

Complex τ Electric Dipole Moment From GeV-Scale New Physics

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

PPC2026

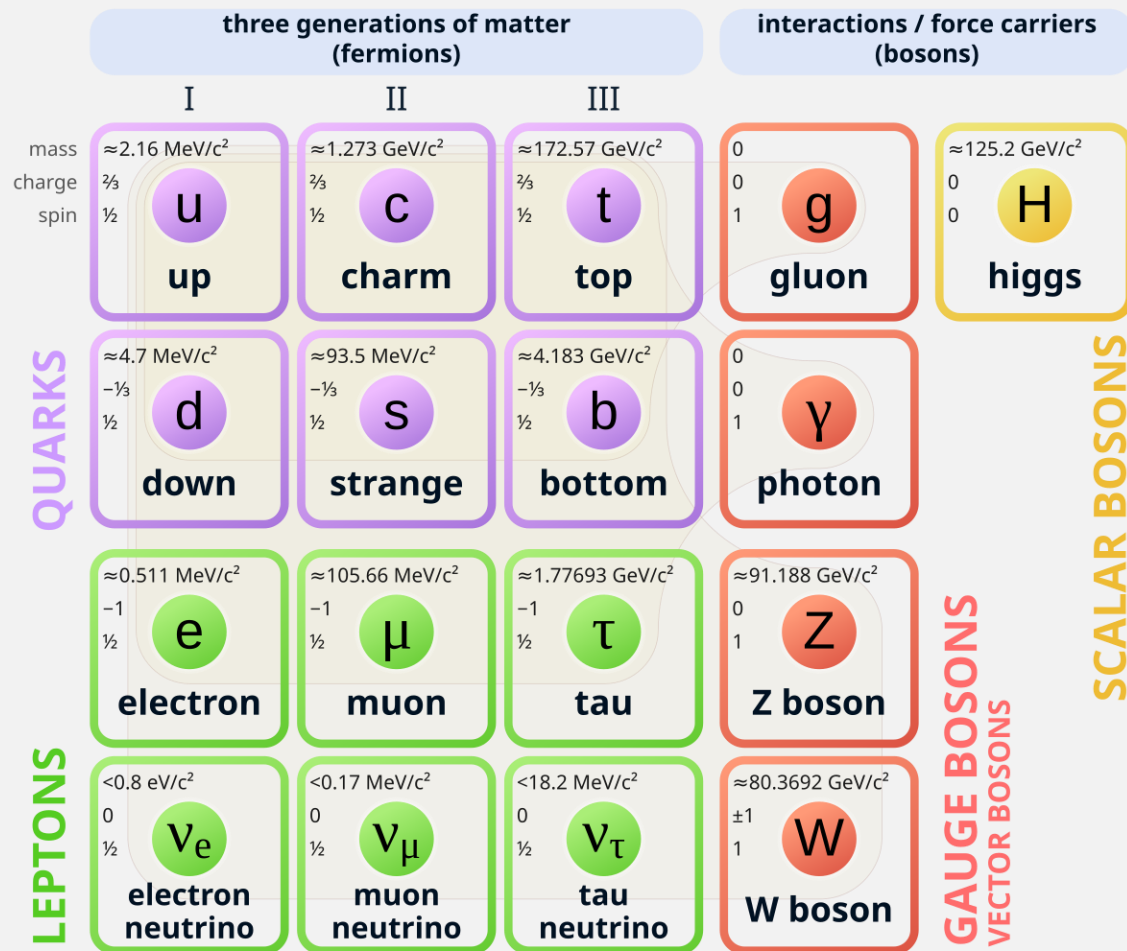
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Standard Model of Elementary Particles



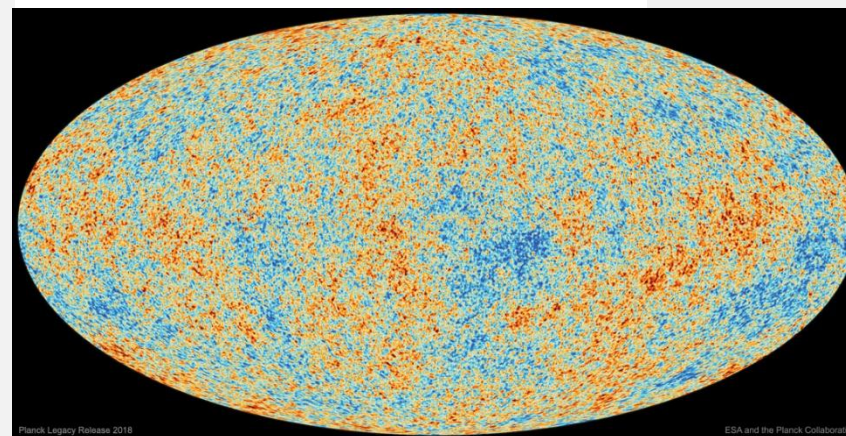
three generations of matter (fermions)			interactions / force carriers (bosons)
I	II	III	
$\approx 2.16 \text{ MeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ up	$\approx 1.273 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ charm	$\approx 172.57 \text{ GeV}/c^2$ $\frac{2}{3}$ $\frac{1}{2}$ top	 gluon
$\approx 4.7 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ down	$\approx 93.5 \text{ MeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ strange	$\approx 4.183 \text{ GeV}/c^2$ $-\frac{1}{3}$ $\frac{1}{2}$ bottom	 photon
$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$ muon	$\approx 1.77693 \text{ GeV}/c^2$ -1 $\frac{1}{2}$ tau	 Z boson
$< 0.8 \text{ eV}/c^2$ 0 $\frac{1}{2}$ electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ muon neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ tau neutrino	 W boson

QUARKS

LEPTONS

SCALAR BOSONS

GAUGE BOSONS
VECTOR BOSONS


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

Particle Data Group (2025)

Planck 2018

Motivation

Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass $\approx 2.16 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ u up	mass $\approx 1.273 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ c charm	mass $\approx 172.57 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ t top	0 0 1 g gluon	mass $\approx 125.2 \text{ GeV}/c^2$ 0 0 0 H higgs
mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ d down	mass $\approx 93.5 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ s strange	mass $\approx 4.183 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ b bottom	0 0 1 γ photon	
mass $\approx 0.511 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ e electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge -1 spin $\frac{1}{2}$ μ muon	mass $\approx 1.77693 \text{ GeV}/c^2$ charge -1 spin $\frac{1}{2}$ τ tau	0 1 1 Z Z boson	
mass $< 0.8 \text{ eV}/c^2$ 0 spin $\frac{1}{2}$ ν_e electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_μ muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ 0 spin $\frac{1}{2}$ ν_τ tau neutrino	1 1 1 W W boson	

