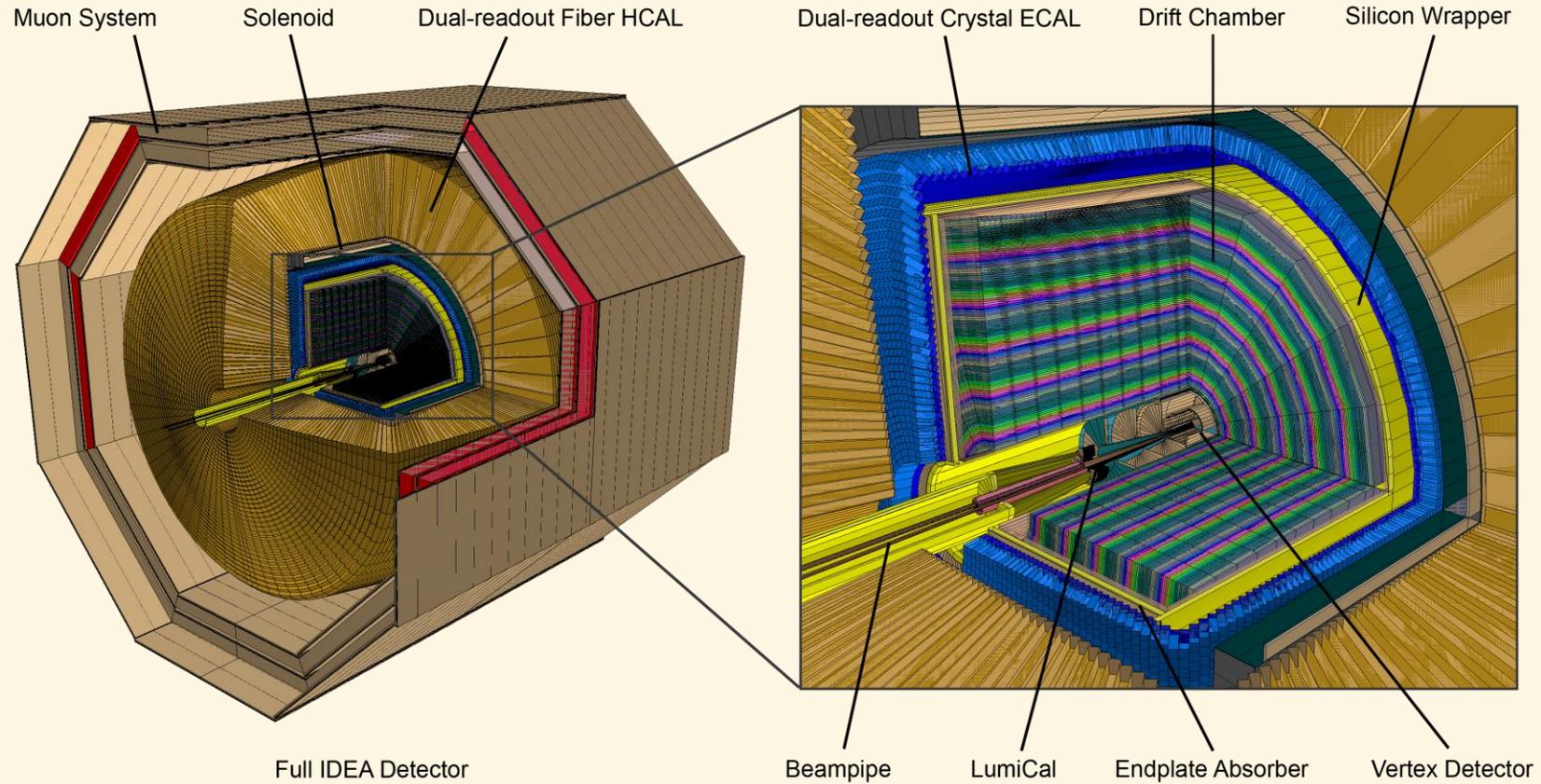


The IDEA Detector Concept for FCC-ee



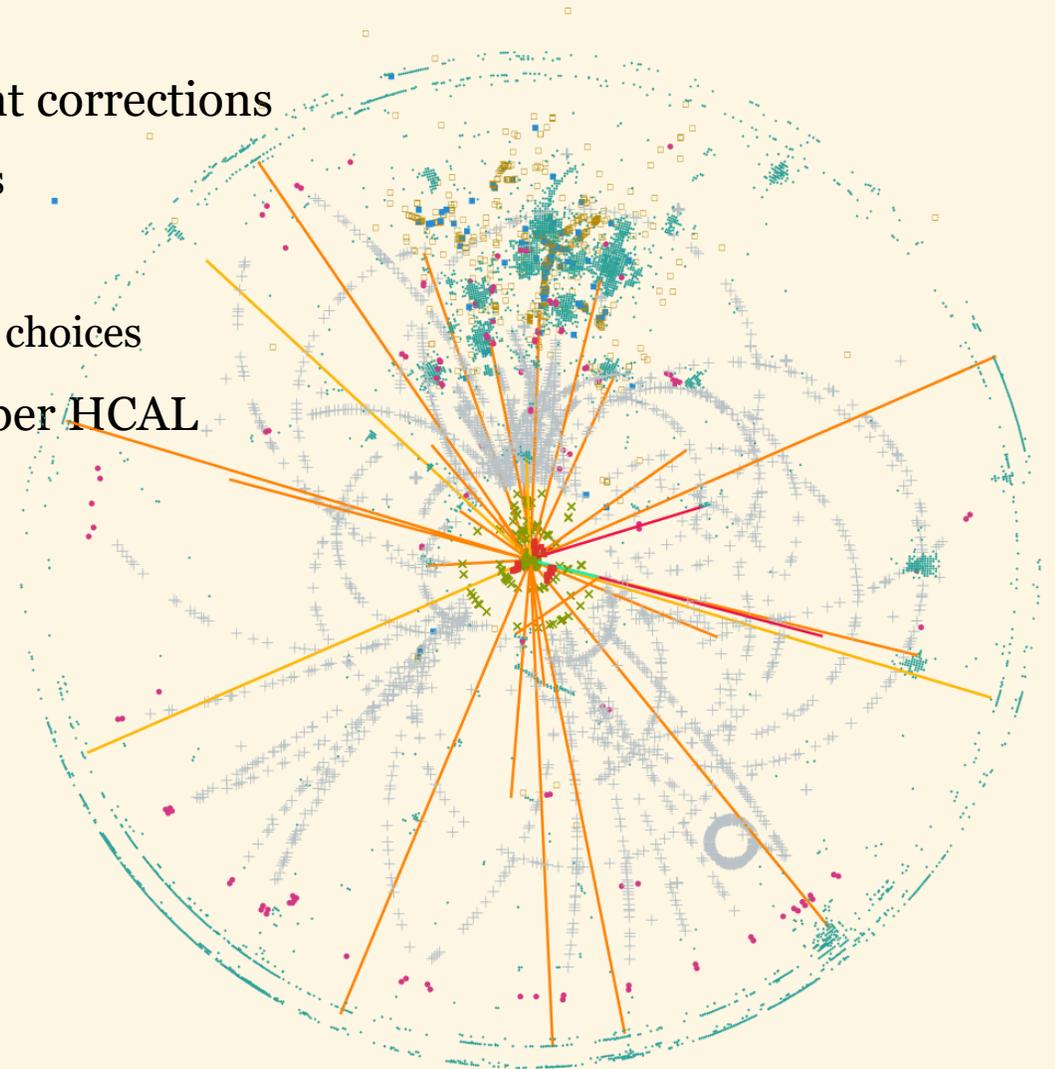
Wonyong Chung
Princeton University

August 2025
Lepton-Photon Symposium

IDEA for FCC-ee: Precision by Design

Precision physics \rightarrow detector performance drivers \rightarrow design choices

- Beyond resolution: design for systematic control and per-event corrections
 - Z, ZH – systematics and reconstruction are the limit, not statistics
 - Accelerator/MDI rewards linearity, timing, calibration control
 - CLD, IDEA, ALLEGRO illustrate calorimetry-driven architectural choices
- Hybrid dual-readout calorimetry: segmented crystal ECAL, fiber HCAL
 - Qualitatively new observables, event-by-event compensation
- Full simulation in key4hep, digitization in progress
 - Now at IRIS-HEP: Bilevel optimization framework
 - Blue-sky AI/ML with synthetic data/representations
- Performance headlines:
 - $\sim 3\text{-}4\%$ at >50 GeV jets
 - Hadronic $\sim 26\%/\sqrt{E}$
 - EM $\sim 3\%/\sqrt{E}$

