Tau Lepton Physics at FCC-ee

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Introduction (1)

Tau Physics topics

- tau properties (mass, lifetime, $g-2$, EDM, CPV ...)
- tau decays measurements and searches for
  - EW precision measurements
  - $|V_{us}|$ determination, low energy QCD
  - LFV
- treated the ones I consider most interesting
- consider only Fcc-ee at Z peak, which is the most interesting context

I prefer to consider the following as not specifically tau topics

- processes where the tau is a decay product
  - $e^+e^- \to Z \to \tau^+\tau^-$ process (EW)
  - $H, Z \to \tau^+\tau^-$ decays (EW)
  - $H, Z \to \mu^+\tau^-$ (LFV in EW heavy boson decays)
  - $W^- \to \tau^-\bar{\nu}_\tau$ (EW)
  - $B \to D^{(*)}\tau\nu$ (B Physics anomalies)
  - heavy flavour hadrons decays with LFV and that involve also tau leptons

Introduction (2)

Past work

- Mogens Dam presented on Tau Physics at Tau 2018 and at Fcc-ee Workshop of Jan 2019
- Tau Physics is also covered on the Fcc CDR
- sensitivity estimates in above documents are fair

Here

- some personal sensitivity estimations
  - using my experience in ALEPH, *BABAR*, SuperB, HFLAV
  - preferentially estrapolating from LEP rather than B-factories
  - some more detail on non-luminosity-scaling systematic contributions
- comparison with other future facilities sensitivity estimates
  - recycled but updated from my Granada 2019 ESG presentation

Hot / interesting Physics topics involving tau measurements

Lepton Flavour Violation

- natural extension of Standard Model, often present in New Physics models
- clean and unambiguous signal of New Physics
- large improvements coming on muon LFV (DeeMe, Mu2e, COMET, Project X/Mu2e, PRISM/PRIME)
- muon LFV present and future limits typically more constraining that tau LFV ones
- tau LFV limits are however prevailing for some specific models
- tau LFV measurements decisive to investigate LFV possibly discovered on muons

Heavy Flavour anomalies $R_{D^{(*)}}$ and $R_{K^{(*)}}$

- lepton universality tests based on tau measurements impose significant constraints

Non-standard neutrino interactions (NSI)

- tau lepton universality tests and tau lifetime can constrain model parameters that determine $\epsilon_{\tau\tau}$

Anomalies in low-energy high precision Standard Model studies

unitarity discrepancy on the first row of the CKM matrix (recent issue)

- inclusive $\tau \to X_s \nu_\tau$ methods to measure $|V_{us}|$ (independent of Lattice QCD)
- depends on Cabibbo-suppressed tau branching fractions and spectral functions

α_s from tau measurements

- spread of different determinations exceeds individual uncertainties
- different opinions on importance and treatment of duality violations
- tau spectral functions required to improve understanding and precision

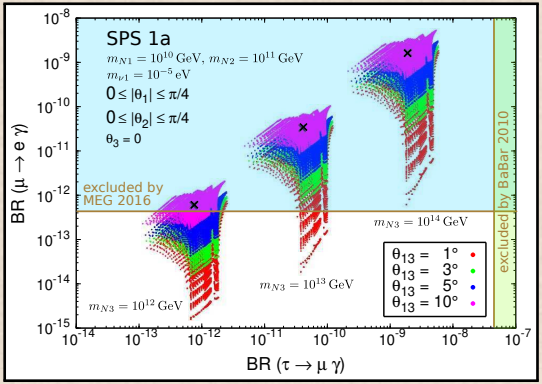
$>3\,\sigma$ discrepancy on muon gyromagnetic anomaly a_μ

- tau spectral functions might complement e^+e^- data to compute HVP contribution

Tau Lepton Flavour Violation

Tau LFV searches probe & constrain New Physics models

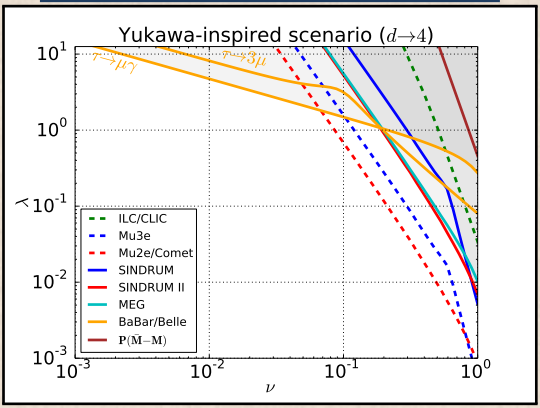
MSSM Seesaw
Antusch, Arganda, Herrero, Teixeira 2006



typical NP models

- $\mathcal{B}(\tau \to \mu\gamma) \sim 10{-}1000 \times \mathcal{B}(\mu \to e\gamma)$
- muon LFV searches more effective

