FCC

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Congrès de la SFP

The Future Circular Colliders (FCC) Feasibility Study and its Physics Potential

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Presentation Layout

- Why do we need a new accelerator after the LHC?
- The FCC Feasibility Study
- The FCC-ee Physics potential
- Next steps

Why do we need a new accelerator after the LHC?

Particle physics appears as a mature branch of fundamental science

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

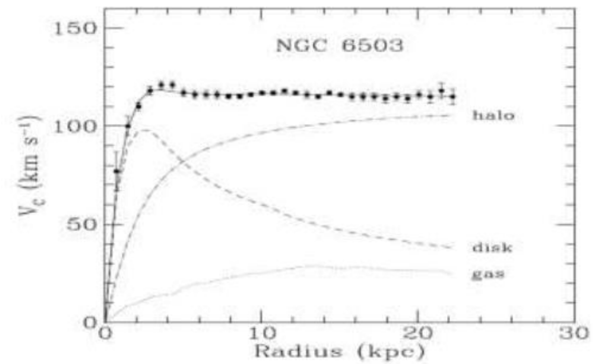
since then we have been discovering all the particles that have **electric charge** or **QCD charge**, or **weak isospin** (SM couplings), and the Higgs boson, **by increasing accelerator energies.**

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

but.. we cannot explain crucial observations with the SM, for instance:

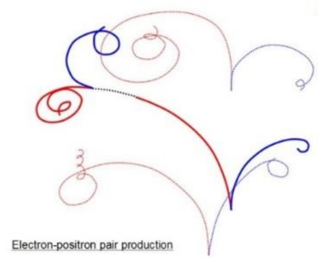
What is Dark matter ?

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



Rotation curve for Galaxy

Were is primordial antimatter gone?



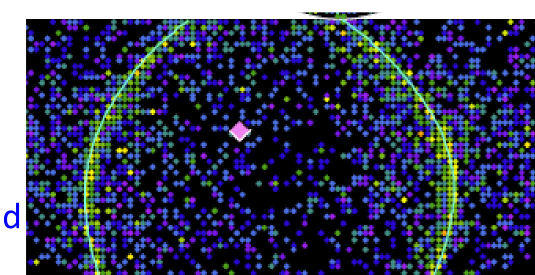
What is the origin of neutrino masses?

Not a unique solution in the SM

Dirac masses (why so small?) or Majorana (why not Dirac?)

➔ heavy right-handed neutrinos?

➔ «sterile», very small coupling to known particles
completely unknown masses (eV to ZeV), hence very difficult to find



... but could perhaps explain all: Dark Matter, Baryon Asymmetry, ν-masses

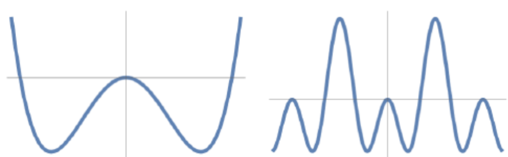
…and the Higgs boson/field still need to be better understood

- → It is a unique object, a scalar particle/field (spin 0), not a matter field, not a boson mediating a gauge interaction, but a field carrying a new type of interaction of the Yukawa type.
- → Many proposals for new accelerators to study it, and to study Beyond Standard Model (BSM) physics
- → Easier choice on the machine now that the Higgs boson has been discovered.

Precise nature of the Higgs boson ?

Origin of electroweak symmetry breaking (EWSB) ?

Shape of the Higgs potential ?



Landau-Ginzburg Higgs   Nambu-Goldstone Higgs

Strength of the electroweak phase transition ?
What is its role just after the big bang ? Inflation ?

We need to determine precisely the Higgs couplings
and the Higgs self-couplings to answer these questions.

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How to best study the Higgs / go beyond the Standard Model ?

- By measuring deviations from precise predictions (ex: Higgs or Electroweak couplings...)
- By observing New Phenomena (ex: Neutrino Oscillations, CP violation..)
- By direct observation of new particles

But we do not have a natural energy scale to search for !

➔ We don't know where to look and what we will find

➔ The next facility must have a reach as broad and powerful as possible,

➔ more Sensitivity, more Precision, more Energy

Circular machines, thanks to synergies and complementarities between ee and hh, offers today the most versatile and adapted response to today's physics landscape

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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 with complementary strengths

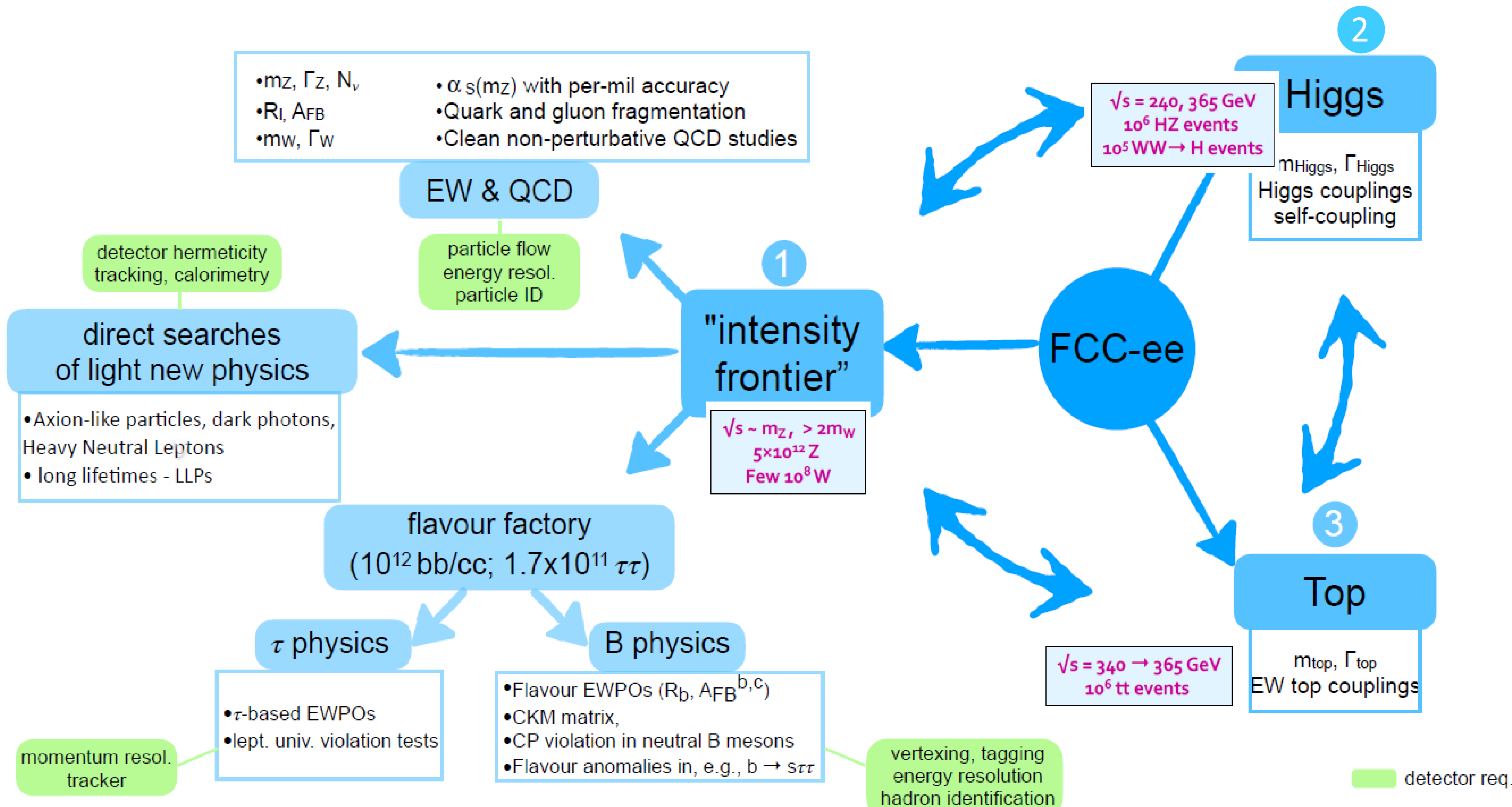
Example of competing constraints for EM calorimeter: high E precision vs. high granularity vs. high stability vs. geometric accuracy vs. PID

- many measurements will serve as input to future programs in particular FCC-hh
- many are statistically limited
- redundancy provided by 4IPs/detectors is essential for high precision measurements (hidden systematic biases)

The limitation in maximum energy (not as strong for a linear collider) is not a crucial drawback, given the current HEP panorama given by the SM, and the subsequent FCC-hh program which will reach the highest energies

The non availability of beam polarization (an advantage of linear colliders) is also not a crucial drawback since FCC-ee will run at different energies and will accumulate much more statistics.

at Circular Colliders ➔ Rich e⁺e⁻ Physics Program …



…plus an excellent hh program beyond ee Circular Colliders

The potential of an hh machine at the energy frontier in the same circular tunnel is also excellent:

- Measurement of Higgs Self-coupling at the 3 to 4% level
- Highest reach in sensitivity for di-higgs studies, dark matter searches and more
- New heavy particles could be directly discovered for masses up to 20-40 TeV
- Large potential also from indirect searches
- Possibility for an eh and/or Heavy-ion program at the highest energies

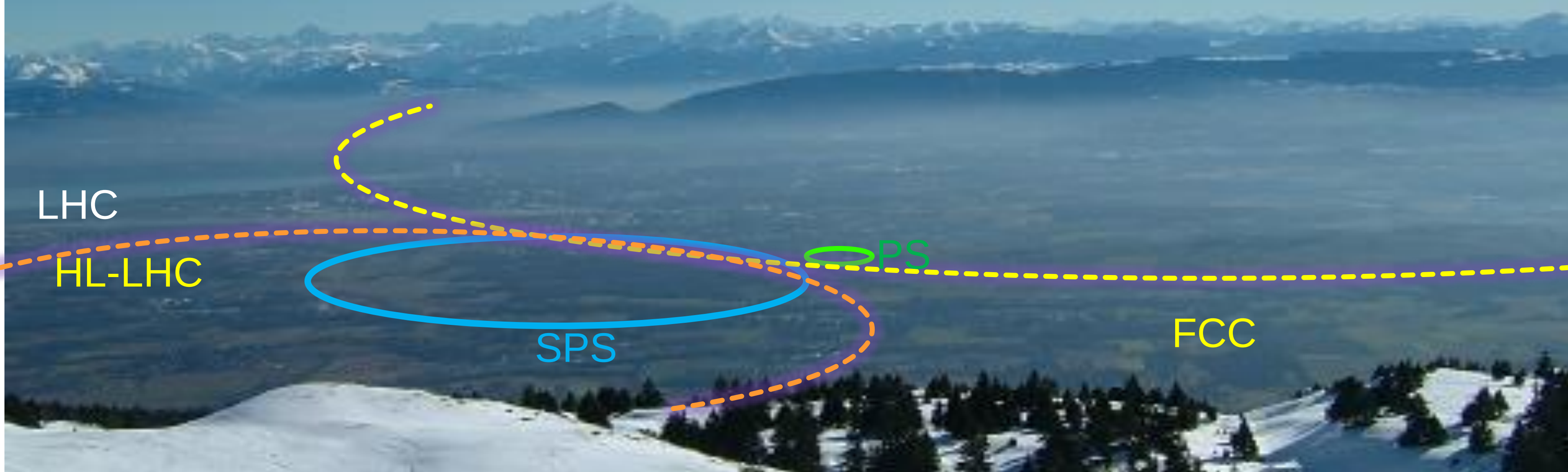
But we are not ready to build the *hh* machine soon, more R&D on the magnets is needed, and reaching the high energy frontier with a Muon Collider could take even more time, if proven possible

