NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

Detector concepts for future e^+e^- colliders

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Future Collider Seminar Series
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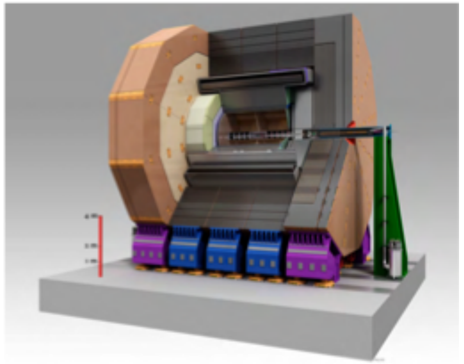
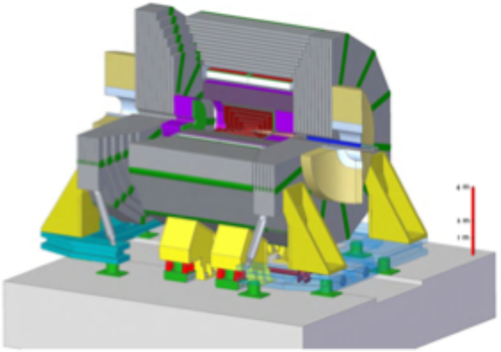
Gratefully acknowleging colleagues from whom material has been borrowed and not in all cases properly referenced

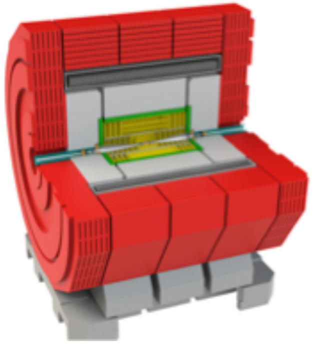
High-energy e^+e^- Collider Detector Concepts

Linear – 1 detector at the time, 2 in ”push-pull”





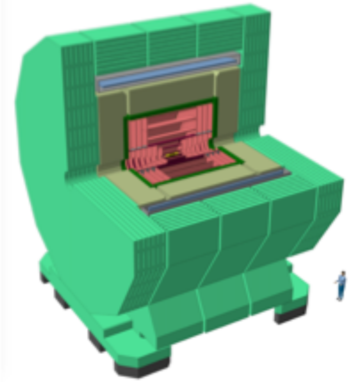
ILC: ILD and **SiD**
√s: 250 – 500 GeV (1 TeV)

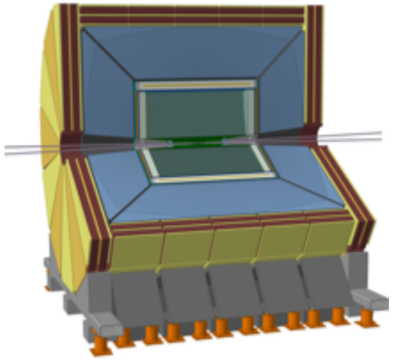


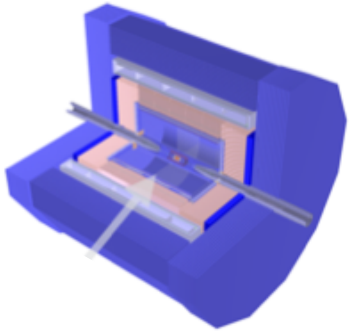
CLIC: CLICdet
√s: 380 GeV, 1.5 TeV, 3 TeV

Strong solenoidal fields: 3.5 – 4 Tesla

Circular – up to 4 detectors







FCC-ee: CLD, IDEA and **Lar-based concept**
CEPC: Baseline Detector, IDEA, …
√s: 90 - 365 GeV

Lower solenoidal fields: 2 Tesla
Beams have to survive crossing of field at 15 mrad angle

e^+e^- collider beam parameters

Linear

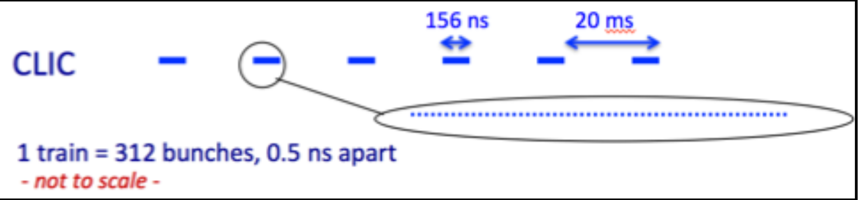
ILC | **CLIC**

Parameter	ILC250	ILC500	CLIC380	CLIC1500	CLIC3000
√s [GeV]	250	500	380	1500	3000
Luminosity L ($10^{34}cm^{-2}sec^{-1}$)	**1.35**	**1.8**	**1.5**	**3.7**	**5.9**
L > 99% of √s ($10^{34}cm^{-2}sec^{-1}$)	1.0	1.0	0.9	1.4	2.0
Repetition frequency (Hz)	5	5	50	50	50
Bunch separation (ns)	554	554	0.5	0.5	0.5
Number of bunches per train	1312	1312	352	312	312
Beam size at IP σ_x/σ_y (nm)	515/7.7	474/5.9	150/2.9	~60/1.5	~40/1
Crossing angle [mrad]	14	14	20	20	20

Very small beams
⇒ beamstrahlung

Very small bunch separation at CLIC drives timing requirements for detector

Very low duty cycle at ILC/CLIC allows for:
- **Triggerless readout**
- **Power pulsing**



Circular

FCC-ee (similar for CEPC)

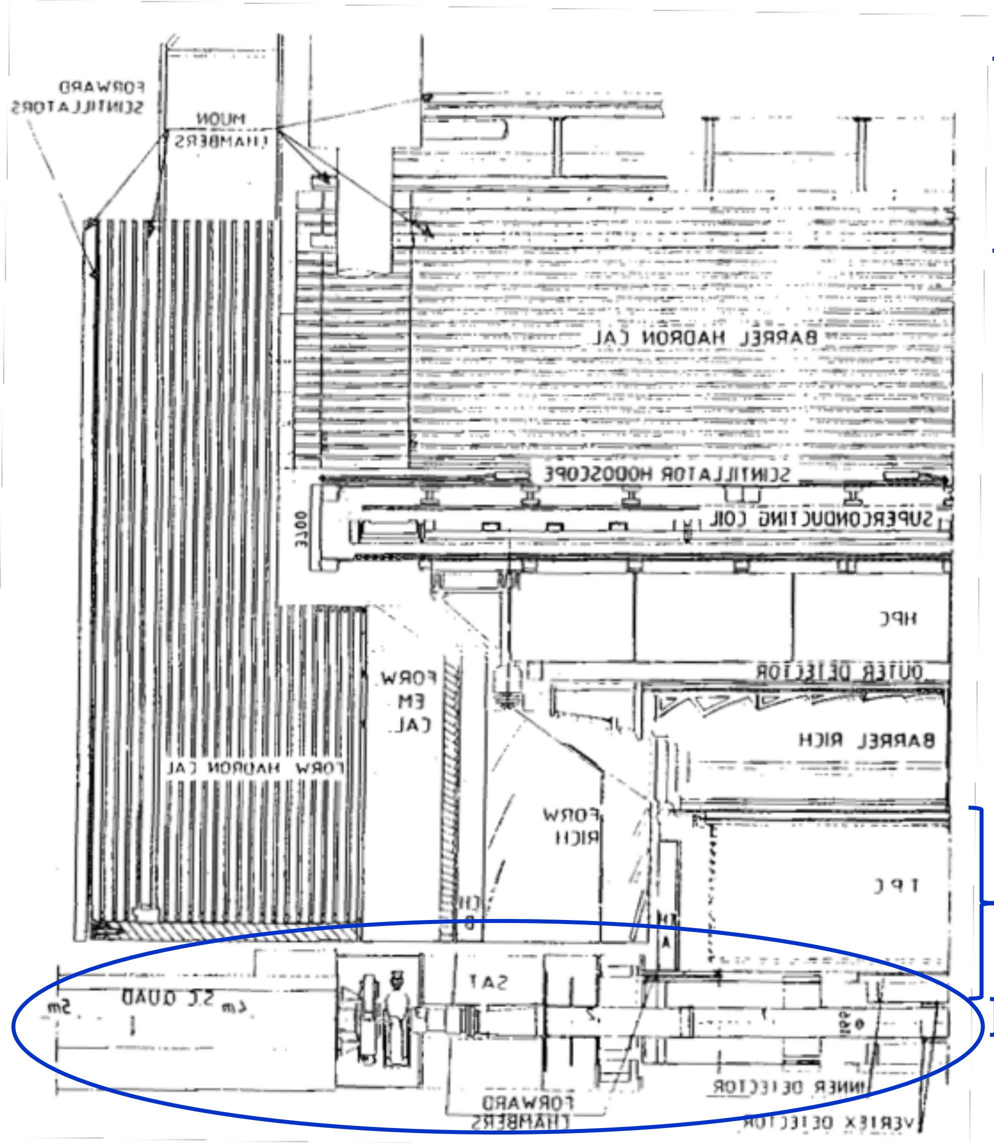
	Z	WW	Higgs	ttbar
√s [GeV]	**91.2**	**80**	**240**	**365**
Luminosity / IP ($10^{34}cm^{-2}s^{-1}$) [4IP]	**182**	**19.4**	**7.3**	**1.33**
no. of bunches / beam	15880	880	248	40
Bunch separation (ns)	20	300	1000	6000
Beam size at IP σ_x/σ_y (μm/nm)	8/34	21/66	14/36	39/69
Crossing angle [mrad]	30			

Beam transverse polarisation
=> beam energy can be measured to very high accuracy (~50 keV, 1ppm)

At Z-peak, very high luminosities and **very high e^+e^- cross section (40 nb)**
- ⇒ **Statistical accuracies at 10^{-6} -10^{-4} level** ⇒ **drives detector performance requirements**
- ⇒ **Small systematic errors required** to match
- ⇒ This also drives requirement on **data rates** (physics rates ~100 kHz)
- ⇒ Triggerless (streaming) readout likely possible (?)

Beam-induced background, from beamstrahlung + synchrotron radiation
- Most significant at 365 GeV
- Well mitigated through MDI design

A e$^+$e$^-$ Detector – DELPHI @ LEP (1989 – 2000)



Muon system

HCAL

Coil

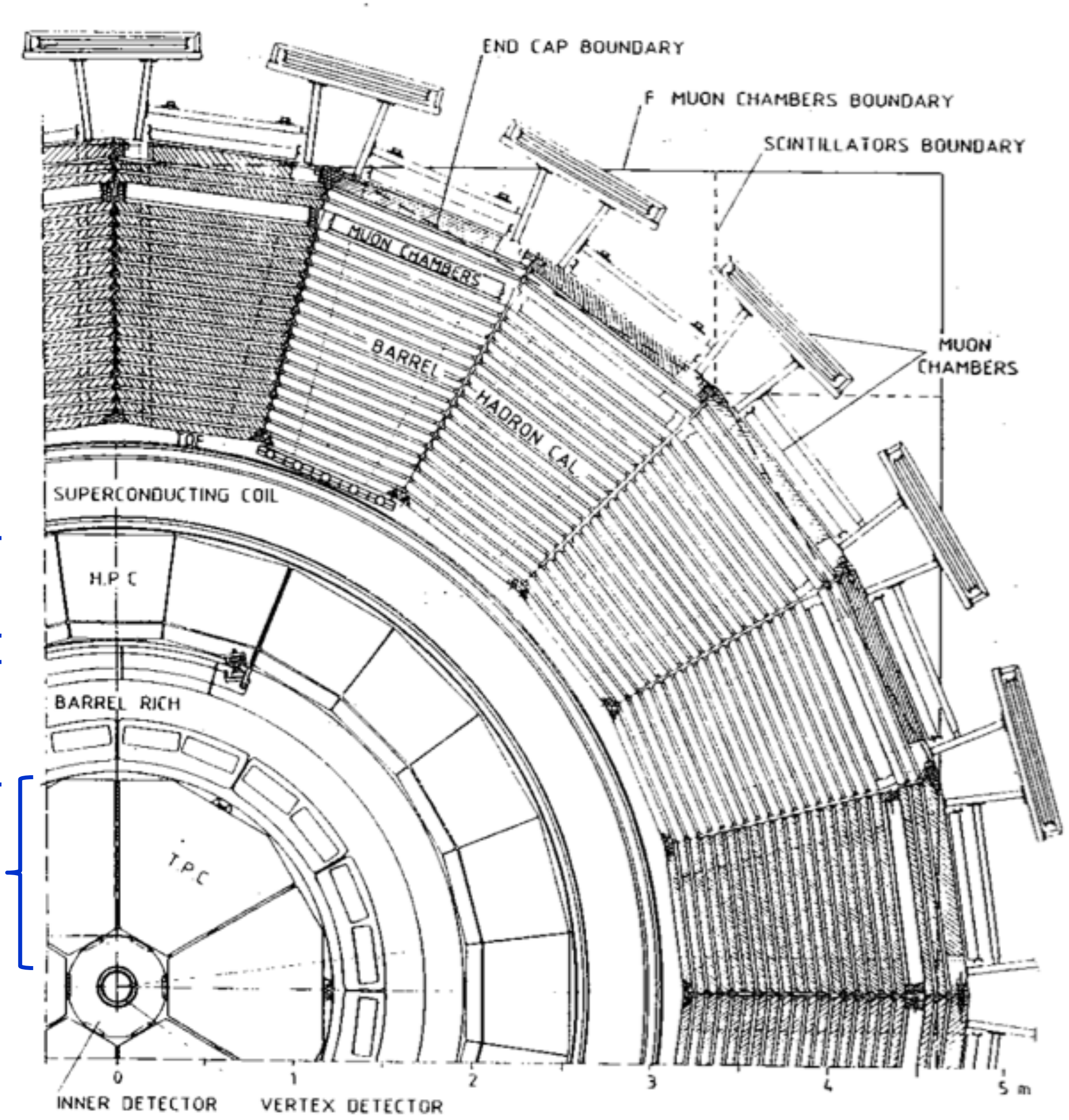
ECAL

RICH (Cherenkov)

