Complex τ Electric Dipole Moment From GeV-Scale New Physics

Zhong-Lv Huang

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collaborated with

X.Y. Du, X.G. He, C.W. Liu, Z.Y. Zou

2026.4.12

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Motivation

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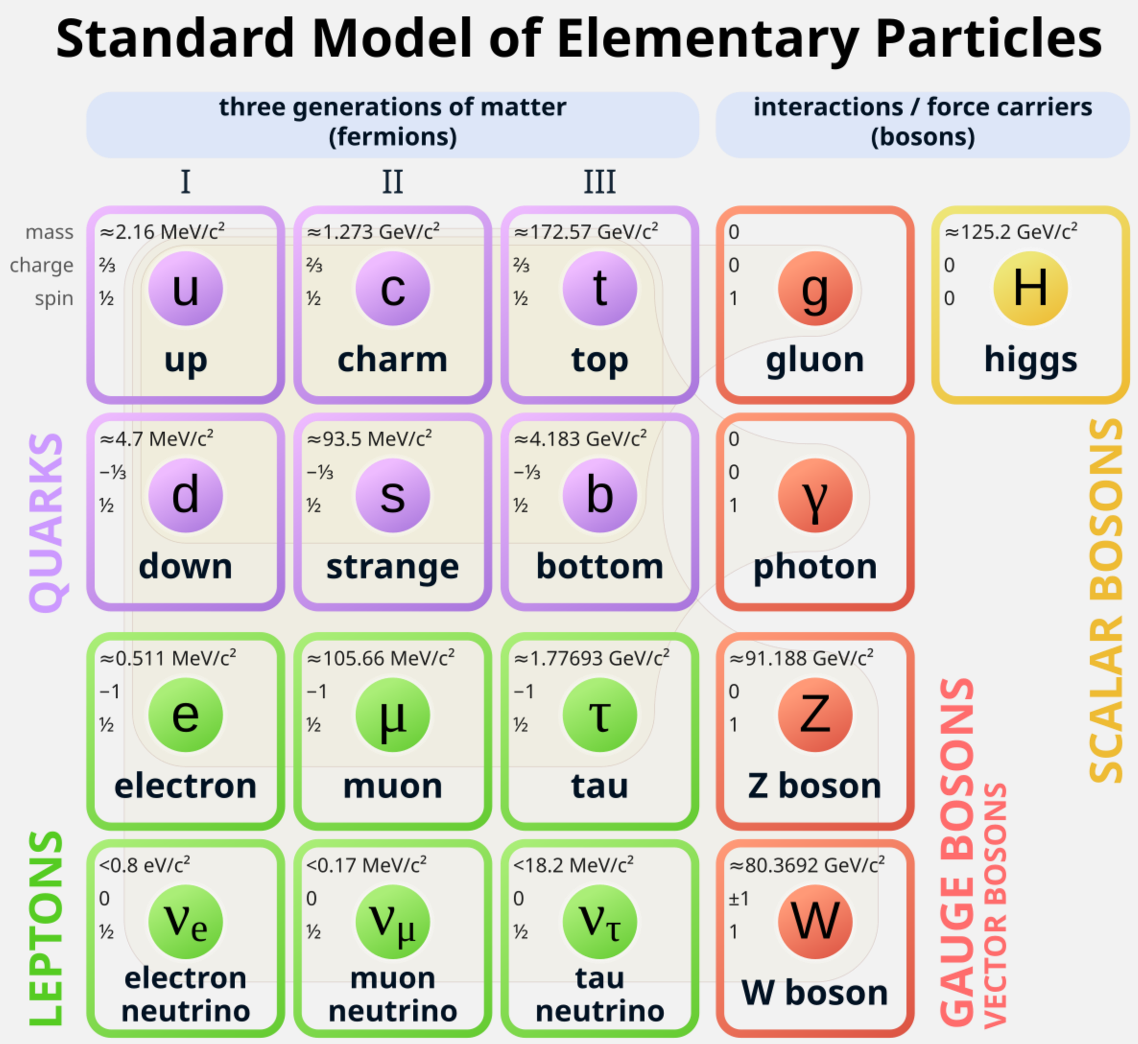

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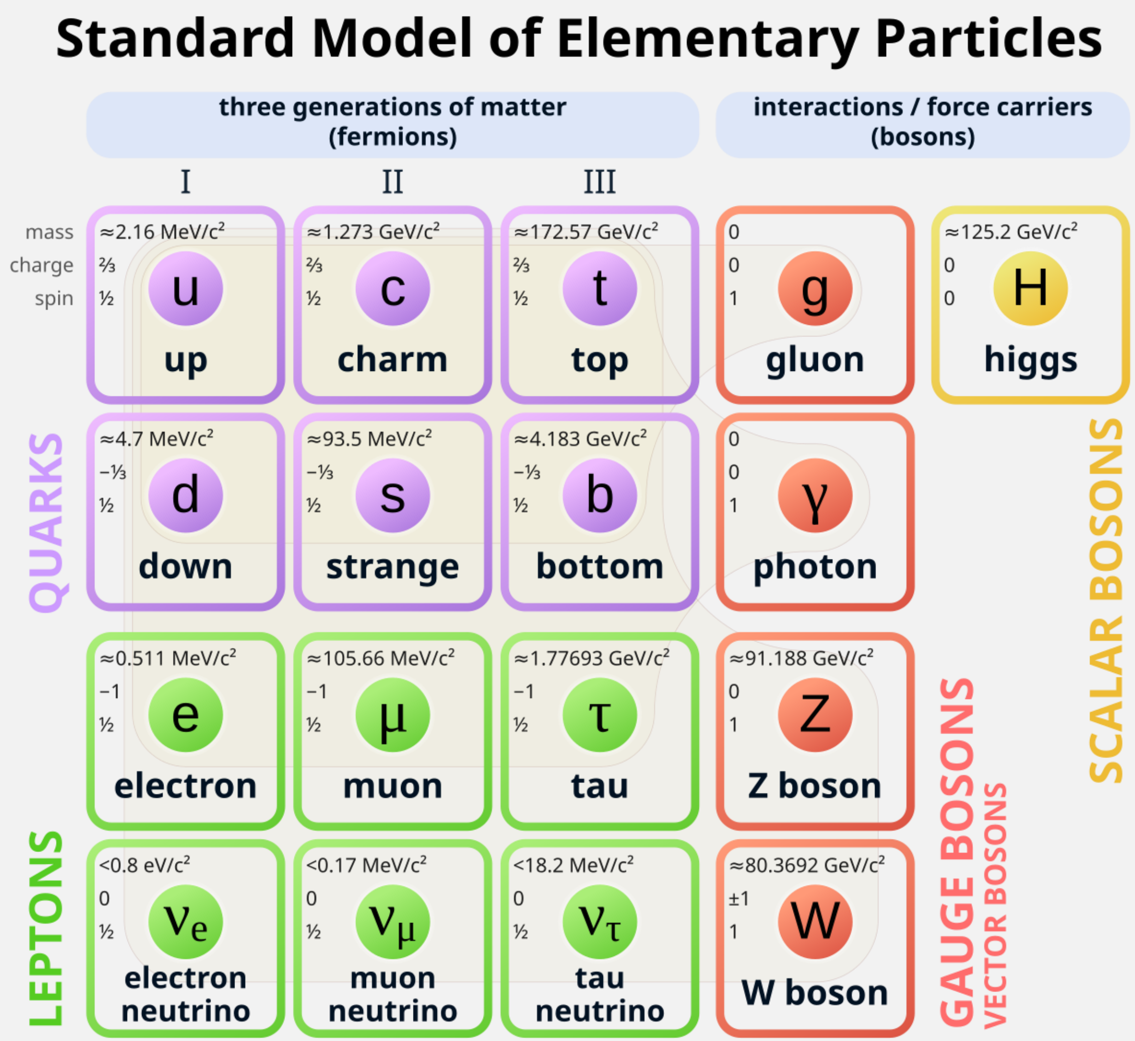
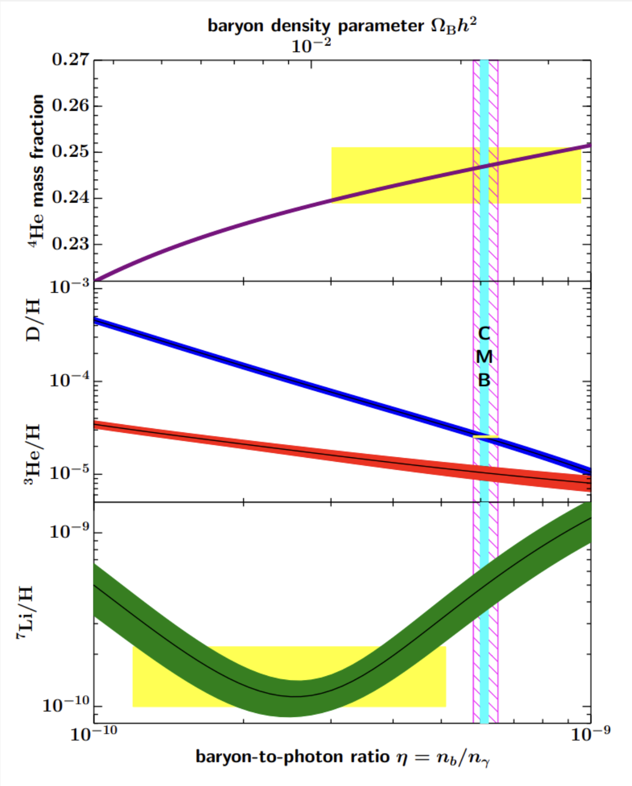
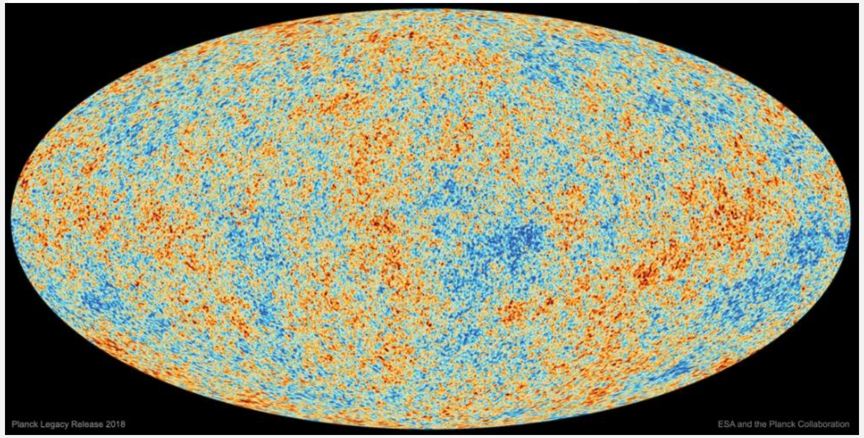




