Development of particle flow algorithms based on Neural Network techniques for the IDEA calorimeter at future colliders

Adelina D'Onofrio[1]
on behalf of the RD-FCC project of INFN

[1]INFN, sez. Roma Tre

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Istituto Nazionale di Fisica Nucleare
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

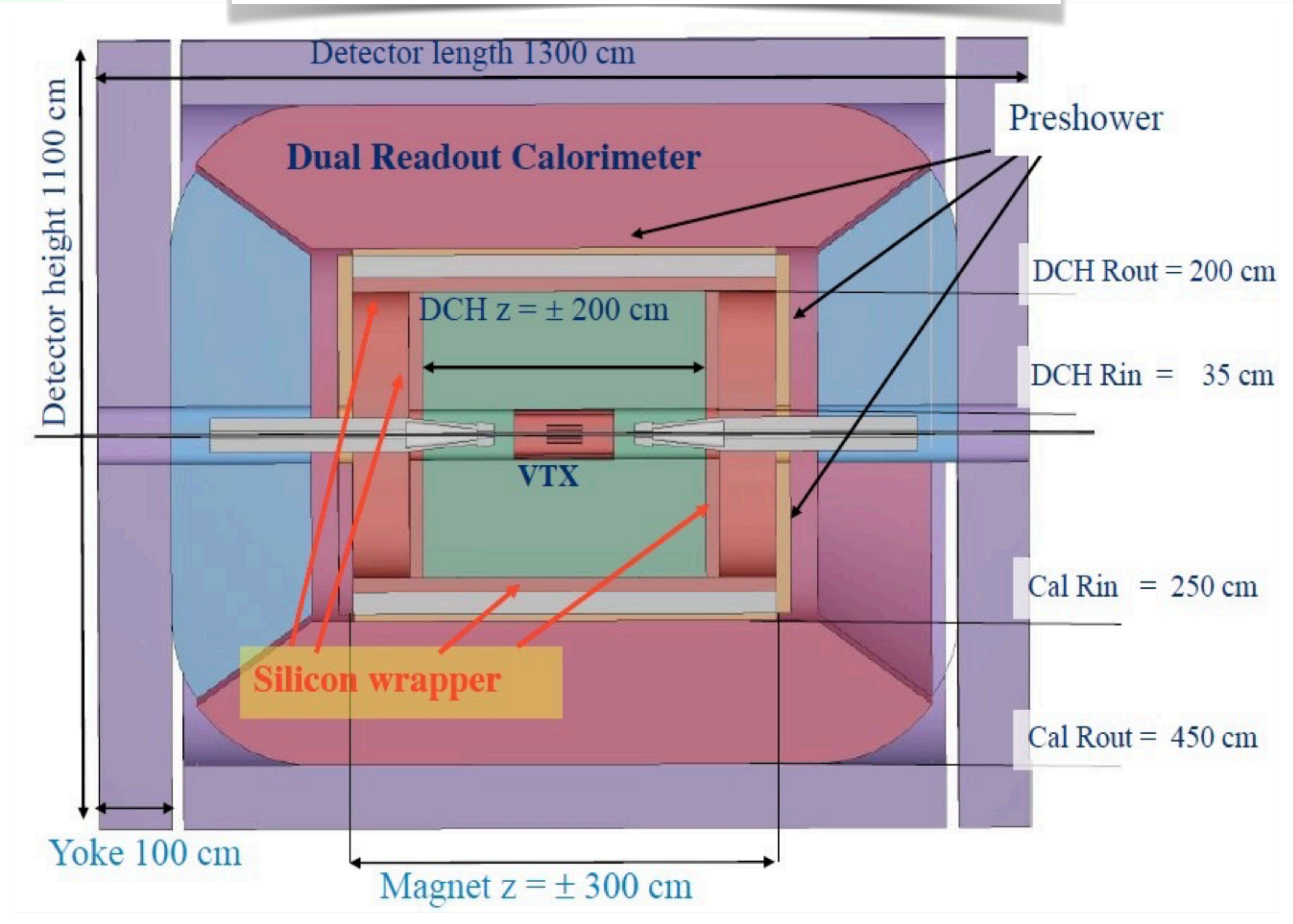
FCCee will be an unique tool for high precision measurements

15 years programme

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

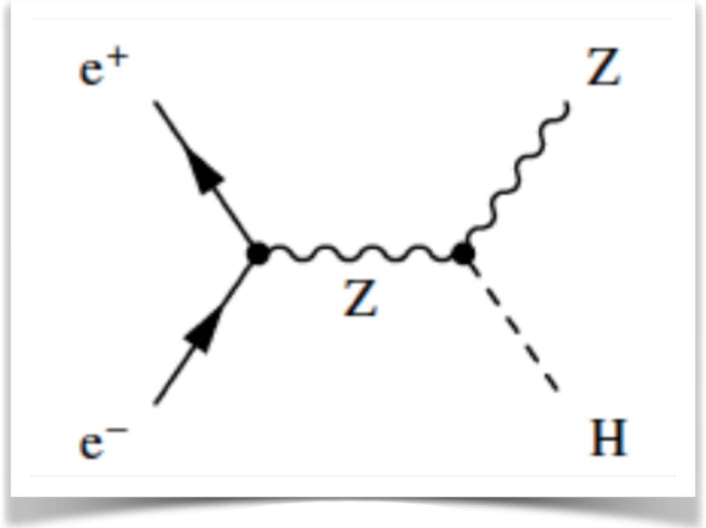
From FCCee TDR

IDEA detector at future e^+e^- colliders



Clean experimental environment

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



Physics and detector requirements

"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 $e^+e^- \to H$ @ $\sqrt{s}$ = 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.

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

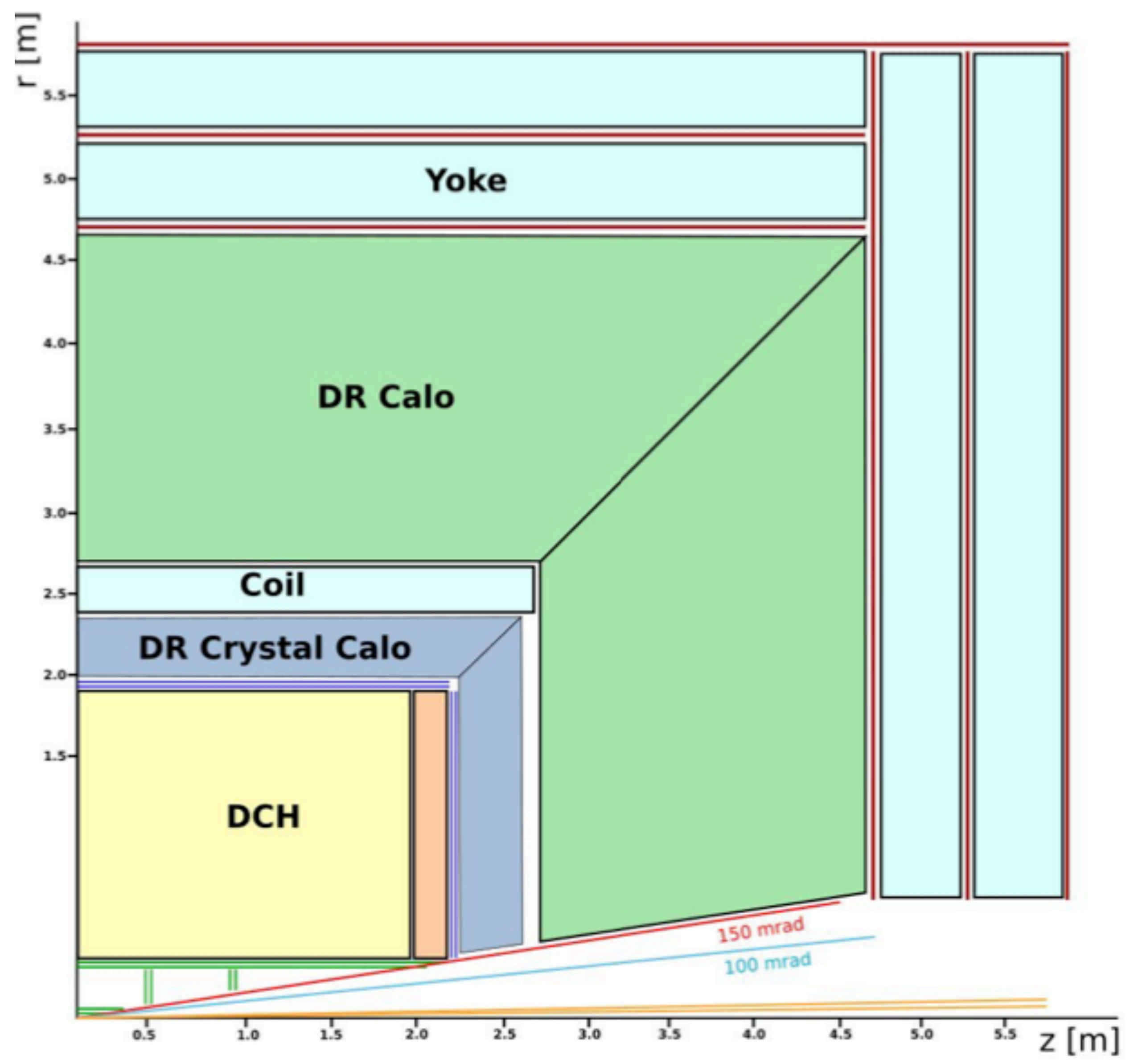
- Momentum resolution
  Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  BR measurements, EWPOs, spectral functions

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

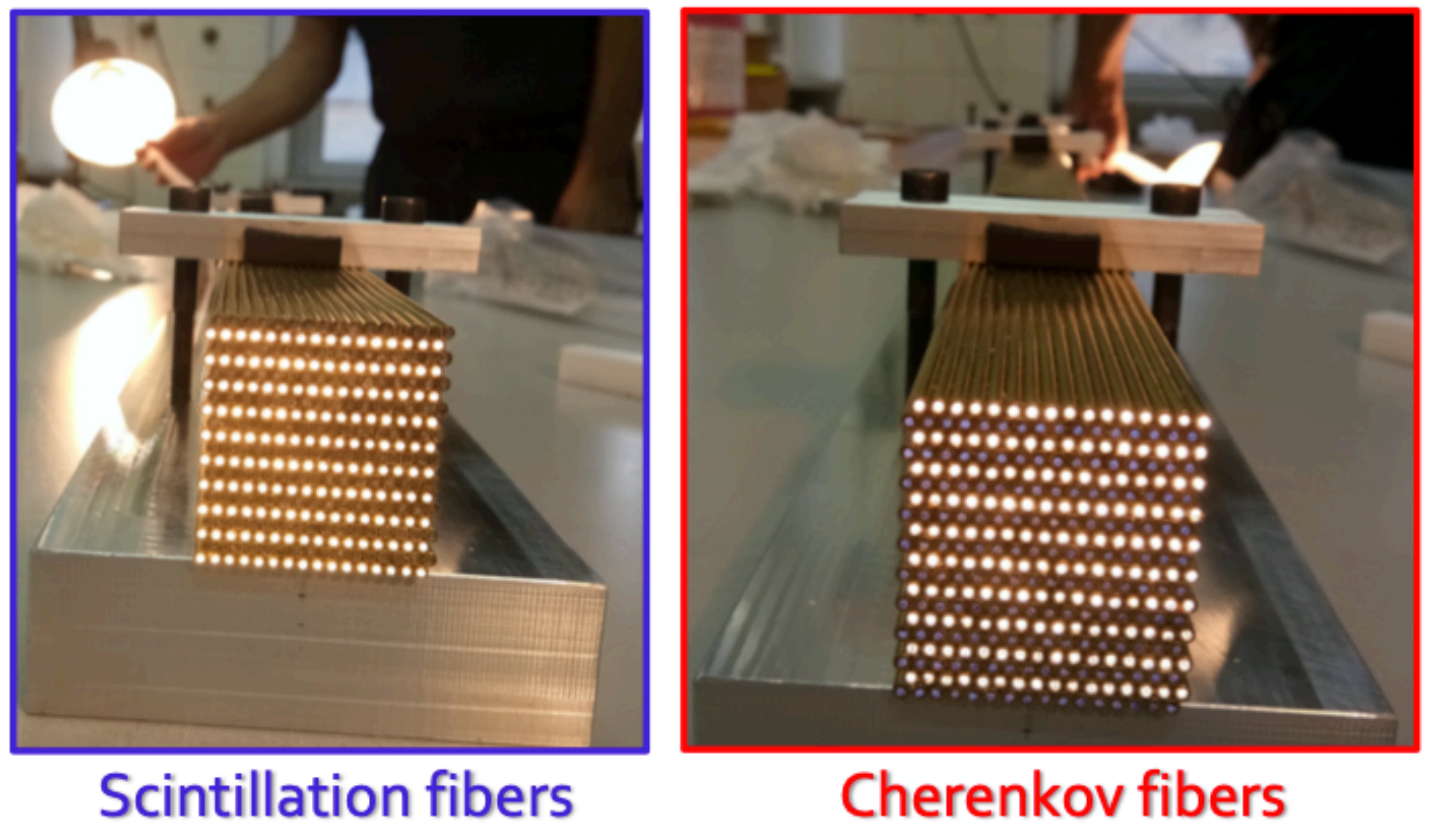
- Sensitivity to far-detached vertices (mm → m)
  1. Tracking: more layers, continuous tracking
  2. Calorimetry: granularity, tracking capability
- Larger decay lengths ⇒ extended detector volume
- Full acceptance ⇒ Detector hermeticity

Dual Read-out Calorimeter for the IDEA detector

- Dual readout calorimeters aim at improving the energy resolution of hadronic calorimeters
  - Generally driven by the fluctuations between the electromagnetic and the hadronic component of showers
- Measure the hadronic component and the electromagnetic component (dual readout) of the showers separately, to derive proper correction factors to be applied to each component to reconstruct the energy of the impinging hadrons
- Exploit a passive/material - fibre layout where two type of fibres, one sensitive to the usual scintillation process, a second type of fibre producing Cherenkov light when ultra-relativistic particles cross with a speed higher than the speed of light in that fibre (S or C fibres)



A. IDEA detector transversal view



B. Current R&Ds

Expected performance

- 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

Overview of the Particle Flow Project

- 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** ✓
2. **Extract particle info at the input layer: position, momentum, particle type** — **Extract calorimeter info: fibre position, fibre type, collected light by the fibre** ✓
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

↓

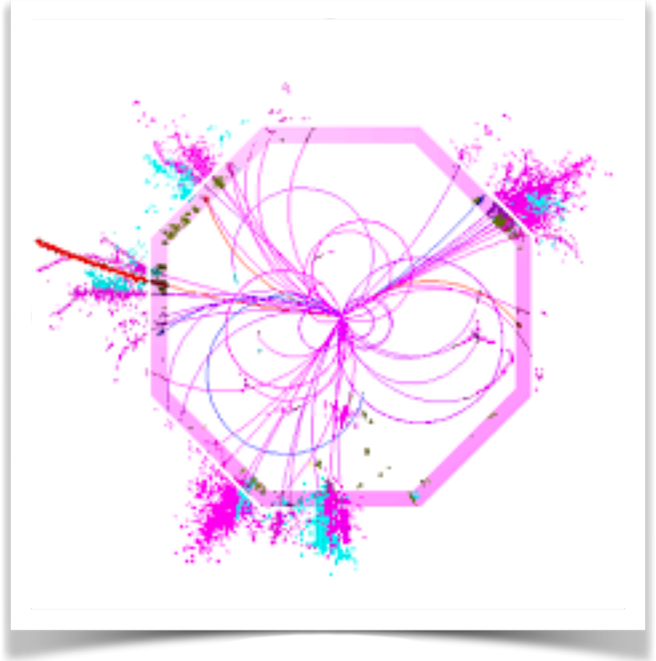
NN training using *Tensorflow* on CPU/GPU

PFA with neural networks at Future Colliders

Software stack

The project will be developed in key4HEP and Pandora → interface Pandora with key4HEP

- key4HEP: general software framework developed for many experiments *https://github.com/key4hep*
  - GEANT4 implementation in KEY4HEP already started



- Pandora Particle Flow Algorithm *https://github.com/PandoraPFA*
  - Collection of pattern recognition algorithm, the idea is to insert our algorithm inside Pandora and compare its performance with already existing algorithms
  - Algorithm already present: several clustering algorithms, non NN based Particle Flow algorithms, NN based reconstruction algorithm for liquid Argon TPC for the DUNE experiment
  - Training outside Pandora, use interfaces to produce input to the training data format and inference

Pandora Interface to NN training

Pandora tool → Input data format

↓

Clustering algorithm

↓

Training NN outside Pandora (using GPU for example)

↓

Inference inside Pandora

Infrastructure & artificial intelligence approaches

- CPU & GPU installation performed on INFN Roma Tre cluster
  - The site is equipped with about 50 server (mainly based on Blade technology) with a total amount of cores available (or VCPU) of about 1500 interconnected with Infiniband (DDR 20Gbps e QDR 40Gbps)
  - The site has also 2 Graphical Processor Unit (GPU) K 80 (4 in total: 2 x K40), where jobs can be parallelised if needed
  - There is a storage system present in the cluster for a total amount of about 700TB
  - **Extensive innovation next year**, in order to double the CPU and storage system

Two neural network (NN) approaches tested

Deep NN (DNN) approach
1. **10 hidden layers architecture**
2. **20 hidden layers architecture**

- Pro:
  - Fully exploits the fibres granularity in the calorimeter
- Cons:
  - Memory issues to process events in the full energy spectrum (0-125 GeV) for input electrons

Convolutional NN (CNN) approach
1. **VGG-like architecture**
2. **VGG-like architecture & proto-clustering**

- Pro:
  - Solves the memory issues → able to exploit electrons info in the full energy range (0-125 GeV) for input electrons
  - Able to obtain also the angular resolution
- Cons:
  - Further studies needed to improve the energy and angular resolution results

