Flavour prospects at FCC-ee

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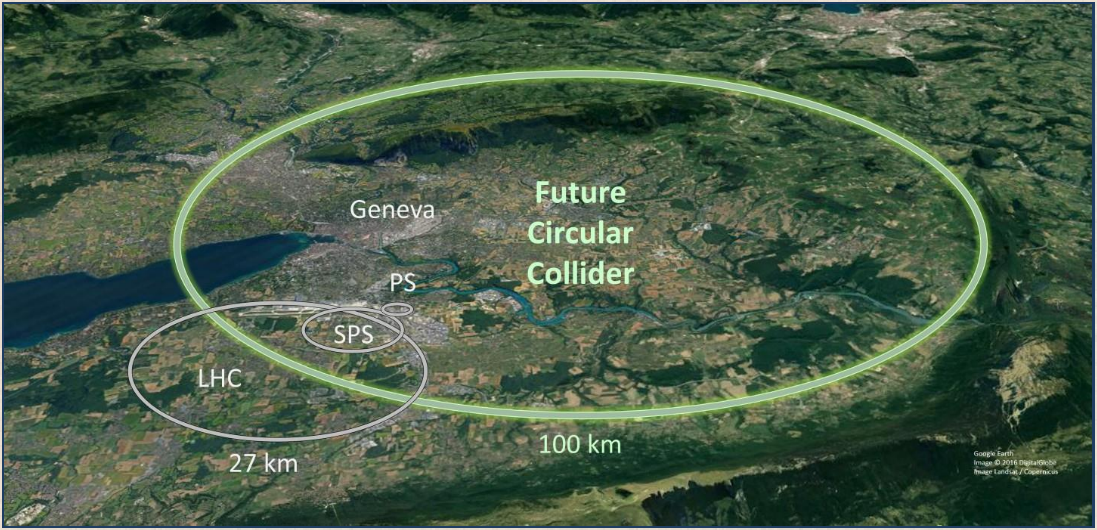
FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union’s H2020 Framework Programme under grant agreement no. 951754.

Future Circular Collider project



content taken from Michael Benedikt presentation at FCC Week, London, June 2023

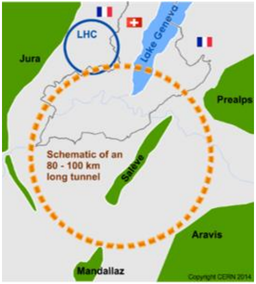
(current design specs have FCC circumpherence = 90.7 Km)

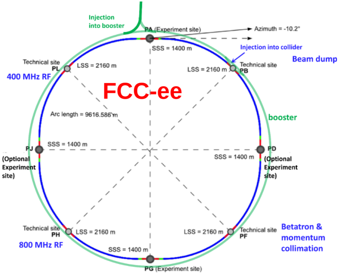
FUTURE CIRCULAR COLLIDER

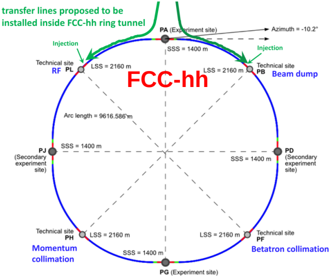
FCC integrated program
inspired by successful LEP – LHC programs at CERN

comprehensive long-term program maximizing physics opportunities

- **stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- complementary physics
- common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC program







2020 - 2040 | **2045 - 2060** | **2065 - 2090**

a similar two-stage project CEPC/SPPC is under study in China

content taken from Michael Benedikt presentation at FCC Week, London, June 2023

FCC design yields

provisional numbers for the FCC mid-term report 2023

- 4 interaction points

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	$6\,10^{12}$ Z		$2.4\,10^{8}$ WW		$1.45\,10^{6}$ HZ + 45k WW $\rightarrow$ H	$1.9\,10^{6}$ $t\bar{t}$ +330k HZ +80k WW $\rightarrow$ H	

very large yield of heavy flavor events at Z peak

event yields [billions]	$B^0/\bar{B}^0$	B^+/B^-	$B_s^0/\bar{B}_s^0$	$B_c^+/\bar{B}_c^-$	$\Lambda_b/\bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	740	740	180	5	160	720	200

- w.r.t. LEP: $2.4{\cdot}10^5\times$ number of Z
- w.r.t. Belle II: $\sim 30\times$ $B^0/\bar{B}^0$
  $\sim 4.5\times$ $\tau^+\tau^-$ + significantly better experimental conditions
- w.r.t. LHC: less production but no pileup, much less background, clean defined initial state

Experimental conditions

baseline FCC-ee detector performance

track momentum	$\frac{\sigma_p}{p} = 0.02{\cdot}10^{-3} \cdot p_T(\text{GeV}) \oplus 1{\cdot}10^{-3}$
track impact parameter	$\sigma_{d_0} = \frac{15\,\mu\text{m}}{\sin^{3/2}\theta} \oplus 5\,\mu\text{m}$
electromagnetic energy	$\frac{\sigma_{E_\gamma}}{E_\gamma} = \frac{15\%}{E_\gamma} \oplus 1\%$
electromagnetic energy *xy* position	$\sigma_{\gamma,xy} = \frac{6\,\text{mm}}{E(\text{GeV})} \oplus 2\,\text{mm}$

advantages w.r.t. Belle II

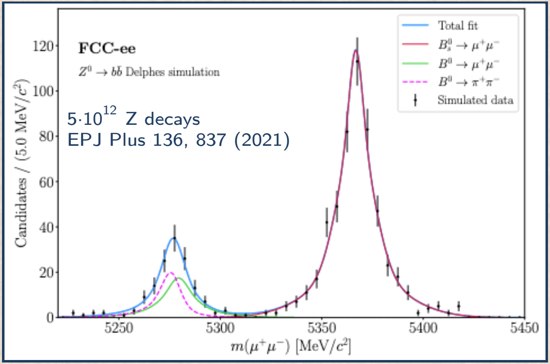
- better momentum resolution and vertexing because less multiple scattering
- better muon id (much lower pion-to-muon misidentification)
- heavier B mesons, and B baryons also produced
- much better $\tau^+\tau^-$ separation from $q\bar{q}$ background because of higher $q\bar{q}$ multiplicity

