Tau EDM+MDM

K.Hayasaka for Belle collaboration
(Niigata Univ.)

Heavy Quarks and Leptons
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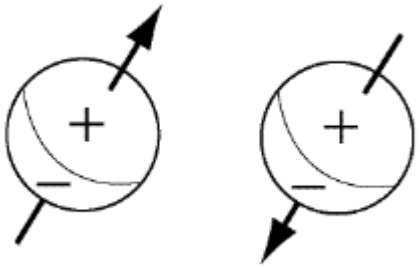
Introduction for lepton EDM



- Electric Dipole Moment (EDM) violates T (time reversal) symmetry.
- Also, CP symmetry is violated if CPT theorem is correct.
  - It can be a source of CPV. In particular, in the lepton sector, the existence of CPV indicates that of the new physics.
    - Neutrino experiments try to measure CP phase of MNS matrix.
  - In reality, lepton EDM is not correctly zero since 3 loop effect from quarks gives EDM, whose origin is CP phase of CKM matrix:

    $\mathcal{O}(10^{-40})\ e$cm for e, $\mathcal{O}(10^{-38})\ e$cm for μ, $\mathcal{O}(10^{-37})\ e$cm for τ.

    Extremely small!

    hep-ph/9301293, Phys.Rev.D54(1996)3377

tau EDM and new physics

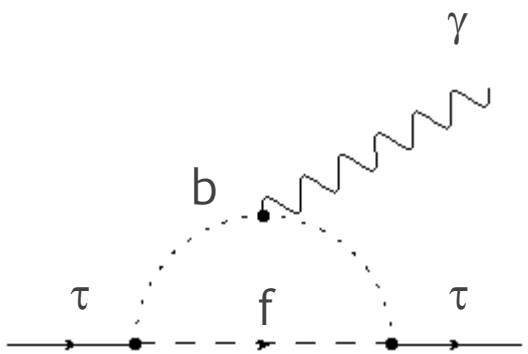
- Sizable EDM of lepton is a signal of New Physics(NP)
  - τ EDM is most promising since τ is expected to have strong coupling to NP.
  - Through a loop diagram with new particles, EDM can appear.

  Ex. A Leptoquark model predicts tau EDM:

$$d_\tau \sim f \times \mathcal{O}(10^{-20})\, e\text{cm}$$

$$f = \mathrm{Im}(\lambda_L^* \lambda_R) \qquad m_{LQ} \sim \mathcal{O}(1)\text{TeV}$$

Phys.Rev.D103(1996)096011



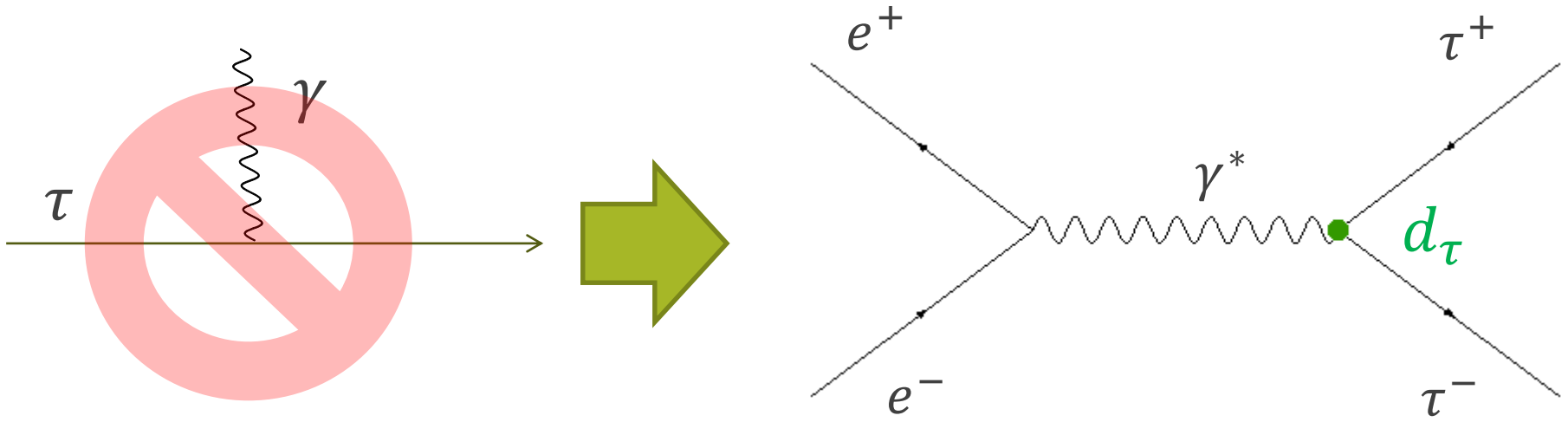
- Current upper limit: Belle: 29.5fb^{-1}
  PLB 551(2003)16

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

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

Where tau EDM appears?

