Search for New Physics using tau leptons at Belle and Belle II

Diptaparna Biswas

UNIVERSITY OF LOUISVILLE

PhiPsi 2022
Fudan University, ShangHai, China
August 18, 2022

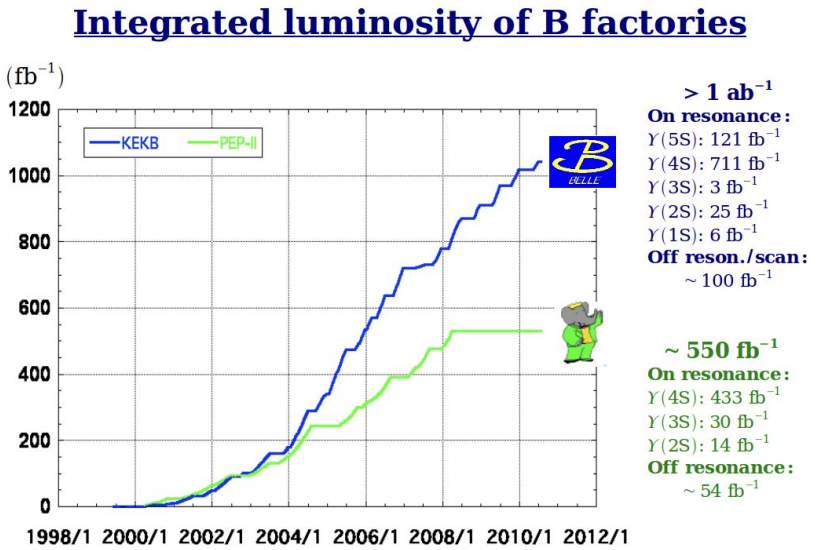
Tau Lepton Physics at B-factories

- τ lepton: the heaviest lepton in the Standard Model
  - ➢ Decays both leptonically and hadronically.
  - ➢ Sensitive to new physics:
    - ■ Lepton Flavor Violation, CP violation, Dark Sector Search.

- B-factories are also τ-factories.
  - ➢ $\sigma(e^+e^- \rightarrow \Upsilon(4S)) = 1.05$ nb
  - ➢ $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92$ nb

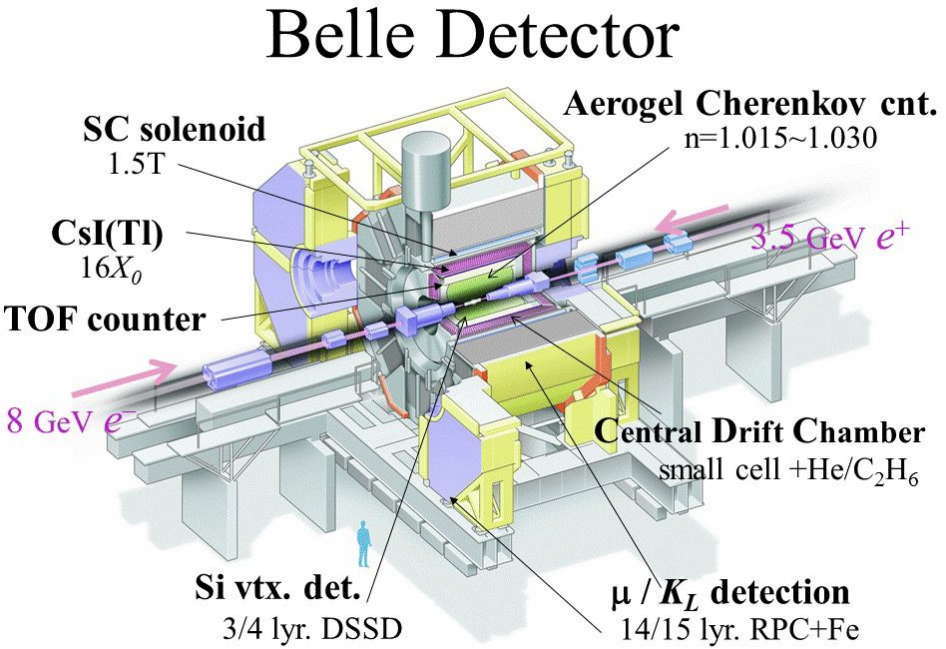
- Latest results from Belle experiment
  - ➢ Search for a dark leptophilic scalar
  - ➢ Search for tau LFV in $\tau \rightarrow \ell\gamma$
  - ➢ Search for electric dipole moment of τ

- Latest results from Belle II experiment
  - ➢ Search for $\tau \rightarrow \ell + \alpha$ (invisible)



