Electric dipole moment of the tau lepton (Belle)

K. Inami (Nagoya univ., Belle collaboration)

13th International Workshop on Tau Lepton Physics,
2014/9/14-19

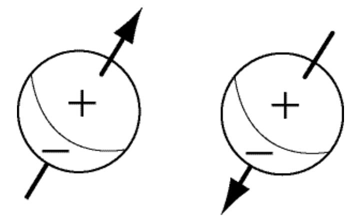
Electric dipole moment of τ lepton

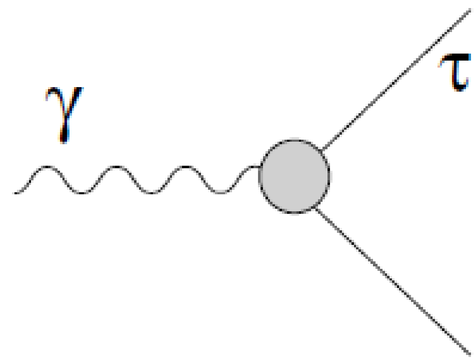
- Charge asymmetry along spin direction
- CP/T violating effect in the interaction with electric field

$$\mathcal{H}_{\rm int} = \rho_{\rm m}\boldsymbol{\sigma}\cdot\boldsymbol{H} + \rho_{\rm e}\boldsymbol{\sigma}\cdot\boldsymbol{E}$$

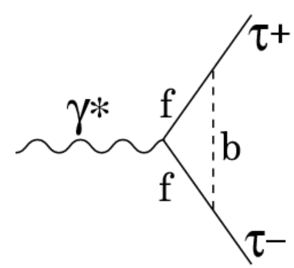
  – Non zero EDM indicates P and T violation
- CP violation parameter in $\gamma\tau\tau$ vertex
- Standard Model prediction: O(10^{-37}) ecm
  – Far below the current sensitivity
- A non-zero EDM may arise from new physics
  – e.g. new particles in a loop diagram
- Current upper limit
  – Belle; 29.5fb^{-1} data [PLB 551(2003)16]

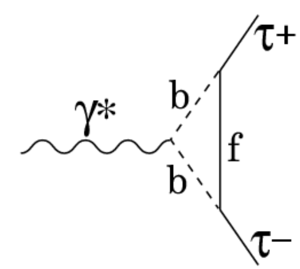
$$-2.2 < Re(d_\tau) < 4.5\ (10^{-17}\, e\,\mathrm{cm})$$
$$-2.5 < Im(d_\tau) < 0.8\ (10^{-17}\, e\,\mathrm{cm})$$





$$\mathcal{L}_{CP} = -\frac{i}{2}\bar{\tau}\sigma^{\mu\nu}\gamma_5\tau d_\tau(s)F_{\mu\nu}$$

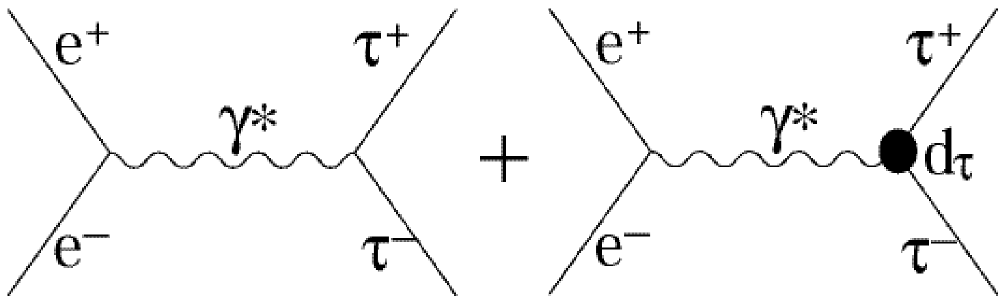




EDM effect on event shape

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

$$\mathcal{L}_{\rm eff} = \bar\psi(i\,\partial\!\!\!/ - eQ\,A\!\!\!/)\psi \qquad -id_\tau\bar\psi\sigma^{\mu\nu}\gamma_5\psi\partial_\mu A_\nu$$



- Squared spin density matrix （~cross section）

$$\mathcal{M}^2_{\rm prod} = \mathcal{M}^2_{\rm SM} + \underline{Re(d_\tau)}\mathcal{M}^2_{Re} + \underline{Im(d_\tau)}\mathcal{M}^2_{Im} + |d_\tau|^2\mathcal{M}^2_{d^2}$$

  - Interference term between lowest order and EDM term

$\rightarrow$ CP violating spin-momentum correlation

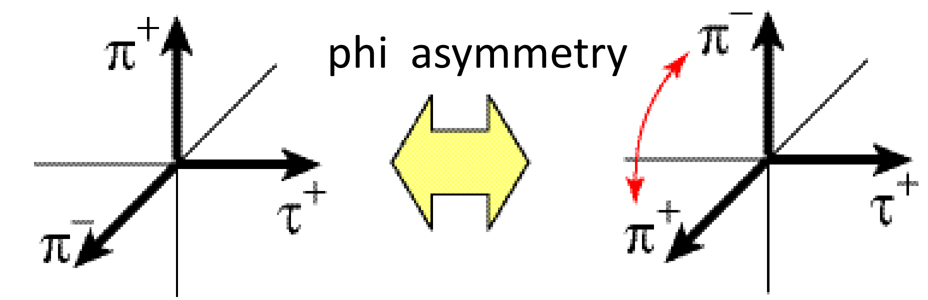
$$\mathcal{M}^2_{Re} \sim (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{k}} \;,\; (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{p}}$$: CP-odd, T-odd

$$\mathcal{M}^2_{Im} \sim (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{k}} \;,\; (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{p}}$$: CP-odd, T-even

