# FCC Software
## Detector full simulation

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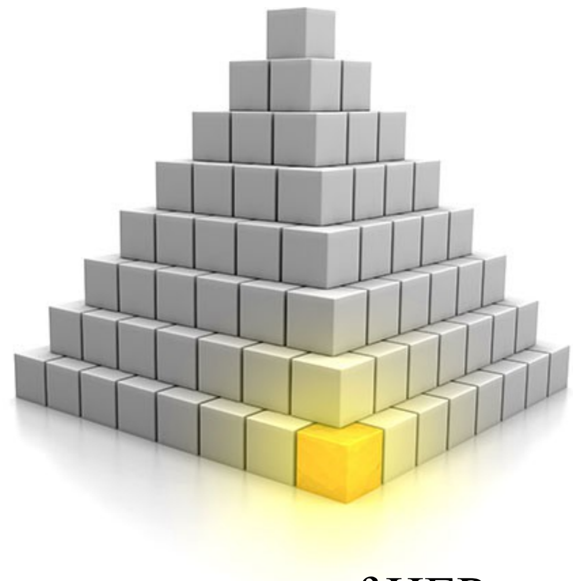
# Content

- Overview of the FCC(-ee) Detector Full Simulation
  - Framework
  - CLD, IDEA, Noble Liquid
- Focus on the Noble Liquid Calorimeter Software
  - Geometry
  - Calibration
  - Noise
  - Clustering
  - Performance Studies

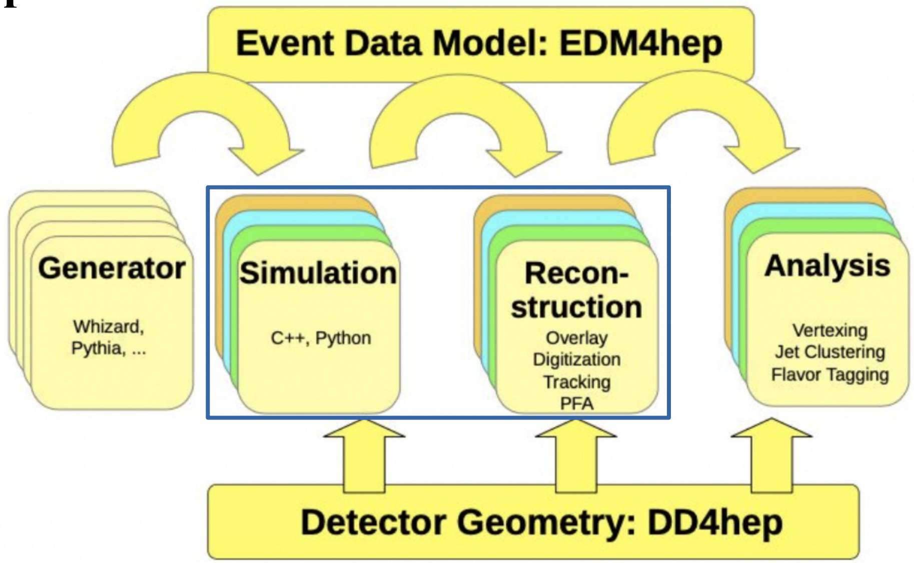
# Motivation



- Detector **full simulation** is a corner stone of HEP experiments
- Already crucial at the 'planning stage' of a future facility
  - Without test-beam data, only way to reliably estimate **detector performance** parameters
    - Feeds fast simulation tools to **estimate the physics reach**
  - One can not prototype every sub-detector option → mandatory for **detector optimization**
  - We have to show that **complete detectors,** meeting **requirements,** can be **designed**
    - Before the final detector is built, full sim is the only place where **all sub-detectors live together and interact with each other** in a realistic way

# General Overview

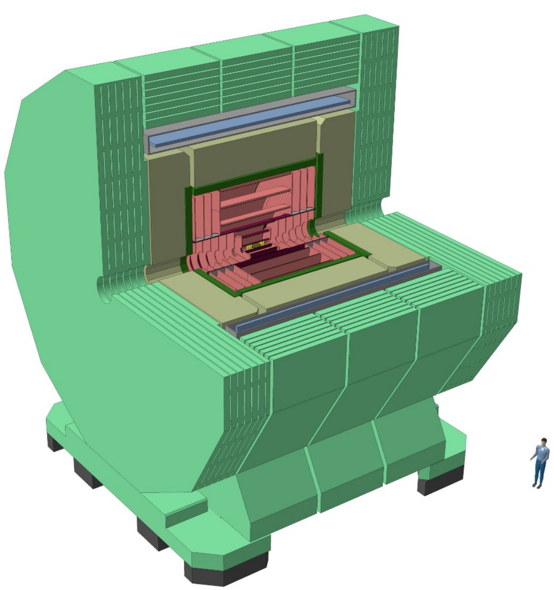
- Detector R&D and optimization campaigns **span over decades**
  - Need a **stable** and continuously **maintained** software framework
- Future collider studies performed by **small teams** (compared to operating detectors)
  - Exploiting **synergies** is a must
- The community agreed on using a common software framework for **all future collider studies**: **Key4hep**
  - Complete set of tools: generation, simulation, reconstruction, analysis
    - State of the art HEP libraries availability: **Spack**
      - Avoid re-inventing the wheel
  - Common data format: **EDM4hep** (PODIO)
    - Easy sharing
  - Detector description with **DD4hep**
    - Next slide
  - **Gaudi** orchestration



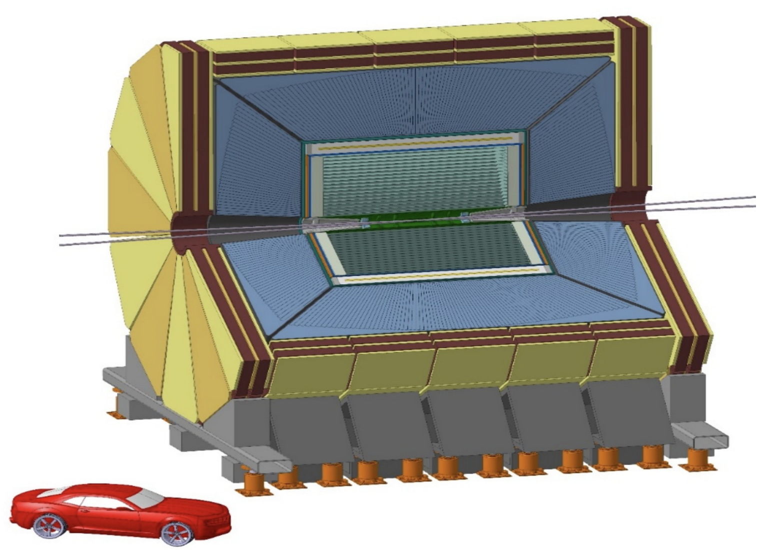
# FCC-ee Detector Concepts

- Two concepts proposed for the FCC-ee CDR: **CLD, IDEA**
- More detectors needed if we have more than 2 IPs
  - New concept based on **High Granularity Noble Liquid calorimeter** under development
- Many different sub-detector technologies on the table!
- Ultimate goal pursued: **full inter-operability of sub-detectors** (eased by DD4Hep plug-and-play approach) and **reconstruction algorithms** (dataformat, more challenging)

