FCC Full Sim and Reco

Status and Needs

Brieuc Francois (CERN), on behalf of the FCC Full Sim team

7th FCC Workshop, Annecy
Jan. 30th, 2024

FUTURE
CIRCULAR
COLLIDER

CERN

Outline

- Context
- Current Simulation Readiness
  - CLD
  - IDEA
  - ALLEGRO
- Ongoing reconstruction efforts
- How can you contribute?

Open projects in this color

Context

- Proposing a new large scale HEP facility such as FCC requires to answer the following questions
  - What is the **physics potential** of the facility?
  - What detector types are the most suitable?
  - What is the **optimal detector configuration**?
  - Uncertainties, technological feasibility, cost, …

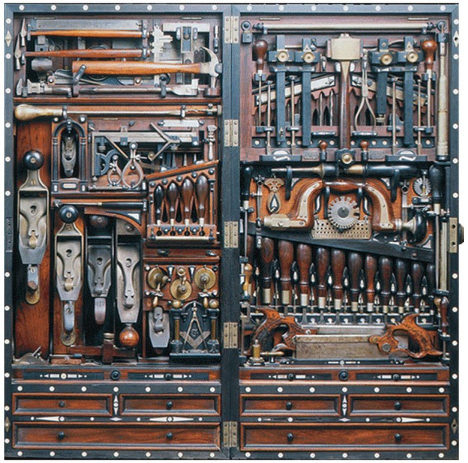
What is the **physics reach** of FCC?

- We can answer the above questions with different level of accuracy (and commitment)

Back of the envelope

Parametrized Simulation

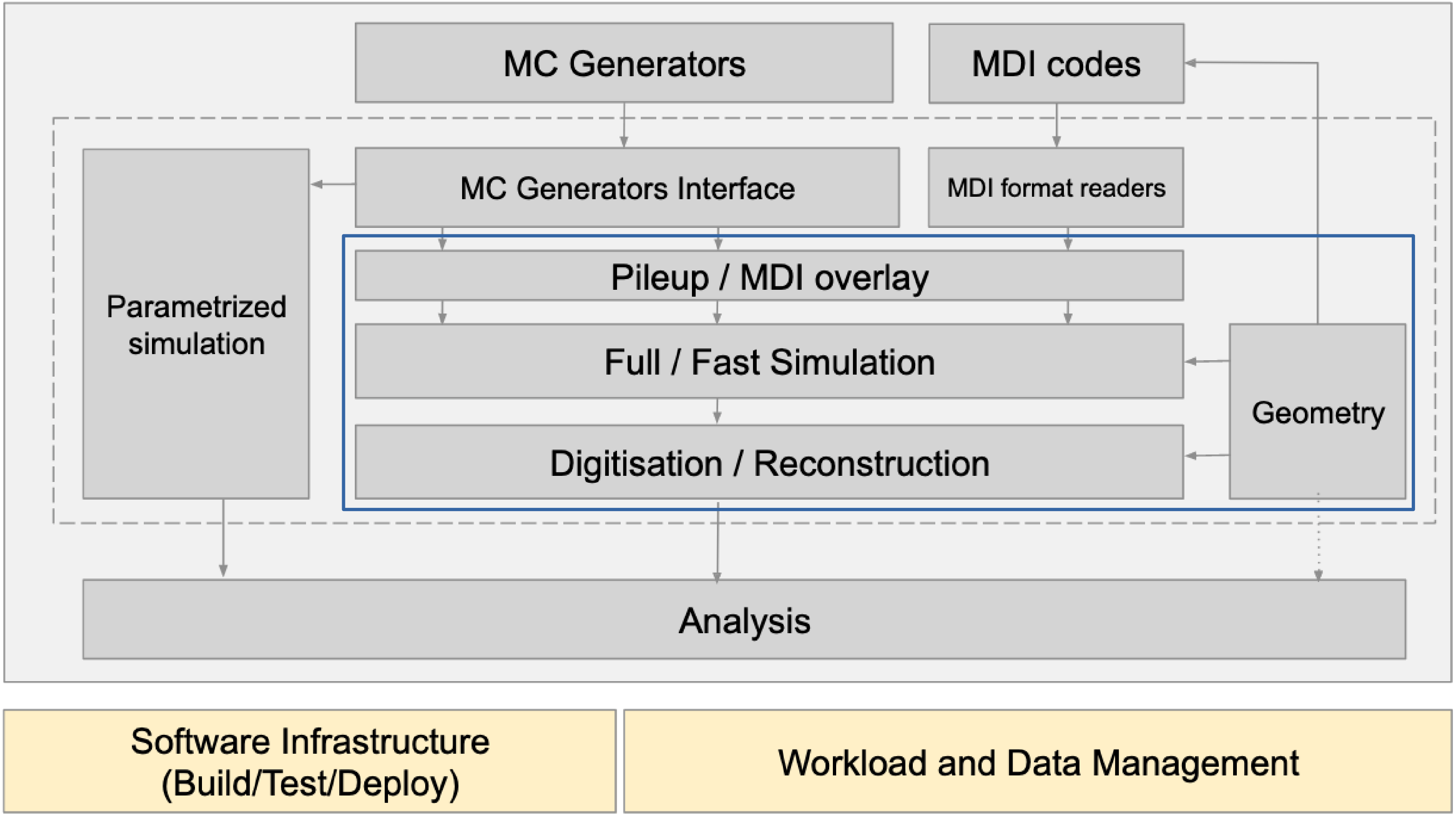
Full(/Fast) Simulation



We now have to get there!

Content

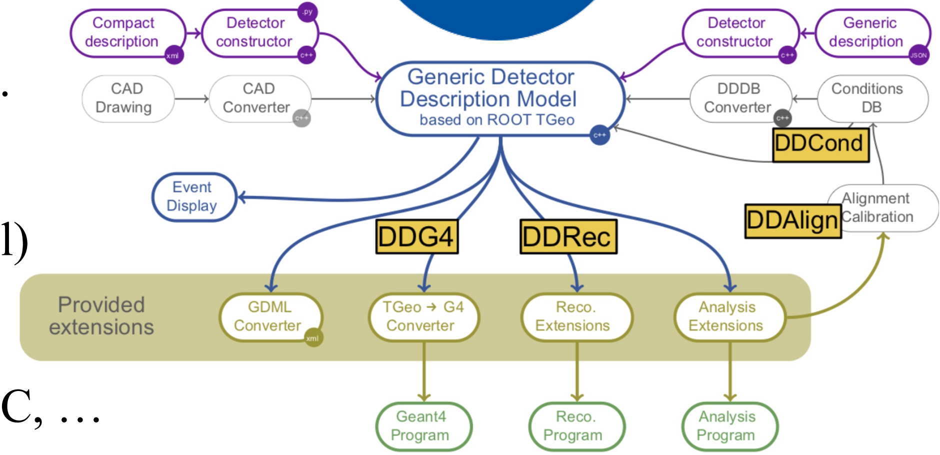
- Description of available tools and needs for further developments (FCC-ee)



Simulation Framework Overview

- The FCC Software **fully adopts** Key4hep (covered yesterday and this morning)
  - **All sub-detectors** and their reconstruction **in a consistent framework**
- Detector **geometry description with DD4hep**
  - Supports full life cycle of the experiment
    - Conceptualization, optimization, operations, …
  - Whole detector description from a single source
  - Convenient factorization (generic C++, specific xml)
  - Enables plug-and-play approach (examples later)
  - Community standard: CMS, LHCb, EIC, CEPC, ILC, …
- **Several interfaces to Geant4:** k4SimGeant4, ddsim (DD4hep), Gaussino (LHCb, WIP)
  - Had to **homogenize this sooner than later** across all sub-detectors to combine them
  - Chose **ddsim for the FSR**: widely adopted, more complete and mature (10+ years of development)
    - Currently migrating detectors which were not using it
  - Opened to other solutions for the post-FSR era

