



Tau Physics experimental status and prospects

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Anomalies and Precision in the Belle II Era - Workshop
Schlosspark Business Hotel in Mauerbach, Vienna, Austria
6-8 September 2021

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 SM ν
- ▶ upper limits are effective constraints on NP models

Other searches for New Physics

- ▶ CPV in tau decay, tau EDM, 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 [B anomalies]
- ▶ Michel parameters

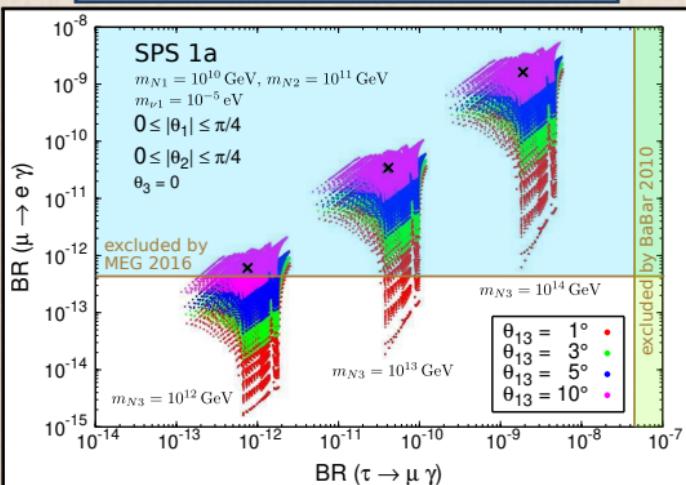
Standard Model with hadrons & QCD tests

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

Tau LFV searches probe & constrain New Physics models

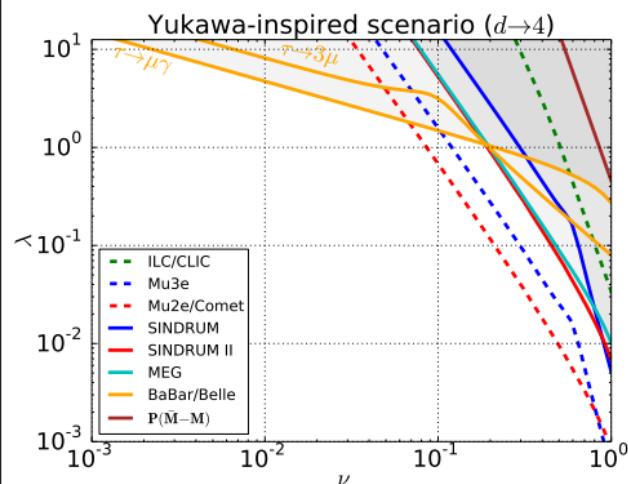
MSSM Seesaw

Antusch, Arganda, Herrero, Teixeira 2006



doubly charged scalar

Crivellin, Ghezzi, Panizzi, Pruna, Signer 2019



typical NP models

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

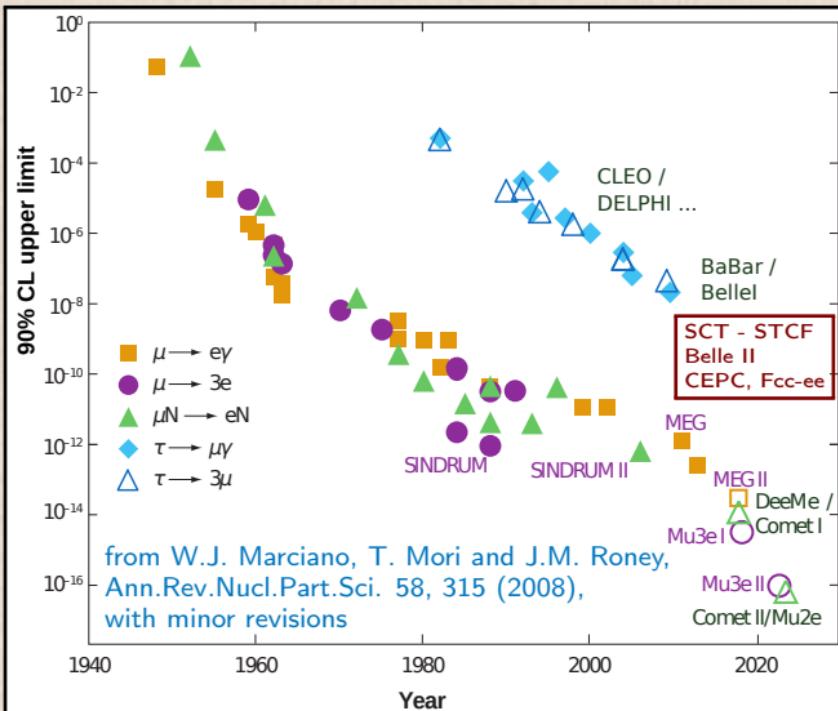
tau LFV experimental reach:

- less powerful but complementary to muon LFV for typical models
- more constraining than muon LFV for specific models

specific models / parameter space regions

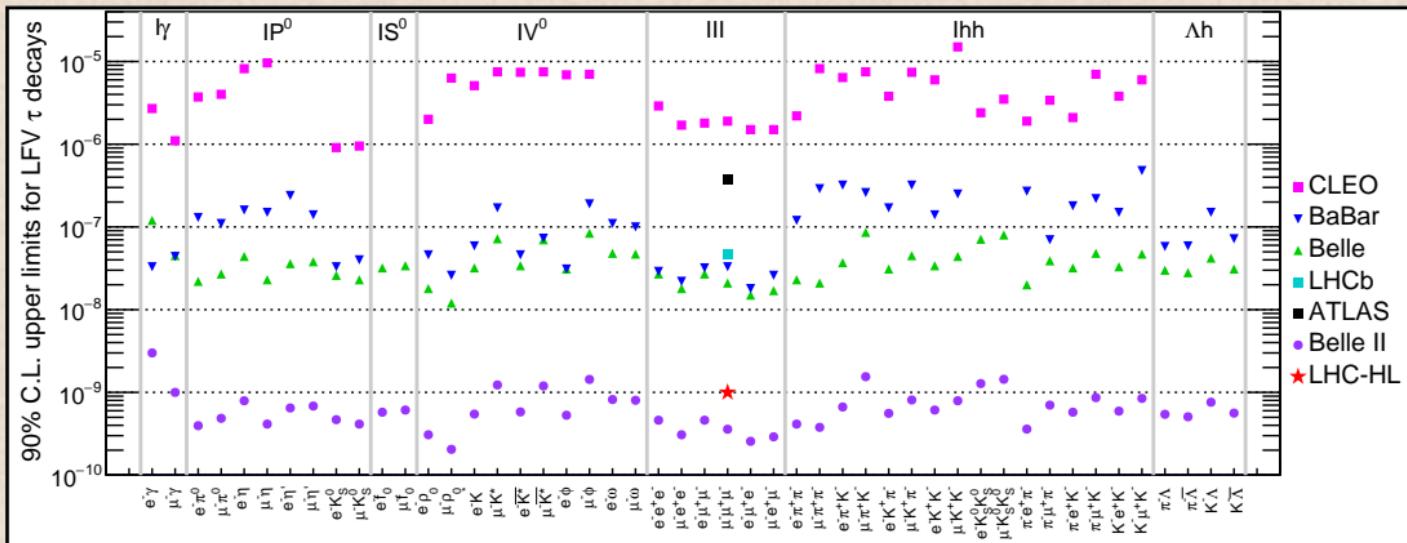
- part of plot only constrained by tau LFV limits