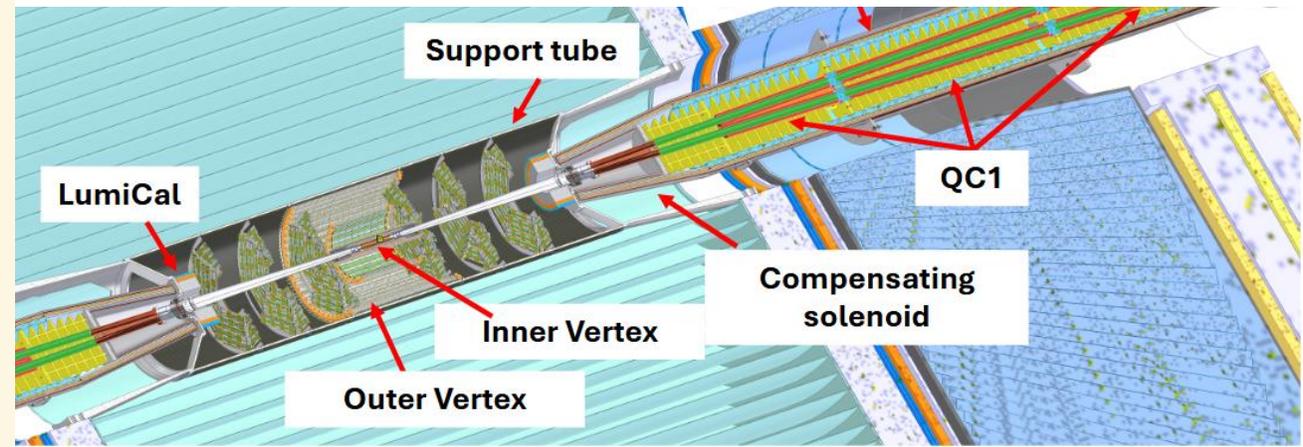
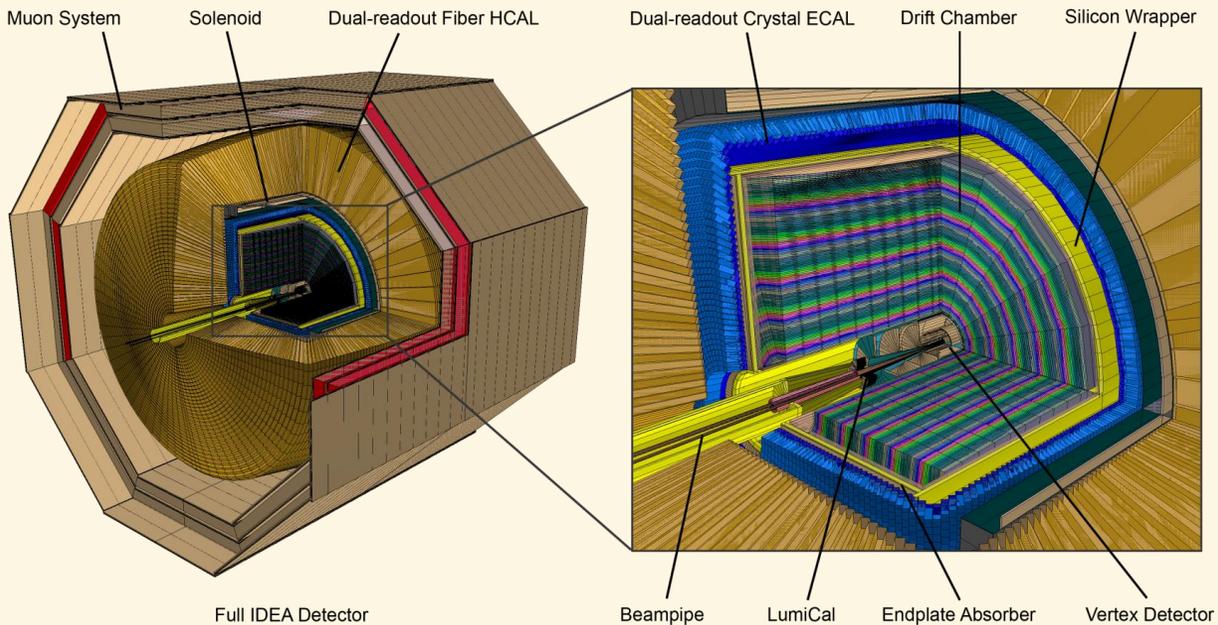
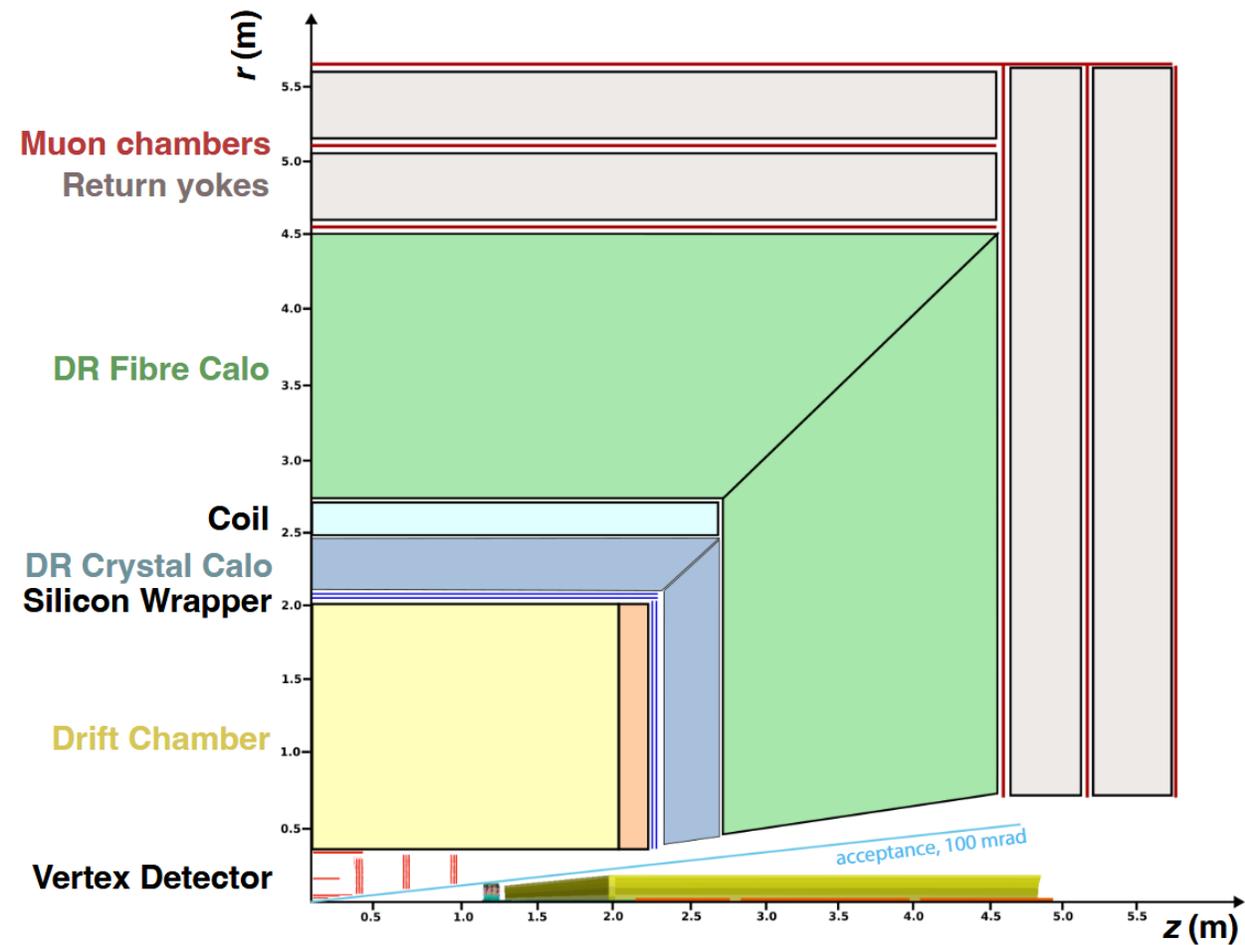