CLD



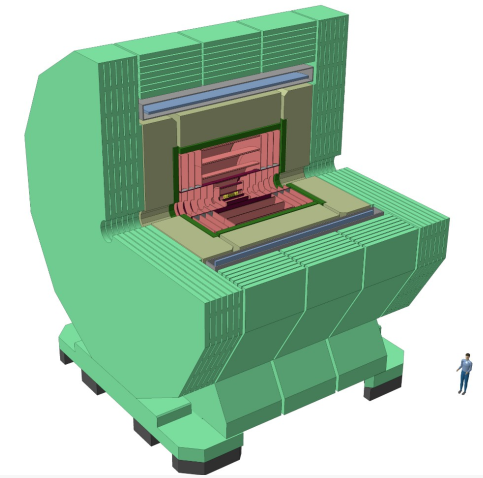
IDEA



Noble Liquid Based

# CLD Full Sim Status

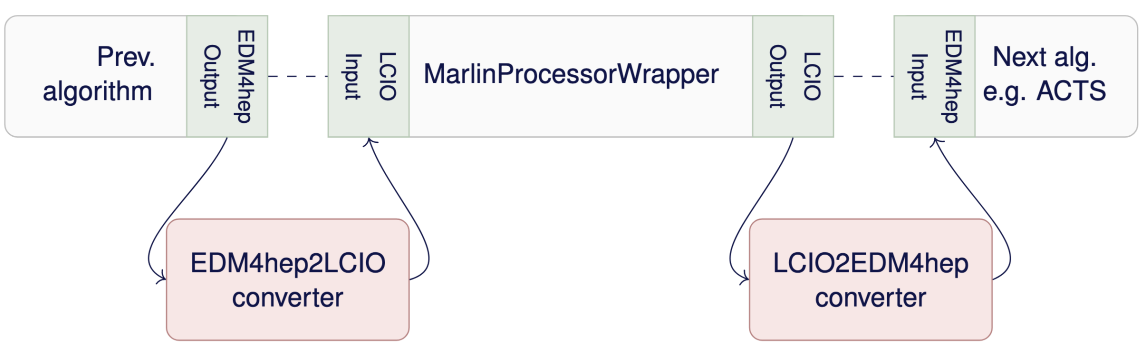
- **All CLD sub-detectors implemented in DD4hep**
  - Several configurations envisaged
- Full simulation + reconstruction workflow available!
  - Simulation through *ddsim*
  - Reconstruction through *Marlin*
    - Background overlay, digitization, conformalTracking, ParticleFlow (PandoraPFA), vertexing and flavor tagging
    - Inherited from ILD/CLICdet



```
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
```

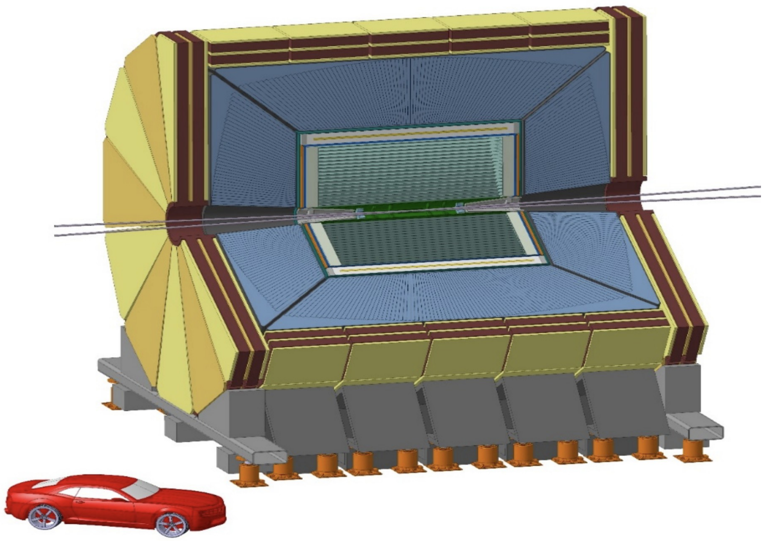
Link to tutorial

- *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



# IDEA Full Sim Status

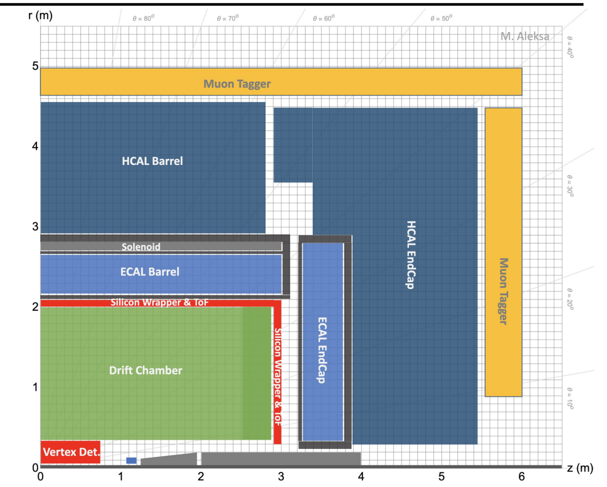
- '**Standalone**' (plain **Geant4**) detector simulation partially available
  - Tracker hits and tracks + calorimeter hits are there
  - Working on Particle Flow implementation
  - Possibility to output hits and tracks in EDM4hep under validation
    - Misses the plug and play feature



- **Ongoing effort towards Key4hep integration**
  - Porting detector description to DD4hep
    - Detailed implementation of the vertex detector in DD4hep almost available
    - Drift chamber implemented, working on its reconstruction/validation
    - Dual readout “bucatoni” available, working on integrating it with other detectors
    - Dual readout crystal ECAL starting
- More details can be found in this morning's talks

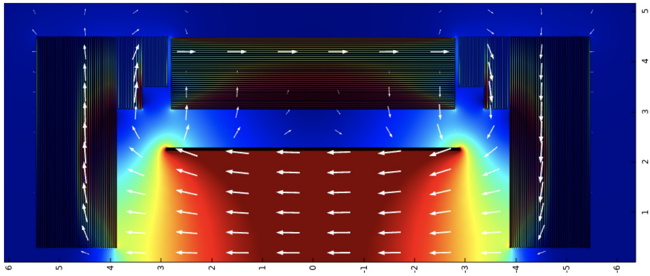
# Noble Liquid Based Full Sim Status

- Detector concept being designed (early stage)
- DD4hep ECAL barrel implementation validated (more later)
- HCAL and ECAL end-cap implementation under validation
- Drift chamber detector from IDEA simplified version
  - Very easy from the 'plug-and-play' approach
- Further developments
  - ECAL/HCAL interface
  - Choice of magnet position based on realistic field maps
    - Tools implemented, impact on tracking to be assessed
  - Particle Flow
    - Needs tracks first
  - …
- More details in the second part of the talk

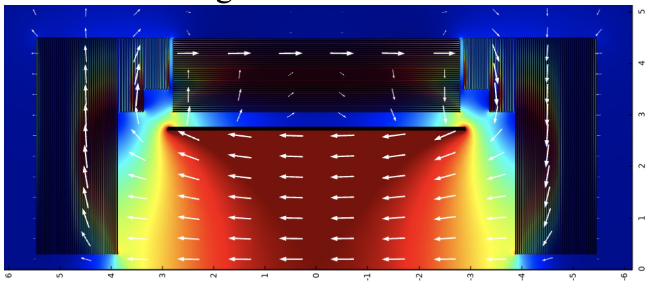



```
<include ref="../../DetFCCeeIDEA/compact/SimplifiedDriftChamber.xml"/>
<include ref="../../DetFCCeeECalInclined/compact/FCCee_ECalBarrel.xml"/>
<include ref="../../DetFCCeeHCalTile/compact/FCCee_HCalBarrel_TileCal.xml"/>
<include ref="../../DetFCCeeCalDiscs/compact/FCCee_EcalEndcaps_coneCryo.xml"/>
```