Tracking
incl. TPC ↷ dE/dx

Vertex detector

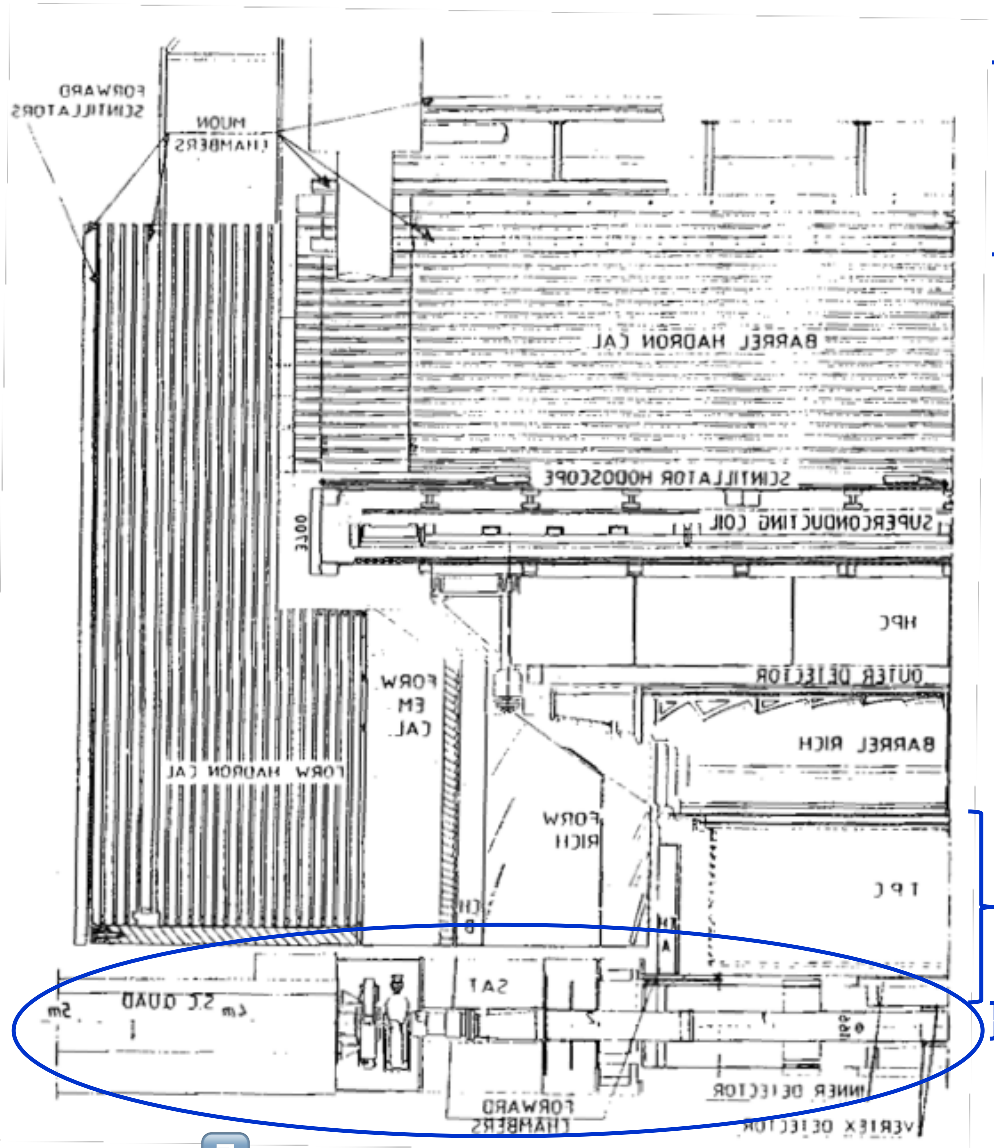
PID = dE/dx + RICH



Machine detector interface

A e^+e^- Detector – DELPHI @ LEP (1989 – 2000)

Outline of talk



4 Muon system

3 HCAL

6 Coil

3 ECAL

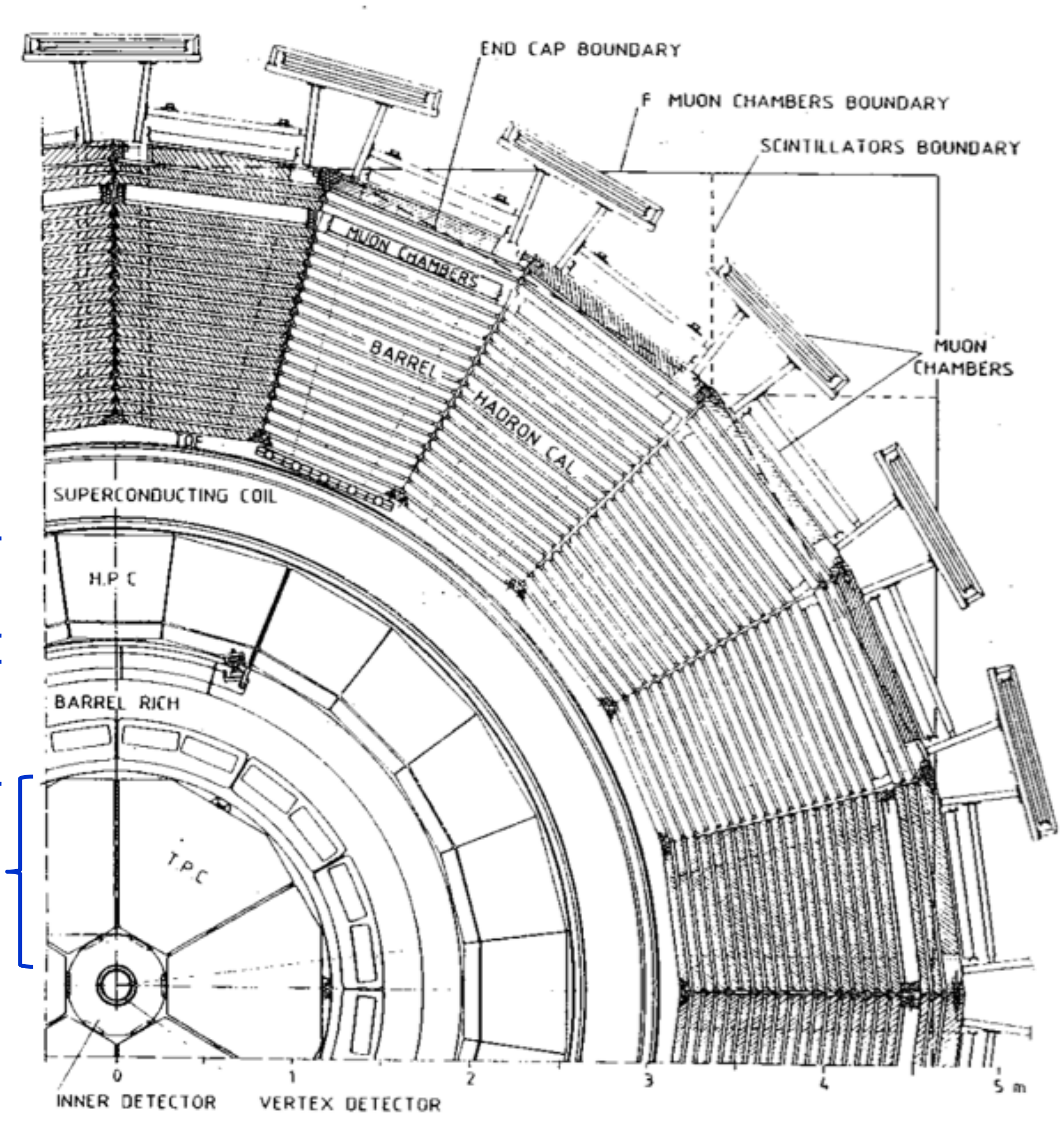
5 RICH (Cherenkov)

2 Tracking
incl. TPC ↷ dE/dx

1 Vertex detector

5 PID = dE/dx + RICH

7 Machine detector interface

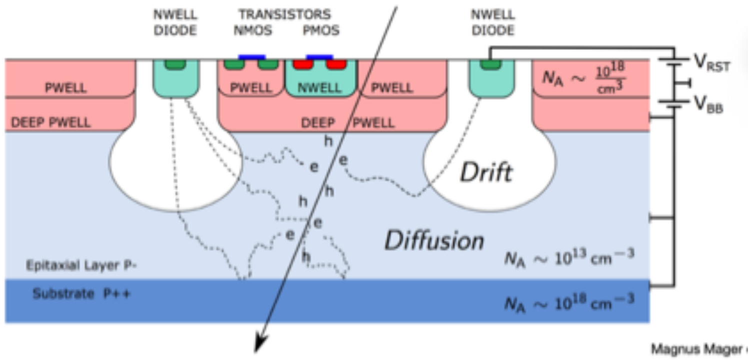


Vertex Detector- technologies

- Measurement of impact parameter, reconstruction of secondary vertices, flavour tagging, lifetime measurements
- Very strong development
  - **Lighter, more precise, closer**

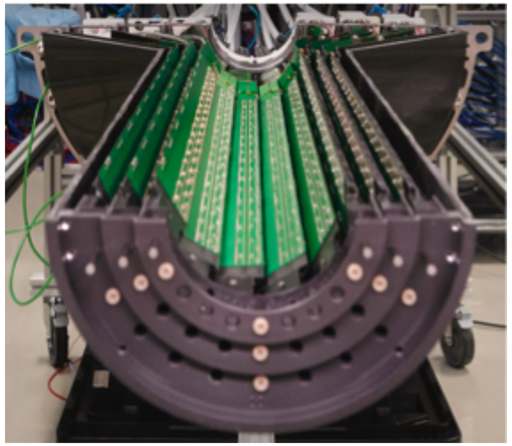
	r beam pipe	1st VTX layer
ILC	12 mm	14 mm
CLIC	29 mm	31 mm
FCC-ee / CEPC	10 mm	12 mm

- MAPS (Monolithic Active Sensors)
  - Single silicon chip contains both detection volume and readout electronics
  - CMOS process; origin in ILC community (Strasbourg)
  - Strong, ongoing development inside ALICE Collaboration

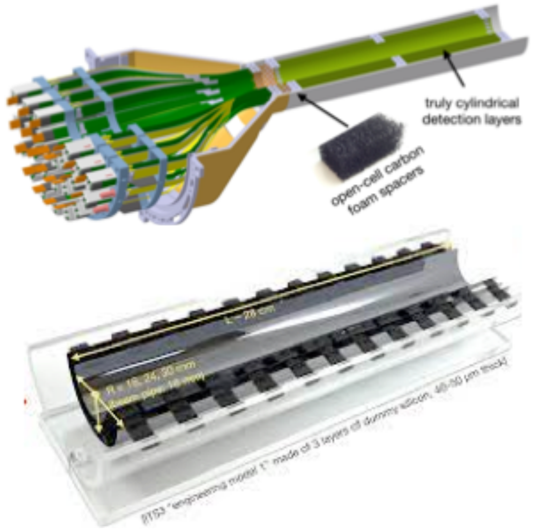


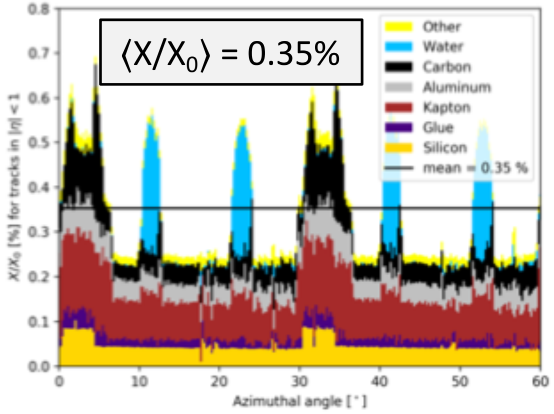
ALICE Vertex detector development

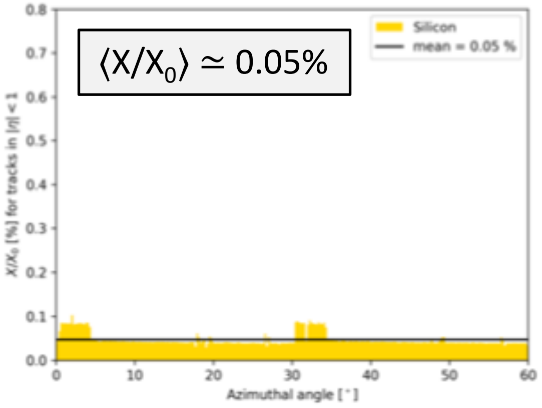
ITS2: installed in 2021



ITS3: installation 2027/2028



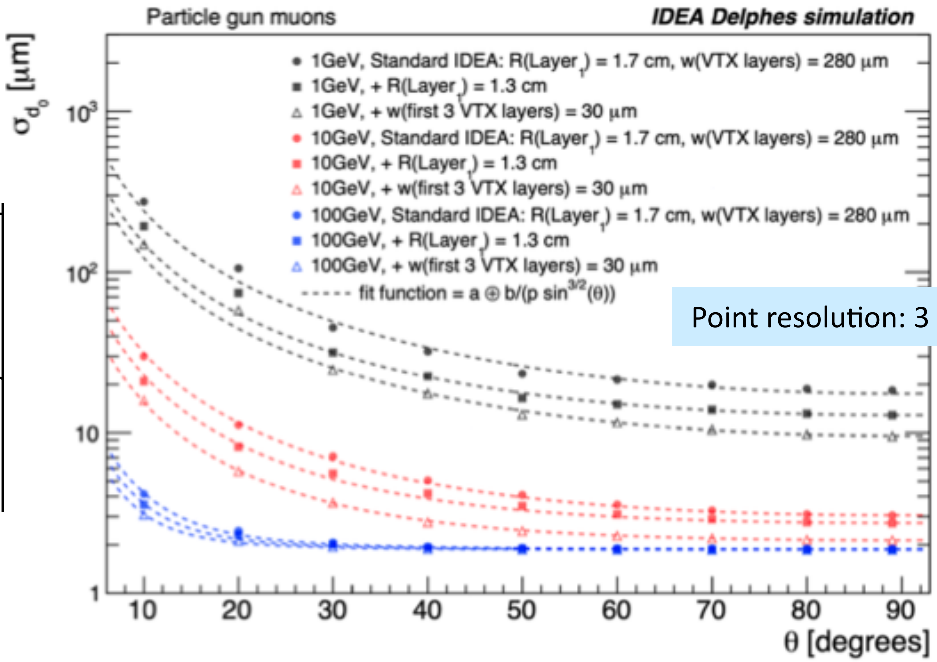




Keywords: thinning (40-50 µm) , bending (r ≳ 10 mm), stitching (one crystal per half barrel)

Vertex Detector- Performance

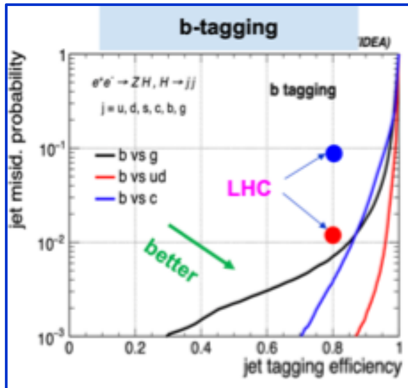
- Many conditions/requirements common between ALICE and e^+e^- colliders
  - Moderate radiation environments
  - No need for picosecond timing
  - High resolution and low multiple scattering is key
- FCC-ee detector simulation
  - Closer (■), lighter (△): Substantial improvement on impact parameter resolution in particular at low momenta



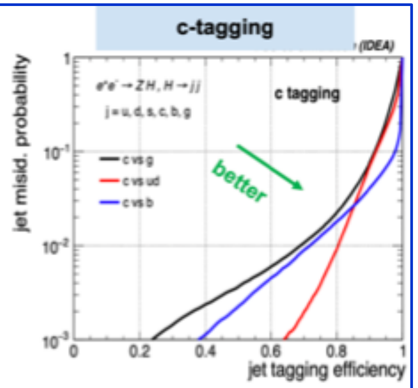
Point resolution: 3 μm

A. Ilg, L. Freitag, 6th FCC Physics Workshop

- Heavy flavour tagging results (simulation)
  - ML based: large lifetimes, displaced vertices/tracks, large track multiplicity, non-isolated e/μ