Present Tau LFV limits, present and future Muon LFV limits



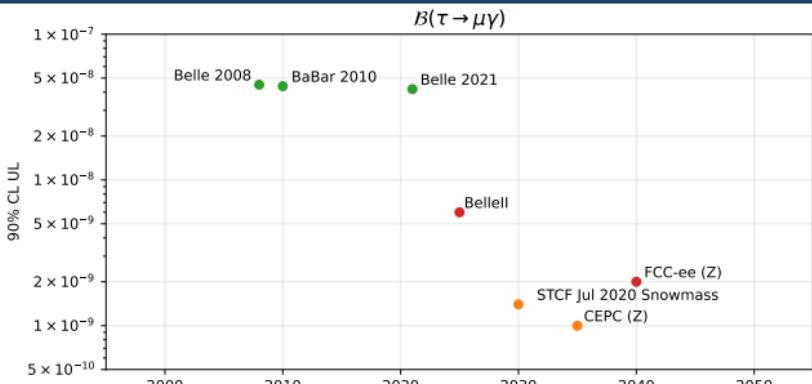
incoming years will provide remarkable progress on Muon LFV searches

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



HL-LHC and HE-LHC opportunities, arXiv:1812.07638 [hep-ph]
 (B-factories results and estimates from BelleII Physics Book)

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



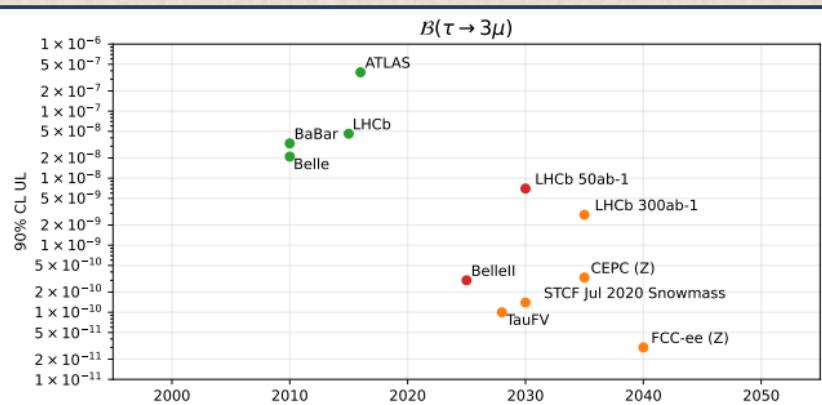
- ▶ Belle II estimates from Physics Book
- ▶ STCF estimate by [Xiaorong Zhou, Snowmass 2021 preparation, Jul 2020](#), assuming 10 ab^{-1}
- ▶ FCC-ee estimate from M. Dam simulation with 2% of full Fcc-ee statistics
- ▶ CEPC estimate from CEPC documentation

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 $\tau \rightarrow 3\mu$ (90% CL upper limit)

- ▶ Belle II estimates from Physics Book
- ▶ STCF estimate by [Xiaorong Zhou](#), [Snowmass 2021 preparation, Jul 2020](#), assuming 10 ab^{-1}
- ▶ FCC-ee limit my estimate
- ▶ CEPC limit from CEPC documentation
- ▶ TauFV (SPS protons on fixed-target, to search for $\tau \rightarrow \mu\mu\mu$) limit from TauFV proposal

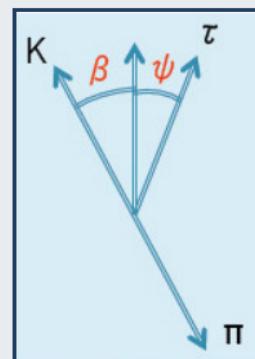
CPV in tau decay measurements

BaBar 2012, CPV in tau decay rates of $\tau^- \rightarrow \pi^- K_S^0 \nu$, SM test

- $A_{\text{CP, rate}} = \frac{\mathcal{B}(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) - \mathcal{B}(\tau^- \rightarrow \pi^- K_S^0 \nu)}{\mathcal{B}(\tau^+ \rightarrow \pi^+ K_S^0 \bar{\nu}_\tau) + \mathcal{B}(\tau^- \rightarrow \pi^- K_S^0 \nu)} = (-0.36 \pm 0.23 \pm 0.11)\%$
- deviates 2.8σ from SM prediction 0.36 ± 0.01

Belle 2011, CPV in angular distributions asymmetries, search for NP

- $\tau^- \rightarrow \pi^- K_S^0 \nu$
- interference of SM model (vector + scalar) with additional scalar interaction
 $\Rightarrow A_{\text{CP, ang}}(Q^2) = (\langle \cos \beta \cos \psi \rangle_{\tau^-} - \langle \cos \beta \cos \psi \rangle_{\tau^+})|_{Q^2}$
 $(\beta \text{ angle between } K_S^0 \text{ and } e^+ e^- \text{ CMS frame}$
 $\psi \text{ angle between } \tau \text{ and } e^+ e^- \text{ CMS frame})$
- $\text{Im}(\eta_S) < 0.026$ 90% CL (scalar interaction coupling)



