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Tau Lifetime measurement at FCC-ee(Z)

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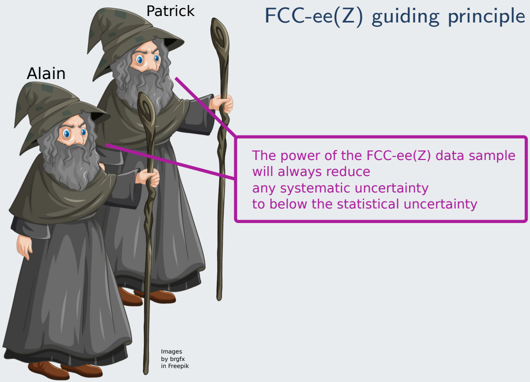
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Introduction

- tau lepton universality is important test of Standard Model
- tau lepton universality test requires
  - tau lifetime
  - tau leptonic branching fractions
  - tau mass
- today LU test precision is limited by both tau lifetime and tau leptonic branching fractions
- what detector features are required to keep tau lifetime systematics $\lesssim$ FCC-ee(Z) statistical precision?

FCC-ee(Z) guiding principle



Lepton universality tests

from HFLAV Tau Winter 2022 report

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\tau_\tau m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^{\tau e}}} = 1.0009 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\tau e}^{\text{SM}}}}$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\tau_\tau m_\tau^5 f_{\tau \mu} R_\gamma^\tau R_W^{\tau \mu}}} = 1.0027 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau \mu}^{\text{SM}}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau e}} \frac{f_{\tau e}}{f_{\tau \mu}}} = 1.0019 \pm 0.0014$$

using Standard Model predictions for leptons $\lambda, \rho = e, \mu, \tau$ (Marciano, 1988):

$$\Gamma[\lambda \to \nu_\lambda \rho \bar{\nu}_\rho(\gamma)] = \Gamma_{\lambda\rho} = \Gamma_\lambda \mathcal{B}_{\lambda\rho} = \frac{\mathcal{B}_{\lambda\rho}}{\tau_\lambda} = \frac{G_\lambda G_\rho m_\lambda^5}{192\pi^3} f\left(m_\rho^2/m_\lambda^2\right) R_W^\lambda R_\gamma^\lambda$$

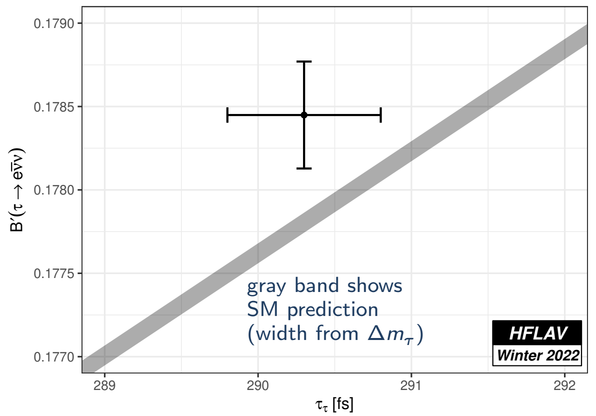
$$G_\lambda = \frac{g_\lambda^2}{4\sqrt{2}M_W^2} \; ; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x \; ; \qquad f_{\lambda\rho} = f\left(m_\rho^2/m_\lambda^2\right)$$

$$R_W^{\lambda\rho} = 1 + \frac{3}{5}\frac{m_\lambda^2}{M_W^2} + \frac{9}{5}\frac{m_\rho^2}{M_W^2} \; ; \qquad R_\gamma^\lambda = 1 + \frac{\alpha(m_\lambda)}{2\pi}\left(\frac{25}{4} - \pi^2\right) \; ;$$

all statistical correlations included

- less precise tests possible with hadronic tau decays

Canonical tau lepton universality test plot



- $\mathcal{B}'(\tau \to e\bar{\nu}\nu)$ = average of $\begin{cases} \mathcal{B}(\tau \to e\bar{\nu}\nu) \\ \mathcal{B}(\tau \to \mu\bar{\nu}\nu) \cdot \frac{f_{\tau e} R_W^{\tau e}}{f_{\tau\mu} R_W^{\tau\mu}} \end{cases}$
- $\frac{\mathcal{B}'(\tau \to e\bar{\nu}\nu)\tau_\mu}{\mathcal{B}(\mu \to e\bar{\nu}\nu)\tau_\tau} = \frac{g_\tau^2}{g_{e\mu}^2} \frac{m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^{\tau e}}{m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}$
- $\left(\frac{g_\tau}{g_{e\mu}}\right)^2 = \frac{\mathcal{B}'(\tau \to e\bar{\nu}\nu)}{\mathcal{B}(\mu \to e\bar{\nu}\nu)} \frac{\tau_\mu}{\tau_\tau} \frac{m_\mu^5}{m_\tau^5} \frac{f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{f_{\tau e} R_\gamma^\tau R_W^{\tau e}}$

$(g_\tau/g_{e\mu}) = 1.0018 \pm 0.0013$
$[g_{e\mu} = g_e = g_\mu$ assuming $g_e = g_\mu]$

