Circular e^+e^- Collider Detector Concepts

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(on behalf of the circular e^+e^- collider community)

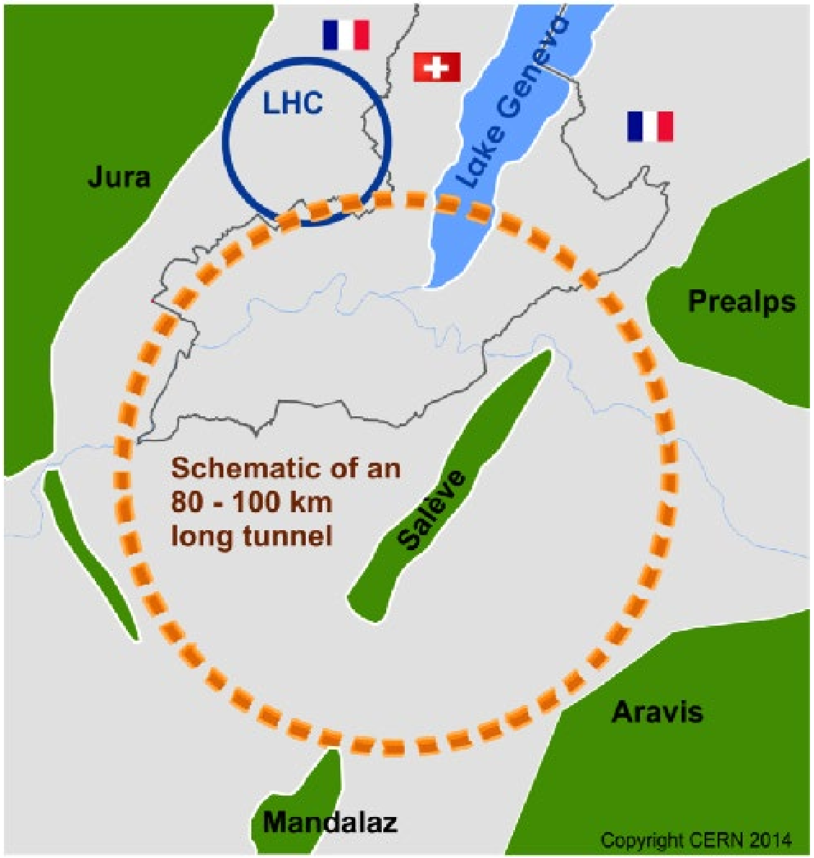
Snowmass e^+e^- collider forum
April 5, 2022

Disclaimer: many slides are from the presentations at
the 5th FCC Physics Workshop at Liverpool early this year

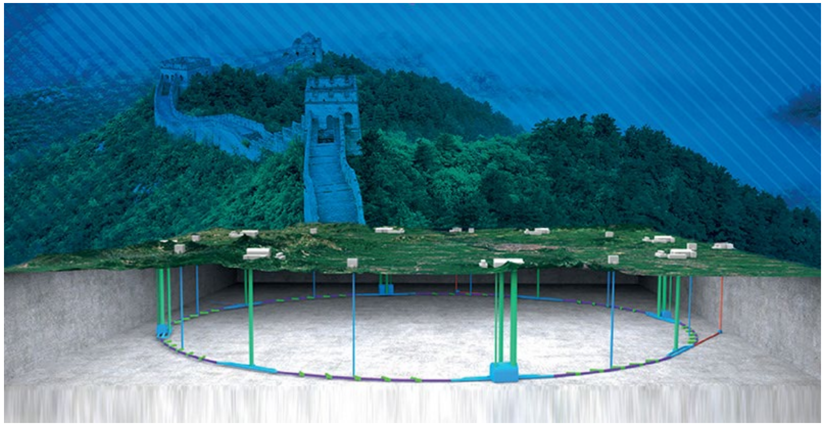
Future Circular e+e- Colliders

Two circular e+e- colliders, FCC-ee and CEPC, have been proposed as Higgs factories and precision Machines.

FCC-ee has been designated as the highest-priority next collider at CERN.



FCC-ee at CERN

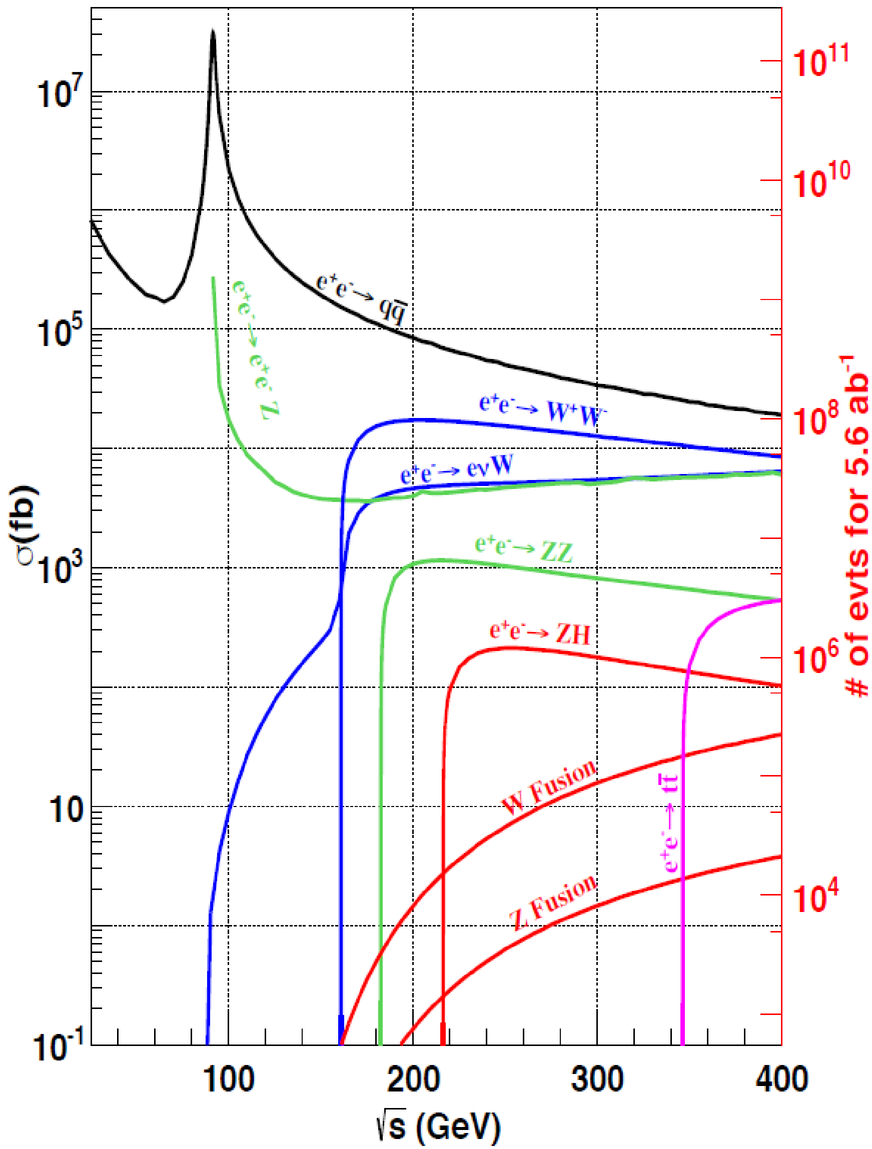


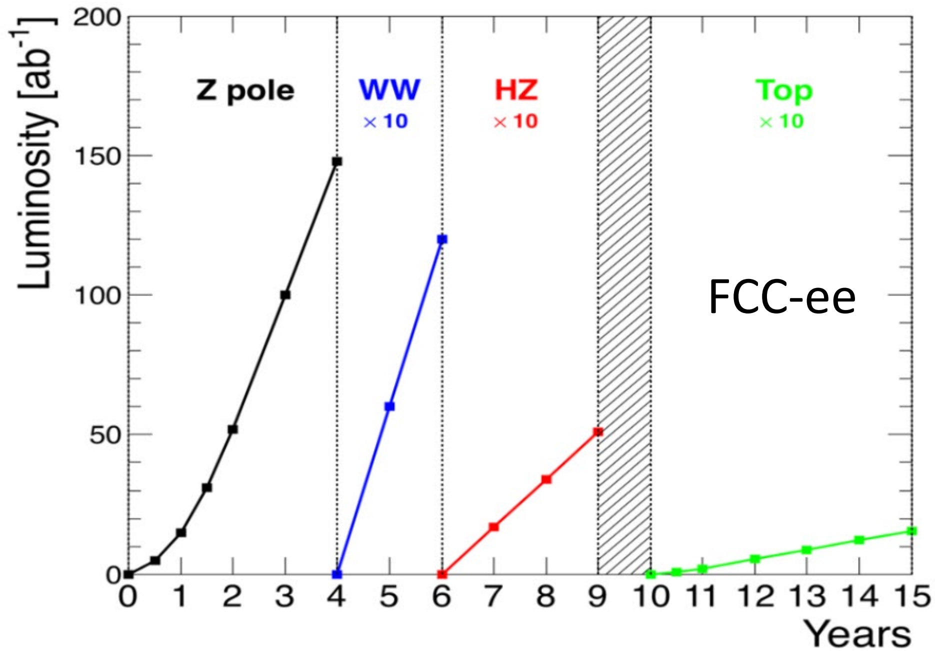
CEPC in China

[FCC-ee: The Lepton Collider](#)

[CEPC Conceptual Design Report](#)

A Precision Physics Program





Targeted statistics (FCC-ee 2IP, ×1.7 for 4IP):