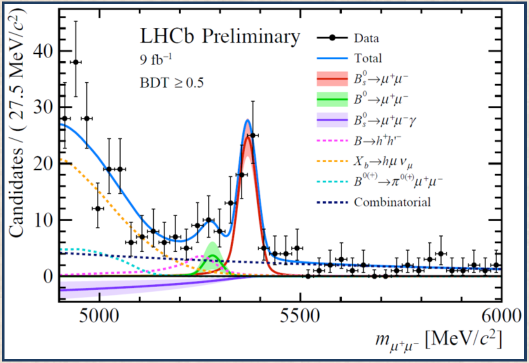
advantages w.r.t. LHC

- similar detector performances but much better for decays with undetected particles and π^0s

$B_s \to \mu^+\mu^-$ and $B_d \to \mu^+\mu^-$ at FCC-ee and LHCb

- FCC-ee provides better resolution and much less background than LHC

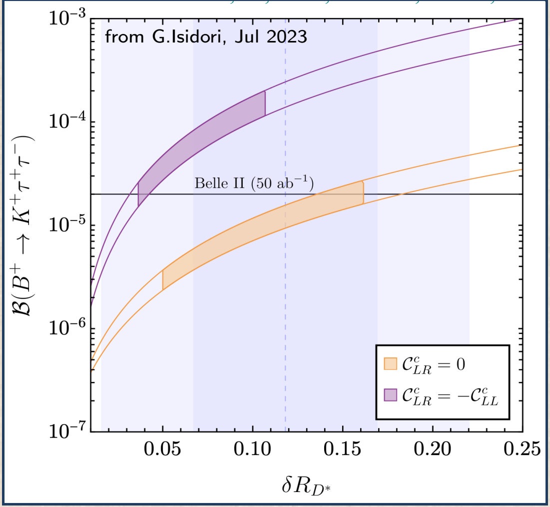




Vector LQ model predicts sizeable $\mathcal{B}(B^+ \to K^+\tau^+\tau^-)$ enhancement

- [Aebischer, Isidori, Pesut, Stefanek, Wilsch, 2023]

today and future Belle II bound



- $\delta R_{D^*} = \frac{R_{D^*}}{R^{\text{SM}}_{D^*}} - 1$

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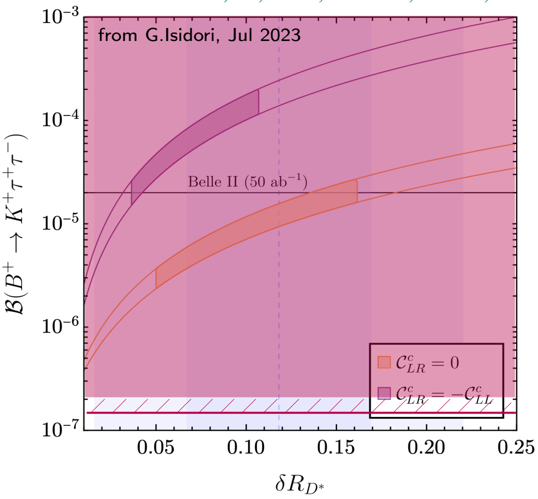
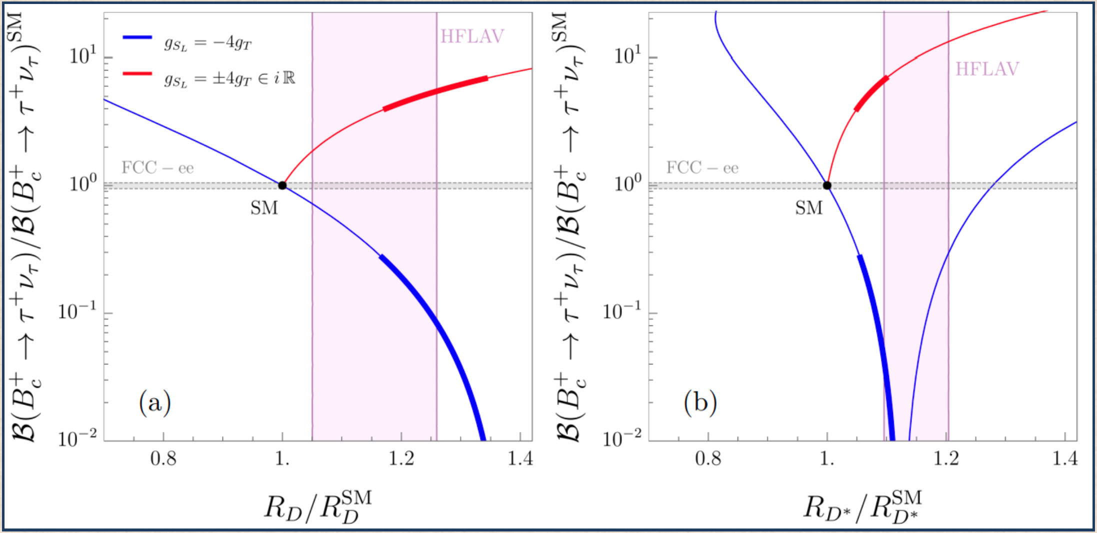