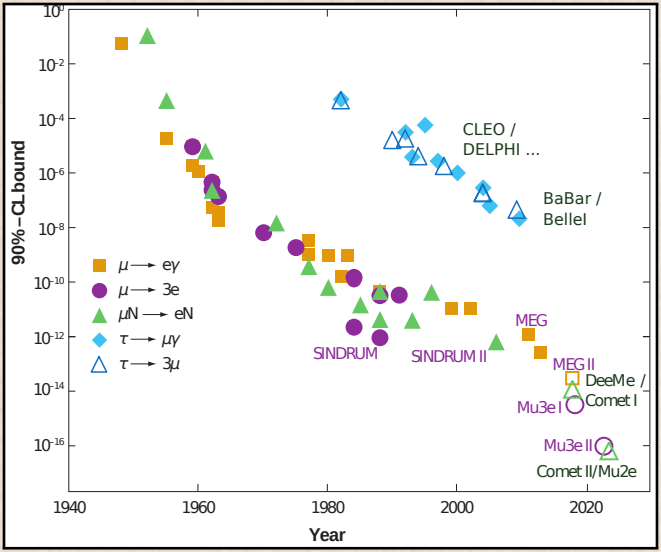
doubly charged scalar
Crivellin, Ghezzi, Panizzi, Pruna, Signer 2019



specific models / parameter space regions

- part of plot only constrained by tau LFV limits

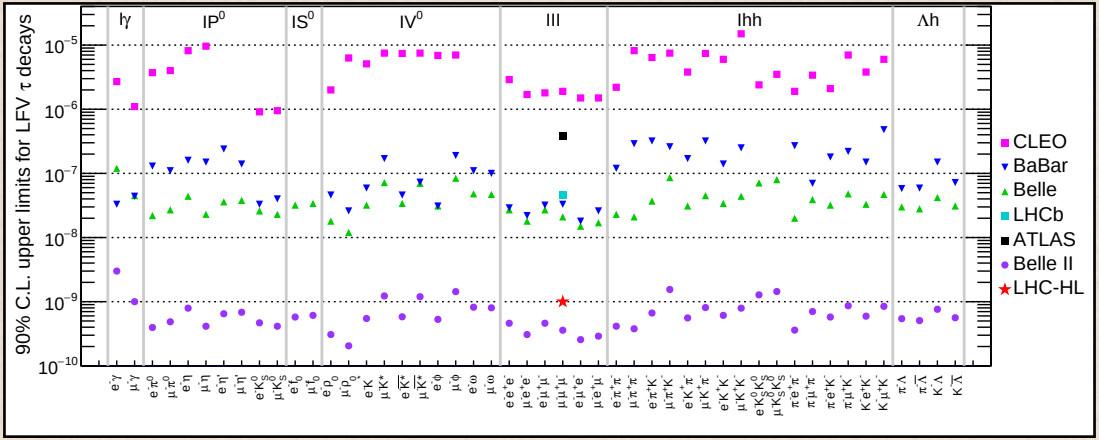
Present Tau LFV limits, present and future Muon LFV limits



[Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)]

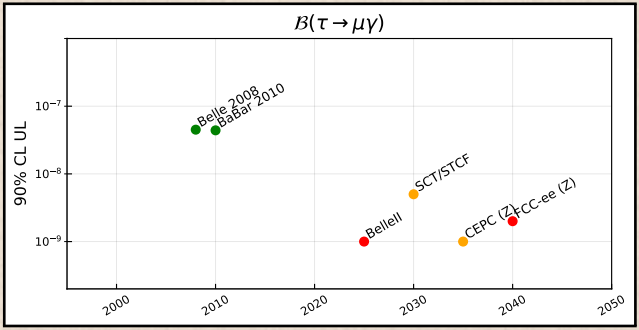
incoming years will provide remarkable progress on Muon LFV searches

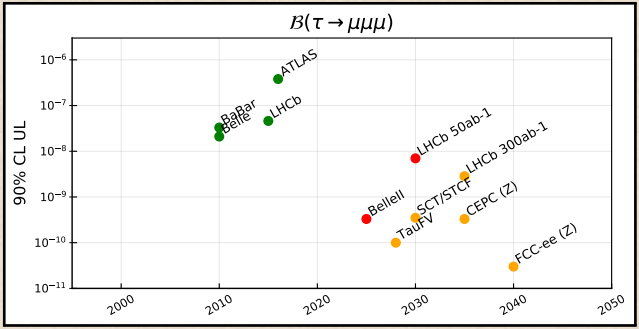
Tau LFV limits: present and future with Belle II and LHCb-HL



HL-LHC and HE-LHC opportunities, arXiv:1812.07638 [hep-ph]

