Tau Physics at Super Charm-Tau Factories (experimental perspective)

Alberto Lusiani
Scuola Normale Superiore and INFN, sezione di Pisa

SCUOLA NORMALE SUPERIORE

INFN PISA

10th International Workshop on Charm Physics (CHARM 2020)
UNIVERSUM, National Autonomous University of Mexico (UNAM), Mexico City
31 May 2021 – 4 June 2021

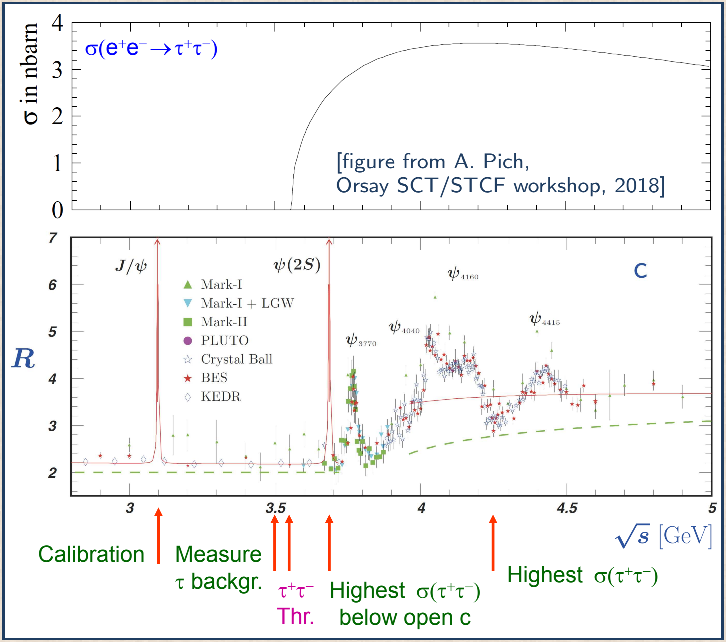
Tau Physics at super tau-charm factories projects

- high-luminosity symmetric e^+e^- colliders
- SCT, Novosibirsk, Russia, https://ctd.inp.nsk.su/c-tau/
- STCF, Hefei, China, http://cicpi.ustc.edu.cn/indico/categoryDisplay.py?categId=2

	SCT	STCF	Belle II	Belle
E_{CM} [GeV]	$2-6$	$2-7$	$\sim$10.58	
luminosity [$cm^{-2}s^{-1}$]	$1{\cdot}10^{35}$		$8{\cdot}10^{35}$	$2{\cdot}10^{34}$
beams polarization	80%		no	
$\sigma(\tau^+\tau^-)$ at 3.68 Gev	2.4 nb			
$\sigma(\tau^+\tau^-)$ at 4.25 Gev	3.6 nb			
$\sigma(\tau^+\tau^-)$ at 10.58 Gev			0.92 nb	
int. lumi. in 1 year-10^7 s	1 ab^{-1}		8 ab^{-1}	0.2 ab^{-1}
tau pairs in 1 year-10^7 s	$(2.4-3.6){\cdot}10^9$		$7.4{\cdot}10^9$	$0.18{\cdot}10^9$

- large tau samples
- general purpose hermetic 4π detectors planned for both

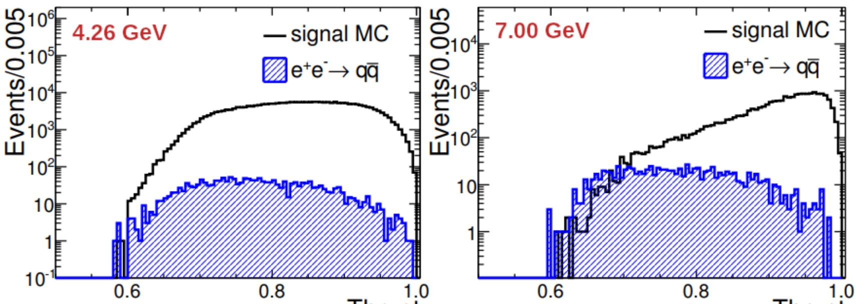
Tau pairs production at charm-tau factories



Tau pairs production and decay at charm-tau factories

- small tau boost ⇒ decay products of both tau's ∼not topologically separated
  - topological separation large and useful especially at Z^0 peak
- small tau decay length, unsuitable for tau lifetime measurements
- $\tau^+\tau^-$ at rest near tau pair threshold ⇒ two-body decays (e.g. $\tau \to \pi\nu$) ∼monochromatic ($E_\pi \simeq k$)

$\tau^+\tau^-$ vs. $q\bar{q}$ thrust distribution



plot by Xiaorong Zhou, 2020

plot by Xiaorong Zhou, 2020

Main motivations of tau lepton experimental measurements

Searches for Lepton Flavour Violation in tau decays

- clean & effective search for "natural" NP processes extremely suppressed in SMν
- upper limits are effective constraints on NP models

Other searches for New Physics

- CPV in tau decay, tau EDM and CPV in tau production, tau $g{-}2$

Standard Model EW tests on leptons only

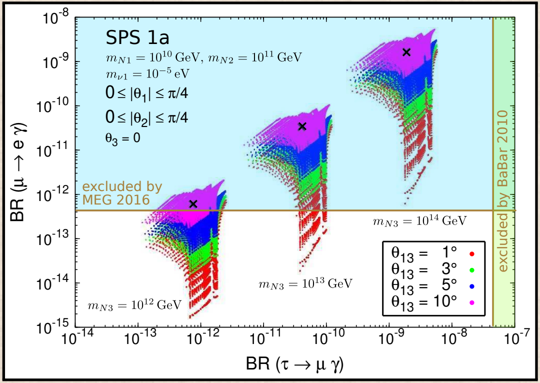
- tau BRs (mainly leptonic), mass, lifetime for lepton universality tests
  - test & constrain B anomalies New Physics models
- Michel parameters