→European Strategy recommendations in 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, 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." ⟹ FCC Feasibility study

Future Circular Collider Feasibility Study



Goal of the study:

Provide by 2025 conclusions on the technical and financial feability of the FCC-INT project, to be submitted/approved at the next European Strategy in 2026, eventually allowing to start digging the tunnel

http://cern.ch/fcc

photo: J. Wenninger

The FCC integrated program (FCC-INT) at CERN is inspired by the successful LEP – LHC (1976-2041) program

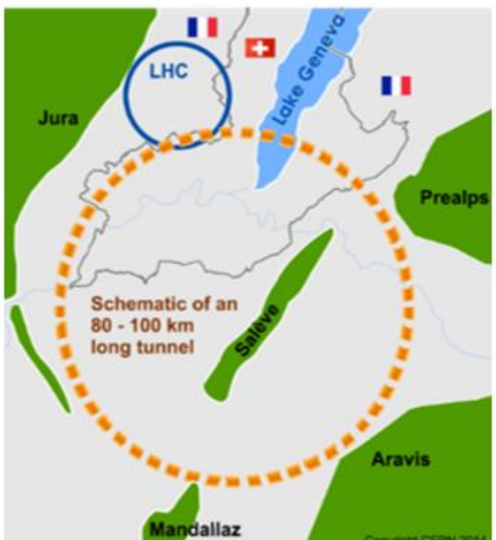
Comprehensive cost-effective program maximizing physics opportunities

- 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 heavy ions and eh options.

Complementary physics

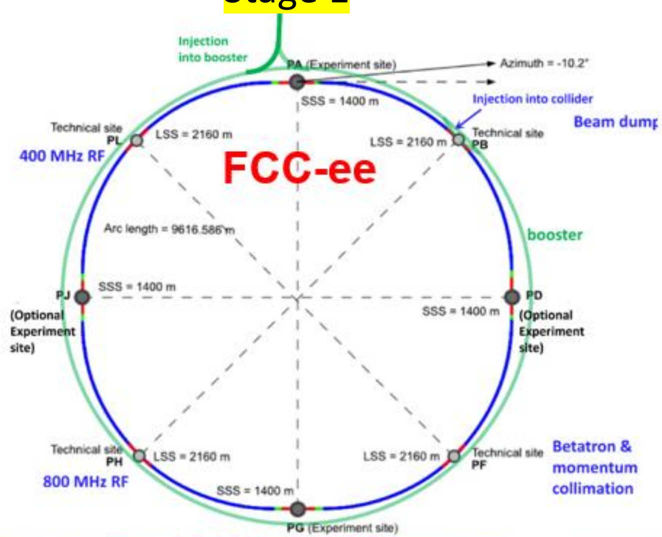
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN’s existing infrastructure.

The FCC-INT project is fully integrated with HL-LHC exploitation and provides a natural transition for higher precision and energy



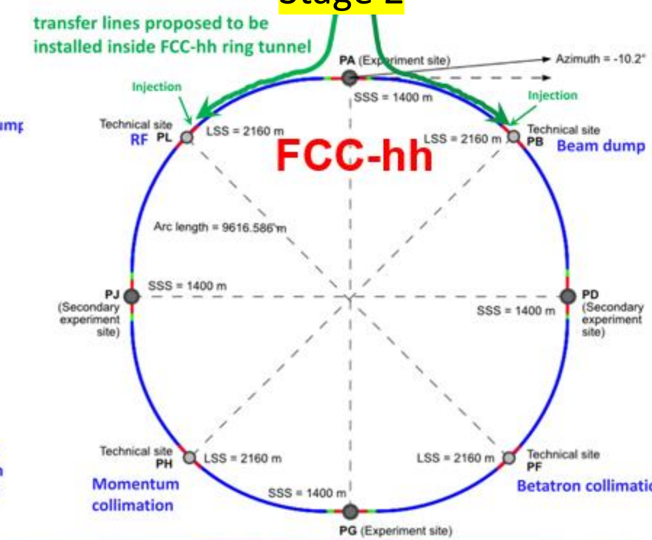
2020 - 2040

Stage 1



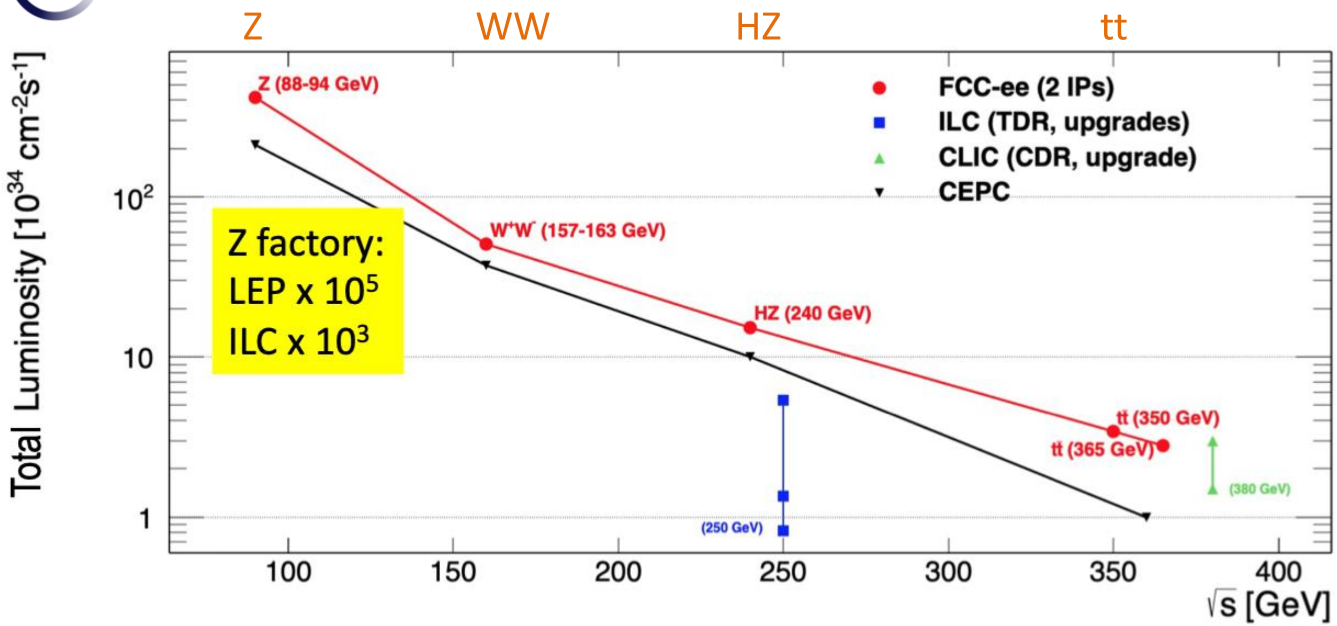
2045 - 2060

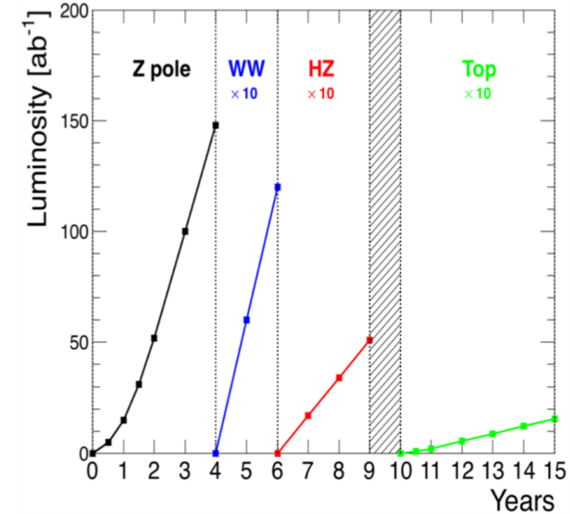
Stage 2



2065 - 2090

FCC-ee run plan





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	LEP * 10^5
FCC-ee-W	2	158-162 <200 KeV	12	10^8 WW events	LEP * 2.10^3
FCC-ee-H	3	240 ± 1 MeV	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365 ± 2 MeV	1.5	10^6 $t\bar{t}$ events	Never done

Extracted from FCC CDR

+ possible Run at the H pole (125 GeV) to access the Hee Yukawa coupling (never done, not doable anywhere else)

Detector requirements (present status)

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

"Higgs Factory" Programme

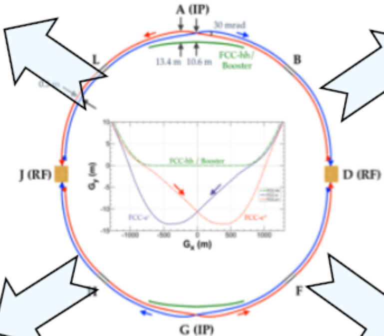
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

rare H decays (e.g. H→ γ + $\varphi/\psi/\Upsilon$)
may benefit from high resolution EM calorimeter

Ultra Precise EW Programme

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. $\Gamma_{had}/\Gamma_{\ell}$) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of √s meast.

lumi and R_{ℓ} require precision fiducial volume definitions (1-10microns)



Heavy Flavour Programme

- Superior impact parameter resolution: secondary vertices, tagging, identification, life-time measts.
- ECAL resolution at the few %/ √E level for inv. mass of final states with π^0s or γs
- Excellent π^0/γ separation and measurement for tau physics
- PID: K/π separation over wide momentum range for b and τ physics

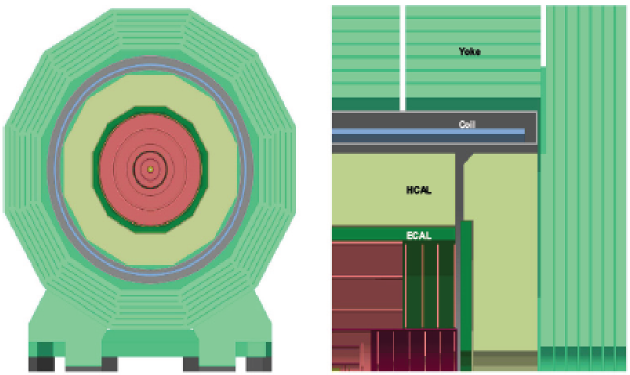
Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

