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Calorimetry for Future Circular Collider

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Overview

Questionnaire

- Are you a fan of new large scale experiments in HEP?
- Are you interested in the progress of the FCC project?
- Would you like to join the preparatory face of the experiment?
- Are you interested in R&D projects or hardware?
- Would you like to know what Juraj and myself are working on?

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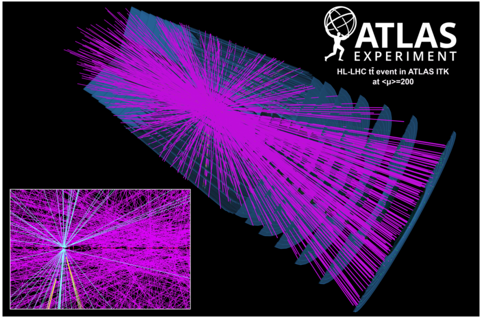
If your interest still remains after the talk, do not hesitate to contact us :)

Future Colliders

Future Colliders

Large Hadron Collider at CERN

- LHC (2008–2024)
  8–13 TeV, 400 fb^{-1}
- HL-LHL (2027–2040)
  14 TeV, 4000 fb^{-1}



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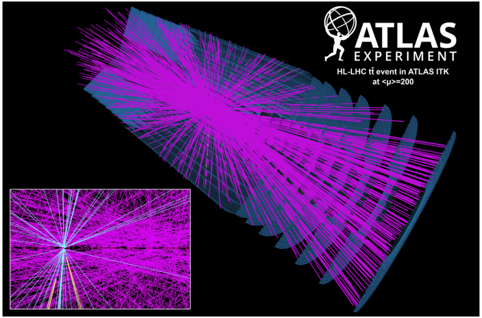

Next generation of colliders after LHC era?

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

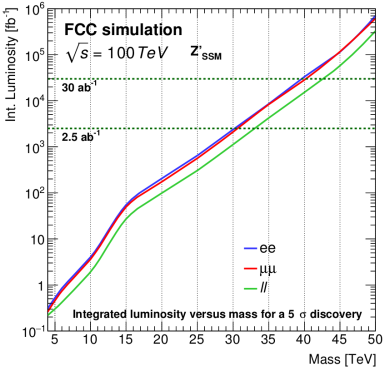

Image: FCC-hh CDR

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)

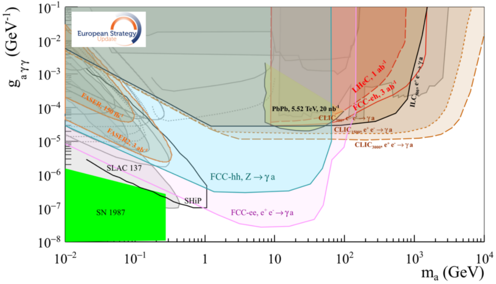

Image: arXiv:1910.11775

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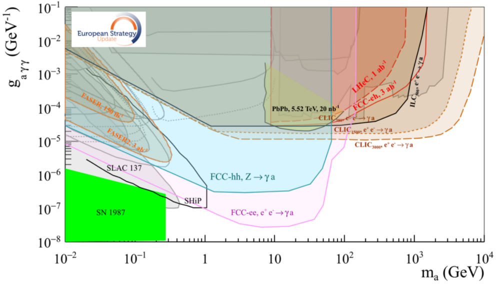


Image: arXiv:1910.11775

Advantages of e^+e^- colliders

- Clean environment $\rightarrow$ 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

