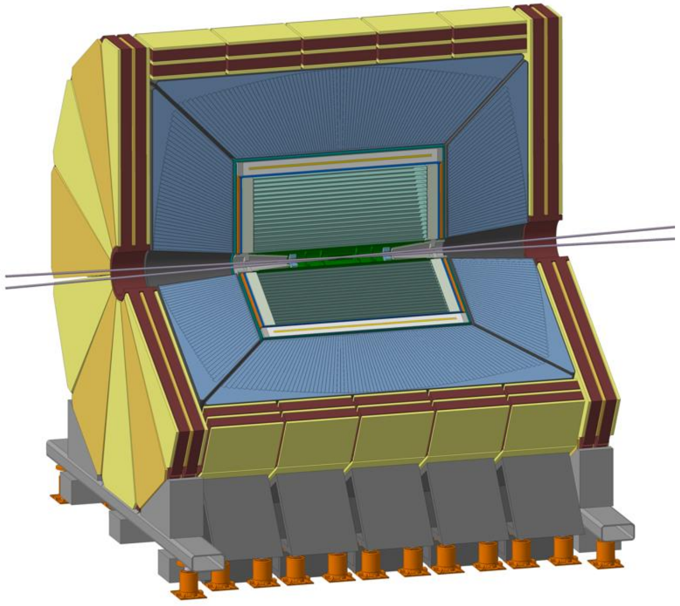
FUTURE CIRCULAR COLLIDER

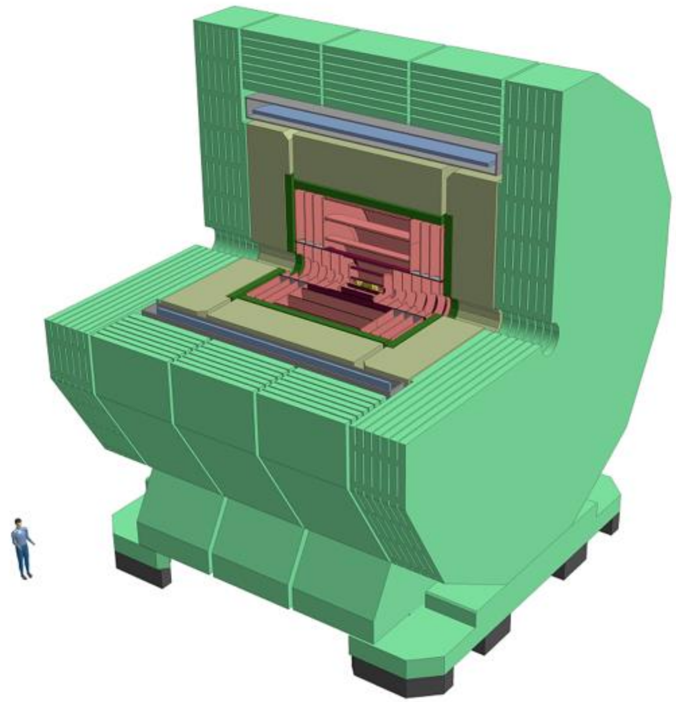
NIELS BOHR INSTITUTE
UNIVERSITY OF COPENHAGEN

