MC study for the lepton flavor violating tau decay into a lepton and an undetected particle

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Abstract

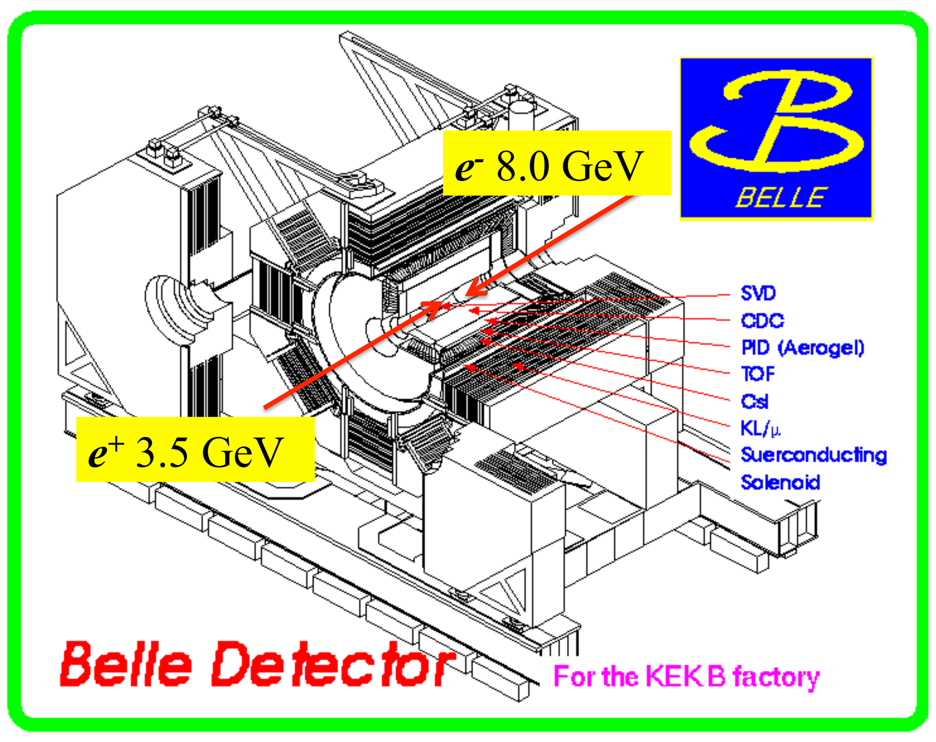
We search for charged Lepton Flavor Violating (cLFV) two-body decay mode $\tau \to lX$ with data samples collected in the Belle experiment, where l is muon or electron and X is a missing particle which cannot be detected with the Belle detector. A candidate of X particle is, for example, Z' boson in the L_μ-L_τ model.

This decay mode was searched for in the ARGUS experiment in 1995, which gave upper limits for Br($\tau \to lX$) / Br($\tau \to l\nu\nu$) with several X masses. With data samples collected in the Belle experiment, we may search more precisely and find it or give more strict upper limits. We search for this mode with two ways of analysis. First one is analysis with heavy hadrons and a neutrino for tag-side tau decays which were used in ARGUS. The other way is assuming X masses. We report a study of Monte Carlo simulations for $\tau \to \mu X$ with the first method.

1. The Belle experiment

1. Ran at KEK, Japan in 1999~2010
2. $e^- e^+$ collider (KEKB accelerator)
3. $\sqrt{s} = 10.58$ GeV
4. Integrated luminosity $\int L dt \sim 1\ \mathrm{ab}^{-1}$
5. B factory and also τ factory
   $\sigma_{B\bar{B}} \sim 1.1$ nb
   $\sigma_{\tau^+\tau^-} \sim 0.9$ nb

$N_{\tau\tau} \sim 9.0 \times 10^8$



2. Physics Motivation

Experimental hint

The muon anomalous magnetic moment : $(g\text{-}2)_\mu$ (BNL E821)

