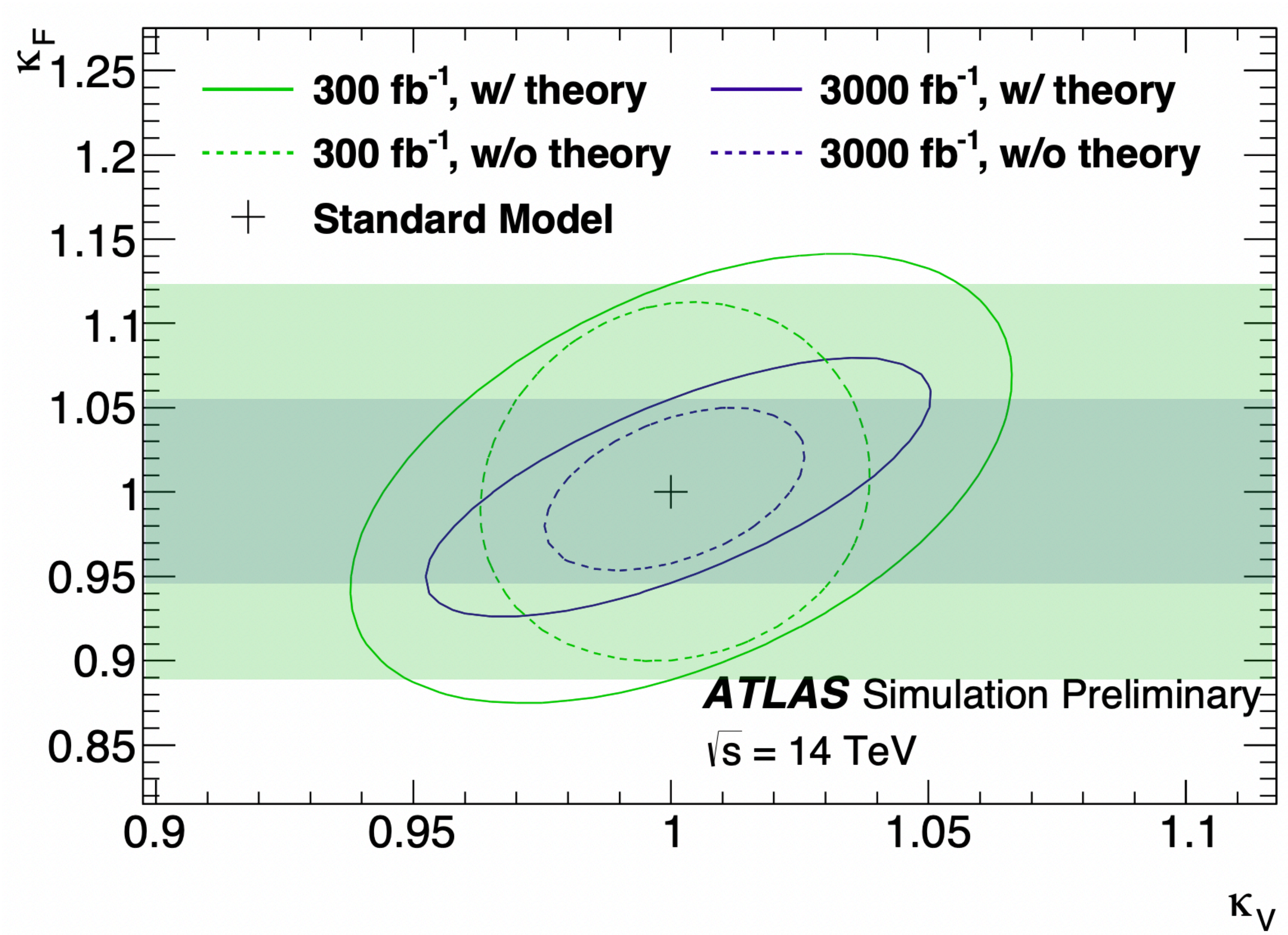
BR	Experimental Bound 95%C.L.	A	$A_{\mu\tau}$	H
$h \to e\mu$	6.1×10^{-5}	3×10^{-9}	10^{-10}	1×10^{-10}
$h \to e\tau$	2.2×10^{-3}	8×10^{-7}	4×10^{-8}	2×10^{-9}
$h \to \mu\tau$	1.5×10^{-3}	8×10^{-7}	8×10^{-7}	9×10^{-8}

→ Higgs and Top FV decays still far or violation of FS!