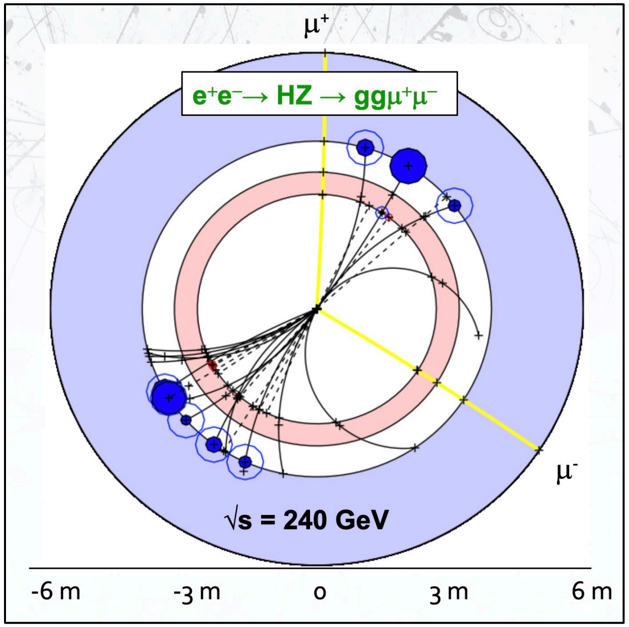
$5\times10^{12}\ e^+e^- \to Z\ \left(\sqrt{s}\sim 90\text{ GeV}\right)$

$10^8\ e^+e^- \to W^+W^-\ \left(\sqrt{s}\sim 160\text{ GeV}\right)$

$10^6\ e^+e^- \to ZH\ \left(\sqrt{s}\sim 240\text{ GeV}\right)$

$10^6\ e^+e^- \to t\bar{t}\ \left(\sqrt{s}\sim 360\text{ GeV}\right)$

Collider Environment



- well defined initial state and energy
  - ⇒ allow kinematic constraints
- mostly electroweak processes
  - ⇒ precision theoretical prediction
- no messy underlying event nor pileup
  - ⇒ less challenging for detectors and triggers

Precision and *Z pole running* are the most challenging aspects of the detector design and operation

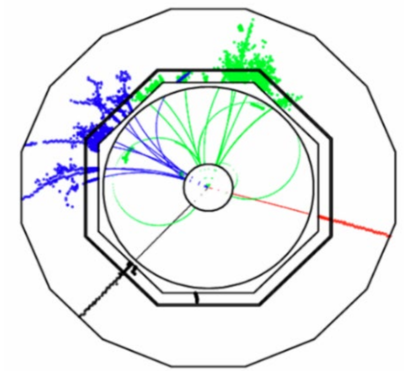
Mogens Dam

FCC-ee parameters		Z	W^+W^-	ZH	ttbar
$\sqrt{s}$	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**230**	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
”Physics” cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	**92,000**	8.4	1	0.1
”Pile up” parameter [μ]	**10^{-6}**	1,800	1	1	1

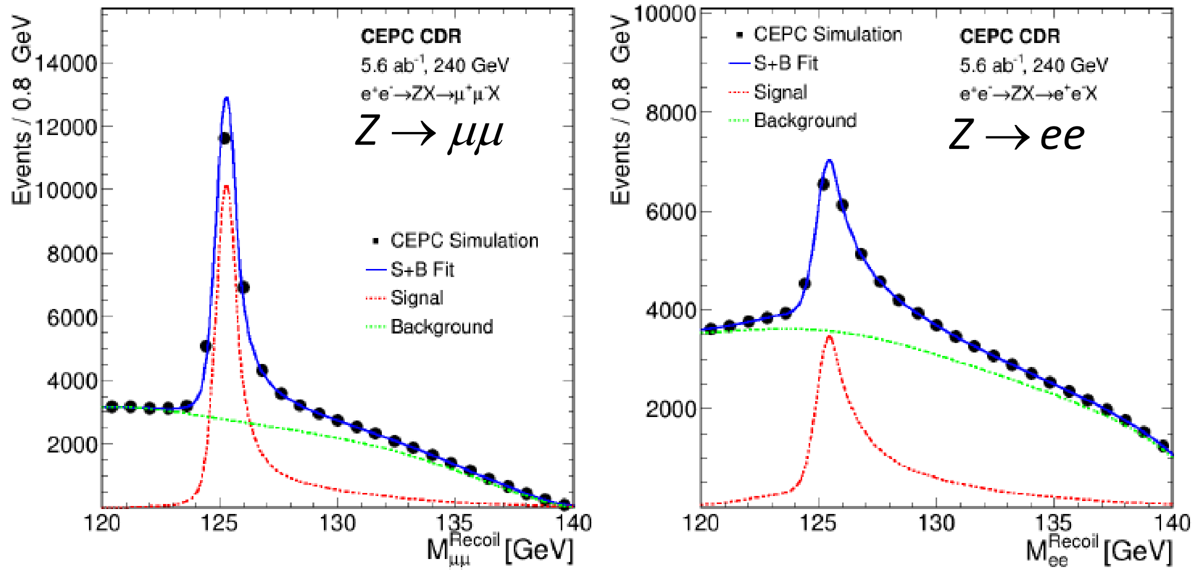
Track Momentum Resolution

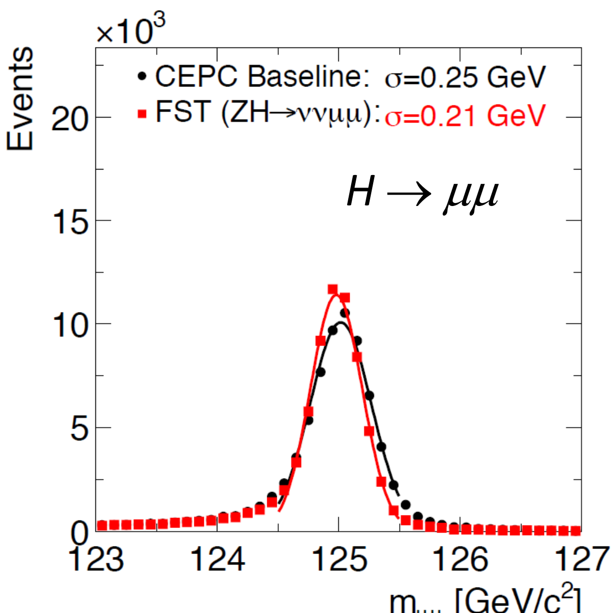
Higgs boson tagging through the recoiling mass method:

$$m_{\text{recoil}}^2 = \left(\sqrt{s} - E_{\ell\ell}\right)^2 - p_{\ell\ell}^2$$



$$ee \to ZH \to \ell^+\ell^-\left(H \to X\right)$$





Also important to have good EM energy resolution to improve the $Z \to ee$ recoil mass resolution.

Tracking momentum resolution benchmark:

$$\Delta\left(\frac{1}{p_T}\right) \sim 2 \times 10^{-5}$$

A few times better than existing trackers

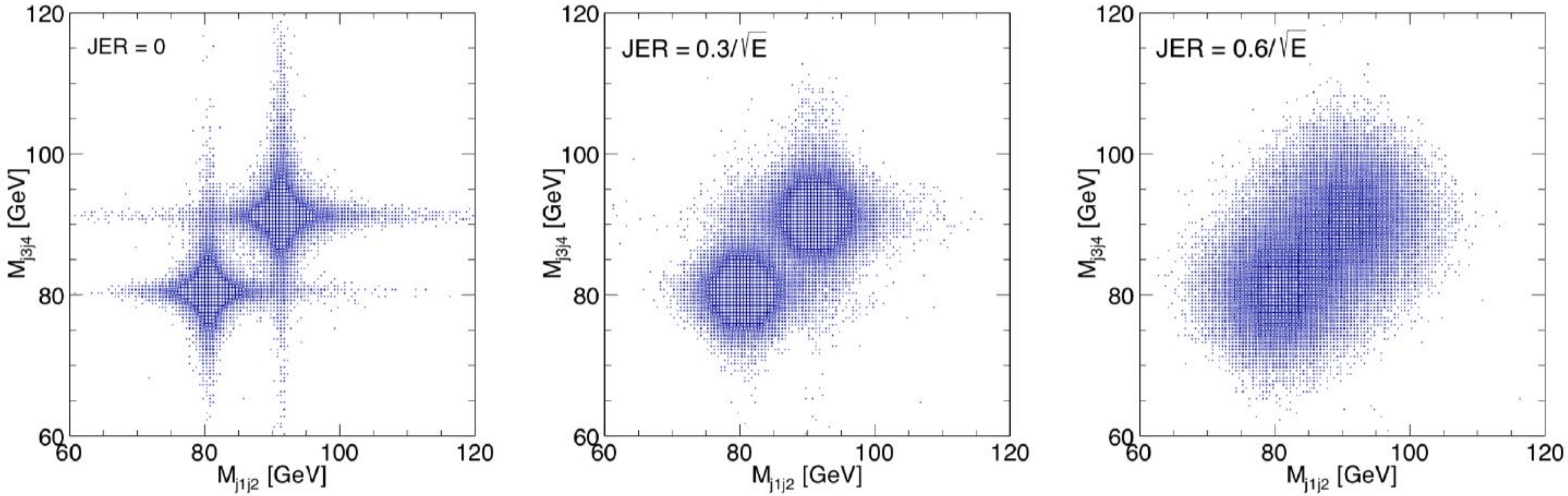
Jet Energy Resolution

Hadronic final states are the dominate final states of e+e- collisions, most of them are the results of the W, Z, and Higgs boson decays.

Separating $W \to jj$ and $Z \to jj$ decays is essential for precision measurements:

$$ee \to WW \to 4j \text{ vs } ee \to ZZ \to 4j, \quad H \to WW^{*} \to 4j \text{ vs } H \to ZZ^{*} \to 4j$$

$ee \to WW/ZZ \to 4j$



Separating the hadronic decays of the W and Z bosons has been the driver of the calorimeter R&D during the past two decades.