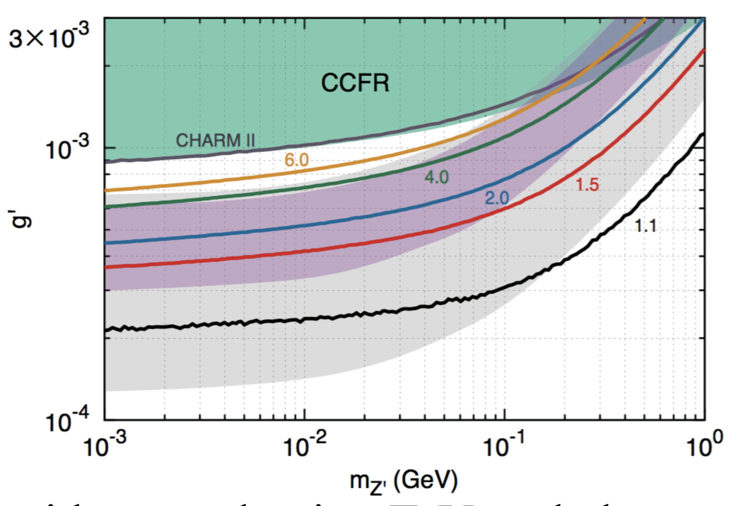
$$\Delta a_\mu = a_\mu^{Exp} - a_\mu^{SM} = (236 \pm 87) \times 10^{-11} \quad (2.7\sigma)$$

Reference: A. Crivellin et al., Phys. Rev. Lett. 116, 081801 (2016)

$L_\mu - L_\tau$ model can explain this hint for physics beyond the Standard Model (SM).

L_μ-L_τ model

1. U(1)$_X$ gauge symmetry model
2. New vector boson : Z'
3. Z' violates lepton universality in all cases in order to avoid strong bounds on electron couplings.



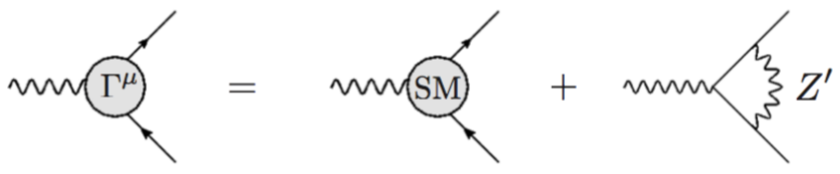
Considering the contribution from neutrino trident production,TeV-scale heavy $M_{Z'}$, which is mass of Z', is strongly constrained by the CCFR and CHARM-II experiments.

Reference: CCFR Collaboration, Phys. Lett. 66, 3117(1991)
CHARM-II Collaboration, Phys. Lett. B 245, 271(1990)

⇨ Light Z' boson with mass below GeV explains $(g\text{-}2)_\mu$.

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{Z'}$$
$$= \mathcal{L}_{\rm SM} - \frac{1}{4}(Z')_{\alpha\beta}(Z')^{\alpha\beta} + \frac{1}{2}m_{Z'}^2 Z'_\alpha Z'^\alpha + g' Z'_\alpha\left(\bar{l}_2\gamma^\alpha l_2 - \bar{l}_3\gamma^\alpha l_3 + \bar{\mu}_R\gamma^\alpha\mu_R - \bar{\tau}_R\gamma^\alpha\tau_R\right)$$

1-loop diagram explaining $(g\text{-}2)_\mu$



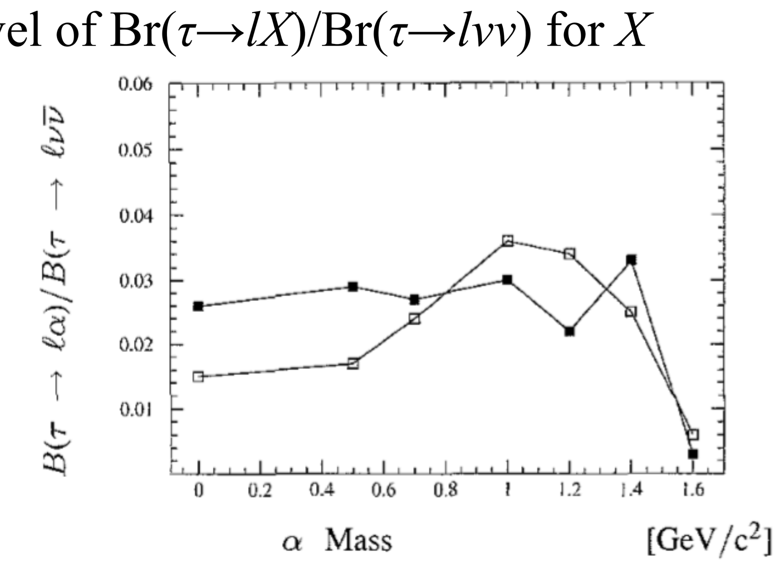
⇨ Searching for $\tau \to \mu Z'$ at Belle (More generally searching for $\tau \to eX$ / $\tau \to \mu X$)