$\Delta(g_\tau/g_{e\mu})$ contributions

input	Δinput	$\Delta(g_\tau/g_{e\mu})$
$\mathcal{B}'_{\tau\to e}$	0.180%	0.090%
τ_τ	0.172%	0.086%
m_τ	0.007%	0.017%
total		0.126%

best measurements

$\mathcal{B}'_{\tau\to e}$	ALEPH
τ_τ	Belle
m_τ	BES III

Tau Lifetime

τ MEAN LIFE

PDG 2019

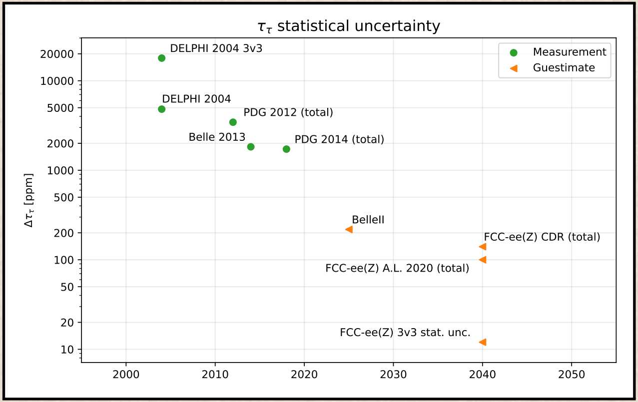
VALUE (10^{-15} s)	EVTS	DOCUMENT ID		TECN	COMMENT
290.3 ± 0.5	**OUR AVERAGE**				
$290.17 \pm 0.53 \pm 0.33$	1.1M	BELOUS	2014	BELL	711 fb^{-1} $E^{ee}_{\rm cm}$=10.6 GeV
$290.9 \pm 1.4 \pm 1.0$		ABDALLAH	2004T	DLPH	1991-1995 LEP runs
$293.2 \pm 2.0 \pm 1.5$		ACCIARRI	2000B	L3	1991--1995 LEP runs
$290.1 \pm 1.5 \pm 1.1$		BARATE	1997R	ALEP	1989--1994 LEP runs
$289.2 \pm 1.7 \pm 1.2$		ALEXANDER	1996E	OPAL	1990--1994 LEP runs
$289.0 \pm 2.8 \pm 4.0$	57.4k	BALEST	1996	CLEO	$E^{ee}_{\rm cm}$= 10.6 GeV

tau lifetime precision

precision (ppm)	
1700	PDG 2014
2100	Belle
5900	DELPHI
6400	ALEPH
7200	OPAL

LEP and Belle II measurements not systematically limited

τ_τ statistical uncertainty



FCC total uncertainty estimates

- M. Dam, 1999, FCC CDR
- A.L. FCC Workshop Jan 2020
- systematically limited, see later

FCC statistical uncertainty estimate

- use 3v3 tau pairs like Belle 2013
- DELPHI 2004 3v3 $\rightarrow$ FCC stat.

Other estimates

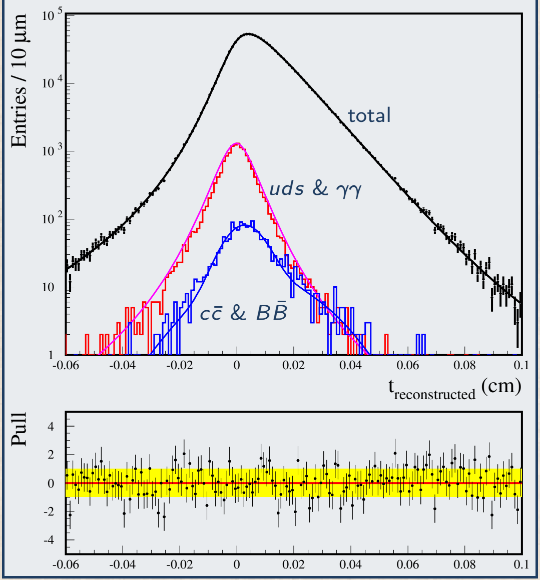
- Belle II Physics Book

precision (ppm)	
4800	DELPHI 2004, 144 pb^{-1}(1991-1995)
18000	DELPHI 2004, only 3v3 events, 144 pb^{-1}(1991-1995), 100 μm per-event i.p. RMS
12	FCC-ee(Z) from DELPHI 2004 3v3 with 150 ab^{-1}, 70 μ per-event i.p. RMS

- LEP: per-event decay length resolution 100 μm $=$ 70 (impact parameter) $\oplus$ 70 (beam spot and vertexing) μm
- FCC: beam spot and vertexing negligible w.r.t. intrinsic impact parameter size 70 μm $= c\tau_\tau \langle\sin\theta\rangle$

Advantages of using 3v3 tau pairs

Belle 2014 reconstructed proper tau decay time



- more precise vertexing (3 tracks)
  - good fit of vertexing resolution on negative tail of reconstructed decay length distribution (resolution has importain bias in Belle 2013)
- using a reconstructed vertex rather than an impact parameter for 1-prong tau decay is less dependent on tau decay dynamics
- spatial tau flight direction from two vertices provides tau flight direction, which cannot be reconstructed from detectable tau decay products, and provides the tau flight polar angle to reconstruct the decay length from its transverse measurement
- about 2.2% of tau events have 3v3 topology

Tau Lifetime systematics at LEP

DELPHI main systematics, Eur.Phys.J.C36:283-296,200

- IP impact parameter difference on 1-1-prong tau pairs
  - trimming, backgrounds, impact parameter resolution, alignment
- MD miss-distance on 1-1-prong tau pairs
  - resolution on MD, bias, selection
- DL transverse decay length on 3-1 and 3-3 prong tau pairs
  - alignment

