The 15th workshop on tau lepton physics

Latest Belle results on Tau decays

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On behalf of Belle collaboration

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Outline

- Introduction to KEKB/Belle

- Measurement of Br for rare decays of tau

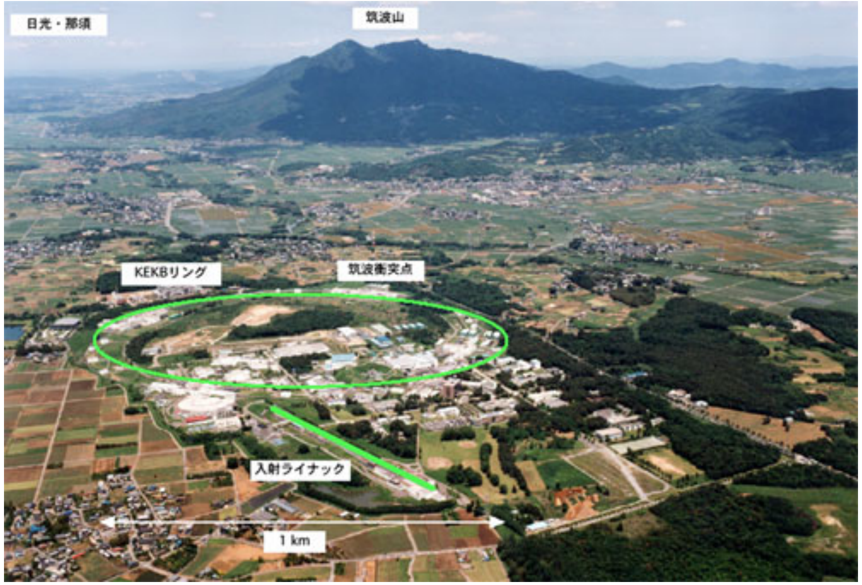
$\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$, ($\ell$ = e or μ)

$\tau^- \to \ell^- \nu_\ell \nu_\tau \ell'^+ \ell'^-$, ($\ell, \ell'$ = e or μ)

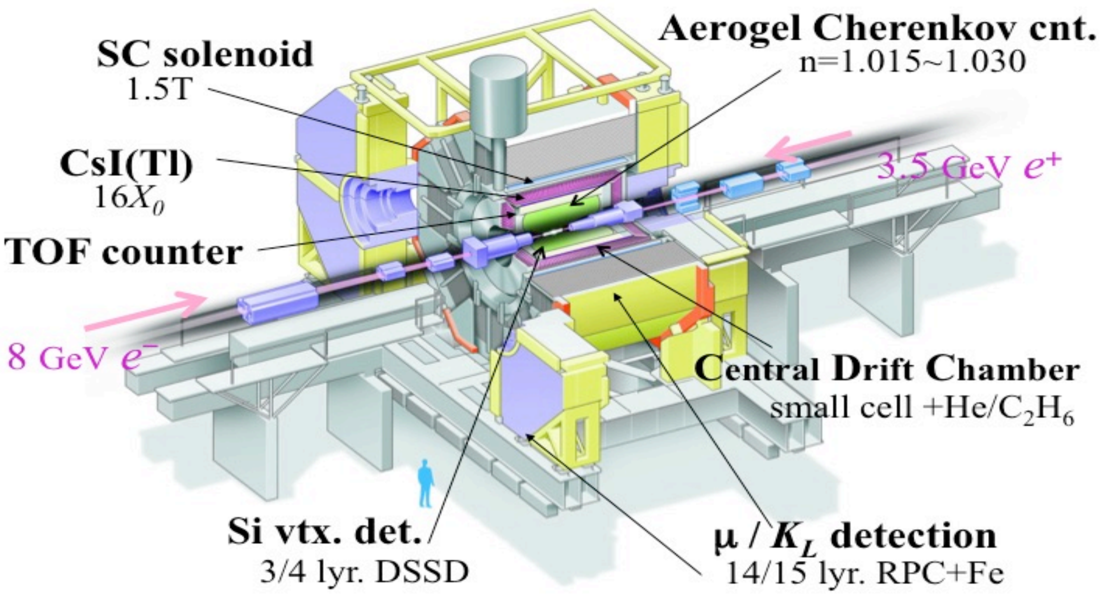
- Summary

KEKB and Belle

- KEKB accelerator:
- located in Tsukuba, Japan,
- 8.0 GeV e^- collides with 3.5 GeV e^+,
- $\sqrt{s} = E_{\Upsilon(4S)} = 10.58$ GeV
- Peak instantaneous luminosity 2.11×10^{34} $cm^{-2} \cdot s^{-1}$.



Belle Detector

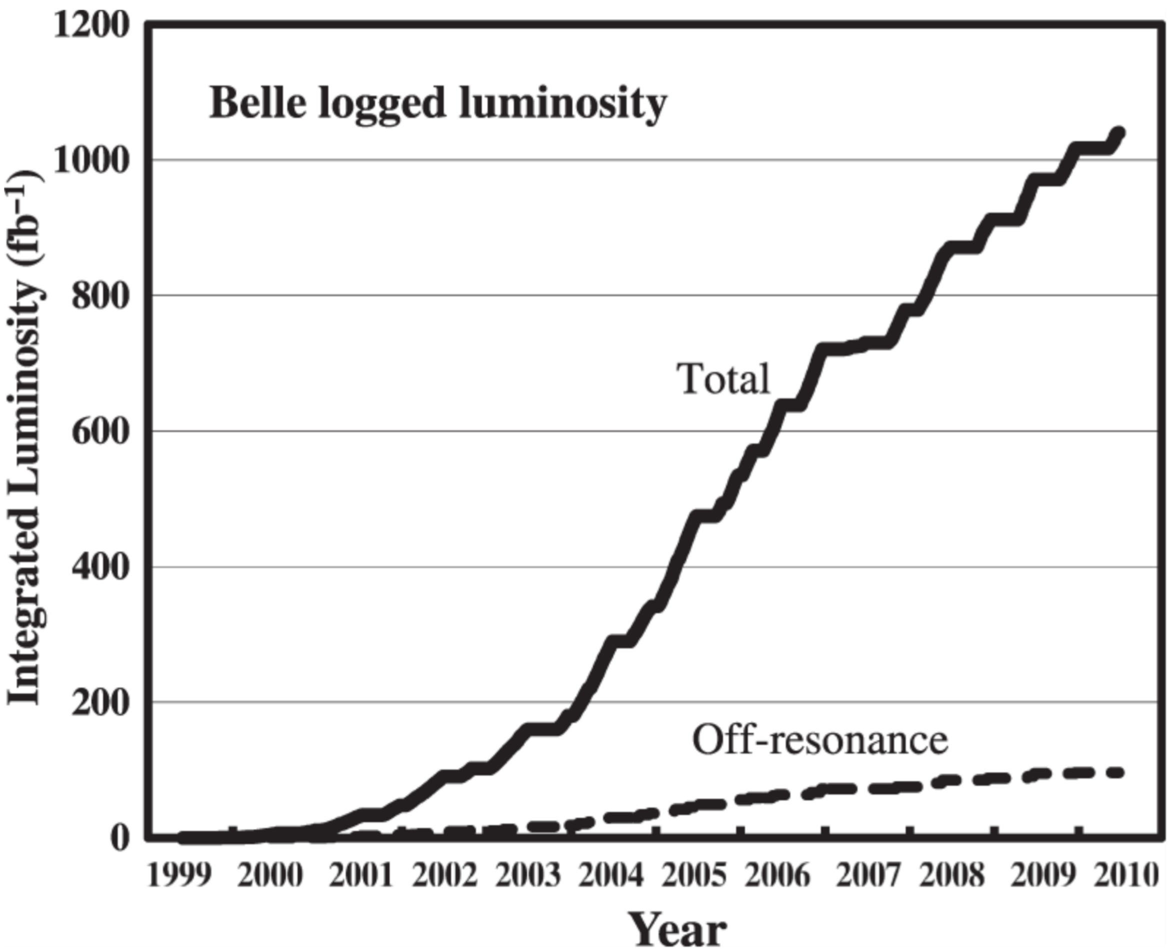


Belle detector is located at the interaction point of KEKB. It has been working not only as a B-factory but also as a Tau-factory.

