FCC Physics

Alberto Lusiani – **SNS & INFN Pisa**

FCC Pisa meeting, 29 May 2025, Pisa

The European Strategy anno 2020

"An *electron-positron Higgs factory is the highest priority next collider*. For the longer term, the European particle physics community *has the ambition to operate a proton-proton collider at the highest achievable energy*."

"Europe, together with its *international partners*, should investigate *the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV* and *with an electron-positron Higgs and electroweak factory as a possible first stage*. Such a feasibility study of the colliders and related infrastructure should be established *as a global endeavour and be completed on the timescale of the next Strategy update*."

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[Jan Eysermans, FCC week May 2025, Vienna]

The European Strategy anno 2020

"An *electron-positron Higgs factory is the highest priority next* European particle physics community *has the ambition to ope* *the highest achievable energy*."

"Europe, together with its *international partners*, should inves *feasibility of a future hadron collider at CERN with a centre-o* and *with an electron-positron Higgs and electroweak factory* feasibility study of the colliders and related infrastructure sho *endeavour and be completed on the timescale of the next St*

Future Circular Collider
Feasibility Study Report

arXiv:2505.00272v1 [hep-ex] 25 Apr 2025

Volume 1

Physics, Experiments, Detectors

May 2, 2025

Submitted to the European Physics Journal ST, a joint publication of EDP Sciences, Springer Science+Business Media, and the Società Italiana di Fisica.

→ Start of the FCC Feasibility Study in 2021

→ Completed and delivered on March 31, 2025

→ Submissions to the ESPPU on the same date

https://cds.cern.ch/record/2928193
https://arxiv.org/abs/2505.00272

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[Jan Eysermans, FCC week May 2025, Vienna]

The Outcome: Higgs Physics

Coupling	HL-LHC	FCC-ee	FCC-ee + FCC-hh
κ_Z (%)	1.3*	0.10	0.10
κ_W (%)	1.5*	0.29	0.25
κ_b (%)	2.5*	0.38 / 0.49	0.33 / 0.45
κ_g (%)	2*	0.49 / 0.54	0.41 / 0.44
κ_τ (%)	1.6*	0.46	0.40
κ_c (%)	–	0.70 / 0.87	0.68 / 0.85
κ_γ (%)	1.6*	1.1	0.30
$\kappa_{Z\gamma}$ (%)	10*	4.3	0.67
κ_t (%)	3.2*	3.1	0.75
κ_μ (%)	4.4*	3.3	0.42
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$	$^{+29}_{-67}$
Γ_H (%)	–	0.78	0.69
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}	2.3×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}	6.7×10^{-3}

FCC-ee and FCC-hh Integrated Programme is complementary and provides ~ order of magnitude improvement of all Higgs couplings w.r.t HL-LHC

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[Jan Eysermans, FCC week May 2025, Vienna]

The Higgs Self Coupling

Measuring the Higgs self-interaction is fundamental to characterise the nature of the Higgs potential

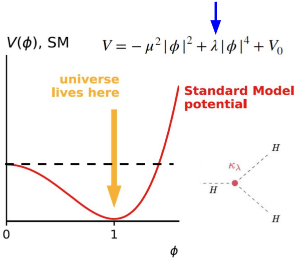
At pp colliders, measurement of λ or $\kappa_\lambda = \lambda_{meas}/\lambda_{SM}$ through direct Higgs pair production

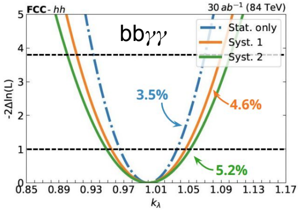
- Cross sections are ~ 1000x smaller than single Higgs production!
- Impressive work already done at LHC → promising projections
- Intensified FCC-hh studies using Fast Simulation and reference detector models

Indirect sensitivity to κ_λ at FCC-ee via one loop-effects in the ZH cross section

HL-LHC	→	+FCC-ee	→	+FCC-hh
26–29%		~18%		2–3%

Expected precision on κ_λ





B.Stapf, X.Zuo

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[Jan Eysermans, FCC week May 2025, Vienna]

Electroweak Precision Physics

J.Bendavid, L.Toffolin

The Tera-Z program (and beyond) yields a data sample size never seen before

- Lineshape scan at the Z pole (~91 GeV) and threshold scan at WW production threshold (~160 GeV)
- Up to 2 orders of magnitude improvement w.r.t. current knowledge

Several challenges to keep systematic uncertainties under control

- Beam calibration (EPOL) ~ 100 keV
- Detectors: acceptance, efficiencies, hermiticity
- Luminosity: using known processes (Bhabha, $\gamma\gamma$)
- Calibration: in situ using available data, monitoring
- Theory: need to cope with orders of magnitude improvement of theoretical calculations and Monte Carlo generators accuracy

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
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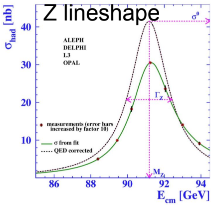
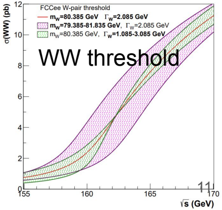
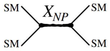




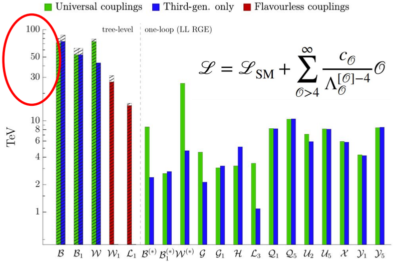
[Jan Eysermans, FCC week May 2025, Vienna]

Discovery potential of New Physics



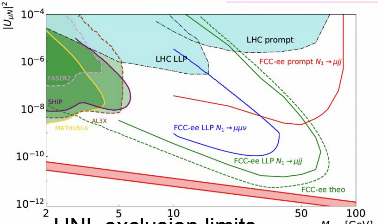
Tera-Z put indirect bounds on New Physics

- Interpretation of results using *effective field theories*, extension of the Standard Model (SMEFT)
- FCC-ee can probe within the 10-100 TeV mass range
- More phase space to cover (e.g. flavour, others)



Direct searches for New Physics at FCC-ee, thanks to its clean environment and large statistics

- Heavy Neutral Leptons (HNLs) – prompt and long-lived
- Axion Like Particles (ALPs)
- Exotic Higgs/Z decays
- Dark Photons, Dark Matter, etc.



HNL exclusion limits 12

Much of this parameter space is orthogonal to, or extends beyond, that of the HL-LHC

P.R.Teles, A.E.Thomsen, L.Allwicher, R.Franceschini, R. Gonzalez Suarez, F.Deppisch

[Jan Eysermans, FCC week May 2025, Vienna]

Importance of the Top Threshold

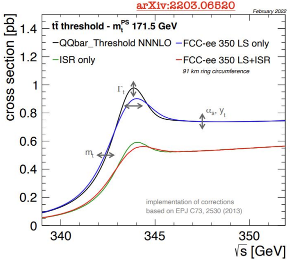
M. Defranchis

Well established programme to study the Top quark at FCC-ee

- Top quark never measured at an e+e– collider; mass ambiguously defined at hadron colliders
- Threshold scan delivers Top mass, width, Yukawa, strong coupling

Observable	present value	±	present uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_{top} (MeV)	172 570	±	290	**4.2**	4.9*	From $t\bar{t}$ threshold scan parametric, beam calibration
Γ_{top} (MeV)	1 420	±	190	**10.0**	6.0*	From $t\bar{t}$ threshold scan parametric, beam calibration
y_{top}		±	10%	**1.5%**	1.5%*	From $\sqrt{s} = 365$ GeV run paramteric, beam calibration

arXiv:2203.06520



Extended Higgs measurements at √s = 365 GeV

- Both Higgs Strahlung (ZH) and Vector Boson Fusion (WW→H) production modes → different signatures
- SM backgrounds more suppressed
- Combined measurements at √s = 240 GeV and 365 GeV maximises Higgs Programme!

$\sqrt{s}$	240 GeV		365 GeV	
channel	**ZH**	**WW → H**	**ZH**	**WW → H**
ZH → any	±0.31		±0.52	
γH → any	±150			
H → bb	±0.21	±1.9	±0.38	±0.66
H → cc	±1.6	±19	±2.9	±3.4
H → ss	±120	±990	±350	±280
H → gg	±0.80	±5.5	±2.1	±2.6
H → $\tau\tau$	±0.58		±1.2	±5.6 (*)
H → $\mu\mu$	±11		±25	
H → WW*	±0.80		±1.8 (*)	±2.1 (*)
H → ZZ*	±2.5		±8.3 (*)	±4.6 (*)
H → $\gamma\gamma$	±3.6		±13	±15
H → Zγ	±11.8		±22	±23

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X. Zuo, A. Maloizel

[Jan Eysermans, FCC week May 2025, Vienna]

Flavour Physics

Reminded several times that FCC-ee is a Flavour Factory

Particle species	B^0	B^-	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

15x Belle-II!

