Lepton Flavor and Universality Violation at FCCee

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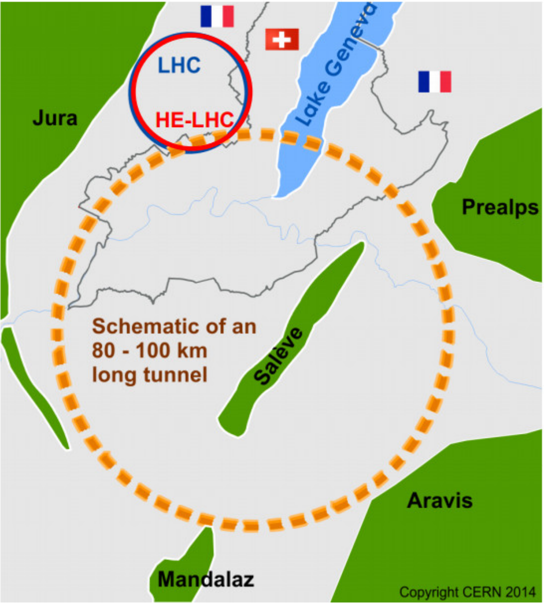
Snowmass, 28^{th} September 2020

FCC



International FCC collaboration with CERN as host lab to study:

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- **e^+e^- collider (*FCC-ee*),**
  → potential first step
- ***pp*-collider (*FCC-hh*)**
  → long-term goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **HE-LHC** with *FCC-hh* technology
- **Ions** and **lepton-hadron** options with hadron colliders

FCC

FCC-ee:

- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) (m_Z, m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , $\alpha_{QED}(m_z)$ $\alpha_s(m_z\, m_W\, m_\tau)$, Higgs and top quark couplings)
- Exploraing 10 - 100 TeV energy scale via couplings with precision measurements
- ➢ Machine design for highest luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge rates for single and multiple production of SM bosons (H,W,Z) and quarks
- ➢ Machine design for ~100 TeV c.m. energy & int. luminosity ~ $20ab^{-1}$ in 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC
- ➢ Machine design within constraints from LHC CE and using HL-LHC and FCC techn.

FCCee Physics

working point	assumed typical luminosity/IP [10^{34} cm^{-2}s^{-1}] = design value minus 15(10)%	total luminosity (2 IPs)/ yr; half of typical luminosity assumed in 1st two years (Z) and 1st year ($t\bar{t}$)	physics goal	run time [yr]
Z first 2 years	100	26 ab^{-1}/year	150 ab^{-1}	4
Z later	200	48 ab^{-1}/year		
W	25	6 ab^{-1}/year	10 ab^{-1}	1-2
H	7.0	1.7 ab^{-1}/year	5 ab^{-1}	3
machine modification for RF installation & rearrangement: 1 year				
top 1st year (350 GeV)	0.8	0.2 ab^{-1}/year	0.2 ab^{-1}	1
top later (365 GeV)	1.4	0.34 ab^{-1}/year	1.5 ab^{-1}	4

total program duration: 15 years – *incl. machine modifications*

phase 1 (*Z*, *W*, *H*): 9 years, phase 2 (top): 6 years

The European Strategy

In the coming decade, the LHC, including its high-luminosity upgrade, will remain the world's primary tool for exploring the high-energy frontier. Given the unique nature of the Higgs boson, there are compelling scientific arguments for a new electron-positron collider operating as a "Higgs factory". Such a collider would produce copious Higgs bosons in a very clean environment, would make dramatic progress in mapping the diverse interactions of the Higgs boson with other particles and would form an essential part of a research programme that includes exploration of the flavour puzzle and the neutrino sector.

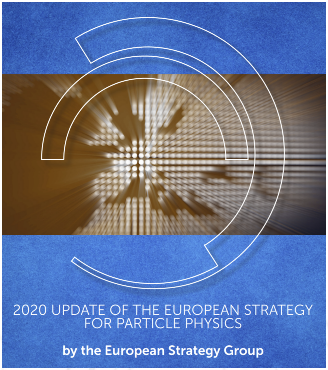
High-priority future initiatives

A. 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. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- ***the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;***

- ***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.***

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.

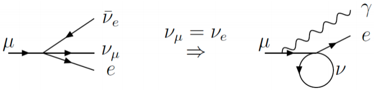


Lepton Flavour/Number Violation

Lepton Flavour Violation(LFV):

After μ^- was discovered it was natural to think of it as an excited e^-.

- Expected: $B(\mu \to e\gamma) \approx 10^{-4}$
- Unless another ν, in intermediate vector boson loop, cancels.



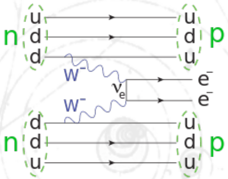
I.I.Rabi:

"Who ordered that?"