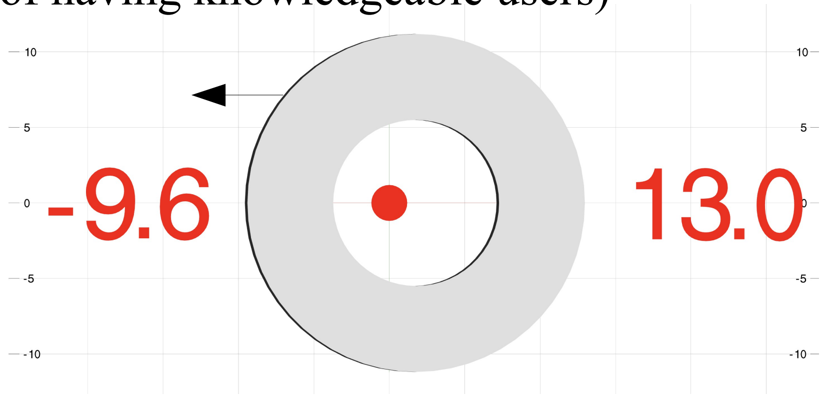
DD4hep



Current Simulation Readiness

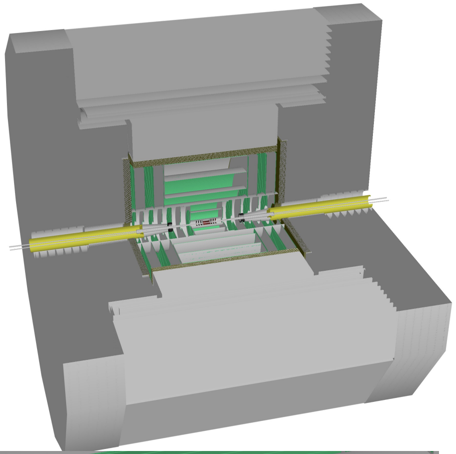
MDI

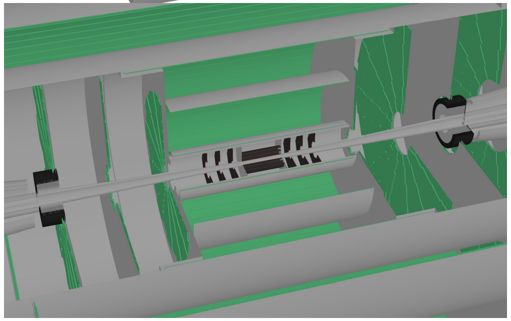
- Native shapes smaller radius beampipe available
  - Some approximation, missing cooling manifold
  - Working on importing the CAD drawing directly in simulation (current version very slow)
- Luminosity monitor (SiW calorimeter)
  - Description available but not effectively used since a long time
  - Revived by Mogens, inconsistencies spotted (benefit of having knowledgeable users)
  - More details in Mogens' talk tomorrow afternoon
- Tool to boost final state according to crossing angle
- Background overlay
  - Several tools available/tested to overlay one file
    - Occupancies
  - Tools to **overlay background on top of physics events** exists but not used recently
    - Should be exercised in the FCC-ee context



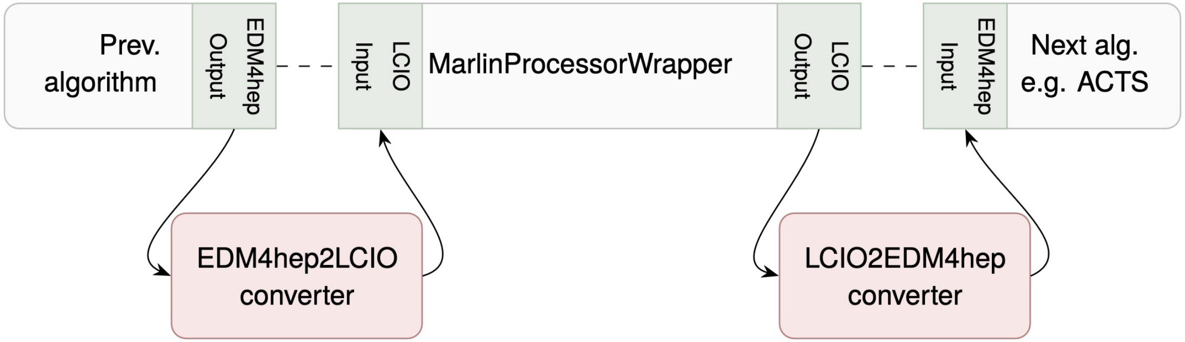
CLD

- Full detector description + reconstruction (PFlow) available: recipe
  - 'Standard' reconstruction configuration prepared
    - More algorithms available to be tried from ILCSoft (e.g. tau reconstruction) through MarlinWrappers/converter
    - Can be used by all the other detectors as well!
  - Very few physics analysis ongoing, more users needed



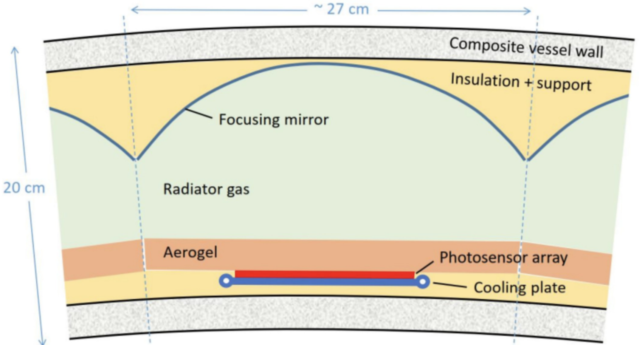


- Recent updates
  - Incorporated smaller radius beampipe, adapted vertex detector
  - Updated reconstruction steering file (geometry impacts reconstruction)
  - Prepared two new CLD models with different detector content
    - Dedicated PID detector (next slide) and Noble Liquid ECAL (more later) for PFlow
  - Investigating CLD with a TPC, more in Thomas' talk

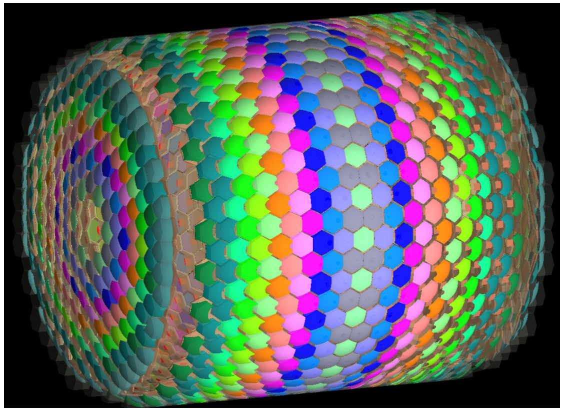


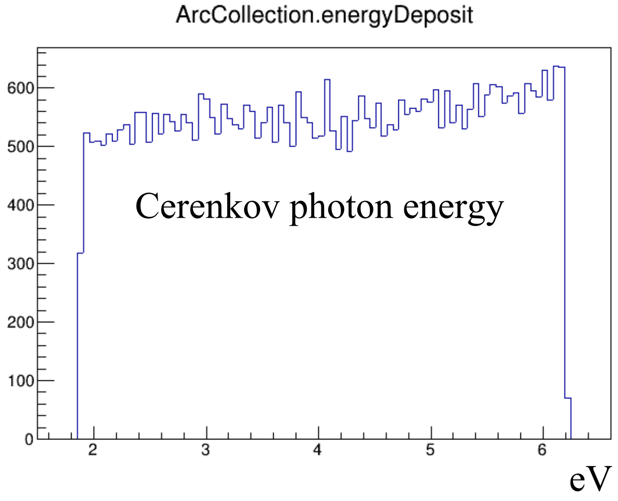
CLD with PID

- Particle Identification detectors can greatly improve flavor/Higgs physics reach, low X_0 (< 10%) technologies proposed
  - Implemented the Array of RICH Cells (ARC) detector in DD4hep
  - Optical physics and material properties should be handled with care
- Implemented a CLD model including the ARC (CLD_o3_v01)
  - First attempt: shrink tracker to accommodate the ARC
  - Studied impact on tracking performance (more later)
  - Ready to study impact on particle flow performance
- Much more details will be provided in Alvaro's talk

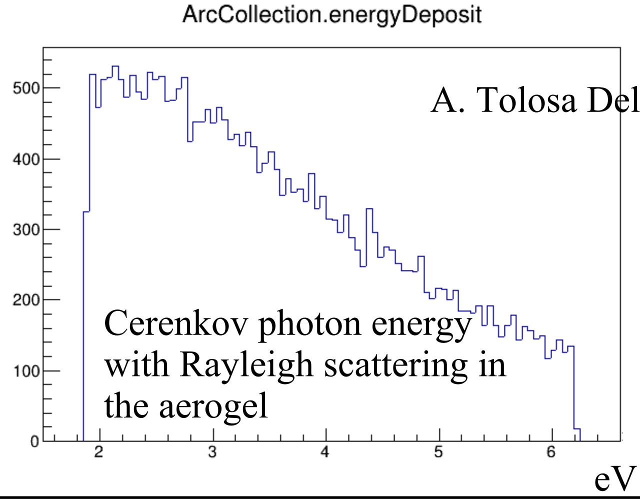


ARC detector (one cell)



