Trigger and DAQ at FCC-ee

Second Annual U.S. Future Circular Collider (FCC) Workshop 2024

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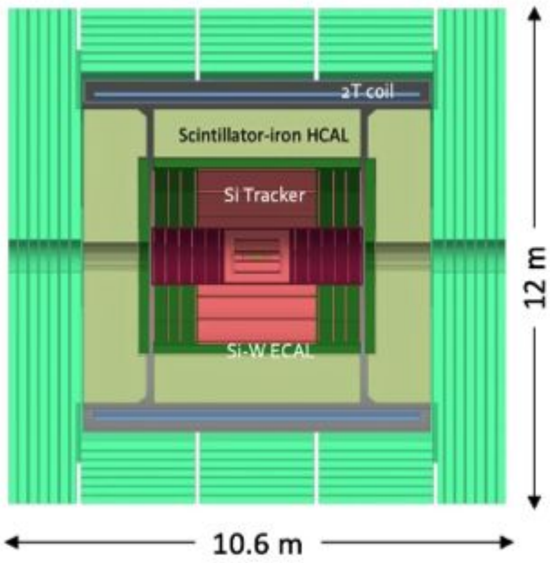
Current Detector Concepts: Broad brush strokes



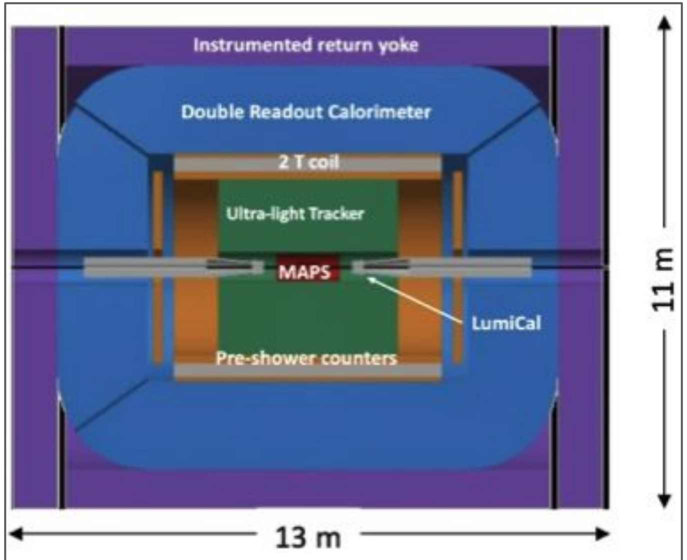
CLD

Si Vtx + Si Tracker

CALICE-like calorimeter

Large coil

Muon System



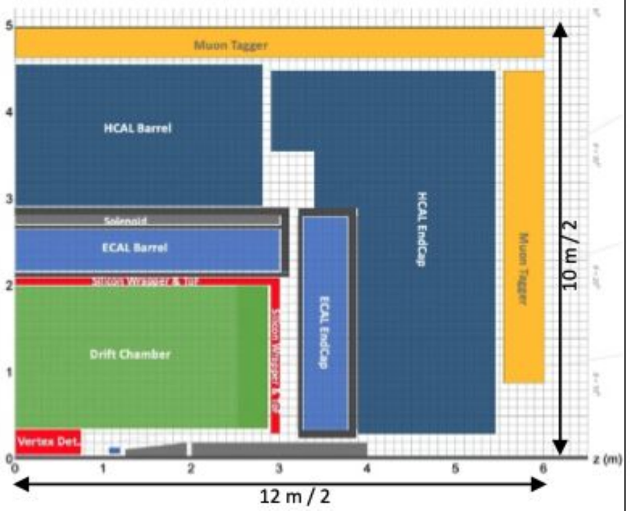
IDEA

MAPS & ultra light drift chamber

compact/light coil

Monolithic dual readout calorimeter

Muon system



ALLEGRO

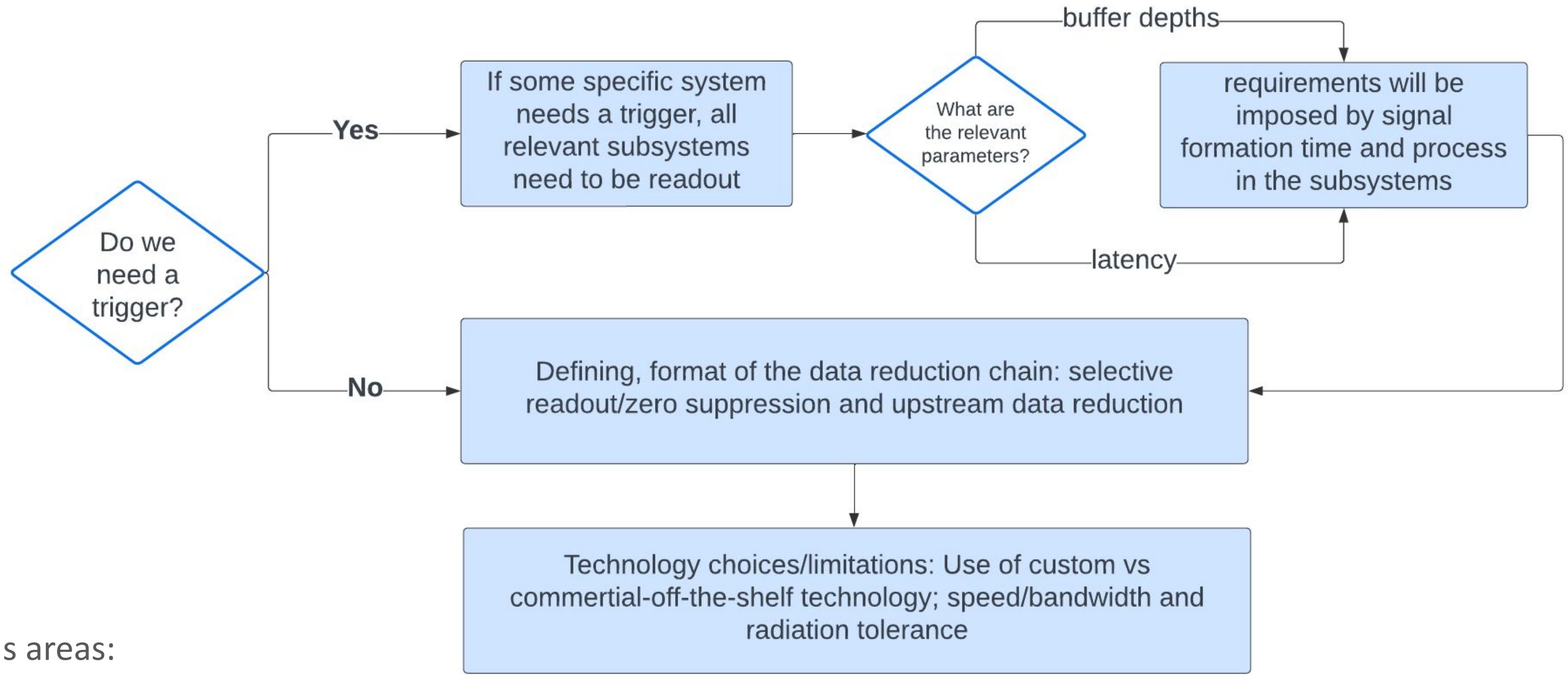
MAPS & ultra light drift chamber

High granularity Noble Liquid ECAL

TileCal-like (or CALICE-like) HCAL

Muon system

Fundamental Concepts to Address: Do we need a trigger?



Focus areas:

- Intelligence on detector: advance data reduction (ML/AI, etc)
- High performance sampling and timing (4D readout, etc)
- Levering emerging technologies (high-speed optical link, etc)

Common R&D Collaborations and Initiatives

TDAQ should be part of the detector design concepts from the start:

