Recent results on tau decays at Belle experiment

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Topics of tau physics at Belle

- New physics search
  - tau LFV
  - tau CPV
- SM precise measurement
  - BF measurement of hadronic decays
  - evaluation of the spectrum of the hadronic current
  - 2nd class current search
  - measurement of |Vus|
- Tau property measurement
  - tau mass measurement
  - tau lifetime measurement
  - tau EDM measurement
  - tau Michel parameter measurement

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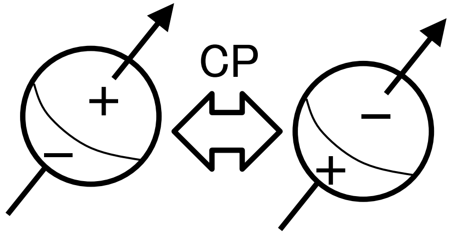
Today's topics

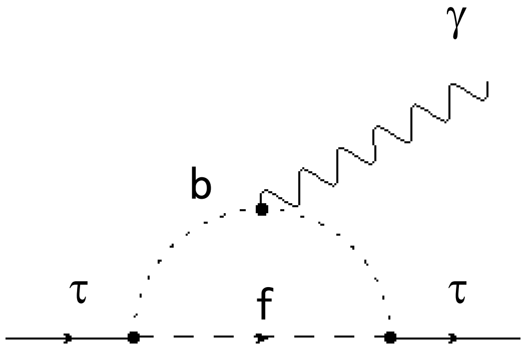
TAU EDM MEASUREMENT

Introduction for tau EDM (1)

- EDM violates CP since it signifies a charge asymmetry along spin direction.



- Standard model prediction: $\mathcal{O}(10^{-37})$ ecm
  - Sizable EDM of tau is a signal of New Physics
  - Through a loop diagram with new particles, EDM can appear.



- Current upper limit:

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

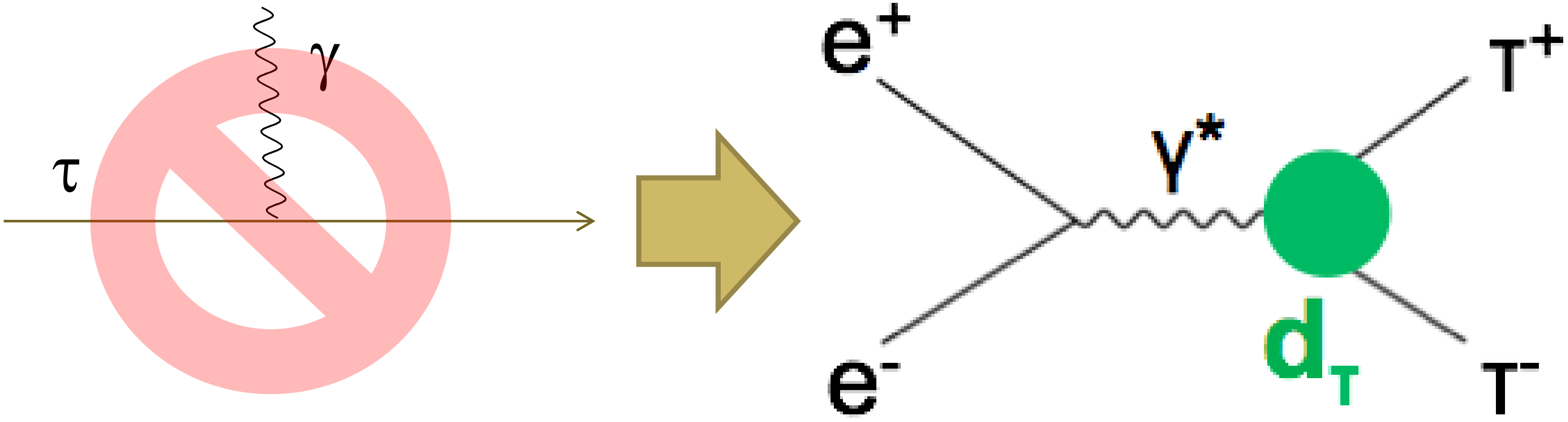
$$-2.2 < \mathrm{Re}(d_\tau)\times 10^{17} < 4.5\,(e\mathrm{cm})$$

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

$$\mathcal{L}_{\mathrm{EDM}} = -\frac{i}{2} d_\tau \bar{\tau}\sigma^{\mu\nu}\gamma_5\tau\, F_{\mu\nu}$$

Introduction for tau EDM (2)

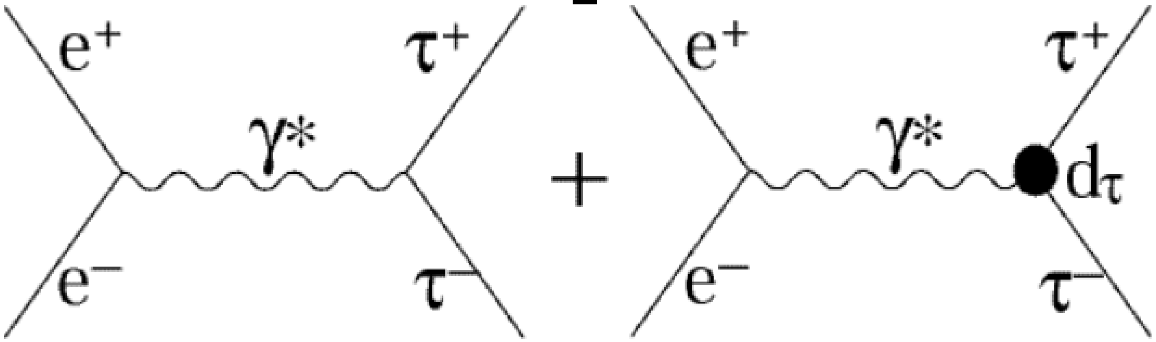
- Due to the short life time of tau (~90μm), a measurement via radiative process is difficult, differently from that for muon.
- In a B-factory, through the tau-pair production vertex, tau EDM can be evaluated.



Effective lagrangian and Spin density matrix element

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

$$\mathcal{L} = \bar{\tau}(i\partial\!\!\!/ - eA\!\!\!/)\tau - \frac{i}{2} d_\tau \bar{\tau}\sigma^{\mu\nu}\gamma_5\tau\, F_{\mu\nu}$$



- Squared spin density matrix

$$\mathcal{M}^2_{prod} = \mathcal{M}^2_{SM} + \boxed{\mathrm{Re}(d_\tau)\mathcal{M}^2_{\mathrm{Re}}} + \boxed{\mathrm{Im}(d_\tau)\mathcal{M}^2_{\mathrm{Im}}} + |d_\tau|^2\, \mathcal{M}^2_{SM}$$