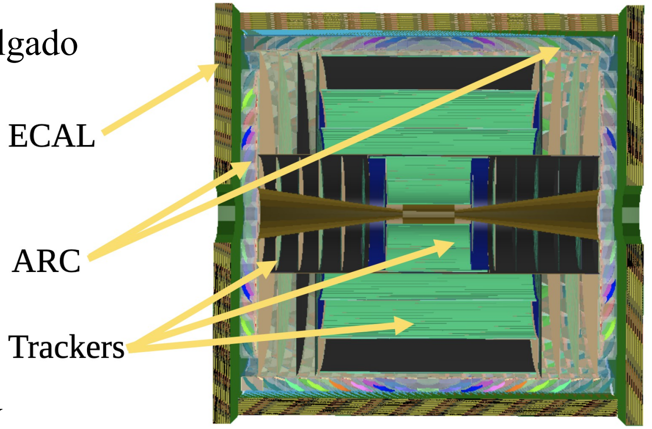


Cerenkov photon energy



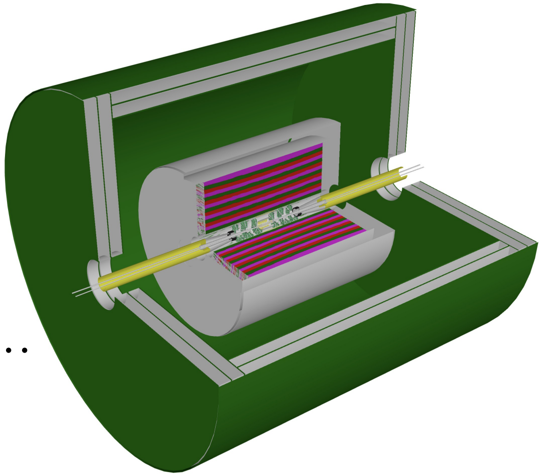
Cerenkov photon energy with Rayleigh scattering in the aerogel

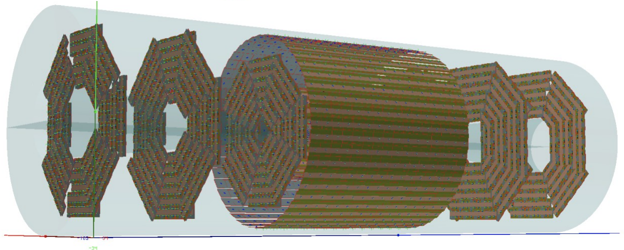
A. Tolosa Delgado

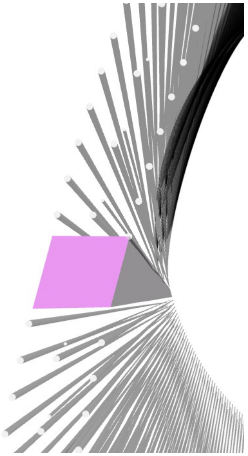


IDEA

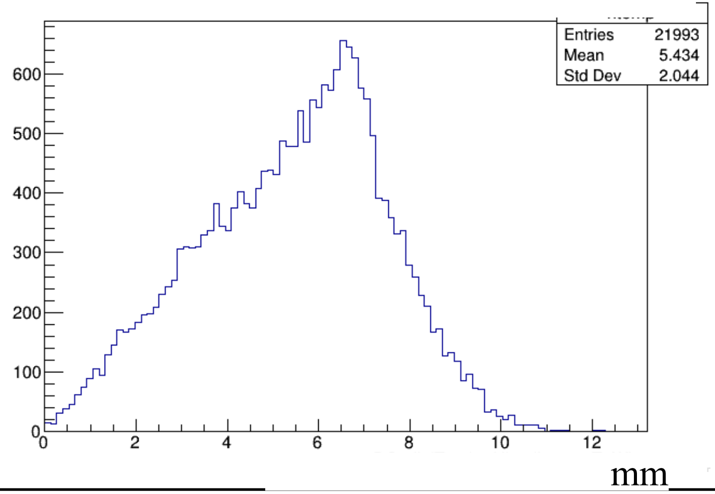
- Important progress in the DD4hep implementation of IDEA!
- New detailed description of the vertex detector: see Armin's talk
  - Simple digitizer available (spatial smearing of simHit)
- New **detailed description of the drift chamber**
  - Include all wires with stereo angle, sensitive volume definition, walls, …
    - Some overlaps to be fixed but already usable
  - Simple **digitizer available:** spatial smearing along/perp. to the wire
    - Required edm4hep extension, went for local coordinates
  - Cluster counting implemented (local fork + hacked Key4hep)
    - Need to be ported centrally

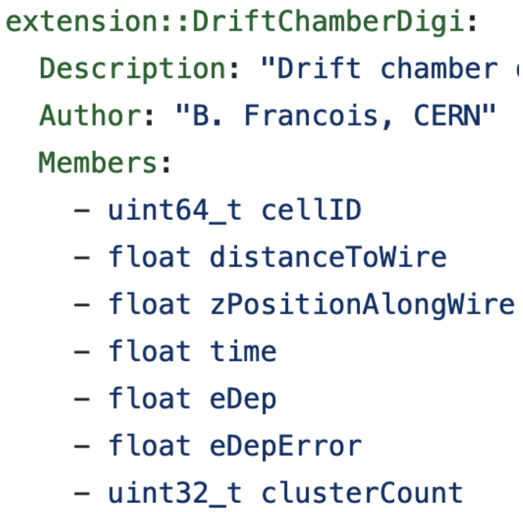




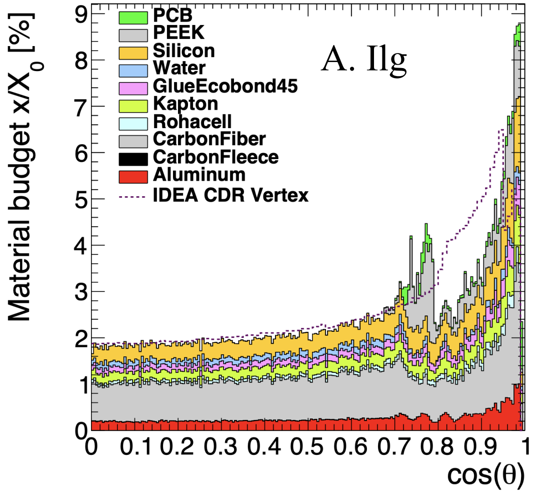


Distance to the wire after digitization



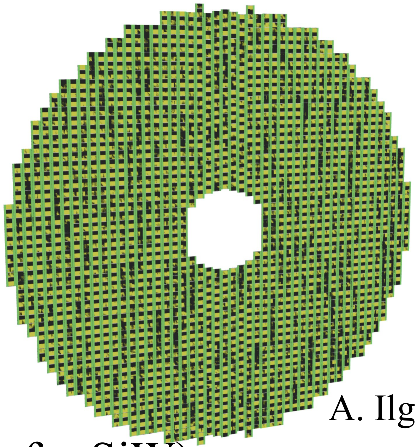


```
extension::DriftChamberDigi:
  Description: "Drift chamber (
  Author: "B. Francois, CERN"
  Members:
    - uint64_t cellID
    - float distanceToWire
    - float zPositionAlongWire
    - float time
    - float eDep
    - float eDepError
    - uint32_t clusterCount
```



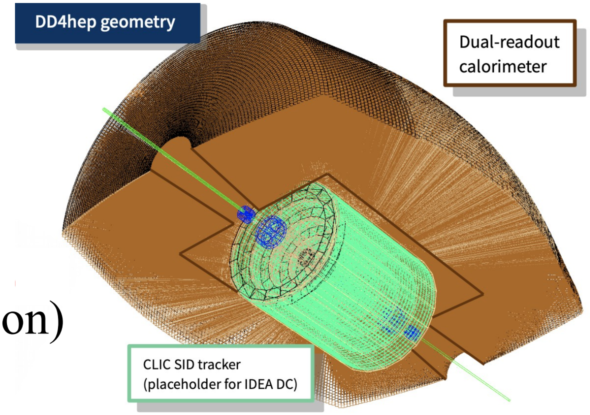
IDEA (II)

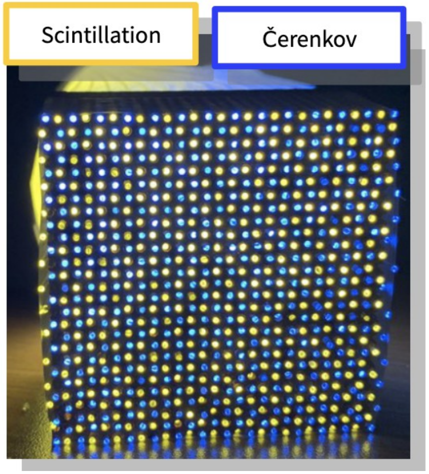
- Silicon Wrapper geometry implemented (PR opened)
  - Re-use the same detector builder and digitizer as for the vertex detector
  - Large surface (112 m^2), tiled with ~ 4x4 cm^2 modules
    - A lot of volumes: slow and memory greedy
    - Need to understand what level of detail is required
      - Will likely implement a simpler description and compare (not only for SiW)



A. Ilg

- Fiber dual readout calorimeter implementation available (up to RecHits)
  - Currently not integrated in the whole IDEA due to computing performance
    - Investigating ways to speed-up and lower the memory usage of the geometry construction
    - Already using fast sim for photon transportation in fiber
  - In parallel, look into clustering
    - k4Clue is a good candidate
    - Only need 2D (no long. segmentation)



