Overview of IDEA rationale and simulation

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on behalf of
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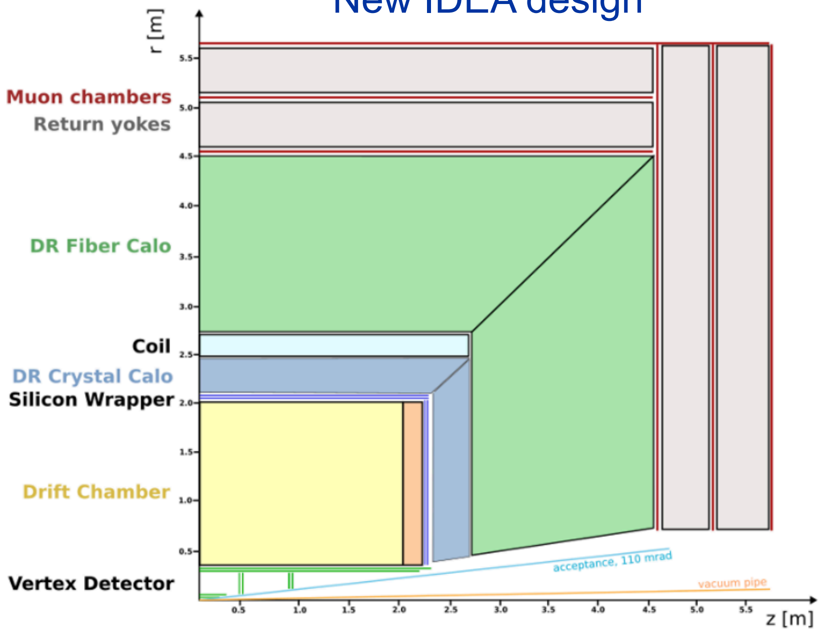
Istituto Nazionale di Fisica Nucleare

IDEA Detector Concept(s)

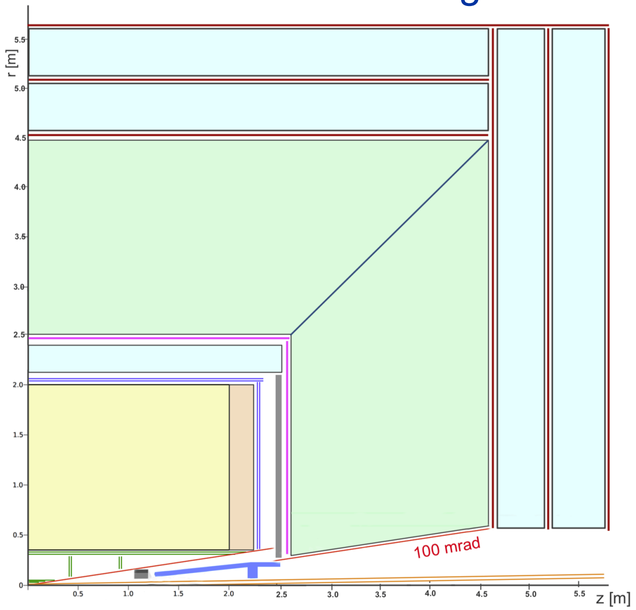
- The goal of this talk is to review the rationale behind the main IDEA subdetectors, the status of the full-simulation and reconstruction, as well as charting what has to be done

- First of all… which IDEA?
  - Recently the IDEA Study Group introduced a new design in which a crystal-em calorimeter is included (before the solenoid) together with a new fiber calorimeter

New IDEA design



Previous IDEA design



- Both designs are available in full-simulation as IDEA_o(ption)1 (previous one) and IDEA_o(ption)2 (new one) and discussed today

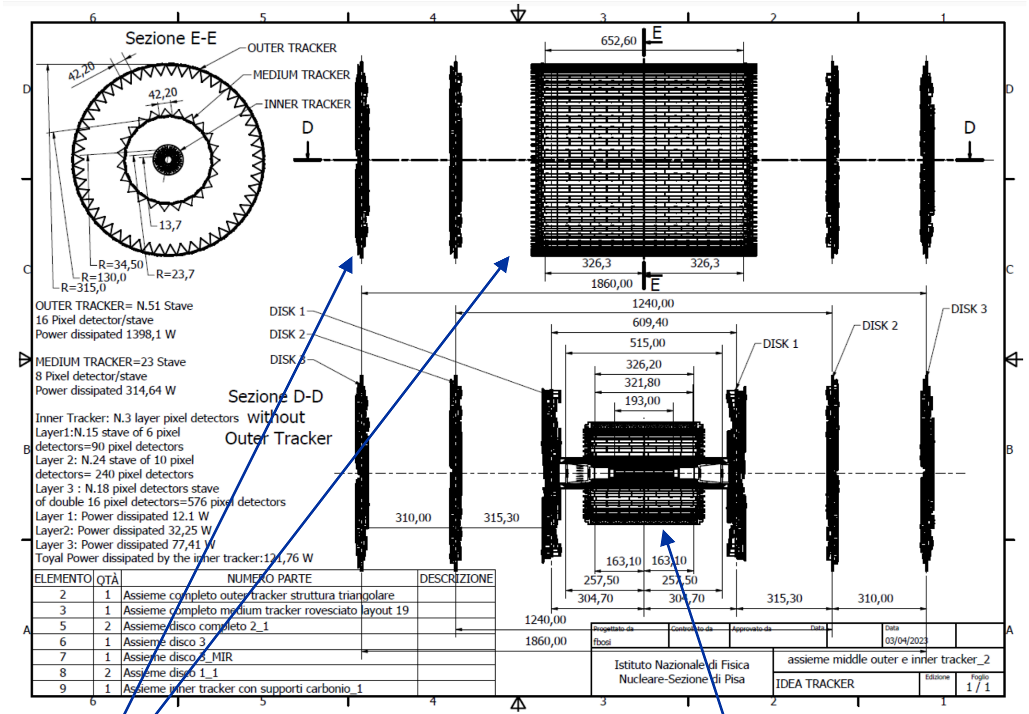
IDEA vertex design

- **Rationale**: minimize the material budget to achieve an impact parameter resolution of

$$\sigma_{d_0} = a \oplus \frac{b}{p \sin^{3/2}\theta} \text{ with } a \simeq 3-4\ \mu\text{m}$$

and $b \simeq 15\ \mu$mGeV

- **Design**:
  - Three inner barrel single layers ($0.25\ \%\ x/X_0$), two outer barrel layers and three disks
  - Engineered design integrated into the machine-detector interface region



Outer vertex tracker
- intermediate layer at 13 cm radius
- outer layer at 31.5 cm radius
- 3 disks on each side

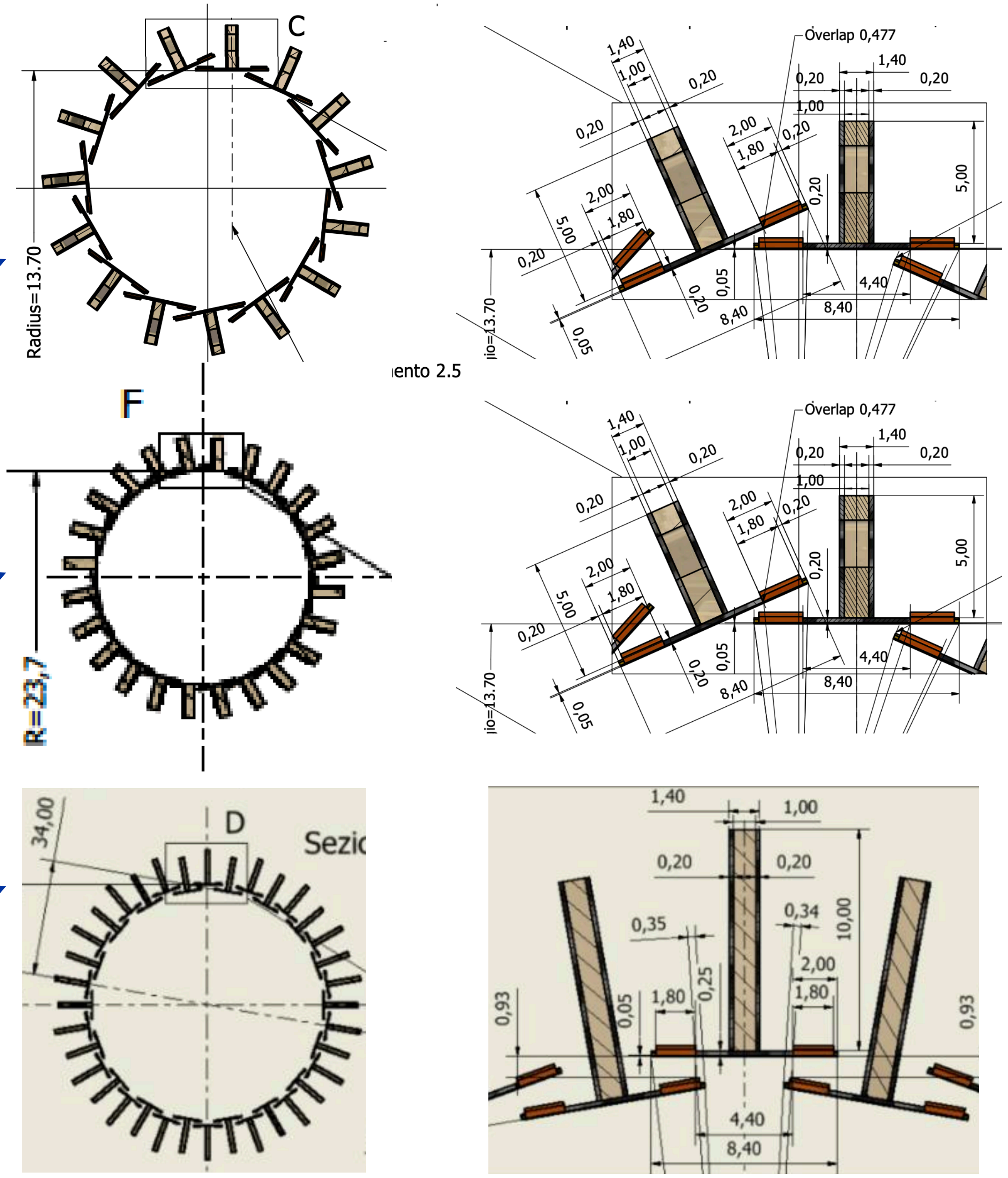
based on the ATLASPix3 sensors with modules of 50 x 150 μm^2 pixel size