Attribute	$\Upsilon(4S)$	pp	Z
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	(✓)
Negligible trigger losses	✓		✓
High geometrical acceptance	✓		✓
Low backgrounds	✓		✓
Flavour-tagging power	✓		✓
Initial-energy constraint	✓		(✓)

Kamenik et al. 2025 See parallel talk by Monteil

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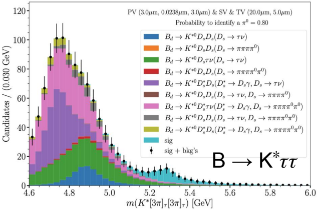
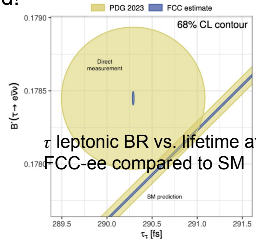
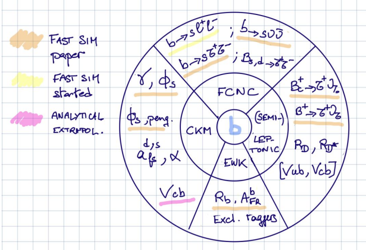
FCC-ee enables rich flavour physics opportunities

- b→s transitions with taus and neutrinos as key measurements
- Tau, charm physics, CKM elements thanks to 10^8 WW events
- Strong requirements on vertex/calorimeter
- Much more to be explored and studied!





τ leptonic BR vs. lifetime at FCC-ee compared to SM



S.Monteil

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[Jan Eysermans, FCC week May 2025, Vienna]

2) Achievements during the Feasibility Study

FCC

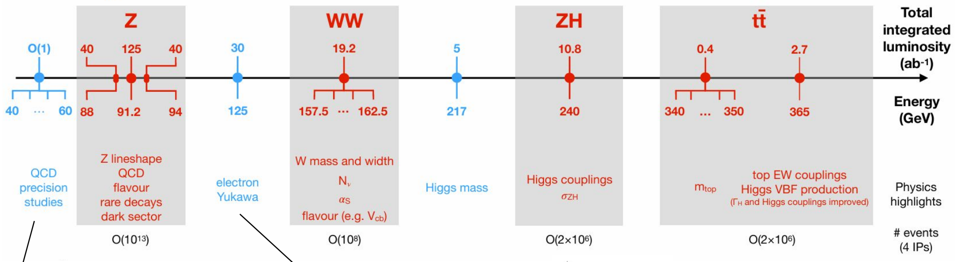
Several avenues explored with (mostly) fast simulation studies:

- Semileptonic decays $b \to s\tau^+\tau^-$ 1705.11106, 2505.00272
- Semileptonic decays $b \to s\nu\bar{\nu}$ 2309.11353
- Leptonic decays $B_c^+, B^+ \to \tau^+\nu_\tau$ 2105.13330, 2305.02998
- CKM *CPV* observables (γ and ϕ_s) 2402.09987, 2205.07823, 2107.02002
- CKM m.e. w/ on-shell *W* decays ($|V_{cs}|, |V_{cb}|$) *e.g.* 2405.08880
- Tau physics 2505.00272, 2401.07564
- EWK observables for heavy quarks with exclusive decays 2502.17281
- Hopefully conveys that these studies are getting published. Worth to join the effort!

S. Monteil FS-Flavours@ FCC 6

[Stephane Monteil, FCC week May 2025, Vienna]

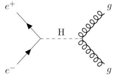
Additional Opportunities



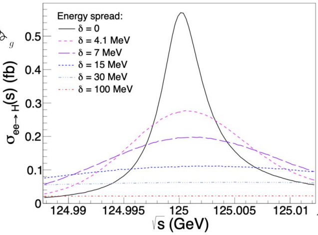
QCD precision studies

- $\sqrt{s}$ = 40–60 GeV
- Study jet fragmentation, QCD, hadronisation
- Tune Monte Carlo generators

Electron-Yukawa



- $\sqrt{s}$ = 125 GeV $e^+e^- \to H$
- Probe first-generation Higgs couplings → *unique at FCC-ee!*
- Requires beam monochromatisation ~ 4 MeV



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S.Kluth, X.Zuo

[Jan Eysermans, FCC week May 2025, Vienna]

A.Sciandra

Detector Requirements

Strong detector requirements from wide Physics Programme

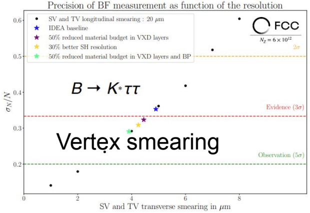
- Also expected to operate across a wide luminosity and energy range, beam backgrounds
- Requires optimised designs, (new) technologies (next talk!)
- Iterative approach to optimize physics potential necessary

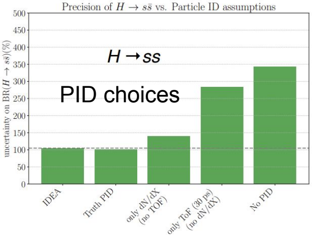
Studied using benchmark physics scenarios

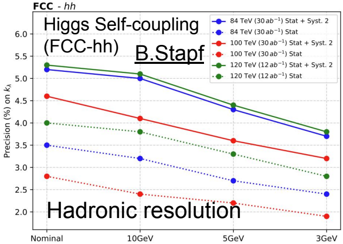
- Key requirements identified (using FastSim/back-of-the-envelope)
- Need more explicit requirements, tailored to different detector designs, studies with FullSim

	Aggressive	Conservative	Comments
Beampipe	$X/X_0 < 0.5\%$	$X/X_0 < 1\%$	$B \to K^*\tau\tau$
Vertex	$\sigma(d_0) = 3 \oplus 15\,/\,(p \sin^{3/2}\theta)\,\mu m$ $X/X_0 < 1\%$	–	$B \to K^*\tau\tau$ R_c
	$\delta L = 5\,ppm$	–	$\delta\tau_\tau < 10\,ppm$
Tracking	$\sigma_p/p < 0.1\%$ for $\mathcal{O}(50)$ GeV tracks	$\sigma_p/p < 0.2\%$ for $\mathcal{O}(50)$ GeV tracks	$\delta M_H = 4\,MeV$ $\delta\Gamma_Z = 15\,keV$ $Z \to \tau\mu$
	t.b.d.	$\sigma_\theta < 0.1\,mrad$	$\delta\Gamma_Z(BES) < 10\,keV$
ECAL	$\sigma_E/E = 3\%/\sqrt{E}$	$\sigma_E/E = 10\%/\sqrt{E}$	$Z \to \nu_e\bar{\nu}_e$ coupling, B physics, ALPs
	$\Delta x \times \Delta y =$ $2 \times 2\,mm^2$	$\Delta x \times \Delta y =$ $5 \times 5\,mm^2$	τ polarisation boosted π^0 decays bremsstrahlung recovery
	$\delta z = 100\,\mu m$, $\delta R_{min} = 10\,\mu m\ (\theta = 20^\circ)$	In-situ constraint with dilepton/diphoton events	alignment tolerance for $\delta\mathcal{L} = 10^{-5}$ with $\gamma\gamma$ events
HCAL	$\sigma_E/E = 30\%/\sqrt{E}$	$\sigma_E/E = 50\%/\sqrt{E}$	$H \to s\bar{s}, c\bar{c}, gg$, invisible HNLs
	$\Delta x \times \Delta y =$ $2 \times 2\,mm^2$	$\Delta x \times \Delta y =$ $20 \times 20\,mm^2$	$H \to s\bar{s}, c\bar{c}, gg$
Muons	low momentum ($p < 1$ GeV) ID	–	$B_s \to \nu\bar{\nu}$
Particle ID	3σ K/π $p < 40$ GeV	3σ K/π $p < 30$ GeV	$H \to s\bar{s}$ $b \to s\nu\bar{\nu}, \ldots$
LumiCal	tolerance $\delta z = 100\,\mu m$, $\delta R_{min} = 1\,\mu m$ acceptance 50–100 mrad	–	$\delta\mathcal{L} = 10^{-4}$ target (Bhabha)
Acceptance	100 mrad	–	$e^+e^- \to \gamma\gamma$ $e^+e^- \to e^+e^-\tau^+\tau^-(c\bar{c})$

