Search for $\tau \to \mu\gamma$ with the full data sample collected by Belle

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for the Belle collaboration

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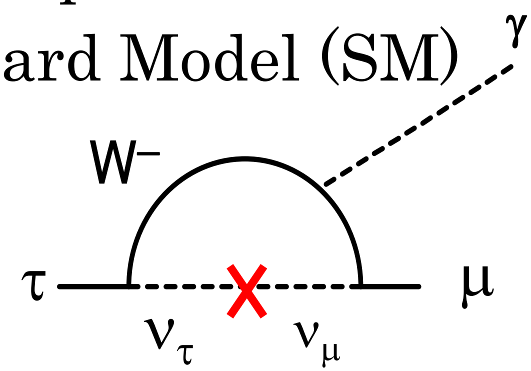
Introduction(1)

- Lepton flavor violation (LFV) in charged leptons

⇒negligibly small probability in the Standard Model (SM) even including neutrino oscillations:



$$\rightarrow \quad Br(\tau \rightarrow \ell\gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 < 10^{-54}$$

Observation of LFV is a clear signature of New Physics (NP)

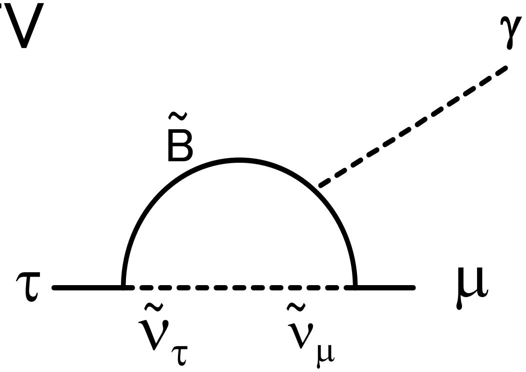
- Many extensions of the SM predict LFV decays.
  - These branching fractions could be enhanced as high as current experimental sensitivity. ($\sim 10^{-8}$)

- Tau lepton = The heaviest charged lepton
  - Expected strong coupling to NP
  - Many possible LFV decay modes

} τ LFV search = ideal probe of NP

Introduction(2)

- $\tau \to \mu\gamma$ is the simplest process among τ LFV decays.
  - Various models predict:
    - MSSM, LHT,…
      - Some of them predict experimentally-reachable branching fraction.



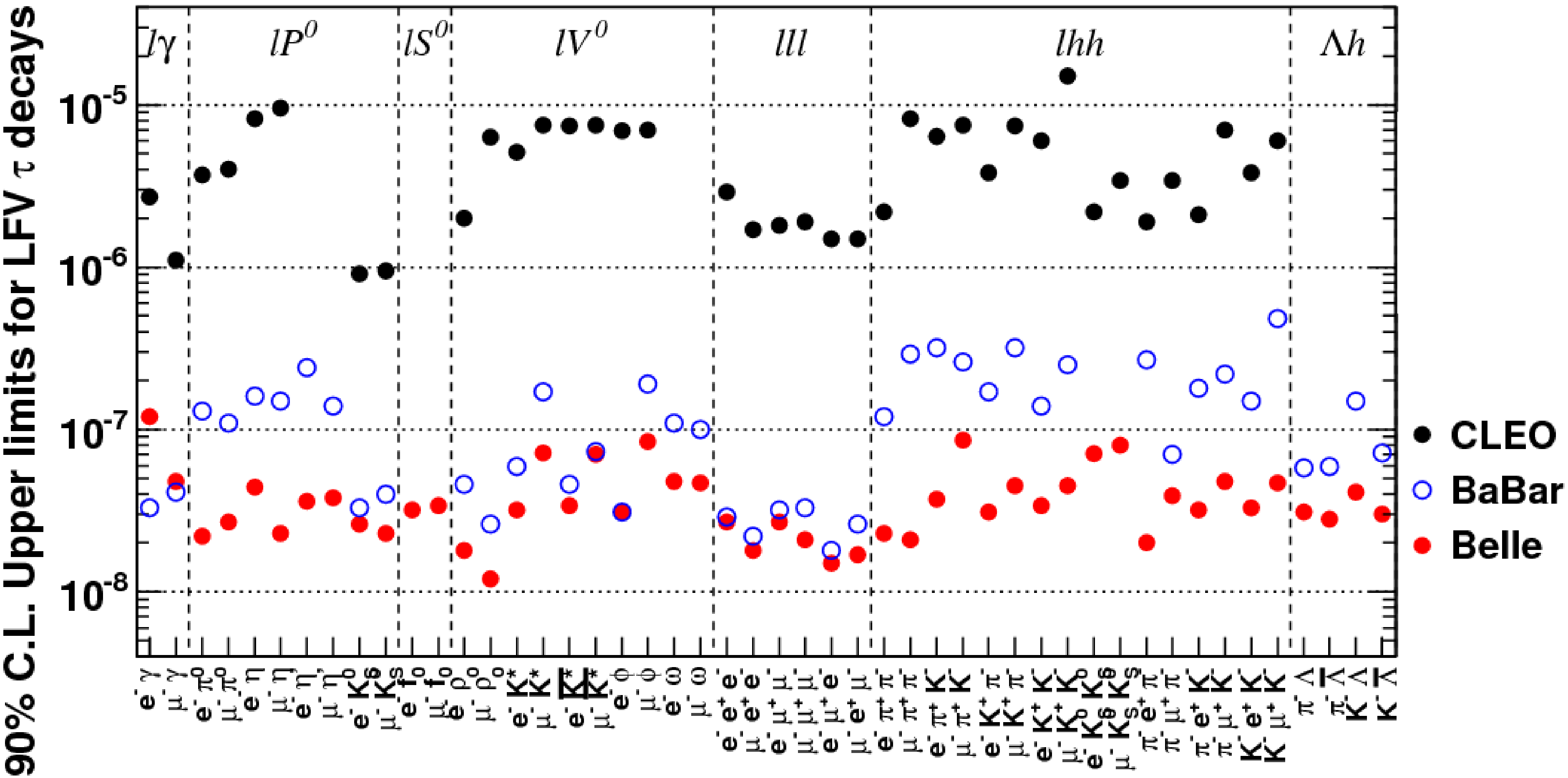
Littlest Higgs model With T-Parity: Phys.Rev.D83,053011(2011)
$SU(3)^3$ symmetry in SUSY model: arXiv:1204.0688v1 [hep-ph]

