Tau physics at Belle

ICHEP2022

Kenta Uno

Niigata university

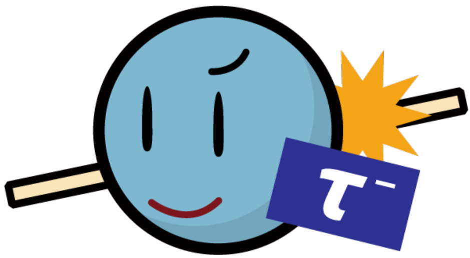
Introduction

τ lepton: heaviest lepton in Standard Model

- Many decay modes: leptonic and hadronic decays

→ Sensitive to new physics

Eg. lepton flavor violation (LFV), CP violation



Recent τ physics results at Belle

- Search for a dark leptophilic scalar $e^+e^- \to \tau^+\tau^-\phi_L$
  - Belle-CONF-2201 will appear soon
- Search for tau LFV $\tau^\pm \to \ell^\pm\gamma$ JHEP 2110, 019
- Electric dipole moment of the tau lepton JHEP 2204, 110

Today, these three results are reported

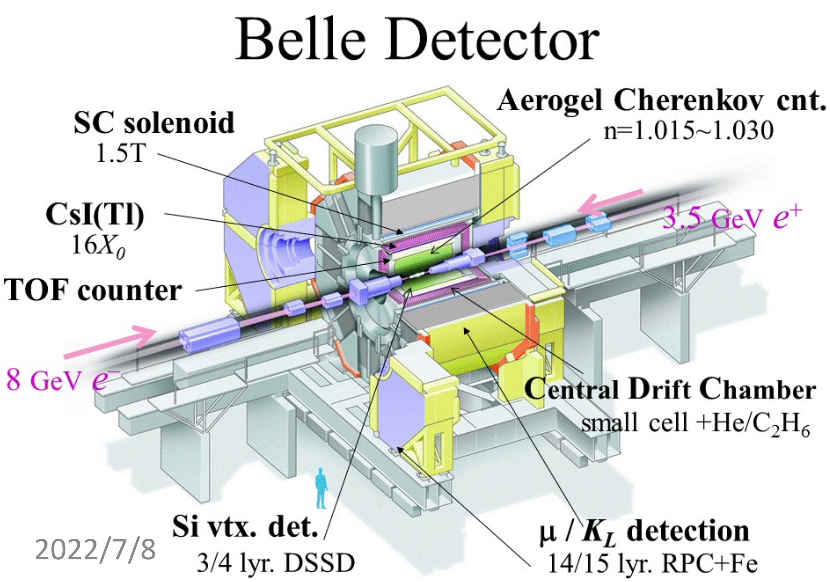
Poster: studies about partial wave analysis of $\tau \to 3\pi\nu$ decay by A.Rabusov

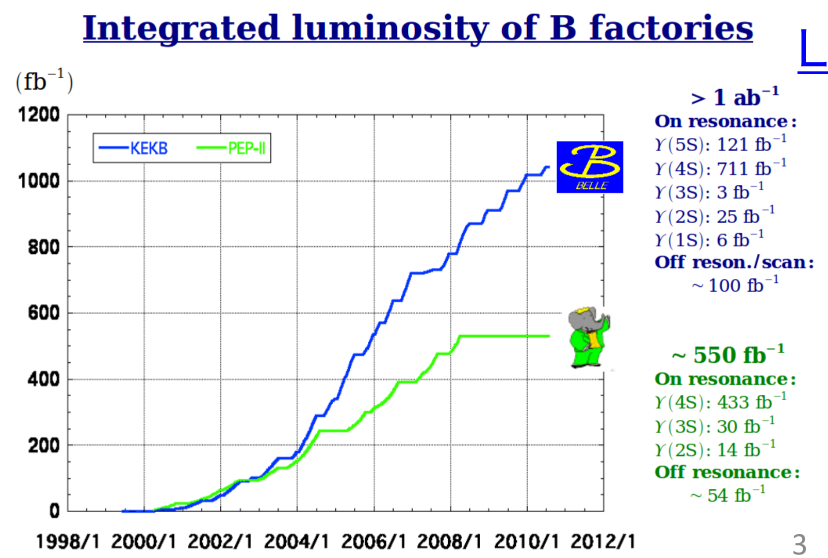
Please see his poster!

Belle experiment

- Operation: 1999 - 2010
- Collision: 8 GeV e^- , 3.5 GeV e^+
  - $\sigma(ee \to bb) \sim 1.1\,\mathrm{nb}, \sigma(ee \to \tau\tau) \sim 0.9\,\mathrm{nb}$ → τ factory!
    - Possible to use all $\Upsilon(nS)$ resonance data ($n = 1..5$)
    - Possible to use off resonance data (~100 fb^{-1})

→ In total, $912\times10^6\ N_{\tau\tau}$





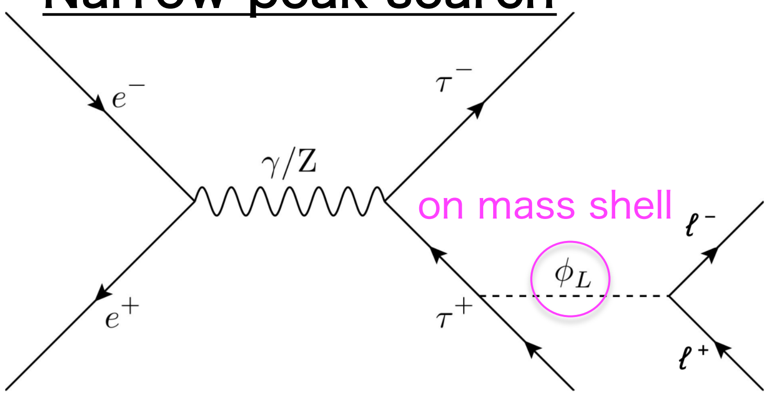
Link

Dark scalar via $ee \to \tau\tau\phi_L$

Dark leptophilic scalar couples only with leptons

- Possible to explain muon g-2 anomaly, lepton flavor universality

Narrow peak search

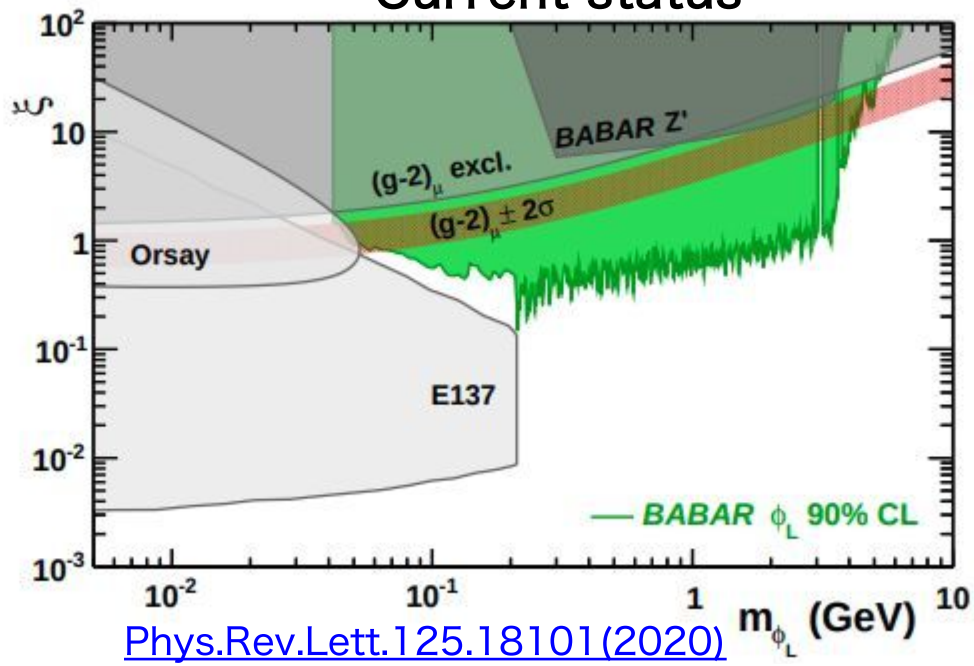


$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\phi_L \ell,$$

m_{ϕ_L}: mass of dark leptophilic scalar

ξ: coupling strength b.t.w ϕ_L and $\ell^\pm$

Current status



Phys.Rev.Lett.125.18101(2020)

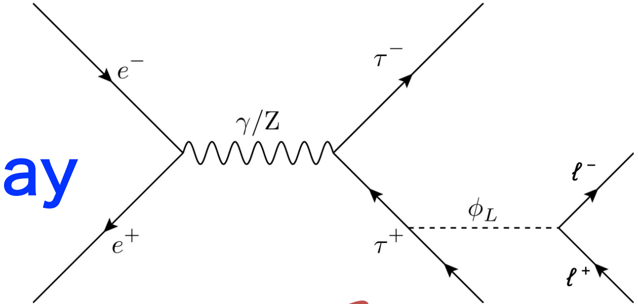
$e^+e^- \to \tau^+\tau^-\phi_L$: A narrow peak in $m_{\ell\ell}$ is search for $40\ \mathrm{MeV} < m_{\phi_L} < 6.5\ \mathrm{GeV}$

$$\phi_L \to e^+e^- \text{ for } m_{\phi_L} < 2m_\mu,\ \phi_L \to \mu^+\mu^- \text{ for } m_{\phi_L} > 2m_\mu$$

The result using 626 fb^{-1} data is shown

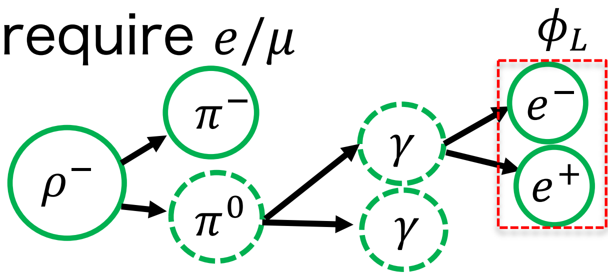
Analysis strategy

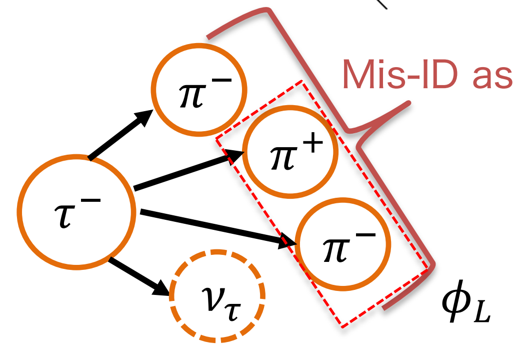
$e^+e^- \to \tau^+\tau^-\phi_L$: Require 1-prong τ decay



- $N_{\rm trk} = 4$ events with net charge zero
  - At least two tracks: require e/μ