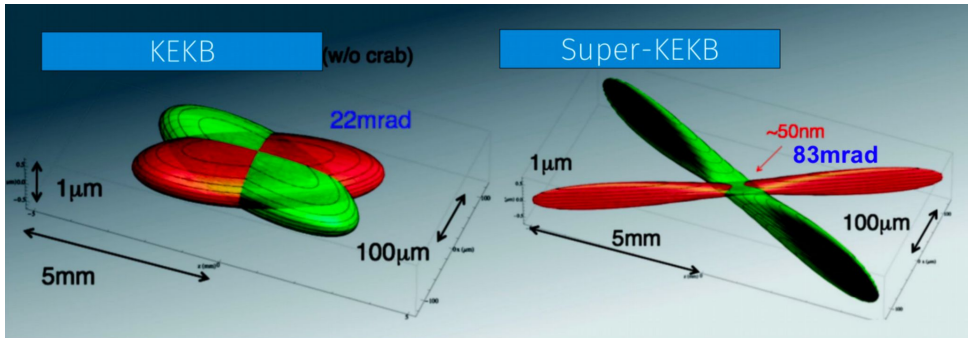
The Belle experiment

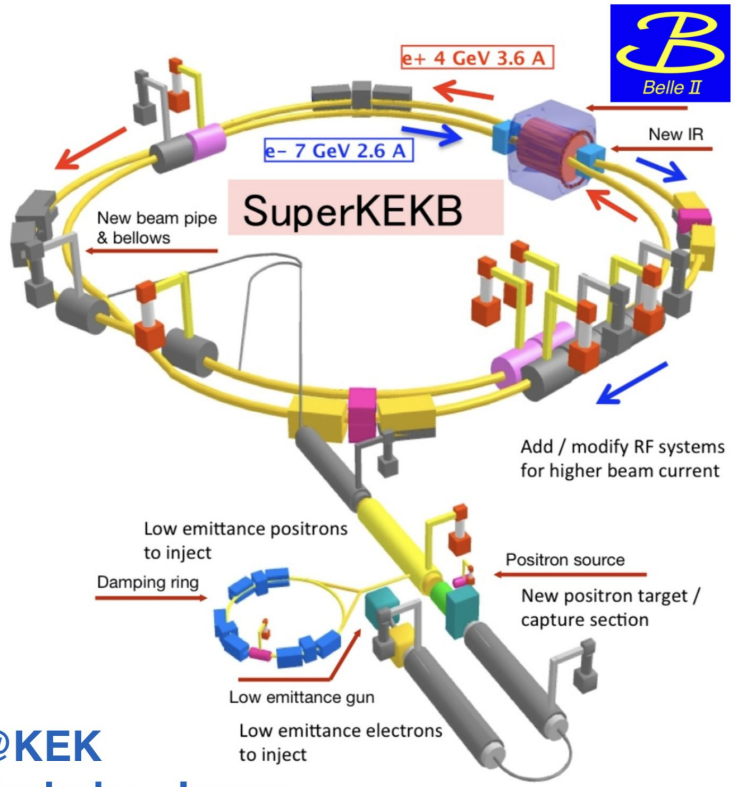
- Performed at KEKB accelerator.
  - ➢ 8 GeV electron and 3.5 GeV positron.
- Collected data from 1999 to 2010.
  - ➢ Integrated luminosity more than 1 ab^{-1}.
  - ➢ Collected ~ 1 billion tau-pair events.



The Belle II experiment

- Successor of Belle experiment at SuperKEKB: next generation B-factory.
  - ➢ Unprecedented design luminosity 6×10^{35} $cm^{-2}s^{-1}$
  - ➢ World record instantaneous luminosity of 4.7×10^{34} $cm^{-2}s^{-1}$ already achieved.
  - ➢ Vertical beta function at IP is smaller by a factor of 20.
  - ➢ Increased LER and HER currents by a factor of 2-3.

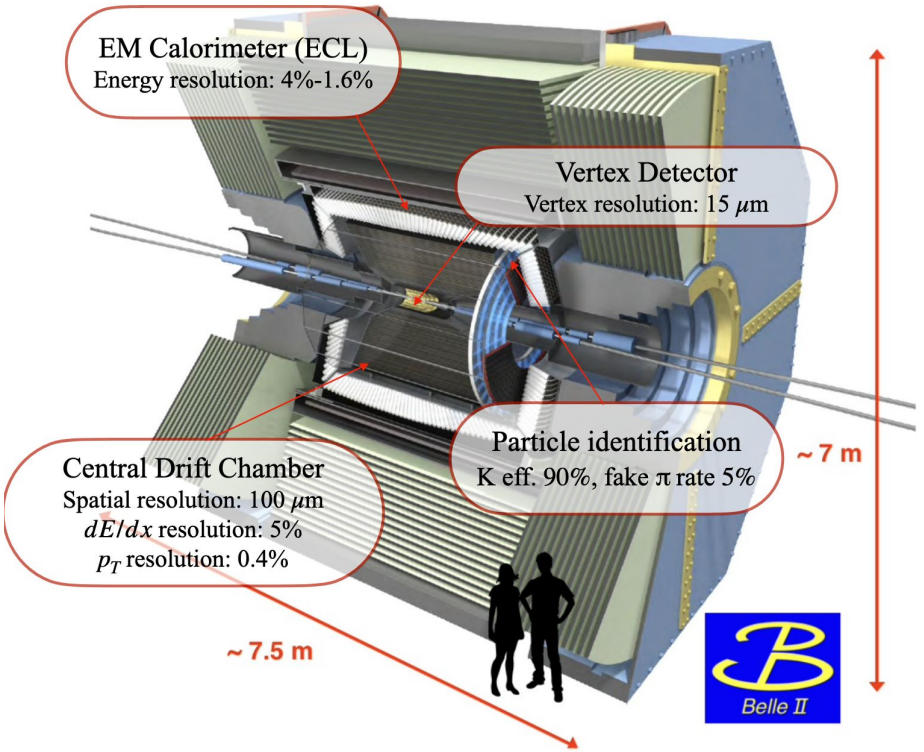




@KEK
Tsukuba, Japan

The Belle II experiment

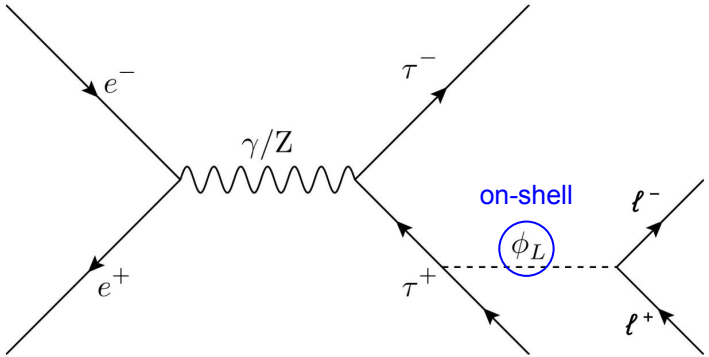
- Increased beam background.
  - ➢ Upgraded sub-detectors and triggers.
- Reduced boost.
  - ➢ βγ = 0.28 (as opposed to 0.42 in KEKB)
  - ➢ Needs improved vertex reconstruction.
- Better solid angle coverage.
  - ➢ Detector coverage is more than 90%.
  - ➢ Higher hermiticity for missing energy measurements.



