Overview of tau physcis at present and future e^+e^- colliders

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Introduction

The tau lepton is a fundamental particle of the Standard Model (SM) and in general it is useful to measure its properties precisely both to test the Standard Model and to search for evidence of physics beyond the Standart model (BSM, NP)

main Standard Model tests and parameters' measurements

- Lepton Flavour Universality (LFU), i.e. (mainly) charged weak coupling is equal for e, μ, τ
  - important NP model constraints for observed B anomalies and CKM 1st row unitarity violation
- SM-predicted Michel parameters, i.e. decay kinematics dictated by $V-A$ charged weak current
- measurement of $\alpha_s(m_\tau)$ and test of running of α_s from m_τ to m_Z
- measurement of $|V_{us}|$ (alternative to kaon decays, less precise)
- alternative measurement of HVP contribution to muon $g-2$ [muon $g-2$ anomaly]

main New Physics searches

- Lepton Flavour Violation (LFV) in tau decay
- CPV in tau decay, tau EDM, tau $g-2$

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

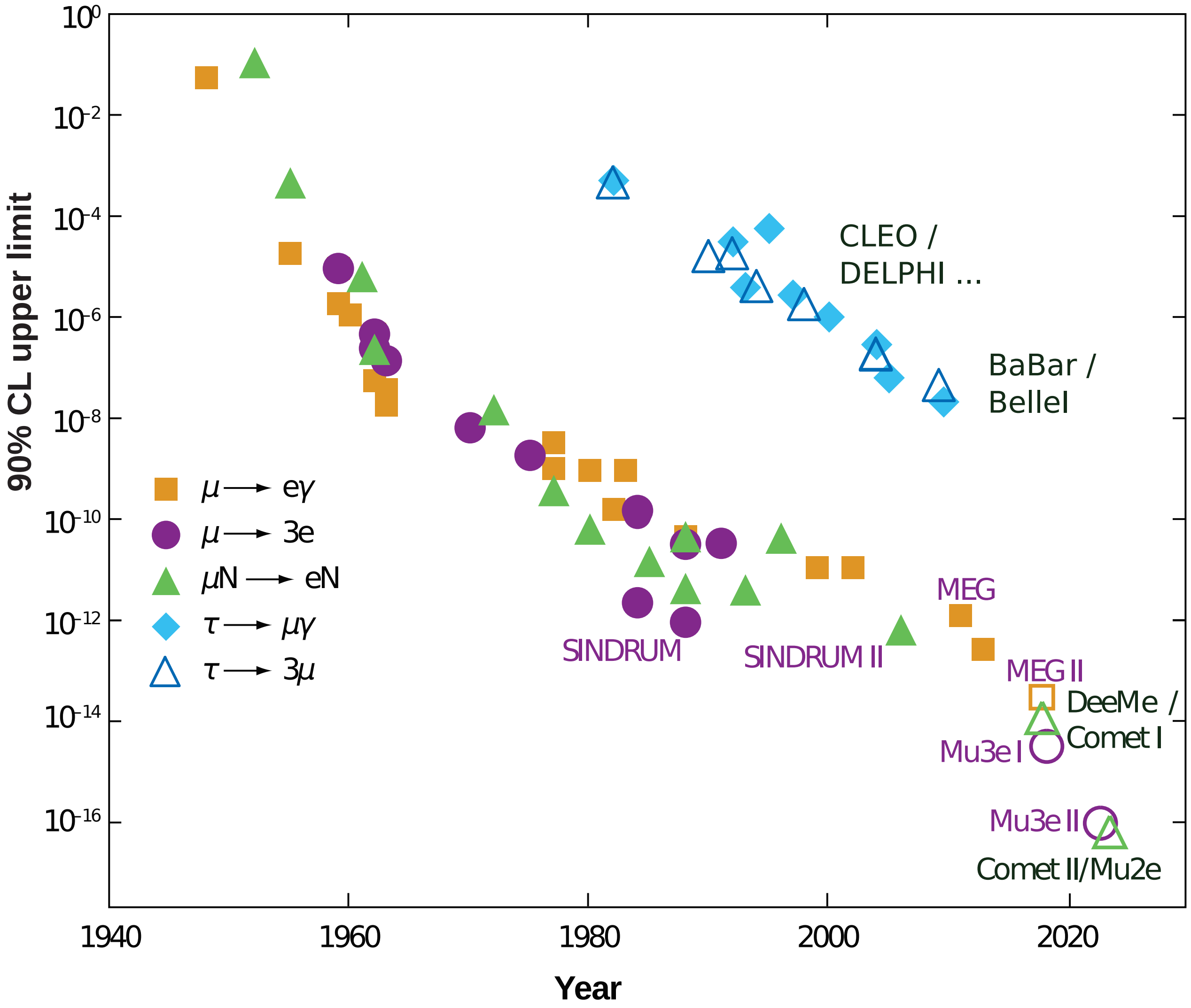
	CLEO, CLEOIII	LEP 100	Belle, BABAR	Belle II	SCT	STCF	CEPC(Z)	FCC-ee(Z)
E_{CM} [GeV]	~10.6	92	~10.6	~10.6	$2-6$	$2-7$	92	
$\int \mathcal{L} dt$ [ab^{-1}]	0.01		1.5	50	10			
tau pairs	$1{\cdot}10^7$	$0.8{\cdot}10^6$	$1.4{\cdot}10^9$	$46{\cdot}10^9$	$30{\cdot}10^9$		$30{\cdot}10^9$	$165{\cdot}10^9$

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

Conditions for tau physics measurements

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

LFV searches vigorously pursued

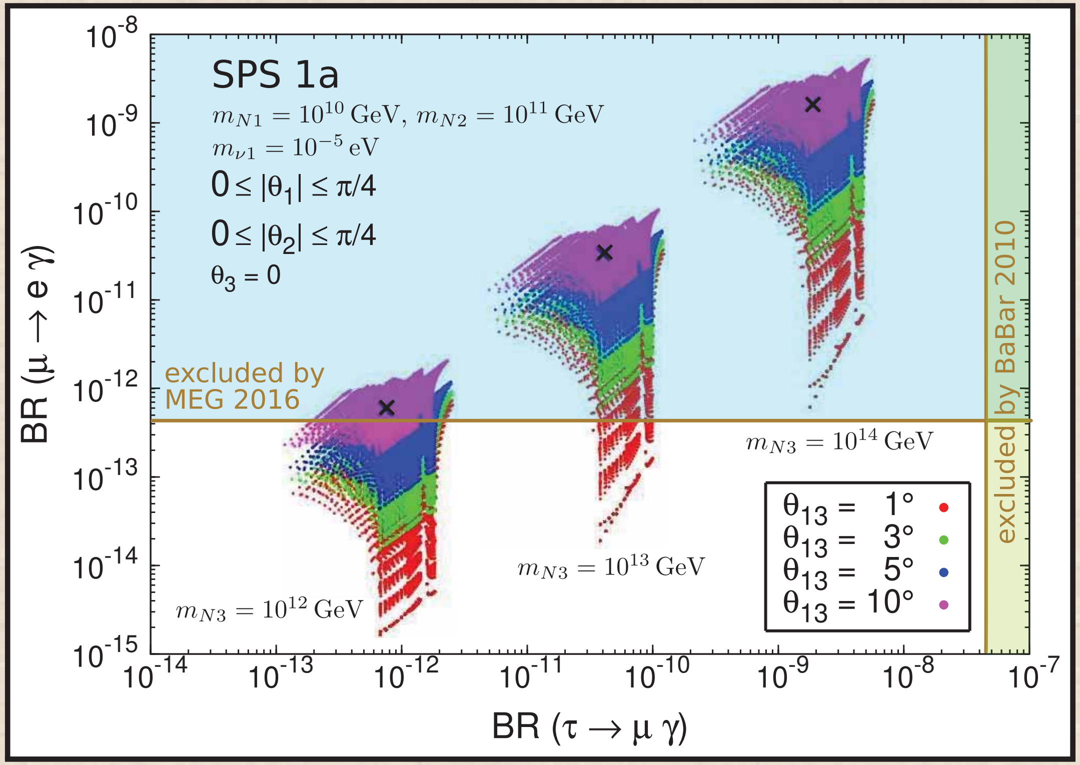


Updated from W.J. Marciano, T. Mori and J.M. Roney, Ann.Rev.Nucl.Part.Sci. 58, 315 (2008)