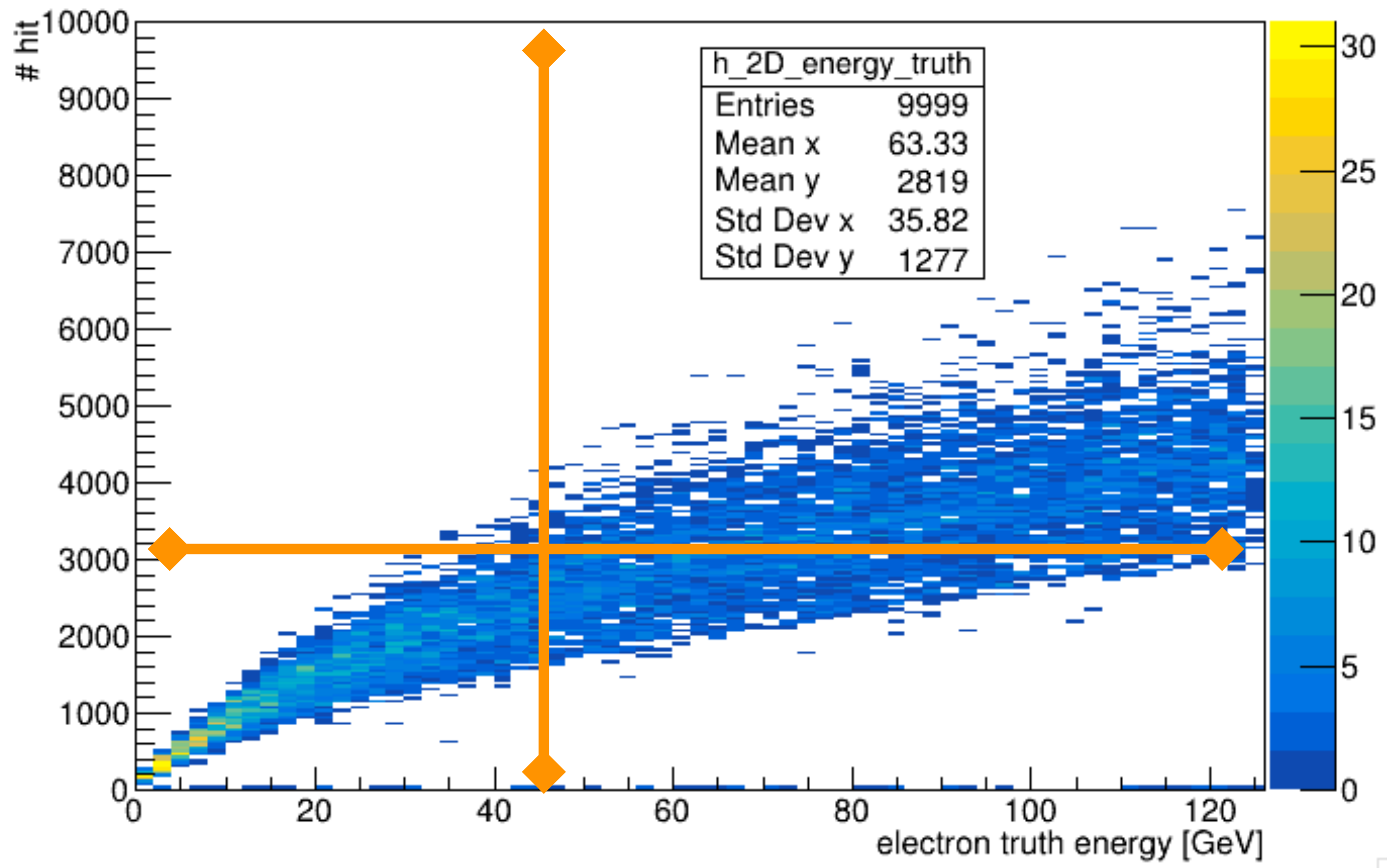
DNN approach

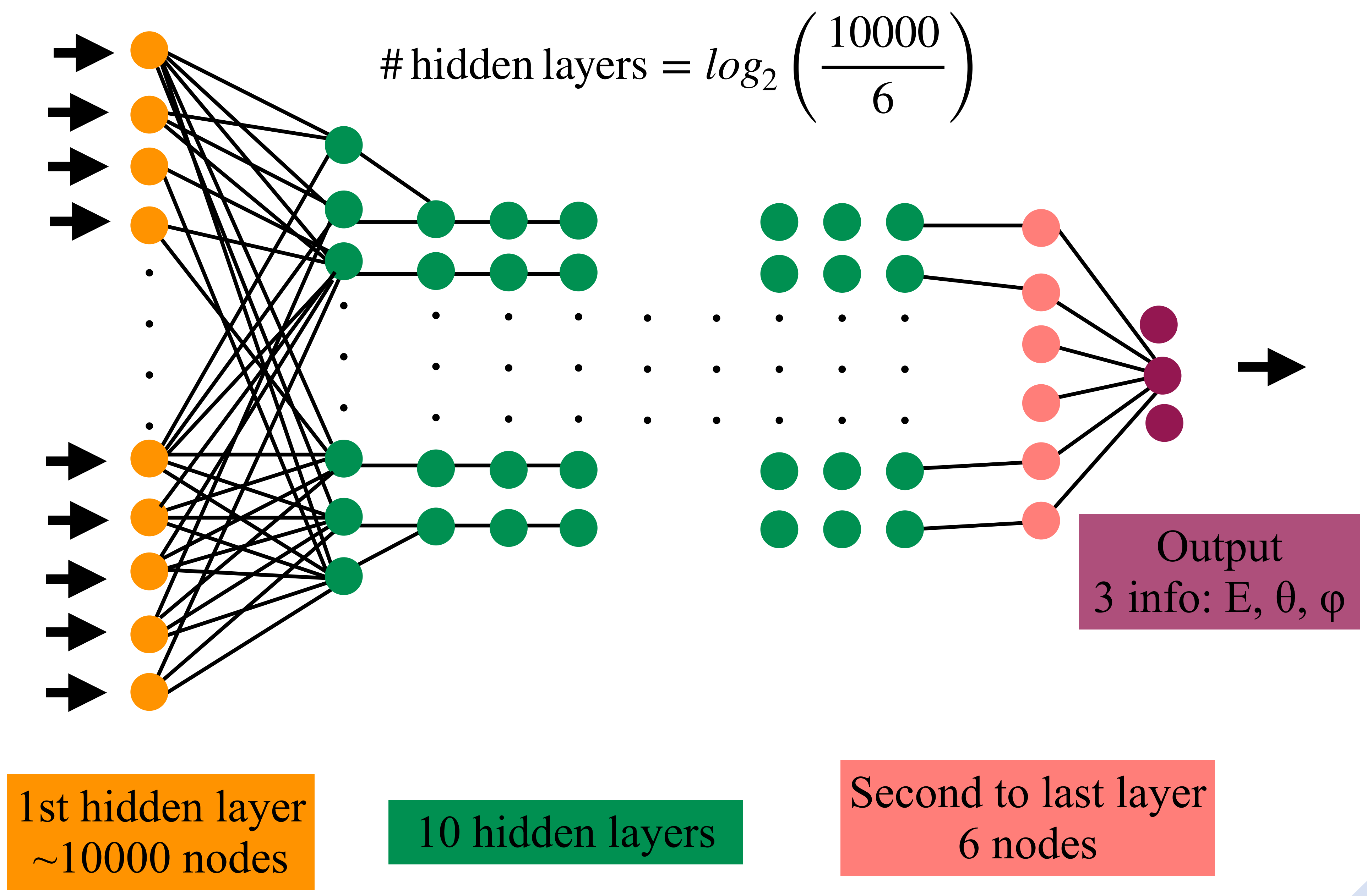
- **Tensorflow**, interfaced with Keras, is used to build and train a NN on CPU and GPUs
- Inputs: energy and position of each hit in the shower generated by the impinging electron and recorded in both S&C fibres → NN input: 6 kinematic variables (*E, x, y, z, t, fibre-type*) multiplied by hit multiplicity
  - Average hit multiplicity: ~ 10'000 hits per impinging electron per event→ ~ 60'000 info per event
  - Maximum hit multiplicity: ~ 22'500 hits per impinging electron per event→ ~ 135'000 info per event
  - Zero padding approach: if the number of hits in the event is less than the max hit multiplicity, set to zero the remaining positions in the array
- # initial nodes = # input info
  - Exploit the average hit multiplicity × kinematic variables as #initial nodes to reduce the complexity of the problem
- Need to reduce the number of inputs due to GPU memory issues (too many trainable parameters)
- Speed of the algorithm:
  ~10 minutes on GPU
  ~2 hours on CPU

Geant4
~10k simulated electrons

↓

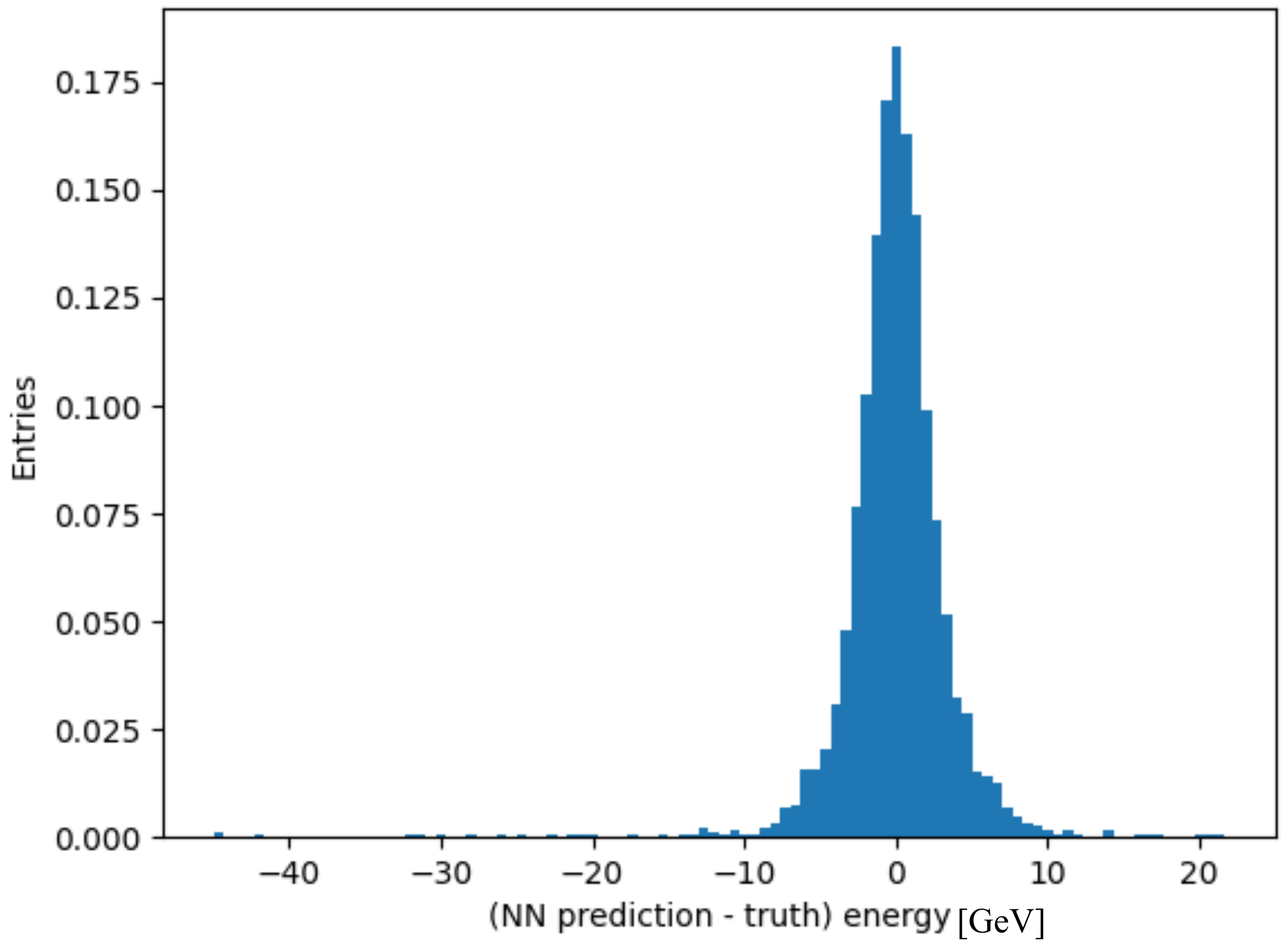
Machine learning
(superior reconstruction)

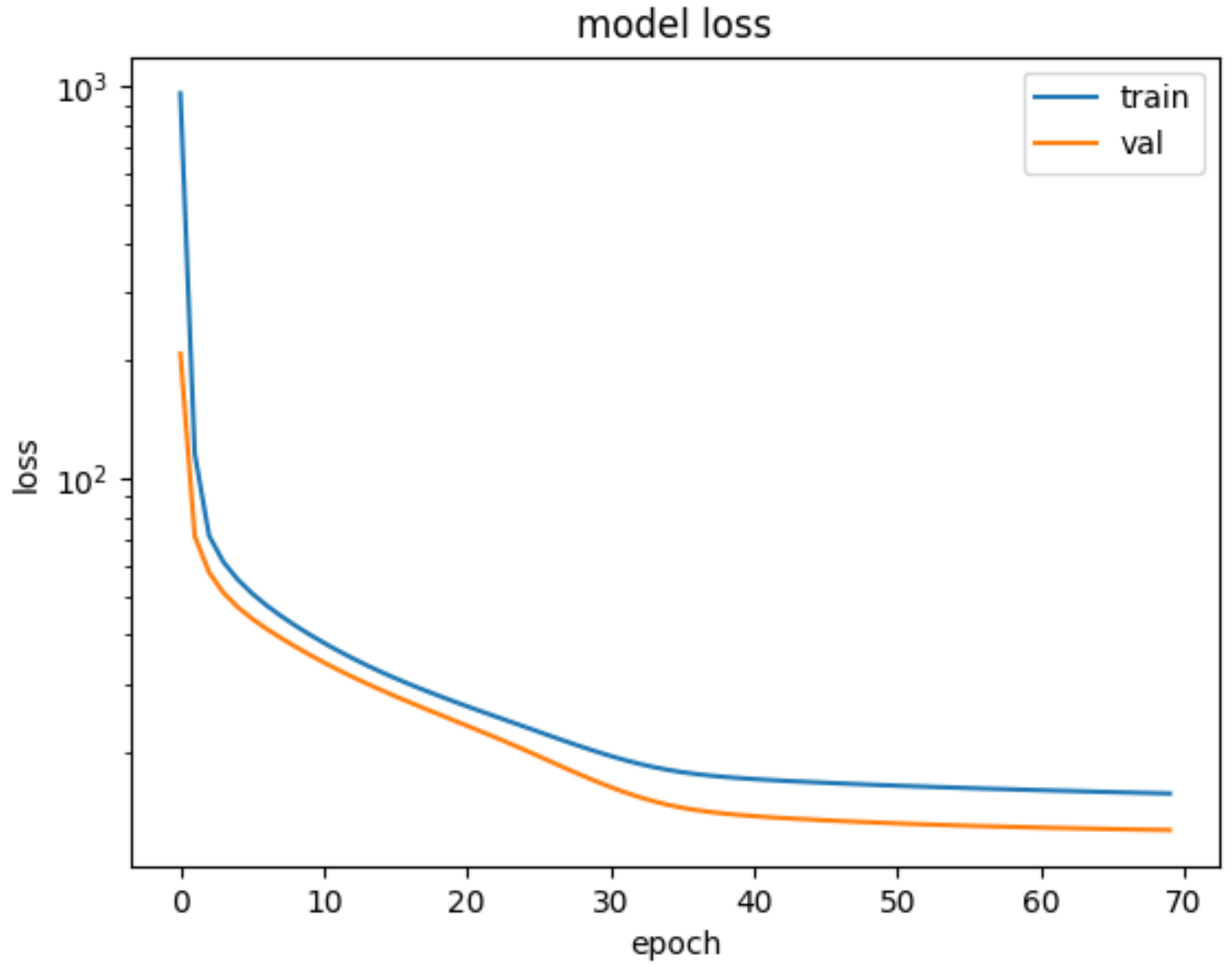


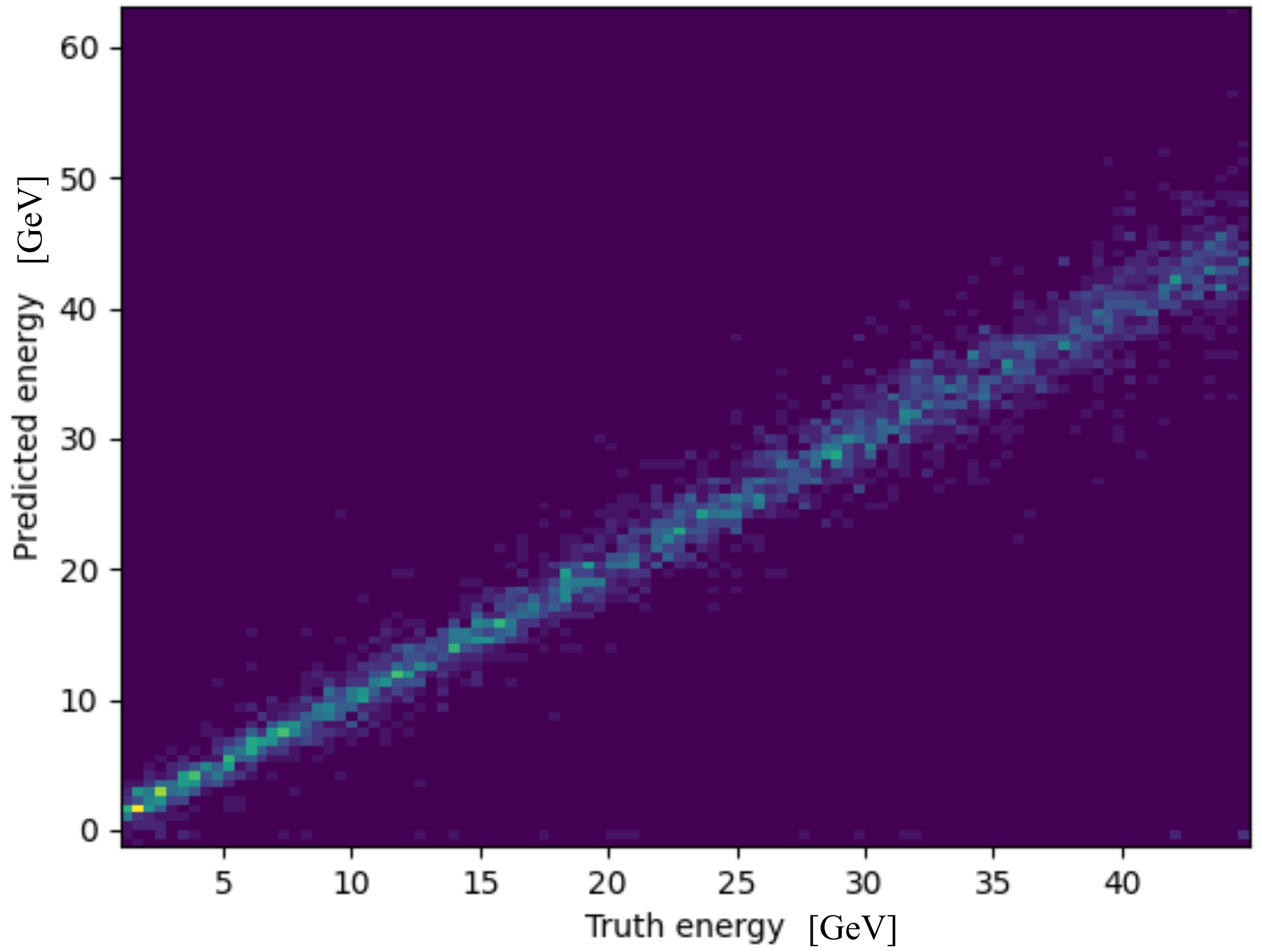


DNN approach: electron energy resolution

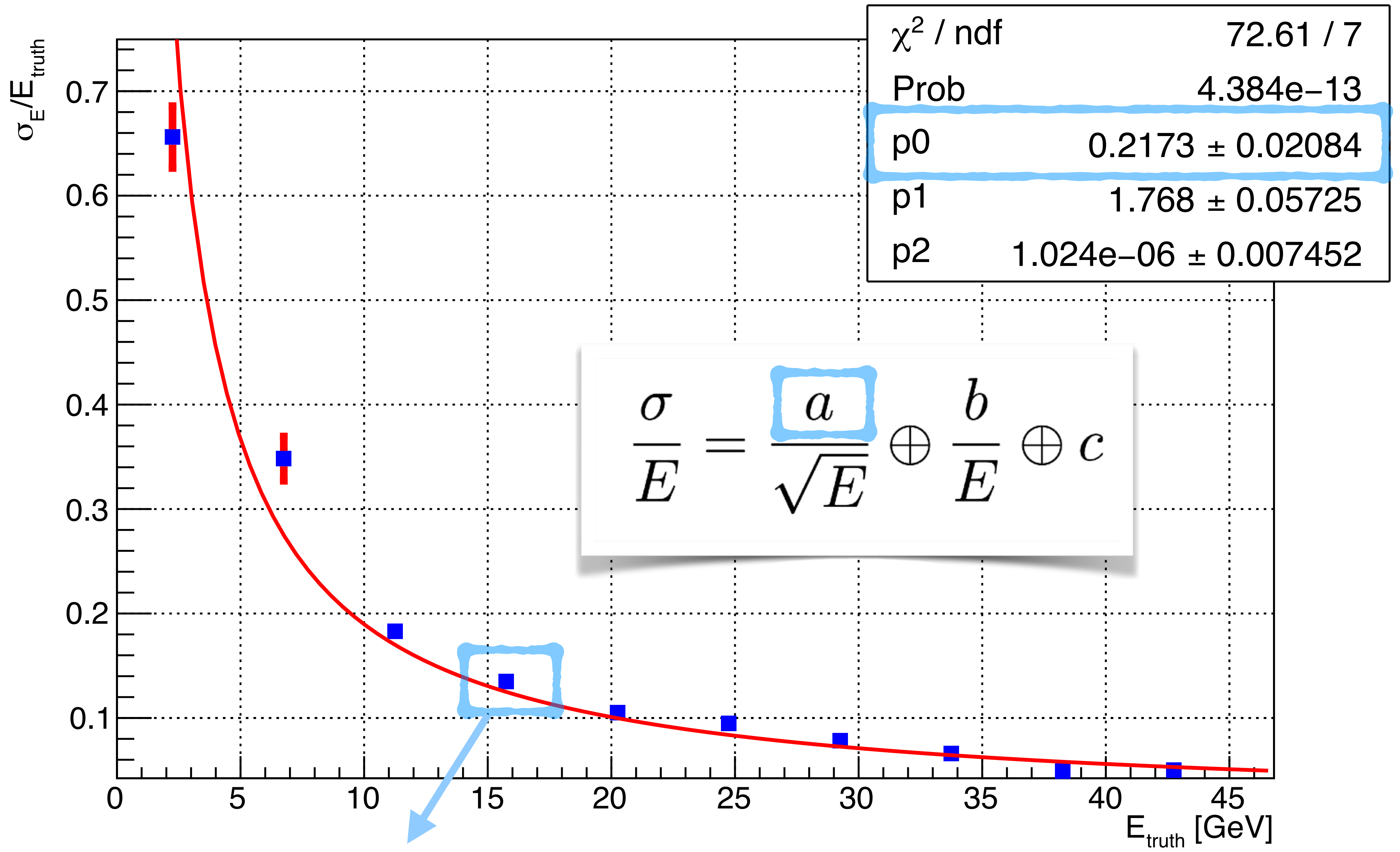
- First attempt: 10 hidden layers
- Halving number of nodes at each layer
- Model loss: MeanSquaredError() $\frac{1}{n}\sum_{i=1}^{n}\left(y_{\text{true}} - y_{\text{pred}}\right)^2$, optimised with respect to the simulated energy of the incoming electrons
- Adam, a stochastic optimiser, is used as optimiser to minimise the loss [Reference]