Inner vertex tracker
- three layer at 13.7, 23.7 and 35.8 mm radius

based on the ARCADIA sensors with modules of 25 x 25 μm^2 pixel size

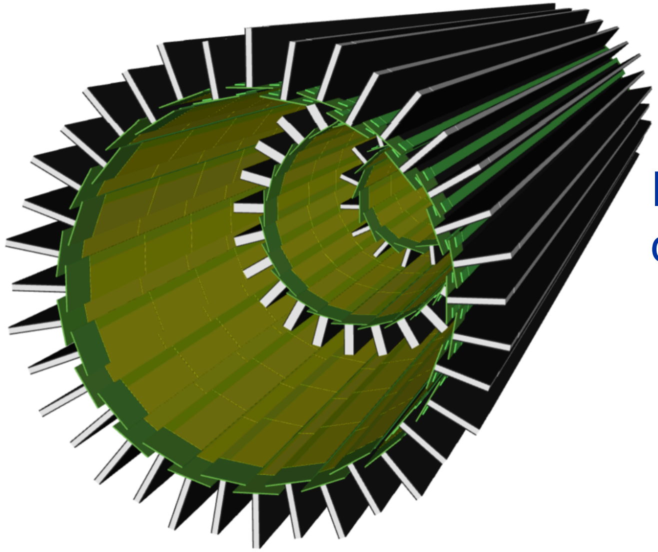
IDEA vertex design

- Recent adaptation of the inner barrel design
  - Layer 1:
    - 15 overlapping staves following a pinwheel geometry (all modules at the same smallest radius)
    - 0.25% X_0, power budget ~12 W
  - Layer 2:
    - 24 overlapping staves with a counter-rotated pinwheel geometry to mitigate charge-asymmetric effects in tracking
    - 0.25% X_0, power budget ~32 W
  - Layer 3 (recently redesigned):
    - 36 staves with a lampshade geometry (charge symmetric track reconstruction)
    - 0.25% X_0, power budget ~77 W

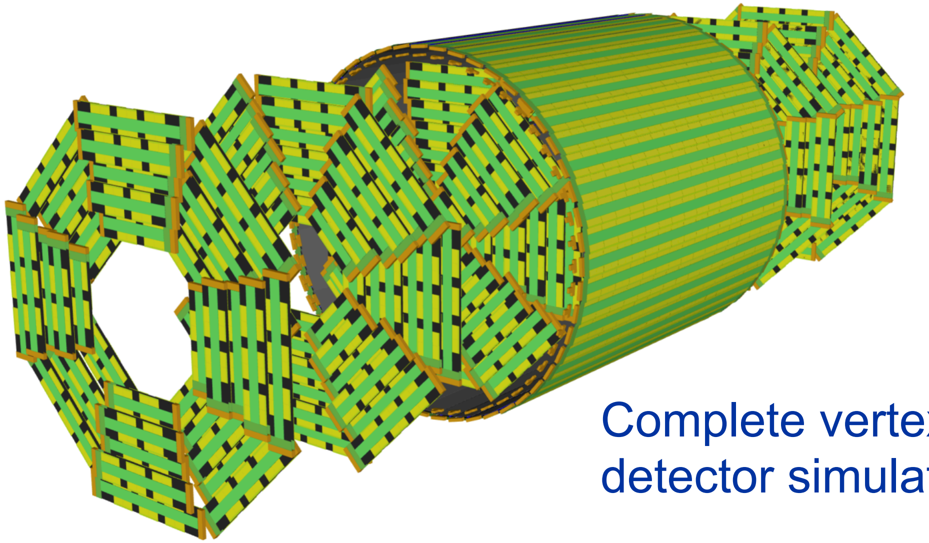


Vertex full-simulation

- Simulation:
  - The vertex full-simulation is completed and integrated into key4hep
  - Takes into account accurate description of engineering details like on-detector services and supports
- The simulated geometry is compatible with the CDR assumption of $0.25\ \%\ \ x/X_0$ at 90°
- It includes a correct description of sensor peripheries which allows for more realistic vertex performance estimation than CLD vertex or fast simulation studies (Delphes)



Inner vertex detector simulation



Complete vertex detector simulation

Vertex full-simulation

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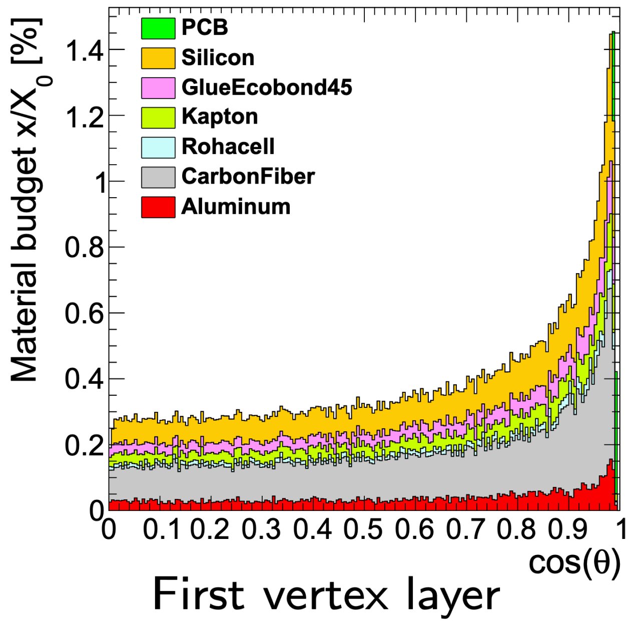

