ECFA HET FACTORY STUDY: WG3 DETECTOR TECHNOLOGIES

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- CIEMAT -

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Detector challenges for e+e- Higgs, EW, top Factories

DETECTOR CHALLENGE

To achieve systematic uncertainties similar or smaller than the statistical

- Clearest environment than hadron colliders

No pileup, no underlying event E and p constraints…

- **Huge number of events** (e.g. $5x10^{12}$ Z vs $18x10^{6}$ at LEP
10^{8} WW pairs vs $8x10^{3}$ W at LEP)

High precision can be achieved

Some Performance requirements driven by physics

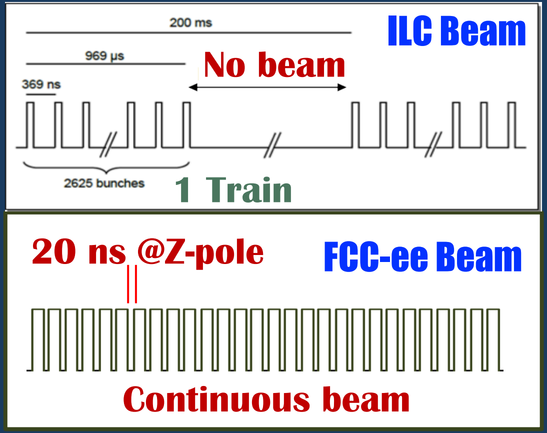
- ✓ Momentum $\sigma_{Pt}/p^2_T \sim 3\text{-}4 \times 10^{-5}$ (~7 μm single hit resolution) (~1/10 of LEP)
- ✓ Angular resolution < 0.1 μrad for 45 GeV muons
- ✓ Impact parameter $\sigma_{do} = 5 \oplus 15 (p \sin \theta^{3/2})^{-1}$ μm (~3 μm single hit resolution) (b and c tagging capability)
- ✓ E.M calorimeter
  resolution $< 10 – 15 \%\sqrt{E}$ (with low constant term) (B physics could need to go down 5 $\%\sqrt{E}$)
  Very good transversal granularity is required for τ physics
- ✓ Jet energy resolution $\sim 30\%\sqrt{E}$ (~ a factor 2 better than present)
- ✓ Particle Identification (PID) Excellent lepton and photon ID (e/π, μ/π, γ/π^0) , π/K, K/p separation (heavy flavor studies)….
  for a broader momentum range for e, μ and hadrons to improve tagging, jet energy…
- ✓ Hermetic coverage
- ✓ Precise timing will play an important role
  Improve PID
  Beam-induced background rejection
  Pile-up rejection
  Improve calorimeter/tracker reconstruction

Circular vs linear e+e- Higgs, EW & top Factories
Main impact on detector

Beam Structure

Implication on power, rates, readout…

ILC experiments use power pulsing (electronics off between trains)
⇒ Power consumption reduction a factor $\mathcal{O}(10)$



Luminosity at Z-pole: Tera-Z vs Giga-Z

@ FCCee L ~1.8 x 10^{36}/cm^{2}.
physic event rates up to 100 kHz. (pile up of 2×10^{-3})

Implication on detectors, electronics, DAQ:
response time, time resolution, size of event, data handling….
Huge statistic → Systematic control down to ~10^{-5} level
Excellent control of acceptances needed
Luminosity measurements $\sigma(L)/L = 10^{-4}$ (for low angle Bhabha events)

Machine Detector Interface (MDI)

	ILC	CLIC	FCCee	CEPC
Cross. angle @ IP (mrad)	14	16.5-20	30	33
L (meters)*	4.1	6	2.2	2.2

Circular Colliders:

- Last focusing magnet (at L*) INSIDE the detector volume (also the LumiCal at 1m from IP – vs 2.5m)

  θ < **100 mrad** reserved to magnets and instrumentation + Lumical (up to 150 mrad)

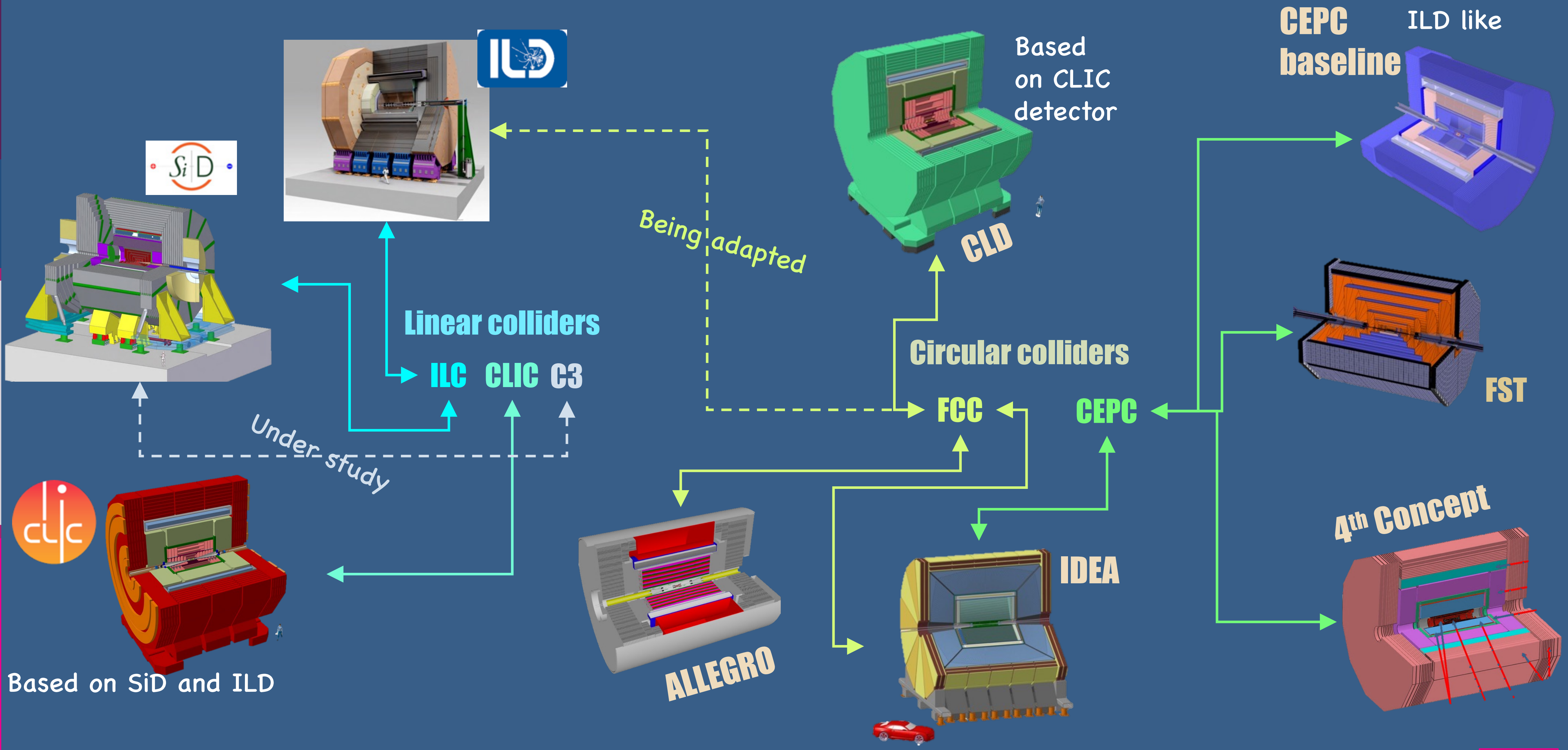
  Forward tracker limitation > **10 deg.**

  Lower tracker acceptance for FCCee vs ILC

- B field limited to 2T at Z-pole operation (~3.5T for linear)

  Larger tracker volume at FCCee vs ILC

Proposed detector Concepts

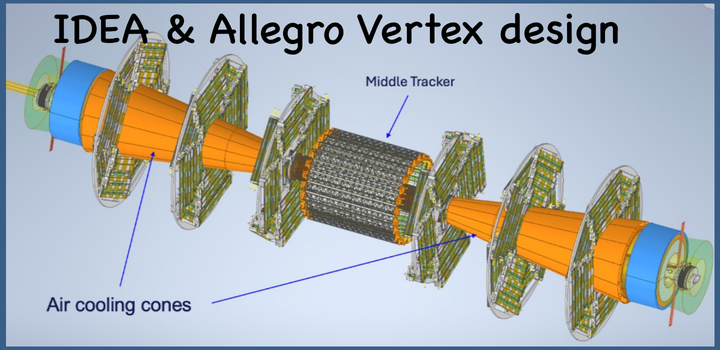


Vertex and tracker detectors at the different concepts

VERTEX

All use pixel silicon detectors

~ 5-6 layers @Barrel and up to 6 @endcap.
single or double layer
Pixel size ≤ 25μm



TRACKER

Two different approaches

- Full silicon system
  Strips or large pixels
- Gaseous detector surounded by a layer of Silicon detector