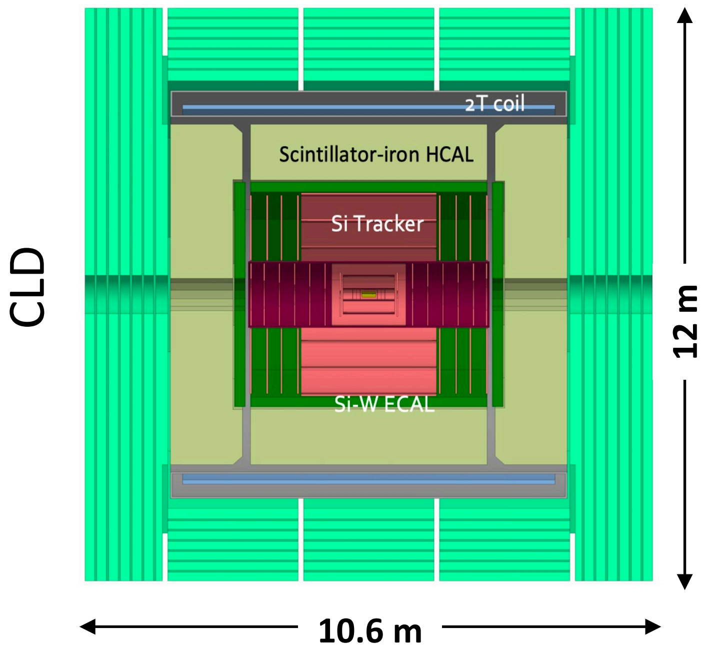
Jet energy resolution benchmark:

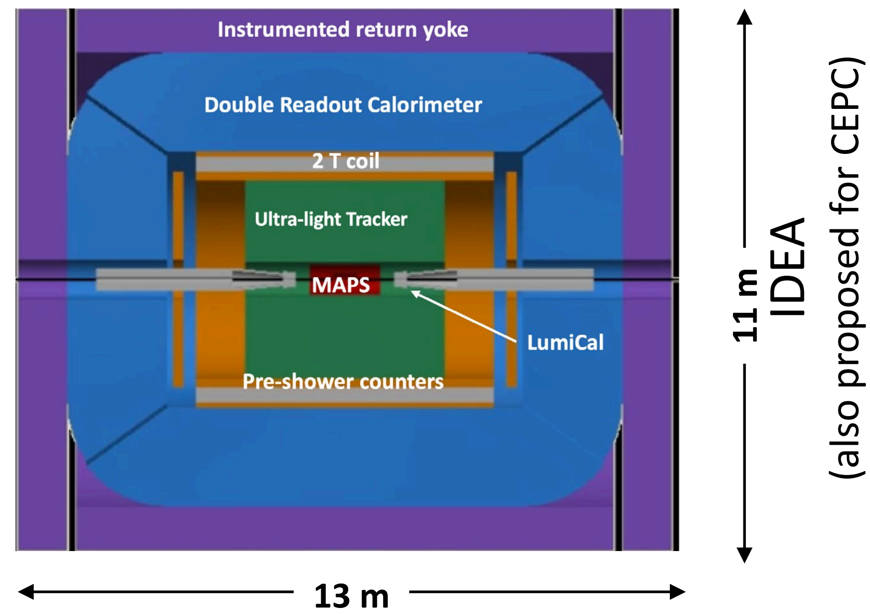
$$\frac{\Delta E}{E} \sim 3-4\% \text{ for } E = 50-100 \text{ GeV}$$

Roughly a factor of two better than existing calorimeters

Detector Concepts

Proposed in FCC-ee CDR: CLD and IDEA





Based on CLIC detector design; profits from developments for Linear Colliders

- All silicon vertex detector and tracker
- Highly-granular calorimeters (CALICE)
- Coil *outside* calorimeter system

https://arxiv.org/abs/1911.12230,
https://arxiv.org/abs/1905.02520

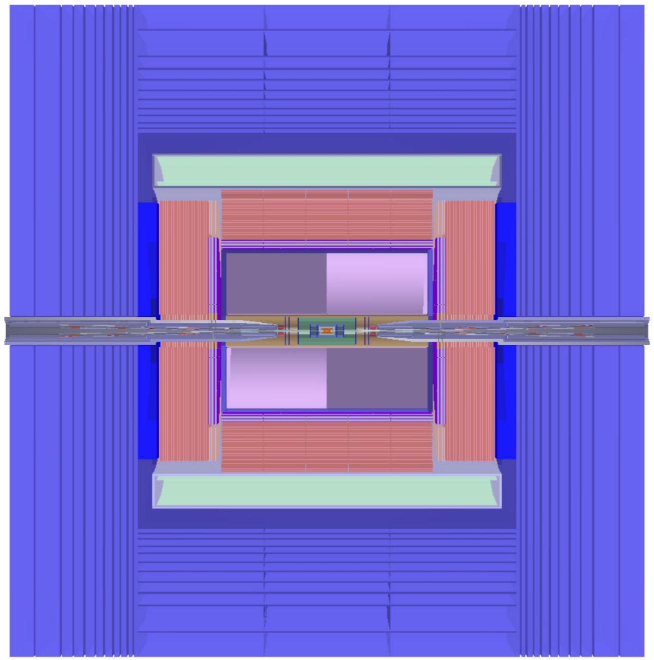
New, innovative, possibly cost-effective concept

- Si vertex detector and Si wrapper
- Ultra-light wire chamber
- Dual-readout calorimeter (RD52)
- Thin and light solenoid coil *inside* calorimeter system

https://pos.sissa.it/390/

Detector Concepts

CEPC baseline



Based on the ILD design for the ILC

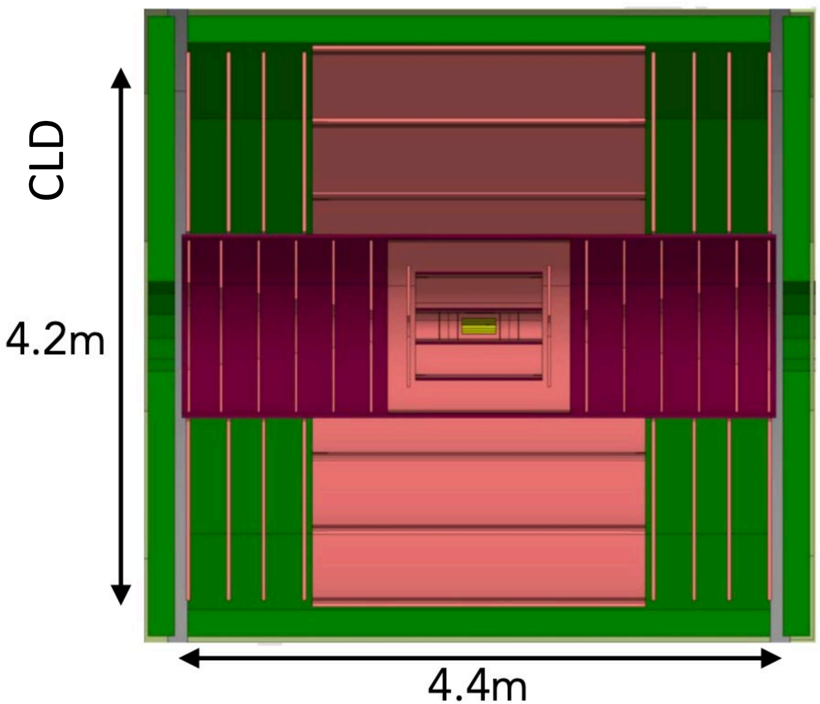
- Silicon vertex detector
- An inner silicon tracker
- An outer TPC with a Si wrapper
- High granular calorimeters (CALICE)
- Coil *outside* calorimetry system

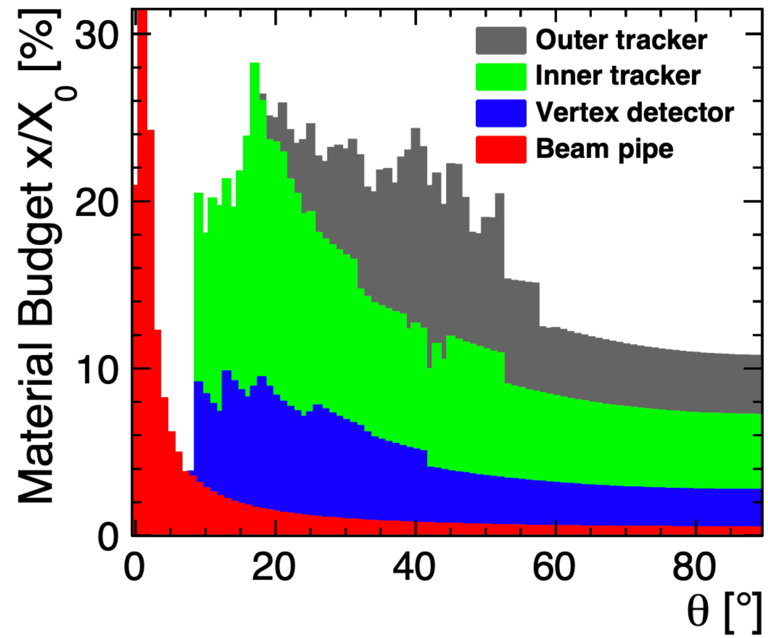
New Concept for FCC-ee

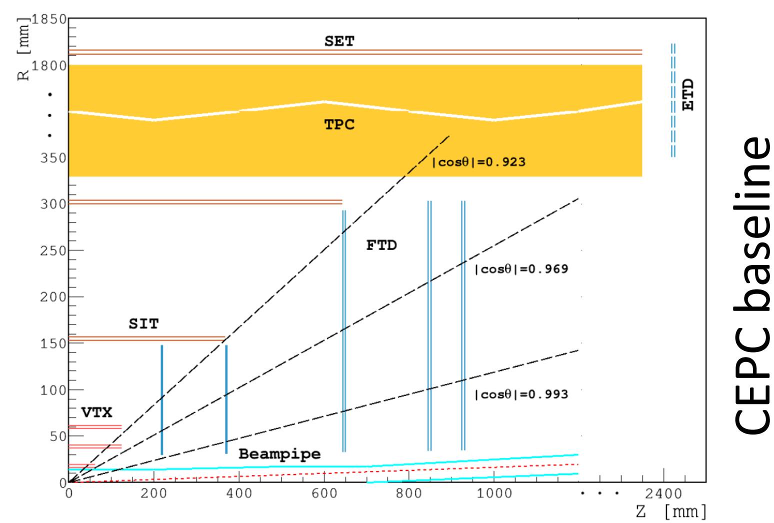
- Silicon vertex detector
- Gas detector with a Si wrapper
- High granular LAr ECAL (a la ATLAS)
- High granular HCAL (a la CALICE?)
- Coil *inside* calorimetry system

https://arxiv.org/abs/1811.10545

Silicon Tracker







Full Silicon tracker for CLD

Partial silicon tracker for CEPC

CLD: All silicon pixel (innermost) + strips

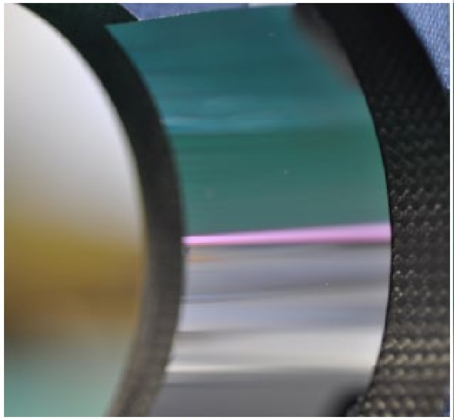
- Inner: 3 (7) barrel (fwd) layers (1% X_0 each)
- Outer: 3 (4) barrel (fwd) layers (1% X_0 each)
- Support tube (2.5% X_0)

