Simulation and tools for the IDEA detector concept

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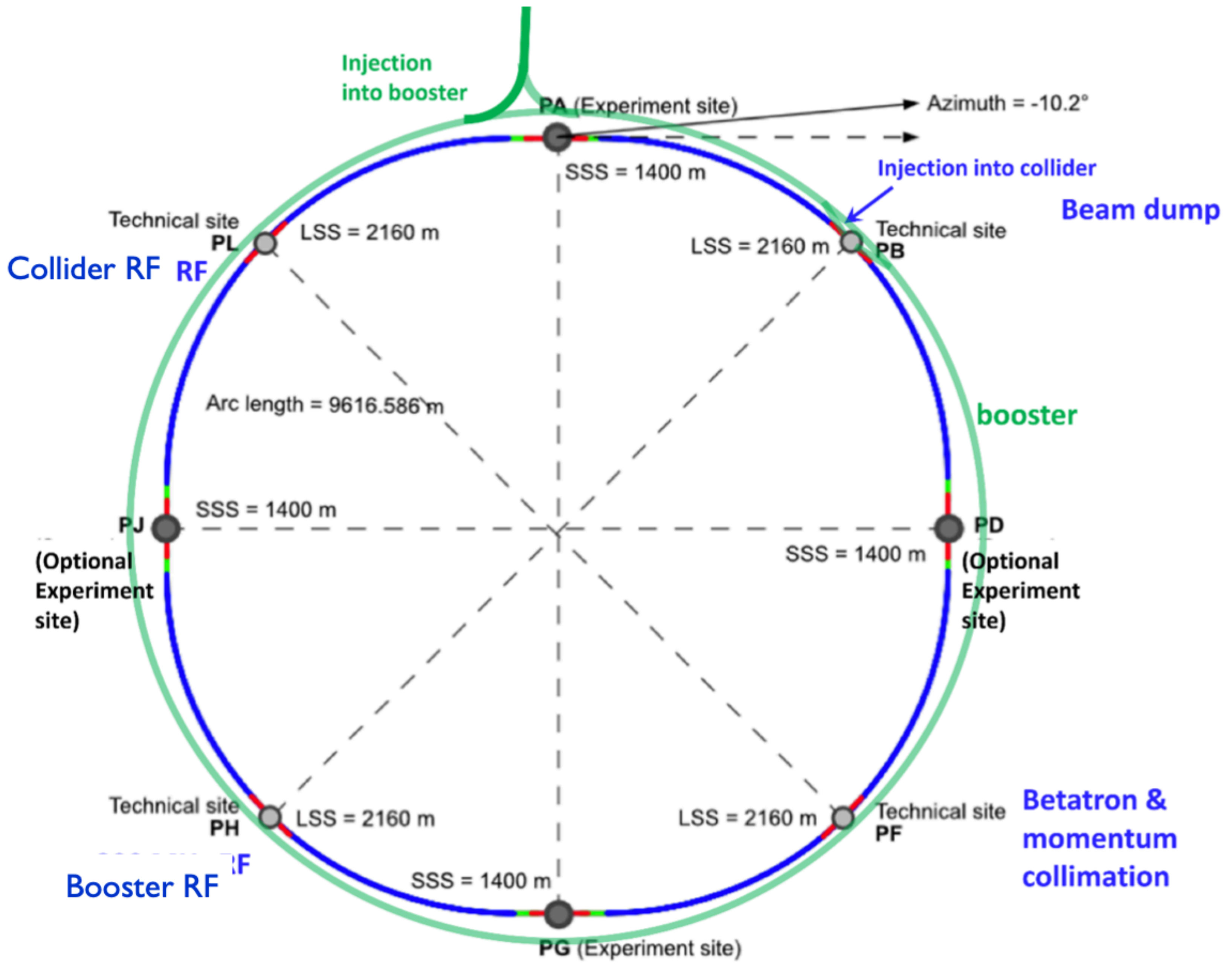
SEZIONE DI ROMA TRE

Motivations

WHY NEW COLLIDER(S) / EXPERIMENTS?

- We need to extend mass & interaction reach for those phenomena that SM cannot explain:
  - Dark matter
    - SM particles constitute only 5% of the energy of the Universe
    - Baryon Asymmetry of the Universe
  - Neutrino Masses
    - Why so small? Dirac/Majorana? Heavier right-handed neutrinos? At what mass?



HOW DO WE TACKLE THESE OPEN QUESTIONS?
WHICH TYPE OF COLLIDER?

- **Energy frontier**: direct access to new resonances
- **Precision frontier**: indirect evidence of deviations at low and high energy

FCC integrated project offers an appropriate answer to these needs

FCCee will be an unique tool for high precision measurements

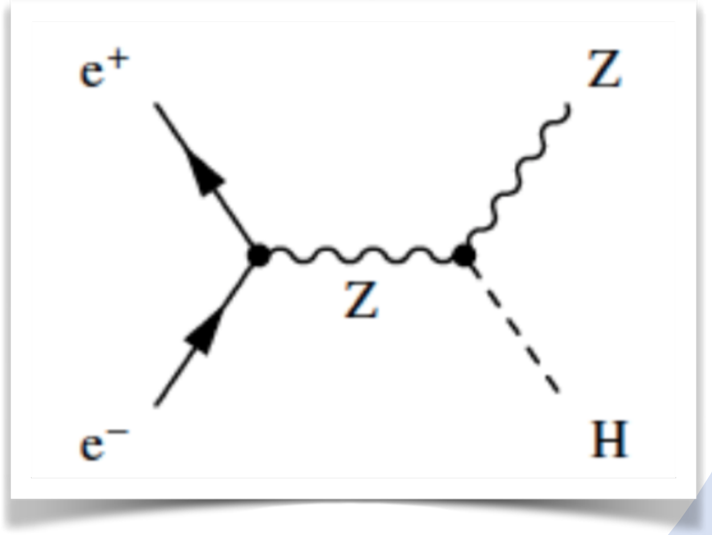
From TDR

15 years programme

						$\sqrt{s}$ uncertainty
ZH maximum	$\sqrt{s}$ ~ 240 GeV	3 years	10^6	$e^+e^- \to ZH$	Never done	2 MeV
$t\bar{t}$ threshold	$\sqrt{s}$ ~ 365 GeV	5 years	10^6	$e^+e^- \to t\bar{t}$	Never done	5 MeV
Z peak	$\sqrt{s}$ ~ 91 GeV	4 years	5×10^{12}	$e^+e^- \to Z$	LEP x 10^5	< 50 keV
WW threshold+	$\sqrt{s} \geq$ 161 GeV	2 years	> 10^8	$e^+e^- \to W^+W^-$	LEP x 10^3	< 200 keV
[s-channel H	$\sqrt{s}$ = 125 GeV	5? years	~5000	$e^+e^- \to H_{125}$]	Never done	< 100 keV

Clean experimental environment

- High efficiency trigger or trigger-less readout
- Low radiation levels, compared to hadronic machines



Physics and detector requirements - FCCee

"Higgs Factory" Programme

- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \rightarrow H$ @ $\sqrt{s}$ = 125 GeV

DETECTOR REQUIREMENTS

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of 30%/$\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,...
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale

DETECTOR REQUIREMENTS

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. Γ_{had}/Γ_ℓ) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6}: stability of $\sqrt{s}$ meast.

Physics and detector requirements - FCCee

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Ultra Precise

Measurement of EW
improvement in *statis*

- 5×10^{12} Z and 10^{8} W
  - m_Z, Γ_Z, Γ_{inv}, si
- 10^{6} tt
  - m_{top}, Γ_{top}, EW

Indirect sensitivity to

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z resonance

QCD + EW programme

- Particle-Flow reconstruction
- Lepton and jet angular and energy resolution ; Lepton ID

More case studies will lead to more detector requirements

Tau physics programme

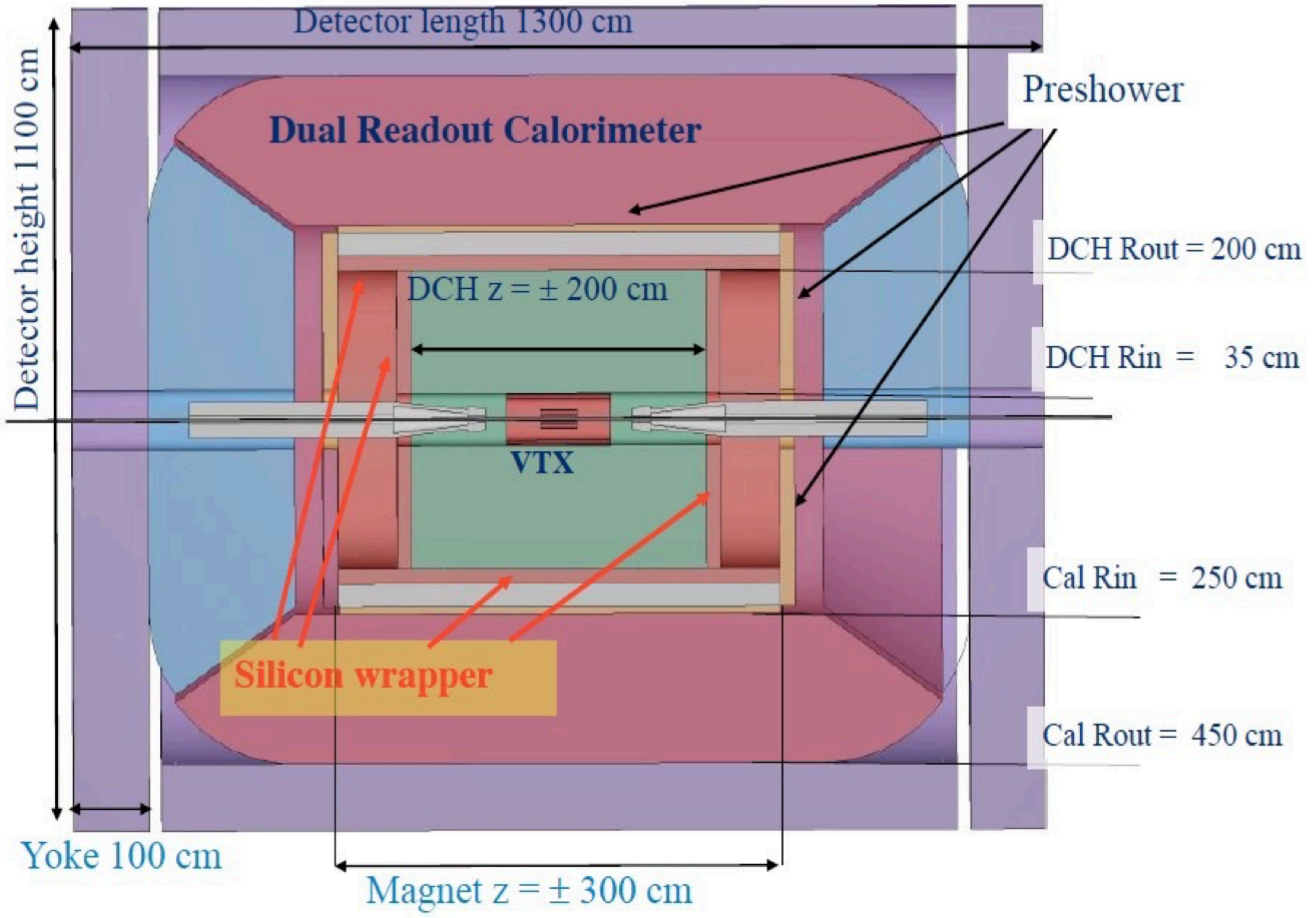
- Momentum resolution
  Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  BR measurements, EWPOs, spectral functions