CPV in tau decay prospects

CPV in tau decay rates of $\tau^- \rightarrow \pi^- K_S^0 \nu$, SM test

- ▶ [Belle II Physics Book](#): uncertainty will be reduced by $\sqrt{70}$
- ▶ similar precision attainable with STCF, [Chinese Physics C Vol. 45, No. 5 \(2021\) 053003](#)

CPV in angular distributions asymmetries, search for NP

- ▶ detailed theory framework in [Belle II Physics Book](#) with proposed measurements
- ▶ tau decay CPV from fit of 12-parameter angular distributions in tau pair $\rightarrow \pi^- K_S \nu \rightarrow \rho \nu$,
[D. Epifanov, STCF Workshop 2019](#)
 - ▶ can be performed at Belle II
 - ▶ advantages from tau polarization can be exploited at STCF
- ▶ tau decay CPV in CP-odd triple product distributions, $\vec{\sigma}_{\text{Pol}(\tau)} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^0})$ in $\tau^- \rightarrow \pi^- \pi^0 \nu$
[D. Epifanov, STCF Workshop 2019](#)
 - ▶ can be performed at Belle II
 - ▶ tau polarization enhances sensitivity at STCF

Tau $g-2$ and EDM

- ▶ discussed yesterday, [M. Fael, tau g-2 in tau decays and other probes of lepton flavour](#)
- ▶ Belle II can do precise measurements of effective a_τ , d_τ on tau pairs kinematic distributions
 - ▶ requires precise Monte Carlo of $e^+ e^- \rightarrow \tau^+ \tau^-$ including high perturbative order contributions
 - ▶ [Chen & Wu, JHEP 10 \(2019\) 089](#):
 $|d_\tau^{\text{NP,HE}}| < 2.04 \cdot 10^{-19} \text{ e cm}$, $|a_\tau^{\text{NP, HE}}| < 1.75 \cdot 10^{-5}$ (1.5% of SM prediction)
 - ▶ [Berreuther, Chen, Nachtmann, Phys.Rev.D 103 \(2021\) 9, 096011](#):
 $\delta \text{Re } d_\tau = 6.8 \cdot 10^{-20} \text{ e cm}$, $\delta \text{Im } d_\tau = 4.0 \cdot 10^{-20} \text{ e cm}$
- ▶ SCTF sensitivity would be enhanced by tau polarization

Lepton universality tests

A.L. elaboration for HFLAV, preliminary

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

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

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

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

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

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

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

Lepton universality tests with hadronic decays

A.L. elaboration for HFLAV, preliminary

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

Averaging the three g_τ/g_μ ratios:

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

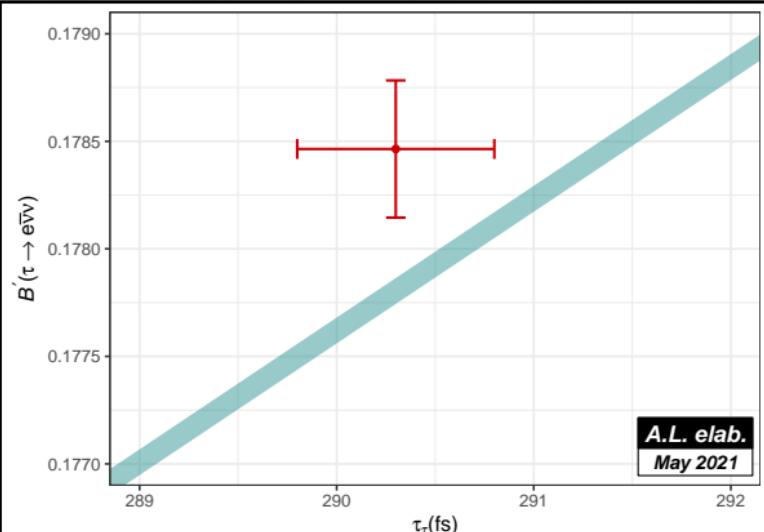
using Standard Model predictions

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

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

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

Canonical tau lepton universality test plot



no significant change w.r.t. HFLAV 2018

$$(g_\tau/g_{e\mu}) = 1.0019 \pm 0.0013$$

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

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

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

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

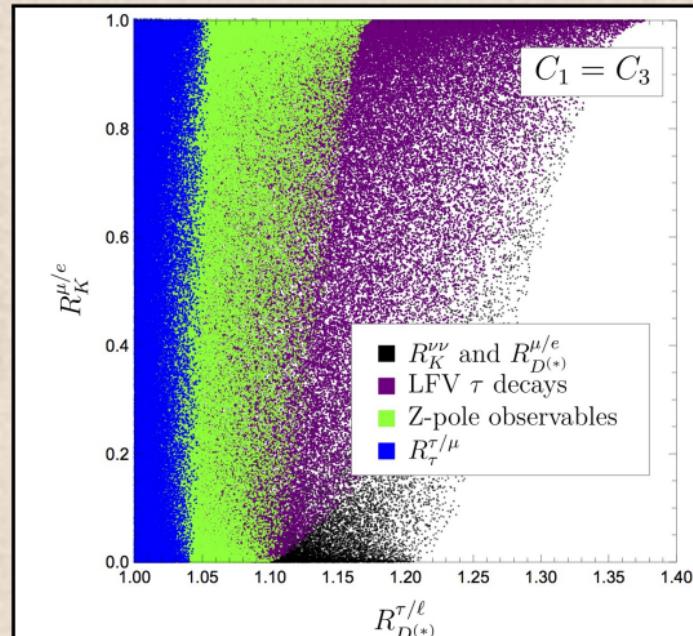
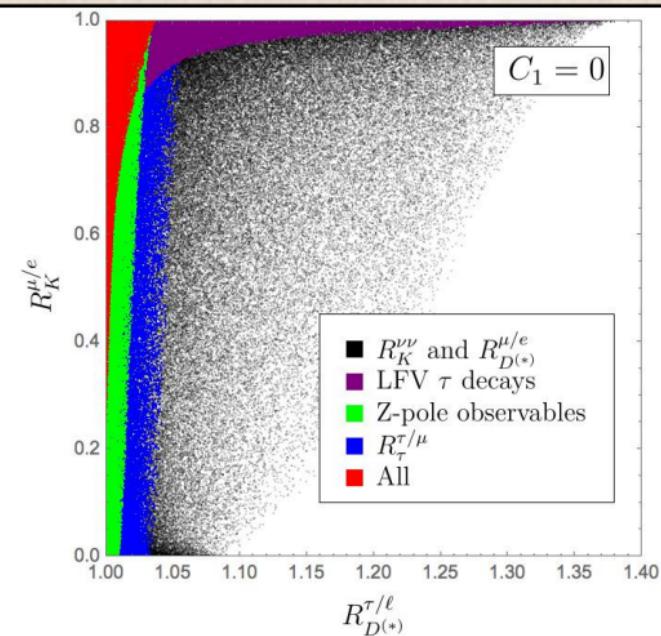
best measurements