Standard Model EW with hadrons & QCD tests

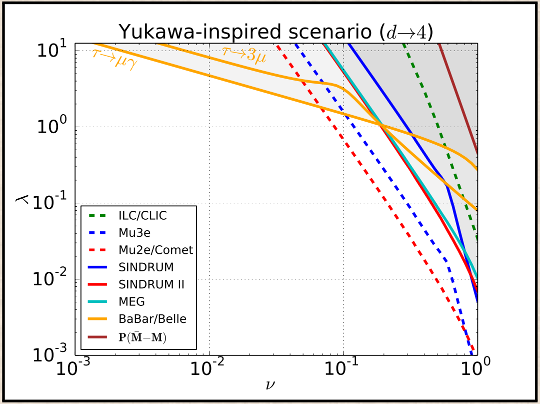
- tau hadronic BRs and spectral functions
- $|V_{us}|$ measurement alternative to kaons and without lattice QCD inputs
- measure $\alpha_s(m_\tau)$ and test running of α_s from m_τ to m_Z
- alternative measurement of HVP contribution to muon $g{-}2$

Tau LFV searches probe & constrain New Physics models

MSSM Seesaw
Antusch, Arganda, Herrero, Teixeira 2006



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



typical NP models

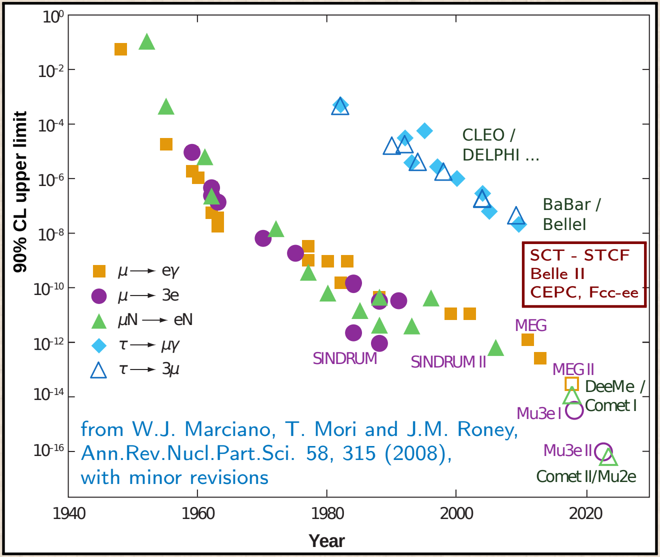
- $\mathcal{B}(\tau \to \mu\gamma) \sim 10\text{–}1000 \times \mathcal{B}(\mu \to e\gamma)$
- muon LFV searches more effective

specific models / parameter space regions

- part of plot only constrained by tau LFV limits

tau LFV experimental reach complementary and for some models more constraining than muon LFV

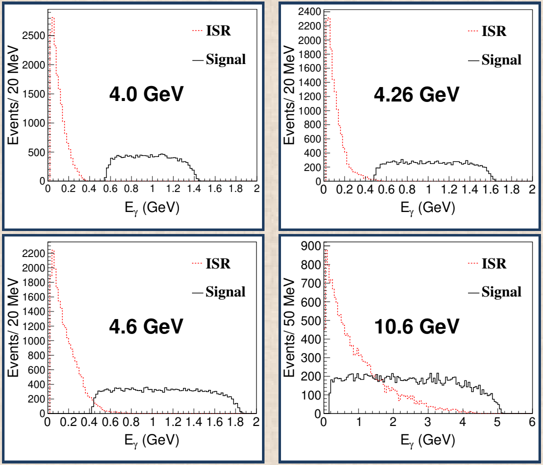
Present Tau LFV limits, present and future Muon LFV limits



incoming years will provide remarkable progress on Muon LFV searches

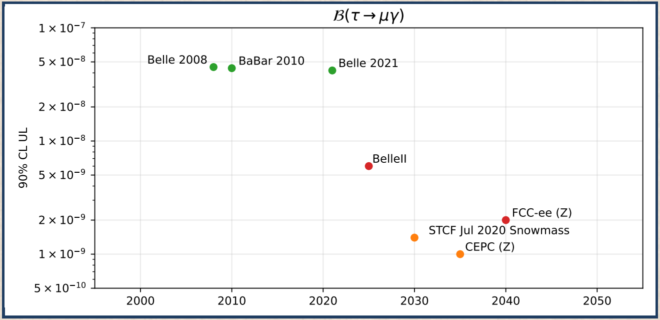
LFV search for $\tau \to \mu\gamma$

- search limited by accidental combinations with ISR photons with leptoninc SM decays $\tau \to \ell\bar{\nu}\nu$
- reduced ISR photon background at SCT-STCF energies, closer to tau production threshold
  - A.V. Bobrov & A.E. Bondar, 2012



plots from "Sensitivity Study of Searching for $\tau \to \mu\gamma$ at HIEPA", Sci.Bull. 61 (2016) 4, 307

Expected reach on $\tau \to \mu\gamma$ (90% CL upper limit)



- Xiaorong Zhou, Snowmass 2021 preparation, Jul 2020, assuming $10\,\text{ab}^{-1}$ (several older estimates for both SCT and STCF also exist)
- BES III Boost simulation & analysis framework, full STCF detector features
- important: 4 mm photon detector granularity, $<3\%$ pion-to-muon mis-id

