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

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

With many thanks to all in the FCC collaboration, in particular
J. Alcaraz, M. Benedikt, A. Blondel, M. Dam, D. d'Enteria, C. Grojean, 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

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

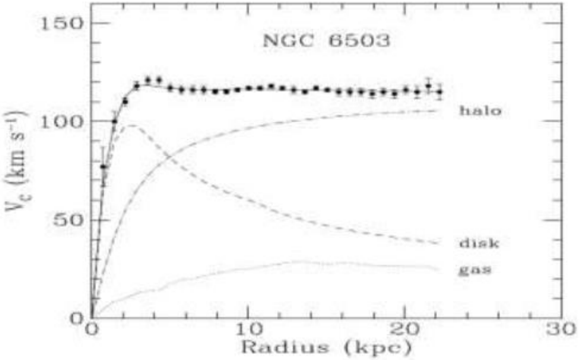
since then we have been discovering all the particles that have **electric charge** or **QCD charge**, or **weak isospin** (SM couplings), and the Higgs boson, **by increasing accelerator energies.**

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

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

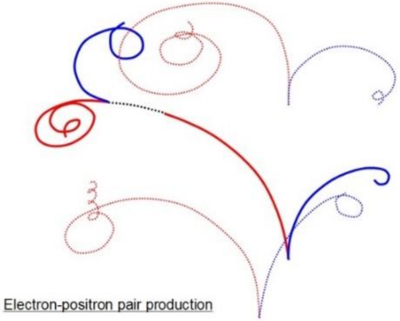
What is Dark matter ?

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



Rotation curve for Galaxy

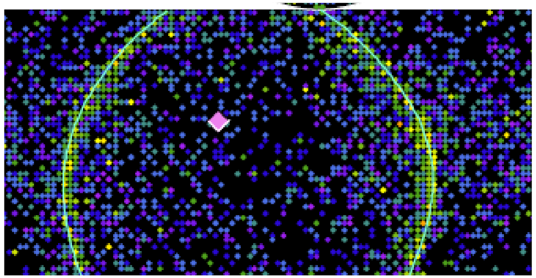
Were is primordial antimatter gone?



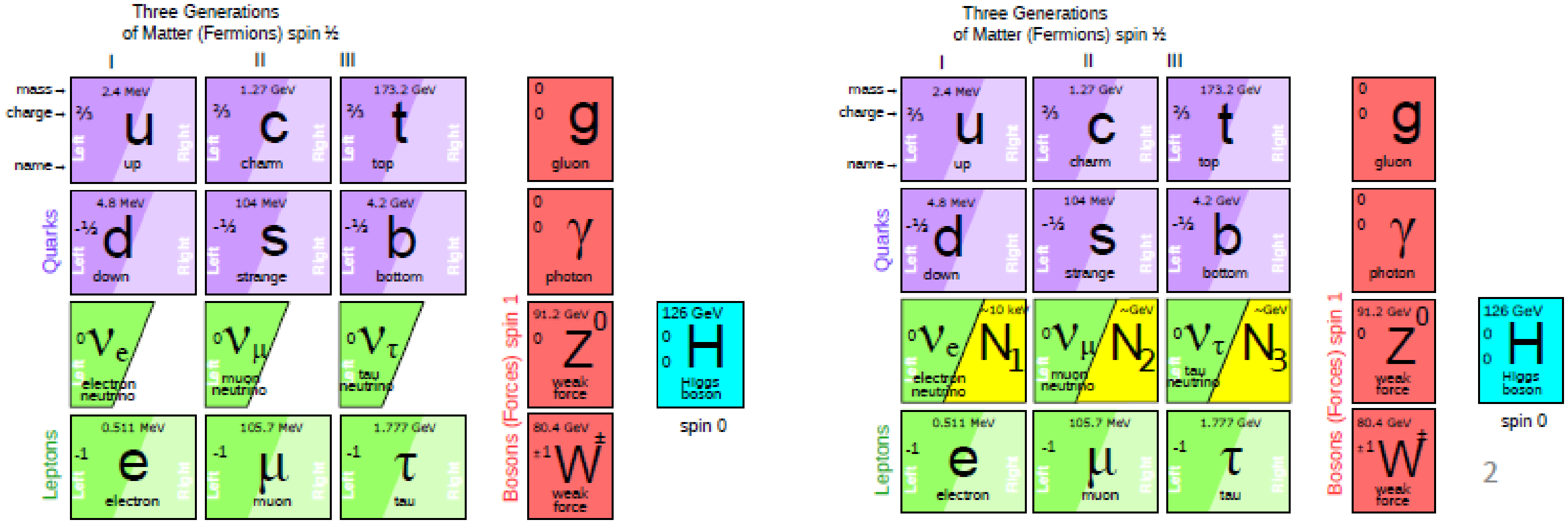
Electron-positron pair production

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?



… some pieces of the SM 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: Dark Matter, Baryon Asymmetry, ν-masses

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

→ It is a unique object, a scalar particle/field (spin 0), not a matter field, not a boson mediating a gauge interaction, but a field carrying a new type of interaction of the Yukawa type.

→ Many proposals for new accelerators to study it, and to study Beyond SM physics

→ Easier choice now that it has been discovered.

Precise nature of the Higgs boson ?

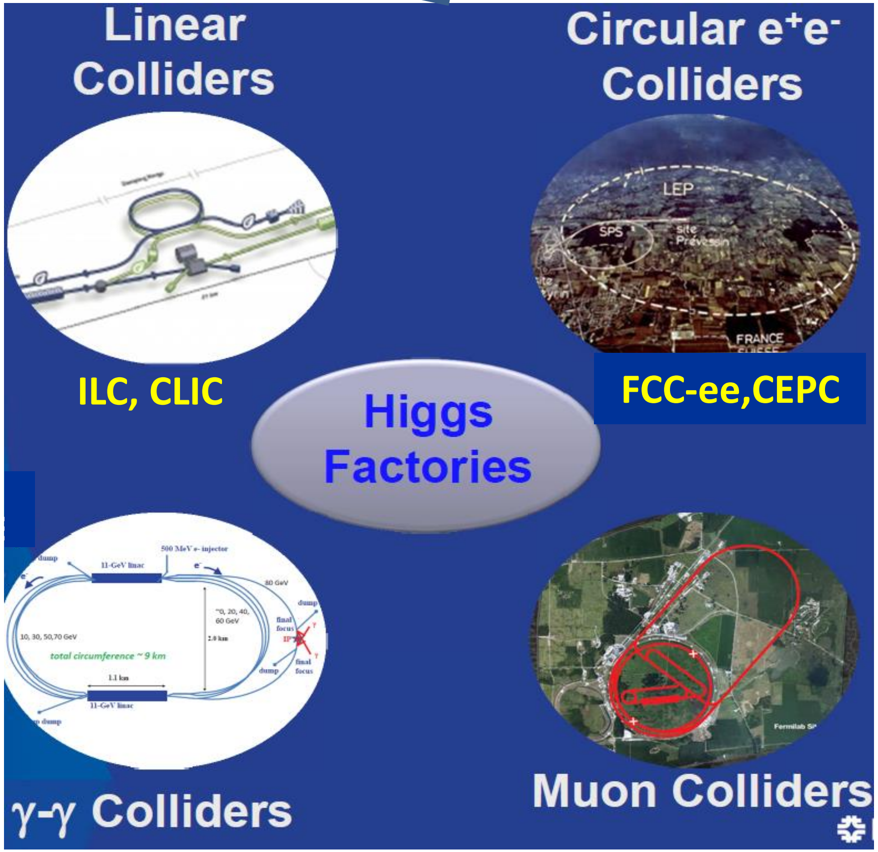
Origin of electroweak symmetry breaking (EWSB) ?

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.



Linear Colliders

Circular e^+e^- Colliders

ILC, CLIC

FCC-ee,CEPC

Higgs Factories

γ-γ Colliders

Muon Colliders

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 between ee and hh, offers the most versatile and adapted response to today’s physics landscape

The Rich FCC-ee physics program

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

"Higgs Factory" Programme

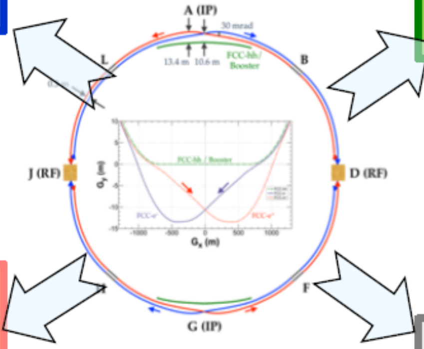
- At two energies, 240 and 365 GeV, collect in total
    - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s} = 125$ GeV

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 physics case for and e+e- collider is well established**

➔ **The potential of the FCC-hh at the energy frontier is also excellent:**

- Measurement of Higgs Self-coupling at the 3 to 5% level
- Highest reach in sensitivity for di-higgs studies, dark matter searches and more
- New possible heavy particles could be directly discovered for masses up to 20-40 TeV
- Large potential also from indirect searches
- **Possibility for a Heavy-ion program at the highest energies**

We are not ready to build the *hh* machine soon, and reaching the high energy frontier with a Muon Collider would take most likely even more time, if it’s even possible.

➔ **European Strategy recommendations in 2020**

Physics Goals and Prospects of the Heavy Ion Programme at FCC-hh

Energy per nucleon-nucleon collision: $\sqrt{sNN}$ = 39 TeV for Pb-Pb and 63 TeV for p-Pb collisions

- Integrated lumi/month is 35 (8) nb^{-1} for baseline scenario, 110 (30) nb^{-1} for ultimate scenario for Pb-Pb (p-Pb)
- Increase by factor 10-30 compared to the future LHC Runs
- 3 main fields of study in a Heavy Ion program at FCC-hh:

1) Novel access to QCD thermodynamics and QCD equilibration processes

- At FCC, creation of denser and hotter systems, thus expanding for a longer duration and over a larger volume → stronger collective phenomena.
- Going from 5.5 TeV to 39 TeV, increases both the initial energy density and the volume of the system by a factor of about two, up to values of about 40 GeV/fm^3 and 11 000 fm^3
- FCC ion collisions reach temperature of ~1 GeV, where charm quarks act as active thermal degrees of freedom in the QGP equation of state

2) Characterization of dense QCD matter through hard scattering processes

- FCC-hh and its large statistics will greatly expand the set of hard-scattering processes available for studies at the LHC, including novel probes such as the top quark and the Higgs boson
- From LHC to FCC-hh, the ttbar cross section increases by a factor of 80 → 3-10x10^5 tt→bb ll $\nu\nu$ reconstructed events in one month of a Pb-Pb run → new tools to study the time evolution of the QGP density and the role of colour coherence
- First observation of Υ from bb recombination is expected

3) Parton Saturation in ultra-dense kinematic domain

- Parton densities rise strongly with decreasing x, and is higher in NN than in pp→ saturation→ study of QCD in a new kin. regime
- Complementarity between pA and eA collisions to study the largest kinematic surface
- Promising observables: a) photon production and photon-hadron correlations at forward rapidity, which are sensitive to the small x & large Q^2 region where saturation is expected to set in; b) heavy quarkonium production in γA collisions; c) production of heavy particles (W,Z,t) which provide strong constraints on the modification of the parton density functions in nuclei at small x &large Q^2

Many more details and studies in: Heavy ions at the future circular collider, A. Dainese et al., arXiv:1605.01389

FCC

➔ Recommendations from the European Strategy for Particle 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, 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 2021-2025

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/detectors is essential for high precision measurements (hidden systematic biases)

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

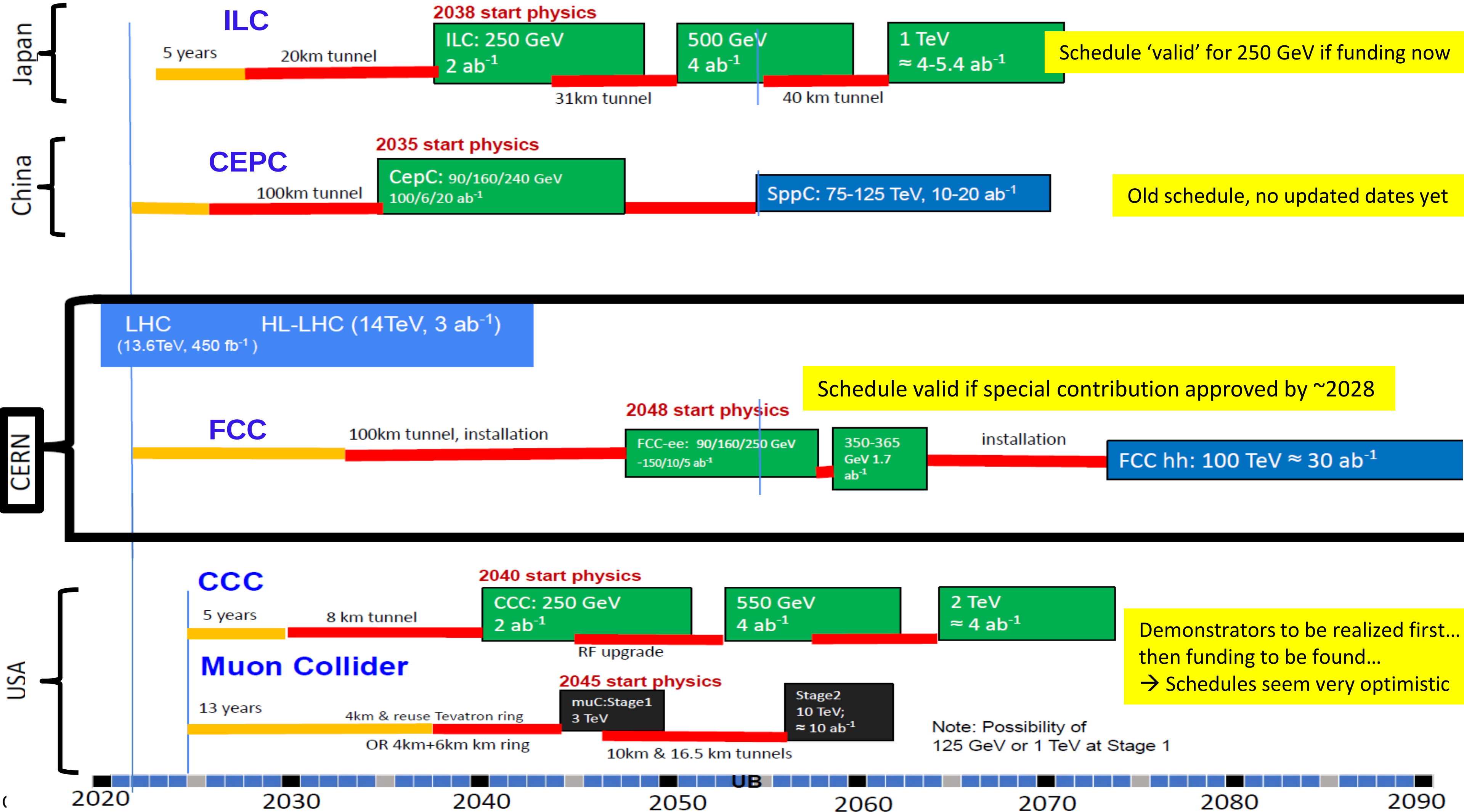
The non availability of beam polarization (an advantage of linear colliders) is also not a crucial drawback since FCC-ee will run at different energies and will accumulate much more statistics.