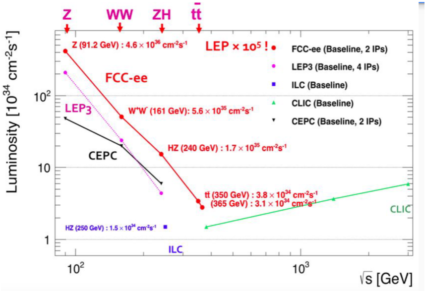


Image: FCC-ee CDR

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

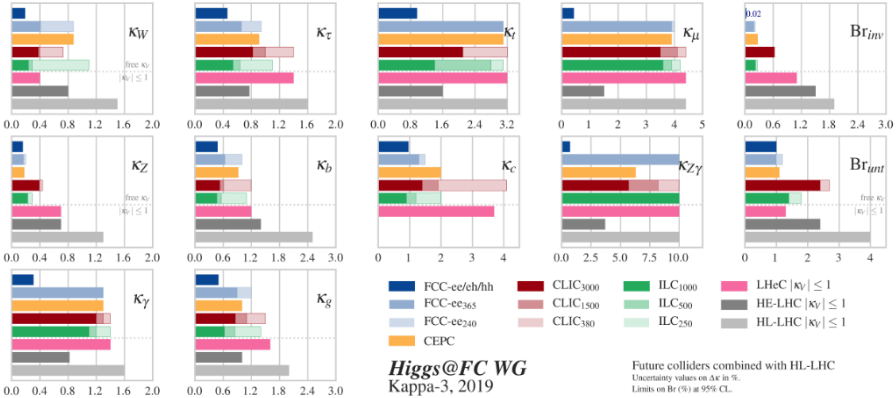


Image: arXiv:1905.03764

Higgs factories: Higgs coupling

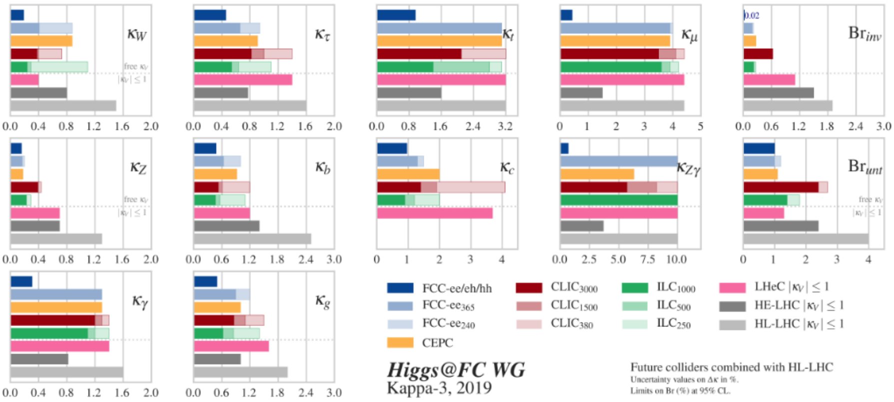
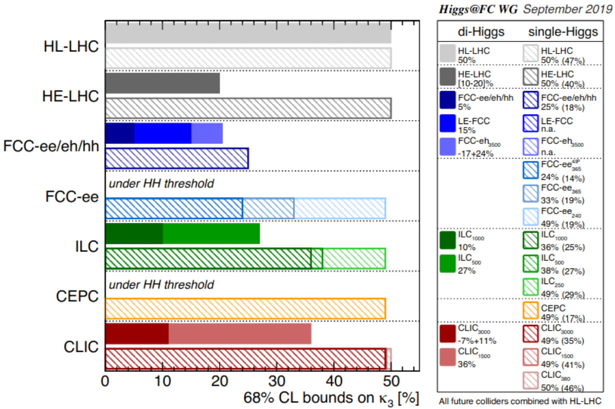


Image: arXiv:1905.03764

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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Higgs factories: Higgs self-coupling

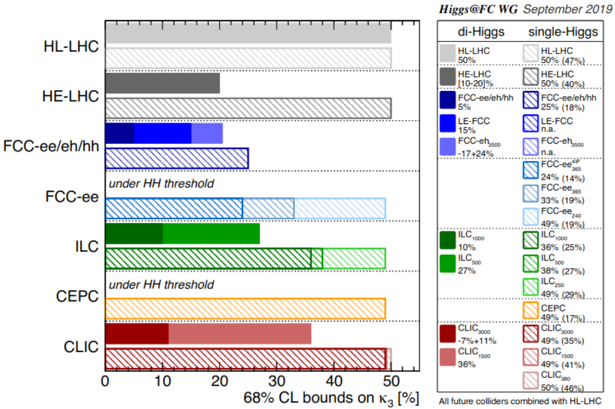
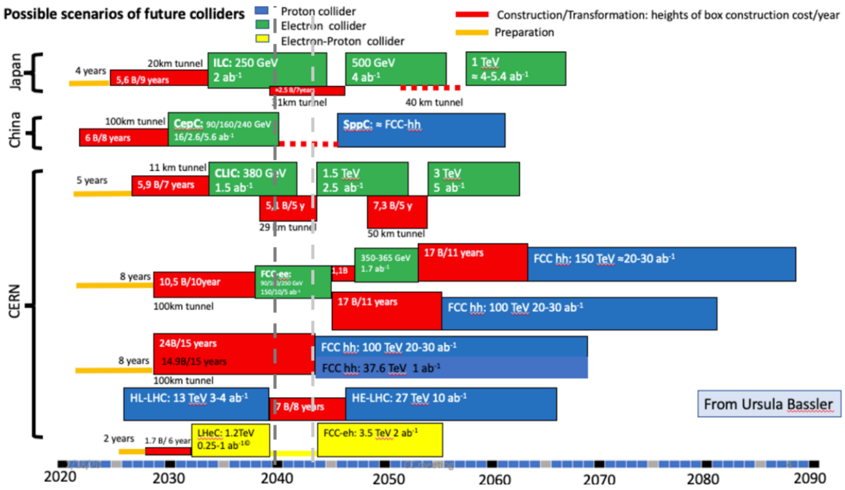


