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Fermilab W&C
November 12th, 2021

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

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With many thanks to all in the FCC collaboration, in particular
J. Alcaraz, M. Benedikt, A. Blondel, M. Dam, D. d’Enteria, P. Janot

Seminar Layout

- Why do we need a new accelerator after the LHC?
- Linear or Circular ?
- The FCC Feasibility Study
- The FCC-ee Physics potential (mainly Higgs / EW)
- Next steps

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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

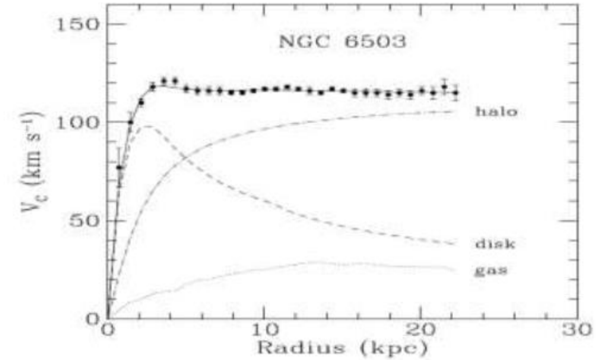
since then we have been discovering all the particles that have **electric charge** or **QCD charge**, or **weak isospin** (SM couplings), and the Higgs boson, **by increasing accelerator energies.**

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

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

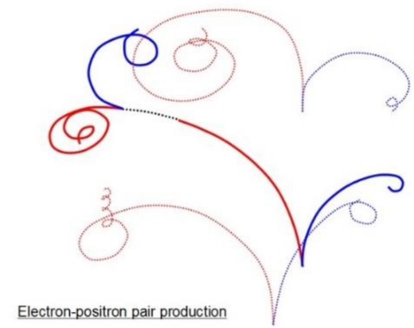
What is Dark matter ?

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



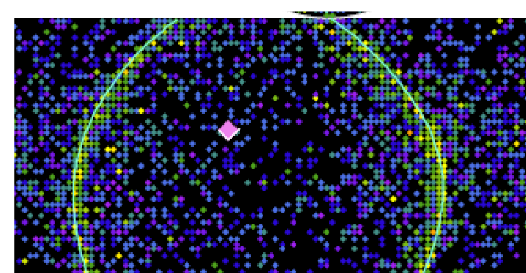
Rotation curve for Galaxy

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?



How to Go beyond the Standard Model ?

- By direct observation of new particles
- By observing New Phenomena (ex: Neutral currents, neutrino oscillations, CP violation..)
- By measuring deviations from precise predictions

The Physics Landscape

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

For the first time since Fermi theory, WE HAVE NO ENERGY SCALE TO SEARCH FOR

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

➔ more Sensitivity, more Precision, more Energy

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

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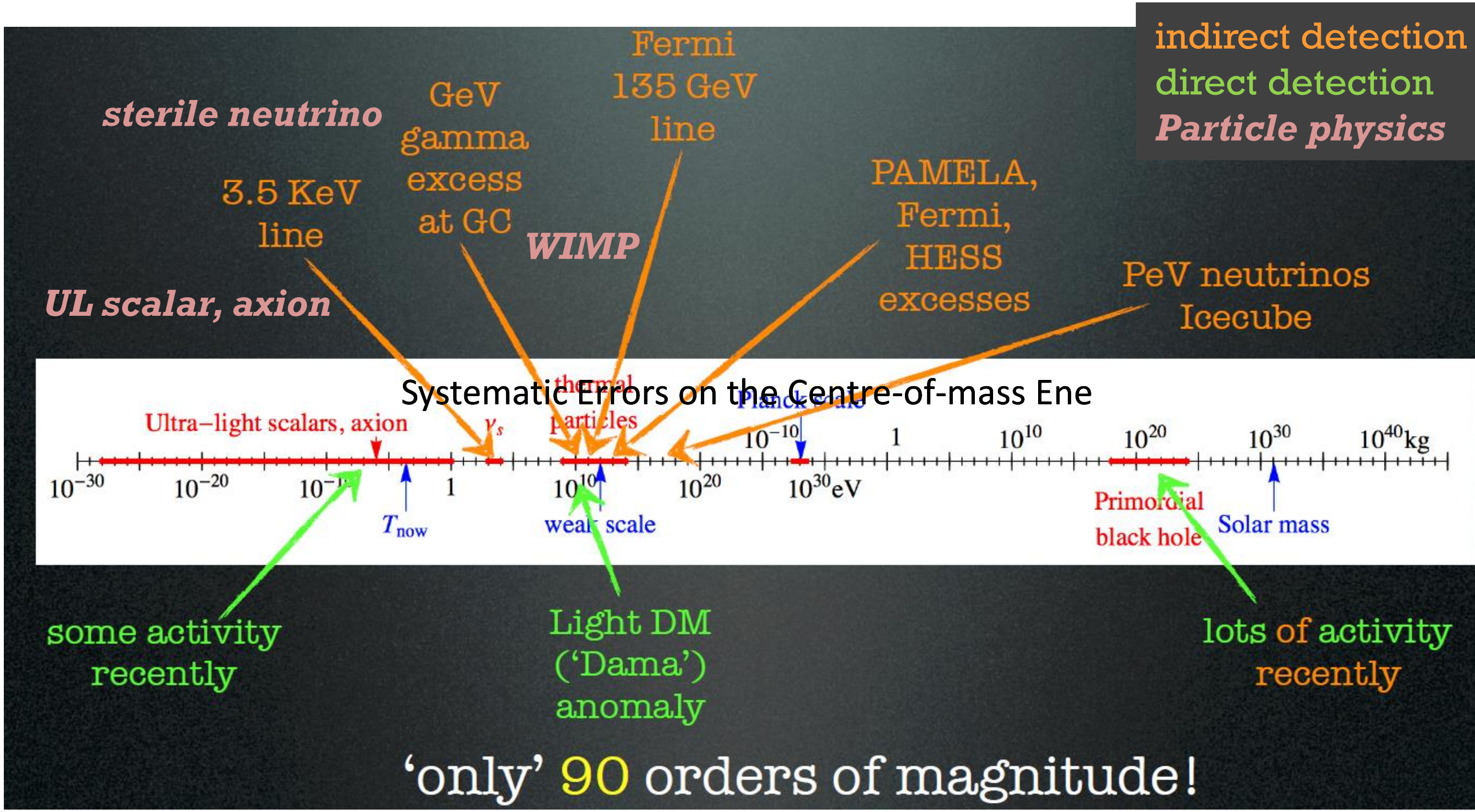
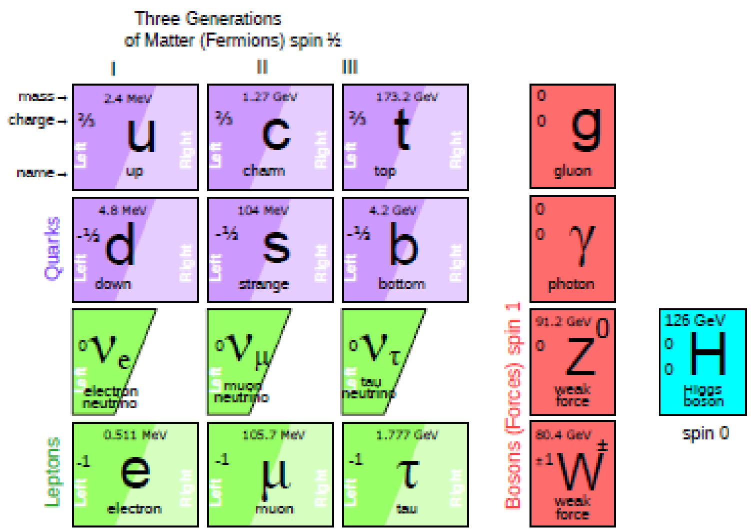
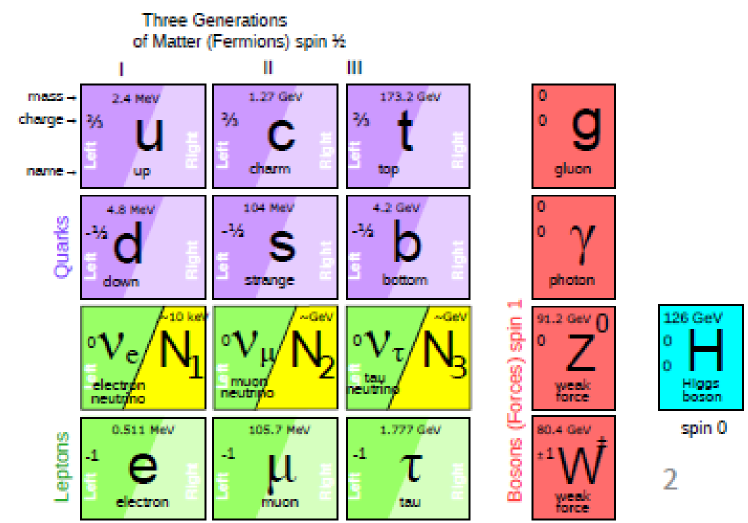
Dark Matter could be made of very long lived neutral particles
Plausible candidates:



M. Cirelli

… and at least 3 pieces could still be missing





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

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

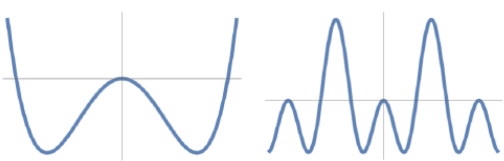
…and the Higgs boson/field still need to be better understood

- → 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 SM physics. Easier choice now that it has been discovered.

Precise nature of the Higgs boson ?

Origin of electroweak symmetry breaking (EWSB) ?

