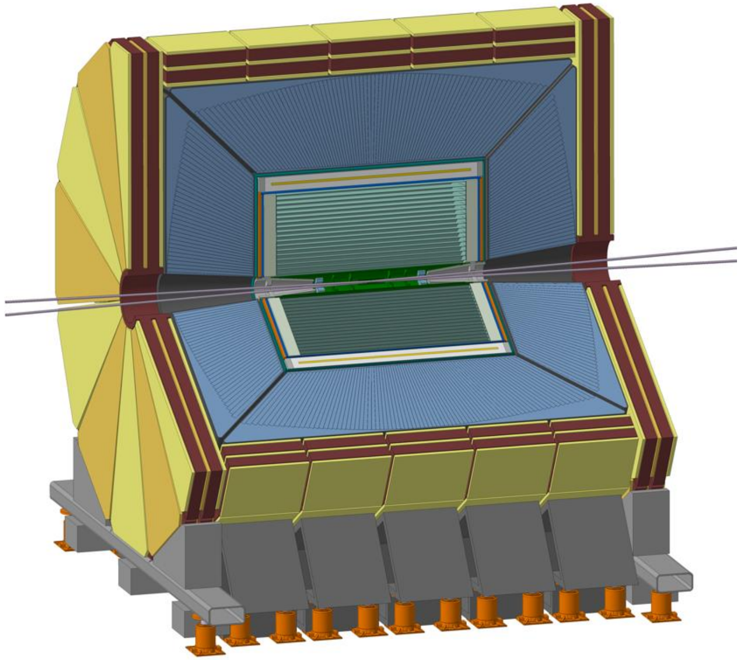
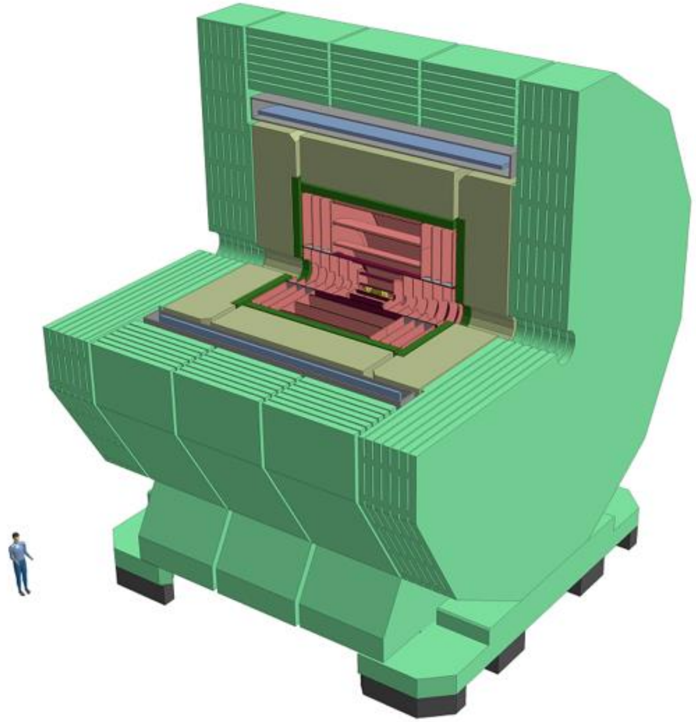
Towards FCC-ee Detector Concepts



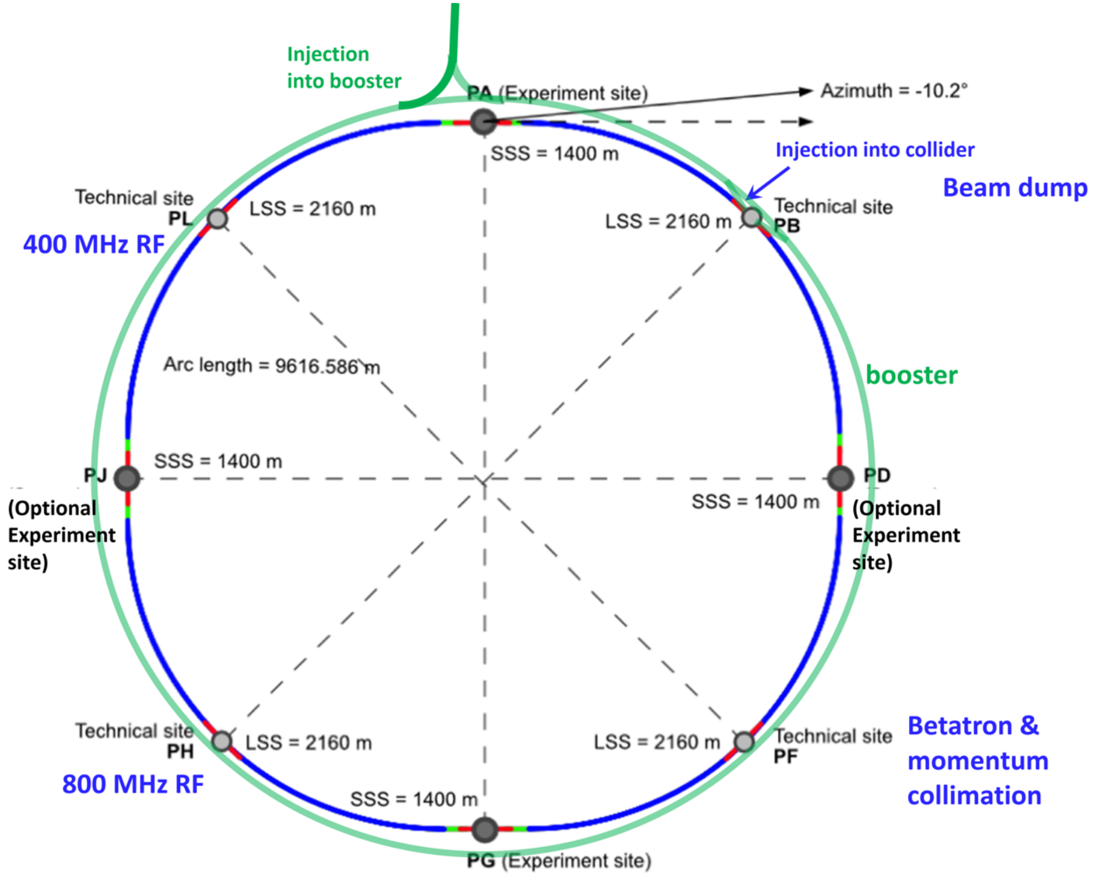
FCC-UK, 11 Nov 2025
Durham

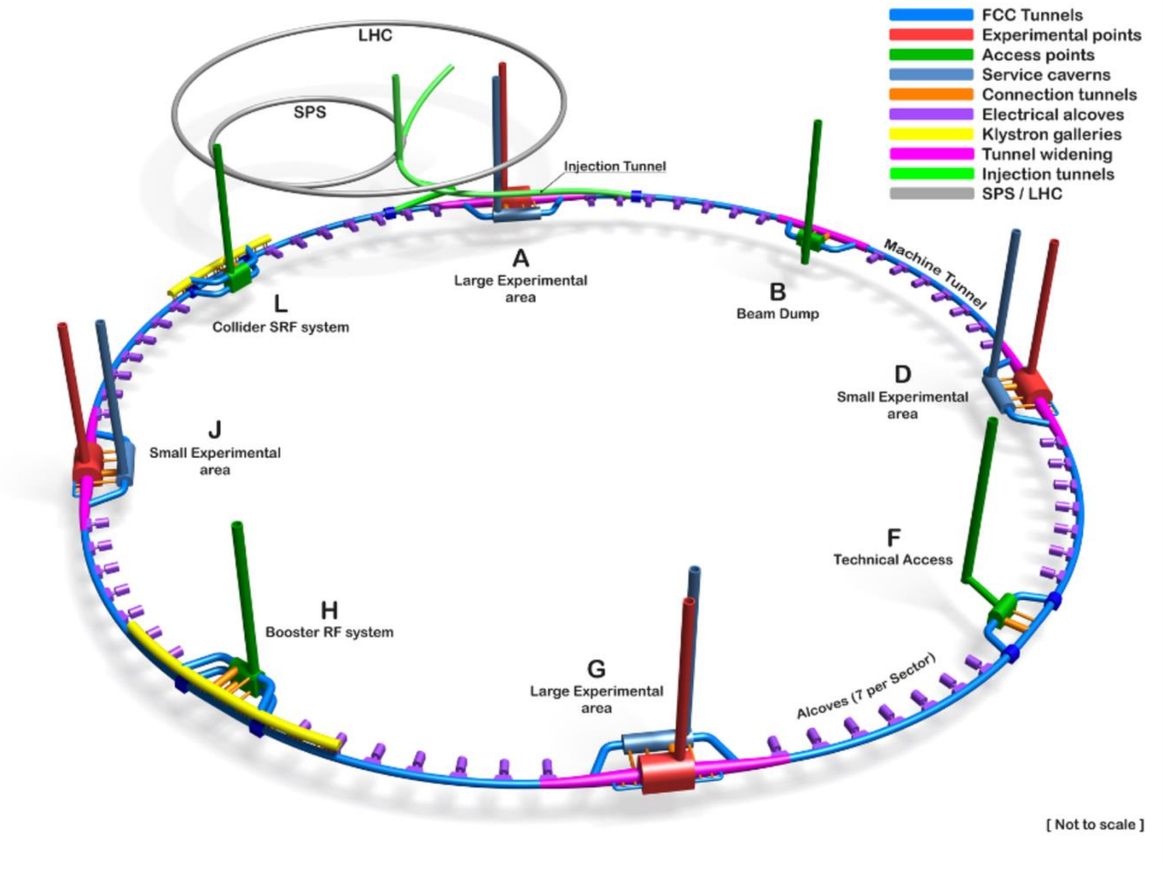
Mogens Dam,
for the
FCC-ee Detector Concepts
Working Group



NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

FCC-ee

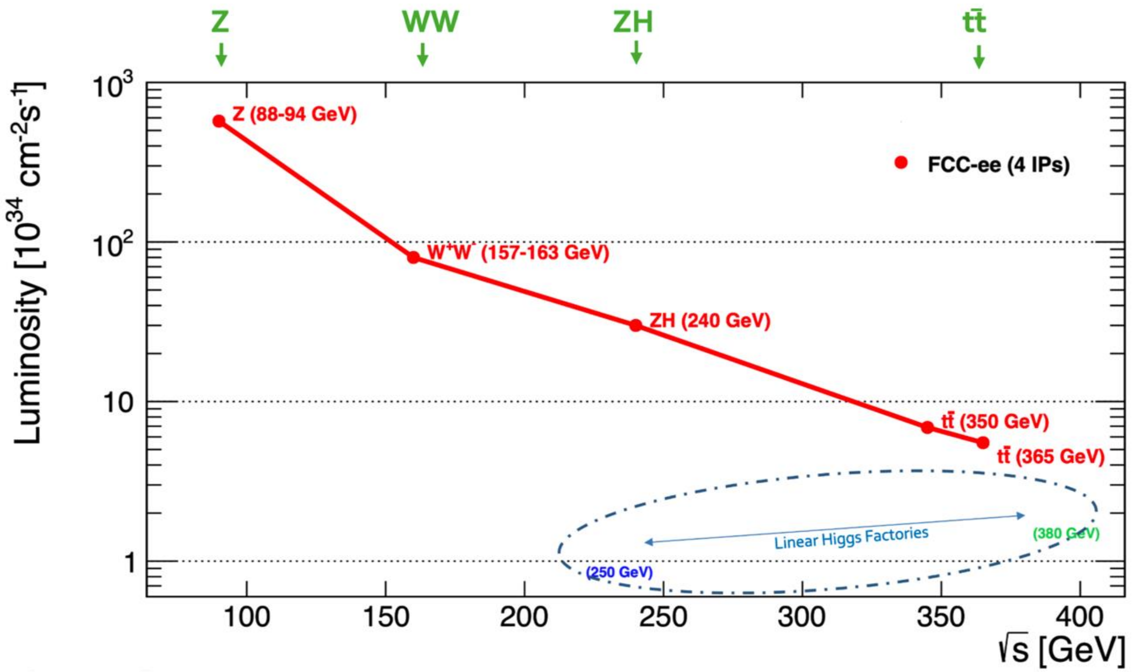




- Double ring e^+e^- collider, 91 km
- Large crossing angle 30 mrad, crab-waist optics
- Top-up injection
  - Separate booster ring

- Four experimental areas / experiments
  - Experimental diversity - control of overall systematic uncertainties
  - Sustainability - physics/TWh

FCC-ee Luminosity and Conditions



Z peak	$\sqrt{s}\sim$ 91 GeV	4 years	6×10^{12}	$e^+e^-\to Z$
WW threshold	$\sqrt{s}\sim$ 160 GeV	2 years	2.4×10^{8}	$e^+e^-\to W^+W^-$
ZH maximum	$\sqrt{s}\sim$ 240 GeV	3 years	2.3×10^{6}	$e^+e^-\to ZH$
$t\bar{t}$ threshold	$\sqrt{s}\sim$ 365 GeV	2 years	2×10^{6}	$e^+e^-\to t\bar{t}$
[s-channel Higgs	$\sqrt{s}$ = 125 GeV	5? years	~5000	$e^+e^-\to H_{125}$]

FCC-ee parameters		Z	W^+W^-	ZH	ttbar
√s	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	**140**	20	7.5	1.5
Bunch spacing	ns	25	160	680	5000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section	pb	70,000	30	10	8
Event rate	Hz	**100,000**	6	0.5	0.1
"Pile up" parameter [μ]	10^{-6}	2,500	1	1	1

Experimentally, Z pole is the most challenging

- Extremely large statistics
- Physics event rates of ~100 kHz
- Bunch spacing at 25 ns
  - "Continuous" beams, no bunch trains, no power pulsing
- However, no pileup, no underlying event
  - …well, pileup of 2.5×10^{-3} at Z pole

Detector Requirements and Challenges

Very Rich Physics Programme → Challenging Detectors

Higgs Factory Programme

- At √s=240 and √s=365 GeV collect 2.6M HZ and 150k WW→ H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (~4 σ) via loop diagrams
- Unique possibility: *s*-channel $e^+e^- \rightarrow$ H at 125 GeV

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^{8} WW events
- × 500 improvement of statistical precision on EWPO: m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, R_b, m_W, Γ_W, …
- 2×10^{8} tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

- **Absolute normalisation of luminosity to 10^{-5} - 10^{-4} level**
- **Relative normalisation to $\mathcal{O}(10^{-6})$ [e.g. $\Gamma_{had}/\Gamma_{\ell}$]**
  - Acceptance definition to $\mathcal{O}$(10 µm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean, boosted): 10 × BelleII stats.
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/√E**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

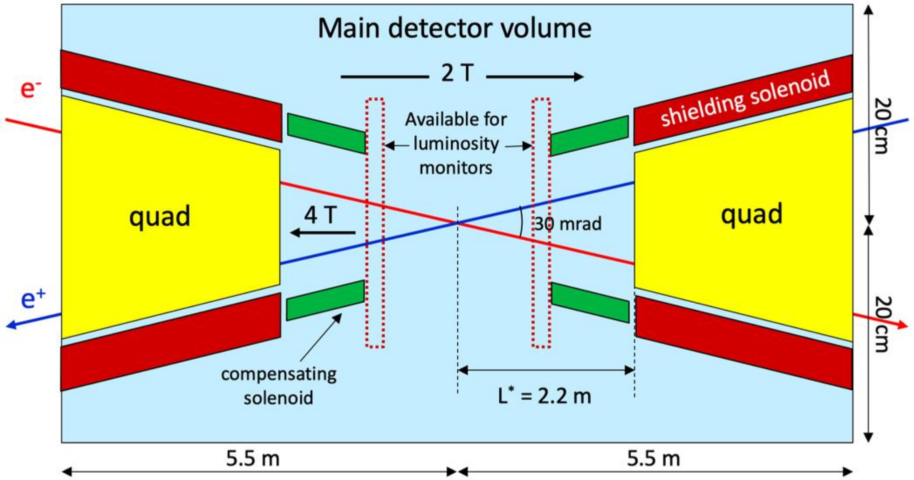
- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

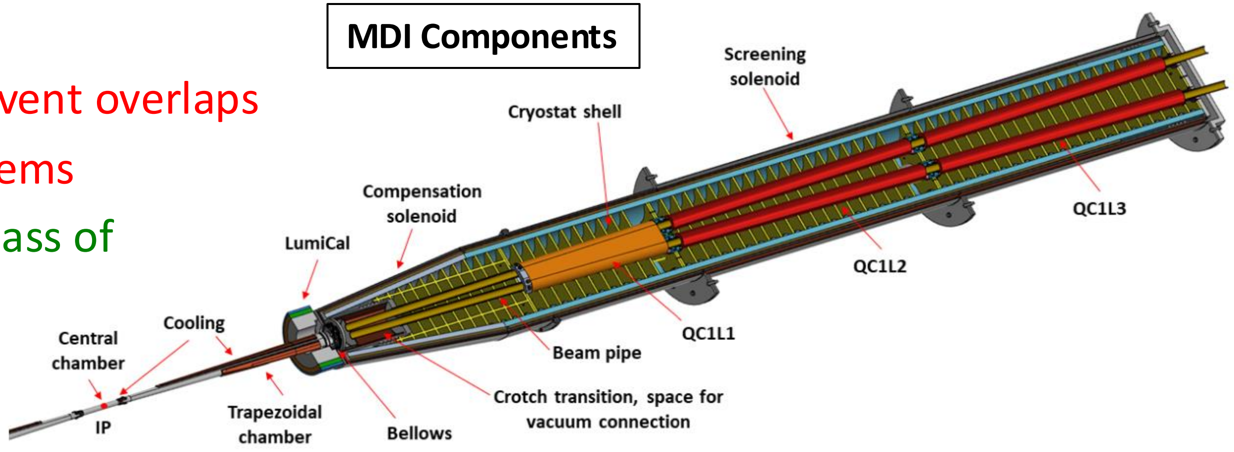
Experimental Challenges

- 30 mrad horizontal crossing angle
  - Detector B-field limited to 2Tesla (@ Z energy) – beam emittance control
    - Alternative compensation scheme under study; may allow ~3 Tesla
  - Tightly packed MDI (Machine Detector Interface) region
    - Last quadrupole at L^*=2.2 m (→2.4m); compensating solenoid in front
- Continuous collisions (no bunch trains); 25 ns bunch spacing
  - Power management and cooling of detectors (no power pulsing)
- Extremely high luminosities
  - High statistical precision -- control of systematics to $\mathcal{O}(10^{-5})$ level
  - Online and offline handling of $\mathcal{O}(10^{13})$ events *for precision physics*
    - "Big Data"
- Physics events at 200 kHz
  - Detector response time ≤ 1 µs to minimise dead-time and event overlaps
  - Strong requirements on front-end electronics and DAQ systems
    - At the same time, keep material budget low: minimise mass of electronics, cables, cooling, …

