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Probing EDM at colliders

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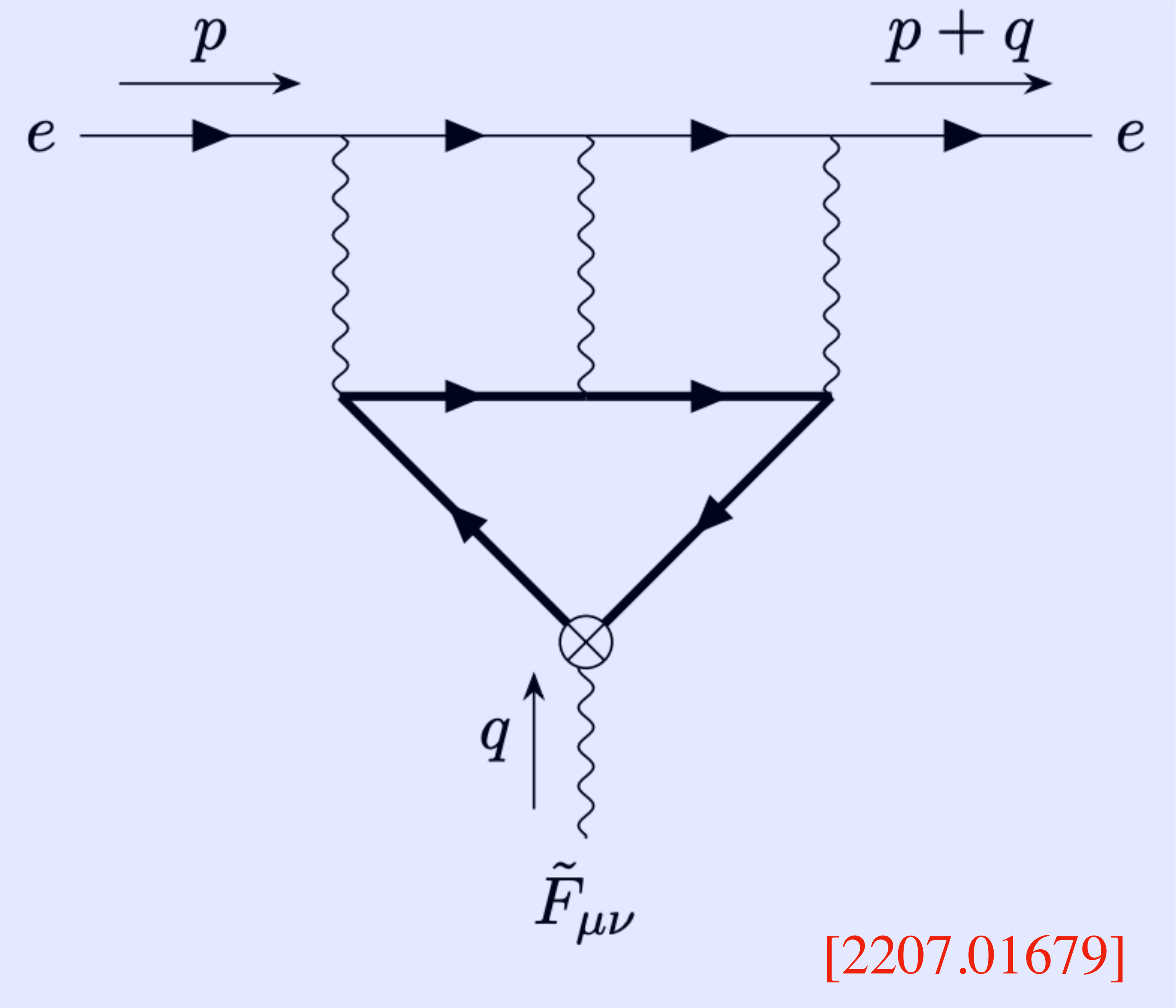
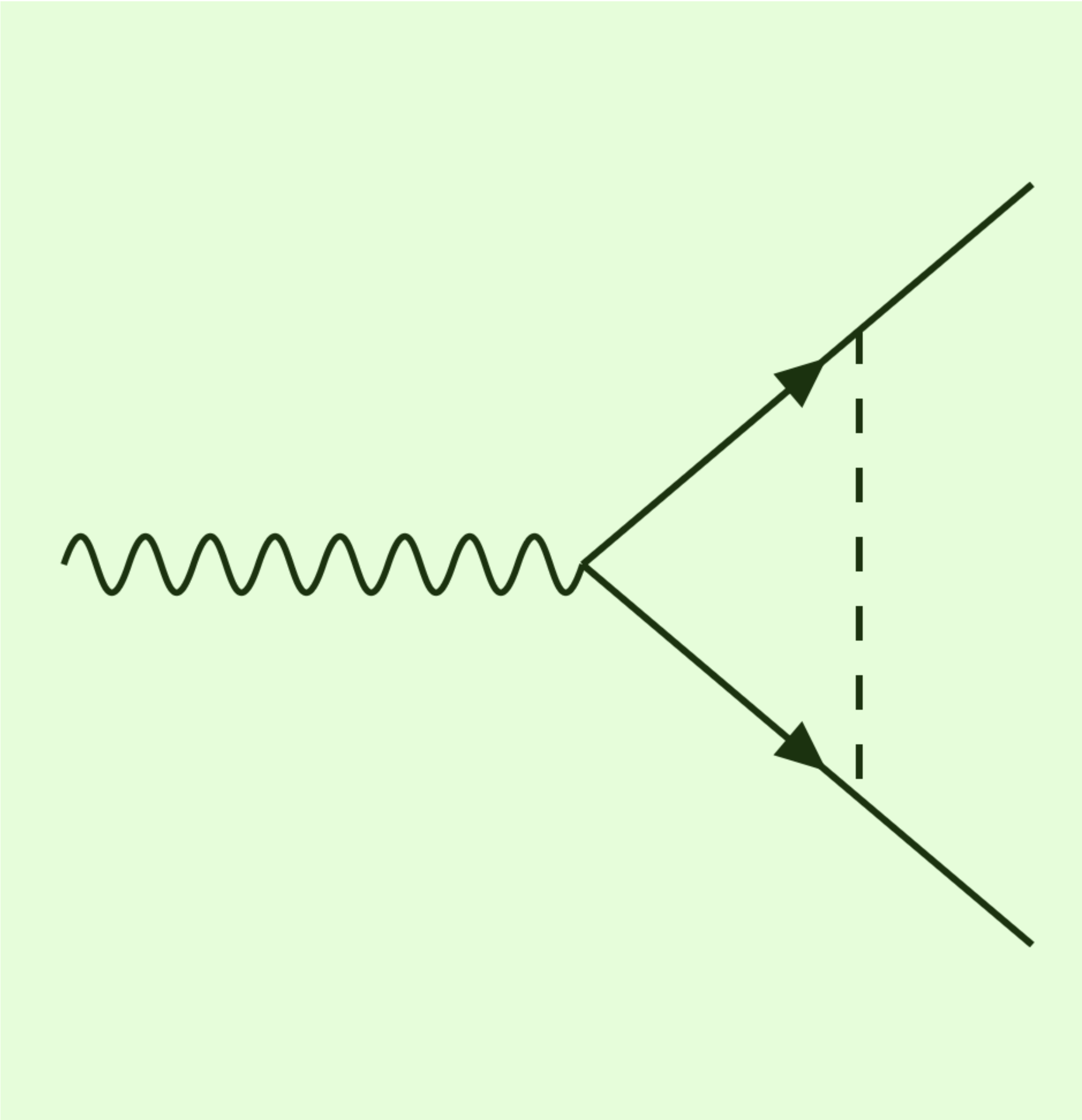
Overview

- 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 (e·cm, C.L. 90%)
e^-	Ion trap	4.1×10^{-30}
μ^-	(g-2) storage ring	1.5×10^{-19}
τ^-	From eEDM	4.1×10^{-19}
τ^-	$e^+e^- \to \tau^+\tau^-$	1.9×10^{-17}
neutron	Hg*	1.4×10^{-26}
proton	Hg*	1.7×10^{-25}