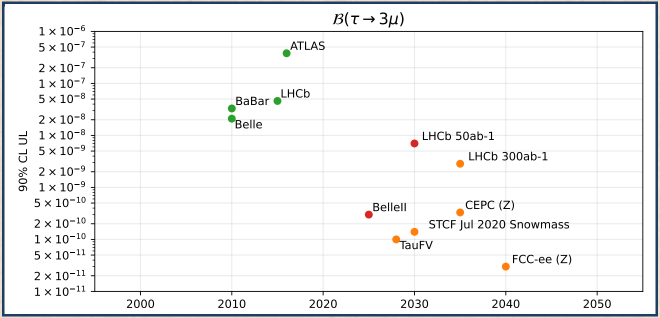
point colors

- Red: more sound estimate
- Orange: more uncertain estimate
- Green: public results

small print cautions

- all estimates, including the ones in Red, are indicative
  - unfeasible to do studies close enough to the final analysis on simulated events
  - realization and operation of future, especially non-approved, projects is uncertain
  - extrapolations are not typically done in an equivalent way for different projects
- dates of estimated results are set primarily for plotting convenience

Expected reach on $\tau \to 3\mu$ (90% CL upper limit)



- Xiaorong Zhou, Snowmass 2021 preparation, Jul 2020, assuming $10\,\text{ab}^{-1}$
- BES III Boost simulation & analysis framework, full STCF detector features
- assumes pion-to-muon mis-id 1% at 1 GeV, critical

CPV in tau decay, $\tau^- \to \pi^- K^0_S \nu$ rate

BaBar 2012

- $A_{\text{CP, rate}} = \dfrac{\mathcal{B}(\tau^+ \to \pi^+ \mathrm{K}^0_S \overline{\nu}_\tau) - \mathcal{B}(\tau^- \to \pi^- \mathrm{K}^0_S \nu)}{\mathcal{B}(\tau^+ \to \pi^+ \mathrm{K}^0_S \overline{\nu}_\tau) + \mathcal{B}(\tau^- \to \pi^- \mathrm{K}^0_S \nu)} = (-0.36 \pm 0.23 \pm 0.11)\%$
  - deviates $2.8\,\sigma$ from SM prediction 0.36 ± 0.01

STCF sensitivity estimate

- $\Delta A_{\text{CP, rate}}$(statistical) $= 0.035\%$ at STCF with $10\,\text{ab}^{-1}$ at 4.26 GeV
  - Chinese Physics C Vol. 45, No. 5 (2021) 053003
  - full simulation, systematic uncertainties estimated to be comparable with statistical
  - comparable to expected Belle II sensitivity

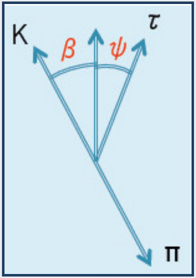
CPV in tau decay, angular distribution asymmetry

Belle 2011

- $\tau^- \to \pi^- K_S^0 \nu$
- interference of SM model (vector + scalar) with additional scalar interaction

  $\Rightarrow A_{\text{CP, ang}}(Q^2) = \left(\langle\cos\beta\cos\psi\rangle_{\tau^-} - \langle\cos\beta\cos\psi\rangle_{\tau^+}\right)\big|_{Q^2}$

  (β angle between K_S^0 and e^+e^- CMS frame
  ψ angle between τ and e^+e^- CMS frame)
- $\text{Im}(\eta_S) < 0.026$ 90% CL (scalar interaction coupling)



D. Epifanov, SCTF-2019 Workshop, Moscow

- extended Belle study to account for beam polarization
- note: tau polarization is maximal at energies close to production threshold
- 3 additional optimal observables can be defined for CPV effects

CPV in tau decay, angular distribution asymmetry

D. Epifanov, SCTF-2019 Workshop, Moscow

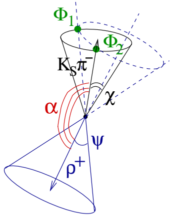
- novel analysys of angular distributions of whole tau pair with $\tau^- \to \pi^- K_S^0 \nu$, $\tau^+ \to \rho^+ \nu$

$$\frac{d\sigma(\vec{\zeta}^*, \vec{\zeta'}^*)}{d\Omega_\tau} = \frac{\alpha^2}{64E_\tau^2}\beta_\tau (D_0 + D_{ij}\zeta_i^*\zeta_j'^*), \quad \frac{d\Gamma(\tau^\pm(\vec{\zeta'}^*) \to \rho^\pm \nu)}{dm^2_{\pi\pi}\, d\Omega^*_\rho\, d\tilde{\Omega}_\pi} = A' \mp \vec{B'}\vec{\zeta'}^*$$

$$\frac{d\Gamma(\tau^\mp(\vec{\zeta}^*) \to (K\pi)^\mp \nu)}{dm^2_{K\pi}\, d\Omega^*_{K\pi}\, d\tilde{\Omega}_\pi} = \begin{matrix} (A_0 + \eta_{CP}A_1) + (\vec{B}_0 + \eta_{CP}\vec{B}_1)\vec{\zeta}^* \\ (A_0 + \eta^*_{CP}A_1) - (\vec{B}_0 + \eta^*_{CP}\vec{B}_1)\vec{\zeta}^* \end{matrix}$$

$$\frac{d\sigma((K\pi)^\mp, \rho^\pm)}{dm^2_{K\pi}\, d\Omega^*_{K\pi}\, d\tilde{\Omega}_\pi\, dm^2_{\pi\pi}\, d\Omega^*_\rho\, d\tilde{\Omega}_\pi\, d\Omega_\tau} = \frac{\alpha^2\beta_\tau}{64E_\tau^2}\begin{pmatrix} \mathcal{F} + \eta_{CP}\mathcal{G} \\ \mathcal{F} + \eta^*_{CP}\mathcal{G} \end{pmatrix}$$