Precision physics → detector performance drivers

- Run points: Z(91 GeV), WW(161 GeV), ZH(240–250 GeV), tt(~ 365 GeV)
- Tera-Z ($O(6 \times 10^{12})$ Z) → 100-200 kHz events, comparable to L1 rates at HL-LHC
- \sqrt{s} dimuon kinematics, ISR/FSR control → superb tracking, angular resolution (~ 0.1 mrad), photon tagging/recovery
- Heavy-flavor program: soft photons → ECAL resolution, π^0 separation
- HZ recoil mass → bremsstrahlung recovery, transparent MDI+tracker
- Electron Yukawa at Higgs pole via monochromatisation → $\delta\sqrt{s}$ vs. integrated L, demands stable EM scales
- ALP/LLP, τ /rare-B signatures → photon angular/energy precision
- 30 mrad crossing-angle → global acceptance calibrations, mechanical tolerances, endcap geometry
- 2 T magnetic field limit to minimize emittance → larger tracking volume, shallow ECAL inside coil
- Continuous ~ 50 MHz crossings, front-end pile-in/time-walk → high S/N, precision timing
- Particle-flow quality → detector segmentation

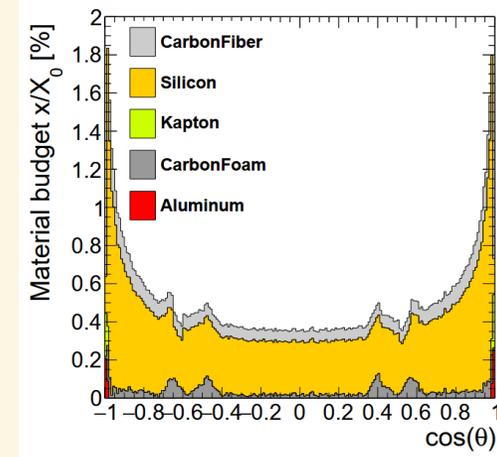
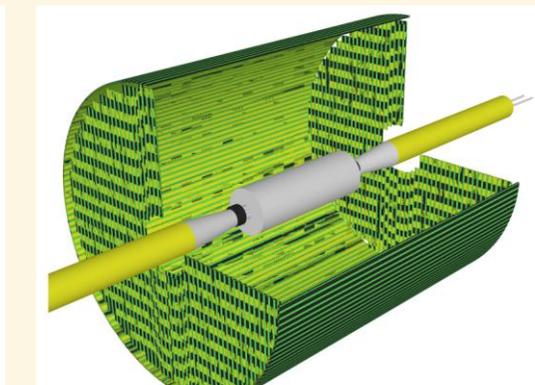
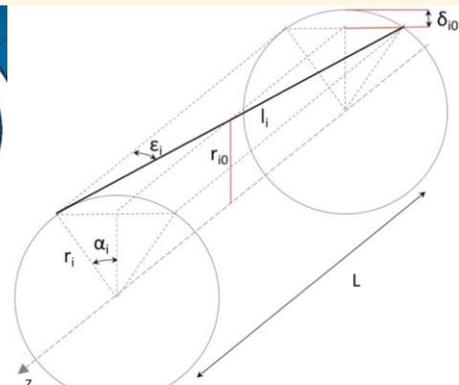
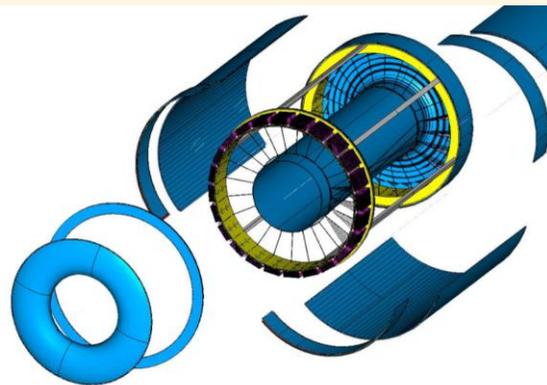
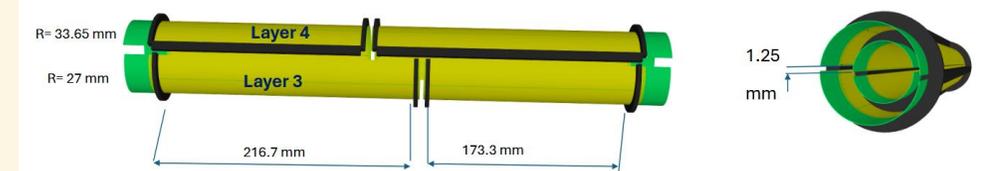
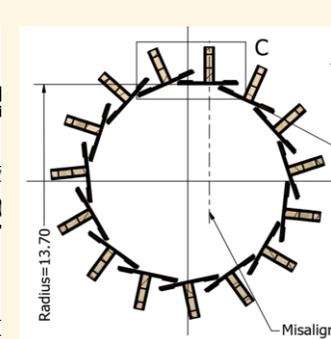
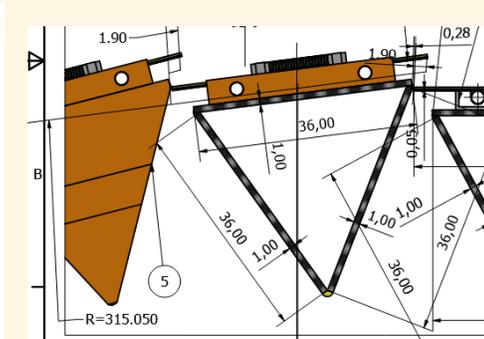
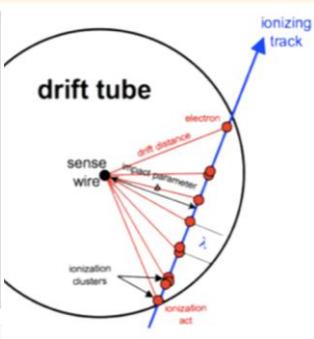
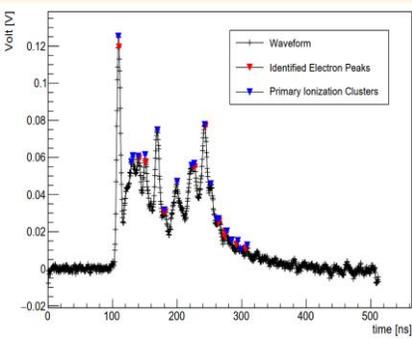
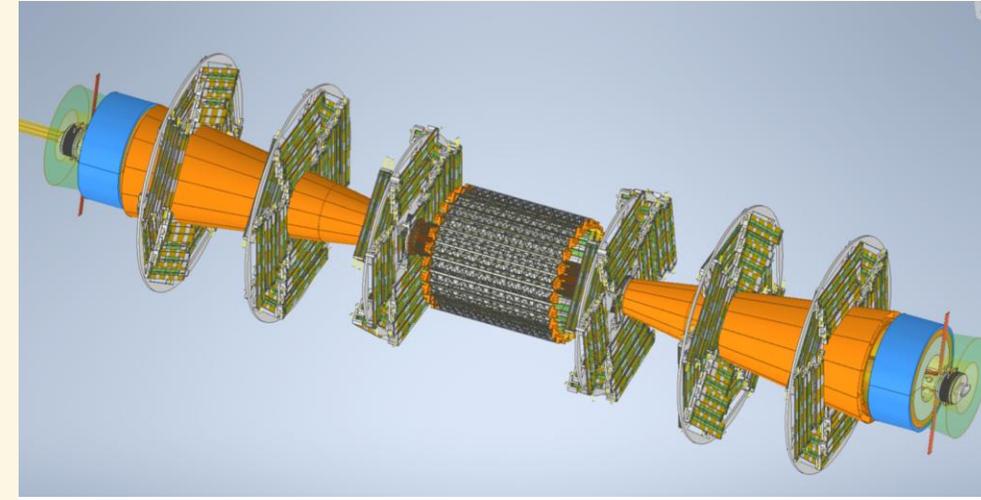
IDEA current baseline

- Vertex, ultra-light drift chamber, silicon wrapper
- Dual-readout segmented crystal ECAL
- Thin, low-mass superconducting solenoid
- Dual-readout fiber HCAL
- μ -RWELL muon system in return yoke
- LumiCal in forward region

