FCC

CEPC

Bangalore
November 15, 2022

The Future Circular Colliders (FCC and CEPC) and their Physics Potential

Gregorio Bernardi
APC Paris, CNRS/IN2P3

With many thanks to all in the FCC collaboration, in particular
M. Benedikt, A. Blondel, D. d'Enteria, C. Grojean, P. Janot
and to the CEPC collaboration, in particular
J. Guimarães da Costa

Layout

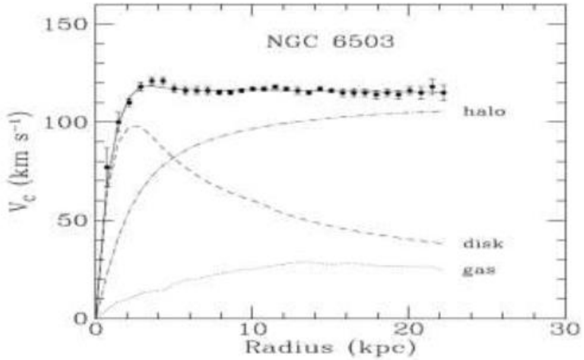
- The FCC Feasibility Study and progress at CEPC
- The Circular Colliders Physics potential (mainly Higgs / EW)
- Next steps

But first, why do we need a new collider after the LHC ?

The Standard Model is "complete" and explains all HEP Physics, but..
we cannot explain crucial observations with the SM, for instance:

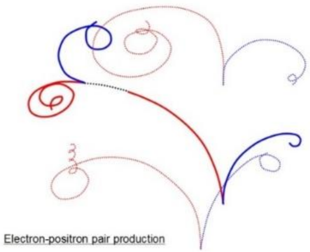
What is Dark matter ?

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



Rotation curve for Galaxy

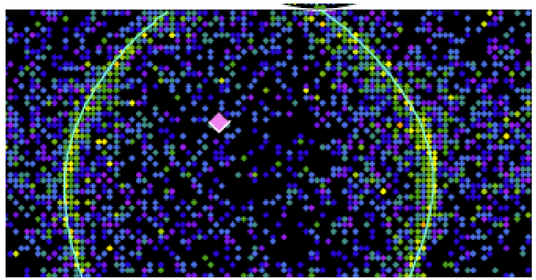
Were is primordial antimatter gone?



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?



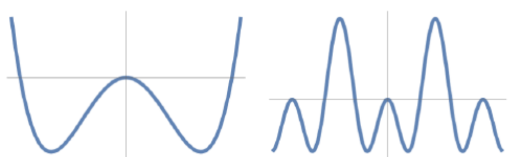
…and the Higgs boson/field still need to be better understood

- → 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.

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

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

But we are in an unusual situation for HEP: **we do not have a natural energy scale to search for !**

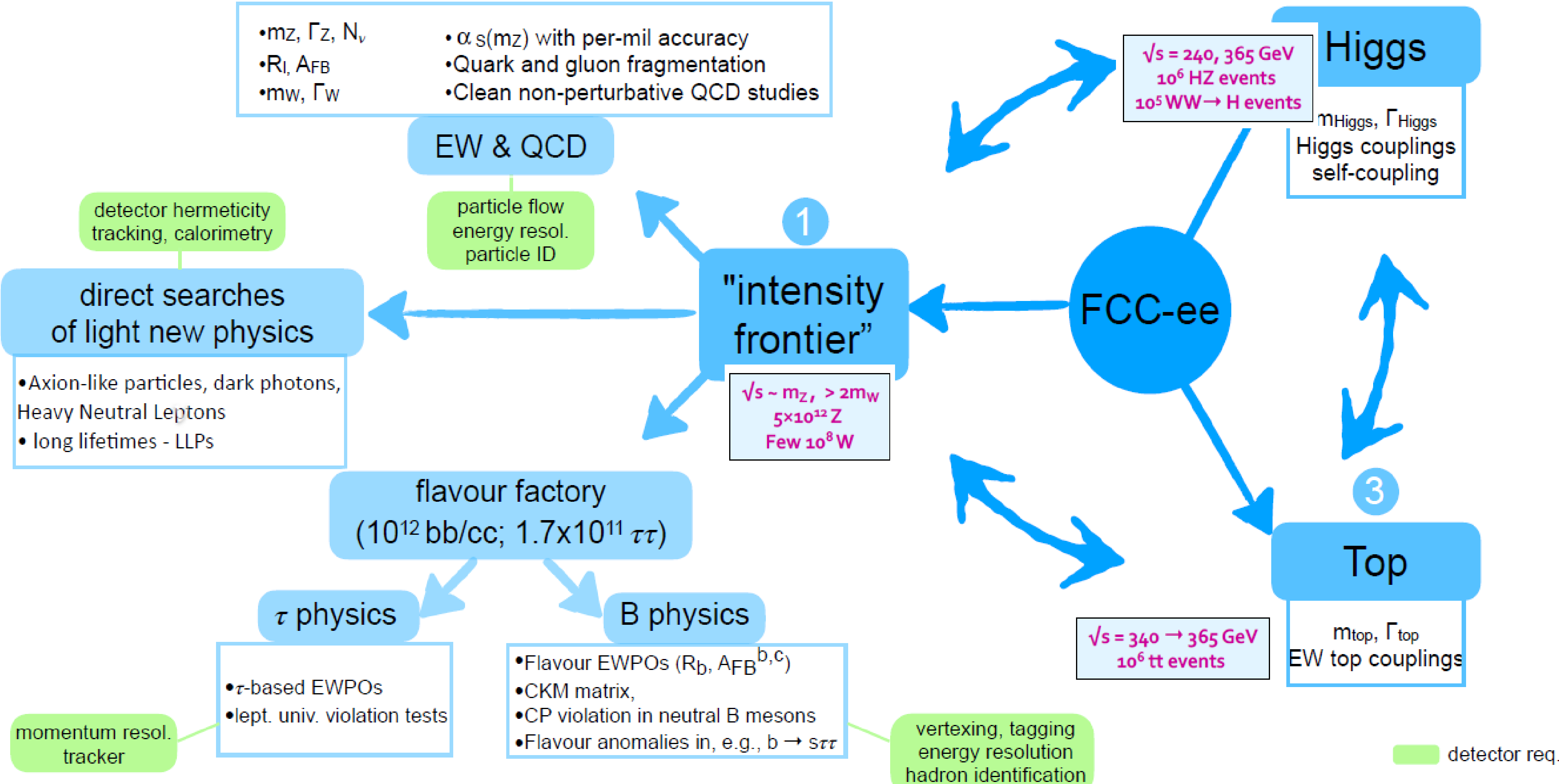
→ We don't know where to look and what we will find

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

→ more Sensitivity, more Precision, more Energy

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

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



…plus an excellent hh program beyond ee Circular Colliders

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

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

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

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."

➔ **ECFA workshops/WG and FCC Feasibility study 2021-2025**

First ECFA Workshop

Hamburg, Oct. 5-7, 2022

Goal: bring the entire e+e- Higgs factory effort together, foster cooperation across various projects, collaborative research programmes are to emerge

- Plenary and parallel sessions organised by WG conveners

◆ **Study will be documented as an ECFA Report**

◆ Vision for the report:
- a major input to the next European Strategy Update
- building on extensive body of previous studies
  - most recently:
    - ILC report to Snowmass
    - FCC CDR
    - CLIC Yellow Reports
    - …etc

=> **this report should focus on new work**

-> brief 'summary of current state' also to be included

- **emphasise what is added:**
  - what can the ECFA Higgs Factory study add beyond the current state-of-the-art?
  - what will a Higgs Factory add beyond the state-of-the-art at the end of HL-LHC?

«Informal Conclusions» of the US Snowmass studies, August 2022

Snowmass 2021

- Snowmass process was very productive
  - Despite of COVID
- 2014 P5 continuing construction projects are strongly supported
  - And will require substantial funding for the coming 5+ years
- Higgs factory is considered as the next preferred option for the energy frontier collider
  - 10 options are presented with FCCee among mostly discussed
- We expect no “decision” about next Higgs factory during this P5 process
  - Rather to emphasize the importance of R&D for accelerators, detectors, physics
- Next Snowmass/P5 might be sooner vs 8-10 years from now
  - Depends on new scientific results, convergence with existing projects (funding) and interest around the world to host Higgs factory
- If CERN will decide to build FCCee US will participate and contribute

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

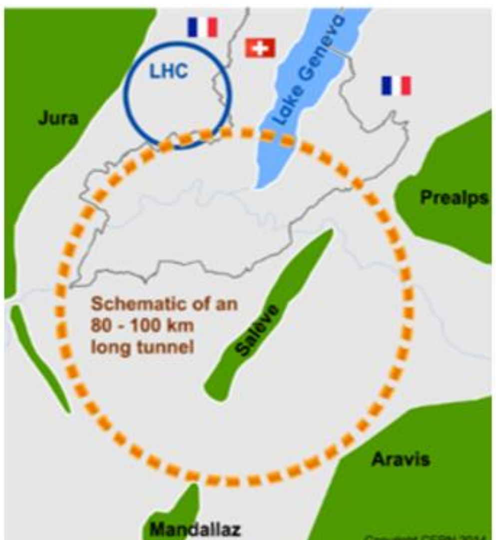
Comprehensive cost-effective program maximizing physics opportunities

