FCC

LIO international conference on *Future Colliders* and the *origin of mass*

Physics and Challenges at FCC-ee

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With many thanks to all in the FCC collaboration, in particular
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Why do we need a new accelerator after the LHC?

Particle physics has reached an important moment of its history

The 'Standard Model' appeared in 1976 after the discoveries of

- Neutrino Neutral currents (Z boson exchange) in 1973 and
- Charmed particles (BNL, SLAC) in 1974-76

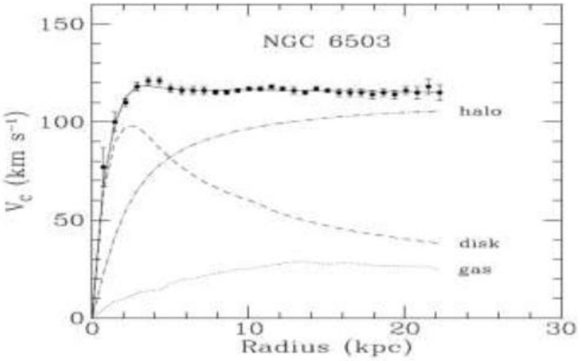
since then we have been discovering all the particles that have **electric charge** or **QCD charge**, or **weak isospin** (SM couplings) **by increasing accelerator energies.**

The Standard Model is "complete" and explains all HEP Physics, but..

We cannot explain crucial observations with the SM, for instance:

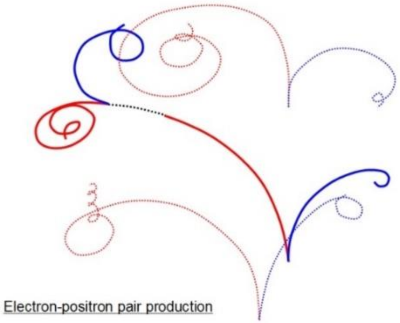
What is Dark matter ?

Standard Model particles constitute only 5% of the energy in the Universe



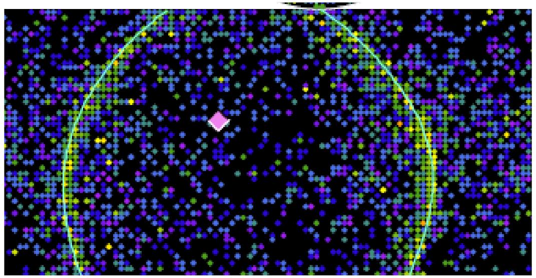
Rotation curve for Galaxy

Were is primordial antimatter gone?



What is the origin of neutrino masses?

Not a unique solution in the SM
Dirac masses (why so small?)
Majorana masses (why not Dirac?)
Both (the preferred scenarios, see-saw…) ?
➔ heavy right-handed neutrinos?



Going beyond the Standard Model

- Direct observation of new particles
- New phenomena (ex: Neutral currents, neutrino oscillations, CP violation..)
- Deviations from precise predictions

The Physics Landscape

We are in an unusual situation for HEP: we don't know where to look and what we will find

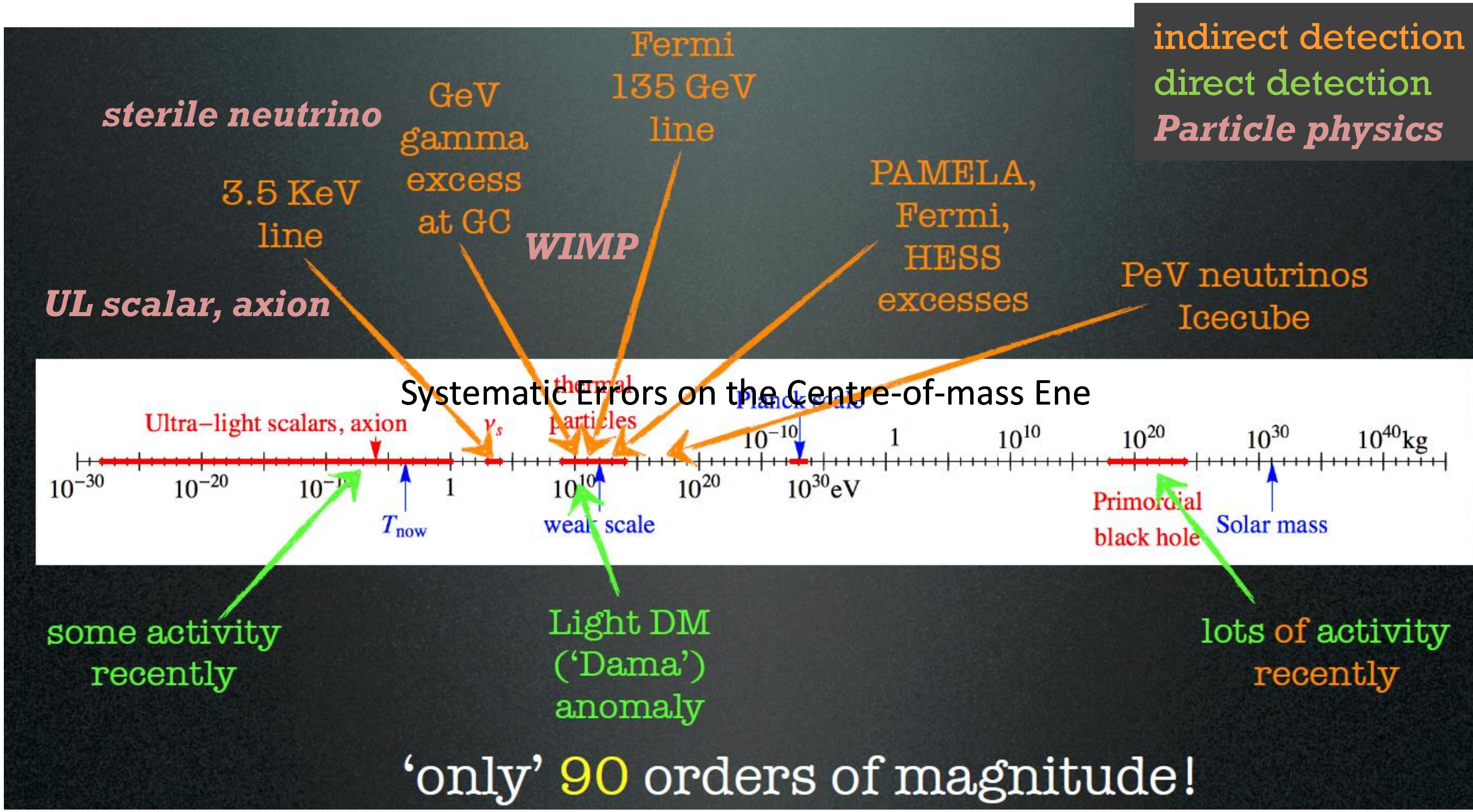
For the first time since Fermi theory, WE HAVE NO SCALE

The next facility must be versatile with as broad and powerful reach as possible, as there is no precise target

➔ more Sensitivity, more Precision, more Energy

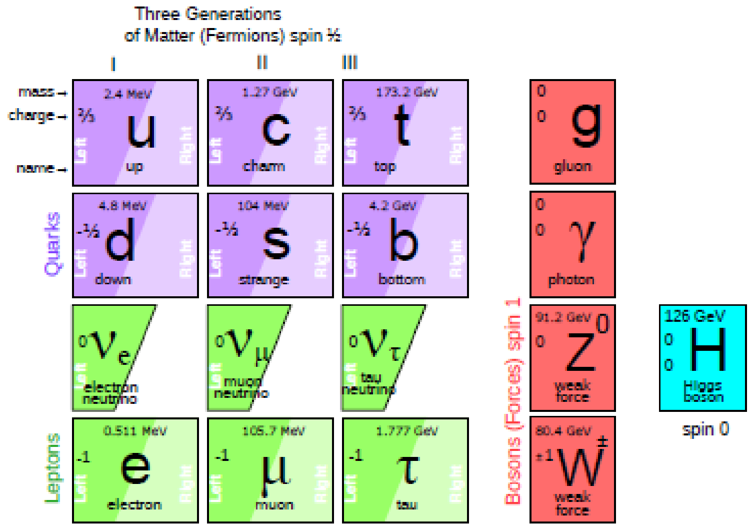
FCC , thanks to synergies and complementarities, offers the most versatile and adapted response to today's physics landscape,

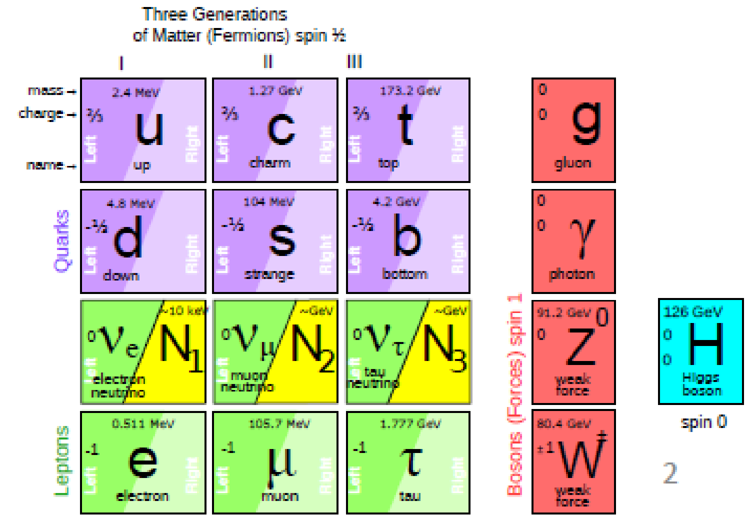
Dark Matter could be made of very long lived neutral particle(s). Plausible candidates:



M. Cirelli

at least 3 pieces could still be missing

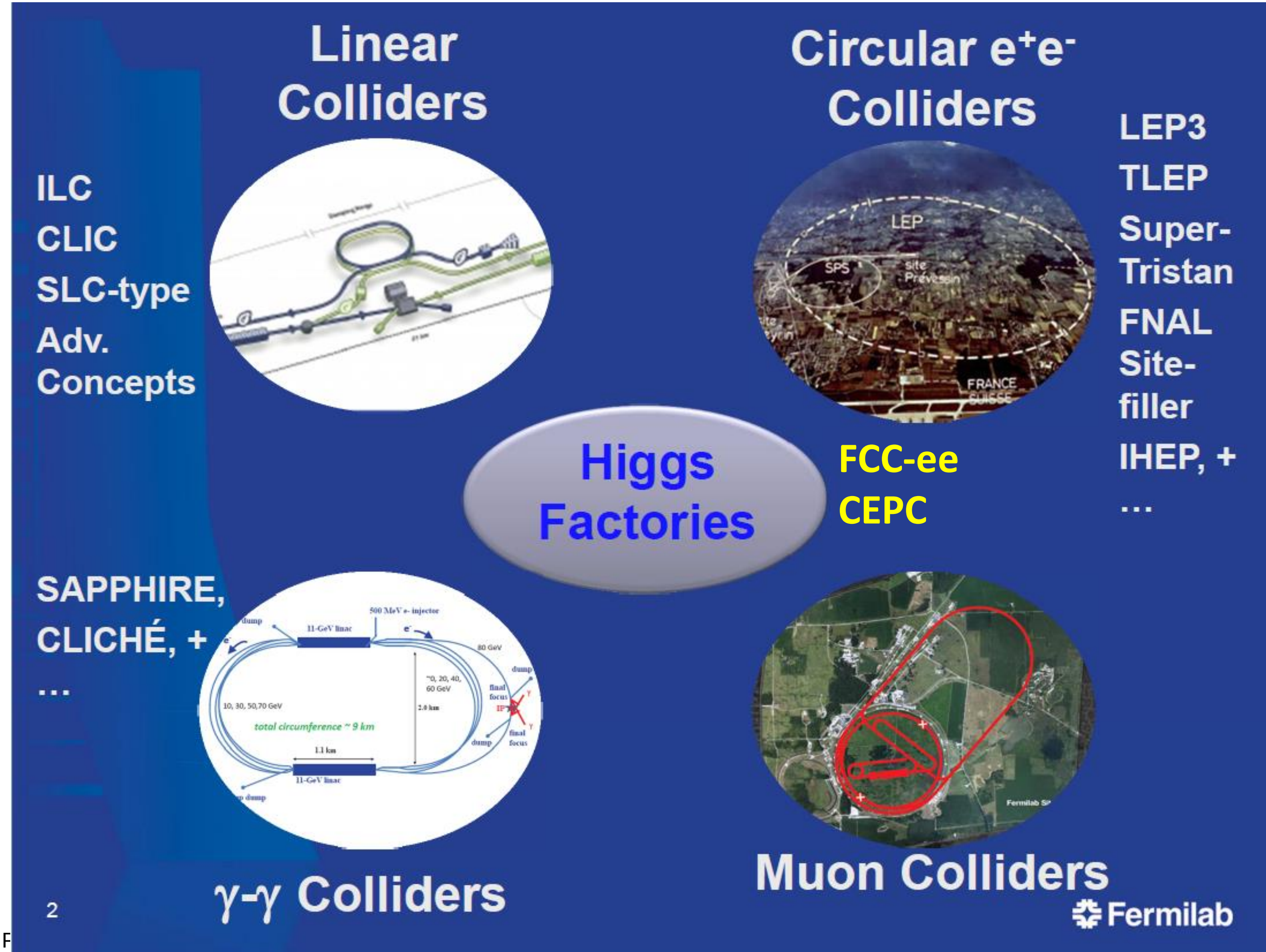




Since 1998 it is established that neutrinos have mass (oscillations)
and this very probably implies new degrees of freedom

➔ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV), nearly impossile to find.
.... but could perhaps explain all: DM, BAU,ν-masses

and the Higgs boson/field still need to be better understood



Recommandations from ESPP 2020:

“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.”

Motivation for a circular collider FCC-ee vs. a linear collider

One of the great advantages of the circular e+ e- colliders is:

- The possibility of using the same beams for many hours and serving several interaction points with net overall gain both in integrated luminosity and luminosity/MW.

FCC-ee is a machine with a very rich menu of physics possibilities, given its luminosity, and the options to run at many differenter center-of-mass energies

- this leads to many detector requirements, which are best satisfied with more than one detector. We are aiming at 4 detectors in 4 interactions points.
An example of competing constraints for EM calorimeter are the following:
high E precision vs high granularity vs high stability vs geometric accuracy vs PID)

Furthermore

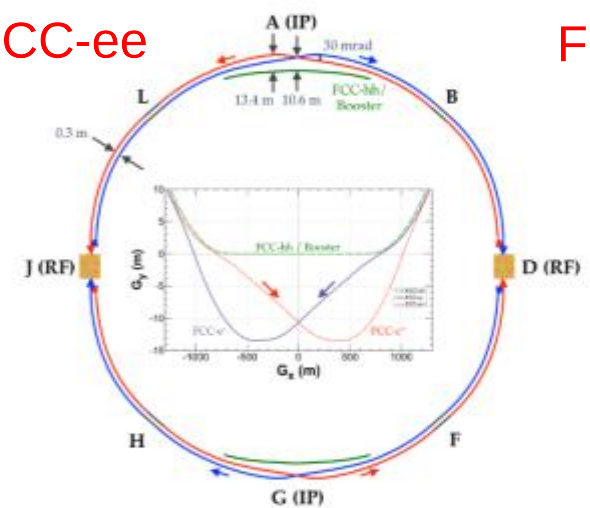
- many measurements will serve as input to future programs in particular FCC-hh
- many are statistically limited
- redundancy provided by 4IPs is essential for high precision measurements
- different detector solutions will be invaluable in uncovering hidden systematic biases.

The FCC integrated program at CERN inspired by successful LEP – LHC (1976-2038) program

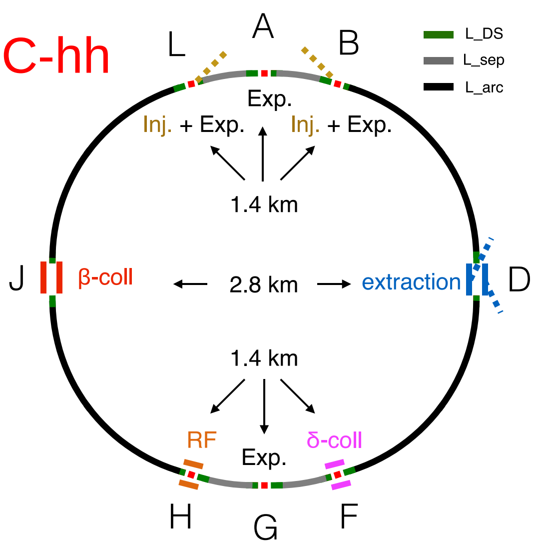
Comprehensive cost-effective program maximizing physics opportunities
- Stage 1: FCC-ee (Z, W, H, tt) as first generation Higgs EW and top factory at highest luminosities.
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options.

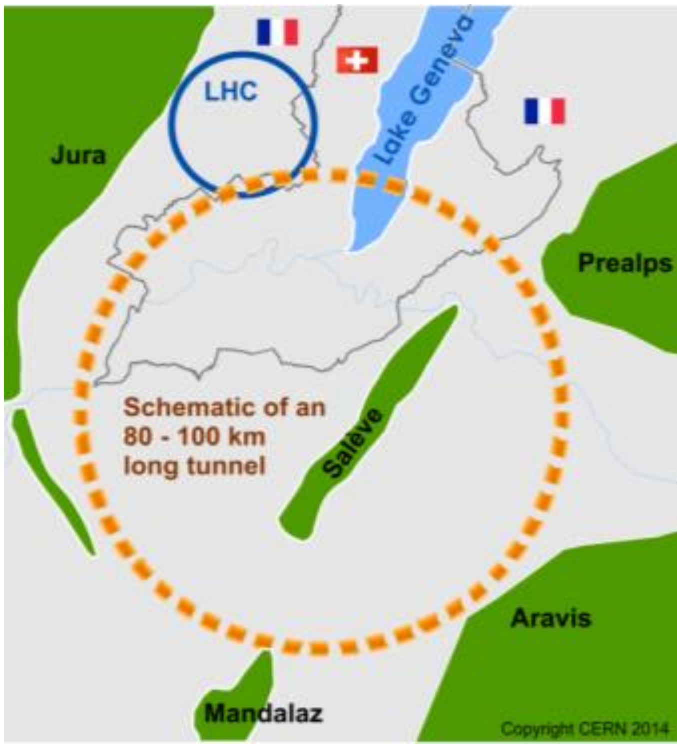
Complementary physics
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN’s existing infrastructure.
- FCC-INT project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP

FCC-ee

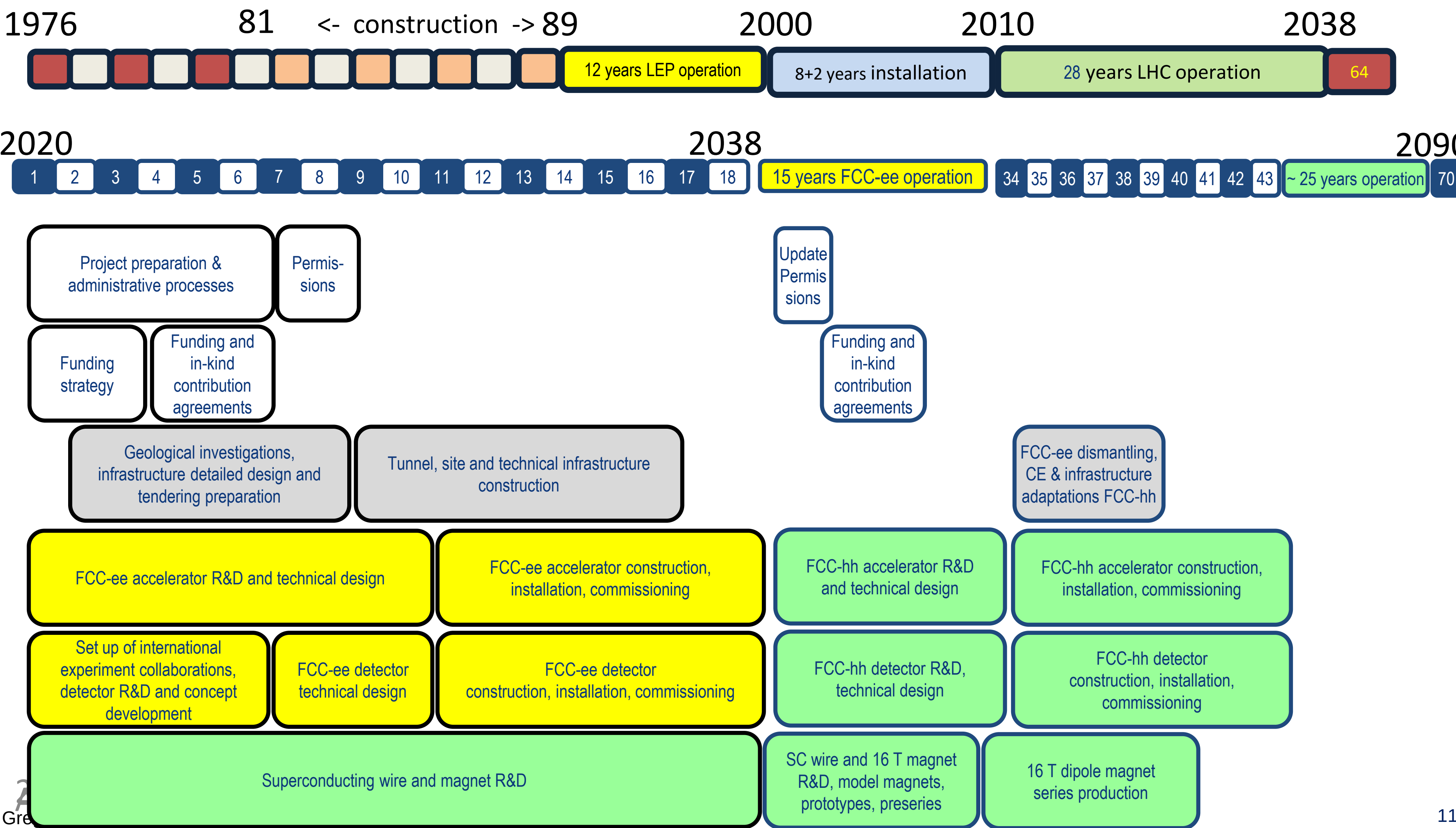


FCC-hh



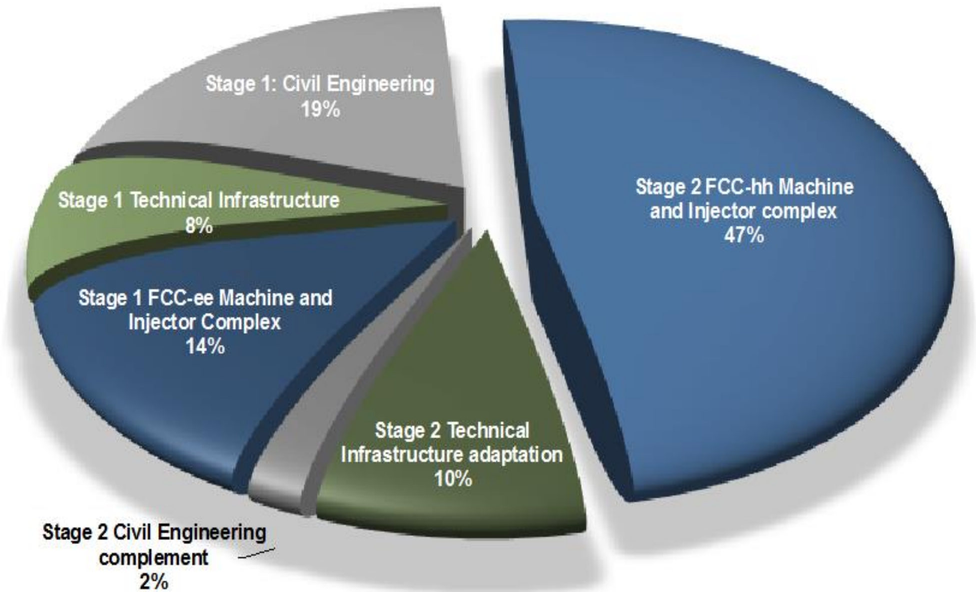


FCC-INT timeline, compared with LEP/LHC



FCC-integrated cost estimate

Domain	Cost in MCHF
Stage 1 - Civil Engineering	5,400
Stage 1 - Technical Infrastructure	2,200
Stage 1 - FCC-ee Machine and Injector Complex	4,000
Stage 2 - Civil Engineering complement	600
Stage 2 - Technical Infrastructure adaptation	2,800
Stage 2 - FCC-hh Machine and Injector complex	13,600
TOTAL construction cost for integral FCC project	**28,600**



Total construction cost FCC-ee (Z, W, H) amounts to 10.5 BCHF + 1.1 BCHF (tt).

- Associated to a total project duration of ~20 years (2025 – 2045)

Total construction cost for subsequent FCC-hh amounts to 17 BCHF.

- Associated to a total project duration of ~25 years (2035 – 2060) (FCC-hh stand alone 25 BCHF)

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FCC-ee run plan

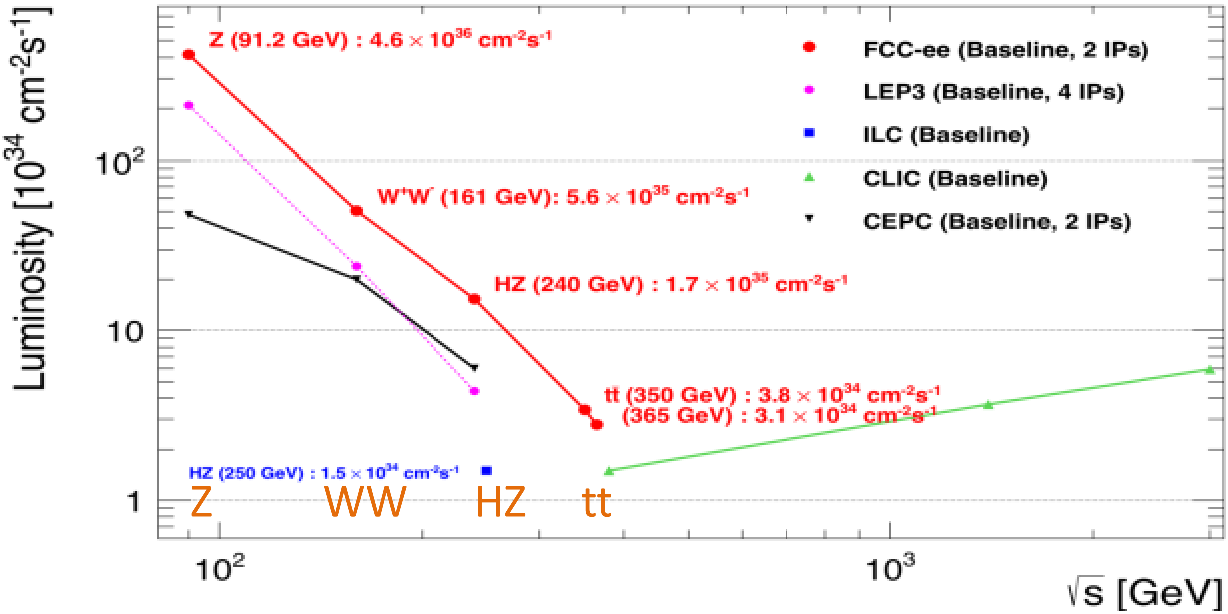

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95 ± <100 KeV	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162 ± <200 KeV	12	10^8 WW events
FCC-ee-H	3	240 ± 2 MeV	5	10^6 ZH events
FCC-ee-tt	5	345-365 ± 5 MeV	1.5	10^6 $t\bar{t}$ events

Extracted from FCC CDR

LEP * 10^5
LEP * 2.10^3
Never done
Never done

FCC-ee physics plans

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M. Dam ECFA R&D road map input
https://indico.cern.ch/event/994685/

"Higgs Factory" Programme

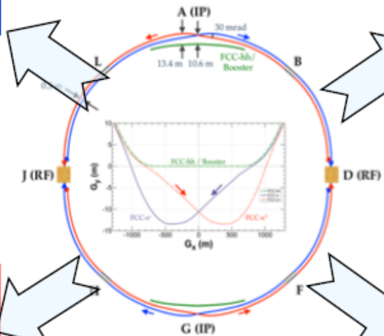
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \to H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays

- CKM matrix, CP measurements, "flavour anomaly" studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

Intensity frontier: Opportunity to directly observe new feebly interacting particles with masses below m_Z :

- Axion-like particles, dark photons, Heavy Neutral Leptons
- Signatures: long lifetimes - LLPs

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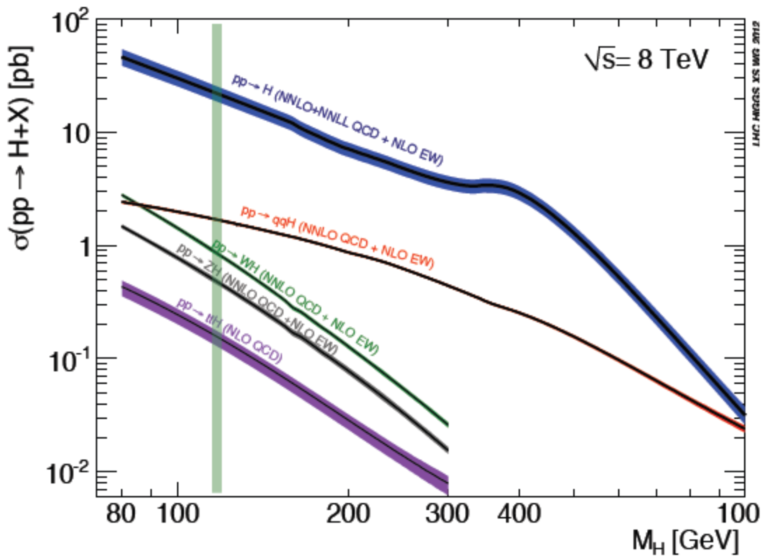
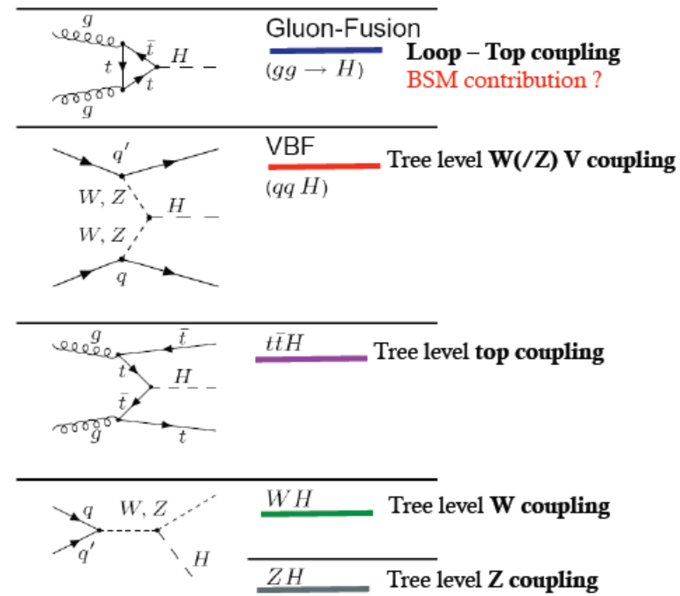
Why do we need another Higgs Factory ?