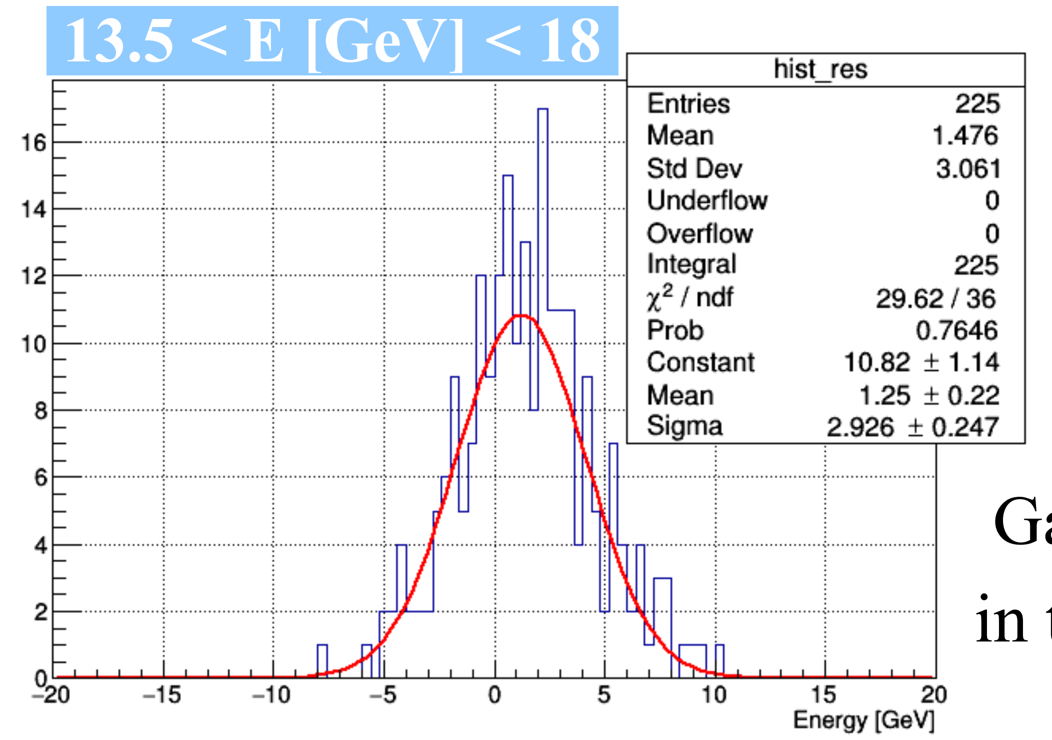






- NN configurations might be under-performing
  - Too easy architecture? **Work in progress**

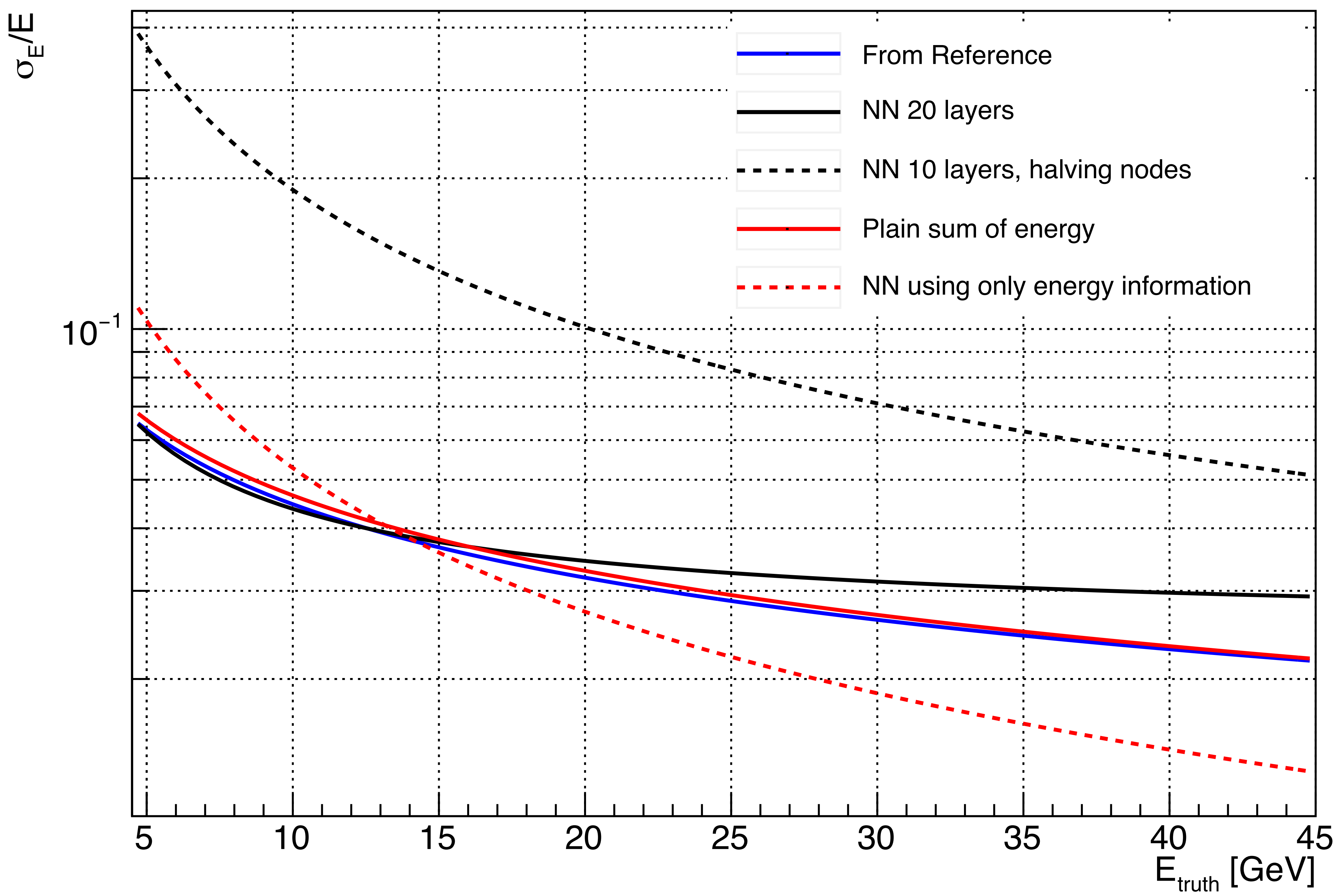




Gaussian fit performed in truth energy slices

DNN: comparing methodologies

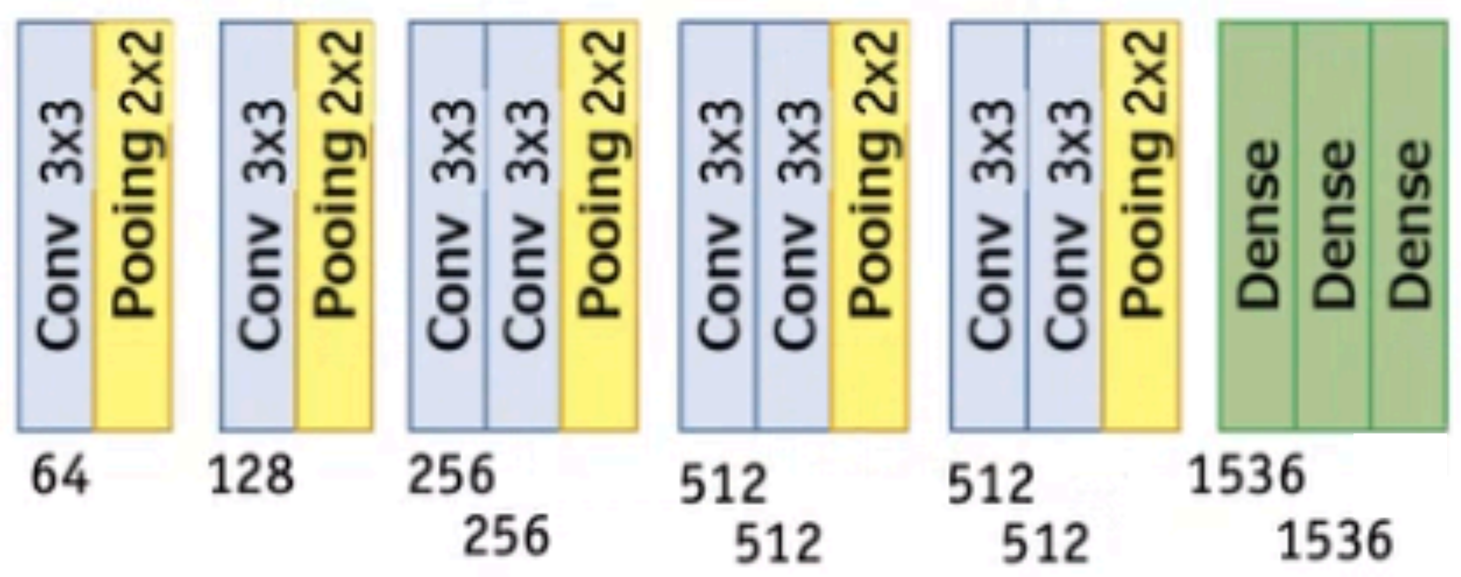
- As a sanity check, we compared our energy resolution results with:
  - A reference https://inspirehep.net/literature/1861660
  - The energy resolution obtained simply summing up the energy deposits in the fibres (S&C)
- The energy resolution improves if we double the NN layers and we keep constant the number of nodes
- **Issue**: the NN performance is still worse than the standard reconstruction → work in progress
- Next steps: increase the statistics of the simulation & improve the NN performance testing other (CNN) architectures



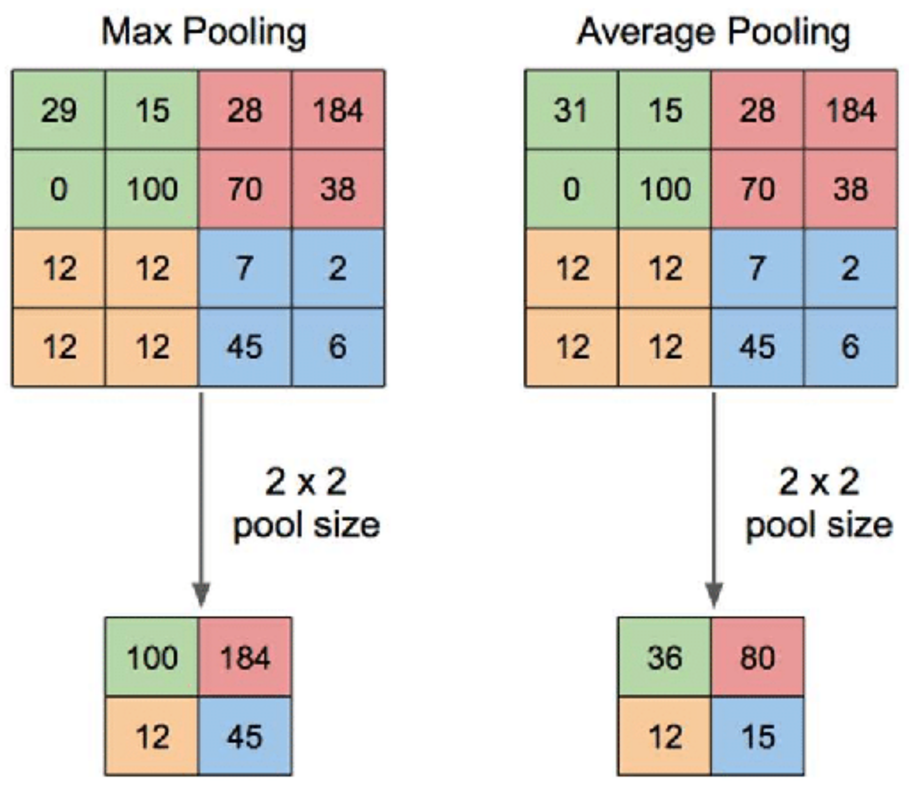
CNN approach

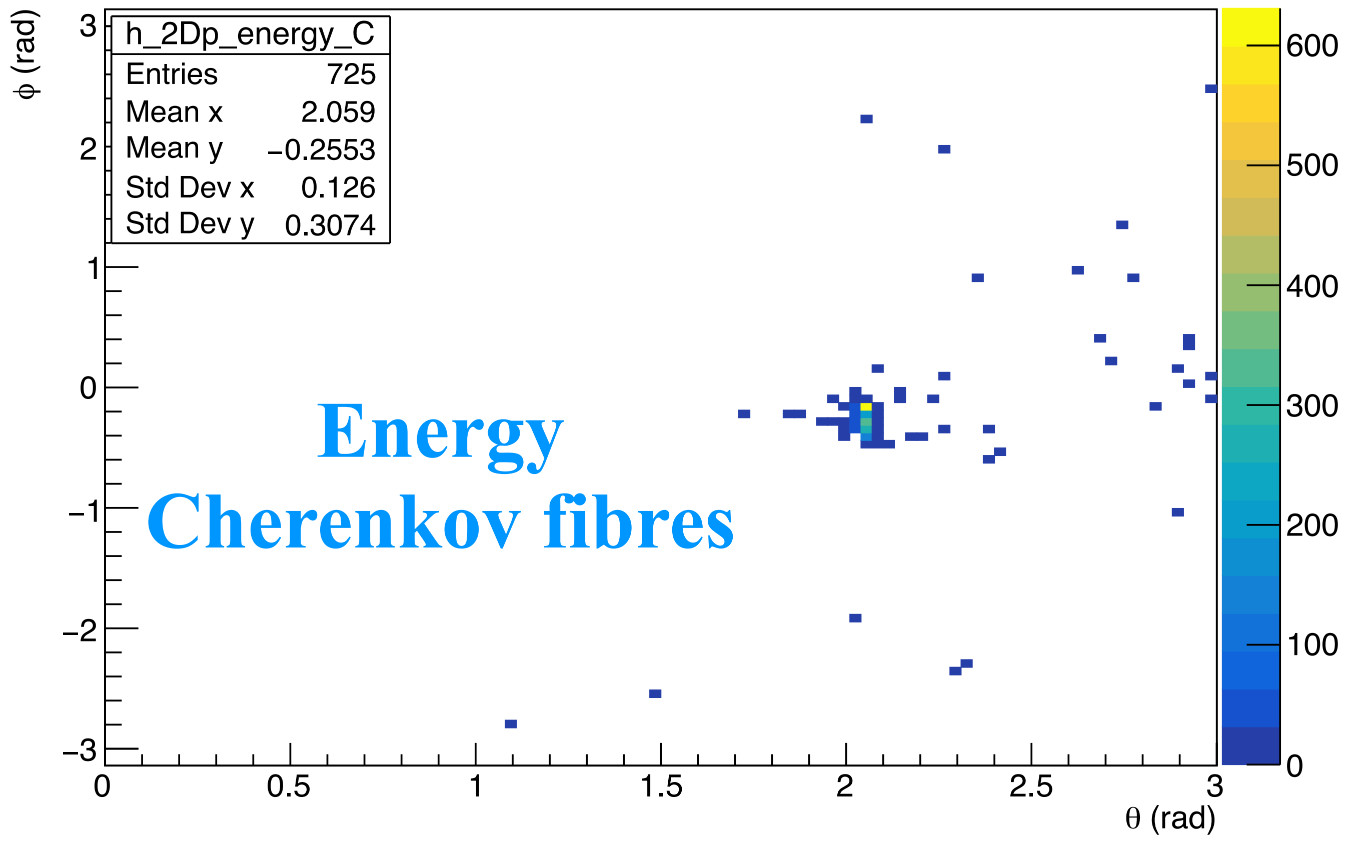
- CNN tests motivated by memory issues with DNN (many fibres for input info)
- VGG-like architecture
  - No batch normalisation
  - 5 convolutional 2D layers
  - Flatten and 3 dense layers
  - 3 outputs
  - Overcome memory issues, possibility to use the full energy range
- Tested both MaxPooling and AveragePooling methods

