Tau lifetime and CP violation in tau decay at Belle

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Outline

- Tau lifetime measurement
  - Motivation
  - Method of the measurement
  - Experimental sensitivity
- CP violation in $\tau^{\pm} \to K_S \pi^{\pm} \nu_{\tau}$
  - Motivation
  - Experimental results
- Summary

Tau-lepton lifetime

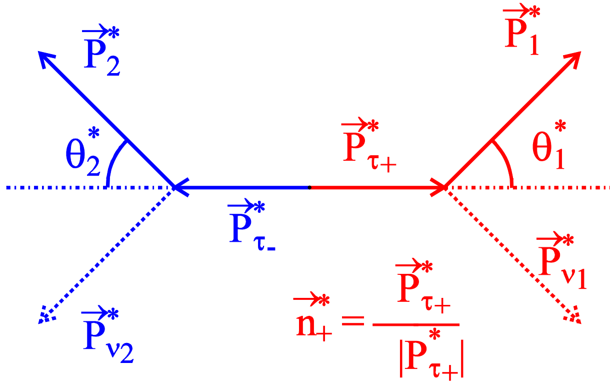
- In Standard Model, tau-lepton mass, lifetime and leptonic branching fraction are related with the muon mass and lifetime as:

$$\tau_\tau = \tau_\mu \left(\frac{g_\mu}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 Br\left(\tau^- \rightarrow e^- \overline{\nu_e} \nu_\tau\right) \frac{f\left(m_e^2/m_\mu^2\right) F_W^\mu F_{rad}^\mu}{f\left(m_e^2/m_\tau^2\right) F_W^\tau F_{rad}^\tau}$$

  for details see PDG formulae 10.4(a-d).

- The present PDG value of the tau-lepton lifetime is dominated by the results obtained by LEP experiments.
- Present Belle analysis uses technique different from those of LEP experiments and is based on much higher statistics.

Analysis method



- We consider $e^+e^- \to \tau^+\tau^- \to 3\pi\nu\ 3\pi\nu$ events
- In CM frame:
  - Flight directions of τ^+ and τ^- are back-to-back;
  - Energy of each tau-lepton is $\sqrt{s}/2$;
  - Assuming neutrino mass to be zero, the angle between tau flight direction and momentum of the hadronic system is determined as:

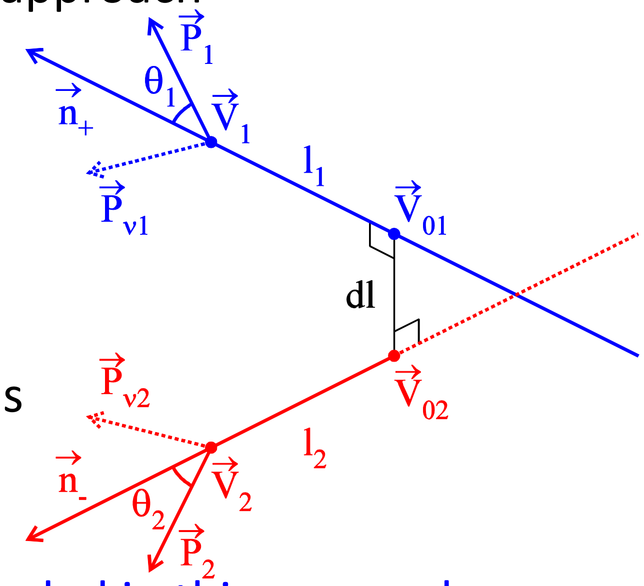
$$\cos\theta^* = \frac{2E_\tau^* E_x^* - m_\tau^2 - m_x^2}{2P_\tau^* P_x^*} = \frac{2E_\tau^* E_x^* - m_\tau^2 - m_x^2}{2\sqrt{\left(E_\tau^{*2} - m_\tau^2\right)}P_x^*}$$

  - The unit vector in the direction of the positive tau-lepton can be obtained as a solution of the following system of equations:

$$\begin{cases} \left(\vec{P}_1^* \cdot \vec{n}_+^*\right) = x^* P_{x1}^* + y^* P_{y1}^* + z^* P_{z1}^* = \left|P_1^*\right| \cos\theta_1^* \\ \left(\vec{P}_2^* \cdot \vec{n}_+^*\right) = x^* P_{x2}^* + y^* P_{y2}^* + z^* P_{z2}^* = -\left|P_2^*\right| \cos\theta_2^* \\ \left(\vec{n}_+^*\right)^2 = \left(x^*\right)^2 + \left(y^*\right)^2 + \left(z^*\right)^2 = 1 \end{cases}$$

Analysis method (continued)

- We perform Lorentz boost of tau-lepton 4-momenta from CM to Laboratory frame.
- Tau decay vertices (V_1 and V_2) are determined as the 3D-points of intersections of the triplets of pions.
- For the tau production point of each tau-lepton we take the points (V_{01} and V_{02}) which are the points of the closest approach of the two crossed lines defined by tau decay vertices and flight directions.