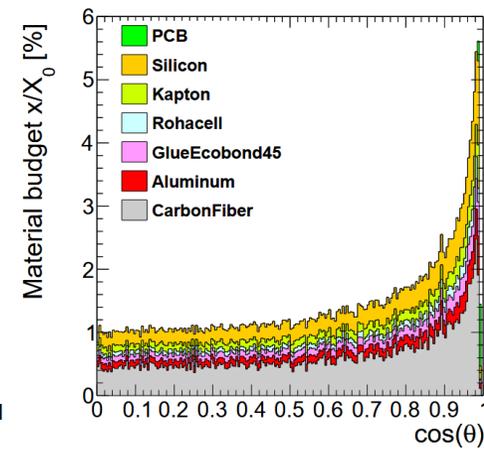


Tracking: Vertex Detector, Drift Chamber, Silicon Wrapper

- Inner/Outer Vertex: 5 total MAPS layers, 3+3 endcap disks
 - Alternative ultra-light curved inner vertex
- Short-drift all-stereo Drift Chamber: 112 layers, He-based gas, 350k wires
 - Cluster counting dN/dx , π/K separation to $O(\text{tens of GeV})$
- Silicon Wrapper: 2-layer microstrips or 1-layer MAPS/LGAD
 - Endpoint precision, $O(\sim 100 \text{ ps})$ timing with LGADs



(c) Ultra-light inner vertex detector



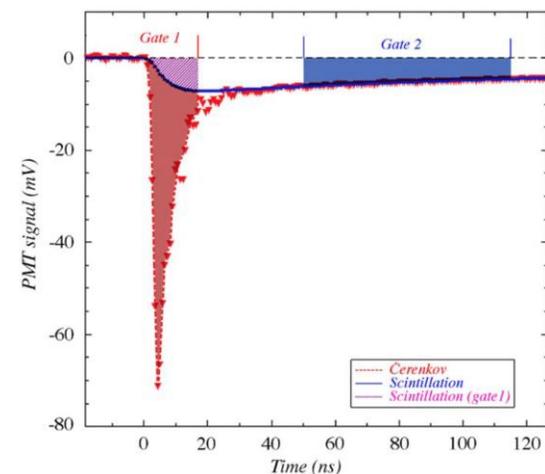
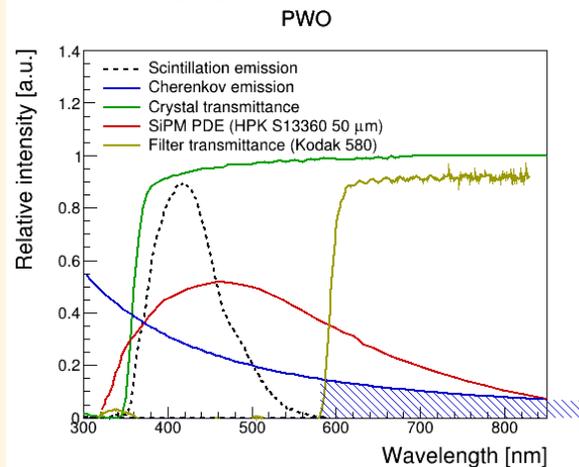
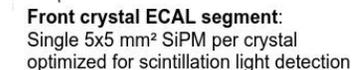
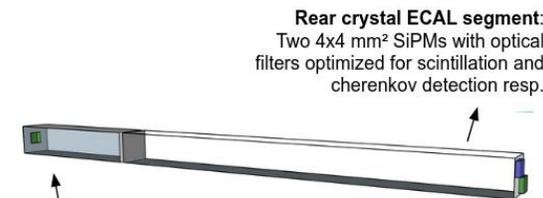
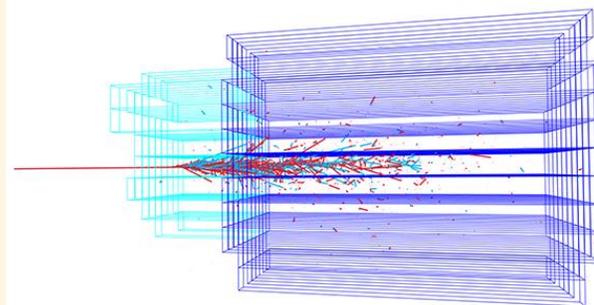
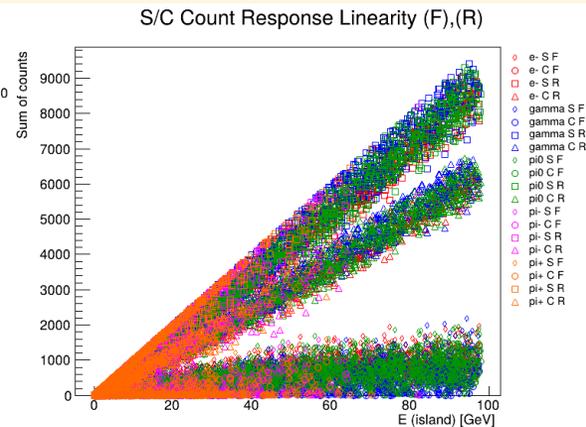
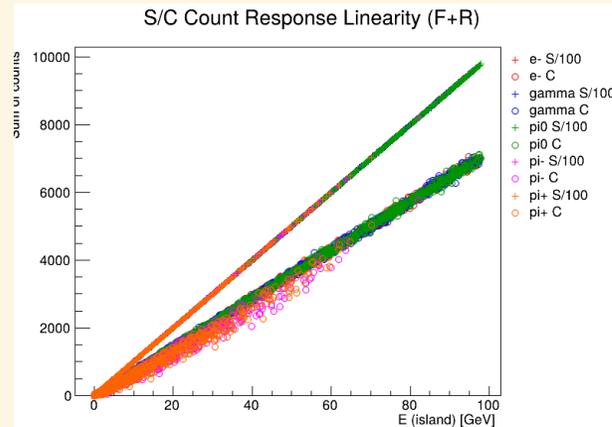
(a) Flat inner vertex

Dual-Readout Calorimetry

- **Technique:** Detect scintillation/Cerenkov light separately to mitigate event-by-event fluctuations in hadronic showers

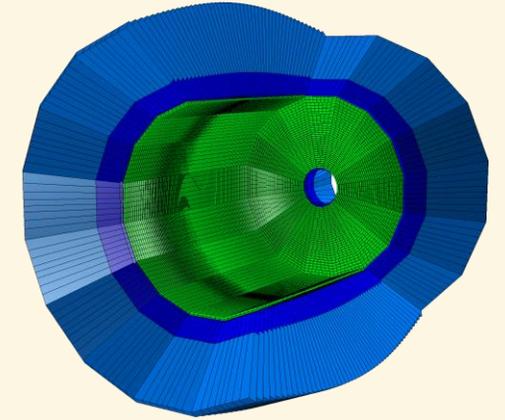
$$\begin{cases} S = E \left[f_{EM} + \frac{1}{(e/h)|_S} (1 - f_{EM}) \right] \\ C = E \left[f_{EM} + \frac{1}{(e/h)|_C} (1 - f_{EM}) \right] \end{cases}$$

- **Procedure:**
 - Calibrate on known EM/hadronic physics processors
 - Obtain the S/C response scaling factors
 - Determine EM fraction event-by-event
- DREAM/RD52 collaborations: fiber HCAL → IDEA
- Dual-readout in crystals: longitudinal segmentation, different channels for S/C
 - By wavelength (PbWO₄): suppress scintillation w/ high-pass filter, detect Cherenkov in blue
 - By time-profile (BGO): slow scintillation vs prompt Cherenkov

