November 8th, 2024

The Future Circular Collider (FCC) Feasibility Study
Physics, Experiments and Detectors Status

Gregorio Bernardi
APC Paris, CNRS/IN2P3
gregorio@in2p3.fr

With many thanks to all FCC colleagues

The FCC integrated program (FCC-INT) at CERN goes well beyond the successful LEP – LHC (1976-2041) program

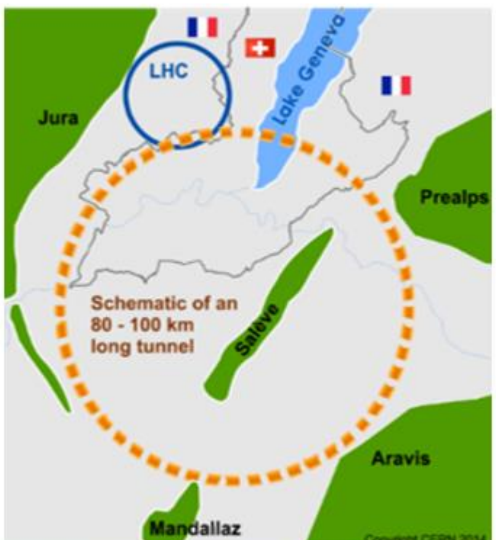
Comprehensive cost-effective program maximizing physics opportunities

- Stage 1: FCC-ee (Z, WW, H, tt, m_H?) as best Higgs, EW, Heavy Flavour and top factory at the highest luminosities
- Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with heavy ions and eh options

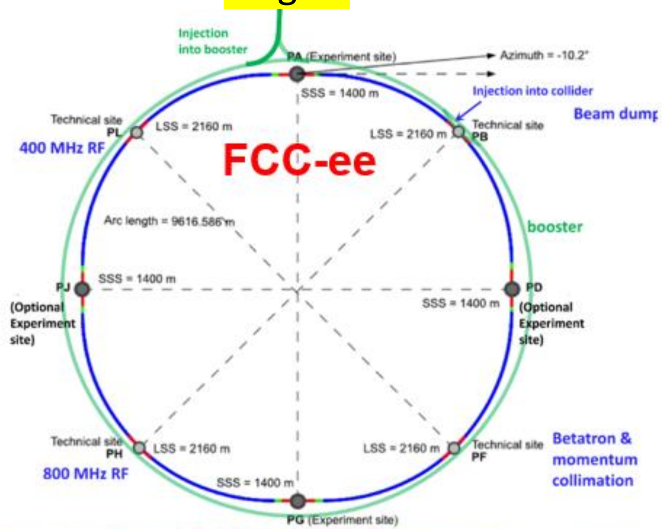
Complementary physics

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

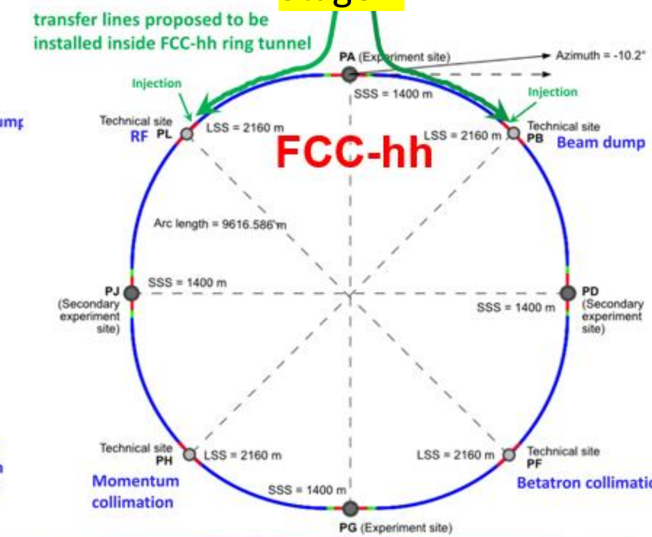
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.



Stage 1



Stage 2



2020 - 2040 | 2045 - 2060 | 2065 - 2090

Feasibility Study Report for March 2025

Structure: Three Volumes

- ***Vol. 1:*** *Physics, Experiments and Detectors (~200 pages)*
- ***Vol. 2:*** *Accelerators, Technical Infrastructures, Safety Concepts (~400 pages)*
- ***Vol. 3:*** *Civil Engineering, Implementation & Sustainability (~200 pages)*
- **Executive Summary of the FCC Feasibility Study: ~40 pages**

Input for Update of European Strategy for Particle Physics

to be prepared with Overleaf & published by EPJ (Springer-Nature) – FCCIS members

In addition:

a. **Documentation on Cost Estimate – Funding Models**

b. **Environmental Report**

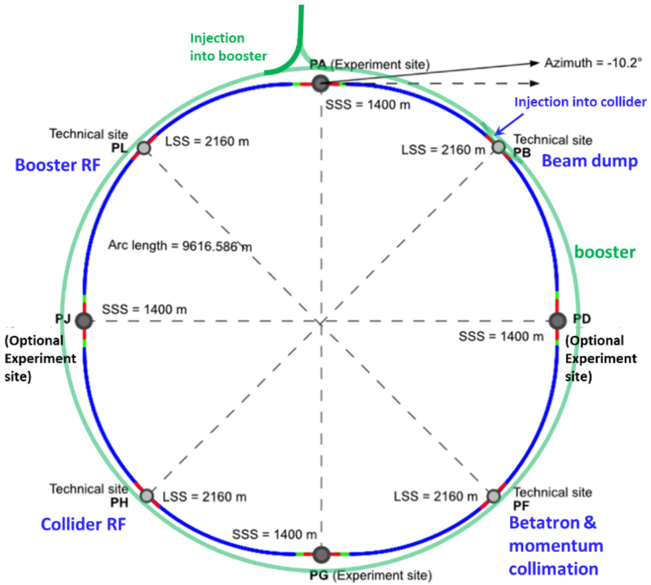
3

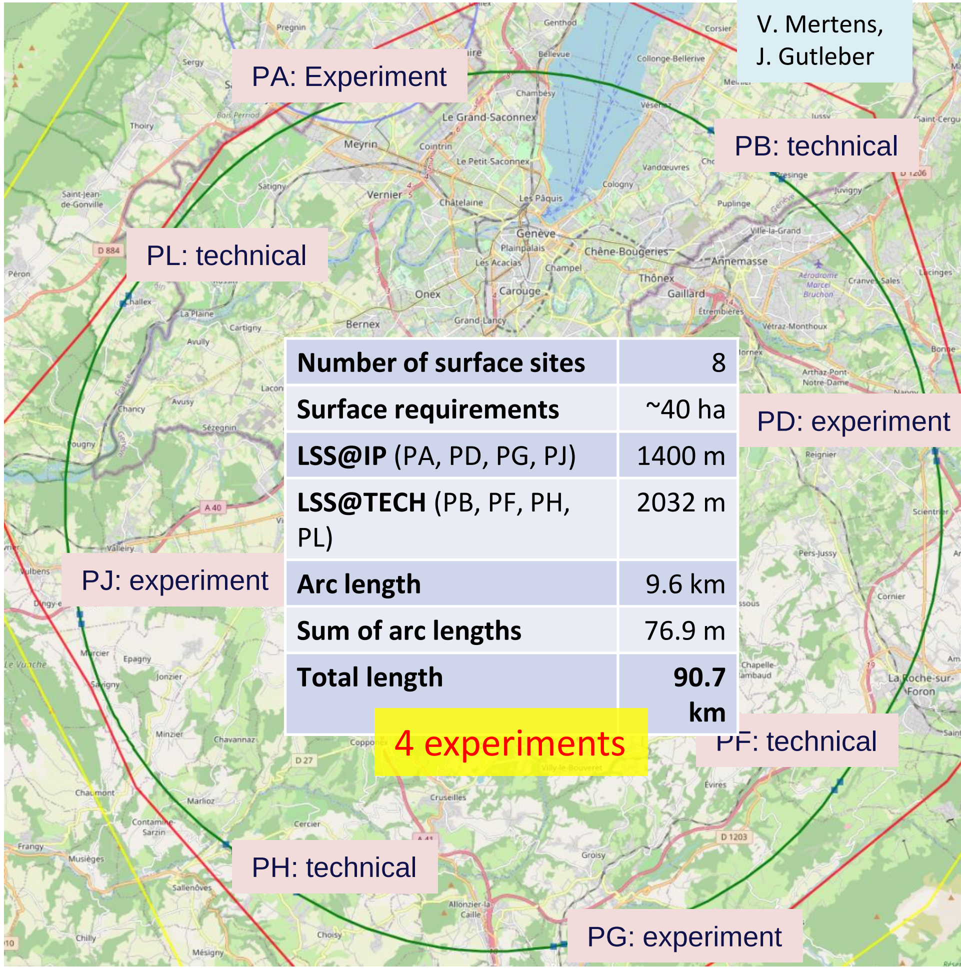
Reference layout and implementation: PA31 - 90.7 km

Layout chosen out of ~ 100 initial variants, based on **geology** and **surface constraints** (land availability, access to roads, etc.), **environment,** (protected zones), **infrastructure** (water, electricity, transport), **machine performance** etc.