ALEPH main systematics, Phys.Lett.B414:362-372,1997

- MIPS, momentum-weighted impact parameter sum
  - resolution on impact parameter sum, bias (from MC)
- 3DIP 3D impact parameter, Z. Phys. C 74, 387–398 (1997)
  - bias (from MC), vertex χ^2 cut
- IPD, impact parameter difference
  - resolution and trimming of outliers
- DL, decay length
  - vertex chisq cut

expect that all these systematics scale with $1/\sqrt{N_{\text{events}}}$
including alignment systematics
(although somehow questionable if up to a factor $1/{\sim}1000$)

Tau Lifetime systematics at Belle 2013

Source	$\Delta\lambda_\tau$ [μm]	
SVD alignment	0.090	scales with luminosity (see in the following)
Asymmetry fixing	0.030	scales with luminosity
Beam energy and ISR/FSR description	0.024	(270 ppm) does not scale trivially with luminosity
Fit range	0.020	scales with luminosity
Background contribution	0.010	scales with luminosity
τ-lepton mass	0.009	(100 ppm) does not scale trivially with luminosity
Total	0.101	

Tau Lifetime vertex detector alignment systematics

M. Dam, SciPost Phys.Proc. 1 (2019) 041

systematic uncertainty:
- take 0.25 μm alignment uncertainty from Belle 2013
- translates immediately, with higher boost, into a FCC systematic precision $\sim$0.04 fs, i.e. 140 ppm

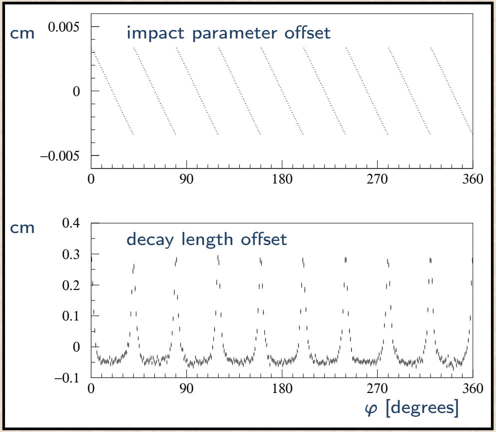
S.R.Wasserbaech, Nucl.Phys.Proc.Suppl. 76 (1999) 107-116

- studies of vertex detector misalignment systematics for ALEPH at LEP
- misalignment effects average to zero at first order
  - measure decay length in transverse plane
  - uniform azymuthal acceptance (note: can be forced by weighting data azymuthally)
- confirmed by more refined studies at BABAR

S.R.Wasserbaech, Nucl.Phys.Proc.Suppl. 76 (1999) 107-116

ALEPH vertex detector misalignment simulation

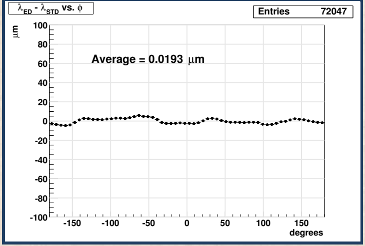
- basic simulation of ALEPH vertex detector with all wafers radially shifted out by 100 μm
- impact parameter offset $= 100\,\mu\text{m} \cdot \sin\alpha$
  - $\alpha =$ track angle w.r.t. normal of wafer
- decay length offset (measured using 3-tracks vertex)
  - negative when 3 tracks hit same wafer
  - positive when 3 tracks hit two wafers



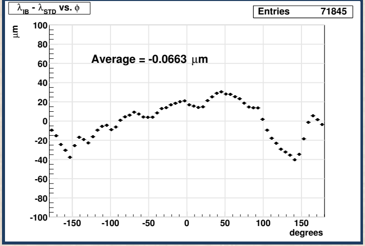
- decay length offset $\sim$ derivative of impact parameter offset
  - can be understood with 1-st order model of most simple misalignments
  - confirmed empirically quite precisely in accurate simulations of real detectors
- averaging decay length over full range of azymuth angle is like integrating $\Rightarrow$ average offset = impact parameter offset variation from 0 to 2π i.e. zero