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

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

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

$\vec{S}_\pm$: spin vector of $\tau^\pm$

$\vec{k}$: momentum for τ^+

$\vec{p}$: momentum for beam e^+

Optimal observable method

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

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

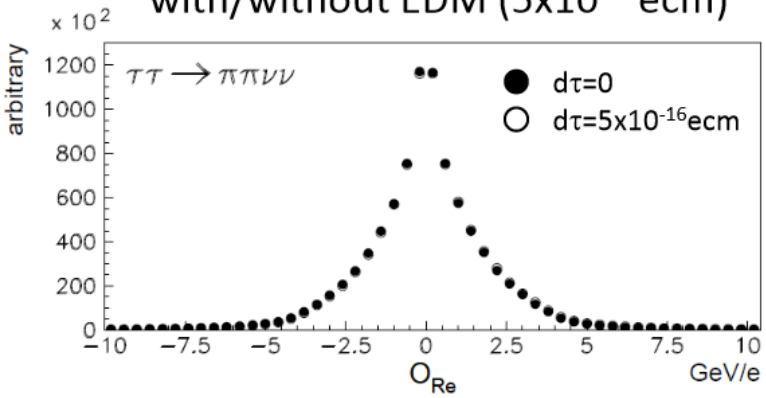
$$\mathcal{M}^2_{\mathrm{Im}} \sim (\vec{S}_+ - \vec{S}_-)\vec{k}, (\vec{S}_+ - \vec{S}_-)\vec{p}$$

$$\boxed{\mathcal{O}_{Re} = \frac{\mathcal{M}^2_{Re}}{\mathcal{M}^2_{SM}}} \qquad \langle \mathcal{O}_{Re} \rangle \propto \int \mathcal{O}_{Re}\, d\sigma \propto \int \mathcal{O}_{Re} \mathcal{M}^2_{prod}\, d\phi$$

$$= \underbrace{\int \mathcal{M}^2_{Re}\, d\phi}_{b} + \underbrace{Re(d_\tau)}_{\text{EDM}} \underbrace{\int \frac{(\mathcal{M}^2_{Re})^2}{\mathcal{M}^2_{SM}}\, d\phi}_{a}$$

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.

MC simulation (ee → ττ → ππνν) with/without EDM (5×10^{-16}ecm)

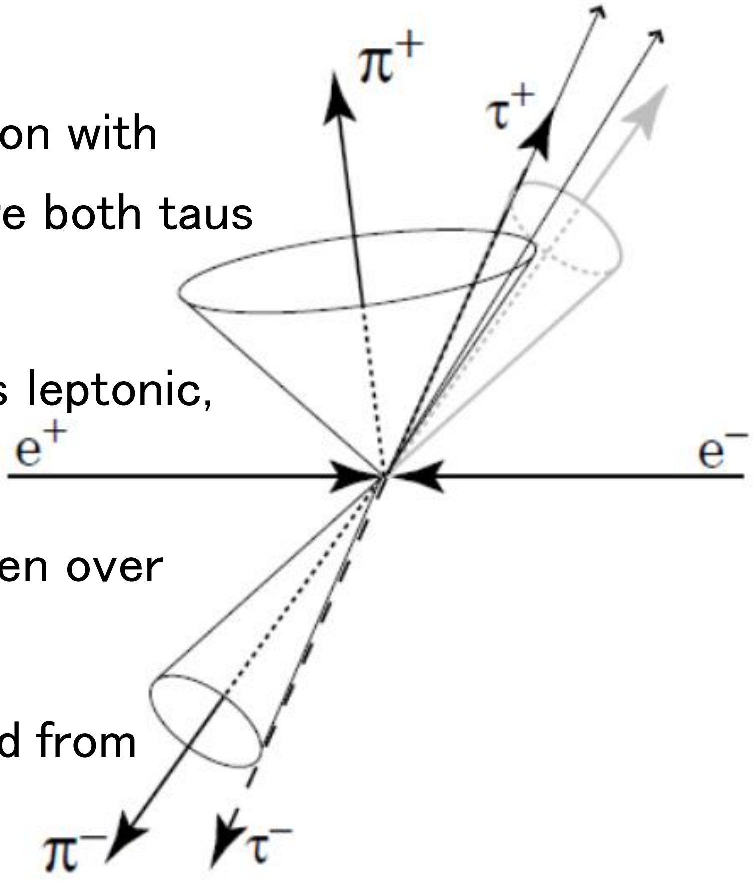


Similar formula of Im(d_τ) can be obtained by replacing Re by Im.

Evaluate OO

- 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.

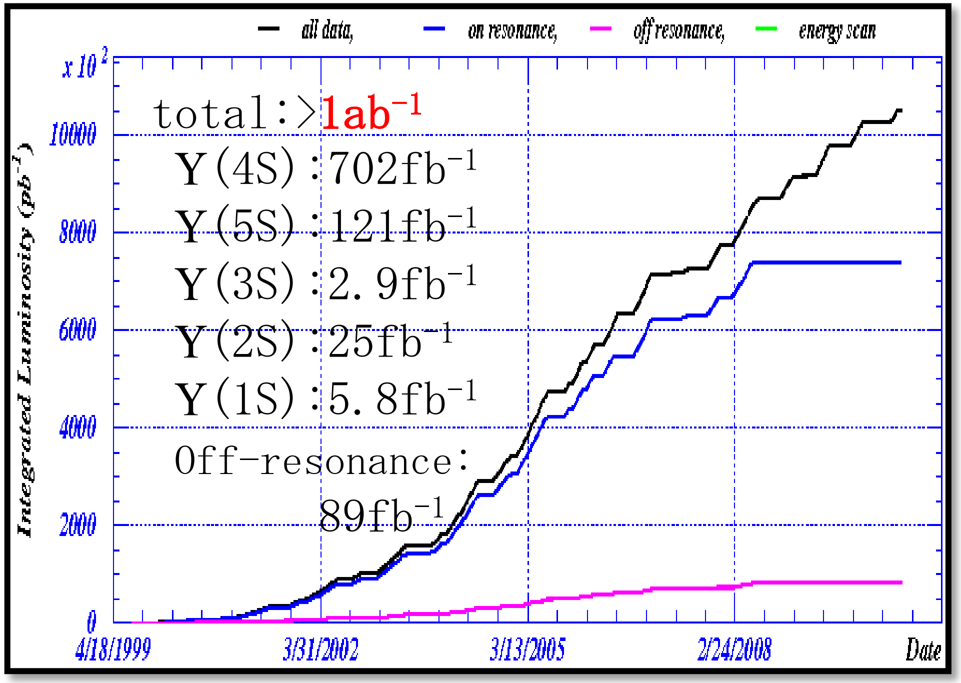
e^+e^- CM frame



Belle experiment

B-factory: E at CM = Υ(4S) [e^+(3.5 GeV) e^-(8 GeV)]

Belle has finished data taking in 2010.