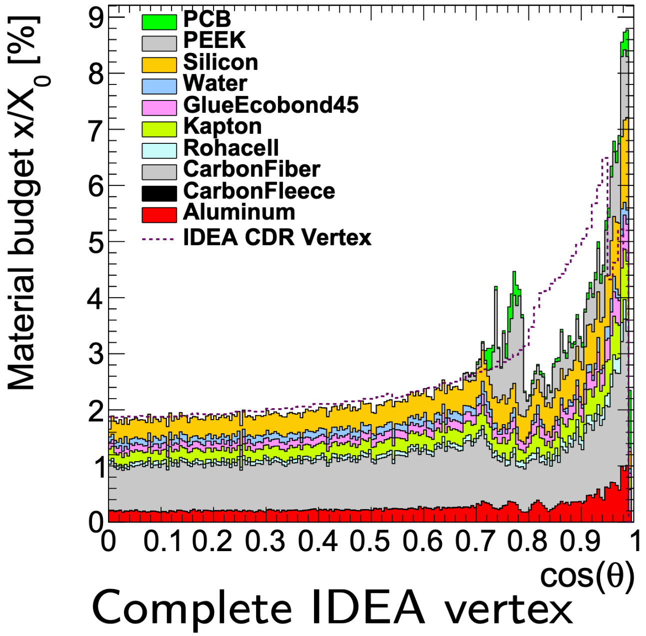

Vertex full-simulation

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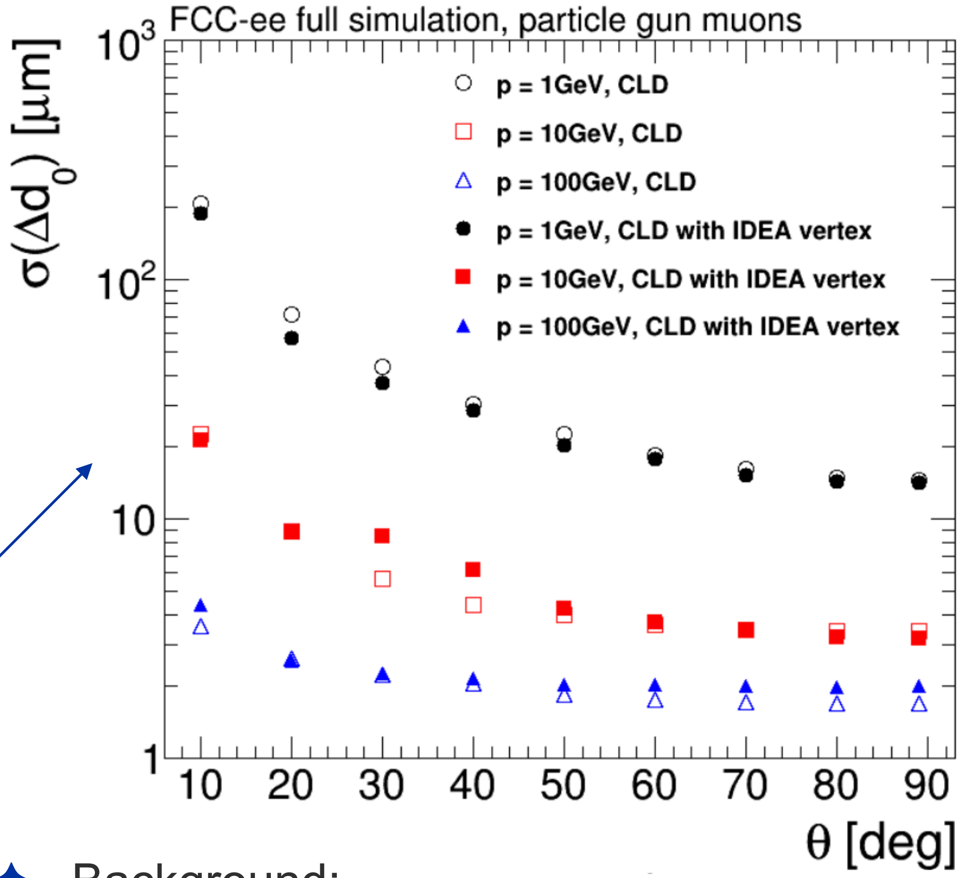
  - Takes into account accurate description of engineering details like on-detector services and supports
- The simulated geometry is compatible with the CDR assumption of $0.25\ \%\ \ x/X_0$ at 90°
- Results:
  - Preliminary studies combining the IDEA vertex with the CLD tracker and reconstruction show an improvement in the impact parameter resolution at low momenta w.r.t. CLD, while CLD is better at higher momenta

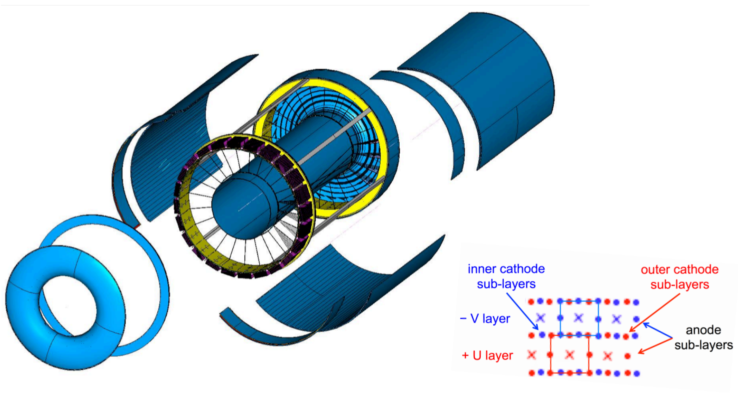
    ⚠️ To be repeated with a dedicated IDEA reconstruction



- Background:
  - Important studies are ongoing to evaluate the impact on the vertex of background radiation
  - See A. Ciarma talk @this workshop

The IDEA drift chamber

- Target:
  - a tracker with a large solid angle coverage ($|\cos(\theta) = 0.99|$), highly granular and highly transparent
  - with a good momentum resolution of $\sigma_{p_t}/p_t \simeq 10^{-5} p_t$ (a factor 10 better than LEP)
- Rationale:
  - the emittance preservation at the IR constraints the B field to be at the 2T level (at least for the Z pole)
  - $\frac{\Delta p_t}{p_t} \simeq \frac{12\sigma_{r\phi} p_t}{0.3 B_0 L_0^2}\sqrt{\frac{5}{N+5}} \oplus \frac{0.0135 GeV/c}{0.3\beta B_0 L_0}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}}$ ⟶ Stay large and light
  - short bunch spacing @ Z-pole (20-30 ns) ⟶ Stay fast
- With the additional benefit of superior PID capability thanks to the cluster counting technique (w.r.t. dE/dx measurements)



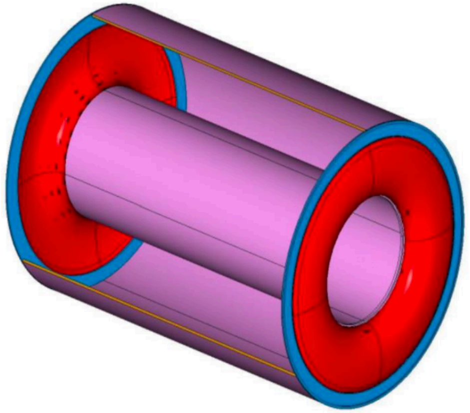
L = 400 cm, R = 35-200
Gas: 90% He - 10% iC4H10
Drift length: 1 cm → drift time: 350 ns

Spatial res: σ_{xy} < 100 μm, σ_z < 1000 μm
56448 drift cells of 12 - 13.5 mm
Layers: 112

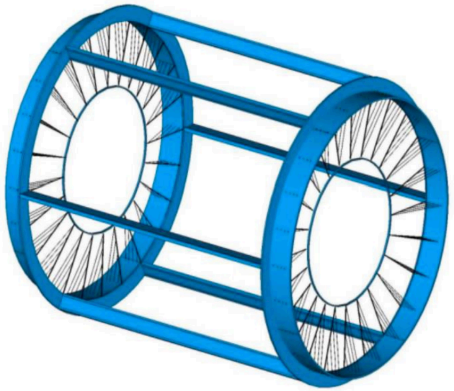
The IDEA drift chamber simulation

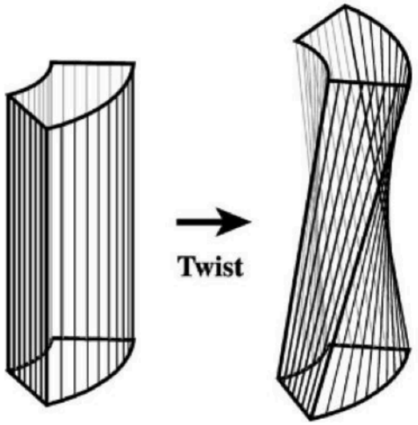
- The IDEA drift chamber simulation is available and integrated in key4hep
- The simulated geometry (version o1_v02) stands on:
  - a cylindrical wall made of carbon fiber
  - a cylindrical volume filled with the gas mixture
  - 112 hyperboloidal layers filled with gas mix
  - cells represented as twisted tubes
  - field (5) and sense (1) wires inside each cell
  - a silicon wrapper around the cage
- Cluster counting in simulation:
  - dN/dx simulation is also present in DELPHES using a parameterization from Garfield++ (by F. Bedeschi and M. Selvaggi)