- In addition, various LFV searches are important because they can distinguish NP models.

depending on the models, predicted ratios btw LFV BFs are different.

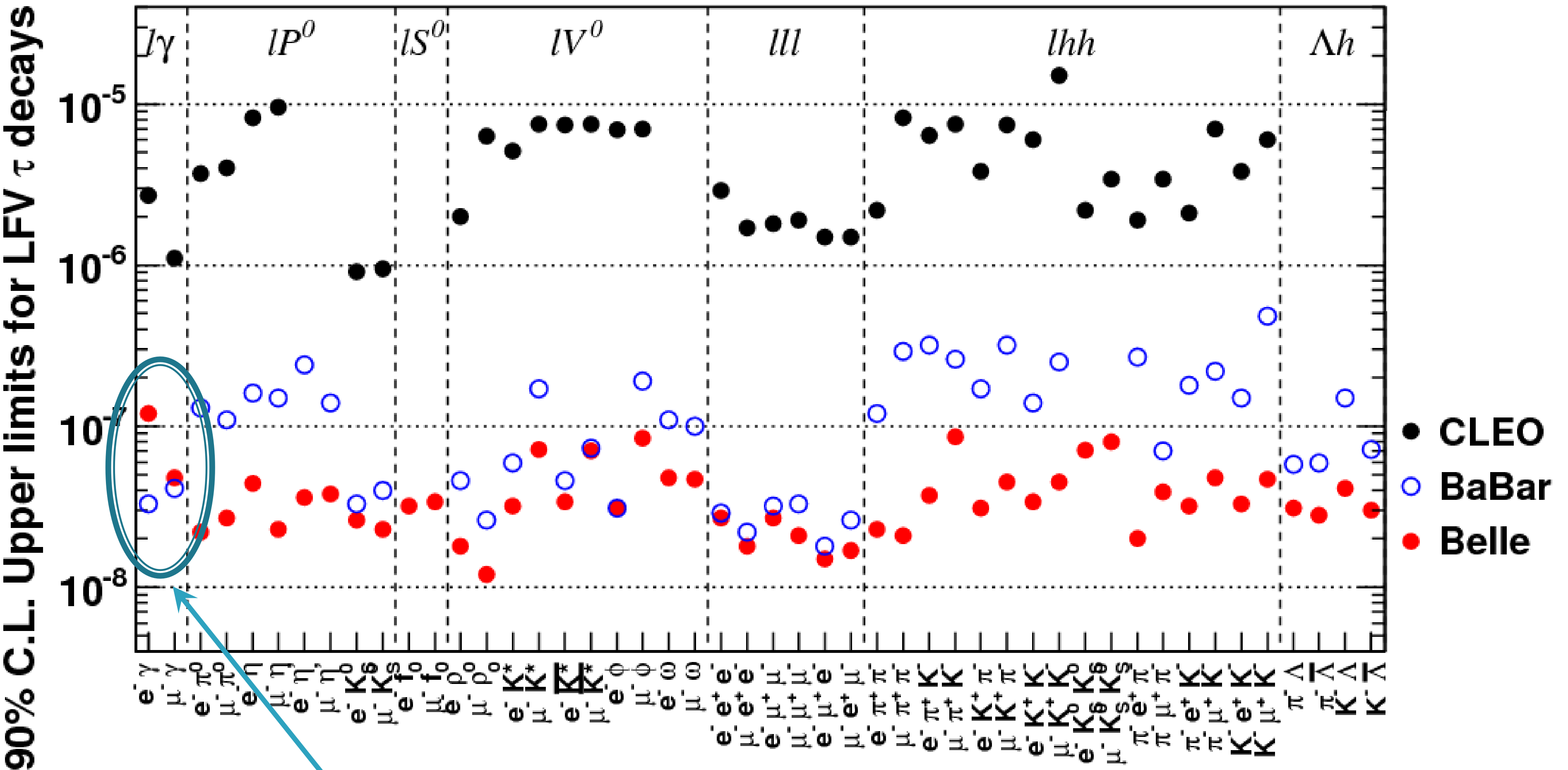
	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z' boson
$\left(\frac{\tau \to \mu\mu\mu}{\tau \to \mu\gamma}\right)$	$\sim 2 \times 10^{-3}$	0.06~0.1	0.4~2.3	~16

Upper Limits on τ LFV Decays



Reach upper limits around 10^{-8} ~100x more sensitive than CLEO

Upper Limits on τ LFV Decays



The remaining mode are $\tau \to \mu\gamma$ and $e\gamma$!