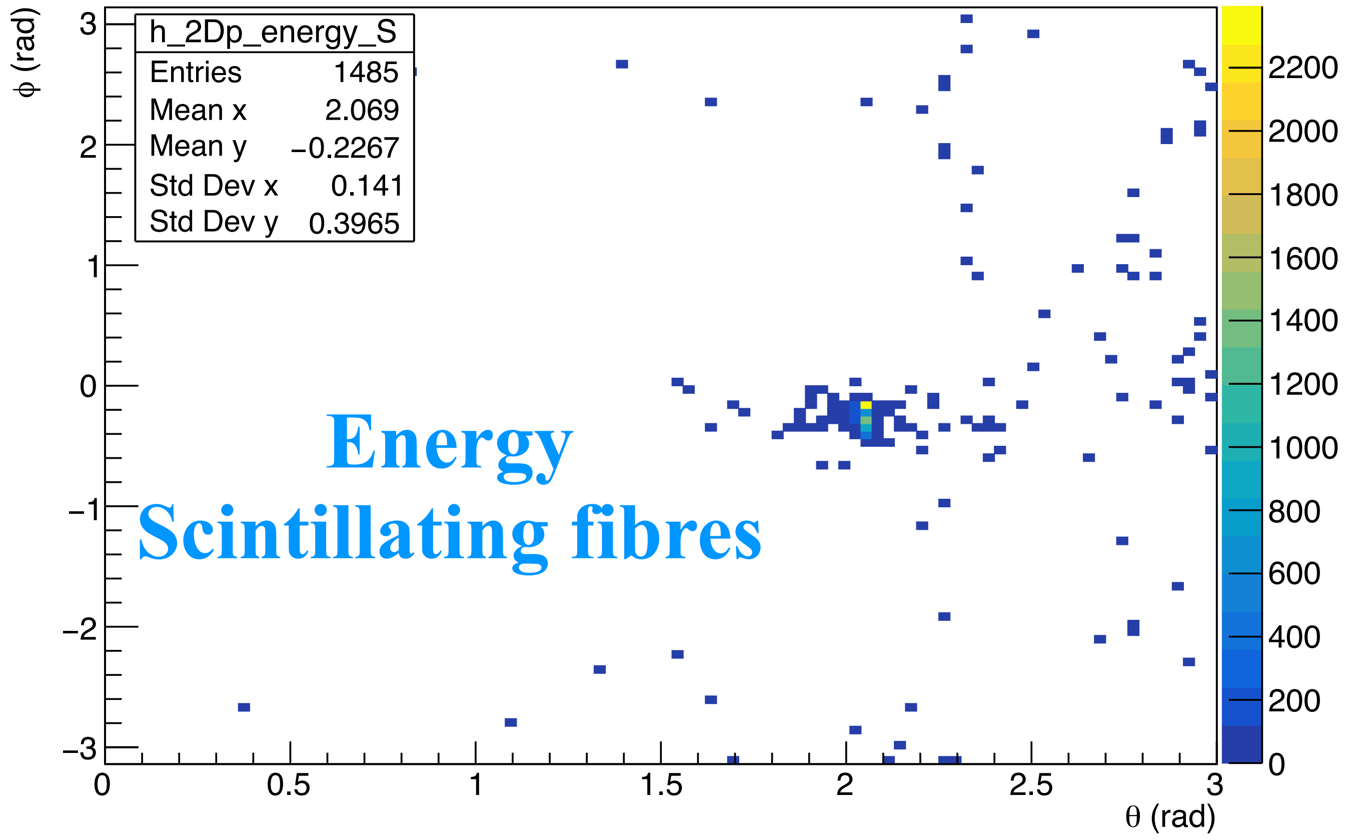
100x100xN
Input tensor



MaxPooling or AveragePooling





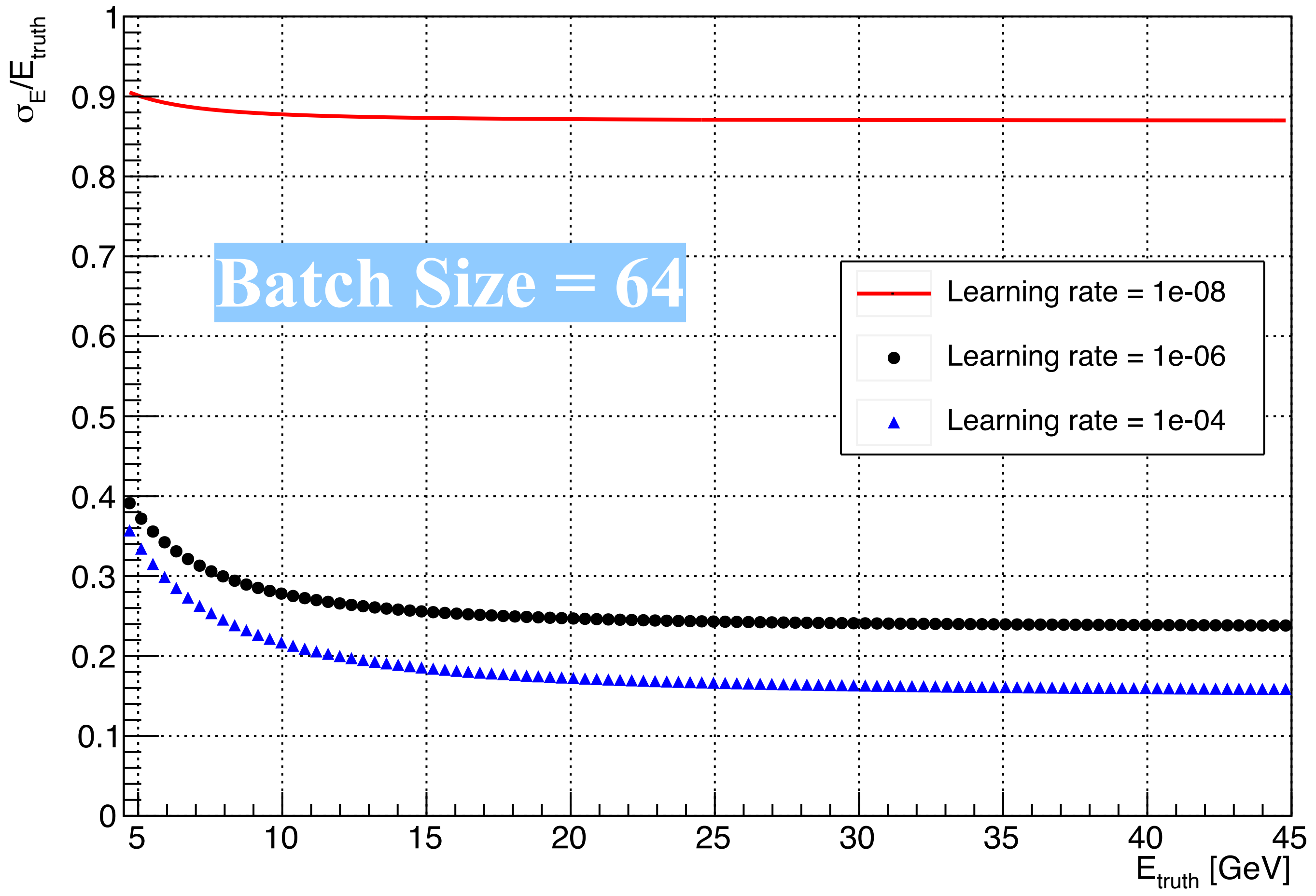


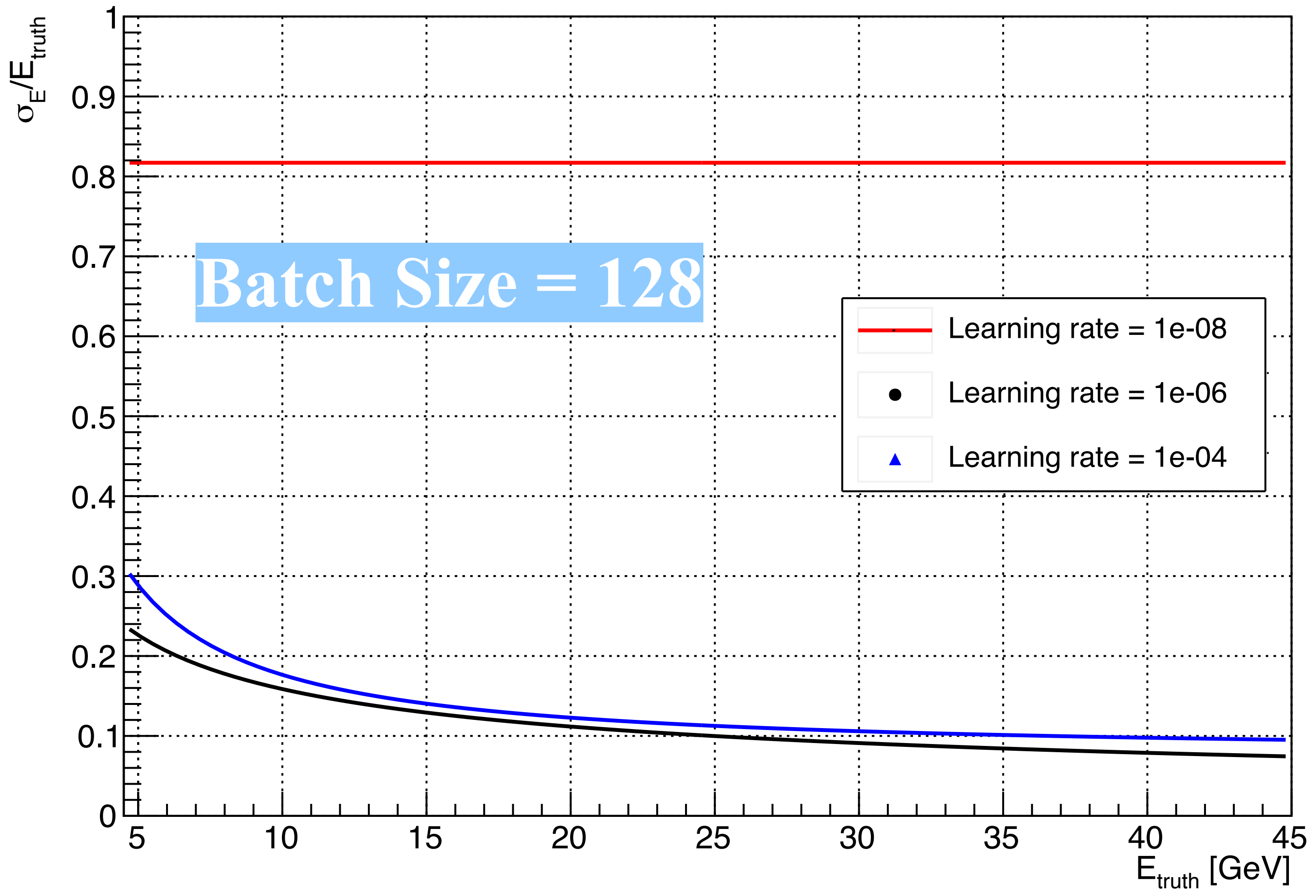
- Testing the CNN approach with zero padding
- Create numpy arrays with shape (N,N,d) where NxN is a matrix for the φ-θ granularity (100x100 bins) and d represents the features associated to each pixel: energy, x, y, z
- Discrimination between scintillating or Cherenkov fibres

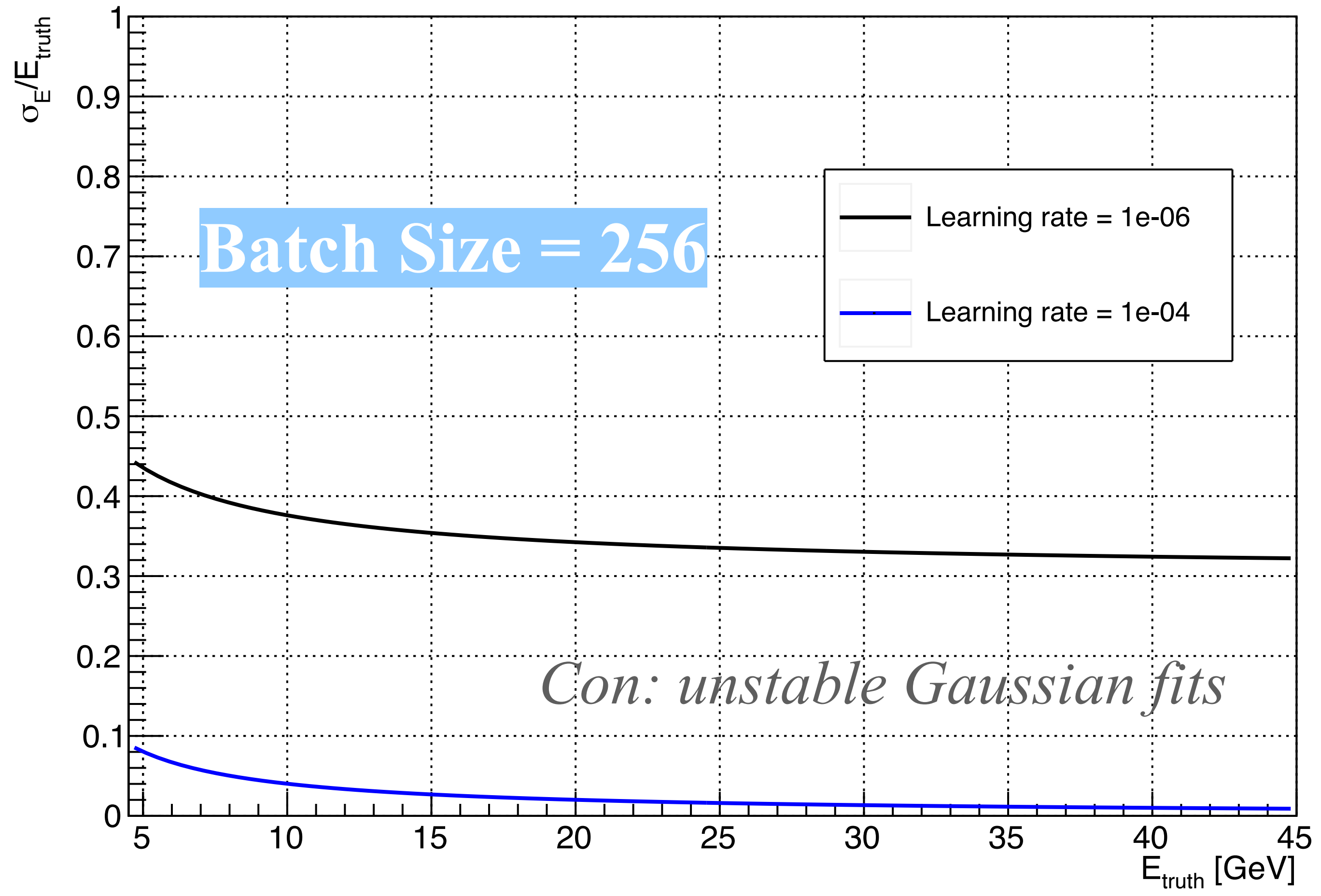
CNN approach: hyper-parameters optimisation

CNN approach
1. VGG-like architecture w/o proto-clustering

- Energy resolution used as figure of merit for batch size and learning rate optimisation







**Batch size: it is a number of samples processed before the model is updated*

**Learning rate: it is a hyper-parameter used to govern the pace at which an algorithm updates or learns the values of a parameter estimate*

CNN approach with proto-clustering

Clustering ?

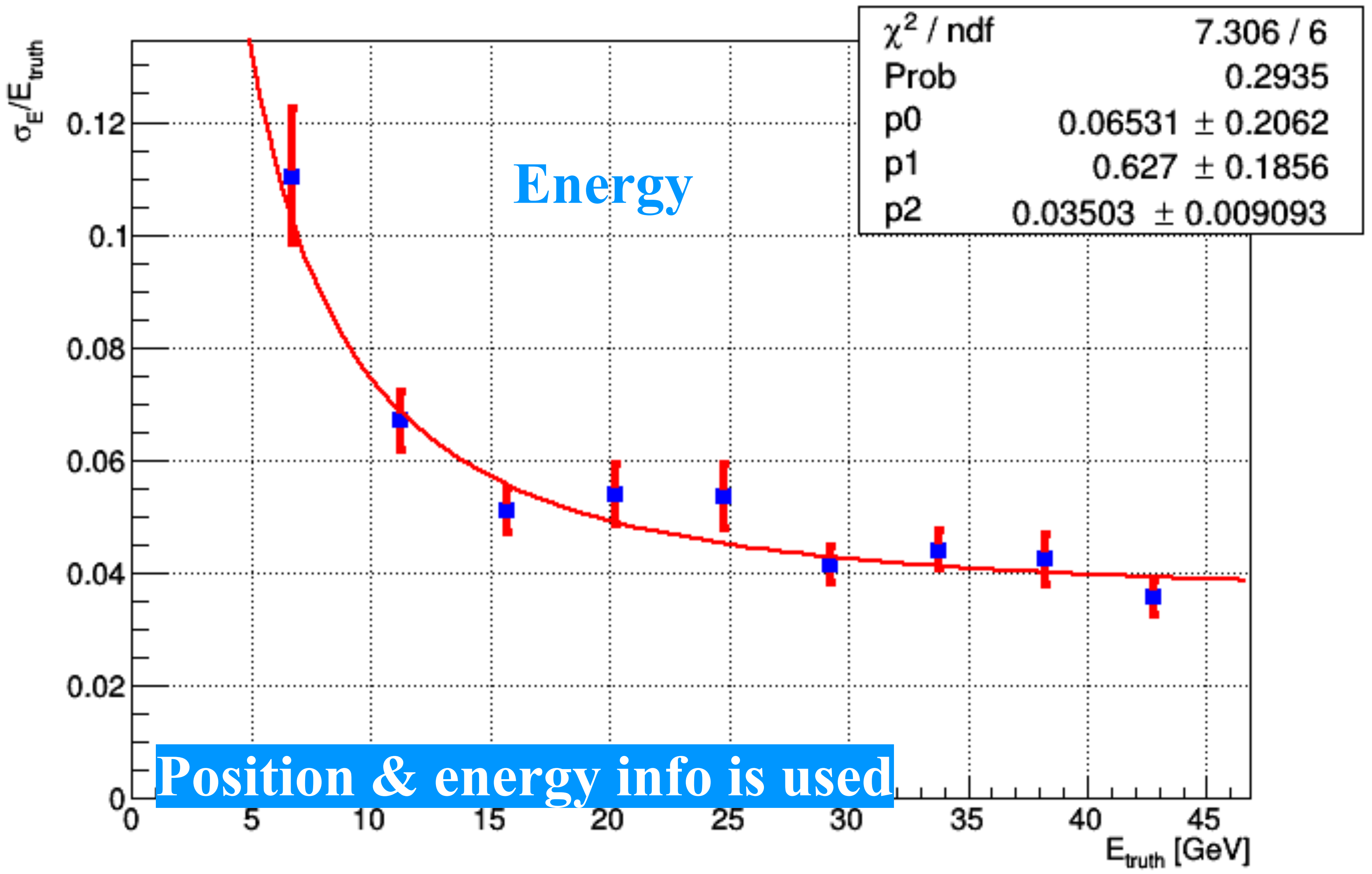
- **Clustering seems the obvious way to simplify conceptually the algorithm**

1. Identify energy deposits released by a single particle, collect them, and apply energy regression at cluster level;

2. Preliminary test: hit energy and distance wrt the centroid used as NN input

$$d_i = \mathrm{position(x, y, z)_i} - \frac{\sum_{i=0}^{i=N_{hits}} \left(\mathrm{position(x, y, z)_i} \cdot \mathrm{energy_i}\right)}{\sum_{i=0}^{i=N_{hits}} \mathrm{energy_i}}$$

3. Next step: exploit clustering algorithm in the Pandora framework

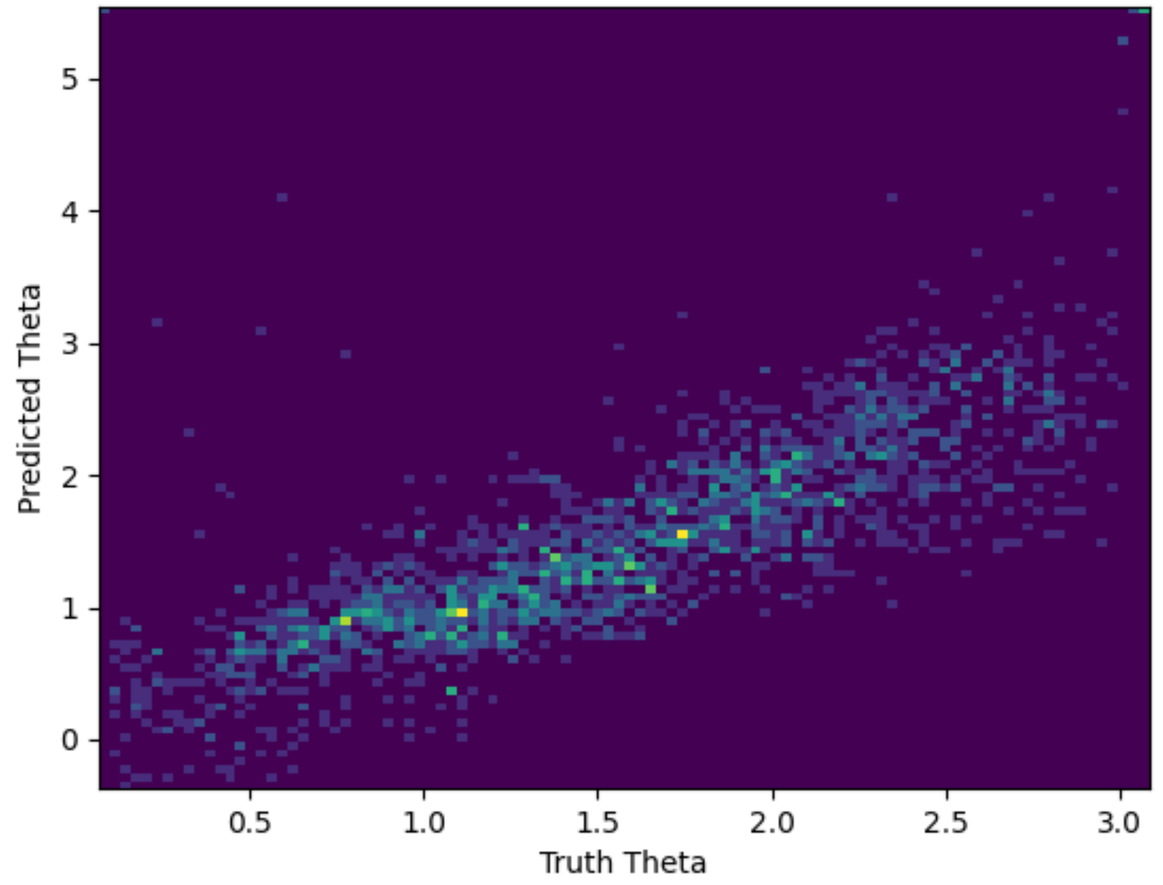


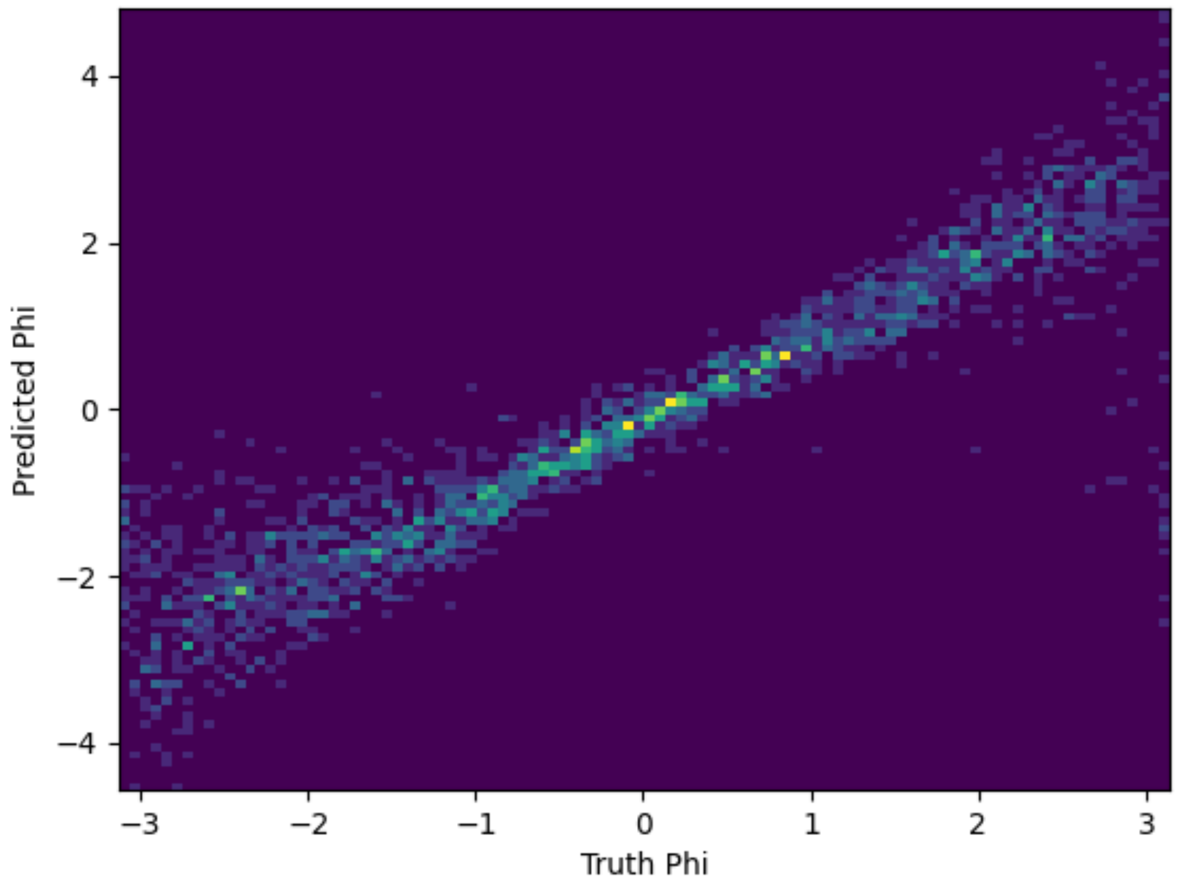
PFA with neural networks at Future Colliders