Image: arXiv:1905.03764

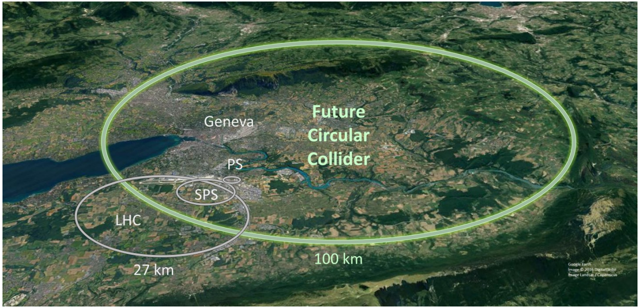
A Higgs factory is needed, even if the ultimate goal is the hadron-hadron collider.

Possible timelines



FCC Collider

Future Circular Collider



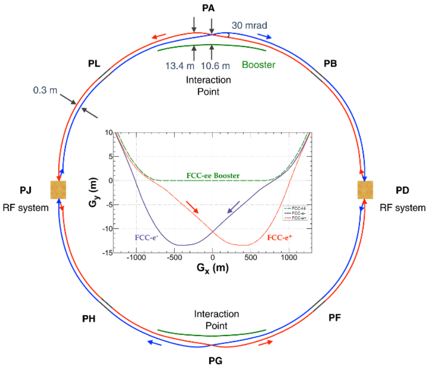
Stage 1: FCC-ee as Higgs factory, electroweak and top factory at highest luminosities

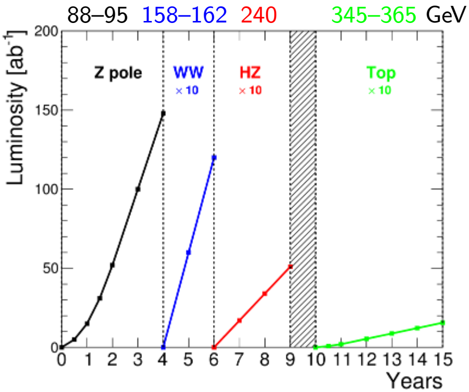
Stage 2: FCC-hh (100 TeV) as a natural continuation, with ion and *eh* option

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

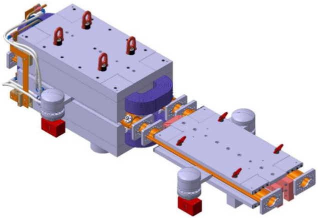
Four working points

$10^5\times$ 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

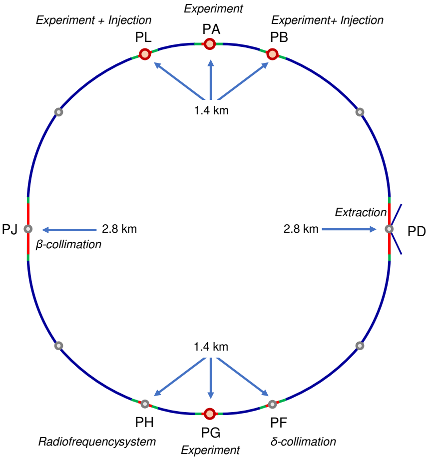


FCC-ee complete vacuum arc half-cell mock up

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

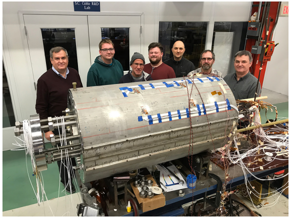
FCC-hh: Hadron collider



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



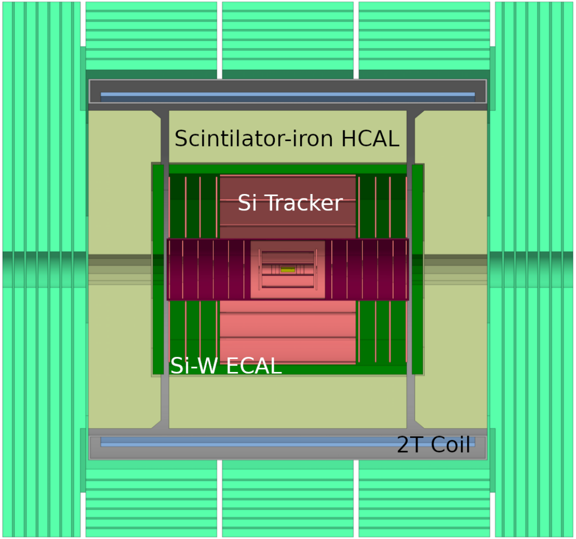
Fermilab: Prototype of 14.1 T Nb_3Sn dipole magnet