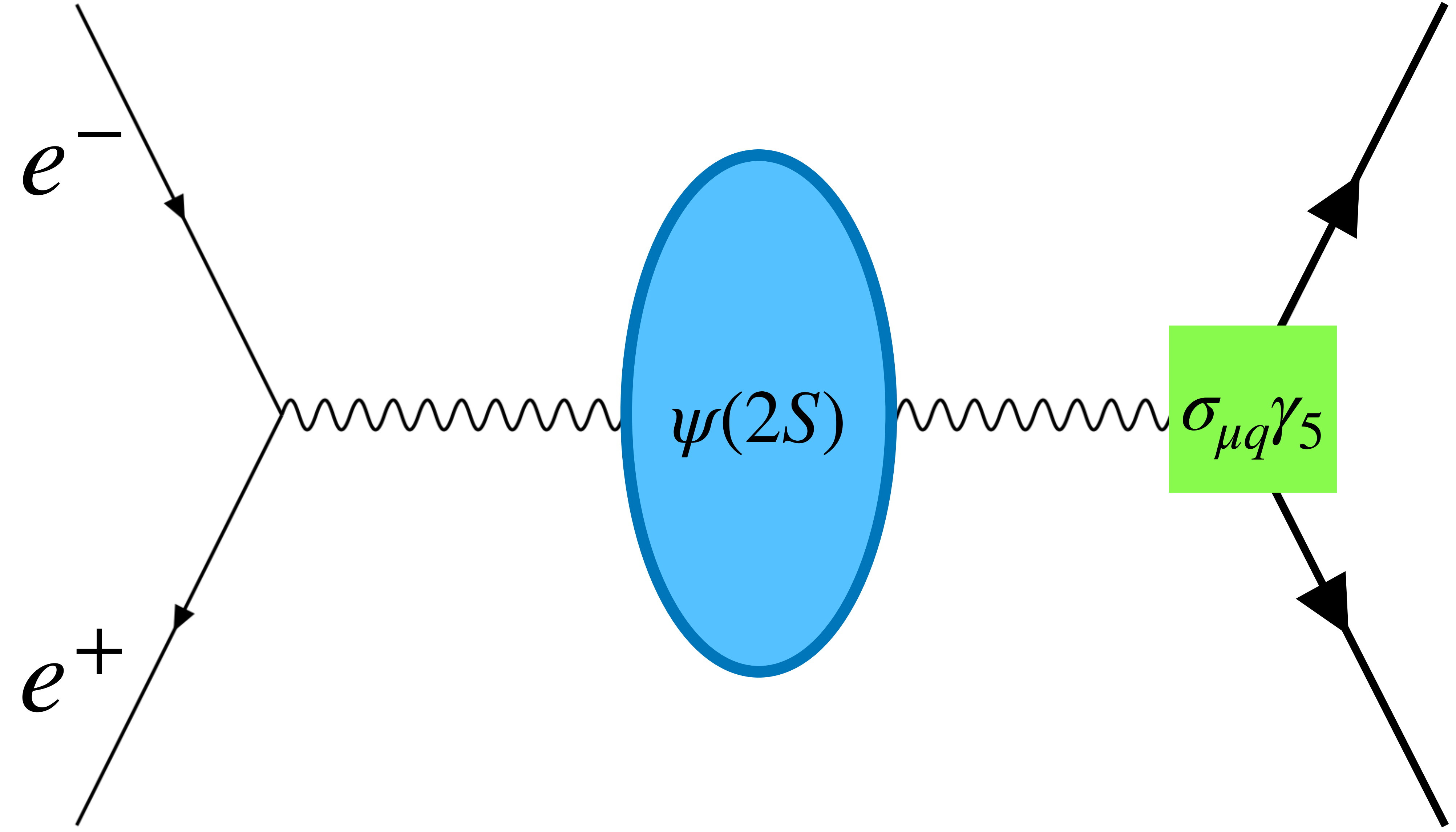
[See Kia Boon Ng's talk]

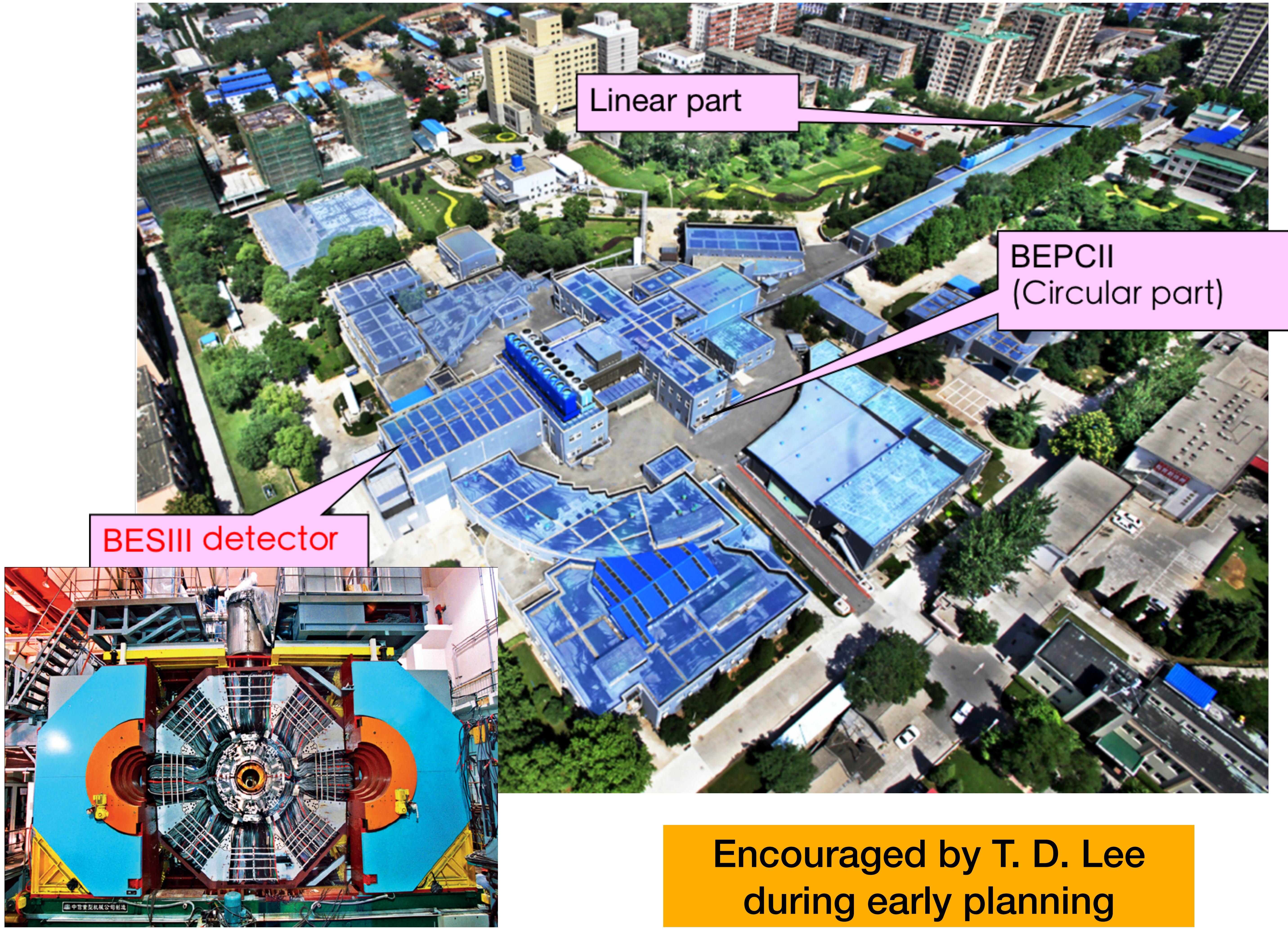
@Belle

[2003.00717]

Colliders in China

- Produced 2.7×10^9 $\psi(2s)$, around 10^7 events of $\psi(2s) \to \tau^-\tau^+$.
- Produced 10^{10} J/ψ, around 10^8 events of $J/\psi \to$ hyperon pairs.
- Luminosity will be shifted forward by **two orders** in STCF.