Indicative scenarios of future colliders

🟦 Proton collider
🟩 Electron collider
⬛ Muon collider

🟥 Construction/Transformation
🟧 Preparation / R&D

Original from ESG by UB
Updated 25/7/22 by MN
(+gb comments 9/22)



Schedule 'valid' for 250 GeV if funding now

Old schedule, no updated dates yet

Schedule valid if special contribution approved by ~2028

Demonstrators to be realized first…
then funding to be found…
→ Schedules seem very optimistic

Note: Possibility of
125 GeV or 1 TeV at Stage 1

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

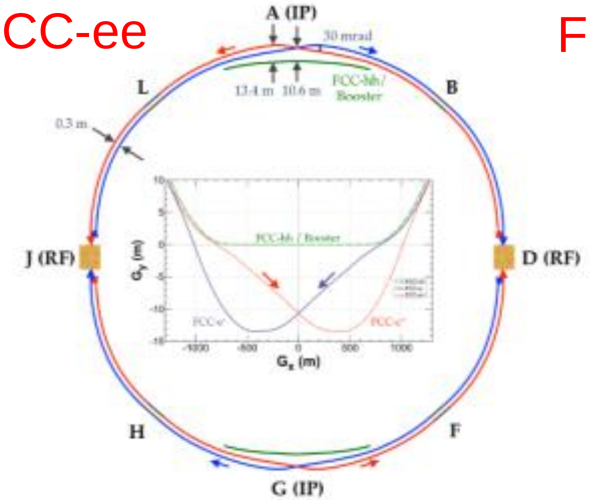
Comprehensive cost-effective program maximizing physics opportunities

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

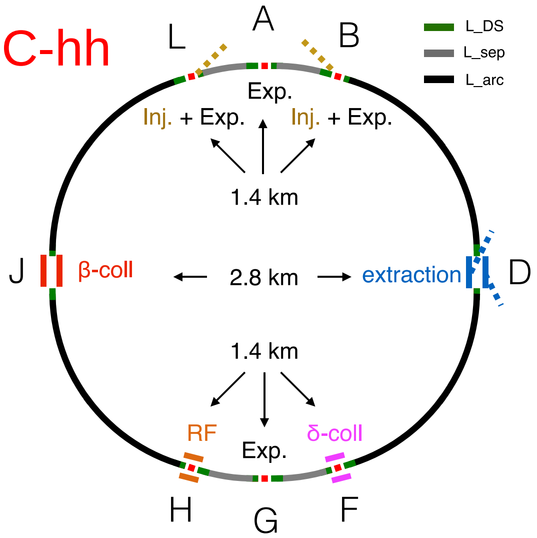
Complementary physics

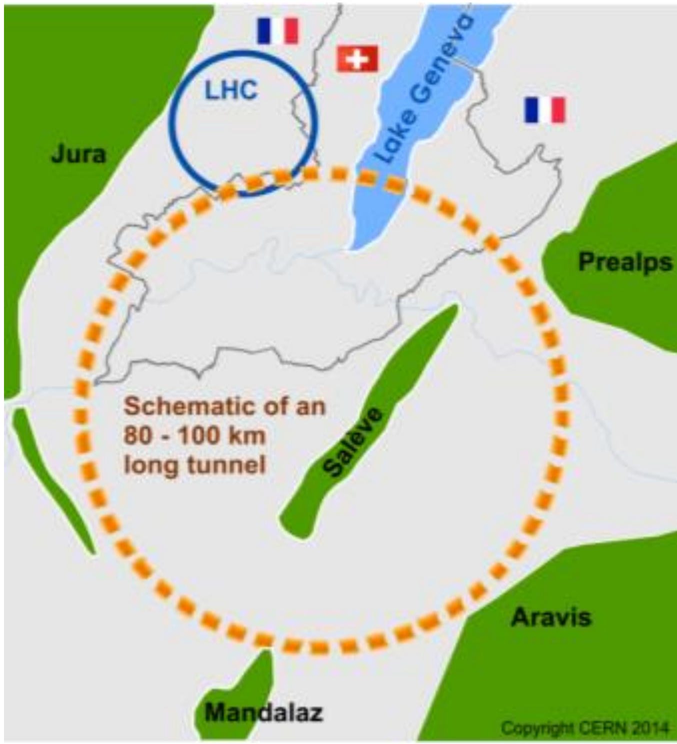
- Integrating an ambitious high-field magnet R&D program
- Common civil engineering and technical infrastructures
- Building on and reusing CERN's existing infrastructure.
- FCC-INT project plan is fully integrated with HL-LHC exploitation and provides for seamless continuation of HEP

FCC-ee



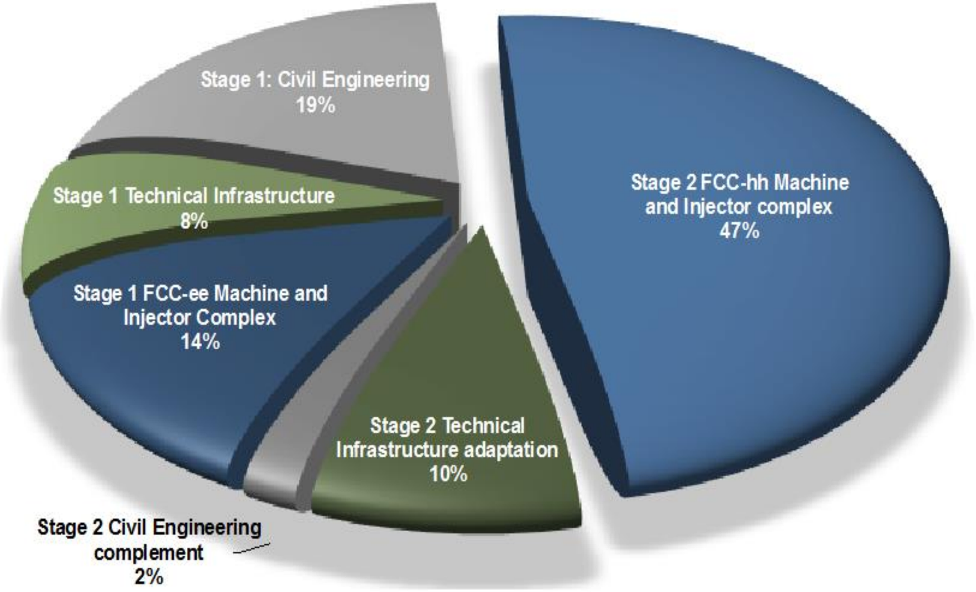
FCC-hh





FCC-ee and FCC-INT cost estimates

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



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

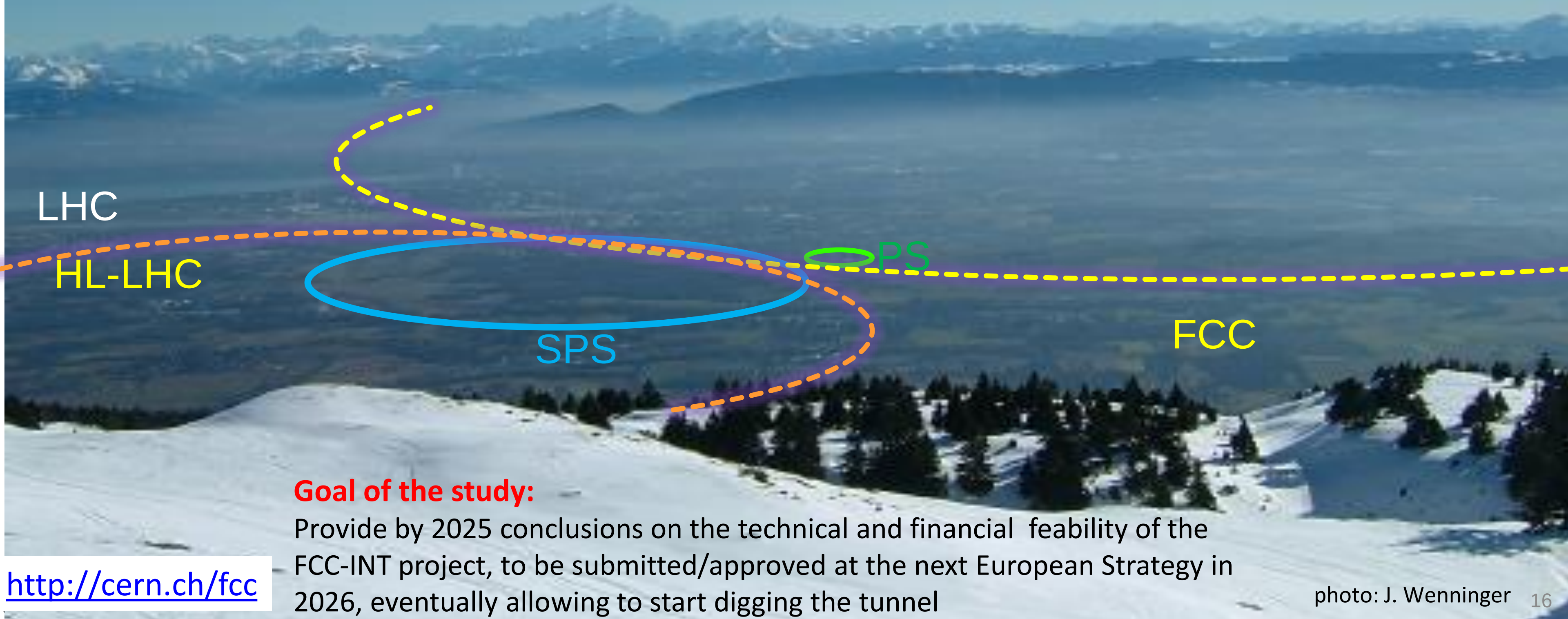
- Associated to a total project duration of ~20 years (2028 – 2048)

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

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

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

Future Circular Collider Feasibility Study



Goal of the study:

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

http://cern.ch/fcc

photo: J. Wenninger

FUTURE CIRCULAR COLLIDER

FCC feasibility study organization -

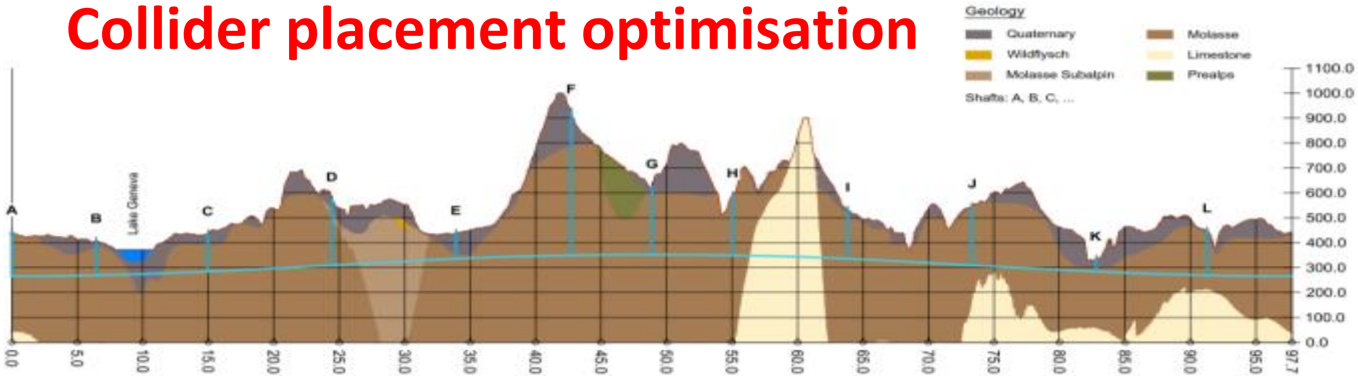
Approved by the CERN Council September 2021

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, C. Grojean	Accelerators T. Raubenheimer, F. Zimmermann	Techn. coordination techn. infrastructure K. Hanke	Host State processes and civil engineering T. Watson (1 Nov. '21)	Organisation and financing models P. Collier (interim)
physics programme M. McCullough, F. Simon	ee design K. Oide, A. Chance	Electricity distribution J.-P. Burnet	administrative processes F. Eder, J. Gutleber	project organisation model NN
detector concepts M. Dam, 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		

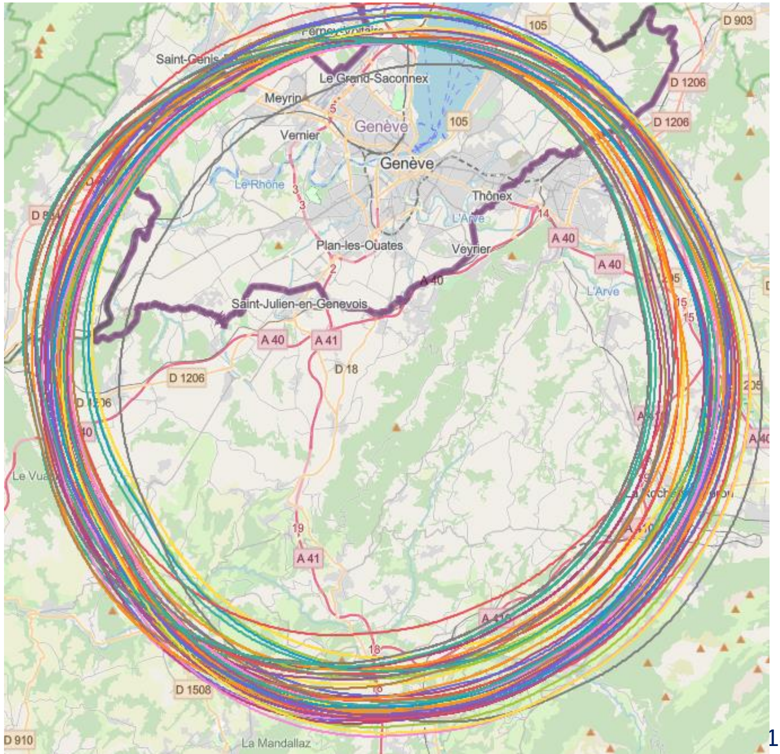
Collider placement optimisation



- 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



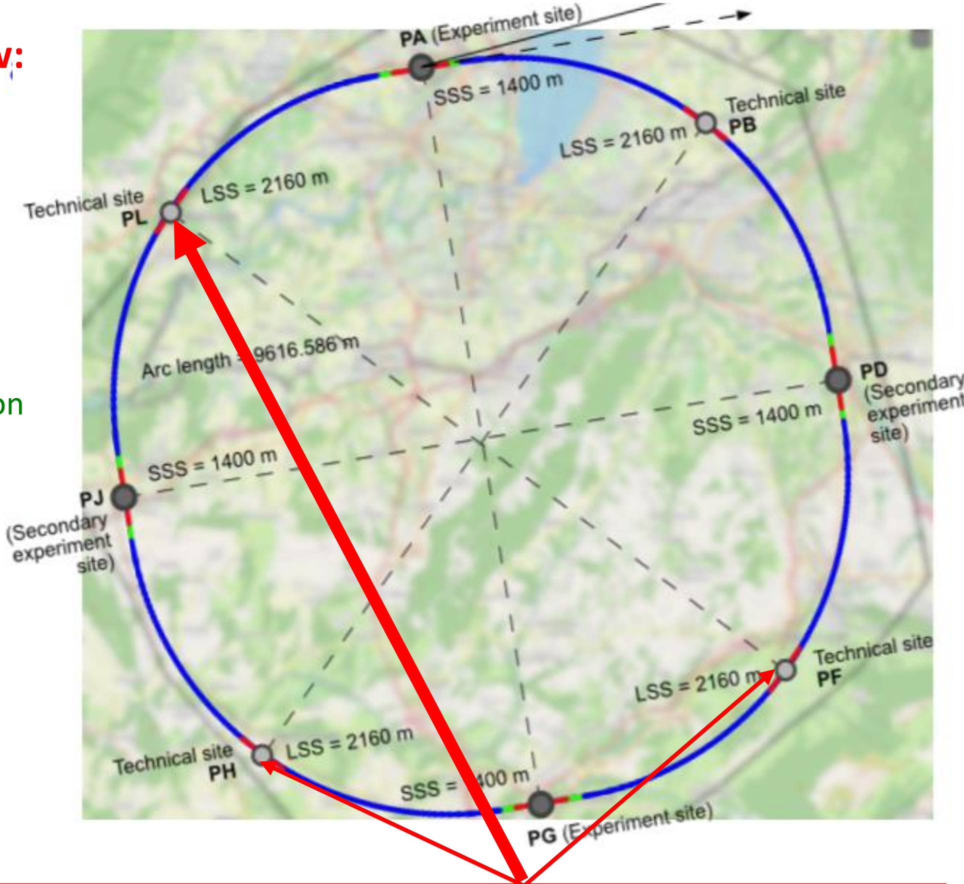
Collider placement optimisation

Main recommendation of the 2021 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."