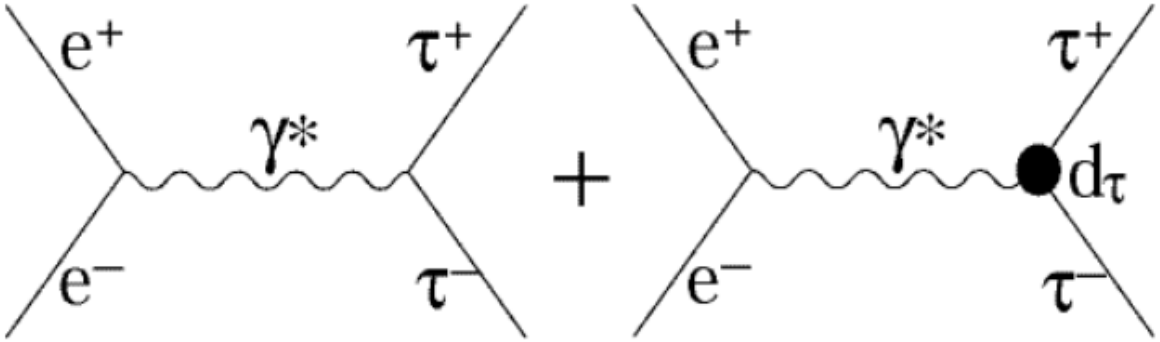
- Due to the short life time of tau (~90μm), a measurement via radiative process is difficult, differently from that for muon.
- In a B-factory, through the tau-pair production vertex, tau EDM can be evaluated.



Effective Lagrangian and spin density matrix element

- Effective Lagrangian with EDM for $e^+e^- \to \tau^+\tau^-$

$$\mathcal{L} = \bar{\tau}\left(i\partial_\mu - eA_\mu\right)\gamma^\mu\tau - \frac{i}{2}d_\tau\bar{\tau}\sigma^{\mu\nu}\gamma_5\tau F_{\mu\nu}$$



Negligibly small

- Squared spin density matrix

$$\chi_{\text{prod}} = \chi_{\text{SM}} + \boxed{\text{Re}(d_\tau)\chi_{\text{Re}}} + \boxed{\text{Im}(d_\tau)\chi_{\text{Im}}} + |d_\tau|^2\chi_{d^2}$$

  - Through the interference term, EDM effect will be seen.

$\chi_{\text{Re}} \sim (\vec{S}_+ \times \vec{S}_-)\cdot\vec{k},\ (\vec{S}_+ \times \vec{S}_-)\cdot\vec{p}$: CP-odd, T-odd $\quad \vec{S}_\pm$: spin vector of $\tau^\pm$, $\vec{k}$: momentum for τ^+

$\chi_{\text{Im}} \sim (\vec{S}_+ - \vec{S}_-)\cdot\vec{k},\ (\vec{S}_+ - \vec{S}_-)\cdot\vec{p}$: CP-odd, T-even $\quad \vec{p}$: momentum for beam e^+

Optimal observable method

- Optimal observable (OO) method is more sensitive than simple cross section measurement:

$$\mathcal{O}_{\mathrm{Re}} = \frac{\chi_{\mathrm{Re}}}{\chi_{\mathrm{SM}}} \qquad \langle \mathcal{O}_{\mathrm{Re}} \rangle \propto \int \mathcal{O}_{\mathrm{Re}} \chi_{\mathrm{prod}} d\phi$$

$$= \underbrace{\int \chi_{\mathrm{Re}} d\phi}_{b\text{:offset}} + \mathrm{Re}(d_\tau) \underbrace{\int \frac{(\chi_{\mathrm{Re}})^2}{\chi_{\mathrm{SM}}} d\phi}_{a\text{:sensitivity}}$$

EDM

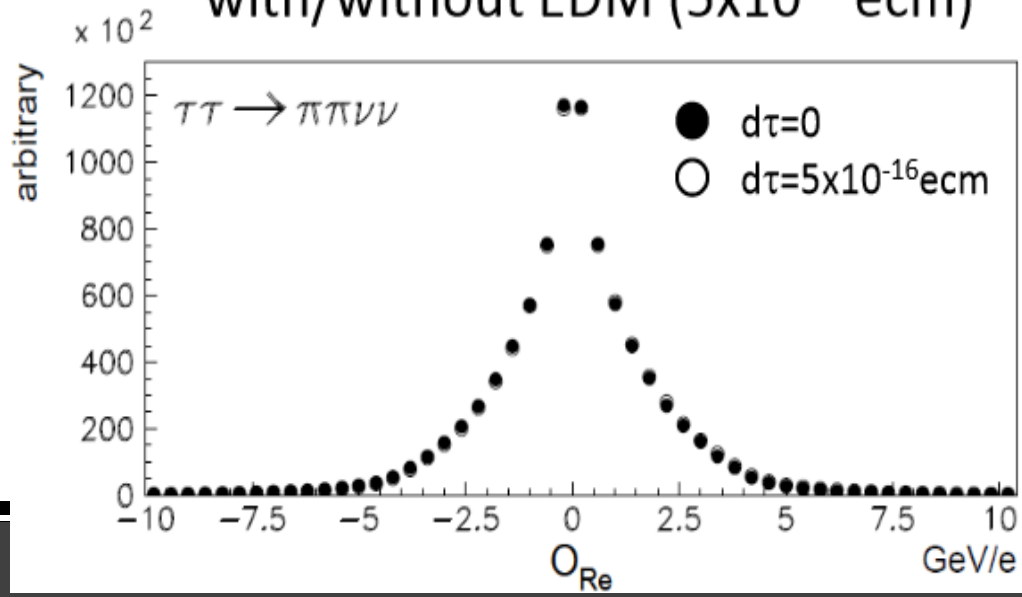
$$\chi_{\mathrm{Re}} \sim (\vec{S}_+ \times \vec{S}_-) \cdot \vec{k},\ (\vec{S}_+ \times \vec{S}_-) \cdot \vec{p}$$

$$\chi_{\mathrm{Im}} \sim (\vec{S}_+ - \vec{S}_-) \cdot \vec{k},\ (\vec{S}_+ - \vec{S}_-) \cdot \vec{p}$$

Calculate OO event by event and take the average of them, that is linear function of EDM. Here, parameters, a and b, should be evaluated using MC samples having various size of EDM.

