Status and prospects for FCC-ee

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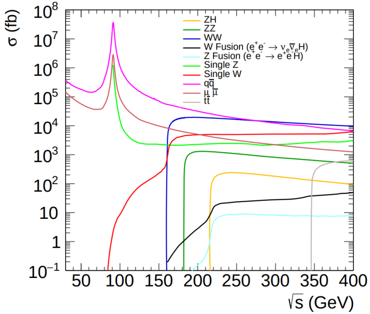
Introduction

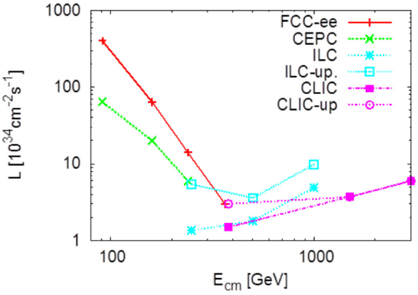
- LHC just started Run3 operation that should take 3 years and after that there will be HL-LHC upgrade with aim to collect 3000 fb^{-1} of pp collisions with 14 TeV
- Belle II experiment at SuperKEKB is already started to take data and they will produce large statistics of the b-hadrons from the $\Upsilon(4S)$ decays (50 ab^{-1} over the six year lifetime)
- It is expected that these two experiments will make great contribution to the precise measurements of weak interaction parameters and find NP (New Physics) beyond the Standard Model of particle physics
- However they are not able to cover all possible measurements especially in some heavier particles like B_s, B_c, Λ_b
- Since there is great effort to design and build new higgs factories, the B-physics can largely benefit from them

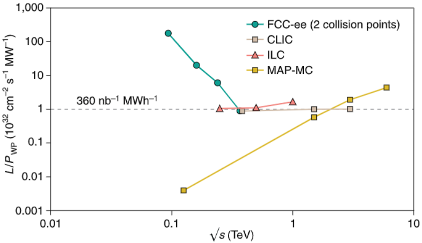
Future collider concepts

- There is several concepts for future colliders
- Linear colliders such as ILC collider (Japan), CLIC collider (CERN) or circular colliders like FCC (CERN), CEPC (China)
- The threshold energy need to be higher to produce high energy states particles:
  - $m(Z) = 91.2\,\mathrm{GeV}$
  - $m(H) = 125.1\,\mathrm{GeV}$ (ZH (240 GeV) and $WW \to H$ (365 GeV))
  - $m(t) = 172.9\,\mathrm{GeV}$ ($t\bar{t}$ production 350 GeV)

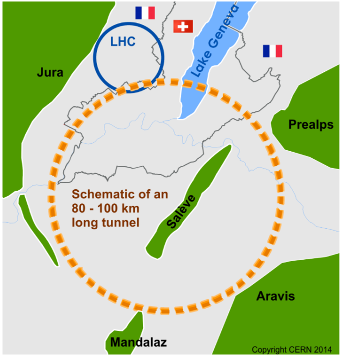


Baseline luminosities expected to be delivered (summed over all interaction points)





- FCC critical infrastructure is a tunnel $>$ 90 km (located close to CERN and Geneva)
- The design is robust and will provide high luminosity over the desired center-of-mass energy range from 90 to 365 GeV
- The most sustainable of all Higgs and electroweak factory proposals (it implies the lowest energy consumption for a given value of total integrated luminosity)
- Possible upgrade to build hadron collider in future using the same tunnel and infrastructure (FCC-hh) with a 100 TeV pp collisions (same as LEP-LHC schema)
- The synergy and complementarity between the FCC-ee and FCC-hh programs are important



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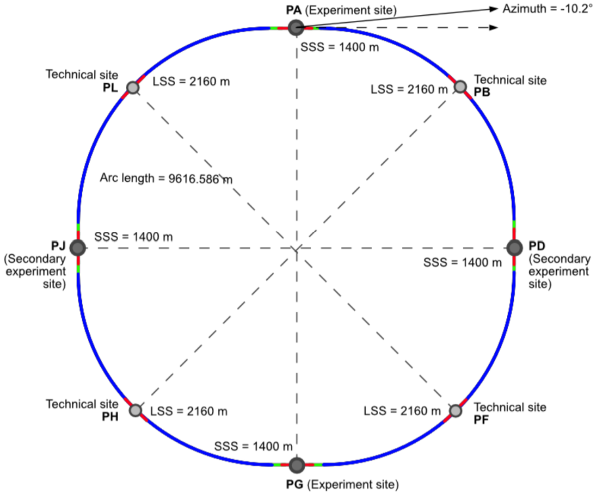
Circular collider concept