"Avoid-reduce-compensate" principle of EU and French regulations

Overall lowest-risk baseline: 90.7 km ring, 8 surface points, 4-fold symmetry

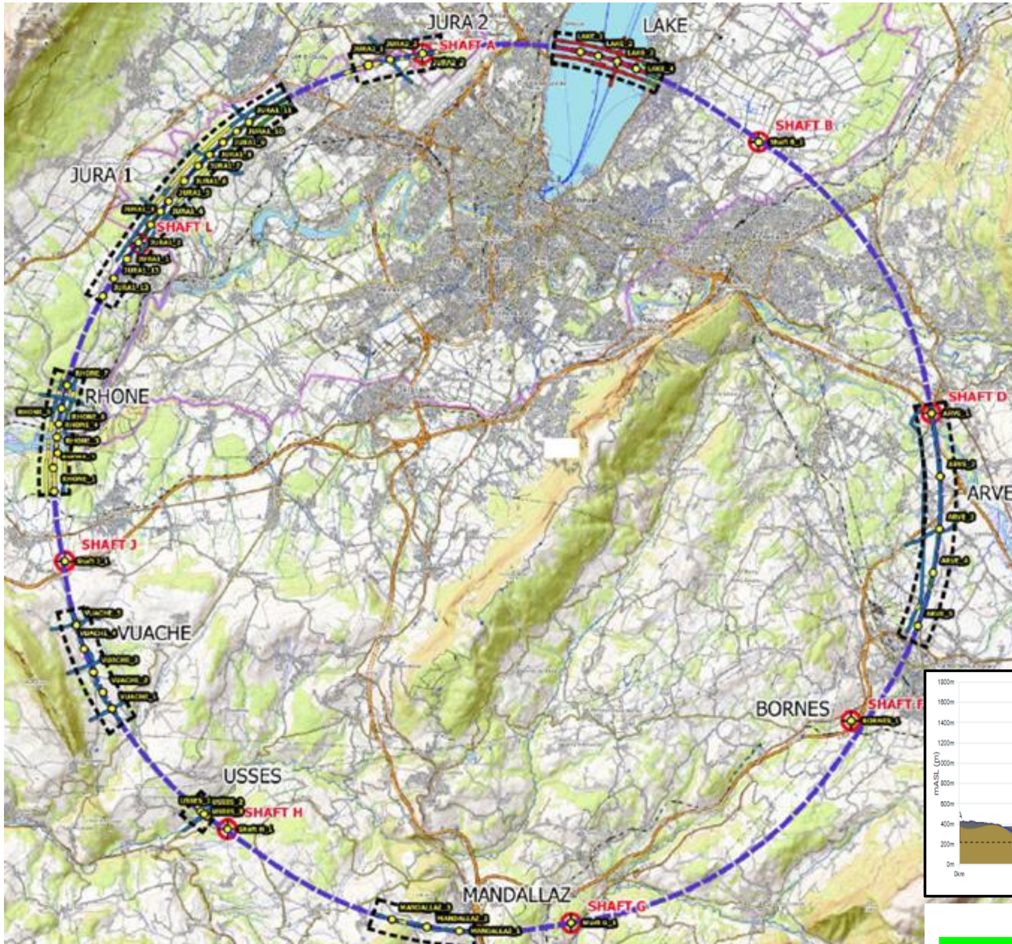




Number of surface sites	8
Surface requirements	~40 ha
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.7 km**

FCC

First series of site investigations



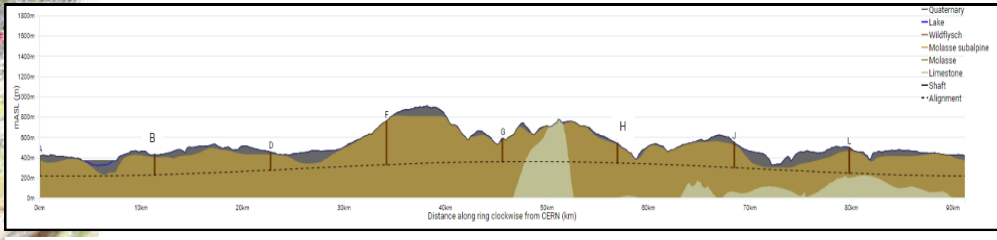
Site investigations to identify exact location of geological interfaces:

- Molasse layer vs moraines/limestone
- ~30 drillings and ~90 km seismic lines

→ **Vertical position and inclination of tunnel**

Sondage A89 (2007) incliné de 45° de 125 ml (surface plateforme estimée : 12 x 12 m soit environ 150 m²)

example of drilling works on a lake the lake



Status of site investigations – drillings:

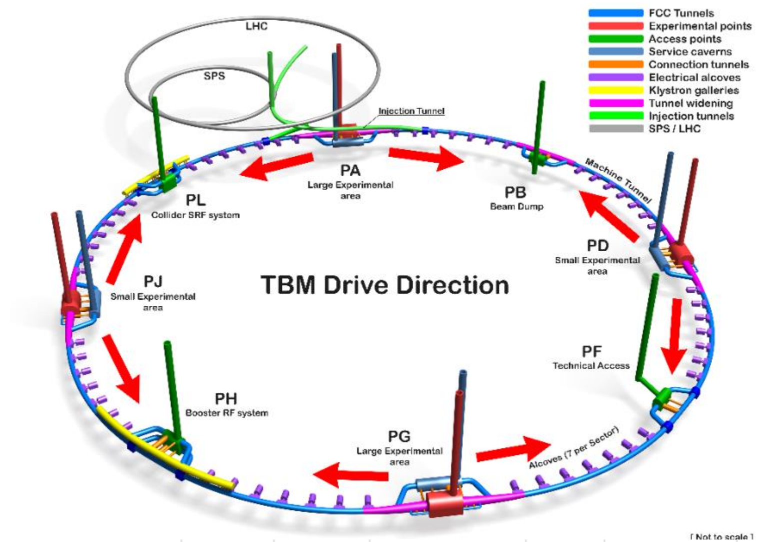
Drilling for first borehole has commenced on 14/10/2024

The drilling (USSES 2) is within the commune of Marlioz

The drill site is located within the storage yard of a private compa

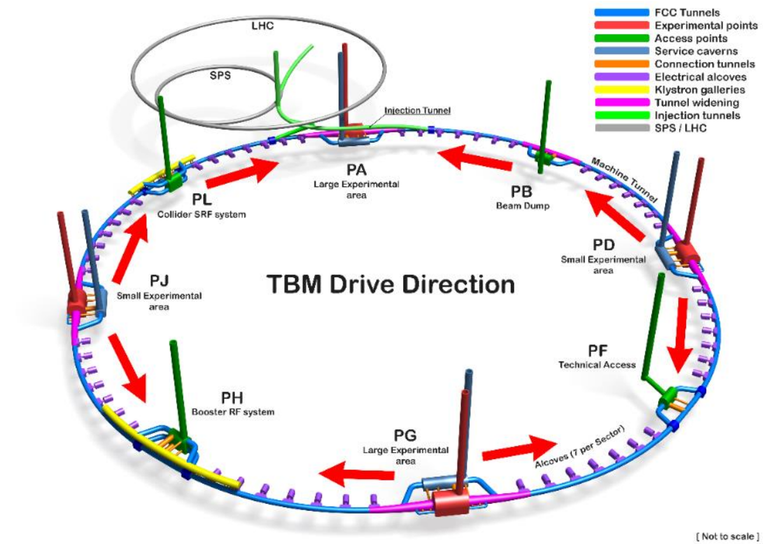
Studies on excavation strategy and material quantities

2 TBMs from each experimental point



	Limestone (m3)	Molasse (m3)	Moraine (m3)	Total (*in-situ*) (m3)	Total (*Bulk factor 1.3*) (m3)	%	Start Excavation	End Excavation
PA	-	1,315,336	62,721	1,378,058	1,791,475	22%	Jan-33	Jun-38
PB	-	137,379	10,473	147,852	192,207	2%	Jan-33	Jul-35
PD	-	1,248,824	24,925	1,273,749	1,655,874	20%	Jan-33	Jun-37
PF	-	165,213	-	165,213	214,777	3%	Jan-33	Apr-35
PG	141,175	1,193,094	30,829	1,365,098	1,774,628	22%	Jan-33	Jun-38
PH	-	304,083	7,482	311,565	405,034	5%	Jan-33	Dec-35
PJ	-	1,258,608	29,910	1,288,518	1,675,073	20%	Jan-33	Sep-37
PL	-	227,088	13,468	240,556	312,723	4%	Jan-33	Dec-35
Inj	-	122,329	-	122,329	159,028	2%	Jan-33	Jun-36
Total	**141,175**	**5,971,954**	**179,808**	**6,292,937**	**8,180,819**	**100%**		

