Search for tau LFV/LNV decays at Belle

Tau2021(ONLINE)

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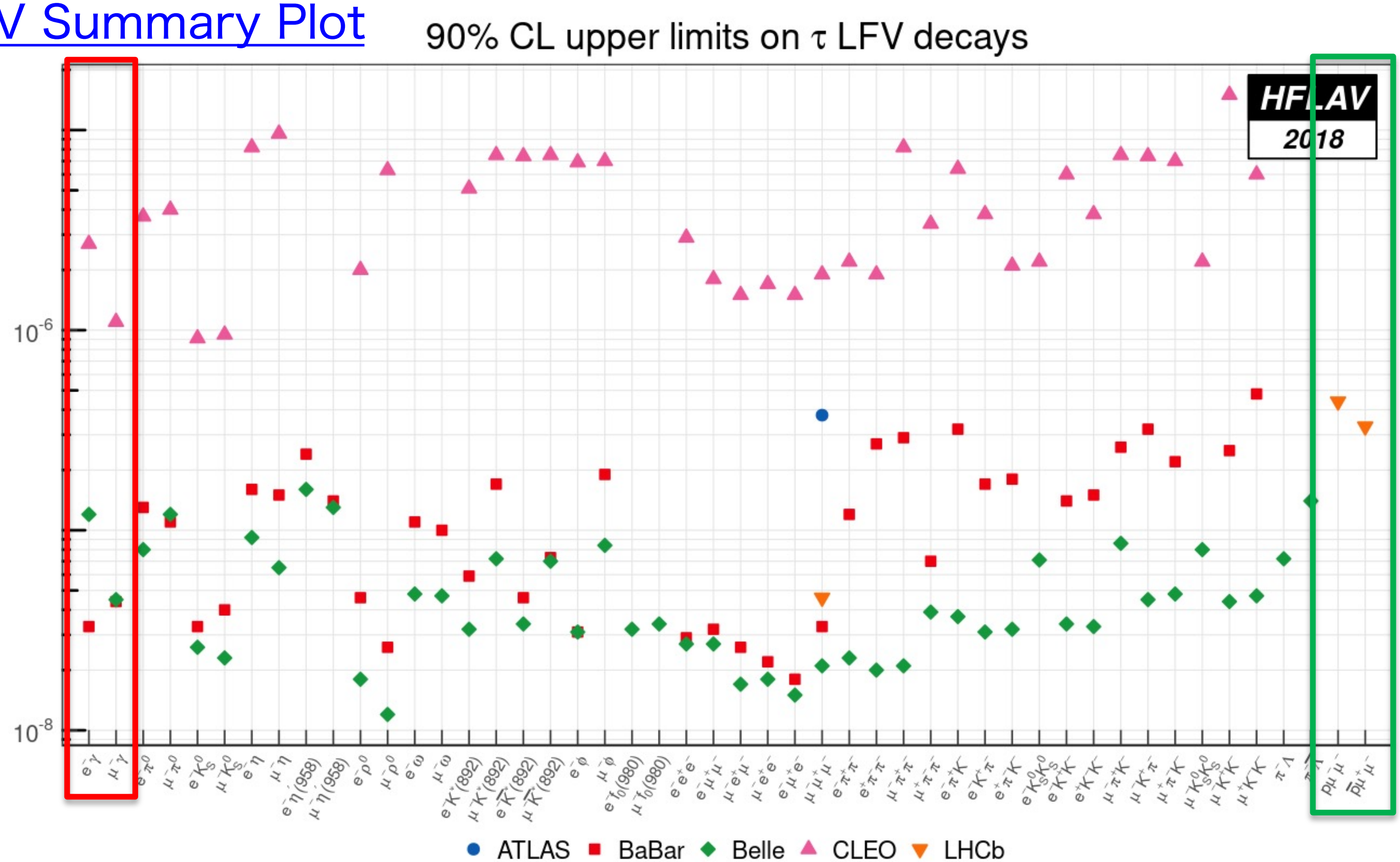
Introduction

- Two results using tau decays at Belle
  - Tau LFV: $\tau \to \ell\gamma \ (\ell = e, \mu)$ — [K.Uno et al. arXiv:2103.12994](#) accepted by JHEP
  - Tau LNV/BNV: $\tau \to p\ell\ell' \ (\ell^{(\prime)} = e, \mu)$ — [D.Sahoo et al. PhysRevD.102.111101](#)

[HFLAV Summary Plot](#)

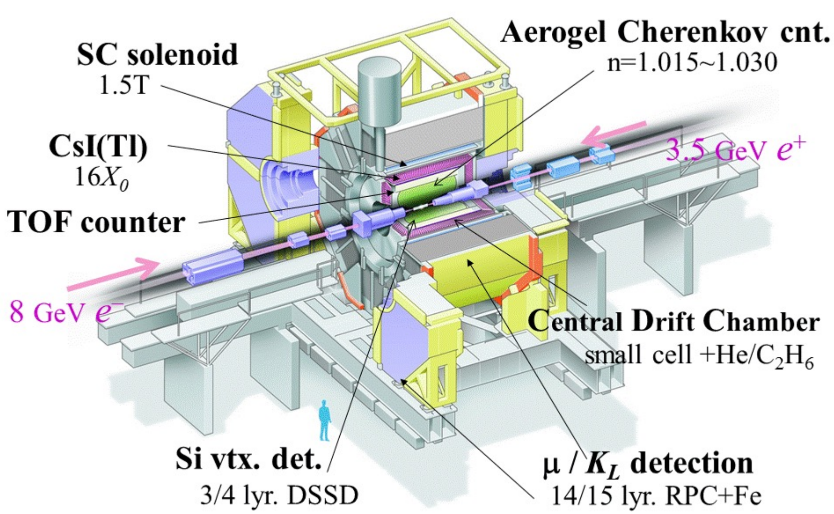


Belle experiment

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

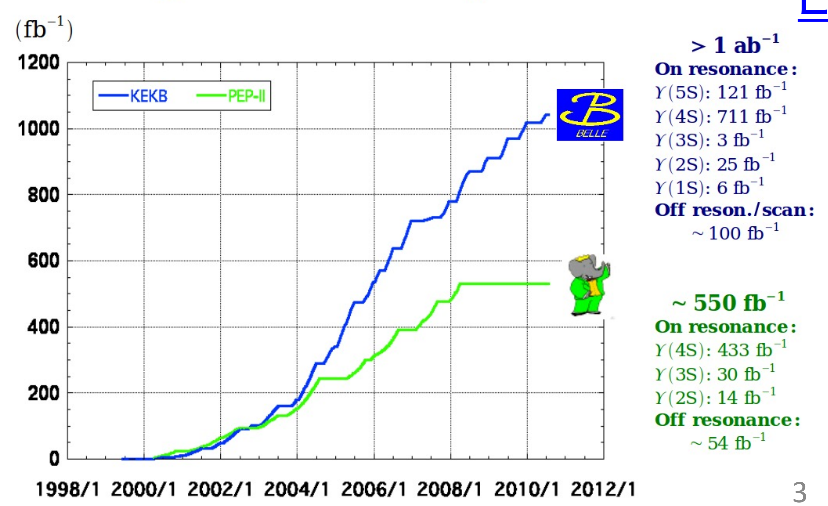
→ In total, $9.1 \times 10^8\ N_{\tau\tau}$ (Ref. BaBar: $4.8 \times 10^8\ N_{\tau\tau}$)

Belle Detector



Integrated luminosity of B factories

Link



Search for tau LFV decays

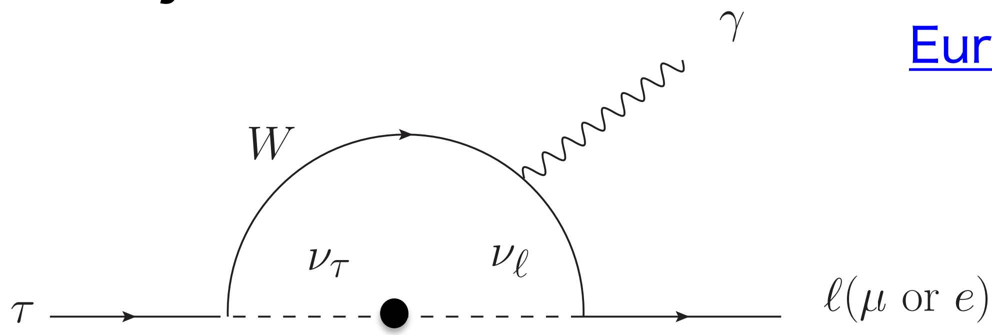
$$\tau \to \ell\gamma$$

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

Charged Lepton Flavor Violation (CLFV)

