The ILD for a future linear or circular e^+e^- collider

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for the ILD collaboration

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HELMHOLTZ

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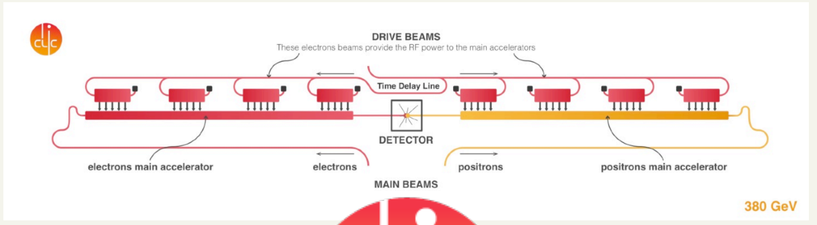
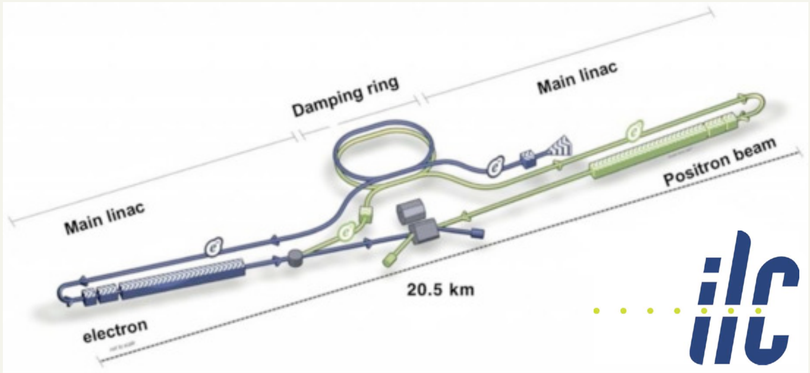
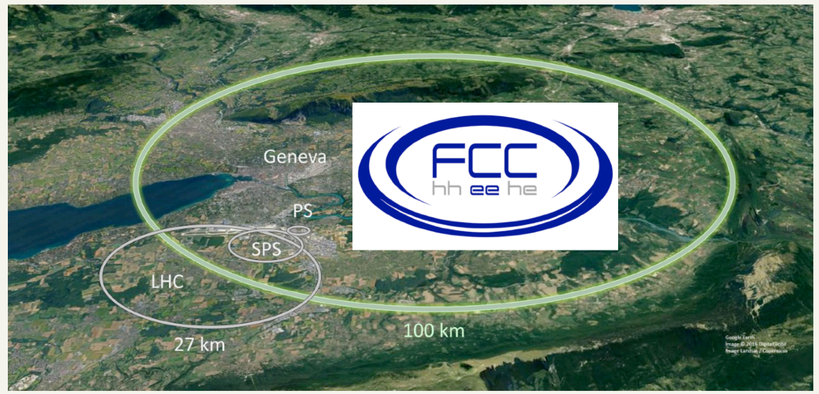
DESY.

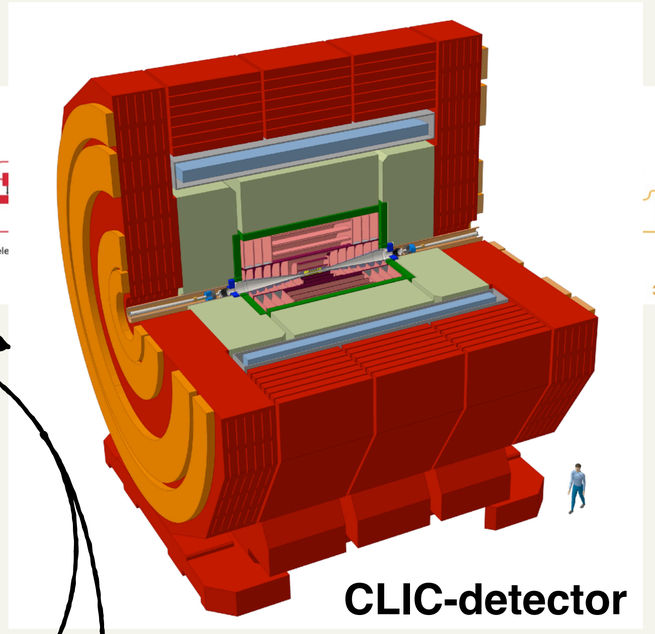
Landscape of possible future e+e- colliders

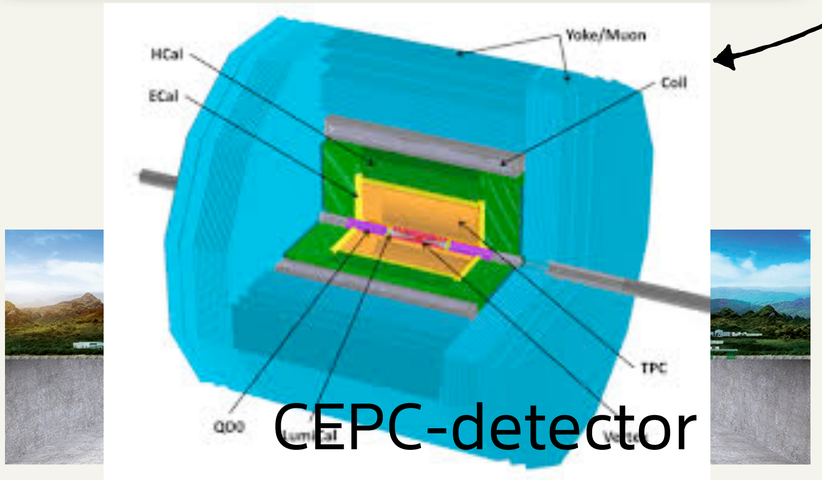


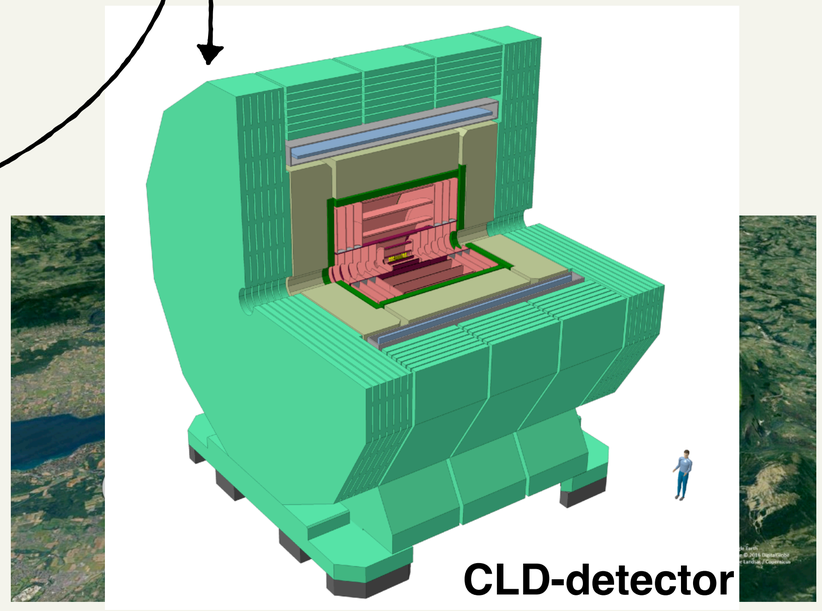




ILD-based concept already proposed!