BaBar studies, tau lifetime with SVT misalignment files

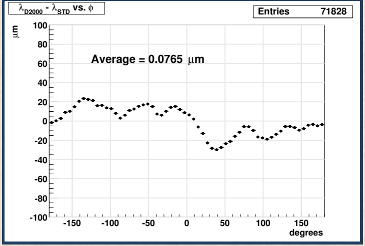
EllipsData SVT misalignment



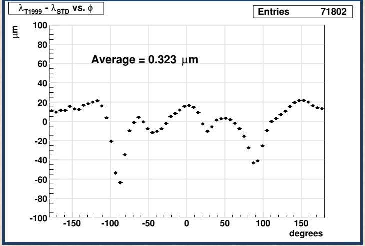
InnerBias SVT misalignment



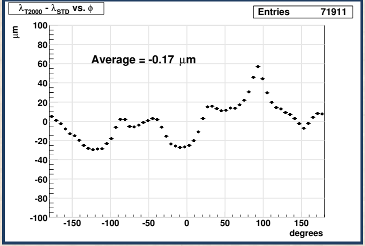
Diff2000 SVT misalignment



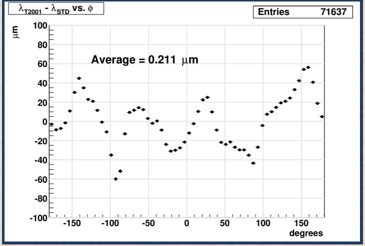
Time1999 SVT misalignment



Time2000 SVT misalignment

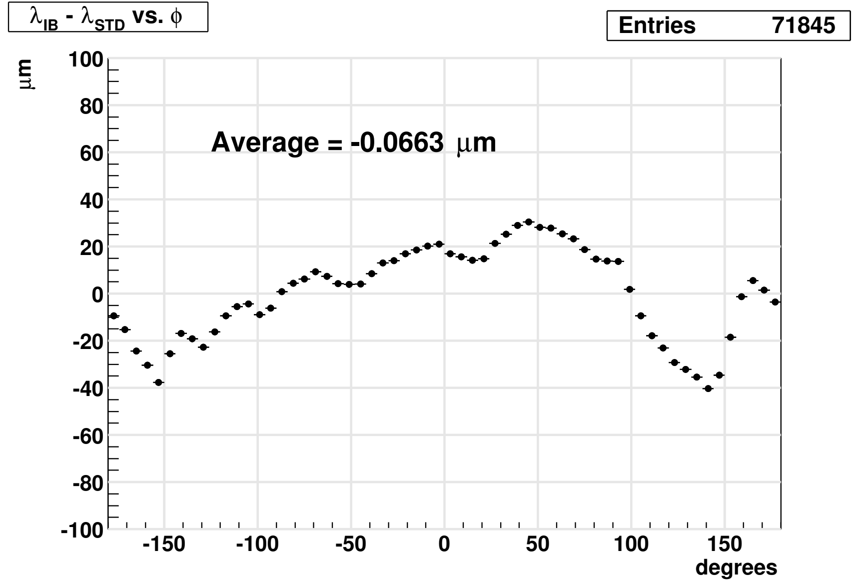


Time2001 SVT misalignment



BaBar studies, tau lifetime with SVT misalignment files

InnerBias SVT misalignment



Vertex detector absolute length scale systematic

- vertex detector misaligment can have large effect but can be suppressed and calibrated
- average radius of the vertex detector can be constrained with data using overlapping wafer modules: radius will be known with the same relative precision of the knowledge of the size of the silicon modules, or equivalently the average strip pitch
- LEP, B-factories, absolute length scale knowledge of silicon vertex detector believed to be 100 ppm
- A.L. Jan 2020 guestimate for FCC tau lifetime uncertainty limited to 100 ppm by this limitation

MUonE interferometric monitoring of detector to 1 μm/50 cm, 2 ppm

- A. Arena, G. Cantatore, M. Karuza, Digital holographic interferometry for particle detector diagnostic, Proceedings of the International Convention MIPRO, May 2022, doi:10.23919/MIPRO55190.2022.9803636
  - During preliminary tests, we have obtained reconstructed holographic images with interference fringes showing a displacement of the monitored object, over time, of the order of $\sim$1 μm. This experimentally demonstrated resolution is already sufficient to satisfy the 10 μm resolution mandated by MUonE. [MUonE silicon modules are 50 cm apart]
- also absolute calibration required in addition to monitoring, appears feasible with optical techniques
- 2 ppm tau lifetime sistematics from vertex detector length scale appears attainable

Tau mass and radiative energy loss systematics

- $\tau_\tau = \frac{\lambda_\tau}{\beta\gamma} = \frac{\lambda_\tau m_\tau}{\sqrt{E_\tau^2 - m_\tau^2}} = \frac{\lambda_\tau m_\tau}{\sqrt{(E_{\text{beam}} - E_{\text{rad}}^{\text{MC}})^2 - m_\tau^2}}$ at Z-peak: $E_{\text{beam}} \gg m_\tau$, $E_{\text{beam}} \gg E_{\text{rad}}^{\text{MC}}$

systematic contribution from tau energy loss with radiation uncertainty

- includes ISR & FSR, is predicted by KKMC
- DELPHI 2004: $E_{\text{rad}}^{\text{MC}} = 1.1\% \cdot (1 \pm 3.1\%) \cdot E_{\text{beam}}$ $\Rightarrow$ 350 ppm on τ_τ for DELPHI 2004
- guestimate KKMC with next rad. order will reduce $\Delta E_{\text{rad}}^{\text{MC}}$ by 30 $\Rightarrow$ 12 ppm on τ_τ for FCC-ee(Z)
- abundant data will permit testing of KKMC prediction for $E_{\text{rad}}^{\text{MC}}$

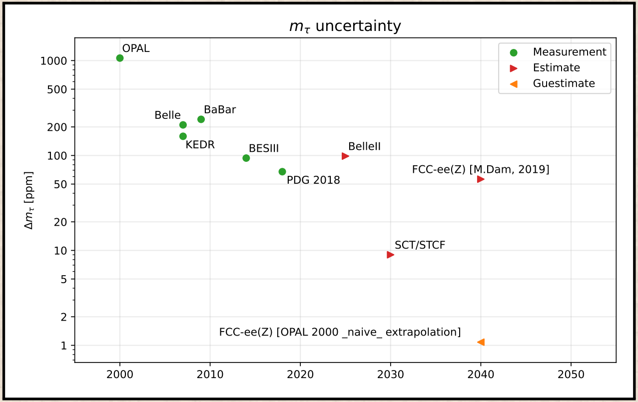
systematic contribution from tau mass uncertainty