Rare/BSM processes, e.g. Feebly Coupled Particles

- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

The IDEA detector at FCCee collider

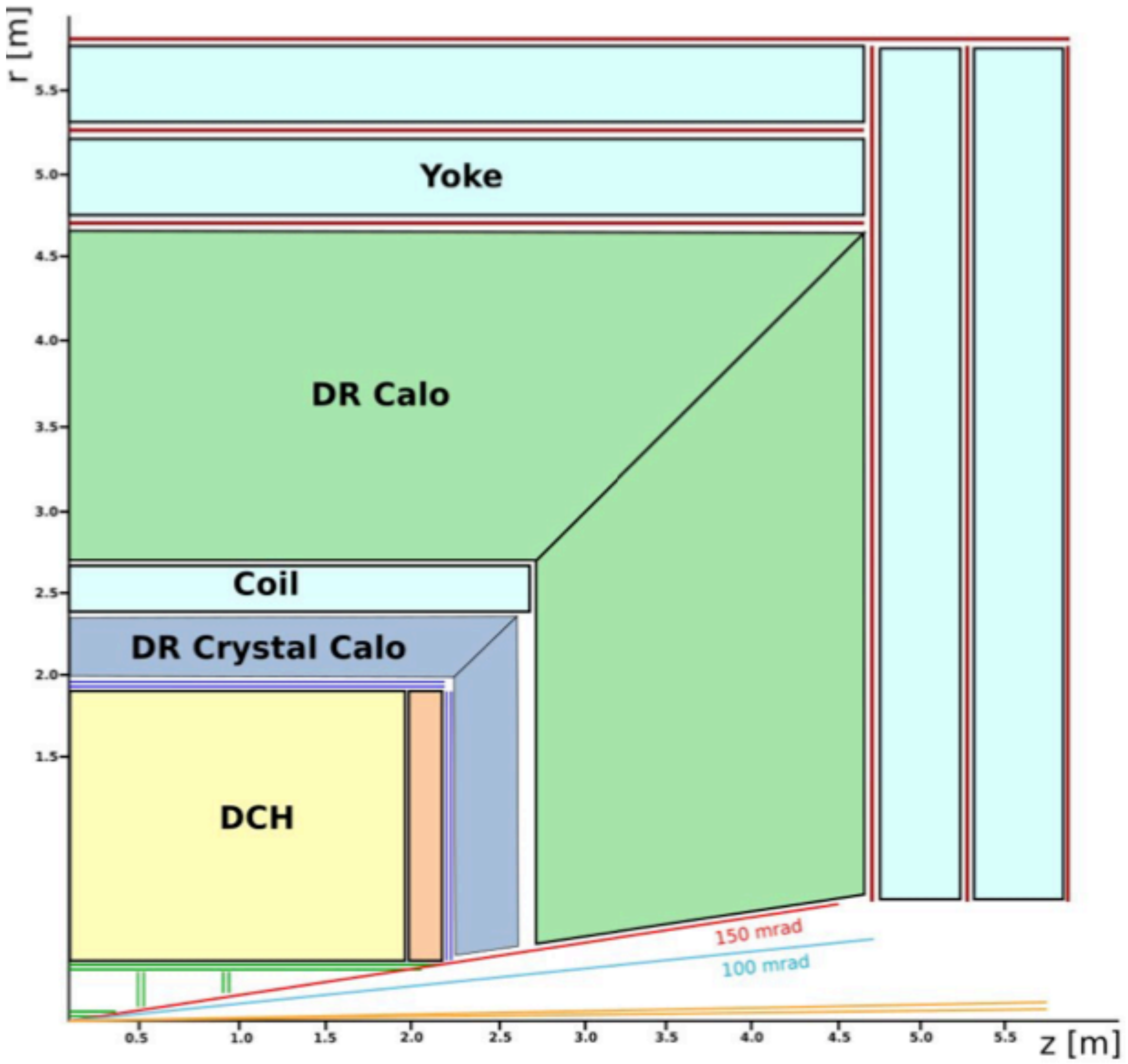
- A silicon pixel **vertex detector**
- A large-volume extremely-light (*90% He – 10% iC4H10*) drift wire chamber for **tracking**
- A layer of silicon micro-strip detectors
- **Magnetic field** provided by a thin low-mass superconducting solenoid coil (optimized at 2 T)
- **Calorimetry**:
  - A dual read-out calorimeter
  - If ECAL crystal calorimeter, no preshower detector needed in this case
- **Muon** chambers inside the magnet return yoke



Simulation and tools for the IDEA detector concept

IDEA Simulation Overview

- A fast simulation in **DELPHES** is fully operational
  - We improved the DELPHES fast simulation adding many features to perform design studies
  - Includes track smearing, PID, jet clustering, flavour tagging... Versatile and extremely fast!
- **GEANT4:** the full simulation is based on GEANT4.
  The description of the IDEA detector is almost complete
  - Expected performances for calo and tracker are very good and in line with IDEA requirements
  - The cluster counting approach for the drift chamber is fully operational



Simulation and tools for the IDEA detector concept

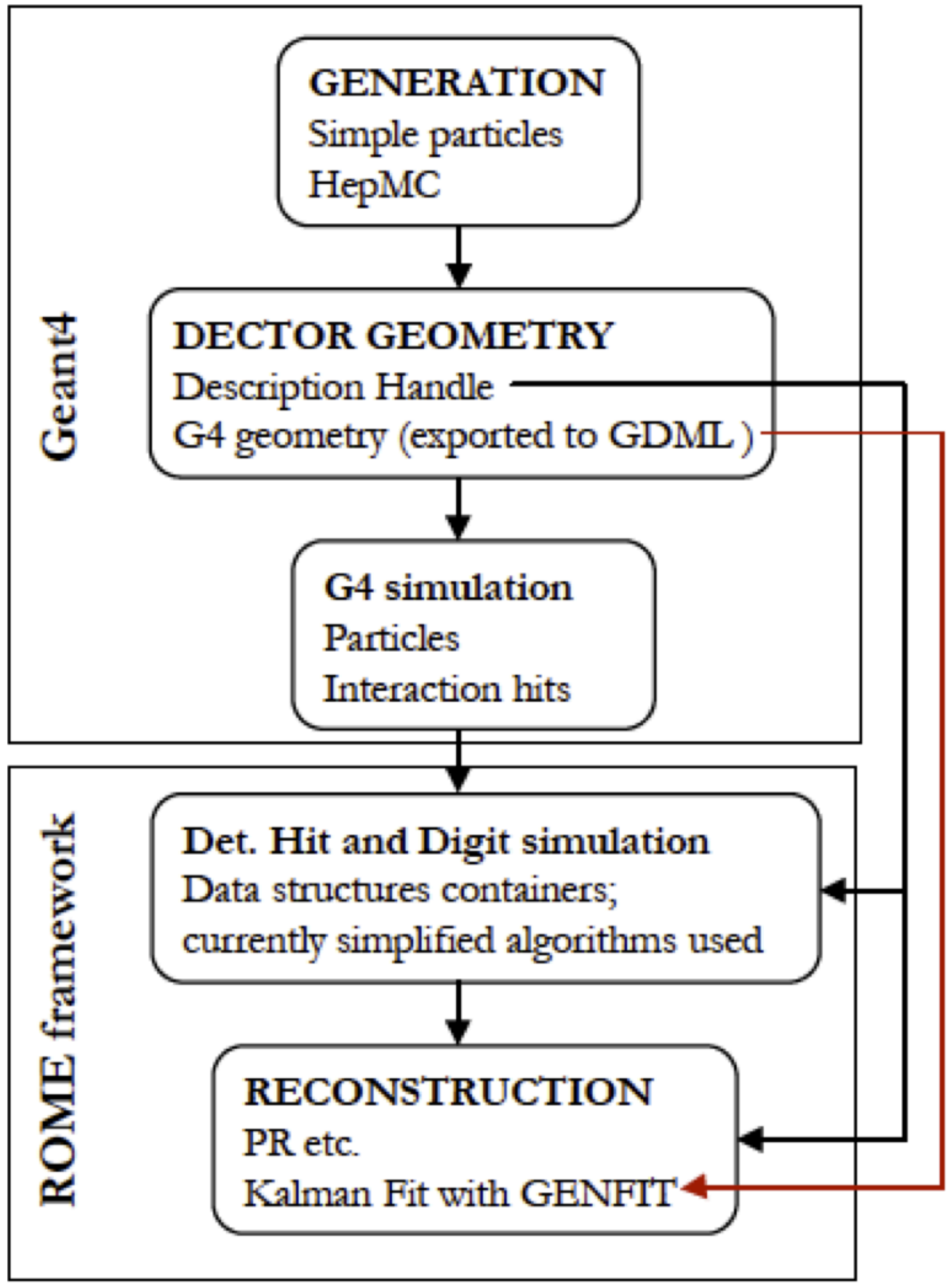
Full detector simulation

There are two options for the geometry description

- **GEANT4**
  - Classic simulation software
  - Standalone simulation fully interfaced to **key4hep**. Full simulation, almost fully implemented
- **DD4hep** is a tool for the description of the detector geometry, part of the new software ecosystem called **key4hep**, that allows to plug and play different configurations (for instance with and without Crystal ECAL options) in a simpler way
  - A more modern framework
  - Can be used also for trigger, reconstruction, alignment... Full simulation, implementation in progress
  - Full description of the DR calorimeter available
  - Drift chamber is ready; a first test of synchrotron radiation background for drift chamber to be expected very soon
- **key4hep**: software framework developed for experiments at future colliders *https://github.com/key4hep*

Key4HEP

- **GEANT4 is our starting point** and the standalone code was adapted for compilation on key4hep stack on CERN lxplus machines (source /cvmfs/sw.hsf.org/key4hep/setup.sh)
- **https://github.com/HEP-FCC/IDEADetectorSIM**