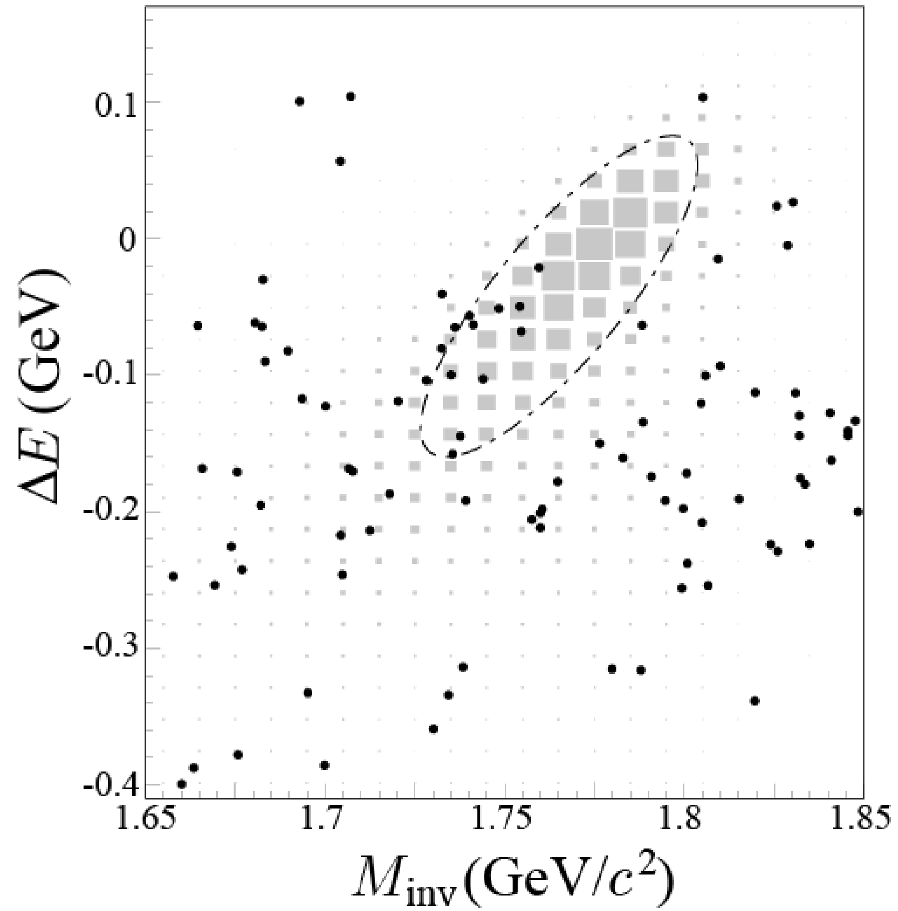
Previously, a 545 fb^{-1} data subsample was analyzed.

Previous result for $\tau \to \mu\gamma$ search

- 545 fb^{-1} Belle data sample
- 94 events are found while (88.4±7.4) BG events are expected in 5σ region and the detection eff. is 6.1%. Main BG comes from $\tau \to \mu\nu\nu$ + ISR γ.
- Upper Limits are evaluated

by 2d UEML fit on M−ΔE plane.