The LHC is a large Higgs Factory…





~100 Million Higgs already produced… more than most "Higgs factory" projects but…

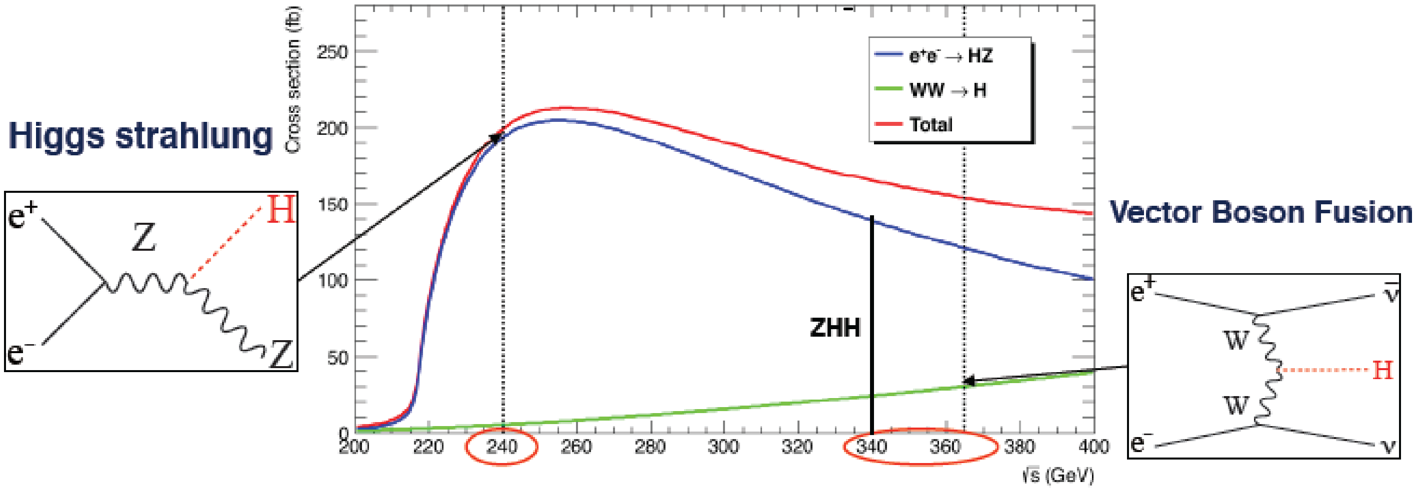
$$\sigma_{i\to f}^{\text{observed}} \propto \sigma_{\text{prod}} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

relative uncertainty scales with 1/purity and 1/√efficiency of signal

We don't know the width until measured directly

difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible+ unmeasured channels) → must do Higgs physics with ratios at LHC

Higgs boson production at FCC-ee



FCC-ee as a Higgs factory:

Higgs-strahlung (e+e → ZH): event rate is largest at √s ~ 240 GeV : σ ~200 fb

- 1.2×10^6 e+e- → ZH events with 5 ab-1
- Target : (few) per-mil precision, statistics-limited.
- Complemented with ~100k events at √s = 350 – 365 GeV (of which 30% are via the WW fusion channel)
  ➔ useful for measuring self-coupling and Γ_H precisely.

- The Higgs-strahlung process is an *s*-channel process → maximal just above the threshold of the process
- Vector Boson Fusion is a *t*-channel process which yields a cross section that grows logarithmically with the c-o-mass energy
- The Higgs boson is also produced in association with fermion pair for instance, a top quark pair.

Physics of the Higgs boson at FCC-ee

Baseline (2IP): at 240 and 365 GeV, collect in total 1.2M HZ events and 0.1M WW →H events

- **Statistics-limited measurements:**

- Higgs couplings to fermions & bosons;
  → Model-independent, normalized to e+e- →ZH cross-section
  → fixed candle for past (HL-LHC) and future (FCC-hh) studies at hadron colliders (H→ ZZ)

- Higgs properties: CP violation, H→ gg , Higgs width...

- **Close to discovery level:**

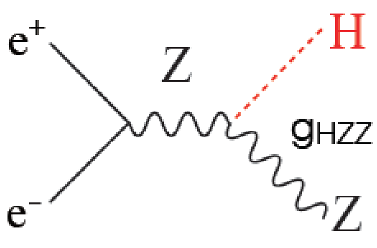
- Higgs self-coupling via loop diagrams :
  complementarity to HH production at higher energy machines, like HL-LHC, or later FCC-hh

- **Unique possibility:**

- Measure Higgs to electron coupling in s-channel production e+e-→H @ $\sqrt{s}$ = 125 GeV
  highly demanding on luminosity, monochromatization with 1, 2 or 4 IPs?
  → test of first generation yukawa coupling

Higgs studies through recoil mass in ZH production, vs. Higgs @LHC

@FCC-ee The Higgs mass can be reconstructed in ZH events using the Z decaying leptonically and beam energy constraints w/o looking at the H decay. Once H is tagged, measure x-section.

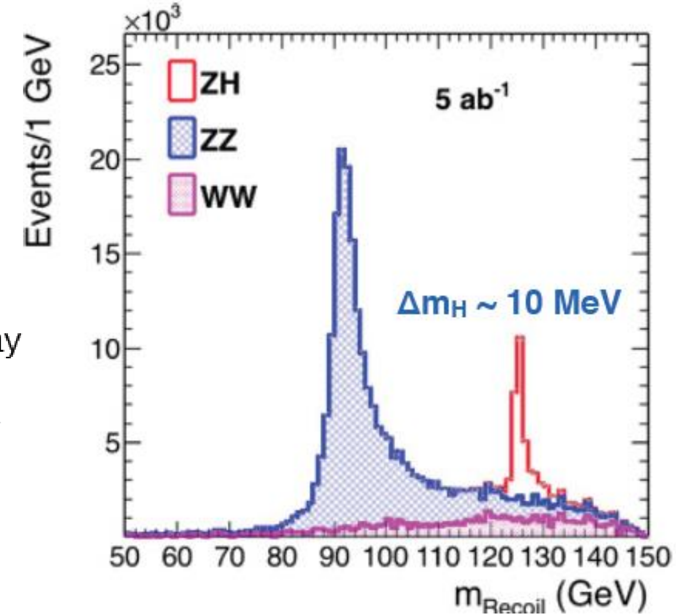


$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

E_+, E_- lepton energies from Z decay

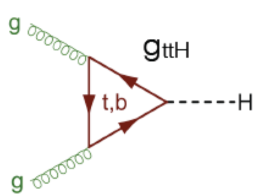
$$\sigma\left(e^+e^- \to ZH\right) \propto g_{HZZ}^2$$

absolute HZZ coupling meas.



@LHC No Higgs boson tag, need to look at specific decays H → XX, LHC typically measures σ·Br(H→XX)

$$\sigma_{\rm ggF} \cdot Br(H \to XX) = \sigma_{\rm ggF} \cdot \frac{\Gamma_{H\to XX}}{\Gamma_H} \propto \frac{g_{ttH}^2\, g_{HXX}^2}{\Gamma_H}$$



LHC can measure only product of couplings over Γ_H, it can measure only ratios of couplings.

In other terms, LHC can measure only relative branching fractions: Br(H→XX)/Br(H→YY),

$$Br(H \to XX) = \frac{\sigma\left(e^+e^- \to ZH, H \to XX\right)}{\sigma\left(e^+e^- \to ZH\right)}$$

FCC Coupling measurement comparison with other ee-machines

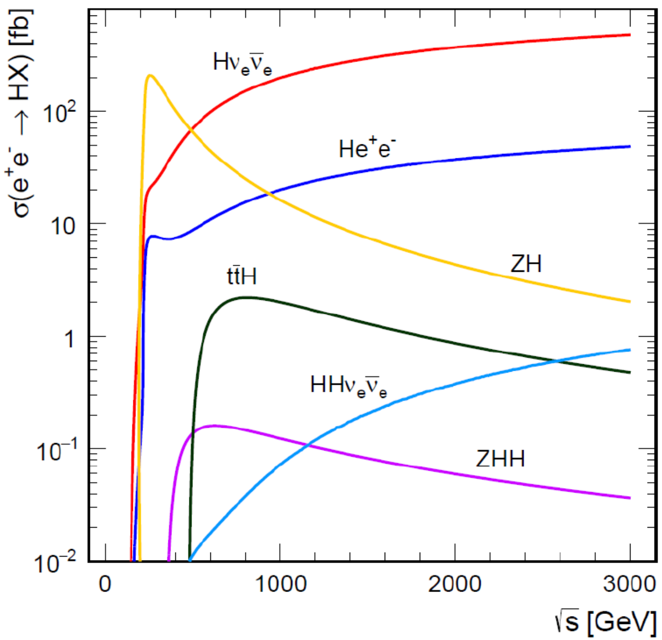
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$LEP3_{240}$	$CEPC_{250}$	$FCC\text{-}ee_{240+365}$		
Lumi (ab^{-1})	3	2	1	3	5	5_{240}	$+1.5_{365}$	+ HL-LHC
Years	25	15	8	6	7	3	+4	
$\delta\Gamma_H/\Gamma_H$ (%)	SM	3.6	4.7	3.6	2.8	2.7	**1.3**	1.1
$\delta g_{HZZ}/g_{HZZ}$ (%)	1.5	0.3	0.60	0.32	0.25	0.2	**0.17**	0.16
$\delta g_{HWW}/g_{HWW}$ (%)	1.7	1.7	1.0	1.7	1.4	1.3	**0.43**	0.40
$\delta g_{Hbb}/g_{Hbb}$ (%)	3.7	1.7	2.1	1.8	1.3	1.3	**0.61**	0.56
$\delta g_{Hcc}/g_{Hcc}$ (%)	SM	2.3	4.4	2.3	2.2	1.7	**1.21**	1.18
$\delta g_{Hgg}/g_{Hgg}$ (%)	2.5	2.2	2.6	2.1	1.5	1.6	**1.01**	0.90
$\delta g_{H\tau\tau}/g_{H\tau\tau}$ (%)	1.9	1.9	3.1	1.9	1.5	1.4	**0.74**	0.67
$\delta g_{H\mu\mu}/g_{H\mu\mu}$ (%)	4.3	14.1	n.a.	12	8.7	10.1	**9.0**	3.8
$\delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$ (%)	1.8	6.4	n.a.	6.1	3.7	4.8	**3.9**	1.3
$\delta g_{Htt}/g_{Htt}$ (%)	3.4	–	–	–	–	–	–	3.1
BR_{EXO} (%)	SM	< 1.7	< 2.1	< 1.6	< 1.2	< 1.2	< 1.0	< 1.0

LHC caveats:

- measures only coupling ratios,
- all couplings to decay channels LHC is unable to see are SM (light quarks, charm, electrons)
- coupling to gluosn measured through gg -> H production cross section

HL-LHC will produce much more Higgs than FCC-ee, couplings ratios :
$gH\mu^+\mu/gHZZ$, $gH\gamma\gamma/gHZZ$ will be set at HL-LHC at % precision level.