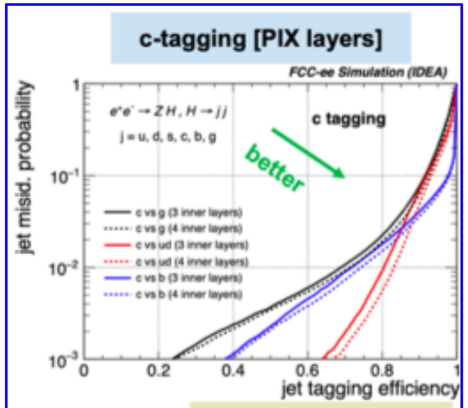


WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.1%	2%
Medium	80%	0.7%	<0.1%	0.3%



WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

Very substantial improvement wrt LHC



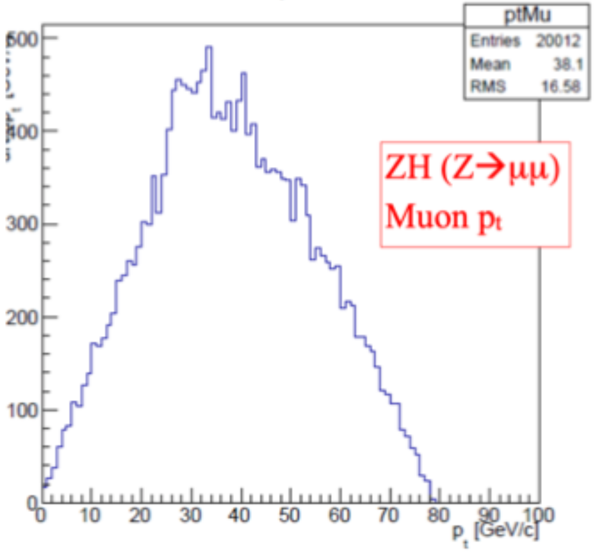
3 layers: closest at 15 mm
4 layers: add layer at 10 mm

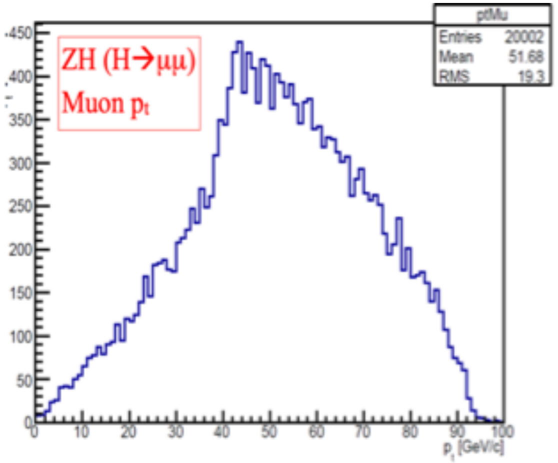
In particular c-tagging benefitting from an extra, closer layer

ML-based - ParticleNet
F.Bedeschi, M.Selvaggi, L.Goukas, EPJ C 82 646 (2022) link

Tracking Systems - Momentum measurement

Particles from Higgs production process are generally of rather low momentum





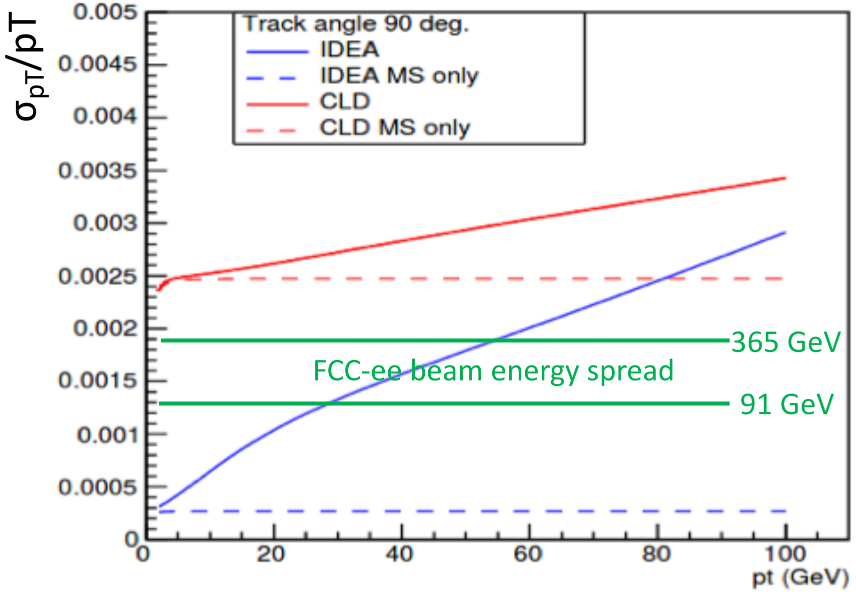
Momentum resolution tends to be multiple scattering dominated

⇒ Asymptotic resolution not reached

$$\sigma(p_\mathrm{T})/p_\mathrm{T}^2 = a \oplus \frac{b}{p\sin\theta}$$

mult.scat

resolution



IDEA: Drift Chamber as main tracking device with a material budget of 1.6%. Supplemented by VTX and Silicon "wrapper" surrounding drift chamber.

CLD: All-Si tracker with total material budget of 11%

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\sin\theta}}$$

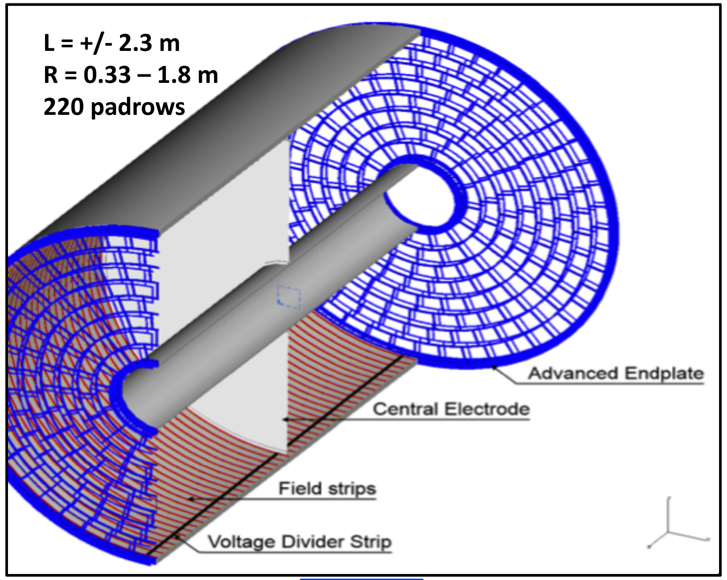
Thinning of Si sensors helps (only) as √ of thickness

https://doi.org/10.1016/j.nima.2018.08.078

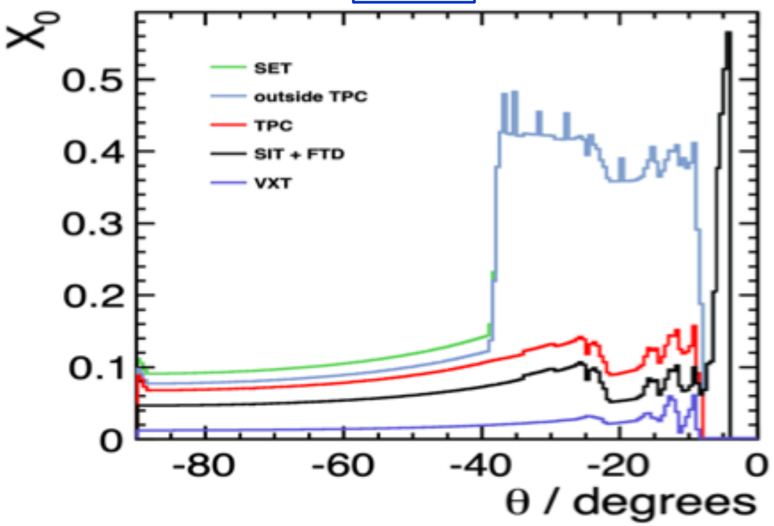
⇒ Detector transparency more important than asymptotic resolution ⇐

Tracking systems and material budgets

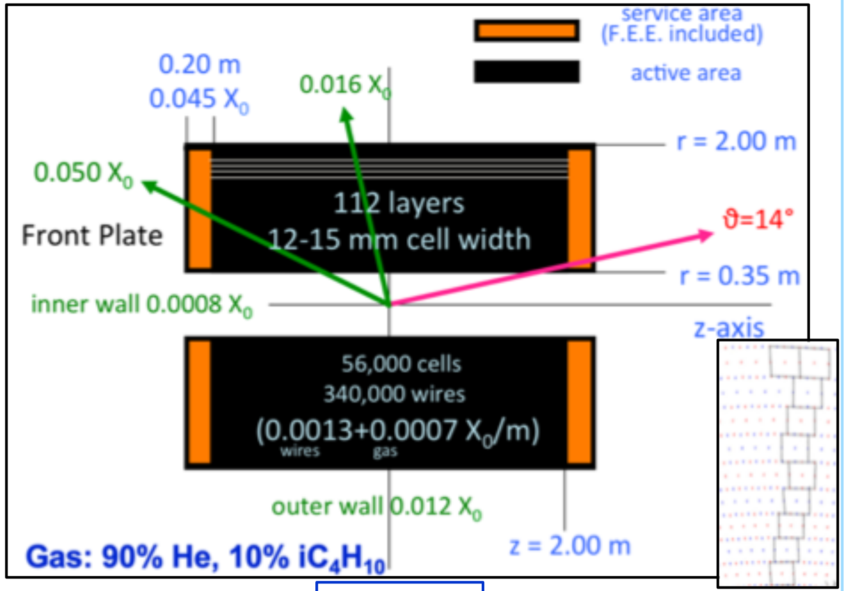
ILD TPC



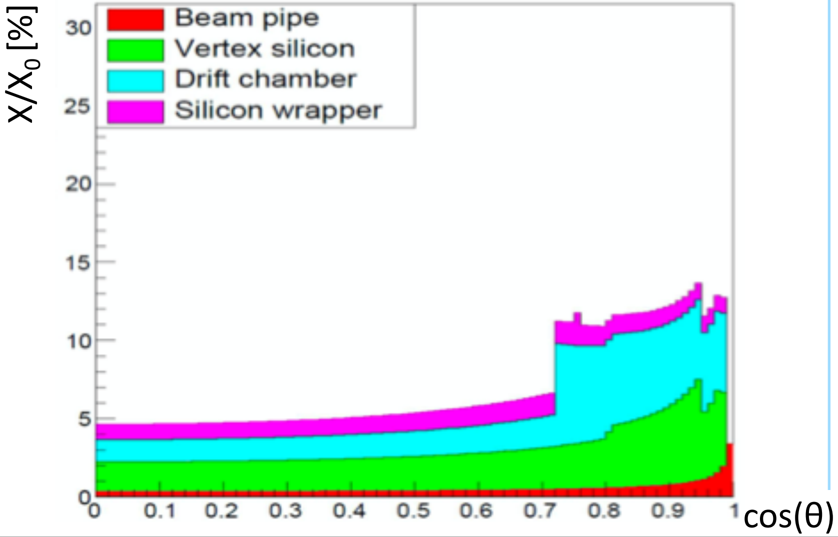
ILC TDR



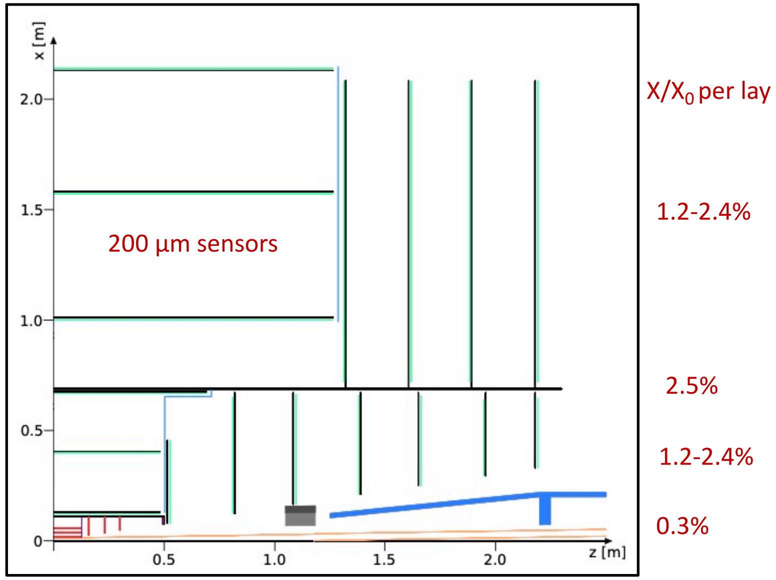
IDEA Drift Chamber



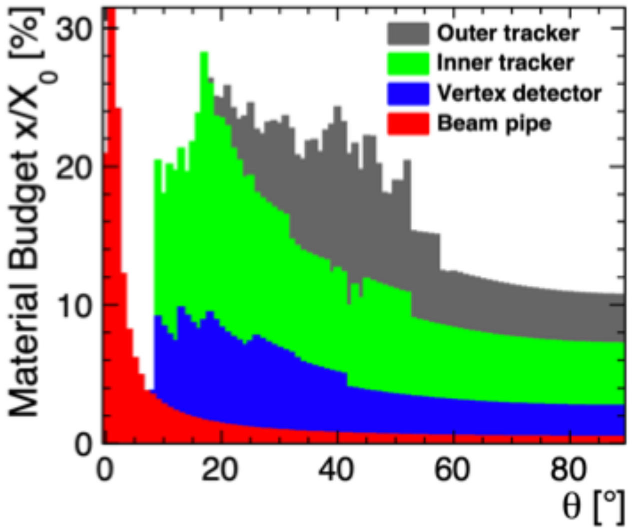
FCC-ee CDR



CLD - Full Silicon tracker

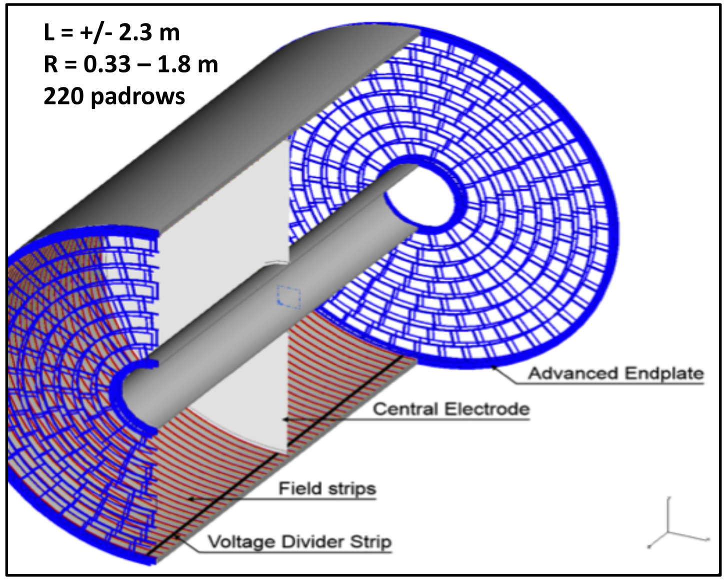


arXiv:1911.12230



Tracking systems overview

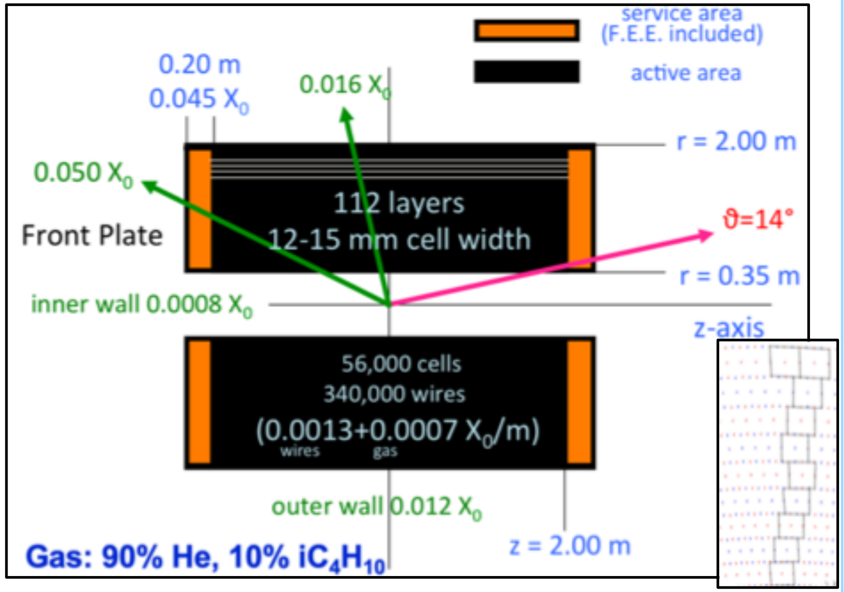
ILD TPC



Pros:
- Low material budget (in barrel)
- Proven technologi, e.g. aleph and delphi at LEP
- Continous tracking; advantage for secondary vertex finding
- Particle ID via dE/dx measurement

