Recent Results on τ Lepton Physics from Belle

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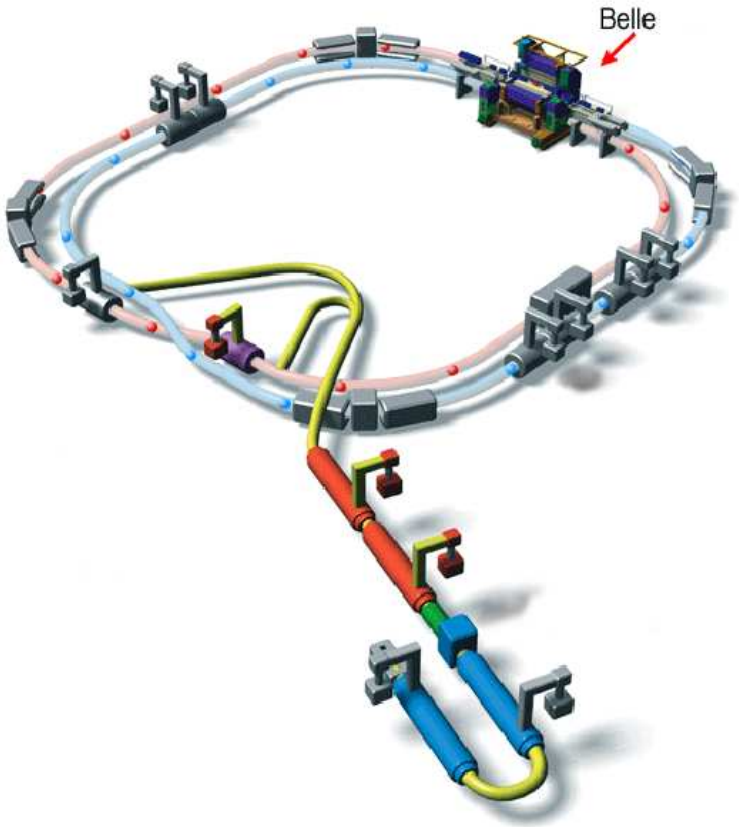
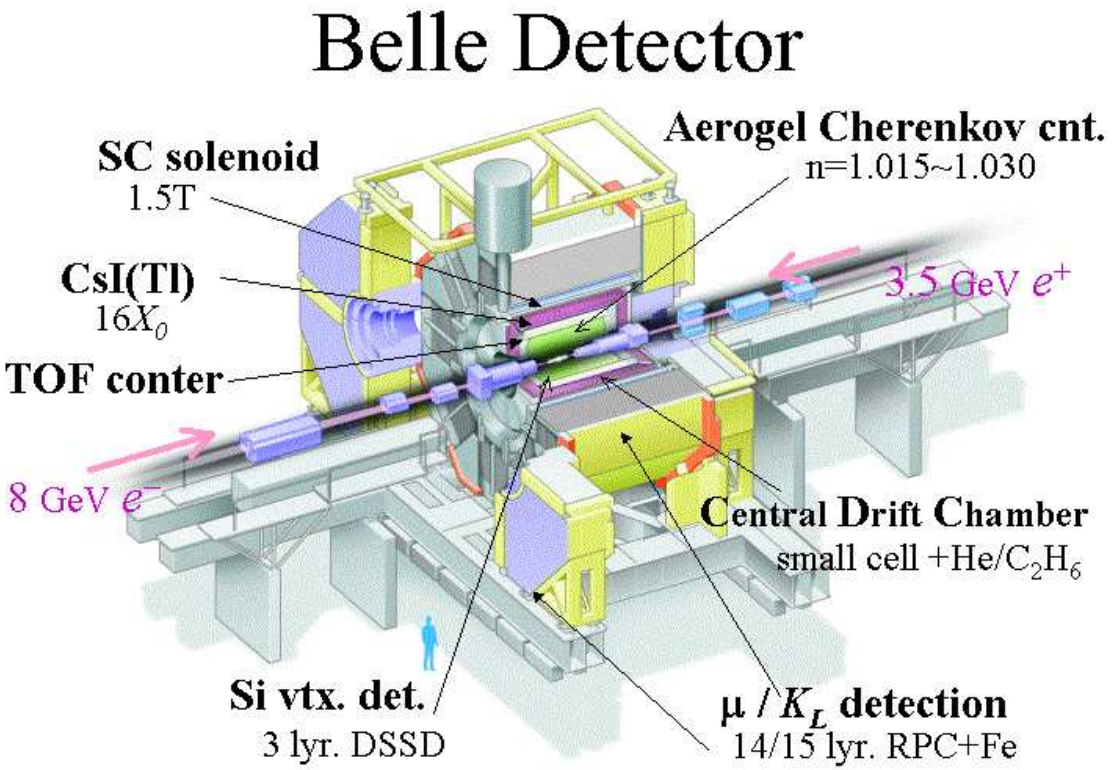
Outline

1. Belle experiment
2. Search for LFV decays
3. Measurement of τ lifetime
4. Study of $\tau^- \to K^0_S X^- \nu_\tau$
5. Summary

Belle Experiment – I



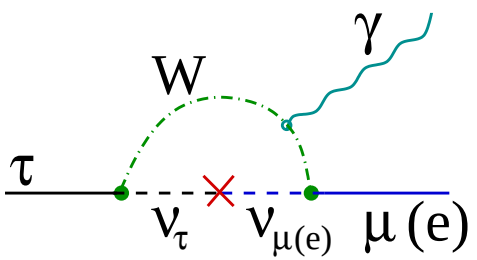


Belle Experiment – II

Process	σ, nb
$e^+e^- \to e^+e^-(\gamma)$ $15^o \le \theta \le 165^o$	123.5
$e^+e^- \to \mu^+\mu^-(\gamma)$	1.005
$e^+e^- \to q\overline{q}$ $(q = u, d, s, c)$	3.39
$e^+e^- \to b\overline{b}$	1.05
$e^+e^- \to e^+e^- f\overline{f}$ $(f = u, d, s, c, e, \mu, \tau)$	72.6
$e^+e^- \to \tau^+\tau^-(\gamma)$	0.919

- $\sim$ 450 members, 80 Inst., 18 countries
- $E_{e^-} = 8$ GeV, $E_{e^+} = 3.5$ GeV
- Continuous injection, record lumi
- $L_{\max} = 2.11 \times 10^{34}$ cm^{-2}s^{-1}
- $\int Ldt \simeq 1$ ab^{-1}, $N_{\tau\tau} \simeq 10^9$
- B-factory is also a τ-factory

