Imaginary yet observable τEDM

Probing CP violation in τ sector

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HIAS, UCAS

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J. P. Ma, C. Yang, Z. Y. Zou

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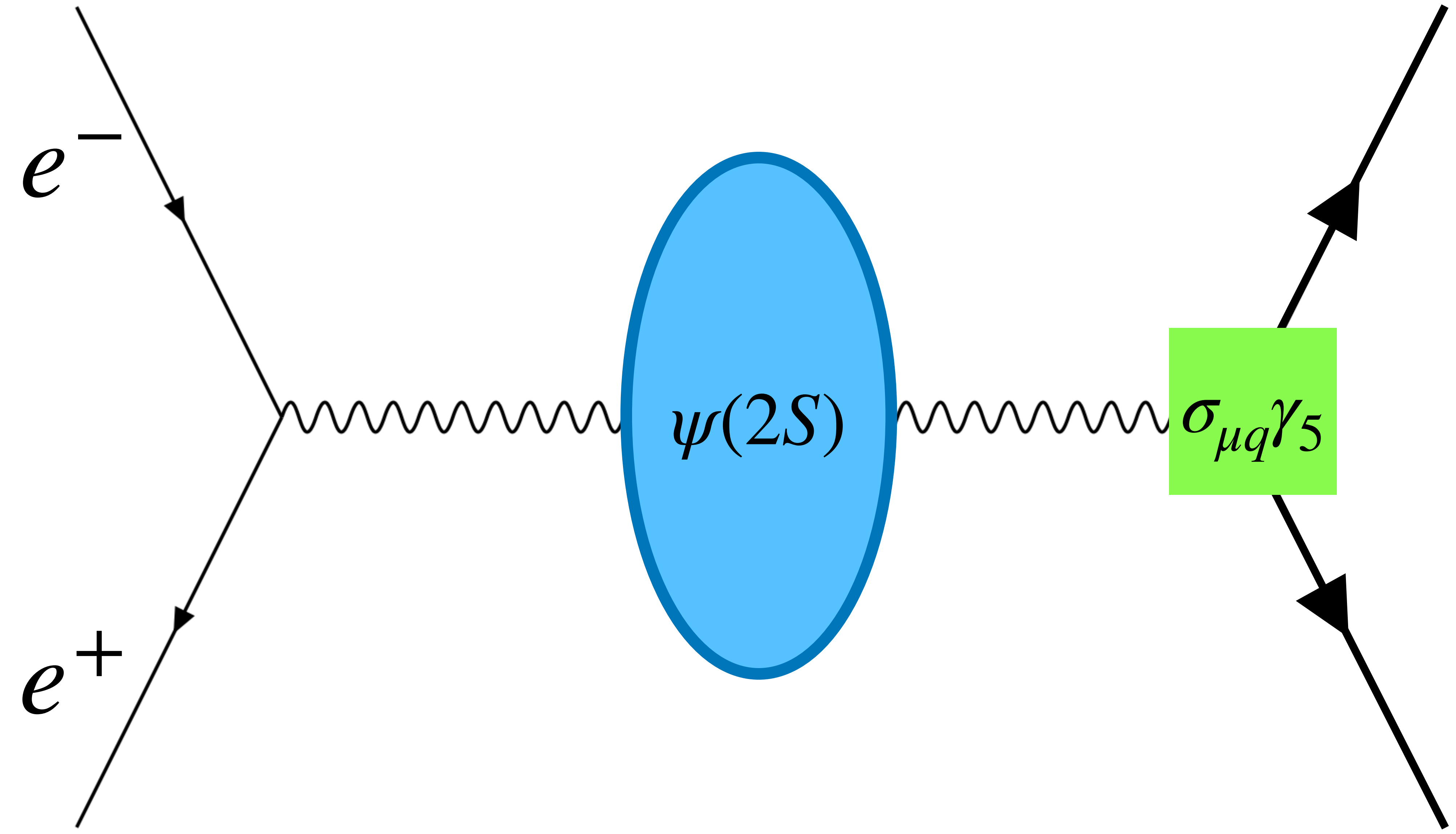
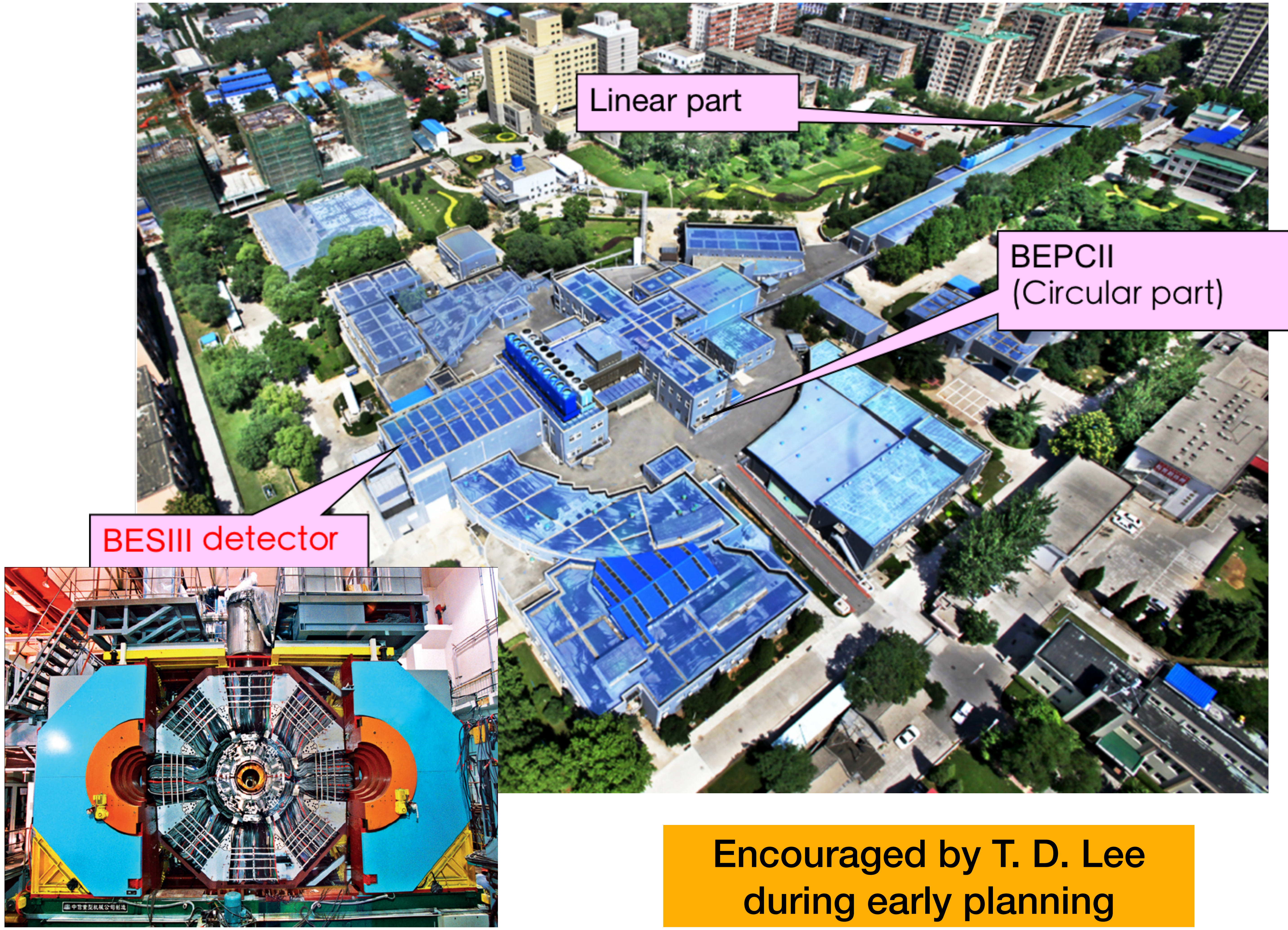
Overview