Magnet inside ECAL

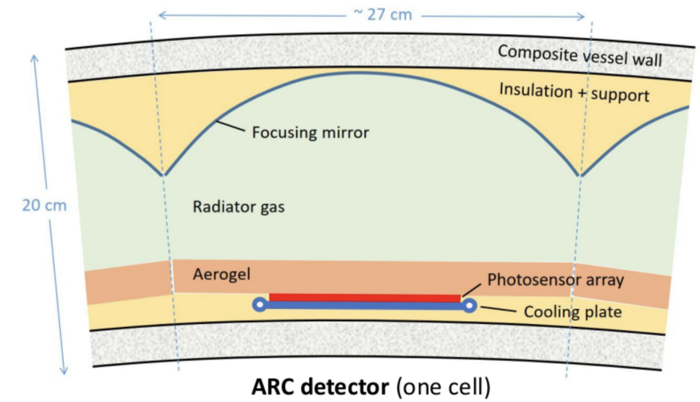


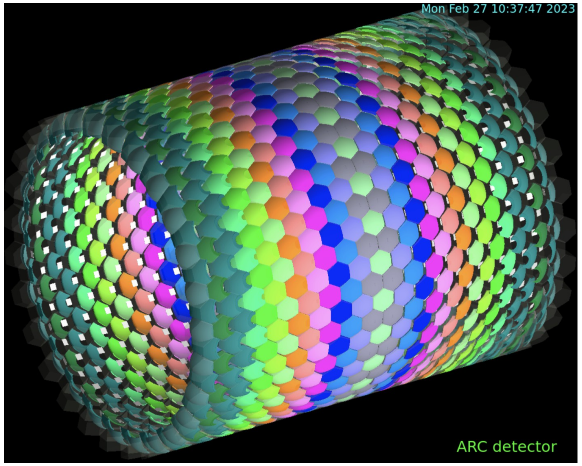
Magnet outside ECAL



# PID Detectors

- Detector layouts are not frozen!
  - Exploring further sub-detector technologies
- Particle ID detectors can complement/replace dE/dx or dN/dx
  - Technology more mature then at the LEP time (DELPHI)
    - LHCb RICH
- Accurate and comprehensive estimation of what it brings needs full sim
  - Photon yield/collection, additional material budget
  - Quite difficult to implement
- Array of RICH Cells (ARC) implemented in DD4hep
- Readout and reconstruction will start soon

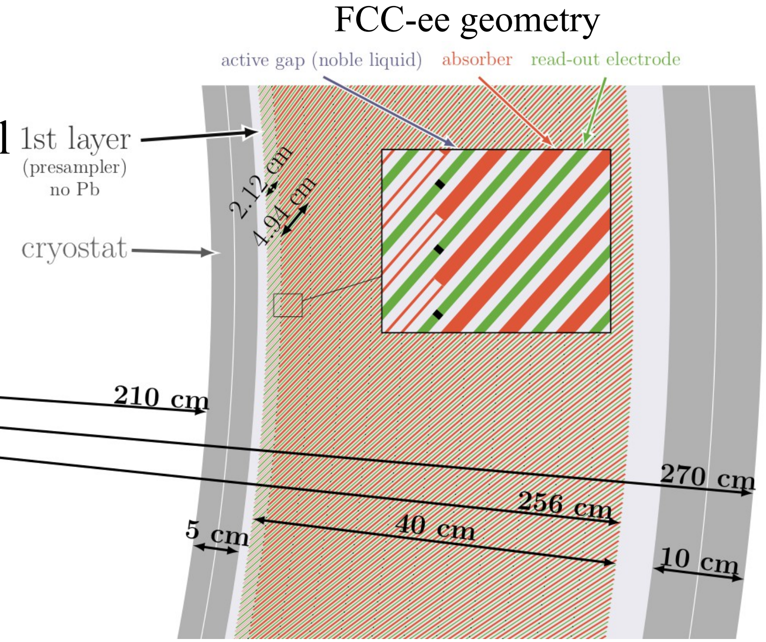


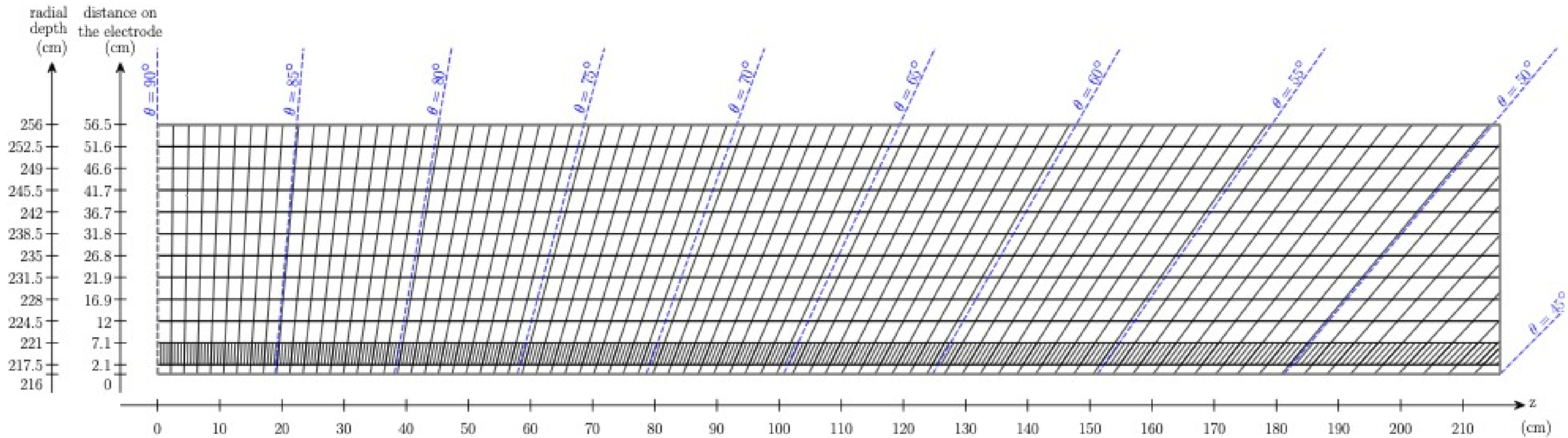



# Focus on the Noble Liquid Calorimeter Software

# Noble Liquid Calorimeter

- **High granularity** Noble Liquid ECAL
  - Absorbers: Lead (Pb) or Tungsten (W) straight or trapezoidal inclined (50°) plates
  - Sensitive media: Liquid Argon (LAr) or Krypton (LKr)
  - Everything inside a cryostat (Aluminum or Carbon Fibre)
  - Target a factor 10-15 increased granularity compared to the ATLAS implementation
    - Multi-layer PCB readout electrodes



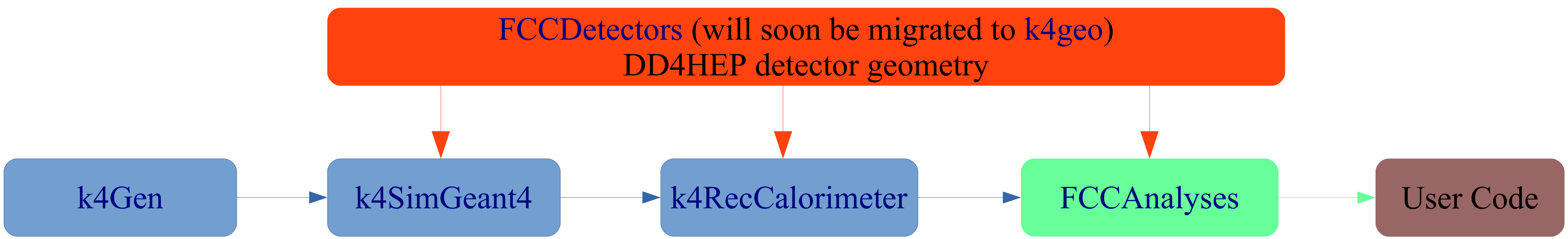



# Full Sim in a nutshell

- Full Sim chain in a nutshell (schematic)
  - Documentation: link

Legend: Gaudi based

Links to code




**k4Gen**

- Monte Carlo Generation
- Physics collision or Particle Gun

**k4SimGeant4**

- Geant4 interface
- Geometry services
- Particle propagation inside the detector
- Simulated Energy deposits ('SimHits')

**k4RecCalorimeter**

- Energy deposits per physical cells/readout channel
- Noise
- Corrections (sampling fraction, dead material correction)
- Clusterings

**FCCAnalyses**

- Plain ROOT n-tuple production
- High-level variable computation

**User Code**

- Automation
- Reco/Gen comparison
- Plots!