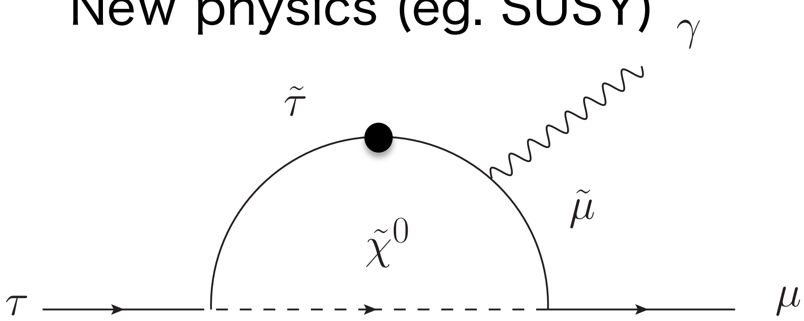
- Small probability via neutrino oscillations: $B(\tau \to \mu\gamma) < O(10^{-40})$

Eur.Phys.J.C8,3(1999)



- $\tau \to \ell\gamma$: 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

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

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

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

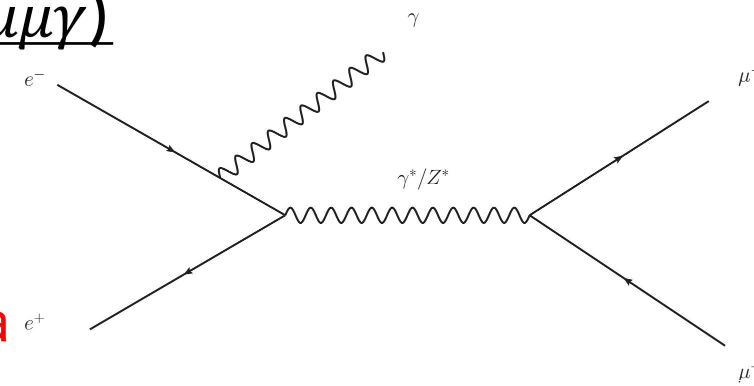
We updated the results of a search for $\tau \to \ell\gamma$

- 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 $ee \to \mu\mu\gamma$

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

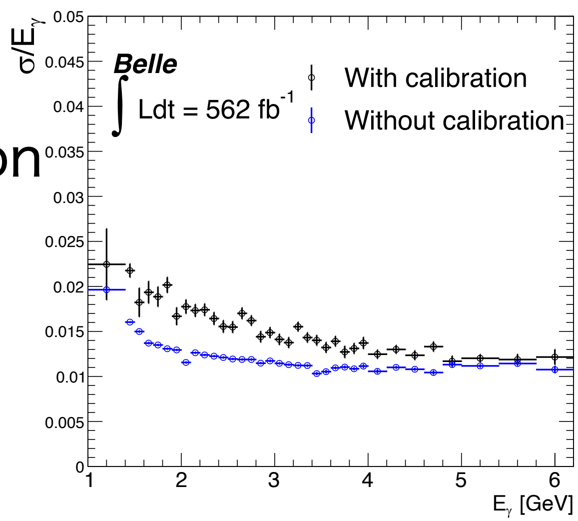


Goal

- 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



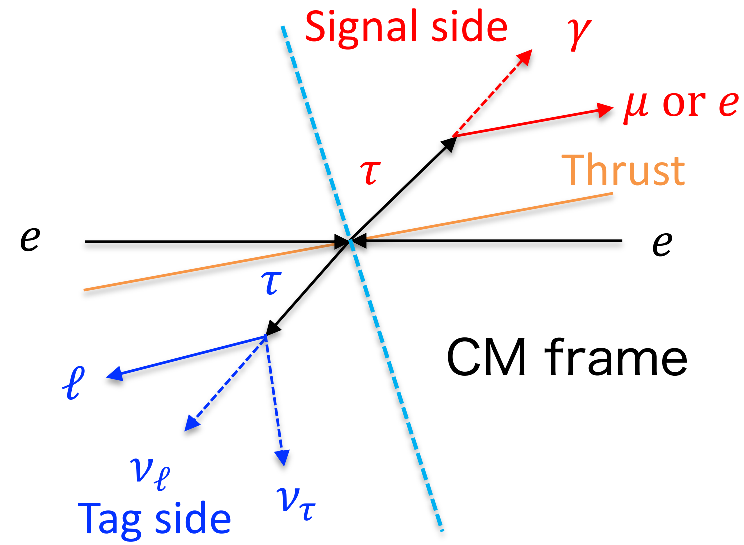
<u>Energy range: 1 GeV – 6 GeV</u> NEW!

- Calibrated resolution agrees with that in data

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

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

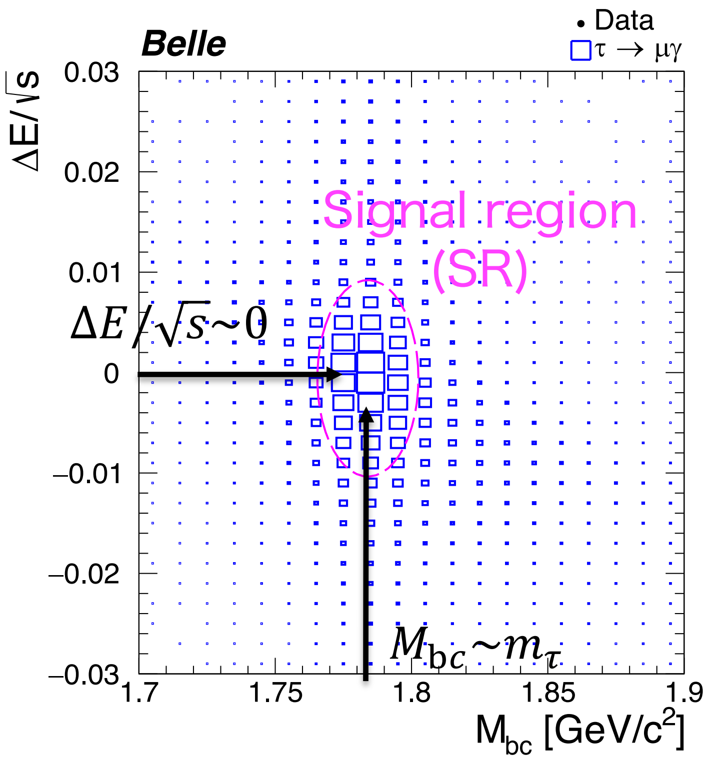
Background component

- $\tau \to \ell\nu\nu$ + ISR γ or beam bkg
- $ee \to \mu\mu/ee$ + ISR γ or beam bkg