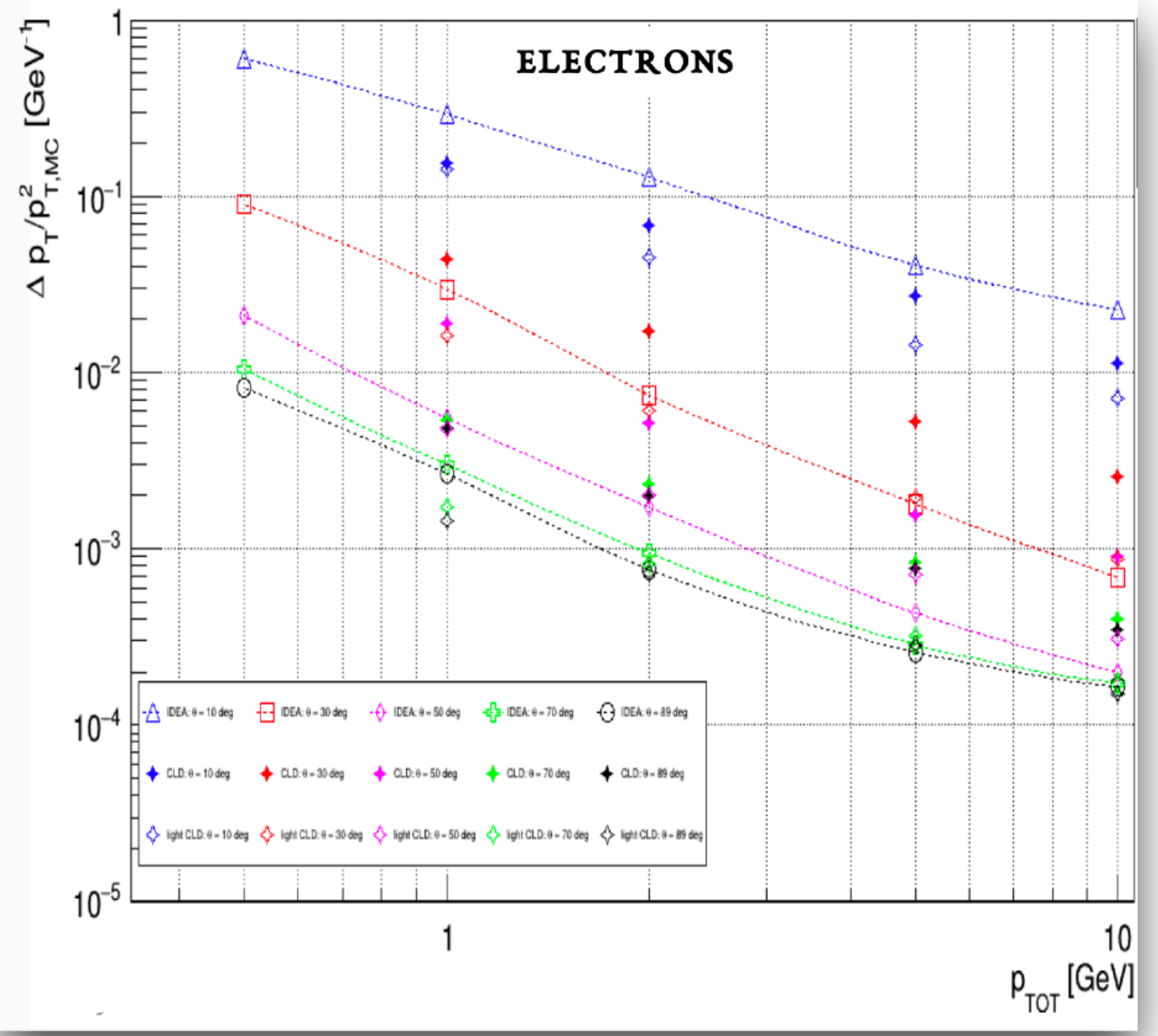
GEANT4 simulation - Tracking system

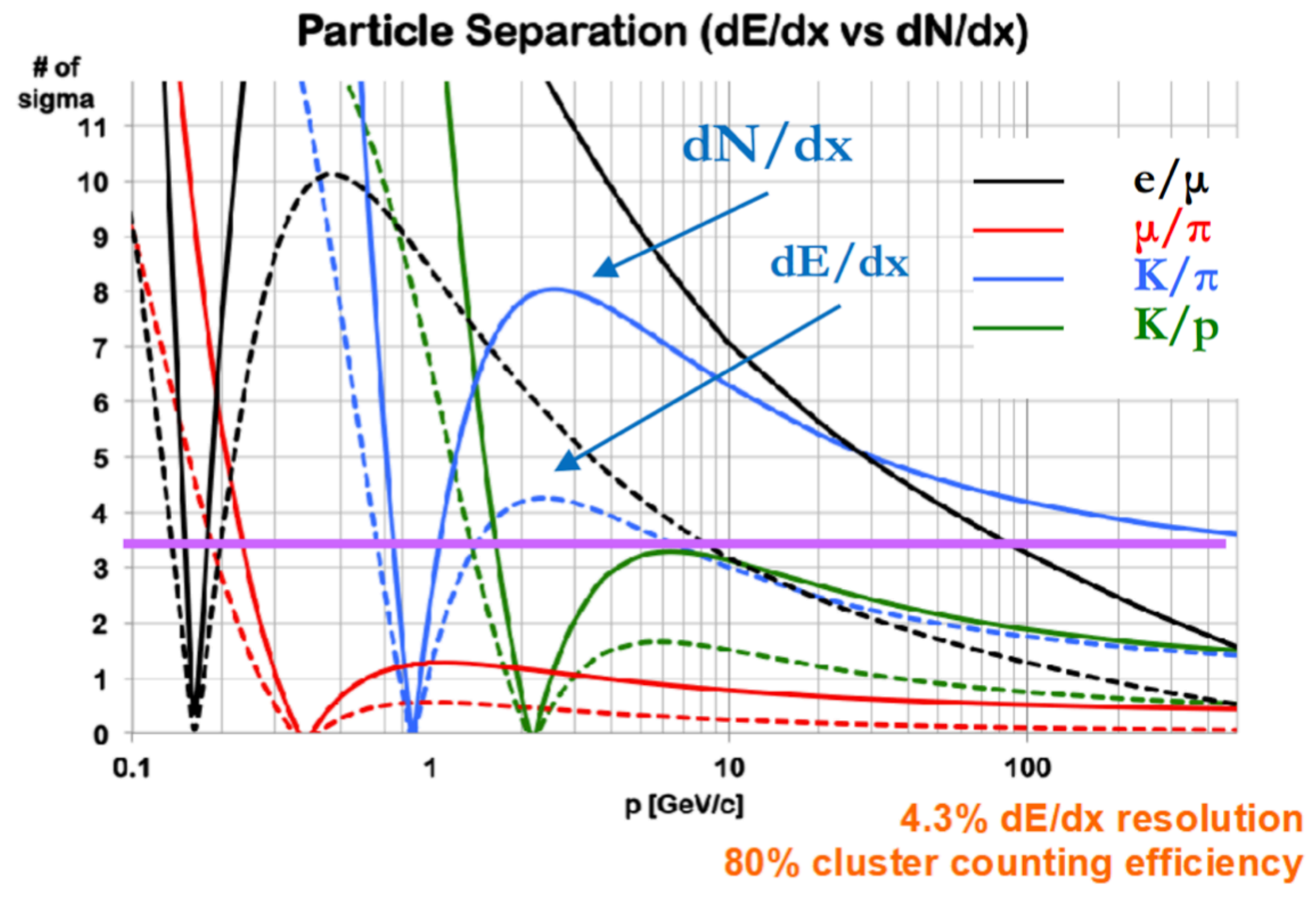
Benchmark geometry

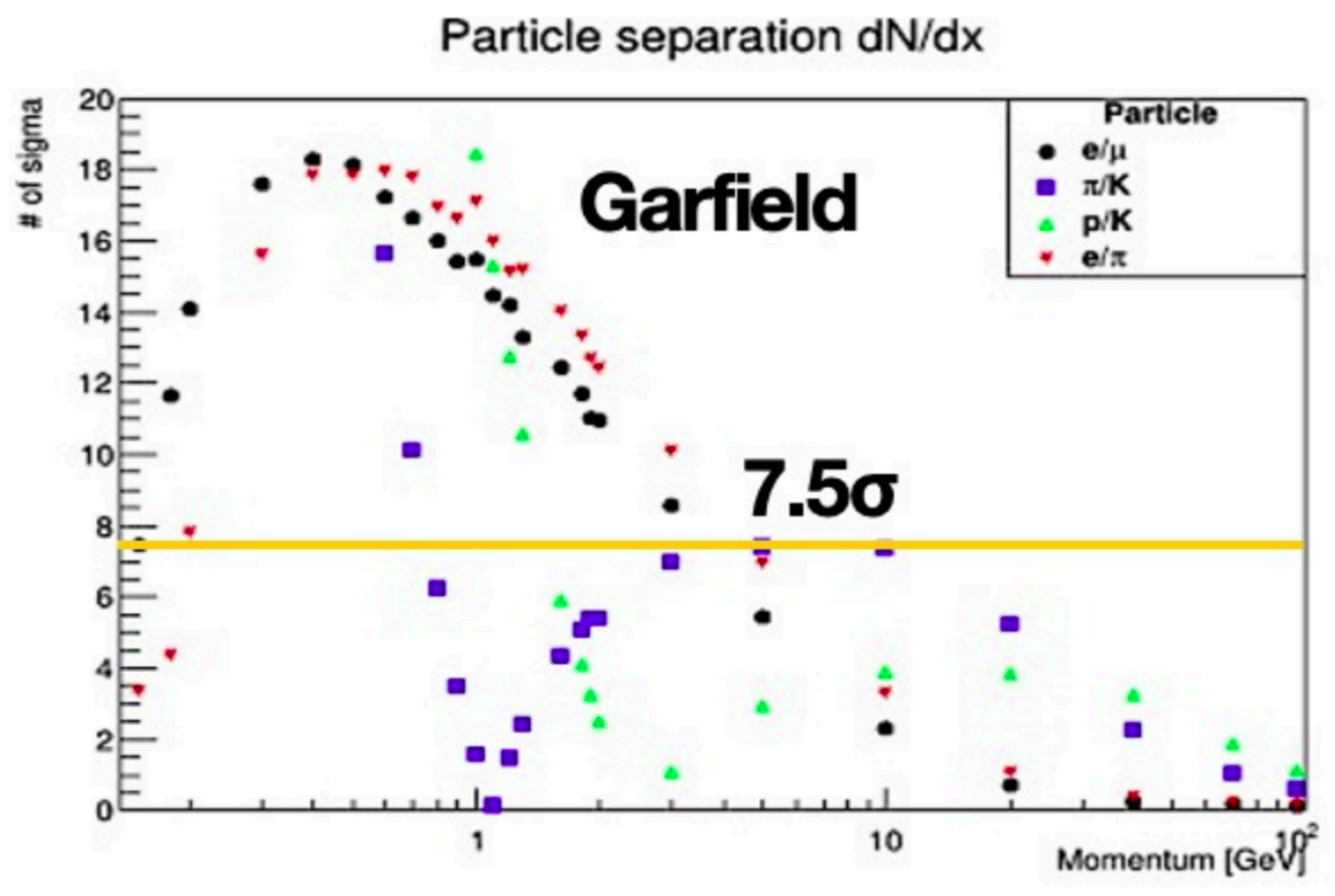
- Ultra light detector
- L = 400 mm
- R = 35÷200 cm
- Total thickness: 1.6% of X_0 at 90^O
- Tungsten wires dominant contribution
- 112 layers foreach 15^o azimuthal sector
- He based gas mixtures (90% He – 10% iC_4H_{10})
  - Ionization signals last few ns
  - Max drift time: 350 ns
    Fast readout (~GHz sampling)
    PID counting dN_{cl}/dx
  - # of ionization acts per unit length
  - PID w/ better resolution than dE/dx
    0.75 < p < 1.05 gap recoverable
    with timing layer
  - 100 ps enough for 3σ K/p

Expected performances

- Good p_T resolution, from ≈ 0.1% at low p_T up to 0.5% for p_T =100 GeV
- More than 99.5% of tracks are reconstructed with > 60% good hits
- PID with a cluster counting technique is under study by using simulations and beam-test data, see [Nicola's talk] at ECFA workshop