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

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

[Feruglio, Paradisi, Pattori JHEP 09 \(2017\) 061](#)

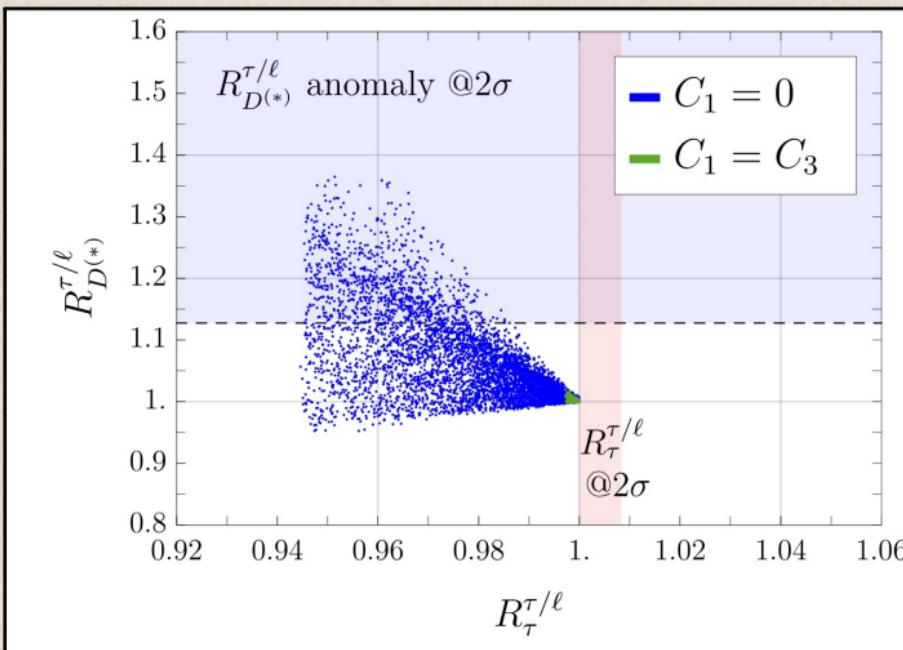
- ▶ black points are predicted by a model explaining the observed B anomalies
- ▶ blue points are 2σ -compatible with experimental bounds on tau lepton universality

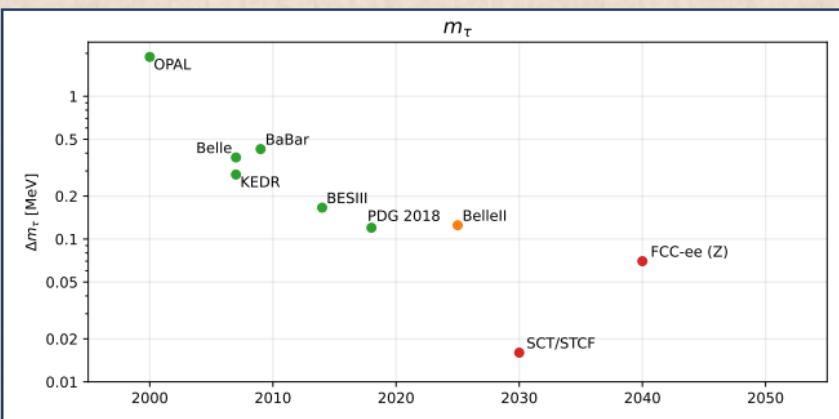


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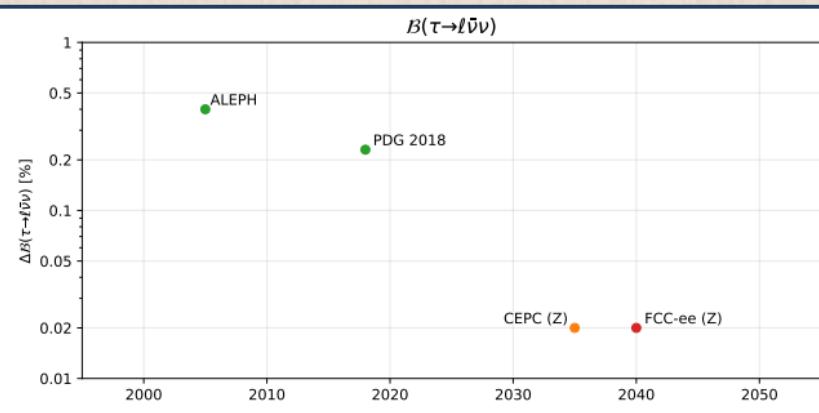
- ▶ blue points are predicted by a model explaining the observed B anomalies
- ▶ shaded areas are experimental 2σ -bounds on R_D and tau universality



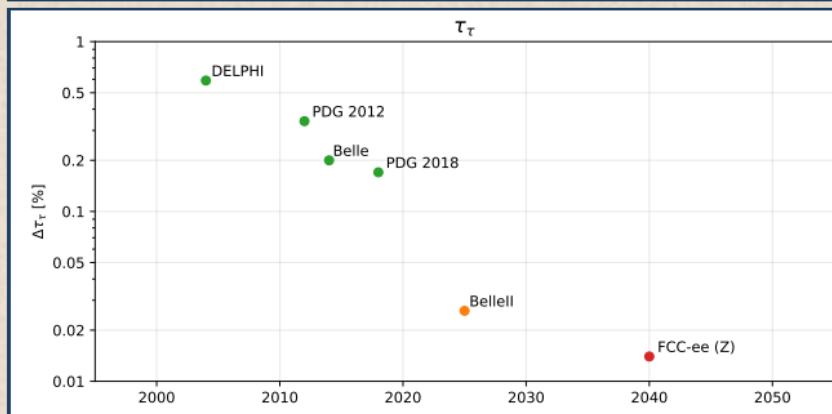
Physics reach on m_τ 

- ▶ best measurement at $e^+ e^- \rightarrow \tau^+ \tau^-$ production threshold, with precise E_{CM} measurement
- ▶ Belle II estimate from [Belle II Physics Book](#)
- ▶ FCC-ee estimate from [M.Dam, Fcc-ee Workshop Jan 2019](#)
- ▶ Tao Luo, [STCF indico web site](#), 10 May 2019: from 0.17 Mev at BES III to [0.016 MeV](#) at STCF