Detectors under Study

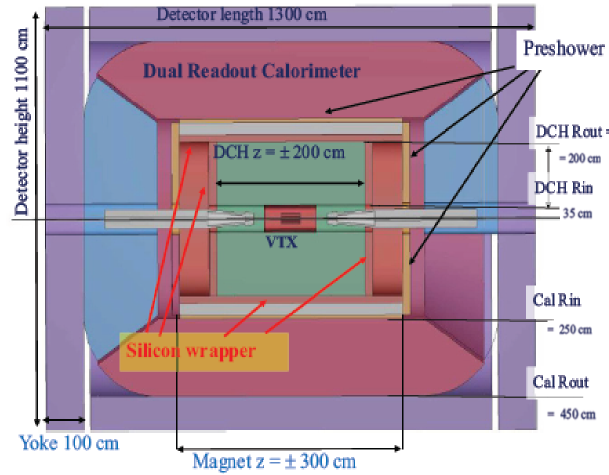
CLD



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

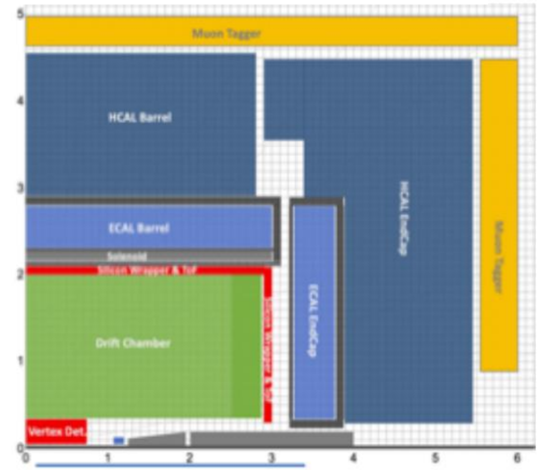
IDEA



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

Noble Liquid ECAL



explicitely designed for FCC-ee, recent concept, under development

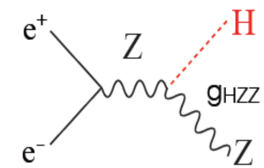
- silicon vertex
- Low X_0 drift chamber
- Thin Solenoid before the Calorimeter
- High Granularity Liquid Argon Calorimetry

But several other options like Crystal Calorimetry (active in US, Italy), are under study (similarly for tracking, muons and particle ID)

With potentially 4 experiments, many complementary options will be implemented

Physics of the Higgs boson at FCC-ee

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

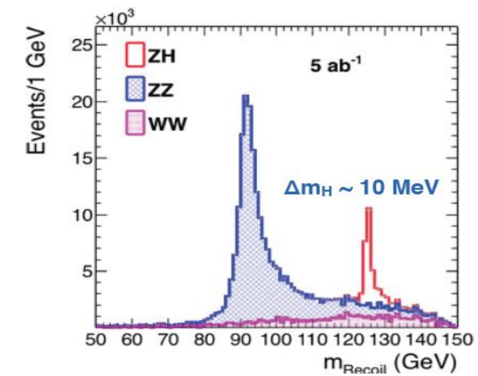


$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

E_+, E_- lepton energies from Z decay

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

absolute HZZ coupling meas.



- **Statistics-limited measurements:**
  - Higgs couplings to fermions & bosons

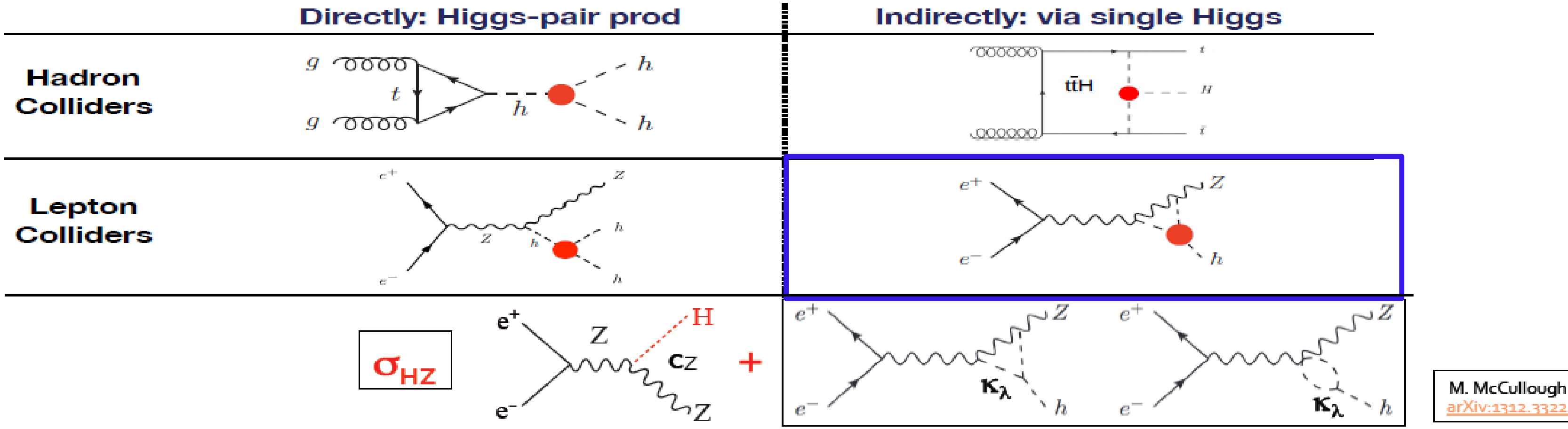
    → Model-independent measurements, normalized to e+e- → ZH cross-section
    → fixed candle (H → ZZ) for past and future (FCC-hh) studies at hadron colliders

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

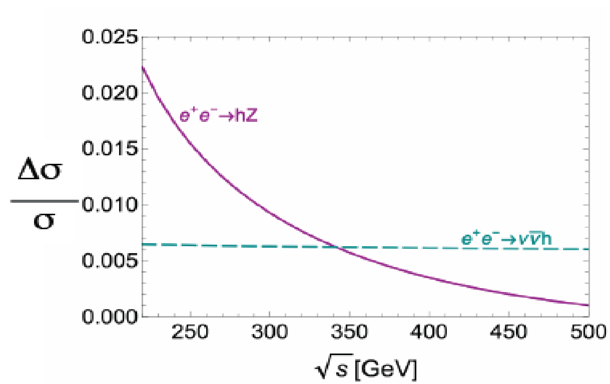
- **Close to discovery level:**
  - Higgs self-coupling via loop diagrams :
    → complementarity to HH production at higher energy machines, like HL-LHC, or later FCC-hh

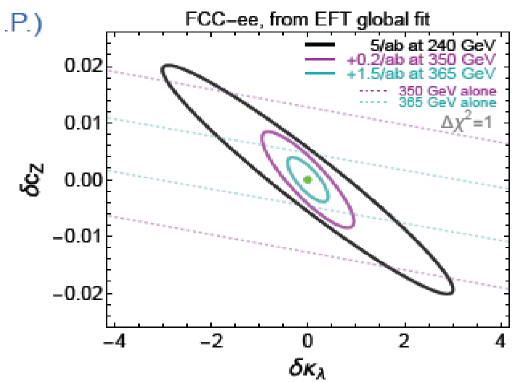
- **Unique possibility studied at FCC-ee:**
  - Measure Higgs to electron coupling in s-channel production e+e-→H @ √s = 125 GeV
    highly demanding on luminosity, monochromatization with 2 or 4 IPs?
    → test of first generation yukawa coupling

Measurement of the Higgs self-coupling



- 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 CM energy helps in reducing correlations

50% sensitivity: establish that $h^3 \neq 0$ at 95%CL
20% sensitivity: 5σ discovery of the SM h^3 coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

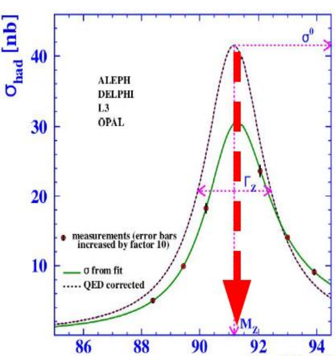
The Tera-Z program at the Z peak and Electroweak Physics

The electroweak program at the Z peak and at the WW threshold is quite unique, most challenging, and could be the most promising part of the program given the statistics !

- L = 230/cm^2/s and 35 nb of Z cross section corresponds to 80 kHZ of events with typically 20 charged and 20 neutral particles (all to be fully recorded, stored, reconstructed)
- 3 years at 10^7 s /year = 2.4 10^{12} evts/exp. ➔ 10^5 LEP Statistics (~10^3 more than ILC)

For the electroweak program we will also have

- 2 years at the WW threshold, 10^8 events/exp. ➔ 2.10^3 LEP Statistics

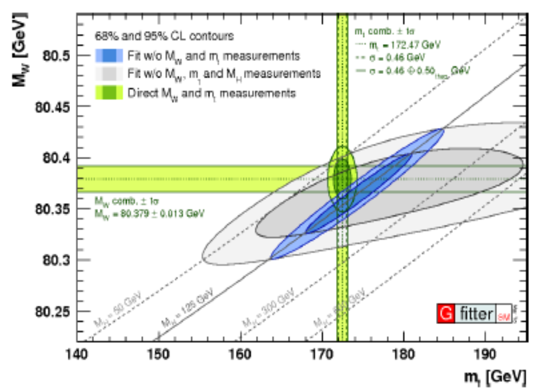


- m_Z: position of Z peak
- Beam energy measured with extraordinary precision ($\Delta\sqrt{s}\approx$100 keV) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, …)
- Beam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

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/ √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

With m_{top}, m_W and m_H fixed by measurements: the SM has nowhere to go !



Increased precision could show first hints of physics beyond the SM.

- Improve the direct determination of MW and Mtop
  - PDG 2020: MW to 12 MeV
- And the SM fit prediction for these quantities, e.g. :

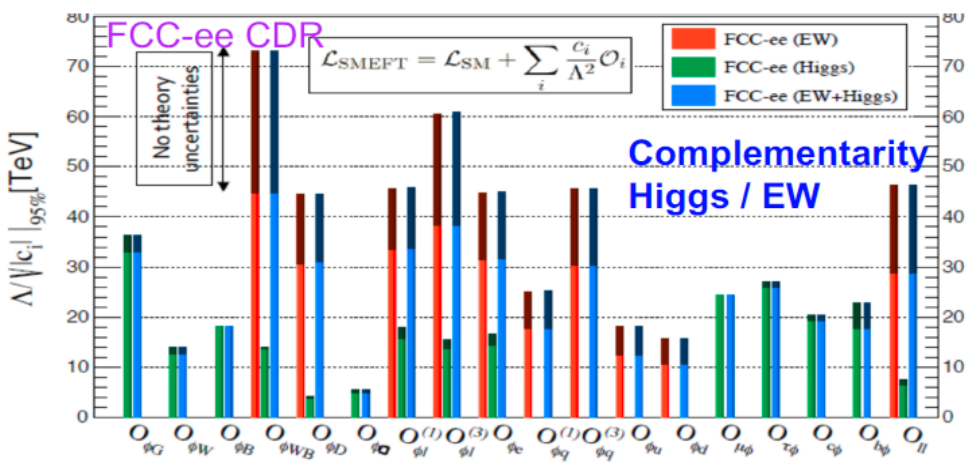
$$m_W = 80.3584 \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040 \ldots \text{ GeV} = 80.358 \pm 0.008_{total} \text{ GeV},$$

Requires improved measurements of m_{top}, m_Z, $\alpha_{QED}(m^2_Z)$, α_S… and more generally all usual EWPO included in the EW fits.