- Expected UL: 7.8×10^{-8} @90%CL
- Obtained UL: 4.5×10^{-8} @90%CL

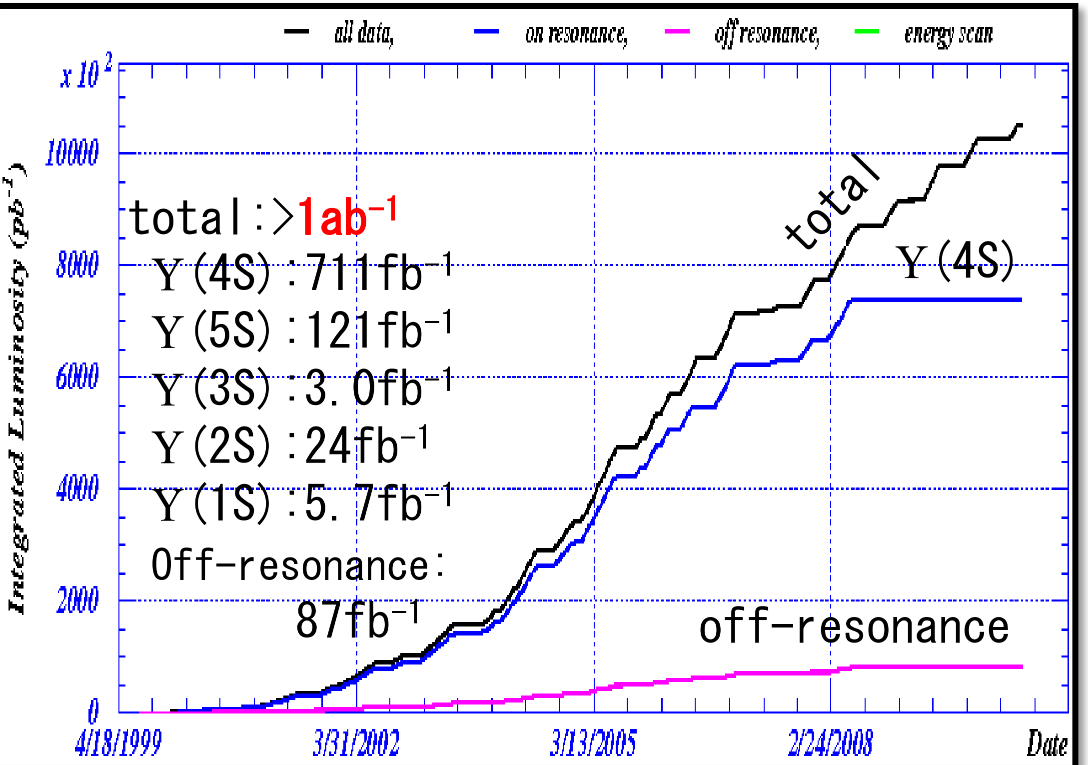


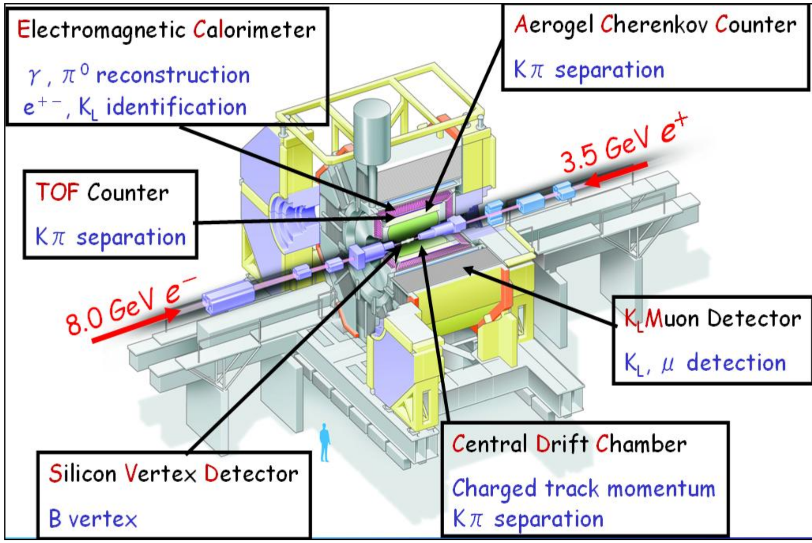
UEML=Unbinned Extended Maximum Likelihood fit

KEKB collider/Belle detector

B–factory: E at CM = Υ(4S)

e^+(3.5 GeV) e^-(8 GeV)





Good track reconstruction and particle identification

Lepton ID ~ (80-90)%
Fake ID ~ (0.1-3)%

$\sigma(\tau\tau)$~0.9nb, $\sigma(b\bar{b})$~1.1nb

A B-factory is also a τ-factory!

World-largest data sample!

~9x10^8 ττ at Belle

Selection Criteria

- 1–1 prong & net charge=0
- Missing momentum should point into the detector volume.
- Visible energy should be smaller than beam energy.
- The charged track should be a muon while none of the tagging tracks can be an identified muon.

Require ττ event

Reject μμ event

To select signal event

- N_γ=1 in signal side.
- $0.5<\cos\theta_{\mu-\gamma}^{CM}<0.8$

(requirement from 2-body decay ($\tau\to\mu\gamma$))

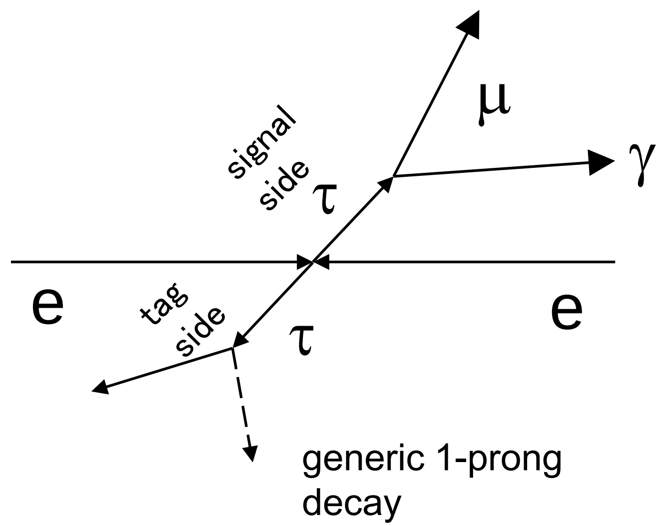
- $|M_\nu^2|<0.5\mathrm{GeV}^2/c^4$ for hadronic tags and $0<M_\nu^2$ for leptonic tags.
- $0.99<\cos\Theta^{CM}$, where Θ means the angle between expected and reconstructed τ directions.
- momentum asymmetry between μ and γ should be less than 0.7

illustrated later

Analysis method

$e^+e^- \rightarrow \tau^+\tau^-$

➡ clean environment



Blind analysis
⇒Blind signal region

Estimate BG level
using sideband data and MC
The signal extraction is performed
by the UEML fit on the $M_{\mu\gamma}^{(c)}$–$\Delta E/\sqrt{s}$ plane