Matter-antimatter asymmetry

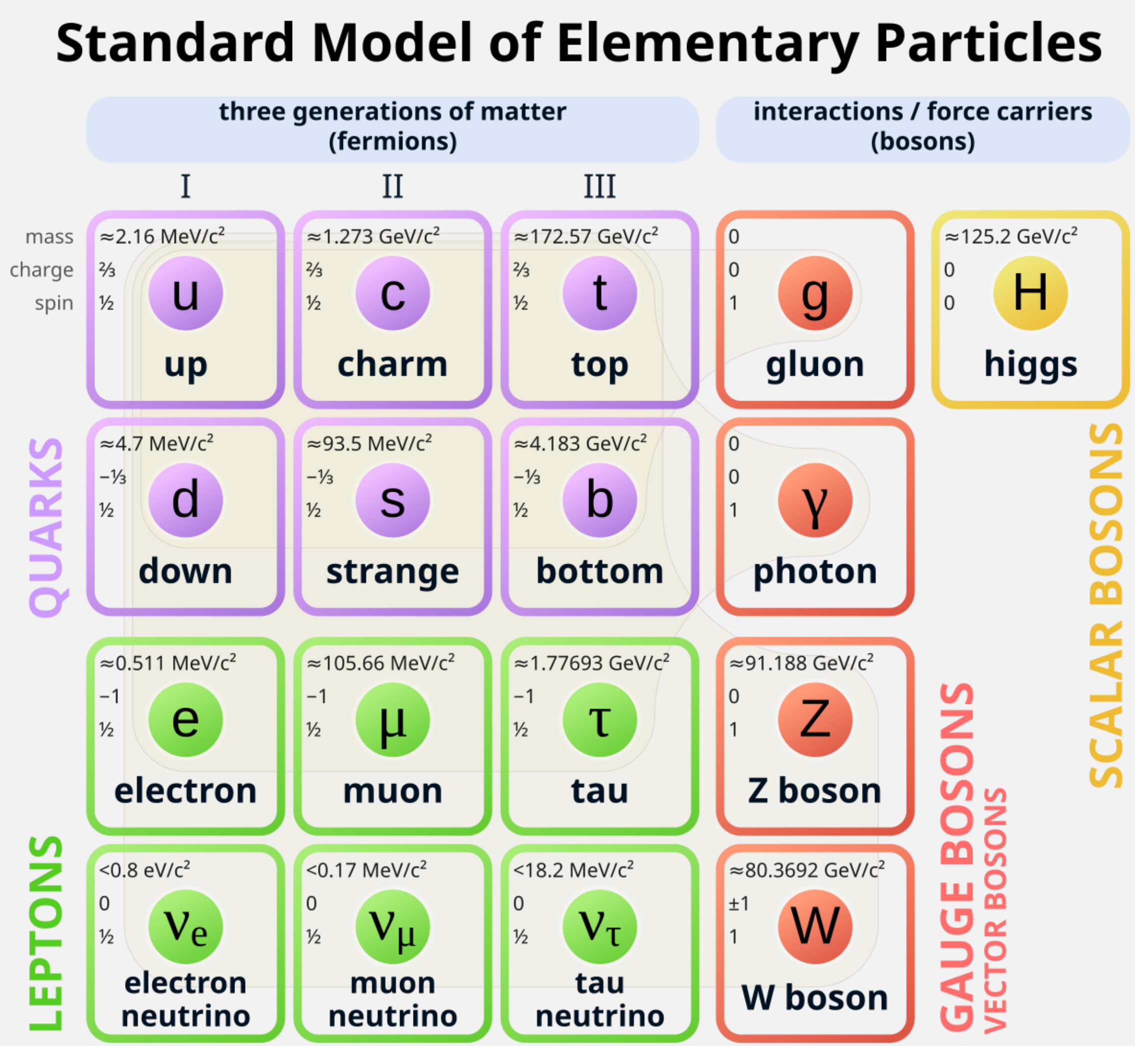
$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \sim 10^{-10}$$

Particle Data Group（2025）

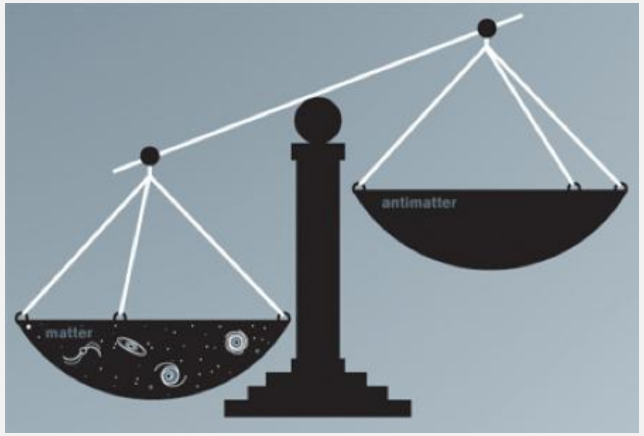


Planck 2018

Motivation



Andrei Sakharov



Sakharov(1967)

Sakharov conditions:

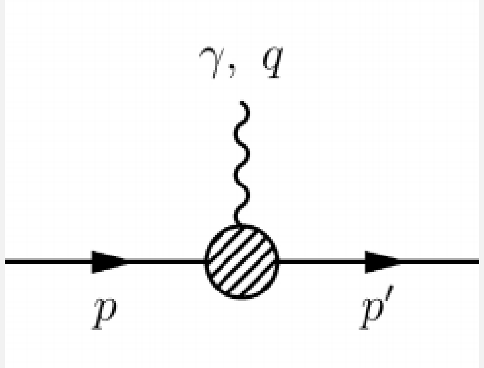
1. Baryon number violating process.
2. Violation of C and CP symmetries.
3. Out of thermal equilibrium.

The CP violation in SM is much smaller than needed.

- There must exist a new source of CP violation.

EDM

$$\langle p' \mid j^{\mu}_{\text{em}} \mid p \rangle = e\bar{u}(p')\left[\gamma^{\mu}F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2) + \frac{\sigma^{\mu\nu}q_\nu\gamma_5}{2m}F_3(q^2) + \left(\gamma^{\mu} - \frac{2mq^{\mu}}{q^2}\right)\gamma_5 F_4(q^2)\right]u(p)$$



$Q = F_1(0)$

$a = \frac{1}{2m}[F_2(0)]$

$d = \frac{e}{2m}F_3(0)$

anapole moment: $F_4(0)$

Electric Dipole Moment (EDM)

P or T transformation

$$\mathcal{L}_{EDM} = -\frac{i}{2}d\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi F_{\mu\nu}$$

$$\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi F_{\mu\nu}$$

$$\rightarrow -\bar{\psi}\sigma^{\mu\nu}\gamma^5\psi F_{\mu\nu}$$

CP violated!