Collider Prospects at 14 TeV

Waiting for HL-LHC - Run III

ATLAS Collaboration, ATL-PHYS-PUB-2014-016



Flavour Observables + **Higgs Physics**

$\Lambda_q \gtrsim 1$ TeV

$\Lambda_\ell \gtrsim 4$ TeV

$0.88 \lesssim r_q^2 \lesssim 1.12$

$0.99 \lesssim r_\ell^2 \lesssim 1.01$

VS

$\Lambda_q \gtrsim 0.8$ TeV

$\Lambda_\ell \gtrsim 0.5$ TeV

$0.82 \lesssim r_{t,c,u}^2 \lesssim 1.61$

$0.67 \lesssim r_{b,s,d}^2 \lesssim 1.52$

$0.49 \lesssim r_{\tau,\mu,e}^2 \lesssim 1.51$

$$\frac{\Delta\kappa_q}{\kappa_q} \approx 6\% \qquad \frac{\Delta\kappa_l}{\kappa_l} \approx 0.5\%$$

Coupling	300 fb^{-1} Theory unc.:			3000 fb^{-1} Theory unc.:		
	All	Half	None	All	Half	None
$\kappa_V = \kappa_Z = \kappa_W$	4.3%	3.0%	2.5%	3.3%	2.2%	1.7%
$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.8%	7.5%	7.1%	5.1%	3.8%	3.2%

Coupling	300 fb^{-1} Theory unc.:			3000 fb^{-1} Theory unc.:		
	All	Half	None	All	Half	None
κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
κ_q	11%	8.7%	7.8%	6.6%	4.5[illegible]	3.6%
κ_l	10%	9.6%	9.3%	6.0%	5.3[illegible]	5.1%

Courtesy of Arturo de Giorgi

Talk at LHC Higgs Working Group - Common WG2 and WG3 -- CP violation and Higgs Sector, 23/06/2022.

Final Remarks

- Complementarity among experiments is fundamental!
- Flavour Syms imply stronger links
- Colliders bounds are still weaker than flavour ones, but this will change soon for quarks

Colliders (diag.)	Flavour (off-diag.)
$\Lambda_q \gtrsim 0.8\ \mathrm{TeV}$	$\Lambda_q \gtrsim 1\ \mathrm{TeV}$
$\Lambda_\ell \gtrsim 0.5\ \mathrm{TeV}$	$\Lambda_\ell = 2 - 4\ \mathrm{TeV}$

- In the Maximal CPV case, eEDMs dominate

eEDM	$\Lambda_q \gtrsim 7.4\ \mathrm{TeV}$
	$\Lambda_\ell \gtrsim 6.0\ \mathrm{TeV}$

- Higgs and Top FV decays still far or violation of FS!

Thanks!

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On eEDM

$$\frac{d_e}{e} = 4\,\frac{\alpha_{\rm em}}{(4\pi)^3}\,\sqrt{2}\,G_F\,m_e \times \tilde{\kappa}^{\rm eff}$$

$$\tilde{\kappa}^{eff} = [2.68\tilde{\kappa}_e + 3.83\tilde{\kappa}_t + 0.018\tilde{\kappa}_b + 0.015\tilde{\kappa}_\tau]$$

Experimentally: $\tilde{\kappa}^{eff} < 0.0045$

In order to relax the bounds found on $\tilde{\kappa}_{e,t}$, there should be a cancellation between the first two terms!

In the absence of any cancellation,

$$\tilde{\kappa}_{e,\mu,\tau} \lesssim 0.0017$$

is completely general.

Flavour Bounds

Eff. Coupl.	Bound on $\|y_{\text{eff.}}\|$	Λ_q [TeV]	Bound on $\|\texttt{Im}(y_{\text{eff.}})\|$	Λ_q [TeV]
$\hat{y}_{sd}\hat{y}^*_{ds}$	2.2×10^{-10}	0.7	8.2×10^{-13}	3
$\hat{y}_{cu}\hat{y}^*_{uc}$	1.8×10^{-9}	0.7	3.4×10^{-10}	1
$\hat{y}_{bd}\hat{y}^*_{db}$	1.8×10^{-8}	0.6	5.4×10^{-9}	0.8
$\hat{y}_{bs}\hat{y}^*_{sb}$	4.0×10^{-7}	0.6	4.0×10^{-7}	0.6
$\hat{y}^2_{ds}$	4.4×10^{-10}	0.6	1.6×10^{-12}	2
$\hat{y}^2_{sd}$	4.4×10^{-10}	0.6	1.6×10^{-12}	2
$\hat{y}^2_{uc}$	2.8×10^{-9}	1	5.0×10^{-10}	2
$\hat{y}^2_{cu}$	2.8×10^{-9}	0.2	5.0×10^{-10}	0.4
$\hat{y}^2_{db}$	2.0×10^{-8}	0.4	6.0×10^{-9}	0.5
$\hat{y}^2_{bd}$	2.0×10^{-8}	1	6.0×10^{-9}	1
$\hat{y}^2_{sb}$	4.4×10^{-7}	0.3	4.4×10^{-7}	0.3
$\hat{y}^2_{bs}$	4.4×10^{-7}	1	4.4×10^{-7}	1