total:>$1ab^{-1}$

Υ(4S):$702fb^{-1}$

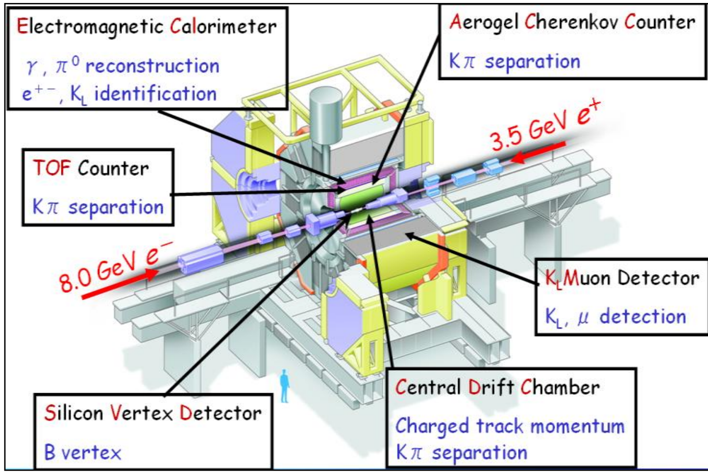
Υ(5S):$121fb^{-1}$

Υ(3S):$2.9fb^{-1}$

Υ(2S):$25fb^{-1}$

Υ(1S):$5.8fb^{-1}$

Off-resonance: $89fb^{-1}$



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

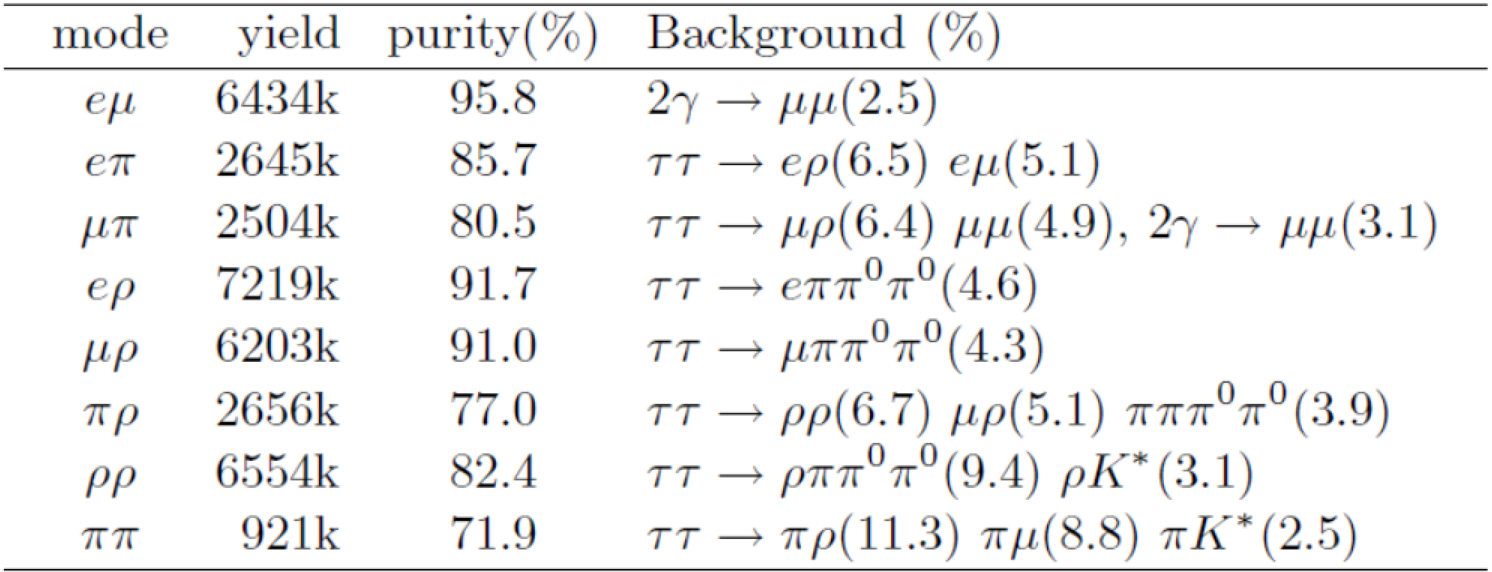
- lepton identification
- hermeticity

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

A B-factory is also a tau factory since the production cross section for BB and τ-pair is very similar. (1.1nb vs 0.9nb)

Selected tau decays and BG

- Select 8 final modes exclusively using 825fb^{-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 foe e, μ, π
    - ρ reconstructed from $\pi\pi^0(\rightarrow\gamma\gamma)$
    - Require high momentum and barrel region to reduce systematic errors
- Total yield: 3.5x10^7 events, Averaged purity: 87.7%
- Background
  - Main: from tau decay: Missing-π^0 and mis-PID