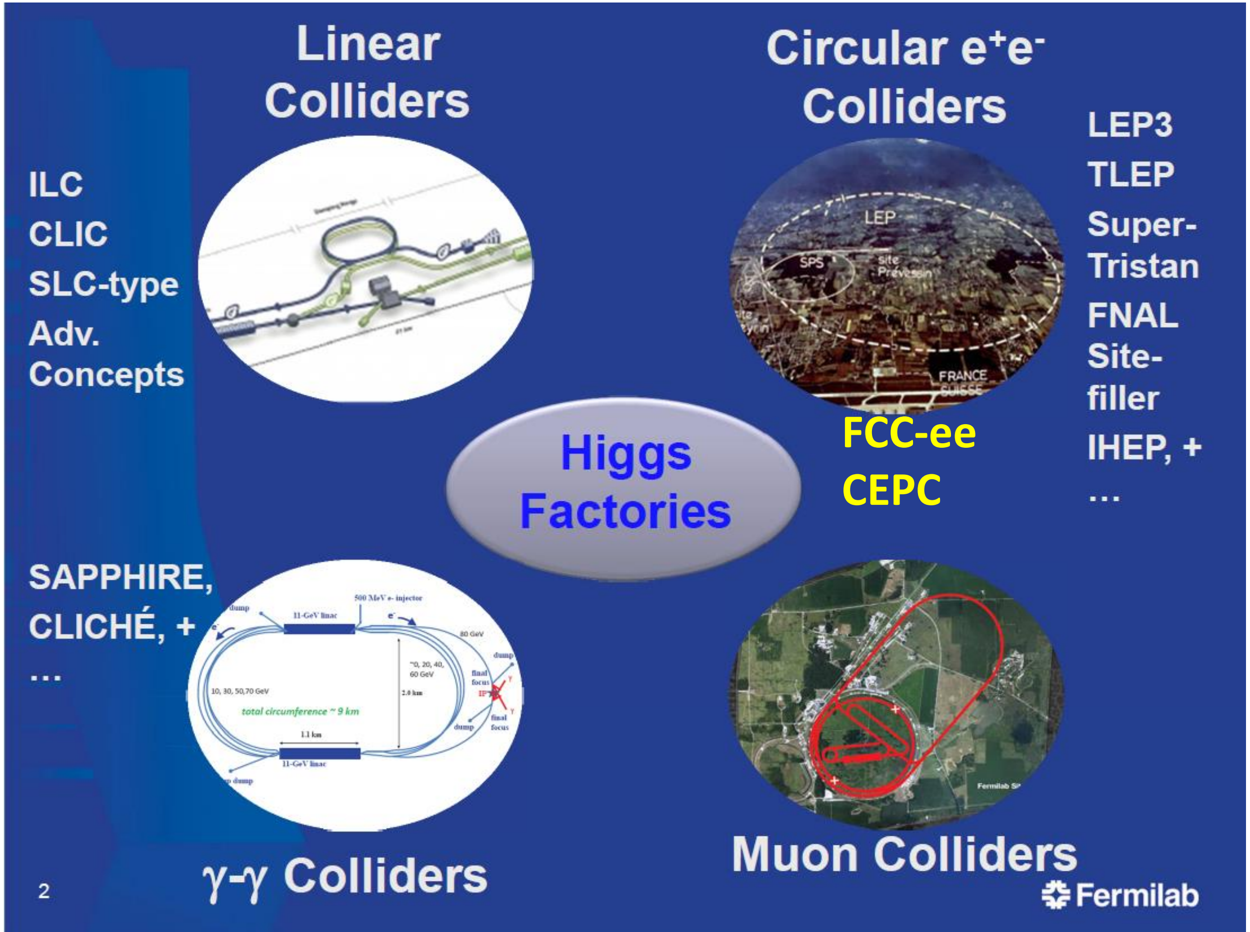
Shape of the Higgs potential ?



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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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
An example of competing constraints for EM calorimeter are the following:
high E precision vs. high granularity vs. high stability vs. geometric accuracy vs PID)

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

The limitation in maximum energy is not a crucial drawback, given the current HEP panorama and the subsequent FCC-hh program which will reach the highest energies

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➔ Recommendations from the European Strategy forParticle Physics (2020):

“Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV, and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.”

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FCC-ee physics plans

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

”Higgs Factory” Programme

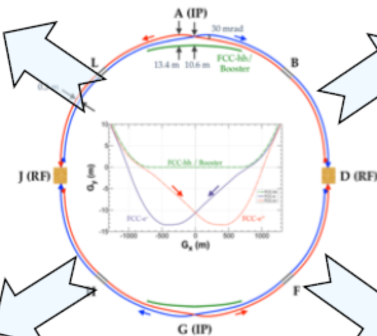
- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

Ultra Precise EW Programme & QCD

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

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

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



Heavy Flavour Programme

- Enormous statistics: 10^{12} bb, cc; 1.7×10^{11} ττ
- Extremely clean environment, favourable kinematic conditions (boost) from Z decays
- CKM matrix, CP measurements, ”flavour anomaly” studies, e.g. b → sττ, rare decays, cLFV searches, lepton universality, PNMS matrix unitarity

Feebly Coupled Particles - LLPs

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

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

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

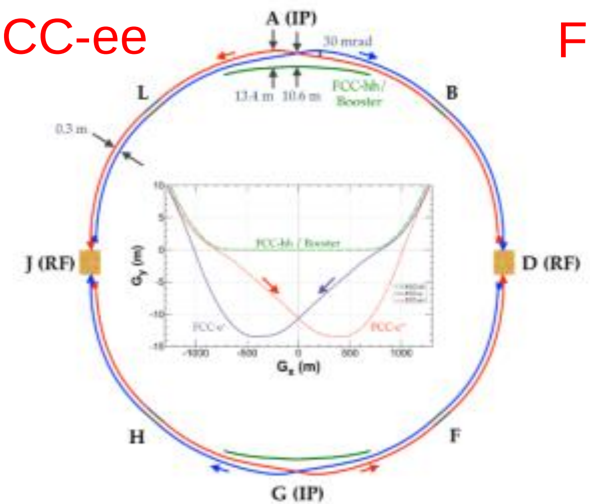
Comprehensive cost-effective program maximizing physics opportunities

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

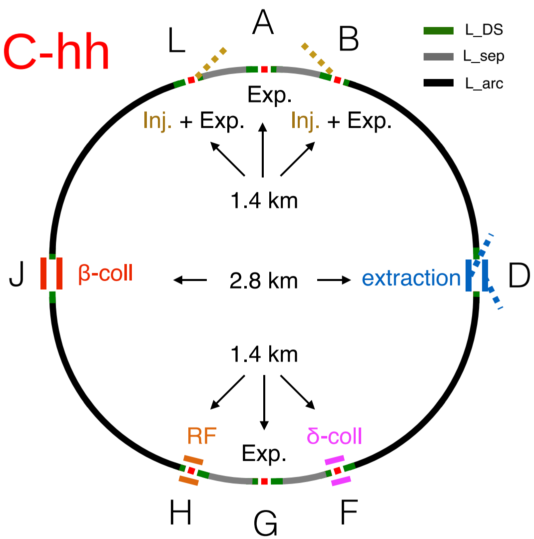
Complementary physics

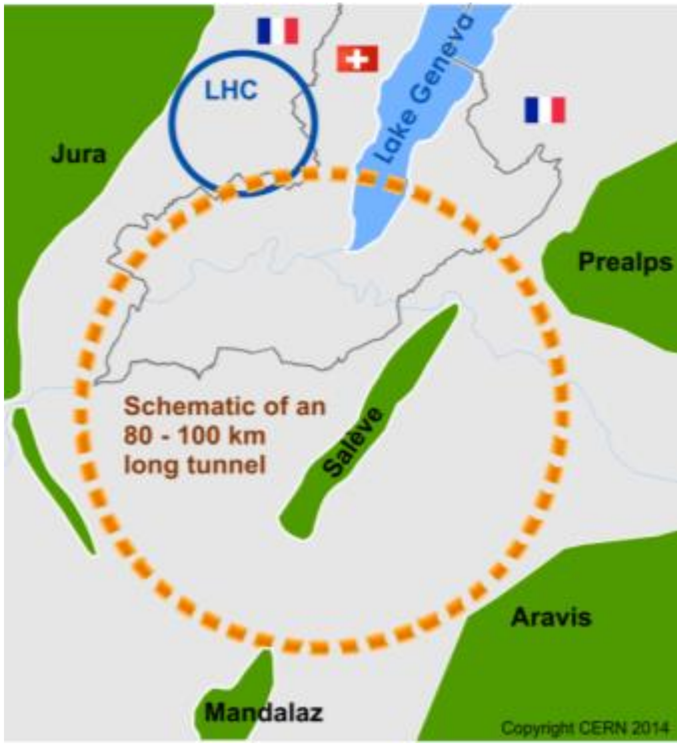
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- FCC-INT project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP

FCC-ee



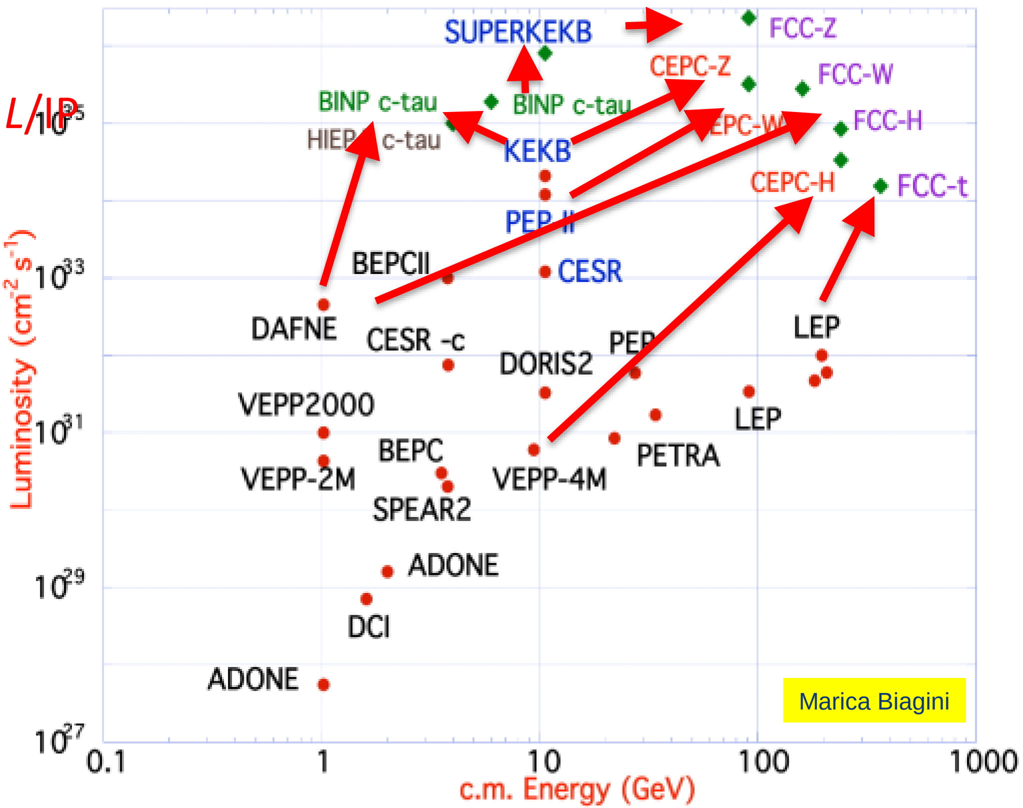
FCC-hh





FCC-ee design

based on lessons and techniques from past colliders



B-factories: KEKB & PEP-II:
- double-ring lepton colliders,
- high beam currents,
- top-up injection

