Measurement of the lifetime of tau-lepton

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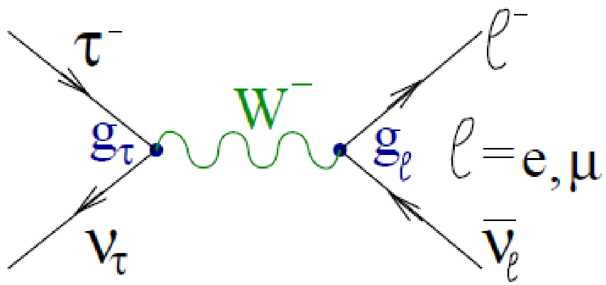
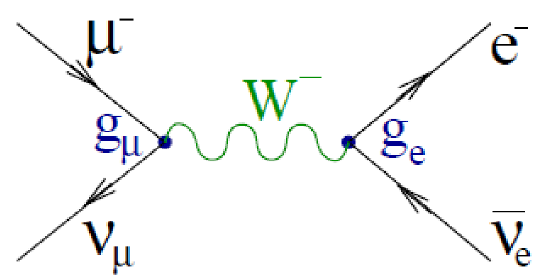
Measurement of τ-lepton lifetime, motivation

Precise measurement of the tau lifetime is necessary for the tests of lepton universality in the SM: $g_e = g_\mu = g_\tau$





$$\Gamma(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma)) = \frac{\mathcal{B}(L^- \to \ell^- \bar{\nu}_\ell \nu_L(\gamma))}{\tau_L} = \frac{g_L^2 g_\ell^2}{32 M_W^4} \frac{m_L^5}{192\pi^3} F_{\rm corr}(m_L, m_\ell)$$

$$F_{\rm corr}(m_L, m_\ell) = f(x)\left(1 + \frac{3}{5}\frac{m_L^2}{M_W^2}\right)\left(1 + \frac{\alpha(m_L)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\right)$$

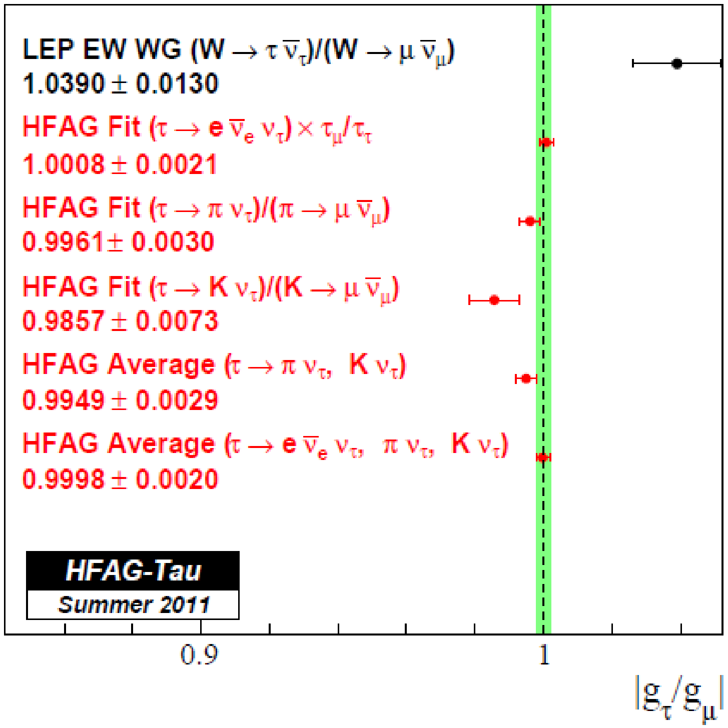
$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x, \; x = m_\ell / m_L$$

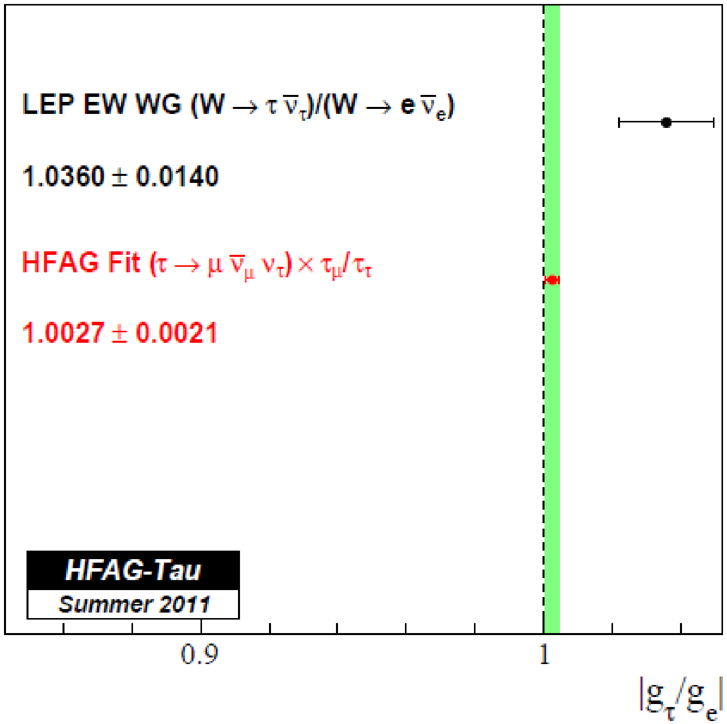
$$\mathcal{B}(\mu^- \to e^- \bar{\nu}_e \nu_\mu(\gamma)) = 1$$

$$\frac{g_\tau}{g_e} = \sqrt{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_\mu)}}, \quad \frac{\mathbf{g}_\tau}{\mathbf{g}_e} = \mathbf{1.0024 \pm 0.0021} \; (\text{HFAG2012})$$

$$\frac{g_\tau}{g_\mu} = \sqrt{\mathcal{B}(\tau^- \to e^- \bar{\nu}_\mu \nu_\tau(\gamma)) \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{F_{\rm corr}(m_\mu, m_e)}{F_{\rm corr}(m_\tau, m_e)}}, \quad \frac{\mathbf{g}_\tau}{\mathbf{g}_\mu} = \mathbf{1.0006 \pm 0.0021} \; (\text{HFAG2012})$$

Measurement of τ-lepton lifetime, motivation





S. Schael *et al.* [ALEPH, DELPHI, L3, OPAL, LEP EWG] Phys. Rep. 532, 119 (2013)

$$\frac{2\mathcal{B}(W \to \tau\nu_\tau)}{\mathcal{B}(W \to \mu\nu_\mu) + \mathcal{B}(W \to e\nu_e)} = 1.066 \pm 0.025$$

2.6σ deviation from the Standard Model

Previous measurements

- Current PDG lifetime
  $\tau = (290.6 \pm 1.0)10^{-15}$ sec
  $c\tau = 87.11 \pm 0.30\ \mu m$
  Obtained at LEP experiments.