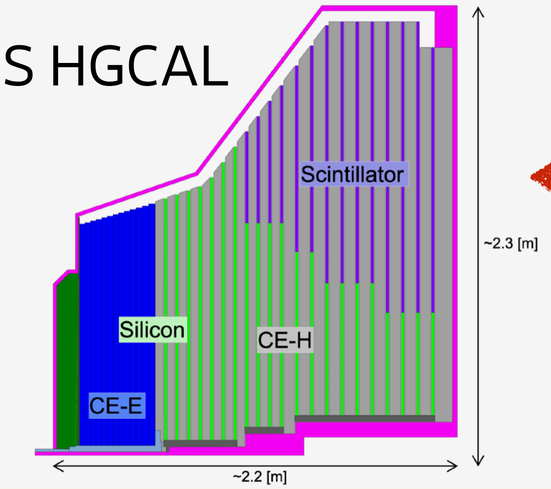




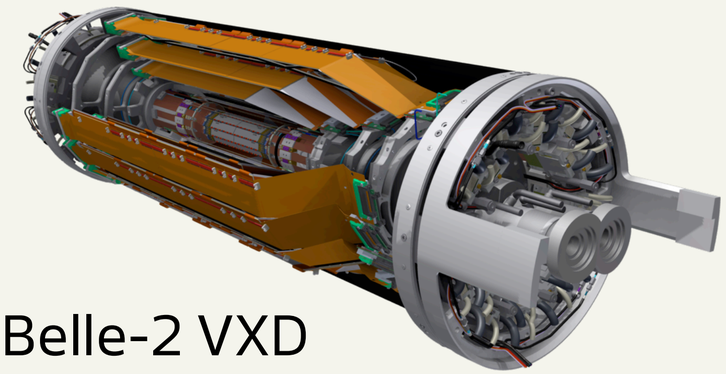


ILD sub-systems at live experiments!

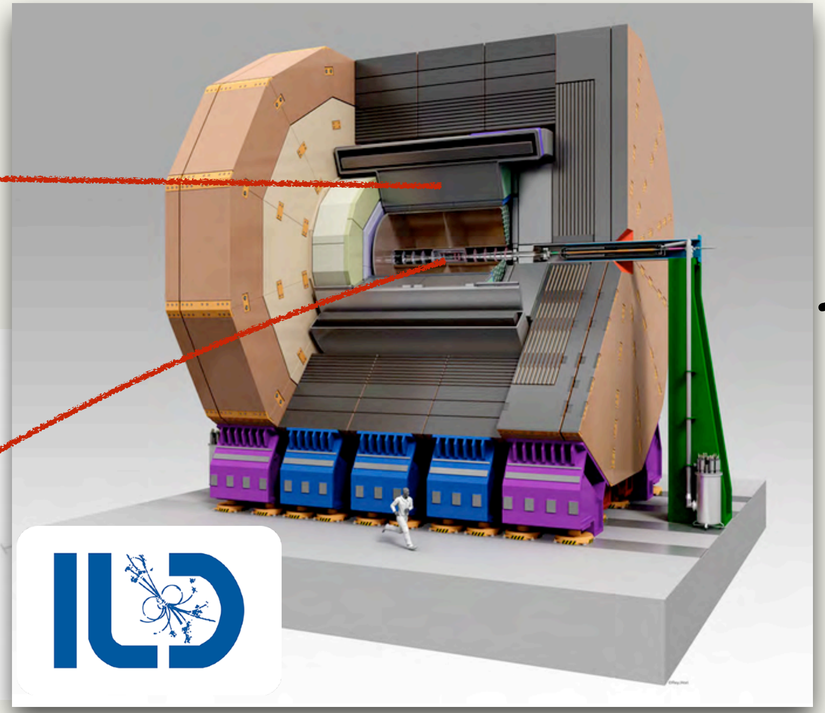
CMS HGCAL

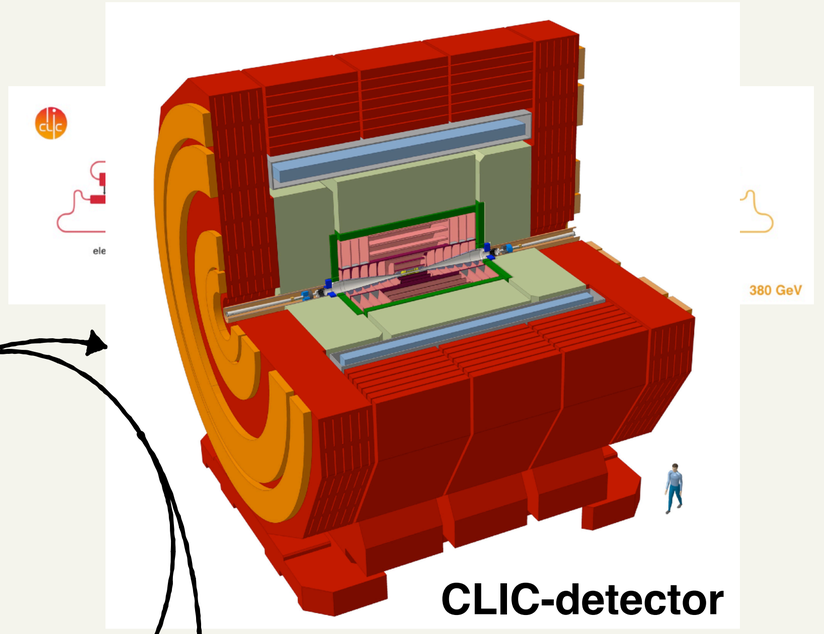


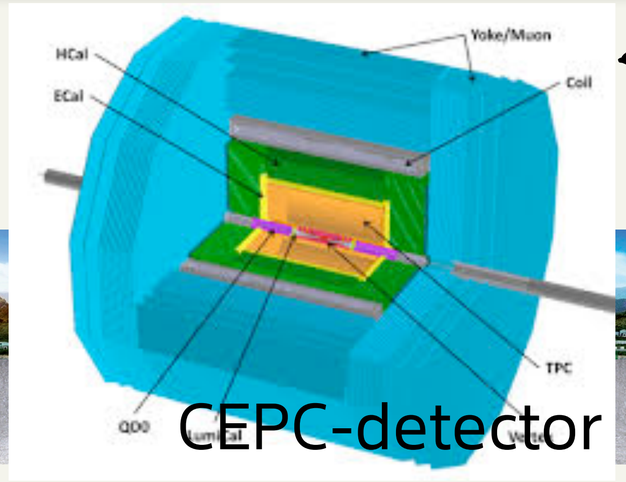
and more...