- $$c\tau_1 = \frac{l_1}{(\beta\gamma)_1}, c\tau_2 = \frac{l_2}{(\beta\gamma)_2}$$
- Two-fold ambiguity from the system of equations on slide 4 is resolved by requiring the minimal value of ***dl*** (the distance between crossed lines).
- No information about the Interaction Point is needed in this approach

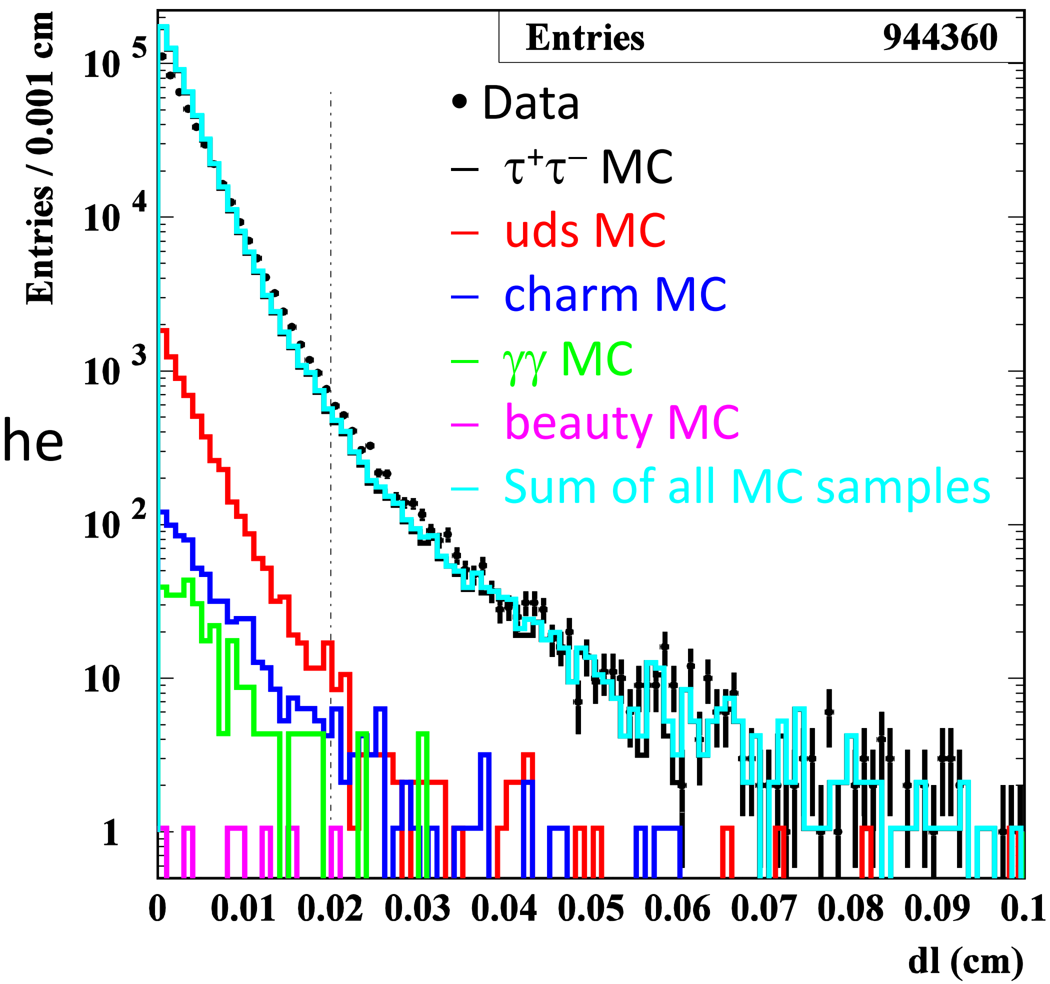
Event selection

1. There are exactly 6 charged tracks compatible with the pion hypothesis with zero net charge;
2. There are no K^0_s, Λ and π^0 in the event;
3. Thrust value (in CM frame) is greater than 0.9;
4. P_T^2 of the 6π system is greater than 0.25 GeV^2;
5. 4 $GeV/c^2 < m(6\pi) <$ 10.25 GeV/c^2;
6. Event is divided into two hemispheres by the plane perpendicular to the thrust axis. In each hemisphere there should be 3 pions with the net charge ±1;
7. Pseudomass of each triplets of pions: $M_{min}(3\pi) < 1.8$ GeV/c^2
   $M_{min}^2 = M_x^2 + 2(E_\tau^* - E_x^*)(E_x^* - P_x^*)$;
8. Each triplet should be fitted to the vertex with $\chi^2 < 20$;

