Future Colliders & IPNP

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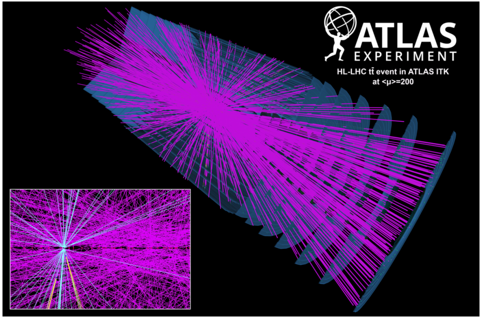
Overview

Future Colliders

Future Colliders

Large Hadron Collider at CERN

- LHC (2008–2025)
  8–13 TeV, 400 fb^{-1}
- HL-LHL (2029–2041)
  14 TeV, 4000 fb^{-1}



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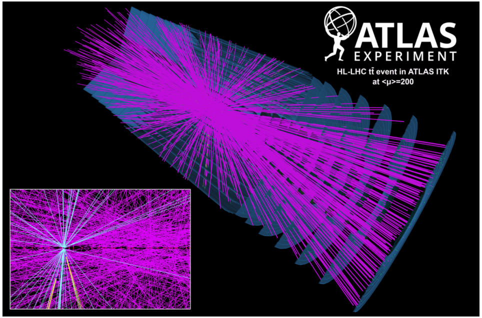

Next generation of colliders after LHC era?

European Strategy of Particle Physics 2020

- New e^+e^- collider (Higgs factory) as the highest-priority
- Hadron collider with E_{cms} at least 100 TeV at CERN as a longer term

Why do we need new hadron collider?

Hadron collider as a discovery machine

Open questions

- Dark matter
- Matter-antimatter symmetry
- Neutrino masses
- ...

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Hadron collider can give answers if

- Mass of new particles is in its reach
- The detectors are sensitive enough

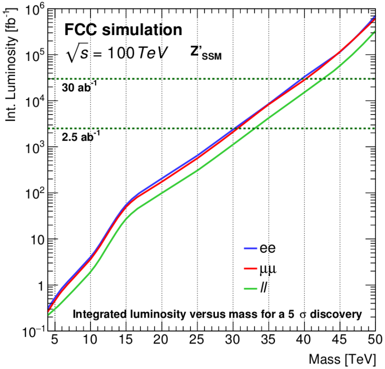

Image: FCC-hh CDR

Why do we need new lepton collider?

Precise measurements of the electroweak sector as a hint of new physics

Highlights from the physics programme

- Higgs boson couplings
- Top quark and Higgs boson masses
- Flavour physics (b, c, τ)

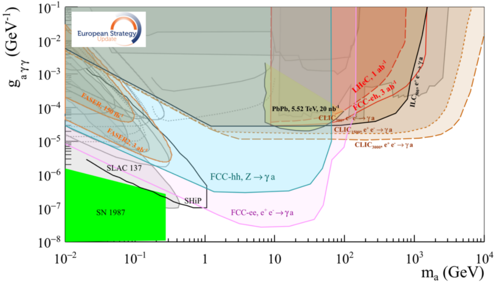

Image: arXiv:1910.11775

Why do we need new lepton collider?

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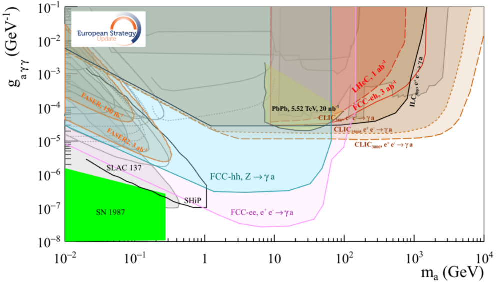

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Advantages of e^+e^- colliders

- Clean environment $\to$ measurements of unprecedented precision
- Higgs factories provides model-independent measurements
- We can starting building the collider (almost) now

Lepton colliders at the market

Linear Colliders

- ILC (International Linear Collider, Japan)
- CLIC (Compact Linear Collider, CERN)

Circular Colliders

- FCC (Future Circular Collider, CERN)
- CEPC (Circular Electron Positron Collider, China)

Circular vs linear colliders

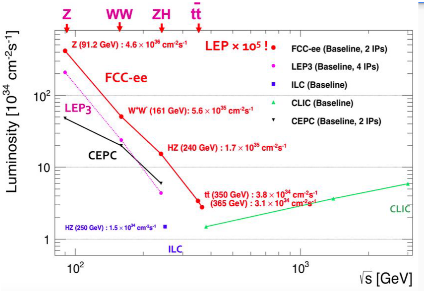


Image: FCC-ee CDR

Linear colliders

- High energy (extendable)
- No synchrotron radiation
- Beams not reusable

Circular colliders

- High luminosity
- Synchrotron radiation
- Circulating beams
- Synergy with future *pp* collider