QUARKS

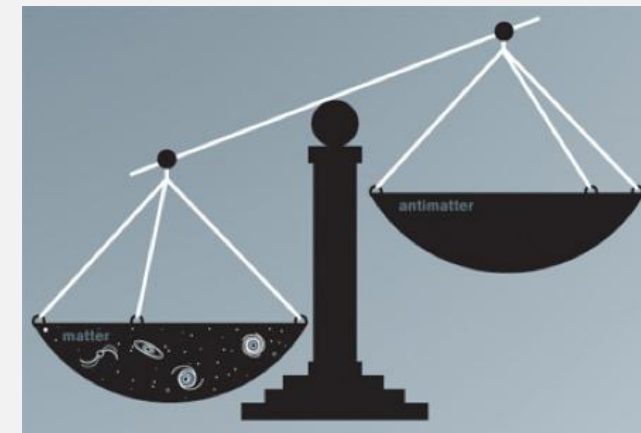
LEPTONS

SCALAR BOSONS

GAUGE BOSONS
VECTOR BOSONS



Andrei Sakharov



Sakharov(1967)

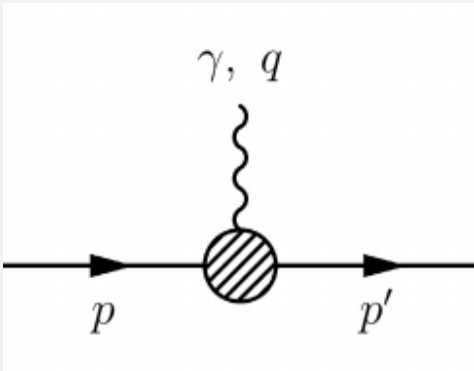
Sakharov conditions:

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.

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



$\downarrow$
 $\downarrow$
 $\downarrow$
 $\downarrow$

$Q = F_1(0)$
 $a = \frac{1}{2m} [F_2(0)]$
 $d = \frac{e}{2m} F_3(0)$
 anapole moment: $F_4(0)$

Electric Dipole Moment (EDM)

P or T transformation

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

CP violated!

Lepton EDM in SM

$$d_e^{(\text{SM})} = 5.8 \times 10^{-40} \text{ ecm},$$

$$d_\mu^{(\text{SM})} = 1.4 \times 10^{-38} \text{ ecm},$$

$$d_\tau^{(\text{SM})} = -7.3 \times 10^{-38} \text{ ecm}.$$

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

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

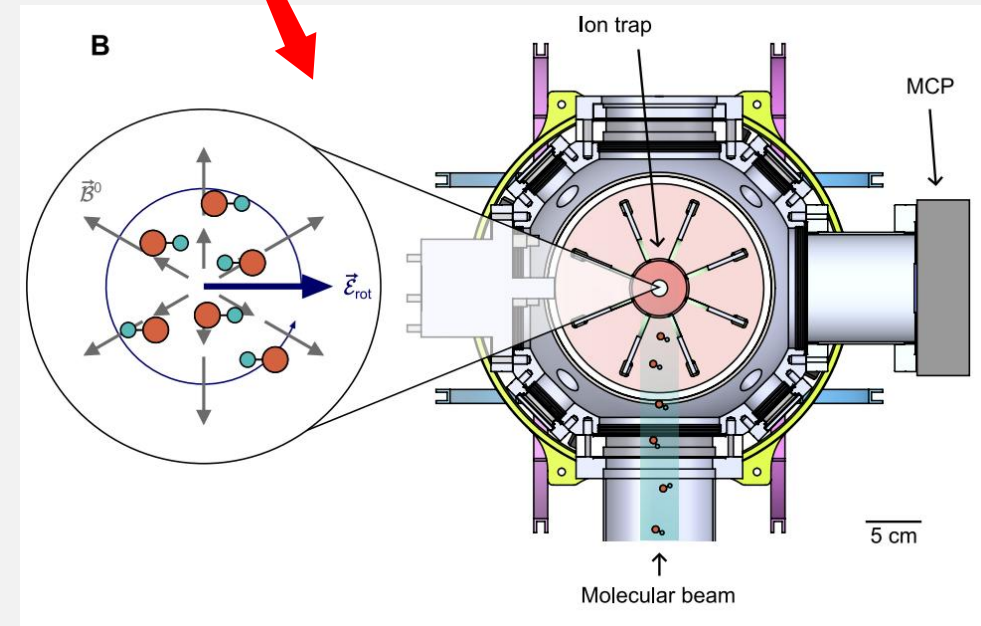
Mass $m = 1776.93 \pm 0.09 \text{ MeV}$

$(m_{\tau^+} - m_{\tau^-})/m_{\text{average}} < 2.8 \times 10^{-4}$, CL = 90%

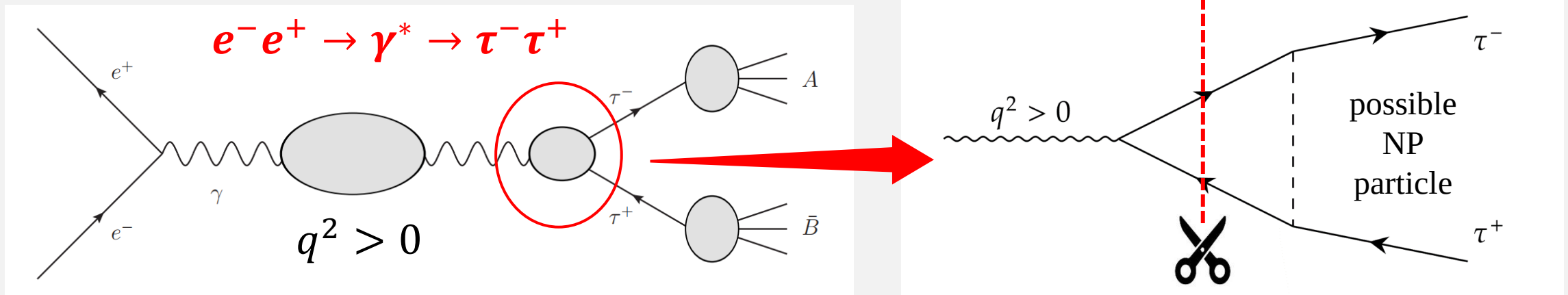
Mean life $\tau = (290.3 \pm 0.5) \times 10^{-15} \text{ s}$

The τ lepton has a very short lifetime!

How can its EDM be detected?