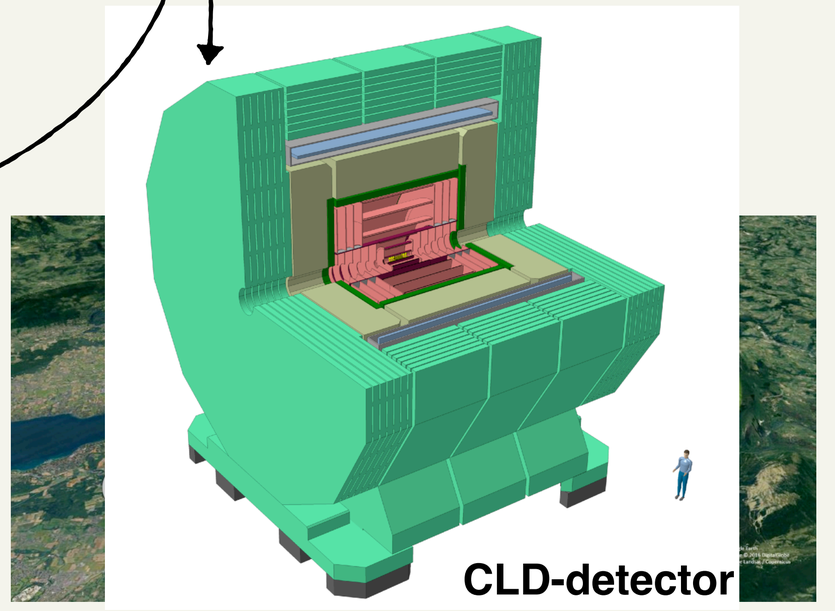
Belle-2 VXD







CEPC-detector



The ILD at linear e+e- colliders

ILD overview

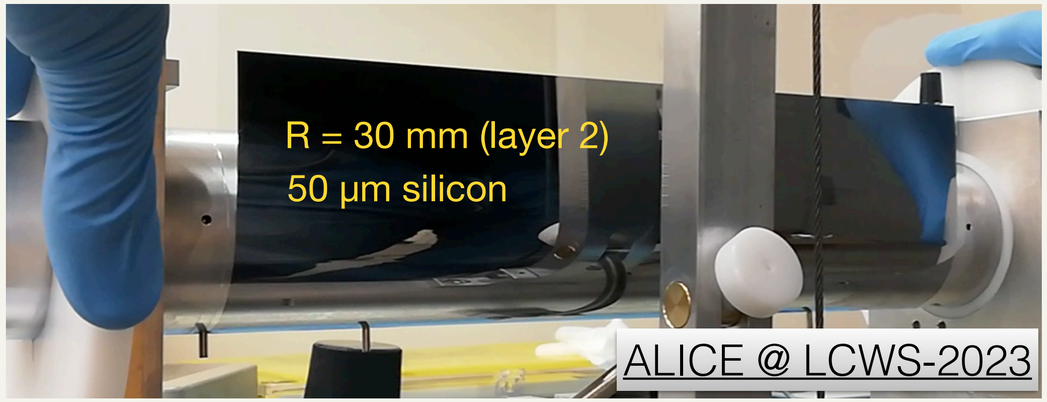
ILD Interim Design Report (2020)

- Multi-purpose detector, original design for the ILC (250 GeV, 500 GeV and 1000 GeV)
  - Optimised for particle flow, with minimal material budget in front of ECAL.
  - 3.5 T solenoid outside of calorimeters.
  - ~4π coverage (5 mrad), with elaborate forward region — ~ LHC / 3
  - Power pulsing => low heat dissipation => lightweight (or no-) cooling
- Vertex detector: silicon $\sigma(d_0) \sim \left(5 \oplus 10/(p \cdot \sin^{3/2}\theta)\right) \mu m$ — ~ LHC / 2
- Tracking: TPC $\sigma(1/p_T) \sim 2 \times 10^{-5}\ \text{GeV}^{-1} \oplus 10^{-3}/(p_T \cdot \sin^{1/2}\theta)$ — ~ LHC / 10
- Calorimeters: high-granularity (CALICE prototypes)
  - e.g.: silicon-W ECAL + scintillator-steel HCAL
  - Jet energy resolution (for a 100 GeV jet): $\sigma_E/E \approx 3-4\,\%$ — ~ LHC / 2
- PID provided by the TPC (dE/dx) $\sigma_{dE/dx}/\mu_{dE/dx} \sim 5\,\%$ — ~ ALICE

Vertex detector and silicon tracking

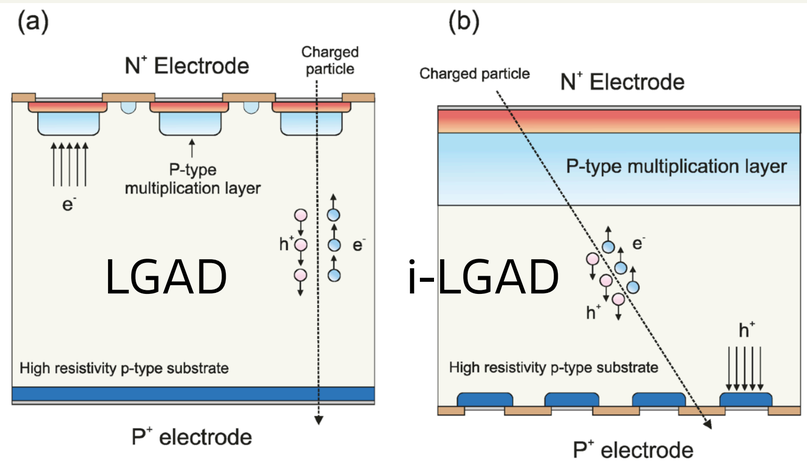
- Current technologies:
  - CMOS (well known)
  - DEPFET (Depleted FET)
  - FPCCD (Fine Pixel CCD)

Target: low material budget
~ 0.15% X0 / layer (3 layers planned)



ALICE @ LCWS-2023

- Future technologies:
  - MAPS (ALICE ITS-3):
    - Bendable wafers!
    - Ultra-low material: 0.05% X0 / layer
    - Working toward sub-ns timing resolution (LCWS-2024)
    - Pixel pitch < 25 µm
    - low power ~ 20 mW/cm2
  - Inverted-LGAD
    - 20 ps timing resolution
    - 100% fill factor



https://doi.org/10.3390/s23073450

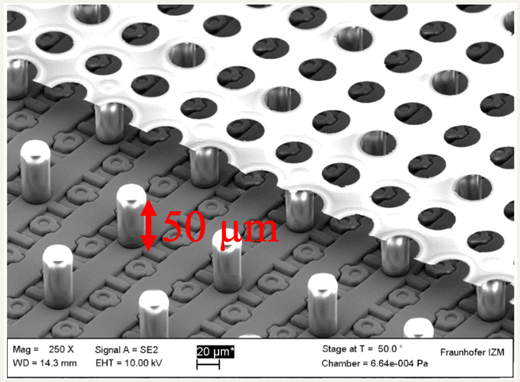
Tracking: TPC or full-silicon?