Similar formula of $\mathrm{Im}(d_\tau)$ can be obtained by replacing Re by Im.

MC simulation (ee → ττ → ππνν) with/without EDM (5x10^{-16}ecm)

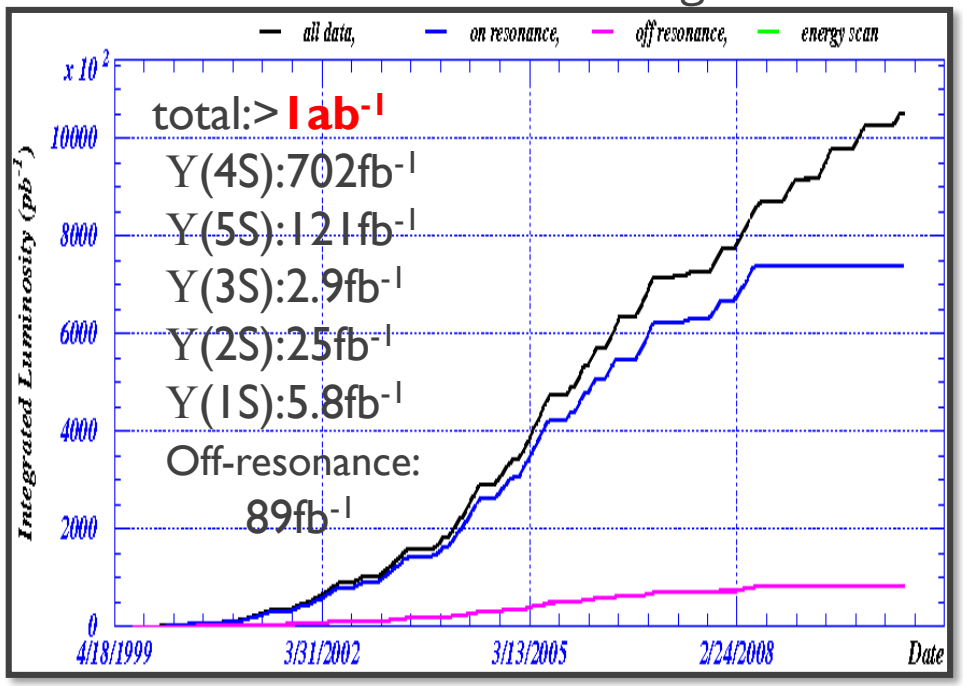


Belle experiment

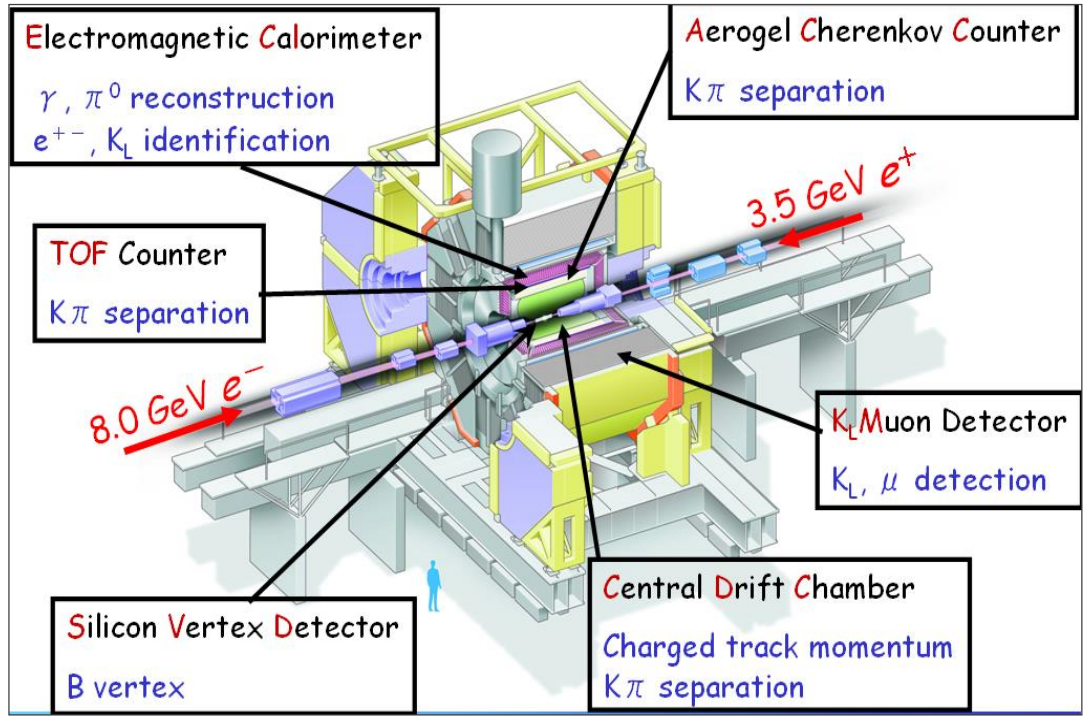
B-factory: $\sqrt{s}$ =mass of $\Upsilon(4S)$ (e^-: 8 GeV, e^+:3.5 GeV @ Belle)

A B-factory is also **a tau factory** since the production cross section for $B\bar{B}$ and τ-pair is very similar. (1.1nb vs 0.9 nb)

Belle has finished data taking in 2010.



τ-pair is produced even in the different energy settings ($1S, 2S, 3S, 5S$).