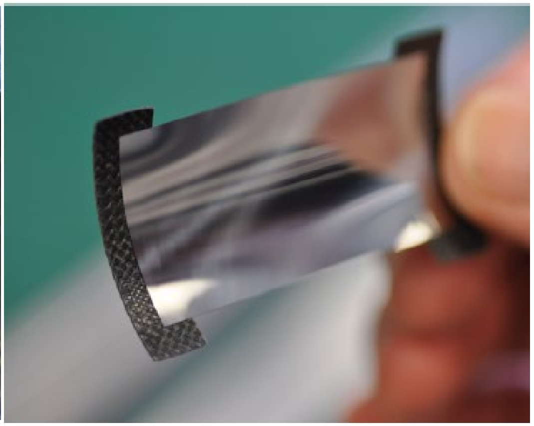
Meet the material budget will be a major challenge!

Silicon Vertex and Tracker R&D

A lot of progress in developing large area curved silicon modules, attractive options for e^+e^- collider tracker

ALICE ITS3 could be a starting design for the vertex detector





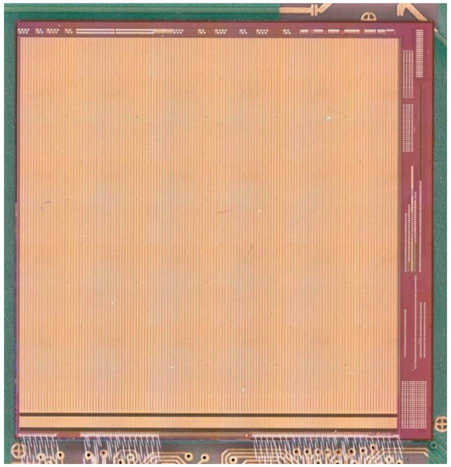
- Radius of curvature shown: 25mm
- Able to bend silicon to radii of 13mm

Adrian Bevan

Attilio Andreazza

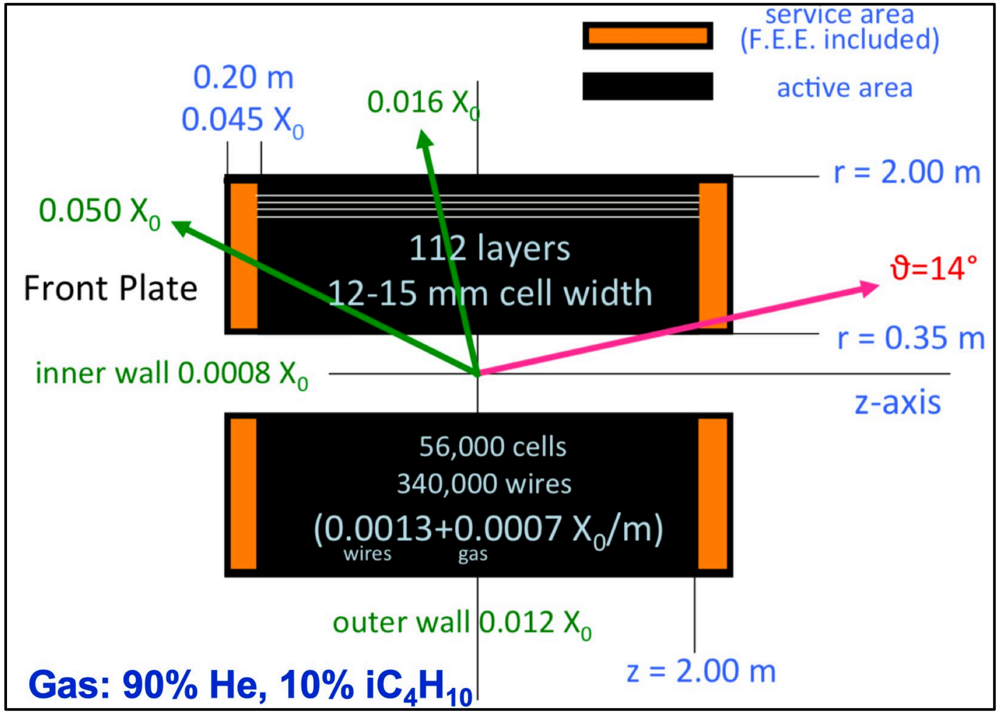
- Similar approaches for ILC, CLIC, FCCee, CepC:
  - High resolution **pixel vertex detector** O(few m^2)
  - Either **full silicon tracker** or **central gas chamber + Si wrapper** O(100 m^2)

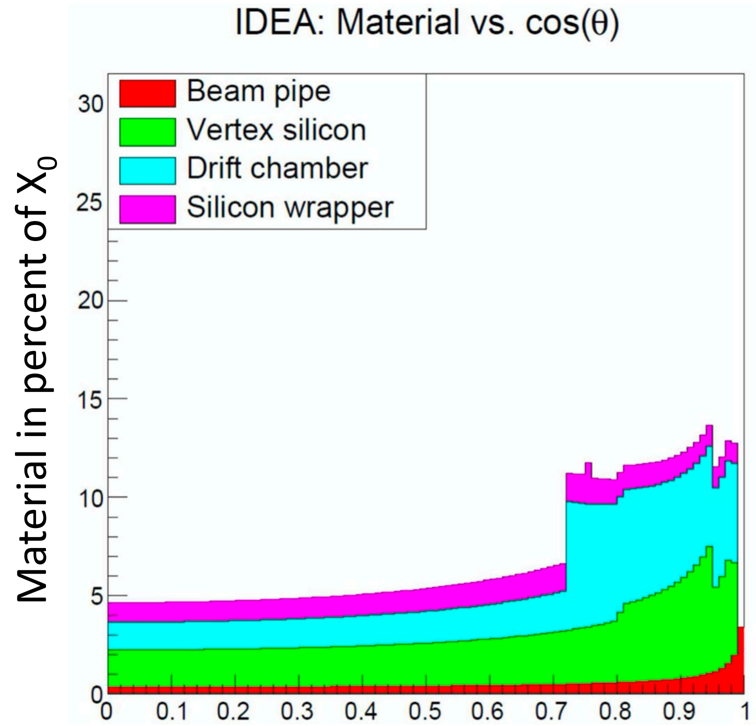
- **Depleted Monolithic Active Pixels Sensors**
  - CMOS process allows to produce **large areas**, **fast** and **cheap**
  - **no hybridization** (bump-bonding) needed
  - **single detection layer**, can be **thinned** keeping high signal efficiency and low noise rate

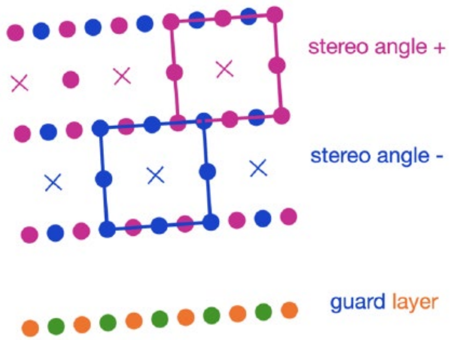


A large community is developing silicon tracker based on the DMAPS technology, the technology used in the ATLASPIX3 design

