Tau Physics Results at Belle

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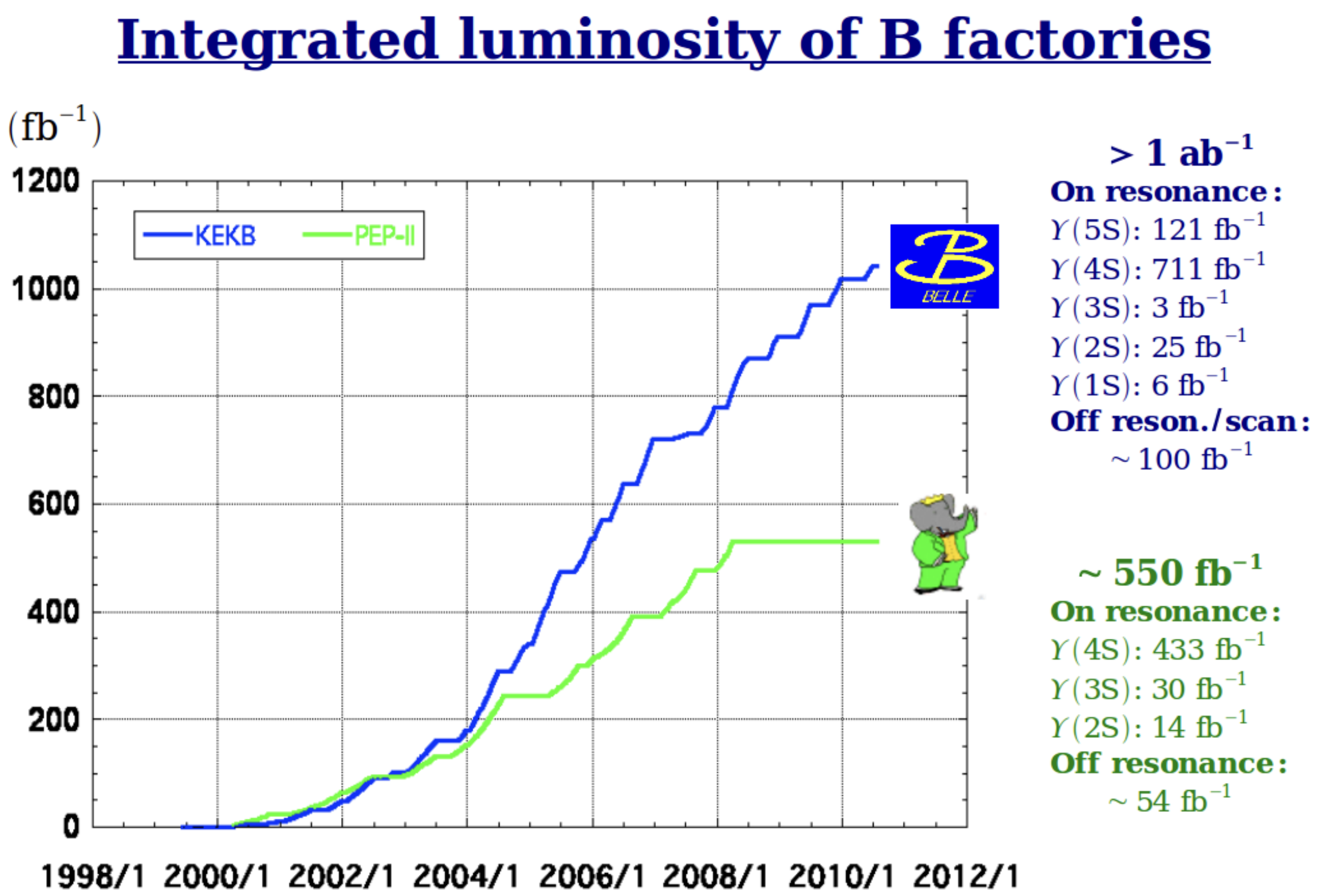
On behalf of the Belle collaboration

BELLE

B factories are also τ factories

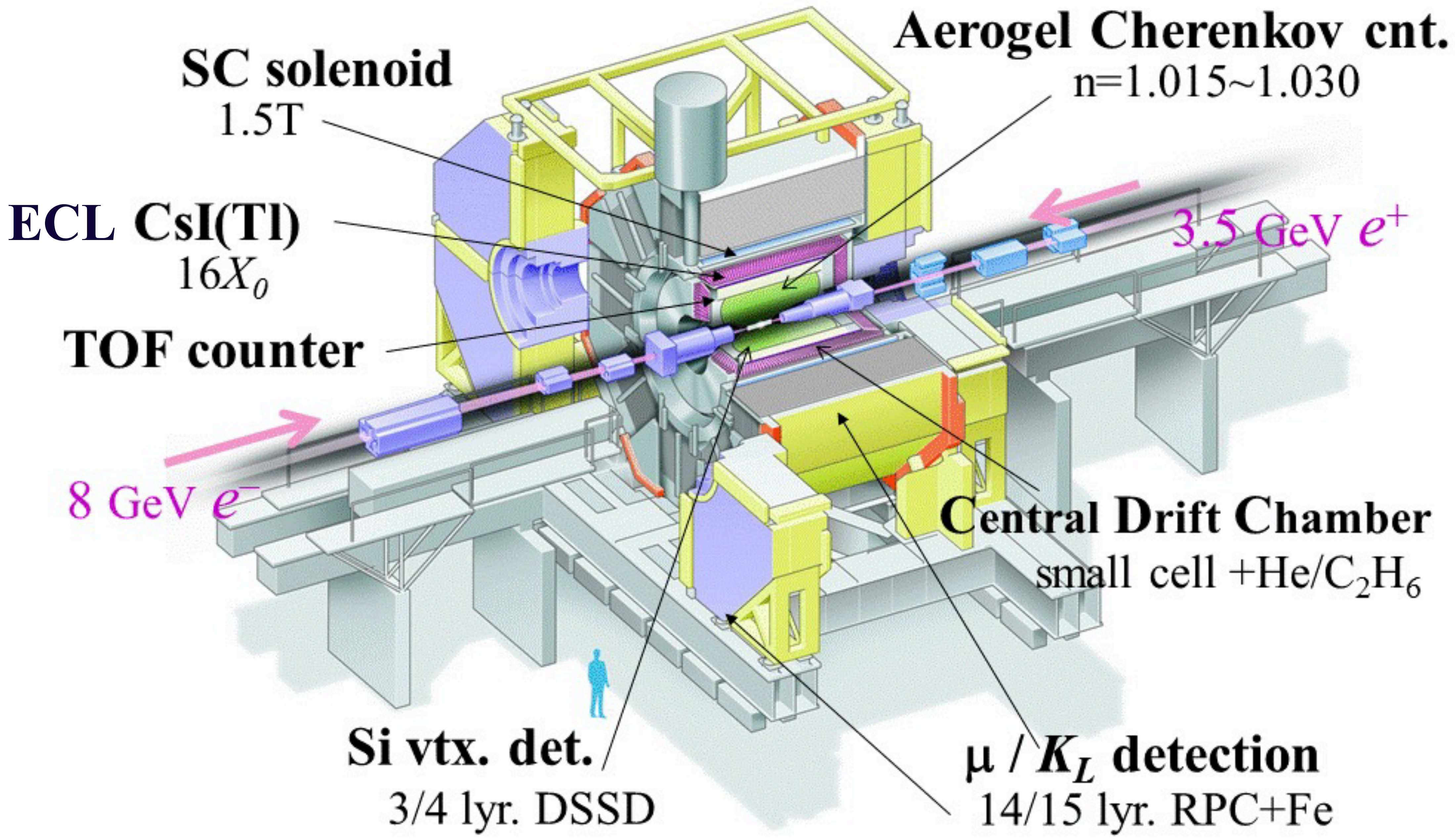


$$\sigma(e^-e^+ \to b\bar{b}) = 1.05\ nb$$

$$\sigma(e^-e^+ \to \tau^-\tau^+) = 0.92\ nb$$

Total number of τ-pairs produced with $\simeq 1\ ab^{-1}$ of data $\simeq 10^9$

Belle Detector



Overview of this talk

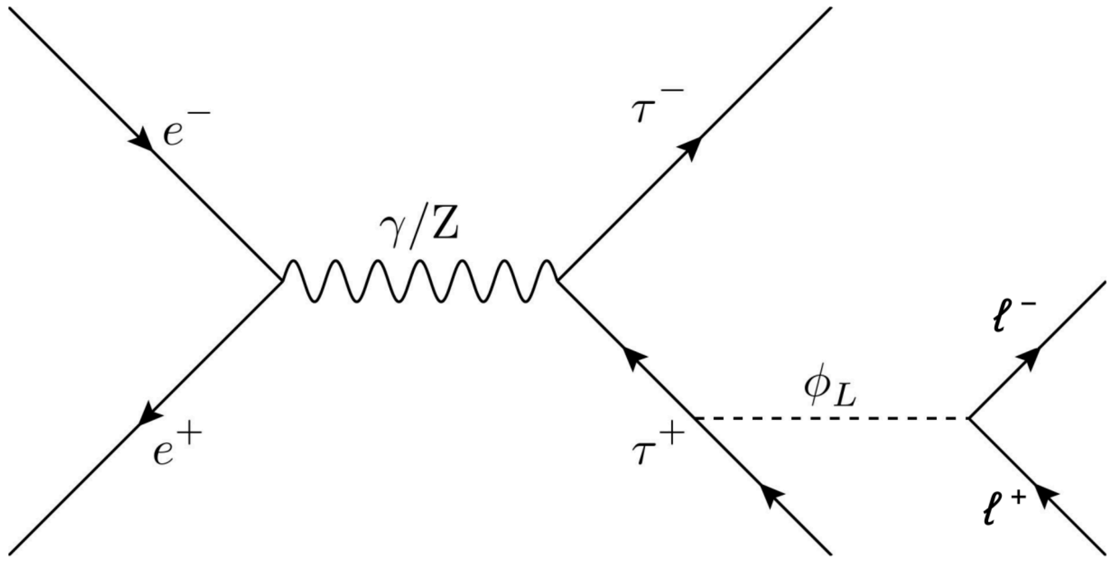
- **Search for dark leptophilic scalar** — New — BELLE-CONF-2201, arXiv:2207.07476 **[hep-ex]**
  - $e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to e^+e^-/\mu^+\mu^-$
- **Search for lepton flavor violation** — JHEP 10 (2021) 19, arXiv:2103.12994 **[hep-ex]**
  - $\tau^\pm \to e^\pm\gamma$
  - $\tau^\pm \to \mu^\pm\gamma$
- **Search for electric dipole moment of the $\tau-$lepton** — JHEP 04 (2022) 110, arXiv:2108.11543 **[hep-ex]**
  - **CP violation in $\tau^+\tau^-\gamma$ production vertex**

Dark leptophilic scalar

Dark sector portal can explain $(g\text{-}2)_\mu$ excess and lepton flavor universality violation:

- Many of the beyond standard model (BSM) theories predict the existence of additional scalars other than the Higgs boson.
- The mixing between this dark scalar and the SM Higgs boson gives rise to couplings proportional to SM fermion masses.
- If this new scalar couples to both quarks and leptons, the existence of such particles is strongly constrained by the searches for rare flavor-changing neutral current decays of mesons, e.g. $B \to K\phi$ and $K \to \pi\phi$.

However, these bounds are evaded if the coupling of the scalar to quarks is suppressed and this scalar interacts preferentially with leptons.



