New Physics in Yukawa Couplings with Flavour Symmetries

Luca Merlo

Based on:

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

Alonso-González, de Giorgi, LM, Pokorski, arXiv:2109.07490

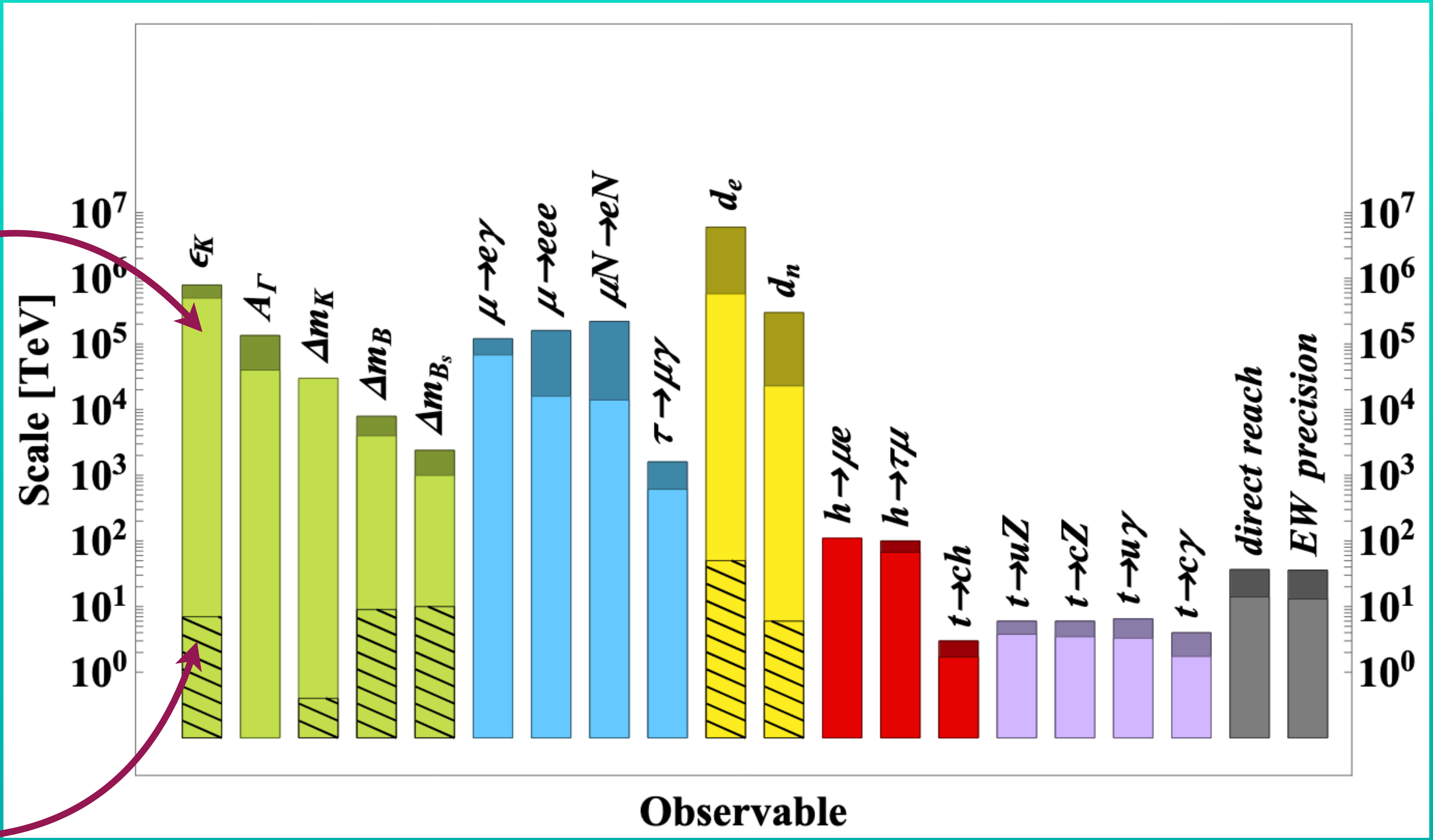
CP Violation in Higgs Interactions, January 20th 2022

Setup

SMEFT with generic d=6 operators:

$\mathcal{O}(1)$ factors

MFV



European Strategy for Particle Physics Update 2020, 1910.11775

Low-energy facilities much stronger than colliders

Focussing on the Yukawas

$$\overline{f_L} H f_R$$

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Higgs Production

Higgs Decays

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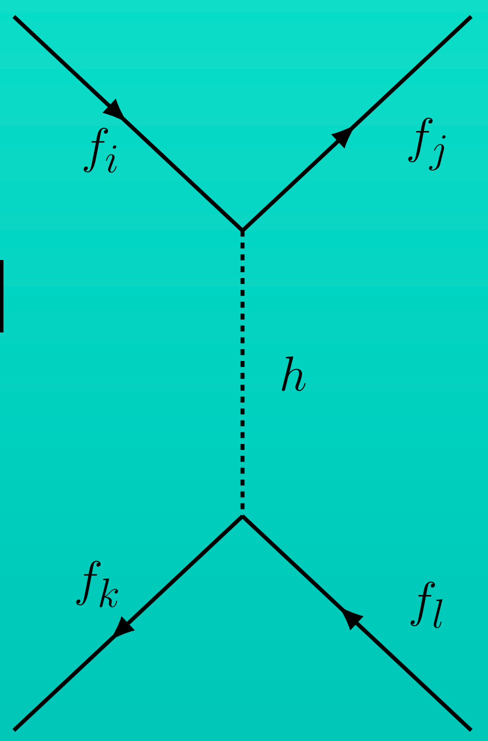
Tree-level
Higgs-mediated



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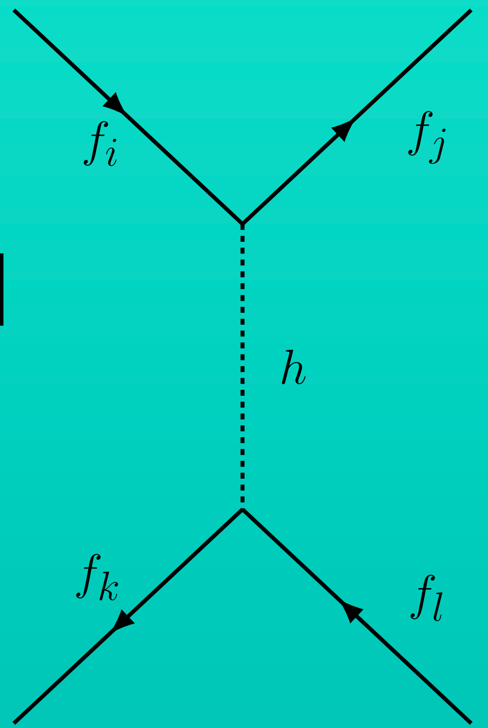
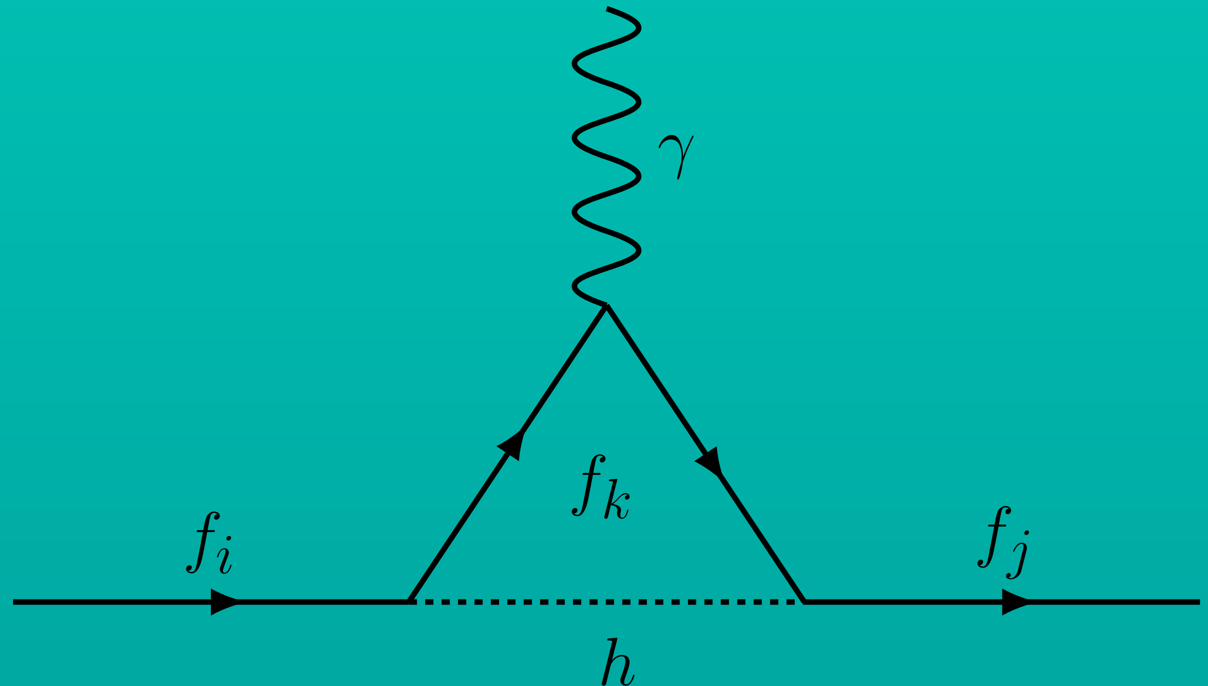
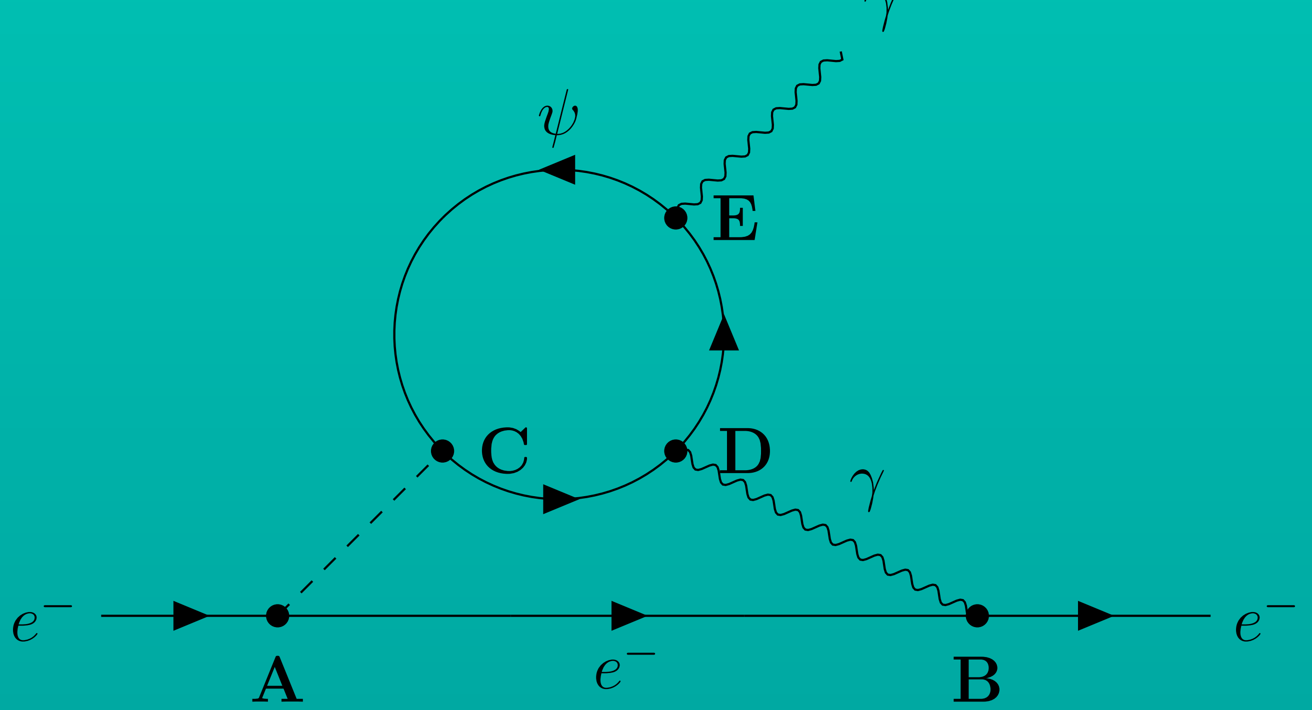