Fcc-ee Tau LFV sensitivity for $\tau \to \mu\gamma$, $\tau \to 3\mu$ (Granada 2019 ESG)





as reported at Granada 2019 ESG

Fcc-ee estimate for $\tau \to \mu\gamma$

M. Dam simulation with 2% of full Fcc-ee statistics

Fcc-ee estimate for $\tau \to \mu\mu\mu$

my guestimate estrapolating *BaBar* limit assuming background free (optimistic)

- Red more solid estimates
- Orange less solid estimates
- dates of future results are arbitrary, for plotting convenience

Revised guestimate for Fcc-ee limit on $\tau \to \mu\mu\mu$

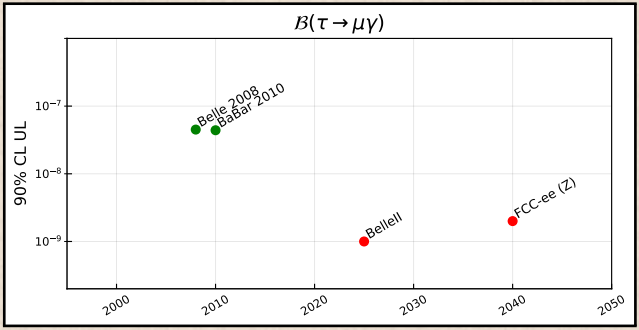
BelleII sensitivity (Physics Book)

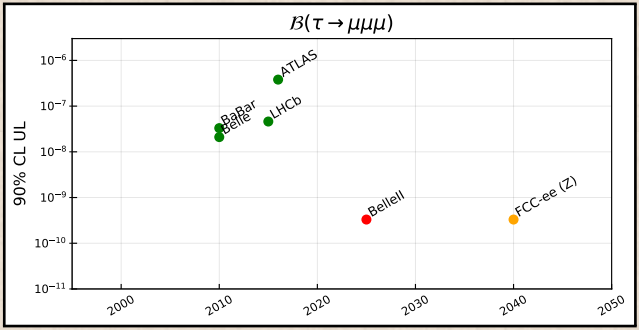
- estrapolated from Belle limit at $0.782\,\mathrm{ab}^{-1}$to $50\,\mathrm{ab}^{-1}$
- assumption background-free efficient selection with $\sim$60$\times$ luminosity ($\sim$fair)

Fcc-ee sensitivity, my guestimate

- tau pairs at Fcc-ee: 5e12 Z $\times$3.3% = 1.65e11, 3.5$\times$ than BelleII
- assume selection efficiency 4$\times$ better from comparison of DELPHI and *BABAR* $\tau \to \mu\gamma$ searches
  - DELPHI Phys.Lett. B359 (1995) 411-421, *BABAR* Phys.Rev.Lett. 104 (2010) 021802
- m_τ resolution comparable with B-factories
- E resolution worse (850 MeV if M. Dam $\tau \to \mu\gamma$ study vs. 50-100 MeV in *BABAR*
- assumption background-free efficient more stressed than at BelleII
- revise my Granada Fcc-ee guestimate to same as BelleII, to account for worse E resolution
- some simulation could produce a better assessment

Fcc-ee Tau LFV sensitivity for $\tau \to \mu\gamma$, $\tau \to 3\mu$





Fcc-ee estimate for $\tau \to \mu\gamma$

Fcc CDR, M. Dam simulation with 2% of full Fcc-ee statistics

Fcc-ee estimate for $\tau \to \mu\mu\mu$

my guestimate extrapolating from Belle and BelleII

Lepton Universality Tests

Lepton universality tests

HFLAV Tau 2018 report

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}}\frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^\mu}{\tau_\tau m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^\tau}} = 1.0010 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\tau e}^{\rm SM}}}$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}}\frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^\mu}{\tau_\tau m_\tau^5 f_{\tau \mu} R_\gamma^\tau R_W^\tau}} = 1.0029 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau \mu}^{\rm SM}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau e}}\frac{f_{\tau e}}{f_{\tau \mu}}} = 1.0018 \pm 0.0014$$

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

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

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

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

Lepton universality tests with hadronic decays

HFLAV Tau 2018 report

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9958 \pm 0.0026 \ , \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9879 \pm 0.0063 \ .$$

Averaging the three g_τ/g_μ ratios:

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 0.9999 \pm 0.0014 \ .$$

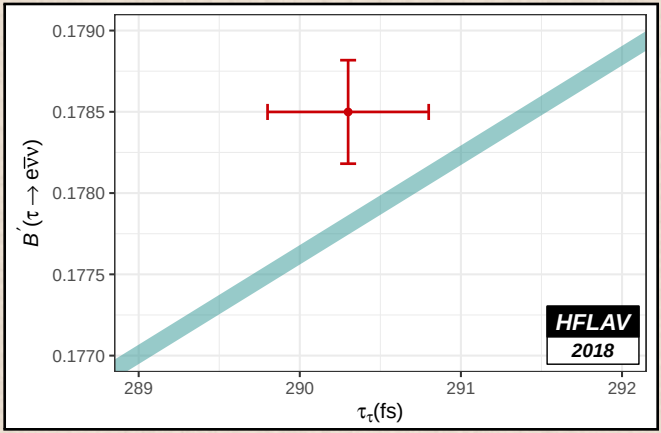
using Standard Model predictions

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(h \to \mu\bar{\nu}_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta_h) m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_h^2}{1 - m_h^2/m_\tau^2}\right)^2 \qquad (h = \pi \text{ or } K)$$

rad. corr. $\delta_\pi = (0.16 \pm 0.14)\%$, $\delta_K = (0.90 \pm 0.22)\%$ (Decker 1994)

note: electron tests less precise because $h \to e\nu$ decays are helicity-suppressed

Canonical tau lepton universality test plot



$(g_\tau/g_{e\mu}) = 1.0020 \pm 0.0013$
$[g_{e\mu} = g_e = g_\mu$ assuming $g_e = g_\mu]$

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

input	Δinput	$\Delta(g_\tau/g_{e\mu})$
$\mathcal{B}'_{\tau\to e}$	0.178%	0.089%
τ_τ	0.172%	0.086%
m_τ	0.007%	0.017%
total		0.125%

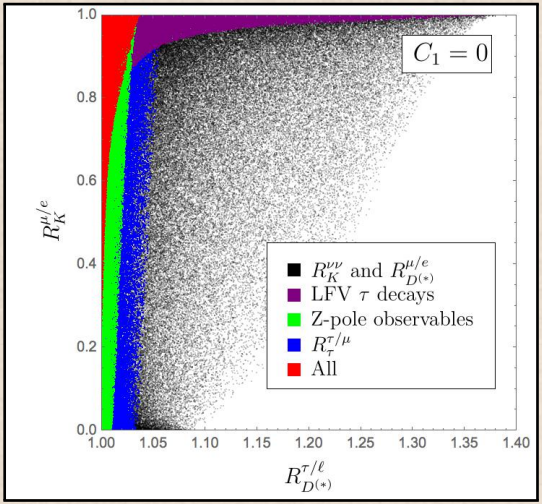
best measurements

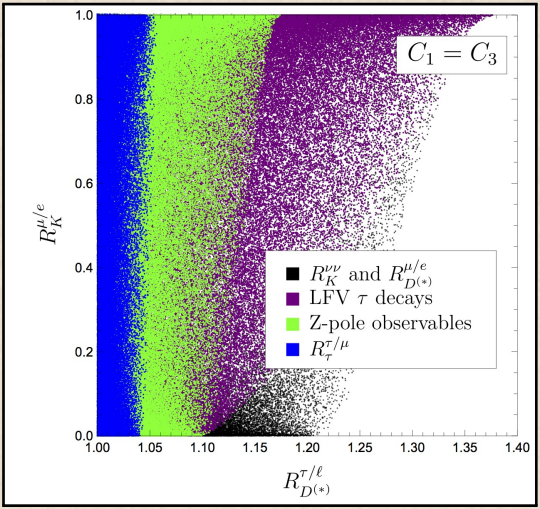
$\mathcal{B}'_{\tau\to e}$	ALEPH
τ_τ	Belle
m_τ	BES III

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

Tau Lepton universality constrains models for B $R^{\tau/\ell}_{D^{(*)}}$- $R^{\mu/e}_{K}$ anomalies

Feruglio, Paradisi, Pattori JHEP 09 (2017) 061
blue points correspond to parameter space region allowed by tau lepton universality





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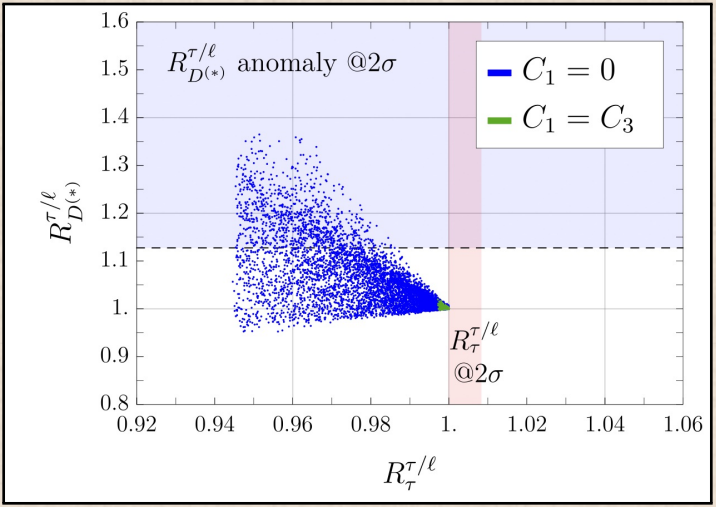