Central part of detector volume – top view



MDI Components

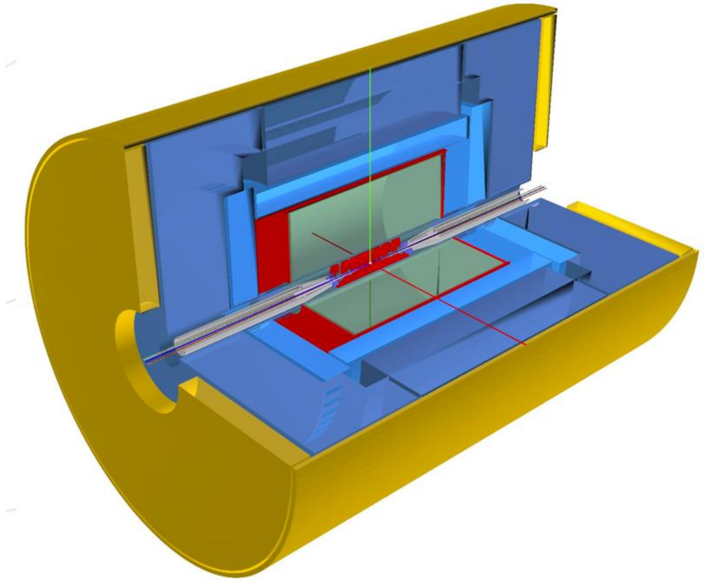


Detector Concepts

Detector Concepts

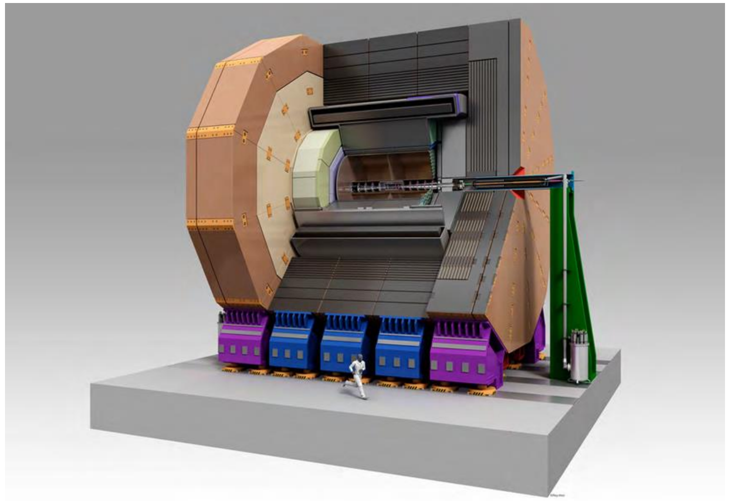
Detector concepts form the link between performance requirements and technological capabilities

- **guide R&D** and give **feedback on performance** impact of technical solutions



Two main ingredients:

- full **simulation** model including **digitisation** and **reconstruction**
  - enable validation of single particle performance with prototypes
  - realistic prediction of full-event performance
- overall **engineering**
  - act and respond to the design of the MDI
  - guide the optimisation of the global structure and parameters



Experimental collaborations forming at a later stage

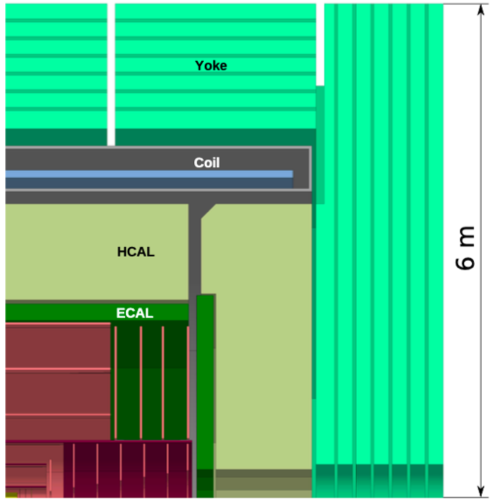
- maintain freedom to combine technologies, e.g. tracking and calorimetry
  - ***"plug & play"***

Currently, four concepts under study

- At least one more on the horizon… Further ideas very welcome

Detector Concepts Currently under study

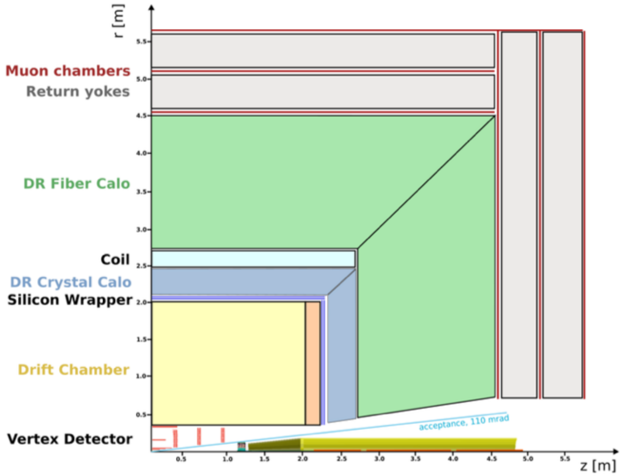
CLD



- Well established design
  - ILC → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry – very high granularity
- Coil outside calorimetry, muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

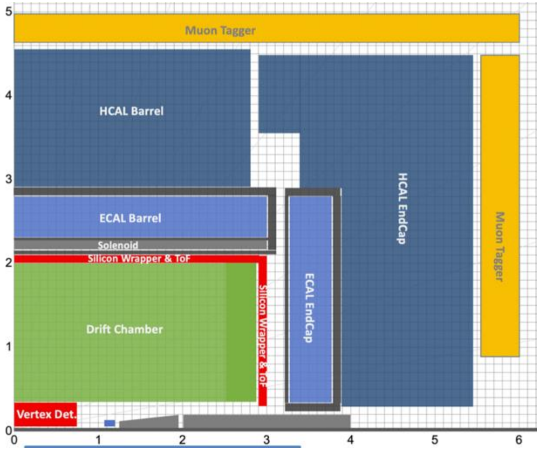
IDEA



- Design developed specifically for FCC-ee and CEPC
- Si VXD; ultra-light drift chamber with powerful PID
- Crystal ECAL w. dual readout
- Compact, light coil;
- Dual readout fibre calorimeter
- Muon system

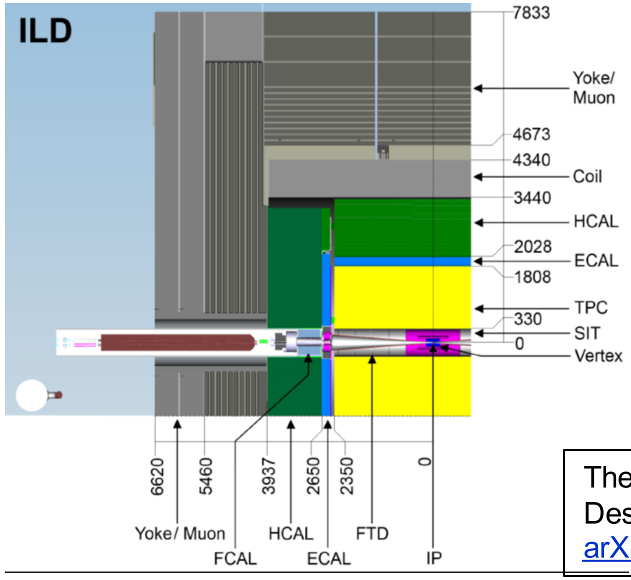
https://doi.org/10.48550/arXiv.2502.21223

Allegro



- Still in early design phase
- Design centred around High granularity **Noble Liquid ECAL**
  - Pb+LAr (or denser W+LKr)
- Si VXD
- Tracker: Drift chamber, straws, or Si
- Steel-scintillator HCAL
- Coil outside ECAL in same cryostat
- Muon system

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391



- Designed originally for operation at the ILC
- Together with SiD, ancestor of CLD.
- Main difference and signature element:
  - Large-volume time projection chamber (TPC)

The International Linear Collider Technical Design Report - Volume 4: Detectors
arXiv:1306.6329

Options for subdetector technologies

Muon System:
- Micromegas, TGC, MWPC, RPC, drift tubes

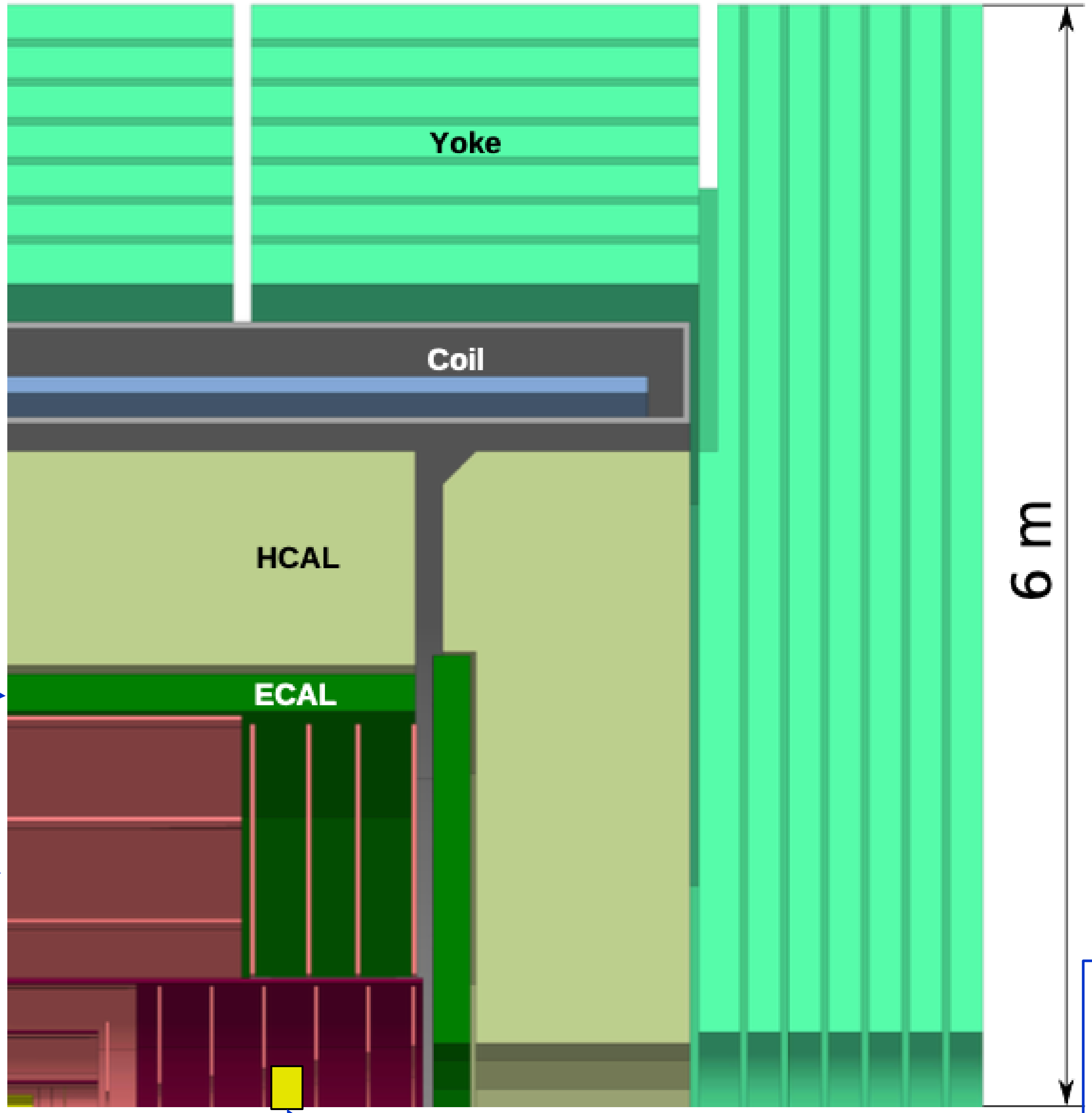
Superconducting Coil:
- Limited to 2 T by beam emittance considerations (30 mrad crossing angle)
- Inside / outside calorimeter system

