TAU physics

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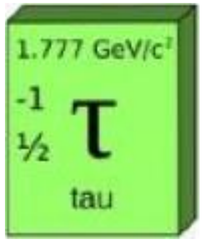
Flavour parallel session

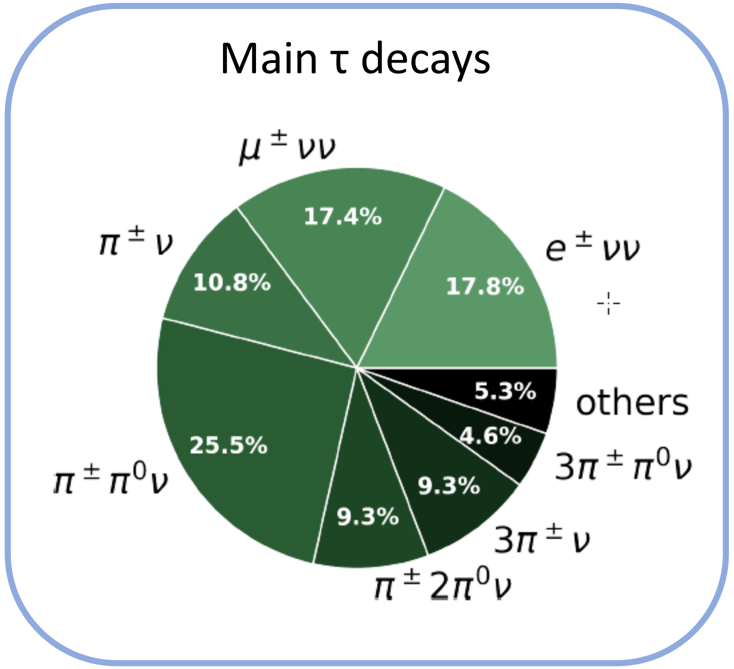
Tau physics motivations



- A special charged lepton!
  - 3500 times more massive than electron
  - 10^{-7} times shorter lifetime than muon
  - Only lepton that can decay into hadrons

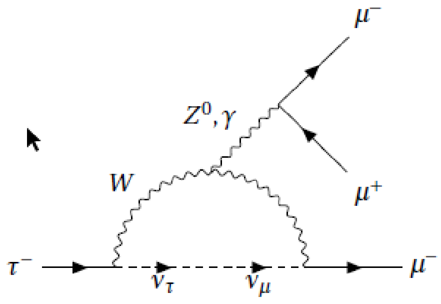
Does NP couple preferentially to the 3rd generation ?

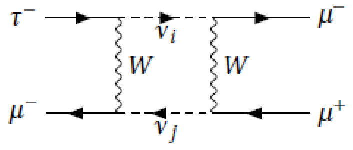
- Search for decays that are forbidden in SM
  - Lepton flavour violating decays
  - Decays to exotic particles such as ALPs
- Tests of SM through τ precision measurements
  - τ properties : mass, lifetime, edm,…
  - Couplings: lepton flavor universality, V_{us}, Michel parameters, α_s, CPV,…
  - Hadronic system: spectral function, partial wave analysis

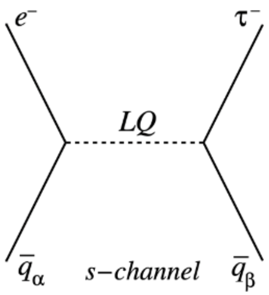


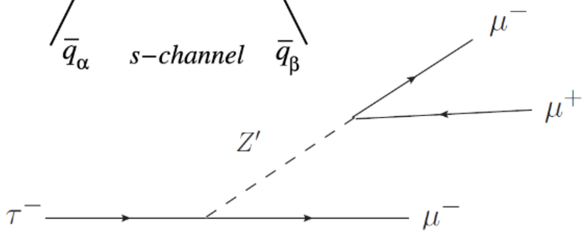
Why cLFV ?

- Charged lepton flavour is conserved in the SM
- Due to neutrino mixing, charge lepton flavor violation is possible but at very low rates ~10^{-50}
- Many BSM models predict cLFV: Z’, leptoquarks, SUSY,…
- An observation would be a clear sign of NP!
- Probing different channels is essential to identify the source of LFV and the mediation mechanism
- While μ→e processes provide the most constraining limits (10^{-13}), BSM couplings to 3rd generation could be larger (motivated by flavor structure in the SM)
- τ leptons allow to probe a large variety of decays: purely leptonic, radiative, semileptonic with 1 or 2 pseudoscalar, vector, baryon,…





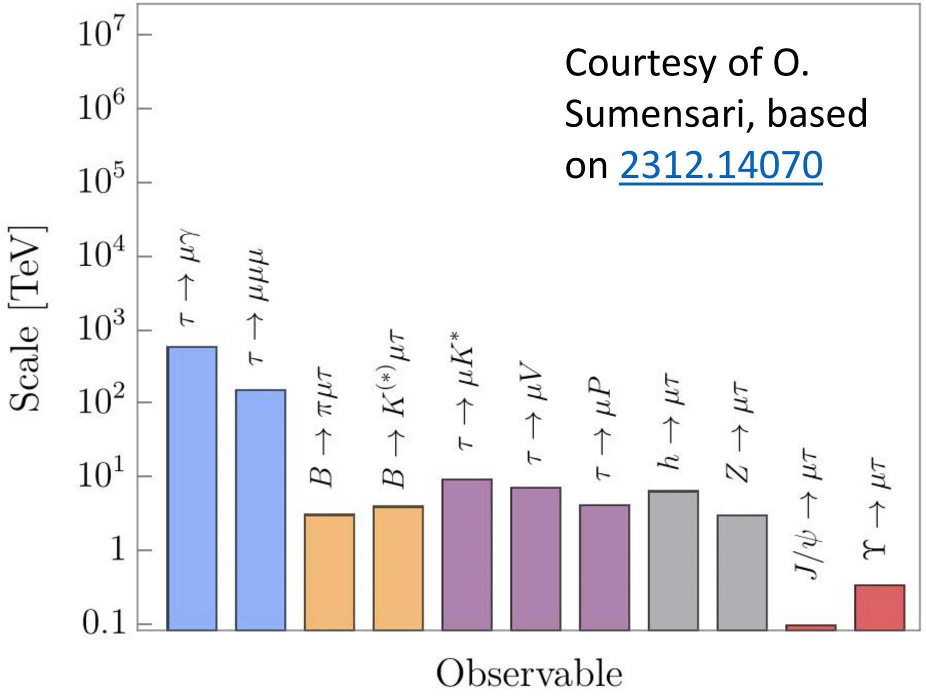




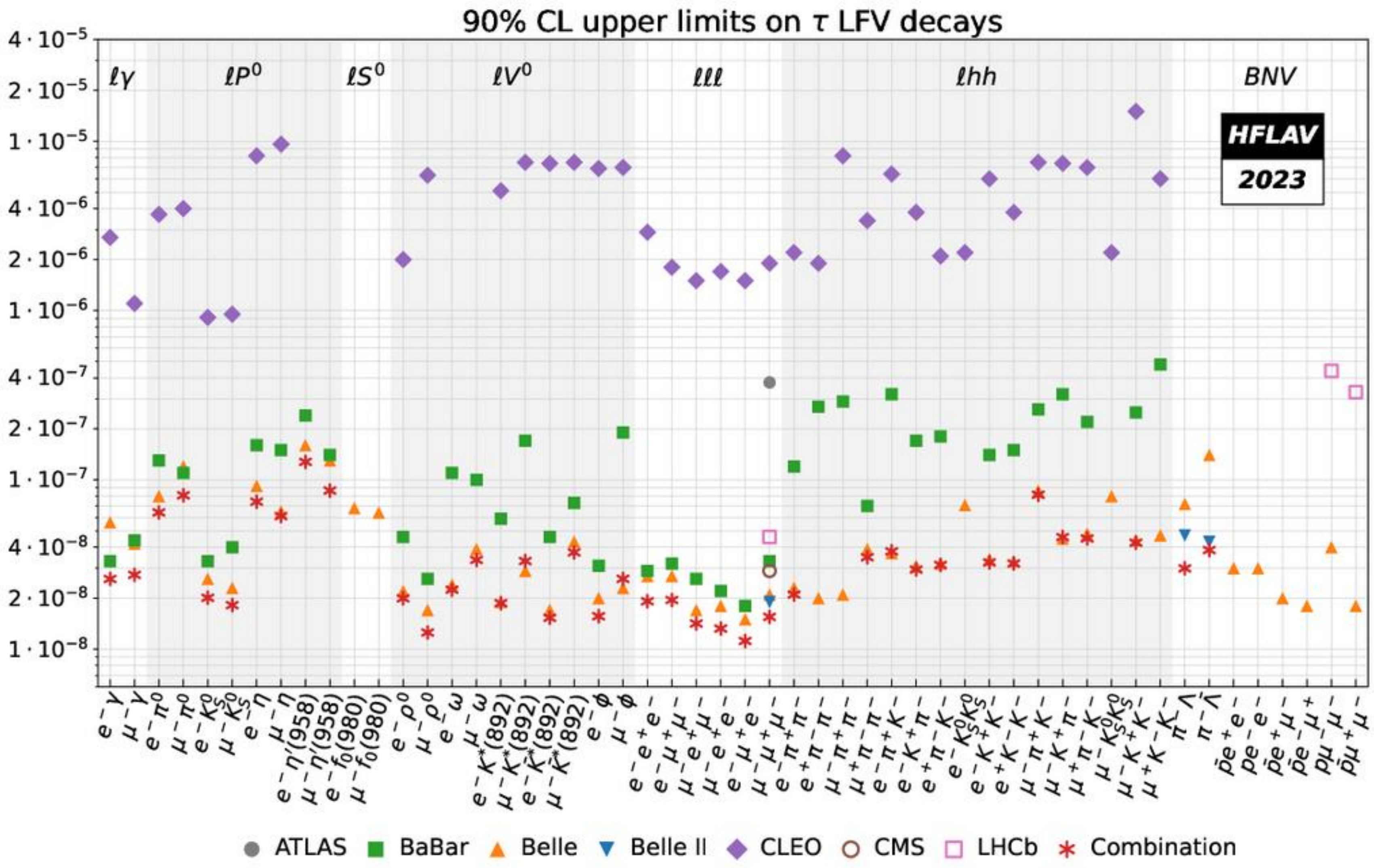
Why cLFV ?