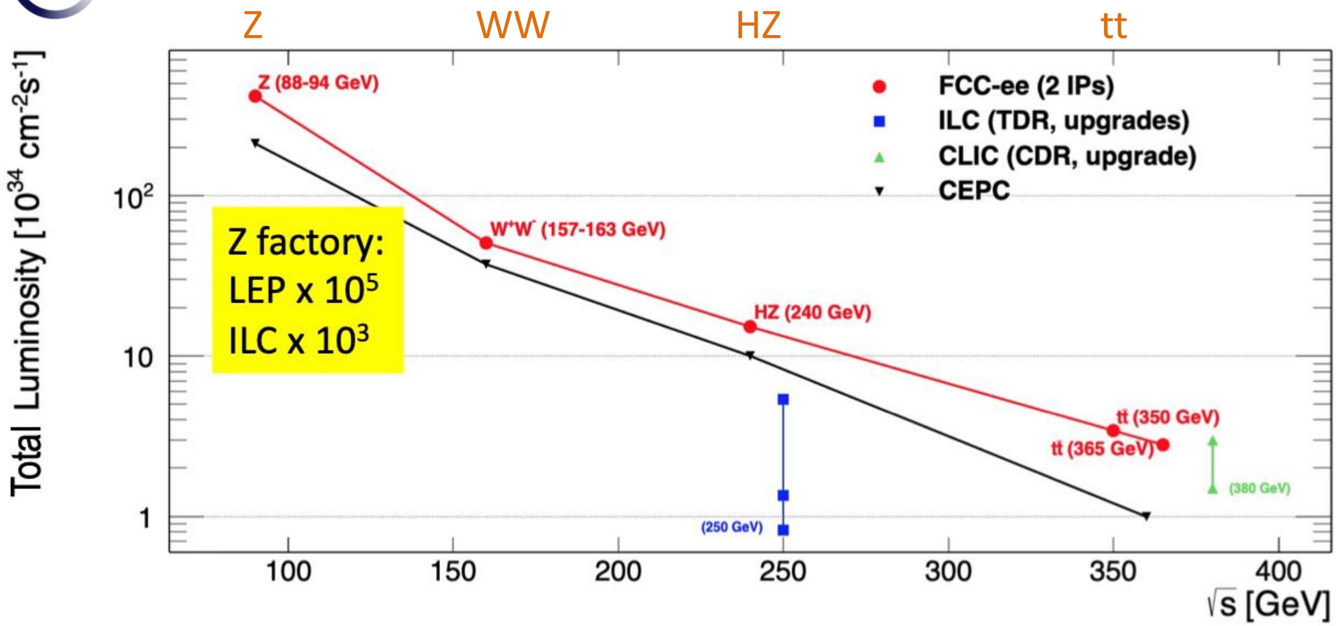
- Number of surface points reduced from 12 to 8
- Fourfold super-periodicity compatible with 2 or 4 Interaction Points (IP) for FCC-ee. Decision to be made later.
- Total length reduced from 97.75 to 91.17 km
  - ➔ PA close to LHC point8
  - ➔PG about 10 km from Annecy

- Seek concertation with local authorities
- Key representatives of French "Ministère de l'Enseignement Supérieur, de la Recherche et de l'Innovation (MESRI)" were met at CERN to discuss FCC placement and feasibility study.

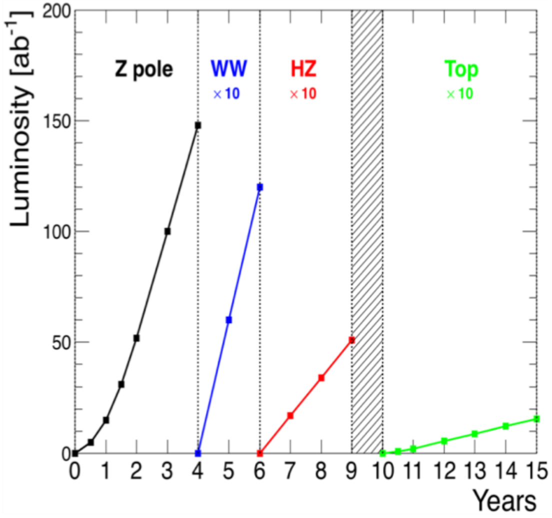


Studies now going on for the placement of the RF stations

FCC-ee run plan



Z factory:
LEP x 10^5
ILC x 10^3



Extracted from FCC CDR

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	
FCC-ee-Z	4	88-95 ± <100 KeV	150	3×10^{12} visible Z decays	LEP * 10^5
FCC-ee-W	2	158-162 <200 KeV	12	10^8 WW events	LEP * 2.10^3
FCC-ee-H	3	240 ± 1 MeV	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365 ± 2 MeV	1.5	10^6 $t\bar{t}$ events	Never done

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

Detector requirements (present status)

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

"Higgs Factory" Programme

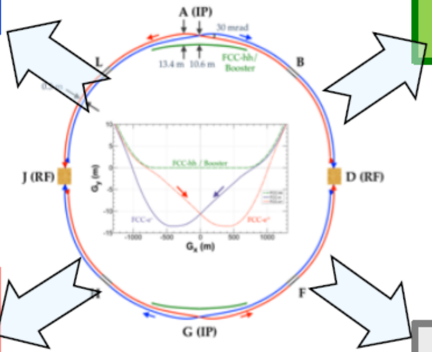
- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}$ GeV^{-1} commensurate with $\mathcal{O}(10^{-3})$ beam energy spread
- Jet energy resolution of 30%/√E in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

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

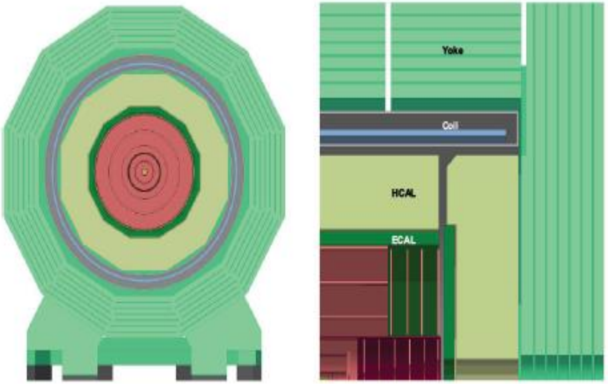
Feebly Coupled Particles - LLPs

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

Detectors under Study

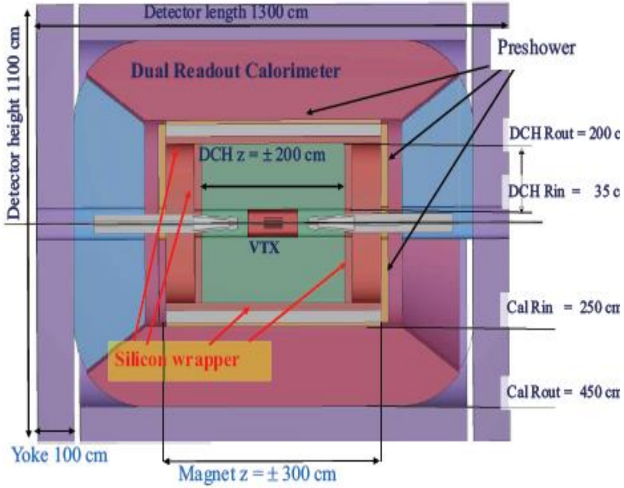
CLD



conceptually extended from the CLIC detector design

- full silicon tracker
- 2T magnetic field
- high granular silicon-tungsten ECAL
- high granular scintillator-steel HCAL
- instrumented steel-yoke with RPC for muon detection

IDEA



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

Noble Liquid ECAL

- explicitely designed for FCC-ee, recent concept, under development
- silicon vertex
- Low X_0 drift chamber
- Thin Solenoid before the Calorimeter
- High Granularity Liquid Argon Calorimetry

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

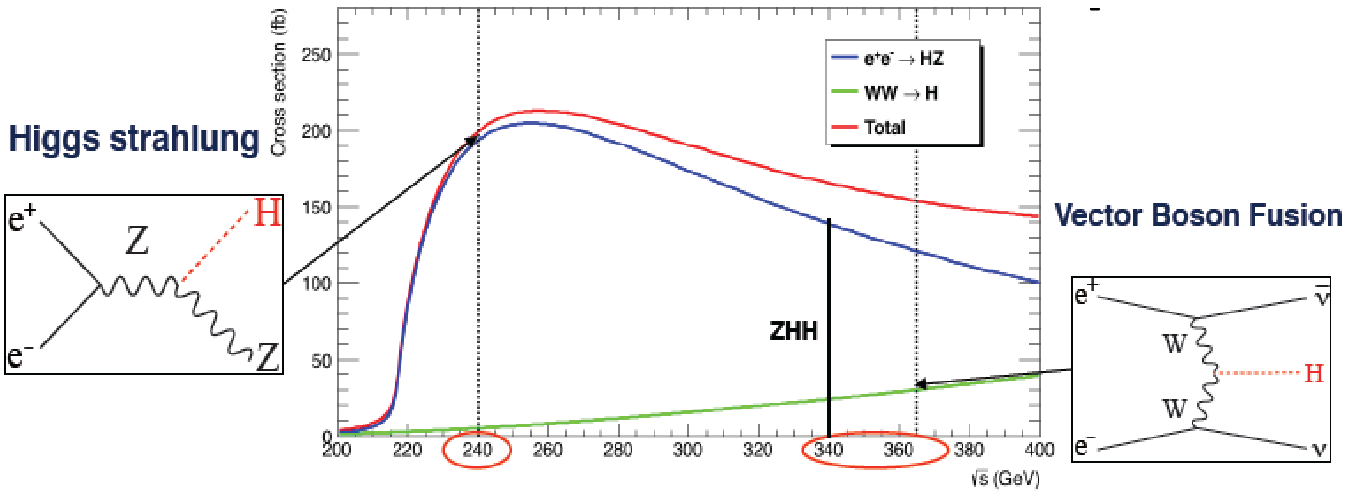
With potentially 4 experiments, many complementary options will be implemented,
Definitely a place to contribute

Physics of the Higgs boson at FCC-ee

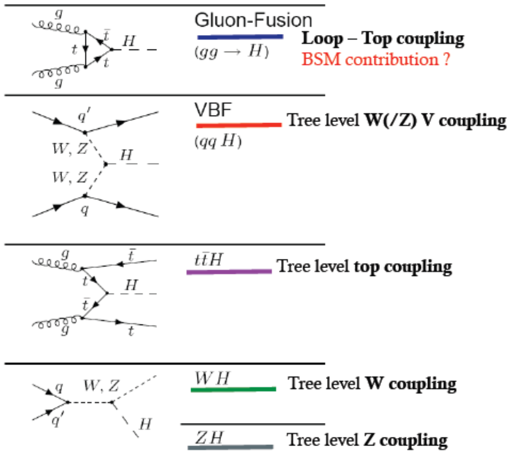
Baseline (2IP): at 240 and 365 GeV, collect in total 1.2M ZH events and 0.1M WW→H events

- **Statistics-limited measurements:**
  - Higgs couplings to fermions & bosons;
    → Model-independent measurements, 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, Higgs mass
- **Close to discovery level:**
  - Higgs self-coupling via loop diagrams :
    → complementarity to HH production at higher energy machines, like HL-LHC, or later FCC-hh
- **Unique possibility:**
  - Measure Higgs to electron coupling in s-channel production e+e-→H @ √s = 125 GeV
    highly demanding on luminosity, monochromatization with 2 or 4 IPs?
    → test of first generation yukawa coupling

Higgs boson production at FCC-ee



Production at LHC



FCC-ee as a Higgs factory:

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

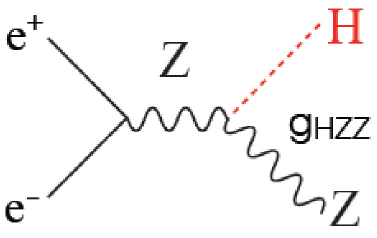
- 1.2 × 10^6 e+e- → ZH events with 5 ab^{-1}
- Target : (few) per-mil precision, statistics-limited.
- Complemented with ~100k events at √s = 350 – 365 GeV (of which 30% are via the WW fusion channel)

➔ 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.

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.

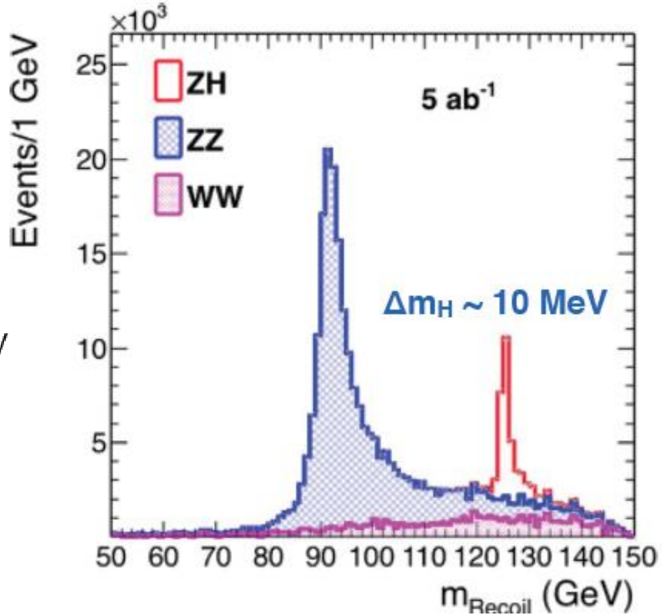


$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

E_+, E_- lepton energies from Z decay

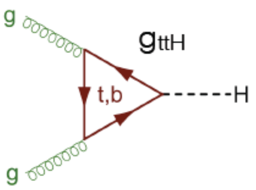
$$\sigma\left(e^+e^- \to ZH\right) \propto g_{HZZ}^2$$

absolute HZZ coupling meas.