Several gaseous detectors options: TPC, Drift Chambers

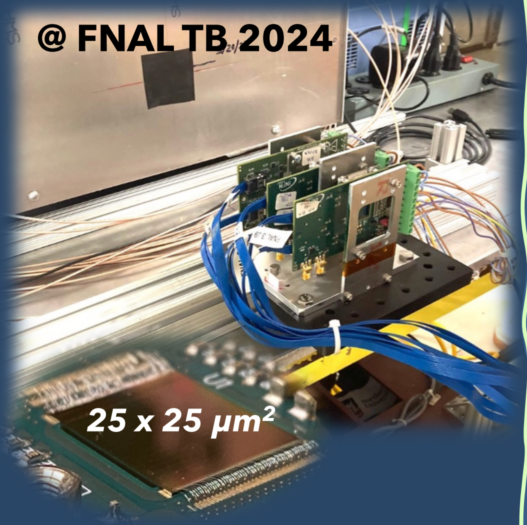
TRACKER OPTIONS	
SID	Silicon Strips
CLICDET	Silicon Pixels
CLD	Silicon Pixels
ALLEGRO	Drift chambers + Silicon Strips or Silicon Pixels
CEPC BASELINE	TPC + Silicon Strips or Silicon Strips
ILD	TPC + Silicon Strips
IDEA	Drift Chamber + Silicon Strips
4TH CONCEPT	TPC + Silicon Strips or Drift Chamber + Silicon Strips

The vertex and silicon trackers (& timing layers)

Different technologies under development and in synergy with other projects (HL-LHC)
Design of chips and solutions for larger structures, demonstrators under test beam…
Inclusion of precise timing (<ns) is an important challenge which also impacts on power consumption
(linear colliders can use power pulsing, for circular extra cooling increase material budget)

Just a few R&D examples

ARCADIA-MD3 (DMAPS)
LF11is 110 nm CMOS



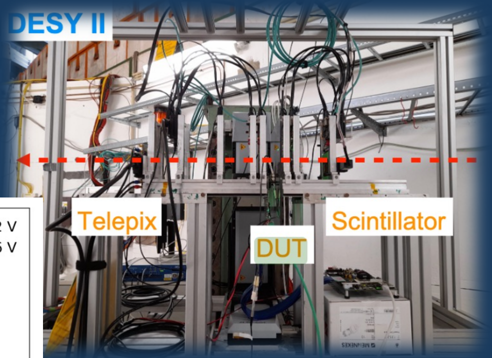
5μm resolution
ultra-low power capability
O(10 mW/cm²);

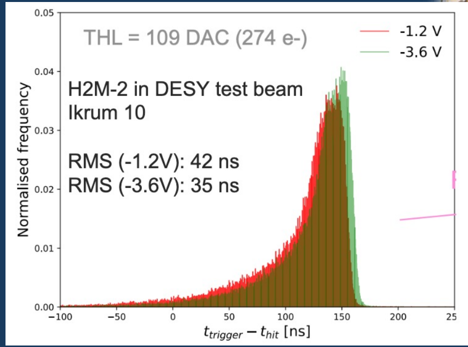
Developments on 65 nm CMOS technology

advantages Better spatial resolution, lower power consumption, lower material budget, larger wafers

Example: **H2M** TPSCo 65nm

50μm thinkness
R&D on thinned samples (20-30μm)

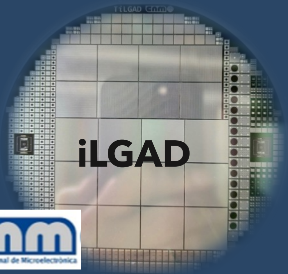




timing limited by non-uniformity of charge collection

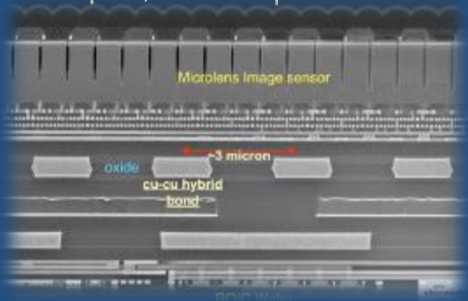
LGADS MAPS devices with linear gain

Different types under development
Ultrafast device (~20ps)



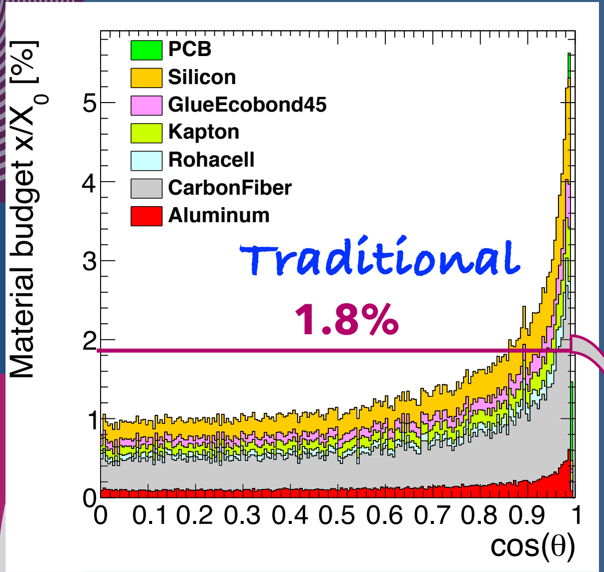
3D—INTEGRATED SENSORS

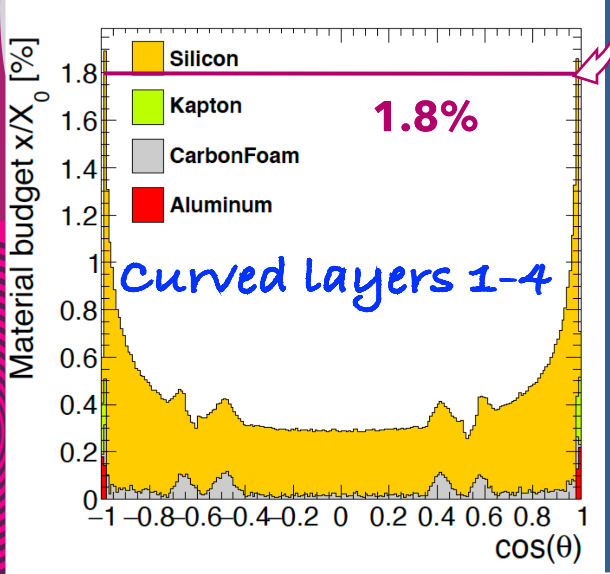
New development, supported by DOE partner with industry leaders
Design goal: 5μm, ~5-10 ps



Material Budget optimisation

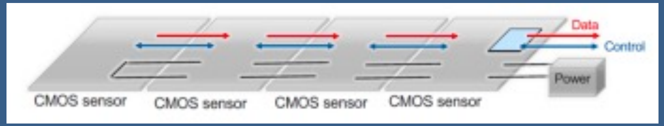
Material budget is dominated by cooling, supports, and cabling





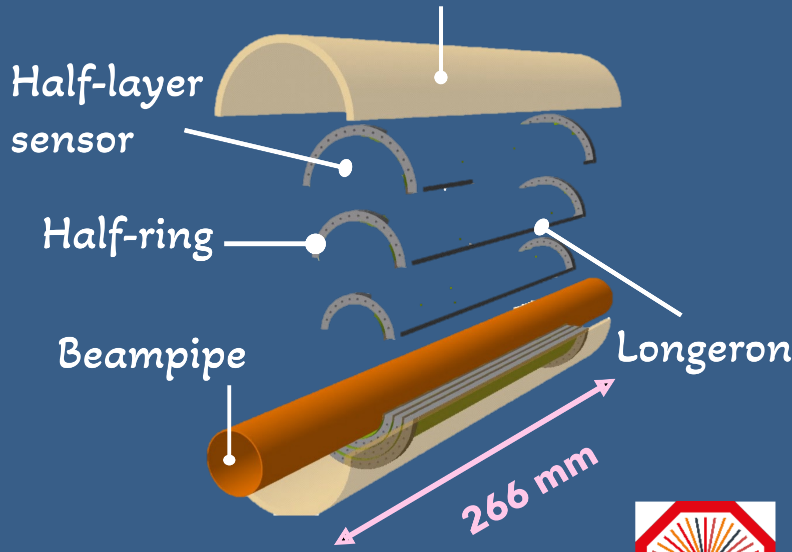
How to reduce it?