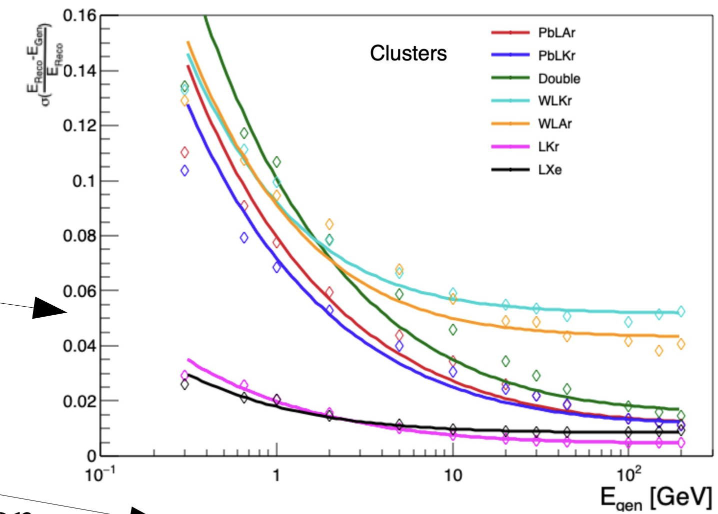
+ k4FWCore For Podio services and very generic tools

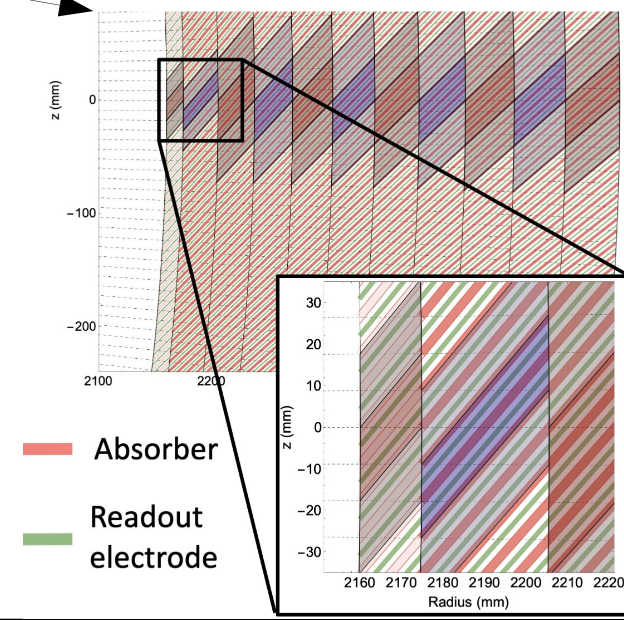
# Detector description

- **Factorized** Detector Building (DD4HEP)
  - C++ detector factory: handles the **generic geometry structure**
    - Cryostat cylinder, inclined plates, …
  - XML file with **specific detector parameters**
    - Inner/Outer radius, materials, inclination, …
  - Allows you to study different scenarios with minimal work
- Detector segmentation based on DD4HEP Readouts
- Readout cells differ in general from physical cells
  - E.g. having high sampling frequency improves energy resolution → phi granularity higher than what physics requires
  - Flexibility choice: do the time consuming Geant4 simulation with atomic granularity, then apply (possibly several) cell recombinations with RedoSegmentation
- Room for improvement
  - The same cell recombination scheme is applied to the whole calorimeter
    - One would like to have smaller cells for e.g. the strip layer
  - Detector segmentation from a fictive grid

FCCDetectors (DD4HEP)

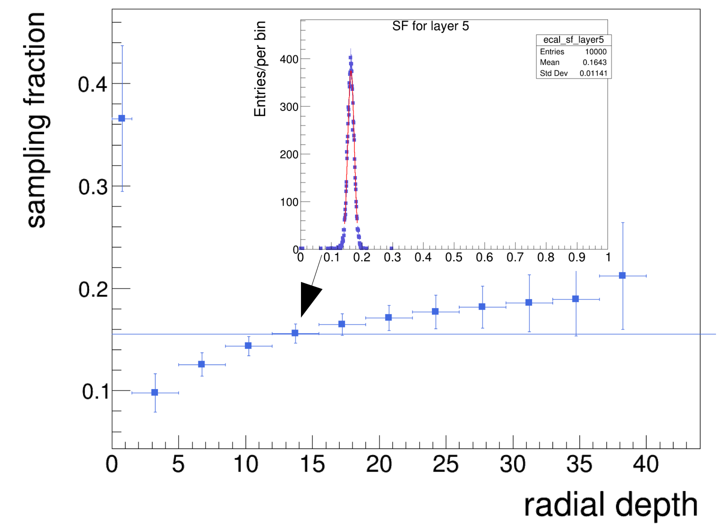
k4SimGeant4

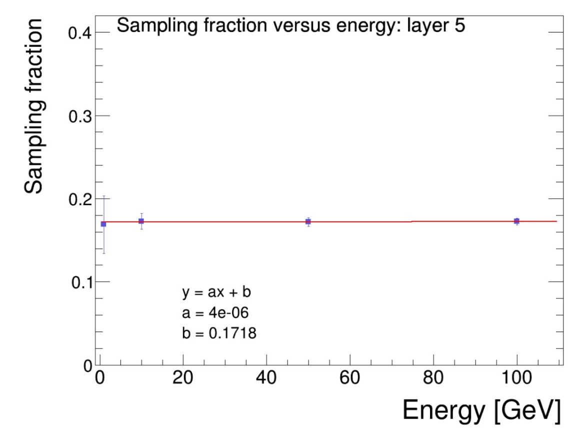


# Sampling Fraction

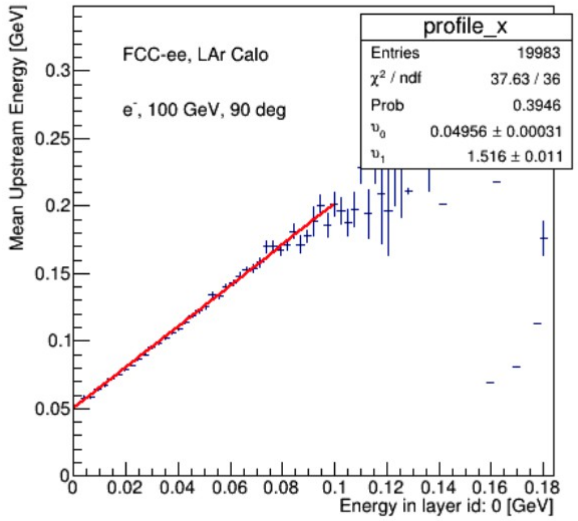
- In a Sampling Calorimeter, only a fraction of the particle energy is measured
  - Scaling of the energy deposited in the sensitive medium to account for energy deposited in the passive components (absorber and readout PCB)
- Modified detector config with everything set as sensitive (XML)
  - SamplingFractionInLayers stores the energy ratio (active/total) per event and per longitudinal layer — k4SimGeant4 — User Code
  - SF = mean of Gaussian fit of the active/passive energy ratio
  - Propagate results to CalibrateInLayersTool — k4RecCalorimeter
  - Fully automatized procedure with control plots
    - Everything defined in a Gaudi config can be passed as command line argument
    - Or you can use sed for more permanent usage
- In a Noble Liquid calorimeter, the sampling fraction has almost **no dependence on the incident particle energy**
  - No need to apply this procedure to many energy points