Loop-level Higgs-mediated





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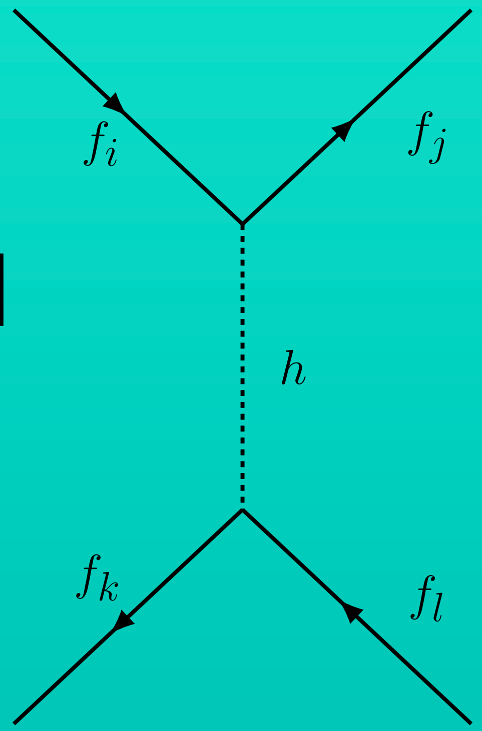
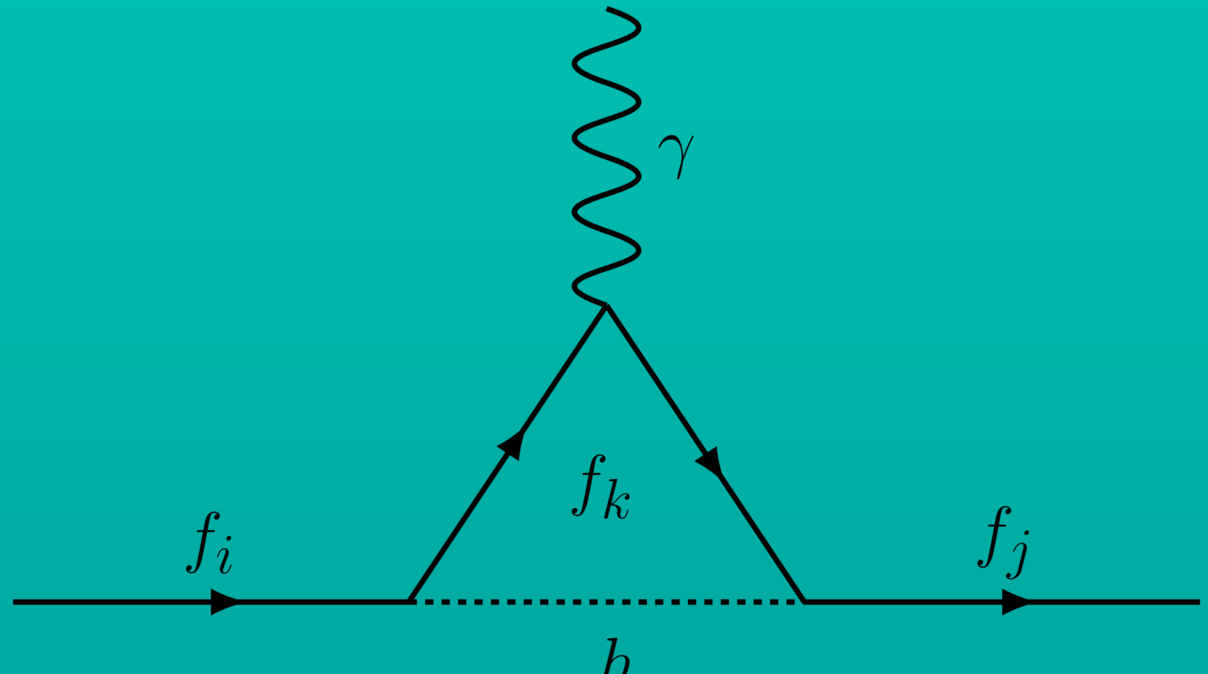
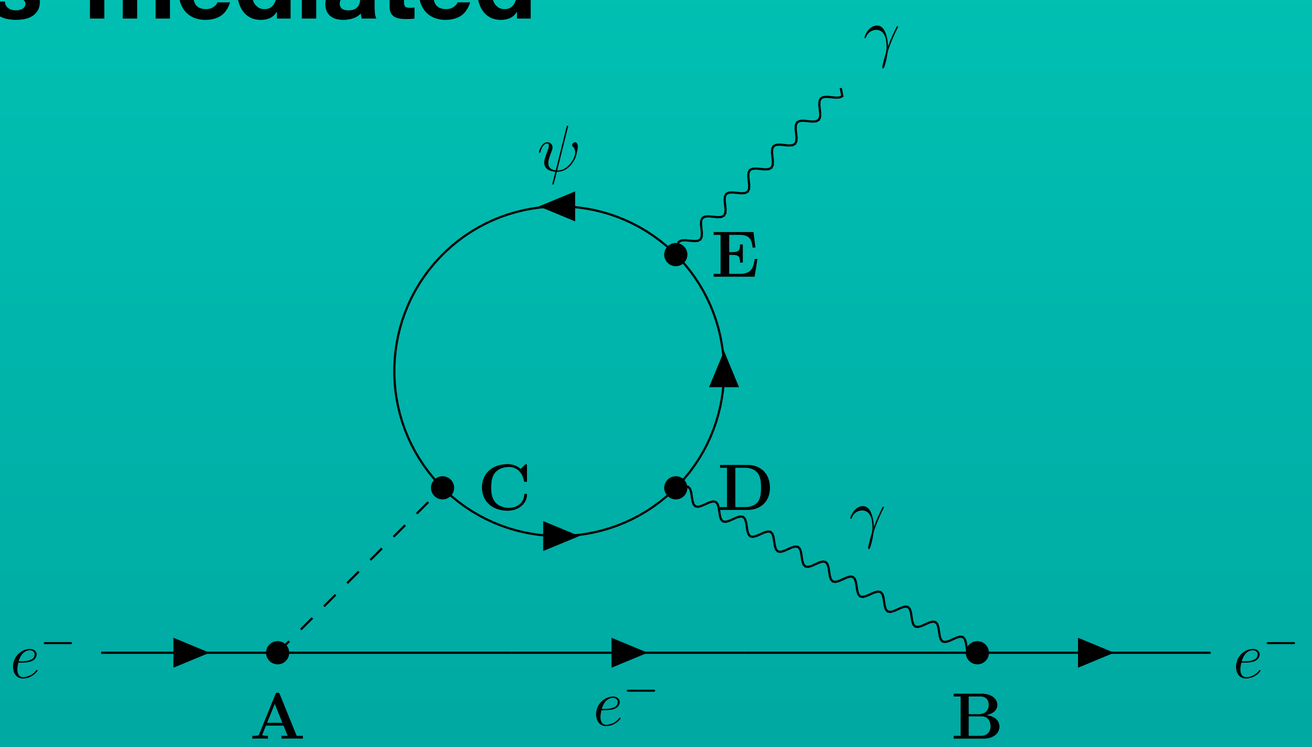


$$\overline{f_L} H f_R$$

Baryogenesis

Loop-level Higgs-mediated





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

- Allows to describe masses and mixings
- Rules Yukawa interactions
- Rules the fermion interactions in any d>4 ops.

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

An Example: eEDM

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ACME II, Nature 562(2018)7727

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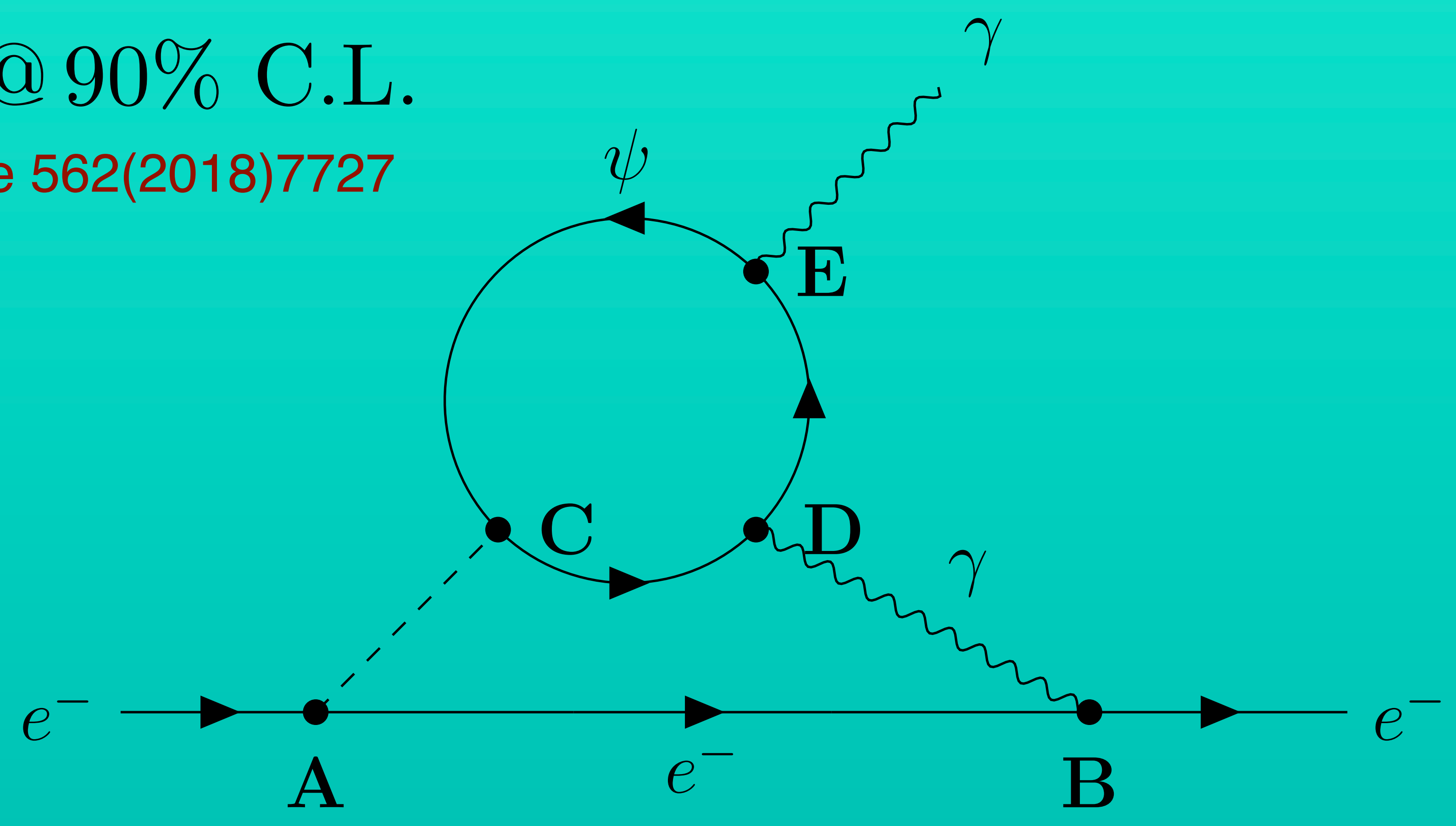

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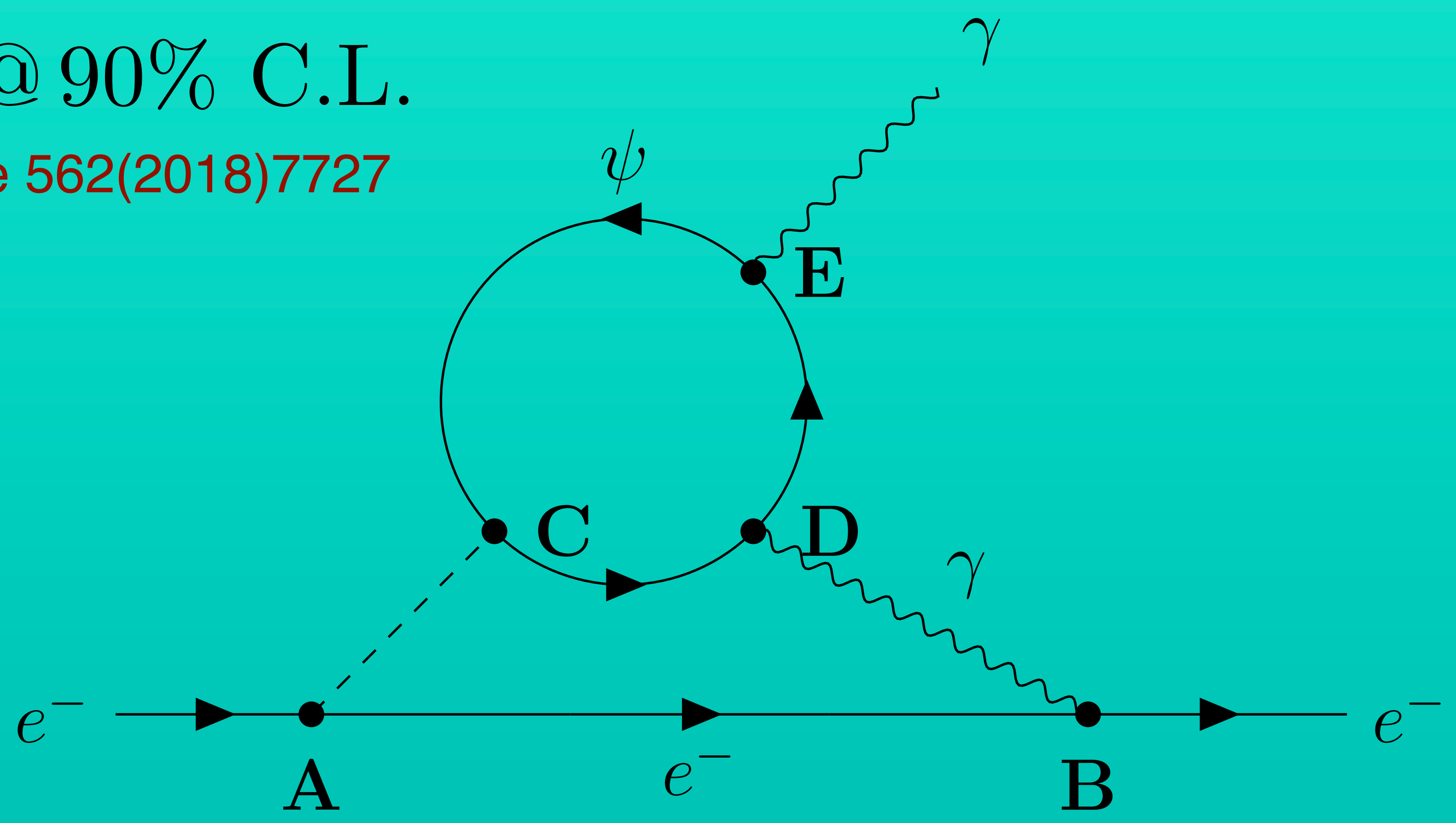

$$\mathcal{L}_{\text{eff}} = -\frac{y_\psi}{\sqrt{2}} \left(\kappa_\psi \overline{\psi}\psi + i\tilde{\kappa}_\psi \overline{\psi}\gamma_5\psi\right) h$$

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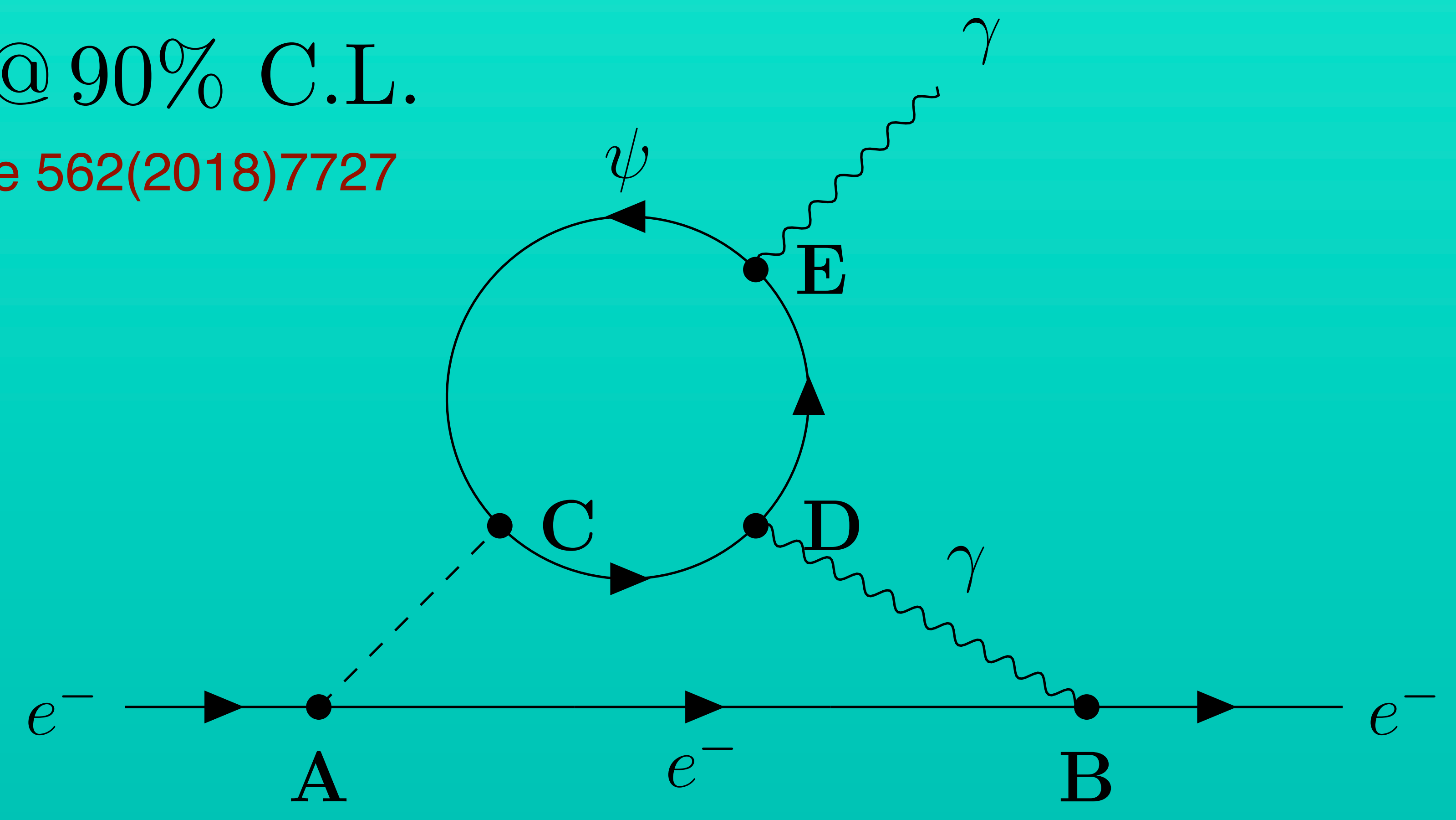

$$\mathcal{L}_{\text{eff}} = -\frac{y_\psi}{\sqrt{2}} \left(\kappa_\psi \overline{\psi} \psi + i \tilde{\kappa}_\psi \overline{\psi} \gamma_5 \psi \right) h$$