- $\delta R_{D^*} = \dfrac{R_{D^*}}{R^{\mathrm{SM}}_{D^*}} - 1$

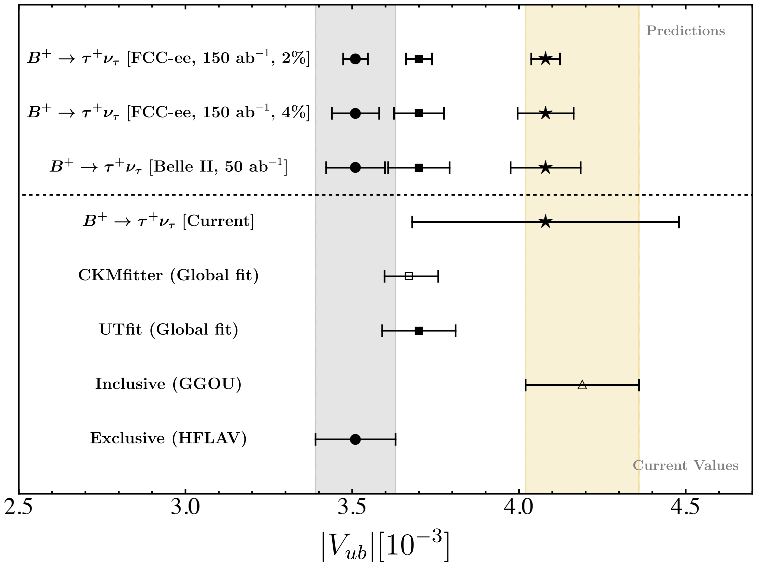
Constraints from $B_c^+ \to \tau\nu / B^+ \to \tau\nu$ on LQ model for B anomalies

- [Amhis, Hartmann, Helsens, Hill, Sumensari, 2023]



$|V_{ub}|$ determination with $B^+ \to \tau\nu$

from arXiv:2305.02998 [hep-ex]



Lepton universality with tau decays

lepton universality from experiment, A.Pich, 2013

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e\rvert$	1.0018 (14)	1.0021 (16)	0.9978 (20)	1.0010 (25)	0.996 (10)

	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0011 (15)	0.9962 (27)	0.9858 (70)	1.034 (13)

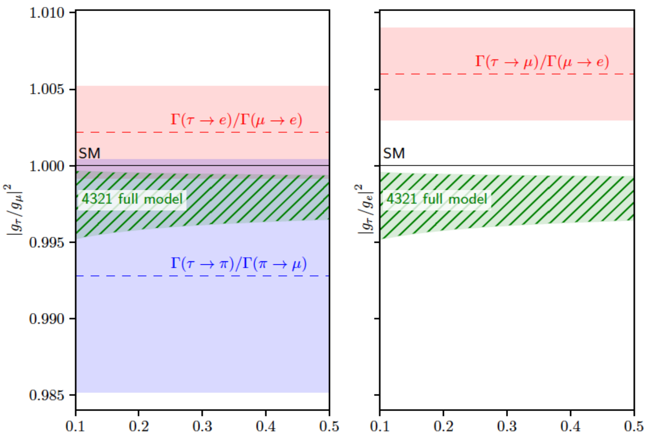
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$	$\Gamma_{W\to\tau}/\Gamma_{W\to e}$
$\lvert g_\tau/g_e\rvert$	1.0030 (15)	1.031 (13)

- *B*-factories did not improve LEP measurements
- dedicated effort in Belle II
- FCC-ee has LEP experimental conditions (much better) and 4.5× the Belle II tau pairs
  - tentative estimated precision $2{\cdot}10^{-4}$ [200 ppm], (purely statistical $\mathcal{O}$(10 ppm))

Lepton universality constraints on 4321 vector lepto-quark model

- lepton universality puts significant constraints on 4321 vector lepto-quark model for B anomalies [Allwicher, Isidori, Selimovic, 2021], [Allwicher, Isidori, Lizana, Selimovic, Stefanek, 2023]

today $\Gamma(\tau \to e)/\Gamma(\mu \to e)$ bound



[from G.Isidori, Jul 2023]

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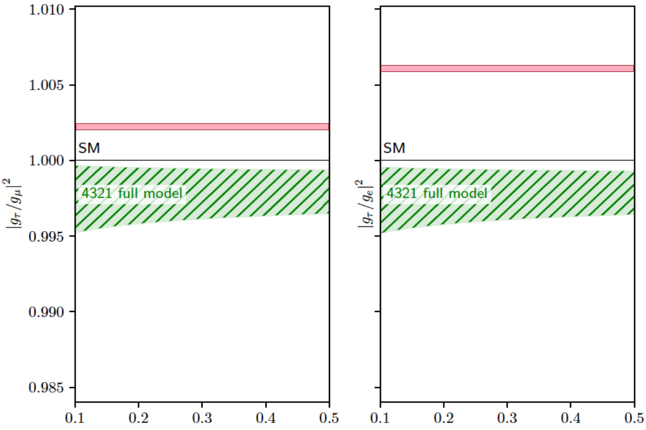
future FCC-ee $\Gamma(\tau \to e)/\Gamma(\mu \to e)$, model escluded



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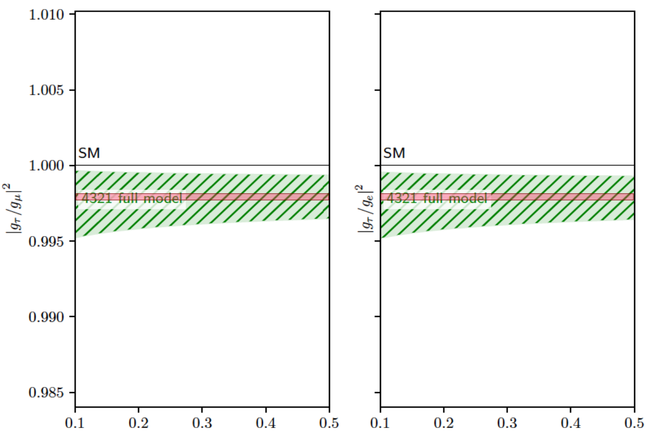
future FCC-ee $\Gamma(\tau \to e)/\Gamma(\mu \to e)$, model confirmed

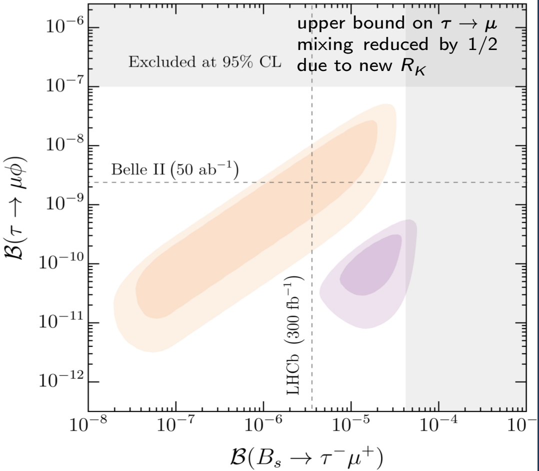


[from G.Isidori, Jul 2023]