FCC-ee Detector Concepts

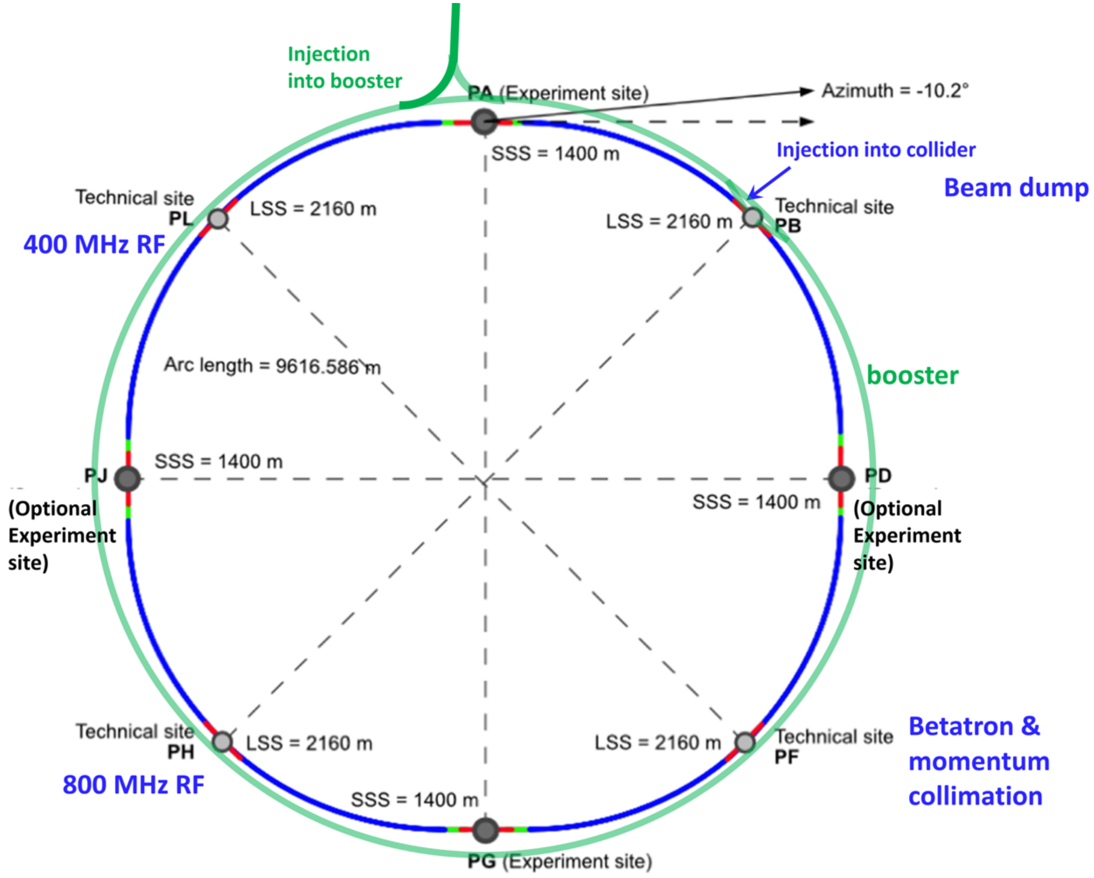
Mogens Dam,
Niels Bohr Institute

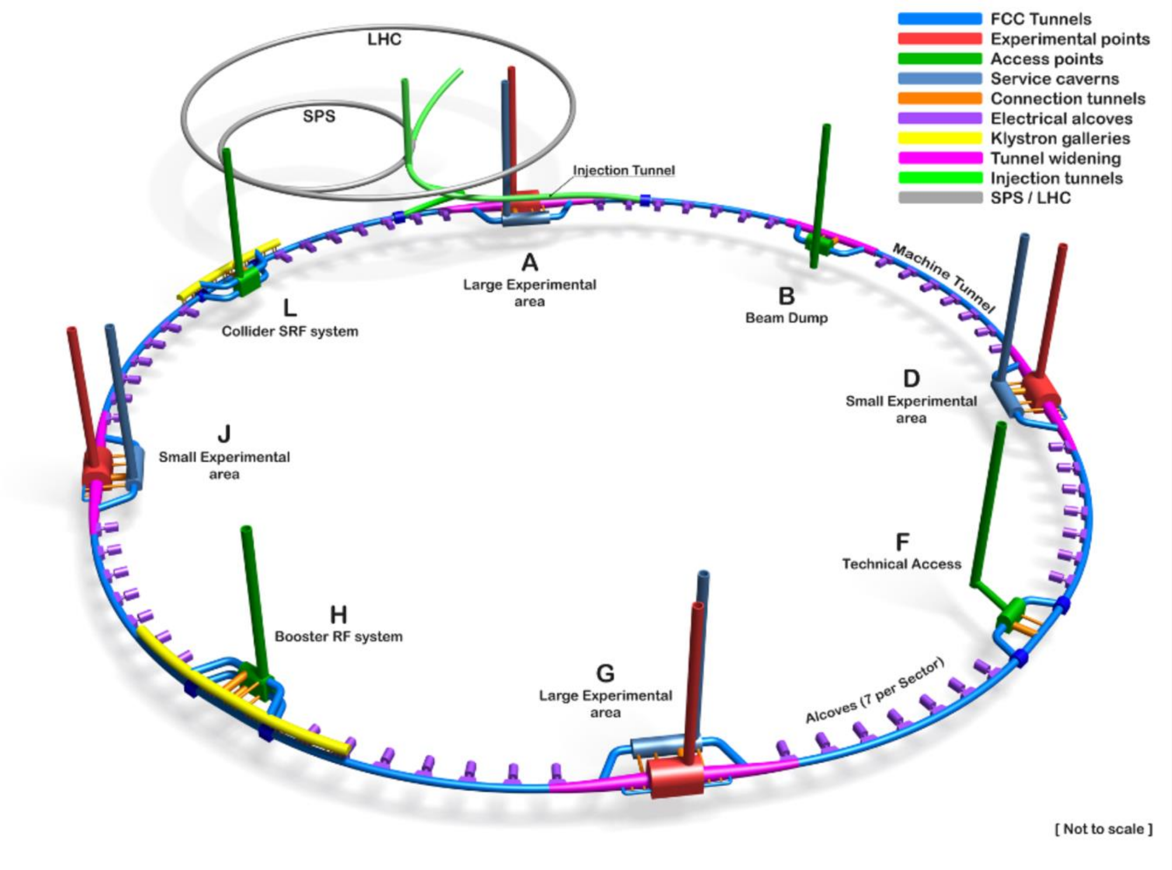


FCC open day
IFIC, Valancia
16th April, 2026



FCC-ee

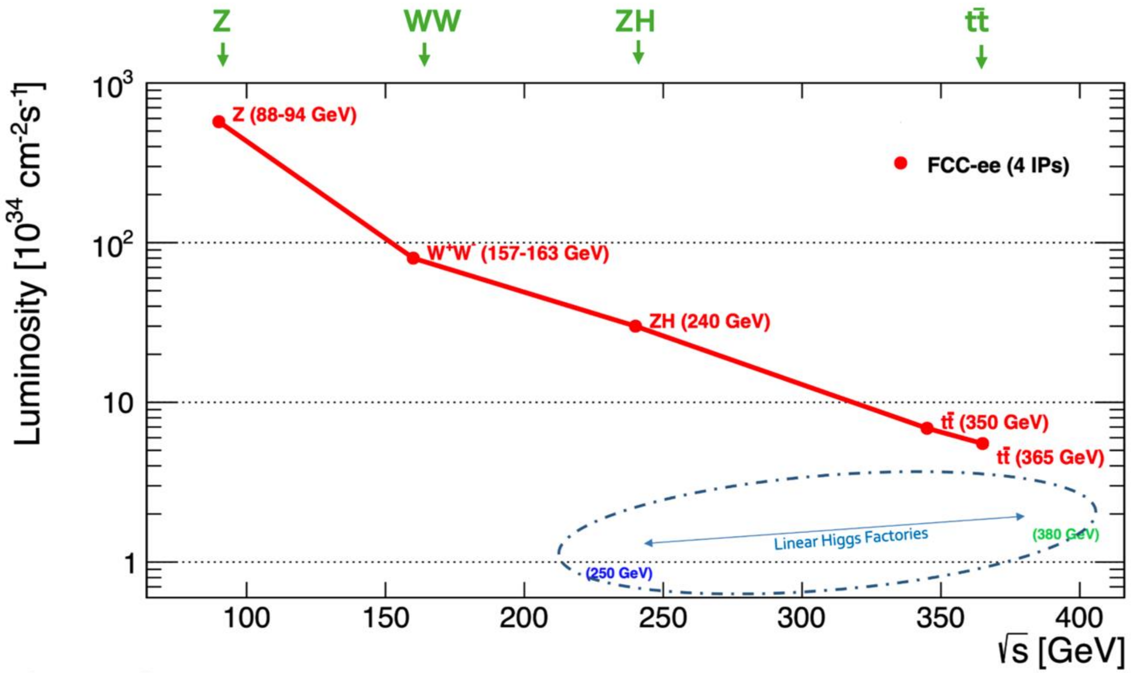




- Double ring e^+e^- collider, 91 km
- Large crossing angle 30 mrad, crab-waist optics
- Top-up injection from separate booster ring

- Four experimental areas / experiments
  - Experimental diversity - control of overall systematic uncertainties
  - Higher statistics
  - 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 $\sqrt{s}$=240 and $\sqrt{s}$=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 $\sigma(p_T)/p_T = \mathcal{O}(10^{-3})$ @ $p_T \sim$ 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 of channels 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^{11} 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 %/$\sqrt{E}$; sensitivity to $\mathcal{O}$(100 MeV) photons**
- **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

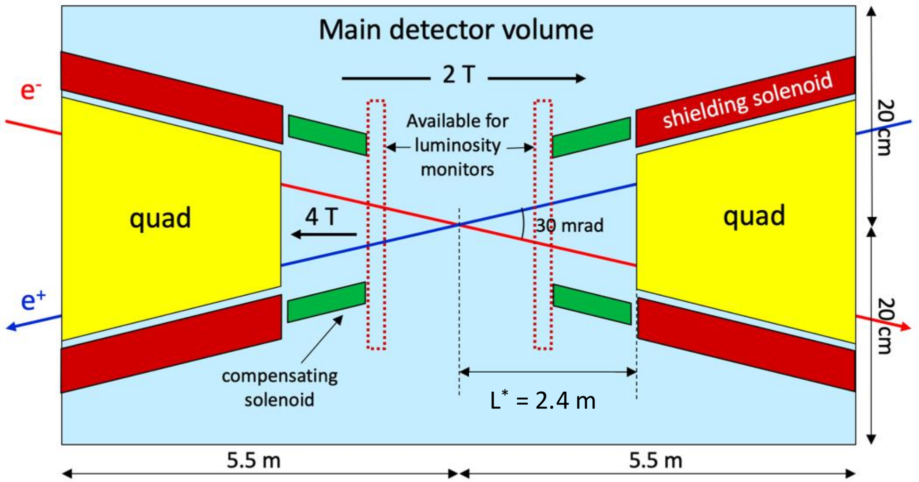
- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

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

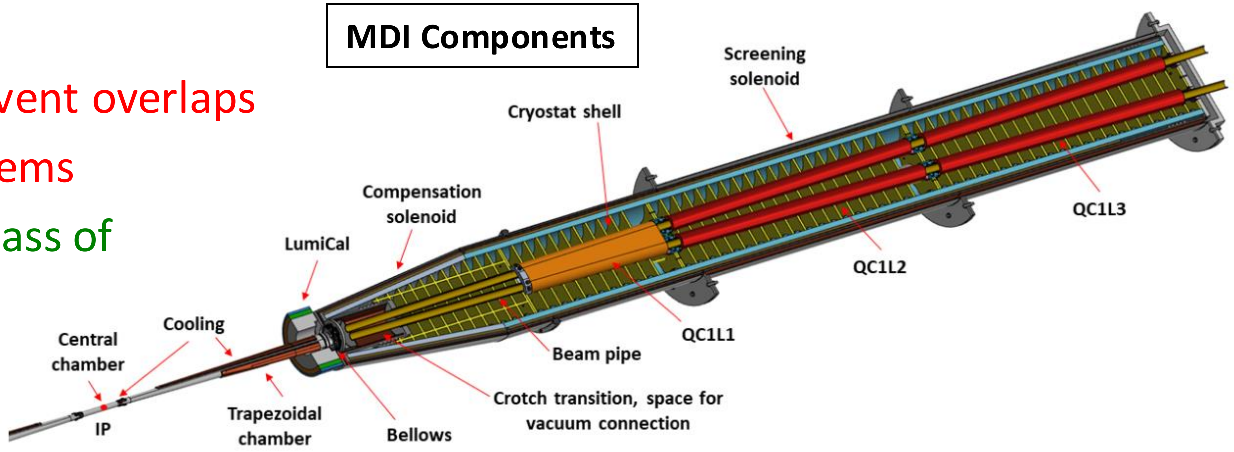
Experimental Challenges

- 30 mrad horizontal crossing angle
  - Detector B-field limited to 2 Tesla (@ 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^*= 2.4m; 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 high precision physics*
    - ”Big Data”
- Physics events at 200 kHz
  - Detector integration time ≤ 1 µs to minimise dead-time & 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:

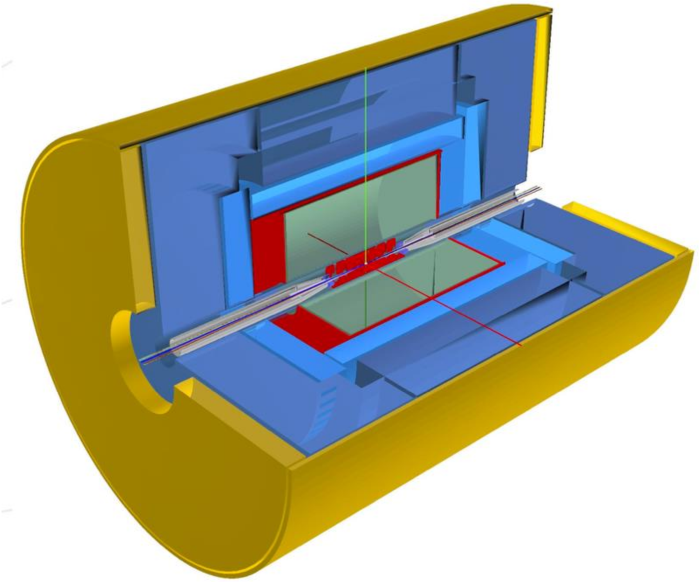
- full **simulation** model including **digitisation** and **reconstruction**
  - enable validation of single particle performance with prototypes
  - realistic prediction of full-event performance
- overall **engineering**
  - act and respond to the design of the MDI
  - guide the optimisation of the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

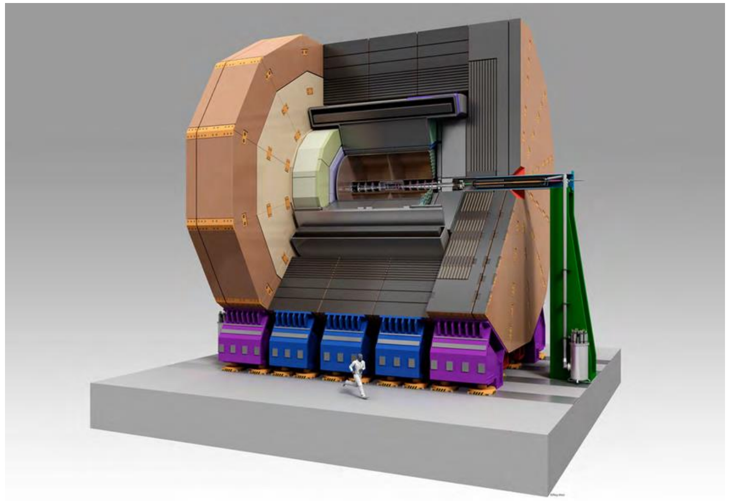
Experimental collaborations forming at a later stage

- maintain freedom to combine technologies, e.g. tracking and calorimetry
  - ***"plug & play"*** (key4hep)

Currently, four concepts under study

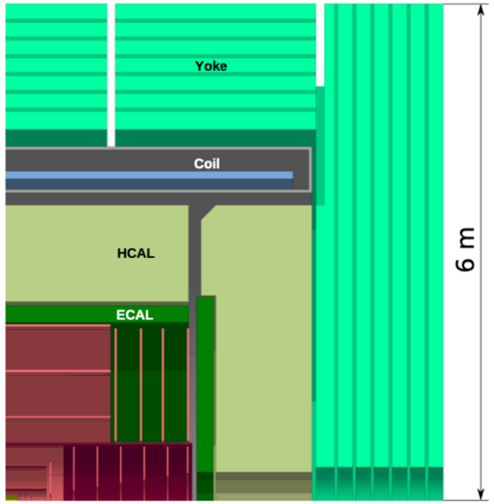
- At least one more ("*alfa*") on the horizon… Further ideas very welcome





Detector Concepts Currently under study

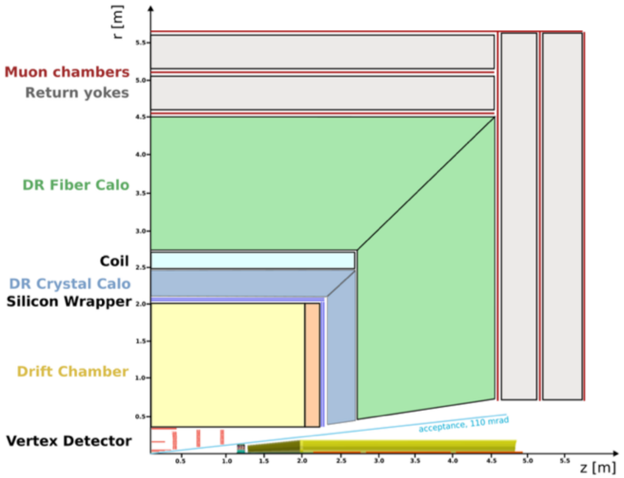
CLD



- Well established design
  - ILC/ILD+SiD → CLIC detector → CLD
- Full Si VXD + tracker
- CALICE-like calorimetry: W/Si + steel/scint. tiles. Very high granularity
- Coil outside calorimetry
- Instrumented yoke as muon system
- Possible detector optimizations
  - Improved σ_p/p, σ_E/E
  - PID: precise timing and RICH

arXiv:1911.12230

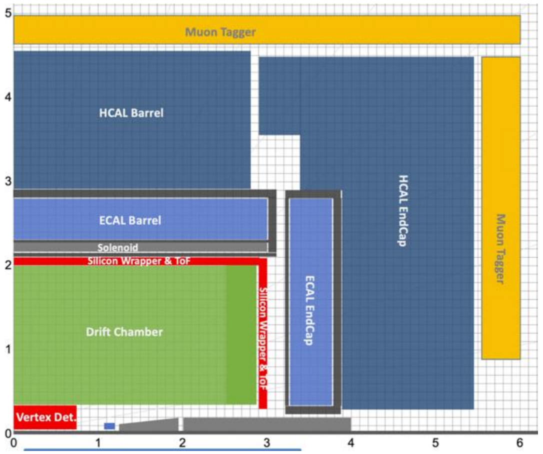
IDEA



- 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 HCAL
- Muon system

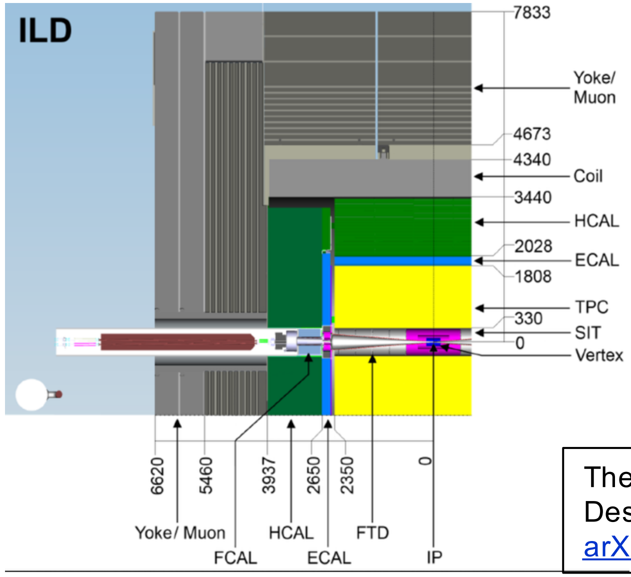
https://doi.org/10.48550/arXiv.2502.21223

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
- Main difference w.r.t. CLD and signature element:
  - Large-volume time projection chamber, TPC
- HCAL based on scintillating tiles or gaseous sensors

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

Proposed options for subdetector technologies

Muon System:
- Muon *tagger* or *tracker*
- µ-megas, MWPC, RPC, drift tubes, scintillator