See talk by Maksym Titov yesterday

- Target:
  - Light: 5% X0
  - momentum resolution 10-4 / GeV => point resolution: 100 µm
  - 5% dE/dx resolution for PID

- Current: pad-based (GEM or micromegas, similar performance)
  - Test beam prototypes for both readouts.

- Under study: pixel readout using TimePix-3 [ILD meeting 2024]
  - 1x6 mm2 -> 55x55 µm2
  - 15% improvement on momentum resolution.



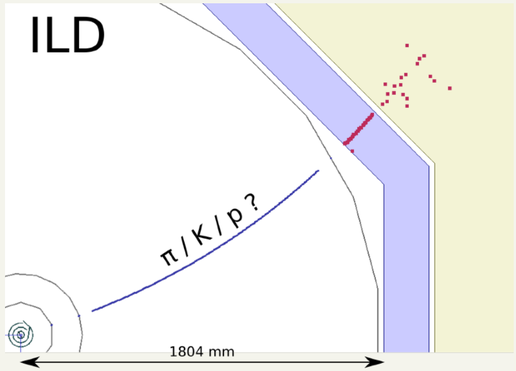
- Main difference between ILD and CLIC-det (fusion of ILD and SiD):
  - full silicon tracking: 1.5% X0 / layer
  - 2.5 -> 4T

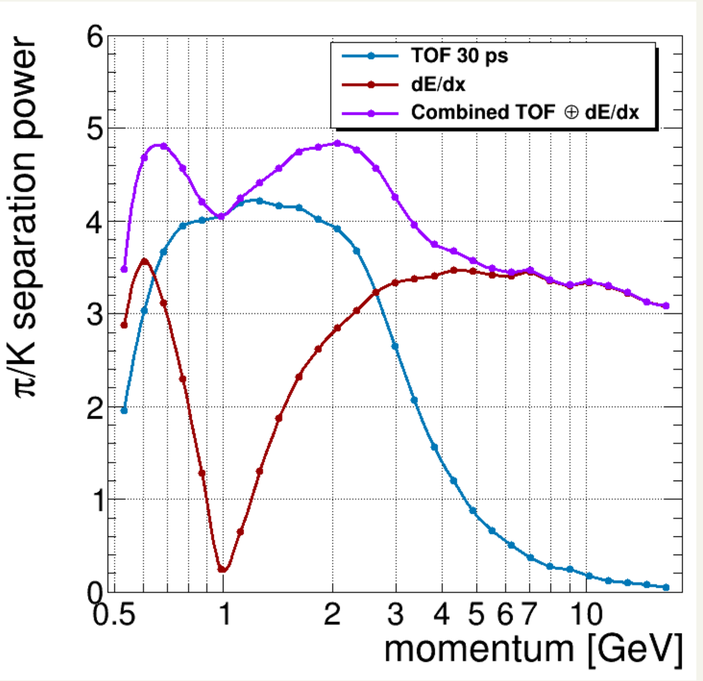
Particle ID improvements

- PID at ILD:
  - energy loss (dE/dx) from the TPC
  - cluster shape from particle flow
  - Time-of-Flight (ToF)

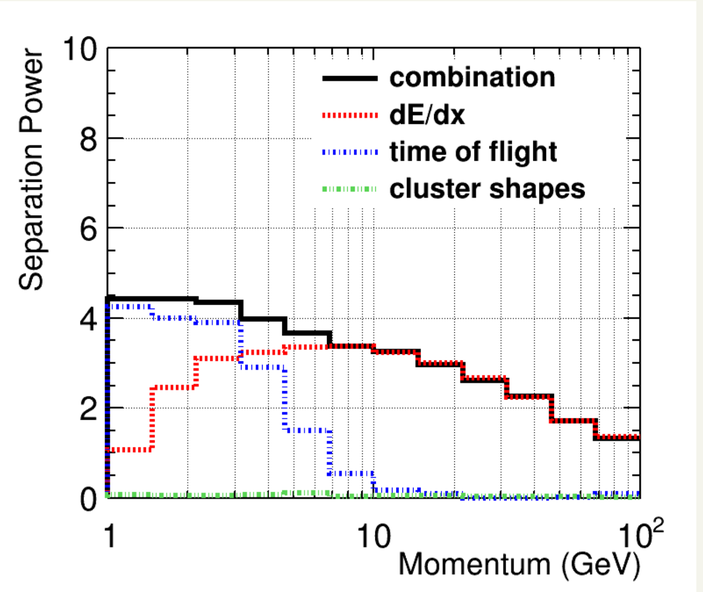
- ToF can be improved by using timing information from the ECAL [Bohdan Dudar @ EPS-2023].
  - Improved track length measurement in the TPC.

- Combine all methods use BDT!
  - => Comprehensive PID framework





Bohdan Dudar @ EPS-2023



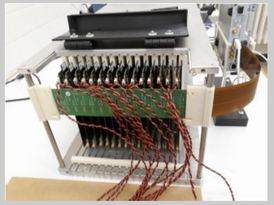
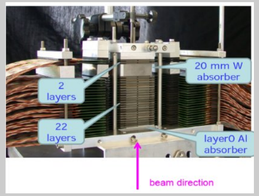
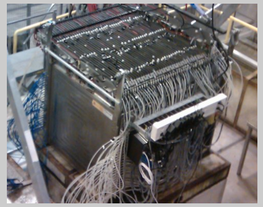
Ulrich Einhaus @ ILD Workshop 2024

Calorimeters

- Calorimeters: developed within CALICE (now DRD-6)
  - High-granularity required for particle-flow reconstruction.