HCAL options:
- Fe / Scintillating tiles
- Dual readout radial fibres

ECAL options:
- W/Si sandwich
- Pb / LAr (or alternatively W / LKr)
- Crystal
- Granita: Crystal grains in heavy liquid

Main tracker options:
- Full silicon (MAPS+Strips, full MAPS)
- Drift chamber or straw chamber
- Time Projection Chamber (TPC)

Vertex detector
- Thin 50 µm MAPS silicon pixels sensors, 3x3 μm^2 resolution



Luminosity monitor
- Small angle Bhabha scattering, $e^+e^- \rightarrow e^+e^-$
- W/Si sandwich calorimeter

Detector Concepts Status and Plans – Towards next phase

- **Sub-systems and subsystem technologies largely interchangeable at this stage**
  - VXD, tracking, muon system
- **Full simulation: huge progress already being made**
- **Still some way to full digitisation / full reconstruction**
  - Digitisation requires technological input from DRD groups
- **Topics for detector concepts group**
  - Full detector, full event **performance:**
    - Tracking-system momentum resolution**,** jet energy resolution**,** jet flavour ID, tau ID, V0 recon, …
  - Physics and background induced **occupancies**, data flow
    - strawman **(T)DAQ architectures**
  - **Services** routing principal paths and volume requirements
  - **Detector opening** and maintenance scenarios (with MDI)
  - Detector **installation sequence** and resulting individual sub-detector assembly timelines
    - Latter driven by fundamental architecture choices
      - Location of coil, large or small (plug) endcaps, readout of calorimeters (radially, tangentially, axially)

Detector Subsystems and Technologies

CERN Hosted Detector R&D Collaborations

Status of DRD collaborations

DRD Meetings:
https://indico.cern.ch/category/6805/

Proposals (search for DRDC public)
https://cds.cern.ch/?ln=en

DRD1	DRD2	DRD4	DRD6	DRD3	DRD5	DRD7	DRD8
Gaseous	Liquid	PID and Photon	Calorimetry	Solid state	Quantum	Electronics	Integration
Ex RD51				Ex RD50, RD42			

DRD1, DRD2, DRD4, DRD6: Fully approved for 3 years by CERN Research Board in **December 2023**

DRD3, DRD5, DRD7: Fully approved for 3 years by CERN Research Board in **June 2024**

DRD8: Fully approved for 3 years in November 2024

5 July 2024 Report from DRDC - Inés Gil-Botella 8

16

FCC Detector Expressions of Interest

Input to ESPPU 2026 - and for the next phase of our work

Purpose of the EoIs

- Build community of institutes interested in development of dedicated sub-detectors
- Trigger interactions in the community to get (self-) organised around sub-detectors
  - Not parallel to, but largely within DRDs - and Detector Concepts WG
- Call launced in October 2024; Asked for few pages
  - Scope of planned activities over next 3-5 years
  - Partners (institutes); contact persons
  - Connection with technological activities in DRD framework, and between subdetectors and concept groups
  - References to detailed documentation
- 39 documents received
  - Documents joined and submitted with "cover letter" to ESPPU:
    - ESPPU submissions: https://indico.cern.ch/event/1530285/
    - Individual EoIs: https://indico.cern.ch/event/1529896/

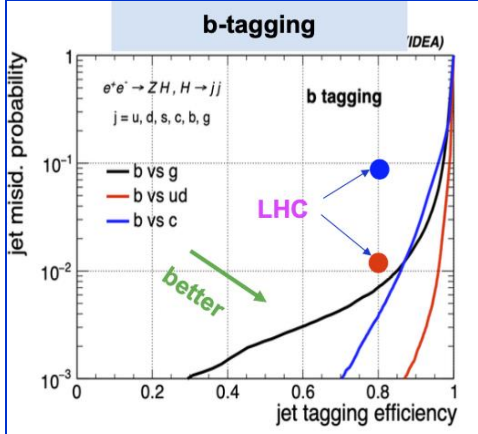
Topic	Number of EoIs
Detector Concepts	4
Vertex Detector	2
Main Tracker and Envelopes	10
Calorimeters	8
Luminometers	2
Particle ID	1
Coil	1
Muon	5
Trigger/DAQ/Electronics	3
Algorithms, AI	2
Machine Detector Interface	1

Measurement of impact parameters
- Secondary vertices, flavour tagging, lifetime measurements

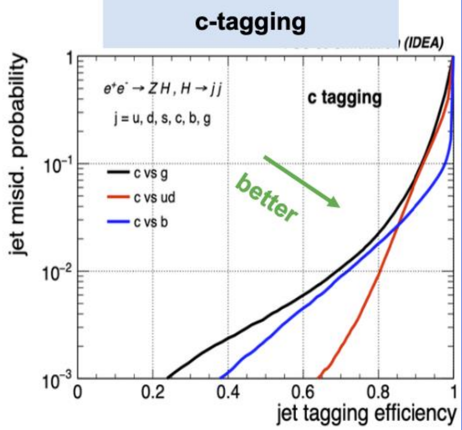
Conditions/requirements
- Moderate radiation environments
- No need for picosecond timing
- High resolution and low multiple scattering i key

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

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



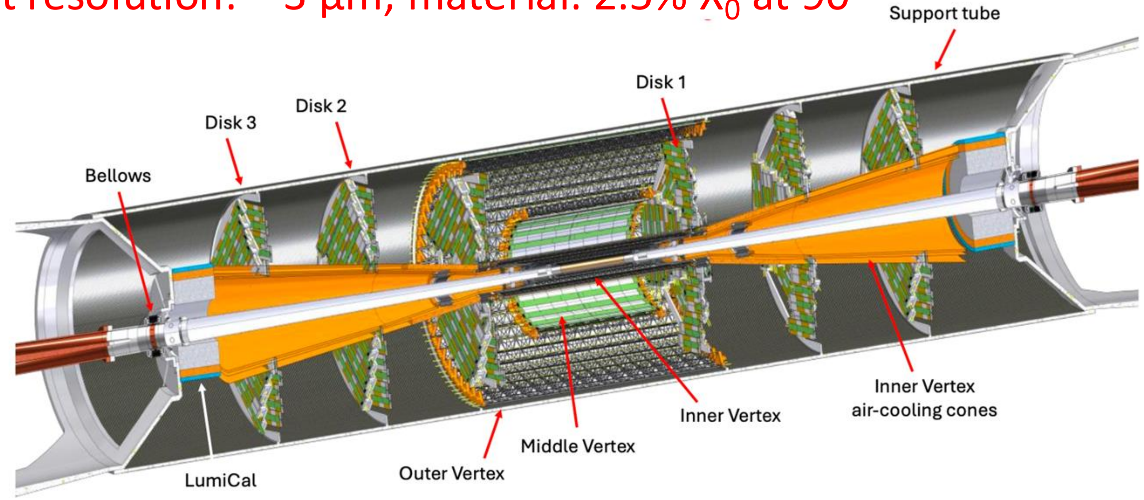
WP	Eff (b)	Mistag (g)	Mistag (ud)	Mistag (c)
Loose	90%	2%	0.1%	2%
Medium	80%	0.7%	<0.1%	0.3%

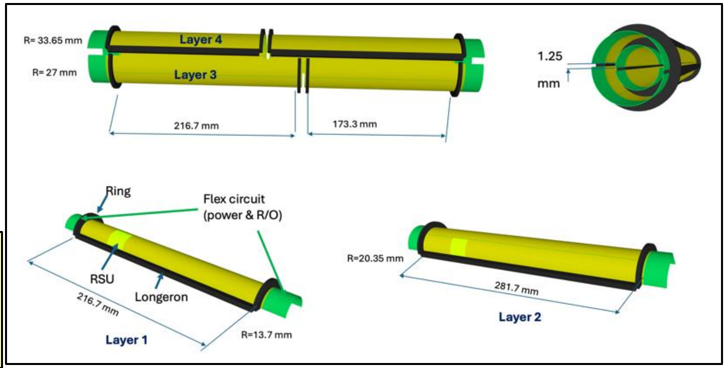


WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

Very substantial improvement w.r.t. LHC

Example: Recent engineering level design study (INFN Pisa, Frascati)
- All sensors are 50 μm MAPS (Monolithic Active Pixel Sensors)
- Three inner barrel layers: 25 x 25 μm^2, 50 mW/cm^2, air cooling
- Middel + outer barrel layers: 150 x 50 μm^2, water cooled
- Three disks in each direction: as middle/outer barrel layers
- Hit resolution: ~3 μm; material: 2.5% X_0 at 90^o