Lepton EDM

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Lepton EDM in SM

$$d_e^{(\mathrm{SM})} = 5.8\times10^{-40}\,e\mathrm{cm},$$
$$d_\mu^{(\mathrm{SM})} = 1.4\times10^{-38}\,e\mathrm{cm},$$
$$d_\tau^{(\mathrm{SM})} = -7.3\times10^{-38}\,e\mathrm{cm}.$$

Phys. Rev. Lett. 125, 241802 (2020)

Table 1: Most stringent limits on electric dipole moments.

EDM	Limit (e cm)		Source
Electron	1.1×10^{-29}	(90% C.L.)	ThO [31]
	4.1×10^{-30}	(90% C.L.)	HfF$^+$ [32]
Muon	1.8×10^{-19}	(95% C.L.)	[33]

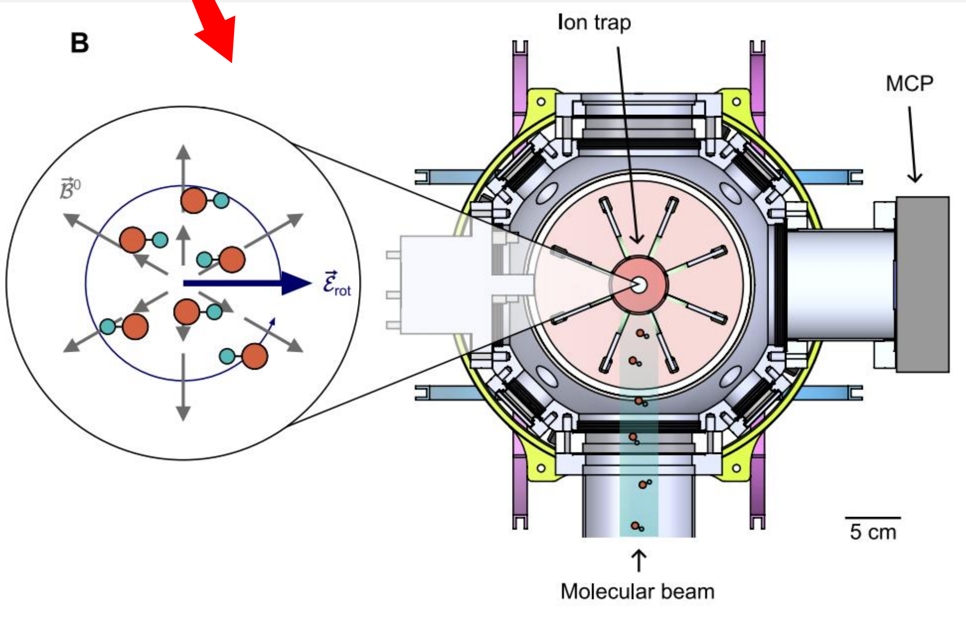
τ

$J = \frac{1}{2}$

Mass $m = 1776.93 \pm 0.09$ MeV

$(m_{\tau^+} - m_{\tau^-})/m_{\mathrm{average}} < 2.8\times10^{-4}$, CL = 90%

Mean life $\tau = (290.3 \pm 0.5)\times10^{-15}$ s

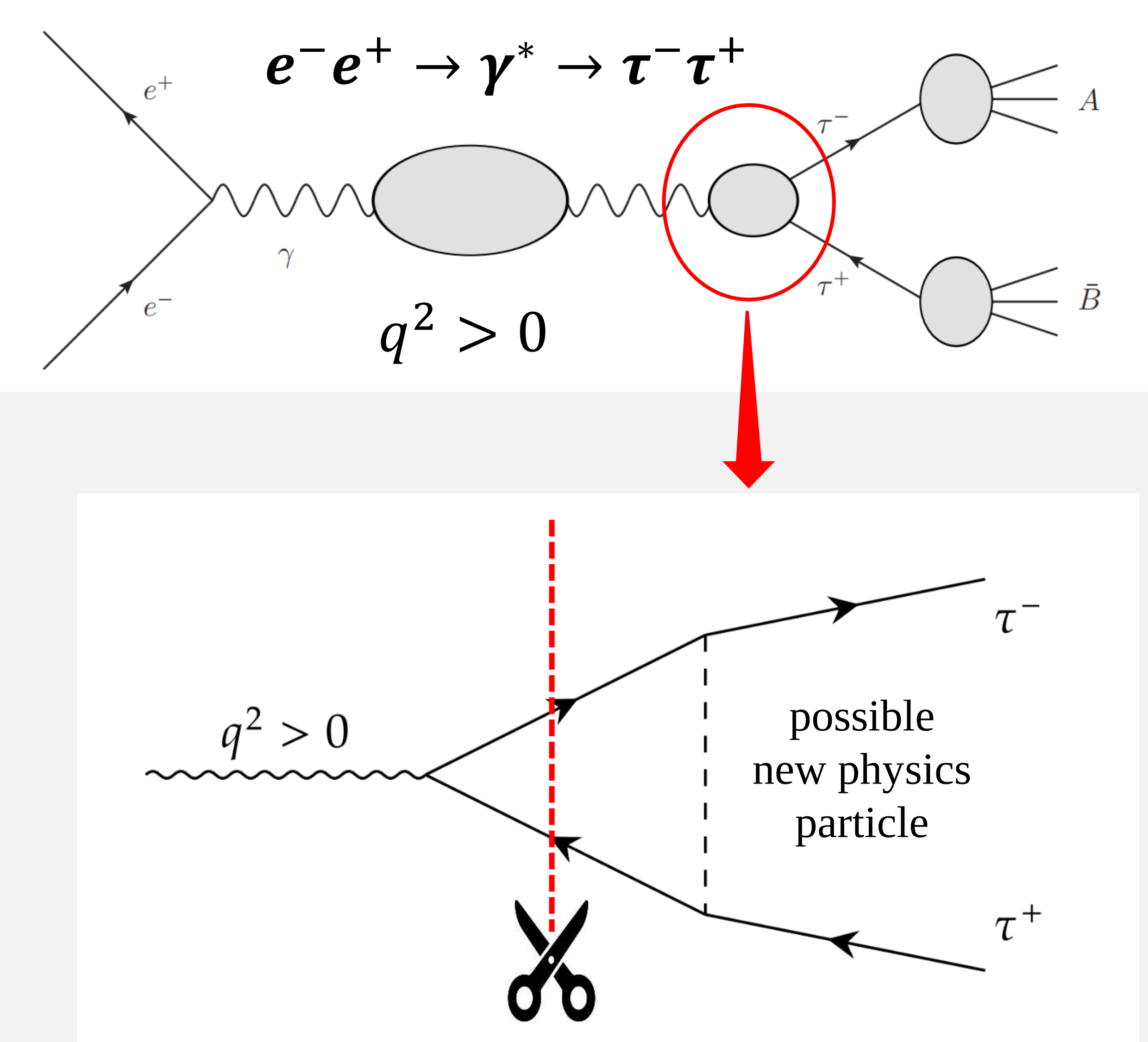


Science 381 (2023) 6653

The τ lepton has a very short lifetime!

How can its EDM be detected?

τ EDM



Intermediate particles are on shell

→EDM develops an imaginary part!

$$\mathrm{Re}(d_\tau) = (-6.2 \pm 6.3) \times 10^{-18}\, e\mathrm{cm},$$

$$\mathrm{Im}(d_\tau) = (-4.0 \pm 3.2) \times 10^{-18}\, e\mathrm{cm},$$

$$\text{at } s = \sqrt{q^2} = 10.58\ \mathrm{GeV}.$$

Belle Collaboration (Aug 25, 2021)

The least constrained lepton EDM!

Future Experiment Limits

Improvement in experimental sensitivity

超级陶粲装置
Super Tau-Charm Facility

$\sqrt{s}$	$m_{\psi(2S)}$	4.2 GeV	4.9 GeV	5.6 GeV	6.3 GeV	7 GeV
$\delta_{\rm Im}$	1.8	0.9	0.7	0.7	0.7	0.7
$\delta_{\rm Re}(0)$	7.7	4.0	3.0	2.8	2.8	2.8