EW & QCD precision measurement examples

(*) current guess

	stat	w/ syst (*)	improvement
M_W	400 keV	500 keV	30
M_Z	4 keV	< 100 keV	> 20
Γ_Z	4 keV	< 25 keV	> 100
$\sin^2\theta_{eff}$ (τ pol)		$3\ 10^{-6}$	60
$\alpha_{QED}(m^2_Z)$	$3\ 10^{-5}$	$3\ 10^{-5}$	4 (stat. lim. !)
Rb	$3\ 10^{-7}$	$2\ 10^{-5}$	30
alphaS(m2Z)	10^{-5}	10^{-4}	30
Mtop	20 MeV	40 MeV	12
…			



- Huge statistics: very small stat errors call for very small syst uncertainties too.
  - E.g. acceptances, should be known to 10-4 – 10-5
- Goal: σ(exp syst) ≈ σ(stat)
- Work on theo. side also critical (and initiated, 1809.01830)

One key experimental handle: knowledge of √s (exquisite at circular collider with resonant depolarisation method, at Z & WW)

In terms of weakly-coupled new physics: FCC-ee precision corresponds to sensitivity on Λ_{NP} up to 70 TeV, anticipating what FCC-pp would focus on.

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Precision Top factory at 340 – 365 GeV

- Expect 1 M $t\bar{t}$ events, not so many compared to LHC, but in a clean environment and with the abilty to scan $\sqrt{s}$

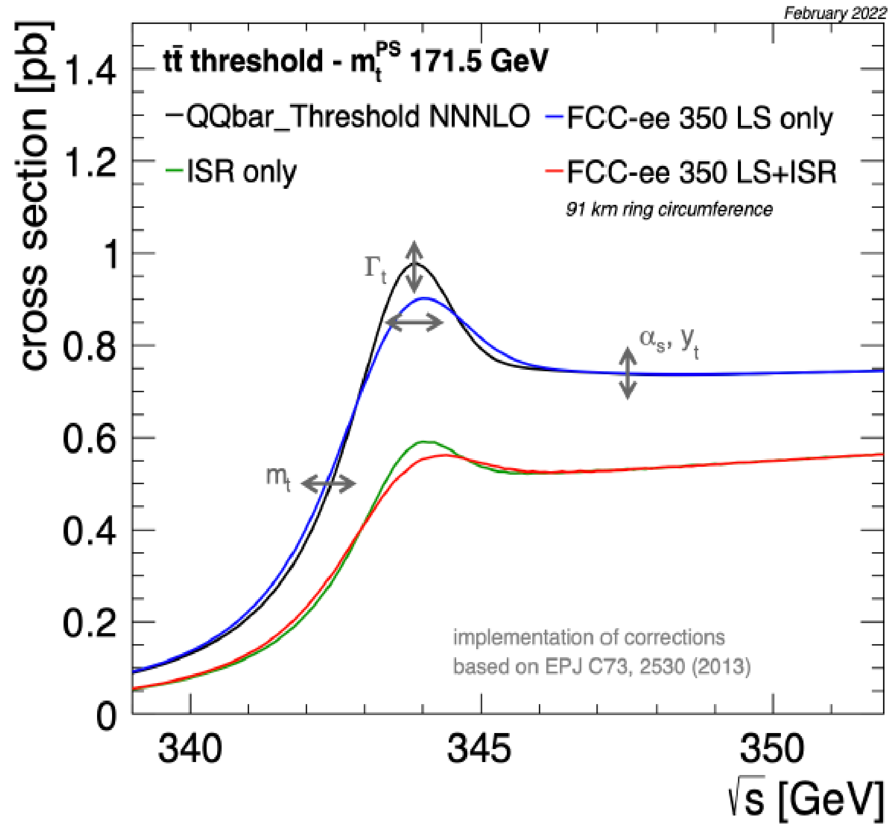
- Test of Higgs mechanism via measurement of top mass and top Yukawa coupling

  - m_t measurement at FCC-ee with clear interpretation from cross section measurement near threshold
  - Simultaneous fit for m_t and Γ_t with statistical uncertainties of 17 MeV and 45 MeV respectively
  - Scale uncertainty of 45 MeV on m_t from N^{3}LO QCD

- Extract *ttZ* coupling from $\sigma(e^+e^- \to Z/\gamma^* \to t\,\bar{t}\,)$

  → uncertainty ~10 times smaller than @HL-LHC

  → key input to extract top Yukawa coupling from FCC with reduced theory uncertainty



More on TeraZ : The Flavor/Tau Factory , QCD

Progress in flavour physics w.r.t. SuperKEKb / BELLE II requires > 10^{11} b pair events,
FCC-ee(Z): will provide ~10^{12} b pairs

Particle production (10^9)	B^0	B^-	B^0_s	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

Precision of CKM matrix elements

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%

FCC CDR Vol 1. Eur.Phys.J.C 79 (2019) 6, 474

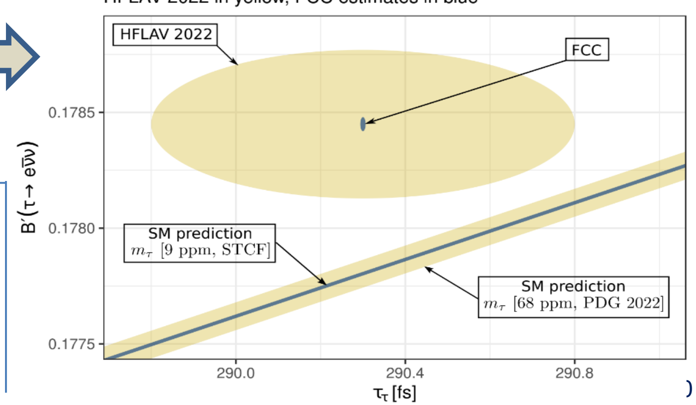
- → Push forward searches for FCNC, CP violation and mixing
- → Study rare penguin EW transitions such as b →s τ+ τ- , spectroscopy (produce b-baryons, B_s …)
- → **Test lepton universality** with **10^{11} τ decays** (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}

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

  ➔ need special detectors (PID) under study

Canonical Tau Lepton Universality test

HFLAV 2022 in yellow, FCC estimates in blue



3×10^{12} hadronic Z decay also provide precious input for QCD studies

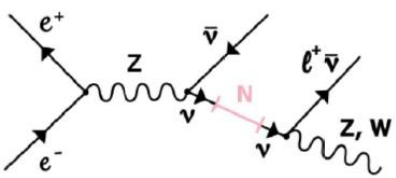
High-precision measurement of α_s(mZ) with Rℓ in Z and W decay, jet rates, τ decays
Large √s lever-arm between 30 GeV and 360 GeV, fragmentation, baryon production ….

➔ **Testing running of α_s and measuring α_s to excellent precision**

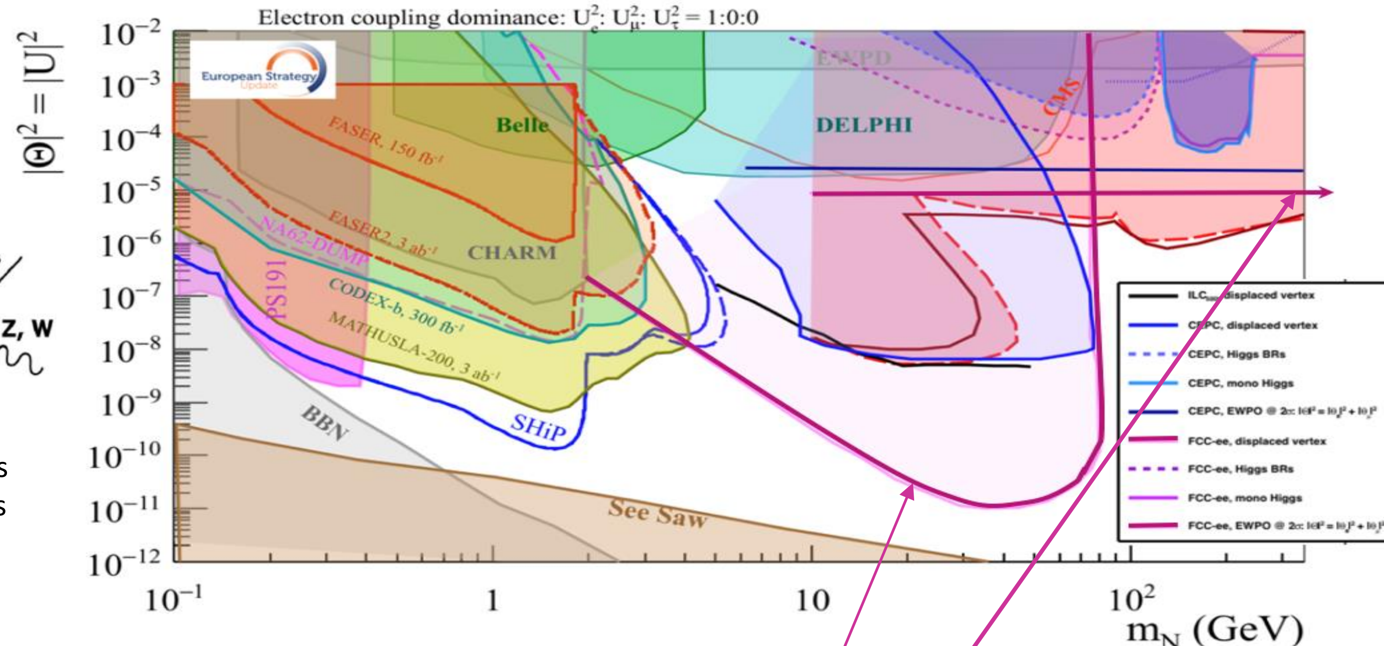
Searches for Feebly Interacting particles

- We need new physics to explain the Universe puzzles without interfering with SM radiative corrections
  ➔ Searches for new feeble interactions/particles
- Dark photons, Axion Like Particles (ALP's), sterile neutrinos, are all *feebly coupled* to SM particles

- FCC-ee can be compared to the other machines for its sensitivity to right-handed (sterile) neutrinos



These limits are relevant for Neutrino, Dark sectors and High Energy Frontiers



- Significant extension reach for observing **heavy neutrino decays** [arXiv:1910.11775] (based on 10^{12} Z)
- Large potential improvement in 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) [arXiv:2011.04725]

Summary: FCC-ee discovery potential and Highlights

FCC-ee could explore, observe and discover :

- **Explore** the 10-100 TeV energy scale (and beyond) with Precision Measurements
  20-100 fold improved precision on many EW quantities (equivalent to factor 5-10 in mass)
  m_Z, m_W, m_{top}, $\sin^2\theta_W^{eff}$, R_b, α_{QED}, α_s, Higgs and top quark couplings,
  and provide model independent Higgs measurements which can be propagated to LHC and FCC-hh

- **Observe** at the > 3σ level, the Higgs couplings to the 1st generation, the Higgs Self-coupling

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

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

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

- Many other opportunities in e.g. QCD (α_s @ 10^{-4}, fragmentations, $H \to gg$) etc….