Science 381 (2023) 6653



Intermediate particles are on shell $\rightarrow$ EDM develops an **imaginary part!**

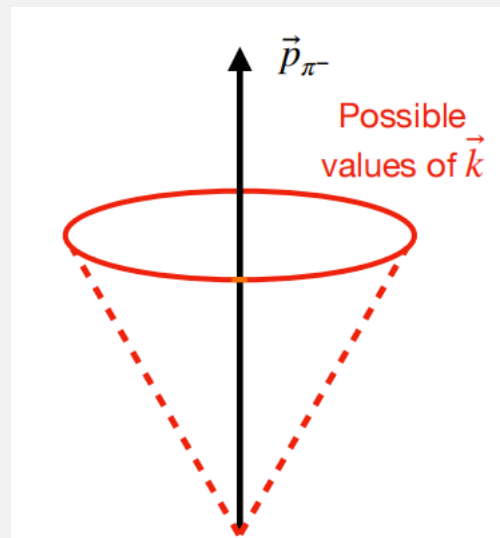
Strictly speaking, it is a form factor, but the PDG adopts the convention:

Re(d_τ)					Im(d_τ)				
PDGID:S035EDM	JSON	INSPIRE Q	PDGID:S035EDI	JSON	INSPIRE Q				
VALUE (10^{-16} e cm)	CL%	DOCUMENT ID	TECN	COMMENT	VALUE (10^{-16} e cm)	CL%	DOCUMENT ID	TECN	COMMENT
-0.185 to 0.061	95	¹ INAMI 2022	BELL	$E_{\text{cm}}^{ee} = 10.6$ GeV	-0.103 to 0.023	95	¹ INAMI 2022	BELL	$E_{\text{cm}}^{ee} = 10.6$ GeV

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

Fortunately, we can use $(k^\mu - p_{\pi^-}^\mu)^2 = m_\nu^2$ to reconstruct $\hat{\mathbf{l}}_- \cdot \mathbf{k}$

$$\hat{l}_{\pm} \cdot \mathbf{k} = \pm \frac{4E_{\pi^{\pm}} m_{\tau}^2 - m_h^2 \sqrt{s} - m_{\tau}^2 \sqrt{s}}{(m_{\tau}^2 - m_h^2) \sqrt{s - 4m_{\tau}^2}}$$



$\delta_{\text{Re}} (10^{-18} \text{ ecm})$

$D (\mu\text{m})$

$\sqrt{s} (\text{GeV})$

STCF

● Future Experiment Limits

Improvement in experimental sensitivity



$\sqrt{s}$	$m_{\psi(2S)}$	4.2 GeV	4.9 GeV	5.6 GeV	6.3 GeV	7 GeV
δ_{Im}	1.8	0.9	0.7	0.7	0.7	0.7
$\delta_{\text{Re}}(30)$	11	4.4	3.2	2.9	2.8	2.9

Given in units of 10^{-18} ecm

Xiao-Gang He et al.(2025)



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

The measurements

$$\text{Re}(a_\tau) = \frac{2(s + 2m_\tau^2)(s + m_\tau^2)}{s(s - 4m_\tau^2)} - \frac{5(s + 2m_\tau^2)^2}{s(s - 4m_\tau^2)} \left\langle \left(\mathbf{p} \cdot \mathbf{k} \right)^2 \right\rangle, \quad \text{Im}(a_\tau) = -\frac{64m_\tau(2m_\tau^2 + s)}{\pi\alpha_{h^\pm}\sqrt{s}(s - 4m_\tau^2)} \left\langle \frac{(\mathbf{p} \cdot \mathbf{k}) [\hat{l}_+ \cdot (\mathbf{p} \times \mathbf{k})]}{|\mathbf{p} \times \mathbf{k}|} \right\rangle.$$



$\sqrt{q^2}$ [GeV]	$ \text{Re}(a_\tau^{QED}) $	$\delta\text{Re}(a_\tau)$	$ \text{Im}(a_\tau^{QED}) $	$\delta\text{Im}(a_\tau)$
$m_{\psi(2S)}$	1.11×10^{-3}	2.17×10^{-3}	6.39×10^{-3}	4.90×10^{-3}
$m_{\Upsilon(4S)}$	2.44×10^{-4}	6.29×10^{-5}	2.18×10^{-4}	5.02×10^{-5}

Reach the level of one-loop QED predictions

Current constraints $a_\tau = -0.5_{-0.9}^{+2.6} \times 10^{-3}$,

2503.19836



SM prediction $a_\tau \approx 1.1721 \times 10^{-3}$.

hep-ph/0701260

● Indirect Limit

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

$$|d_e| \leq 4.1 \times 10^{-30} \text{ ecm} \longrightarrow |d_\tau^0| \leq 4.1 \times 10^{-19} \text{ ecm}.$$

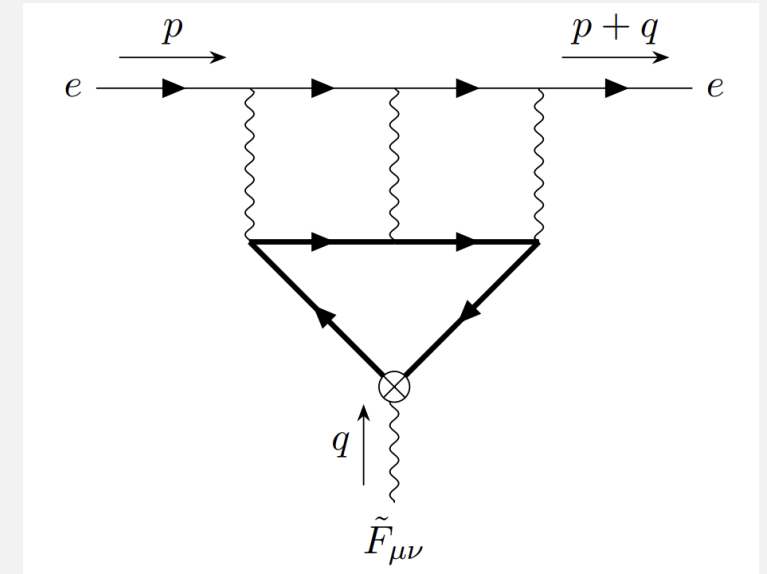
Consider the low energy effective field theory

$$\mathcal{L}_{\text{eff}} \supset \frac{i}{\Lambda^2} C_{SP}^{\tau\tau} (\bar{\tau} \gamma_5 \tau) (\bar{\tau} \tau) - d_\tau^0 \frac{i}{2} F^{\mu\nu} \bar{\tau} \sigma_{\mu\nu} \gamma_5 \tau.$$

No direct constraint on $C_{SP}^{\tau\tau}(m_\tau)$ but from the running :

$$d_\tau^0(\mu) = d_\tau^0(\Lambda) + \frac{m_\tau}{\Lambda^2} \frac{e}{4\pi^2} C_{SP}^{\tau\tau}(\Lambda) \ln \frac{\Lambda}{\mu},$$

Needs **fine-tuning** or **NP at low energies** to evade the eEDM constraint !!