DAFNE: crab waist, double ring

SuperB-factories, S-KEKB: low β_y^*

LEP: high energy, SR effects

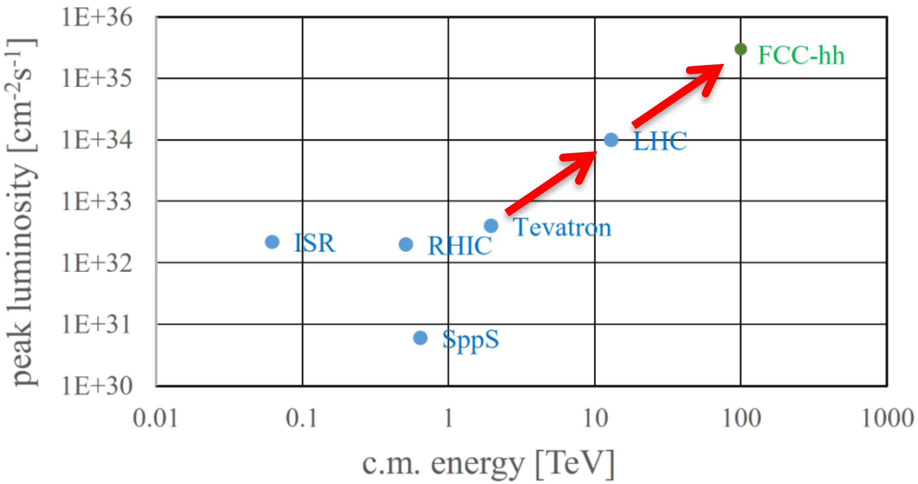
VEPP-4M, LEP: precision E calibration

KEKB: e^+ source

HERA, LEP, RHIC: spin gymnastics

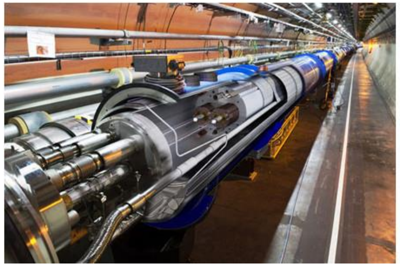
combining successful ingredients of several recent colliders
→ highest luminosities & energies

FCC-hh: highest collision energies



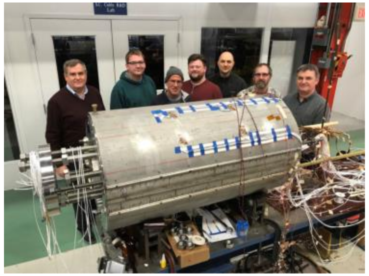
- order of magnitude performance increase in both energy & luminosity
- 100 TeV cm collision energy(vs. 14 TeV for LHC)
- 20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)
- similar increase as from Tevatron to LHC
- key technology: high-field magnets

from
LHC technology
8.3 T NbTi dipole

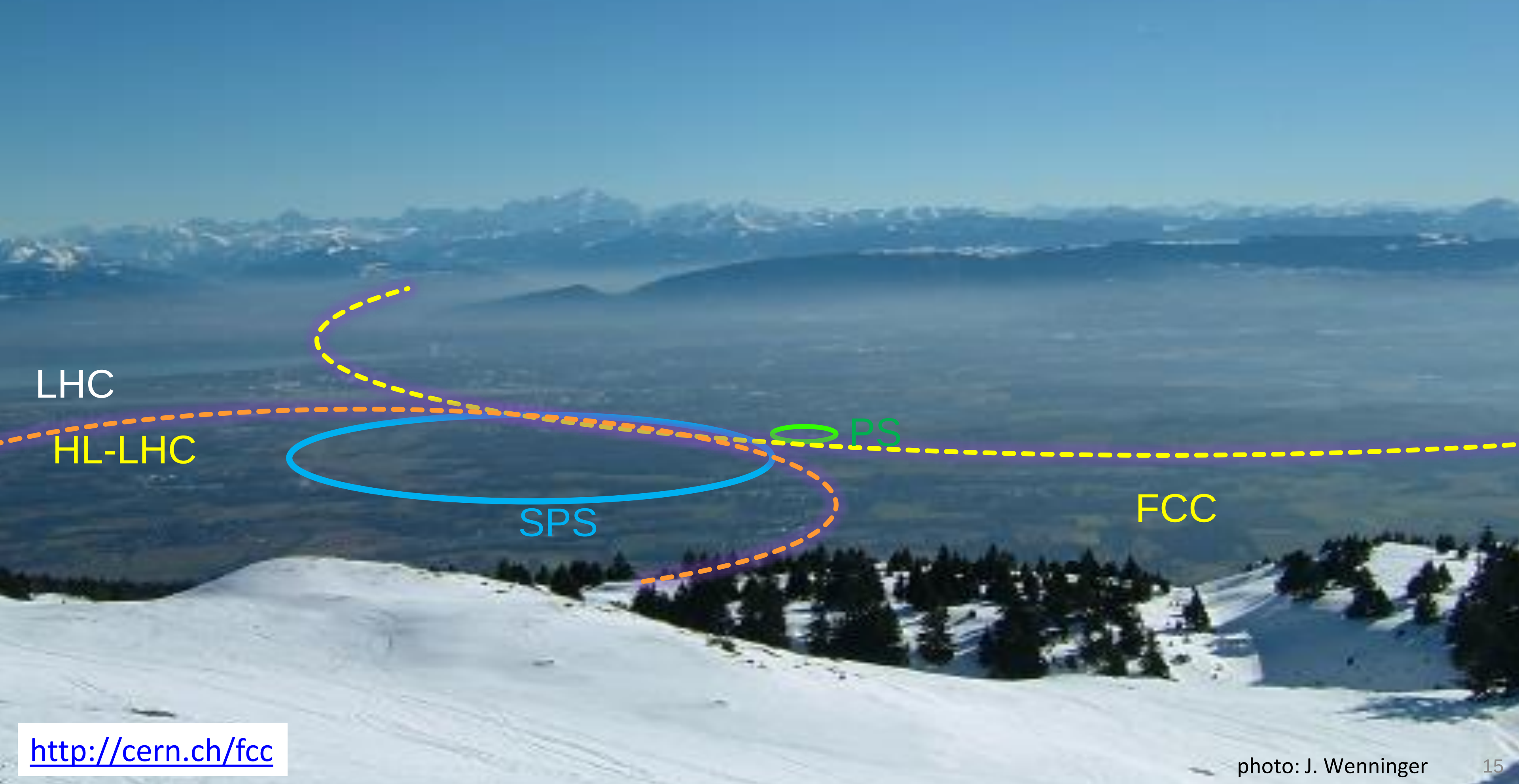


via
HL-LHC technology
12 T Nb_3Sn quadrupole

FNAL dipole demonstrator
14.5 T Nb_3Sn



Future Circular Collider Feasibility Study



http://cern.ch/fcc

photo: J. Wenninger

FCC feasibility study organization -

Approved by the CERN Council September 2021

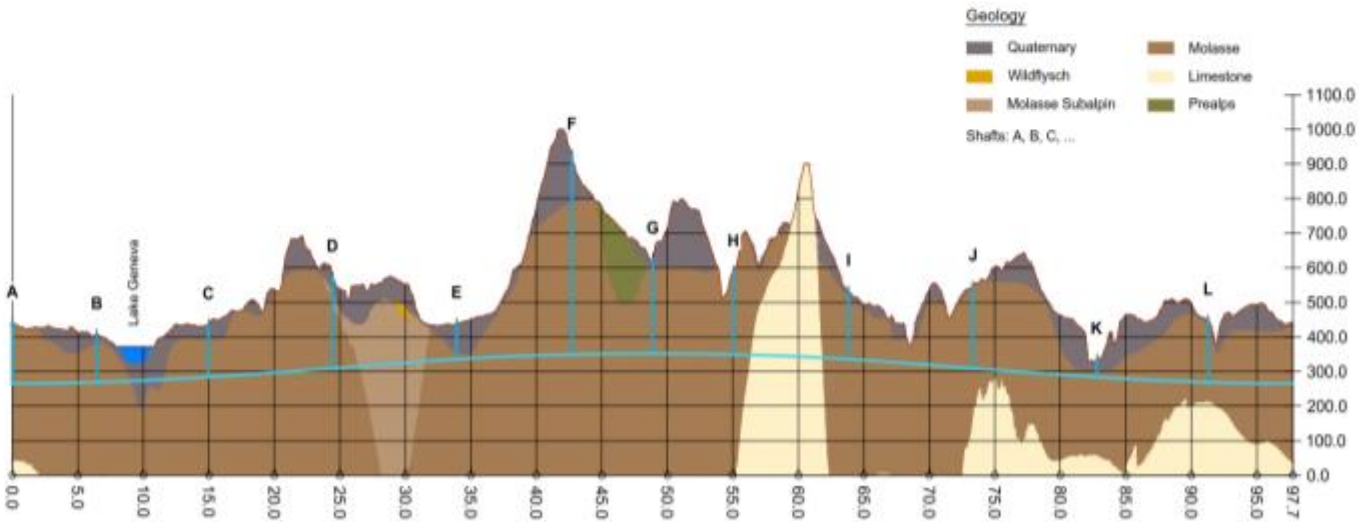
FUTURE CIRCULAR COLLIDER

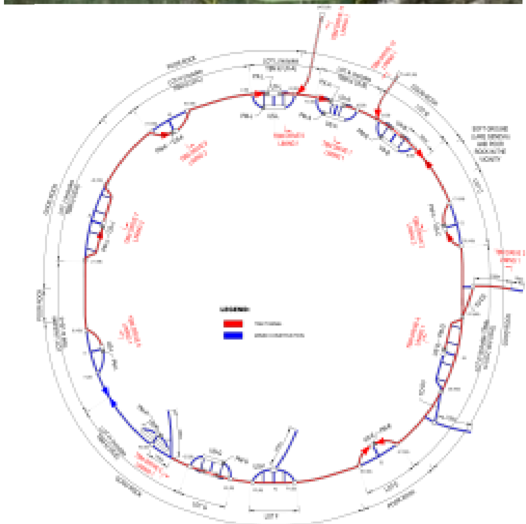
FCC Study Study leader M. Benedikt

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

Physics, experiments and detectors P. Janot, G. Salam	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, NN	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, NN		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		

FCC implementation - footprint baseline





Present baseline position was established considering:

- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

- More than 75% tunnel in France, 8 (9) / 12 access points in France.
- next step review of surface site locations and machine layout

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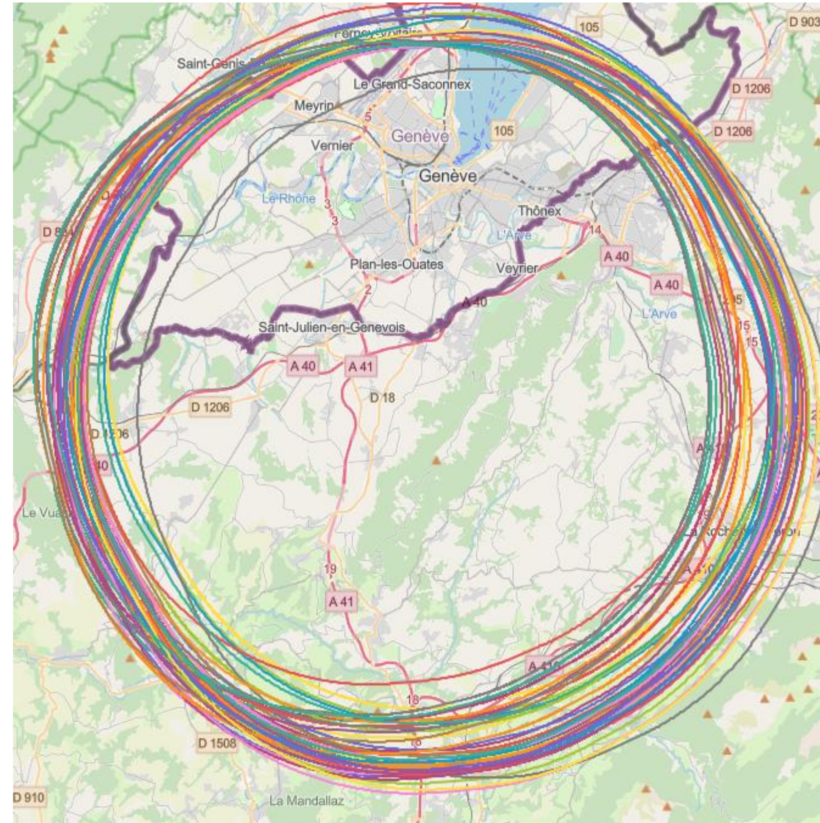
Collider placement optimisation