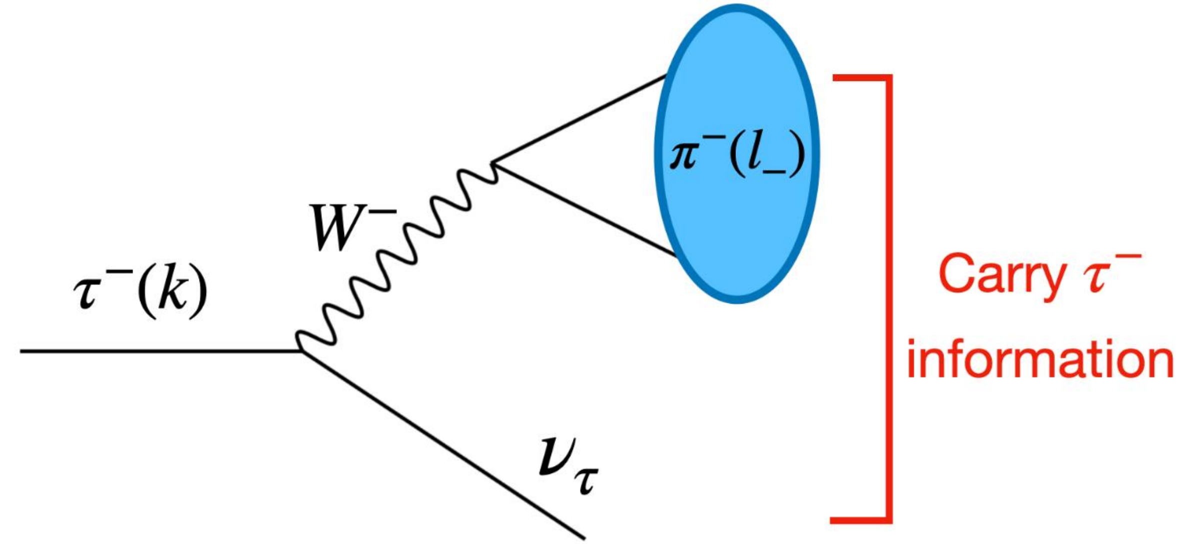
Given in units of $10^{-18}\, e$cm

Xiao-Gang He et al.(2025)

$$\mathrm{Im}(d_\tau) = \frac{-e\left(3s+6m_\tau^2\right)}{4m_\tau\sqrt{s}\sqrt{s-4m_\tau^2}}\left(\frac{\langle \hat{\boldsymbol{l}}_- \cdot \boldsymbol{k}\rangle}{\alpha_h} + \frac{\langle \hat{\boldsymbol{l}}_+ \cdot \boldsymbol{k}\rangle}{\bar{\alpha}_{h'}}\right),$$

$$\mathrm{Re}(d_\tau)^a = e\frac{9}{4}\frac{s+2m_\tau^2}{\alpha_h\bar{\alpha}_{h'}m_\tau\sqrt{s^2-4sm_\tau^2}}\langle(\hat{\boldsymbol{l}}_- \times \hat{\boldsymbol{l}}_+)\cdot\boldsymbol{k}\rangle,$$

$$\mathrm{Re}(d_\tau)^b = e\frac{45}{2}\frac{(s+2m_\tau^2)\langle(\boldsymbol{p}\cdot\boldsymbol{k})(\hat{\boldsymbol{l}}_- \times \hat{\boldsymbol{l}}_+)\cdot\boldsymbol{p}\rangle}{\alpha_h\bar{\alpha}_{h'}\sqrt{s}(\sqrt{s}-2m_\tau)\sqrt{s-4m_\tau^2}}.$$



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Xiao-Gang He et al.(2025)

Belle II

	$\delta\text{Red}_\tau^{\text{V}}$ $[ecm]$		$\delta\text{Imd}_\tau^{\text{V}}$ $[ecm]$	
	$E_{ab}[T_{33}]$	$E_{ab}[\mathcal{O}_{Red_\tau}]$	$E_{ab}[\hat{O}_{33}]$	$E_{ab}[\mathcal{O}_{Imd_\tau}]$
$\sqrt{s}$=10.58 GeV ($N_{\tau^+\tau^-}=5.5\times10^{10}$)	2.93×10^{-19}	9.42×10^{-20}	5.08×10^{-20}	2.43×10^{-20}

Peng-Cheng Lu, Zong-Guo Si, Han Zhang (2025)

A non-zero EDM would be a clear signal of new CP source.

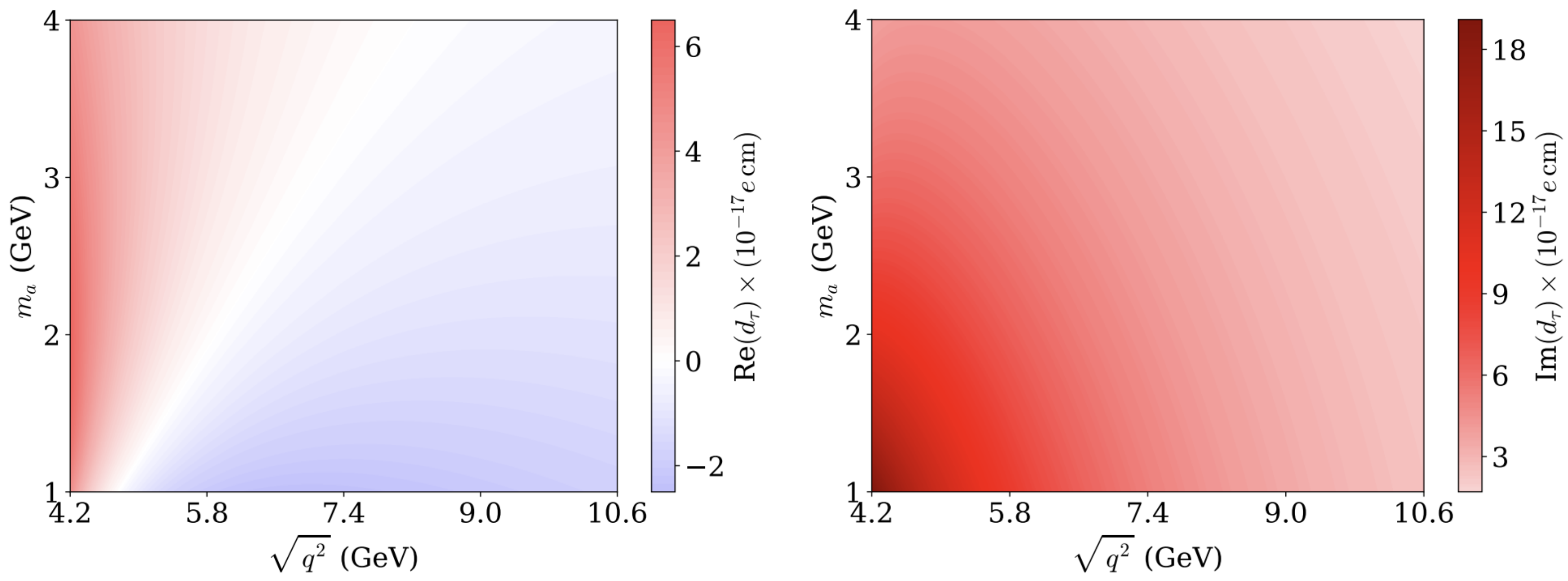
Axion-Like Particle (ALP)

Let us start with a CP-violated axion-like particle (ALP)

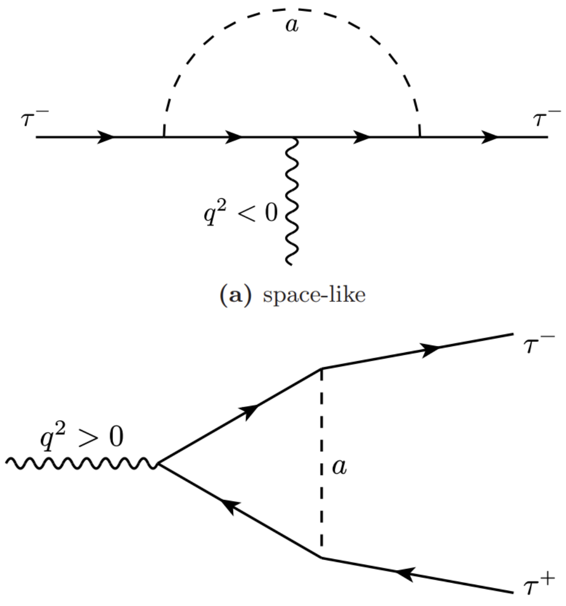
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2} m_a^2 a^2 + a\bar{\tau}\left(a_a + i b_a \gamma_5\right)\tau,$$

arXiv:2312.17310, Phys.Rev.D 94 (2016) 11, 115033

$$d_\tau(q^2) = \frac{e}{4\pi^2 m_\tau (q^2 - 4m_\tau^2)} a_a b_a \Big[m_\tau^2 B(m_\tau^2, m_\tau, m_a) - m_\tau^2 (B(q^2, m_\tau, m_\tau))$$
$$+ m_a^2 \left(\log(m_\tau / m_a) - m_\tau^2 C_0(m_\tau^2, m_\tau^2, q^2, m_\tau, m_a, m_\tau) \right) \Big].$$