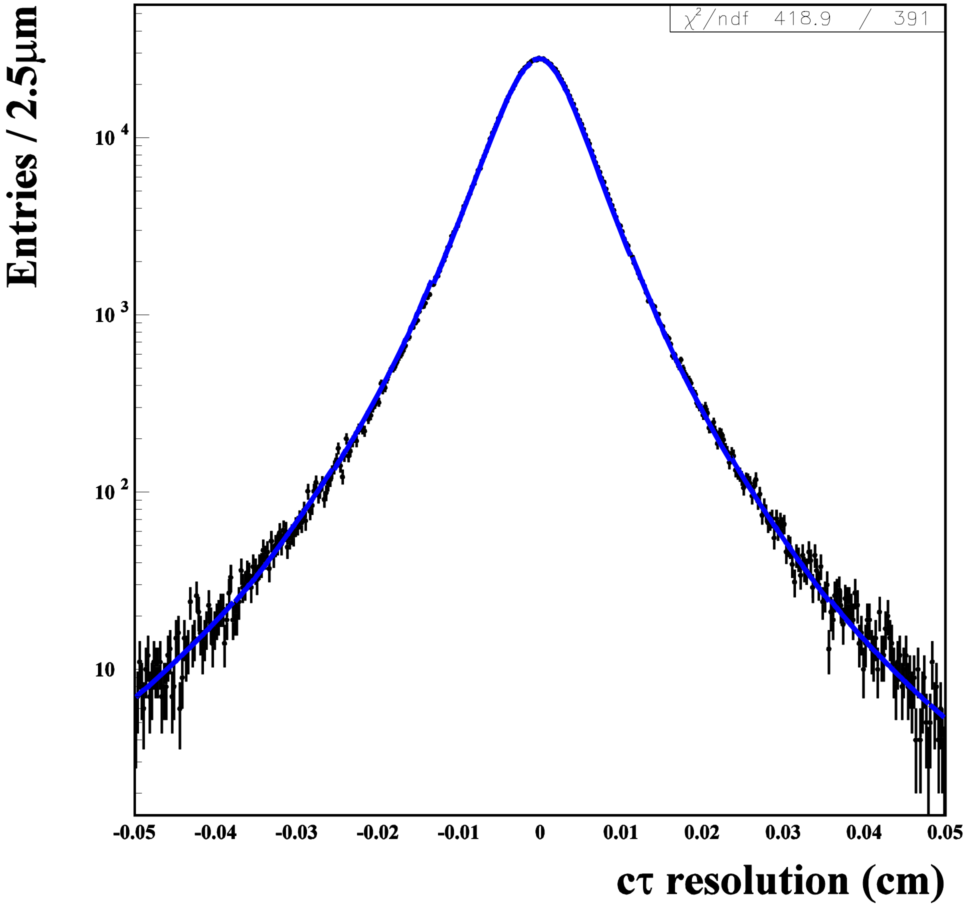
Event selection (continued)

9. Distance between two crossed lines ***dl*** < 0.02 cm.

- Integrated luminosity of the data is 711 fb^{-1};
- All the MC samples are normalized to the luminosity of the data.