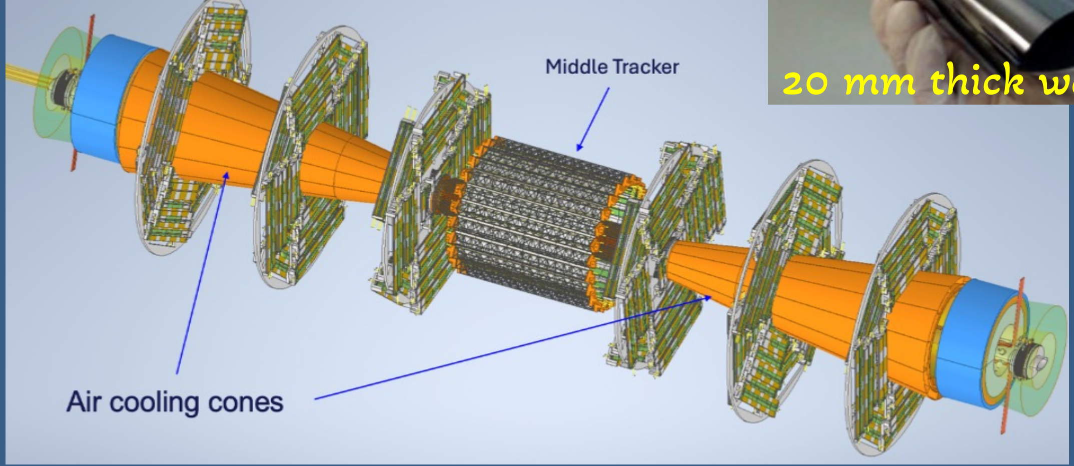
- ✓ Minimize cooling and mechanical structures
- ✓ Silicon sensors only component in the active area
  - Power supply and transfer data cannot be on the chip
  - ➔ Circuits located at the short edges of the chip

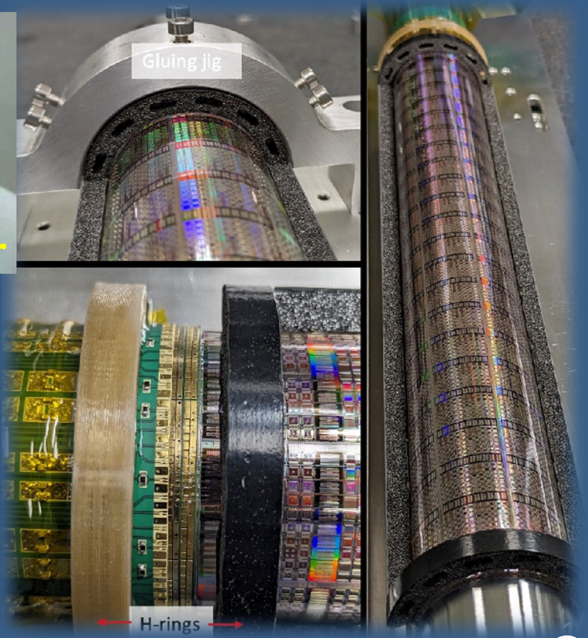


-> Stitching

- ✓ Cooling by air flow ➔ Power limit 20mW/cm2

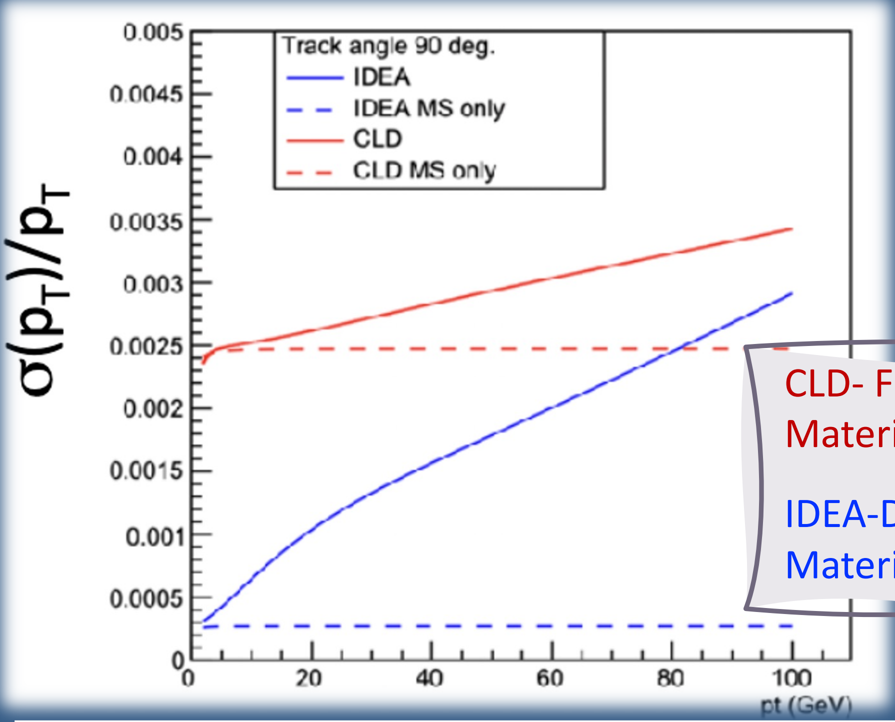






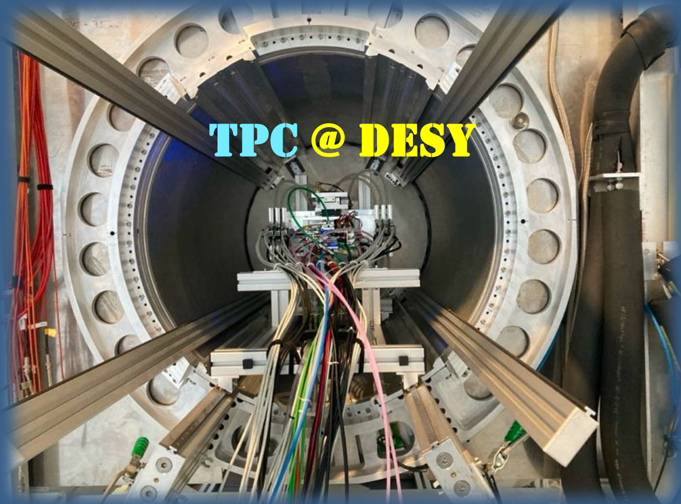
Tracking based on Gaseous Detectors
Some advantages

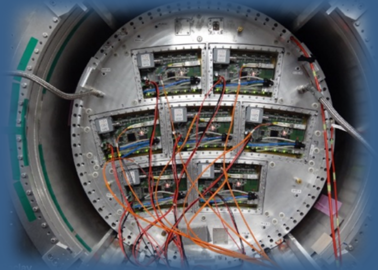
- Low material budget
  - Better resolution
- Particle ID (complementary to TOF)
  - dE/dx or dN/dx (Cluster counting)
- Continuous tracking
  - Of interest for long-lived particles vertex



CLD- Full silicon
Material budget 11%

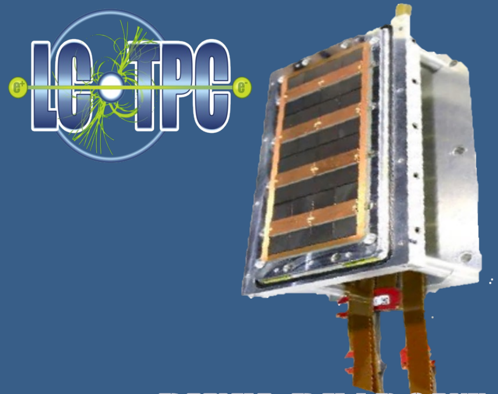
IDEA-Drift chamber
Material budget <2%.



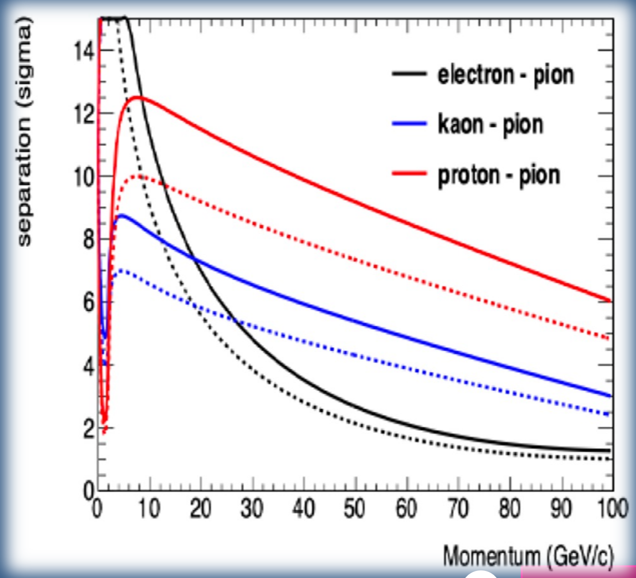


Diferent readouts under development
- GEM
- MicromeGAS
- PIXEL

Test beam 2021 using Pixel readout
B=1T



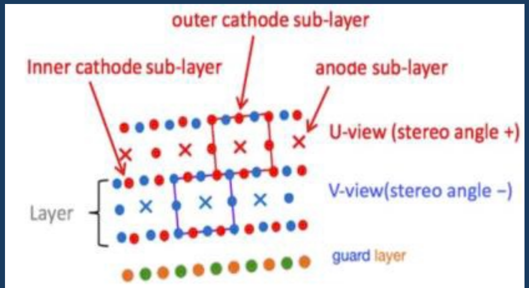
PIXEL READOUT MODULE TIMEPIX3



Tracking based on Gaseous Detectors
Drift chambers

IDEA - Wire chamber

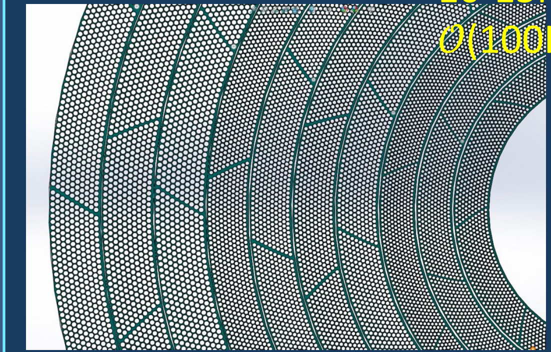
112 layers
4 m long, R = 35-200 cm
343968 wires