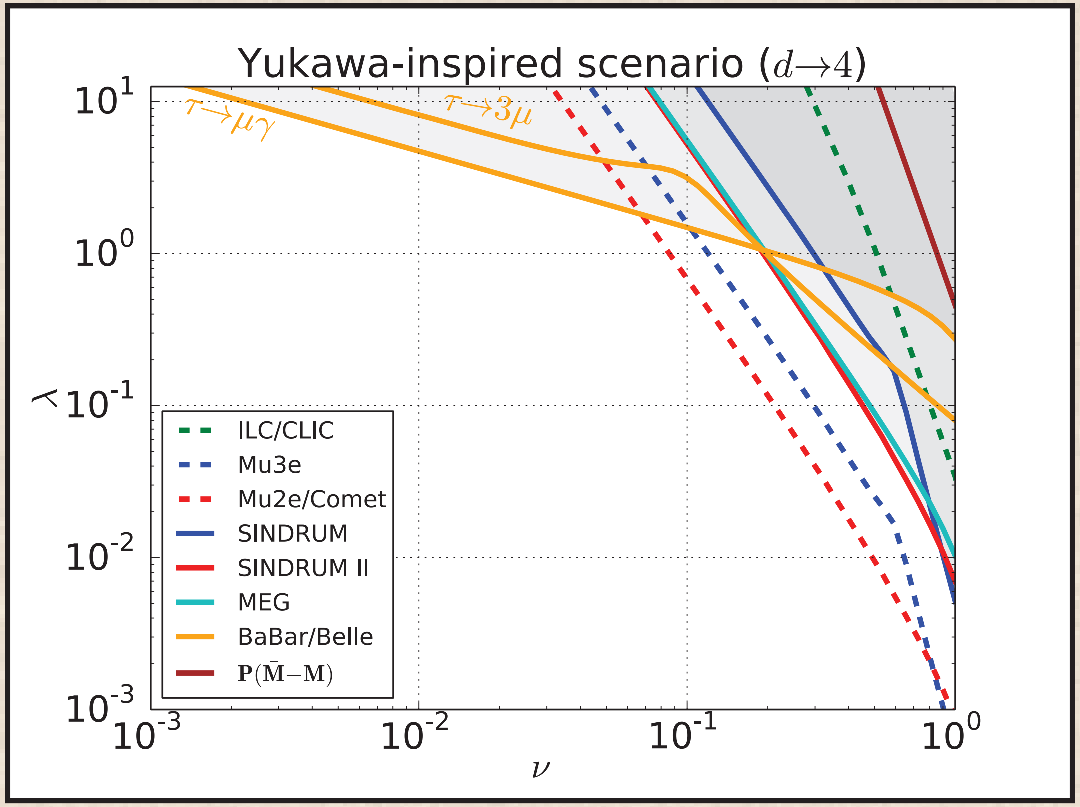
- NP effects usually scale as $\frac{m_\tau^2}{m_\mu^2}$
- muon LFV searches more powerful
- tau LFV has more channels
  $\Rightarrow$ discrimination on NP models
  $\Rightarrow$ more powerful for specific models

Tau LFV searches probe & constrain New Physics models

MSSM Seesaw
Antusch, Arganda, Herrero, Teixeira 2006



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



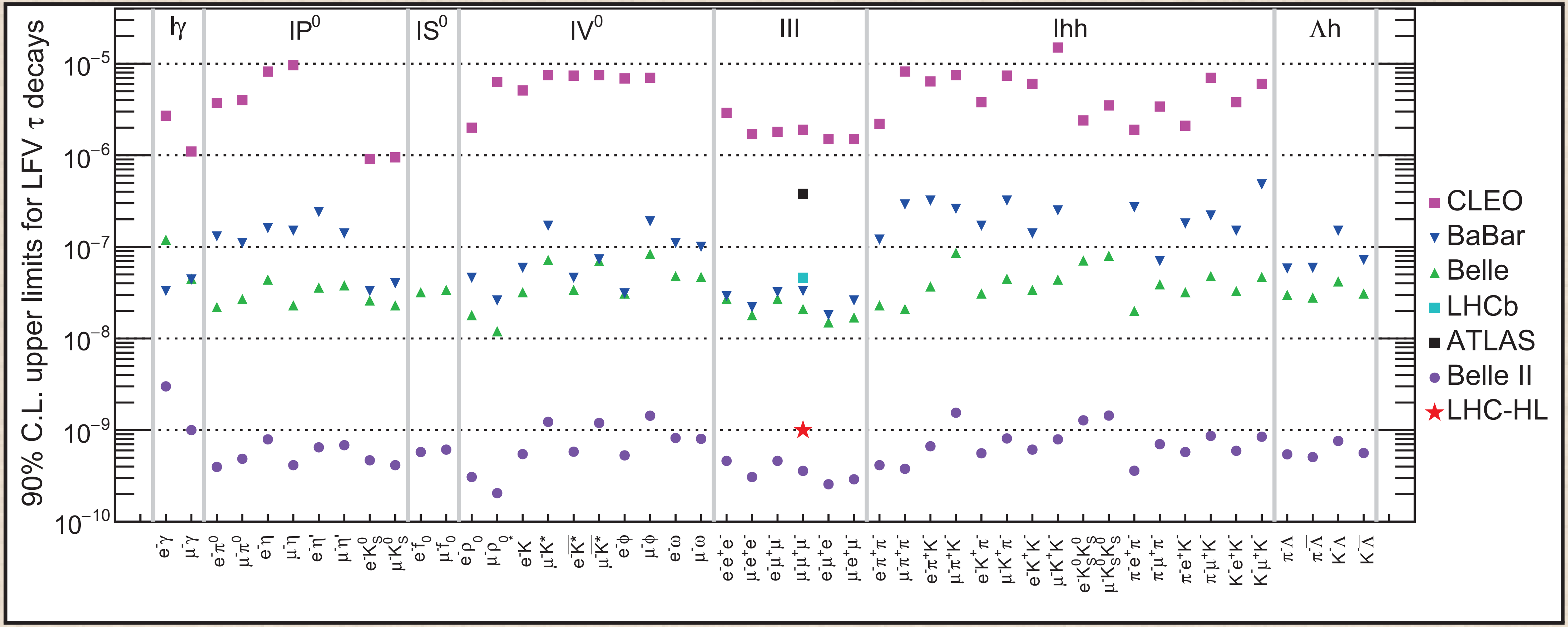
typical NP models

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

specific models / parameter space regions

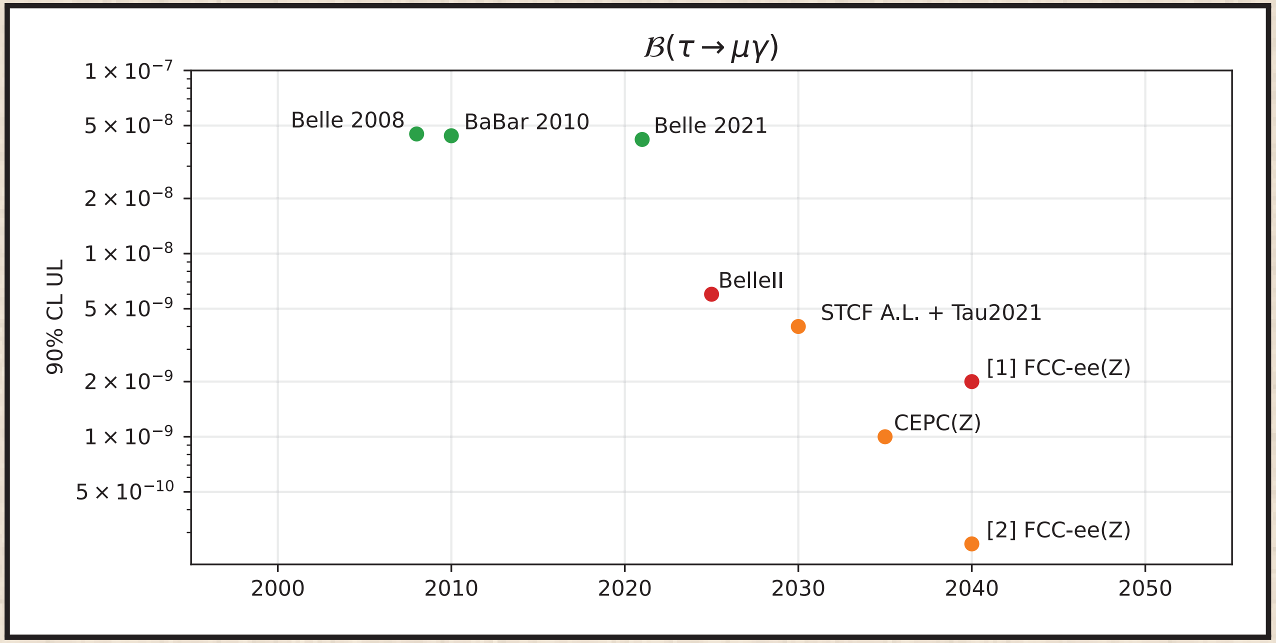
- part of plot only constrained by tau LFV limits