➔ **Not only a Higgs Factory! Z, Heavy Flavour, QCD and top are also important for 'discovery potential'**

- More info at the FCC Physics in Cracow (1/2023): https://indico.cern.ch/event/1066234/
- & at the 6th Annual FCC Week in London (6/2023): https://indico.cern.ch/event/1064327/

FCC

FCC main goals until 2025, Outlook

Overall goal:

- Perform all necessary steps and studies to enable a project decision by 2026/27, 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 all required project preparatory and administrative processes with the host states
- Perform site investigations to enable Civil Engineering planning and to prepare its 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 2021-22 → detector requirements
- reach out to all 'European and International Partners'
- Establish user communities, work towards proto experiment collaboration by 2025/26
- **R&D/detector concept studies** and **physics potential:**
  - Higgs (including self-coupling and 1st generation)
  - Precision EW, top, and QCD measurements
  - Heavy Flavor Physics and Tau physics
  - LLP's detection and other BSM searches

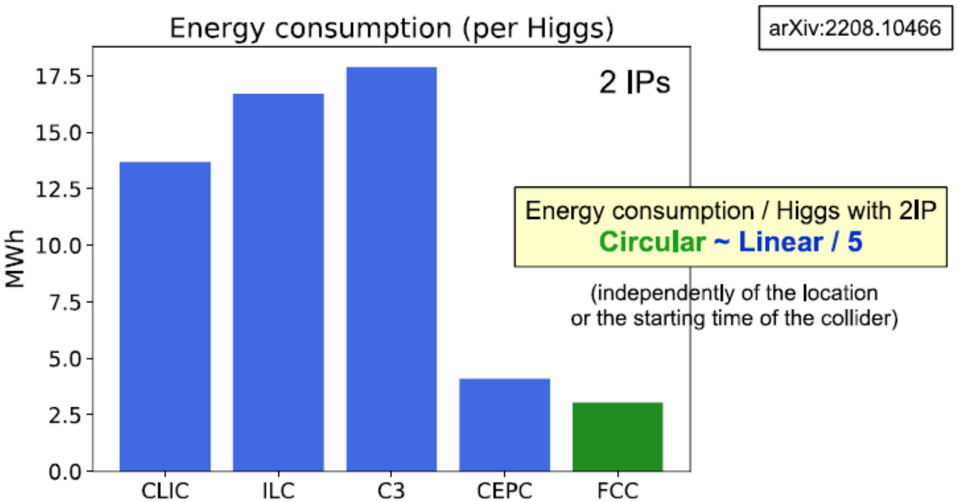
FCC, thanks also to synergies and complementarities between ee and hh machines,
offers the best approach to today's physics landscape
FCC-ee can be constructed while accomplishing the HL-LHC program

FCC

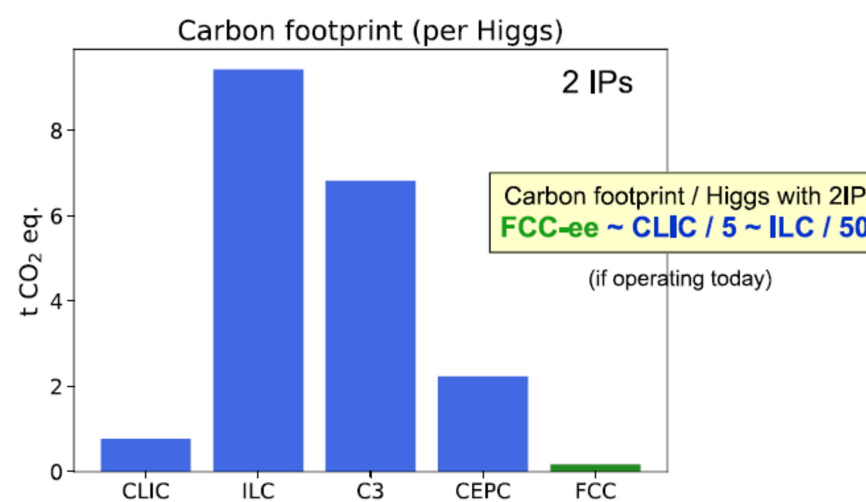
backup

Energy consumption and Carbon footprint: FCC vs. other projects

- Our first responsibility (as particle physicists) is to do the maximum of science
  - With the minimum energy consumption and the minimum environmental impact for our planet
    - Should become one of our top-level decision criteria for design, choice and optimization of a collider
- All Higgs factories have a "similar" physics outcome (ESU'20 and Snowmass'21)
  - Natural question: what is their energy consumption or carbon footprint for the same physics outcome?
    - Circular colliders have a much larger instantaneous luminosity and operate several detectors
    - FCC-ee is at CERN, where electricity is already almost carbon-free



arXiv:2208.10466



FUTURE CIRCULAR COLLIDER ee design choices & new "lowest risk" layout

Double ring e+ e- collider

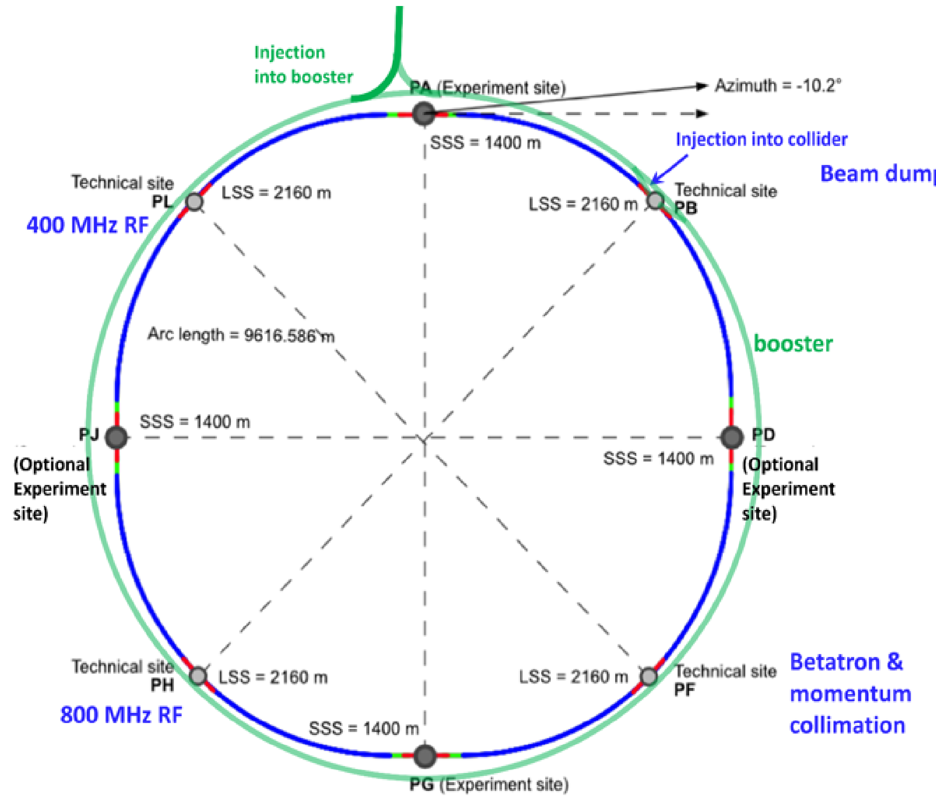
Common footprint with FCC-hh,
except around IPs

Asymmetric IR layout and optics to limit synchrotron radiation towards the detector

2 or 4 IPs, large horizontal crossing angle **30 mrad, crab-waist collision optics**
(layouts with 4 IPs under study now)

Synchrotron radiation power 50 MW/beam at all beam energies

Top-up injection scheme for high luminosity
Requires **booster synchrotron in collider tunnel**



FCC Accelerator Science & Technology
Frank Zimmermann

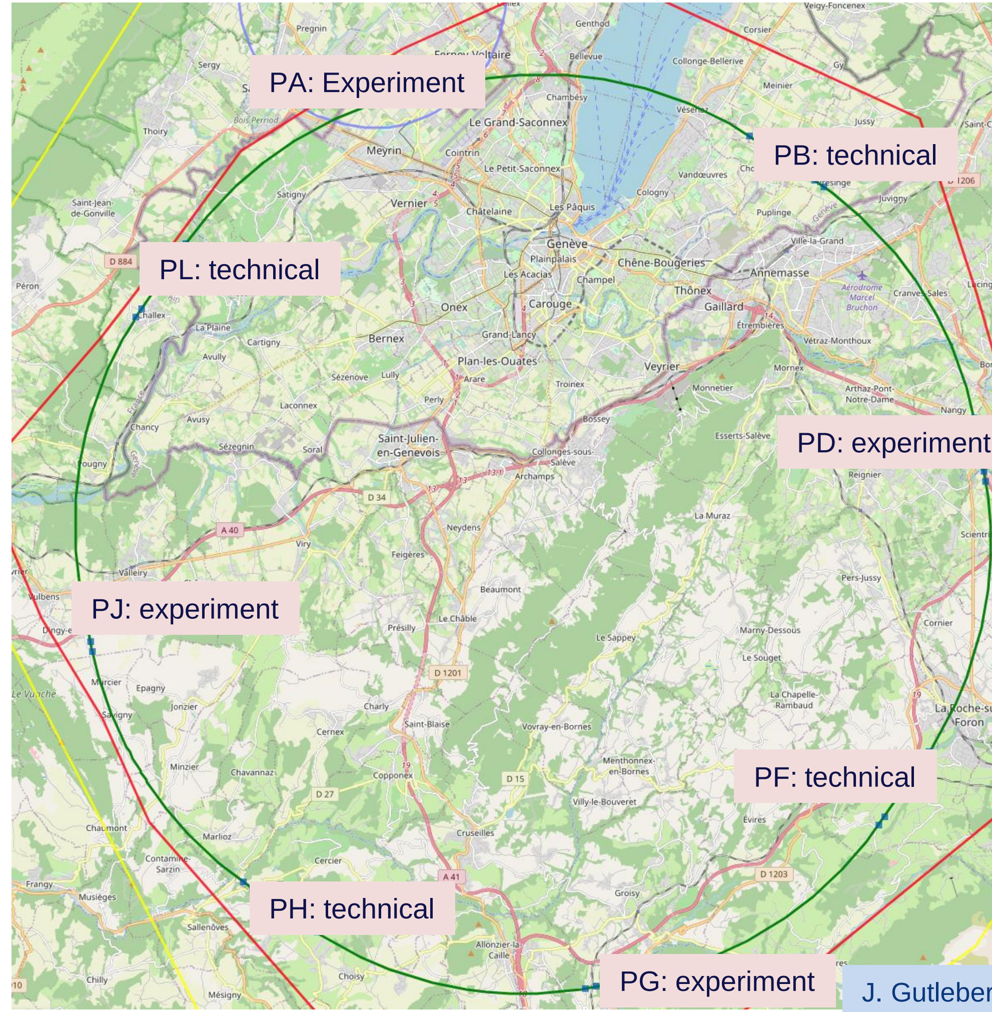
FCC : optimized placement and layout

Following extensive placement review, choice made

8-site baseline "PA31"

Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2143 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**91.1 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructure (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP
- **Exchanges with ~40 local communes in preparation**



FCC

FUTURE CIRCULAR COLLIDER — FCC feasibility study organization -

Approved by CERN Council September 2021

FCC Study Leader
M. Benedikt

Study support and coordination

study/collaboration secretariat	study support unit	EU projects	collaboration building	Communications
			E. Tsesmelis	J. Gillies (local com.