Backgrounds



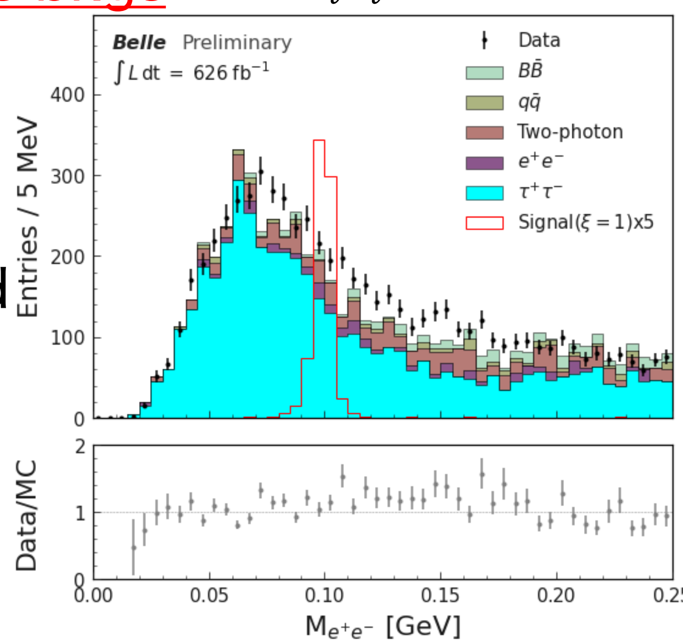


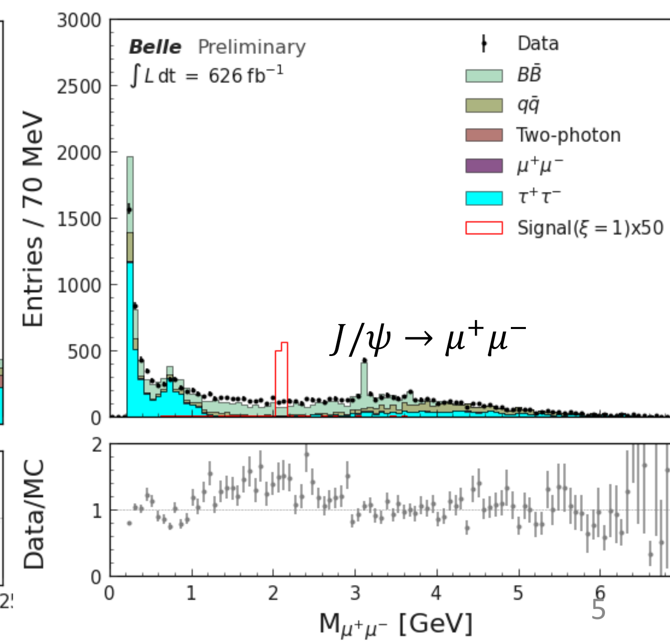
$e^+e^- \to \tau^+\tau^-$ or $q\bar{q}$ where

- $\tau^\pm \to \rho^\pm\nu$ for $\phi_L \to e^+e^-$, $\tau^\pm \to 3\pi^\pm\nu$ for $\phi_L \to \mu^+\mu^-$

→ BDT to suppress bkgs

$M_{\ell^+\ell^-}$ distribution after BDT selection





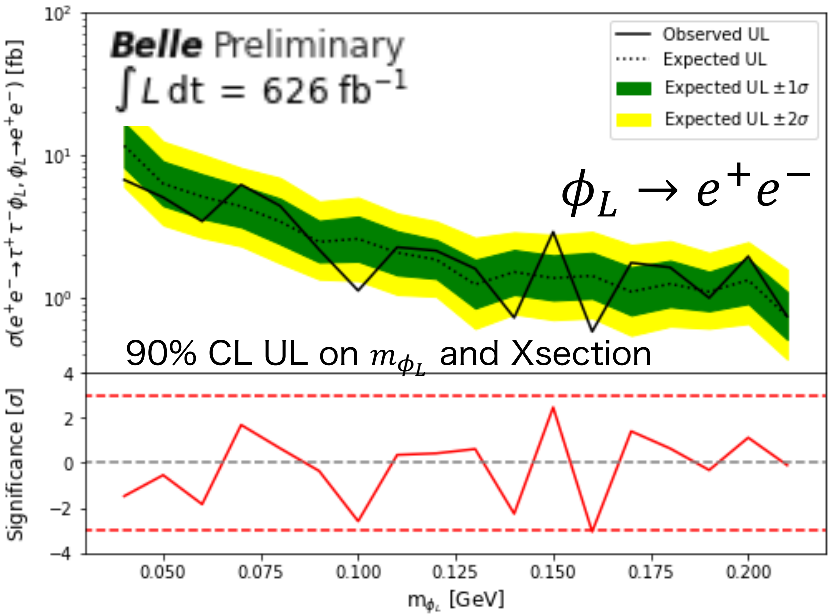
UL of the signal

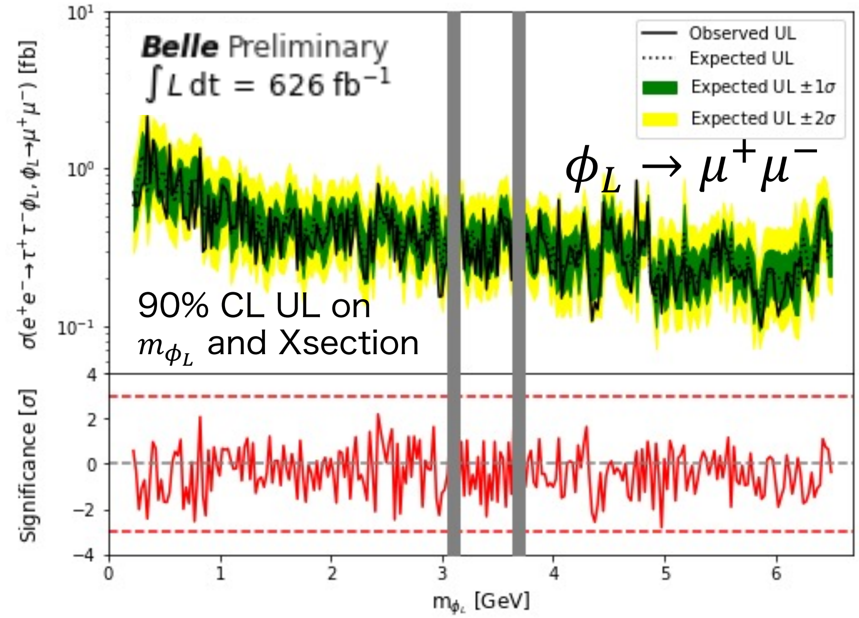
- Profile likelihood

→ Evaluate for each mass point

Result

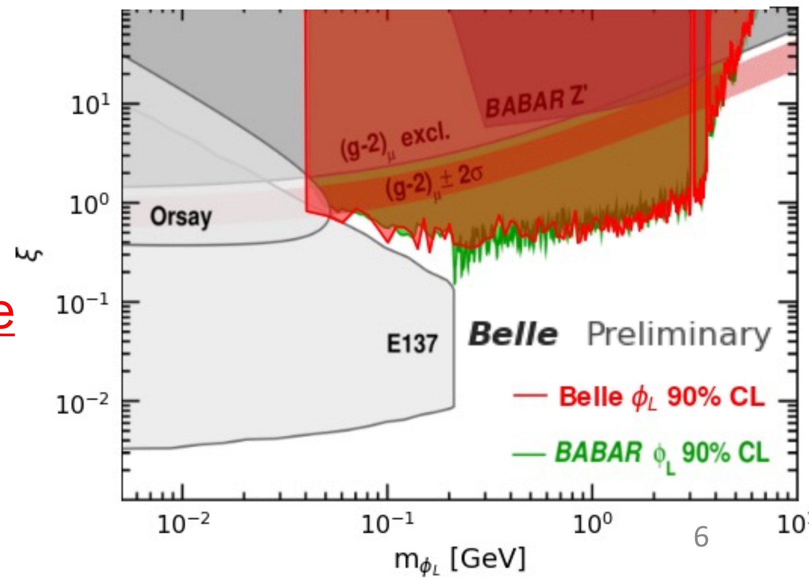
No significant excess in all mass regions: ~2σ in a few points





90% CL UL on m_{ϕ_L} and ξ

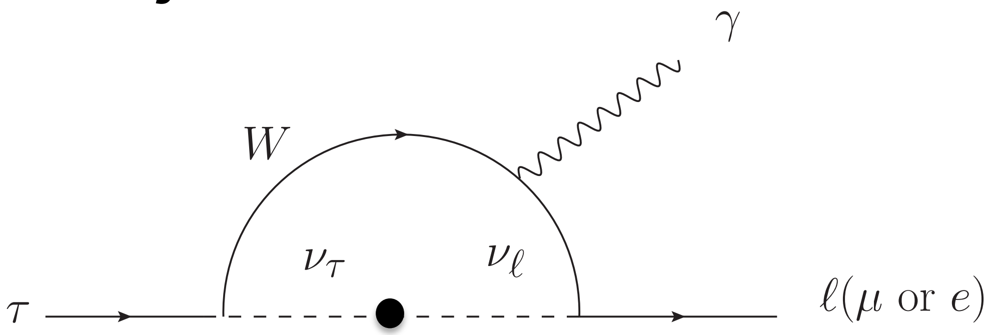
- Most stringent and comparable with BaBar's result Phys.Rev.Lett.125.18101(2020)
- Exclude a wide range of parameter space of the model favored by muon g-2



Motivation: $\tau \to \ell\gamma$ ($\ell = e, \mu$)

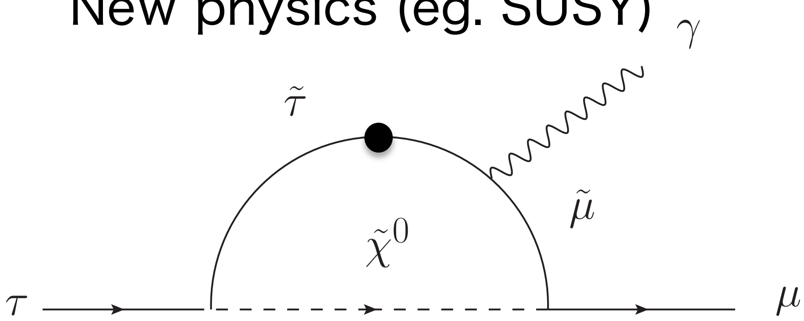
Charged Lepton Flavor Violation (CLFV)

- Small probability via neutrino oscillations: $B(\tau \to \mu\gamma) < O(10^{-54})$



- $\tau^\pm \to \ell^\pm\gamma$: Sizeable probability in several models

New physics (eg. SUSY)



Model	Reference
SM + ν Oscillations	EPJ C8 (1999) 513
SM + heavy Maj ν_R	PRD 66 (2002) 034008
Non universal Z'	PLB 547 (2002) 252
SUSY SO(10)	PRD 68 (2003) 033012
mSUGRA + seesaw	PRD 66 (2002) 115013
SUSY Higgs	PLB 566 (2003) 217

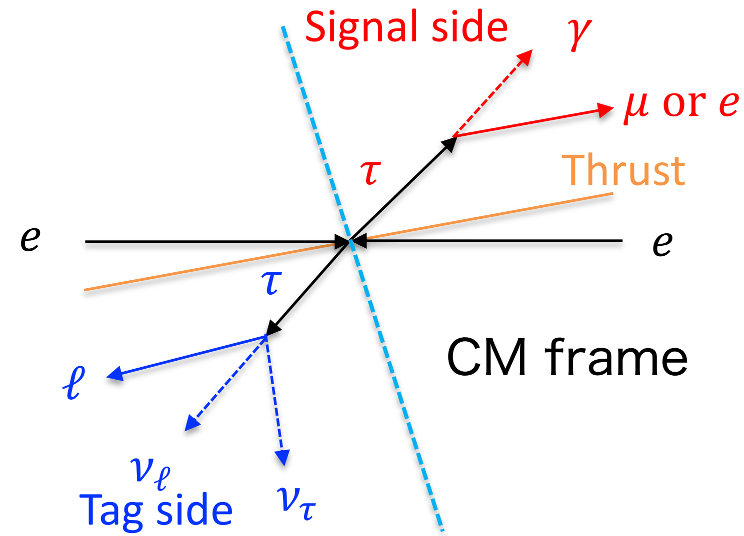
Observation of CLFV → clear signature of new physics

$\tau^\pm \to \ell^\pm\gamma$: Sensitive to several models!