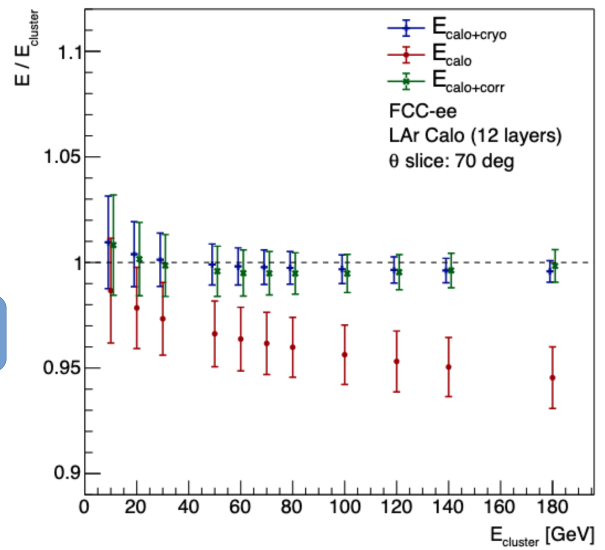


# Upstream/Downstream energy correction

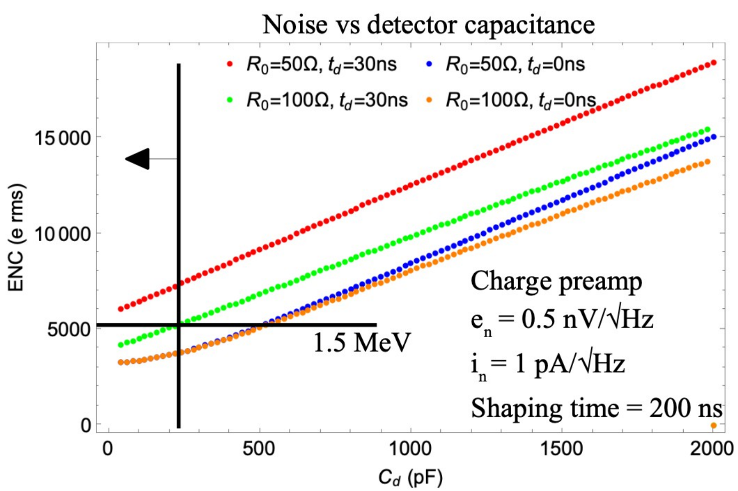
- Unmeasured **energy deposited in upstream material**: calorimeter supporting structure/cryostat, magnet, services, …
- Always try to minimize calorimeter radial extent + stochastic nature of shower depth → **energy deposited after the calorimeter**
- **Strong correlation** between energy in first(last) sensitive layer and energy deposited upstream(downstream) → **one can correct for that!**
  - EnergyInCaloLayers → stores energy in various dead materials and in all the active layers (modified XML) k4SimGeant4
  - Centrally available scripts perform the fits
  - CorrectCaloClusters → applies the correction based on cluster total energy and energy from first/last layer k4RecCalorimeter
- Again, fully automatized procedure with intermediate diagnostic plot production

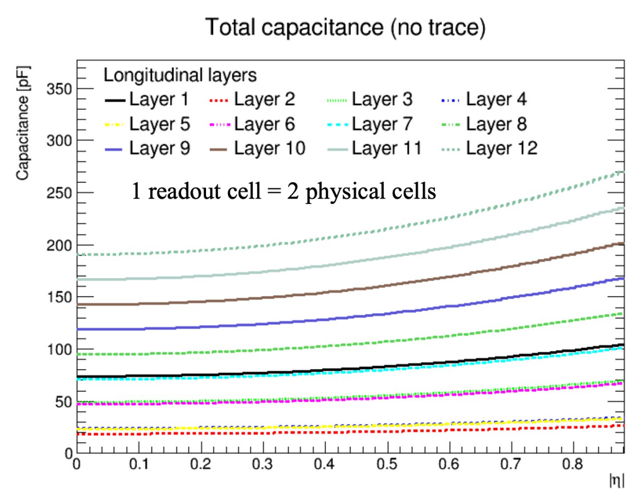


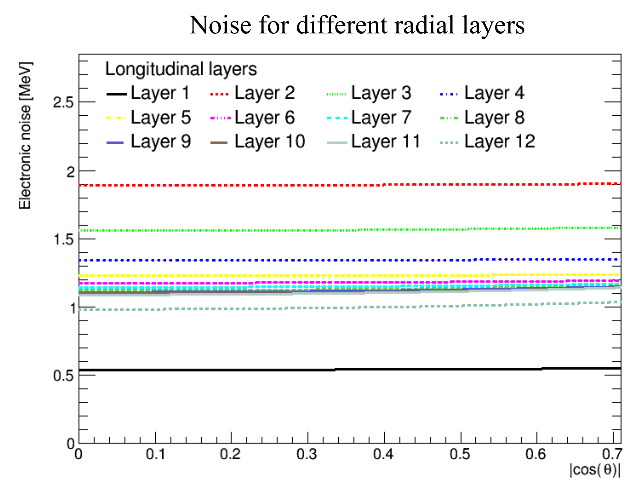



# Noise

- Noise depends on many factors
  - Detector capacitance, signal extraction scheme, front-end electronics, etc...
  - **Estimated outside of the main software** framework: Finite Element Method tools (Ansys) + analytical implementation (Mathematica)
  - Stored in a rootfile, per longitudinal layer and as a function of polar angle
- Introduced in the simulation by NoiseCaloCellsFromFileTool k4RecCalorimeter
  - Random number from Gaussian whose width is taken from the rootfile (layer/Θ dependent)



# Clustering

- Three clustering algorithms available
  - CreateCaloClustersSlidingWindow
    - Simple sliding window with fixed size trying to find local maxima
  - CaloTopoCluster
    - Find seeds and iteratively collects neighboring cells in several steps of S/N thresholds
  - CLUE (currently only in 2D)
    - Energy density based algorithm