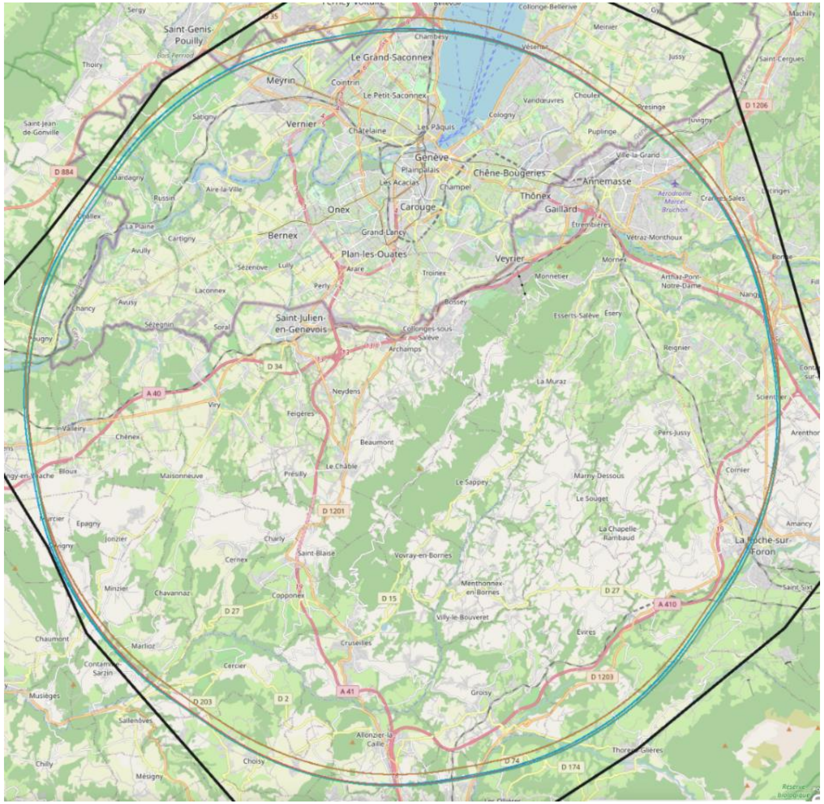
- Overall layout and placement optimisation process across both host states that follows the "avoid-reduce-compensate" directive according to European and French regulatory frameworks.
- Process integrates requirements and constraints, such as
  - civil engineering technical feasibility and subsurface constraints
  - territorial constraints at surface and subsurface
  - nature, accessibility, technical infrastructure and resource needs and constraints
  - economic factors including the development of benefits for and synergies with the regional developments
- Work takes place as a collaborative effort by technical experts at CERN, consultancy companies and government notified bodies



Collider placement optimisation

Main recommendation of the placement review:

- "The lowest-risk 8 point option should be chosen as the preferred variant for carrying out the next concrete steps towards understanding the FCC feasibility."
  - Number of surface points reduced from 12 to 8
  - Fourfold super-periodicity compatible with 2 or 4 Interaction Points (IP) for FCC-ee, decision to be made later.
  - Total length reduced from 97.75 to 91.17 km
    - ➔ PA close to LHC point8
    - ➔PG about 10 km from Annecy
- Seek concertation with local authorities
- Key representatives of French "Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation (MESRI)" were met in August at CERN to discuss FCC placement and feasibility study.



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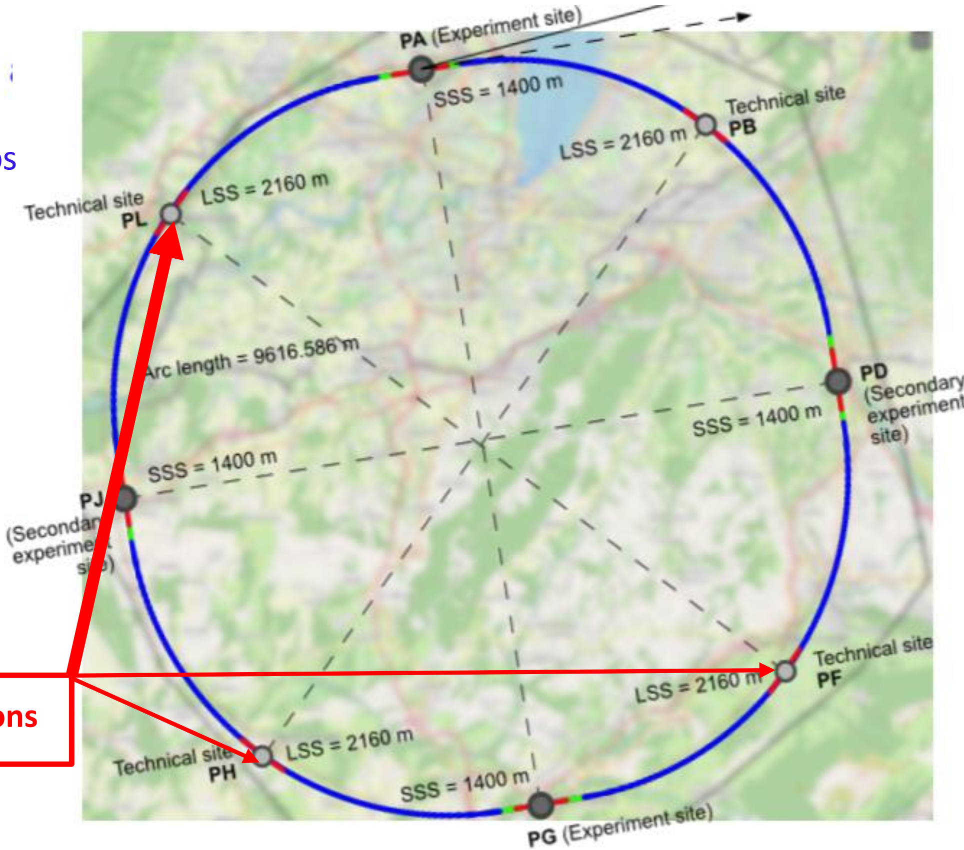
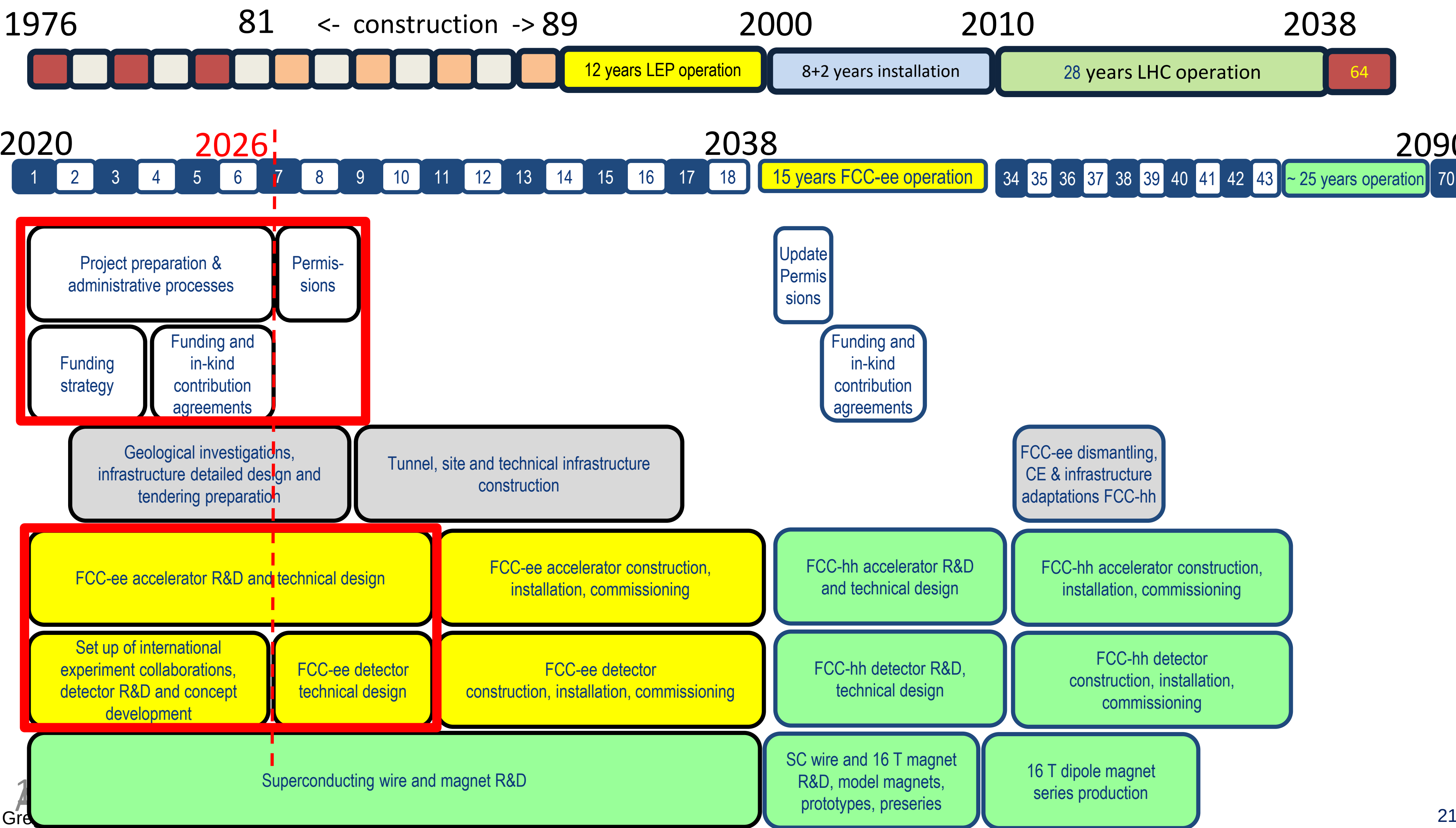