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

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

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

(See also Fuchs et all, JHEP 05 (2020) 056; Brod & Stamou, JHEP 07 (2021) 080)

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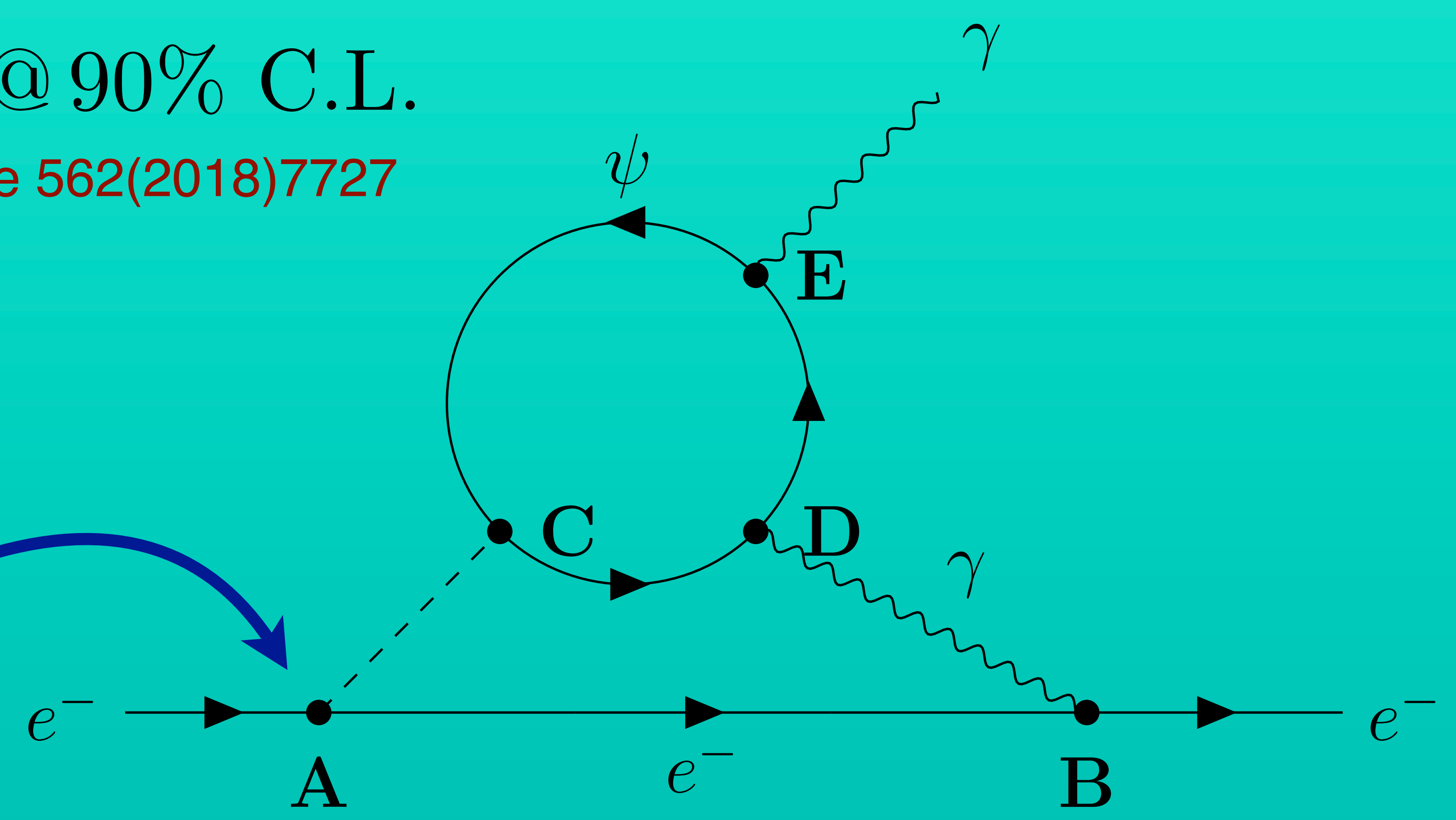

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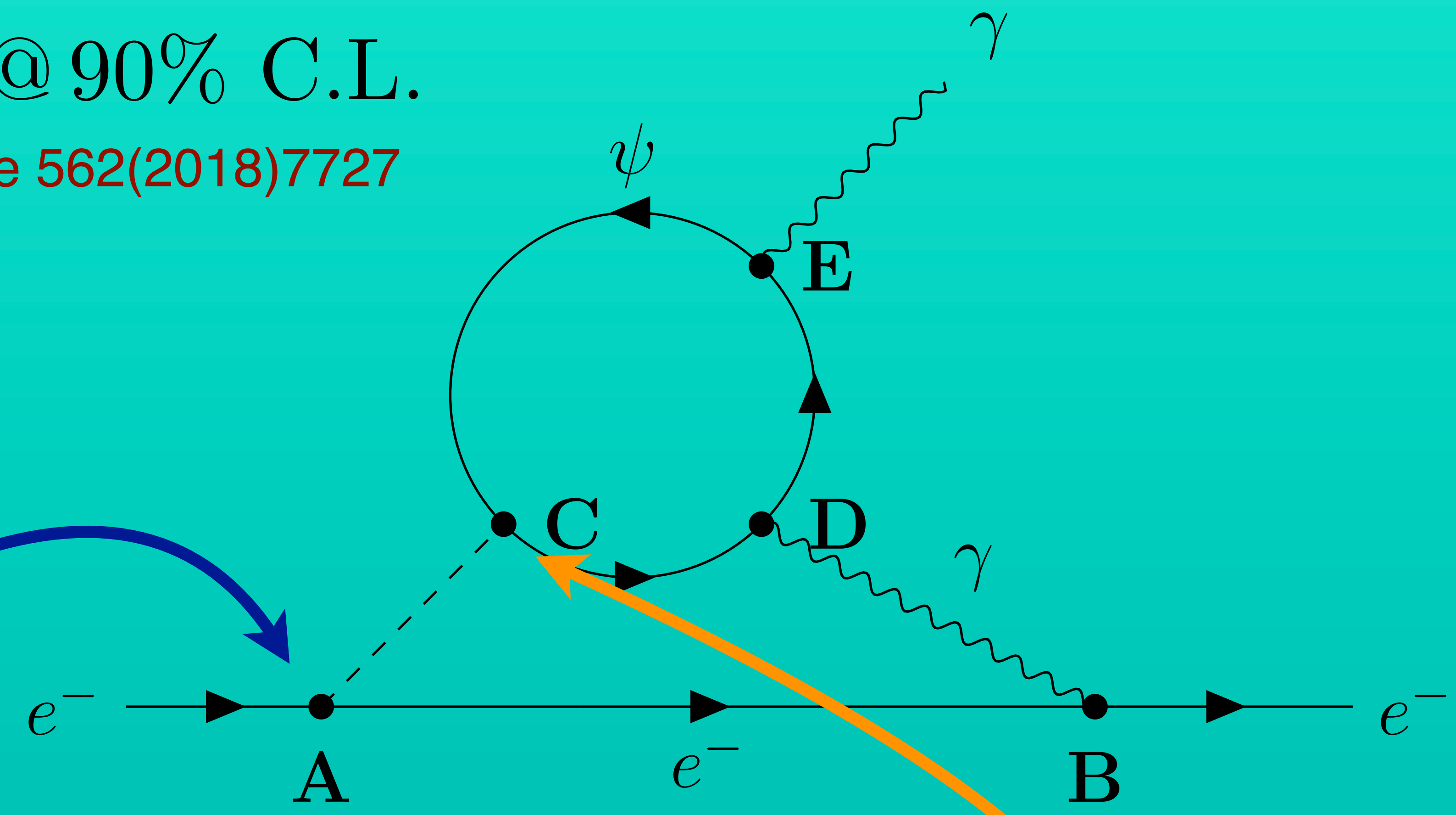

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Direct bounds:		Indirect bounds:
$\lvert\tilde{\kappa}_e\rvert \lesssim 0.0017$ $\lvert\tilde{\kappa}_\mu\rvert \lesssim 31$ $\lvert\tilde{\kappa}_\tau\rvert \lesssim 0.29$	$\longrightarrow$	$\tilde{\kappa}_{e,\mu,\tau} \lesssim 0.0017$
$\lvert\tilde{\kappa}_c\rvert \lesssim 0.37$ $\lvert\tilde{\kappa}_t\rvert \lesssim 0.0012$	$\longrightarrow$	$\tilde{\kappa}_{u,c,t} \lesssim 0.0012$
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<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?

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

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

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

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→ Froggatt-Nielsen (FN)

Simplest flavour model, but low predictivity power!

The Formalism

SMEFT with d=6 operators affecting the Yukawas:

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

primed fields in the flavour basis!

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After EWSB:

$$\mathcal{L} = -\left[\overline{u'_L}\left(Y'_u + \frac{v^2}{2\Lambda_q^2}C'_u\right)u'_R + \overline{d'_L}\left(Y'_d + \frac{v^2}{2\Lambda_q^2}C'_d\right)d'_R + \overline{e'_L}\left(Y'_e + \frac{v^2}{2\Lambda_\ell^2}C'_e\right)e'_R\right]\frac{v}{\sqrt{2}} +$$
$$-\left[\overline{u'_L}\left(Y'_u + \frac{3v^2}{2\Lambda_q^2}C'_u\right)u'_R + \overline{d'_L}\left(Y'_d + \frac{3v^2}{2\Lambda_q^2}C'_d\right)d'_R + \overline{e'_L}\left(Y'_e + \frac{3v^2}{2\Lambda_\ell^2}C'_e\right)e'_R\right]\frac{h}{\sqrt{2}} +$$
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$$+\text{h.c.} + \ldots$$

masses ≠ Higgs couplings!

going to the mass basis:

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

$$\begin{aligned}\mathcal{L} = & - \overline{u_L} Y_u u_R \frac{v}{\sqrt{2}} - \overline{d_L} Y_d d_R \frac{v}{\sqrt{2}} - \overline{e_L} Y_e e_R \frac{v}{\sqrt{2}} + \\ & - \left[\overline{u_L} \left(Y_u + \frac{v^2}{\Lambda_q^2} C_u \right) u_R + \overline{d_L} \left(Y_d + \frac{v^2}{\Lambda_q^2} C_d \right) d_R + \overline{e_L} \left(Y_e + \frac{v^2}{\Lambda_\ell^2} C_e \right) e_R \right] \frac{h}{\sqrt{2}} + \\ & + \text{h.c.} + \dots \end{aligned}$$

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

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The matching with the κ formalism is:

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

$$\begin{cases} Y_f K_f = Y_f + \dfrac{v^2}{\Lambda^2} \texttt{diag}(\texttt{Re} C_f) \\ Y_f \tilde{K}_f = \dfrac{v^2}{\Lambda^2} \texttt{diag}(\texttt{Im} C_f) \end{cases}$$

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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

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

and similarly for the down quarks and the charged leptons.

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

FN case

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

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$$\downarrow$$

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

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

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

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Off-diagonal:

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

Back to the eEDM

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

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

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

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Back to the eEDM

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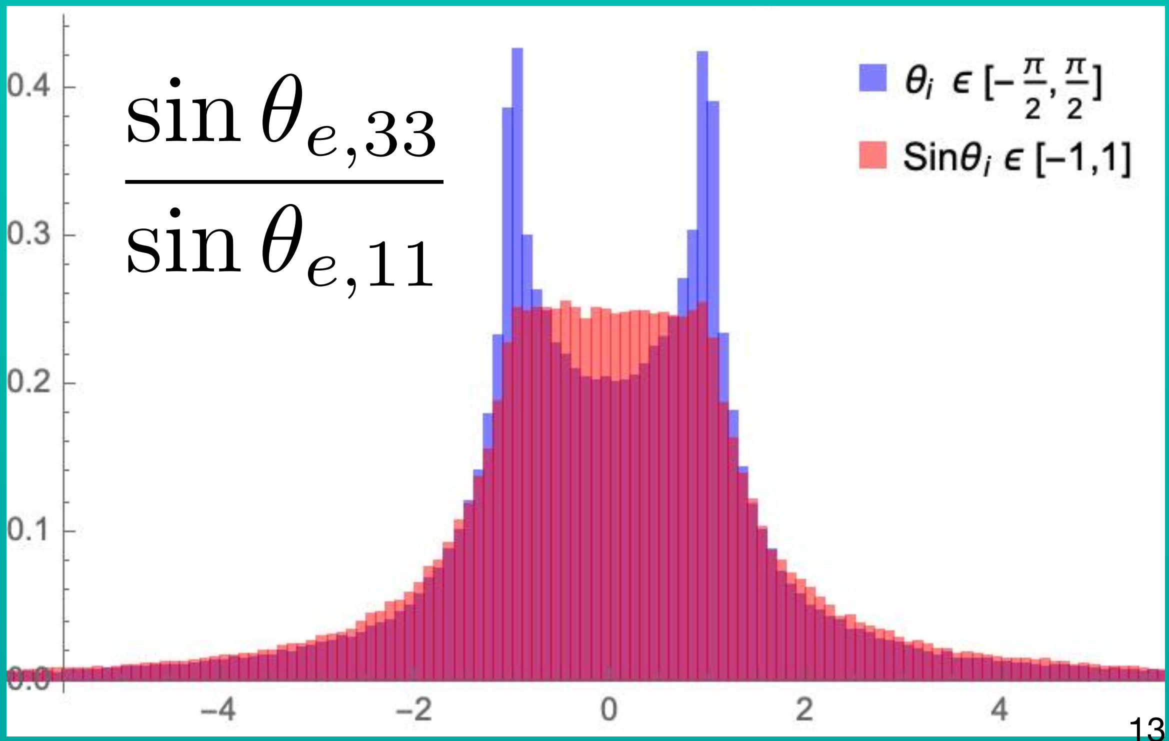