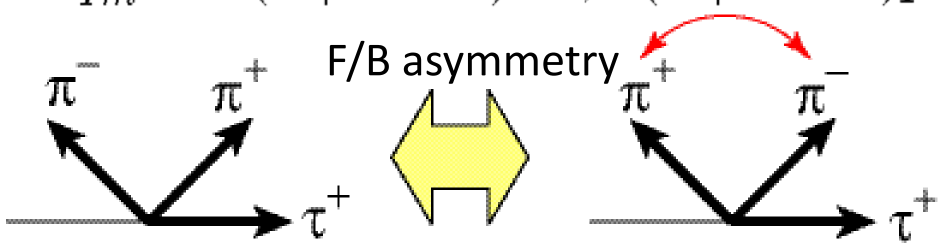
$\boldsymbol{S}_\pm$: Spin vectors of $\tau^\pm$
$\hat{\boldsymbol{k}}, \hat{\boldsymbol{p}}$: Momenta of τ^+ and e^+ beam

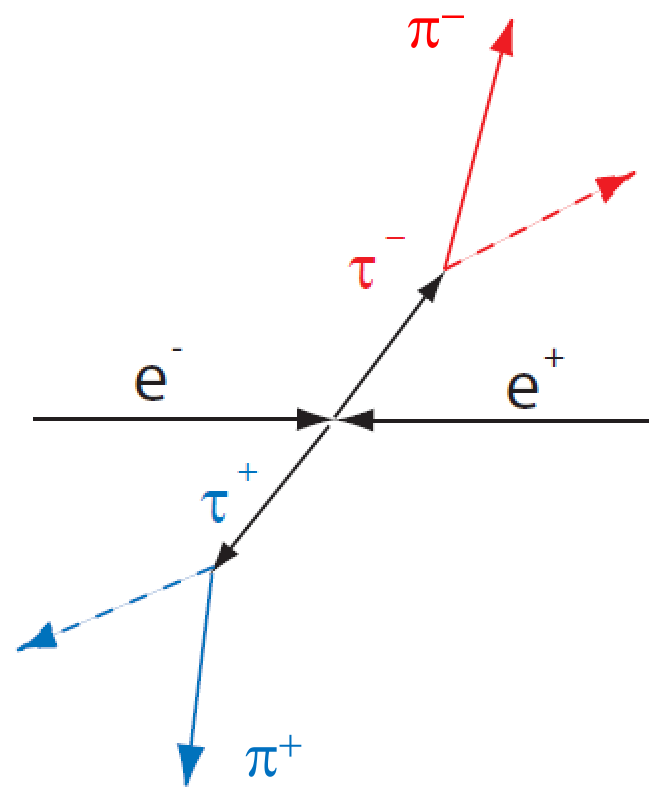
Asymmetry in event shape

$$\mathcal{M}^2_{Re} \sim (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{k}} \quad , \quad (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{p}}$$



$$\mathcal{M}^2_{Im} \sim (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{k}} \quad , \quad (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{p}}$$

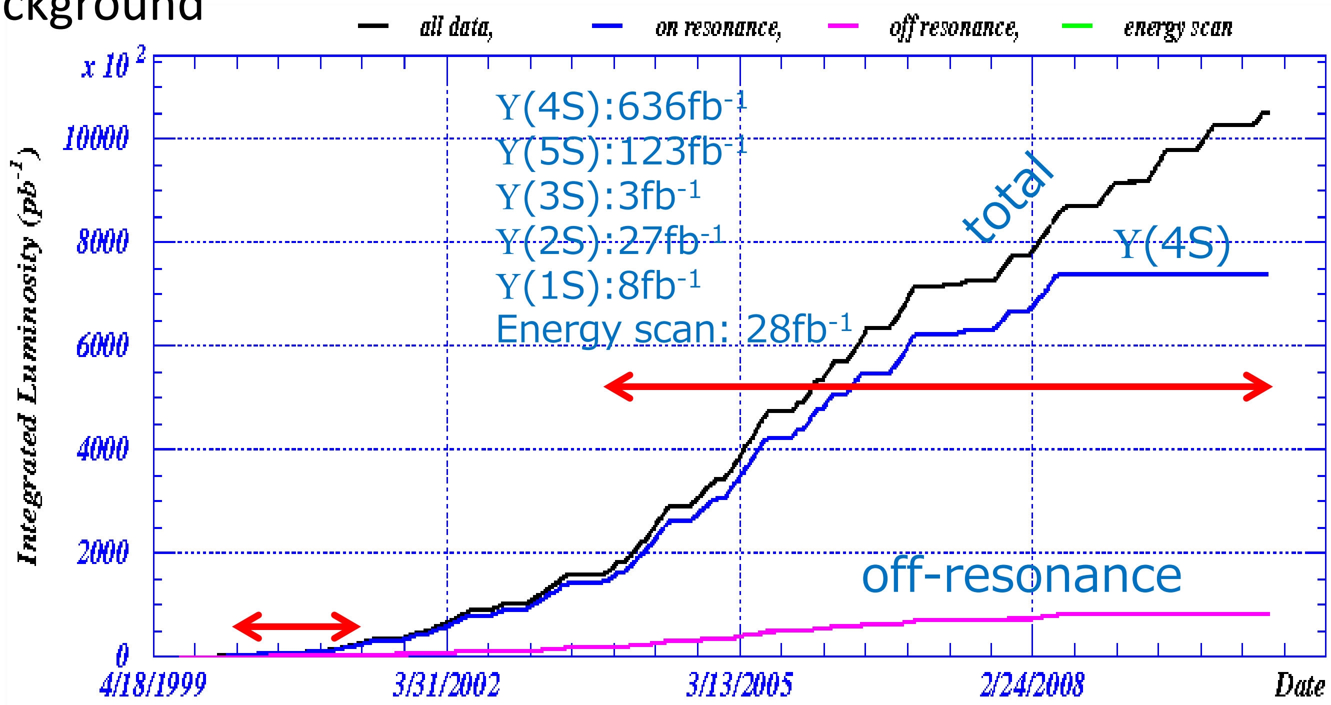




- Spin direction correlates with momentum of decay products
- Re(d_τ): phi asymmetry, Im(d_τ): forward/backward asymmetry