- Event rates is significantly lower than a hadron collider…
    - but precision requirements are different and and material budget is tighter.
- If we start now, we can reduce the system complexity of the readout
    - Enables developing common standards using common technological platforms.

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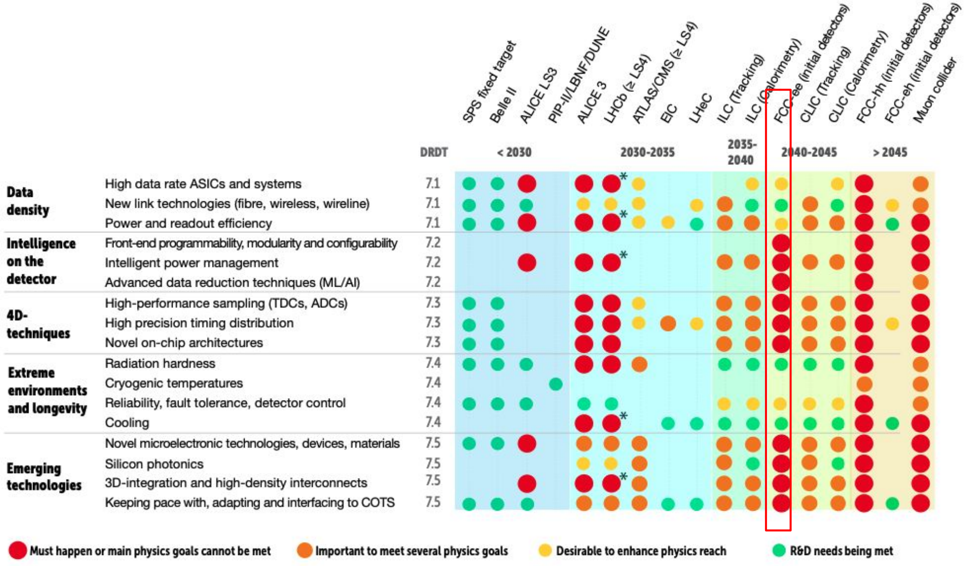

A few roadmaps for common R&D:

- The 2021 ECFA Detector R&D
  - ***DRD7 collaboration*** on electronics and on-detector processing
- The 2019 DOE Basic Research Needs for HEP Detector R&D
  - The Coordinating Panel for Advanced Detectors (CPAD) ***RDC5 group*** on TDAQ
- US Focused detector R&D needs for the next generation e+e− collider: arxiv:2306.13567

Physics Processes and Backgrounds

At FCC-ee the instantaneous luminosity per interaction point for all running scenarios are:

- Z pole: 230 x 10^{34} $cm^{-2}s^{-1}$ => Most rate demanding scenario
- WW: 28, ZH: 8.5, and tt: 1.8

At the Z pole, expected total event rate ~200 kHz, beam background expected to be 10% of the rate.