Higgs factories: Higgs coupling

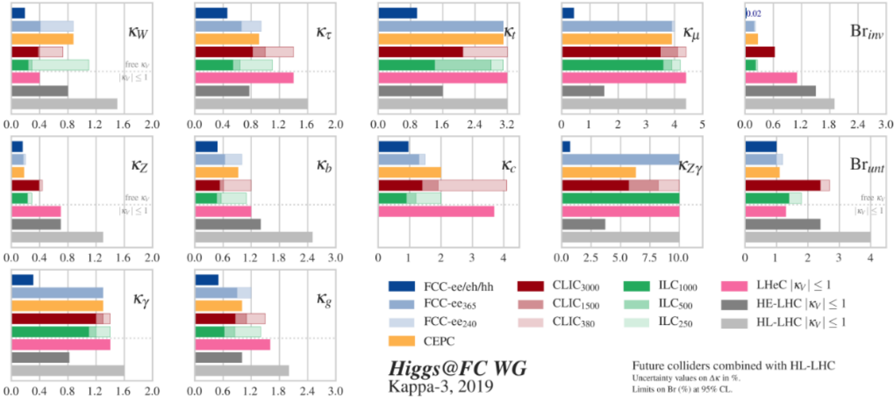


Image: arXiv:1905.03764

Higgs factories: Higgs coupling

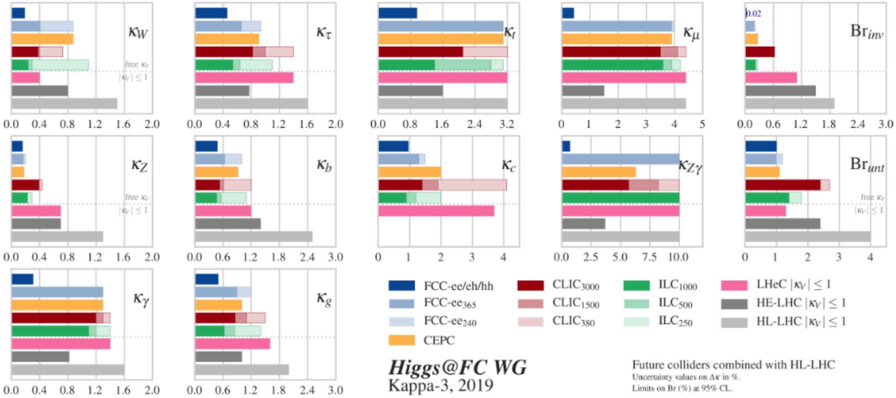
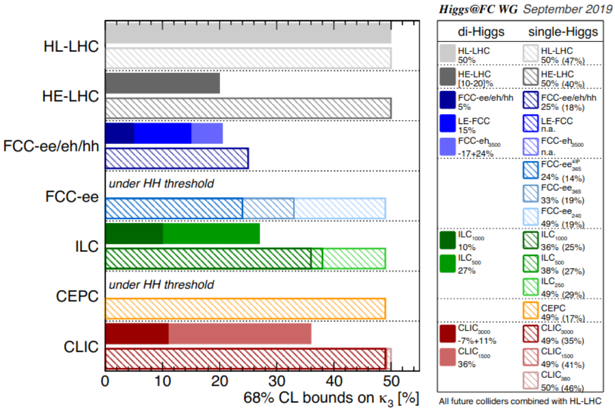


Image: arXiv:1905.03764

Factor 2–10 improvement with e^+e^- colliders wrt HL-LHC

Comparable sensitivities in initial stages of e^+e^- colliders (factor of 2 max)

Higgs factories: Higgs self-coupling



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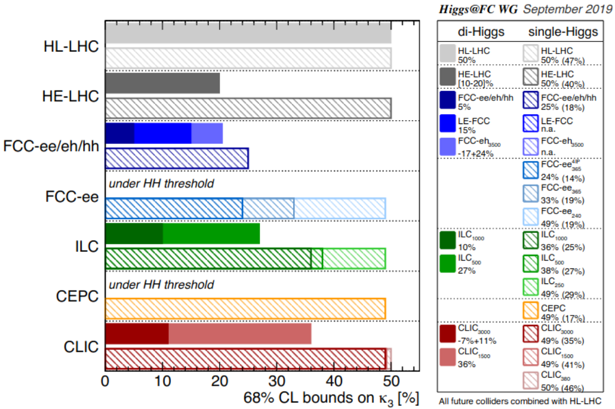