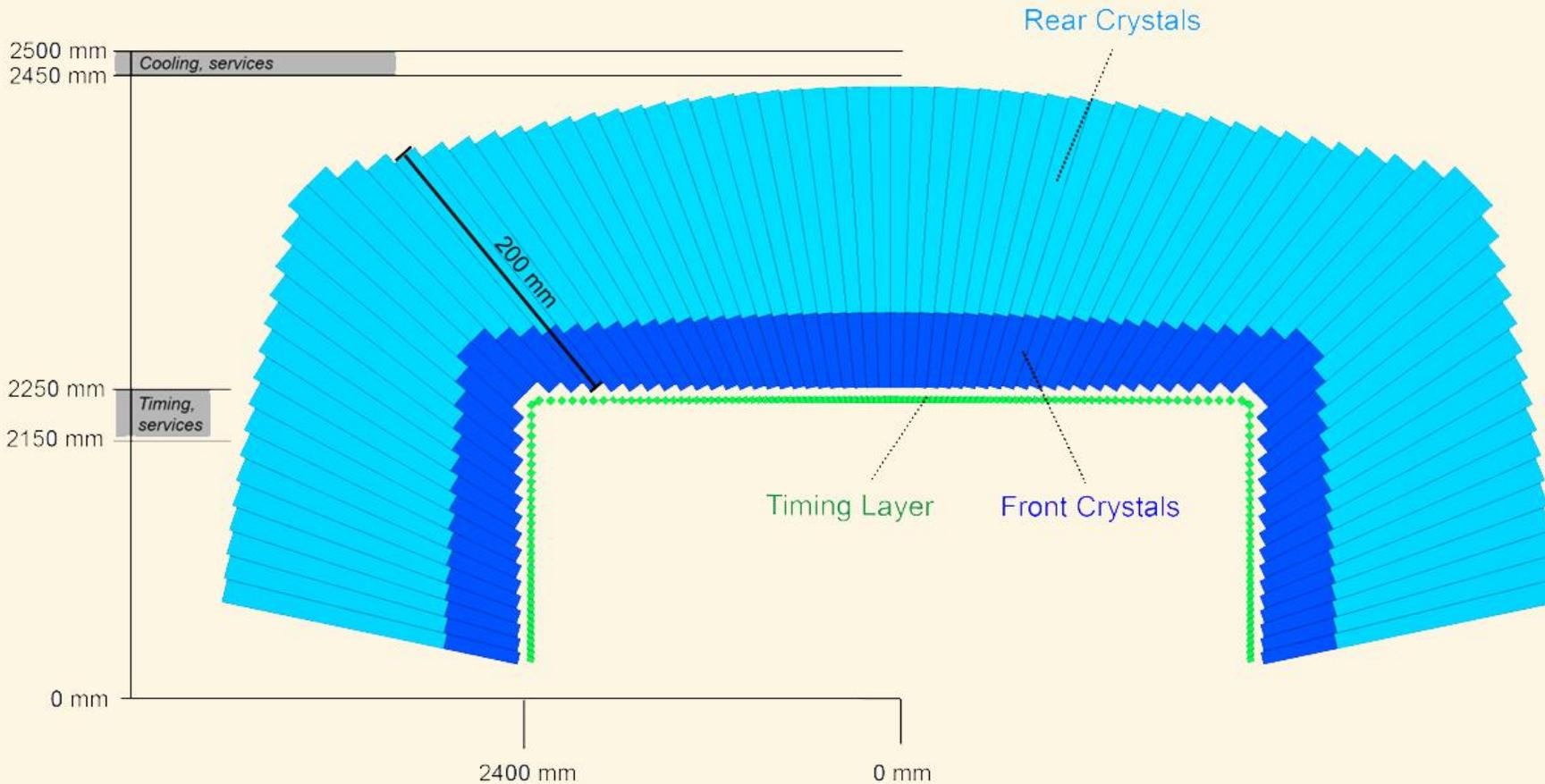
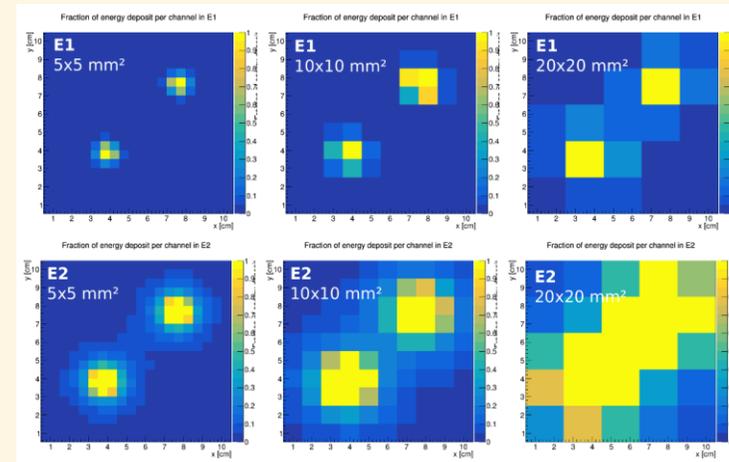
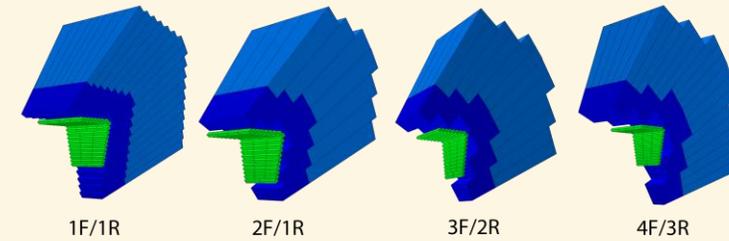


Segmented Crystal ECAL

- Baseline: PbWO₄ crystals 6 X₀ (Front) +16 X₀ (Rear) = 22 X₀
- 10x10 mm transverse granularity (barrel, endcap)
- ~1 X₀ fast-scintillating precision, projective timing layer (e.g. LYSO)
- Fully reconfigurable/differentiable geometry in dd4hep

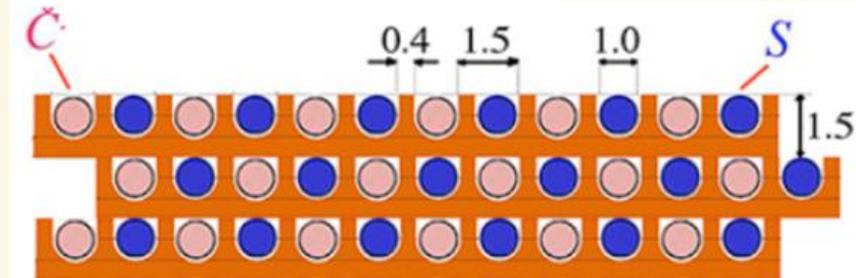
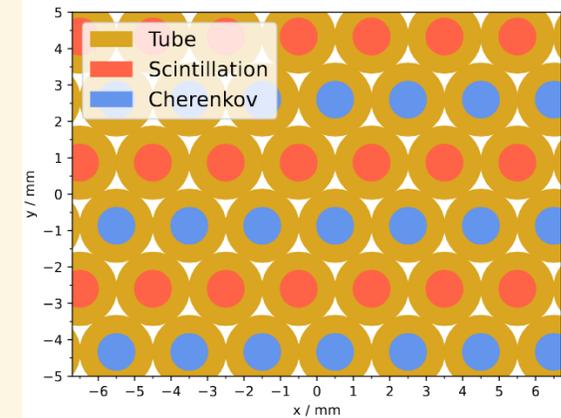
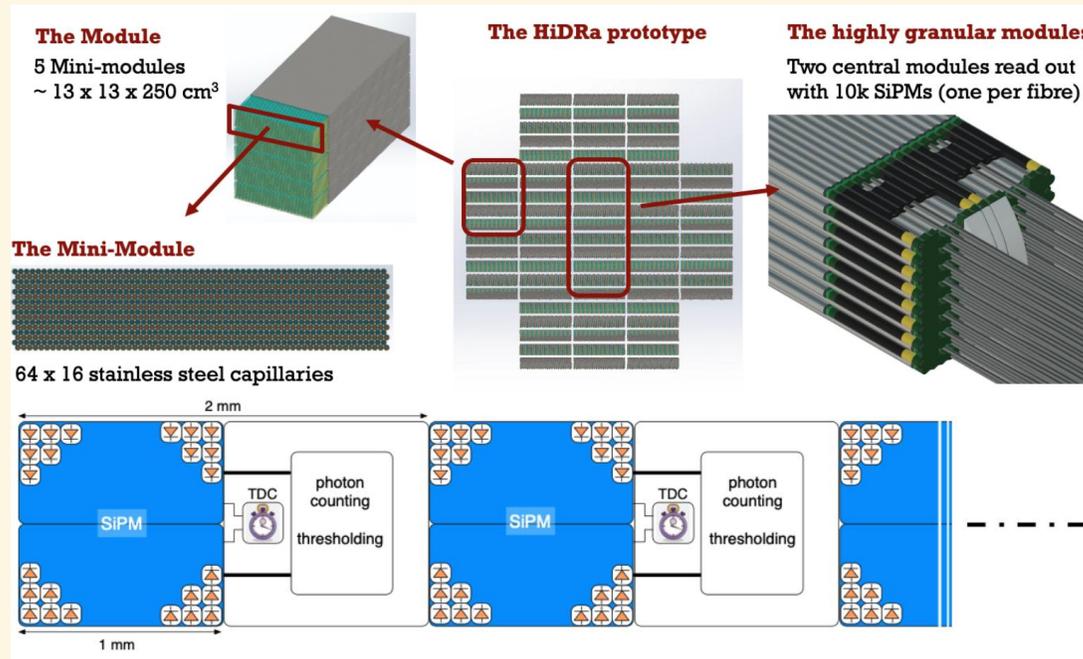


