Probing new physics at τ-charm factories

Strange and τ electric dipole moments

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HIAS, UCAS

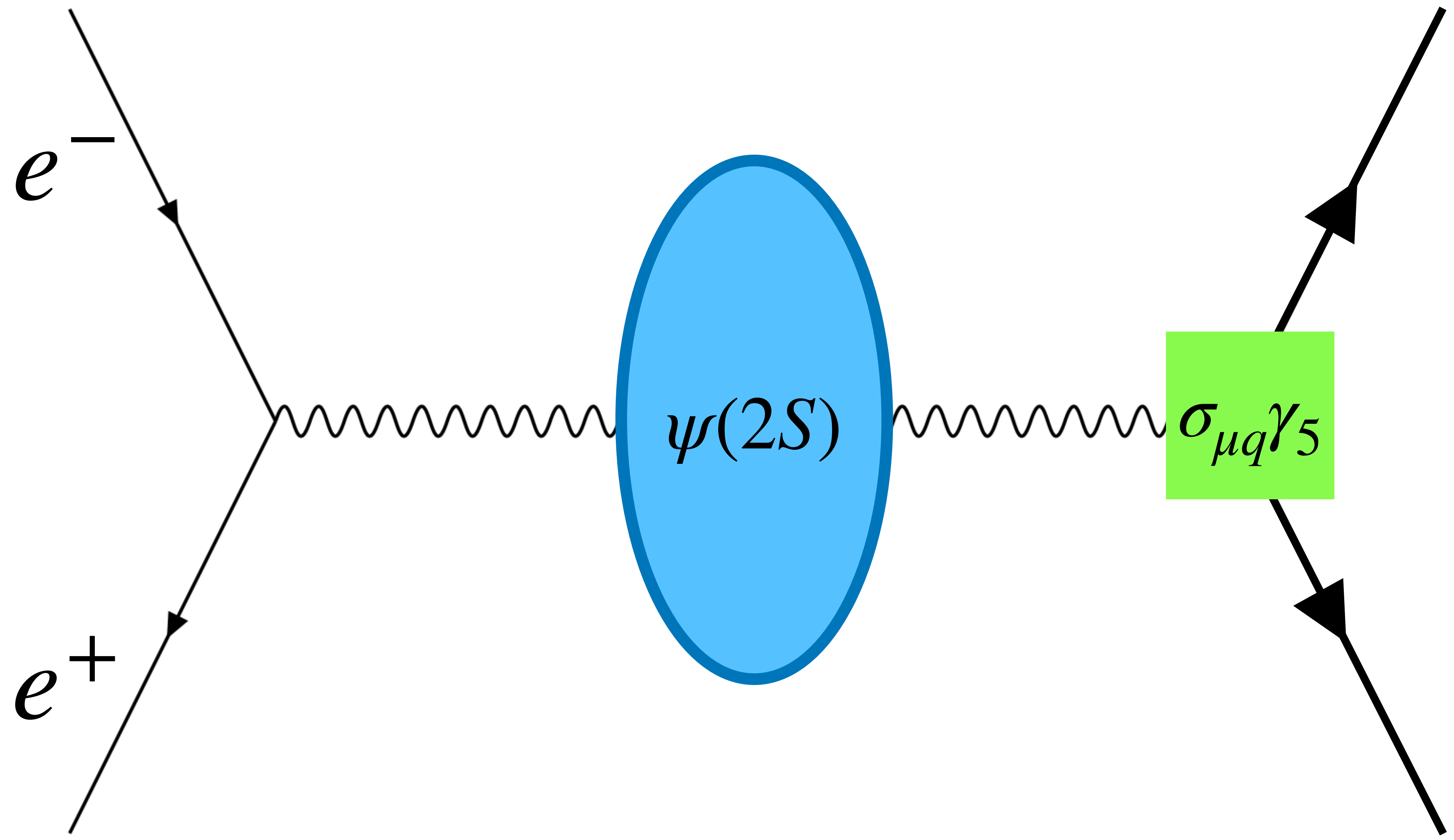
2501.06687,2602.14906;
X. G. He et al.
2602.14906;
C. Q. Geng et al.

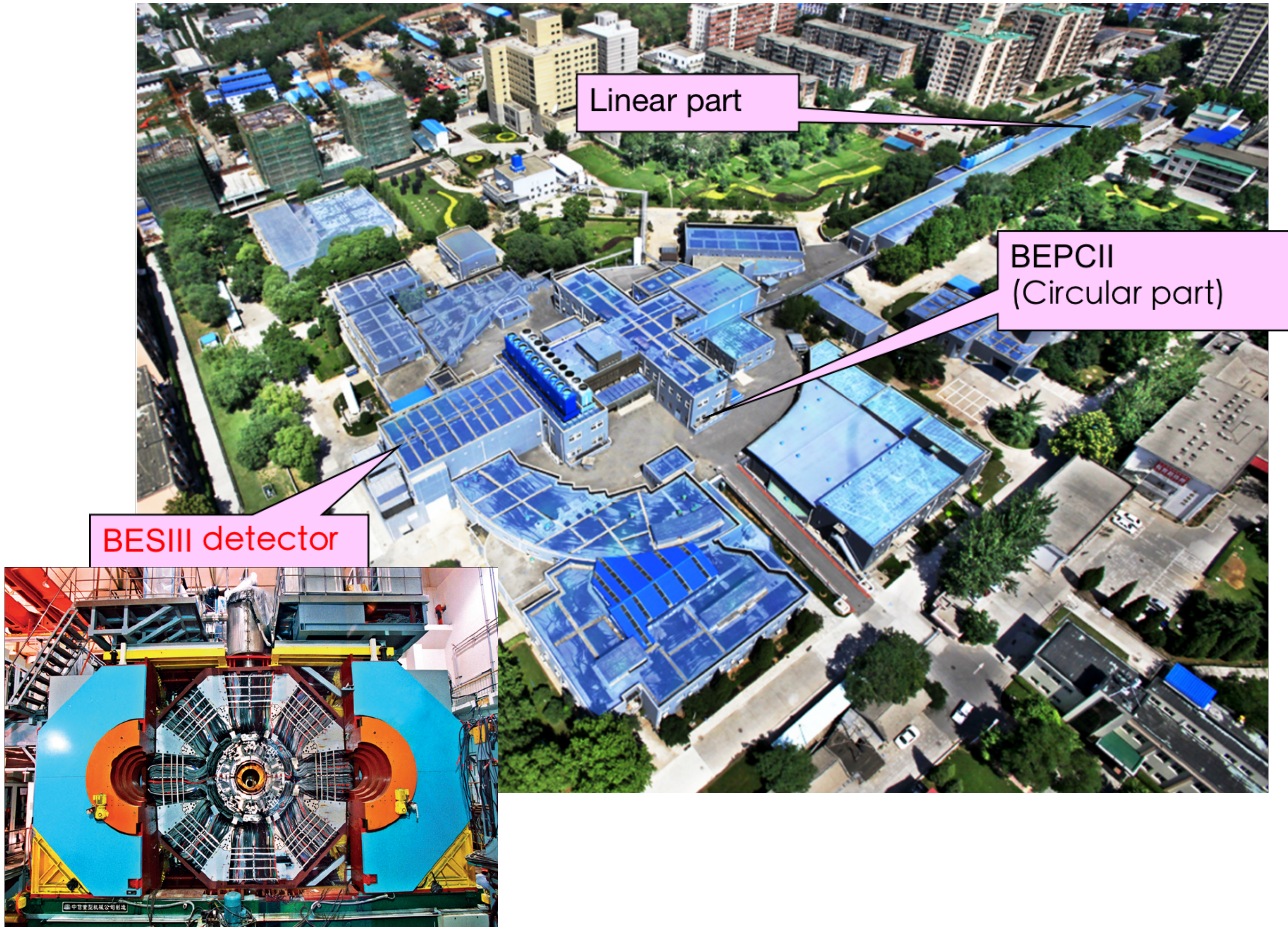
Apr 18, 2026

Overview

- Produced 2.7×10^9 $\psi(2s)$, around 10^7 events of $\psi(2s) \to \tau^-\tau^+$.

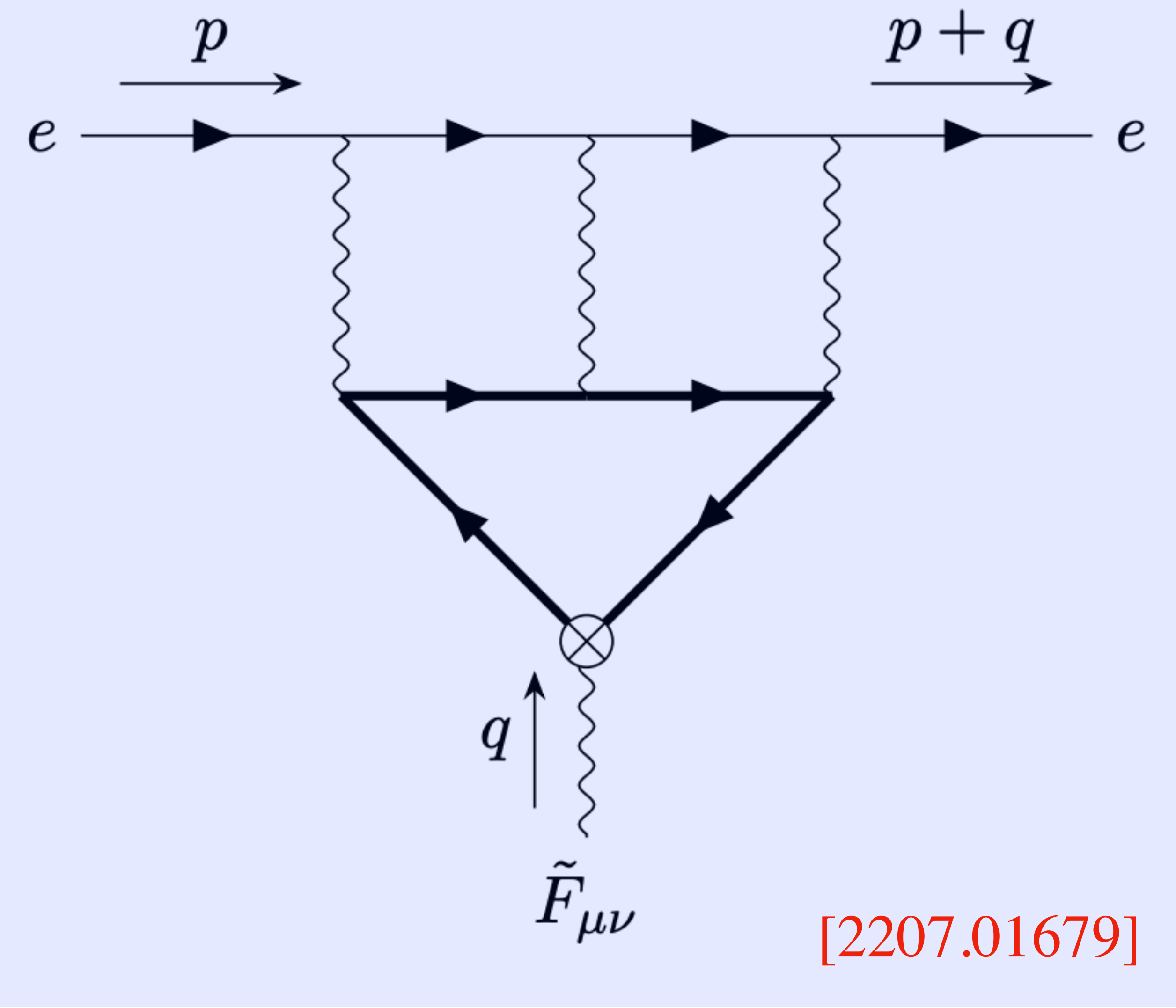
- Luminosity will be shifted forward by **two orders** in STCF.