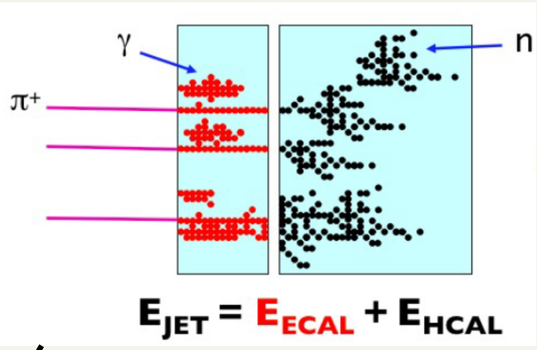
Technological & new Physics Prototypes

4.5 prototypes, 15⁺ years of R&D, all tested

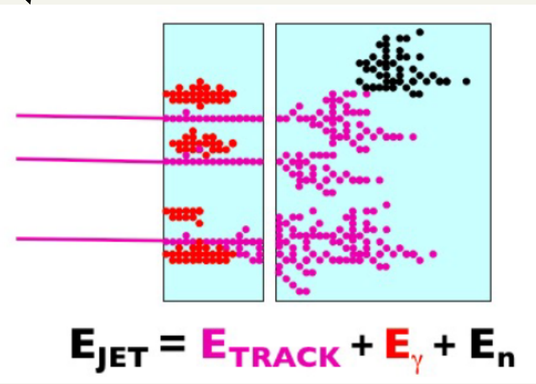
Si-W ECAL	(ALICE FoCAL)	Scint-W ECAL	AHCAL	SDHCAL
				
0,5×0,5 cm² ×15 (→30) Si layers + W	0,003×0,003 cm² × 24 MIMOSA layers + W	0,5×4,5 cm² ×30 Scint+SiPM lay. + SS	3×3 cm² × 38 Scint+SiPM lay. + SS	1×1 cm² × 48 layers GRPC + SS

Purposes:

- Prove technological feasibility: electronics inside, thermal capacity, mechanical, DAQ, calibration, …
- Extend physical prototypes : uniformity, “large” production, methods, …



Particle flow

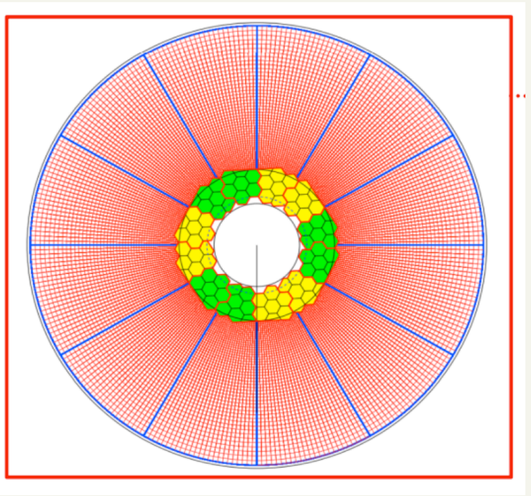


CALICE review talk by Vincent Boudry @ CALOR 2024

Calorimetry developments

- AHCAL:
  - Megatiles: segmented board-sized scintillator in a single piece.
  - Timing studies

CMS HGCAL



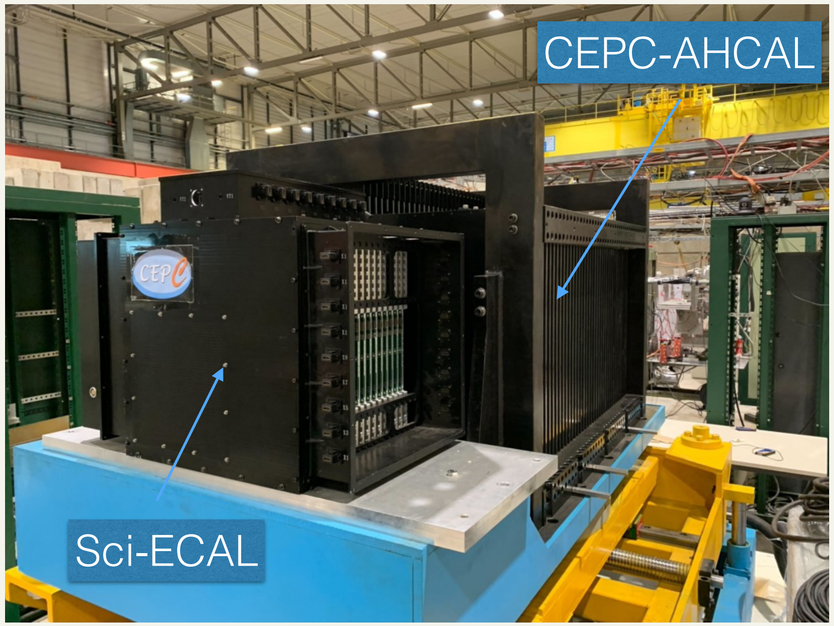
To be installed in 2027

- SiW ECAL:
  - Working on improving hybridisation (gluing of electronics and sensor) and mechanical stress.
  - Test beams in 2022 and 2023.
  - Now building new, improved layers.

Roman Pöschl @ CALOR 2024

- Scintillator-ECAL + CEPC-AHCAL
  - common test beam in 2023
  - Analysis ongoing

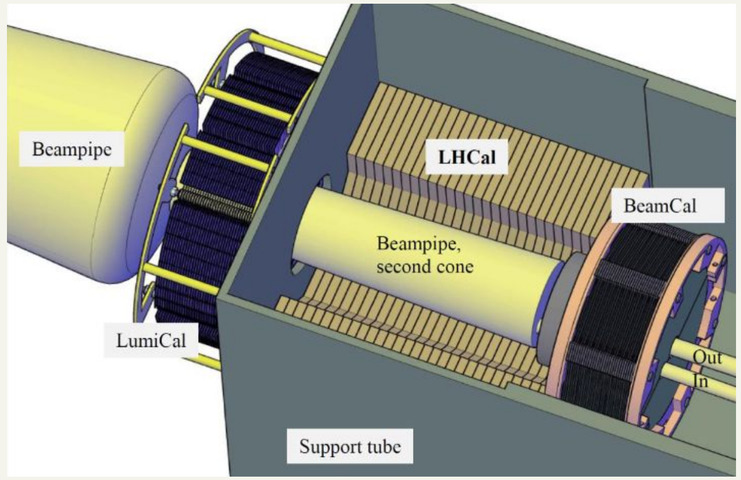
Tatsuki Murata @ CALOR 2024



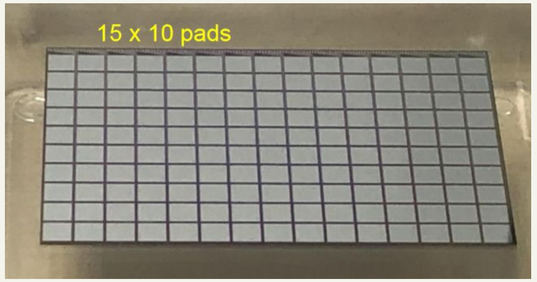
- Digital ECAL using MAPS [Jim Brau @ CALOR 2024]
- Dual readout calorimeters (scintillation + Cherenkov)
- Crystal calorimeters…