$$\mathcal{F} = D_0 A_0 A' - D_{ij} B_{0i} B'_j, \quad \mathcal{G} = D_0 A_1 A' - D_{ij} B_{1i} B'_j$$



$$\frac{d\sigma((K\pi)^\mp, \rho^\pm)}{dp_{K\pi}\, d\Omega_{K\pi}\, dm^2_{K\pi}\, d\tilde{\Omega}_\pi\, dp_\rho\, d\Omega_\rho\, dm^2_{\pi\pi}\, d\tilde{\Omega}_\pi} = \sum_{\Phi_1,\Phi_2} \frac{d\sigma((K\pi)^\mp, \rho^\pm)}{dm^2_{K\pi}\, d\Omega^*_{K\pi}\, d\tilde{\Omega}_\pi\, dm^2_{\pi\pi}\, d\Omega^*_\rho\, d\tilde{\Omega}_\pi\, d\Omega_\tau}\left|\frac{\partial(\Omega^*_{K\pi}, \Omega^*_\rho, \Omega_\tau)}{\partial(p_{K\pi}, \Omega_{K\pi}, p_\rho, \Omega_\rho)}\right|$$

- η_{CP} extracted with simultaneous unbinned maximum likelihood fit of 12D phase space distribution

CPV in tau decay, CP-odd triple product

- CPV in tau decay may be detected by measuring CP-odd triple product
  $\vec{\sigma}_{\text{Pol}(\tau)} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^0})$ in $\tau^- \to \pi^- \pi^0 \nu$

with beam polarization

- measurement can be done on each tau decay separately
- figure of merit depends on produced tau average polarization, highest at threshold and then decreasing (FOM decreases by factor 7.7 for $E_{\text{CM}} = 4\,\text{GeV} \to 12\,\text{GeV}$, Y.S. Tsai, PRD 51 (1995) 3172)
- however, close to threshold smaller tau pair cross-section and possibly background suppression harder

without beam polarization (e.g. Belle II)

- must use other tau decay as spin analyzer
- lower figure of merit in comparison to when there is significant beam polarization

Tau $g-2$, EDM and CPV in tau production

- New Physics can appear as non-zero tau EDM, CPV in tau production or as a deviation from $g-2_{\text{SM}}$
- all these effects can be measured from momenta distributions of tau pairs decay products
- J. Bernabeu *et al.*, Nucl.Phys.B 701 (2004) 87, Nucl.Phys.B 763 (2007) 283, Nucl.Phys.B 790 (2008) 160
- beam polarization increases experimental resolution (a factor 10 better is plausible)

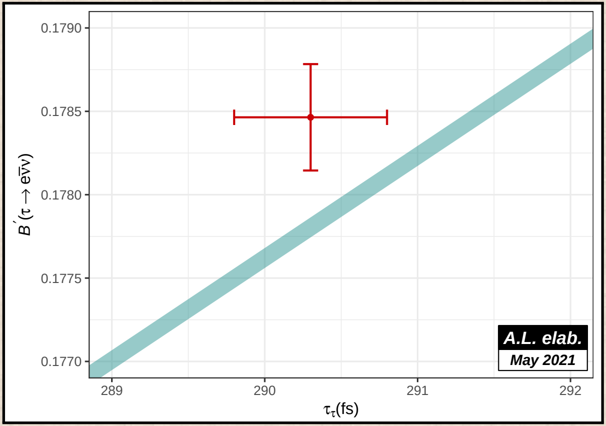
Belle II studies

- JHEP 10 (2019) 089: $|d_\tau^{\text{NP,HE}}| < 2.04\cdot10^{-19}\,\text{e cm}$, $|a_\tau^{\text{NP, HE}}| < 1.75\cdot10^{-5}$ (1.5% of SM prediction)
- Phys.Rev.D 103 (2021) 9, 096011: $\delta\,\text{Re}\,d_\tau = 6.8\cdot10^{-20}\,\text{e cm}$, $\delta\text{Im}d_\tau = 4.0\cdot10^{-20}\,\text{e cm}$

SCT, STCF

- w.r.t. Belle II, expect at most 1/2 tau pairs statistics
- $+$ beam polarization
- $-$ no resolution of two-fold ambiguity in tau direction reconstruction for low-momentum tau's
- good prospects, but difficult measurement

Canonical tau lepton universality test plot



$$(g_\tau/g_{e\mu}) = 1.0019 \pm 0.0013$$
$$[g_{e\mu} = g_e = g_\mu \text{ assuming } g_e = g_\mu]$$

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

input	Δinput	$\Delta(g_\tau/g_{e\mu})$
$\mathcal{B}'_{\tau\to e}$	0.179%	0.089%
τ_τ	0.172%	0.086%
m_τ	0.007%	0.017%
total		0.125%