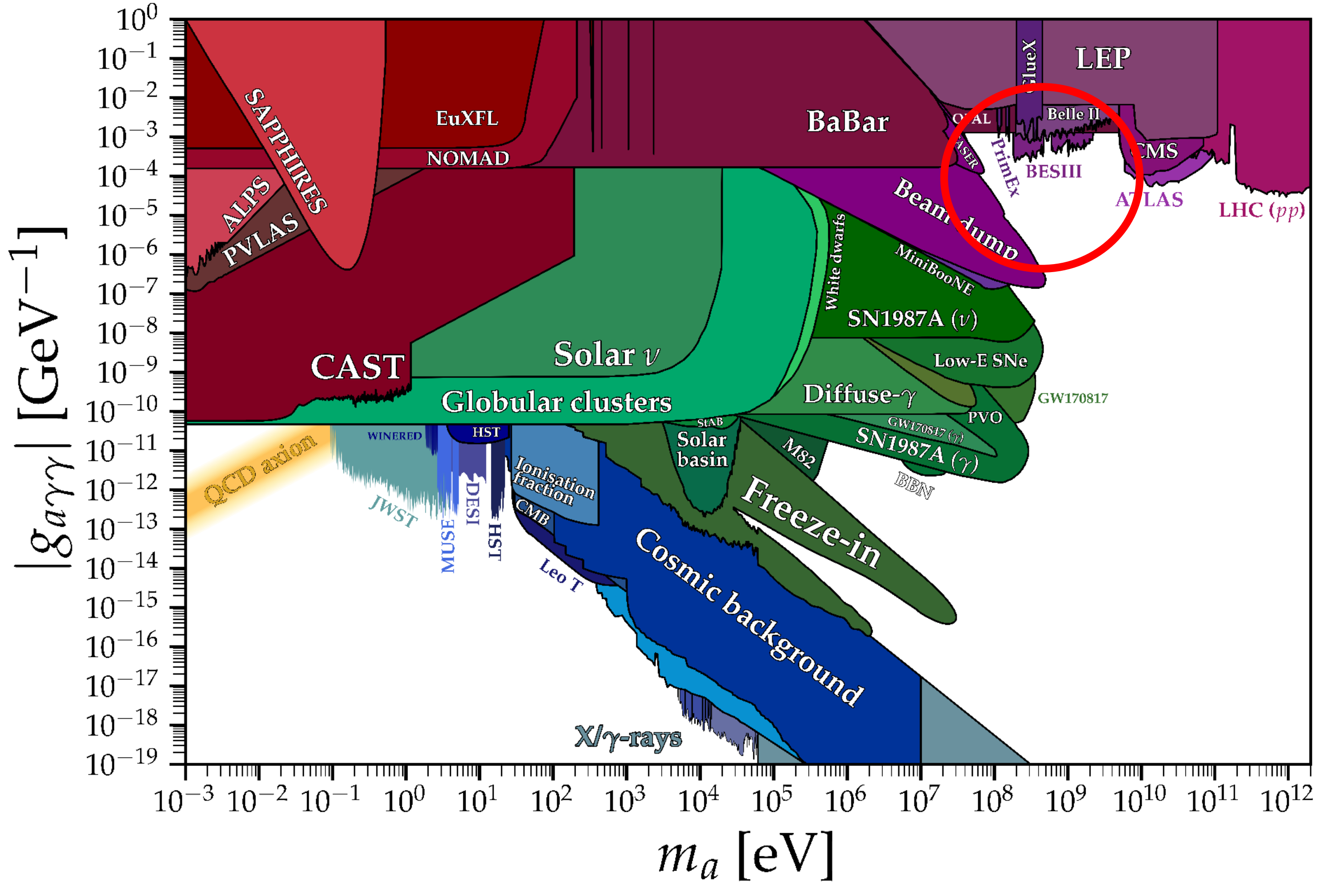


(a) $\mathrm{Re}[d_\tau]/(a_a b_a)$ **(b)** $\mathrm{Im}[d_\tau]/(a_a b_a)$

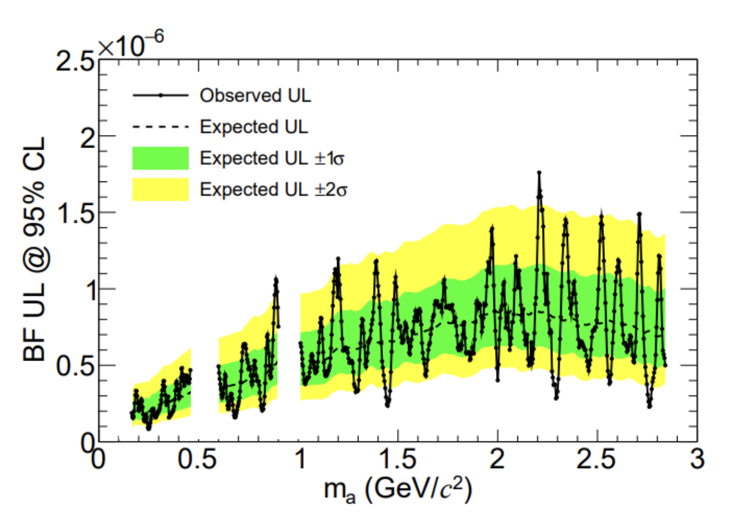


(a) space-like **(b)** time-like

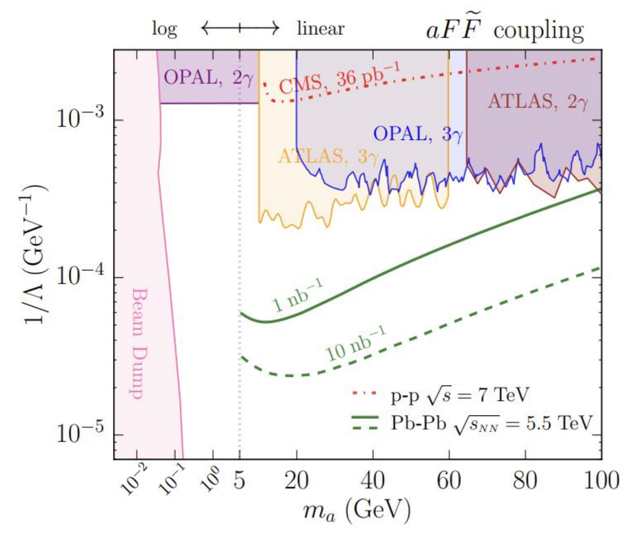
Axion-Like Particle (ALP)



https://github.com/cajohare/AxionLimits

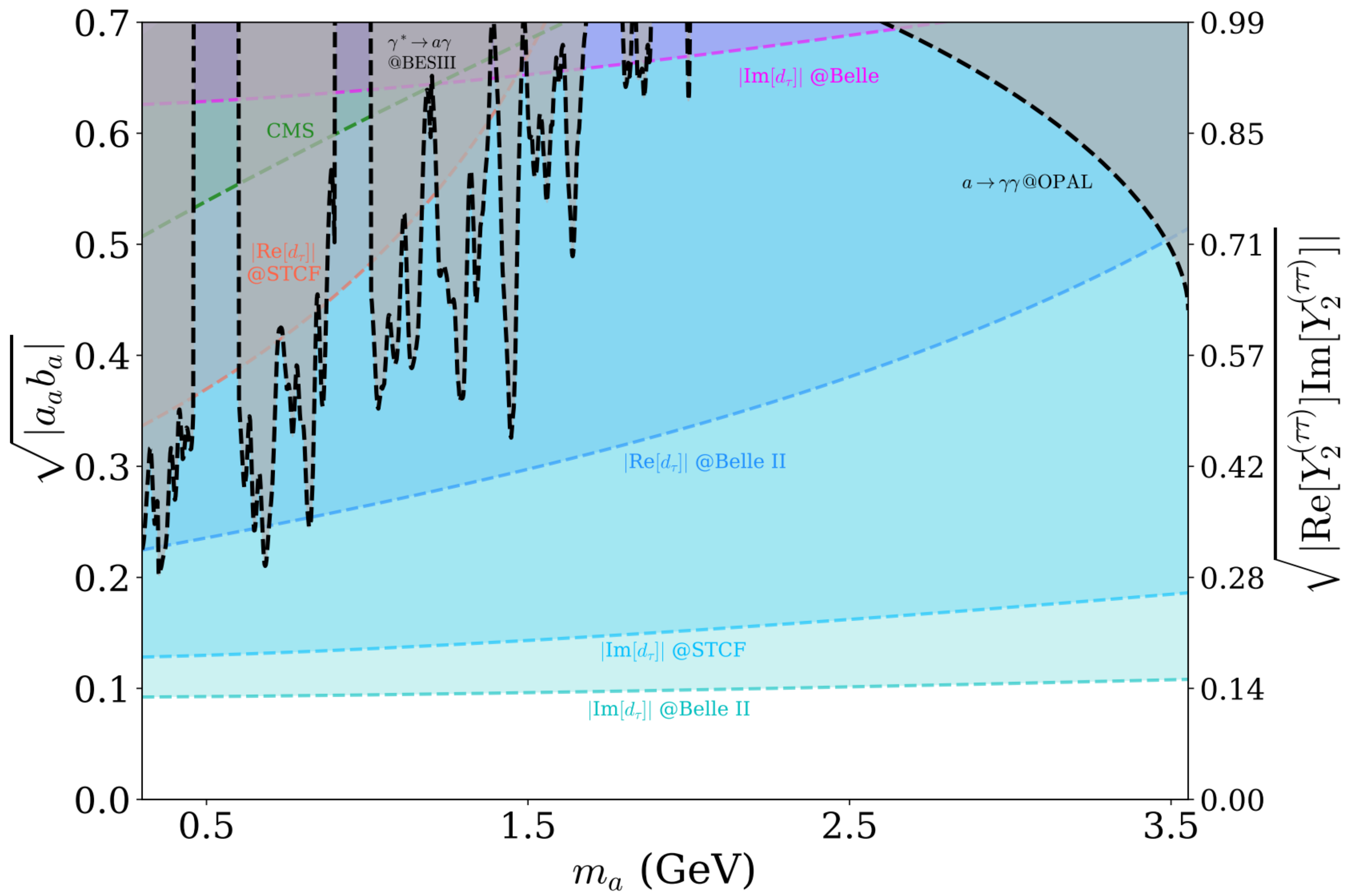


BESIII Collaboration(2022)



Phys.Rev.Lett. 118 (2017) 17, 171801

Axion-Like Particle (ALP)



The limit obtained from the imaginary part is more stringent than that from the real part.