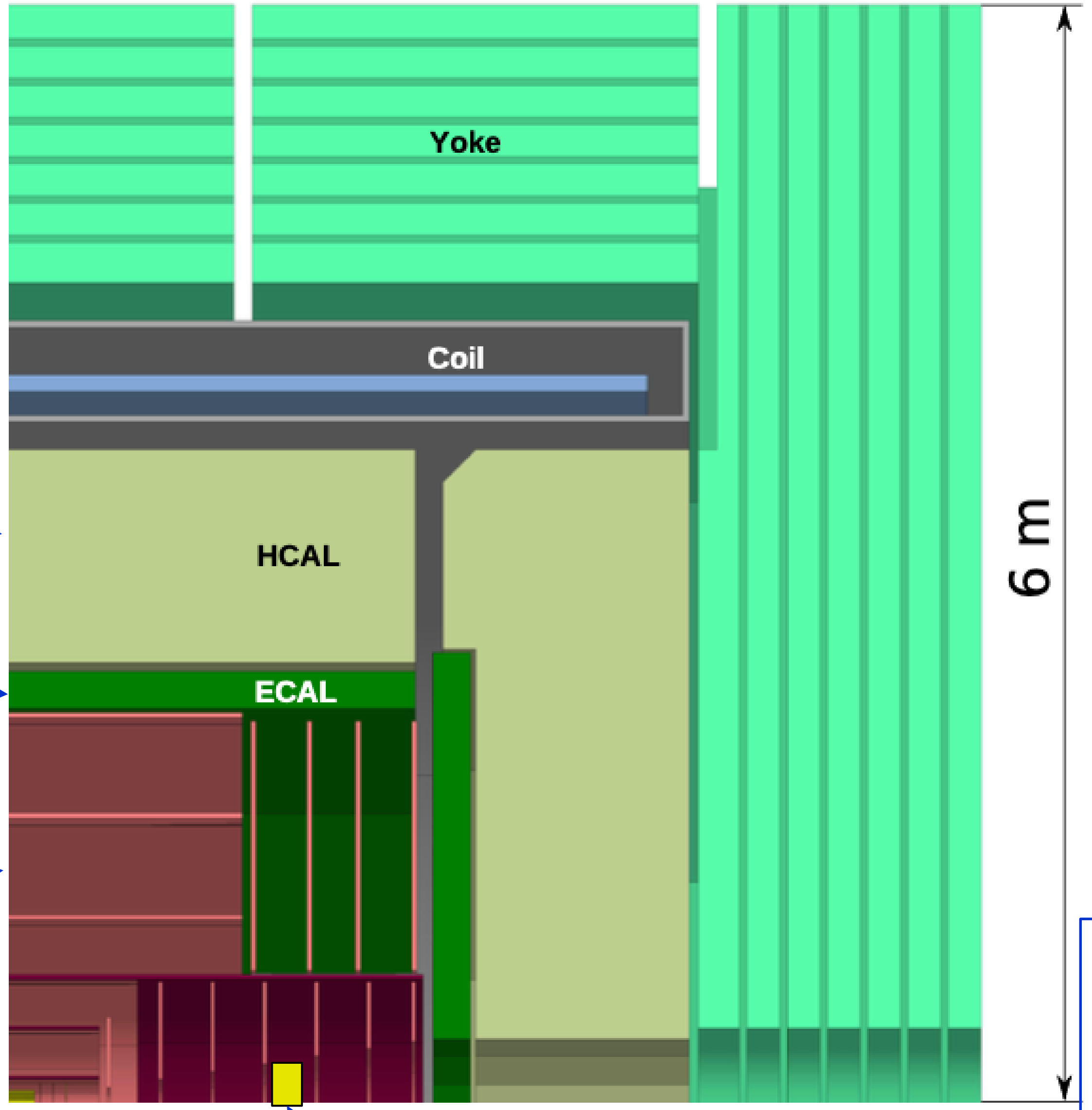
Superconducting Coil:
- Limited to 2 T (possibly 3T) by beam emittance considerations (crossing angle)
- Between ECAL and HCAL or ourside HCAL
- LTS or HTS technologies

HCAL options:
- Fe (steel) + scintillating tiles/gaseous (RPC/MPGD)
- Dual readout radial fibres

ECAL options:
- W/Si sandwich
- Noble Liquid: Pb/LAr (or denser W/LKr)
- Crystals
- 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 (possibly curved sensors)

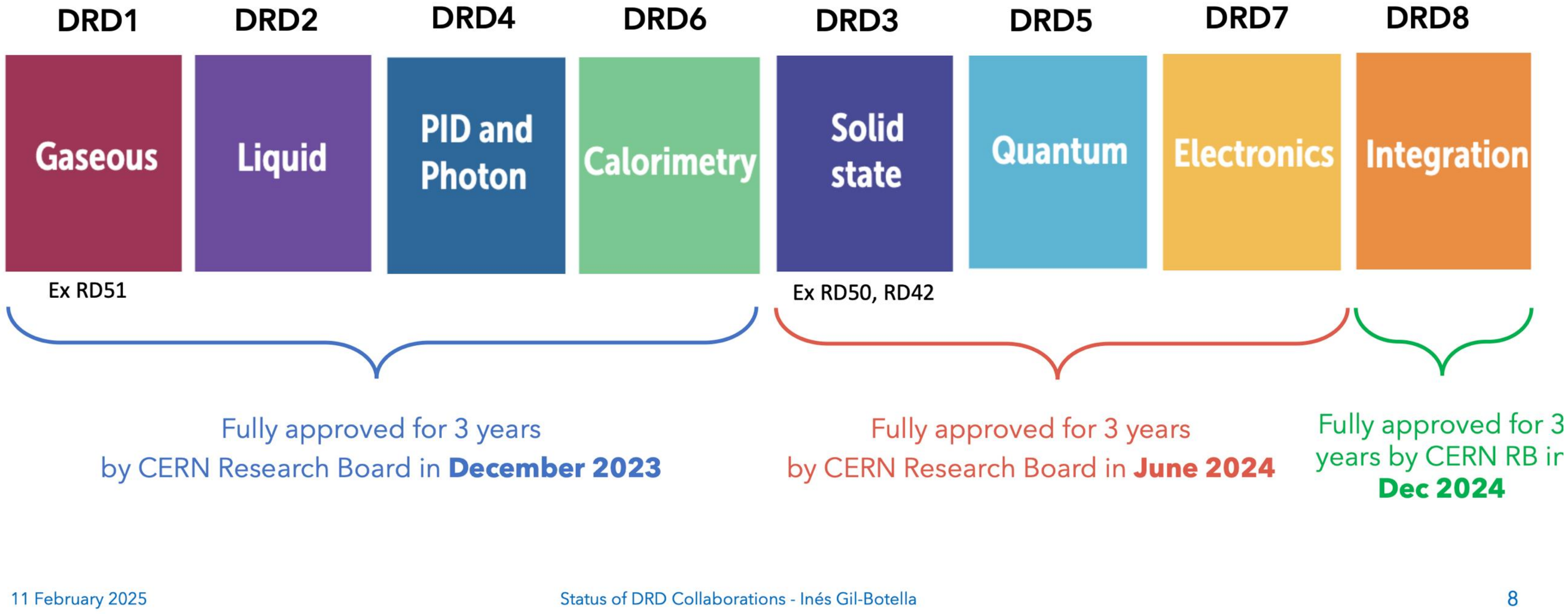


Luminosity monitor
- Small angle Bhabha scattering, $e^+e^- \rightarrow e^+e^-$
- Compact W/Si sandwich calorimeter

Detector Subsystems and Technologies

CERN Hosted Detector R&D Collaborations

Detector R&D performed inside the DRD Collaborations



FCC Detector Expressions of Interest

Input to ESPPU2026, March 2025

- 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 FCC Detector Concepts WG
- 39 documents received
  - 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

Progress since EoI submission:

→ A 5^{th} concept on the stairs; more welcome!
→ Vertex Detector Workshop, Pisa, Oct. 2025
→ Tracker Workshop, BNL, May 2025
→ DRD6 meetings
→ Workshop to be arranged

→ Upcoming workshop, 2-3 July 2026
→ Workshop to be arranged
→ 1st FCC TDAQ Workshop, CERN, November 2025

→ Series of monthly meetings

Vertex Detector

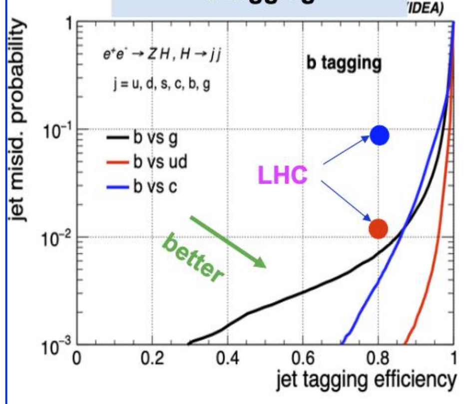
Measurement of impact parameters
- Secondary vertices, flavour tagging, lifetime measurements