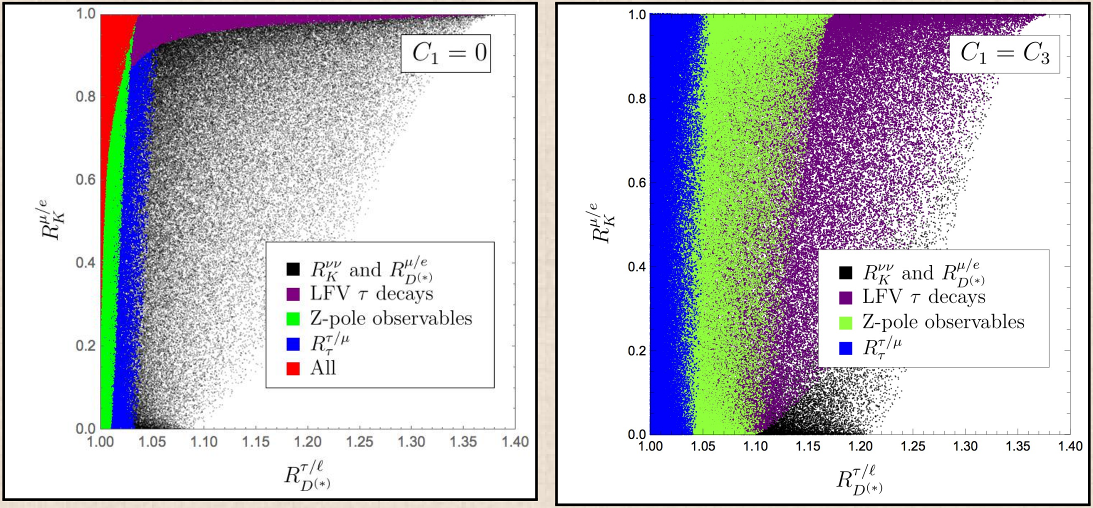
best measurements

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

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

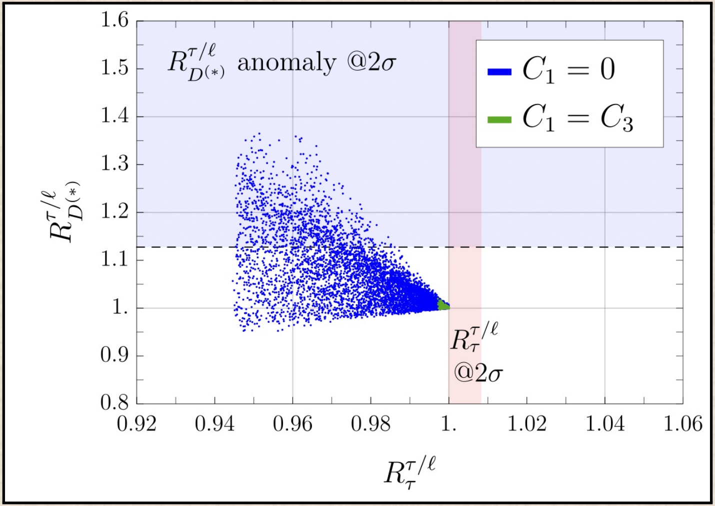
Tau Lepton universality constrains models for B $R^{\tau/\ell}_{D^{(*)}}$- $R^{\mu/e}_{K}$ anomalies

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

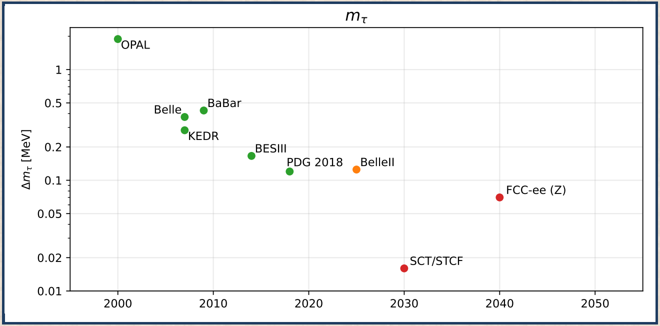


Tau Lepton universality constrains models for B $R^{\tau/\ell}_{D^{(*)}}$- $R^{\mu/e}_{K}$ anomalies

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

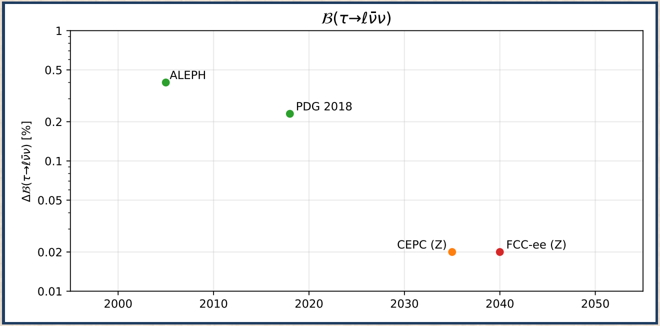


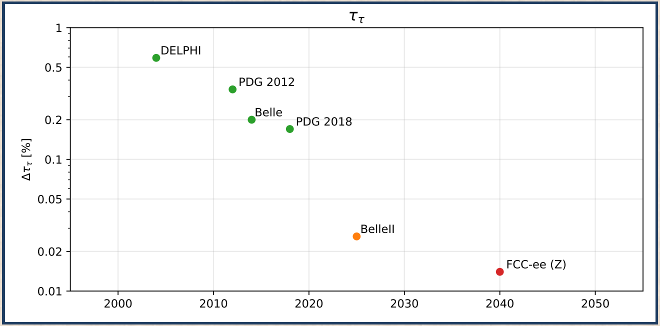
Physics reach on m_τ



- Tao Luo, STCF indico web site, 10 May 2019: from 0.17 Mev at BES III to 0.016 MeV at STCF
- STCF luminosity ∼100× higher than BES III
- requires 10× reduction of systematics as well
- critical: beam energy measurement with resonant depolarization or Compton back-scattering

Physics reach on $\mathcal{B}(\tau \to \ell\bar{\nu}\nu)$, τ_τ





- SCT & STCF might contribute
- measurement of $\dfrac{\mathcal{B}(\tau \to \mu\bar{\nu}\nu)}{\mathcal{B}(\tau \to e\bar{\nu}\nu)}$ to 10 ppm may be possible, V. Vorobyev, Charm 2020 (W.A. precision now 2800 ppm)