Analysis approach

Signal-side: $N_\ell = 1$ and $N_\gamma = 1$

Tag-side: 1prong τ (Eg. $\ell\nu\nu, \pi\nu, \rho\nu$)



Signal region definition

- $$M_{bc} = \sqrt{\left(E_{beam}^{CM}\right)^2 - \left(p_{\ell\gamma}^{CM}\right)^2}$$ $E_{beam}^{CM} \sim \frac{\sqrt{s}}{2}$
- $$\Delta E/\sqrt{s} = \left(E_{\ell\gamma}^{CM} - E_{beam}^{CM}\right)/\sqrt{s}$$

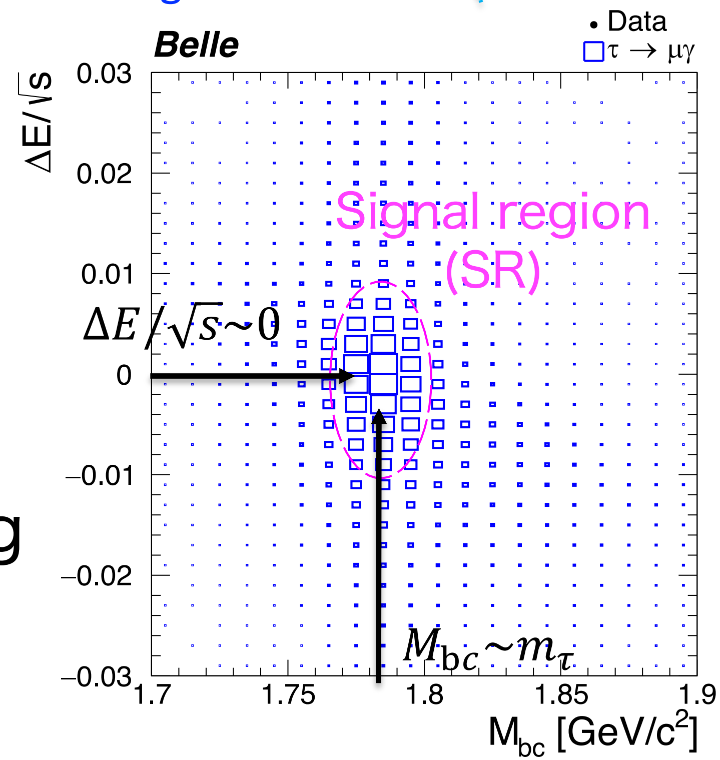
Background component

- $\tau^\pm \to \ell^\pm \nu\nu$ + ISR γ or beam bkg
- $e^+e^- \to \ell^+\ell^-$ + ISR γ or beam bkg

Signal extraction

- Perform UEML fit to the SR

Unbinned Extended Maximum Likelihood

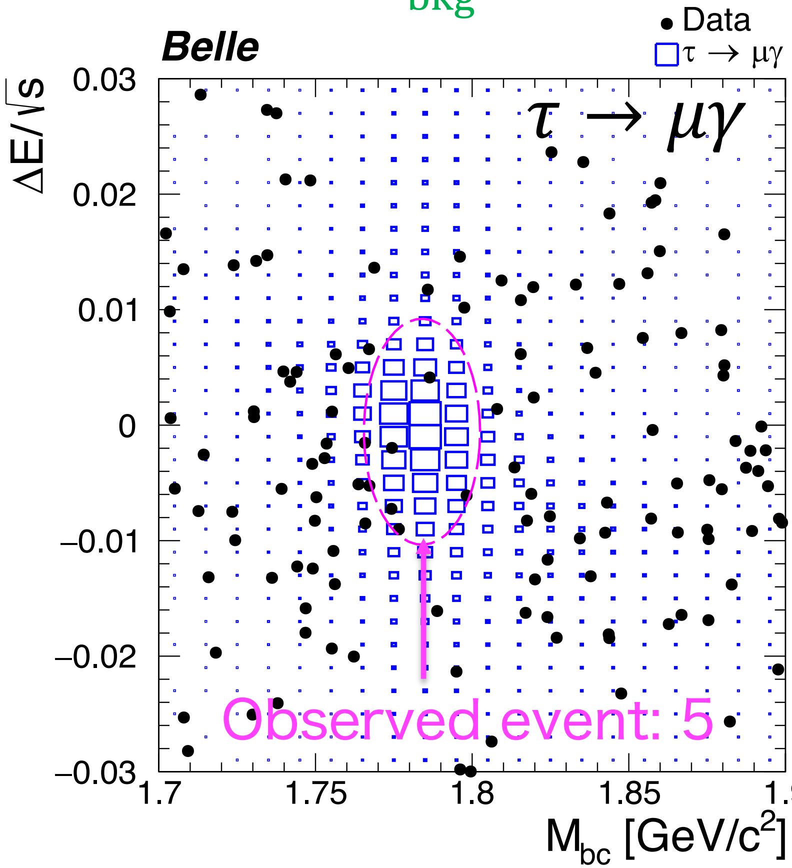


※ use M_{bc} instead of M_{inv} to suppress E_γ resolution

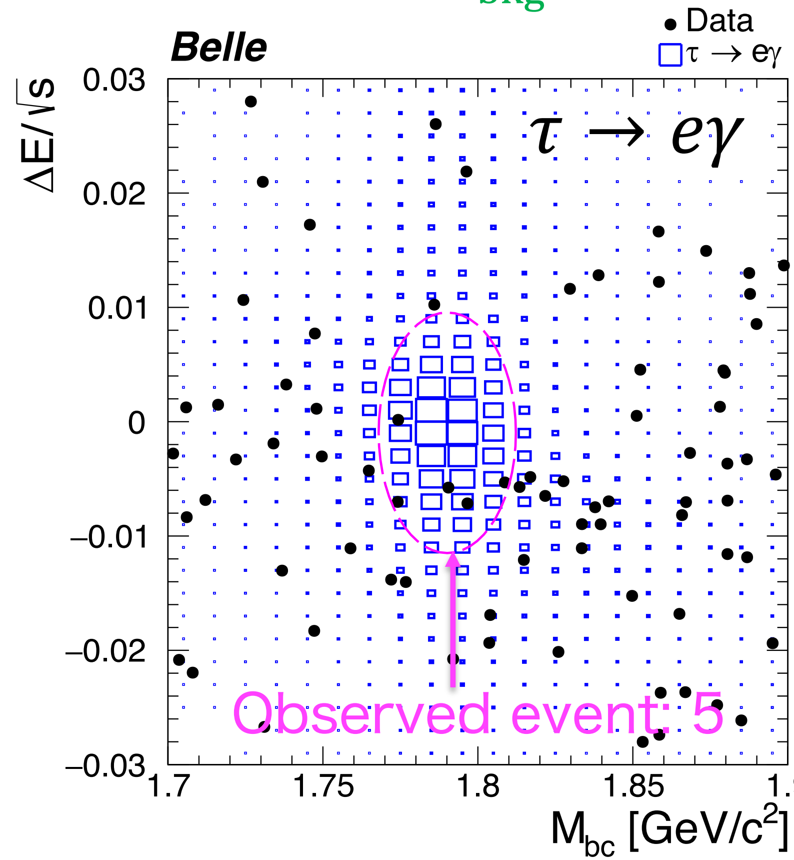
Result

Luminosity: 988 fb^{-1} : $9.1\times10^{8} N_{\tau\tau}$

Signal eff. = 3.7% $N_{\rm bkg}^{\rm exp} = 5.8 \pm 0.4$



Signal eff. = 2.9% $N_{\rm bkg}^{\rm exp} = 5.1 \pm 0.4$



Unbinned Extended ML fit result

$s = -0.3^{+1.8}_{-1.3}, b = 5.3^{+3.2}_{-2.3}$

$s = -0.5^{+4.4}_{-3.6}, b = 5.5^{+5.2}_{-4.1}$

No significant excess over SM background predictions

Upper limits at 90% CL

Upper limit on branching fraction at 90% CL

$$\mathcal{B}(\tau^{\pm} \to \mu^{\pm}\gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 4.2 \times 10^{-8},$$

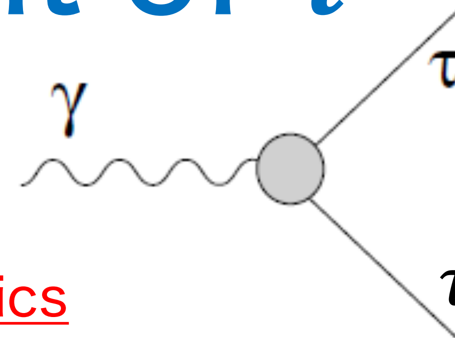
$$\mathcal{B}(\tau^{\pm} \to e^{\pm}\gamma) < \frac{\tilde{s}_{90}}{2\epsilon N_{\tau\tau}} = 5.6 \times 10^{-8},$$

$B\times10^{-8}$ at 90% CL	BaBar $N_{\tau\tau} = 477\times10^{6}$		Belle $N_{\tau\tau} = 480\times10^{6}$		Belle $N_{\tau\tau} = 912\times10^{6}$	
	Exp	Obs	Exp	Obs	Exp	Obs
$B(\tau^{\pm} \to \mu^{\pm}\gamma)$	8.2	4.4	8.0	4.5	4.9	4.2
$B(\tau^{\pm} \to e^{\pm}\gamma)$	9.8	3.3	12	12	6.5	5.6

- Expected limits: factor 1.5 – 1.7 improved compared past analysis
- Observed limits, $\tau^{\pm} \to \mu^{\pm}\gamma$: Most stringent limit to date

Electric dipole moment of τ

CP/T violation parameter in $\gamma\tau\tau$ vertex

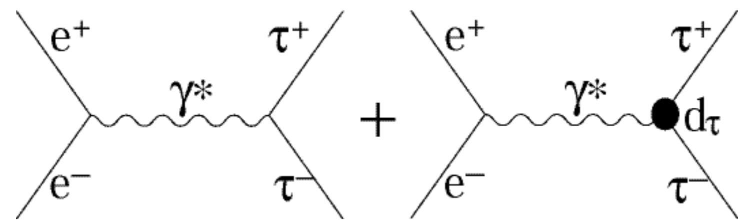


- SM prediction: τ EDM, $d_\tau \sim O(10^{-37})$ ecm

→ <u>A non-zero d_τ would be clear sign of new physics</u>

Squared spin density matrix χ_{prod}

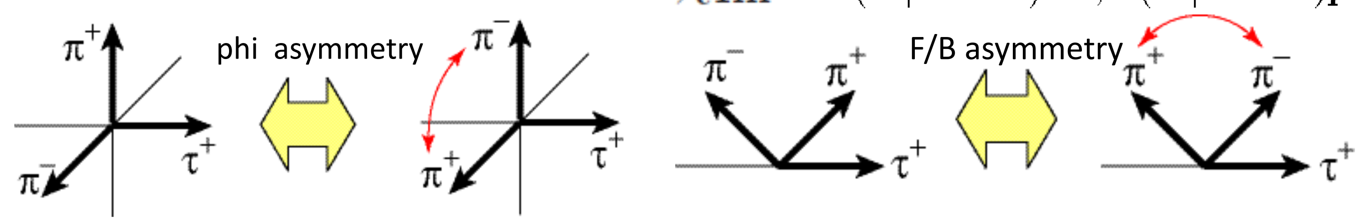
$$\chi_{\text{prod}} = \chi_{\text{SM}} + \text{Re}(d_\tau)\chi_{\text{Re}} + \text{Im}(d_\tau)\chi_{\text{Im}} + |d_\tau|^2 \chi_{d^2},$$