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

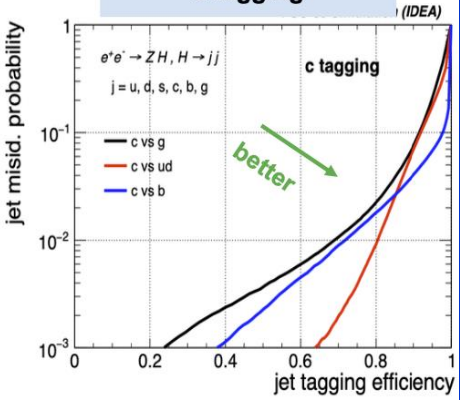
ML-based - ParticleNet
F.Bedeschi, M.Selvaggi, L.Goukas, EPJ C 82 646 (2022) link

b-tagging



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

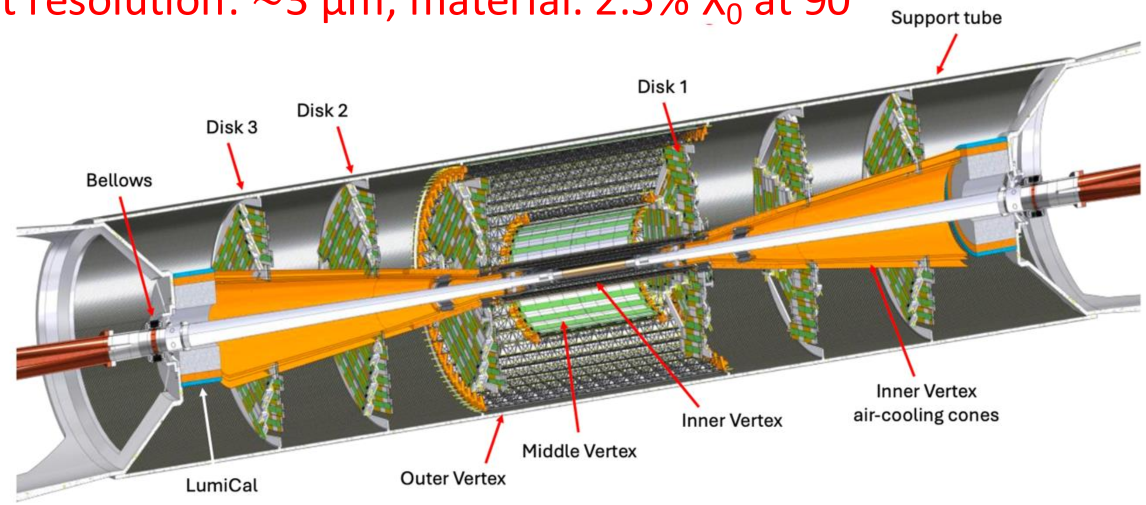
c-tagging

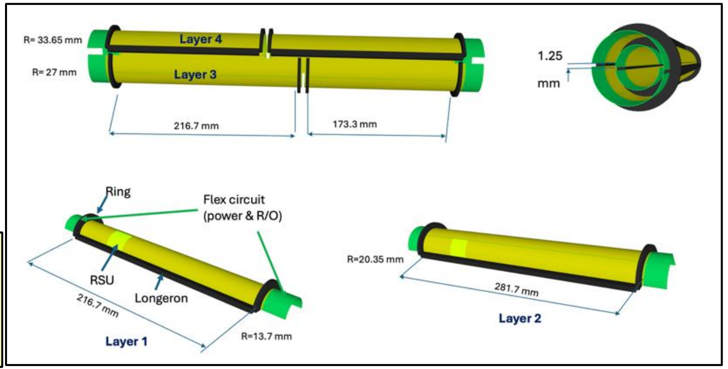


WP	Eff (c)	Mistag (g)	Mistag (ud)	Mistag (b)
Loose	90%	7%	7%	4%
Medium	80%	2%	0.8%	2%

Very substantial improvement w.r.t. LHC

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°

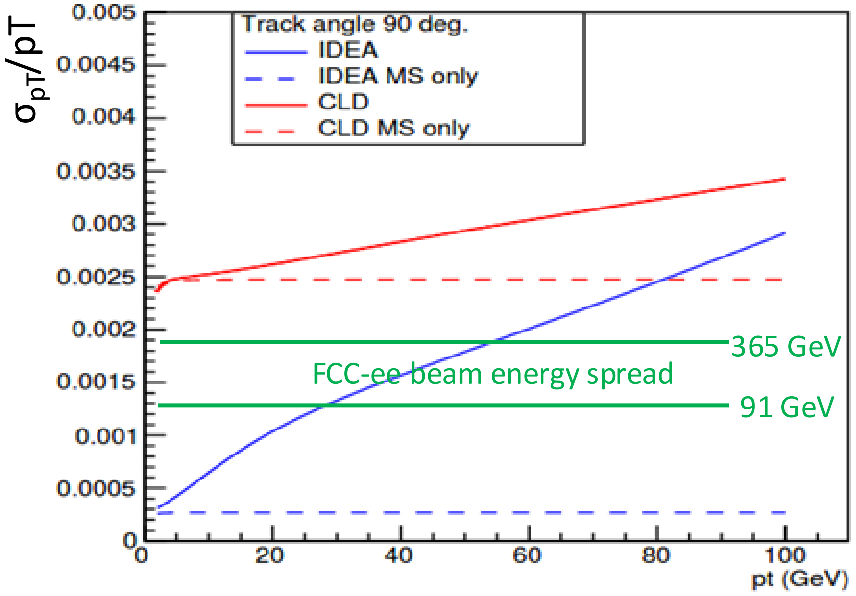




Study of alternate ultralight layout of inner layers:
- Sensors bent around beam pipe
- ~60% reduction of material

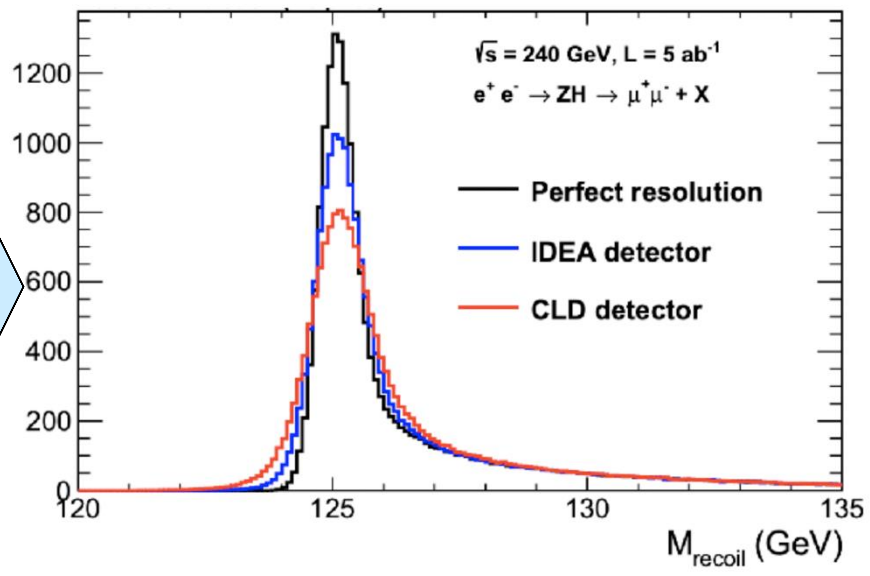
Tracking Systems - Momentum Measurement

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



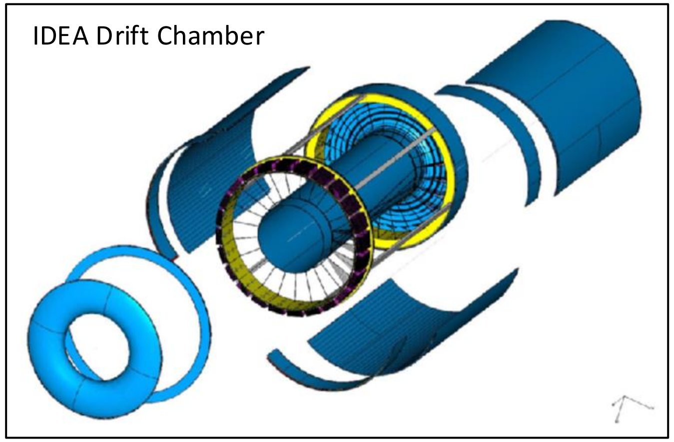
At relevant momenta, transparency more important than point resolution