Lifetime resolution

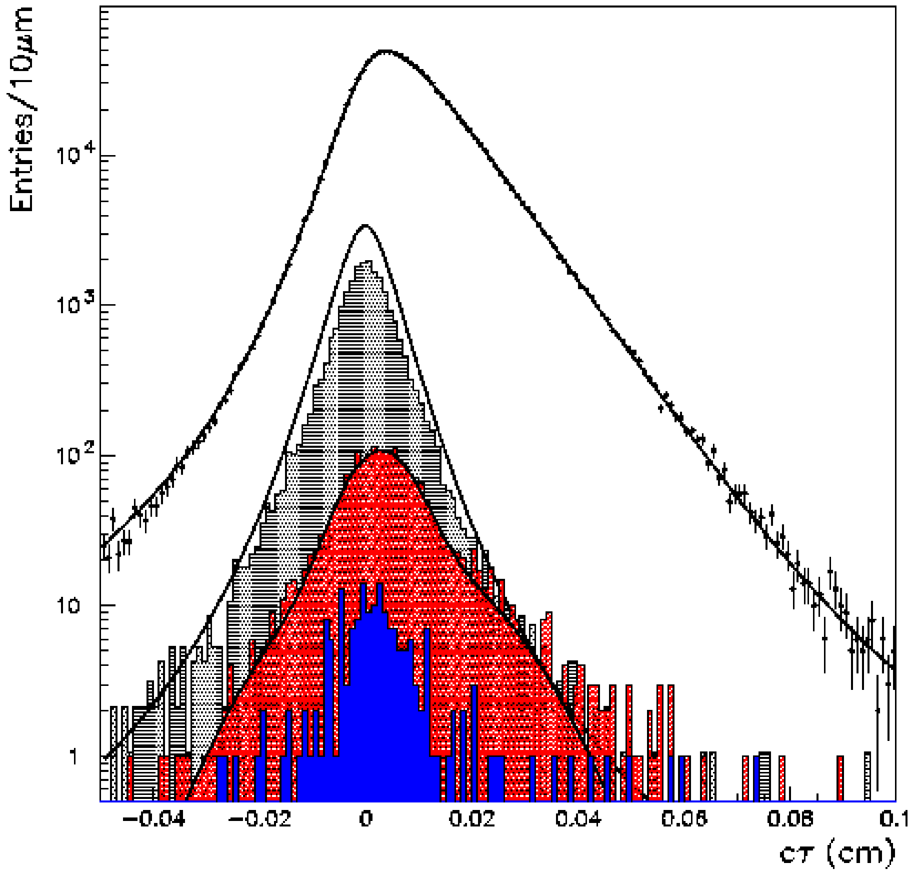


- Difference between reconstructed and true values of ***cτ*** for Monte Carlo events
  $$e^+e^- \to \tau^+\tau^- \to 3\pi\nu\, 3\pi\nu$$
- Fitting function: $A \cdot \mathrm{R}(x) =$
  $$A \cdot (1 + B \cdot x) \cdot e^{\frac{-(x-x_0)^2}{2\cdot(\sigma_0 + \sigma_1 \cdot |x - x_0|)^2}}$$

  A, B, x_0, σ_0 and σ_1 are free parameters.

- Parameters: B, x_0, σ_0 and σ_1 will be fixed in all subsequent fits to the values obtained in this fit.

- Data
- – uds+γγ contribution
- – charm contribution
- – beauty contribution



- Data distribution is fitted by the function:

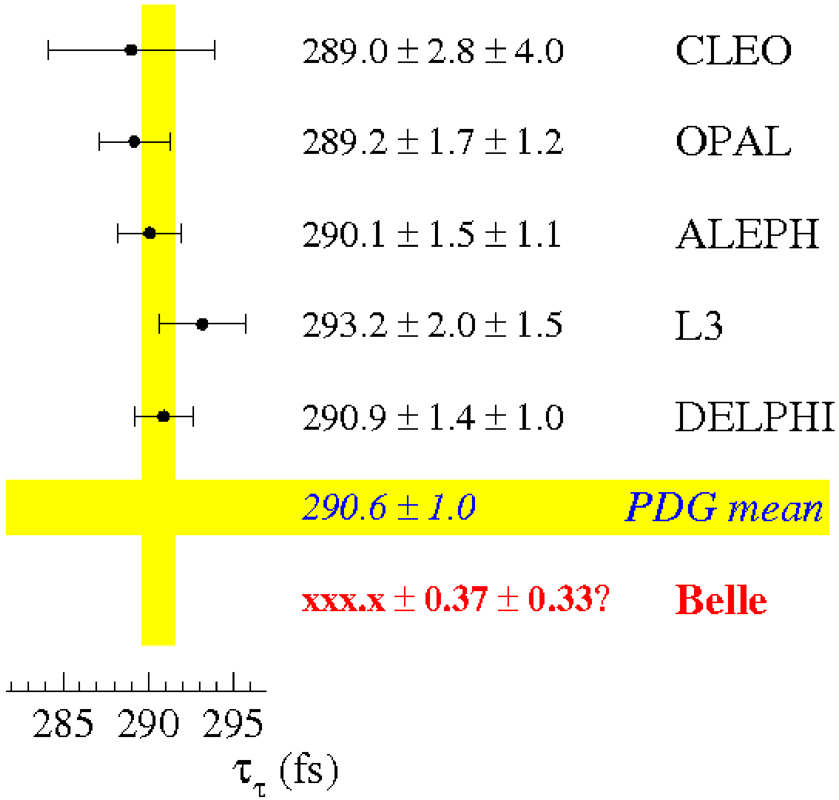
$$F(x) = A\int e^{-t/c\tau} R\big((t-x)(1+\delta)\big)dt + \\ + A_{uds} R\big(x(1+\delta)\big) + Bkg_{cb}(x)$$

  A, $c\tau$, δ – free fitting parameters.
- Statistical accuracy of the $c\tau$-parameter obtained from the fit is 0.11 μm or $\Delta\tau$ = 0.37 fs

Analyzed sources of systematic uncertainties

Source of Systematics	$\Delta(c\tau)$ in μm
MC statistics	0.088
Fit range	0.020
ISR & FSR description	0.018
Beam energy	0.016
SVD alignment	0.015
Background contribution	0.010
Error of the τ-lepton mass	0.009
Systematics study is going on…	