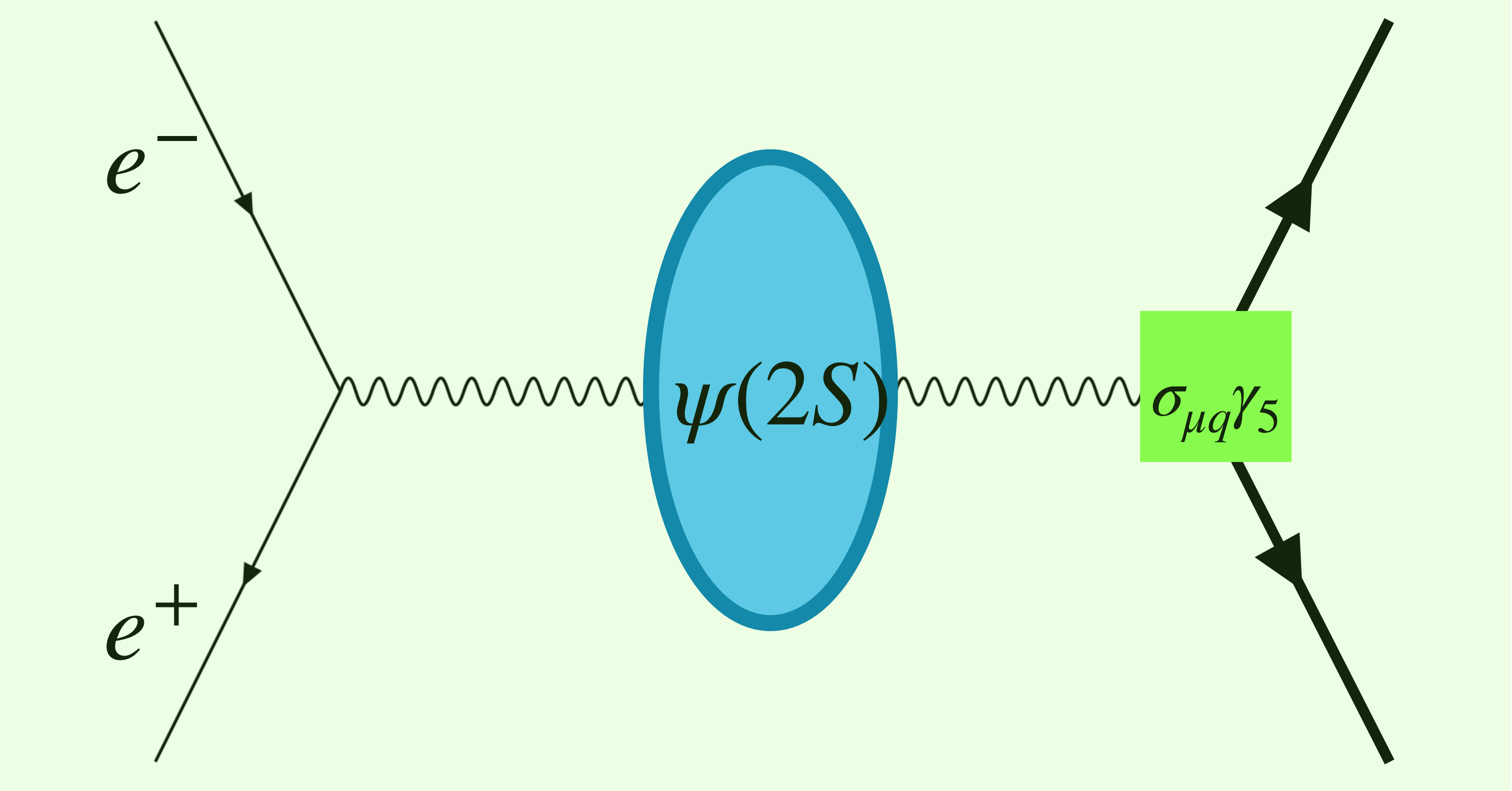


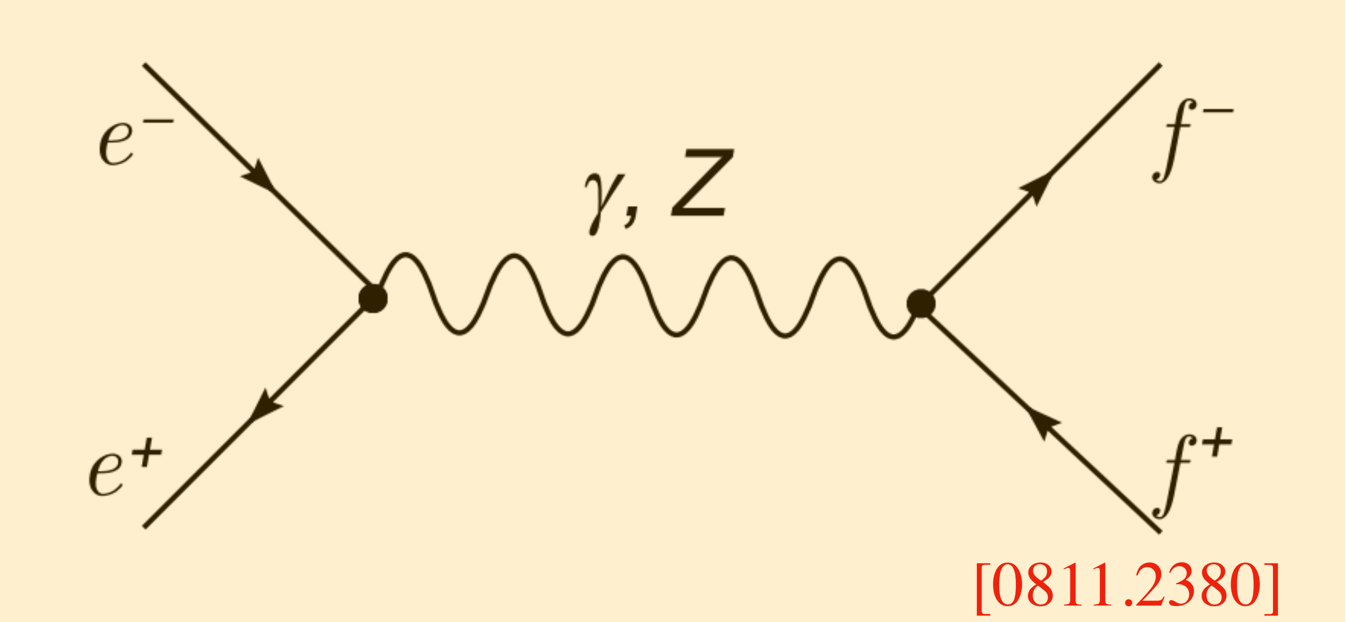
Overview

- Beyond the first generation, EDM measurements are limited by **short lifetimes**.
- Can be probed directly at **colliders**.



[2207.01679]





[0811.2380]

$\sim d_f^2$

Particle	Direct	Upper limit	Particle	Indirect	Upper limit
e^-	Ion trap	4.1×10^{-30} $e\cdot$cm	b	LEP	2×10^{-17} $e\cdot$cm
μ^-	(g-2) ring	1.5×10^{-19} $e\cdot$cm	c	LEP	5×10^{-17} $e\cdot$cm
neutron	Hg	1.4×10^{-26} $e\cdot$cm	τ^-	LEP	3×10^{-17} $e\cdot$cm
τ^-	e^+e^-	1.9×10^{-17} $e\cdot$cm	τ^-	eEDM	4.1×10^{-19} $e\cdot$cm
Λ	e^+e^-	5.5×10^{-19} $e\cdot$cm	Λ	nEDM	2×10^{-22} $e\cdot$cm

@ BELLE

@ BESIII

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

Timelike EDM

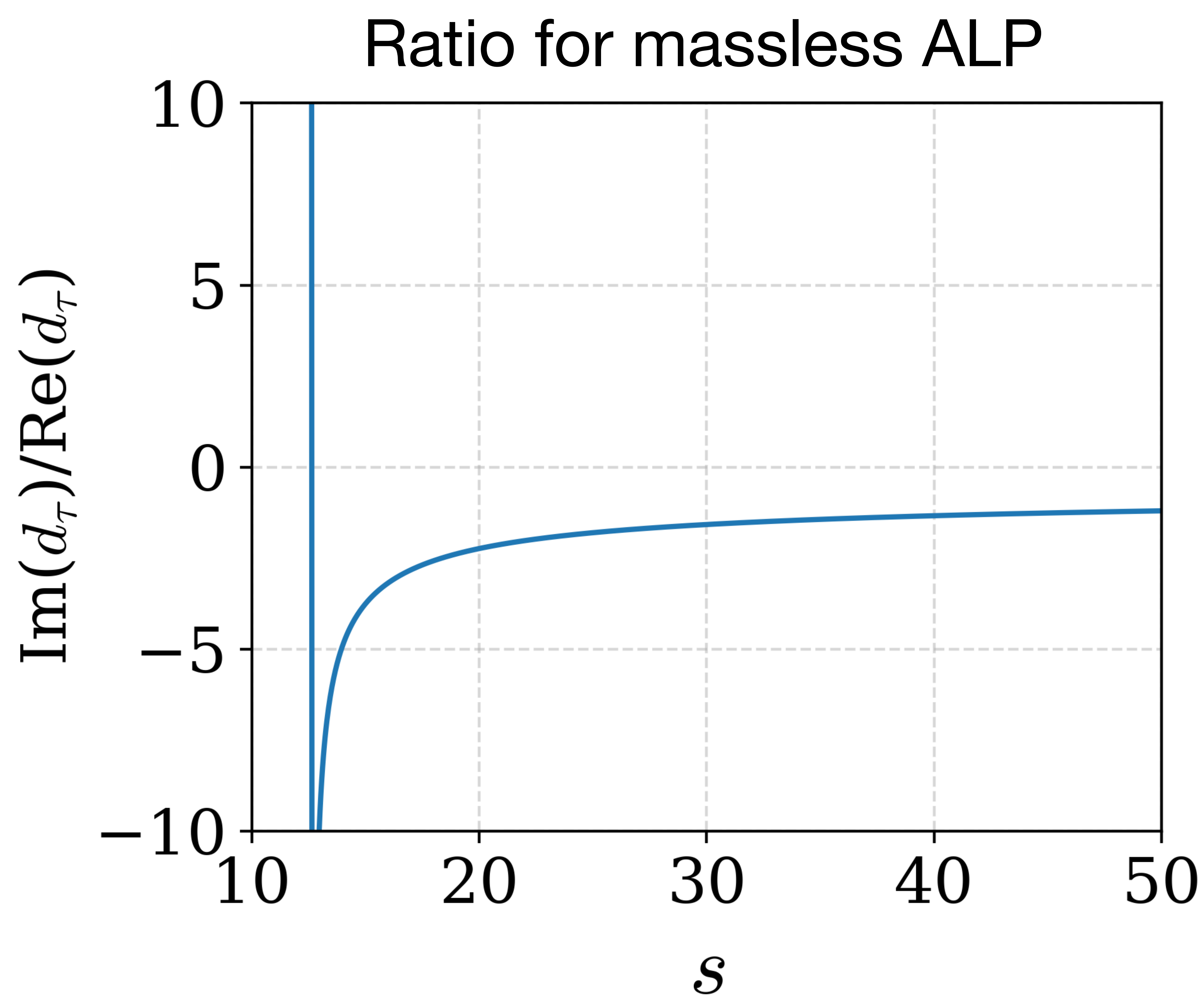
- EDM ***form factor*** is **timelike** here

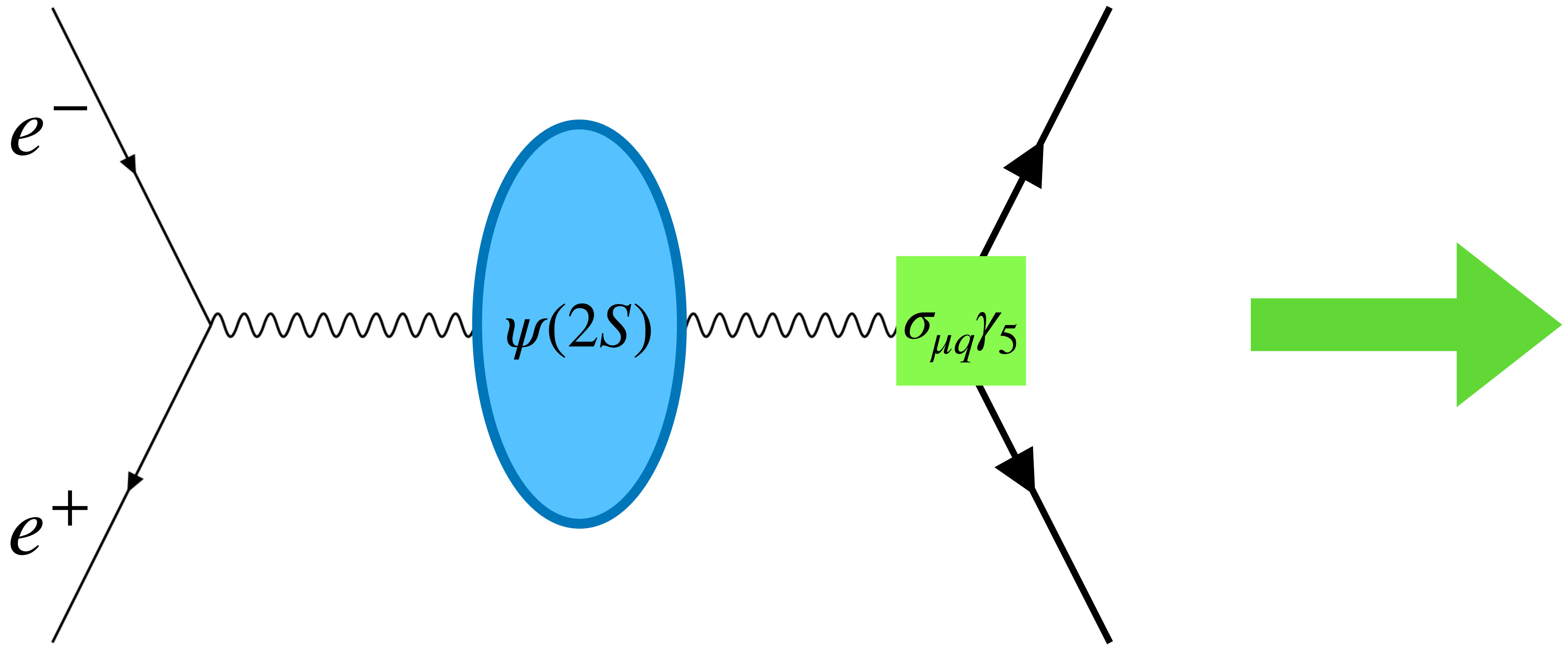
$$\mathscr{A}^{\mu} = \bar{u}\left(\gamma^{\mu}F_1 + \frac{i}{2m}\sigma^{\mu q}F_2 + \sigma^{\mu q}\gamma^5 F_3\right)v$$

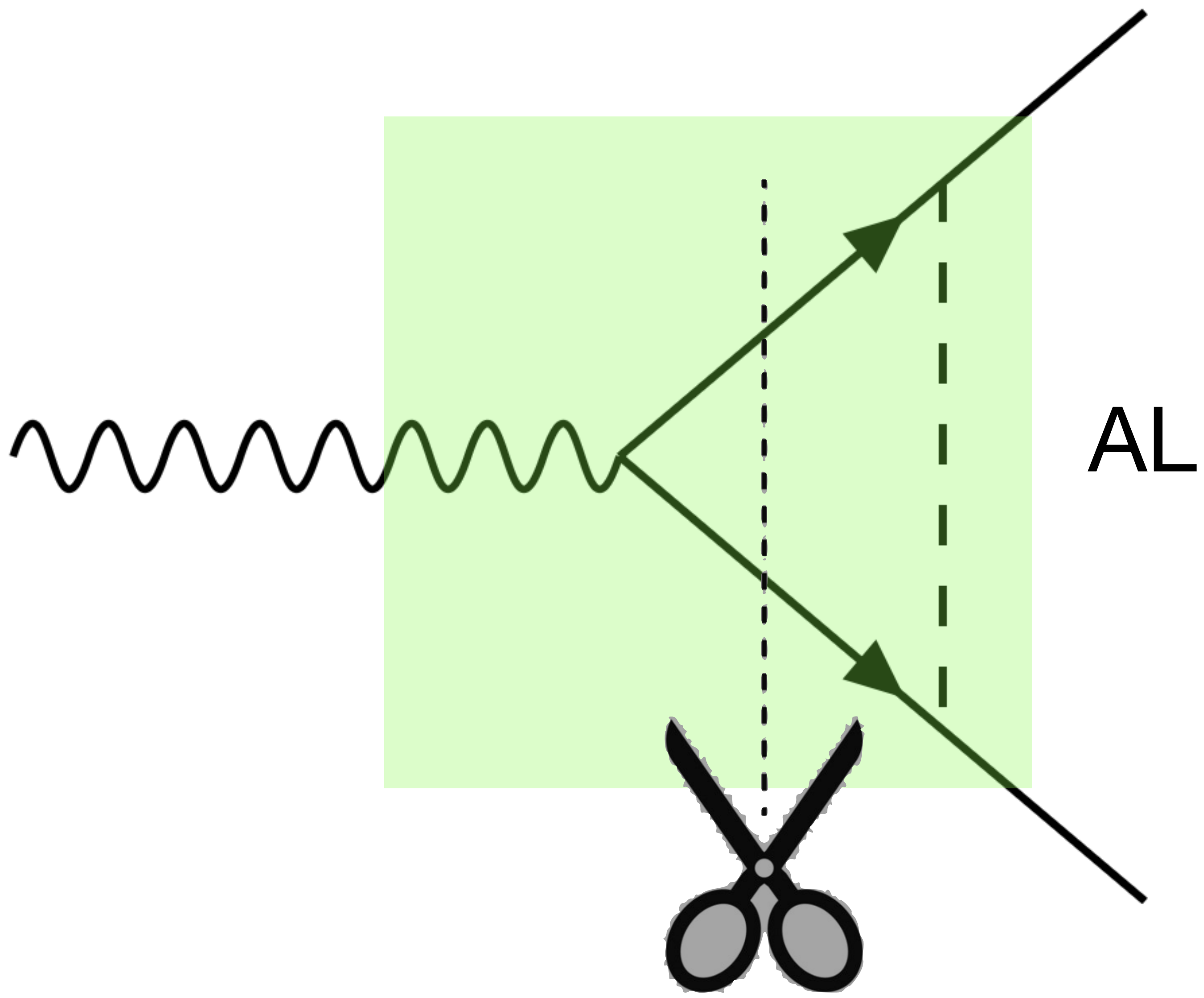
- Intermediate particles are on shell :

  → It develops an **imaginary** part.

- It is more sensitive to some NP scenarios.