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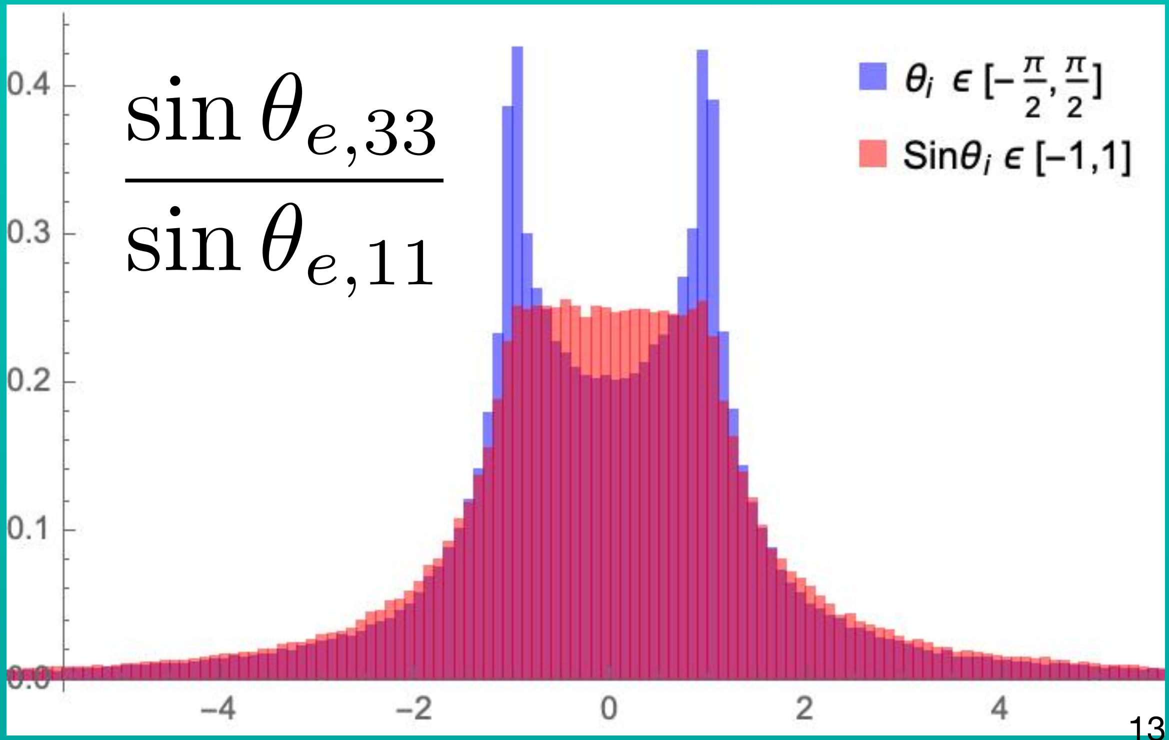

Collider Bounds

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

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for the relevant processes

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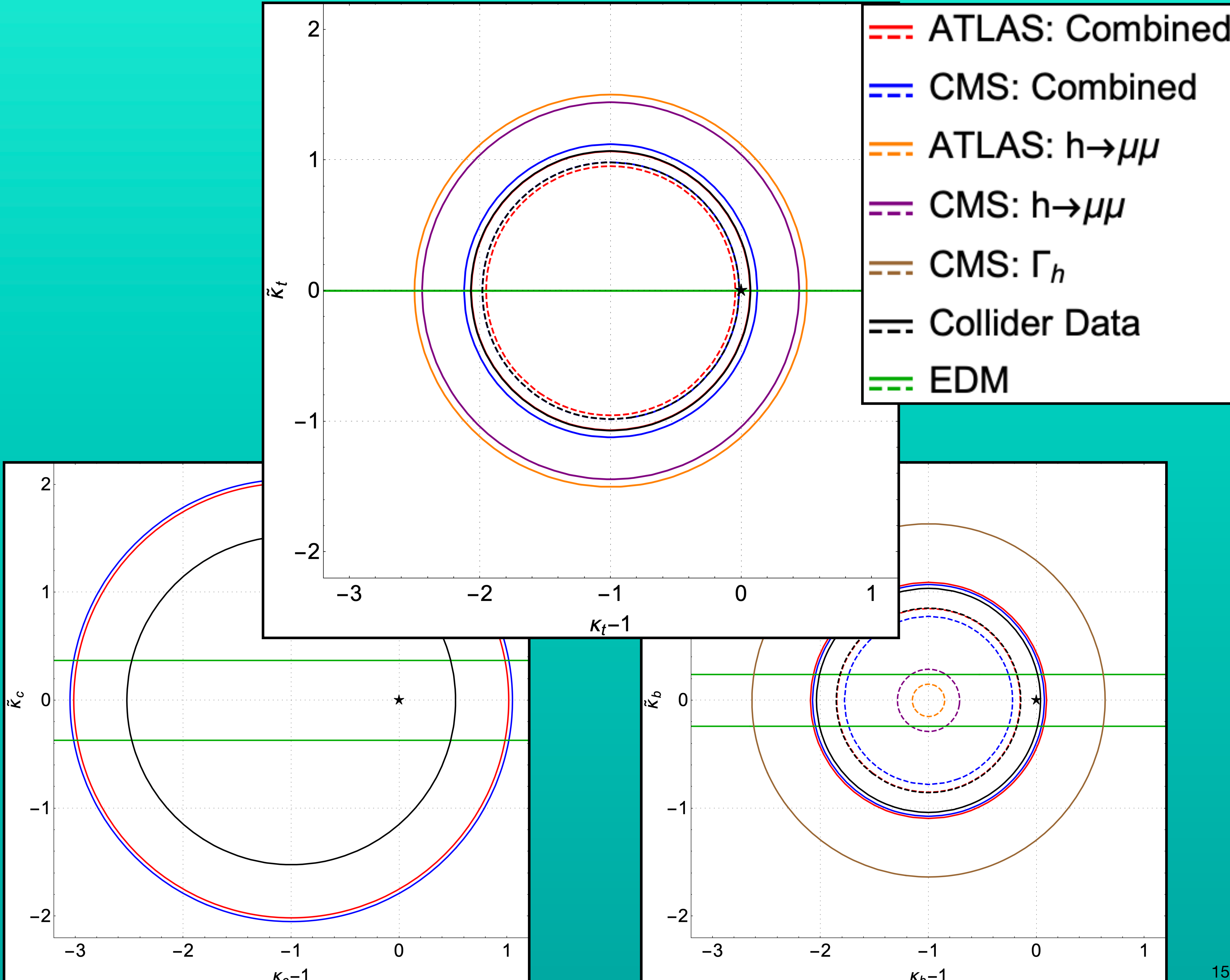
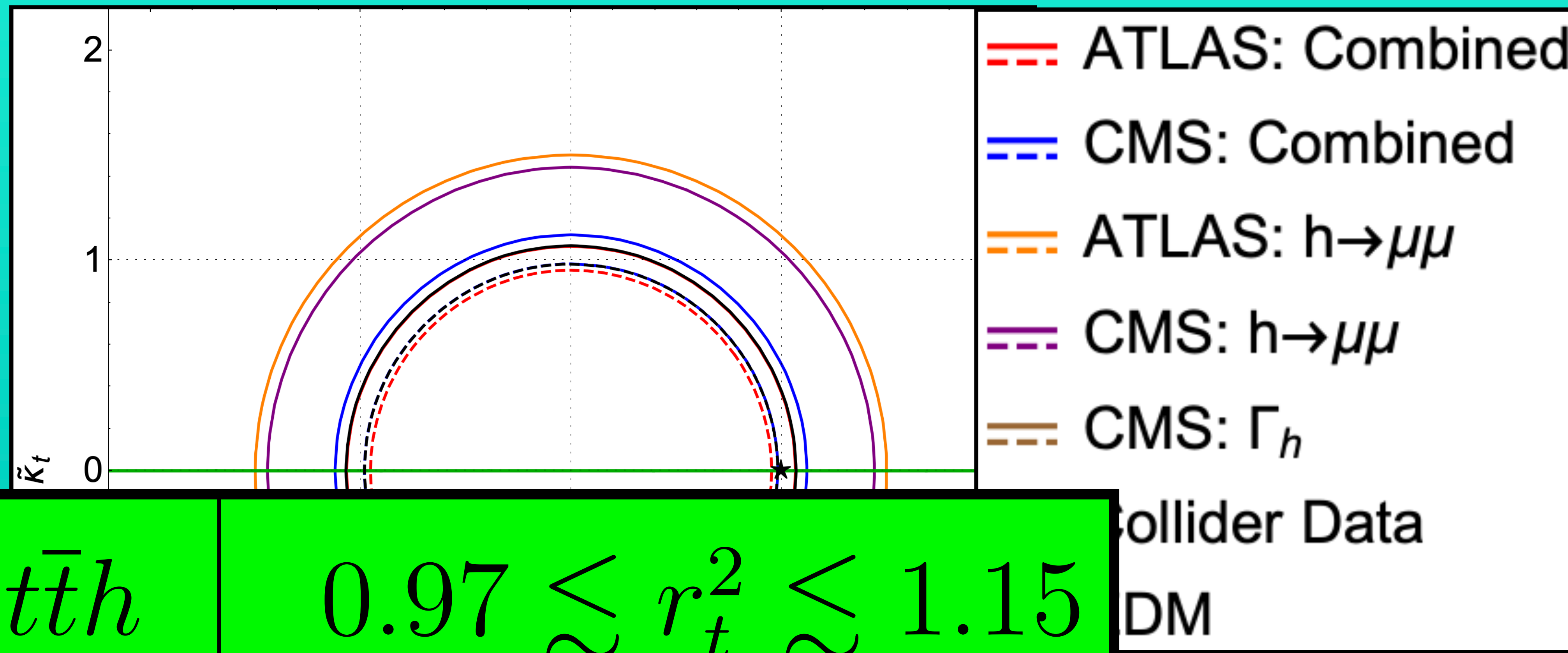
for the relevant processes

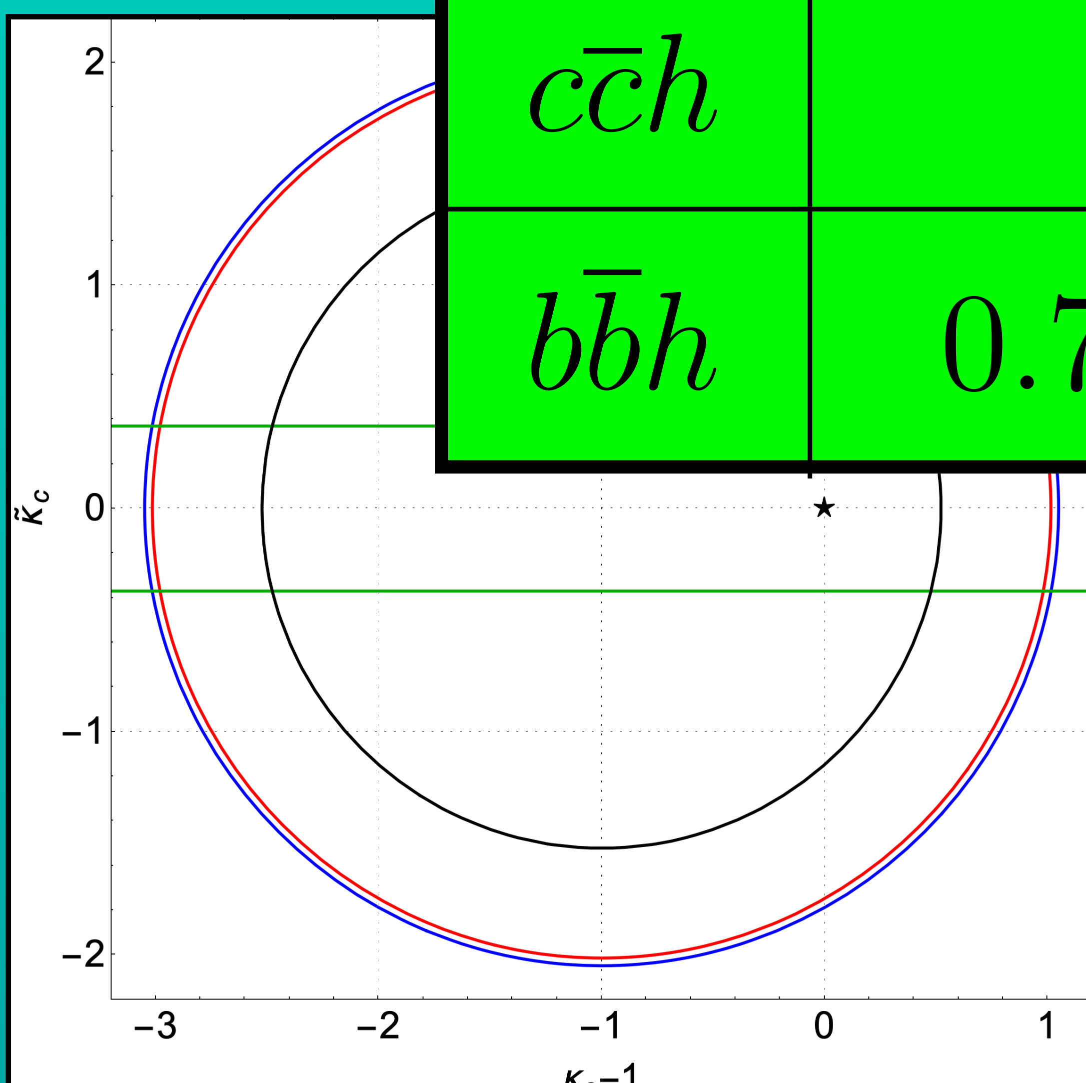
$$\frac{\Gamma_{h,\rm tot.}}{\Gamma_{h,\rm tot.}^{\rm SM}} = 1 + {\rm BR}_{bb}^{\rm SM}\left(r_b^2 - 1\right) + \left({\rm BR}_{gg}^{\rm SM} + {\rm BR}_{\gamma\gamma}^{\rm SM} + {\rm BR}_{cc}^{\rm SM}\right)\left(r_t^2 - 1\right) + {\rm BR}_{\tau\tau}^{\rm SM}\left(r_\tau^2 - 1\right)$$

