Tau Physics prospects update

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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

- studying & understanding FCC sensitivities on tau physics measurements & searches for
  - FCC motivation
  - FCC detectors requirements & optimization

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

facility	Z [million]	$\tau^+\tau^-$ [million]	r$\tau^+\tau^-$ elative sample size	
LEP	25	0.84		
Belle II	-	$45{\cdot}10^3$		
STCF at 4.26 GeV, 10 years	-	$35{\cdot}10^3$		
CEPC	$4{\cdot}10^6$	$135{\cdot}10^3$	$1.6{\cdot}10^5\times$LEP	$3.0\times$Belle II
FCC-ee	$6{\cdot}10^6$	$200{\cdot}10^3$	$2.4{\cdot}10^5\times$LEP	$4.5\times$Belle II

experimental conditions of tau pairs much better at Z peak compared to lower energies

- better momentum resolution and vertexing because less multiple scattering with higher track momenta
- better higher momentum muon id (much lower pion-to-muon misidentification)
- much better $\tau^+\tau^-$ separation from $q\bar{q}$ background because of higher $q\bar{q}$ multiplicity at Z peak
- LHC produces more tau leptons, but with much less favourable experimental conditions

Lepton universality with tau decays

lepton universality from experiment [A.Pich, 2013]

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$	
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)	
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$			
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)			

- most precise lepton universality tests come from tau decays' measurements
  - (some competition from $\mathcal{B}(\pi \to \mu\nu)/\mathcal{B}(\pi \to e\nu)$)
- B-factories did not significantly improve LEP measurements
- dedicated effort in Belle II, first result on tau mass and $\mathcal{B}(\tau \to \mu\bar{\nu}\nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$
- FCC-ee luminosity & conditions ideal for high precision tau measurements for lepton universality tests

Lepton universality tests

today status [HFLAV 2023 report, preliminary]

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\tau_\tau m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^{\tau e}}} = 1.0016 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\tau e}^{\text{SM}}}}$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\tau_\tau m_\tau^5 f_{\tau \mu} R_\gamma^\tau R_W^{\tau \mu}}} = 1.0018 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau \mu}^{\text{SM}}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau e}} \frac{f_{\tau e}}{f_{\tau \mu}}} = 1.0002 \pm 0.0011$$

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

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

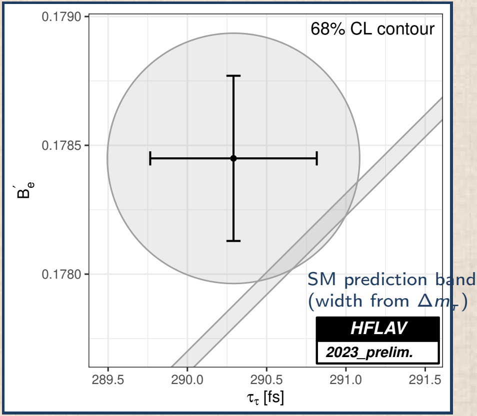
$$G_\lambda = \frac{g_\lambda^2}{4\sqrt{2}M_W^2}\ ; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x\ ; \qquad f_{\lambda\rho} = f\left(m_\rho^2/m_\lambda^2\right)$$

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

all statistical correlations included

- less precise tests possible with hadronic tau decays

Canonical tau lepton universality test plot



[HFLAV 2023 prelim.]

$(g_\tau/g_{e\mu}) = 1.0017 \pm 0.0013$

$[g_{e\mu} = g_e = g_\mu$ assuming $g_e = g_\mu]$

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

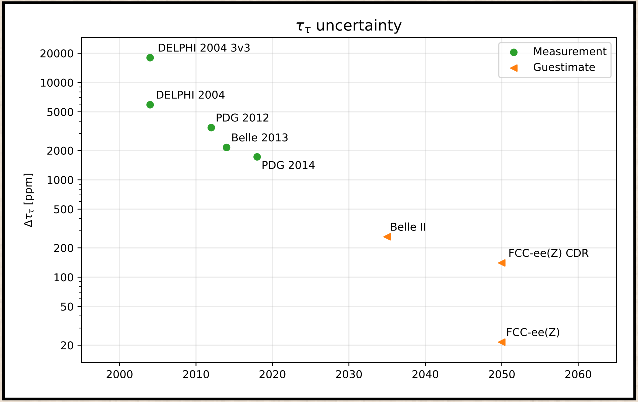
input	Δinput	$\Delta(g_\tau/g_{e\mu})$
$\mathcal{B}'_{\tau\to e}$	0.180%	0.180%
τ_τ	0.181%	0.181%
m_τ	0.005%	0.005%
total		0.128%

best measurements

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

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

Tau Lifetime uncertainty



FCC total uncertainty estimates

- FCC-ee(Z) CDR M. Dam, 1999
- FCC-ee(Z) A.Lusiani, Tau Physics Prospects at FCC-ee, doi:10.17181/57pxj-6xd43