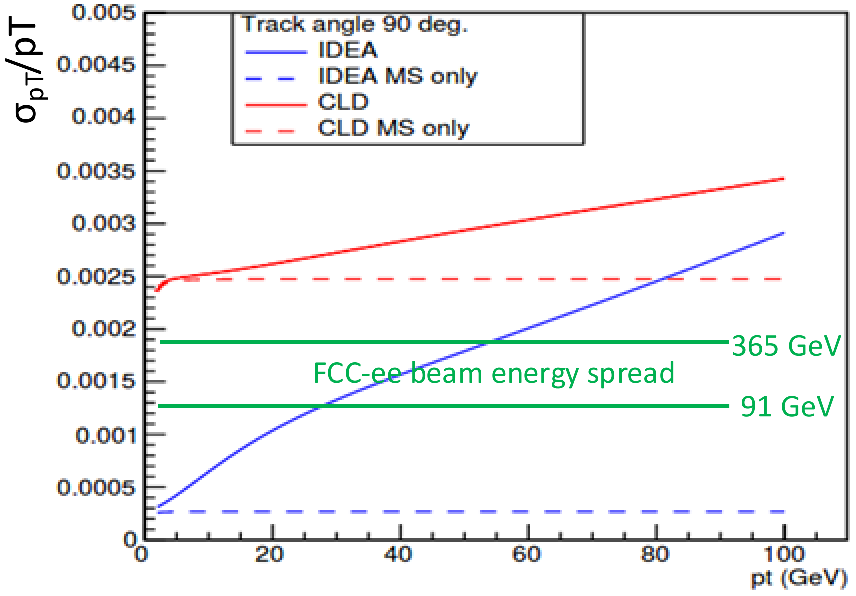




Study of alternate ultralight layout of inner layers:
- Sensors bent around beam pipe
- ~60% reduction of material

Tracking Systems - Momentum Measurement

Momentum resolution tends to be multiple scattering dominated

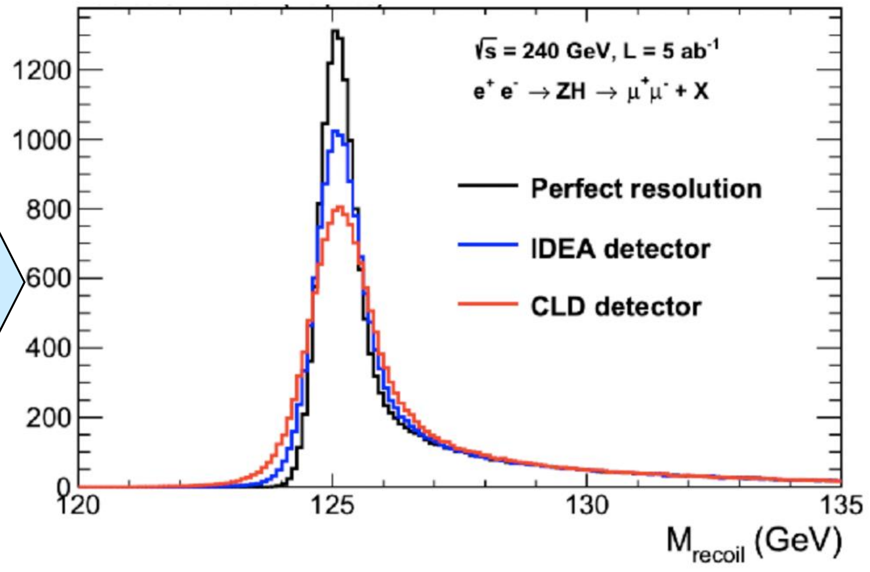


Example Si tracker: CLD

- All-Si tracker
- total material budget 11% X_0

Example gaseous: IDEA

- Drift Chamber [< 2% X_0]
- vtx [2.5% X_0]
- Si "wrapper" surrounding drift chamber



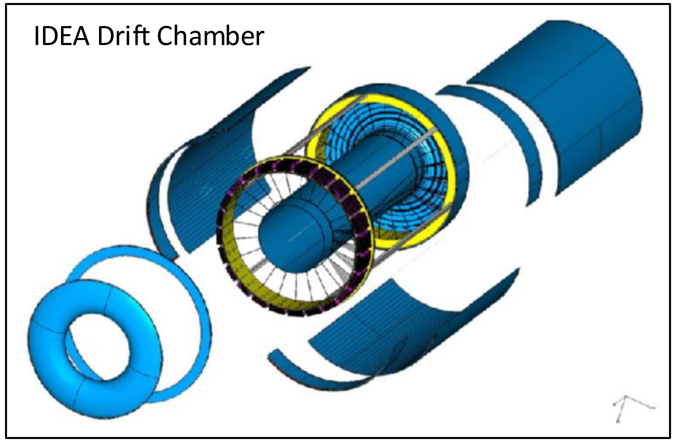
At relevant momenta, transparency more important than point resolution

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

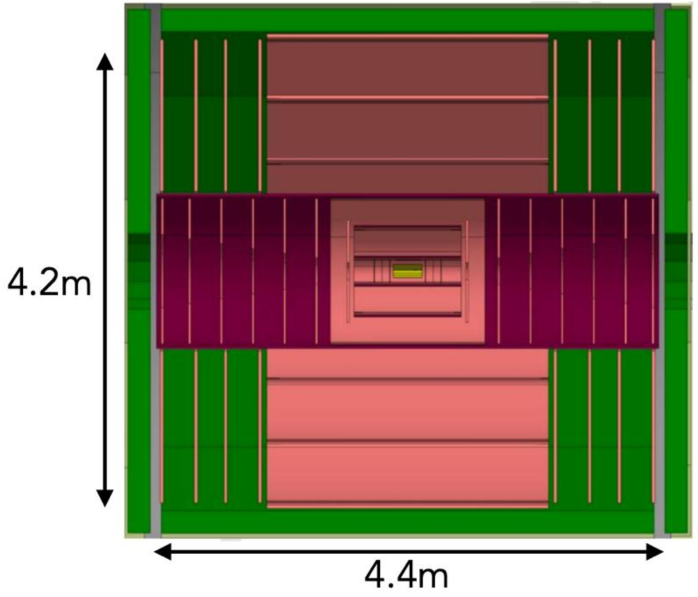
mult.scat

resolution

Strong case for gaseous trackers

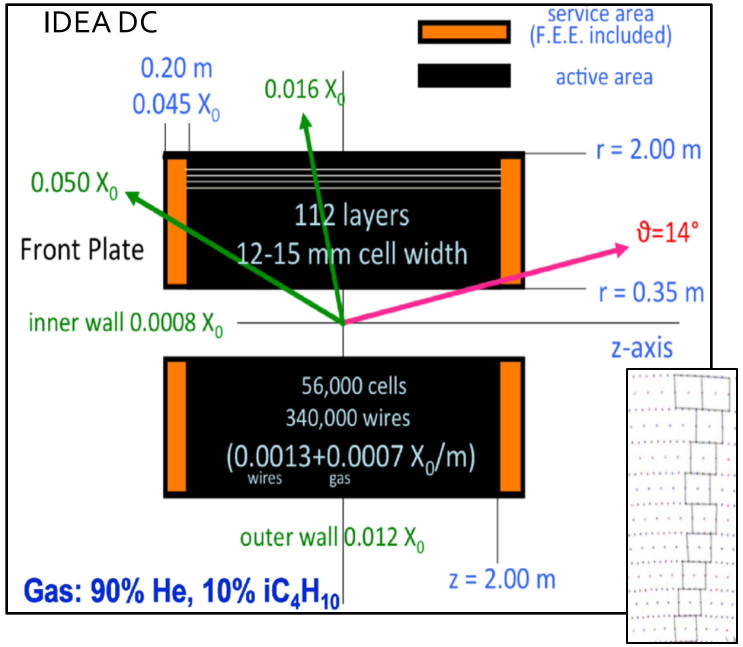


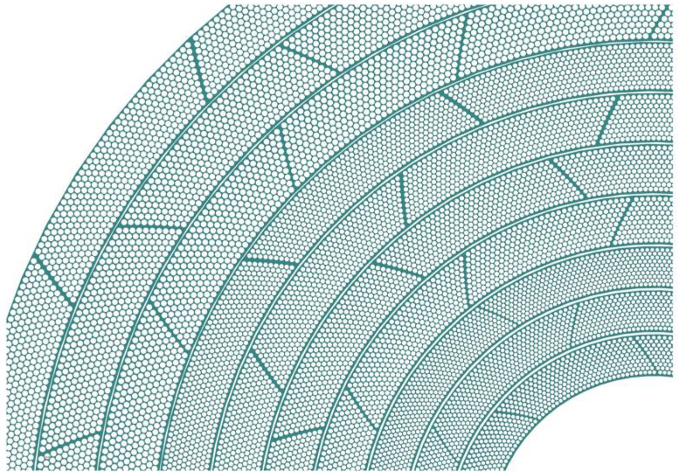
Several Main Tracker Options under Study



Full silicon
- CLD

Drift Chamber
- IDEA

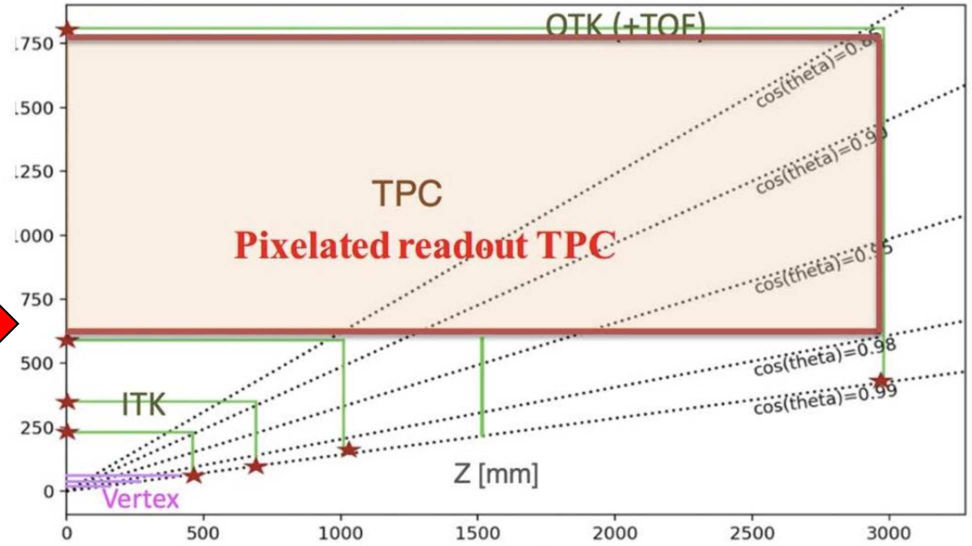




Straw Tracker

Time Projection Chamber

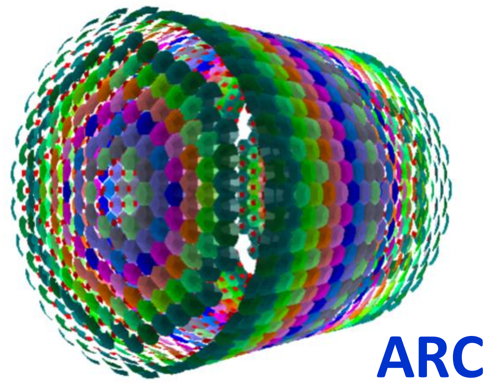
Here shown with an inner radius of 60 cm, outside Si [CEPC reference detector]