- SCT & STCF not competitive

Tau hadronic decays: $|V_{us}|$ measurement

Gamiz *et al.* 2003 method

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

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

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

δR_{theory} from OPE calculation + tau spectral functions

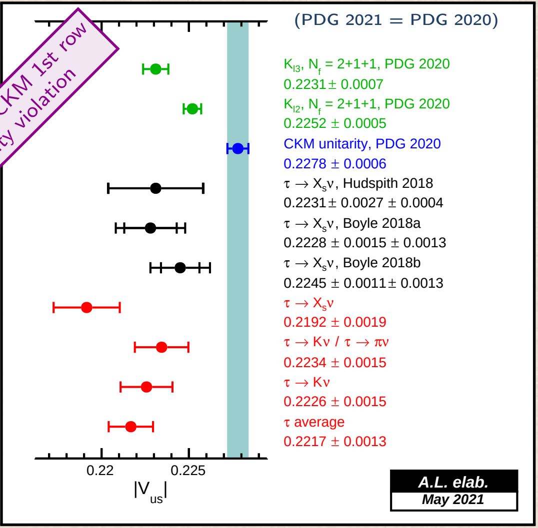
does not require lattice QCD inputs

other methods for $|V_{us}|$ from tau

- 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

Tau hadronic decays: α_s

- $\alpha_s(m_\tau)$ 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

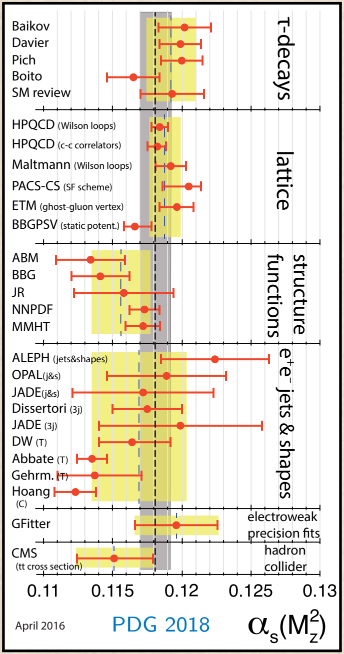
poor consistency among α_s determinations

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

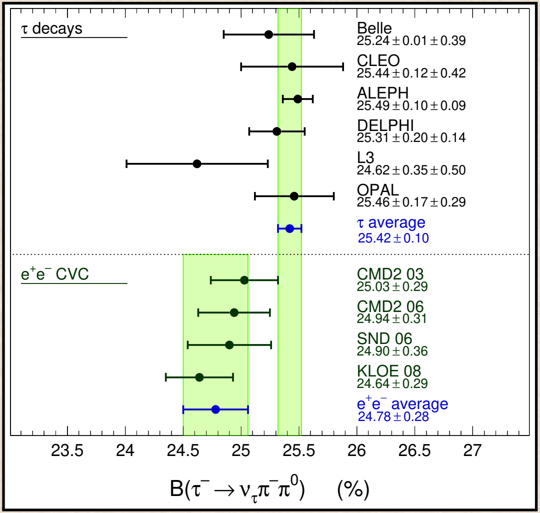
Required tau measurements

- tau spectral functions
- tau branching fractions



Tau hadronic decays: compute muon $g-2$ HVP contribution

EPJC C66, 127 (2010)



$\alpha_\mu^{\text{HVP, LO},2\pi}$ with tau measurements

- ingredients
  - distribution $\tau \to \pi\pi^0\nu$ spectral function
  - normalization $\mathcal{B}(\tau \to \pi\pi^0\nu)$ & τ_τ
  - isospin rotation effect from theory
- $\mathcal{B}(\tau \to \pi\pi^0\nu)$ deviates from prediction based on $\sigma(e^+e^- \to \text{hadrons})$ measurements
- a_μ^{th} with tau HVP ~consistent with a_μ^{exp}

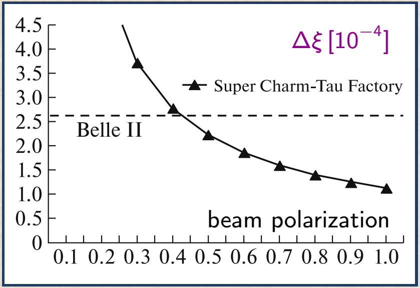
- more precise tau spectral functions may help understanding the muon $g-2$ deviation w.r.t. the theory prediction

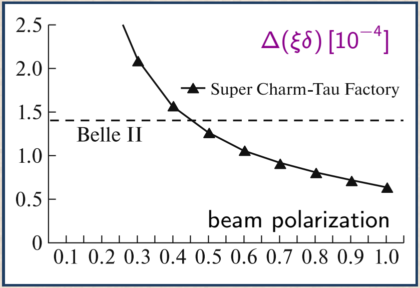
Tau hadronic branching fractions and spectral functions

- best measured at Z^0 peak e^+e^- collision facilities because tau's are boosted and topologically separate, facilitating measurements with reduced systematics
- SCT and STCF may have good prospects for $\mathcal{B}(\tau^- \to h^- \nu_\tau)$ close to tau pair production threshold () where the hadronic system momentum is almost monochromatic