Realization in a Renormalizable Model

Two-Higgs-doublet Model (2HDM)

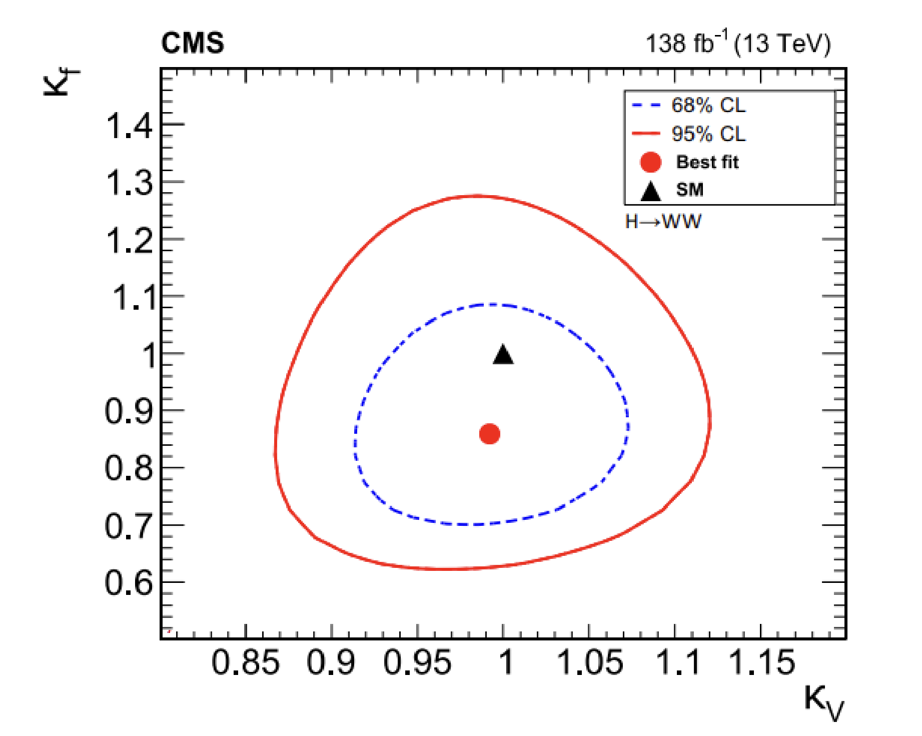
$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_1^\dagger\Phi_2 - \left(m_{12}^2\Phi_1^\dagger\Phi_2 + \text{c.c.}\right) + \frac{1}{2}\lambda_1\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{1}{2}\lambda_2\left(\Phi_2^\dagger\Phi_2\right)^2$$
$$+\lambda_3\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \lambda_4\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) + \left(\frac{1}{2}\lambda_5\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_2^\dagger\Phi_2\right)\left(\Phi_1^\dagger\Phi_2\right) + \text{c.c.}\right).$$

In the Higgs basis $(v_1,v_2) = (v,0)$

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v+h+iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(-H+iA) \end{pmatrix}$$

$$\frac{M^2}{v^2} = \begin{pmatrix} \lambda_1 & \text{Re}[\lambda_6] & -\text{Im}[\lambda_6] \\ \text{Re}[\lambda_6] & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(\lambda_4 + \text{Re}[\lambda_5]) & -\frac{1}{2}\text{Im}[\lambda_5] \\ -\text{Im}[\lambda_6] & -\frac{1}{2}\text{Im}[\lambda_5] & \frac{M_{H^\pm}^2}{v^2} + \frac{1}{2}(\lambda_4 - \text{Re}[\lambda_5]) \end{pmatrix},$$

In the alignment limit, $\lambda_6 = 0$



CMS Collaboration (2022)

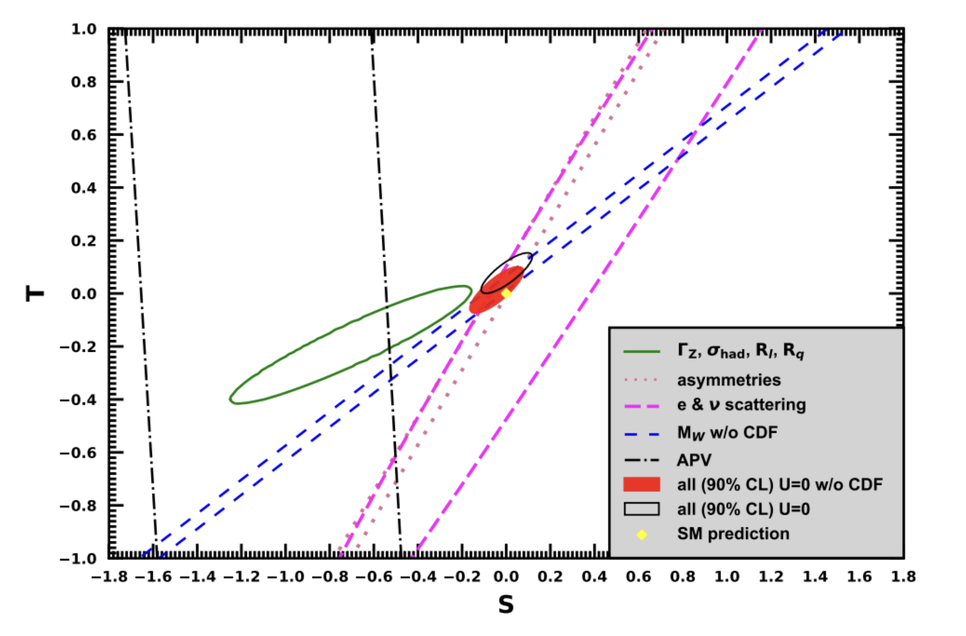
Realization in a Renormalizable Model

$$\Delta T \approx \frac{F\left(m_{H^\pm}, m_H\right) + F\left(m_{H^\pm}, m_A\right) - F\left(m_H, m_A\right)}{16\pi^2 \alpha v^2},$$

$$F(x,y) = \frac{x^2+y^2}{2} - \frac{x^2 y^2}{x^2-y^2} \ln\left(\frac{x^2}{y^2}\right).$$

$$m_H \approx m_{H^\pm} > 80\ \text{GeV} \quad \longrightarrow \quad \lambda_4 \approx -\lambda_5$$

LEP, ALEPH, DELPHI, L3 and OPAL Collaborations (2001)



Realization in a Renormalizable Model

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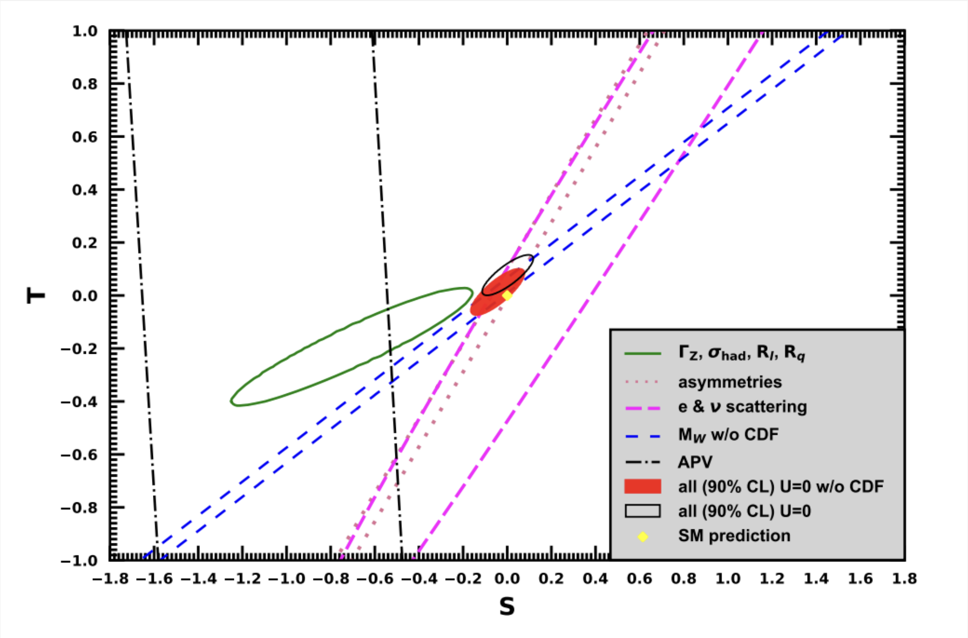