Lepton universality constraints on UV complete vector lepto-quark model

- lepton universality puts significant constraints on UV complete vector lepto-quark model for B anomalies [Cornella *et al.*, 2021]

today and future Belle II, LHCb 300 fb^{-1} bounds



[from G.Isidori, Jul 2023]

Lepton universality constraints on UV complete vector lepto-quark model

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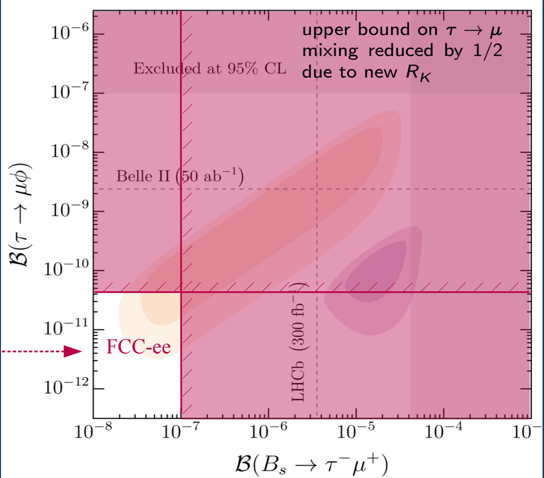
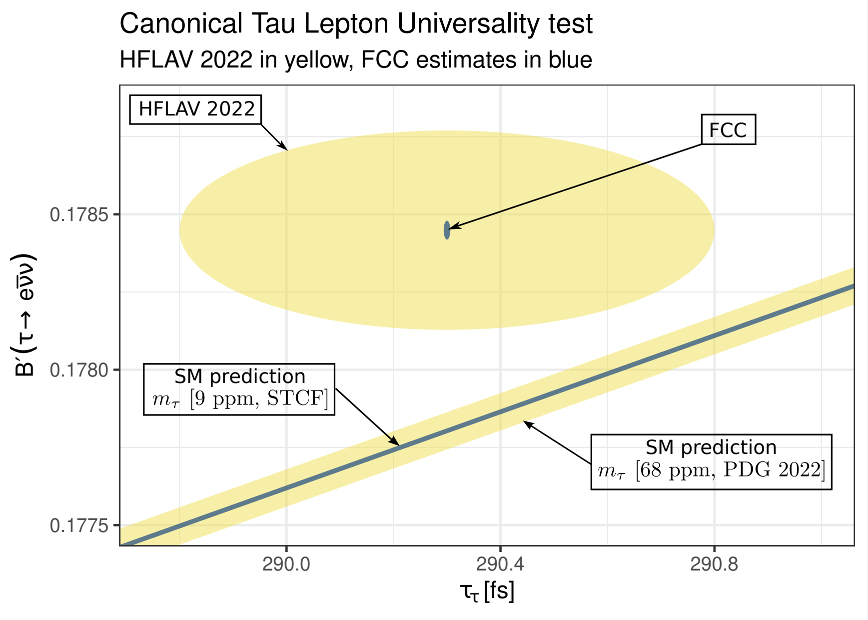
future FCC-ee bounds, G.Isidori naive estimate



[from G.Isidori, Jul 2023]

Canonical tau lepton universality plot extrapolation to FCC-ee

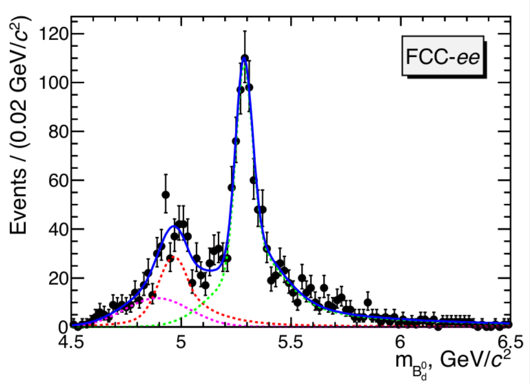


$B^+ \to K^+\tau^+\tau^-$

FCC study in EPJC 77 (2017) 701

- at FCC full reconstruction when both tau leptons decay hadronically, with 4-fold ambiguity
- expect $\sim 10^3$ selected events
- more details on Tuesday presentation by Tristan Miralles

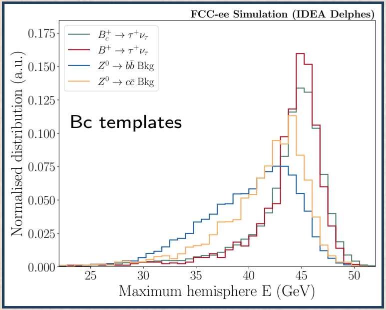
$B^+ \to K^+\tau^+\tau^-$ candidates

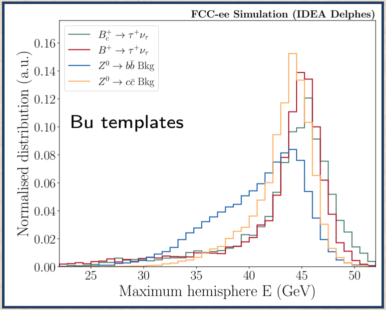


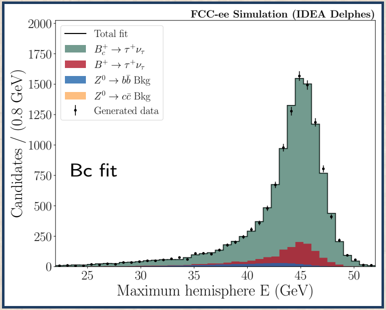
$B_c^+ \to \tau\nu$ and $B^+ \to \tau\nu$