High Energy Higgs factories: $ILC_{500-1000}$, $CLIC_{3000}$, FCC-INT



FCC-INT =FCC-ee + FCC-hh has the best expectations

Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT	
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16	ee
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19	ee
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48	ee
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96	ee
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50	ee
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46	ee
$g_{H\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43	hh
$g_{H\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32	hh
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70	hh
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95	hh
g_{HHH} (%)	27.	10.	9.	±2(sta)±~3(sys)*	hh
Γ_H (%)	1.1	1.0	1.6	0.91	ee
BR_{inv} (%)	0.23	0.22	0.61	0.024	hh
BR_{EXO} (%)	1.4	1.4	2.4	1.0	ee

(*)see M. Selvaggi, 3rd FCC physics workshop, 9% precision in 3 years run of FCC-hh, 2004.03505v1

FCC-hh > 10^{10} H produced
+
FCC-ee measurement of g_{HZZ}
→ g_{HHH} , $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, BR_{inv}

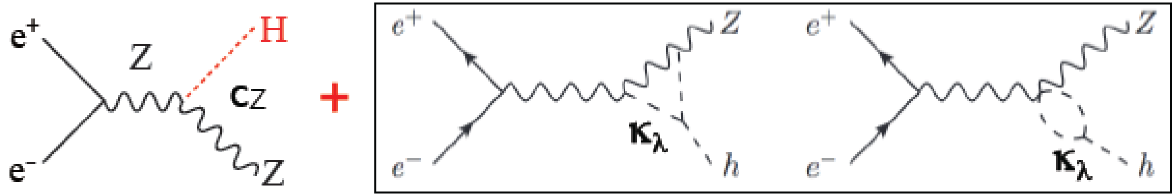
Improvement with 4 Interaction Points (IP) (arxiv 1809.10041)

- First scenario: keep the same operation model as with 2 IP
  - Total luminosity increases by a factor 1.7
    - Precision on Higgs couplings and Higgs width improves by a factor 1.3
- Second scenario: optimize the operation model towards the Higgs
  - For example, maximize the sensitivity to the Higgs self-coupling
  - spend 10 years at 240 and 365 GeV, instead of the baseline 7 years
    - Say 3.5 years at 240 GeV and 6.5 years at 365 GeV (plus 0.5 yr at 340-350 GeV)
    - With a total luminosity / year ~1.7 larger than in the baseline

<<<<<	κ_Z	κ_W	κ_b	κ_c	κ_g	κ_τ	κ_μ	κ_γ	BR_{inv}	Γ_H
2 IP	0.17%	0.43%	0.61%	1.21%	1.01%	0.74%	9.0%	3.9%	< 0.3%	1.3%
4 IP	0.10%	0.24%	0.36%	0.73%	0.60%	0.43%	5.5%	3.0%	<0.2%	0.77%

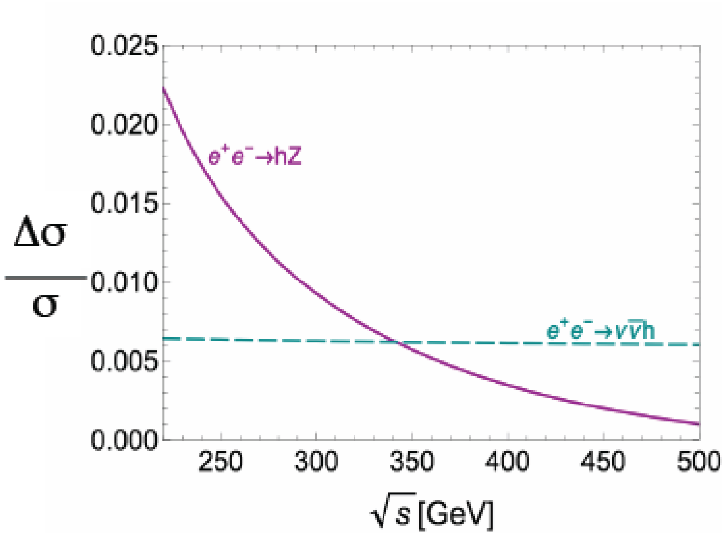
Measurement of the Higgs self-coupling

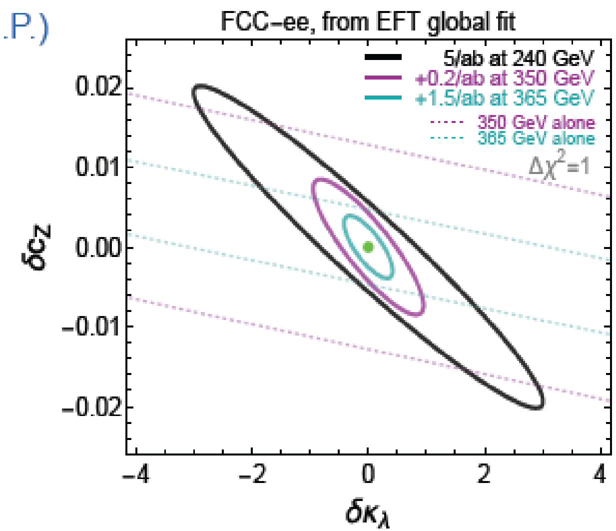
σ_{HZ}



M. McCullough
arXiv:1312.3322

- assuming all other couplings at MS, $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 19% (12% 4 I.P.)
- maximum sensitivity at the threshold production





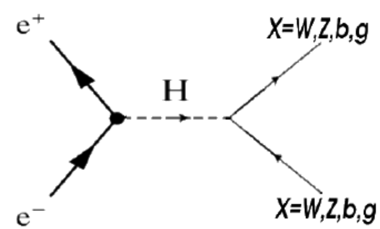
- from a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 21% (4 IPs)
- changing CMS energy helps in reducing correlations

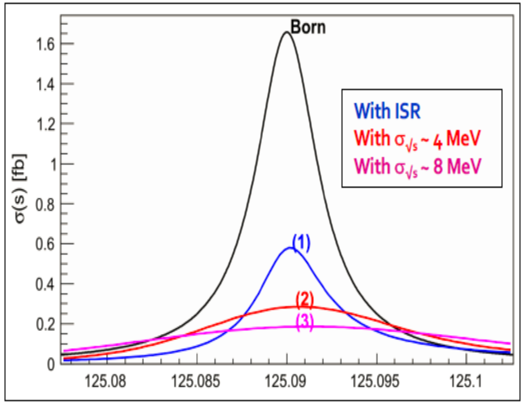
Yukawa coupling to electrons via s-channel e+e- → H production

First generation Yukawa coupling will not be accessible at HL-LHC, FCC-hh or any other ee machine

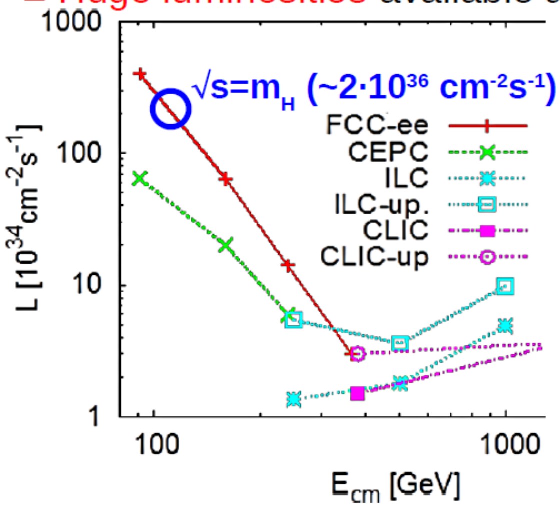
- Higgs decay to e^+e^- is unobservable: $BR(H\to e^+e^-) \propto m_e^2 \approx 5\cdot 10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny κ_e Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$:

$$\sigma(e^+e^-\to H) = \frac{4\pi\Gamma_H^2 Br(H\to e^+e^-)}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2} = 1.64\ \text{fb}\ (m_H=125\ \text{GeV},\ \Gamma_H=4.2\ \text{MeV})$$





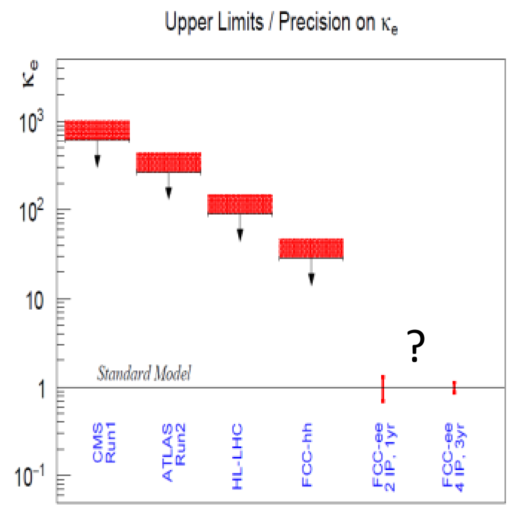
- Huge luminosities available at FCC-ee:



In theory, FCC-ee running at H pole-mass $L_{int} \approx 20\ ab^{-1}$/yr would produce O(30.000) H's

IF we can control: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds, then:

→ Electron Yukawa coupling measurable.
→ Higgs width measurable (threshold scan)?
→ Separation of possible nearly-degen. H's?