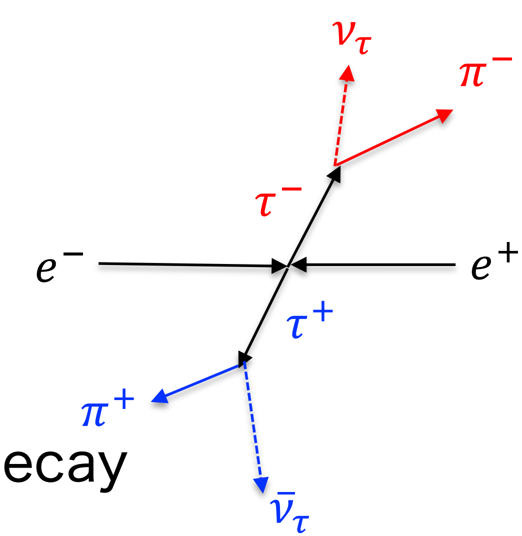


Interference term b.t.w the SM and the EDM

→ Proportional to CP spin-momentum correlation

$\chi_{\text{Re}} \sim (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{k} \;,\; (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{p}$ $\quad\chi_{\text{Im}} \sim (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{k} \;,\; (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{p}$





- Spin information is obtained by momentum of decay
- <u>Re(d_τ), Im(d_τ): phi, forward/backward asymmetry</u>

Event selection, observable

Select 8 final modes exclusively

- $\tau\tau \to (e\nu\bar{\nu})(\mu\nu\bar{\nu}), (e\nu\bar{\nu})(\pi\nu), (\mu\nu\bar{\nu})(\pi\nu), (e\nu\bar{\nu})(\rho\nu), (\mu\nu\bar{\nu})(\rho\nu), (\pi\nu)(\rho\nu), (\rho\nu)(\rho\bar{\nu}), (\pi\nu)(\pi\bar{\nu})$

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

→ Take the events with high purity

Use optimal observable to measure EDM

$$\mathcal{O}_{\rm Re} = \frac{\chi_{\rm Re}}{\chi_{\rm SM}}, \quad \mathcal{O}_{\rm Im} = \frac{\chi_{\rm Im}}{\chi_{\rm SM}}.$$

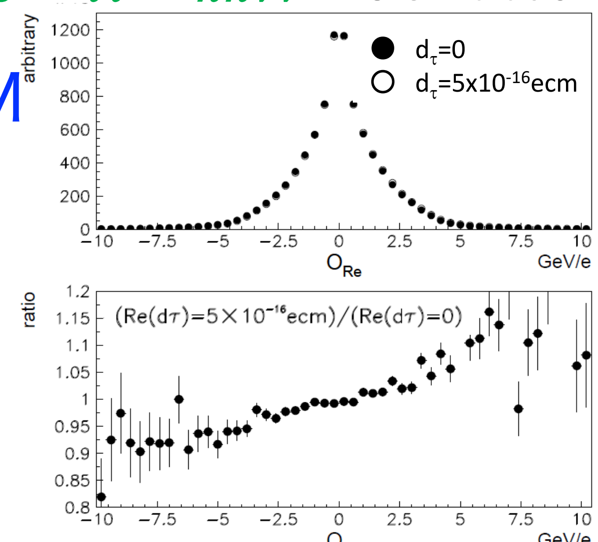
PRD 45(1992)2405

$$\langle \mathcal{O}_{\rm Re} \rangle \propto \int \mathcal{O}_{\rm Re}\chi_{\rm prod} d\phi = \int \chi_{\rm Re} d\phi + {\rm Re}(d_\tau) \int \frac{(\chi_{\rm Re})^2}{\chi_{\rm SM}} d\phi$$

Average value is proportional to EDM

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

$ee \to \tau\tau \to \pi\pi\nu\nu$ MC simulation

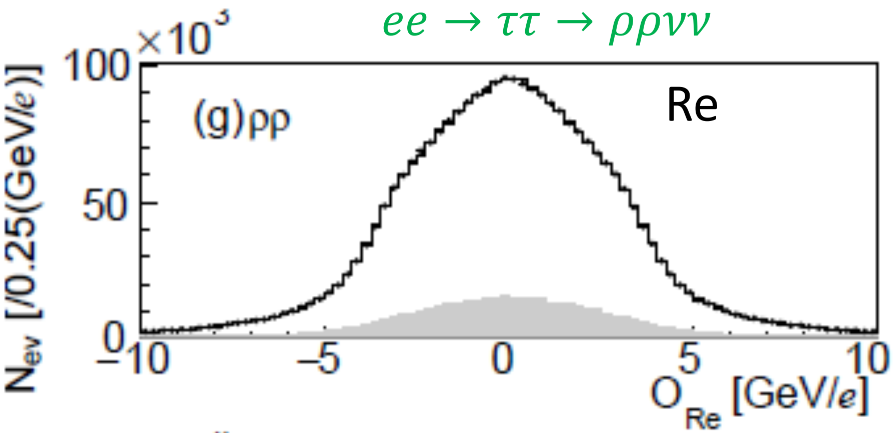


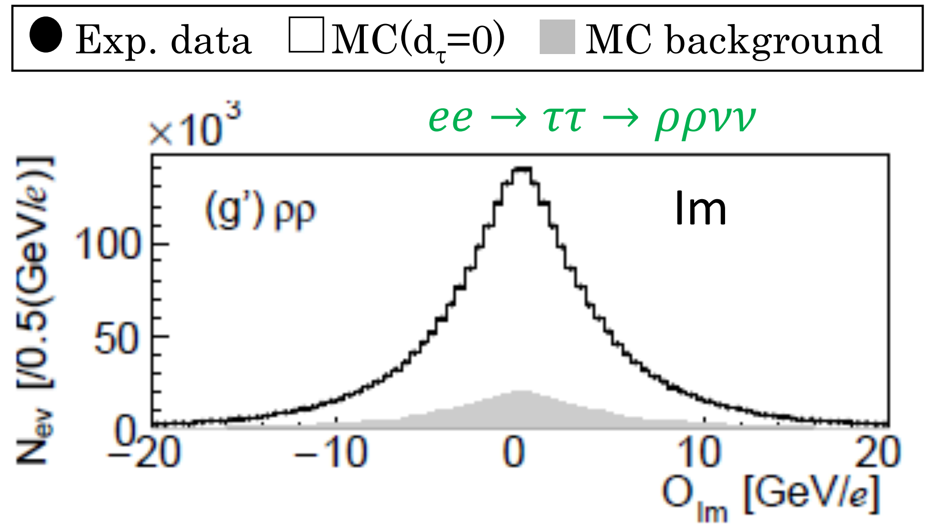
$Re(d_\tau) \neq 0$: clear difference in $O(R_e)$

Compute $O_{Re/Im}$ in data and MC

Distribution, EDM extraction

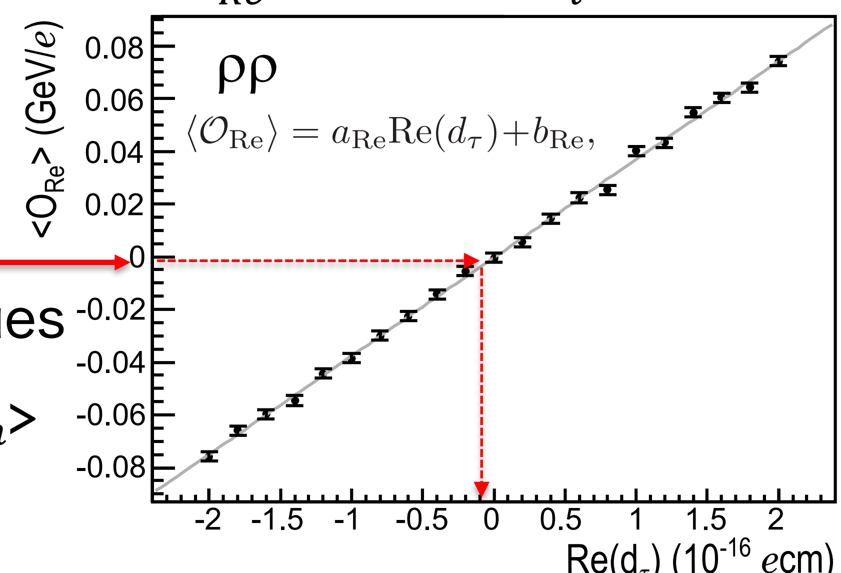
Good agreement in the distribution





→ $\langle O_{Re} \rangle = -0.00136 \pm 0.00166$

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



$d_\tau = (-0.4 \pm 0.5 \pm 0.9) \times 10^{-17}$ ecm

EDM extraction

- Generate MC for various EDM values

→ Extract EDM from obtained $\langle O_{Re/Im} \rangle$

Result

Systematic uncertainty

- Improved simulation, correction
- The larger MC statistics

→ The uncertainty much reduced from previous analysis

$\mathrm{Re}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Detector alignment	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.03
Momentum reconstruction	0.01	0.06	0.05	0.01	0.03	0.02	0.01	0.15
Charge asymmetry	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00
Mismatch of distribution	0.32	0.48	0.38	0.09	0.22	0.09	0.09	0.36
Background variation	0.16	0.03	0.17	0.04	0.02	0.02	0.02	0.35
Radiative effects	0.07	0.05	0.06	0.02	0.02	0.00	0.00	0.01
Total	0.36	0.48	0.43	0.10	0.22	0.10	0.09	0.52

$\mathrm{Im}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Detector alignment	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Momentum reconstruction	0.02	0.05	0.04	0.00	0.01	0.01	0.01	0.01
Charge asymmetry	0.02	0.20	0.24	0.01	0.01	0.11	0.00	0.00
Mismatch of distribution	0.10	0.09	0.06	0.05	0.08	0.04	0.04	0.12
Background variation	0.14	0.00	0.07	0.03	0.01	0.01	0.01	0.01
Radiative effects	0.01	0.01	0.01	0.01	0.01	0.00	0.00	0.00
Total	0.18	0.22	0.26	0.06	0.08	0.12	0.04	0.12

Result of each decay mode

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

Weighted average of EDM

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

Belle 833 fb^{-1} data

Previous results Belle 29.5 fb^{-1} data

$$\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}\ e\,\mathrm{cm},$$
$$\mathrm{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}\ e\,\mathrm{cm}$$

PLB 551(2003)16

- Consistent with zero EDM
- ~ 2.7 times smaller error than previous results

Summary

Search for dark leptophilic scalar, $e^+e^- \to \tau^+\tau^-\phi_L$ NEW

- New search at Belle. Analyzed 626 fb^{-1} data
- Better understanding of background events
- **Most stringent limits for m_{ϕ_L}, ξ.** **Exclude g-2 anomaly favored spaces**

Tau LFV, $\tau^\pm \to \ell^\pm\gamma$ $(\ell = e, \mu)$

- Use 988 fb^{-1} data and improve analysis technique
- **Most stringent limits for $\tau^\pm \to \mu^\pm\gamma$ at 90% CL**