Requirements Summary Table







[Jan Eysermans, FCC week May 2025, Vienna]

Why Software Matters

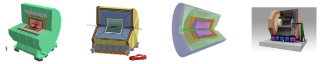
B.Francois
A. Tolosa-Delgado
S.H.Ko
J.Smiesko

Software is the connection between physics/detectors/performance

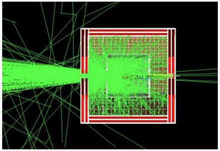
- Need a common, sustainable, flexible, and collaborative software ecosystem
- Crucial for the ongoing and future detector requirements studies

Key4hep as common framework, covering full chain from detector simulation to analysis tools

- Matured a lot over the past years – now used by FCC, ILC, Muon Collider, EIC, …
- Modular geometries (CLD, IDEA, ALLEGRO, ILD) allow iterative optimization and performance studies; background overlay tools integrated
- Reconstruction & Analysis: tracking, clustering, and ML-based algorithms under development; support for both FullSim and FastSim
- Incorporate complex MDI/services for more accurate detector modeling



Concept	CLD	IDEA	ALLEGRO	ILD
Vertex	Si	Si	Si	Si
Tracker	Si	Gas	Gas	Gas
ECAL/HCAL	Si	Scintillator	Lar / Plastic	Si/Scintillator
Muon syst.	Gas	Gas	Gas	Scintillator
Mag. Field	2T	2T	2T	3.5T
PID	Opt with ARC	Tracker	Tracker	Tracker



Beam backgrounds in IDEA detector

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[Jan Eysermans, FCC week May 2025, Vienna]

What's Next?

With the FSR released, we now have a clear quantitative picture of what the FCC Integrated Programme can deliver

Need to switch gears and interpret these numbers using different detector concepts

- Formulate detector requirements to the next level
- Further identify and consolidate systematic uncertainties and link them with detector requirements
- Requires precise FullSim studies of different detector concepts and technologies
- In turn requires scaling up FullSim: generic/agnostic reconstruction algorithms, Particle Flow, Machine Learning for fast detector iterations, etc.

But, as always, we should aim to sharpen the FCC Physics Case even further

- Many unexplored territories in all areas (EWK, Flavour, Higgs, BSM, …)
- Even more at FCC-hh

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[Jan Eysermans, FCC week May 2025, Vienna]

Introduction on Tau Physics at FCC

FCC-ee will provide largest $e^+e^- \to \tau^+\tau^-$ sample ever

facility	Z [million]	$\tau^+\tau^-$ [million]	$\tau^+\tau^-$ relative sample size	
LEP	25	0.84		
BABAR	-	$0.5{\cdot}10^3$		
Belle	-	$1.0{\cdot}10^3$		
Belle II	-	$45{\cdot}10^3$		
STCF at 4.26 GeV, 10 years	-	$35{\cdot}10^3$		
CEPC	$4{\cdot}10^6$	$135{\cdot}10^3$	$1.6{\cdot}10^5\times$LEP	$3.0\times$Belle II
FCC-ee	$6{\cdot}10^6$	$200{\cdot}10^3$	$2.4{\cdot}10^5\times$LEP	$4.5\times$Belle II

FCC-ee experimental conditions much better for Tau Physics than at B-factories energies

- better momentum resolution and vertexing because less multiple scattering with higher track momenta
- better higher momentum muon id (much lower pion-to-muon misidentification)
- much better $\tau^+\tau^-$ separation from $q\bar{q}$ background because of higher $q\bar{q}$ multiplicity at Z peak
- LHC produces more tau leptons, but with much less favourable experimental conditions

Tau Physics FCC flagship measurements

- 3 Tau Physics FCC-ee flagship precision measuremets [p.7 of FSR Physics, Experiments, Detectors] →
- Lepton Flavour Violation Searches (e.g., $\tau \to \mu\gamma$)
- documentation in:

  FCC FSR April 2025, [Future Circular Collider Feasibility Study Report Volume 1: Physics and Experiments, doi:10.17181/CERN.9DKX.TDH9]

  ESPPU 2026 FCC inputs, [Prospects in flavour physics at the FCC, doi:10.17181/jnzpp-1fw39]

  FCC Tau Physics note, [A.L., Tau Physics Prospects at FCC-ee, doi:10.17181/57pxj-6xd43]

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$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

Lepton universality tests with tau compared with other measurements

2013 [A.Pich, Precision Tau Physics (2014)]

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e \rvert$	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)

2025 [V.Cirigliano *et al.*, 2022] [HFLAV 2023 report] [PDG 2024]

	$\Gamma_{\tau\to\mu}/\Gamma_{\tau\to e}$	$\Gamma_{\pi\to\mu}/\Gamma_{\pi\to e}$	$\Gamma_{K\to\mu}/\Gamma_{K\to e}$	$\Gamma_{K\to\pi\mu}/\Gamma_{K\to\pi e}$	$\Gamma_{W\to\mu}/\Gamma_{W\to e}$
$\lvert g_\mu/g_e \rvert$	1.002(11)	1.0010(9)	0.9978(18)	1.0009(18)	1.001(3)
	$\Gamma_{\tau\to e}/\Gamma_{\mu\to e}$	$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$		$\Gamma_{W\to\tau}/\Gamma_{W\to\mu}$
$\lvert g_\tau/g_\mu \rvert$	1.0016(14)	0.9958(38)	0.9856(75)		1.007(10)
	$\Gamma_{\tau\to\mu}/\Gamma_{\mu\to e}$				$\Gamma_{W\to\tau}/\Gamma_{W\to e}$
$\lvert g_\tau/g_e \rvert$	1.0018(14)				1.008(10)

- only $\mathcal{B}(\pi^- \to e^- \bar{\nu}_e)/\mathcal{B}(\pi^- \to \mu^- \bar{\nu}_\mu)$ more precise (PEN, PIENU)
- for tau, only limited improvements since LEP-100

Lepton universality tests with tau leptonic branching fractions

Standard Model predictions for leptons $\mathcal{L}$, $\ell = e, \mu, \tau$

[Marciano, 1988], [Pich, Precision Tau Physics, 2014]

$$\Gamma[\mathcal{L} \to \nu_{\mathcal{L}} \ell \bar{\nu}_\ell(\gamma)] = \Gamma_{\mathcal{L}\ell} = \Gamma_{\mathcal{L}} \mathcal{B}_{\mathcal{L}\ell} = \frac{\mathcal{B}_{\mathcal{L}\ell}}{\tau_{\mathcal{L}}} = \frac{G_{\mathcal{L}} G_\ell m_{\mathcal{L}}^5}{192\pi^3} f_{\mathcal{L}\ell} \left(1 + \delta R_W^{\mathcal{L}\ell}\right)\left(1 + \delta R_\gamma^{\mathcal{L}}\right)$$

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

$$\delta R_W^{\mathcal{L}\ell} = \frac{3}{5}\frac{m_{\mathcal{L}}^2}{M_W^2} + \frac{9}{5}\frac{m_\ell^2}{M_W^2} \; ; \qquad \delta R_\gamma^{\mathcal{L}} = \frac{\alpha(m_{\mathcal{L}})}{2\pi}\left(\frac{25}{4} - \pi^2\right) .$$

- 2nd order QED radiative correction term is available

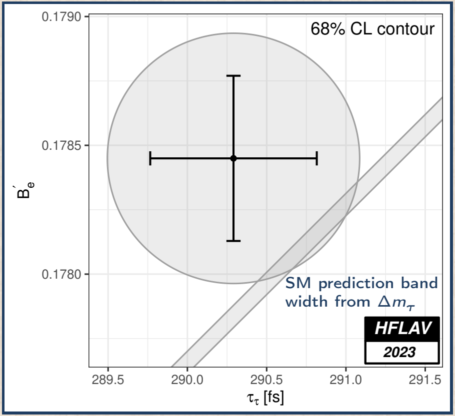
[HFLAV 2023 report]

$$\left(\frac{g_\tau}{g_\mu}\right) = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\tau_\tau m_\tau^5 f_{\tau e} R_\gamma^\tau R_W^{\tau e}}} = 1.0016 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau e}}{\mathcal{B}_{\tau e}^{\text{SM}}}}$$

$$\left(\frac{g_\tau}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\mu e}} \frac{\tau_\mu m_\mu^5 f_{\mu e} R_\gamma^\mu R_W^{\mu e}}{\tau_\tau m_\tau^5 f_{\tau \mu} R_\gamma^\tau R_W^{\tau \mu}}} = 1.0018 \pm 0.0014 = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau \mu}^{\text{SM}}}}$$

$$\left(\frac{g_\mu}{g_e}\right) = \sqrt{\frac{\mathcal{B}_{\tau \mu}}{\mathcal{B}_{\tau e}} \frac{f_{\tau e}}{f_{\tau \mu}}} = 1.0002 \pm 0.0011$$