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

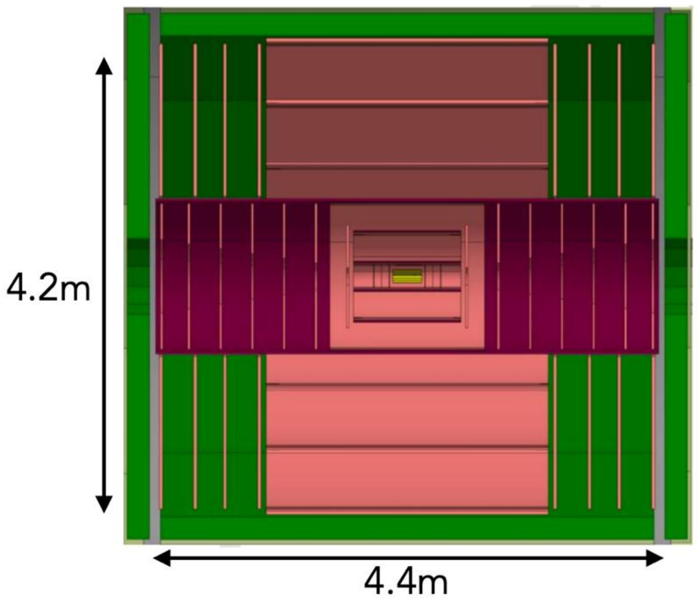
mult.scat

resolution

Strong case for gaseous trackers

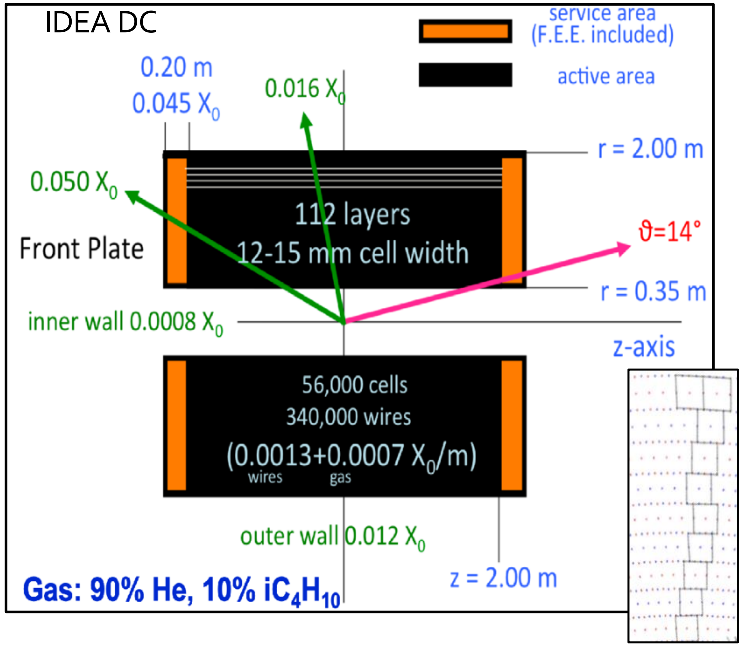


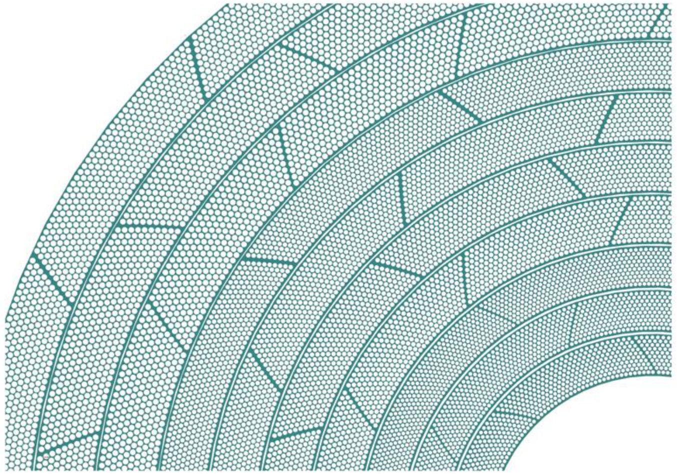
Several Main Tracker Options under Study



Full silicon
- CLD
- “5th concept”

Drift Chamber
- IDEA

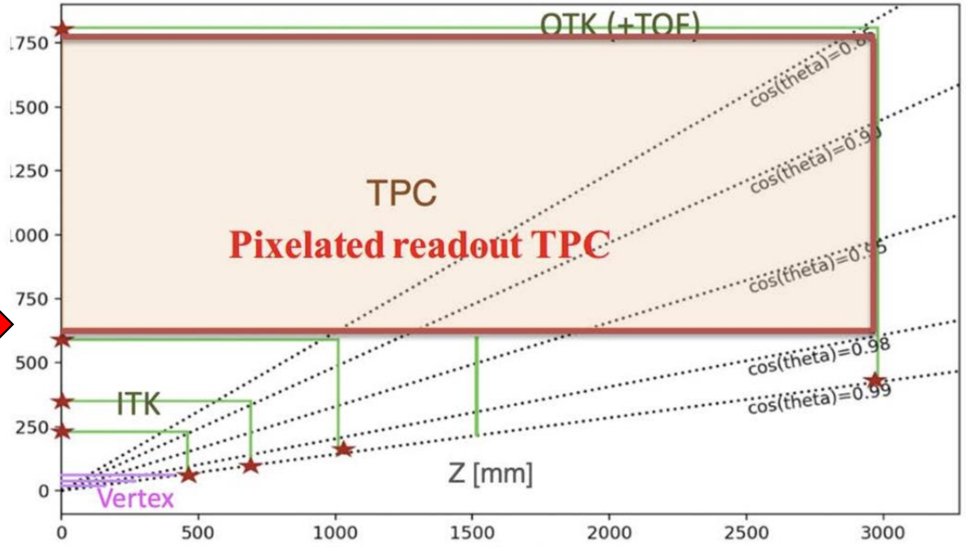




Straw Tracker
- More robust than DC?

Time Projection Chamber

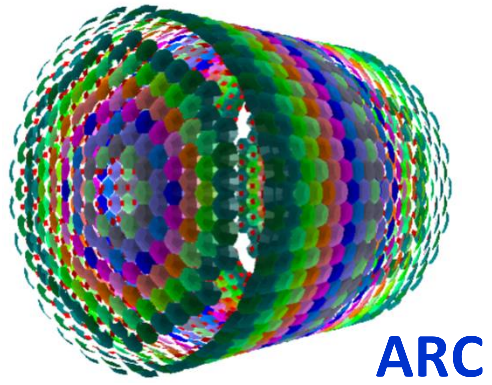
Here shown with an inner radius of 60 cm, outside Si [CEPC reference detector]

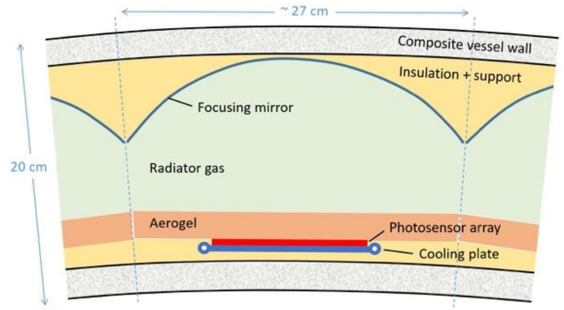


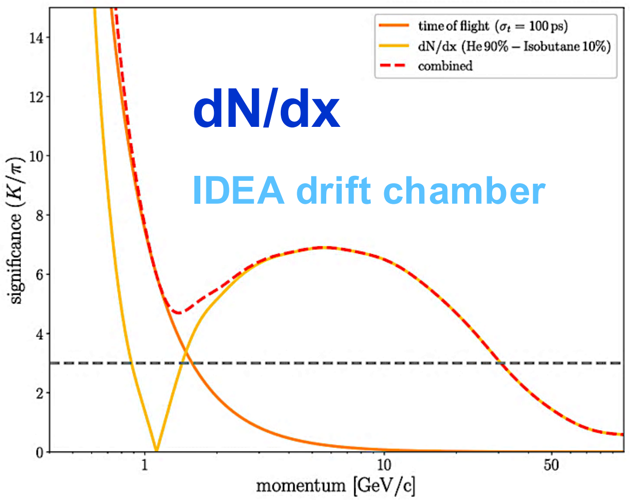
Charged Particle Identification

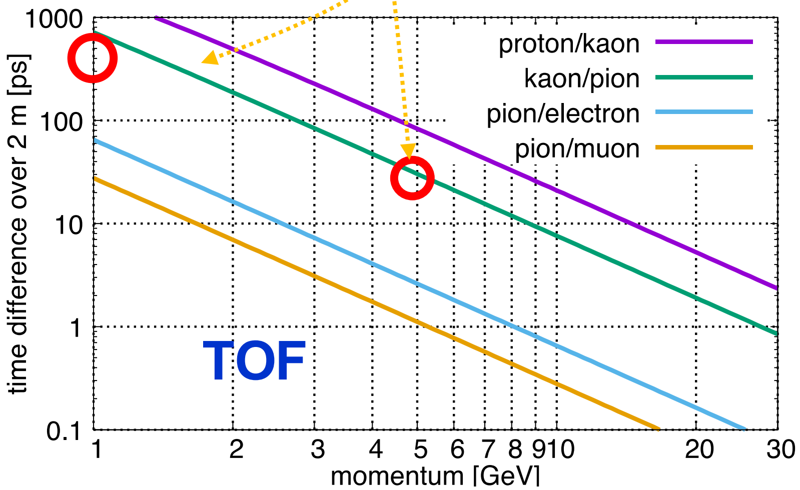
PID capabilities across a wide momentum range is essential for flavour physics