Alternative with no TBMs from PA



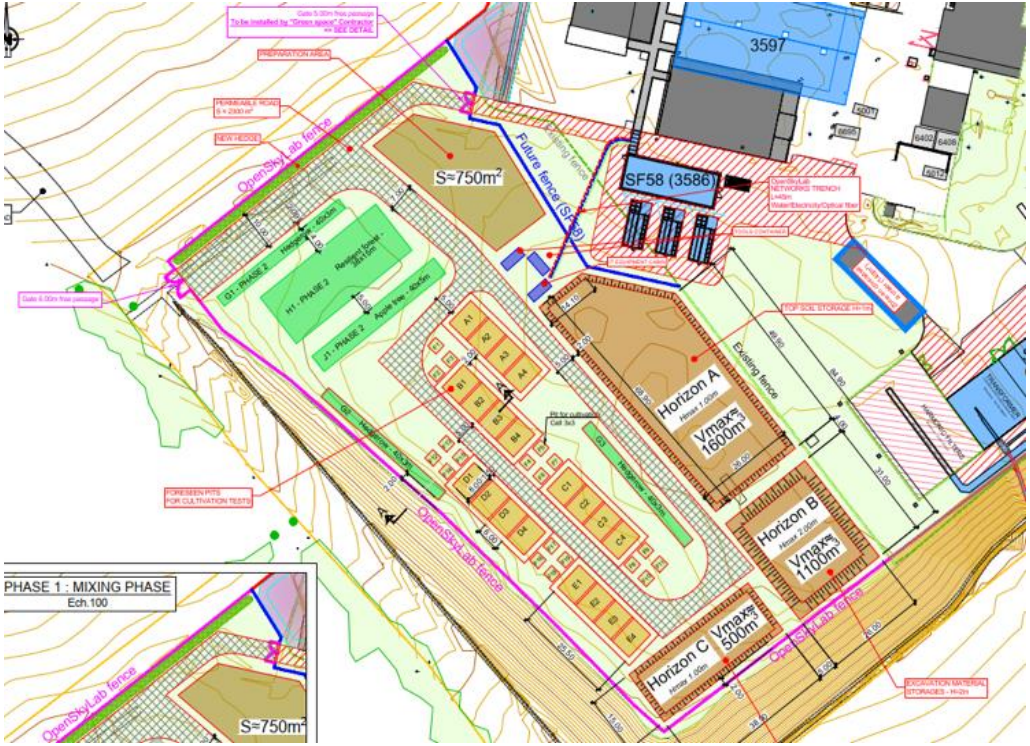
	Limestone (m3)	Molasse (m3)	Moraine (m3)	Total (*in-situ*) (m3)	Total (*Bulk factor 1.3*) (m3)	%	Start Excavation	End Excavation
PA	-	562,457	62,721	625,178	812,731	10%	Jan-33	Jun-38
PB	-	499,592	10,473	510,066	663,085	8%	Jan-33	Jul-35
PD	-	1,248,824	24,925	1,273,749	1,655,874	20%	Jan-33	Jun-37
PF	-	165,213	-	165,213	214,777	3%	Jan-33	Apr-35
PG	141,175	1,193,094	30,829	1,365,098	1,774,628	22%	Jan-33	Jun-38
PH	-	304,083	7,482	311,565	405,034	5%	Jan-33	Dec-35
PJ	-	1,258,608	29,910	1,288,518	1,675,073	20%	Jan-33	Sep-37
PL	-	617,754	13,468	631,222	820,589	10%	Jan-33	Dec-35
Inj	-	122,329	-	122,329	159,028	2%	Jan-33	Jun-36
Total	**141,175**	**5,971,954**	**179,808**	**6,292,937**	**8,180,819**	**100%**		

Studies of environmental aspects ongoing

- **Studies of relevant environmental aspects over 18 months (> 4 seasons to see full cycle) with a consortium of specialized companies**
- **Necessary inventory for the “Avoid-reduce-compensate” approach and costing (compensation measures)**
- **Input for surface site designs, installation and operation aspects**
- **Pre-requisite for the required initial state report, before an environmental impact assessment**
- **Exhaustive list of topics covered:**
  - Topography, geology, hydrogeology, surface water, natural risks, urbanistic planning, fauna & flora survey, habitats and wetland analysis, soil quality and pollution, noise, light, radiation, technological risks, demography, economic activities, landscape and visibility, patrimony
- **Central management of all data in an “Environmental Information System” to be able to document the evolutions of the territory, the civil construction designs and the technical infrastructure development integrated with classical “Geographical Information System”**

Development of excavation material re-use opportunities OpenSkyLab: academic and industrial collaboration @LHC P5 CMS

- **Transformation of Molasse (FCC ~8 Mm^3 volume) into fertile soil for agricultural and other uses**
- **Materials: Molasse from the HL-LHC construction**
- **Duration: 4+ years (2024 -)**
- **Trials with 5 000 t molasse**
  - Soil fertilisation process (micro-organisms, mixing with fertile soil, etc.)
  - Development of ferilisation mix products
  - Development of quality managed processes
  - Experimental phase with scientific protocol and field monitoring and control system support



Preparatory phase planning - authorisations and CE

To start the excavation of the first shafts in 2033, a significant amount of preparatory work is required. An initial consideration of these preparatory works including scheduling and resource aspects has been made:

2025-2026	**Permits and authorization for complementary site investigations**
	Tendering for environmental impact and authorisation processes contract, tendering for subsurface investigations
2027-28	**Complementary subsurface investigations**
	Tendering for CE consultants, environmental impact studies, public concertation
2028	**Project approval**
	Award of CE consultant contracts
2029-30	**Tender design**
	Preparing calls for tenders for CE construction,
	Project authorisations in France and Switzerland obtained
2031 mid 2032	**Construction design, Tendering for construction**
mid 2032	**Award of CE construction contracts**
	Preparation of site (road access, electricity, water…)
2033	**Ground breaking**

FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11
	4 years 5 x 10^{12} Z LEP x 10^5	2 years > 10^8 WW LEP x 10^4	3 years 2 x 10^6 H	5 years 2 x 10^6 tt pairs

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam.
- Independent vacuum systems for electrons and positrons
- full energy booster ring with top-up injection, collider permanent in collision mode

- ❑ x 10-50 improvements on all EW observables
- ❑ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ❑ x10 Belle II statistics for b, c, τ
- ❑ indirect discovery potential up to ~ 70 TeV
- ❑ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

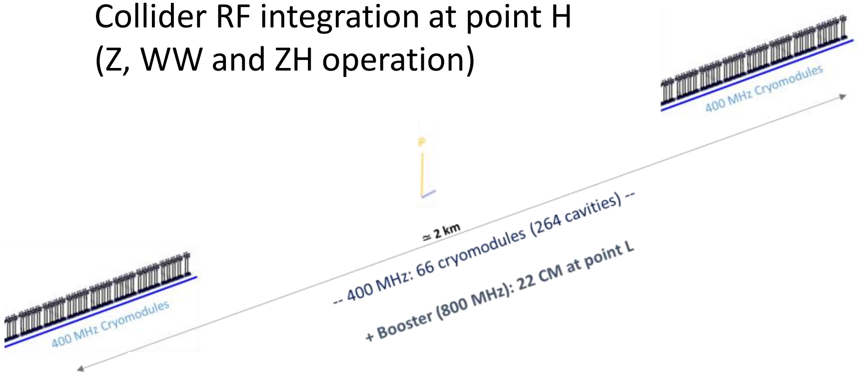
Optimisation for operation: 400 MHz SRF and beam switchyard

Beam switching between (Z, W) and ZH operation

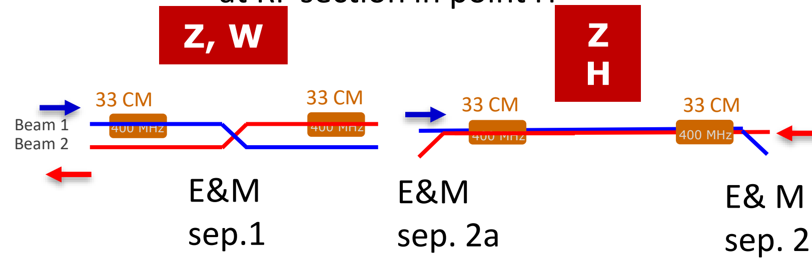
- 2-cell 400 MHz cavities for all three working points, identical configuration
- ES separators + magnetic field for switching beams
- Allows quasi "instantaneous" switching between Z, W, ZH

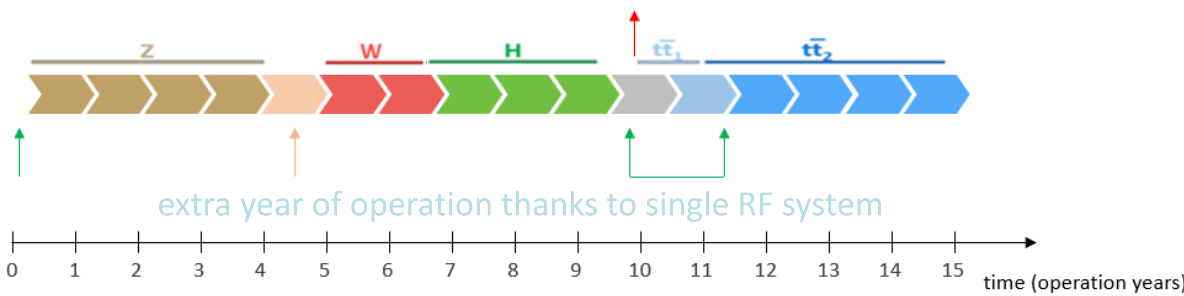
	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.08
W	80	135	1
H	120	26.7	2.08
ttb	182.5	5	11.67

Collider RF integration at point H
(Z, WW and ZH operation)