- BaBar result (at L = 80 fb^{-1}, Tau'04 workshop)
  Nucl. Phys. B (Proc. Suppl.) **144** (2005) 105-112)
  $\tau = (289.40 \pm 0.91(stat) \pm 0.90(syst))\ 10^{-15}$ sec

- BaBar analyzed topology 3-1. The analyzed variable was

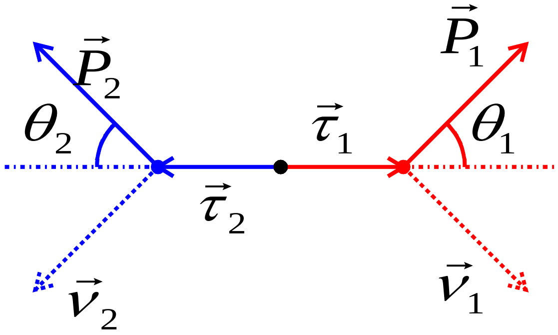
$$\lambda_t = \left(x_p - x_d\right) \cdot \vec{p}_t / \sin\theta$$

Data and Monte Carlo samples

- Data: L = 711 fb^{-1} (on- and off-resonance of ϒ(4S)).
- Monte Carlo:
  - Standard tau-tau sample prepared with KKMC generator with statitistics equal to the luminosity of the Data.
  - We generated two additional **$e^+e^- \rightarrow \tau^+\tau^- \rightarrow 3\pi\gamma\ 3\pi\gamma$** samples with the life times **$c\tau$ = 84 μm** and **$c\tau$ = 90 μm** (about **±10σ** (PDG) from the nominal value)
  - For the background estimation we used:
    - Standard EVTGEN light quarks, charm and beauty samples corresponding to the luminosity of the Data
    - gamma-gamma → hadrons generated with PYTHIA

Measurement of τ-lepton lifetime, method

- In the CM frame for the reaction $e^+e^- \to \tau^+\tau^- \to 3\pi\nu\, 3\pi\nu$ flight directions of τ^+ and τ^- are back-to-back.
- Energy of each τ-lepton is $\sqrt{s}/2$.
- Each τ-lepton is decayed into $\tau \to 3\pi\nu$; mass of τ-lepton is taken from PDG; neutrino mass assumed to be zero.

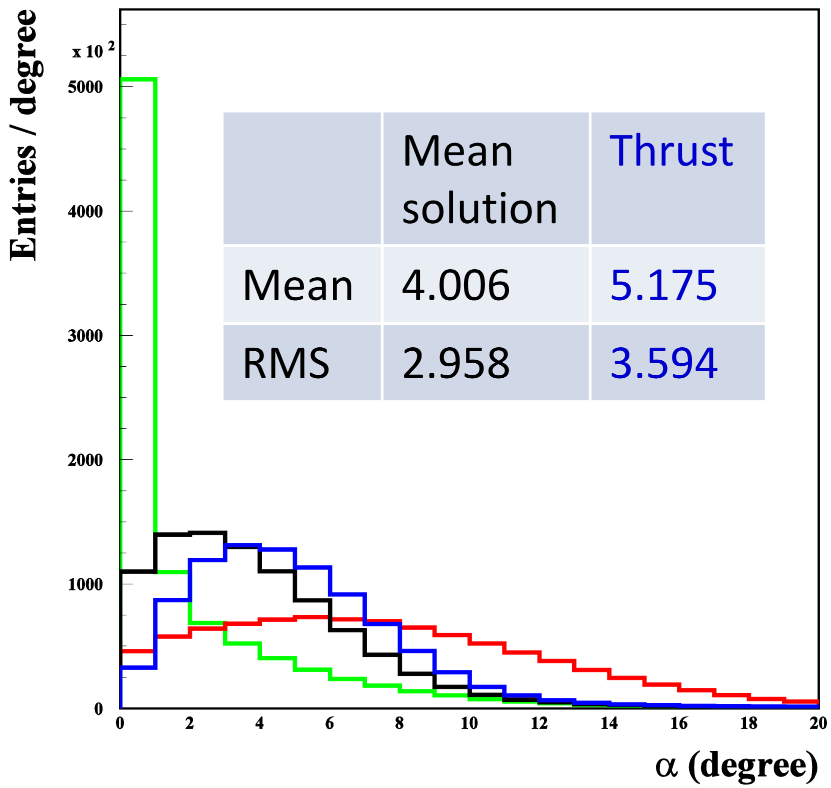


- $$\cos\theta = \frac{2E_\tau E_x - m_\tau^2 - m_x^2}{2P_\tau P_x} = \frac{2E_\tau E_x - m_\tau^2 - m_x^2}{2\sqrt{(E_\tau^2 - m_\tau^2)}P_x}$$
- $$\begin{cases} (\vec{P}_1 \cdot \vec{n}_+) = xP_{x1} + yP_{y1} + zP_{z1} = |P_1|\cos\theta_1 \\ (\vec{P}_2 \cdot \vec{n}_+) = xP_{x2} + yP_{y2} + zP_{z2} = -|P_2|\cos\theta_2 \\ (\vec{n}_+)^2 = x^2 + y^2 + z^2 = 1 \end{cases}$$

$\vec{n}_+$ is the unit vector in the direction of the positive τ-lepton

- Two solutions of quadratic equation are possible τ-lepton flight directions.

τ-lepton direction resolution



	Mean solution	Thrust
Mean	4.006	5.175
RMS	2.958	3.594

Angle between reconstructed and true τ-direction for ττ Monte Carlo events.

Monte Carlo samples:

— Mean solution

$$\vec{n} = \frac{\vec{n}_1 + \vec{n}_2}{2}$$

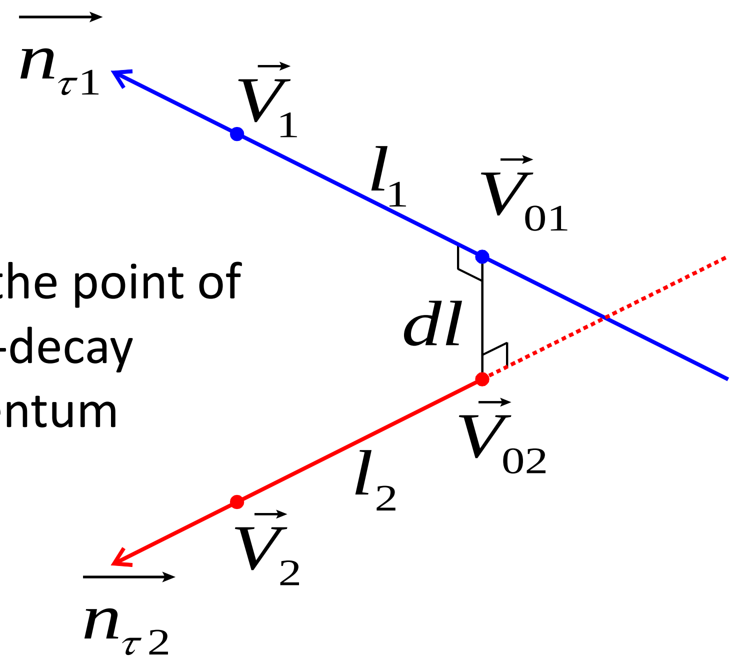
— n_1 - True solution

— n_2 - Wrong solution

— Thrust direction as τ-direction

Obtaining the lifetime

- In laboratory frame we have two vertices and two momenta of τ-leptons (two directions)
- This crossed-lines system has the following parameters:
  - *dl* – distance between crossed-lines
  - $l_1 = \left(\overrightarrow{V_1} - \overrightarrow{V_{01}}\right) \cdot \overrightarrow{n_1}$ – signed distance from the point of closest approach to the corresponding τ-decay vertex in the direction of τ-lepton momentum