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

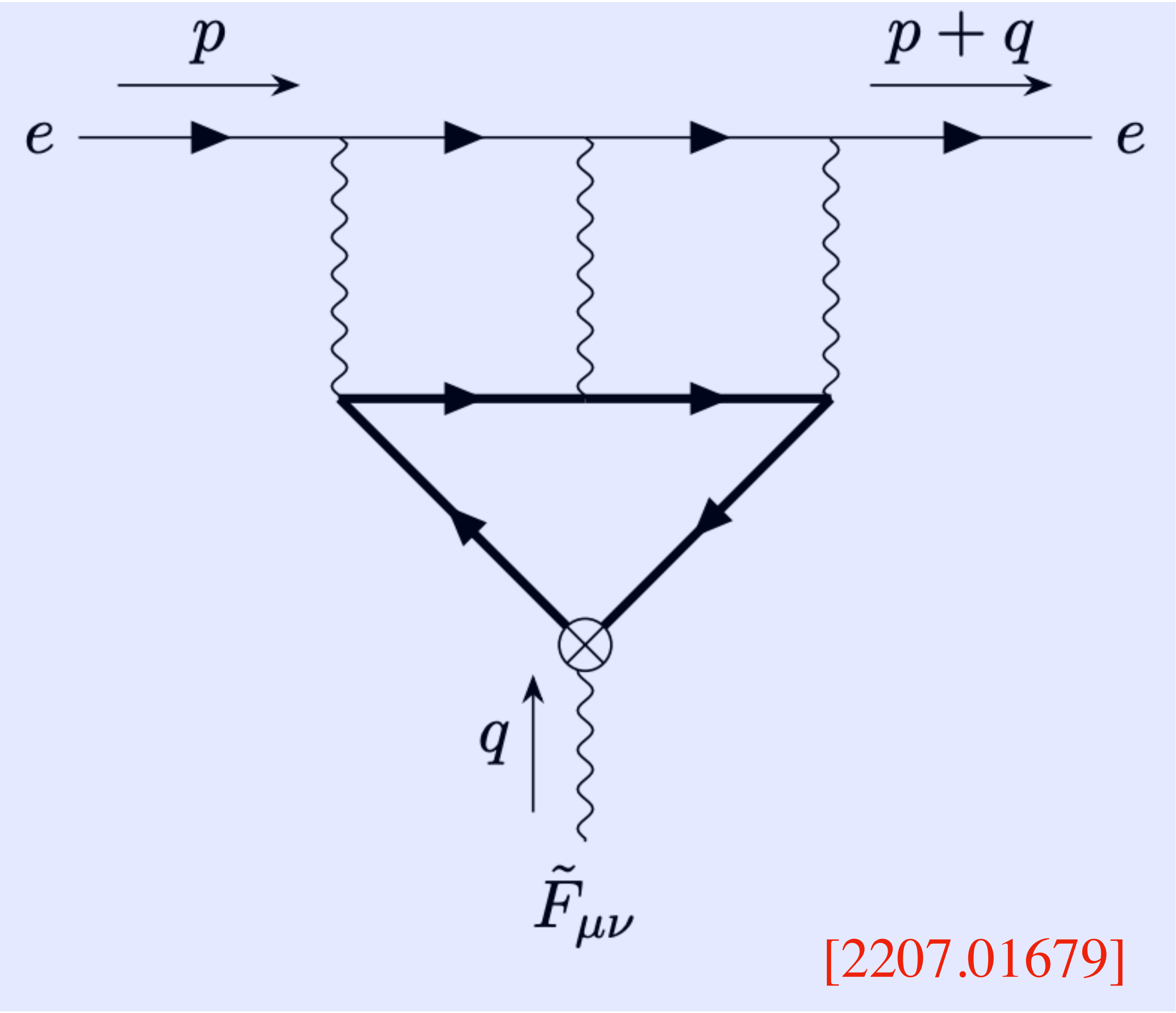




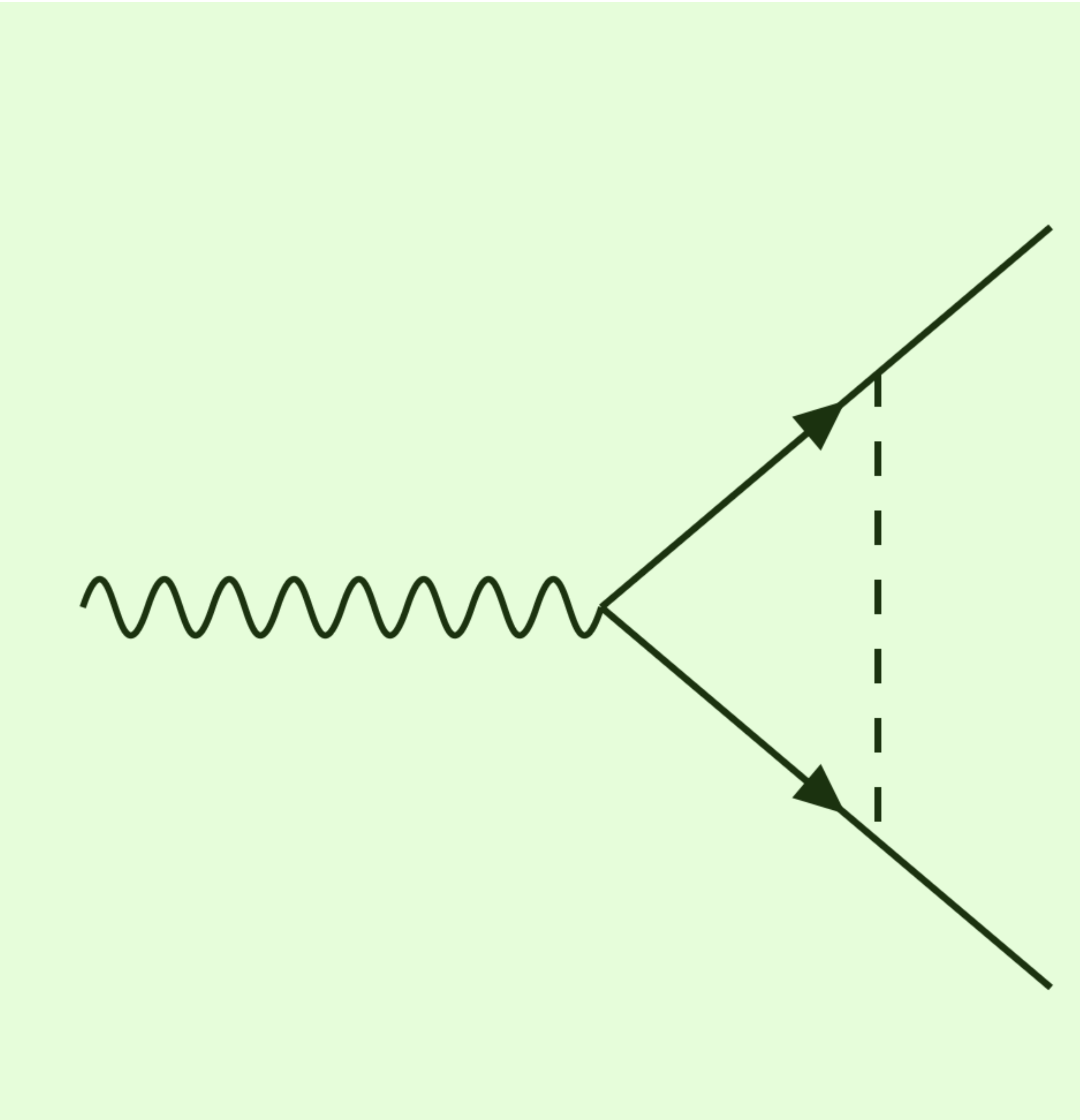
Encouraged by T. D. Lee during early planning

Overview

- τ and hyperons have **short lifetimes**.
- Traditional EDM measurement techniques are **not feasible**.
- May **induce** electron EDM.
- Can be probed directly at **colliders**.
- Experimental constraints on hyperon EDMs are currently in poor precisions.



[2207.01679]



Particle	Method	Upper limit	Particle	Method	Upper limit
e^-	Ion trap	4.1×10^{-30} e·cm	neutron	Hg*	1.4×10^{-26} e·cm
μ^-	(g-2) storage ring	1.5×10^{-19} e·cm	proton	Hg*	1.7×10^{-25} e·cm
τ^-	From eEDM	4.1×10^{-19} e·cm	Λ	From nEDM	2×10^{-22} e·cm
τ^-	e^+e^- colliders	1.9×10^{-17} e·cm	Λ	e^+e^- colliders	5.5×10^{-19} e·cm

@ BELLE

@ BESIII

State-of-the-art upper limits of $|d_f|$ at 90% confidence level

Timelike EDM

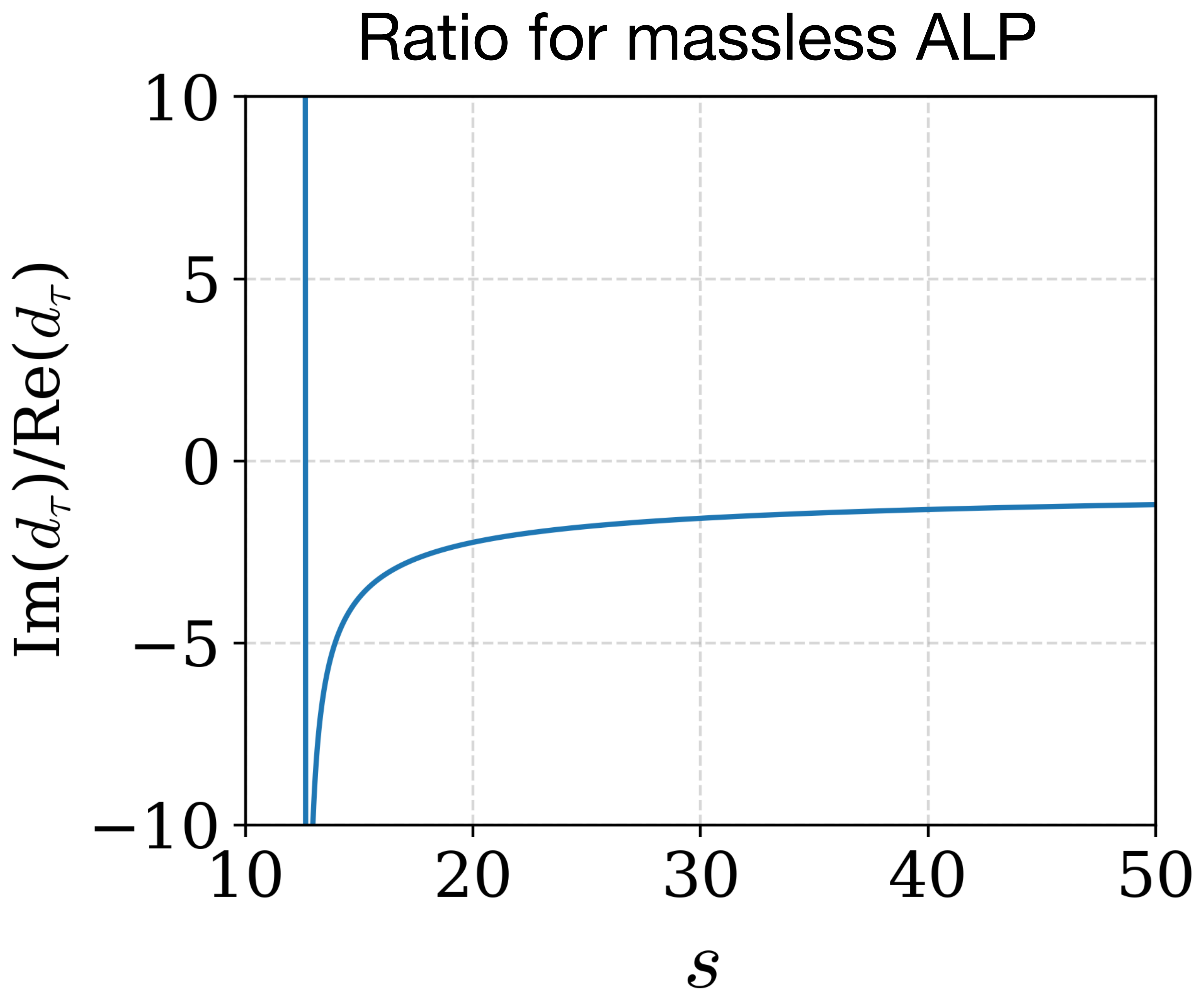
- EDM is **timelike** here, unlike the usual case.

