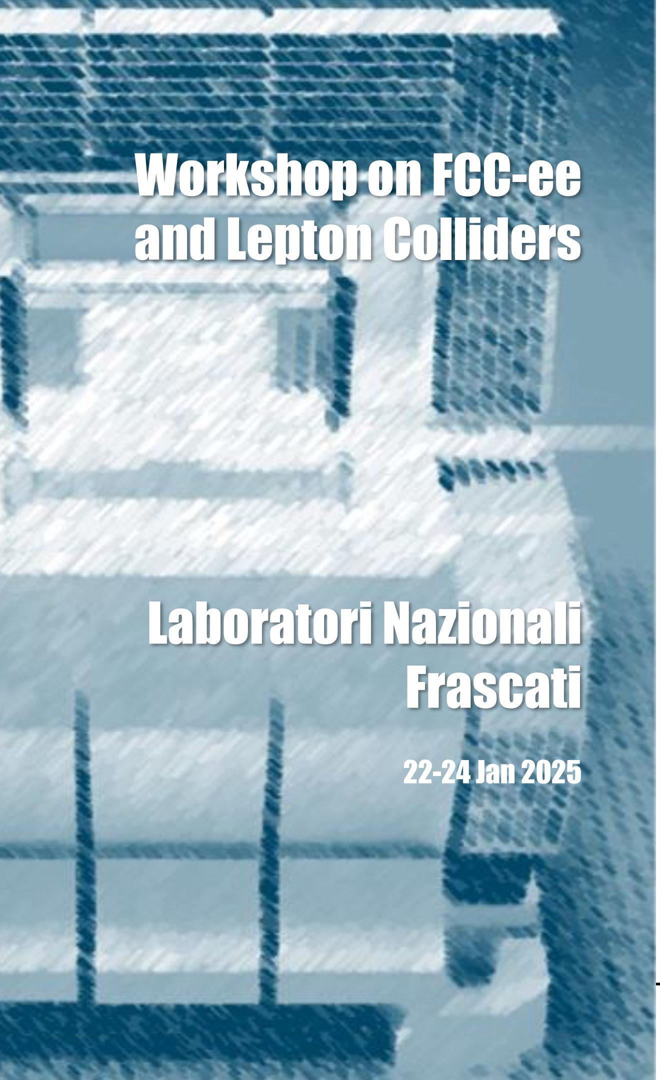
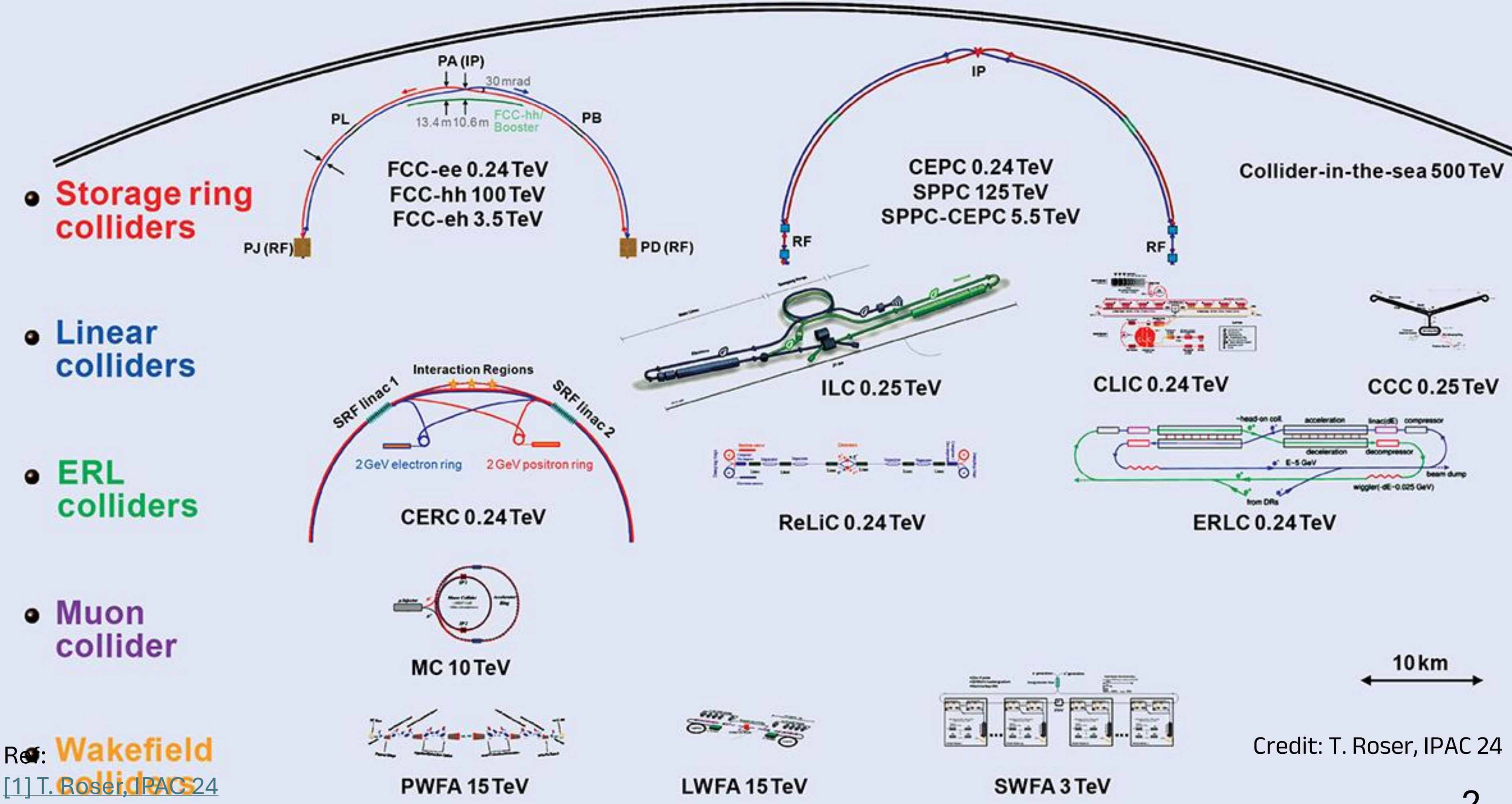


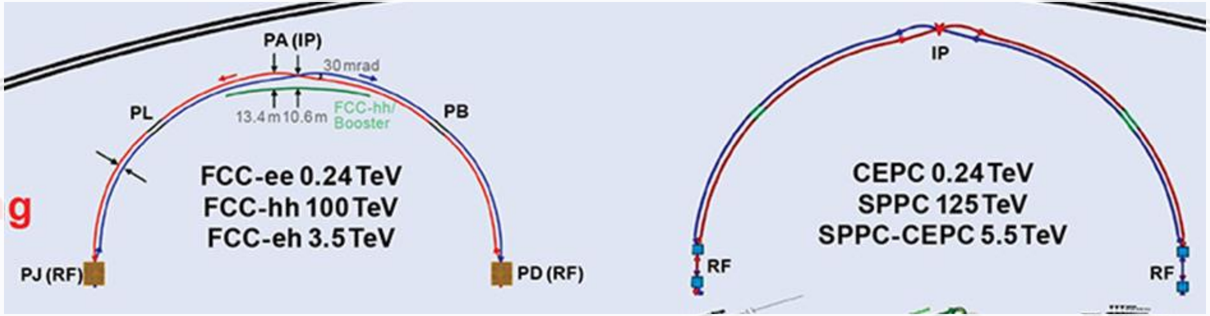
Overview of Future Circular (lepton) Colliders detectors

Nicolò Valle, INFN Pavia



Credit: T. Roser, IPAC 24

Ref:
[1] T. Roser, IPAC 24
[2] CERN Courier

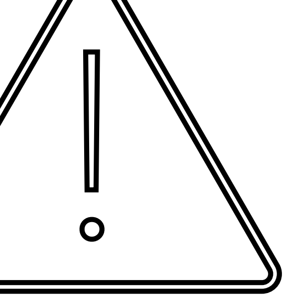


In this presentation:

Challenges at future lepton colliders

Detector requirement and proposed technolgies

Detector concepts for FCC



Future Circular Collider feasibility studies

Speakers: Prof. Iacopo Vivarelli (University of Sussex),

Solid states and gaseous tracking detectors

Speaker: Riccardo Farinelli (INFN Sezione di Bologna)