Phys.Lett.B 835 (2022) 137496

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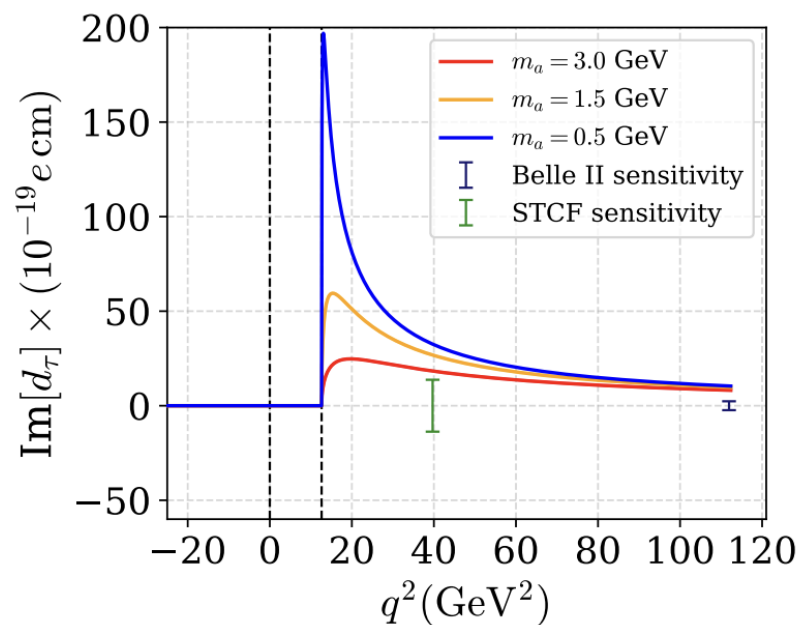
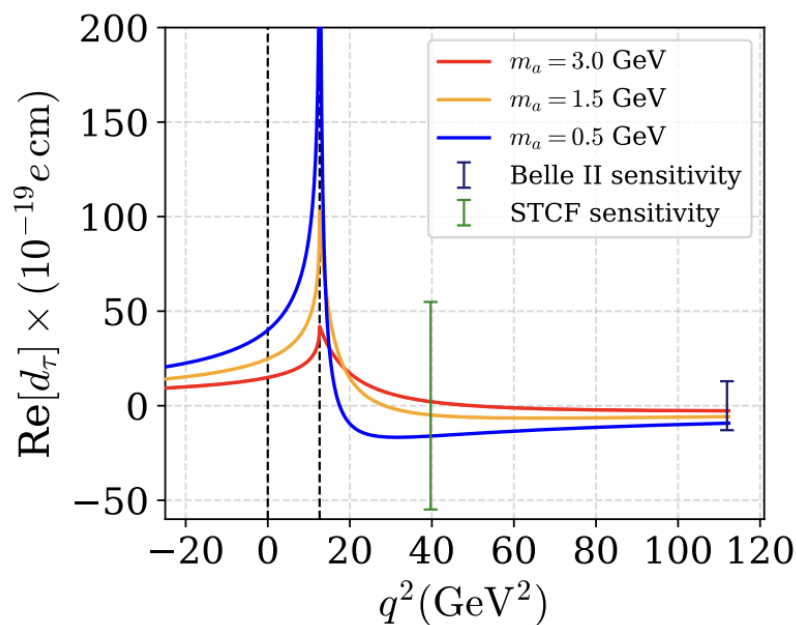
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + a\bar{\tau}(a_a + ib_a\gamma_5)\tau,$$


● Light new physics



Let us start with a CP-violated ALP

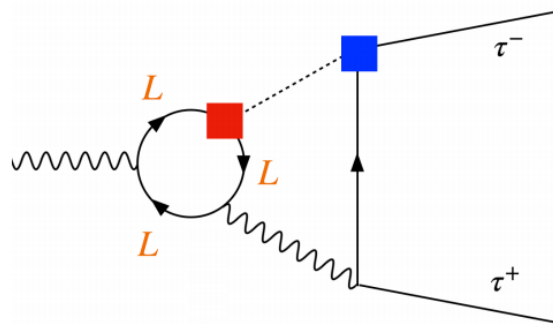
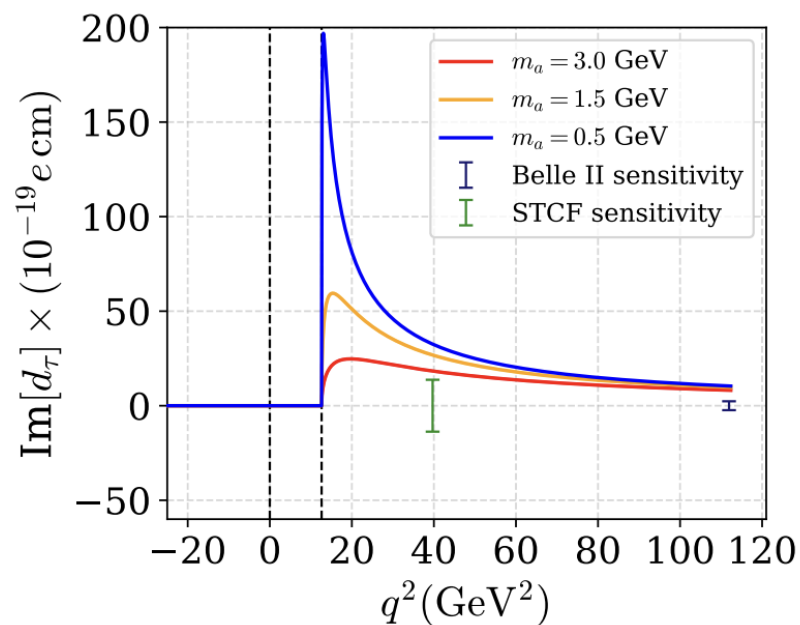
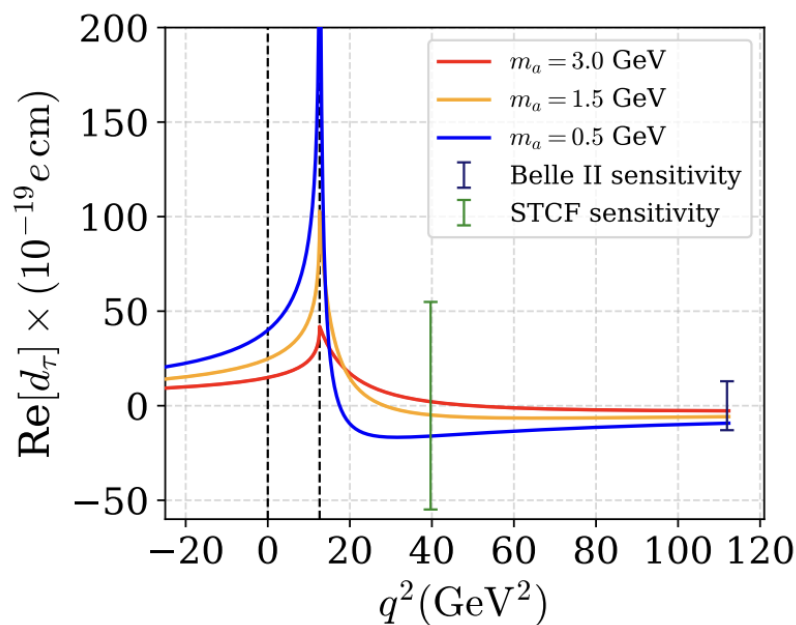
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + a\bar{\tau}(a_a + ib_a\gamma_5)\tau,$$