ALP, 2HDM…

Timelike EDM

- Consider the low energy effective field theory:

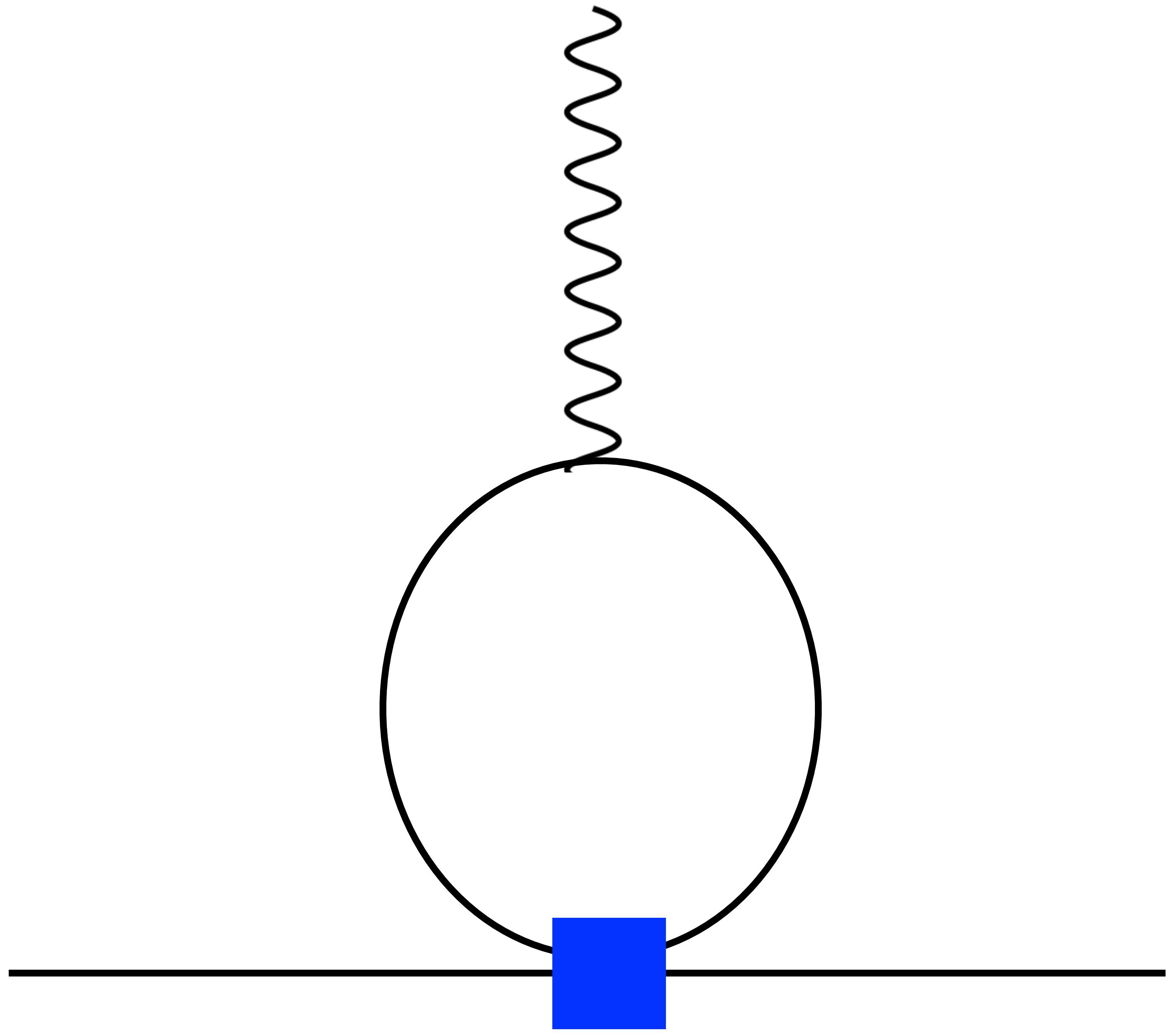
$$\mathscr{L}_{\rm eff} = \frac{i}{\Lambda^2} C_{SP}^{\tau\tau} (\bar{\tau}\gamma_5\tau)(\bar{\tau}\tau) - d_\tau^0 \frac{i}{2} F^{\mu\nu} \bar{\tau}\sigma_{\mu\nu}\gamma_5\tau$$

See Yu's talk for full set of operators

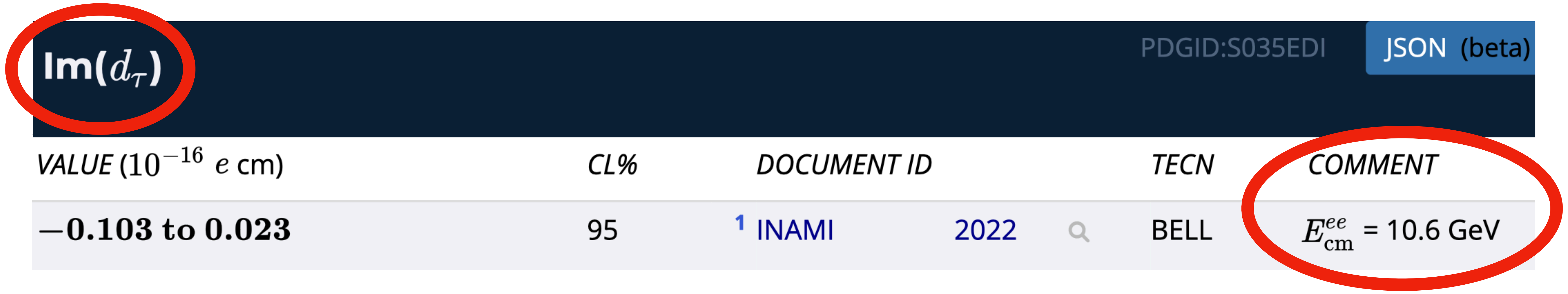
which induces the CPV ***form factors*** **:**

$$F_3(s) = d_\tau^0 + \frac{e m_\tau C_{SP}^{\tau\tau}}{8\pi^2\Lambda^2}\left[2 + \beta_\tau \log\left(1 - \frac{s}{2m_\tau^2}(1 - \beta_\tau)\right)\right]$$

$\sqrt{s}$: energy of photon; β_τ : speed of τ.



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



Im(d_τ)

PDGID:S035EDI

JSON (beta)

VALUE (10^{-16} e cm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
−0.103 to 0.023	95	[1] INAMI	2022	BELL	$E^{ee}_{\rm cm}$ = 10.6 GeV

Timelike EDM

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

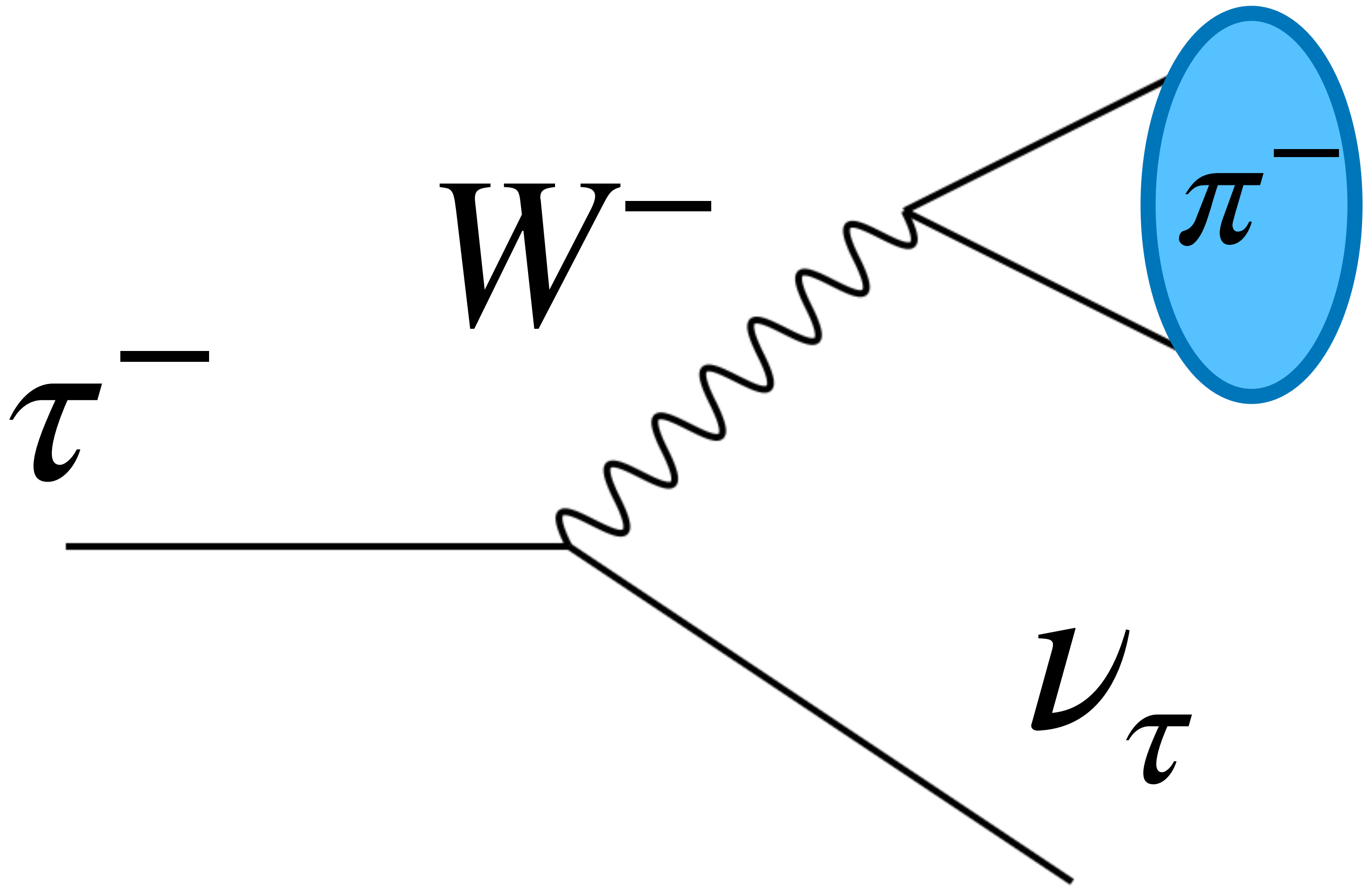
Polarization fraction

$$\frac{\partial\Gamma}{\partial\vec{\Omega}} = \sum_{\epsilon} P_{\epsilon} \left| \epsilon_\mu \, \bar{u}\left(\gamma^\mu F_1 + \frac{i}{2m}\sigma^{\mu q}F_2 + \sigma^{\mu q}\gamma^5 F_3\right) v \right|^2$$

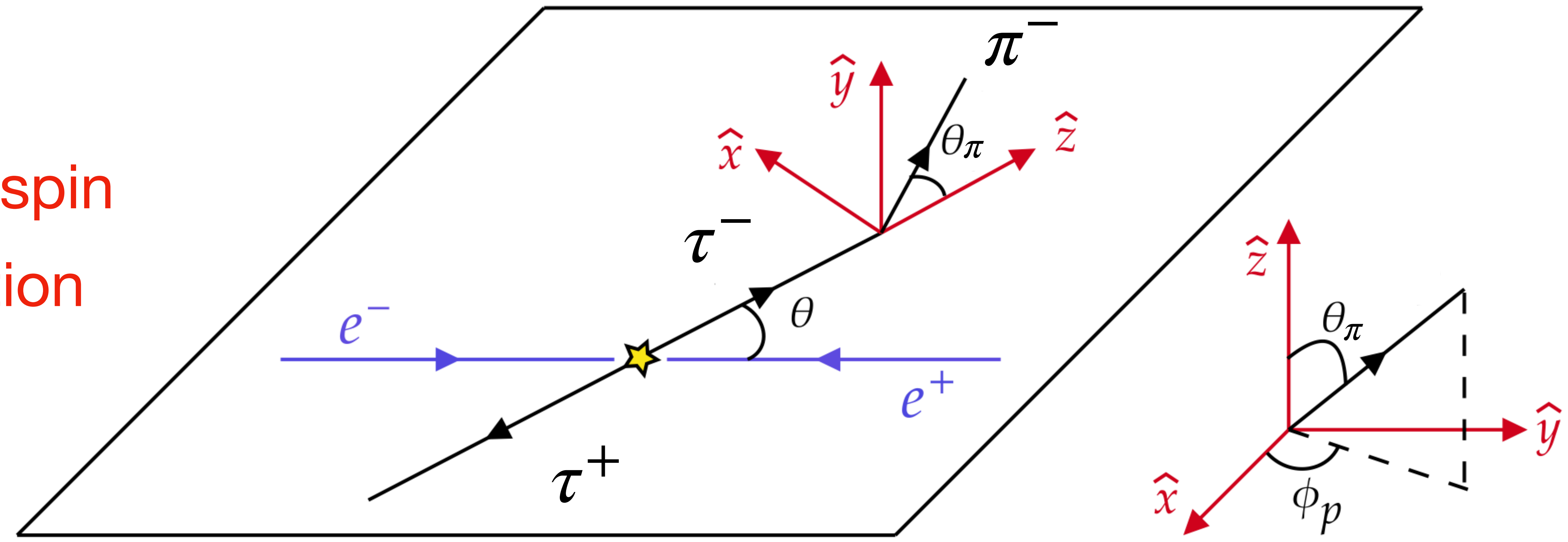
$$\propto 1 + \vec{B}_+ \cdot (\vec{s}_- + \vec{s}_+) + \vec{B}_- \cdot (\vec{s}_- - \vec{s}_+) - \vec{s}_+ \cdot \overleftrightarrow{C} \cdot \vec{s}_-$$

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

$\vec{B}, \overleftrightarrow{C}$ are CP even, while $\vec{s}_+ \overset{CP}{\longleftrightarrow} \vec{s}_-$



Carry τ^- spin information



[2204.11058]