Forward calorimeters

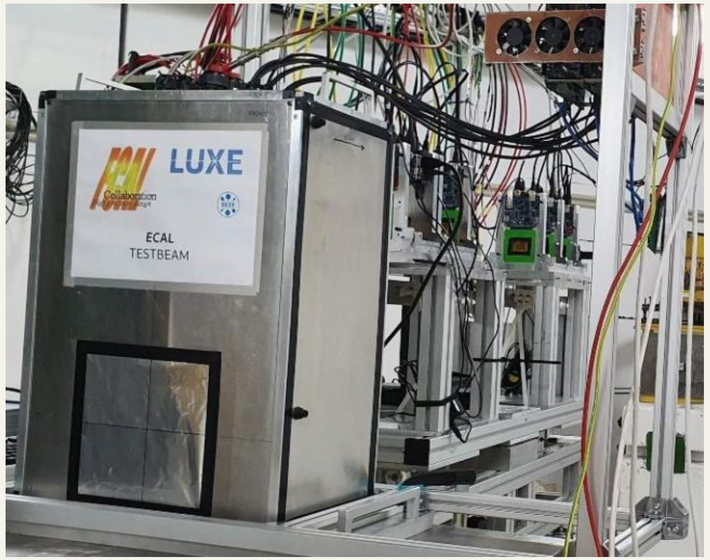
- Down to θ = 6 mrad (η = 5.8)
- High granularity



- BeamCal: fast luminosity measurement using beam-strahlung
  - GaAs readout + W-absorbers.
  - New GaAs sensors with integrated signal routing.
  - Test beam data analysis ongoing.



- LumiCal: precise luminosity measurement (Bhabha counting)
  - Based on SiW-ECAL design
  - applied to CMS lumi cal
  - applied to LUXE ECAL



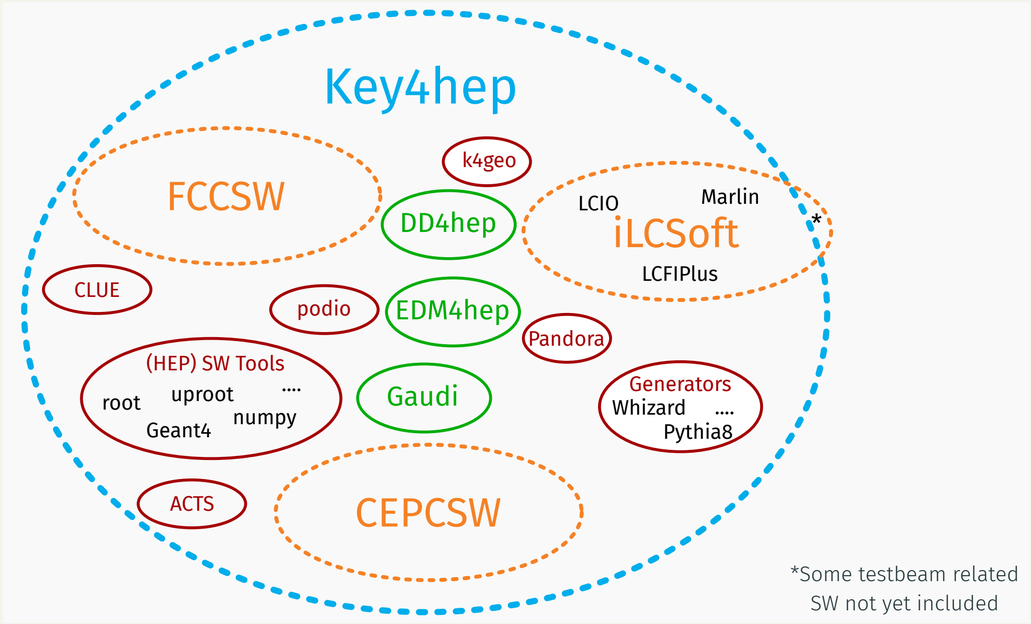
- New idea: measure ee -> γγ instead of Bhabha [Graham Wilson @ ILD workshop 2024]

https://agenda.linearcollider.org/event/9625/#1-status-and-plans-of-the-fcal

Software

And a quick note on PID

- Common software stack: Key4HEP
  - iLCSoft, FCC-SW, CEPC-SW…
  - Detector models included (DD4hep)
  - Generators
  - Reconstruction algorithm (eg. Pandora, ACTS)
  - …