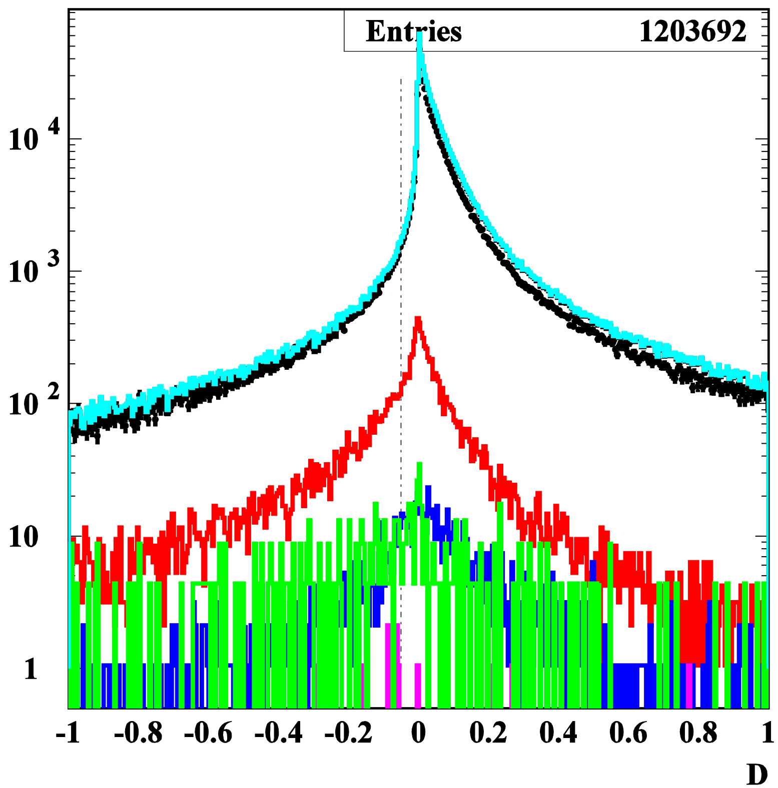


- $$c\tau_1 = \frac{l_1}{(\beta\gamma)_1}$$
- From the analogous calculation $$c\tau_2 = \frac{l_2}{(\beta\gamma)_2}$$

Event selection

- The analyzed topology is 3-3 without π^0s.
  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.
  3. Thrust value (in CM frame) is greater than 0.9
  4. Pt^2 of the pion system is greater than 0.25 GeV^2
  5. 4 GeV < m(6π) < 10.25 GeV
  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; mMin(3π) < 1.8 GeV
  8. Each triplet should be fitted to the vertex with $\chi^2 < 20$
  9. Discriminant for the system of equations D>-0.05
  10. Distance between crossed lines dl < 0.02 cm

Discriminant distribution for solution of τ-lepton direction



D – disriminant of quadratic equation

All above cuts are applied except the cut on dl.

- Data

Monte Carlo samples:

— Evtgen-uds

— Evtgen-charm

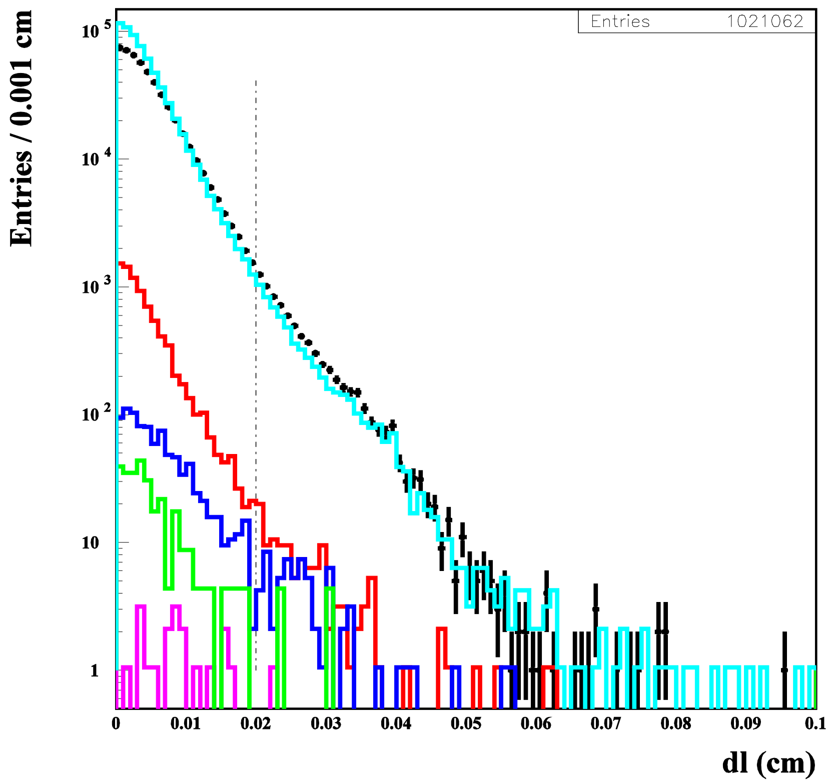
— Evtgen-charged + mixed

— $\gamma\gamma \rightarrow$ hadrons

All Monte Carlo samples are normalized to the integrated luminosity of the Data.

We use events with D > -0.05, For negative D we take D=0.

Distance between crossed-lines



All above cuts are applied.

- Data

Monte Carlo samples:

— Evtgen-uds

— Evtgen-charm

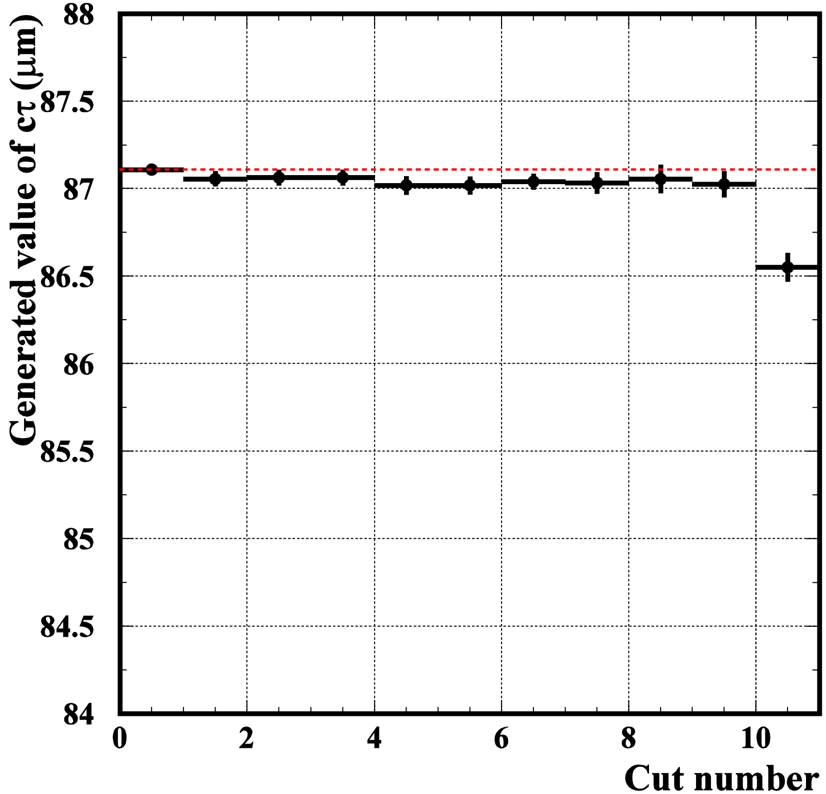
— Evtgen-charged + mixed

— $\gamma\gamma \rightarrow$ hadrons

All Monte Carlo samples are normalized to the integrated luminosity of the Data.