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



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

LFV $\tau \to \mu\gamma$ measured / expected upper limits



FCC estimate for $\tau \to \mu\gamma$

[1] M. Dam simulation with 2% of full FCC statistics

[2] M. Dam 2021, guestimate with improved longitudinally segmented crystal EM calorimeter

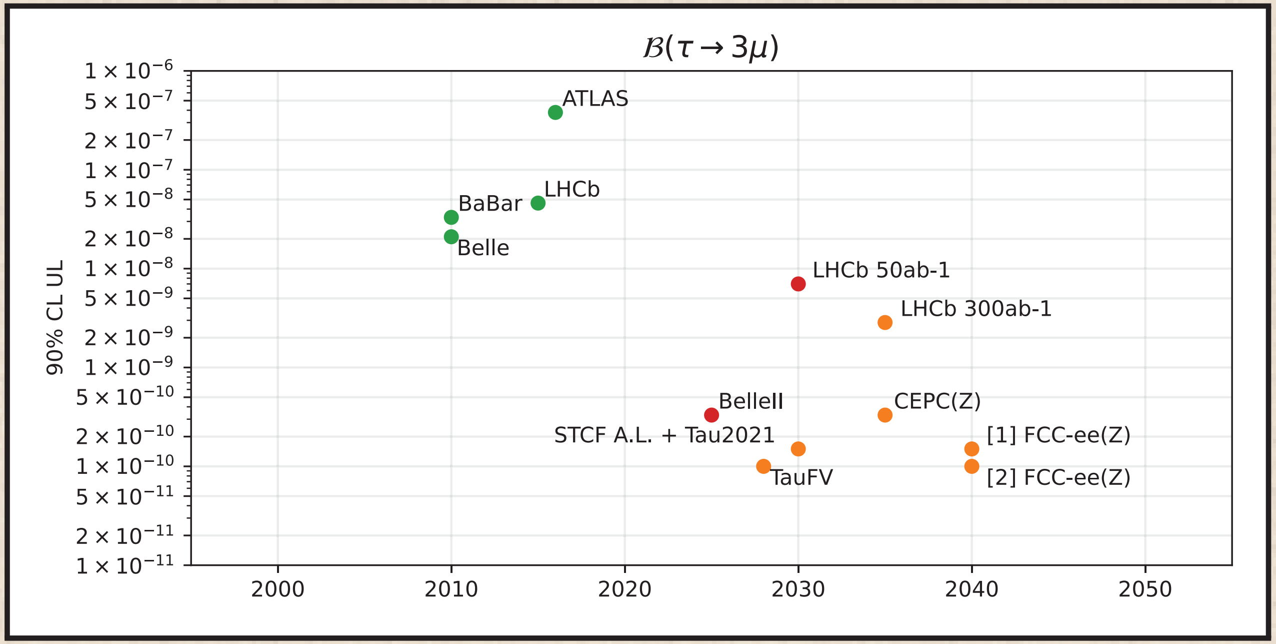
Other estimates

- ESG 2019 docs
- my extrapolation to 10y of SCTF limits presented at Tau2021

Plot notes

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

LFV $\tau \to 3\mu$ measured / expected upper limits



FCC estimate for $\tau \to \mu\mu\mu$

[1] my guestimate

[2] M. Dam, Tau2021

Other estimates

- ESG 2019 doc
- my extrapolation to 10y of SCTF limits presented at Tau2021

Guestimate of FCC expected 90% upper limit on $\tau \to \mu\mu\mu$

- $2.1{\cdot}10^{-8}$ published Belle limit at 0.782 ab^{-1}
- $/(50\ \text{ab}^{-1}/0.782\,\text{ab}^{-1}) = 3.3{\cdot}10^{-10}$, BelleII expected upper limit assuming background-free search
- FCC: $5{\cdot}10^{12}$ Z^0, 3.3% tau pair decays, $165{\cdot}10^{9}$ tau pairs, $\sim 3.6 \times 46{\cdot}10^{9}$ BelleII tau pairs
- estimate $4\times$ better efficiency at FCC vs. BelleII
  - from DELPHI Phys.Lett. B359 (1995) 411-421 vs. BABAR Phys.Rev.Lett. 104 (2010) 021802
- muon PID efficiency and purity expected to be better for FCC
- in the improbable assumption that search remains backgroound free
  - $3.3{\cdot}10^{-10}/3.6/4.0 = 0.23{\cdot}10^{-10}$ estimated FCC 90% upper limit
- estimate / assume that
  - m_τ resolution comparable with B-factories
  - E resolution worse (850 MeV in M. Dam $\tau \to \mu\gamma$ study vs. 50-100 MeV $\approx$ 75 MeV in BABAR)
  - therefore search remains background free until $N^{\text{BelleII}}_{\tau^+\tau^-}/(850\,\text{MeV}/75\,\text{MeV})$
  - additional tau pairs improve upper limit proportionally to the square root (estimated bkg uncertainty)
- $3.3{\cdot}10^{-10} \cdot (850\,\text{MeV}/75\,\text{MeV})/\sqrt{[3.6 \cdot (850\,\text{MeV}/75\,\text{MeV})]}/4.0 \simeq 1.5{\cdot}10^{-10}$ FCC upper limit

Notes for tau LFV searches at FCC

- $\tau \to \mu\gamma$ reach improves with
  - energy resolution of EM calorimeter
  - angular precision (granularity) of EM calorimeter
  - efficiency & purity of muon PID
- $\tau \to 3\mu$ reach improves with
  - momentum resolution and tracking reconstruction accuracy
  - efficiency & purity of muon PID
  - other LFV searches profit from electron, pion, kaon PID
- existing Monte Carlo simulation technology seems sufficient

Lepton universality tests

from HFLAV Tau winter 2022 report

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

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

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

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

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

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

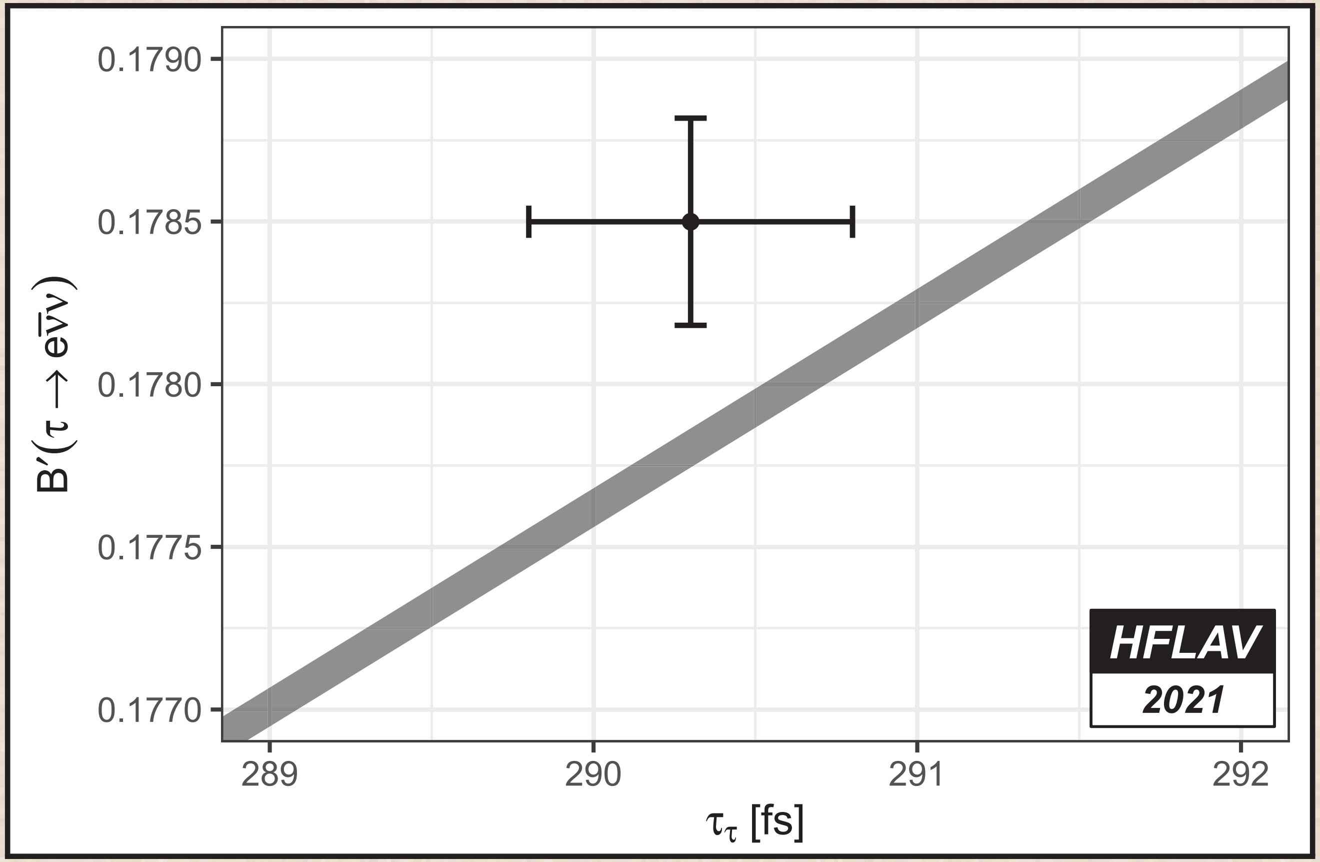
$$R_W^\lambda = 1 + \frac{3}{5}\frac{m_\lambda^2}{M_W^2} + \frac{9}{5}\frac{m_\rho^2}{M_W^2}\ ; \qquad R_\gamma^\lambda = 1 + \frac{\alpha(m_\lambda)}{2\pi}\left(\frac{25}{4} - \pi^2\right)\ ;$$