Belle detector is a multi-purpose and asymmetric detector and has good:

- lepton identification
- hermeticity

Lepton ID ~ 80% for μ, 90% for e
Fake ID ~ 3% for μ, 0.1% for e

Selected tau decays and BG

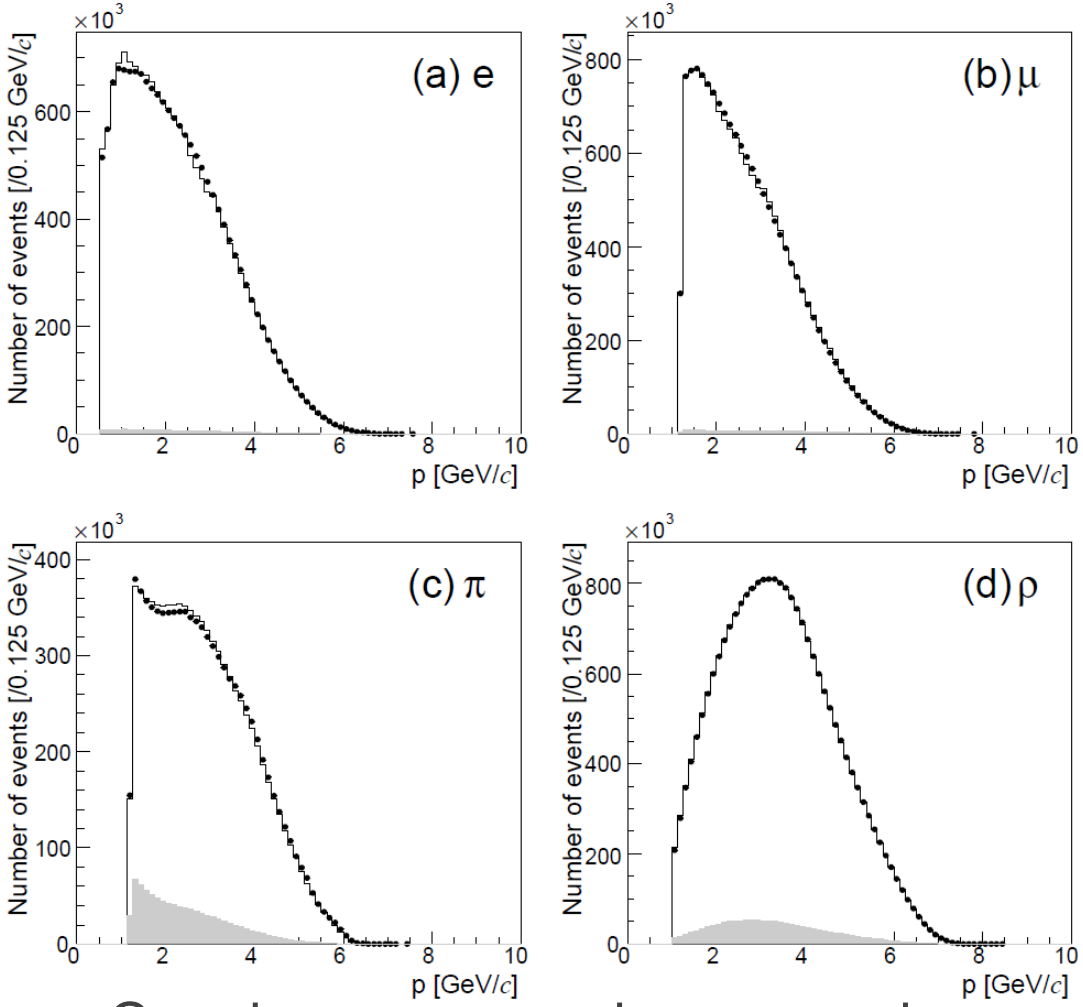
- Select 8 final modes exclusively using 833fb^{-1} data sample
  - $\tau\tau\rightarrow e\mu(4\nu)$, $e\pi(3\nu)$, $\mu\pi(3\nu)$, $\mu\rho(3\nu)$, $\pi\rho(2\nu)$, $\rho\rho(2\nu)$, $\pi\pi(2\nu)$
    - PID for e, μ, π (K-veto as well)
    - ρ reconstructed from $\pi\pi^0(\rightarrow\gamma\gamma)$
    - Require high momentum and barrel region to reduce systematic errors
- Total yield: 3.1x10^7 events, Averaged purity: 88.5%
- Background
  - Main: from different tau decay: Missing-π^0 and mis-PID

$\tau\tau\rightarrow ab(n\nu)$ means
$\tau^+\rightarrow a^+\nu$/ $\tau^-\rightarrow b^-\nu$
and n is # of ν in total.
as well as charge conjugate