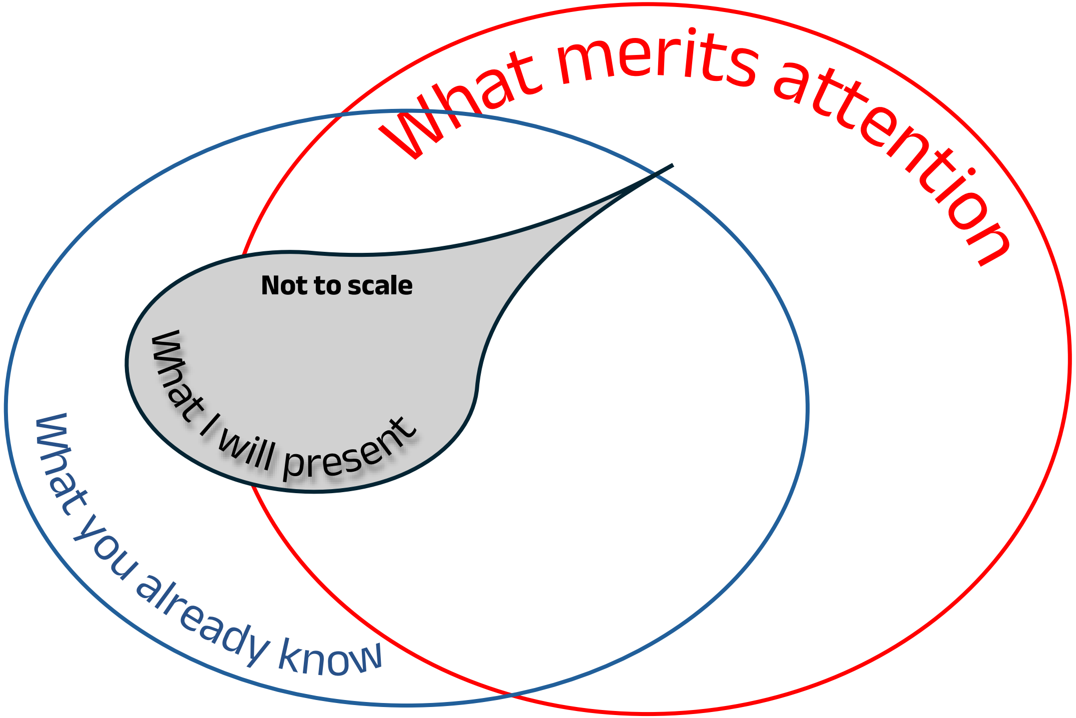
Calorimeters

Speaker: Ivano Sarra (Istituto Nazionale di Fisica Nucleare)

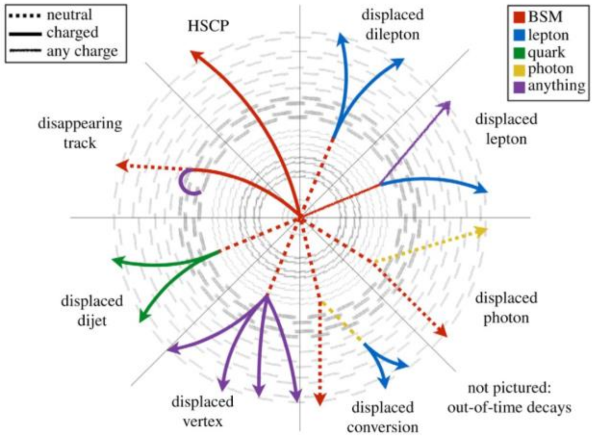
Electronics

Speaker: Stefano Durando (Istituto Nazionale di Fisica Nucleare)

+ MDI, Physics talks



Challenging opportunities

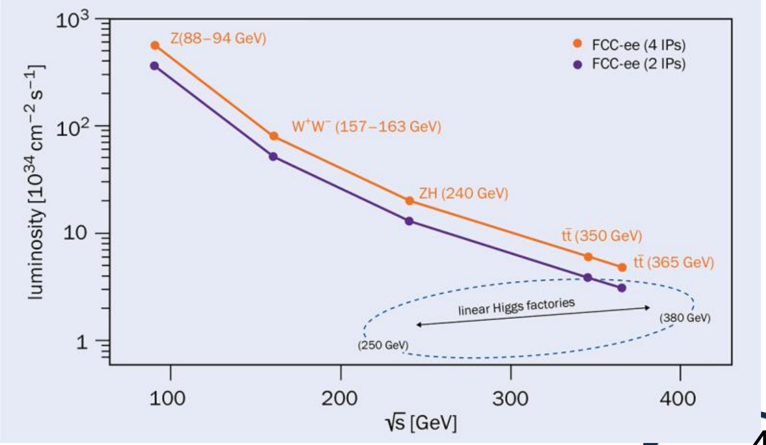


Pushing the intensity frontier at multiple energies:

EW/Higgs/top SM parameters

Tera-Z datasets: unique flavour opportunities

BSM sensitivity to feebly interacting particles



Detector requirements:

- ❑ Working in a large dynamic range, in energy and luminosity
- ❑ Withstanding the machine-induced limitations

Challenging technology

Typical values

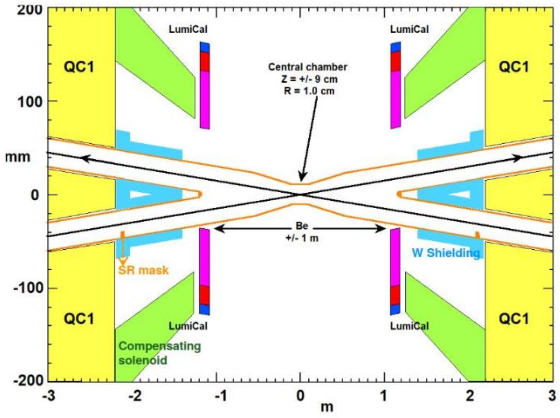
Achieving unprecedented luminosities and exceptional particle reconstruction demands innovative accelerator and detector technologies

Parameter	FCC-ee (Z)	FCC-ee (H)	FCC-ee (top)	CEPC (Z)	CEPC (H)	CEPC (top)
√s [GeV]	91.2	240	365	91.0	240	360
Luminosity/IP [10^34/cm^2/s]	182	7.3	1.33	192	8.3	0.8
Bunches/beam	10000	248	36	19918	415	58
Bunch separation [ns]	30	1200	8400	15	385	2640
Beam size at IP σx/σy [nm]	8/34	14/36	39/69	6/35	15/36	39/113
Crossing angle [mrad]	30	30	30	33	33	33

Detector concepts studied by linear colliders

Must adapt to meet the greater challenges of circular colliders

- Smaller bunch distances, more parasitic interactions
- Continuous beams, no power pulsing possible
- Radiation background from squeezed beams
- Synchrotron radiation near the interaction points
- Complex machine-detector interface
- Fast detector / triggerless design to cope with $O(10^5)$ Hz physics rates



Physics at e^+e^-

Higgs factory

B, D, τ factory

QCD-EWK precision

BSM

Observables (partial)

Higgs mass, width…

ZH xsec ↔ self coupling

$\sin^2\theta_W$

FCNCs

b-, c- tagging

τ mass, lifetime, …

α_s

Z lineshape

W mass

HNLs, APLs, …

Delayed signatures

Detectors

Momentum resolution, low material budg.

Vertex resolution

PID capabilities

Flavour tagging

Photon resolution, π^0 reconstruction

Jet energy/angular resolution

Particle Flow

Precise alignment down to O(10 μm)

Luminosity measurement, $10^{-4/-5}$ level

Large decay volumes

High segmentation

Displacement reconstruction

Timing

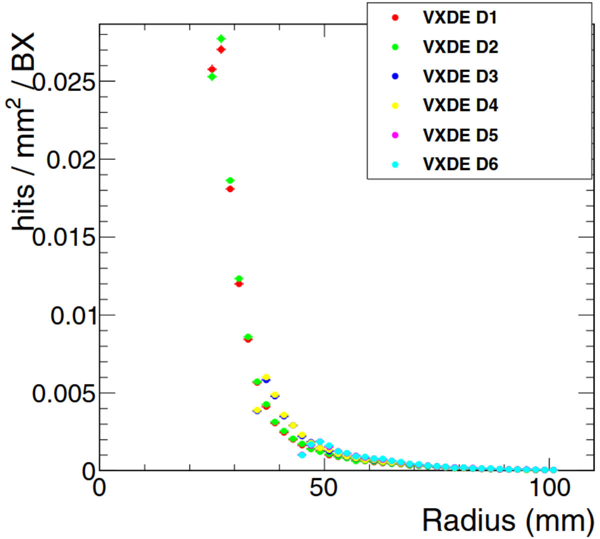
Triggerless

Ref:
[1] M.Selvaggi, FCC Physics Week

Vertexing and tracking

Silicon detectors

Gas detectors (drift chambers, straw tubes, TPC)