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Physics process	Rate (kHz)
Z decays	100
$\gamma\gamma \to$ hadrons	30
Bhabha	50
Beam background	20
Total	$\sim$ 200

https://arxiv.org/pdf/2111.04168v1.pdf

Process Rates dominated by two sources:

- Physics events (Z boson)
- Backgrounds:
  - Interaction Region Backgrounds: Beamstrahlung induced bkgs (coherent/incoherent pair creation $\gamma\gamma \to$ e+e- pairs), $\gamma\gamma \to$ hadrons and radiative Bhabha (small)
  - Beam Effects: Synchrotron radiation (dominant for top but can be shielded), beam-gas (small), etc.

Bandwidth calculations

For TDAQ systems, the parameters of interests are:

- Rate of interesting physics events
- Rate of irreducible backgrounds (beam and physics)
- Average event size

Bandwidth = Process rate x Average Event Size

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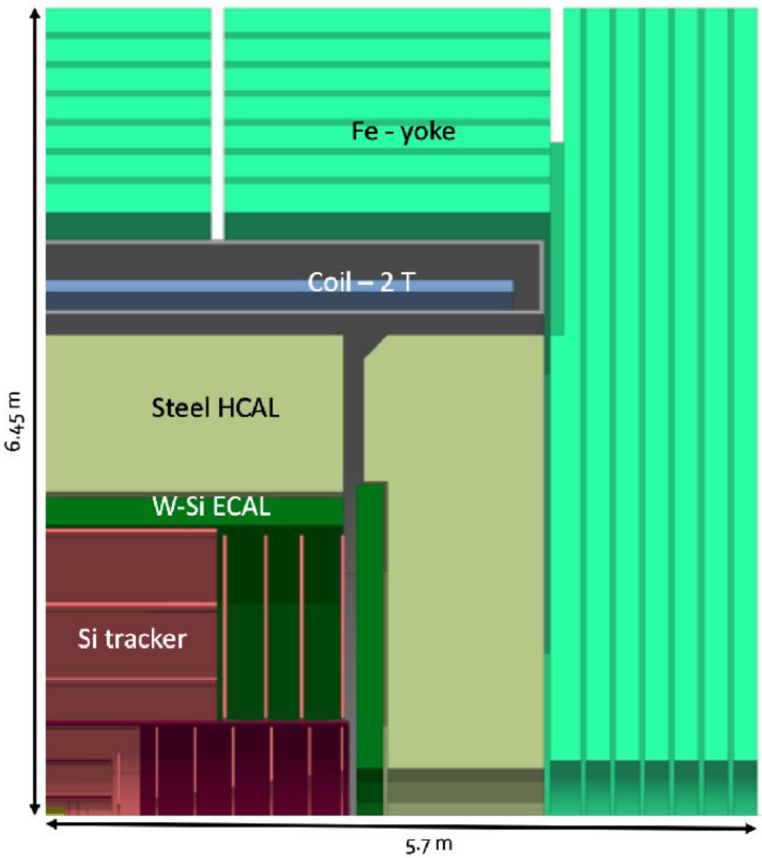
Detector input:

- Occupancy → depends on the implementation of zero suppression & integration time
- Buffer size → data format is subdetector dependent

CLD: Preliminary Rate Estimates

Rates at Z Pole, arxiv:2111.04168v1



Adaptation from the CLIC detector:

- Silicon vertex detector:
  - 0.53 m^2 ⟶ 0.84 G channels
- Silicon central tracker:
  - 200 m^2 ⟶ 2 + 0.75 G channels
- High granularity calorimeter
  - ECAL (20cm) 5mm×5mm Si-W (1.9mm W)
    - 40 layers, 4000 m^2 ⟶ 160 M ch
  - HCAL (117cm) 30mm×30mm Sci-steel
    - 44 layers, 8000 m^2 ⟶ 9.2 M ch
- Solenoid outside of calorimeter
- Muon systems (RPC Muon chambers, 30mmx30mm)
  - 3250 m^2 – 3.6 M channels