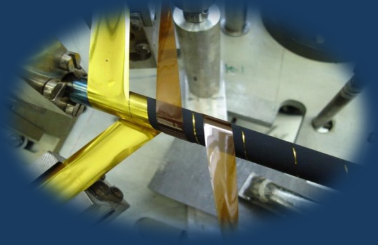
stereo angle for second coordinate

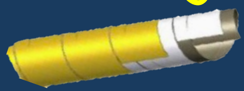
Ultra-light weight straw tracker

10-15mm Straw
O(100K) tubes



Assembly can be done by
- Winding (as Mu2e) , or
- ultrasonic welding (as DUNE)

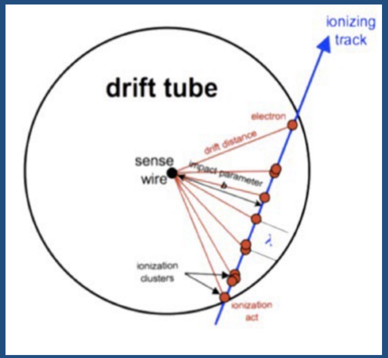




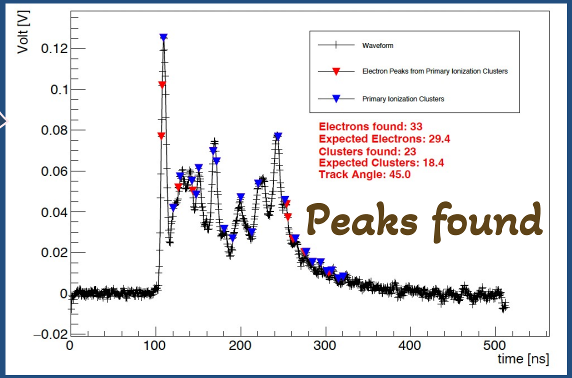
Winding

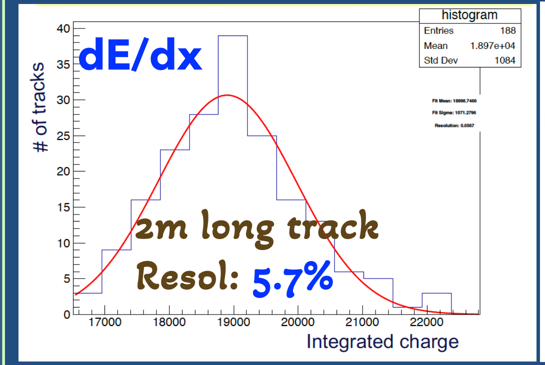
Counting Cluster Technique

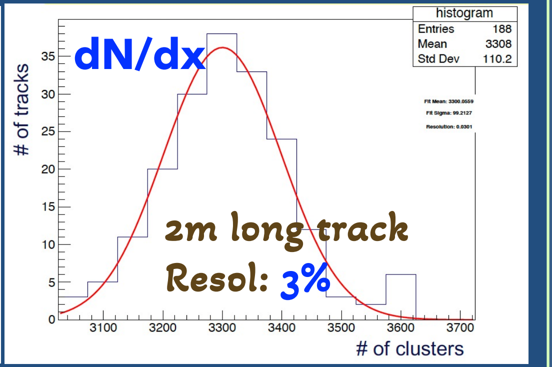
Counting the number of ionization acts per unit length (dN/dx)



Test beam results







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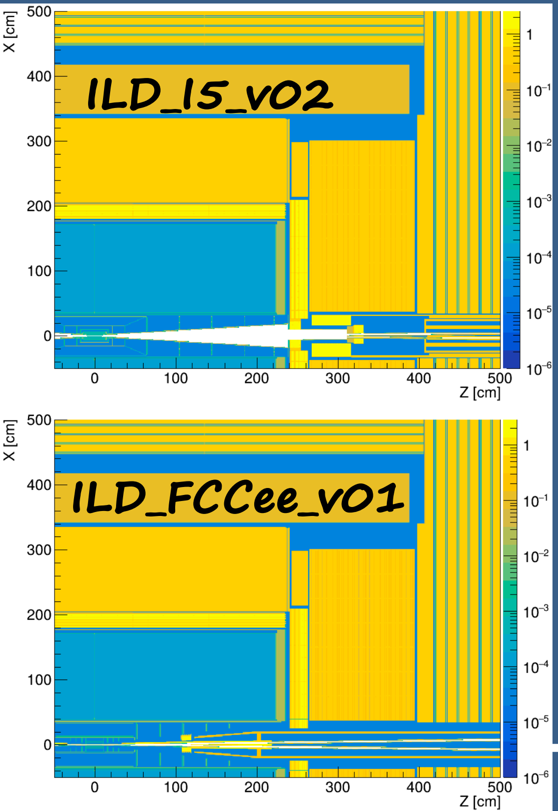
Tracking based on Gaseous Detectors
TPC challenges at Z pole for circular colliders

TPC is the detector proposed for ILD (initially only for linear colliders now being studied for FCCee) and it has been approved for the CEPC baseline detector

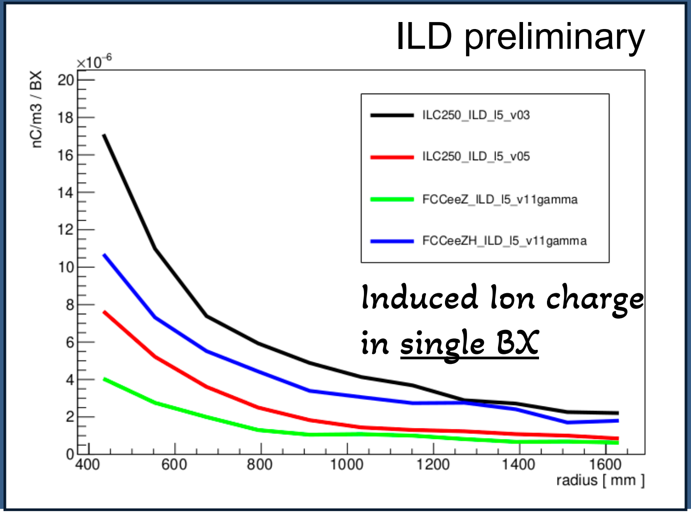
TPC integrates over many collisions. Maximum ion drift time ~0.44 s. ➔ ION backflow could be an issue at Z pole
Studies ongoing to fully understand the implications

New ILD Models



	ILC250	FCC240	FCC91
BX freq	6.6 K	800 K	30000 K
Max.Primary ions.	0,01 nC/m³	2 nC/m³	26 nC/m³

Values for IBF=0



ALICE TPC UPGRADE

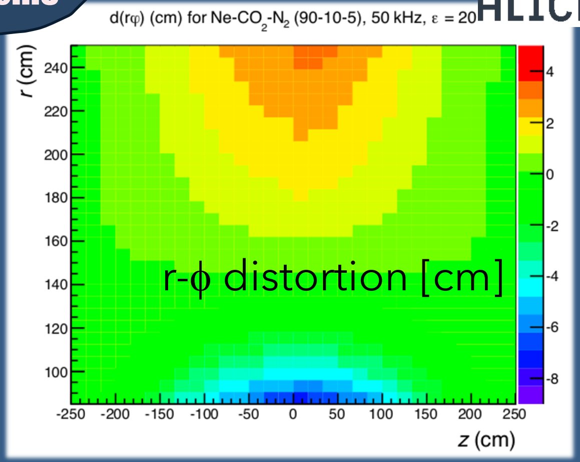
20-120 fC/cm3

IBF ~ 4 ➔

FCC 91 similar to ALICE TPC

(1-10) cm max. distortions

(~0.6mm residuals after corrections in ALICE)