$e^+e^- \to B\,\bar{B}$: 1.05 nb

$e^+e^- \to \tau^+\tau^-$: 0.919 nb

Belle datasets

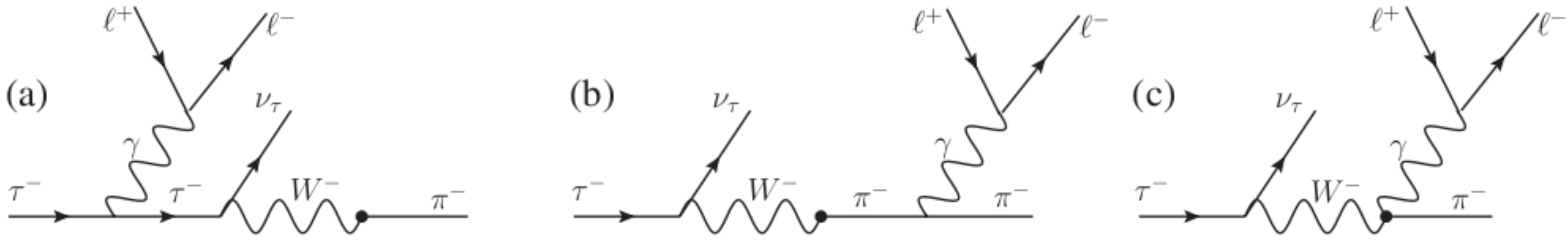


	On-peak	Off-peak
$\Upsilon(1S)$	5.7 fb^{-1}	1.8 fb^{-1}
$\Upsilon(2S)$	24.9 fb^{-1}	1.7 fb^{-1}
$\Upsilon(3S)$	2.9 fb^{-1}	0.25 fb^{-1}
$\Upsilon(4S)$ SVD1	140.0 fb^{-1}	15.6 fb^{-1}
$\Upsilon(4S)$ SVD2	571.0 fb^{-1}	73.8 fb^{-1}
$\Upsilon(5S)$	121.4 fb^{-1}	1.7 fb^{-1}
Scan		27.6 fb^{-1}

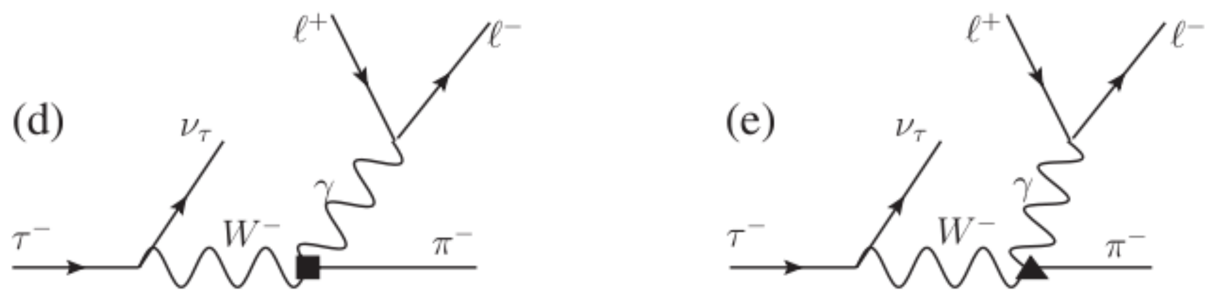
Data taking:
June 1999 – June 2010.
The world's largest statistics of tau, 9×10^8 $\tau^+\tau^-$ pair events, was collected by Belle.

$$\tau^- \rightarrow \pi^- \nu_\tau \ell^+ \ell^-$$

$\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$



P. Roig, PRD 88, 033007(2013)



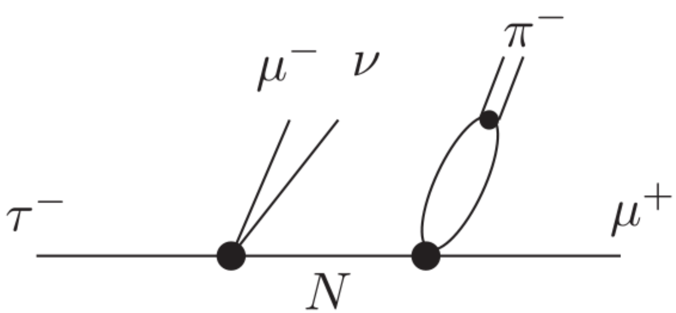
The first three are QED contributions of a γ emitted off the τ, π and vertex. The solid square (triangle) represents the vector (axial-vector) current contribution.

This decay mode is not observed yet.

	Central value of Br (Theoretical prediction)	Error band of Br
$\tau \to \pi \nu_\tau e^+ e^-$	1.710×10^{-5}	[1.4×10^{-5}, 2.8×10^{-5}]
$\tau \to \pi \nu_\tau \mu^+ \mu^-$	1.938×10^{-6}	[3×10^{-7}, 1×10^{-5}]

Physics Motivations

PRL. 102.10 (2009): 101802. arXiv:1805.12028



C. Dib, et al., PRD, 85 (2012) 011301

Br < $1.3\text{x}10^{-5}$

1, Probe the New Physics contribution. Heavy long-lived sterile neutrinos have been introduced to explain the excess of electron-like events at the MiniBooNE experiment, which could also result in an observable enhancement to the branching ratio of $\tau^- \rightarrow \pi^- \ell^+ \ell^- \nu_\tau$.

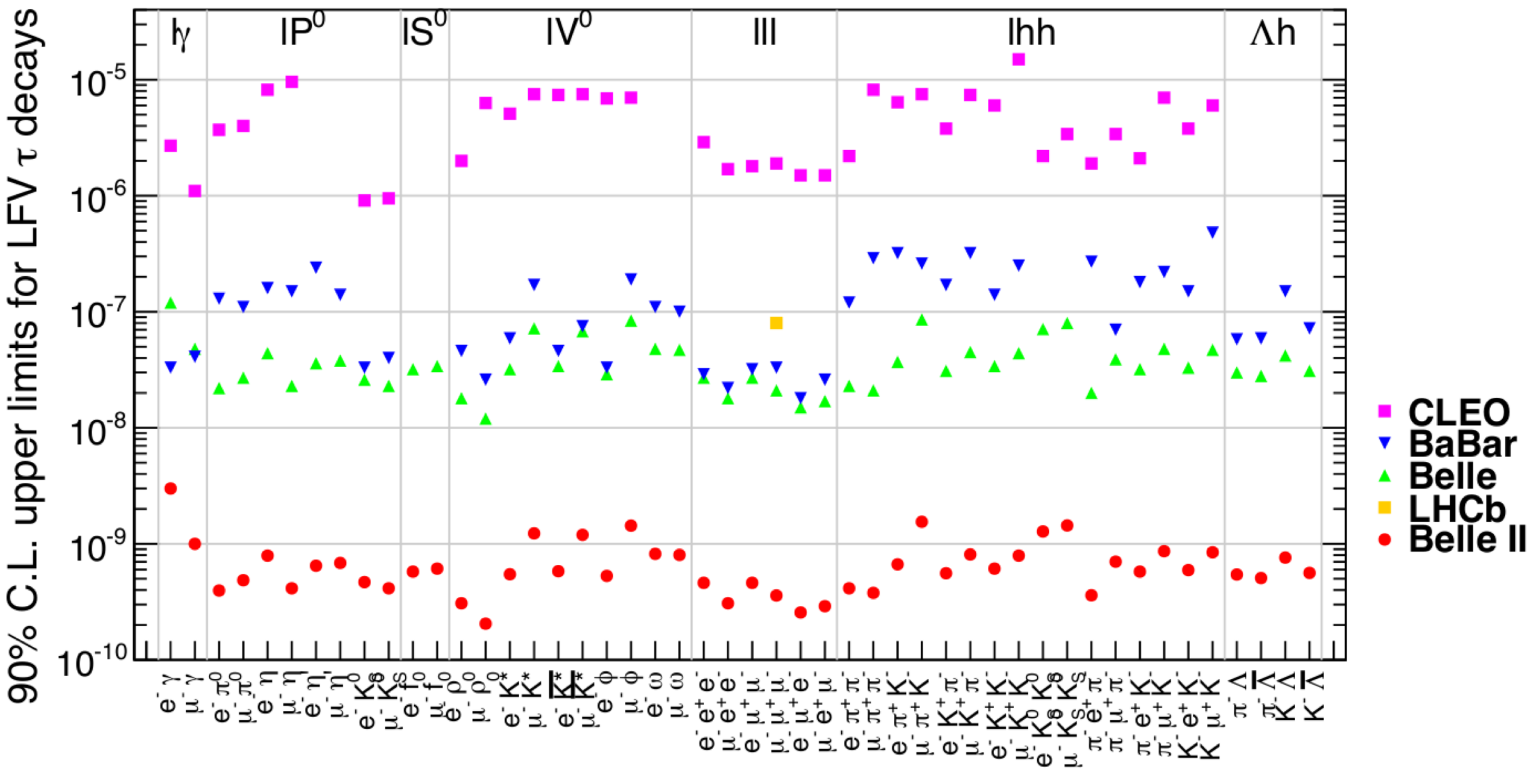
2, $\mathcal{F}_{\pi^\pm W^\mp \gamma^*}$ (the $\pi^\pm W^\mp \gamma^*$ vertex in d and e).