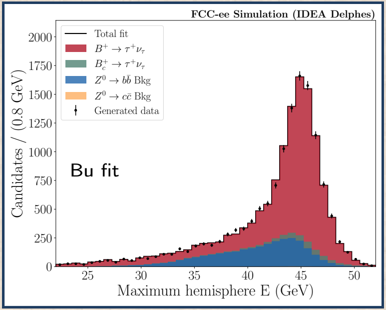
- FCC-ee sensitivity study arXiv:2305.02998 [hep-ex] (2023), (extends older one JHEP 12 (2021) 133)
- use Delphes fast simulation
- divide event in two hemispheres using thrust axis
- expect $B_c^+ \to \tau\nu$, $B^+ \to \tau\nu$ in "minimum" hemisphere, with less reconstructed energy
- require 3 pions compatible with coming from displaced common vertex in minimum hemisphere
- BDT multi-classifiers trained to distinguish $B_c^+ \to \tau\nu$ (Bc) vs. $B^+ \to \tau\nu$ (Bu) vs. background (Bkg)
  - shape and other summary variables of minimum hemisphere
  - properties of 3π system
  - properties of reconstructed D mesons in signal hemisphere
- fit reconstructed energy distribution of "maximum" hemisphere as sum of 4 components
  - $B_c^+ \to \tau\nu$, $B^+ \to \tau\nu$, $Z \to b\bar{b}$ background, $Z \to c\bar{c}$ background
- $B_c^+ \to \tau\nu$ requires normalization mode $B_c^+ \to J/\psi\mu\nu$ since $f(B_c^\pm)$ poorly known
  - requires LQCD prediction of $\mathcal{B}(B_c^+ \to J/\psi\mu\nu)$
- FCC-ee with $5{\cdot}10^{12}$ Z precision $\sim$1.8% for $B_c^+ \to \tau\nu$, $\sim$2.0% for $B^+ \to \tau\nu$
- SM predictions $\mathcal{B}(B_c^+ \to \tau^+\nu_\tau)^{\text{SM}} = 2.29(9) \times 10^{-2}$, $\mathcal{B}(B^+ \to \tau^+\nu_\tau)^{\text{SM}} = 0.87(5) \times 10^{-4}$

$B_c^+ \to \tau\nu$ and $B^+ \to \tau\nu$









Lepton universality tests

from HFLAV Tau Winter 2022 report

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

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

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

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

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

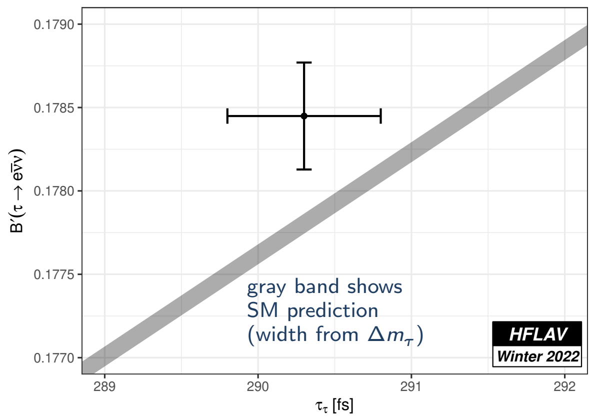
$$G_\lambda = \frac{g_\lambda^2}{4\sqrt{2}M_W^2}\ ; \qquad f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x\ ; \qquad f_{\lambda\rho} = f\left(m_\rho^2/m_\lambda^2\right)$$

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

all statistical correlations included

- less precise tests possible with hadronic tau decays

Canonical tau lepton universality test plot



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

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

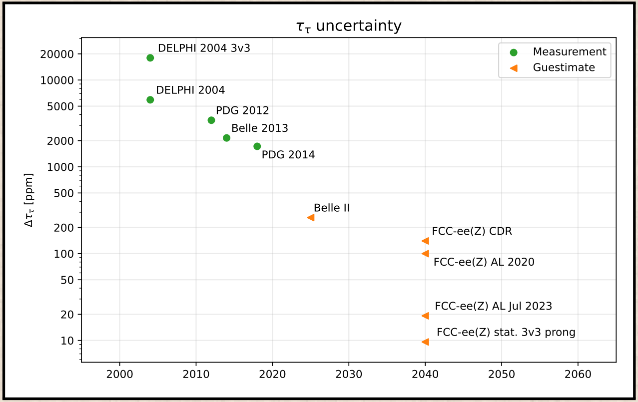
$\Delta(g_\tau/g_{e\mu})$ contributions

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 Lifetime uncertainty



FCC total uncertainty estimates

- M. Dam, 1999, FCC CDR
- A.L. FCC Krakow Jan 2023
- A.L. FCC London Jun 2023

Other estimates

- Belle II Physics Book

τ_τ statistical precision [ppm]	
4800	DELPHI 2004, 144 pb^{-1}
18000	DELPHI 2004, 3-prong vs. 3-prong (3v3), 144 pb^{-1}
11.3	FCC-ee(Z) $5{\cdot}10^{12}$ Z, 180 ab^{-1}, from DELPHI 2004 3v3 and factor 0.7 (*)

(*) factor 0.7 for smaller beam spot and better impact parameter resolution at FCC-ee w.r.t. LEP, see later

Tau Lifetime uncertainty notes

- consider just tau pairs in 3-prong vs. 3-prong topology (3v3)
  - Belle 2013 best measurement uses these events
  - τ direction reconstruction using vertices reduces importance of simulation
- extrapolate FCC-ee statistical precision starting from Delphi 2004 3v3 events statistical precision
  - expect no significant differences on selection efficiency
  - Delphi 2004 3v3 precision by rescaling 3v1+3v3 measurement to number of 3v3 candidates
  - τ_τ measurement is a measurement of transverse i.p. $\langle d_0 \sin\theta \rangle \approx 70\,\mu\text{m}$
  - Delphi 2004 3v3 precision consistent with a d_0 resolution $\approx 70\,\mu\text{m}$ (tracking, beam spot)
  - assume FCC-ee has both transverse beam spot and can have d_0 resolution $\ll 70\mu\text{m}$
    $\Rightarrow$ resolution improvement factor $\sim 70\,\mu\text{m}/(70\,\mu\text{m} \oplus 70\,\mu\text{m}) \simeq 0.7$
- assume DELPHI systematics for background, reconstruction bias and alignment (total 1.3 fs) scale with luminosity to 3.5 ppm at FCC-ee (very optimistic)
- assume 30$\times$ better KKMC simulation can reduce uncertainty on ISR+FSR energy loss in tau pair production to reduce the associated systematic contribution from 350 ppm to 12 ppm
- assume 9 ppm tau mass measurement at SCT/STCF or at FCC-ee
- assume 2 ppm vertex detector length scale (possible with optical methods proposed for MuonE)