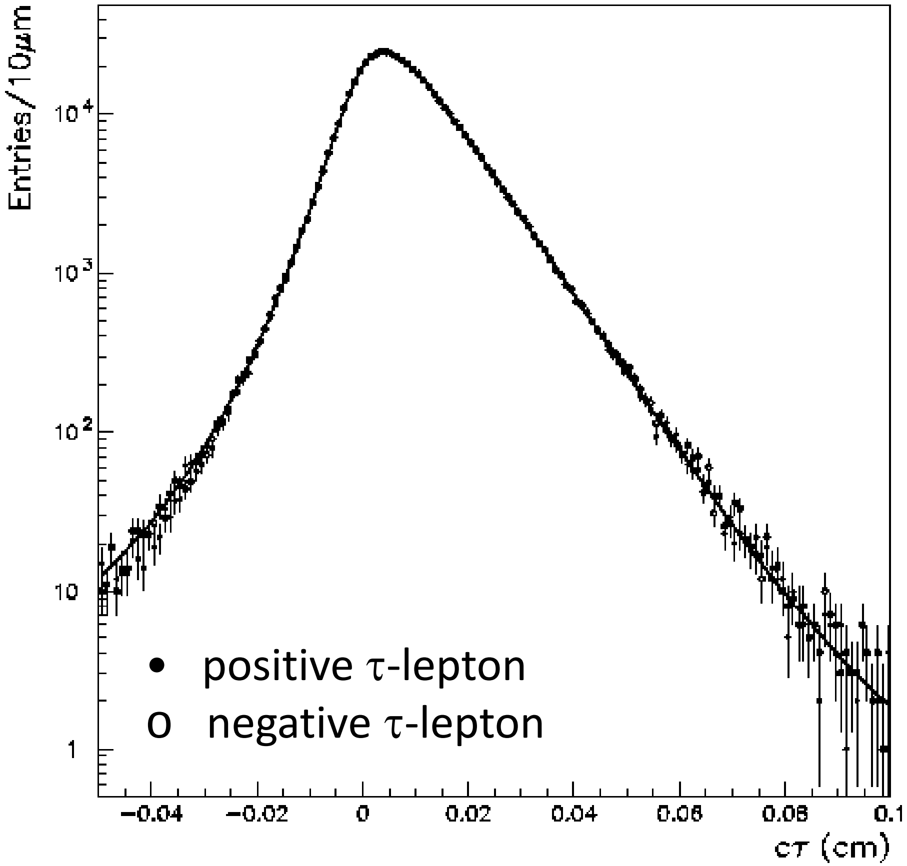
Compilation of tau-lepton lifetime measurements



- ❑ If the final value of systematic uncertainty will be at the level of statistical accuracy, the final Belle measurement will be twice more precise than the current PDG mean.

Lifetime difference for τ^+ and τ^-

The first attempt to measure difference between τ^+ and τ^- lifetimes



- Belle compared lifetimes for τ^+ and τ^- separately and found that they are equal within the statistical accuracy.
- Most systematic uncertainties cancel in the difference of lifetimes.

$$\frac{\left|\tau_{\tau^+} - \tau_{\tau^-}\right|}{\tau_{\text{average}}} < 6.0 \cdot 10^{-3} \quad \text{at } 90\% \text{ CL}$$

- For comparison:

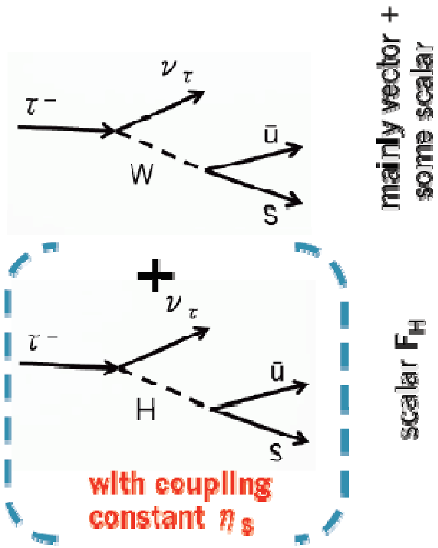
$$\frac{\tau_{\mu^+}}{\tau_{\mu^-}} = 1.00002 \pm 0.00008$$

CP violation in $\tau^{\pm} \to K_s \pi^{\pm} \nu_\tau$

- In New Physics models such as multi-Higgs models a CP violating phase can exist in the scalar form factor

$$J_\beta = < h_1(q_1) h_2(q_2) | \bar{u} \gamma_\beta d | 0 >$$
$$= (q_1 - q_2)^\delta \left(g_{\delta\beta} - \frac{Q_\delta Q_\beta}{Q^2}\right) F(Q^2) + Q_\beta F_S(Q^2)$$

Form factors **F** and **F$_S$** (vector and scalar)



Introduce Higgs exchange by:

$$F_S(Q^2) \to \tilde{F}_S(Q^2) = F_S(Q^2) + \frac{\eta_S}{m_\tau} F_H(Q^2)$$

Try to determine CPV Parameter: Im(η_S)