all statistical correlations included

LFU tests with hadronic tau decays

- are possible and performed, but less precise

Canonical tau lepton universality test plot



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

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

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

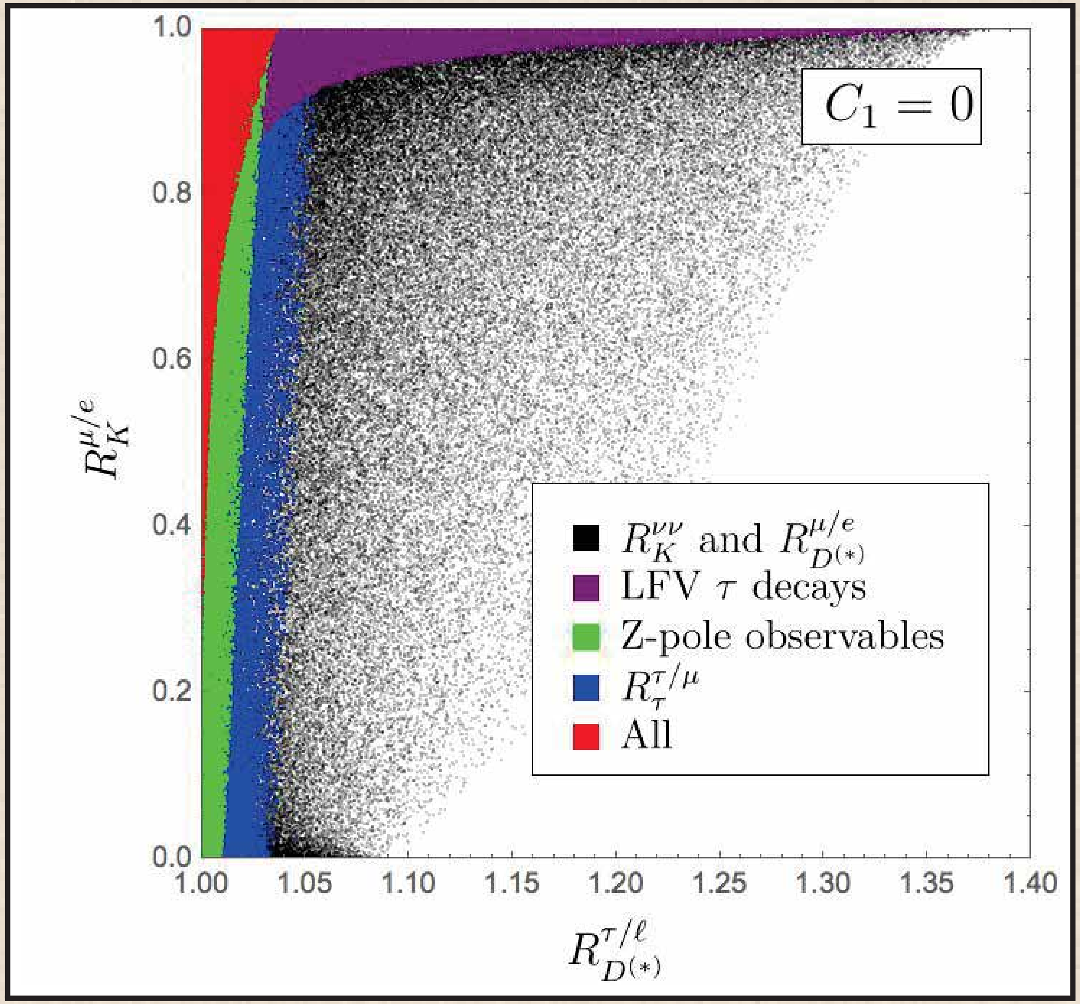
input	Δinput	$\Delta(g_\tau/g_{e\mu})$
$\mathcal{B}'_{\tau\to e}$	0.180%	0.090%
τ_τ	0.172%	0.086%
m_τ	0.007%	0.017%
total		0.126%