CNN approach: angular resolution

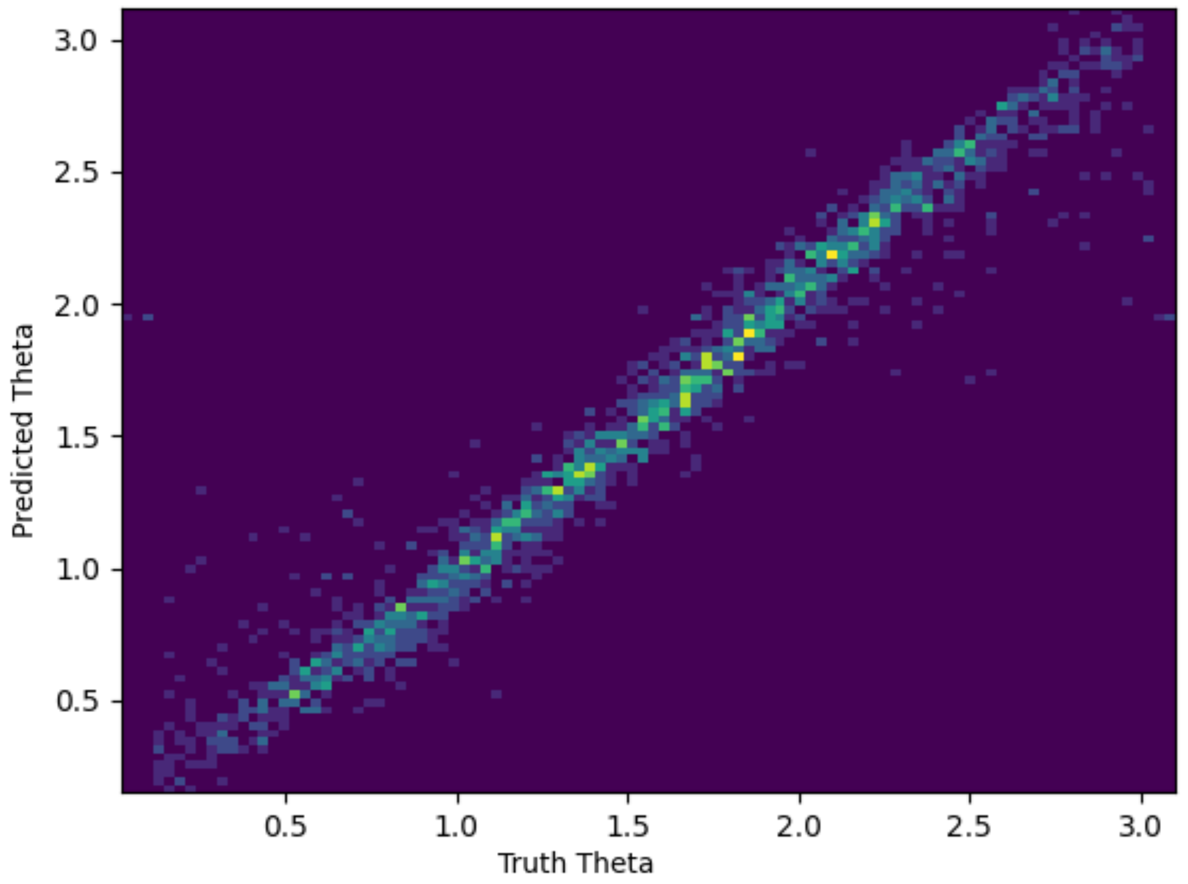
- Improvements observed if a proto-clustering is applied

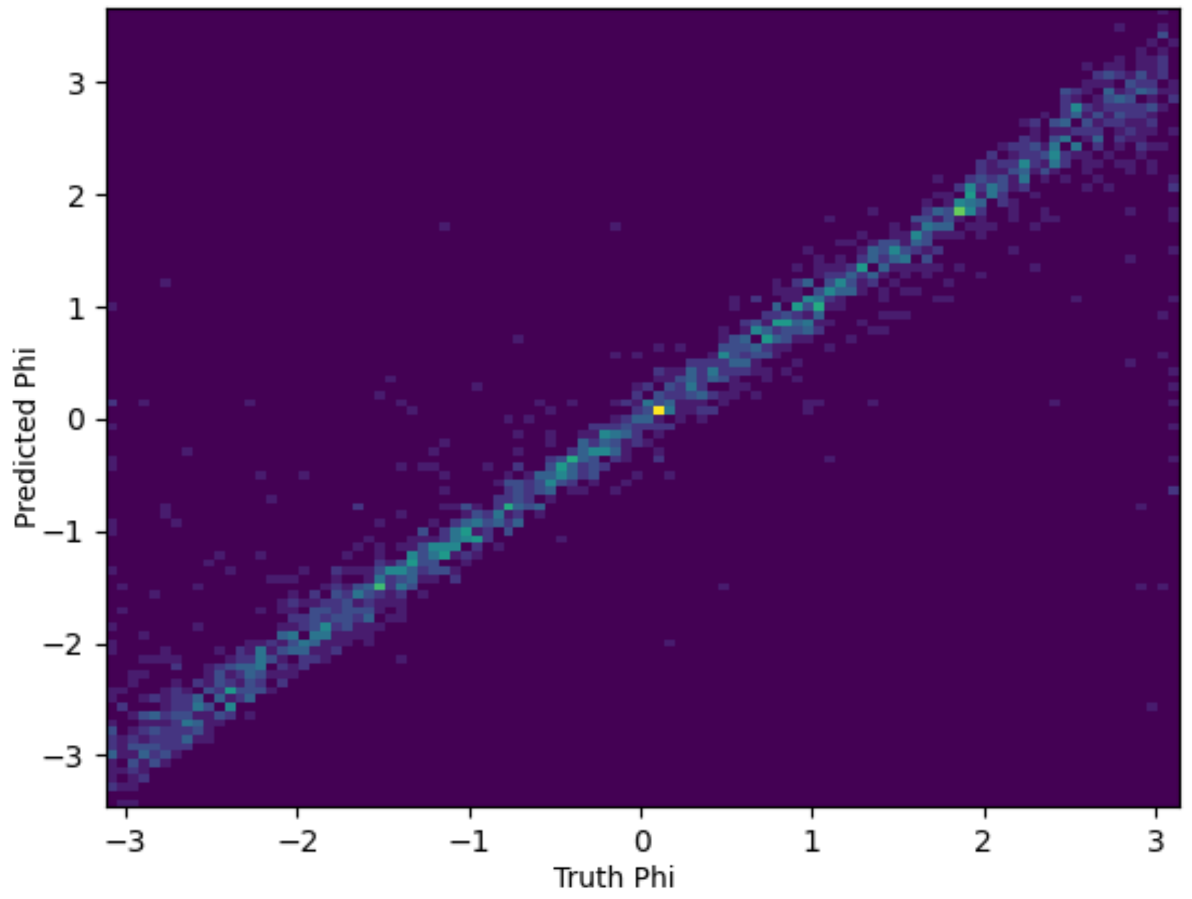
CNN approach
1. **VGG-like architecture w/o proto-clustering**





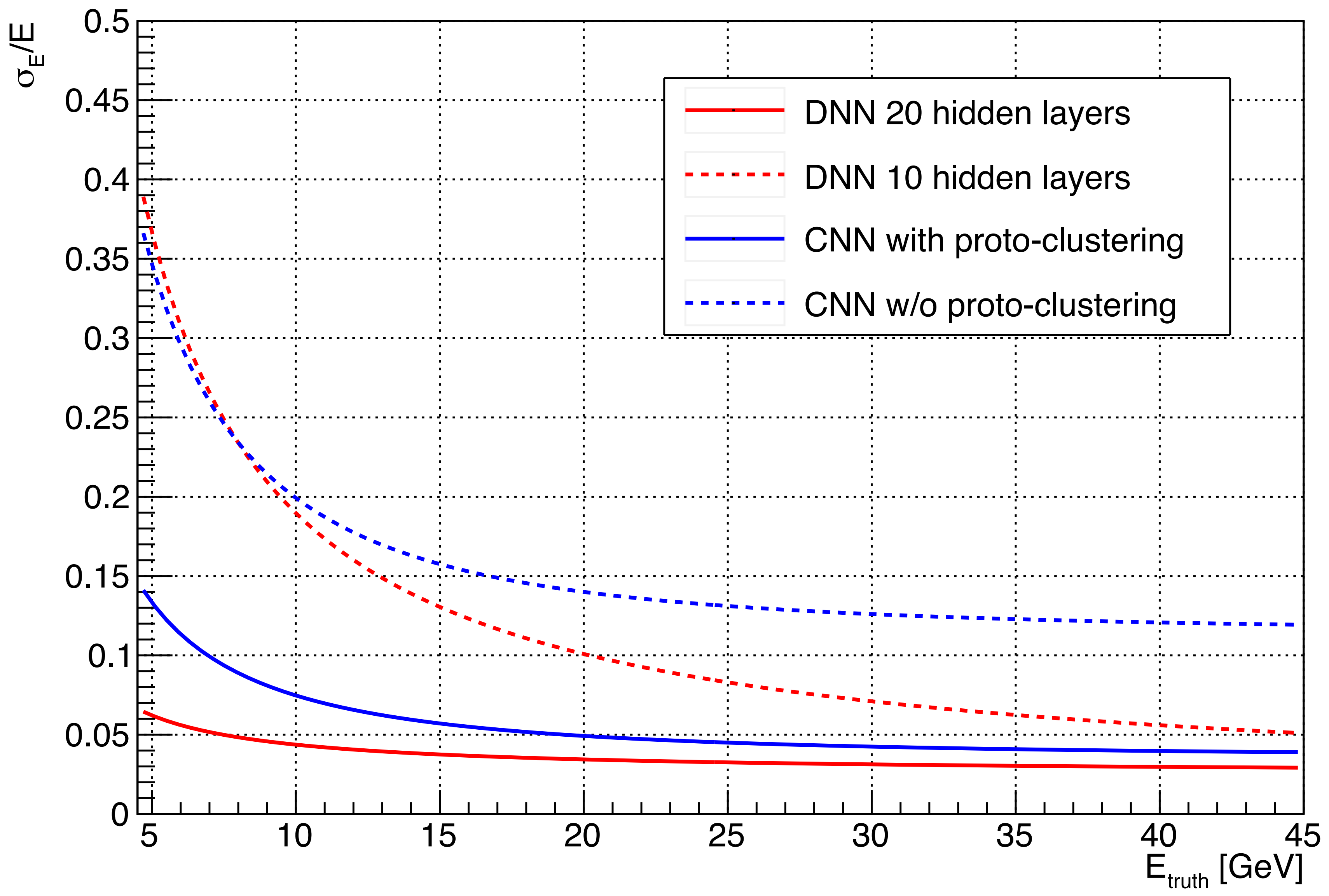
CNN approach
2. **VGG-like architecture with proto-clustering**





Conclusions & next steps

- 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
- The simulation works, the machinery for the PFA is in place and the first distributions are reasonable using electrons as input
  - The CNN approach seems reasonable, especially considering the angular resolution
  - Next step in the early future: test a GNN approach
- Determine the energy and position resolution from NN, for electrons
- Repeat the above procedure also for π, K, μ, γ
- Plan to move to Pytorch for better optimisation with Pandora
- Long term goal: NN-based particle identification and jets reconstruction

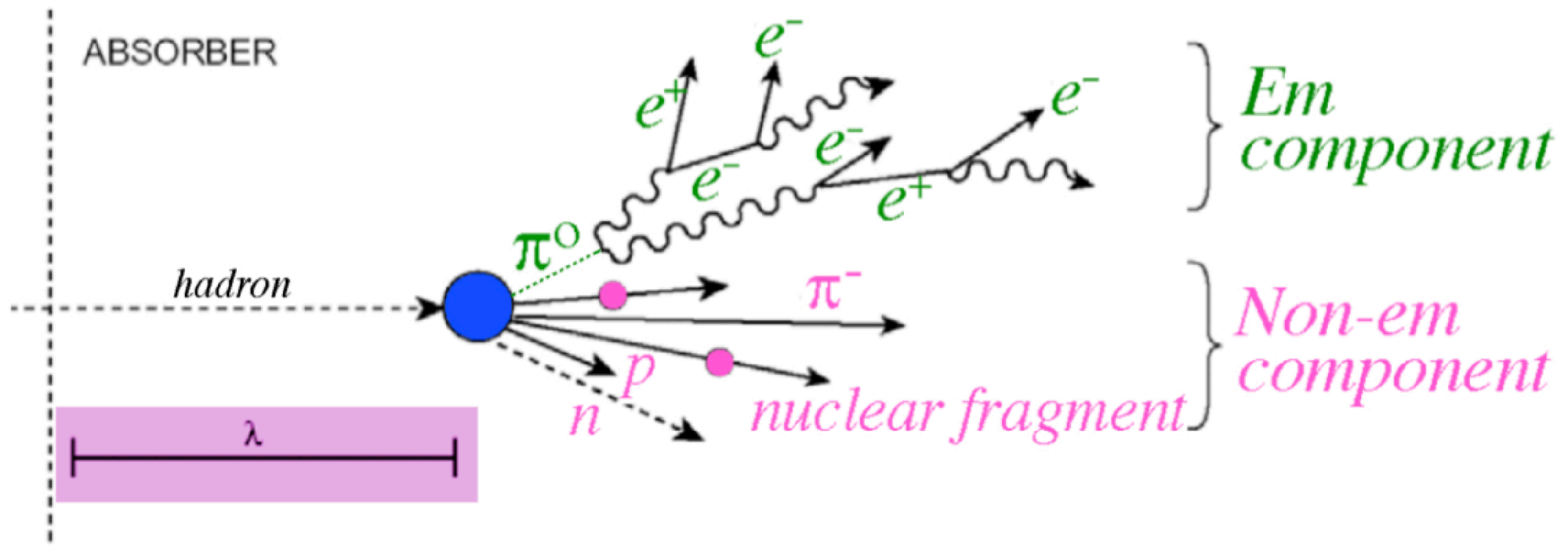


Thanks for listening

Back-Up Slides

Energy Measurement in DR Calorimeters

- **Non-compensating calorimeters**: response to EM part different from that to non-EM part.
- The response ratio for electrons and charged hadrons is: $\frac{h}{e} = \eta < 1$
- The EM fraction of the shower, $< f_{em} >$, is energy dependent $\Rightarrow$ Non-linear calorimeter **response** to hadrons
- $< f_{em} >$ fluctuations largely determine energy **resolution** $\Rightarrow$ sampling the hadronic shower with two calorimeters with different *e/h* **boosts energy resolution**

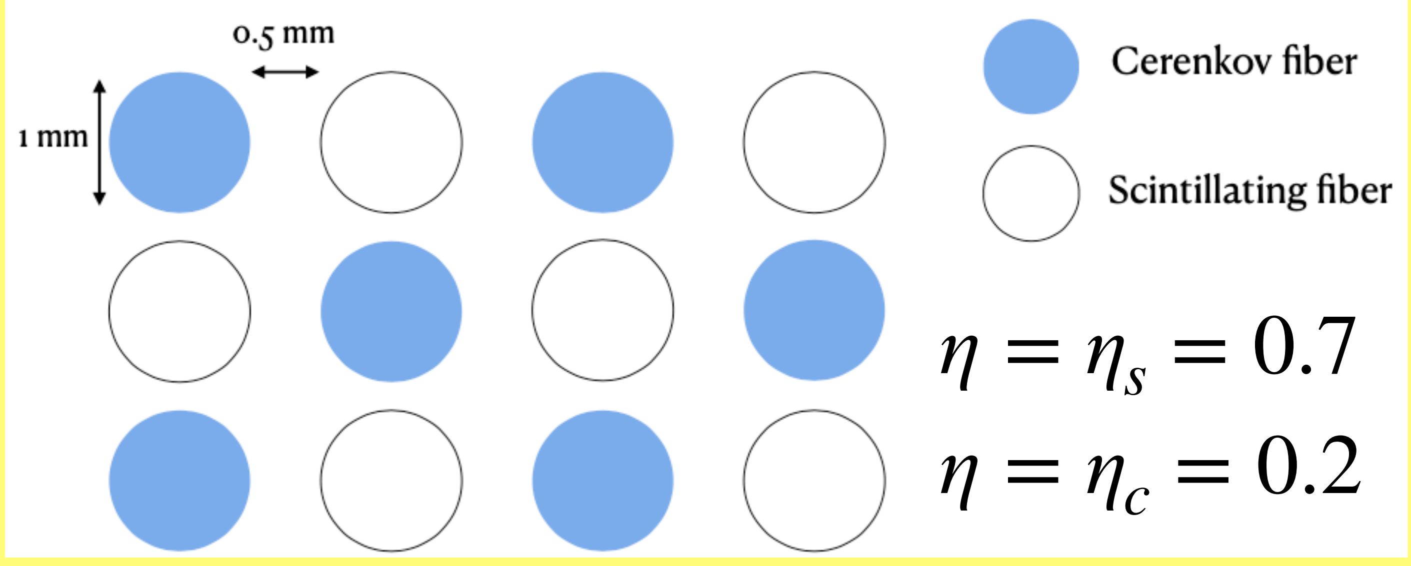


Hadron shower

$$S = E\left[f_{em} + \eta_s \cdot (1 - f_{em})\right]$$

$$C = E\left[f_{em} + \eta_c \cdot (1 - f_{em})\right]$$

$$\Rightarrow \quad \frac{C}{S} = \frac{\left[f_{em} + \eta_c \cdot (1 - f_{em})\right]}{\left[f_{em} + \eta_s \cdot (1 - f_{em})\right]}$$