Physics, experiments and detectors P. Janot, C. Grojean	Accelerators T. Raubenheimer, F. Zimmermann	Techn. coordination techn. infrastructure K. Hanke	Host State processes and civil engineering T. Watson (1 Nov. '21)	Organisation and financing models P. Collier (interim)
physics programme M. McCullough, F. Simon	ee design K. Oide, A. Chance	Electricity distribution J.-P. Burnet	administrative processes F. Eder, J. Gutleber	project organisation model NN
detector concepts M. Dam, F Sefkow, P.Roloff	hh design M. Giovannozzi	cooling & ventilation G. Peon	placement studies J. Gutleber, V. Mertens	financing model F. Sonnemann
physics performance P. Azzi, E. Perez	technology R&D R. Losito	integration, installation, transport, logistics, JP Corso, C Colloca, C Prasse	environmental evaluation J. Gutleber	procurement strategy and rules NN
software and computing G. Ganis, C. Helsens	ee injector P. Craievich, A. Grudiev	general safety, access, radiation protection, T. Otto	tunnel, subsurface design J. Osborne	in-kind contributions NN
ee MDI M. Boscolo, M. Sullivan		Computing, controls, communication, networks D. Duellmann	surface buildings design NN	operation model P. Collier & J. Wenninger
ee energy calibration & polarization (EPOL) J. Wenninger A. Blondel		geodesy & survey H. Mainaud Durand, A. Wieser	surface sites layout and access NN	
		Cryogenics systems L.P. Delprat		
		Operation, maintenance, availability, reliability J. Nielsen		

Status of Global FCC Collaboration

Increasing international collaboration as a prerequisite for success:

links with science, research & development and **high-tech industry** will be essential to further advance and prepare the implementation of FCC

147 Institutes

30 Companies

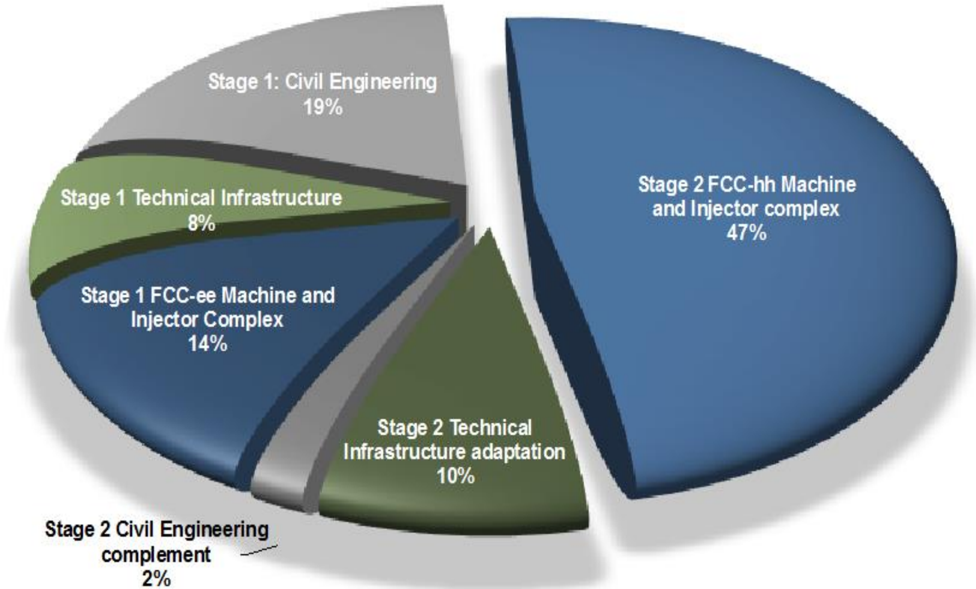
34 Countries

EC H2020

FCC Feasibility Study: 58 fully-signed previous members, 17 new members, MoU renewal of remaining CDR participants in progress

FCC-ee and FCC-INT cost estimates

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**



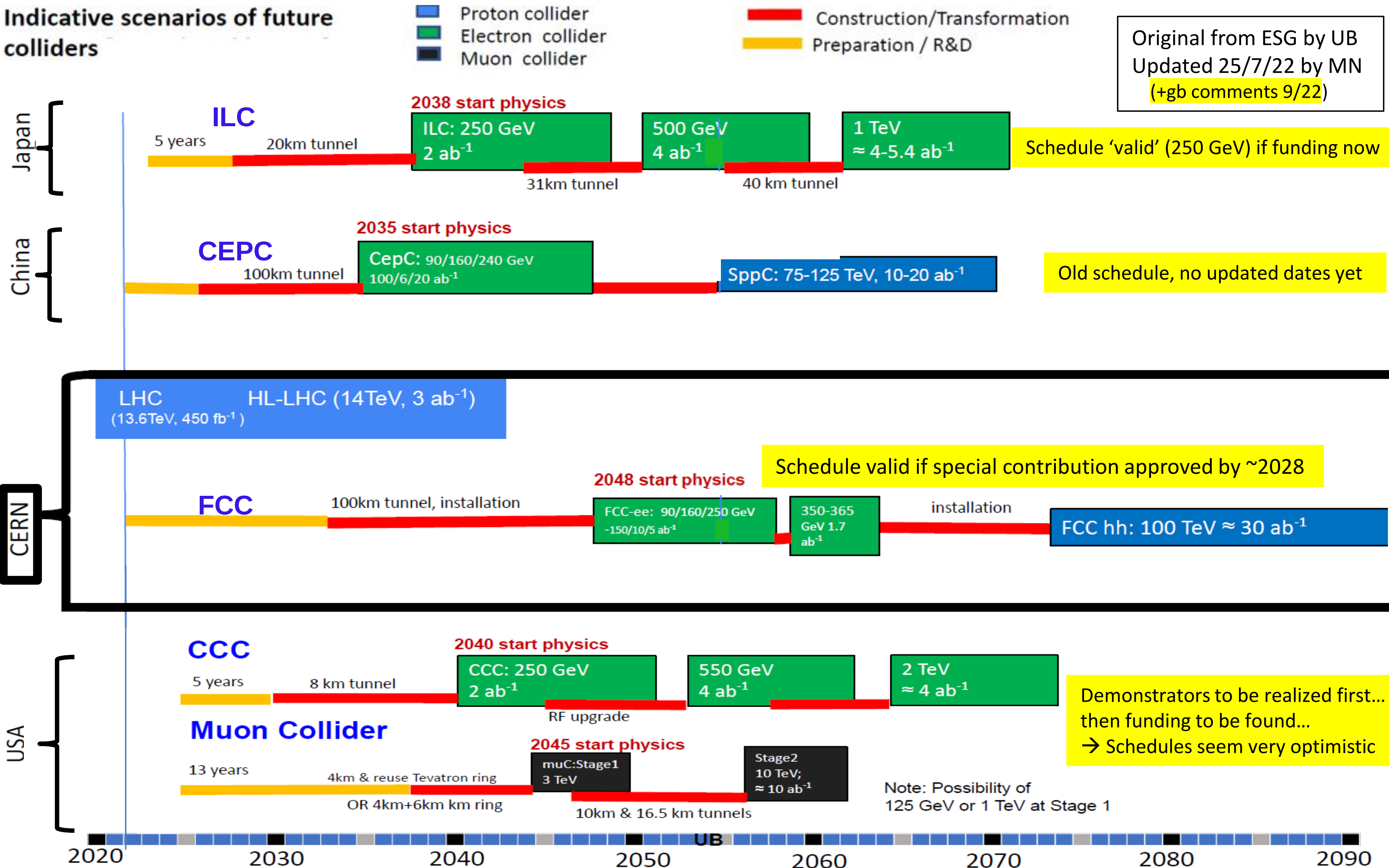
Total construction cost FCC-ee (Z, W, H) amounts to 10.5 BCHF + 1.1 BCHF (tt)

- Associated to a total project duration of ~20 years (2028 – 2048)

Need for the tunnel a special contribution of about 5 BCH.

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

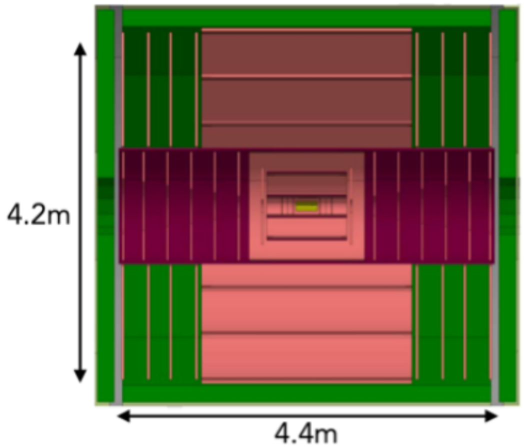
- Associated to a total project duration of ~25 years (2040 – 2065)
- (FCC-hh standalone would cost ~25 BCHF, so not building FCC-ee in a first stage would be a marginal saving)