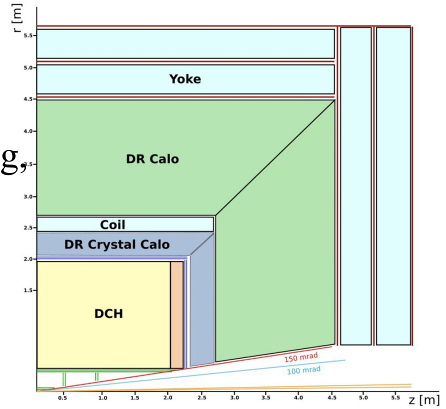


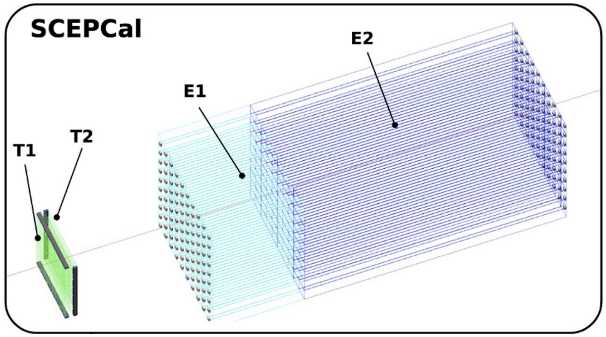
S. Ko and S. Kim

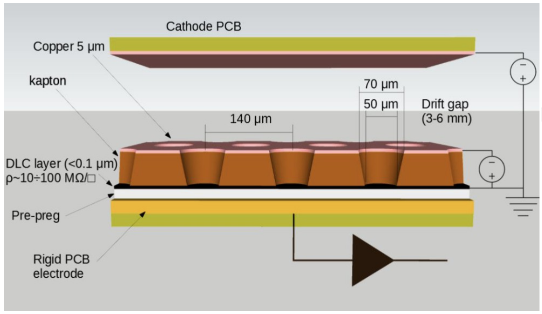
IDEA (III)

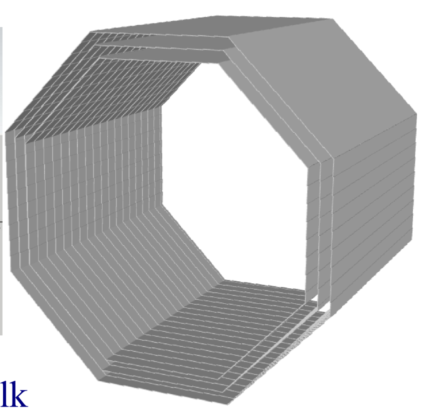
- Preparing a version of IDEA adding dual readout crystals
  - Increased EM resolution + longitudinal segmentation
  - To start with: drift chamber untouched, fiber DR calo pushed away
  - Detector geometry implemented (w/o timing layer), being validated
- Cylinder based μ-RWELL detector builder ready
  - Used to **implement pre-shower and muon chambers + yoke**
  - Digitizer ongoing
- Detailed non cylindrical version with μ-RWELL tiling ongoing
  - Trying to keep high flexibility (radius, PCB size, number of face)

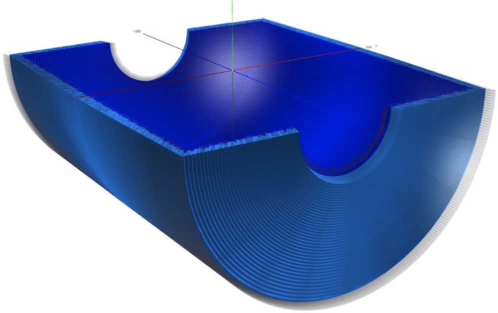
M. Lucchini, F. Cetorelli, W. Chung, talk





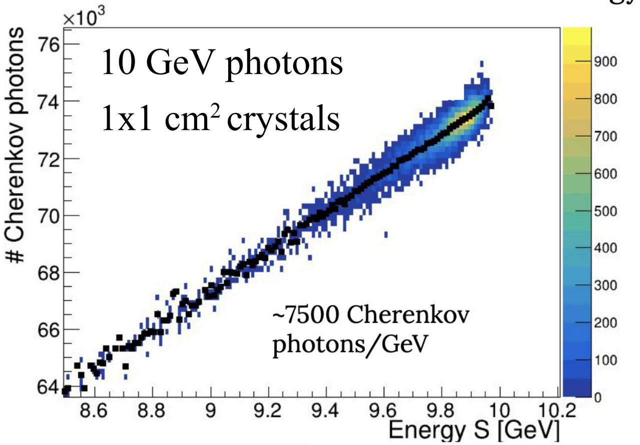




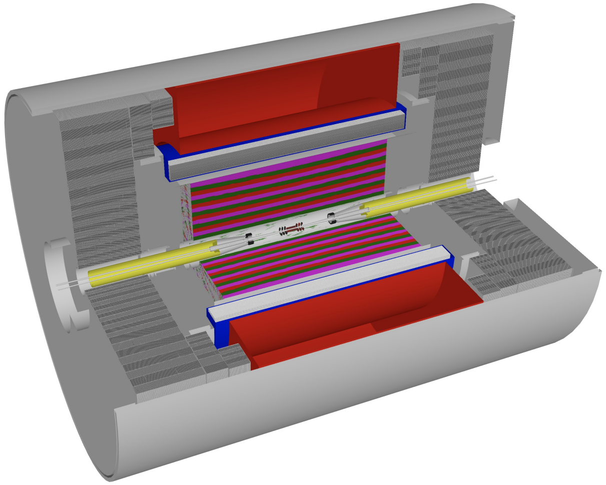


M. Ali, talk

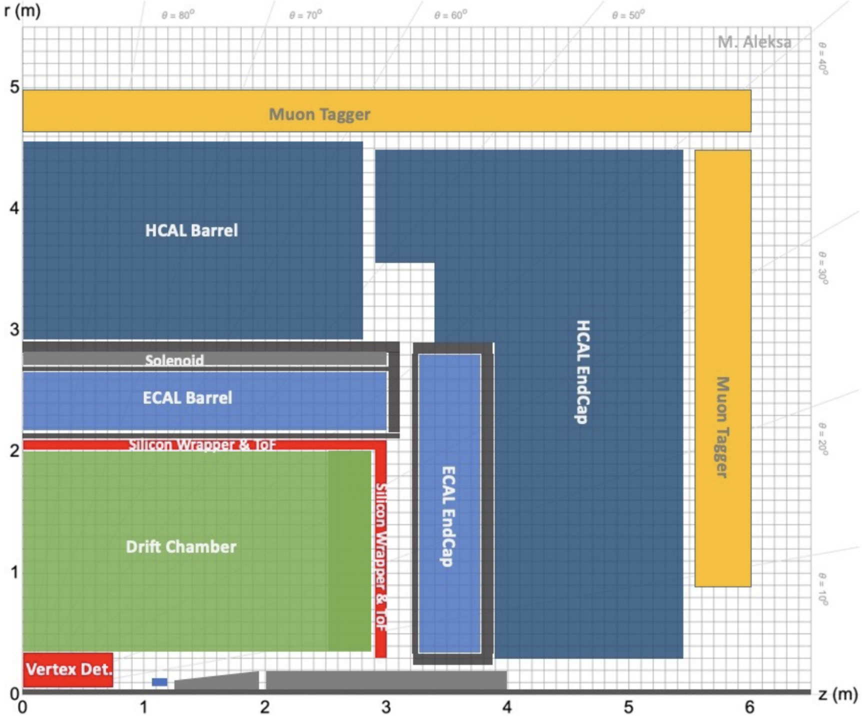
Correlation Cherenkov VS Scintillation energy



ALLEGRO



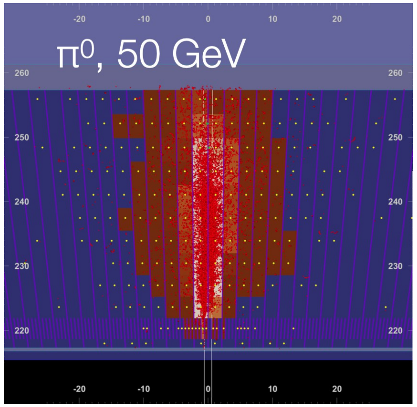
- A first 'complete' DD4hep implementation available
  - Still some place-holder detectors
  - Only calorimeters really used for physics so far
- Vertex + SiW detectors (will be) from IDEA
- Detailed IDEA drift chamber recently included
  - Will need a new layout optimization from R&D team because of longer z-extent (2.6 vs 2 m)
    - Not a problem software-wise
    - z-extent to be optimized
- ECAL and HCAL on the next slides
- Muon tagger place-holder, without return yoke (done by HCAL)