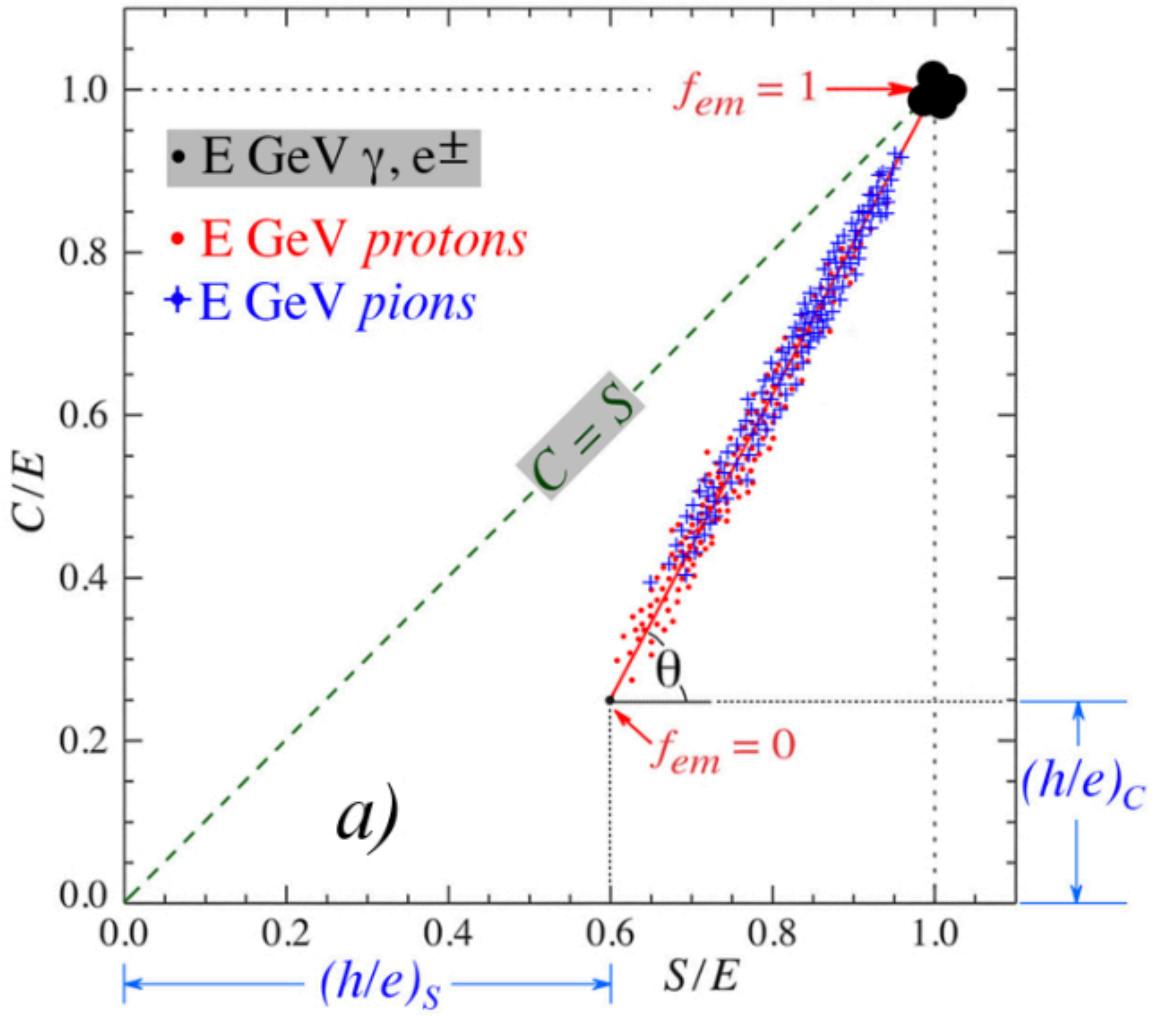


$$\eta = \eta_s = 0.7$$

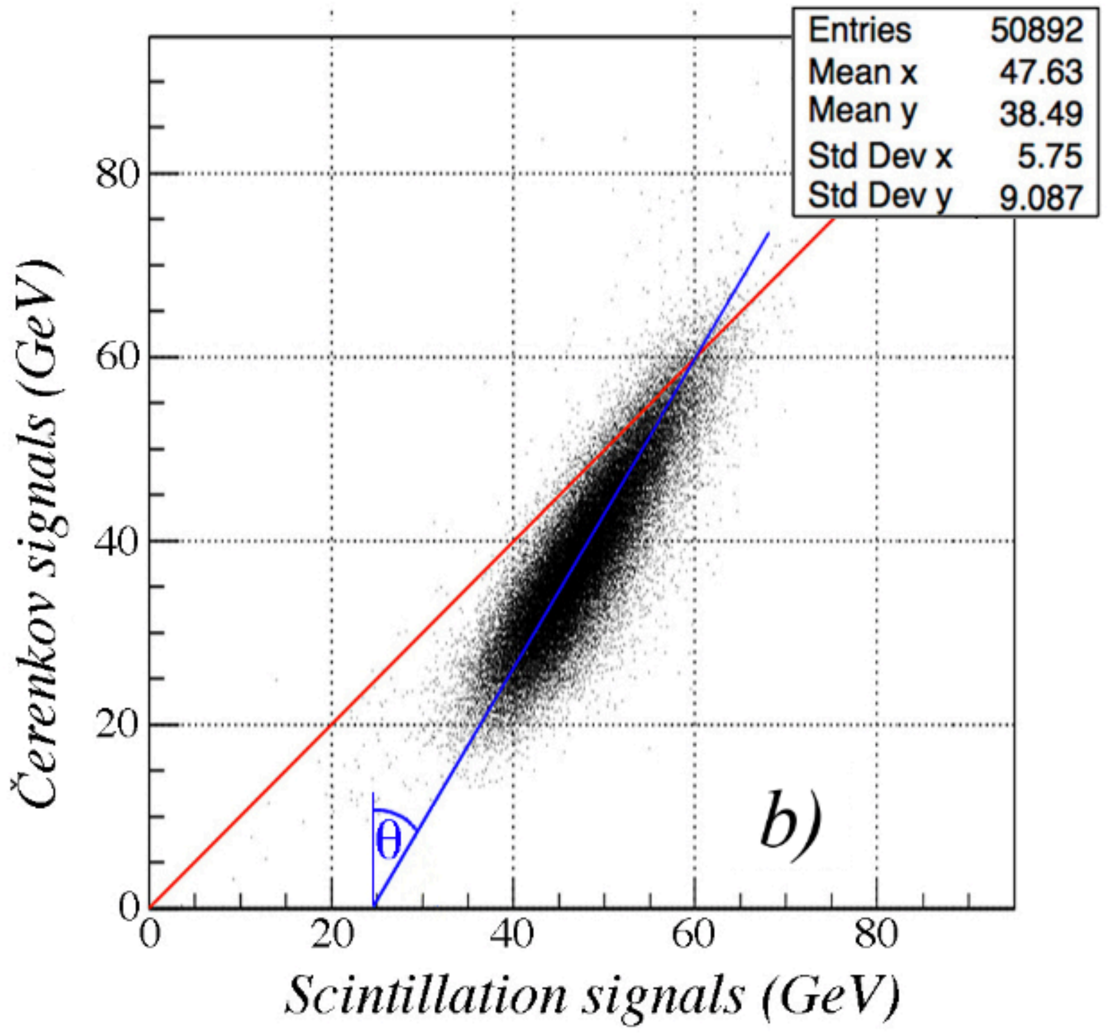
$$\eta = \eta_c = 0.2$$

$$\chi = \frac{1 - \eta_s}{1 - \eta_c} = \cot(\theta)$$

$$E = \frac{S - \chi C}{1 - \chi}$$

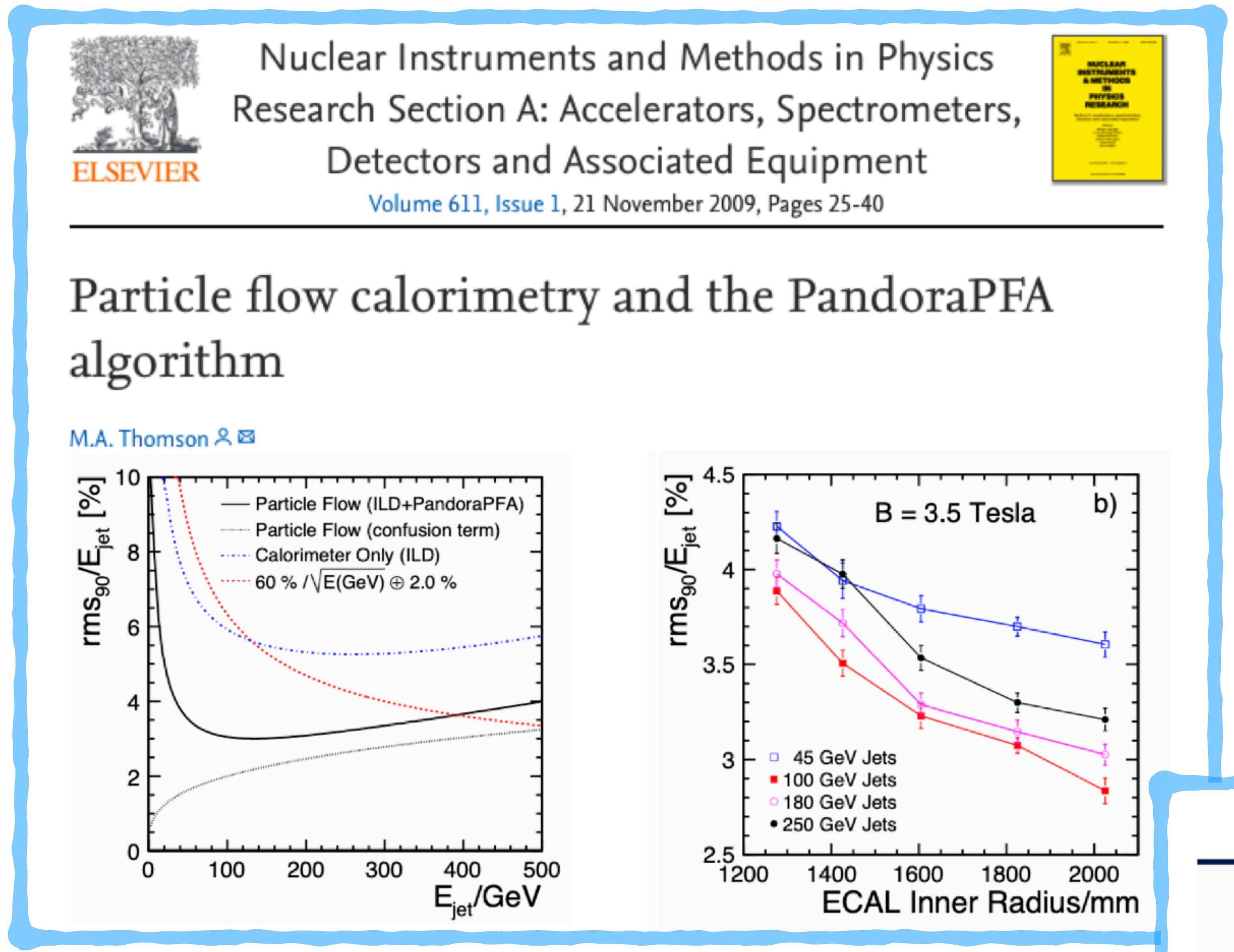


a) **Scatter plot of C/E versus S/E in a dual-readout calorimeter for p and π**



b) **Scatter plot of C and S signals for 60 GeV pions in the RD52 lead-fiber calorimeter**

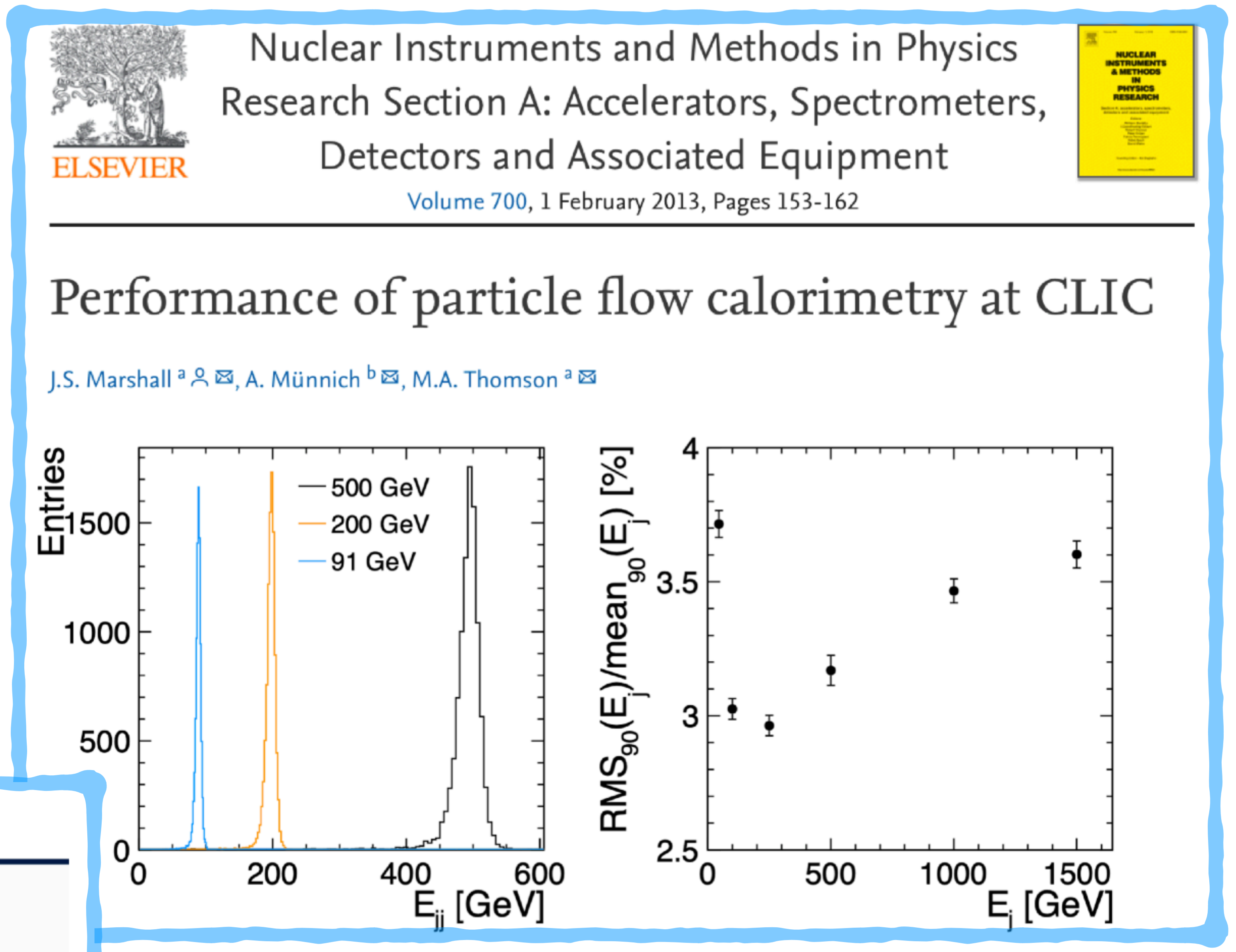
Examples of PFA at ILC/CLIC


Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 611, Issue 1, 21 November 2009, Pages 25-40

Particle flow calorimetry and the PandoraPFA algorithm

M.A. Thomson

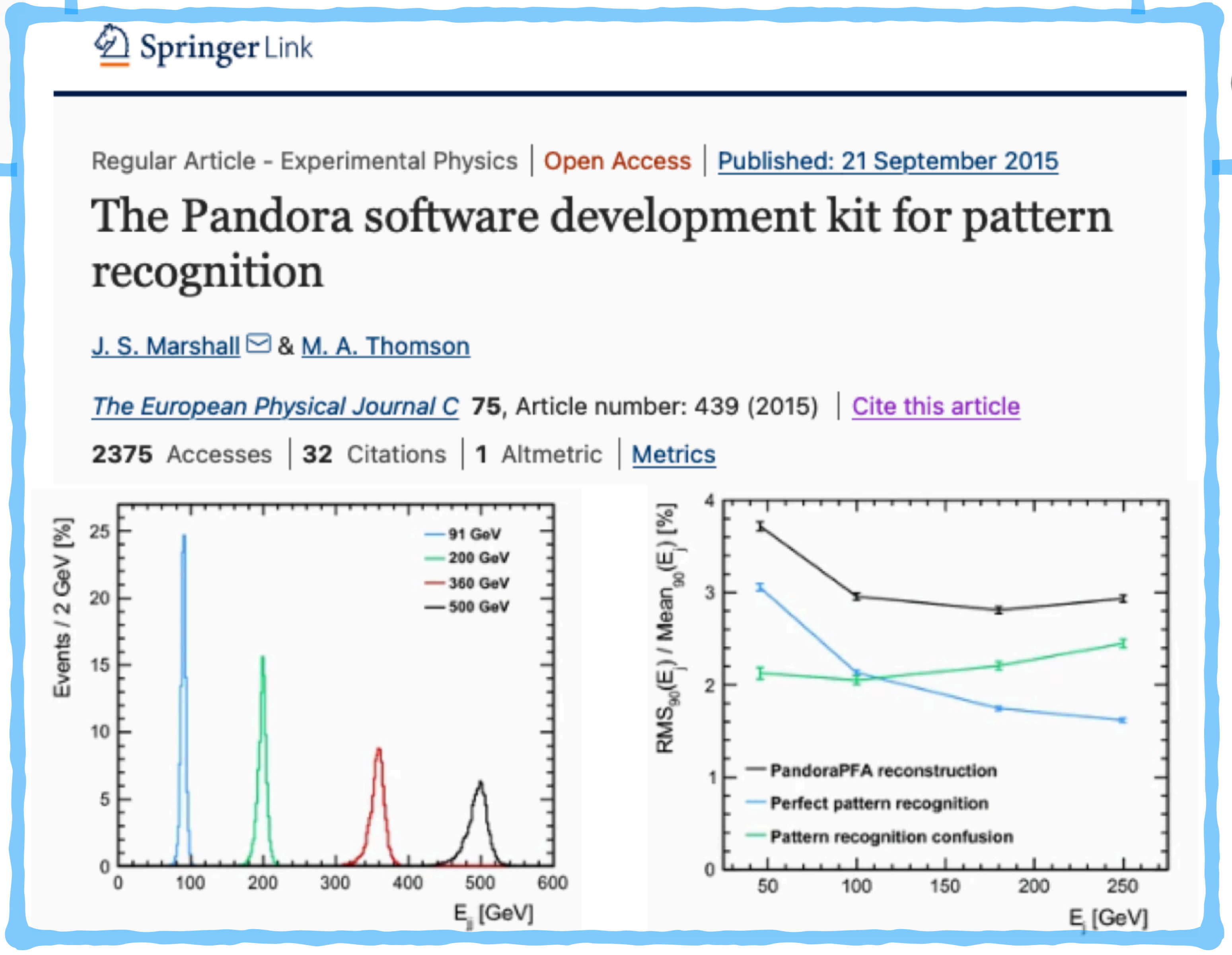
Nucl. Instrum. Meth.A611, 25 (2009)


Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment
Volume 700, 1 February 2013, Pages 153-162

Performance of particle flow calorimetry at CLIC

J.S. Marshall [a], A. Münnich [b], M.A. Thomson [a]

Nucl. Instrum. Meth.A700, 153 (2013)


SpringerLink

Regular Article - Experimental Physics | Open Access | Published: 21 September 2015

The Pandora software development kit for pattern recognition

J. S. Marshall & M. A. Thomson

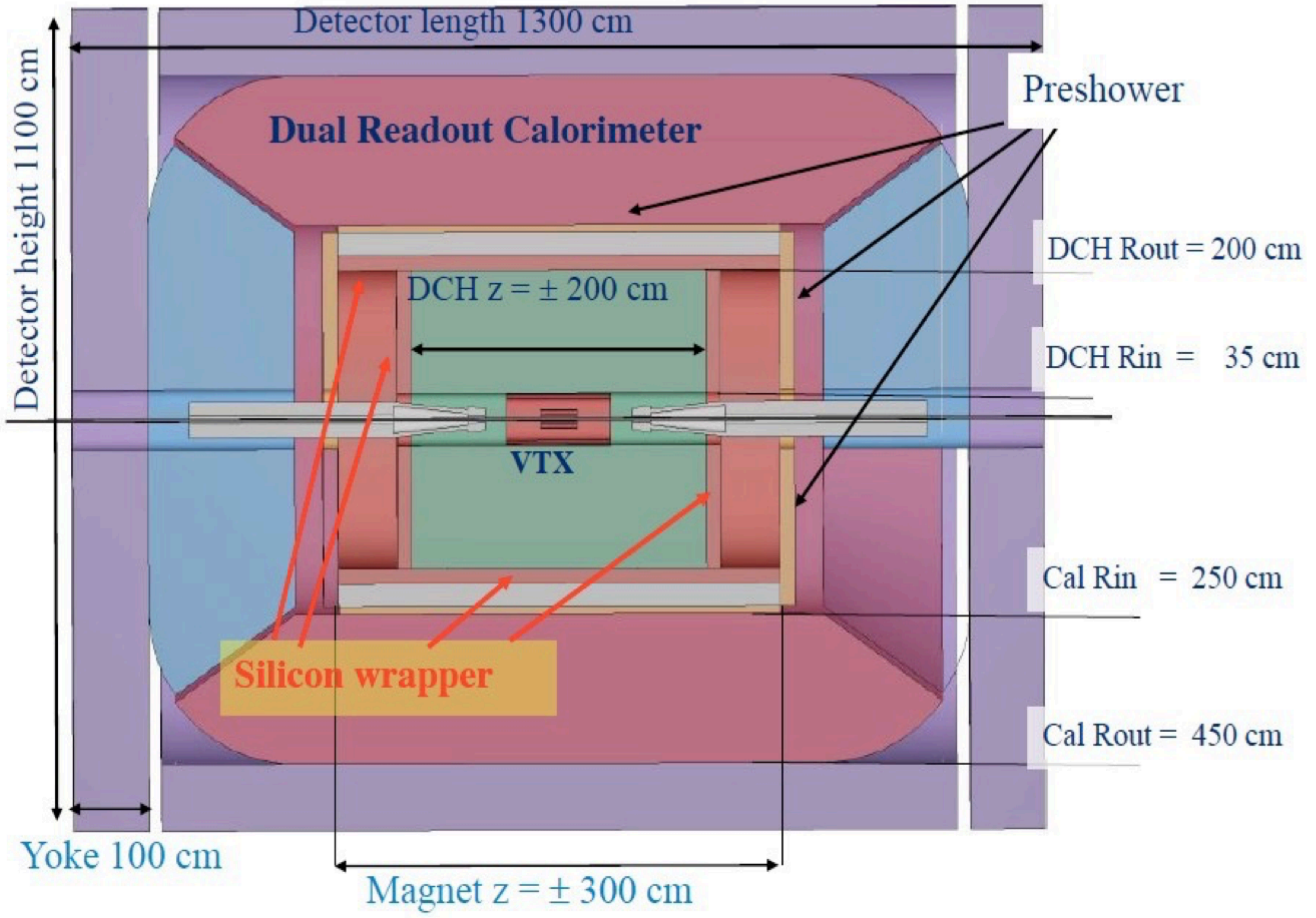
The European Physical Journal C 75, Article number: 439 (2015) | Cite this article