- $\Delta m_\tau = 68$ ppm (PDG 2019) $\Rightarrow$ induces about equal size systematic uncertainty contribution
- SCT/STCF may measure m_τ to 7 ppm
- alternatively, FCC-ee(Z) may also measure m_τ

Measurement of average tau momentum at FCC

- can infer average tau momentum by measuring momentum of charged track of two-body tau decays and leptonic decays, free from hadronic uncertainties
- statistical precision better than 1 ppm
  but must also estimate radiation in tau decays (PHOTOS) very well

m_τ uncertainty



FCC estimates

- M. Dam, 2019; FCC CDR
- extrapolation OPAL 2000 → FCC

Other estimates

- Tao Luo, 2019
- Belle II Physics Book

- note: precise FCC momentum scale calibration possible by matching E_{cm} [1 ppm] and $m_{J/\psi}$ [2 ppm]

Tau Lifetime at FCC-ee(Z) uncertainty budget

uncertainty [ppm]	
12	statistical, extrapolated from DELPHI 2004 tau 3v3 decays
2	length scale of vertex detector
1-7	m_τ, either FCC-ee(Z) (very difficult) or SCT/SCTF
12	average tau radiative energy loss
12	remaining systematics, reduced using FCC-ee(Z) statistics
21-22	total

Conclusions

- optimistic prospects for tau lifetime measurements at FCC with $\sim$20 ppm precision
- requirements:
  - vertex detector length scale to $\ll$ 12 ppm, appears feasible with optical techniques
  - 30$\times$ better simulation of tau energy average radiative loss (KKMC next order)
  - 10$\times$ more precise tau mass measurement than today, difficult at FCC
  - existing expected detector performance

Thanks for your attention!

Backup Slides

Tau pairs at past, present and future e^+e^- colliders

	CLEO, CLEOIII	LEP 100	Belle, BABAR	Belle II	SCT	STCF	CEPC(Z)	FCC-ee(Z)
E_{CM} [GeV]	$\sim$10.6	92	$\sim$10.6	$\sim$10.6	$2-6$	$2-7$	92	
$\int \mathcal{L}dt$ [ab^{-1}]	0.01		1.5	50	10			
tau pairs	$1{\cdot}10^7$	$0.8{\cdot}10^6$	$1.4{\cdot}10^9$	$46{\cdot}10^9$	$30{\cdot}10^9$		$30{\cdot}10^9$	$170{\cdot}10^9$

note: SCT & SCFT tau pairs estimate assuming 10 years of tau-pairs-optimized CM energies running

Conditions for tau physics measurements

- Z peak collisions best for most measurements
  - pure and efficient tau pair selection selecting on just one of the two taus
  - track multiplicity separates very well $\tau^+\tau^-$ from $q\bar{q}$
  - high momenta reduce multiple scattering uncertainty in impact parameter measurements
- threshold measurements at $E = 2m_\tau \sim 3.5$ GeV best for tau mass
  - threshold measurements help some LFV searches and tau BRs (super charm-tau factories)
- B-factories bested LEP with statistics on e.g. small branching fractionss, LFV searches, tau lifetime

Tau pairs at past, present and future e^+e^- colliders

	CLEO, CLEOIII	LEP 100	Belle, BABAR	Belle II	SCT	STCF	CEPC(Z)	FCC-ee(Z)
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note: SCT & SCFT tau pairs estimate assuming 10 years of tau-pairs-optimized CM energies running

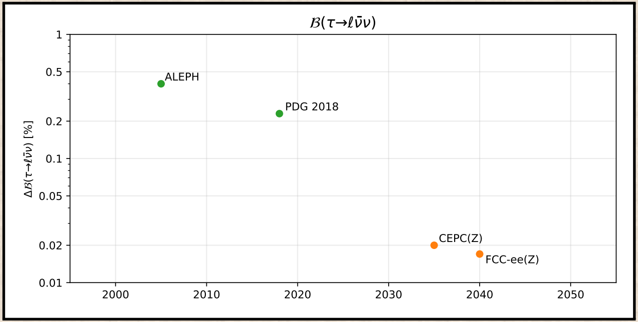
Additional FCC advantages

- Z significantly better vertex resolution than at LEP
- higher momoe ntum tracks, less multiple scattering than at B-factories
- better tau pair vs. hadrons separation than at B-factories

FCC tau physics references (non exhaustive)

- FCC CDR, EPJC 79 (2019) 474
- Mogens Dam
  - Tau2021
  - M. Dam, EPJ+ 136 (2021) 963, doi:10.1140/epjp/s13360-021-01894-y, arXiv:2107.12832 [hep-ex]
  - M. Dam, SciPost Phys.Proc. 1 (2019) 041
- A.L.
  - FCC meetings Jan 2020, Dec 2021, Feb 2022, Sep 2022
  - Charm 2021, Tau 2021
  - European Strategy Update 2019, arXiv:1910.11775 [hep-ex]

FCC sensitivity for $\mathcal{B}(\tau \to \ell\bar{\nu}\nu)$



FCC estimate

- M. Dam Tau2018, Tau2021

Other estimates

- ESG 2019 docs

- sensitivity estimates very difficult, mostly guestimates
- best results from ALEPH global analysis of all tau decays