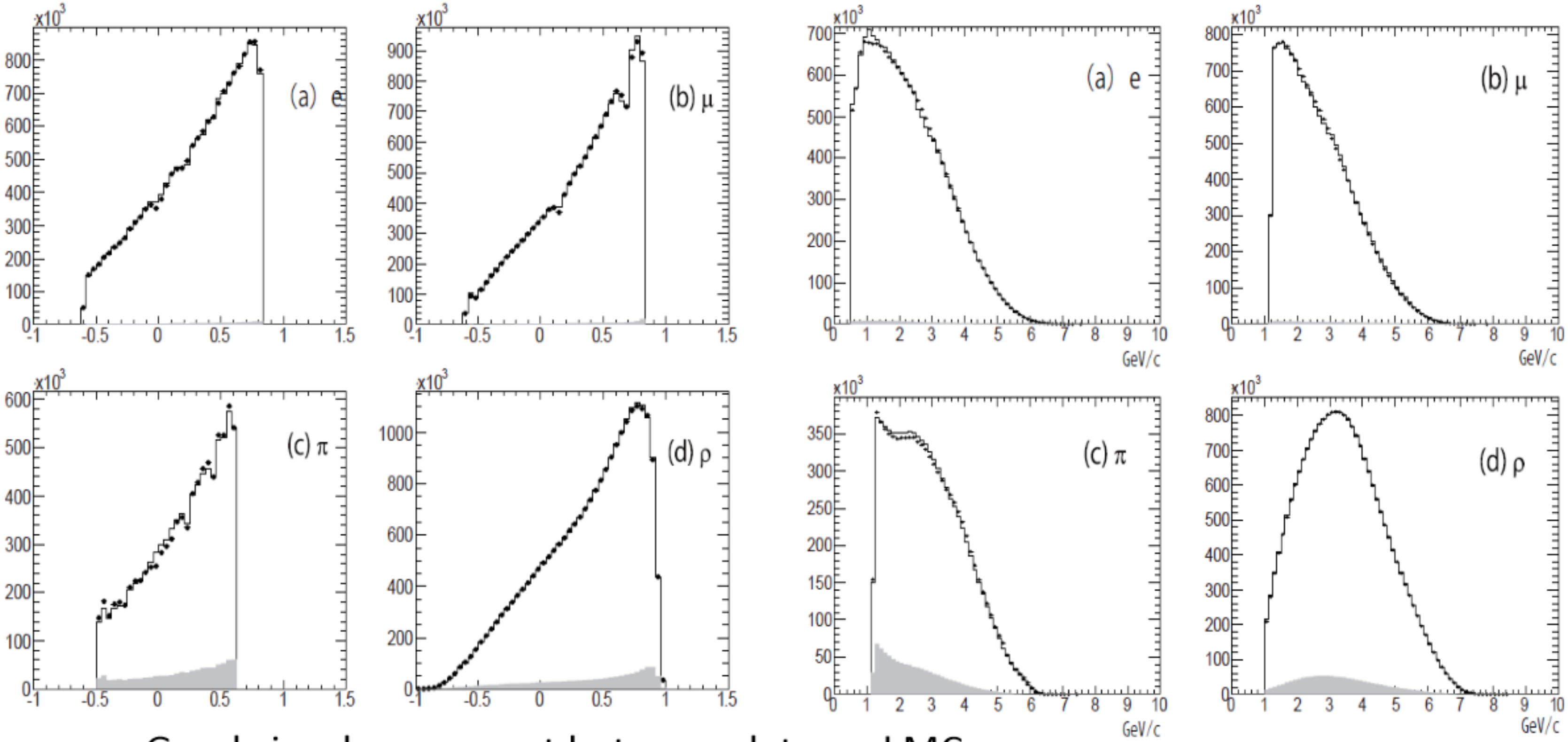


mode	yield	purity(%)	Background (%)
$e\mu$	6434k	95.8	$2\gamma \rightarrow \mu\mu(2.5)$
$e\pi$	2645k	85.7	$\tau\tau \rightarrow e\rho(6.5)\ e\mu(5.1)$
$\mu\pi$	2504k	80.5	$\tau\tau \rightarrow \mu\rho(6.4)\ \mu\mu(4.9)$, $2\gamma \rightarrow \mu\mu(3.1)$
$e\rho$	7219k	91.7	$\tau\tau \rightarrow e\pi\pi^0\pi^0(4.6)$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

Selected data and MC samples

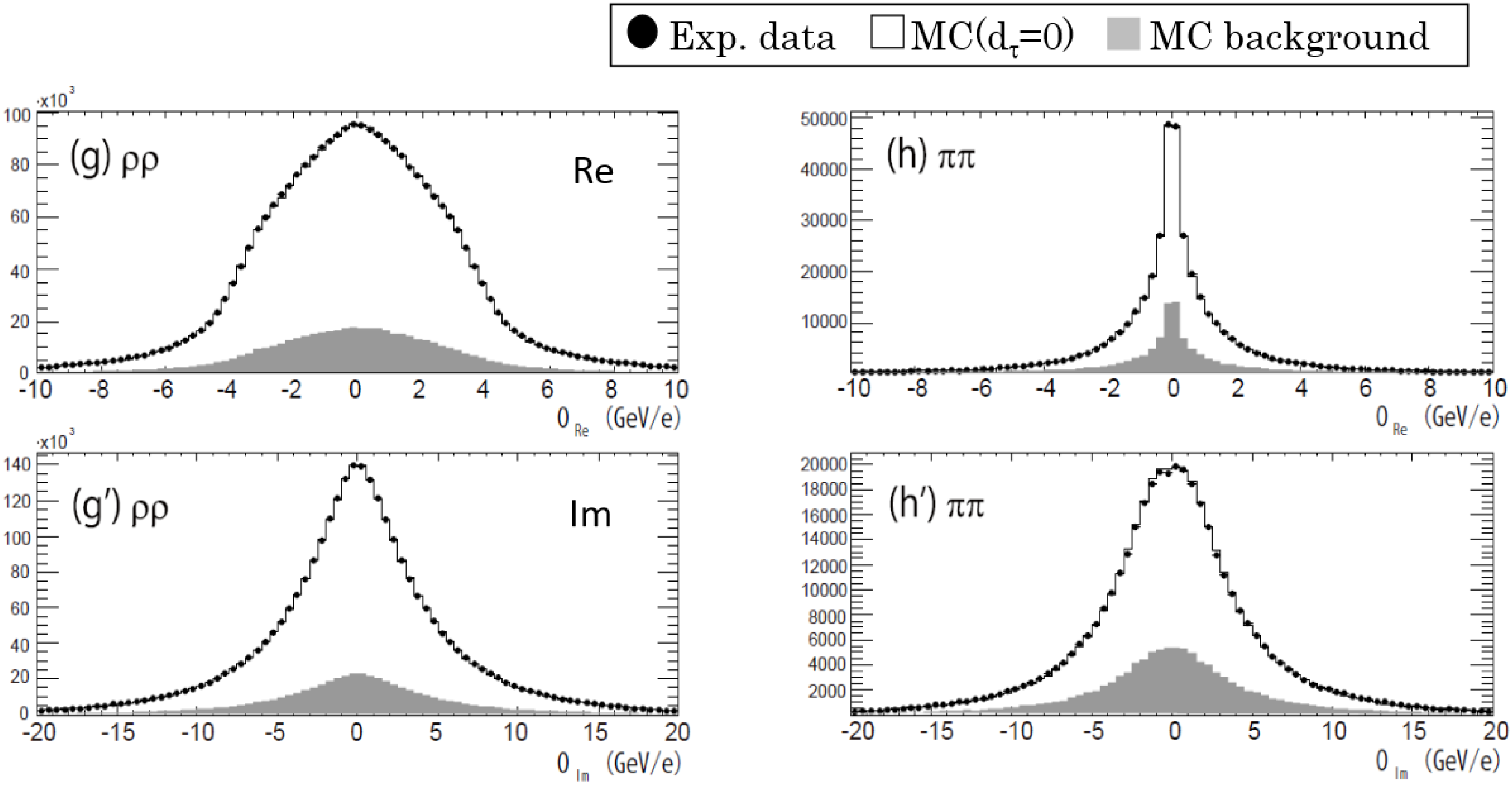
● Exp. data ☐ MC(d_τ=0) ▨ MC background

- 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

OO distributions

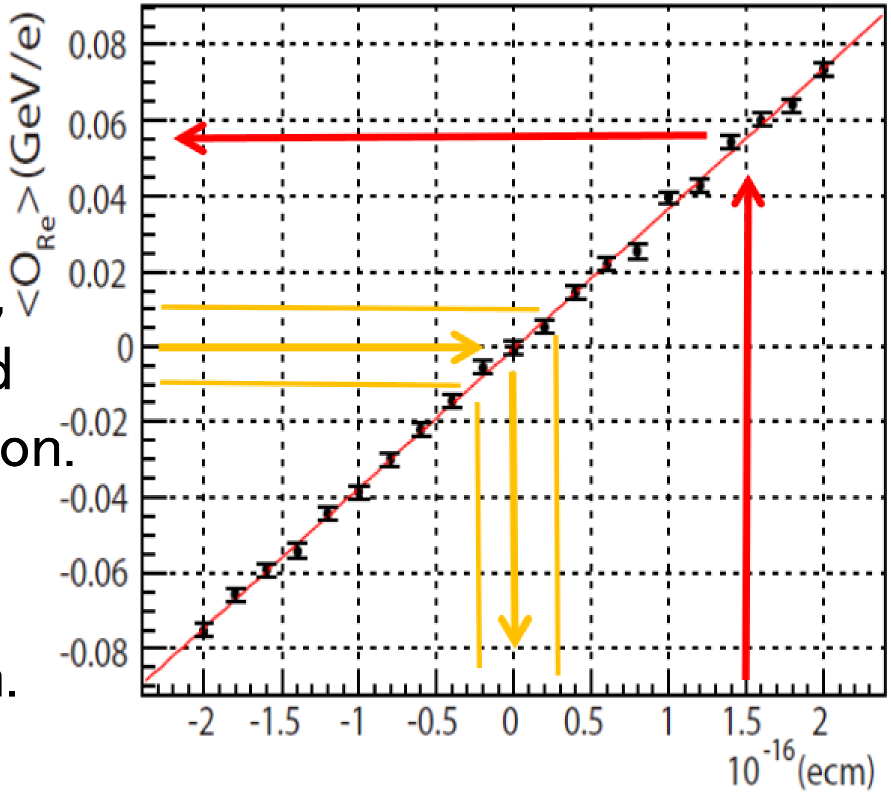


- Good agreement in the distributions

Extract EDM from OO

- Since $\overset{=b_{\mathrm{Re}}}{\int \mathcal{M}_{\mathrm{Re}}^2\, d\phi}$ and $\overset{=a_{\mathrm{Re}}}{\int \frac{(\mathcal{M}_{\mathrm{Re}}^2)^2}{\mathcal{M}_{\mathrm{SM}}^2}\, d\phi}$ 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.