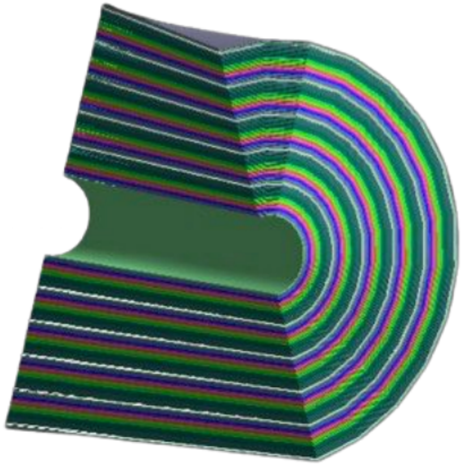
Gas containment volume



Wire cage

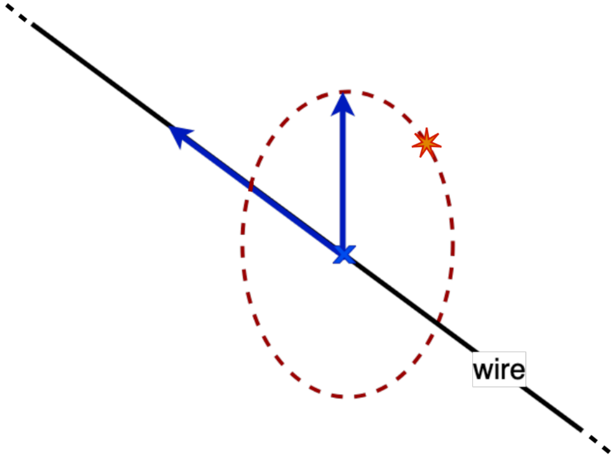


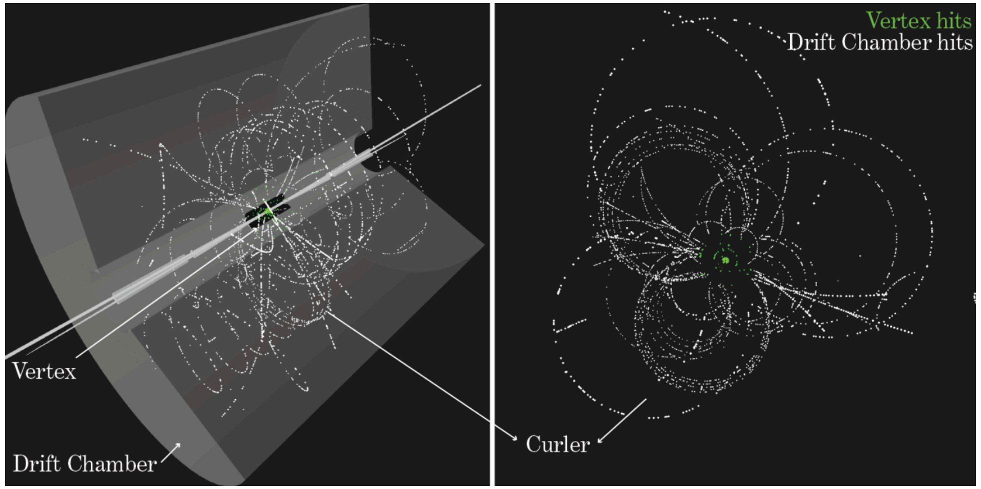




Generalized tracking in IDEA

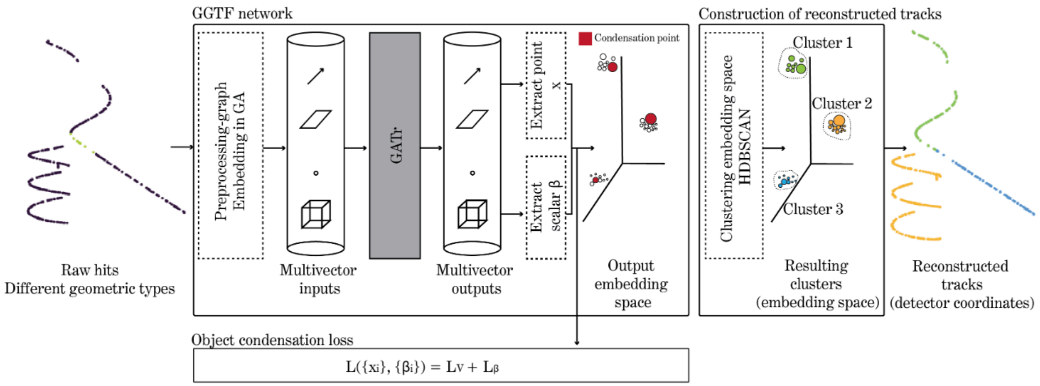
- A generic end-to-end method for track-finding is available
  - It takes in input digitized hits from IDEA tracking system (vertex + DCH)
- Drift chamber hits digitization must assume that the true hit position may be located along a circle around the sensing wire. Two digitizers have been implemented:
  - The first one reduces the ambiguity to a left/right positioning of the digitized hit w.r.t. the wire
  - A more recent one considers the point of the wire closest to the hit in gas, the corresponding radius, and the direction of the wire
- Estensive details on the topic @this workshop:
  - talk on the tracking and ML-based Particle Flow by A. De Vita
  - talk on the DCH digitization by N. De Filippis





Generalized tracking in IDEA

- The pipeline designed is detector agnostic and can handle in input either points, vectors (e.g. in the DCH case) and planes
- A first ML-based approach transforms such input in points represented in an embedding space clustered around condensation points
- A second analytical step uses the DBSCAN clustering algorithm to reconstruct tracks (collection of hits in the detector coordinate system)



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- A first ML-based approach transforms such input in points represented in an embedding space clustered around condensation points
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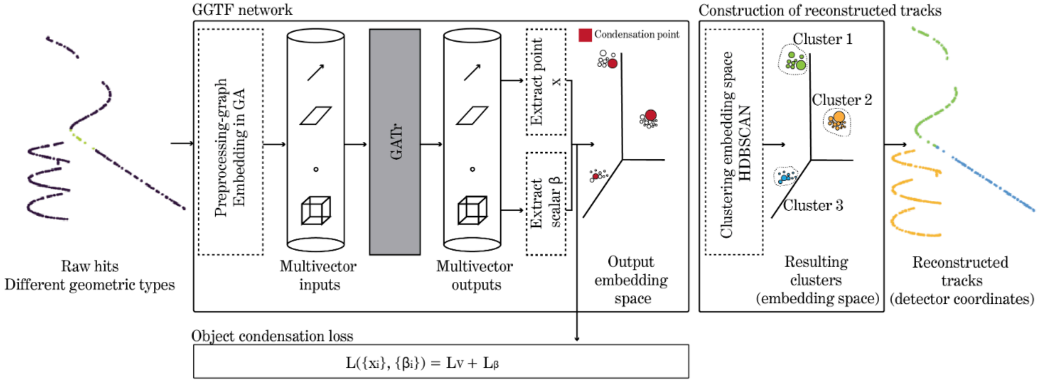
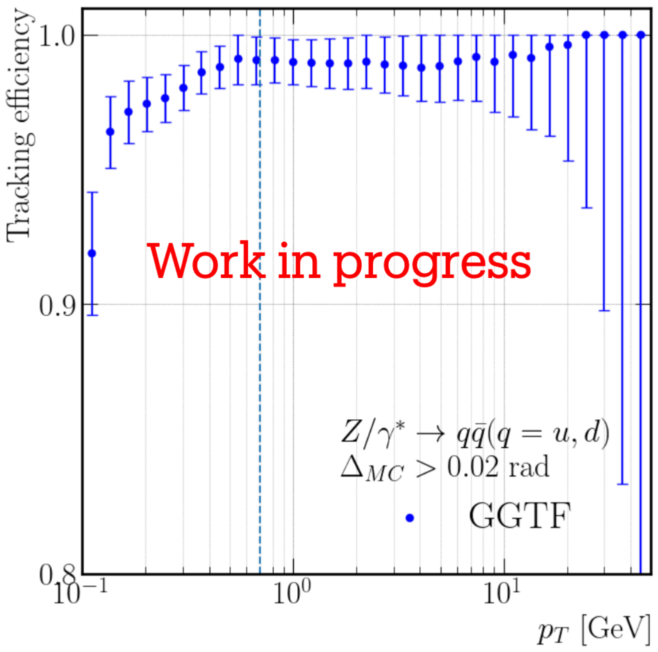
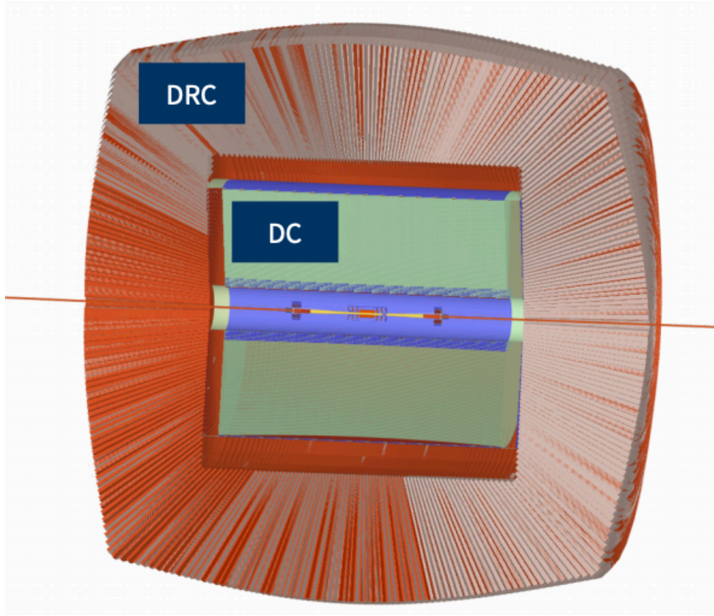
- Results:
  - Encouraging results on the estimated tracking efficiency are found, however …
  - Track fitting still to be developed in order to extract p, p_t and σ_{p_t} from tracks