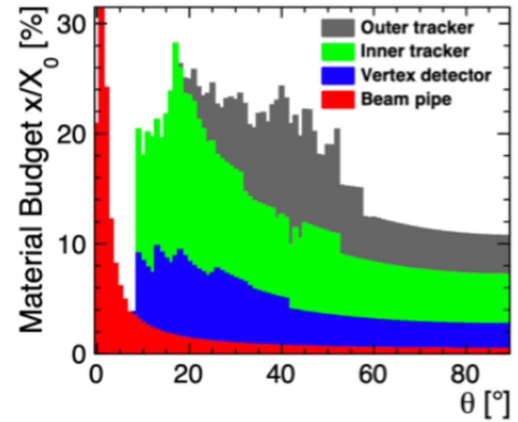

Indicative scenarios of future colliders
Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Original from ESG by UB
Updated 25/7/22 by MN
(+gb comments 9/22)
Japan
ILC
5 years
20km tunnel
2038 start physics
ILC: 250 GeV
2 ab-1
500 GeV
4 ab-1
1 TeV
≈ 4-5.4 ab-1
31km tunnel
40 km tunnel
Schedule 'valid' (250 GeV) if funding now
China
CEPC
100km tunnel
2035 start physics
CepC: 90/160/240 GeV
100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
Old schedule, no updated dates yet
CERN
LHC
(13.6TeV, 450 fb-1)
HL-LHC (14TeV, 3 ab-1)
Schedule valid if special contribution approved by ~2028
FCC
100km tunnel, installation
2048 start physics
FCC-ee: 90/160/250 GeV
-150/10/5 ab-1
350-365
GeV 1.7
ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
USA
CCC
5 years
8 km tunnel
2040 start physics
CCC: 250 GeV
2 ab-1
550 GeV
4 ab-1
2 TeV
≈ 4 ab-1
RF upgrade
Demonstrators to be realized first…
then funding to be found…
→ Schedules seem very optimistic
Muon Collider
13 years
4km & reuse Tevatron ring
OR 4km+6km km ring
2045 start physics
muC:Stage1
3 TeV
Stage2
10 TeV;
≈ 10 ab-1
10km & 16.5 km tunnels
Note: Possibility of
125 GeV or 1 TeV at Stage 1
UB
2020
2030
2040
2050
2060
2070
2080
2090

Tracking

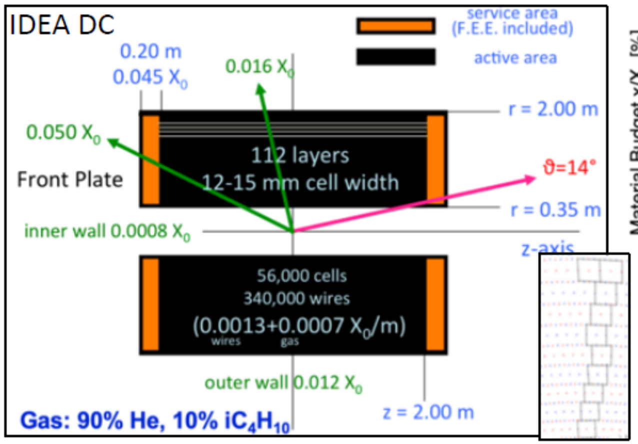
Two solutions under study

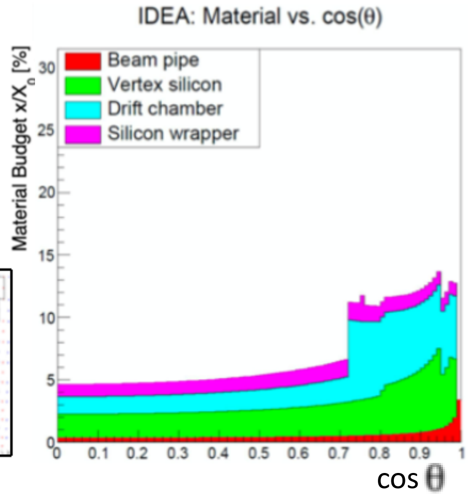
- CLD: All silicon: pixel VTX + strips tracker
  - Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
  - Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
  - Separated by support tube @ r= 675 mm (2.5% X_0)





- IDEA: Extremely transparent Drift Chamber
  - GAS: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - Tungsten wires dominant contribution
  - Full system includes Si VXT and Si "wrapper"





Calorimetry – Jet Energy Resolution

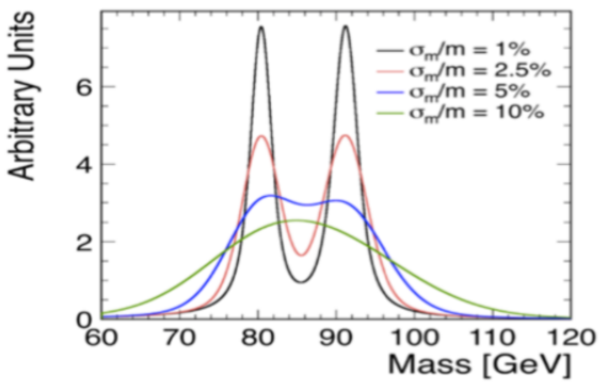
Energy coverage $\lesssim$ 180 GeV : 22 X_0, 7λ

Jet energy: $\delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}$ [GeV]

⇒ **Mass reconstruction from jet pairs**

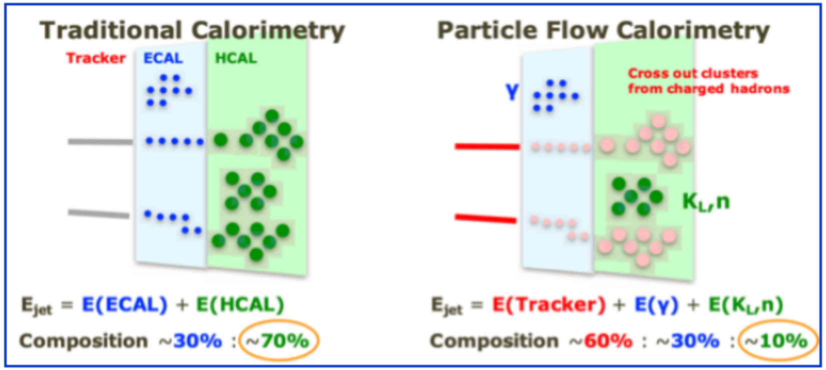
Resolution important for control of (combinatorial) backgrounds in multi-jet final states

- Separation of HZ and WW fusion contribution to ννH
- HZ → 4 jets, $t\bar{t}$ events (6 jets), etc.
- At $\delta E/E \simeq 30\% / \sqrt{E}$ [GeV], detector resolution is comparable to natural widths of W and Z bosons



To reach jet energy resolutions of ~3%, detectors employ

- **highly granular calorimetry**
- **Particle Flow Analysis techniques**



Technologies being pursued

a) **CALICE** like – extremely fine segmentation (ILC, CLIC, **CLD**)
- ECAL: W/Si or W/scint+SiPM
- HCAL: steel/scint+SiPM or steel/glass RPC

b) Parallel fiber **dual readout** calorimeter (**IDEA**)
- Fine transverse segmentation; longitudinal inf. via timing

c) **Noble Liquid** (e.g. **LAr**) ECAL + **CALICE-like** HCAL
- Fine segmentation, high stability, $\delta E_{EM}/E_{EM} \sim$ 6-9%

ILD and FCC

Ties Behnke

9.2.2023

ILD as a group got started around 2008

ILD's roots are linear colliders, ILC in particular

ILD's main objective is to develop the best possible experiment for a Higgs/ Electroweak and beyond facility

Result of recent membership confirmation:

- 58 institutes confirmed ILD membership
- Around 10 institutes as guests members

ILD has a concept of the detector, well defined with technological options where

The main components of ILD have been validated and beam-tested.

A coherent System design has been developed.

A complete and detailed Geant4 model of ILD exists and is used

Particle Flow:

The central guiding principle for the design of ILD:

- Granularity
- Hermeticity

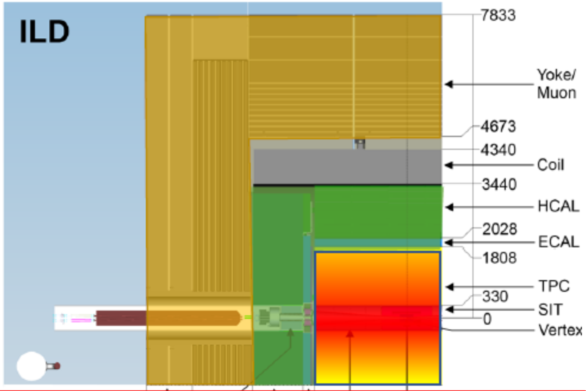
Low material inner region

- Very thin Silicon
- Large volume TPC

Particle ID is important

- PID in TPC
- Timing as additional handle

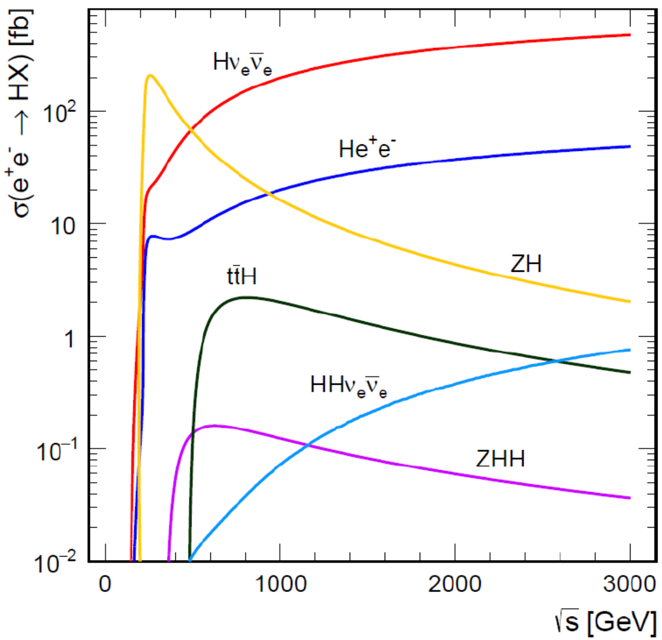
A quarter view of ILD



ILD is very interested to contribute to the studies of such detectors at linear and circular collider concepts, to develop the best possible experimental proposal for a future Higgs factory

Higgs with High Energy colliders: $ILC_{500\text{-}1000}$, $CLIC_{3000}$, 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.	±3.8*	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