- Current Limits (CLEO): **$-4.1 < \mathrm{Im}(\eta_S) < 1.6$**

CPV asymmetry measurement

$$A_w^{\mathrm{CP}} = \frac{1}{\Gamma_{Q^2}} \int w(Q^2,\psi,\beta) \underbrace{\left[\frac{d\Gamma(\tau^-)}{dQ^2 d\cos\theta d\cos\beta} - \frac{d\Gamma(\tau^+)}{dQ^2 d\cos\theta d\cos\beta} \right]}_{\boxed{\Delta = \mathrm{Im}(\eta_S)\mathrm{Im}(FF^*_H)A(Q^2)\cos\psi\cos\beta}} dQ^2 d\cos\theta d\cos\beta$$

$$\int_{Q_1^2}^{Q_2^2} \frac{d\Gamma}{d\cos\theta d\cos\psi} d\cos\beta d\cos\psi$$

$$\cos\theta = \frac{2xm_\tau^2 - m_\tau^2 - Q^2}{\left(m_\tau^2 - Q^2\right)\sqrt{1-4m_\tau^2/s}},\ x = 2\frac{E_h}{\sqrt{s}},\ Q = P_{K_s} + P_\pi;\ \cos\psi = \frac{x\left(m_\tau^2 + Q^2\right) - 2Q^2}{\left(m_\tau^2 - Q^2\right)\sqrt{x^2 - 4Q^2/s}};\ \cos\beta = \vec{n}_{CM}\vec{n}_{K_s}$$

- Since scalar form factor F^*_H is not well known, we will first determine model-independent limits for: **Im(η$_S$)Im(FF*$_H$)** as a function of Q^2
- Later we will set limits for the coupling: **Im(η$_S$)** for different parameterizations of the scalar form factor F_H

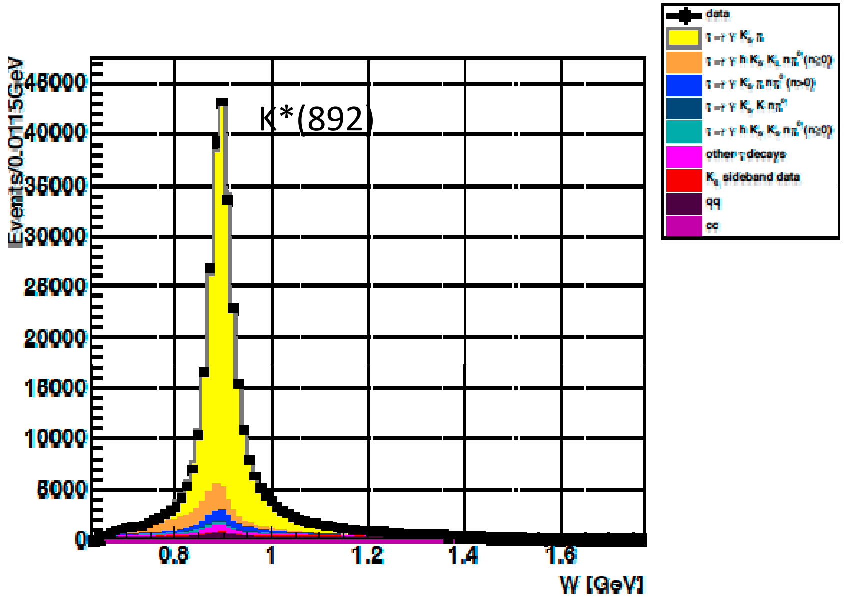
Model independent limits can be determined by using an angular weight:

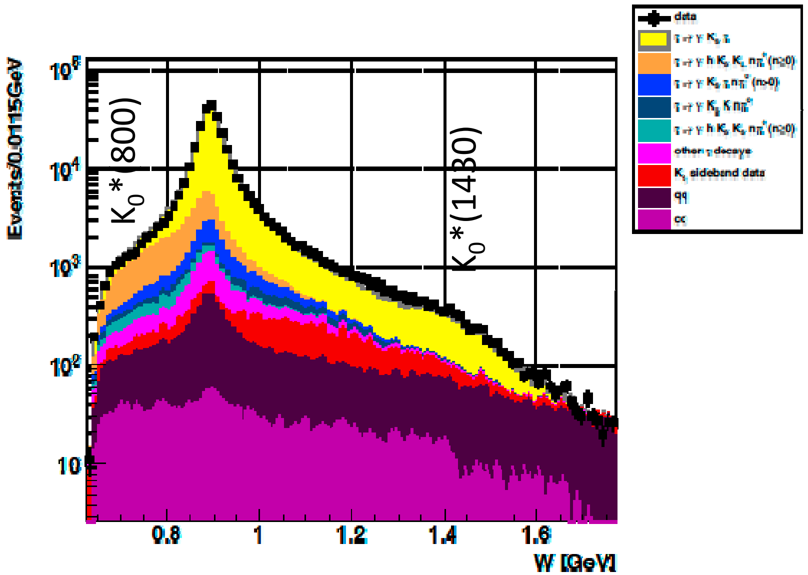
- **w =cosψcosβ**

$$\boxed{A_{\psi\beta}^{\mathrm{CP}} \simeq \frac{1}{N^-}\sum_{i\in\tau^-}\cos\psi_i\cos\beta_i - \frac{1}{N^+}\sum_{j\in\tau^+}\cos\psi_j\cos\beta_j \equiv \langle\cos\psi\cos\beta\rangle_- - \langle\cos\psi\cos\beta\rangle_+}$$