Encouraged by T. D. Lee during early planning

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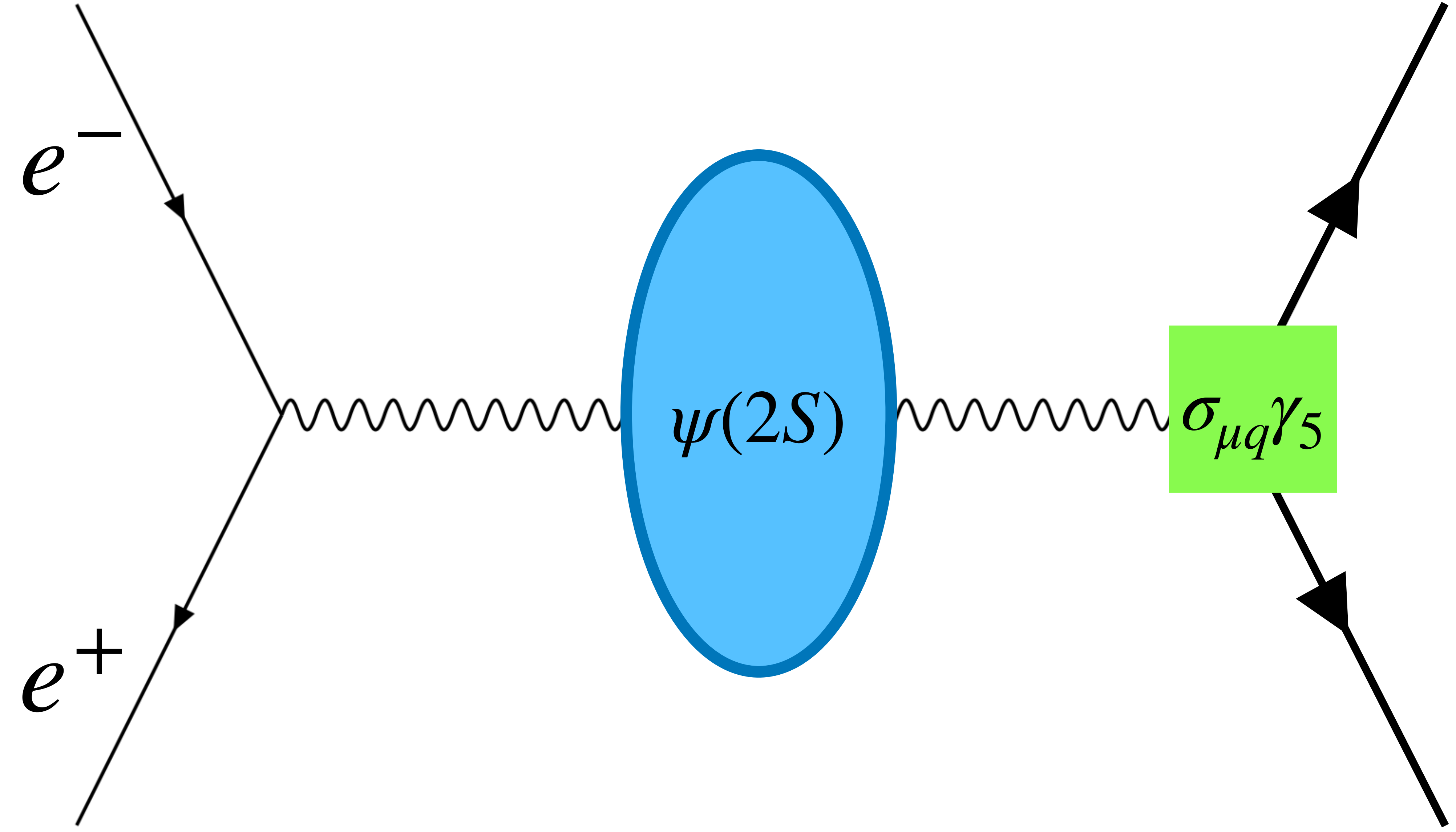
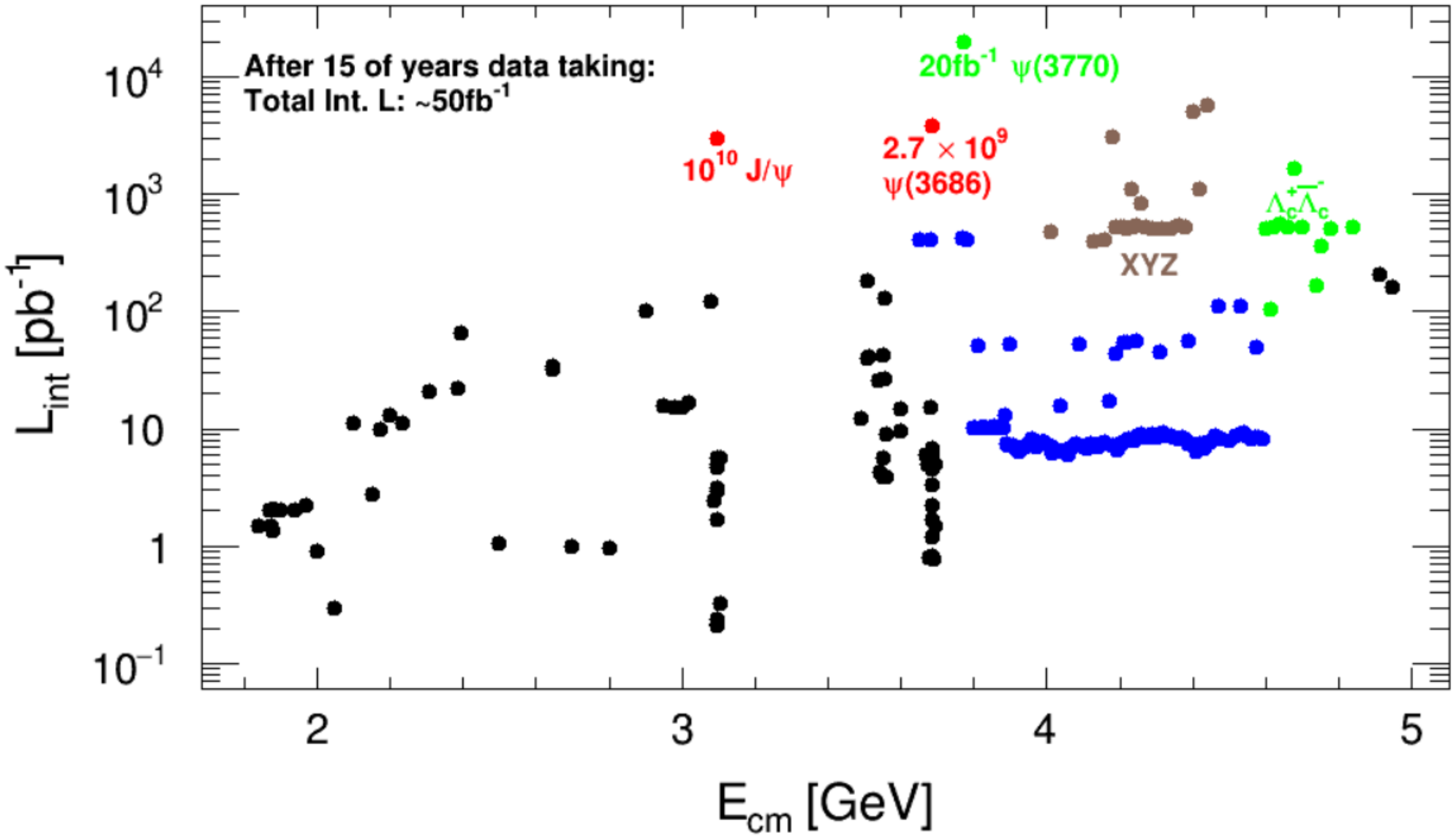




Timelike EDM

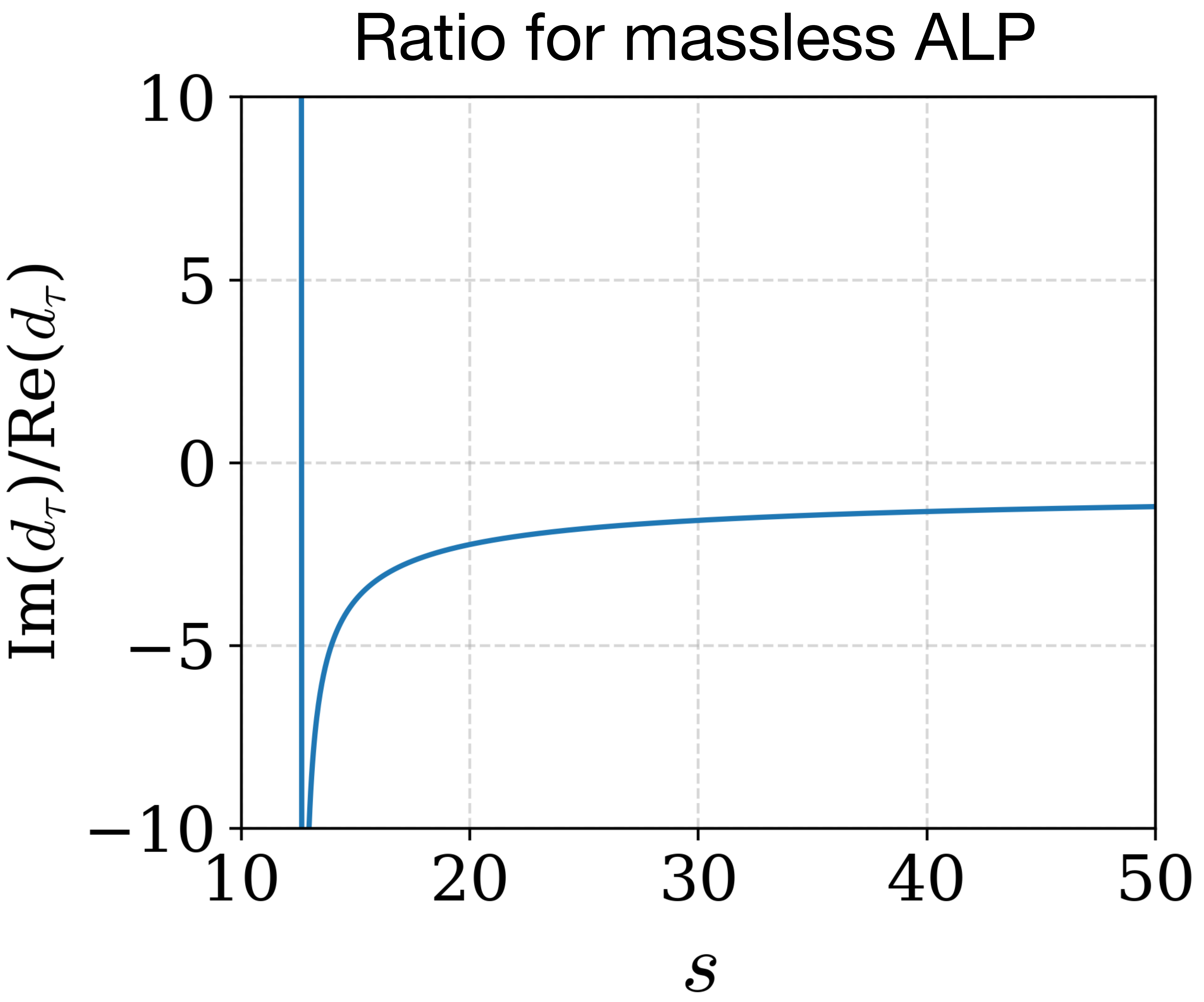
- EDM is **timelike** here, unlike the usual case.