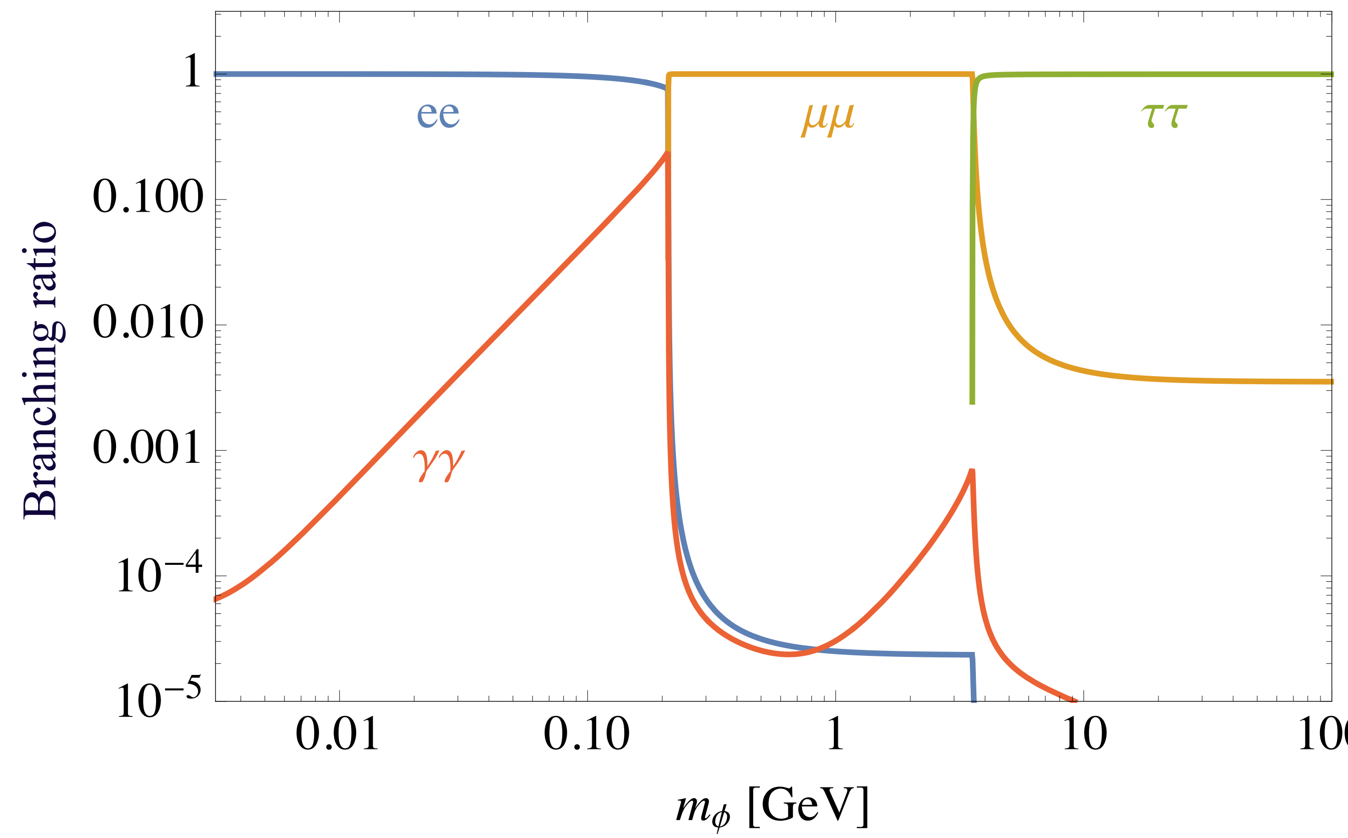
$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\, \phi_L \ell$$

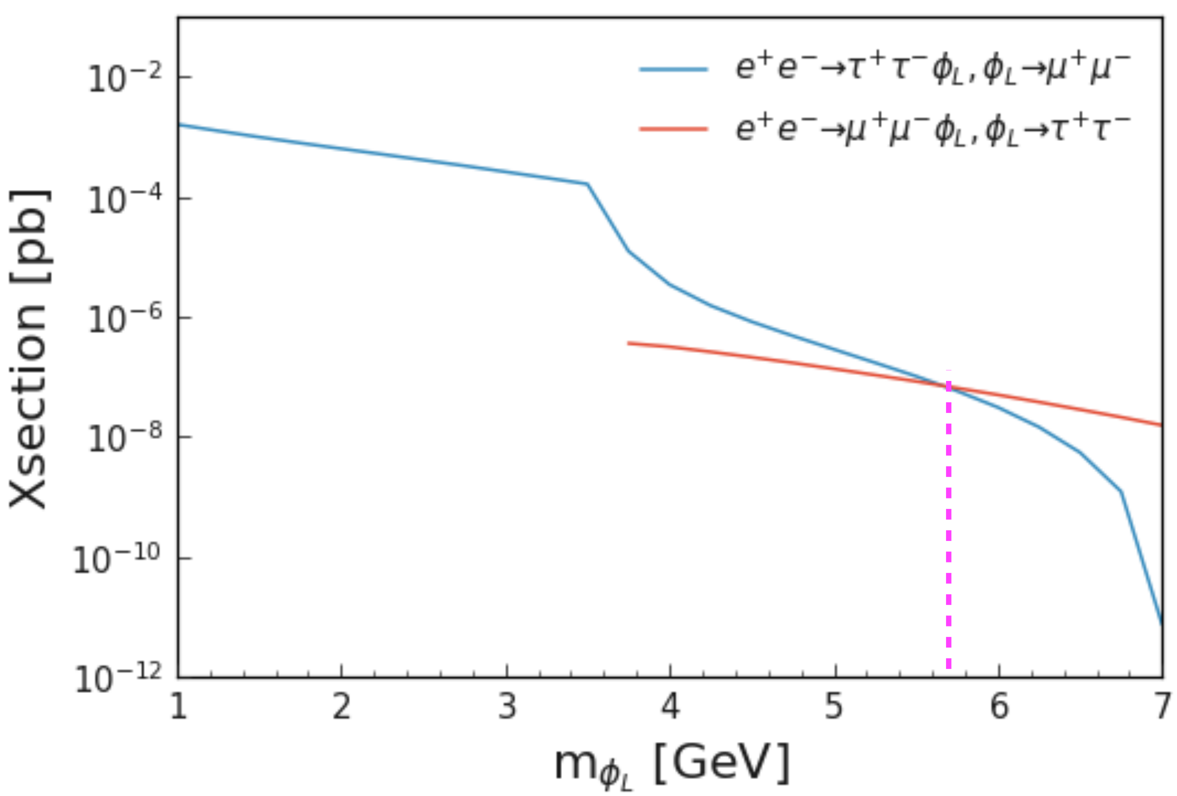
ξ is the lepton flavor independent coupling constant,
m_ℓ is mass of the lepton the dark scalar couples with,
v is the vacuum expectation value = 246 GeV

B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, "Muon anomalous magnetic moment through the leptonic higgs portal," Phys. Rev. D 95 (2017) 075003.

$e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to e^+e^-/\mu^+\mu^-$

- φ_L decays to a lepton pair: search for narrow peak in lepton pair invariant mass distribution.
  - $\varphi_L \to e^+e^-$ for $m_\varphi < 2m_\mu$ and $\varphi_L \to \mu^+\mu^-$ for $m_\varphi > 2m_\mu$
- High production cross-section times branching ratio in the region 40 MeV < m_φ < 6.5 GeV.



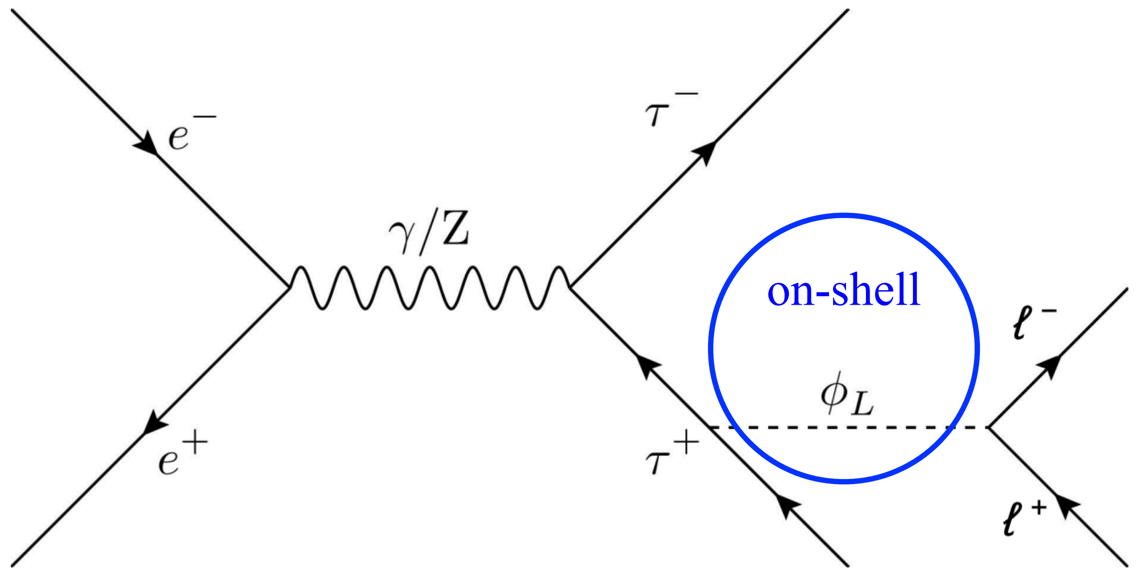


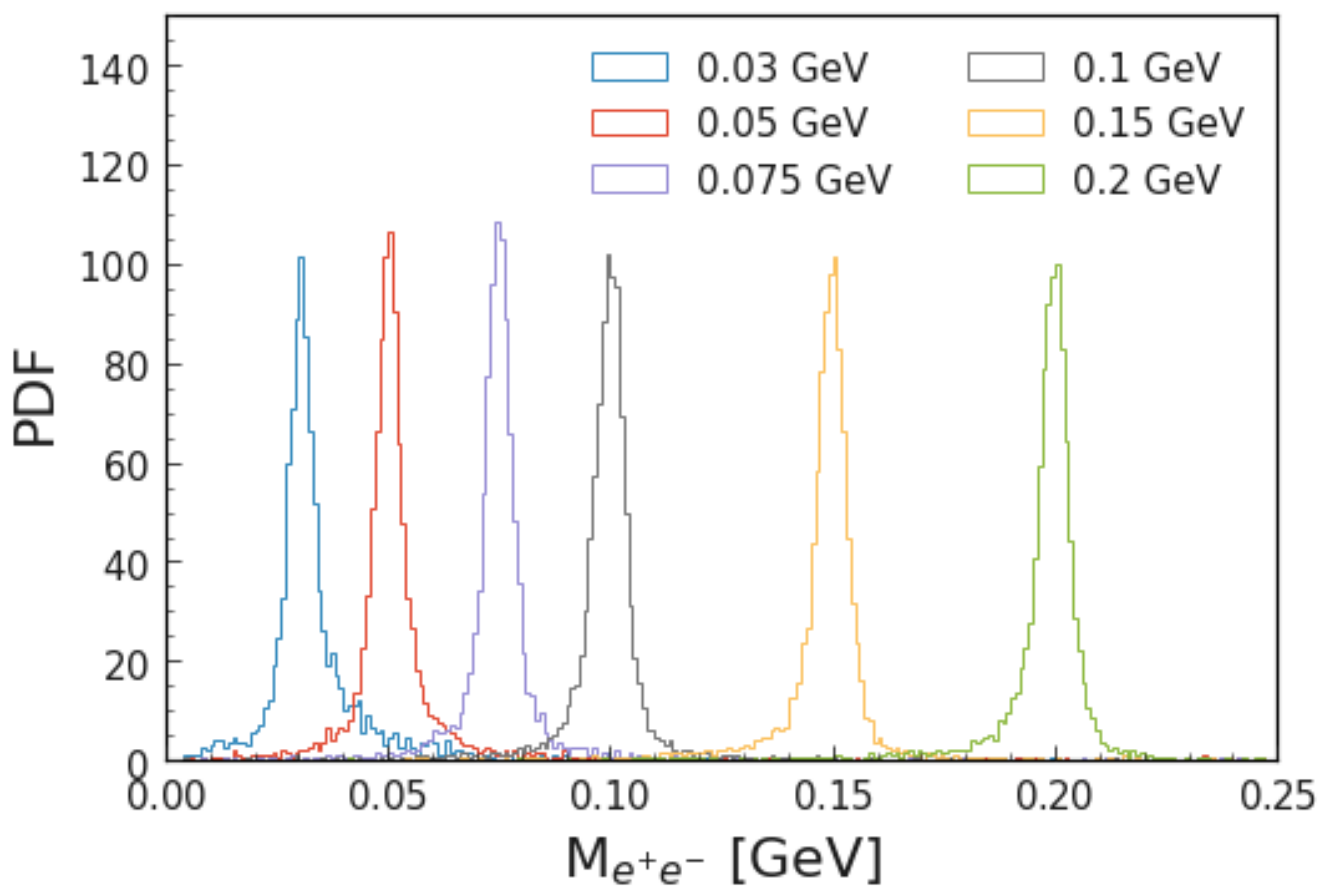
- Comparison between our signal process:
  - $e^+e^- \to \tau^+\tau^-\phi_L;\ \phi_L \to \mu^+\mu^-$

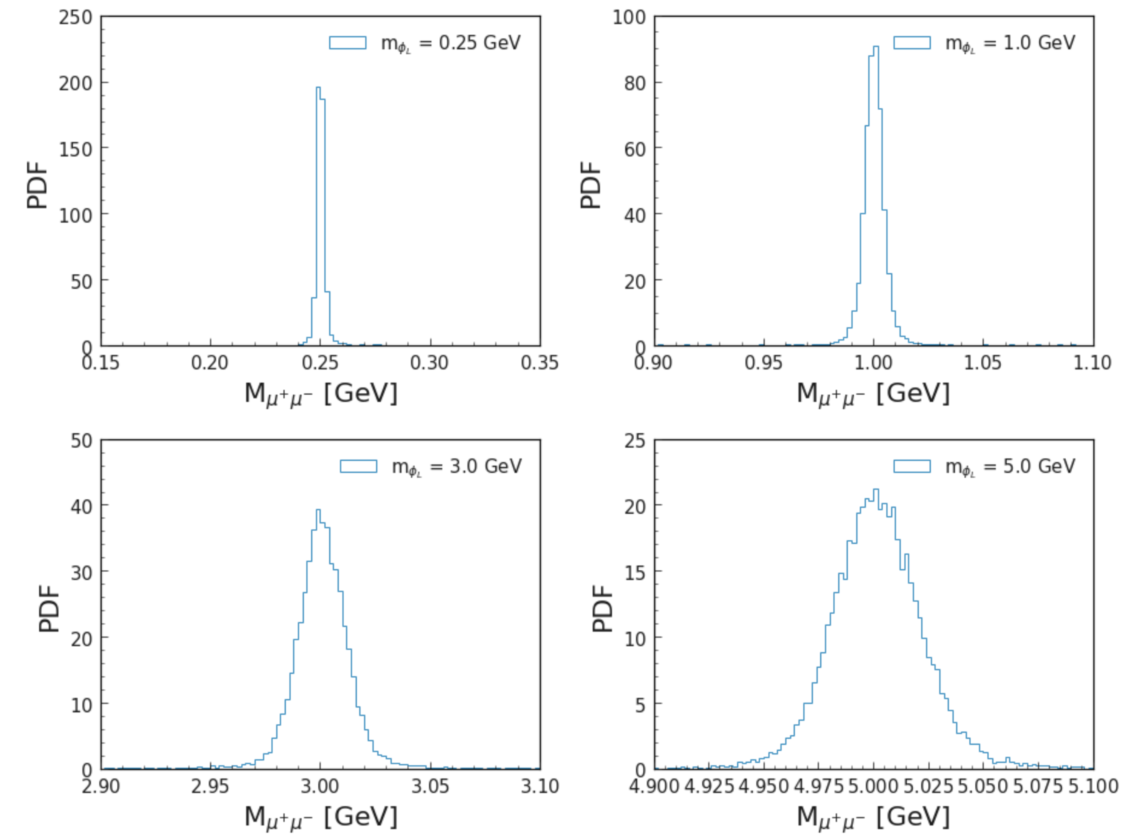
  and complementary process:
  - $e^+e^- \to \mu^+\mu^-\phi_L;\ \phi_L \to \tau^+\tau^-$

  shows signal process has higher rate till 5.7 GeV.
- Our search has sensitivity to place competitive limits on ξ till m_φ < 6.5 GeV.