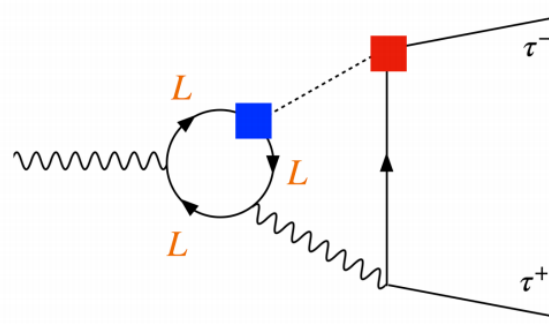
Light new physics

Let us start with a CP-violated ALP

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



or

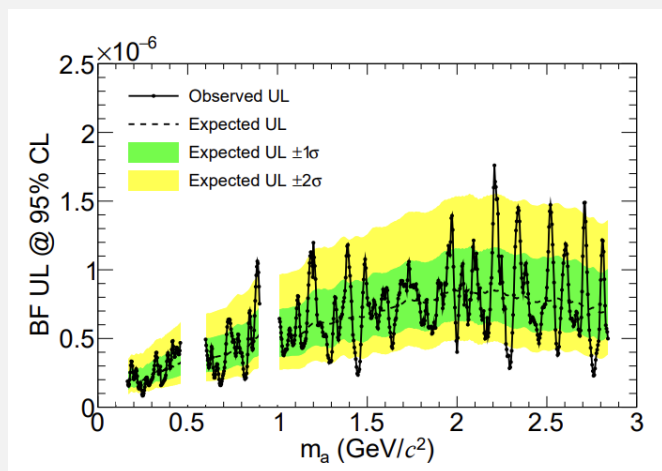


- no chiral enhancement
- at least two orders smaller than experiment sensitivity

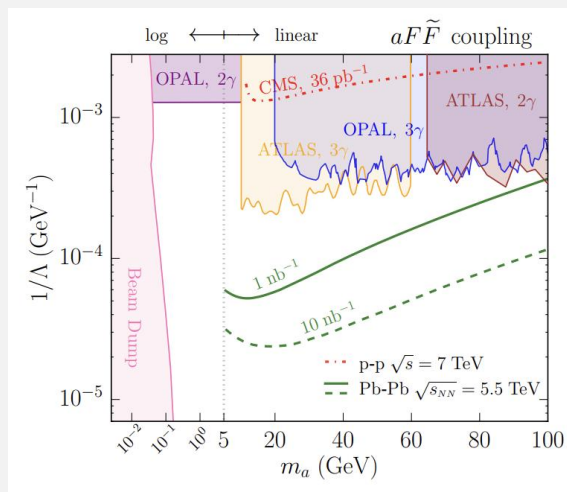
● Light new physics

Let us start with a CP-violated ALP

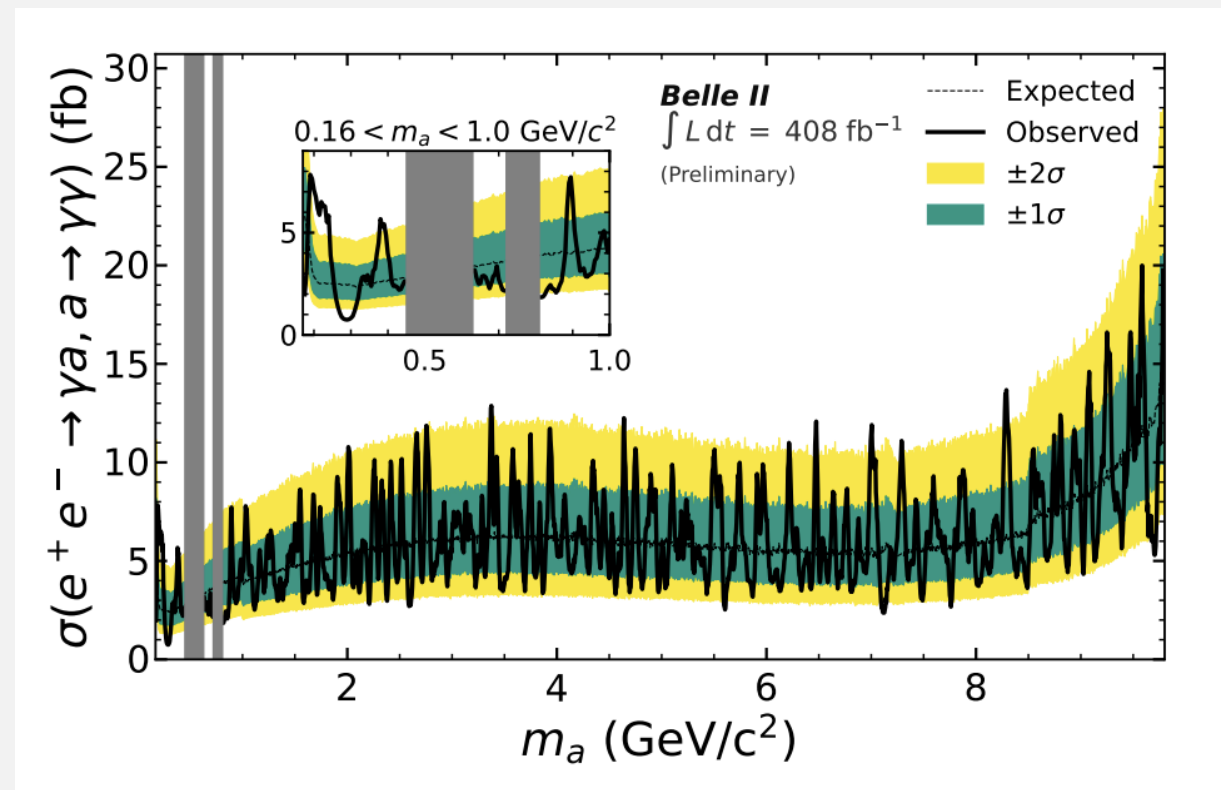
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2}m_a^2 a^2 + a\bar{\tau}(a_a + ib_a\gamma_5)\tau,$$



BESIII Collaboration(2022)