Canonical tau lepton universality test plot



[HFLAV 2023 report]

$(g_\tau/g_{e\mu}) = 1.0017 \pm 0.0013$

$[g_{e\mu} = g_e = g_\mu$ 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	0.181%	0.090%
m_τ	0.005%	0.012%
total		0.128%

best measurements

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

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

Tau-muon universality using tau hadronic branching fractions

[HFLAV 2023 report]

$$\left(\frac{g_\tau}{g_\mu}\right)_h^2 = \frac{\mathcal{B}(\tau \to h\nu_\tau)}{\mathcal{B}(h \to \mu\bar{\nu}_\mu)} \frac{2m_h m_\mu^2 \tau_h}{(1+\delta R_{\tau/h}) m_\tau^3 \tau_\tau} \left(\frac{1-m_\mu^2/m_h^2}{1-m_h^2/m_\tau^2}\right)^2 ,$$

- $h = \pi, K$
- $\delta R_{\tau/\pi} = (0.18 \pm 0.57)\%$ [PhysRevD.104.L091502 (2021)]
- $\delta R_{\tau/K} = (0.97 \pm 0.58)\%$ [PhysRevD.104.L091502 (2021)]
- $\mathcal{B}(\tau \to \pi\nu_\tau)$ $\mathcal{B}(\tau \to K\nu_\tau)$ [HFLAV 2023 report]
- $\mathcal{B}(\pi \to \mu\bar{\nu}_\mu)$, $\mathcal{B}(K \to \mu\bar{\nu}_\mu)$ [PDG 2023]

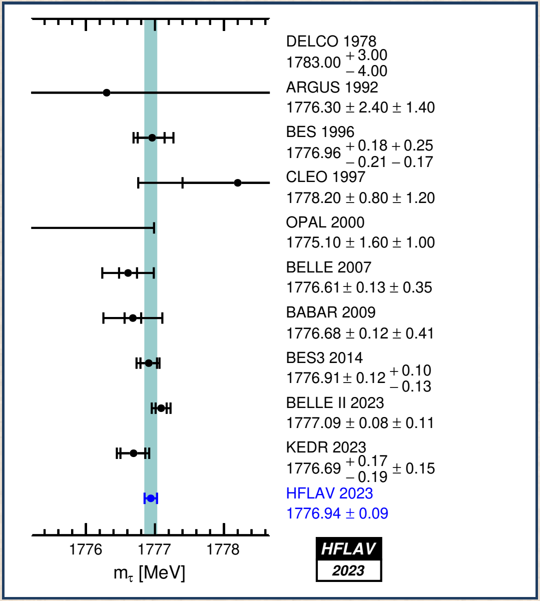
$$\left(\frac{g_\tau}{g_\mu}\right)_\pi = 0.996 \pm 0.004 , \qquad \left(\frac{g_\tau}{g_\mu}\right)_K = 0.986 \pm 0.008 .$$

- precision limited to $\sim$0.29% from $\delta R_{\tau/\pi}$, $\delta R_{\tau/K}$

$$\left(\frac{g_\tau}{g_\mu}\right)_{\tau+\pi+K} = 1.0011 \pm 0.0014 , \quad \text{average of} \quad \left(\frac{g_\tau}{g_\mu}\right)_\tau , \left(\frac{g_\tau}{g_\mu}\right)_\pi , \left(\frac{g_\tau}{g_\mu}\right)_K$$

- assuming uncorrelated $\delta R_{\tau/\pi}$ and $\delta R_{\tau/K}$

Tau mass measurements



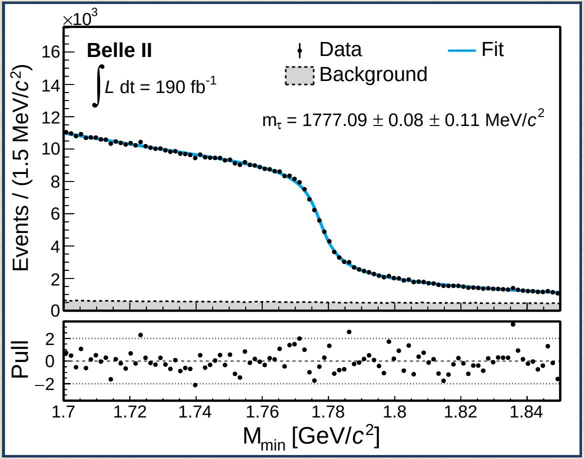
threshold scan technique

- measure onset of $\sigma(e^+e^- \to \tau^+\tau^-)(\sqrt{s})$
- DELCO, BES (92, 96), KEDR and BES III
- require precise E_{beam} using
  - either resonant depolarization of polarized $e^\pm$
  - or laser-beam Compton scattering

pseudo-mass technique

- select $e^+e^- \to \tau^+\tau^-$ events
- fit pseudo-mass using visible tau-decay products
  - empirical function, potential systematic
- ARGUS, OPAL, Belle, *BABAR*, Belle II (2023)
- require
  - good momentum scale calibration

Tau mass Belle II 2023 measurement



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
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	< 0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	< 0.01
Tracking efficiency correction	< 0.01
Trigger efficiency	< 0.01
Background processes	< 0.01
Total	0.11

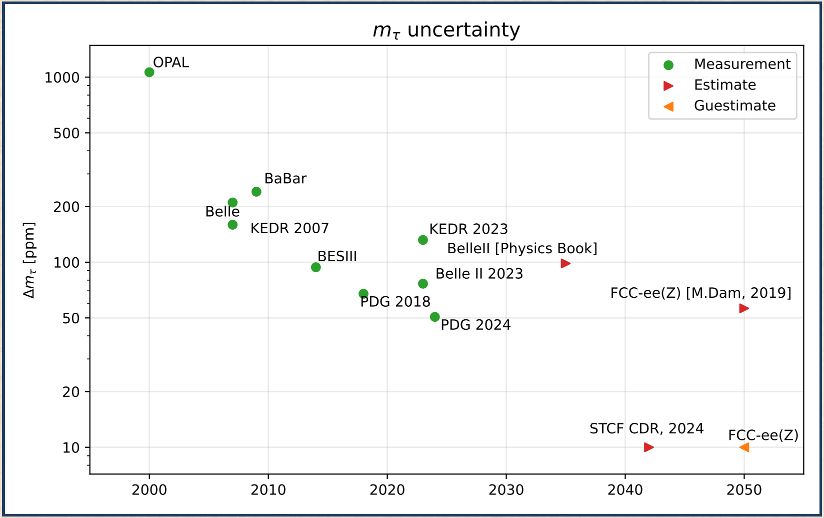
- empirical pseudo-mass distribution

[Belle II, PRD 108 (2023) 032006]

Tau mass prospects at FCC-ee

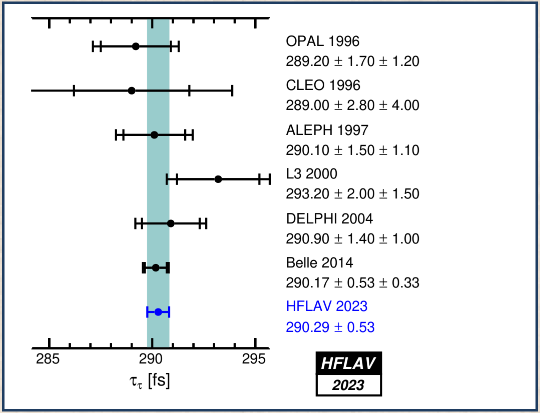
- $\Delta\tau_\tau^{\text{stat}} = 45\,\text{ppm}$ at Belle II with $190\,\text{fb}^{-1}$, 175 M tau pairs
- $\Delta\tau_\tau^{\text{stat}} = 1.3\,\text{ppm}$ at FCC-ee with $6{\cdot}10^{12}$ Z, $2.0{\cdot}10^{11}$ tau pairs
  - neglecting expected better FCC-ee efficiency
- $\Delta\tau_\tau^{\text{stat}} = 0.9\,\text{ppm}$ at FCC-ee when rescaling OPAL 2000 tau mass uncertainty
- Belle II dominant systematics expected to be significantly 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
- Belle II limiting systematics 29 ppm
  - estimator bias (0.03 MeV/c2)
  - pseudo-mass fit function (0.02,MeV/c2)
  - detector material (0.03 MeV/c2)
  - modeling of ISR, FSR and tau decay (0.02 MeV/c2)
- may expect to reduce non-luminosity-scaling systematics by factor 3 at FCC-ee, to 10 ppm
- guestimate FCC-ee tau mass precision at 10 ppm
- no particular detector requirements are needed, a baseline realistic detector is sufficient