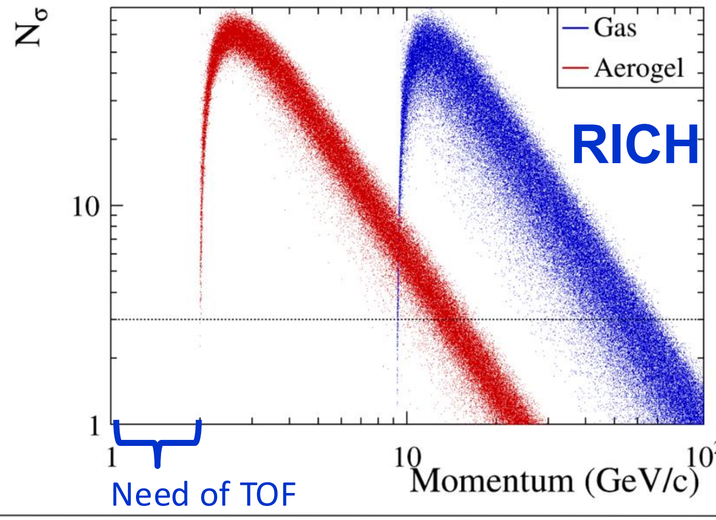
- Drift Chamber and Straw Tracker promise >3σ π/K separation up to ~35 GeV based on **cluster counting, dN/dx.** Similar performance from TPC.
  - dE/dx cross-over window at 1 GeV, can be alleviated by unchallenging TOF measurement of δT ≲ 100 ps
- **Time of flight (TOF) alone** with δT of ~10 ps over 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

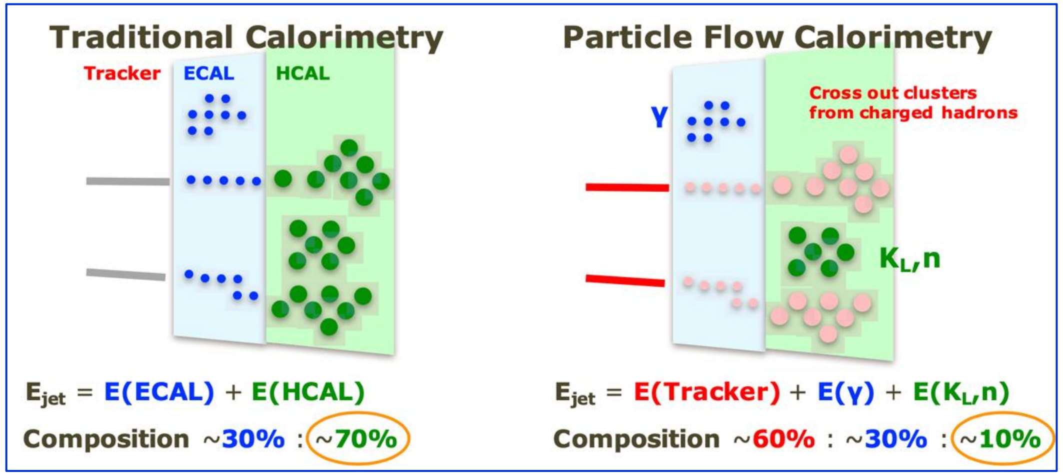
Energy coverage < 180 GeV ⇒ moderate depth: **22 X_0, 6-8 λ_{int}**

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:

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

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

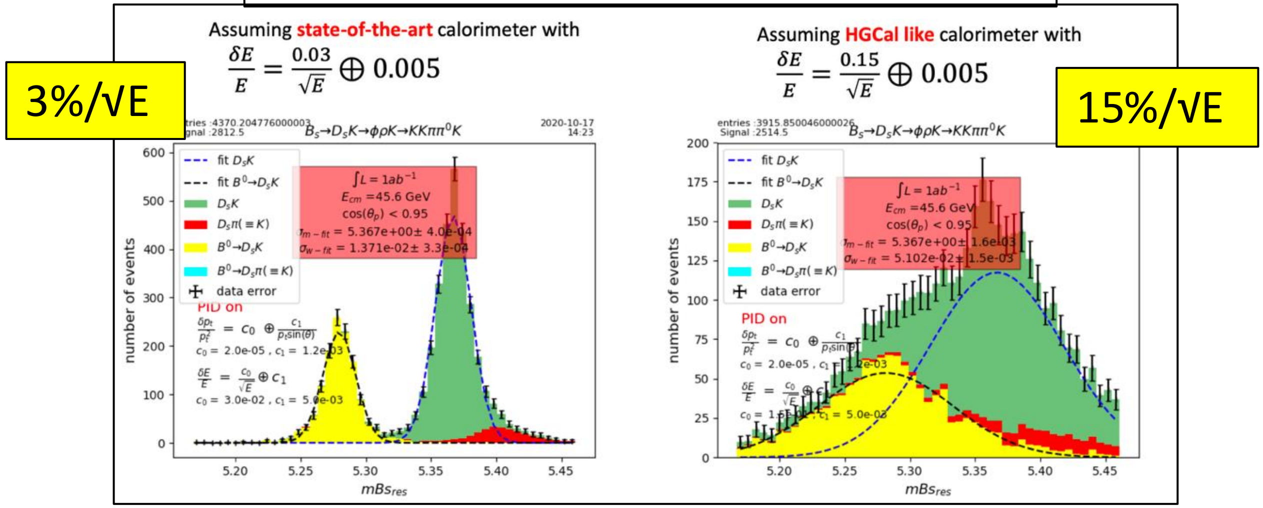


☞ High granularity !
☞ Possibly combined with Dual Readout

Further requirements

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

Example of B-physics final state with π^0



Calorimeter Technologies being pursued

All concepts aim at Particle Flow reconstruction

- with different emphasis on granularity, energy resolution, stability

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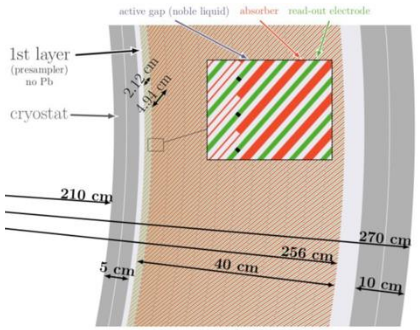
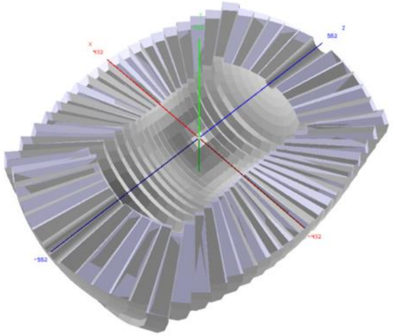


Noble Liquid ECAL + Tile HCAL:

- 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

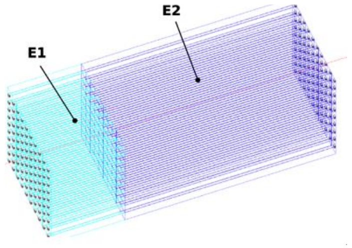
EM: σ(E)/E ≃ 8-10%/$\sqrt{E}$
Jet: σ(E)/E ≃ 4% @ 50 GeV



Fibre-based Dual-Readout :

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

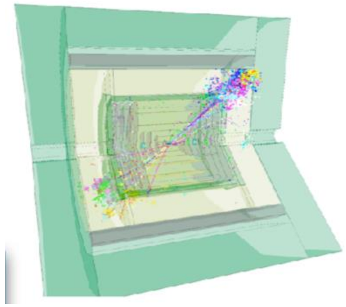
EM: σ(E)/E ≃ 11%/$\sqrt{E}$
Jet: σ(E)/E ≃ 3-4% @ 50 GeV



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: σ(E)/E ≃ 3%/$\sqrt{E}$
Jet: σ(E)/E ≃ 3-4% @ 50 GeV



CALICE-style sandwich with embedded front-end electronics:

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

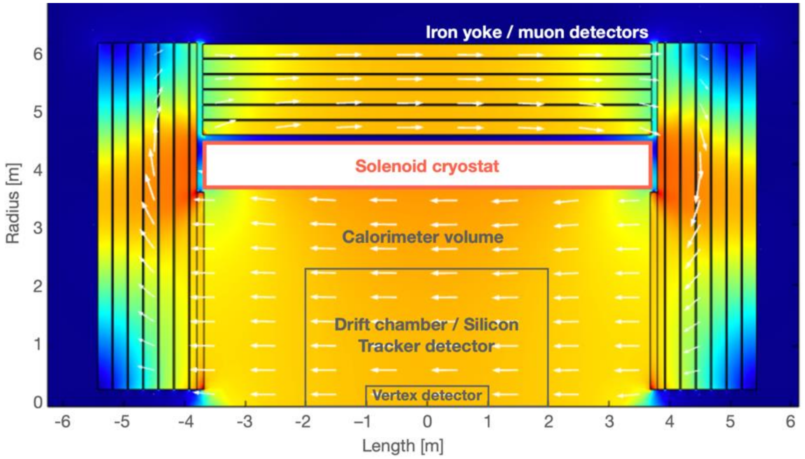
EM: σ(E)/E ≃ 16%/$\sqrt{E}$
Jet: σ(E)/E ≃ 3-4% @ 50 GeV