$K_s\pi$ mass spectrum

- data: $700 fb^{-1}$
  - 324000 reconstructed events where one tau-lepton decays to one charged particle and the other one into $K_s\pi\nu$
- Background:
  - total: 23.4%
    - mainly from other τ decay modes:
      - $\tau \to \nu K_S K_L \pi$: 9.5%
      - $\tau \to \nu K_S \pi\pi^0$: 3.7%
    - qq: ~3.5%
- Resonance spectrum:
  - Dominant peak from vector resonance K*(892)
  - Possible contribution from scalar resonances $K_0^*(800)$ and $K_0^*(1430)$

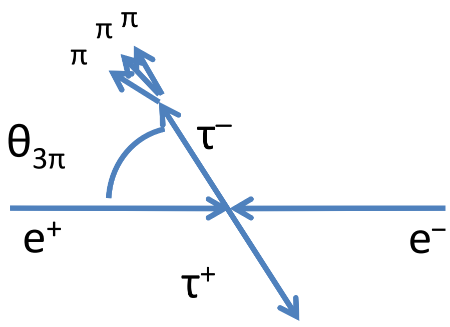




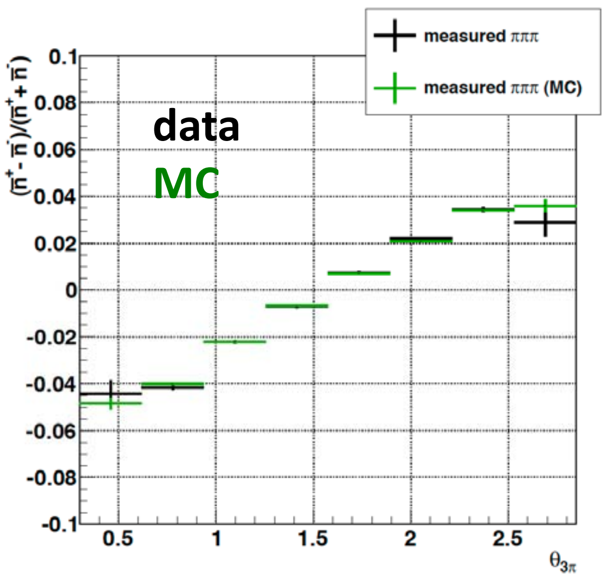
Forward-backward asymmetry for control sample

Asymmetry is a function of τ polar angle: θ_τ

- Using the $\tau \rightarrow \nu\pi\pi\pi$ decays as control sample to measure asymmetry
  - tau direction in cms approximated by $P_{3\pi} = p_\pi + p_\pi + p_\pi$
  - because of missing neutrino, use polar angle and momentum:
    - count events $n_i^\pm$ in bins of $\theta_{3\pi}$ and $|P_{3\pi}|$
    - $\pm$ refers to charge sum = charge of τ
    - normalize to the total number of events: $\check{n}_i = n_i/N^\pm$
    - Asymmetry: $A_{ch} = \dfrac{\overline{n}^+ - \overline{n}^-}{\overline{n}^+ + \overline{n}^-}$



→ Use MC events to determine correction weights



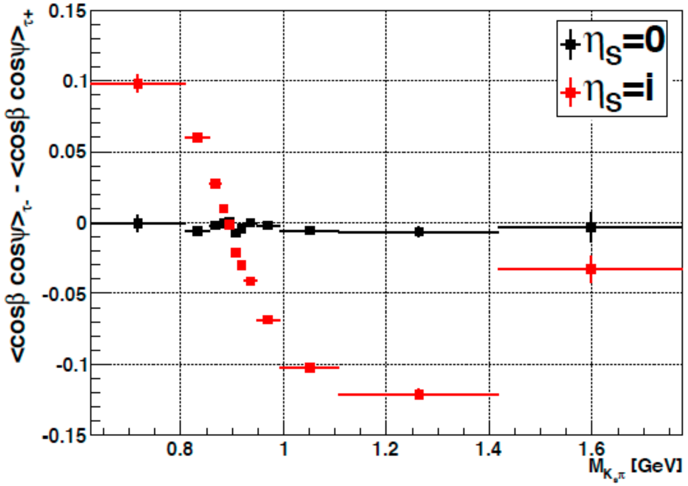
Expected CP violating asymmetry

- expected CPV for Im(η_S) = 1 (Current Limits (CLEO): **$-4.1 <$ Im(η_S) < 1.6**)
- Only very small asymmetry effect in control sample: **$O(10^{-3})$**
  - corrections for Forward-Backward and detector asymmetries (both up to 4%) only have a small effect: O(0.01%) and O(0.1%)
  - **remaining effect will be used as systematic error**