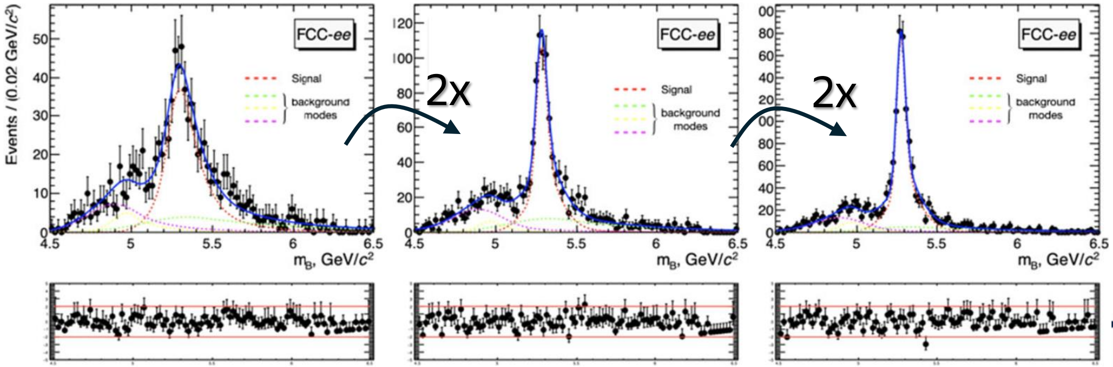


Desirable

$$\sigma_d = a \oplus \frac{b}{p\,(\sin\theta)^{3/2}}$$

- O(5 μm) of single hit resolution
- σ_p/p < few permille for p ~ 100 GeV
- Material budget $0.1\%X_0$/layer
- Large volume (limited B-field)
- Coping with O(250 MHz/cm^2) background

$B \rightarrow K^*\tau\tau$ with ILD-like performances



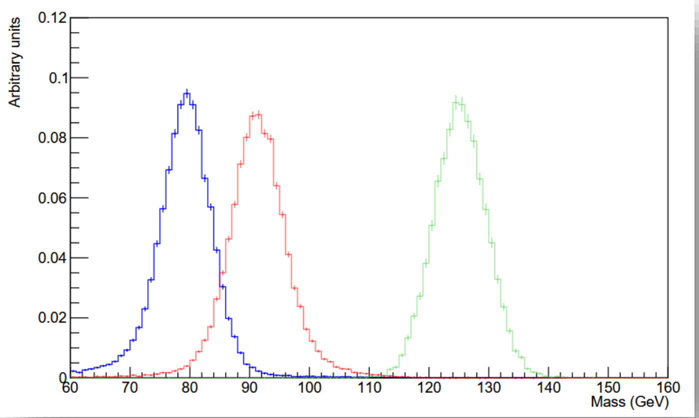
Ref:

[1] Tracking and Vertex detectors at FCCee

[2] A.Andreazza, ICHEP24

Calorimetry

W/Z/H → jj events in a dual-readout fibre calorimeter

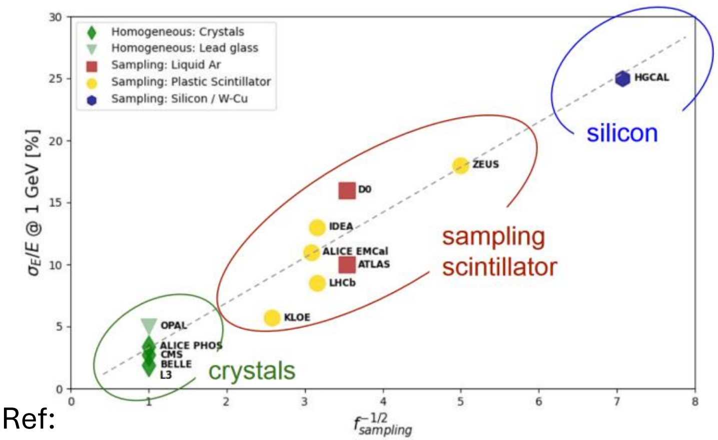


EM shower measurement not necessarily in a dedicated ECAL

Several promising candidates of technologies

High granularity, **dual-readout**, **tracking enhancement** approach as cornerstones of many detector concepts

A sample of existing and future calorimeters



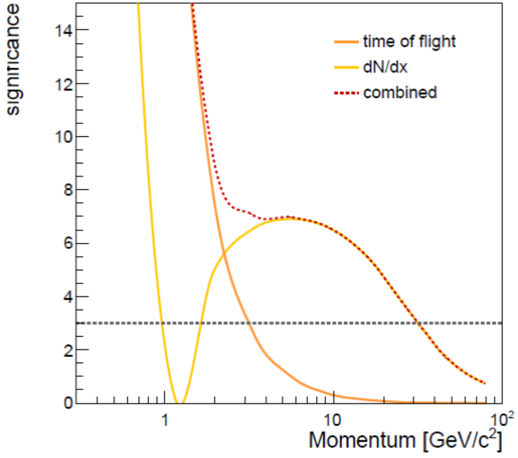
Detector technology (ECAL & HCAL)	E.m. energy res. stochastic term	E.m. energy res. constant term	ECAL & HCAL had. energy resolution (stoch. term for single had.)	ECAL & HCAL had. energy resolution (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 %	1 %	45 – 50 %	≈ 6 %
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 %	< 1 %	≈ 40 %	≈ 6 %
Dual-readout Fibre calorimeter	11 %	< 1 %	≈ 30 %	4 – 5 %
Hybrid crystal and Dual-readout calorimeter	3 %	< 1 %	≈ 26 %	5 – 6 %

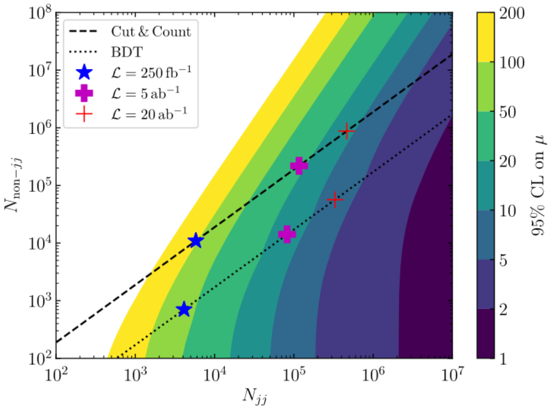
Ref:
[1] Calorimetry at FCCee
[2] M. Lucchini, Higgs/EW factory workshop

PID and TOF

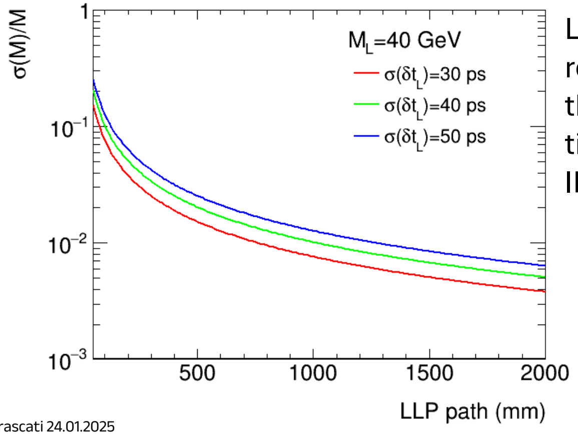
The charged particles PID can be provided by complementary information:

- [gas] dE/dx
- [gas] Cluster counting
- [silicon] time-of-flight
- RICH





Desirable: 3σ K/π separation up to 30 GeV, to fully utilize the flavour physics capabilities at the collider



LLP mass resolution through timing with IDEA

TOF to complement PID at ~ 1 GeV, and to measure mass and lifetime of (new) particles

Ref:
[1] A.Coccaro, Corfu Future Acc 2024
[2] PID at FCCee
[3] Exotic particles timing-based mass measurement

Muons

Most of the detectors rely on instrumenting the return yoke outside the coil

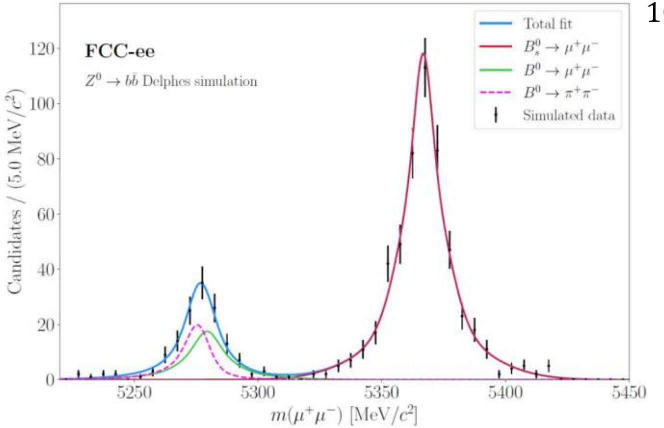
Scintillator bars

RPCs

μRWELLs

… drift tubes, RPC, micromegas,..