Signal extraction

- Perform UEML fit to the SR

Unbinned Extended Maximum Likelihood

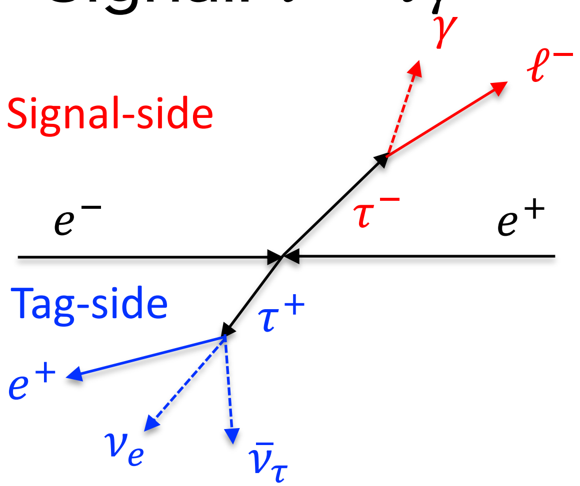


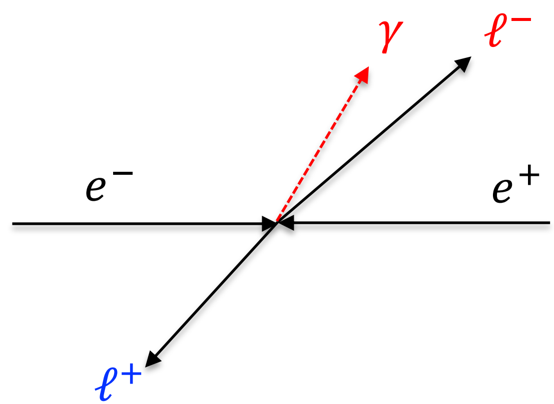
※ use M_{bc} instead of M_{inv}

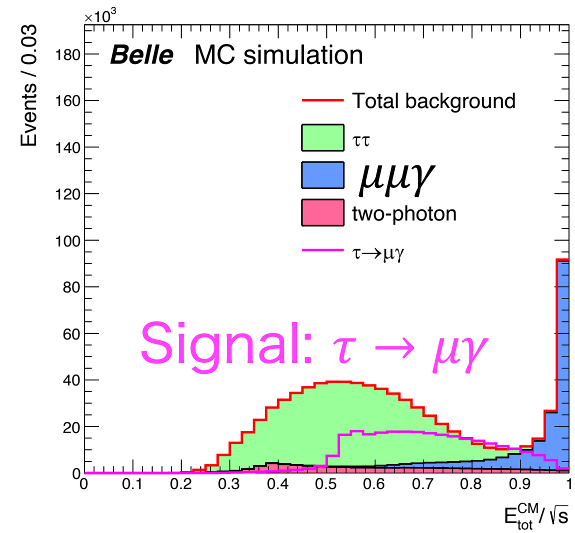
Event Selection 1

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 ($E_{\mathrm{tot}}^{\mathrm{CM}}/\sqrt{s}$)

- $\tau \to \ell\gamma$: $N_\nu > 0$ 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!

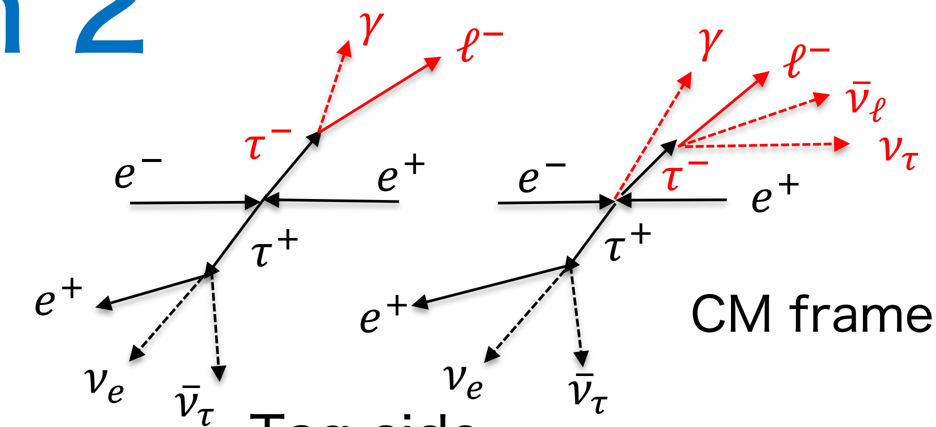
Optimized selection per channel: ℓ, π, ρ channel

※ All selection criteria are optimized to maximize search sensitivity

Event Selection 2

New observable

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



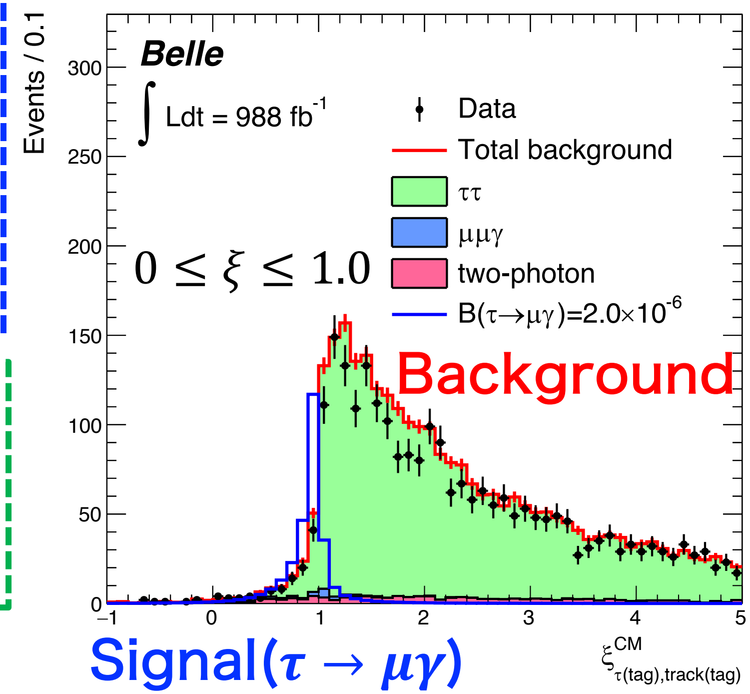
Ideal signal events,

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

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

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

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



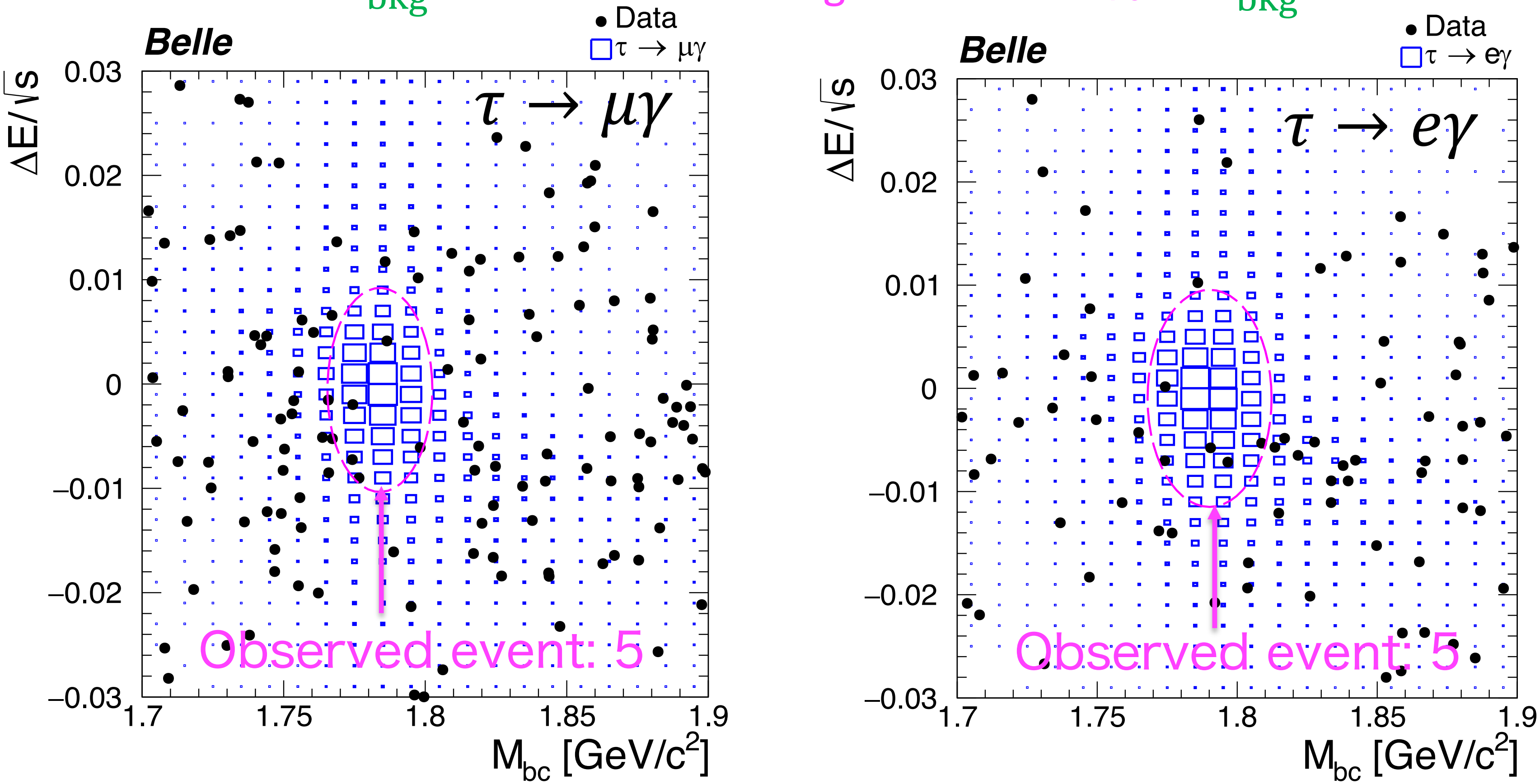
NEW!