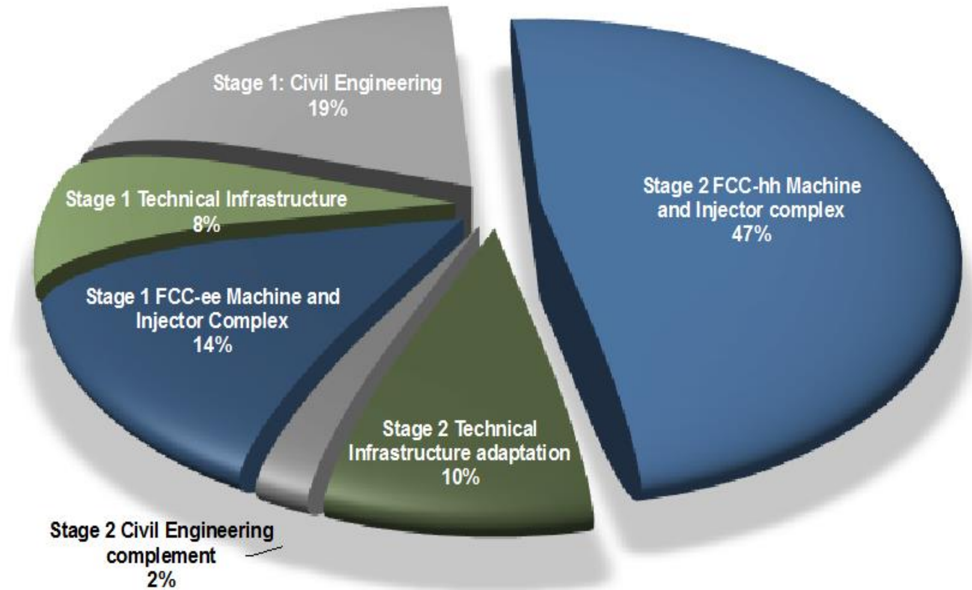
Discussions now going on for the placement of the RF stations

FCC-INT timeline, compared with LEP/LHC



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 (2025 – 2045)

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

- Associated to a total project duration of ~25 years (2035 – 2060)
- (FCC-hh standalone would cost 25 BCHF, so not building FCC-ee in a first stage would be a marginal saving)

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FCC-ee run plan

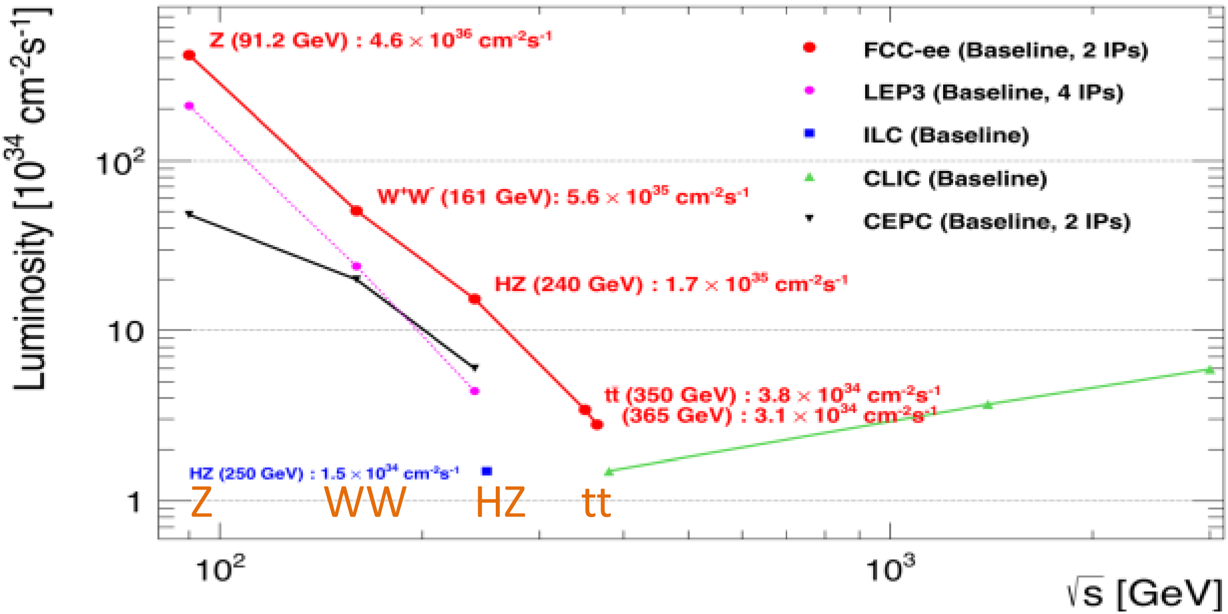


Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

Phase	Run duration (years)	Center-of-mass Energies (GeV)		Integrated Luminosity (ab^{-1})	Event Statistics	Extracted from FCC CDR
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	± 2 MeV	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365	± 5 MeV	1.5	10^6 $t\bar{t}$ events	Never done

Detector requirements (present status)

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

"Higgs Factory" Programme

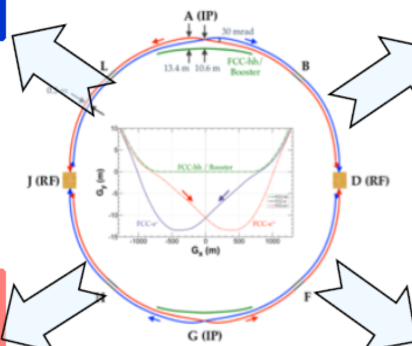
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\ \mathrm{GeV}^{-1}$ commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

rare H decays (e.g. H→ 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

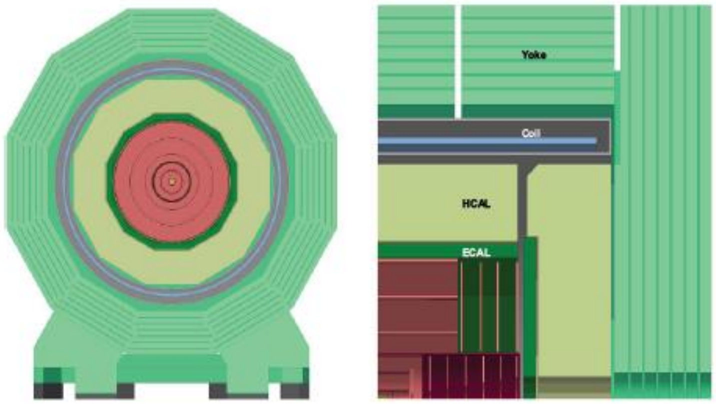
Feebly Coupled Particles - LLPs

Benchmark signature: Z → νN, with N decaying late

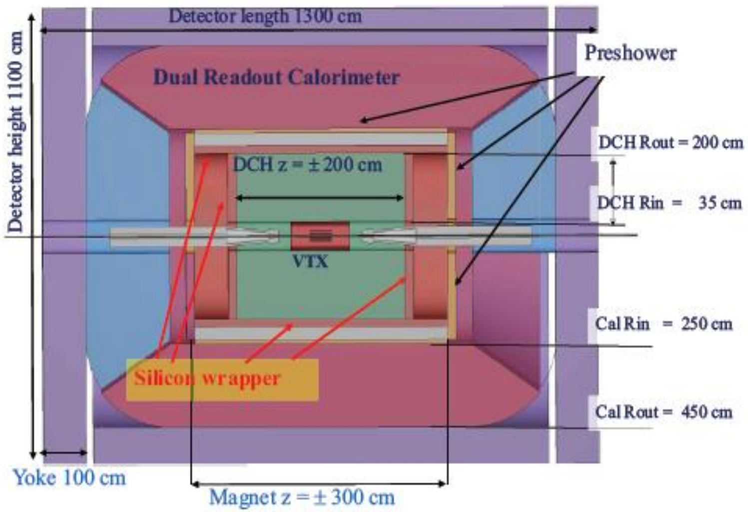
- Sensitivity to far detached vertices (mm → m)
  - Tracking: more layers, continous tracking
  - Calorimetry: granularity, tracking capability
- Large decay lengths ⇒ extended detector volume
- Hermeticity

Detectors under Study

CLD



IDEA



- 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

- 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

But several other options like Liquid Argon or Crystal Calorimetry, are under study (similarly for tracking, muons and particle ID)
With potentially 4 experiments, many complementary options will be implemented,
Definitely a place to contribute

Physics of the Higgs boson at FCC-ee

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

- **Statistics-limited measurements:**

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

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

- **Close to discovery level:**

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

- **Unique possibility:**

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

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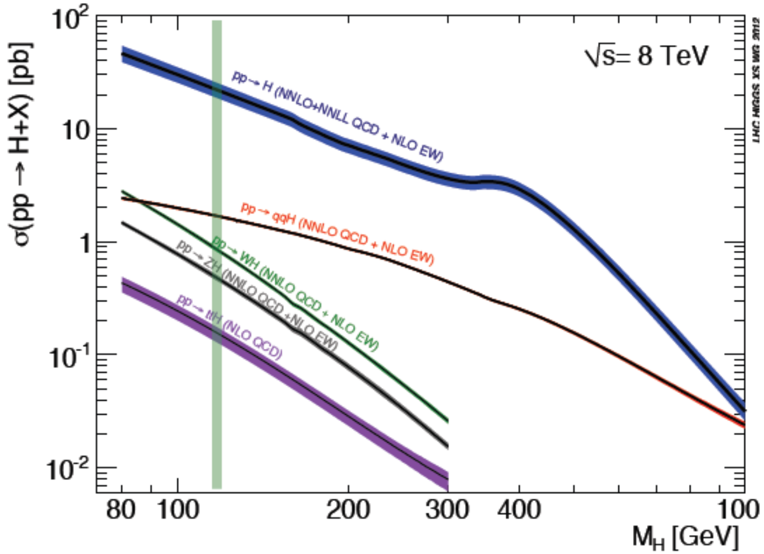
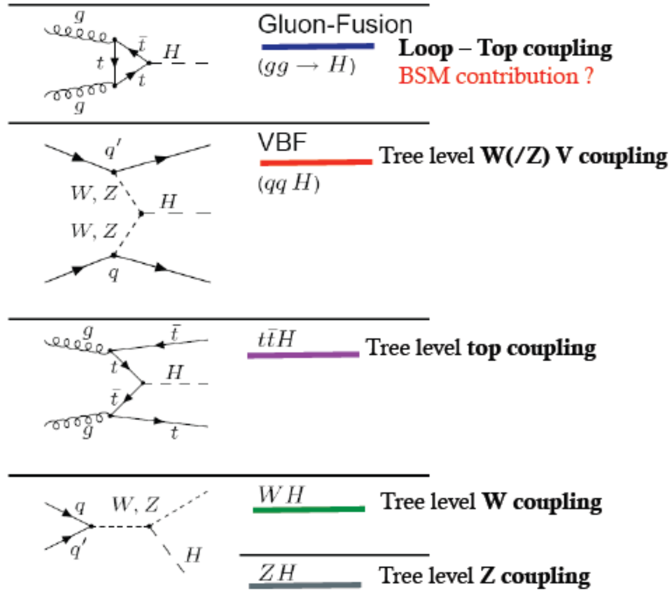
Moving from a *pp* Higgs Factory to an e^+e^- one