Lepton-flavor-violating (LFV) τ Decays

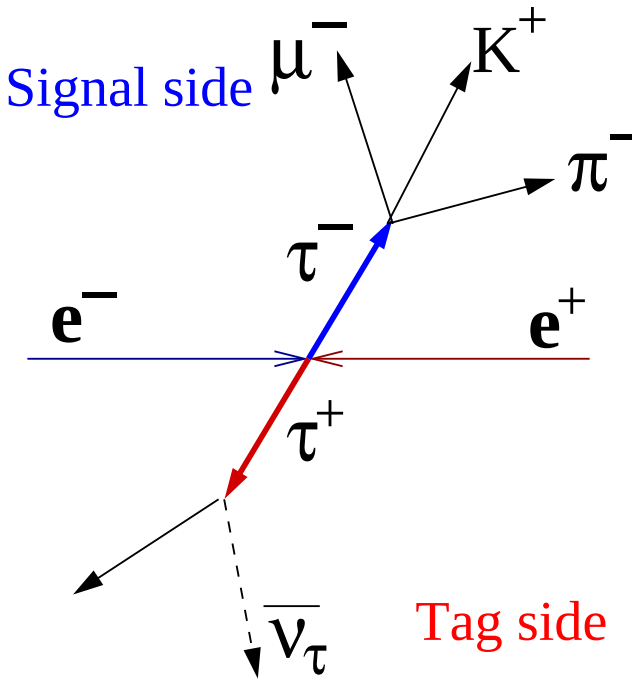


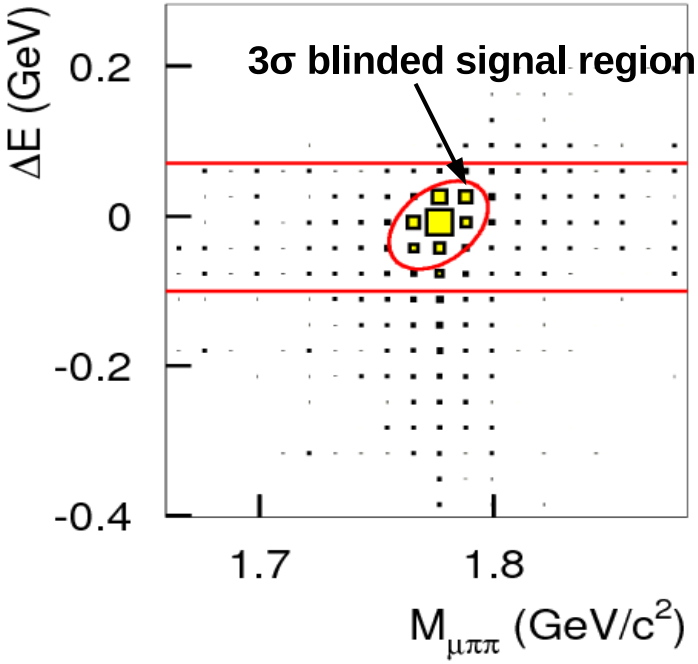
Model	$\mathcal{B}(\tau \to \mu\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw	10^{-8}	10^{-9}
SUSY+SO(10)	10^{-8}	10^{-10}
SM+seesaw	10^{-9}	10^{-10}
Non-universal Z'	10^{-9}	10^{-8}
SUSY+Higgs	10^{-10}	10^{-8}

- Probability of LFV decays of charged leptons is extremely small in the Standard Model (SM), $\mathcal{B}(\tau \to \ell\gamma) \sim \left(\frac{\Delta m^2_\nu}{m^2_W}\right)^2 < 10^{-54}$
- Many models beyond the SM predict LFV decays with the branching fractions up to $\sim 10^{-8}$. LFV observation – clear signature of New Physics (NP)
- τ lepton is an excellent laboratory to search for the LFV decays: enhanced couplings to new particles and large number of LFV decay modes
- Different τ LFV decay modes test various NP models

Search for $\tau \to \ell hh'$, $\ell = e, \mu$; $h, h' = \pi^{\pm}, K^{\pm}$

14 modes were studied with 854 fb^{-1}: 8 LFV $\tau^- \to \ell^- h^+ h'^-$ and
6 lepton-number-violating $\tau^- \to \ell^+ h^- h'^-$ decays