Search for a Dark Leptophilic Scalar

626 fb^{-1} of Belle data

- $e^+ e^- \rightarrow \tau^+ \tau^- \varphi_L$, $\varphi_L \rightarrow \ell^+\ell^-$ (where $\ell = e$ or μ, and φ_L is the dark leptophilic scalar)
  - ➢ Leptophilic: couples only to leptons
  - ➢ Decays to a lepton pair: search for narrow peak in lepton pair invariant mass distribution.
    - $\varphi_L \rightarrow e^+e^-$ for $m_\varphi < 2m_\mu$ and $\varphi_L \rightarrow \mu^+\mu^-$ for $m_\varphi > 2m_\mu$
  - ➢ High cross-section in the region 40 MeV < m_φ < 6.5 GeV.
- Can possibly explain $(g-2)_\mu$ and lepton flavor universality.

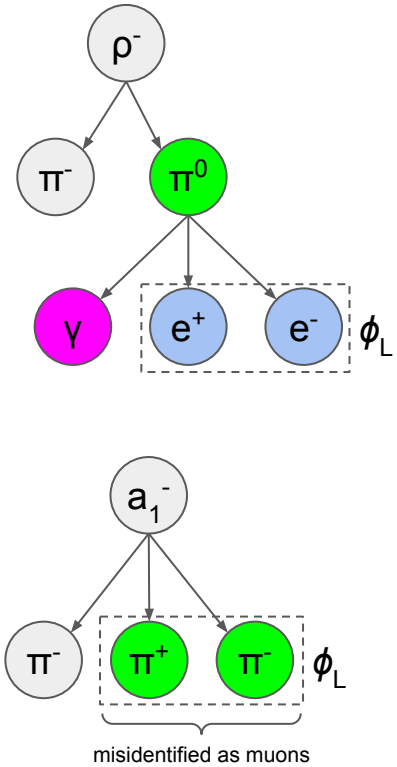


$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\, \phi_L \ell$$

ξ is the lepton flavor independent coupling constant between φ_L and $\ell^\pm$.
m_ℓ is the mass of the lepton it couples to.

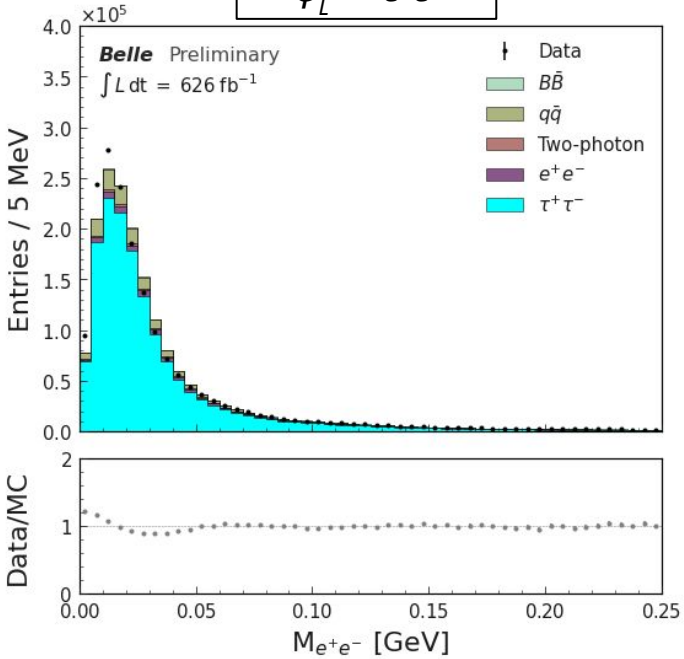
Search for a Dark Leptophilic Scalar

- Event reconstruction:
  - Require 4 track events with net charge 0.
  - At least two tracks are identified as ℓ, for $\varphi_L \to \ell^+\ell^-$ channel ($\ell = e$ or μ).
  - ℓ^+ and ℓ^- tracks are required to come from the same vertex.
- Backgrounds:
  - $\tau^- \to \rho^-\nu$, for $\varphi_L \to e^+e^-$ channel. ρ^- decay produces e^+ and e^- as shown.
  - $\tau^- \to a_1^-\nu$, for $\varphi_L \to \mu^+\mu^-$ channel. π^- from a_1^- decay is misidentified as μ^-.
  - Some $q\bar{q}$, $\ell^+\ell^-$, $\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^-h^+h^-$ backgrounds in both of the channels.
- Backgrounds have been suppressed using BDT.
- Signal extraction:
  - Fit to $\ell^+\ell^-$ invariant mass distribution.
  - Evaluate at each φ_L mass point.