Drift Chamber





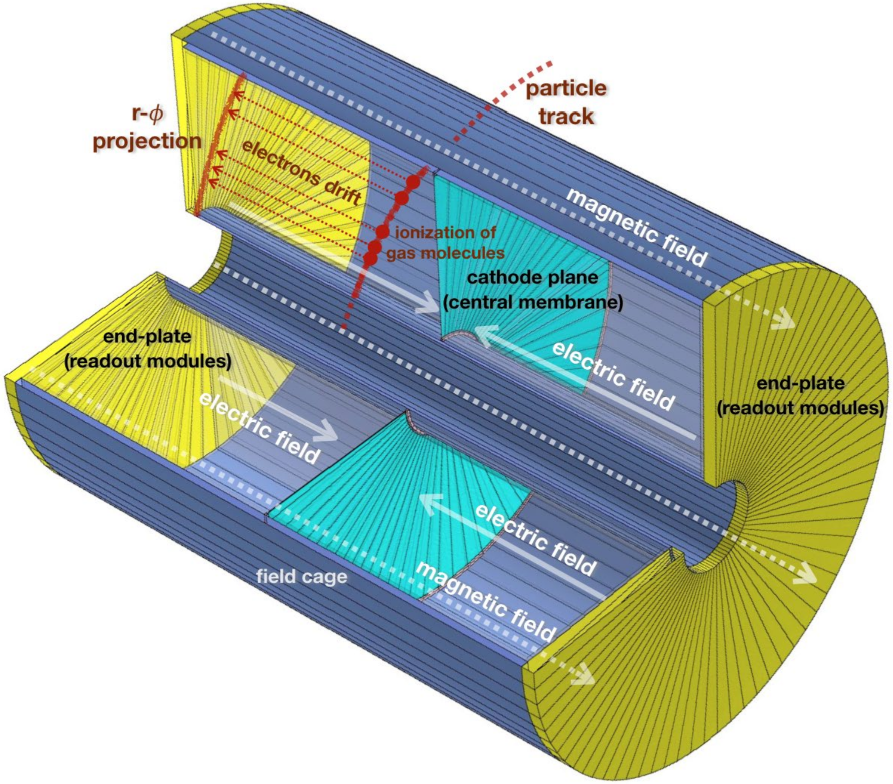


A cross-sectional segment

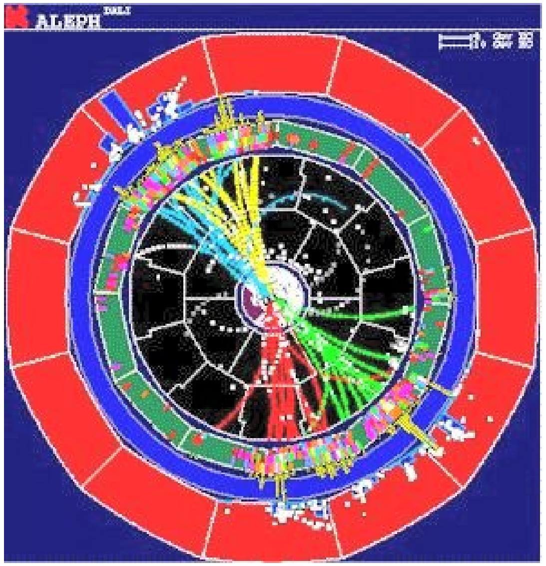
IDEA: Extremely transparent Drift Chamber based on MEG2

- GAS: 90% He – 10% iC_4H_{10}
- Total thickness: 1.6% of X_0 at 90°
  Tungsten wires dominant contribution
- Full system includes Si VXT and Si "wrapper"
- Solenoid field limited to 2T

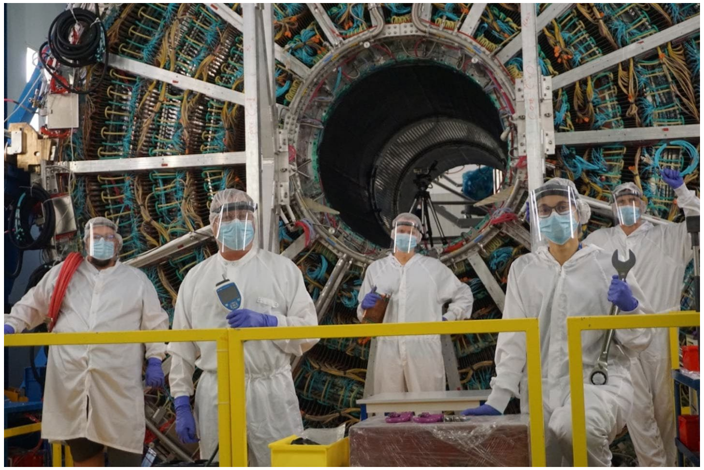
Time Projection Chamber



ALEPH TPC



Upgraded ALICE TPC



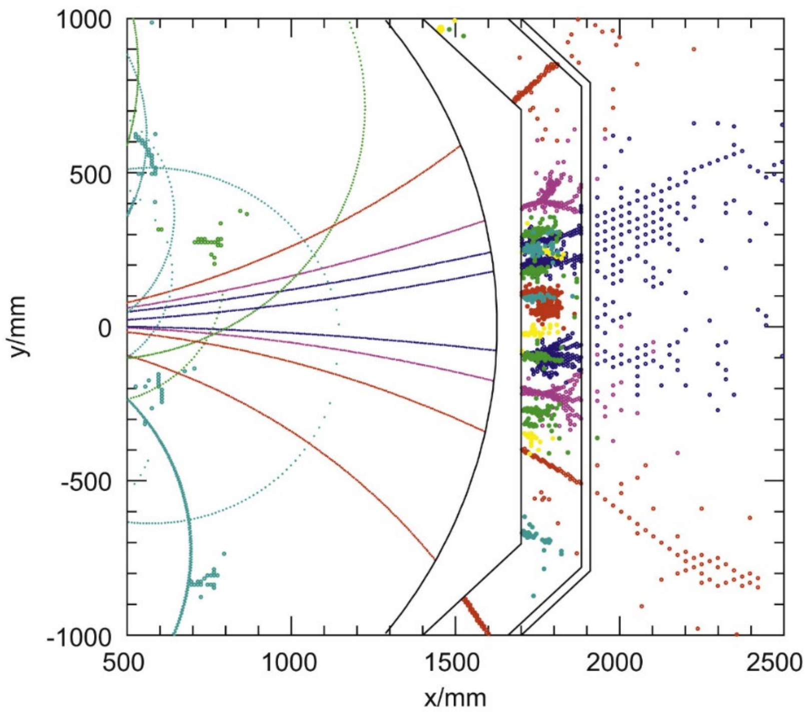
Proposed for the outer tracker of the CEPC baseline

- 1% X_0 in the central region, significant more material in endcap
- 3D hit information
- Performance at Z pole running might be problematic

High Granular Calorimetry

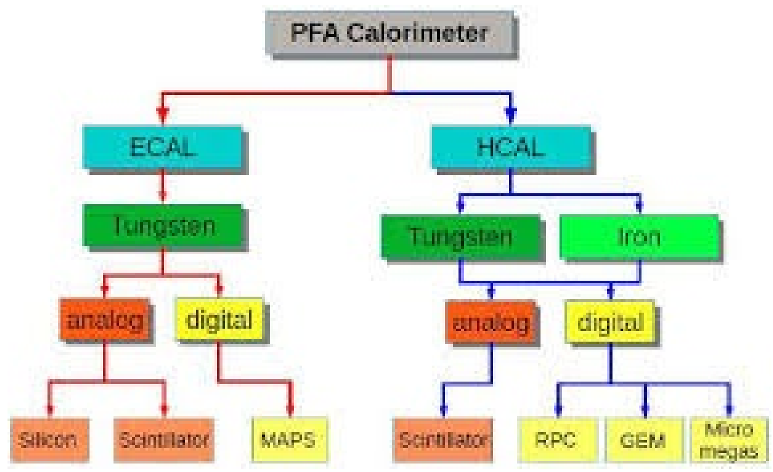
Particle Flow (PF) sampling calorimeter, also called *Imaging Calorimeter* reconstruction and identification of individual particles in showers, measuring energy in the most suitable sub-detector for the particle type:

- Charged particles in the tracking detector;
- Photons in the electromagnetic calorimeter;
- Neutral hadrons in the hadronic calorimeter



Main Characteristics:

- High granularities $\Rightarrow$ large channel counts;
- Relatively small sampling fractions

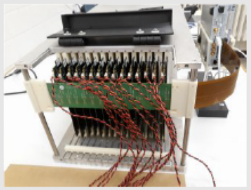
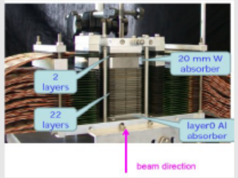


High Granular Calorimetry

Extensive R&D by the CALICE Collaboration

4,5 prototypes, 15⁺ years of R&D, all [to be] tested

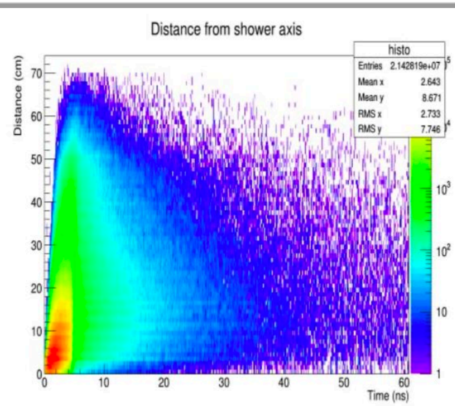
personal opinion, not the collaboration's

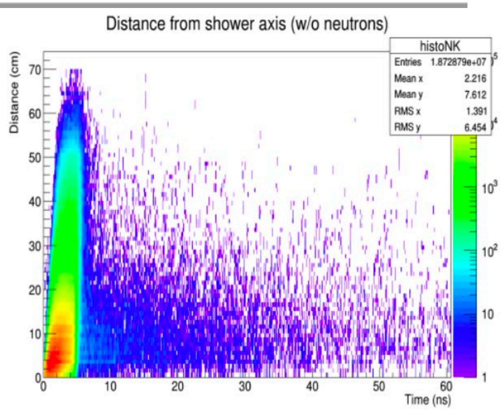
Si-W ECAL	(ALICE FoCAL)	[Scint-W ECAL]	AHCAL	SDHCAL
				
0,5×0,5 cm² ×15 (→30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS
Resolution – R_M ✔ Intégration ✔ Cost – Calibration ✔	Resolution ✔ R_M ✔✔ Intégration ?? Cost ?? Calibration ?	Resolution ✔ R_M ? Intégration ✔ Cost ✔ Calibration –	Resolution ✔ λ ✔ Intégration ✔ Cost ✔ Calibration –	Resolution ✔ λ ✔ Intégration (Gaz) – Cost ✔ Calibration –
LLR, IJCLab, LPNHE, (LPSC) IFIC, Kyushu, KEK, Ω	NIKHEF, EMMEΦ, CERN, Bergen, IPHC	Shinshu U, U. Tokyo, IHEP (CN), USTC, Ω	DESY, HH, MPI, Mainz, Wuppertalm, Heidelberg, IPASCR, Bergen, Ω	IP2I, LPC, Ghent,(LAPP) CIEMAT, SJTU, Ω

Vincent.Boudry@in2p3.fr FCC France | 02/12/2021 4/17

Recent development:

Using timing information to identify delayed neutrons to further improve jet energy resolution.