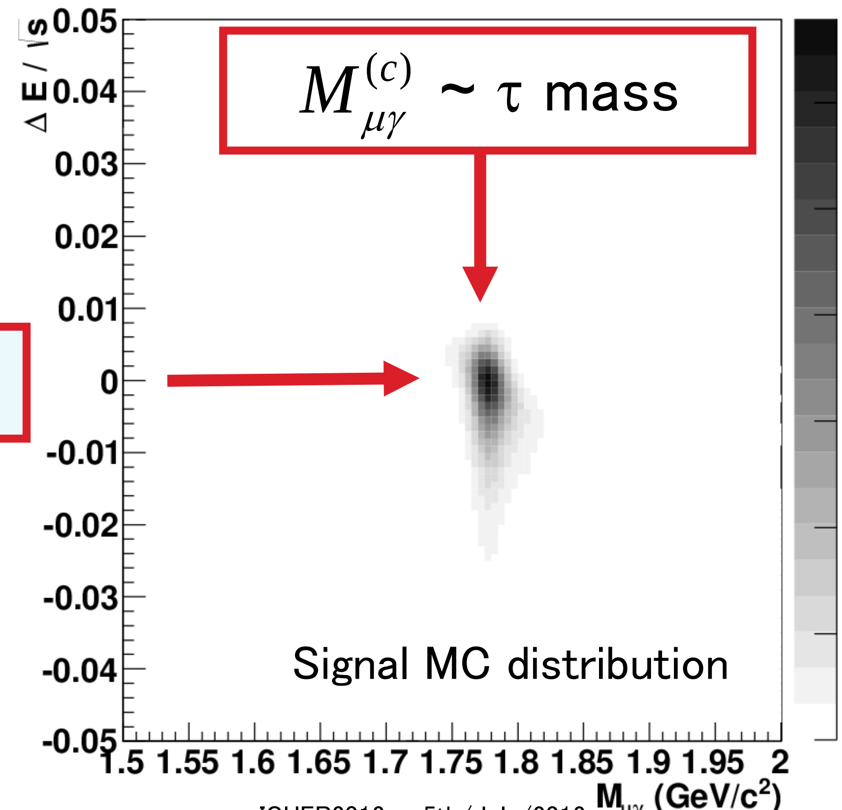
If no excess is found,
set upper limits @ 90%CL
using the UEML fit and toy MC

Signal Extraction

$$M_{\mu\gamma}^{(c)} = \sqrt{\left(E_{\text{beaml}}^{\text{CM}}\right)^2 - \left(p_{\text{signal}}^{\text{CM}}\right)^2}$$

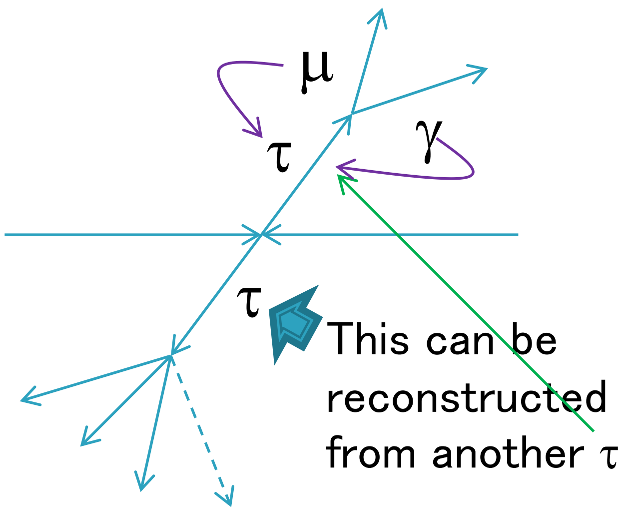
$$\Delta E = E_{\text{signal}}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$$

$\Delta E/\sqrt{s} \sim 0$



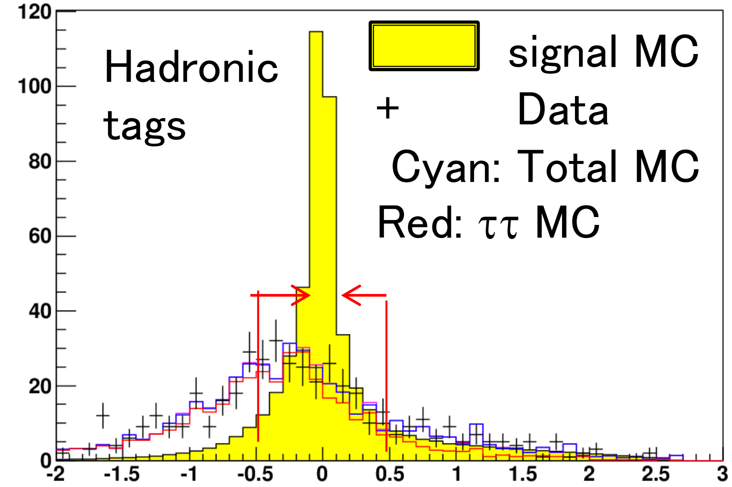
Tag side missing mass

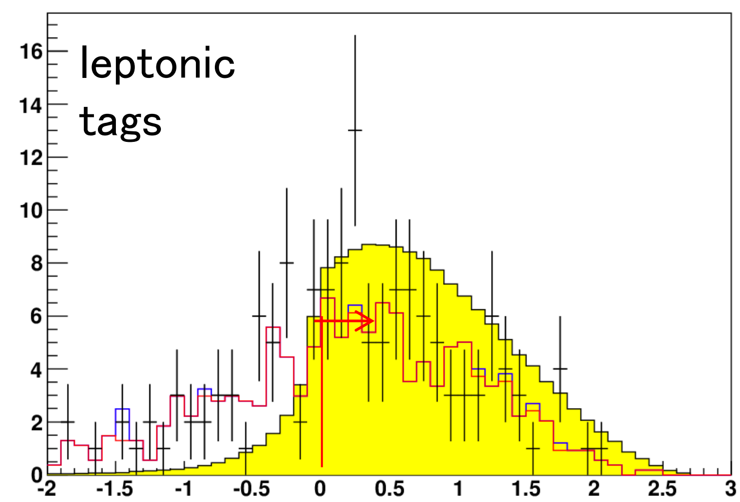
- Tag side missing mass.