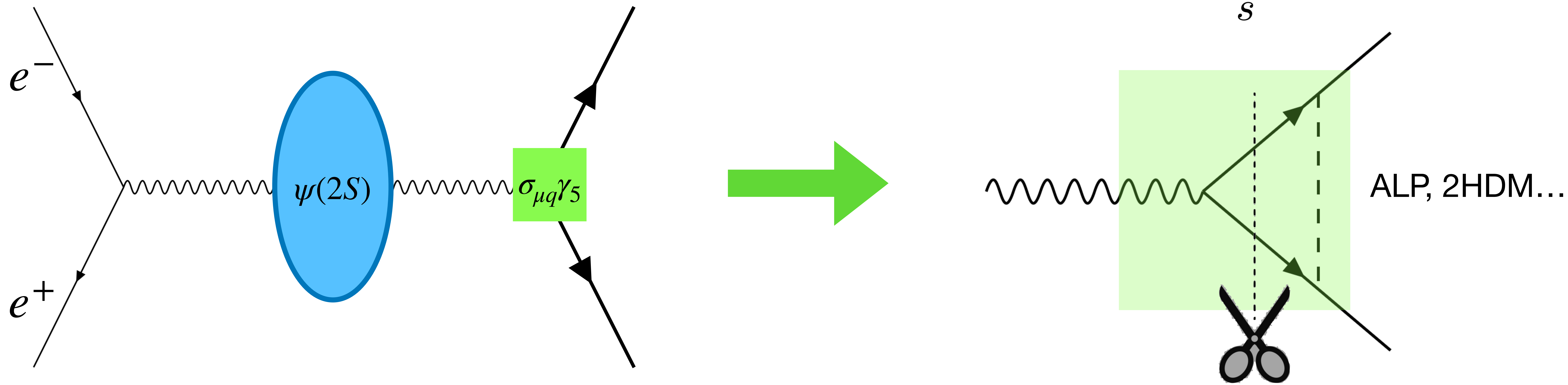
$$\mathscr{A}^{\mu}=\bar{u}\Big(\gamma^{\mu}F_V+\frac{i}{2m}\sigma^{\mu q}H_{\sigma}+\gamma^{\mu}\gamma^{5}F_A+\sigma^{\mu q}\gamma^{5}H_T\Big)v$$

- 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:

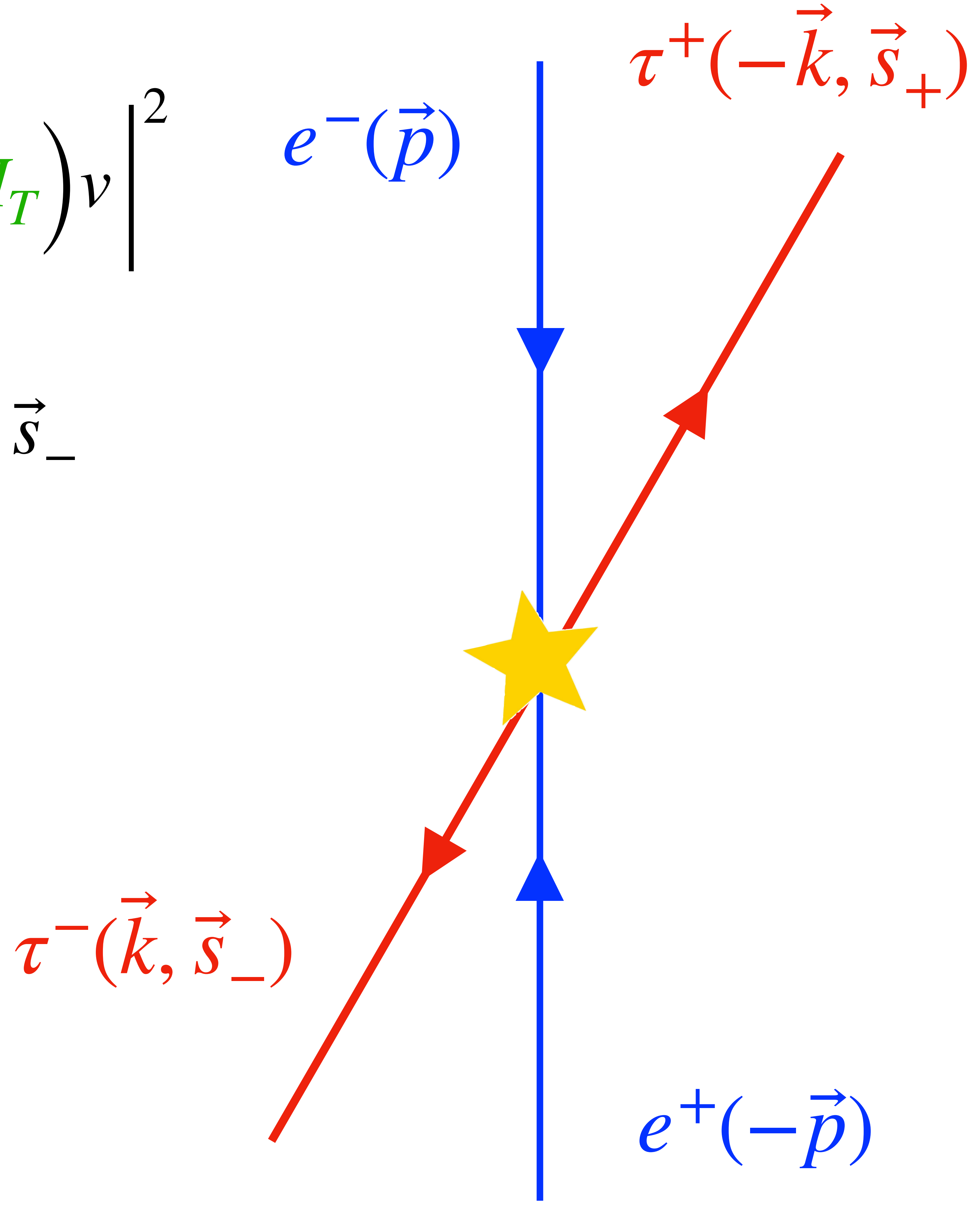
Polarization fraction

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

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

$$\vec{B}_{-}(\vec{p},\vec{k}) = \left(b_{p}\hat{p} + b_{k}\hat{k}\right)\mathrm{Im}\left(H_{T}\right)$$

$$C^{ij}(\vec{p},\vec{k}) = \underbrace{\delta^{ij}c_{0}\cdots}_{\text{CP-even}} + \underbrace{\epsilon^{ijk}\left(\hat{p}^{k}c_{1} + \hat{k}^{k}c_{2}\right)}_{\text{CP-odd}}\mathrm{Re}\left(H_{T}\right)$$



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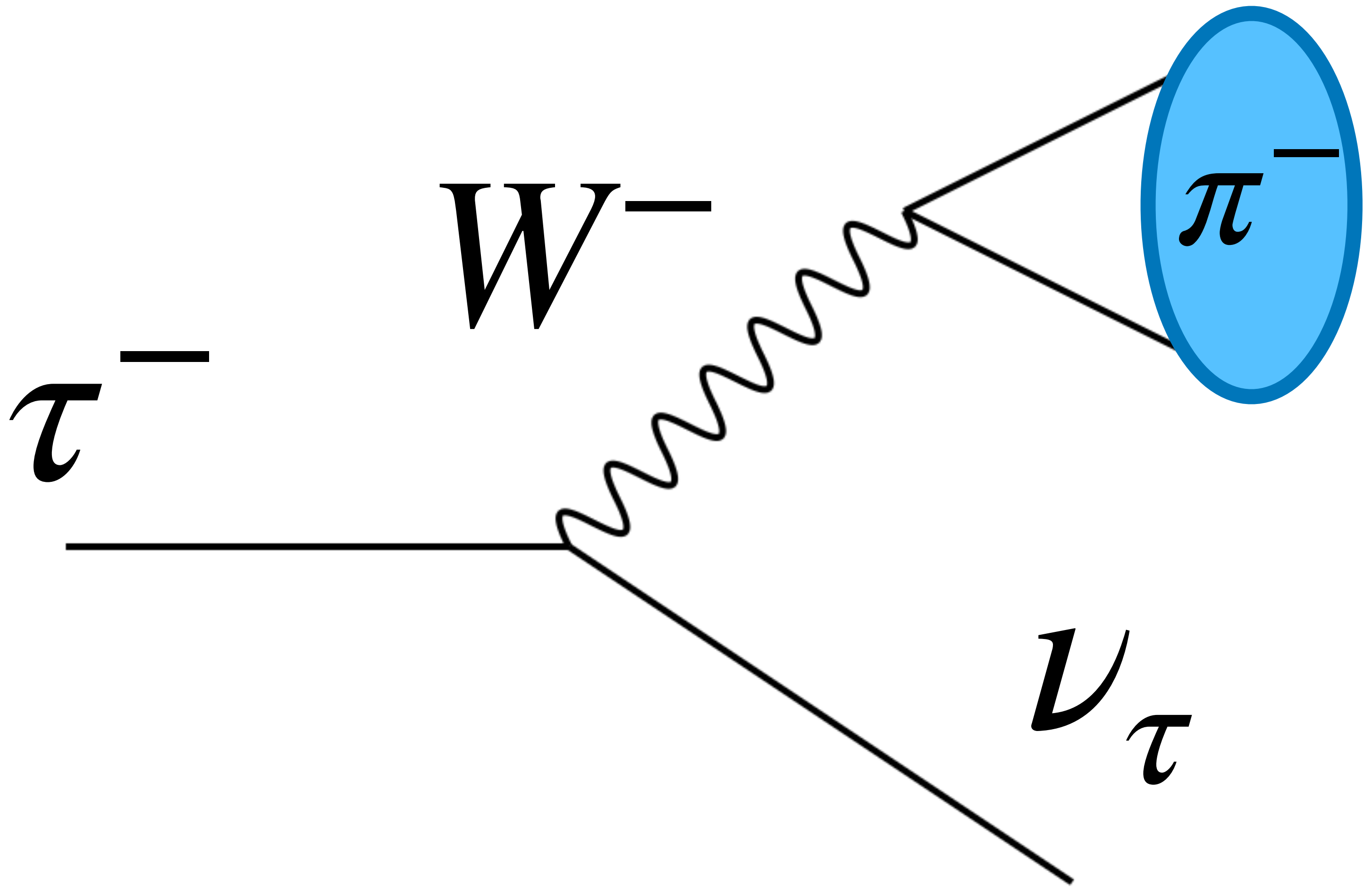
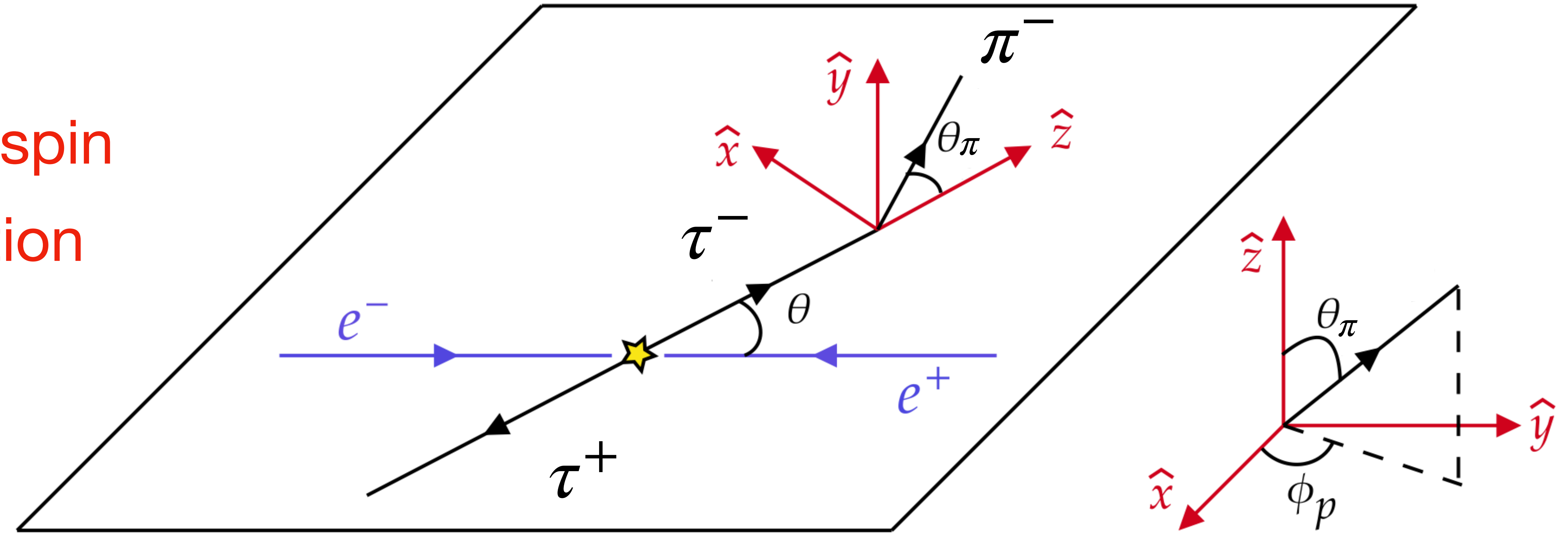
$$\frac{\partial\Gamma}{\partial\overrightarrow{\Omega}} = \sum_{\epsilon} P_\epsilon \left| \epsilon_\mu \, \bar{u}\left(\gamma^\mu F_V + \frac{i}{2m}\sigma^{\mu q} H_\sigma + \gamma^\mu\gamma^5 F_A + \sigma^{\mu q}\gamma^5 H_T\right) v \right|^2$$