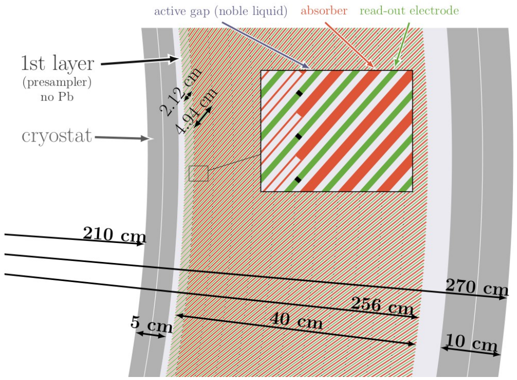


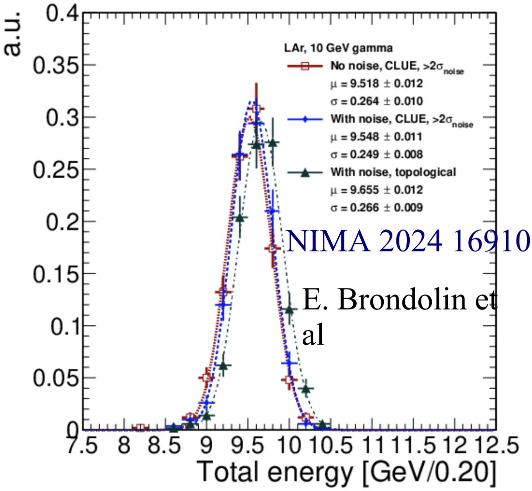
ALLEGRO (II)

- **ECAL barrel ready**: calibration, noise, 3 clustering algorithms (sliding window, topological clustering, CLUE), flexibility in granularity definition (optimization)
  - Recent updates
    - New visualization tool
    - Θ based segmentation (instead of η)
    - More flexibility in segmentation
  - Further starting activities
    - Cross-talk emulation → input for readout electrode R&D
    - Vertexing with calorimeter clusters: displaced photons (e.g. ALP's) → longitudinal granularity optimization…
    - General optimization of the absorber material/shape, noble liquid, granularity (e.g. πᾌγ ID) …
- **ECAL endcap 'turbine' geometry implemented**, working on its segmentation, digitization and optimization
  - Phi homogeneity, signal extraction from high-z

G. Marchiori



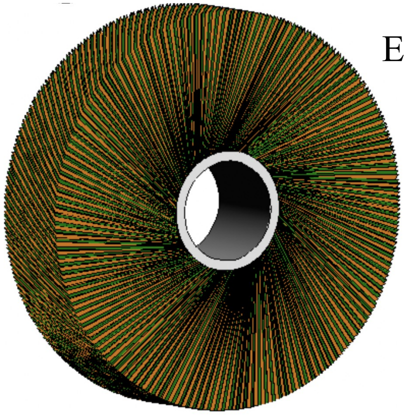




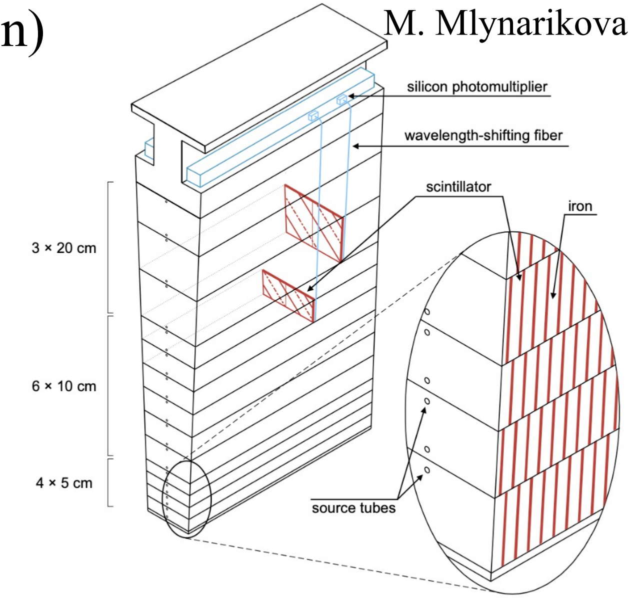
NIMA 2024 169100

E. Brondolin et al

E. Varnes



ALLEGRO (III)



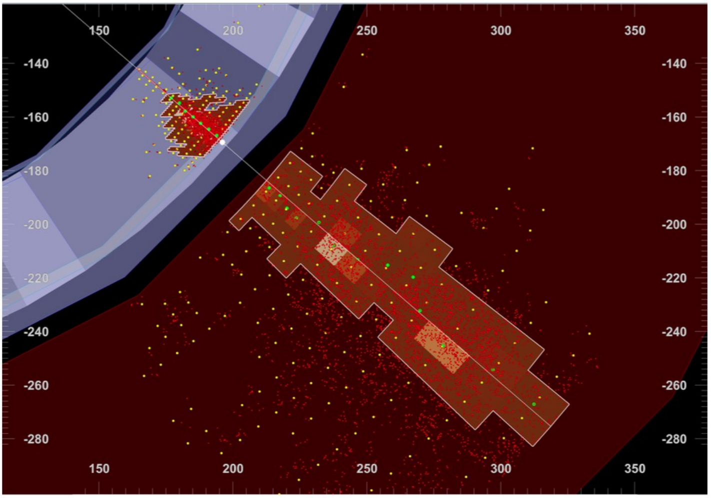
M. Mlynarikova

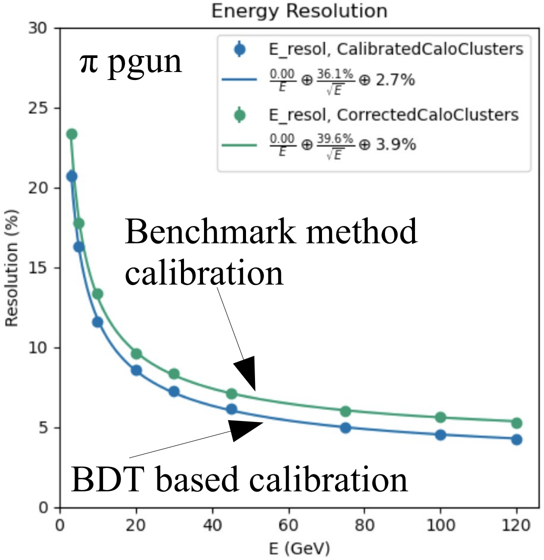
- HCAL geometry and reconstruction implemented (TileCal design)
  - Act as the return yoke (solenoid between ECAL and HCAL)
  - Work ongoing on the geometry optimization and calibration
- Brought together ECAL and HCAL for reconstruction
  - Both for sliding window (Tong Li) and topological clustering
- Performance studies with the barrels (Sliding window clusters)
  - Benchmark method calibration

$$E_{\mathrm{rec}}^{\mathrm{bench}} = p_0 \cdot E_{\mathrm{EB}}^{\mathrm{EM}} + p_1 \cdot E_{\mathrm{HB}}^{\mathrm{HAD}} + p_2 \sqrt{\left|p_0 \cdot E_{\mathrm{EB}}^{\mathrm{last\ layer}} \cdot E_{\mathrm{HB}}^{\mathrm{first\ layer}}\right|} + p_3 (p_0 \cdot E_{\mathrm{EB}}^{\mathrm{EM}})^2 + p_4 \cdot E_{\mathrm{EB}}^{\mathrm{first\ layer}}$$

  - Boosted decision tree calibration
- More about ALLEGRO calorimeters simulation in Giovanni's talk

G. Marchiori





π pgun

Benchmark method calibration

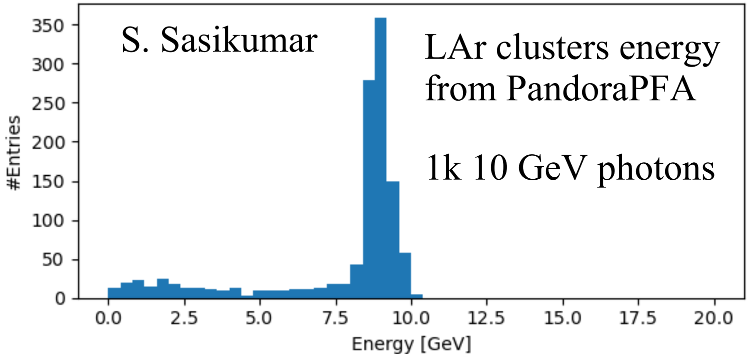
BDT based calibration

Ongoing Efforts on Reconstruction

Ongoing Effort on Reconstruction

Some examples of ongoing efforts on reconstruction

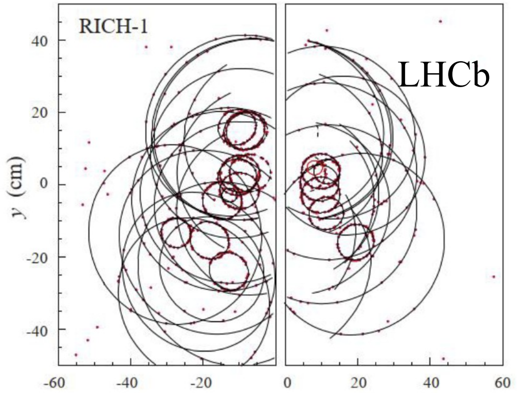
- Pandora Particle Flow algorithm application to the ALLEGRO detector
  - Start with a modified CLD including Noble Liquid ECAL (since ALLEGRO local reco is not finished)
  - First PandoraPFA ECAL clusters available
  - More details in Swathi's talk
- Particle identification with the Array of RICH Cells
  - Works well in the complicated LHC environment
  - FCC-ee environment is much cleaner
    - Try basic algo first: track/photon pair angles, peak finding
  - More details in Alvaro's talk
- ACTS tracking in Key4hep: Leonhard's talk
- Machine learning based flavor tagging, PFlow and drift chamber tracking (starting)
  - More details in Dolores' talk