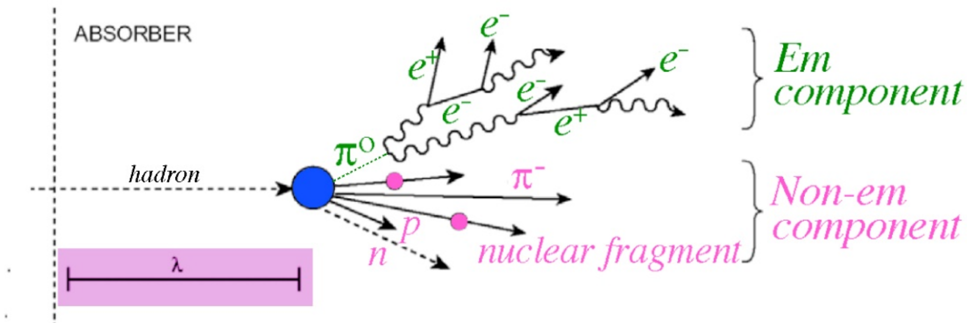




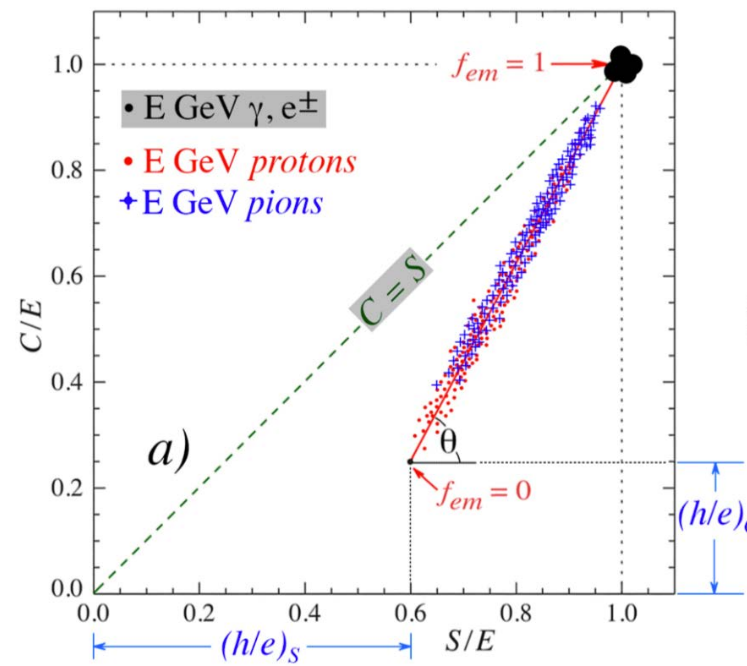
Dual Readout Calorimetry

Sampling calorimeter, reading out both scintillation and Cherenkov light to disentangle EM and hadronic components shower-by-shower, allowing for the corrections for different EM and hadronic responses.

- Scintillation – sensitive to dE/dx energy loss ⇒ charged particles;
- Cherenkov – relativistic charged particles, mostly electrons.



$$\left.\begin{aligned}\frac{S}{E} &= f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em}) \\ \frac{C}{E} &= f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\end{aligned}\right\} \Rightarrow E = \frac{S - \chi C}{1 - \chi}$$

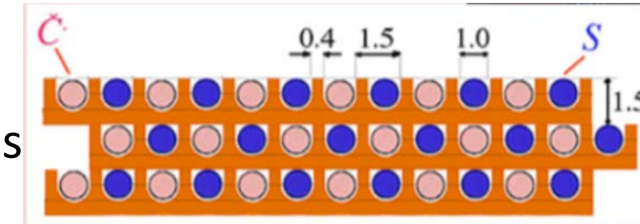


$$\chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

The detector response parameter χ is measured separately, from test beam for example.

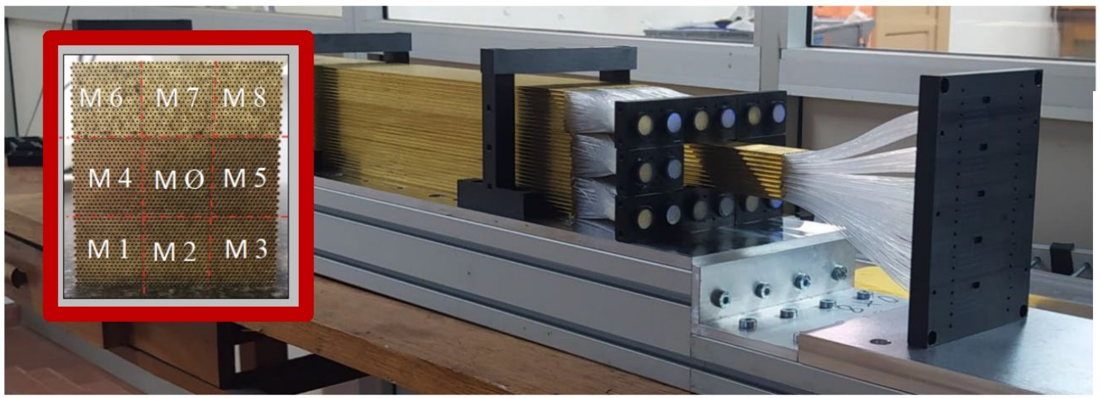
Dual-Readout Fiber Calorimeter

Extensive R&D by the DREAM/RD52 collaborations, clear and scintillation fibers for C/S readout, ECAL and HCAL in one uniform system, several generations of prototype have been studied in test beams



An example geometry with Copper absorber

2021 test beam prototype



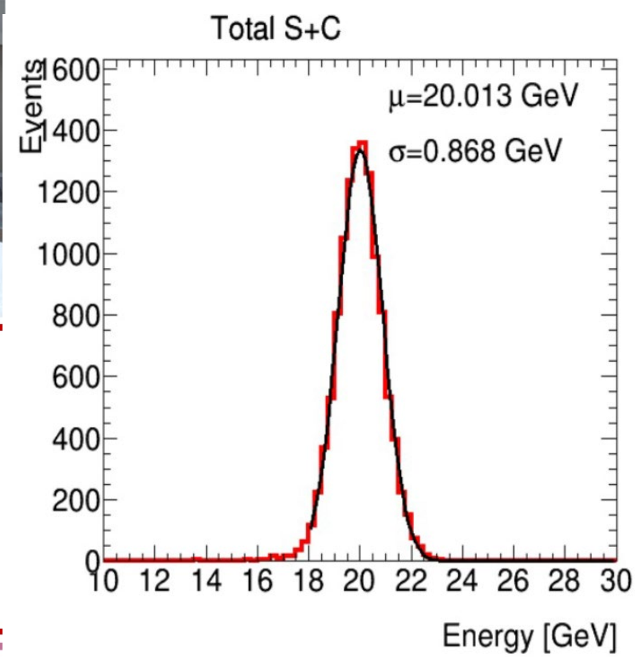
10x10 cm² divided in 9 towers, 1m long
16x20 capillary each (160 C + 160 S fibres)

Capillary:
2mm OD, 1.1 mm ID
Material: Brass

- Hi-quality commercially available capillary tubes
- Quite easy and fast assembly system
- Test the viability of this mechanical solution

G. Gaudio - 5° FCC Physics Workshop

08.02.2022



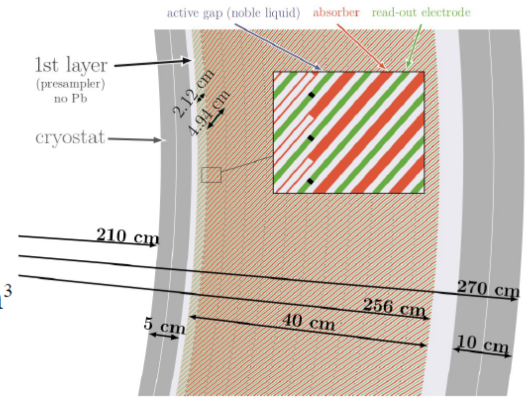
CERN SPS 20 GeV e⁻

Challenges: large channel count, lots of fibers!

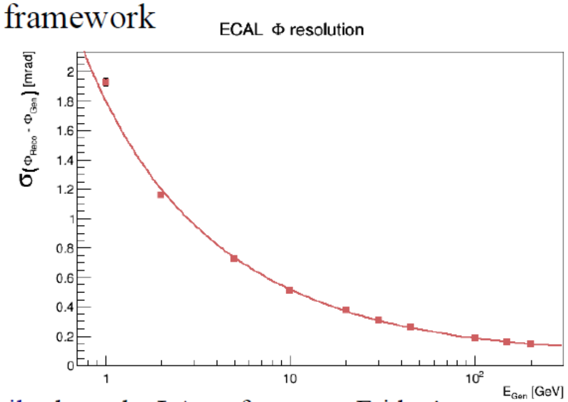
High Granular Noble-Liquid ECAL

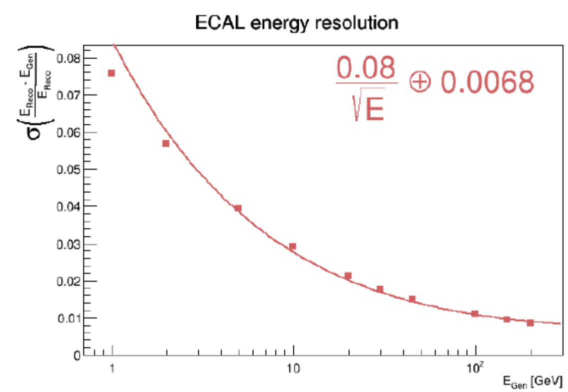
Based on the ATLAS ECAL experiences, multi-layer electrodes to allow more longitudinal components

- The FCC-ee ECAL barrel geometry has been implemented in FCCSW (DD4hep)
  - 12 longitudinal layers
  - Conservative benchmark: 1536 phi cells (2x1.2 mm LAr + 2 mm Pb/Steel + 1.2 mm PCB), inclined plate (50°), Aluminum cryostat, 40 cm depth sensitive area, 22 X_0 in total
  - Typical readout cell size: $\theta \times \Phi \times r \sim 2$ (0.5 strip) x 1.8 x 3 cm^3



- Everything was ported to Key4Hep* (reconstruction, clustering algorithms, dead material corrections, …)
  - First Full Sim performance results produced within this framework





*More details about the LAr software on Friday!