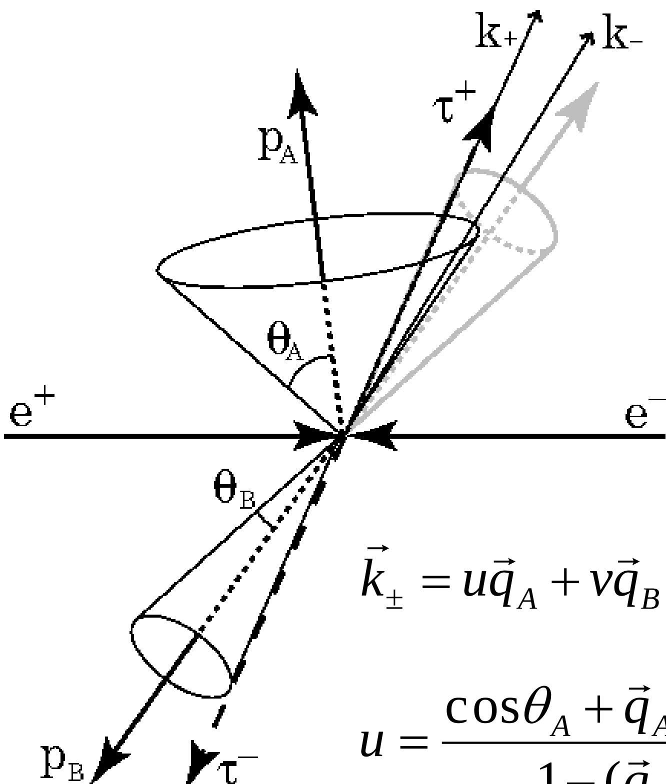
(tag side missing)= (reconstructed tag-side τ)
−(visible tracks and gammas belonging to tag side)

(tag-side missing mass)^2





Expected τ direction



$$\vec{k}_{\pm} = u\vec{q}_A + v\vec{q}_B \pm w\frac{\vec{p}_A \times \vec{p}_B}{\left|\vec{p}_A \times \vec{p}_B\right|},$$

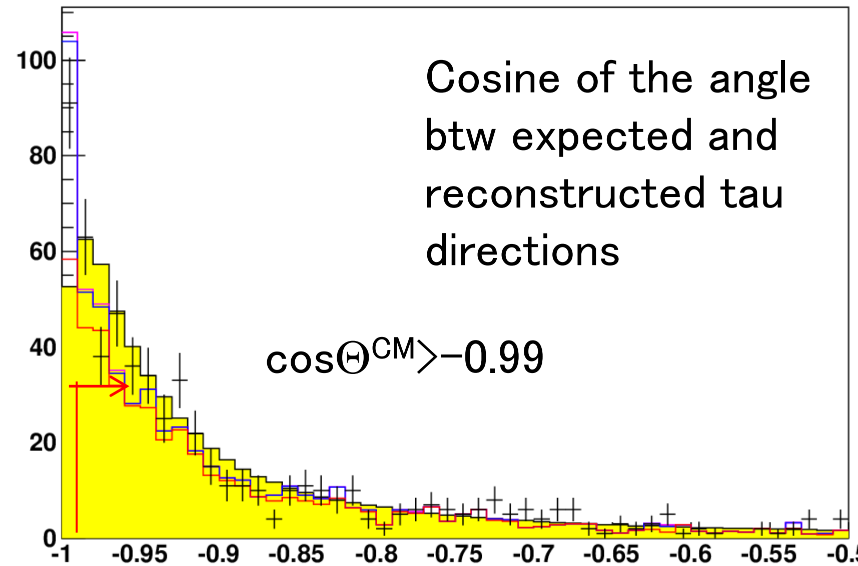
$$u = \frac{\cos\theta_A + \vec{q}_A \cdot \vec{q}_B \cos\theta_B}{1 - (\vec{q}_A \cdot \vec{q}_B)^2},$$

$$v = -\frac{\cos\theta_B + \vec{q}_A \cdot \vec{q}_B \cos\theta_A}{1 - (\vec{q}_A \cdot \vec{q}_B)^2},$$

$$w = \sqrt{1 - u^2 - v^2 - 2uv(\vec{q}_A \cdot \vec{q}_B)}$$

- In the CM frame, tau direction can be calculated from the charged tracks.

This direction is compared w/ reconstructed one from μ and γ.



Here, p_A (p_B) means 3-vector for μ (hadron) in CM frame and q_A (q_B) is a unit vector parallel to p_A (p_B).