- Beside BR, additional observables can provide more information: Dalitz analysis, angular and kinematical distributions, *if a signal is observed!*
- Results can be interpreted in EFT, probe NP scale of few hundreds of TeV (NP couplings=1)
- Complementarity with Z and Higgs LFV decays

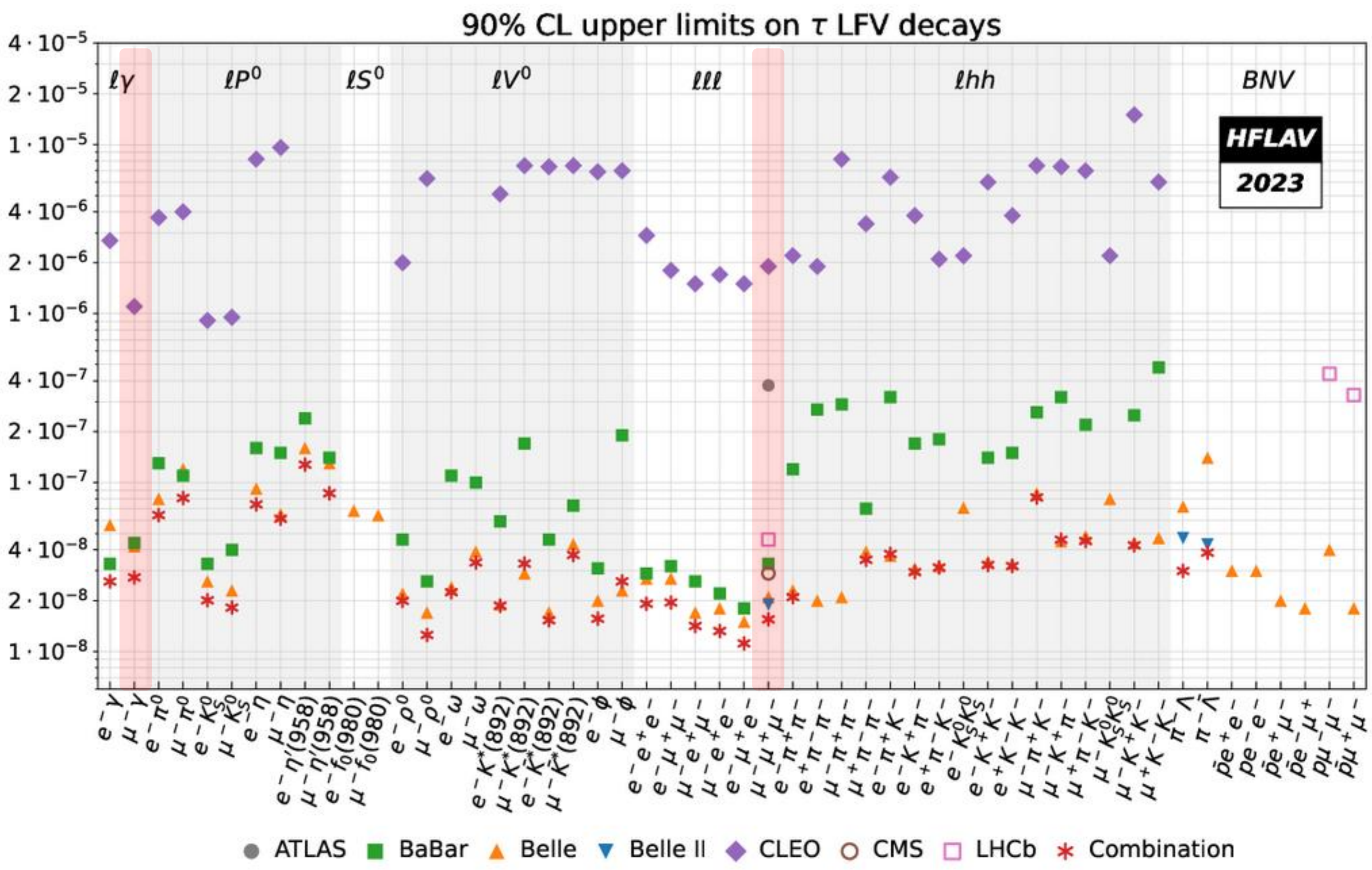
Here, we consider as benchmark the 'golden channels' τ→ 3μ and τ→ μγ that are usually the most enhanced in BSM models, with BR close to the current experimental bounds



cLFV : current status



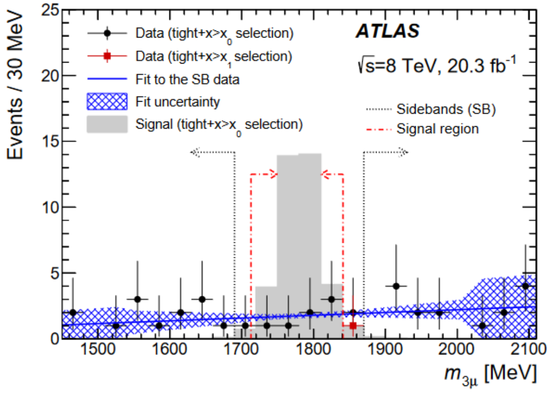
cLFV : current status



Benchmark channels

cLFV measurements

- Expect a clean peak in reconstructed τ mass
- Reconstruction of the opposite τ can be used at e+e- machines to lower the background
- τ→3μ is almost background free
- τ→μγ is polluted by radiative events. Needs very good spatial and energy resolution of the calorimeter



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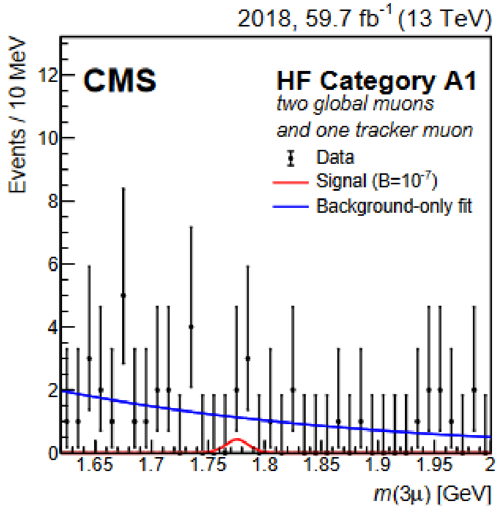

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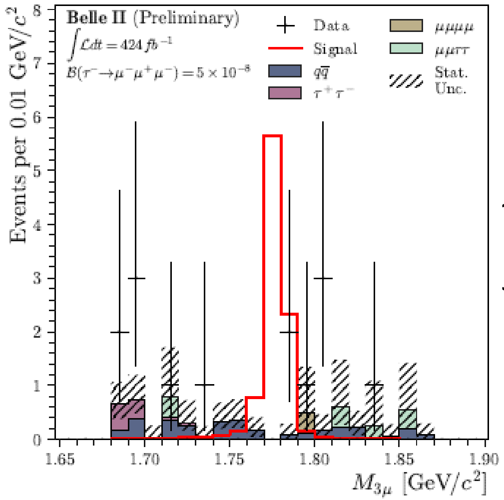

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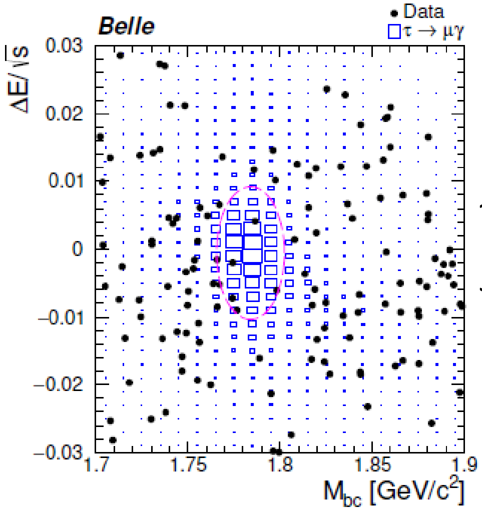


(a) $\tau^{\pm} \to \mu^{\pm}\gamma$.