Adapting the ILD to circular e+e- colliders

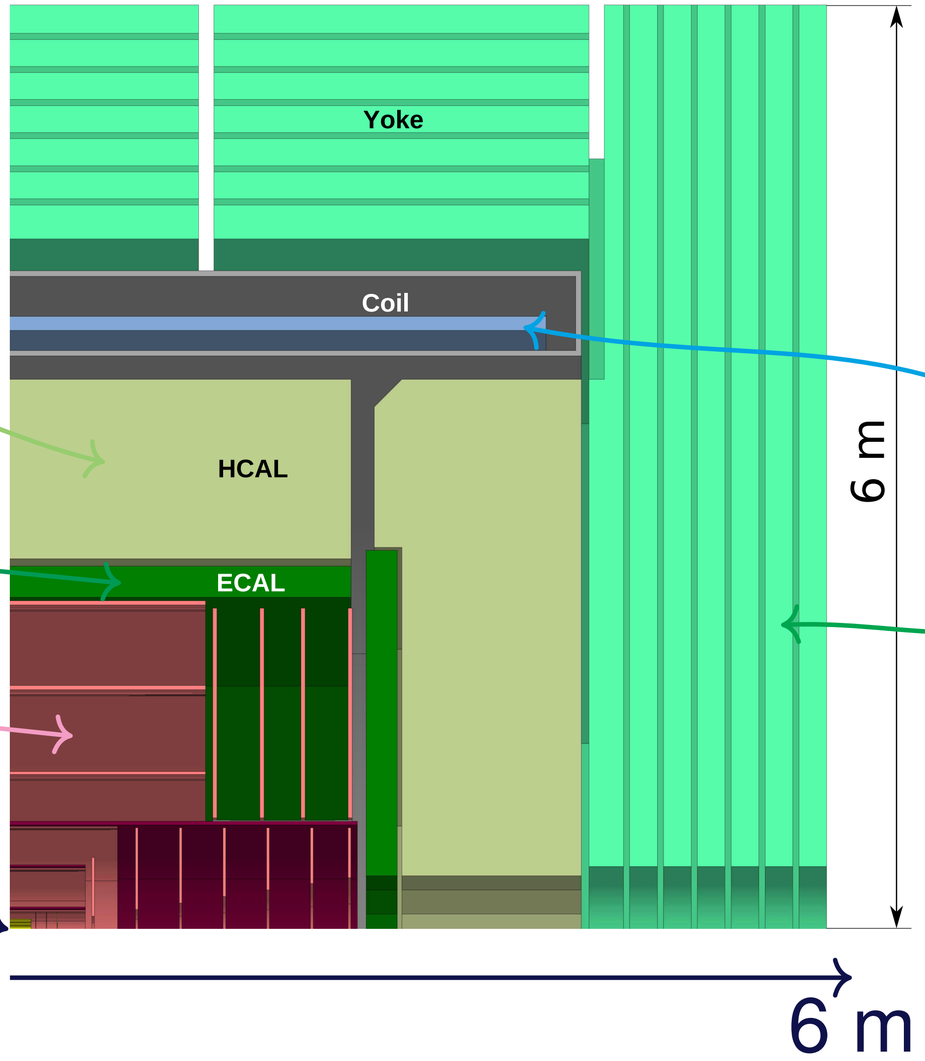
The CLD detector

arxiv:1911.12230

Ancestry: ILD => CLIC-det => CLD

Main changes wrt. ILD

- Steel–Scintillator HCal with 3 cm cell-size
- Silicon–Tungsten ECal with 5 mm cell-size
- Silicon Tracker, mostly 50 μm pitch strips
- Vertex Detector with 25 μm pixels



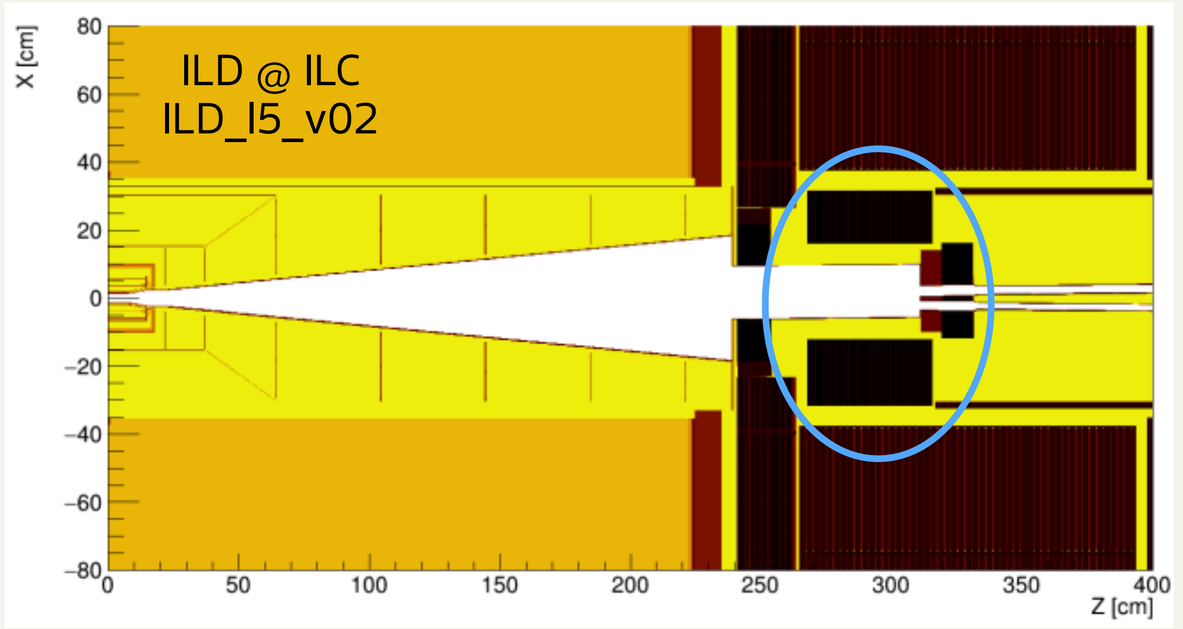
- Superconducting Solenoid of 2 T
- Iron Yoke with RPCs for Muon ID

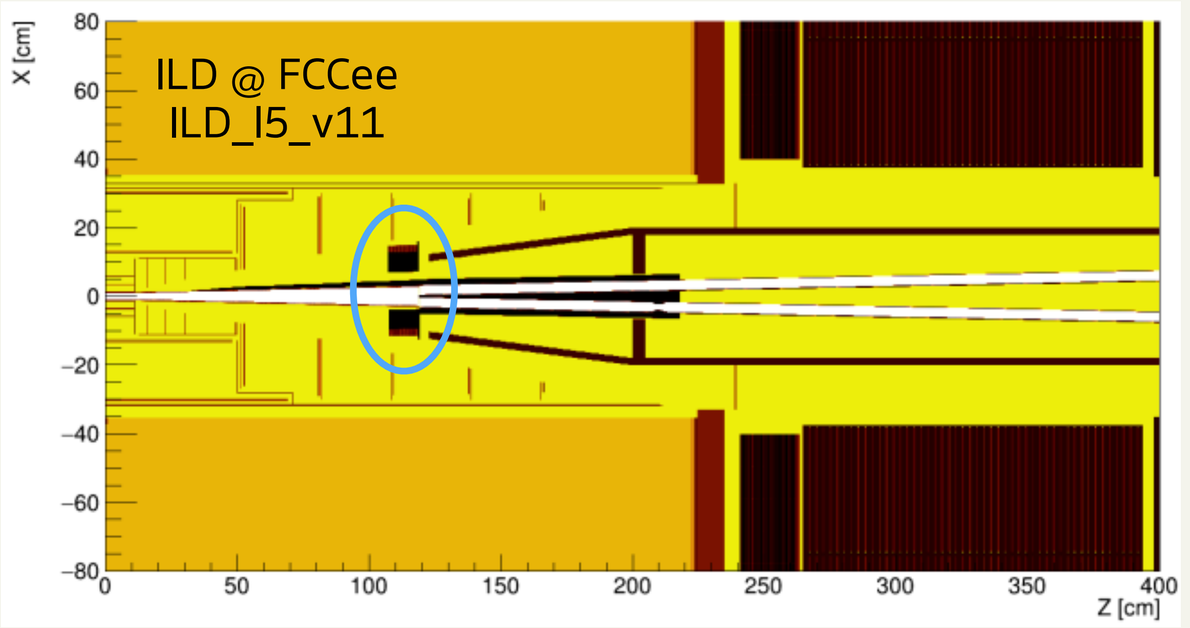
Stolen from Andre Sailer

ILC -> FCCee

- Large changes to the Machine-Detector Interface
  - Crossing angle 14 mrad => 30 mrad.
  - Last focusing quad 4 m => 2.2 m
  - Additional compensating or screening coils.
  - Limits B field to 2 T (at the Z peak).
    - Can be 3 T at lower lumi.