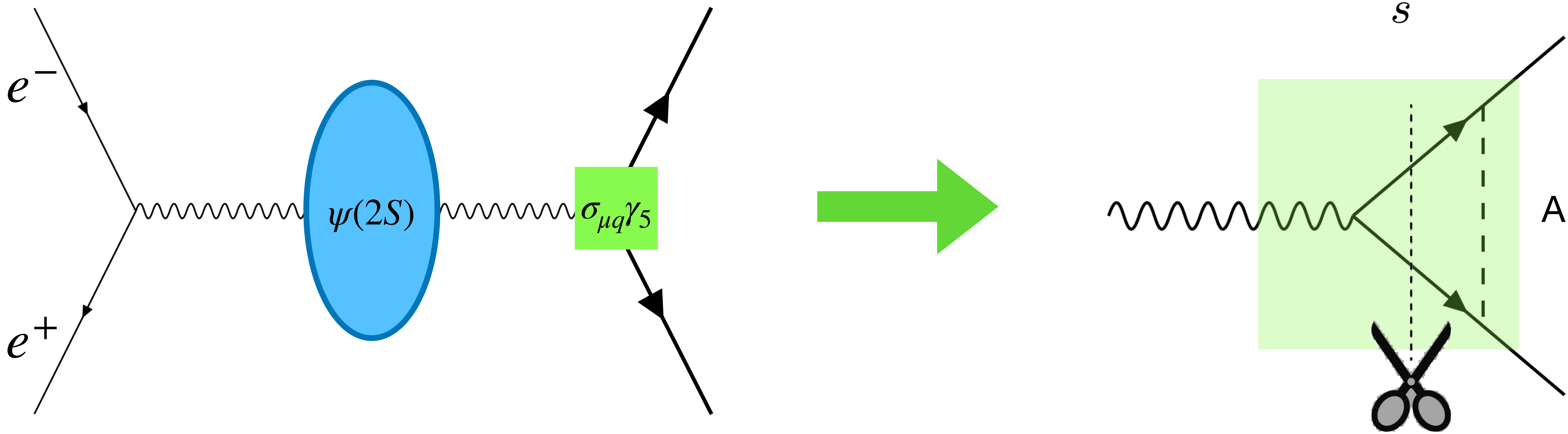
$$\mathscr{A}^{\mu} = \bar{u}\left(\gamma^{\mu}F_V + \frac{i}{2m}\sigma^{\mu q}H_{\sigma} + \gamma^{\mu}\gamma^5 F_A + \sigma^{\mu q}\gamma^5 H_T\right)v$$

- Intermediate particles are on shell :

  → EDM develops a **imaginary** part.

- It is more sensitive to some of the NP model.





ALP, 2HDM…

Timelike EDM

- To extract the timelike EDM, we square the amplitude:

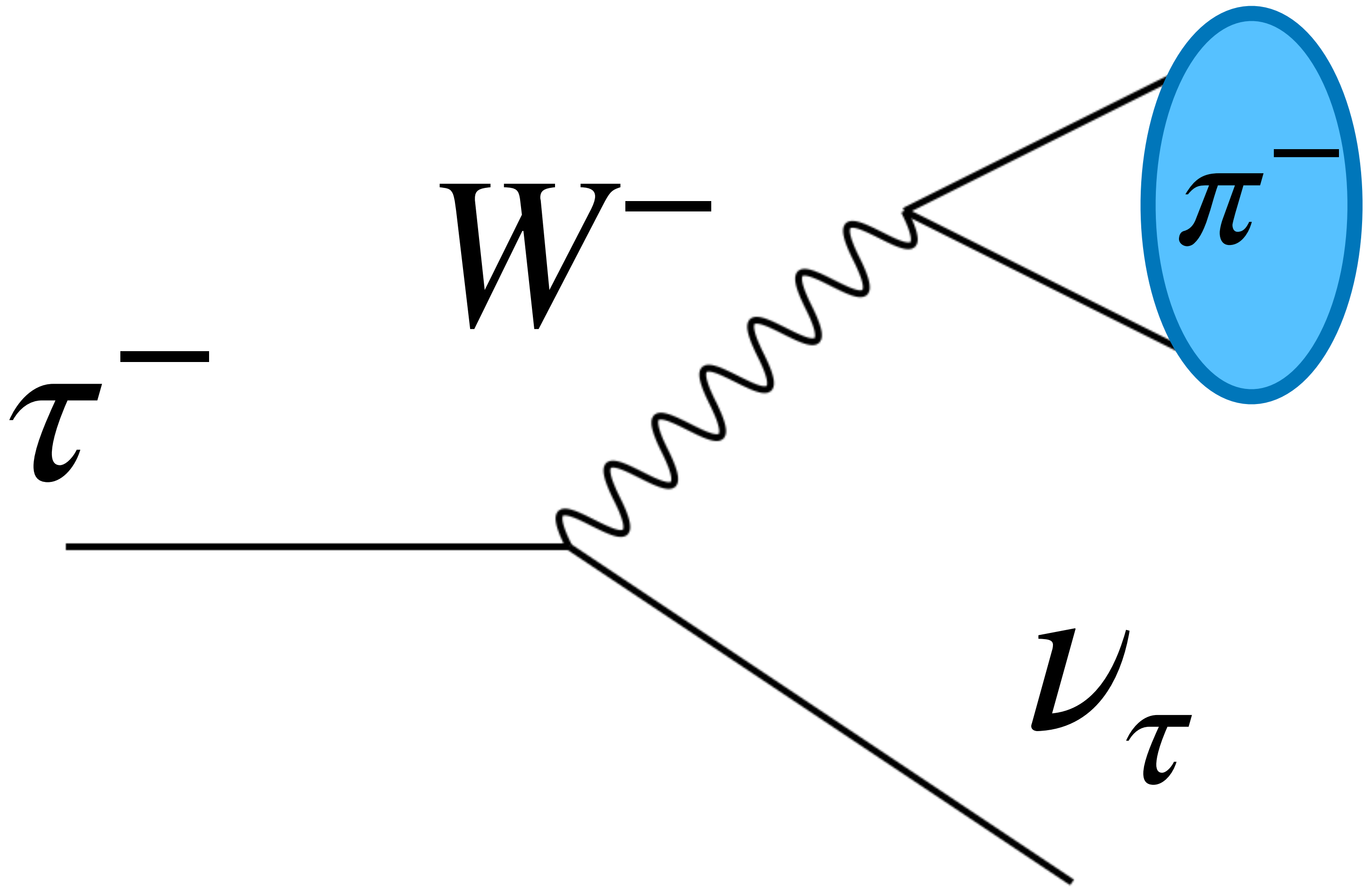
Polarization fraction

$$\frac{\partial\Gamma}{\partial\vec{\Omega}} = \sum_{\epsilon} P_{\epsilon} \left| \epsilon_\mu \, \bar{u}\left(\gamma^\mu F_V + \frac{i}{2m}\sigma^{\mu q}H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu q}\gamma^5 H_T\right)v \right|^2$$

$$\propto 1 + \vec{B}_+ \cdot (\vec{s}_- + \vec{s}_+) + \vec{B}_- \cdot (\vec{s}_- - \vec{s}_+) - \vec{s}_+ \cdot \overleftrightarrow{C} \cdot \vec{s}_-$$

$\vec{s}_\pm =$ spin of $\tau^\pm$

$\vec{B}, \overleftrightarrow{C}$ are CP even, while $\vec{s}_+ \xleftrightarrow{CP} \vec{s}_-$. CPV is gauged by the asymmetry of $\vec{s}_\pm$.

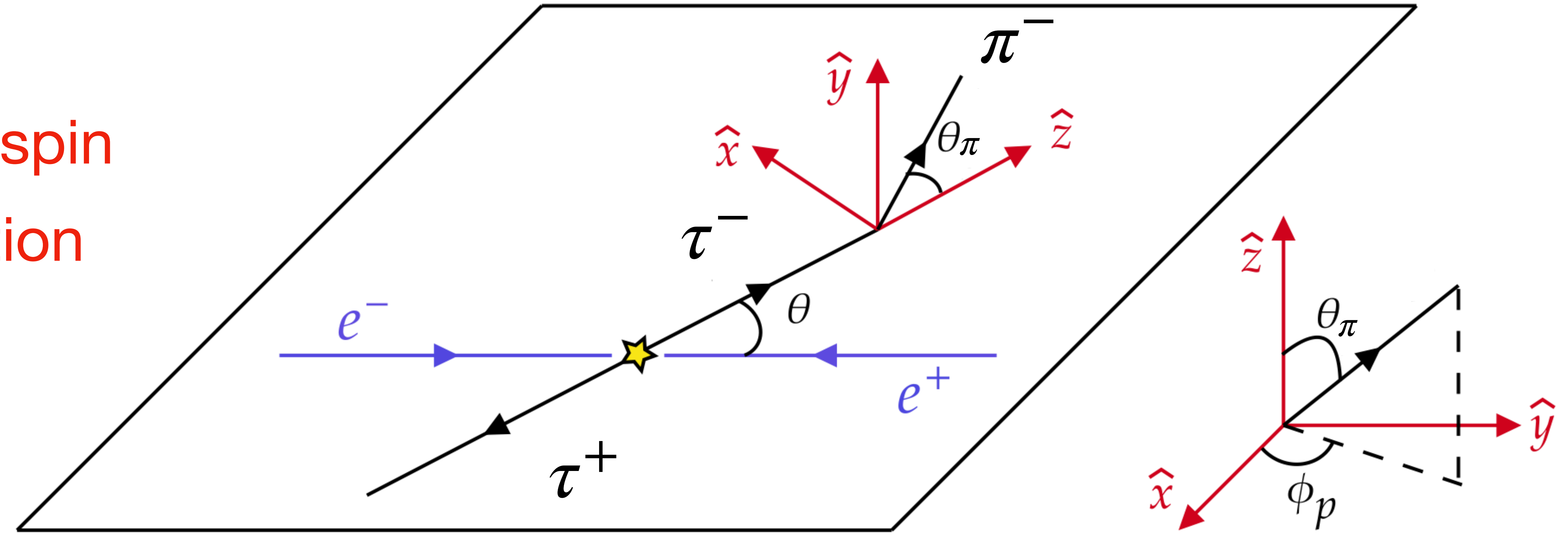


Carry τ^- spin information

In the SM, ν_τ must be left-handed

$\rightarrow \langle \vec{p}_{\pi^-} \rangle = \langle \vec{s}_{\nu_\tau} \rangle = \langle \vec{s}_- \rangle$ and $\langle \vec{p}_{\pi^+} \rangle = -\langle \vec{s}_{\bar{\nu}_\tau} \rangle = -\langle \vec{s}_+ \rangle$.

*Special thanks to Stephen Olsen



[2204.11058]

Timelike EDM

- Net results of the EDM formula:

Polarization fraction of τ^-

Polarization fraction of τ^+

$$\mathrm{Im}\left(d_\tau\right) = -\frac{3}{4}\frac{e\left(s+2m_\tau^2\right)}{m_\tau\sqrt{s}\sqrt{s-4m_\tau^2}}\left(\left\langle \hat{p}_{\pi^-}\cdot\hat{k}\right\rangle + \left\langle \hat{p}_{\pi^+}\cdot\hat{k}\right\rangle\right)$$

No need for simultaneous detection of $\tau^- \to \pi^-\nu_\tau$ and $\tau^+ \to \pi^+\overline{\nu}_\tau$.

$$\mathrm{Re}\left(d_\tau\right) = e\frac{9}{4}\frac{s+2m_\tau^2}{m_\tau\sqrt{s^2-4sm_\tau^2}}\left\langle\left(\hat{p}_{\pi^-}\times\hat{p}_{\pi^+}\right)\cdot\hat{k}\right\rangle$$

Need for simultaneous detection of $\tau^- \to \pi^-\nu_\tau$ and $\tau^+ \to \pi^+\overline{\nu}_\tau$.