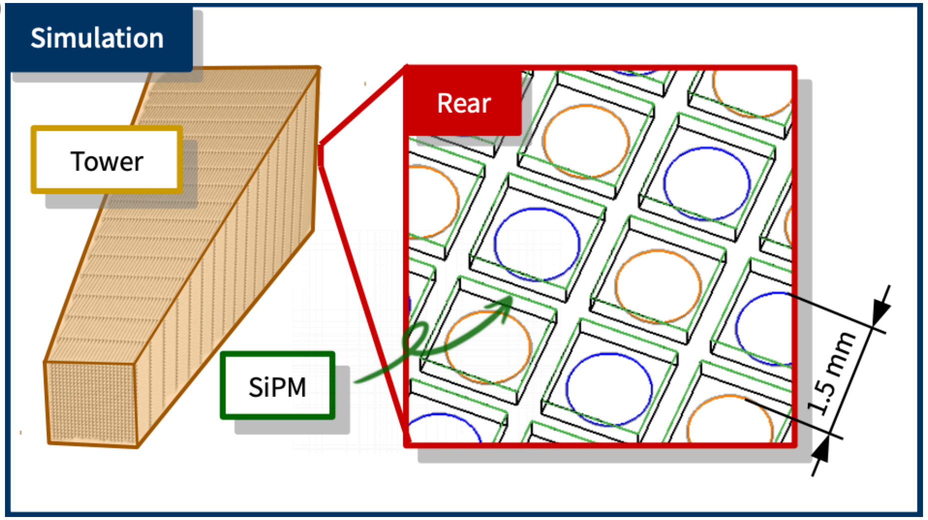




Monolithic dual-readout calo @IDEA_o1

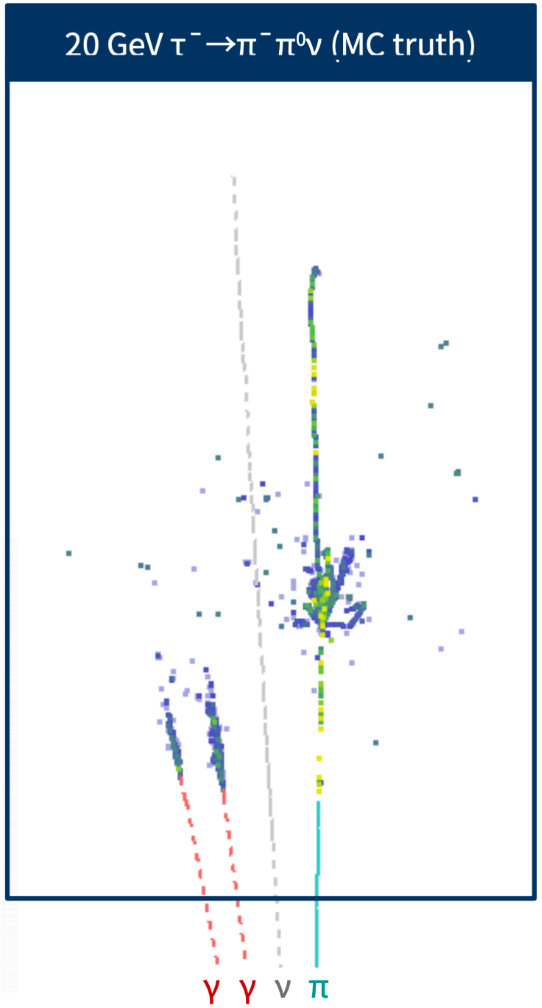
- Target: excellent hadronic-jet energy resolution ($\sigma/E \simeq 30\,\%/\sqrt(E)$)
- Rationale: reduce intrinsic signals fluctuations by measuring the f_{em} of hadronic showers *event-event* + improve the jet-energy resolution with Particle Flow Analysis
- Simulation: optical-fiber dual-readout calorimeter implemented in k4geo for IDEA_o1
  - *Monolithic* as fibers are *simply inserted* in copper-based towers (trapezoids) (iron material also to be tested in full-sim)
  - measure both electromagnetic & hadronic components with two different channels
  - Projective geometry with a uniform sampling fraction
    - more fibers in the rear than the front
  - Longitudinally unsegmented → performs both em and had-shower measurements

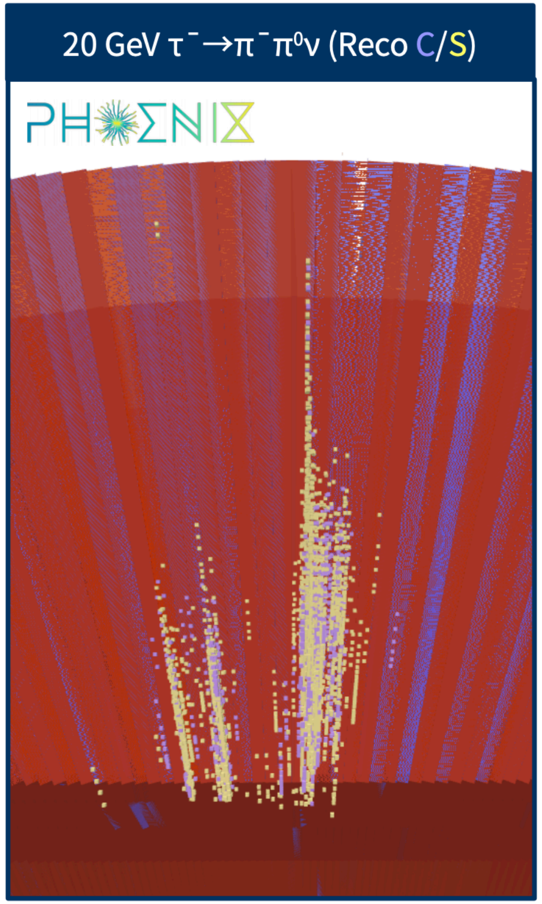




Monolithic dual-readout calo @IDEA_o1

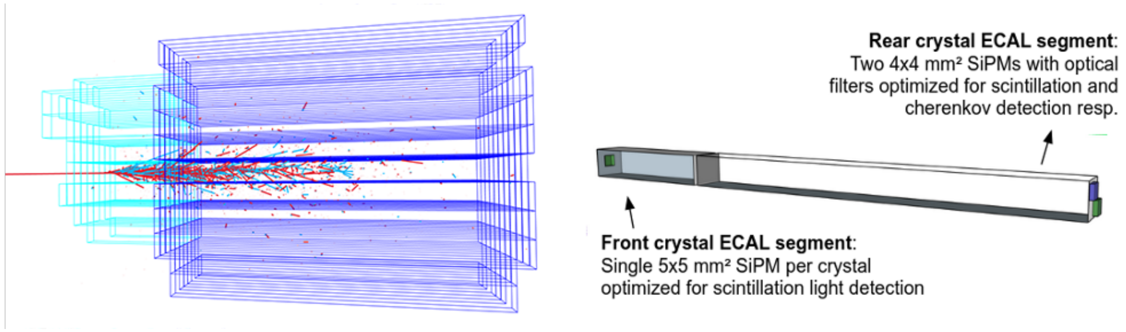
- Digitization:
  - A SiPM simulation library is developed using
  - parameterized inputs from the datasheet (dark counts, crosstalk, afterpulses, saturation, noise, …) and
  - It is included in the key4hep stack as an external library
- Reconstruction:
  - Reconstruction codes are implemented including a novel 3D reconstruction using Fourier analysis with timing information from SiPM signals
  - Isolated hits position successfully reconstructed along fibers → excellent example of timing in calorimetry