k4RecCalorimeter

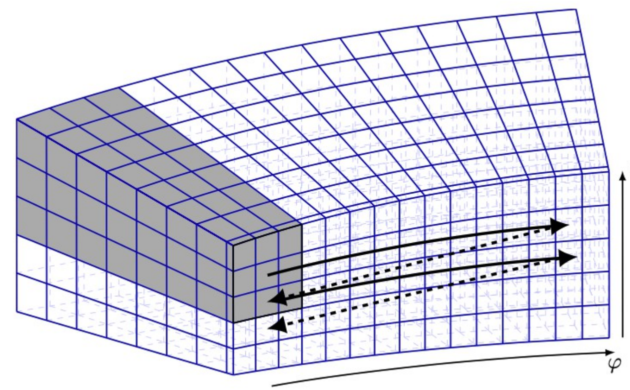
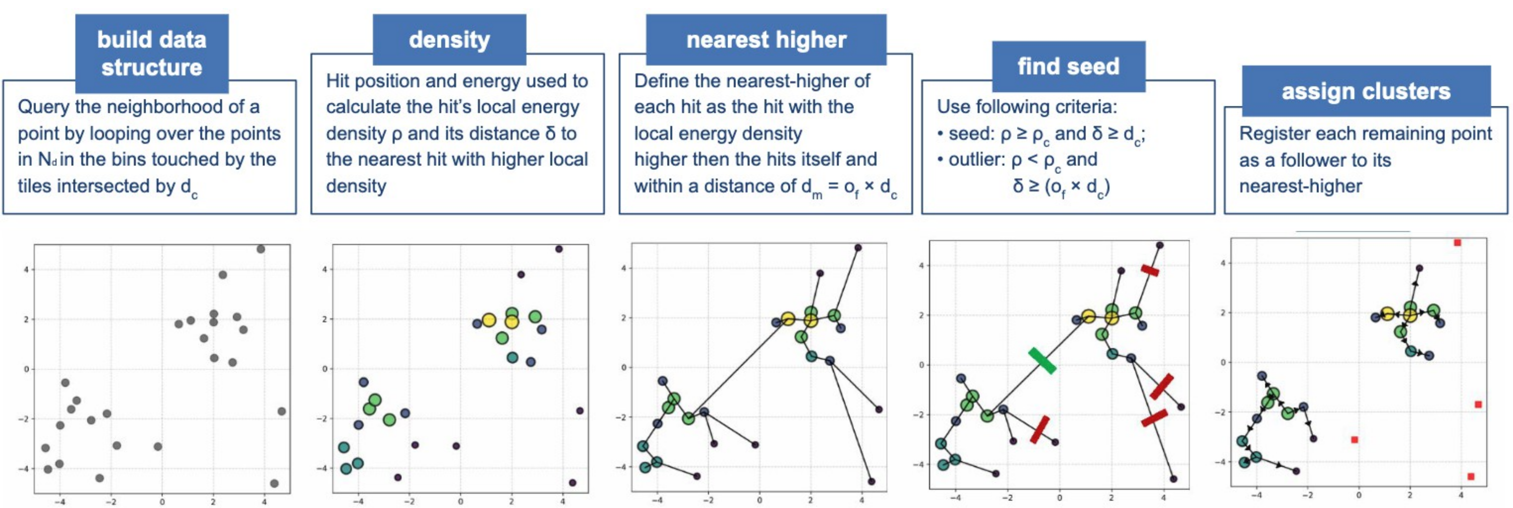
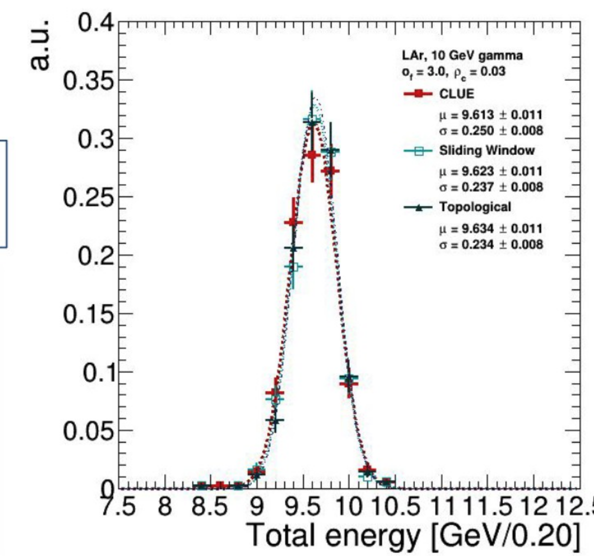



Figure 28: An illustration of the basic concept of the sliding window algorithm. A window of fixed size (here $N_\eta^{seed} \times N_\varphi^{seed} = 3 \times 3$) is moved across the tower grid.