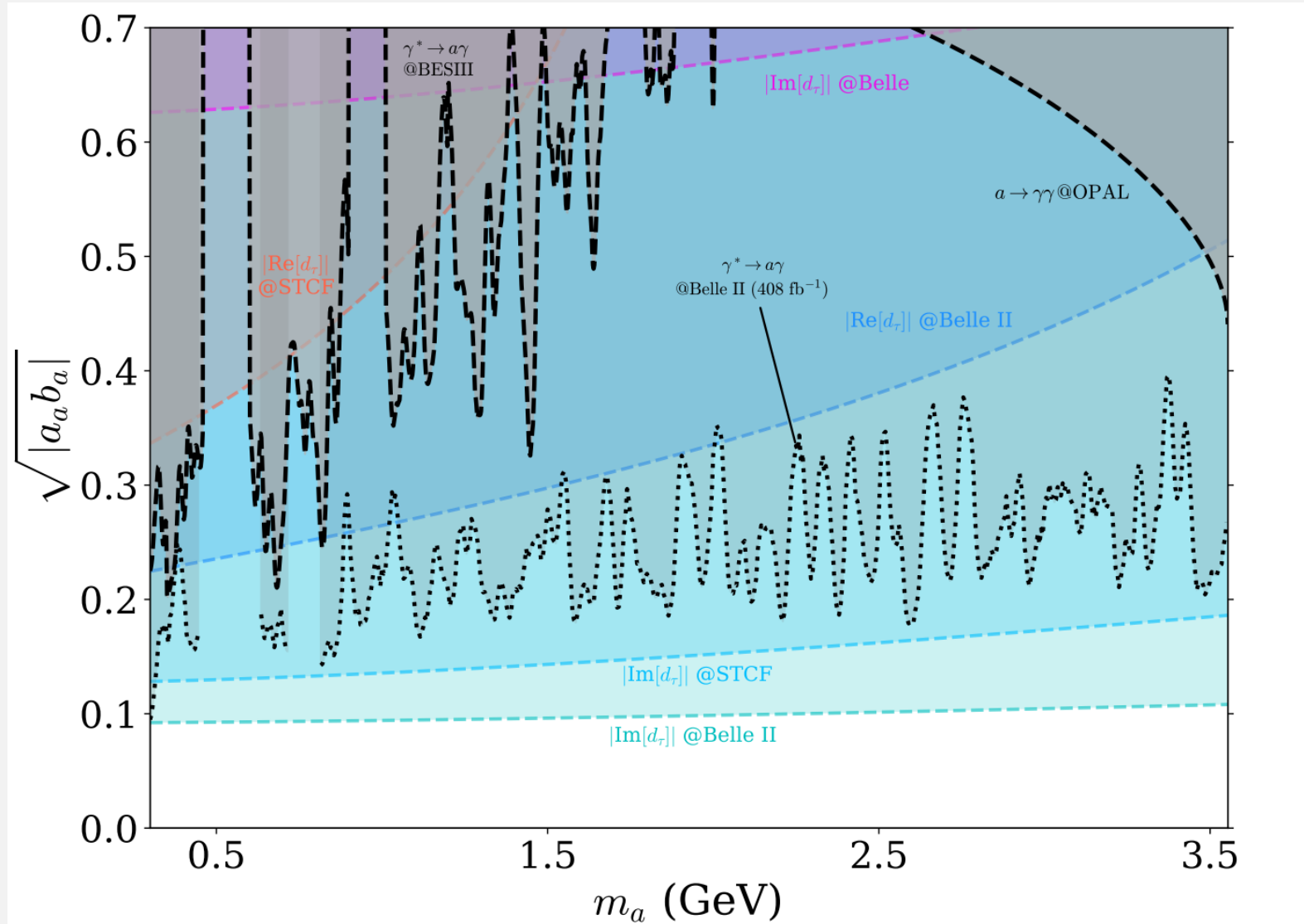


Phys.Rev.Lett. 118 (2017) 17, 171801



See also Robin Leboucher's talk

arXiv:2607.07800



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)

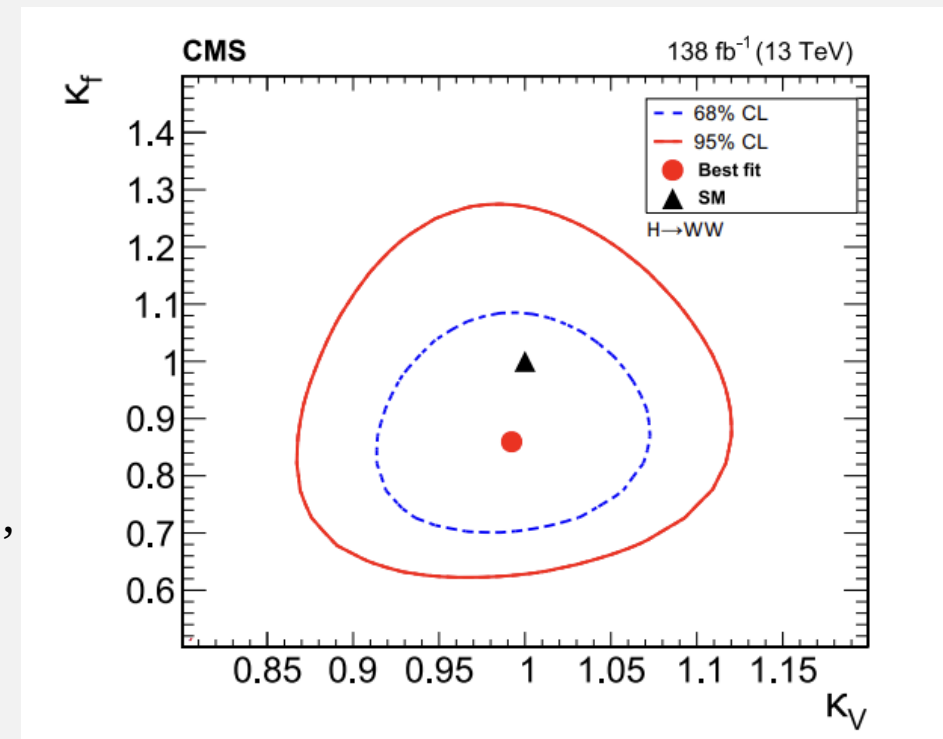
$$\begin{aligned}
 V(\Phi_1, \Phi_2) = & m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - (m_{12}^2 \Phi_1^\dagger \Phi_2 + \text{c.c.}) + \frac{1}{2} \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2} \lambda_2 (\Phi_2^\dagger \Phi_2)^2 \\
 & + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger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

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 aligned limit, $\lambda_6 = 0$



● Realization in a Renormalizable Model

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

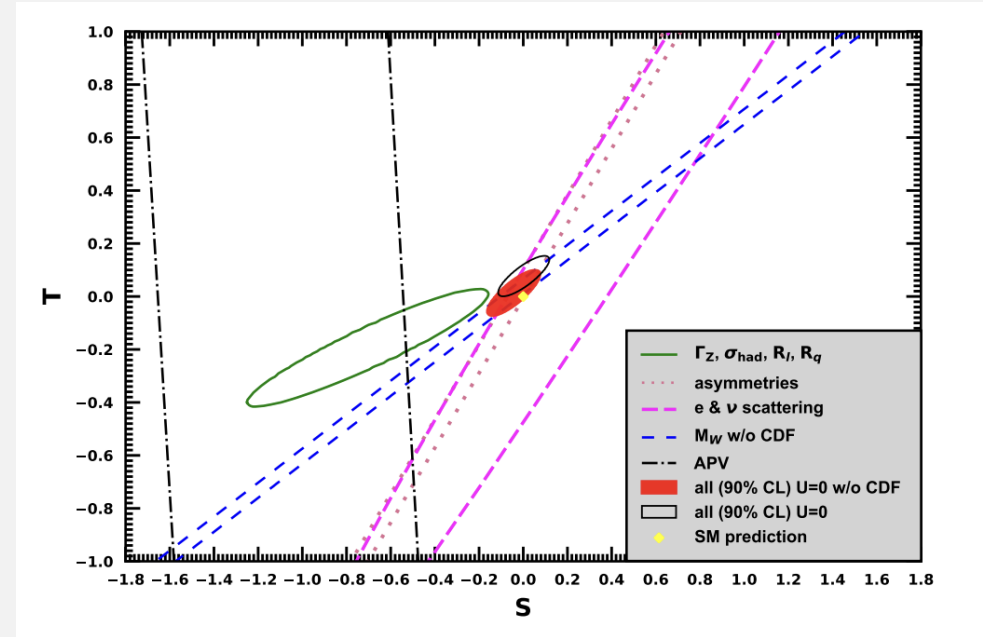
$$F(x, y) = \frac{x^2 + y^2}{2} - \frac{x^2 y^2}{x^2 - y^2} \ln\left(\frac{x^2}{y^2}\right).$$