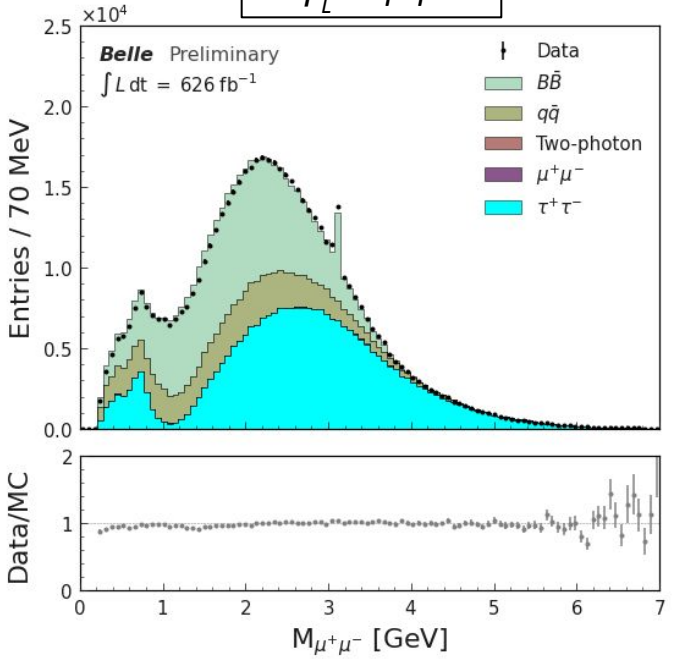


Search for a Dark Leptophilic Scalar

$\varphi_L \to e^+e^-$



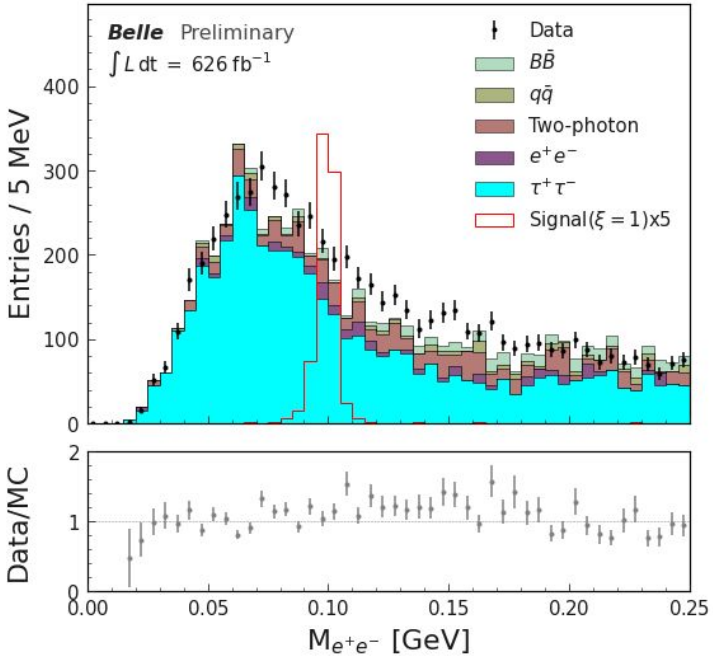
$\varphi_L \to \mu^+\mu^-$



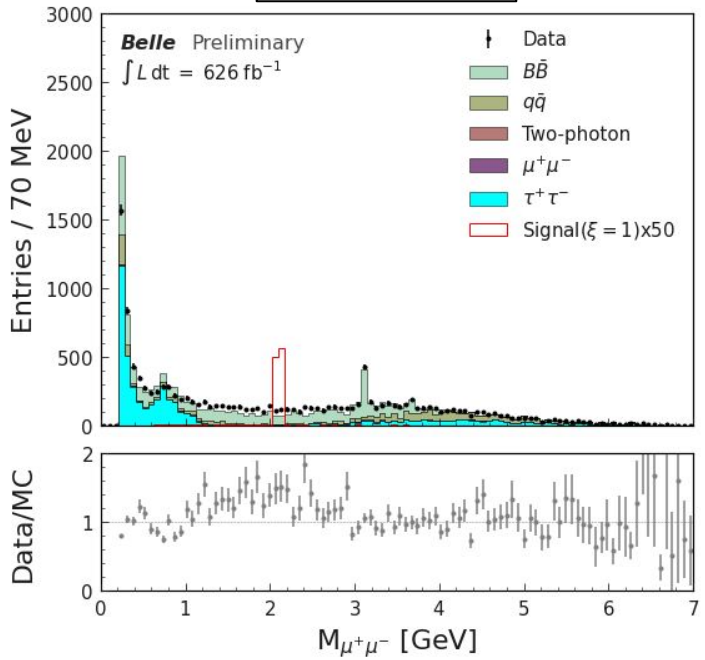
Data-MC agreement in control region

Search for a Dark Leptophilic Scalar

$\varphi_L \to e^+e^-$



$\varphi_L \to \mu^+\mu^-$

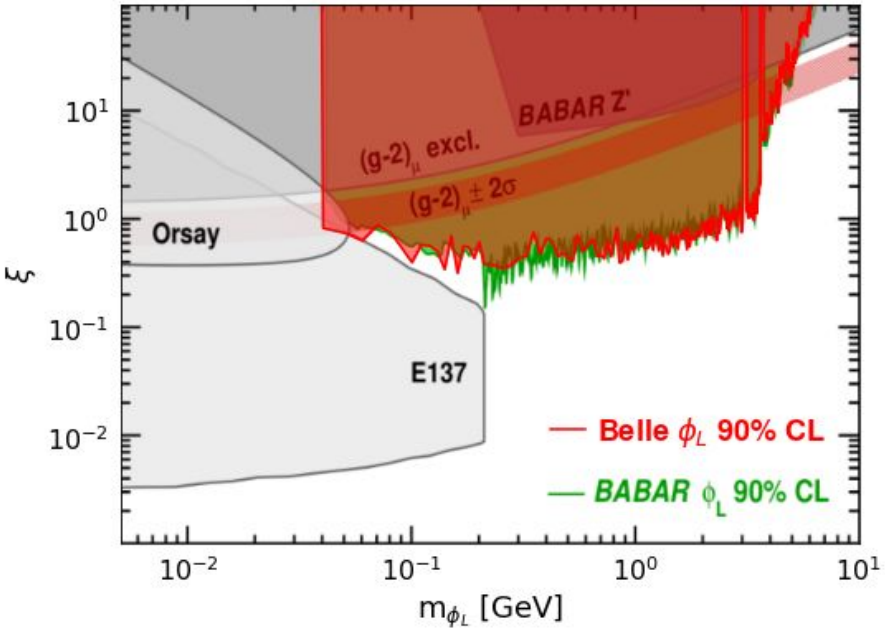


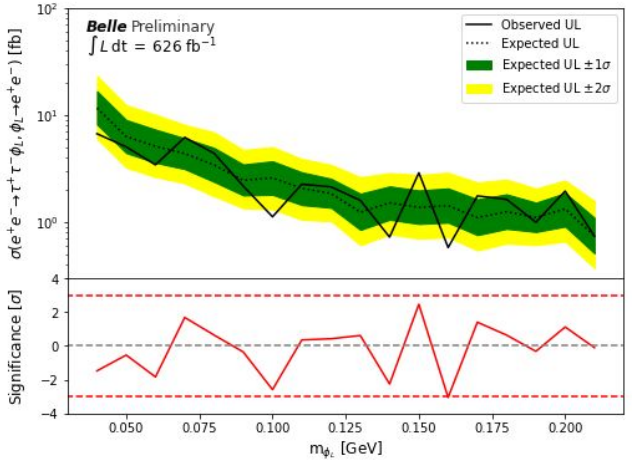
Data-MC agreement in signal region

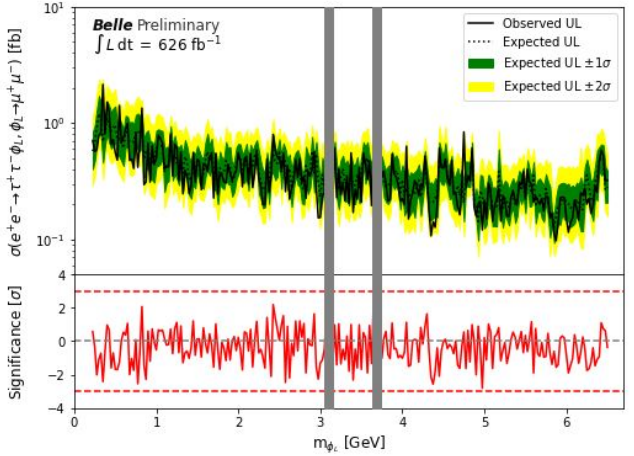
Search for a Dark Leptophilic Scalar

- 90% CL upper limits on the cross-section of the signal processes and the coupling constant.