Beam crossing and combination at RF section in point H

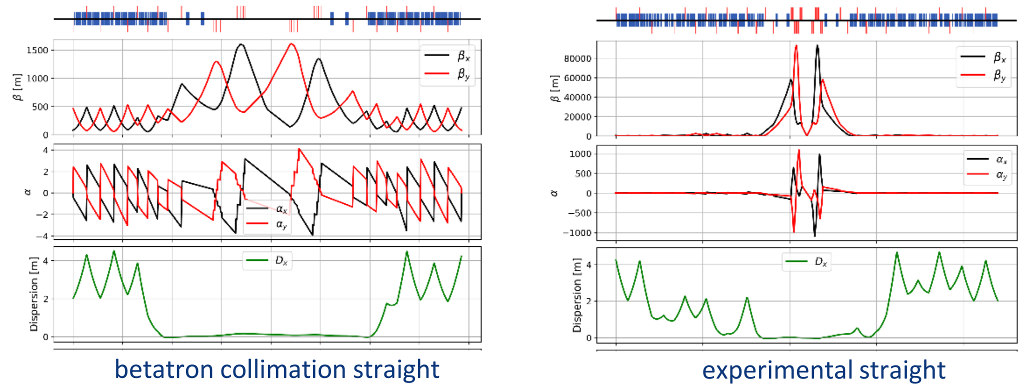




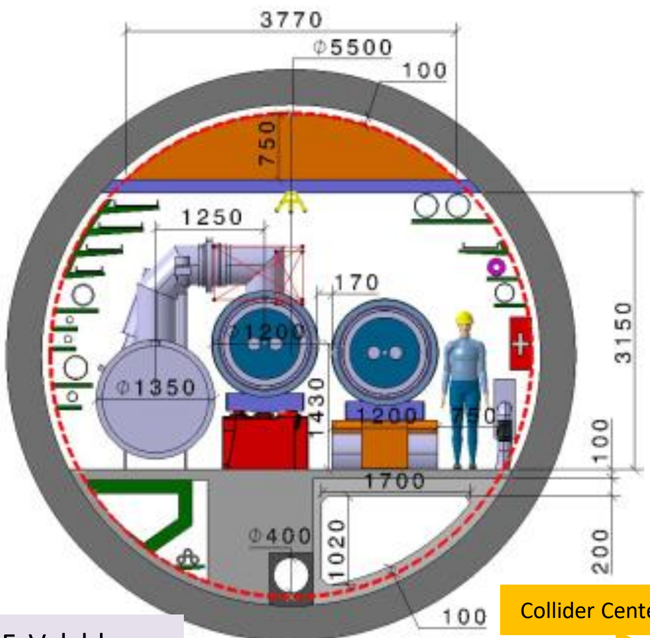
Key activities on FCC-hh: cryo magnet system, optics design

Optics design activities:

- adaptation to new layout and geometry
- shrink β collimation & extraction by ~30%
- optics optimisation (filling factor etc.)



M. Giovannozzi. G. Perez, T. Risselada



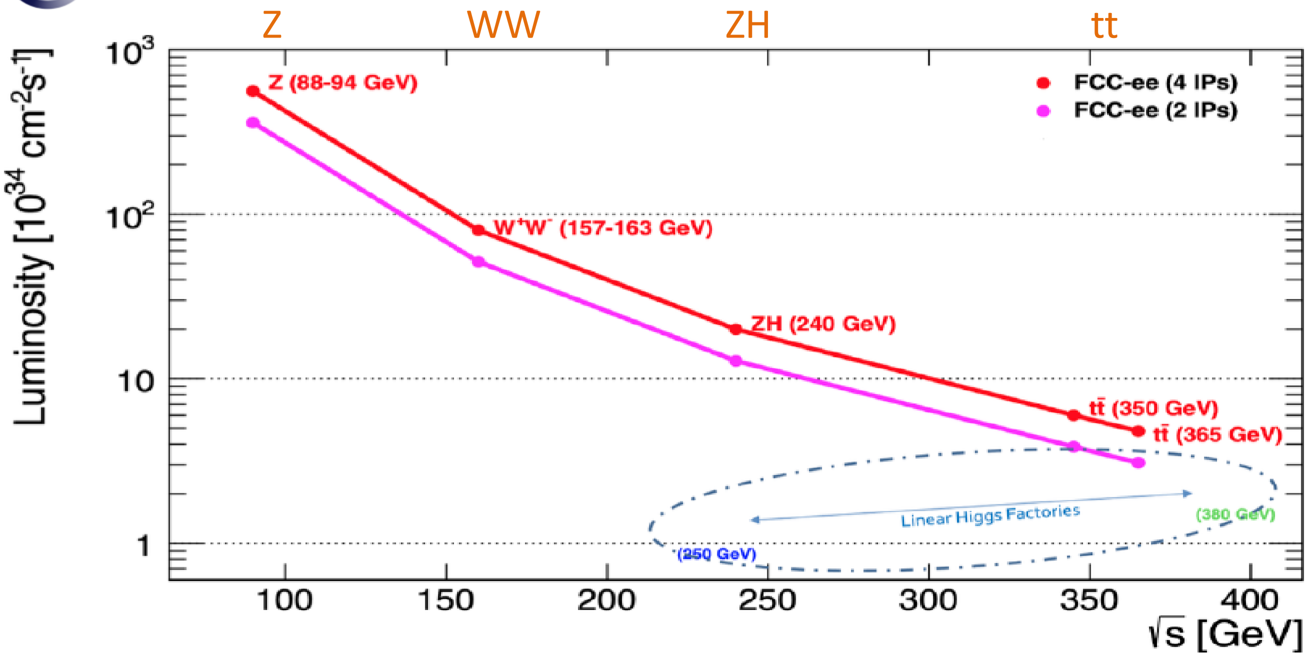
F. Valchkova

Collider Center

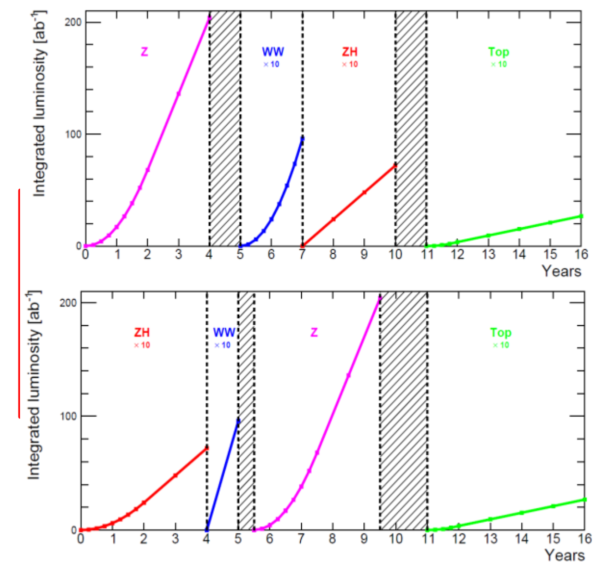
High-field cryo-magnet system design

- Conceptual study of cryogenics concept and temperature layout for LTS and HTS based magnets, in view of electrical consumption.
- Update of integration study for the ongoing HFM designs and scaling to preliminary HTS design.
  → **Confirmation of tunnel diameter!**
- HFM R&D (LTS and HTS) on technology and magnet design, aiming also at bridging the TRL gap between HTS and Nb_3Sn.

FCC-ee run plan



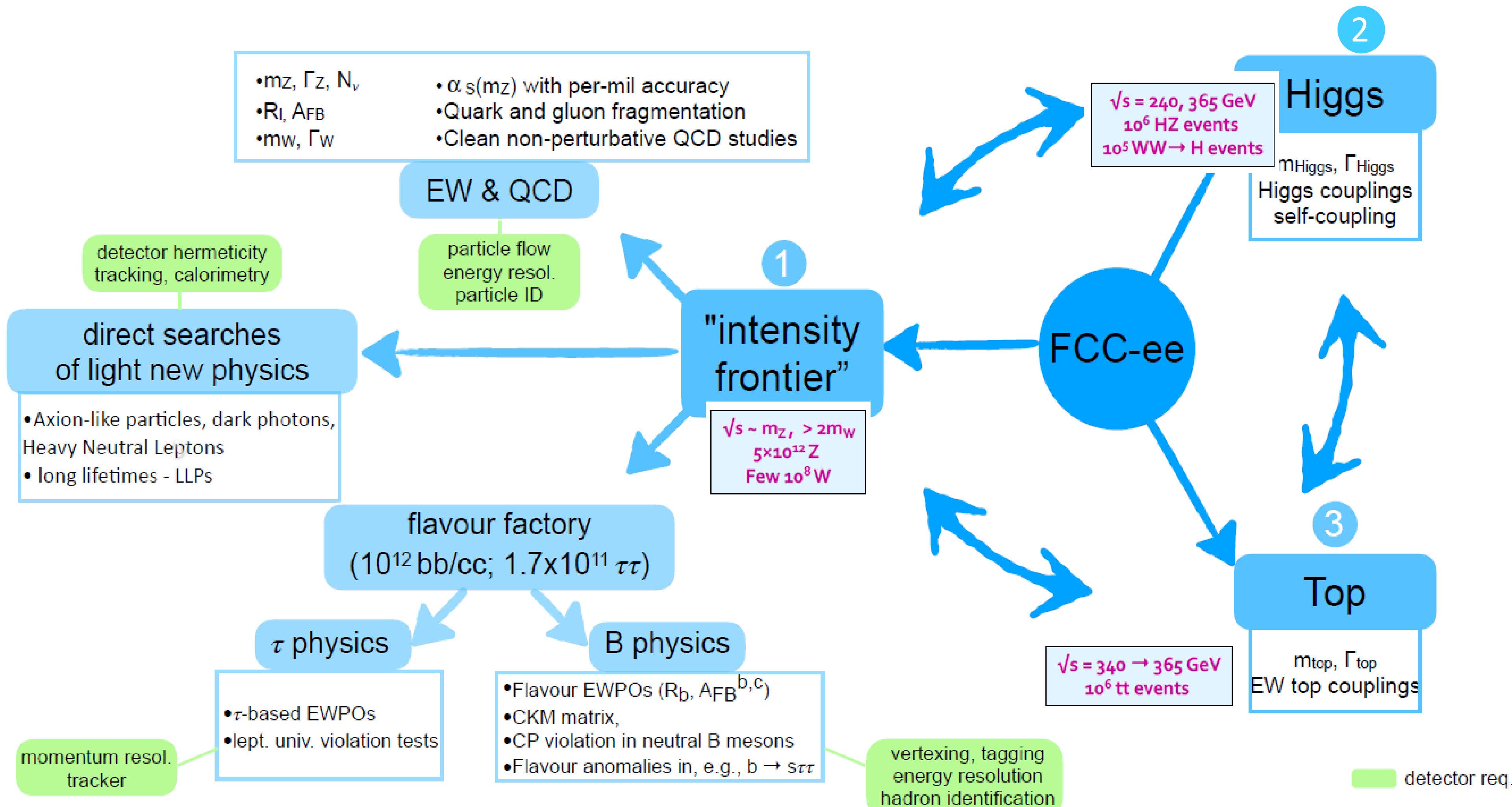
Examples of two running scenarios



Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	0	3	1	4
Number of events	6×10^{12} Z		2.4×10^8 WW		1.45×10^6 ZH + 45k WW → H	1.9×10^6 $t\bar{t}$ +330k ZH +80k WW → H	