JHEP10(2021)019

Tests of SM through τ measurements

- Focus on test of lepton flavour universality (but many other interesting measurements!)
- In the SM, electroweak gauge bosons couple similarly to the three lepton generations, but there is no reason why NP should do the same
- Tests of LFU have been performed in various processes: pions, kaons, B, W, τ
- The best precision is achieved in pion decays, followed by τ decays
- Measurement of R_μ can constraint the ratio of effective coupling of e and μ to W

$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{\mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

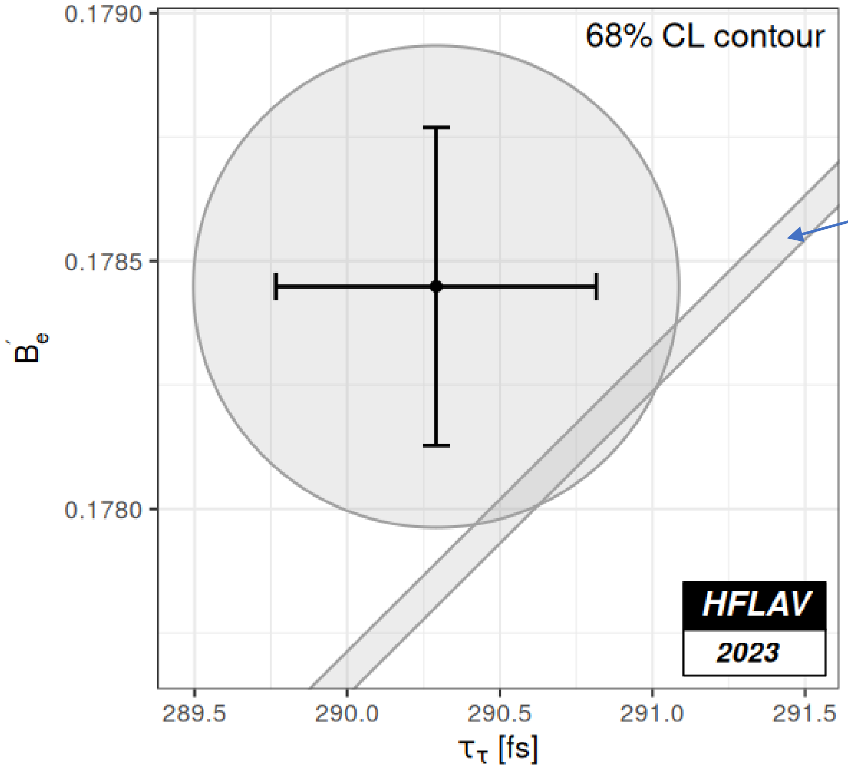
$$\left|\frac{g_\mu}{g_e}\right|_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}.$$

Current HFLAV average : $\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0002 \pm 0.0011$

Lepton flavor universality test

An other test of lepton flavor universality can be made from τ mass, lifetime and BR(τ→lνν)

B'$_e$ average the direct BR(τ→ eνν) measurement with BR(τ→ μνν) assuming electron and muon have similar weak couplings



SM prediction, limited by τ mass precision

$$\mathcal{B}_e^{\tau_\tau} = \mathcal{B}(\mu \to e\overline{\nu}_e\nu_\mu)\frac{\tau_\tau}{\tau_\mu}\frac{m_\tau^5}{m_\mu^5}\frac{f(m_e^2/m_\tau^2)}{f(m_e^2/m_\mu^2)}\frac{R_W^{\tau e}}{R_W^{\mu e}}\frac{R_\gamma^\tau}{R_\gamma^\mu}$$

$$R_W^{\mathcal{L}\ell} = 1 + \frac{3}{5}\frac{m_\mathcal{L}^2}{M_W^2} + \frac{9}{5}\frac{m_\ell^2}{M_W^2}$$

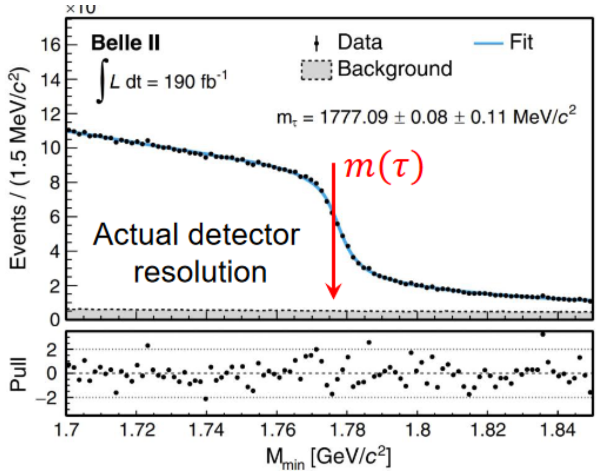
$$R_\gamma^\mathcal{L} = 1 + \frac{\alpha(m_\mathcal{L})}{2\pi}\left(\frac{25}{4} - \pi^2\right)$$

Measurements of τ properties

Those measurements are already or will be soon limited by systematic uncertainties, extrapolations are thus more difficult

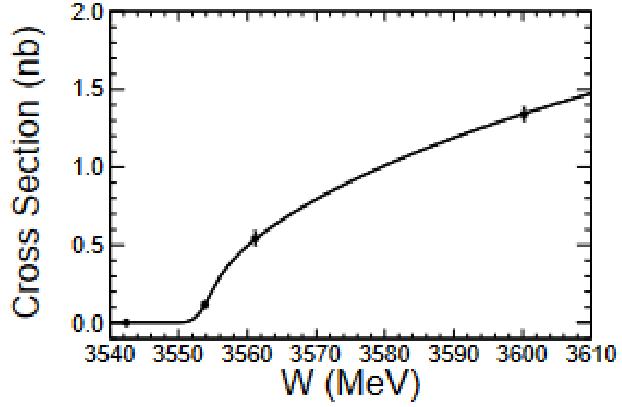
- Mass: B factories and LEP used pseudo mass technique. Main systematics are beam energy and momentum scale. BESIII use threshold scan method, limitations are beam energy and beam energy spread
- Lifetime: Belle used both τ→ 3πν. LEP uses both 1-prong and 3-prong decays measuring the lifetime from the impact parameter or from de distance between the production and decay vertex.
- BR(τ→lνν): Complex analysis by ALEPH, determining BR for 13 classes of decays simultaneously. No results from B factories.
- R_{μ}: measured by Belle II, main uncertainty is coming from PID efficiency

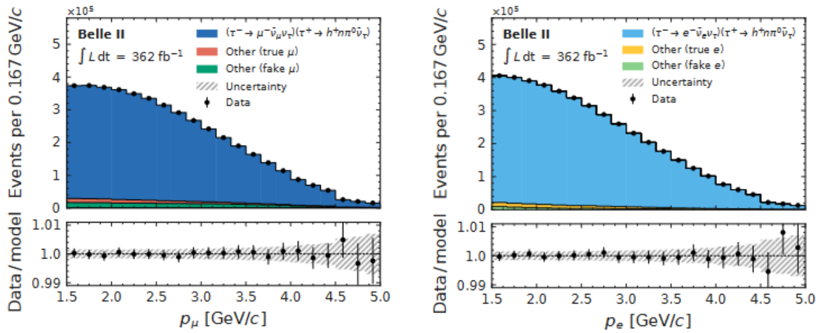
PRD108(2023)032006



$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \leq m_\tau$$

BESIII, PRD90(2014)012001





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Current status: BR(τ→lνν)