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

FCC Detectors

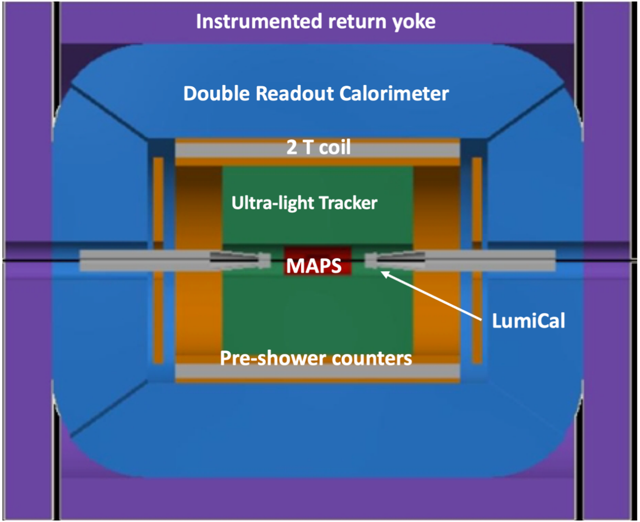
FCC-ee: CLD Detector



- Based on the detector for CLIC
- Silicon vertex detector and tracker
- 3D-imaging highly-granular calorimeter
- Coil outside calorimeter system
- Proved concept, understood performance

source: 4th FCC Physics and Experiments Workshop

FCC-ee: IDEA Detector



- New, innovative, possibly more cost-effective design
- Silicon vertex detector
- Short-drift, ultra-light wire chamber
- Dual-readout calorimeter
- Thin and light solenoid coil inside calorimeter system

source: 4th FCC Physics and Experiments Workshop

Calorimetry for FCC-ee

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% to sustain jet resolution
  - $B_S \to D_S K$ requires $\sim 5\%$
- Crystal and LAr — good EM resolution
- CALICE and Dual Readout — good jet resolution

Energy resolution param.:

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

Typical values:

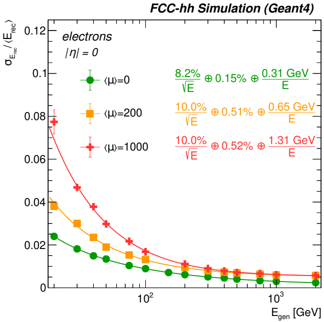
Technology	a [%]	c [%]
CALICE	15	1
Dual Readout	10	1
LAr	9	—
Crystal	3–5	0.5

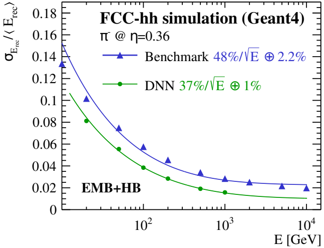
High granularity and Particle Flow needed to achieve energy resolution of 3%

Noble Liquid Calorimetry for FCC-ee

Key features:

- Tested technology in ATLAS, DØ, H1, NA31/48/62
- Radiation hardness, long term stability
- Linear response, uniformity, high control over systematics
- Good energy and timing resolution
- Less than $10\%/\sqrt{E}$ demonstrated