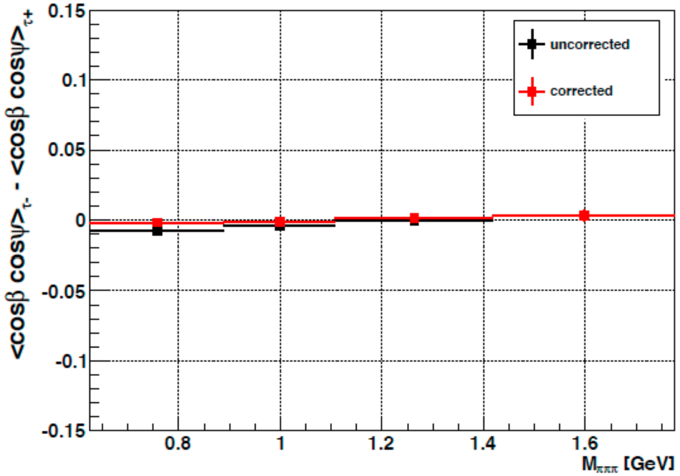
Measure the CP asymmetry in 4 bins of $K_S\pi$ mass:

- bin boundaries at Q^2 values where the sign of Im(FF^*_H) can change in typical models
- Determine limits for Im(η_S)Im(FF^*_H) for these bins

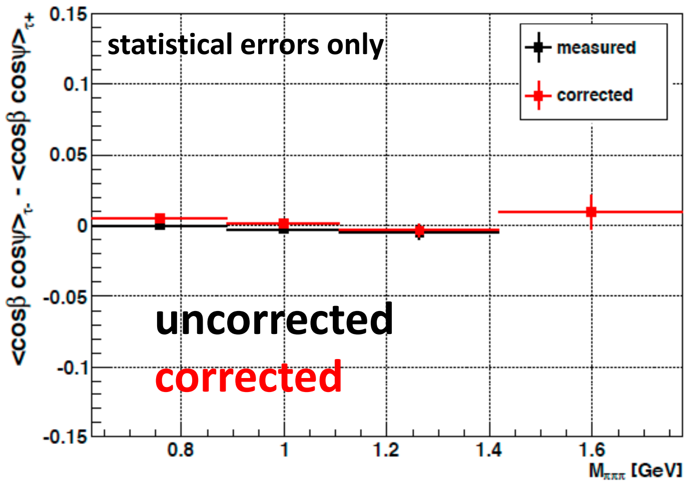
MC results



Control Data Sample

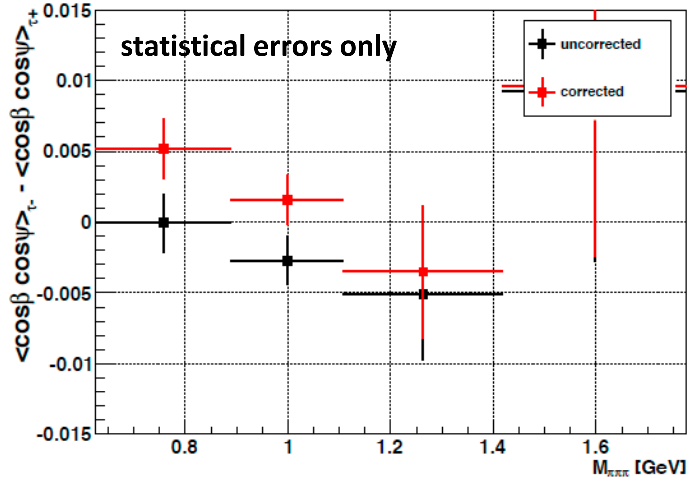


Results



Zoom in:

before background subtraction



- asymmetry small and within errors except for lowest mass bin
- With $\sigma^2=\sigma^2_{stat}+\sigma^2_{syst}$
  - 1.8 σ effect in first bin
- Preliminary limits for Im(η_s) for typical models for FF_H: |Im(η_s)|<0.05–0.2 at 90% C.L.

(~10x smaller than CLEO)

Results after background subtraction

$M_{K_s\pi}$ in (GeV)	(10^{-3})		
	$A^{CP}_{\psi\beta}$	σ_{stat}	σ_{syst}
0.625 – 0.890	7.97	3.35	2.85
0.890 – 1.110	1.74	2.19	1.40
1.110 – 1.420	4.92	8.02	1.62
1.420 – 1.775	-3.15	22.09	5.47

Summary

- The method of tau-lepton lifetime measurement at Belle is reported. The statistical accuracy of the method is 0.37 fs. The work on systematics is going on.
- Upper limit on the difference of the lifetimes for positive and negative tau-leptons is obtained.

$$\frac{\left|\tau_{\tau^+} - \tau_{\tau^-}\right|}{\tau_{\text{average}}} < 6.0 \cdot 10^{-3} \text{ at } 90\% \text{ CL}$$

- Search for CP violation in the decays $\tau^{\pm} \to K_s \pi^{\pm} \nu_{\tau}$ has been performed. Upper limit on CP violating coupling constant η_S is obtained. It is about ten times better than in the previous measurements.