- Tightly packed forward region.
- Forward calorimeters pulled back in the tracker area.



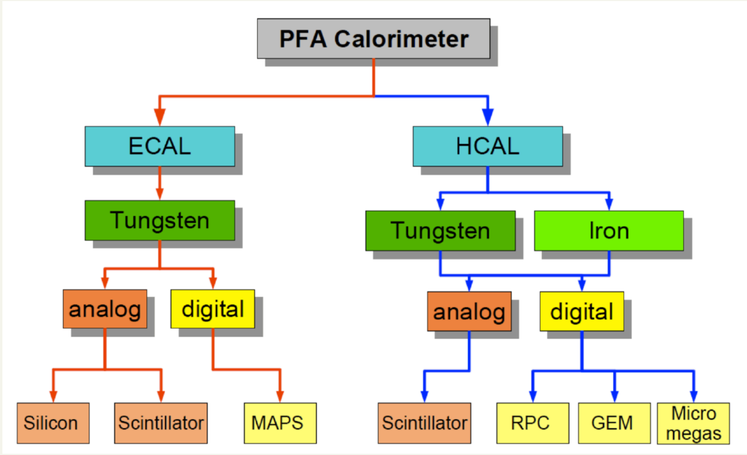


Calorimeters & readout

- Same technologies can be reused: high-granularity for particle-flow.

- Real challenge = “continuous” beam:
  bunch spacing down to < 20 ns
  - => no power pulsing
  - AHCAL (SPIROC): ~40 µW / channel
  - HGCAL (HGCROC): ~5 mW / channel

x100



- Expect physics rate of ~100 kHz at the Z-peak.
  - => cannot (or hardly) go trigger-less.
  - Though it might be acceptable at lower lumi (WW / Higgs / ttbar)

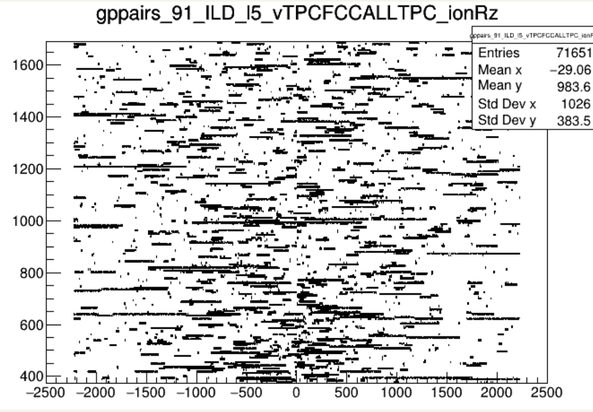
- Cooling and trigger requirement also applies to the tracking systems…

A TPC at high-luminosity?

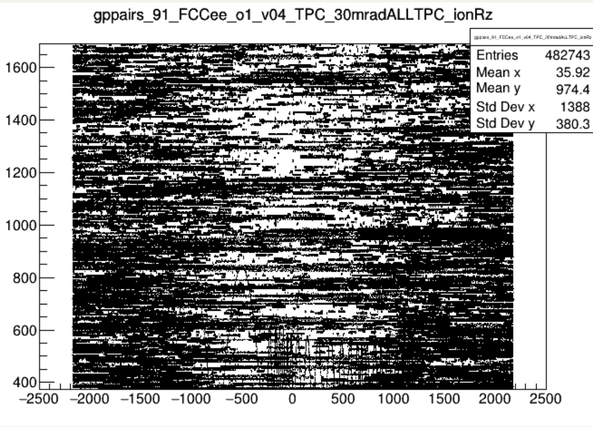
- Potential issues:
  - Inter-bunch spacing much less than at ILC?
    - Electronics speed can cope with that.
    - Especially pixel-TPC: ~1 ns
  - Occupancy due to physics events and backgrounds?
    - Granularity is fine enough.

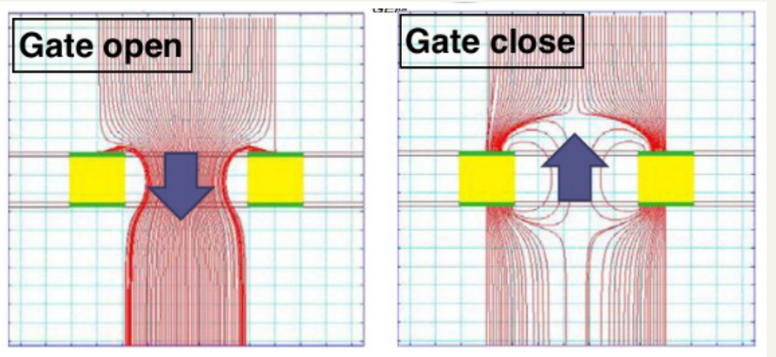
- Actual issue: charge build-up in the TPC
  - Due to beam-strahlung background.
  - => TPC field distortion due to primary ions and ion back-flow.
    - Distortions at the 100 µm level.
  - Solved at ILC/CLIC by “gating” (reverse polarity of the collection surface outside of bunch crossing to capture the ions).
    - Not straightforward at FCC/CEPC, but some ideas (corrections from silicon layers).

ILC



FCCee





Other ideas?

- SiD-side of life: full-silicon tracker (6 or 7 silicon layers)
  - Each 1-2% X0 (compared to a total 5% X0 for TPC)
  - No dE/dx => no PID => add RICH detectors [Gaelle Sadowski @ LCWS 2024]

- Other idea: drift chamber
  - Less sensitive to distortion (since drift path is shorter: ~ few cm), but requires studies.
  - Can also do some PID
  - But more material (dominated by Tungsten wires) and robustness issues for 50'000 wires.

Summary

- ILD (CLIC-det) for ILC (CLIC) is a mature detector.
  - Concepts have been worked on for > 15 years, including simulations, large prototypes, and test beams with real data analysis.
  - Ideas have been applied to running or about-to-run detectors (CMS HGCAL, ALICE ITS), and are a source of inspiration for other R&D projects (LUXE).
  - Great playground for new ideas (pixel readout for TPC, dual readout calorimeters, …)!
  - Software improvements are going on.

- ILD at circular colliders requires non-trivial adjustments.
  - Continuous running forbids power-pulsing operation => need for heavier cooling
    - => more material, in an already-packed detector.
  - MDI implies major layout changes: LumiCAL and forward detectors.
  - Main challenge from the tracking: TPC lives at the limits, particularly at the Z peak
    - Beam-strahlung background leading to large ion back-flow.
- However no definitive show-stopper, with people working on solutions!

Thanks for your attention!

Questions?