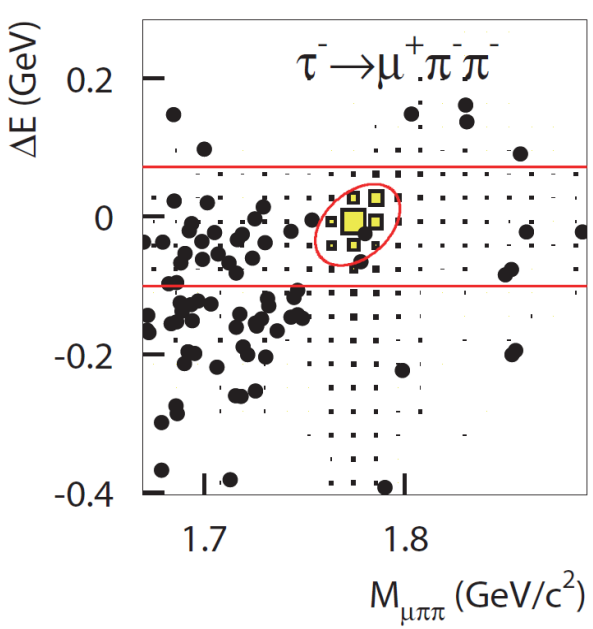


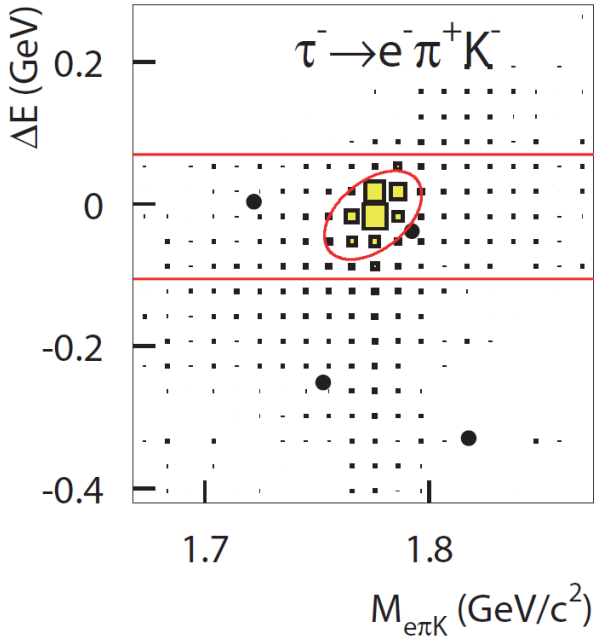


Y. Miyazaki et al. Phys. Lett. B 719 (2013) 346

Results for $\tau \to \ell hh'$

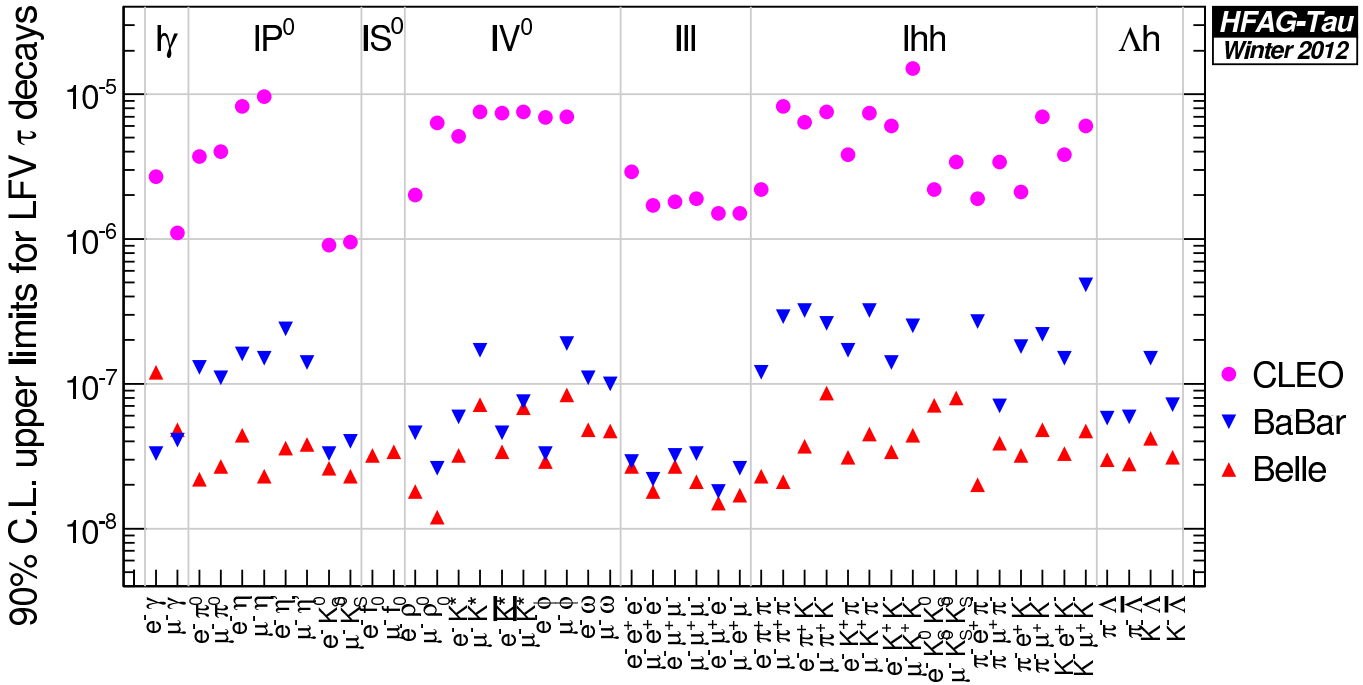
One event in the signal region was found for $\tau^- \to \mu^+\pi^-\pi^-$ and $\tau^- \to \mu^-\pi^+K^-$, no events for the other 12 modes. For all modes the number of observed signal events agrees with the number of expected background events.





Obtained upper limits at 90% CL: $\mathcal{B}(\tau \to \ell hh') < (2.0 \div 8.6) \times 10^{-8}$

Results on LFV decays of τ



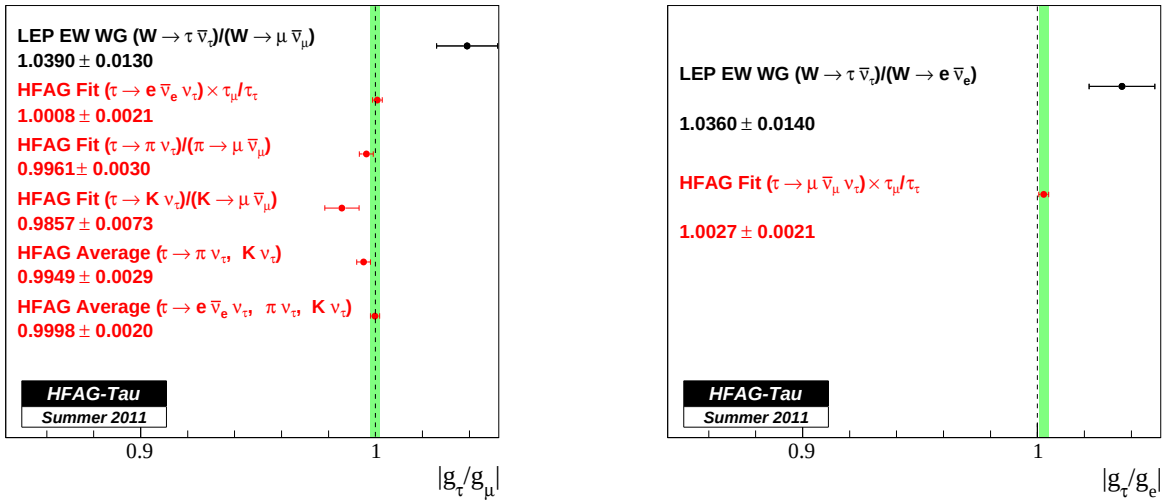
48 different LFV modes were studied at Belle

46 modes were analysed with almost full Belle statistics (~ 1 ab^{-1}) and the world best upper limits were obtained. A full statistics study of $\tau \to \mu(e)\gamma$ is in progress and will be completed soon

Measurement of τ_τ – General

Ongoing studies of the general properties of τ at Belle: Lifetime of τ-lepton, electric dipole moment, Michel parameters in leptonic and radiative leptonic τ decays, anomalous magnetic moment of τ in radiative leptonic decays

Precise measurement of τ_τ – a test of lepton universality

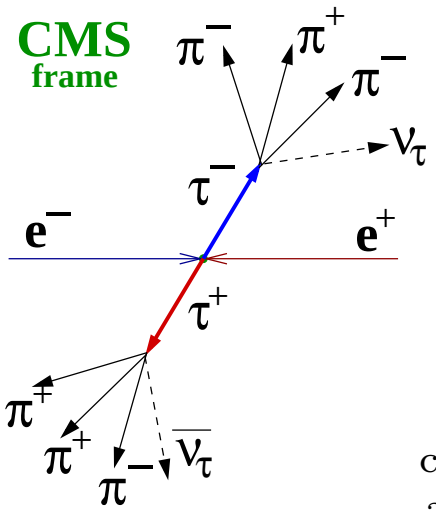


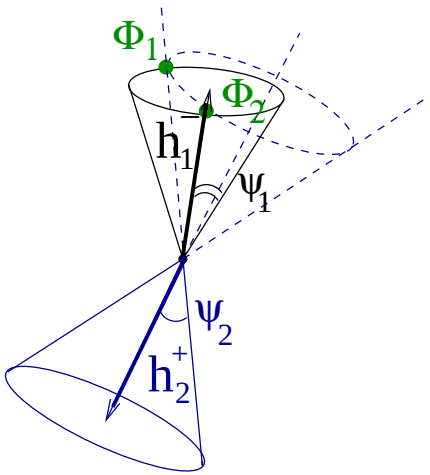
$\frac{2\mathcal{B}(W\to\tau\nu_\tau)}{\mathcal{B}(W\to\mu\nu_\mu)+\mathcal{B}(W\to e\nu_e)} = 1.066 \pm 0.025$: 2.6σ deviation from the SM