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

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

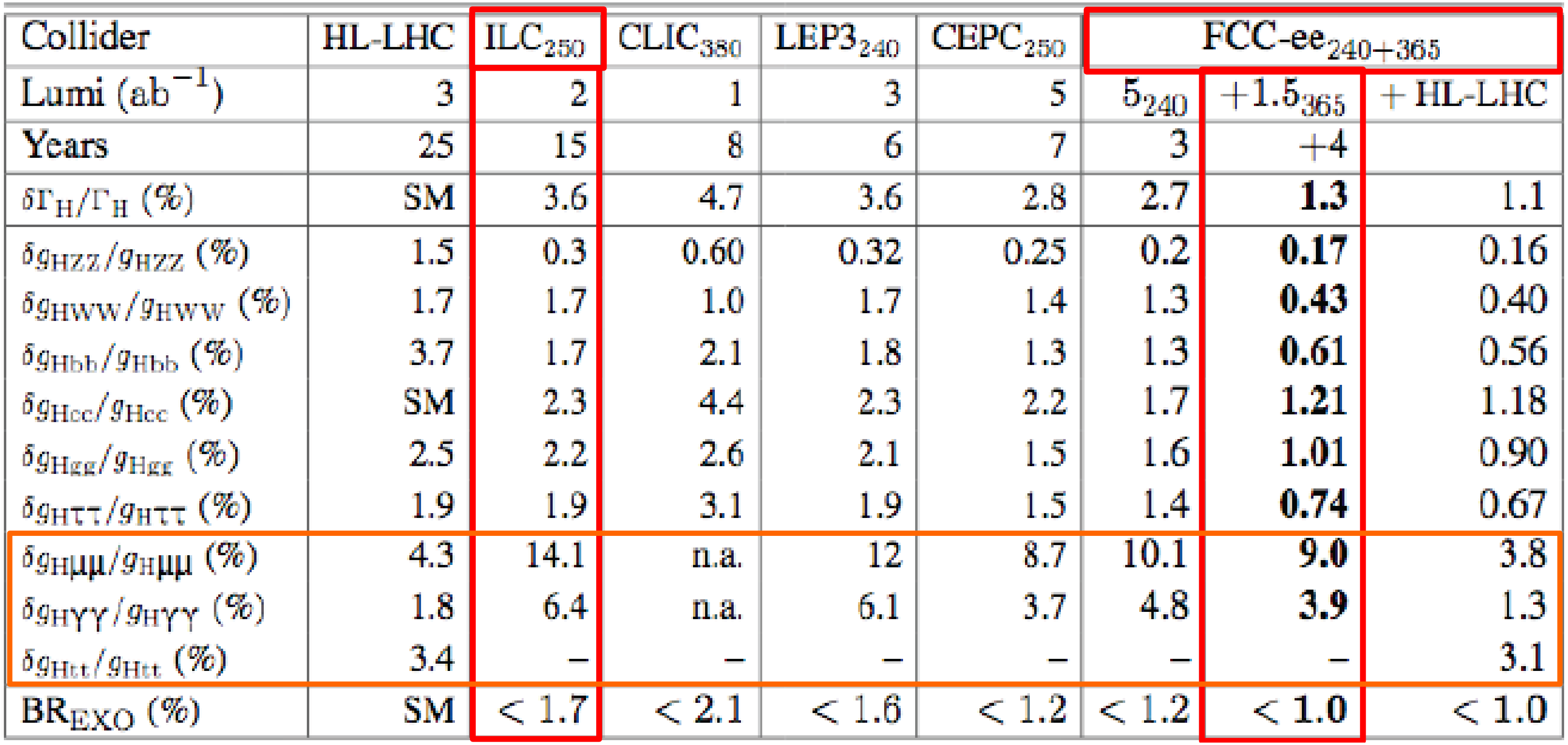


LHC can measure only product of couplings over Γ_H, it can measure only ratios of couplings.

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

LHC caveats:

- 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

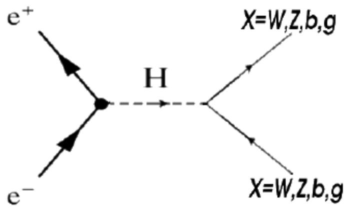
FCC-ee numbers are given for 2 IP. Precision on Couplings improve by ~30% with 4IP

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

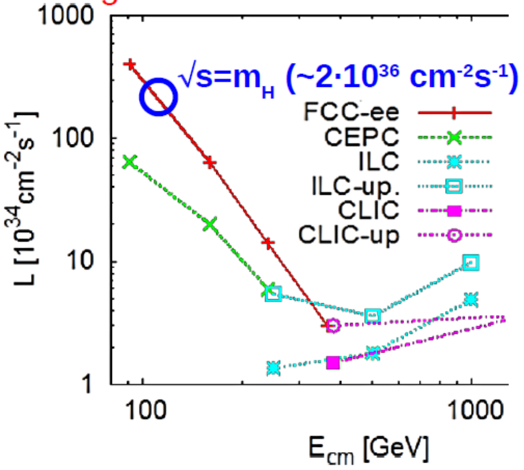
First generation Yukawa coupling will not be accessible at HL-LHC, FCC-hh or any other ee machine

- Higgs decay to e^+e^- is unobservable: $BR(H\to e^+e^-) \propto m_e^2 \approx 5\cdot10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny κ_e Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$:

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



- Huge luminosities available at FCC-ee:

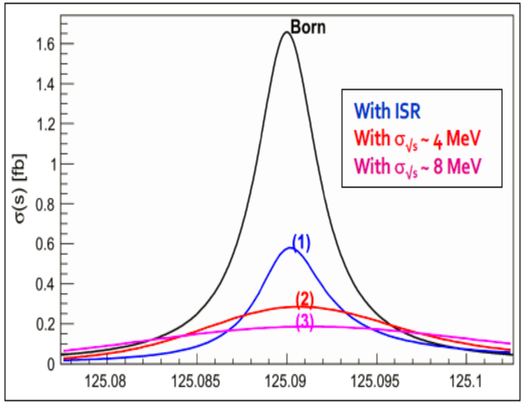


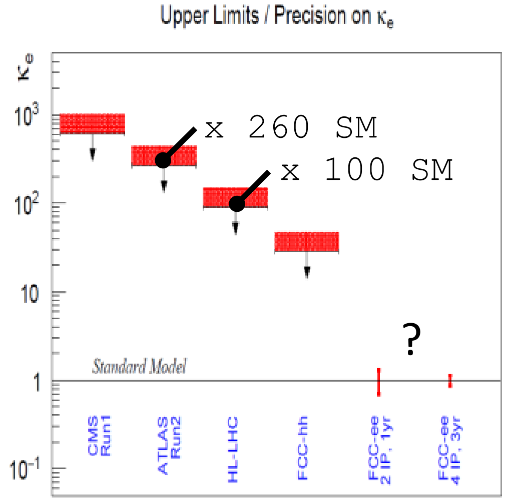
In theory, FCC-ee running at H pole-mass $L_{int} \approx 20$ ab^{-1}/yr would produce O(30.000) H's

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

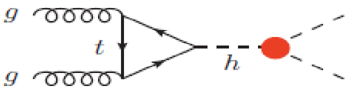
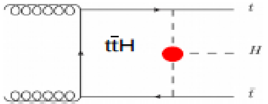
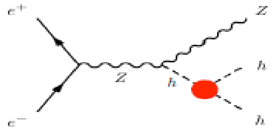
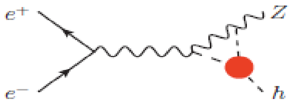
→ Electron Yukawa coupling measurable.
→ Higgs width measurable (threshold scan)?
→ Separation of possible nearly-degen. H's?

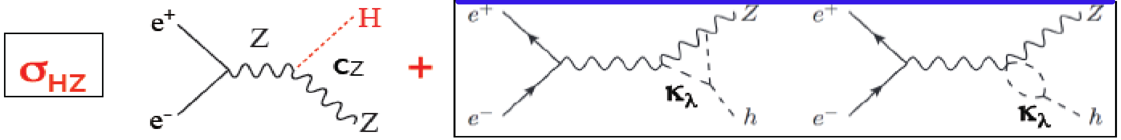
Most significant channel: e^+e^- → H → gg → jj final state





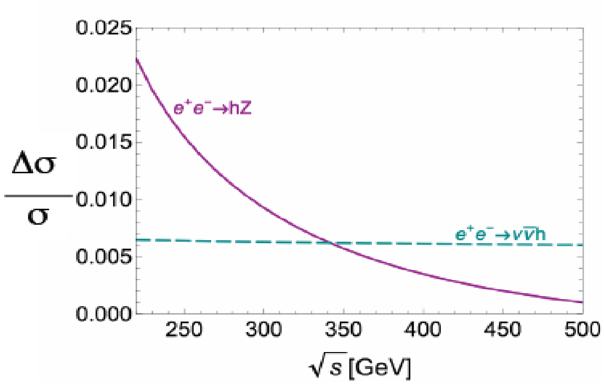
Measurement of the Higgs self-coupling

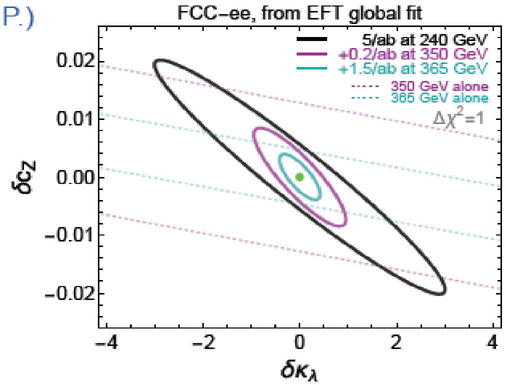
	Directly: Higgs-pair prod	**Indirectly: via single Higgs**
Hadron Colliders		
Lepton Colliders		



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



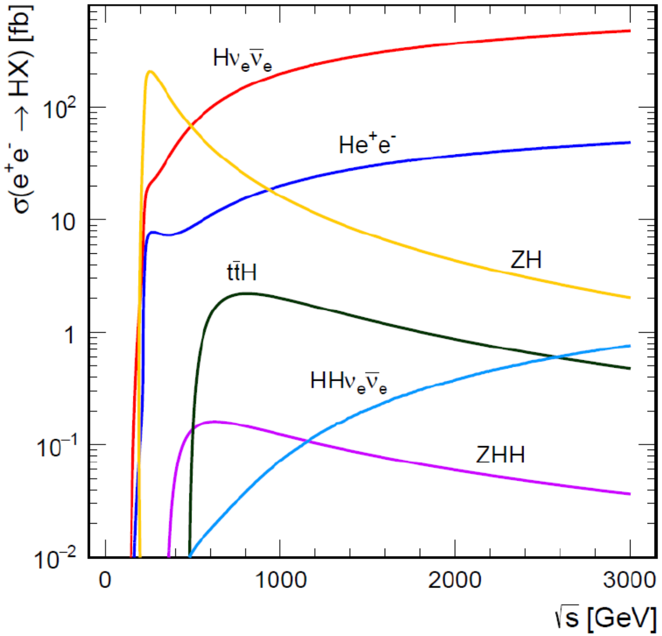


- from a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 21% (4 IPs)
- changing CMS energy helps in reducing correlations

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

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

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



Collider	ILC_{500}	ILC_{1000}	CLIC	FCC-INT	
g_{HZZ} (%)	0.24 / 0.23	0.24 / 0.23	0.39 / 0.39	0.17 / 0.16	ee
g_{HWW} (%)	0.31 / 0.29	0.26 / 0.24	0.38 / 0.38	0.20 / 0.19	
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48	
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96	
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50	
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46	
$g_{H\mu\mu}$ (%)	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	
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70	
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95	
g_{HHH} (%)	27.	10.	9.	±3.8*	
Γ_H (%)	1.1	1.0	1.6	0.91	ee
BR_{inv} (%)	0.23	0.22	0.61	0.024	hh
BR_{EXO} (%)	1.4	1.4	2.4	1.0	ee

*arXiv:2004.03505

FCC-hh > 10^{10} H produced

+

FCC-ee measurement of g_{HZZ}

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

The Z peak and the Electroweak Physics

The electroweak program at the Z peak and at the WW threshold is quite unique,

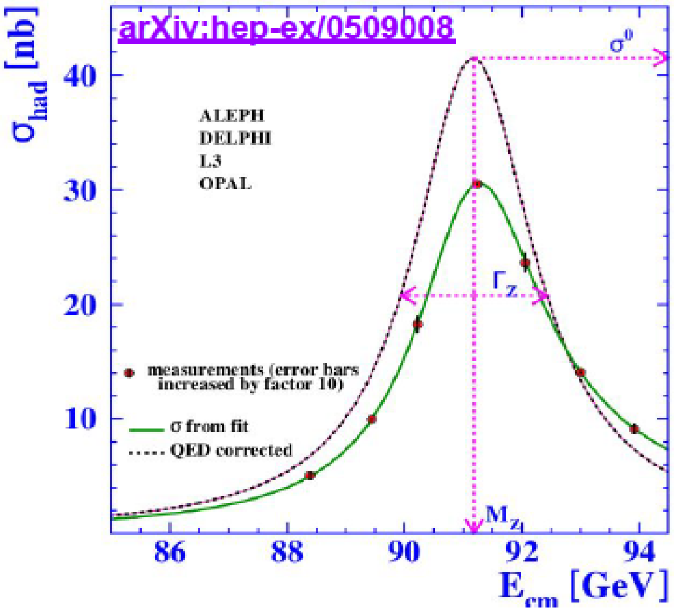
most challenging and maybe the most promising part of the program given the statistics !