We select events with distance smaller than 0.02 cm.

Dependence of the lifetimes of the selected taus on the applied cuts



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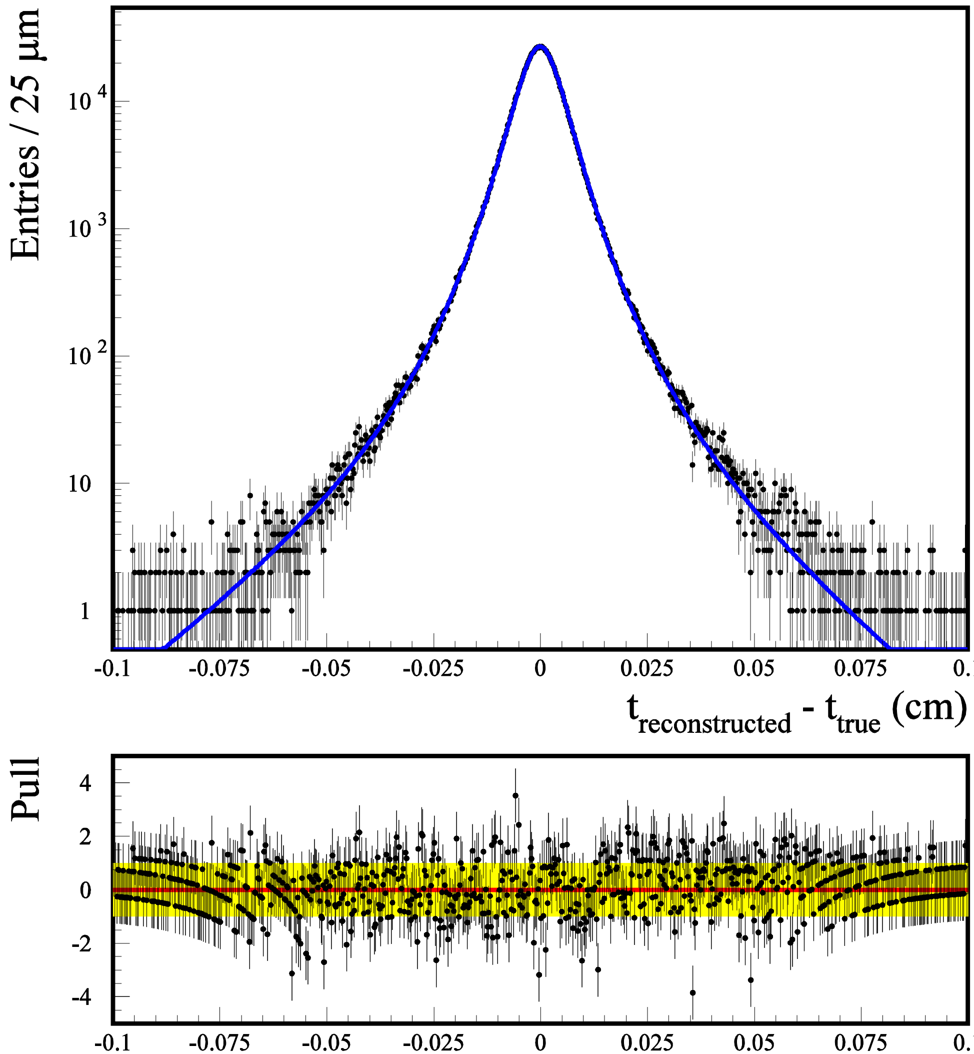
The strongest dependence is on the last cut dl<0.02cm

Resolution function



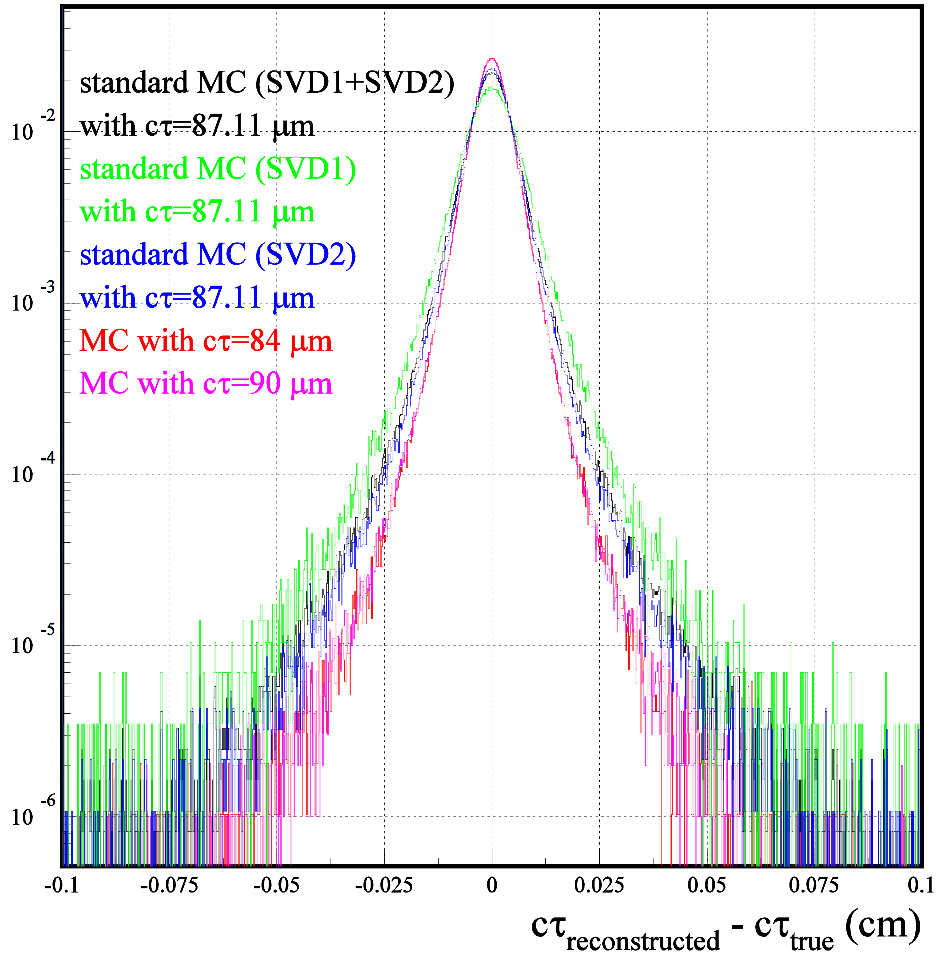
Parameterization of the resolution function

$$H(x) = P_1 \cdot R(x, P_2, ..., P_6) =$$

$$= P_1 \cdot (1 - 2.5x) \cdot \exp\left[- \frac{(x - P_2)^2}{2(P_3 + P_4|x - P_2|^{1/2} + P_5|x - P_2| + P_6|x - P_2|^{3/2})^2} \right]$$