3. Previous experiment searching for $\tau \to lX$

The previous experiment, ARGUS searched for a $\tau \to lX$ signal, and set the following upper limits at 95% confidence level of Br($\tau \to lX$)/Br($\tau \to l\nu\nu$) for X masses up to 1.6 GeV/c^2.

For a massless X they obtain
Br($\tau \to eX$)/Br($\tau \to e\nu\nu$) < 1.5%
Br($\tau \to \mu X$)/Br($\tau \to \mu\nu\nu$) < 2.6%

Integrated luminosity 472pb^{-1}
$N_{\tau\tau} = 4.25 \times 10^5$
Belle collected about 2000 times statistics of tau-pairs.



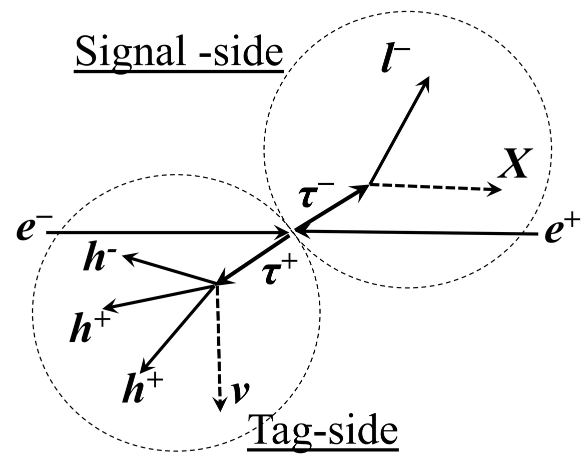
Br($\tau \to lX$)/Br($\tau \to l\nu\nu$) for electrons (open squares) and muons (full squares)

⇨ We may observe $\tau \to lX$ signals or improve upper limits.

4. Method

$\tau \to lX$

1. Two-body decay : difference from 3-body decay $\tau \to l\nu\nu$ (main background in SM)
2. Peak position of the l momentum disribution depends on the X mass in τ rest frame.
3. X : an undetectable particle (e.g. Z' boson)

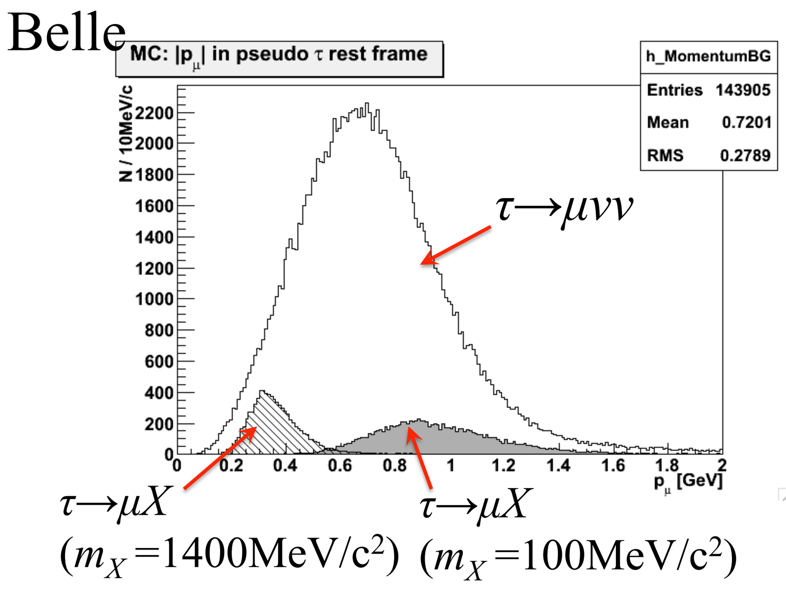


To observe μ momentum in the τ rest frame, we need to know τ flight direction.This is not directly measured in Belle.