BELLE-CONF-2201

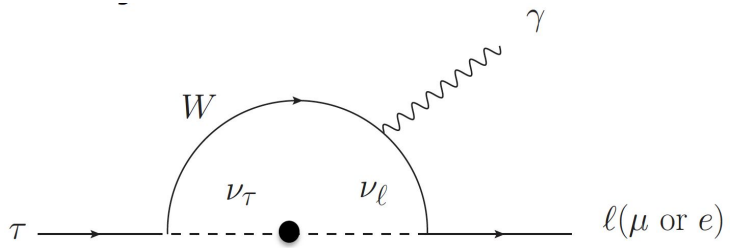




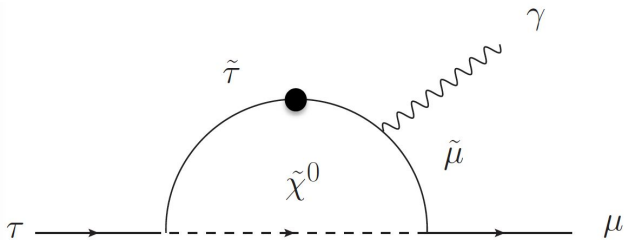


Search for tau LFV in $\tau \to \ell\gamma$

- Charged Lepton Flavor Violation (CFLV) in $\tau^{\pm} \to \ell^{\pm}\gamma$ (ℓ = *e* or μ)
  - ➢ Allowed in SM via neutrino oscillation but with **extremely low probability**, e.g. $B(\tau^- \to \mu^-\gamma) < O(10^{-54})$



  - ➢ Experimentally detectable probability in several new physics models.



Model	Reference
SM + heavy Majorana ν_R	PRD 66 (2002) 034008
Non-universal Z'	PLB 547 (2002) 252
SUSY SO(10)	PRD 68 (2003) 033012
SUSY Higgs	PLB 566 (2003) 217

  - ➢ Observation of CFLV ⇒ clear signature of new physics.

Search for tau LFV in $\tau \to \ell\gamma$

Luminosity: 988 fb^{-1}

$N_{\tau\tau} = 9.1\times10^8$

- Event reconstruction:
  - Signal side: 1 ℓ + 1 γ
  - Tag side: 1 prong decay of τ

$$M_{\rm bc} = \sqrt{\left(E^{\rm CM}_{\rm beam}\right)^2 - \left(p^{\rm CM}_{\ell\gamma}\right)^2}$$

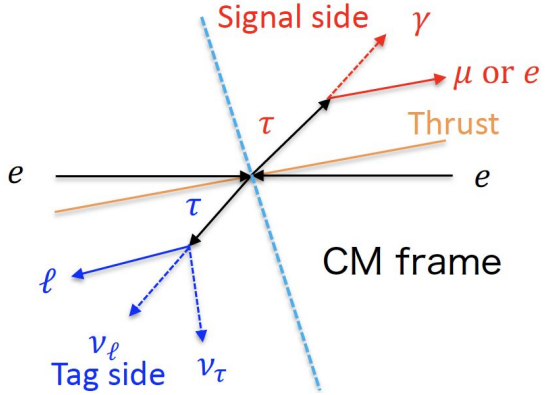
Beam constraint mass

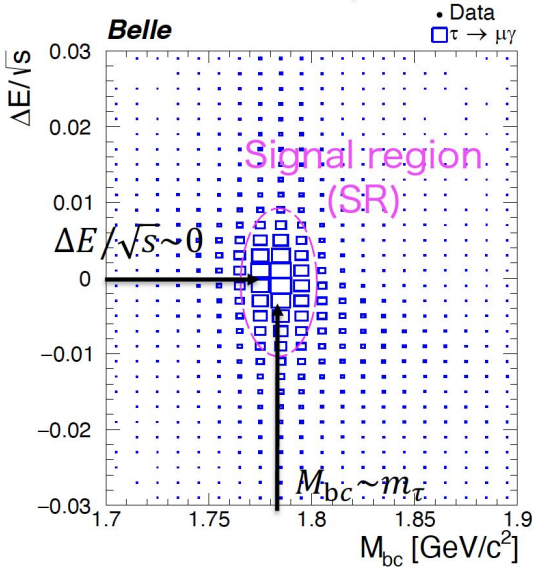
$$\Delta E/\sqrt{s} = (E^{\rm CM}_{\ell\gamma} - E^{\rm CM}_{\rm beam})/\sqrt{s}$$

- Backgrounds:
  - $\tau^\pm \to \ell^\pm \nu\bar{\nu}$ + ISR γ or beam background
  - $e^+e^- \to \ell^+\ell^-$ + ISR γ or beam background
- Most stringent limit for $\tau^\pm \to \mu^\pm\gamma$ to date.