$B \rightarrow \mu\mu$ with an assumption of a π/μ misidentification rate of 2×10^{-5}

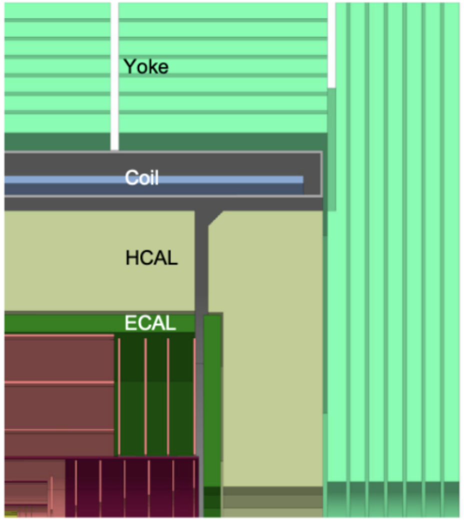


- High efficiency muon identification (momentum measured by tracking system)
- Serving as tail-catcher for the hadron showers not fully contained in the calorimeter
- Standalone momentum measurement for long-lived particles

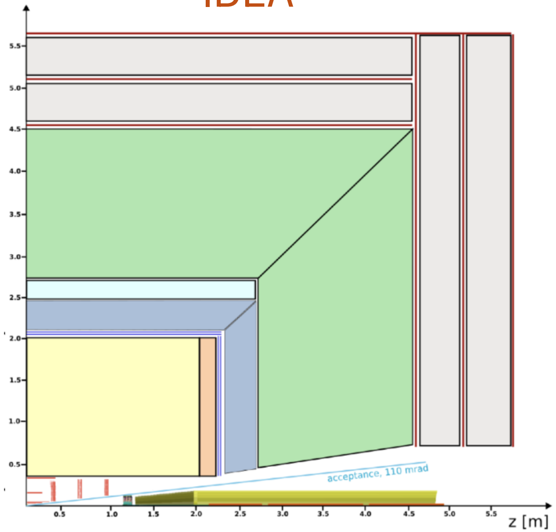
Ref:
[1] Heavy quarks at FCCee
[2] J.Zhu, FCC Week 2024

Future Circular ee Collider(s) detectors

CLD / ILD'



IDEA

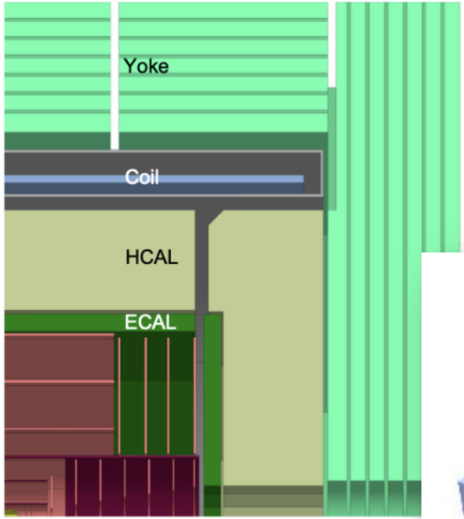


ALLEGRO

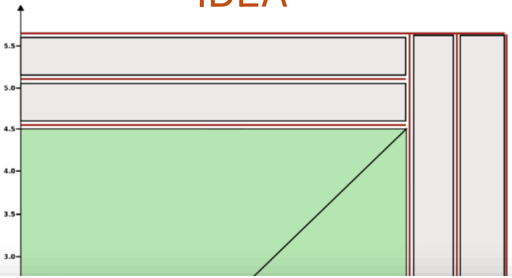
Ref:
[1] FCC CDR

Future Circular ee Collider(s) detectors

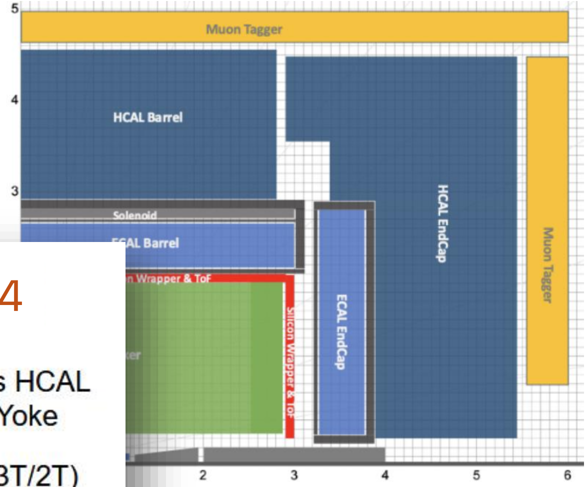
CLD / ILD'



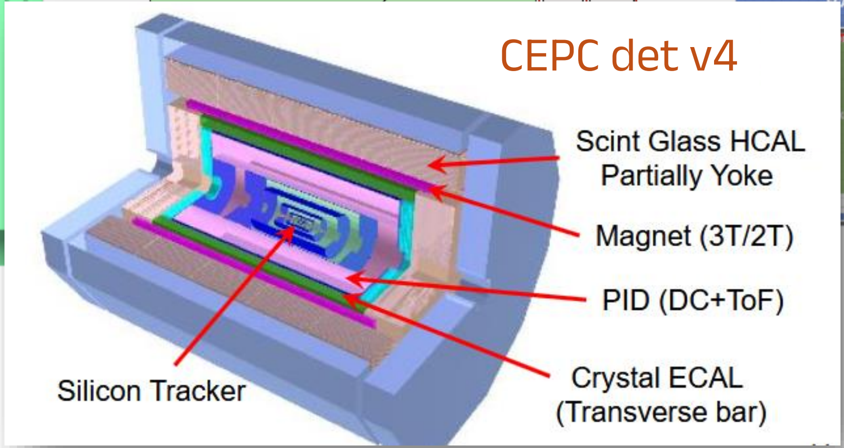
IDEA



ALLEGRO



CEPC det v4



Ref:
[[1] J.Wang, FCC Workshop]

CLD (the CLIC-like Detector)

Evolving from **ILD, SiD**

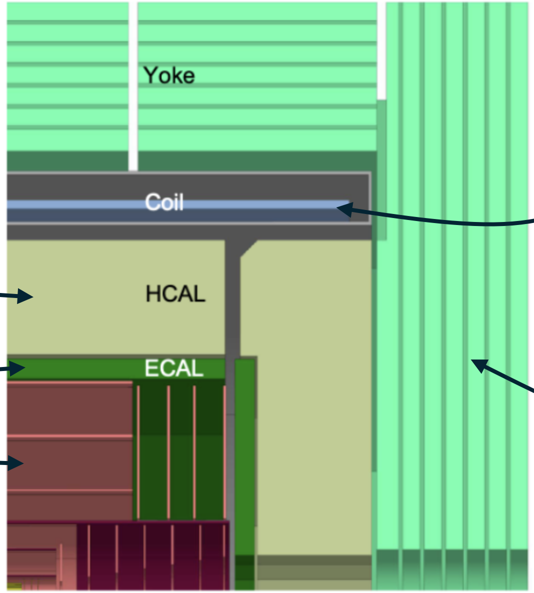
General purpose concept for **Particle Flow** reconstruction

Steel-scintillator Hcal

Silicon-Tungsten Ecal

Silicon Tracker, strips

Vertex pixel detector



2T superconducting solenoid

Iron yoke instrumented for muons (RPCs)

Ref:

[1] B.Pasquier, FCC Week 2022

[2] CLD Detector Concept

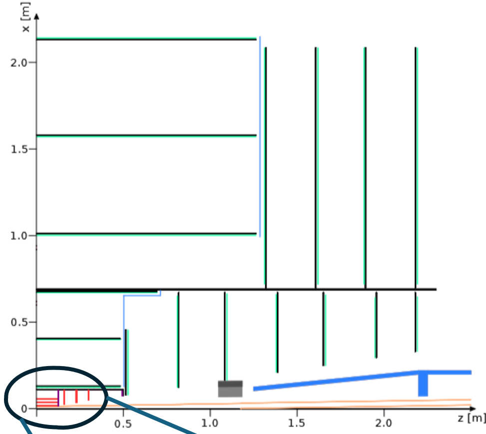
CLD (the **CL**IC-like **D**etector)

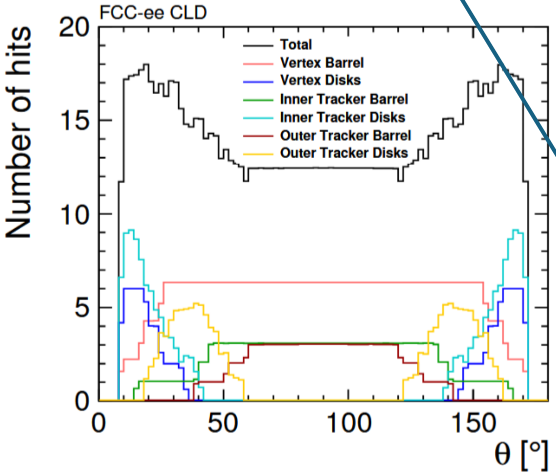
Vertex detector:

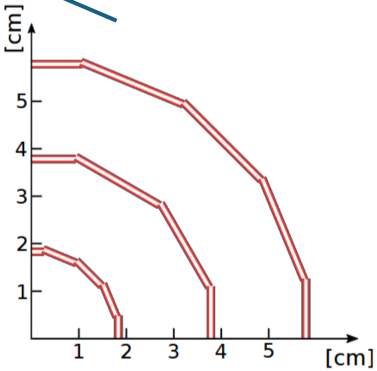
- 25 x 25 μm pixels, 3 μm single point resolution
- 0.3% X_0 per layer, 50 μm silicon thickness
- First layer position: 17.5 mm

Silicon tracking:

- 6 barrel layers + (7+4) endcaps
- 1.1 to 2.2% X_0 / layer (200 μm thick)
- 50 x 300 μm cell size







Pro/cons of using a full silicon tracker:

Robust technology
High single point res
Tune to sustain high particle rate
Large material budget
No (much) space for PID

Ref:

[1] B.Pasquier, FCC Week 2022
[2] CLD Detector Concept

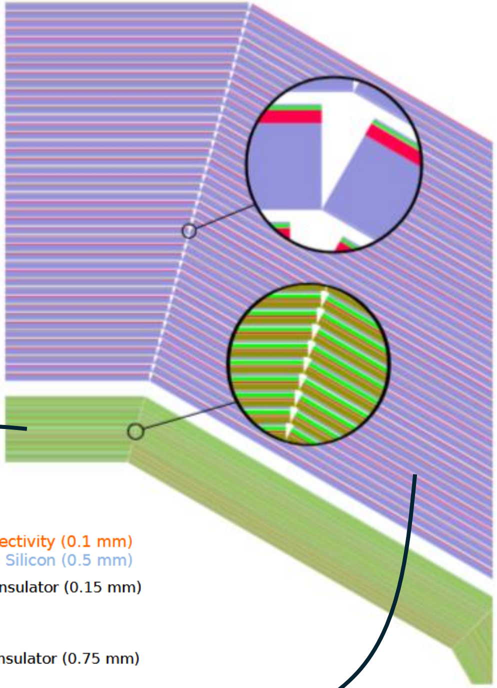
CLD (the CLIC-like Detector)

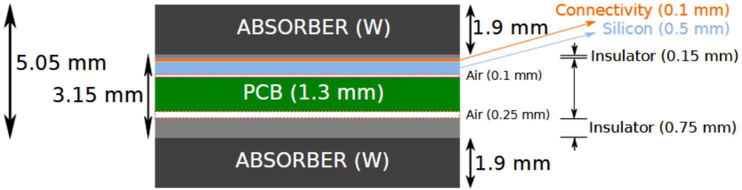
key word:
Granularity!

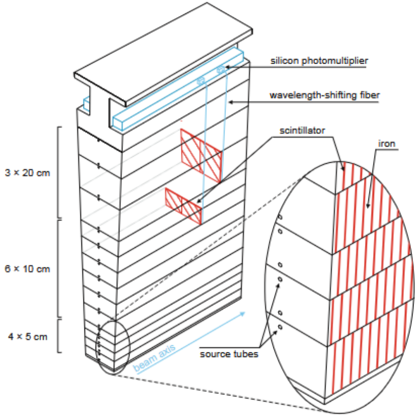
CALICE imaging calorimeters

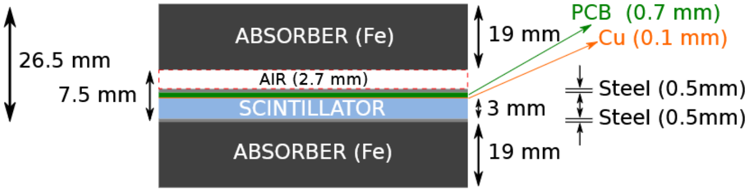
ECAL: 40 layers of 1.9 mm W plates (22 X_0) + 0.5 mm thick silicon sensors with 5x5 mm2 granularity

HCAL: 44 layers, 19 mm steel absorber + 3 mm thick scintillator tiles with 3x3 cm^2 granularity







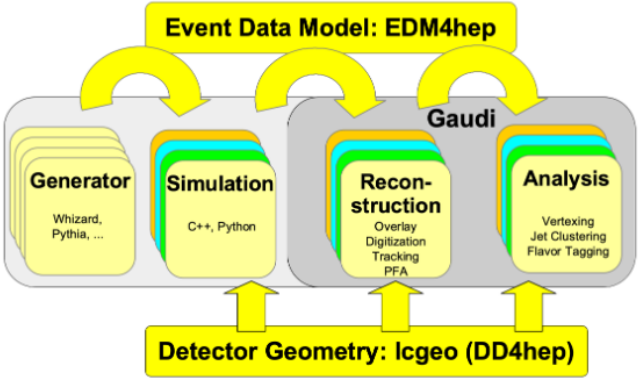


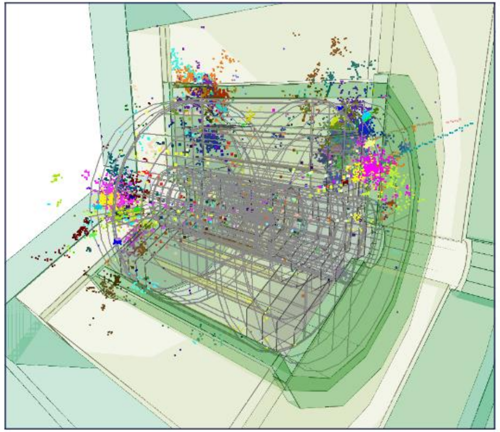
Ref:
[1] B.Pasquier, FCC Week 2022
[2] CLD Detector Concept

CLD (the **CL**IC-like **D**etector)

Large reconstruction code developed over >15 years for (linear) lepton colliders

Complete full simulation and reconstruction software chain available in **Key4hep**

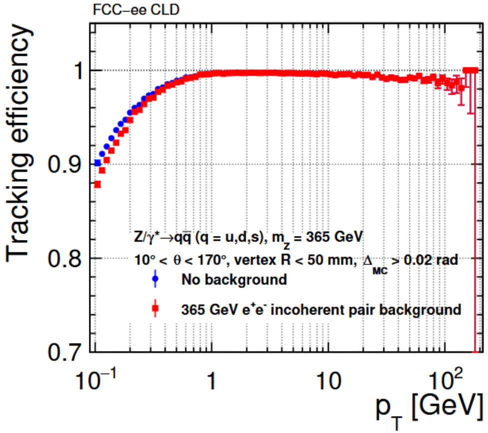


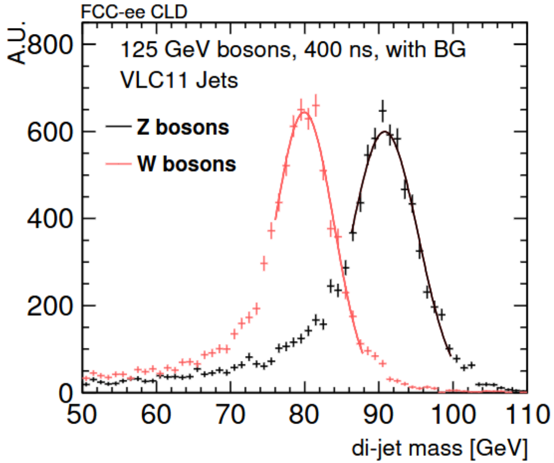


Event display

Z/W separation power

Tracking efficiency in jets





Ref:

[1] F.Gaede, FCC Physics Workshop 2024

[2] F.Gaede, FCC Week 2024

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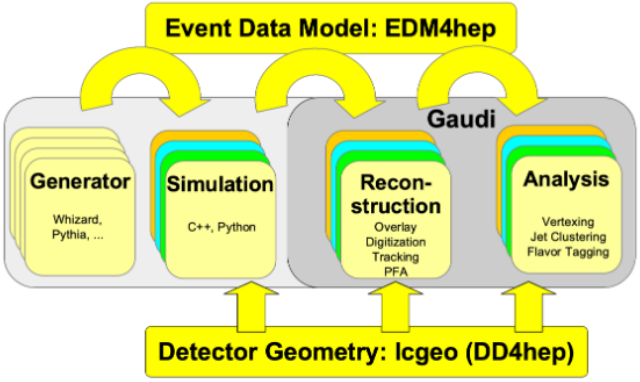
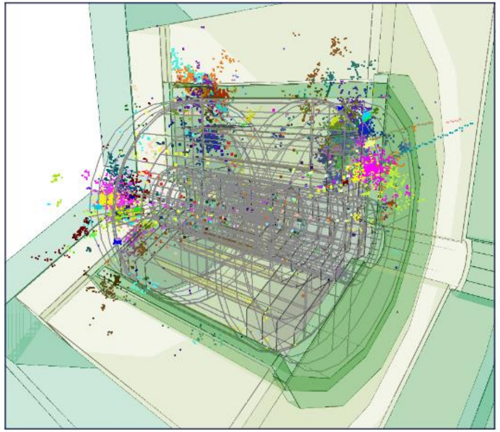
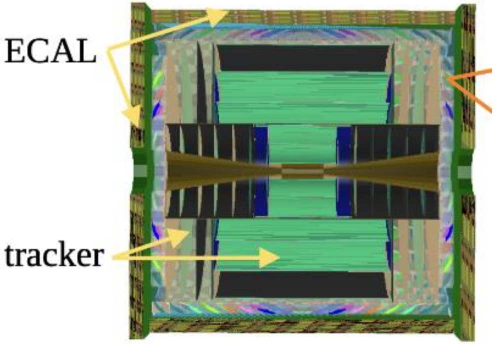
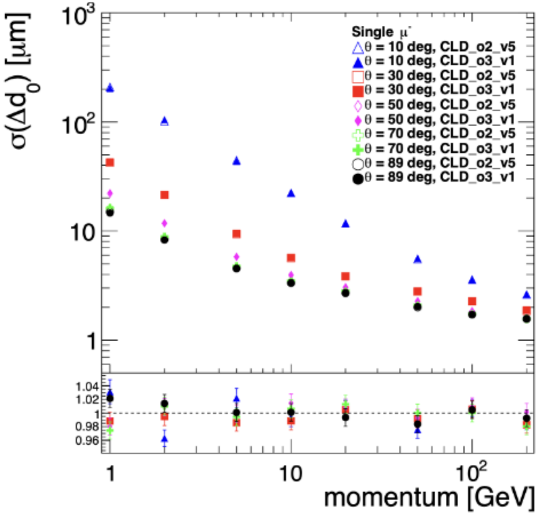




Variants with **RICH** (“ARC”) detector and reduced tracking volume, or with LAr calo



CLD option 3



Ref:
[1] F.Gaede, FCC Physics Workshop 2024
[2] F.Gaede, FCC Week 2024

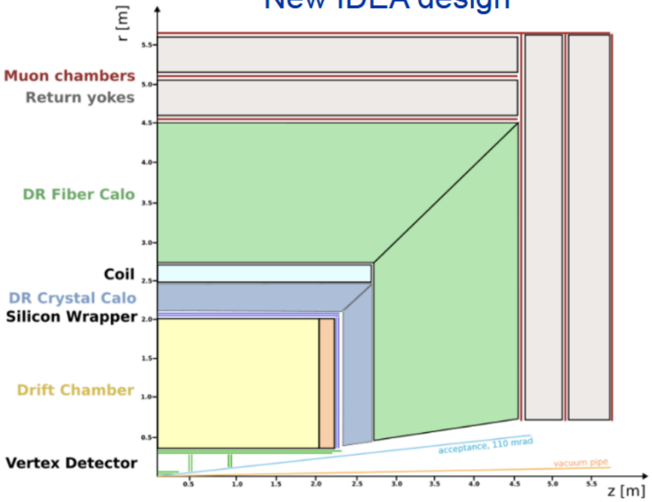
Innovative Detector for E$^+$e$^-$ Accelerator

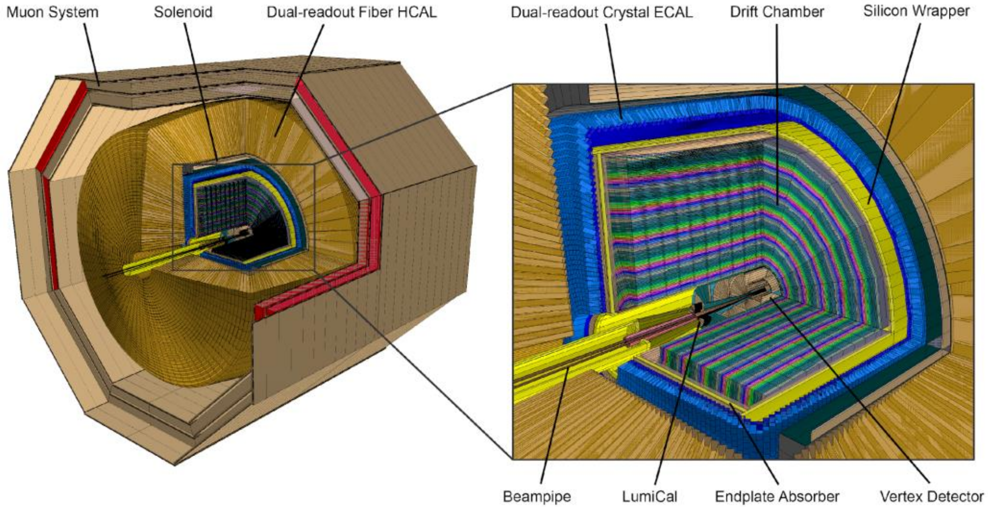
Sophisticated tracker

Dual-readout calorimetry

Recently introduced design **with crystal-EM calo** within the solenoid + DR fibre calo outside the coil

New IDEA design





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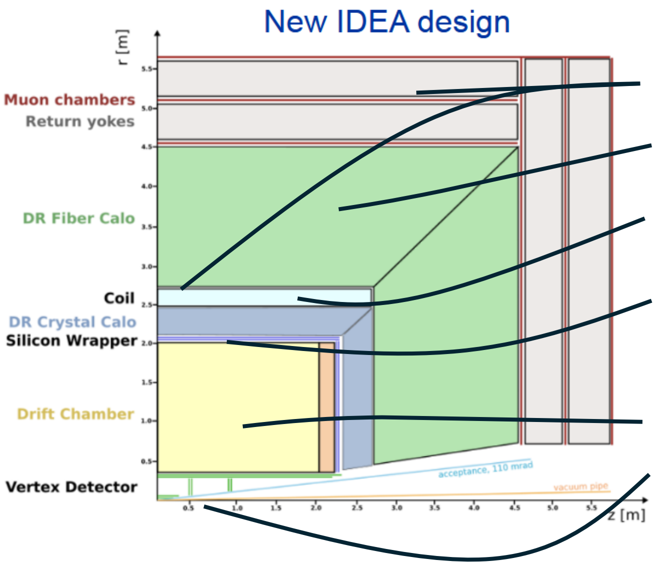


mu-RWELL for (preshower and) muon system

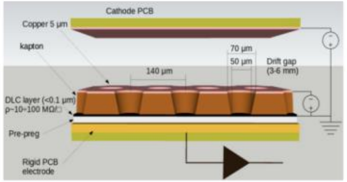
Capillary tubes hadronic calo

Crystal calo

Outer wrapper with silicon strip detectors (ATLASPix3, LGAD under consideration). < 100 ps

Drift chambers

CMOS pixels



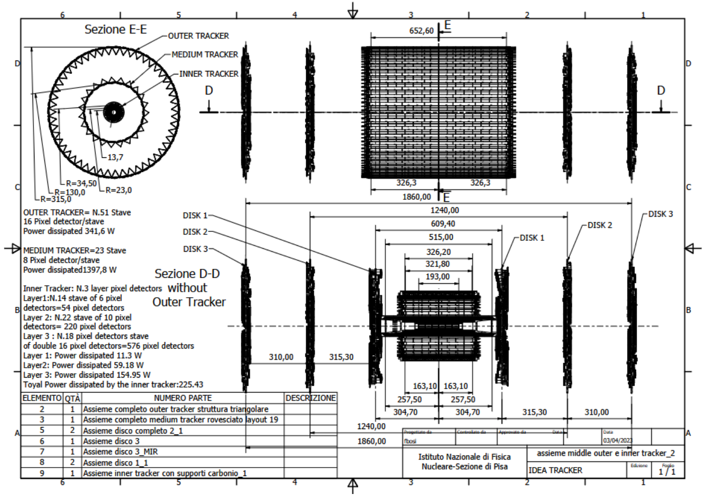
Ref:

[1] L.Pezzotti, FCC Physics Workshop 2025

Innovative Detector for E$^+$e$^-$ Accelerator

Vertex detector

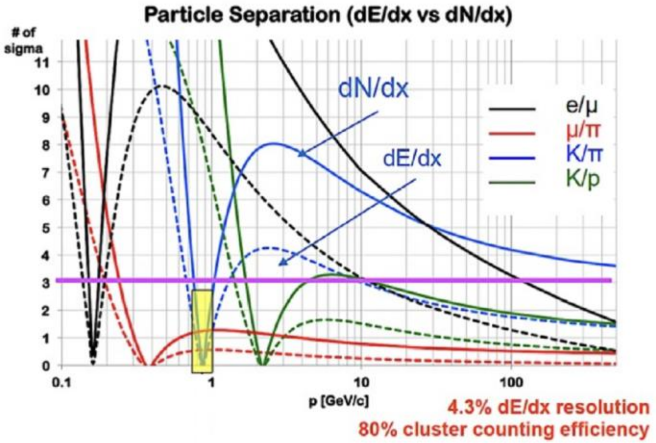
CMOS sensors. Inner layers based on ARCADIA with 25x25 μm pixels size + Outer layers based on ATLASPix3 sensors (50x150 μm) → 0.25% X_0

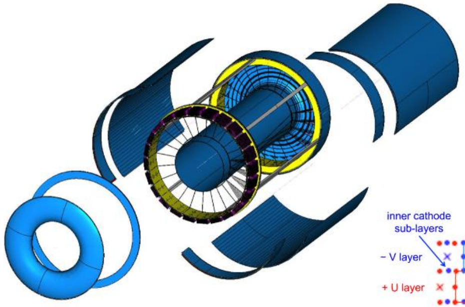


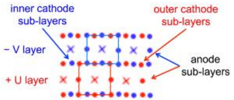
Drift chambers

Large, light and fast, to cope with short bunch spacing and low (2T) B-field.

Excellent PID capabilities with cluster counting (dN/dx)







Ref:

[1] L.Pezzotti, FCC Physics Workshop 2025

[2] PID with IDEA drift chambers

Innovative Detector for E$^+$e$^-$ Accelerator

Targeting $30\%/\sqrt{E}$ hadronic resolution & $\sim 3\%/\sqrt{E}$ em resolution

Fiber-based dual readout (DR) calorimeter + Crystal calorimeter

Reduce intrinsic signals fluctuations by measuring f_{em} of hadro showers event by event

SiPM single fibre readout → millimetric sampling

Excellent em energy resolution, without spoiling DR

Solve the channelling effect for em-showers entering the fibre-calorimeter

Help identification of γ's in jets

Ref:
[1] L.Pezzotti, FCC Physics Workshop 2025

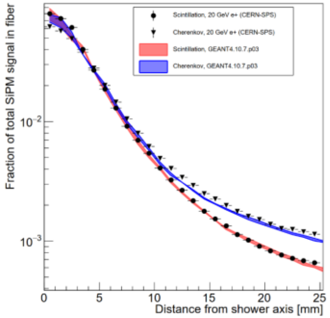
Innovative Detector for E^+e^- Accelerator

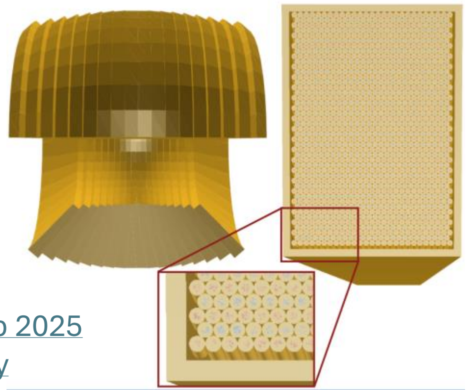
Targeting $30\%/\sqrt{E}$ hadronic resolution & $\sim 3\%/\sqrt{E}$ em resolution

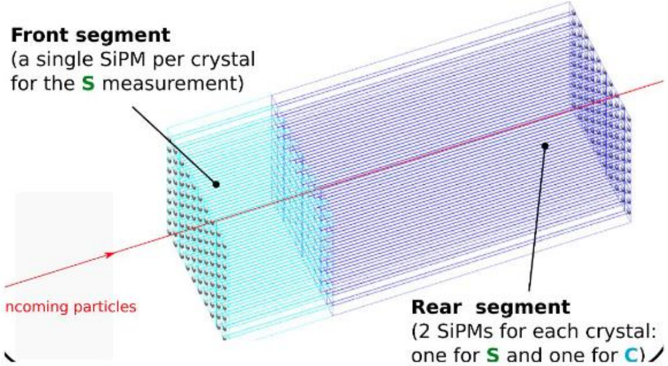
Fiber-based dual readout (DR) calorimeter + Crystal calorimeter

New construction technique housing optical-fibres into capillary-tubes

Geant4 Monte-Carlo recently validated on test-beam data







R&D on technology and proof-of-principle

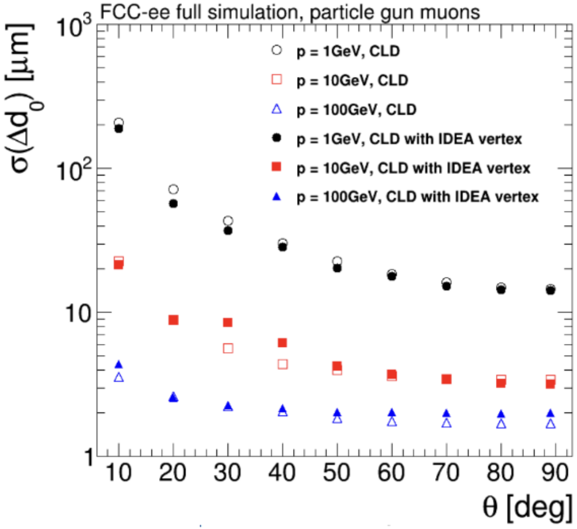
EM crystal section with dual readout capabilities

PBWO4 20 cm (22 X_0) crystals instrumented with SiPMs ↔ available in full sim

Ref:
[1] L.Pezzotti, FCC Physics Workshop 2025
[2] A.Pareti, dual-readout calorimetry
[3] M.Lucchini, crystal calorimetry

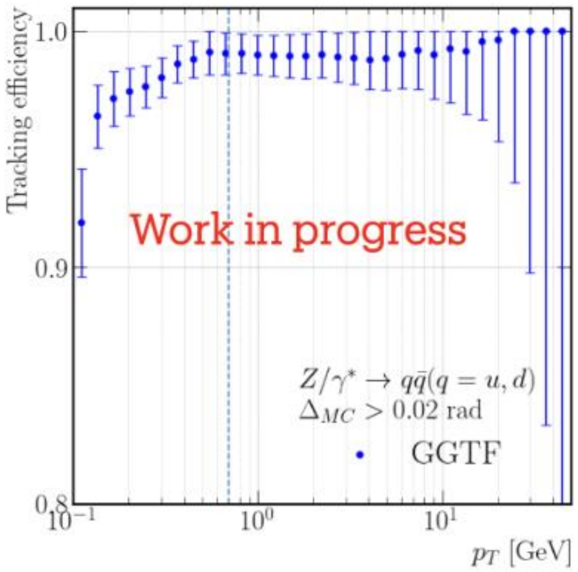
Innovative Detector for E$^+$e$^-$ Accelerator

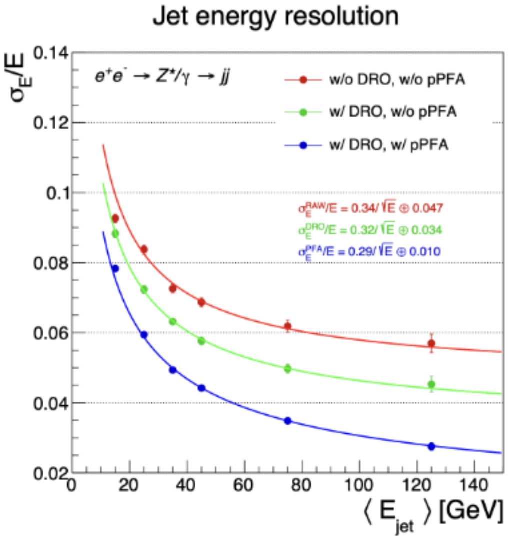
Designs with and without crystal calo are available in **full sim**



Combining the IDEA vertex with the CLD tracker and reconstruction

ML-based end-to-end method for track finding





Particle flow + hybrid segmented calorimetry

Ref:

[1] L.Pezzotti, FCC Physics Workshop 2025

[2] Particle flow with hybrid calo

ALLEGRO (A Lepton-Lepton collider Experiment with Granular Read-Out)