The LHC is a large Higgs Factory…





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

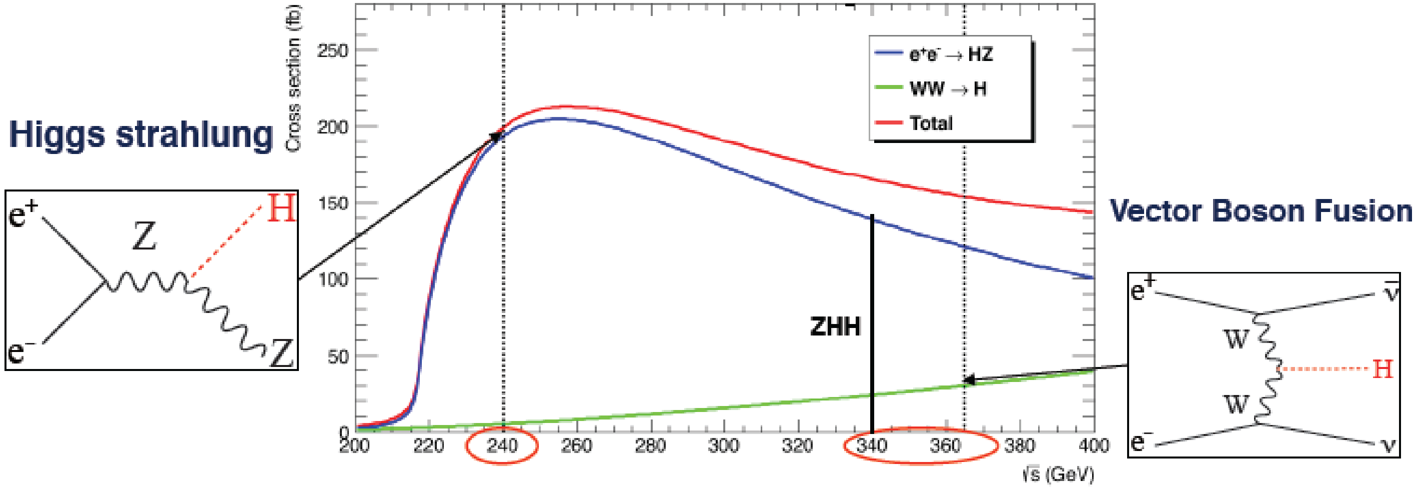
$$\sigma_{i\rightarrow f}^{\text{observed}} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

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

We don't know the width until measured directly

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

Higgs boson production at FCC-ee



FCC-ee as a Higgs factory:

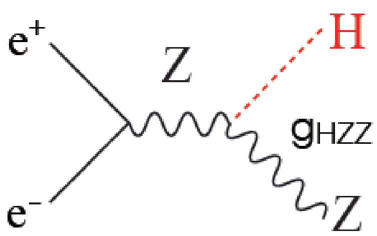
Higgs-strahlung (e+e → ZH): event rate & Signal/Bkgd are optimal at √s ~ 240 GeV : σ ~200 fb

- 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.

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

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

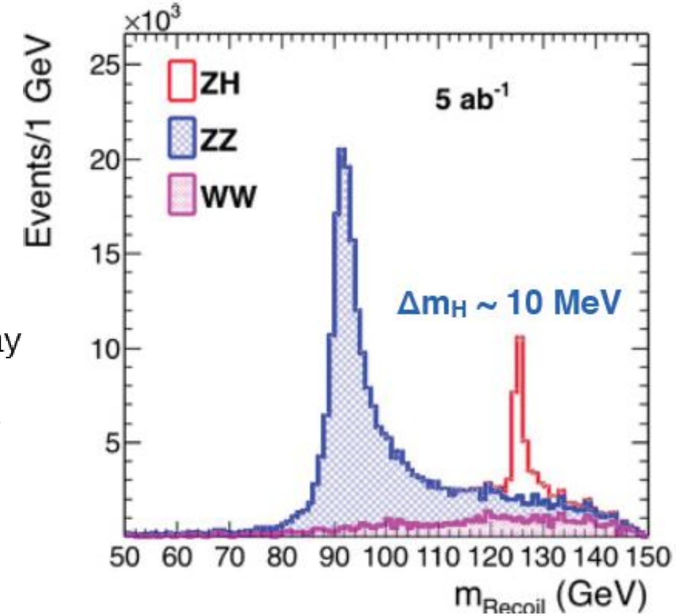


$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

E_+, E_- lepton energies from Z decay

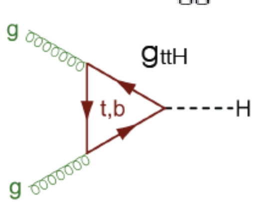
$$\sigma\left(e^+e^- \to ZH\right) \propto g_{HZZ}^2$$

absolute HZZ coupling meas.



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

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



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

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

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

Couplings measurement comparison with other ee-machines

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

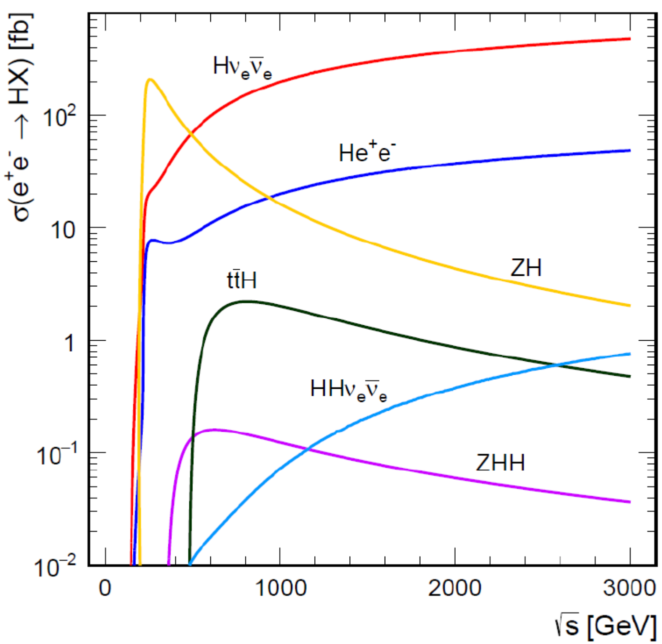
LHC caveats:

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

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

FCC-ee numbers are given for 2 IP. Precision on Couplings improve by ~30% with 4IP

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

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

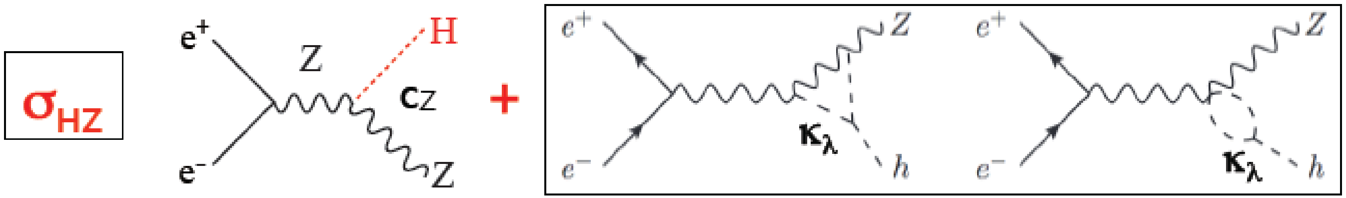
FCC-hh > 10^{10} H produced

\+

FCC-ee measurement of g_{HZZ}

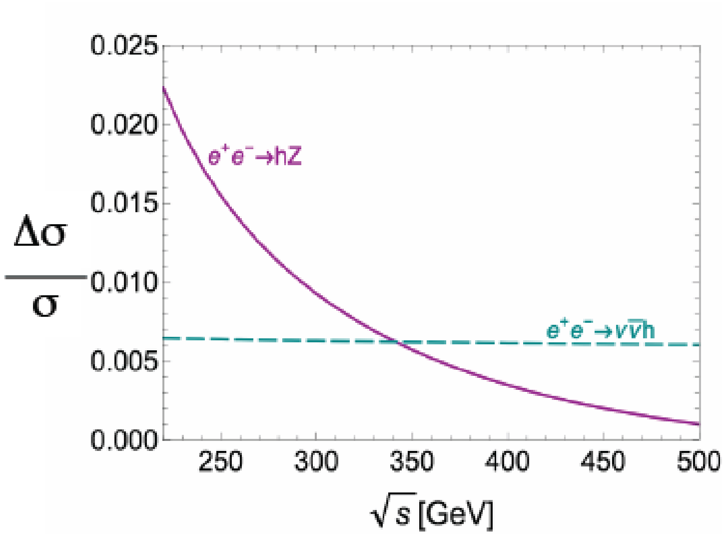
→ g_{HHH} , $g_{H\gamma\gamma}$, $g_{HZ\gamma}$, $g_{H\mu\mu}$, Br_{inv} at high precision

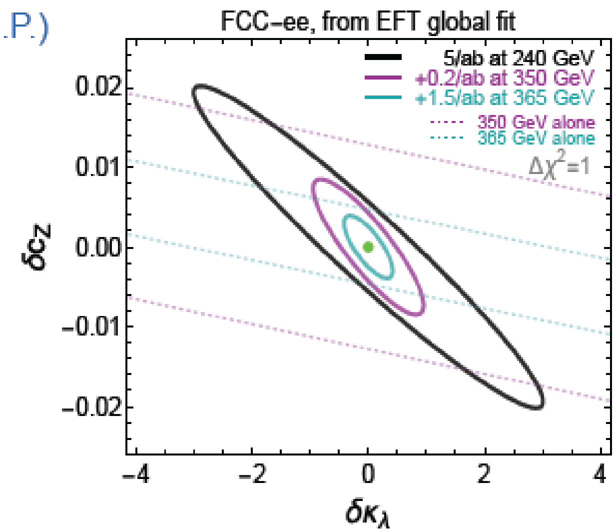
Measurement of the Higgs self-coupling



M. McCullough
arXiv:1312.3322

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





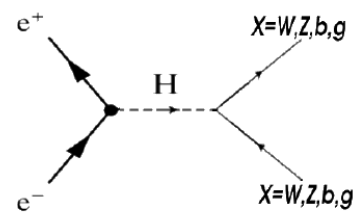
- from a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 21% (4 IPs)
- changing CMS energy helps in reducing correlations

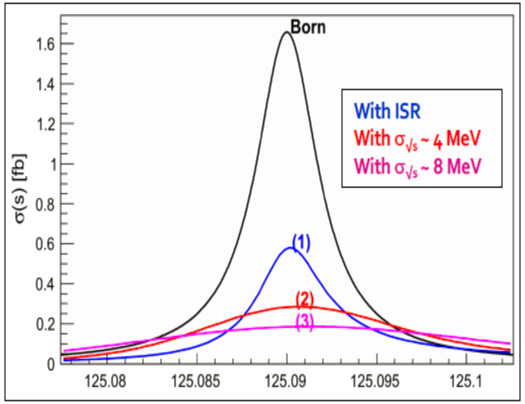
Yukawa coupling to electrons via s-channel e+e- → H production