[JHEP 2110, 019]

$B\times10^{-8}$ 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





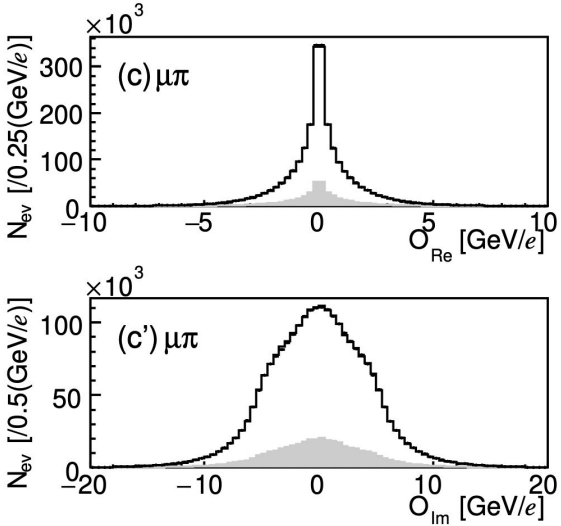
Search for tau EDM

833 fb^{-1} of Belle data

- A non-zero electric dipole moment of τ can provide signatures of new physics.
  - ➢ CP/T violating parameter in γττ vertex.
  - ➢ SM prediction of τ EDM, $d_\tau \sim O(10^{-37})$ e cm
- Method of optimal observable is used to perform this measurement.
  - ➢ Introduced in this paper: PRD 45 (1992) 2405
  - ➢ The optimal observables used in this analysis are:

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

  - ➢ The squared spin density matrix (χ_{prod}) for the $\tau^+\tau^-$ production vertex is $\chi_{\mathrm{prod}} = \chi_{\mathrm{SM}} + \mathrm{Re}(d_\tau)\chi_{\mathrm{Re}} + \mathrm{Im}(d_\tau)\chi_{\mathrm{Im}} + |d_\tau|^2\chi_{d^2}$
  - ➢ χ_{SM} is the SM term. χ_{Re} and χ_{Im} are the interference terms between the SM and the real and imaginary parts of d_τ.
  - ➢ χ_{Re} and χ_{Im} are measured from the asymmetry in azimuthal and polar angles of τ daughter tracks momenta, respectively.



Search for tau EDM

833 fb^{-1} of Belle data

$\mathrm{Re}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
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
Kinematic dependence of reconstruction efficiency	3.2	4.8	3.8	0.9	2.2	0.9	0.9	3.6
Data–MC difference in backgrounds	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
Kinematic dependence of reconstruction efficiency	1.0	0.9	0.6	0.5	0.8	0.4	0.4	1.2
Data–MC difference in backgrounds	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

JHEP 04 (2022) 110

Combined results

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

Previous results (Belle 29.5 fb^{-1}):

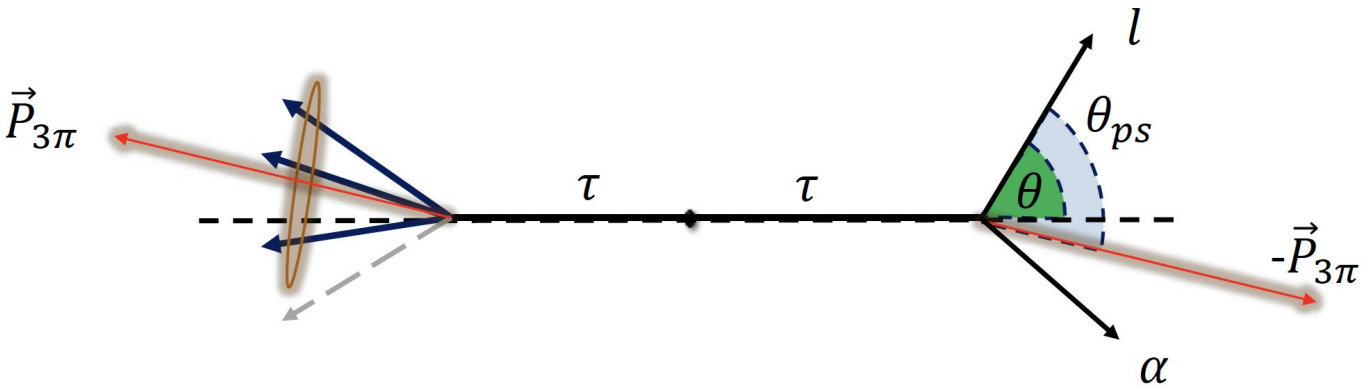
$$\mathrm{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}\ e\,\mathrm{cm},$$
$$\mathrm{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}\ e\,\mathrm{cm}$$

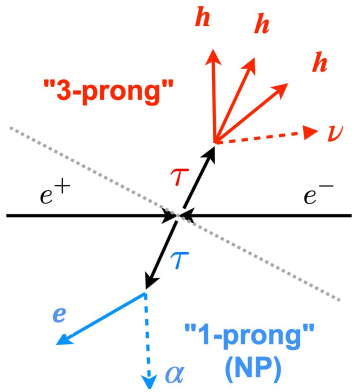
- Agrees with SM prediction of 0 EDM.
- ~2.7 times smaller error than previous Belle result: PLB 551 (2003) 16

Search for $\tau \to \ell + \alpha$ (invisible)

62.8 fb^{-1} of Belle II data

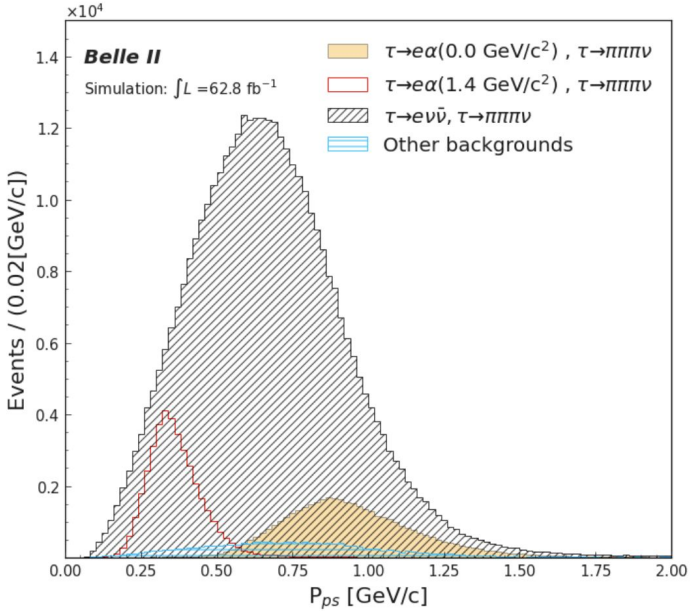
- LFV decay: $\tau^{\pm} \to \ell^{\pm}\alpha$ (where $\ell = e$ or μ, and α is an invisible boson)
- Model independent search. α can enter from different new physics models:
  - ➢ Light axion like particles (ALP), LFV Z', etc.
- Individual $\tau^{\pm} \to \ell^{\pm}\alpha$ events are indistinguishable from $\tau^{\pm} \to \ell^{\pm}\nu\bar{\nu}$.
  - ➢ This makes the SM process an irreducible background.
  - ➢ However, the distributions of the lepton momenta in the τ pseudo-rest (ps) frame will be different.