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



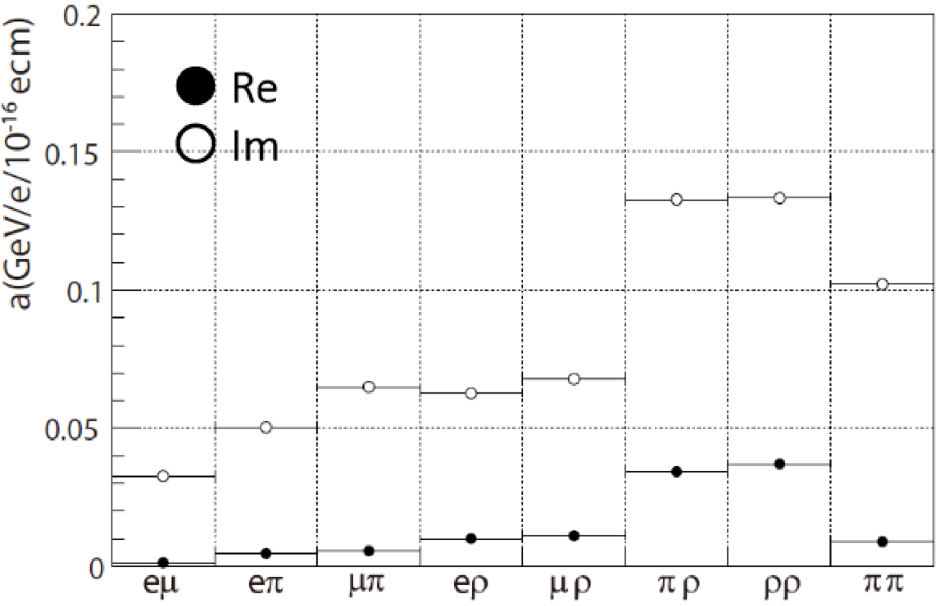
$$\langle O_{\mathrm{Re}} \rangle = a_{\mathrm{Re}}\, \mathrm{Re}(d_\tau) + b_{\mathrm{Re}}$$

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

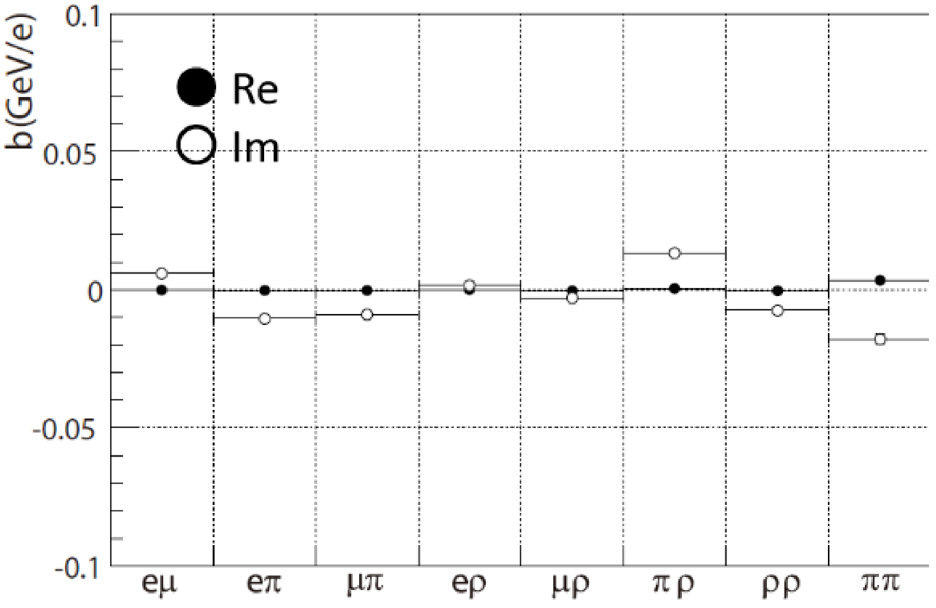
Parameters to extract EDM

- We evaluate a and b mode by mode as well as finally EDM value mode by mode. And then, average those EDM values.

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 uncertainties

(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
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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

Mismatch of distribution gives large contribution.
The systematic uncertainties are comparable to the statistical one.

Sensitivity of this measurement

- By adding statistical and systematic uncertainties for each mode quadratically, the error can be evaluated for the final result.
- The error of this measurement:

$$\mathrm{Re}(d_\tau)\times 10^{17} : \pm 0.33\,(e\mathrm{cm})$$

$$\mathrm{Im}(d_\tau)\times 10^{17} : \pm 0.30\,(e\mathrm{cm})$$

Very preliminary

Previous result

$$\mathrm{Re}(d_\tau)\times 10^{17} : 1.15 \pm 1.70\,(e\mathrm{cm})$$

$$\mathrm{Im}(d_\tau)\times 10^{17} : -0.83 \pm 0.86\,(e\mathrm{cm})$$

  - The error of Re(d_τ) is around 5 times smaller than previously.
    - Almost proportional to $1/\sqrt{N_{\tau\tau}}$
  - The error of Im(d_τ) is dominated by the systematics.

The result will be shown soon.

TAU MICHEL PARAMETERS MEASUREMENT

Introduction for tau Michel parameters

- Michel parameters (MP) well express the property of Weak interaction in tau decay and definition is:

$$\frac{d\Gamma(\tau\to\ell\nu\nu)}{d\Omega dx}=\frac{4G_F^2M_\tau E_{\max}^4}{(2\pi)^4}\sqrt{x^2-x_0^2}\left(x(1-x)+\frac{2}{9}\underline{\rho}(4x^2-3x-x_0^2)+\underline{\eta}x_0(1-x)\right.$$