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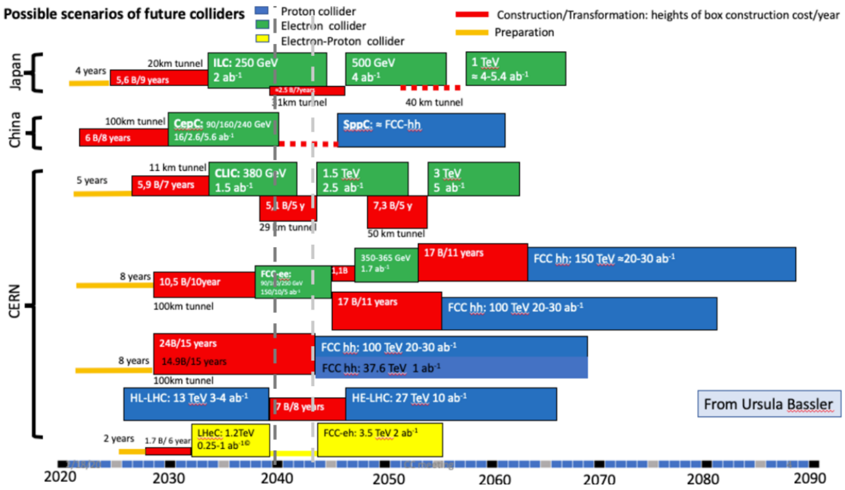
A Higgs factory is needed, even if the ultimate goal is the hadron-hadron collider.

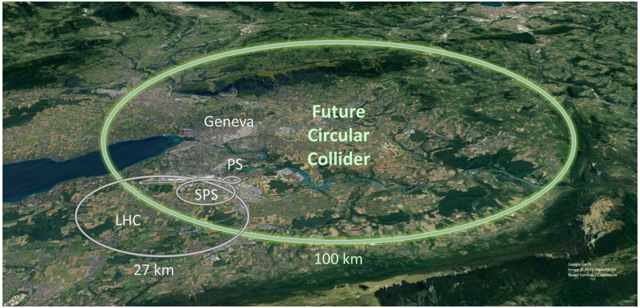
Possible timelines



FCC Collider

Future Circular Collider

FCC



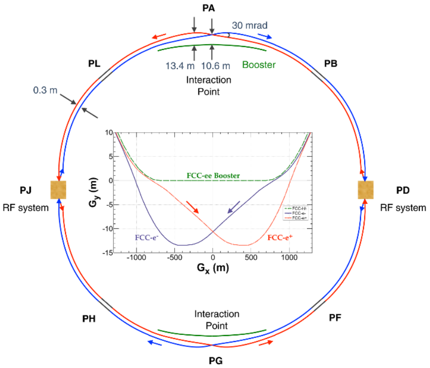
Stage 1: FCC-ee as Higgs factory, electroweak and top factory at highest luminosities

Stage 2: FCC-hh (100 TeV) as a natural continuation, with ion and *eh* option

Complementary physics, common civil engineering and technical infrastructres

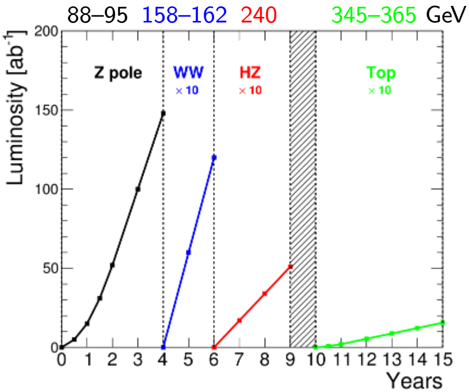
Building on and reusing CERN's existing infrastructures

FCC-ee: Lepton collider



Double ring e^+e^- collider (100 km)