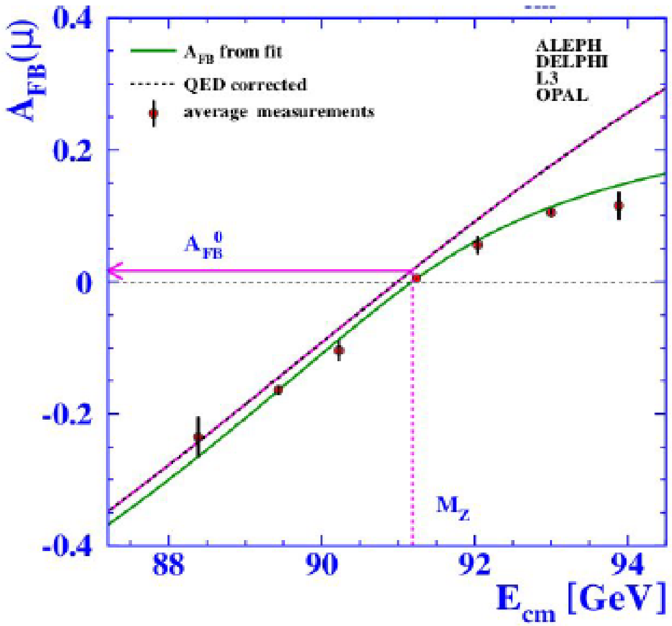
- L = 230/cm^2/s and 35 nb of Z cross section corresponds to 80 kHZ of events with typically 20 charged and 20 neutral particles (all to be fully recorded, stored, reconstructed)
- 3 years at 10^7 s /year = 2.4 10^{12} evts/exp. ➔ 10^5 LEP Statistics (~10^3 more than ILC)

For the electroweak program we will also have

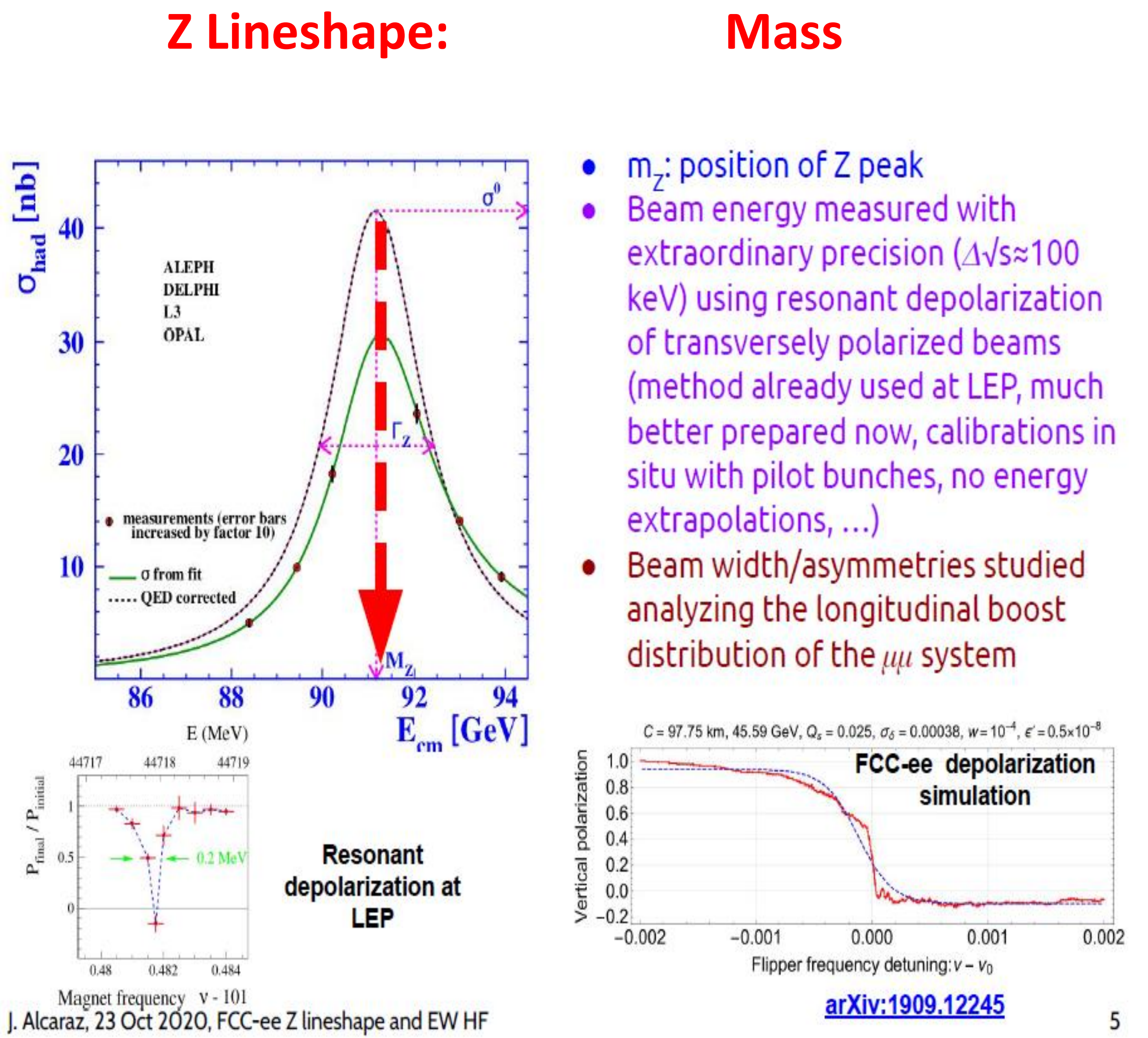
- 2 years at the WW threshold, 10^8 events/exp. ➔ 2.10^3 LEP Statistics

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 $\sigma(ee\to\gamma\gamma)$ 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

- 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

Resonant depolarization at LEP

FCC-ee depolarization simulation

arXiv:1909.12245

J. Alcaraz, 23 Oct 2020, FCC-ee Z lineshape and EW HF

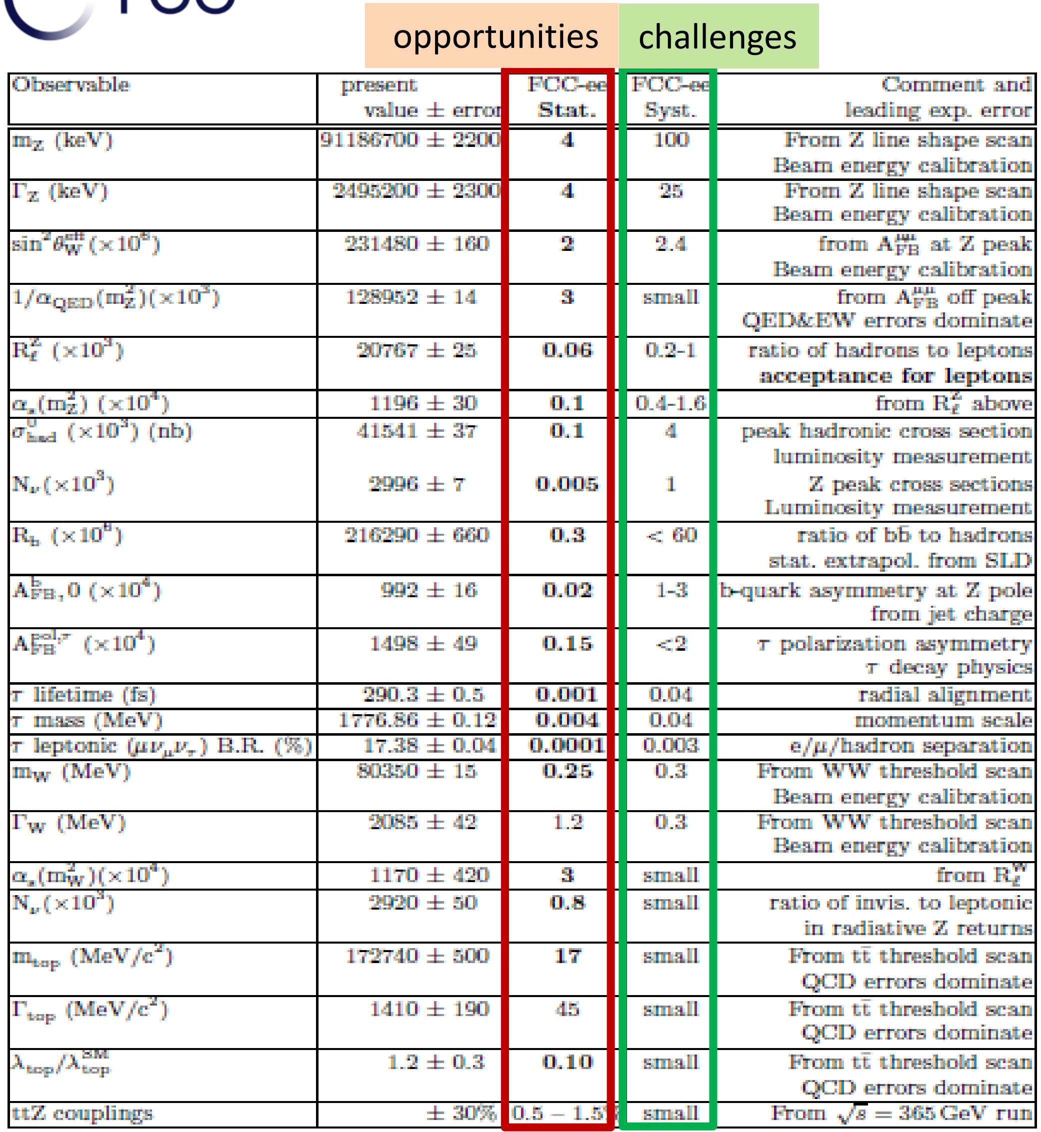
5

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

- 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)**

Systematic uncertainties



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
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)$($\times 10^3$)	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
$\sigma_{\rm had}^0$ ($\times 10^3$) (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
N_ν($\times 10^3$)	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
A_{FB}^b, 0 ($\times 10^4$)	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{{\rm pol},\tau}$ ($\times 10^4$)	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
$m_{\rm top}$ (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	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

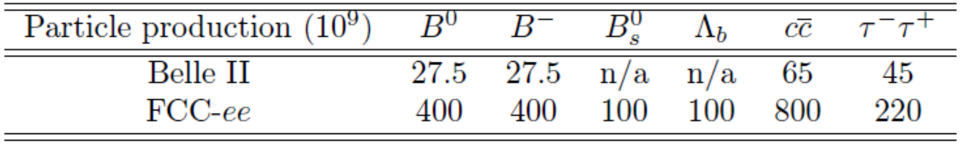
It is important now to concentrate on finding the potential 'show stoppers' or 'stumbling blocks', to guide the detector R&D and detector requirements.

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

Theory work is critical and initiated (1809.01830)

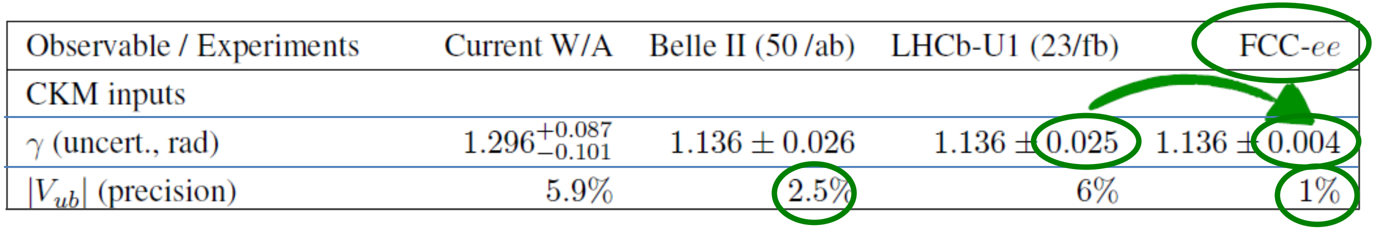
More on TeraZ : The Flavor/Tau Factory , QCD

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



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

Precision of CKM matrix elements



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

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

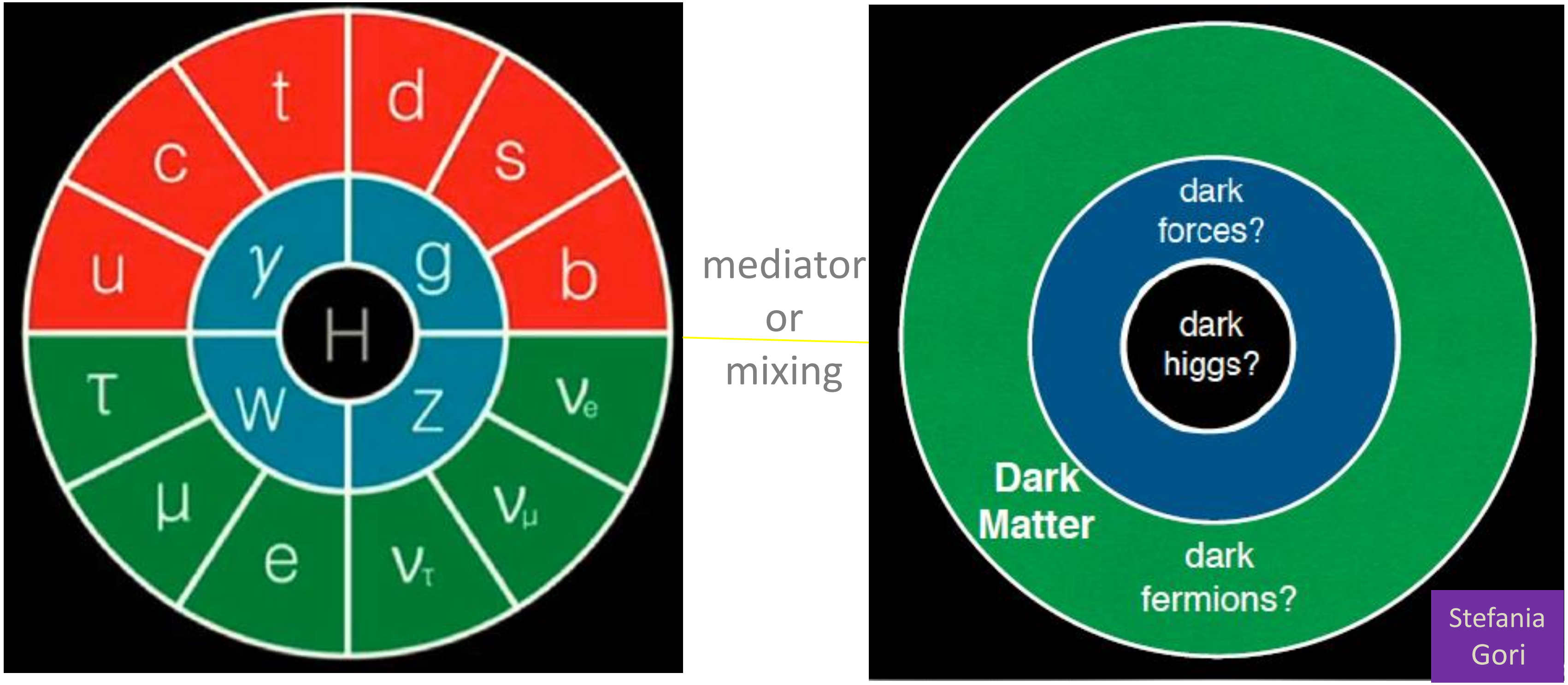
→ Push forward searches for FCNC, CP violation and mixing
→ Study rare penguin EW transitions such as b →s τ+ τ- , spectroscopy (produce b-baryons, B_s …)
→ Test lepton universality with 10^{11} τ decays (with τ lifetime, mass, BRs) at 10^{-5} level, LFV to 10^{-10}
- all very important to constrain / (provide hints of) new BSM physics.
➔ need special detectors (PID) under study

3.5 × 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, etc. : 10^{-3} →10^{-4}
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**

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



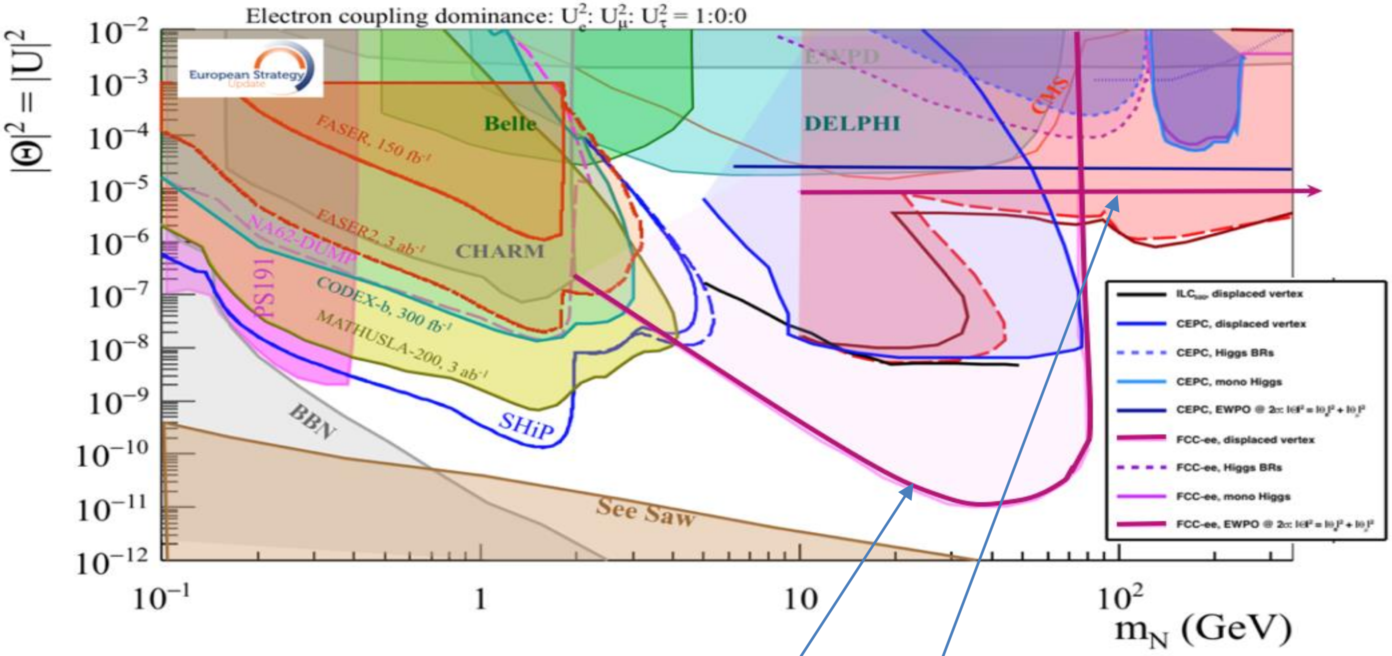
Stefania Gori

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

Feebly interacting particles

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

(The following limits are relevant for Neutrino, Dark sectors and High Energy Frontiers)



- 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 $\sin^2\theta_W^{\text{eff}}$ 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 and discover :

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

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

- **Discover** a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
  FCNC (Z --> μτ , eτ) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ τ τ
  + flavour physics (10^{12} bb events) (B→s τ τ 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→ gg) etc….