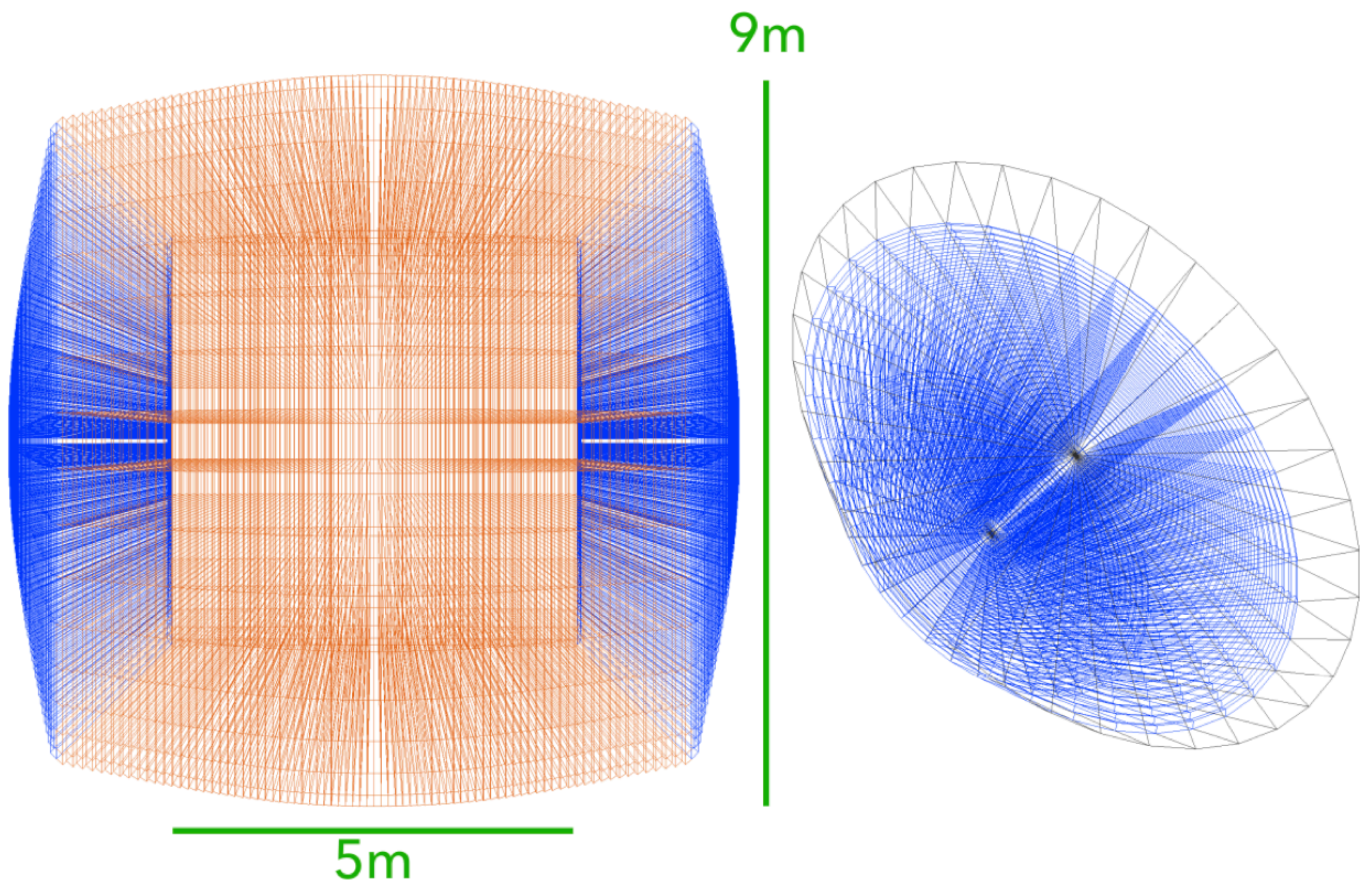


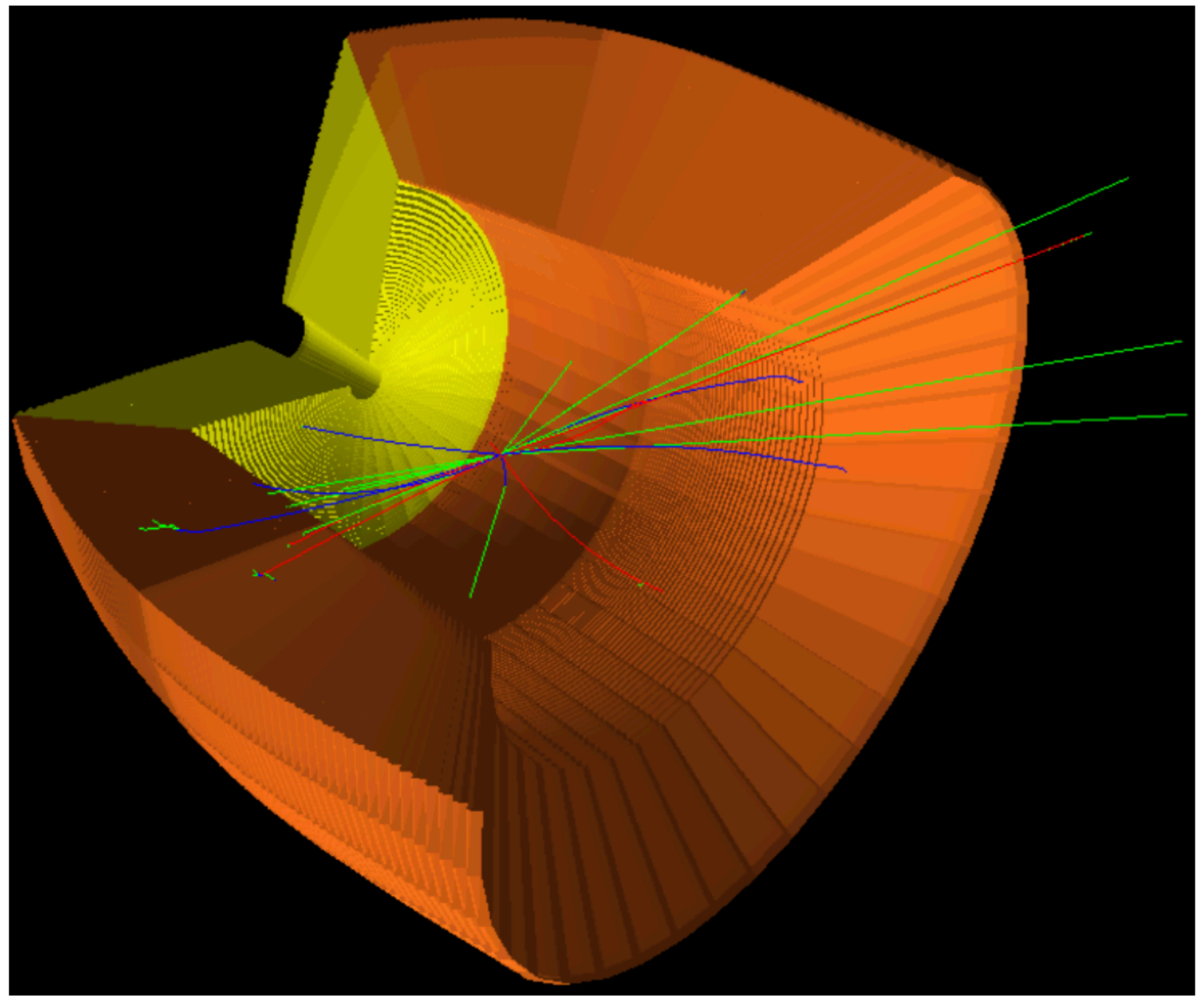
Simulation and tools for the IDEA detector concept

GEANT4 simulation - DR Calorimeter

A benchmark geometry

- 54000 Cu towers with high-granularity scintillating and Cherenkov fibers
- $\Delta\theta = 1.125°$, $\Delta\varphi = 10.0°$
- Theta coverage up to ~0.100 rad
- 36 rotations around the beam axis
- Inner diameter: 5 m
- Outer diameter: 9 m @ 90°

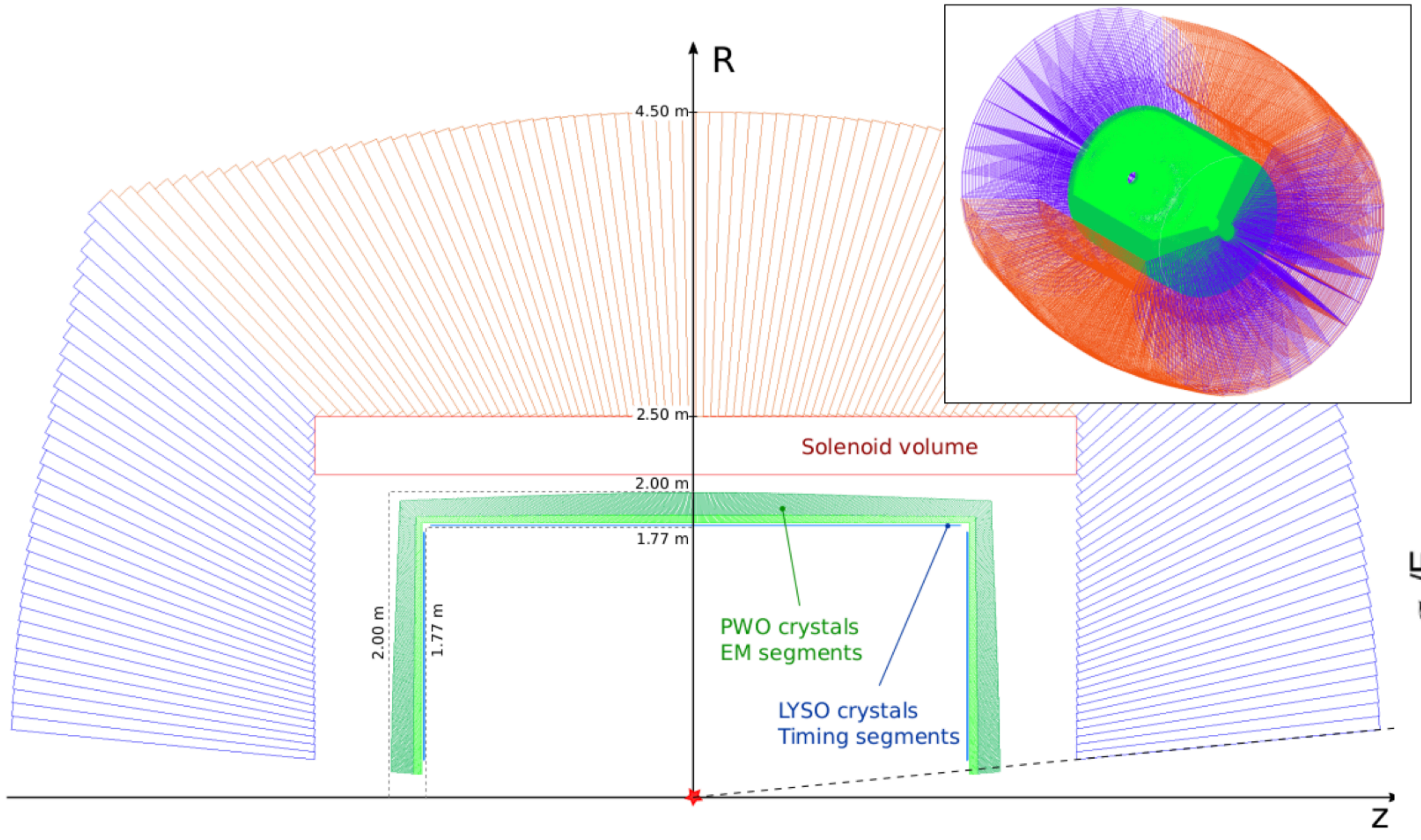




Expected performances

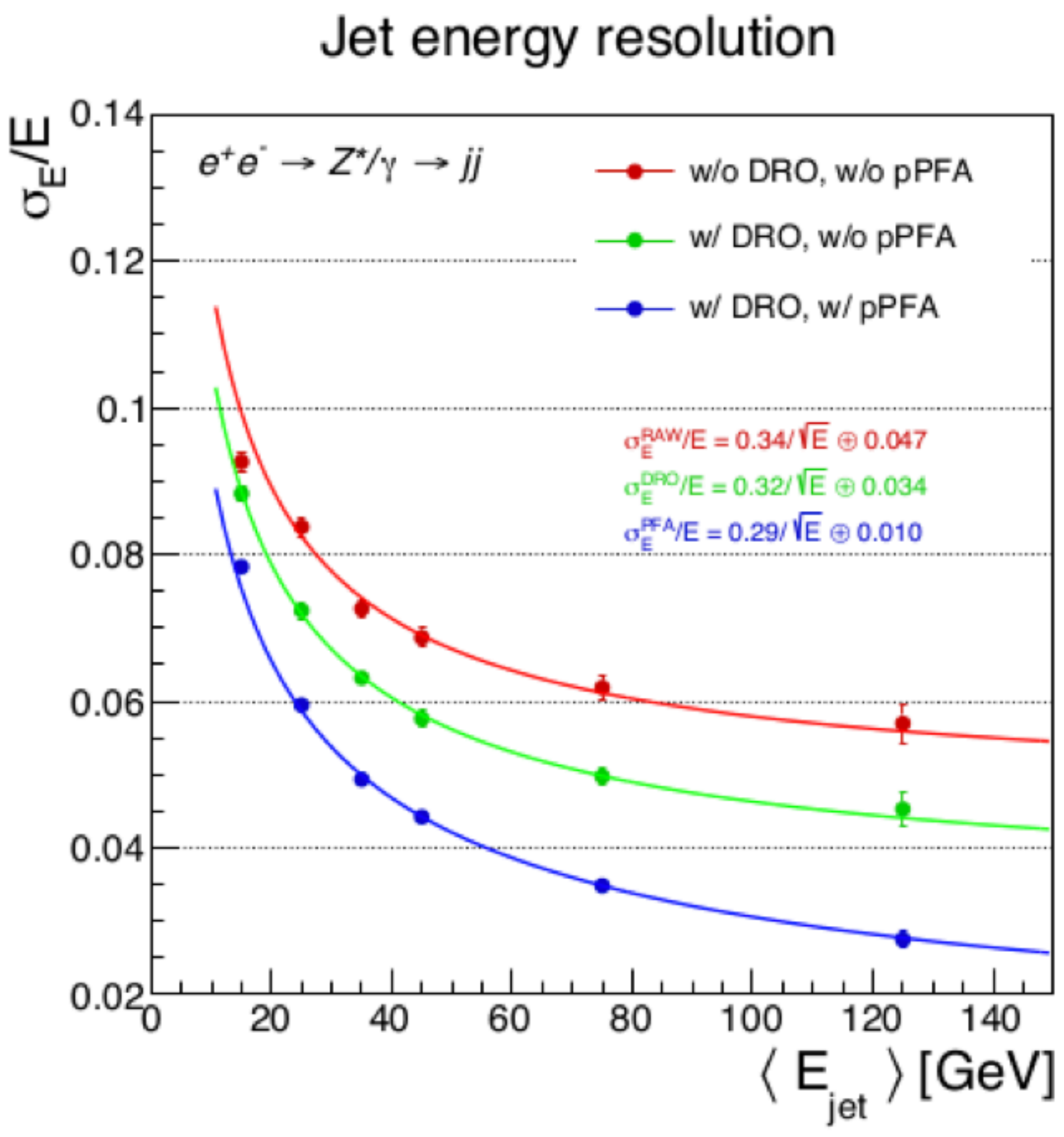
- 20% EM energy resolution
- 25-30% single-hadron energy resolution (also neutral)
- 5% jets energy resolution at 50 GeV
- < 1% linearity in FCCee energy ranges for e^-, γ, hadrons and jets