Tau mass measurement prospects



FCC-ee(Z) with $6{\cdot}10^{12}$ Z

Tau lifetime measurements



Belle 2014 tau lifetime measurement

analysis

- select 3-prong vs. 3-prong events
- kinematically reconstruct the $\tau^+\tau^-$ direction in the center-of-mass frame
- reconstruct signed decay length in lab frame
- fit decay length distribution, accounting for resolution
- compute tau lifetime using tau average velocity (momentum)
  - initial and final state radiation reduce average tau momentum

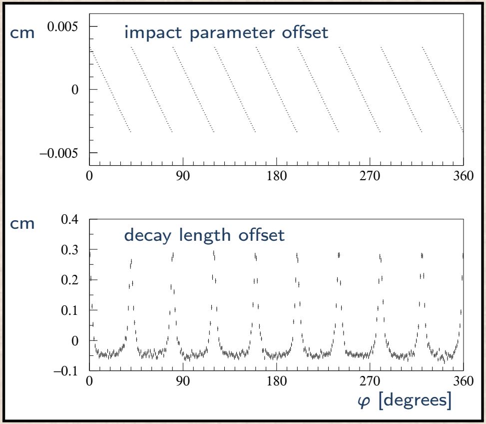
Belle 2014 tau lifetime: systematics

Source of Systematics	$\Delta(c\tau)$ in μm
SVD alignment	0.090
Asymmetry of R-function	0.030
Fit range	0.020
ISR and FSR description	0.018
Beam energy calibration	0.016
Background contribution	0.010
Error of the τ-lepton mass	0.009
Total	**0.101**

[M.Shapkin, Tau2014]

Tau lifetime systematics from detector misalignment

- crude simulation of ALEPH vertex detector with all wafers radially shifted out by 100 μm
- impact parameter offset $= 100\,\mu\text{m} \cdot \sin\alpha$
  - α = track angle w.r.t. normal of wafer
- decay length offset (measured using 3-tracks vertex)
  - negative when 3 tracks hit same wafer
  - positive when 3 tracks hit two wafers



- decay length offset $\sim$ derivative of impact parameter offset
  $\Rightarrow$ decay length offset due to misalignment averages to zero over azymuth 2π
  - requires uniform acceptance (can be insured by event weighting)
  - approximately works over polar angle due to incomplete detector acceptance
- well confirmed with Monte Carlo full simulations
- [S.Wasserbaech, Nucl.Phys.Proc.Suppl. 76 (1999) 107]

Tau Lifetime prospects at FCC-ee

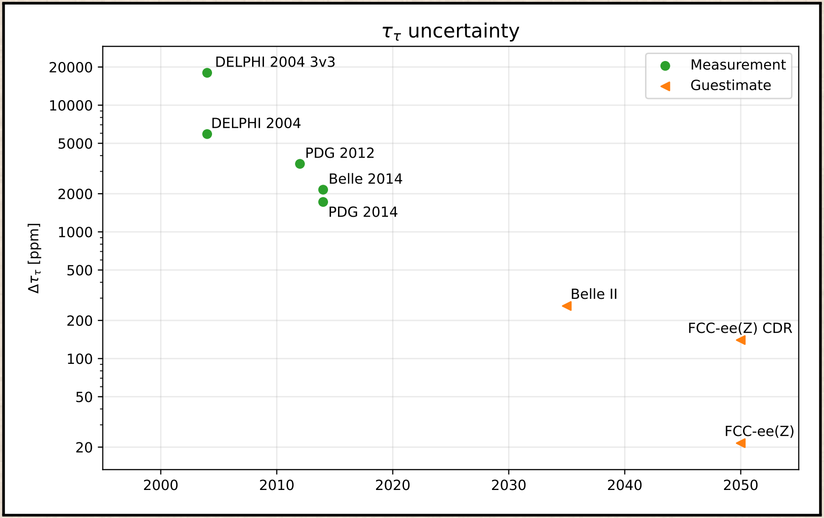
- consider just tau pairs in 3-prong vs. 3-prong topology (3v3)
  - Belle 2014 best measurement uses these events
  - τ direction reconstruction using vertices reduces dependence from simulation
- extrapolate FCC-ee statistical precision starting from Delphi 2004 3v3 events statistical precision
  - 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. $\langle d_0 \sin\theta \rangle \approx 70\,\mu$m
  - Delphi 2004 3v3 precision consistent with a d_0 resolution $\approx 70\,\mu$m (tracking, beam spot)
  - assume FCC-ee has both transverse beam spot and can have d_0 resolution $\ll 70\mu$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 3.9 ppm at FCC-ee (very optimistic)
- assume 30$\times$ less uncertain KKMC simulation on ISR+FSR energy loss in tau pair production to reduce the associated systematic contribution from 350 ppm to 11.5 ppm
- assume 10 ppm tau mass measurement at SCT/STCF or at FCC-ee
- assume 5 ppm vertex detector length scale (possible with optical methods proposed for MuonE)

Tau Lifetime measurement prospects at FCC-ee(Z)

- extrapolate from DELPHI 2004 tau lifetime measurement using 3-3 prong topology tau pairs
- assume future tau mass uncertainty 10 ppm
- assume future 30× better simulation of radiation in $e^+e^- \to \tau^+\tau^-$

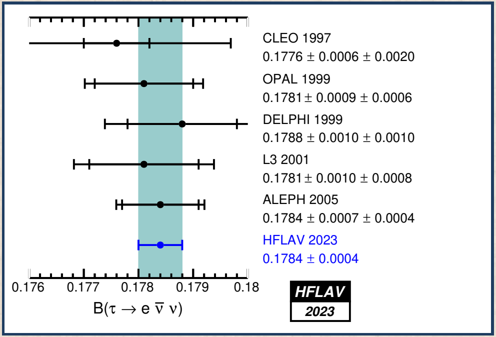
	DELPHI 2004 [fs]	DELPHI 2004 [ppm]	FCC-ee(Z) $6{\cdot}10^{12}$ Z [ppm]
statistical uncertainty	5.2	18000	15.0
luminosity-dependent systematics	1.3	4500	3.9
- background	0.2		
- reconstruction bias	0.8		
- vertex detector alignment	1.0		
luminosity-independent systematics			
- detector length scale	-	100	5.0
- average tau energy	-	-	1.0
- radiative energy loss	0.1	350	11.5
- tau mass	-	68	10.0
total systematics			15.9
total uncertainty			22.3

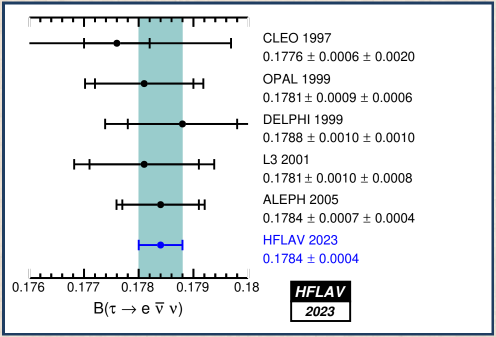
Tau Lifetime measurement prospects

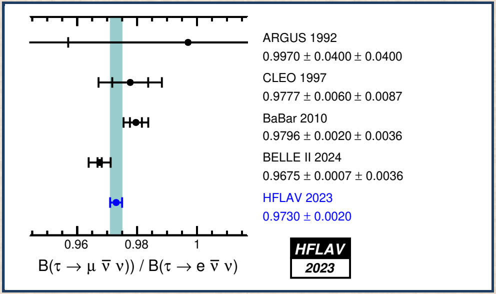


- FCC-ee(Z) CDR estimate [M. Dam, 1999]
- FCC-ee(Z) estimate [A.L., Tau Physics Prospects at FCC-ee, doi:10.17181/57pxj-6xd43]
- Belle II estimate [Belle II Physics Book]

Tau branching fractions measurements







Tau branching fractions measurements features

- branching fraction measurement: $\mathcal{B}(\tau \to X) = \dfrac{N(\tau \to X)}{N(\tau)}$