If CP violation is from Yukawa sector

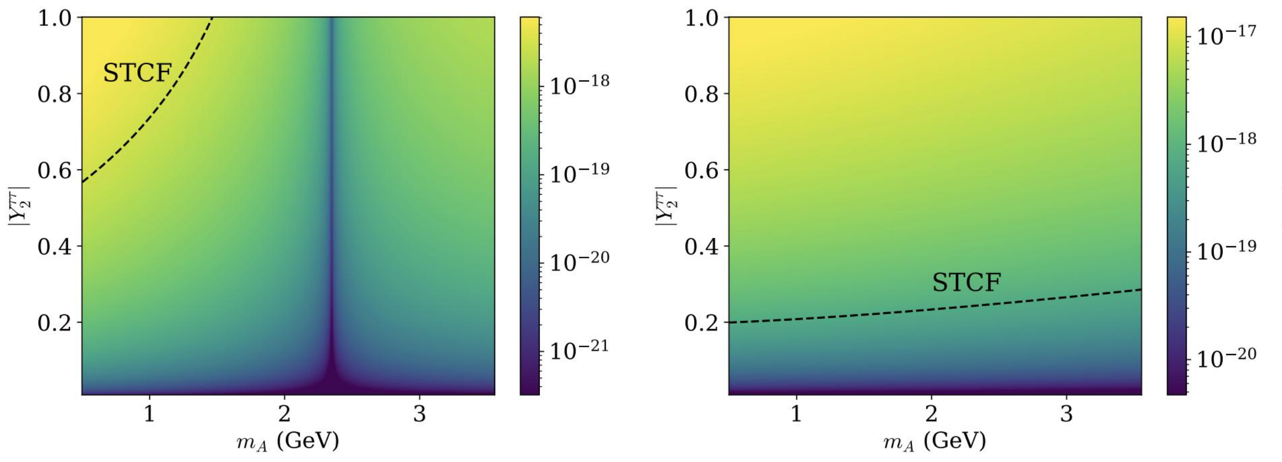
Just like ALP!

$$-\mathcal{L}_Y = \overline{L}_L Y_1' \Phi_1 l_R + \overline{L}_L Y_2' \Phi_2 l_R + \text{h.c.}$$

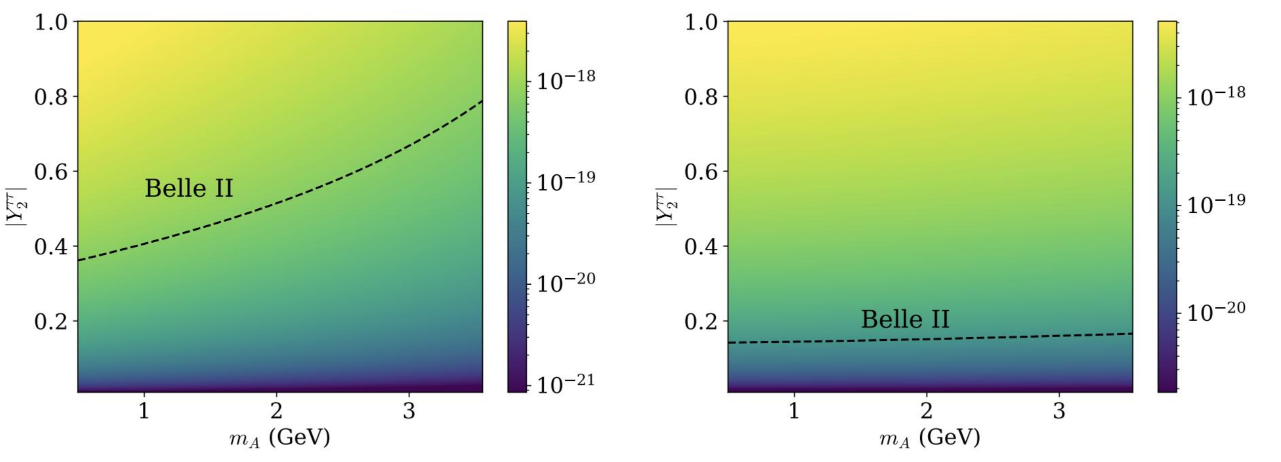
$$= \bar{l}\hat{M}_l l + \bar{l}\left(-\frac{\mathrm{Re}(Y_2)}{\sqrt{2}} - i\frac{\mathrm{Im}(Y_2)}{\sqrt{2}}\gamma_5\right) l H + \bar{l}\left(-\frac{\mathrm{Im}(Y_2)}{\sqrt{2}} + i\frac{\mathrm{Re}(Y_2)}{\sqrt{2}}\gamma_5\right) l A + (\bar{\nu}_L Y_2 l_R H^+ + \text{h.c.}),$$

Take $Y_2^{\tau\tau} = \sqrt{2}(b_a - i a_a)$, A can be a few GeV, generating a τ EDM of $10^{-19} e$cm.

Realization in a Renormalizable Model



(a) $|\mathrm{Re}[d_\tau]|$ (b) $|\mathrm{Im}[d_\tau]|$



(a) $|\mathrm{Re}[d_\tau]|$ (b) $|\mathrm{Im}[d_\tau]|$

$$arg(Y_2^{\tau\tau}) = \pi/6$$

If CP violation is from Yukawa sector

Just like ALP!

$$-\mathcal{L}_Y = \overline{L}_L Y_1' \Phi_1 l_R + \overline{L}_L Y_2' \Phi_2 l_R + \text{h.c.}$$

$$= \bar{l}\hat{M}_l l + \bar{l}\left(-\frac{\mathrm{Re}(Y_2)}{\sqrt{2}} - i\frac{\mathrm{Im}(Y_2)}{\sqrt{2}}\gamma_5\right) lH + \bar{l}\left(-\frac{\mathrm{Im}(Y_2)}{\sqrt{2}} + i\frac{\mathrm{Re}(Y_2)}{\sqrt{2}}\gamma_5\right) lA + (\bar{\nu}_L Y_2 l_R H^+ + \text{h.c.}),$$

Take $Y_2^{\tau\tau} = \sqrt{2}(b_a - i a_a)$, A can be a few GeV, generating a τ EDM of 10^{-19}ecm.

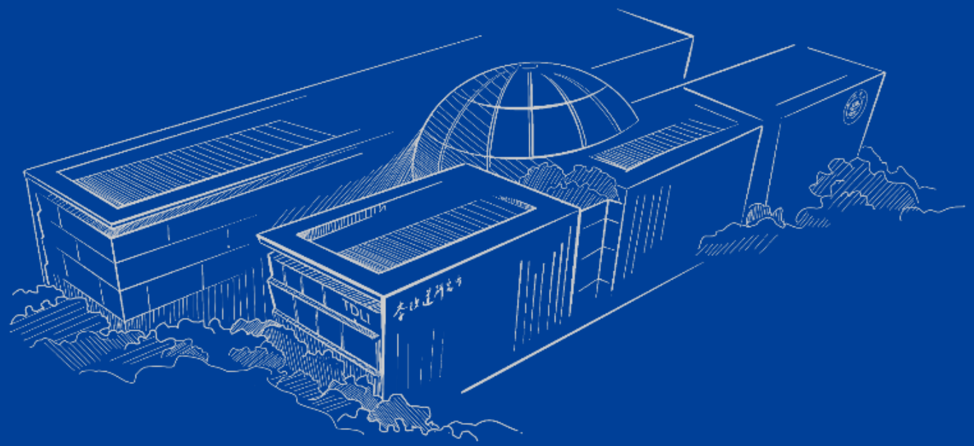
Conclusion

- In this work, we have investigated the $d_\tau(q^2)$ as a probe of CP violation beyond the SM, highlighting its q^2 dependence.

- GeV-scale ALPs can induce sizable $d_\tau(q^2)$ within Belle II and STCF sensitivities.

- A CP-violating 2HDM offers a renormalizable framework testable in future experiments.

Thank You!