Tau EDM

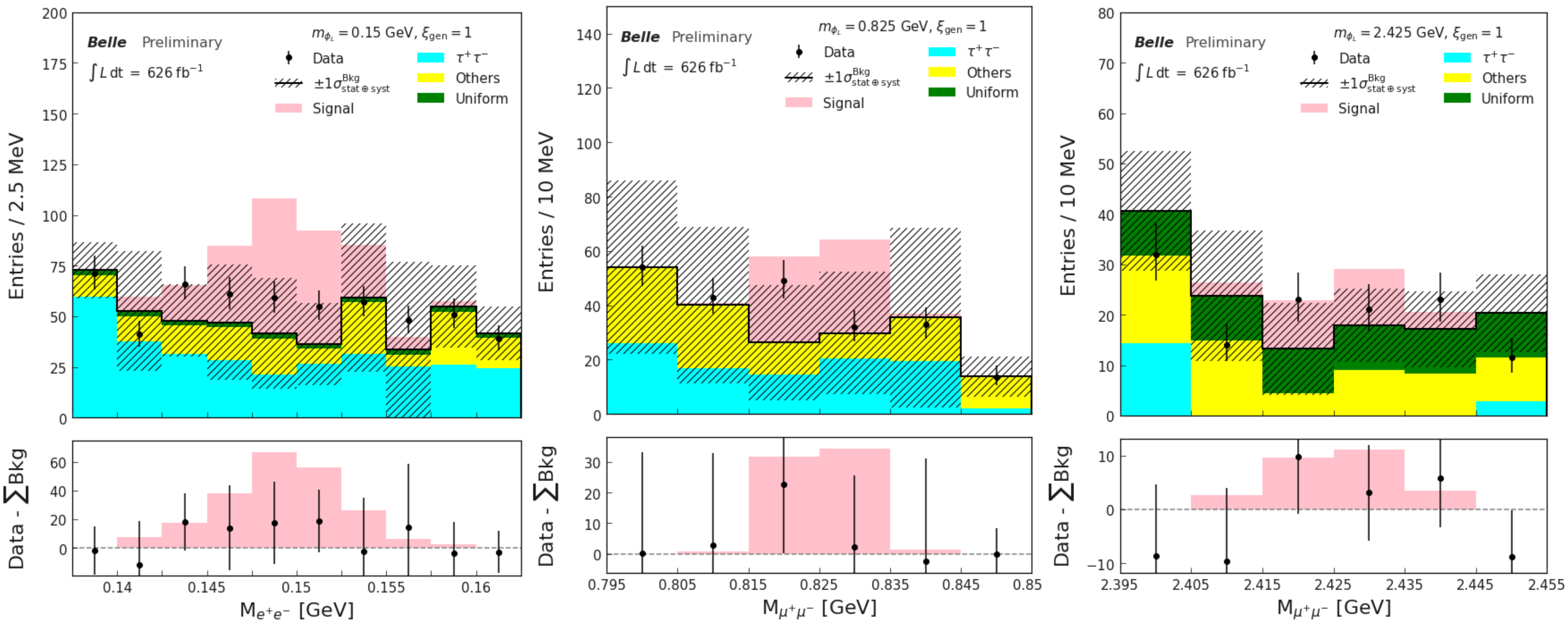
- Analyzed 833 fb^{-1} data and use optimal observable method
- **30 times larger data and improved understanding the data**

→ Reached the UL of the tau EDM in 10^{-18} ecm level

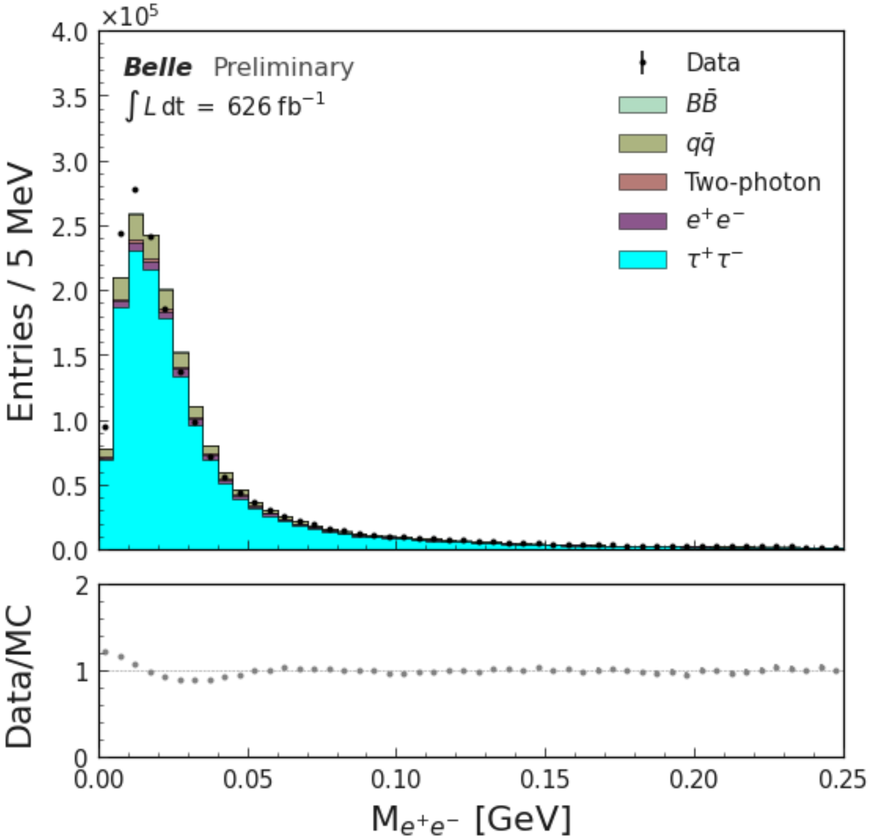
Backup

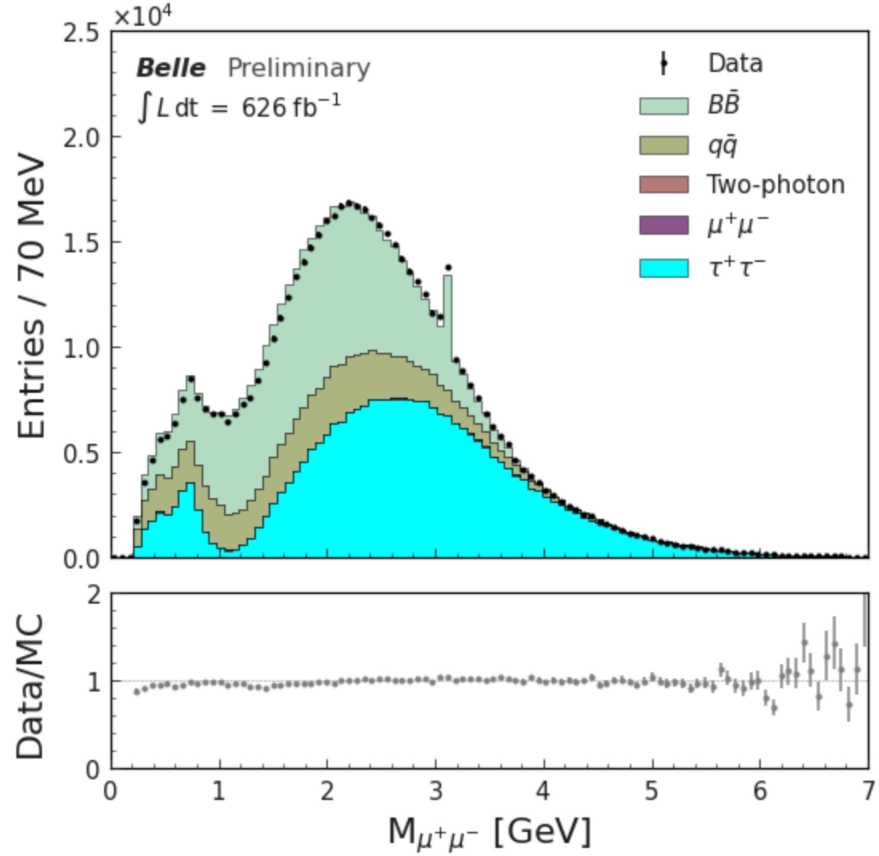
Di-lepton distribution

$m_{\ell^+\ell^-}$ distribution **Belle** Preliminary



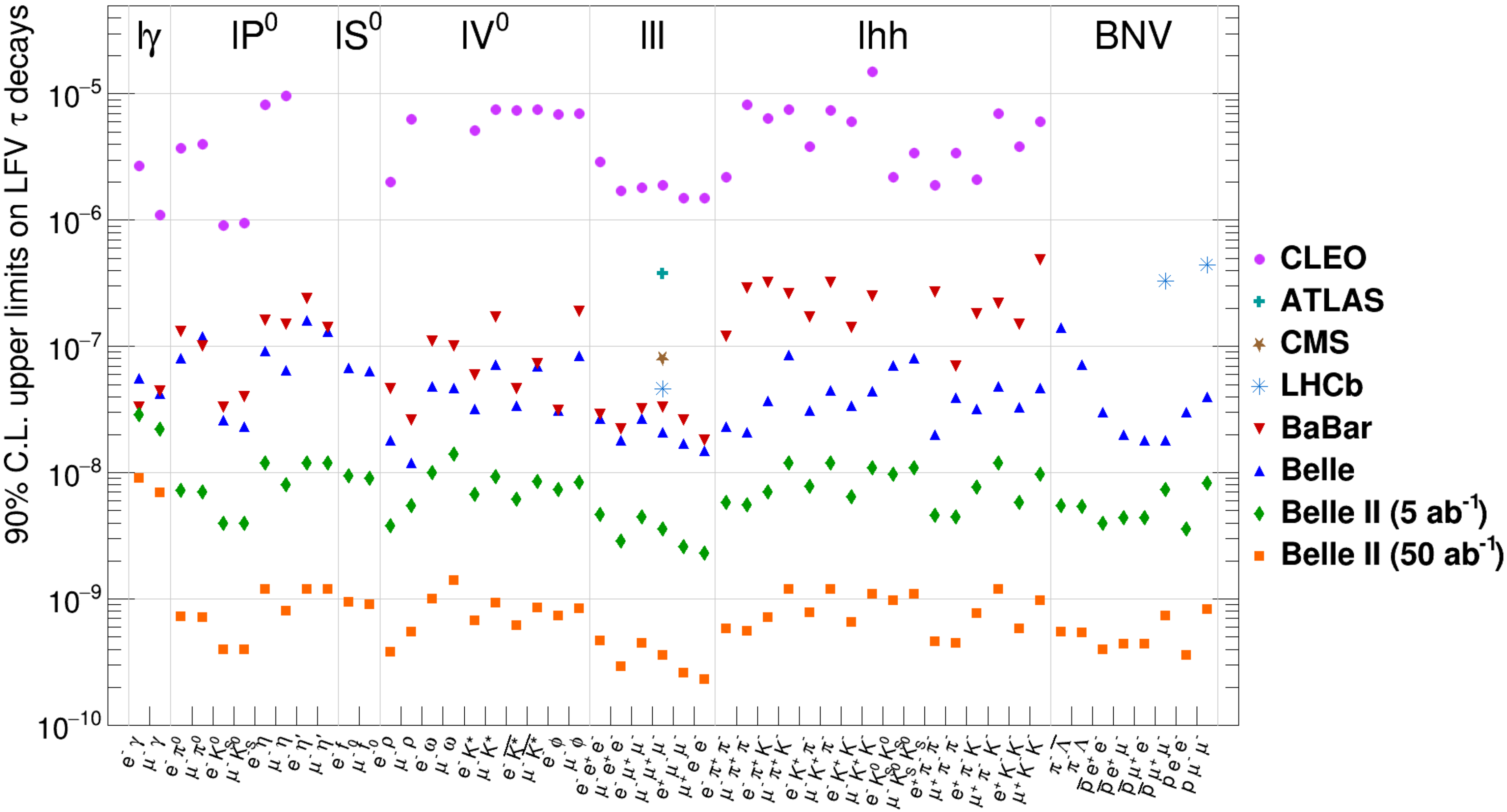
Control region





Summary of LFV in tau decay

arXiv.2203.14919



Past searches for $\tau \rightarrow \ell\gamma$

90%CL	Belle	BaBar
Luminosity	535 fb^{-1}	516 fb^{-1}
$N_{\tau\tau}$	4.8×10^{8}	4.8×10^{8}
$B(\tau \rightarrow \mu\gamma)$	4.5×10^{-8}	4.4×10^{-8}
$B(\tau \rightarrow e\gamma)$	12×10^{-8}	3.3×10^{-8}
Reference	PLB (2008)666	PRL (2010)021802