Noble Liquid Calorimetry for FCC-ee   Brieuc Francois   10

Full detector concept under development…

Performance Comparisons

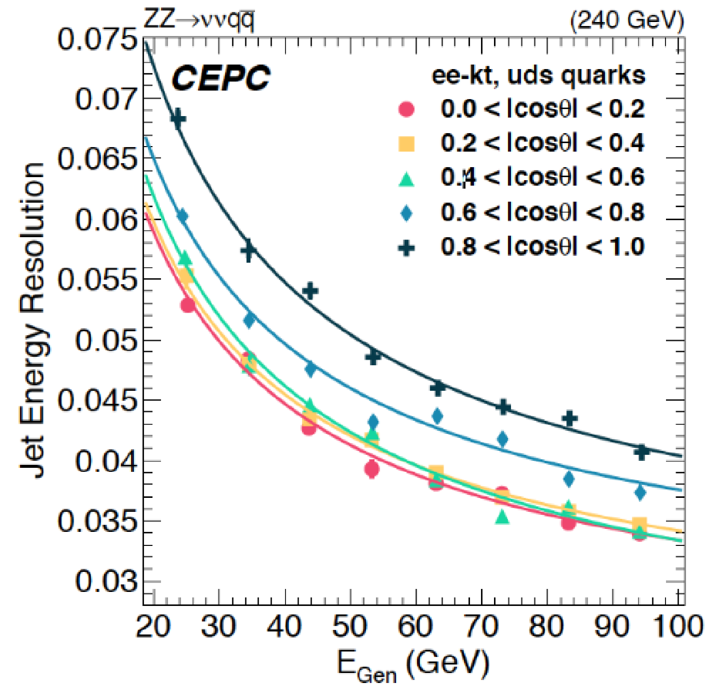
Both PFA and DRO calorimeters are optimized for hadronic Energy Resolution: $\sim 40\%/\sqrt{E}$.

EM Energy Resolutions are mediocre at the best

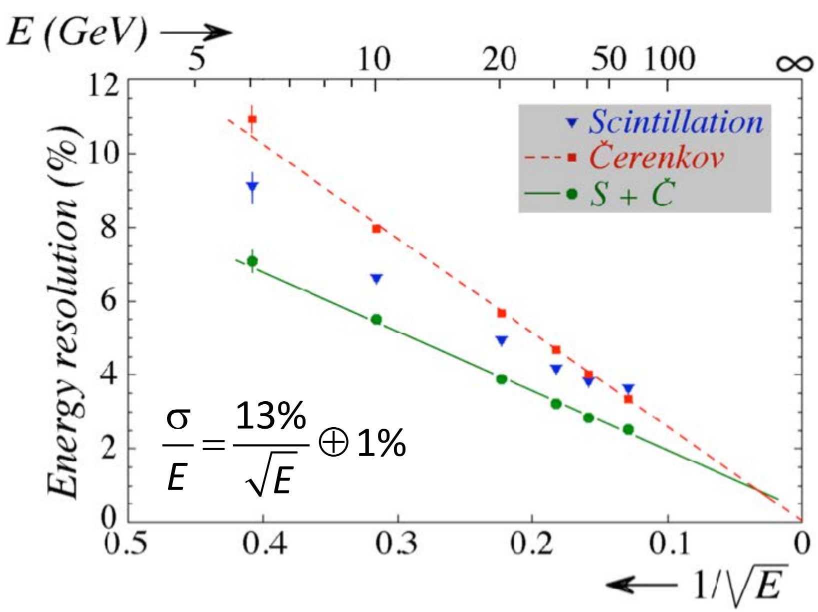
$\sim 20\%/\sqrt{E}$ for a PFA calorimeter

$\sim 13\%/\sqrt{E}$ for a DRO calorimeter

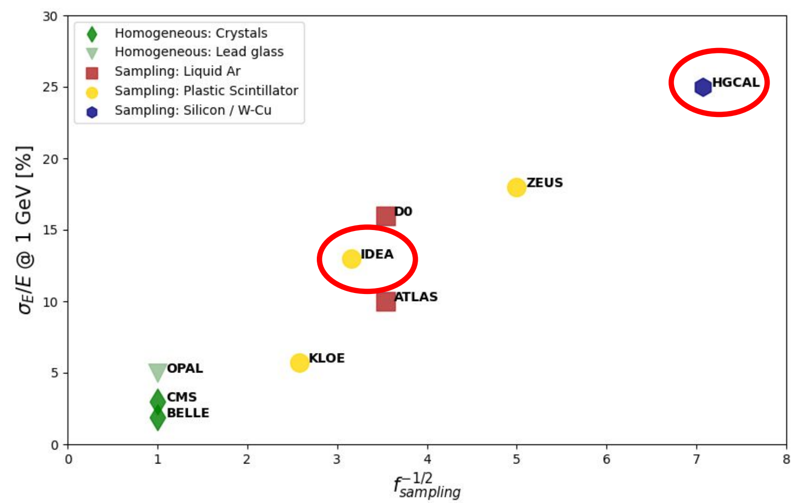
largely due to poor sampling fractions.



PFA jet energy resolution (simulation)



DRO EM energy resolution



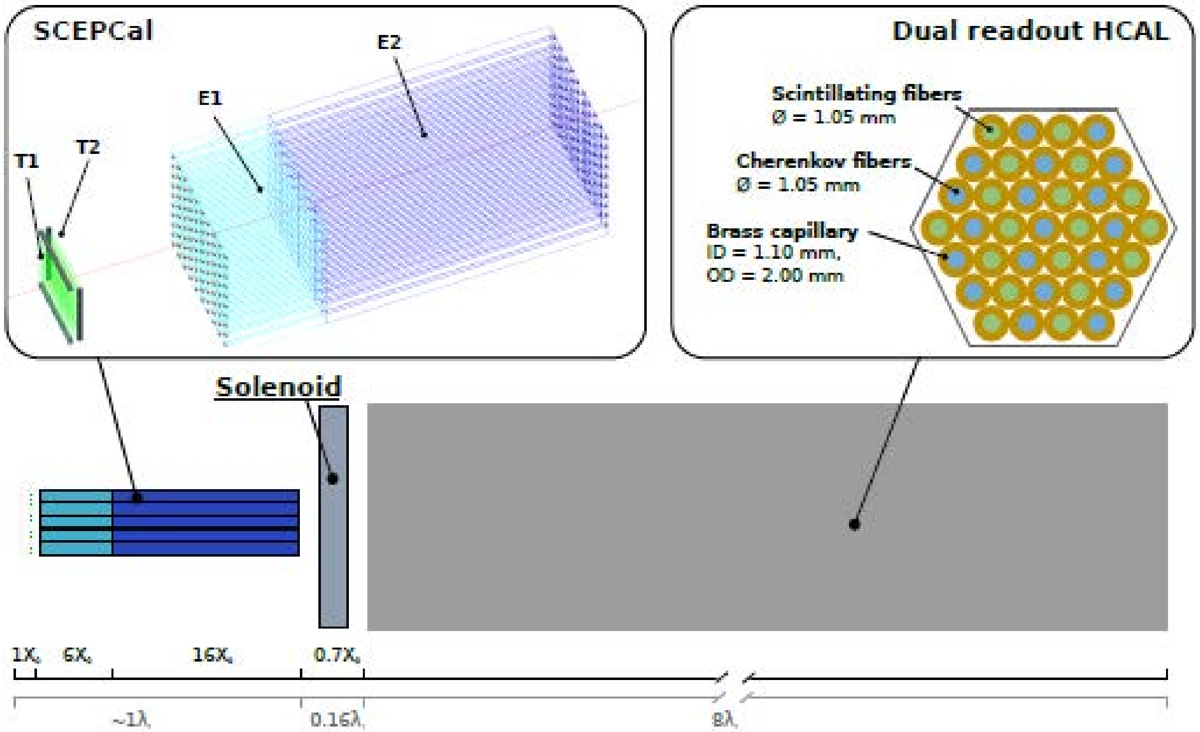
Comparison of EM energy resolution

A DRO Calorimeter with a Crystal ECAL?

Crystal ECALs have very good EM resolutions, $\sim 3\%/\sqrt{E}$ or better, but they suffer from large non-uniform h/e responses.

Can we combine the strengths of a crystal ECAL with that of a DRO calorimeter?
Can a DRO crystal ECAL help to mitigate its impact on hadronic energy resolution?

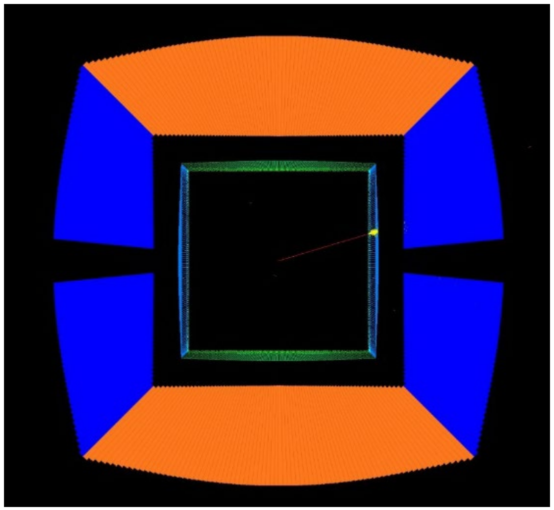
An example design by Eno, Lucchini, and Tully et al. (arXiv:2008.00338)