- The FCC-ee design is now being developed for either 2 or 4 symmetric IP's located at four of the access points and with RF, collimation, and injection/extraction occupying the other 4 straight sections
- The limitation is not from the magnets, but from the accelerating part
- Total synchrotron radiation power is limited to 100 MW
- The accelerating part need to be tuned for specific energy
- The baseline configuration is based on 400 MHz RF systems with Nb/Cu cavities, that will be further upgraded to achieve higher energies

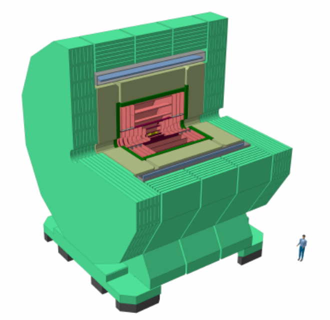


An example of a 15 year run plan

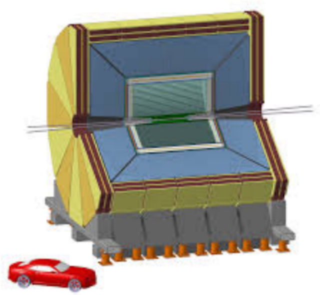
- The operation model has the FCC-ee collider first operating at 91 GeV to study the Z boson
- Each energy will need upgrade(change) of the accelerating part
- The $t\bar{t}$ run will need additional 800 MHz RF system in the second RF region

Working point	Z years 1-2	Z, later	WW	HZ	$t\bar{t}$		(s-channel H)
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340–350	365	m_H
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55	(30)
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34	(7)
Physics goal (ab^{-1})	150		10	5	0.2	1.5	(20)
Run time (year)	2	2	2	3	1	4	(3)
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\rightarrow$ H	10^6 $t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H		(6000)

- Two complementary detector design concepts have been proposed for FCC-ee, (a) the ”CLIC-like Detector” (CLD) and (b) the ”International Detector for Electron-positron Accelerator” (IDEA)
- The concepts are evolution of the detectors for the past and current colliders incorporating the latest results from years of R&D as well as the newest technologies



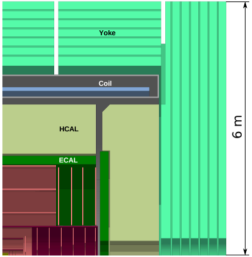
(a)

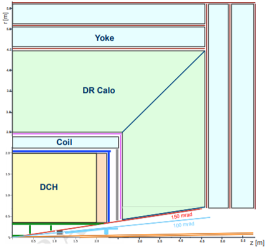


(b)

FCC detectors

- Both detector concepts feature a 2 Tesla solenoidal magnetic field
- The CLD detector features a silicon pixel vertex detector, a silicon tracker, followed by a highly granular calorimeters (a silicon-tungsten ECAL and a scintillator-steel HCAL) surrounded by a 2T superconduting solenoid and muon chambers interleaved with steel return yokes.
- The IDEA detector comprises a silicon vertex detector, a large-volume extremely-light drift chamber surrounded by a layer of silicon detector, a thin low-mass superconducting solenoid, a preshower detector, a dual-readout fiber calorimeter and muon chambers within the magnet return yoke.





Physics opportunities at FCC-ee

- Higgs physics
- Precision electroweak physics
- Top quark physics
- Beyond the Standard Model
- QCD physics
- **Flavor physics – our focus**

Flavor at FCC-ee

- The Z run of the FCC-ee will provide unprecedentedly statistics of $\mathcal{O}(5 \times 10^{12})$ Z events decaying to $Z \to \bar{b}b$ and $Z \to \bar{c}c$ events that will be recorded without any triggers or pre-scales.
- This gives opportunity to further enrich the knowledge of flavor physics of quarks and leptons.
- The flavor program of FCC-ee experiment will be natural continuation of upgraded LHCb experiment run at LHC and the Belle II experiment.