Same vertex in cross channel $\pi \rightarrow \ell\ \nu_l\ e^+\ e^-$: $Br(\pi \rightarrow e\ \nu_e\ e^+\ e^-) = (3.2 \pm 0.5)$ x 10^{-9}, lepton universality can be checked. $Br(\pi \rightarrow \mu\ \nu_\mu\ e^+\ e^-)$ is not observed yet, thus can be inferred.

Phys. Lett. B 222 533 (1989)

Physics Motivations

3, Notable BKG to the Lepton Flavor (number) Violation searches: $\tau \to \ell \ell \ell$, $\ell \pi \pi$, $\pi \ell \ell$, whose upper limit of branching fraction have been reduced to the order of 10^{-8}. (π-μ mis-id ~%)



HFLAV summary plot for τ LFV decays,
overlaid with Belle II extrapolation to 50 ab^{-1} assuming zero background

More details can be referred to at Ami's talk

Br of $\tau^- \to \pi^- \nu_\tau e^+ e^-$

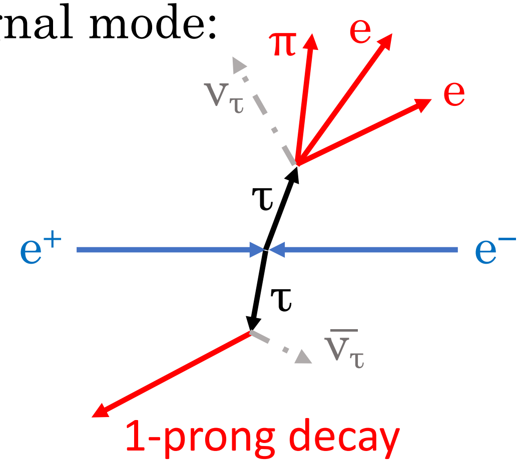
$(\ell = e)$

$\tau^- \to \pi^- \nu_\tau e^+ e^-$: Signal topology/Expected BKG

The analysis is carried out as a blind analysis of counting events. The signal mode is embedded in TAUOLA with the form factor provided by P. Roig. π^0 reconstruction is calibrated by $\tau^- \to \pi^- e^+ e^- \gamma \nu_\tau$.

BKG components	
$\tau^- \to \pi^- \pi^0(e^+ e^- \gamma) \nu_\tau$	55.83%
$\tau^- \to \pi^- \pi^0(\gamma \gamma) \nu_\tau$	24.22%
Other τ decays	13.85%
Continuum processes	2.59%
2-photon processes	2.55%
B decays	0.04%
5-lepton	0.08%
Bhabha	0.84%
Expected number of BKG	478 ± 23

Signal mode:



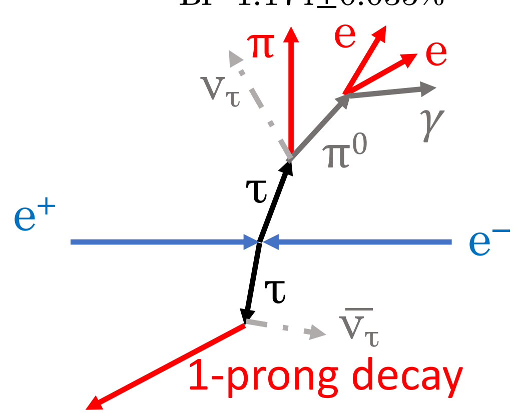
Signal mode	$\tau \to \pi \nu_\tau e^+ e^-$
Assumed Br	1.7×10^{-5}
Detection eff	(1.88 ± 0.07) %
Expected number of signal	165.4 ± 6.3
Figure of Merit	6.5

Main BKG: $\tau^- \to \pi^- \pi^0 \nu_\tau$ (Belle pion form factor)

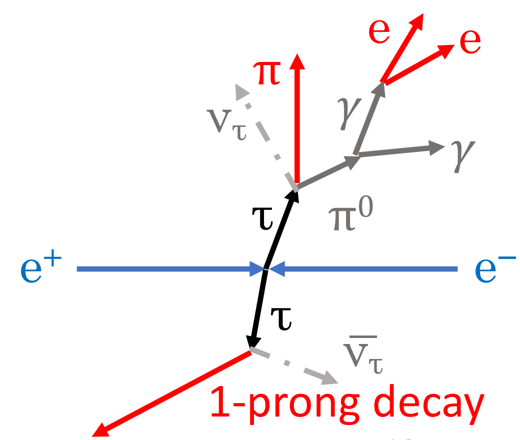
PRD 78, 072006 (2008)

Dalitz decay of π^0

Br=1.174 ± 0.035%



γ-conversion



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π^0 reconstruction is calibrated by $\tau^- \rightarrow \pi^- e^+ e^- \gamma \nu_\tau$.

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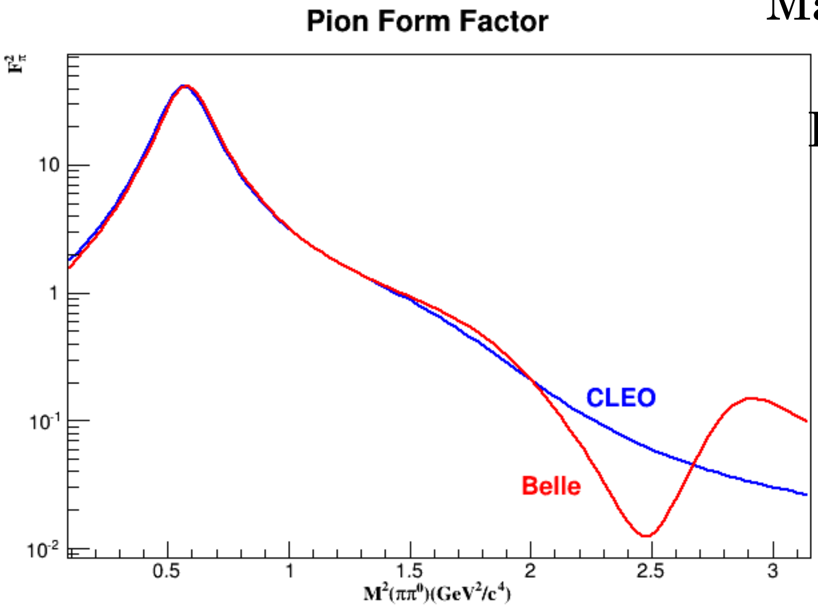