Different Front/Rear Crystal Tower Divisions



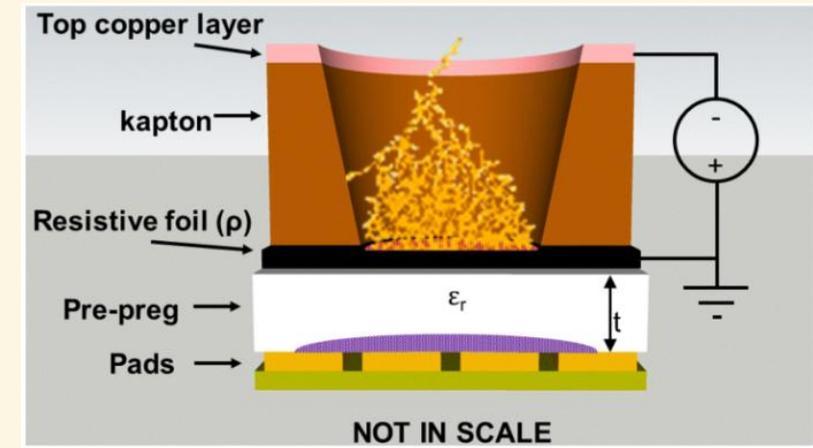
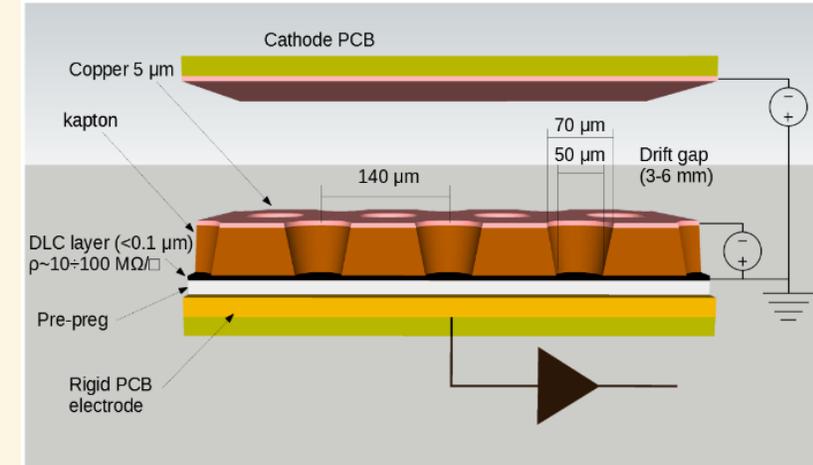
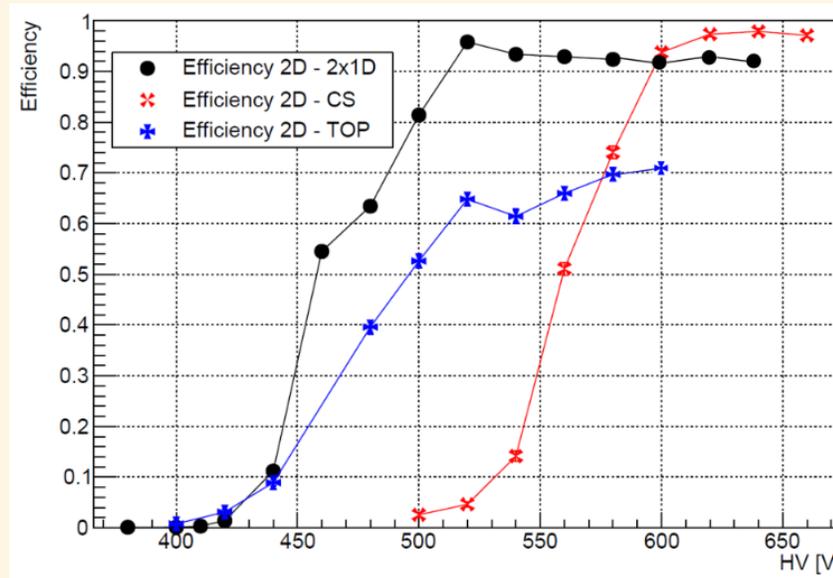
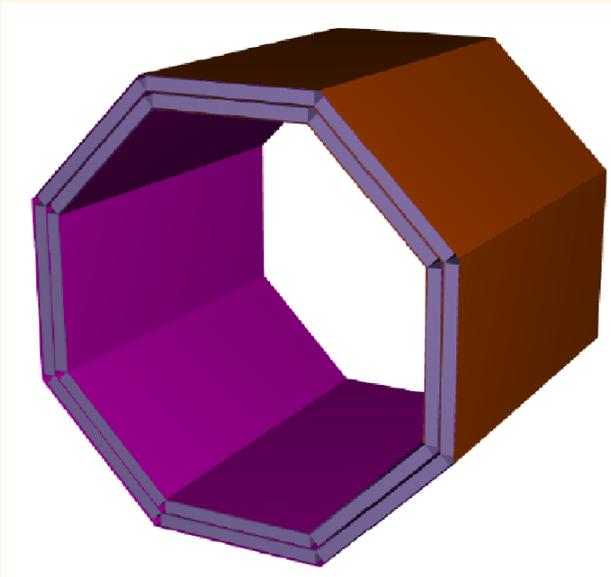
Fiber HCAL

- Baseline: 1mm fibers in brass/iron capillary tubes (bucatini, HiDRa)
 - Scintillation fibers: polystyrene core w/ PMMA single or double cladding
 - Cerenkov fibers: fused silica/PMMA cores w/ fluorinated polymer single cladding
 - Alternative: fibers set in skived fin heat sink (SFHS) copper plates
- Baseline: 1 SiPM per fiber
 - Alternatives: MCP-PMTs, dSiPMs