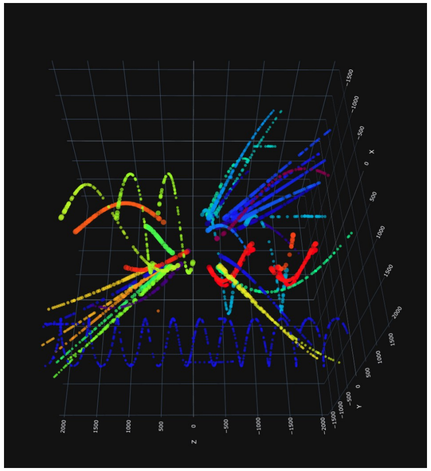


S. Sasikumar

LAr clusters energy from PandoraPFA

1k 10 GeV photons



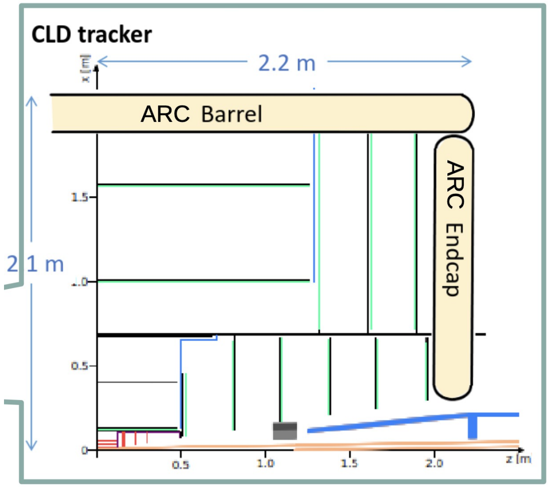


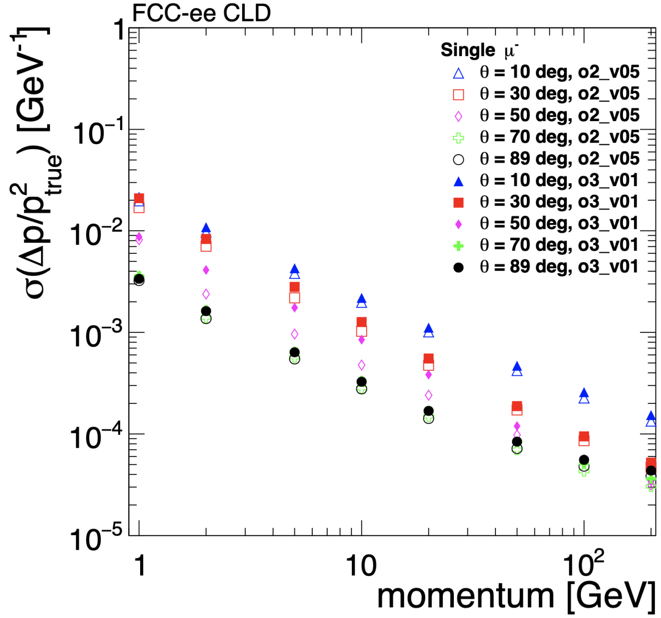
IDEA drift chamber hit visualization

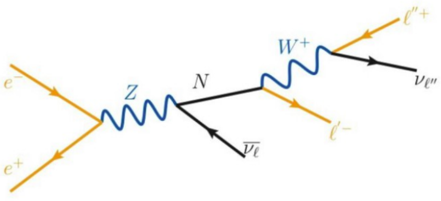
D. Garcia

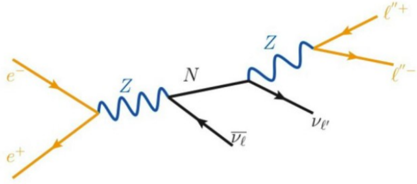
CLD Tracker Studies + HNL Analysis

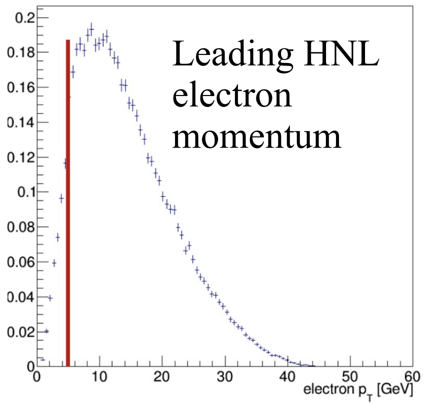
- CLD tracker studies
  - Impact of material budget and single point resolution on vertexing
  - CLD tracking performance with (o3_v01) and without (o2_v05) the ARC
    - ARC eating tracker space
    - Expected loss from smaller lever arm (res ö $1/L^2$)
    - Other configurations possible: ARC after tracker, add one tracking layer after ARC, …
  - Validation of Delphes CLD tracking with Full Sim
- Starting Heavy Neutral Lepton Full Sim analysis
- All the above discussed in Gaelle's talk











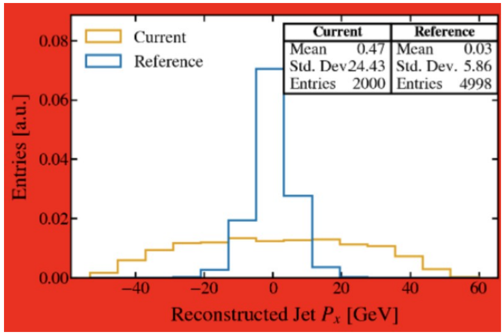
Leading HNL electron momentum

G. Sadowski, J. Andrea, Z. El Bitar, A. Besson

How can you contribute?

Open Projects (I)

We **need people to take responsibilities/coordination roles** (see here) and we also have many open 'specific' tasks. Some examples:



- Validate Delphes cards with full sim (only CLD tracker done so far)
- Implement physics validation plots in Key4hep
- Implement and study realistic magnetic fields (all)
- Implement tracking for the IDEA detector
  - People interested (ML, intuition based), but more are welcome
- Study multiple scattering up to muon chambers (or silicon wrapper) to set lower limit on spatial resolutions (or make the case for lighter inner detectors)
- Improve cell positions assignment in ALLEGRO calorimeter
- Study the impact of wires in the drift chamber (slows down simulation, some studies might not need them if small impact)
- Validate detector implementation with available test beam data
  - Drift chamber, muRWELL, dual readout calorimeter, …

Open Projects (II)

More examples of open specific tasks:

- Reproduce detector performance studies with the latest CLD version
- Migrate ILCSoft algorithms to native edm4hep based Gaudi algorithms
- Revive, maintain and optimize existing reconstruction algorithms (e.g. flavor tagging training, tau reconstruction)
- Study GNN based flavor tagging (as we do currently for Delphes output) for full sim output
- Exercise the background overlay tools and migrate them to an EDM4HEP native algorithm
- Study Particle Flow performance w/ and w/o PID
- Update lumiCal position and segmentation
- **Prepare and maintain Full Sim physics analyses** (with CLD first, applied to other detectors with minimal changes)
- …

Summary

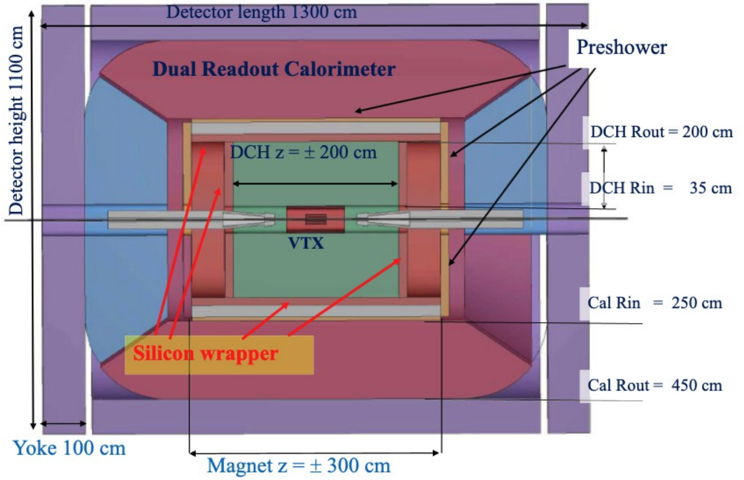
- CLD is available for detector performance studies and physics analyses
- IDEA DD4hep implementation getting close to completion
  - Moving on to the digitization/reconstruction
- ALLEGRO DD4hep implementation also close to completion
  - Some dimensions tuning required and place holder detectors to improve (e.g. muon chamber)
- Many tools already available, we need people (expert on the relevant physics aspects) to use and validate them!
- There are many opened 'specific' projects ready to be tackled but we also **need more people acting as 'engines' to steer the efforts**
- Detailed description of all detectors harms performance and flexibility
  - We have to understand what level of detail is needed, for which sub-detector
- Having full sim physics analyses for the FSR is challenging but we have to try
  - A minima, we have to provide robust detector performance studies