Challenges:
- Not obvious if can be operated at ~100kHz FCC-ee physics rate

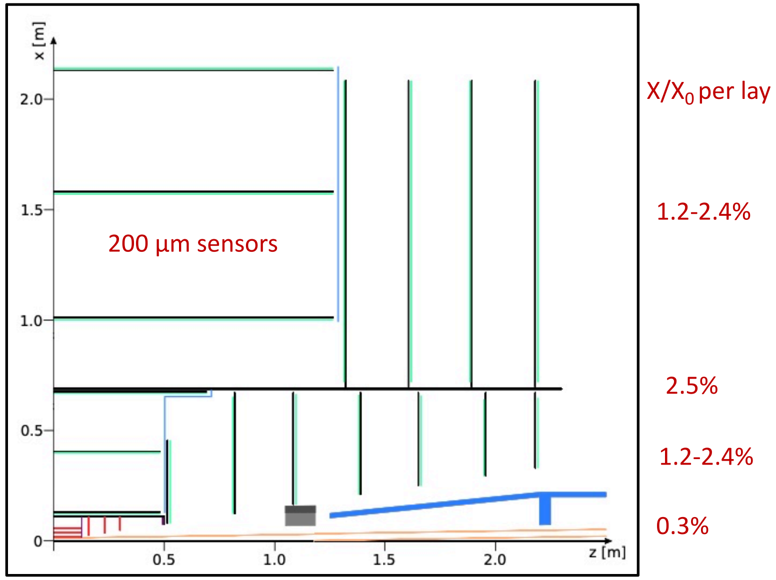
IDEA Drift Chamber



Pros:
- Very low material budget
- Proven technologi: KLOE at Daϕne
- Continous tracking; advantage for secondary vertex finding
- Particle ID via dE/dx (dN/dx) measurement

Challenges:
- Need to prove operation at ~100 kHz FCC-ee physics rate and realistic backgrounds via full simulation studies

CLD - Full Silicon tracker



Pros:
- Very precise space points
- Proven technologi, e.g. LHC detectors
- No gas system

Challenges:
- No precise Particle Identification
  - Possibly TOF
- Optimisation of sensor thickness for lower material budget
- Design of (light) cooling system for operation at continous collisions

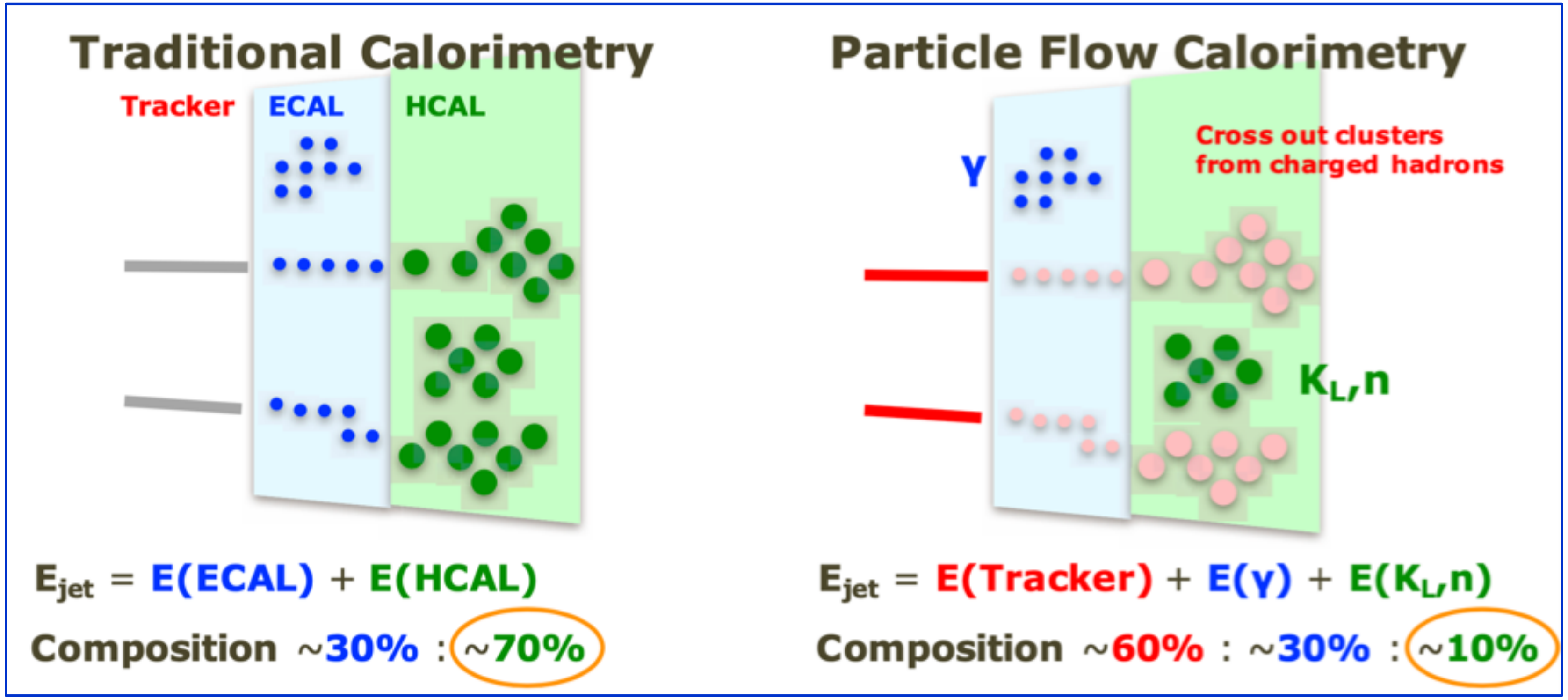
Calorimetry – Particle Flow Approach

Typical jet composition:

- 60% charged particles (primarily $\pi^{+/-}$)
- 30% photons (from π^0 decays)
- 10% neutral hadrons (n, K_L)

Particle Flow (PF):
Measure particles i "strongest" detectors

- ➢ Tracker, excellent measurement, negligible resolution
- ➢ ECAL: 5% - 20% / √E
- ➢ HCAL: 60% - 100+% / √E



CALICE – Sandwich calorimeters with embedded electronics

Optimised for PFA:
- Very fine resolution ”Imaging Calorimeters”
  - Linear Colliders: ILD, SiD, CLICdp
  - Circular Colliders: CLD, CEPC Baseline

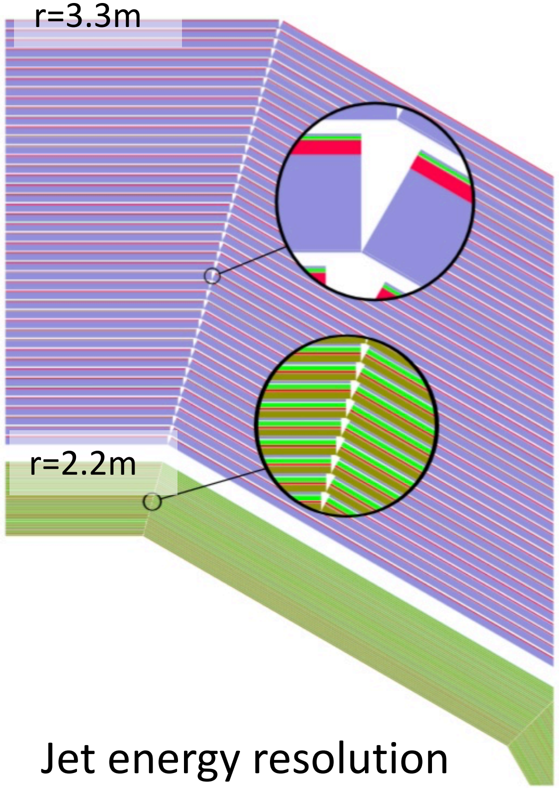
Example, CLD

HCAL
- 44 layers, 19 mm steel absorber, 5.5 (+1) λ
- 3 mm thick scintillator tiles with 3×3 cm^2 granularity

ECAL
- 40 layers, 1.9 mm tungsten absorbers, 22 X_0
- 0.5 mm thick silicon sensors with 5×5 mm^2 granularity

$$\frac{\sigma}{E} \approx \frac{16\,\%}{\sqrt{E}}$$

- Optimisation studies ongoing



Jet energy resolution ~4% at 50 GeV

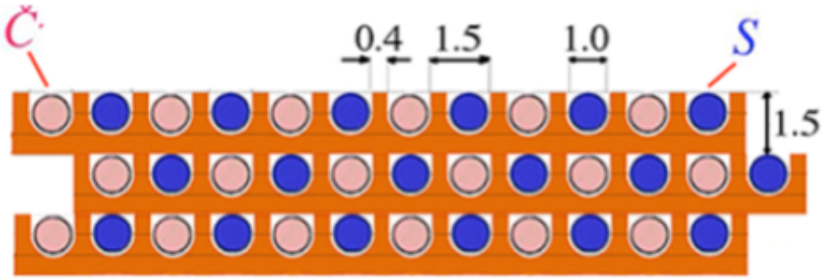
Very strong R&D activities over 15+ years including construction of 5 prototypes

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

Pros:
- Very fine 3D resolution (ongoing work on 4D, adding timing)
  - Excellent PFA performance
  - Excellent reconstruction of ”difficult” final states, e.g. τ decays
  - Sensitivity to late decays of neutrals, i.e. LLPs

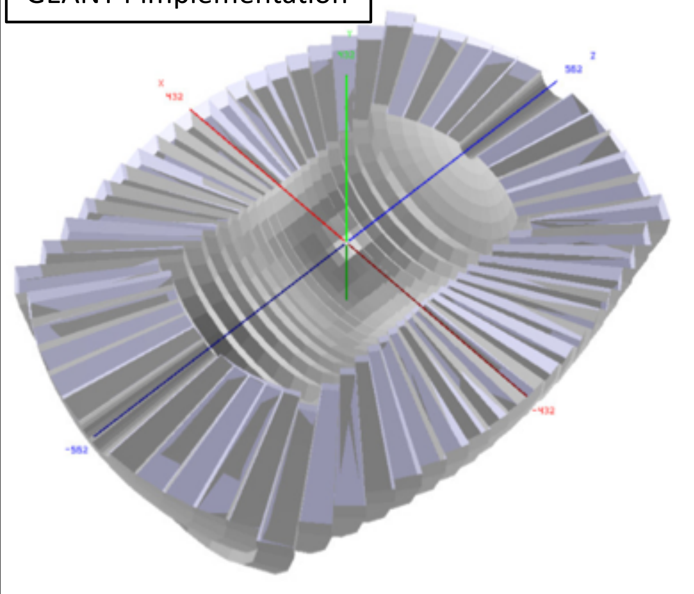
Challenges:
- Relative high price tag;
  - e.g. CLD ECAL employs ~3000 m^2 of Si sensors
- Cooling of electronics at circular colliders not obvious
  - No power pulsing, continous operation, very high data rates
- ECAL resolution not optimal for heavy flavour physics

Dual Readout Calorimetry – IDEA Detector Concept



- Measure simultaneously:
  - Scintillation signal (*S*)
  - Cherenkov signal (*C*) (mainly from $e^{+/-}$)
- Calibrate both signals with e^-
- Unfold event-by-event using *C* and *S* signals to obtain energy corrected for non-compensation (*h*/*e* < 1)

GEANT4 implementation



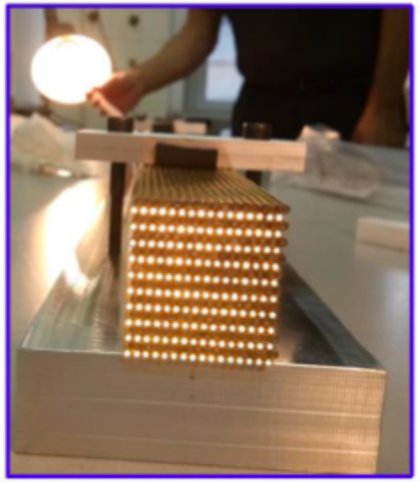
Full GEANT4 simulation:

Single hadron

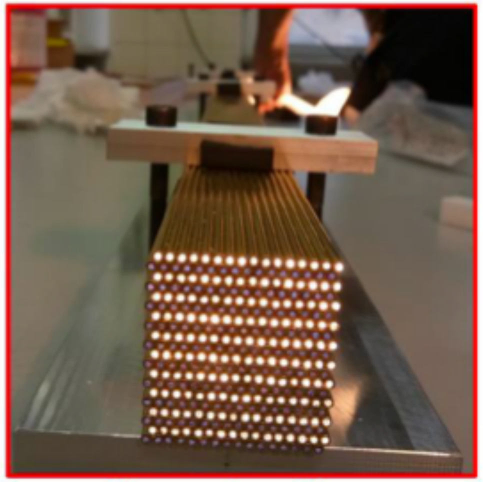
$$\frac{\sigma}{E} = \frac{31\%}{\sqrt{E}} + 0.4\%$$