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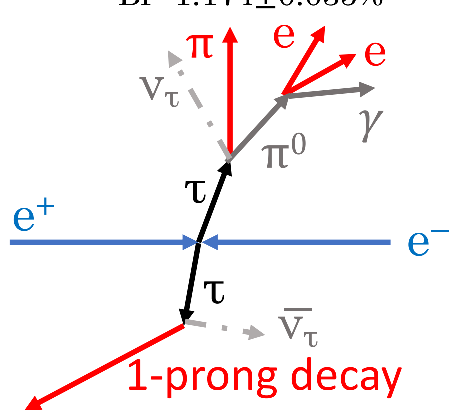
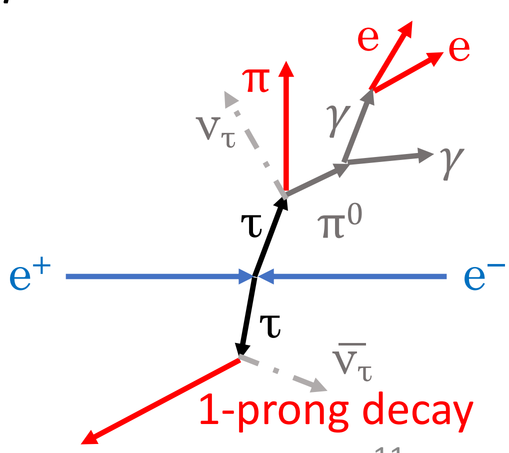
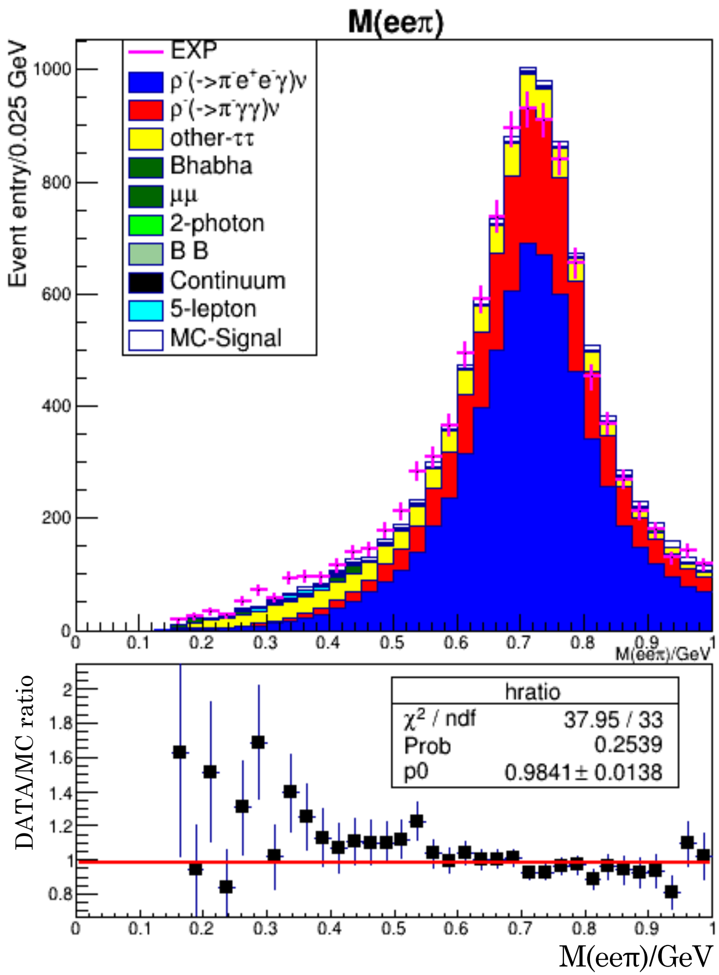


γ-conversion



$\tau^- \to \pi^- \nu_\tau e^+ e^-$: Sideband



Invariant Mass of 3 prongs is used to define the signal box/sideband.

Signal box: [1.05, 1.8] GeV.

Sideband: [0, 1] GeV.

Sideband is used to validate the MC and various corrections upon the MC. (see left figure)

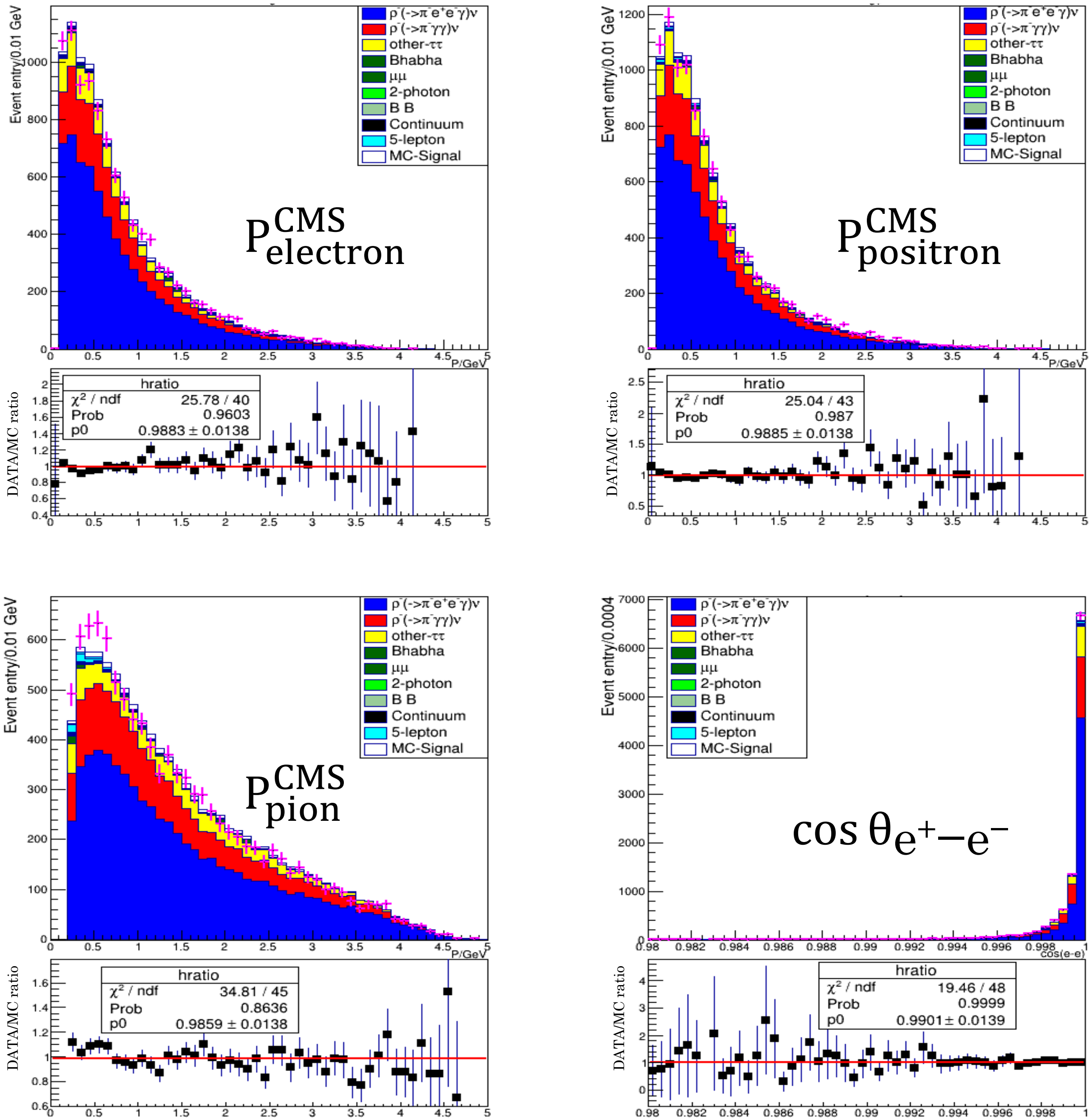
Here Br=1.7x10^{-5} is used for signal Br during MC study and sideband study. (The signal contamination in sideband is 2.0%, a very tiny fraction.)

In the sideband region:

Observed events	MC BKG events	MC signal events
10243	10083±504	202.5±8.1

Data agrees with the known BKG within 1σ.