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

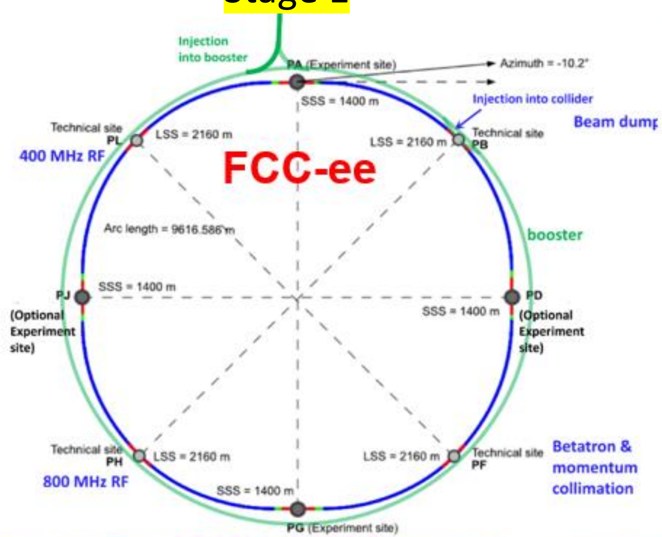
Complementary physics

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

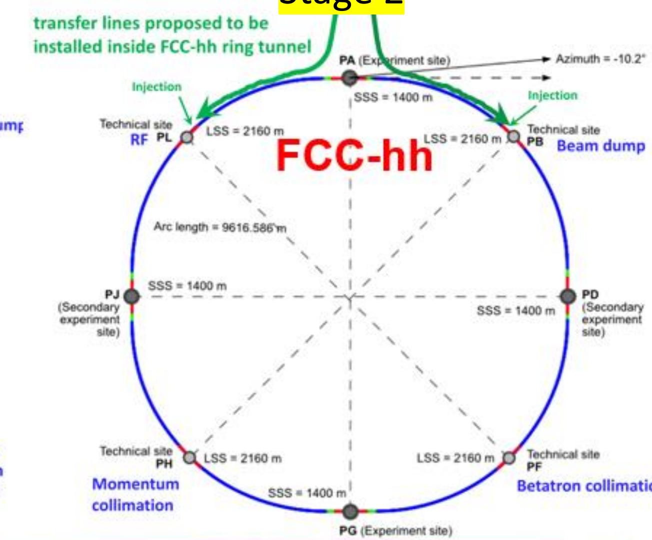
The FCC-INT project is fully integrated with HL-LHC exploitation and provides a natural transition for higher precision and energy



Stage 1



Stage 2



2020 - 2040 | 2045 - 2060 | 2065 - 2090

FCC : optimized placement and layout

Following extensive placement review, choice made

8-site baseline "PA31"

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

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

FUTURE CIRCULAR COLLIDER

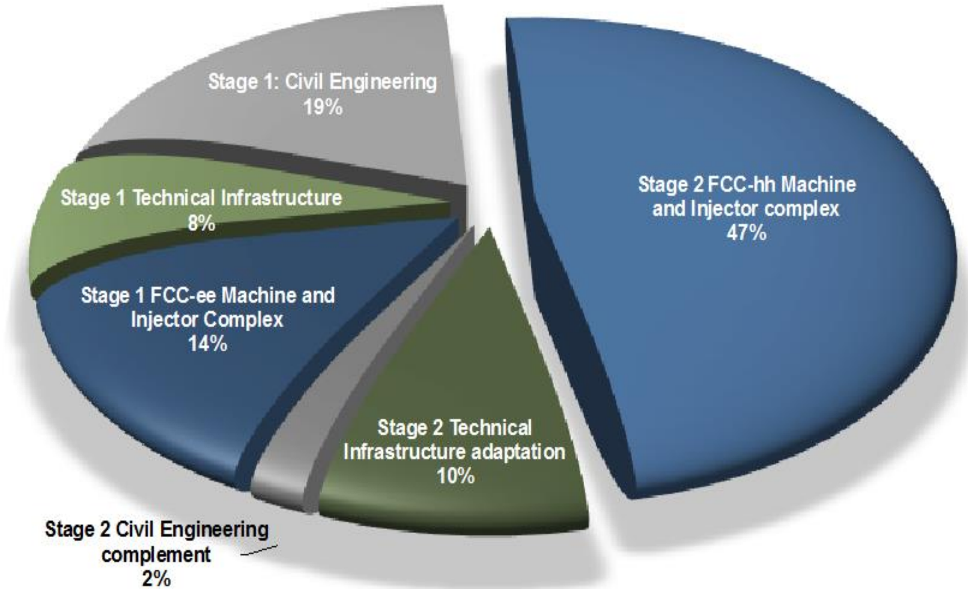
FCC-ee : updated parameters

K. Oide, D. Shatilov,

Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
beam lifetime rad Bhabha + BS [min]	19	18	6	9
luminosity per IP [10^{34} cm^{-2}s^{-1}]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65

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.

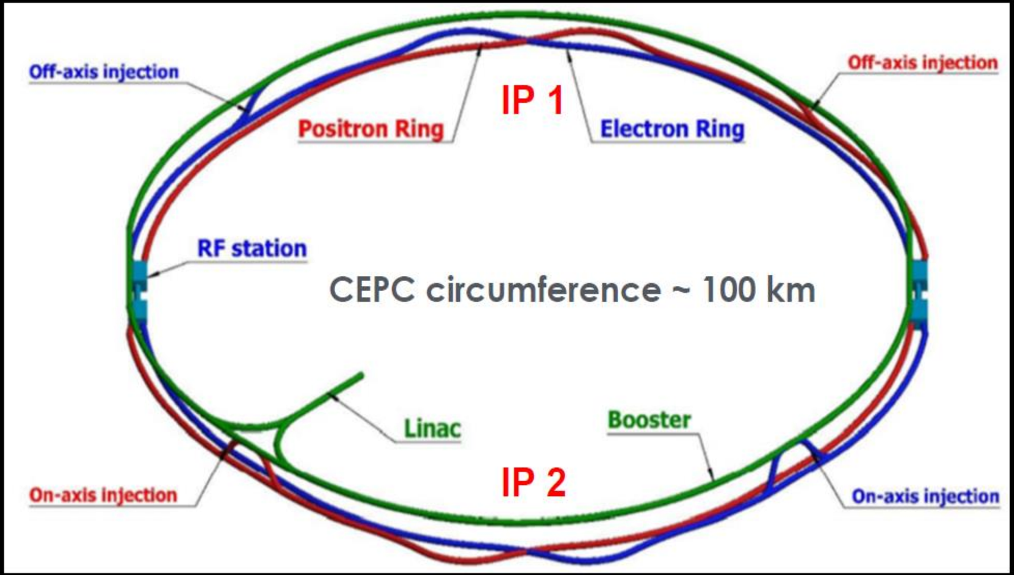
- Associated to a total project duration of ~25 years (2040 – 2065)
- (FCC-hh standalone would cost ~25 BCHF, so not building FCC-ee in a first stage would be a marginal saving)

Circular Electron Positron Collider (CEPC) Overview

CEPC is an e^+e^- Higgs factory producing Higgs, W and Z bosons
aims at discovering new physics beyond the Standard Model

Proposed in 2012 right after the Higgs discovery

Upgrade path
1. Higher energy → top quark pair production
2. Super pp Collider (SppC) at > 100 TeV

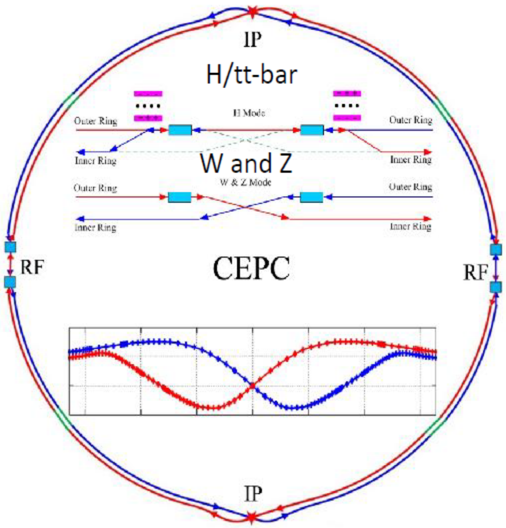


Proposed to commence construction in ~2026 and deliver Higgs data in 2030s

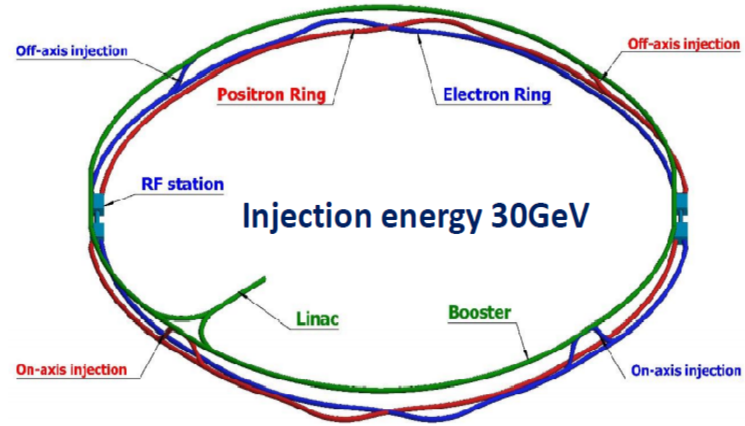
Circular Electron Position Collider (CEPC) - TDR Layout

CEPC as a Higgs Factory： H, W, Z, upgradable to tt-bar, followed by a SppC ~125TeV

30MW SR power per beam (upgradable to 50MW)



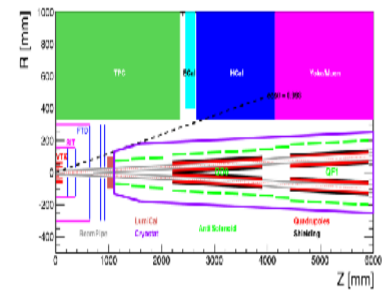
CEPC collider ring (100km)



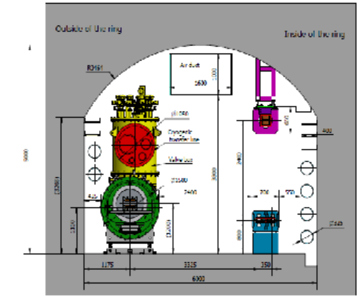
CEPC booster ring (100km)

Common tunnel for booster/collider & SppC

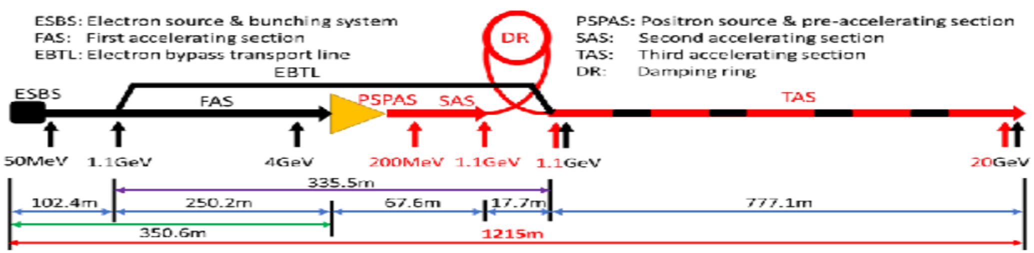
CEPC MDI



CEPC Civil Engineering



CEPC TDR S+C-band 30 GeV linac injector



Operation mode		ZH	Z	W^+W^-	tt
		~240	~91.2	158-172	~360
L / IP [$\times10^{34}$ cm^{-2}s^{-1}]	CDR (2018)	3	32	10	
	TDR (30MW)	5.0	115	16	0.5