2375 Accesses | 32 Citations | 1 Altmetric | Metrics

Eur. Phys. J. C 75, 439 (2015)

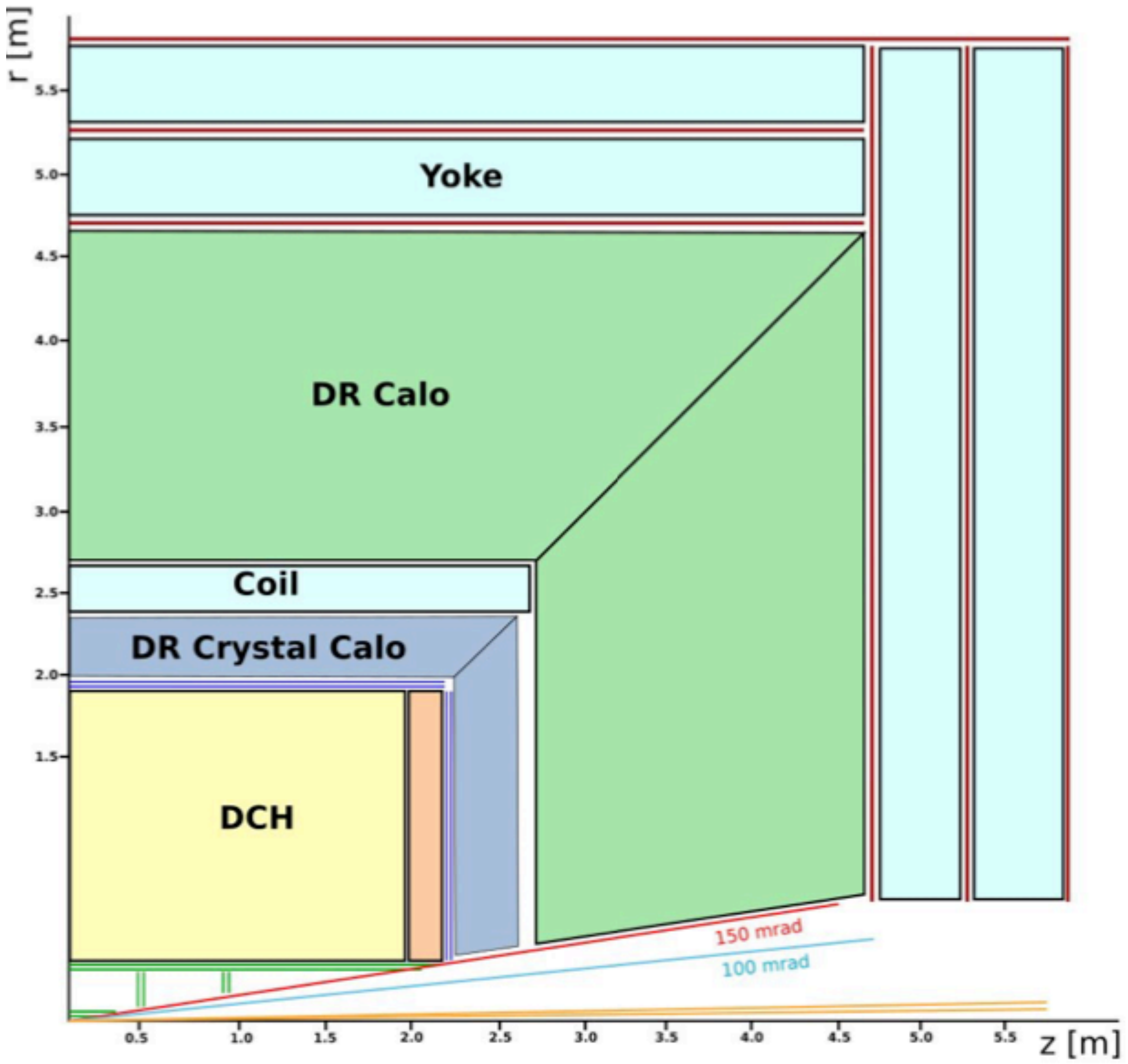
The IDEA detector at FCCee collider

- 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



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



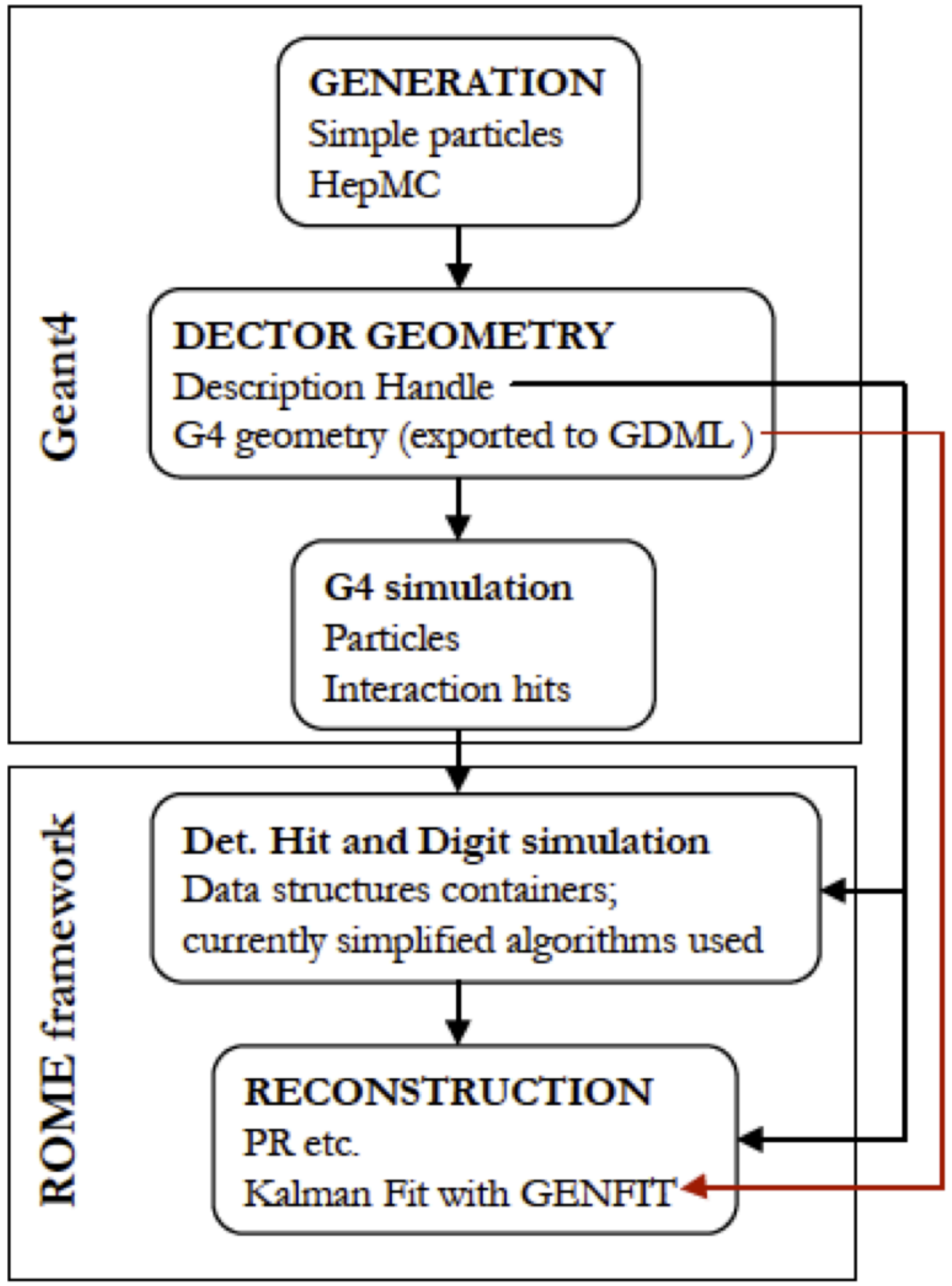
Full detector simulation

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

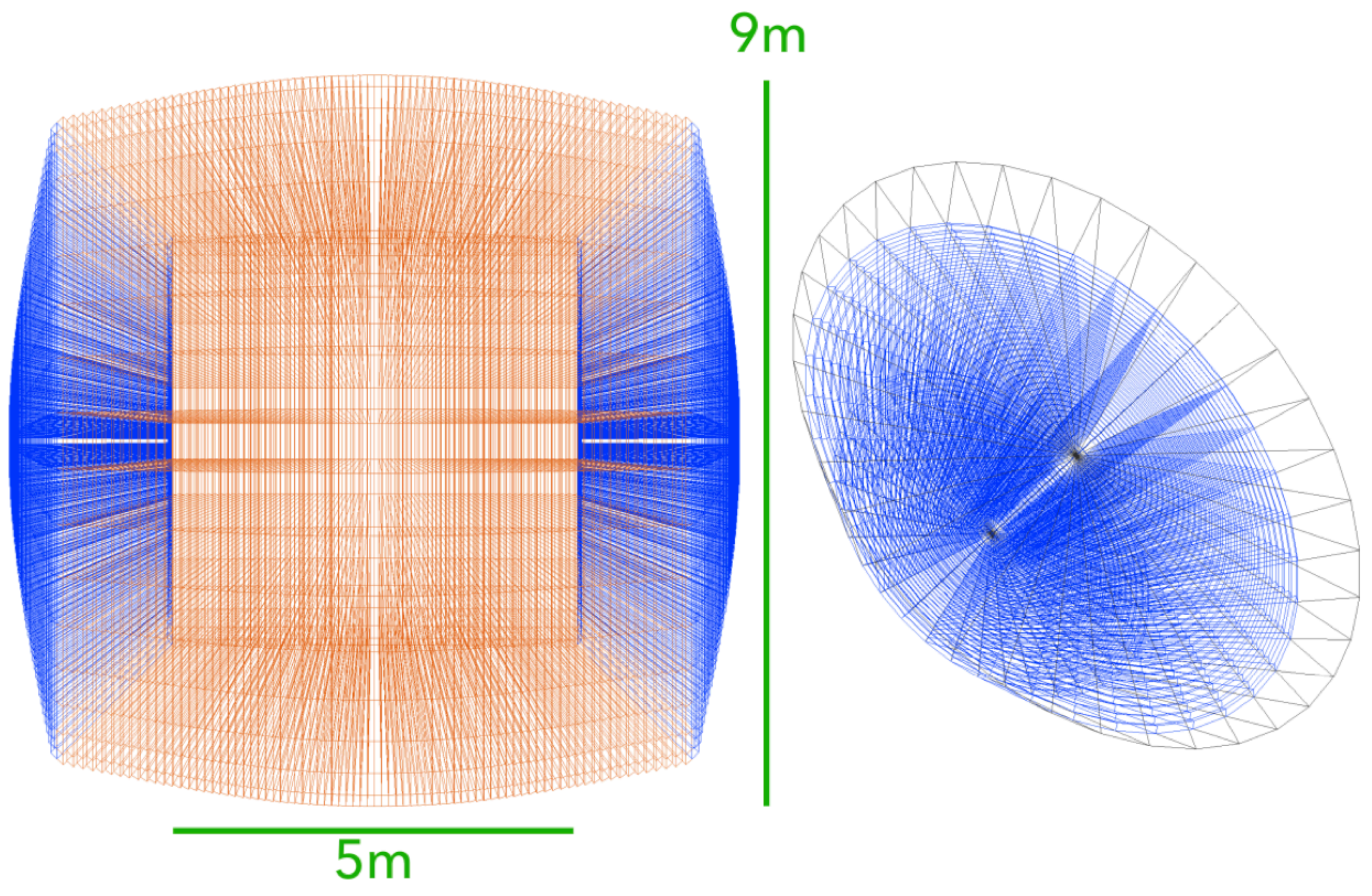
- **GEANT4 is our starting point** and the standalone code was adapted for compilation on key4hep stack on CERN lxplus machines (source /cvmfs/sw.hsf.org/key4hep/setup.sh)
- **https://github.com/HEP-FCC/IDEADetectorSIM**