Signal distribution of the discriminating variable



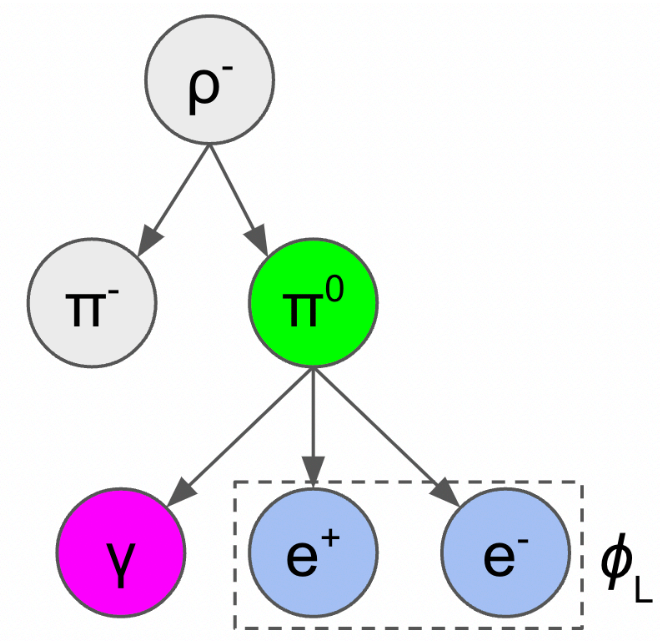


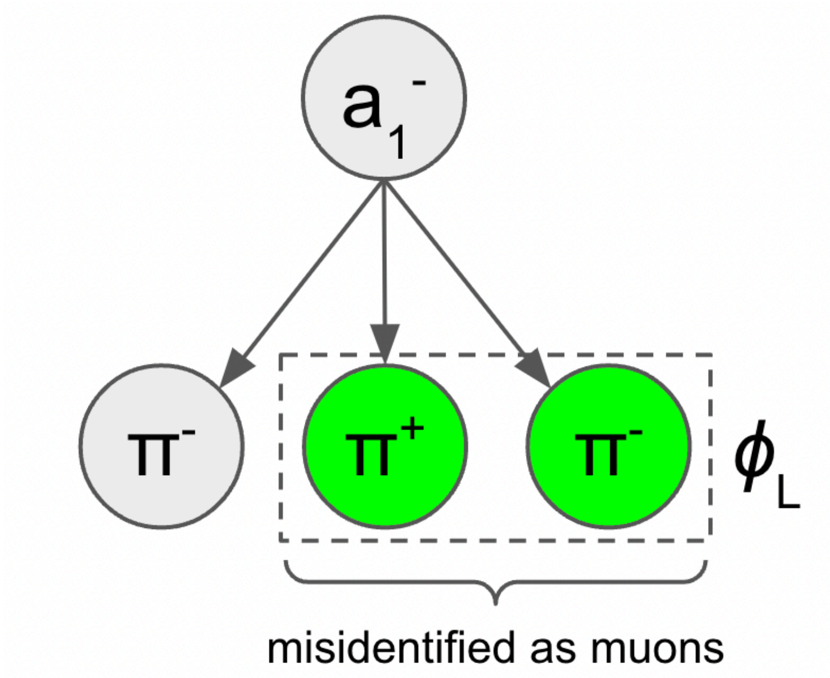


Resolution varies from 5 to 30 MeV, increasing at larger values of m_{ϕ_L}

Search strategy

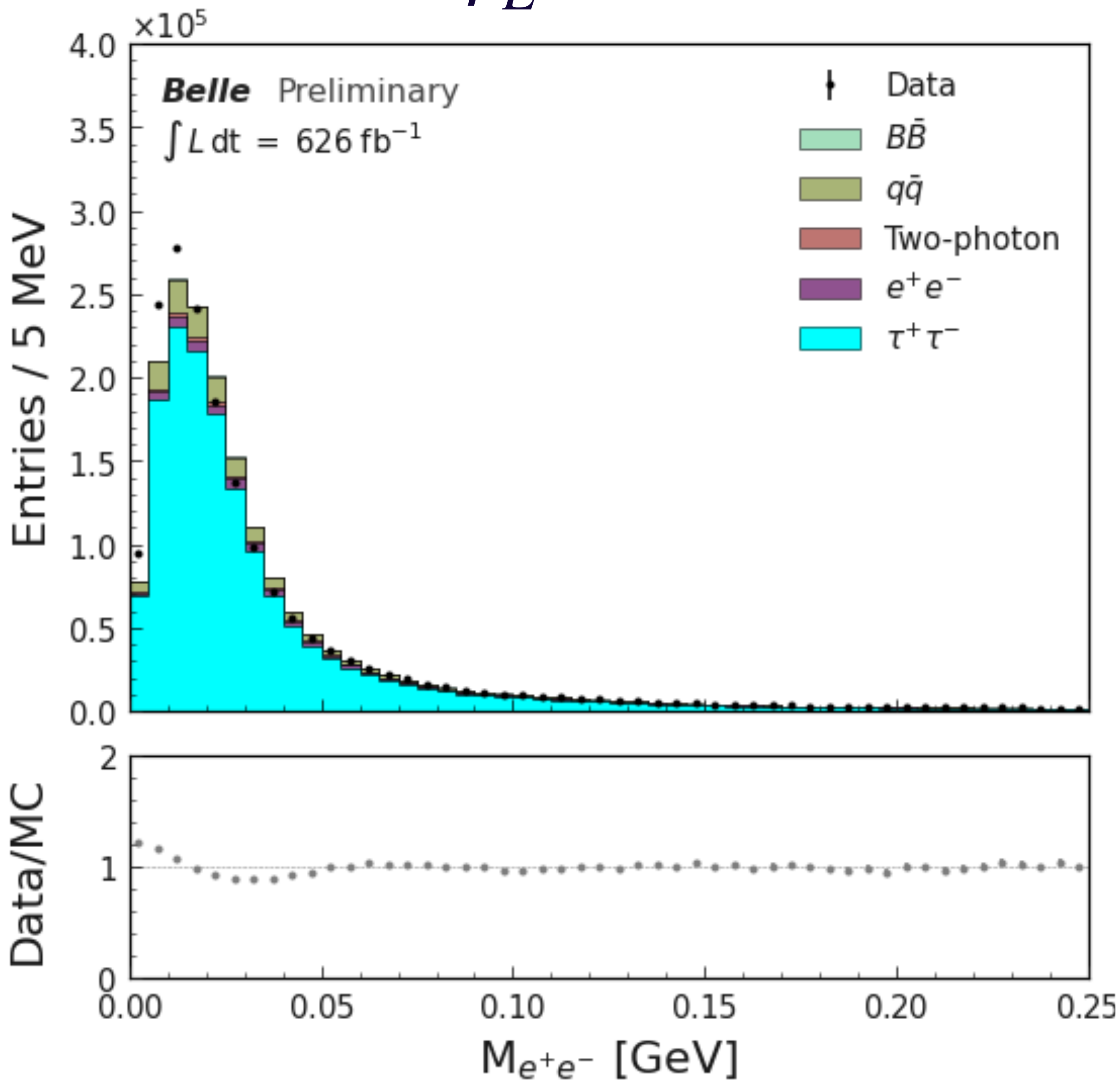
- Event reconstruction:
  - Require 4 track events with net charge 0.
  - At least two tracks are identified as ℓ, for $\varphi_L \to \ell^+\ell^-$ channel ($\ell = e$ or μ).
  - ℓ^+ and ℓ^- tracks are required to come from the same vertex.
- Backgrounds:
  - $\tau^- \to \rho^-\nu$, for $\varphi_L \to e^+e^-$ 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 Boosted Decision Tree (BDT).
- Signal extraction:
  - Fit to $\ell^+\ell^-$ invariant mass distribution.
  - Evaluate at each φ_L mass point.



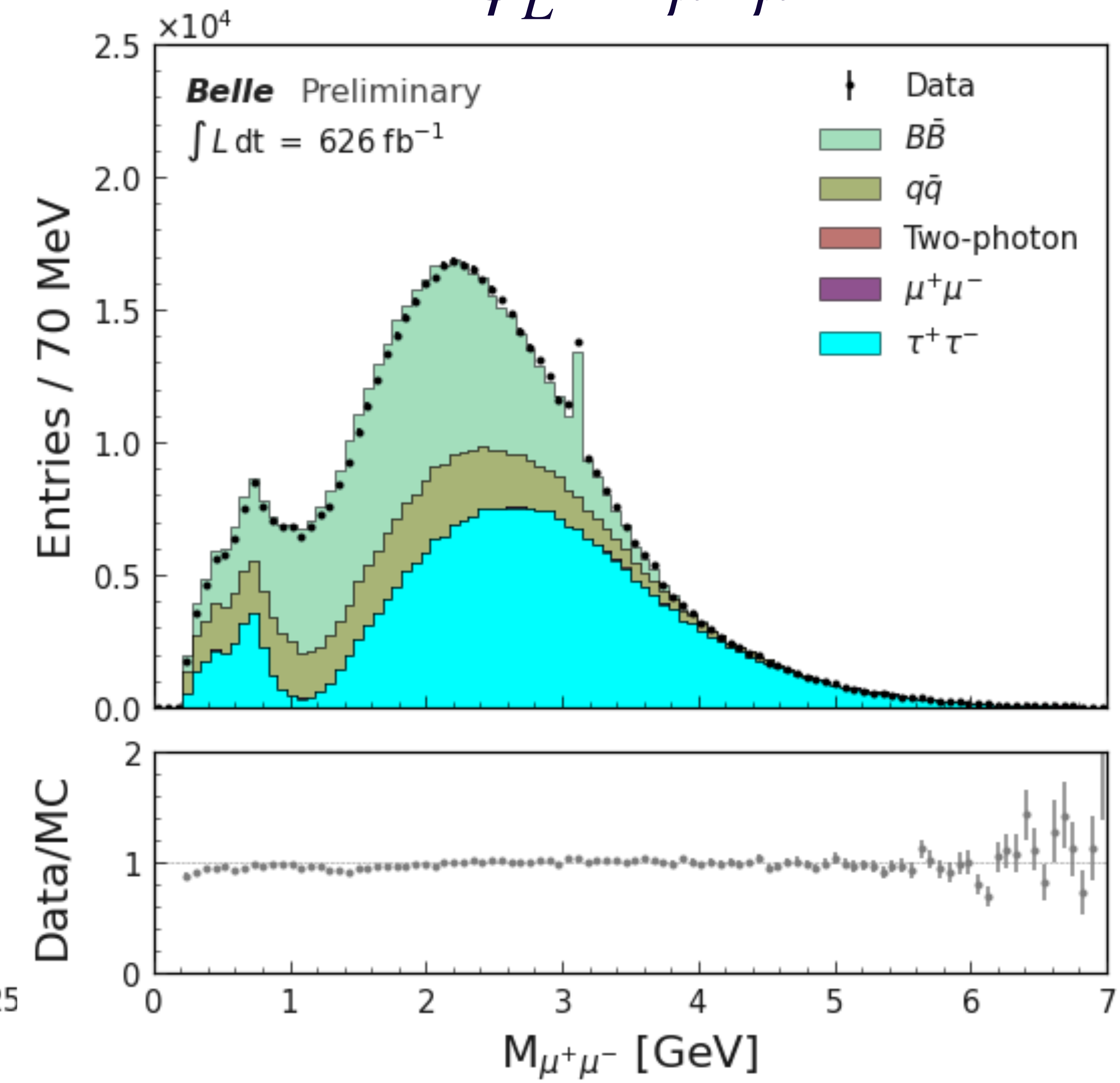


Good agreement seen in data vs. Monte Carlo comparison in control regions: BDT < 0.5