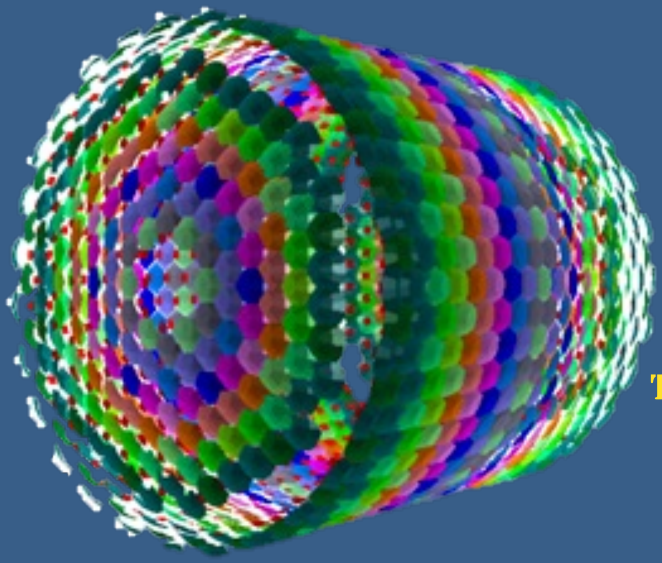
Distortion corrections will be needed
Some more work needed to demonstrate the feasibility of using TPC for Z-pole at Circular colliders

More ideas for PID - The ARC concept

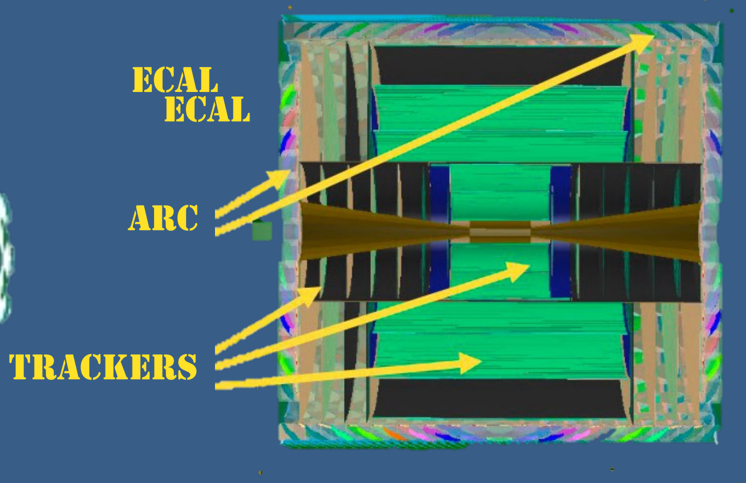
ARC=Array of RICH Cells

each cell acts as an independent RICH detector

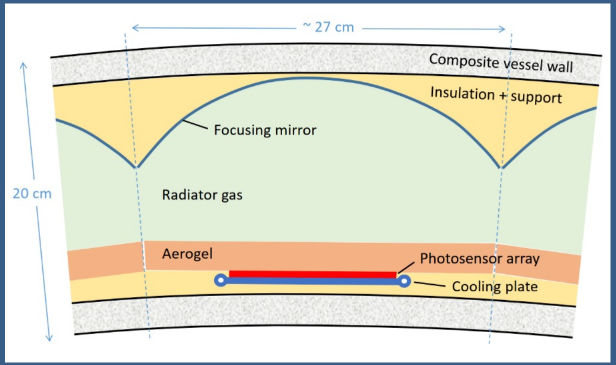
Lightweight and compact



CLD versión with ARC



Single cell geometry



Radiator	Max p [GeV/c]
C_4F_{10} @ 1 bar	45
Xe @ 2 bar	38
Xe @ 3.5 bar	33

Two radiators:

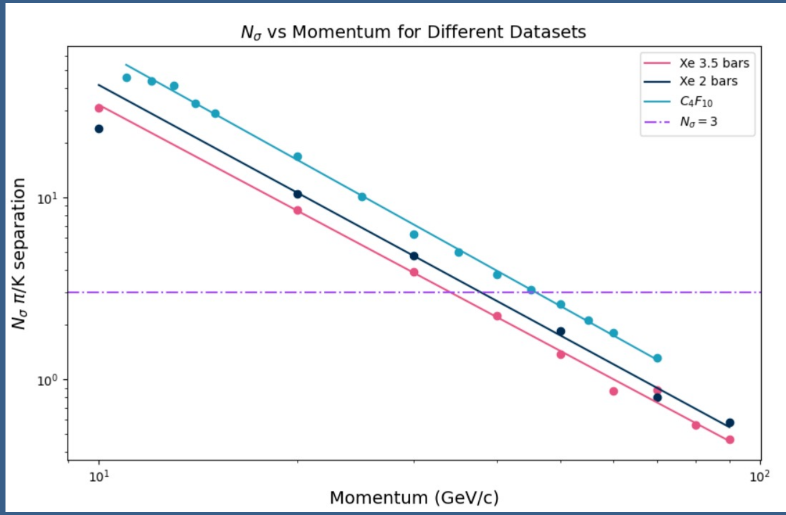
C4F10 (or a more eco-friendly alternative)

\+ Aerogel (for low p tracks)

Aerogel also as thermal insulator between SiPM array and gas radiator

Xenon could be suitable, but must be pressurized to achieve sufficient photon yield

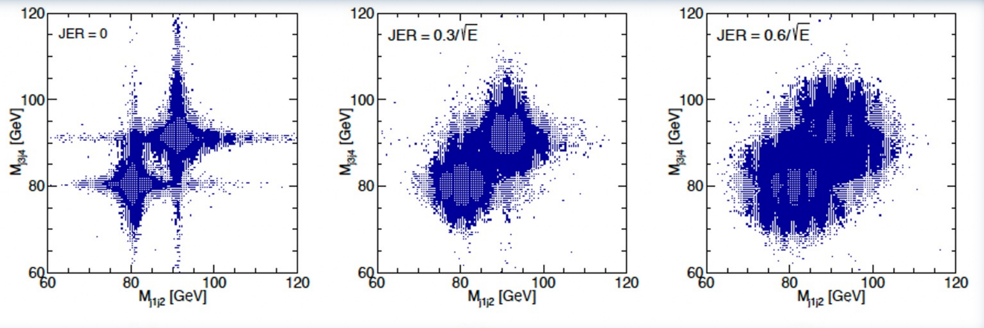
→ the vessel needs to be reinforced



Single cell prototype foreseen in 3 years (DRD4)

Facing the calorimeter challenges. Jet energy resolution

Hadronic final states are very relevant players, opening sometimes the access to rare process and helping on increasing statistics
Precision on the jet energy determination plays a very important role



(a) (b) (c)

30%/√E needed (~a factor 2 with respect to the present experiments).
The value is driven by the precise separation of Z and W in their hadronic decays and it is comparable to the natural width of Z and W

Many R&D activities are ongoing, approaching the problems in different ways.
Two main approaches:

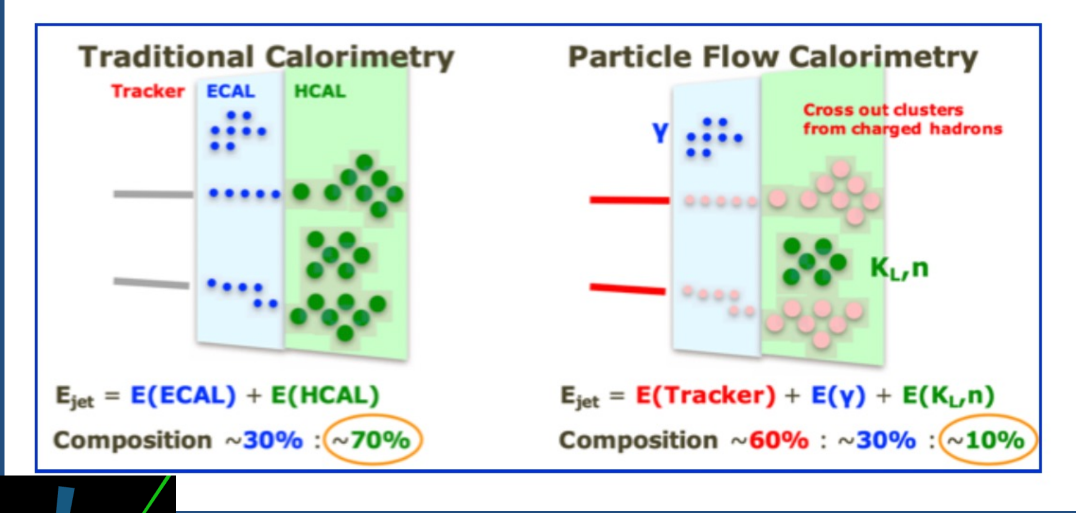
- ***High granular calorimeters with embedded electronics to apply PFA (Particle Flow Algoritms)***
  - Concepts with PFA fully oriented calorimeters
    - CEPC Baseline, CLD, CLIC, ILD, SiD, FST,
- ***Dual readout Calorimeter***
  - Concepts with Dual Readout
    - IDEA

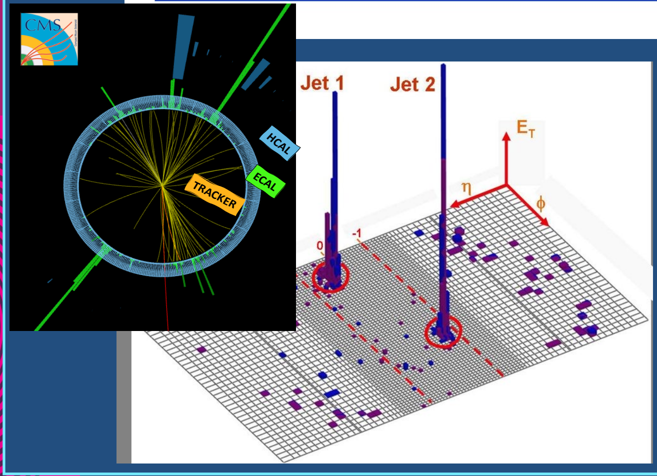
The measurement of jets with the needed precision is the main challenge for the calorimeters