Z peak

- $\dfrac{N_{\text{obs}}(\tau \to X)/\epsilon(\tau \to X) - N_{\text{bkg}}(\tau \to X)}{N_{\text{obs}}(\tau)/\epsilon(\tau)}$
  - $N(\tau)$ from counting, not from luminosity
- $\epsilon(\tau \to X) \sim 100\%$
  small systematics from related MC modeling
- small non-tau N_{bkg}
  - easier to suppress hadrons, e^+e^-, $\mu^+\mu^-$
- $\Delta\mathcal{L} \sim 0.1\%$

$\Upsilon(4s)$ peak

- $\dfrac{N_{\text{obs}}(\tau \to X)/\epsilon(\tau \to X) - N_{\text{bkg}}(\tau \to X)}{2\sigma(e^+e^- \to \tau^+\tau^-)\mathcal{L}}$
  - $N(\tau)$ from from integrated luminosity
- $\epsilon(\tau \to X) \ll 100\%$
  large systematics from related MC modeling
- large non-tau N_{bkg}
  - more contamination of hadrons, e^+e^-, $\mu^+\mu^-$
- $\Delta\mathcal{L} \sim 1\%$

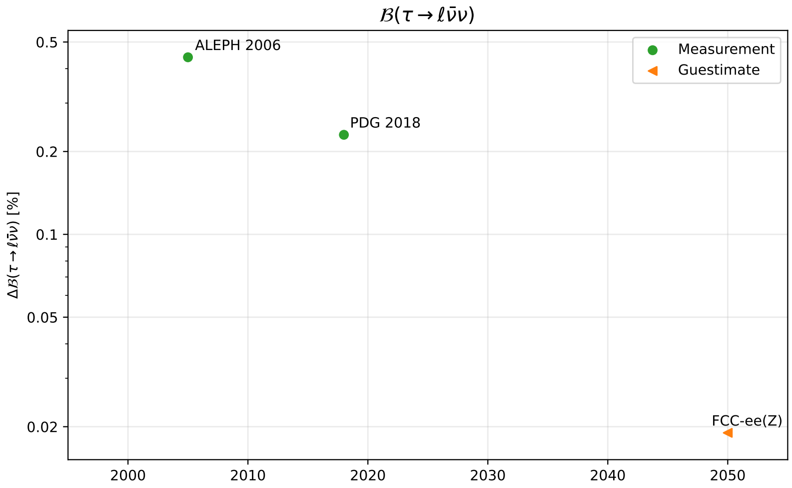
ALEPH at Z peak

- single analysis for all topological $\mathcal{B}$s
  (by n. of tracks and n. of π^0)
- non-tau bkg from cross-feed of other channels
  all channels and almost all bkg fit on data

Tau leptonic branching fractions measurement prospects at FCC-ee(Z)

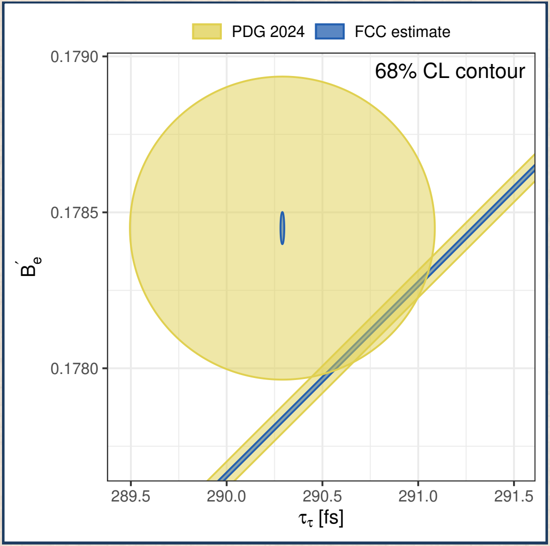
- ALEPH 2006 measurement precision: $4400\,\text{ppm} = [4000(\text{stat.}) \oplus 1900(\text{syst.})]\,\text{ppm}$ (average of the two similar electron and muon decays branching fractions)
  - complex simultaneous measurement of 12 tau branching fractions
  - many systematic uncertainties, no reliable extrapolations to FCC-ee statistics
  - several systematics related to photon and $\pi^0 \to \gamma\gamma$ reconstruction
- $\Delta^{\text{FCC}}_{\text{stat}}\mathcal{B}(\tau \to \ell\bar{\nu}\nu) = 4000\,\text{ppm} \cdot \sqrt{\dfrac{6.2{\cdot}10^6\,(\text{ALEPH Z bosons})}{6{\cdot}10^{12}}} = 4.1\,\text{ppm}\,(\text{FCC Z bosons})$
- $\Delta^{\text{FCC}}_{\text{syst}}\mathcal{B}(\tau \to \ell\bar{\nu}\nu) = \dfrac{1}{10} \cdot 1900\,\text{ppm} = 190\,\text{ppm}$
  [assume also 100% correlated between $\mathcal{B}(\tau \to e\bar{\nu}\nu)$ and $\mathcal{B}(\tau \to \mu\bar{\nu}\nu)$]
- $\Delta^{\text{FCC}}\mathcal{B}(\tau \to \ell\bar{\nu}\nu) \simeq 190\,\text{ppm}$ systematically dominated

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



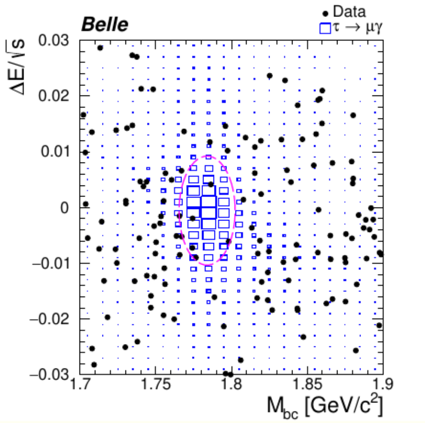
- FCC-ee(Z) with $6{\cdot}10^{12}$ Z
- Belle II is working on these measurements

Canonical tau lepton universality plot extrapolation at FCC-ee

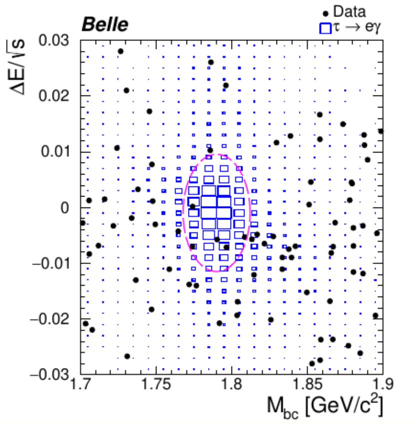


FCC-ee(Z) with $6{\cdot}10^{12}$ Z

Typical tau LFV search



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



(b) $\tau^{\pm} \to e^{\pm}\gamma$.

- search for reconstructed tau leptons matching
  - invariant mass of tau decay products = the tau mass
  - sum of energy of tau decay products in CM frame = $\sqrt{s}/2$
- count events in excess of expected background

LFV $\tau \to \mu\gamma$

FCC expected reach, 2019 study

- 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
- simulated sample of 2% of total assumed FCC statistics
- signal region with $E_{\mu\gamma}^{\mathrm{CM}} = \sqrt{s}/2$, $m_{\mu\gamma} = m_\tau$
- sensitivity reported as 2σ background fluctuation (20K events extrapolated in signal region)

FCC expected reach with $6 \cdot 10^{12}$ Z, as 90% CL upper limit

- converted 2σ background fluctuation to expected 90% CL upper limit
- rescale to $6 \cdot 10^{12}$ Z (search is background-dominated and improves with $\sqrt{\mathcal{L}}$)
- $\mathcal{B}(\tau \to \mu\gamma) < 1.2 \cdot 10^{-9}$ at 90% CL