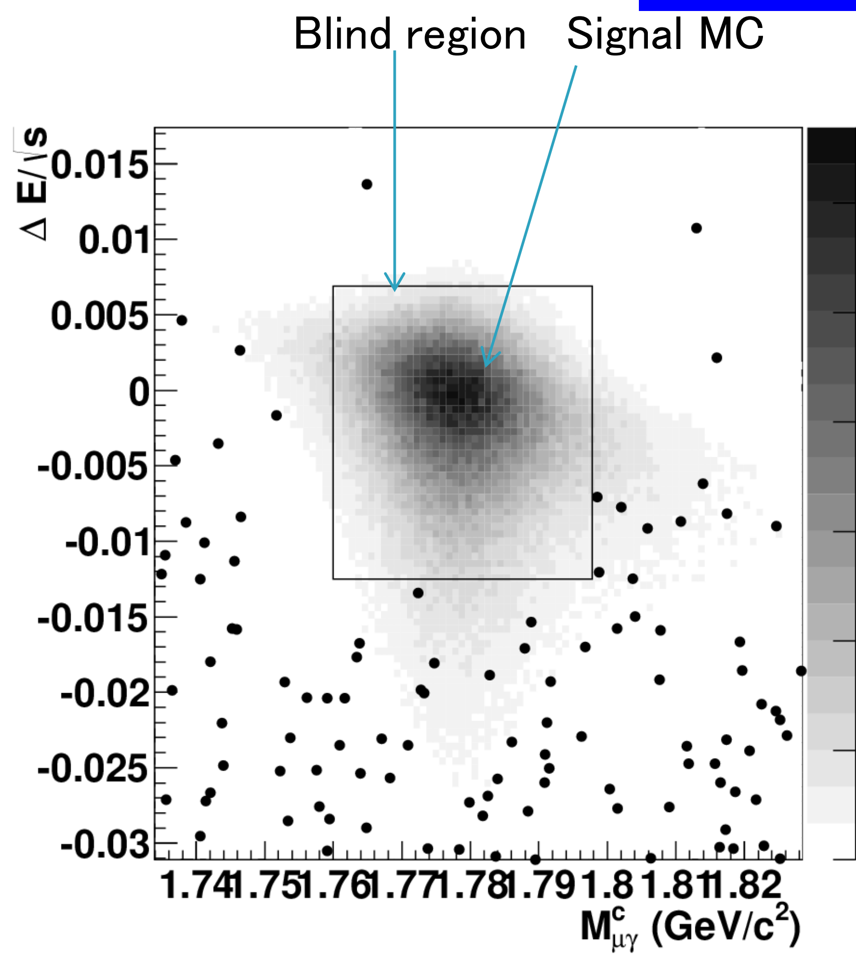
Remaining events and eff.

- After applying all selections,

105 events are found and the detection efficiency is 6.5%.

For the blinded region, 10.2±2.2 BG events are expected.

In total, 115.2±11.4 events are expected. →BG level reduced by 33% while efficiency is similar to the previous analysis.



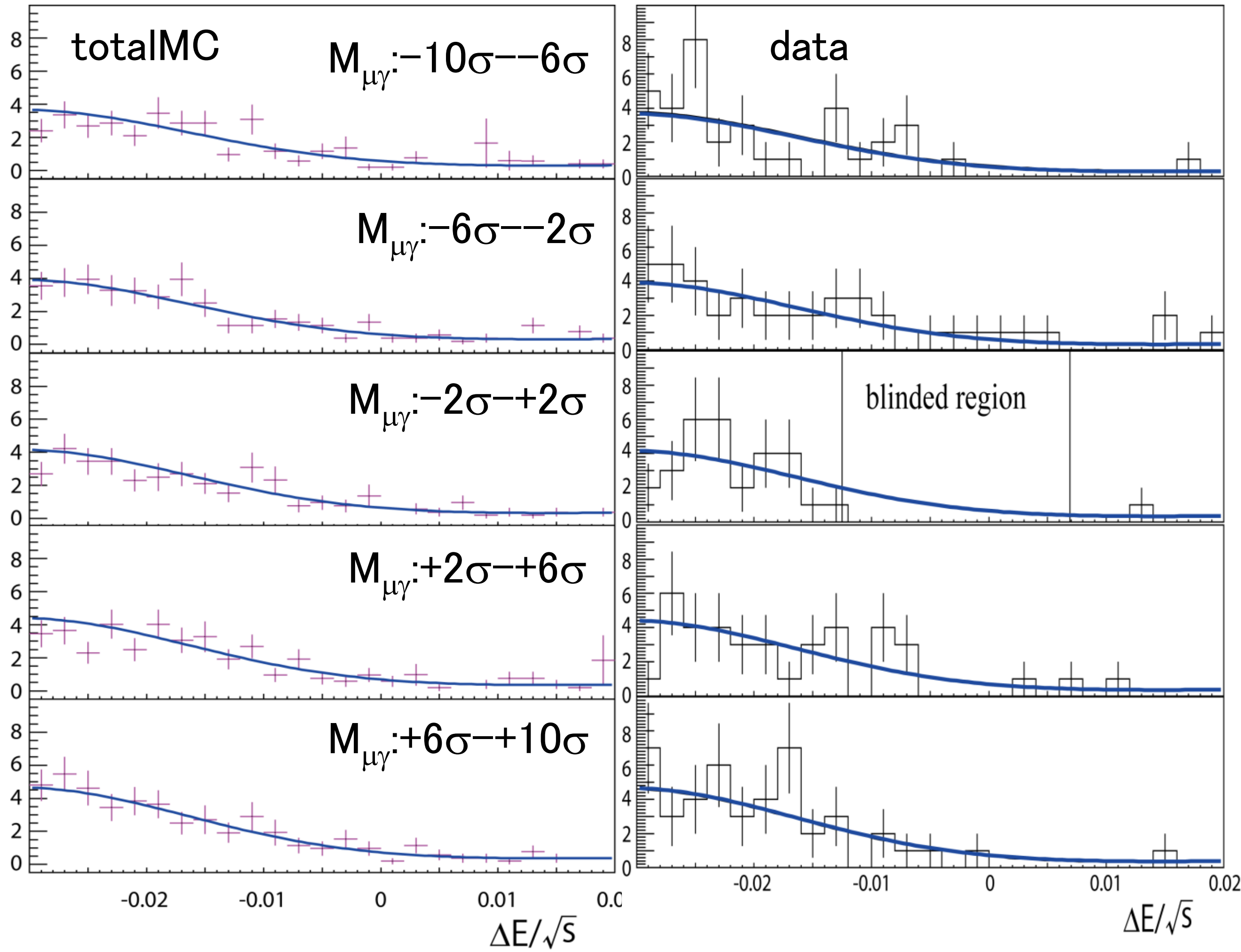
BG distribution

The function

$$D(x,y) = h(1+\alpha(x-1.78)) \times (a + e^{-\frac{(y-c)^2}{2\sigma^2}})$$

reproduced the BG distribution in the narrow region ($M_{\mu\gamma}$:±10s, $\Delta E/\sqrt{s}$:±5s), where (x,y) means ($M_{\mu\gamma}$, $\Delta E/\sqrt{s}$).