Good separation between signal and background

Result

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

Signal eff. = 3.7% $N_{bkg}^{exp} = 5.8 \pm 0.4$ Signal eff. = 2.9% $N_{bkg}^{exp} = 5.1 \pm 0.4$



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 $N_{\tau\tau} = 4.8\times10^8$		Belle $N_{\tau\tau} = 4.8\times10^8$		Belle $N_{\tau\tau} = 9.1\times10^8$	
	Exp	Obs	Exp	Obs	Exp	Obs
$B(\tau \to \mu\gamma)$	8.2	4.4	8.0	4.5	4.9	4.2
$B(\tau \to e\gamma)$	9.8	3.3	12	12	6.5	5.6

- Expected limits: factor 1.5 – 1.7 improved
- Observed limits, $\tau \to \mu\gamma$: Most stringent limit to the date

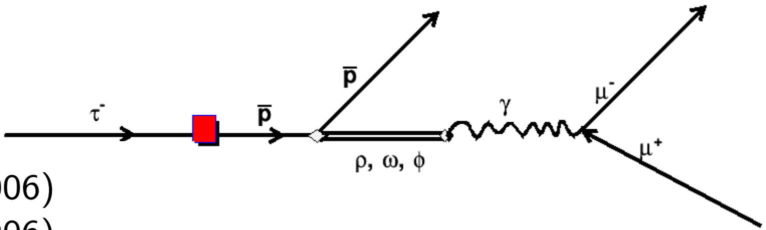
Search for tau LNV/BNV decays $\tau \to p\ell\ell'$

Motivation

Matter-antimatter asymmetry in nature

- Need Baryon number violation (BNV) Sakharov's condition
- BNV in charged lepton decays → lepton number violation (LNV)

Past search in BNV/LNV



Belle: $\mathcal{B}(\tau^- \to \Lambda\pi^-) < 0.72 \times 10^{-7}$ Phys.Lett.B 632, 51-57 (2006)
Belle: $\mathcal{B}(\tau^- \to \overline{\Lambda}\pi^-) < 1.4 \times 10^{-7}$ Phys.Lett.B 632, 51-57 (2006)

CLEO: $\mathcal{B}(\tau^- \to \overline{p}\gamma) < 3.5 \times 10^{-6}$ Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}\pi^0) < 1.5 \times 10^{-5}$ Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}2\pi^0) < 3.3 \times 10^{-5}$ Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}\eta) < 8.9 \times 10^{-6}$ Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}\pi^0\eta) < 2.7 \times 10^{-5}$ Phys. Rev. D 59, 091303(R) (1999)

LHCb: $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$ Phys. Lett. B 724 (2013)
LHCb: $\mathcal{B}(\tau^- \to \overline{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$ Phys. Lett. B 724 (2013)

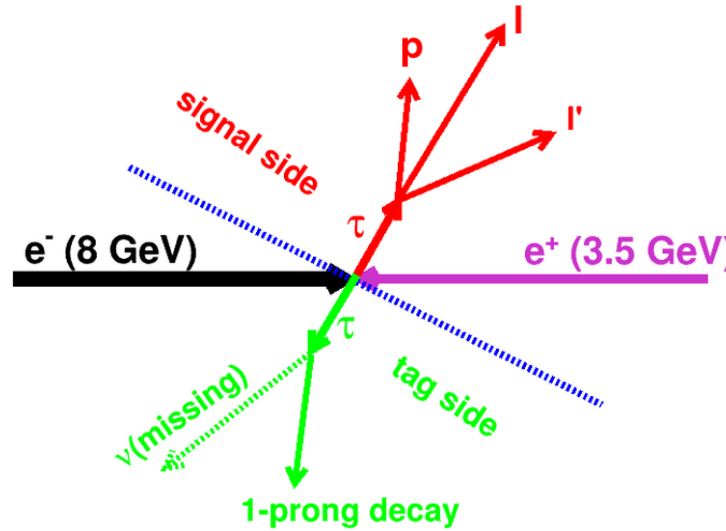
We search for six decays $\tau^- \to \bar{p}e^+e^-, pe^-e^-, \bar{p}e^+\mu^-, \bar{p}e^-\mu^+, p\mu^-\mu^-$ and $\bar{p}\mu^+\mu^-$ using 921 fb^{-1} at Belle

※ This search uses $\Upsilon(4S), \Upsilon(5S)$ and off-resonance data

Analysis approach

Signal-side: Reconstruct p, ℓ, ℓ'

Tag-side: 1prong τ decays

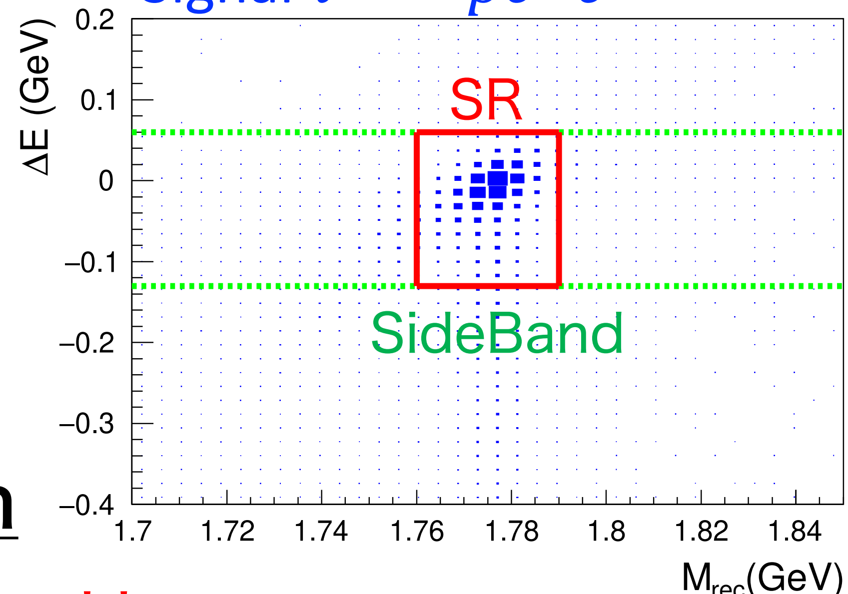


Signal region (SR) definition

$$M_{\text{rec}} = \sqrt{(E_{p\ell\ell'})^2 - (\vec{p}_{p\ell\ell'})^2}$$

$$\Delta E = (E^{\text{CM}}_{p\ell\ell'} - E^{\text{CM}}_{\text{beam}})$$

Signal $\tau^- \to \bar{p}e^+e^-$



Background component

- $\tau\tau$ SM decay, $ee \to \ell\ell$, $ee \to ee\ell\ell$

SideBand region definition

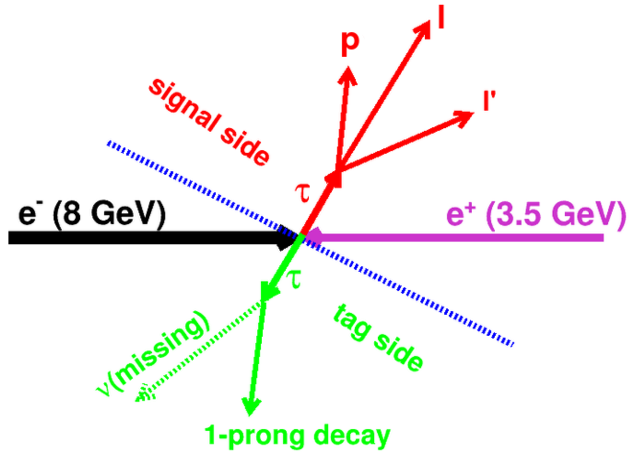
- $\Delta\text{E} - \text{M}_{\text{rec}}$ region outside the red box