FCC Full Sim webpage and Bi-weekly working meeting

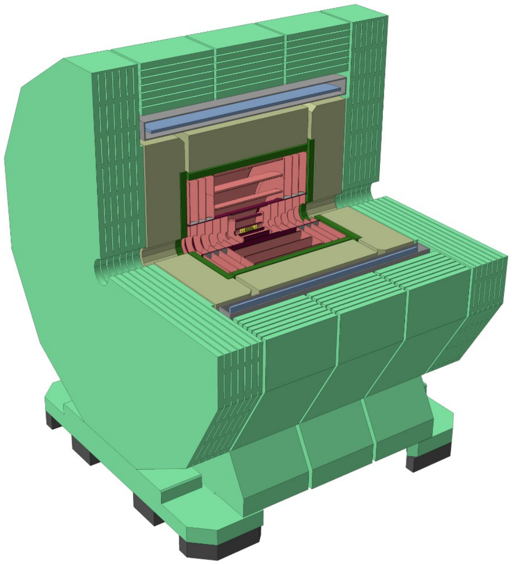
Additional Material

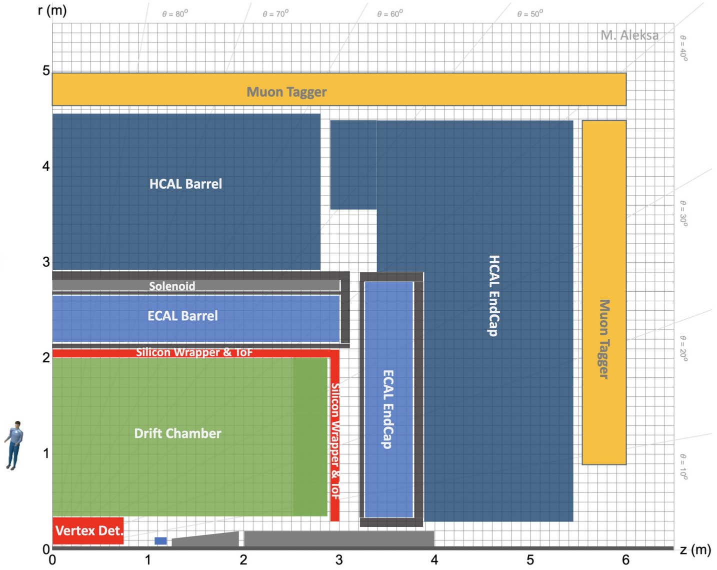
IDEA

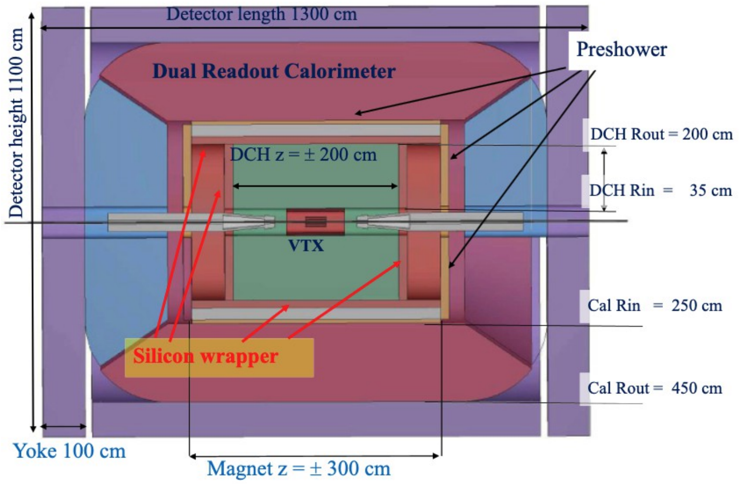
- IDEA: Innovative Detector for Electron-positron Accelerator
  - Light vertex detector (DMAPS)
    - Low material budget beneficial for vertex position resolution
  - Light gaseous tracker (2 - 5 % of X_0) + silicon wrapper
    - Large volume needed due to small magnetic field (~2 T, beam emittance)
    - Good PID capabilities thanks to cluster counting
  - Ultra-thin solenoid inside calorimeter
    - Low cost, low material budget needed for particle flow performance
  - Pre-shower and dual readout calorimeter
    - 30 - 40 % / √E jet energy resolution (H → ZZ^{π} → 4j and H → W W^{π} → 4j discrimination)
  - μ-RWELL in return yoke
- Alternative option under study: add a dual readout segmented crystal ECAL
  - Greatly improves EM energy resolution and brings some longitudinal segmentation



FCC-ee Detectors

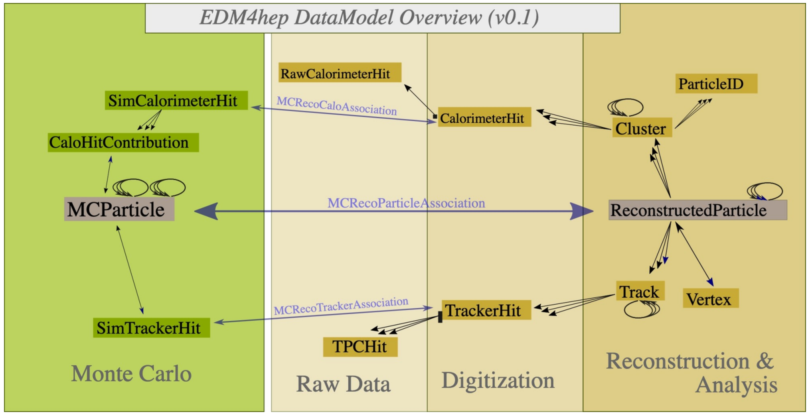


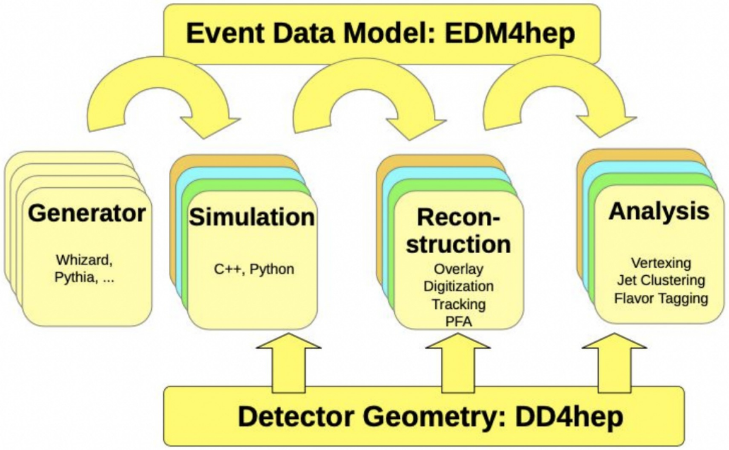




FCC Software Ecosystem in a Nutshell

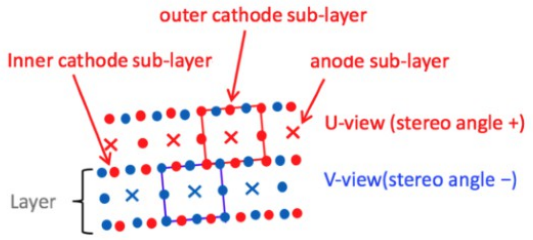
- FCC software fully relies on **Key4hep**
  - Framework meant to **support all future colliders** studies
  - Centrally provides a set of useful HEP packages in a consistent stack
- edm4hep data format, relying on podio
- Well advanced, though not frozen yet: bi-weekly discussion
- Chains of algorithms (Gen, Sim, Digi, Reco) orchestrated with Gaudi
- Detector description based on DD4hep



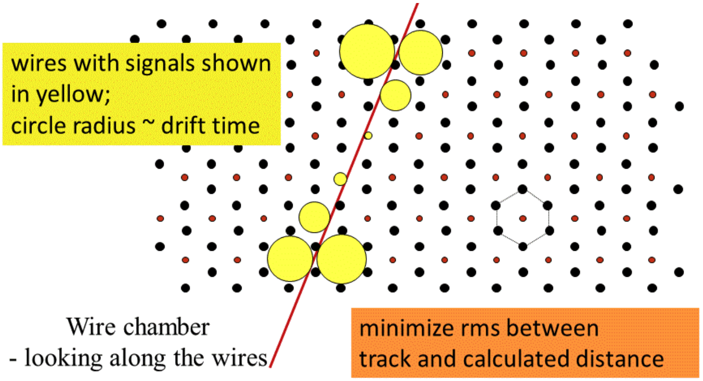


Drift Chamber Reconstruction

- Next step is to implement the DCH reconstruction in Key4hep
  - DCH segmentation into sensitive region (hit ↔ wire)
  - SimHit → RecHit in edm4hep data format, including cluster counting