Experimental data

- $825 fb^{-1}$ of recent Belle data
  - 28 times larger than previous analysis
    - ~5 times less statistical error
  - Improved detector understanding
    - Better correction parameters for tracking, particle IDs
    - Improvement on the MC simulation
  - More beam background



Event Selection

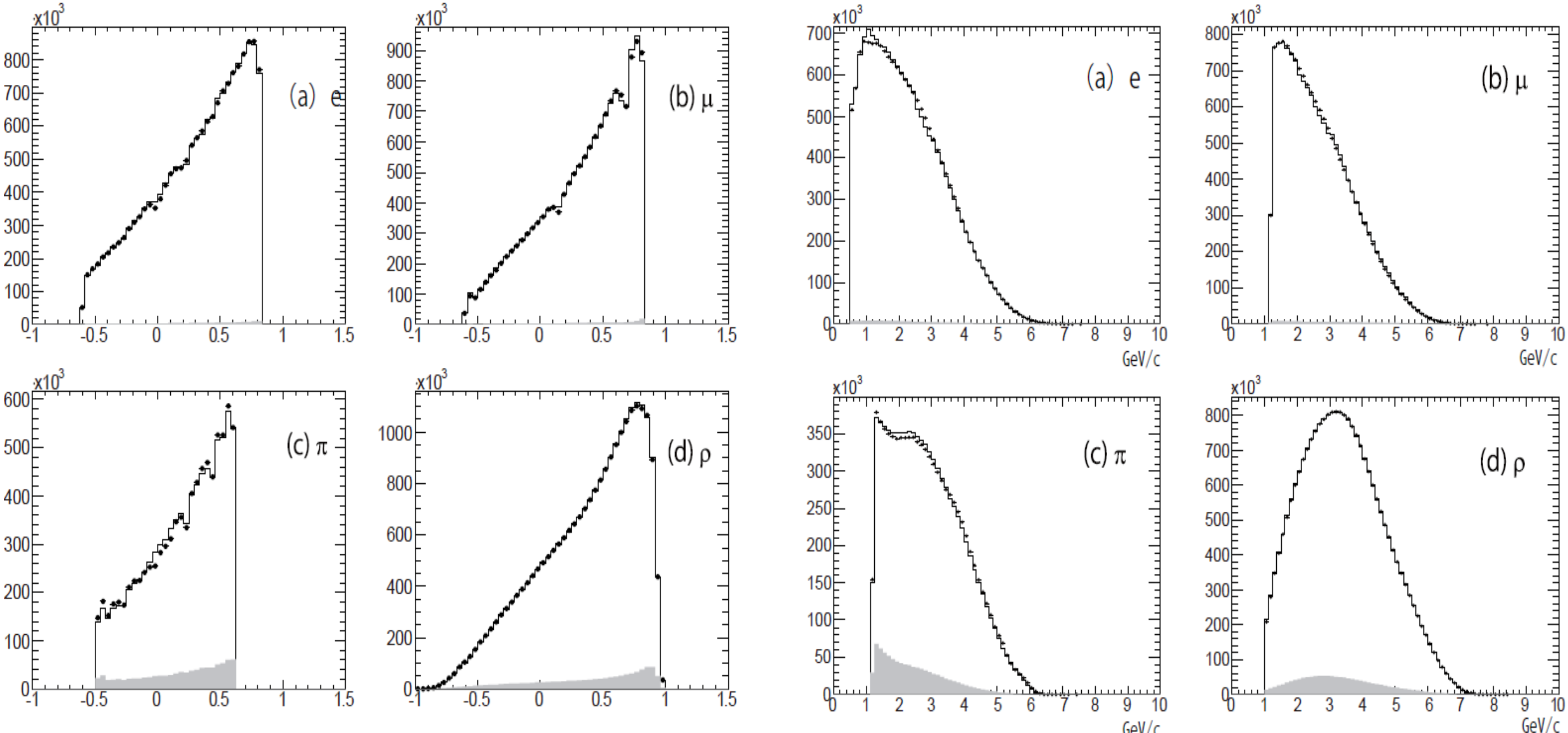
- Select 8 final modes exclusively
  - $\tau\tau \to e\mu4\nu$, $e\pi3\nu$, $\mu\pi3\nu$, $e\rho3\nu$, $\mu\rho3\nu$, $\pi\rho2\nu$, $\rho\rho2\nu$, $\pi\pi2\nu$
  - PID for e, μ, π
  - ρ reconstructed from $\pi\pi^0(\to\gamma\gamma)$
  - Require high momentum and barrel region, to reduce systematic errors
- Total yield : 3.5×10^7 events, Averaged purity : 87.7%
- Background
  - Main : from tau decay : Multi-π^0 and mis-PID
  - Non-τ process: negligibly small

mode	yield	purity(%)	Background (%)
$e\mu$	6434k	95.8	$2\gamma \to \mu\mu(2.5)$
$e\pi$	2645k	85.7	$\tau\tau \to e\rho(6.5)\ e\mu(5.1)$
$\mu\pi$	2504k	80.5	$\tau\tau \to \mu\rho(6.4)\ \mu\mu(4.9),\ 2\gamma \to \mu\mu(3.1)$
$e\rho$	7219k	91.7	$\tau\tau \to e\pi\pi^0\pi^0(4.6)$
$\mu\rho$	6203k	91.0	$\tau\tau \to \mu\pi\pi^0\pi^0(4.3)$
$\pi\rho$	2656k	77.0	$\tau\tau \to \rho\rho(6.7)\ \mu\rho(5.1)\ \pi\pi\pi^0\pi^0(3.9)$
$\rho\rho$	6554k	82.4	$\tau\tau \to \rho\pi\pi^0\pi^0(9.4)\ \rho K^*(3.1)$
$\pi\pi$	921k	71.9	$\tau\tau \to \pi\rho(11.3)\ \pi\mu(8.8)\ \pi K^*(2.5)$