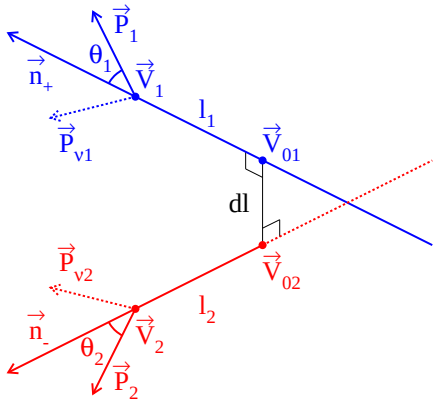
S. Schael et al. arXiv:1302.3415

Measurement of τ_τ – Method

$e^+e^- \to \tau^+\tau^- \to (\pi^+\pi^+\pi^-\bar{\nu}_\tau,\ \pi^+\pi^-\pi^-\nu_\tau)$ with $\int Ldt = 711\ \mathrm{fb}^{-1}$, $N_{\tau\tau} = 650 \times 10^6$







$$\frac{\cos\psi_{1,2}}{\frac{2E_\tau E_{h_{1,2}} - M_\tau^2 - m_{h_{1,2}}^2}{2p_\tau p_{h_{1,2}}}} = x = \frac{\ell}{\beta_\tau \gamma_\tau}$$

- p_τ direction – two-fold ambiguity in CMS, we use the average axis
- Asymmetric-energy layout $\Rightarrow$ $\tau^+\tau^-$ production point in LAB determined independently of IP
- CPT test from separate τ^- and τ^+ lifetimes

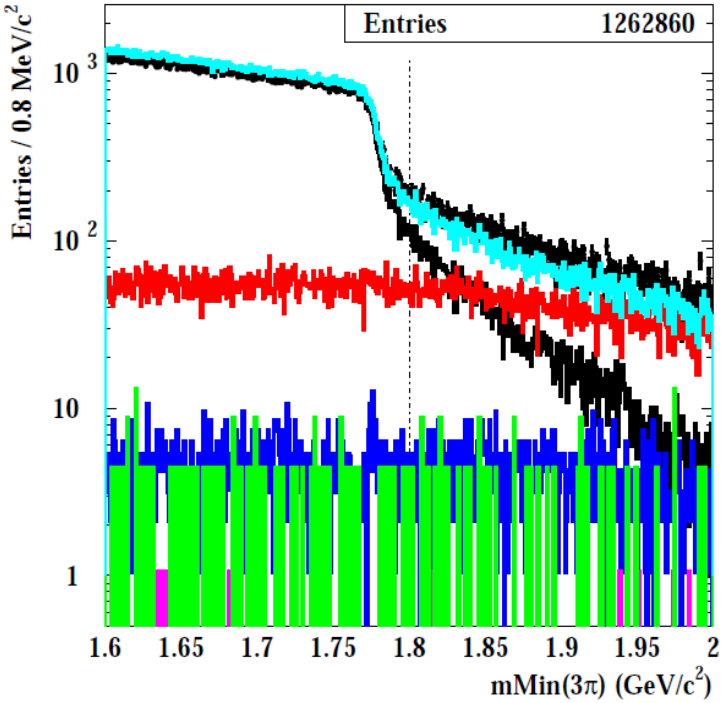
Measurement of τ_τ – Selection 1

Selection criteria:

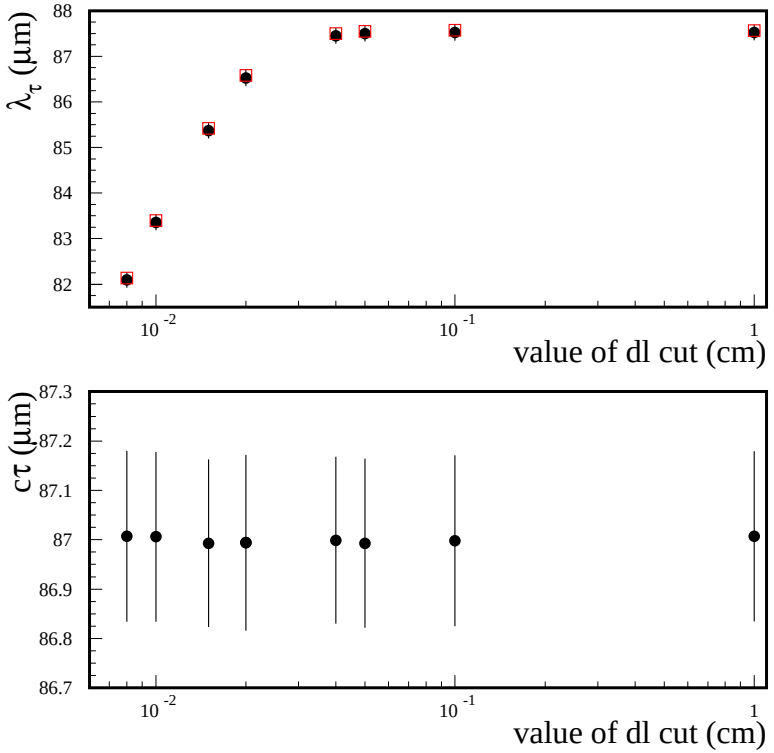
- Event is separated into two hemispheres in CMS, thrust>0.9
- Each hemisphere contains 3 charged pions with the ± 1 net charge
- There are no additional K^0_S, Λ, π^0 candidates, the number of additional photons $N_\gamma < 6$ with $E_\gamma^{TOT} < 0.7$ GeV
- $P_\perp(6\pi) > 0.5$ GeV/c, 4 GeV/c^2 $< M_{inv}(6\pi) <$ 10.25 GeV/c^2
- Pseudomass $\sqrt{M_h^2 + 2(E_{beam} - E_h)(E_h - P_h)} < 1.8$ GeV/c^2, $h = (3\pi)^-,\ (3\pi)^+$
- Cuts on the quality parameters of the vertex fits and τ axis reconstruction
- Minimal distance between τ^- and τ^+ axes in LAB $dl < 0.02$ cm

1.15×10^6 events selected with ~2% background, mainly from $e^+e^- \to q\bar{q}$ (q =u,d,s)

Measurement of τ_τ – Selection 2



Pseudomass spectrum,
black - data, blue - MC



Stability of the *dl*-cut

Measurement of τ_τ – A Fit of the Decay Length Distribution

Decay length PDF

$$\mathcal{P}(x) = \mathcal{N} \int e^{-x'/\lambda_\tau} R(x - x'; \vec{P}) dx' + \mathcal{N}_{uds} R(x; \vec{P}) + \mathcal{P}_{cb}(x),$$