Non standard neutrino interactions

Babu, Bhupal Dev, Jana, Thapa, arXiv:1907.09498 [hep-ph]
blue region = model parameters' ($Y_{\tau e}$, $\sin\phi$, m_{h^+}) consistent with tau LU & lifetime, given $\epsilon_{\tau\tau}$

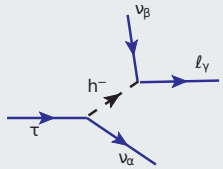
NSI parameters' definition

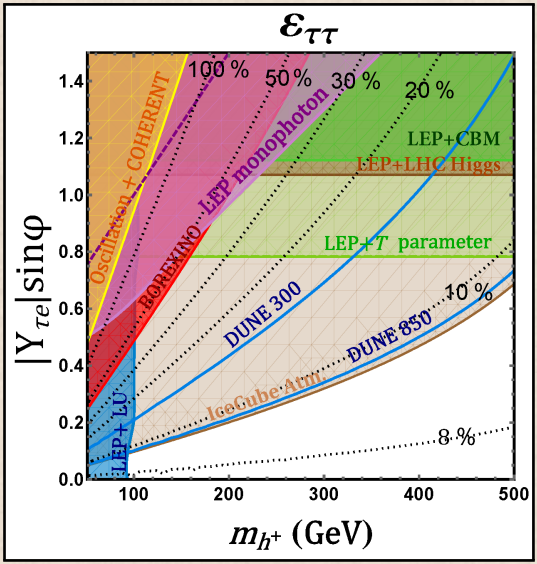
$$\mathcal{L}_{\rm NC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P f)$$

$$\mathcal{L}_{\rm CC} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)(\bar{f}\gamma_\mu P f')$$

where G_F is Fermi's constant and the ε terms quantify the size of the new interaction relative to the weak scale. The sum is over matter fermions, typically $f, f' \in \{e, u, d\}$ and $P \in \{P_L, P_R\}$ are the chirality projection operators. These projection operators can also be reparameterized

NSI model opens new tau decays





Required measurements for Tau Lepton Universality

$\mathcal{B}_{\tau\to\ell\bar{\nu}\nu}$, $\mathcal{B}_{\tau\to h\nu}$

- best existing experimental inputs: ALEPH, then other LEP experiments
- valuable experimental assets
  - tau statistics, PID and photon systematics
  - e^+e^- at Z-peak significantly better than B-factories energies

τ_τ

- best existing experimental inputs: Belle, then LEP experiments
- valuable experimental assets
  - tau statistics, vertexing
  - e^+e^- at Z-peak better than B-factories energies

m_τ

- best existing experimental inputs: BES III then KEDR i.e. e^+e^- at $\tau^+\tau^-$ threshold, then B-factories
- valuable experimental assets
  - e^+e^- at tau production threshold, small uncertainty on beam energy
  - tau-charm factories at threshold are best
  - Fcc-ee can provide interesting measurement, limited by systematics understanding

Precision Standard Model Studies

Unitarity violation in first row of CKM matrix

New radiative correction changes $|V_{ud}|$ and spoils unitarity (from E. Passemar, Kaon 2019)

$$|V_{ud}|^2 = \frac{2984.432(3)\,\mathrm{s}}{ft\Delta_R^V}$$

used so far up to CKM 2018, PDG 2019

$$\Delta_R^V = 0.02361(38)$$

Marciano *et al.*, PRL 96, 032002 (2006)

$$|V_{ud}| = 0.97418(10)_{ft}(18)_{\Delta_R^V}$$

$$\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.00062(45)$$

$-1.4\,\sigma$

new dispersive calculation

$$\Delta_R^V = 0.02467(22)$$

Seng *et al.*, PRL 121, 241804 (2018)

$$|V_{ud}| = 0.97379(10)_{ft}(11)_{\Delta_R^V}$$

$1.8\,\sigma$ smaller and more precise

$$\Delta_{CKM} = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = -0.00154(32)$$

$-4.8\,\sigma$

$|V_{us}|$ determinations (non-exhaustive)