Selected data

● Exp. data □ MC(d_τ=0) ■ MC background

- cosθ(polar angle) and momentum distribution



- Good visual agreement between data and MC
  - However, there are small mismatches in the distribution, which are the dominant contribution to the systematic error. →Discuss later

Observable

- Optimal observable
  [PRD 45(1992)2405]

$$\mathcal{M}^2_{\rm prod} = \underline{\mathcal{M}^2_{\rm SM}} + Re(d_\tau)\underline{\mathcal{M}^2_{Re}} + Im(d_\tau)\underline{\mathcal{M}^2_{Im}} + |d_\tau|^2\mathcal{M}^2_{d^2}$$

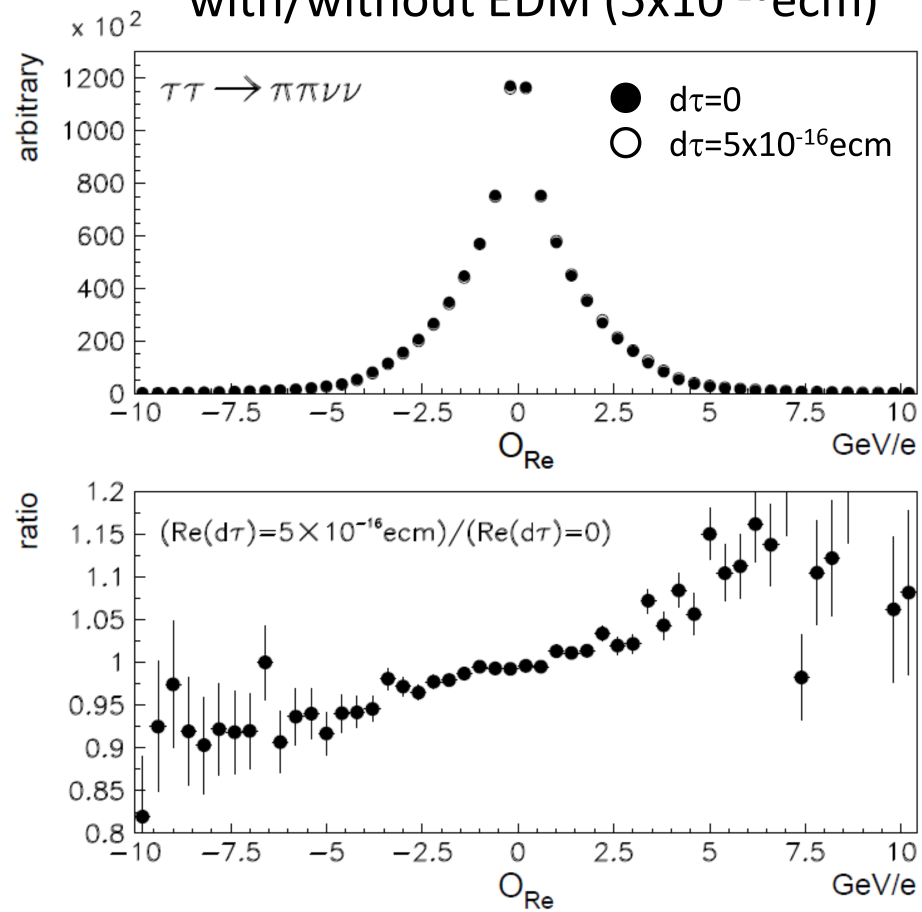
$$\mathcal{O}_{Re} = \frac{\mathcal{M}^2_{Re}}{\mathcal{M}^2_{\rm SM}}, \quad \mathcal{O}_{Im} = \frac{\mathcal{M}^2_{Im}}{\mathcal{M}^2_{\rm SM}}$$

  - Maximize sensitivity (S/N)
  - Calculate event-by-event
    - Using tau flight direction and spin direction (from decay products)
  - Average value is proportional to EDM

$$\langle\mathcal{O}_{\rm Re}\rangle \propto \int \mathcal{O}_{\rm Re}\mathcal{M}^2_{\rm prod}\, d\phi$$

$$= \int \mathcal{M}^2_{\rm Re}\, d\phi + {\rm Re}(d_\tau)\int \frac{(\mathcal{M}^2_{\rm Re})^2}{\mathcal{M}^2_{\rm SM}}\, d\phi$$

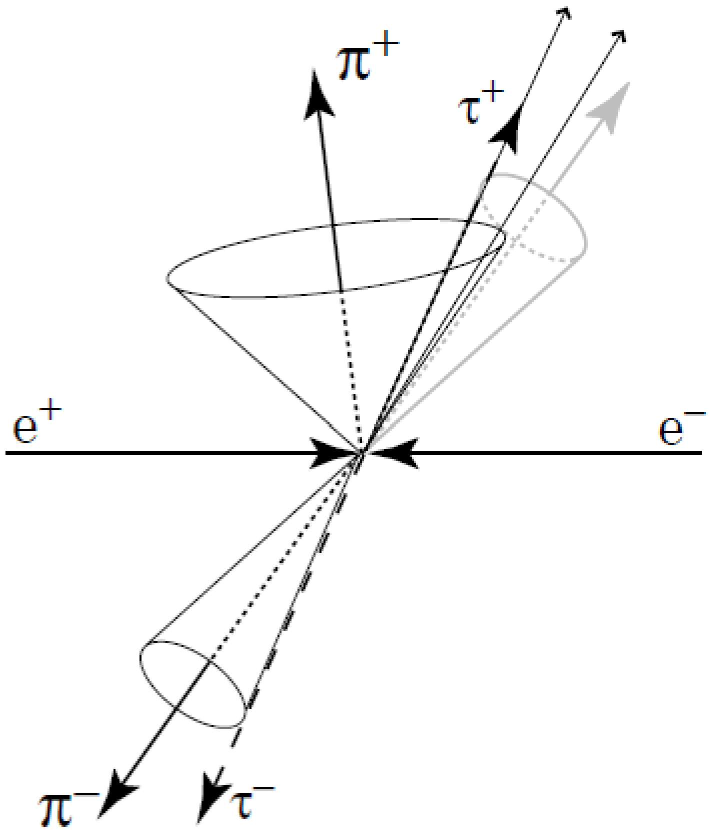
MC simulation (ee → ττ → ππνν) with/without EDM (5x10^-16 ecm)