Asymmetric IR layout & optics to limit synchrotron radiation



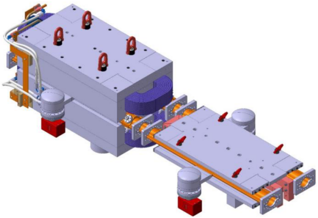
Four working points

$10^5\times$ more Z bosons compared to LEP

FCC-ee: Parameters

parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1390	147	29	5.4
no. bunches/beam	16640	2000	393	48
bunch intensity [10^{11}]	1.7	1.5	1.5	2.3
SR energy loss / turn [GeV]	0.036	0.34	1.72	9.21
total RF voltage [GV]	0.1	0.44	2.0	10.9
long. damping time [turns]	1281	235	70	20
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horiz. geometric emittance [nm]	0.27	0.28	0.63	1.46
vert. geom. emittance [pm]	1.0	1.7	1.3	2.9
bunch length with SR / BS [mm]	3.5 / 12.1	3.0 / 6.0	3.3 / 5.3	2.0 / 2.5
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	230	28	8.5	1.55
beam lifetime rad Bhabha / BS [min]	68 / >200	49 / >1000	38 / 18	40 / 18

FCC-ee: Key technologies

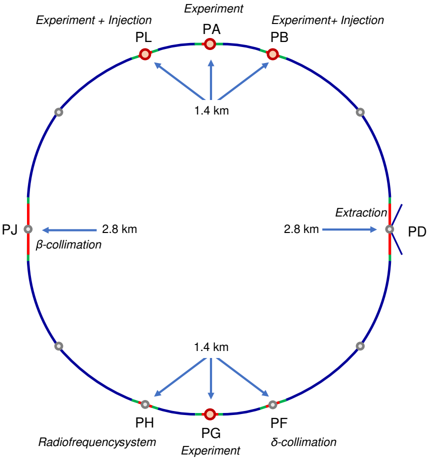


FCC-ee complete vacuum arc half-cell mock up

including girder, vacuum system with antechamber + pumps, dipole, quadrupole + sext. magnets, BPMs, cooling + alignment systems, technical infrastructure interfaces

- 400 MHz SRF cryomodule
- Prototype multi-cell cavities for FCC *ZH* operation
- High-efficiency RF power sources

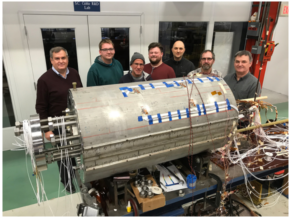
FCC-hh: Hadron collider



Order of magnitude increase wrt HL-LHC

- Centre of mass energy: 14 TeV $\rightarrow$ 100 TeV
- Total integrated luminosity: 4 $ab^{-1} \rightarrow$ 20 ab^{-1}

Key technology: 16 T dipole magnets



Fermilab: Prototype of 14.1 T Nb_3Sn dipole magnet

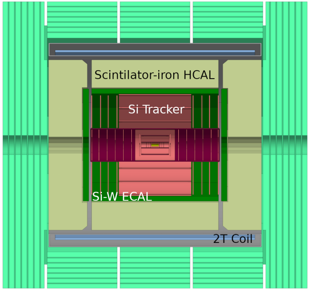
FCC-hh: parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

Detectors for FCC-ee

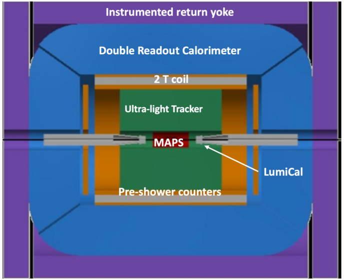
Candidates for FCC-ee detectors

CLD detector



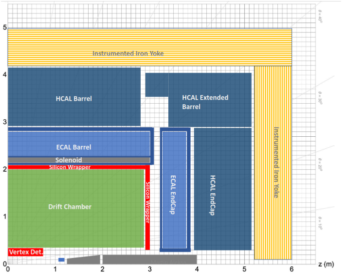
- Highly-granular calorimeter
- Proved concept

IDEA detector



- Ultra-light wire chamber
- Dual-readout calorimeter

'Detector awaiting a name'



- Ultra-light wire chamber
- Liquified noble gas calorimeter

FCC-ee Calorimetry

Requirements

- Jet-jet inv. mass resolution to resolve W from Z
  - requires $\sim 3\%$ ($\sim 30\%/\sqrt{E}$)
- EM resolution at minimum 15% sampling term

In general

- Crystal and Noble liquids — good EM resolution
- CALICE and Dual Readout — good jet resolution