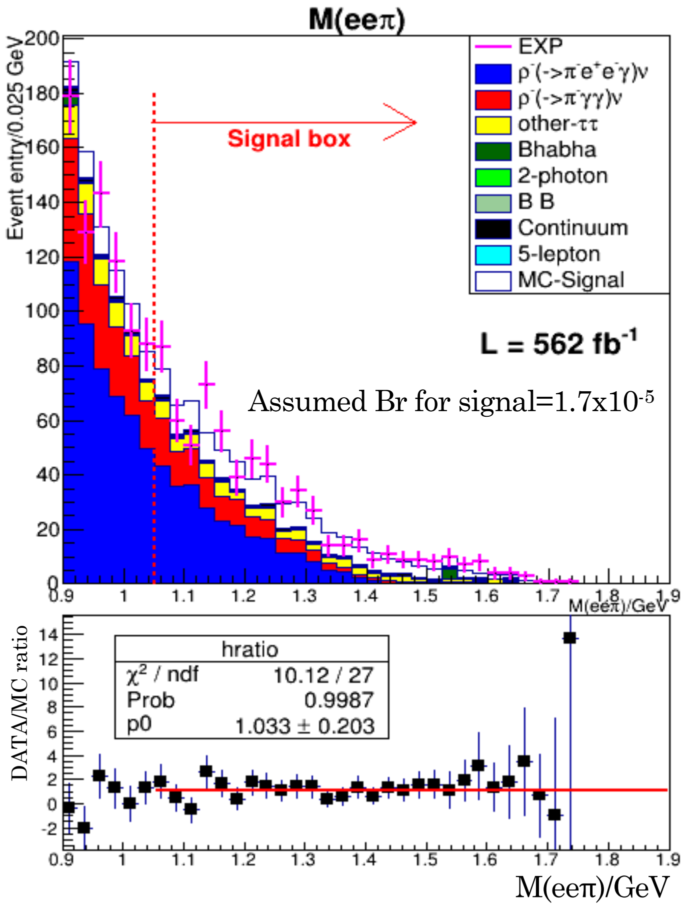
$\tau^- \to \pi^- \nu_\tau e^+ e^-$: Distributions of data in sideband



Various distributions in the sideband are also well explained by background (Mainly from $\tau^- \to \pi^-\pi^0\nu_\tau$).

CMS: center mass frame of the beams

$\tau^- \to \pi^- \nu_\tau e^+ e^-$: Signal region



Observed events	MC BKG events
682	477±23

There is an clear excess of data over the expected background (>5.9σ). (First observation)

Determination of branching fraction:

$$\boldsymbol{Br}(\tau^\pm \to \pi^\pm l^+ l^- \nu_\tau) = \frac{N_{\mathrm{obs}} - N_{\mathrm{BKG}}}{\sigma_{\tau\tau} \cdot \mathcal{L} \cdot \epsilon_{\mathrm{sig}}}$$

$Br(\tau^- \to \pi^- \nu_\tau e^+ e^-)$ (preliminary)

$$Br = (2.11 \pm 0.19 \pm 0.30) \times 10^{-5}$$

Stat. Syst.

Theoretical range: $[1.4 \times 10^{-5}, 2.8 \times 10^{-5}]$

Contents	Syst. error
MC size	3.74%
$\tau\tau$ cross section	0.3%
Trigger	1.16%
π^0 veto	1.86%
Br's of BKG	4.42%
Luminosity	4.66%
Tracking	4.66%
PID	11.14%
Total:	14.4%

Br of $\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$

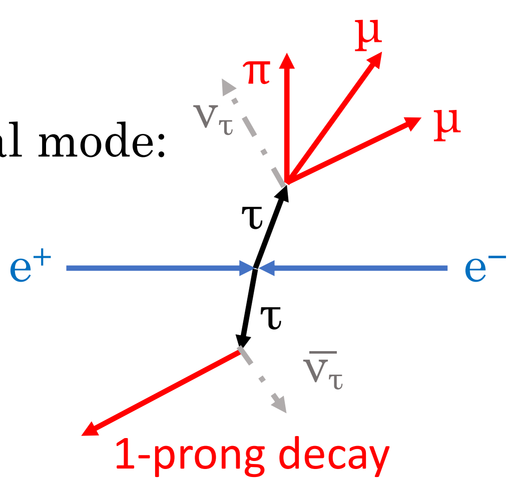
$(\ell = \mu)$

$\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$: Signal topology/Expected BKG

Main background is from $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$, where two π's are misidentified as μ's. The PID(π fake rate) is calibrated by $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$.

BKG components	
$\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$	81.88%
$\tau^- \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$	8.26%
Other τ decays	1.64%
Continuum processes	2.25%
2-photon processes	0.11%
B decays	5.60%
5-lepton	0.26%
Expected number of BKG	1129 ± 55

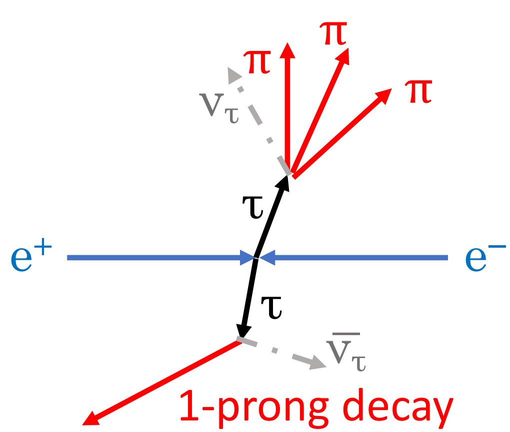
Signal mode:

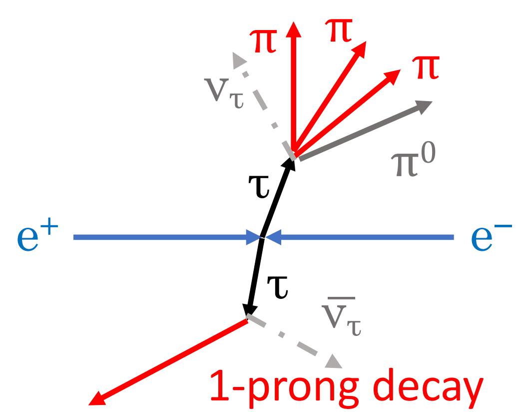


Signal mode	$\tau \to \pi \nu_\tau \mu^+ \mu^-$
Assumed Br	1.0×10^{-5}
Detection eff	(4.13±0.16) %
Expected number of signal	213.4 ± 8.3
Figure of Merit	5.8

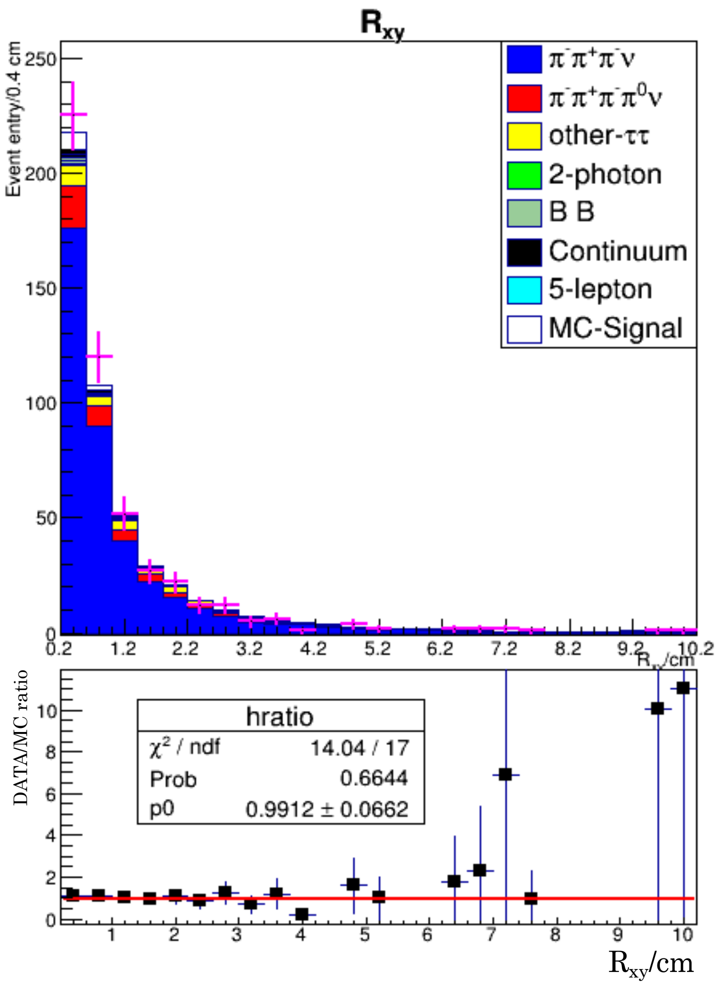
Main BKG: $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$

$\pi \to \mu$ misID





$\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$: Sideband



Transverse distance of $\mu^+\mu^-$ vertex (R_{xy}) is used to define the signal box/sideband, as main BKG comes from $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$.