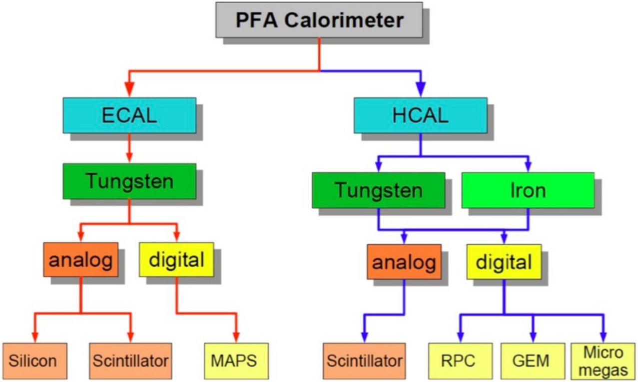
arXiv: 1912.09962

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

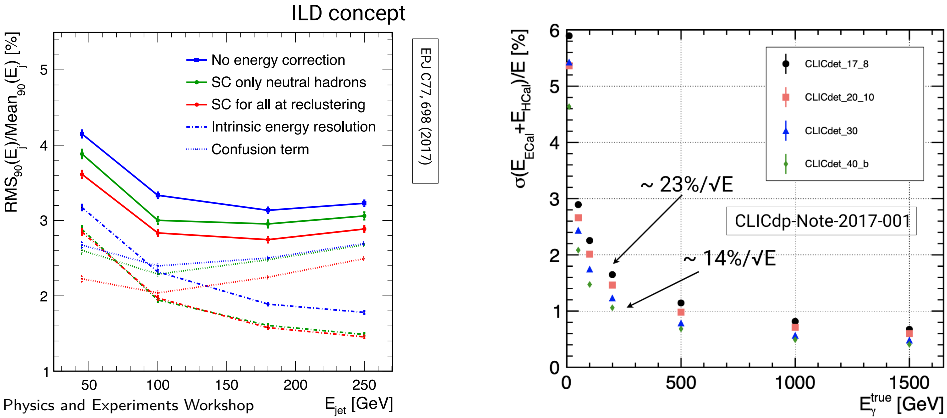


source: 4th FCC Physics and Experiments Workshop

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)

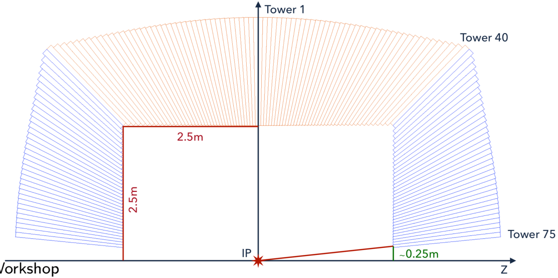


source: 4th FCC Physics and Experiments Workshop

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

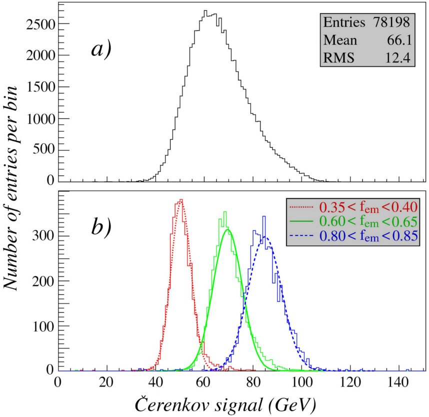
Dual Readout Calorimeter

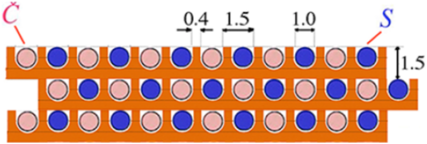
Principle:

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

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

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



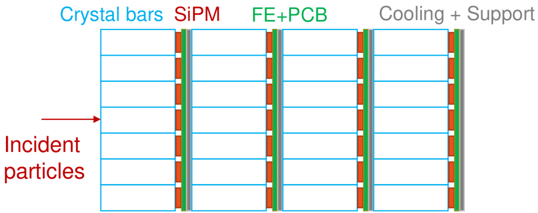


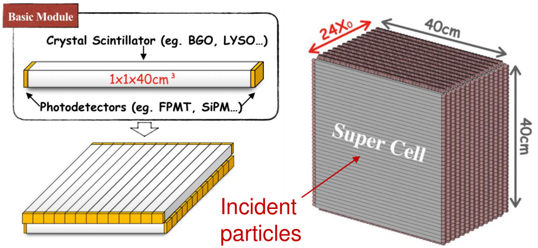
source: 4th FCC Physics and Experiments Workshop

Crystal Calorimeters

Traits:

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



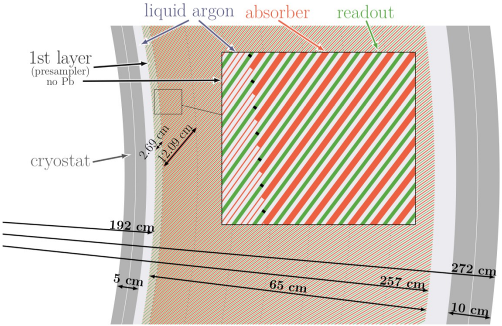


source: 4th FCC Physics and Experiments Workshop

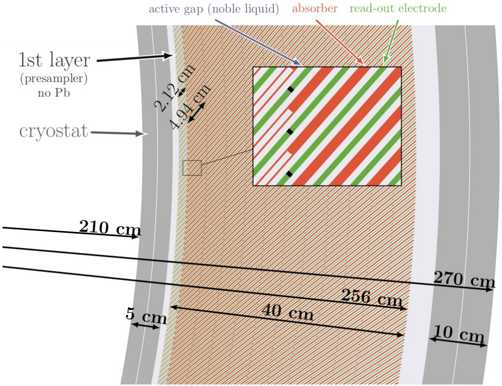
Improvements in Noble-liquid for FCC-ee

Improvements in Noble Liquid Calorimetry

- Noble liquid is viable technology for FCC-ee detectors
- New round of optimizations started with multiple R&D projects
- Both hardware and software improvements are required to get to 3%
- Design driven by Particle Flow