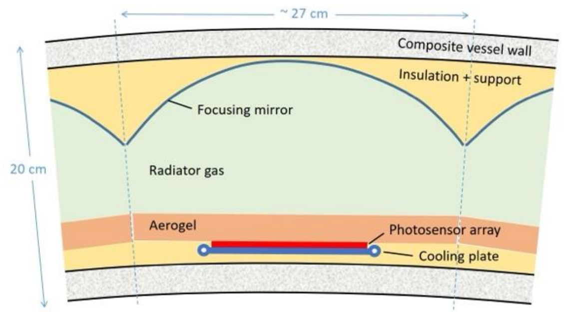


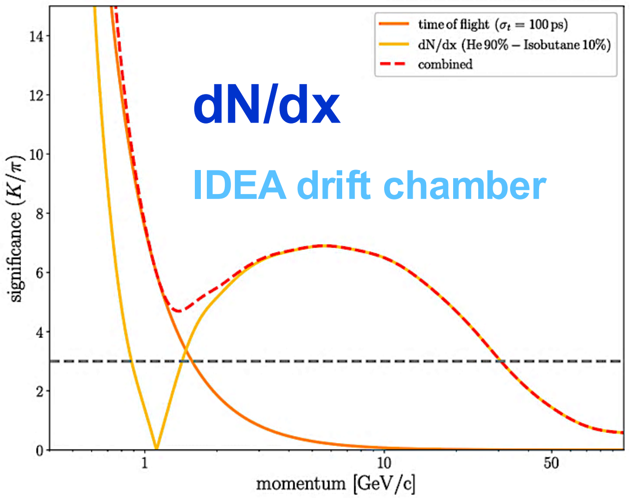
Charged Particle Identification

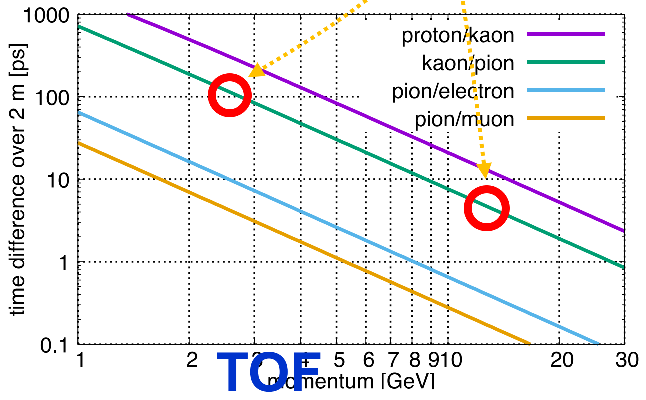
PID capabilities across a wide momentum range is essential for flavour physics

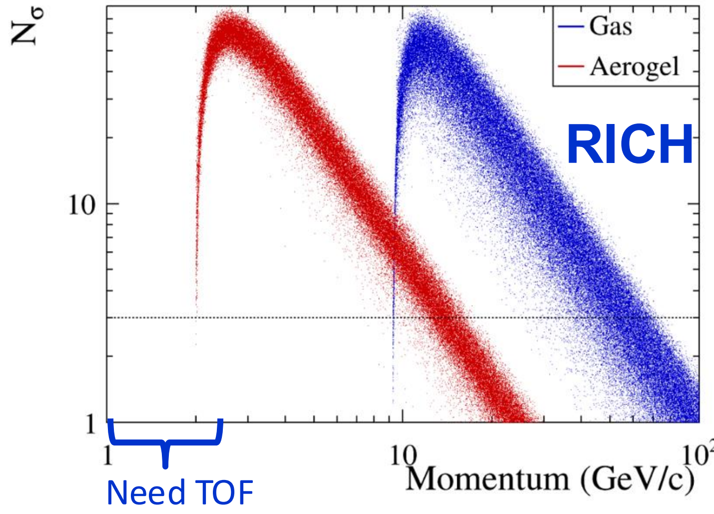
- Drift Chamber and Straw Tracker promise >3σ π/K separation up to ~35 GeV based on **cluster counting, dN/dx.** Similar (or better) performance from TPC.
  - Cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of δT ≲ 100 ps
- **Time of flight (TOF) alone** with δT of ~10 ps over 2 m (LGAD,…)
  - could provide 3σ π/K separation up to ~5 GeV (only)
- **RICH counter** being investigated (for silicon-based trackers): Array of RICH Cells – **ARC**
  - Compact geometry (depth: 20 cm, 0.1 X_0) via use of SiPMs
  - Aerogel + Gas (C_4F_{10} or pressurised Xe): 3σ π/K separation in 2.5 - 50 GeV range
  - Need ~50 ps TOF measurement to cover momenta < 2.5 GeV











Calorimetry – Requirements

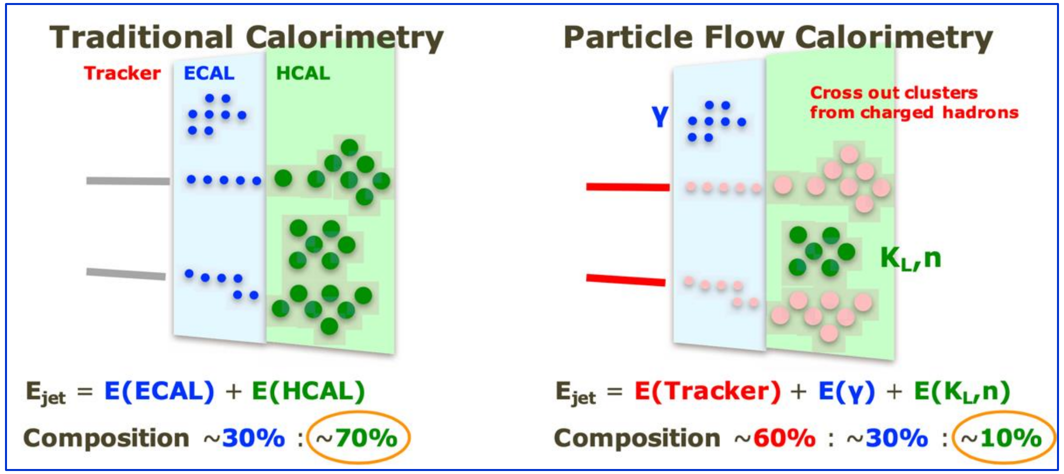
Energy coverage < 180 GeV ⇒ moderate depth: **22 X_0, 6-8 λ_{int}**

3-4 % di-jet mass resolution needed to differentiate between W- and Z-origin of di-jet systems

☞ Translates into requirement on jet energy resolution:

$\boxed{\text{Jet energy:} \quad \delta E_{jet}/E_{jet} \simeq 30\% / \sqrt{E}\ [\text{GeV}]}$

Improved jet energy resolution via **Particle Flow** method



☞ High granularity !
☞ Possibly combined with Dual Readout

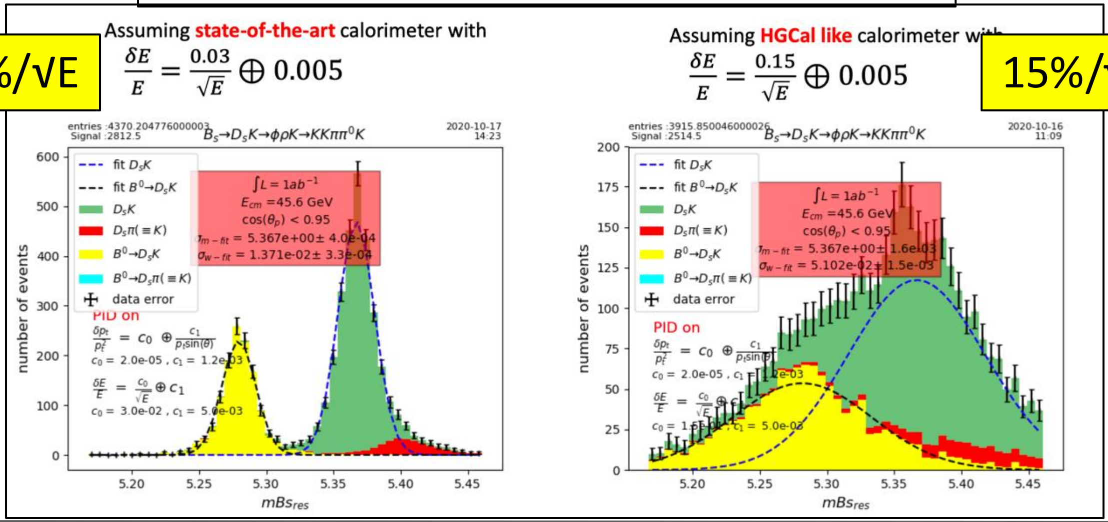
(Some) requirements

- Energy resolution
  - γs & neutral hadrons for Pflow; e/π separation via E/p
- Dynamic range: 200 MeV – 180 GeV
  - Flavour & τ phys: sensitivity to π^0s down to few-100 MeV
- Granularity: for Pflow and PID
  - e/π separation from shower shape; γ/π^0 separation
- Hermeticity, uniformity, calibrability, stability
  - Low systematics !!!