Signal box: [0, 0.15] cm.

Sideband: > 0.2 cm.

Here, maximum value $1\text{x}10^{-5}$ for Br is assumed during MC study and sideband study. (The signal contamination in sideband is 2.3%.)

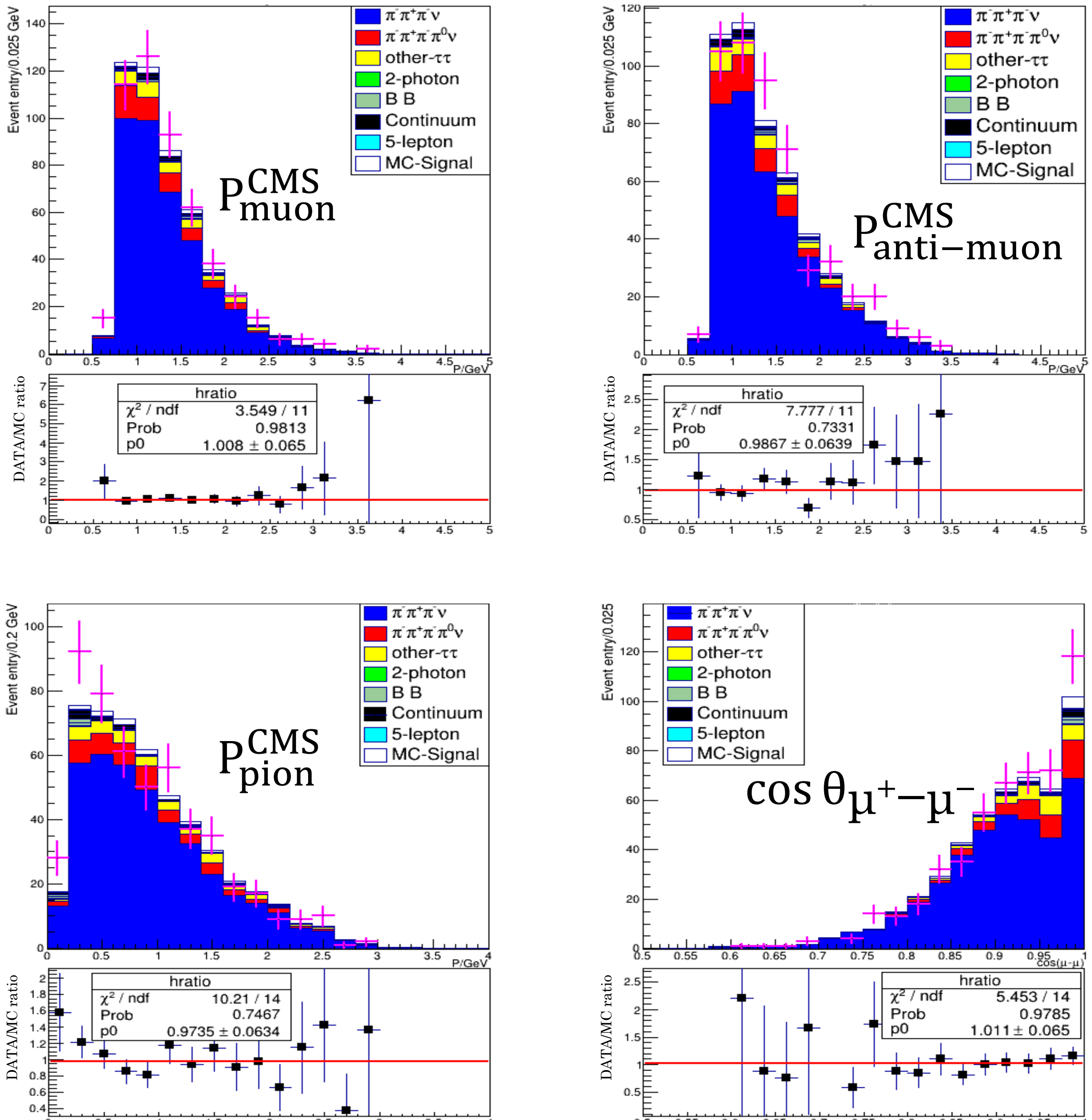
Contents in signal box and sideband have similar components.

In the sideband region:

Observed events	MC BKG events	MC signal events
505	477±23	11.4±0.4

Data agrees with the known BKG within 1σ.

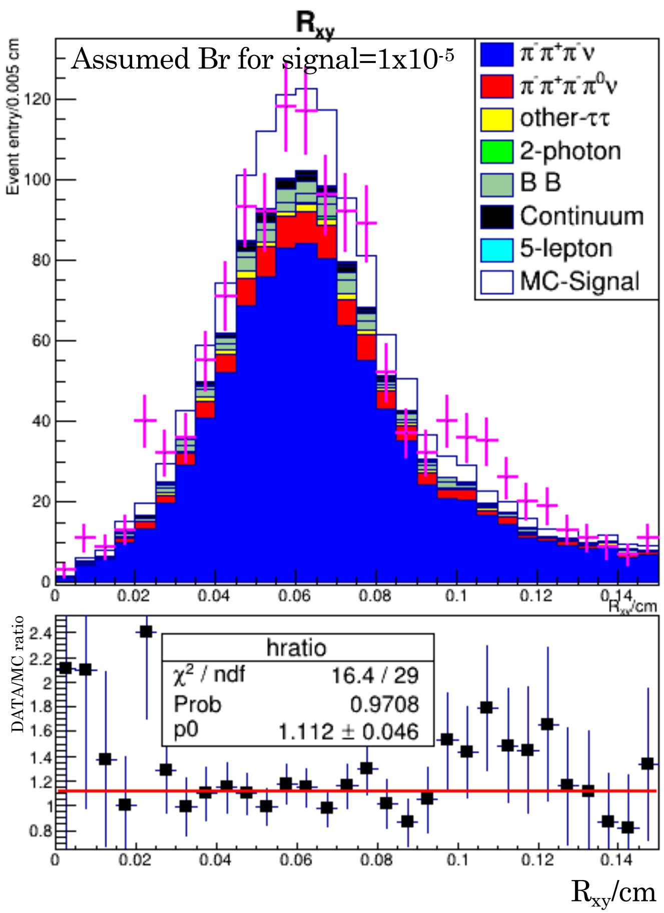
$\tau^- \rightarrow \pi^- \nu_\tau \mu^+ \mu^-$: Distributions of data in sideband



Various distributions in the sideband are also well explained by background (Mainly from $\tau^- \rightarrow \pi^-\pi^+\pi^-\nu_\tau$).

Preliminary result of Br($\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$)

$$\boldsymbol{Br}(\tau^\pm \to \pi^\pm l^+ l^- \nu_\tau) = \frac{N_{\rm obs} - N_{\rm BKG}}{\sigma_{\tau\tau} \cdot \mathcal{L} \cdot \epsilon_{\rm sig}}$$



Observed events	MC BKG events
1289	1122 ± 55

Data is consistent with the background expectation within 3σ.
Br < 1.06 x 10^{-5} @90% CL

Systematic uncertainty of N_{BKG}	
MC size	1.7%
Luminosity	1.4%
Tracking	1.4%
Trigger	0.3%
PID	3.7%
Br's of BKG modes	1.0%
π -> μ mis-id	1.5%
Total	4.9%

Status of $\tau^- \to \ell^- \nu_\ell \nu_\tau \ell^+ \ell^-$

$\tau^- \to \ell^- \nu_\ell \nu_\tau \ell^+ \ell^-$

JHEP 1604, 185 (2016)

Modes	Theoretical prediction on Br
$\tau \to e \nu_e \nu_\tau e^+ e^-$	$(4.21 \pm 0.01) \times 10^{-5}$
$\tau \to \mu \nu_\mu \nu_\tau e^+ e^-$	$(1.984 \pm 0.004) \times 10^{-5}$
$\tau \to e \nu_e \nu_\tau \mu^+ \mu^-$	$(1.247 \pm 0.001) \times 10^{-7}$
$\tau \to \mu \nu_\mu \nu_\tau \mu^+ \mu^-$	$(1.183 \pm 0.001) \times 10^{-7}$

Calculation of NLO can be referred to Matteo's talk

PRL.76.2637(1996)

CLEO result with 3.60 fb^{-1}	
$Br(\tau \to e \nu_e \nu_\tau e^+ e^-)$	$(2.7^{+1.5}_{-1.1}{}^{+0.4}_{-0.4}{}^{+0.1}_{-0.3}) \times 10^{-5}$
$Br(\tau \to \mu \nu_\mu \nu_\tau e^+ e^-)$	$< 3.2 \times 10^{-5}$ @90%CL

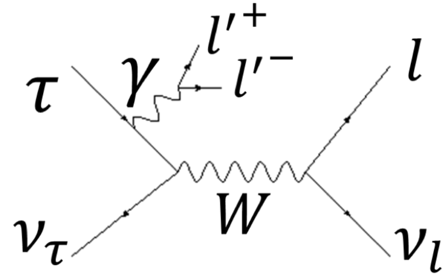
This leptonic decay $\tau \to \ell \nu_\ell \nu_\tau \ell^+ \ell^-$ can probe the Lorentz structure of the weak charged current.