CLD: Preliminary Rate Estimates

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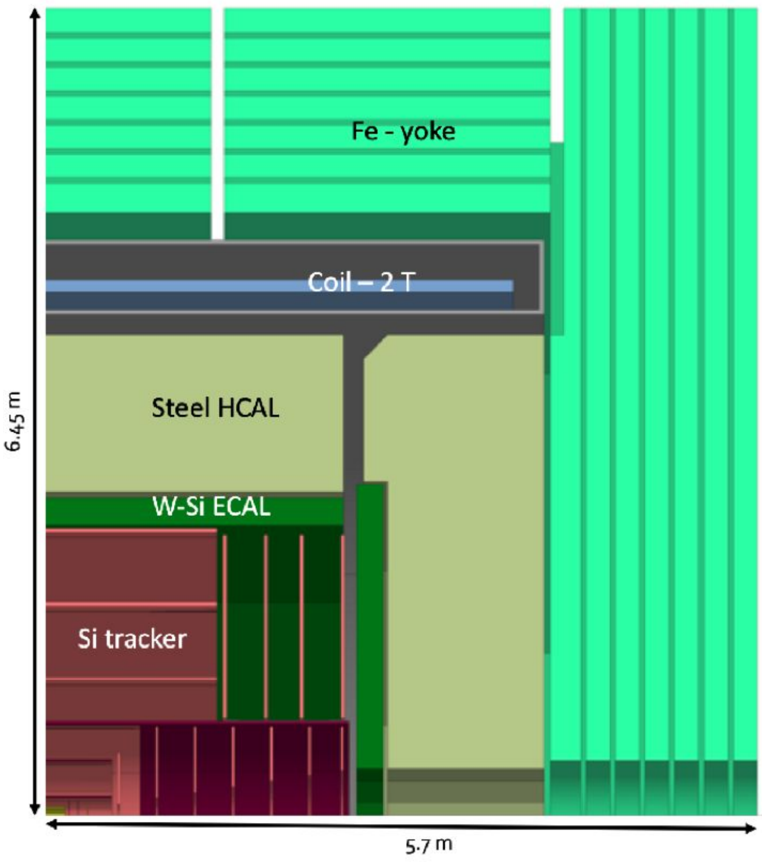
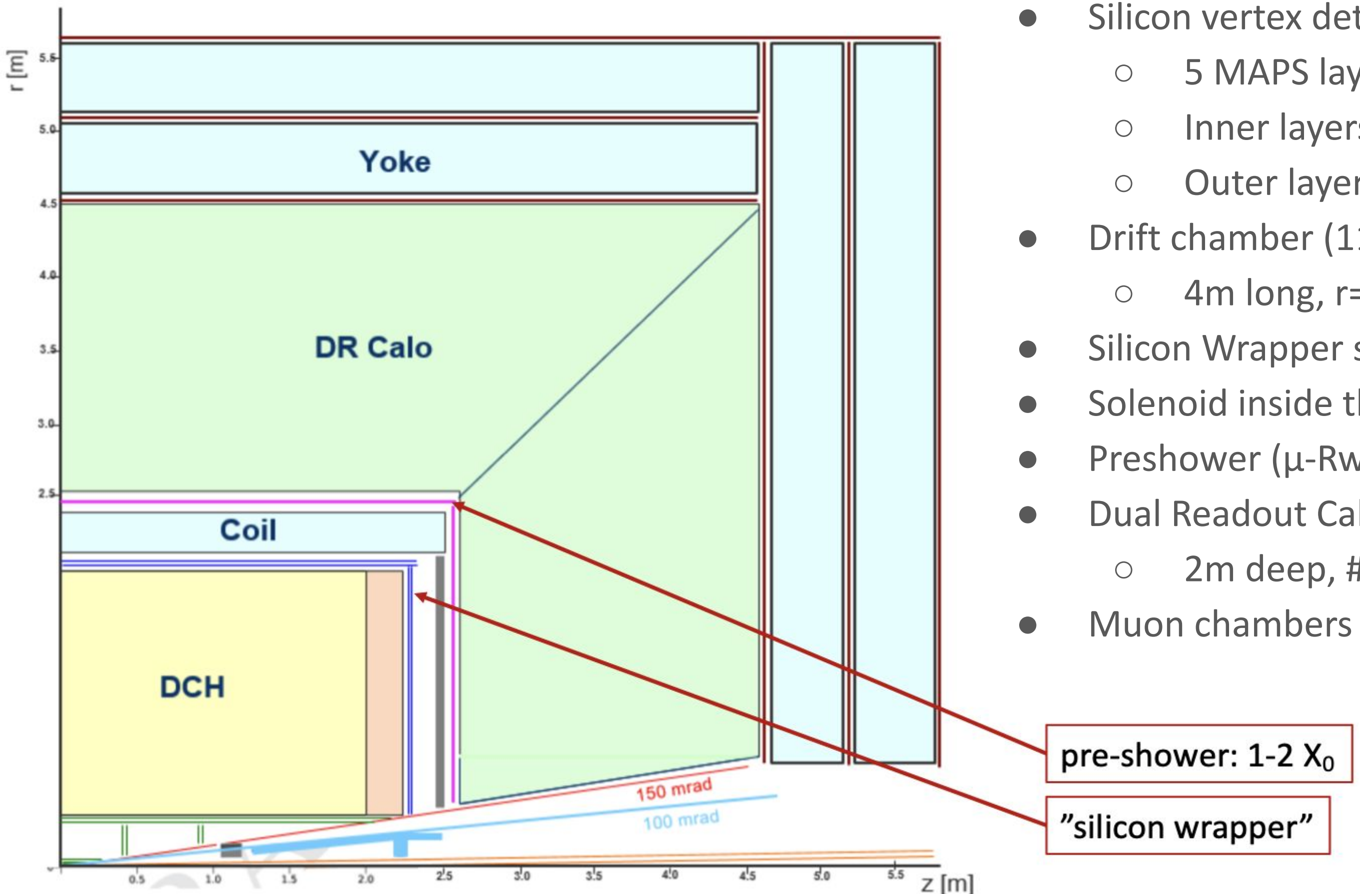


Assuming 100 kHz Z at 50 MHz BX:

- Silicon vertex detector:
  - 150MB/s from physics, 6 GB/s from Bkg (IPC)
- Silicon central tracker:
  - 160MB/s from physics, 10 GB/s from Bkg (IPC)
- High granularity calorimeter
  - ECAL (21 GB/s) + HCAL (1.8 GB/s) based on CEPC studies (similar calorimeter design but different number channels).