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

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



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● Realization in a Renormalizable Model

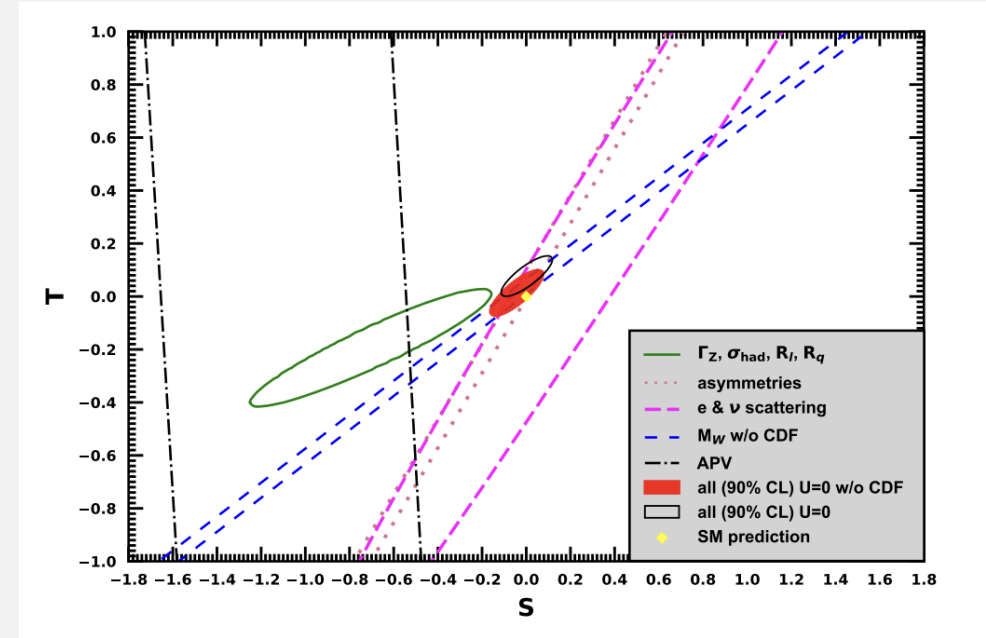


$$\Delta T \approx \frac{F(m_{H^\pm}, m_H) + F(m_{H^\pm}, m_A) - F(m_H, m_A)}{16\pi^2 \alpha v^2},$$

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

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

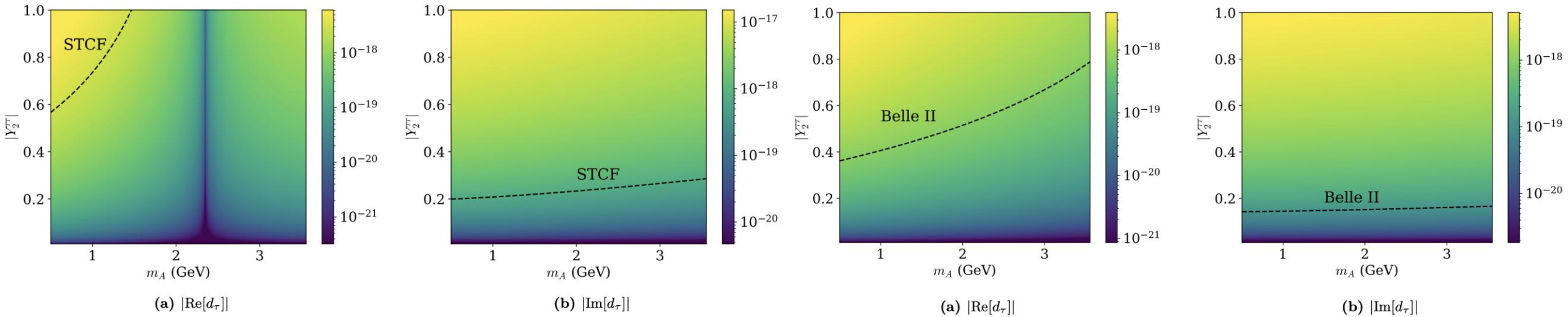


$$-\mathcal{L}_Y = \bar{L}_L Y'_1 \Phi_1 l_R + \bar{L}_L Y'_2 \Phi_2 l_R + \text{h.c.}$$

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

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

Realization in a Renormalizable Model



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

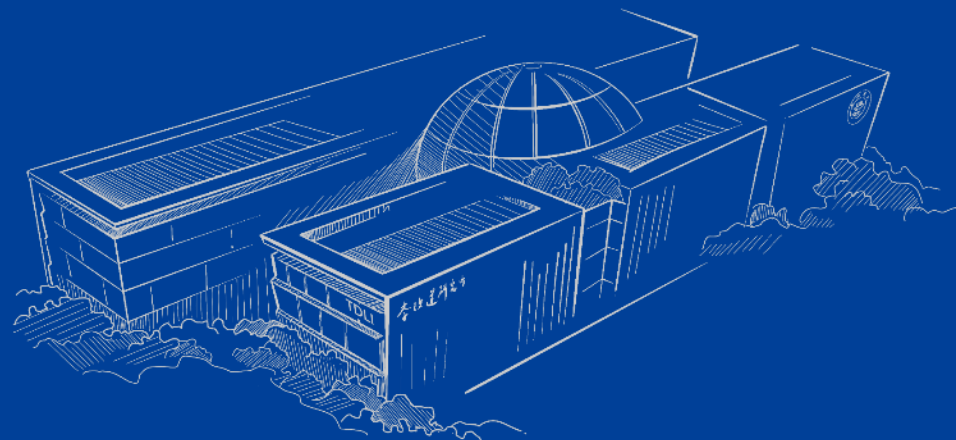
$$\begin{aligned} -\mathcal{L}_Y &= \bar{L}_L Y_1' \Phi_1 l_R + \bar{L}_L Y_2' \Phi_2 l_R + \text{h.c.} \\ &= \bar{l} \hat{M}_l l + \bar{l} \left(-\frac{\text{Re}(Y_2)}{\sqrt{2}} - i \frac{\text{Im}(Y_2)}{\sqrt{2}} \gamma_5 \right) l H + \bar{l} \left(-\frac{\text{Im}(Y_2)}{\sqrt{2}} + i \frac{\text{Re}(Y_2)}{\sqrt{2}} \gamma_5 \right) l A + (\bar{\nu}_L Y_2 l_R H^+ + \text{h.c.}), \end{aligned}$$