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



- ▶ difficult measurement at B -factories
- ▶ FCC-ee own estimate
- ▶ CEPC own estimate
- ▶ STCF might measure $\frac{\mathcal{B}(\tau \rightarrow \mu \bar{\nu} \nu)}{\mathcal{B}(\tau \rightarrow e \bar{\nu} \nu)}$ to 10 ppm, [V. Vorobyev, Charm 2020](#) (present W.A. precision 2800 ppm)



- ▶ with same statistics, Z-peak measurements are more precise than at lower energies
- ▶ my estimate for Belle II
- ▶ my estimate for FCC-ee [[FCC-ee meeting Jan 2020](#)]

$|V_{ud}| - |V_{us}|$ anomaly

- ▶ presented yesterday, [M. Kirk, The Cabibbo angle anomaly](#)
- ▶ $|V_{us}|$ can be obtained using tau measurements
 - ▶ one tau $|V_{us}|$ determination is independent from lattice QCD form factors and decay constants

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

Conventional, using kaon measurements and lattice QCD, most precise

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

Using tau measurements and OPE, no lattice QCD: : “tau-inclusive $|V_{us}|$ ”

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

Using tau measurements and lattice QCD

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

$|V_{us}|$ determinations using tau measurements

Gamiz et al. 2003 method

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

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

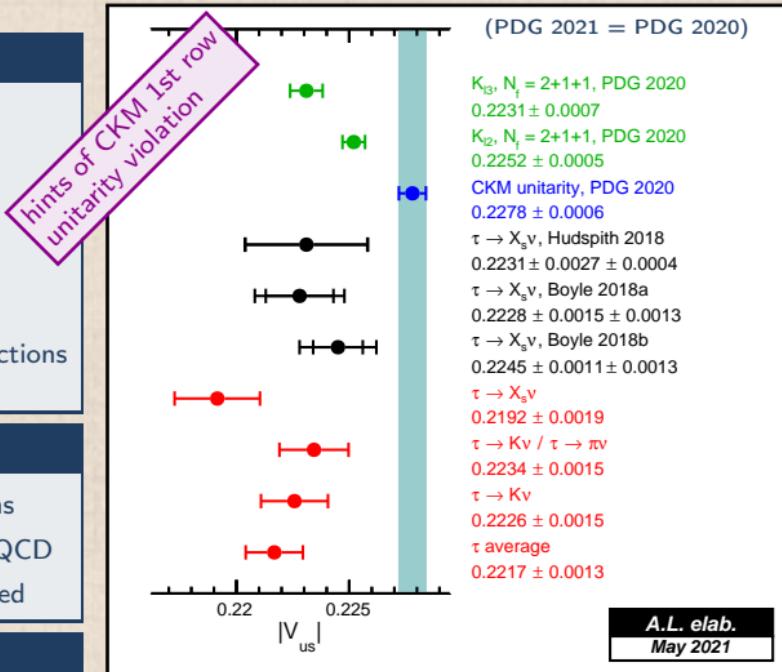
Gamiz, Jamin, Pich, Prades, Schwab 2003/2005
 δR_{theory} from OPE calculation + tau spectral functions
 does not require lattice QCD inputs

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

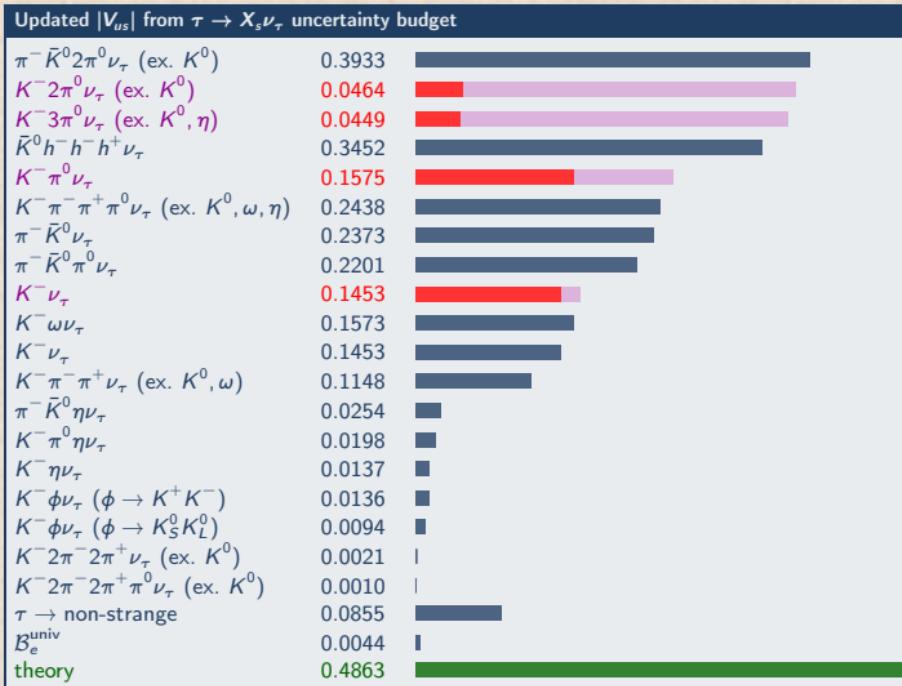
- ▶ Cabibbo-suppressed tau BRs
- ▶ tau spectral functions