9

Comparison FCC / CEPC

Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA] FCC / CEPC	1280 / 804	135 / 84	26.7 / 16.7	5.0 / 3.3
number bunches/beam	10000 / 11951	880 / 1297	248 / 249	36 / 35
bunch intensity [10^{11}]	2.43 / 1.40	2.91 / 1.40	2.04 / 1.40	2.64 / 2.00
SR energy loss / turn [GeV]	0.039 / 0.037	0.37 / 0.36	1.87 / 1.8	10.0 / 9.1
horizontal beta* [m]	0.1 / 0.13	0.2 / 0.21	0.3 / 0.33	1.0 / 1.04
vertical beta* [mm]	0.8 / 0.9	1 / 1	1 / 1	1.6 / 1.4
horizontal geometric emittance [nm]	0.71 / 0.27	2.17 / 0.87	0.64 / 0.64	1.49 / 1.4
vertical geom. emittance [pm]	1.42 / 1.4	4.34 / 1.7	1.29 / 1.3	2.98 / 4.7
horizontal rms IP spot size [μm]	8 / 6	21 / 13	14 / 15	39 / 39
vertical rms IP spot size [nm]	34 / 35	66 / 42	36 / 36	69 /113
rms bunch length with SR / BS [mm]	4.4 / 14.5	3.6 / 8.0	3.3 / 6.0	2.0 / 2.9
rms bunch length with SR / BS [mm]	2.5 / 8.7	2.5 / 4.9	2.3 / 3.9	2.2 / 2.9
beam lifetime [min]	19 / 80	18 / 55	6 / 20	9 / 18
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182 / 115	19.4 / 16	7.3 / 5.0	1.33 / 0.5
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65

Budget for CEPC construction

CEPC Cost estimation from CDR

Tier I	Tier II	Amount (100 M CNY)
Accelerator	Collider	99.2
	Booster	39.2
	Linac and sources	9.1
	Damping ring	0.44
	Common: Cryogenics	10.6
	Survey & alignment	4
	Radiation protection	1.7
Conventional facilities	-	102
Detectors	-	40
γ-ray beam lines	-	3
Project management (1%)	-	3
Contingency (15%)	-	46
Total	-	358

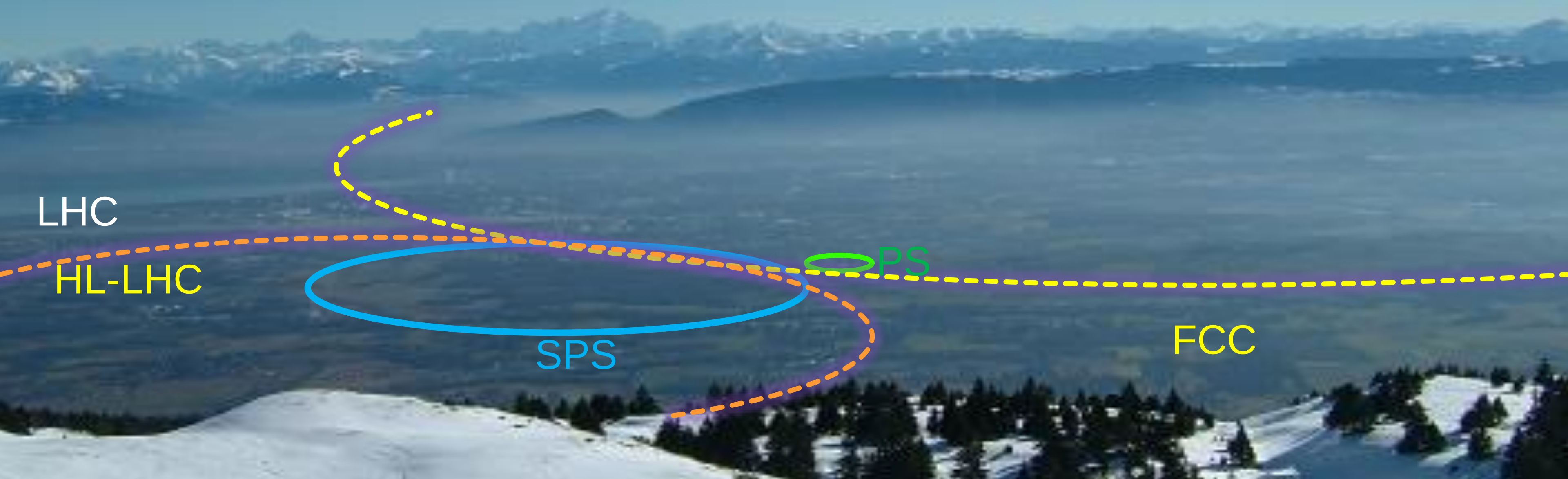
- **Cost estimated with two indpendent methods, agrees at 10% level**
- **CEPC design relies on well studied, or mature tech. reducing uncertainties on cost estimation**

Total required funding: 36 Billion RMB (5 Billion CHF at today's exchange rate)

Funding Sources	Funding Model #1 (B RMB)	Funding Model #2 (B RMB)
Central Government	25	10
Local Government	5	20
International contributions	6	6
Donations	0-3.5	0-3.5

- CEPC less expensive than FCC
- May be done faster if funding arrives
- But many things still need to be decided
- International Collaboration is less advanced
- Political situation not favorable

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

Mid-Term Review & Cost Review, Autumn '23

Mid-term review report, supported by additional documentation on each deliverable, will be submitted to review committees and to Council as input for the review.

Results of both general mid-term review and the cost review should indicate the main directions and areas of attention for the second part of the Feasibility Study

FCCIS Week 2022
5-9 December 2022 (confirmed by majority vote of FCC pillar coordinators and FCCIS WP leaders)

+ First FCC Scientific Advisory Committee (SAC) executive session

Infrastructure & placement

- Preferred placement and progress with host states (territorial matters, initial states, dialogue, etc.)
- Updated civil engineering design (layout, cost, excavation)
- Preparations for site investigations

Technical Infrastructure

- Requirements on large technical infrastructure systems
- System designs, layouts, resource needs, cost estimates

Accelerator design FCC-ee and FCC-hh

- FCC-ee overall layout with injector
- Impact of operation sequence: Z, W, ZH, $t\bar{t}$ vs start at ZH
- Comparison of the SPS as pre-booster with a 10-20 GeV linac
- Key technologies and status of technology R&D program
- FCC-hh overall layout & injection lines from LHC and SC-SPS

Physics, experiments, detectors:

- Documentation of FCC-ee and FCC-hh physics cases
- Plans for improved theoretical calculations to reduce theoretical uncertainties towards matching FCC-ee statistical precision for the most important measurements.
- First documentation of main detector requirements to fully exploit the FCC-ee physics opportunities

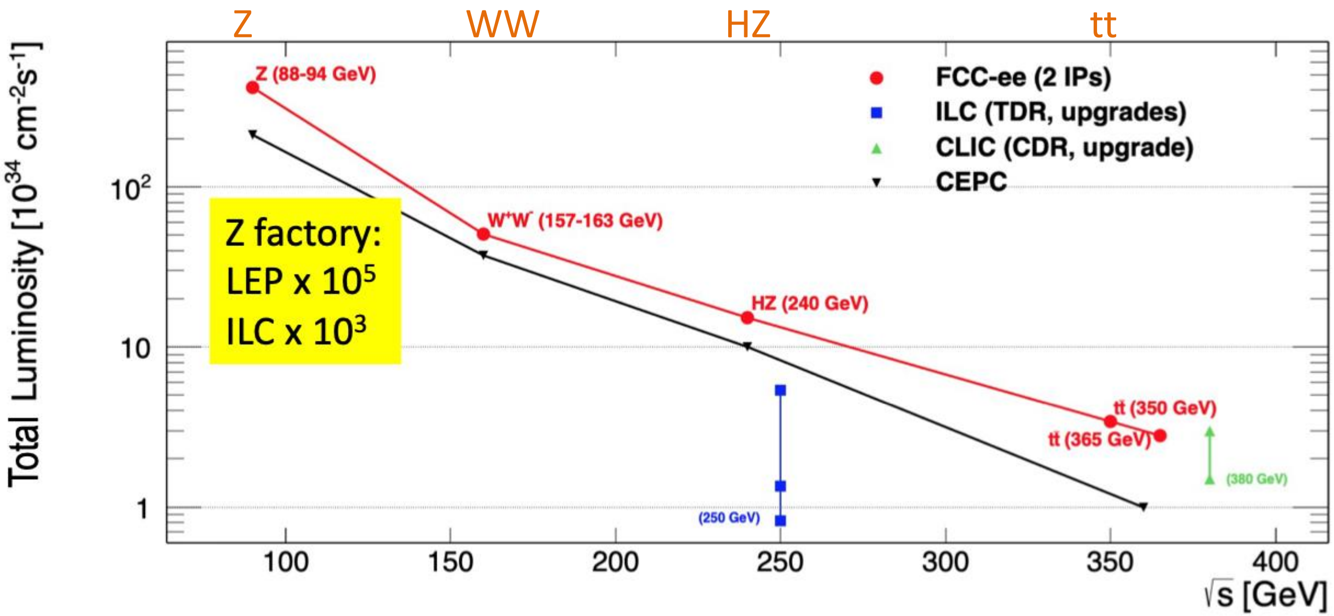
Organisation and financing:

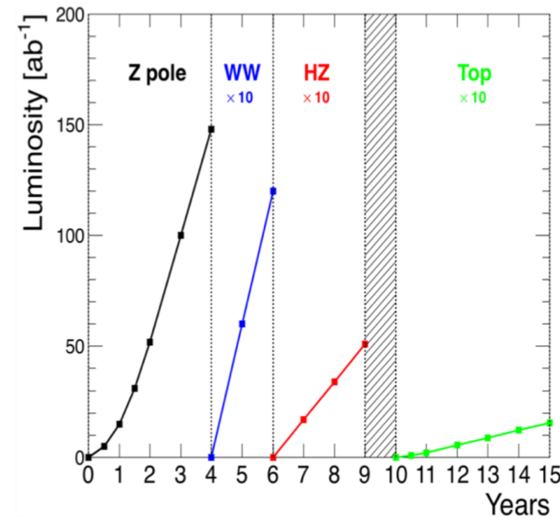
- Overall cost estimate & spending profile for stage 1 project