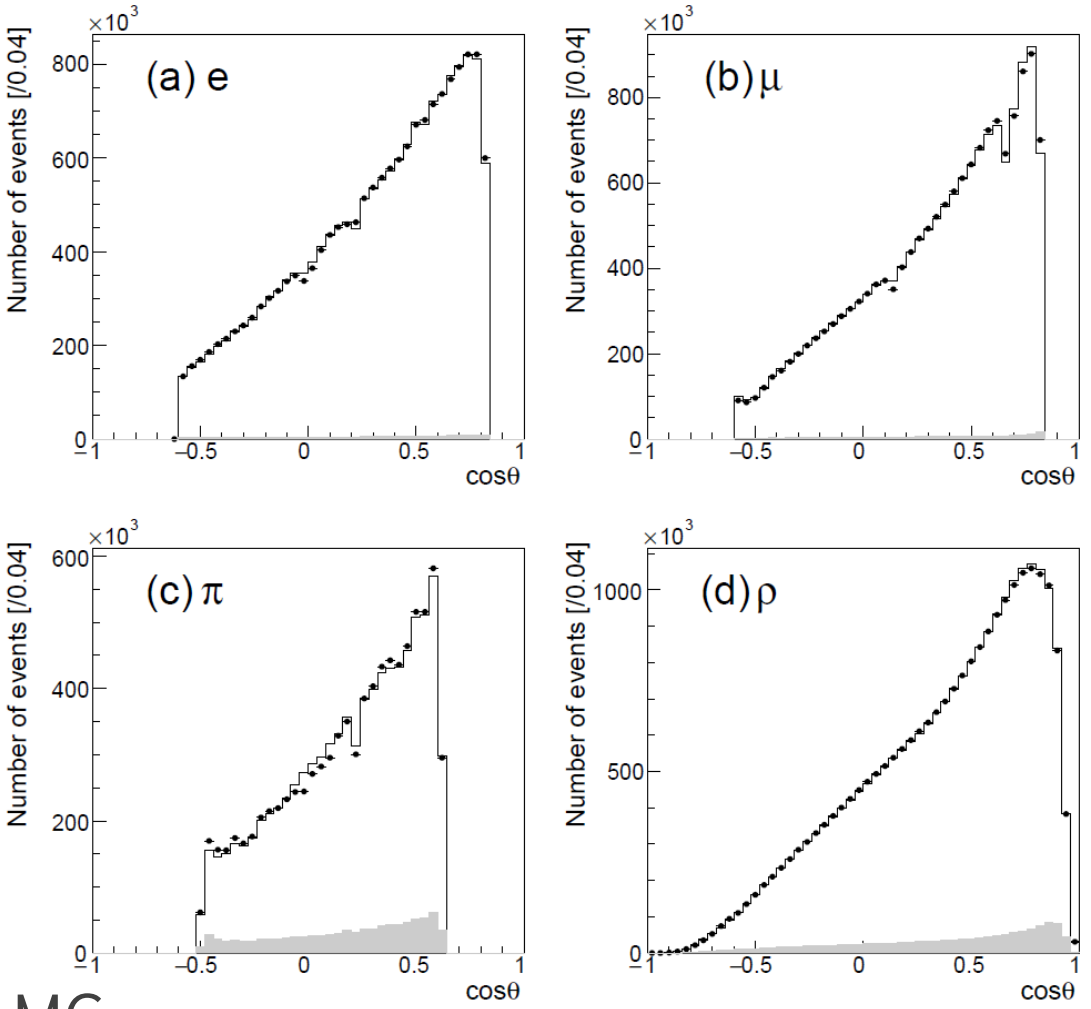
Mode	Yield	Purity(%)	Background (%)
$e\mu$	6434268	95.8	$\gamma\gamma \rightarrow \mu\mu(2.5)$, $\tau\tau \rightarrow e\pi(1.3)$
$e\pi$	2644971	85.7	$\tau\tau \rightarrow e\rho(6.5)$, $e\mu(5.1)$, $eK^*(1.3)$
$\mu\pi$	2503936	80.5	$\tau\tau \rightarrow \mu\rho(6.4)$, $\mu\mu(4.9)$, $\mu K^*(1.3)$, $2\gamma \rightarrow \mu\mu(3.1)$
$e\rho$	7218823	91.7	$\tau\tau \rightarrow e\pi\pi^0\pi^0(4.6)$, $eK^*(1.7)$
$\mu\rho$	6203489	91.0	$\tau\tau \rightarrow \mu\pi\pi^0\pi^0(4.3)$, $\mu K^*(1.6)$, $\pi\rho(1.1)$
$\pi\rho$	2655696	77.0	$\tau\tau \rightarrow \rho\rho(6.7)$, $\pi\pi\pi^0\pi^0(3.9)$, $\mu\rho(5.1)$, $\rho K^*(1.4)$, $\pi K^*(1.4)$
$\rho\rho$	3277001	82.4	$\tau\tau \rightarrow \rho\pi\pi^0\pi^0(9.4)$, $\rho K^*(3.1)$
$\pi\pi$	460288	71.9	$\tau\tau \rightarrow \pi\rho(11.3)$, $\pi\mu(8.8)$, $\pi K^*(2.5)$

Selected data and MC samples

Track momentum (lab)



Cosine of track polar angle (lab)