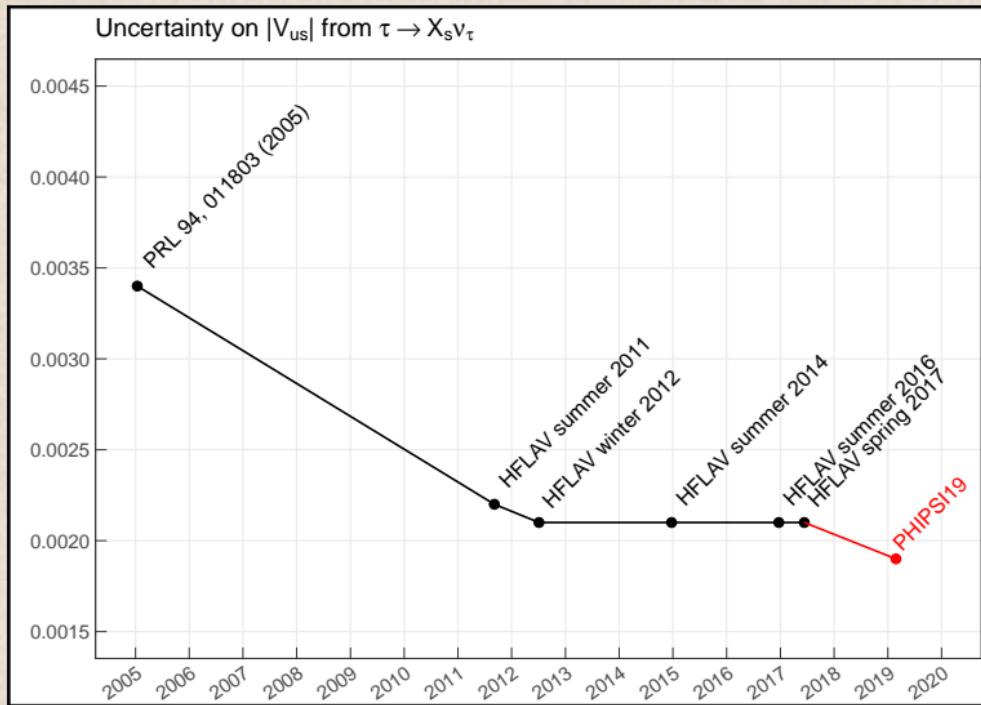
A.L. elab.
May 2021

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

$|V_{us}|$ from $\tau \rightarrow X_s \nu_\tau$ uncertainties budget: improvements with *BABAR* 2018 results



► shaded magenta bars report HFLAV Spring 2017 uncertainties before *BABAR* 2018 results

Uncertainty on $|V_{us}|$ from $\tau \rightarrow X_s \nu$ over time

- $|V_{us}|$ from $\tau \rightarrow X_s \nu$ uncertainty reduced significantly for the 1st time since 2013

Tau-inclusive $|V_{\mu s}|$ using kaon-BR-fraction-inferred tau branching fractions

M. Antonelli *et al.*, JHEP 10 (2013) 76

- ▶ predict tau BRs $\mathcal{B}(\tau \rightarrow K\nu)$
 $\mathcal{B}(\tau \rightarrow K\pi^0\nu)$ from kaon BRs $\mathcal{B}(K \rightarrow \ell\nu)$
 $\mathcal{B}(\tau \rightarrow K_s^0\pi\nu)$ $\mathcal{B}(K \rightarrow \ell\pi^0\nu)$
 - ▶ replace measurements of above tau branching fractions their predictions
 - ▶ compute $|V_{us}|$ with Gamiz *et al.* technique
 - ▶ other tau branching fractions from HELAV 2012

A.L., SciPost Phys. Proc. 1 (2019) 1

- ▶ use Antonelli 2013 predictions of 3 tau branching fractions, but rather than replacing the respective tau measurements, **statistically combine predictions and measurements in modified HFLAV tau BRs fit**
 - ▶ compute $|V_{us}|$ with Gamiz *et al.* technique
 - ▶ other tau branching fractions from:
 - ▶ HFLAV Spring 2017
 - ▶ *BABAR* ICHEP 2018 results (6 channels), *BABAR* 2018 paper (1 channel)

Tau hadronic decays: α_s

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

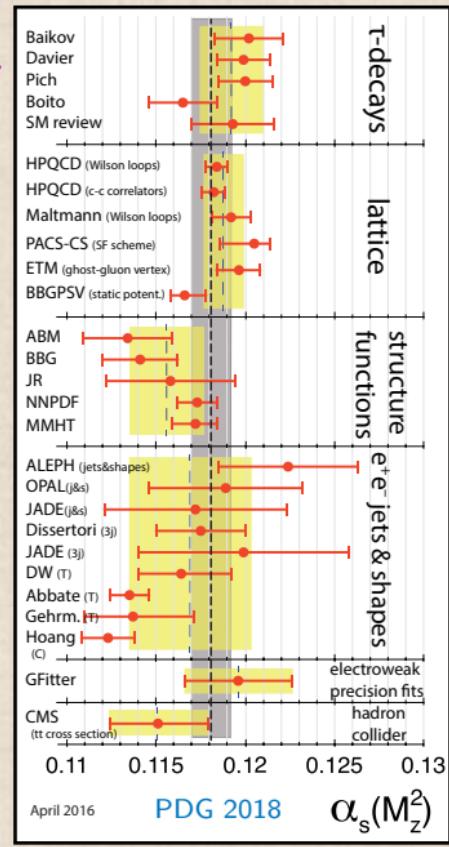
poor consistency among
 α_s determinations

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

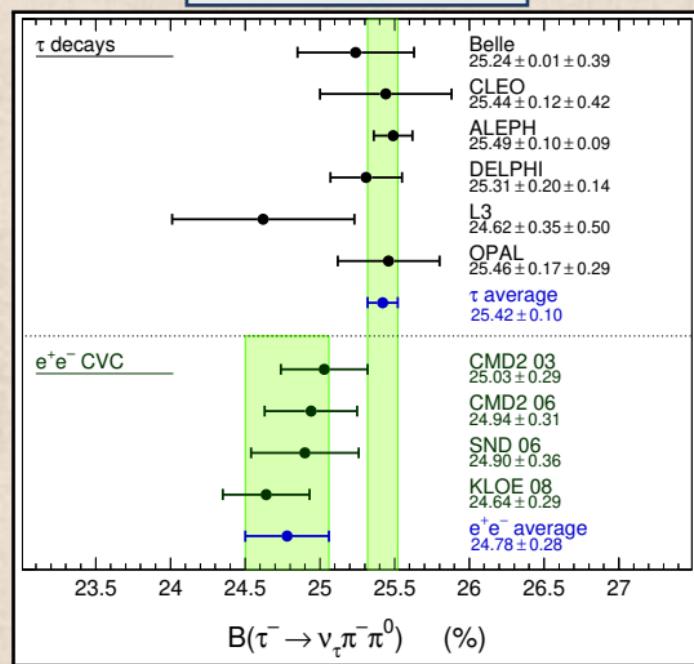


Tau hadronic decays: compute muon $g-2$ HVP contribution

EPJC C66, 127 (2010)