Environmental impact, socio-economic impact:

- Initial state analysis, carbon footprint, management of excavated materials, etc.
- Socio-economic impact and sustainability studies

FCC-ee (CEPC) Run Plan





Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4 (2)	88-95 ± <100 KeV	150 (96)	3×10^{12} visible Z decays
FCC-ee-W	2 (1)	158-162 <200 KeV	12 (7)	10^8 WW events
FCC-ee-H	3 (10)	240 ± 1 MeV	5 (20)	10^6 ZH events
FCC-ee-tt	5 (5)	345-365 ± 2 MeV	1.5 (1.0)	10^6 $t\bar{t}$ events

Extracted from FCC CDR

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

(in blue) are given the latest CEPC values (for 30 MW SR power)

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

Detector requirements (present status)

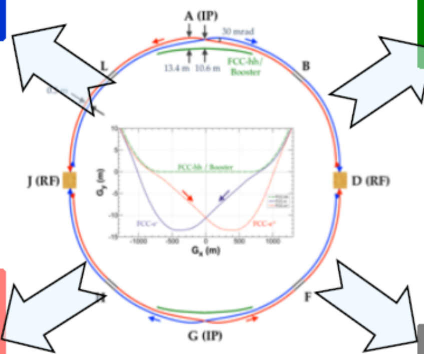
M. Dam ECFA R&D road map input
https://indico.cern.ch/event/994685/

"Higgs Factory" Programme

- Momentum resolution of $\sigma_{p_T}/p_T^2 \simeq 2 \times 10^{-5}\,\text{GeV}^{-1}$ 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

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.



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

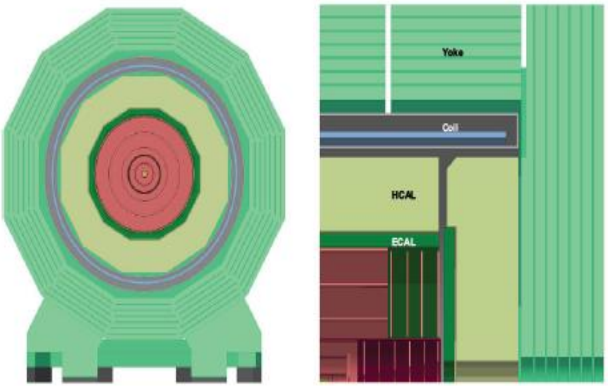
Feebly Coupled Particles - LLPs

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 for FCC-ee

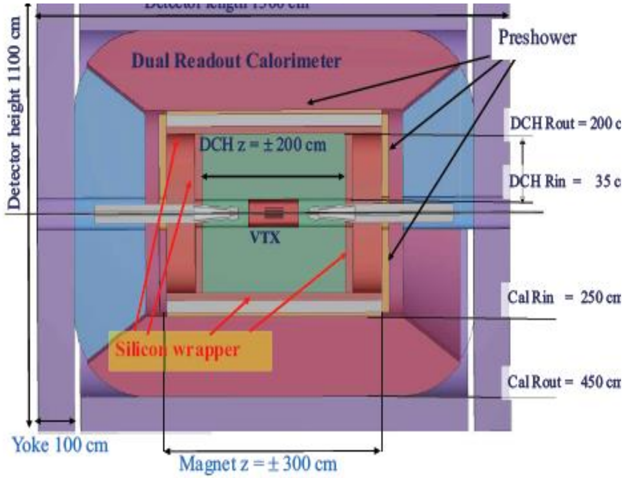
CLD



conceptually extended from the CLIC detector design

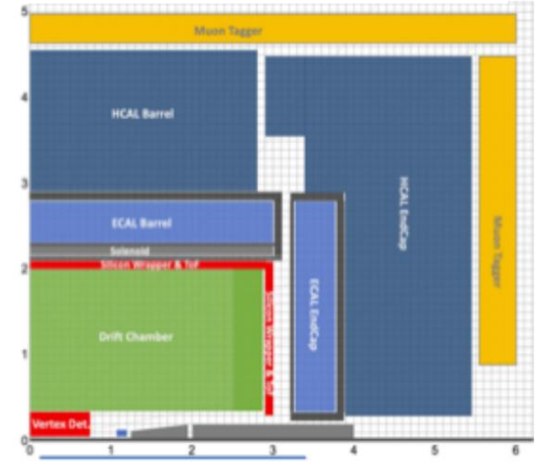
- full silicon tracker
- 2T magnetic field
- high granular silicon-tungsten ECAL
- high granular scintillator-steel HCAL
- instrumented steel-yoke with RPC for muon detection

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

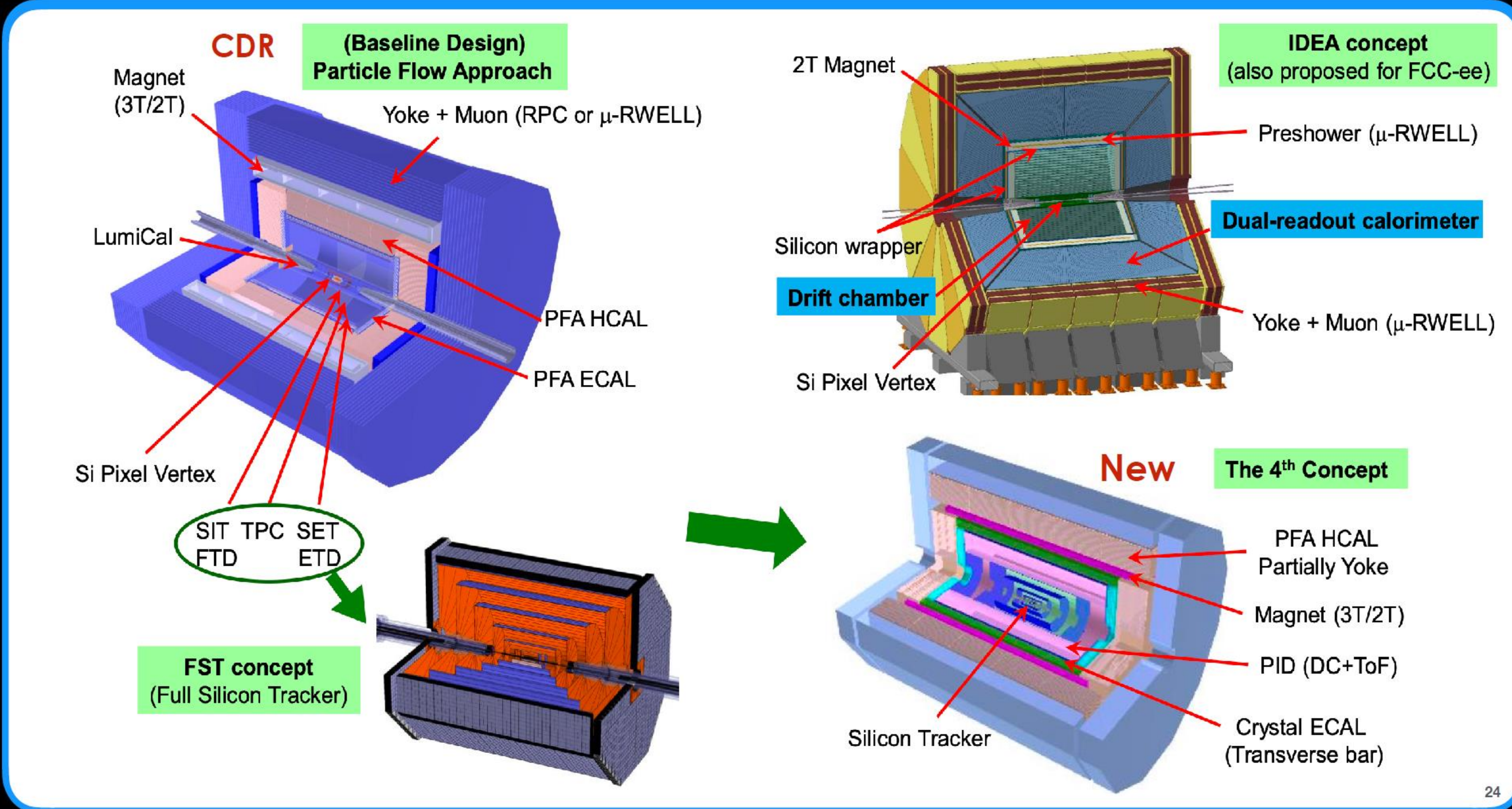


- explicitely designed for FCC-ee, recent concept, under development
- silicon vertex
- Low X_0 drift chamber
- Thin Solenoid before the Calorimeter
- High Granularity Liquid Argon Calorimetry

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

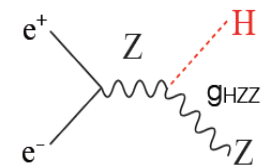
With potentially 4 experiments, many complementary options will be implemented,
Definitely a place to contribute

CEPC Detector Concept Designs



Physics of the Higgs boson at FCC-ee and CEPC

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

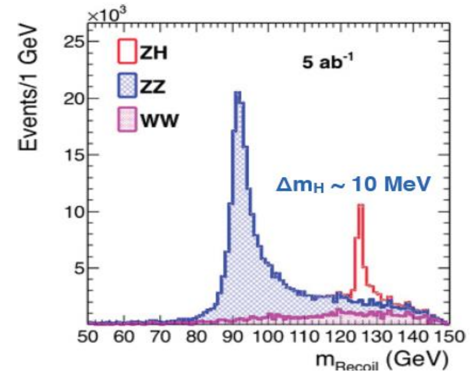


$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

E_+, E_- lepton energies from Z decay

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

absolute HZZ coupling meas.



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

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

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

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

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

Couplings Measurements Comparison across Machines

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

The **CEPC** precision has been improved with the upgraded proposal → now comparable to the FCC-ee ones.