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

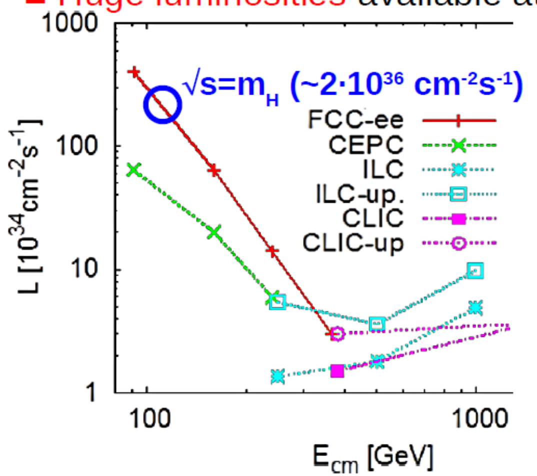
- Higgs decay to e^+e^- is unobservable: $BR(H \to e^+e^-) \propto m_e^2 \approx 5 \cdot 10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu \to H) \approx 70$ pb. Tiny κ_e Yukawa coupling ⇒ Tiny $\sigma(ee \to H)$:

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





- Huge luminosities available at FCC-ee:

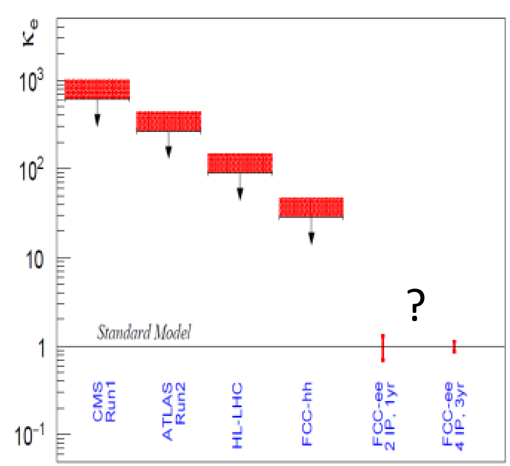


<u>In theory</u>, FCC-ee running at H pole-mass $L_{int} \approx 20$ ab^{-1}/yr would produce O(30.000) H's

IFF 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?

Upper Limits / Precision on κ_e



Most significant channel: $e^+e^- \to H \to gg \to jj$ final state

The Z peak and the Electroweak Physics

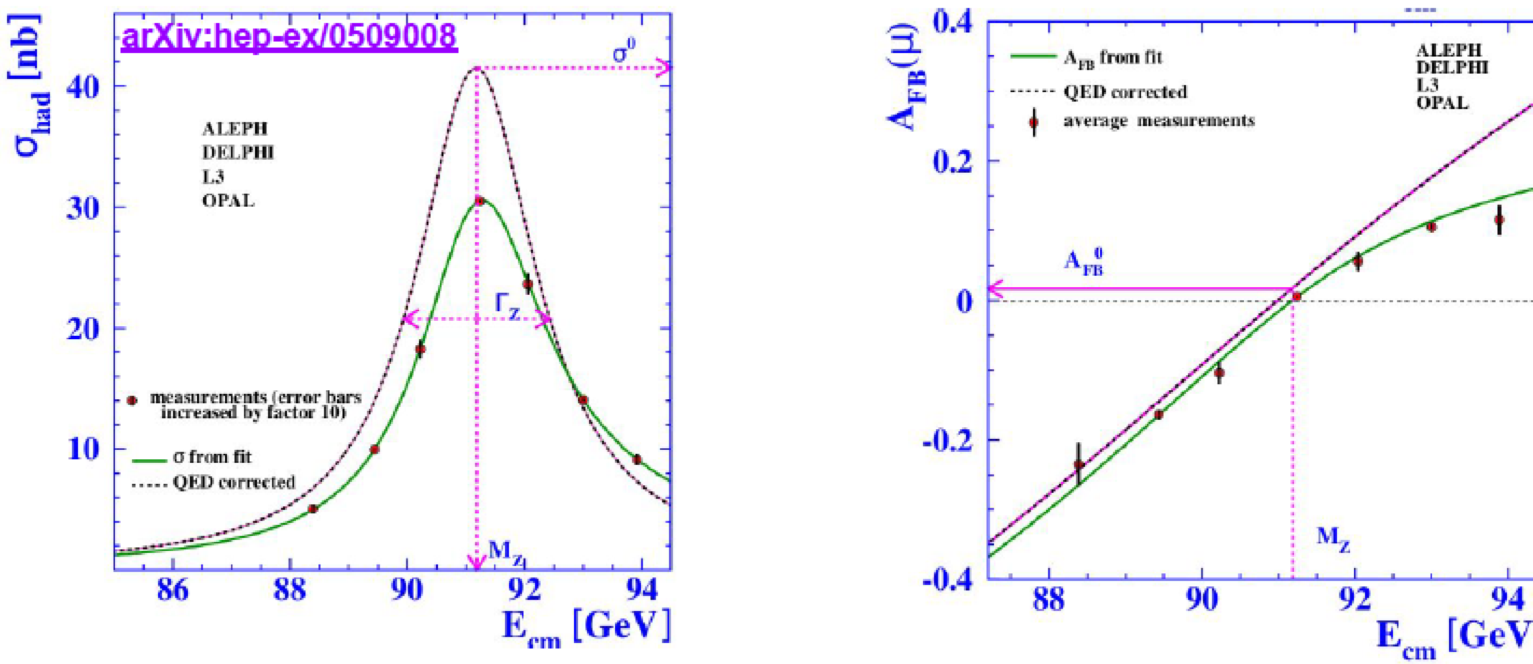
The electroweak program at the Z peak and at the WW threshold
is quite unique, most challenging and
maybe
the most promising part of the program
given the upward jump in statistics !

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

For the electroweak program we will also have

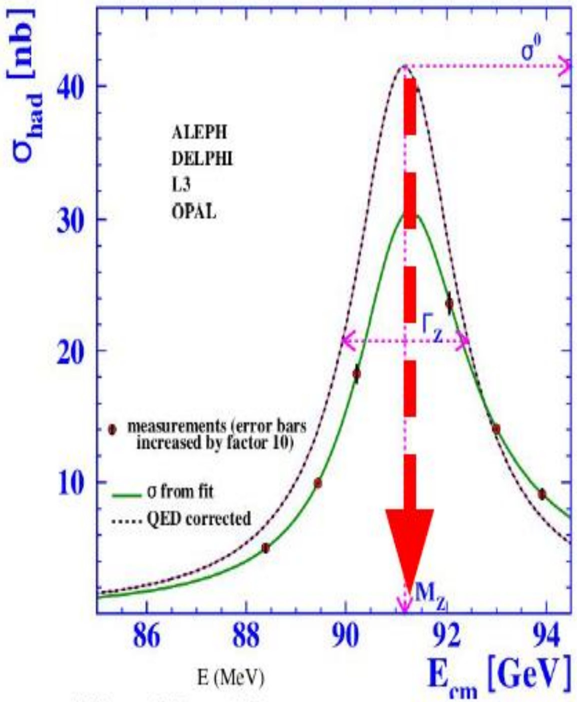
- 2 years at the WW threshold, 10^8 events/exp. ➔ 2.10^3 LEP Statistics

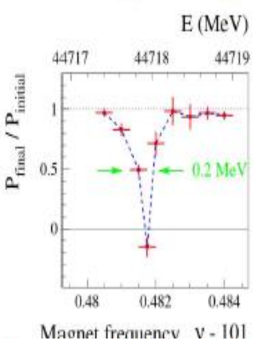
Z Lineshape Measurements



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

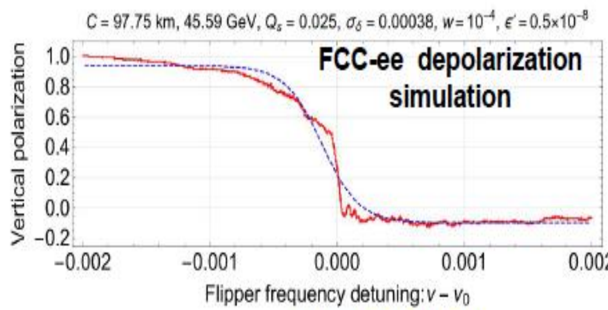
Z Lineshape: Mass





Resonant depolarization at LEP

- m_Z: position of Z peak
- Beam energy measured with extraordinary precision ($\Delta\sqrt{s}\approx100$ keV) using resonant depolarization of transversely polarized beams (method already used at LEP, much better prepared now, calibrations in situ with pilot bunches, no energy extrapolations, …)
- Beam width/asymmetries studied analyzing the longitudinal boost distribution of the $\mu\mu$ system



arXiv:1909.12245

5

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

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

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

FCC

Systematic uncertainties

opportunities (FCC-ee Stat.) — challenges (FCC-ee Syst.)

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^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross section luminosity measurement
N_ν ($\times 10^3$)	2996 ± 7	0.005	1	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216290 ± 660	0.3	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
A_{FB}^b, 0 ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	0.001	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	0.004	0.04	momentum scale
τ leptonic ($\mu\nu_\mu\nu_\tau$) B.R. (%)	17.38 ± 0.04	0.0001	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	0.25	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)$ ($\times 10^4$)	1170 ± 420	3	small	from R_ℓ^W
N_ν ($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	17	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	0.10	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

Systematics in the table are preliminary and often largely dominant

We should use 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

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

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

Theory work is critical and initiated (1809.01830)

More on TeraZ : The Flavor/Tau Factory

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
$\|V_{ub}\|$ (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 $\tau_+ \tau_-$, spectroscopy (produce b-baryons, B_s …)
- Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}

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

➔ need special detectors (PID) under study

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

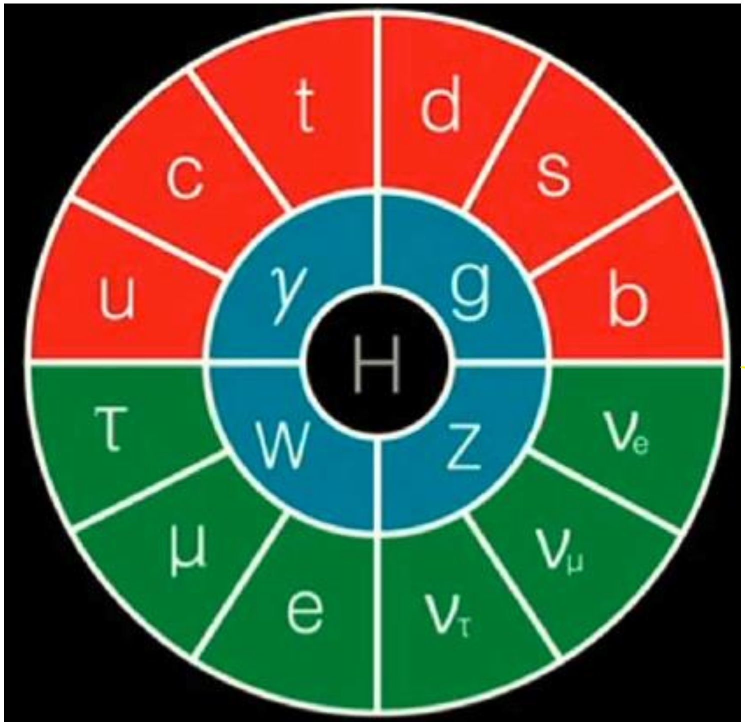
High-precision measurement of $\alpha_s(m_Z)$ with R_ℓ in Z and W decay, jet rates, τ decays, etc. : 10^{-3} →10^{-4}

Large √s lever-arm between 30 GeV and 360 GeV, fragmentation, baryon production ….