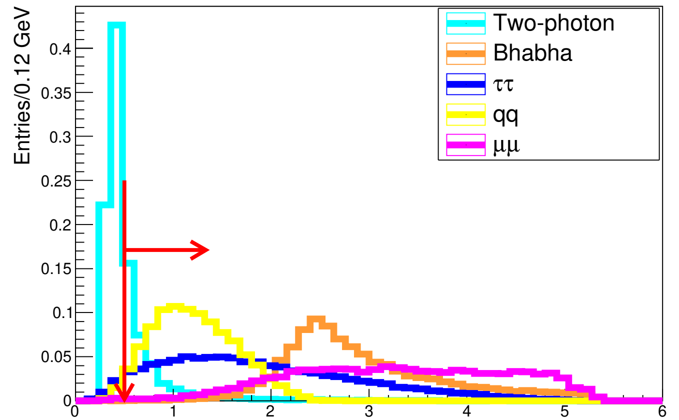
→ Used it to calculate expected N_{bkg} in the SR

Event Selection

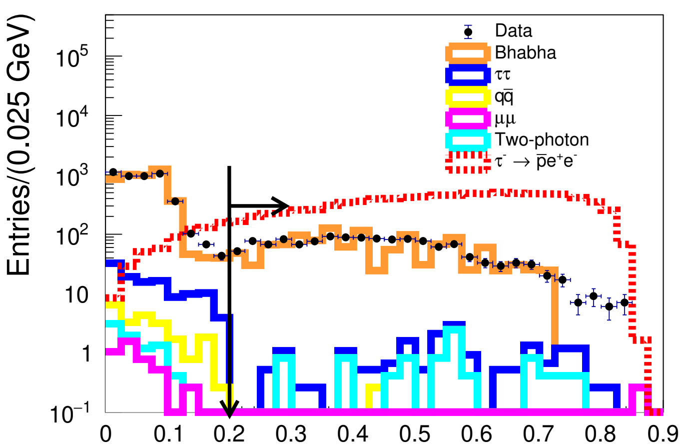
Several observables are used

- Maximum p_T of charged tracks
- Event shape variable: Thrust
- $cos\theta^{\mathrm{CM}}_{\mathrm{tag,miss}}$ and θ_{miss}
- γ conversion veto
  - Photon conversion in the detector material constitutes a major bkg for $\tau^- \to \bar{p}e^-e^+, pe^-e^-, \bar{p}e^+\mu^-, p\mu^-\mu^+$

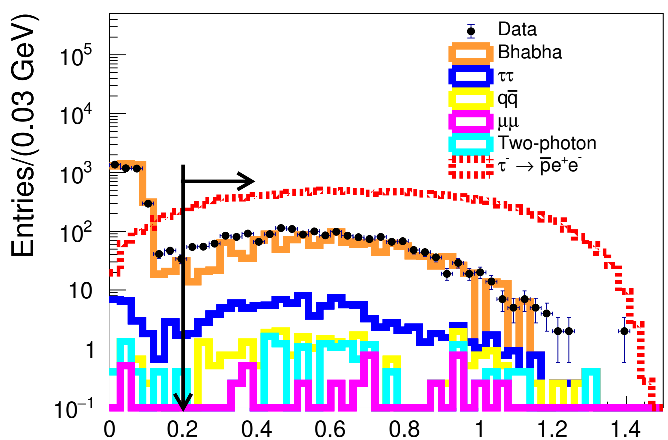




p_T^{max} [GeV]



M_{ee} [GeV]

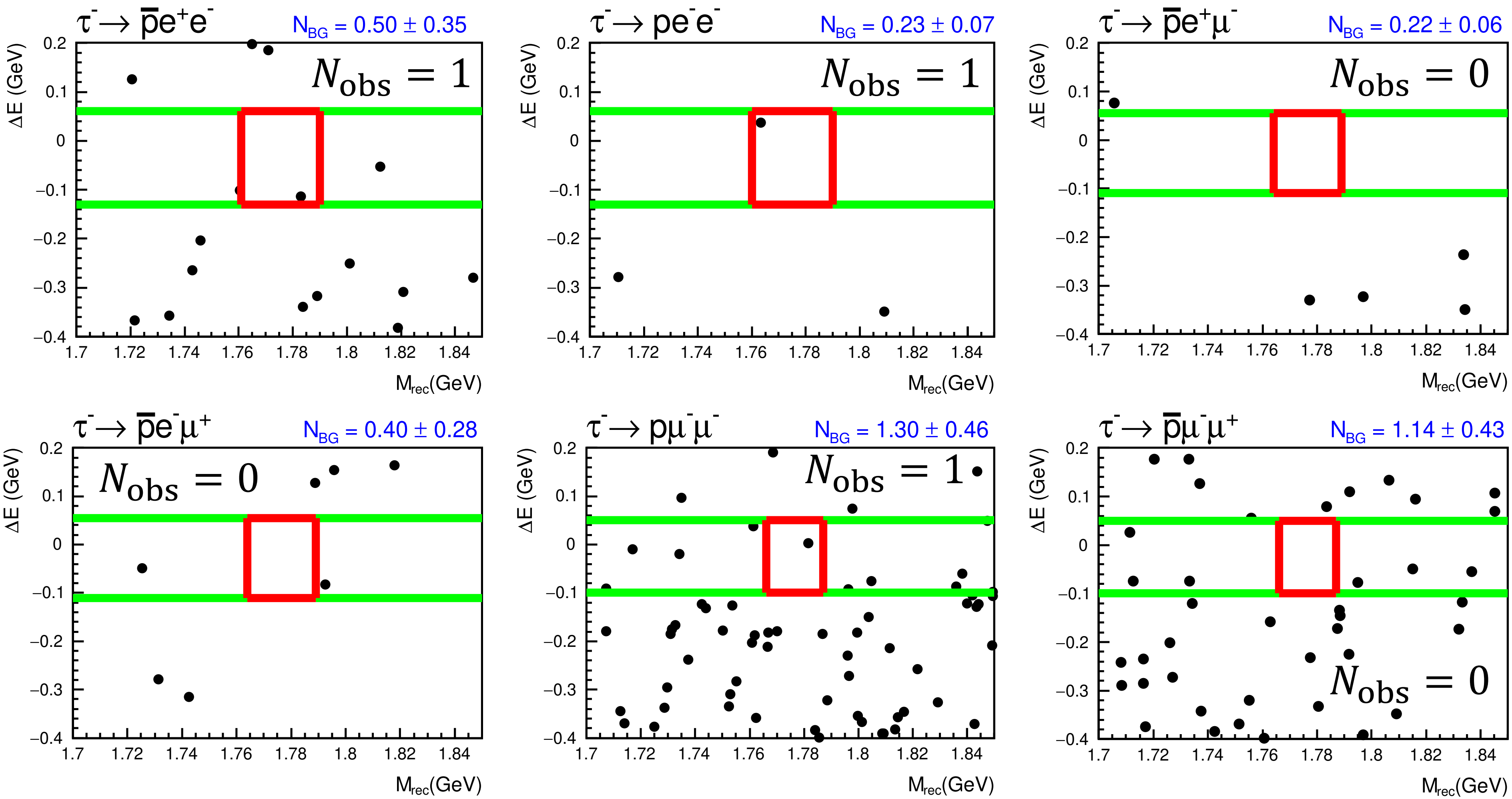


M_{pe} [GeV]

Assume electron mass hypothesis

Result

Luminosity: 921 fb^{-1} $(8.4\times10^{8} N_{\tau\tau})$



No significant excess over SM background predictions

Upper limits

Upper limit on branching fraction at 90% CL

$$\mathcal{B}(\tau^- \to p\mu^-\mu^-) < \frac{N_{\text{sig}}^{\text{UL}}}{2N_{\tau\tau}\epsilon},$$