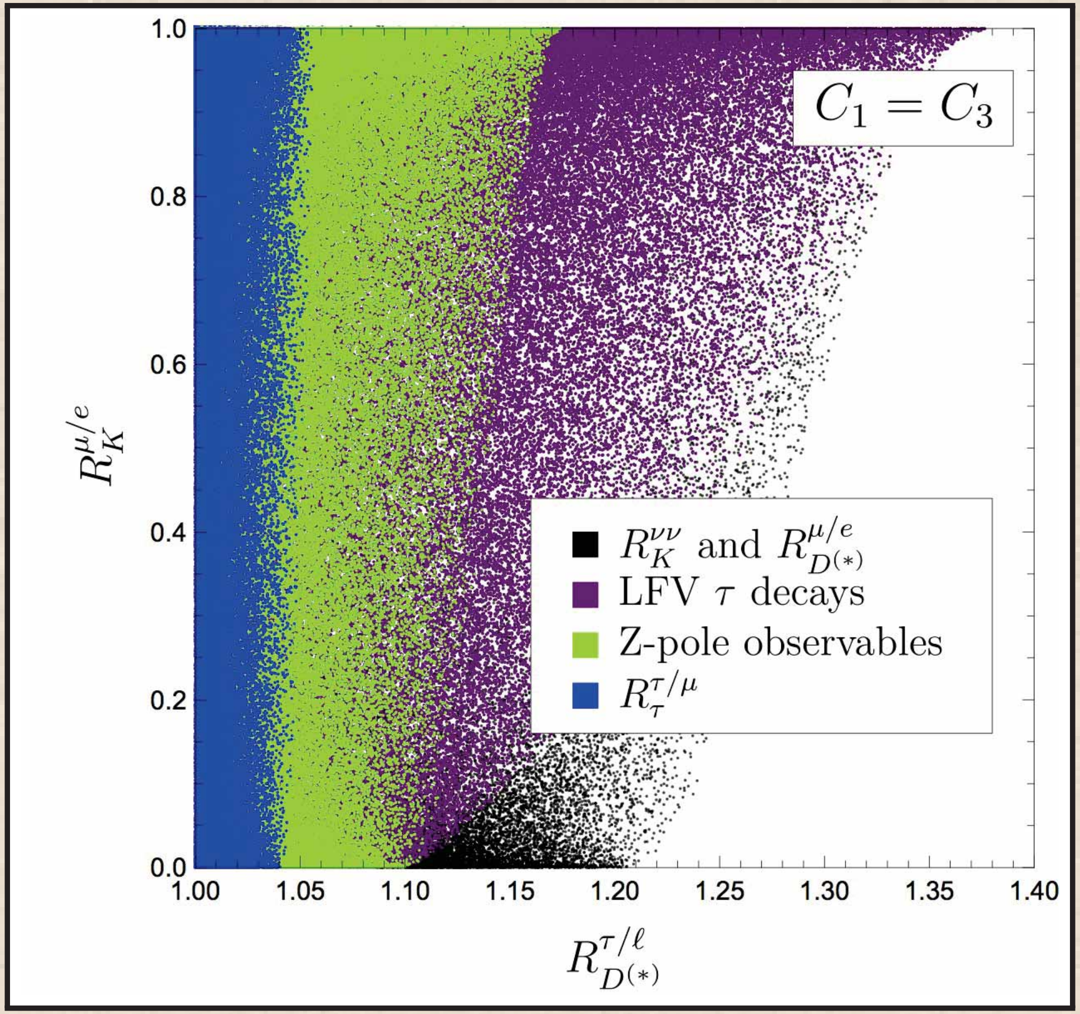
best measurements

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

Tau 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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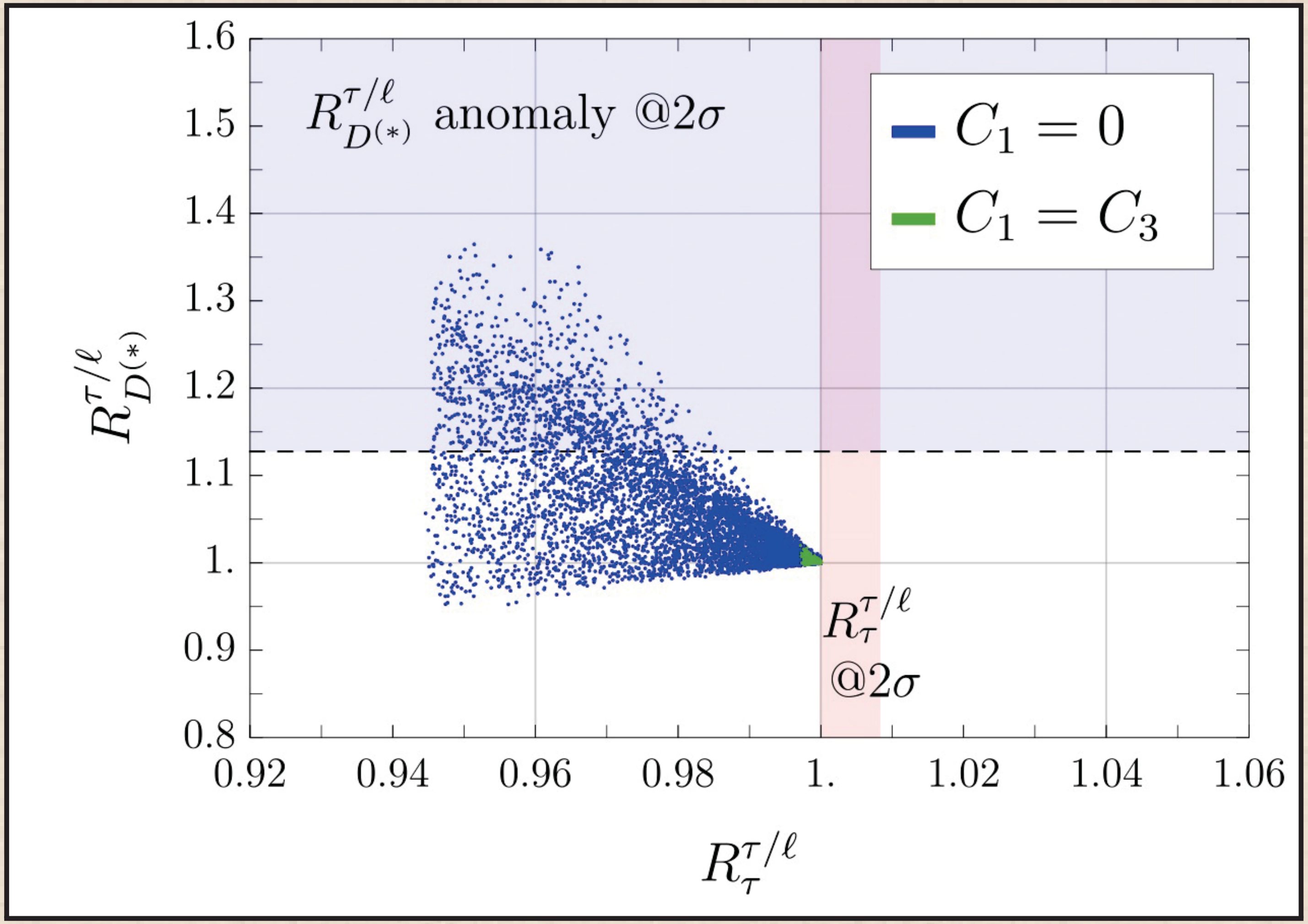
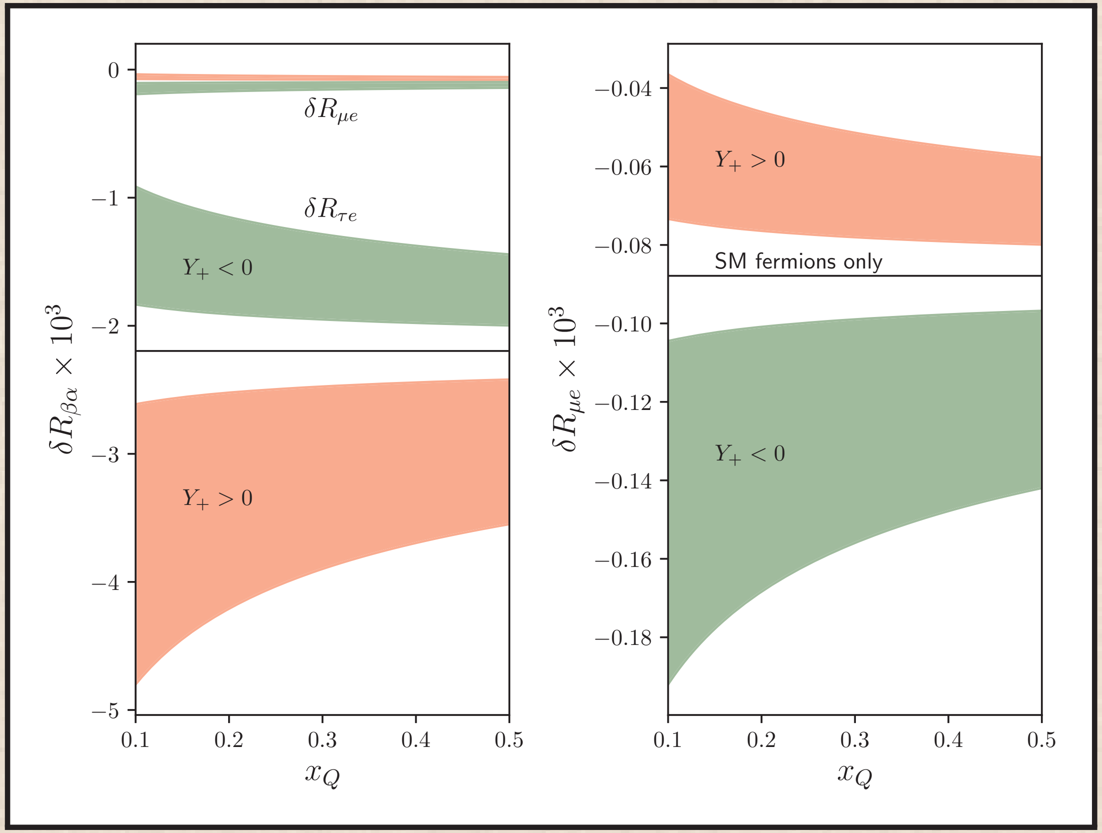
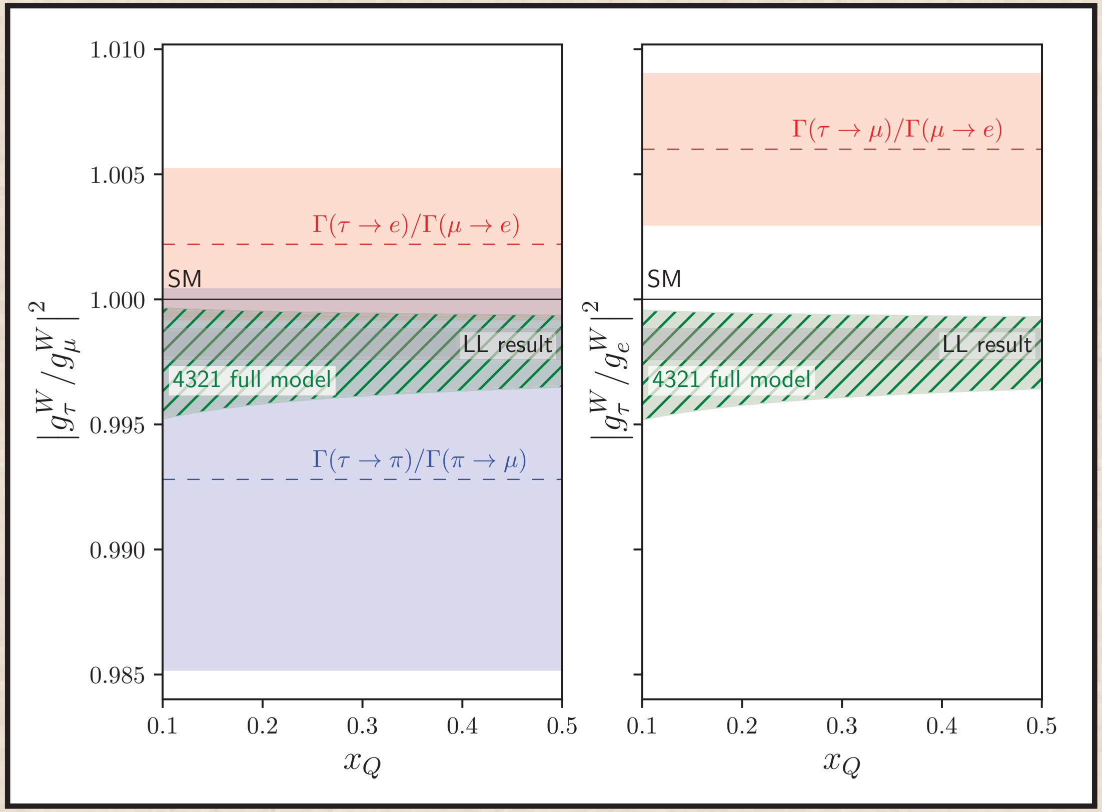