Tau Michel parameters, test of $V-A$ charged weak interation in tau decay

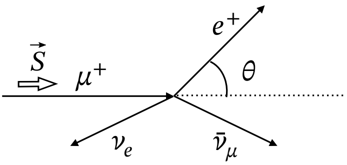
- $$\frac{d\Gamma(\tau^{\mp} \to \ell^{\mp} \overset{\scriptscriptstyle(-)}{\nu}_{\ell} \overset{\scriptscriptstyle(-)}{\nu}_{t} au)}{d\Omega dx} = \frac{4G^2 M_{\tau} E_{\max}^4}{(2\pi)^4} \sqrt{x^2 - x_0^2} \cdot$$
  $$\cdot \left(x(1-x) + \frac{2}{9}\rho(4x^2 - 3x - x_0^2) + \eta x_0(1-x) \mp \frac{1}{3} P_{\tau} \cos\theta_{\ell} \xi \sqrt{x^2 - x_0^2} \left[1 - x + \frac{2}{3}\delta \left(4x - 4 + \sqrt{1 - x_0^2} \right) \right] \right)$$
  $$x = \frac{E_{\ell}}{E_{\max}}, \quad E_{\max} = \frac{M_{\tau}}{2}(1 + \frac{m_{\ell}^2}{M_{\tau}^2}), \quad x_0 = \frac{m_{\ell}}{E_{\max}}$$
- beam polarization allows analyzing just one tau instead of the tau pair together
- SCT better than Belle II for ρ, η, and (with $\mathrm{Pol}_{\tau} > 0.5$) also for ξ, $\xi\delta$
- effective $\mathrm{Pol}_{\tau} > 0.5$ can be measured by analyzing $\tau \to \pi\nu$ and $\tau \to \rho\nu$
- D. Epifanov, Phys.Atom.Nucl. 83 (2020) 6, 944



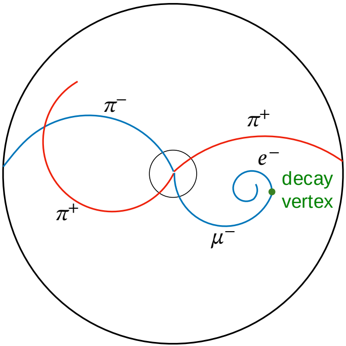


Tau Michel parameters, additional sensitivity measuring muon polarization

- $\tau \to \mu(\to e\bar{\nu}\nu)\bar{\nu}\nu$, at SCT energy expect $5{\cdot}10^4$ well reconstructed events with muon decay in tracker
- muon polarization reconstructed from muon decay angular distribution
- D. Bodrov, SCTF-2019 Workshop, Moscow

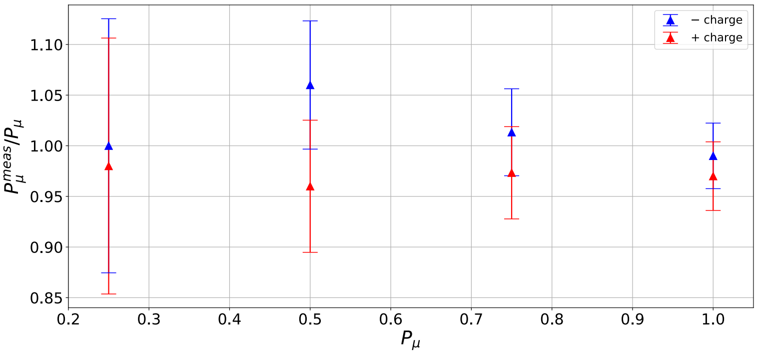


$$\frac{1}{\Gamma}\frac{d\Gamma(\cos\theta)}{d\cos\theta} = \frac{1}{2}\,(\,1 + \frac{P_L}{3}\cos\theta\,)$$



Tau Michel parameters, additional sensitivity measuring muon polarization

$\text{Pol}_\mu^{\text{measured}} / \text{Pol}_\mu^{\text{true}}$ value and uncertainty vs. $\text{Pol}_\mu^{\text{true}}$



- resolution seems insufficient for a significant measurement (WA precision on ξ, $\xi\delta$ is 3–5%)
- but "statistical and systematic precision of the proposed measurement strongly depends on the Hardware and Software requirements for the SCT detector"

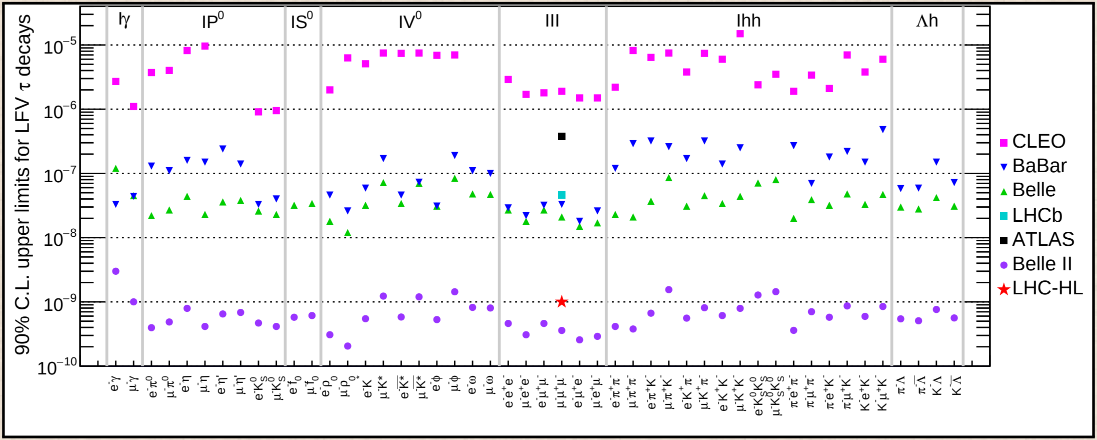
Conclusions

- remarkable prospects for tau physics measurements at Super Tau-Charm factories
- beam polarization and production close to threshold facilitate some measurements
- tau pair decay products are mixed and less distinct from hadronic background
- useful detector features: low pion-to-muon mis-id, granular electromagnetic calorimeter
- unique precision for tau mass
- very interesting prospects for the most interesting tau LFV mode $\tau \to \mu\gamma$
- good prospects for several precision tau measurements

Thanks for your attention!