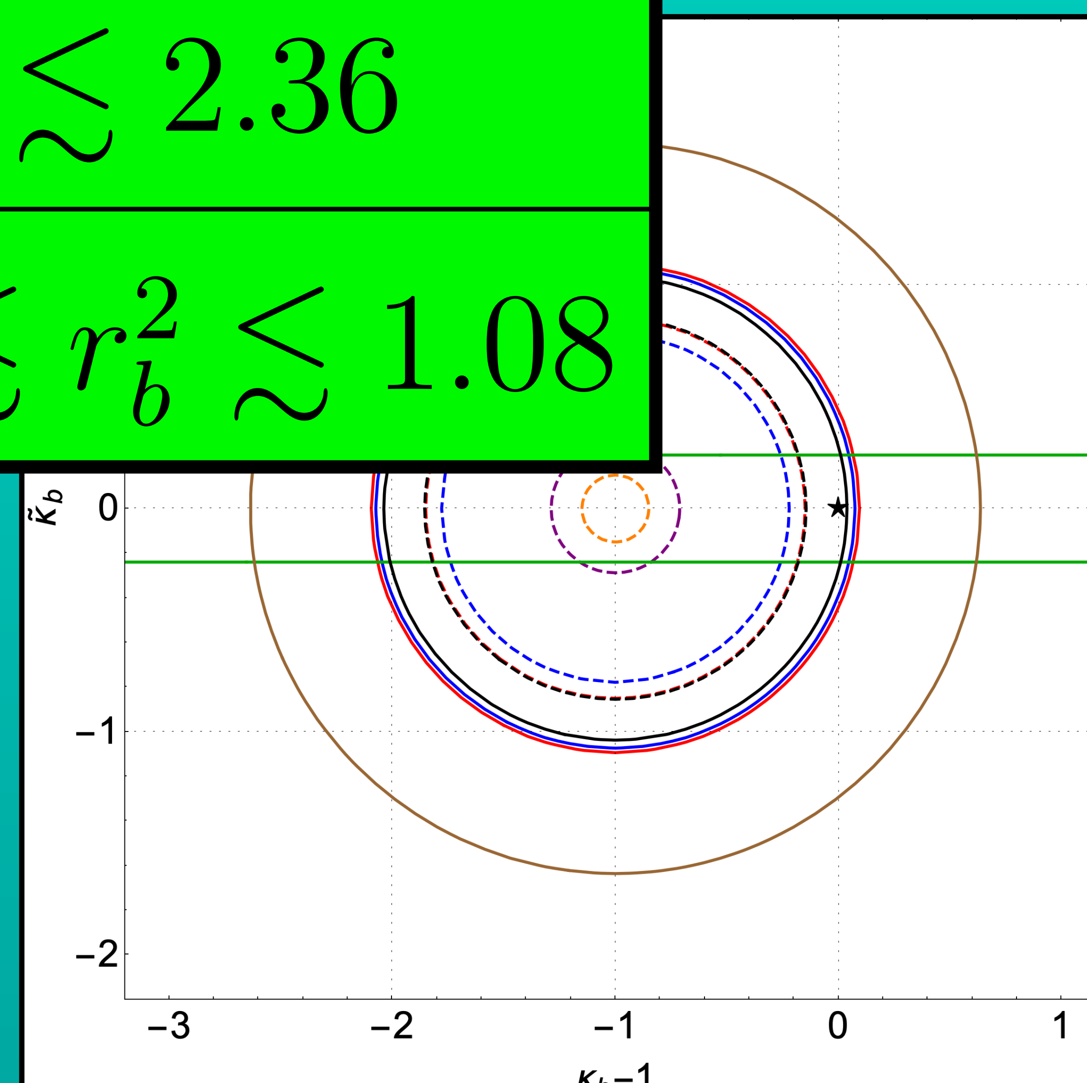


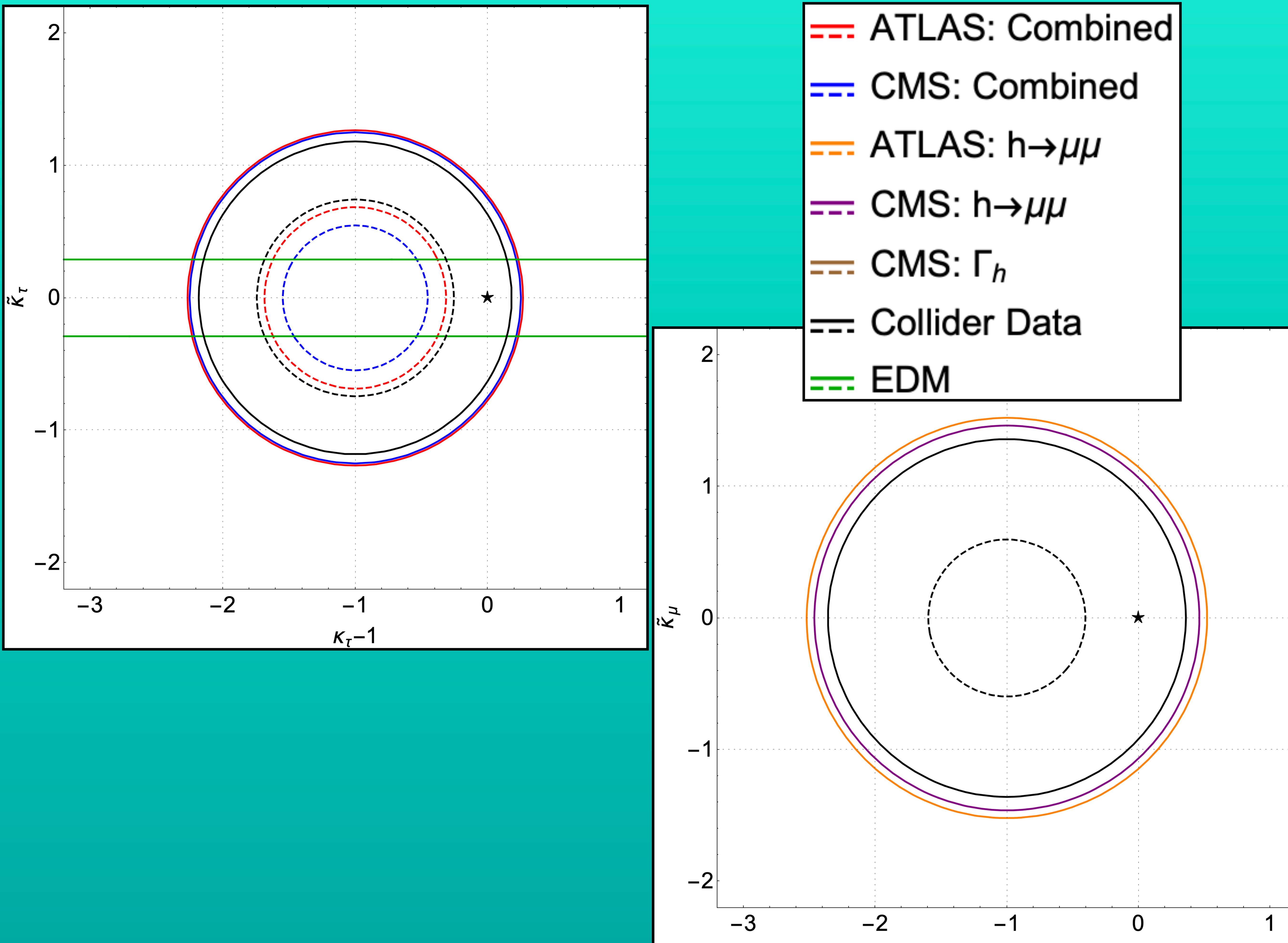
ATLAS: Combined
CMS: Combined
ATLAS: h→μμ
CMS: h→μμ
CMS: Γ_h
Collider Data
EDM
κ̃_t
κ_t−1
κ̃_c
κ_c−1
κ̃_b
κ_b−1



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



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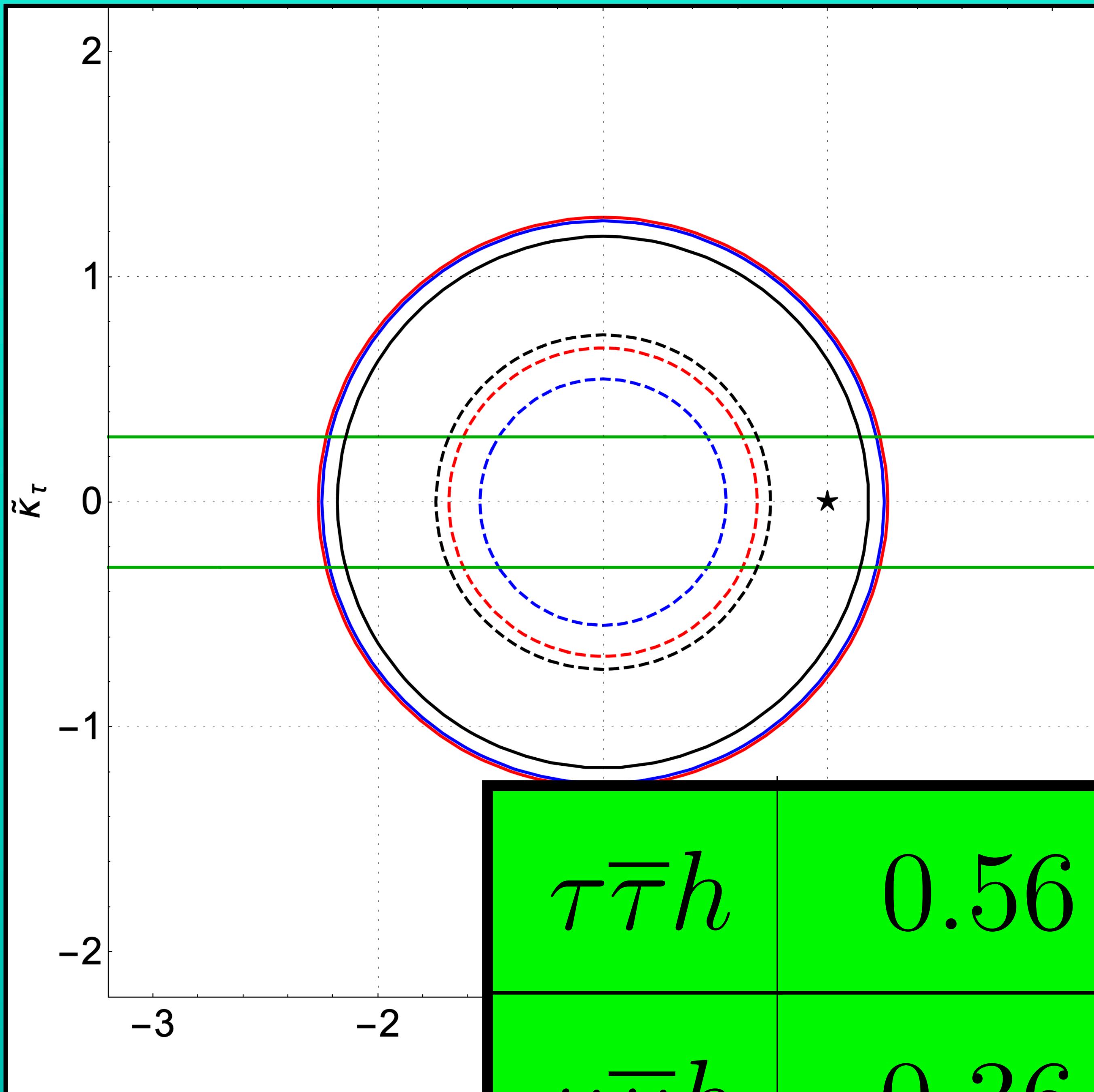
Collider Data
EDM
$\tilde{\kappa}_\tau$
$\kappa_\tau - 1$
$\tilde{\kappa}_\mu$
$\kappa_\mu - 1$
−3
−2
−1
0
1
2



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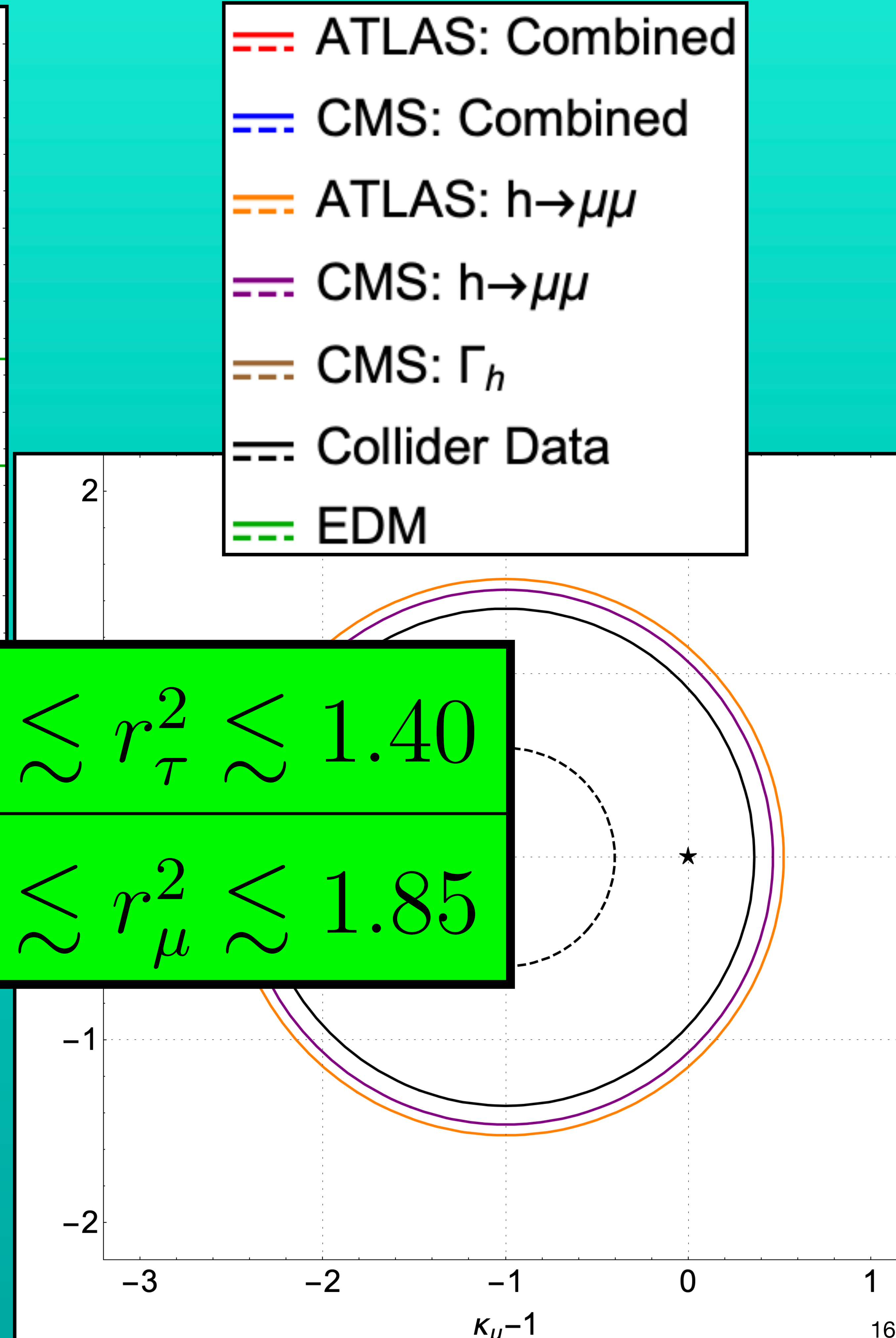
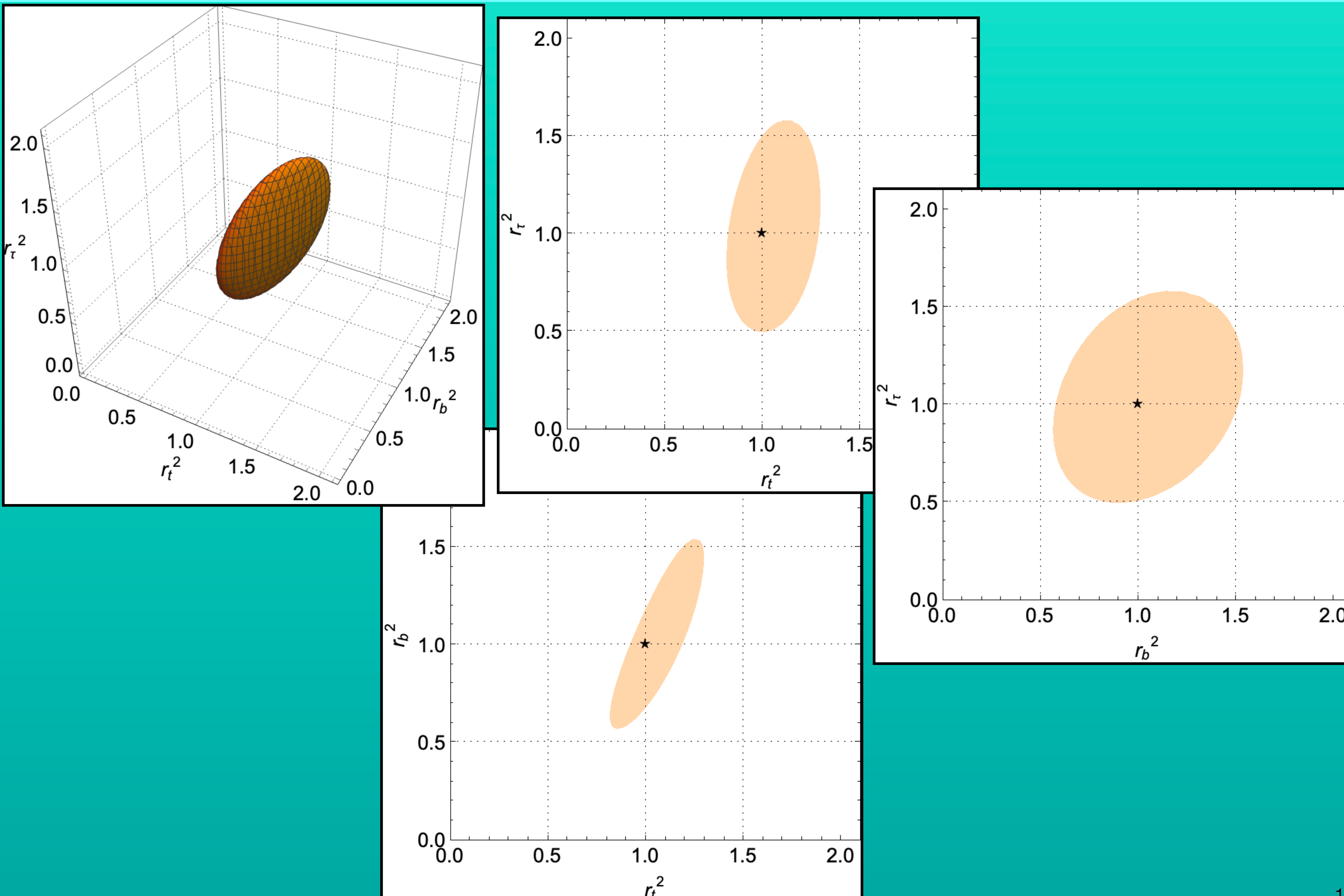