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

FCC main goals until 2025

Overall goal:

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

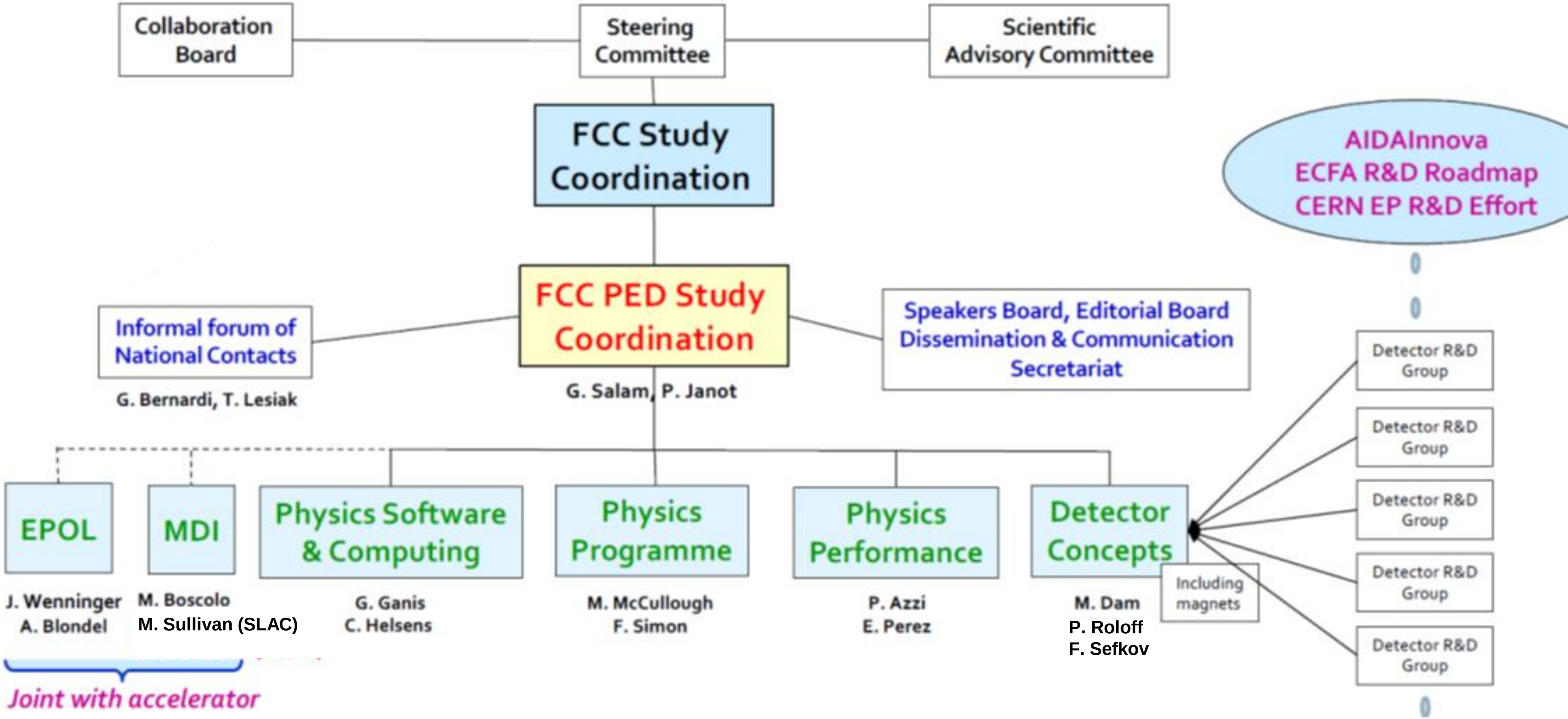
This requires successful completion of the following four main activities:

- 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

- **LHC community can bring enormously to the project,** by contributing (**at a small fraction of FTE**) to **R&D/detector concept studies** and/or by further reinforcing even further the excellent **physics potential:**
  - Higgs (self-coupling and 1st generation)
  - Precision EW and QCD measurements
  - Heavy Flavor Physics and Tau physics (lifetime, mass etc.)
  - LLP's detection and other BSM searches



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P. Roloff
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Including magnets

Detector R&D Group

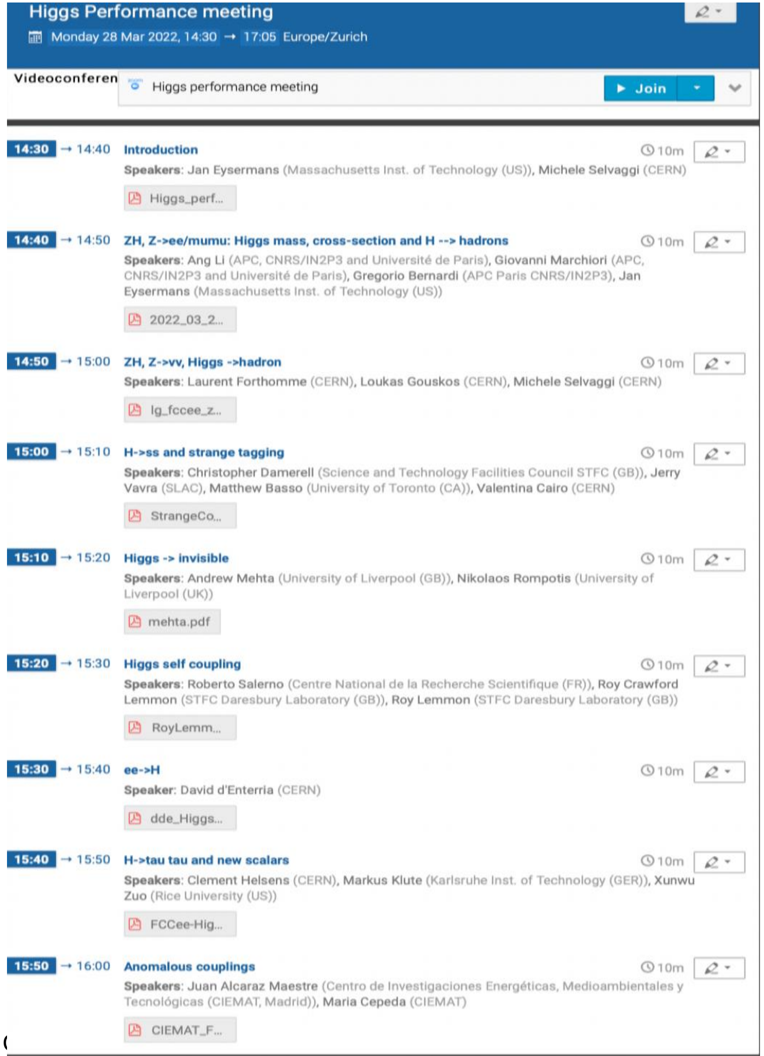
Detector R&D Group

Detector R&D Group

Detector R&D Group

Detector R&D Group

On-Going Studies



Higgs Performance meeting

Monday 28 Mar 2022, 14:30 → 17:05 Europe/Zurich

Videoconferen Higgs performance meeting ▶ Join

14:30 → 14:40 **Introduction** 10m
Speakers: Jan Eysermans (Massachusetts Inst. of Technology (US)), Michele Selvaggi (CERN)
Higgs_perf...

14:40 → 14:50 **ZH, Z->ee/mumu: Higgs mass, cross-section and H --> hadrons** 10m
Speakers: Ang Li (APC, CNRS/IN2P3 and Université de Paris), Giovanni Marchiori (APC, CNRS/IN2P3 and Université de Paris), Gregorio Bernardi (APC Paris CNRS/IN2P3), Jan Eysermans (Massachusetts Inst. of Technology (US))
2022_03_2...

14:50 → 15:00 **ZH, Z->vv, Higgs ->hadron** 10m
Speakers: Laurent Forthomme (CERN), Loukas Gouskos (CERN), Michele Selvaggi (CERN)
lg_fccee_z...

15:00 → 15:10 **H->ss and strange tagging** 10m
Speakers: Christopher Damerell (Science and Technology Facilities Council STFC (GB)), Jerry Vavra (SLAC), Matthew Basso (University of Toronto (CA)), Valentina Cairo (CERN)
StrangeCo...

15:10 → 15:20 **Higgs -> invisible** 10m
Speakers: Andrew Mehta (University of Liverpool (GB)), Nikolaos Rompotis (University of Liverpool (UK))
mehta.pdf

15:20 → 15:30 **Higgs self coupling** 10m
Speakers: Roberto Salerno (Centre National de la Recherche Scientifique (FR)), Roy Crawford Lemmon (STFC Daresbury Laboratory (GB)), Roy Lemmon (STFC Daresbury Laboratory (GB))
RoyLemm...

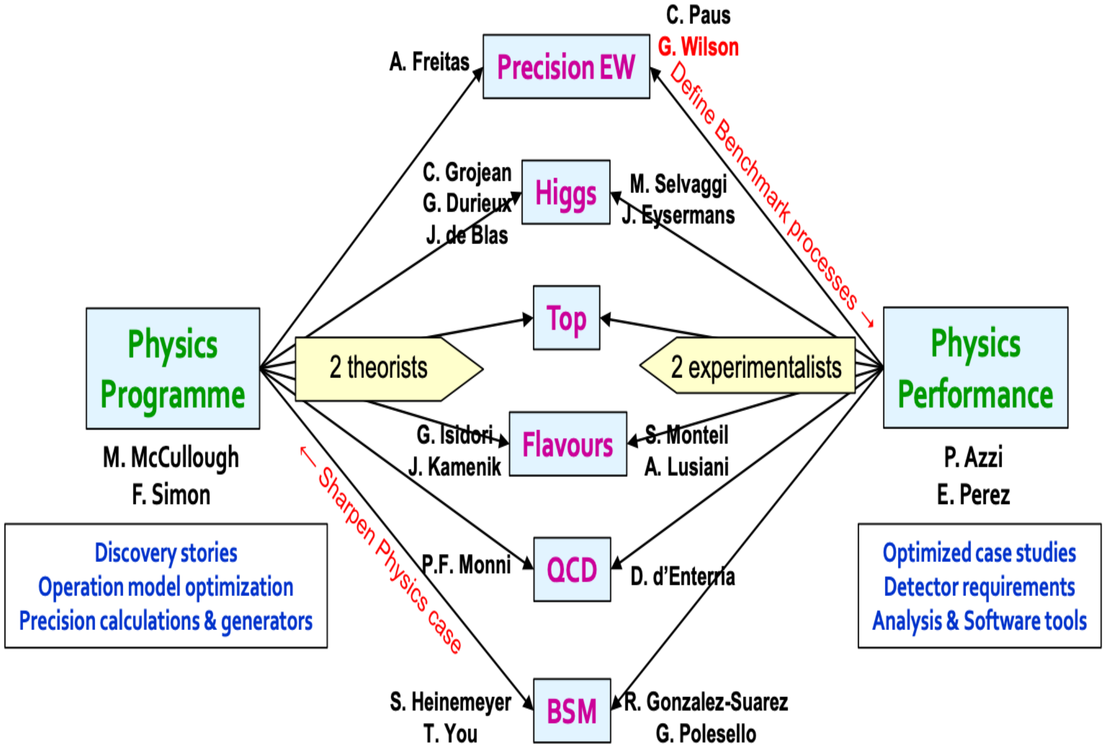
15:30 → 15:40 **ee->H** 10m
Speaker: David d'Enterria (CERN)
dde_Higgs...

15:40 → 15:50 **H->tau tau and new scalars** 10m
Speakers: Clement Helsens (CERN), Markus Klute (Karlsruhe Inst. of Technology (GER)), Xunwu Zuo (Rice University (US))
FCCee-Hig...

15:50 → 16:00 **Anomalous couplings** 10m
Speakers: Juan Alcaraz Maestre (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT, Madrid)), Maria Cepeda (CIEMAT)
CIEMAT_F...