Energy resolution

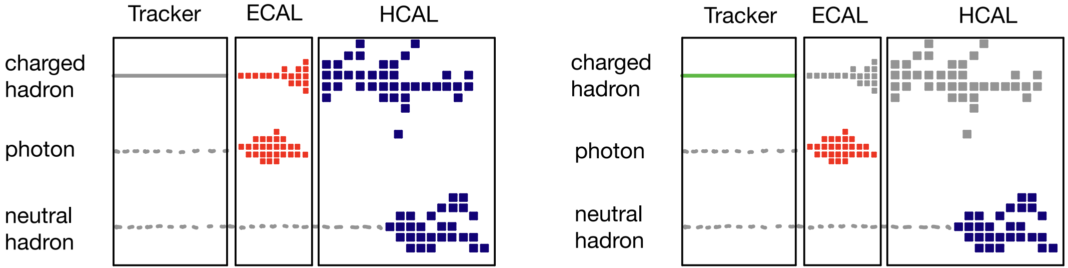
$$\frac{\sigma_\mathrm{E}}{\langle E \rangle} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Typical values for EM showers

Technology	a [%]	c [%]
CALICE	15	1
Dual Readout	10	1
LAr	9	—
Crystal	3–5	0.5

High granularity and Particle Flow needed to achieve energy resolution of 3%

Particle Flow



$$E_{jet} = E_{ECAL} + E_{HCAL}$$

$$E_{jet} = E_{charged} + E_{\gamma} + E_{neutral}$$

- Reconstruct every particle in the event with the best possible precision
- Combine the measurements in subdetectors in an optimal way

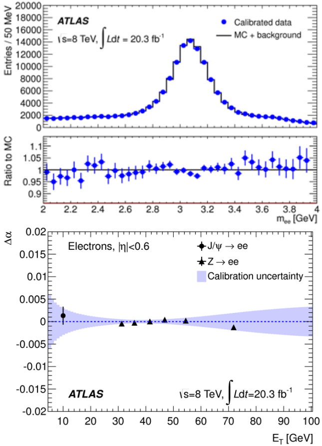
- Charged particles dominated by tracker
- Calorimetry mostly for neutral particles

source: 4th FCC Physics and Experiments Workshop

Liquified noble gas calorimeter

Key features:

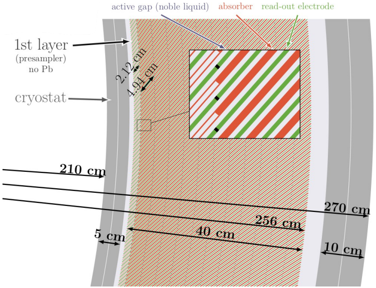
- Well proven concept (DO, H1, NA48/62, ATLAS)
- Radiation hardness, long term stability
- Linear response, uniformity, high control over systematics
- Good energy and timing resolution
- Less than $10\%/\sqrt{E}$ demonstrated

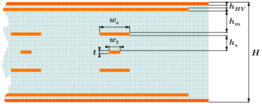


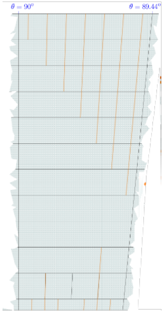
arXiv: 1407.5063

Liquified noble gass calorimeter for FCC-ee

- Noble liquid is suitable technology for FCC-ee detectors
- Design driven by Particle Flow: high granularity achieved by straight multilayer electrodes







Project is a part of DRD6

source: Brieuc François (CERN)

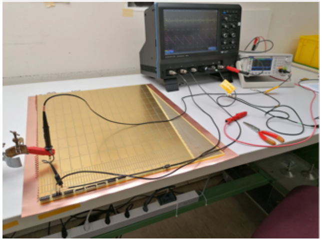
Development of our calorimeter

Several R&D projects

- design of the readout system
- lightweight cryostat
- high densitity feedthroughs

Alternative ideas

- LKr instead of LAr
- shape of the passive plates
- cold electronics



Goal of a module suitable for test beam around 2026

Conclusions

Future Circular Collider

- FCC Integrated program is an ambitious CERN project
- Feasibility to be proved by the next European HEP Strategy

Our group is involved in the development of the liquified noble gas calorimeter

New souls are welcome!

Backup

R&D FCC-ee LAr Projects

CERN EP R&D projects relevant for Noble Liquid Calorimetry:

1. Read-Out Electrode Design and Performance Optimization
2. High Density Feed Through Design Investigations
3. Carbon Composite Cryostats
4. General SW framework

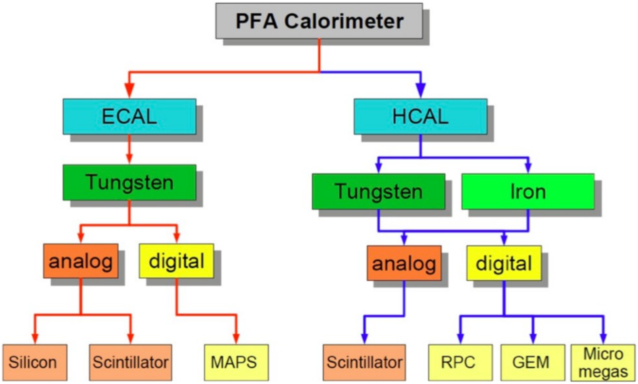
CERN, Charles U. and LAL Orsay: H2020 project AIDAInnova