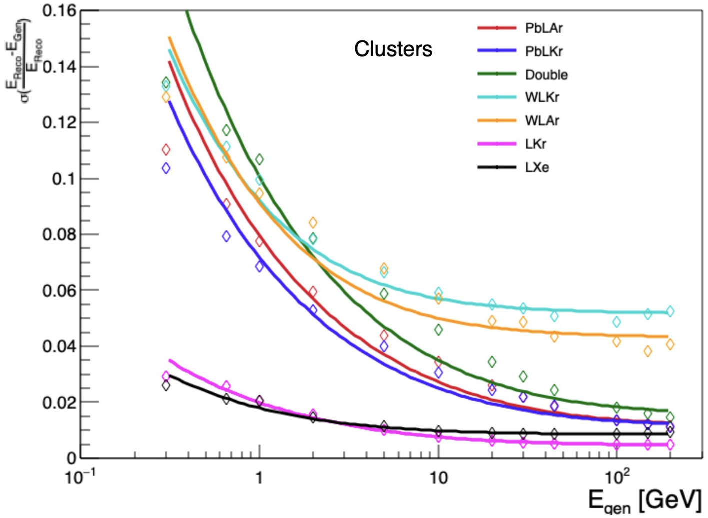


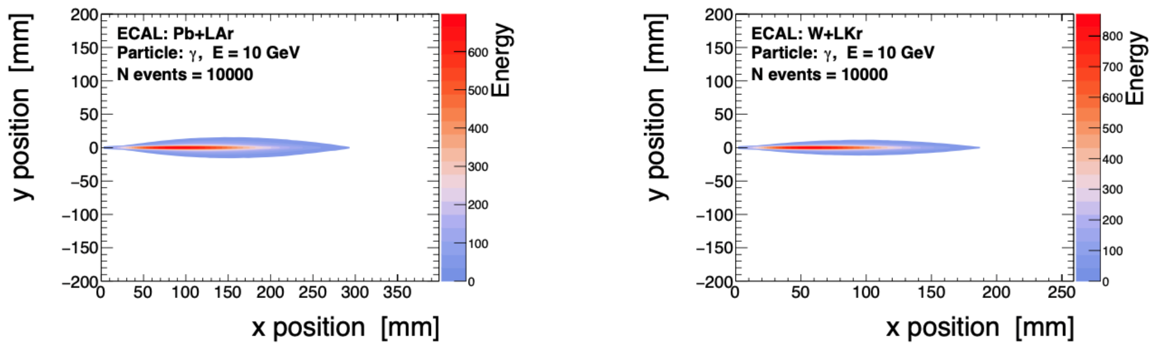
# Performance results

- Example of performance results produced recently with FCC-ee LAr ECAL SW

Energy resolution for **different absorbers and noble liquids**

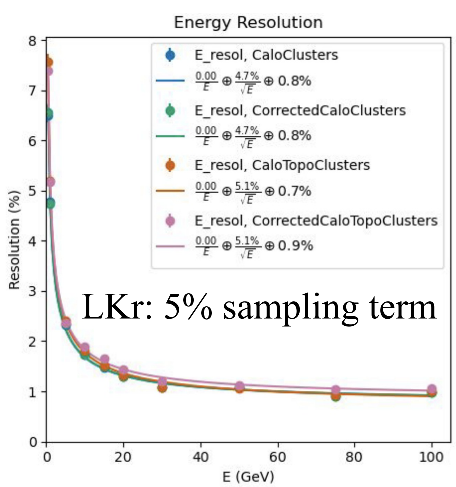



**Moliere Radius** comparison between Pb + LAr and W + LKr

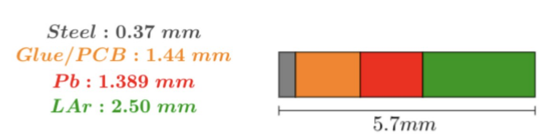


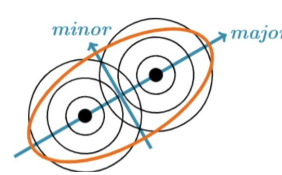

$R_M = 41$ mm $R_M = 27$ mm

**Trapezoidal absorbers** (cst sampling fraction per layer)




**τ final state categorization** confusion matrix ($\pi^0$ count)

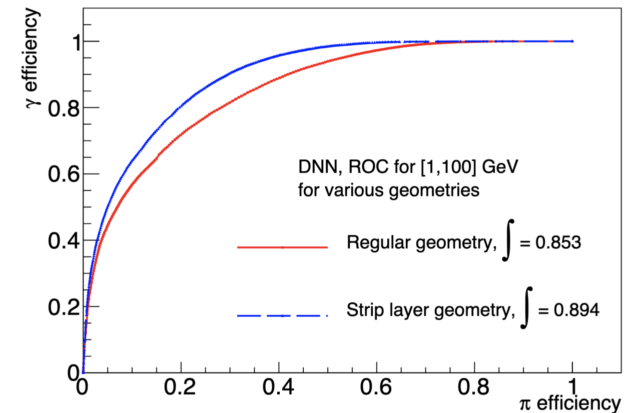


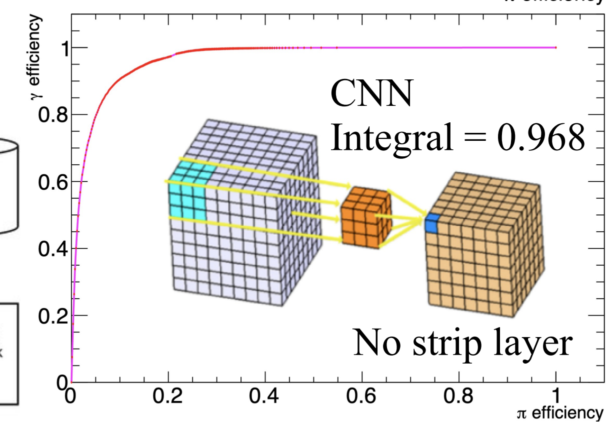



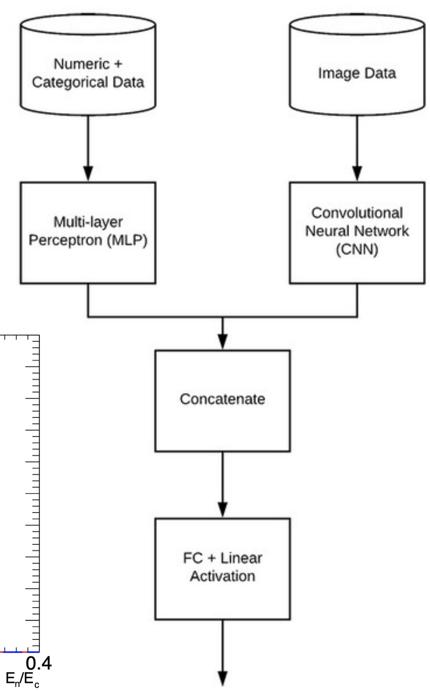

| Recon → / Gen ↓ | $\pi^\pm \nu$ | $\pi^\pm \pi^0 \nu$ | $\pi^\pm 2\pi^0 \nu$ | $\pi^\pm 3\pi^0 \nu$ | $\pi^\pm 4\pi^0 \nu$ |
|---|---|---|---|---|---|
| $\pi^\pm \nu$ | **0.9560** | 0.0425 | 0.0010 | 0.0003 | 0.0002 |
| $\pi^\pm \pi^0 \nu$ | 0.0374 | **0.9020** | 0.0586 | 0.0016 | 0.0002 |
| $\pi^\pm 2\pi^0 \nu$ | 0.0090 | 0.1277 | **0.7802** | 0.0808 | 0.0022 |
| $\pi^\pm 3\pi^0 \nu$ | 0.0036 | 0.0372 | 0.2679 | **0.5972** | 0.0910 |

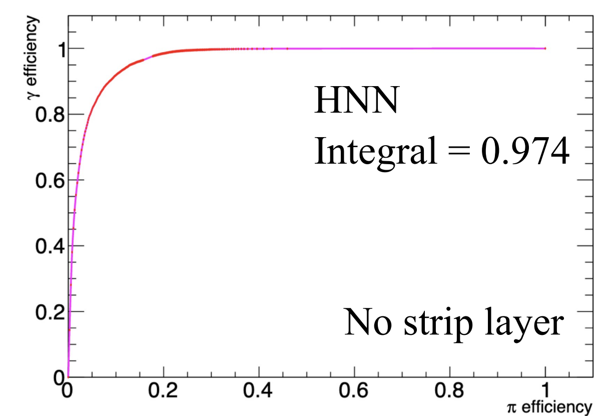
# Particle Identification

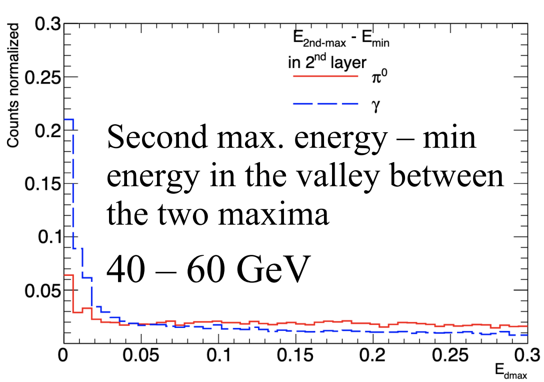
- $\pi^0/\gamma$ separation studied with different MVA and geometries
  - $\pi^0$ and $\gamma$ particle gun, 100 k events each, [1 – 100] GeV uniformly distributed in $\Phi$ and $\theta$, with and without strip layer
  - DNN with ~15 variables
    - No loss of perf. w/ one training for the whole energy range w.r.t. energy specific trainings (parametrized DNN with $E_{Cluster}$ )
  - 3D Convolutional NN (CNN) with 10 x 10 x 12 window
    - Tremendous improvement w.r.t. DNN
  - Hybrid NN (**HNN**) with both DNN and CNN
    - **95% $\gamma$ efficiency for 10% $\pi^0$ contamination** for the whole energy range (**no strip layer** + baseline **conservative** geometry)

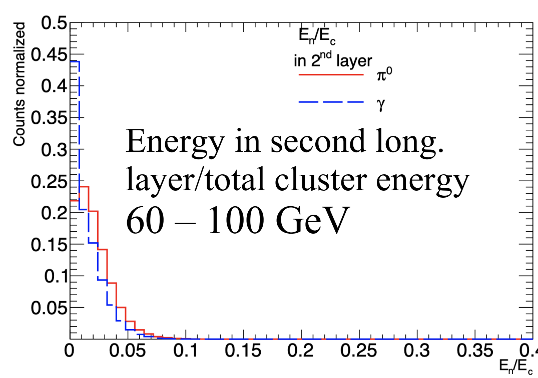


# Summary

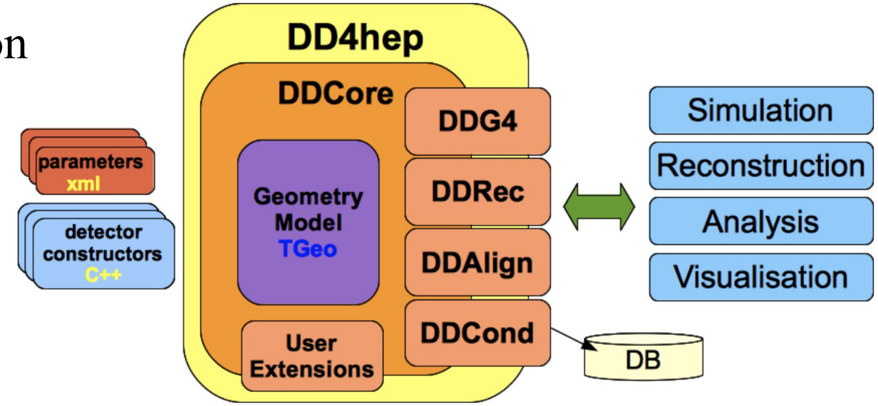
- The FCC software full simulation is under active development
- Most core components are available
- CLD can already be fully simulated and reconstructed through ddsim + MarlinWrapper
- IDEA is being implemented in DD4hep
- Noble Liquid ECAL available for performance studies through Gaudi
  - Include all the dominant effect (calibration, upstream material correction, noise)
  - Currently implementing missing detectors to have a full detector concept
- There is a lot left to do!
- Working on detector simulation gives the opportunity to learn both about software and detector physics
  - You are more than welcome to join the effort!

Thank you!