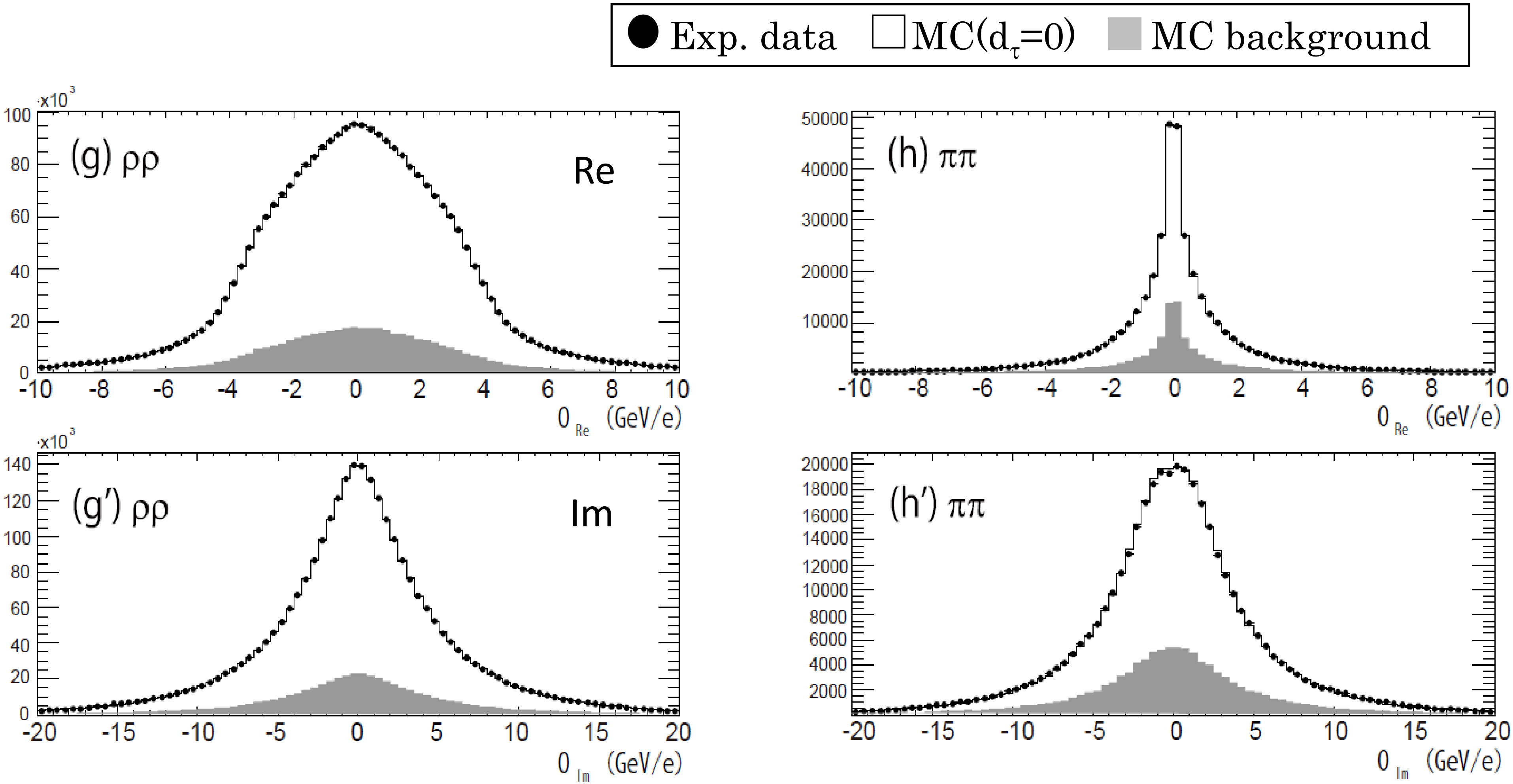
Observable from data

- Need tau flight direction
- Due to missing neutrinos from tau decays, there is uncertainty in the reconstructed tau direction
  - Two-fold ambiguity in case that both tau leptons decay hadronically
  - Continuous ambiguity if tau decays leptonically