Electromagnetic

$$\frac{\sigma}{E} = \frac{13.0\%}{\sqrt{E}} + 0.2\%$$



Scintillation fibers



Cherenkov fibers

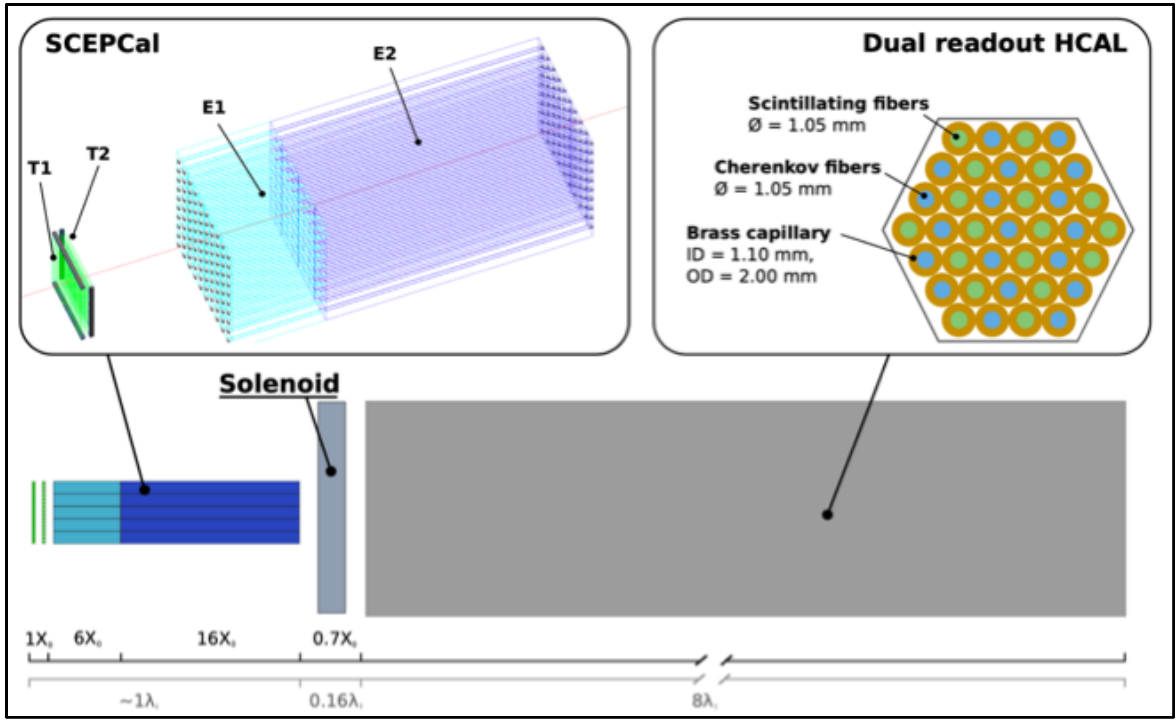
Pros:
- Good intrinsic energy resolution for isolated hadrons and jets
- Excellent transverse granularity
  - down to ~2 mm for individual readout of each fiber (>10^8)
  - promising for "difficult" final states, e.g. τ decays

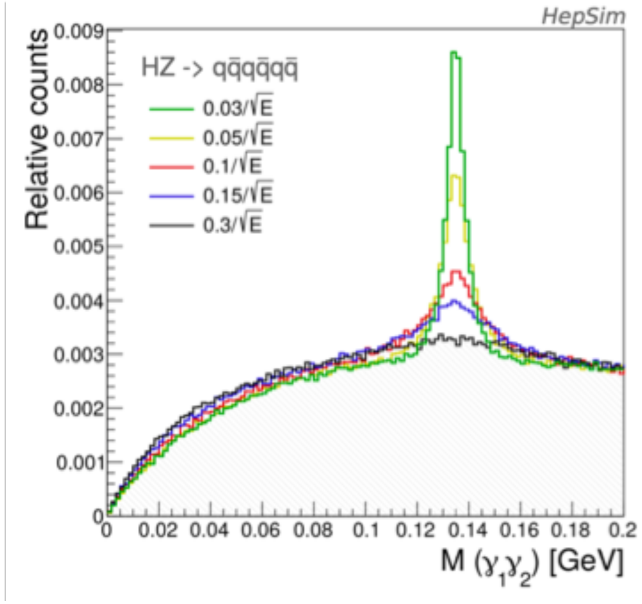
Challenges:
- More than 10^8 fibres; equal no. channels for full granularity read-out
  - Likely needs to group fibres to reduce read-out comlexity and cost
- Lack of longitudinal segmentation
  - Exploit timing via recording of full waveform?
    Costly. Need for proof of principle via beam tests

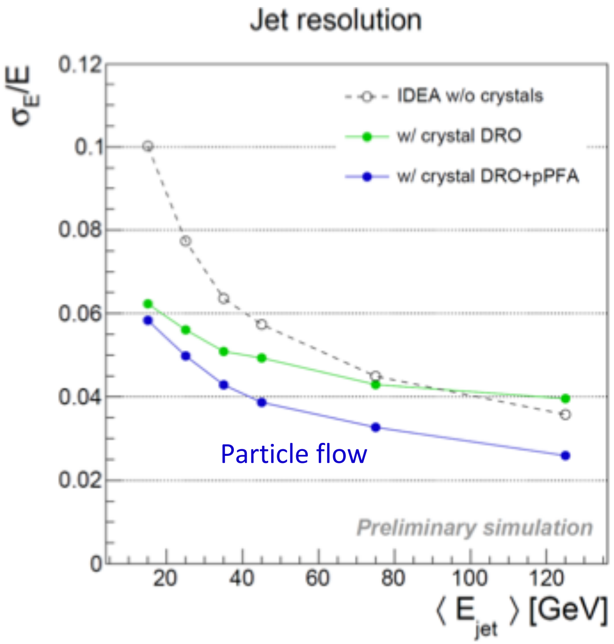
IDEA Hybrid calorimeter option - Crystal ECAL

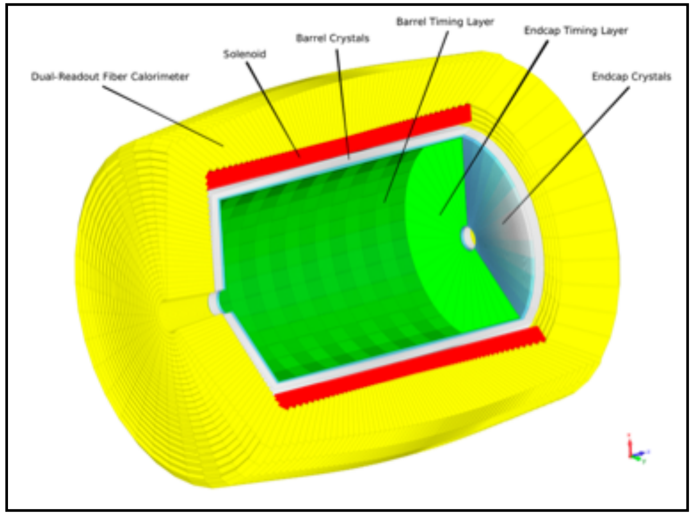
- Place crystal ECAL in front of dual-readout fibre calorimeter
- PbWO crystals – two longitudinal layers
  - $10 \times 10 \times [\,50\ (\text{front}) + 150\ (\text{rear})\,]\ \text{mm}^3$
  - Dual readout via separation of light spectrum (*S* vs. *C*)
- $\sigma_{EM} \approx 3\% / \sqrt{E}$
- Timing layer: LYSO 20-30 ps

Notably improvement in jet energy resolution from performing π^0 identification *prior to* jet reconstruction



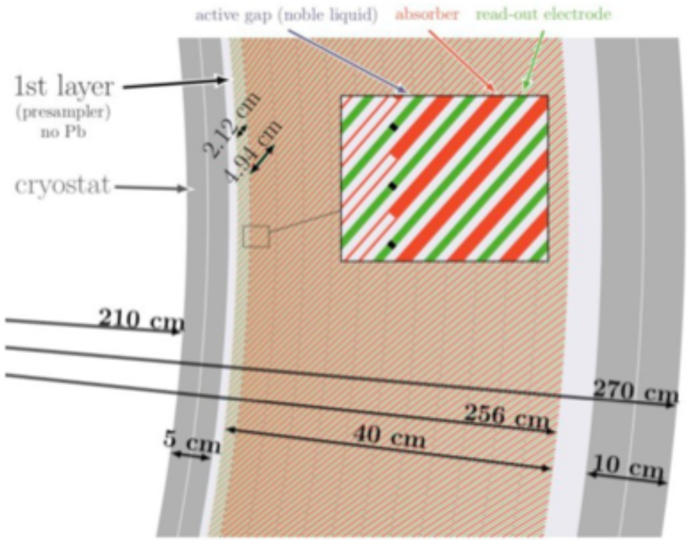


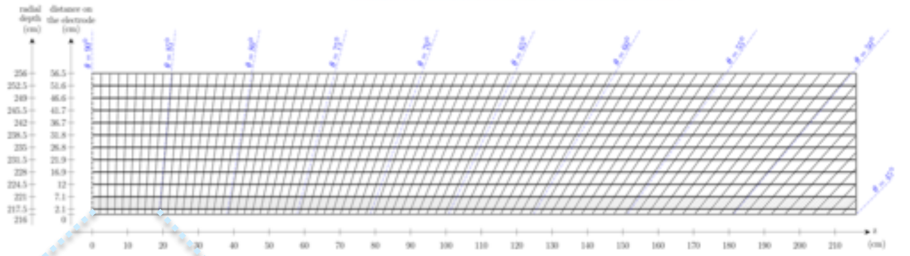


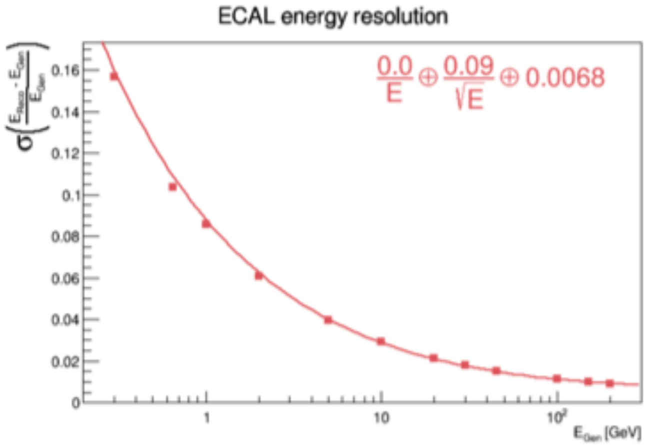


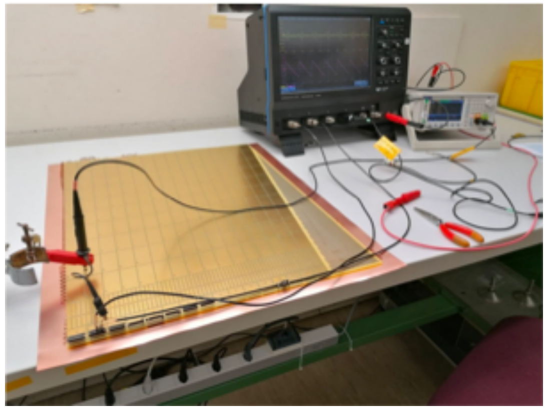
High Granularity Noble-Liquid ECAL

- Good experience with noble liquid ECALs in a number of experiments, e.g. DØ, H1, NA48/62, ATLAS
  - Good energy resolution, $\sigma_{EM} \sim 10\%/\sqrt{E}$
  - Linearity, uniformity, stability of response
    - Low systematics
- Baseline design for FCC-ee detector
  - 1536 straight inclined (50.4°) 1.8mm Pb absorber plates, 22 X_0
  - Multi-layer PCBs as readout electrodes. Segmentation:
    - 11 longitudinal compartments
    - $\Delta\theta$ = 10 (2.5) mrad for regular (1st comp. strip) cells,
    - $\Delta\phi$ = 8 mrad
  - Implemented in FCC-SW Fullsim
    - $\sigma_{EM} \sim 9\%/\sqrt{E}$
  - Definition of end-cap geometry ongoing
  - ECAL shares cryostat with coil (as in ATLAS)
    - Coil outside ECAL
  - Possible options, R&D ongoing
    - LKr or Lar actives; W or Pb absorber
    - Al or carbon fibre cryostat
    - Warm or cold electronics









Calorimetry for e^+e^- - Summary

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)	Ultimate hadronic energy res. incl. PFlow (for 50 GeV jets)
Highly granular Si/W based ECAL & Scintillator based HCAL	15 – 17 % [12,20]	1 % [12,20]	45 – 50 % [45,20]	≈ 6 % ?	4 % [20]
Highly granular Noble liquid based ECAL & Scintillator based HCAL	8 – 10 % [24,27,46]	< 1 % [24,27,47]	≈ 40 % [27,28]	≈ 6 % ?	3 – 4 % ?
Dual-readout Fibre calorimeter	11 % [48]	< 1 % [48]	≈ 30 % [48]	4 – 5 % [49]	3 – 4 % ?
Hybrid crystal and Dual-readout calorimeter	3 % [30]	< 1 % [30]	≈ 26 % [30]	5 – 6 % [30,50]	3 – 4 % [50]

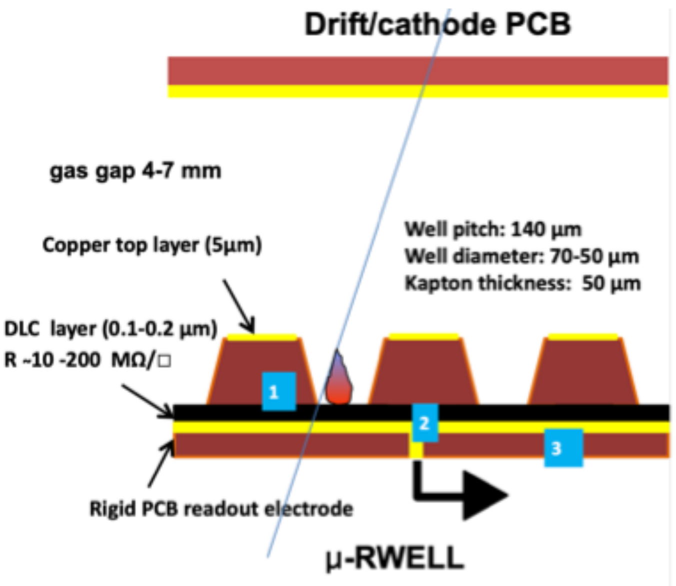
Table 1. Summary table of the expected energy resolution for the different technologies. The values are measurements where available, otherwise obtained from simulation. Those values marked with "?" are estimates since neither measurement nor simulation exists.