Join the team!

https://e-groups.cern.ch/e-groups/EgroupsSubscription.do?egroupName=FCC-PED-PhysicsGroup-Higgs



Physics Programme
M. McCullough
F. Simon

Discovery stories
Operation model optimization
Precision calculations & generators

2 theorists

2 experimentalists

Physics Performance
P. Azzi
E. Perez

Optimized case studies
Detector requirements
Analysis & Software tools

Precision EW
A. Freitas
C. Paus
G. Wilson

Higgs
C. Grojean
G. Durieux
J. de Blas
M. Selvaggi
J. Eysermans

Top

Flavours
G. Isidori
J. Kamenik
S. Monteil
A. Lusiani

QCD
P.F. Monni
D. d'Enterria

BSM
S. Heinemeyer
T. You
R. Gonzalez-Suarez
G. Polesello

Define Benchmark processes →

← Sharpen Physics case

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

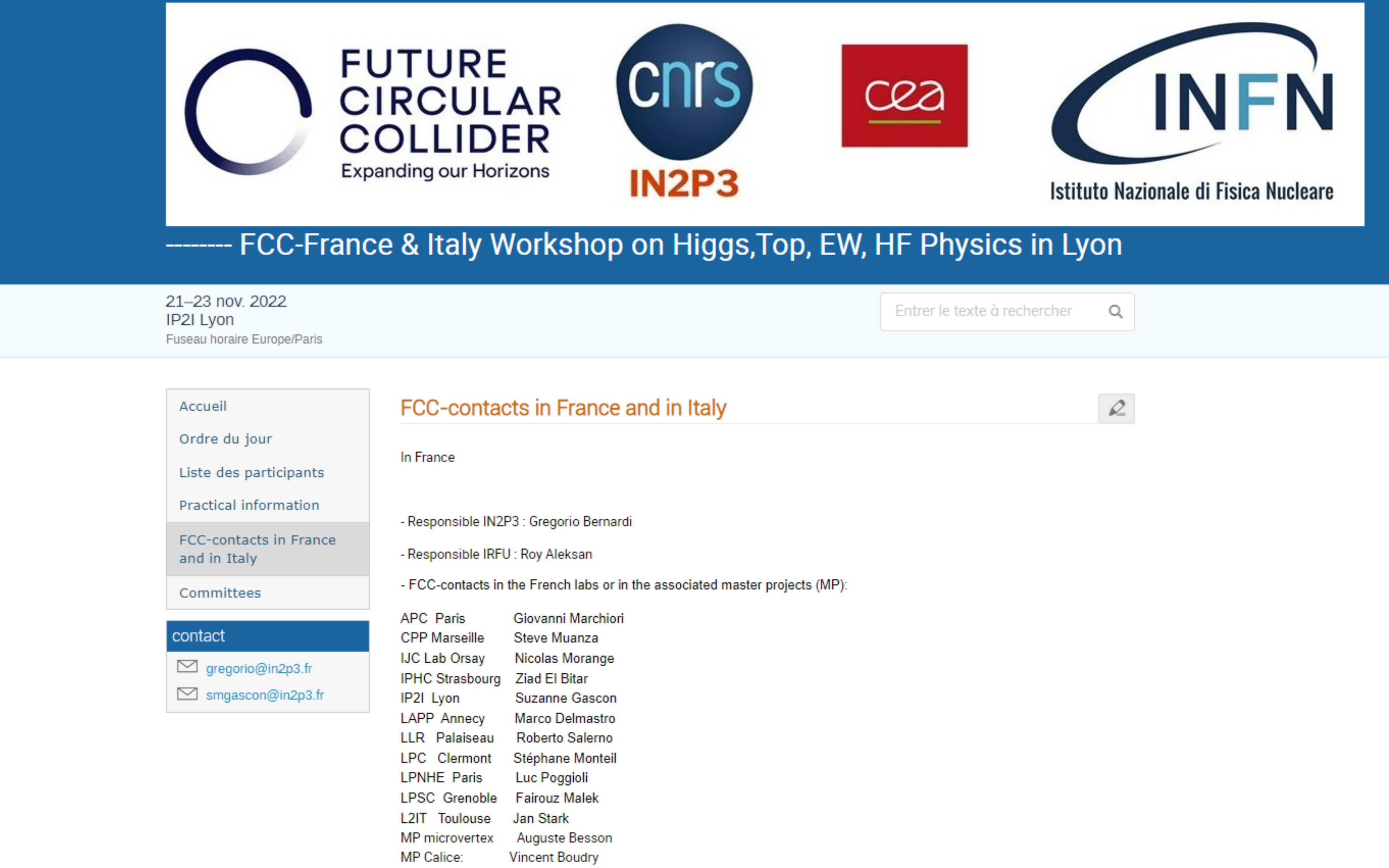
Many opportunities and challenges are offered by the energy range (from the Z pole to 100 TeV or more) and from the huge rates (from 10^{12} Z @ FCC-ee to 10^{13} Ws / 10^{10} H at FCC-hh) offered by the FCC.

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

- The FCC Physics Workshop took place in Liverpool in Feb. 2022: https://indico.cern.ch/event/1066234/
- The 5th Annual FCC Week took place in Paris in June 2022: https://indico.cern.ch/event/1064327/

- The joint FCC-France-Italy workshop will take place in Lyon Nov-21st to 23rd https://indico.in2p3.fr/event/27968/

Please join the effort, the presence of all is needed to make it happen !



-------- FCC-France & Italy Workshop on Higgs,Top, EW, HF Physics in Lyon

21–23 nov. 2022
IP2I Lyon
Fuseau horaire Europe/Paris

contact
gregorio@in2p3.fr
smgascon@in2p3.fr

FCC-contacts in France and in Italy

In France

- Responsible IN2P3 : Gregorio Bernardi

- Responsible IRFU : Roy Aleksan

- FCC-contacts in the French labs or in the associated master projects (MP):

APC Paris	Giovanni Marchiori
CPP Marseille	Steve Muanza
IJC Lab Orsay	Nicolas Morange
IPHC Strasbourg	Ziad El Bitar
IP2I Lyon	Suzanne Gascon
LAPP Annecy	Marco Delmastro
LLR Palaiseau	Roberto Salerno
LPC Clermont	Stéphane Monteil
LPNHE Paris	Luc Poggioli
LPSC Grenoble	Fairouz Malek
L2IT Toulouse	Jan Stark
MP microvertex	Auguste Besson
MP Calice:	Vincent Boudry

backup

FCC

CDR + Documentation

- **FCC-Conceptual Design Reports:**
  - **Vol 1 – Physics**
    Vol 2 – FCC-ee,
    Vol 3 – FCC-hh,
    Vol 4 – HE-LHC
    1338 authors

A public presentation of the CDR was given on 4-5 March at CERN https://indico.cern.ch/event/789349/

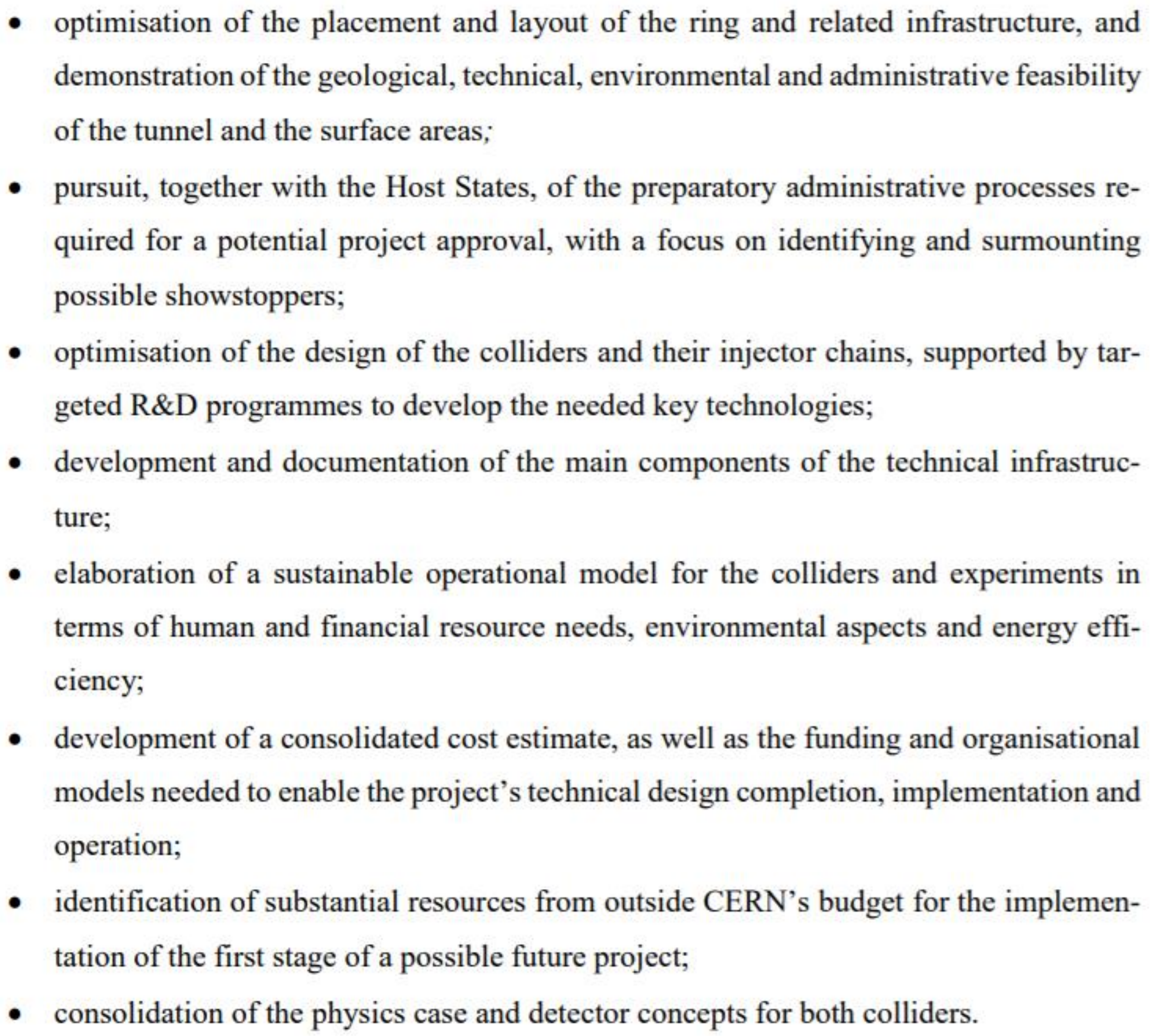
+ FCC Phys. Workshop Jan 20 https://indico.cern.ch/event/838435/
FCC Phys workshop Nov 9-13 2020 https://indico.cern.ch/event/932973/
→ many further details can be found there!

  - Preprints since 15 January 2019 on http://fcc-cdr.web.cern.ch/ and INSPIRE
  - **CDRs published in European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**
  - **ESPP summaries: FCC-integral, FCC-ee, FCC-hh, HE-LHC** http://fcc-cdr.web.cern.ch/
  - FCC-ee «Your questions answered» https://arxiv.org/abs/1906.02693v1
  - “Circular vs linear, another story of complementarity” arXiv:1912.11871v2
  - LOIs to Snowmass, **challenges**: https://indico.cern.ch/event/951830/

References

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

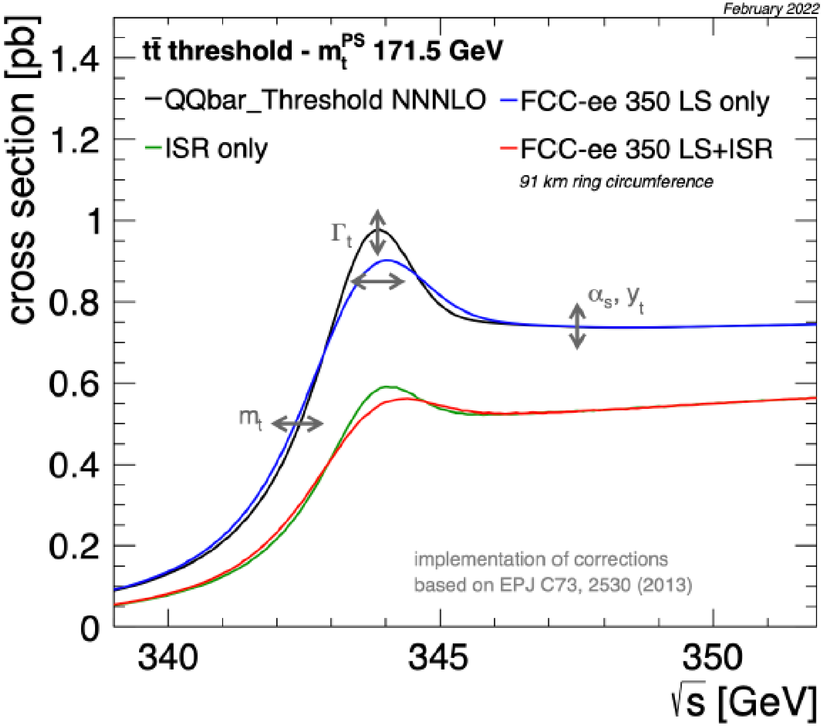
Goals of the feasibility study



- optimisation of the placement and layout of the ring and related infrastructure, and demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and the surface areas;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval, with a focus on identifying and surmounting possible showstoppers;
- optimisation of the design of the colliders and their injector chains, supported by targeted R&D programmes to develop the needed key technologies;
- development and documentation of the main components of the technical infrastructure;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, environmental aspects and energy efficiency;
- development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project;
- consolidation of the physics case and detector concepts for both colliders.

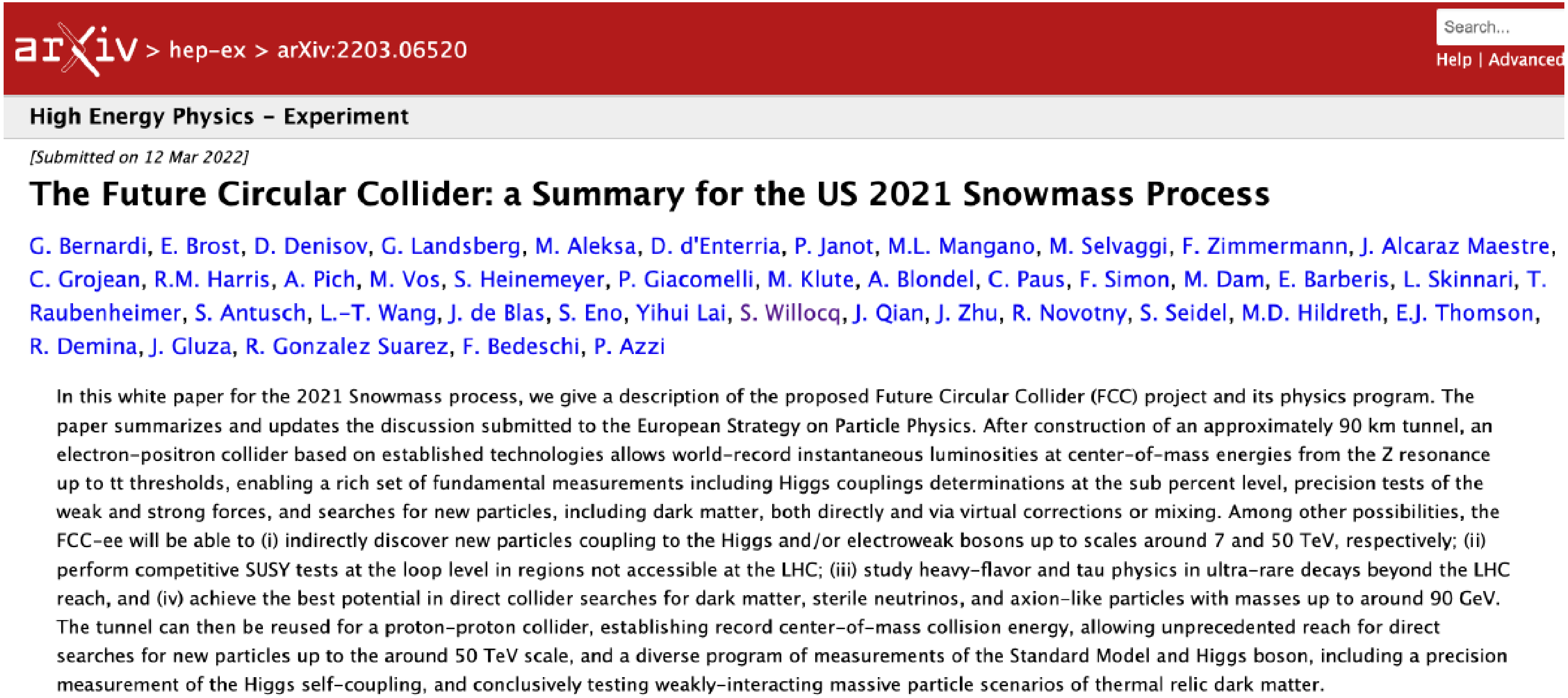
Top Quark Physics

- Expect 1M $t\bar{t}$ events
  w/ clean environment and ability to scan $\sqrt{s}$
- **Test of Higgs mechanism** via measurement of top mass and top Yukawa coupling
  - m_t measurement at FCC-ee with clear interpretation from cross-section measurement near threshold
  - Simultaneous fit for m_t and Γ_t with statistical uncertainties of 17 MeV and 45 MeV, resp.
    - Scale unc. of 45 MeV on m_t from N^{3}LO QCD
  - Extract ttZ coupling from $\sigma(e^+e^- \to Z/\gamma^* \to t\bar{t})$
    - Uncertainty ~10x smaller than @HL-LHC
    - Key input to extract top Yukawa from FCC-hh with reduced theory uncertainty