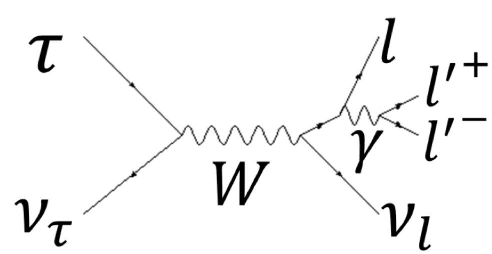
Michel parameters can be constrained from the measured Br's.

Also the tau g-2.

A dominant BKG for LFV searches

A candidate for sterile neutrino searches.





$\tau^- \to \ell^- \nu_\ell \nu_\tau \ell^+ \ell^-$ @Belle

Analysis is ongoing using the entire Belle $\Upsilon(4S)$ data. The MC study and sideband check are complete. We are ready to open the signal box.

Modes:	$\tau \to e\, \nu_e\, \nu_\tau\, e^+ e^-$	$\tau \to \mu\, \nu_\mu \nu_\tau\, e^+ e^-$	$\tau \to e\, \nu_e\, \nu_\tau\, \mu^+ \mu^-$	$\tau \to \mu\, \nu_\mu\, \nu_\tau\, \mu^+ \mu^-$
Detection efficiency	(1.790±0.001) %	(1.090±0.003) %	(3.561±0.006) %	(1.674±0.004) %
Main BKG	$e\, \nu_e \nu_\tau \gamma(\to e\, e)$; $\pi\, \pi^0\, \nu_\tau$	$\mu\, \nu_\mu\, \nu_\tau \gamma(\to e\, e)$; $\pi\, \pi^0\, \nu_\tau$	$\pi\, \pi^0\, \nu_\tau$	$\pi\, \pi^+\, \pi^-\, \nu_\tau$
Expected number of signal	1300	430	8	4
Purity of signal region	47%	50%	37%	16%

We expect to observe the first two modes with Belle data and to set upper limits on the other two modes.

Summary

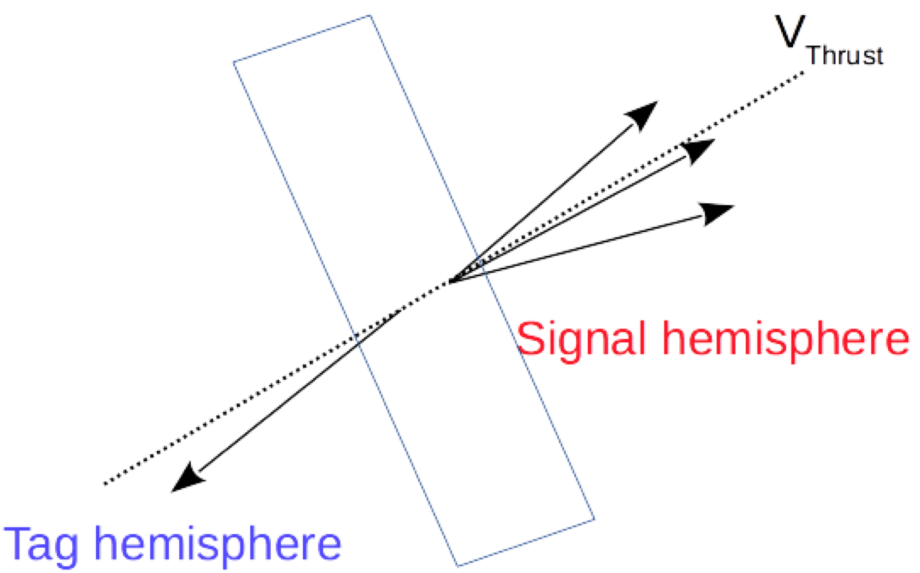
- Using a 562 fb^{-1} data set collected at $\Upsilon(4S)$, Br of a rare decay of tau, $\tau^- \to \pi^- \nu_\tau \ell^+ \ell^-$ (ℓ = e or μ), is measured.

1. The Br of $\tau^- \to \pi^- \nu_\tau e^+ e^-$ is measured FOR THE FIRST TIME. **Br = (2.11 ± 0.19 ± 0.30) x 10^{-5}**. No obvious enhancement from SM on Br (sterile neutrino). A precise Br measurement is important to understand the $\pi^\pm W^\mp \gamma^*$ vertex.
2. An upper limit is set on the Br of $\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$ at 90% CL. **Br < 1.06 x 10^{-5}**. It is the FIRST upper limit on this decay mode.
3. These measurements can be used to constrain parameters of the sterile neutrino models, such as mass, mixing strength, lifetime. Improvement of one order of magnitude on upper limit is expected for $\tau^- \to \pi^- \nu_\tau \mu^+ \mu^-$ at Belle II.

- Meanwhile, analysis of $\tau^- \to \ell^- \nu_\ell \nu_\tau \ell^+ \ell^-$ is ongoing using entire $\Upsilon(4S)$ samples. The signal box of $\tau^- \to \ell^- \nu_\ell \nu_\tau \ell^+ \ell^-$ will be opened soon, and preliminary results will be obtained soon.

Thank you !

Back up

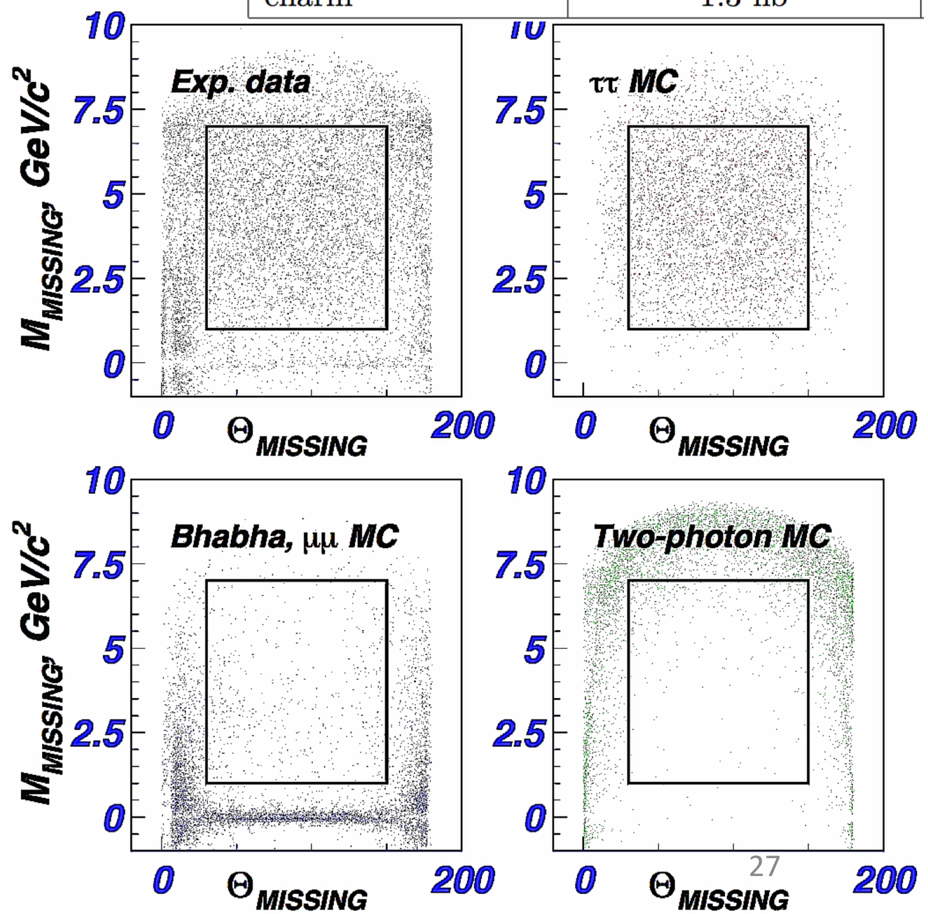


Pre-selection of τ τ events

There are numerous processes occur at $\Upsilon(4S)$. A pre-selection is applied to select $e^+ e^- \rightarrow \tau^+ \tau^-$ events and suppress BKG.