CALICE

Collaboration of mostly Si/Tungsten based high granularity calorimeters

Traits:

- Large area silicon detectors
- Si Photomultipliers
- Highly integrated front-end electronics with timing
- Very large number of channels



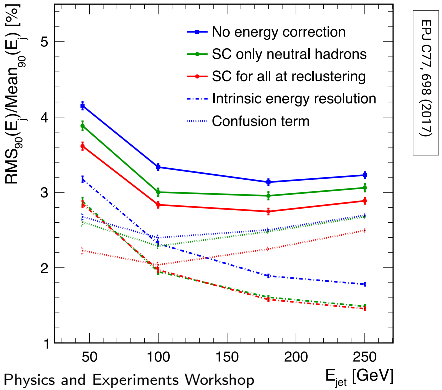
source: 4th FCC Physics and Experiments Workshop

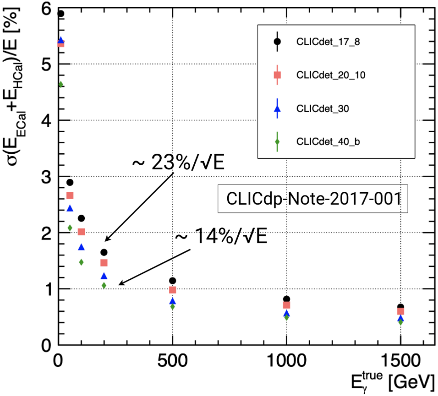
FCC-ee: CLD Calorimeter

CLD proposal:

- 40 layers SiW ECAL (22 X_0)
- 60 layers Scint/Steel HCAL (7.5 λ_I + 1 λ_I in ECAL)

ILD concept



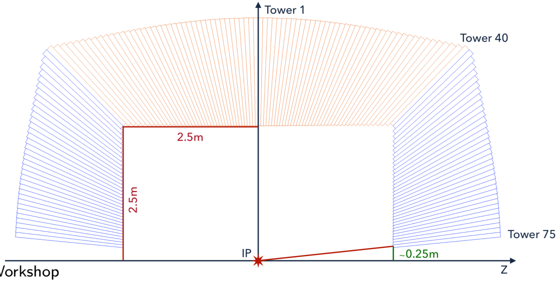


source: 4th FCC Physics and Experiments Workshop

FCC-ee: IDEA Calorimeter

Traits:

- Dual readout calorimeter with 1.5 mm pitch between Cherenkov and Scintillation fibers
- Single EM + HAD sampling calorimeter
- No mechanical longitudinal segmentation ($\sim 7\lambda_I$)
- Good EM intrinsic energy resolution
- Excellent hadronic resolution



source: 4th FCC Physics and Experiments Workshop

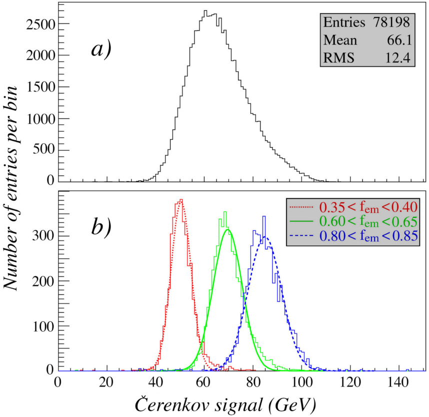
Dual Readout Calorimeter

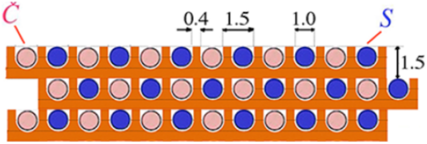
Principle:

$$S = E\left[f_{em} + (h/e)_S(1 - f_{em})\right]$$

$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

- Correct f_{em} in every event
  - Main source of fluctuations
- Fibers pointing toward IP
  - Scintillating: sense all
  - Clear: sense Cherenkov, mostly electrons



