Tau EDM and magnetic moment measurements with beam polarization upgrade of Belle II

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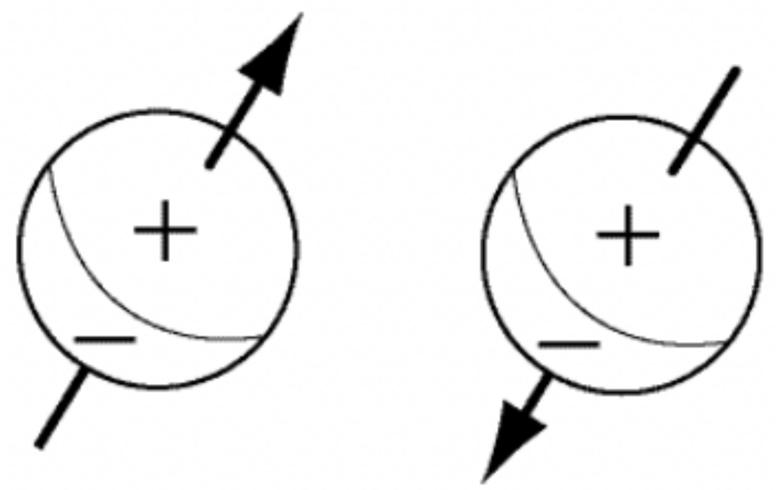
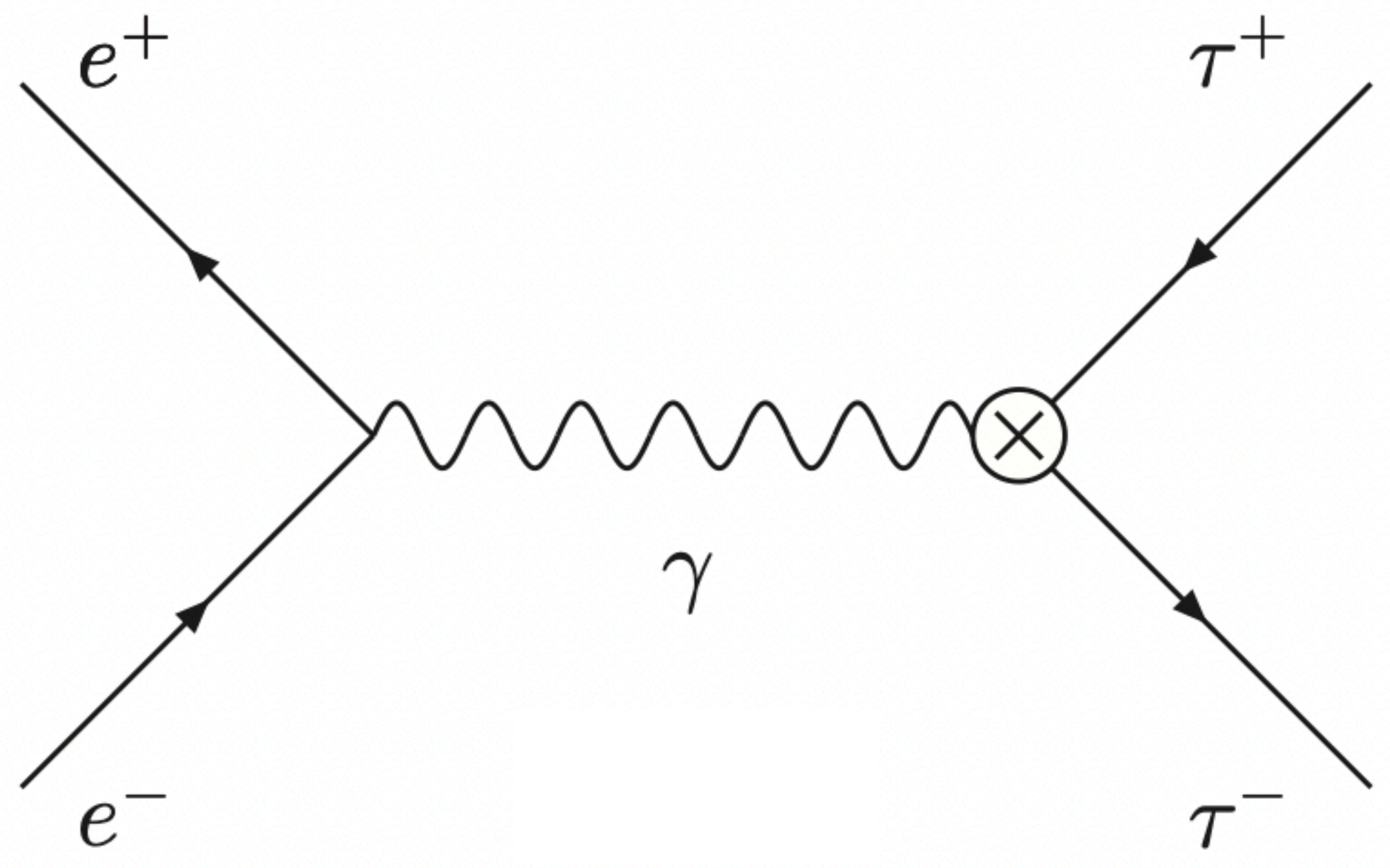
20 Oct 2021
B2GM Meeting,
KEK