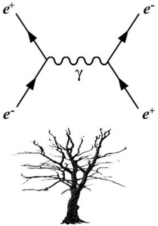
Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B^0_s/\overline{B}^0_s$	$B^+_c/\overline{B}^-_c$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

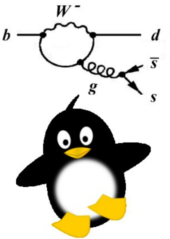
B-Physics analysis can be categorized into following groups:

- Decays of b-flavored hadrons
- Precise CKM and CP-violation parameters studies
- Charged-lepton flavor violating decays

Flavour-changing neutral-currents

- In the SM of particle physics, the electroweak couplings of leptons to gauge bosons are independent of their flavor and the model is referred to as exhibiting lepton universality (LU)
- Flavour-changing neutral-current (FCNC) processes, where a quark changes its flavor without altering its electric charge, provide an ideal laboratory to test LU
- The SM forbids FCNCs at tree level and only allows amplitudes involving electroweak loop (penguin and box) Feynman diagrams

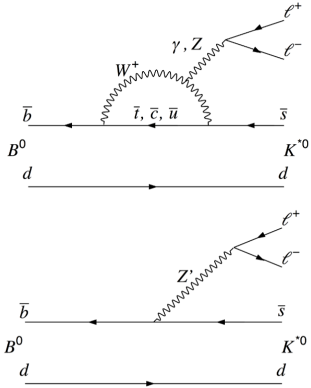




- The absence of a dominant treelevel SM contribution implies that such transitions are rare, and therefore sensitive to the existence of new particles

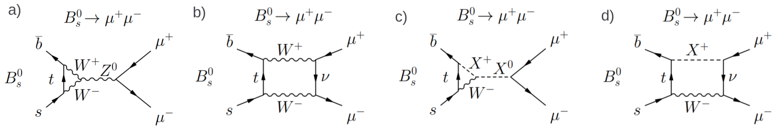
$B \to K^{(*)} l^+ l^-$

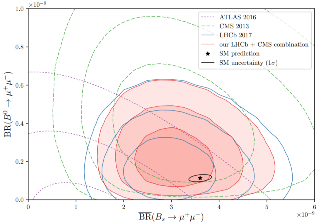
- In recent years, the semileptonic decays $B \to K^{(*)} e^+ e^-$ and $B \to K^{(*)} \mu^+ \mu^-$ have attracted considerable attention due to a number of persistent $2\sigma - 3\sigma$ tensions between data and SM expectations
- In particular in the lepton flavor universality ratios $R_{K^{(*)}}$ and the angular observable P_5'
- Measurement is independent confirmation of these so-called "B anomalies"
- If confirmed, the anomalies in the rare B decays establish a generic new physics scale of ~ 35 TeV

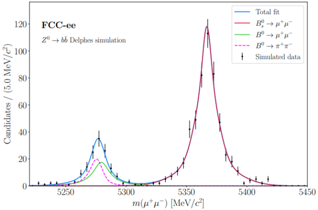


$B \to l^+ l^-$

- The leptonic decays $B_s \to \mu^+\mu^-$ and $B_0 \to \mu^+\mu^-$ have extremely small branching ratios in the SM of $(3.66 \pm 0.14) \times 10^{-9}$ and $(1.03 \pm 0.05) \times 10^{-10}$, respectively
- Their well known tiny branching ratios make them highly sensitive probes of new physics
- One advantage of FCC-ee over the LHC is the excellent mass resolution that allows a clear separation of the Bs and B0 signals in the dimuon invariant mass spectrum
- We expect $\sim$ 540 reconstructed $B_s \to \mu^+\mu^-$ events and $\sim$ 70 reconstructed $B_d \to \mu^+\mu^-$ events in the SM