Statistics is suppressed by $\sqrt{\mathscr{BF}}$.

$\sqrt{s}$	$m_{\psi(2S)}$	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
$\delta_{\mathrm{Re}}(130\mu\mathrm{m})$	83	9.4	5.0	4.0	3.6	3.5

Resolution of detectors

Expected Precisions @ STCF in units of $10^{-18}e$cm

Timelike EDM

- The momenta **cannot** be fully reconstructed.

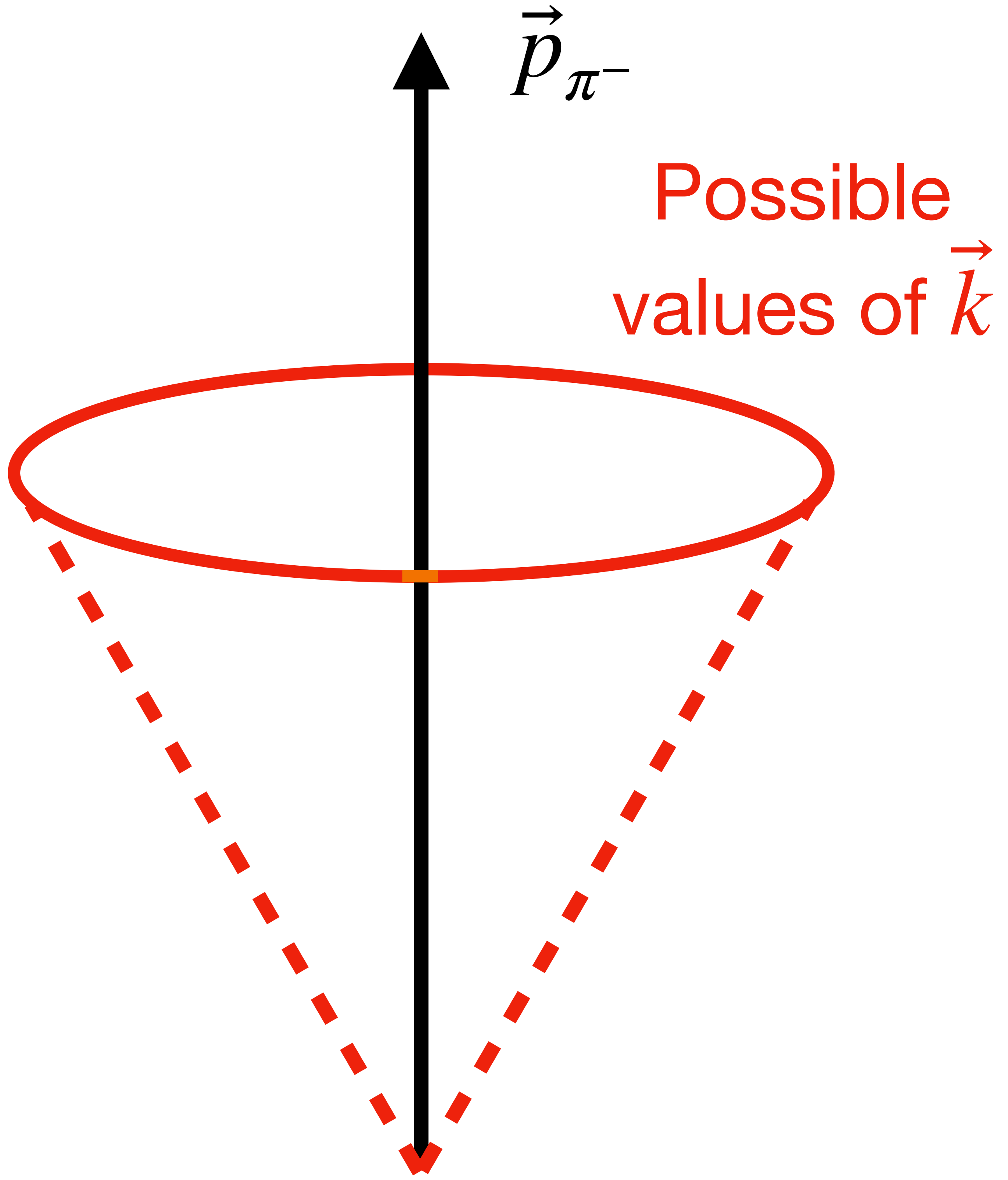
Undetermined

$$\mathrm{Im}\left(d_\tau\right) = -\frac{3}{4}\frac{e\left(s+2m_\tau^2\right)}{m_\tau\sqrt{s}\sqrt{s-4m_\tau^2}}\left(\left\langle \hat{p}_{\pi^-}\cdot\hat{k}\right\rangle + \left\langle \hat{p}_{\pi^+}\cdot\hat{k}\right\rangle\right)$$

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

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

- With E_π , we can determine $\hat{p}_{\pi^\pm}\cdot\hat{k}$ and $\hat{k}$ up to a circle.



$\sqrt{s}$	$m_{\psi(2S)}$	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

Table. Precision at STCF in units of $10^{-18}e$cm, an order better than current data.

Timelike EDM

$\sigma_{xy} = 130\ \mu\text{m} \longrightarrow 30\ \mu\text{m}$

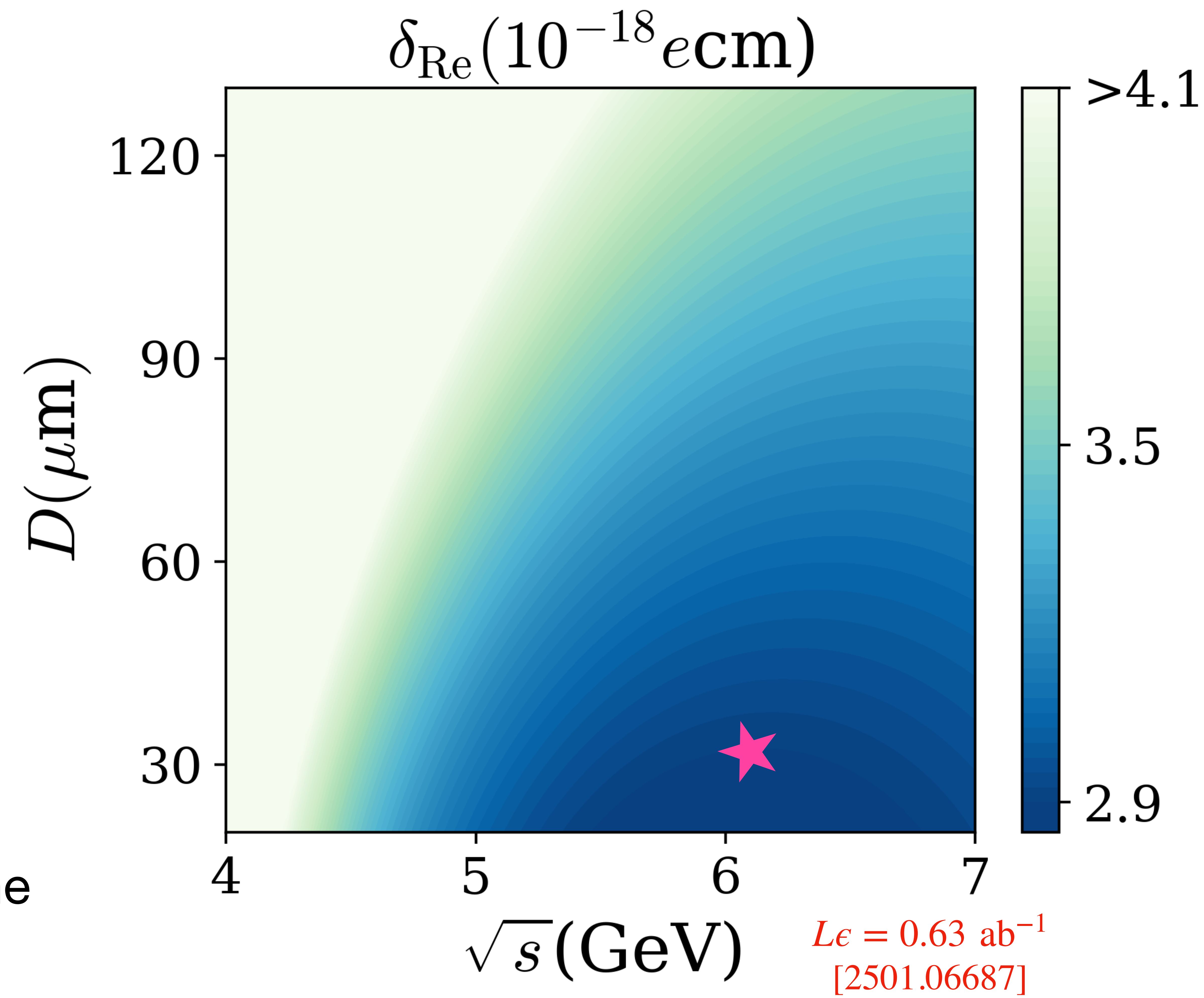
- We propose to add **silicon pixel detectors** at **STCF** and filter the fast decay events.

$\sqrt{s}$	$m_{\psi(2S)}$	5.6 GeV	6.3 GeV
δ_{Im}	1.8	0.7	0.7
$\delta_{\text{Re}}(180)$	235	4.9	4.2
$\delta_{\text{Re}}(130)$	83	4.0	3.6
$\delta_{\text{Re}}(80)$	29	3.3	3.1
$\delta_{\text{Re}}(30)$	11	2.9	2.8

Table. Precision of d_τ with $D = 180,\ 130\ldots$

- As the central energy $\sqrt{s}$ goes up $D_0 \uparrow$ but scattering width $\sigma \downarrow$.

- ★ sweet spot @$\sqrt{s} = 6.3\ \text{GeV}$, pushing the upper bound to $10^{-18}\ e\text{cm}$.