- Up to this day charged LFV is being searched for in various decay modes.
- LFV was already found in neutrino sector (oscillations).

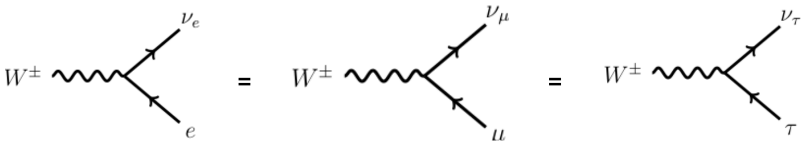
Lepton Number Violation (LNV)

- Even with LFV, lepton number can be a conserved quantity.
- Many NP models predict it violation(Majorana neutrinos)
- Searched in so called Neutrinoless double β decays.



Lepton Universality

⇛ What is Lepton Universality?



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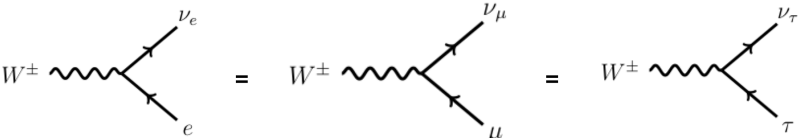


⇛ Or mathematically speaking:

$$\mathcal{L}_f = \bar{f} i D_\mu \gamma^\mu f, \quad f = l_L^i$$

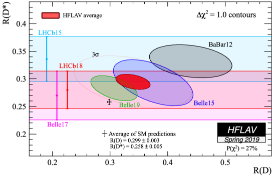
$$D_\mu = \partial_\mu + i\frac{g}{2}\sigma_j W_\mu^j$$

⇛ Basic property of SM!

Lepton Universality Violation

⇛ Charge currents:

$$R(D^*) = \frac{\mathrm{Br}(B \to D^* \tau\nu)}{\mathrm{Br}(B \to D^* \mu\nu)}$$

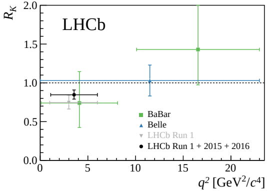


⇛ Discrepancy reduced to $3.1\ \sigma$.

⇛ Theoretical uncertainties are still negligible.

⇛ FC Neutral currents:

$$R_{K/K^*} = \frac{\mathrm{Br}(B \to K/K^* \mu\mu)}{\mathrm{Br}(B \to K/K^* ee)}$$



$$R_K = 0.846^{+0.060}_{-0.054}(\mathrm{stat.})^{+0.016}_{-0.014}(\mathrm{syst})$$

⇛ $2.5\ \sigma$ deviation from SM.

Lepton Universality Violation

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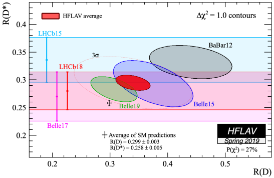

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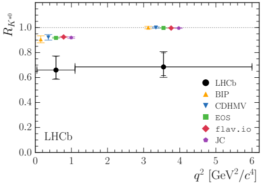


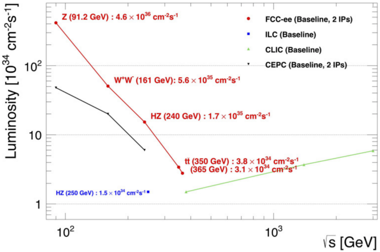
⇛ Discrepancy reduced to $3.1\ \sigma$.

⇛ Theoretical uncertainties are still negligible.

$$R_{K^*}^{\text{low q}^2} = 0.66^{+0.11}_{-0.07}(\text{stat.}) \pm 0.03(\text{syst})$$

$$R_{K^*}^{\text{mid q}^2} = 0.69^{+0.11}_{-0.07}(\text{stat.}) \pm 0.05(\text{syst})$$

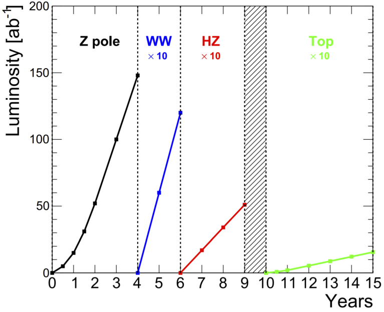
Expected data



⇛ Huge luminosity compared to other projects.
⇛ Especially in the "lower" energy spectrum.

Amount of Bosons produced

- ⇛ Z: 5×10^{12}
- ⇛ WW : 10^{8}
- ⇛ ZH: 10^{6}
- ⇛ $t\bar{t}$: 10^{6}



LFV at Z

$\Rightarrow$ Testing anomalous couplings of the Z boson:

- $Z \to \ell\ell'$

Γ_{63}	$\nu\bar{\nu}\gamma\gamma$	[7]	$< 3.1 \times 10^{-6}$
Γ_{64}	$e^{\pm}\mu^{\mp}$	[4]	$< 7.5 \times 10^{-7}$
Γ_{65}	$e^{\pm}\tau^{\mp}$	[4]	$< 9.8 \times 10^{-6}$
Γ_{66}	$\mu^{\pm}\tau^{\mp}$	[4]	$< 1.2 \times 10^{-5}$
Γ_{67}	pe		$< 1.8 \times 10^{-6}$

$\Rightarrow$ Currently the measurements are in range $10^{-5} - 10^{-6}$, dominated by LEP and ATLAS experiments.