EDM of τ

- Charge asymmetry along spin direction



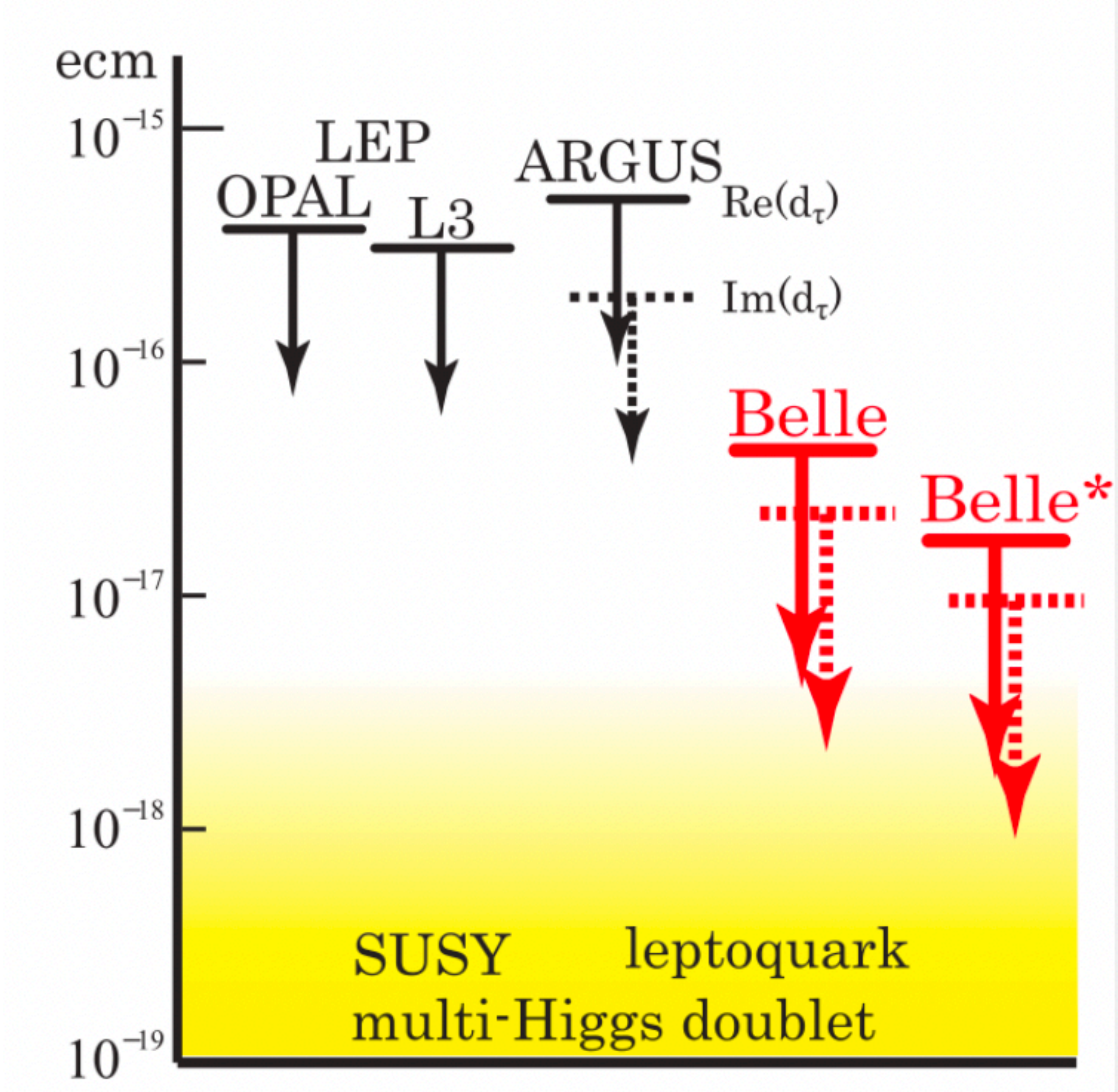
- EDM $\neq 0 \Rightarrow$ P, T violation. Search for CP violation in $\tau^-\tau^+\gamma$ vertex.