Example of B-physics final state with π^0

3%/√E

15%/√E



Calorimeter Technologies being pursued

Eur.Phys.J.Plus 136 (2021) 10, 1066, arXiv:2109.00391

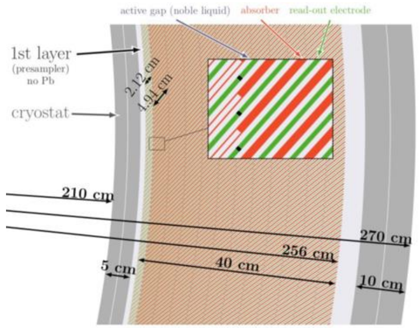
All concepts aim at Particle Flow reconstruction

- with different emphasis on granularity, energy resolution, stability

Noble Liquid ECAL + Tile HCAL:

- fine longitudinal sampling (w.r.t. ATLAS, 4 → 12 layers)
- PB+LAr or denser W+LKr; warm or cold electronics
- CALICE or ATLAS style scintillating tile HCAL

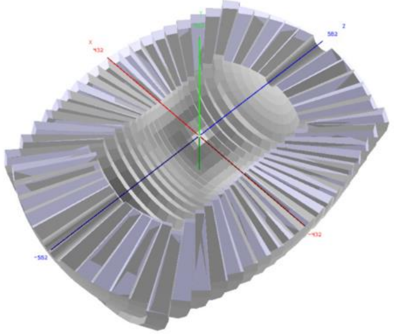
EM: $\sigma(E)/E \simeq$ 8-10%/$\sqrt{E}$
Jet: $\sigma(E)/E \simeq$ 4% @ 50 GeV



Fibre-based Dual-Readout :

- copper or steel matrix; Cherenkov and scintillating fibres, SiPMs
- very fine transverse granularity, longitudinal information via timing

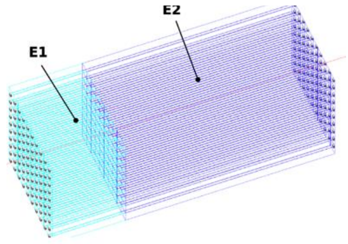
EM: $\sigma(E)/E \simeq$ 11%/$\sqrt{E}$
Jet: $\sigma(E)/E \simeq$ 3-4% @ 50 GeV



Segmented crystals with Dual Readout:

- Fine transverse segmentation, two longitudinal layers; SiPMs
- Excellent EM energy resolution of ~3%/√E
- Combined with fibre-based DR calorimeter as HCAL

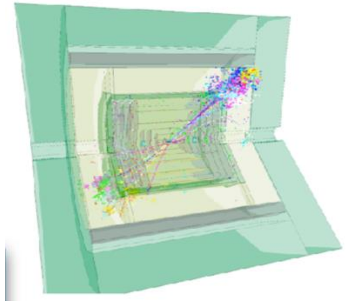
EM: $\sigma(E)/E \simeq$ 3%/$\sqrt{E}$
Jet: $\sigma(E)/E \simeq$ 3-4% @ 50 GeV



CALICE-style sandwich with embedded front-end electronics:

- Tungsten-silicon ECAL; Extremely fine segmentation: (0.5 cm)^3
- Steel-scintillator HCAL; SiPM-on-Tile; Fine segmentation: (2.5 cm)^3
  - ❑ alternatives: scintillator strip ECAL, gaseous HCAL

EM: $\sigma(E)/E \simeq$ 16%/$\sqrt{E}$
Jet: $\sigma(E)/E \simeq$ 3-4% @ 50 GeV

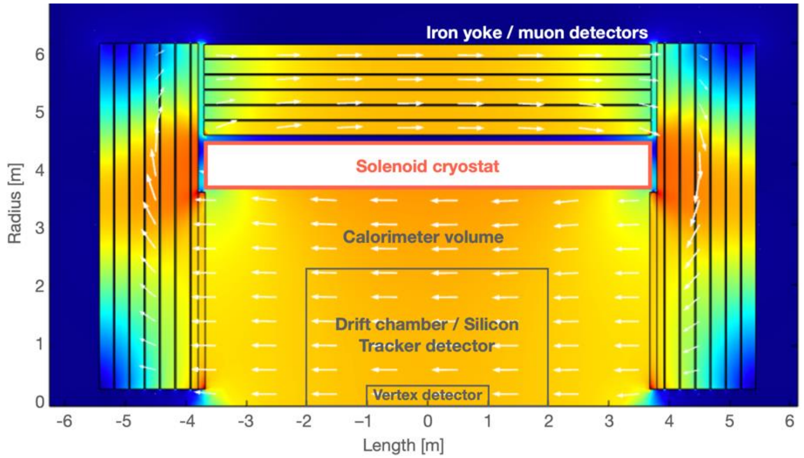


Detector Solenoid

Two placement options being pursued

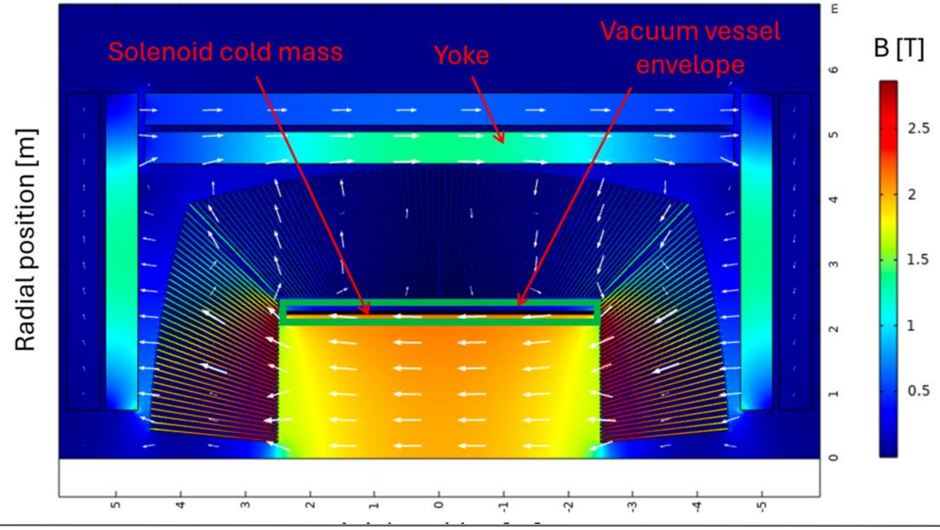
CLD + ILD

Coil outside calorimeter system



IDEA + ALLEGRO

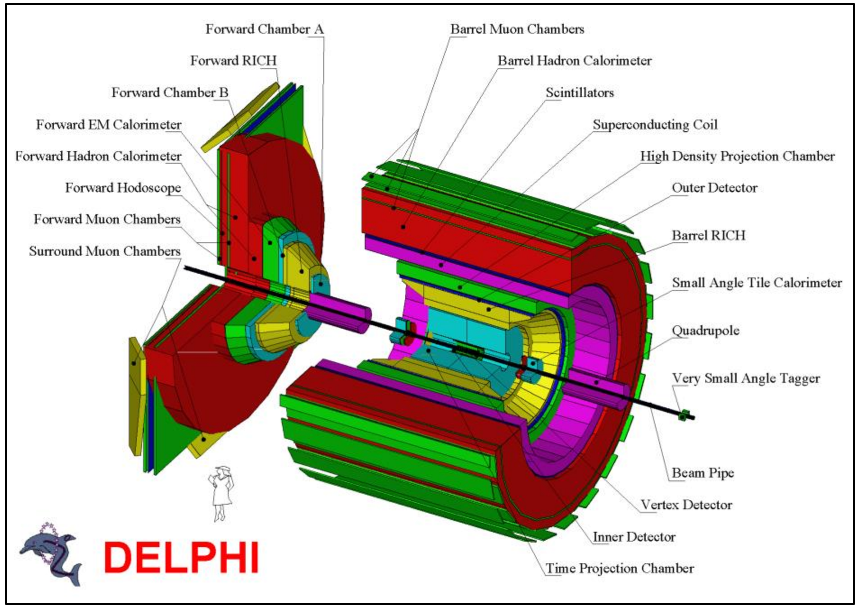
Coil between outside ECAL inside HCAL

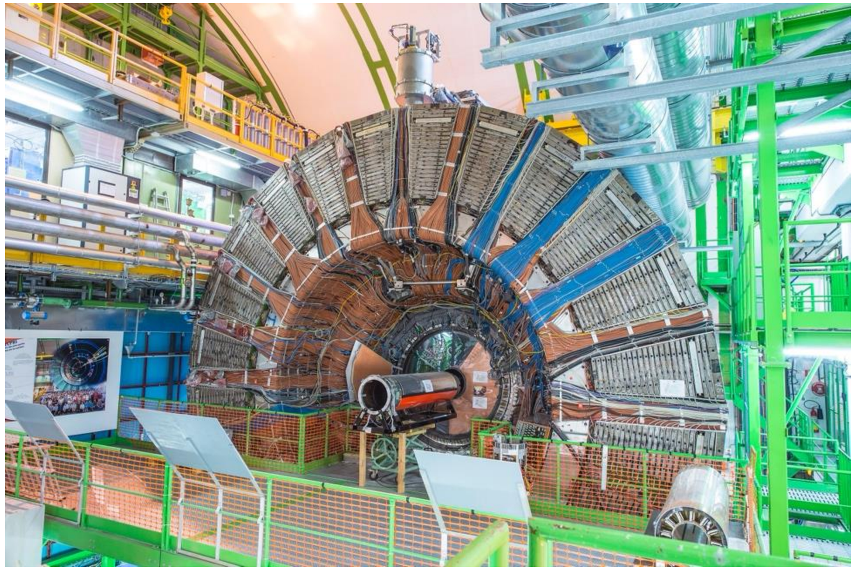


Current efforts

- CERN detector magnet group
  - Conceptual design of ultra-light 2 T solenoid
    - Operational temperature: 4 K
    - Radial envelope ~30 cm; total material ~ 0.8 X_0
- EoI (INFN, Uni. Milan, CERN, et al.)
  - 3 Tesla HTS Superconducting Solenoid for IDEA
    - Operational temperature: 20 K
    - Radial envelope ~12 cm; total material 1.5 X_0
- CERN magnet group: *"Experience tells that development & construction of large superconducting coil takes ≳ a decade"*
  - Early design needed as input general detector design
  - Need to identify labs with appropriate expertice and strength