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

- ▶ ingredients
 - ▶ distribution $\tau \rightarrow \pi\pi^0\nu$ spectral function
 - ▶ normalization $\mathcal{B}(\tau \rightarrow \pi\pi^0\nu)$ & τ_τ
 - ▶ isospin rotation effect from theory
- ▶ $\mathcal{B}(\tau \rightarrow \pi\pi^0\nu)$ deviates from prediction based on $\sigma(e^+e^- \rightarrow \text{hadrons})$ measurements
- ▶ a_μ^{th} with tau HVP \sim 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
- ▶ background separation from dileptons and hadrons much better
- ▶ higher selection purity and efficiency
- ▶ tau's are boosted and topologically separate, facilitating reconstruction
- ▶ possible to tag single tau with good efficiency and purity and observe the other one
⇒ very useful to systematics reduction
- ▶ B -factories improved on small branching fractions using statistics
- ▶ limited progress on spectral functions with B -factories
- ▶ Belle II may contribute exploiting its larger statistics
- ▶ STCF may contribute in specific channels that profit from tau pair production close to threshold
- ▶ non-trivial to improve w.r.t. LEP measurements

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

$$\begin{aligned} \blacktriangleright \frac{d\Gamma(\tau^\mp \rightarrow \ell^\mp \bar{\nu}_\ell \bar{\nu}_t au)}{d\Omega dx} &= \frac{4G^2 M_\tau E_{\max}^4}{(2\pi)^4} \sqrt{x^2 - x_0^2} \cdot \\ &\cdot \left(x(1-x) + \frac{2}{9} \textcolor{red}{p}(4x^2 - 3x - x_0^2) + \textcolor{violet}{n}x_0(1-x) \mp \frac{1}{3} P_\tau \cos \theta_\ell \xi \sqrt{x^2 - x_0^2} \left[1 - x + \frac{2}{3} \textcolor{blue}{d}(4x - 4 + \sqrt{1 - x_0^2}) \right] \right) \\ x = \frac{E_\ell}{E_{\max}}, \quad E_{\max} &= \frac{M_\tau}{2} \left(1 + \frac{m_\ell^2}{M_\tau^2} \right), \quad x_0 = \frac{m_\ell}{E_{\max}} \end{aligned}$$

- ▶ best measurements from LEP, about 1% precision
- ▶ on-going analysis using Belle data (D. Epifanov)
- ▶ good prospects at Belle II
- ▶ SCTF could profit from tau polarization [D. Epifanov, Phys. Atom. Nucl. 83 (2020) 6, 944]

Conclusions

- ▶ tau searches are effective probes for New Physics effects
- ▶ several tau precision measurements can contribute to understanding the presently observed anomalies
- ▶ Belle II promises significant progress in the near future
- ▶ future facilities may further contribute

Thanks for your attention!

Backup Slides

CPV in tau decay, angular distribution asymmetry

D. Epifanov, SCTF-2019 Workshop, Moscow

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

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

$$\frac{d\Gamma(\tau^\mp(\vec{\zeta}^*) \rightarrow (K\pi)^\mp \nu)}{dm_{K\pi}^2 d\Omega_{K\pi}^* d\tilde{\Omega}_\pi} = \begin{cases} (A_0 + \eta_{CP} A_1) + (\vec{B}_0 + \eta_{CP} \vec{B}_1) \vec{\zeta}^* \\ (A_0 + \eta_{CP}^* A_1) - (\vec{B}_0 + \eta_{CP}^* \vec{B}_1) \vec{\zeta}^* \end{cases}$$

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

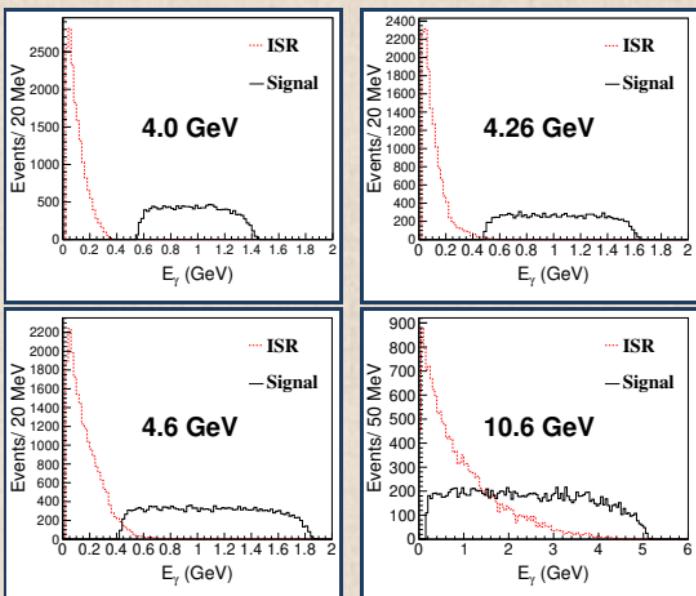
$$\mathcal{F} = D_0 A_0 A' - D_{ij} B_{0i} B'_j, \quad \mathcal{G} = D_0 A_1 A' - D_{ij} B_{1i} B'_j$$

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

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

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

- ▶ search limited by accidental combinations with ISR photons with leptonic SM decays $\tau \rightarrow \ell\bar{\nu}\nu$
- ▶ 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 $\tau \rightarrow \mu\gamma$ at HIEPA", Sci.Bull. 61 (2016) 4, 307

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 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
- ▶ $\mathcal{B}(\tau \rightarrow \mu\gamma) < \sim 1 \cdot 10^{-9}$ 90% CL detailed study with BelleII sample, may be optimistic
- ▶ $\mathcal{B}(\tau \rightarrow 3\mu) < 3.3 \cdot 10^{-10}$ 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 $\mathcal{B}(\tau \rightarrow \ell\bar{\nu}\nu)$ 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]