For references and more information see https://link.springer.com/article/10.1140/epjp/s13360-021-02034-2

- **Excellent Jet resolution:** ≈ 30-40 %/√E
- **ECAL resolution:** Higgs physics ≈ 15%/√E; but for heavy flavour programme better resolution beneficial → 8%/√E → 3%/√E
- **Fine segmentation for PF algorithm** and powerful **γ/π^0 separation** and measurement
- **Other concerns:** Operational stability, cost, …
- **Optimisation ongoing for all technologies:** Choice of materials, segmentation, read-out, …

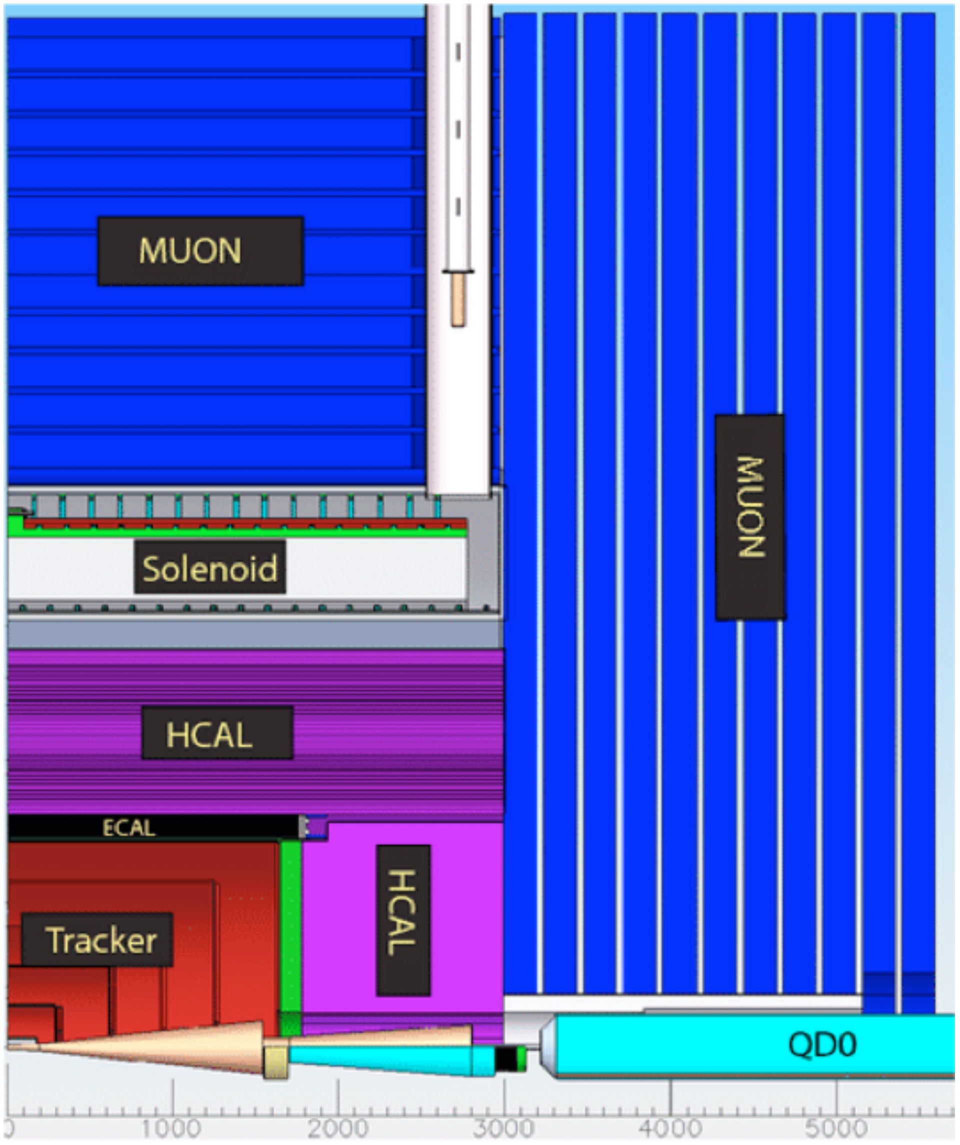
Muon System

- Muon system in instrumented return yoke
  - Objective: Identification of muons penetrating calorimetry
  - 3-9 layers being considered – very large area, 3000-6000 m^2
    - High statistics simulation studies required for optimisation, estimation of punch-through rates
  - Several different detector technologies being considered, e.g.
    - Crossed double layers of scintillator strips
    - RPCs
    - μ-RWell chambers



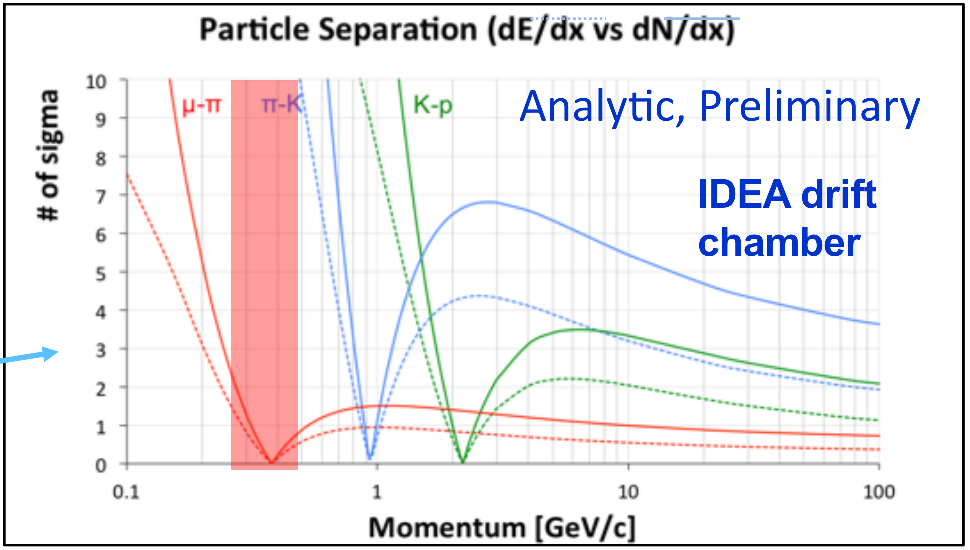
G. Bencivenni et al., 2015_JINST_10_P02008

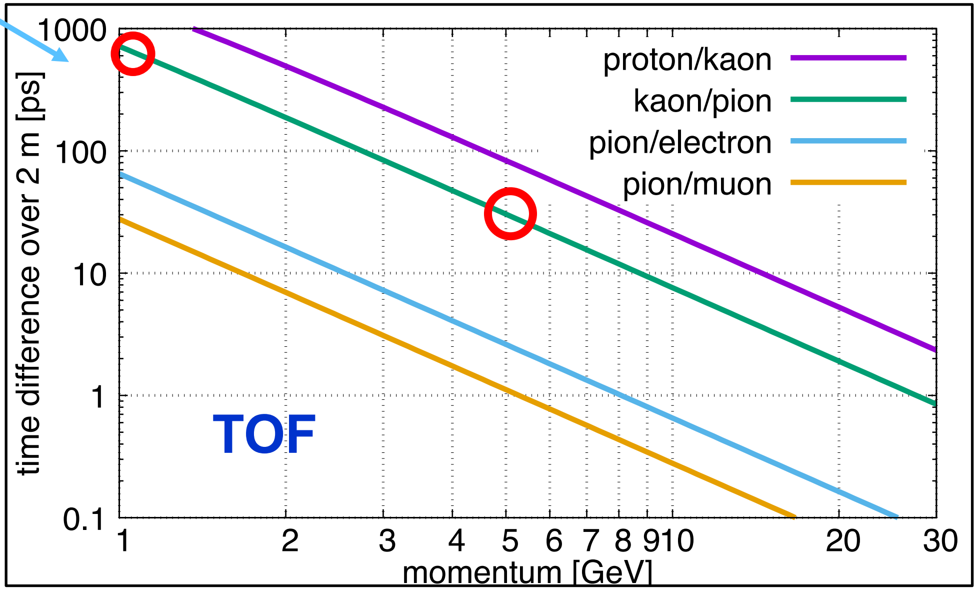
SiD



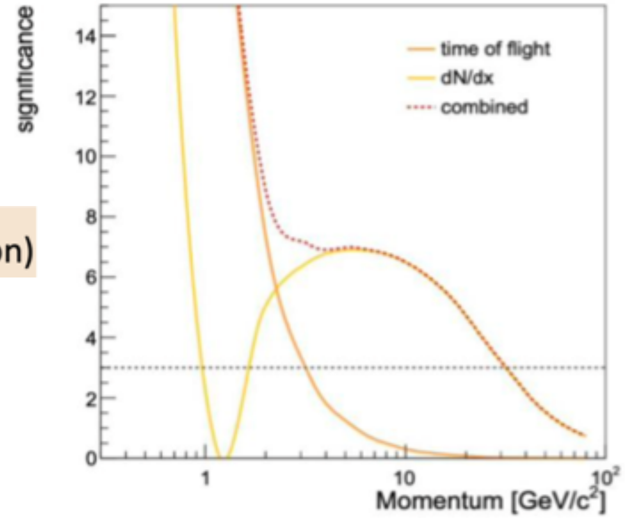
Particle Identification- PID

- Separation of π/K, K/p, over a wide momentum range
  - Prime importance for heavy flavour physics
  - Also provides important (invaluable!) independent means for e/π, π/μ separation
- Gaseous trackers: powerfull separation via ionisation measurement, **dE/dx** or **dN/dx**
  - Example, IDEA Drift Chamber
  - Cross-over window at 1 GeV can be alleviated by unchallenging TOF measurement $\delta T \lesssim 0.5$ ns
- **Time of flight (TOF) alone** δT of ~10 ps over 2 m (LGAD, TORCH)
  - could give 3σ π/K separation up to ~5 GeV



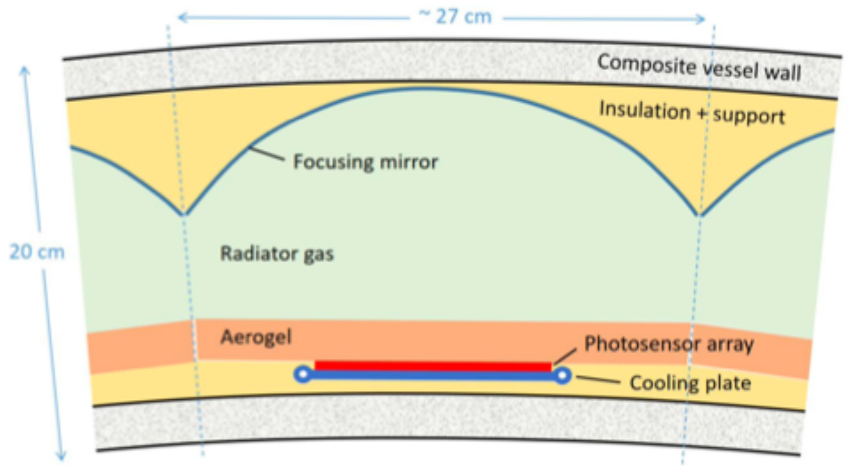


dN/dx + TOF (IDEA simulation)



Compact RICH detector for FCC-ee

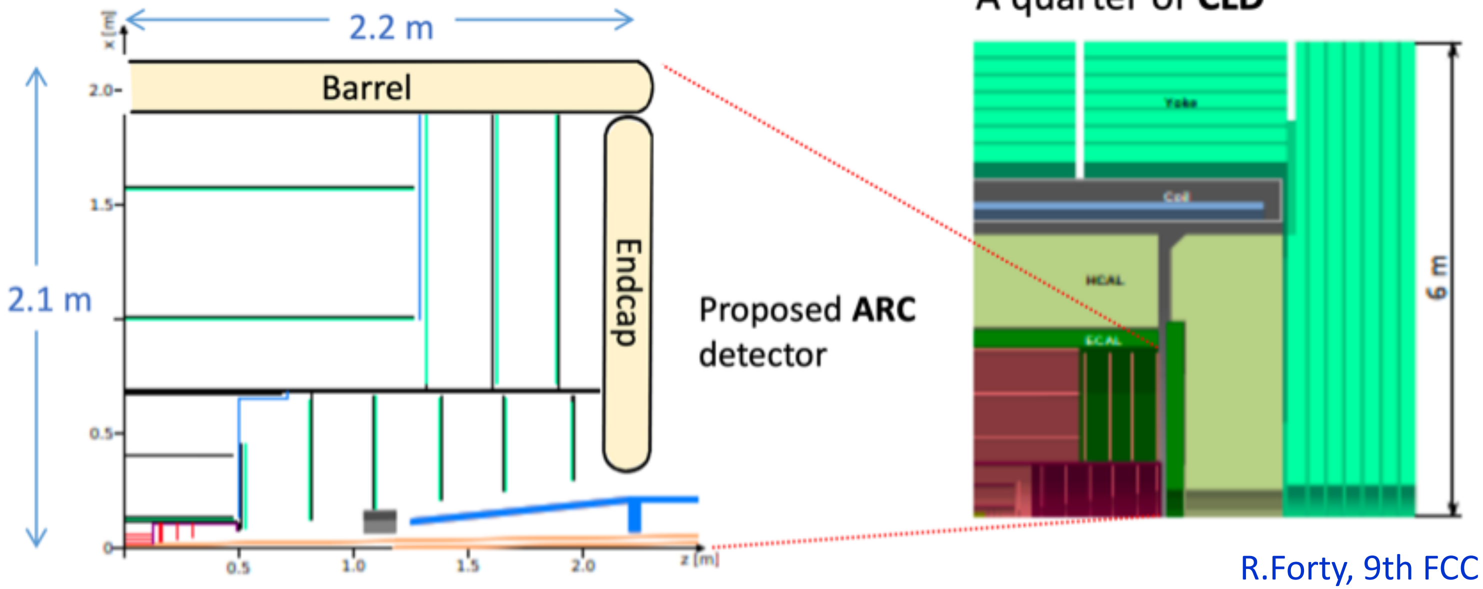
- Design goal: Compact design, max 20 cm depth, few % X_0
- Use spherical focussing mirrows, *r* = 30 cm, for radiator thickness of 15 cm
- Two radiators
  - Aerogel
  - Gas
    - Unpressurised C_4F_{10} gives good momentum range for K-π separation, with acceptable photon yield
    - Pressurised Xenon may provide similar performance if fluorocarbons unacceptable



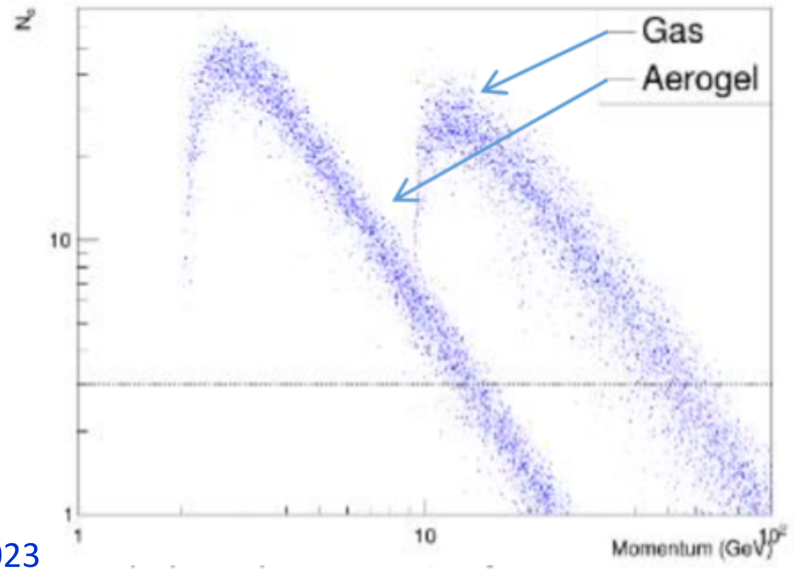
ARC detector (one cell)