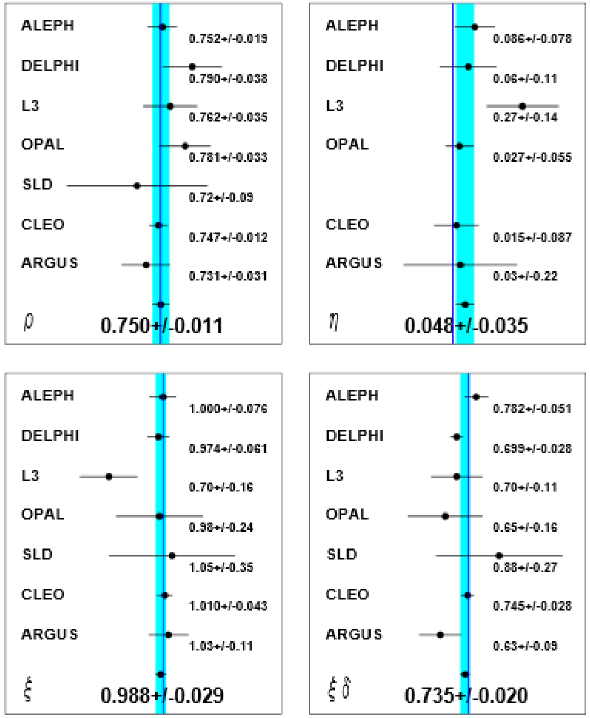
$$\left.\mp\frac{1}{3}P_\tau\cos\theta_\ell\underline{\xi}\sqrt{x^2-x_0^2}\left[1-x+\frac{2}{3}\underline{\delta}\left(4x-4+\sqrt{1-x_0^2}\right)\right]\right),\ x=\frac{E_\ell}{E_{\max}},\ x_0=\frac{m_\ell}{E_{\max}}$$

- SM predicts: $\rho=\frac{3}{4},\eta=0,\xi=1,\delta=\frac{3}{4}$
- Type II 2HFM predicts: $\eta=\frac{m_\mu M_\tau}{2}\left(\frac{\tan^2\beta}{M_{H^\pm}^2}\right)^2$

Similarly, new physics effects can appear in Michel parameters, that more strongly couple to tau than muon.

Current status of the measurement of MPs

Michel par.	Measured value	Experiment	SM value
ρ (e or μ)	$0.747 \pm 0.010 \pm 0.006$ 1.2%	CLEO-97	3/4
η (e or μ)	$0.012 \pm 0.026 \pm 0.004$ 2.6%	ALEPH-01	0
ξ (e or μ)	$1.007 \pm 0.040 \pm 0.015$ 4.3%	CLEO-97	1
$\xi\delta$ (e or μ)	$0.745 \pm 0.026 \pm 0.009$ 2.8%	CLEO-97	3/4
ξ_h (all hadr.)	$0.992 \pm 0.007 \pm 0.008$ 1.1%	ALEPH-01	1



Using 300x more data sample at Belle than the previous experiment, one-order-magnitude improvement of the measurement is expected since Belle and BaBar have never evaluated them yet so far.

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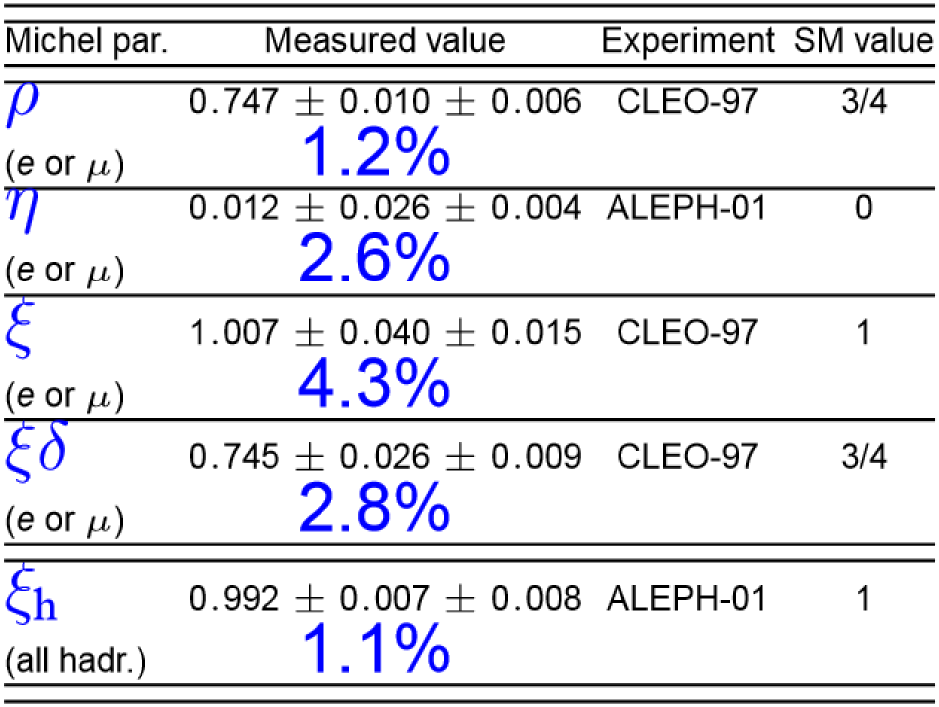

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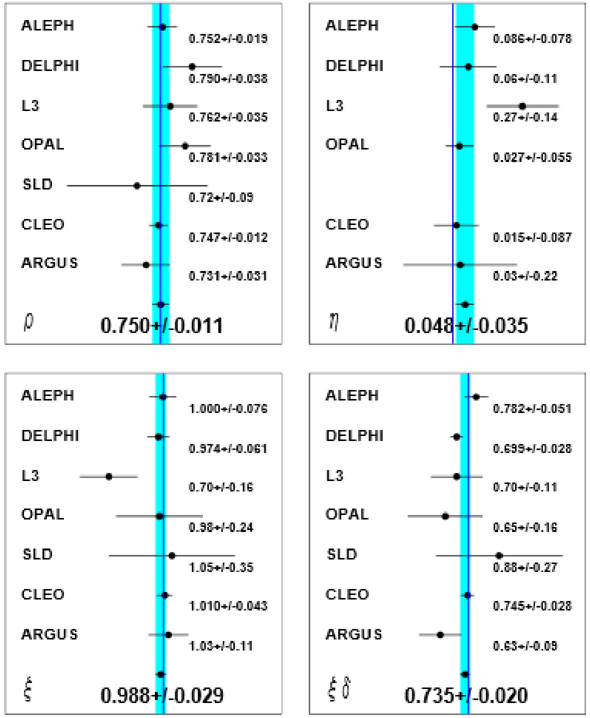

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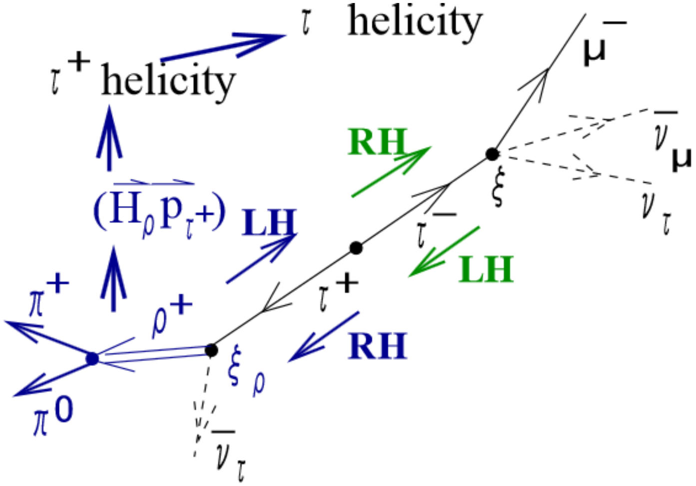
O(0.1)%!