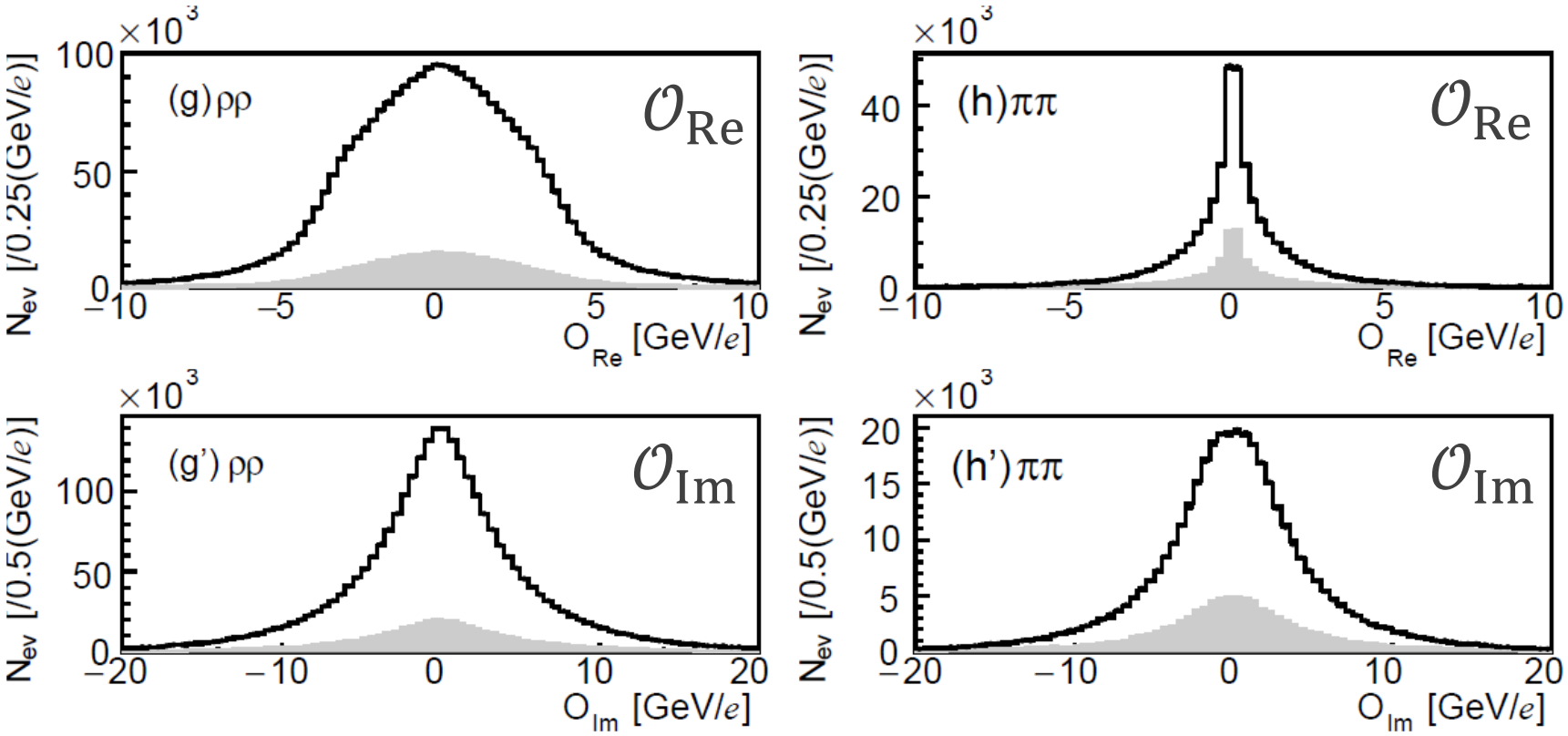


- data
- signal
- MC($d_\tau = 0$)
- BG MC

Good agreement between data and MC

OO distributions

- Also for OO distributions, good agreement between data and MC is seen.



- data
- signal MC($d_\tau = 0$)
- BG MC

→Take average of $\mathcal{O}$ and extract tau EDM from $\langle \mathcal{O}_{\mathrm{Re/Im}} \rangle = a \times \mathrm{Re/Im}(d_\tau) + b$.

Result of tau EDM measurement

- Using 833fb^{-1}

Mode	$\mathrm{Re}(d_\tau)(10^{-17}\ e\mathrm{cm})$	$\mathrm{Im}(d_\tau)(10^{-17}\ e\mathrm{cm})$
$e\mu$	$-3.2 \pm 2.5 \pm 3.6$	$0.6 \pm 0.4 \pm 1.8$
$e\pi$	$0.7 \pm 2.3 \pm 4.8$	$2.4 \pm 0.5 \pm 2.2$
$\mu\pi$	$1.0 \pm 2.2 \pm 4.3$	$2.4 \pm 0.5 \pm 2.6$
$e\rho$	$-1.2 \pm 0.8 \pm 1.0$	$-1.1 \pm 0.3 \pm 0.6$
$\mu\rho$	$0.7 \pm 1.0 \pm 2.2$	$-0.5 \pm 0.3 \pm 0.8$
$\pi\rho$	$-0.6 \pm 0.7 \pm 1.0$	$0.4 \pm 0.3 \pm 1.2$
$\rho\rho$	$-0.4 \pm 0.5 \pm 0.9$	$-0.3 \pm 0.3 \pm 0.4$
$\pi\pi$	$-2.2 \pm 4.3 \pm 5.2$	$-0.9 \pm 0.9 \pm 1.2$

First err.:stat, Second err.: syst

Systematic error is reduced by a factor of 3 from that of the previous result, thanks to improved simulation and correction and the larger MC samples.
Main source of systematic uncertainties comes from disagreement between data and MC for low momentum tracks.

Previous result with 29.5fb^{-1}

$-2.2 < \mathrm{Re}(d_\tau) \times 10^{17} < 4.5\ (e\mathrm{cm})$

$-2.5 < \mathrm{Im}(d_\tau) \times 10^{17} < 0.8\ (e\mathrm{cm})$

The mean of all of them:

$$\mathrm{Re}(d_\tau) = (-0.62 \pm 0.63) \times 10^{-17}\ e\mathrm{cm}$$
$$\mathrm{Im}(d_\tau) = (-0.40 \pm 0.32) \times 10^{-17}\ e\mathrm{cm}$$

95% confidence intervals:

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

arXiv:2108.1154[hep-ex], submitted to JHEP

Prospect for tau EDM

- Learn from this update

	@Belle II
☺Newly introduce K-veto	☺Better PID
☺Better tracking	☺Much better tracking
☺Increase of MC statistics and better detector sim.	☺Much increase of MC statistics and much better detector sim.
☹Increase of beam BG	☹Much increase of beam BG

➡ At Belle II, we can expect much more improvement than that obtained by the extrapolate from the Belle result.

Better PID and tracking : higher efficiency
MC statistics / better detector sim.: give better understandings of MC
→Key : understandings of the beam BG (Need study run by run)

Since Belle II aims to collect 50ab^{-1}, around 10x more sensitive result can be expected for stat. (Lum. increase: $\sqrt{50000/800}\sim 8$)

Tau Magnetic Dipole Moment(MDM)?