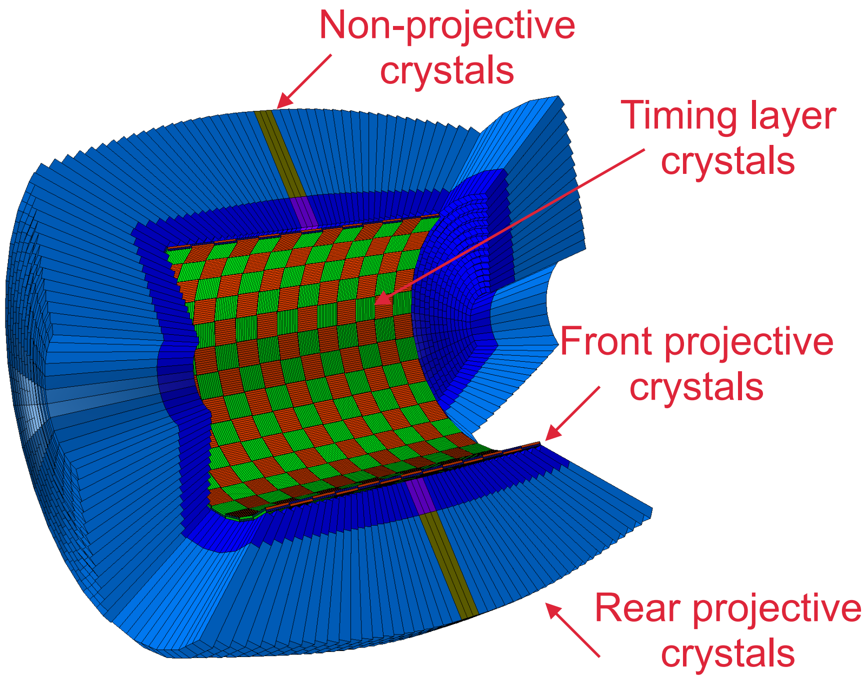




Dual-readout crystals @IDEA_o2

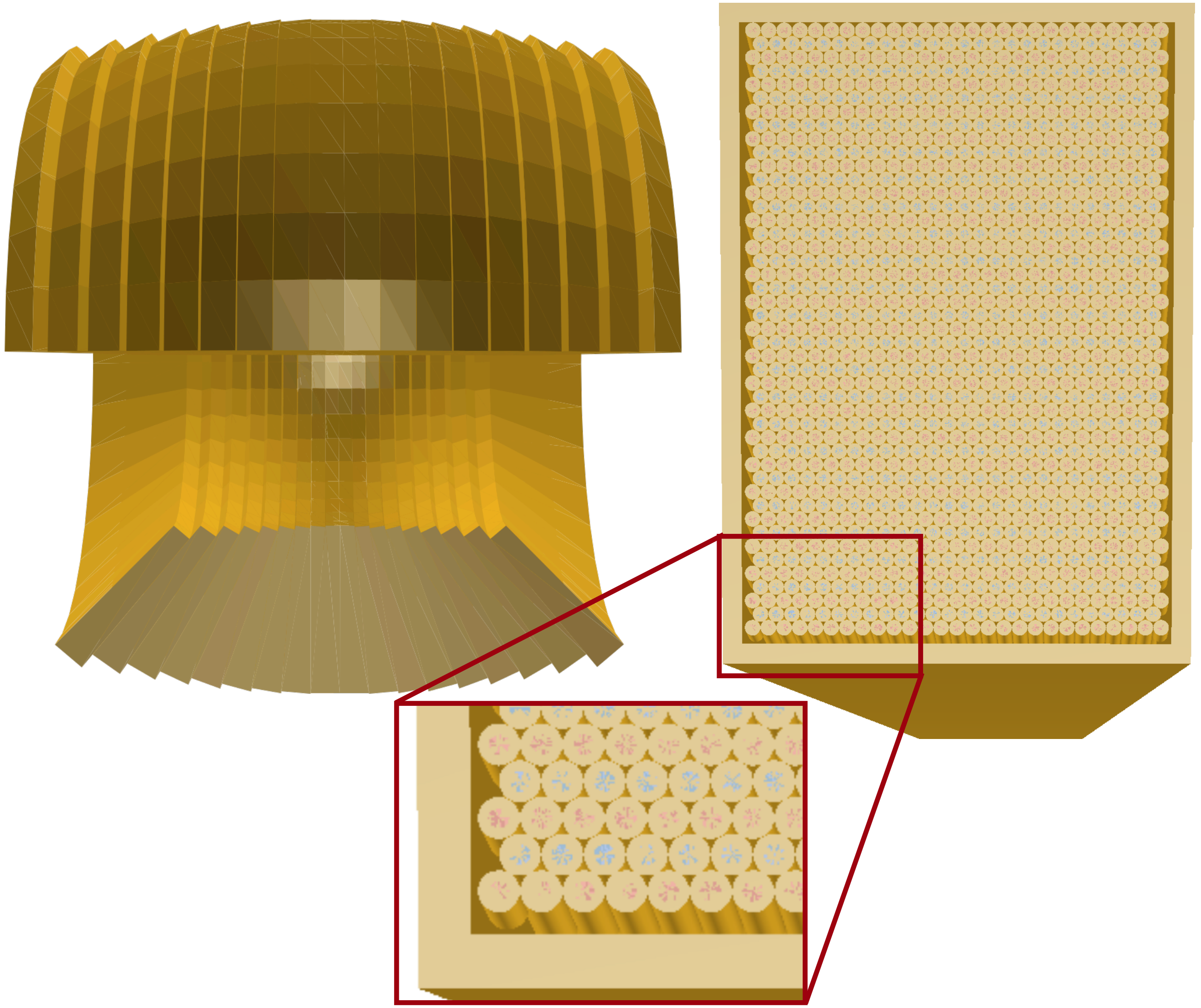
- Target: achieve an em-energy resolution of $\sigma/E \simeq 3\,\%/\sqrt{(E)}$
- Rationale: do not spoil the dual-readout compensation technique when hadronic showers start showering in crystals, solve the channelling effect for em-showers entering the fiber-calorimeter, help identification of γ's in jets
- Simulation: projective homogeneous ($PBWO_4$) crystal calorimeter
  - Each crystal is longitudinally segmented with front/rear section (6:16 ratio 22 X_0 (~20 cm))
  - Dual-readout capability ensured by two dedicated SiPMs instrumented on the rear section
  - Timing layer placed in front comprises two layers of fast-scintillating LYSO crystals with opposite orientation
  - New DD4hep implementation recently carried out
    - A PR is open on k4geo for inclusion in IDEA_o2





Tubes-based dual-readout calo @IDEA_o2

- Rationale: migrate the simulation to a geometry based on viable construction techniques
- Simulation: a novel dual-readout calorimeter design was included in key4hep for IDEA_o2,
  - a new construction technique housing optical-fibers into capillary-tubes
  - Good Monte-Carlo to test-beam data agreement recently found [article]