Timelike EDM

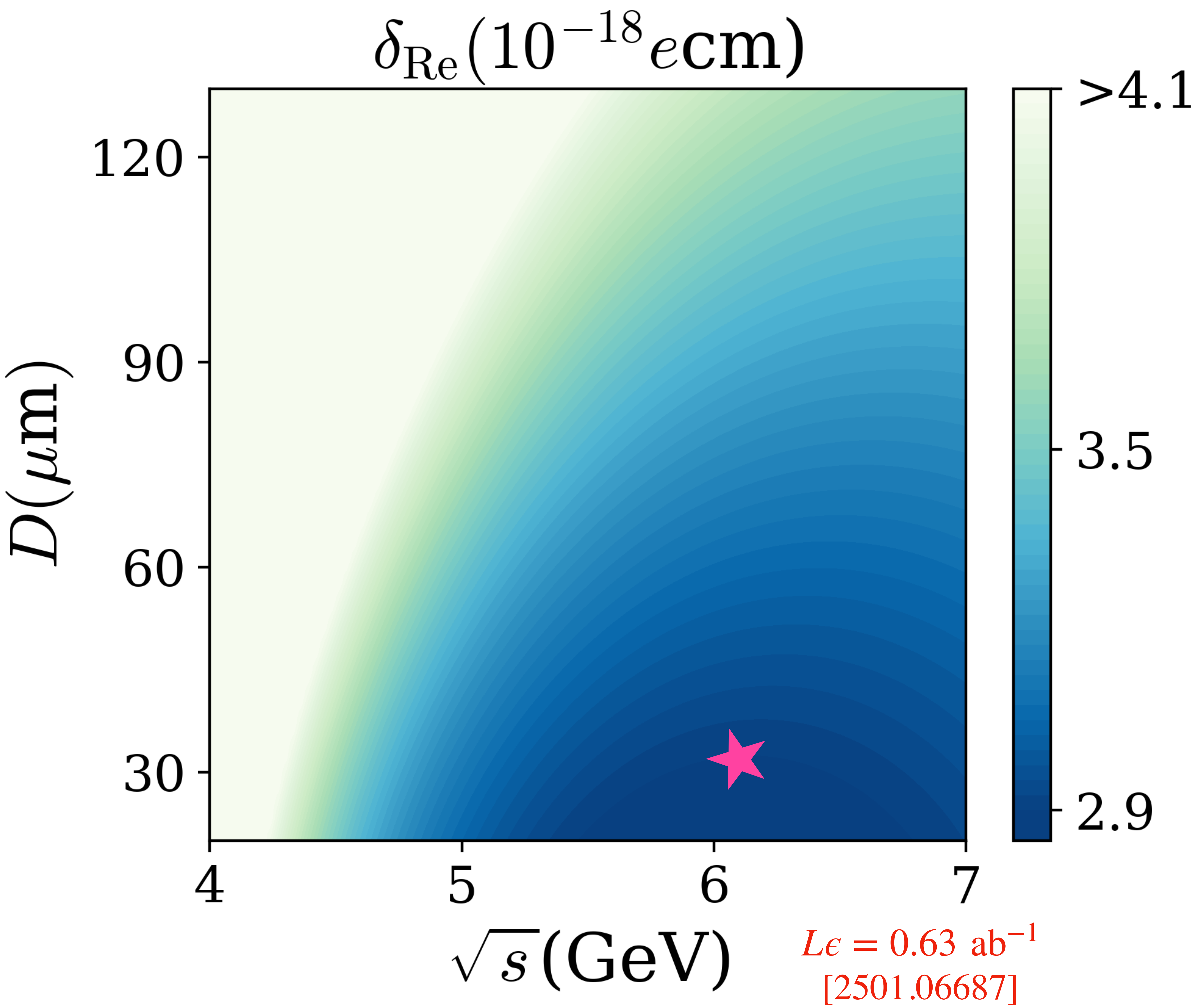
$\sigma_{xy} = 130\ \mu\mathrm{m} \longrightarrow 30\ \mu\mathrm{m}$

- 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
$\delta_{\mathrm{Re}}(180)$	235	4.9	4.2
$\delta_{\mathrm{Re}}(130)$	83	4.0	3.6
$\delta_{\mathrm{Re}}(80)$	29	3.3	3.1
$\delta_{\mathrm{Re}}(30)$	11	2.9	2.8

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

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



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

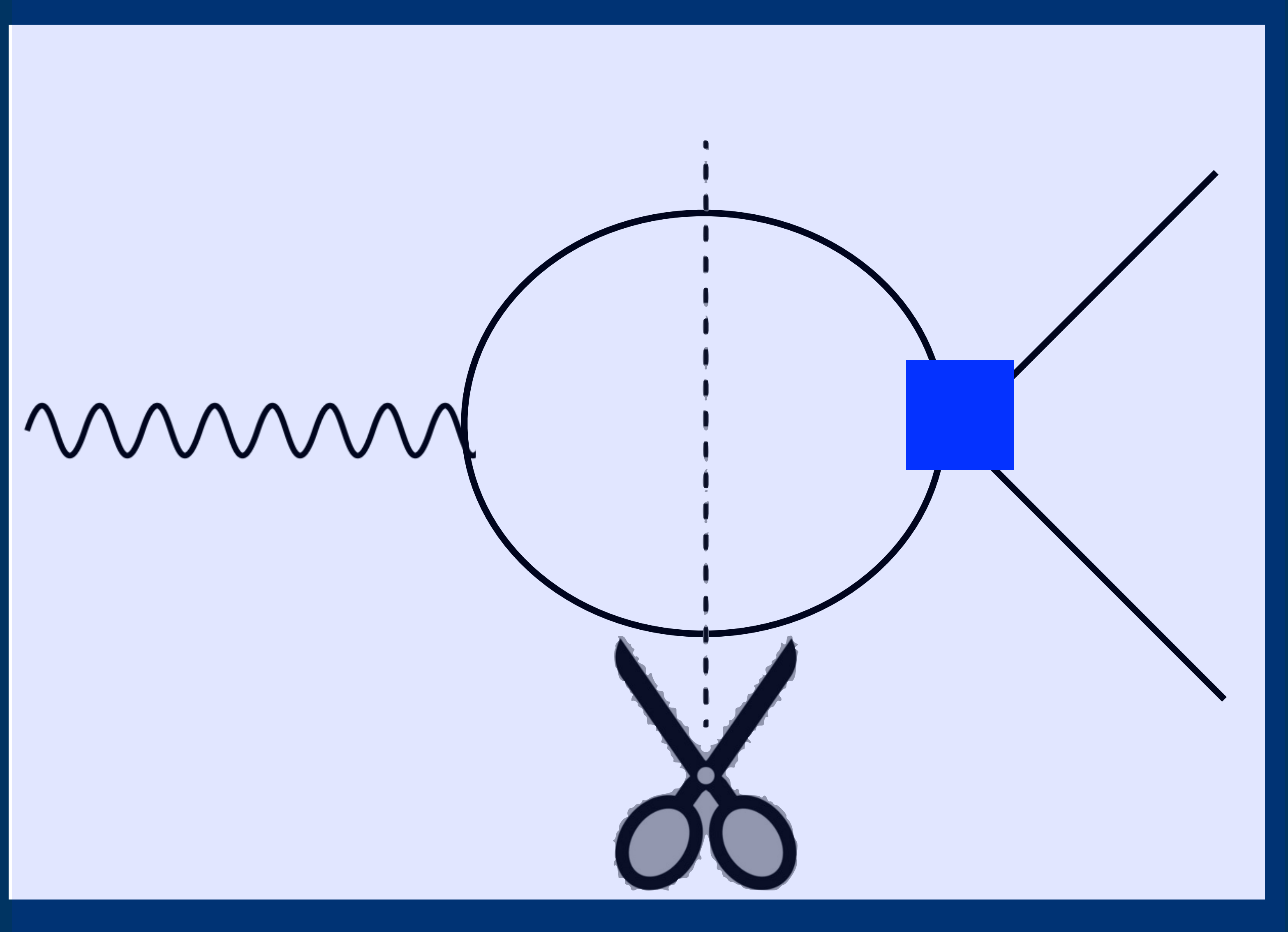
See Jinlin's talk tomorrow

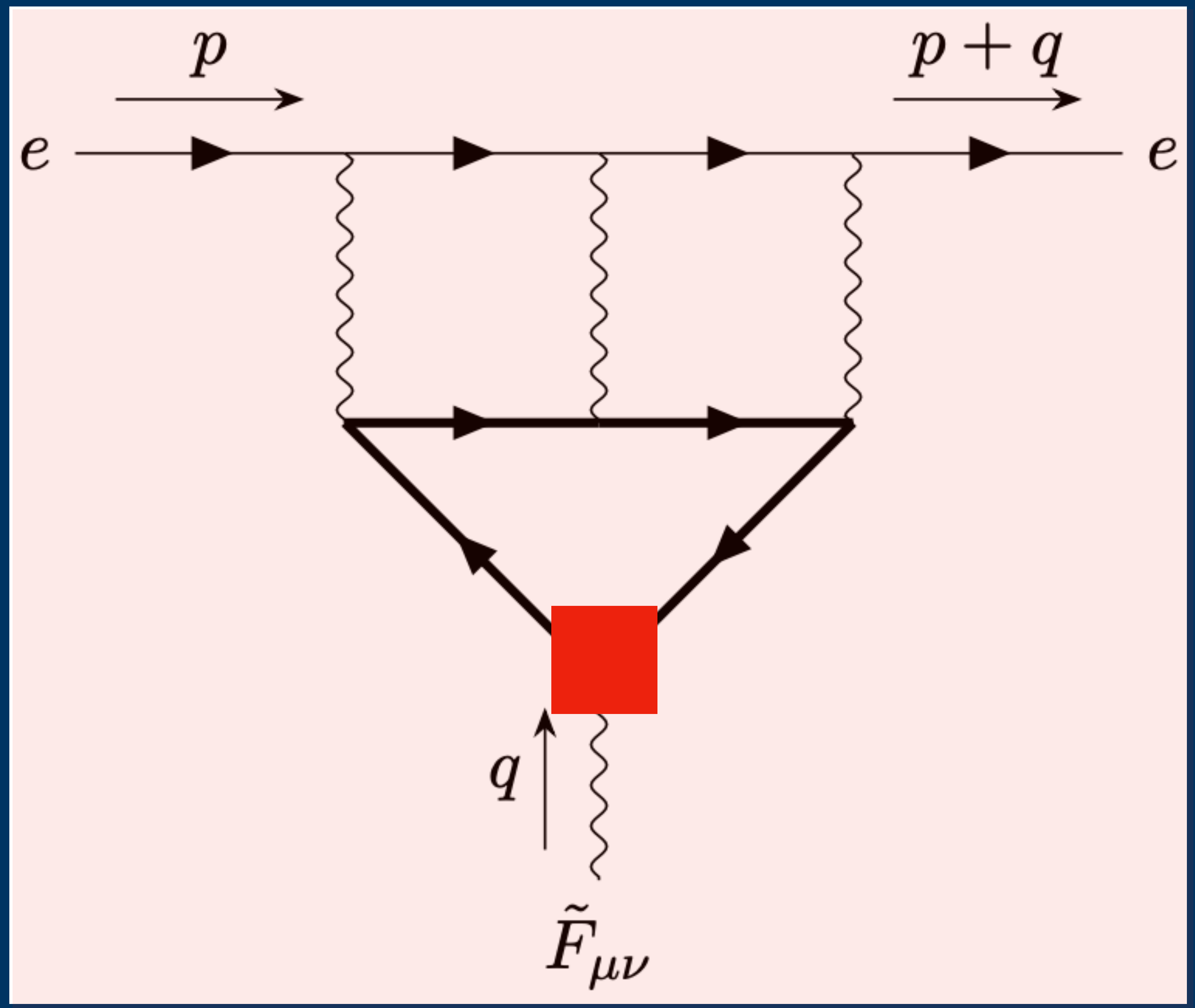
What NP we are looking at?

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

Colliders are sensitive to …

Tightly constrained by …





See also [2511.03786]

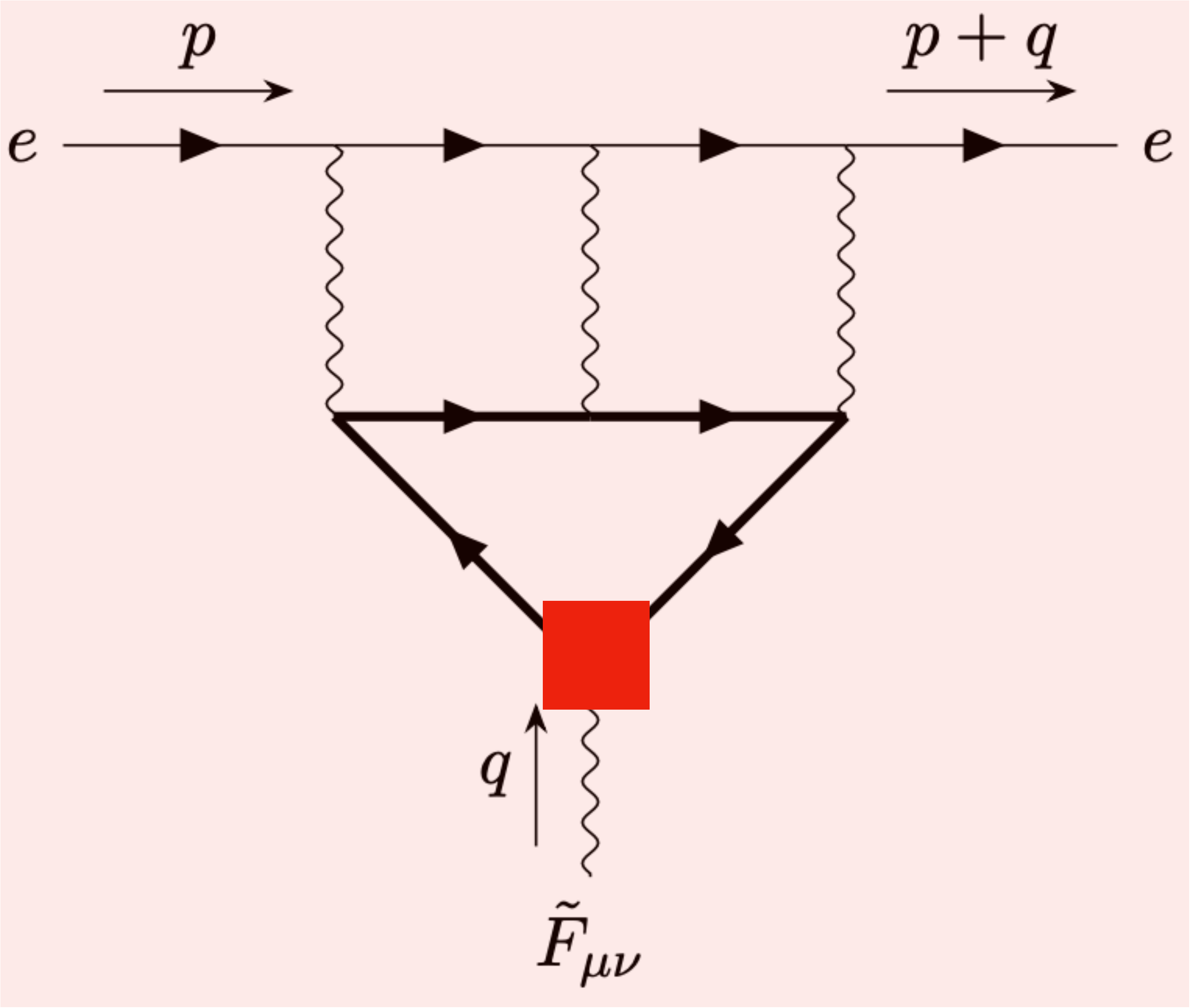
• τ EDM - EFT

- Consider the low energy effective field theory:

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

See Yu's talk for full set of operators

At $s = 0$ and $\mu = m_\tau$ in the $\overline{\mathrm{MS}}$ scheme : $d_\tau = d_\tau^0$.



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

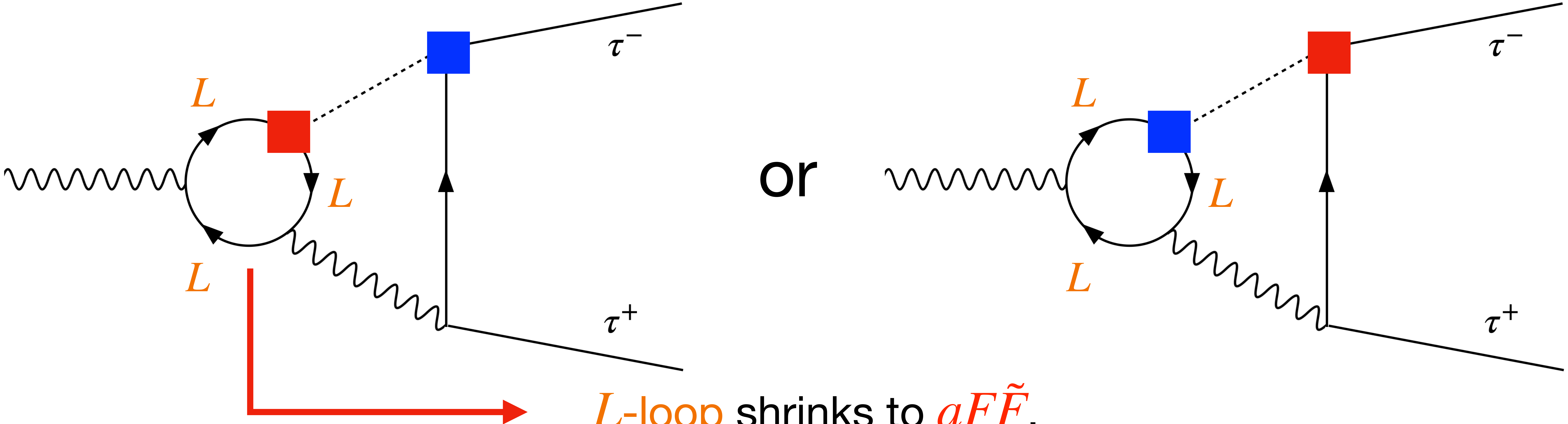
$$d_\tau^0(\mu) = d_\tau^0(\Lambda) + \frac{m_\tau}{\Lambda^2} \frac{e}{4\pi^2} C_{SP}^{\tau\tau}(\Lambda) \ln \frac{\Lambda}{\mu} \,,$$

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

τ EDM - ALP

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

- 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 .