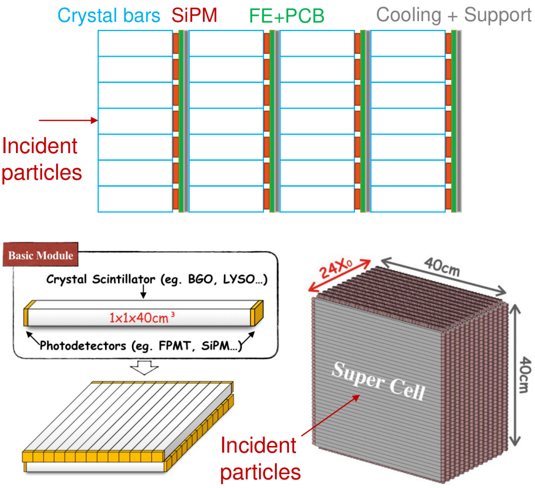


source: 4th FCC Physics and Experiments Workshop

Crystal Calorimeters

Traits:

- Mostly investigated for CEPC
- Used by CMS
- Homogeneous structure
- Has optimal intrinsic energy resolution: $\sim 3\%/\sqrt{E} \oplus \sim 1\%$



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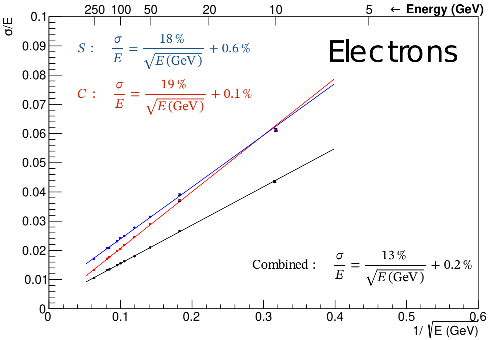
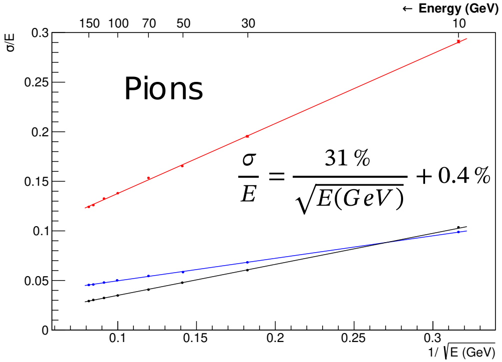
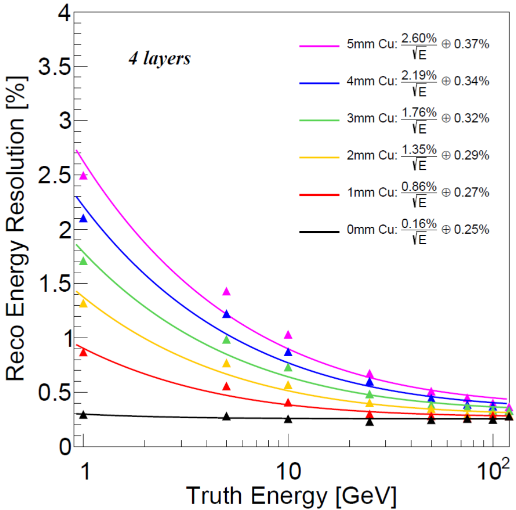
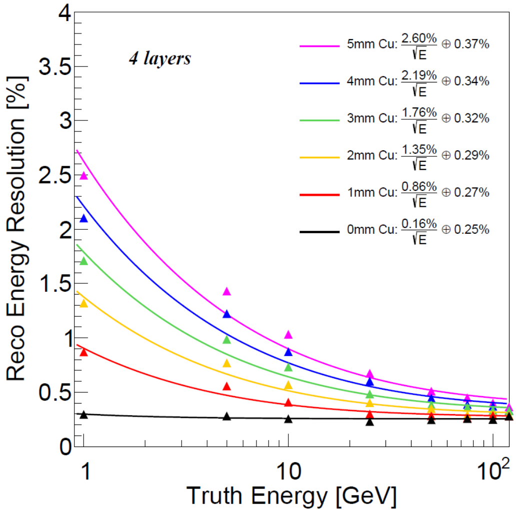
Dual Readout Performance