LFV $\tau \to \mu\gamma$

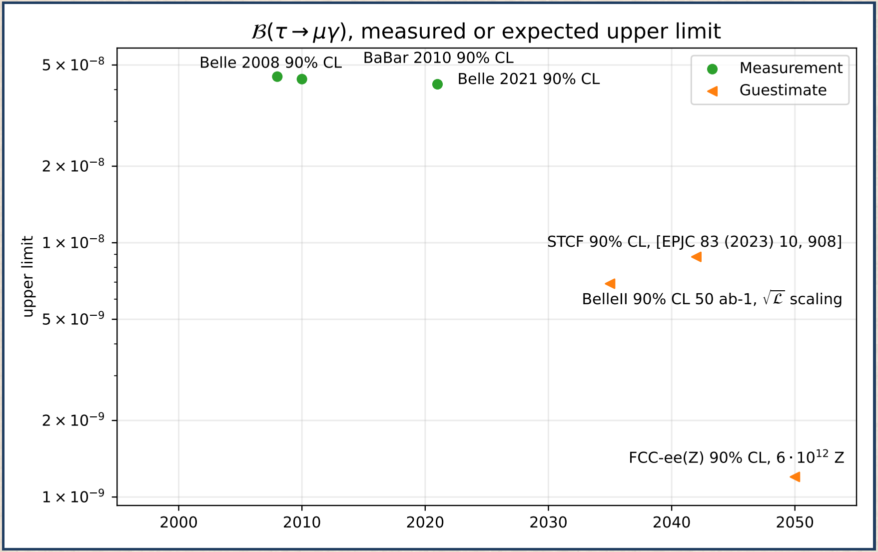
Belle II expected reach

- Belle II Physics Books
  - based on BaBar and Belle published upper limits
  - assumes all tau LFV searches background-free (inappropriate for $\tau \to \mu\gamma$)
- Belle, 2021 upper limit $\mathcal{B}(\tau \to \mu\gamma) < 4.9{\cdot}10^{-8}$ 90% CL, integrated luminosity 988 fb^{-1}
- personal Belle II 50 ab^{-1} limit estimate starting from Belle 2021 search
  - $\mathcal{B}(\tau \to \mu\gamma) < 0.97{\cdot}10^{-9}$ 90% CL "aggressive", assuming linear integrated luminosity ($\mathcal{L}$) scaling
  - $\mathcal{B}(\tau \to \mu\gamma) < 6.9{\cdot}10^{-9}$ 90% CL "conservative", assuming $\sqrt{\mathcal{L}}$ scaling (background-limited search)
- $\mathcal{B}(\tau \to \mu\gamma) < 7{\cdot}10^{-9}$ 90% CL
  [Belle II and LHC Flavour input to ESPPU 2026]
  [L.Aggarwal *et al.* [Belle II], [arXiv:2207.06307 [hep-ex]]]

STCF expected reach

- $\mathcal{B}(\tau \to \mu\gamma) < 8.8{\cdot}10^{-9}$ at 90% CL [Eur.Phys.J.C 83 (2023) 10, 908]
  - STCF CDR (2024) quotes better limit citing a preliminary arXiv preprint of above published paper

LFV $\tau \to \mu\gamma$



LFV $\tau \to 3\mu$ expected reach

FCC

- start from $\mathcal{B}(\tau \to 3\mu) < 1.9{\cdot}10^{-8}$ 90% CL [Belle II 2024], sample size $390{\cdot}10^{6}$ tau pairs
  - 20.4% efficiency, much larger than 7.6% of previous Belle search
  - efficiency now comparable to 24.5% of DELPHI 1995 LEP search
- extrapolate to $2{\cdot}10^{11}$ tau pairs for FCC-ee
  - assume FCC-ee can reach 35% efficiency
  - assume no-background-limited search (linear luminosity scaling) thanks to
    - expected excellent muon identification
    - good momentum and vertexing resolution
- $\mathcal{B}(\tau \to 3\mu) < 2.0{\cdot}10^{-11}$ 90% CL
  - MC simulations on severals details would be welcome

LFV $\tau \to 3\mu$ expected reach

Belle II

- $\mathcal{B}(\tau \to 3\mu) < 3.0{\cdot}10^{-10}$ 90% CL [Belle II Physics Book]
  - (optimistic) linear $\mathcal{L}$ scaling from Belle 90% limit, $2.1{\cdot}10^{-8}$, with 782 fb^{-1}integrated luminosity
- $\mathcal{B}(\tau \to 3\mu) < (2\text{--}17){\cdot}10^{-10} \sim 5.8{\cdot}10^{-10}$ 90% CL
  [Belle II and LHC Flavour input to ESPPU 2026] with final data sample

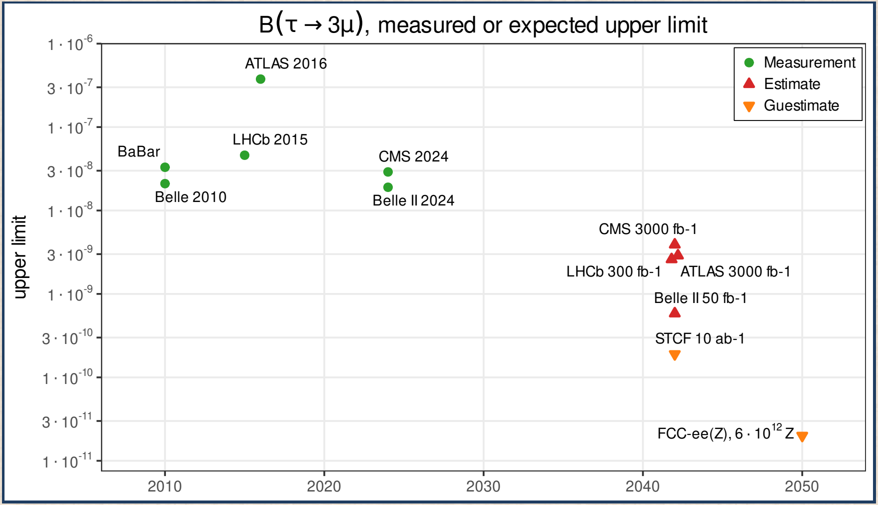
STCF

- $\mathcal{B}(\tau \to 3\mu) < 1.9{\cdot}10^{-10}$ 90% CL [STCF CDR (2024)]

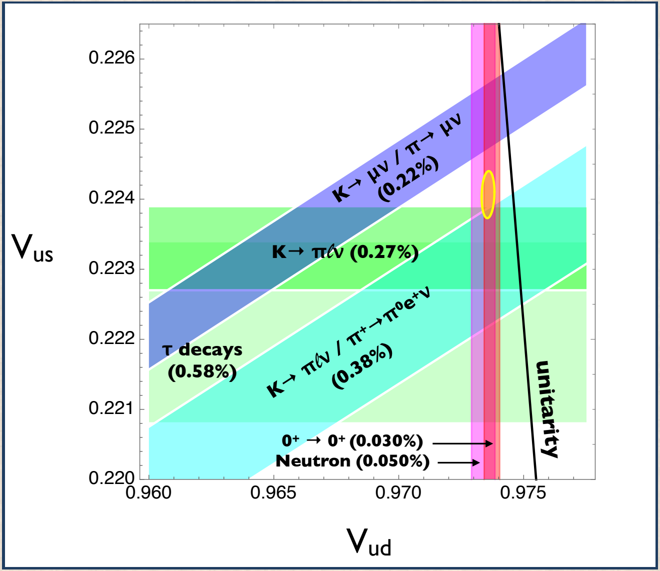
LHC experiments

- [Belle II and LHC Flavour input to ESPPU 2026] with final data samples

LFV $\tau \to 3\mu$



FCC tau BR measurements & Cabibbo angle anomaly



- tau measurements 2nd best
- almost no progress since LEP on large tau hadronic tau BR measurements
- Belle II will need hard work to progress
- FCC has ideal conditions for progress
- discussion in Backup slides

[Bryman *et al.*, Ann.Rev.Nucl.Part.Sci. 72 (2022) 69-91]

Summary

- estimated FCC precision on tau properties measurements
  - tau mass
  - tau lifetime
  - tau leptonic branching fractions
- estimated FCC precision on lepton universality test
- estimated FCC reach for LFV searches
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$
- FCC tau BR measurements for Cabibbo angle anomaly discussed in backup slides

– end –

Backup Slides

References

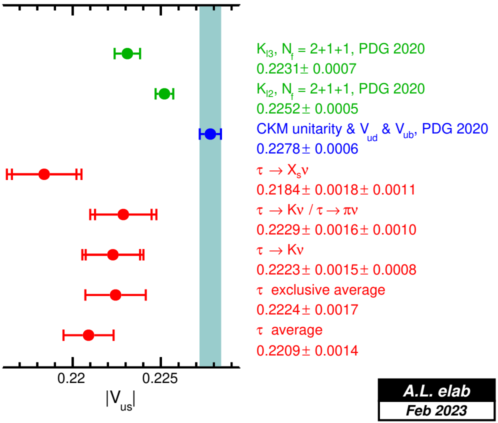
- Belle II and LHC Flavour input to ESPPU 2026
  [Projections for Key Measurements in Heavy Flavour Physics https://indico.cern.ch/event/1439855/contributions/6461613/]
- STCF conceptual design report (Volume 1): Physics & detector, [doi:10.1007/s11467-023-1333-z]