# Additional material

# DD4hep

- DD4hep: generic detector description supporting the full life cycle of the experiment
  - Conceptualization, optimization, construction and operations
- Complete description
  - Geometry readout, alignment, calibration, …
- DD4hep uses ROOT TGeo as geometry implementation
  - Output format/interfaces: Geant4, GDML, easily extensible
- From the user perspective
  - C++ for generic geometry structure construction
  - XML configuration for detector parameters



# Noble Liquid/Absorber study

| Absorber | Liquid | Gap size [mm] | Absorber size [mm] | Phi bins | Radial extend [mm] | Radial length 22 X0 [mm] |
|---|---|---|---|---|---|---|
| **Pb** | LAr | 1.239 * 2 | 1.8 | 1536, 768, 512, 384, 256 | 400 | |
| | LAr | 3.079 * 2 | 3.8 | 768 | 400 | |
| | LKr | 1.239 * 2 | 1.8 | 768 | 400 | ~337.5 |
| **W** | LKr | 1.239 * 2 | 1.8 | 768 | ~207.5 | |
| | LAr | 2.156 * 2 | 1.8 | 576 | ~323.9 | |
| **none** | LKr (homo) | ~4.2 | 0.001 | 768 | ~1034 | |
| | LXe (homo) | ~4.2 | 0.001 | 768 | ~647.5 | |

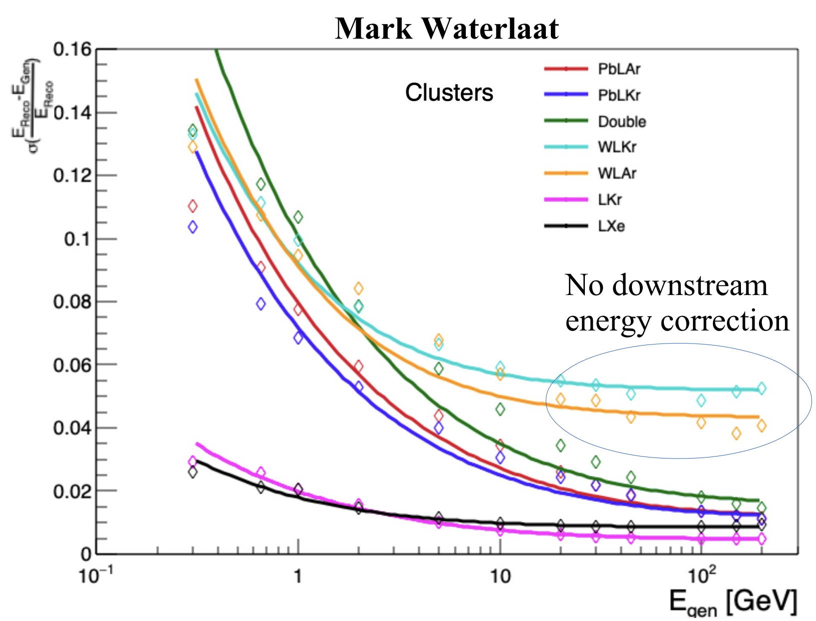
| | Avg sampling fraction |
|---|---|
| **Pb + LAr baseline** | 0.17 |
| **Pb + LKr** | 0.23 |
| **Pb + LAr double** | 0.17 |
| **W + LKr** | 0.15 |
| **W + LAr** | 0.16 |
| **LKr** | 0.97 |
| **LXe** | 0.97 |

Clusters

| | A/E | B/sqrt(E) | C |
|---|---|---|---|
| **Pb + LAr** | 0 | 0.079 | 0.011 |
| **Pb + LKr** | 0 | 0.071 | 0.011 |
| **Double** | 0 | 0.099 | 0.015 |
| **W + LKr** | 0 | 0.075 | 0.052 |
| **W + LAr** | 0 | 0.086 | 0.041 |
| **LKr** | 0 | 0.019 | 0.005 |
| **LXe** | 0 | 0.016 | 0.008 |

Cells

| | A/E | B/sqrt(E) | C |
|---|---|---|---|
| **Pb + LAr** | 0 | 0.077 | 0.021 |
| **Pb + LKr** | 0 | 0.070 | 0.050 |
| **Double** | 0 | 0.098 | 0.027 |
| **W + LKr** | 0 | 0.083 | 0.050 |
| **W + LAr** | 0 | 0.085 | 0.041 |
| **LKr** | 0.004 | 0 | 0.008 |
| **LXe** | 0 | 0.007 | 0.010 |



# Noise for Charge Preamp & CR²-RC²

- **Series noise:** Case of charge preamp and CR²-RC² shaper
  - ideal transmission line of length *L* with $t_d = L/v$ the line delay
    - no attenuation, no skin effect, but these effects are small (negligible) at cryogenic temperatures
  - charge preamplifier, CR²-RC² shaper (different to ATLAS LAr!),
  - see NIM A330 (1993) 228-242

$$V_n^2 = \int_0^\infty \frac{e_n^2}{|R_0 + Z|^2} \frac{1}{\omega^2 C_f^2} |H(i\omega)|^2 \frac{d\omega}{2\pi}$$

- **Similar procedure for parallel noise** (not shown here)

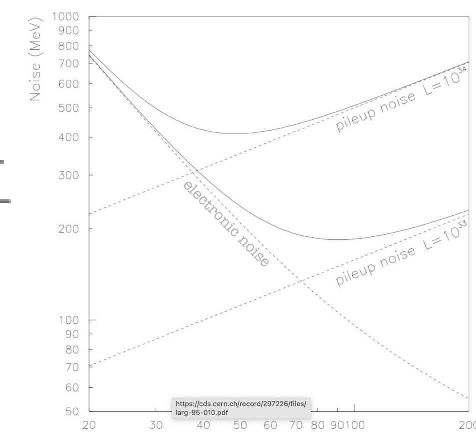
$$V_n^2 = \int_0^\infty \frac{e_n^2}{|R_0 + Z|^2} \frac{1}{\omega^2 C_f^2} |H(i\omega)|^2 \frac{d\omega}{2\pi}$$

with

$$Z = \frac{iR_0 \tan(\omega t_d) - \frac{i}{\omega C_d}}{\frac{\tan(\omega t_d)}{R_0 \omega C_d} + 1}$$

$$V_n^2 = \frac{\tau^4 C_d^2 e_n^2}{2\pi \tau_p^2 C_F^2} \int_0^\infty \frac{\omega^2 \left(\tau_p \omega \cos(\omega t_d) + \sin(\omega t_d)\right)^2}{\left(\tau^2\omega^2 + 1\right)^4 \left(\tau_p^2 \omega^2 + 1\right)} d\omega$$

$$\tau_p = R_0 C_d$$

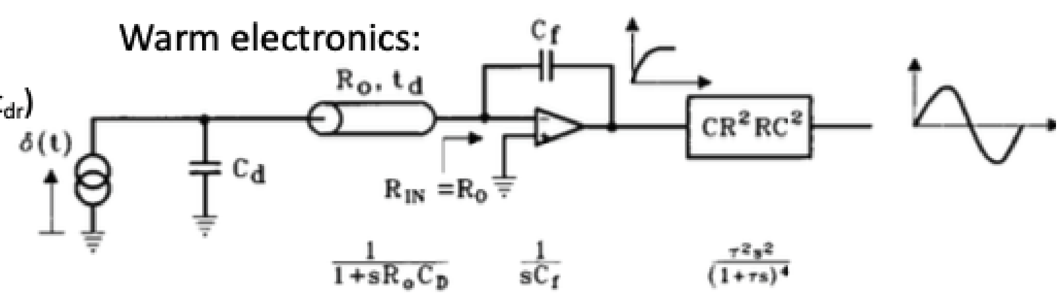


ATL-LARG-95-010

- This series noise needs to be normalised to signal response V(x) of unit charge $Q_0$:
  - either Dirac delta-function $Q_0\delta(t)$,
  - or triangular signal ($t_{dr}$ is the e⁻-drift time): $2Q_0/t_{dr}(1 - t/t_{dr})$

$$\text{ENC} = Q_0 \frac{V_n}{\max|_x(V(x))}$$

Warm electronics:



# Readout Electrodes

- Horizontal axis expanded by a factor 10