Other estimates

- Belle II Physics Book

τ_τ statistical precision [ppm]	
4800	DELPHI 2004, 144 pb^{-1}
18000	DELPHI 2004, 3-prong vs. 3-prong (3v3), 144 pb^{-1}
15	FCC-ee(Z) $6{\cdot}10^{12}$ Z, 200 ab^{-1}, from DELPHI 2004 3v3

(*) FCC-ee vertex resolution and beam spot $\ll c\tau_\tau$ while they were comparable at DELPHI

Tau Lifetime uncertainty notes

- consider just tau pairs in 3-prong vs. 3-prong topology (3v3)
  - Belle 2013 best measurement uses these events
  - τ direction reconstruction using vertices reduces dependence from simulation
- extrapolate FCC-ee statistical precision starting from Delphi 2004 3v3 events statistical precision
  - expect no significant differences on selection efficiency
  - Delphi 2004 3v3 precision by rescaling 3v1+3v3 measurement to number of 3v3 candidates
  - τ_τ measurement is a measurement of transverse i.p. $\langle d_0 \sin\theta \rangle \approx 70\,\mu\text{m}$
  - Delphi 2004 3v3 precision consistent with a d_0 resolution $\approx 70\,\mu\text{m}$ (tracking, beam spot)
  - assume FCC-ee has both transverse beam spot and can have d_0 resolution $\ll 70\mu\text{m}$
    $\Rightarrow$ resolution improvement factor $\sim 70\,\mu\text{m}/(70\,\mu\text{m} \oplus 70\,\mu\text{m}) \simeq 0.7$
- assume DELPHI systematics for background, reconstruction bias and alignment (total 1.3 fs) scale with luminosity to 3.9 ppm at FCC-ee (very optimistic)
- assume $30\times$ better KKMC simulation can reduce uncertainty on ISR+FSR energy loss in tau pair production to reduce the associated systematic contribution from 350 ppm to 11.5 ppm
- assume 10 ppm tau mass measurement at SCT/STCF or at FCC-ee
- assume 5 ppm vertex detector length scale (possible with optical methods proposed for MuonE)

Tau Lifetime at FCC-ee(Z) uncertainty budget

τ_τ precision [ppm]	
15.0	statistical
5.0	length scale of vertex detector
10.0	$\sigma(m_\tau)$
1.0	center-of-mass energy
11.5	average tau pair production radiative energy loss
3.9	systematics optimistically expected to scale with statistics - detector alignment - background - fit model
22.3	total

detector requirements to limit effects below 1/2 of statistical uncertainty

- impact parameter resolution for tau decay tracks $\leq 70/2 \cdot \sqrt{3} = 61\,\mu\text{m}$
  - taking into account that each single event measurement uses three tracks
- uncertainty on average length scale of vertex detector elements $\leq 7.5\,\text{ppm}$ (15 ppm / 2)

other detector requirements

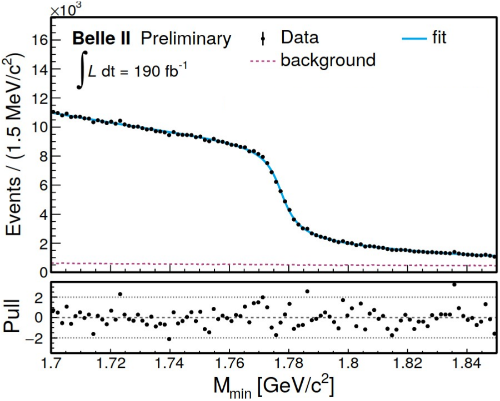
- $30\times$ precision improvement for simulation of radiation in tau pair production
  - not detector but worth noting

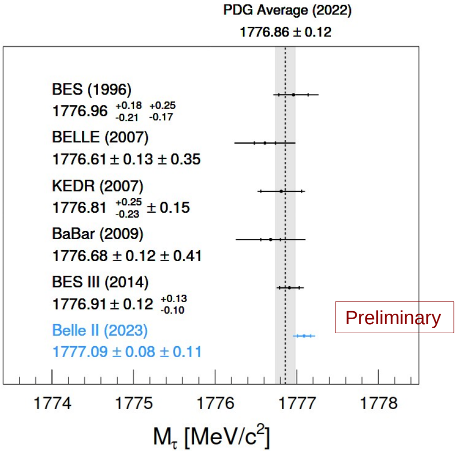
Tau mass Belle II preliminary measurement [Moriond 2023]

NEW for Moriond!

World's most precise measurement

- World's most precise measurement of $\mathbf{m_\tau = 1777.09 \pm 0.08_{stat} \pm 0.11_{sys}}$ **MeV/c^2**





Proof of high precision capability of Belle II!

arXiv:2305.19116 [hep-ex], May 30, 2023

L.Zani - Dark sectors and tau phsyics at Belle II - Moriond 2023 13

Tau mass Belle II preliminary measurement [Moriond 2023], systematics

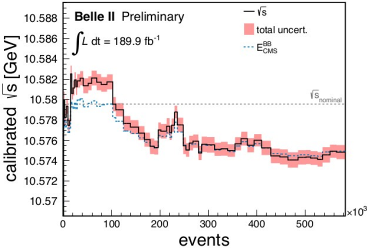
NEW for Moriond!