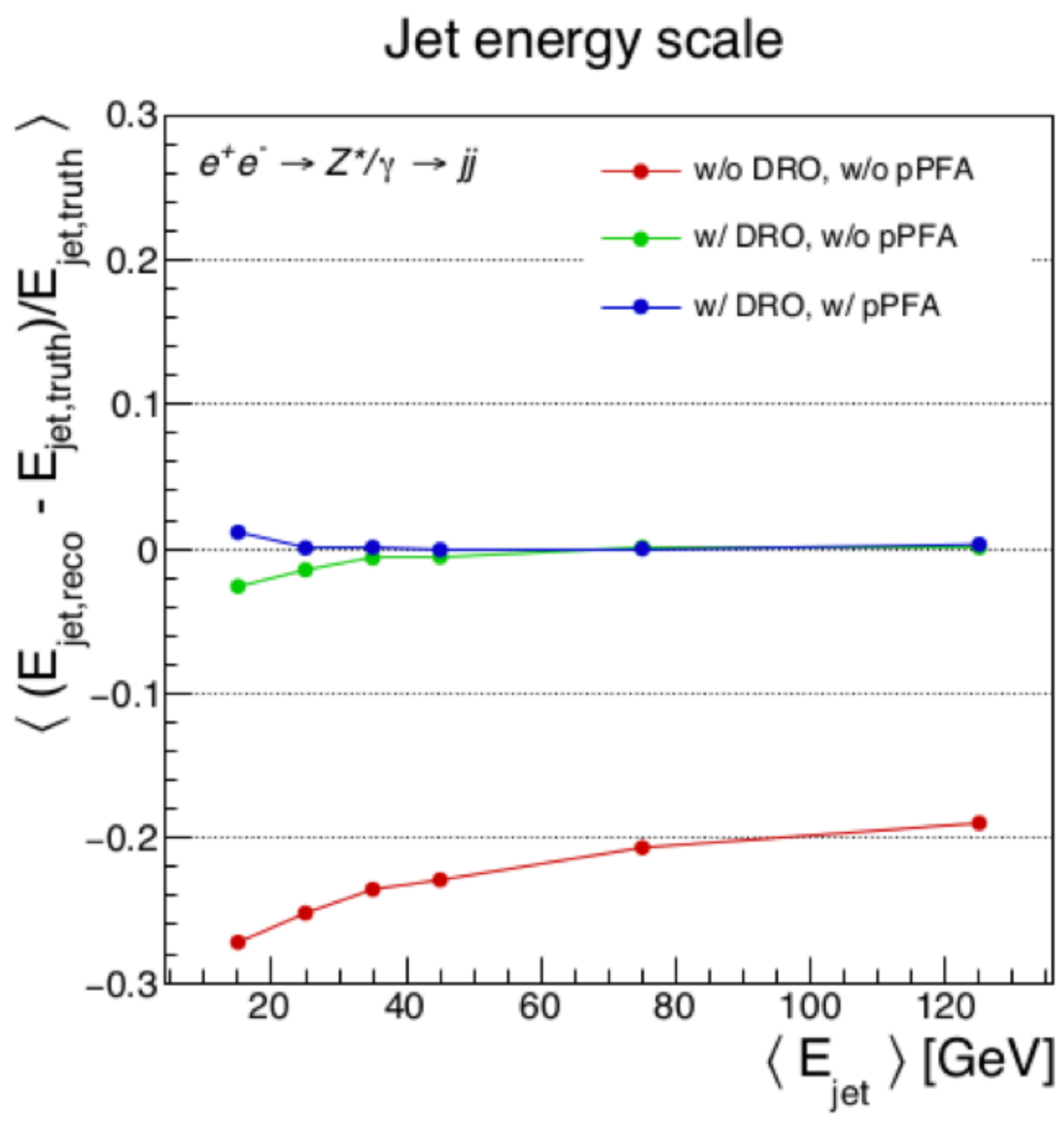
GEANT4 simulation - DR Calorimeter & crystals



- Integration of a crystal calorimeter option in the GEANT4 IDEA simulation:
  - Barrel crystal section inside solenoid 1x1 cm² PWO segmented crystals granularity
  - Radial envelope ≈ 1.8 − 2.0m