IDEA: Preliminary Rate Estimates

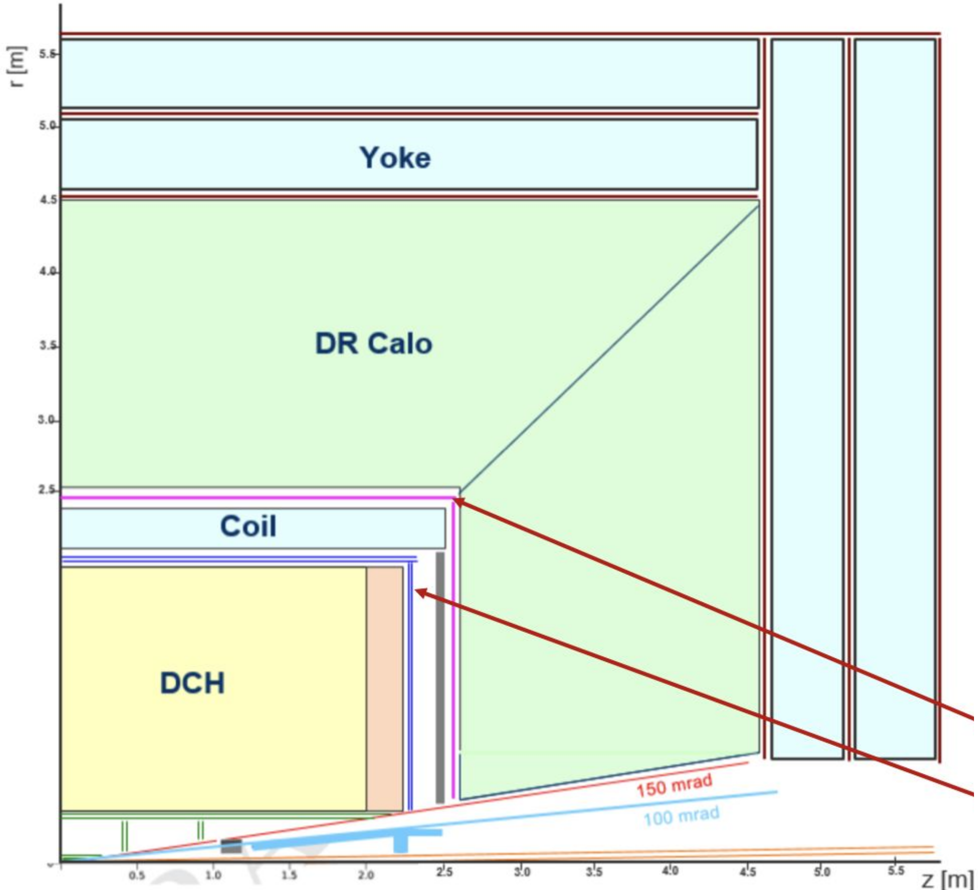
Rates at Z Pole, arxiv:2111.04168v1, Annecy FCC - Idea



- Silicon vertex detector:
  - 5 MAPS layers
  - Inner layers: 0.3% of X_0 / layer
  - Outer layers: 1% of X_0 / layer
- Drift chamber (112 layers)
  - 4m long, r=35–200cm
- Silicon Wrapper strips
- Solenoid inside the calorimeter
- Preshower (μ-Rwell)
- Dual Readout Calorimeter
  - 2m deep, # of SiPM = 130 M
- Muon chambers (μ-Rwell)

IDEA: Preliminary Rate Estimates

[Rates at Z Pole](), [arxiv:2111.04168v1](),[Annecy FCC - Idea]()



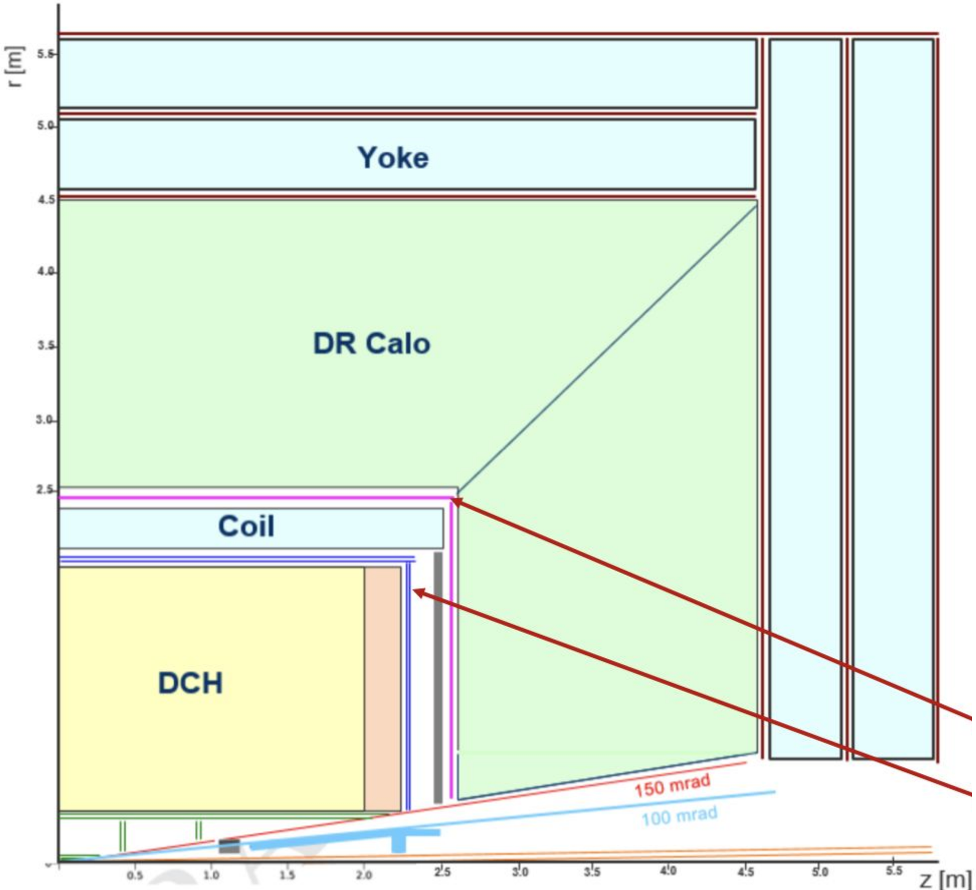
Assuming 100 kHz Z rate, γγ ⟶ hadrons, Bhabha and Noise at 50 MHz BX:

- Vertex detector (ARCADIA Readout):
  - Overall occupancy (assume 10µs integration): 2-3% at the Z pole, with Layer 1 being the largest rate.
  - 2.2 Tbit/sec (NoTrigger)

- Drift Chambers:
  - Unfiltered/suppression:
    - ~360 GB/s of Z + ~80 GB/s other
    - ~50 GB/s noise (electronics)
    - ~300 GB/s IPC
  - *Using real-time analysis on the FPGA:*
    - ~44 GB/s of Z + ~8 GB/s other
    - Noise ~0 + IPC ⟶ 2 GB/s

IDEA: Preliminary Rate Estimates

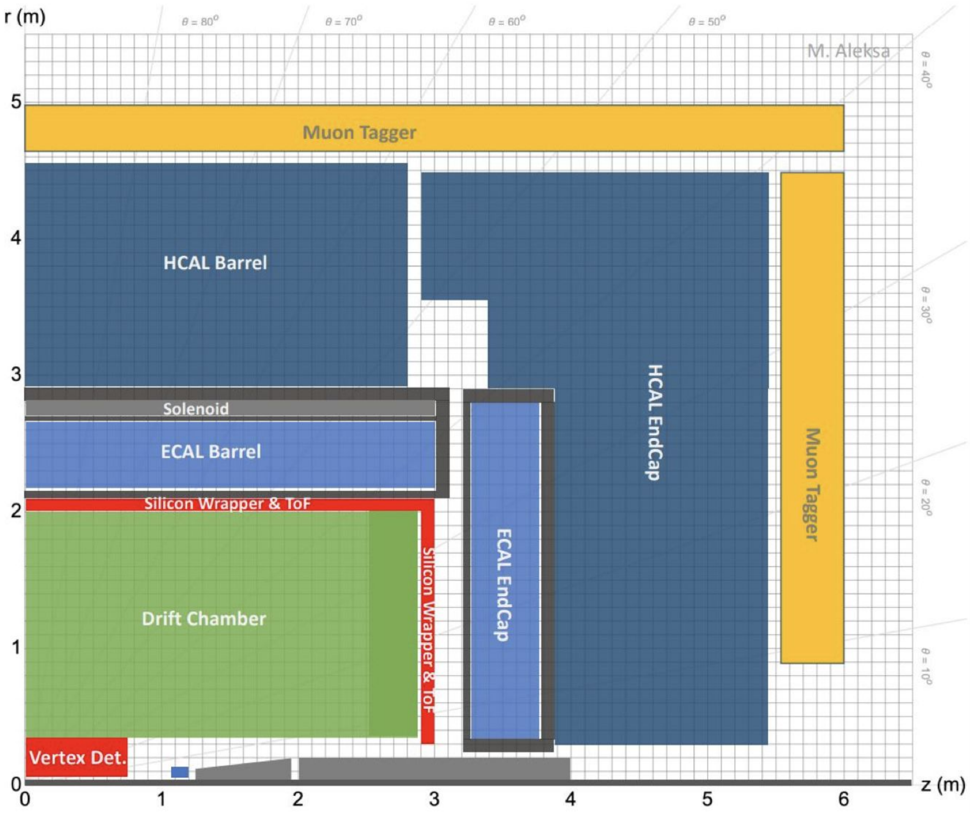
Rates at Z Pole, arxiv:2111.04168v1,Annecy FCC - Idea



- DR Calorimeter (fiber calorimeter):
  - With zero-suppression and 16B readout → 10 GB/s physics
  - In this configuration, noise (*dark counts*) are *estimated to be over 1 TB/s*. Additional noise suppression would be necessary.
- Alternate with crystals:
  - # Fibers reduced by x2-3 if crystals in front with 1x1 cm^2 crystal section
  - at 100 kHz trigger rate: <1GB/s with dark count < MIP readout threshold.
- Preshower, muon systems are noise dominated however < 1GB/s