From HFLAV

$B_5 = B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)$

0.1784 ± 0.0004		average
0.1785 ± 0.0004		average with u.c
0.1784 ± 0.0007 ± 0.0004	⬅ Most precise	ALEPH
0.1776 ± 0.0006 ± 0.0017		CLEO
0.1788 ± 0.0011 ± 0.0011		DELPHI
0.1781 ± 0.0010 ± 0.0008		L3
0.1781 ± 0.0009 ± 0.0006		OPAL

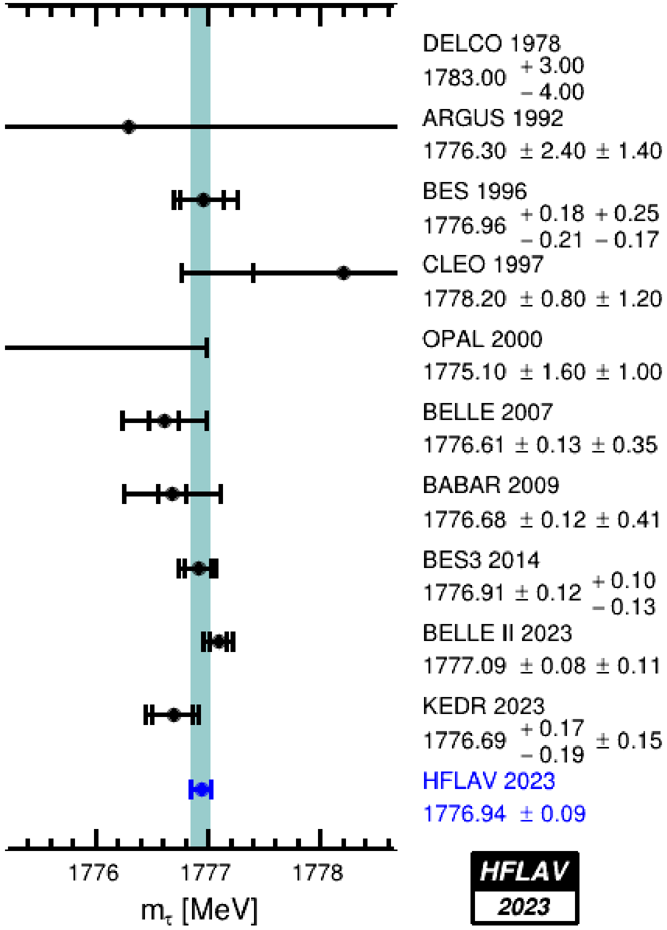
$B_3 = B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)$

0.17360 ± 0.00037		average
0.17366 ± 0.00036		average with u.c.
0.17319 ± 0.00070 ± 0.00032	⬅ Most precise	ALEPH
0.17325 ± 0.00095 ± 0.00077		DELPHI
0.17342 ± 0.00110 ± 0.00067		L3
0.17340 ± 0.00090 ± 0.00060		OPAL

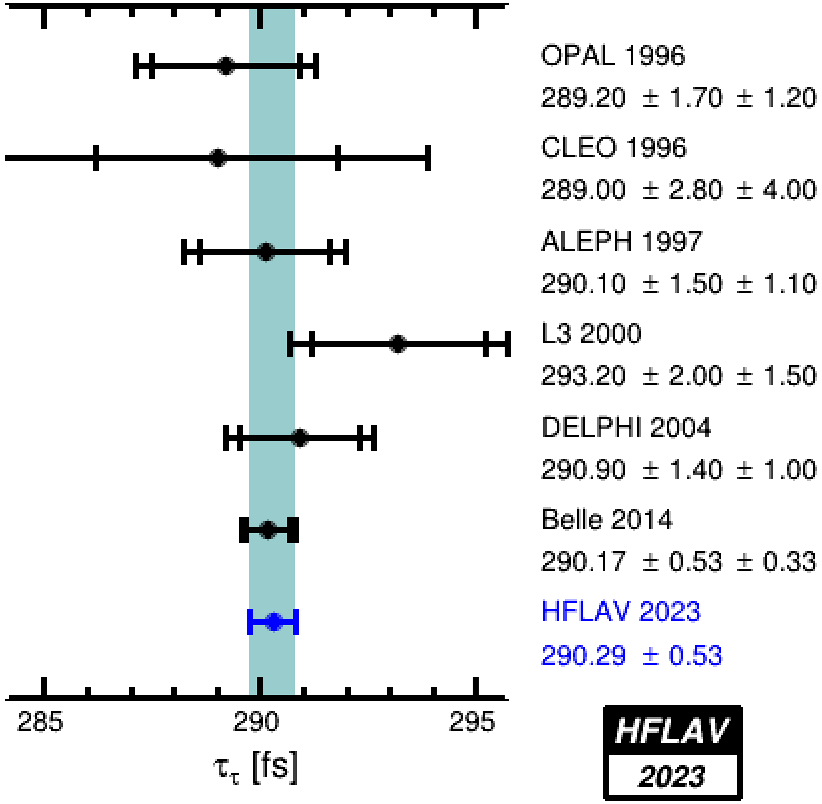
$$B_{3/5} = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

0.9730 ± 0.0022		average
0.9730 ± 0.0022		average with u.c.
0.9970 ± 0.0350 ± 0.0400		ARGUS
0.9796 ± 0.0016 ± 0.0036		BaBar
0.9675 ± 0.0007 ± 0.0036	⬅ Most precise	Belle II
0.9777 ± 0.0063 ± 0.0087		CLEO

Current status: mass and lifetime



Most precise



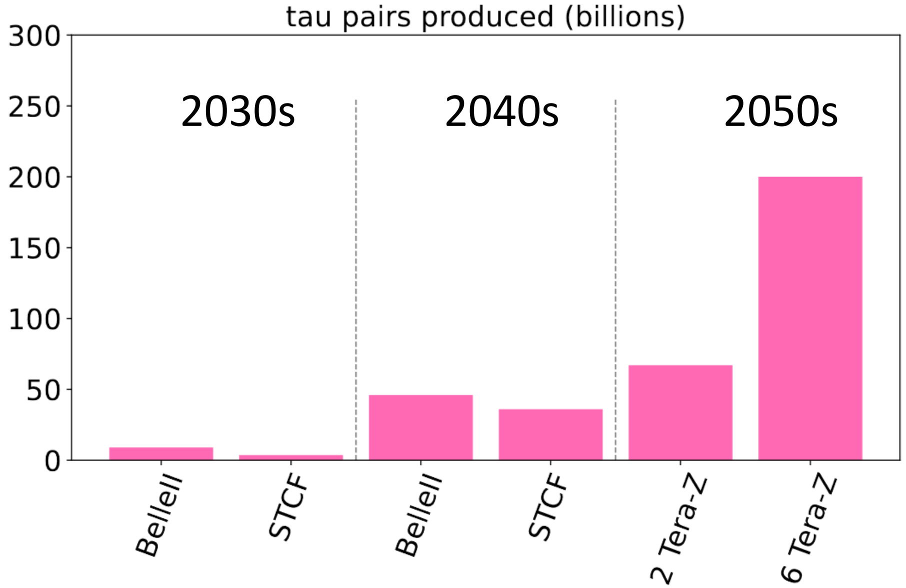
Most precise

Tau physics at future facilities

Three types of collider considered:

- pp : ATLAS, CMS, LHCb upgrade II
  - High backgrounds. High statistics but low efficiency. Use τ produced in heavy-flavour hadron and W decays. Mainly limited to the search for $\tau \to 3\mu$ (+ anomalous magnetic moment from heavy ion collisions)
- e+e- at low energy : Belle II, Super Tau Charm Factory
  - Clean environment, tau pairs produced directly $e^+e^- \to \tau^+\tau^-$ (few tracks per event, can reconstruct neutral particles easily), but limited statistics
- e+e- at the Z pole : FCCee, LEP3, LEPZ
  - Clean environment, high statistics $BR(Z \to \tau\tau) = 3.37\%$

e+e- machines



Others: linear collider facility, FCChh, LHeC

Less clear. LCF has lower statistics ($1.7\ 10^8$ tau pairs). FCChh can certainly search for $\tau \to 3\mu$, LHeC can probably measure anomalous magnetic moment and edm of τ. No prediction for benchmark channels, not considered in the following