- Tau Magnetic Dipole Moment (g-2) in SM is predicted as

$$a_\tau \sim 1.1 \times 10^{-3}$$

Mod. Phys. Lett. A22(2007)159

Similarly, we can set the effective Lagrangian as

$$\mathcal{L} = \bar{\tau}\left(i\partial_\mu - eA_\mu\right)\gamma^\mu\tau + \frac{1}{2}\Delta\mu_\tau\bar{\tau}\sigma^{\mu\nu}\tau F_{\mu\nu} \qquad \Delta\mu_\tau = \frac{e}{2m_\tau}a_\tau$$

$$\rightarrow \chi_{\mathrm{MDM}} \sim (\vec{S}_+ \cdot \vec{k})(\vec{S}_- \cdot \vec{k}),\ (\vec{S}_+ \cdot \vec{p})(\vec{S}_- \cdot \vec{p}),\ (\vec{S}_\pm \cdot \vec{k})(\vec{S}_\mp \cdot \vec{p})$$

χ_{SM} also has such terms; $\mathcal{O}_{\mathrm{MDM}}$ has less sensitivity than $\mathcal{O}_{\mathrm{EDM}}$, where χ_{EDM} is completely perpendicular to χ_{SM}.

Prospect for tau MDM

☆Rough estimation

- For EDM, from LEP to Belle: 1 or 2 order improvement
- LEP MDM result: $|a_\tau|$<0.1 @95%CL

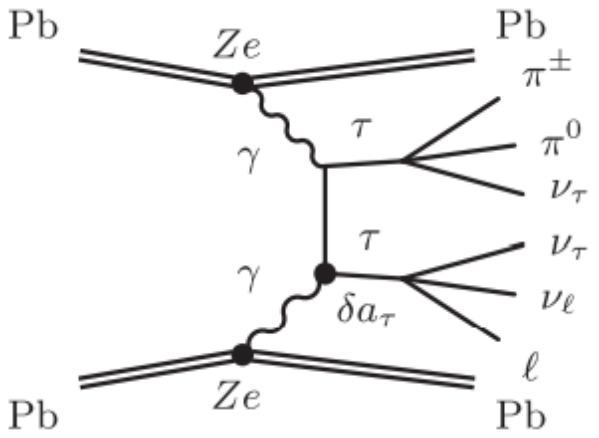
  → $|a_\tau|$<0.01-0.001 would be expected at Belle.

At Belle II, we expect that we can confirm the first (and second) digit of the SM prediction for a_τ with 50ab^{-1}.

- Other measurements are also proposed.
  - Ex. 2 photon collision process at LHCb.

  →$-0.0080 < a_\tau < 0.0046$ @ 68%CL with 2nb^{-1}

Phys.Rev.D102(2020)113008



Summary

- Using 833fb^{-1} Belle data sample, we evaluate τ EDM.
  - As a 95% confidence interval

$$-1.85 < \mathrm{Re}(d_\tau) \times 10^{17} < 0.61\, e\mathrm{cm},$$

$$-1.03 < \mathrm{Im}(d_\tau) \times 10^{17} < 0.23\, e\mathrm{cm},$$

is obtained. This is one order sensitive result from that of the previous result.

  - Belle II future prospect is considered.
    - We can expect more sensitive result thanks to the increased luminosity, improved systematic accuracy.
- Possibility of τ MDM measurement is also discussed.
  - Though sensitivity is worse than that of EDM, we can expect to confirm the first digit of the SM prediction at Belle II.

Evaluate OO and tau spin

- Tau spin is also input to OO.
  - Need tau direction.
  - We can reconstruct tau direction with twofold ambiguity in case where both taus make hadronic decay.
  - In the case where one decay is leptonic, ambiguity gets continuous.
  - In any case, the average is taken over the possible tau directions.
  - The size of helicity is evaluated from daughters' kinematical information.