τ mass: precision challenge

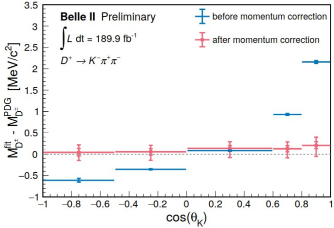
- Excellent control of systematic uncertainties thanks to precise understanding of beam energies and tracking: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E^*_{3\pi})(E^*_{3\pi} - P^*_{3\pi})} \le M_\tau$

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	≤ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	≤ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	≤ 0.01
Neutral particle reconstruction efficiency	≤ 0.01
Tracking efficiency correction	≤ 0.01
Trigger efficiency	≤ 0.01
Background processes	≤ 0.01
Total	0.11

Beam energy calibration with B-meson hadronic decays method and Υ(4S) lineshape measurement to get $\sqrt{s}$



Momentum scale factor cures the bias due to imperfect B-field: extract corrections dependent on $\cos\theta_{track}$ by comparing $D^0 \to K\pi$ mass peak w.r.t PDG mass.



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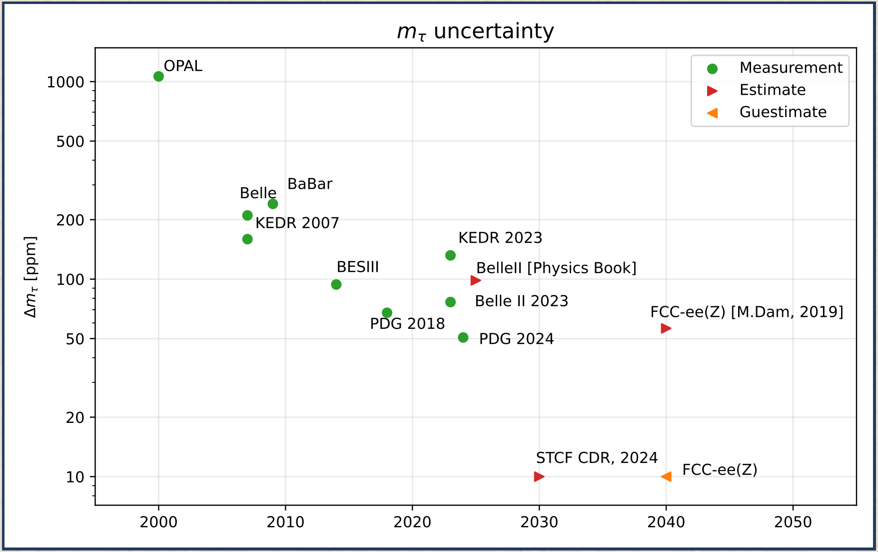
Tau mass prospects at FCC-ee

- $\Delta\tau_\tau^{\text{stat}} = 45\,\text{ppm}$ at Belle II with $190\,\text{fb}^{-1}$, 175 M tau pairs
- $\Delta\tau_\tau^{\text{stat}} = 1.3\,\text{ppm}$ at FCC-ee with $6{\cdot}10^{12}$ Z, $2.0{\cdot}10^{11}$ tau pairs
  - neglecting surely better FCC-ee efficiency
- $\Delta\tau_\tau^{\text{stat}} = 0.9\,\text{ppm}$ at FCC-ee when rescaling OPAL 2000 tau mass uncertainty
- Belle II dominant systematics expected to be significantly reduced at FCC-ee
  - beam energy (1 ppm at FCC-ee)
  - track momentum scale (2 ppm calibration maybe possible at FCC-ee with $m_{J/\psi}$)
- alignment systematics can be expected to scale with statistics
- Belle II limiting systematics 29 ppm
  - estimator bias (0.03 MeV/c2)
  - pseudo-mass fit function (0.02,MeV/c2)
  - detector material (0.03 MeV/c2)
  - modeling of ISR, FSR and tau decay (0.02 MeV/c2)
- may expect to reduce non-luminosity-scaling systematics by factor 3 at FCC-ee, to 10 ppm
- guestimate FCC-ee tau mass precision at 10 ppm
- no particular detector requirements are needed, a baseline realistic detector is sufficient