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

LHC caveats:

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

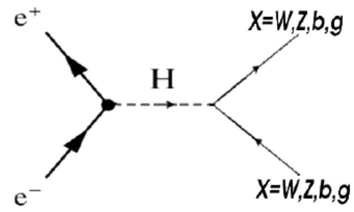
HL-LHC will produce many more Higgs than FCC-ee, hence dominate precisions for Hμμ, Hγγ

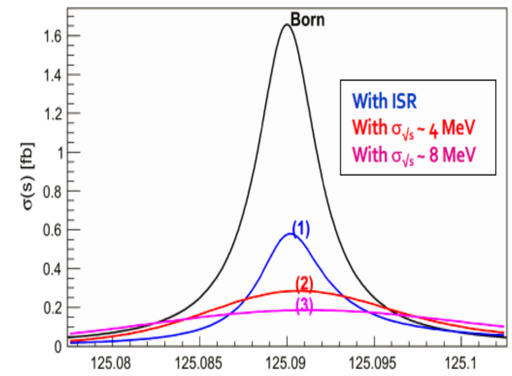
Yukawa coupling to electrons via s-channel e+e- → H production

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

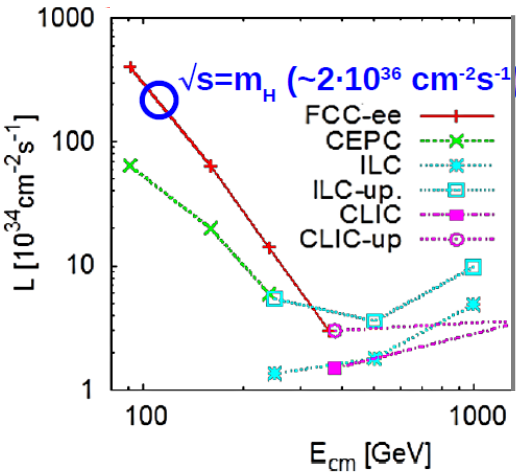
- Higgs decay to e^+e^- is unobservable: BR($H \to e^+e^-$) $\propto m_e^2 \approx 5\cdot10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny κ_e Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$:

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





- Huge luminosities available at FCC-ee:

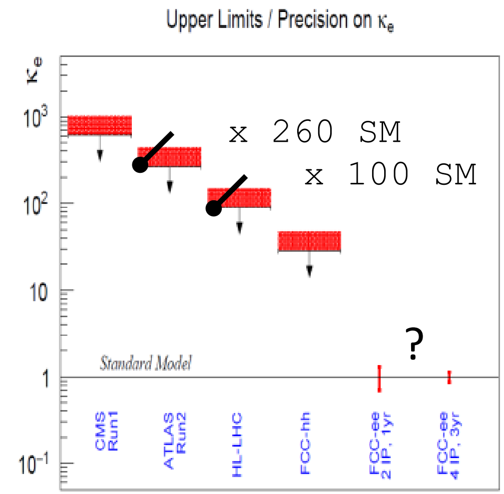


In theory, FCC-ee running at H pole-mass $L_{int} \approx 20$ ab^{-1}/yr would produce O(30.000) H's

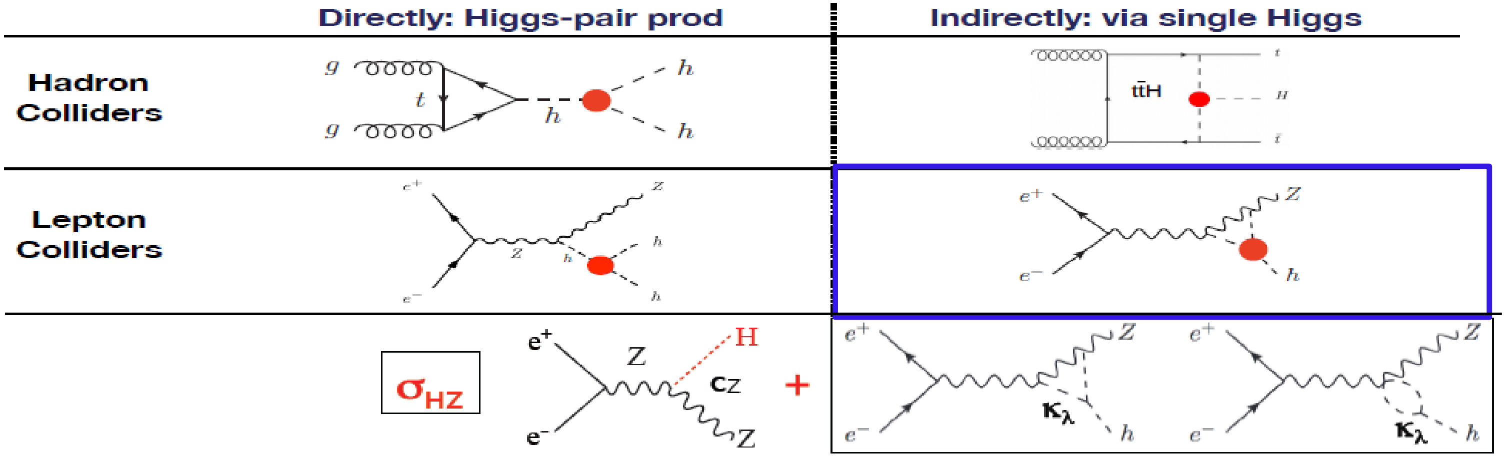
IF we can control: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds, then:

→ 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

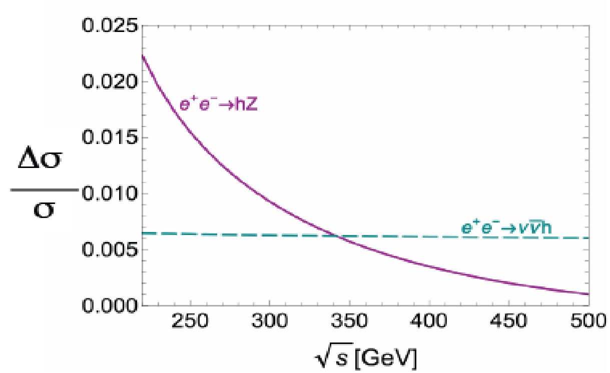


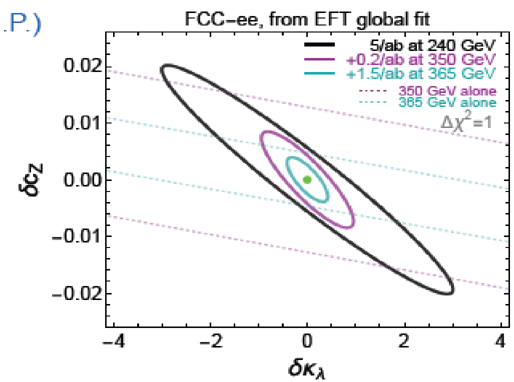
Measurement of the Higgs self-coupling



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 CM energy helps in reducing correlations

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

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

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

most challenging and could be the most promising part of the program given the statistics !

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

For the electroweak program we will also have

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

Uncertainties in EWPO

Statistical opportunities | Systematics challenges

Observable	present value ± error	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}(\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	small	from $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2-1	ratio of hadrons to leptons **acceptance for leptons**
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4-1.6	from R_ℓ^Z above
σ_{had}^0 $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	peak hadronic cross section luminosity measurement
$N_\nu(\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.2	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	small	from R_ℓ^W
$N_\nu(\times 10^3)$	2920 ± 50	**0.8**	small	ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV/c^2)	172740 ± 500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
Γ_{top} (MeV/c^2)	1410 ± 190	45	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2 ± 0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	± 30%	0.5 – 1.5%	small	From $\sqrt{s} = 365$ GeV run

Systematics 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

We are concentrating now on finding the potential 'show stoppers' or 'stumbling blocks', to guide the detector R&D and detector requirements.

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

Theory work is critical and initiated (1809.01830)

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

Precision of CKM matrix elements

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

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

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

FCC

Top factory at 340 – 365 GeV

- Expect 1 M $t\bar{t}$ events,
  in a clean environment and abilty to scan $\sqrt{s}$

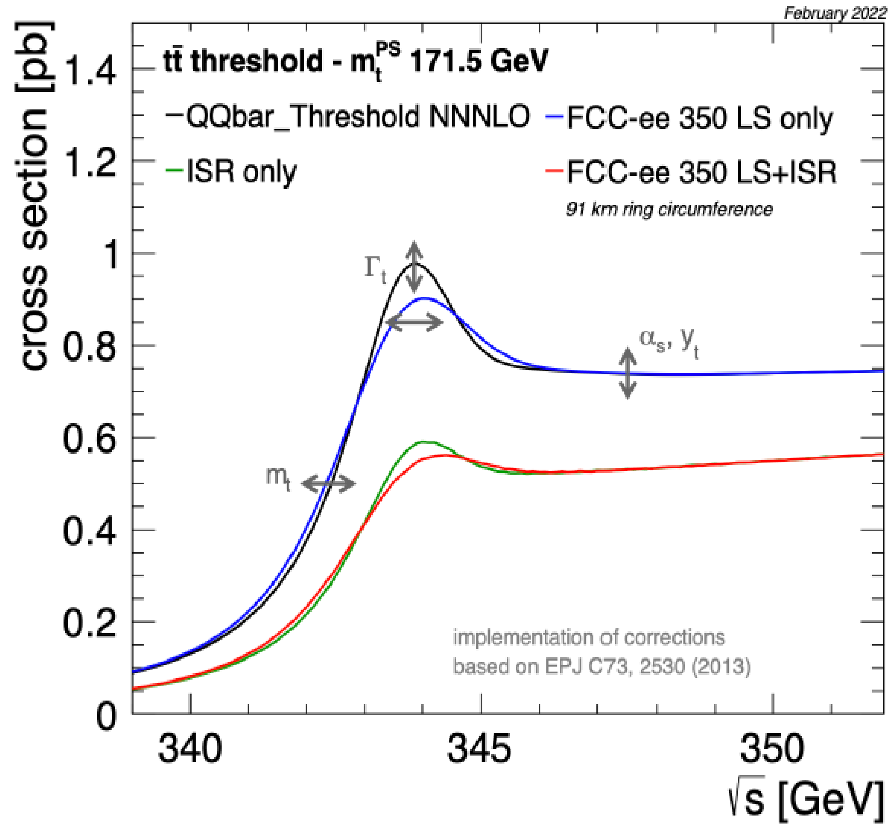
- Test of Higgs mechanism via measurement of top mass and top Yukawa coupling