White Paper for Snowmass https://arxiv.org/abs/2203.06520

- Effort coordinated by Sarah Eno (Maryland U)
- 10 chapters written by two US editors each & reviewed by international readers



High Energy Physics – Experiment

[Submitted on 12 Mar 2022]

The Future Circular Collider: a Summary for the US 2021 Snowmass Process

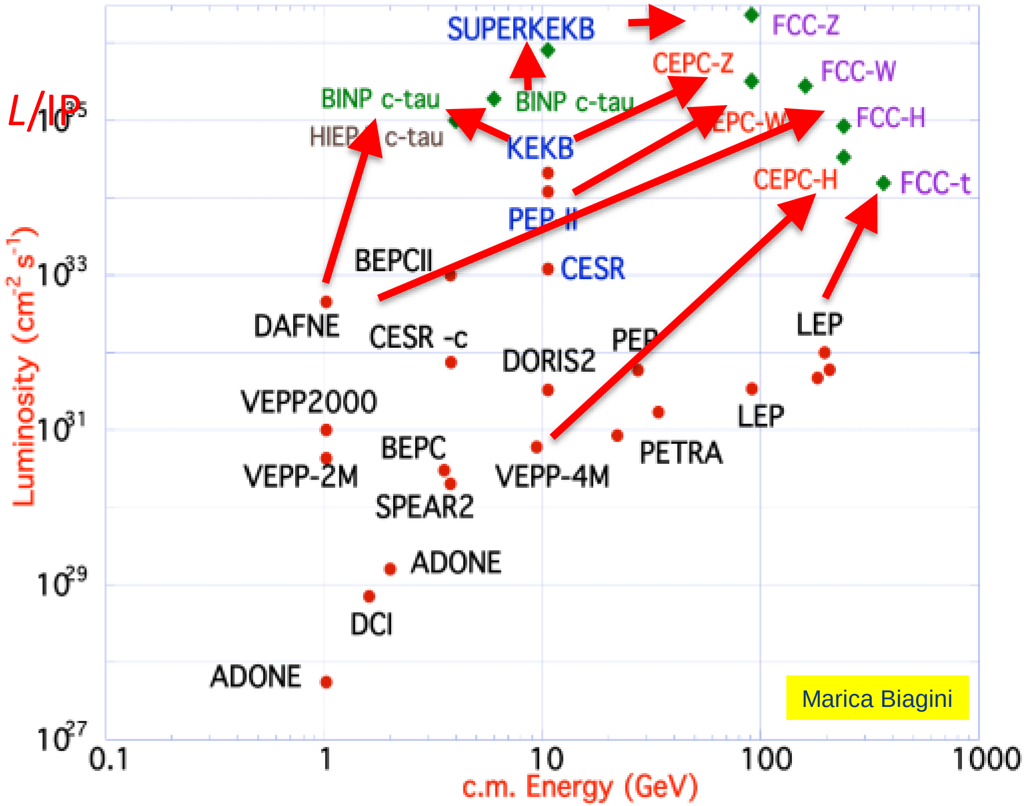
G. Bernardi, E. Brost, D. Denisov, G. Landsberg, M. Aleksa, D. d'Enterria, P. Janot, M.L. Mangano, M. Selvaggi, F. Zimmermann, J. Alcaraz Maestre, C. Grojean, R.M. Harris, A. Pich, M. Vos, S. Heinemeyer, P. Giacomelli, M. Klute, A. Blondel, C. Paus, F. Simon, M. Dam, E. Barberis, L. Skinnari, T. Raubenheimer, S. Antusch, L.-T. Wang, J. de Blas, S. Eno, Yihui Lai, S. Willocq, J. Qian, J. Zhu, R. Novotny, S. Seidel, M.D. Hildreth, E.J. Thomson, R. Demina, J. Gluza, R. Gonzalez Suarez, F. Bedeschi, P. Azzi

In this white paper for the 2021 Snowmass process, we give a description of the proposed Future Circular Collider (FCC) project and its physics program. The paper summarizes and updates the discussion submitted to the European Strategy on Particle Physics. After construction of an approximately 90 km tunnel, an electron-positron collider based on established technologies allows world-record instantaneous luminosities at center-of-mass energies from the Z resonance up to tt thresholds, enabling a rich set of fundamental measurements including Higgs couplings determinations at the sub percent level, precision tests of the weak and strong forces, and searches for new particles, including dark matter, both directly and via virtual corrections or mixing. Among other possibilities, the FCC-ee will be able to (i) indirectly discover new particles coupling to the Higgs and/or electroweak bosons up to scales around 7 and 50 TeV, respectively; (ii) perform competitive SUSY tests at the loop level in regions not accessible at the LHC; (iii) study heavy-flavor and tau physics in ultra-rare decays beyond the LHC reach, and (iv) achieve the best potential in direct collider searches for dark matter, sterile neutrinos, and axion-like particles with masses up to around 90 GeV. The tunnel can then be reused for a proton-proton collider, establishing record center-of-mass collision energy, allowing unprecedented reach for direct searches for new particles up to the around 50 TeV scale, and a diverse program of measurements of the Standard Model and Higgs boson, including a precision measurement of the Higgs self-coupling, and conclusively testing weakly-interacting massive particle scenarios of thermal relic dark matter.

- Appendix with list of US supporters (~170 to date), ***visit*** this link ***or contact Sarah to add your name to list***

FCC-ee design

based on lessons and techniques from past colliders



Marica Biagini

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

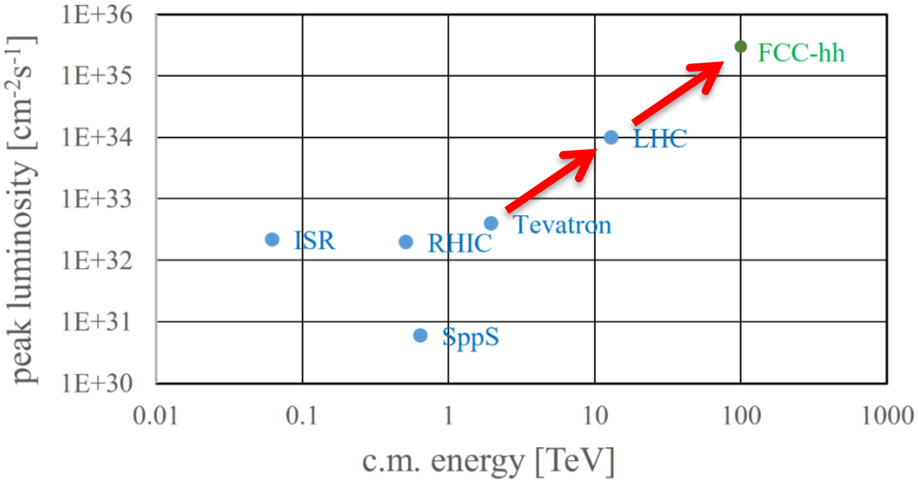
VEPP-4M, LEP: precision E calibration

KEKB: *e*$^+$ source

HERA, LEP, RHIC: spin gymnastics

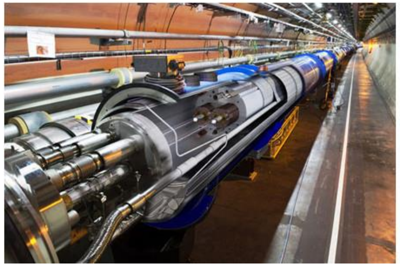
combining successful ingredients of several recent colliders
→ highest luminosities & energies

FCC-hh: highest collision energies



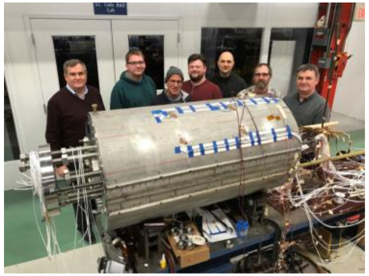
- order of magnitude performance increase in both energy & luminosity
- 100 TeV cm collision energy(vs. 14 TeV for LHC)
- 20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)
- similar increase as from Tevatron to LHC
- key technology: high-field magnets

from
LHC technology
8.3 T NbTi dipole

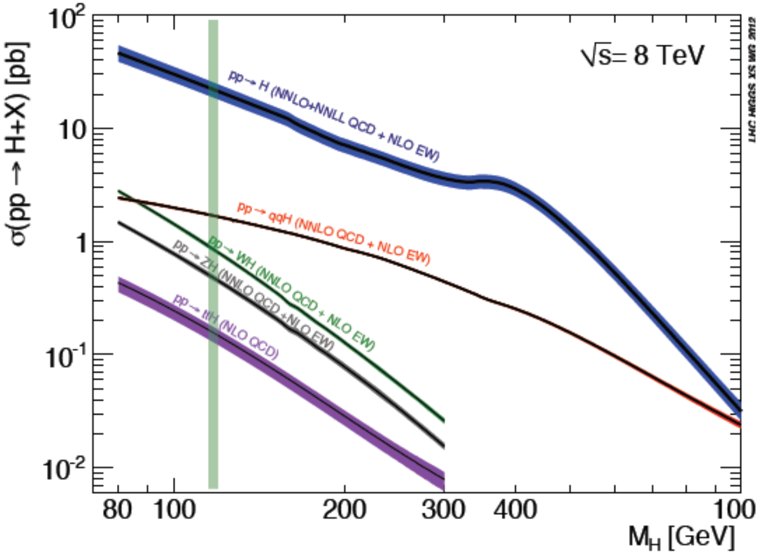


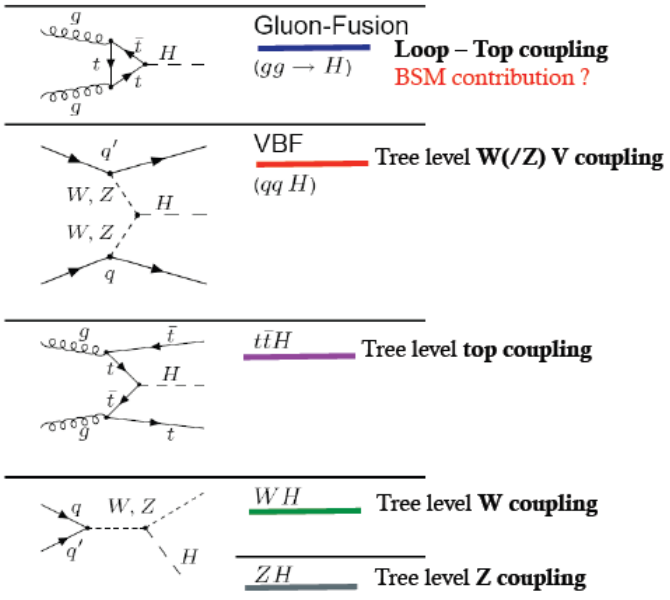
via
HL-LHC technology
12 T Nb_3Sn quadrupole

FNAL dipole demonstrator
14.5 T Nb_3Sn



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





The LHC is a huge Higgs Factory…

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

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

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

We don't know the width in a model independent way until measured directly

Model dependency in extracting the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible+ unmeasured channels) → must do Higgs physics with ratios at LHC

Yukawa coupling to s-quarks

Improved jet flavour tagging opens up new opportunities

$BR(H \to ss) = BR(H \to cc)\,(m_s/m_c)^2 \sim 2.3\ 10^{-4}$

FCCee: σ_{ZH}~200fb, L ~ 5 ab^{-1} (2 IP): **~1M ZH**
[600k H→bb, 100k H→gg, 30k H→cc, **200 H→ ss**]

Use Loose WP:
[**s-tag: 90%**, **g-mist: 10%**, c-mist: 1%, b-mist: 0.4%

- **Scenario 1:** Z(→all)H:

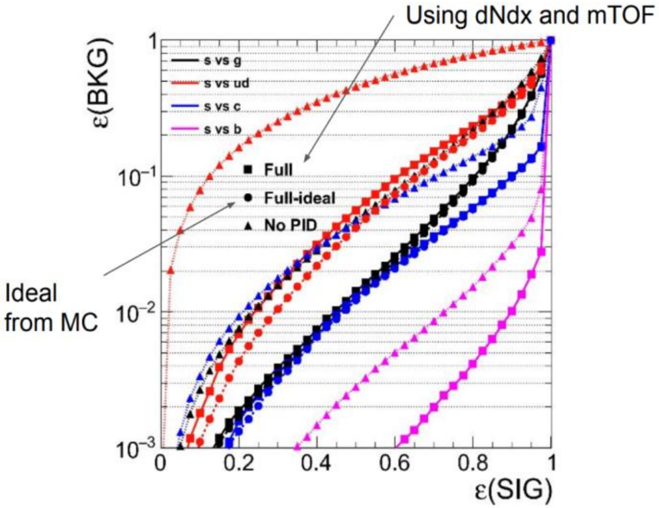
N_{ss} = 150, N_b = 1000
(neglecting ee→ VV backgrounds)

δ(σxBR)/σxBR (%) ~ 21 % (~ 5σ) [no systematics, only higgs backgrounds, no combinatorics]

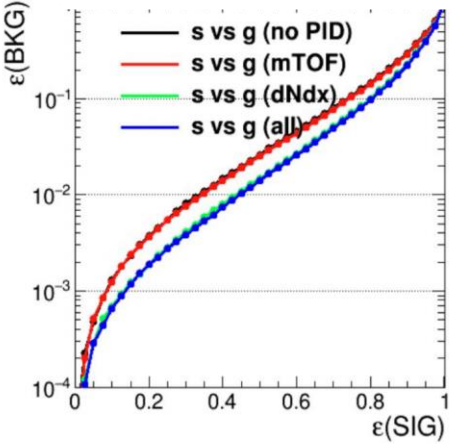
- **Scenario 2:** Z(→νν)H:

N_{ss} = 30, N_b = 200
(neglecting ee → ννqq and ee → qq, can be important given large q → s fake prob.)

δ(σxBR)/σxBR (%) ~ 49% (~ 2σ) [no systematics]



Selvaggi @ FCC week 2021



WP	Eff (s)	Mistag (g)	Mistag (ud)	Mistag (c)	Mistag (b)
Loose	90%	20%	40%	10%	1%
Medium	80%	10%	20%	6%	0.4%