$\phi_L \to e^+e^-$



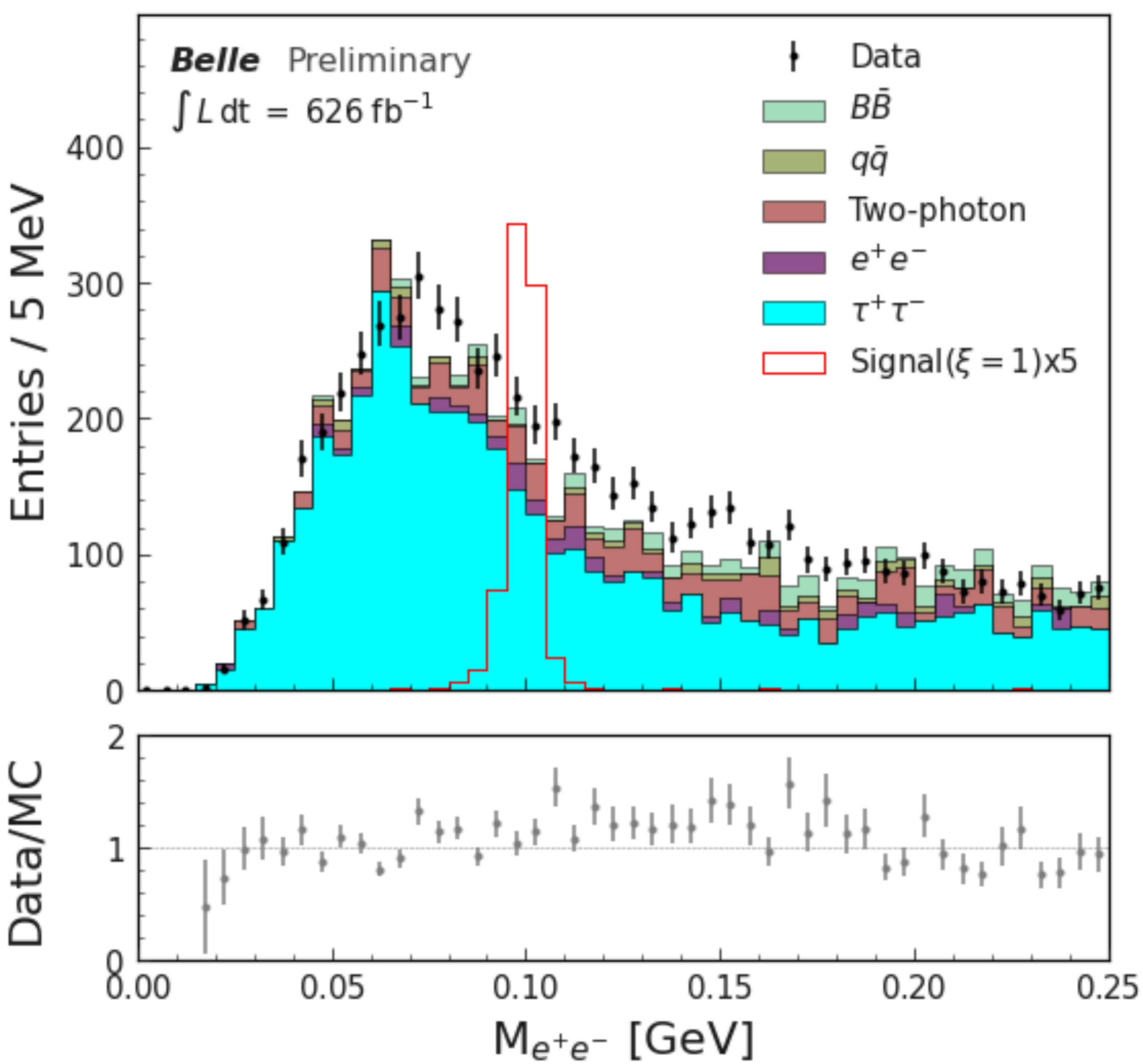
$\phi_L \to \mu^+\mu^-$



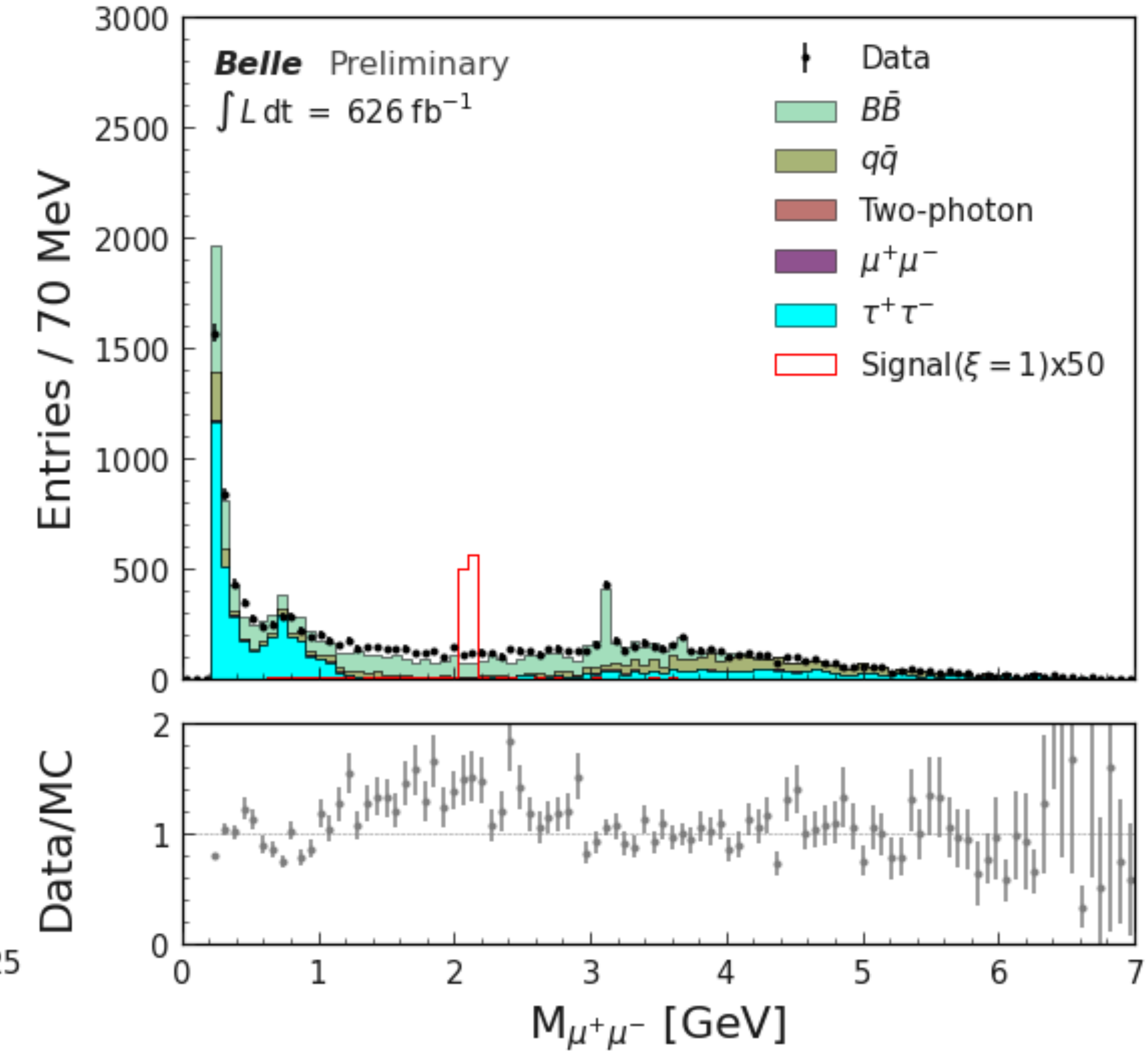
Search strategy

Data vs. Monte Carlo comparison in signal regions: BDT > 0.95 (0.65) for $\phi_L \to e^+e^-/\mu^+\mu^-$