Tau Lepton universality constrains 4321 models for B $R_{D^{(*)}}^{\tau/\ell}$- $R_K^{\mu/e}$ anomalies

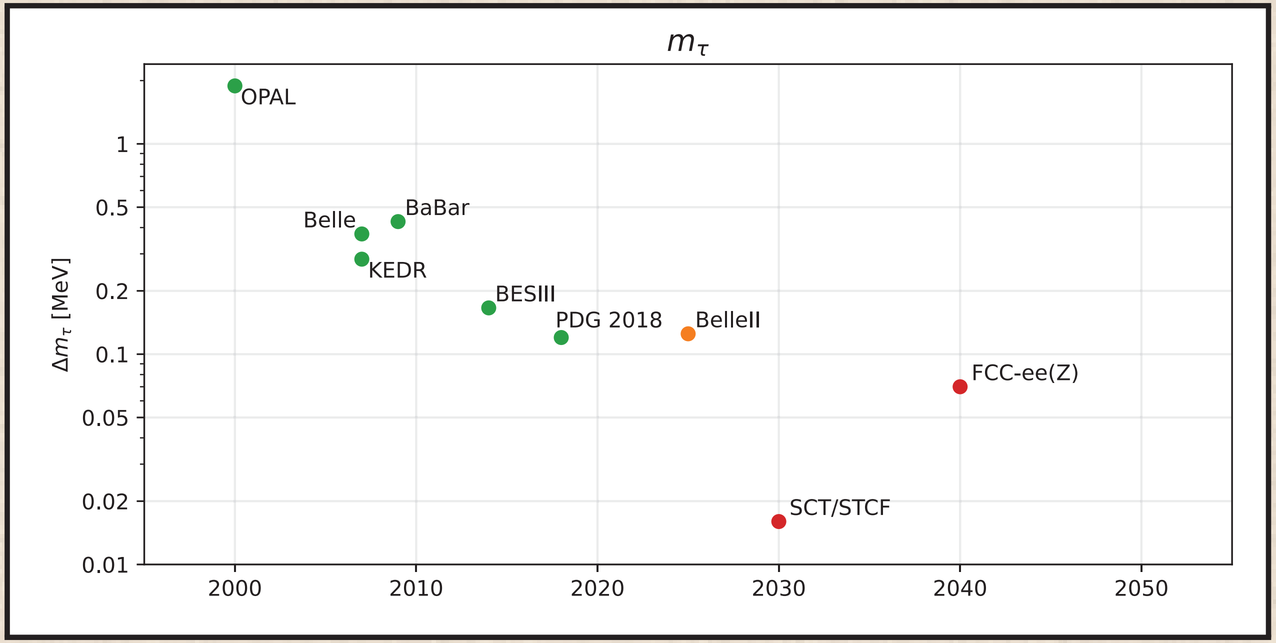
LFU violations in leptonic τ decays and B-physics anomalies

- Allwicher, Isidori, Selimovic, PLB 826 (2022) 136903
- finite 1-loop corrections for 4321 [$SU(4)\times SU(3)\times SU(2)\times U(1)$)] models from matching conditions at NP scale
- smaller impact on tau LU than "Effective Field Theory leading-log" calculations
  $\Rightarrow$ future precision measurements of leptonic τ decay widths important for testing 4321 models





m_τ experimental precision



FCC estimate

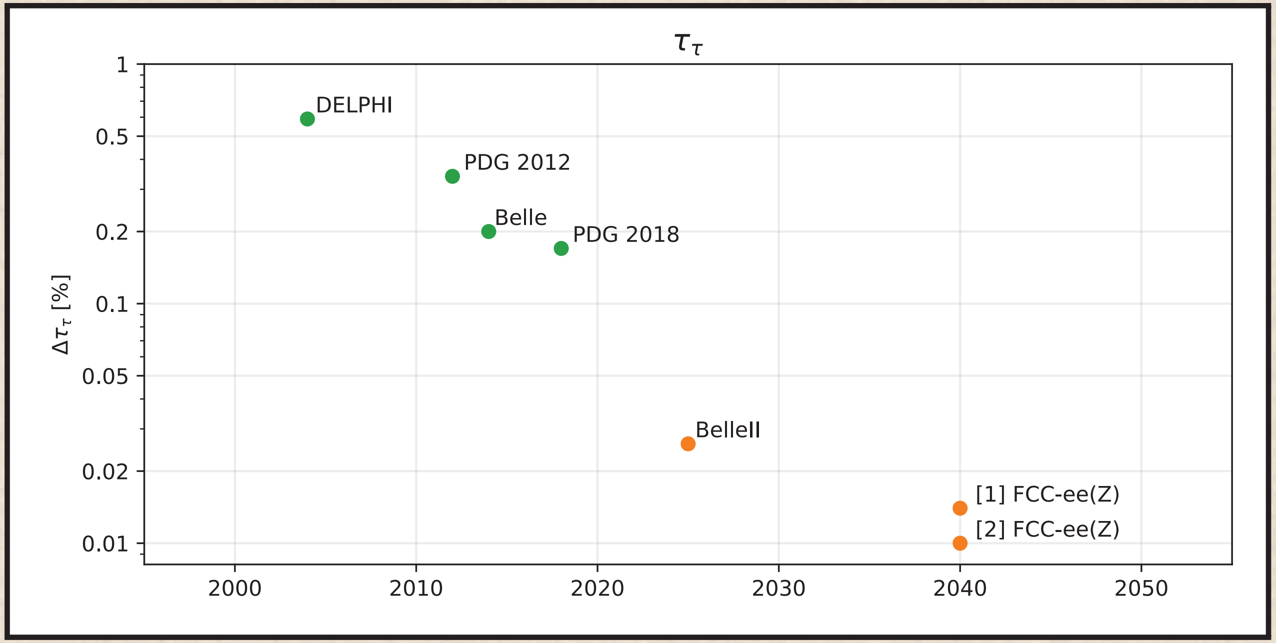
- M. Dam 11th FCC-ee Workshop 2019, limiting systematics of 0.1 MeV on pseudomass distribution modeling

Other estimates

- ESG 2019 docs

- best experimental facilities are e^+e^- at $\tau^+\tau^-$ threshold, then B-factories
- FCC
  - challenge is systematics from pseudomass distribution modeling
  - can use 5-prong decays (narrower pseudomass distribution drop)
  - attainable precision on momentum measurement scale appears not to be limiting