Conventional, using kaon measurements and lattice QCD, most precise

- $\Gamma(K \to \pi \ell \bar{\nu}_\ell[\gamma]) = \frac{G_F^2 m_K^5}{192\pi^3} C_K^2 S_{\rm EW}^K \left(|V_{us}| f_+^{K\pi}(0)\right)^2 I_K^\ell \left(1 + \delta_{\rm EM}^{K\ell} + \delta_{\rm SU(2)}^{K\pi}\right)^2$ $\boxed{K_{\ell 3}}$
- $\frac{\Gamma(K^- \to \ell^- \bar{\nu}_\ell)}{\Gamma(\pi^- \to \ell^- \bar{\nu}_\ell)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \left(\frac{f_{K\pm}}{f_{\pi\pm}}\right)^2 \frac{m_K(1 - m_\ell^2/m_K^2)^2}{m_\pi(1 - m_\ell^2/m_\pi^2)^2} (1 + \delta_{\rm EM})$ $\boxed{K_{\ell 2}}$

Using tau measurements and OPE, no lattice QCD

- $\frac{R(\tau \to X_{\rm strange}\, \nu)}{|V_{us}|^2} = \frac{R(\tau \to X_{\rm non\text{-}strange}\, \nu)}{|V_{ud}|^2} - \delta R_{\tau,\rm SU3\ breaking}$, $\boxed{\tau \to X_s \nu}$

Using tau measurements and lattice QCD

- $\frac{\Gamma(\tau^- \to K^- \nu_\tau)}{\Gamma(\tau^- \to \pi^- \nu_\tau)} = \frac{|V_{us}|^2}{|V_{ud}|^2} \left(\frac{f_{K\pm}}{f_{\pi\pm}}\right)^2 \frac{\left(1 - m_K^2/m_\tau^2\right)^2}{\left(1 - m_\pi^2/m_\tau^2\right)^2} \frac{R_{\tau/K}}{R_{\tau/\pi}} R_{K/\pi}$ $\boxed{\tau \to K / \tau \to \pi}$
- $\Gamma(\tau^- \to K^- \nu_\tau) = \frac{G_F^2}{16\pi\hbar} f_{K\pm}^2 |V_{us}|^2 m_\tau^3 \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 R_{\tau/K} R_{K\mu 2}$ $\boxed{\tau \to K}$

"$\tau \to X_s \nu$ inclusive" $|V_{us}|$ determination

Gamiz *et al.* 2003 method

$$|V_{us}|_{\tau s} = \sqrt{R_s / \left[\frac{R_{VA}}{|V_{ud}|^2} - \delta R_{\text{theory}} \right]}$$, where

$$\begin{cases} R_s = \mathcal{B}(\tau \to X_s \nu)/\mathcal{B}(\tau \to e \bar{\nu} \nu) \\ R_{VA} = \mathcal{B}(\tau \to X_d \nu)/\mathcal{B}(\tau \to e \bar{\nu} \nu) \\ \delta R_{\text{theory}} = SU(3)\text{-breaking correction} \end{cases}$$

Gamiz, Jamin, Pich, Prades, Schwab 2003/2005

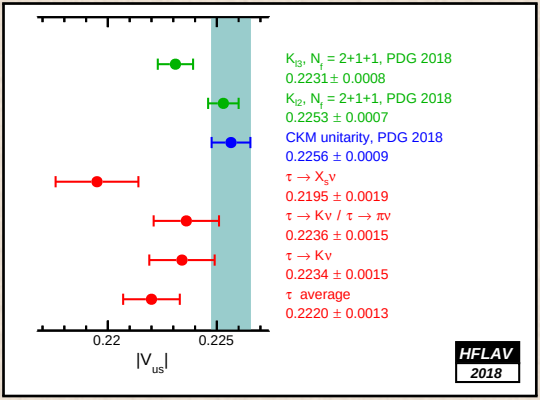
δR_{theory} from OPE calculation + tau spectral functions does not require lattice QCD inputs

other methods

- Hudspith 2018, uses also tau spectral functions
- Boyle 2018, tau spectral function and lattice QCD
- reliability of Gamiz method has been questioned

Required tau measurements

- Cabibbo-suppressed tau BRs
- tau spectral functions



- comparison with CKM unitarity determination of $|V_{us}|$ is equivalent to testing the unitarity of the first row of the CKM matrix

α_s from tau decay measurements

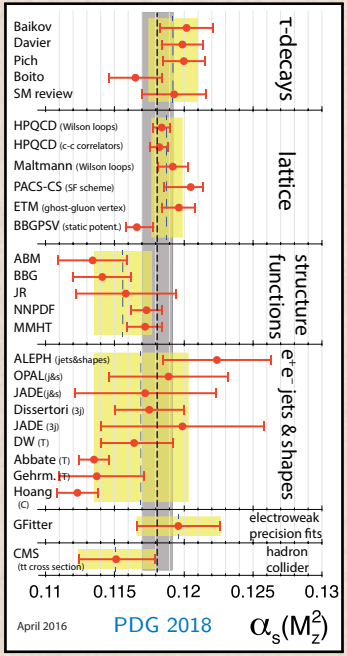
- $\alpha_s(m_\tau)$ from
  - $R_{VA} = \mathcal{B}(\tau \to X_d \nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$
  - tau spectral functions
- extrapolation to M_Z competitive with other methods
- $\alpha_s(m_\tau)$ confirms running of α_s