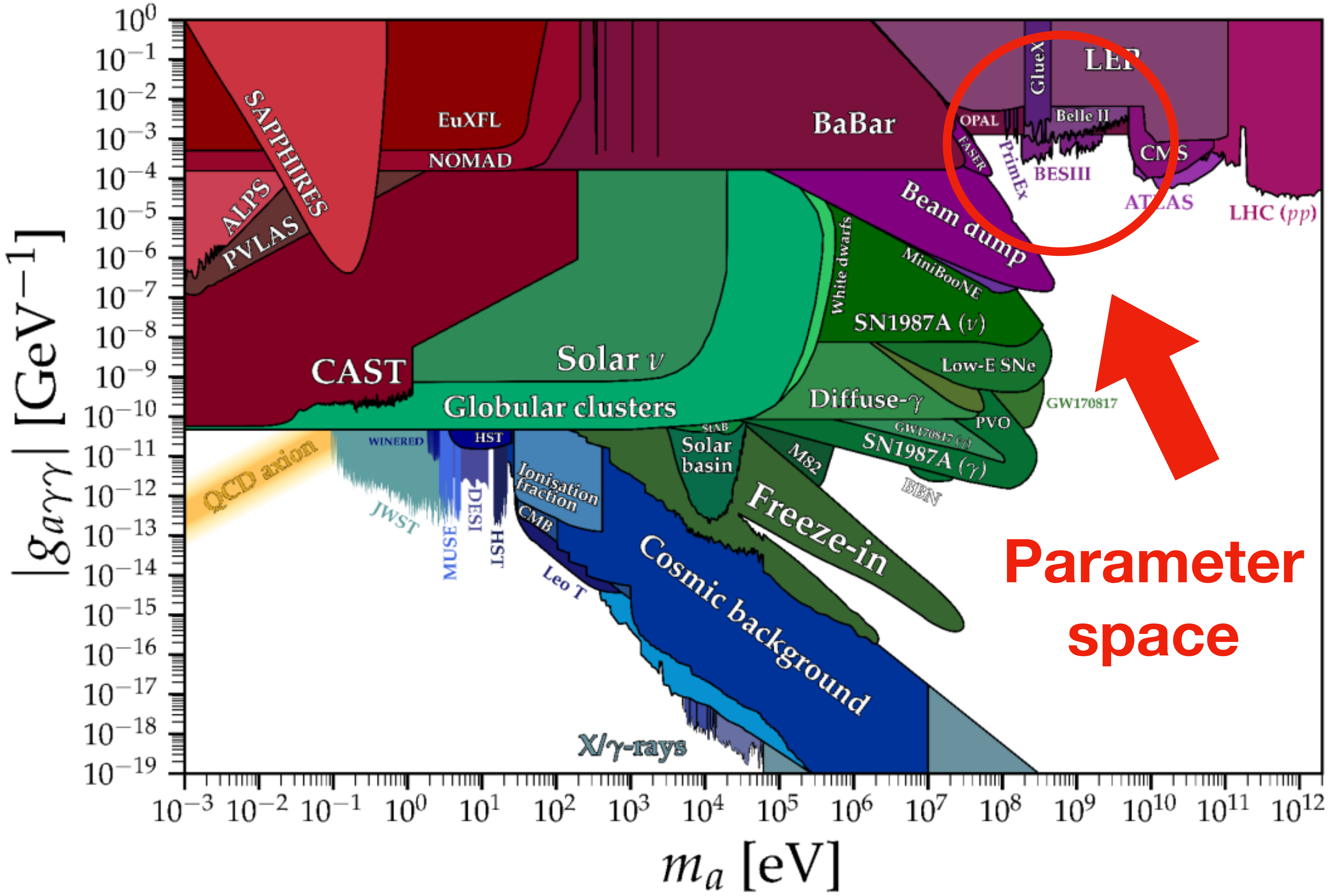


L-loop shrinks to $aF\tilde{F}$.

• τ EDM - ALP

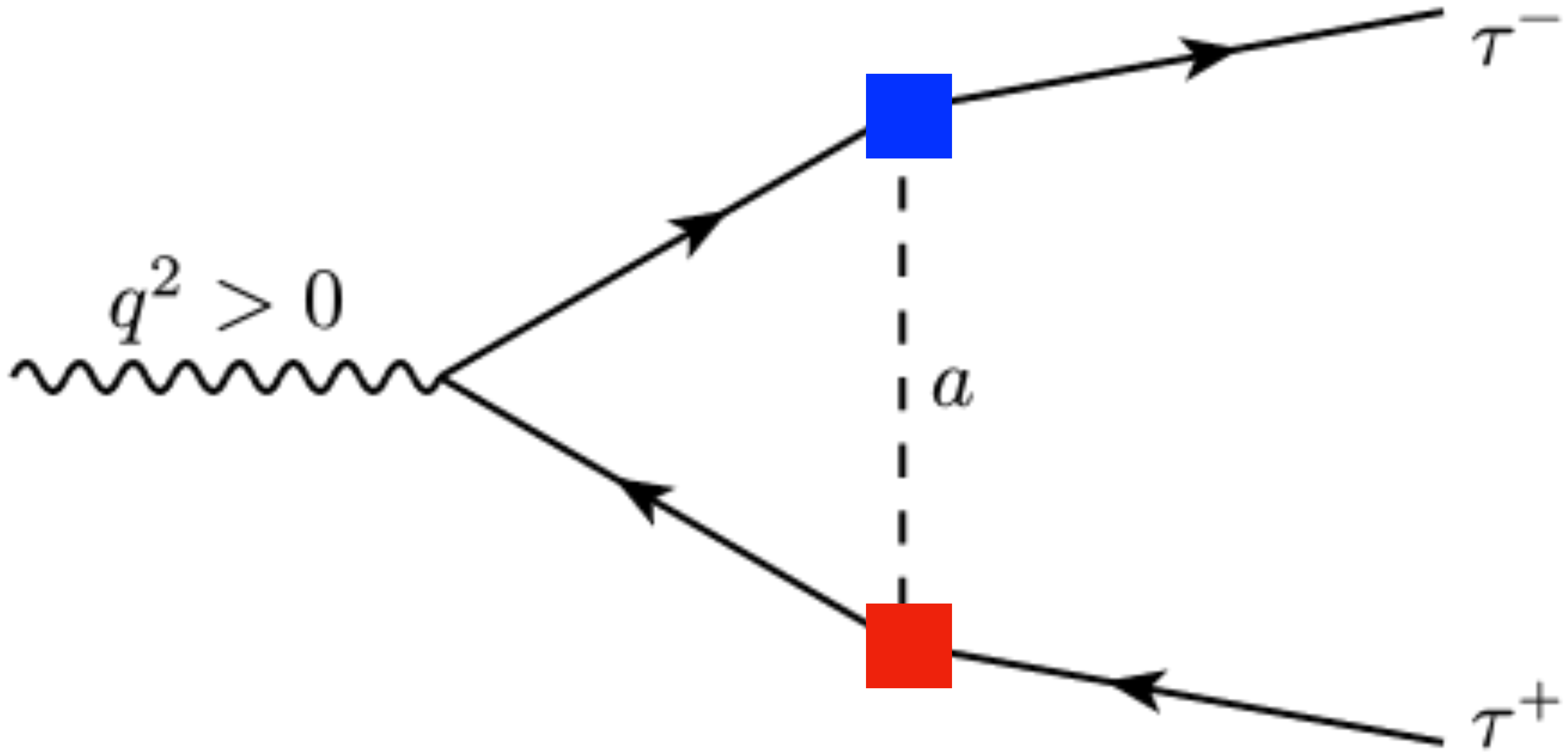
Scenario 2: $\mathscr{L}_{\text{int}} = a\bar{\tau}(\tilde{g}_\tau + ig_\tau\gamma_5)\tau$

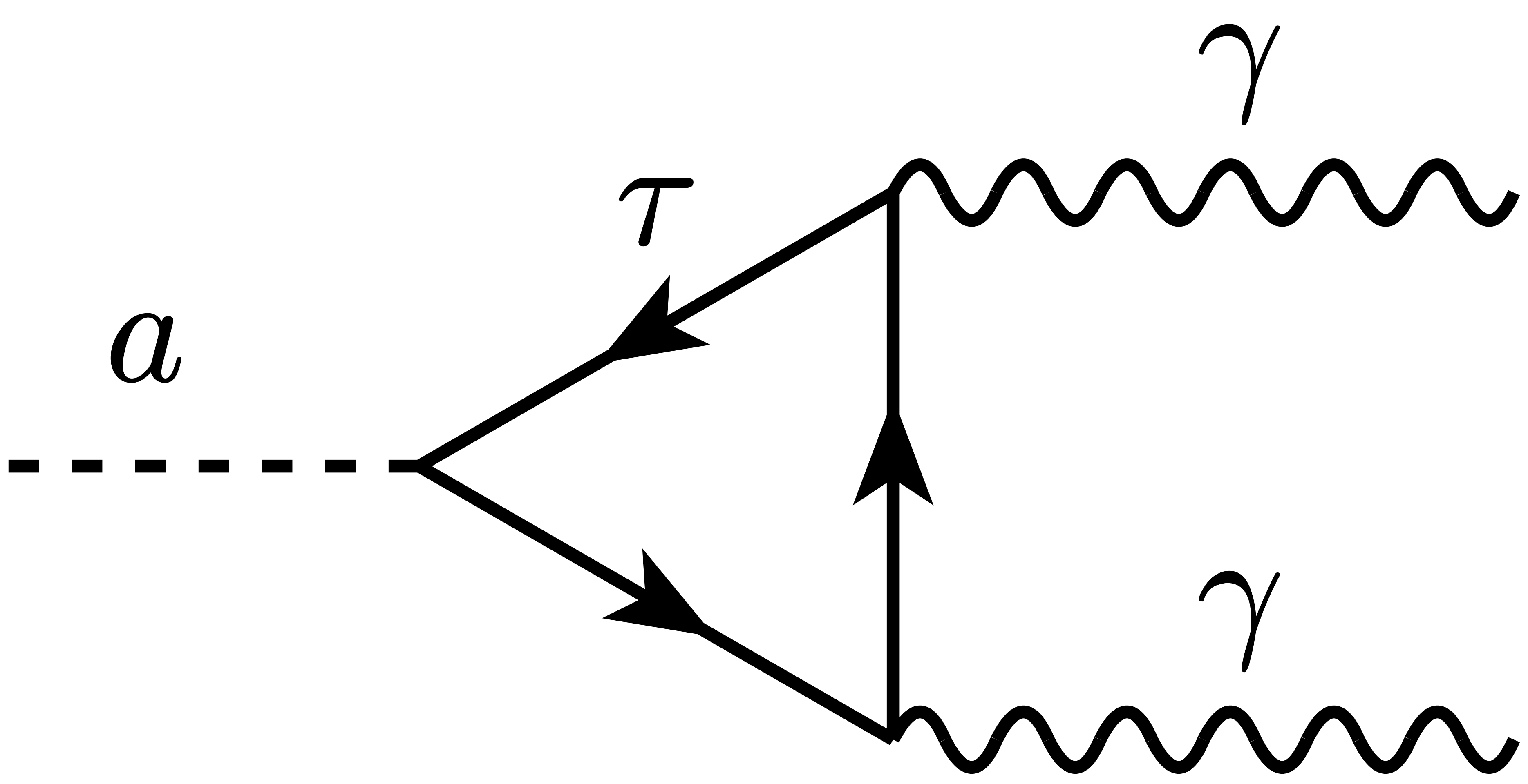
- ALP couples to τ with both ***parities***.
- The tightest constraint : $\gamma^* \rightarrow a\gamma$.