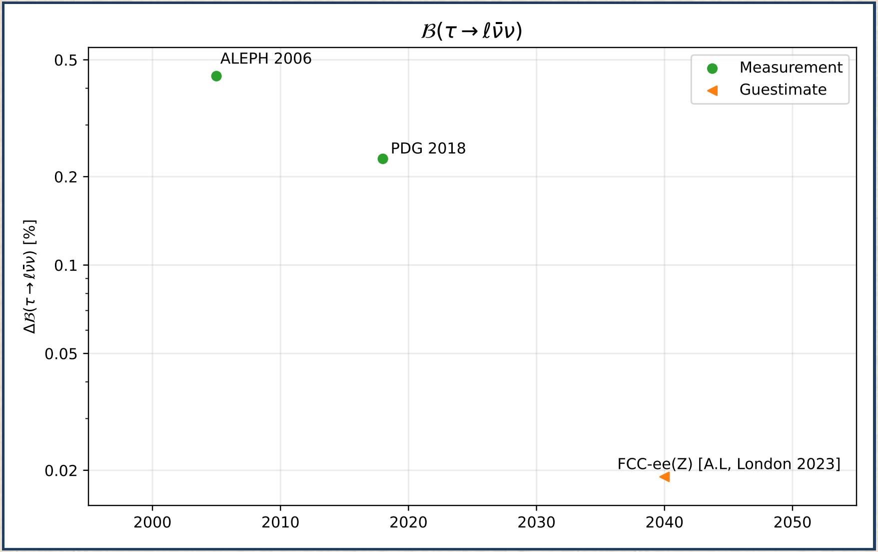
Tau mass prospects at FCC-ee and other facilities



Tau leptonic branching fractions prospects at FCC-ee

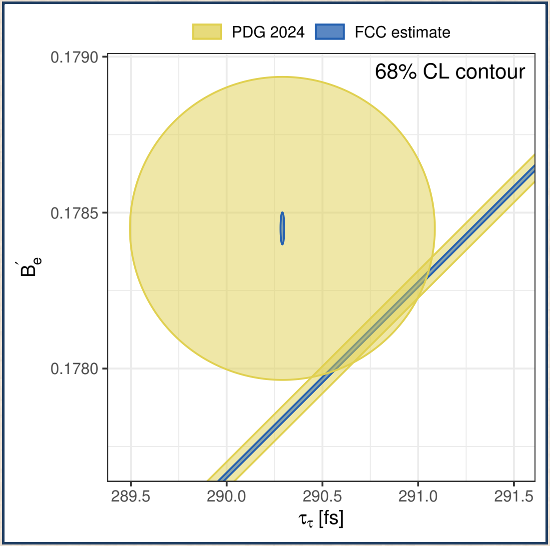
- ALEPH 2006 measurement precision: $4400\,\text{ppm} = [4000(\text{stat.}) \oplus 1900(\text{syst.})]\,\text{ppm}$ (average of the two similar electron and muon decays branching fractions)
  - complex simultaneous measurement of 12 tau branching fractions
  - many systematic uncertainties, no reliable extrapolations to FCC-ee statistics
  - several systematics related to photon and $\pi^0 \to \gamma\gamma$ reconstruction
- FCC-ee extrapolated statistical precision: $4000\,\text{ppm} \cdot \sqrt{6.2 \cdot 10^6\,(\text{ALEPH Z bosons})/8 \cdot 10^{12}} = 4.5\,\text{ppm}$
- today guestimate: FCC-ee precision may be limited to about 1/10 of ALEPH systematics, 190 ppm

Tau leptonic Branching fractions prospects at FCC-ee and other facilities

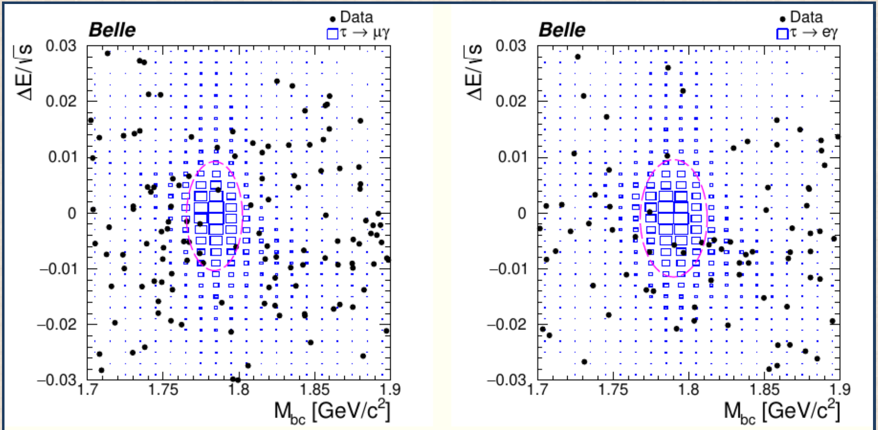


- Belle II is working on these measurements

Canonical tau lepton universality plot extrapolation to FCC-ee



Typical tau LFV search



(a) $\tau^{\pm} \to \mu^{\pm}\gamma$. (b) $\tau^{\pm} \to e^{\pm}\gamma$.