τ pseudo rest frame

1. tag-side : $3h^\pm$ and ν (h:hadron)
2. direction of $3h^\pm \sim \tau$ direction
3. the τ energy coinsides with $E_{\rm beam}$
4. transformation to the τ pseudo rest frame

μ momentum spectum in τ pseudo rest frame shown in the right figure.(Br($\tau \to \mu X$) is too large for display)



5. MC study

Event generator

Signal MC (2M events): one side of τ decays into μ and X, another side of τ decays with SM
Generic MC (45M events): B.G. estimation

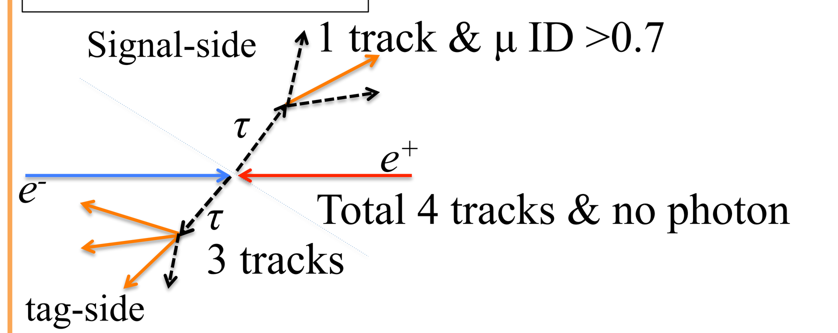
Signal-side B.G. events

Decay mode	ratio
$\tau \to \mu\nu\nu$	97.60 %
$\tau \to \pi\nu$	1.84 %
$\tau \to \pi\pi^0\nu$	0.20 %
$\tau \to K\nu$	0.19 %
$\tau \to K^*\nu$	0.06 %
$\tau \to \pi\pi^0\pi^0\nu$	0.06 %
other τ decay	0.05 %

Tag-side events

Decay mode	ratio
$\tau \to \pi\pi\pi\nu$	88.60 %
$\tau \to K\pi\pi\nu$	3.40 %
$\tau \to \pi\pi\pi\pi^0\nu$	2.87 %
$\tau \to \pi\pi^0\nu$	1.74 %
$\tau \to K\pi K\nu$	1.36 %
$\tau \to K^*\nu$	0.87 %
other τ decay	1.16 %