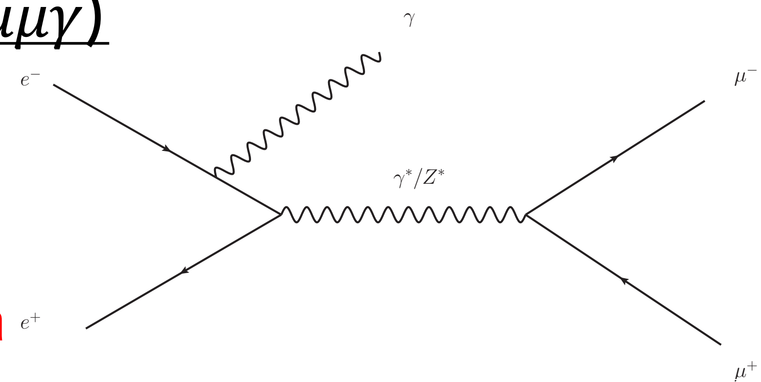
We updated the results of a search for $\tau \rightarrow \ell\gamma$

- Increased $N_{\tau\tau}$: 4.8×10^{8} →9.1×10^{8} (535 fb^{-1}→988 fb^{-1})
- Introduced new observables and improved selection
- Calibrated photon energy resolution using $ee \rightarrow \mu\mu\gamma$

Photon energy resolution calibration

Revised the photon-energy resolution calibration

- <u>Use radiative muon event ($ee \to \mu\mu\gamma$)</u>
  - Cover a broad energy range

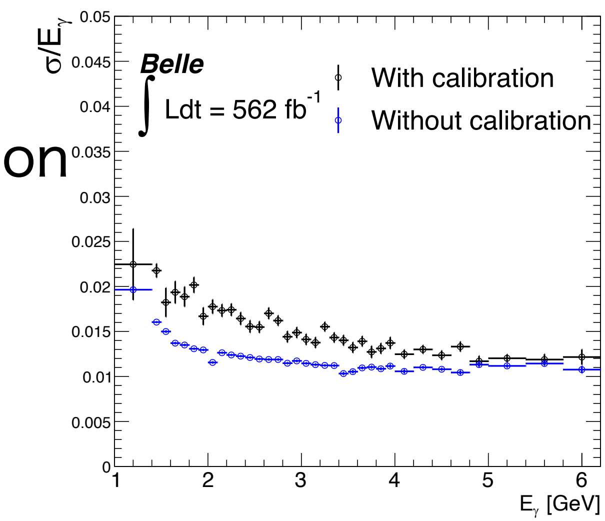


Goal

- Measure the energy resolution in data
- Calibrate it in simulation to agree with that in data

Evaluation

- Subtract E_{recoil} from E_γ for data and simulation
  - $E_{\text{recoil}} = E_{\text{beam}} - E_{\mu^-} - E_{\mu^+}$
  - E_γ: measured in the calorimeter



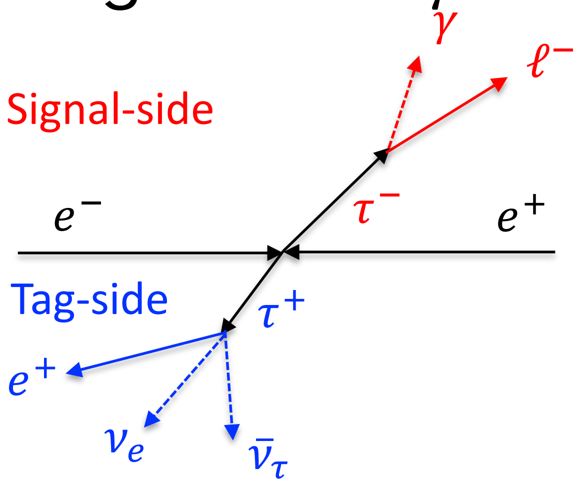
<u>Energy range: 1 GeV – 6 GeV</u> NEW!

- Calibrated resolution agrees with that in data

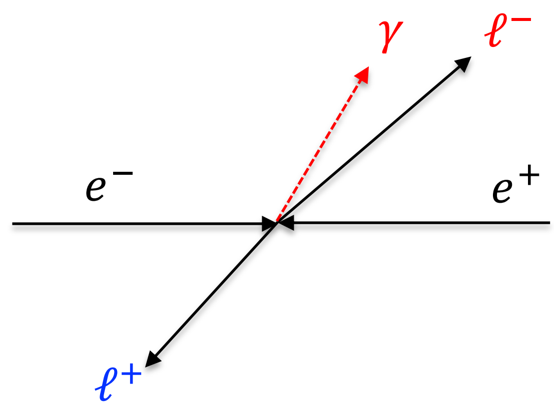
Event Selection 1

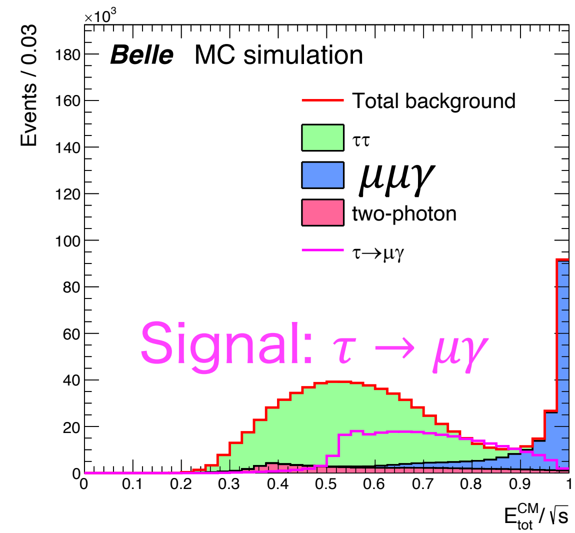
Several observables are used: eg. Total energy, missing angle

Signal: $\tau \to \ell\gamma$



Background: $ee \to \ell\ell\gamma$





Eg. Total energy in CM frame ($E^{\mathrm{CM}}_{\mathrm{tot}}/\sqrt{s}$)

- $\tau \to \ell\gamma$: $N_\nu > 0$ in tag-side, $ee \to \ell\ell\gamma$: $N_\nu = 0$

→ Signal distribution depends on tag-side decays ($\tau \to \ell\nu\nu, \pi\nu, \rho\nu$)

NEW!

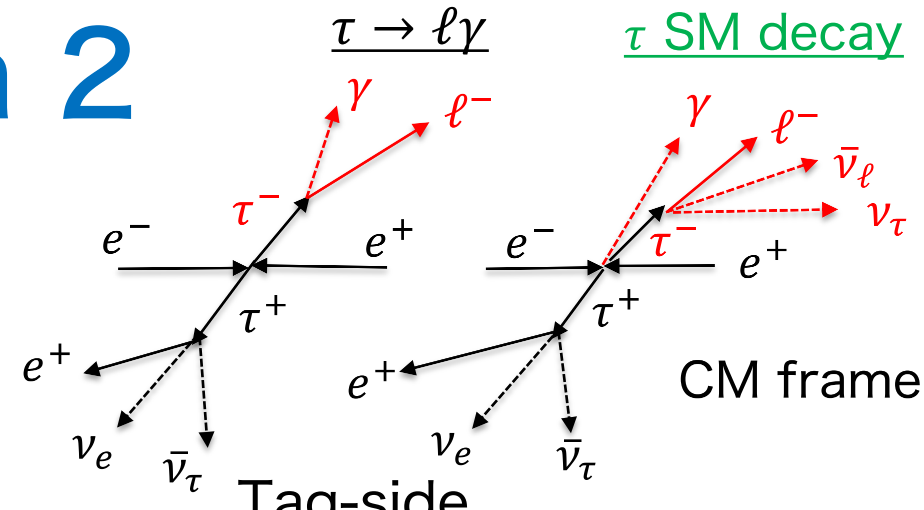
Optimized selection per channel: ℓ, π, ρ channel

※ All selection criteria are optimized to maximize search sensitivity

Event Selection 2

New observable

$$\xi^{CM}_{\tau(tag),track(tag)} = \frac{(p^{CM}_{\tau(tag)} \cdot p^{CM}_{track(tag)})}{|p^{CM}_{\tau(tag)}||p^{CM}_{track(tag)}|}$$



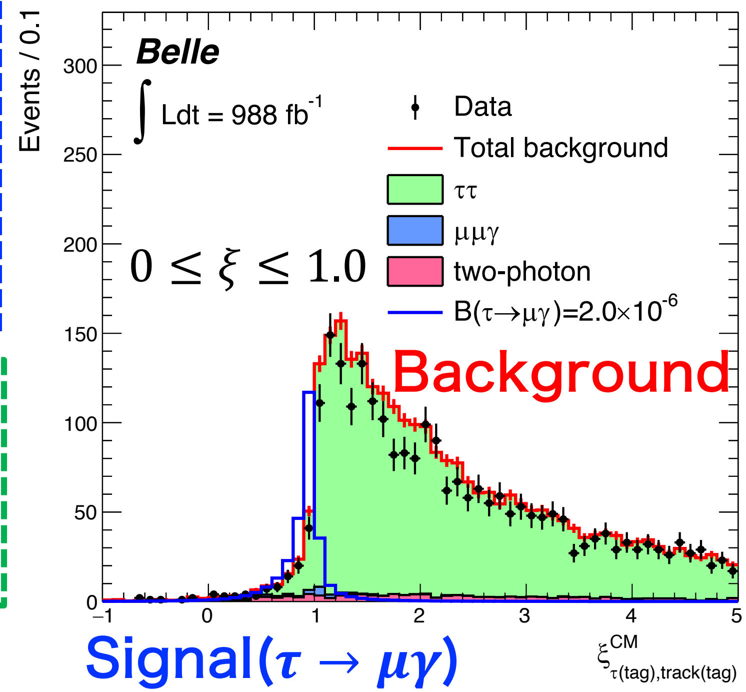
Ideal signal events,

$$p^{CM}_{\tau(tag)} = -p^{CM}_{\tau(sig)} = -(p^{CM}_{\ell} + p^{CM}_{\gamma})$$

→ $\xi^{CM}_{\tau(tag),track(tag)} = \cos\theta_{\tau(tag),track(tag)}$

τ SM decay: $p^{CM}_{\tau(sig)} \neq p^{CM}_{\ell} + p^{CM}_{\gamma}$

→ $\xi^{CM}_{\tau(tag),track(tag)} \neq \cos\theta_{\tau(tag),track(tag)}$



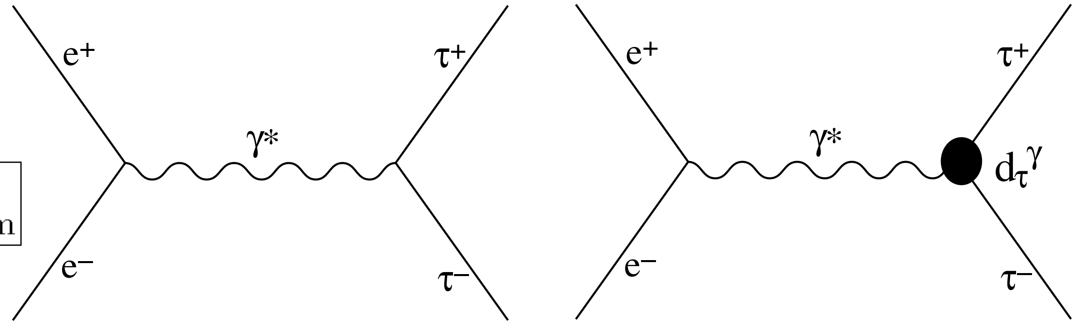
NEW!