Recent discussions on tau determinations

- FOPT and CIPT extractions get significantly different results
- different groups get significantly different results
- disagreement on treatment of duality violations
- Pich 2019
  Boito, Golterman, Maltman, Peris 2019
  Pich, Rojo, Sommer, Vairo 2018
  Boito, Golterman, Maltman, Peris 2017
  Pich, Rodríguez-Sánchez 2016

Required tau measurements

- tau spectral functions
- tau branching fractions

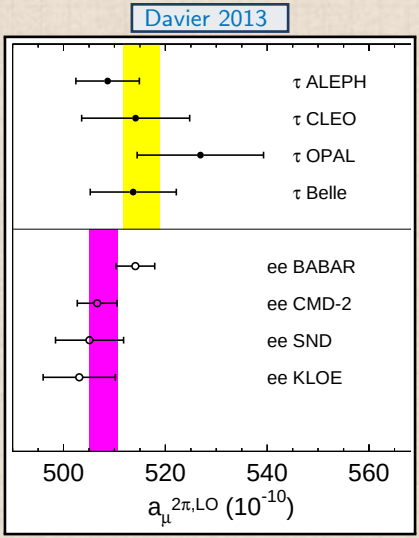


Muon $g-2$ hadronic contribution from tau

- $\alpha_\mu^{2\pi,\mathrm{LO}}$ from
  - $\tau \to \pi\pi^0\nu$ spectral function
  - normalization could come from $\mathcal{B}(\tau \to \pi\pi^0\nu)$, τ_τ
  - isospin rotation (associated theory systematics)
- tau data $\Rightarrow$ reduced discrepancy with exp.
- presently e^+e^- data more precise and complete

Required tau measurements

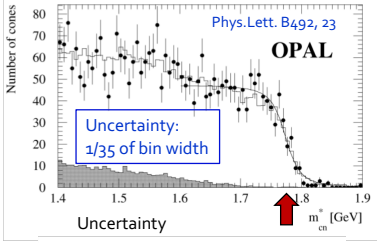
- tau spectral functions
- tau branching fractions



Tau Mass

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

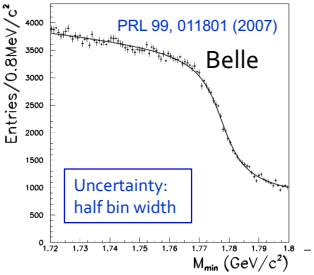
- **Current world average: m_τ = 1776.86 ± 0.12 MeV**
- Best in world: BES3 (threshold scan) $m_\tau = 1776.91 \pm 0.12\ (\text{stat.})\ ^{+0.10}_{-0.13}\ (\text{syst.})$ MeV
- Best at LEP: OPAL $m_\tau = 1775.1 \pm 1.6\ (\text{stat.}) \pm 1.0\ (\text{syst.})$ MeV
  - About factor 10 from world's best
  - Main result from endpoint of distribution of pseudo-mass in $\tau \to 3\pi^\pm(n\pi^0)\nu_\tau$
  - 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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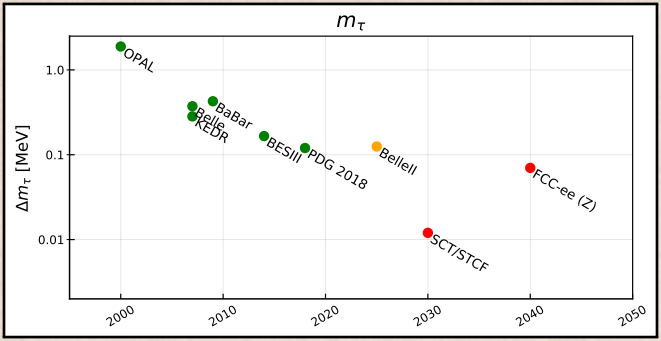
Fcc-ee sensitivity for m_τ



Tau Lifetime

Tau Lifetime

τ MEAN LIFE

PDG 2019

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

tau lifetime precision

precision (ppm)	
1700	PDG 2019
2100	Belle
5900	DELPHI
6400	ALEPH
7200	OPAL
260	Belle II guestimate, extrapolating from 0.711 ab^{-1}to 50 ab^{-1}
5	Fcc-ee, stat. only extrapolation from ALEPH (1e5) to Fcc-ee (1.65e11) tau pairs

$\Rightarrow$ what are the limiting systematics?