Backup Slides

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



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

Belle II Tau Physics

- The Belle II experiment at SuperKEKB: input to the European Particle Physics Strategy
- The Belle II Physics Book arXiv:1808.10567 [hep-ex]
- $50\,\text{ab}^{-1}$, 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
- $\Delta m_\tau = \pm 0.10 - 0.15\,\text{MeV}$ "very optimistically" (BESIII $\pm 0.17\,\text{MeV}$)
- 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

HL-LHC and HE-LHC Tau Physics

HL-LHC and HE-LHC

- inputs to the European Particle Physics Strategy
- Opportunities in Flavour Physics at the HL-LHC and HE-LHC, arXiv:1812.07638 [hep-ph]
- $\mathcal{B}(\tau \to 3\mu)$ 90% CL

Table 23: Actual and expected limits on BR($\tau \to 3\mu$) for different experiments and facilities. The ATLAS projections are given for the medium background scenario, see main text for further details.

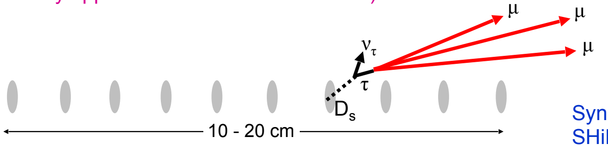
BR($\tau \to 3\mu$) (90% CL limit)	Ref.	Comments
3.8×10^{-7}	ATLAS [429]	Actual limit (Run 1)
4.6×10^{-8}	LHCb [428]	Actual limit (Run 1)
3.3×10^{-8}	BaBar [417]	Actual limit
2.1×10^{-8}	Belle [423]	Actual limit
3.7×10^{-9}	CMS HF-channel at HL-LHC	Expected limit (3000 fb^{-1})
6×10^{-9}	ATLAS W-channel at HL-LHC	Expected limit (3000 fb^{-1})
2.3×10^{-9}	ATLAS HF-channel at HL-LHC	Expected limit (3000 fb^{-1})
$\mathcal{O}(10^{-9})$	LHCb at HL-LHC	Expected limit (300 fb^{-1})
3.3×10^{-10}	Belle-II [196]	Expected limit (50 ab^{-1})
7.9×10^{-9}	LHCb	M.Chrząszcz priv.comm. (50 fb^{-1})

TauFV, project, SPS protons on fixed-targed, dedicated to tau LFV searches

TauFV, project, SPS protons on fixed-targed, dedicated to tau LFV searches

- inputs to the European Particle Physics Strategy

Instead, design dedicated experiment upstream of SHiP, with thin, distributed targets, to bleed off ~2% of the beam intended for SHiP → 2 mm of tungsten (this value also set by upper limit of data rates in VELO).



Synergetic with SHiP operation !

- leverages on LHCb expertise, success and upgrade-related R&D, synergic with SHiP
- n. of tau decays: 900×BelleII, 60×LHCb(50 fb^{-1}), 10×LHCb(300 fb^{-1})
- target and detector optimized for tau LFV searches
- earliest date 2026-2027
- $\mathcal{B}(\tau \to 3\mu)$ 90% CL UL “down to 10^{-10}”
- also sensitive to other $\mathcal{B}(\tau \to \ell_1\ell_2\ell_3)$, one less order of magnitude for $e^+\mu^-\mu^-$
- promising enterprise, could match and improve on BelleII for $\mathcal{B}(\tau \to 3\mu)$

Tau Physics at 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 historical 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 best conditions for about all tau Physics measurements

Tau Physics at 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 $\Delta\mathcal{B}(\tau \rightarrow \ell\bar{\nu}\nu) \sim 0.02\%$ (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 $\pm 0.12\,\text{MeV}$)
- $\mathcal{B}(\tau \rightarrow \mu\gamma) < 2{\cdot}10^{-9}$ 90% CL Monte Carlo study on 2% of full FCC-ee statistics
- $\mathcal{B}(\tau \rightarrow 3\mu) < [1{-}0.1]{\cdot}10^{-10}$ 90% CL guestimate
- significant advances possible on about all measurements and LFV limits
- Z peak offers best conditions for about all tau Physics measurements

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

BelleII sensitivity (Physics Book)

- estrapolated from Belle limit at 0.782 ab^{-1} to 50 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 $\times 3.3\% = 1.65$e11, 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 in 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

Lepton universality tests

HFLAV Tau 2018 report

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

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^\mu}{\tau_\tau m_\tau^5 f_{\tau \mu} R_\gamma^\tau R_W^\tau}} = 1.0028 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau \mu}^{\text{SM}}}}$$

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

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

$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.9956 \pm 0.0026 \; , \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.9877 \pm 0.0063 \; .$$

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

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

Hints of unitarity violation in first row of CKM matrix

New calculation of radiative correction for $|V_{ud}|$, from E. Passemar, Kaon 2019

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

used so far up to CKM 2018, PDG 2019

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

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

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

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

PDG $|V_{ud}|$ $|V_{us}|$ review 2020

- $|V_{ud}| = 0.97370(10)_{\text{exp.,nucl.}}(10)_{\text{RC}}$, $|V_{us}| = 0.2245(4)$, $N_f = 2+1+1$
- $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985(3)_{|V_{ud}|}(4)_{|V_{us}|}$ 3 sigma deviation from unitarity
- PDG 2019: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9994(4)_{|V_{ud}|}(2)_{|V_{us}|}$ consistent

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

Conventional, using kaon measurements and lattice QCD, most precise

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

Using tau measurements and OPE, no lattice QCD

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

Using tau measurements and lattice QCD

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

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^{ee}_{cm}=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^{ee}_{cm}= 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

⇒ 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 $1/\sqrt{N_{\text{events}}}$
including alignment systematics
although questionable if up to a factor $1/{\sim}1300$

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

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).

- 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)

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
- tau-charm factories plausibly even less effective than 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