Assuming $\mathcal{G}_F$



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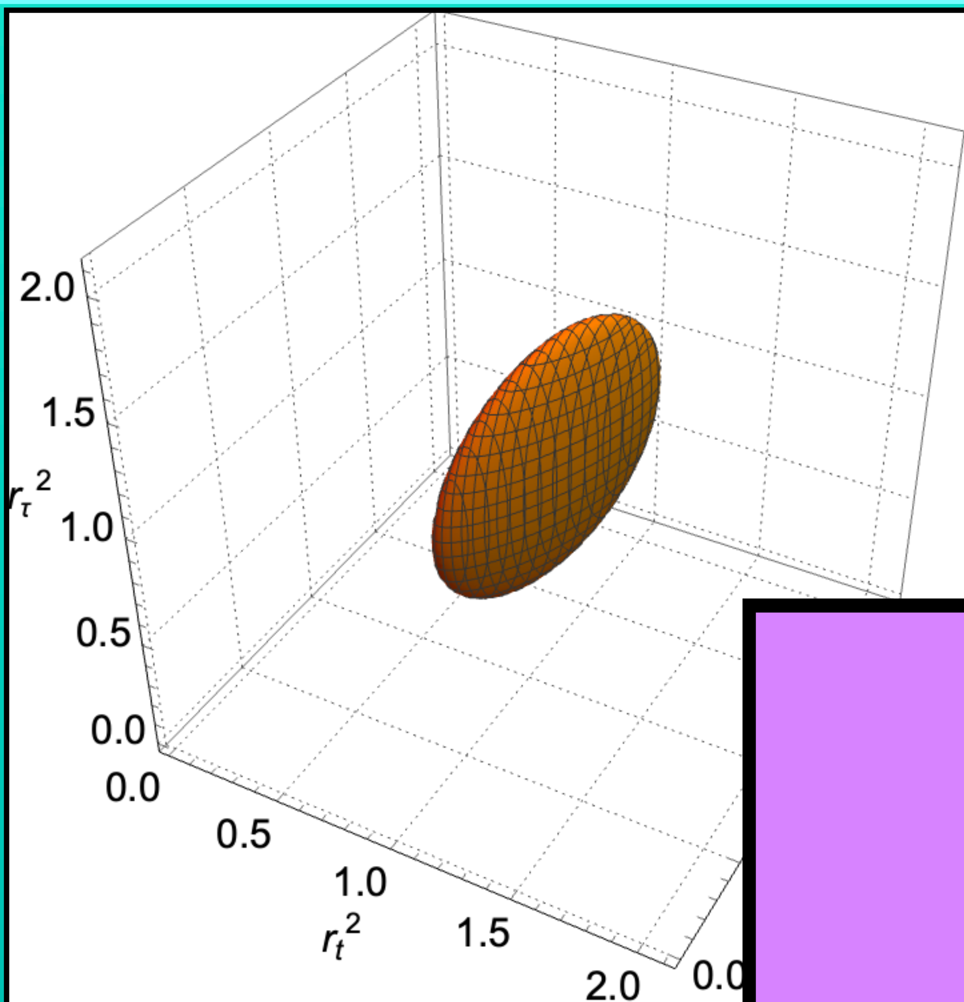