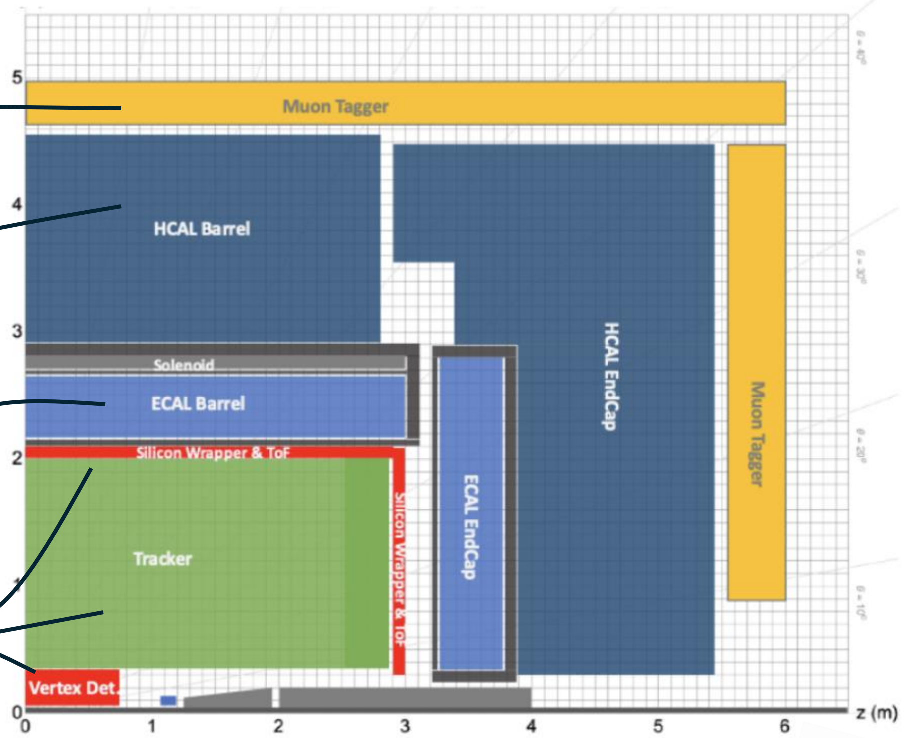
Detector concept centred around a high-granularity noble-liquid ECAL

Light-weight, simple, muon tagger (Drift tubes and scintillating strips / RPCs / MPGDs / Micromegas)

High granularity Steel/Scintillator TileCal HCAL, as return yoke

ECAL: LAr or LKr as active medium, Pb or W as absorber material.
High granularity achieved using multi-layer PCBs as readout electrodes.

IDEA like ultra-light tracking system with PID capabilities

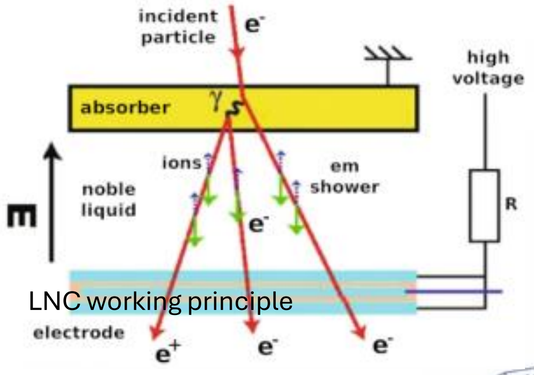


Ref:
[1] B.Fracois, FCC Week 2024
[2] ALLEGRO and NLC

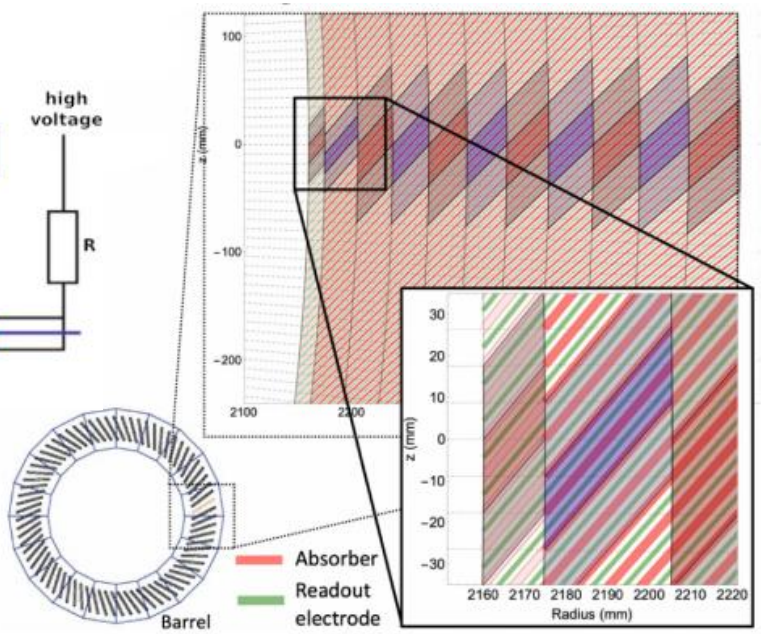
ALLEGRO (A Lepton-Lepton collider Experiment with Granular Read-Out)

Noble liquid calorimetry (NLC) successfully used in several major experiments:

- energy resolution
- timing properties
- ➢ finely sample ionizing radiation using liquified noble gases



LNC working principle



The design is being optimised.

ECAL absorber already exists and tested in liquid nitrogen bath.

Ref:

[1] ALLEGRO and NLC

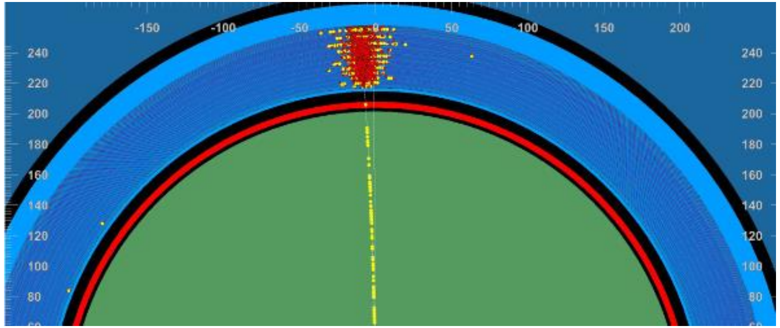
[2] Z.Wu, R&D LNC

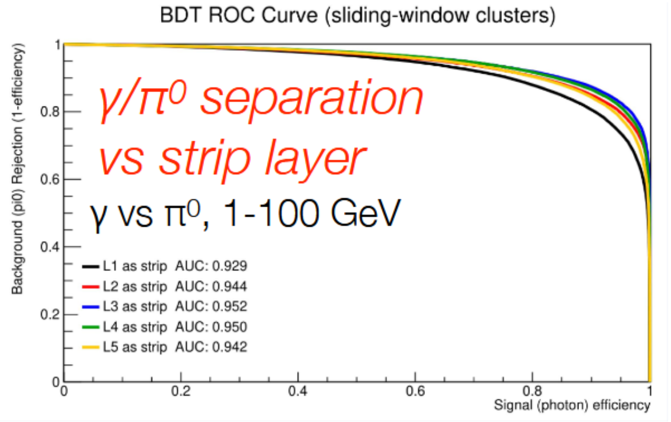
ALLEGRO (A Lepton-Lepton collider Experiment with Granular Read-Out)

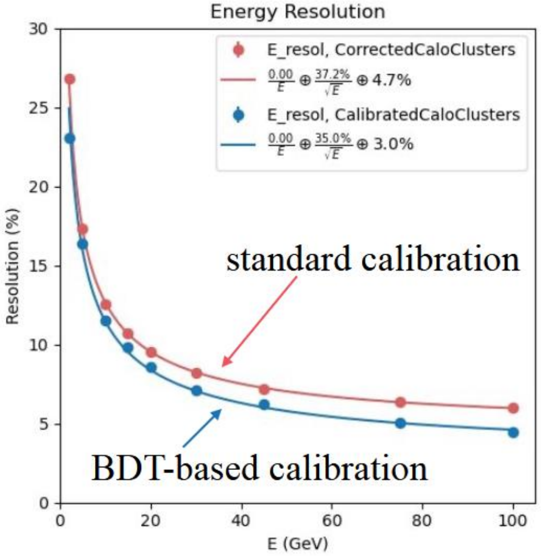
Full-sim

Full implementation of “reference" detector model in DD4hep/key4hep recently completed

Noble-liquid ECAL: baseline with straight inclined Pb-Steel absorbers







Ref:

[1] E.Warnes, ICHEP 2024

SUMMARY

Detector technologies for future circular e+e- colliders are evolving to meet challenges posed by complex machine requirements and reach physics programmes.

The exploration of PID capabilities and high granularity detectors supports advanced flavour physics and sensitivity to feebly interacting particles.

Collaborative advancements in simulation and full-scale testing frameworks are critical for refining detector technologies.

The European Strategy update is coming soon; many inputs from latest feasibility studies.