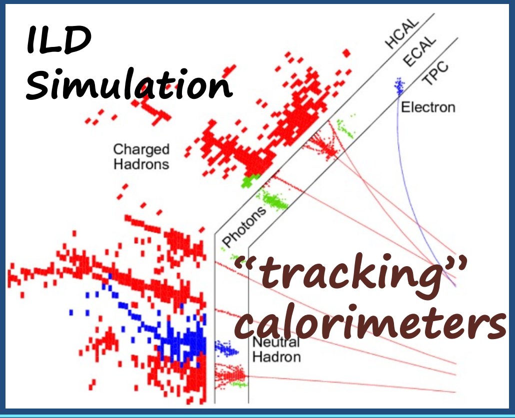
Facing the calorimeter challenges. Jet energy resolution

High granularity calorimeters for PFA

Reconstruct **every single particle** in the event and measure it **only** with the detector providing the best resolution







Dual Readout Calorimeter

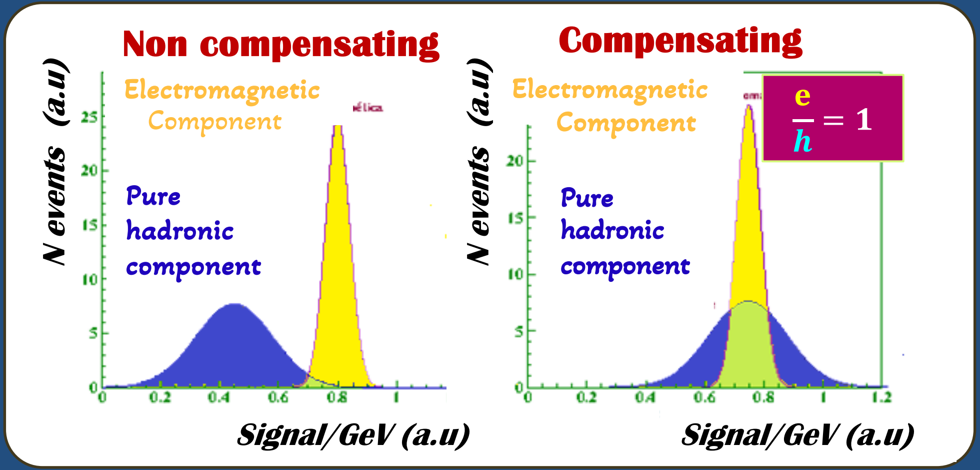
$$Signal = S_{em} + S_{had} = ef_{em}E + hf_{had}E$$

$$f_{had} = 1 - f_{em}$$

If it could be possible to distinguish in the calorimeter the electromagnetic fraction , compensation is not needed

Use two different materials for producing different response type:

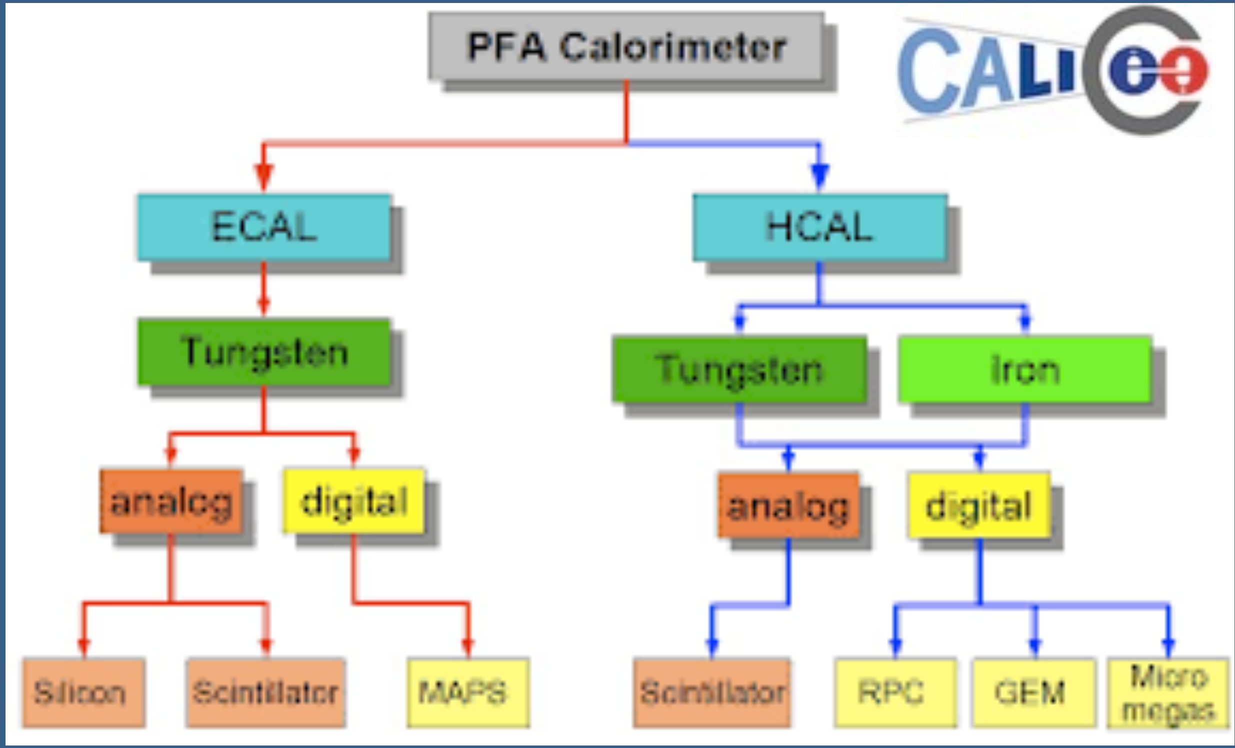
1. Cherenkov light, produced by relativistic particles dominated by electromagnetic components (80% of the hadronic component is not relativistic)
2. Scintillator light

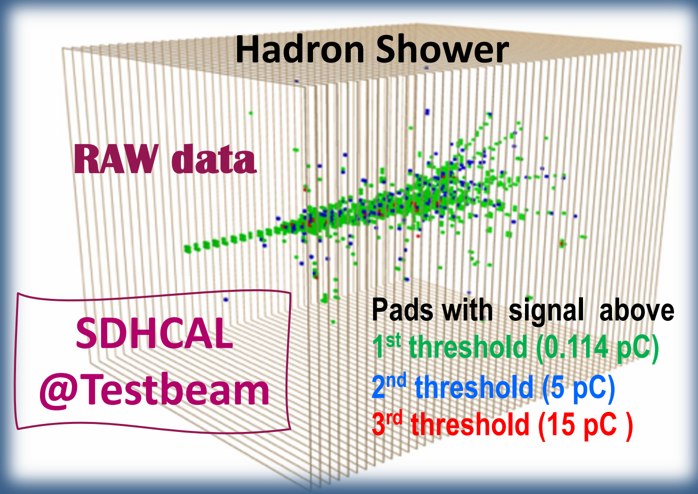


High granularity calorimeters

Developed by the CALICE Collaboration along >20 years (approach also used for the upgrade of the CMS endcap calorimeter for the HL-LHC).
They are sampling calorimeters and several technologies as active medium under study: Silicon detectors, scintillators, gaseous detectors

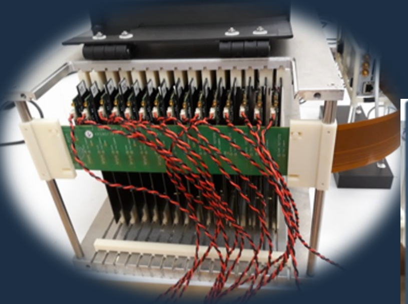
- FE electronics is embedded into the layer structure
- Dead spaces must be minimize ➔ High precision mechanics needed
- For Linear Colliders final electronics implements power pulsing mode,





Tracking capabilities!!