- SM prediction $\simeq \mathcal{O}(10^{-37} e \cdot cm)$ far below experimental sensitivity
- EDM $\neq 0 \Rightarrow$ New Physics contributions from new particles in loops

EDM of τ

- **Current Status:**



- Belle; 29.5fb^{-1} data [PLB 551(2003)16]

$$-2.2 < Re(d_\tau) < 4.5 \ (10^{-17}\, e\, \mathrm{cm})$$
$$-2.5 < Im(d_\tau) < 0.8 \ (10^{-17}\, e\, \mathrm{cm})$$

- Belle; 833 fb^{-1} data (arXiv:2108.11543 **[hep-ex])**
  - 95% confidence intervals

$$-1.85 \times 10^{-17} < \ \mathrm{Re}(d_\tau) \ < 0.61 \times 10^{-17} \ \mathrm{ecm},$$
$$-1.03 \times 10^{-17} < \ \mathrm{Im}(d_\tau) \ < 0.23 \times 10^{-17} \ \mathrm{ecm}.$$

- Consistent with zero EDM
- ~2.7 times smaller error than the previous results
- Systematic errors are comparable with the statistical errors.

Courtesy: K. Inami's presentation at Tau 2021

EDM of τ

CP violation and electric-dipole-moment at low energy τ production with polarized electrons

J. Bernabeu G.A. Gonzalez-Sprinberg J. Vidal

Nucl.Phys.B763:283-292,2007, hep-ph/0610135

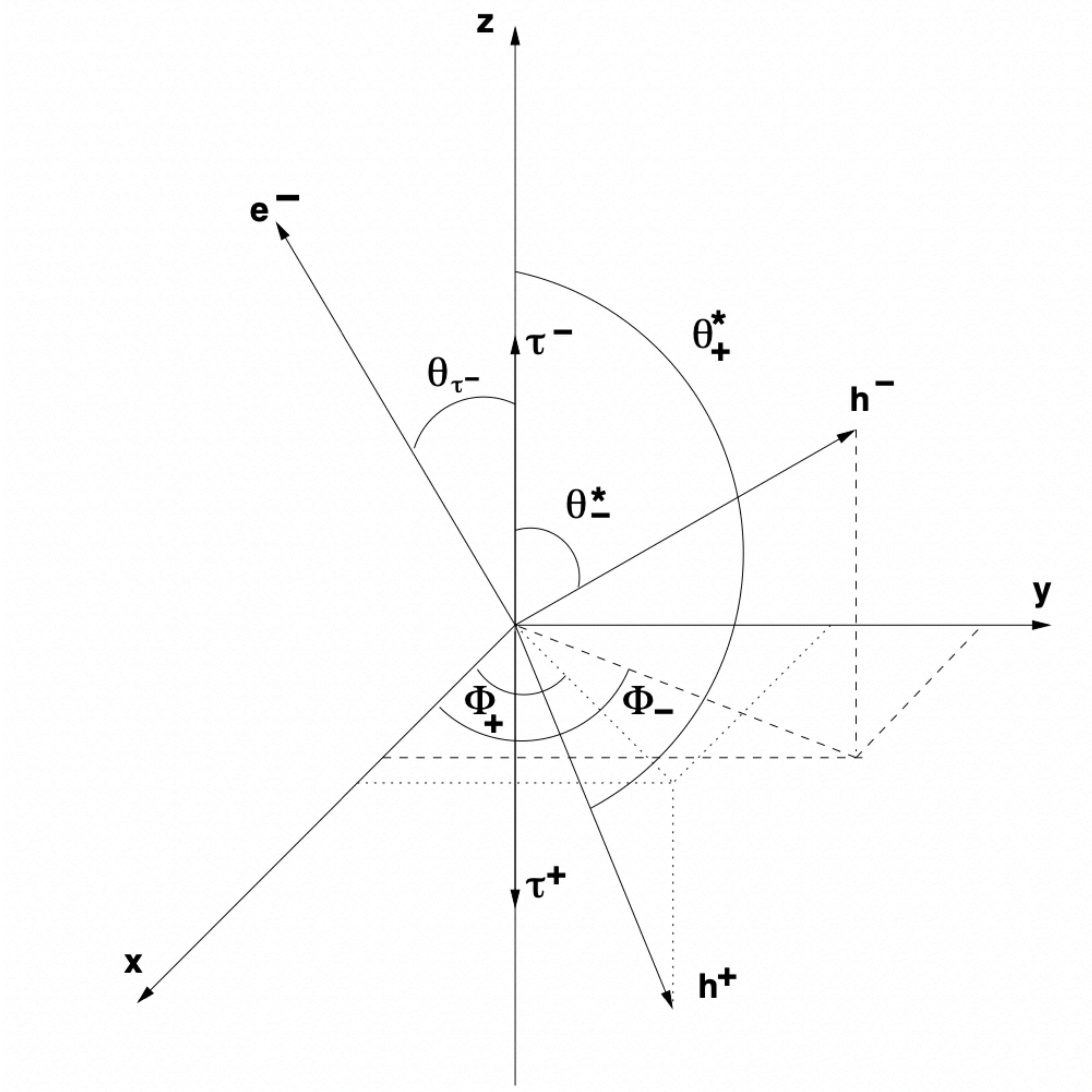


Fig. 2. Coordinate system for $h^{\pm}$ production from the $\tau^{\pm}$

Now, to be sensitive only to the EDM we can define the azimuthal asymmetry as:

$$A_N^{\mp} = \frac{\sigma_L^{\mp} - \sigma_R^{\mp}}{\sigma} = \alpha_{\mp} \frac{3\pi\gamma\beta}{8(3-\beta^2)} \frac{2m_\tau}{e} d_\tau^\gamma \qquad (14)$$

where

$$\sigma_L^{\mp} = \int_0^{2\pi} d\phi_{\pm} \left[\int_0^{\pi} d\phi_{\mp} \left. \frac{d^2\sigma^S}{d\phi_- d\phi_+} \right|_{Pol(e^-)} \right] = Br(\tau^+ \to h^+ \bar{\nu}_\tau) Br(\tau^- \to h^- \nu_\tau)\, \alpha_{\mp} \frac{(\pi\alpha\beta)^2\gamma}{8s} \frac{2m_\tau}{e} d_\tau^\gamma \qquad (15)$$

$$\sigma_R^{\mp} = \int_0^{2\pi} d\phi_{\pm} \left[\int_{\pi}^{2\pi} d\phi_{\mp} \left. \frac{d^2\sigma^S}{d\phi_- d\phi_+} \right|_{Pol(e^-)} \right] = -Br(\tau^+ \to h^+ \bar{\nu}_\tau) Br(\tau^- \to h^- \nu_\tau)\, \alpha_{\mp} \frac{(\pi\alpha\beta)^2\gamma}{8s} \frac{2m_\tau}{e} d_\tau^\gamma \qquad (16)$$

EDM of τ

CP violation and electric-dipole-moment at low energy τ production with polarized electrons

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P_N^{τ} :polarization of one of the τ's normal to the scattering plane.

With beam polarization λ :

$$P_N^{\tau} \propto \lambda \gamma \beta^2 \cos\theta_\tau \sin\theta_\tau \frac{m_\tau}{e} \mathrm{Re}(d_\tau^\gamma)$$

Angular asymmetries (P_N^{τ}) are proportional to EDM

$$A_N^m = \frac{\sigma_L^m - \sigma_R^m}{\sigma_L^m + \sigma_R^m} = \alpha_m \frac{3\pi\gamma\beta}{8(3-\beta^2)} \frac{2m_\tau}{e} \mathrm{Re}(d_\tau^\gamma)$$

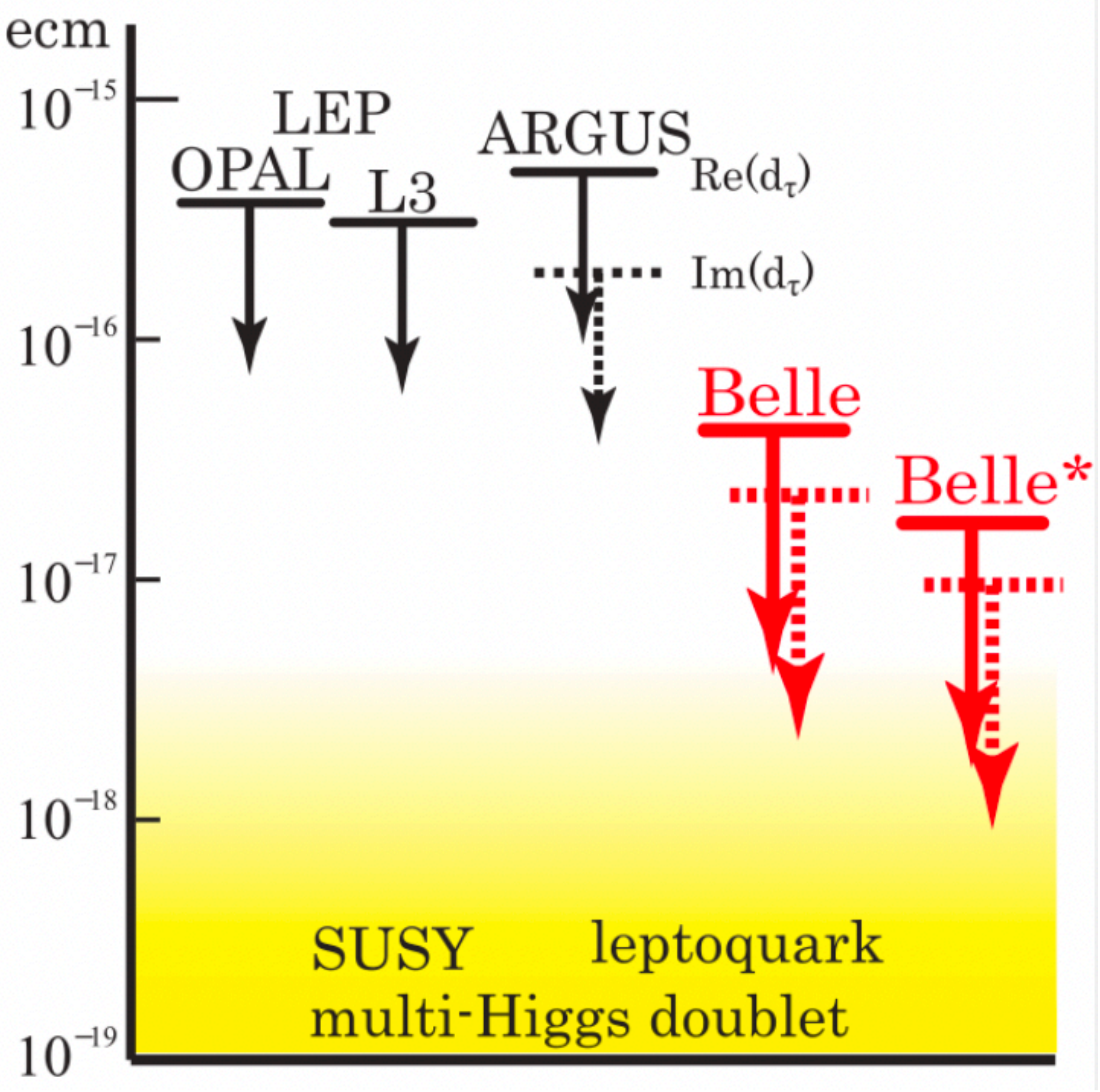
One can also measure A for τ^+ and/or τ^-