+ possible 5 years Run at the H pole (125 GeV) to access the Hee Yukawa coupling

at Circular Colliders ➔ Rich e^+e^- Physics Program …



FCC

…plus an excellent hh program soon afterwards

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

Physics of the Higgs boson at FCC-ee

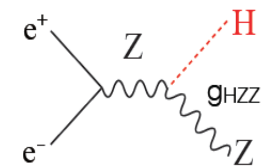
Baseline (4IP): at 240 and 365 GeV, collect in total 2M ZH events and 0.2M WW→H events

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

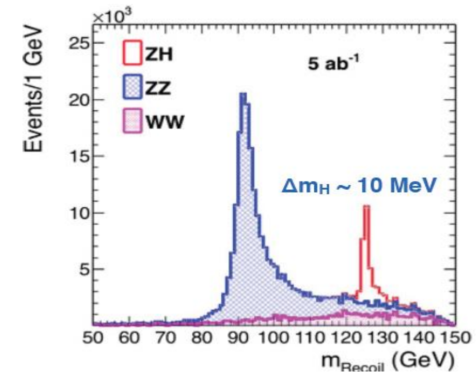


$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

E_+, E_- lepton energies from Z decay

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

absolute HZZ coupling meas.



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 4 IPs
  → test of first generation yukawa coupling

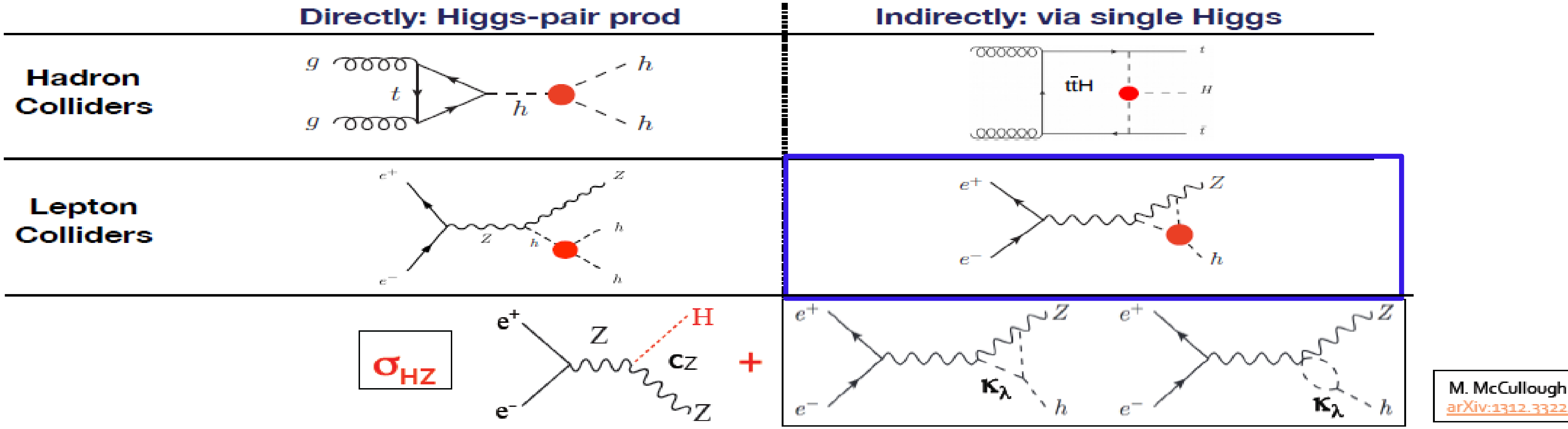
Higgs couplings precision expectation at FCC

Coupling	HL-LHC	FCC-ee (240–365 GeV) 2 IPs / 4 IPs
κ_W [%]	1.5*	0.43 / 0.33
κ_Z [%]	1.3*	0.17 / 0.14
κ_g [%]	2*	0.90 / 0.77
κ_γ [%]	1.6*	1.3 / 1.2
$\kappa_{Z\gamma}$ [%]	10*	10 / 10
κ_c [%]	–	1.3 / 1.1
κ_t [%]	3.2*	3.1 / 3.1
κ_b [%]	2.5*	0.64 / 0.56
κ_μ [%]	4.4*	3.9 / 3.7
κ_τ [%]	1.6*	0.66 / 0.55
$\mathrm{BR_{inv}}$ (<%, 95% CL)	1.9*	0.20 / 0.15
$\mathrm{BR_{unt}}$ (<%, 95% CL)	4*	1.0 / 0.88

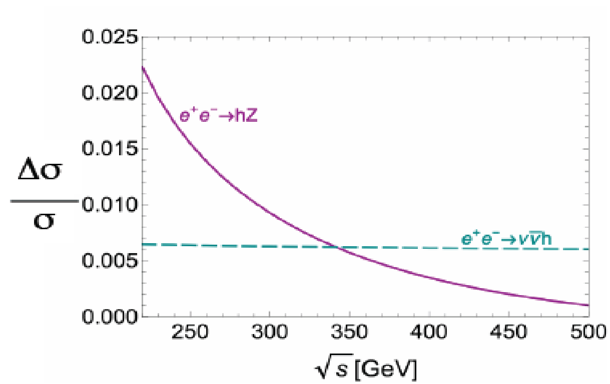
$$\kappa_X = \frac{g_{hXX}}{g_{hXX}^{\mathrm{SM}}}$$

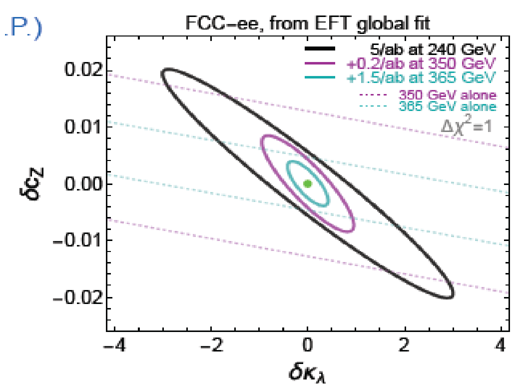
- FCC-ee measures g_{HZZ} to 0.2% (absolute, model-independent, standard candle) from $\sigma(ZH)$
  - $\Gamma(H)$, g_{Hbb} , g_{Hcc} , $g_{H\tau\tau}$, g_{HWW} , follow
  - Standard candle fixes all HL-LHC couplings
- FCC-hh produces over 10^{10} Higgs bosons, 10^8 ttH and 2×10^7 HH pairs:
  - Improving precision on g_{Htt}, g_{HHH}
    - with top EW couplings (and other BRs) measured at FCC-ee
  - Access to Rare Decays: $\mu\mu, \gamma\gamma, Z\gamma$
- **FCC-ee + FCC-hh is outstanding:**
  - All accessible couplings with per-mil precision
  - Self-coupling with per-cent precision

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

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

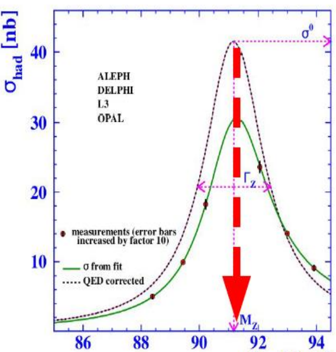
The Tera-Z program at the Z peak and Electroweak Physics

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, in 4IP)
- 4 years at 10^7 s /year = 6 10^{12} evts/exp. ➔ 2 10^5 LEP Statistics (~ 2 10^3 more than ILC)

For the electroweak program we will also have

- 2 years at the WW threshold, 2.4 10^8 events/exp. ➔ 4 10^3 LEP Statistics

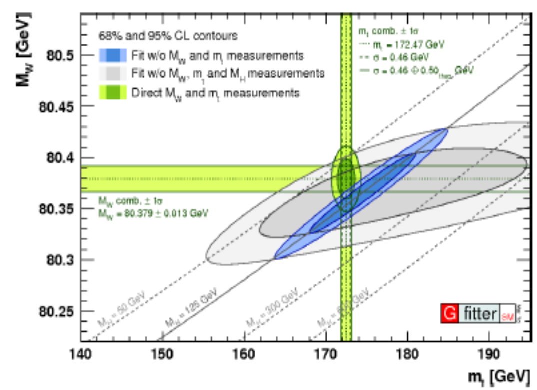


- m_Z: position of Z peak
- Beam energy measured with extraordinary precision ($\Delta\sqrt{s}\approx$100 keV) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, …)
- Beam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

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

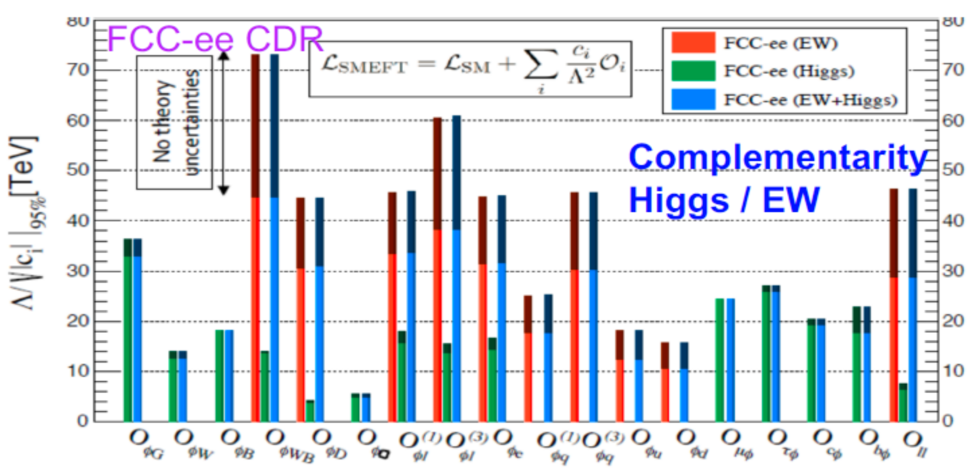
Requires improved measurements of m_{top}, m_Z, $\alpha_{QED}(m^2_Z)$, α_S… and more generally all usual EWPO included in the EW fits.