https://github.com/cajohare/AxionLimits

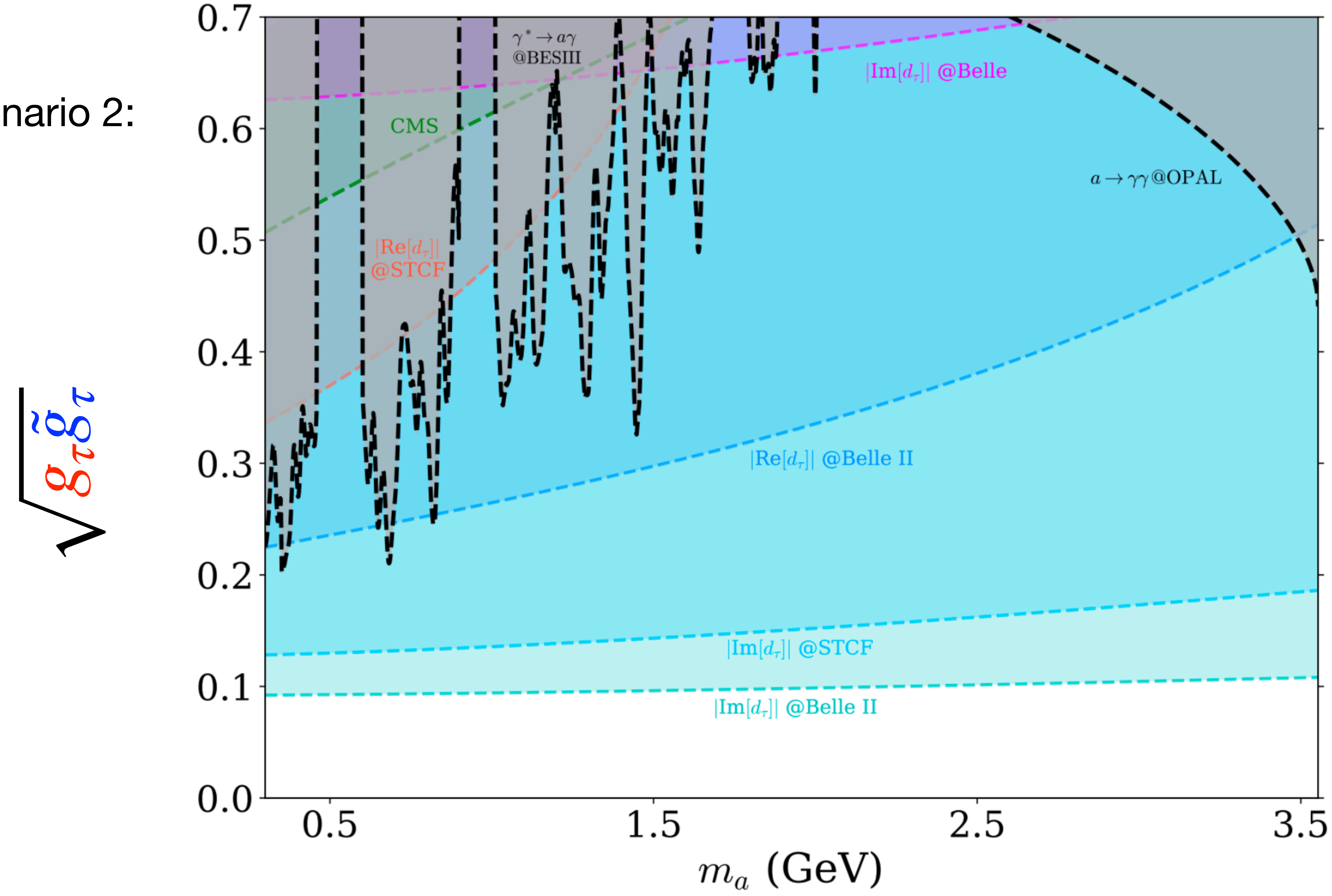
Parameter space



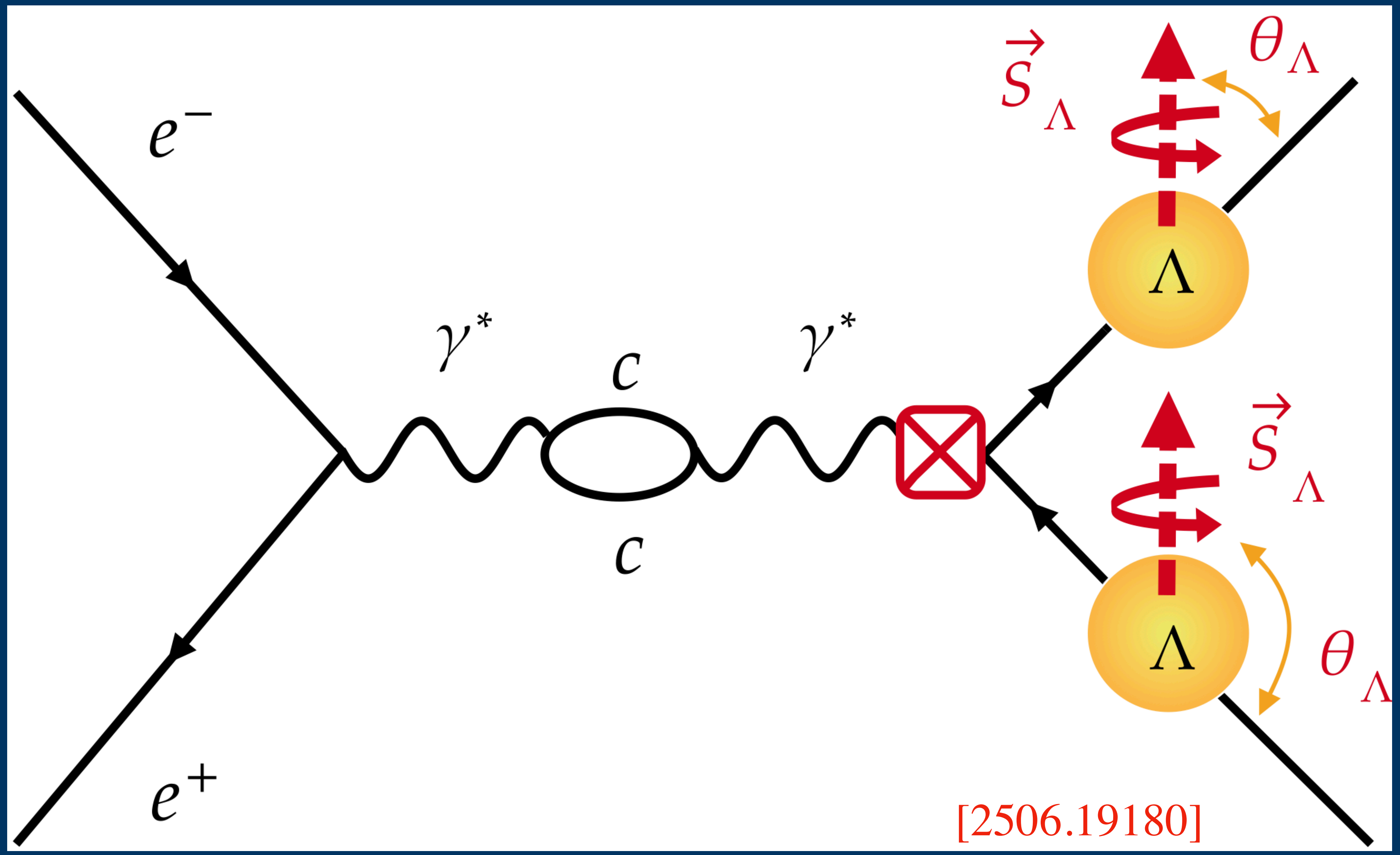


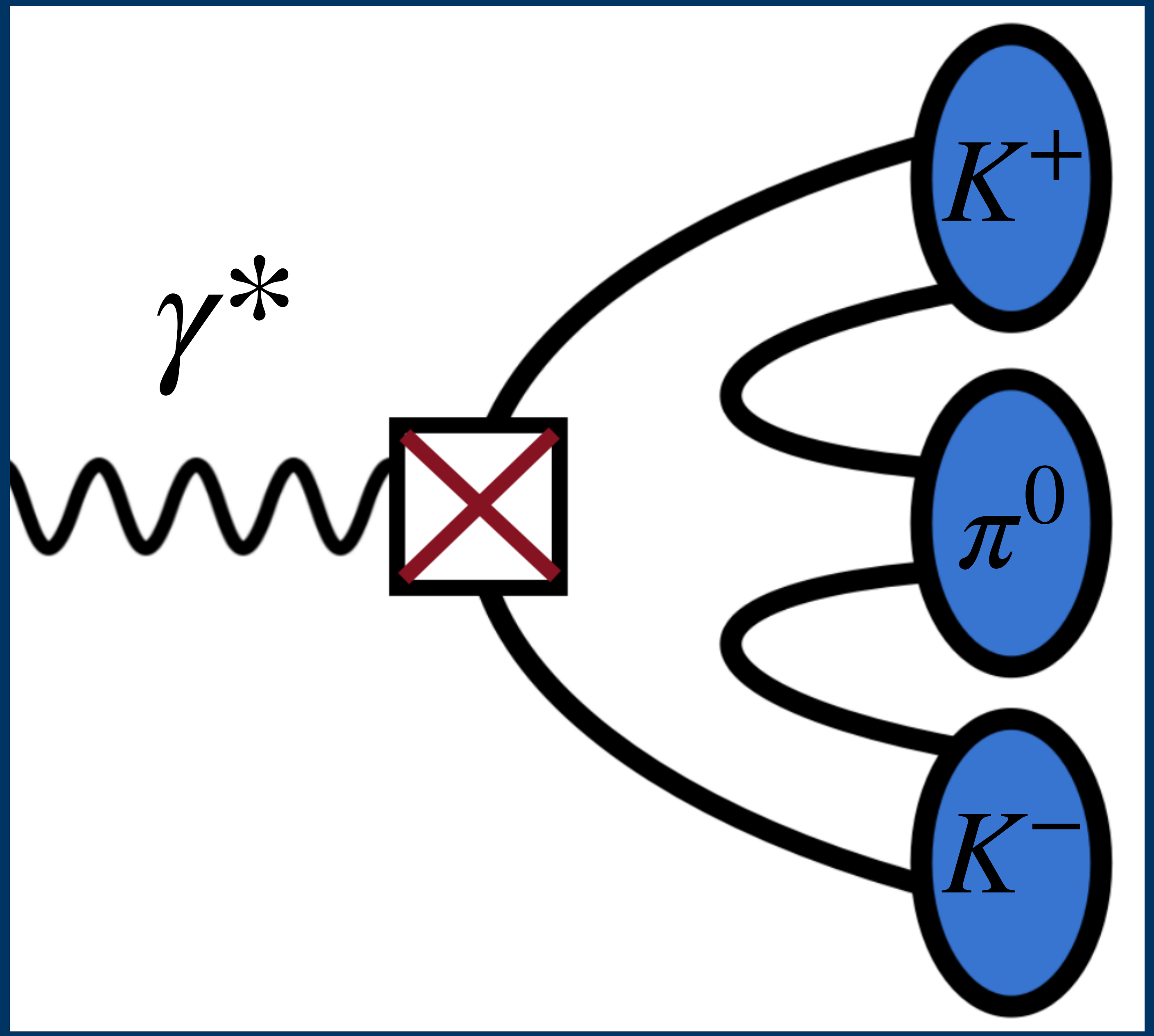
τ EDM - ALP

Scenario 2:



From leptons to quarks





$$d_\Lambda \approx d_s \text{ at } \sqrt{s} = 0$$

See Jinlin's talk tomorrow

[2506.19180]

[2509.22087]

Newly proposed

Anomalous sector and strange EDM

- We start with the EDM operator at the quark level:

$$\mathscr{L}_{\text{eff}} = \frac{d_s}{2}\,\tilde{F}^{\mu\nu}\,\bar{s}\,\sigma_{\mu\nu}\,s \quad\longrightarrow\quad \mathscr{L}_{\text{eff}} = \frac{d_s}{2}\,\tilde{F}^{\mu\nu}\left(\bar{q}_L\,\sigma_{\mu\nu}\,t\,q_R + \bar{q}_R\,\sigma_{\mu\nu}\,t^\dagger\,q_L\right)$$

- The auxiliary field $t = \text{diag}(0{,}0{,}1)$ with $t \to g_L\,t\,g_R^\dagger$ restores $SU(3)_L \otimes SU(3)_R$:

$$\mathscr{L}_{\chi PT} = \frac{d_s\Lambda_2}{16}\,\tilde{F}^{\mu\nu}\left[i\,\text{Tr}\Big[(tU^\dagger + Ut^\dagger)\,[\alpha_\mu, \alpha_\nu]\Big] - \epsilon_{\mu\nu\lambda\sigma}\,\text{Tr}\Big[(tU^\dagger - Ut^\dagger)\,\alpha^\lambda\alpha^\sigma\Big]\right]$$

$$U = \exp(2i\pi/F_\pi), \quad \alpha_\mu = -\,i\partial_\mu U U^\dagger\,.$$

[1203.0712]

- Expanding $\mathscr{L}_{\chi PT}$ gives the **CP-odd** $\gamma^* \to K^+K^-\pi^0$ vertex relevant.

Anomalous sector and strange EDM

- $\gamma^* \to K^+K^-\pi^0$ in the Standard Model requires $\mathcal{S}_{\mathrm{WZW}}$ to break **intrinsic parity**.

$\pi \to -\pi$

- The dim-4 χPT action conserves **intrinsic parity** and **spatial inversion** separately.

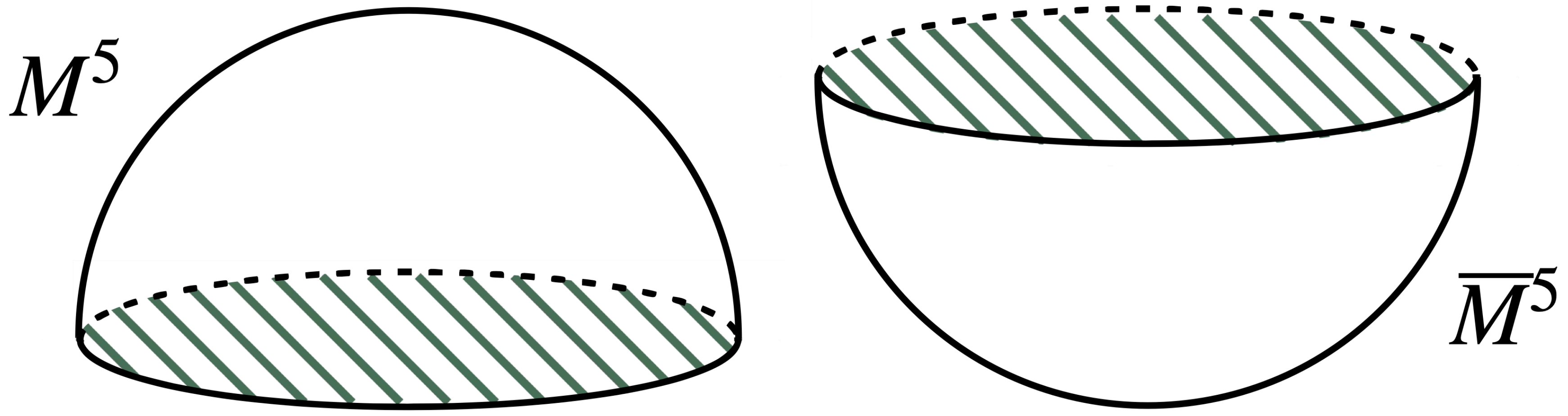
$\partial_\mu \to \partial^\mu$

$$\mathscr{L}_{\chi PT} = \frac{F_\pi^2}{16}\mathrm{Tr}\left(D_\mu U D^\mu U^\dagger\right)$$

- QCD conserves them only ***jointly***. A dim-5 action is needed to break the **separate** symmetry.

$$\mathcal{S}_{\mathrm{WZW}} = \frac{N_c}{240\pi^2}\int_{M^5} \mathrm{Tr}\left(\alpha^5\right)$$

[Wess-Zumino-Witten]