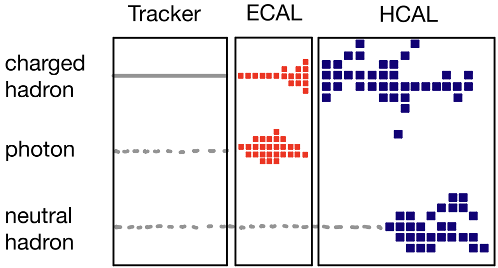
FCC-hh



FCC-ee

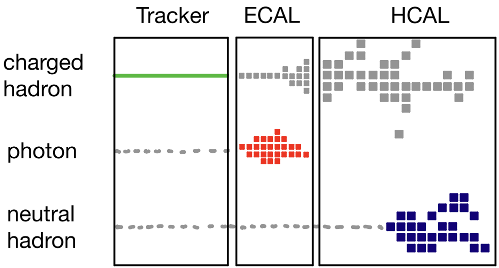
source: Brieuc François (CERN)

Particle Flow



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

30% + 70%



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

60% + 30% + 10%

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

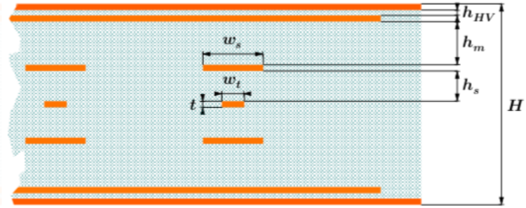
- Charged particles dominated by tracker
- Calorimetry mostly for neutral particles
- Enemy: Confusion

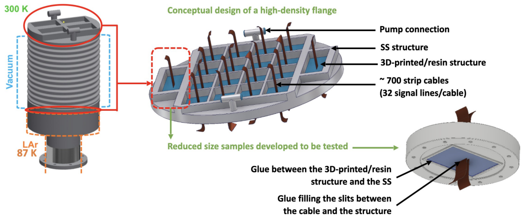
source: 4th FCC Physics and Experiments Workshop

Hardware Improvements FCC-ee I

Higher granularity:

- Both transverse and in depth
- Factor of 10x in comparison to ATLAS LAr (220k $\rightarrow$ 2M cells)
- Using simpler design — PCBs
- Signal traces are embedded in PCB
- More signal traces $\rightarrow$ more noise
- High longitudinal segmentation mitigates gap widening towards high radius
- More signal traces $\rightarrow$ high density feedthroughs





sources: B. François (CERN), M. Barba (CERN)

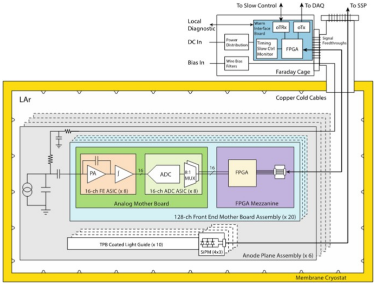
Hardware Improvements for FCC-ee II

Cryostat vessel:

- Important for low energy particle measurements (bellow 300 MeV)
- Carbon fiber reinforced cryostat under investigation
- Vacuum vessel shared between solenoid and calorimeter

Electronics:

- Warm or Cold electronics
- Charge or current pre-amplifiers
- Dynamic range: 14–16 bits
- Time resolution optimization

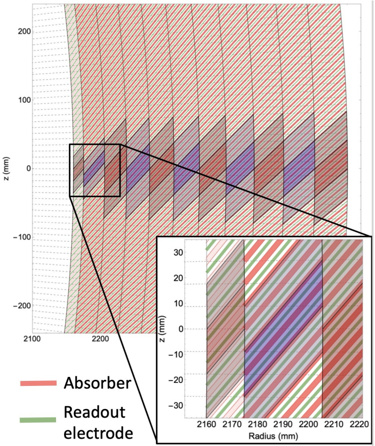


sources: 10.1088/1748-0221/15/06/P06017, NASA

Hardware Improvements for FCC-ee III

Material & Construction

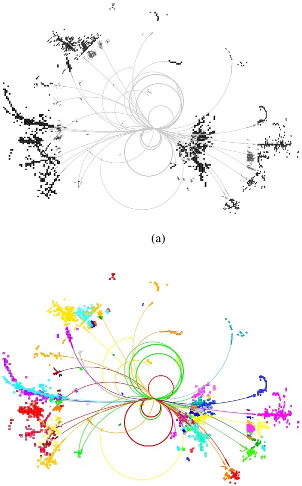
- Alignment and uniformity affects constant term
- Active material (Krypton, ...)
- Absorber material (Tungsten, ...)
- Absorber and sensitive gap thickness
- Plate inclination, layer depths, cell merging
- Interplay between sub-systems



source: Brieuc François (CERN)