$\not{CP}$:

$$A_N^{CP} \equiv \frac{1}{2}(A_N^+ + A_N^-)$$

Courtesy: J.M. Roney's presentation at Tau 2021

EDM of τ



- cBelle can improve precision on EDM of τ

$$|d_\tau^\gamma| \leq 4.4\ 10^{-19}\ ecm \quad \text{Babar + Belle at } 2ab^{-1}$$
$$|d_\tau^\gamma| \leq 1.6\ 10^{-19}\ ecm \quad \text{Super B/Flavor factory, 1 yr running, } 15ab^{-1}$$
$$|d_\tau^\gamma| \leq 7.2\ 10^{-20}\ ecm \quad \text{Super B/Flavor factory, 5 yrs running, } 75ab^{-1}$$

These bounds improve present ones by 3 orders of magnitude.

Bernabeu, et al. Nucl.Phys.B763:283-292,2007, hep-ph/0610135

Using Bernabéu *et al* from this study one can calculate for 40ab^{-1} Chiral Belle data with 70% polarization:

$|d_\tau^\gamma| < 1.4 \times 10^{-20}$ (Statistical error only)

World best measurement from Belle - arXiv:2108.11543 -

$$-1.85 \times 10^{-17} < \mathcal{R}(\tilde{d}_\tau) < 0.61 \times 10^{-17} ecm\ (95\,\%\,CL)$$
$$-1.03 \times 10^{-17} < \Im(\tilde{d}_\tau) < 0.23 \times 10^{-17} ecm\ (95\,\%\,CL)$$

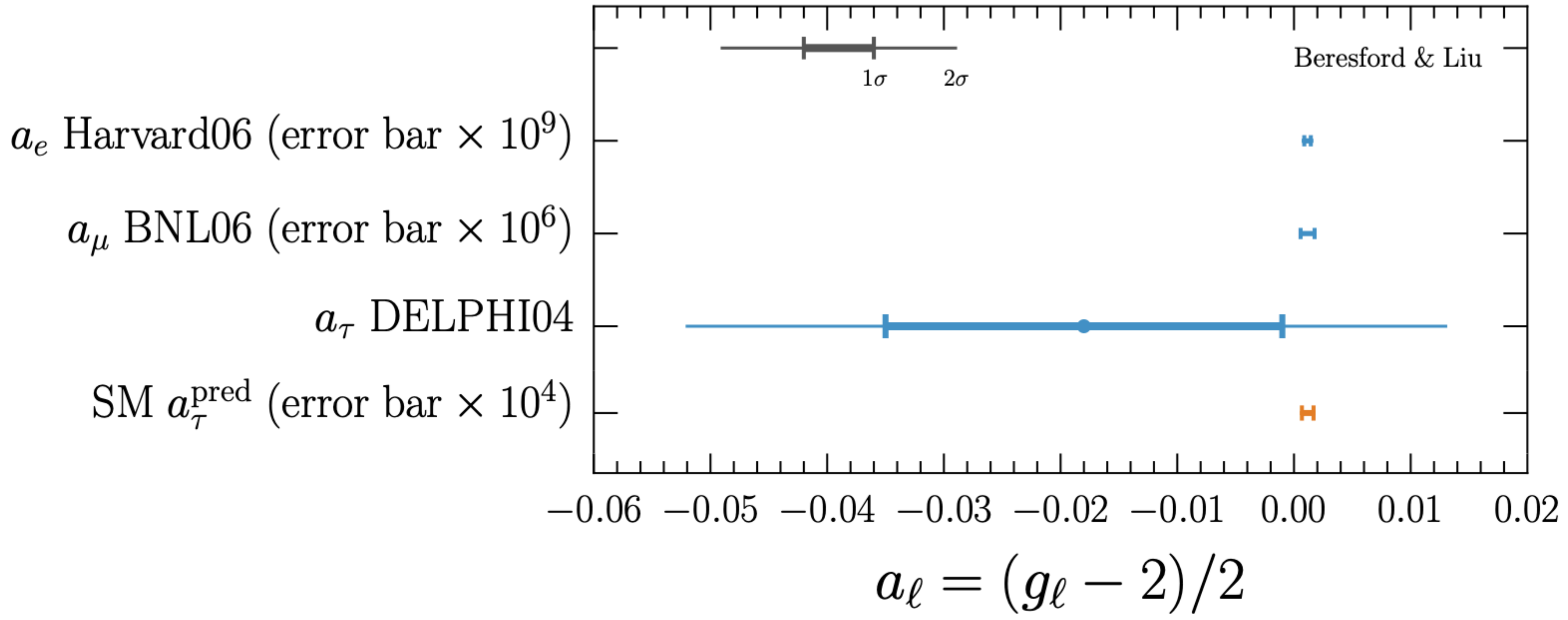
Note: extrapolating statistical error from Belle results shown by Kenji Inami on Tuesday would give a limit of ~5x10^{-19} for unpolarized Belle II data with 50ab^{-1}