Most significant channel: e_+e_- → H → gg → jj final state

Summary of targets for the Higgs boson at FCC

- After the Higgs discovery, the next step in Higgs Physics is to study the Higgs couplings with the highest possible precision, to discover possible deviations from the Standard Model predictions
- Together with the electroweak precision measurements at the Z resonance mass, WW and ttbar thresholds, measurements in the Higgs sector will be sensitive to new physics mass scale of 70 TeV, well beyond HL-LHC.
- Observation of Higgs couplings to charm quarks, gluons, électrons will be further steps towards our understanding of the Higgs boson/field.
- The measurement of the Higgs self-coupling is fundamental to access the last missing piece of the SM (the Higgs potential), assuming that the SM is correct in the couplings of the Higgs to gauge bosons, the potential term can be probed down to the 20% level.
- FCC-ee will provide ultimate precision to Higgs boson couplings. Together with other high precision EWK measurements, it will greatly enhance our understanding of the Higgs boson

The Z peak

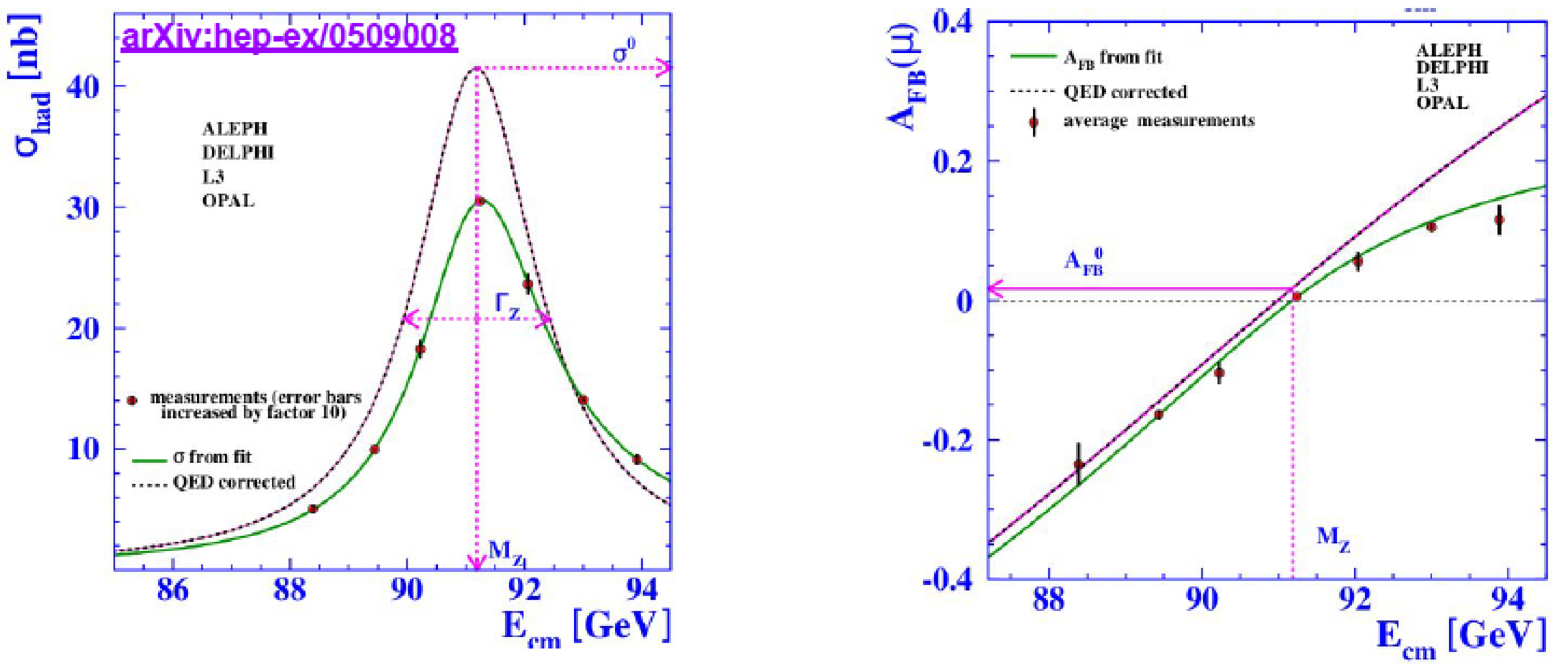
The electroweak program at the Z peak
is quite unique, most challenging and
maybe
the most promising part of the program
given the upward jump in statistics !

L = 230 $/cm^2$ /s and 35 nb of Z cross section corresponds to 80 kHZ of events with typ. 20 charged and 20 neutral particles
(all to be preciously and fully recorded, stored, reconstructed)

3 years at 10^7 s /year = 2.4 10^{12} evts per exp.

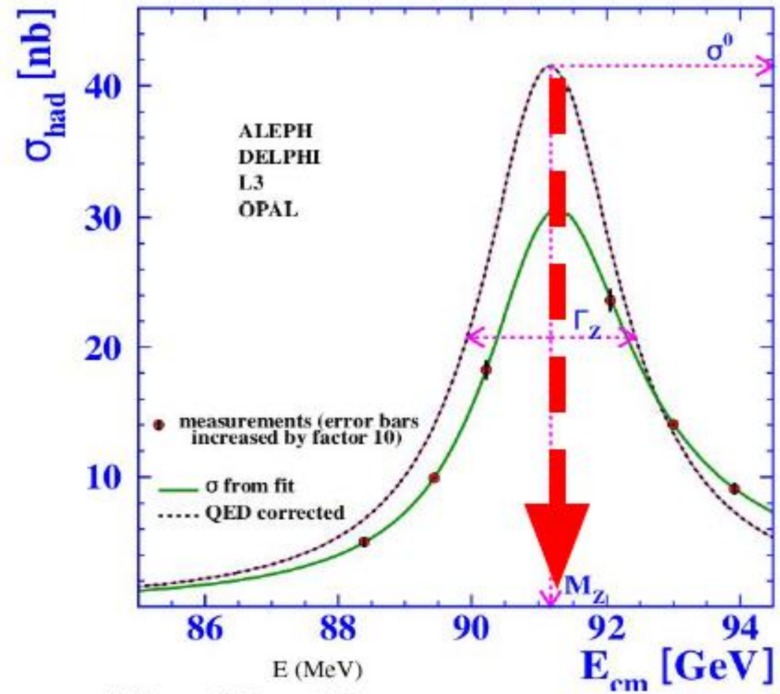
Processing time 1ms/evt → 240 years of processing…. + Monte Carlo.

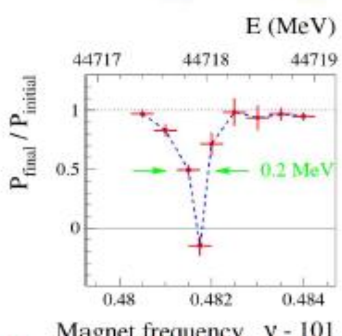
Z Lineshape Measurements



- Expected precisions in a nutshell:
  - ≈ 10^{-4} on cross sections (aimed luminosity uncertainty); possibility to reduce it by an order of magnitude using the measured $\sigma(ee\rightarrow\gamma\gamma)$ as reference
  - ≈ 10^{-6} statistical uncertainties (≈ $1/\sqrt{N}$) on relative measurements like forward-backward charge asymmetries
  - Ultimate uncertainties typically dominated by systematics; precious value of "Tera" Z samples to study / constrain many of those uncertainties

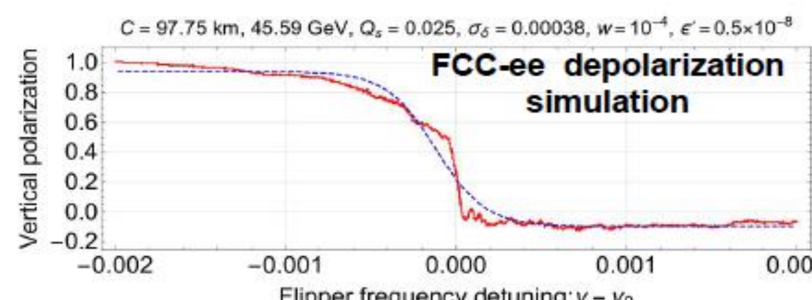
Z Lineshape: Mass





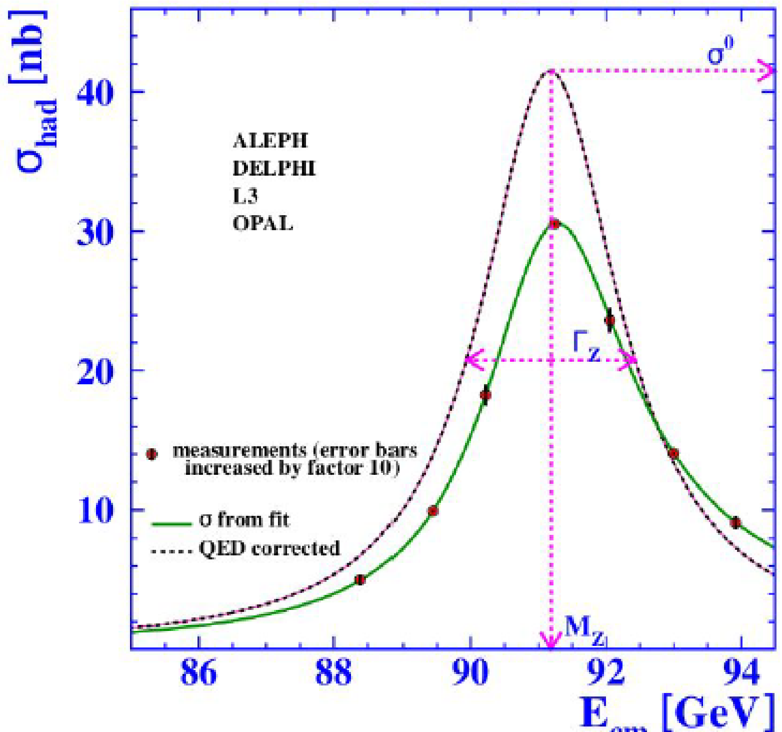
Resonant depolarization at LEP

- m_Z: position of Z peak
- Beam energy measured with extraordinary precision ($\Delta\sqrt{s}\approx 100$ keV) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, …)
- Beam width/asymmetries studied analyzing the longitudinal boost distribution of the $\mu\mu$ system



arXiv:1909.12245

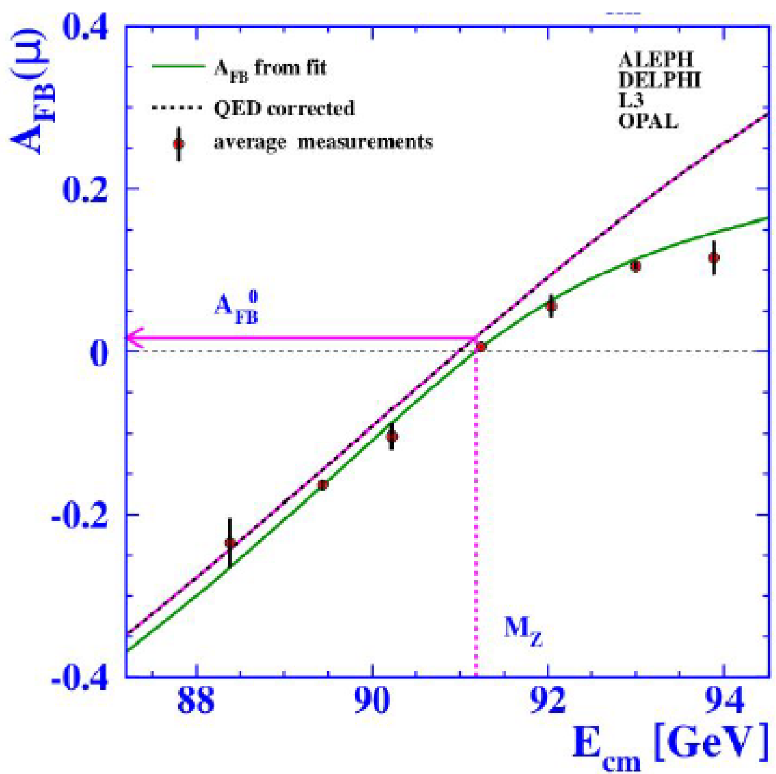
$R_L = \Gamma_{had} / \Gamma_{lep}$



- Relative measurement, independent of luminosity: aiming for a 10^{-5} precision
- Extremely sensitive to new physics deviations (ϱ,T parameters: deviations of custodial symmetry)
- $\alpha_s(m^2{}_Z)$ modifies the hadronic partial width → R_l provides an ultra-precise measurement