$$\propto 1 + \overrightarrow{B}_+ \cdot (\vec{p}_{\pi^-} - \vec{p}_{\pi^+}) + \overrightarrow{B}_- \cdot (\vec{p}_{\pi^-} + \vec{p}_{\pi^+}) - \vec{p}_{\pi^+} \cdot \overleftrightarrow{C} \cdot \vec{p}_{\pi^-}$$



Carry τ^- spin information



[2204.11058]

In the SM, ν_τ must be left-handed

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

Hyperon EDMs

Polarization fraction of τ^-

Polarization fraction of τ^+

- Net results of the EDM formula:

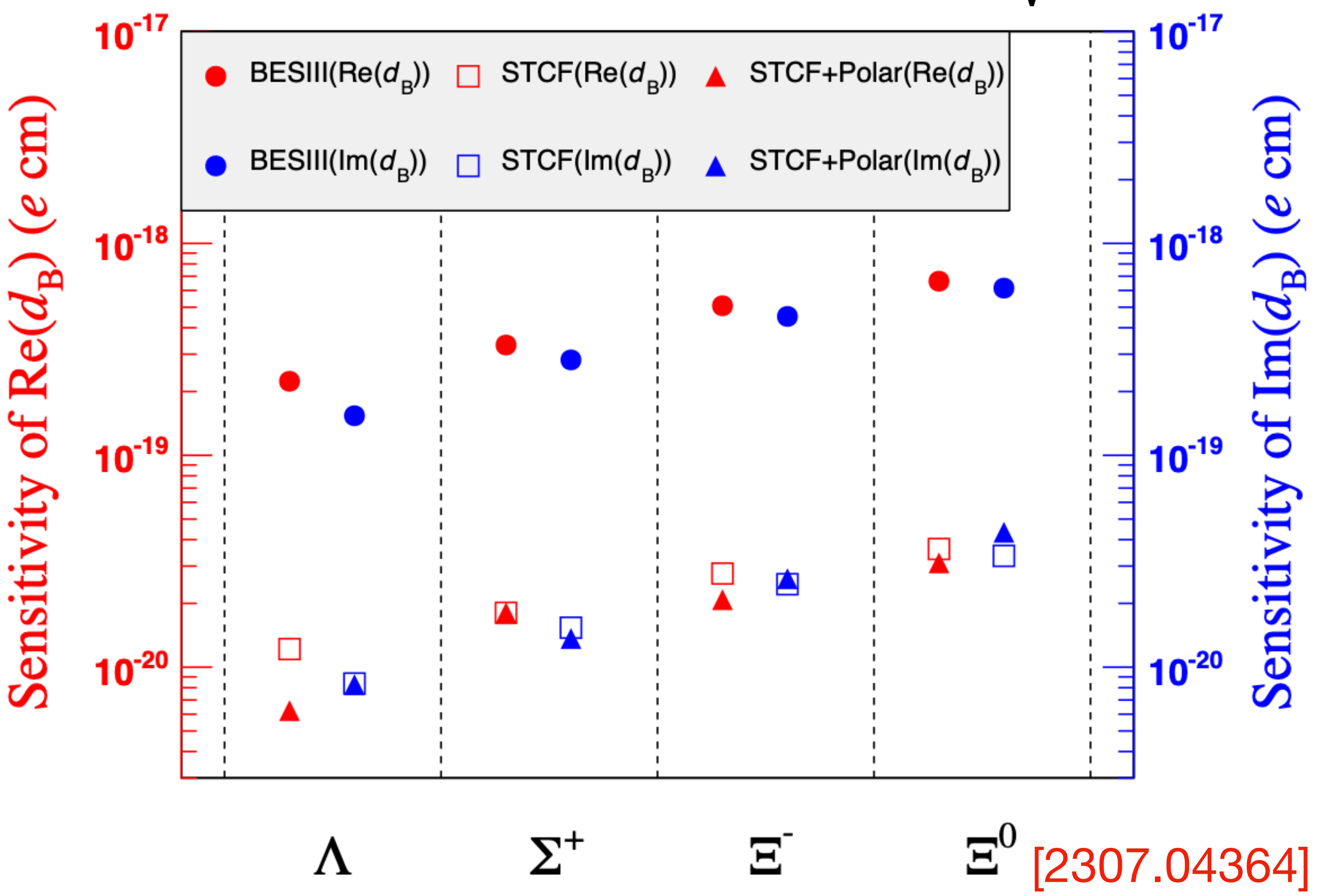
$$\mathrm{Im}\left(d_\tau\right) = -\frac{3}{4}\frac{e\left(s+2m_\tau^2\right)}{m_\tau\sqrt{s}\sqrt{s-4m_\tau^2}}\left(\left\langle \hat{p}_{\pi^-}\cdot\hat{k}\right\rangle + \left\langle \hat{p}_{\pi^+}\cdot\hat{k}\right\rangle\right)$$

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 $\sqrt{\mathscr{BF}}$.



[2307.04364]

CP violation	$\mathrm{Im}(d_B)$ ($\times10^{-18}$ e cm)		$\mathrm{Re}(d_B)$ ($\times10^{-18}$ e cm)	
	BESIII	STCF	BESIII	STCF
Λ ($\epsilon = 0.4$)	2.62	0.14	8.64	0.47
Σ^+ ($\epsilon = 0.2$)	1.47	0.08	18.4	1.00
Ξ^0 ($\epsilon = 0.2$)	6.12	0.33	82.6	4.41
Ξ^- ($\epsilon = 0.2$)	6.79	0.37	95.9	5.20

With 10^{10} J/ψ, Du[2], He, Ma, [2405.09625]

• τ EDM, oops!