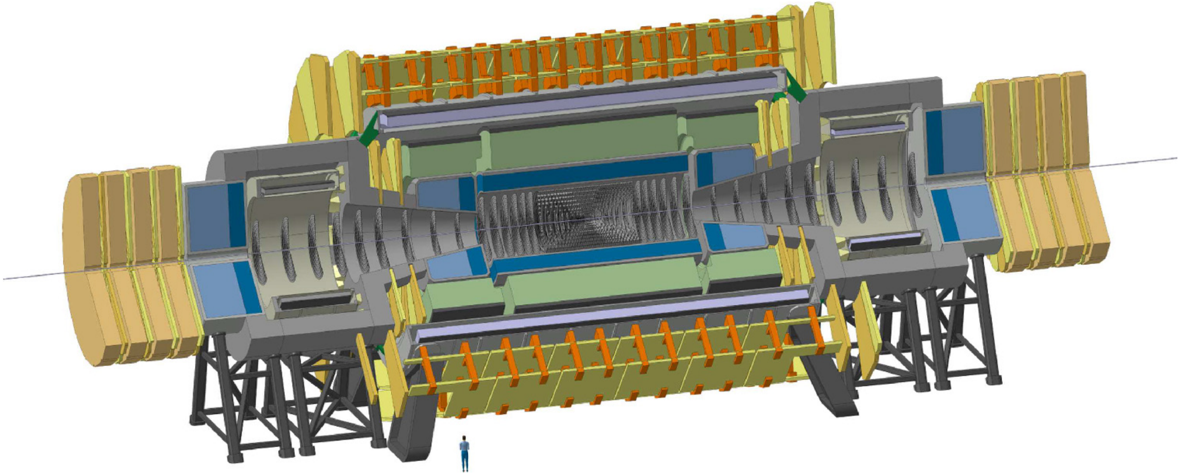


Crystals Performance





FCC-hh: Reference Detector



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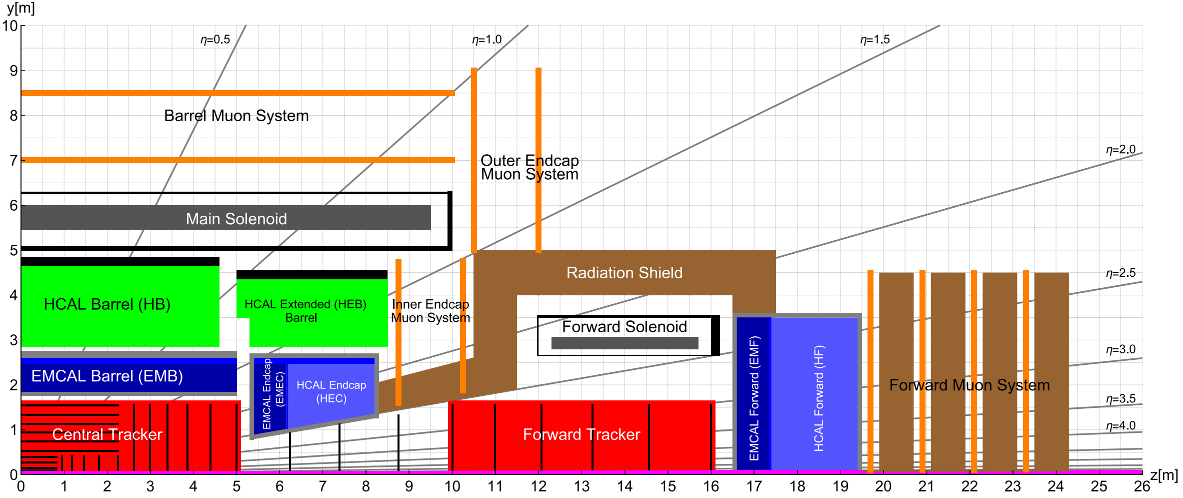
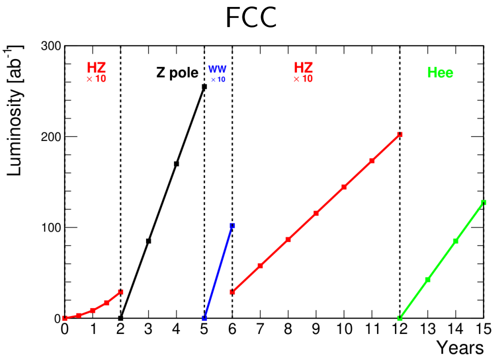


FCC and ILC proposal



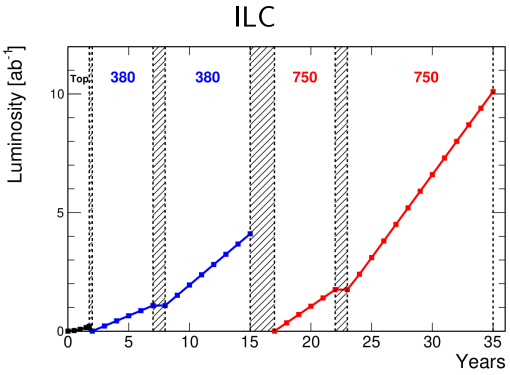


Image: arXiv:1912.11871