Detector Solenoid

Two placement options being pursued

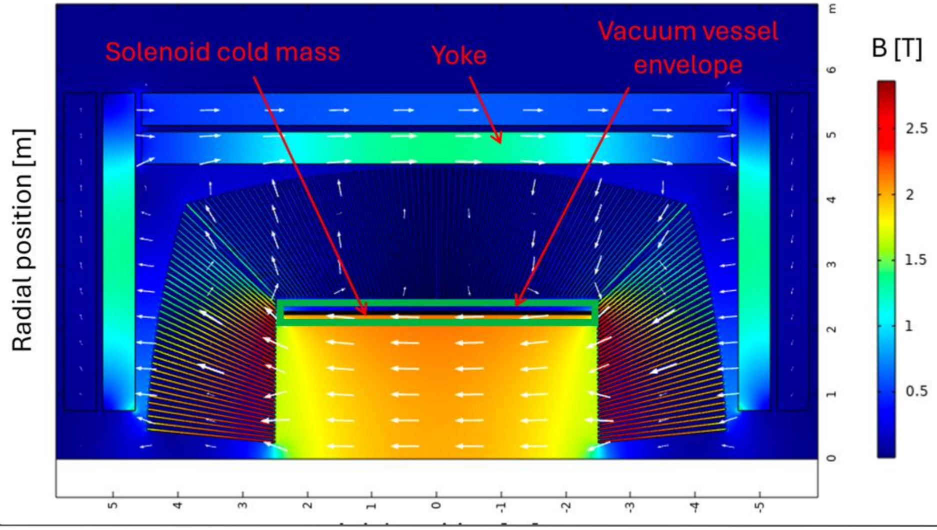
CLD + ILD

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 to general detector design
  - Need to identify labs with appropriate expertice and strength

Upcoming FCC-ee Coil Workshop, 2-3 July

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

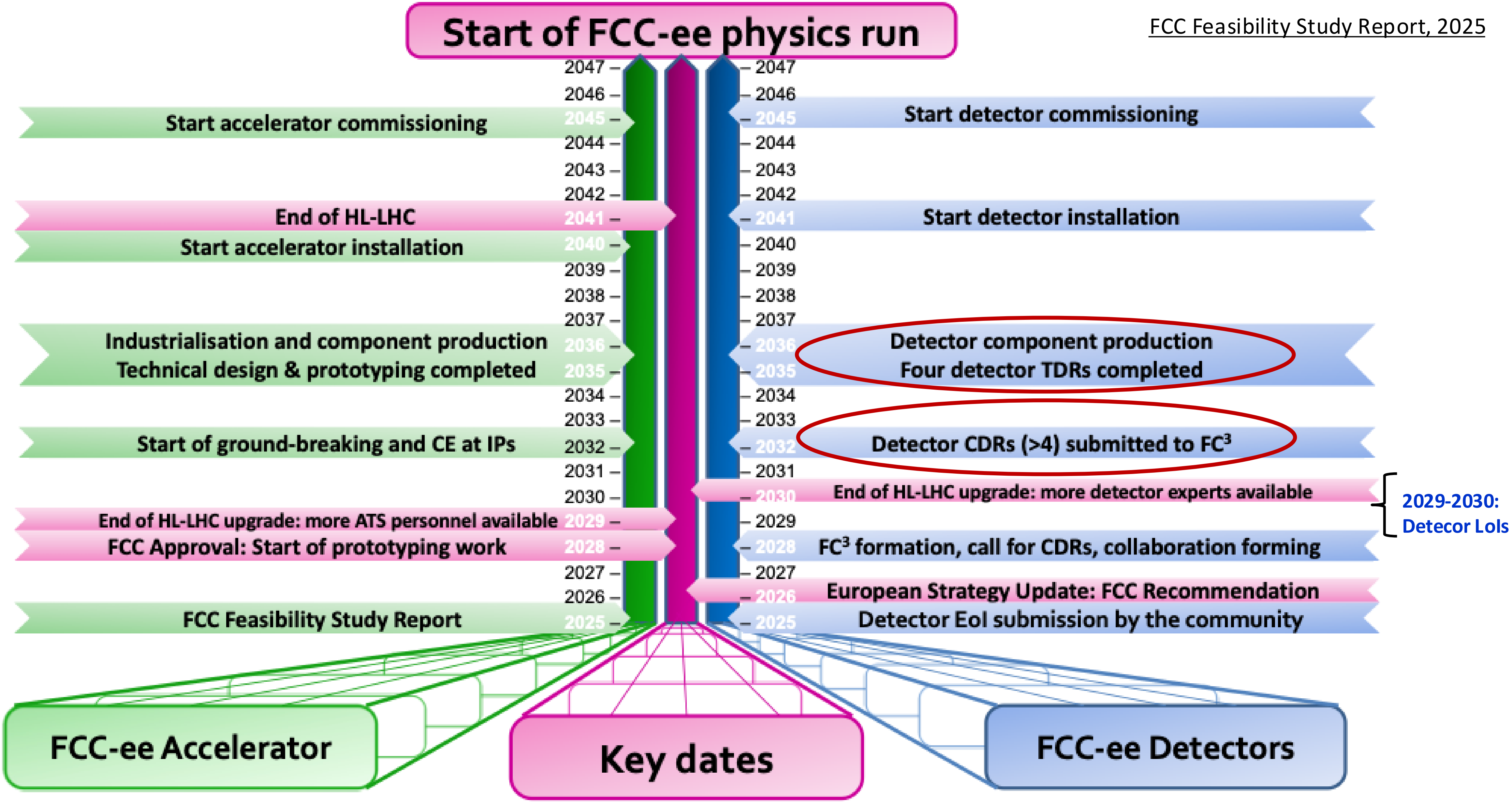
      $\Rightarrow$ **$\mathcal{O}$(5 Gbit/cm^2/sec)**
    - Would saturate "standard" 1 Gbit/cm^2/sec link

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



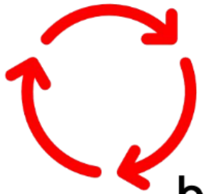
Evolution of Detector Concepts Work Package

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)

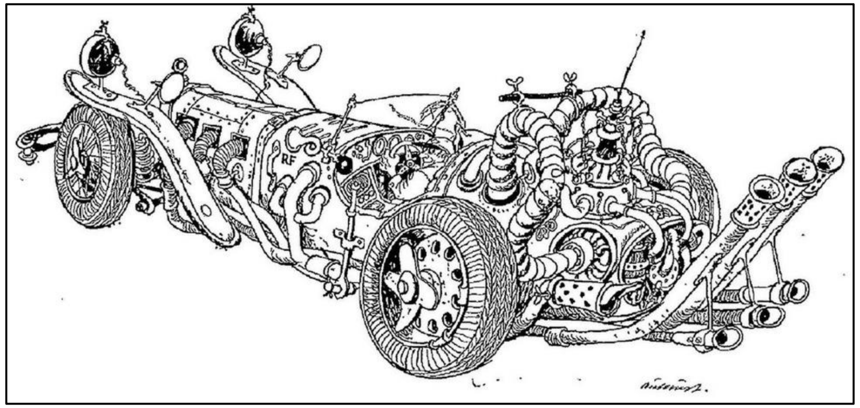
- Allegro
- CLD
- IDEA
- ILD
- …

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

Conclusions

- Extremely rich physics programme ⇒ formidable detector challenge
  - Very high rates; very high precision
- Detector (sensor) R&D concentrated inside DRD collaborations
- FCC-ee project is aiming for 4 experiments
- EoI submission to ESPP demonstrated strong community interest in developing detector and sub-detector systems
  - Self-organisation on-going
  - New ideas continue to appear
- Currently, 4 + 1 concepts are being pursued
  - Software allows **"plug & play"** ⇒ Selection of optimal combinations of subdetectors
- Still ample room and time for new technologies and concepts
  - New ideas / contributions are very welcome!

Il Tempo Gigante.



… from concept to reality …

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
  - 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