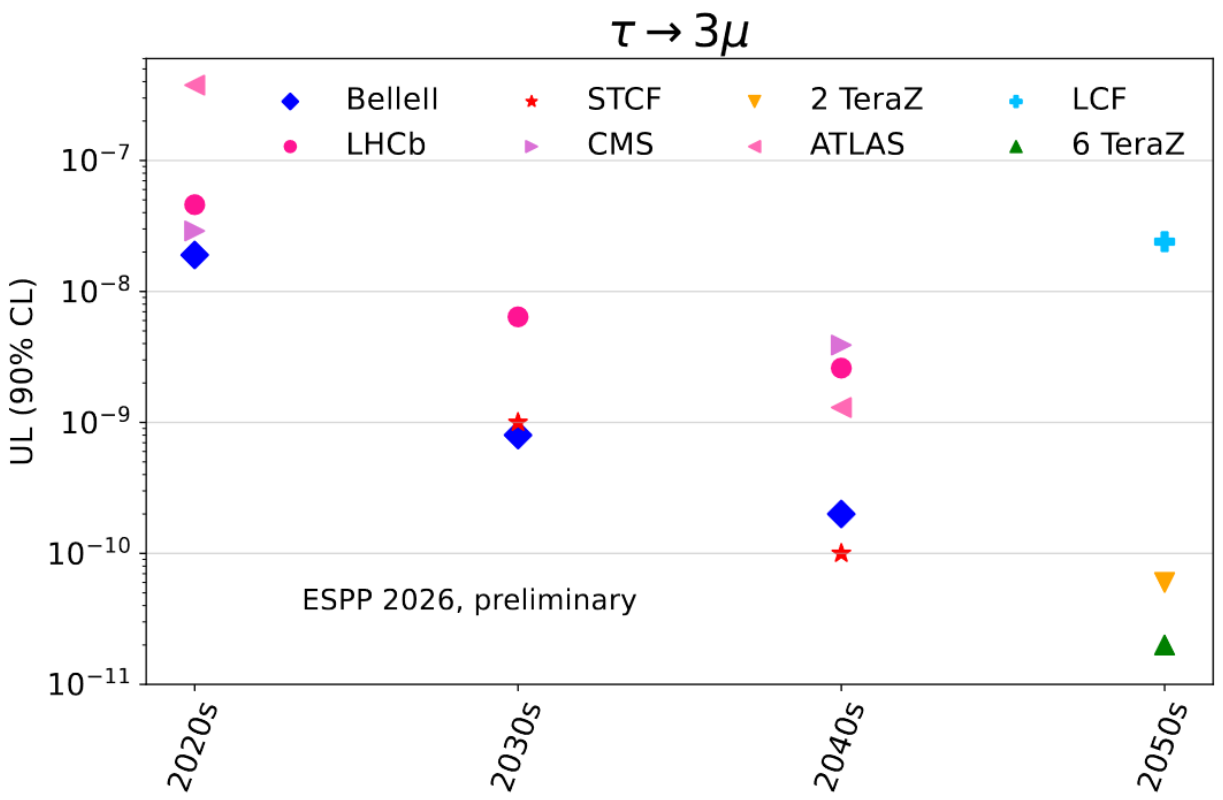
Projections for BR($\tau \to 3\mu$) and BR($\tau \to \mu\gamma$)

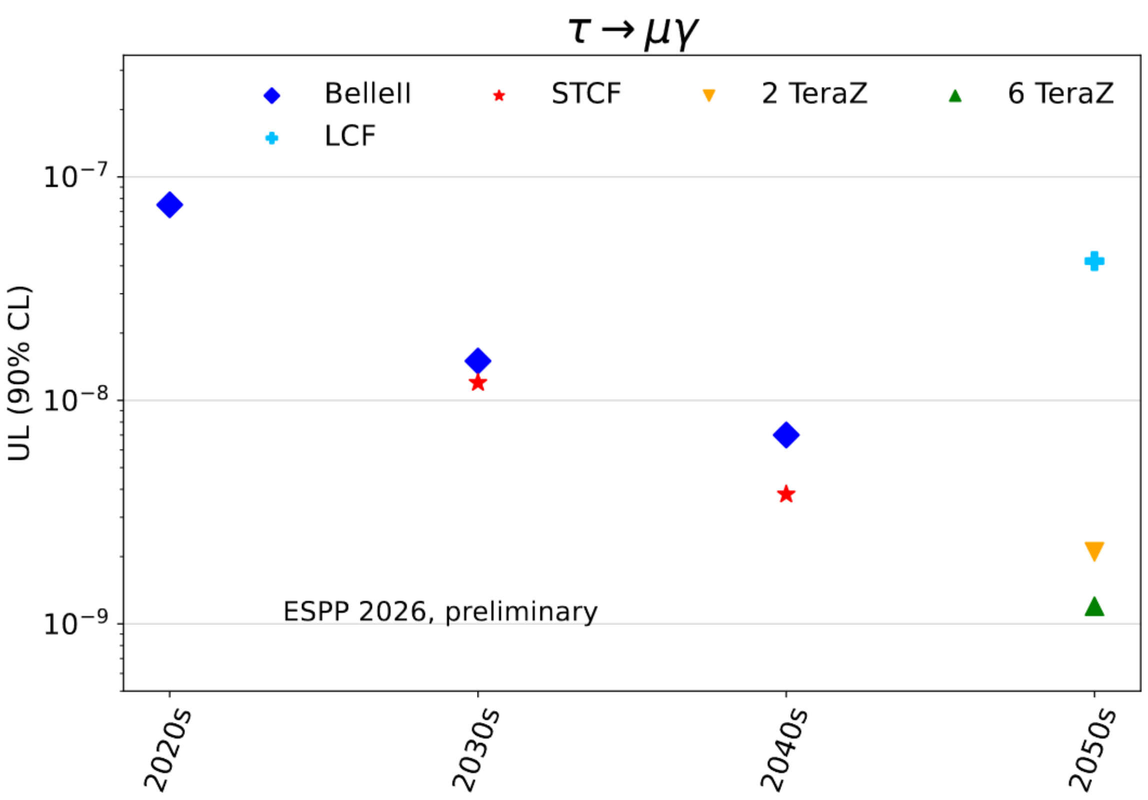
mode	Belle II 10 ab-1	LHCb 50 fb-1	Belle II 50 ab-1	LHCb 300 fb-1	ATLAS 3 ab-1	CMS 3 ab-1	6 TeraZ	2 TeraZ	STFC 1 (10)ab-1	LCF
BR($\tau \to 3\mu$) x10^9	0.8	6.4	0.2-1.7	2.6	1.3-6.4	3.9	0.02	0.06	1 (0.1)	24
BR($\tau \to \mu\gamma$) x10^9	15	-	7	-	-	-	1.2	2.1	12 (3.8)[1]	42

Numbers taken from submissions [165,188,196,223,231] except LCF and 2 TeraZ (LEP3/Z) extrapolated from FCCee, following 1/L for 3μ (assuming background free analysis) and $1/\sqrt{L}$ for $\mu\gamma$.
In case a range is given, take the more optimistic option.
STCF BR($\tau \to \mu\gamma$) limit taken from [1] https://arxiv.org/pdf/2203.14919

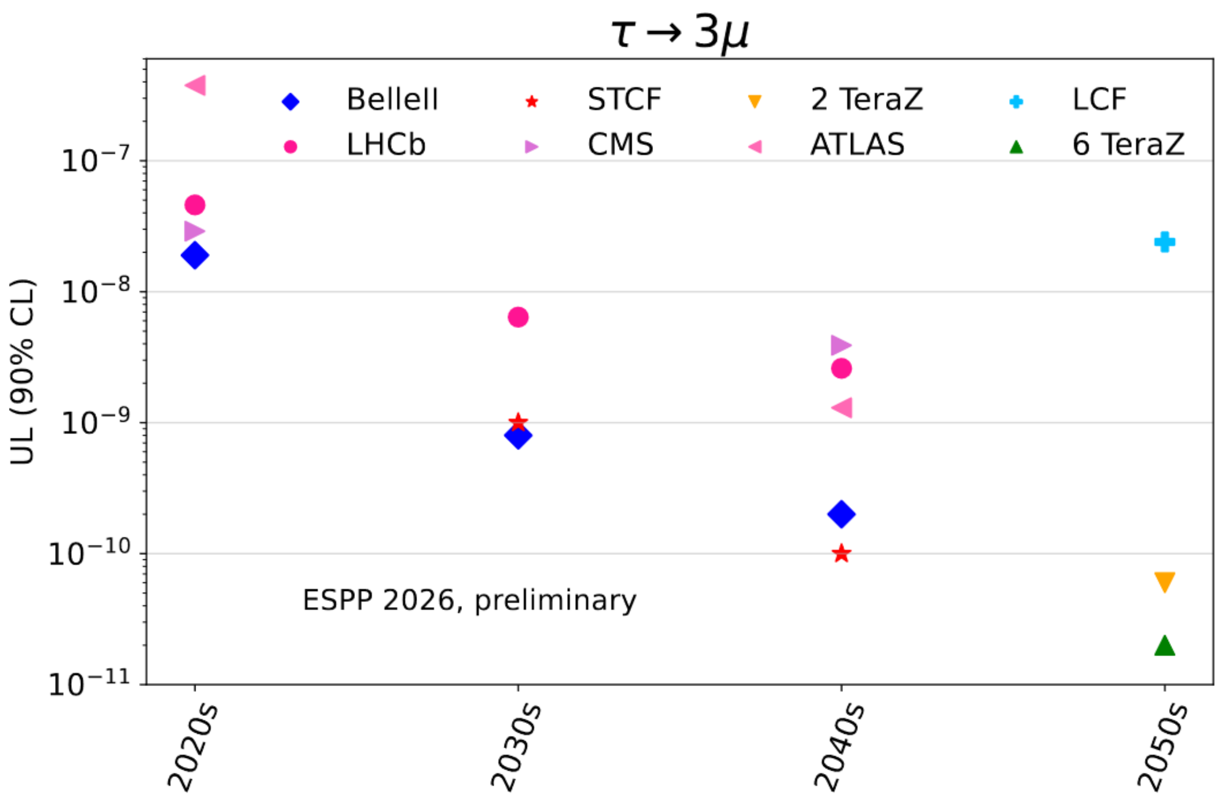
In the next plots, results are shown by decades:
- 2020s: current status
- 2030s: Belle II 10 ab^{-1}, STCF 1 ab^{-1}, LHCb 50 fb^{-1}
- 2040s: Belle II 50 ab^{-1}, STCF 10 ab^{-1}, LHCb 300 fb^{-1}, ATLAS and CMS 3 ab^{-1}
- 2050s: 6x10^{12} Z, 2x10^{12} Z, LCF 5 10^9 Z