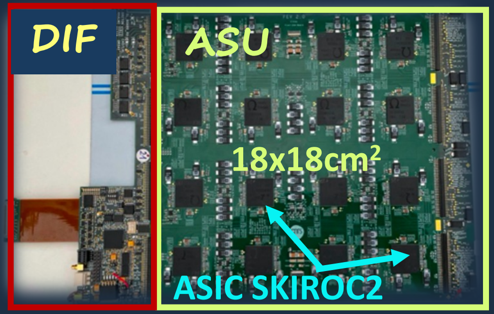
High granularity calorimeters – few examples



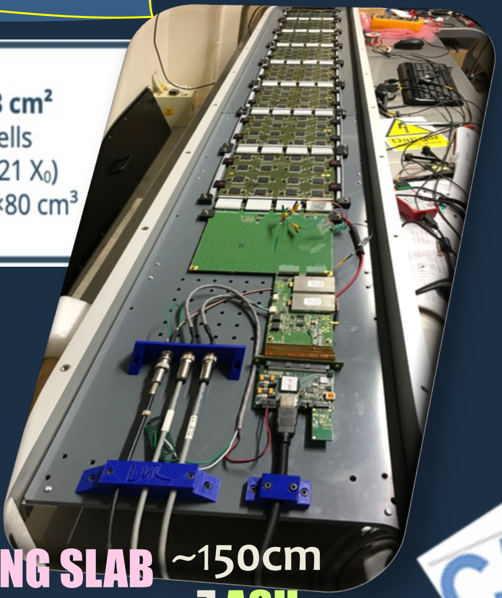
Silicon-W ECAL

SiW-ECAL
- 15 layers 18×18 cm²
- 0.5×0.5 cm² Si cells
- 2.8+5.6 mm W (21 X_0)
- 100 kg, 0.4×0.4×80 cm³
- 15k channels

Embedded electronics



Pads on bottom



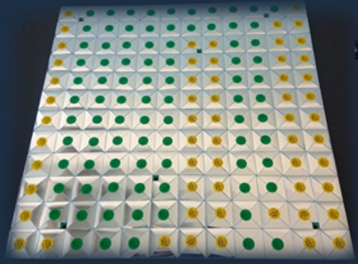
LONG SLAB ~150cm
7 ASU

ASU = ASIC+PCB+SiWafer
DIF = Detector InterFace:

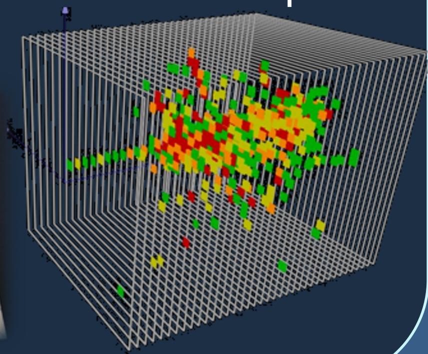
Scintillator HCAL - AHCAL

144 channels

Tiles 3x3x0.3 cm³
38 layers 0.72 x 0.72 m²
~22.000 channels

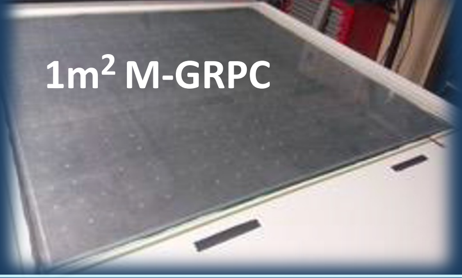


80 GeV pion



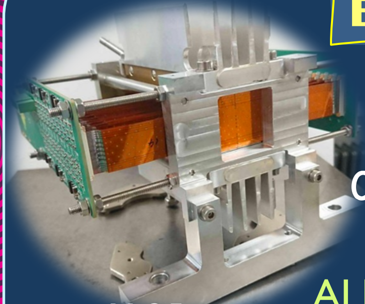
SDHCAL – Semidigital HCAL

from SDHCAL to T-SDHCAL

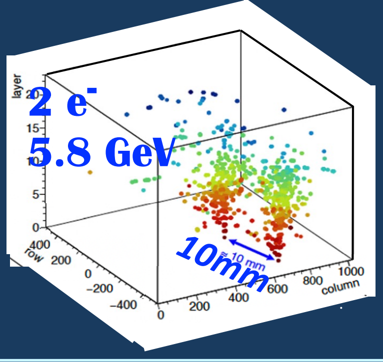


Starting to implement precise timing (tens ps) using Multigap Glass RPCs instead of single gap & new electronics with better timing capabilities

EPICAL-2 prototype



Active cross section
3x3cm²
0.03x0.03mm² Si-pixels
28 layers
ALPIDE CMOS sensors



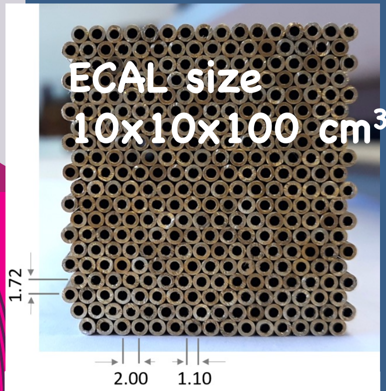
M.C Fouz

Dual readout calorimeter

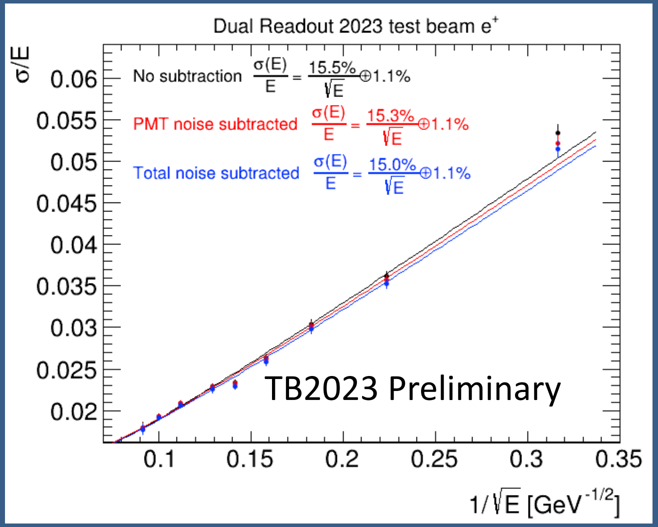
Dual-readout calorimeter can be used for EM and HAD calorimetry as a single device
Possibility of adding a dedicated Crystal ECAL in front

Geometry based on metal capillaries acting as absorber with inserted fibers (Cherenkov and scintillator)
No longitudinal segmentation (time could be exploited)

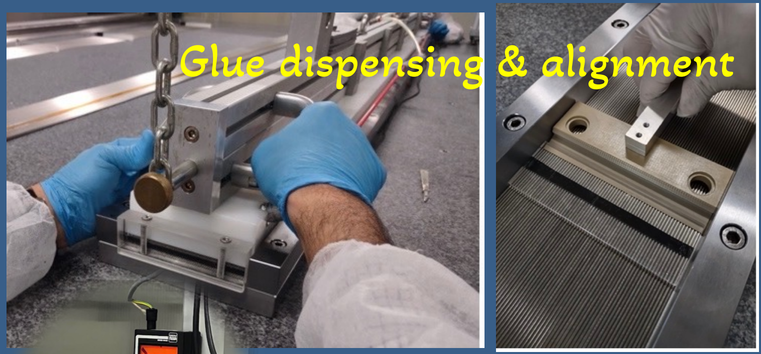
ECAL Prototype (Bucatini)



320 brass tubes



HiDRa:
High-resolution, highly granular Dual-Readout Calorimeter
(Prototype for Hadronic containment)



Planarity measurement

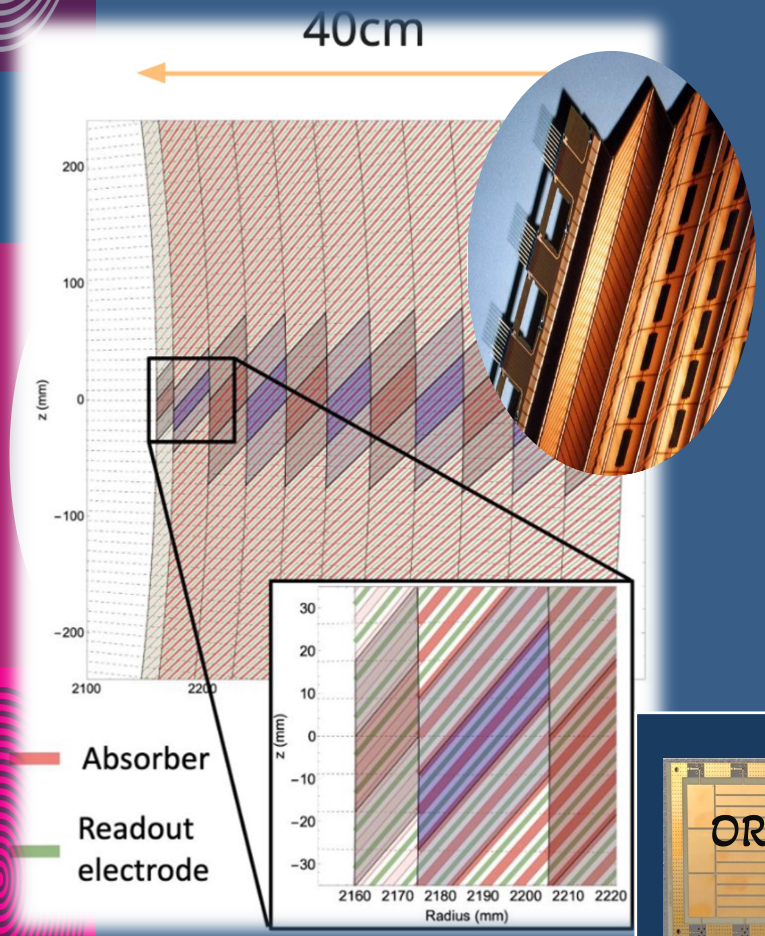
Investigating assembly procedures including some automatization