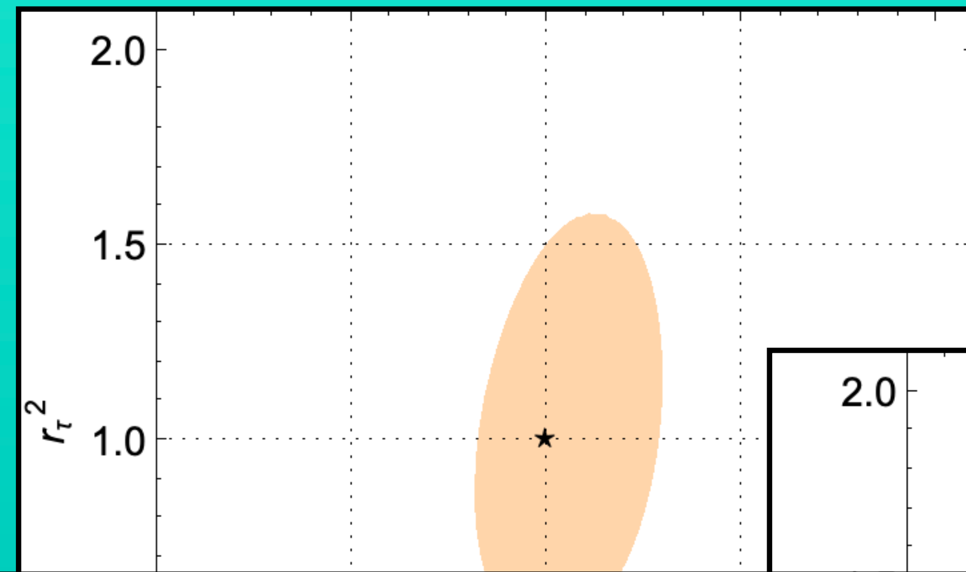

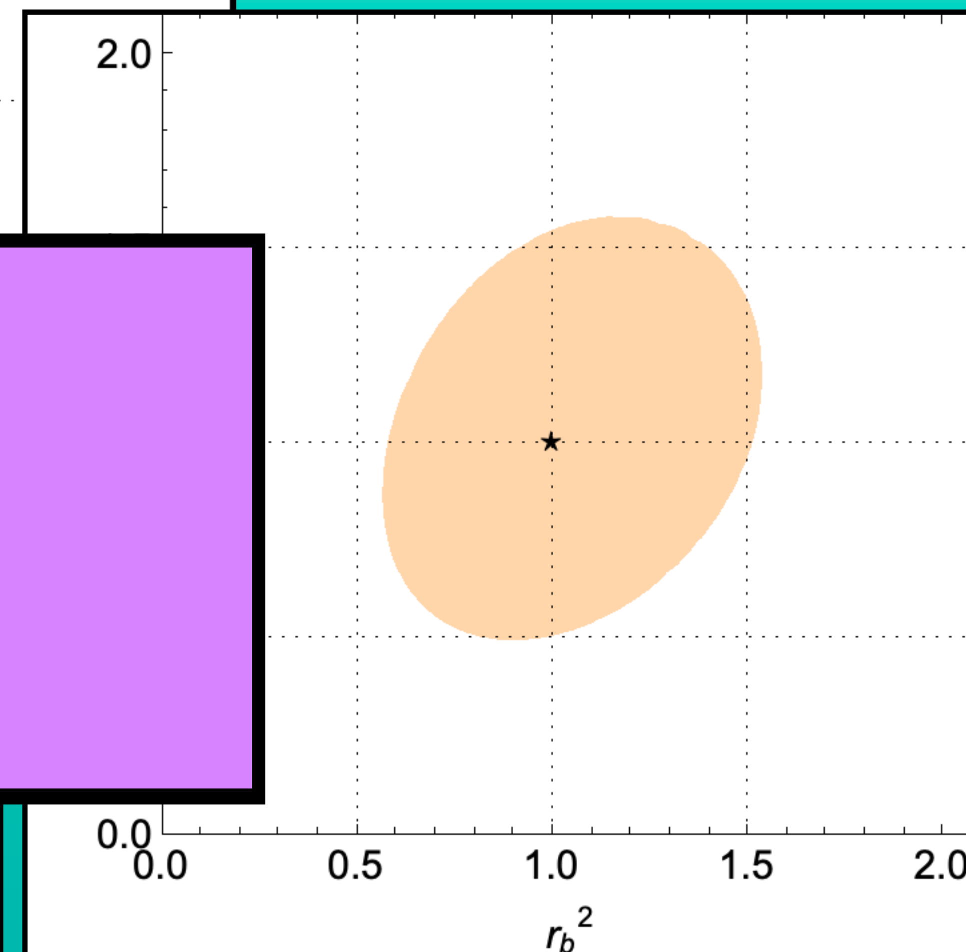

$$0.83 \lesssim r^2_{t,c,u} \lesssim 1.32$$

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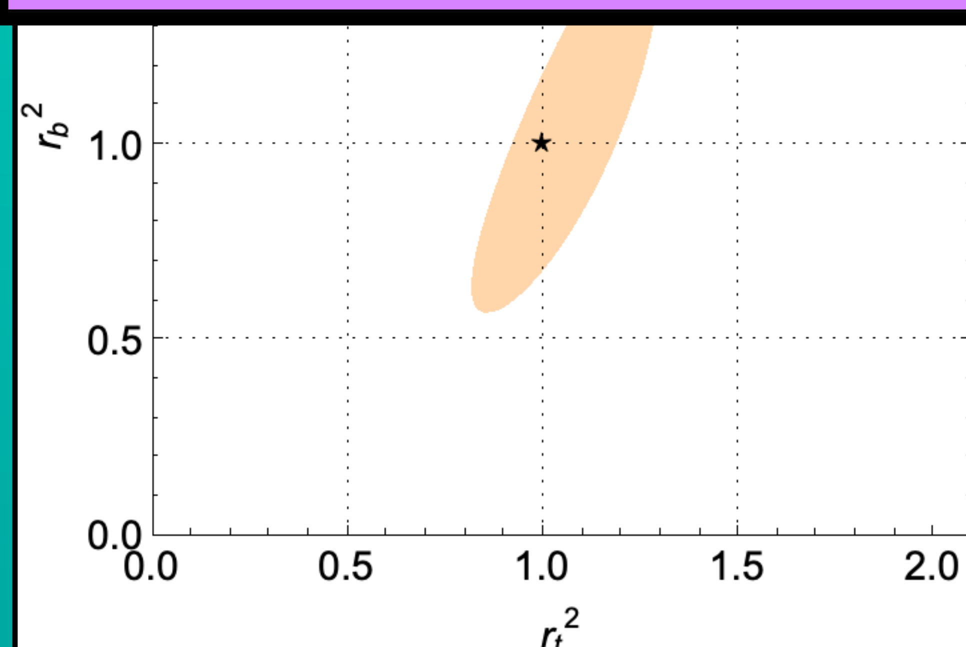
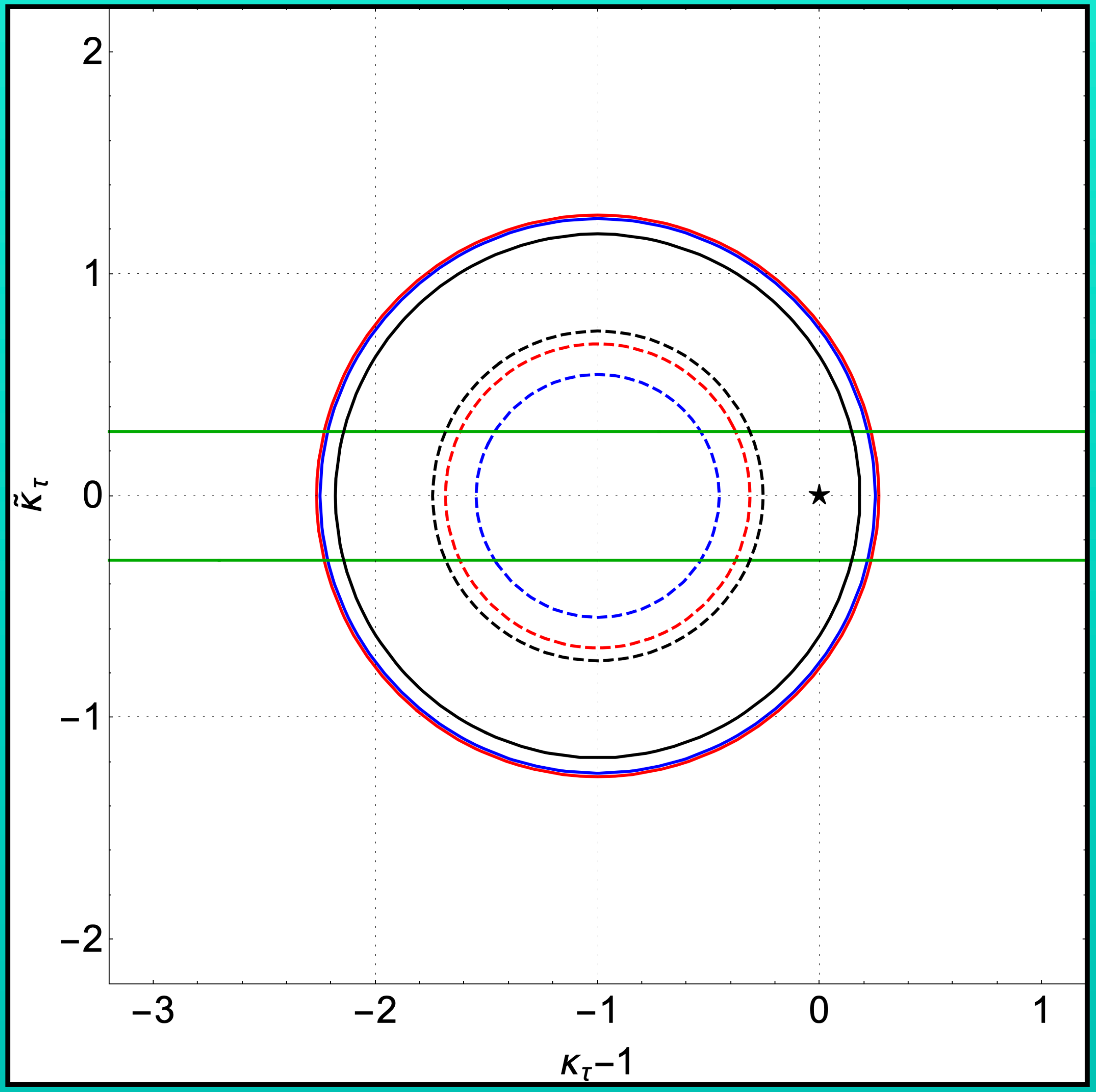
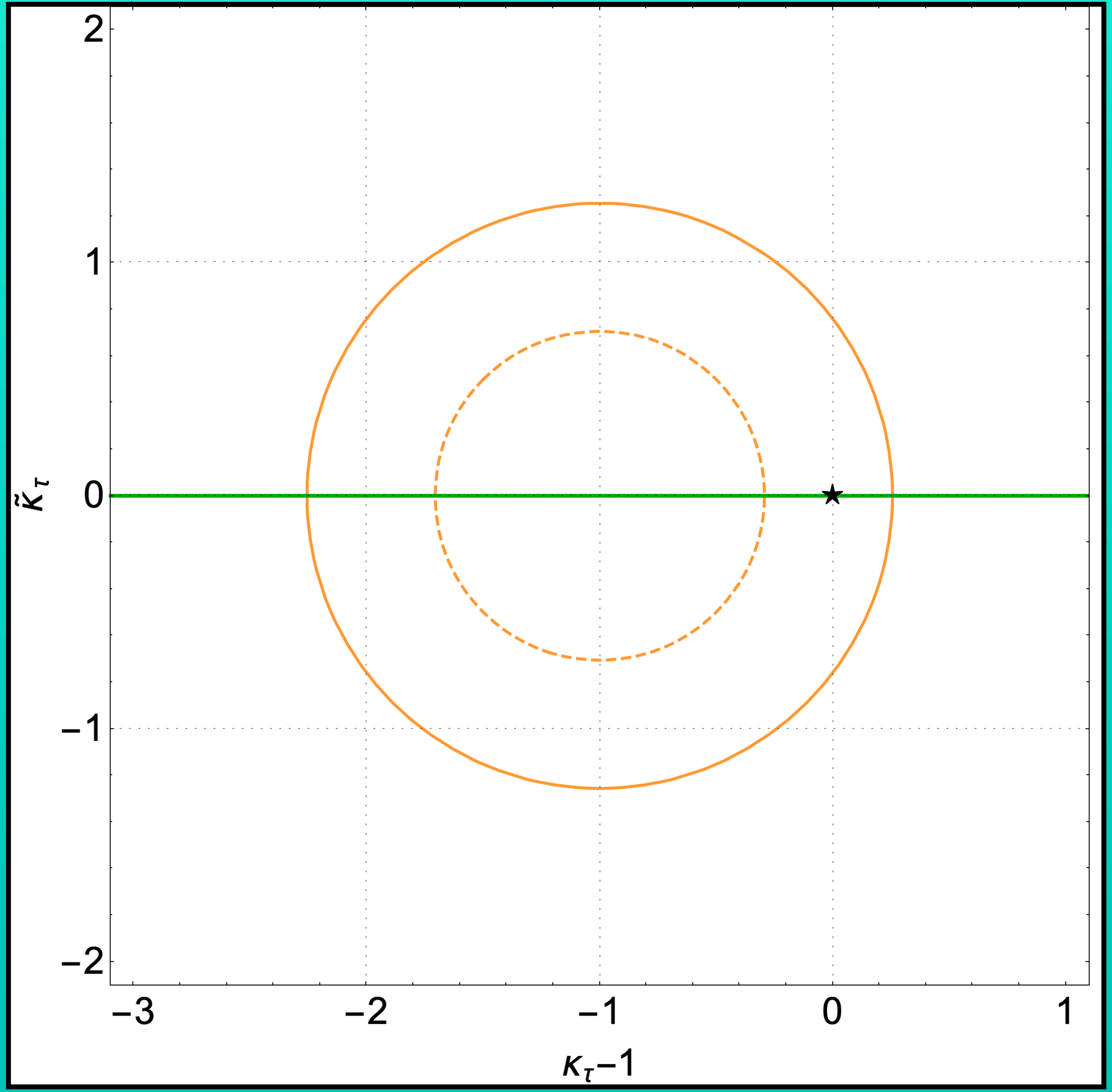
$$0.50 \lesssim r^2_{\tau,\mu,e} \lesssim 1.60$$







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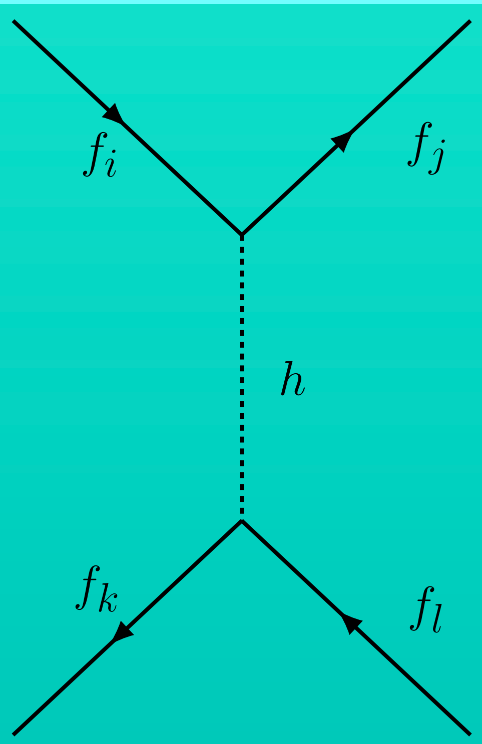
Bounds on Λ assuming $\mathcal{G}_F$

	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

Flavour Bounds on Λ

Tree-level Higgs-mediated



Many different bounds on any Yukawa entry

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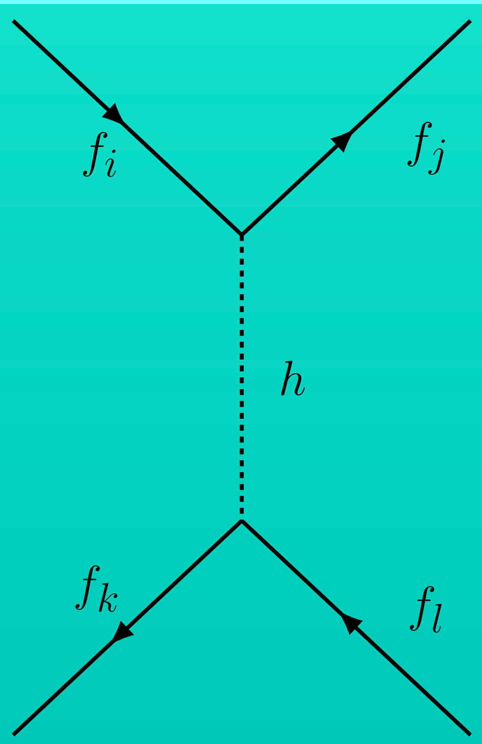

Many different bounds on any Yukawa entry

Meson oscillations → $\Lambda_q \gtrsim 1$ TeV CP conservation; $\Lambda_q \gtrsim 3$ TeV Maximal CPV

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

Flavour Bounds on Λ

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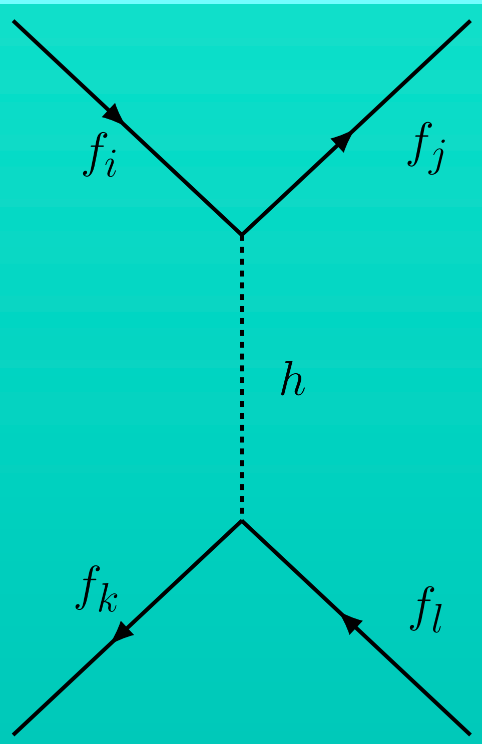

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Meson oscillations $\longrightarrow$
- $\Lambda_q \gtrsim 1$ TeV CP conservation
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Muon radiative decay $\longrightarrow$ $\Lambda_\ell \gtrsim 2-4$ TeV

Additional NP contributions may be present: cancellations?

Flavour Bounds on r_ψ^2

From Colliders:

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From Flavour:

$$\Lambda_q \gtrsim 1 \text{ TeV}$$

$$\Lambda_\ell \gtrsim 4 \text{ TeV}$$

$\rightarrow$

$$0.88 \lesssim r^2_q \lesssim 1.12$$

$$0.99 \lesssim r^2_\ell \lesssim 1.01$$

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→

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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}

Final Remarks

- Complementarity among experiments is fundamental!
- Flavour Syms imply stronger links
- Colliders bounds are still weaker wrt flavour ones, but very close in the CP conserving case

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!

Projects PID2019-108892RB-I00, CEX2020-001007-S, 860881-HIDDeN founded by

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UNIÓN EUROPEA

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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.

FN Models

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)	$(2,1,0)$	$(8,4,3)$

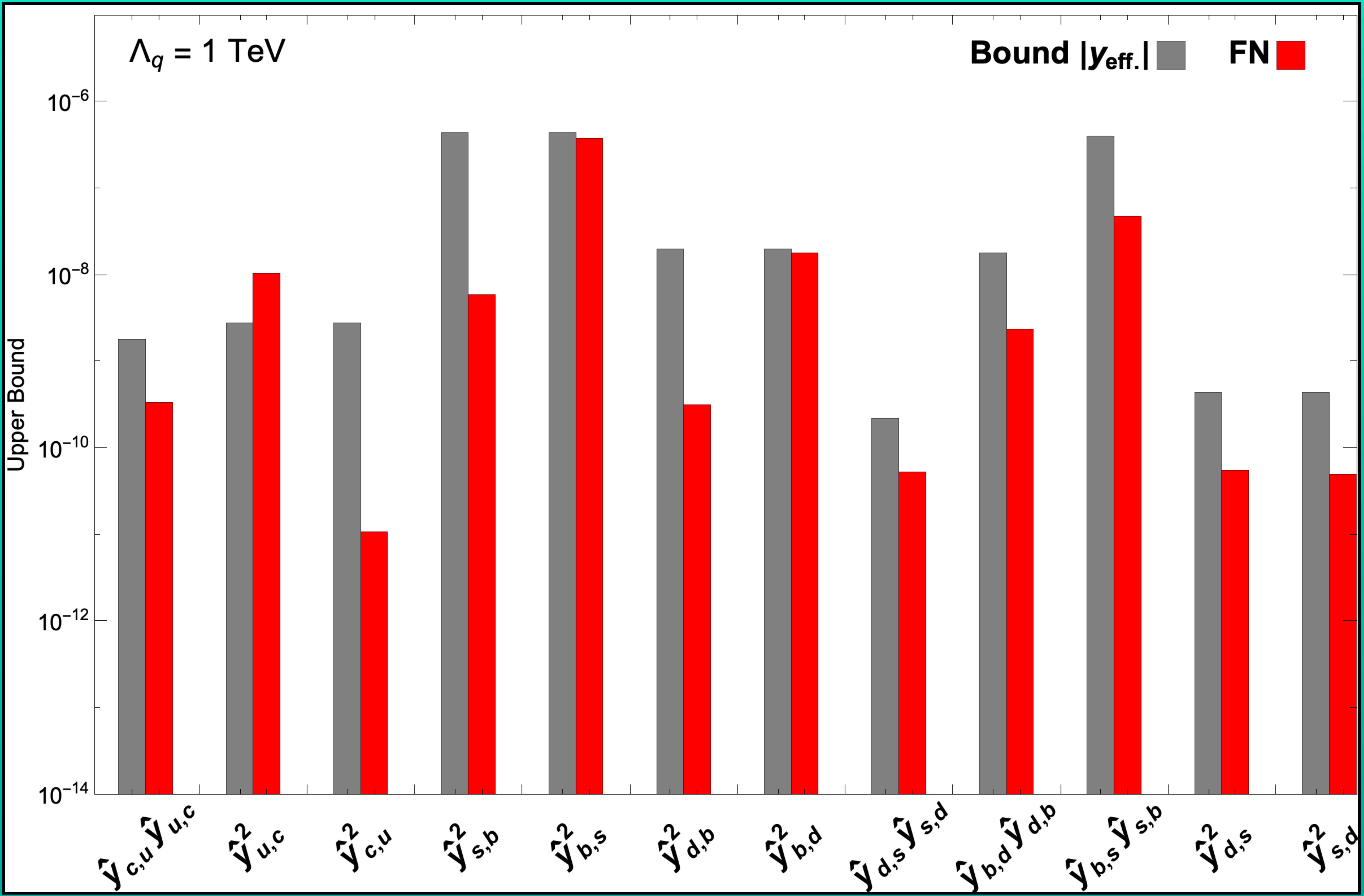
$$
\begin{aligned}
\mathscr{L}_{\rm FN} = & - y'_{u,ij}\,\overline{Q'_{L i}}\tilde{H} u'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{Q_i}+n_{u_j})} - y'_{d,ij}\,\overline{Q'_{L i}} H d'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{Q_i}+n_{d_j})} + \\
& - y'_{e,ij}\,\overline{L'_{L i}} H e'_{Rj}\left(\frac{\phi}{\Lambda_F}\right)^{(n_{L_i}+n_{e_j})}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