Appendix

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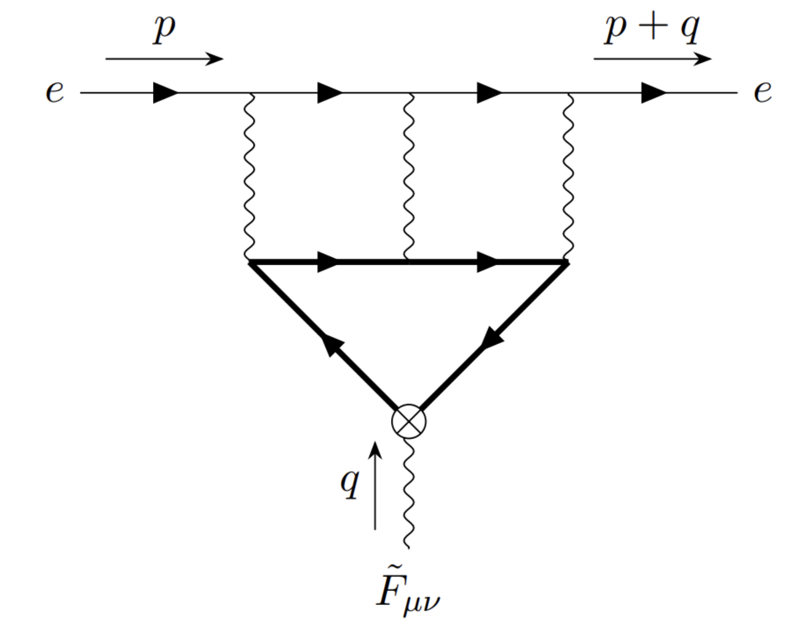
Although direct measurements of $d_\tau(0)$ are not currently feasible, it is indirectly constrained by the electron EDM.

$$|d_e| \leq 4.1\times10^{-30}\,ecm \;\longrightarrow\; |d_\tau^0| \leq 4.1\times10^{-19}\,ecm.$$

In the SM effective field theory (SMEFT) framework

$$\mathcal{L}_{\rm SMEFT} \supset \frac{C^{33}_{(eH)^2}}{\Lambda^4}\left[(\bar{L}_\tau H)\tau_R\right]^2 + \frac{C^{33}_{eB}}{\Lambda^2}(\bar{L}_\tau \sigma^{\mu\nu}\tau_R)HB_{\mu\nu} + \frac{C^{33}_{eW}}{\Lambda^2}(\bar{L}_\tau \sigma_{\mu\nu}\tau_R)\sigma_a HW_a^{\mu\nu} + \text{h.c.},$$



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$$\mathcal{L}_{\rm eff} = \frac{i}{\Lambda^2}C^{\tau\tau}_{SP}(\bar{\tau}\gamma_5\tau)(\bar{\tau}\tau) - d_\tau^0\,\frac{i}{2}F^{\mu\nu}\bar{\tau}\sigma_{\mu\nu}\gamma_5\tau.$$

Belle

$$\left|\mathrm{Re}\left[d_\tau\left((10.58\mathrm{GeV})^2\right)\right]\right| = \left|d_\tau^0 - 1.3\frac{em_\tau C^{\tau\tau}_{SP}}{8\pi^2\Lambda^2}\right| \leq 1.66\times10^{-17}\,ecm,$$

$$\left|\mathrm{Im}\left[d_\tau\left((10.58\mathrm{GeV})^2\right)\right]\right| = \left|\frac{3em_\tau C^{\tau\tau}_{SP}}{8\pi^2\Lambda^2}\right| \leq 0.93\times10^{-17}\,ecm,$$

$\mathrm{Im}(d_\tau)$ is less constrained by eEDM!

Appendix

We discuss some general aspects of generating the τ EDM from new scalar bosons.

$$\mathcal{L}_{NP} = \sum_{n}^{N} \left(S_n \bar{\tau} (a_n - i b_n \gamma_5) \tau \right).$$

The corresponding Wilson coefficients are found to be

$$\frac{C_{SP}^{\tau\tau}}{\Lambda^2} = \sum_{n}^{N} \frac{(a_n b_n)}{m_n^2}, \quad d_\tau^0 = -\frac{e m_\tau}{8\pi^2} \sum_{n}^{N} \frac{(a_n b_n)}{m_n^2} \log\left(\frac{m_\tau^2}{m_n^2} \right).$$

To obtain a large $C_{SP}^{\tau\tau}$ but a small $d_\tau(0)$, a delicate cancellation must occur in the summation for $d_\tau(0)$ but not for $C_{SP}^{\tau\tau}$.

Alternatively, one may evade these constraints by considering light NP, where the OPE is no longer valid.

Appendix

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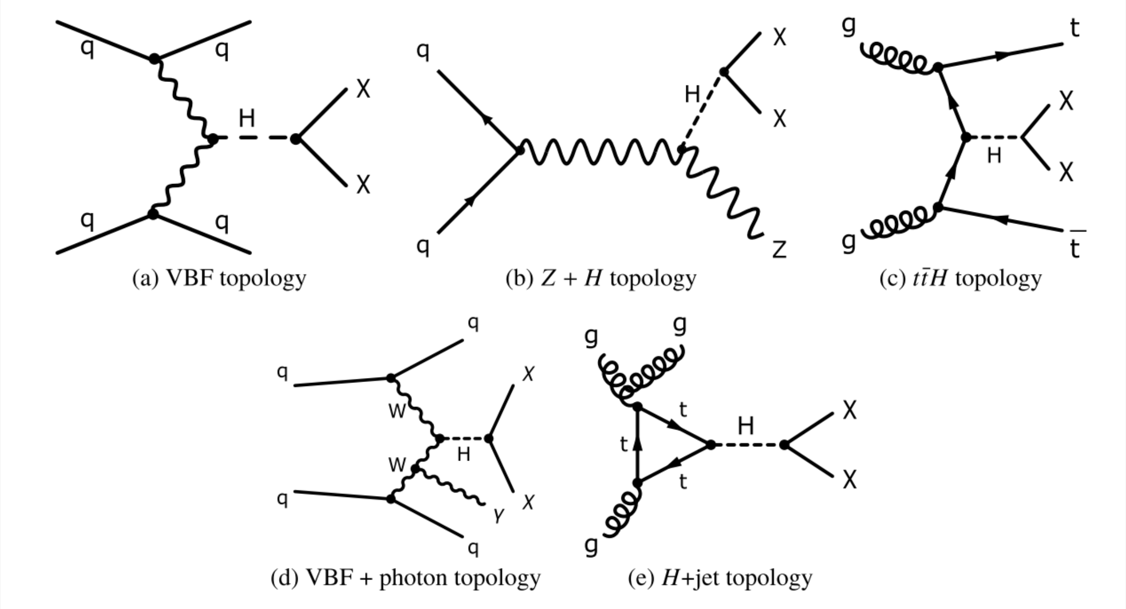
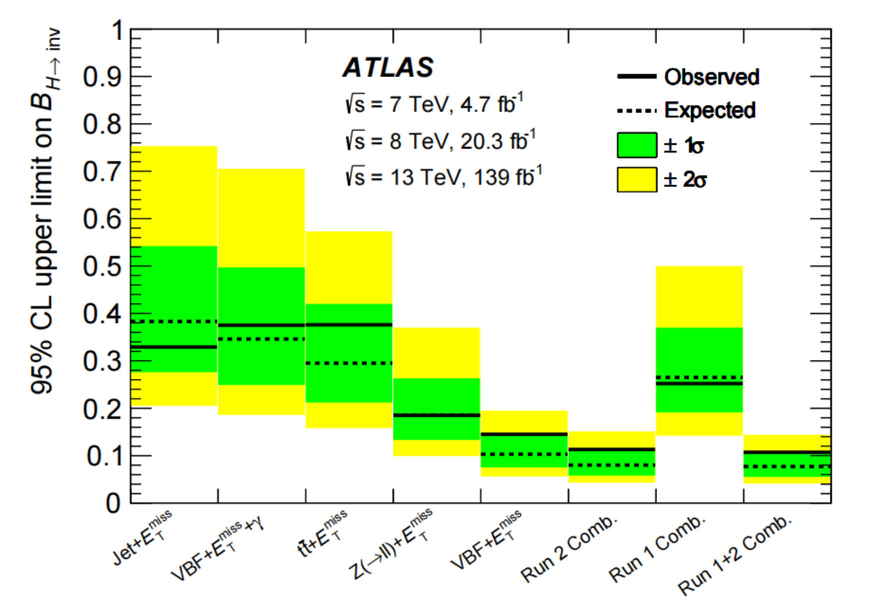
when $m_h \gg m_A,\ h_1 \to AA$ can happen $\qquad \Gamma(h \to AA) = \dfrac{v^2(\lambda_3+\lambda_4-\lambda_5)^2}{32\pi m_h}.$

$\mathcal{B}(h \to \text{ invisible }) < 10.7\%$

$\lambda_3 = \lambda_5 - \lambda_4 = 2\lambda_5$





ATLAS Collaboration (2023)