Search for $\tau \to \ell + \alpha$ (invisible)

- Event reconstruction:
  - ➢ Split event into two hemispheres using thrust.
  - ➢ Require exactly 4 tacks: 1 in signal + 3 in tag.
  - ➢ Veto neutrals (π^0,γ) to suppress hadronic background.
- Reducible backgrounds:
  - ➢ $q\bar{q}$, $\ell^+\ell^-$, $\ell^+\ell^-\ell^+\ell^-$, $\ell^+\ell^- h^+h^-$ and $\tau^+\tau^-$ with misidentified signal (e.g. $\tau \to \pi\nu$)
  - ➢ These backgrounds are suppressed using cuts.



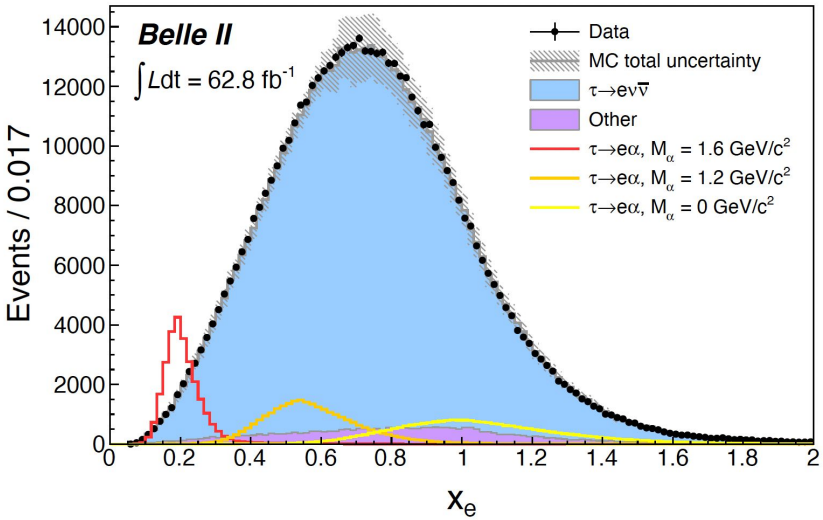
Signature of the signal process

2-body $\tau^\pm \to \ell^\pm\alpha$ decay will appear as a bump in the p_ℓ distribution in the τ pseudo-rest frame, against the SM 3-body $\tau^\pm \to \ell^\pm\nu\bar{\nu}$ background.

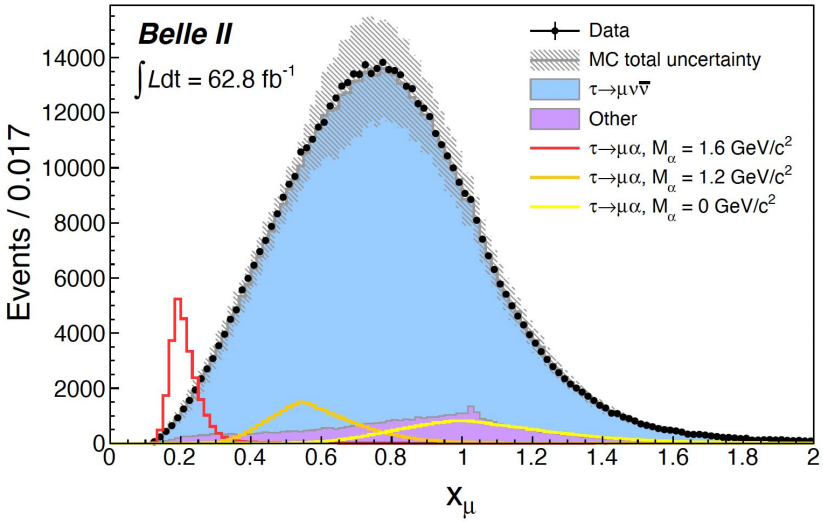
Search for $\tau \to \ell + \alpha$ (invisible)

- Data-MC agreement in the discriminating variable, $x_\ell \equiv \dfrac{E_\ell^{\mathrm{ps}}}{m_\tau/2}$