EW & QCD precision measurement examples

	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.

EW measurements to be studied in detail:

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

FCC

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 (with 2IP)

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
$\|V_{ub}\|$ (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

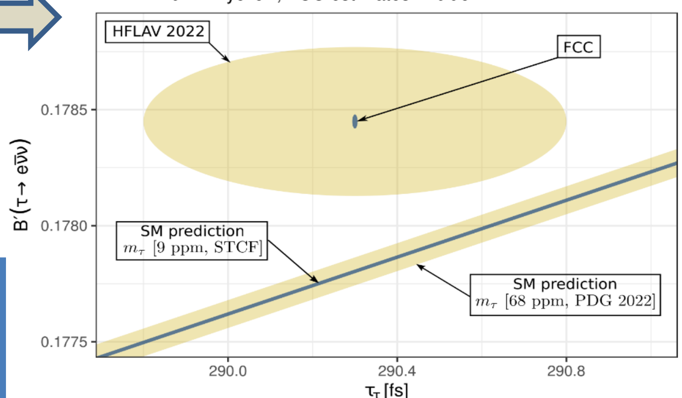
→ Study rare penguin EW transitions such as b →s τ+ τ- , spectroscopy (produce b-baryons, B_s …)

→ **Test lepton universality** with **10^{11} τ decays** (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}

→ need special detectors (PID), under study

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
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

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**

Flavour physics measurements to be studied in detail

	Measurement	Requirements
Z peak	CP violation in Bs $\to \Phi\Phi$	PID, vertex, track resolution
	B0 $\to \pi 0 \pi 0$ ($\to$ eeγ)	Low energy γ 's in jets (ECAL resolution and granularity)
	Bs $\to$ $\tau\,\tau$	Vertexing
	Meas of γ from B+ $\to$ DK+	Ks reconstruction
	$\tau \to$ 3μ, $\tau \to$ 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

Precision Top factory at 340 – 365 GeV

- Expect 2M *tt* events (4 IP). Not as many compared to LHC, but in a clean environment and with the abilty to scan $\sqrt{s}$

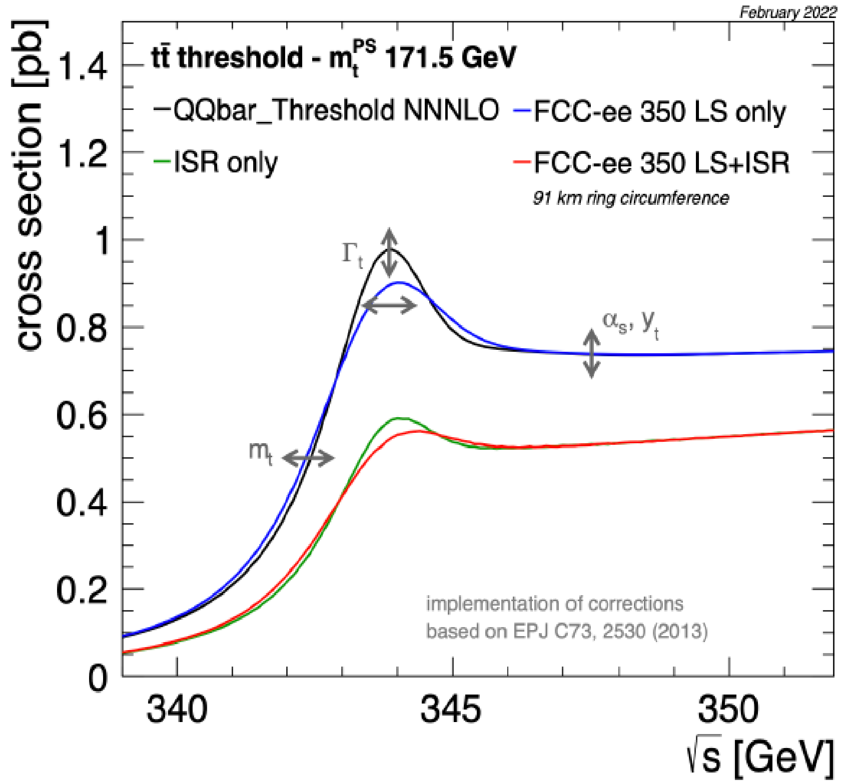
- Test of the Higgs mechanism via the measurement of the top mass and top Yukawa coupling

  - 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 44 MeV on m_t from N^3LO QCD

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

  → uncertainty ~10 times smaller than @HL-LHC

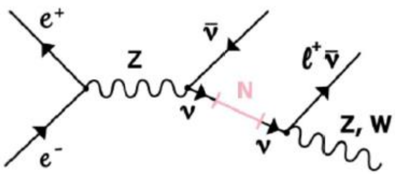
  → key input to extract top Yukawa coupling from FCC with reduced theory uncertainty



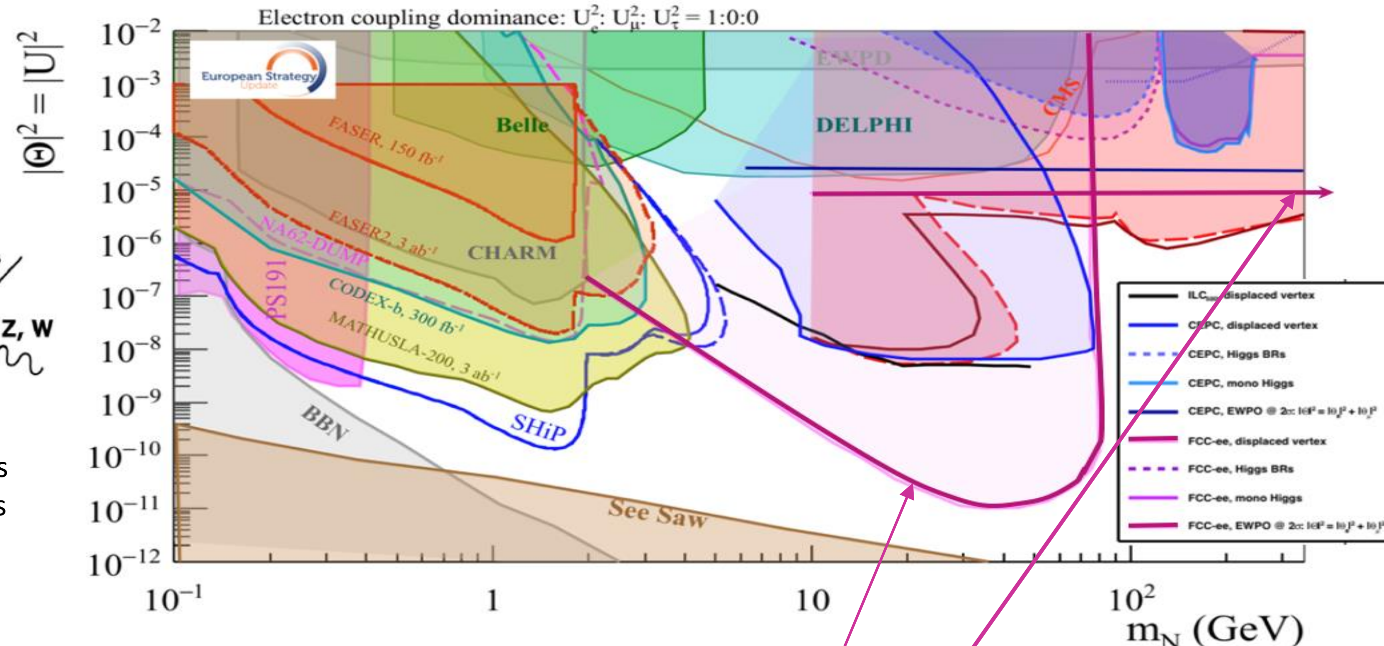
Searches for Feebly Interacting particles

- 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



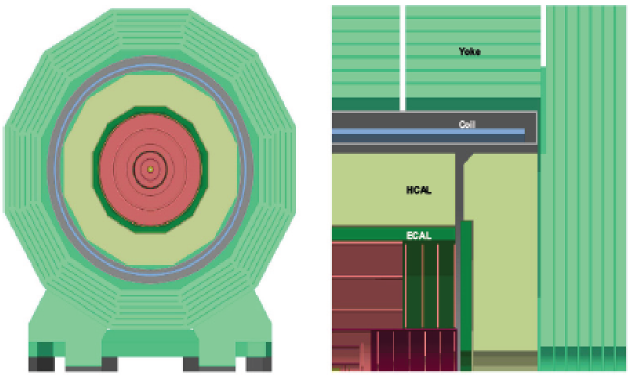
These limits are relevant for Neutrino, Dark sectors and High Energy Frontiers



- Significant extension reach for observing **heavy neutrino decays** [arXiv:1910.11775]
- 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 up to very high energies (500-1000 TeV) [arXiv:2011.04725]