τ_τ experimental precision



FCC estimate

[1] M. Dam and CDR

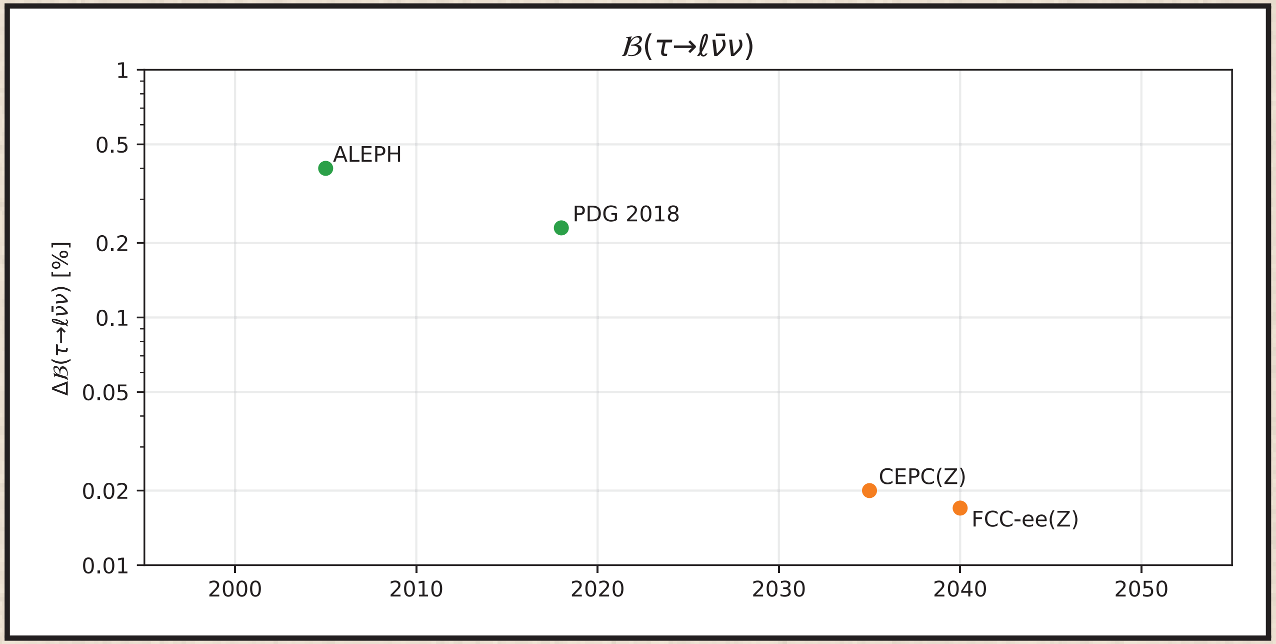
[2] A.L. FCC Workshop Jan 2020

Other estimates

- ESG 2019 docs

- best measurement by Belle on 3-prong vs. 3-prong tau pairs
- expect limiting systematics from absolute length scale calibration on minivertex detector, 100 ppm
- 68 ppm systematics from Δm_τ at current precision
- potential systematics from modeling of measurement bias subtraction
- potential systematics from accuracy of simulation of average radiation energy loss
  - would profit from improvements of tau pairs generators
- profits from high-resolution vertex detector close to interation region

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



FCC estimate

- M. Dam Tau2018, Tau2021

Other estimates

- ESG 2019 docs

- sensitivity estimates very difficult, mostly guestimates
- best results from ALEPH global analysis of all tau decays
- important:
  - PID efficiency, purity, accurate PID modeling with control samples
  - efficiency, purity of π^0 reconstruction, accurate modeling with control samples
  - improve current poor simulation of high multiplicity inv. mass distributions
  - improvements on tau pairs Monte Carlo simulations highly desirable
- high statistics samples will help very much on first 3 points, but analyses will be very complex

Tau branching fractions notes

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

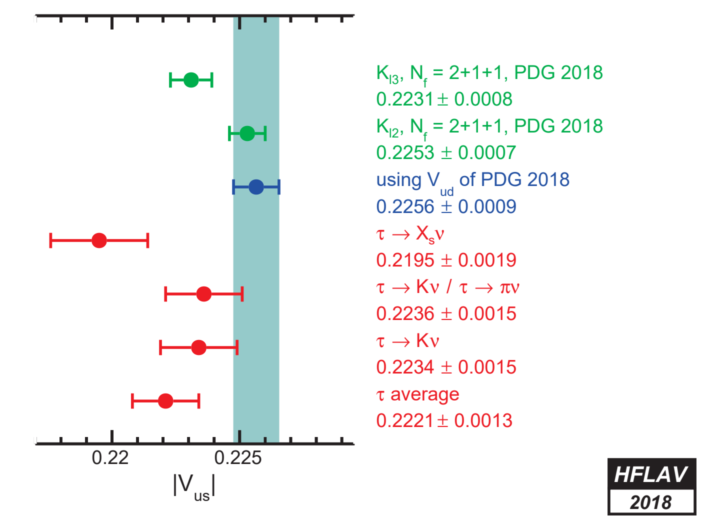
- non-tau backgrounds
  - estimated by varying MC estimate by 30%
  - does not trivially scale with luminosity, but can be improved
- tau pair selection
  - use break-mix method on data and MC, 0.1-0.2% uncertainties
    dominant systematics from data statistics of tau vs. hadron cut separation
  - scales 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 $> 3\,\text{GeV}$ 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)

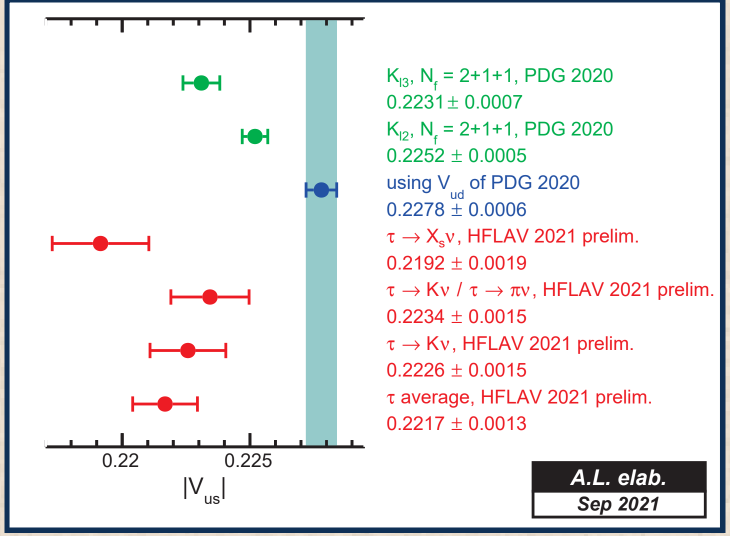
$|V_{us}|$-centric CKM matrix first row unitarity test

PDG 2018 review



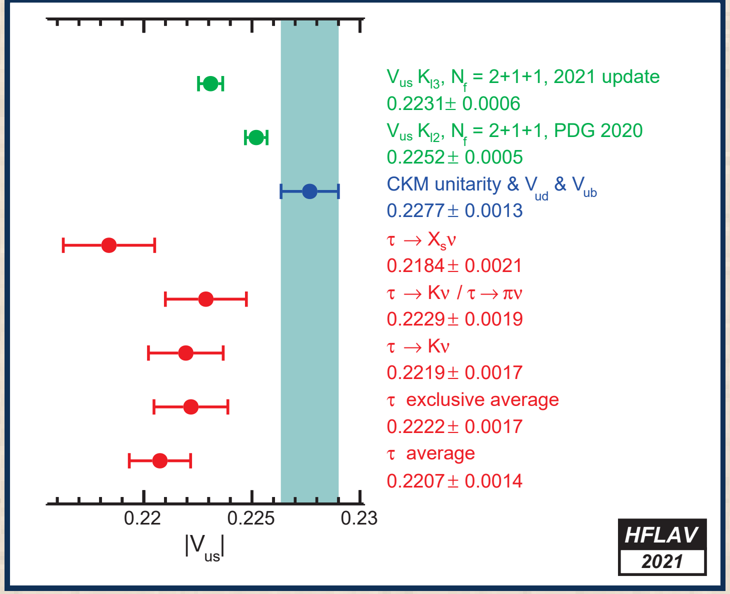
- CKM unitarity OK with kaons

PDG 2020 review



- new dispersive calculation of Δ_R^V inner or universal electroweak radiative corrections (RC) to superallowed nuclear beta decays Seng, Gorchtein & Ramsey-Musolf, Phys. Rev. D 100, 013001 (2019)

2021 update



- J.C.Hardy & Ii.S.Towner, PRC 102, 045501 (2020)
  - inflated $|V_{us}|$ systematics
- Seng, Gorchtein & Ramsey-Musolf, 2021
- Seng, Galviz, Marciano, Meißner, 2021

- $\Delta\,|V_{us}|_\tau \approx \Delta\,|V_{us}|_{V\,ud}$ in 2021!