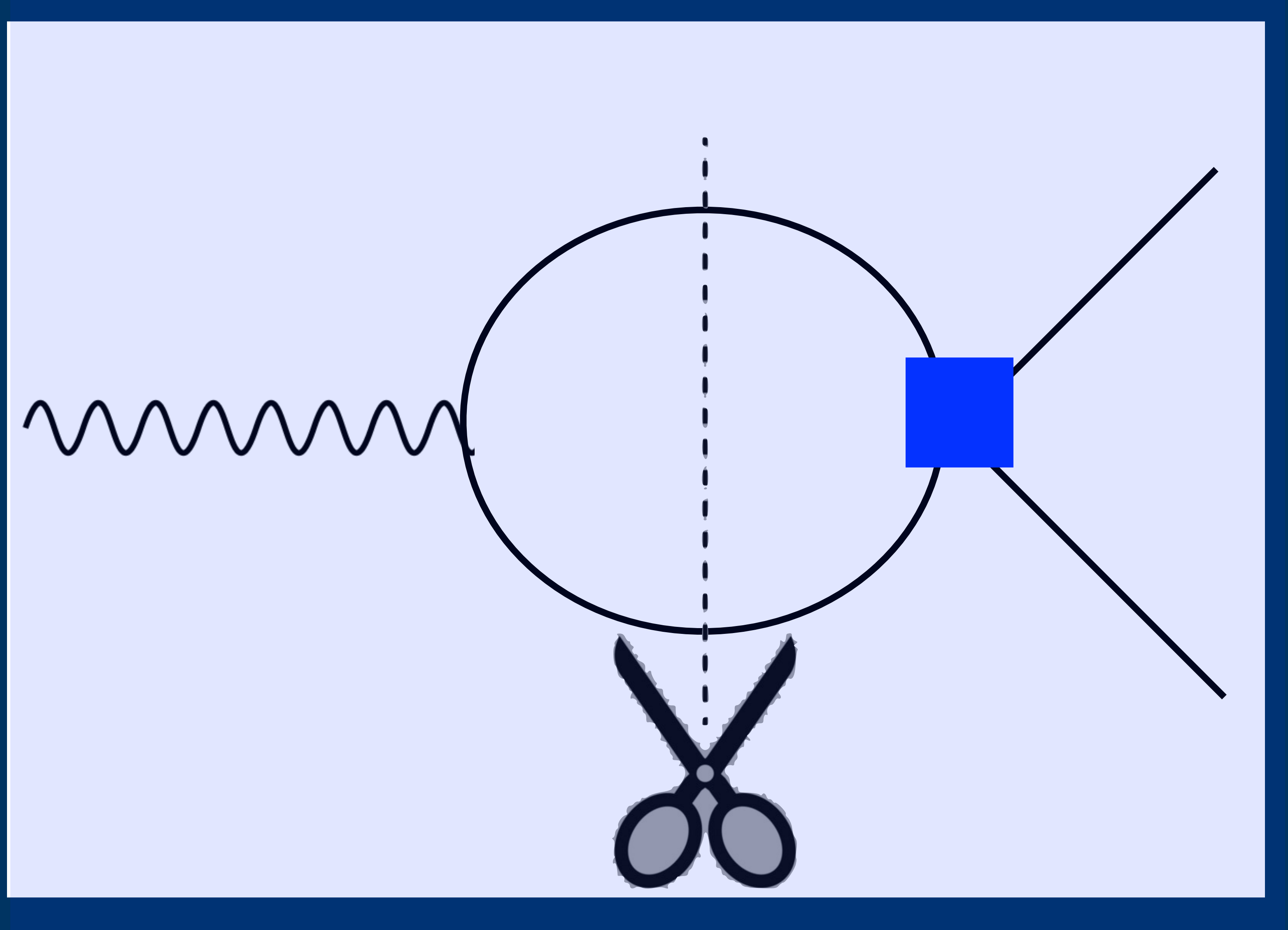
$L\epsilon = 0.63\ \text{ab}^{-1}$
[2501.06687]

See also [2511.03786]

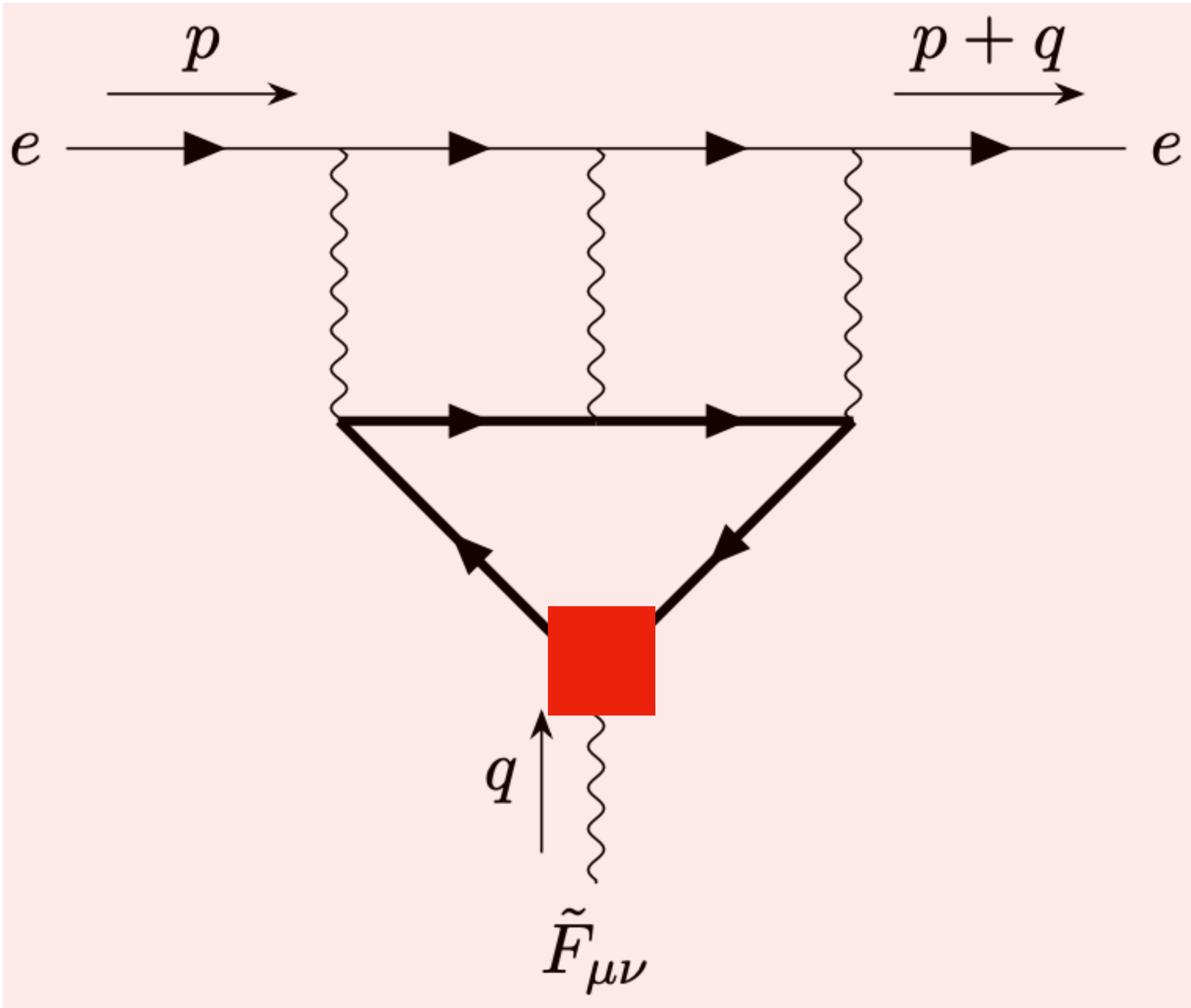
What NP we are looking at?

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

Colliders are sensitive to …



Tightly constrained by …

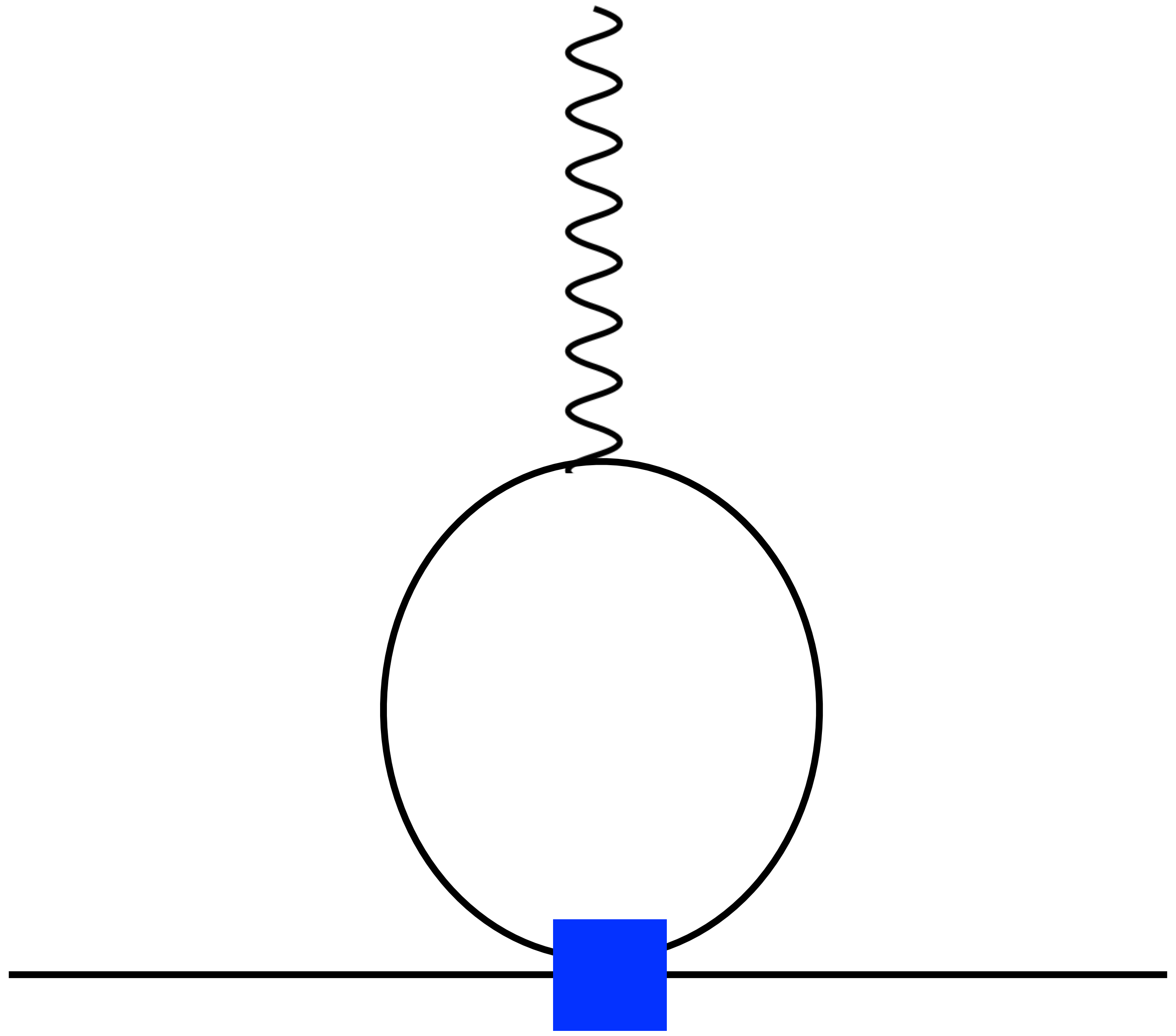


[2510.23348] with X. Y. Du, X. G. He, Z. L. Huang, Z. Y. Zou. See also [2511.03786]