$\phi_L \to e^+e^-$



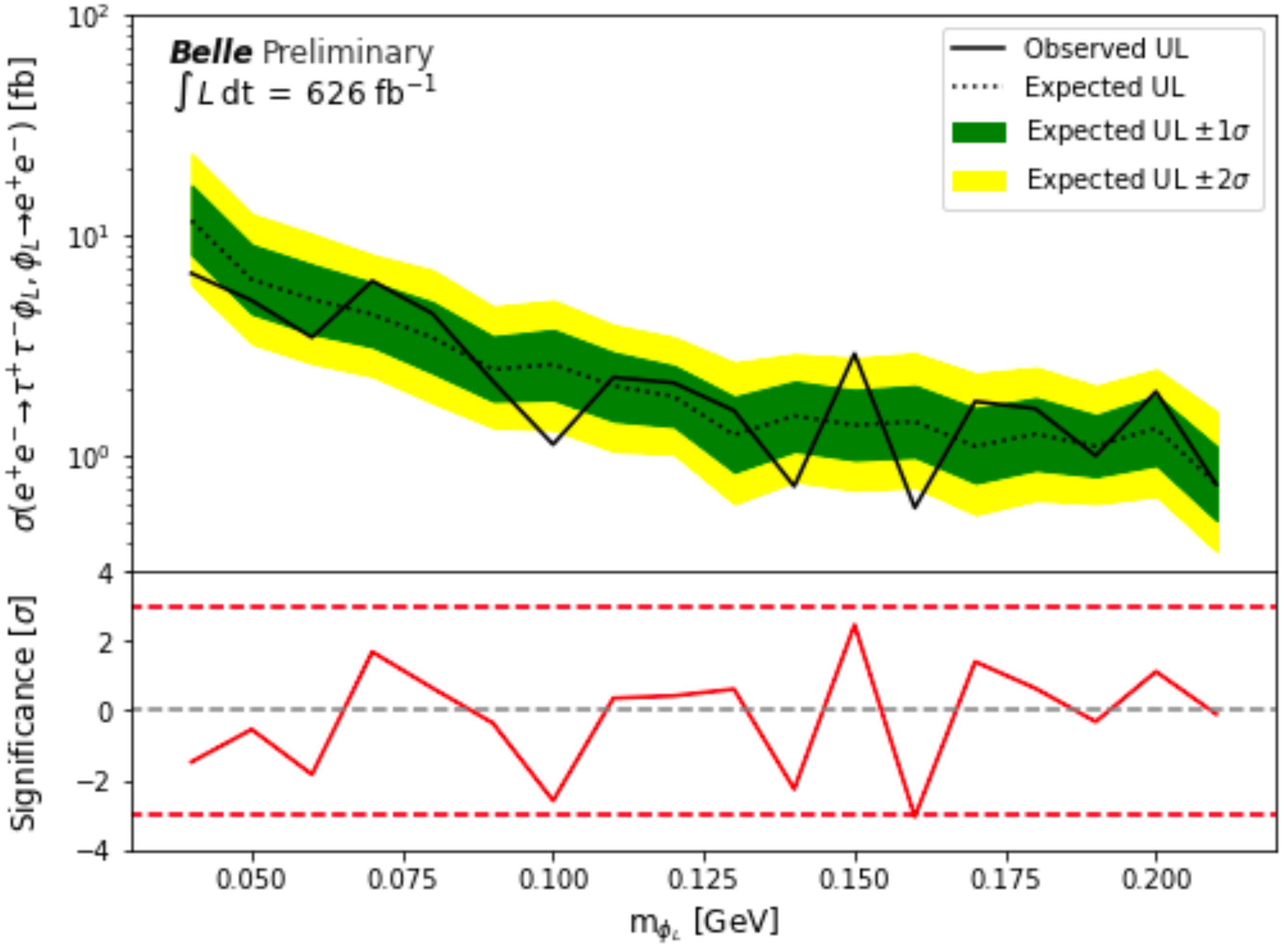
$\phi_L \to \mu^+\mu^-$



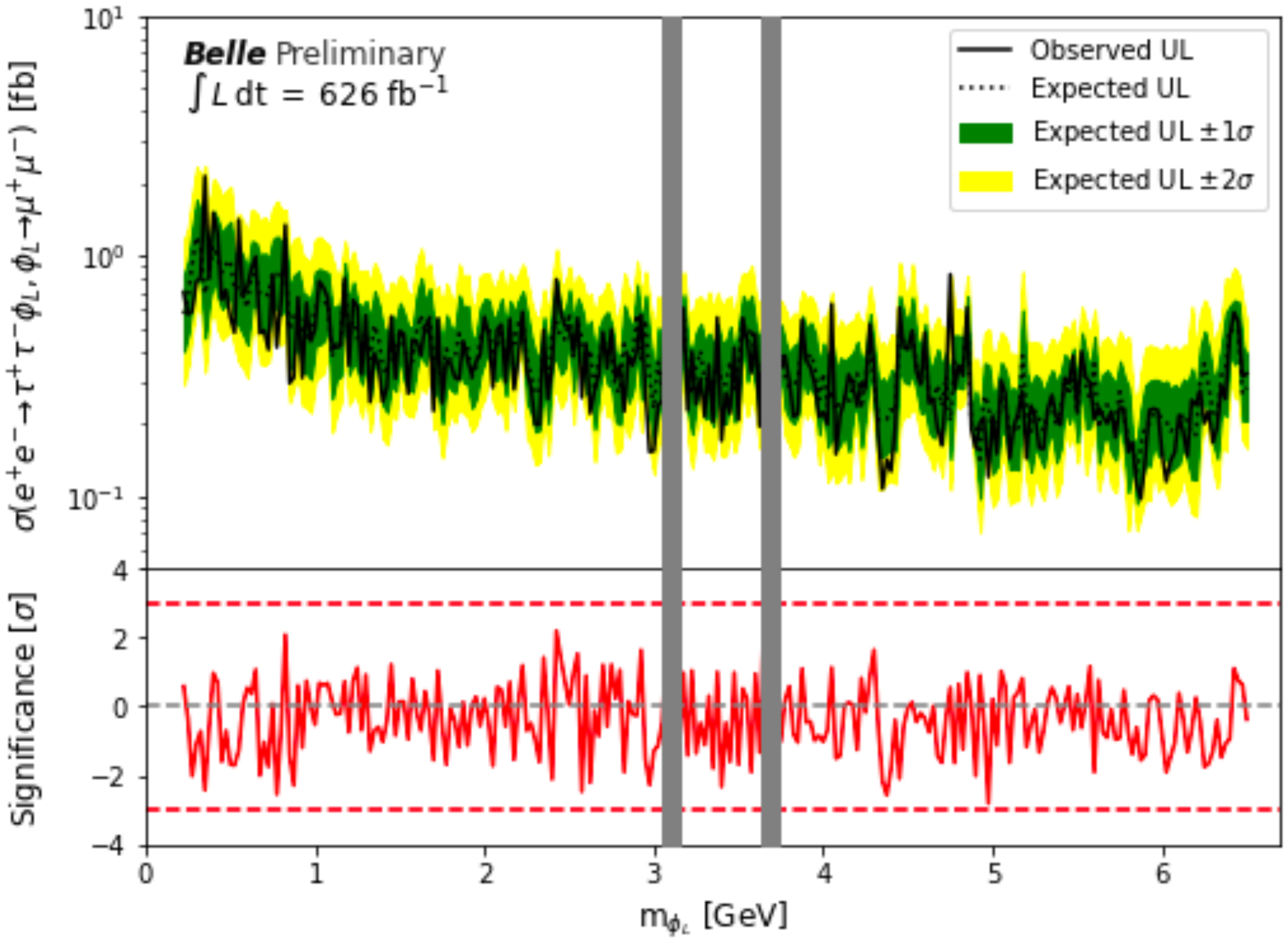
Results

90% confidence level upper limits on the signal cross-section

$\phi_L \to e^+e^-$



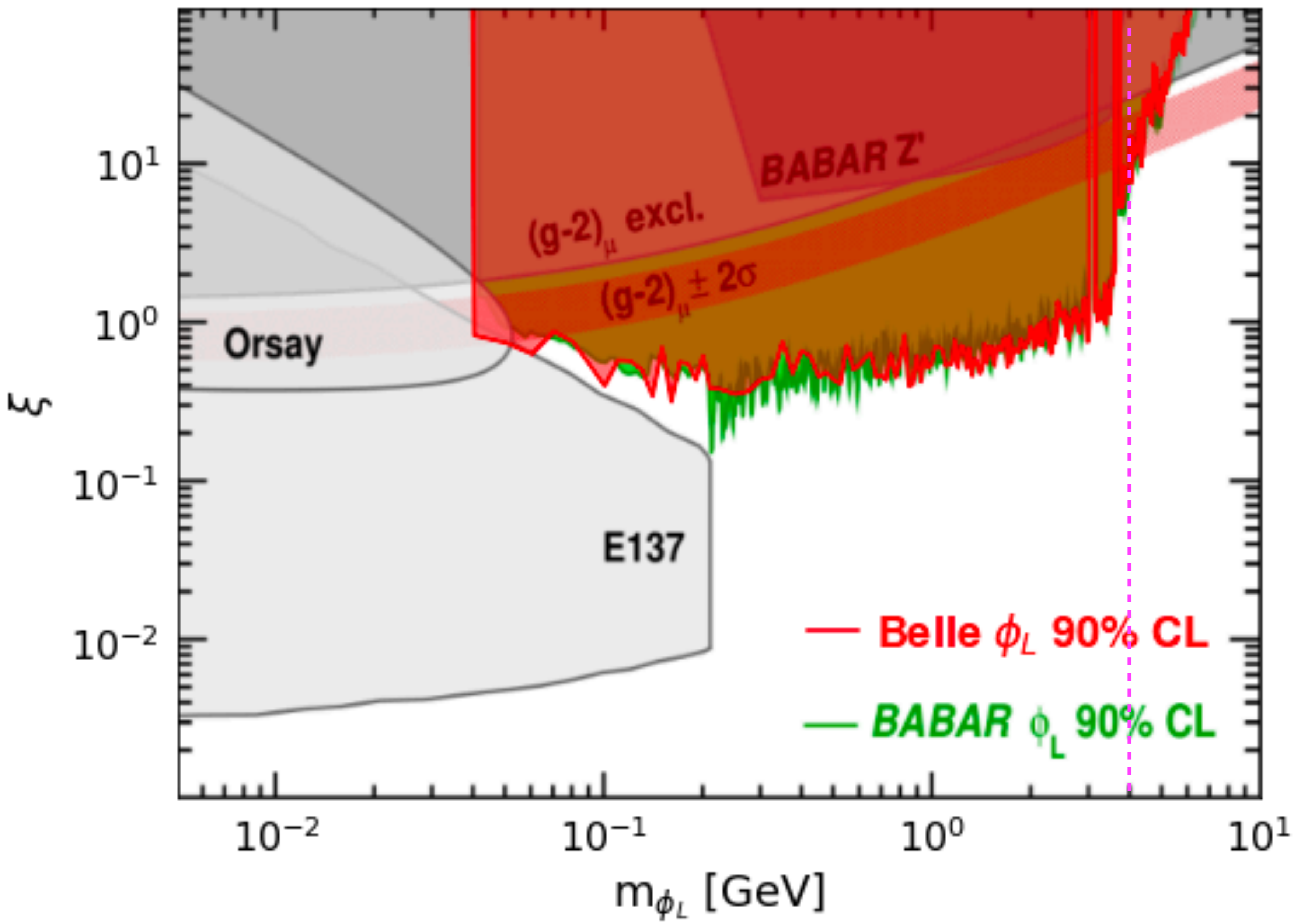
$\phi_L \to \mu^+\mu^-$



Significance < 3 standard deviations for all scan points

Results

90% confidence level upper limits on the coupling constant



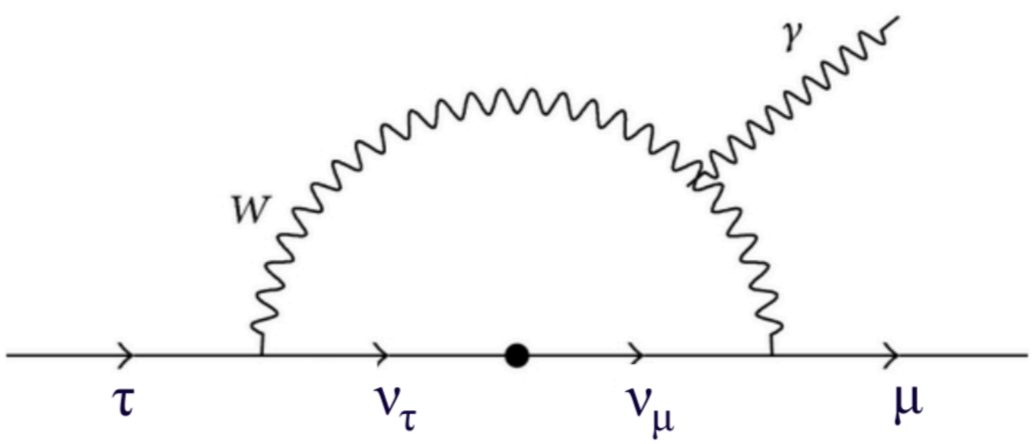
BELLE-CONF-2201

arXiv:2207.07476 **[hep-ex]**

No ϕ_L can explain observed excess in (g-2)$_\mu$ for $m_{\phi_L} < 4$ GeV

Charged Lepton flavor violation in τ decays

LFV is not forbidden by any continuous symmetry
$\Rightarrow$ most new physics (NP) models naturally includes LFV



$\mathcal{B}(\tau^\pm \to \mu^\pm \gamma)$ Lee & Shrock: Phys.Rev.D 16 (1977) 1444

$= \frac{3\alpha}{128\pi}\left(\frac{\Delta m^2_{23}}{M^2_W}\right)^2 \sin^2 2\theta_{\rm mix}\mathcal{B}(\tau \to \mu\bar{\nu}_\mu\nu_\tau)$

With $\Delta \sim 10^{-3}\,\mathrm{eV}^2$, $M_W \sim \mathcal{O}(10^{11})\,\mathrm{eV}$

$\approx \mathcal{O}(10^{-54})$ ($\theta_{\rm mix}$: max)

many orders below experimental sensitivity!

Any observation of LFV $\Rightarrow$ unambiguous signature of NP

LFV in tau sector is complementary to muon sector in NP parameter space: current limit on $\mathscr{B}(\mu \to e\gamma) \sim 10^{-13}$ does not forbid $\mathscr{B}(\tau \to \ell\gamma) \sim 10^{-8}$

Leptonic MFV:	$BR(\mu \to e\gamma)$ / $BR(\tau \to \mu\gamma) \sim s_{13}^2 \sim 10^{-2}$
GUT models:	$BR(\mu \to e\gamma)$ / $BR(\tau \to \mu\gamma) \sim \lvert V_{us}\rvert^6 \sim 10^{-4}$

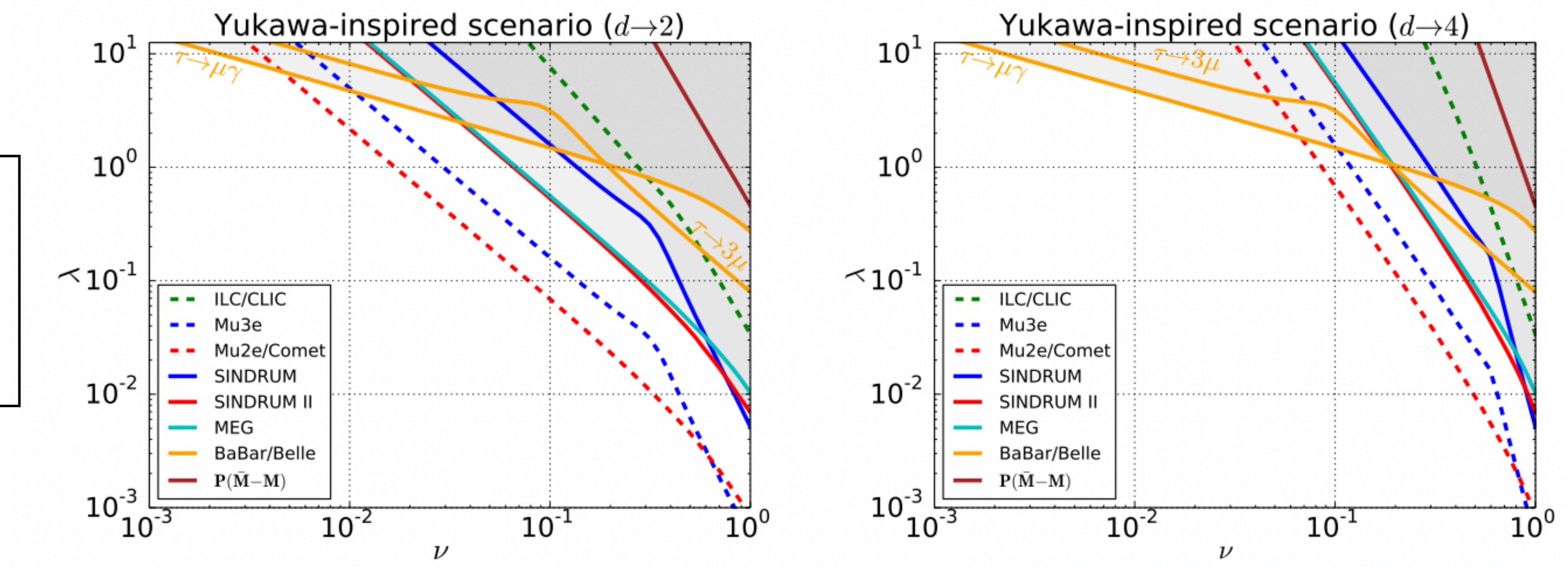
Vincenzo Cirigliano, Benjamin Grinstein, Gino Isidori, Mark B. Wise: hep-ph/0507001 [hep-ph], hep-ph/0608123 [hep-ph]
R. Barbieri, L. Hall, A. Strumia: hep-ph/9501334 [hep-ph]

New Physics expectations

- Mass dependent couplings enhance tau LFV w.r.t. lighter leptons

Low– and high–energy phenomenology of a doubly charged scalar

A. Crivellin et. al.
Phys. Rev. D 99, 035004 (2019)



$$\lambda_{ab} \sim \left(y_a^l y_b^l\right)^{-1}$$

$$\lambda_{ab} = \lambda \begin{pmatrix} \pm 1 & \nu^2 & \nu^3 \\ \nu^2 & \nu^4 & \nu^5 \\ \nu^3 & \nu^5 & \nu^6 \end{pmatrix}$$