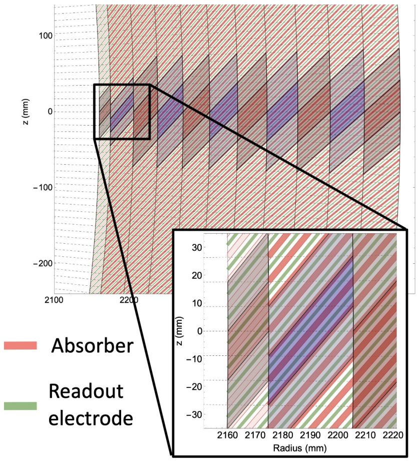
- Prepared k4RecTracker: Key4hep compliant repository to host general VTX and Tracker reconstruction in edm4hep native data format + Tracking
- Tracking
  - Only one algorithm ready to be used in Key4hep: iLCSoft MarlinTracker (CLIC/CLD)
    - Silicon oriented
  - Several solutions could be investigated and wrapped in Gaudi
    - ACTS: needs some data format gymnastic and a way to ship the geometry
      - Solution implemented by EIC
    - ILD approach
      - Track segments built separately in inner Si-tracking and TPC, then combined
    - BES III solution: TrackNETv2 (machine learning based)
    - Genfit: already available as a Key4hep package, only for track fitting
  - Implement our own Key4hep native drift chamber tracking algorithm?

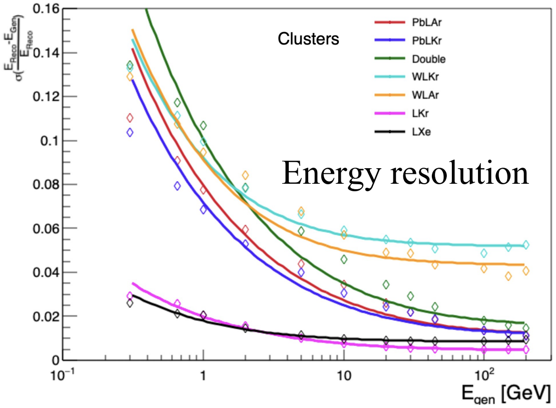

wires with signals shown in yellow;
circle radius ~ drift time
minimize rms between track and calculated distance

Wire chamber
- looking along the wires

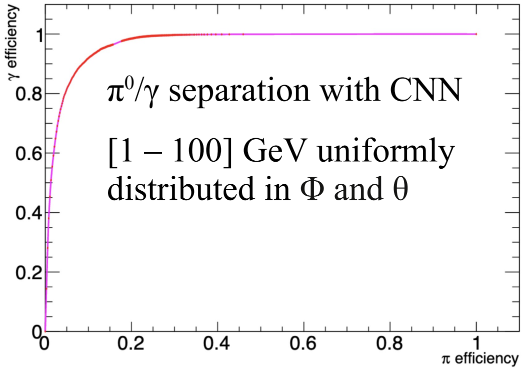
Noble Liquid Based Concept in Key4hep

- Current detector description in DD4hep: link
  - Simplified vertex (CLD), will be updated to the detailed IDEA one
  - Simplified drift chamber (no tracking available)
  - **ECAL Barrel fully available in Key4hep**
    - Inclined absorber plates that can be made trapezoidal
    - Cryostat, services and solenoid material budget included
    - **Calibration, noise and clusterings available** as edm4hep native Gaudi algorithms!
    - **Plug-and-play compliant**
      - Good factorization between xml and cpp builders
      - Automatic rescaling upon geometry changes
    - **First performance studies performed**
    - Need **Particle Flow** to optimize granularity, requires tracks
      - Prepared a detector configuration with CLD + LAr ECAL
        - Temporary hack to exercise the technical machinery
      - Working now on PandoraPFA integration
  - ECAL endcaps under validation





Energy resolution

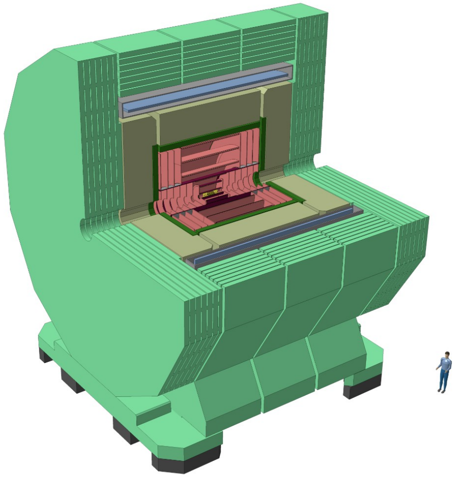


π^0/γ separation with CNN

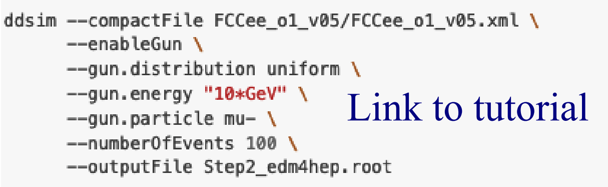
[1 – 100] GeV uniformly distributed in Φ and θ

CLD Full Sim Status

- Full simulation + reconstruction workflow available!
  - Simulation through *ddsim*
  - Reconstruction through *Marlin*
    - Background overlay, digitization, conformalTracking, ParticleFlow (PandoraPFA), vertexing and flavor tagging
    - Inherited from ILD/CLICdet



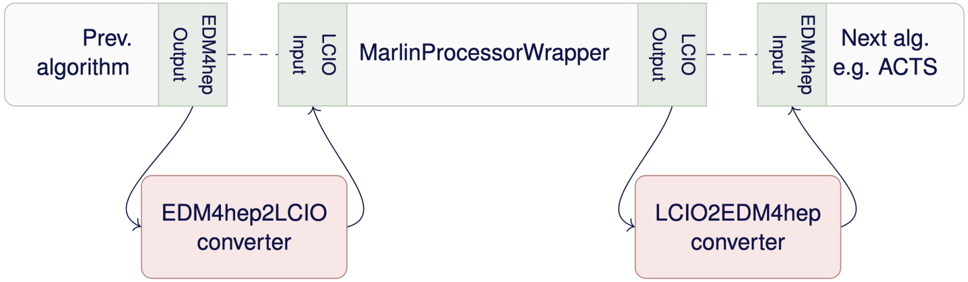
- *Marlin* reconstruction based on LCIO data format but can be **integrated in EDM4hep Gaudi based workflows** through the *MarlinWrappers* + data format translation
  - Example of steering file



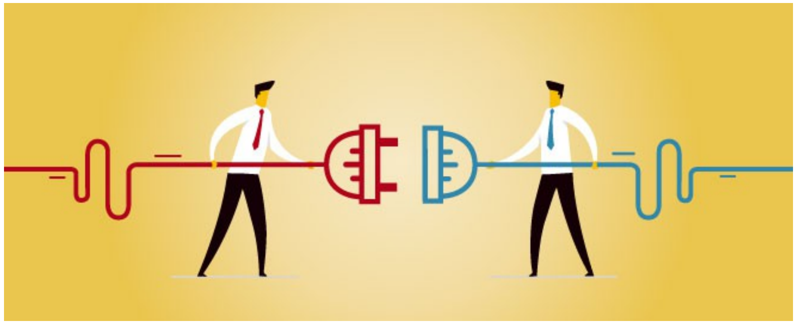
```
ddsim --compactFile FCCee_o1_v05/FCCee_o1_v05.xml \
      --enableGun \
      --gun.distribution uniform \
      --gun.energy "10*GeV" \
      --gun.particle mu- \
      --numberOfEvents 100 \
      --outputFile Step2_edm4hep.root
```

Link to tutorial

- Improvement towards inter-operability
  - Be able to run Marlin Reco after having simulated CLD with k4SimGeant4
    - Differences in the way Geant4 hits are stored (modifs could be applied to k4SimGeant4)



Inter-operability



- "Only" three detector concepts at the moment
  - Already **a lot of sub-detectors** to model and more are to come!
- All concepts are still evolving → need flexibility and inter-operability
  - Want to be able to easily **study** many **different detector concept configurations**
    - Sub-detector content, extent, position, …
  - **Plug-and-play** approach made **possible** by DD4hep **but not granted**
    - Some ingenuity required in designing the C++/xml architecture
  - A common data format is not enough, needs additional prescriptions
    - Strategy to store Geant4 hits, fields with freedom left to the user (e.g. calo clusters shape parameters), …
- FCC detector geometries are being moved from FCCDetectors to k4geo
  - Linear collider detectors already hosted there
  - Having all sub-detector geometries in a common place will ease inter-operability, grid submission
  - This repository could also host test-beam module description
    - A flexible enough detector builder (C++) should allow us to easily write the xml for a small module