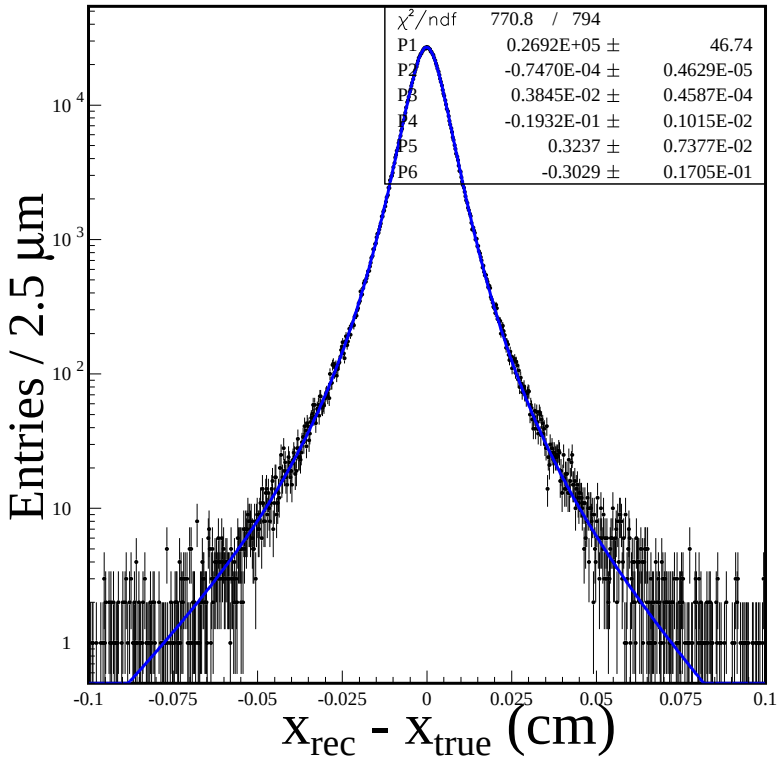
$$R(x; \vec{P}) = (1 - 2.5x) \cdot \exp\left(-\frac{(x - P_1)^2}{2\sigma^2}\right),$$

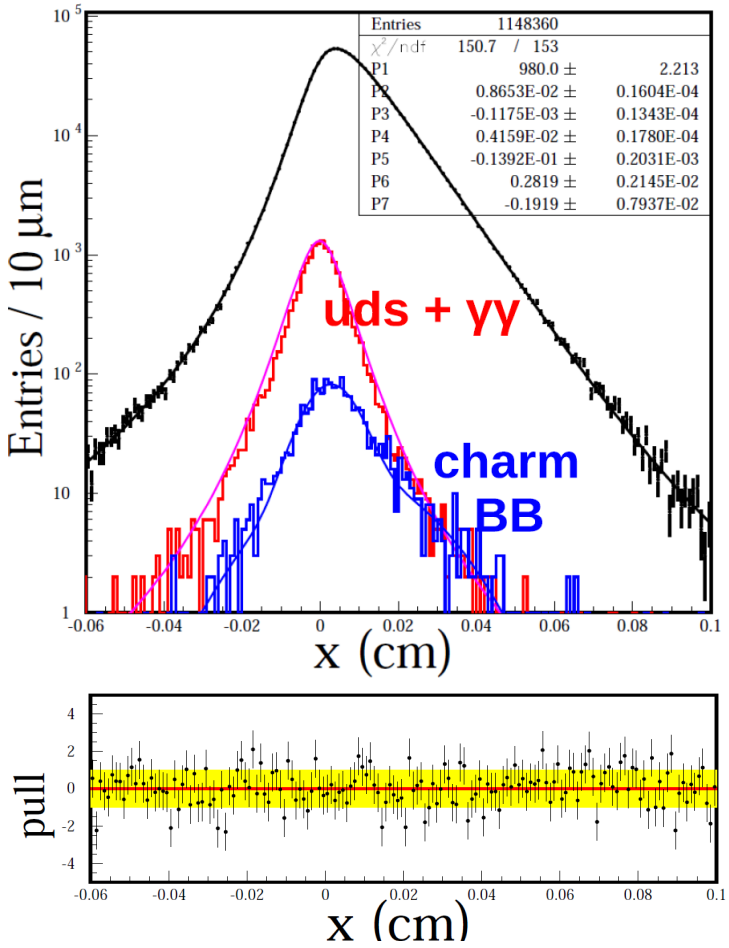
$$\sigma = P_2 + P_3|x - P_1|^{1/2} + P_4|x - P_1| + P_5|x - P_1|^{3/2}$$

- Free parameters of the fit: λ_τ, $\mathcal{N}$, $\vec{P} = (P_1, ..., P_5)$
- λ_τ - estimator of $c\tau_\tau$, $c\tau_\tau = \lambda_\tau + \Delta_{\rm corr}$, $\Delta_{\rm corr}$ is determined from MC;
- $R(x; \vec{P})$ - detector resolution function;
- $\mathcal{N}_{uds}$ - contribution of background from $e^+e^- \to q\bar{q}$ ($q = u,\ d,\ s$) (predicted by MC)
- $\mathcal{P}_{cb}(x)$ - PDF for background from $e^+e^- \to q\bar{q}$ ($q = c,\ b$) (fixed from MC)

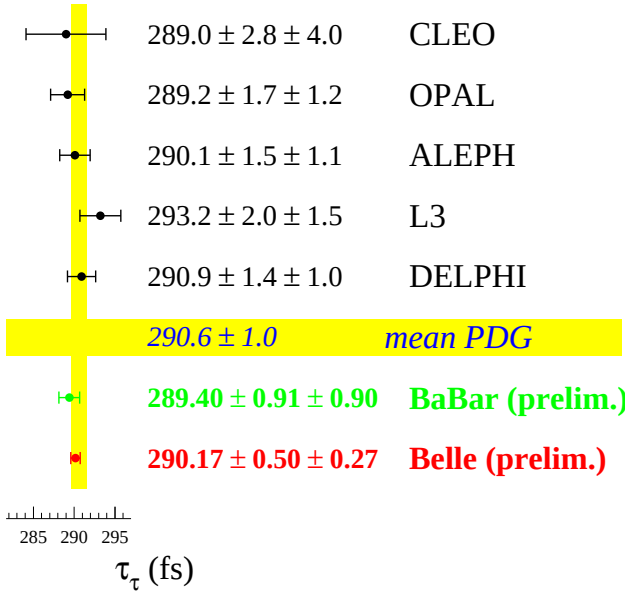
From the fit $\lambda_\tau = 86.53 \pm 0.16$ μm and with $\Delta_{\rm corr} = 0.46$ μm: $c\tau_\tau = 86.99 \pm 0.16$ μm