Tau Lifetime at FCC-ee(Z) uncertainty budget

τ_τ precision [ppm]	
11.3	statistical
2.0	length scale of vertex detector
9.0	$\sigma(m_\tau)$
12.0	average tau pair production radiative energy loss
3.5	systematics optimistically expected to scale with statistics
	- detector alignment
	- background
	- fit model
19.2	total

detector requirements to limit effects below 1/2 of statistical uncertainty

- impact parameter resolution for tau decay tracks $\leq 70/2 \cdot \sqrt{3} = 61\,\mu\text{m}$
  - taking into account that each single event measurement uses three tracks
- uncertainty on average length scale of vertex detector elements $\leq 9.6/2 = 4.8\,\text{ppm}$

other detector requirements

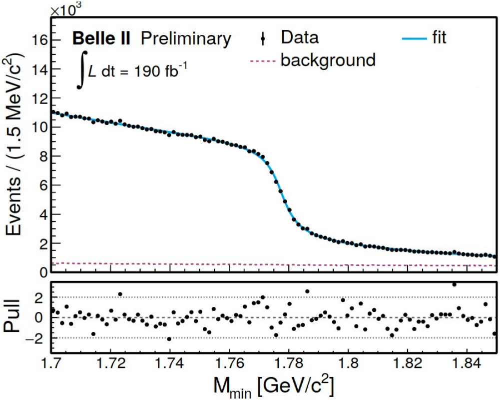
- $75\times$ precision improvement for simulation of radiation in tau pair production
  - not detector but worth noting
  - $30\times$ assumed to be more realistic in the uncertainty bugget

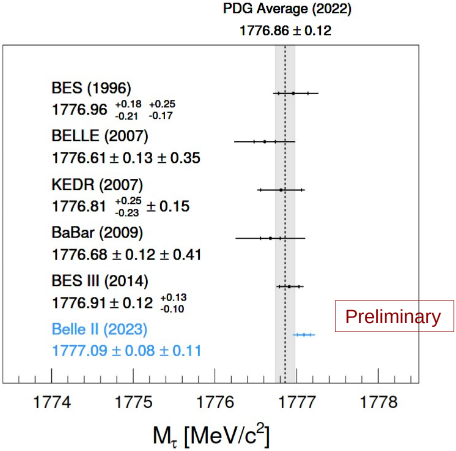
Tau mass Belle II preliminary measurement [Moriond 2023]

NEW
for Moriond!

World's most precise measurement

- World's most precise measurement of $\mathbf{m_\tau = 1777.09 \pm 0.08_{stat} \pm 0.11_{sys}\ MeV/c^2}$





Proof of high precision capability of Belle II!

arXiv:2305.19116 [hep-ex], May 30, 2023

L.Zani - Dark sectors and tau phsyics at Belle II - Moriond 2023 13

Tau mass Belle II preliminary measurement [Moriond 2023], systematics

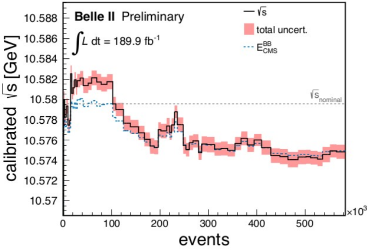
NEW for Moriond!

τ mass: precision challenge

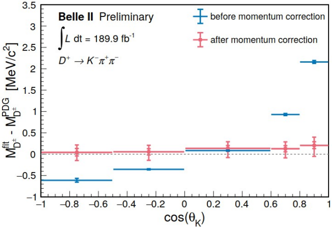
- Excellent control of systematic uncertainties thanks to precise understanding of beam energies and tracking: $M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau$

Source	Uncertainty [MeV/c^2]
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	≤ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	≤ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	≤ 0.01
Neutral particle reconstruction efficiency	≤ 0.01
Tracking efficiency correction	≤ 0.01
Trigger efficiency	≤ 0.01
Background processes	≤ 0.01
Total	0.11

Beam energy calibration with B-meson hadronic decays method and Υ(4S) lineshape measurement to get $\sqrt{s}$



Momentum scale factor cures the bias due to imperfect B-field: extract corrections dependent on $\cos\theta_{track}$ by comparing $D^0 \to K\pi$ mass peak w.r.t PDG mass.



arXiv:2305.19116 [hep-ex], May 30, 2023

L.Zani - Dark sectors and tau phsyics at Belle II - Moriond 2023

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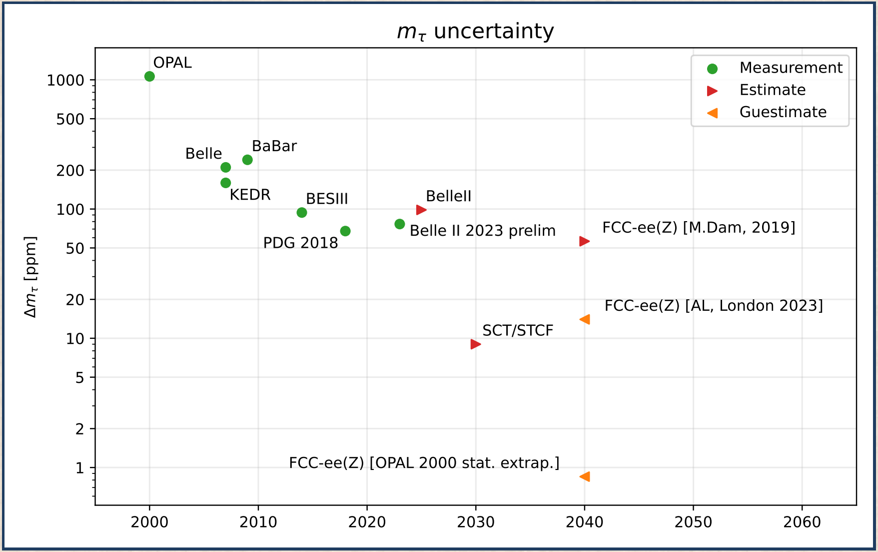
Tau mass prospects at FCC-ee