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

Undetermined

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

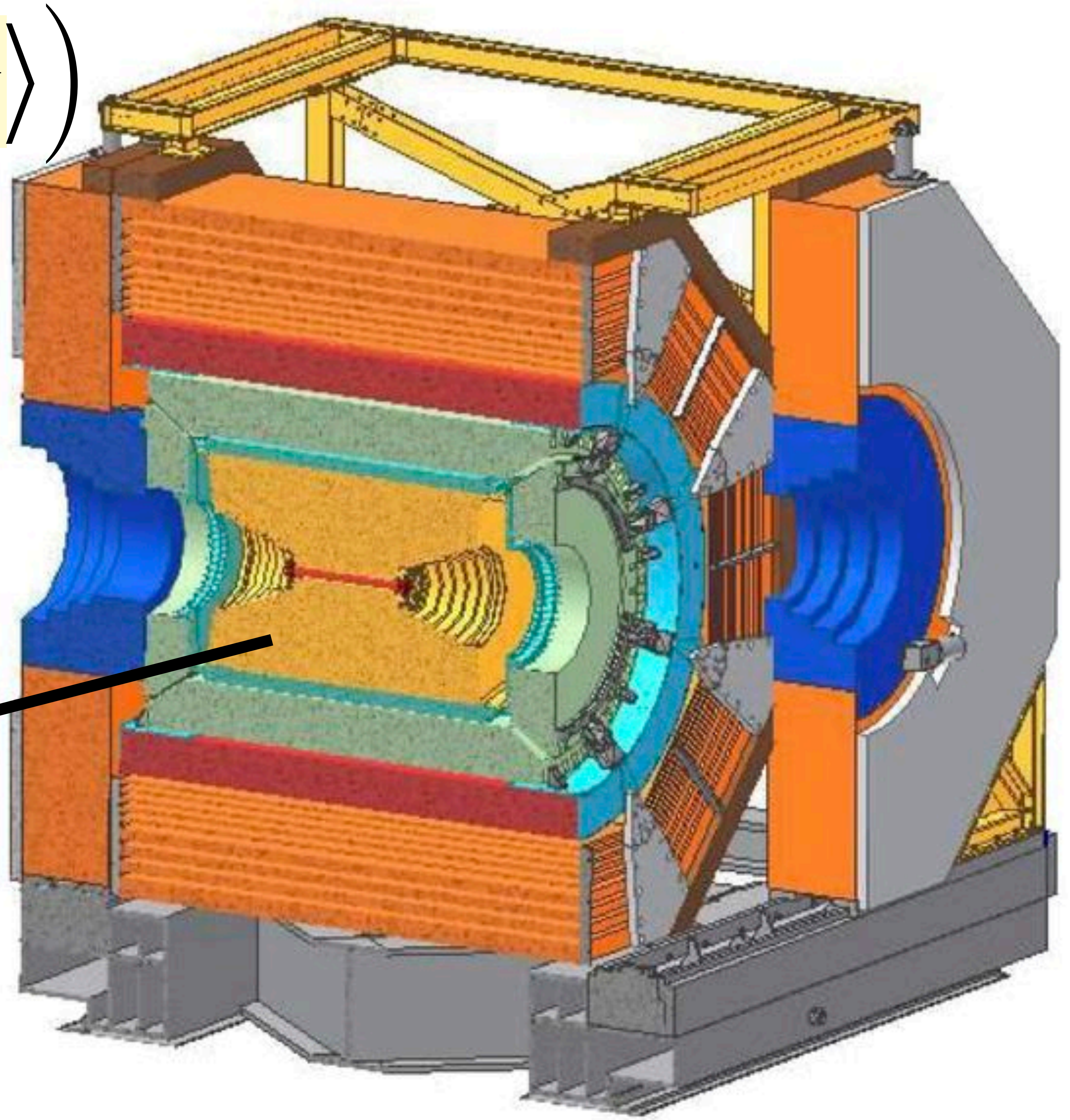
- Travel distance of τ is $\mathbf{87}\ \mu\mathrm{m}$, much **shorter** than the current resolution of detector.

- What's worse, there will always be at least **two** neutrinos in the final state.

Main Drift Chamber

$\sigma_{xy} = \mathbf{130}\ \mu\mathrm{m}$

$\sigma_{p_z}/p = 0.5\,\%\ @\,1\ \ \mathrm{GeV}$



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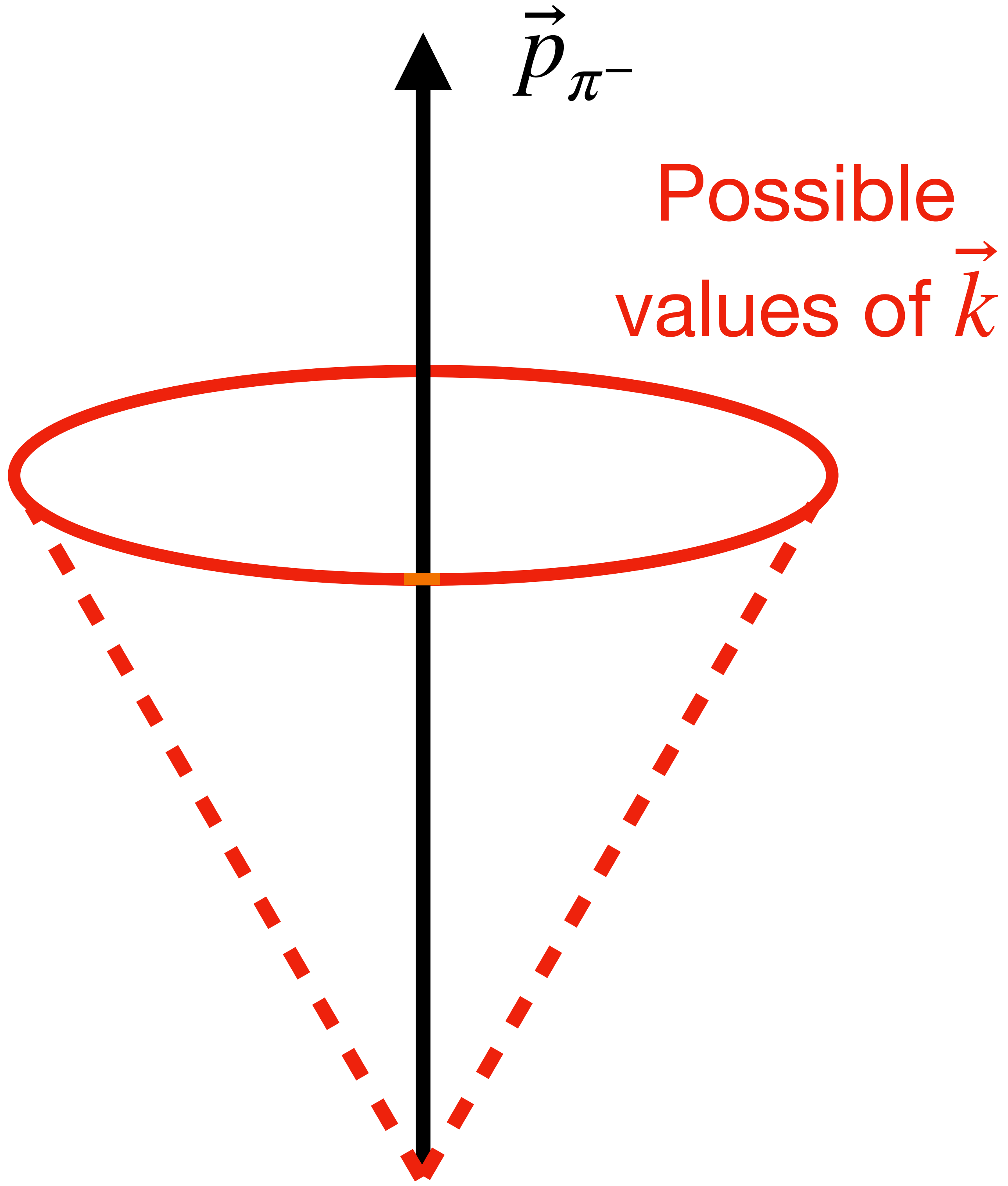
$$\mathrm{Im}\left(d_\tau\right) = -\frac{3}{4}\frac{e\left(s+2m_\tau^2\right)}{m_\tau\sqrt{s}\sqrt{s-4m_\tau^2}}\left(\left\langle \hat{p}_{\pi^-}\cdot\hat{k}\right\rangle + \left\langle \hat{p}_{\pi^+}\cdot\hat{k}\right\rangle\right)$$

- 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.



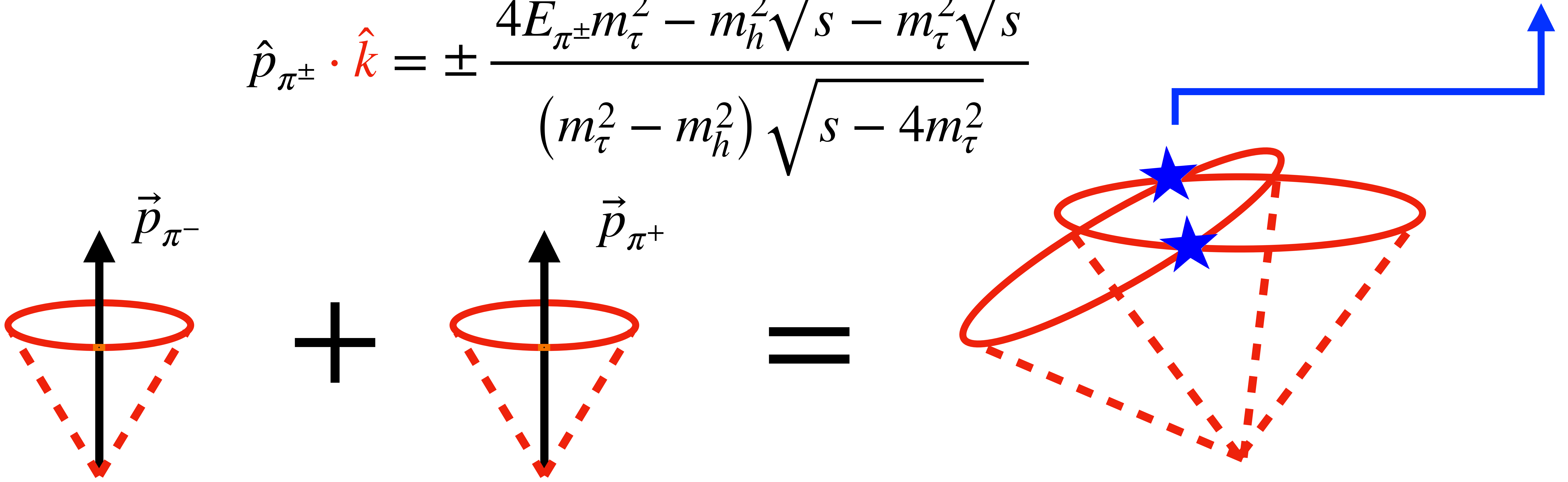
$\sqrt{s}$	$m_{\psi(2S)}$	4.2 GeV	4.9 GeV	5.6 GeV	6.3 GeV	7 GeV
δ_{Im}	1.8	0.9	0.7	0.7	0.7	0.7