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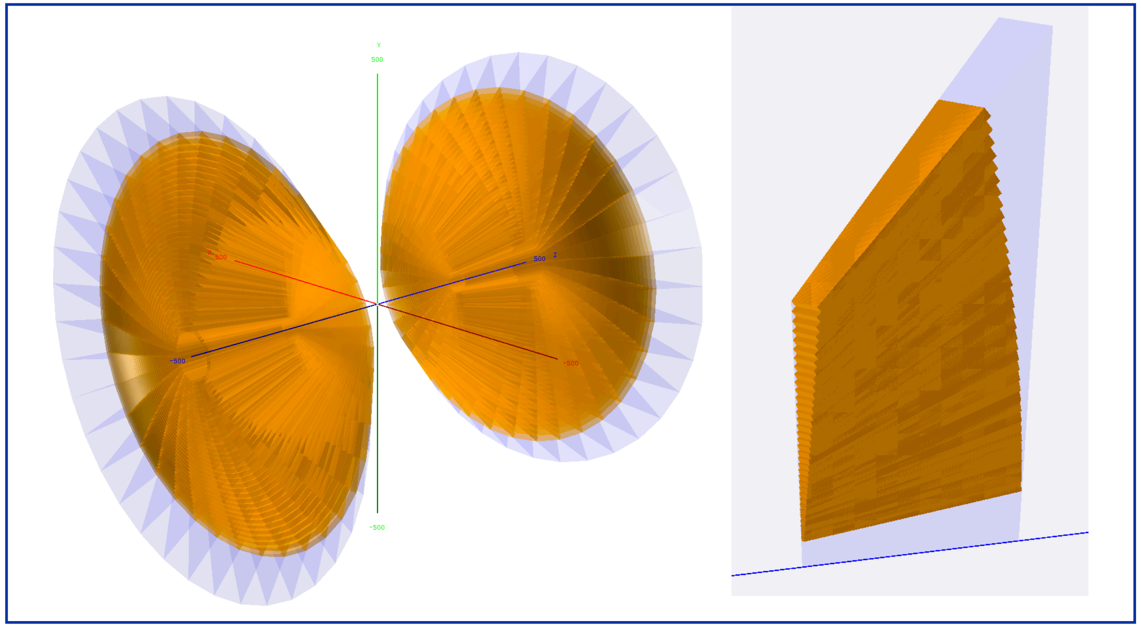
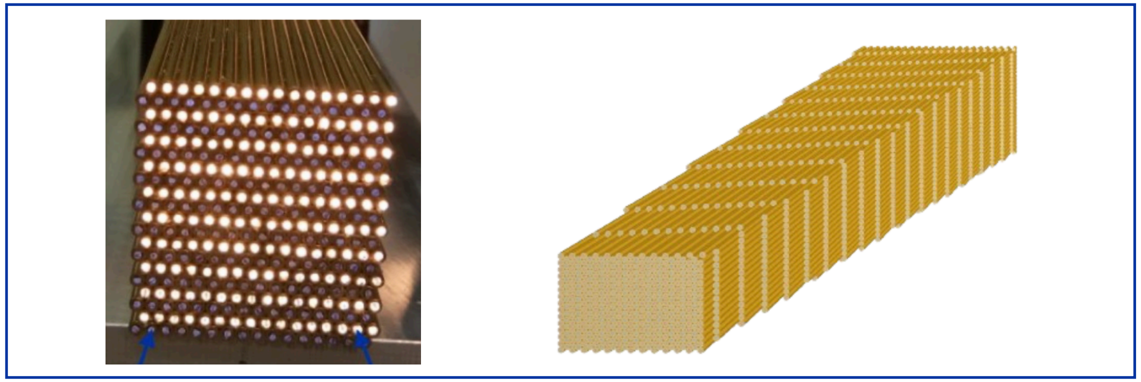
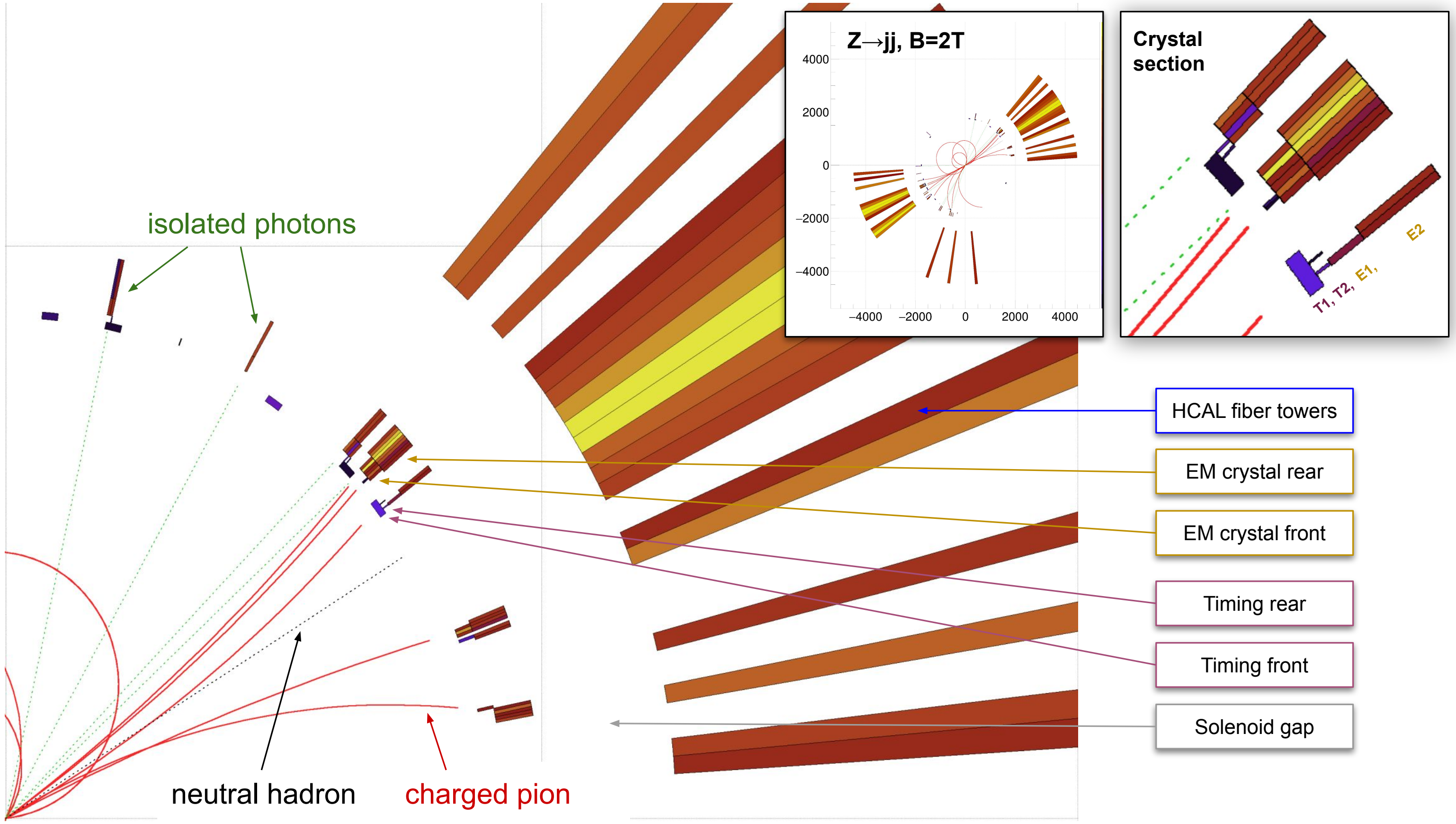
- The full calorimeter (barrel + endcap) simulation corresponds to 70×10^6 tubs (touchable volumes)
  - Most of the IDEA_o2 volumes and hits are located in this subdetector
  - Extensive work reduced memory and cpu-time to $\simeq 7-8$ s/evt for 100 GeV e^- and $\simeq 4$ Gb memory footprint





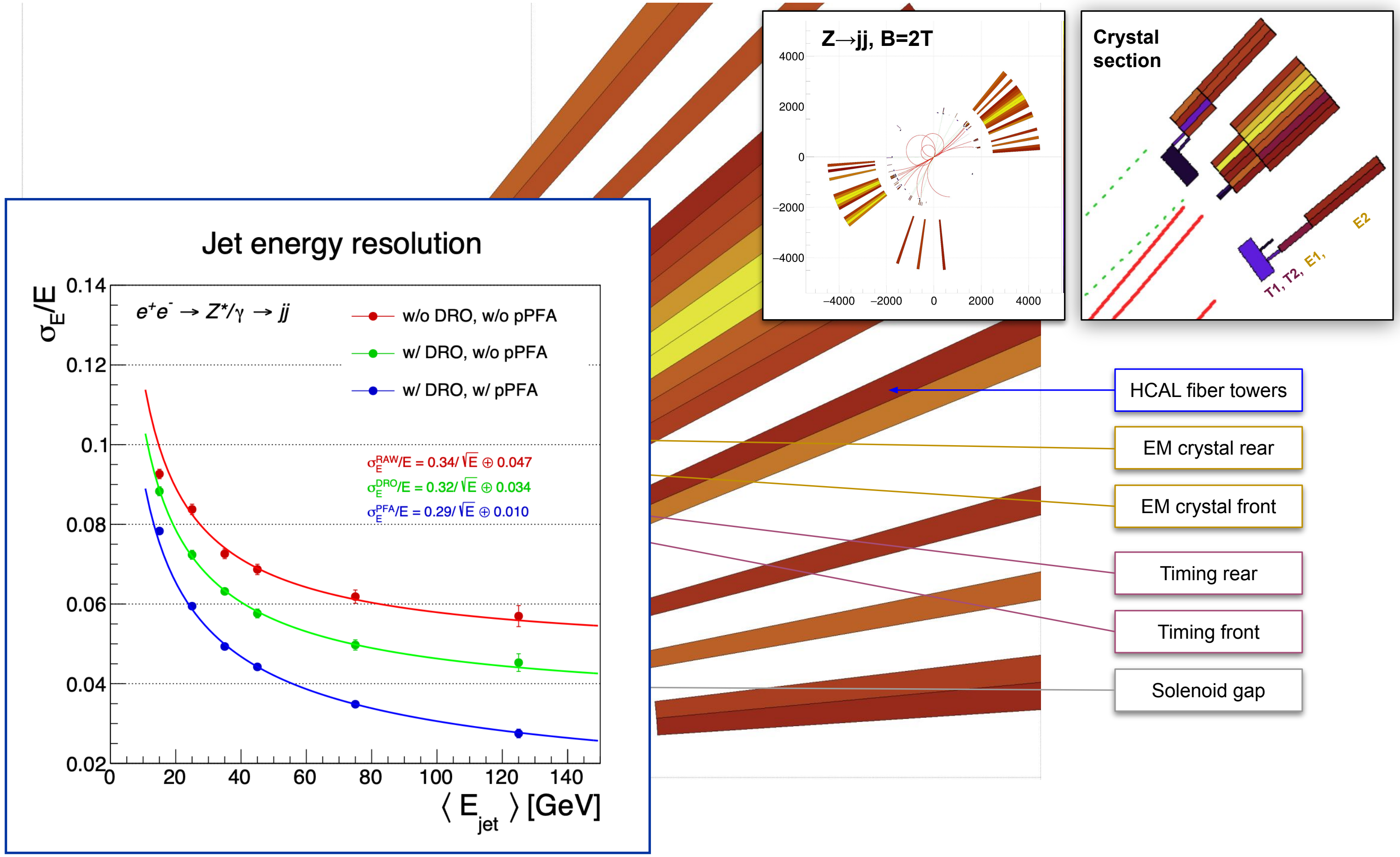
Dual-Readout Particle Flow studies for IDEA_o2