*arXiv:2004.03505

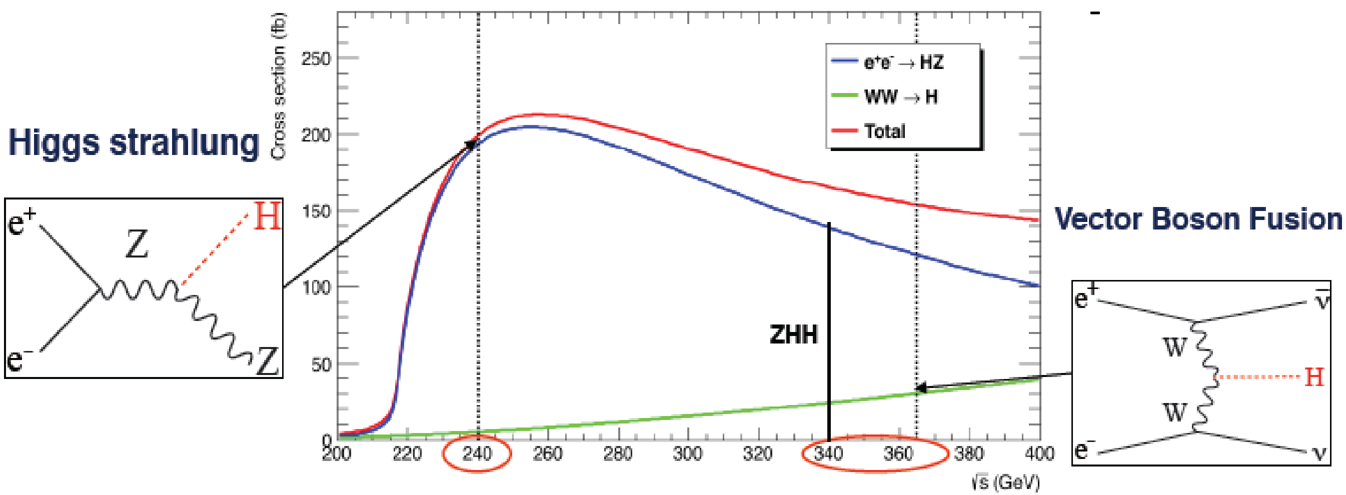
FCC-hh > 10^{10} H produced

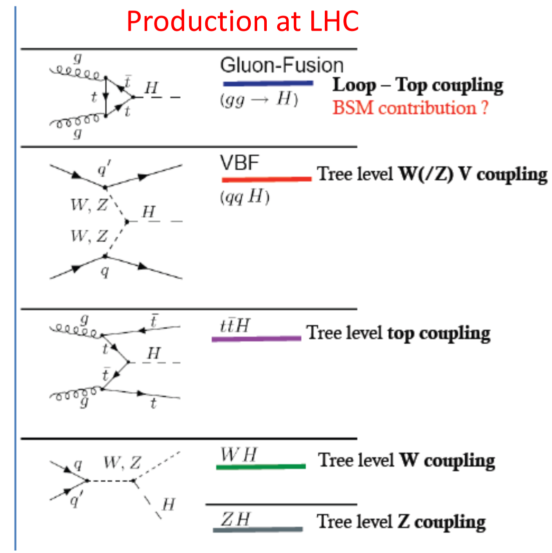
+

FCC-ee measurement of g_{HZZ}

→ g_{HHH} , $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, Br_{inv} at high precision

Higgs boson production at FCC-ee





FCC-ee as a Higgs factory:

Higgs-strahlung (e+e → ZH): event rate & Signal/Bkgd are optimal 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.

Couplings Measurements Comparison across 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

The precisions on these **FCC-ee** couplings are given for 2 IP. They will improve by ~30% with 4IP

LHC caveats:

- Measure only couplings ratios
- Many SM couplings cannot be seen at LHC (light quarks, charm, electrons)
- Couplings to gluons are measured through gg→H production cross section

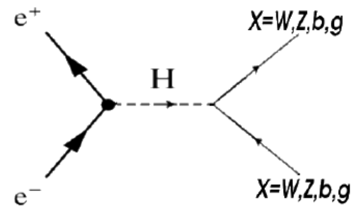
HL-LHC will produce many more Higgs than FCC-ee, hence dominate precisions for Hμμ, Hγγ, Htt

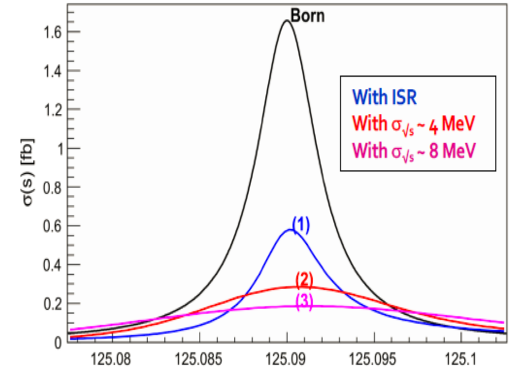
Yukawa coupling to electrons via s-channel e+e- → H production

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

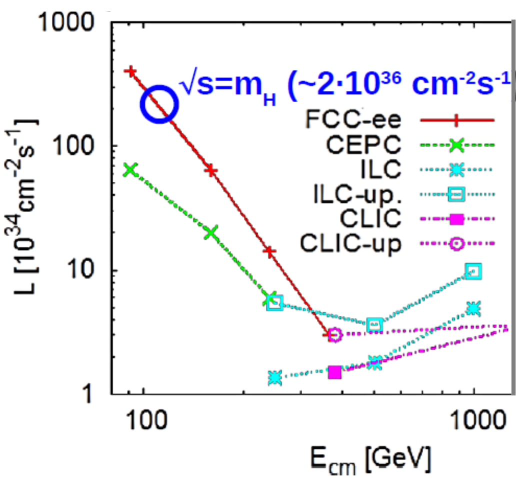
- Higgs decay to e^+e^- is unobservable: $BR(H\to e^+e^-) \propto m_e^2 \approx 5\cdot 10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny κ_e Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$:

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





- Huge luminosities available at FCC-ee:

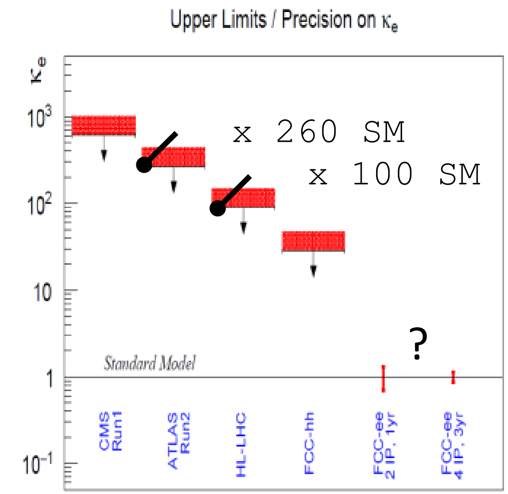


In theory, FCC-ee running at H pole-mass $L_{int} \approx 20\ ab^{-1}$/yr would produce O(30.000) H's

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: $e^+e^- \to H \to gg$
➔ jj final state



Physics of the Higgs boson at FCC-ee

Higgs measurements that are already studied at FCC-ee:

- σ(ZH) and mH from Higgs recoil, Z → ll
- Higgs couplings to b, c, g, s
- Higgs to invisible
- Higgs self-coupling from precise σ(ZH) measurements at 240 and 365 GeV
- ee → H production in s-channel at 125 GeV
- σ(*ZH) in Z → qq (starting)*

Higgs measurements which are not studied yet:

Measurement	Requirements
Direct reconstruction of mH in hadronic final states	jet angular resolution, kinematic fits, b-tag effi & purity *(Possible link with meas. of σ(ZH) in Z → qq)*
Γ(H) • H → ZZ • ZH(WW), ZH(bb), $\nu\nu$H(bb)	• Lepton ID efficiencies; jet clustering algorithms, jet directions, kinematic fits • Visible and missing mass resolutions *[expression of interest, but many channels]*
HZγ coupling (production and decay)	photon identification, energy and angular scale
Rare decays: H → $\gamma\gamma$ and H → μμ (unlikely to do better than HL-LHC..)	Photon ID and resolution, track resolution
H → $\tau\tau$ and CP studies	Tau reconstruction, Pi0 id

FCC

Uncertainties in EWPO

Statistical opportunities | Systematics challenges

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	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
$N_\nu(\times 10^3)$	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
$N_\nu(\times 10^3)$	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
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

Systematics on the Electroweak Precision Observables in the table are preliminary and often largely dominant

We use the statistical errors (after 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 and additional theoretical calculations

We are concentrating now 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)

FCC

EW measurements to be studied in detail:

	Measurement	Requirements
Z peak	Total width of the Z	scale (magnetic field) stability
Z peak	Rb, Rc, (AFB)	Flavour tagging, acceptance, QCD corrections
Z peak	Ratio Rl = Gamma_had / Gamma_l	Geometrical acceptance for lepton pairs
Z peak	Tau polarisation	ECAL granularity
Z peak	AFB (muons)	QED corrections
Z peak	Luminosity from diphoton events	e/gamma separation, gamma acceptance
WW threshold	Coupling of Z to nu_e	Photon energy resolution, acceptance, track eff
WW threshold	$\sigma(ee \to WW)$ and MW (threshold scan ; direct reco also above threshold)	$\sqrt{s}$ determination, bckgd control; angles, kinem. fits
WW threshold	Vcb via W -> cb	Flavour tagging
WW threshold	W leptonic BRs	Lepton ID, acceptance
WW threshold	Meas of $\sqrt{s}$ via radiative return	lepton and jet angular resolutions, acceptance
ttbar	Top properties from threshold scan	Jet reco, b-tagging, kine fits
ttbar	EW couplings of the top	Jet reco, b-tagging, kine fits

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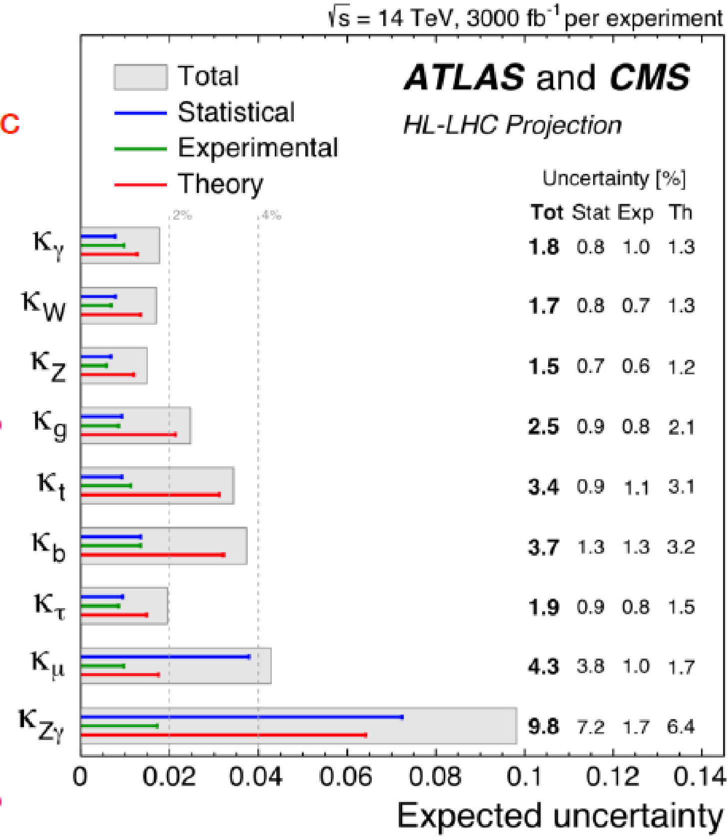
Flavour physics measurements to be studied in detail

	Measurement	Requirements
Z peak	CP violation in Bs → ΦΦ	PID, vertex, track resolution
	B0 → π0π0 (→ eeγ)	Low energy γ 's in jets (ECAL resolution and granularity)
	Bs → τ τ	Vertexing
	Meas of γ from B+ → DK+	Ks reconstruction
	τ → 3μ, τ → μγ	resolutions
	τ lifetime	Alignment, scale of vertex detector,
	τ BRs	Lepton ID, PID, e/pi separation
	τ mass	Track reco & resolution (in multi-track collimated environment)
	Charm physics	
	Masses, spectroscopy, exotics…	
WW	EW parameters, exclusive modes (Vcb, etc)	Flavour tagging

Higgs @ (HL)-LHC

Credit: M. Kado '22

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



TH Uncertainties dominant (assumed to be 1/2 of Run 2)