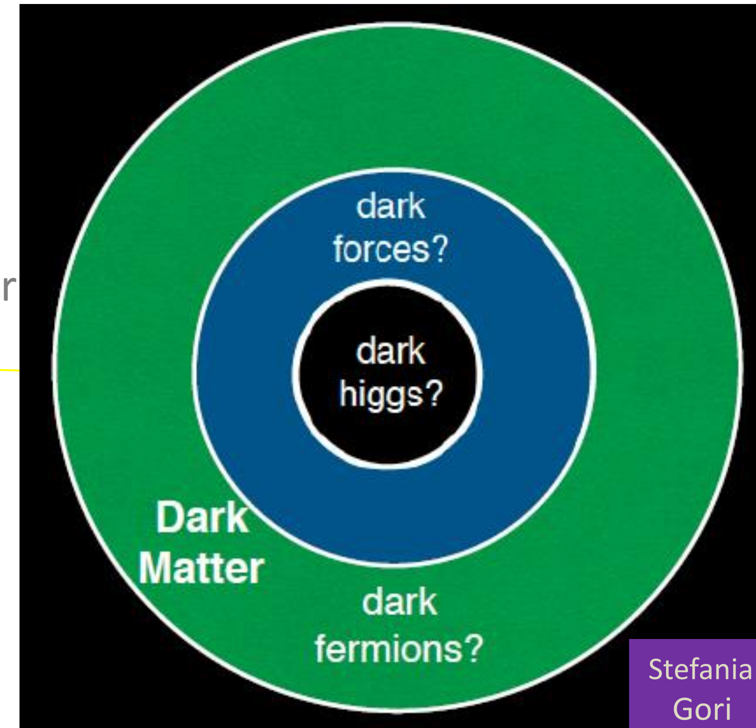
→ **Testing running of α_s to excellent precision**

Dark Sector at Z factory

With the Higgs discovery SM works well, yet we need new physics to explain the baryon asymmetry of the Universe, the dark matter etc… without interfering with SM radiative corrections



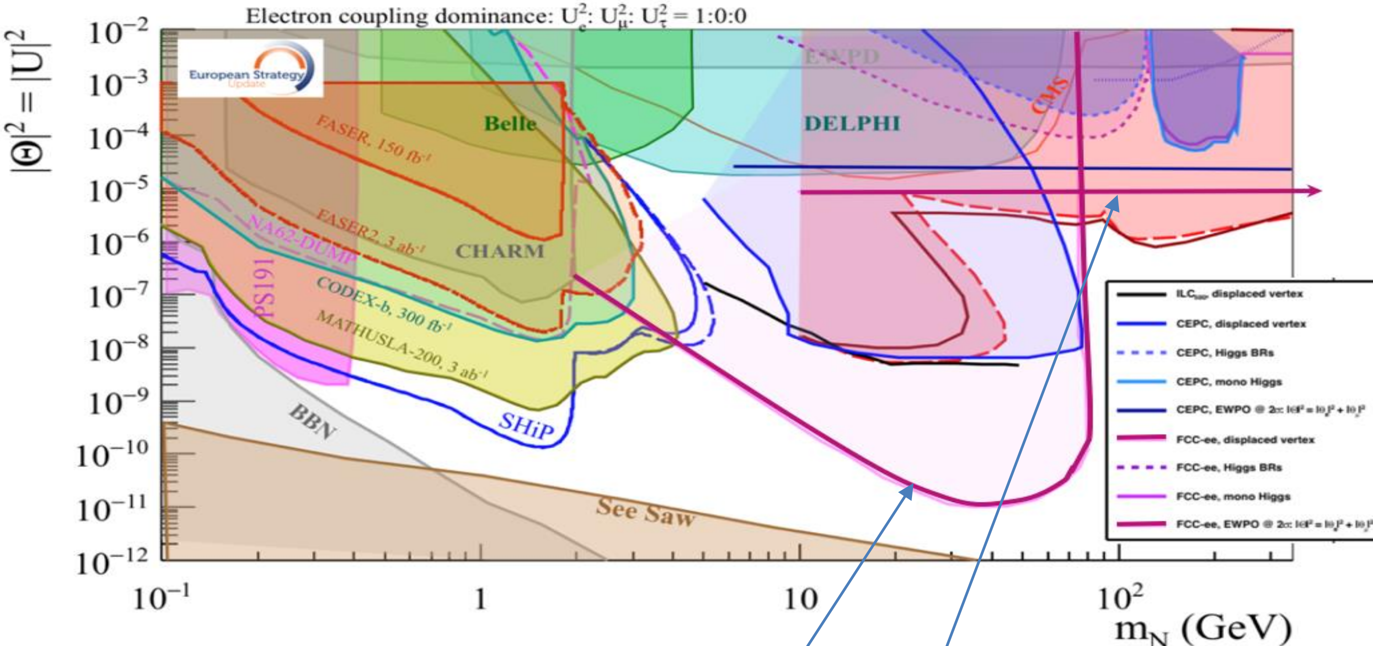
mediator
or
mixing



Dark photons, Axion Like Particles, sterile neutrinos, all *feebly coupled* to SM particles

Feebly interacting particles

This example figure is relevant to Neutrino, Dark sectors and High Energy Frontiers.
FCC-ee compared to the other machines for right-handed (sterile) neutrinos



- Significant extension reach for observing **heavy neutrino decays** (here for 10^{12} Z) 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, all the way to very high energies (500-1000 TeV): arXiv:2011.04725

FCC-ee discovery potential and Highlights

FCC-ee could explore, observe or 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 ($Z \dashrightarrow \mu\tau$, $e\tau$) in 5 10^{12} Z decays and τ BR in 2 10^{11} $Z \rightarrow \tau\tau$
  + flavour physics (10^{12} bb events) ($B \rightarrow s \tau\tau$ 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, $H \rightarrow gg$) etc….

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

FCC main goals for 2021 - 2026

Overall goal:

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

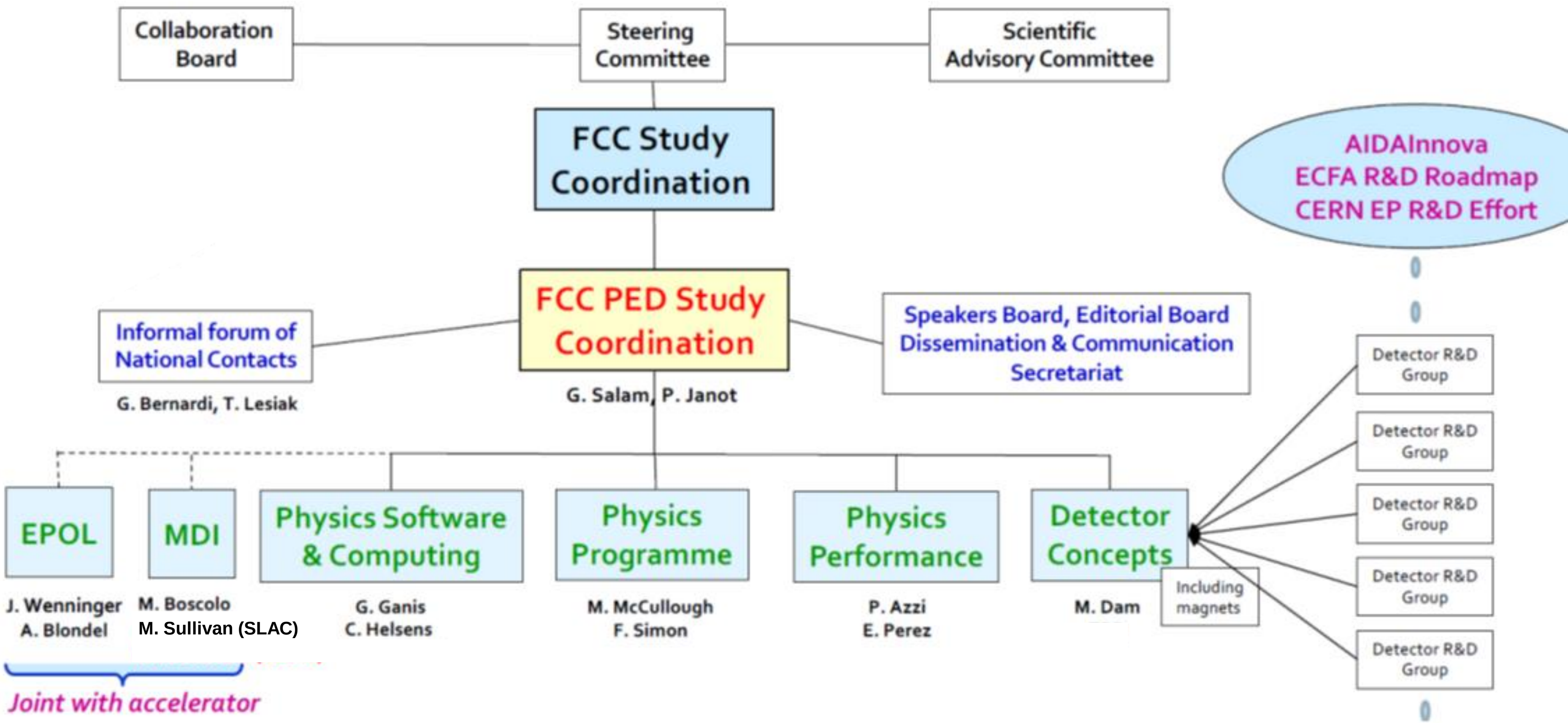
This requires successful completion of the following four main activities:

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

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

- Machine designs and main technology R&D lines
- completion of first physics case studies in 2021-22 → detector requirements
- reach out to all 'European and International Partners'
- Establish user communities, work towards proto experiment collaboration by 2025/26

- US community can bring enormously to the project, by starting or contributing to R&D studies to render the challenging FCC physics a success: precision EW measurements
  Tau physics (lifetime, mass etc.)
  -- LLP's detection, & Higgs of course (self-coupling and 1st generation)


Collaboration Board
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Scientific Advisory Committee
FCC Study Coordination
AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort
FCC PED Study Coordination
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Informal forum of National Contacts
G. Bernardi, T. Lesiak
Speakers Board, Editorial Board
Dissemination & Communication
Secretariat
Detector R&D Group
Detector R&D Group
Detector R&D Group
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Detector R&D Group
EPOL
J. Wenninger
A. Blondel
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M. Boscolo
M. Sullivan (SLAC)
Physics Software & Computing
G. Ganis
C. Helsens
Physics Programme
M. McCullough
F. Simon
Physics Performance
P. Azzi
E. Perez
Detector Concepts
M. Dam
Including magnets
Joint with accelerator

Outlook

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

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

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

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

- The 4th Annual FCC Week took place in June 2021: https://indico.cern.ch/event/995850/
- FCC Physics Workshop will be on 7-11 February 2022 in Liverpool
- The 5th Annual FCC Week will take place in Paris in May-30th to June 3rd 2022

Please join the effort, together we will be much stronger !

We hope there will soon be a strong FCC-US group