- search for reconstructed tau leptons matching
  - invariant mass of tau decay products = the tau mass
  - sum of energy of tau decay products in CM frame = $\sqrt{s}/2$
- count events in excess of expected background

LFV $\tau \to \mu\gamma$

FCC expected reach

- M. Dam, Tau-lepton Physics at the FCC-ee circular e+ e- Collider, SciPost Phys. Proc. 1 (2019) 041. arXiv:1811.09408
- assuming FCC-ee(Z) with $1.3{\cdot}10^{11}$ tau pairs
- assuming 25% efficiency
- MC truth with smearing to simulate reconstruction
- simulated sample of 2% of total assumed FCC statistics
- signal region with $E_{\mu\gamma}^{\text{CM}} = \sqrt{s}/2$, $m_{\mu\gamma} = m_\tau$
- sensitivity reported as 2σ background fluctuation (20K events extrapolated in signal region)

90% CL upper limit at FCC-ee with $6{\cdot}10^{12}$ Z

- converted 2σ background fluctuation to expected 90% CL upper limit
- rescale to $6{\cdot}10^{12}$ Z (search is background-dominated and improves with $\sqrt{\mathcal{L}}$)
- $\mathcal{B}(\tau \to \mu\gamma) < 1.2{\cdot}10^{-9}$ at 90% CL

LFV $\tau \to \mu\gamma$

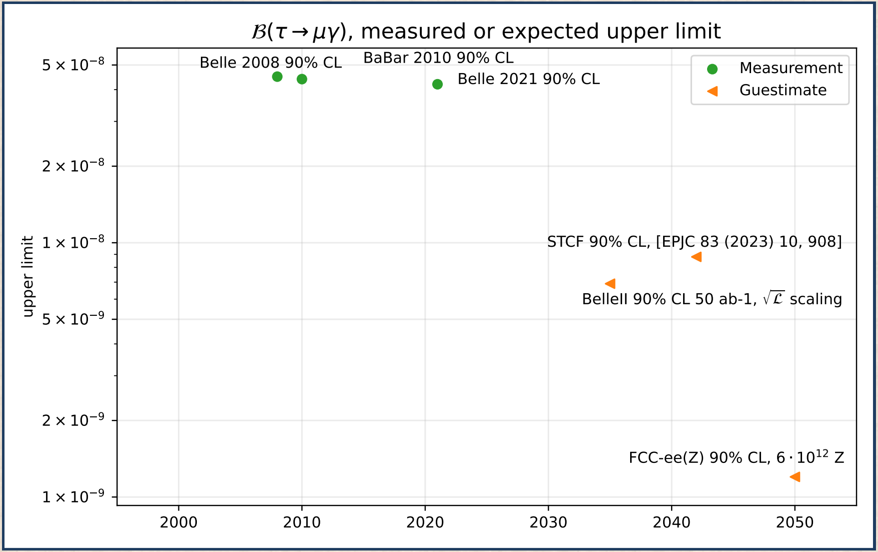
Belle II expected reach

- Belle II Physics Books
  - based on BaBar and Belle published upper limits
  - assumes all tau LFV searches background-free (inappropriate for $\tau \to \mu\gamma$)
- Belle, 2021 upper limit $\mathcal{B}(\tau \to \mu\gamma) < 4.9 \cdot 10^{-8}$ 90% CL, integrated luminosity 988 fb^{-1}
- personal Belle II 50 ab^{-1} limit estimate starting from Belle 2021 search
  - $\mathcal{B}(\tau \to \mu\gamma) < 0.97 \cdot 10^{-9}$ 90% CL "aggressive", assuming linear integrated luminosity ($\mathcal{L}$) scaling
  - $\mathcal{B}(\tau \to \mu\gamma) < 6.9 \cdot 10^{-9}$ 90% CL "conservative", assuming $\sqrt{\mathcal{L}}$ scaling (background-limited search)

STCF expected reach

- $\mathcal{B}(\tau \to \mu\gamma) < 8.8 \cdot 10^{-9}$ at 90% CL [Eur.Phys.J.C 83 (2023) 10, 908]
  - STCF CDR quotes better limit citing a preliminary arXiv preprint of above published paper

LFV $\tau \to \mu\gamma$



LFV $\tau \to 3\mu$

FCC expected reach

- start from $\mathcal{B}(\tau \to 3\mu) < 1.9{\cdot}10^{-8}$ 90% CL [Belle II 2024], sample size $390{\cdot}10^{6}$ tau pairs
  - 20.4% efficiency, much larger than 7.6% of previous Belle search
  - efficiency now comparable to 24.5% of DELPHI 1995 LEP search
- extrapolate to $2{\cdot}10^{11}$ tau pairs for FCC-ee
  - assume FCC-ee can reach 35% efficiency
  - assume no-background-limited search (linear luminosity scaling) thanks to
    - expected excellent muon identification
    - good momentum and vertexing resolution
- $\mathcal{B}(\tau \to 3\mu) < 2.0{\cdot}10^{-11}$ 90% CL
  - MC simulations on severals details would be welcome