- **Studies to define detector requirements to ensure negligible systematic uncertainties on acceptance (a priori more critical on leptons)**

$\sin^2\theta_W^{eff}$ and $\alpha_{QED}(m^2_Z)$



- $\sin^2\theta_W$ effective: g_V/g_A coupling ratio → forward-backward charge asymmetries (most precise in $\mu\mu$ final state)
- $\alpha_{QED}(m^2_Z)$: off-peak/peak evolution of the asymmetry (due to interference with γ^* exchange)
- Measurement approaching the ultimate statistical sensitivity: 3 x 10^{-6}
- 3 energy points (≈88, 91.2, 94 GeV)

- **Studies to establish the experimental/theoretical needs (energy resolutions, exact angular description at this level of precision, …)**

Systematic uncertainties

Observable	present value ± erro	FCC-ee Stat. (opportunities)	FCC-ee Syst. (challenges)	Comment and leading exp. error
m_Z (keV)	91186700 ± 220	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 230	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\text{eff}}$ ($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z ($\times 10^3$)	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ ($\times 10^4$)	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν ($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic ($\mu\nu_\mu\nu_\tau$) B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)$ ($\times 10^4$)	1170 ± 420	**3**	small	from R_ℓ^W
N_ν ($\times 10^3$)	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate

Systematics in the table are preliminary and often largely dominant

However, we should use statistical errors (with appropriate selection efficiencies and background subtractions) as the best way to assess the physics potential of a facility, since the systematic uncertainties get generally reduced making clever use of the statistics.

It is however important to concentrate on finding the potential 'show stoppers' or 'stumbling blocks', to guide the detector R&D and detector requirements.

Strong support for theoretical calculations will be needed if the program is to be successful

Theory work is critical and initiated (1809.01830)

τ – lepton Properties and Lepton Universality

Snowmass2021 - Letter of Interest

Tau lepton properties and lepton universality measurements at the FCC-ee

Thematic Areas:
- EF04: EW Physics: EW Precision Physics and constraining new physics
- EF03: EW Physics: Heavy flavor and top quark physics

Contact Information:
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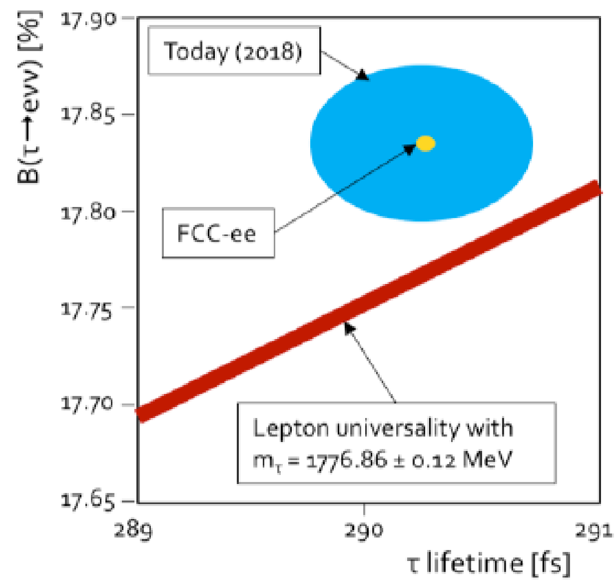
Authors:
Alain Blondel[1], Mogens Dam[2], Patrick Janot[3]

Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100-TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z decays will be produced at multiple interaction points. The five orders of magnitude larger statistics than at LEP opens the possibility of much improved measurements of τ-lepton properties—lifetime, (leptonic) branching fractions, and mass—in $\tau^+\tau^-$ final states. Such measurements provides interesting tests of lepton universality, in effect probing whether the Fermi coupling constant is the same in τ decays as in μ decays. The ultimate goal, that experimental errors match the statistical accuracy, leads to highly demanding requirements on detector design. This Letter of Interest describes some of the many challenges presented by this benchmark measurement.

a) Mass
b) Lifetime
c) Leptonic branching fractions



More on TeraZ

The Flavour Factory

Progress in flavour physics wrt SuperKEKb/BELLEII requires > 10^{11} b pair events,
FCC-ee(Z): will provide ~10^{12} b pairs. "Want at least 5 10^{12} Z…"

- Precision of CKM matrix elements
- Push forward searches for FCNC, CP violation and mixing
- Study rare penguin EW transitions such as b $\rightarrow$s $\tau^+ \tau^-$, spectroscopy (produce b-baryons, B_s ...)
- Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}

-- all very important to constrain / (provide hints of) new BSM physics.

need special detectors (PID) under study

The 3.5×10^{12} hadronic Z decay also provide precious input for QCD studies

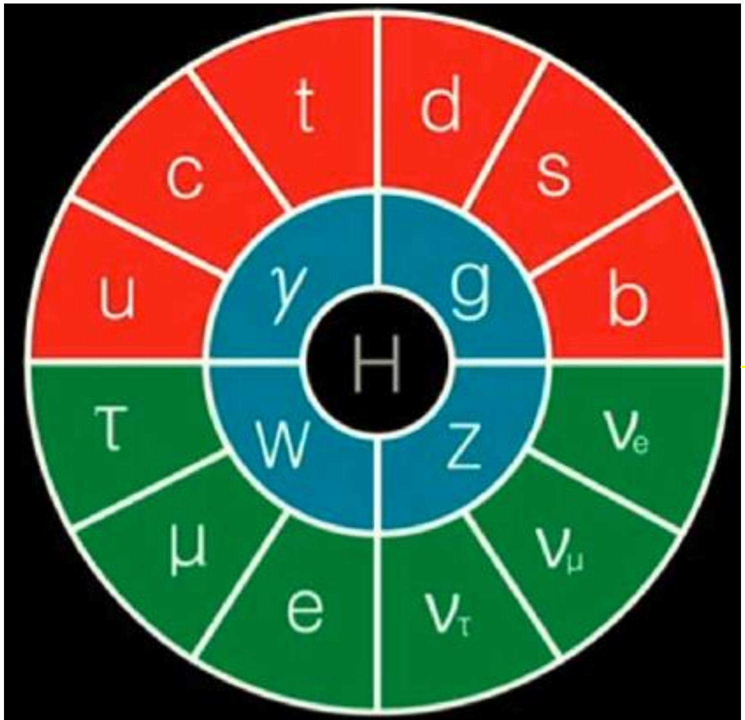
High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : $10^{-3} \rightarrow 10^{-4}$

huge $\sqrt{s}$ lever-arm between 30 GeV and 1 TeV (FCC vs ILC), fragmentation, baryon production ….

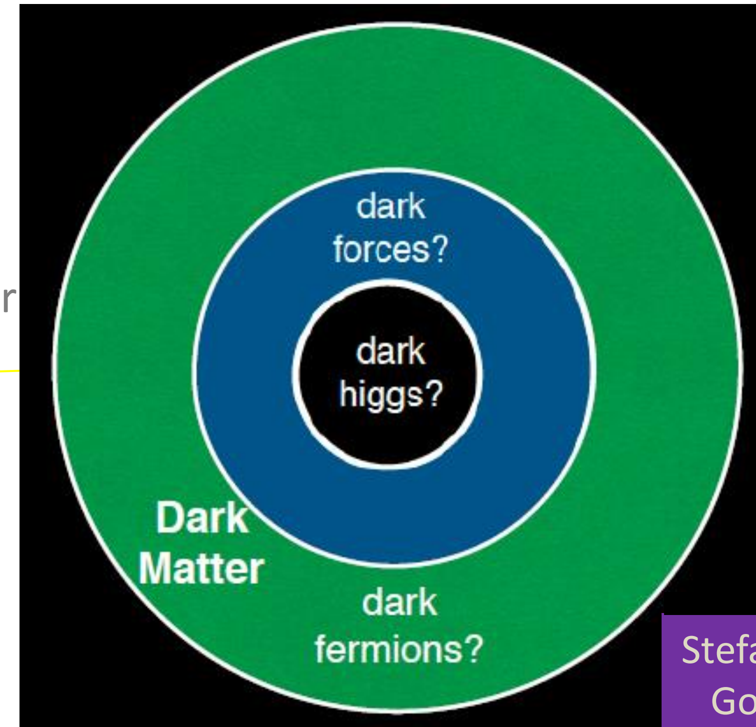
Testing running of α_s to excellent precision

Dark Sector at Z factory

With the Higgs discovery SM works perfectly, yet we need new physics to explain the baryon asymmetry of the Universe, the dark matter etc… without interfering with SM rad. corr.