$\tau \to e\alpha$

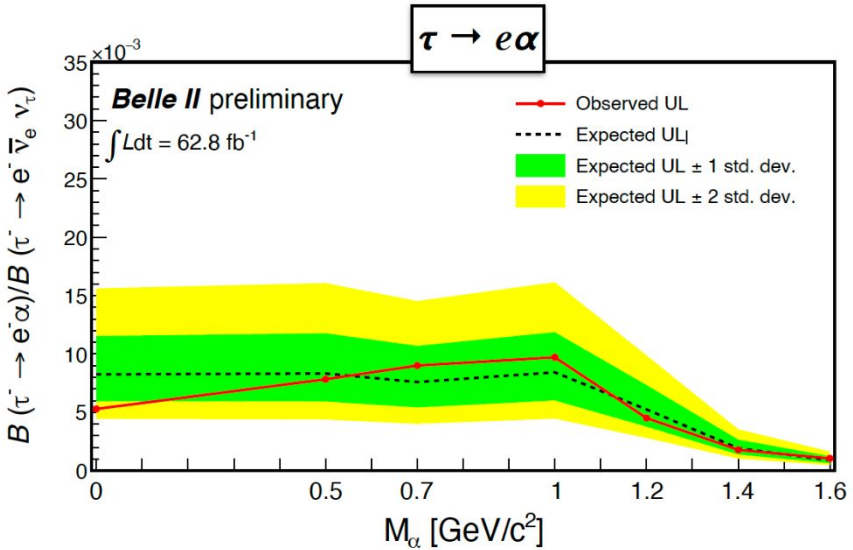


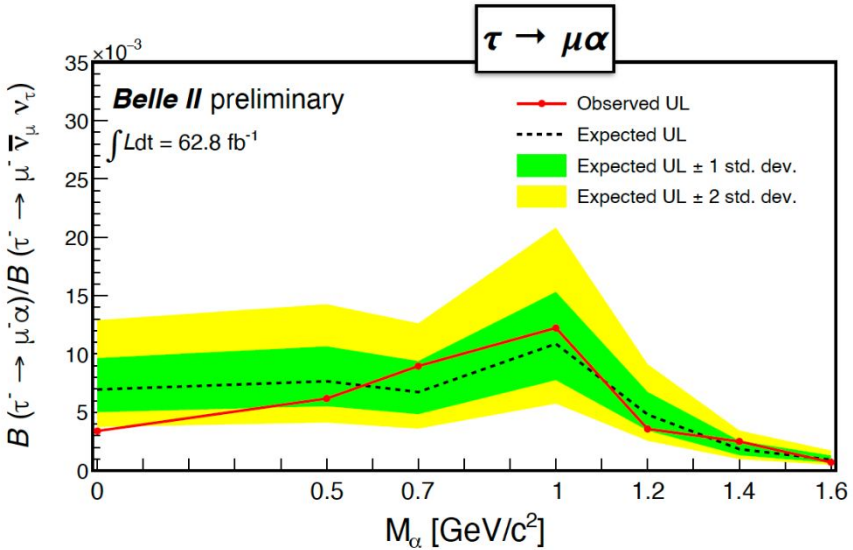
$\tau \to \mu\alpha$



Search for $\tau \to \ell + \alpha$ (invisible)

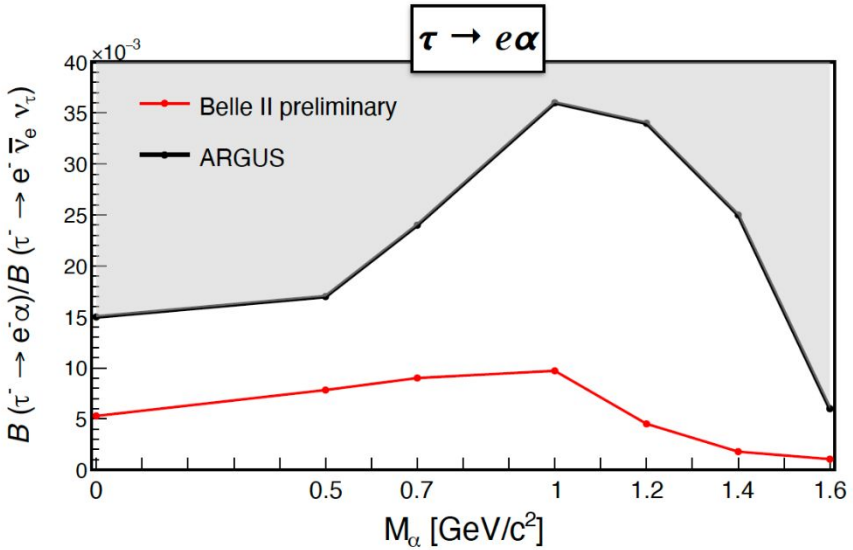
- No evidence of signal is observed, and 95% upper limit is set on the ratio of the branching fractions of the signal and the corresponding SM background process.

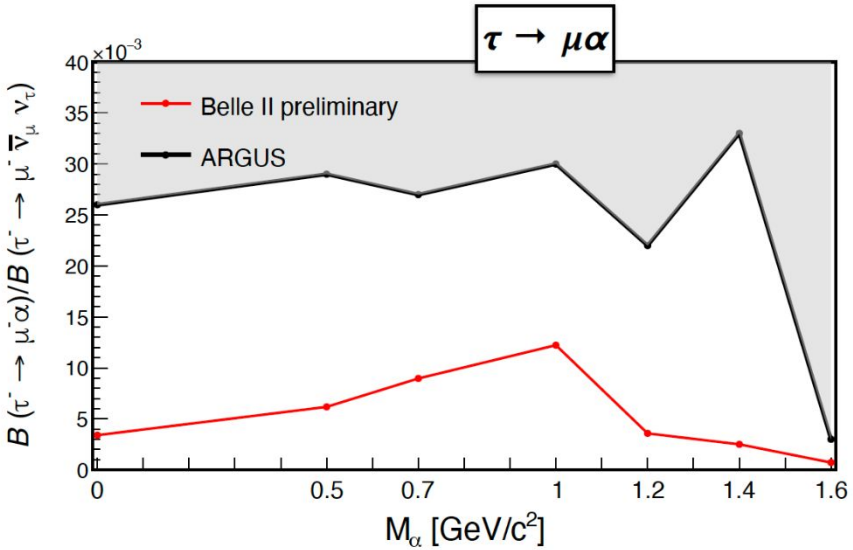




Search for τ → ℓ + α (invisible)

- Comparison with the previous result.
  - ➢ With 62.8 fb^{-1} of data, Belle II obtains the most stringent upper limits in the world. (ARGUS used 0.472 fb^{-1} data to perform this search)





Summary

- Search for dark leptophilic scalar, $e^+ e^- \to \tau^+ \tau^- \varphi_L$, $\varphi_L \to \ell^+\ell^-$
  - ➢ Performed using 626 fb^{-1} of Belle data.
  - ➢ The analysis has been performed in a data-blinded manner: good understanding of the backgrounds.
  - ➢ Completely excludes the region favored by the $(g-2)_\mu$ anomaly, till φ_L mass of 4 GeV.
- Search for tau LFV, $\tau \to \ell\gamma$
  - ➢ Performed using 988 fb^{-1} of Belle data and improved analysis technique.
  - ➢ Most stringent limits for $\tau \to \mu\gamma$ at 90% CL.
- Search for tau EDM
  - ➢ Performed using 833 fb^{-1} of Belle data and optimal observable technique.
  - ➢ Improved simulation and MC statistics: reduced uncertainty.
- Search for $\tau \to \ell + \alpha$ (invisible)
  - ➢ Performed using 62.8 fb^{-1} Belle II data.
  - ➢ Most stringent upper limits in the world.