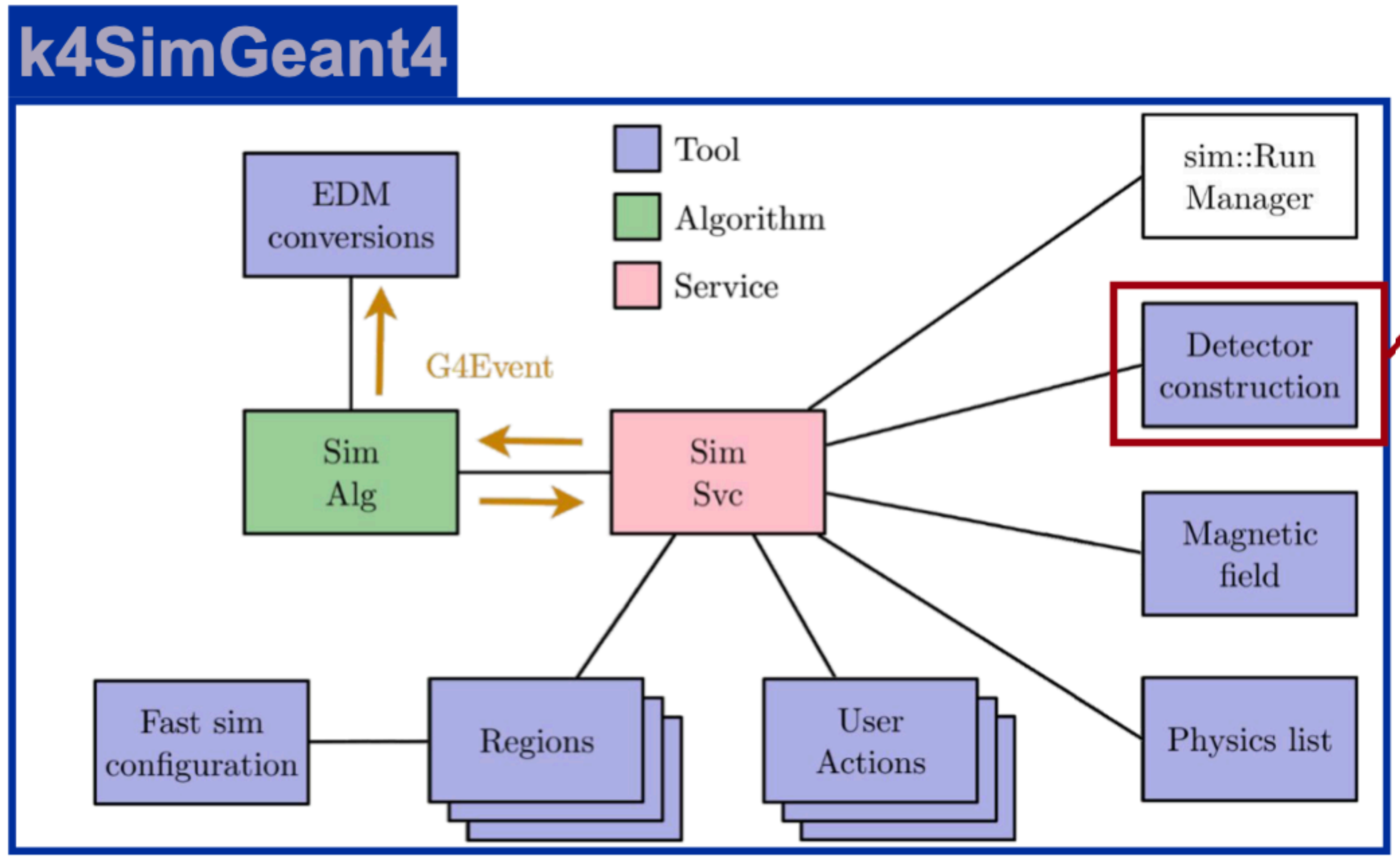
Expected performances

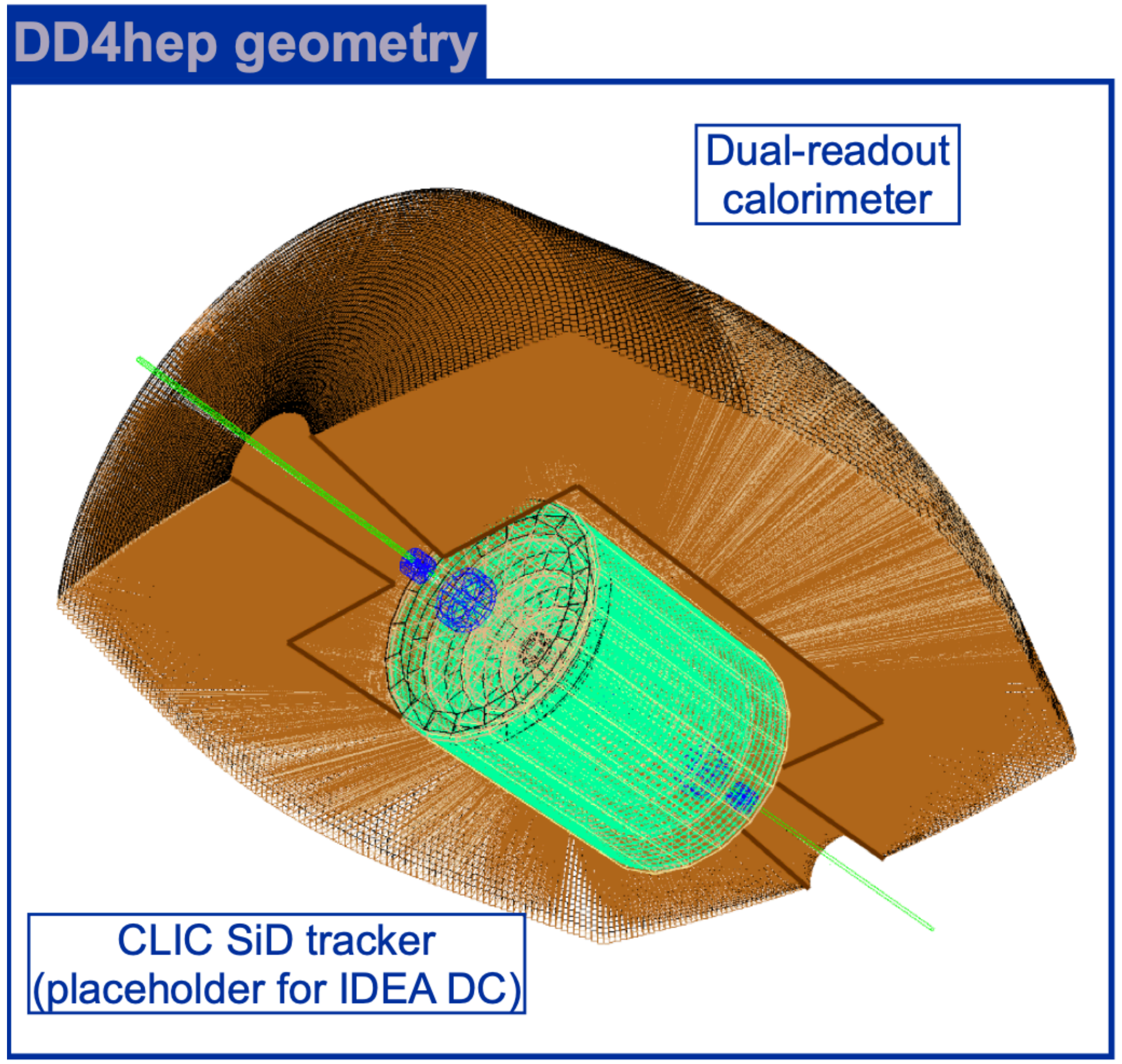




DD4hep geometry migration - DR Calorimeter

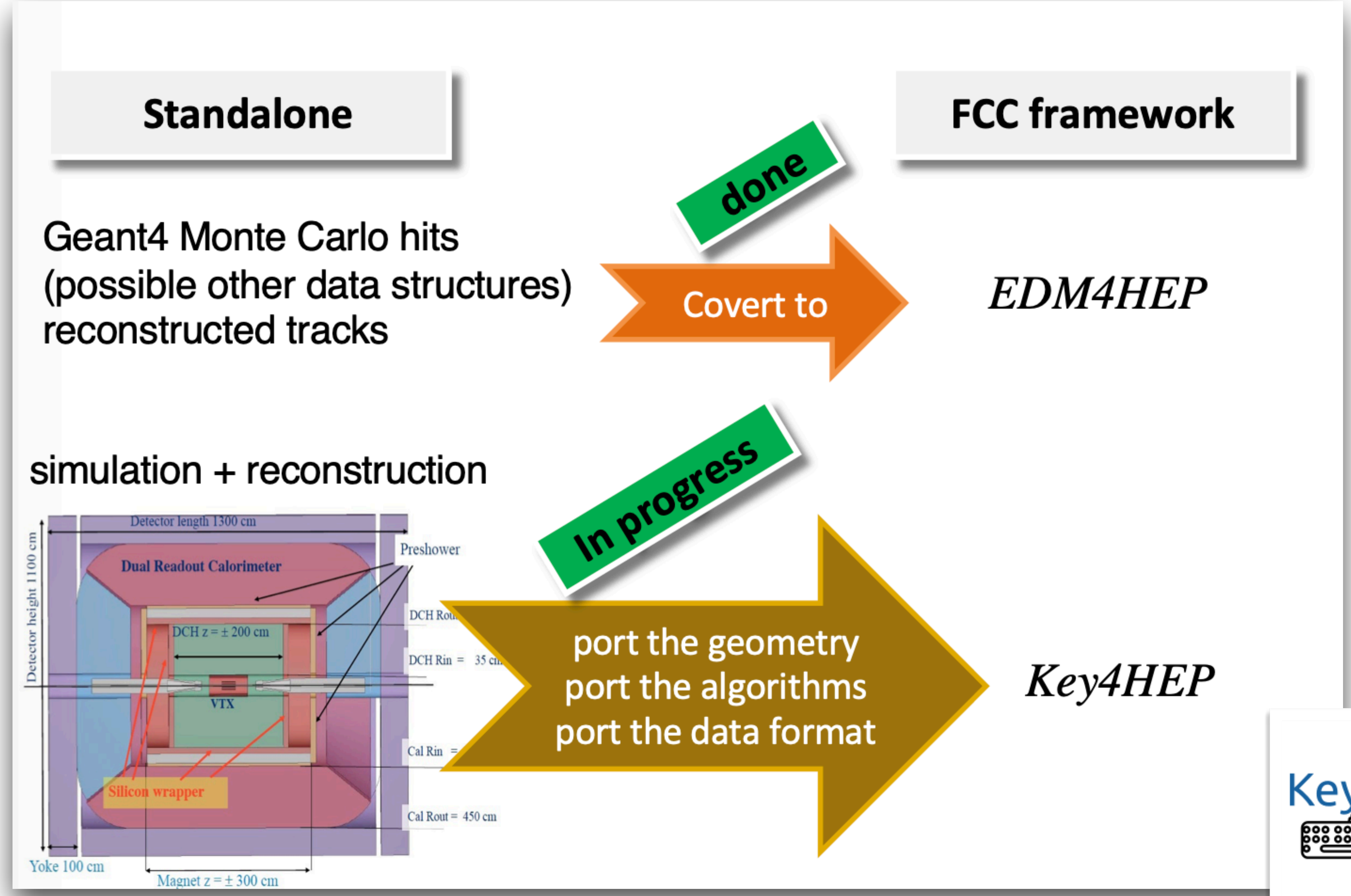
- DD4hep is a main framework for **detector description**
- It is a first step to migrate to key4hep, common **SW stack** for FCC, ILC, CLIC, CEPC
- An **IDEA DR-Calo** description was implemented in **DD4hep** [*git*]
- To be coupled with a DD4hep description of the IDEA Drift Chamber



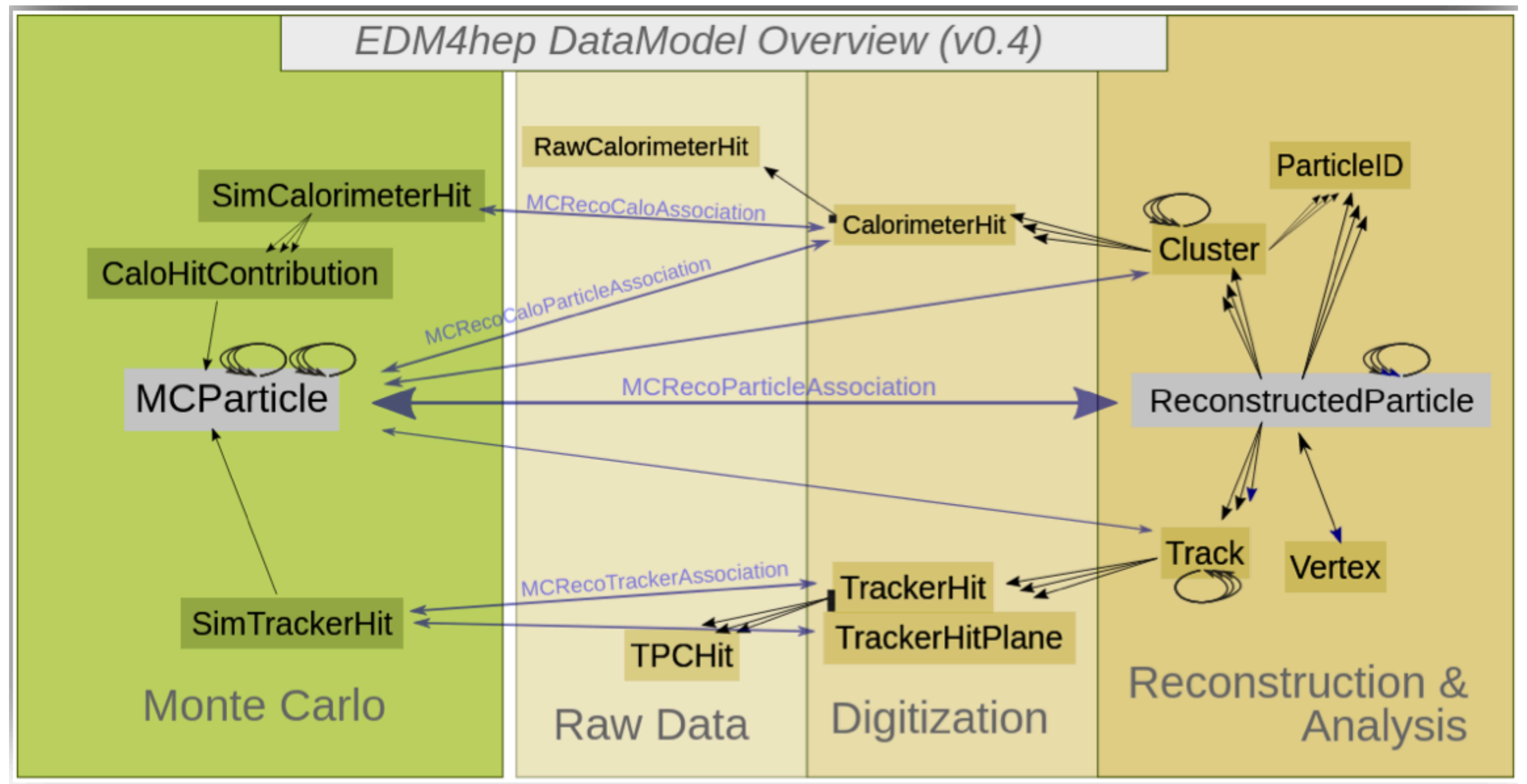


Migration to EDM4hep and key4hep

- **Goal**: port the simulation and the algorithms to a common FCC framework to develop studies, physics analysis and algorithms in the standard/final environment



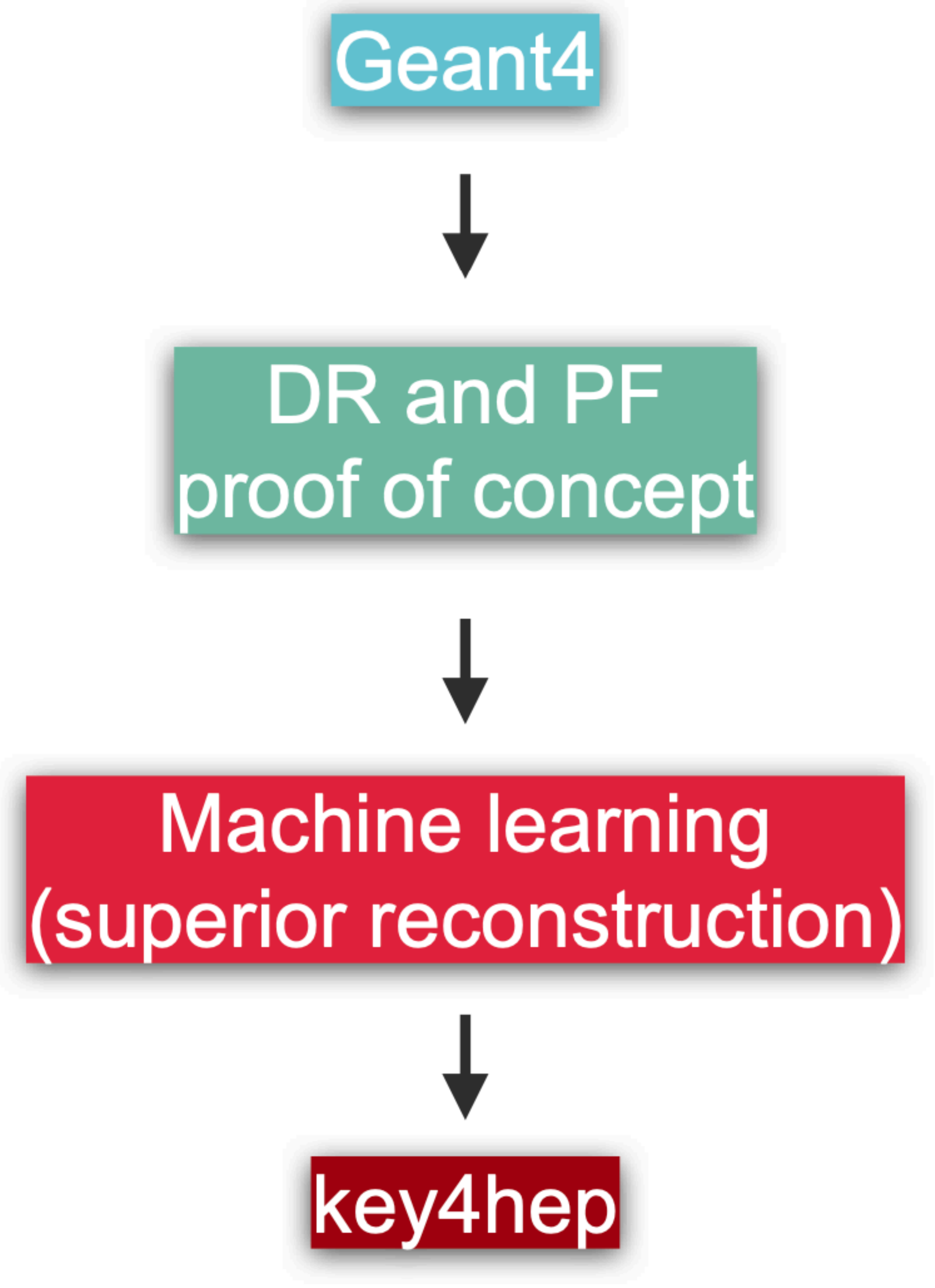
- EDM4hep is a common EDM that can be used by all communities in the key4hep project