LFV $\tau \to 3\mu$

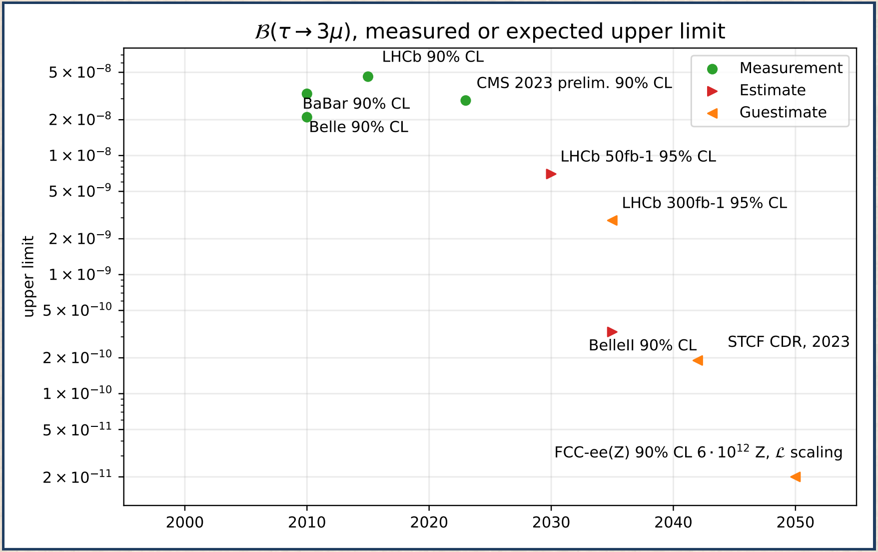
Belle II expected reach

- $\mathcal{B}(\tau \to 3\mu) < 3.0{\cdot}10^{-10}$ 90% CL [Belle II Physics Book]
  - (optimistic) linear $\mathcal{L}$ scaling from Belle 90% limit, $2.1{\cdot}10^{-8}$, with 782 fb^{-1} integrated luminosity

STCF expected reach

- $\mathcal{B}(\tau \to 3\mu) < 1.9{\cdot}10^{-10}$ 90% CL [STCF CDR, 2023]

LFV $\tau \to 3\mu$



Summary

- estimated FCC expected precision on tau properties measurements
  - tau mass
  - tau lifetime
  - tau leptonic branching fractions
- estimated FCC precision on lepton universality test
- estimated FCC reach for LFV searches
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$
- several updates w.r.t. past presentations
- documentation in A.L., Tau Physics Prospects at FCC-ee, doi:10.17181/57pxj-6xd43
  - short version recently submitted to ECFA as three analysis summaries

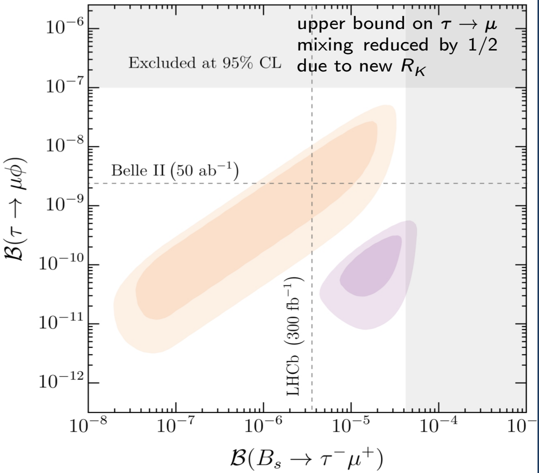
– end –

Backup Slides

Impact of tau LFV decay limits from future Tera-Z colliders

- constraints on UV-complete vector lepto-quark model for B anomalies [Cornella *et al.*, 2021]

today and future Belle II, LHCb 300 fb^{-1} bounds



[from G.Isidori, Jul 2023]

Impact of tau LFV decay limits from future Tera-Z colliders

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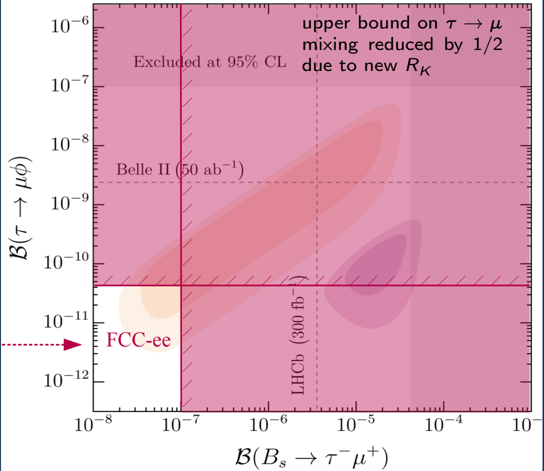
future FCC-ee bounds, G.Isidori naive estimate



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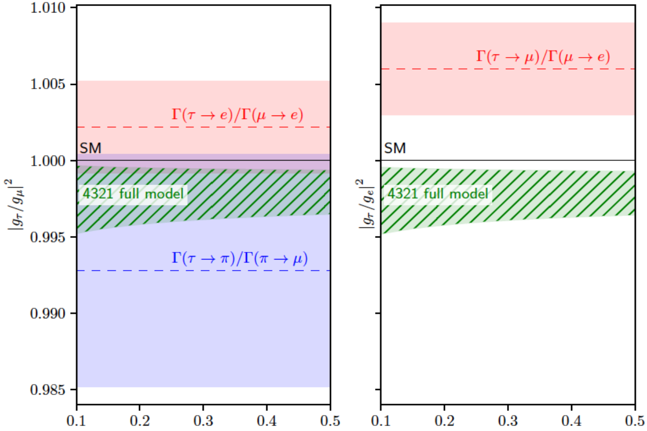
Impact of tau lepton universality measurements from future Tera-Z colliders