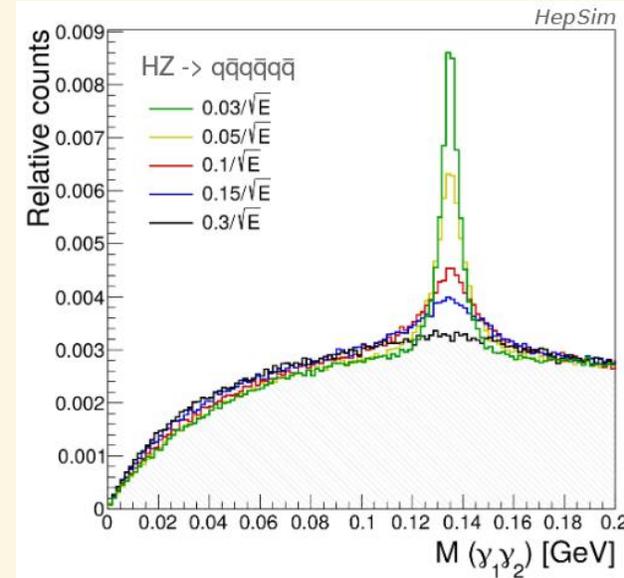
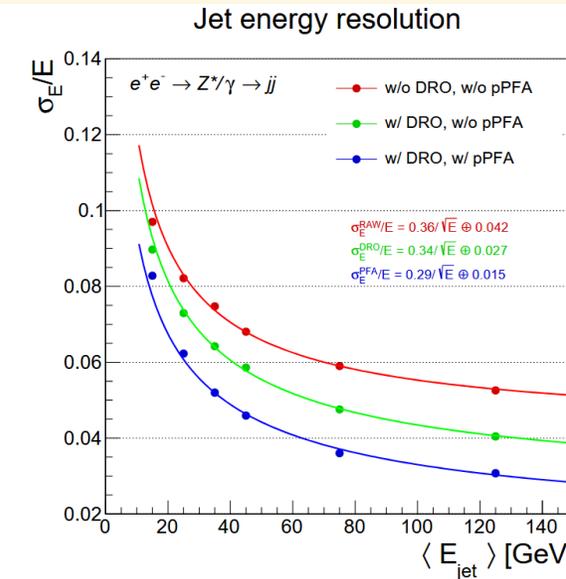
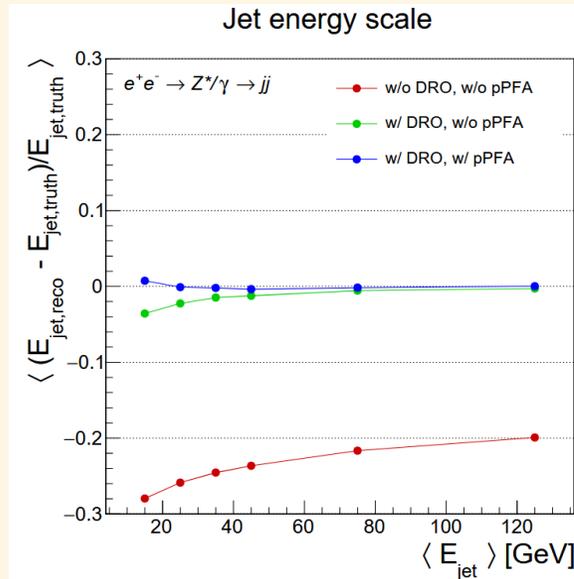
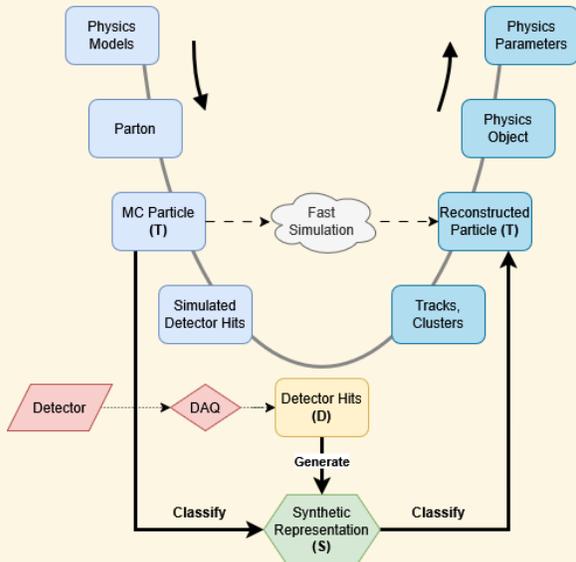
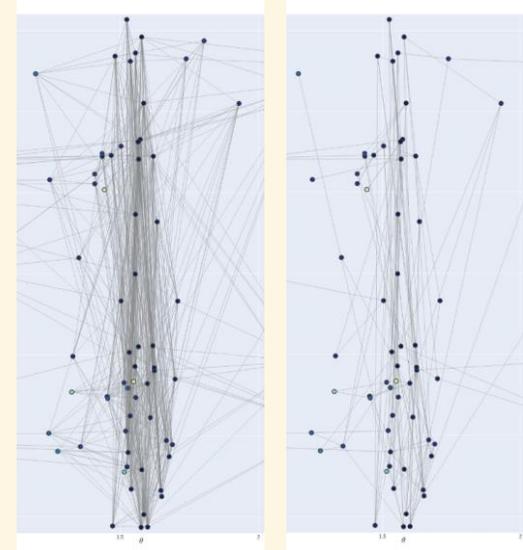
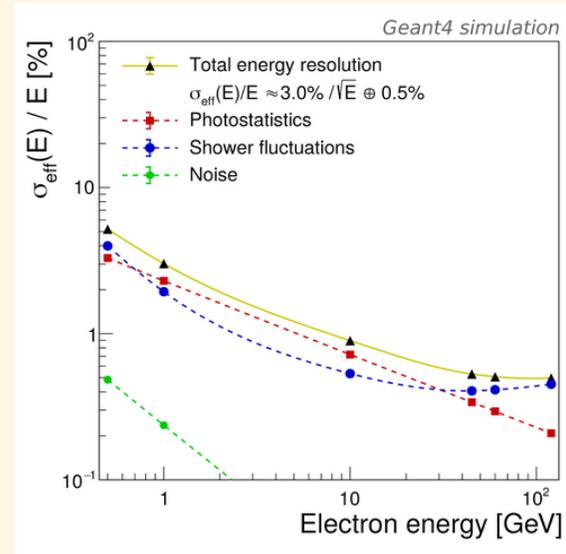
μ -RWELL Muon System

- Single-stage micro-pattern gaseous detectors, 50x50 cm 2D strips
- 3+ layers within return yoke
- ~100 micron spatial resolution for LLPs



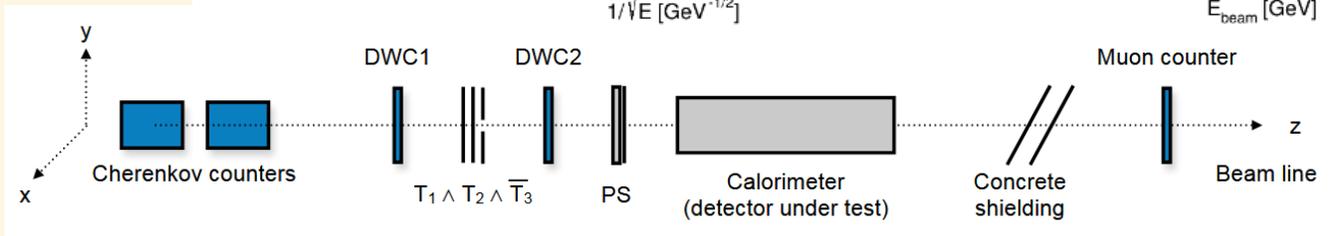
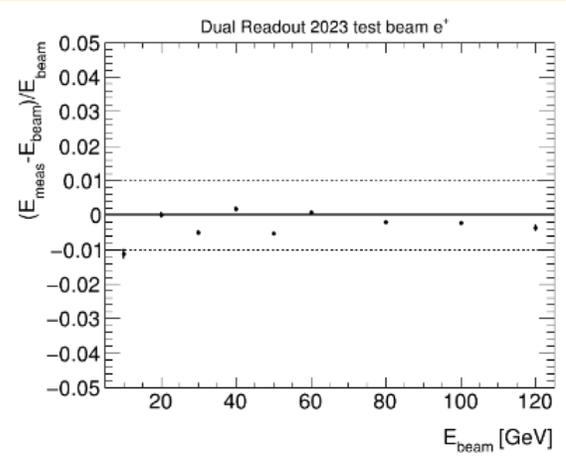
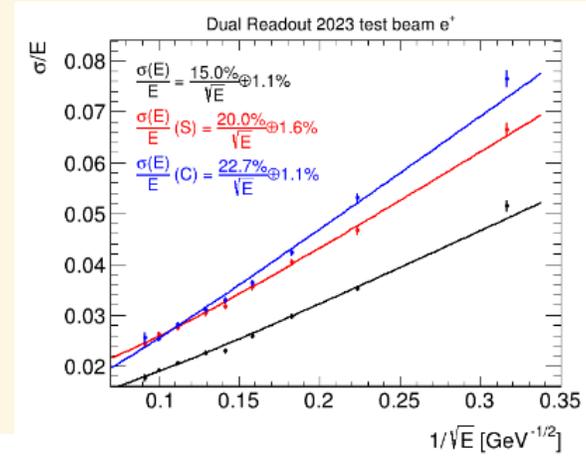
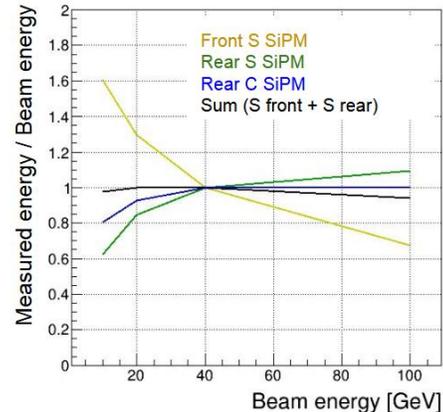
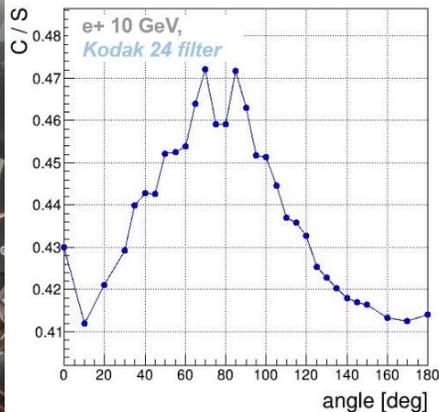
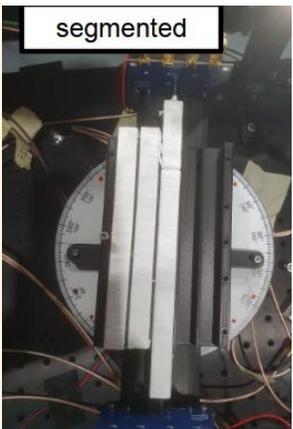
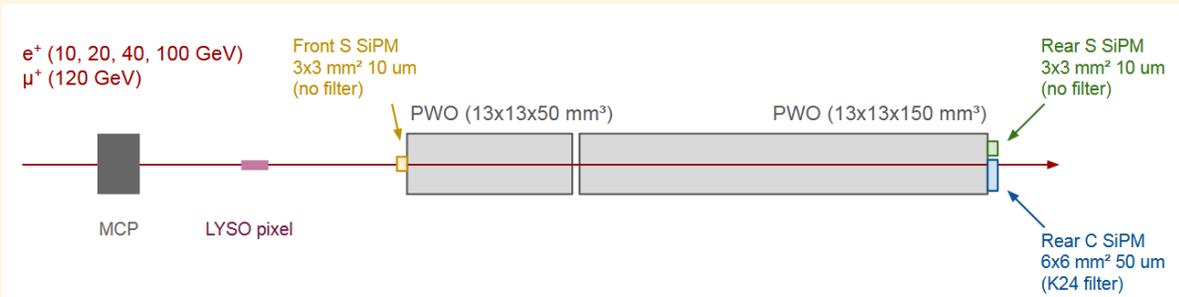
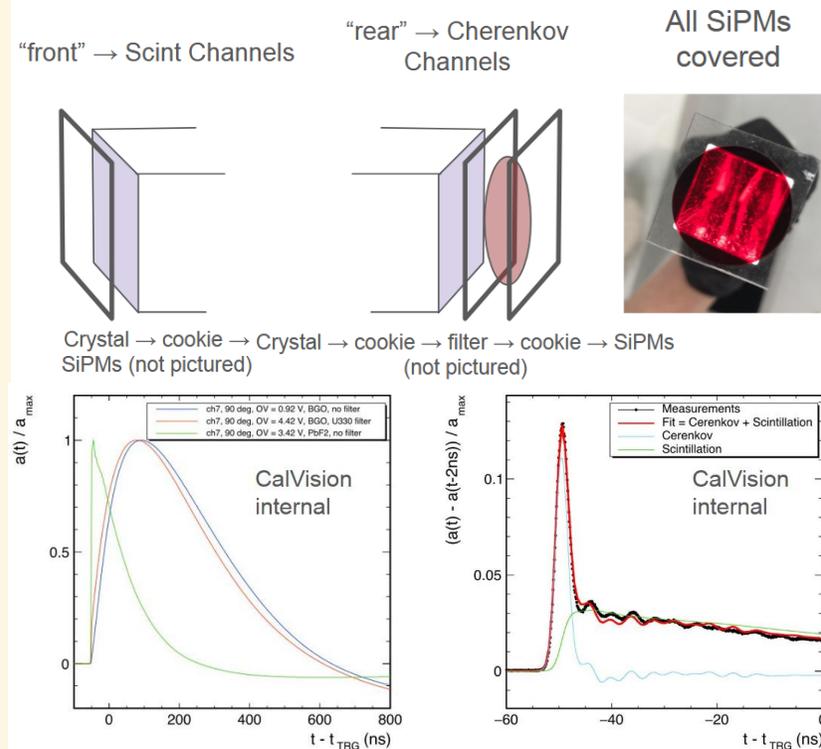
Dual-Readout Particle Flow