Measurement of τ_τ – Resolution





Measurement of τ_τ – Preliminary Result



Systematic uncertainties

Source	$\Delta c\tau$ (μm)
SVD alignment	0.090
Fit range	0.020
ISR and FSR description	0.018
Beam energy	0.016
Background contribution	0.010
τ-lepton mass accuracy	0.009
Total	0.096

$$\tau_\tau = (290.17 \pm 0.50(\text{stat.}) \pm 0.33(\text{syst.})) \times 10^{-15} \text{ s} \quad (290.6 \pm 1.0) \times 10^{-15} \text{ s}$$

$$|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3} \text{ at 90\% CL}$$

Hadronic τ Decays

Cabibbo-allowed decays ($\mathcal{B} \sim \cos^2\theta_c$)

$\mathcal{B}(S=0) = (61.85 \pm 0.11)\%$ (PDG)

Cabibbo-suppressed decays ($\mathcal{B} \sim \sin^2\theta_c$)

$\mathcal{B}(S=-1) = (2.87 \pm 0.07)\%$ (PDG)

- Search for CP violation
- High-precision measurement of branching fractions, studies of rare decays
- Measurement of low-energy hadronic spectral functions
  - Determination of intermediate mechanisms
  - Precise measurement of masses and widths of the intermediate mesons
- Comparison with hadronic form factors from e^+e^- experiments to check CVC
- Measurement of $\Gamma_{\rm inclusive}(S=-1)$ to determine s-quark mass and $V_{\rm us}$:

$$|V_{\rm us}| = \sqrt{\frac{R_{\rm strange}}{\frac{R_{\rm non-strange}}{|V_{\rm ud}|^2} - \delta R_{\rm theory}}}$$

- $R_{\rm strange} = \mathcal{B}_{\rm strange}/\mathcal{B}_{\rm e}$
- $R_{\rm non-strange} = \mathcal{B}_{\rm non-strange}/\mathcal{B}_{\rm e}$
- $\delta R_{\rm theory}$ - SU(3)-breaking contribution

Study of $\tau^- \to K^0_S X^- \nu_\tau$ decays

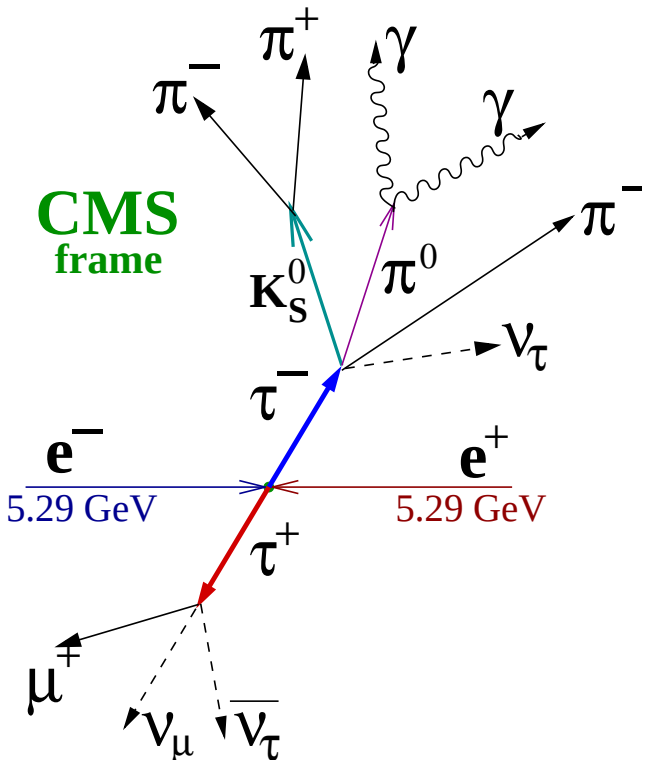
A data sample of $\int Ldt = 669$ fb^{-1} with $N_{\tau\tau} = 616 \times 10^6$ was used to study inclusive decay $\tau^- \to K^0_S X^- \nu_\tau$ as well as 6 exclusive modes:

$\pi^- K^0_S \nu_\tau$ $K^- K^0_S \nu_\tau$ $\pi^- K^0_S K^0_S \nu_\tau$

$\pi^- K^0_S \pi^0 \nu_\tau$ $K^- K^0_S \pi^0 \nu_\tau$ $\pi^- K^0_S K^0_S \pi^0 \nu_\tau$

After the standard $\tau\tau$ preselection
we select events with particular configuration.

- Event is separated into two hemispheres in CMS, thrust>0.9
- Tag side: 1-prong (e, μ or $\pi/K(n \geq 0)\pi^0$)
- Signal side:
  - $K^0_S \to \pi^+\pi^-$: $0.485 < M_{\pi\pi} < 0.511$ GeV/c^2 ($\pm 5\sigma$), 2 cm$< L_{K^0_S} <$ 20 cm, $\Delta Z_{1,2} < 2.5$ cm
  - $\pi^0 \to \gamma\gamma$: $-6 < S_{\gamma\gamma}(= \frac{m_{\gamma\gamma} - m_{\pi^0}}{\sigma_{\gamma\gamma}}) < 5$
  - Charged kaon (pion): $\mathcal{P}_{K/\pi} = \frac{\mathcal{L}_K}{\mathcal{L}_\pi + \mathcal{L}_K} > 0.7 (< 0.7)$
- $E^{\rm LAB}_{\gamma extra} < 0.2$ GeV



Calculation of Branching Fractions

Mode	$K^0_S X^-$	$\pi^- K^0_S$	$K^- K^0_S$	$\pi^- K^0_S \pi^0$	$K^- K^0_S \pi^0$	$\pi^- K^0_S K^0_S$	$\pi^- K^0_S K^0_S \pi^0$
$N^{\rm data}$	397806 ± 631	157836 ± 541	32701 ± 295	26605 ± 208	8267 ± 109	6684 ± 96	303 ± 33
ε_{det} (%)	9.66	7.09	6.69	2.65	2.19	2.47	0.82
$\frac{N^{\rm bg}}{N^{\rm data}}$ (%)	4.20 ± 0.46	8.86 ± 0.05	3.55 ± 0.07	5.60 ± 0.10	2.43 ± 0.10	7.89 ± 0.24	11.60 ± 1.60
$(\frac{\Delta\mathcal{B}}{\mathcal{B}})_{\rm syst}$(%)	2.4	2.5	4.0	3.9	5.2	4.4	8.1

The main non-$\tau\tau$ background comes from $e^+e^- \to q\bar{q}$ ($q = u,\ d,\ s,\ c$). To take into account cross-feed background, 6 decay modes are analysed simultaneously:

$$N_i^{\rm sig} = \sum_j (\mathcal{E}^{-1})_{ij} (N_j^{\rm data} - N_j^{\rm bg})$$