Tau branching fractions notes

- world averages of large BRs still dominated by LEP
  - background separation from dileptons and hadrons much better
  - higher selection purity and efficiency
  - possible to tag single tau with good efficiency and purity and observe the other one
    $\Rightarrow$ wonderful base for reducing systematics using data, exploited in particular by ALEPH
- *B*-factories improved on small branching fractions using statistics
  $\Rightarrow$ FCC statistics $1300^2\times$ ALEPH, $175\times$ Belle, $3.5\times$ BelleII (& better efficiency w.r.t. *B*-factories)

Important ingredients for precise BR measurements

- PID efficiency, purity, accurate PID modeling with control samples
- efficiency, purity of π^0 reconstruction, accurate modeling with control samples
- improve current poor simulation of high multiplicity invariant mass distributions
- improvements on tau pairs Monte Carlo simulations highly desirable
- high statistics samples will help very much on first 3 points, but analyses will be very complex
- FCC is best imaginable context for tau BR measurements

Systematics of main ALEPH tau BR paper, Phys. Rept. 421 (2005) 191

systematics

Total systematic errors for branching ratios measured from the 1994–1995 data sample

Topology	π^0	sel	bkg	pid	int	trk	dyn	mcs	Total
e	0.011	0.021	0.029	0.019	0.009	0.000	0.000	0.015	0.045
μ	0.004	0.020	0.020	0.021	0.008	0.000	0.000	0.015	0.039
h	0.071	0.016	0.010	0.022	0.022	0.014	0.000	0.019	0.083
$h\pi^0$	0.063	0.027	0.019	0.011	0.045	0.009	0.000	0.027	0.090
$h2\pi^0$	0.089	0.021	0.014	0.004	0.007	0.003	0.040	0.028	0.105
$h3\pi^0$	0.056	0.012	0.015	0.000	0.008	0.001	0.008	0.030	0.068
$h4\pi^0$	0.029	0.005	0.011	0.000	0.015	0.000	0.000	0.019	0.040
$3h$	0.047	0.021	0.018	0.004	0.012	0.014	0.006	0.015	0.059
$3h\pi^0$	0.033	0.017	0.029	0.002	0.041	0.009	0.007	0.018	0.066
$3h2\pi^0$	0.027	0.008	0.015	0.000	0.009	0.003	0.012	0.014	0.038
$3h3\pi^0$	0.010	0.012	0.002	0.000	0.002	0.001	0.010	0.006	0.019
$5h$	0.002	0.000	0.002	0.000	0.000	0.001	0.000	0.003	0.004
$5h\pi^0$	0.002	0.000	0.006	0.000	0.000	0.000	0.000	0.002	0.007
Class 14	0.013	0.003	0.022	0.002	0.024	0.000	0.000	0.011	0.037

All numbers are absolute in per cent. The labels are defined as follows: photon and π^0 reconstruction (π^0), event selection efficiency (sel), non-τ background (bkg), charged particle identification (pid), secondary interactions (int), tracking (trk), Monte Carlo dynamics (dyn), Monte Carlo statistics (mcs), total systematic uncertainty (total).

π^0 systematics

Total systematic errors for branching ratios measured from the 1994–1995 data sample

Topology	π^0	sel	bkg	pid	int	trk	dyn	mcs	Total
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h	0.071	0.016	0.010	0.022	0.022	0.014	0.000	0.019	0.083
$h\pi^0$	0.063	0.027	0.019	0.011	0.045	0.009	0.000	0.027	0.090
$h2\pi^0$	0.089	0.021	0.014	0.004	0.007	0.003	0.040	0.028	0.105
$h3\pi^0$	0.056	0.012	0.015	0.000	0.008	0.001	0.008	0.030	0.068
$h4\pi^0$	0.029	0.005	0.011	0.000	0.015	0.000	0.000	0.019	0.040
$3h$	0.047	0.021	0.018	0.004	0.012	0.014	0.006	0.015	0.059
$3h\pi^0$	0.033	0.017	0.029	0.002	0.041	0.009	0.007	0.018	0.066
$3h2\pi^0$	0.027	0.008	0.015	0.000	0.009	0.003	0.012	0.014	0.038
$3h3\pi^0$	0.010	0.012	0.002	0.000	0.002	0.001	0.010	0.006	0.019
$5h$	0.002	0.000	0.002	0.000	0.000	0.001	0.000	0.003	0.004
$5h\pi^0$	0.002	0.000	0.006	0.000	0.000	0.000	0.000	0.002	0.007
Class 14	0.013	0.003	0.022	0.002	0.024	0.000	0.000	0.011	0.037

All numbers are absolute in per cent. The labels are defined as follows: photon and π^0 reconstruction (π^0), event selection efficiency (sel), non-τ background (bkg), charged particle identification (pid), secondary interactions (int), tracking (trk), Monte Carlo dynamics (dyn), Monte Carlo statistics (mcs), total systematic uncertainty (total).