P_1-P_6 are free parameters

Resolution functions for different MC samples



Fitting function for cτ distributions in data and MC

$$F(x) = P_1 \int e^{-t/P_2} R((x-t), P_3, ..., P_7)dt + A_{uds} R(x, P_3, ..., P_7) + Bkg_{cb}(x)$$

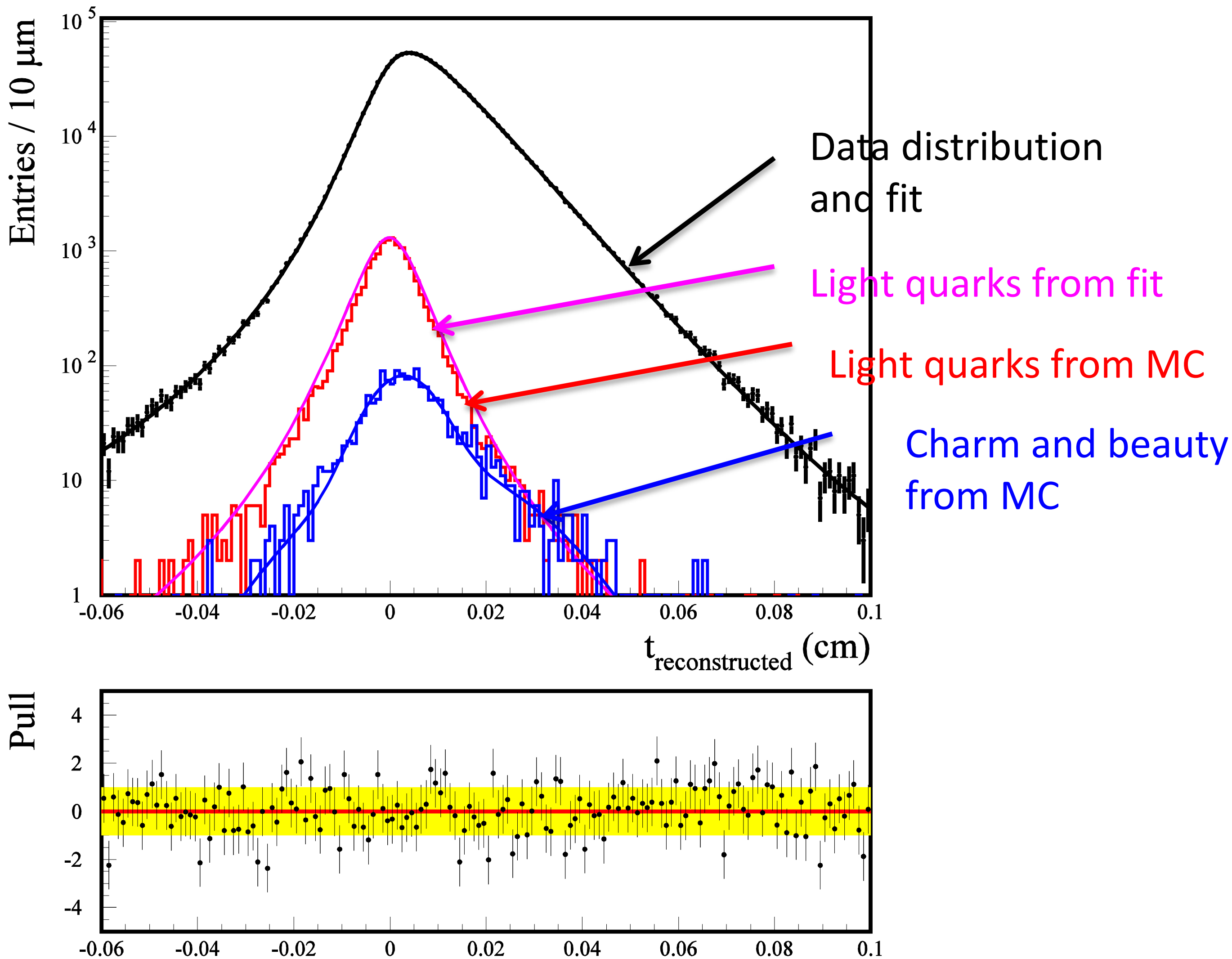
7 free parameters P_1-P_7

A_{uds}- fixed parameter for contribution of the background from light quarks events.

cτ distributions for them is well described by resolution function $R(x,P_3,...,P_7)$

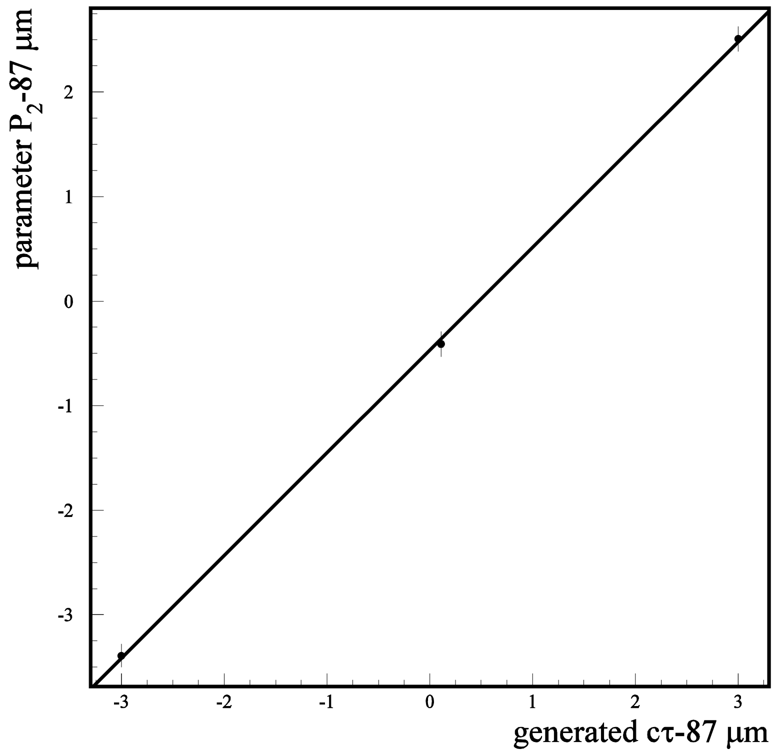
Contribution from charm and beauty events Bkg_{cb} was determined from MC

Result of the fit of the real data



MC correction of the fit parameter P_2

Dependence of the lifetime parameter P2 obtained from the fit (P2-87) мкм on the true input lifetime in the generator $c\tau$-87 мкм.