- τ EDM - NP

For NP without new fermions : $d_\tau^0 \propto m_\tau/\Lambda^2 \sim C_{SP}^{\tau\tau}/\Lambda^2$, ($m_\tau$ for chiral flip)

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



At $q^2 = 0$, we have that :

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

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

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

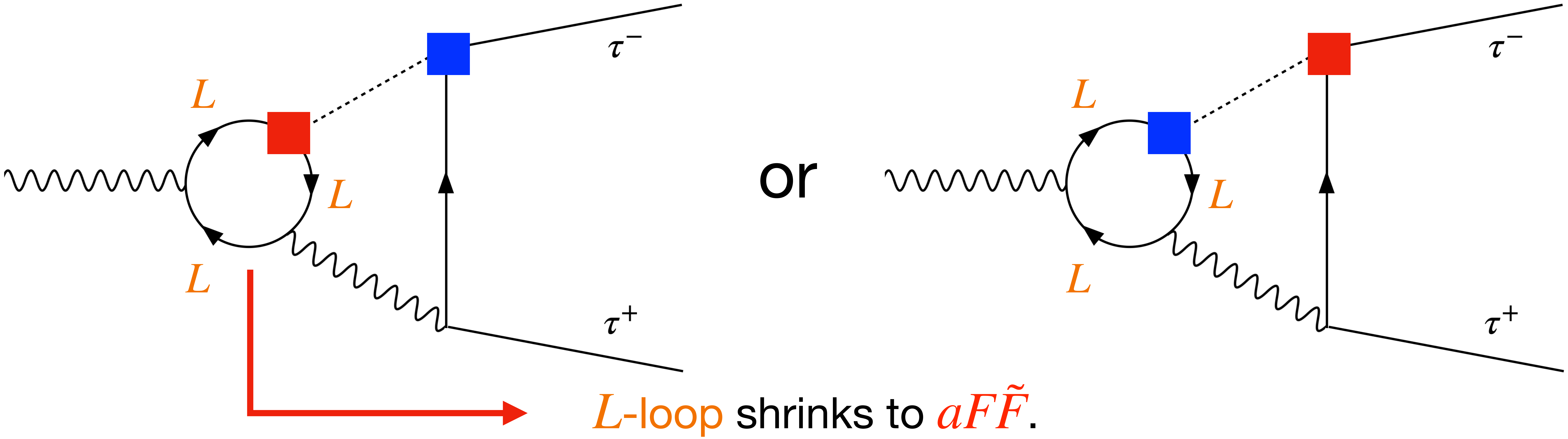
≈ 7 for TEV NP ←

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

τ EDM - ALP

Scenario 1: $\mathscr{L}_{\text{int}} = \tilde{g}_\tau a \bar{\tau}\tau + \frac{g}{4} aF\tilde{F}$, or $\mathscr{L}_{\text{int}} = g_\tau a \bar{\tau} i\gamma_5 \tau + \frac{\tilde{g}}{4} aF^2$

- ALP couples to new heavy fermion L and τ with ***opposite parities***.
- The Bar-Zee diagram receives ***no*** chiral enhancement, $m_\tau \sim m_a \sim \sqrt{q^2}$.
- $d_\tau \sim 10^{-21} e\text{cm}$, two orders smaller than precision at STCF 超级陶粲装置 Super Tau-Charm Facility .



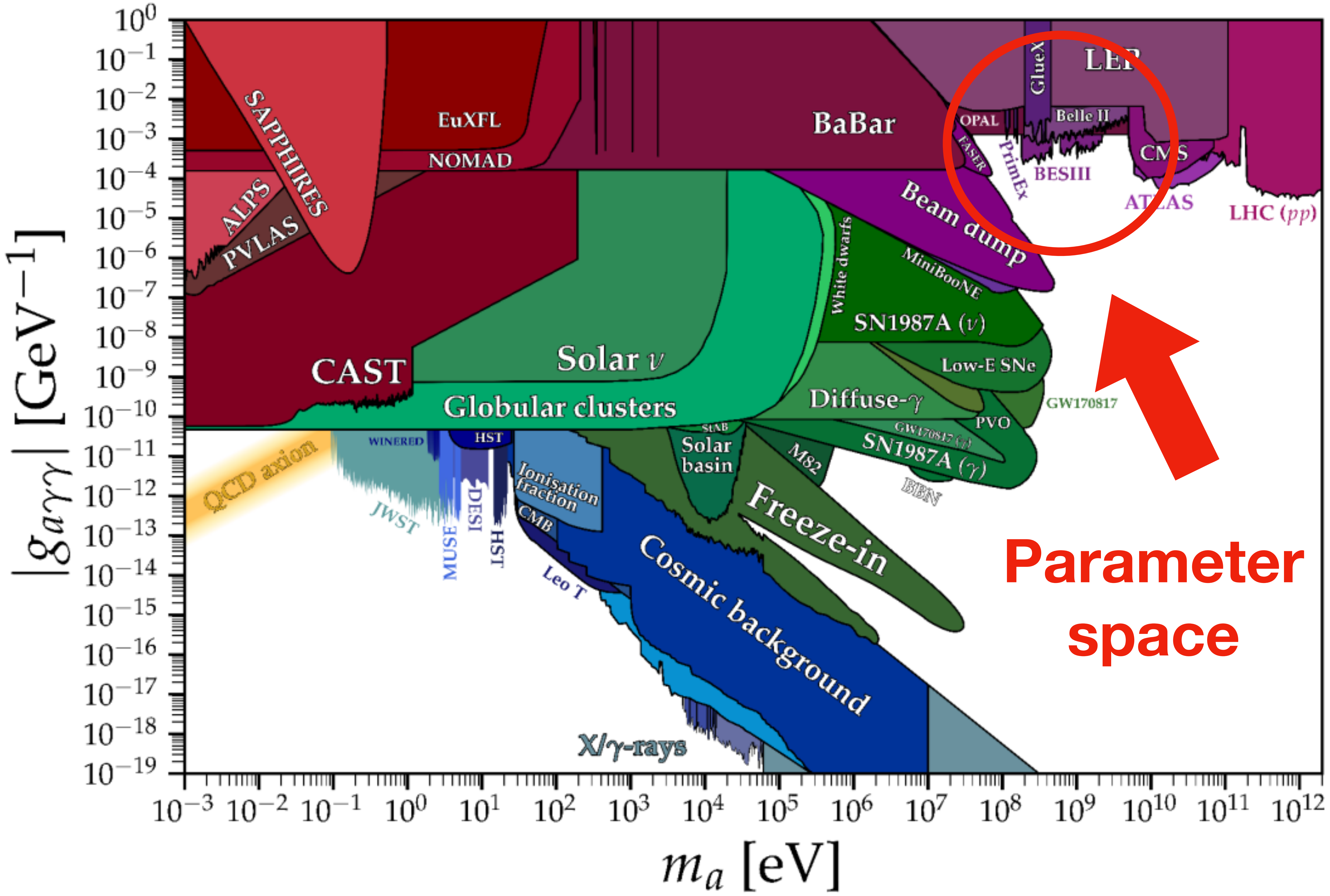
or

L-loop shrinks to $aF\tilde{F}$.

• τ EDM - ALP

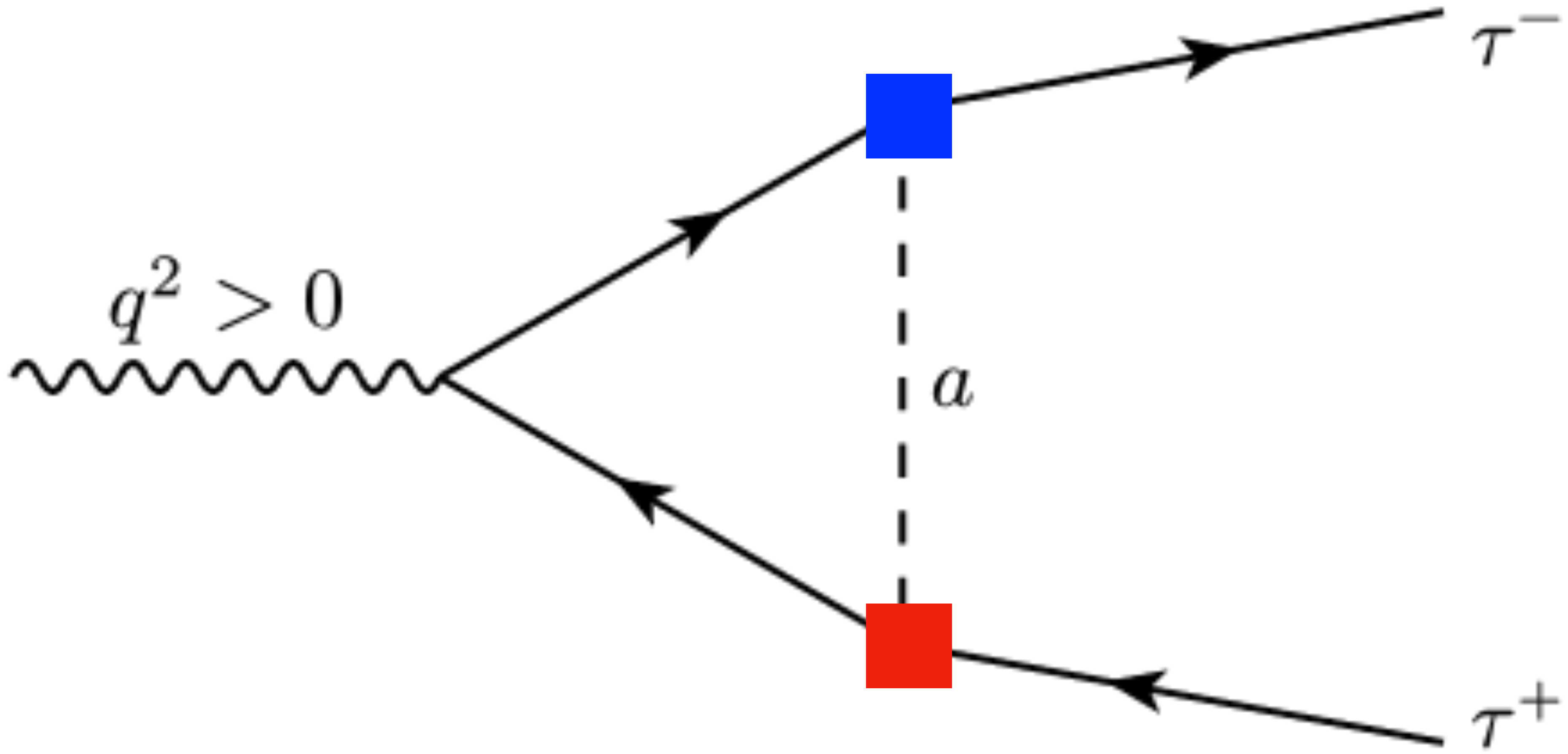
Scenario 2: $$\mathscr{L}_{\text{int}} = a\bar{\tau}(\tilde{g}_\tau + ig_\tau\gamma_5)\tau$$