Analysis method

- Since tau spin information is necessary to measure some MPs, we utilize both tau decays:



In $\tau^+ \rightarrow \rho^+\nu$ / $\tau^- \rightarrow \ell^-\nu\nu$ events, to evaluate helicity of τ^-, (Similarly to the case of EDM) we use $\tau^+ \rightarrow \rho^+\nu$ decay. Since $\tau \rightarrow \rho\nu$ decay includes another MP, we also evaluate $\tau^+ \rightarrow \rho^+\nu$ / $\tau^- \rightarrow \rho^-\nu$ events.

- Background: $\tau^+ \rightarrow \pi^+\pi^0\pi^0\nu$ / $\tau^- \rightarrow \ell^-\nu\nu$ (~10%),
  $\tau^+ \rightarrow \rho^+\nu$ / $\tau^- \rightarrow \pi^-\nu$ (~1.5%),
  others(~2.0%),non-$\tau\tau$<0.1%
- By an unbinned maximum likelihood fit, we evaluate MPs and amount of signal and BG.

Likelihood function

$$\mathcal{P}(x) = \frac{\bar{\varepsilon}(x)}{\varepsilon}\left((1-\sum_i \lambda_i)\frac{S(x)}{\int \frac{\bar{\varepsilon}(x)}{\varepsilon} S(x)dx} + \lambda_{3\pi}\frac{\tilde{B}_{3\pi}(x)}{\int \frac{\bar{\varepsilon}(x)}{\varepsilon}\tilde{B}_{3\pi}(x)dx} + \lambda_{\pi} \frac{\tilde{B}_{\pi}(x)}{\int \frac{\bar{\varepsilon}(x)}{\varepsilon}\tilde{B}_{\pi}(x)dx}\right.$$

$$\left. + \lambda_{other}\frac{B^{MC}_{other}(x)}{\int \frac{\bar{\varepsilon}(x)}{\varepsilon}B^{MC}_{other}(x)dx}\right), \tilde{B}_{3\pi}(x) = \int (1-\varepsilon_{\pi^0}(y))\varepsilon_{add}(y)B_{3\pi}(x,y)dy, \tilde{B}_{\pi}(x) = \frac{\varepsilon^{\mu ID}_{\pi\to\mu}(x)}{\varepsilon^{\mu ID}_{\mu\to\mu}(x)}B_{\pi}(x)$$

$$x = (p_{\ell}, \Omega_{\ell}, p_{\rho}, \Omega_{\rho}, m^2_{\pi\pi^0}, \Omega_{\pi}),\ y = (p_{\pi^0}, \Omega_{\pi^0}) \longleftarrow$$

Multi–dimensional fit!

$S(x)$: density of signal ($\ell^{\mp},\pi^{\pm}\pi^0$) events

$B_{3\pi}(x)$: density of background ($\ell^{\mp},\pi^{\pm}2\pi^0$) events

$B_{\pi}(x)$: density of background ($\pi^{\mp},\pi^{\pm}2\pi^0$) events

$B^{MC}_{others}(x)$: MC density of the remaining background

$\varepsilon(x)$: detection efficiency for signal events

$\varepsilon_{\pi^0}(x)$: π^0 efficiency

$\varepsilon_{add}(x)$: additional efficiency background ($\ell^{\mp},\pi^{\pm}2\pi^0$) events

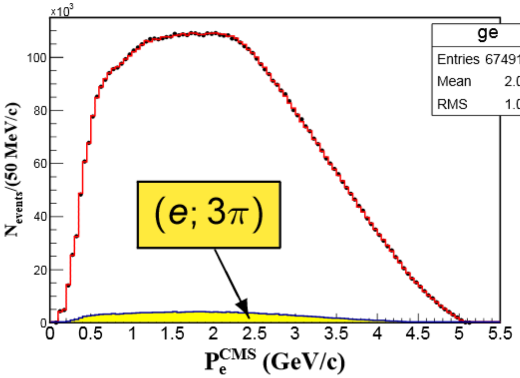
$\varepsilon_{\pi}(x)$: detection efficiency for ($\pi^{\mp},\pi^{\pm}2\pi^0$) events

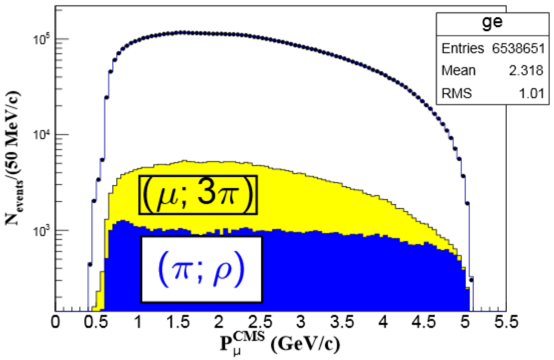
Test of the fitter with MC

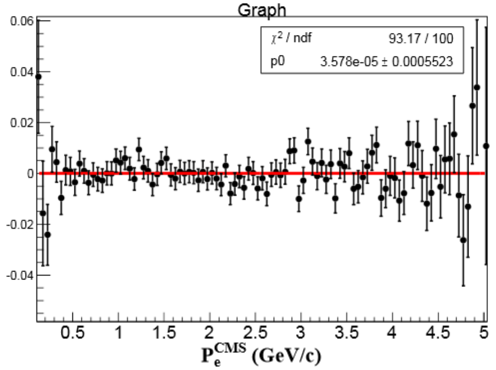
For each configuration 5M MC sample is fitted. The other, statistically independent, 5M MC sample was used to calculate normalization.

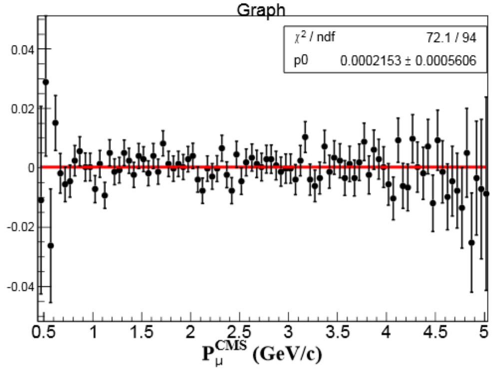
($e^+;\pi^-\pi^0$)				
ρ	=	0.7517	$\pm$	0.0010
η	=	0	–	fixed
ξ	=	1.0092	$\pm$	0.0043
$\xi\delta$	=	0.7538	$\pm$	0.0027

($\mu^+;\pi^-\pi^0$)				
ρ	=	0.7494	$\pm$	0.0027
η	=	0.0052	$\pm$	0.0101
ξ	=	0.9995	$\pm$	0.0050
$\xi\delta$	=	0.7519	$\pm$	0.0033