Cabibbo angle anomaly

Cabibbo angle anomaly

- 2018: CMK 1st row unitarity OK
- 2019: $\Delta_{\text{CKM}} > 3\sigma$ unitarity violation
  - dispersive calculation of Δ_R^V inner or universal electroweak radiative corrections (RC) to super-allowed nuclear beta decays
    Seng, Gorchtein & Ramsey-Musolf, Phys. Rev. D 100, 013001 (2019)
    - $\sim 2\times$ more precise
    - significant shift
- 2020: revision & inflation of $|V_{ud}|$ th. syst. unc.
- 2020-2023: PDG reviews quote $\Delta_{\text{CKM}} \sim 3\sigma$
- 2023: short review [Cirigliano *et al.*, 2023]
- 2024: PDG review quotes $\Delta_{\text{CKM}} \sim 2\sigma$

$|V_{us}|$ after [Seng *et al.* 2019]



$|V_{us}|$ determinations from kaons

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

$|V_{us}|$ calculation with "inclusive" tau branching fractions

$|V_{us}|_{\tau\text{-OPE}}$ from $\mathcal{B}(\tau \to X_s \nu)$ and OPE

- $$|V_{us}|_{\tau\text{-OPE}} = \sqrt{R_s / \left[\frac{R_{ud}}{|V_{ud}|^2} - \delta R_{\tau,\text{SU3 breaking}}\right]}$$ τ-OPE
  - $R_s = \mathcal{B}(\tau \to X_s \nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$, $R_{ud} = \mathcal{B}(\tau \to X_{ud} \nu)/\mathcal{B}(\tau \to e\bar{\nu}\nu)$
  - $\delta R_{\tau,\text{SU3 breaking}}$ computed with Operator Product Expansion (OPE) perturbative QCD, $+\, m_s$ W.A.
  - E. Gamiz *et al.*, JHEP 01 (2003) 060, PRL 94 (2005) 011803, Nucl. Phys .Proc. Suppl. 169 (2007) 85, PoS KAON (2008) 008
  - no strong isospin breaking correction

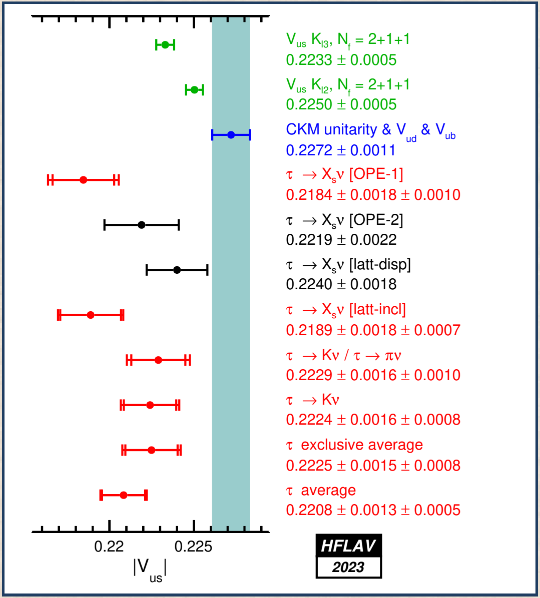
$|V_{us}|_{\tau\text{-latt}}$ from $\mathcal{B}(\tau \to X_s \nu)$ and lattice QCD

- $$|V_{us}|_{\tau\text{-latt}} = \sqrt{\left(\frac{|V_{us}|^2}{R_s}\right)_{\text{latt-incl}} \cdot R_s}$$ τ-latt
  - $(|V_{us}|^2 / R_s)$ computed with lattice QCD
  - Extended Twisted Mass collaboration, Phys. Rev. D 104 7, (2021) 074520
  - no strong isospin breaking correction

$|V_{us}|$ calculation with "exclusive" tau branching fractions

- $\Gamma(\tau \to \pi \bar{K} \nu_\tau[\gamma]) = \frac{G_F^2 m_\tau^5}{96\pi^3} C_K^2 S_{\text{EW}}^\tau \left(|V_{us}| f^{K\pi}\right)^2 I_K^\tau \left(1 + \delta_{\text{EM}}^{K\tau} + \delta_{\text{SU(2)}}^{K\pi}\right)^2$ $\boxed{\tau \to K\pi}$
  - C_K Clebsch-Gordan coefficients, $= 1$ for K^0, $= 1/2$ for K^-
  - $I_K^\ell =$ phase-space form factor integral
  - Antonelli *et al.*, JHEP 1310 (2013) 070 (2013)
  - (not updated for HFLAV 2023 report, prelim.)
- $\frac{\mathcal{B}(\tau^- \to \mathcal{B}(\tau^- \to K^- \nu_\tau))}{\mathcal{B}(\tau^- \to \mathcal{B}(\tau^- \to \pi^- \nu_\tau))} = \left(\frac{f_{K\pm}}{f_{\pi\pm}}\right)^2 \frac{|V_{us}|^2_{\tau K/\pi}}{|V_{ud}|^2} \frac{\left(m_\tau^2 - m_K^2\right)^2}{\left(m_\tau^2 - m_\pi^2\right)^2} (1 + \delta R_{\tau K/\tau\pi})$ $\boxed{\tau \to K/\tau \to \pi}$
  - note that $\Delta\delta R_{\tau K/\tau\pi} = \Delta\delta R_{\tau\pi} \oplus \Delta\delta R_{\tau K}$ [PRD 104 9 (2021) L091502]
- $\mathcal{B}(\tau^- \to K^- \nu_\tau) = \frac{1}{16\pi} \left(\frac{G_F}{\hbar^3 c^3}\right)^2 |V_{us}|^2_{\tau K} f_{K\pm}^2 \frac{\tau_\tau}{\hbar} m_\tau^3 c^3 \left(1 - \frac{m_K^2}{m_\tau^2}\right)^2 S_{EW}^\tau (1 + \delta R_{\tau K})$ $\boxed{\tau \to K}$

$|V_{us}|$ from tau measurements [HFLAV 2023 report]



$|V_{us}|_{\tau\text{-OPE}}$ uncertainty budget [%]

$\pi^- \bar{K}^0 2\pi^0 \nu_\tau$ (ex. K^0)	0.3933
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.3789
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.3715
$\bar{K}^0 h^- h^- h^+ \nu_\tau$	0.3452
$K^- \pi^0 \nu_\tau$	0.2561
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2438
$\pi^- \bar{K}^0 \nu_\tau$	0.2373
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.2201
$K^- \nu_\tau$	0.1646
$K^- \omega \nu_\tau$	0.1573
$K^- \nu_\tau$	0.1453
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.1148
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0254
$K^- \pi^0 \eta \nu_\tau$	0.0198
$K^- \eta \nu_\tau$	0.0137
$K^- \phi \nu_\tau$ ($\phi \to K^+ K^-$)	0.0136
$K^- \phi \nu_\tau$ ($\phi \to K^0_S K^0_L$)	0.0094
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0021
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0010
$\tau \to$ non-strange	0.0855
$\mathcal{B}_e^{\text{univ}}$	0.0044
theory	0.4863

- $|V_{us}|_{\tau\text{-latt}}$ uncertainty budget is similar

Prospects of $|V_{us}|$ with tau inclusive branching fraction to strange

- tau strange branching fractions can be measured more precisely by Belle II (hard work)
- measurements tau strange and non-strange spectral functions may help constrain OPE calculations, can be done at Belle II but are not easy
- lattice QCD techniques will plausibly progressively improve theory prediction of $\mathcal{B}(\tau \to X_s \nu)$ and compute the related strong-isospin-breaking correction

Uncertainty budget of $|V_{us}|$ with exclusive tau measurements

input	Δinput [%]	$\Delta \|V_{us}\|_{\tau K/\pi}$ [%]	$\Delta \|V_{us}\|_{\tau K}$ [%]
$\mathcal{B}(\tau^- \to K^- \nu_\tau)$		0.69	0.69
$\mathcal{B}(\tau^- \to \pi^- \nu_\tau)$		0.24	
$f_{K\pm}/f_{\pi\pm}$		0.16	
$f_{K\pm}$			0.19
S_{EW}^{τ}			0.02
$\delta R_{\tau K}$		0.28	0.29
$\delta R_{\tau\pi}$		0.28	
$\|V_{ud}\|$		0.03	
tau lifetime			0.09

prospects

- hard & clever work by Belle II reequired to improve tau branching fractions
- if $\Delta\mathcal{B}(\tau^- \to \pi^- \nu_\tau)$ reduced by ≥ 3, radiative corrections will be limiting
- lattice QCD may provide more progressively precise radiative corrections

$\mathcal{B}(\tau^- \to \pi^- \nu_\tau)$ & $\mathcal{B}(\tau^- \to K^- \nu_\tau)$ measurements