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

$\text{BR}(\tau \rightarrow 3\mu)$ (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})

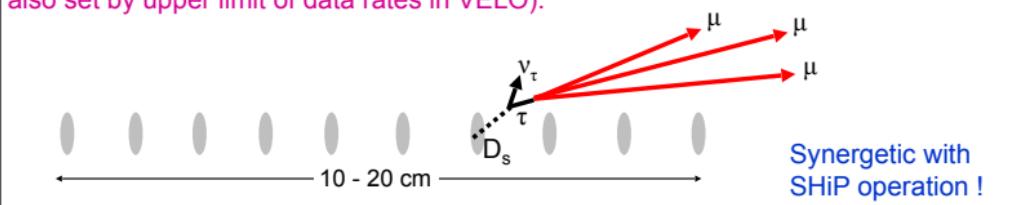
- ▶ $\mathcal{B}(\tau \rightarrow 3\mu)$ 90% CL

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

TauFV, project, SPS protons on fixed-target, 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).



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

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 $\Delta\mathcal{B}(\tau \rightarrow \ell\bar{\nu}\nu) \sim 0.02\%$ (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 $5 \cdot 10^{12} Z$ s, $15 \cdot 10^{10}$ 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 $\Delta m_\tau \sim 0.07$ MeV (by calibrating on m_{D^+} , PDG 2018 WA ± 0.12 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 $\tau \rightarrow \mu\mu\mu$

BelleII sensitivity (Physics Book)

- ▶ extrapolated 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: $5\text{e}12 Z \times 3.3\% = 1.65\text{e}11$, $3.5\times$ than BelleII
- ▶ assume selection efficiency $4\times$ better from comparison of DELPHI and *BABAR* $\tau \rightarrow \mu\gamma$ 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 $\tau \rightarrow \mu\gamma$ 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

Required measurements for Tau Lepton Universality

$\mathcal{B}_{\tau \rightarrow l \bar{\nu} \nu}$, $\mathcal{B}_{\tau \rightarrow h \nu}$

- ▶ 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)

new dispersive calculation

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

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

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

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

1.8 σ 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

Tau Lifetime

τ MEAN LIFE

PDG 2019

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

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 Lifetime systematics at Fcc-ee

Alignment systematic

- ▶ alignment calibration precision improves with statistics
- ▶ misalignment effects zero at first order for uniform azimuthal 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, reliable 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)

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-t 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-t 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

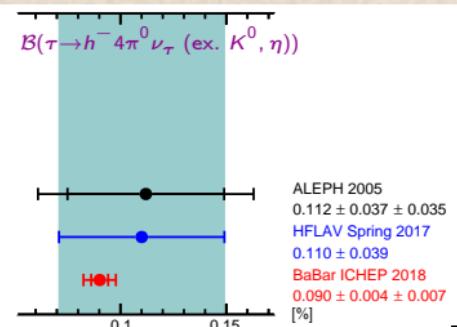
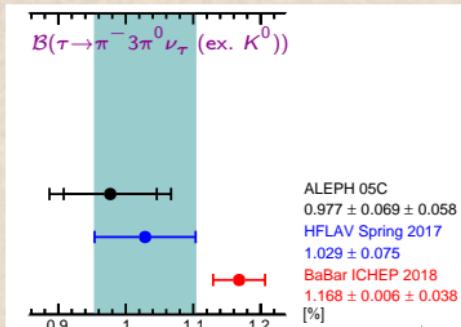
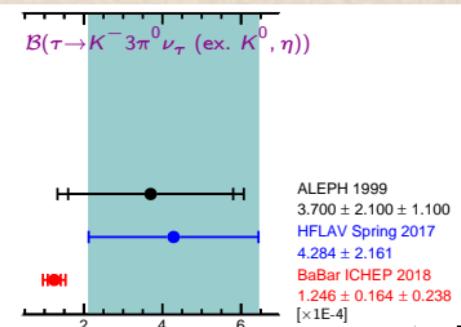
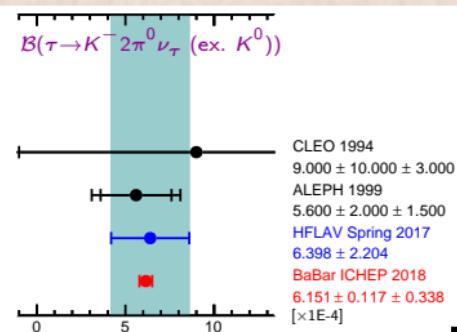
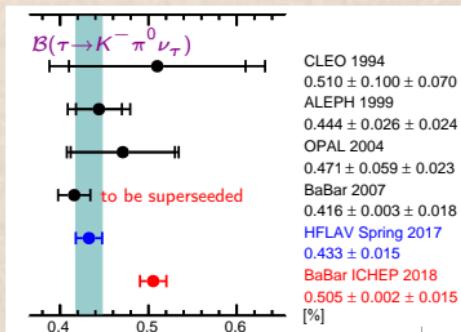
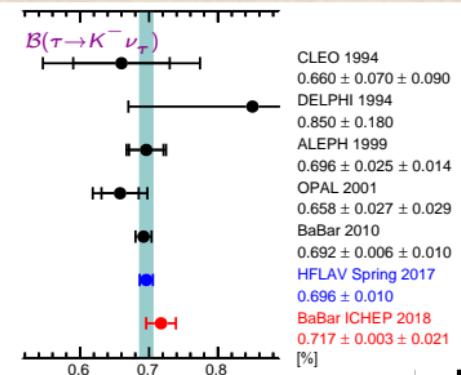
Main systematics of ALEPH tau BR paper, Phys. Rept. 421 (2005) 191

- ▶ 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 energy in calorimeter cells
- ▶ radiative and bremsstrahlung photons
 - ▶ compare data and MC distributions
 - ▶ compare PHOTOS vs. exact calculation for $\tau \rightarrow \pi\pi^0\nu$ with radiative $E_\gamma > 12$ 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 reliable way
- ▶ guesstimate: assume total uncertainty 10× better than WA, which is about 20× better than ALEPH

BaBar 2018 preliminary tau BR measurements



► B_{BABAR} 2007 $\mathcal{B}(\tau \rightarrow K^- \pi^0 \nu_\tau)$ measurement will be superseeded (less refined than this study)