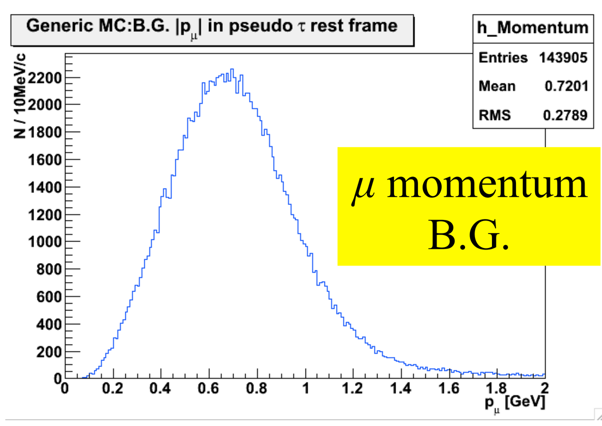
Selection criteria

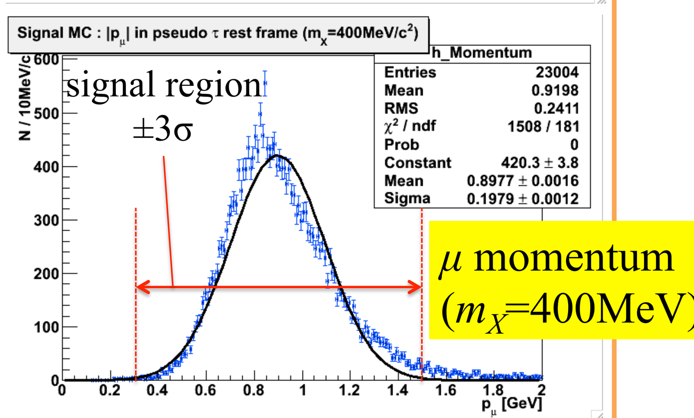


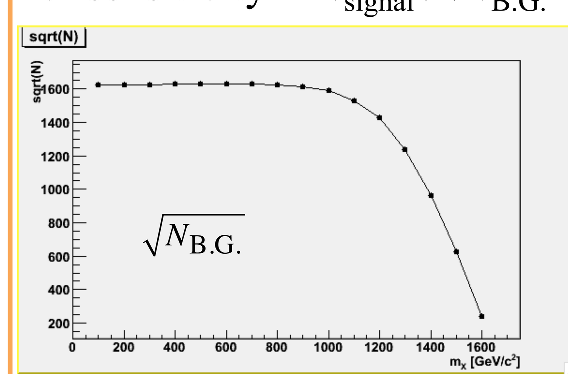
Estimated sensitivity and upper limit with 1ab^{-1}

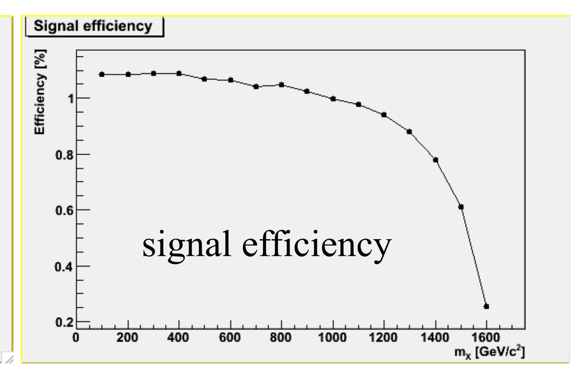
To estimate signal and B.G. events with 1ab^{-1},

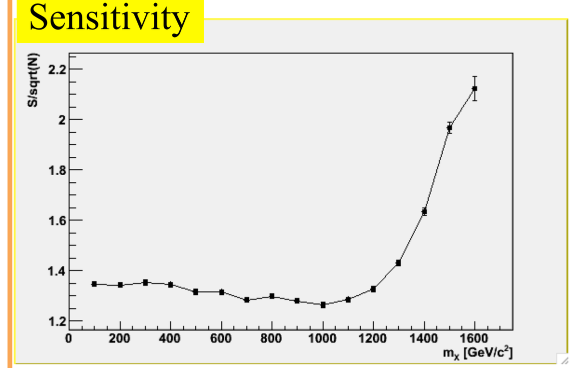
1. signal region : ±3σ deviation area of gaussian fitting to signal $|p_\mu|$ distribution
2. estimate number of signal and B.G. events in signal region with 1 ab^{-1}
3. Br($\tau \to \mu X$) : ARGUS upper limit (~5.0×10^{-3}) ×1/√(2000)
4. sensitivity = $N_{\rm signal}/\sqrt{N_{\rm B.G.}}$