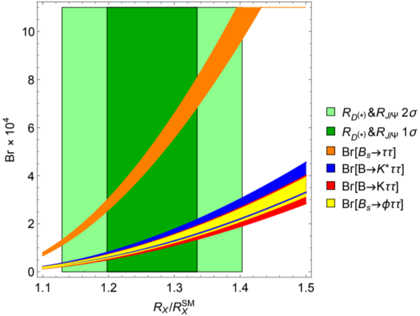






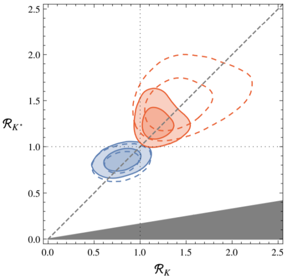
$B \to x\tau^+\tau^-$

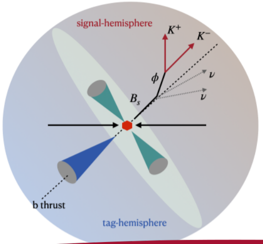
- Of particular interest are tauonic and semitauonic decays, for which FCC-ee has unique sensitivities. Current bounds on the branching ratios of decays like $B_s \to \tau^+\tau^-$, $B_0 \to \tau^+\tau^-$, and $B \to K^{(*)}\tau^+\tau^-$, are still several orders of magnitude above the SM predictions
- Sensitivities will improve at the HL-LHC and at Belle II but cannot reach the SM.
- Precision measurements of these decays are highly motivated to complete the studies of lepton flavor universality in $b \to sll$ and $b \to dll$ decays
- Many BSM scenarios predict characteristic effects in the decays with taus in the final state
  - At the FCC-ee, $\mathcal{O}(10^3)$ cleanly reconstructed SM events can be expected
  - Such an event sample will not only allow a precision measurement of the $B \to K^{(*)}\tau^+\tau^-$ branching ratio, but also opens up the possibility of measuring the angular distribution of the decay



Decays with missing energy

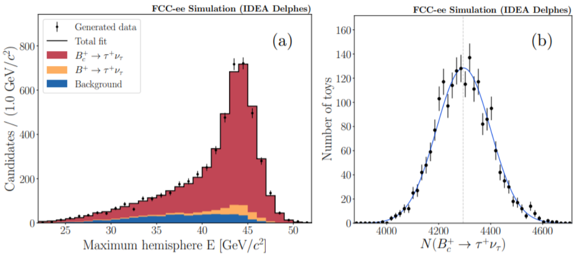
- The FCNC decays $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$ are well established probes of new physics
- Belle II is expected to make first observation of these decays and measure their branching ratios with an uncertainty of $\sim 10\%$
- FCC-ee should be able to further improve these measurements, which is highly motivated given that theses decays are theoretically well understood
- FCC-ee has the unique opportunity to measure the related decays $B_s \to \phi\nu\bar{\nu}$, $\Lambda_b \to \Lambda\nu\bar{\nu}$, and even $B_c \to D_s\nu\bar{\nu}$
- Combining the results from the whole family of $b \to s\nu\bar{\nu}$ decays will be a powerful way to probe BSM physics





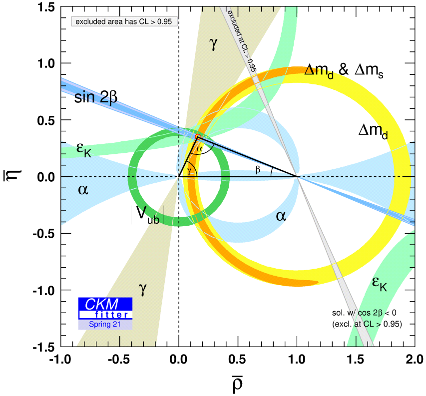
B_c physics

- The B_c meson is still largely uncharted territory
- Very interesting are the theoretically clean leptonic decays $B_c \to \tau\nu$ and $B_c \to \mu\nu$ that have new physics sensitivity
- This complements the well studied decay modes $B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$
- The ratio $\mathcal{B}(B_c \to \mu\nu)/\mathcal{B}(B_c \to \tau\nu)$ is of particular interest in view of the existing anomalies in the lepton flavor universality ratios $R_* D^{(*)}$
- B_c mesons are not produced at Belle II, and the limited final state information that is available renders a measurement of $B_c \to \tau\nu$ infeasible at hadron colliders



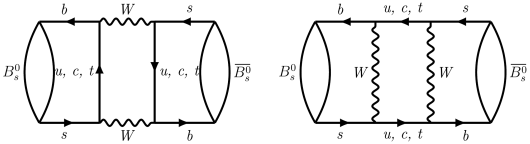
Precise CKM and CP-violation parameters studies