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

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

  → uncertainty ~10 times smaller than @HL-LHC

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



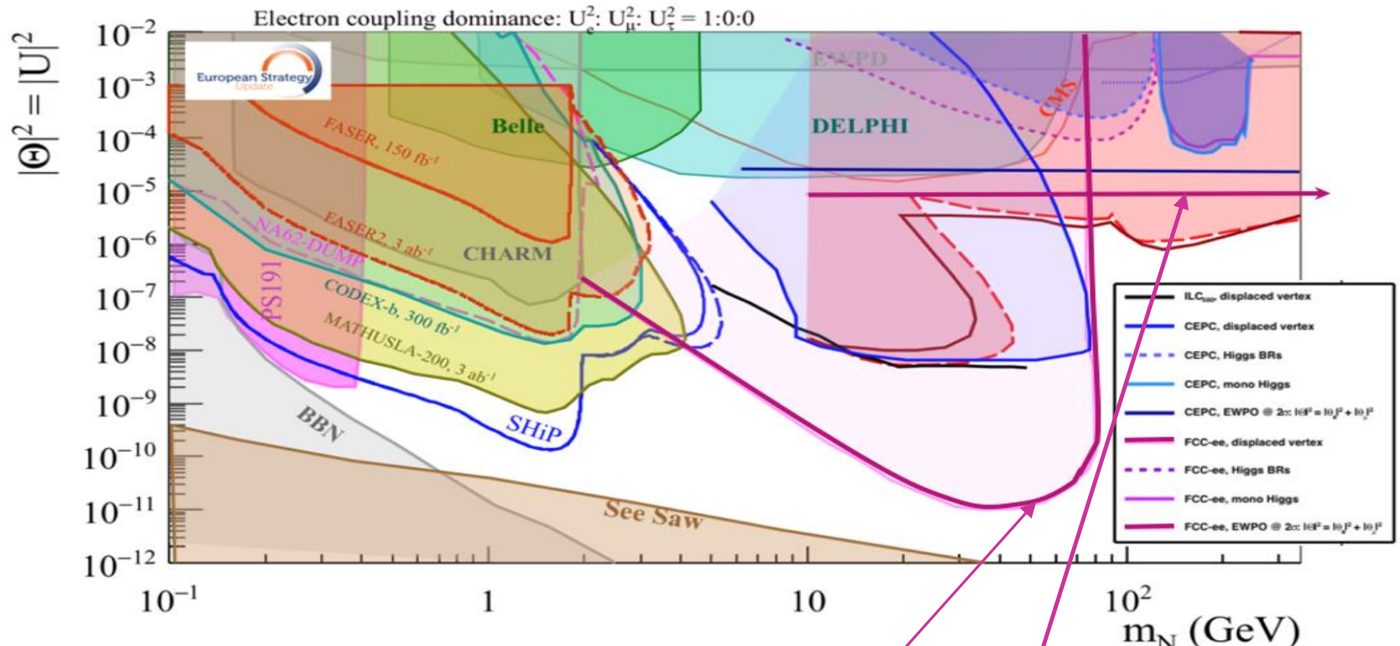
Feebly interacting particles

SM works well, yet we need new physics to explain the Universe puzzles without interfering with SM radiative corrections

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

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

(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 $\sin^2\theta_W^{eff}$ and m_Z, m_W, tau decays) which extends sensitivity to 10^{-5} mixing, all the way to very high energies (500-1000 TeV): arXiv:2011.04725

Summary: FCC-ee/CEPC Discovery Potential and Highlights

ee Circular Colliders 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 (FCC-ee)

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

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

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

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

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

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 → Circular Collider

FCC or CEPC, thanks also to synergies and complementarities with a future hh machine, offers the best approach to today's physics landscape

FCC-ee can be constructed while accomplishing the HL-LHC program

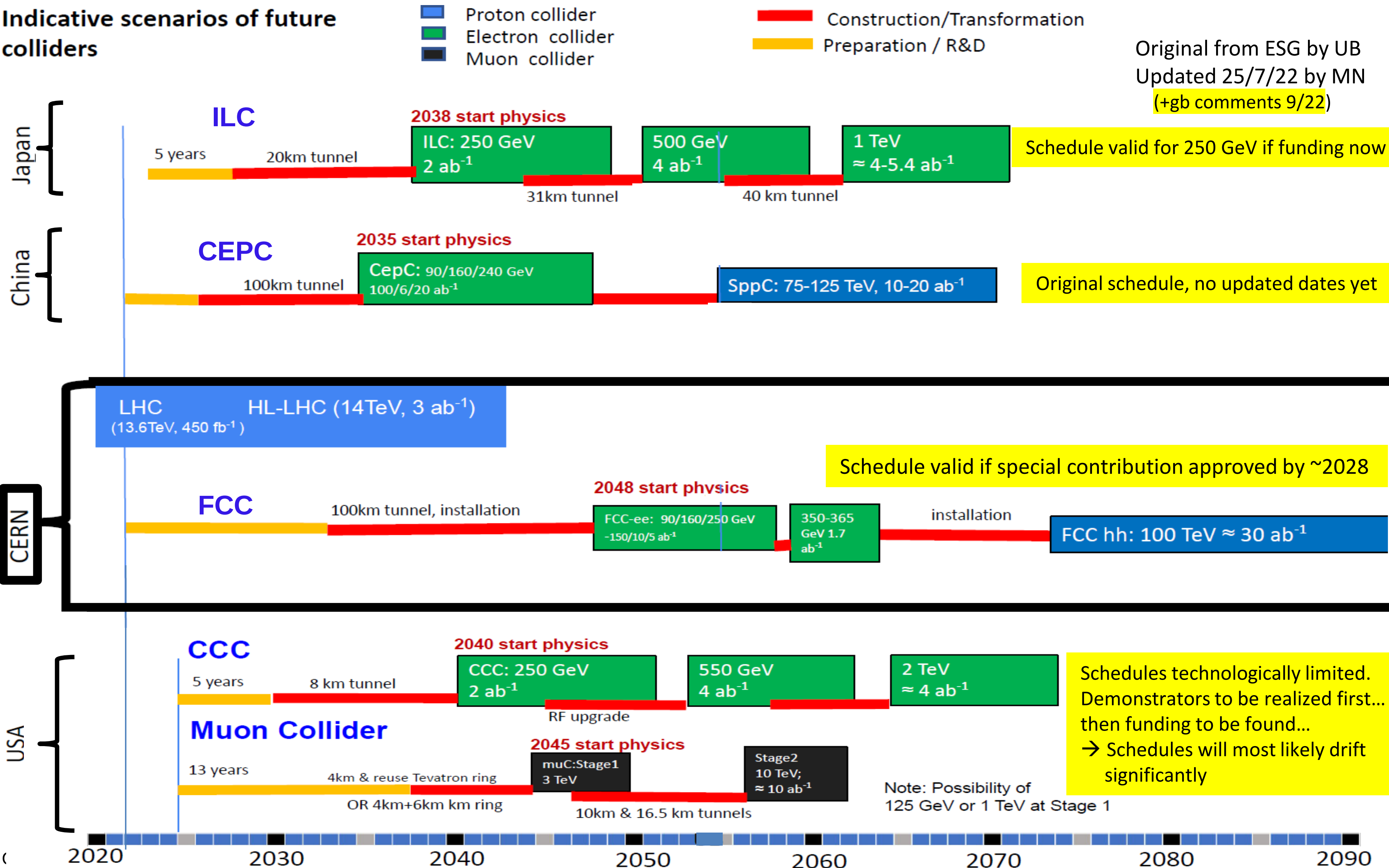
Many opportunities and challenges are offered by the energy range (from the Z pole to 100 TeV or more) and from the huge rates offered by the circular machines, from 10^{12} Z @ FCC-ee to 10^{13} Ws and 10^{10} H at FCC-hh.

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

Please join the effort, the presence of all is needed to make a Future Collider happen !

- The FCC Physics Workshop will take place in Cracow in Jan. 2023: https://indico.cern.ch/event/1066234/
- The 6th Annual FCC Week will take place in London in June 2023: https://indico.cern.ch/event/1064327/

FCC

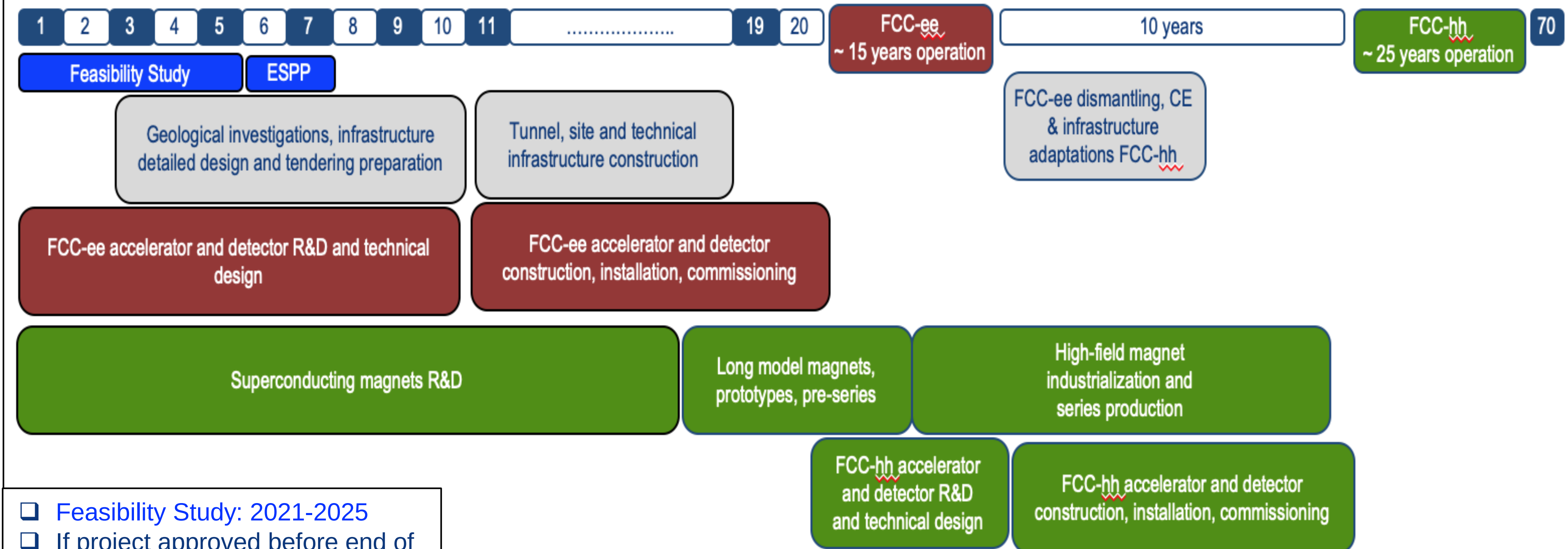


Indicative scenarios of future colliders
Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Original from ESG by UB
Updated 25/7/22 by MN
(+gb comments 9/22)
Japan
ILC
5 years
20km tunnel
2038 start physics
ILC: 250 GeV
2 ab^{-1}
31km tunnel
500 GeV
4 ab^{-1}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