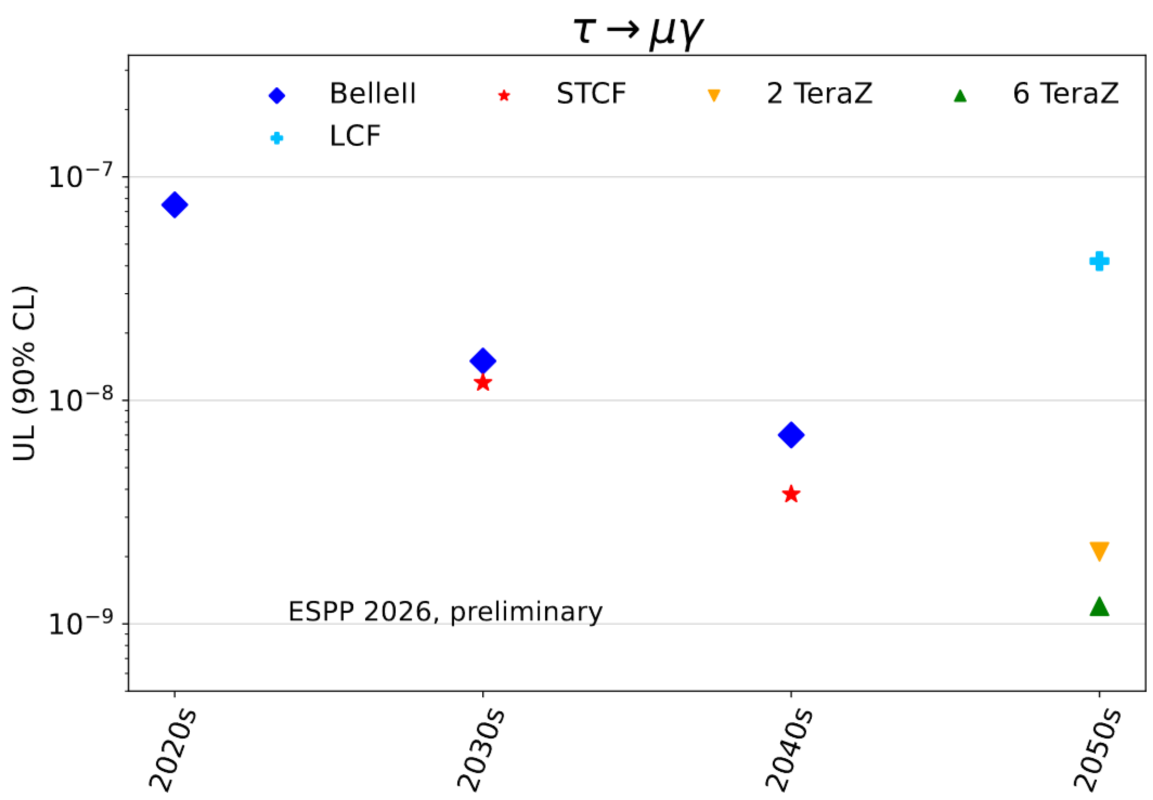
Projections for BR(τ→ 3μ) and BR(τ→μγ)





Projections for BR(τ→ 3μ) and BR(τ→μγ)





Belle II and STCF will provide the best limits until Tera-Z experiments enter the game. Those can improve the limit by up to one order of magnitude, down to few 10^{-11} for BR(τ→ 3μ) and few 10^{-9} for BR(τ→μγ)

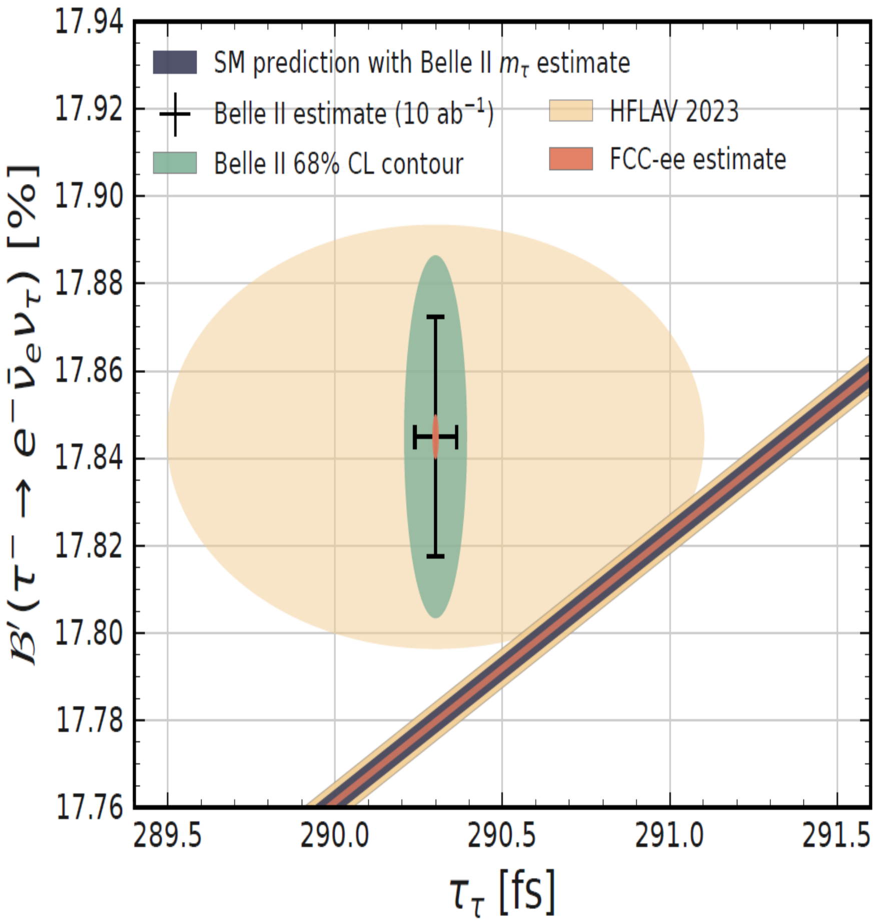
Projections for τ property measurements

		2030		2050	
observable	Current best	Belle II 10 ab-1	STCF 1ab-1	6 TeraZ	2 TeraZ
τ lifetime x10^{12} s	0.62	0.062	-	0.003	0.01
τ mass [MeV]	0.14	0.056	O(0.01)	0.02	0.02
BR(τ→ lνν) [%]	0.08	0.047	-	0.003	0.003
R_μ	0.0037	0.0018	-		