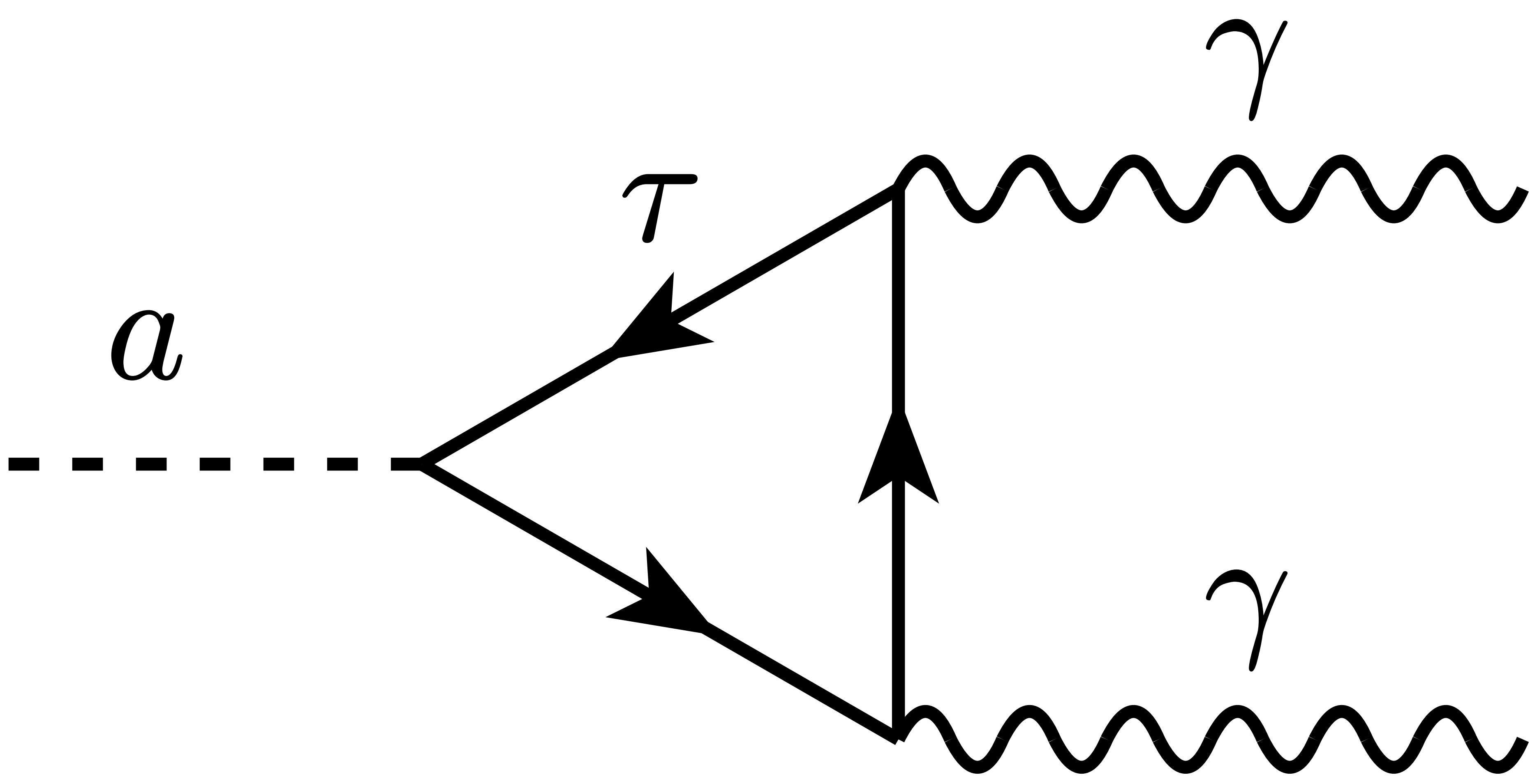
- ALP couples to τ with both ***parities***.
- The tightest constraint : $\gamma^* \to a\gamma$.



https://github.com/cajohare/AxionLimits

Parameter space

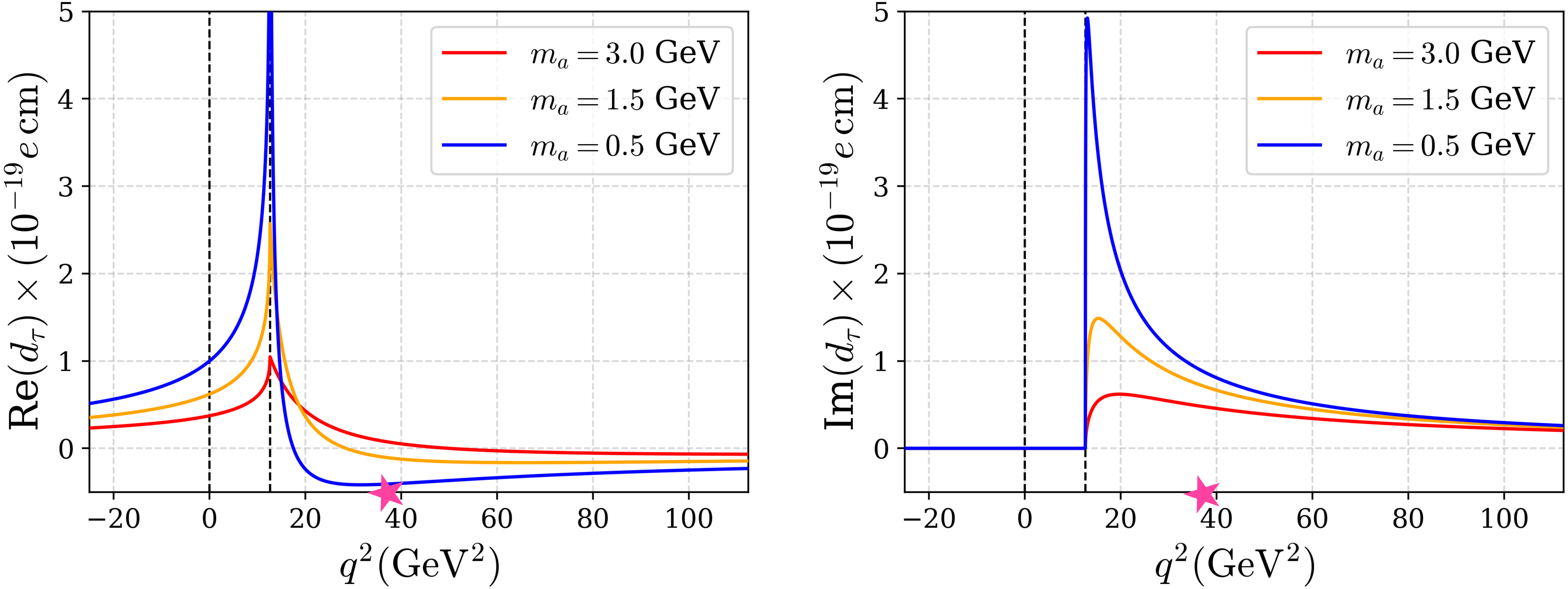




• τ EDM - ALP

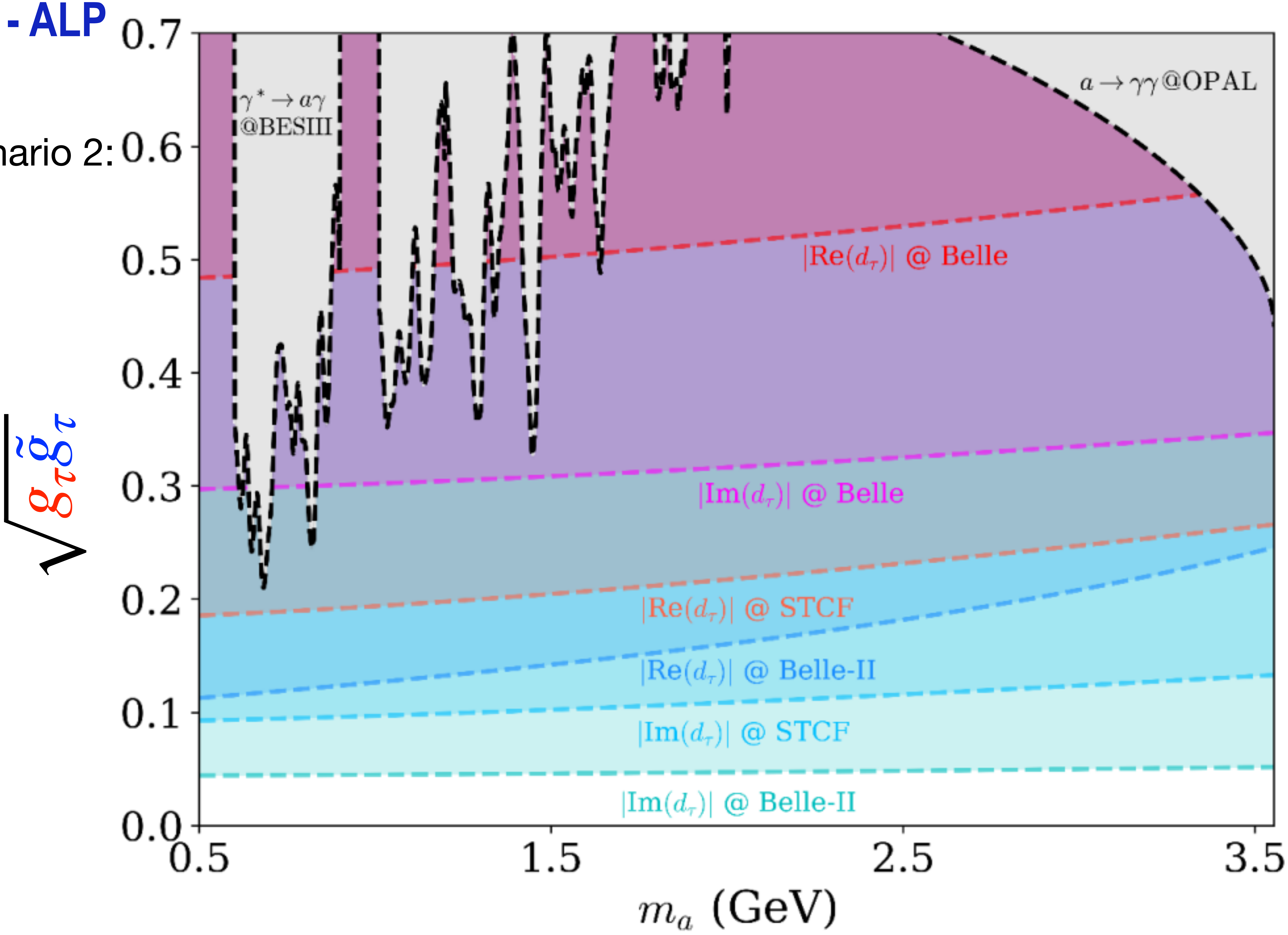
Scenario 2: $\mathscr{L}_{\text{int}} = a\bar{\tau}(\tilde{g}_\tau + i g_\tau \gamma_5)\tau$