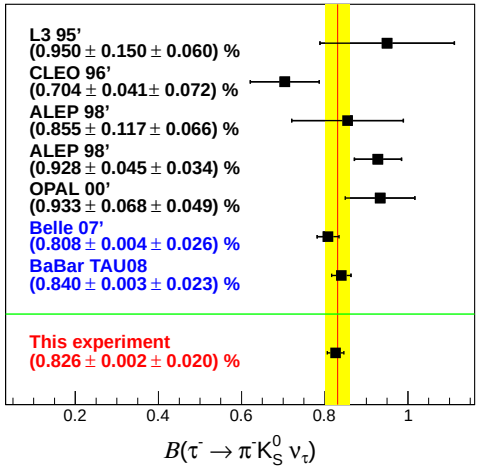
For the $\pi^- K^0_S \nu$, $K^- K^0_S \nu$, $\pi^- K^0_S \pi^0 \nu$ and $K^- K^0_S \pi^0 \nu$ modes lepton tag is applied and normalisation to the two-lepton events ($\tau^\mp \to e^\mp \nu\nu,\ \tau^\pm \to \mu^\pm \nu\nu$) method is used to calculate branching fractions:

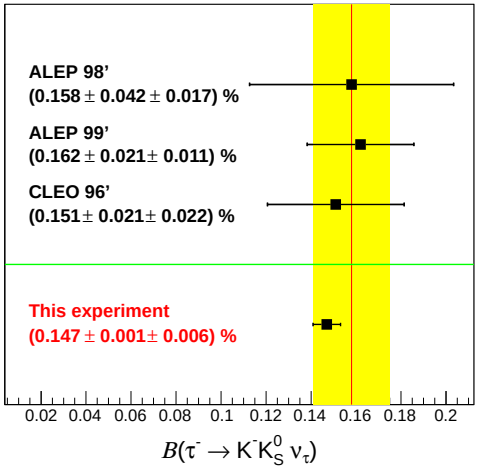
$$\mathcal{B}_i = \frac{N_i^{\rm sig}}{N_{e\text{-}\mu}^{\rm sig}} \frac{\mathcal{B}_e \mathcal{B}_\mu}{\mathcal{B}_e + \mathcal{B}_\mu}$$

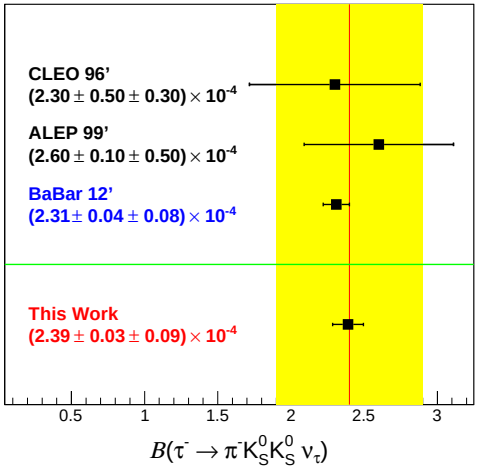
To increase statistics for the remaining $\pi^- K^0_S K^0_S \nu$ and $\pi^- K^0_S K^0_S \pi^0 \nu$ modes, the one-prong tag and luminosity normalisation method are used:

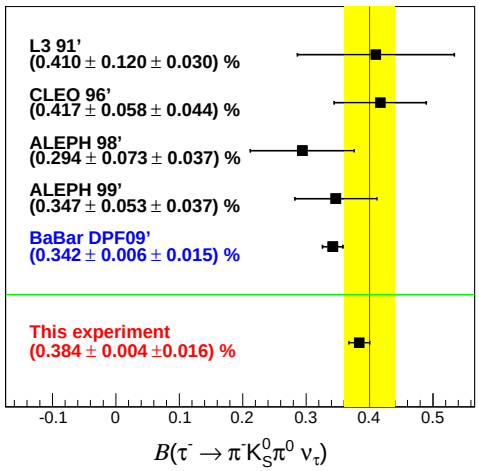
$$\mathcal{B}_i = \frac{N_i^{\rm sig}}{2\mathcal{L}\sigma_{\tau\tau}\mathcal{B}_{1-{\rm prong}}}$$

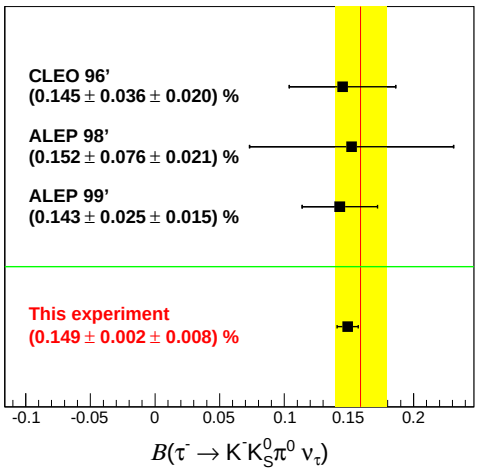
Preliminary Results on Branching Fractions