Allegro: Preliminary Rate Estimates

Annecy FCC, Allegro

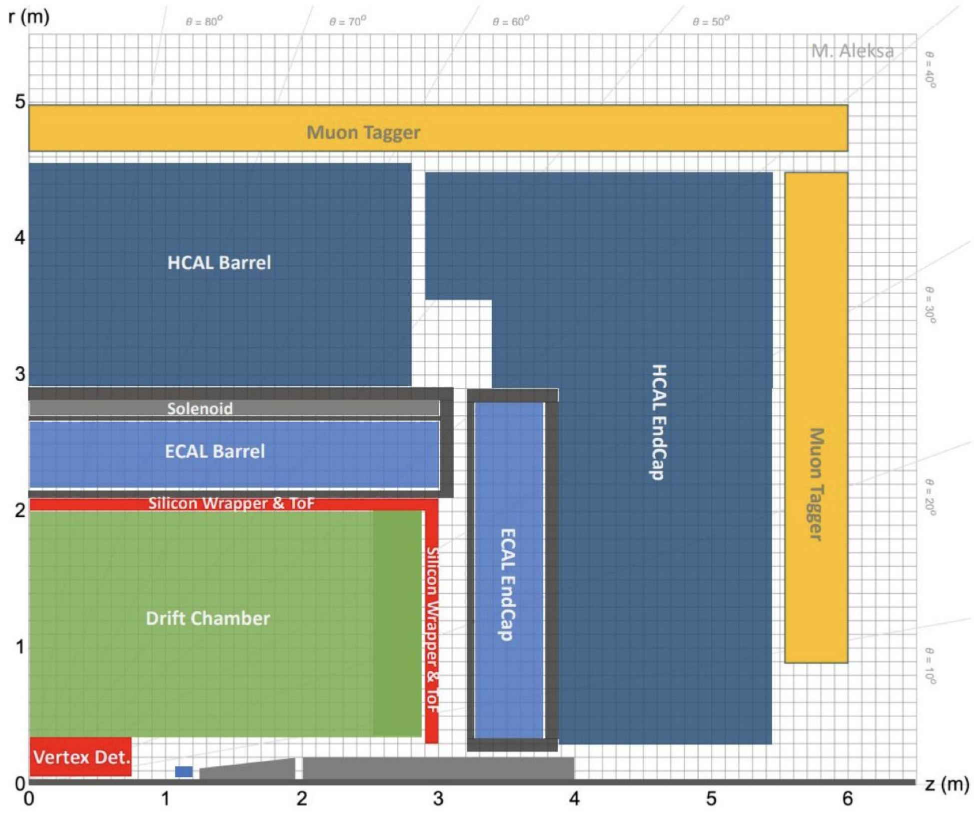


A "newer" experiment proposal, still developing

- Tracker assume similar structure as IDEA:
  - 5 MAPS layers for vertex detector
  - Drift Chamber (112 layers)
- Highly granular ECAL with a Noble liquid technology, inside super transparent CF cryostat
  - LAr or LKr with Pb or W absorbers
  - Multi-layer PCB as read-out
- Solenoid after ECAL (in same cryostat)
- CALICE-like or TileCal-like (baseline) HCAL
- Simple muon tagger

Allegro: Preliminary Rate Estimates

Annecy FCC, Allegro



A "newer" experiment proposal, still developing

- Tracker assume similar structure as IDEA:
  - Estimations based on IDEA results; on detector cluster finding based on amplitude and time of peaks needed.
- Rate studies for ECAL ongoing:
  - Assuming zero suppression above the electronics noise level: 8 GB/s physics
  - Bkg simulation on going
- Similarly for HCAL & Muon system - simulation studies are underway
  - Expect manageable rates for physics from HCAL.

Comparing Results & Conclusions

General design principle is to the readout the data with low material and low power budget

with nearly ~100% efficiency..

The current detector concepts have various similarities and also differences. Regardless, each subdetector needs to evaluate occupancies and data buffer needs, so that bandwidths can be estimated.

This requires:

- simulations to estimate the machine-induced & physics backgrounds. It is shown that there are large contributions also from beamstrahlung induced bkgs (coherent/incoherent pair creation)
- detailed signal formation studies (times) to understand latencies

Preliminary studies (as shown in the Annecy workshop most recently) show that on-detector processing beyond zero suppression is necessary for data reduction.

Outlook

For TDAQ, the requirements are driven by the Z pole running with physics rates up to 200 kHz.

The big picture question is still to understand if we need a “hardware” trigger

- this then evolves into more questions on buffer size and latency requirements
- whether all or subset of detectors to provide triggers …

Nevertheless the obvious need/question are:

- On-detector processing beyond zero suppression
- What to record on the tape? (a high level software trigger)

Moving forward, the focus on technology R&Ds:

- High performance sampling & novel on-chip architectures
- Intelligence (AI/ML) on/off detector for: data reduction, power management, autonomous control/calibration
- Emerging technologies → microelectronics, high density data links and COTS (heterogeneous computing)

Back up

Vertex detector: **6 GB/s**

Z decays

- 20 trks/ev × 8 hits/trk × 5 pix/hit = 800 pix/ev
  800 pix/ev ×13 bit/pix / 8 bit/B × 100 kHz = **130 MB/s**

γγ→ hadrons

- 10 trks/ev × 8 hits/trk × 5 pix/hit = 400 pix/ev
  400 pix/ev ×13 bit/pix / 8 bit/B × 30 kHz = **20 MB/s**