★ sweet spot of STCF



- **τ EDM - ALP**

Scenario 2:



Conclusions

Timelike EDM opens a new window to probe NP at future τ colliders

STCF
超级陶粲装置
Super Tau-Charm Facility

$\mathrm{Im}(d_f)$ is sensitive to light NP and can be served as a complementary test of the conventional EDM.

Timelike EDM

- The momenta **cannot** be fully reconstructed.

Undetermined

$$\mathrm{Im}\left(d_\tau\right) = -\frac{3}{4}\frac{e\left(s+2m_\tau^2\right)}{m_\tau\sqrt{s}\sqrt{s-4m_\tau^2}}\left(\left\langle \hat{p}_{\pi^-}\cdot\hat{k}\right\rangle + \left\langle \hat{p}_{\pi^+}\cdot\hat{k}\right\rangle\right)$$

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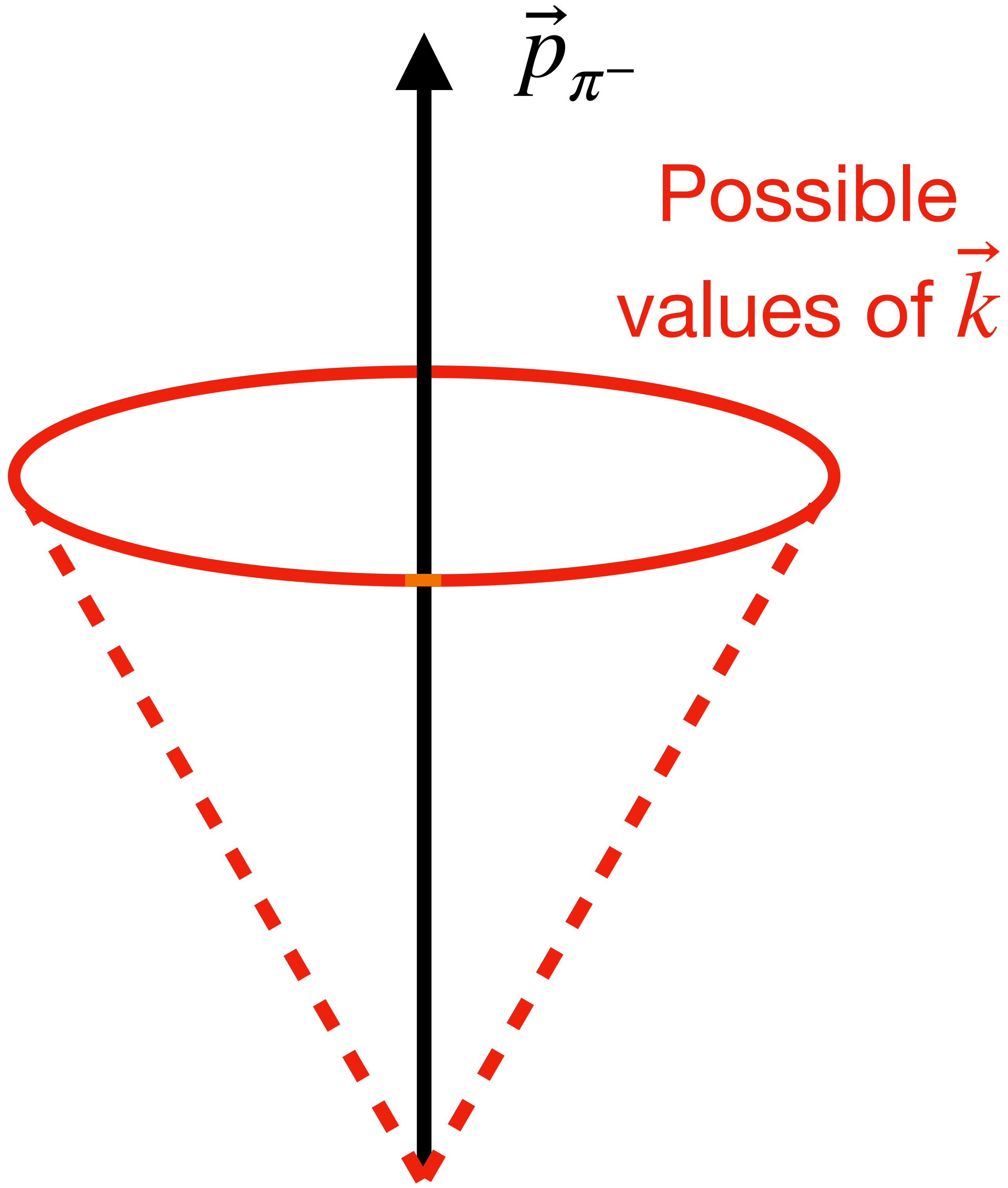

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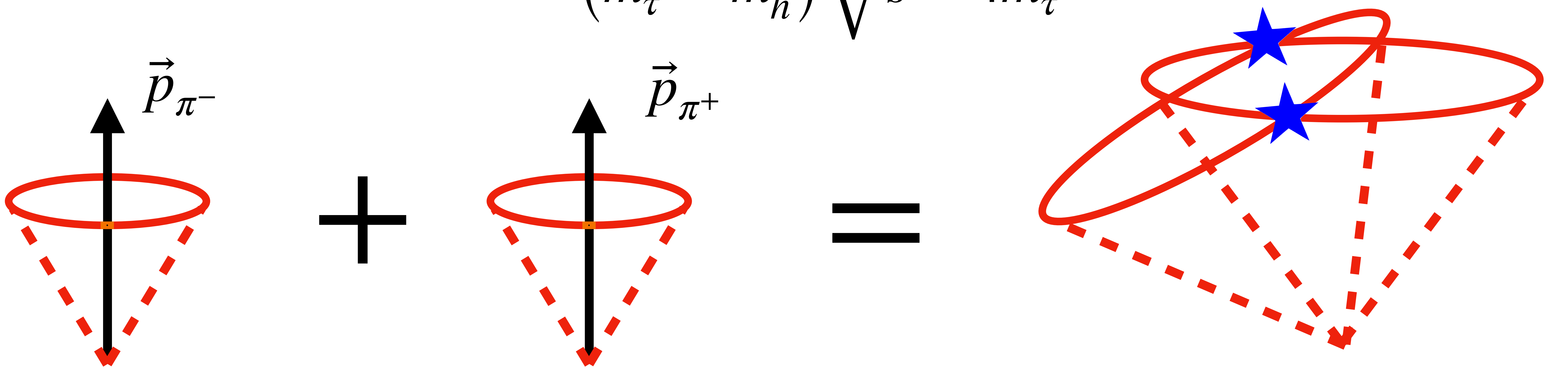
Table. Precision at STCF in units of $10^{-18}e$cm, an order better than current data.

• τ EDM

- Probing Re(d_τ) requires full construction of $\hat{k}$.

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



Two points related by CP transformation

- Combining constraints from both $\hat{p}_{\pi^+} \cdot \hat{k}$ and $\hat{p}_{\pi^-} \cdot \hat{k}$, we constrain $\hat{k}$ up to two points ★. Geometrical pictures are shown above.

$$\hat{k} = u\hat{p}_{\pi^+} + v\hat{p}_{\pi^-} \pm w\left(\hat{p}_{\pi^+} \times \hat{p}_{\pi^-}\right)$$

- The $u,\ v,\ w$ are known but $\pm$ represents the ambiguity of ★.

τ EDM

- At Belle, the **ambiguity** is treated as a random number.

$$\hat{k} = u\hat{p}_{\pi^+} + v\hat{p}_{\pi^+} \pm w\left(\hat{p}_{\pi^+} \times \hat{p}_{\pi^-}\right) \quad \rightarrow \quad \hat{k}_r = u\hat{p}_{\pi^+} + v\hat{p}_{\pi^+} + rw\left(\hat{p}_{\pi^+} \times \hat{p}_{\pi^-}\right)$$

- The r is taken to be either +1 or -1 ***randomly***.

$$\mathrm{Re}\left(d_\tau\right) = e\frac{9}{4}\frac{s + 2m_\tau^2}{m_\tau\sqrt{s^2 - 4sm_\tau^2}}\left\langle\left(\hat{p}_{\pi^-} \times \hat{p}_{\pi^+}\right) \cdot \hat{k}\right\rangle \neq 0\,,$$

but $\left\langle\left(\hat{p}_{\pi^-} \times \hat{p}_{\pi^+}\right) \cdot \hat{k}\right\rangle \neq \left\langle\left(\hat{p}_{\pi^-} \times \hat{p}_{\pi^+}\right) \cdot \hat{k}_r\right\rangle \propto \langle r \rangle = 0$ 😭

- $\mathrm{Re}\left(d_\tau\right) = (-6.2 \pm 6.3) \times 10^{-18} e\ \mathrm{cm}$ @Belle may be improved.

[2108.11543]

- Brief conclusion: measuring the full $\vec{k}$ is necessary for measuring $\mathrm{Re}\left(d_\tau\right)$.