Software Improvements for FCC-ee

- New generic framework Key4HEP emerges from the FCCSW and iLCSoft
- Based on Gaudí but uses Podio
- Integrates tools from simulation, detector description to reconstruction
- Integration of Particle Flow algorithm (Pandora SDK)
- Reimplementation of clustering algorithm (CLUE)



(a)

(b)

source: 10.1140/epjc/s10052-015-3659-3

Conclusions and Plans

Conclusion and Plans

Future Circular Collider

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

Noble Liquid Calorimeters

- Noble Liquid calorimeter in reference FCC-hh detector, option in FCC-ee
- Multiple R&D projects directed at noble liquid calorimetry at FCC-ee

Our involvement

- Performance optimization in the FCC-ee framework
- Implement particle flow algorithm for LAr calorimeter

New souls are welcome!

Backup

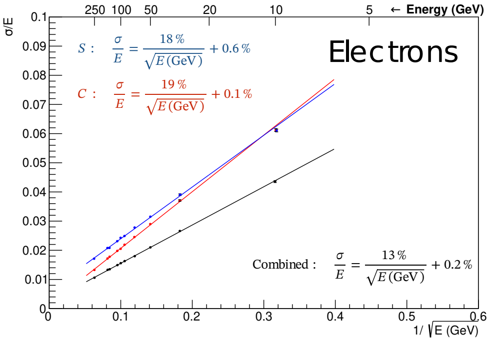
R&D FCC-ee LAr Projects

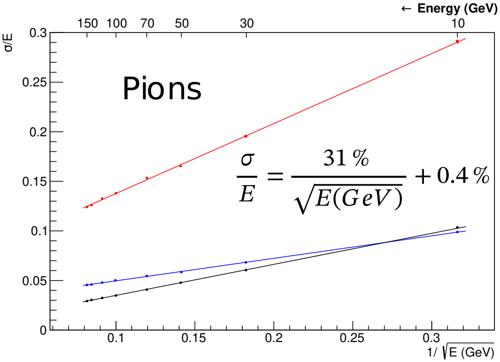
CERN EP R&D projects relevant for Noble Liquid Calorimetry:

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

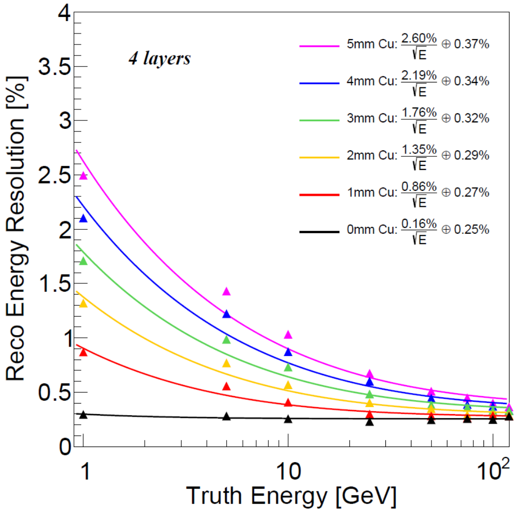
CERN, Charles U. and LAL Orsay: H2020 project AIDAInnova