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

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

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

[2108.11543]

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

• τ 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.

$$P_\tau = 1 - \underbrace{\left(\int_0^{D/D_0} \exp(-x)dx\right)^2}_{\text{Probability of } not \text{ being detected}}$$

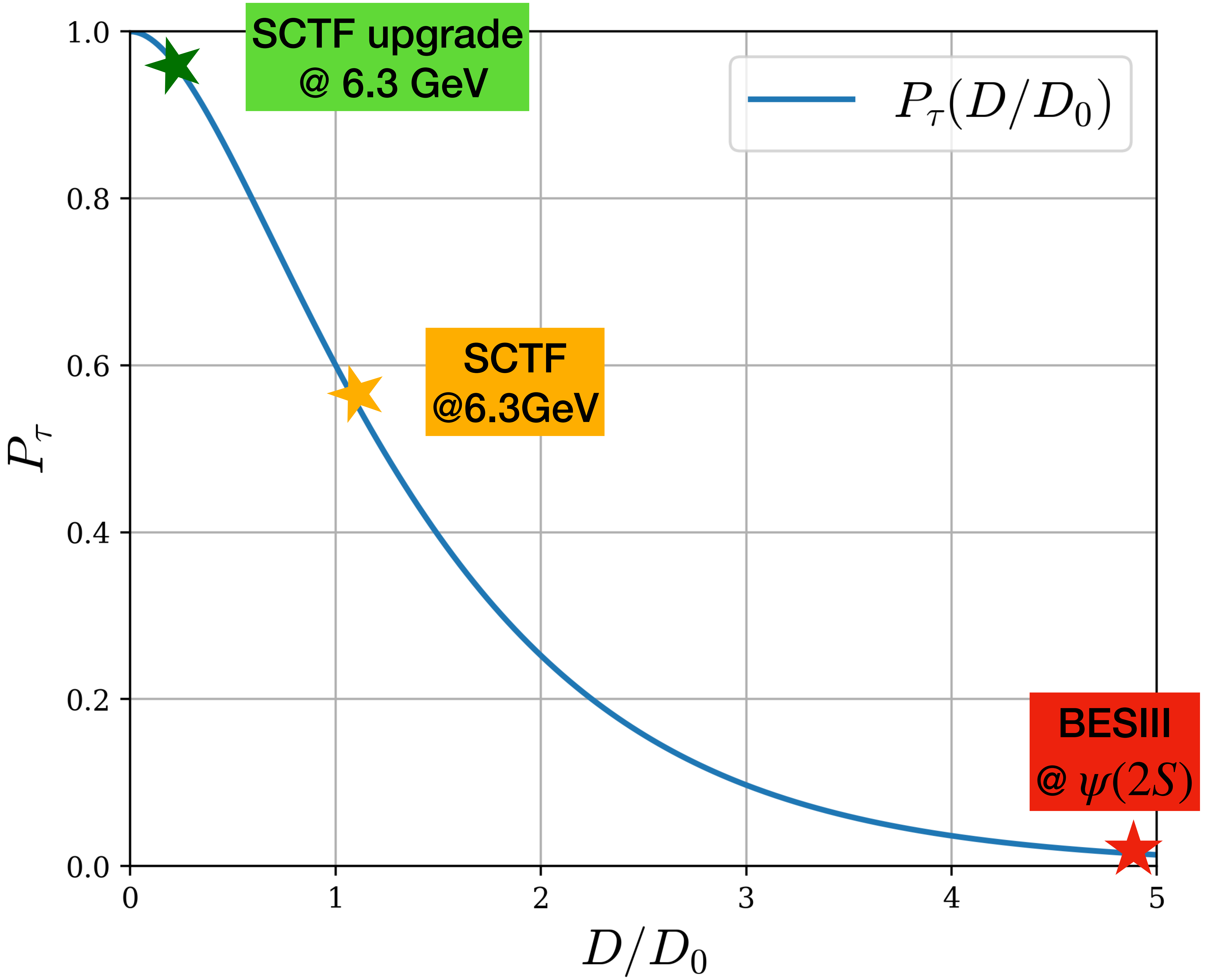
Probability of being detected

D : the detector resolution

D_0 : the average flight distance.

- We have to ***sacrifice*** some statistics when $\hat{k}$ cannot be detected.

- $P = 2\,\%$, nearly impossible to probe $\mathrm{Re}(d_\tau)$ @ **BESIII** but excellent at **SCTF**.



τ EDM

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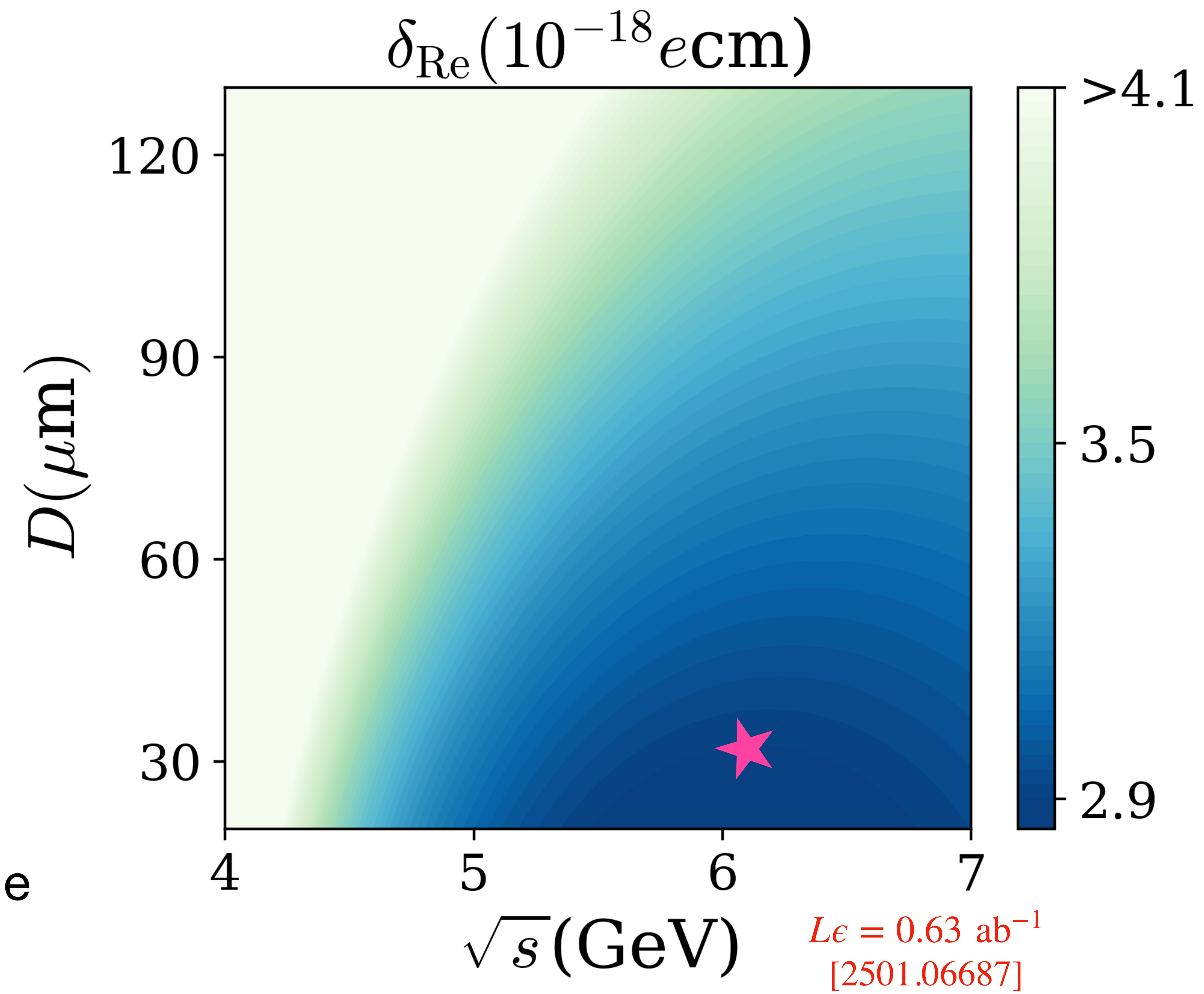
$\sqrt{s}$	$m_{\psi(2S)}$	5.6 GeV	6.3 GeV
δ_{Im}	1.8	0.7	0.7
$\delta_{\text{Re}}(180)$	235	4.9	4.2
$\delta_{\text{Re}}(130)$	83	4.0	3.6
$\delta_{\text{Re}}(80)$	29	3.3	3.1
$\delta_{\text{Re}}(30)$	11	2.9	2.8