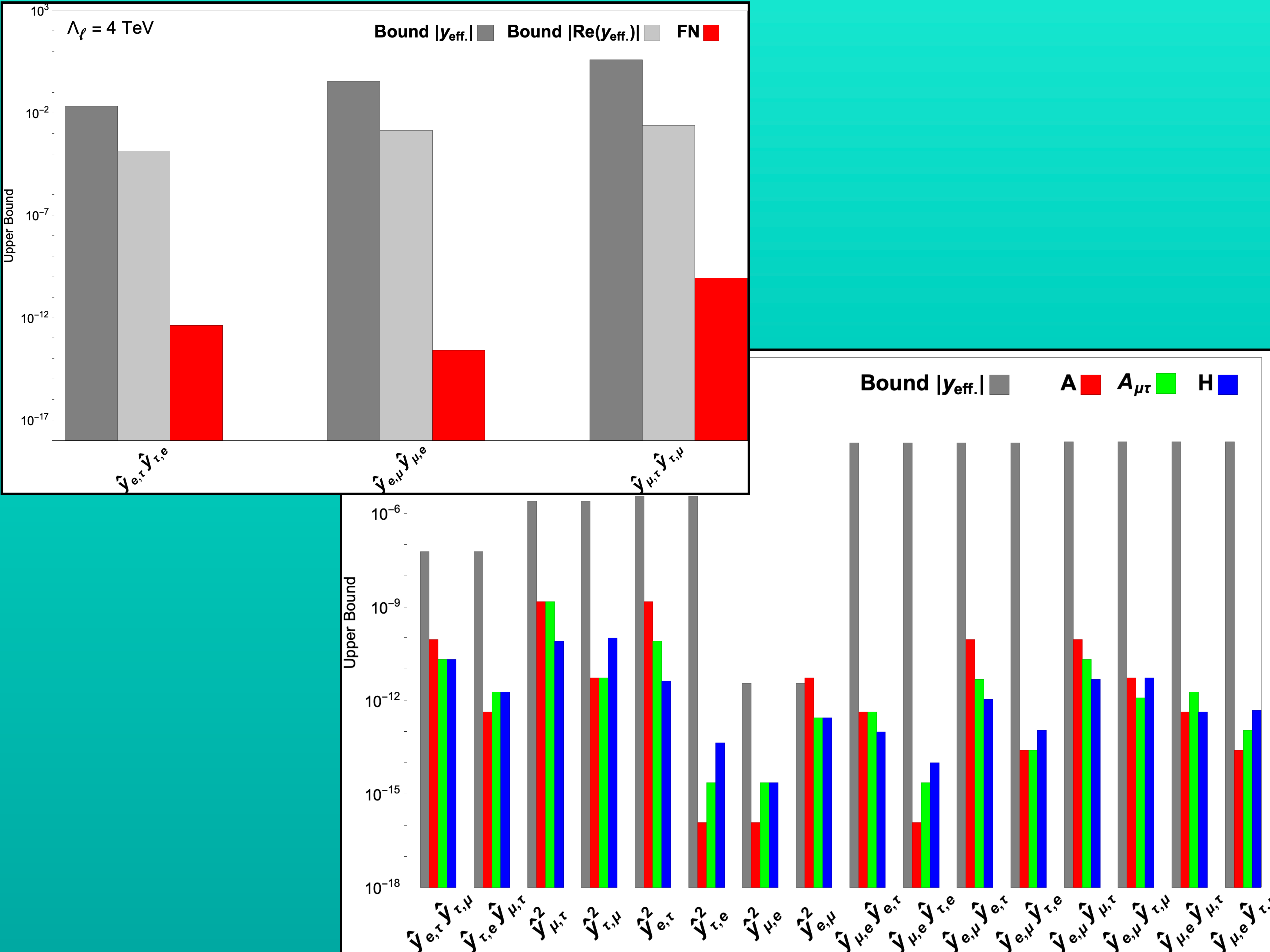
Flavour Bounds

Eff. Coupl.	Bound on $\lvert y_{\mathbf{eff.}}\rvert$	Λ_q [TeV]	Bound on $\lvert \mathtt{Im}(y_{\mathbf{eff.}})\rvert$	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}	$8. \times 10^{-3}$	=	=
$\lvert\mathtt{Re}(\hat{y}_{e\tau}\hat{y}_{\tau e})\rvert$	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}

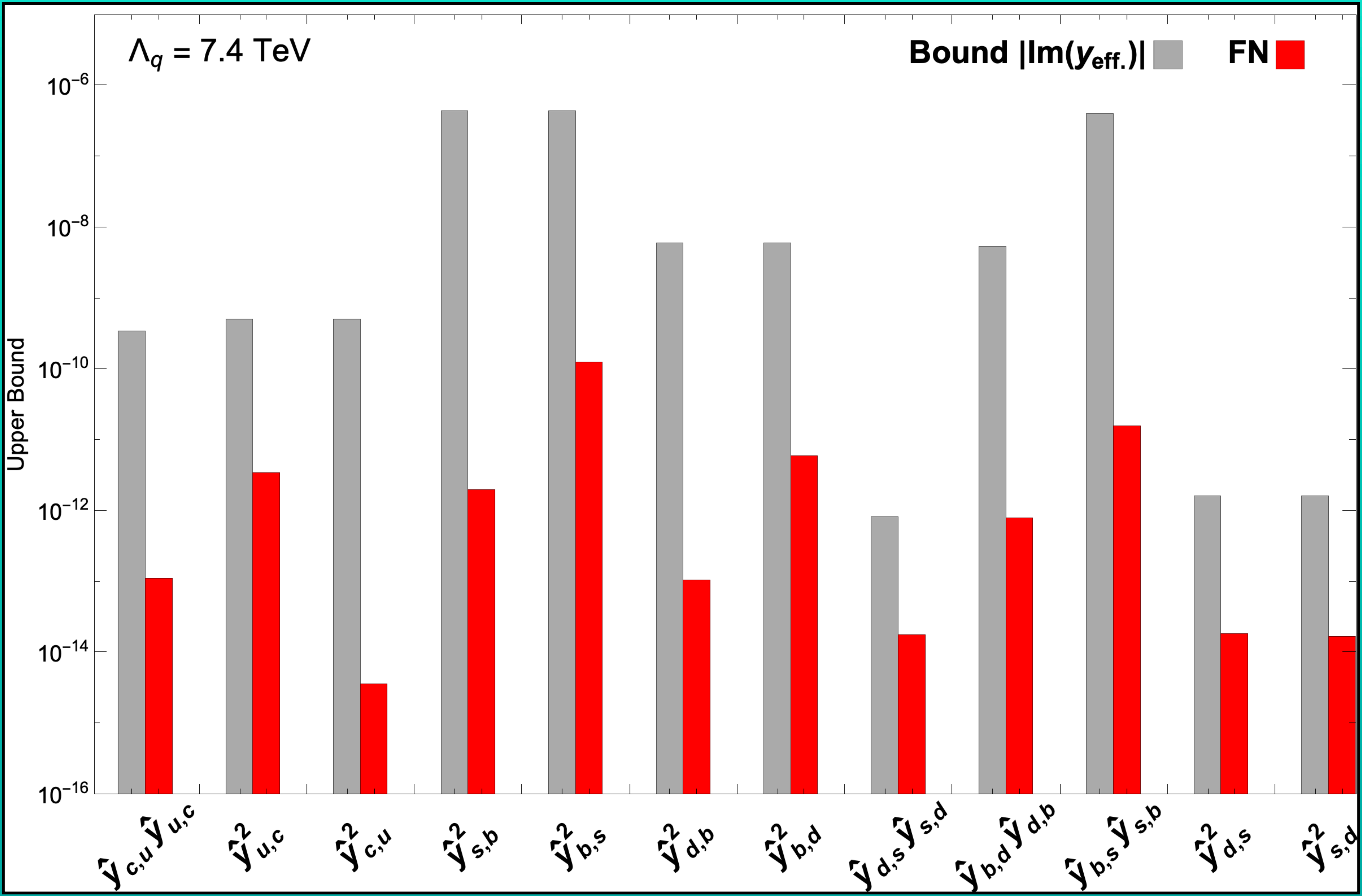
CV Conservation



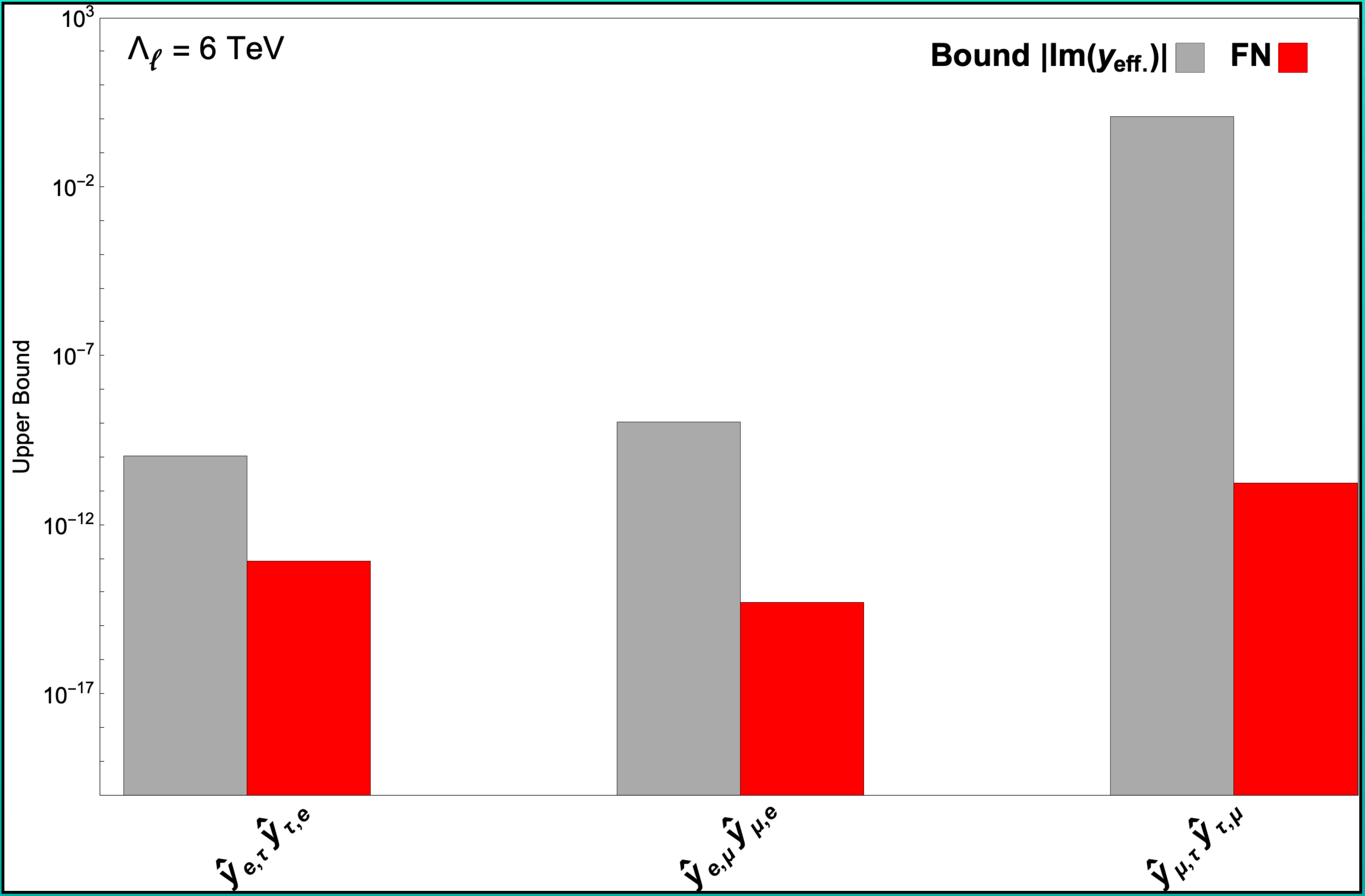


Λ_ℓ = 4 TeV
Bound $|y_{\mathrm{eff.}}|$
Bound $|\mathrm{Re}(y_{\mathrm{eff.}})|$
FN
Upper Bound
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{-17}
$\hat{y}_{e,\tau}\hat{y}_{\tau,e}$
$\hat{y}_{e,\mu}\hat{y}_{\mu,e}$
$\hat{y}_{\mu,\tau}\hat{y}_{\tau,\mu}$
Bound $|y_{\mathrm{eff.}}|$
A
$A_{\mu\tau}$
H
Upper Bound
10^{-6}
10^{-9}
10^{-12}
10^{-15}
10^{-18}
$\hat{y}_{e,\tau}\hat{y}_{\tau,\mu}$
$\hat{y}_{\tau,e}\hat{y}_{\mu,\tau}$
$\hat{y}^2_{\mu,\tau}$
$\hat{y}^2_{\tau,\mu}$
$\hat{y}^2_{e,\tau}$
$\hat{y}^2_{\tau,e}$
$\hat{y}^2_{\mu,e}$
$\hat{y}^2_{e,\mu}$
$\hat{y}_{\mu,e}\hat{y}_{e,\tau}$
$\hat{y}_{\mu,e}\hat{y}_{\tau,e}$
$\hat{y}_{e,\mu}\hat{y}_{e,\tau}$
$\hat{y}_{e,\mu}\hat{y}_{\tau,e}$
$\hat{y}_{e,\mu}\hat{y}_{\mu,\tau}$
$\hat{y}_{e,\mu}\hat{y}_{\tau,\mu}$
$\hat{y}_{\mu,e}\hat{y}_{\mu,\tau}$
$\hat{y}_{\mu,e}\hat{y}_{\tau,\mu}$

Maximal CPV



Λ_q = 7.4 TeV
Bound $|\mathrm{Im}(y_{\mathrm{eff.}})|$
FN
Upper Bound
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
$\hat{y}_{c,u}\hat{y}_{u,c}$
$\hat{y}^2_{u,c}$
$\hat{y}^2_{c,u}$
$\hat{y}^2_{s,b}$
$\hat{y}^2_{b,s}$
$\hat{y}^2_{d,b}$
$\hat{y}^2_{b,d}$
$\hat{y}_{d,s}\hat{y}_{s,d}$
$\hat{y}_{b,d}\hat{y}_{d,b}$
$\hat{y}_{b,s}\hat{y}_{s,b}$
$\hat{y}^2_{d,s}$
$\hat{y}^2_{s,d}$



Λ_ℓ = 6 TeV
Bound $|\mathrm{Im}(y_{\mathrm{eff.}})|$
FN
Upper Bound
10^{3}
10^{-2}
10^{-7}
10^{-12}
10^{-17}
$\hat{y}_{e,\tau}\hat{y}_{\tau,e}$
$\hat{y}_{e,\mu}\hat{y}_{\mu,e}$
$\hat{y}_{\mu,\tau}\hat{y}_{\tau,\mu}$