$\partial M^5 = S^4$, and $d\mathrm{Tr}(\alpha^5) = 0$

Anomalous sector and strange EDM

- Consider $e^+e^- \to K^+K^-\pi^0$

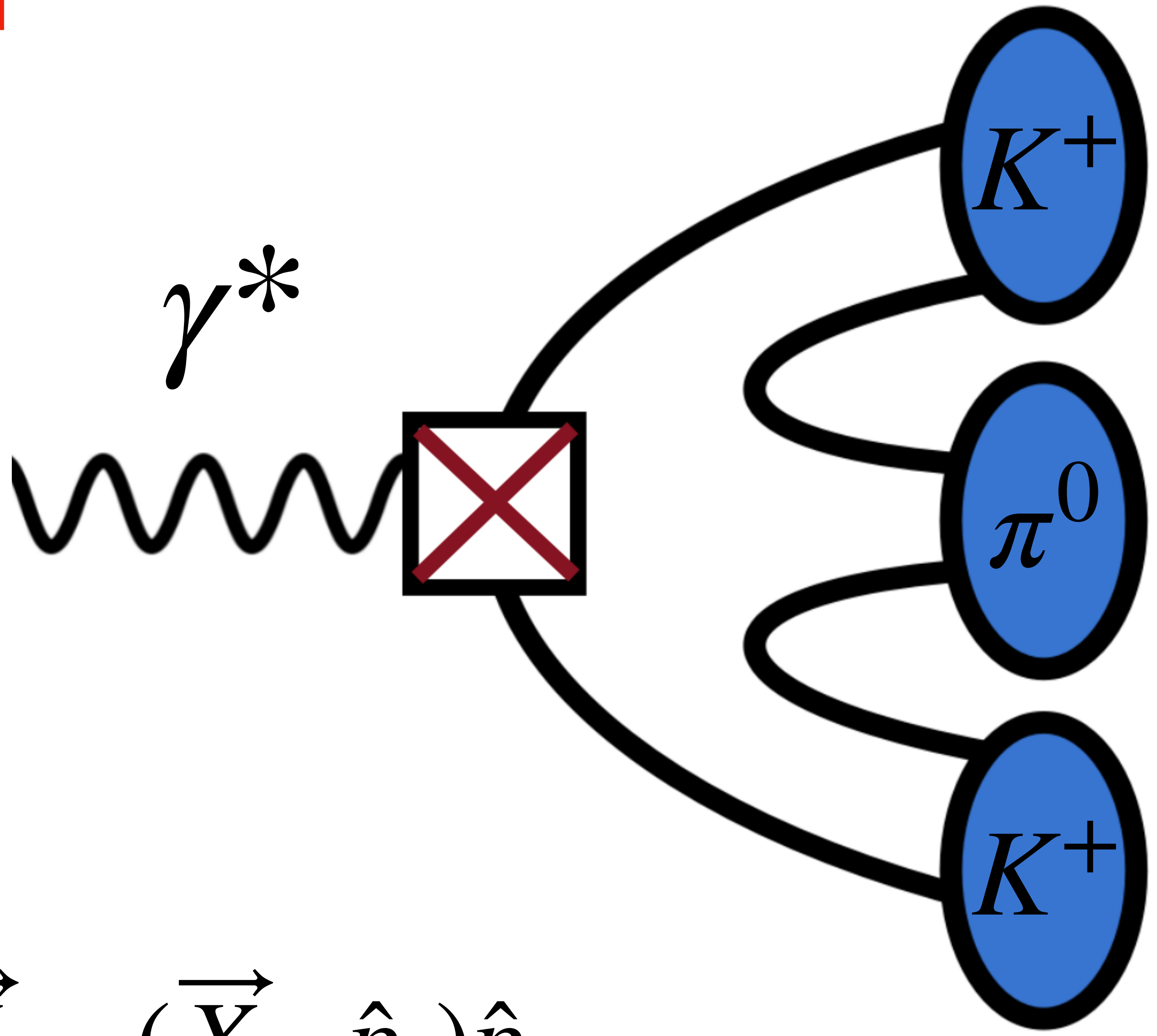
$$\mathcal{M} = \epsilon_\mu(q)\, J^\mu$$

$$J^\mu = \underbrace{F_V\, \epsilon^{\mu\nu\alpha\beta}\, p_{+\nu}\, p_{-\alpha}\, p_{0\beta}}_{V^\mu;\ \text{C-even, P-even}} + F_A \Big[\underbrace{(q\cdot p_0)\,(p_+ - p_-)^\mu - \big(q\cdot(p_+ - p_-)\big)\, p_0^\mu}_{A^\mu;\ \text{C-even, P-odd}} \Big]$$

- At the chiral limit of vanishing masses :

$$\frac{F_A}{F_V} = -\frac{6\pi^2}{N_c\, e}\, d_s\, \Lambda_2$$

[1203.0712]

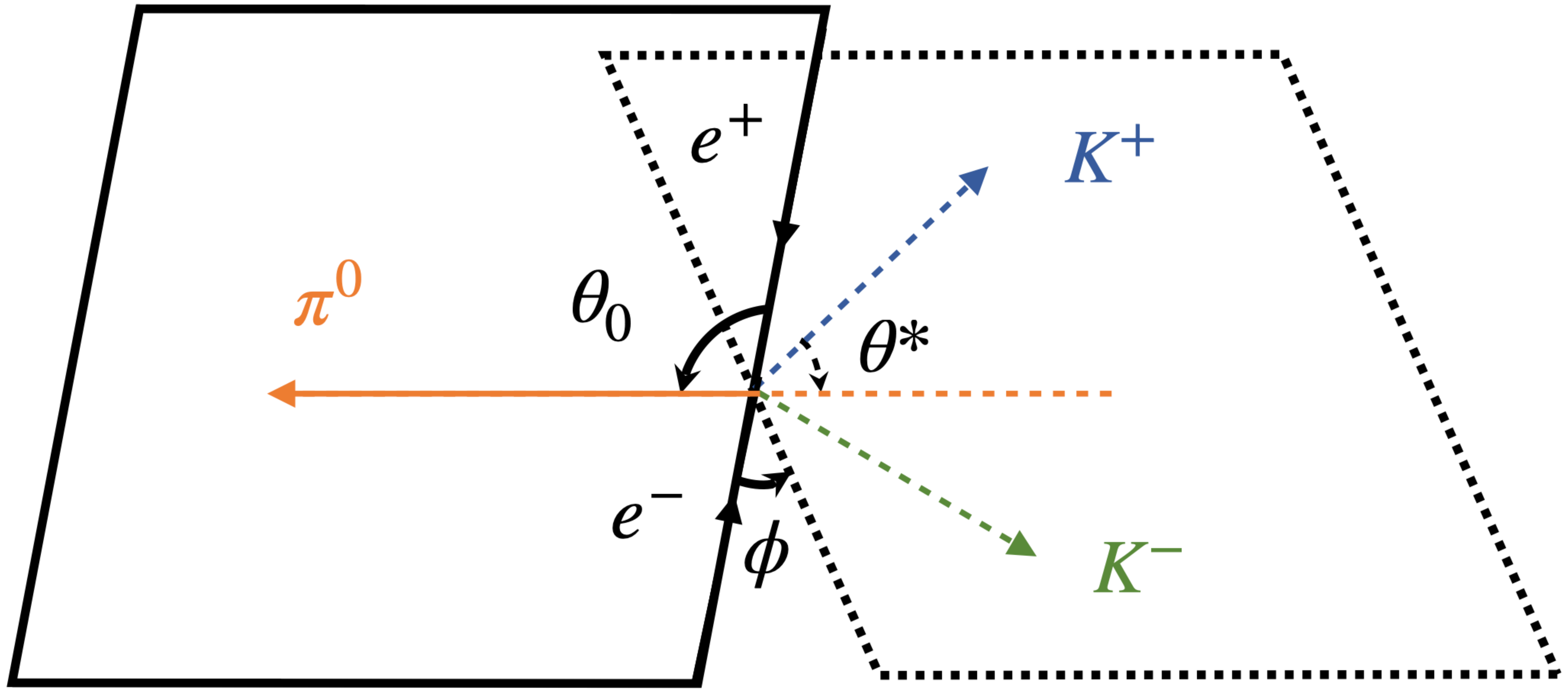


- Square the amplitude M^*M and sum over $\epsilon_\nu^*(q)\epsilon_\mu(q)$:

$$\sum_\epsilon |M|^2 = \frac{1}{2}\left| \left(F_V\, \vec{V} + F_A\, \vec{A}\right)_\perp \right|^2, \qquad \vec{X}_\perp \equiv \vec{X} - (\vec{X}\cdot\hat{p}_e)\hat{p}_e$$

Anomalous sector and strange EDM

- Consider $e^+e^- \to K^+K^-\pi^0$



$$A_T \equiv \frac{N(\vec{V}_\perp \cdot \vec{A}_\perp > 0) - N(\vec{V}_\perp \cdot \vec{A}_\perp < 0)}{N(\vec{V}_\perp \cdot \vec{A}_\perp > 0) + N(\vec{V}_\perp \cdot \vec{A}_\perp < 0)}$$

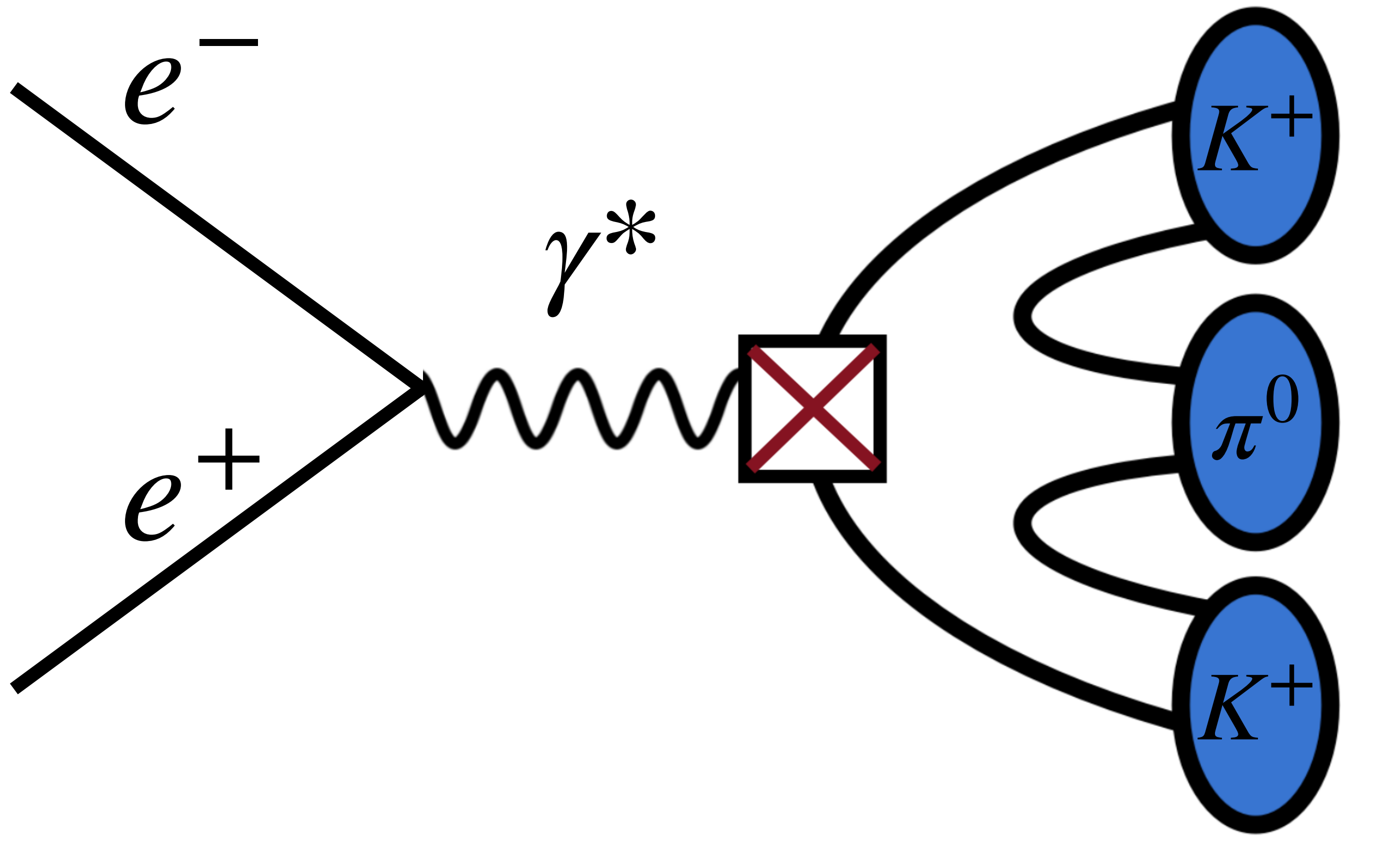
*May use optimal observables instead

- QED corrections modify the parameterization, but A_T itself is still ***CP*-odd.**

$$\delta d_s \sim (3.5 \sim 11.1) \times 10^{-16}\, e \cdot \mathrm{cm}$$

VEPP-2000, $\sqrt{s} = 1.4 \sim 1.6$ GeV, $N_{\mathrm{tot}} = 10^3 \sim 10^4$, Russia

[1108.6174]