After the MC correction of the parameter P2 obtained from the fit of the data we get

$\langle c\tau \rangle = 86.99 \pm 0.16$ (stat.) μm

$\langle \tau \rangle = 290.17 \pm 0.53$ (stat.) $\cdot 10^{-15}$ s

Analysis of the systematics

1. Calibration of the alignment of the vertex detector
2. Asymmetry of the resolution function R
3. Choice of the range of the fit of reconstructed cτ distribution
4. Calibration of the beam energy
5. Accuracy of the description of ISR and FSR by MC
6. Accuracy of the estimation of the contributions of background events
7. Stability of the result with respect to the value of the last cut on dl
8. Accuracy of the knowledge of the mass of τ-lepton
9. We also checked the stability of the result for the different periods of the Belle operation and for different configurations of the tacking system

Uncertainty due to alignment of the vertex detector

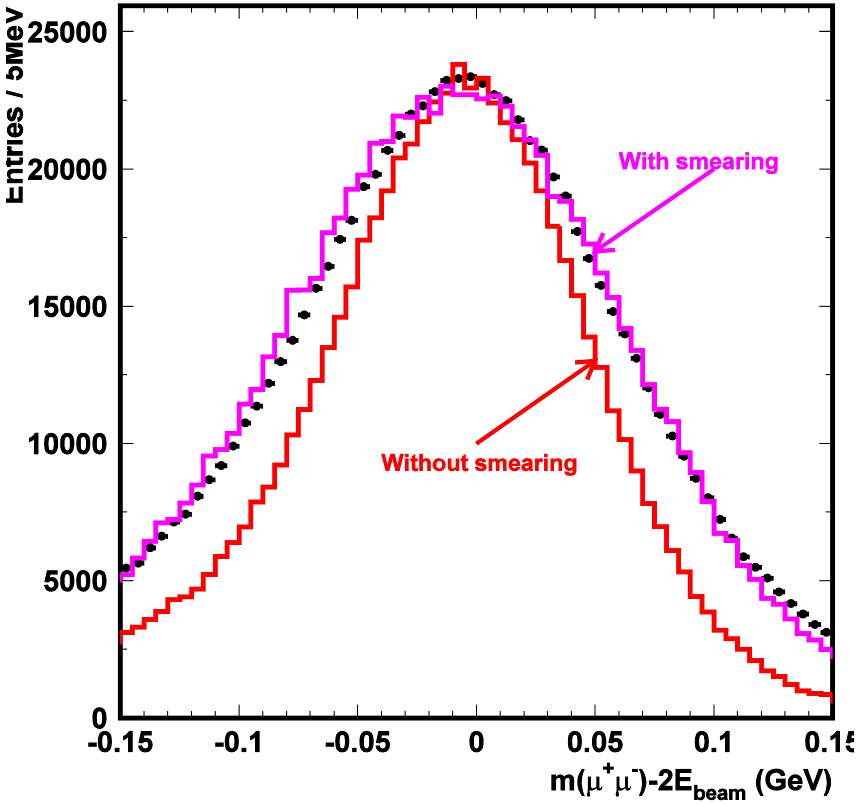
- We generated five MC samples of $\tau^+\tau^-$ events which decay to $3\pi\nu3\pi\nu$ with the statistics of each sample ~1.2 of the statistics of the data
- For these events shifts of the DSSD plates were done randomly by 10 μm along X/Y/Z axis
- For these events the random rotations of DSSD plates were done by angle 0.1 mrad
- The maximal deviation of the parameter P_2 (distorted) from P_2 (without distortion) is 0.07 μm
- For the same samples we performed the global SVD shifts and rotations with respect to drift chamber by 20 μm and 1 mrad respectively
- The maximal deviation of the P_2 is 0.06 μm
- For the estimation of the uncertainty we take the value $\sqrt{0.07^2 + 0.06^2} = 0.09$ μm

Asymmetry of the resolution function and accuracy of ISR and FSR description by KKMC generator

- Monte Carlo predicts some asymmetry of the resolution function (factor (1+2.5·x) in the parameterization of R) with accuracy 2.5±0.2

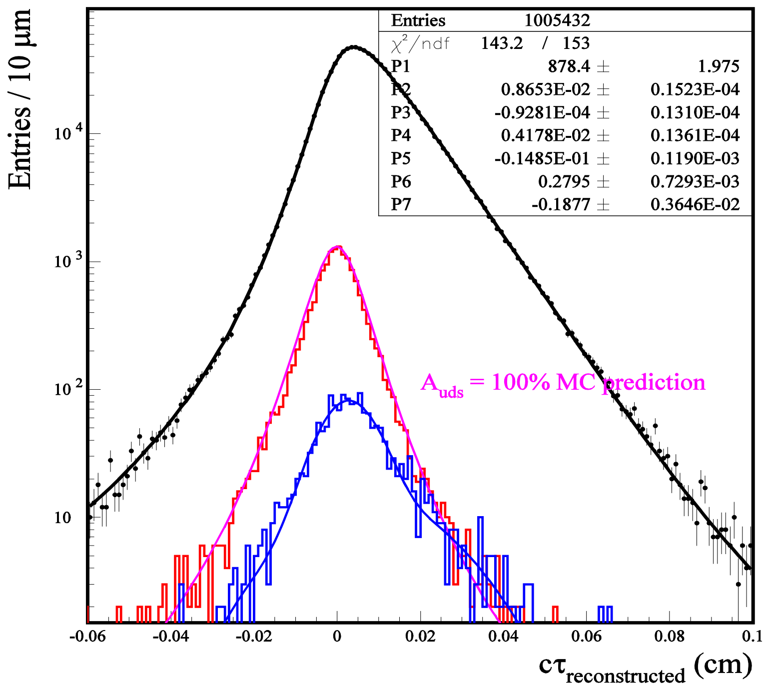
The result, obtained from the fit without this factor is different by 0.03 μm. This value is taken as the systematics estimation

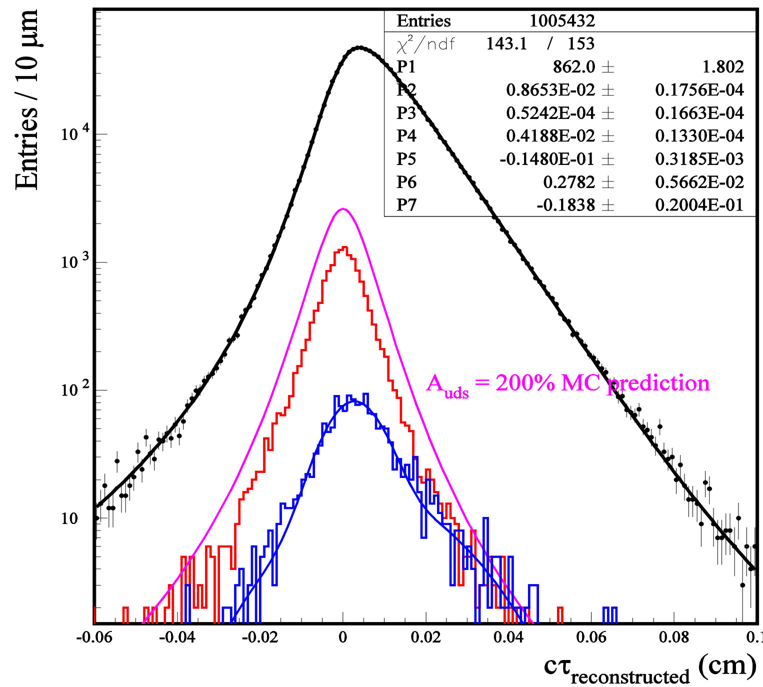
- The accuracy of the ISR and FSR description is checked by comparison of the data and MC events for the reaction $e^+e^- \rightarrow \mu^+\mu^-$ (n γ) reaction. Comparing the distributions $M(\mu^+\mu^-)$-2·Ebeam we found the relative accuracy $2.1\cdot10^{-4}$ in the τ lifetime