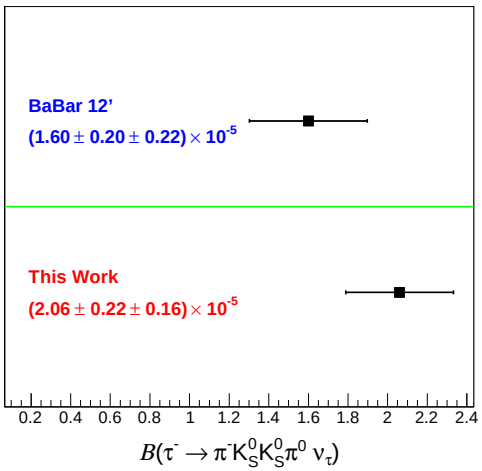








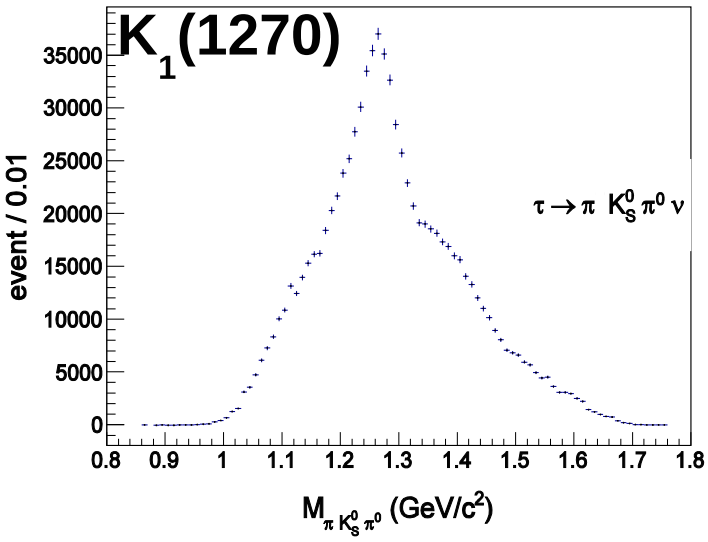


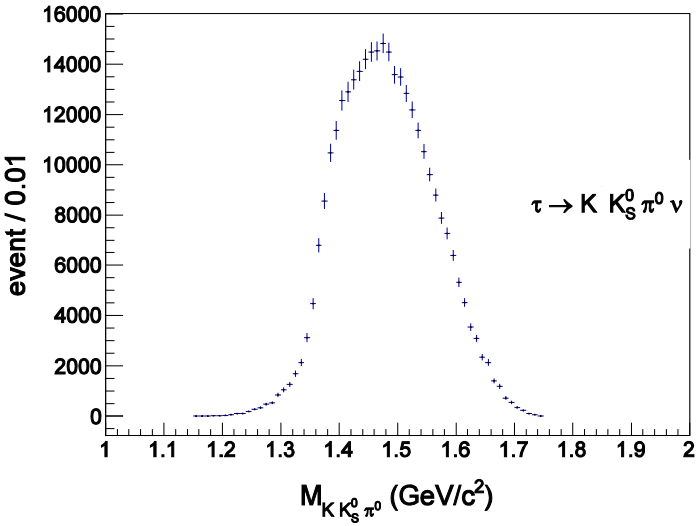


$$\mathcal{B}(\tau^- \to K^0_S X^- \nu_\tau) = (9.15 \pm 0.01 \pm 0.15) \times 10^{-3}$$

Analysis of Decay Mechanisms – I

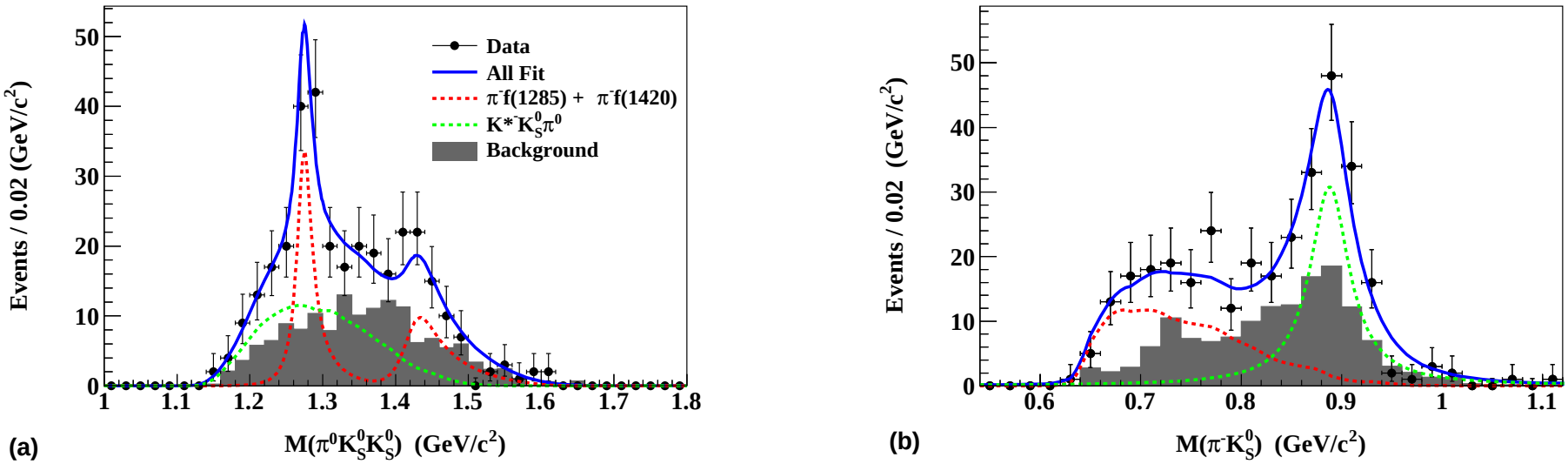
Unfolded invariant mass distributions (all combinations) were obtained for the $\tau^- \to K^0_S \pi^- \pi^0 \nu_\tau$ and $\tau^- \to K^0_S K^- \pi^0 \nu_\tau$ modes





Analysis of Decay Mechanisms – II

In the study of visible invariant mass spectra for $\tau^- \to \pi^- K^0_S K^0_S \pi^0 \nu_\tau$ events



$f_1(1285)\pi^-\nu_\tau$ (5.9σ) and $K^{*-}(892)K^0_S\nu_\tau$ intermediate structures are observed, as well as indication of the $f_1(1420)\pi^-\nu_\tau$ (2.7σ) mechanism is seen.

$$\mathcal{B}(\tau^- \to (f_1(1285) \to K^0_S K^0_S \pi^0)\pi^-\nu_\tau) = (0.74 \pm 0.12 \pm 0.07) \times 10^{-5}$$

$$\mathcal{B}(\tau^- \to (K^{*-} \to K^0_S \pi^-) K^0_S \pi^0 \nu_\tau) = (1.06 \pm 0.15 \pm 0.09) \times 10^{-5}$$

Ongoing Studies of Hadronic τ Decays at Belle

- Spectral function of $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ decay
- Spectral function of $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ decay
- Search for CP violation in $\tau^- \to K^-\pi^-\pi^+\nu_\tau$ decay
- Branching fractions of $\tau^- \to \pi^- \geq 2\pi^0\nu_\tau$
- Branching fractions of $\tau^- \to h_1^- h_2^- h_3^+\nu_\tau$, $h_{1,2,3} = \pi,\ K$
- Search for 2nd class currents in $\tau^- \to \eta\pi^-\nu_\tau$ and $\tau^- \to \eta'\pi^-\nu_\tau$

Summary

- Belle collected the world largest data sample of ~ 1 ab^{-1} ($N_{\tau\tau} \simeq 10^9$) near the $\Upsilon(4S)$ opening a new era in precise τ physics
- 48 different LFV modes studied, upper limits on $\mathcal{B}$ of the order of 10^{-8} obtained
- With 711 fb^{-1} the τ lifetime measured using a new method:
  $\tau_\tau = (290.17 \pm 0.50(\text{stat.}) \pm 0.33(\text{syst.})) \times 10^{-15}$ s
  $|\tau_{\tau^+} - \tau_{\tau^-}|/\tau_{\text{average}} < 7.0 \times 10^{-3}$ at 90% CL
- Branching fractions for six τ decay modes with K^0_S and for the inclusive decay $\tau^- \to K^0_S X^- \nu_\tau$ have been measured. Unfolded invariant mass spectra have been obtained for the $\tau^- \to K^0_S \pi^- \pi^0 \nu_\tau$ and $\tau^- \to K^0_S K^- \pi^0 \nu_\tau$ modes, for the latter $f_1(1285)\pi^- \nu_\tau$ and $K^{*-}(892) K^0_S \nu_\tau$ mechanisms observed
- Various ongoing analyses of τ decays, new results expected soon