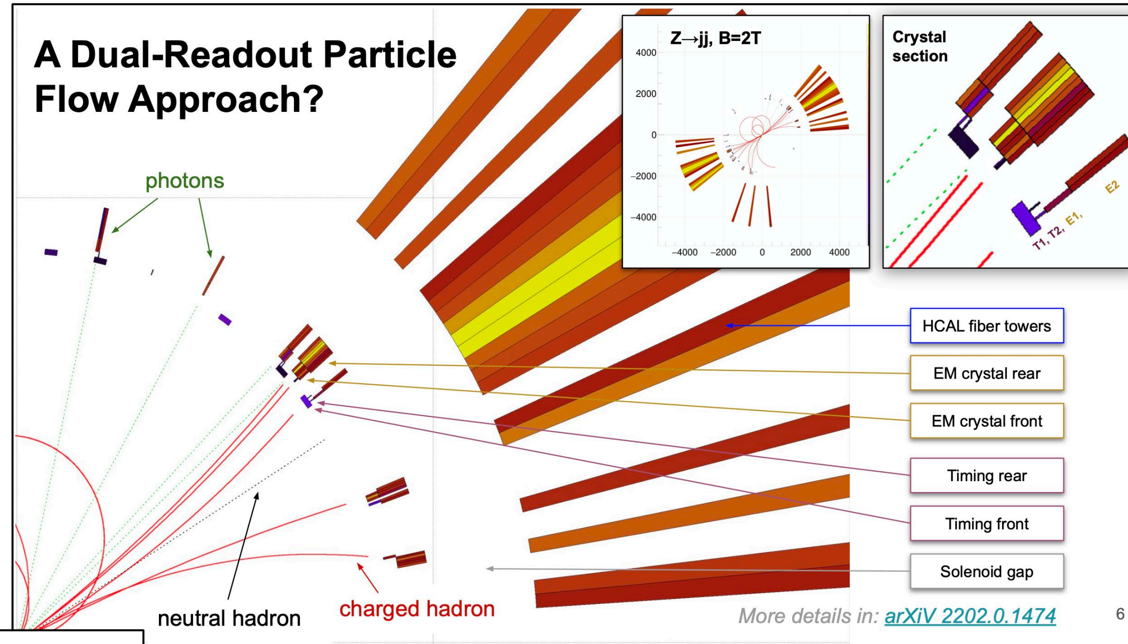


Explore crystal DRO using both wavelength filters and timing structure

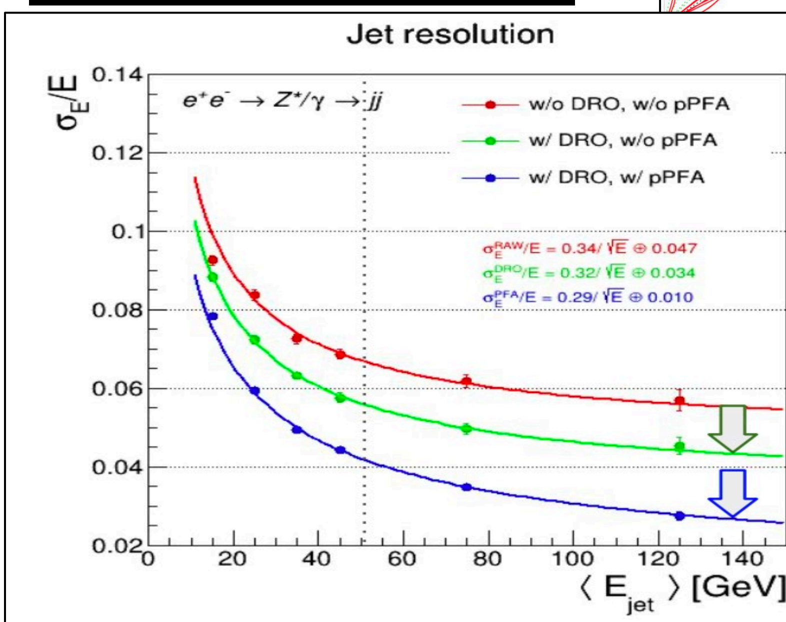
A DR Crystal ECAL with a DR Fiber HCAL

Implemented in the IDEA concept





Marco Lucchini



Sensible improvement in jet energy Resolution using DR information combined with particle flow approach

$\Rightarrow$ 3-4% for energies above 50 GeV

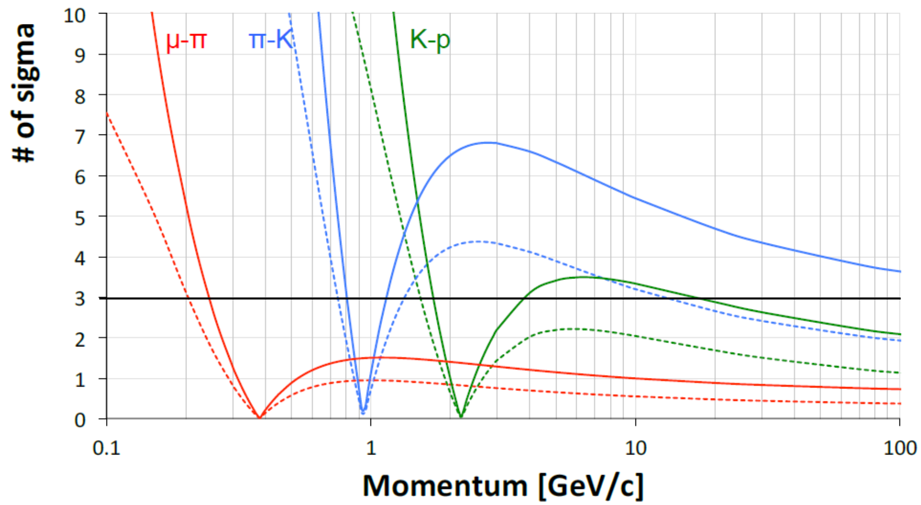
Possible to have both good EM and jet energy resolutions!

Particle Identifications

PIDs are essential for flavor physics, flavor tagging, and for long-lived particle searches.

$dE(dN)/dx$ and TOF are popular options for a *general purpose* detector.
A timing resolution of ~ 20 ps or better should be possible.

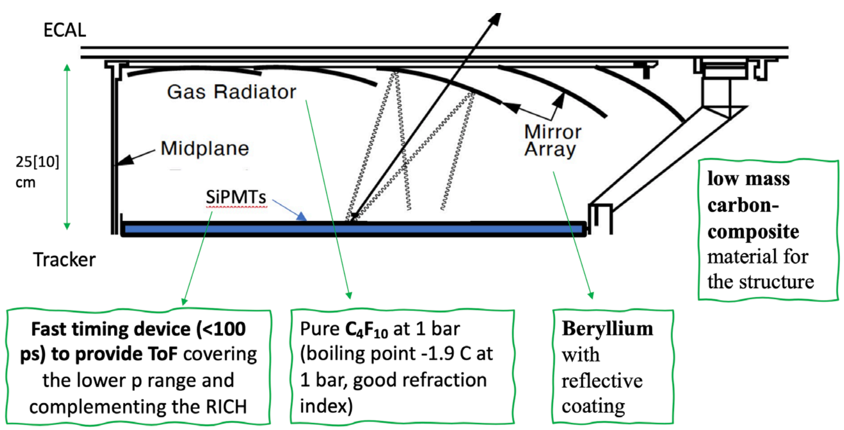
IDEA



arXiv:1811.10545

Dedicated RICH-type PID detector is also being studied

V. Cairo



Compact Gaseous RICH with SiPMTs

Ongoing test beams to validate its performance.

A 3σ π-K separation up to ~ 30 GeV should be possible when combined with a TOF detector.

Requirements for Precision

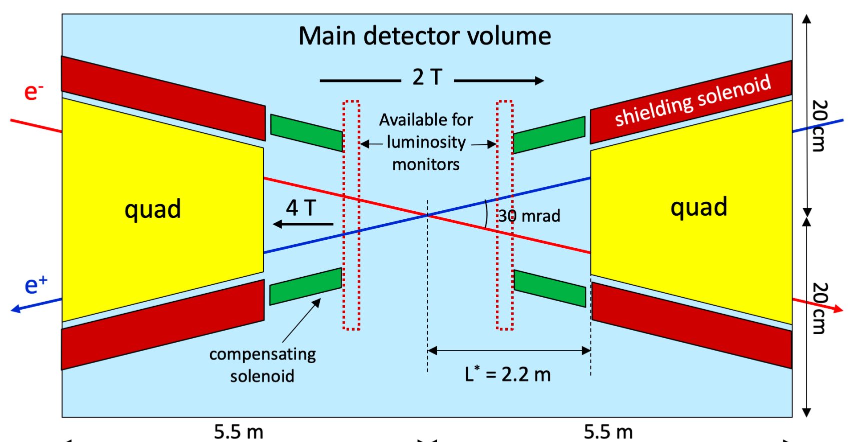
Z pole measurements are likely driving the requirements for precision.

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	$0.2 - 1.0$	Ratio of hadrons to leptons; acceptance for letpons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	$0.4 - 1.6$	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
$\sigma^0_{\rm had}$ ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{{\rm pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

arXiv:2203.06520

Z lineshape scan calls for an absolute luminosity precision of 10^{-4} $\Rightarrow$
$\sim 1\mu$m precision on the radial dimension of the LumiCal in the complex MDI region.

The precision requirements on fiducial volume likely extend to leptons, O(10μm)



Other Comments

- Many concepts have muon taggers outside while relying the measurements in inner trackers, standalone measurements are proposed for the IDEA concept

- Benefiting from the clean event environment and low event rate, “trigger-less” DAQ system is an attractive option.

- (HL-)LHC scale computing should be nearly sufficient for the needs even at the Z pole. Raw data size is expected to be similar to that of the HL-LHC due to likely the finer detector segmentation. Analysis-level data should be similar to that of Run2/3.

- The baseline FCC-ee design now allows for 4 IPs, offering the flexibility for special detector capability (e.g. RICH PID detector) to maximize the physics opportunities.

Concluding Remark

Circular e^+e^- colliders offer enormous potentials for precision measurements of electroweak parameters, studying Higgs boson properties, searching for BSM physics, and for exploring heavy-flavor physics.

Detector designs to exploit the potential are challenging because of wide spectrum of the physics program and the unprecedented precision. May require dedicated experiment to focus on specific physics, eg heavy flavor. 4IPs will make this possible.

Many concepts based on past experiences have been proposed, new ideas will likely emerge. There are plenty of rooms for innovations and improvements. Final detector designs will likely be mixes and matches of different ideas and technologies.

Circular e^+e- colliders are the compelling option for the next project after the LHC. Please join the effort!

(Thank Alain Blondel, Mogens Dam, and Markus Klute for their assistance in preparing this presentation)