PED Deliverables for the FCC mid-term review

- A mid-term report is expected by fall 2023, with three main deliverable categories for PED
  - Section 1: Physics case
    - Documentation of the specificities and complementarity of the FCC-ee and FCC-hh physics cases, in particular for the Standard Model Higgs boson characterization.
      - Should include the FCC-ee standalone physics case (Council specific request)
      - Should include specificities and complementarity with other colliders (other e+e- Higgs factories, Multi-TeV muon collider)
      - Should extend to topics beyond the SM Higgs boson characterization
      - Carbon footprint during operation (and installation) is explicitly requested
  - Section 2: Theoretical calculations
    - Strategic plan for improved calculations needed to reduce theoretical uncertainties towards matching the FCC-ee expected statistical precision on the most important measurements.
      - Should include a detailed plan for MC generators as well
  - Section 3: Detector requirements
    - First documentation of the main detector requirements to fully exploit the FCC-ee physics opportunities, in particular to reduce experimental uncertainties towards matching the expected statistical precision on the most important measurements.
      - Should include a complete list of requirements, also those for which we don't have a complete study yet

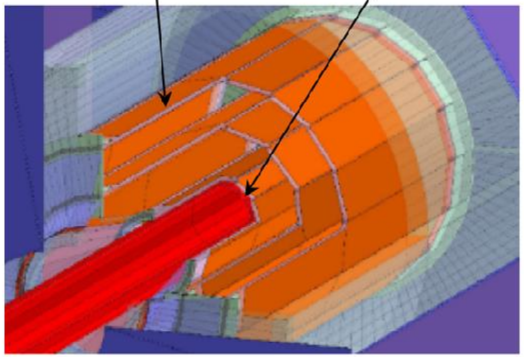
technical timeline of FCC integrated programme



- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

F. Gianotti

CEPC R&D: Silicon Pixel Sensors



Goal: σ(IP) ~ 5 μm for high P track

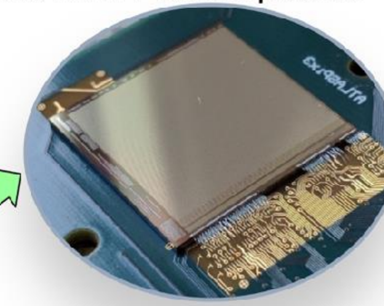
CDR design specifications

- Single point resolution ~ 3μm
- Low material (0.15% X_0 / layer)
- Low power (< 50 mW/cm²)
- Radiation hard (1 Mrad/year)

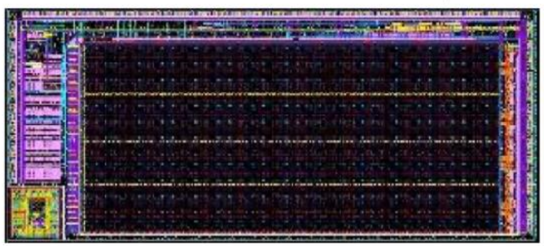
Silicon pixel sensor develops in 5 series:
JadePix, TaichuPix, CPV, Arcadia, CEPCPix

Develop **CEPCPix** for a CEPC tracker based on **ATLASPix3** **CN/IT/UK/DE**

TSI 180 nm HV-CMOS process



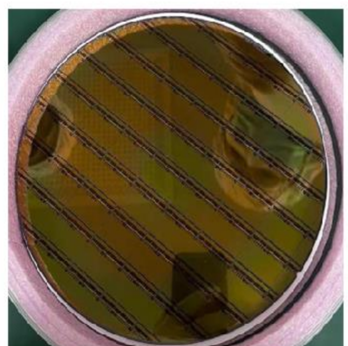
JadePix-3 Pixel size ~16×23 μm²



Tower-Jazz 180nm CiS process
Resolution 5 microns, 53mW/cm²

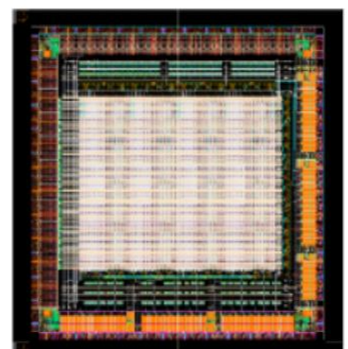
MOST 1

TaichuPix-3, FS 2.5x1.5 cm²
25×25 μm² pixel size

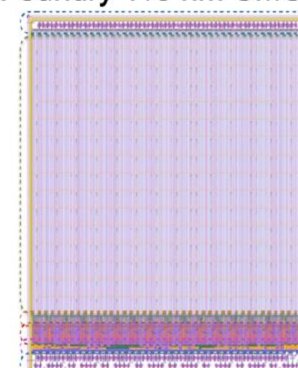


MOST 2

CPV4 (SOI-3D), 64×64 array
~21×17 μm² pixel size



Arcadia by Italian groups
for IDEA vertex detector
LFoundry 110 nm CMOS

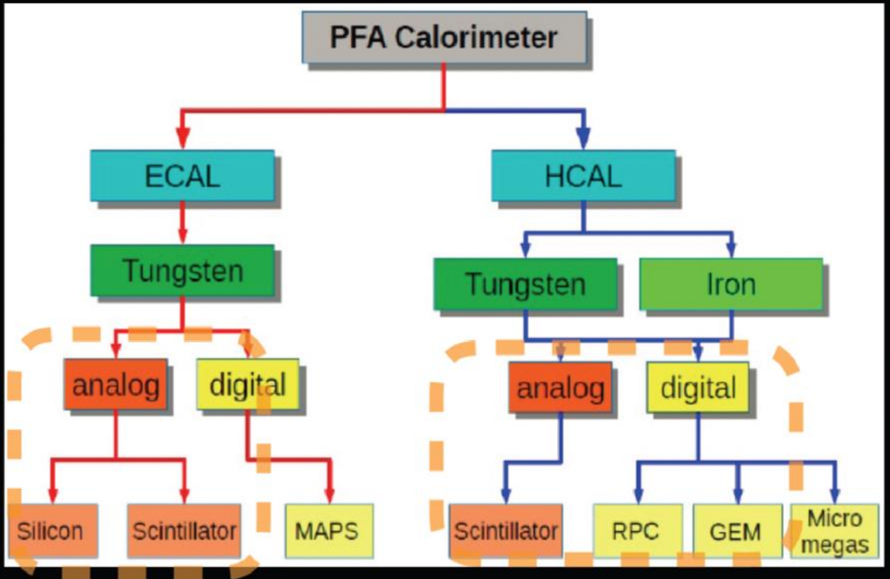


27

Calorimeter options

Chinese institutions have been focusing on Particle Flow calorimeters

R&D supported by MOST, NSFC and IHEP seed funding



High Granularity

Electromagnetic	ECAL with Silicon and Tungsten (LLR, France) ECAL with Scintillator+SiPM and Tungsten (IHEP + USTC)
Hadronic	SDHCAL with RPC and Stainless Steel (SJTU + IPNL, France) SDHCAL with ThGEM/GEM and Stainless Steel (IHEP + UCAS + USTC) HCAL with Scintillator+SiPM and Stainless Steel (IHEP + USTC + SJTU)

Newer Options

Some longitudinal granularity	Crystal Calorimeter (LYSO:Ce + PbWO) Dual readout calorimeters (INFN, Italy + Iowa, USA) — RD52

46

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

Motivation for a circular collider 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

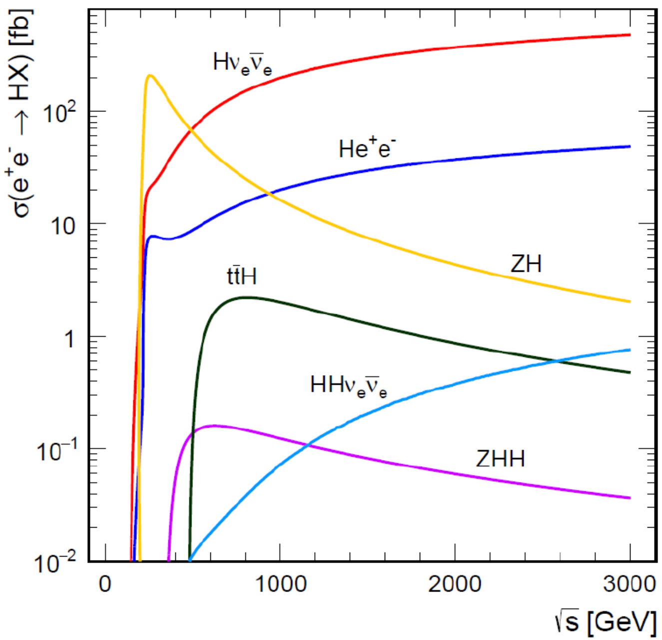
this leads to many detector requirements, which are best satisfied with more than one detector → we are aiming at 4 detectors in 4 interactions points with complementary strengths
An example of competing constraints for EM calorimeter are the following:
high E precision vs. high granularity vs. high 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.