Zoom on tracker

A quarter of **CLD**



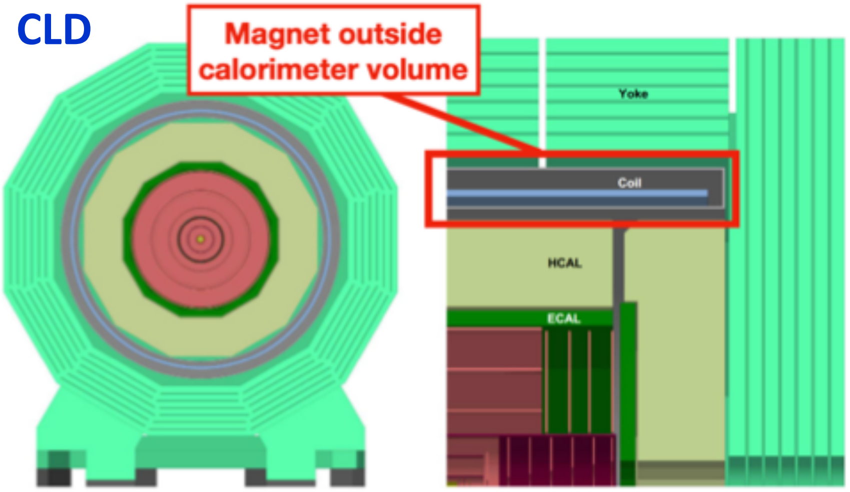
K-π separation

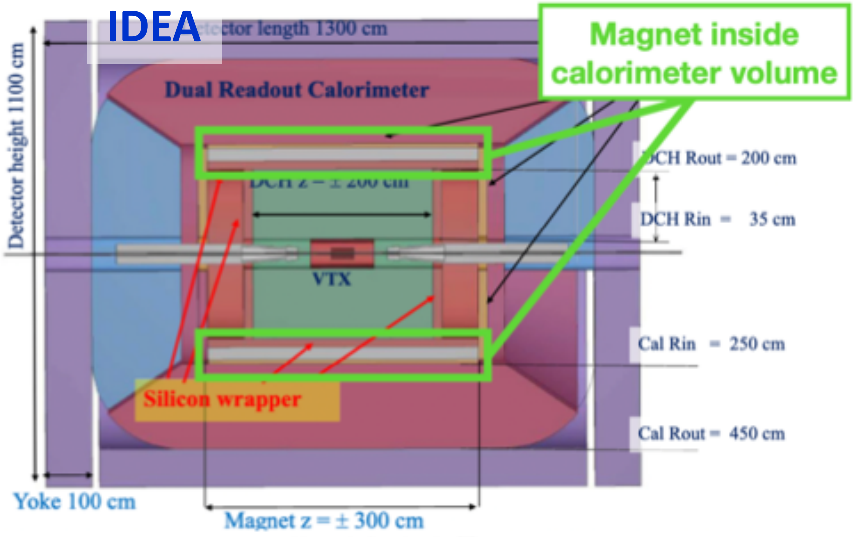


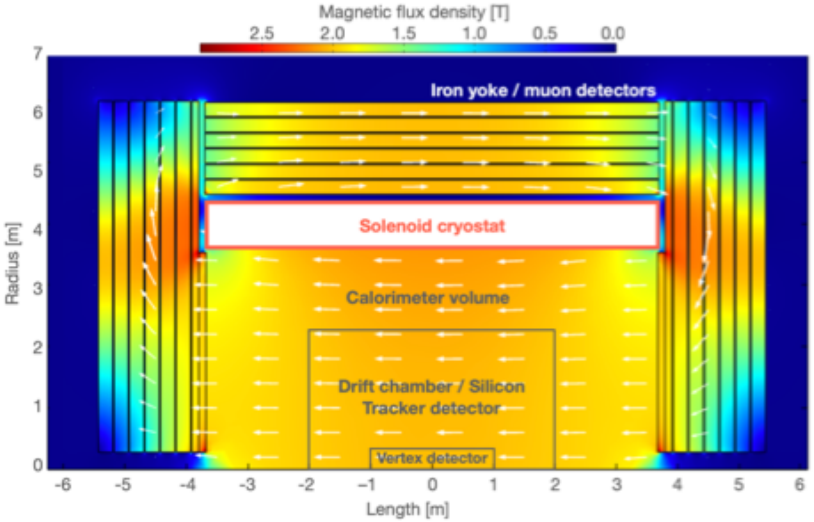
R.Forty, 9th FCC Week, 2023

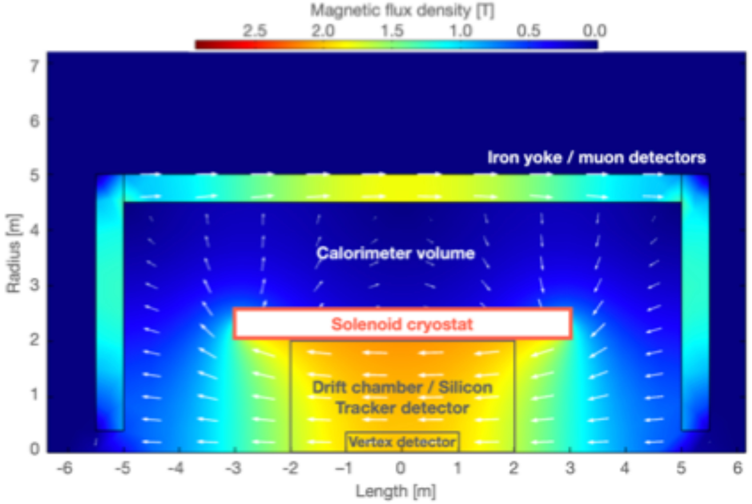
Solenoid Magnet

- Placement of coil different for different detector concepts



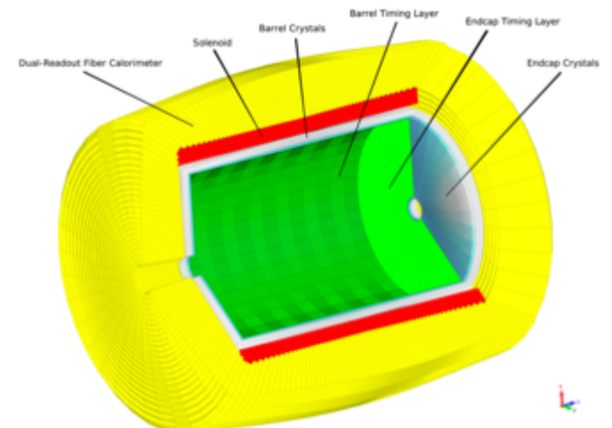






Nikkie Deelen,, 6th FCC Workshop, Feb. 2023

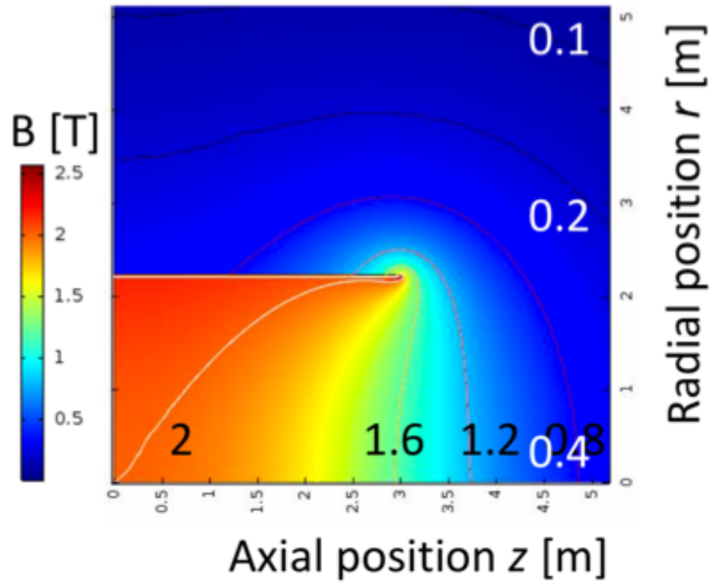
- For Noble Liquid concept and for IDEA with crystal option, coil *between* ECAL and HCAL
  - As aleph and delphi at LEP



IDEA w crystal ECAL + DR fiber HCAL

- Detailed simulation studies needed to understand pros and cons of the different placements

2 T "light and thin" Solenoid inside Calorimeter



Property	Value
Magnetic field in center [T]	**2**
Free bore diameter [m]	4
Stored energy [MJ]	**170**
Cold mass [t]	8
Cold mass inner radius [m]	2.2
Cold mass thickness [m]	0.03
Cold mass length [m]	6

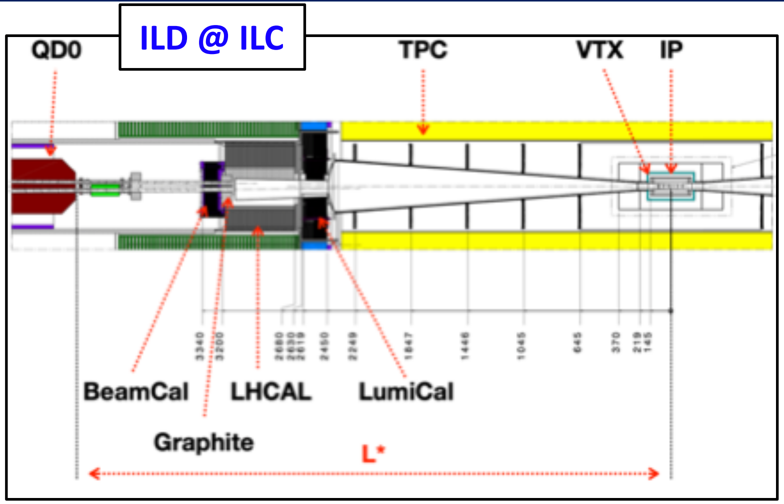
H. Ten Kate et al.

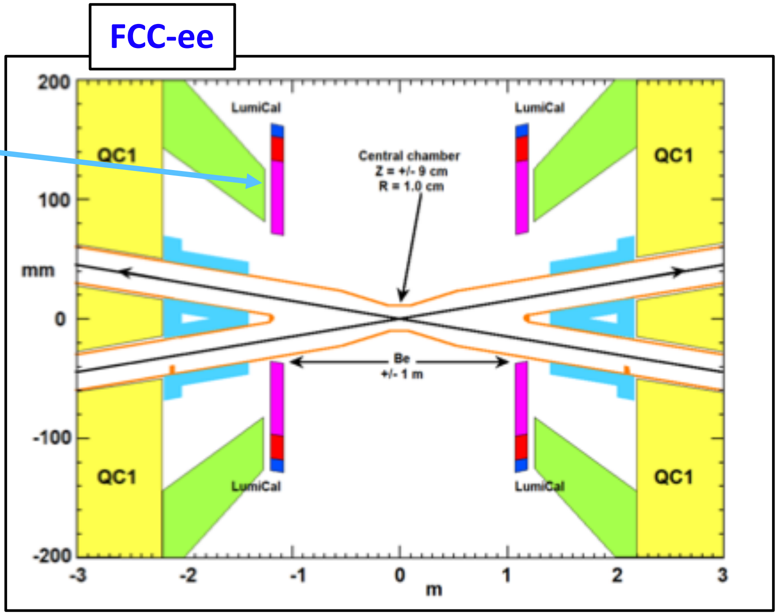
Ongoing / needed R&D

- Objectives
  - **Light**: certainly less than 1 X_0
  - **Thin**: As thin as possible for optimal tracker-to-calorimeter matching
- Self-supporting single layer coil
  - High yield strength conductor fully bonded
  - Thin Al support cylinder
- Coil composition
  - Aluminum (77 vol.%)
  - NbTi (5 vol.%) / copper (5 vol.%)
  - Glass-resin-dielectric films (13 vol.%)
- Radiation thickness (preliminary studies)
  - Cold mass: $X_0 \approx 0.46$
  - Cryostat (25 mm Al): $X_0 \approx 0.28$
  - **Total $X_0 \approx 0.75$ achievable**
  - **Total radial envelope less than 30 cm**
- Prospects for even lighter and thinner outer shell

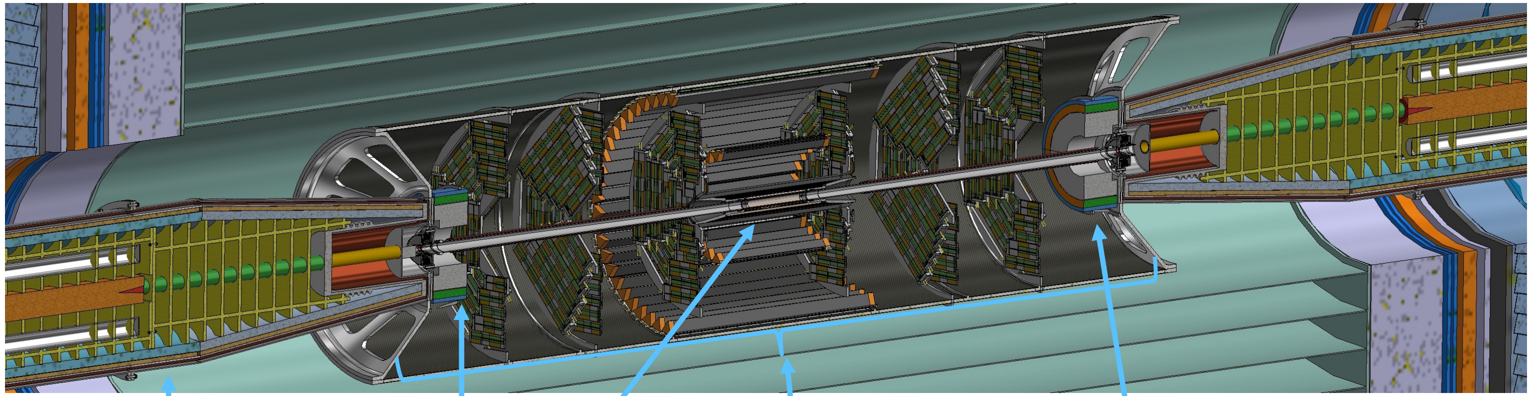
Machine Detector Interface

- Interaction regions layouts are substantially different between linear and circular colliders
  - ILC: Last focusing quadrupole at $L^* = 4.1$ m
    - Forward calorimeters (LumiCal, LHCAL, BeamCal) "outside" detector volume
      - LumiCal face in same plane as forward ECAL (z=2.4 m)
  - FCC-ee: Last focusing quadrupole at $L^* = 2.2$ m
    - Compensating solenoid down to z = 1.2 m
      - Required to allow beams to cross detector solenoid at 15 mrad angle
    - LumiCal face at z = ~1.1 m
    - Challenging engineering design!