- Take an average over the possible tau directions

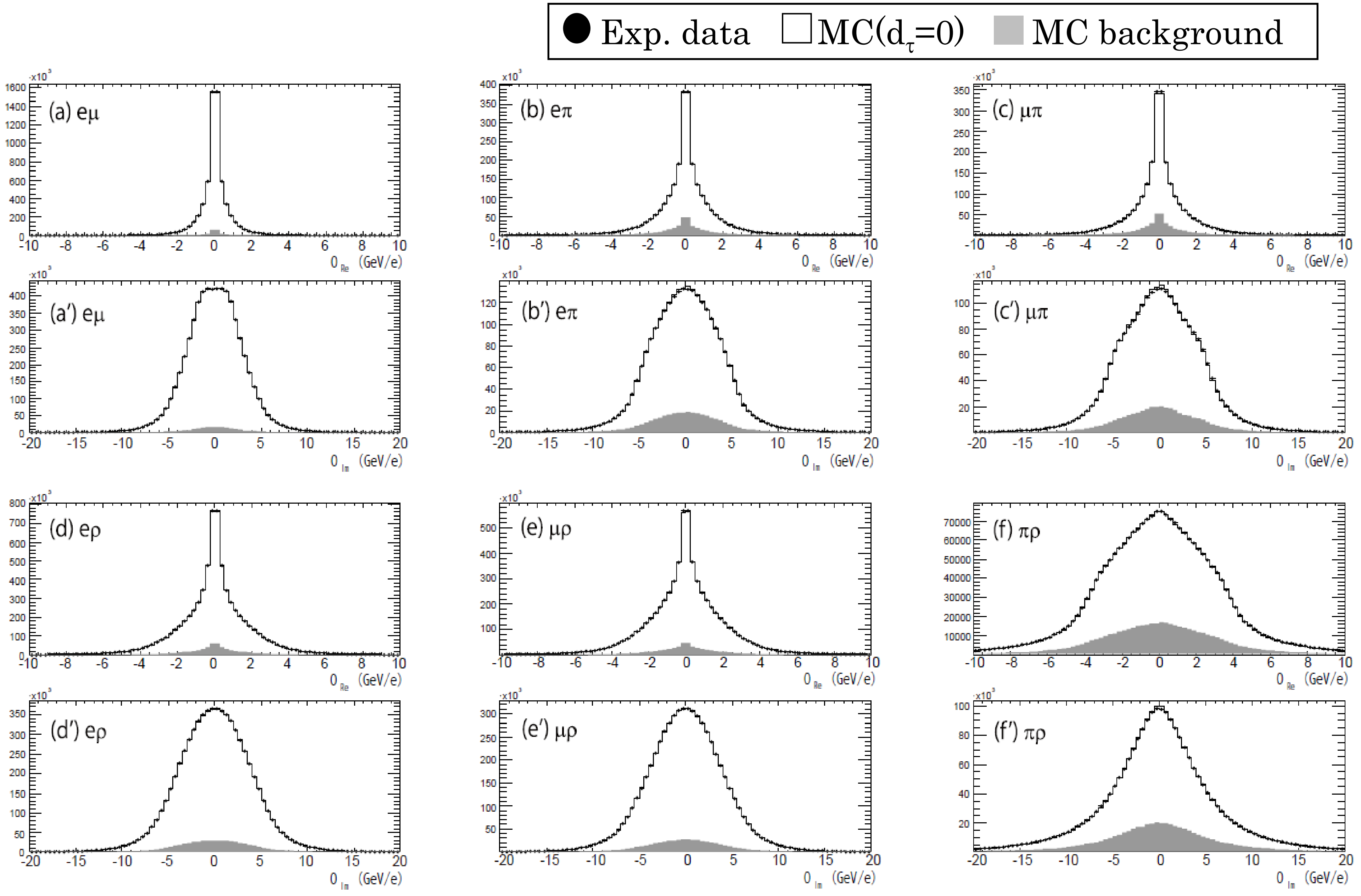


Observable distribution



- Good agreement in the distributions

Observable distribution



Extraction of EDM

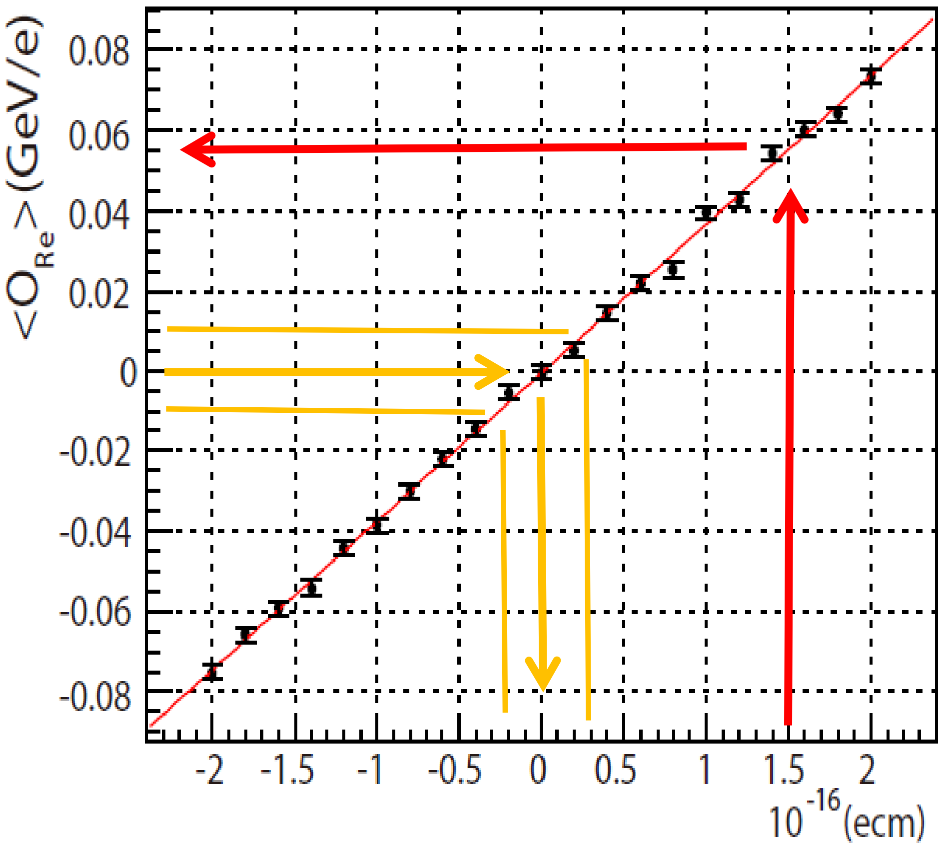
- EDM is extracted by

$$\langle \mathcal{O}_{Re} \rangle = a_{Re} \cdot Re(d_\tau) + b_{Re}$$
$$\langle \mathcal{O}_{Im} \rangle = a_{Im} \cdot Im(d_\tau) + b_{Im}$$

- Due to complicated detector acceptance distribution, parameters cannot be calculated analytically.