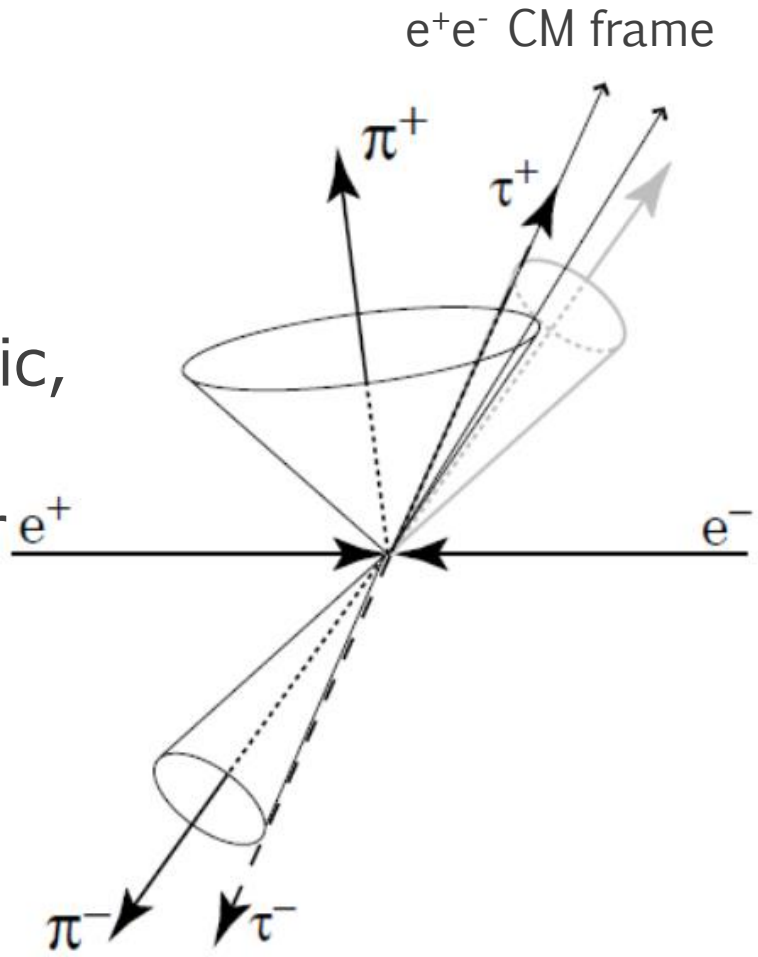


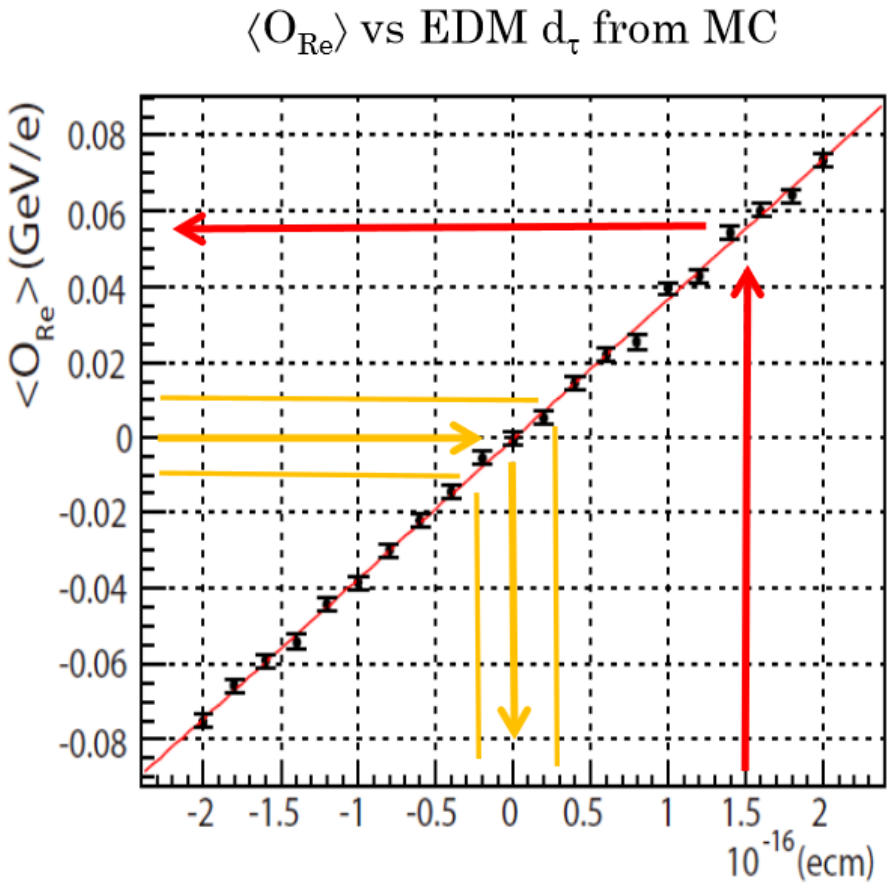
TABLE II: Systematic uncertainties for $\mathrm{Re}(d_\tau)$ and $\mathrm{Im}(d_\tau)$ in units of $10^{-17}\,e\,\mathrm{cm}$.

$\mathrm{Re}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Detector alignment	0.2	0.2	0.1	0.1	0.2	0.1	0.1	0.3
Momentum reconstruction	0.1	0.6	0.5	0.1	0.3	0.2	0.1	1.5
Charge asymmetry	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0
Mismatch of distribution	3.2	4.8	3.8	0.9	2.2	0.9	0.9	3.6
Background variation	1.6	0.3	1.7	0.4	0.2	0.2	0.2	3.5
Radiative effects	0.7	0.5	0.6	0.2	0.2	0.0	0.0	0.1
Total	3.6	4.8	4.3	1.0	2.2	1.0	0.9	5.2
$\mathrm{Im}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Detector alignment	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0
Momentum reconstruction	0.2	0.5	0.4	0.0	0.1	0.1	0.1	0.1
Charge asymmetry	0.2	2.0	2.4	0.1	0.1	1.1	0.0	0.0
Mismatch of distribution	1.0	0.9	0.6	0.5	0.8	0.4	0.4	1.2
Background variation	1.4	0.0	0.7	0.3	0.1	0.1	0.1	0.1
Radiative effects	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
Total	1.8	2.2	2.6	0.6	0.8	1.2	0.4	1.2

Extract EDM from OO

Since $\int \chi_{\mathrm{Re}} d\phi$ ($= b_{\mathrm{Re}}$) and $\int \frac{(\chi_{\mathrm{Re}})^2}{\chi_{\mathrm{SM}}} d\phi$ ($= a_{\mathrm{Re}}$) includes complicated detector and acceptance effects, they cannot be obtained by the analytic calculation.

So, we use MC samples having different EDM values to evaluate them.



$$\langle O_{\mathrm{Re}} \rangle = a_{\mathrm{Re}}\,\mathrm{Re}(d_\tau) + b_{\mathrm{Re}}$$

$$\langle O_{\mathrm{Im}} \rangle = a_{\mathrm{Im}}\,\mathrm{Im}(d_\tau) + b_{\mathrm{Im}}$$