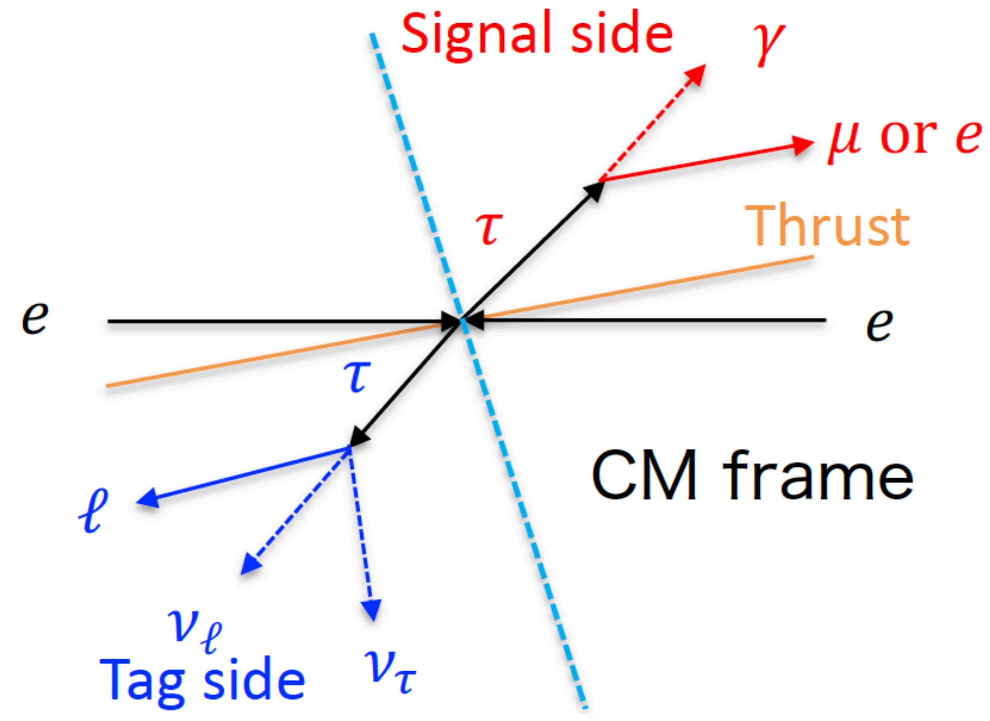
- Some models predict LFV up to existing experimental bounds

	$\mathcal{B}(\tau \to \ell\gamma)$
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}
Non-Universal Z′ (PLB547(2002)252)	10^{-9}
SM+Heavy Majorana ν_{R} (PRD66(2002)034008)	10^{-9}

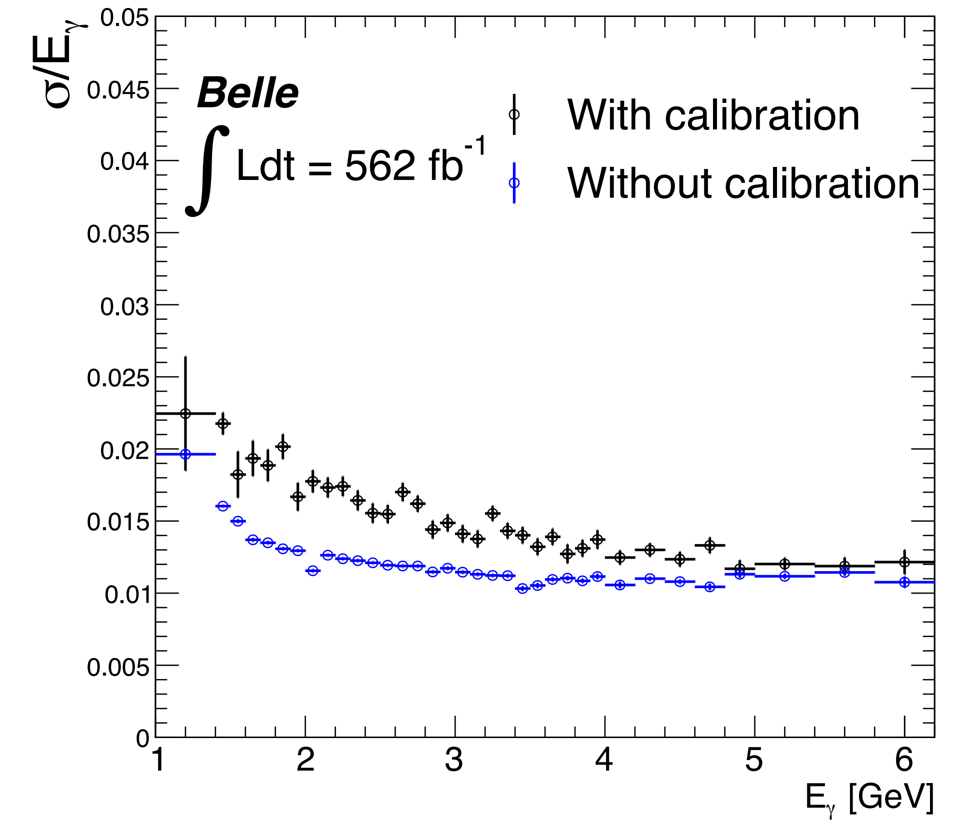
- Normal (Inverted) hierarchy for slepton $\Rightarrow \tau \to \mu\gamma$ ($\tau \to e\gamma$)
  eg. SUSY models: non-diagonal slepton mass matrix $\Rightarrow \mathrm{LFV}$

$\tau^\pm \to \ell^\pm \gamma$

- Event reconstruction:
  - Split event into hemispheres ⊥ to thrust axis ($\hat{n}_T$) which maximizes Thrust = $\max\left(\sum |\vec{p}_i| \cdot \hat{n}_T\right) / \left(\sum |\vec{p}_i|\right)$
  - Require exactly 2 tracks: 1 in signal-side, 1 in tag-side
  - Signal side: $E_\gamma \in [0.1, 6]$ GeV identified in ECL



- Major improvement w.r.t previous analysis performed by the Belle Collaboration [Phys. Lett. B 666, 16 (2008)]:
  - Photon energy calibration with $e^+e^- \to \mu^+\mu^-\gamma$ events
  - Calibrated energy cross-checked with test beam data
    H. Ikeda et al., Nucl.Instrum.Meth.A 441 (2000) 401



Signal characteristics

Beam constraint mass: $M_{\rm bc} = \sqrt{(E^{\rm CM}_{\rm beam})^2 - |\vec{p}^{\,\rm CM}_{\ell\gamma}|^2} \simeq m_\tau$

$$\Delta E/\sqrt{s} = (E^{\rm CM}_{\ell\gamma} - \sqrt{s}/2)/\sqrt{s} \simeq 0$$

Signal PDF fitted to asymmetric Gaussian function: JHEP 10 (2021) 019

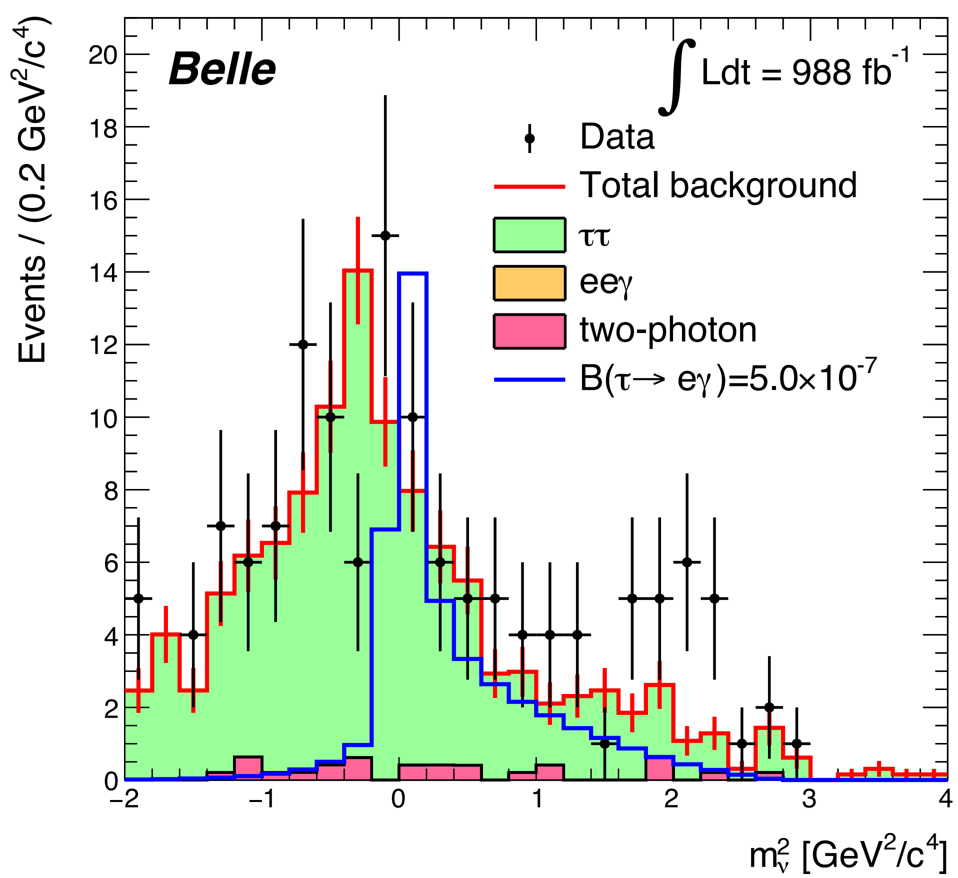
$\tau^\pm \to e^\pm\gamma$	Mean	Width (lower side)	Width (higher side)
$M_{\rm bc}$	1.79 MeV/c^2	(10.59 ± 0.19) MeV/c^2	(11.55 ± 0.27) MeV/c^2
ΔE / $\sqrt{s}$	-1.0 x 10^{-3}	(4.4 ± 0.3) x 10^{-3}	(6.1 ± 0.7) x 10^{-3}

$\tau^\pm \to \mu^\pm\gamma$	Mean	Width (lower side)	Width (higher side)
$M_{\rm bc}$	1.78 MeV/c^2	(7.46 ± 0.23) MeV/c^2	(11.08 ± 0.08) MeV/c^2
ΔE / $\sqrt{s}$	-0.6 x 10^{-3}	(4.2 ± 0.2) x 10^{-3}	(5.6 ± 0.4) x 10^{-3}

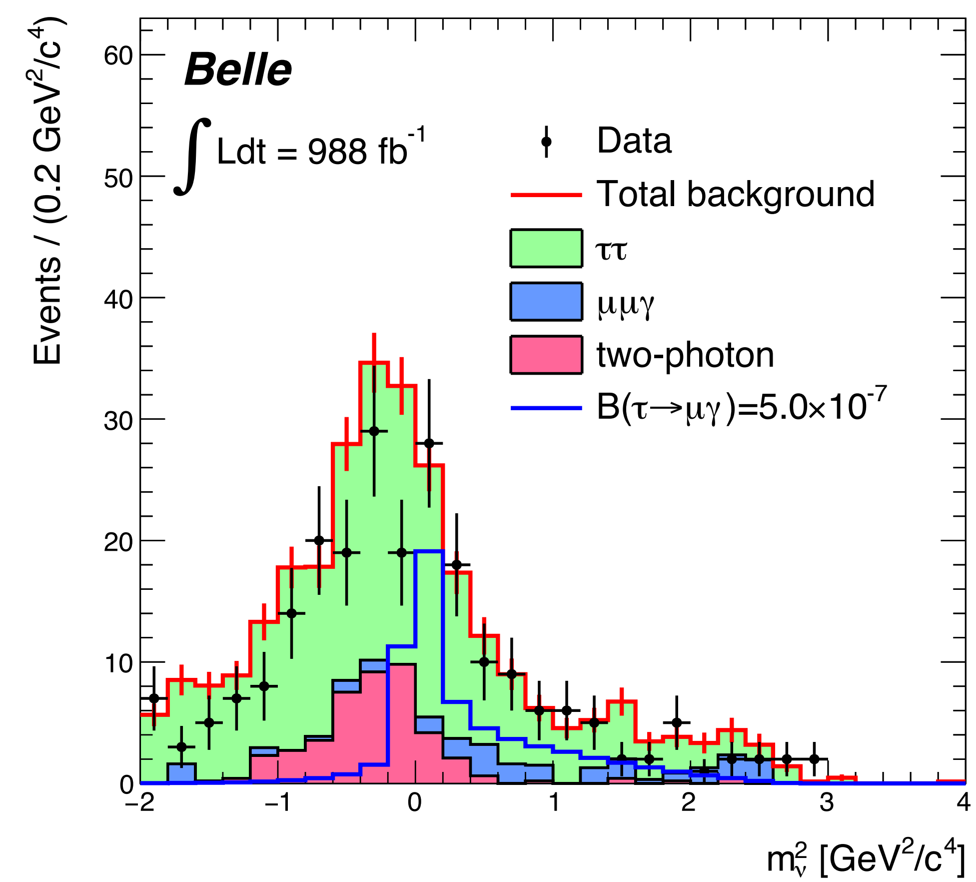
Beam constraint mass has about factor of two better resolution than invariant mass.