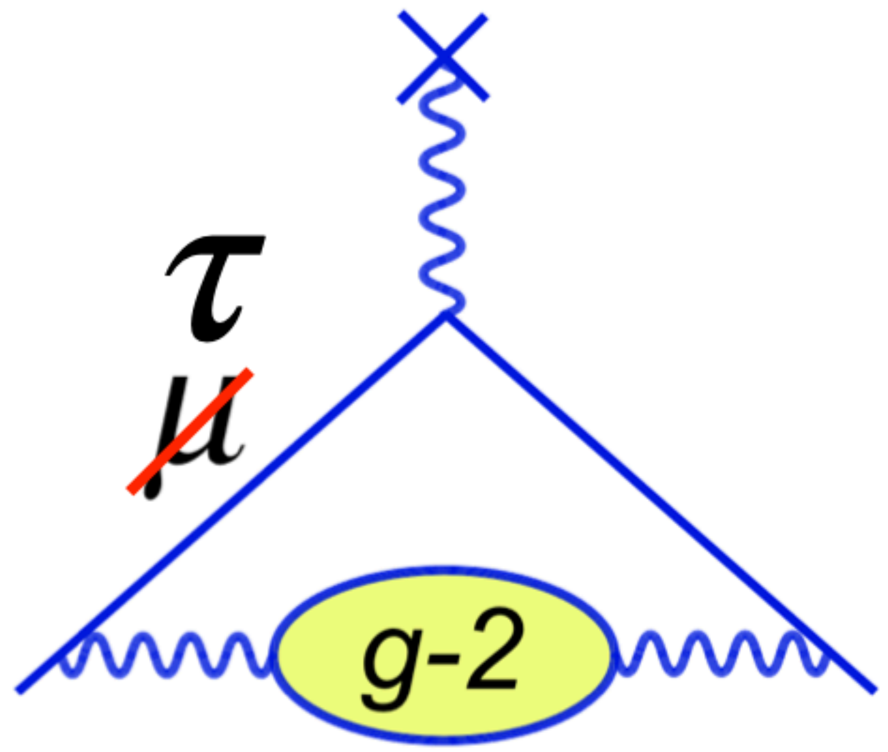
- **Projection (cBelle):** ★

Courtesy: K. Inami's and J.M. Roney's presentations at Tau 2021

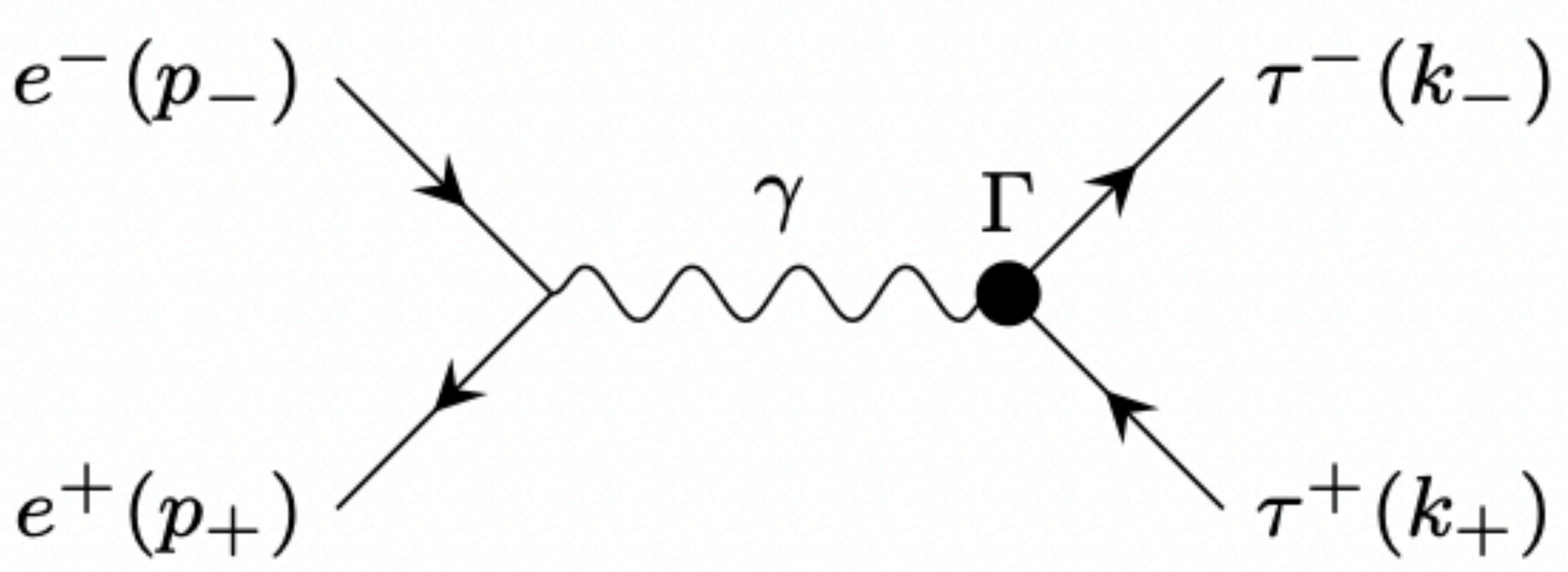
a=(g-2) of τ

- Tensions seen in electron and muon. cBelle can explore $(g\text{-}2)_\tau$





EFT Extension for τ-Pair Production



$$q = k_+ + k_-; \quad q^2 \geq 4m_\tau^2 \quad e > 0; \quad \sigma^{\mu\nu} = \frac{\mathrm{i}}{2}\left[\gamma^\mu, \gamma^\nu\right]$$

$$\langle \tau^-(k_-), \tau^+(k_+), \mathrm{out}| J^\mu_{\mathrm{em}} |0\rangle = -e\bar{u}(k_-)\,\Gamma^\mu v(k_+)$$

$$\Gamma^\mu = \underbrace{F_1(q^2)\,\gamma^\mu}_{\text{radiative corrections}} + \underbrace{F_2(q^2)\,\frac{1}{2m_\tau}\mathrm{i}\sigma^{\mu\nu}q_\nu}_{\text{MDM}} + \underbrace{F_3(q^2)\,\frac{1}{2m_\tau}\sigma^{\mu\nu}q_\nu\gamma_5}_{\text{EDM}}$$

a=(g-2) of τ

Tau anomalous magnetic moment form factor at super B/flavor factories

J. Bernabéu [a,b], G.A. González-Sprinberg [c], J. Papavassiliou [a,b], J. Vidal [a,b,*]