- constraints on 4321 vector lepto-quark model for B anomalies
  [Allwicher, Isidori, Selimovic, 2021], [Allwicher, Isidori, Lizana, Selimovic, Stefanek, 2023]

today g_tau/g_μ, g_e/g_μ bounds



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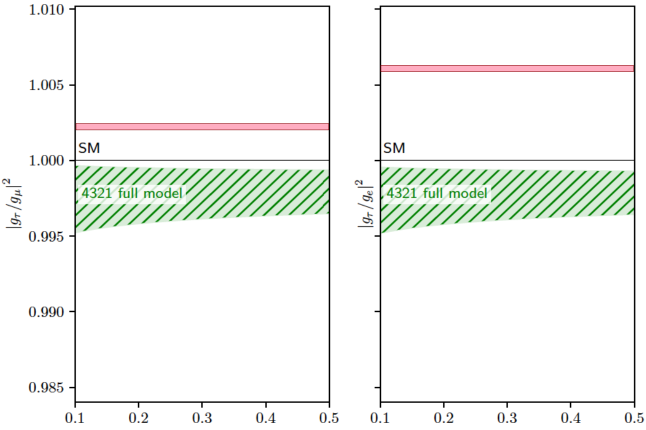
future FCC-ee g_τ/g_μ, g_e/g_μ, model escluded



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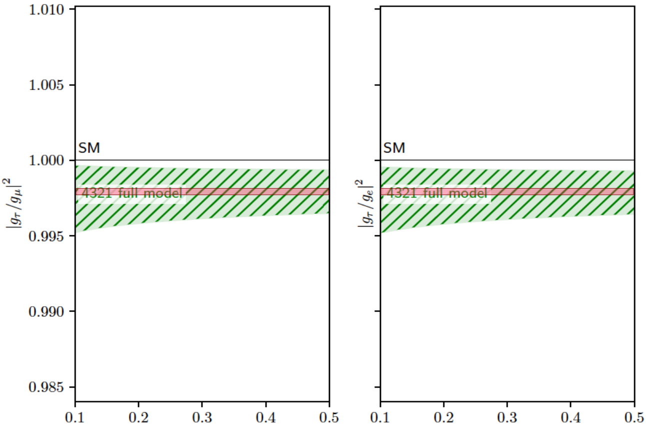
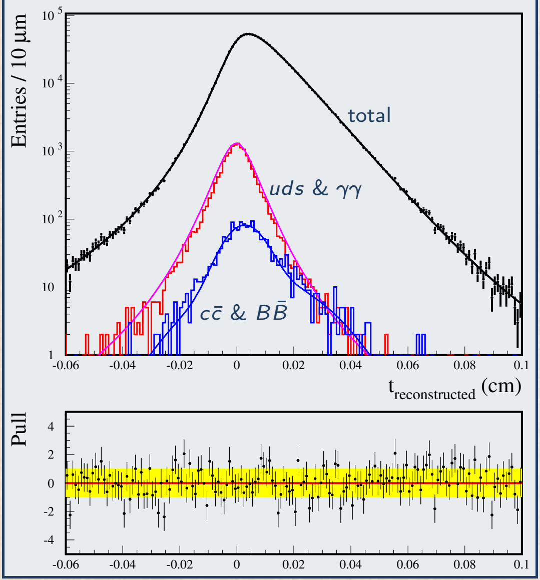
future FCC-ee g_τ/g_μ, g_e/g_μ, model confirmed



[from G.Isidori, Jul 2023]

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

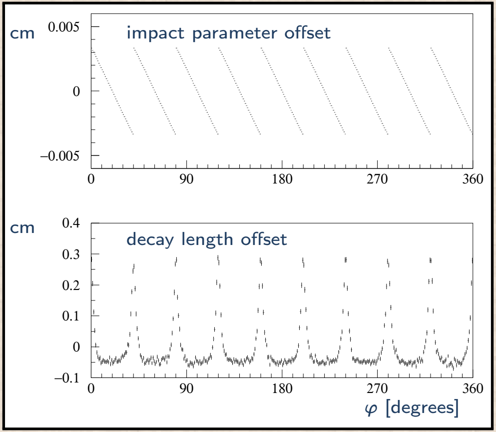
S.R.Wasserbaech, Nucl.Phys.Proc.Suppl. 76 (1999) 107-116