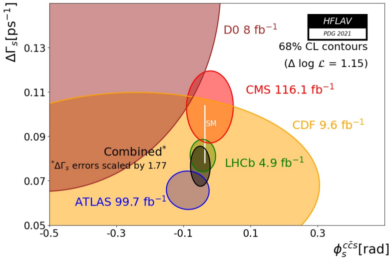
- The CKM matrix induces flavour-changing transitions inside and between generations in the charged sector at tree level
- Many of the observables in CP-violation studies are very precisely predicted so they warrant continued experimental attention
- We expect improved knowledge of the Unitarity Triangle angles α, β and γ, and the phase φ_s
- The decay modes involving B_s, B_c or b-baryons with neutral final state particles will be very interesting at the FCC-ee
- Due to better particle identification, it is expected that flavor-tagging efficiency will be significantly higher than in the LHC era
- This will be a large advantage for any time-dependent measurement

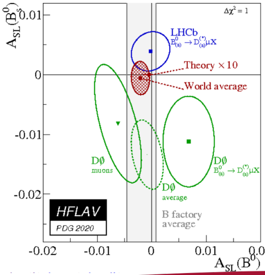


CP violation in the $B_{d,s}$ meson mixing

- These systems are very sensitive to any new BSM contribution because the box diagrams that drive the oscillations and carry CP-violating phases are the neutral entry point for any new BSM particle
- First observation of CP violation in B mixing will be within reach
- The semileptonic asymmetries $a_{sl} = \frac{\Gamma(\bar{B}^0_q \to \bar{f}) - \Gamma(B^0_q \to f)}{\Gamma(\bar{B}^0_q \to \bar{f}) + \Gamma(B^0_q \to f)}$ are very small, but precisely predicted and very valuable in providing sensitivity to h_d and h_s .



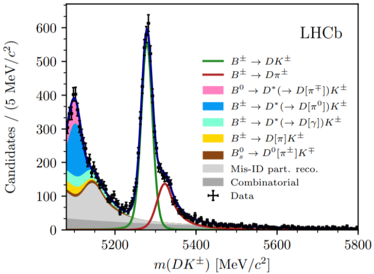




- Test of BSM physics up to an energy scale of 20 TeV, assuming Minimal Flavor Violation

Asymmetries with neutrals

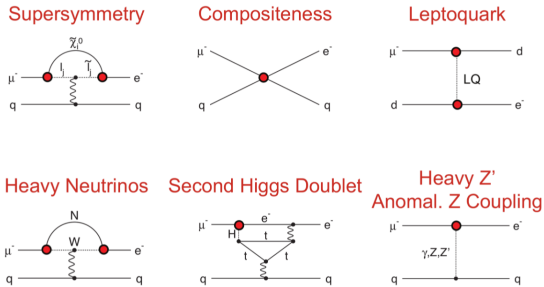
- A particular strength of the FCC-ee flavor program will be the ability to make very sensitive studies of decays containing neutral particles
- This possibility will enable to measure various CP-violating asymmetries such as time-dependent CP asymmetry in $B_0 \to \pi^0\pi^0$ decay or measurement of CP asymmetry in $B^- \to DK^-$ (where D indicates a admixture of D^0 and $\bar{D}^0$) and $B_s \to D_s^{(*)\pm} D^{\mp}$
- Important for the γ measurement
- Another benefit of the FCC-ee environment will be the possibility to measure semileptonic CP-violating asymmetries and determinations of the $|V_{ub}/V_{cb}|$ performed with B_s mesons and Λ_b baryons that are not accessible at current experiments with enough precision



Charged-lepton flavor violating decays

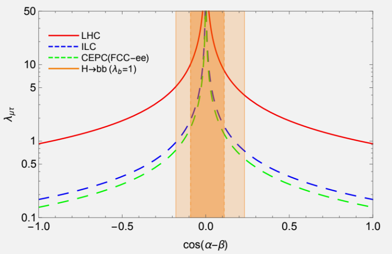
- Charged-lepton flavor violating (CLFV) decays are a transitions among e, μ, τ that does not conserve lepton family number:
  - Example of lepton flavor conservation is a muon decay $\mu^- \to e^- \bar{\nu}_e \nu_\mu$ has two neutrinos
  - Example of CLFV: neutrinoless decay $\mu \to e\gamma$ or $\mu \to 3e$
- The B meson decay channels in which the flavor anomalies are observed are always polluted by complicated strong dynamics, while the CLFV decays are much cleaner