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 chisq cut
- IPD, impact parameter difference
  - resolution and trimming of outliers
- DL, decay length
  - vertex chisq cut

expect that all these systematics scale with $1/\sqrt{N_{events}}$
including alignment systematics
although questionable if up to a factor $1/\sim 1300$

Tau Lifetime systematics at Fcc-ee

Alignment systematic

- alignment calibration precision improves with statistics
- misalignment effects zero at first order for uniform azymuthal acceptance
  S.R.Wasserbaech, Nucl.Phys.Proc.Suppl. 76 (1999) 107-116
  - still, questionable how far this holds
- related systematic that does not scale
  absolute length scale of vertex detector average elements spacing, realiable to 10^{-4} or 100 ppm

Systematics from kinematics of tau decay

- $\tau_\tau = \lambda_\tau/\beta\gamma = \lambda_\tau / \frac{\sqrt{E_\tau^2 - m_\tau^2}}{m_\tau} = \lambda_\tau / \frac{\sqrt{(E_{\text{beam}} - E_{\text{rad}}^{\text{MC}})^2 - m_\tau^2}}{m_\tau}$

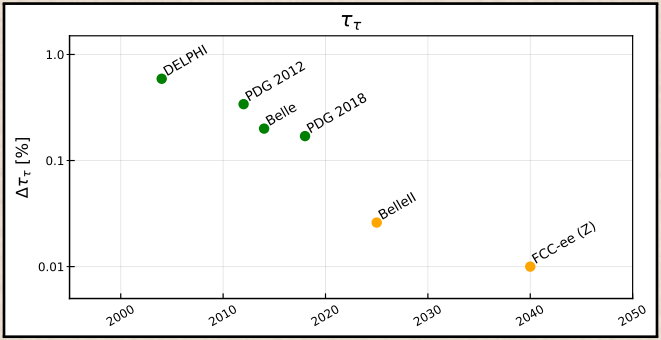
systematic [ppm]	
1	E_{beam}
68	m_τ PDG 2019
7	m_τ possible measurement at Super Charm-Tau Factories
?	MC accuracy on average radiation energy loss (*) (estimated 100 ppm for *BABAR*)

(*) depends on

- accuracy of generator, can be checked measuring momentum distribution of di-muon events
- accuracy of simulation of efficiency of selection procedure vs. E_τ (scales with luminosity)

Fcc-ee sensitivity for τ_τ

- replace M.Dam / CDR estimate of 0.004 fs / 140 ppm with 0.0029 fs / 100 ppm
- more precise measurement not excluded in principle
- to be investigated accuracy of simulation of average radiation energy loss (neglected here)



Tau branching fractions and spectral functions

Tau branching fractions

- 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-ee statistics 1300$\times$ ALEPH, 175$\times$ Belle, 3.5$\times$ BelleII (& better efficiency w.r.t. B-factories)
- Fcc-ee is best imaginable context for tau BR measurements
- what are the limiting systematics?

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 $E_\gamma > 12\,\mathrm{MeV}$
- 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)

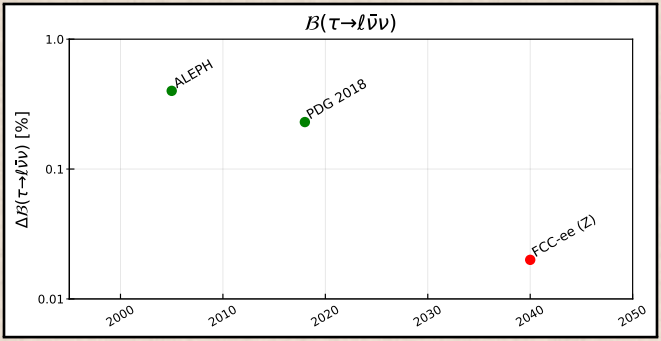
Conclusion

- potential improvement w.r.t. ALEPH is ~ 1300 in precision
- only future actual analysis will be able to estimate limiting systematics in a realiable way
- guestimate: assume total uncertainty $10\times$ better that WA, which is about $20\times$ better than ALEPH

Tau spectral functions

- reasonably complete sets only measured at LEP (ALEPH, OPAL)
- limited contributions from B-factories
- studies at the Z peak are by far the most favourable context
- significant improvements are possible at Fcc-ee especially for the poorly measurer rare modes
- analyses are complex and may be limited by manpower availability

Fcc-ee sensitivity for $\mathcal{B}(\tau \to \ell\bar{\nu}\nu)$



Conclusions

- Fcc-ee (or comparable Z-peak e^+e^- facilities) are the best for tau Physics
- there are several interesting measurements to be improved
- Fcc-ee permits impressive precision improvements
- fair share of systematics scale with luminosity if enough human effort is available
- identified possibly limiting systematics still allow large and interesting margins of improvement
- improvements on tau lifetime and leptonic BRs make desirable improvements on m_τ (SCTF?)

Thanks for your attention!