Nucl.Phys.B790:160-174,2008

4.1. Transverse asymmetry

To get an observable sensitive to the relevant signal define the azimuthal transverse asymmetry as

$$A_T^{\pm} = \frac{\sigma_R^{\pm}|_{\text{Pol}} - \sigma_L^{\pm}|_{\text{Pol}}}{\sigma} = \mp\alpha_{\pm}\frac{3\pi}{8(3-\beta^2)\gamma}\left[|F_1|^2 + (2-\beta^2)\gamma^2\,\text{Re}\{F_2\}\right], \tag{29}$$

where

$$\sigma_L^{\pm}|_{\text{Pol}} \equiv \int_{\pi/2}^{3\pi/2} d\phi_{\pm}\left[\frac{d\sigma^S}{d\phi_{\pm}}\bigg|_{\text{Pol}(e^-)}\right]$$
$$= \pm\text{Br}(\tau^+ \to h^+\bar{\nu}_\tau)\,\text{Br}(\tau^- \to h^-\nu_\tau) \times \alpha_{\pm}\frac{(\pi\alpha)^2\beta}{8s}\frac{1}{\gamma}\left[|F_1|^2 + (2-\beta^2)\gamma^2\,\text{Re}\{F_2\}\right], \tag{30}$$

$$\sigma_R^{\pm}|_{\text{Pol}} \equiv \int_{-\pi/2}^{\pi/2} d\phi_{\pm}\left[\frac{d\sigma^S}{d\phi_{\pm}}\bigg|_{\text{Pol}(e^-)}\right] = -\sigma_L^{\pm}|_{\text{Pol}}. \tag{31}$$