$|V_{us}|$ determinations using τ branching fractions measurements

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

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

$\tau \to K / \tau \to \pi$

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

$\tau \to K$

Requirements

- Cabibbo-suppressed tau BRs
- tau spectral functions

α_s from tau decay measurements

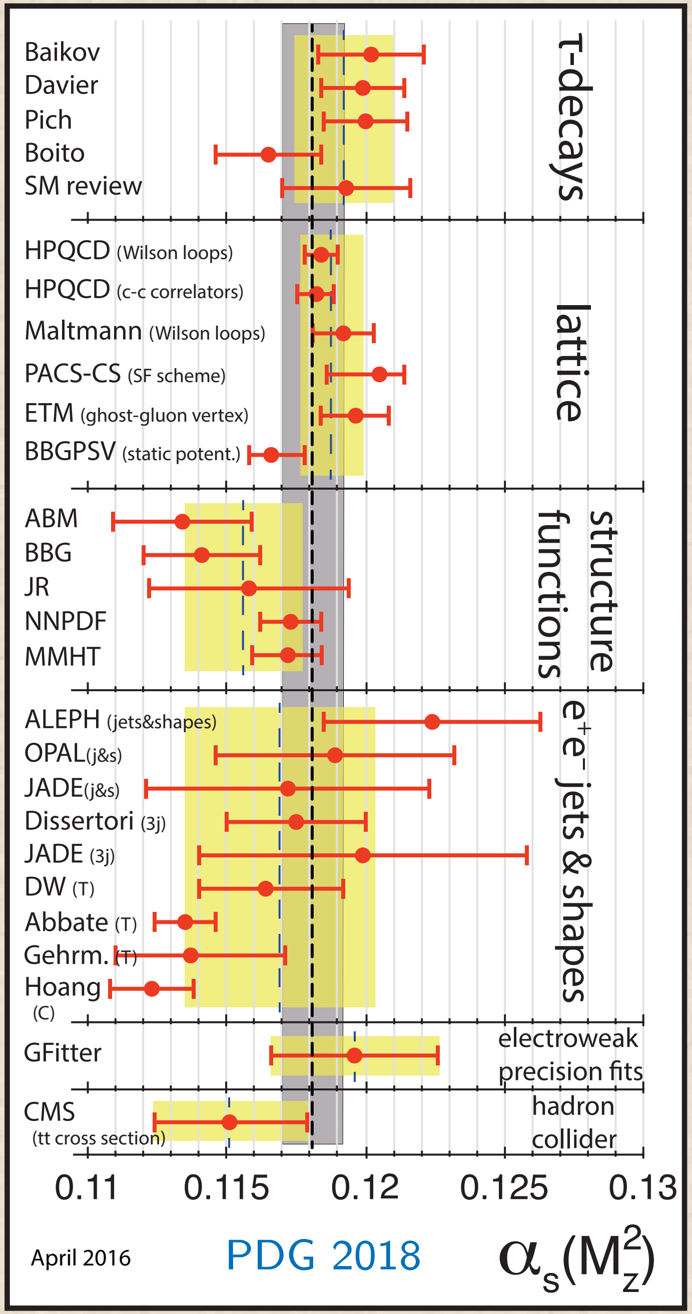
- $\alpha_s(m_\tau)$ from
  - $R_{VA} = \mathcal{B}(\tau \to X_d \nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$
  - tau spectral functions
- tau data competitive
- $\alpha_s(m_\tau)$ confirms running of α_s
- best experimental inputs e^+e^- facilities at the Z peak
  - modest experimental progress since LEP times
  - statistics, clean data, non-trivial analysis needed
  - non-trivial exp. and theory systematics

Recent discussions

- different groups get somewhat inconsistent results disagreements on non-perturbative effects, duality violations
- Pich 2019
  Boito, Golterman, Maltman, Peris 2019
  Pich, Rojo, Sommer, Vairo 2018
  Boito, Golterman, Maltman, Peris 2017
  Pich, Rodríguez-Sánchez 2016

Requirements

- tau spectral functions, tau branching fractions



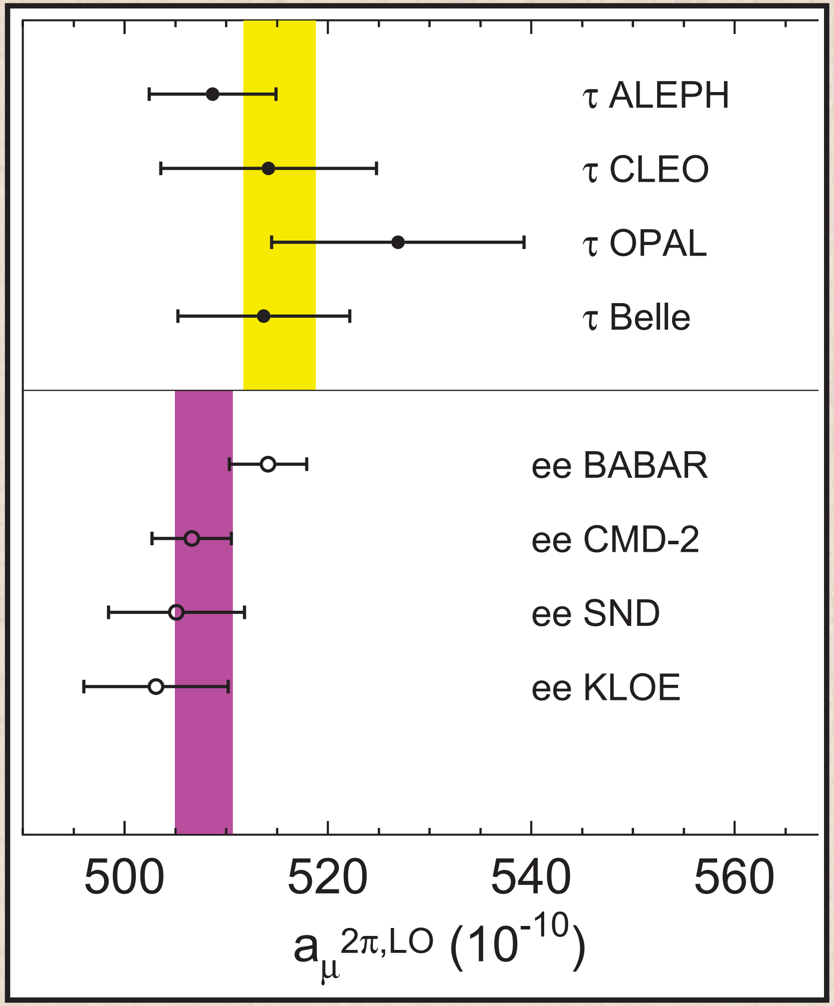
Muon $g-2$ hadronic contribution from tau

- $\alpha_\mu^{2\pi,\mathrm{LO}}$ 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)
- best experimental inputs e^+e^- facilities at the Z peak
  - modest experimental progress since LEP times
  - statistics, clean data, non-trivial analysis needed
- tau data $\Rightarrow$ reduced discrepancy with exp.
- presently e^+e^- data more precise and complete

Requirements

- improved isospin-violating and EM corrections for $\tau \to \pi^0\pi\nu_\tau$
- tau spectral functions
- tau branching fractions

Davier 2013



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 especially for the poorly measurer rare modes
- analyses are complex and may be limited by manpower availability
- improvements on Monte Carlo simulation desirable

Other tau physics topics

- many additional tau physics topics have not been discussed
- recent Belle paper extends tau EDM measurement from 29.5fb^{-1}to 833fb^{-1}
- large analysis efforts on tau EDM and $g-2$ at Belle II
  - these measurements benefit significantly from beam polarization and precise vertexing
- large analysis effort on tau Michel parameters at Belle / Belle II and super charm-tau factories

Conclusions

- tau physics best done on e^+e^- colliders
- Z-peak conditions are best for most measurements
- threshold tau pair production best for tau mass
- useful experimental features
  - precise knowledge of beam energies
  - small luminous region
  - precise vertex detector close to luminous region
  - beams polarization

Thanks for your attention!