Good separation between signal and background

Tau EDM: spin density matrix

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

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



From the effective Lagrangian, the spin density matrix with the EDM in the process $e^+(\boldsymbol{p})e^-(-\boldsymbol{p}) \to \tau^+(\boldsymbol{k}, \boldsymbol{S}_+)\tau^-(-\boldsymbol{k}, \boldsymbol{S}_-)$, is given as [2]

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

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

$$\chi{\rm Re} \sim \mathcal{M}^2_{Re} = 4\frac{e^3}{k_0}|\boldsymbol{k}|[\; -(m_\tau + (k_0 - m_\tau)(\hat{\boldsymbol{k}}\hat{\boldsymbol{p}})^2)(\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{k}} + k_0(\hat{\boldsymbol{k}}\hat{\boldsymbol{p}})(\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{p}} \;], \tag{4}$$

CP-odd, T-odd

$$\chi{\rm Im} \sim \mathcal{M}^2_{Im} = 4\frac{e^3}{k_0}|\boldsymbol{k}|[\; -(m_\tau + (k_0 - m_\tau)(\hat{\boldsymbol{k}}\hat{\boldsymbol{p}})^2)(\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{k}} + k_0(\hat{\boldsymbol{k}}\hat{\boldsymbol{p}})(\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{p}} \;], \tag{5}$$

CP-odd, T-even

$$\mathcal{M}^2_{d^2} = 4e^2|\boldsymbol{k}|^2 \cdot \;(1 - (\hat{\boldsymbol{k}}\hat{\boldsymbol{p}})^2)(1 - \boldsymbol{S}_+\boldsymbol{S}_-), \tag{6}$$

Tau EDM: calculation from data

- Need tau flight direction to obtain χ_{Re}, χ_{Im} JHEP 2204, 110

Both tau leptons decay hadronically : $\tau\tau \to (\pi\nu)(\pi\nu)$

- CM frame: $p_\nu^2 = (p_\tau - p_\pi)^2 \to 0 = m_\tau^2 + m_\pi^2 + 2E_\tau E_\pi - 2|\vec{p}_\tau||\vec{p}_\pi| cos\theta_\pi$

→ $cos\theta_{\pi^\pm} = \frac{2E_\tau E_{\pi^\pm} - m_{\pi^\pm}^2 - m_\tau^2}{2|\vec{p}_\tau||\vec{p}_{\pi^\pm}|}$

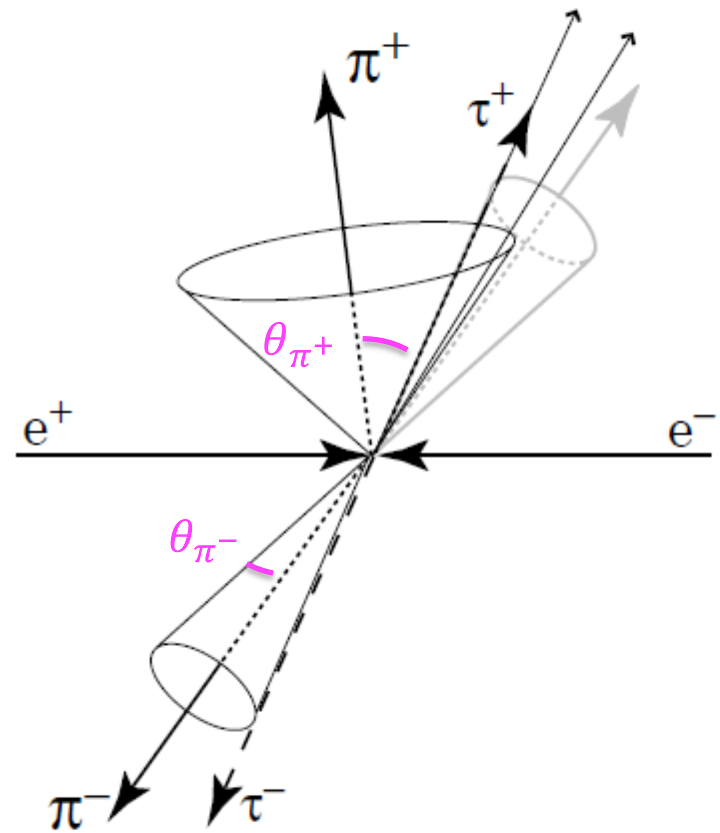
- $ee \to \tau\tau$: back-to-back

→ Two-fold ambiguity

Tau leptons decay leptonically

- $cos\theta_{\pi^\pm} = \frac{2E_\tau E_{\pi^\pm} - m_{\pi^\pm}^2 - m_\tau^2 + m_{\nu\nu}^2}{2|\vec{p}_\tau||\vec{p}_{\pi^\pm}|}$

→ Additional ambiguity ($m_{\nu\nu}^2$)



Take an average over the possible tau directions

Tau EDM: spin density matrix

We can reconstruct the τ's spin vectors, S, using the flight direction of the τ and the observed daughter particles

- Spin vector shows the most probable direction of the spin in the τ rest frame

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For $\tau \to \ell \nu_\ell \nu_\tau$,

$$\boldsymbol{S}_\pm = A\left(\pm m_\tau \boldsymbol{p}_{\ell^\pm} - \frac{c_\pm + E_{\ell^\pm} m_\tau}{k_0 + m_\tau}\boldsymbol{k}\right), \qquad (20)$$

$$A = \frac{4c_\pm - m_\tau^2 - 3m_\ell^2}{3m_\tau^2 c_\pm - 4c_\pm^2 - 2m_\ell^2 m_\tau^2 + 3c_\pm m_\ell^2},$$

$$c_\pm = k_0 E_{\ell^\pm} \mp \boldsymbol{k}\cdot\boldsymbol{p}_{\ell^\pm},$$

where k_0 is the energy of the $\tau^\pm$, m_τ is the τ mass, $\boldsymbol{k}$ is the three-momentum of the τ^+, $\boldsymbol{p}_{\ell^\pm}$, $E_{\ell^\pm}$ and m_ℓ are the monentum, energy and mass of $\ell^\pm$, respectively.

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

$$\boldsymbol{S}_\pm = \mp A\left(\mp H_0^\pm \boldsymbol{k} + m_\tau \boldsymbol{H}^\pm + \frac{\boldsymbol{k}(\boldsymbol{k}\cdot\boldsymbol{H}^\pm)}{(k_0 + m_\tau)}\right), \qquad (21)$$

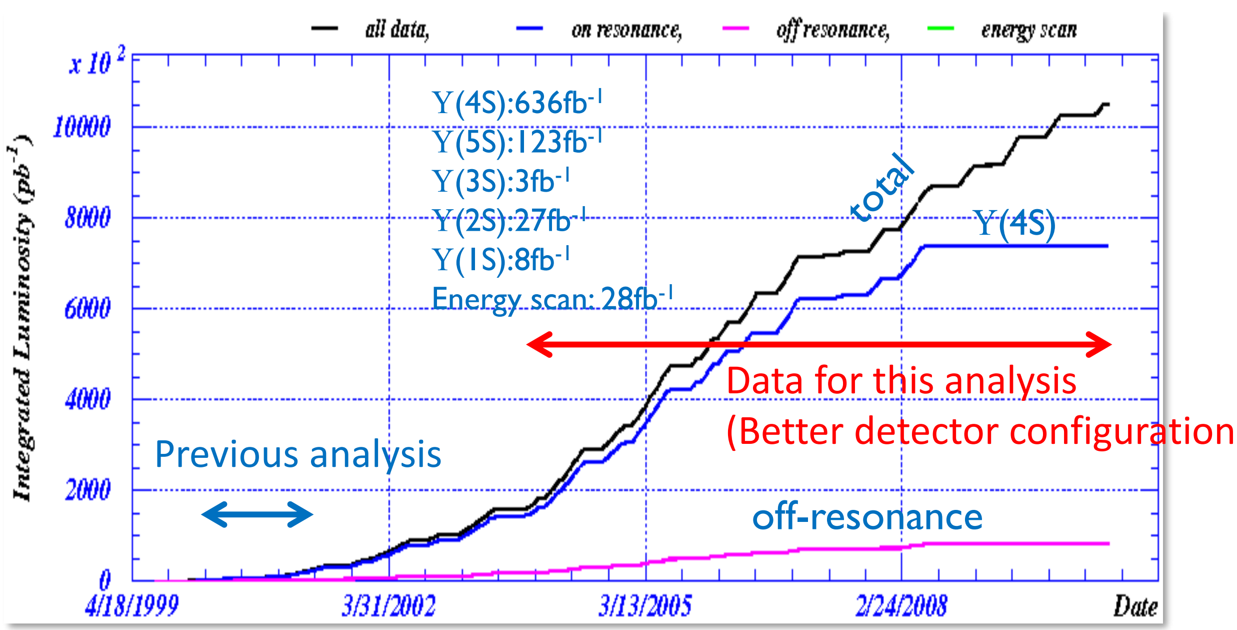
$$A = \frac{1}{(k_\pm H^\pm) - m_\tau^2 (p_{\pi^\pm} - p_{\pi^0})^2},$$

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

where $k_\pm = (k_0, \pm\boldsymbol{k})$, $H^\pm = (H_0^\pm, \boldsymbol{H}^\pm)$, and $k_\pm H^\pm$ is the four-vector product. Here, $p_{\pi^\pm}$ and p_{π^0} are the four-momenta of the final state $\pi^\pm$ and π^0.