Detectors under Study

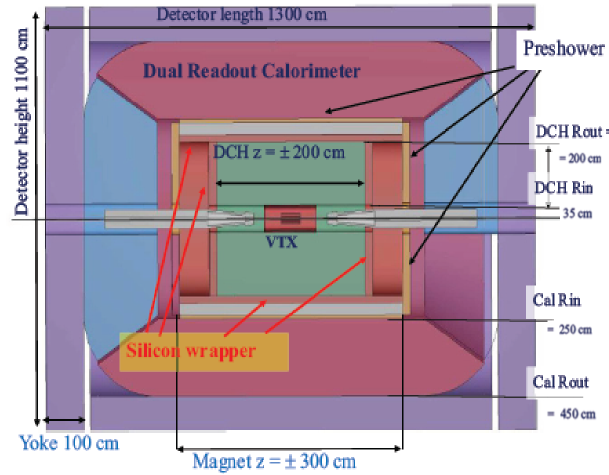
CLD or ILD-CC



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

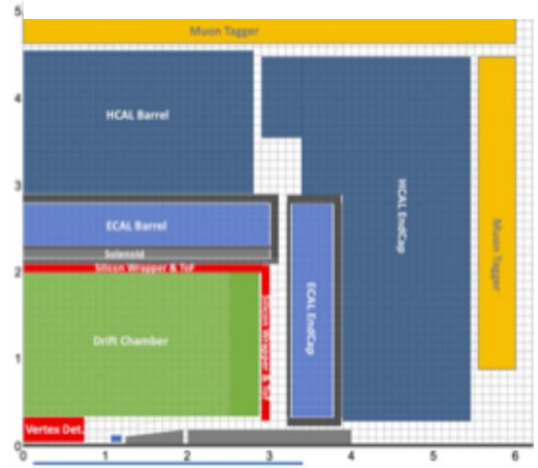
IDEA



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

ALLEGRO



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

- silicon vertex
- low X_0 drift chamber + silicon wrapper
- 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

Detector requirements (initial studies)

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

"Higgs Factory" Programme

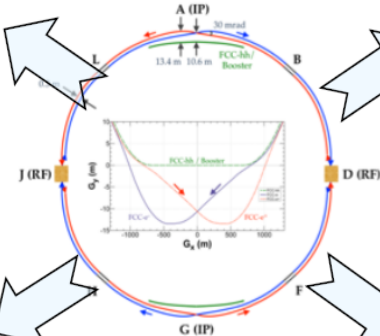
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

rare H decays (e.g. $H \rightarrow \gamma + \varphi/\psi/\Upsilon$)
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

Studies on the experimental constraints in the mid-term review report

- All these studies provide first constraints that the different detectors will need to fullfill.
- Need to be developped further before making definite technological choices, as a function of the physics priorities (may depend on the detector).
- Crucial activities are also needed on the centre-of-mass energy calibration, polarisation, and monochromatisation
- In the machine-detector interface domain, need to evaluate the impact of the integration of the main elements of the interaction region on the performance of the detector systems closest to the beams and the interaction point (vertex detector and Luminosity monitors).
- First results/questions from the mid-term studies in the next slides

Software and Computing Outloook

- Improve the accuracy of Monte Carlo physics generators to the statistical precision expected at FCC-ee, in particular at the Z pole.
  In addition to theoretical refinements (higher EW and QCD orders, improved treatment of initial and final state radiation etc.), this also includes the simulation of beam-energy spread, bunch length & transverse size, final state particle deflection by colliding bunches

- Complete the simulation of the interaction region (also know as Machine Detector Interface (MDI) in view of the final evaluation and mitigation of beam-related backgrounds in the detectors.

- Proceed with the full and parameterised simulations (and their interplay) of the relevant sub-detectors currently considered, including digitisation and sub-detector interchange with a “plug’n’play” framework, to enable the study of the performance of a large variety of detector concepts.

- Develop and implement the various reconstruction and analysis tools for use by all collaborators, reaping the benefits, whenever relevant, from LHC experience and past linear collider studies.

- Continue with the development of the common software framework (Key4hep) and common data format (edm4hep), as well as the procedures for software building, testing, and deployment.

- Evaluate the need for computing resources and proceed with regular simulated data production.

- Provide the users with detailed documentation and regular didactic tutorials

Physics Performance Outlook

Some first results/questions from the mid-term studies:

- The needs for very precise timing measurements, in particular in the innermost region, must be better assessed
- What is the internal precision with which the detectors must be designed and built? to which extent in-situ measurements can achieve the required systematic precisions on alignments and other fiducial markers?
- The impact of a better position resolution and a longitudinal segmentation of the calorimeter needs more quantitative studies that can only be obtained with full simulation of the specific detectors.
- More studies are needed to devise data driven methods that would reduce the systematic contributions to the precision of physics results from the detector performance.
- The dominant challenge for the FCC-ee detector design remains the precision with which the basic electroweak observables can be measured. Work on the hadronic, dilepton, and diphoton x-section measurements has been initiated but much remains for the lepton pairs and for the luminosity measurement with photon pairs and low-angle Bhabha scattering.
- Most studies done so far use a fast simulation of the detector response. The necessary next step is a full simulation description of the proposed detector concepts and the development of the full event reconstruction (cf software/computing outlook)

Detector Concepts Outloook

- Recent restructuring of the detector R&D community ➔ formation of DRD collaborations (1/1/2024)
- The detector community is well connected worldwide and this is now reflected by the ongoing integration of non-European groups and projects into the new DRD structure.
- The DRD's need an adequate ramp-up of resources, and will benefit from proper guidance through the detector conceptual activities in the PED effort.

The timeline for FCC-ee foresees:

- Physics in the second half of the 2040s
- TDRs in the mid 2030s, backed by realistic prototypes
- CDRs in the early 2030s, with demonstrators that address the main integration challenges

➔ the R&D in the next 3-year period (2024-26) will have to focus on conceptual and component studies, with system aspects in focus from the beginning, to prepare for the development of demonstrators soon after, and for the construction of realistic modules by 2035

The work on other aspects of technology R&D already started during the conceptual design study will be pursued (e.g., highly-granular liquid argon calorimeter, silicon vertex detectors, CALICE-based calorimeters, particle identification detectors, dual readout calorimeters, gaseous trackers, luminosity monitors, etc...).

many R&D issues are common to linear and circular colliders, and can now be addressed in joint efforts.
➔ For this, the ECFA Higgs/EW/top factory study is currently the best framework.

➔ Expression of Interests for the detectors/subdetectors expected in 2025

FCC

Status of FCC global 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

FCC Feasibility Study:
Aim is to increase further the collaboration, on all aspects, in particular on Accelerator and Particle/Experiments/Detectors

141 Institutes

32 countrie s + CERN

FUTURE CIRCULAR COLLIDER
Feasibility Study

Enlarging the Collaboration

FCC

FCC Global Collaboration Working Group (FGC)

International Forum of National Contacts (IFNC)

Two approaches, one globally-oriented (FGC), the other more PED oriented (IFNC), both to engage with countries with mature communities, a long-standing participation in CERN's programmes and the potential to contribute substantially to the Organization's long-term scientific objectives, to facilitate opportunities for national participation in the Feasibility Study

Work with national laboratories, institutes and universities as well as **industry** to carry out the following mandate:

- Encourage an **expanded membership**.
- Explore **opportunities** for future prospective participants, in particular on the Accelerator side
- Support new participants in **application process**.
- Assist the new participants in defining **areas of collaboration**.
- Conclude relevant **agreements**.
- Facilitate the **integration** process.
- Facilitate interest in **CERN non-core areas** - geology, geodesy, logistics, materials science.
- Prepare the foundations for research and contributions by **industry.**
- Liaise with **National Contact persons**

→ MoU and Collaboration Board

Convened by E. Tsesmelis (CERN international relations)

Contact directly Physics groups in a country, typically from LHC or Future Colliders groups to ask them **to join as new institution**

- Discuss the physics case and the opportunities
  - → To study **R&D/ Detector concepts** for FCC
  - → To expand the FCC Physics scope via the study of **physics case studies**
  - → To improve the **theoretical calculations** to exploit the FCC physics potential
- Help **forming a national FCC group**, with strong PED component, which can hold its national FCC meetings, including the Accelerator community when possible
- Identify at least one **National Contacts** to exchange information between country situation and FCC management, and to strengthen the national community
- Exchange experience across countries (**IFNC meetings**)

→ MoU (through FGC) and IFNC

Convened by G. Bernardi and T. Lesiak (National Contacts)

FCC Week 2024 - San Francisco – 10 to 14 June

449 participants, 50 public sessions, 216 oral presentations, 32 posters
US efforts getting organized, towards completing the FS by March 2025

Progress on international collaboration

Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science

The United States and CERN intend to:

- Enhance collaboration in future planning activities for large-scale, resource-intensive facilities with the goal of providing a sustainable and responsible pathway for the peaceful use of future accelerator technologies;
- Continue to collaborate in the feasibility study of the Future Circular Collider Higgs Factory (FCC-ee), the proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise and providing a clear pathway for future activities in open and trusted research environments; and
- Discuss potential collaboration on pilot projects on incorporating new analytics techniques and tools such as artificial intelligence (AI) into particle physics research at scale.

Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals.

26 April 2024

White House Office of Science and Technology Policy Principal Deputy U.S. Chief Technology Officer Deirdre Mulligan signed for the United States while Director-General Fabiola Gianotti signed for CERN.