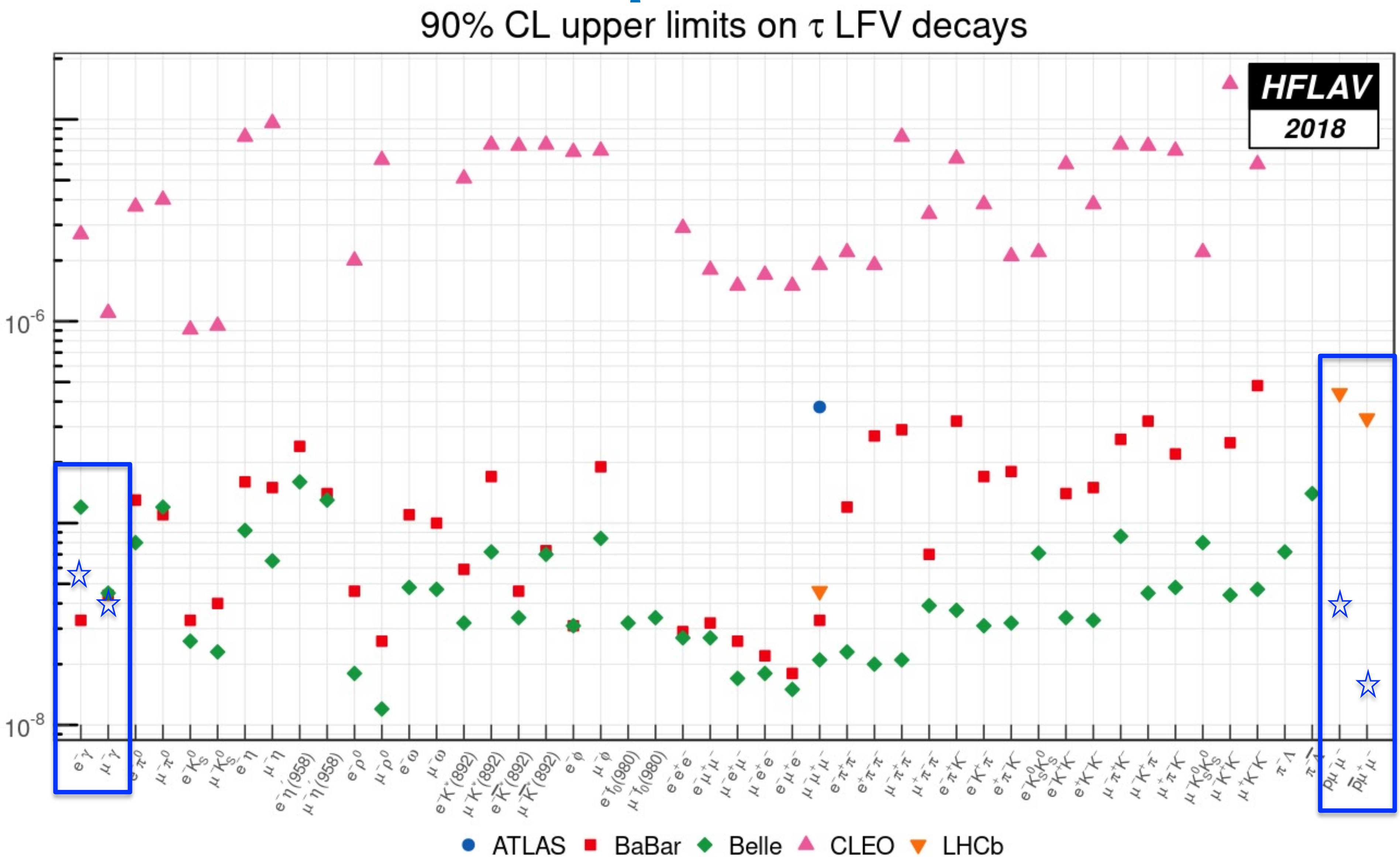
$$N_{\tau\tau} = 8.4\times10^8$$

Channel	ϵ (%)	N_{bkg}	N_{obs}	$N_{\text{sig}}^{\text{UL}}$	$\mathcal{B}\,(\times10^{-8})$
$\tau^- \to \overline{p}e^+e^-$	7.8	0.50 ± 0.35	1	3.9	< 3.0
$\tau^- \to pe^-e^-$	8.0	0.23 ± 0.07	1	4.1	< 3.0
$\tau^- \to \overline{p}e^+\mu^-$	6.5	0.22 ± 0.06	0	2.2	< 2.0
$\tau^- \to \overline{p}e^-\mu^+$	6.9	0.40 ± 0.28	0	2.1	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	1.30 ± 0.46	1	3.1	< 4.0
$\tau^- \to \overline{p}\mu^-\mu^+$	5.0	1.14 ± 0.43	0	1.5	< 1.8

LHCb: $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$
LHCb: $\mathcal{B}(\tau^- \to \overline{p}\mu^+\mu^-) < 3.3 \times 10^{-7}$

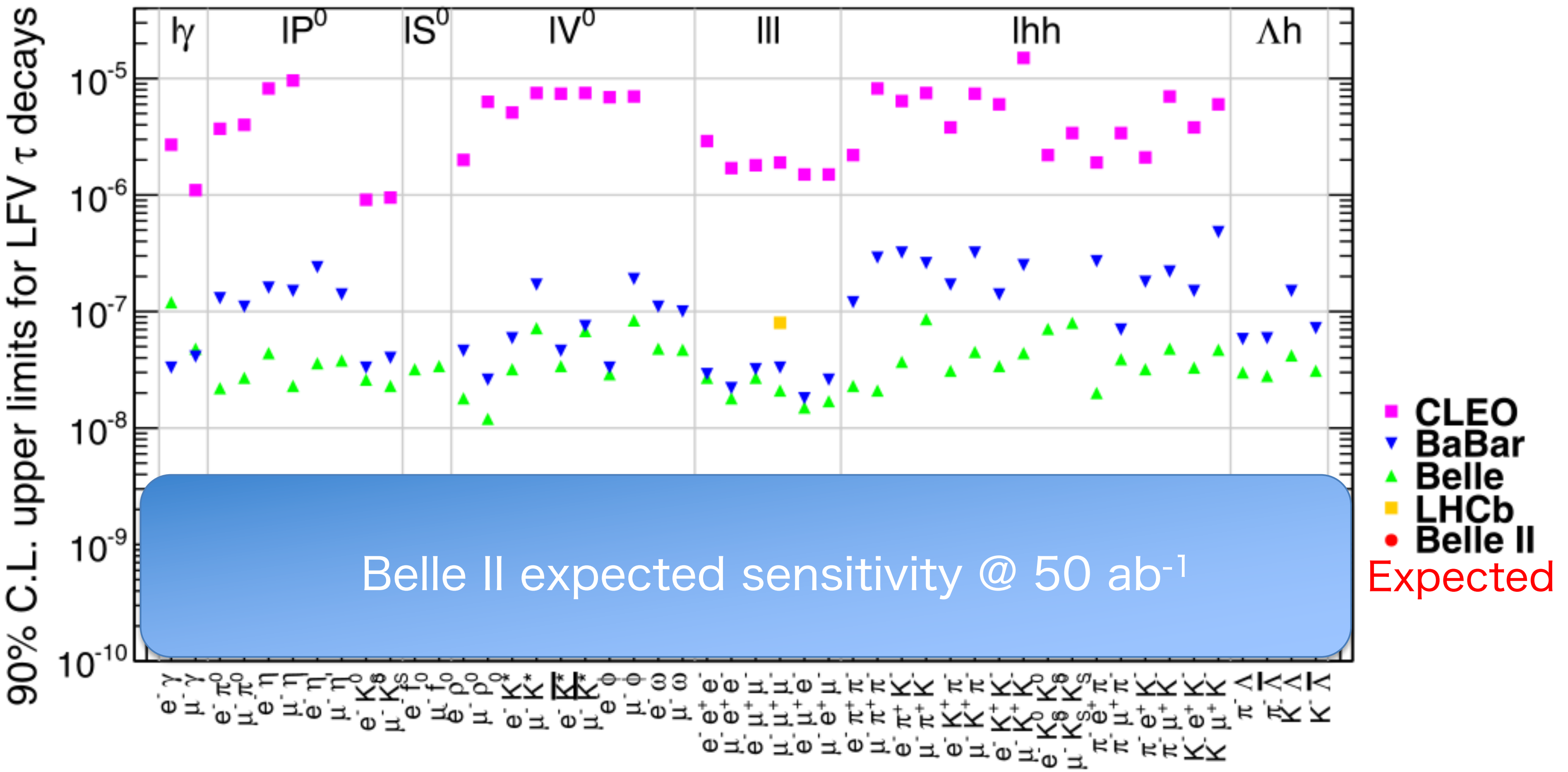
- $\tau^- \to p\mu^-\mu^-, \tau \to \bar{p}\mu^-\mu^+$: One order improve
- Other four channels: First measurement

90% CL ULs reported in this talk



☆ Results reported in this talk

Expected sensitivity at Belle II



Belle II data taking: 50 ab^{-1}

- Search sensitivity: $< O(10^{-9})$ → Stay tuned!