- An article explored a dual-readout Particle Flow algorithm to combine calo-clusters and tracks in a longitudinally segmented dual-readout calorimeter (almost identical to the IDEA_o2 design)



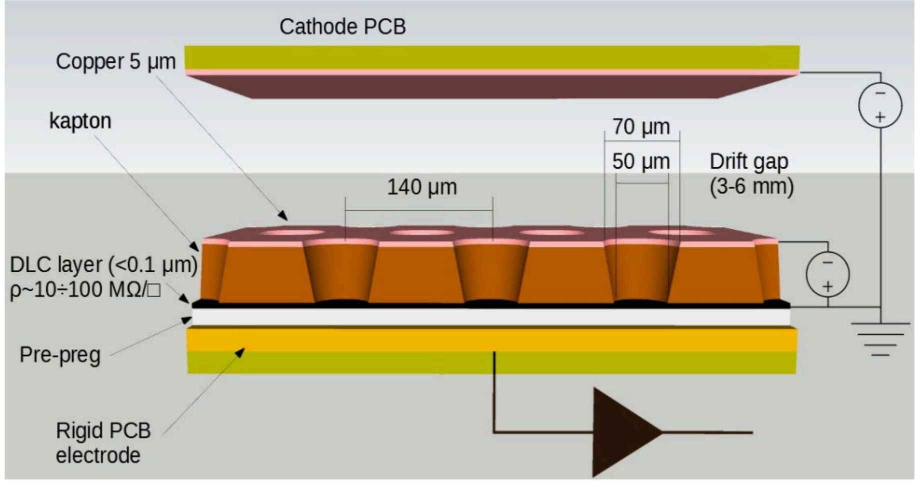
Dual-Readout Particle Flow studies for IDEA_o2

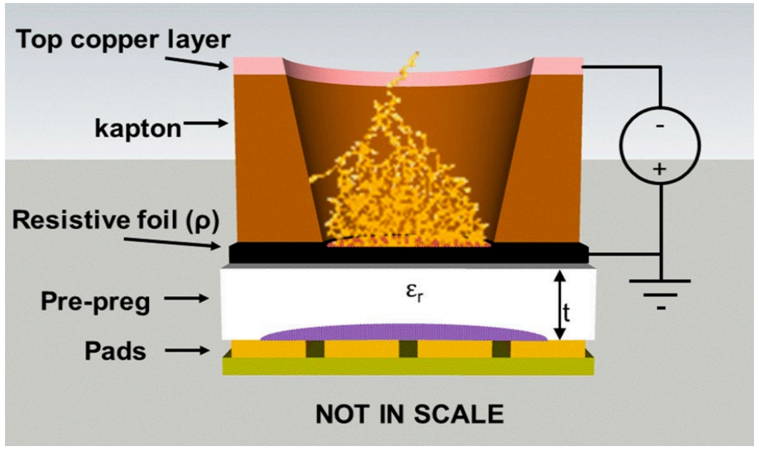
- An article explored a dual-readout Particle Flow algorithm to combine calo-clusters and tracks in a longitudinally segmented dual-readout calorimeter (almost identical to the IDEA_o2 design)
- Even with just two sections, clear cluster-tracks matching was possible and an improvement in the energy resolution (w.r.t. dual-readout performance) was found
- IDEA_o2 is now considering a 3 T (HTS) solenoid (not a Z pole) which will improve this result obtained with 2 T



Muon system & Preshower

- Rationale: Cover an instrumented surface of 130 m^2 for the preshower and 1500 m^2 for the muon system, with a single layer efficiency of ~98% and space resolutions of 100 μm (preshower) and 400 μm (muon chambers)
- Technology choice:
  - The μ-RWELL technology can meet such requirements considering
    - Tiles covering an area of 50×50 cm^2
    - 520 detectors and $3x10^5$ channels for the preshower (0.4 mm strip pitch)
    - 6000 detectors and $5x10^6$ channels for the muon system (1.2 mm strip pitch)



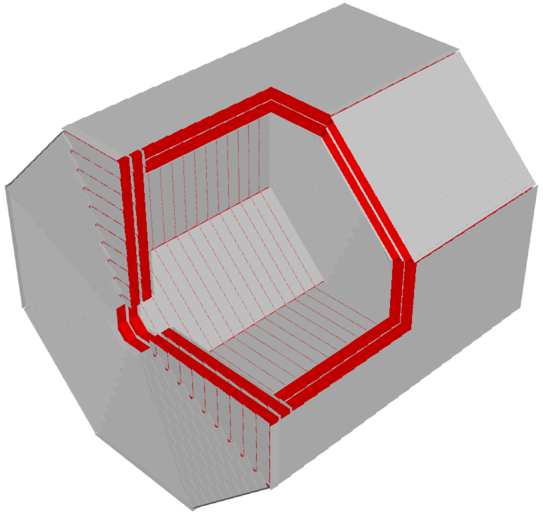


With the additional benefit of largely suppressing spikes w.r.t. traditional MPGDs by means of a wedge patterned kapton foil acting as the amplification stage

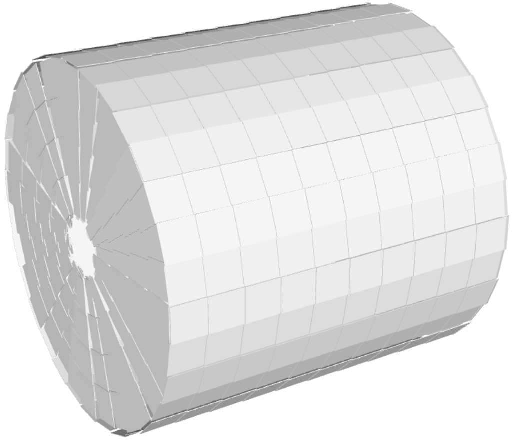
The muon system simulation

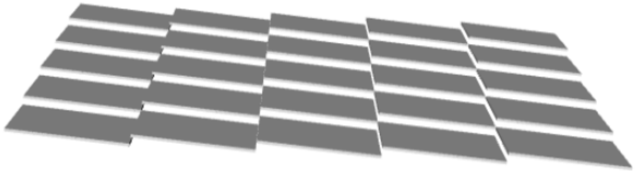
- Simulation: ready in key4hep
  - It consists of three sensitive layers
  - and two stations of the iron yoke that closes the magnetic field
  - Each station is a mosaic of μ-RWELL tiles with an area of 50x50 cm^2
  - Tile positioning creates small overlaps among tiles to prevent dead areas through which muon tracks can escape undetected
- Digitization: available an algorithm that smears the hit position in the local µRWELL chamber plan, according to space resolution and efficiency
- First results on muons reconstruction @this workshop talk by M. Ali

Muon chambers and return yokes

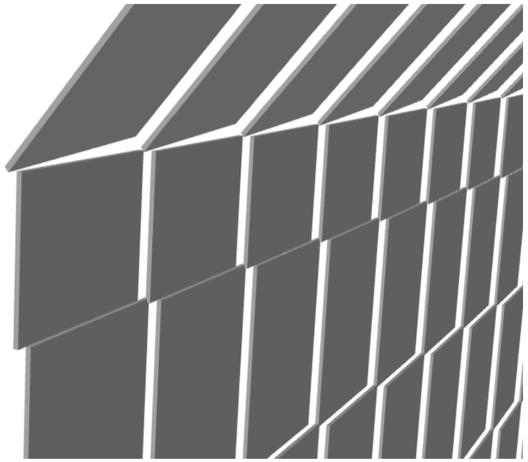


Preshower





Every chamber has a 2D Cartesian grid readout



Conclusion

- Both *IDEA_o1* and *IDEA_o2* full-simulations have been completed and integrated in key4hep
  - We want to support and develop both codes in the coming years
- Some dedicated reconstruction and performance studies on specific sub-detectors found good agreement w.r.t. CDR requirements (*e.g.* using the vertex, calorimeter, …)
- However, important contributions are *still needed*, for instance
  - on reconstruction algorithms (e.g. analytical tracking with DCH and muon system, topo-clustering on the calorimeter hits, …)
  - combination of reconstructed objects from subdetectors in a PF-fashion

IDEA_o2_v01 full-simulation