- Conversion parameters are obtained from MC.
  - Systematic error will come from the MC mismatch with data

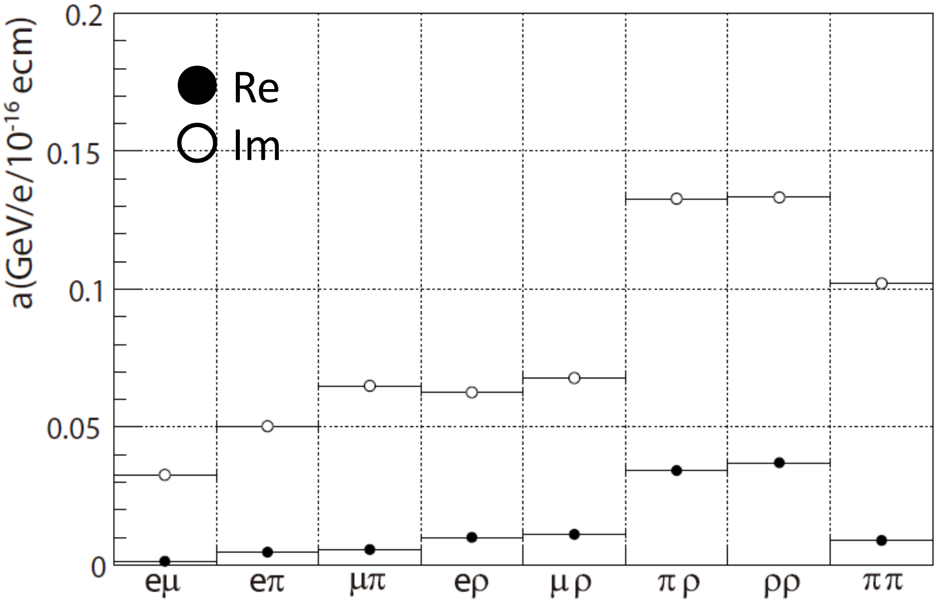
$\langle O_{Re} \rangle$ vs EDM d_τ from MC



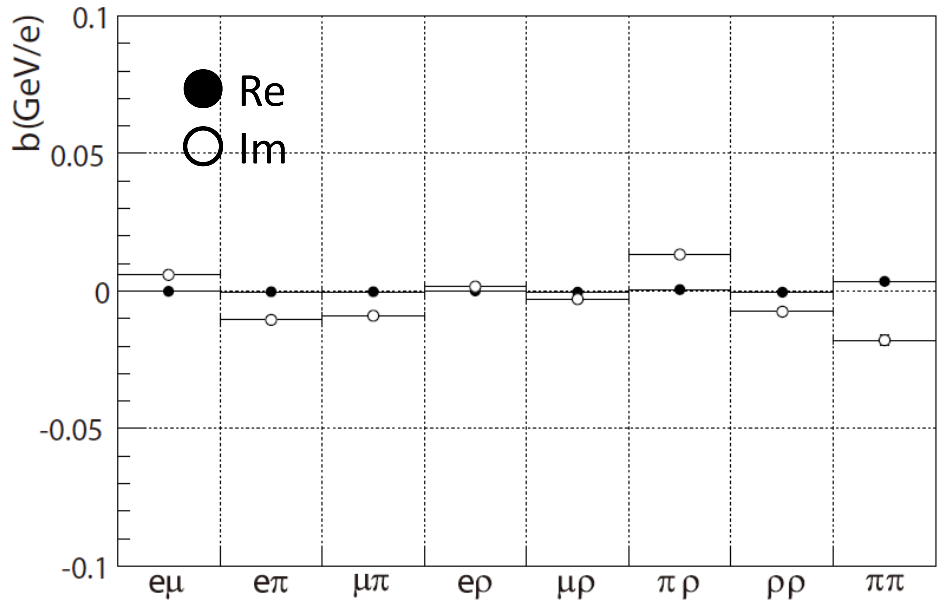
Conversion parameters

$$\langle \mathcal{O}_{Re} \rangle = a_{Re} \cdot Re(d_\tau) + b_{Re}$$
$$\langle \mathcal{O}_{Im} \rangle = a_{Im} \cdot Im(d_\tau) + b_{Im}$$

Coefficient a (~sensitivity)



Offset b



- Reduced sensitivity for leptonic decays due to additional missing neutrinos
- Offset b_{Im} due to the F/B asymmetric acceptance

Systematic uncertainty

- Difference between data and MC make systematic uncertainty.
- Systematic errors are comparable with the statistical errors.

(10^{-16} ecm)

Preliminary result

$Re(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Mismatch of distribution	0.30	0.47	0.35	0.08	0.17	0.08	0.08	0.34
Charge asymmetry	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Background variation	0.16	0.03	0.16	0.04	0.02	0.02	0.02	0.33
Momentum reconstruction	0.01	0.06	0.05	0.00	0.02	0.02	0.01	0.14
Detector alignment	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.03
Radiative effects	0.07	0.05	0.05	0.02	0.02	0.00	0.00	0.09
Total	0.35	0.47	0.39	0.09	0.17	0.08	0.08	0.50
Statistical error	0.23	0.21	0.20	0.08	0.08	0.08	0.05	0.35

$Im(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Mismatch of distribution	0.09	0.09	0.05	0.05	0.07	0.04	0.04	0.12
Charge asymmetry	0.02	0.19	0.23	0.01	0.01	0.11	0.00	0.00
Background variation	0.14	0.01	0.07	0.03	0.01	0.01	0.01	0.01
Momentum reconstruction	0.02	0.05	0.04	0.00	0.01	0.01	0.00	0.01
Detector alignment	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Radiative effects	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Total	0.17	0.22	0.24	0.06	0.07	0.11	0.04	0.12
Statistical error	0.04	0.05	0.04	0.02	0.03	0.03	0.02	0.06

Obtained precision on EDM

- By adding the statistical and systematic errors quadratically, we obtain the weighted average of EDM and its error