FCC-ee MDI being designed inside light *r* = 300 mm support tune



Mike Koratsinos

Fabrizio Palla, 2023 FCC Week

A few words on Readout, DAQ, Data Handling

- In particular at Giga-Z operation, challenging conditions
  - 50 MHz BX rate
  - Physics rate at 100 kHz plus similar LumiCal rate
  - Absolute normalisation goal of 10^{-4} or better
- Different detector components tend to prefer different integration times
  - Silicon VTX/tracker sensors: $\mathcal{O}(1\ \mu s)$ [also to save power]
    - BX identification via time-stamping (at least at track level) will be needed
  - LumiCal: Preferential at ~BX frequency (20 ns)
    - Avoid additional event pileup
- How to organize readout?
  - **Hardware trigger** with latency buffering a la LHC ??
    - Probably not…
    - Which detector element would anyway provide the trigger to the required precision?
  - **Free streaming** of self-triggering sub-detectors; event building based on time stamping
    - Need careful treatment of relative normalisation of sub-detectors – 10^{-5} level

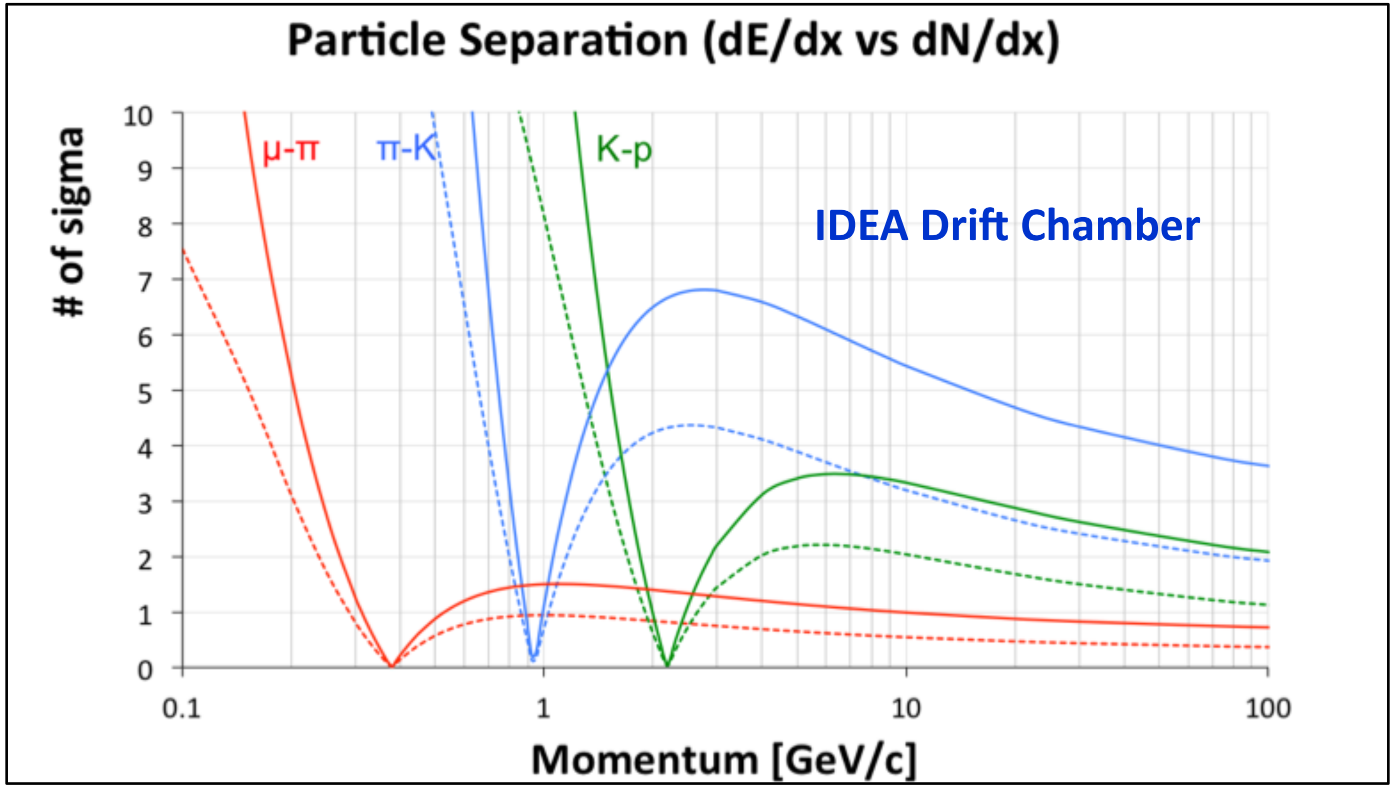
- Need to consider Trigger(?) & DAQ issues as an integral part of detector design
  - ”Thinking about the DAQ later” will very likely lead us into trouble
- Need to plan for off-line handling of $\mathcal{O}(10^{13})$ events for precision physics
  - Plus Monte Carlo

Hardware trigger
- trigger buckets as in ATLAS/CMS

Free streaming
-LHCb DAQ upgrade
-Detectors at EIC

Redundancy, redundancy, redundancy

- For the control of systematic uncertaities, experimental redundancy is essential
  - Example: calorimetric separation of e/π, e/μ, π/μ
  - A powerful, independent, non-destructive identification tool allows to establish clean test samples of e, π, μ to study their calorimetric response
  - This is what a powerful dE/dx measurement provides you

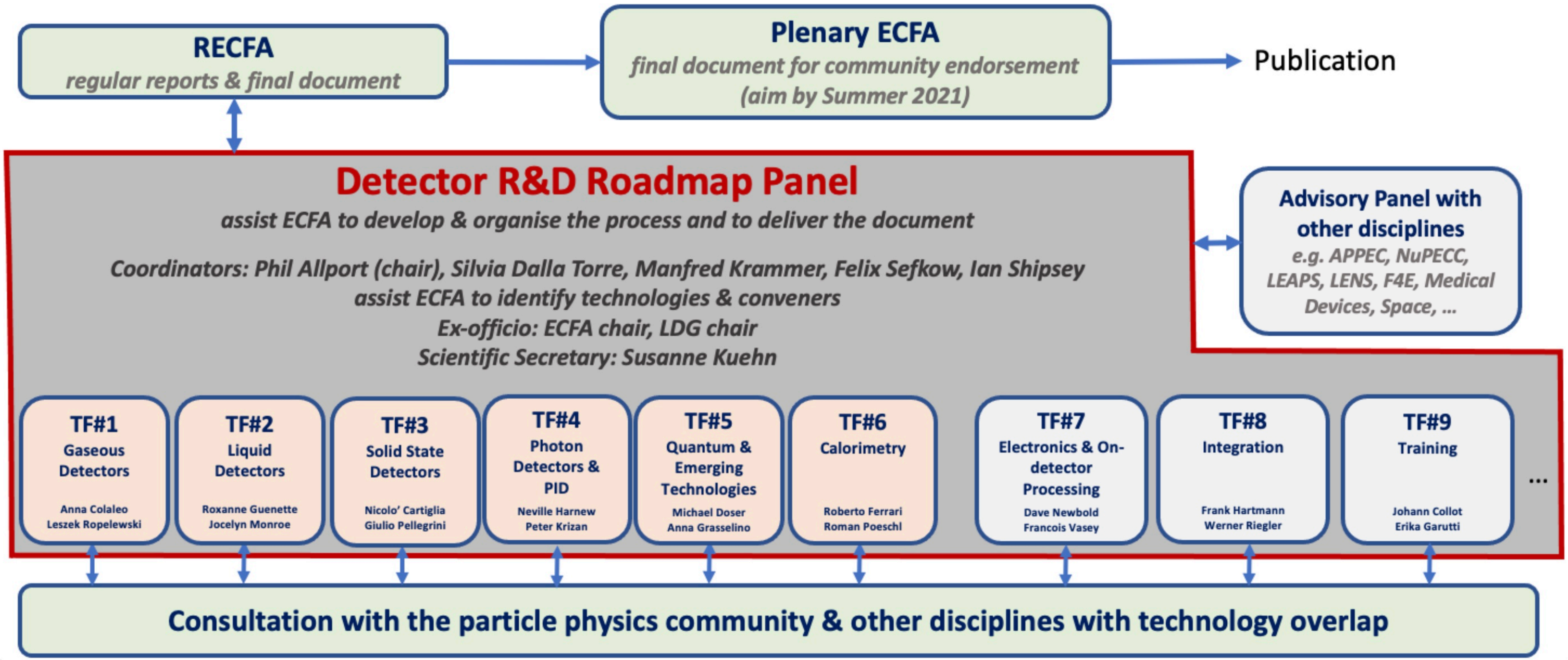


Summary

- Large experience in designing detectors for high-energy e^+e^- colliders from LEP and LC design studies
- With Giga-Z option, increasing emphasis on minimization of systematics, heavy flavour physics, FIP searches, …
  - The understanding of the physics landscape is in rapid development
- Directions/challenges:
  - Silicon-based tracking
    - Minimise multiple scattering, lighter sensors and support, less power, cooling,…
  - Gaseous trackers
    - Operation of TPC at circular colliders? Optimisation of Drift Chamber design including high-rate front-end data handling
  - Calorimetry
    - Resolutions, granularity, low threshold for γs, data handling from multi-million channels, power consumption, cooling
  - Muon system
    - Optimisation for minimal punch through, large areas, industrial production
  - PID:
    - dE/dx (dN/dx) for gaseous trackers, precise TOF (timing also for time-stamping), compact RICH detector
  - Solenoidal coil
    - Development of coil that are thin both in terms of X_0 and physical depth
  - Trigger, DAQ, data-handling
    - Challenge for Giga-Z operation, not much activity so far, design needs to be an integral part of (sub-)detector design
  - MDI
    - Challenging, engineering work ongoing

Detector R&D - ECFA Detector Roadmap Implementation

https://indico.cern.ch/event/957057/



- Focus on the technical aspects given the EPPSU process as input.
- Development of a matrix, where for each Task Force the identified future science programmes that they will need to address in terms of the main technology challenges to be met and estimate the lead-time over which the required detector R&D programmes may be expected to extend.
- Create a time-ordered R&D requirements roadmap in terms of key capabilities not currently achievable.

Extras

Very high statistics Z factories - TeraZ

Running conditions:

- Extremely large statistics / statistical precision
    - …need small systematics (10^{-5}) to match
- Physics event rates up to 100 kHz
- Bunch spacing down to 20 ns
    - Continous beams, no power pulsing
- No pileup, no underlying event, …
    - …however, still pile-up at the 10^{-3} level

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	40,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	**92,000**	8,400	1	0.1
"Pile up" parameter [μ]	**10^{-6}**	1,800	1	1	1

Detector optimization to be done for extremely rich physics capabilities especially at the Z pole with up to 5×10^{-5} Z decays: 10^{12} bb, cc, 2×10^{11} $\tau\tau$, etc…

- Search for rare processes: Excellent acceptance definition, hermeticity, sensitivity to displaced vertices
- Luminosity measurement at 10^{-4} (abs), 10^{-5} (rel)
- Acceptance definition at $\leq 10^{-5}$
- Excellent b/c/gluon separation
- **PID**: TOF, dE/dx, Cherenkov?

The Z physics programme is still under development, in particular for rare processes and for heavy flavours:

- Detailed detector requirements still to be finalised, especially for PID.

e^+e^- colliders experimental conditions

Linear Colliders

- **Beam-induced background**:
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons)
  - **High occupancies** in the detector => **small readout cells** needed
  - **O(1-5 ns) timing** required at CLIC
- **Low duty cycle**
  - **Power pulsing** of electronics possible
  - **Triggerless readout**
- **Beam crossing angle** 14 mrad (ILC), 20 mrad (CLIC)

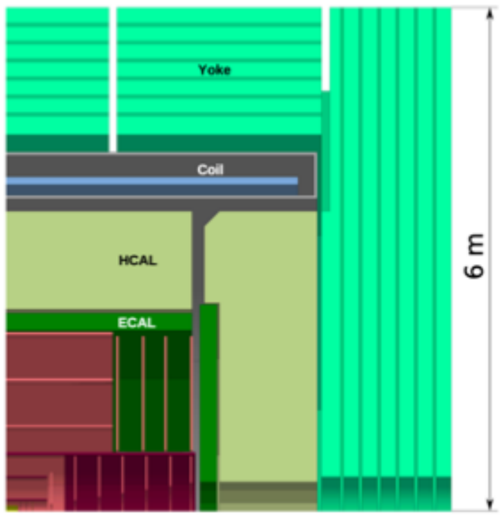
Circular Colliders

- **Beam-induced background**
  - Beamstrahlung (incoherent pairs and $\gamma\gamma \rightarrow$ hadrons) + Synchrotron radiation
- **Circulating beams**
  - Maximum detector solenoid field of ~2 T (3 T) => requires **larger tracker radius**
  - Complex **magnet shielding** schemes near the beam
  - Beam focusing quadrupole closer to IP (~2.2m)

  } **Stronger engineering and layout constraints**
  - No power pulsing
- **High luminosity and many bunches at Z pole**
  - Drives detector performance, moderate timing requirements, high data rates
  - Larger challenge to **keep systematics very low**
- **Beam crossing angle** 30 mrad (FCC-ee), 33 mrad (CEPC)

FCC-ee Evolving Detector Concepts Fast Overview

CLD



CDR

Conceptually extended from CLIC detector design

- Full silicon tracker
- High granularity silicon-tungsten ECAL
- High granularity scintilator-steel HCAL
- Instrumented return-yoke for muon detection
- Large 2 T coil surrounding calorimeter system

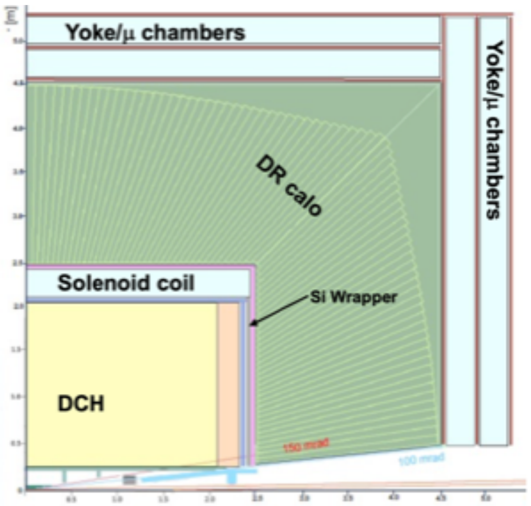
Engineering needed for adaptation to continous beam operation (no power pulsing)

- Cooling of Si-sensors & calorimeters

Possible detector optimisations

- Improved ECAL and momentum resolutions
- Particle identification (TOF and/or RICH)

IDEA



Specifically designed for FCC-ee (and CEPC)

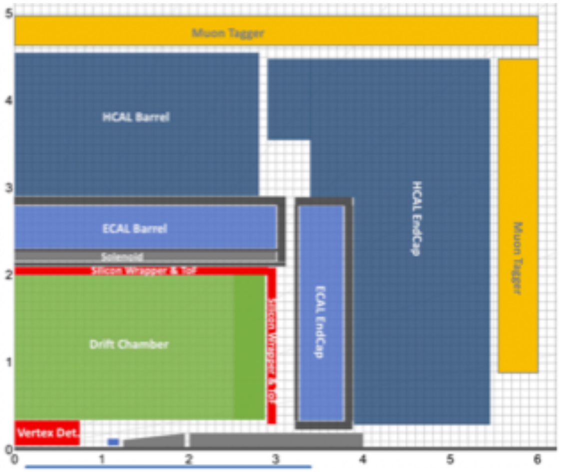
- Silicon vertex detector
- Low X_0 drift chamber with high-resolution particle ID via ionisation measurement
- Silicon wrapper around drift chamber
- Light, thin 2T coil inside calorimeter system
- Pre-shower detector based on MPGC
- Dual-readout calorimeter; copper -- scintilating + Cherenkov fibres
- Instrumented yoke with MPGC muon system

Possible detector optimisation

- Much improved EM energy resolution via crystal ECAL in front of coil

Noble-Liquid ECAL based

new



Specifically designed for FCC-ee, recent concept, under development

- Silicon vertex detector
- Low X_0 drift chamber with high-resolution particle ID via ionisation measurement
- Light, thin 2T coil inside same cryostat as ECAL
- High granularity Lead / Noble Liquid ECAL (LAr, possibly LKr)
- HCAL and muon systems to be specified