- many systematics but in general all limited only by data vs. MC comparisons
- non-trivial to extrapolate to 1300^2 more data

Main systematics of ALEPH tau BR paper, Phys. Rept. 421 (2005) 191

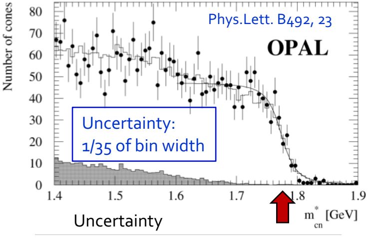
- non-tau backgrounds
  - estimated by varying MC estimate by 30%
  - does not trivially scale with luminosity, but can be improved
- tau pair selection
  - use break-mix method on data and MC, 0.1-0.2% uncertainties
    dominant systematics from data statistics of tau vs. hadron cut separation
  - scales with luminosity, but correlations between hemispheres limit how much
- PID
  - uncertainties from control samples studies
  - partially scales with luminosity, but limited by achievable purity of control samples
- photon efficiency
  - uncertainties from control samples studies data-MC comparisons
    - fit data using predicted MC fake and genuine photon distributions and compare number of genuine photons
    - compare photons $> 3\,\text{GeV}$ as function of separation from tracks
    - compare converted photons
    - compare hadron to electron misidentification
    - compare photon identification efficiency
    - photon energy scale calibrated with momentum measurement on high-energy e from tau decay
    - compare fake photons

Main systematics of ALEPH tau BR paper, Phys. Rept. 421 (2005) 191

- π^0 efficiency
  - compare data and MC D_{ij} distributions (probability γ_i, γ_j) of π^0 mass fit
- efficiency for π^0 with unresolved photons
  - compare data and MC 2nd moment of transverse evergy in calorimeter cells
- radiative and bremsstrahlung photons
  - compare data and MC distributions
  - compare PHOTOS vs. exact calculation for $\tau \to \pi\pi^0\nu$ with radiative $E_\gamma > 12\,\text{MeV}$
- tracking
  - compare data and MC on same sign events events (two tracks missing in one hemisphere)
- tau decay dynamic
  - reduced because acceptances are large and flat
  - will become important with higher statistics
  - can be partially addressed with iterative concurrent measurements where also invariant mass distributions are fitted on data (complicate)

Tau Mass (from M.Dam, FCC-ee Workshop Jan 2019)

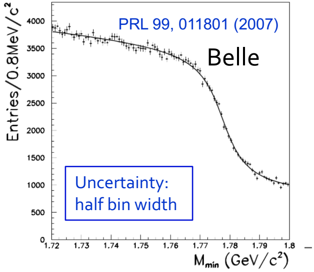
- **Current world average:** **m_τ = 1776.86 ± 0.12 MeV**
- Best in world: BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12\ (\text{stat.})\ ^{+0.10}_{-0.13}\ (\text{syst.})$ MeV
- Best at LEP: OPAL $m_\tau = 1775.1 \pm 1.6\ (\text{stat.}) \pm 1.0\ (\text{syst.})$ MeV
  - About factor 10 from world's best
  - Main result from endpoint of distribution of pseudo-mass in $\tau \rightarrow 3\pi^{\pm}(n\pi^0)\nu_\tau$
  - Dominant systematics:
    - Momentum scale: 0.9 MeV
    - Energy scale: 0.25 MeV (including also π^0 modes)
    - Dynamics of τ decay: 0.10 MeV



- Same method from Belle
  - Main systematics
    - Beam energy & tracking system calib.: 0.26 MeV
    - Parameterisation of the spectrum edge: 0.18 MeV

$m_\tau = 1776.61 \pm 0.13\ (\text{stat.}) \pm 0.35\ (\text{syst.})$ MeV

Pseudo-mass: $M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$



Mogens Dam / NBI Copenhagen 11th FCC-ee Workshop, CERN 10/01/2019

Tau Mass (from M.Dam, FCC-ee Workshop Jan 2019)

- Prospects for FCC-ee:
  - 3 prong, 5 prongs, (perhaps even 7 prongs?)
  - Statistics 10^5 times OPAL: δ_{stat} = **0.004 MeV**
  - Systematics:
    - At FCC-ee, E_{BEAM} known to better than 0.1 MeV (~ 1 ppm) from resonant depolarisation
      - Negligible effect on m_τ
    - Likely dominant experimental contribution comes from understanding of the mass scale
      - Use high stats $e^+e^- \rightarrow \mu^+\mu^-$ sample to fix momentum scale. Extrapolate down to momenta typical for $\tau \rightarrow 3\pi$.
      - Use $D^0 \rightarrow K^-\pi^+$ / $K^- \pi^+\pi^-\pi^-$ and $D^+ \rightarrow K^-\pi^+\pi^+$ to fix mass scale (m_D known to 50 keV)
    - Reduce uncertainty from parametrisation of spectrum edge by use of theoretical spectrum checked against high statistics data
    - Cross checks using 5-prongs
  - Suggested overall systematics: δ_{syst} = **0.1 MeV**
    - Could potentially touch current precision but probably no substantial improvement ?