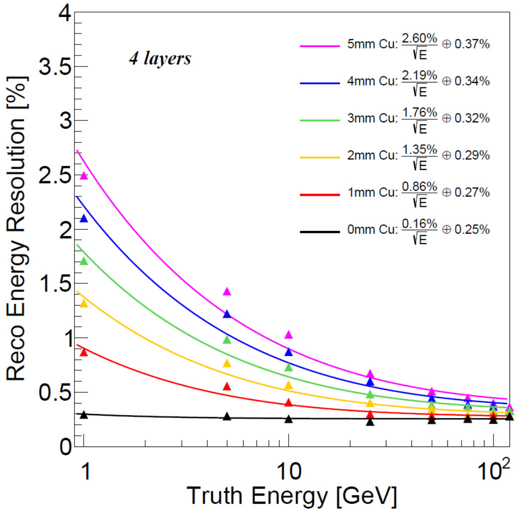
Dual Readout Performance



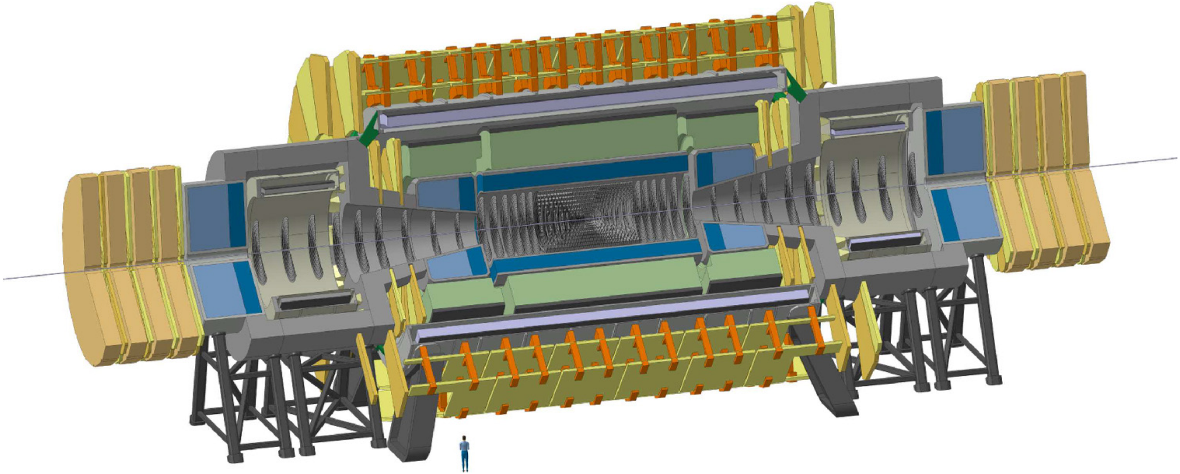


Crystals Performance

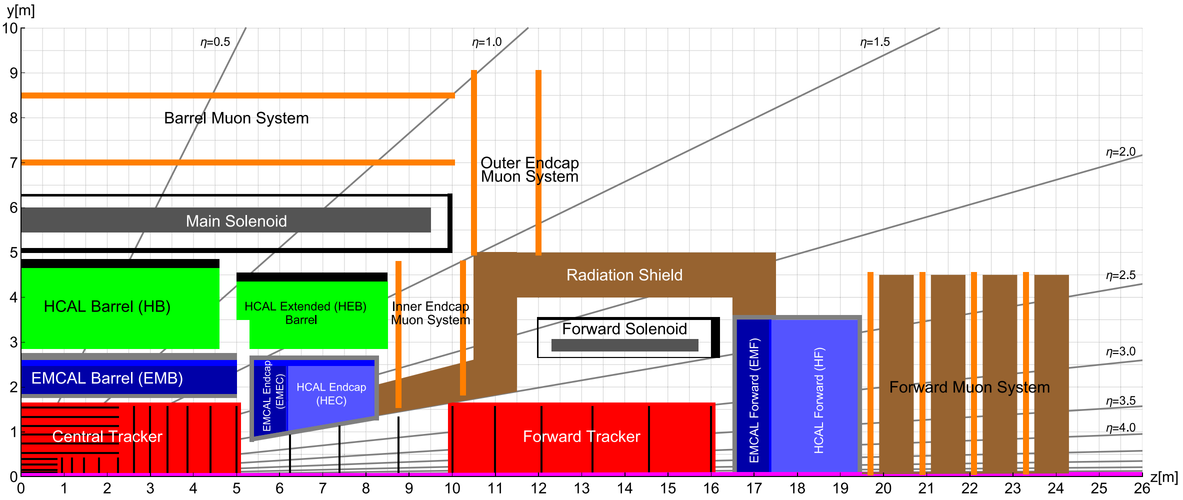




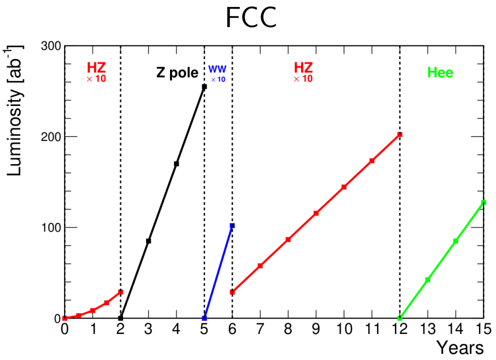
FCC-hh: Reference Detector



FCC-hh: Reference Detector



FCC and ILC proposal



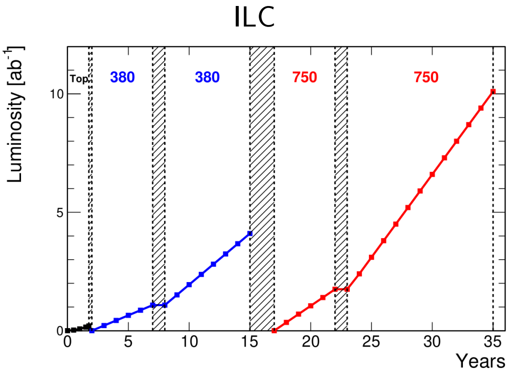


Image: arXiv:1912.11871