mediator
or
mixing



Stefania Gori

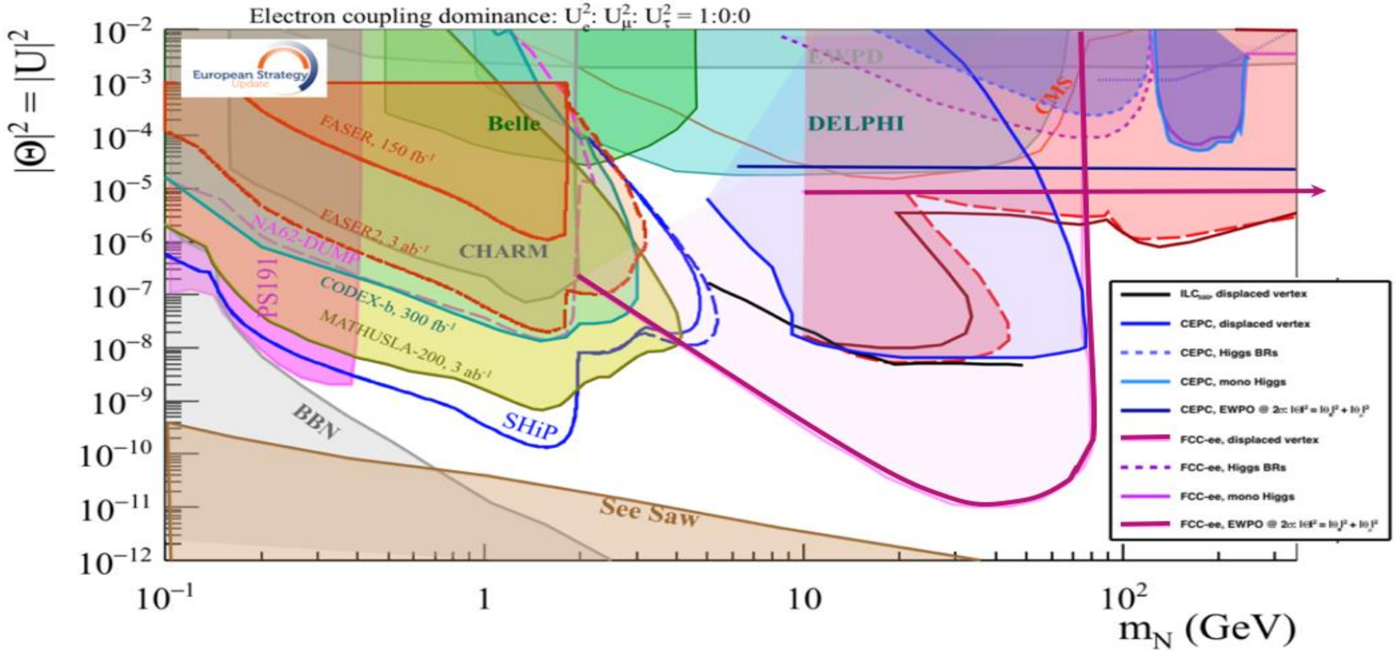
Dark photons, axion like particles, sterile neutrinos, all *feebly coupled* to SM particles

FCC

Feebly interacting particles

This picture is relevant to Neutrino, Dark sectors and High Energy Frontiers.

FCC-ee (Z) compared to the other machines for right-handed (sterile) neutrinos



- the purple line shows the reach for observing **heavy neutrino decays** (here for 10^{12} Z)

- the horizontal line represents the sensitivity to **mixing of neutrinos** to the dark sector, using EWPOs (G_F vs $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing all the way to very high energies (500-1000 TeV at least). arxiv:2011.04725

FCC

FCC-ee discovery potential and Highlights

Things that FCC-ee could explore or discover :

- EXPLORE the 10-100 TeV energy scale (and beyond) with Precision Measurements
  20-100 fold improved precision on many EW quantities (equiv. to factor 5-10 in mass)
  $m_{Z,}$ m_W, m_{top} , $\sin^2\theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings
  model independent «fixed candle» for Higgs measurements, ee-H coupling.

- DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
  FCNC (Z --> $\mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ $\tau\tau$
  + flavour physics (10^{12} bb events) (B→s $\tau\tau$ etc..)

- DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

- DISCOVER very weakly coupled particle in 5-100 GeV energy scale
  such as: Right-Handed neutrinos, Dark Photons, ALPS, etc…

- and many opportunities in e.g. QCD (α_s @ 10^{-4}, fragmentations, H→ gg) etc….

→ Not only a «Higgs Factory»! «Z factory» and «top» are important for 'discovery potential'

FCC main goals for 2021 - 2026

Overall goal:

- Perform all necessary steps and studies to enable a definitive project decision by 2025/26, at the anticipated date for the next ESU, and a subsequent start of civil engineering construction by 2028/29.

This requires successful completion of the following four main activities:

- Develop and establish a governance model for project construction and operation
- Develop and establish a financing strategy, including in-kind contributions
- Prepare and successfully complete all required project preparatory and administrative processes with the host states (debat public, EIA, etc.)
- Perform site investigations to enable Civil Engineering planning and to prepare CE tendering.

In parallel development preparation of TDRs and physics/experiment studies:

- Machine designs and main technology R&D lines
- completion of first physics case studies in 2021 → detector requirements
- reach out to all 'European and International Partners'
- Establish user communities, work towards proto experiment collaboration by 2025/26.

Outlook

The next facility must be complete with as broad and powerful reach as possible,
as there is no precise target → more Sensitivity, more Precision, more Energy

FCC, thanks to synergies and complementarities, offers the best approach to today's physics landscape

Many opportunities and challenges are offered by the energy range
(from the Z pole to 100 TeV or more) and from the huge rates
(from 10^{12} Z FCC-ee to 10^{13} Ws / 10^{10} H at FCC-hh) offered by the FCC.

Let's take on the challenges, both on theory and experiment,

Don't hesitate to join the effort, in particular the theory session(s) of the
3rd FCC-France workshop in Annecy, from 30/11 to 1/12/2021
The indico page of the 2nd FCC-France workshop is at: https://indico.in2p3.fr/event/23012/
(Giacomo Cacciapaglia and Benjamin Fuks are the theory-contacts,
Roy Aleksan and GB overall FCC-France (CEA and IN2P3) responsibles)

- The 4th Annual FCC Week will take place next week, https://indico.cern.ch/event/995850/
- FCC Physics Workshop will be on 7-11 February 2022 in Liverpool

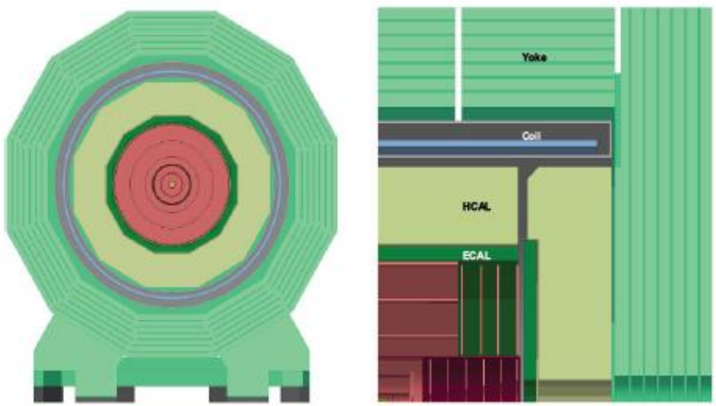
backup

References

- **FCC CDR**:
  - Vol.1: Physics Opportunities (CERN-ACC-2018-0056) http://cern.ch/go/Nqx7
  - Vol.2: The Lepton Machine (CERN-ACC-2018-0057) http://cern.ch/go/7DH9
  - Vol.3: The Hadron Machine (CERN-ACC-2018-0058), http://cern.ch/go/Xrg6
  - Vol.4: High-Energy LHC (CERN-ACC-2018-0059) http://cern.ch/go/S9Gq
- **"Physics at 100 TeV"**, CERN Yellow Report: https://arxiv.org/abs/1710.06353
- **CEPC CDR**: Physics and Detectors

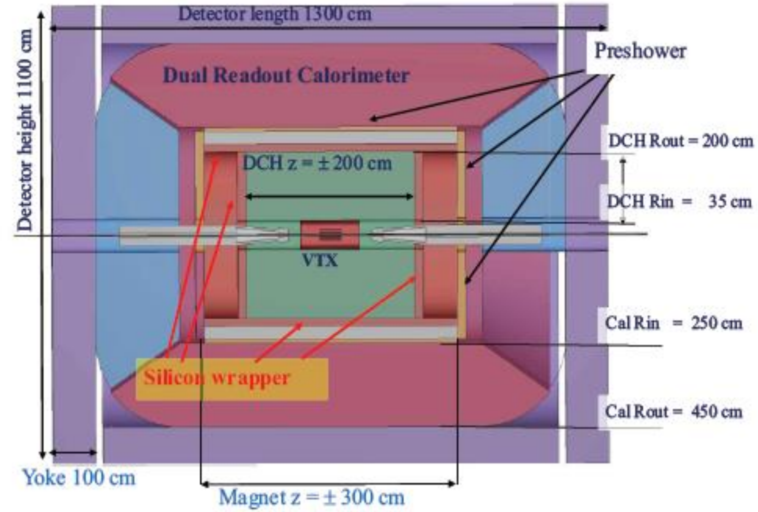
Detectors under Study

CLD



- conceptually extended from the CLIC detector design
  - full silicon tracker
  - 2T magnetic field
  - high granular silicon-tungsten ECAL
  - high granular scintillator-steel HCAL
  - instrumented steel-yoke with RPC for muon detection

IDEA



- explicitly designed for FCC-ee/CepC
  - silicon vertex
  - low X_0 drift chamber
  - drift-chamber silicon wrapper
  - MPGD/magnet coil/lead preshower
  - dual-readout calorimeter: lead-scintillating/ cerenkhov fibers
- µRwell for muon detection

Higgs couplings after FCC-ee / hh

	HL-LHC	FCC-ee	FCC-hh
$\delta\Gamma_H / \Gamma_H$ (%)	SM	**1.3**	tbd
$\delta g_{HZZ} / g_{HZZ}$ (%)	1.5	**0.17**	tbd
$\delta g_{HWW} / g_{HWW}$ (%)	1.7	**0.43**	tbd
$\delta g_{Hbb} / g_{Hbb}$ (%)	3.7	**0.61**	tbd
$\delta g_{Hcc} / g_{Hcc}$ (%)	~70	**1.21**	tbd
$\delta g_{Hgg} / g_{Hgg}$ (%)	2.5 (gg->H)	**1.01**	tbd
$\delta g_{H\tau\tau} / g_{H\tau\tau}$ (%)	1.9	**0.74**	tbd
$\delta g_{H\mu\mu} / g_{H\mu\mu}$ (%)	4.3	9.0	**0.65** (*)
$\delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ (%)	1.8	3.9	**0.4** (*)
$\delta g_{Htt} / g_{Htt}$ (%)	3.4	~10 (indirect)	**0.95** (**)
$\delta g_{HZ\gamma} / g_{HZ\gamma}$ (%)	9.8	–	**0.9** (*)
$\delta g_{HHH} / g_{HHH}$ (%)	50	~44 (indirect)	**5**
BR_{exo} (95%CL)	$BR_{inv} < 2.5\%$	**< 1%**	**$BR_{inv} < 0.025\%$**

NB

$BR(H \to Z\gamma, \gamma\gamma) \sim O(10^{-3}) \Rightarrow$ **$O(10^7)$ evts for Δ_{stat}~%**

$BR(H \to \mu\mu) \sim O(10^{-4}) \Rightarrow$ **$O(10^8)$ evts for Δ_{stat}~%**

pp collider is essential to beat the % target, since no proposed ee collider can produce more than $O(10^6)$ H's

* From BR ratios wrt $B(H \to ZZ^*)$ @ FCC-ee

** From $pp \to ttH$ / $pp \to ttZ$, using $B(H \to bb)$ and ttZ EW coupling @ FCC-ee