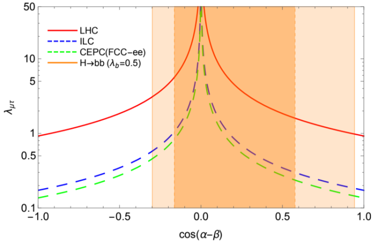
- Evidence of CLFV would be a clear signal of new physics and it would directly addresses the physics of flavor and of generations
- CLFV will provide a better chance to study the mechanism generating the lepton flavor violation or non-universality once they are discovered



Higgs boson flavor violating decays to leptons

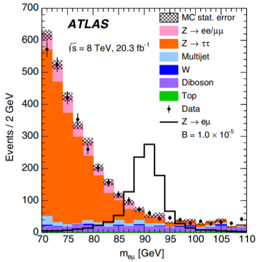
- The present best direct limits on the branching fractions of the $H \to e\mu$, $H \to e\tau$, and $H \to \mu\tau$ decays are 6×10^{-5}, 2.2×10^{-3}, and 1.5×10^{-3} at 95% CL, respectively
- With about one million Higgs bosons produced in association with the Z boson at FCC-ee about the same sensitivity in the eμ channel and about a factor of two better sensitivity in the other two channels as after full HL-LHC running can be obtained
- The CLFV Higgs decays are interesting, because their observation may provide insight into some fundamental questions in nature, e.g., whether there is a secondary mechanism for the electroweak symmetry breaking, why the neutrino masses are tiny, and whether there is an extra dimension responsible for the gauge hierarchy generation

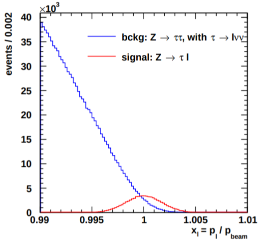




Z boson charged-lepton flavor violating decays

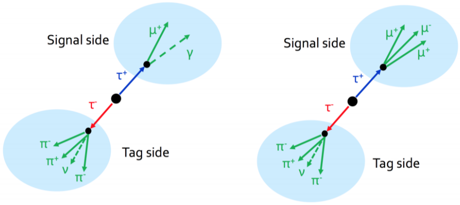
- The improvement compared to the HL-LHC is expected to be significantly better for the LFV Z boson decays for the branching fractions of the $Z \to e\mu$, $Z \to e\tau$, and $Z \to \mu\tau$
- The improvement depending on to which degree the major background from $Z \to \mu\mu$ decays with a muon being misreconstructed as an electron can be controlled (e.g., using dE/dx information)
- It is possible to achieve up to three orders of magnitude improvement at FCC-ee





Charged Lepton Flavour Violation in τ Decays

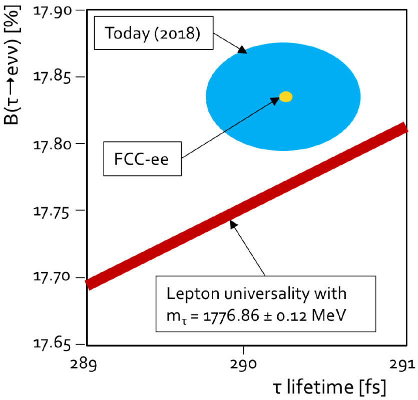
- Very stringent tests of cLFV have been performed in muon decay experiments on both $\mu^- \to e^-\gamma$ and $\mu^- \to e^-e^+e^-$
- CLFV in τ decays is often enhanced by several orders of magnitude
- Since the τ is heavy, more CLFV processes are kinematically allowed
- The focus here is on $\tau \to 3\mu$ and $\tau \to \mu\gamma$



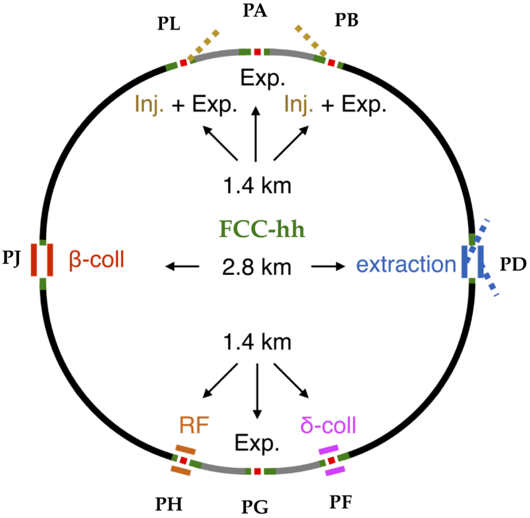
- With the excellent FCC-ee invariant mass resolution, the search for $\tau \to 3\mu$ mode is expected to be essentially background free, and a sensitivity down to a branching fractions of $\mathcal{O}(10^{-10})$ should be within reach.