IPC background*

- 6 trks/ev/BX × 50 BX × 8 hits/trk × 5 pix/hit = 12000 pix/ev
  12000 pix/ev ×13 bit/pix / 8 bit/B × 100 kHz × 3 (SF) = **6 GB/s**

*based on full simulation of **CLD**. Assume similar rates for **IDEA**

CEPC CDR: DAQ for ECAL

ECAL

- Maximum event rate: 100 kHz
  - Peak event rate: ~32kHz at Z-pole
  - Safety margin: a factor of ~3
  - 10 µs time window for readout
- ECAL: 2 options in CDR
  - Si-W ECAL: $10 \times 10\ \mathrm{mm}^2$ silicon pads
  - Sc-W ECAL: $45 \times 5\ \mathrm{mm}^2$ scintillator strips
  - Longitudinal depth: 24X0

ECAL options	#Channels [Million]	Occupancy [%]	#bit per channel	#readout channels/evt	Data Volume per event	Data rate at 100kHz
SiW ECAL Barrel	17	0.17	32	28.8 k	117 kByte	11.7 GBytes/s
SiW ECAL Endcap	7.3	0.31	32	22.4 k	90 kByte	9.0 Gbytes/s
ScW ECAL Barrel	7.7	0.17	32	13.1 k	53 kByte	5.3 GBytes/s
ScW ECAL Endcap	3.3	0.31	32	10.2 k	41 kByte	4.1 Gbytes/s

CEPC CDR: DAQ for HCAL

HCAL

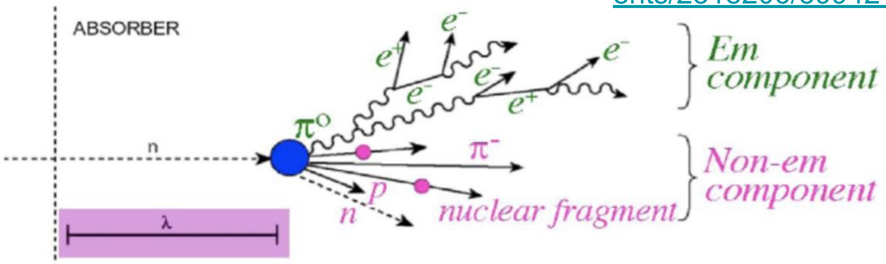
- Maximum event rate: 100 kHz
  - Peak event rate: ~32kHz at Z-pole
  - Safety margin: a factor of ~3
  - 10 µs time window for readout
- HCAL: 2 options in CDR
  - Scintillator HCAL: $30 \times 30\ \mathrm{mm}^2$ scintillator tiles
  - RPC HCAL (SDHCAL): $10 \times 10\ \mathrm{mm}^2$ RPC pads
  - Longitudinal depth: 40 layers (~4.7λ)

ECAL options	#Channels [Million]	Occupancy [%]	#bit per channel	#readout channels/evt	Data Volume per event	Data rate at 100kHz
Scintillator HCAL Barrel	3.6	0.02	32	0.72 k	2.9 kByte	0.3 GBytes/s
Scintillator HCAL Endcap	3.1	0.12	32	3.72 k	15 kByte	1.5 Gbytes/s
RPC HCAL Barrel	32	0.004	8	1.28 k	1.28 kByte	0.13 GBytes/s
RPC HCAL Endcap	32	0.01	8	3.2 k	3.2 kByte	0.32 Gbytes/s

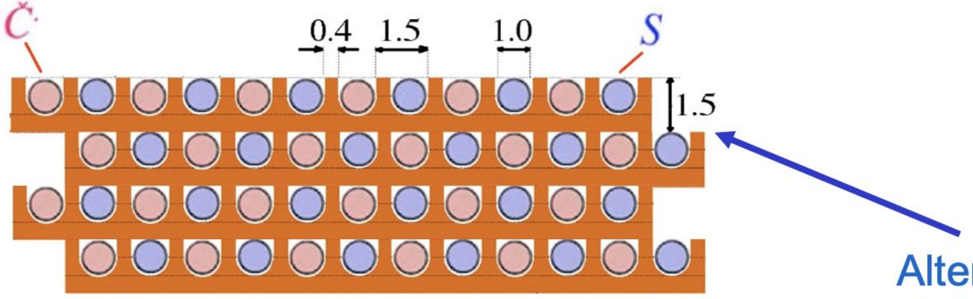
Principle of the Dual Readout calorimeter

https://indico.cern.ch/event/1077114/attachments/2318206/3994245/DeFilippis_IDEA.pdf

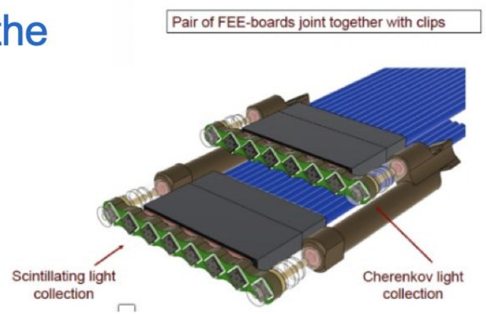
- Event by event correction for EM-had fluctuations
  - Principle demonstrated by DREAM/RD-52



- EM and hadron calorimeter in a single package
  - All electronics in back easy to cool and access
- Electrons/photons are independently sampled by the two kind of fibers (Scintillating and Cherenkov).



Fiber pattern RD52



Alternating scintillating and clear fibers in metal matrix