- key4HEP: general software framework developed for many experiments *https://github.com/key4hep*
  - GEANT4 implementation in key4hep already started

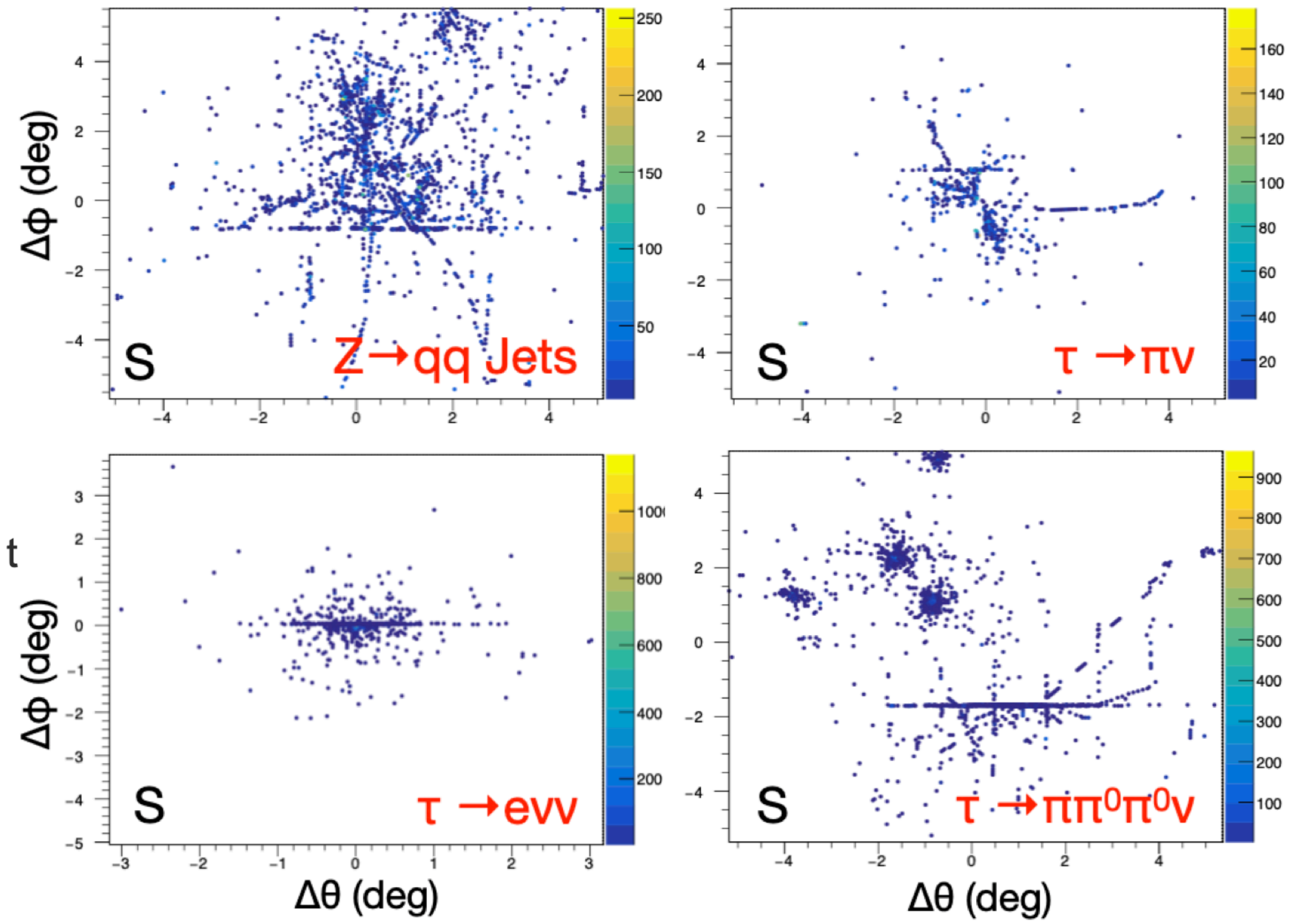
Machine Learning Tools Overview

- Taus: classification of τ decays and separation from QCD jets based on Dynamic Graph Neural Networks (DGCNN)
- Particle flow algorithm for DR Calorimeter based on CNN



Machine Learning Tools Overview

- **Point-cloud-based data representation:** unordered sets of entities distributed irregularly in space, analogous to the point cloud representation of 3D shapes
  - Easy to incorporate additional information of the fibers (fibre type, energy, time information, …)
  - The architecture of the neural network has to be carefully designed to fully exploit the potential of this representation → **Dynamic Graph CNN**



Using coordinates, fiber type (S/C) and p.e. in each fiber

Average accuracy 90.8%

Truth BR \ Predicted BR	τ→eνν	τ→πν	τ→ππ⁰ν	τ→ππ⁰π⁰ν	τ→πππν	τ→ππππ⁰ν	τ→μνν	Z→qq jets
τ→eνν	98.53	0.45	0.65	0.03	0.00	0.00	0.34	0.00
τ→πν	3.20	91.35	2.21	0.25	1.71	0.19	0.94	0.14
τ→ππ⁰ν	1.34	3.49	86.87	4.97	1.12	1.67	0.11	0.44
τ→ππ⁰π⁰ν	0.46	0.25	12.09	83.19	0.14	3.24	0.00	0.63
τ→πππν	0.11	3.14	1.24	0.16	87.39	6.79	0.00	1.16
τ→ππππ⁰ν	0.16	0.30	1.82	1.57	6.42	87.04	0.03	2.66
τ→μνν	1.24	0.25	0.06	0.00	0.03	0.00	98.42	0.00
Z→qq jets	0.13	0.21	0.21	0.59	1.87	2.29	0.03	94.67

- The calorimeter geometry alone allows excellent τ ID

Particle Flow for DR Calorimeter

- The aim of the project is to build a Neural Network based algorithm that, from a given collection of energy deposits in the calorimeter, is able to completely reconstruct a jet in the detector and maximise the energy resolution of the dual read-out calorimeter

Workflow

1. **Geant4 simulation of a jet**
2. **Extract particle info at the input layer: position, momentum, particle type** / **Extract calorimeter info: fiber position, fiber type, collected light by the fiber**
3. **Clustering**
4. **NN based particle identification: charged: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p, neutral: γ, π^0, $K_{L,S}$, n, Λ. Output: momenta of the particles and particle identification (PID) weights**

NN based jet reconstruction: starting from particle lists, their momenta, and PID weight build a jet using NN regression algorithm