Other measurements with tau leptons

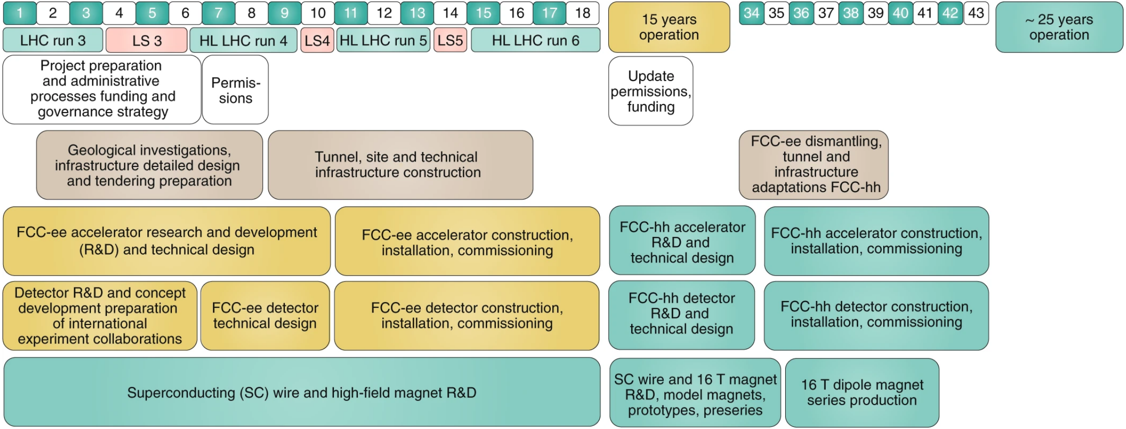
- Finally, the large τ samples expected at FCC-ee, should allow to measure the τ lepton lifetime to an absolute precision of 0.04 fs and leptonic branching fractions to an absolute precision of 3×10^5
- This would allow to measure the Fermi constant in τ decays to a similar or even higher precision
- Comparing this number with the canonical GF measurement based on the muon lifetime, offers another way of probing new physics possibly responsible for non-flavor-universal couplings
- Together with the measurements of τ branching fractions (to an absolute precision of 3×10^{-5}), one could use this to test lepton universality to even higher precision



- The key technological challenge for FCC-hh is the design optimization, feasibility demonstration and cost-effective production of the high-field accelerator magnets.
- The current Nb_3Sn superconductor magnets are limited to a maximum field of about 16 T
- Possible solution might be high-temperature superconductor (HTS), which might enable higher fields, operation at elevated temperature
- The total proton-proton luminosity production of FCC-hh over 25 years of operation is expected to exceed $30\,\mathrm{ab}^{-1}$.



Timeline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LHC run 3
LS 3
HL LHC run 4
LS4
HL LHC run 5
LS5
HL LHC run 6
15 years operation
34 35 36 37 38 39 40 41 42 43
~ 25 years operation
Project preparation and administrative processes funding and governance strategy
Permis- sions
Update permissions, funding
Geological investigations, infrastructure detailed design and tendering preparation
Tunnel, site and technical infrastructure construction
FCC-ee dismantling, tunnel and infrastructure adaptations FCC-hh
FCC-ee accelerator research and development (R&D) and technical design
FCC-ee accelerator construction, installation, commissioning
FCC-hh accelerator R&D and technical design
FCC-hh accelerator construction, installation, commissioning
Detector R&D and concept development preparation of international experiment collaborations
FCC-ee detector technical design
FCC-ee detector construction, installation, commissioning
FCC-hh detector R&D and technical design
FCC-hh detector construction, installation, commissioning
Superconducting (SC) wire and high-field magnet R&D
SC wire and 16 T magnet R&D, model magnets, prototypes, preseries
16 T dipole magnet series production

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Summary

- The near future of the particle physics research is already approved and build now like SuperKEKB or HL-LHC
- What will follow after is still not decided but conceptual design reports were prepared and there is still ongoing development in this way
- The anomalies that we see in some decay might be a hint of physics beyond Standard Model and need to be studied
- The FCC-ee would be perfect laboratory for such searches

Stay tuned!