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

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

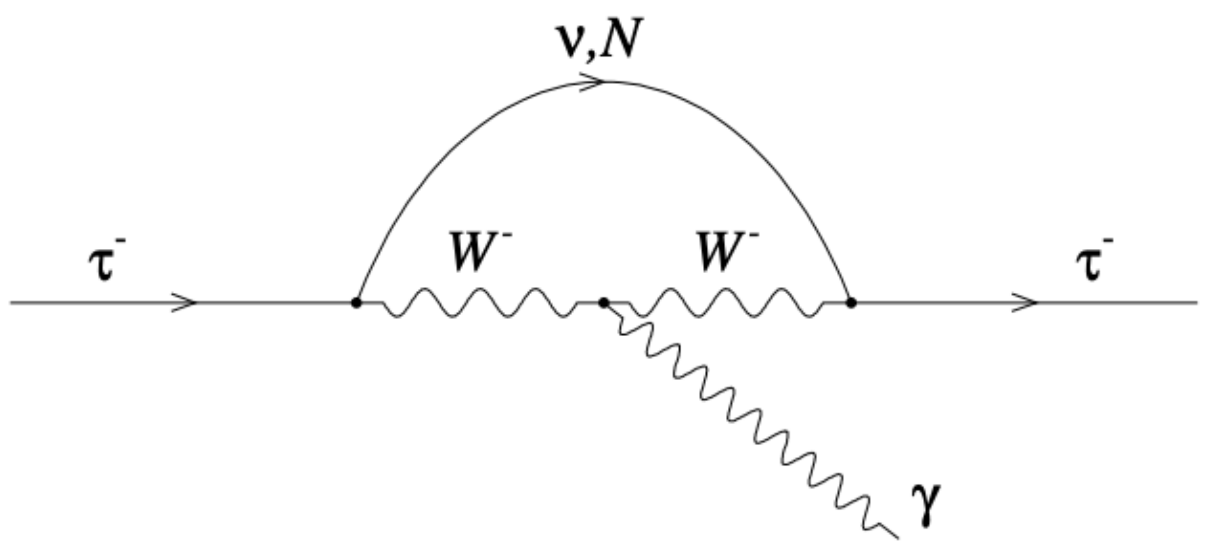
- ★ sweet spot @$\sqrt{s} = 6.3$ GeV, pushing the upper bound to $10^{-18}\ e$cm.



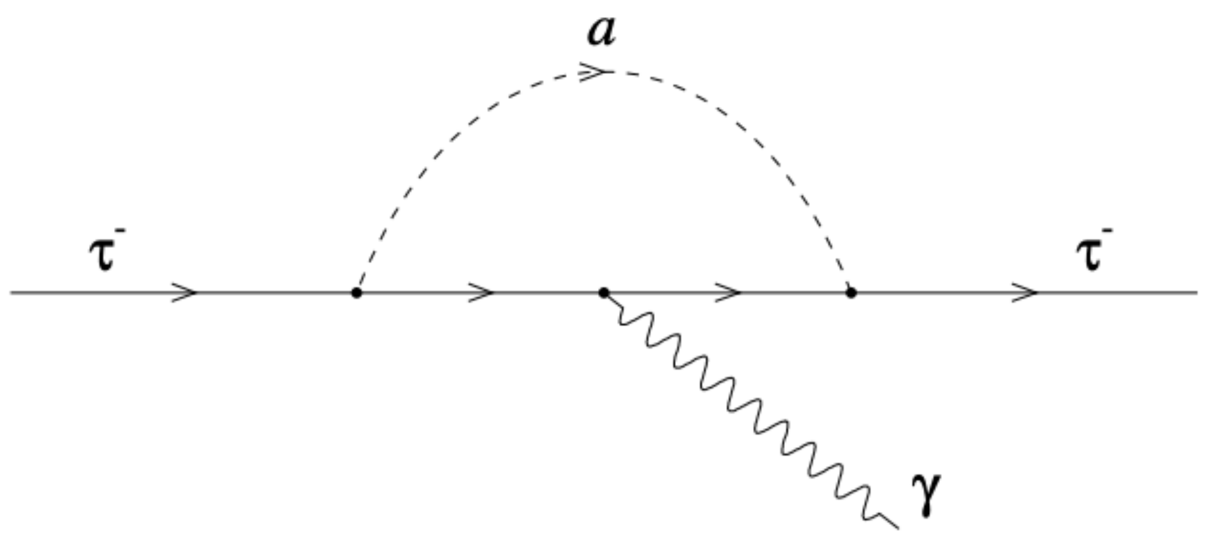
$L\epsilon = 0.63\ \text{ab}^{-1}$
[2501.06687]

τ EDM - future aspect

- We are currently studying NP that can give τ and hyperon EDM at $10^{-19}\ e\mathrm{cm}$ level.

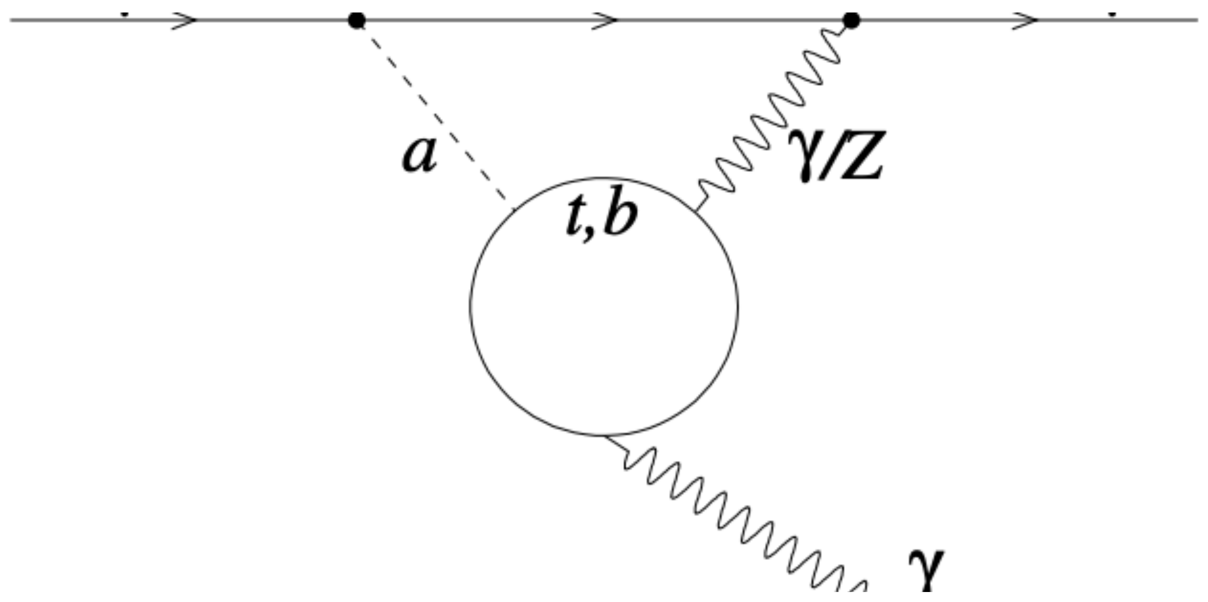


Heavy neutrino

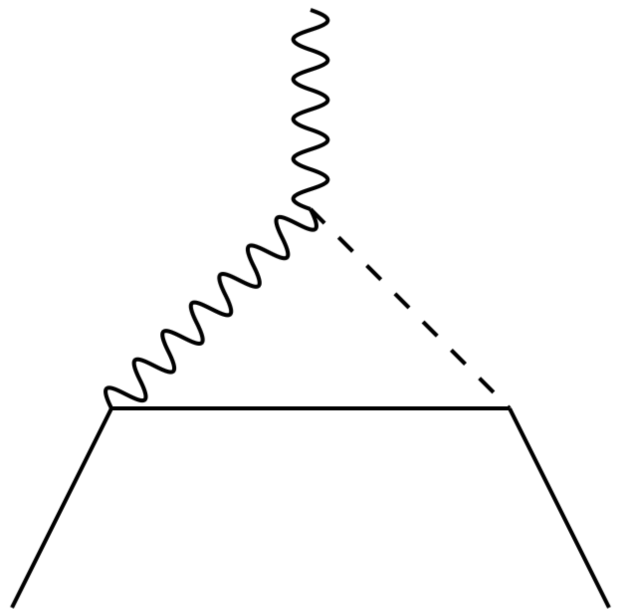


Light scalar

[1803.00501]



2 loop Zee-Bar



$m_E(TeV)$	$m_N(TeV)$	$d_\tau^W e.cm$	$d_\tau^{\chi^+} e.cm$	$d_\tau^{\chi^0} e.cm$
0.1	0.2	6.5×10^{-18}	-3.4×10^{-18}	5.0×10^{-19}
2.0	1.0	4.0×10^{-20}	-7.2×10^{-22}	3.0×10^{-23}

Minimal supersymmetric [1001.0231]

$\sqrt{s}$ [GeV]	3.6	4	10.58	12
Model I: Re$d_\tau(s)$ [$10^{-20} f_{\mathrm{I}}\ e\mathrm{cm}$]	14.44	14.44	14.45	14.45
	7.89	7.89	7.89	7.89
	5.04	5.04	5.04	5.04

Leptoquark model [1001.0231]

- It remains challenging for NP to appear naturally only in the third generation.

Conclusions

Timelike EDM opens a new window to probe NP

@ colliders BESIII LHCb BELLE

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

Special thanks to Z. L. Huang in preparation for NP predictions