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Tau Physics plans of relevant facilities (as of 2019)

Belle II

- The Belle II experiment at SuperKEKB: input to the European Particle Physics Strategy
- The Belle II Physics Book arXiv:1808.10567 [hep-ex]
- 50 ab^{-1}, improved detector w.r.t. Belle/BaBar, 50$\times$ Belle statistics, $9{\cdot}10^{10}$ tau decays
- B-factories scored well on LFV, less well on precision measurements and spectral functions
- $\mathcal{B}(\tau \to \mu\gamma) < \sim 1{\cdot}10^{-9}$ 90% CL detailed study with BelleII sample, may be optimistic
- $\mathcal{B}(\tau \to 3\mu) < 3.3{\cdot}10^{-10}$ 90% CL extrap. from Belle assuming selection remains bkg-free
- similar improvements on many other tau LFV modes
- $\Delta m_\tau = \pm 0.10 - 0.15$ MeV "very optimistically" (BESIII ± 0.17 MeV)
- my personal statistics-only-driven estimate $\Delta\tau_\tau = 0.026\%$ (Belle 0.21%)
- improvements w.r.t. today WA expected on $\mathcal{B}(\tau \to \ell\bar{\nu}\nu)$ and τ_τ but non-trivial & non-assured
- significant improvements on Cabibbo-suppressed BRs and spectral functions, but non-trivial
- significant advances possible on many more measurements:
  Michel parameters, spectral functions, *CPV*, radiative decays, $g-2$, EDM...
- Belle III: luminosity upgrade of Belle II would advance the reach of the LFV searches

Tau Physics plans of relevant facilities (as of 2019)

Super Charm-Tau Factories: SCT (BINP, Novosibirsk) and STCF/HIEPA (China)

- SCT/Russia inputs to the European Particle Physics Strategy
- STCF/China Haiping Peng, priv.comm., $\tau \to \mu\gamma$ study arXiv:1511.07228 [hep-ex]
- very similar projects, common description
- $E = 2\text{–}6$ or $2\text{–}7$ GeV, $\mathcal{L} = 10^{35}\,\text{cm}^{-2}\text{s}^{-1}$, polarized e^- beam
- begin datataking 2029-2030
- max $\tau^+\tau^-$ cross-section at 4.25 GeV (3.5 nb), unknown how many years at that CM energy
  - I rescaled estimates to 2 years at 4.25 GeV (each year $2{\cdot}10^7$ s and $7{\cdot}10^9$ tau pairs)
- Δm_τ from ± 0.166 MeV (BESIII) to ± 0.012 MeV [10× better systematic uncertainty]
- $\mathcal{B}(\tau \to \mu\gamma) < 5{\cdot}10^{-9}$ 90% CL
  - extrapolated from 3 fb^{-1}assuming search bkg free (my understanding)
  - note that background is significantly less than at B-factories energies
- $\mathcal{B}(\tau \to 3\mu) < 3.5{\cdot}10^{-10}$ 90% CL sensitive also to all other $\mathcal{B}(\tau \to \ell_1\ell_2\ell_3)$
- many LFV modes and other tau measurements possible, but little guiding past experience
  - both projects actively investigating/planning many tau Physics measurements

Tau Physics plans of relevant facilities (as of 2019)

CEPC at the Z peak

- inputs to the European Particle Physics Strategy
- The CEPC Conceptual Design Report, Vol II: Physics and Detector, arXiv:1811.10545 [hep-ex]
- could be approved in 2022!
- $1{\cdot}10^{12}$ Z, $3{\cdot}10^{10}$ tau pairs (comparable to $4.5{\cdot}10^{10}$ of BelleII)
- expect tau LFV sensitivities similar to BelleII
  - but historic LEP LFV limits are much better than B-factories, for the same number of tau
- stat. uncertainties $\mathcal{O}(450)\times$ better than LEP $\Rightarrow$ must estimate reasonable limiting systematics
- expect $\Delta\mathcal{B}(\tau \to \ell\bar{\nu}\nu) \sim 0.02\%$ (by improving $10\times$ ALEPH systematics 0.2%)
- expect $\Delta\tau_\tau \sim 0.02\%$ (by improving $10\times$ w.r.t. Belle total uncertainty of 0.2%)
- significant advances possible on about all measurements and LFV limits
- Z peak offers by far best conditions for about all tau Physics measurements

Tau Physics plans of relevant facilities (as of 2019)

FCC-ee at the Z peak

- inputs to the European Particle Physics Strategy
- Future Circular Collider, Vol. 1 : Physics opportunities (December 2018)
- Dam 2019 (Tau 2018 proc.)
- 8y preparation, 10y construction, 15y operation
- Z peak phase delivers $5{\cdot}10^{12}$ Zs, $15{\cdot}10^{10}$ tau pairs (BelleII $4.5{\cdot}10^{10}$)
- stat. uncertainties $\mathcal{O}(1000)\times$ better than LEP $\Rightarrow$ must estimate reasonable limiting systematics
- expect $\Delta\mathcal{B}(\tau \to \ell\bar{\nu}\nu) \sim 0.02\%$ (by improving $10\times$ ALEPH systematics 0.2%)
- expect $\Delta\tau_\tau \sim 0.01\%$ (by improving $9\times$ w.r.t. Belle detector alignment systematics of 0.1%)
- expect $\Delta m_\tau \sim 0.07\,\text{MeV}$ (by calibrating on m_{D^+}, PDG 2018 WA $\pm 0.12\,\text{MeV}$)
- $\mathcal{B}(\tau \to \mu\gamma) < 2{\cdot}10^{-9}$ 90% CL Monte Carlo study on 2% of full FCC-ee statistics
- $\mathcal{B}(\tau \to 3\mu) < [1{-}0.1]{\cdot}10^{-10}$ 90% CL guestimate
- significant advances possible on about all measurements and LFV limits
- Z peak offers by far best conditions for about all tau Physics measurements