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	ee
g_{Hbb} (%)	0.60 / 0.56	0.50 / 0.47	0.53 / 0.53	0.48 / 0.48	ee
g_{Hcc} (%)	1.3 / 1.2	0.91 / 0.90	1.4 / 1.4	0.96 / 0.96	ee
g_{Hgg} (%)	0.98 / 0.85	0.67 / 0.63	0.96 / 0.86	0.52 / 0.50	ee
$g_{H\tau\tau}$ (%)	0.72 / 0.64	0.58 / 0.54	0.95 / 0.82	0.49 / 0.46	ee
$g_{H\mu\mu}$ (%)	9.4 / 3.9	6.3 / 3.6	5.9 / 3.5	0.43 / 0.43	hh
$g_{H\gamma\gamma}$ (%)	3.5 / 1.2	1.9 / 1.1	2.3 / 1.1	0.32 / 0.32	hh
$g_{HZ\gamma}$ (%)	– / 10.	– / 10.	7. / 5.7	0.71 / 0.70	hh
g_{Htt} (%)	6.9 / 2.8	1.6 / 1.4	2.7 / 2.1	1.0 / 0.95	hh
g_{HHH} (%)	27.	10.	9.	±3.8*	hh
Γ_H (%)	1.1	1.0	1.6	0.91	ee
BR_{inv} (%)	0.23	0.22	0.61	0.024	hh
BR_{EXO} (%)	1.4	1.4	2.4	1.0	ee

*arXiv:2004.03505

FCC-hh > 10^{10} H produced

+

FCC-ee measurement of g_{HZZ}

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

FCC feasibility study organization - Approved by the CERN Council September 2021

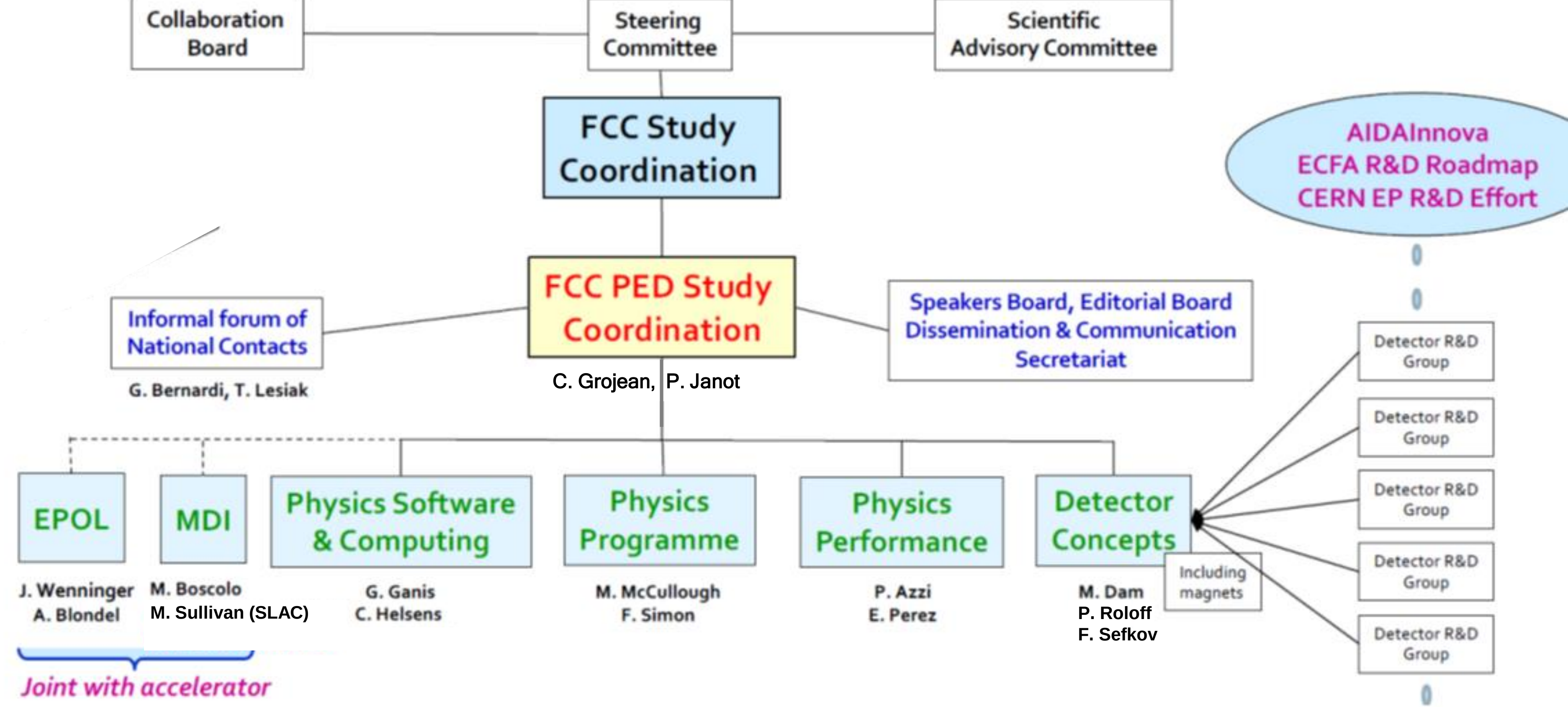
FUTURE CIRCULAR COLLIDER

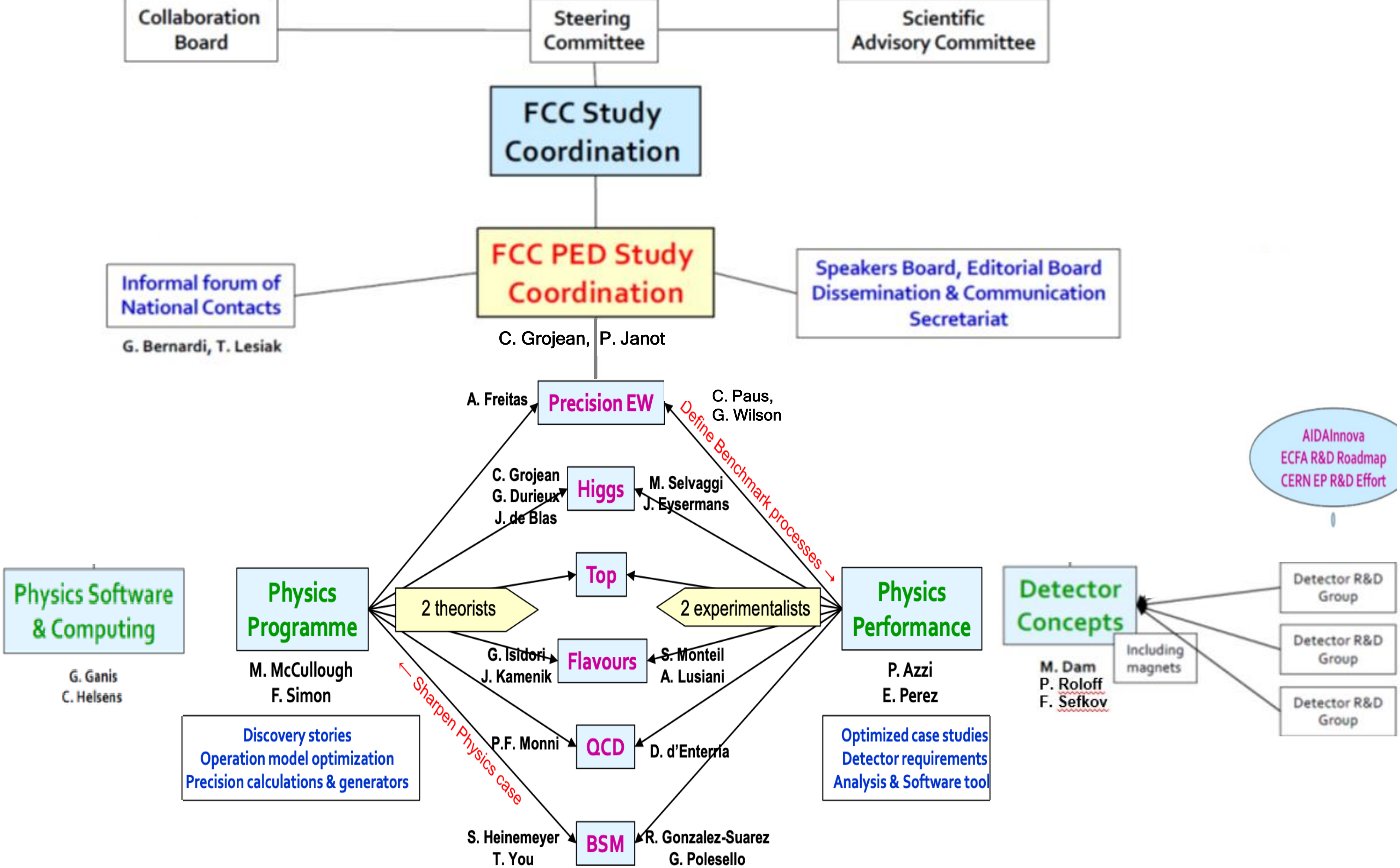
FCC Study Study leader M. Benedikt

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, 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		


Collaboration Board
Steering Committee
Scientific Advisory Committee
FCC Study Coordination
AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort
Informal forum of National Contacts
G. Bernardi, T. Lesiak
FCC PED Study Coordination
C. Grojean, P. Janot
Speakers Board, Editorial Board
Dissemination & Communication
Secretariat
Detector R&D Group
Detector R&D Group
Detector R&D Group
Detector R&D Group
Detector R&D Group
EPOL
J. Wenninger
A. Blondel
MDI
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
Including magnets
M. Dam
P. Roloff
F. Sefkov
Joint with accelerator



Collaboration Board
Steering Committee
Scientific Advisory Committee
FCC Study Coordination
FCC PED Study Coordination
C. Grojean, P. Janot
Informal forum of National Contacts
G. Bernardi, T. Lesiak
Speakers Board, Editorial Board
Dissemination & Communication
Secretariat
A. Freitas
Precision EW
C. Paus,
G. Wilson
Define Benchmark processes →
C. Grojean
G. Durieux
J. de Blas
Higgs
M. Selvaggi
J. Eysermans
Top
2 theorists
2 experimentalists
G. Isidori
J. Kamenik
Flavours
S. Monteil
A. Lusiani
P.F. Monni
QCD
D. d'Enterria
← Sharpen Physics case
S. Heinemeyer
T. You
BSM
R. Gonzalez-Suarez
G. Polesello
Physics Software & Computing
G. Ganis
C. Helsens
Physics Programme
M. McCullough
F. Simon
Discovery stories
Operation model optimization
Precision calculations & generators
Physics Performance
P. Azzi
E. Perez
Optimized case studies
Detector requirements
Analysis & Software tool
Detector Concepts
Including magnets
M. Dam
P. Roloff
F. Sefkov
AIDAInnova
ECFA R&D Roadmap
CERN EP R&D Effort
Detector R&D Group
Detector R&D Group
Detector R&D Group