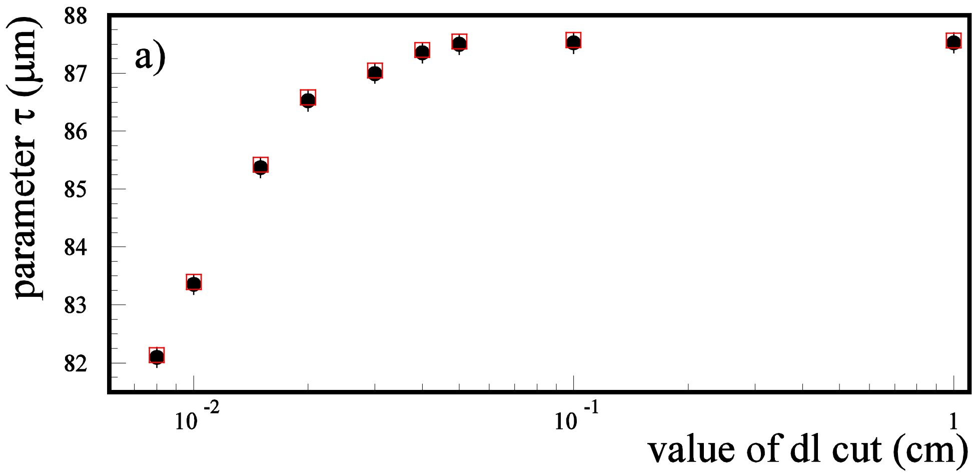
Accuracy of the estimation of background contribution

Variation of the background contribution in the fitting function. In particular performed the fits of the data distributions with uds contribution at the level of 50%, 100%, 150% and 200% of MC prediction. The variation of P2 parameter is within ±0.01 µm

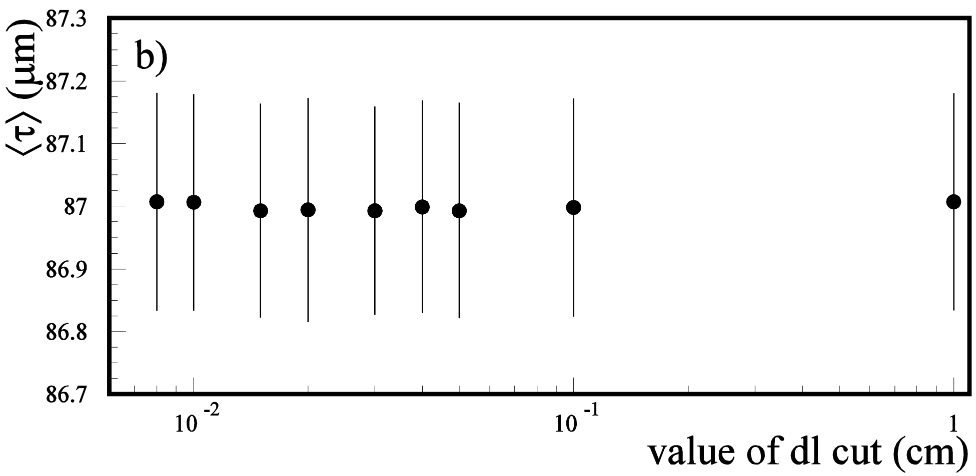




The stability of the result to the variation of the selection criteria, in particular to the cut on dl



The values of the fit parameter P2 in data and MC as function of the value of the cut on dl



MC corrected measured values of the τ lifetime as function of the value of the cut on dl

Systematics summary

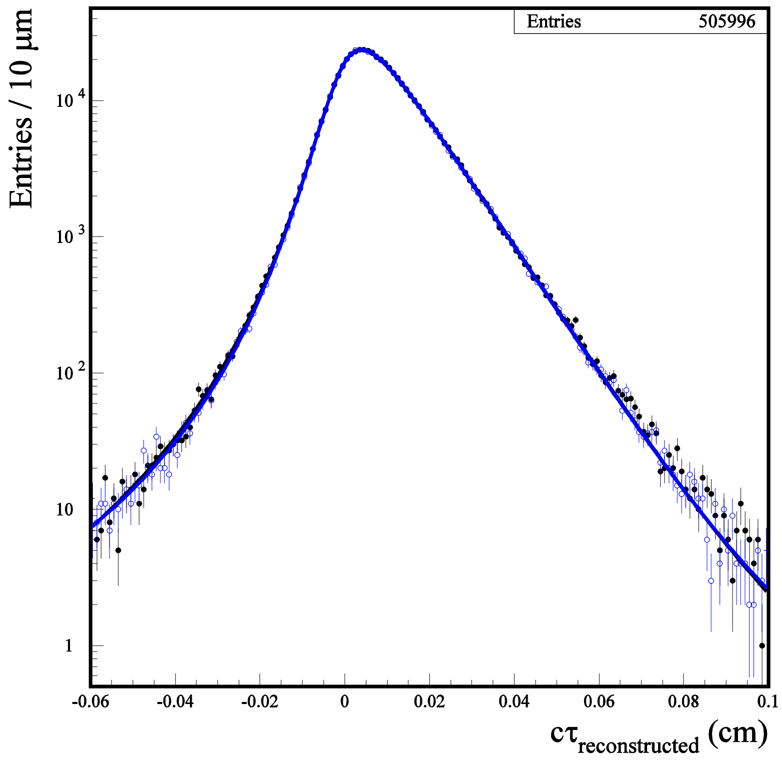
Source of Systematics	$\Delta(c\tau)$ in μm
SVD alignment	0.090
Asymmetry of R-function	0.030
Fit range	0.020
ISR and FSR description	0.018
Beam energy calibration	0.016
Background contribution	0.010
Error of the τ-lepton mass	0.009
Total	**0.101**

Final result

$\langle c\tau \rangle = 86.99 \pm 0.16\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \mu\text{m}$

$\langle \tau \rangle = (290.17 \pm 0.53\ (\text{stat.}) \pm 0.33\ (\text{syst})) \cdot 10^{-15}\ \text{s}$