- Belle II statistical uncertainty is 45 ppm with 190 fb^{-1}, 175 M tau pairs
- FCC-ee statistical uncertainty with $6{\cdot}10^{12}$ Z, $2.0{\cdot}10^{11}$ tau pairs would be 1.3 ppm
  - neglecting surely better FCC-ee efficiency
- Belle II dominant systematics expected very reduced at FCC-ee
  - beam energy (1 ppm at FCC-ee)
  - track momentum scale (2 ppm calibration maybe possible at FCC-ee with $m_{J/\psi}$)
- alignment systematics can be expected to scale with statistics
- limiting systematics from empirical fit function, 0.05 MeV or 28 ppm
- may expect to reduce this limiting systematic uncertainty to 1/2 of 14 ppm at FCC-ee
- guestimate FCC-ee tau mass precision at 14 ppm
- no particular detector requirements are needed, just baseline

Tau mass prospects at FCC-ee and other facilities



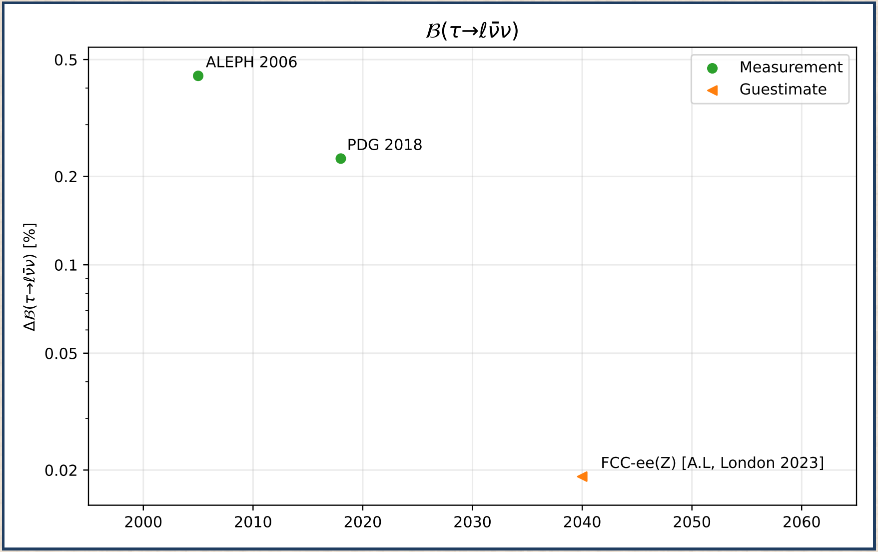
Tau leptonic branching fractions prospects at FCC-ee

- ALEPH 2006 measurement precision: $4400\,\text{ppm} = [4000(\text{stat.}) \oplus 1900(\text{syst.})]\,\text{ppm}$
  (average of the two similar electron and muon decays branching fractions)
  - complex simultaneous measurement of 12 tau branching fractions
  - many systematic uncertainties, no reliable extrapolations to FCC-ee statistics
  - several systematics related to photon and $\pi^0 \to \gamma\gamma$ reconstruction
  - more details in presentation at FCC Liverpool Feb 2022
- FCC-ee extrapolated statistical precision: $4000\,\text{ppm} \cdot \sqrt{6.2 \cdot 10^6\,(\text{ALEPH Z bosons}) / 8 \cdot 10^{12}} = 4.5\,\text{ppm}$
- today guestimate: FCC-ee precision may be limited to about 1/10 of ALEPH systematics, 190 ppm

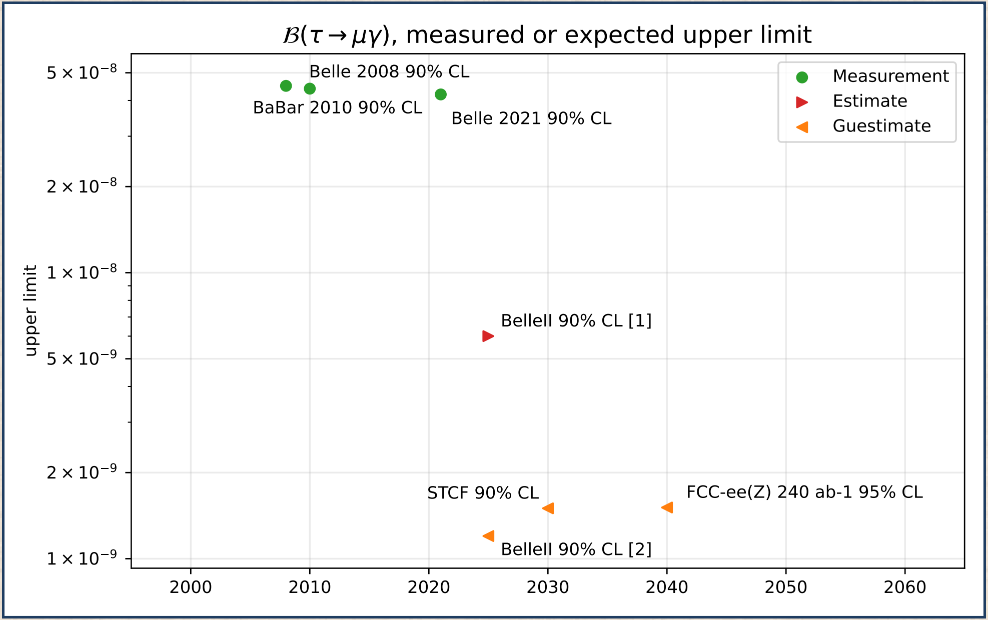
detector requirements

- unable to reliably estimate detector requirements corresponding to 1/2 of 190 ppm precision
- generic requirements (probably better ascertained on some other simpler Flavour measurement)
  - good electromagnetic energy resolution, at least better than LEP $20\%/\sqrt{E(\text{GeV})}$
  - granular electromagnetic calorimeter, at least better than LEP $15 \times 15\,\text{mrad}^2$