Example: DELPHI Coil constructed at RAL in the 1980'ies





Parameters:

B = 1.2 T; bore: R $\simeq$2m, L $\simeq$ 5m

Complicated transport from RAL to CERN
- Here close to the goal in P8: Col de la Faucille

Trigger(?) and Readout System

Workshop, Nov. 2025

Goal of readout system

- *Full efficiency* for all SM annihilation physics events
  - Aiming at $\mathcal{O}(10^{-6} - 10^{-5})$ relative normalisations
- No loss of potential BSM signatures
  - e.g., heavy (slow) particles decaying late, LLPs

In particular at Tera-Z, challenging conditions

- 40 MHz BX rate
- Physics rate at $\mathcal{O}$(200 kHz)
  - Physics event in every 1/200 BX
- Example Challenge - VXD:
  - Pixel hit rate: ~200 MHz/cm^2 in VXD inner layer
    - Incoherent pairs from beam-beam interactions
    - Including cluster size of 5 and safety factor of 3

      $\Rightarrow$ **$\mathcal{O}$(5 Gbit/cm^2/sec)**
    - Would saturate "standard" 1 Gbit/cm^2/sec link

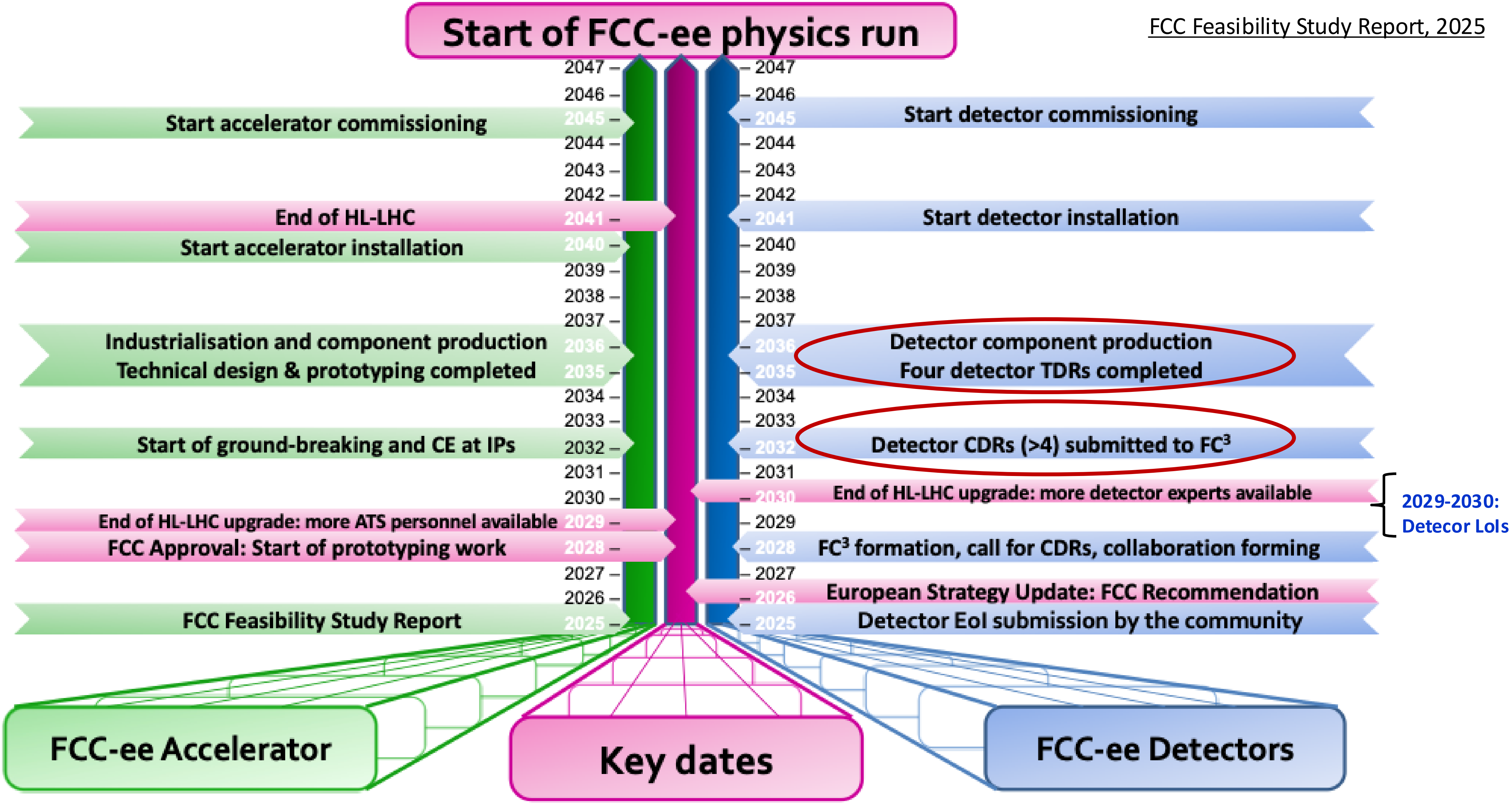
How to organise readout? *"To TDAQ or to DAQ"*

- **Hardware** (or software?) **trigger** as at LEP and LHC
  - Which sub-detectors can a trigger decision be based on?
  - High BX rate: Need for local **latency buffering** a la LHC?
    - Material / power / cooling for on-detector buffering?
- **Free streaming** of *self-triggered* detector sensors
  - **Push** data off detector elements
    - all front-ends are free-running, self-triggered
  - Off-detector event building based on precise time-stamping
  - Potential enormous data rate out of sub-detectors
    - Easily Tbit/sec (Tbps) from VXD alone
    - Technical feasibly? Power needs,…?
      - In comparison: ePIC @ EiC plans to stream at max $\mathcal{O}$(100 Tbps) off detectors, $\mathcal{O}$(10 Tbps) to counting room, $\mathcal{O}$(100 Gbps) to tape

Need to consider TDAQ vs DAQ architecture as integral part of detector design

Possible Timeline

FCC Feasibility Study Report, 2025



Evolution of Detector Concepts Work Package

In DRDs:

RnD / technologies

- Gaseous Detectors (DRD1)
- Liquid Detectors (DRD2)
- Semiconductor Detectors (DRD3)
- Photodetectors & PID (DRD4)
- Quantum Sensors (DRD5)
- Calorimetry (DRD6)
- Electronics (DRD7)
- Mechanics (DRD8)

US R&D Collaborations (RDCs) focus on generic (non-targeted), interdisciplinary and blue sky R&D – will collaborate where possible.

In FCC Detector concepts:

a) Generic system-level studies
(create structure as needed or organize workshops)

- Tracker (e.g. Si + straw tracker) & PID
- Calorimetry
- Muons
- TDAQ
- Luminometry
- Magnet

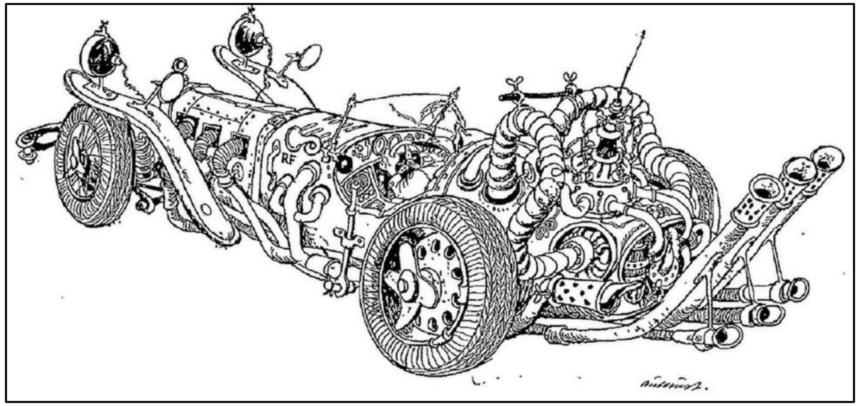
b) Concept-specific studies
(using specific envelopes/support structures, or physics benchmarks)

- Allegro
- CLD
- IDEA
- ILD
- …

Non-exclusive membership, need to preserve synergies and unity of the community!

Conclusions

- Rich physics programme translates into formidable detector challenge
  - Very high precison; very high rates
- Sensor R&D concentrated in DRD groups
- It is timely – and soon possible -- to ramp up efforts significantly
  - Demonstrators by 2030, scalable prototypes by 2035
    - Indicative - likely different for vertex detector and calorimeters
- Detector concepts working group have challenges to tackle
  - Full simulation / digitisation / reconstruction for performance studies
  - Overall engineering
    - Support, cabling routes, cooling, installation
- EoI submission to ESPP demonstrated strong community interest to develop detector and sub-detector systems
  - Self-organisation on-going
  - Concrete plans for next phase
  - New ideas continue to appear
- Still ample room and time for new technologies and concepts



Contacts for getting involved

e-groups

- [FCC-PED-DetectorConcepts]
- [FCC-PED-DetectorConcepts-Allegro]
- [FCC-PED-DetectorConcepts-Calorimetry]
- [FCC-PED-DetectorConcepts-Cld]
- [FCC-PED-DetectorConcepts-Idea]
- [FCC-PED-DetectorConcepts-Ild]
- [FCC-PED-DetectorConcepts-Luminometry]
- [FCC-PED-DetectorConcepts-Magnet]
- [FCC-PED-DetectorConcepts-Muon]
- [FCC-PED-DetectorConcepts-TDAQ]
- [FCC-PED-DetectorConcepts-TDAQ-workshop]
- [FCC-PED-DetectorConcepts-Tracker]

Personal contacts

- Detector Concepts Working Group
  - Felix Sefkow, DESY
  - Marc-André Pleier, NBL
  - Mogens Dam, NBI
- Allegro Detector Concept
  - Martin Aleksa, CERN
- CLD Detector Concept
  - Jinlong Zhang, Argonne
- IDEA Detector Concept
  - Paolo Giacomelli, INFN Bolonga
- ILD Detector Concept
  - Ties Benhke, DESY

Extras