4.2. Longitudinal asymmetry

Then, we define the longitudinal asymmetry as

$$A_L^{\pm} = \frac{\sigma_{\text{FB}}^{\pm}(+)|_{\text{Pol}} - \sigma_{\text{FB}}^{\pm}(-)|_{\text{Pol}}}{\sigma} = \mp\alpha_{\pm}\frac{3}{4(3-\beta^2)}\left[|F_1|^2 + 2\,\text{Re}\{F_2\}\right], \tag{34}$$

where

$$\sigma_{\text{FB}}^{\pm}(+)|_{\text{Pol}} \equiv \int_0^1 d(\cos\theta_{\pm}^*)\frac{d\sigma_{\text{FB}}^S}{d(\cos\theta_{\pm}^*)}\bigg|_{\text{Pol}(e^-)}$$
$$= \mp\alpha_{\pm}\,\text{Br}(\tau^+ \to h^+\bar{\nu}_\tau)\,\text{Br}(\tau^- \to h^-\nu_\tau)\frac{\pi\alpha^2}{4s}\beta\left[|F_1|^2 + 2\,\text{Re}\{F_2\}\right], \tag{35}$$

$$\sigma_{\text{FB}}^{\pm}(-)|_{\text{Pol}} \equiv \int_{-1}^0 d(\cos\theta_{\pm}^*)\frac{d\sigma_{\text{FB}}^S}{d(\cos\theta_{\pm}^*)}\bigg|_{\text{Pol}(e^-)} = -\sigma_{\text{FB}}^{\pm}(+)|_{\text{Pol}}. \tag{36}$$

Combining Eq. (29) and Eq. (34) one can determine the real part of $F_2(s)$.

$$\text{Re}\{F_2(s)\} = \mp\frac{8(3-\beta^2)}{3\pi\gamma\beta^2}\frac{1}{\alpha_{\pm}}\left(A_T^{\pm} - \frac{\pi}{2\gamma}A_L^{\pm}\right).$$

a=(g-2) of τ

J. Bernabéu et al. / Nuclear Physics B 790 (2008) 160–174 173

Table 1
Sensitivity of the F_2 measurement at the Υ energy (ab = attobarn = $10^{-18} b$)

Experiment ⇓	Observable		
	Cross-section $\mathrm{Re}\{F_2\}$	Normal asymmetry $\mathrm{Im}\{F_2\}$	Transverse and longitudinal asymmetry combined* $\mathrm{Re}\{F_2\}$
BaBar + Belle $2ab^{-1}$	4.6×10^{-6}	2.1×10^{-5}	1.0×10^{-5}
Super B/flavor factory (1 yr running) $15ab^{-1}$	1.7×10^{-6}	7.8×10^{-6}	3.7×10^{-6}
Super B/flavor factory (5 yr running) $15ab^{-1}$	7.5×10^{-7}	3.5×10^{-6}	1.7×10^{-6}

* Polarized electrons required.

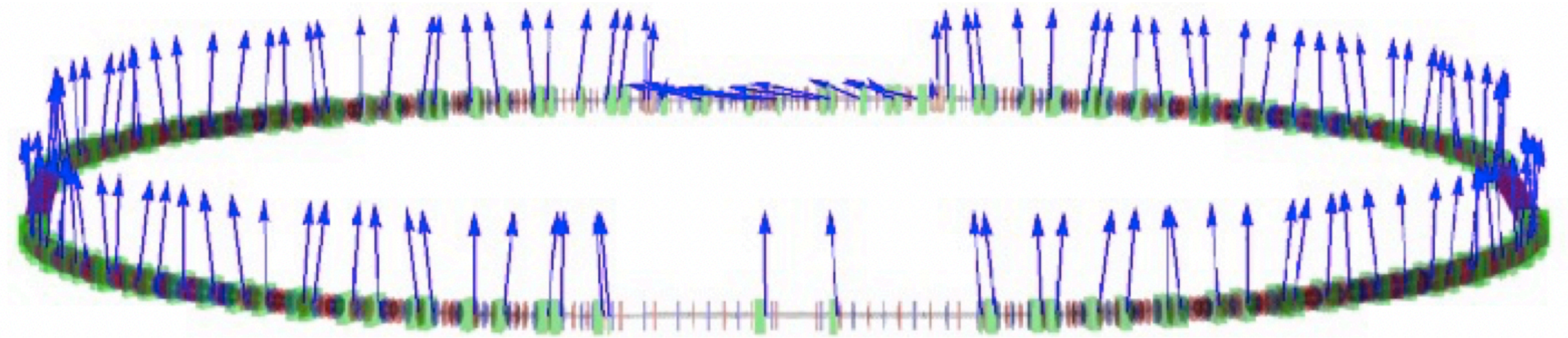
Using Bernabéu *et al* from this study one can calculate for $40ab^{-1}$ Chiral Belle data with 100% polarization:

$\mathrm{Re}\{F_2(10\mathrm{GeV})\} \sim 2 \times 10^{-6}$ (Statistical error only)

Note: extrapolating statistical error for unpolarized Belle II data with $50ab^{-1}$ would give a sensitivity of $\sim 4 \times 10^{-6}$

Courtesy: J.M. Roney's presentation at Tau 2021

Summary



- Polarized electron beam upgrade at SuperKEKB can improve EDM measurements of τ by 3 orders of magnitude
- Polarized electron beam upgrade at SuperKEKB can improve MDM measurements of τ by factor of 2