Fit to total MC dist., and then compare it with the data dist.

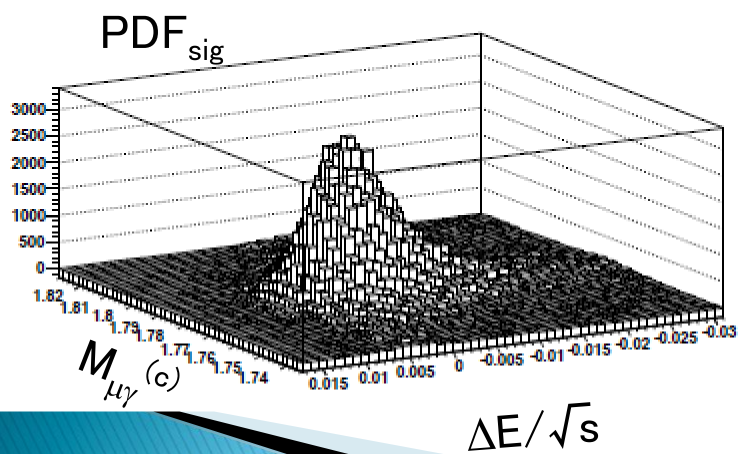


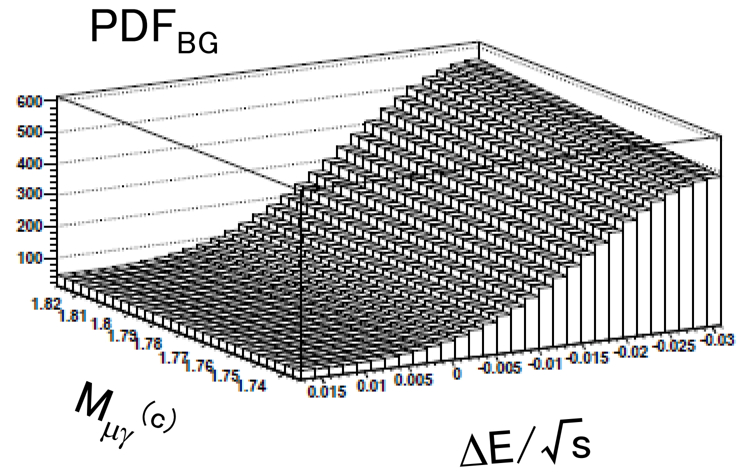
UEML fit with PDFs

- Unbinned Extended Maximal Log Likelihood fit

$$L = \frac{e^{-s-b}}{N!}\prod_{i=1}^{N}\left(s \times PDF_{\rm sig}((M^{(c)}_{\mu\gamma})_i, (\Delta E)_i/\sqrt{s}) + b \times PDF_{\rm bg}((M^{(c)}_{\mu\gamma})_i, (\Delta E)_i/\sqrt{s})\right),$$

where N is a number of observed events in $\pm 5\sigma$ region, $(M^{(c)}_{\mu\gamma})_i$ and $(\Delta E)_i/\sqrt{s}$ are the coordinate of i-th observed event on $M^{(c)}_{\mu\gamma}$-$\Delta E/\sqrt{s}$ plane and s and b are free parameters, those corresponds to the number of signal and BG events, respectively.





Expected 90% CL upper limit

- Since we still have a blind for the ±2σ region, we assume that we obtain s_{fit}=0, b_{fit}=115.2 as an UEML fit result to the data events.

  expected # of BG in ±5σ region

- Upper limit for s is obtained by using toy MC samples, where b is fixed and s is varied until finding s that gives a 90% chance of s^{MC} being larger than s. Here s^{MC} means the result of an UEML fit to events generated by toy MC and we generate 50,000 toy MC events for each s.
- As a result, s_{90}=5.7 is obtained.→ $\mathcal{B}<4.8\times10^{-8}$@ 90%CL
  - Including systematics → $\mathcal{B}<5.3\times10^{-8}$@ 90%CL

    (largest contribution: uncertainty in BG PDF shape)

Summary

- Belle completed operation with a $980fb^{-1}$ data sample, which contains ~10^9 tau-pairs. This is the world's largest τ data sample.
- Search for $\tau \to \mu\gamma$ is being performed with the full data sample.
  - By adding more data and optimizing the analyses to suppress BGs, the sensitivity to τ LFV is improved significantly.
  - If the observed signal is consistent with the background, the expected upper limit is $\mathcal{B}(\tau \to \mu\gamma) < 5.3 \times 10^{-8}$ @90%CL.

The highest sensitivity for this mode. (preliminary)

→The blinded region is not opened yet.

Final results for $\tau \to \mu\gamma$ as well as $\tau \to e\gamma$ will be shown soon.

- All major τ LFV modes have been investigated with the final ~$1000fb^{-1}$ data sample.