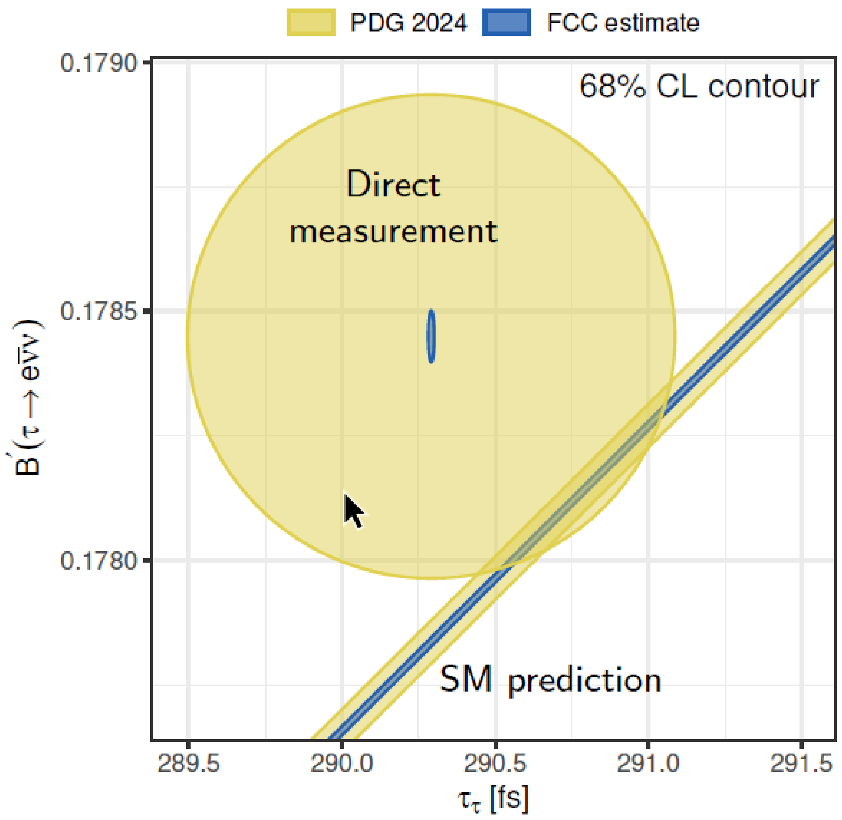
- Lifetime: Z pole machines will improve Belle II measurements by factor 6 to 20 (FCCee quotes 3 times more precise result than LEPZ). Main uncertainties are alignment, material budget, trigger (Belle II) initial state radiation before tau pair production (FCCee)
- Mass: all experiments are in the same ballpark O(10) KeV
- BR(τ→lνν): Z pole machines can gain one order of magnitude with respect to Belle II. FCCee assumes a factor 10 reduction of systematic uncertainty compared to ALEPH. No measurement from B factories so far, need precise knowledge of number of τ produced, or use of a normalization channel. Particle identification efficiency also needs to be known precisely
- R_μ: Belle II dominates, can also be done at Z pole machine

Lepton flavor universality test

2030



2050



Conclusion

2030s-2040s:

- Belle II and STCF will provide the best limits on LFV channels (benchmark and others)
- Belle II will improve the lifetime and mass measurements, STCF the mass one with different technique
- Belle II will improve R_{μ} by a factor 2, limited improvement on absolute BR

2050:

- e+e- machines running at the Z pole can improve by up to 1 order of magnitude the limits on BR($\tau \rightarrow 3\mu$) and BR($\tau \rightarrow \mu\gamma$), the precision of the lifetime and leptonic branching fractions
- Projections for FCCee and LEPZ are quite similar, with factor 3 maximum difference

Numbers should be taken with a grain of salt, especially for property measurements

More about taus

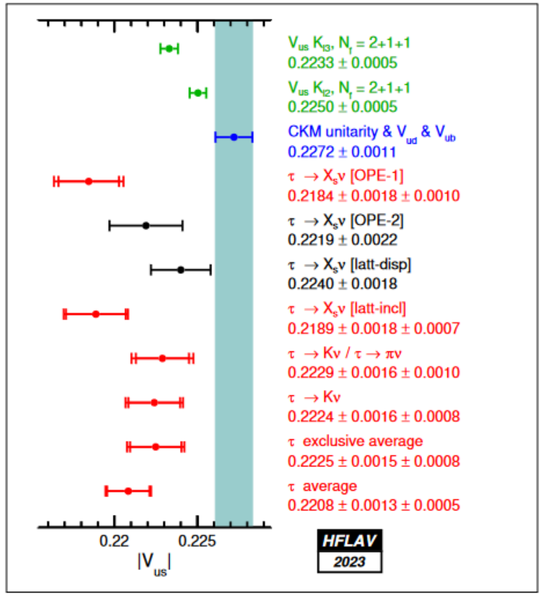
Super Tau Charm Factory (STCF)

- e+e- collider operating at √s = 2 – 7 GeV (BEPCII is 2-5 GeV)
- Peak luminosity larger than 5 10^{34} cm-2 s-1 at 4 GeV, expect to integrate 1ab^{-1} per year
- Approval is expected in 2026, data taking would start in ~2035
- Clean environment, maximum cross section is $\sigma_{\tau\tau}$(4.2GeV) = 3.6 nb
- τ mass can be measured but boost of τ leptons too small to measure the lifetime
- Other possible τ measurements (see also arXiv:2207.06307v2): CP violation, EDM, LFV, …
- Projections are given as orders of magnitude

Other measurements

- Magnetic dipole moment a_τ : SM prediction is ~0.0012, best measurement is from ATLAS using heavy ion collisions [-0.057-0.024]. Future measurements : Belle II with e- polarized beams, LHeC, FCCee (done at LEP using ee → eeττ cross section)?
- Electric dipole moment : SM predicts ~10^{-37} ecm, NP can predict enhancement up to 10^{-19} ecm. Best precision obtained by Belle at ~10^{-18} ecm.
  Belle II could reach 10^{-19} ecm with 50 ab-1 [Snowmass 2203.14919]. Precision could be also enhanced using polarized e- beam since the main contribution to systematics is coming from forward backward asymmetry, that cancels using opposite beam polarization state. STCF is expected to reach O(10^{-18}) ecm
- Cabibbo angle anomaly: disagreement between determination of |Vus| and prediction based on CKM unitarity. Most precise determination from K decay but help with measuring BR(τ →Knu)/BR(τ →pinu) combined with LQCD, or ratio of inclusive strange vs non-strange final states.
  Can be made at STCF and Belle II, FCCee ?
- CPV: for ex, 2.8σ deviation measured by Babar in $\tau \to K_S \pi \nu$

$$A_\tau^{SM} = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$



Other experiments

BR(Z → ττ) = 3.37%

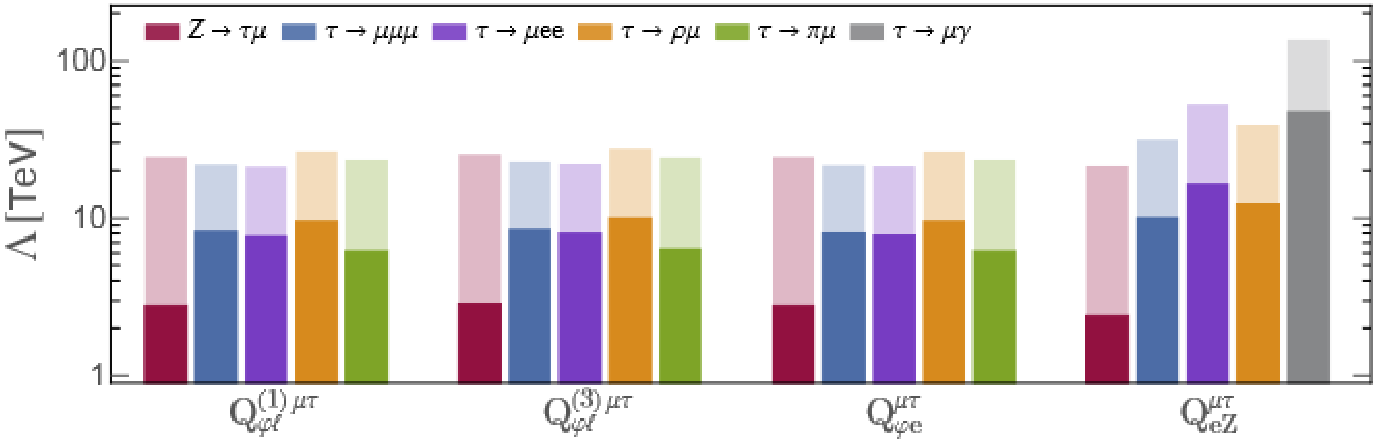
- Z0 : 6 10^{12} (FCCee), 2 10^{12} (LEP3), 5 10^{9} (ILC)
- Tau pairs: 2.10^{11} (FCCee), 6.7 10^{10} (LEP3), 1.7 10^{8} (ILC), 46. 10^{9} (Belle II at 50 ab-1), 3.6 10^{9} for 1 ab-s (STFC),10^{8} (LHeC) from in https://pos.sissa.it/476/329/pdf

Number of τ pairs produced in billions :
3.6 (STFC 1 ab-1)
46 (Belle II 50 ab-1)
0.17 (LCF)
67 (2 TeraZ)
200 (6 Tera Z)

LHeC submission: 'Already with an integrated ep luminosity of 100 fb−1, the expected LHeC sensitivity is an order of magnitude better than that achieved at the LHC. As a result, for the first time the experimental uncertainties will be better than the higher order corrections to the τ magnetic moment in the SM.'