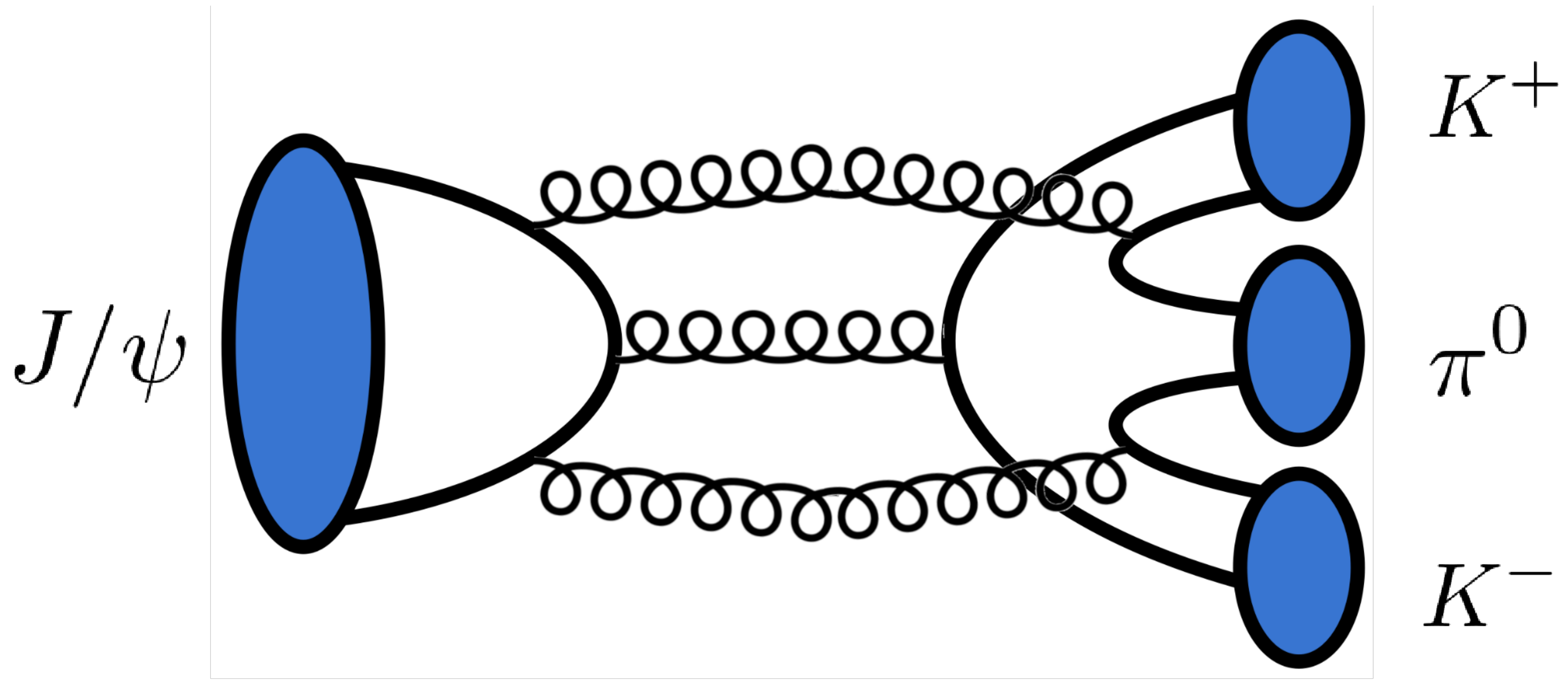


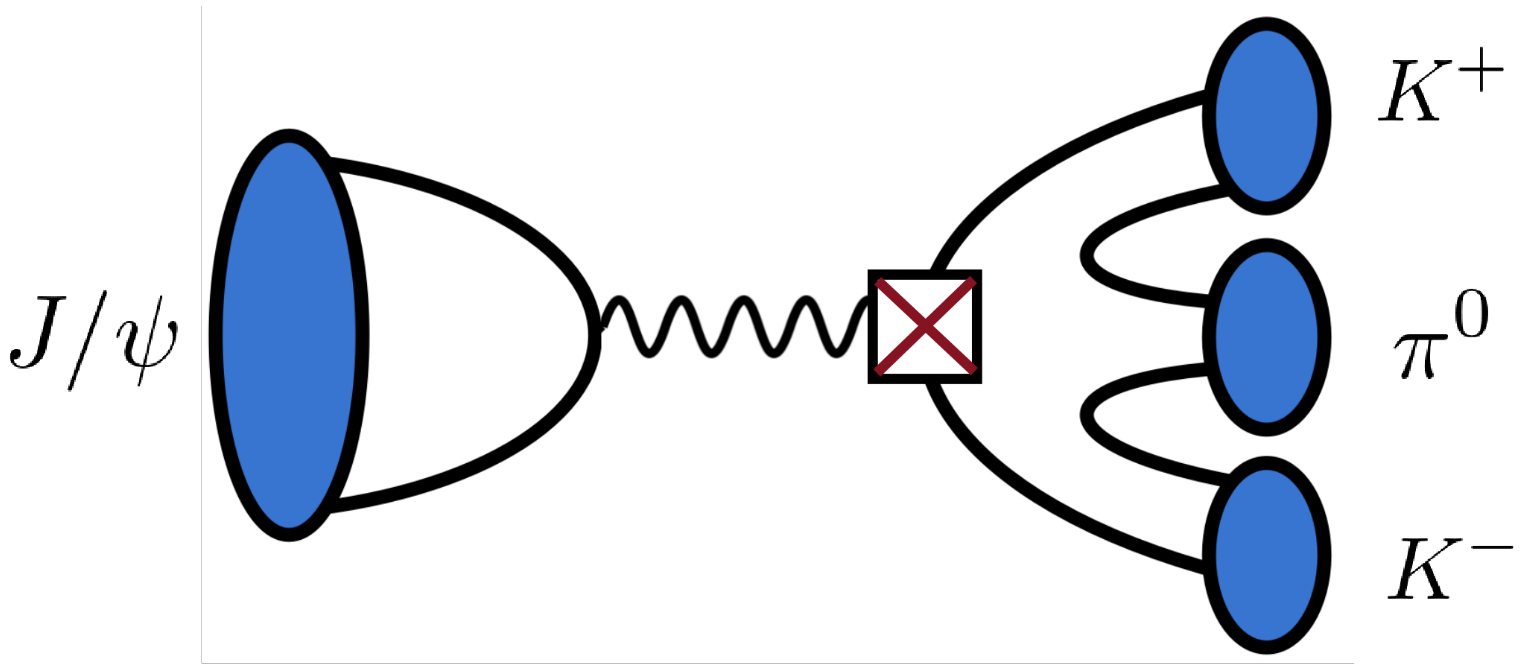
Anomalous sector and strange EDM

- BESIII has an overwhelming statistical advantage in $J/\psi \to K^+K^-\pi^0$ with $N_{\rm tot} \sim 10^7$.
- We adopted the VMD $J/\psi \to K^\mp K^{*\pm}$, $93.4^{+1.8}_{-5.8}\,\%$ saturation is found at BESIII :

$$\delta d_s \;\simeq\; (4.2 \sim 26.9) \times 10^{-18}\; e \cdot {\rm cm}\,.$$

- The main uncertainty is the common extrapolation of F_V and F_A.
- Relative statistics vs. Λ : $\dfrac{\mathscr{B}(J/\psi \to \Lambda\overline{\Lambda})}{\mathscr{B}(J/\psi \to K^+K^-\pi^0)}\mathscr{B}^2(\Lambda \to p\pi^-)\alpha_\Lambda^2 \approx \dfrac{1}{6}$.





Outlooks

- Look for C-odd, P-even CPV operators that evade the eEDM bound.
- Reduce hadronic uncertainty with better form factors and amplitude control.
- Extend timelike CPV searches to more channels at BESIII, STCF, and Belle II.

Backup slides

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

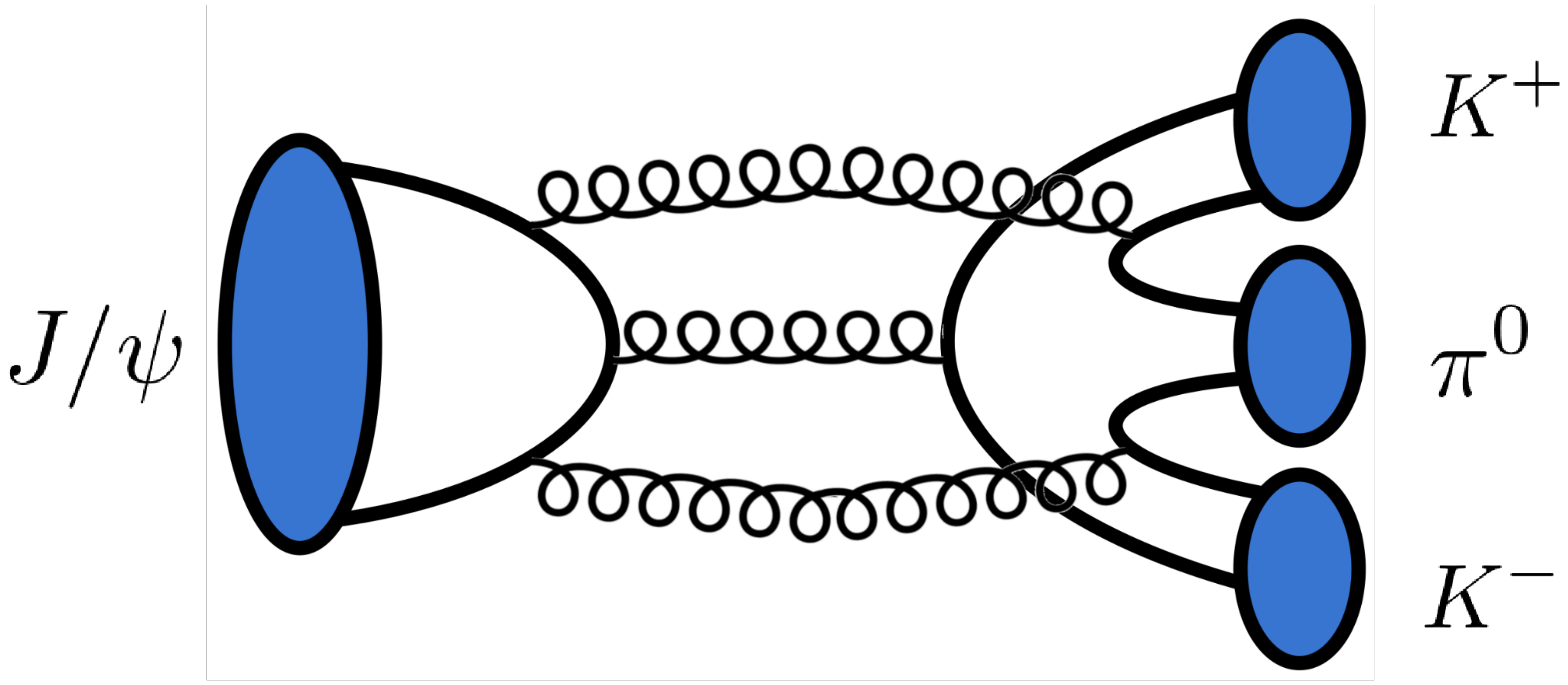
Anomalous sector and strange EDM

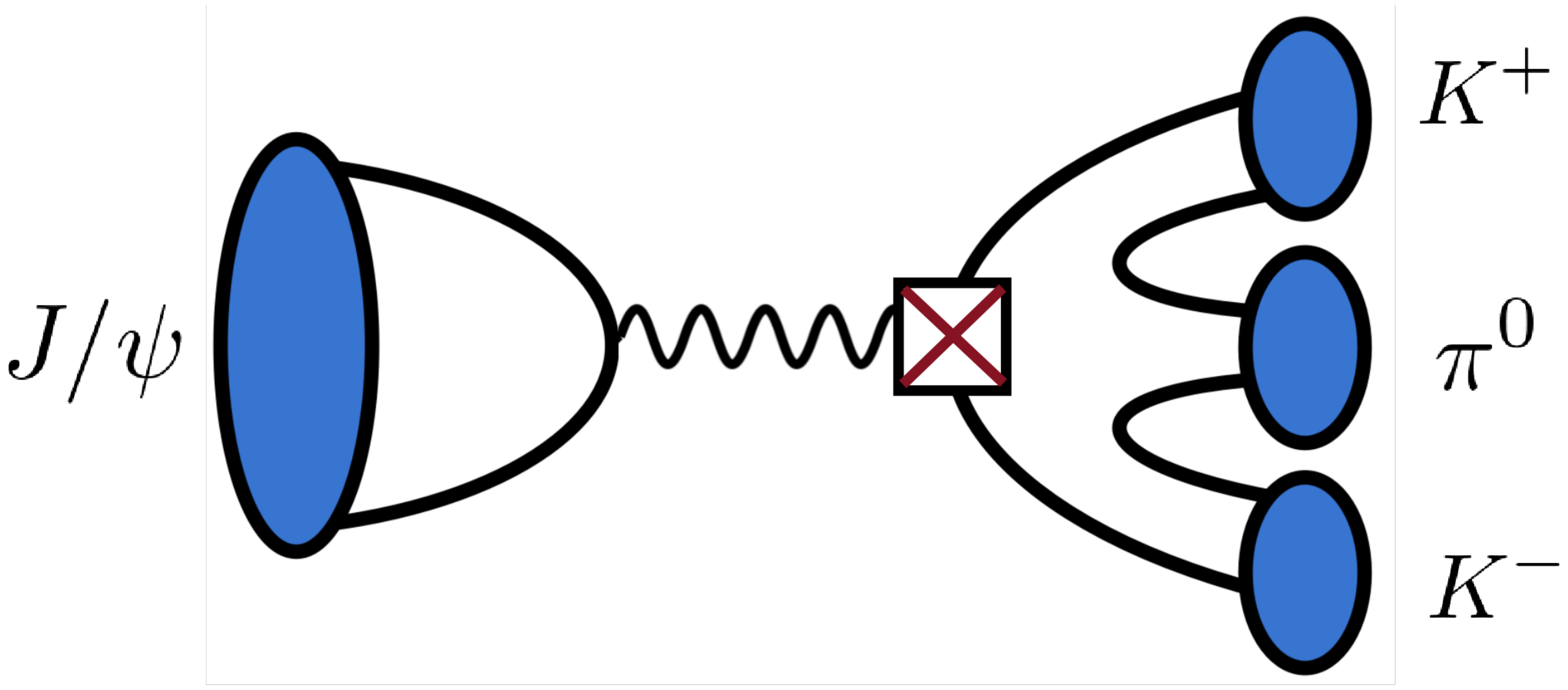
- But the theory suffers from uncertainties due to mixing with **three-gluon** contributions.

$$F_{V,A}(s_+, s_-) = \frac{F_{V,A}(s_+, s_-)}{2} \left(\frac{m_{K*}^2}{m_{K*}^2 - s_+ - i\Gamma_{K*}\sqrt{s_+}} + \frac{m_{K*}^2}{m_{K*}^2 - s_- - i\Gamma_{K*}\sqrt{s_-}} \right).$$

- We adopted the VMD saturation $J/\psi \to K^{\mp}K^{*\pm}$, $93.4^{+1.8}_{-5.8}\,\%$ situation is found at BESIII.

$$\delta d_s \simeq (4.2 \sim 26.9) \times 10^{-18}\, e \cdot \mathrm{cm}\,.$$

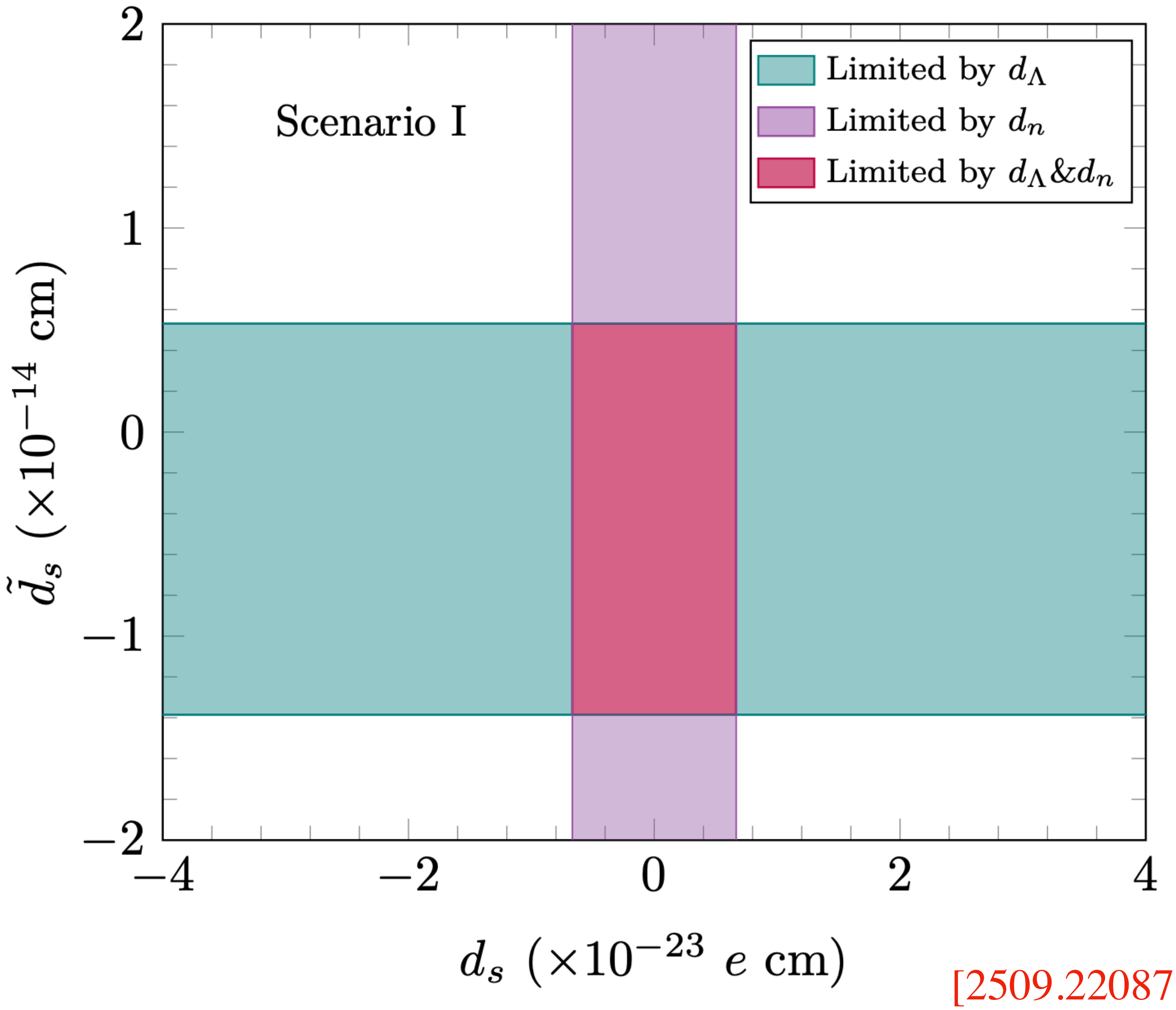




Anomalous sector and strange EDM

$$d_n = -(1.5 \pm 0.7) \times 10^{-16} \overline{\theta} e \cdot \mathrm{cm} - (0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d + (2.7 \pm 1.6) \times 10^{-3} d_s$$

$$d_\Lambda = 5.29 \times 10^{-4} d_s + 4.61 \times 10^{-5} \left(d_u + d_d\right) + 6.21 \times 10^{-5} e\tilde{d}_s + 1.98 \times 10^{-5} e\tilde{d}_d - 2.14 \times 10^{-5} e\tilde{d}_u$$



[2509.22087]