Background rejection

- Dominant backgrounds:
  - $\tau^{\pm} \longrightarrow \ell^{\pm}\nu\bar{\nu}$ + ISR γ or beam background
  - $e^{+} e^{-} \longrightarrow \ell^{+}\ell^{-}$ + ISR γ or beam background

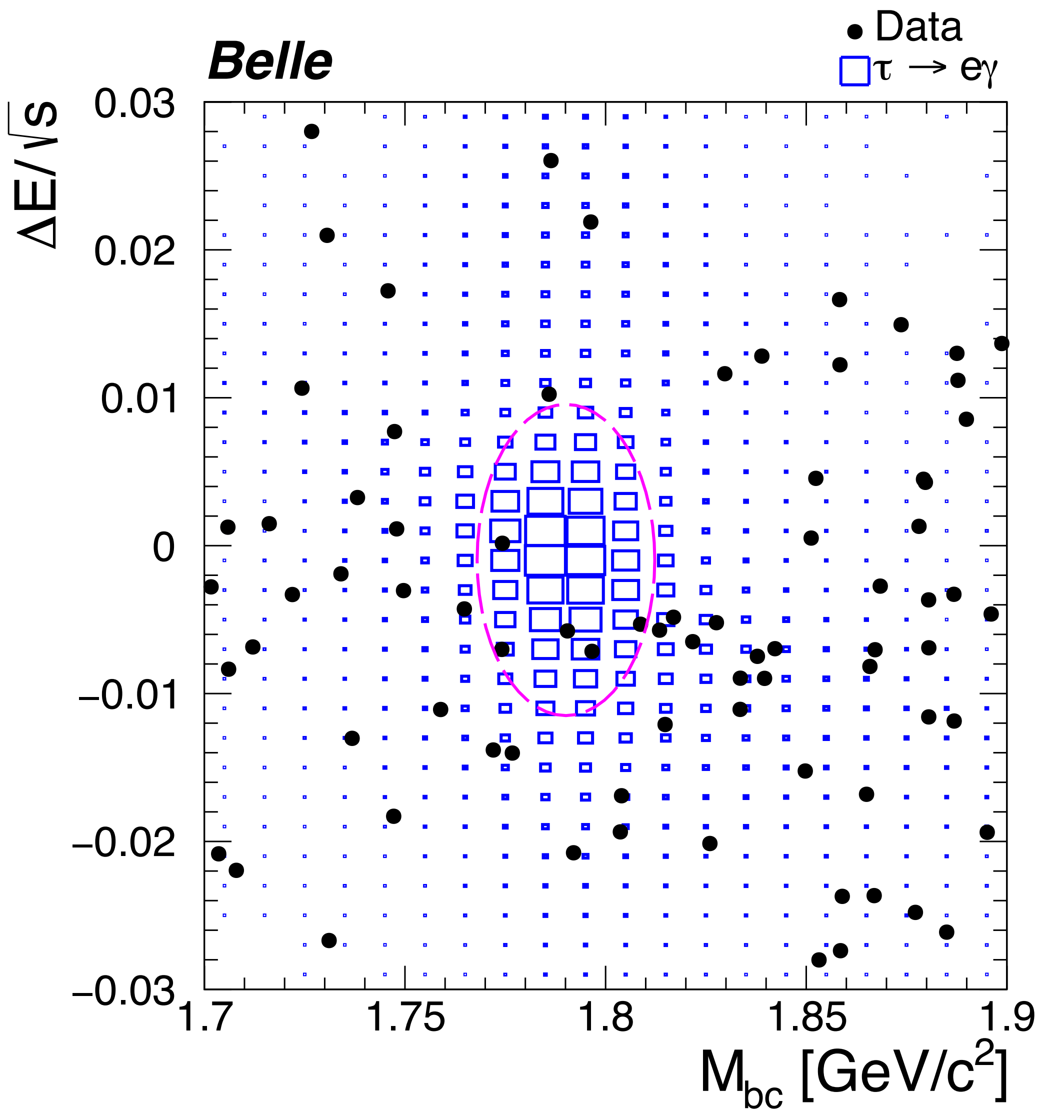


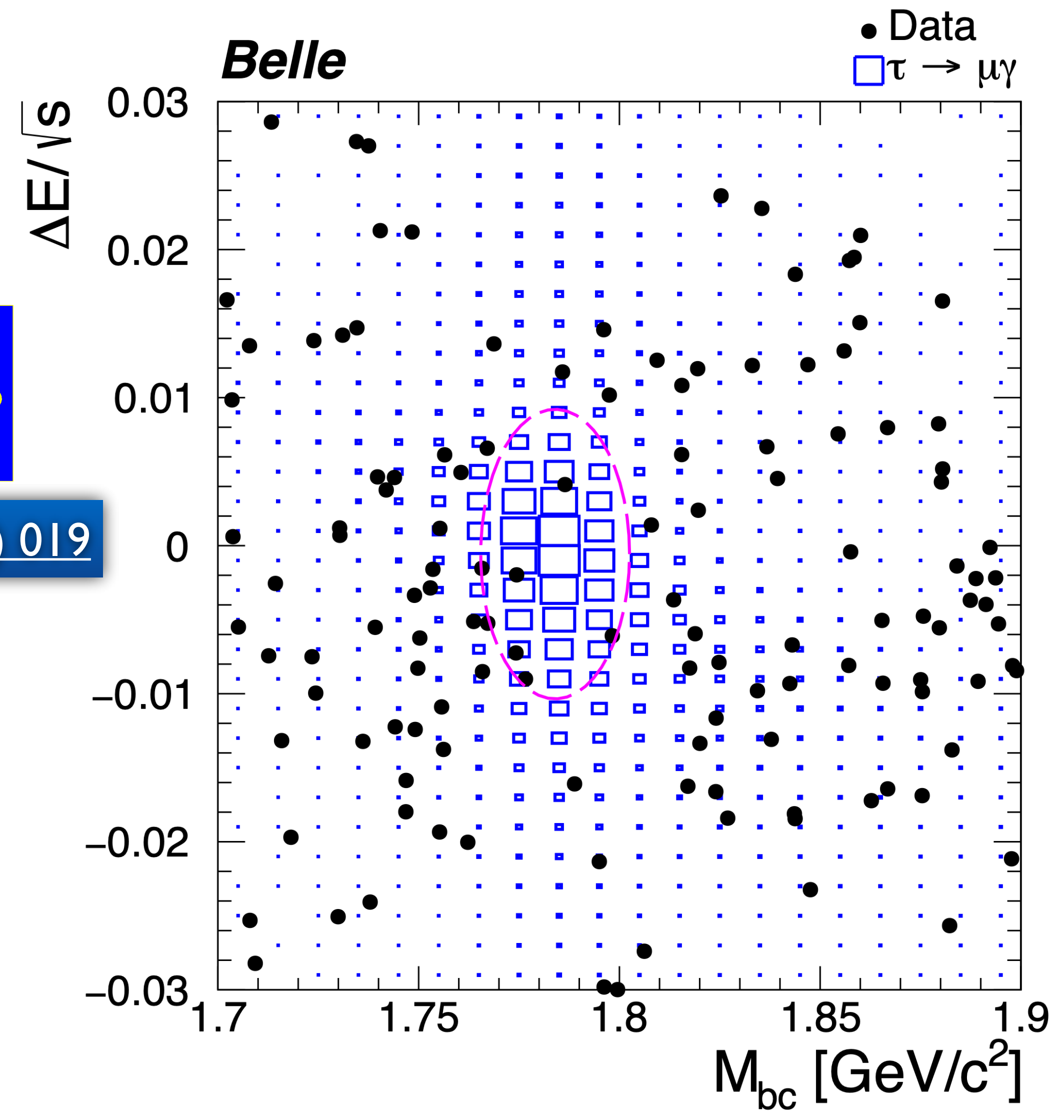
JHEP 10 (2021) 019



# of ν(s) in Signal-side	Signal: 0	$\tau^{+}\tau^{-}$: 1-2	Bhabha, di-muon, $q\bar{q}$: 0
# of ν(s) in Tag-side	Signal: 1-2	$\tau^{+}\tau^{-}$: 1-2	Bhabha, di-muon, $q\bar{q}$: 0

Results





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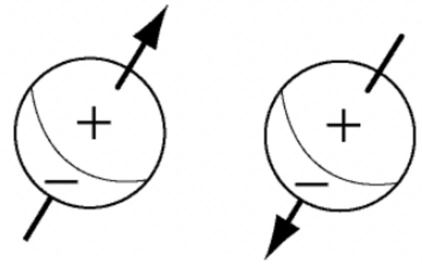
$B\times10^{-8}$ at 90% CL	BaBar $N_{\tau\tau}=477\times10^6$		Belle $N_{\tau\tau}=480\times10^6$		Belle $N_{\tau\tau}=912\times10^6$	
	Exp	Obs	Exp	Obs	Exp	Obs
$B(\tau^\pm\to\mu^\pm\gamma)$	8.2	4.4	8.0	4.5	4.9	4.2
$B(\tau^\pm\to e^\pm\gamma)$	9.8	3.3	12	12	6.5	5.6

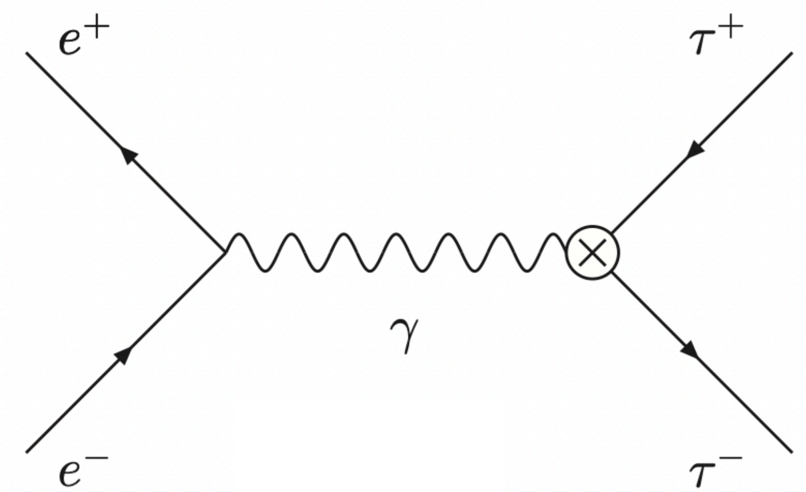
PRL 104 (2010) 021802 | PLB 666 (2008) 16 | JHEP 10 (2021) 019

Electric dipole moment of τ

- Charge asymmetry along spin direction



- EDM $\neq 0 \Rightarrow$ CP, T violation. Search for CP violation in $\tau^-\tau^+\gamma$ vertex.



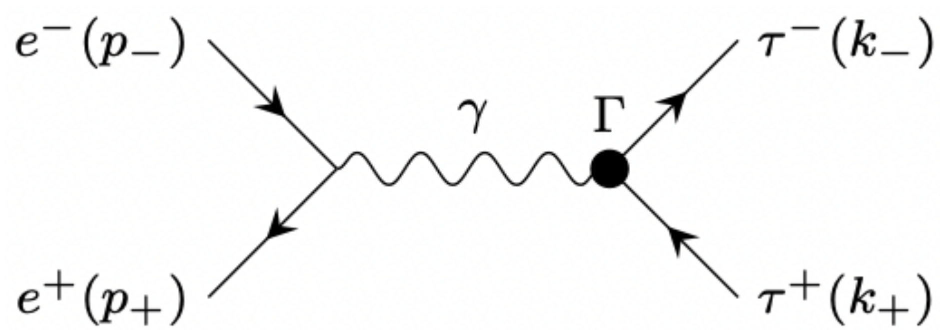
- SM prediction $\simeq \mathcal{O}(10^{-37} e \cdot cm)$ far below experimental sensitivity
- New Physics contributions in loops can enhance EDM $\simeq \mathcal{O}(10^{-19} e \cdot cm)$

W. Bernreuther, O. Nachtmann and P. Overmann, Phys.Lett.B 391 (1997) 413-419, Phys.Lett.B 412 (1997) 425-425 (erratum)

Huang, W. Lu, and Z. Tao, Phys. Rev. D 55 (1997)1643

- EDM $\neq 0 \Rightarrow$ unambiguous signature of New Physics

Electric dipole moment of τ



Incorporating EDM of the τ–lepton: d_τ

$$\mathcal{L} = \bar{\tau}[-eQ\gamma^\mu A_\mu - i d_\tau \sigma^{\mu\nu}\gamma_5 \partial_\mu A_\nu]\tau$$

Cross-section is proportional to squared spin density matrix (χ_{prod}) for the $\tau^+\tau^-$ production vertex :

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

- χ_{SM} is SM term. χ_{Re} and χ_{Im} are interference terms between SM and real and imaginary parts of d_τ.
- χ_{Re} and χ_{Im} : measured from asymmetry in azimuthal and polar angles of τ daughter momenta.

$$\chi_{\text{Re}} \propto -\{m_\tau + (k_0 - m_\tau)(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2\}(\boldsymbol{S}_+ \times \boldsymbol{S}_-)\cdot\hat{\boldsymbol{k}} + k_0(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})(\boldsymbol{S}_+ \times \boldsymbol{S}_-)\cdot\hat{\boldsymbol{p}},$$

$$\chi_{\text{Im}} \propto -\{m_\tau + (k_0 - m_\tau)(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})^2\}(\boldsymbol{S}_+ - \boldsymbol{S}_-)\cdot\hat{\boldsymbol{k}} + k_0(\hat{\boldsymbol{k}}\cdot\hat{\boldsymbol{p}})(\boldsymbol{S}_+ - \boldsymbol{S}_-)\cdot\hat{\boldsymbol{p}},$$