Lifetime difference between τ^+ and τ^-



The difference of the P_2 parameters for τ^+ and τ^- is 0.07 ± 0.33 μm

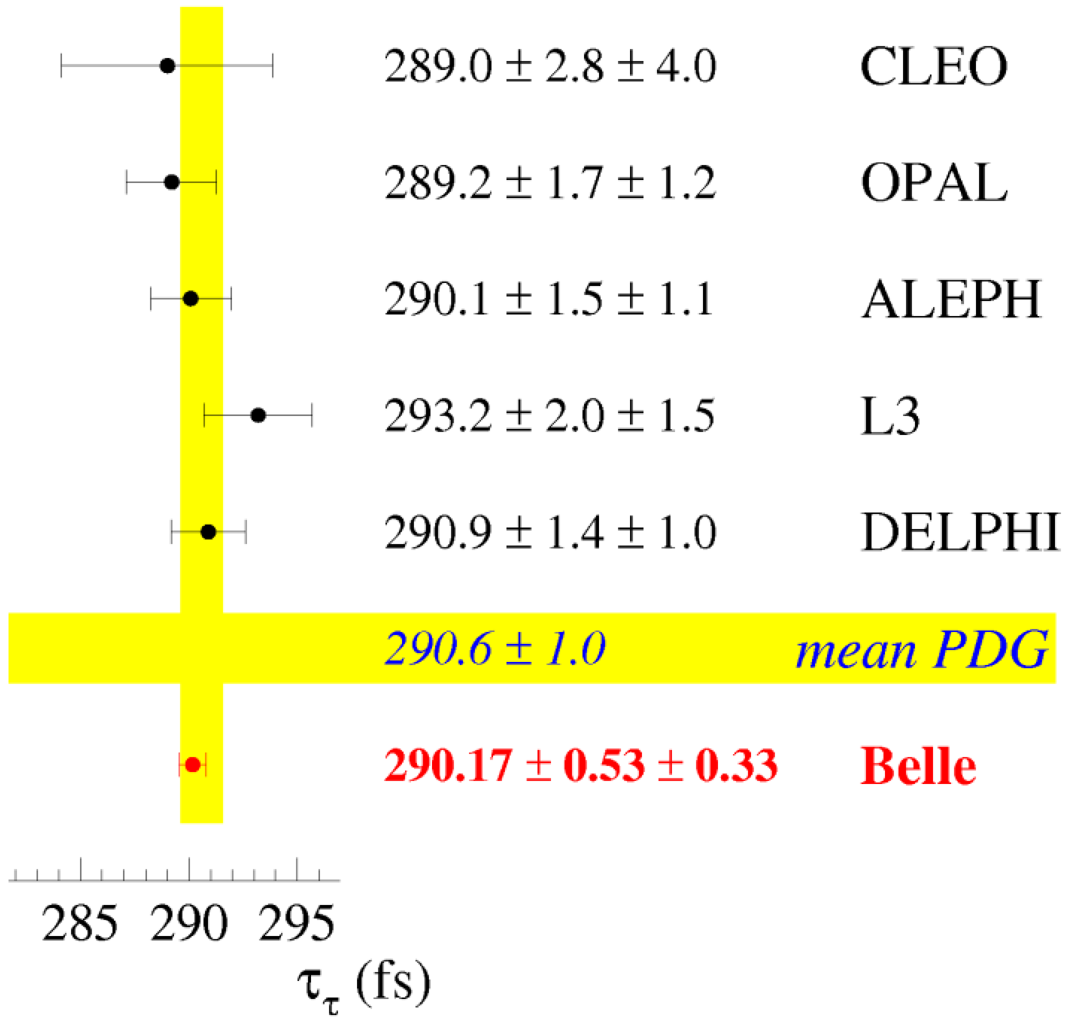
The systematics uncertainty is at least order of magnitude smaller than the statistical one

Upper limit is

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

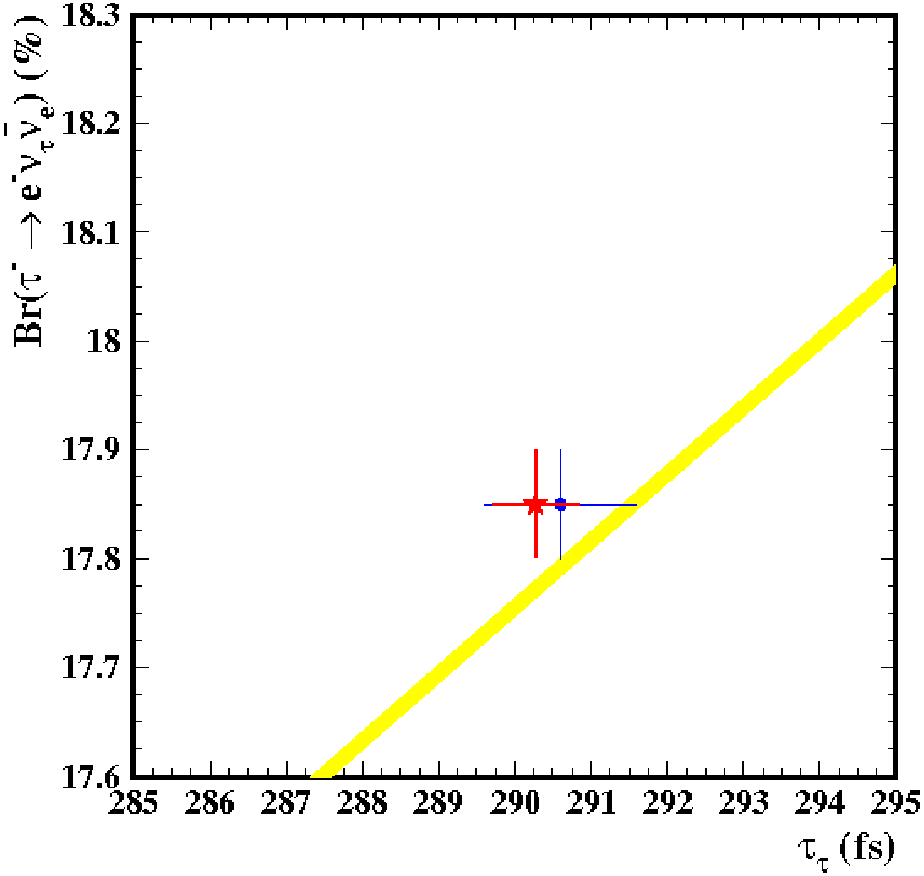
This measurement is done for the first time!

Comparison with the previous measurements



Lepton universality test

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



Belle result:

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = 1.0041 \pm 0.0035$$

Prospects for Belle II

- In the present result the dominant uncertainty is statistical one
- For the statistics ~50 times of Belle I we expect the dominance of systematics uncertainty. From the present overall uncertainty of $c\tau$ 0.2 μm we will have overall accuracy 0.1 μm

Prospects for LHCb

For the present integrated luminosity $3fb^{-1}$ the estimated statistics of τ-leptons is about $120\cdot10^9$ in LHCb acceptance. This should be compared with $2\cdot10^9$ τ-leptons at Belle or $100\cdot10^9$ at Belle II.

LHCb has big potential for the search of LFV decays of τ-leptons such as $\tau\rightarrow3\mu$.

On the other hand for the lifetime measurement almost all LHCb τ's are not useful because they are the products of the decays of Ds-mesons and b-hadrons. For the lifetime measurement only prompt τ's are useful.

The other problem for LHCb is the knowledge of the energy spectrum of τ-leptons which is needed for the evaluation of mean kinematic factor βγ.

Our conclusion from the all above: for the τ-lepton lifetime measurement the LHCb is not competitive with the e^+e^- B-factories

Conclusions

- Belle performed the measurement of τ-lepton lifetime with the accuracy 1.6 times better than the present PDG value: $\tau=(290.17\pm0.62)\cdot10^{-15}$s
- For the first time the upper limit on the lifetime difference between τ^+ and τ^- was obtained: $|\tau(\tau^+) - \tau(\tau^-)|/\tau_{average} < 7.0 \cdot 10^{-3}$ at 90% CL
- At Belle II we expect the improvement of the τ lifetime accuracy by factor ~2