Eff. Coupl.	Bound	Λ_ℓ [**TeV**]		
		A	$A_{\mu\tau}$	H
$\lvert\hat{y}_{e\tau}\hat{y}_{\tau e}\rvert$	2.2×10^{-2}	$8.\times10^{-3}$	=	=
$\lvert\mathtt{Re}(\hat{y}_{e\tau}\hat{y}_{\tau e})\rvert$	1.4×10^{-4}	3×10^{-2}	=	=
$\lvert\mathtt{Im}(\hat{y}_{e\tau}\hat{y}_{\tau e})\rvert$	1.1×10^{-10}	1	=	=
$\lvert\hat{y}_{e\mu}\hat{y}_{\mu e}\rvert$	3.6×10^{-1}	2×10^{-3}	=	=
$\lvert\mathtt{Re}(\hat{y}_{e\mu}\hat{y}_{\mu e})\rvert$	1.4×10^{-3}	8×10^{-3}	=	=
$\lvert\mathtt{Im}(\hat{y}_{e\mu}\hat{y}_{\mu e})\rvert$	1.1×10^{-9}	0.3	=	=
$\lvert\hat{y}_{\mu\tau}\hat{y}_{\tau\mu}\rvert$	4.0	9×10^{-3}	=	=
$\lvert\mathtt{Re}(\hat{y}_{\mu\tau}\hat{y}_{\tau\mu})\rvert$	2.5×10^{-3}	5×10^{-2}	=	=
$\lvert\mathtt{Im}(\hat{y}_{\mu\tau}\hat{y}_{\tau\mu})\rvert$	1.2	1×10^{-2}	=	=
$\lvert\hat{y}_{e\tau}\hat{y}_{\tau\mu}\rvert$	6×10^{-8}	0.8	0.5	0.5
$\lvert\hat{y}_{\tau e}\hat{y}_{\mu\tau}\rvert$	6×10^{-8}	0.2	0.3	0.3
$\lvert\hat{y}_{\mu\tau}\rvert^2$	2.5×10^{-6}	0.6	0.6	0.3
$\lvert\hat{y}_{\tau\mu}\rvert$	2.5×10^{-6}	0.2	0.2	0.3
$\lvert\hat{y}_{e\tau}\rvert^2$	3.6×10^{-6}	0.6	0.3	0.1
$\lvert\hat{y}_{\tau e}\rvert^2$	3.6×10^{-6}	1×10^{-2}	2×10^{-2}	4×10^{-2}
$\lvert\hat{y}_{\mu e}\rvert^2$	3.5×10^{-12}	0.3	0.6	0.6
$\lvert\hat{y}_{e\mu}\rvert^2$	3.5×10^{-12}	4	2	2
$\lvert\hat{y}_{\mu e}\hat{y}^*_{e\tau}\rvert$	1.8×10^{-4}	3×10^{-2}	3×10^{-2}	2×10^{-2}
$\lvert\hat{y}_{\mu e}\hat{y}_{\tau e}\rvert$	1.8×10^{-4}	4×10^{-3}	8×10^{-3}	1×10^{-2}
$\lvert\hat{y}^*_{e\mu}\hat{y}^*_{e\tau}\rvert$	1.8×10^{-4}	0.1	5×10^{-2}	4×10^{-2}
$\lvert\hat{y}^*_{e\mu}\hat{y}_{\tau e}\rvert$	1.8×10^{-4}	1×10^{-2}	1×10^{-2}	2×10^{-2}
$\lvert\hat{y}_{e\mu}\hat{y}^*_{\mu\tau}\rvert$	2.0×10^{-4}	0.1	7×10^{-2}	5×10^{-2}
$\lvert\hat{y}_{e\mu}\hat{y}_{\tau\mu}\rvert$	2.0×10^{-4}	5×10^{-2}	4×10^{-2}	5×10^{-2}
$\lvert\hat{y}^*_{\mu e}\hat{y}^*_{\mu\tau}\rvert$	2.0×10^{-4}	3×10^{-2}	4×10^{-2}	3×10^{-2}
$\lvert\hat{y}^*_{\mu e}\hat{y}_{\tau\mu}\rvert$	2.0×10^{-4}	1×10^{-2}	2×10^{-2}	3×10^{-2}