Tau leptonic Branching fractions prospects at FCC-ee and other facilities



LFV $\tau \to \mu\gamma$



LFV $\tau \to \mu\gamma$ (2)

- M. Dam, Tau-lepton Physics at the FCC-ee circular e+ e- Collider, SciPost Phys. Proc. 1 (2019) 041. arXiv:1811.09408
- assuming FCC-ee(Z) with $1.3{\cdot}10^{11}$ tau pairs
- assuming 25% efficiency
- MC truth with smearing to simulate reconstruction
- 2% of total assumed FCC statistics
- signal region with $E_{\mu\gamma}$ = half CM energy, $m_{\mu\gamma} = m_\tau$
- 20k bkg events in signal region
- may improve by factor 5-10 with detector improvements(long. segmented electromagnetic calorimeter)

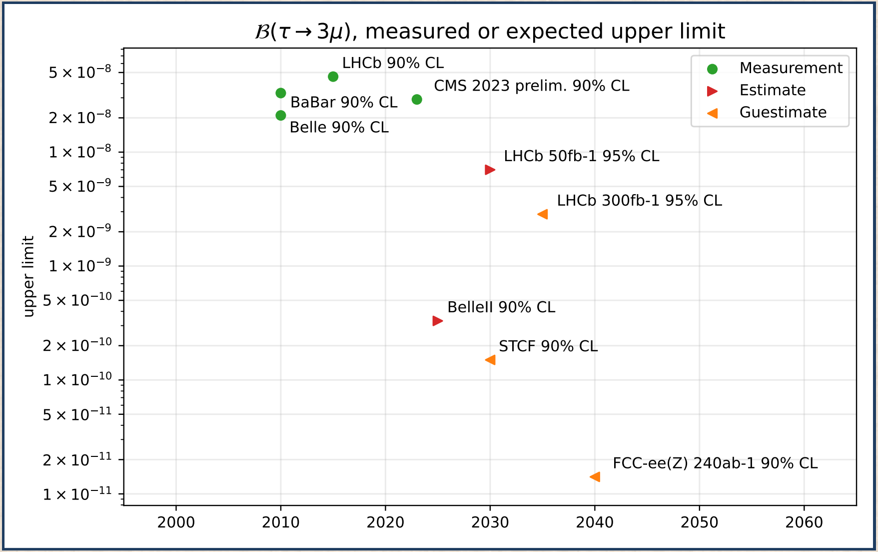
A.L. revisions, 2023

- assume efficiency 50% instead of 25%
- 95% CL upper limit computed corresponding to $2\,\sigma$ bkg fluctuation
- rescaled integrated luminosity to $240\,\mathrm{ab}^{-1}$

Belle II

- 2nd better estimate using better beam constraint to suppress backgrounds

LFV $\tau \to 3\mu$



Notes on guestimate of FCC expected 90% CL upper limit on $\tau \to 3\mu$

- $2.1{\cdot}10^{-8}$ published Belle limit at 0.782 ab^{-1}
- $\ldots/(50\ \text{ab}^{-1}/0.782\,\text{ab}^{-1}) = 3.3{\cdot}10^{-10}$, BelleII expected upper limit assuming background-free search
- FCC: $8{\cdot}10^{12}$ Z^0, $2.7{\cdot}10^{11}$ tau pairs, $\sim 5.9 \times 46{\cdot}10^{9}$ 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
- pion mis-id rate to muon much smaller at FCC momenta than at *B*-factories
  $\Rightarrow$ expect FCC search also bacground-free
- expect $m_{3\mu}$, $E_{3\mu}$ resolution comparable with *B*-factories (using expected p_T resolution)
- $3.3{\cdot}10^{-10}/(4.0 \cdot 5.9) \simeq 1.4{\cdot}10^{-11}$ FCC 90% CL UL
- guestimate to be improved with Monte Carlo studies

Conclusions

- FCC-ee will provide huge samples of heavy flavour particles and very favourable experimental conditions to perfom Flavor Physics measurements
- on-going studies on proper detector solutions to fully exploit the future large clean FCC data samples

– end –

Backup Slides

Vertex detector absolute length scale systematic

- vertex detector misaligment can have large effect but can be suppressed and calibrated
- average radius of the vertex detector can be constrained with data using overlapping wafer modules: radius will be known with the same relative precision of the knowledge of the size of the silicon modules, or equivalently the average strip pitch
- LEP, *B*-factories, absolute length scale knowledge of silicon vertex detector believed to be 100 ppm
- A.L. Jan 2020 guestimate for FCC tau lifetime uncertainty limited to 100 ppm by this limitation

MUonE interferometric monitoring of detector to 1 μm/50 cm, 2 ppm

- A. Arena, G. Cantatore, M. Karuza, Digital holographic interferometry for particle detector diagnostic, Proceedings of the International Convention MIPRO, May 2022, doi:10.23919/MIPRO55190.2022.9803636
  - During preliminary tests, we have obtained reconstructed holographic images with interference fringes showing a displacement of the monitored object, over time, of the order of $\sim$1 μm. This experimentally demonstrated resolution is already sufficient to satisfy the 10 μm resolution mandated by MUonE. [MUonE silicon modules are 50 cm apart]
- also absolute calibration required in addition to monitoring, appears feasible with optical techniques
- 2 ppm tau lifetime sistematics from vertex detector length scale appears attainable

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]	$\sim$10.6	92	$\sim$10.6	$\sim$10.6	$2-6$	$2-7$	92	
$\int \mathcal{L} dt$ [ab^{-1}]	0.01		1.5	50	10			240
tau pairs	$1{\cdot}10^7$	$0.8{\cdot}10^6$	$1.4{\cdot}10^9$	$46{\cdot}10^9$	$30{\cdot}10^9$		$30{\cdot}10^9$	$270{\cdot}10^9$

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

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)

Important ingredients for precise BR measurements

- 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 invariant 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
- FCC is best imaginable context for tau BR measurements

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)