Tau EDM: experimental data

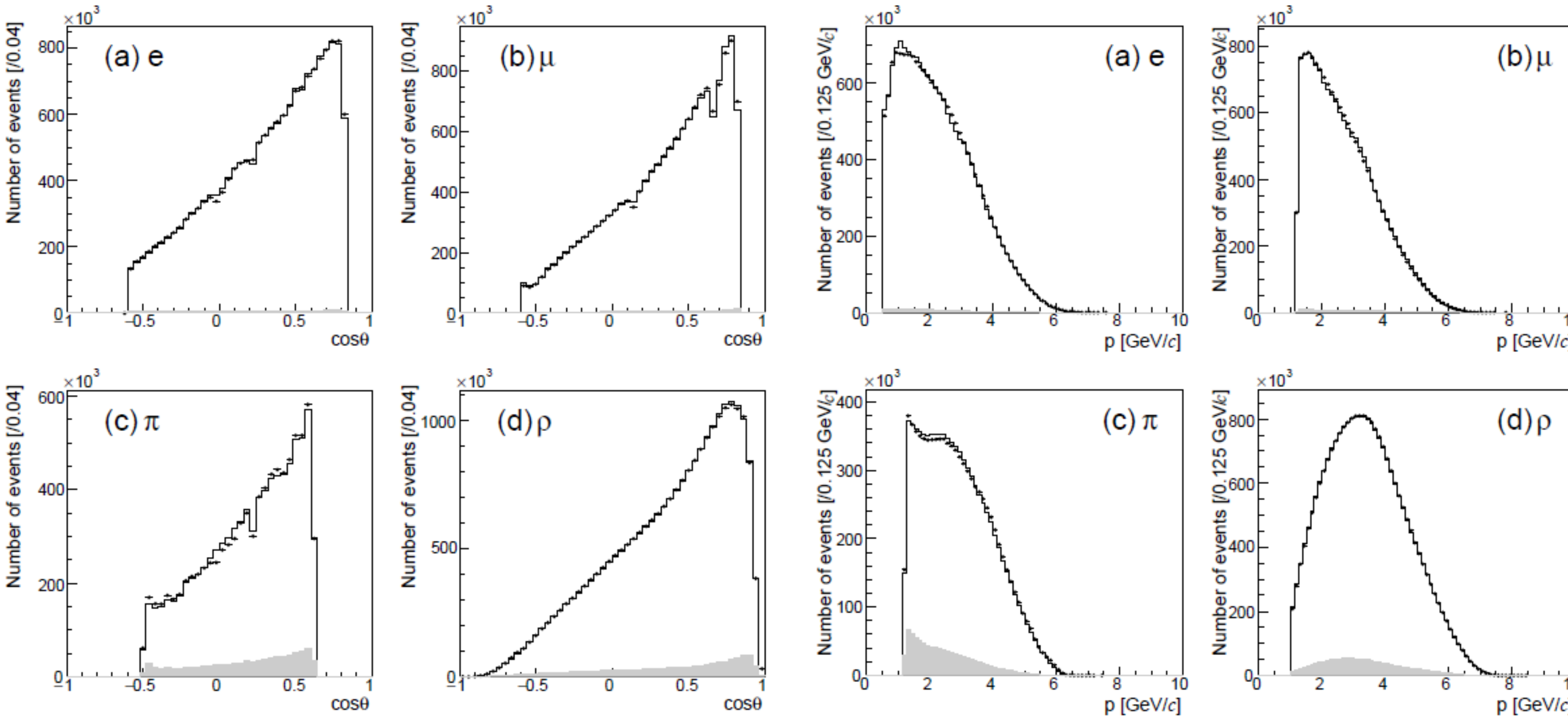
- 833 fb^{-1} of Belle data
- 28 times larger than previous analysis (~5 times less stat error)
- Improved detector understanding compared to previous analysis
  - Better correction parameters for tracking, particle IDs
  - Improvement on the MC simulation
- More beam background contribution to photons (beam bkg)



Tau EDM: selected data

$cos\theta$ and momentum

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



- Good agreement between data and MC simulation
- There are small mismatches in the distribution, which will be taken into account for the systematic error

Tau EDM: Observable

Use optimal observable to measure EDM

$$\mathcal{O}_{\rm Re} = \frac{\chi_{\rm Re}}{\chi_{\rm SM}}, \quad \mathcal{O}_{\rm Im} = \frac{\chi_{\rm Im}}{\chi_{\rm SM}}.$$

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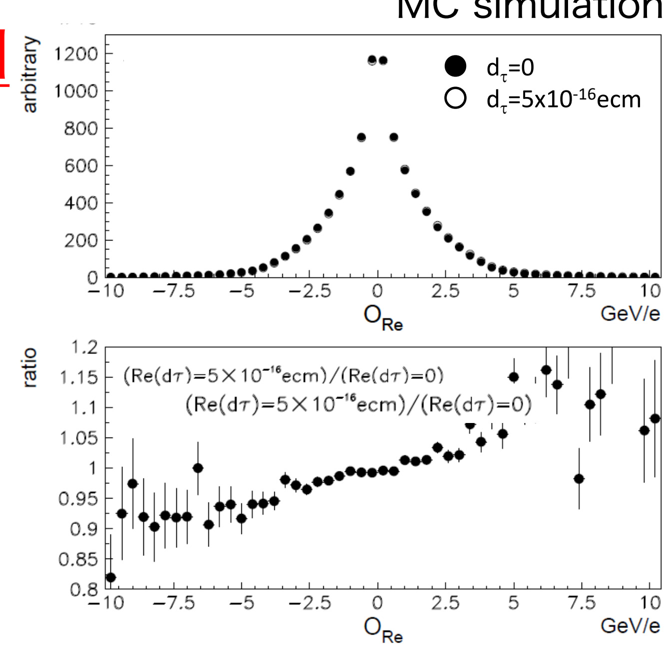
Calculate event-by-event

- Using tau flight direction and spin direction from decay products

$ee \to \tau\tau \to \pi\pi\nu\nu$

MC simulation

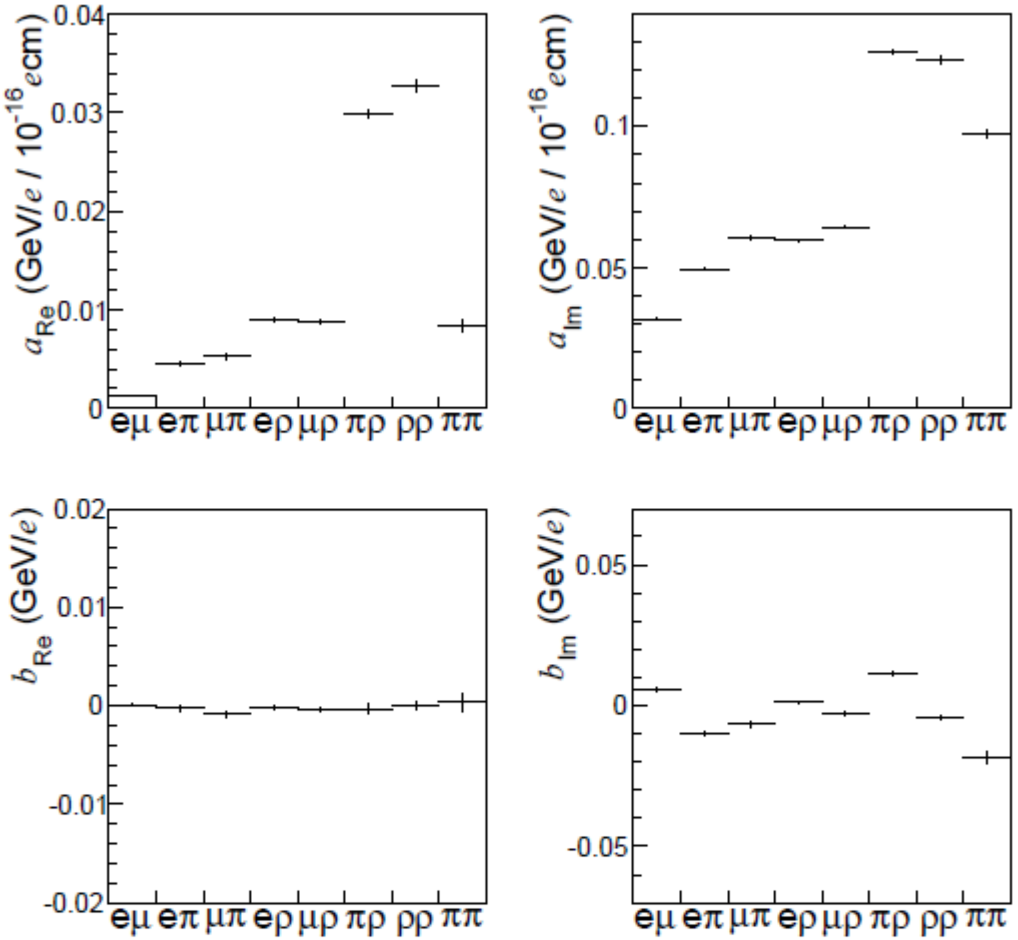


Average value is proportional to EDM

$$\langle \mathcal{O}_{\rm Re} \rangle \propto \int \mathcal{O}_{\rm Re}\chi_{\rm prod} d\phi = \int \chi_{\rm Re} d\phi + {\rm Re}(d_\tau) \int \frac{(\chi_{\rm Re})^2}{\chi_{\rm SM}} d\phi$$

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

Tau EDM: conversion parameters



Coefficient a (~ sensitivity)

Offset b

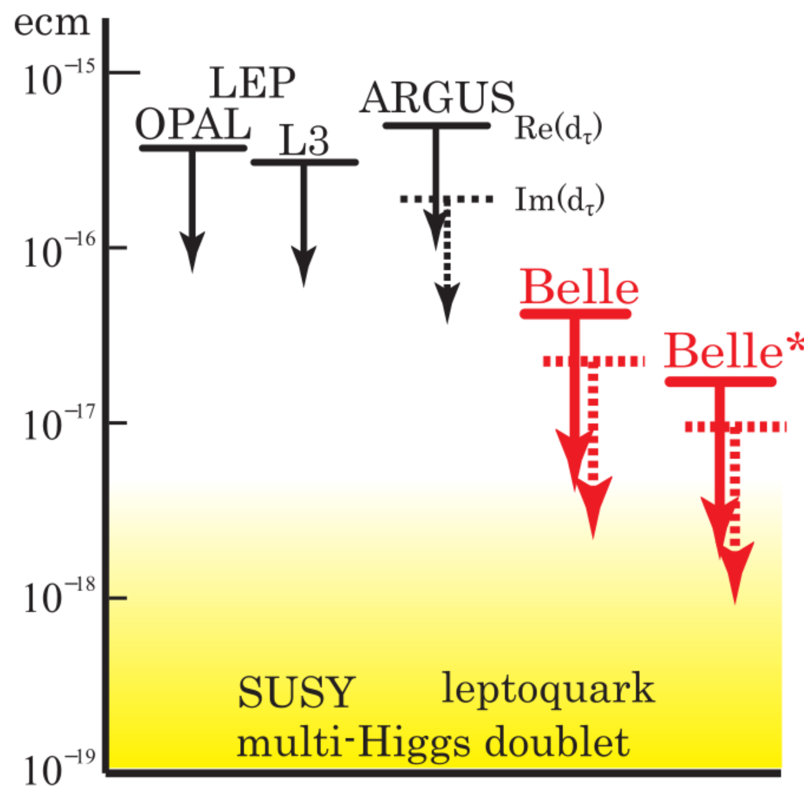
- The $\rho\rho$ and $\pi\rho$ modes have higher sensitivity, because of less neutrinos
- Offset b_{Im} due to the forward/backward asymmetric acceptance

Tau EDM: sensitivity

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

– 95% confidence intervals

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



- Detector modeling limits our results
- Good event vertex resolution to obtain tau direction information will improve the sensitivity for future analysis