EU Competitiveness Report

edited by Mario Draghi, and officially handed over to Ursula von der Leyen in September 2024

***"One of CERN's most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider.**.*

***Refinancing CERN and ensuring its continued global leadership in frontier research should be regarded as a top EU priority**, given the objective of maintaining European prominence in this critical area of fundamental research, which is expected to generate significant business spillovers in the coming years."*

https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en

Supporting statements at CERN's 70 anniversary

"….No European country alone could have built the world's largest particle collider. CERN has become a global hub because it rallied Europe and this is even more crucial today.

I am proud that we have financed the feasibility study for CERN's Future Circular Collider (FCC). This could preserve Europe's scientific edge and could push the boundaries of human knowledge even further. *And as the global science race is on, I want Europe to switch gears. To do so, European unity is our greatest asset. …."*

Ursula von der Leyen, President of the European Commi*ssion*

FCC Week 2025 - Vienna

Event Overview

- **Venue**: **Hofburg Palace**, a historical and cultural landmark in **Vienna, Austria**.
- **Dates**: **Monday 19 to Friday 23 May 2025**
- **Presentation of the Feasibility Study Report and review of its findings and opportunities for future R&D projects**
- **Please save the date and join us in Vienna**

FCC Main Goals and Outlook

Overall goal:

- Perform all necessary steps and studies to enable a project decision by 2028/29, and a subsequent start of civil engineering construction by 2032/33.

This requires successful completion of the following main activities:

- Develop and establish a governance model for project construction and operation and 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 R&D, and physics/experiment studies:

- Machine designs and main technology R&D lines
- Completion of physics case studies → detector requirements → detector concepts & focused R&D
- Reach out to all 'European and International Partners'
- Establish user communities, work towards proto experiment collaboration by 2028/29
- **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 welcomes / needs new collaborators !

FCC

FCC Special Session at 10.30,

to see the opportunities where to contribute,

Just after the coffee break

10:30 General Introduction

Presenter(s): Prof. Emmnuel TSESMELIS *(CERN)*

10:40 Organization of FCC PED activities, including theory

Presenter(s): Prof. Christophe GROJEAN *(DESY)*

10:50 Physics performance and detector requirements

Presenter(s): Prof. Emmanuel PEREZ *(CERN)*

11:00 Towards FCC detector conceptual design

Presenter(s): Prof. Mogens DAM *(Niels Bohr Institute)*

11:10 FCC Software and computing

Presenter(s): Prof. Brieuc FRANCOIS *(CERN)*

11:20 MDI (backgrounds and detector integration)

Presenter(s): Prof. Fabrizio PALLA *(CERN)*

11:30 Possible contributions in Accelerator

Presenter(s): Prof. Frank ZIMMERMANN *(CERN)*

11:45 Remarks from Mexico

Presenter(s): Prof. Arturo FERNANDEZ TELLEZ *(Benemerita Universidad Autonoma de Puebla)*, Prof. Ricardo LÓPEZ FERNÁNDEZ *(Cinvestav)*

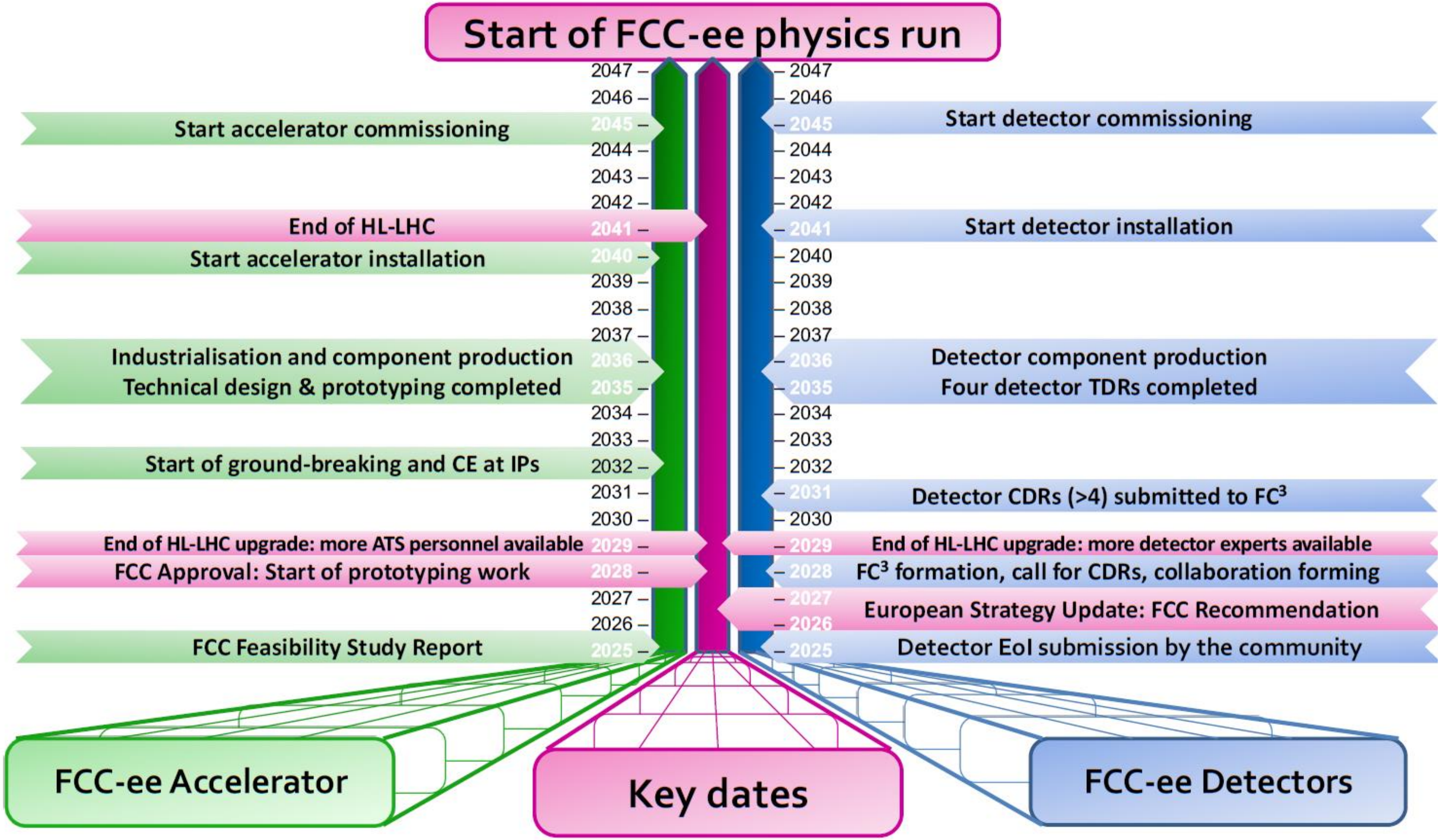
12:00 Remarks from other American countries

Presenter(s): Prof. Gustavo GIL DA SILVEIRA *(CERN)*

12:15 Discussion

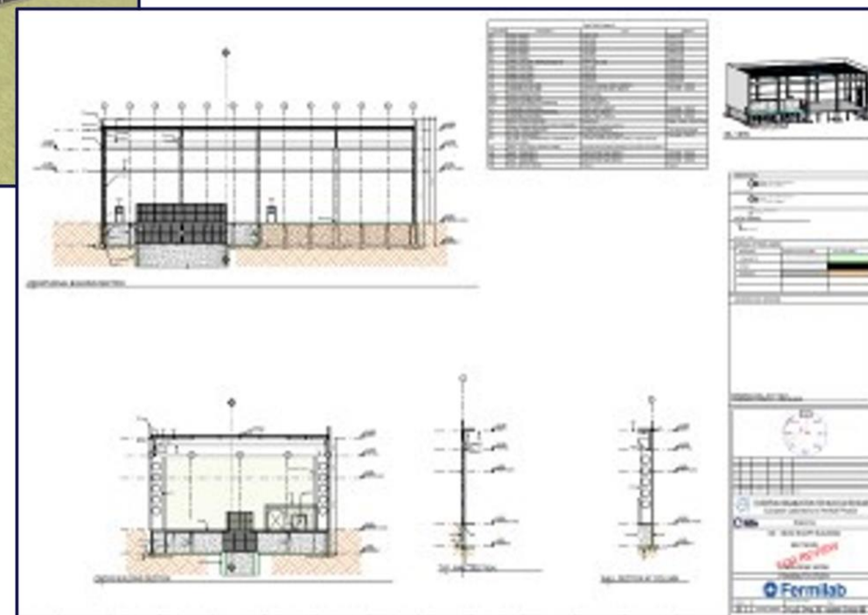
FCC

backup


Start of FCC-ee physics run
2047
2046
Start accelerator commissioning
2045
Start detector commissioning
2044
2043
2042
End of HL-LHC
2041
Start detector installation
Start accelerator installation
2040
2039
2038
2037
Industrialisation and component production
2036
Detector component production
Technical design & prototyping completed
2035
Four detector TDRs completed
2034
2033
Start of ground-breaking and CE at IPs
2032
2031
Detector CDRs (>4) submitted to FC³
2030
End of HL-LHC upgrade: more ATS personnel available
2029
End of HL-LHC upgrade: more detector experts available
FCC Approval: Start of prototyping work
2028
FC³ formation, call for CDRs, collaboration forming
2027
2026
European Strategy Update: FCC Recommendation
FCC Feasibility Study Report
2025
Detector EoI submission by the community
FCC-ee Accelerator
Key dates
FCC-ee Detectors

CE surface progress

Generic study of experiment site and technical site by FNAL



Examples of Fermilab Deliverables

- bills of quantities extracted from FNAL designs
- basis for cost estimate by consultant with experience on industrial constructions in CH-FR area.
- next steps: individual integration studies and design optimization with municipalities concerned