- 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

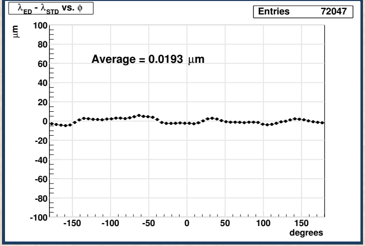
- basic simulation of ALEPH vertex detector with all wafers radially shifted out by 100 μm
- impact parameter offset $= 100\,\mu\text{m} \cdot \sin\alpha$
  - $\alpha =$ track angle w.r.t. normal of wafer
- decay length offset (measured using 3-tracks vertex)
  - negative when 3 tracks hit same wafer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



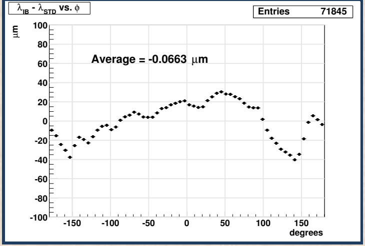
- decay length offset $\sim$ derivative of impact parameter offset
  - can be understood with 1-st order model of most simple misalignments
  - confirmed empirically quite precisely in accurate simulations of real detectors
- averaging decay length over full range of azymuth angle is like integrating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

BaBar studies, tau lifetime with SVT misalignment files

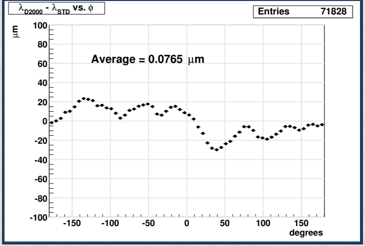
EllipsData SVT misalignment



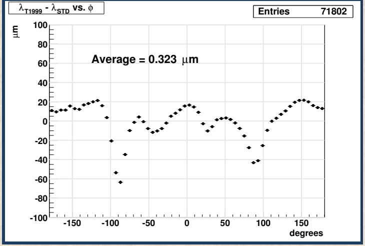
InnerBias SVT misalignment



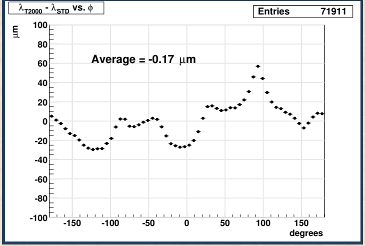
Diff2000 SVT misalignment



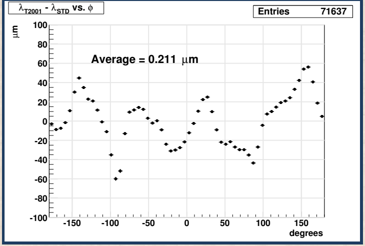
Time1999 SVT misalignment



Time2000 SVT misalignment

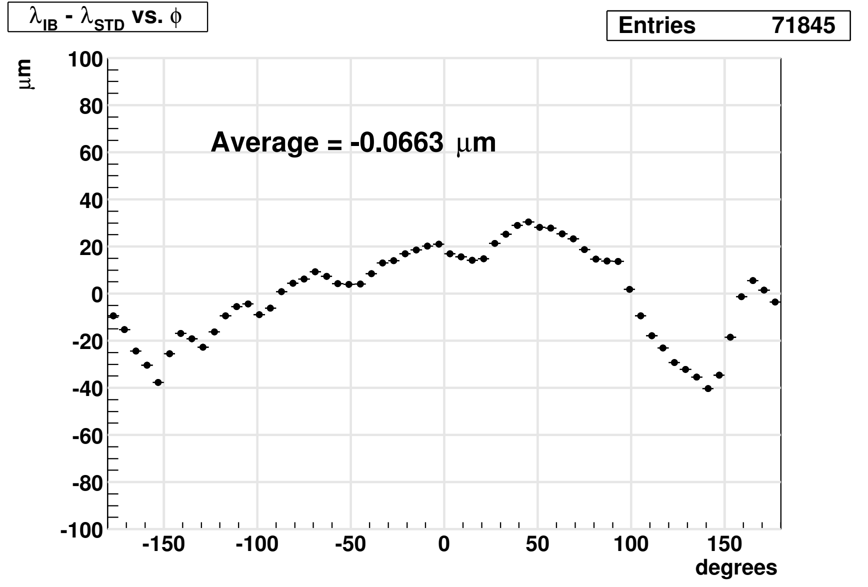


Time2001 SVT misalignment



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

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- 2 ppm tau lifetime sistematics from vertex detector length scale appears attainable

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			180
tau pairs	$1\cdot10^7$	$0.84\cdot10^6$	$1.4\cdot10^9$	$46\cdot10^9$	$30\cdot10^9$		$135\cdot10^9$	$200\cdot10^9$

- as of August 2023
- SCT & SCFT tau pairs estimate assuming 10 years of tau-pairs-optimized CM energies running

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

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- 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 $> 3\,\mathrm{GeV}$ 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 dynamics
  - reduced because acceptances are large and flat
  - will become important with higher statistics
  - theory models of tau decay hadrons kinematic distributions approximate or unavailable
  - unknonw invariant mass distributions can be fit on high-statistics data (complex)