- Estimated error of EDM
  - $\mathrm{Re}(d_\tau)$: $(\pm 0.33) \times 10^{-17}$ecm
  - $\mathrm{Im}(d_\tau)$: $(\pm 0.30) \times 10^{-17}$ecm

⟺

Previous results
$\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}$ecm
$\mathrm{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}$ecm

  - ~5 times smaller error for $\mathrm{Re}(d_\tau)$ than previous result
    - Almost scaled by sqrt(L)
  - Systematic error dominates for $\mathrm{Im}(d_\tau)$

Summary

- We have analyzed 825fb^{-1} of recent Belle data to measure the electric dipole moment of tau lepton.
  - With optimal observable method
  - 28 times more data than in the previous analysis by Belle
  - Obtained samples agree well with the MC expectation.
- Reduced the systematic uncertainties as well as the statistical errors.
  - Improved detector understanding and careful MC preparation
  - Expected sensitivity:
    - Re(d_τ): $(\pm 0.33) \times 10^{-17}$ecm
    - Im(d_τ): $(\pm 0.30) \times 10^{-17}$ecm
  - Will show the central value soon.

Spin density matrix

$$e^+(\boldsymbol{p})e^-(-\boldsymbol{p}) \rightarrow \tau^+(\boldsymbol{k}, \boldsymbol{S}_+)\tau^-(-\boldsymbol{k}, \boldsymbol{S}_-)$$

$$\begin{aligned}
\mathcal{M}^2_{\rm prod} &= \mathcal{M}^2_{\rm SM} + Re(d_\tau)\mathcal{M}^2_{Re} + Im(d_\tau)\mathcal{M}^2_{Im} + |d_\tau|^2\mathcal{M}^2_{d^2},\\
\mathcal{M}^2_{\rm SM} &= \frac{e^4}{k_0^2}[k_0^2 + m_\tau^2 + |\boldsymbol{k}^2|(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2 - \boldsymbol{S}_+\cdot\boldsymbol{S}_-|\boldsymbol{k}|^2(1-(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2)\\
&+2(\hat{\boldsymbol{k}}\cdot\boldsymbol{S}_+)(\hat{\boldsymbol{k}}\cdot\boldsymbol{S}_-)(|\boldsymbol{k}|^2 + (k_0-m_\tau)^2(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2) + 2k_0^2(\hat{\boldsymbol{p}}\cdot\boldsymbol{S}_+)(\hat{\boldsymbol{p}}\cdot\boldsymbol{S}_-)\\
&-2k_0(k_0-m_\tau)(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})((\hat{\boldsymbol{k}}\cdot\boldsymbol{S}_+)(\hat{\boldsymbol{p}}\cdot\boldsymbol{S}_-) + (\hat{\boldsymbol{k}}\cdot\boldsymbol{S}_-)(\hat{\boldsymbol{p}}\cdot\boldsymbol{S}_+))],\\
\mathcal{M}^2_{Re} &= 4\frac{e^3}{k_0}|\boldsymbol{k}|[\ -(m_\tau + (k_0-m_\tau)(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2)(\boldsymbol{S}_+\times\boldsymbol{S}_-)\cdot\hat{\boldsymbol{k}}\\
&\qquad + k_0(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})(\boldsymbol{S}_+\times\boldsymbol{S}_-)\cdot\hat{\boldsymbol{p}}\ ],\\
\mathcal{M}^2_{Im} &= 4\frac{e^3}{k_0}|\boldsymbol{k}|[\ -(m_\tau + (k_0-m_\tau)(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2)(\boldsymbol{S}_+-\boldsymbol{S}_-)\cdot\hat{\boldsymbol{k}}\\
&\qquad + k_0(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})(\boldsymbol{S}_+-\boldsymbol{S}_-)\cdot\hat{\boldsymbol{p}}\ ],\\
\mathcal{M}^2_{d^2} &= 4e^2|\boldsymbol{k}|^2\cdot\ (1-(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2)(1-\boldsymbol{S}_+\cdot\boldsymbol{S}_-),
\end{aligned}$$

Spin vector

$\tau \to l \nu_l \nu_\tau$

$$\boldsymbol{S}_\pm = \frac{4c_\pm - m_\tau^2 - 3m_l^2}{3m_\tau^2 c_\pm - 4c_\pm^2 - 2m_l^2 m_\tau^2 + 3c_\pm m_l^2} \left(\pm m_\tau \boldsymbol{p}_{l\pm} - \frac{c_\pm + E_{l\pm} m_\tau}{k_0 + m_\tau} \boldsymbol{k} \right)$$

$$c_\pm = k_0 E_{l\pm} \mp \boldsymbol{k} \cdot \boldsymbol{p}_{l\pm}$$

$\tau \to \pi \nu_\tau$

$$\boldsymbol{S}_\pm = \frac{2}{m_\tau^2 - m_\pi^2} \left(\mp m_\tau \boldsymbol{p}_{\pi^\pm} + \frac{m_\tau^2 + m_\pi^2 + 2m_\tau E_{\pi^\pm}}{2(E_\tau + m_\tau)} \boldsymbol{k} \right)$$

$\tau \to \rho \nu_\tau \to \pi \pi^0 \nu_\tau$

$$\boldsymbol{S}_\pm = \mp \frac{1}{(k_\pm H_\pm) - m_\tau^2 (p_{\pi^\pm} - p_{\pi^0})^2} \left(\mp H_0^\pm \boldsymbol{k} + m_\tau \boldsymbol{H}^\pm + \frac{\boldsymbol{k}(\boldsymbol{k} \cdot \boldsymbol{H}^\pm)}{(E_\tau + m_\tau)} \right)$$

$$(H^\pm)^\nu = 2(p_{\pi^\pm} - p_{\pi^0})^\nu (p_{\pi^\pm} - p_{\pi^0})^\mu (k_\pm)_\mu + (p_{\pi^\pm} + p_{\pi^0})^\nu (p_{\pi^\pm} - p_{\pi^0})^2$$