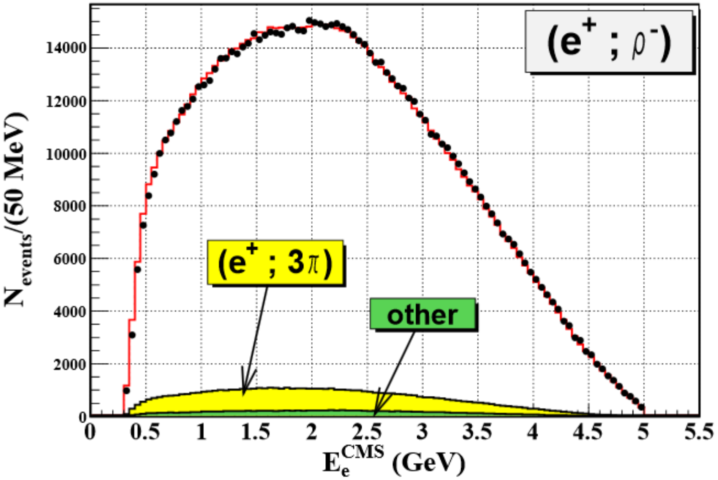


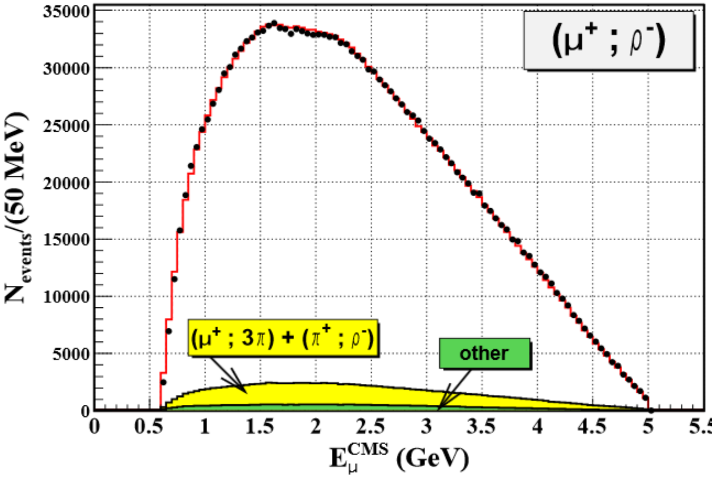
Corrections

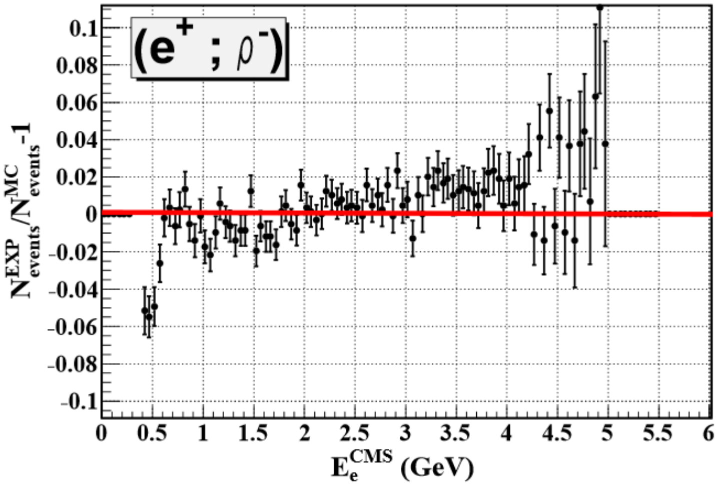
- Effects which should be included into the fit are listed up.
  - Physics corrections
    - Higher order corrections of EW for $e^+e^- \rightarrow \tau^+\tau^-$ reaction upto $O(\alpha^3)$
    - Radiative decays $\tau^- \rightarrow \ell^- \nu\nu\gamma$, $\tau^- \rightarrow \pi\pi^0\nu\gamma$
  - Detector effects
    - Track momentum resolution
    - γ energy and angular resolution
    - Beam energy spread
    - Effect of bremsstrahlung for e
    - DATA/MC efficiency correction for trigger, track rec., PID and so on.

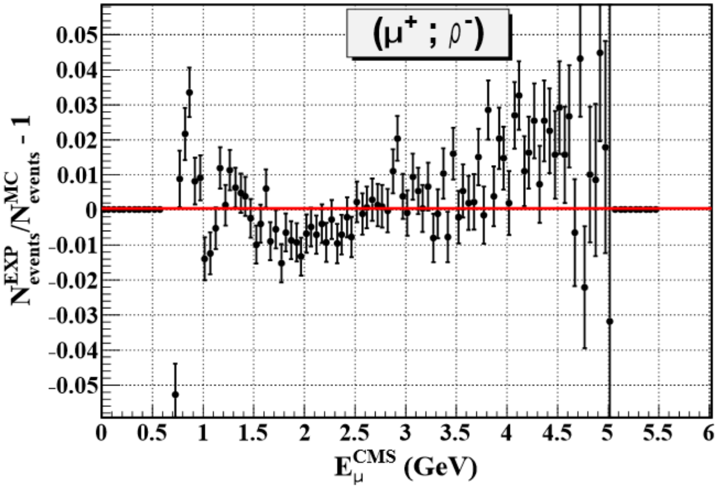
Fit for the experimental data

Here, 4.5×10^6 tau-pair events are used.









Systematic uncertainties

Very preliminary

Unit is in %.

Source	$\sigma(\rho)$	$\sigma(\eta)$	$\sigma(\xi_\rho \xi)$	$\sigma(\xi_\rho \xi \delta)$
Physics corrections				
ISR+O(α^3)	**0.10**	**0.30**	**0.20**	**0.15**
$\tau \to \ell \nu \nu \gamma$	**0.03**	**0.10**	**0.09**	**0.08**
$\tau \to \rho \nu \gamma$	**0.06**	**0.16**	**0.11**	**0.02**
Apparatus corrections				
Resolution +brems.	**0.10**	**0.33**	**0.11**	**0.19**
$\sigma(E_{beam})$	**0.07**	**0.25**	**0.03**	**0.15**
Normalization corrections				
ΔN	**0.21**	**0.60**	**0.38**	**0.26**
Total	**0.27**	**0.81**	**0.47**	**0.40**

- O(0.1)% measurements will be achieved.

Now, studying details for the fit bias, which increases the systematics.

After understanding the fit result, we can show the final result.

Summary

- We are measuring tau EDM and tau Michel parameters using the world largest tau data sample. ~$O(10^9)$
- Tau EDM

$$\mathrm{Re}(d_\tau)\times 10^{17}: \pm 0.33\,(e\mathrm{cm})$$

$$\mathrm{Im}(d_\tau)\times 10^{17}: \pm 0.30\,(e\mathrm{cm})$$

Previous result

$$\mathrm{Re}(d_\tau)\times 10^{17}: 1.15 \pm 1.70\,(e\mathrm{cm})$$

$$\mathrm{Im}(d_\tau)\times 10^{17}: -0.83 \pm 0.86\,(e\mathrm{cm})$$

  - For Re(d_τ), improvement by $\sqrt{N_{\tau\tau}}$, For Im(d_τ), systematic dominant.
- Tau Michel parameters
  - Errors of four parameters will be $\mathcal{O}(0.1)\%$

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Around summer, we will show the final results for both!

Contents of this talk

a. Topics of tau physics at Belle
b. Tau EDM measurement
c. Tau Michel parameter measurement