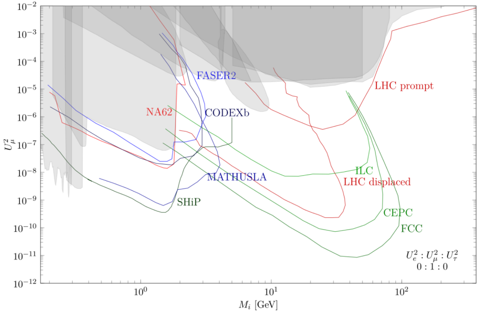
$\Rightarrow$ With 5×10^{12} Z decays the FCC is expected to probe region of $\mathcal{O}(10^{-9})$.

LFV at Z, RHN

$\Rrightarrow$ Huge amount of Z means also huge amount of neutrinos!
$\Rrightarrow$ Can test the Right Handed Neutrino Model:

- $Z \rightarrow \nu_R \bar{\nu}$
- $\nu_R \rightarrow \nu Z^*$, $Z^* \rightarrow \nu\bar{\nu}/\ell\bar{\ell}/q\bar{q}$
- $\nu_R \rightarrow \ell W^*$, $W^* \rightarrow \nu\ell/q\bar{q}'$

$\Rrightarrow$ Possible to probe the mass of RHN in range $[0.5, 80]\ \mathrm{GeV/c^2}$
Credit to M. Drewers



LFV with heavy flavours

⇛ The Z runs is also a Flavour factory:

Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B^0_s/\overline{B}^0_s$	$\Lambda_b/\overline{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	550	170

$\tau \to \ell\gamma$

⇛ Sensitivity 2×10^{-9}.
⇛ Compatible with Belle II.
⇛ Background dominated.

$\tau \to \ell\ell\ell$

⇛ Sensitivity 1×10^{-10}.
⇛ Factor of 2 better then Belle II.
⇛ Background free.

Lepton Universality with heavy flavors

⇛ LU is essentially a test of coupling constant of charge currents.
⇛ The easiest is to measure: $\frac{g_\mu}{g_e}$.
⇛ This can be obtained using partial width: $\tau \to \mu\nu\nu$ and $\tau \to e\nu\nu$.
Known to $0.14~\%$ precision.

⇛ The ratios $\frac{g_\tau}{g_e}$ and $\frac{g_\tau}{g_\mu}$ require the measurements:

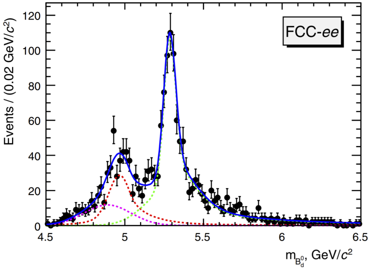
- $\tau \to \mu\nu\nu$ or $\tau \to e\nu\nu$.
- $\mu \to e\nu\nu$.

⇛ FCCee aims to improve these measurements with an order of magnitude!!!

Lepton Universality with heavy flavors

⇛ FCCee can shade the light on the LUV anomalies.
⇛ We expect over 1000 events of $B \to K^{*}\tau\tau$.
⇛ Allows to measure the angular observables, but also to test LUV:

$$R_{K^*}^{\tau/\ell} = \frac{\mathrm{Br}(B \to K/K^{*}\tau\tau)}{\mathrm{Br}(B \to K/K^{*}\ell\ell)}$$



⇛

- ⇛ Can achieve precision of 5% for $R_{K^*}^{\tau/\ell}$.
- ⇛ Allows to measure the LUV in angular observables.
- ⇛ More of the $b \to s$ transitions with τ leptons will have similar sensitivities!

Conclusions

⇛ FCCee after the recent European Strategy Update the FCC is progressing towards TDR.
⇛ Thanks to the Tera Z run the FCCee is electroweak and flavor factory.
⇛ Measurements of LFV and LUV parameters will complement other B-factories ($b \to s$ transitions), and in most cases be the most precise measurements to date.
⇛ Check out the FCC:

⇛ Visit our web page and sign up for updates:
`https://fcc-ee.web.cern.ch/`

Referneces

⇛ FCC Physics Opportunities, CERN-ACC-2018-0056
⇛ FCC-ee: The Lepton Collide, CERN-ACC-2018-0057
⇛ And others: 1906.02693, 1809.01830, 1506.00918

Backup