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

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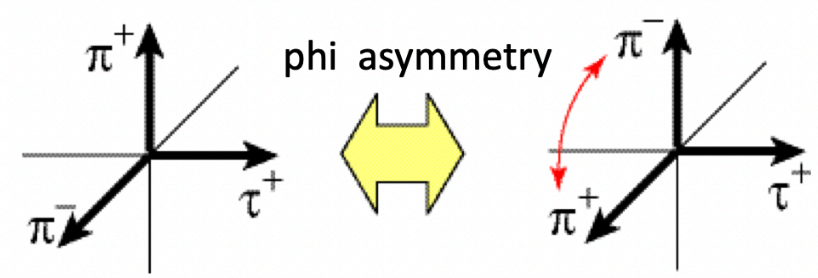
$\chi_{\text{Re}} \sim (\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{k}}$, $(\boldsymbol{S}_+ \times \boldsymbol{S}_-)\hat{\boldsymbol{p}}$ CP-odd, T-odd



$\chi_{\text{Im}} \sim (\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{k}}$, $(\boldsymbol{S}_+ - \boldsymbol{S}_-)\hat{\boldsymbol{p}}$ CP-odd, T-even

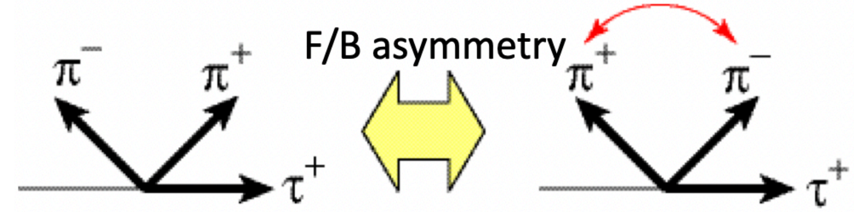


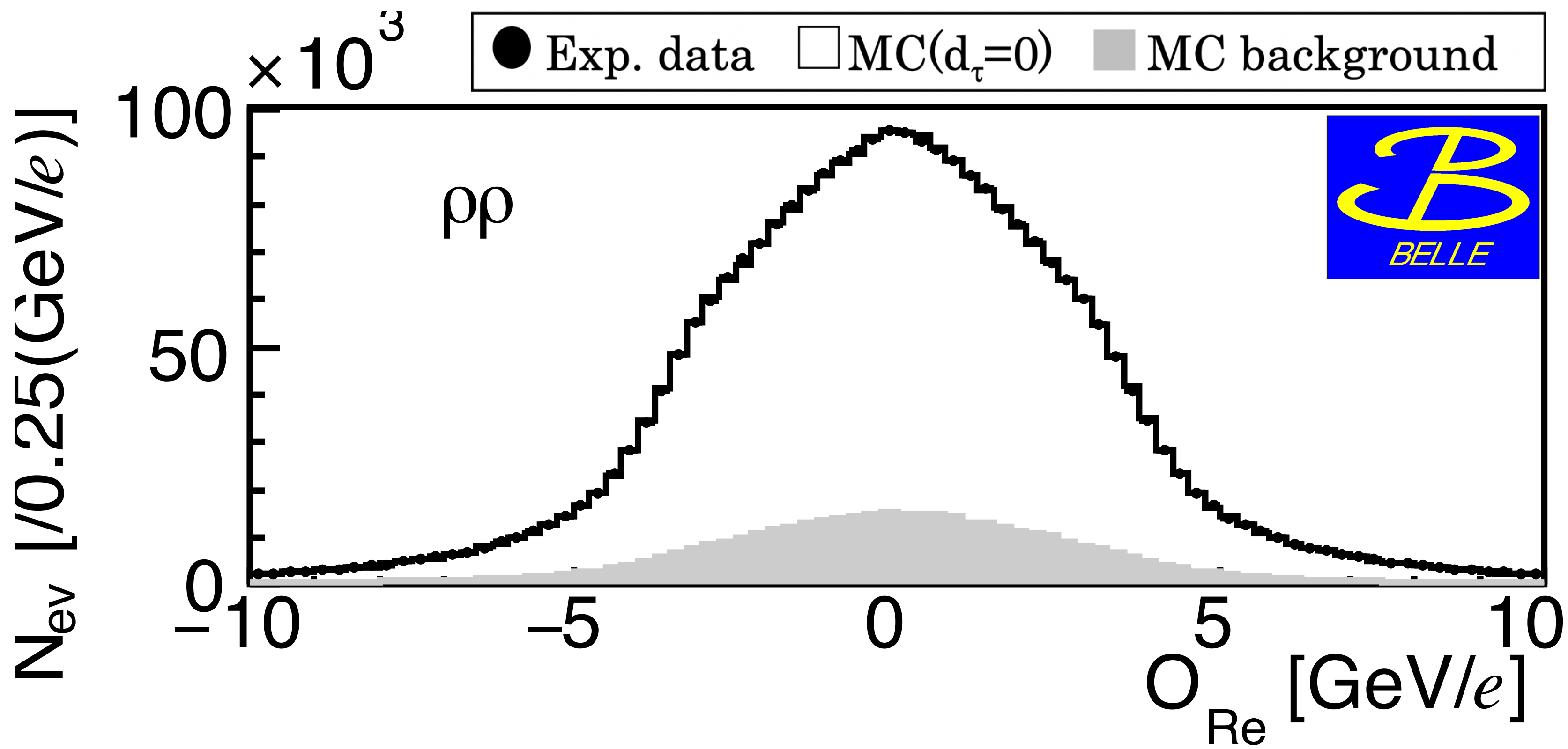
Image courtesy: K. Inami (Tau2021)

Electric dipole moment of τ

- Mean values of optimal observable ($\mathcal{O}$) linearly depend on EDM (d_τ) :

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

W. Bernreuther, O. Nachtmann, P. Overmann, Phys.Rev.D 48 (1993) 78 D. Atwood, A. Soni, Phys.Rev.D 45 (1992) 2405



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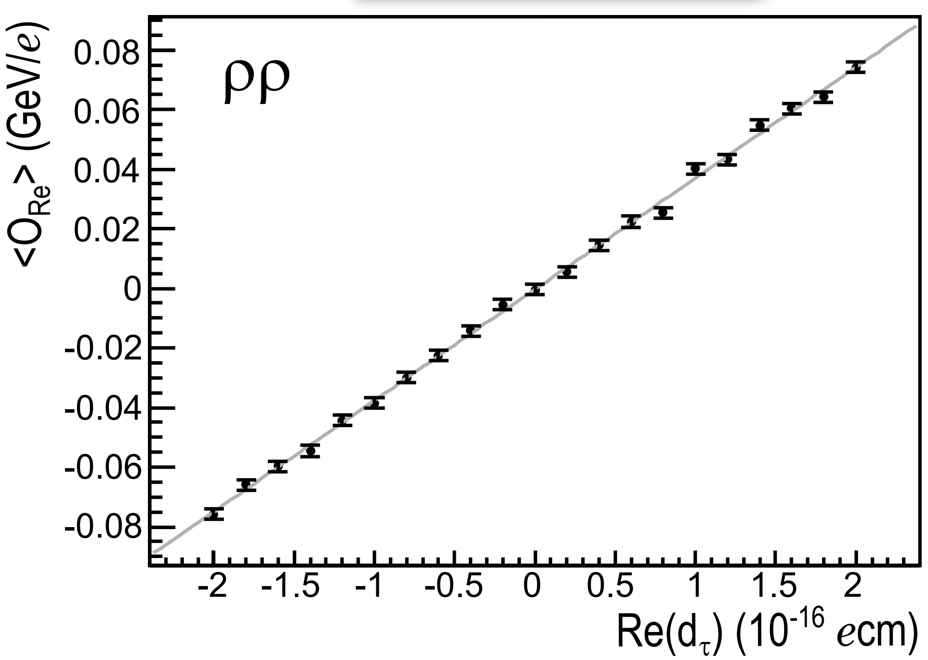

- 8 final states studied: $e\mu, e\pi, e\rho, \mu\pi, \mu\rho, \pi\pi, \pi\rho, \rho\rho$
- Most probable direction of spin vector obtained by averaging over all possible $\tau-$directions:
  - 2-fold ambiguity in case both the $\tau-$leptons decay hadronically
  - Additional ambiguity if any of 2 $\tau-$leptons decay leptonically: MC scan 100 points in $m^2_{\nu\bar{\nu}}$

Systematic uncertainties

$\mathrm{Re}(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
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 diffedence 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 diffedence 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

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Results

Summary of previous results

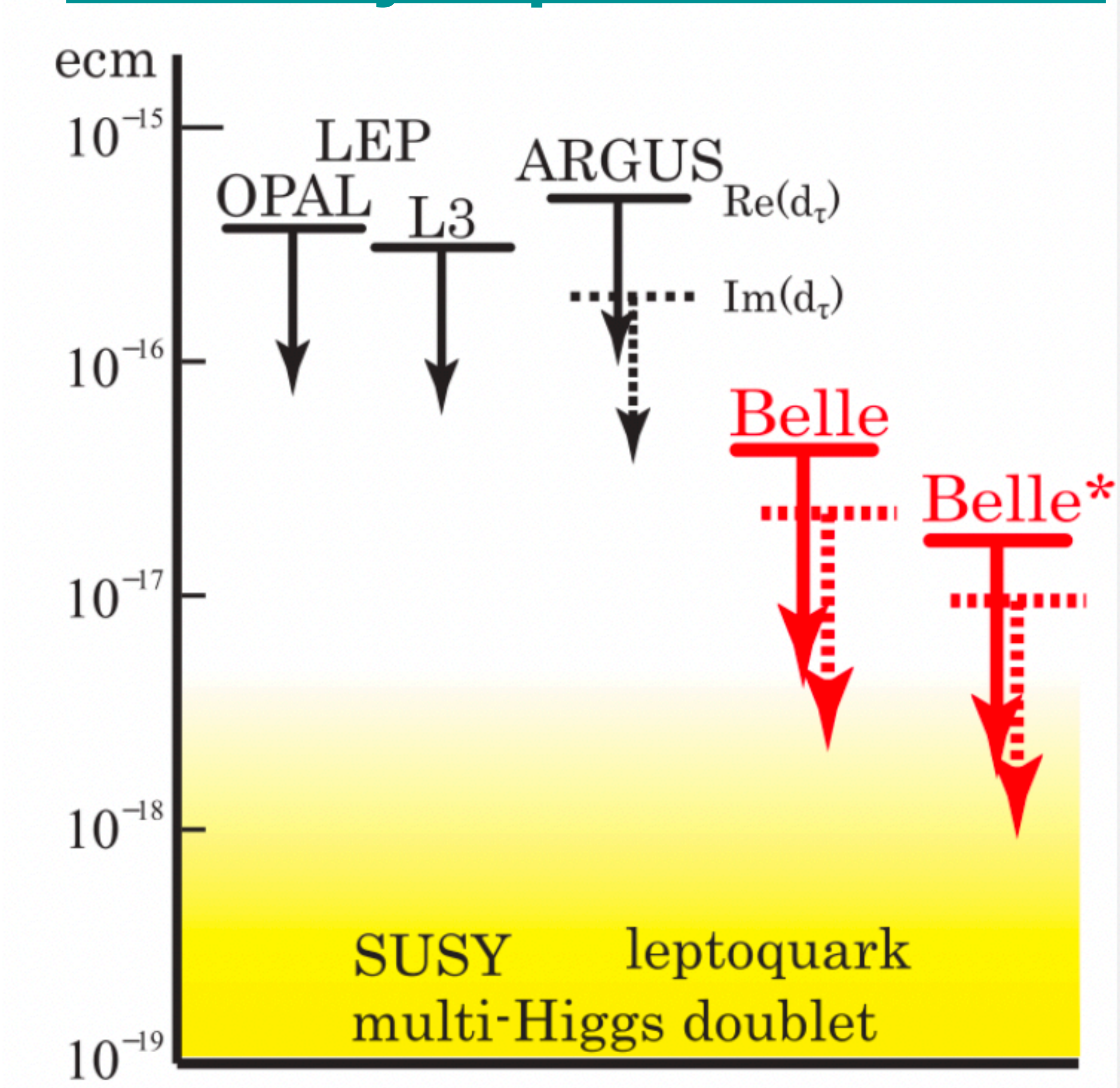

Image courtesy: K. Inami (Tau2021)

– Belle; 29.5fb^{-1} data [PLB 551(2003)16]

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

- Belle; 833 fb^{-1} data (arXiv:2108.11543 **[hep-ex]**)
  – 95% confidence intervals JHEP 04 (2022) 110

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

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

- Consistent with zero EDM
- Systematic errors similar to statistical
- 2.7 times more precise than previous result

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 $(g\text{-}2)_\mu$ anomaly, till φ_L mass of 4 GeV.

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arXiv:2207.07476 **[hep-ex]**

- Search for LFV in $\tau \to \ell\gamma$ decays
  - Performed using 988 fb^{-1} of Belle data and improved analysis technique.
  - Most stringent limits for $\tau \to \mu\gamma$ at 90% CL.

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- Search for tau EDM
  - Performed using 833 fb^{-1} of Belle data and optimal observable technique.
  - Improved simulation and MC statistics: reduced uncertainty.

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