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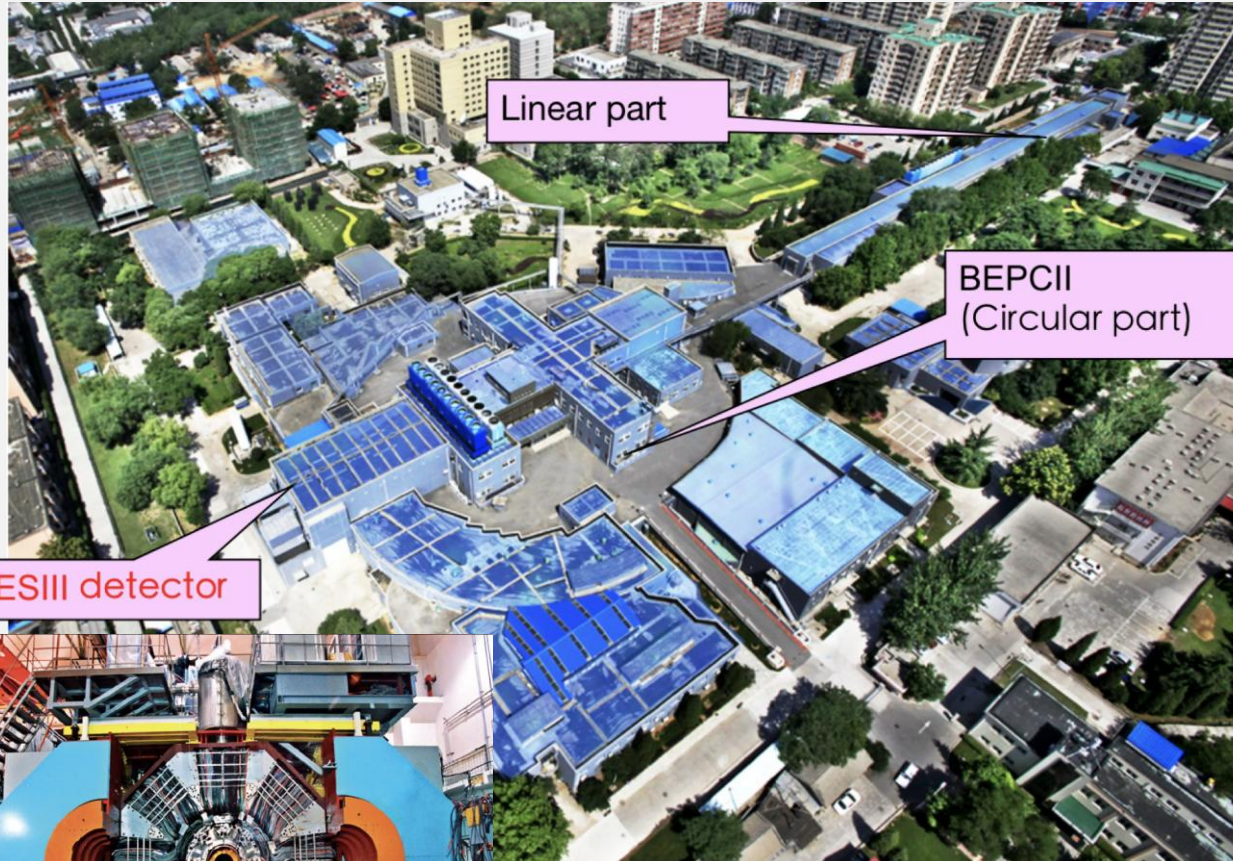
- Timelike τ dipole moments open a new window for probing new physics at future e^+e^- colliders, with its q^2 dependence.
- GeV-scale light new scalars can induce sizable $d_\tau(q^2)$ within Belle II and STCF sensitivities.
- $\text{Im}[d_\tau(q^2)]$ is usually more sensitive to light NP than $\text{Re}[d_\tau(q^2)]$.
- Meanwhile, a precise measurement of a_τ is still needed to test the QED prediction.



———— Thank You! ————

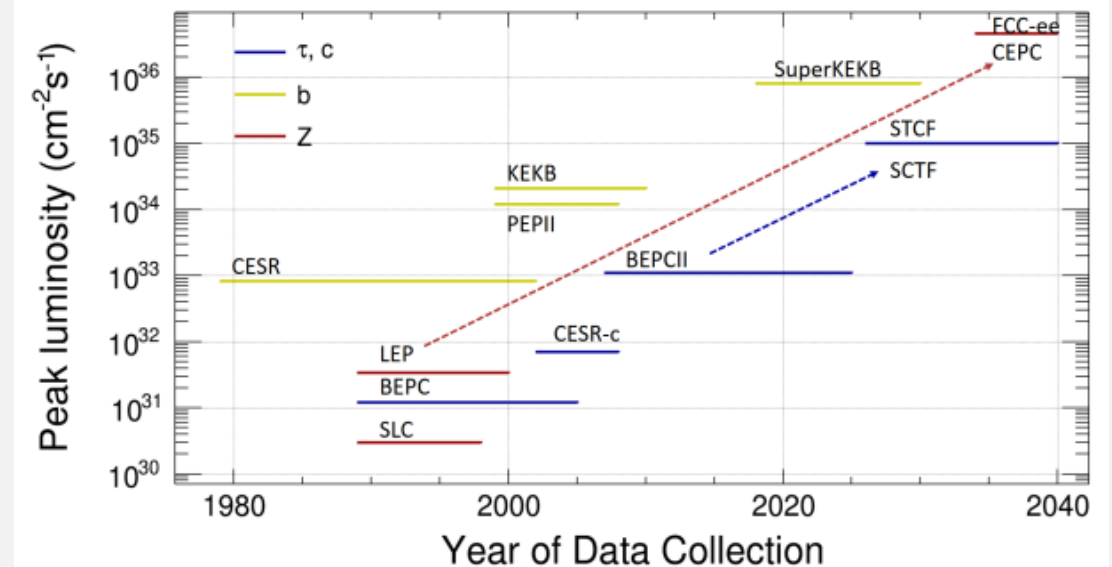


● Colliders in China



Encouraged by T. D. Lee during early planning

- Produced $2.7 \times 10^9 \psi(2S)$, around 10^7 events of $\psi(2S) \rightarrow \tau^+ \tau^-$.
- Luminosity will be shifted forward by two orders in **STCF**.



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

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

The corresponding Wilson coefficients are found to be

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

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

Alternatively, one may evade these constraints by considering light NP.