Process	cross section at $\Upsilon(4S)$
$\tau^+\tau^-$	0.919 ± 0.003 nb
Bhabha	123.5 ± 0.2 nb
di-muon	1.005 ± 0.001 nb
2 photon-eeee	40.9 nb
2 photon-ee$\mu\mu$	18.9 nb
2 photon-eeuu/eedd	12.498 nb
2 photon-eecc	0.03 nb
2 photon-eess	0.227 nb
B^+B^-	0.525 nb
$B^0\bar{B}^0$	0.525 nb
uds	2.09 nb
charm	1.3 nb

1. Number of charged track = 4
2. Net charge = 0
3. Sum of momenta of charged track (P^{CM}) <10 GeV
4. Sum of energy deposit in ECL < 10 GeV
5. Max transverse momentum of charge track ($P_{t_{max}}$)>0.5 GeV
6. Primary vertex to IP <0.5 cm (in x-y plane), <2.5 cm (in z)
7. Sum of P^{CM} + sum of E_γ^{CM} >3 GeV or $P_{t_{max}}$ >1 GeV
8. $P^{CM} + E_\gamma^{CM} + |P_{missing}^{CM}| < 9$ GeV or max opening angle <175°
9. Number of track in barrel ≥ 2 or energy deposit of tracks in ECL<5.3GeV
10. 1 GeV < $M_{missing}$< 7 GeV
11. 30° < $\theta_{missing}$< 150°



CM: the center of mass frame of $e^+ e^-$ beams

$\mathbf{P_{missing}^{CM} = P_{beam}^{CM} - P_{observed}^{CM}}$

Selection criteria for τ -> π ν_τ e^+ e^-

Descriptions	Relevant cuts
Energy-Momentum	$P_t^{LAB} > 0.1GeV/c$, $P_\pi^{CMS/LAB} > 0.2GeV/c$
PID	eID($e^\pm$)>0.5, μID(π)<0.95, eID(π)<0.2, $\pi ID(\pi) > 0.4$
Secondary e^+e^- vertex	$\|R_{xy}\| < 1.2$ cm, $-1 < Z < 1.5$ cm
Angular distribution	$\|cos(\tau - 3prongs)\| \leq 1$
Invariant mass	$1.05 < M_{3prongs} < 1.8$ GeV/c^2
Event shape	$0.85 < \frac{\sum_i \|\vec{p_i} \cdot \vec{n_T}\|}{\sum_i \|\vec{p_i}\|} < 0.99$ (in CMS)
Gamma	$N_{signal\_hemisphere\_\gamma} \leq 1$, $E_{signal\_hemisphere\_\gamma\_max} \leq 300$ MeV
π^0 veto	$110 < M_{\gamma\gamma} < 160$ MeV, $110 < M_{e^+e^-\gamma} < 165$ MeV

In the sideband study, discrepancy of $\pi^0(e^+ e^- \gamma)$ veto is observed. So, a reference mode $\tau^- \rightarrow \pi^- \nu_\tau e^+ e^- \boldsymbol{\gamma}$ is studied to correct the $\pi^0(e^+ e^- \gamma)$ reconstruction efficiency and introduce the correction on π^0 veto upon MC data.

Selection criteria for $\tau \to \pi \nu_\tau \mu^+ \mu^-$

Descriptions	Relevant cuts
Energy-Momentum	$P_t^{LAB} > 0.1GeV/c$, $P_t(\mu^\pm) > 720$ MeV/c, $E_\pi + E_{\mu^+} + E_{\mu^-} < E_{beam}$
Mass	Pseudo Mass$(\pi\mu^+\mu^-)$ <1.8 GeV/c^2
PID	πID(π)>0.4, eID(π)<0.8, μID($\mu^\pm$)>0.97, KID($\mu^\pm$)<0.8
$\mu^-\mu^+$ vertex	$\lvert r_{xy}\rvert < 0.15$ cm
Event shape	$\frac{\lvert\vec{P_{e^+}}+\vec{P_{e^-}}+\vec{P_\pi}+\vec{P_{sig\gamma}}-\vec{P_{tag}}-\vec{P_{tag\gamma}}\rvert}{\lvert P_{e^+}\rvert+\lvert P_{e^-}\rvert+\lvert P_\pi\rvert+\lvert P_{sig\gamma}\rvert+\lvert P_{tag}\rvert+\lvert P_{tag\gamma}\rvert} > 0.9$ (in CMS)
Gamma Veto	$E_{total\_signalside\_\gamma} < 300$ MeV, $N_{\gamma\_bothsides} < 6$

Very high cut on μID is applied. As μID in Belle is mainly validated by hadronic process, it is crucial to study the μID under the environment of tau decays and apply this correction on the MC.
The main background: $\tau \to 3\pi \nu_\tau$. The $\pi \to \mu$ mis-id efficiency is investigated via $\tau \to 3\pi \nu_\tau$ events.

Uncertainty of the branching fraction

$$\boldsymbol{Br}(\tau^{\pm} \to \pi^{\pm} l^{+} l^{-} \nu_{\tau}) = \frac{N_{\text{obs}} - N_{\text{BKG}}}{\sigma_{\tau\tau} \cdot \mathcal{L} \cdot \epsilon_{\text{sig}}} \qquad N_{\text{BKG}} = \mathcal{L} \cdot (\sum_i \sigma_i \cdot \epsilon_i)$$

$$\epsilon = \epsilon_{initial} \cdot R_{trk} \cdot R_{PID}$$

$$\frac{\Delta \mathcal{B}}{\mathcal{B}} = \sqrt{(\frac{\Delta\sigma_{\tau\tau}}{\sigma_{\tau\tau}})^2 + (\frac{\Delta\mathcal{L}}{\mathcal{L}})^2 + (\frac{\Delta\epsilon_{sig}}{\epsilon_{sig}})^2 + (\frac{\Delta R_{sig}}{R_{sig}})^2 + (\frac{\Delta N_{BKG}}{N_{obs} - N_{BKG}})^2 + (\frac{\Delta N_{obs}}{N_{obs} - N_{BKG}})^2}$$

The systematics uncertainty includes:

- **Cross section of ττ**: 0.919 ± 0.003 nb, by KKMC.
- **Luminosity**: 1.4% using Bhabha events.
- **Statistic error of MC**: Poisson variance
- **Tracking efficiency**: Using partially reconstructed $D^* \to D^0 \pi_{slow}$, $D^0 \to K_S^0 \pi^- \pi^+$, $K_S^0 \to \pi^- \pi^+$ (one daughter here allowed not to be reconstructed). Comparing track finding in MC and EXP, 0.35% per track. Low momentum region is checked by $B^0 \to D^{*-} \pi^+$, π_{slow}^- in D^{*-} serves as probe.
- **Particle identification**: $D^{*+} \to D^0 \pi_{slow}^+ \to K^- \pi^+ \pi_{slow}^+$ for πID (π_{slow}^+ serve as tag; K^-, π^+ as probe), $\gamma\gamma \to l^+ l^-$ and $J/\psi \to l^+ l^-$ for lepton ID
- **Trigger**: by Belle simulation study
- **Br of BKG components**: taken from PDG.
- **π^0 veto**: statistic error of the reference study.
- **π -> μ mis-identification**: statistic error of the reference study.