Summary

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

- Use **full data** and improve analysis technique
- No significant excess over the predicted background

$B(\tau \to \mu\gamma) < 4.2\times10^{-8}$ → Most stringent limit

$B(\tau \to e\gamma) < 5.6\times10^{-8}$ at 90% CL

Tau BNV/LNV: $\tau \to p\ell\ell'$ $(\ell^{(\prime)} = e, \mu)$

- $B(\tau^- \to p\mu^-\mu^-) < 4.0\times10^{-8}, B(\tau^- \to \bar{p}\mu^-\mu^+) < 1.8\times10^{-8}$

→ Upper limit at LHCb: $\sim10^{-7}$ → One order improve

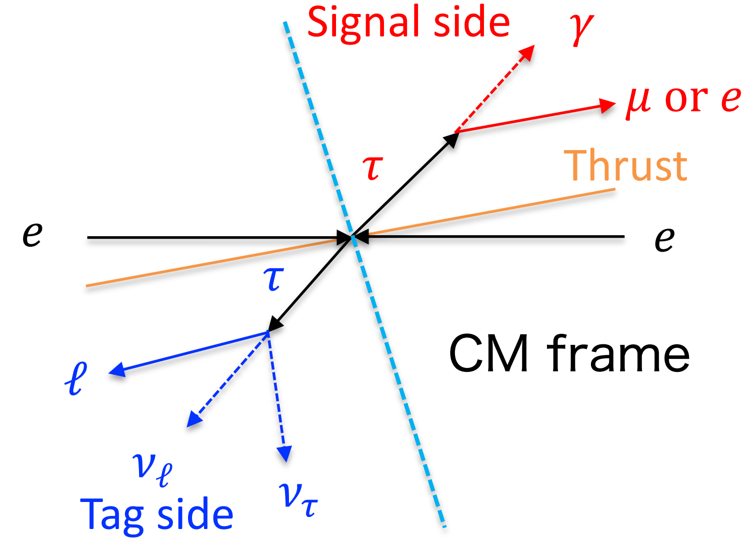
- $\tau^- \to \bar{p}e^+e^-, pe^-e^-, \bar{p}e^+\mu^-, \bar{p}e^-\mu^+$: First measurement

Backup

Previous analysis and Mbc

Beam constrained mass: $M_{bc} = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - \left(p_{\mu\gamma}^{CM}\right)^2}$

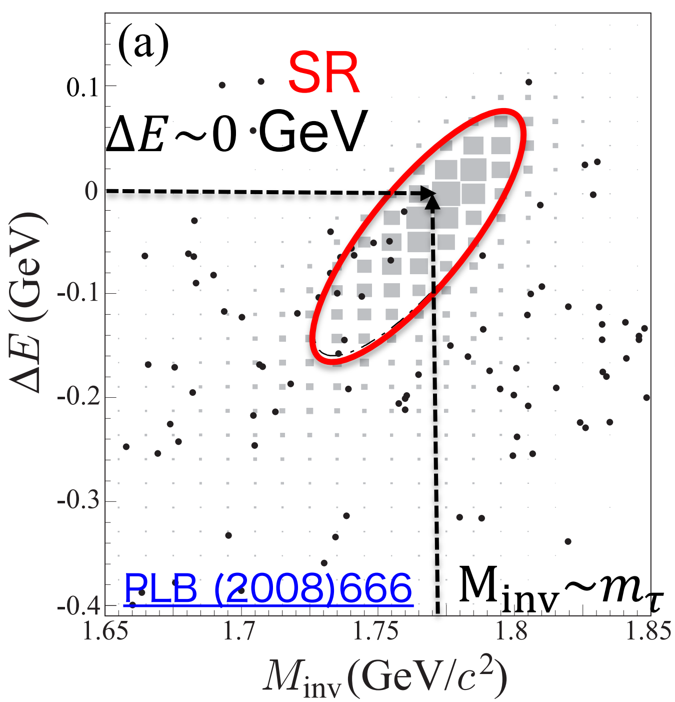
※ Scale $|p_{\gamma}^{CM}| = (\frac{\sqrt{s}}{2} - p_{\mu}^{CM})$

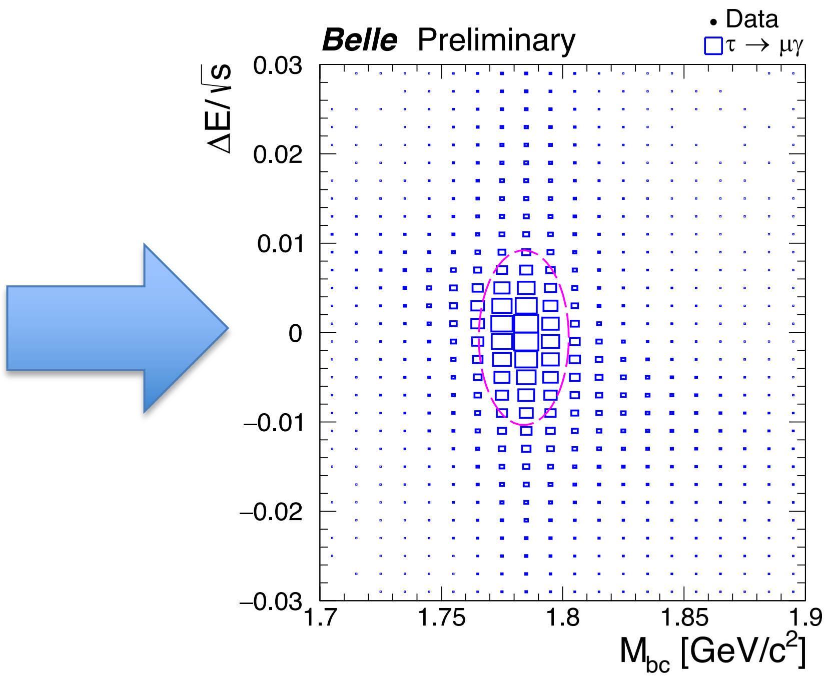


Previous analysis

$$M_{inv} = \sqrt{\left(E_{\mu\gamma}\right)^2 - \left(p_{\mu\gamma}\right)^2}$$

$$\Delta E = E_{\mu\gamma}^{CM} - E_{beam}^{CM}$$





Background estimation

Make background PDFs depending on $M_{bc},\ \Delta E/\sqrt{s}$.