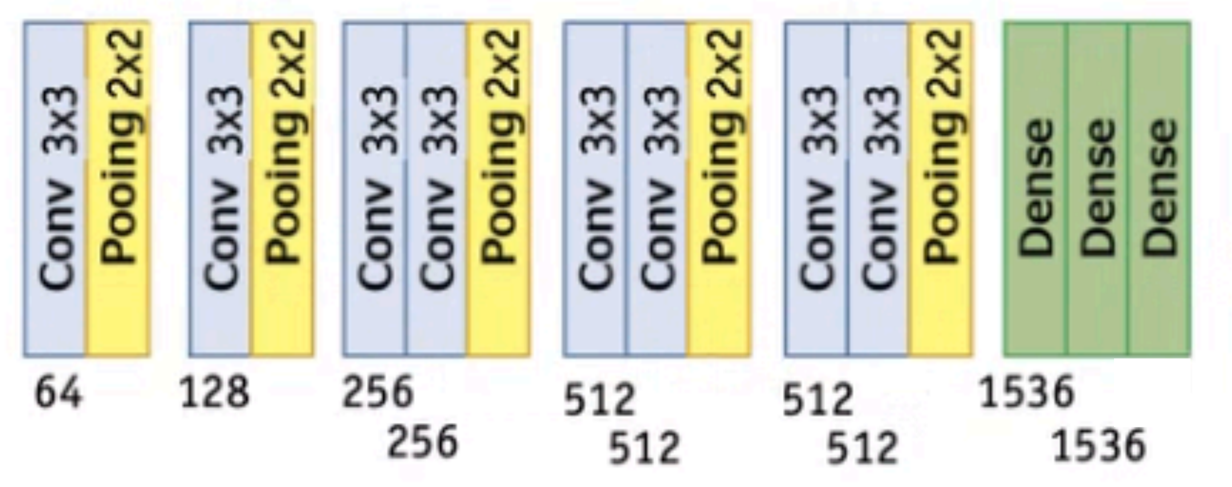
Work in progress

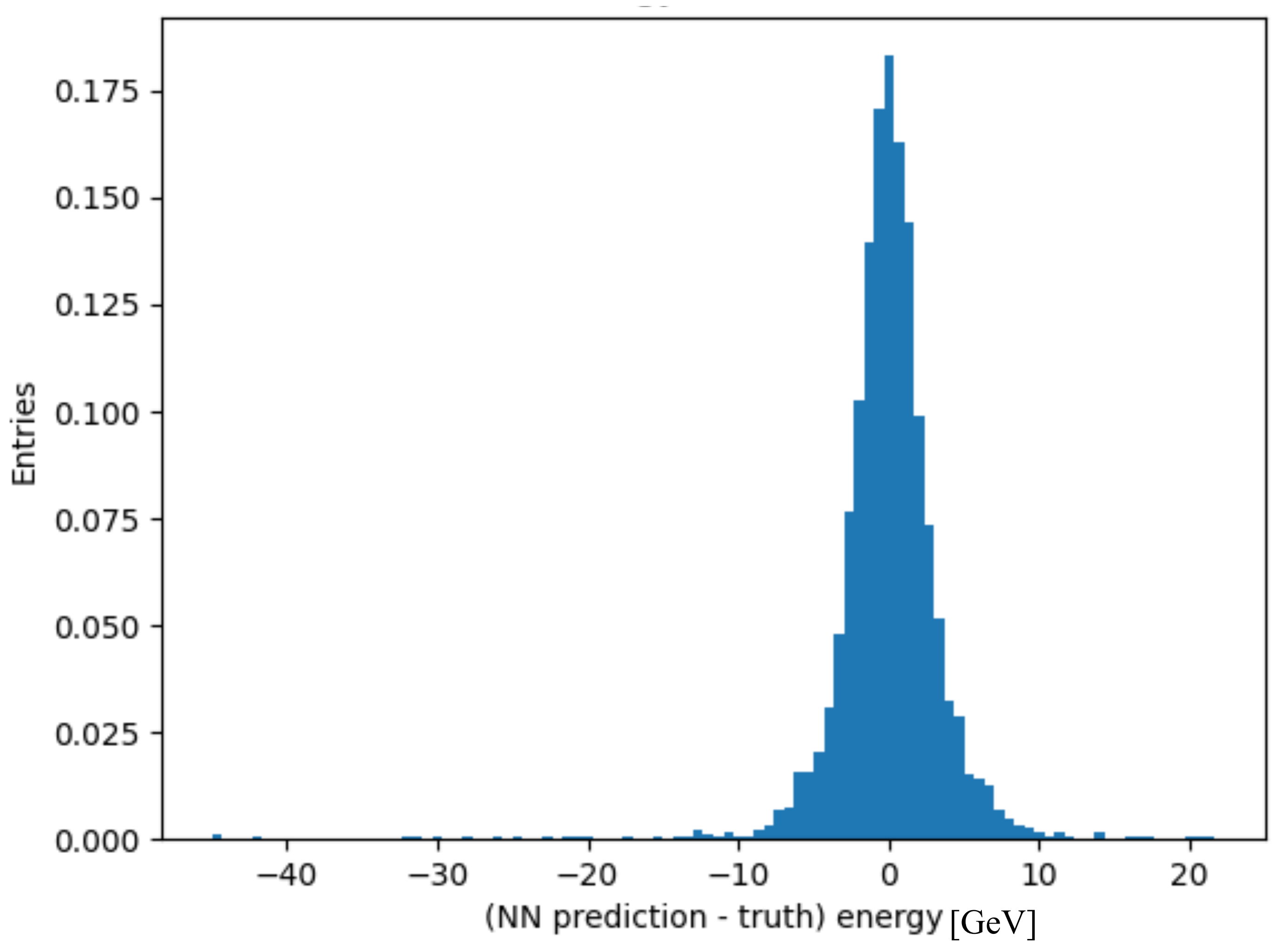
Software Implementation

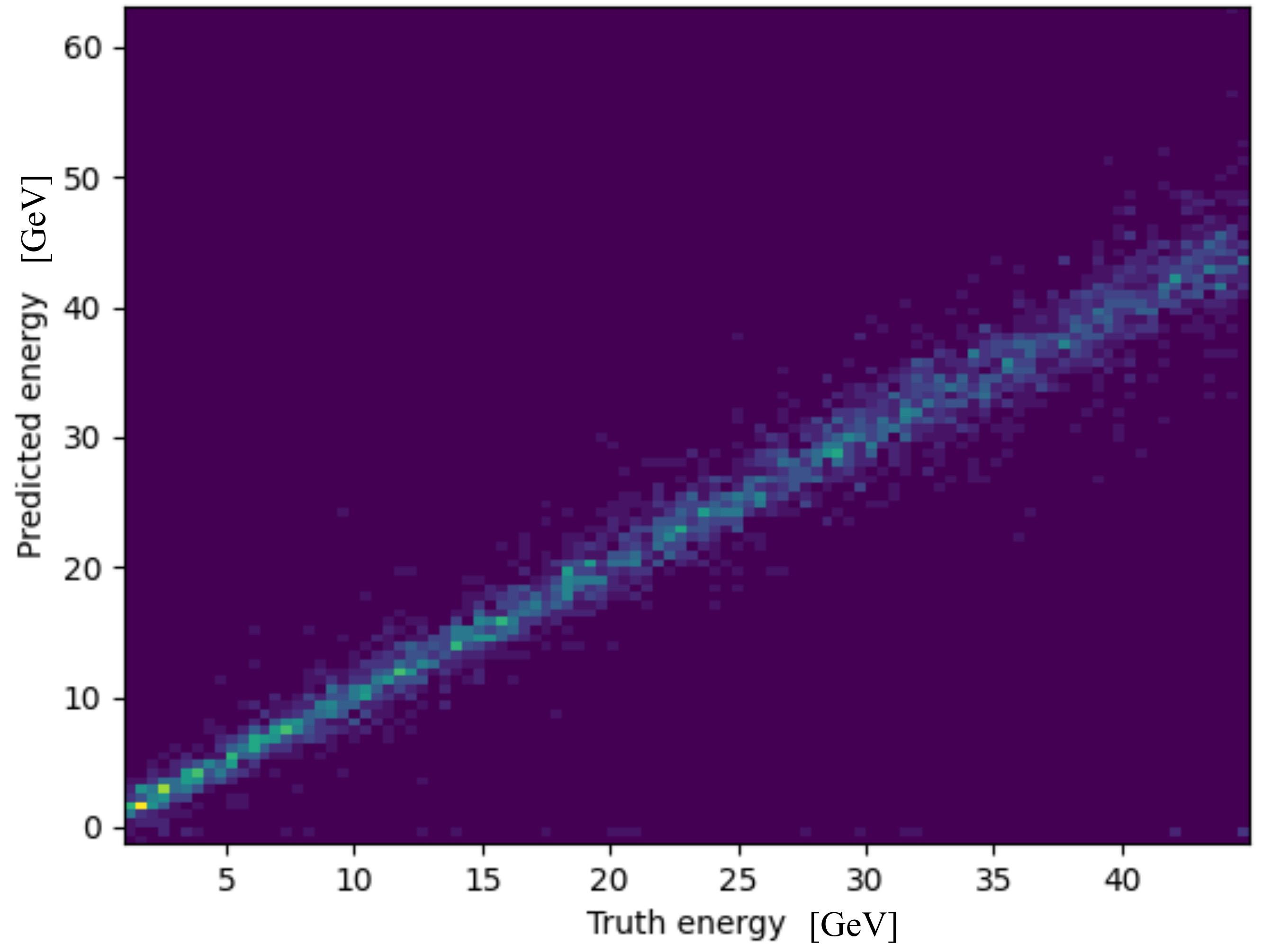
- **Input from detector simulation (EDM4HEP) format**
- **Reading using key4hep *code***
- **Dumping algorithm, input variables for NN training**
- **NN training using *Tensorflow* on CPU/GPU**

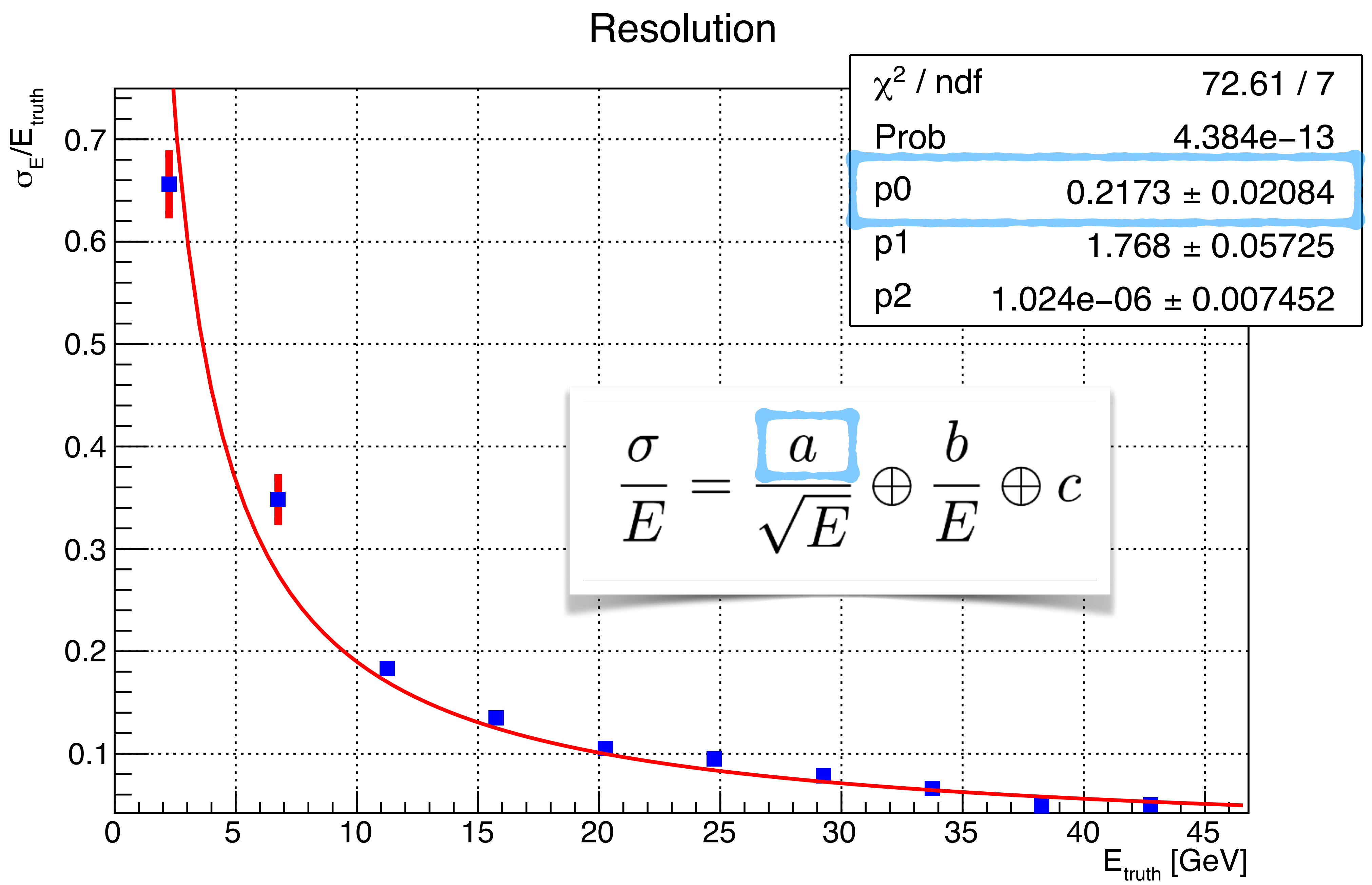
Preliminary results on electron resolution

- VGG-like CNN approach
- Model loss: MeanSquaredError()
  $\frac{1}{n}\sum_{i=1}^{n}\left(y_{\text{true}} - y_{\text{pred}}\right)^2$, optimised with respect to the simulated energy of the incoming electrons
- Adam, a stochastic optimiser, is used as optimiser to minimise the loss
  [Reference]









- Very preliminary results
- NN configurations might be under-performing
  - Too easy architecture? **Work in progress**

Conclusions

- Future colliders are foreseen in the European (and Chinese) strategy for particle physics
- IDEA is a feasible detector concept at future colliders
- R&D studies for detector and software solutions
- Developing simulations and tools for new detectors
- Stay tuned for the European Strategy updates in the next months

Thanks for listening

Back-Up Slides

Physics and detector requirements (Patrizia)

Flavour physics programme

- Enormous statistics 10^{12} bb, cc
- Clean environment, favourable kinematics (boost)
- Small beam pipe radius (vertexing)

1. Flavour EWPOs (R_b, $A_{FB}^{b,c}$) : large improvements wrt LEP
2. CKM matrix, CP violation in neutral B mesons
3. Flavour anomalies in, e.g., $b \rightarrow s\tau\tau$

QCD programme

- Enormous statistics with $Z \rightarrow \ell\ell$, qq(g)
- Complemented by 100,000 $H \rightarrow gg$

1. $\alpha_S(m_Z)$ with per-mil accuracy
2. Quark and gluon fragmentation studies
3. Clean non-perturbative QCD studies

Often statistics-limited
5. 10^{12} Z is a minimum

Tau physics programme

- Enormous statistics: 1.7 10^{11} $\tau\tau$ events
- Clean environment, boost, vertexing
- Much improved measurement of mass, lifetime, BR's

1. τ-based EWPOs (R_τ, A_{FB}^{pol}, P_τ)
2. Lepton universality violation tests
3. PMNS matrix unitarity
4. Light-heavy neutrino mixing

Rare/BSM processes, e.g. Feebly Coupled Particles

Intensity frontier offers the opportunity to directly observe new feebly interacting particles below m_Z

- Signature: long lifetimes (LLP's)
- Other ultra-rare Z (and W) decays

1. Axion-like particles
2. Dark photons
3. Heavy Neutral Leptons