- Pandora/Arbor favor shower imaging, longitudinal segmentation \rightarrow track-cluster topology
- DR-PF: compact showers, fine transverse segmentation, moderate longitudinal segmentation \rightarrow emphasize energy, timing
- Detector-specific algorithms: e.g. combinatorial π^0 merging
- High S/N, linearity \rightarrow ripe for AI/ML, new approaches



Recent Test Beams

- 2023 FNAL: 120 GeV protons → PbF₂/BGO light collection, S/C discrimination
- 2023 CERN: 10-120 GeV positrons → capillary tubes, linearity, resolution
- 2024 DESY: 2 GeV electrons → crystal/filter combinations, heavy glasses
- 2024 CERN: 10/20 GeV electrons, 120 GeV muons, hadrons → crystals, shower segmentation, filters, light yield, waveform, SiPM dynamic range
- 2025-2026 : Joint ECAL-HCAL test beam

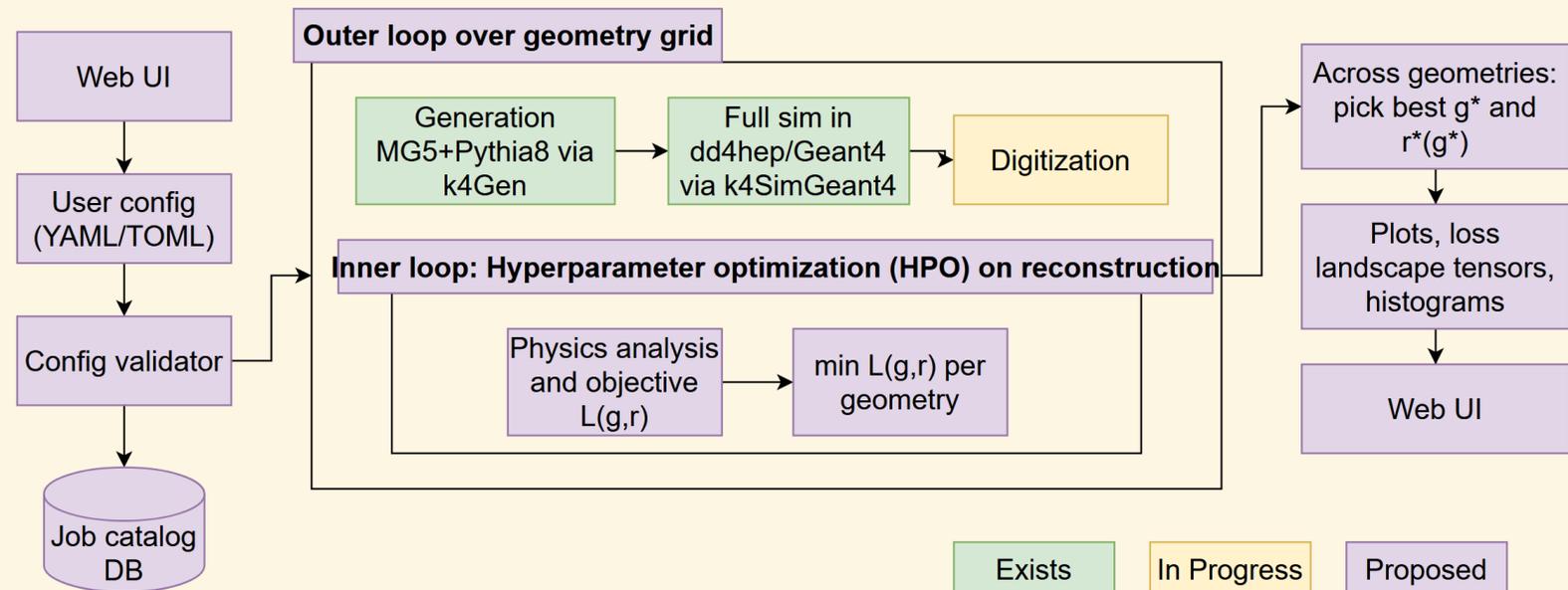


Bilevel Optimization

- Optimize detector geometry and reconstruction parameters simultaneously with ML methods
 - Pick a detector, pick an algorithm, specify the optimization goal, physics process
 - Pipeline generates/retrieves events, runs the varied simulations and algorithm template, optimizes the specified parameters against the physics objective
 - Output: The n-dimensional hypersurface for the objective (tensor of the loss landscape)

- Strongly geometry-dependent objectives:

- Di-jet mass resolution $Z \rightarrow qq^-$
- Light jet background
- Photon energy/angular resolution
- Jet resolution vs polar angle
- b-tagging (tracker dominated)
- Missing-energy tails in $ZH \rightarrow \nu\nu^- + X$



Outlook

- 2025-2026: joint test beam with HCAL, full sim digitization, bilevel optimization, advanced reconstruction
- 2026+: technology down-selection (crystals, SiPMs), large-scale module integration studies