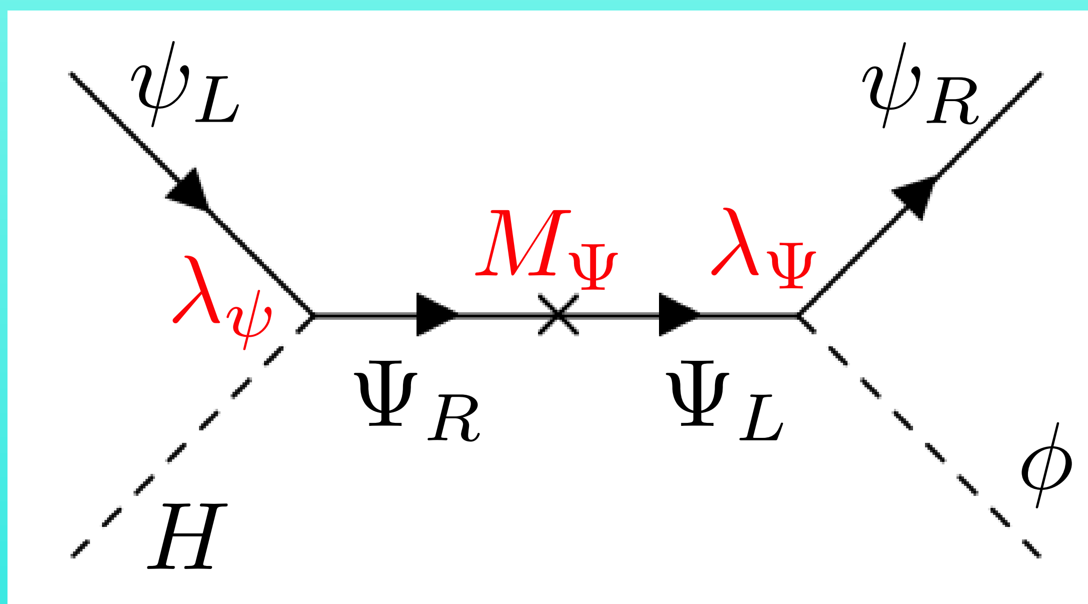
Toy-model UV Completion

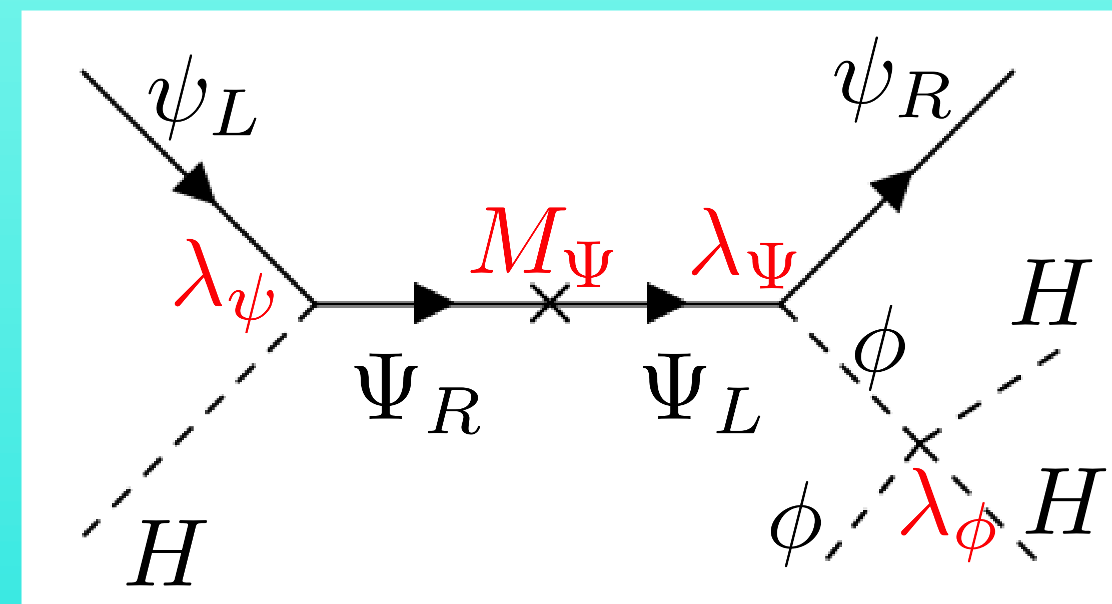
Vector-like Exotic fermions: $\Psi_{L,R}$

MFV-inspired symmetry: $\psi_L, \Psi_L, \Psi_R \sim 3 \subset SU(3)_L$

$$\psi_R \sim 3 \subset SU(3)_R$$

New bi-triplet scalar: $\phi \sim (3, \bar{3})$





$$Y_\psi \sim \lambda_\psi \frac{1}{M\psi} \lambda_\Psi v_\phi$$

$$\frac{c_\psi^{d=6}}{\Lambda^2} \sim \lambda_\psi \frac{1}{M\psi} \lambda_\Psi v_\phi \frac{1}{M_\phi^2} \lambda_\phi$$