HiDRa prototype instrumented only with PMTs (TB2024)

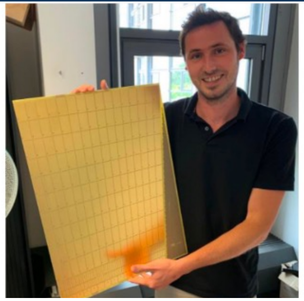
Liquid argon calorimeter (ECAL)

Based on LiAr ATLAS Calorimeter

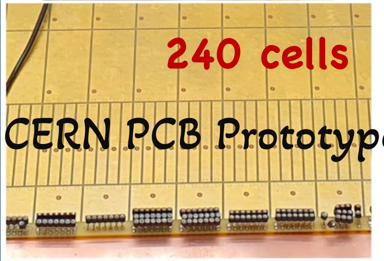
Target 10-**15** times higher granularity than ATLAS for PFA in high pile-up environment.
(ATLAS Cu/Kapton electrode but PCB allows high granularity)

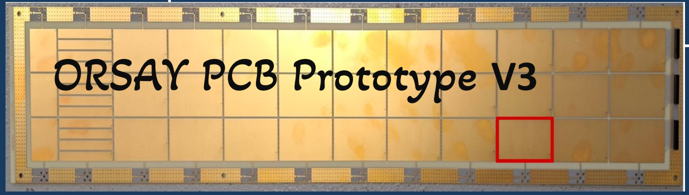


Developments on PCB design and tests



58x44 cm²

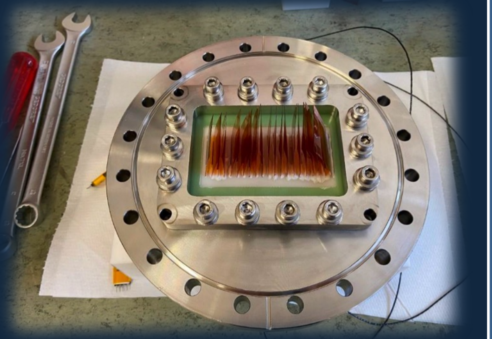




59x9 cm²

Low mass cryostats needed

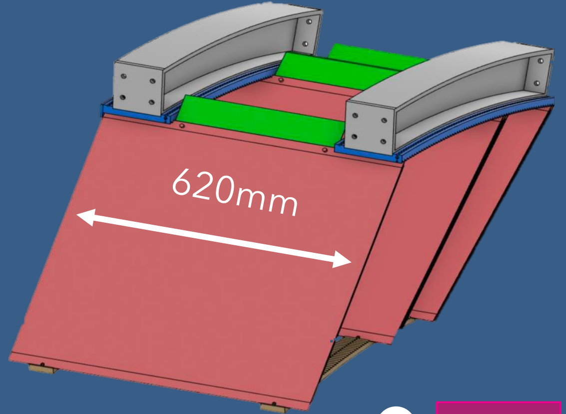
- ✓ R&D carbon fiber including a full carbon composite honeycomb
- ✓ Developping a connectorless feedthrough



3D printed epoxy resine structure with slits for strip cables, glued to the flange

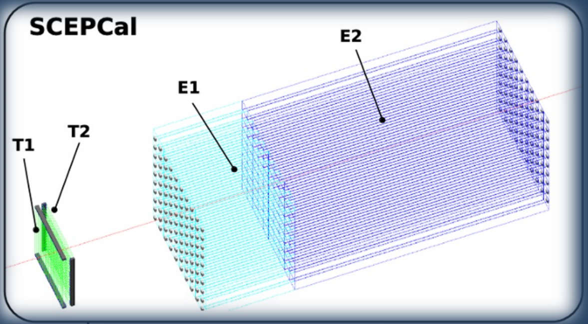
Beam Test Prototype
Foreseen for 2028-29

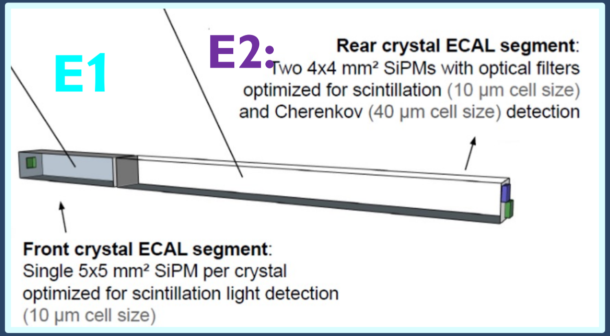
~ 20 % Allegro barrel module



Crystal Calorimeters

SCEPCAL: Segmented Electromagnetic Precision CALorimeter





Dual readout *Scintillator and Cherenkov from the same active medium, disentangle using optical filters*

E1,E2: Dense crystal with dual-readout capabilitities (PBWO4, BFP, BSO)
Precise measurement EM showers

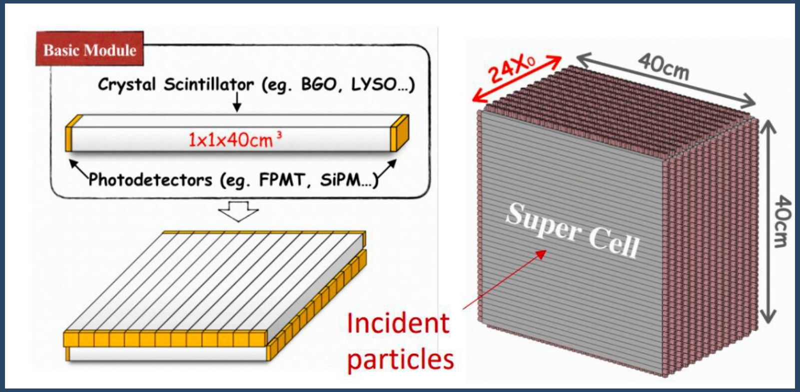
FT1, T2 Fast and bright Scintillator MIP tag 20 ps

For IDEA

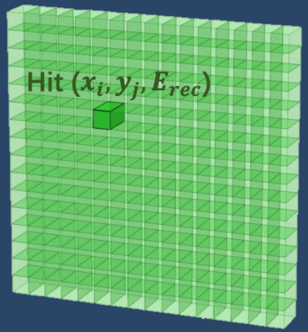
Crystal Bar ECAL

Single readout + FPA

Double-end readout with SiPM (Q, t).



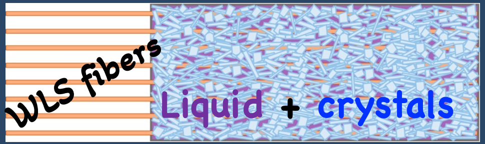
Reconstruction

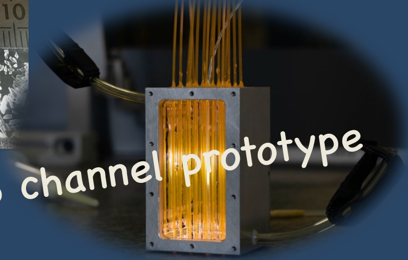


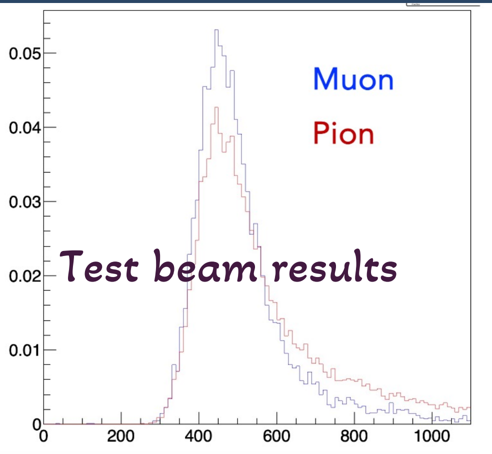
Under development for CEPC

GRAiNITA

Based on grains of inorganic scintillating crystal readout by wave length shifting







ECFA HET Factory study: WG3 Summary

Parallel sessions on 3 ECFA General Workshops + 2 dedicated WG3 :
Vertex and Calorimetry, PID and Photodetectors
(Some other in the pipeline discarded due to bringing forward the European Strategy process)

~78 talks in total covering many R&D topics under development
(Not all included in the today´s talk)

ECFA HET Factory Study WG3 Report will include

1. Experimental conditions
2. Detector requirements (linear vs circular requirements)
3. R&D plans for the next 3-5 years (with inputs from DRDs)
    - Technical challenges
    - Activities targeted at Higgs Factories
    - Goals
    - ….
4. Detector concepts status & plans (inputs from ILD, SiD, CEPC, CLD, IDEA, ALLEGRO) status & plans
    - On simulation, reconstruction, performance studies, optimisation…

Thank you
for your attention