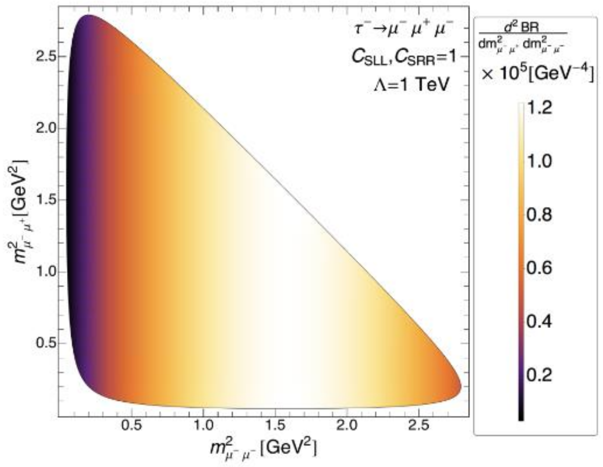
Why cLFV ?

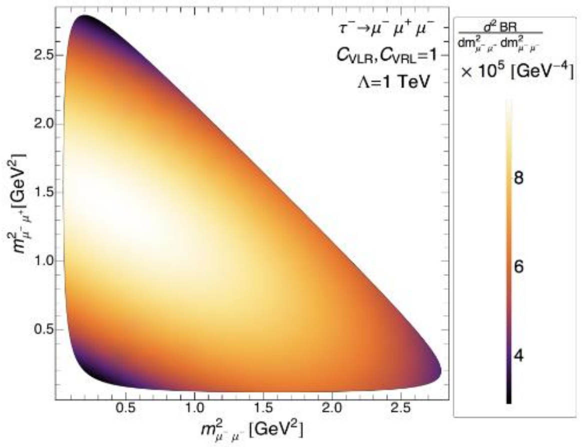
Calibbi et al 2107.10273

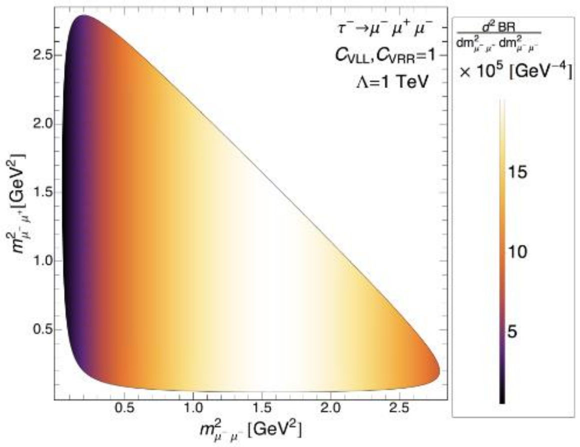


- Complementarity with Z and Higgs LFV decays
- Informations such as Dalitz can help constraining NP models

Celis et al. https://arxiv.org/abs/1403.5781







Vectors

ALEPH BR measurements

Table 11: Total systematic errors for branching ratios measured from the 1994-1995 data sample. 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).

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

From FCCee submission

- $\tau \to \mu\gamma$: A selection efficiency of 8% is assumed, together with a calorimeter energy resolution of 3%/p E [GeV] and ∼1mm spatial resolution, which leads to an upper limit of $1.2 \times 10{-}9$, at the 90% CL
- $\tau \to 3\mu$: the expected performance can be estimated by scaling the Belle II result to the Tera-Z sample size, with a reconstruction efficiency of 35%, which gives a limit of $2.0 \times 10{-}11$
- Mass : statistical precision is 0.9 ppm obtained scaling OPAL result. At FCC-ee the collision energy will be known to 1 ppm and it will be possible to calibrate the momentum scale to a precision approaching 2 ppm from J/ψ decays. The dominant systematic uncertainty is expected to come from sources such as the choice of fit function to the pseudo-mass distribution, knowledge of the detector material, and modelling of the initial and final-state radiation, and the tau decay. At Belle II the uncertainties from such components contribute a total of 29 ppm. It is assumed that at FCC-ee it will be possible to reduce these uncertainties by a factor of around three, to give an overall precision on the tau mass of 10 ppm, or 0.02MeV.
- Lifetime: The FCC-ee performance can be estimated by taking the DELPHI measurement performed at LEP [35] with the same topology, and scaling the FCC-ee sample size. It is also important to account for the better single-event uncertainty that FCC-ee detectors will have on account of improved impactparameter resolution and the smaller beamspot. These considerations lead to an expected statistical precision of 15 ppm from the full Tera-Z sample. Optical interferometry techniques will allow the length scale of the vertex detector to be controlled to a level where it will contribute a possible bias of 5 ppm or less to the measurement The knowledge of the tau mass, improved by FCC-ee itself, will contribute an uncertainty of 10 ppm. The largest uncertainty will most likely arise from the estimation of the average radiated energy in the initial state before the production of the tau pair, which is assigned to be 11.5 ppm. This value assumes a large (factor 30) improvement on the DELPHI assignment, but there the uncertainty was very sub-dominant and so did not warrant close attention.
- BR: At FCC-ee the extrapolated statistical precision is 4.0 ppm and the challenge will be in suppressing the sources of systematic bias. If the systematic uncertainty can be improved by an order of magnitude with respect to LEP, it will be possible to measure the leptonic branching fractions at FCC-ee with a relative precision of 0.019%.

From FCCee submission

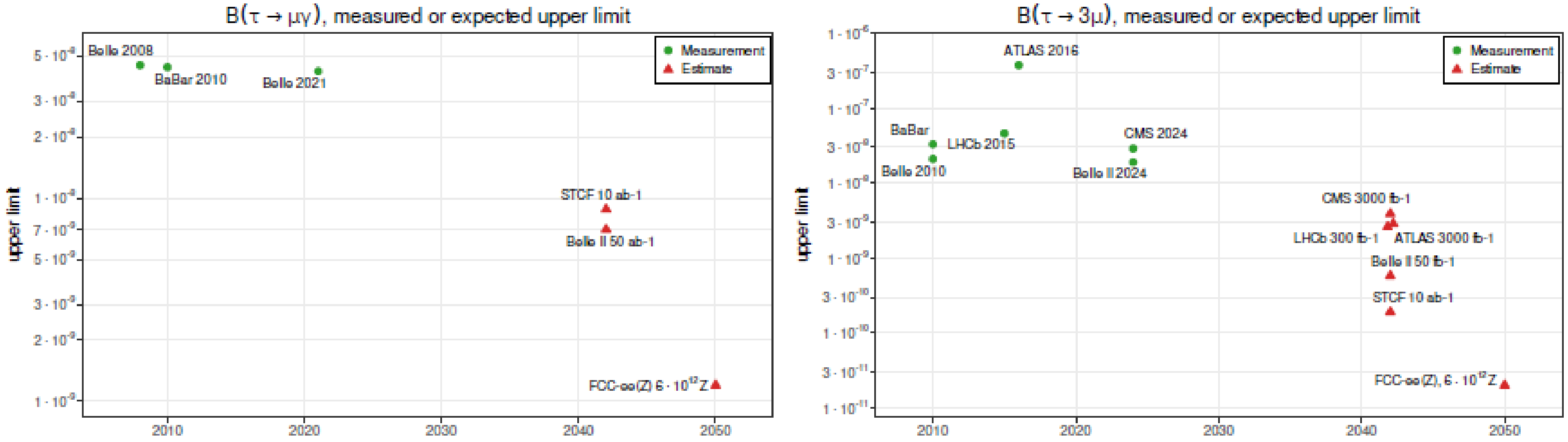


Fig. 3: Current and future experimental upper limits at 90% confidence level for $\mathcal{B}(\tau^- \to \mu^-\gamma$ (left) and $\mathcal{B}(\tau^- \to \mu^+\mu^-\mu^+)$ (right). The future estimates for LHC and Belle II are extrapolated from published results, and taken from Ref. [31] for STCF. The dates of the future measurements are indicative.

$\sigma\,(e^+e^- \rightarrow \tau^+\tau^-)$