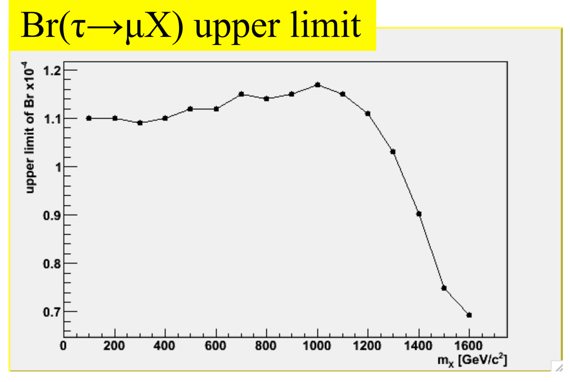


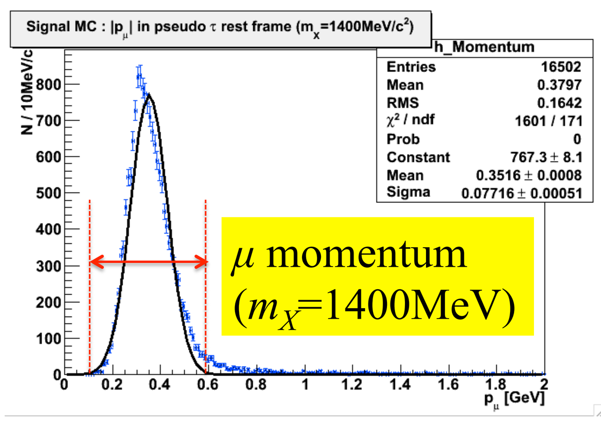






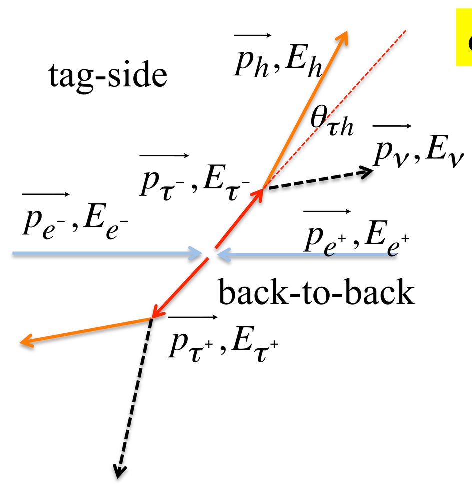






6. Discussion

To observe signals with low m_X we have to shape signal distrbution.
In previous measurement at ARGUS and this MC study, heavy hadrons (3π or 3ππ^0) were selected for tag-side events and approximated to τ directions.
For approximation to τ direction more precisely, we can select the tag-side events in order to make smaller angle between the direction of hadrons and τ direction.
This angle can be calculated as follows…



on center-of-mass frame

$$\vec{p}_{\tau^-} + \vec{p}_{\tau^+} = \vec{0}$$
$$|\vec{p}_{\tau^-}| = |\vec{p}_{\tau^+}| \equiv |\vec{p}_\tau|$$
$$E_{\tau^-} = E_{\tau^+} \equiv E_\tau$$
$$E_{e^-} = E_{e^+} \equiv E_e$$
$$E_e = E_\tau = \frac{1}{2} m_{\Upsilon(4S)} \quad \text{constant}$$
$$|\vec{p}_\tau| = \sqrt{E_\tau^2 - m_\tau^2}$$

$p_\tau = p_h + p_\nu$ (4 momentum of τ, hadrons and ν)

$$p_\tau - p_h = p_\nu$$
$$(p_\tau - p_h)^2 = (p_\nu)^2$$
$$(E_\tau - E_h)^2 - |\vec{p}_\tau - \vec{p}_h|^2 = m_\nu^2 = 0$$

observable

$$\begin{cases} (E_\tau - E_h)^2 = \left(\frac{1}{2}m_{\Upsilon(4S)} - \sqrt{m_h^2 + |\vec{p}_h|^2}\right)^2 = |\vec{p}_\nu|^2 \\ |\vec{p}_\tau - \vec{p}_h|^2 = |\vec{p}_\tau|^2 + |\vec{p}_h|^2 - 2|\vec{p}_\tau||\vec{p}_h|\cos\theta_{\tau h} \end{cases}$$

$$\cos\theta_{\tau h} = \frac{|\vec{p}_\tau|^2 + |\vec{p}_h|^2 - |\vec{p}_\nu|^2}{2|\vec{p}_\tau||\vec{p}_h|}$$

7. Summary & Next plan

To explain the 2.7σ discrepancy between the theoretical value and experimental one of the muon's anomalous magnetic moment, light Z' boson with below GeV mass in L_μ-L_τ model and neutrino trident producton is suitable. To discover this Z' boson, we are searching for $\tau \to lX$ decay with Belle 1ab^{-1} statistics.

We reported MC study and estimated the sensitivities (maximum 2.12, m_X=1600MeV/c^2) and upper limits lower than the previous result with several mass of X (~10^{-4}).

For the next plan a more pricise approximation of τ direction is needed for the low X mass.