- $\tau\tau, \mu\mu\gamma$ background events: Determine PDFs using MC simulation
- $ee\gamma$: Determine PDF using the data by applying the eID in tag-side

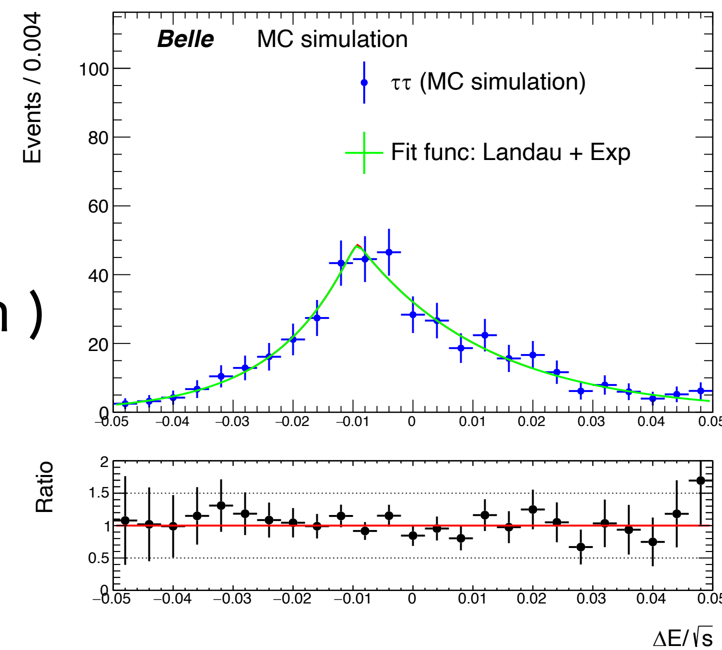
$M_{bc},\ \Delta E/\sqrt{s}$: almost independent from one another

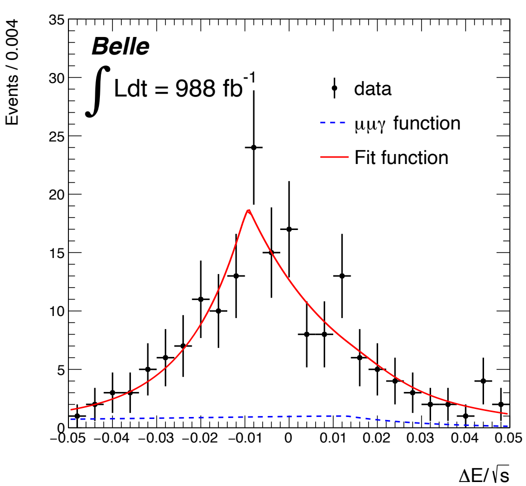
- Background PDF = $F(M_{bc})\times G(\Delta E/\sqrt{s})$

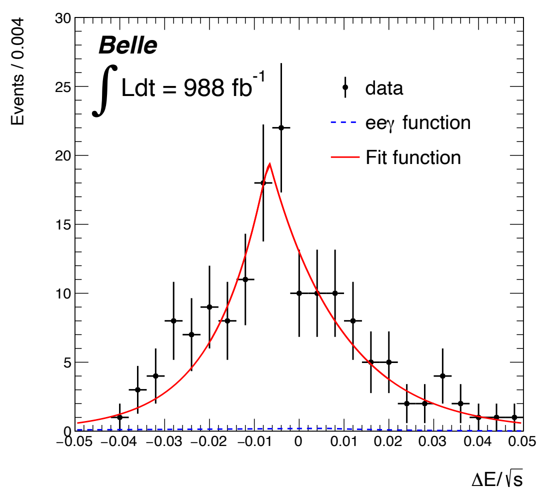
The total background PDFs:

- $C_0 F_{\tau\tau} + C_1 G_{\mu\mu\gamma}$ or $C_2 F_{\tau\tau} + C_3 G_{ee\gamma}$

→ C_i by fitting the data (in sideband region)





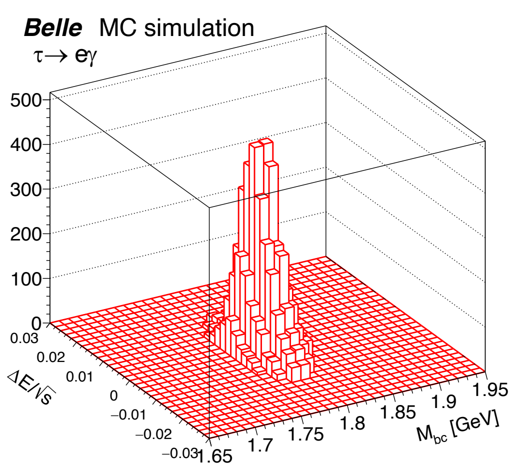


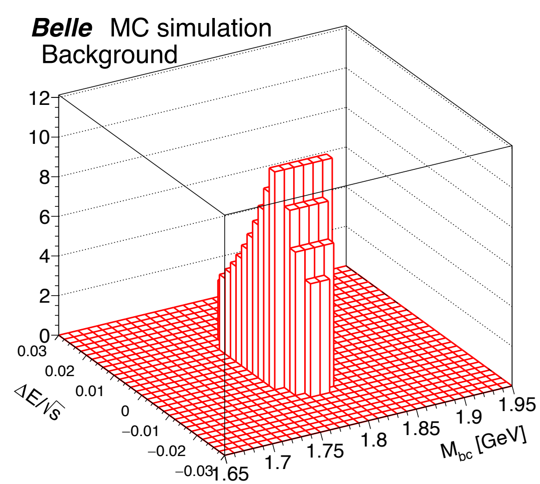
Likelihood fit

2D unbinned maximum likelihood fit

$$\mathcal{L} = \frac{e^{-(s+b)}}{N!} \prod_{i=1}^{N} (sS_i + bB_i) \, .$$

- s: number of signal from fit
- b: number of background from fit
- S_i: Signal PDF → use signal MC simulation
- B_i: Background PDF



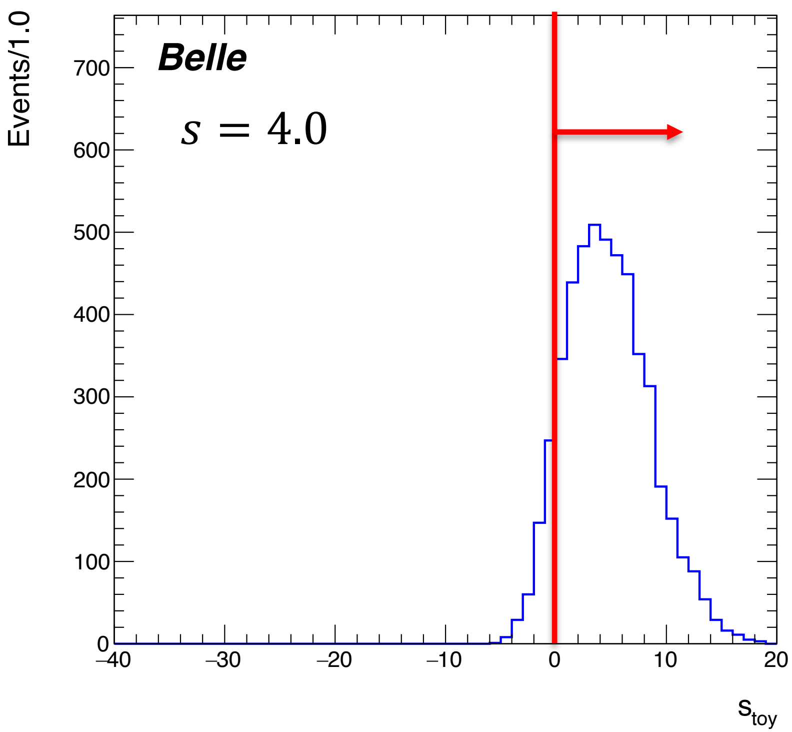


How to get upper limits

- Signal event: Poisson(s), Background event: Poisson(b)

→ Generate eg. 10000 toys based on each PDF

- b: Expected background event
- s is varied until finding s_{toy}, where $\mathrm{P}(s_{\mathrm{toy}} > s_{\mathrm{obs}})$ is 90% → s_{90}
  - In order to get expected limit, we assume $s_{\mathrm{obs}} = 0$



$P(s_{toy} > 0) > 90\%$

Observed upper limit

- 2D likelihood fit is performed to the data
  - $s_{obs} = -0.25^{+1.78}_{-1.27}$ for $\tau \to \mu\gamma$
  - $s_{obs} = -0.49^{+4.37}_{-3.64}$ for $\tau \to e\gamma$
- Observed s_{90} and upper limit is
  - $s_{90} = 2.8,\ \ Br(\tau \to \mu\gamma) < 4.2\times10^{-8}$ for $\tau \to \mu\gamma$
  - $s_{90} = 3.0, Br(\tau \to e\gamma) < 5.6\times10^{-8}$ for $\tau \to e\gamma$