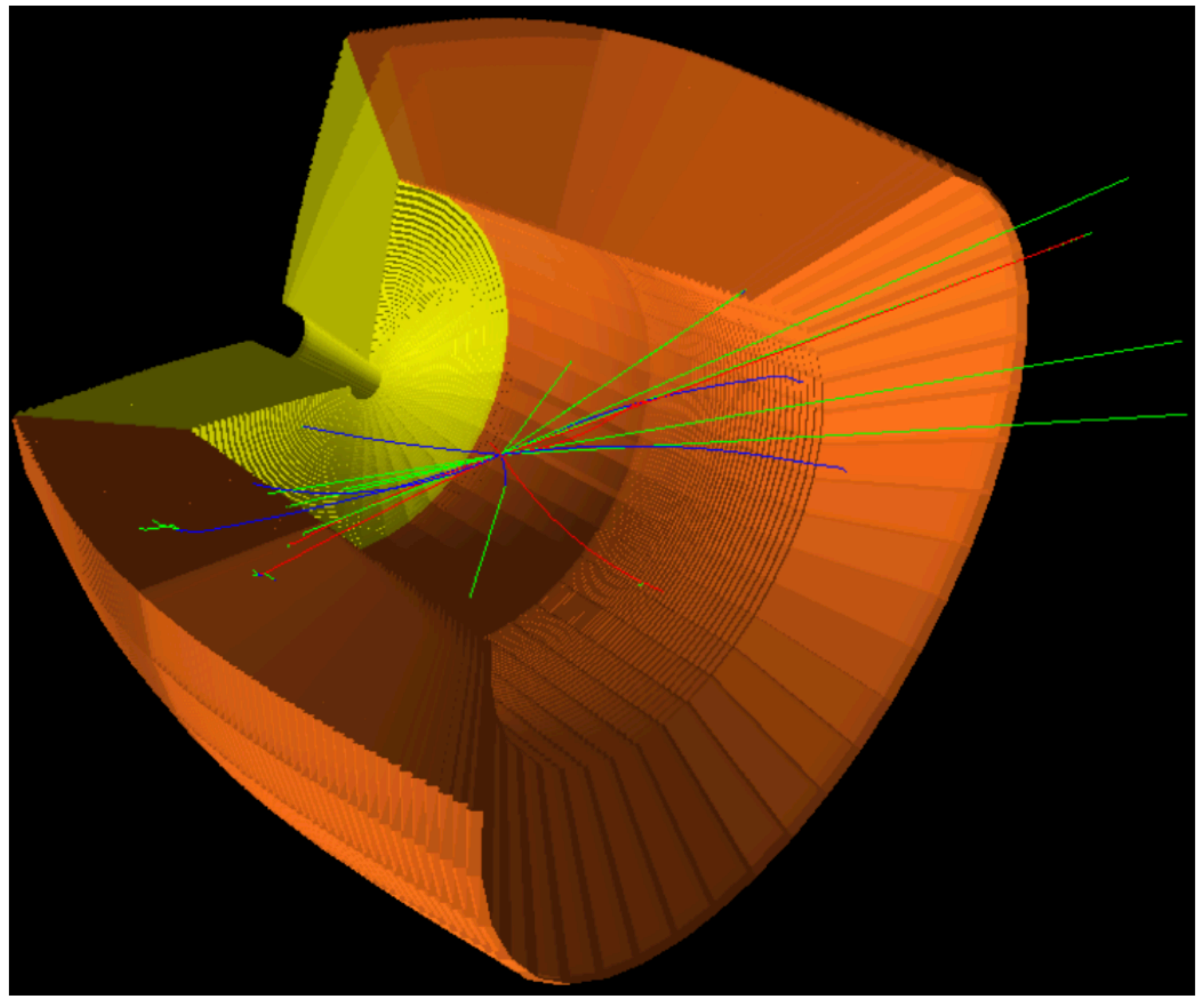


GEANT4 simulation - DR Calorimeter

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°



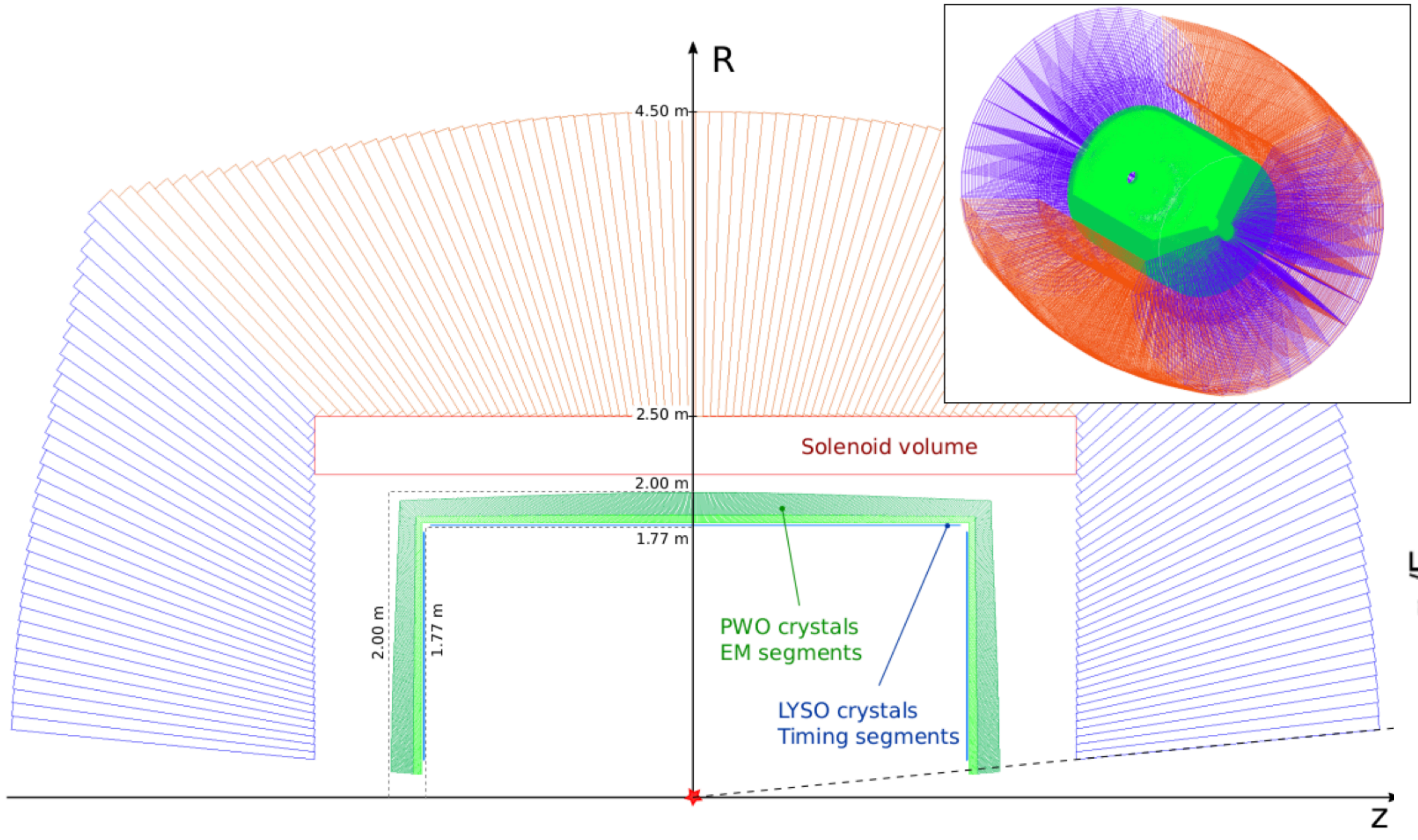


Expected performances

- 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

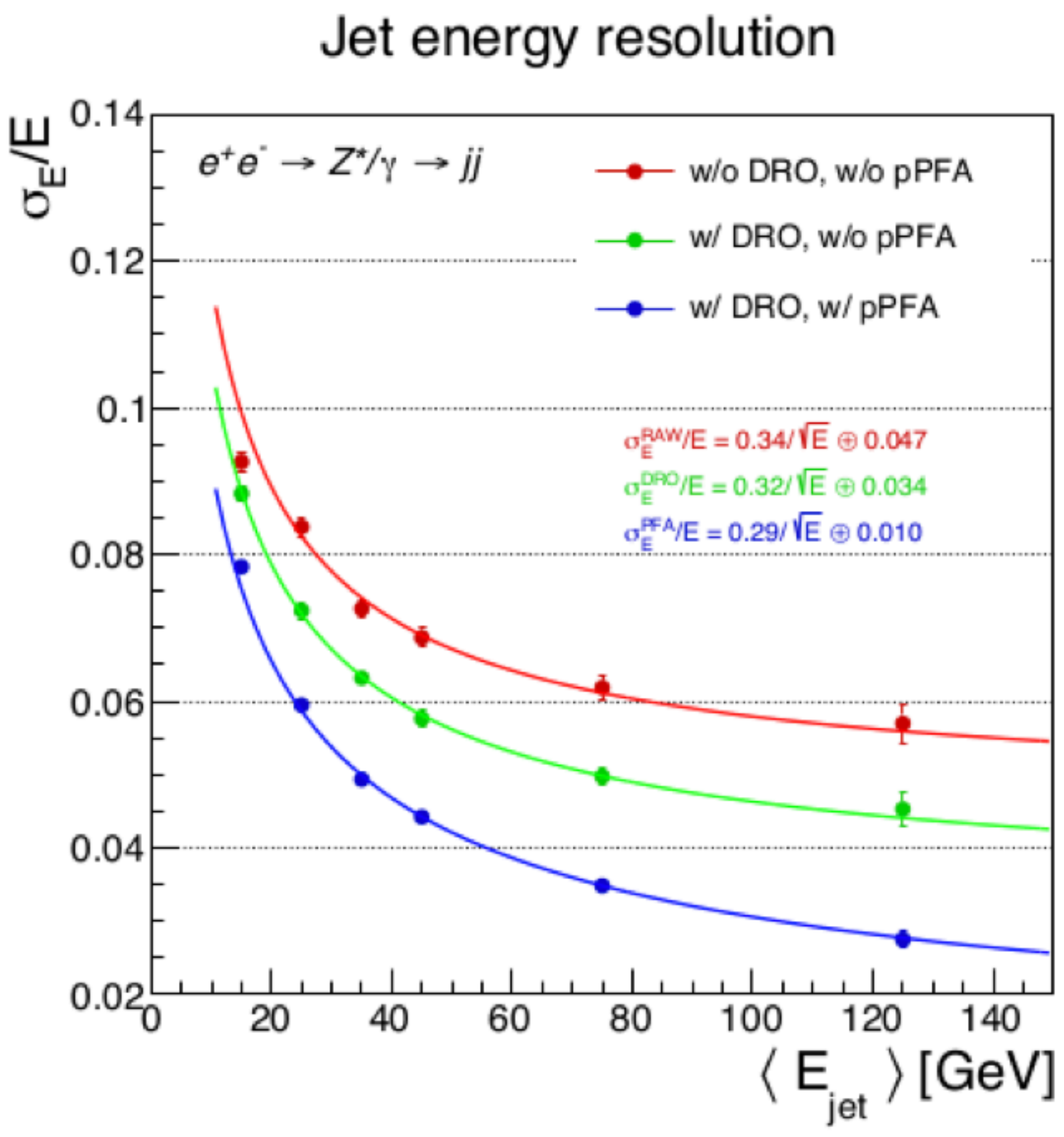
PFA with neural networks at Future Colliders

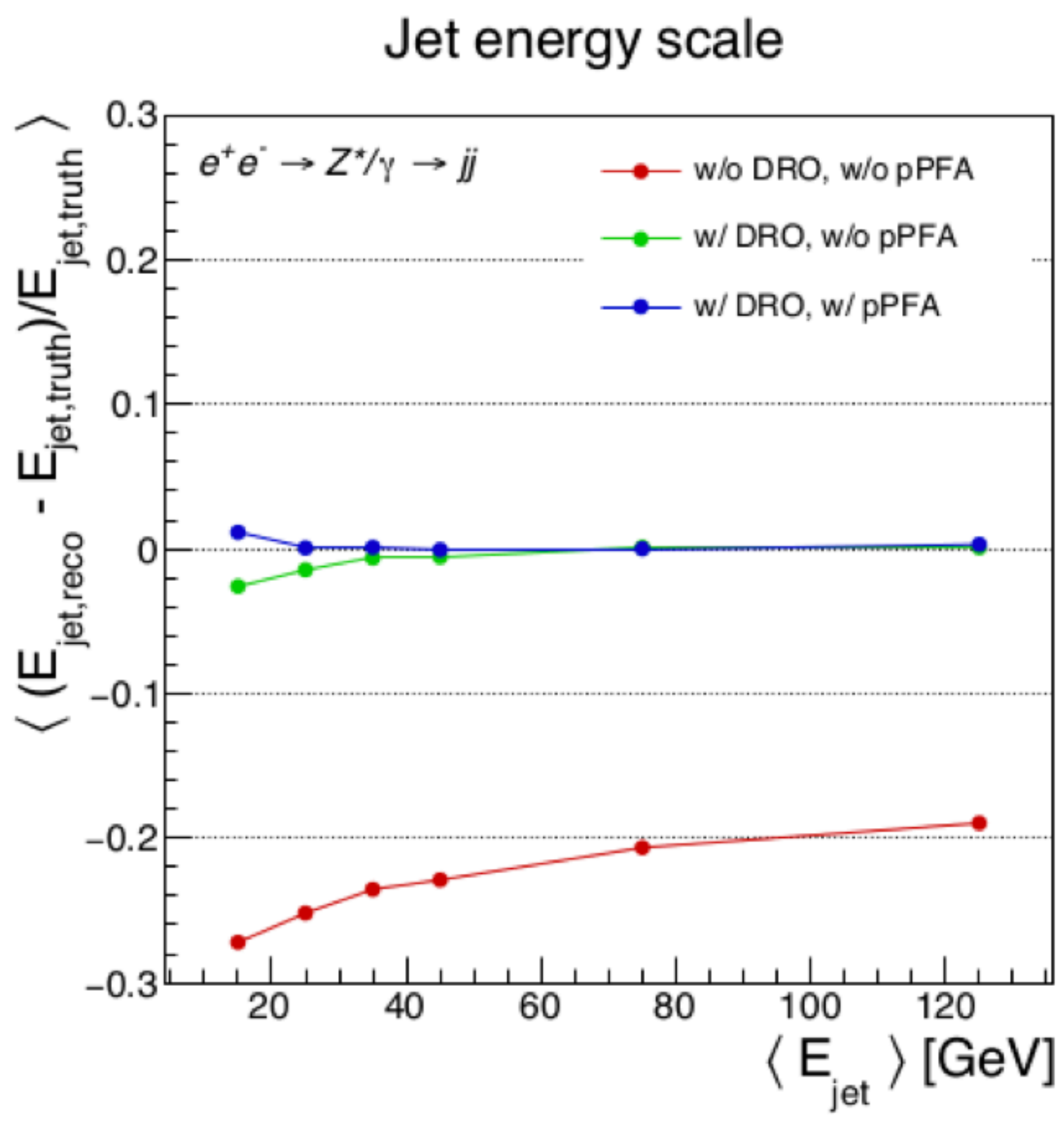
GEANT4 simulation - DR Calorimeter & crystals



- 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





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

Standalone

Geant4 Monte Carlo hits
(possible other data structures)
reconstructed tracks

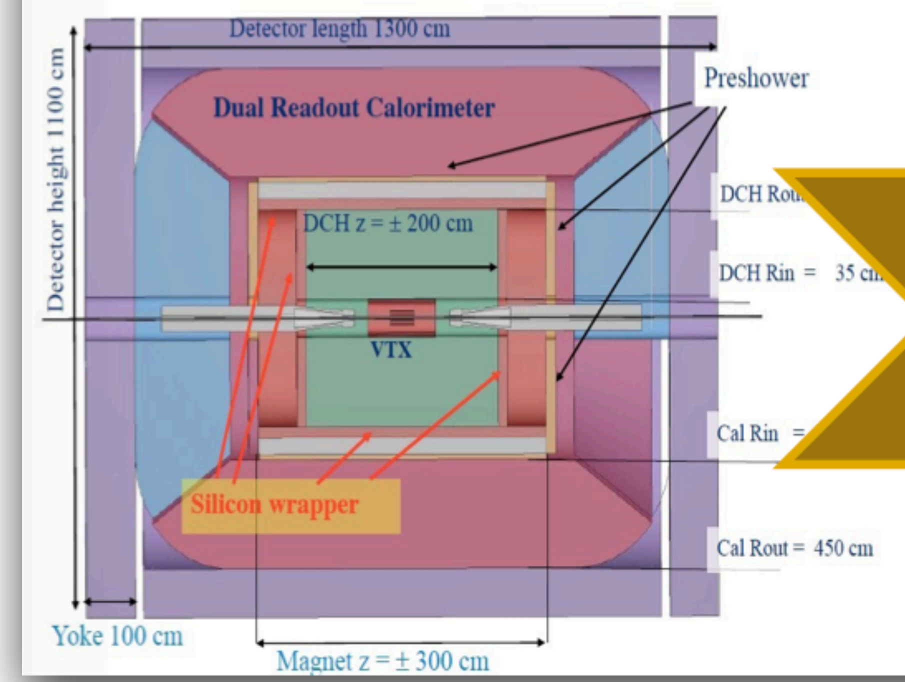
done

Covert to

FCC framework

EDM4HEP

simulation + reconstruction

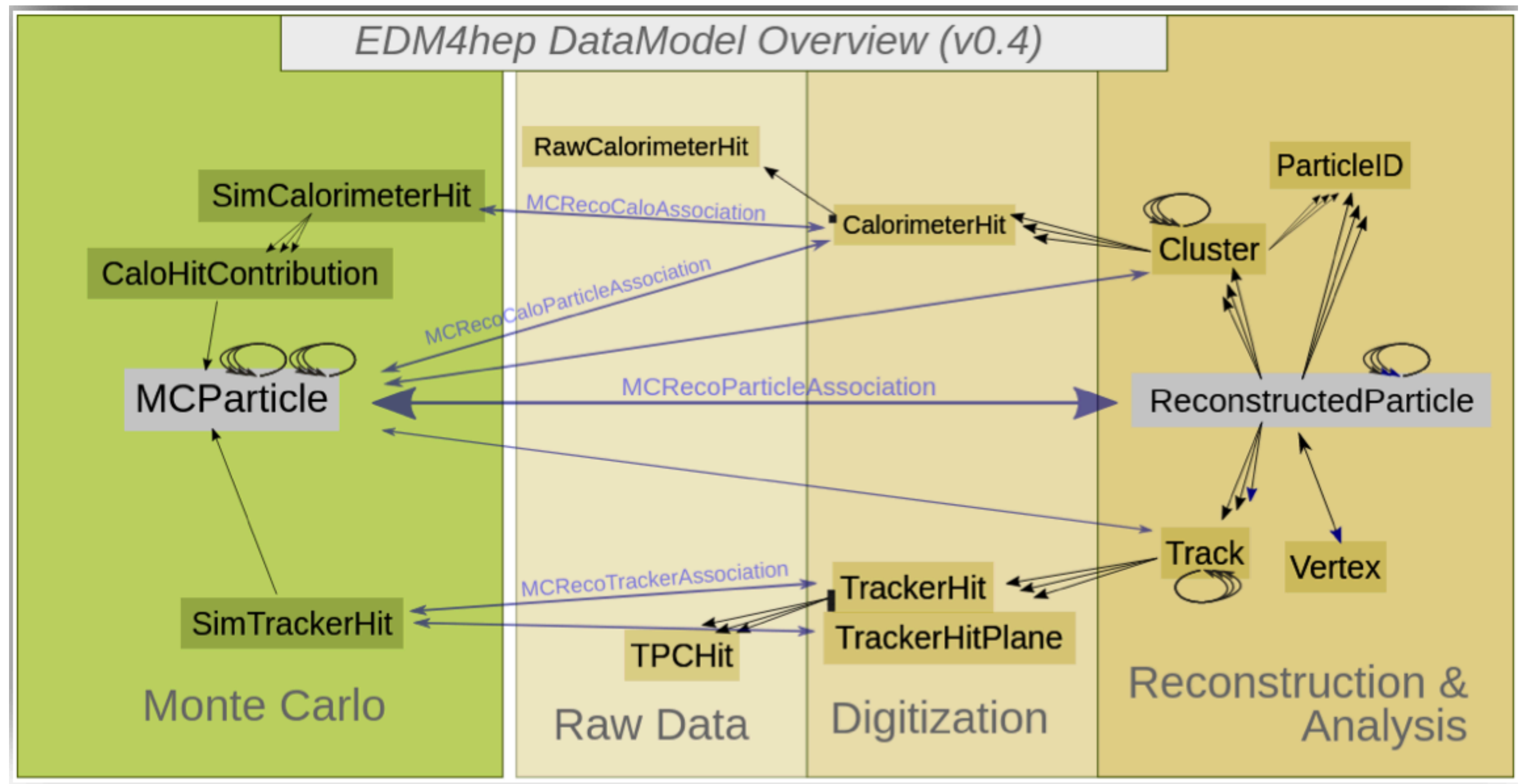


In progress

port the geometry
port the algorithms
port the data format

Key4HEP

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



Key4HEP

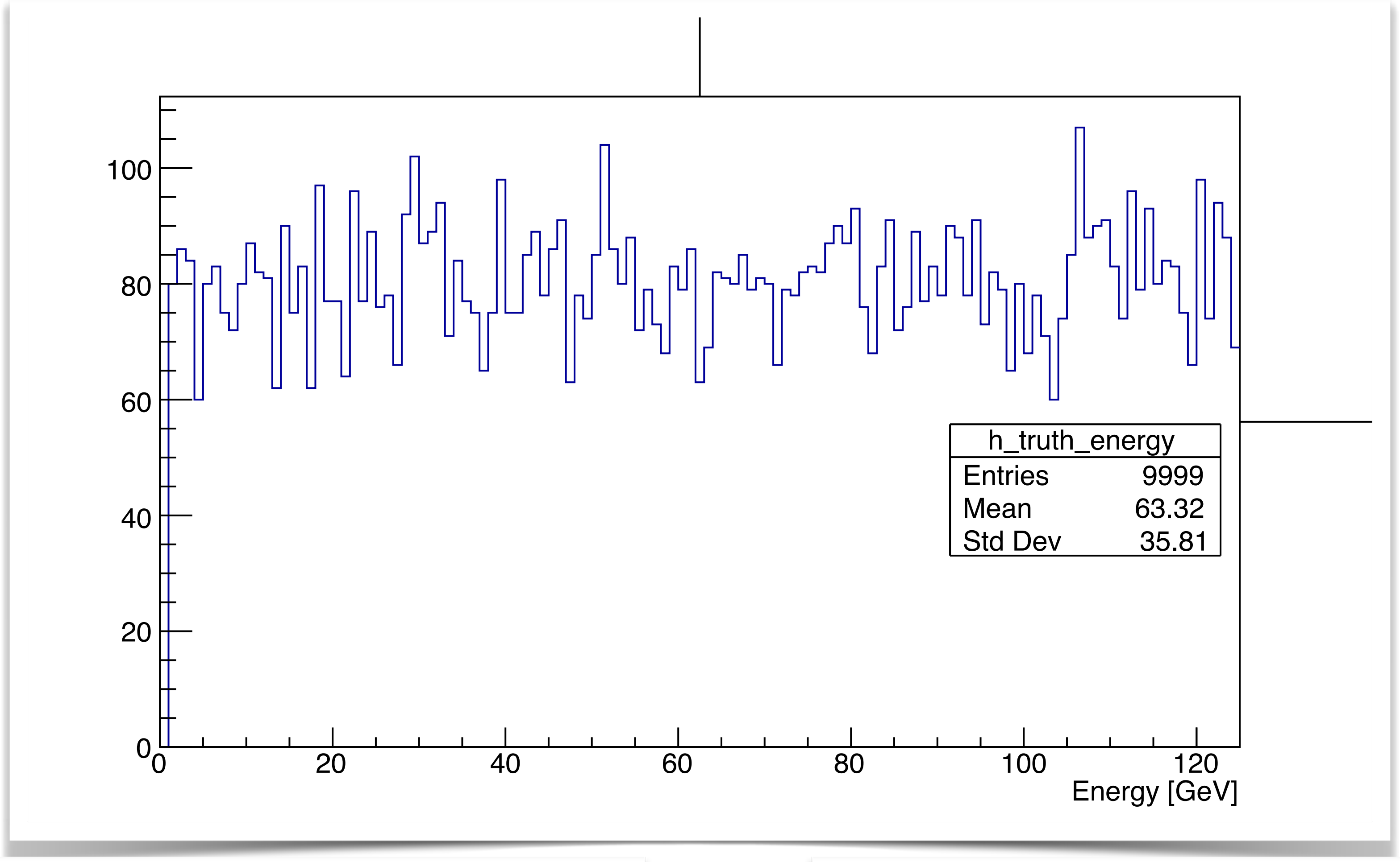
- key4HEP: general software framework developed for many experiments *https://github.com/key4hep*
    - GEANT4 implementation in key4hep already started

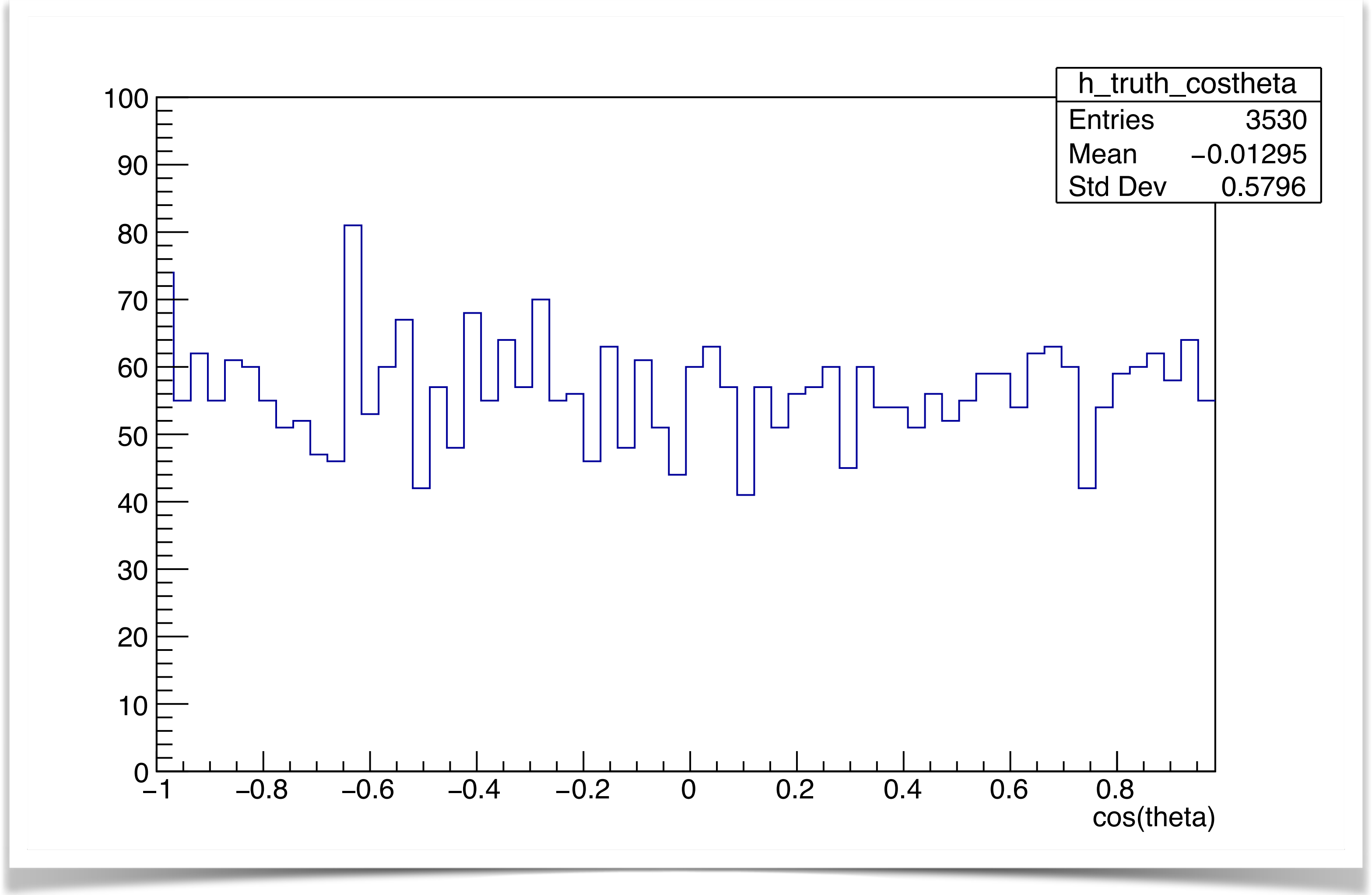
Kinematic distributions - Electrons

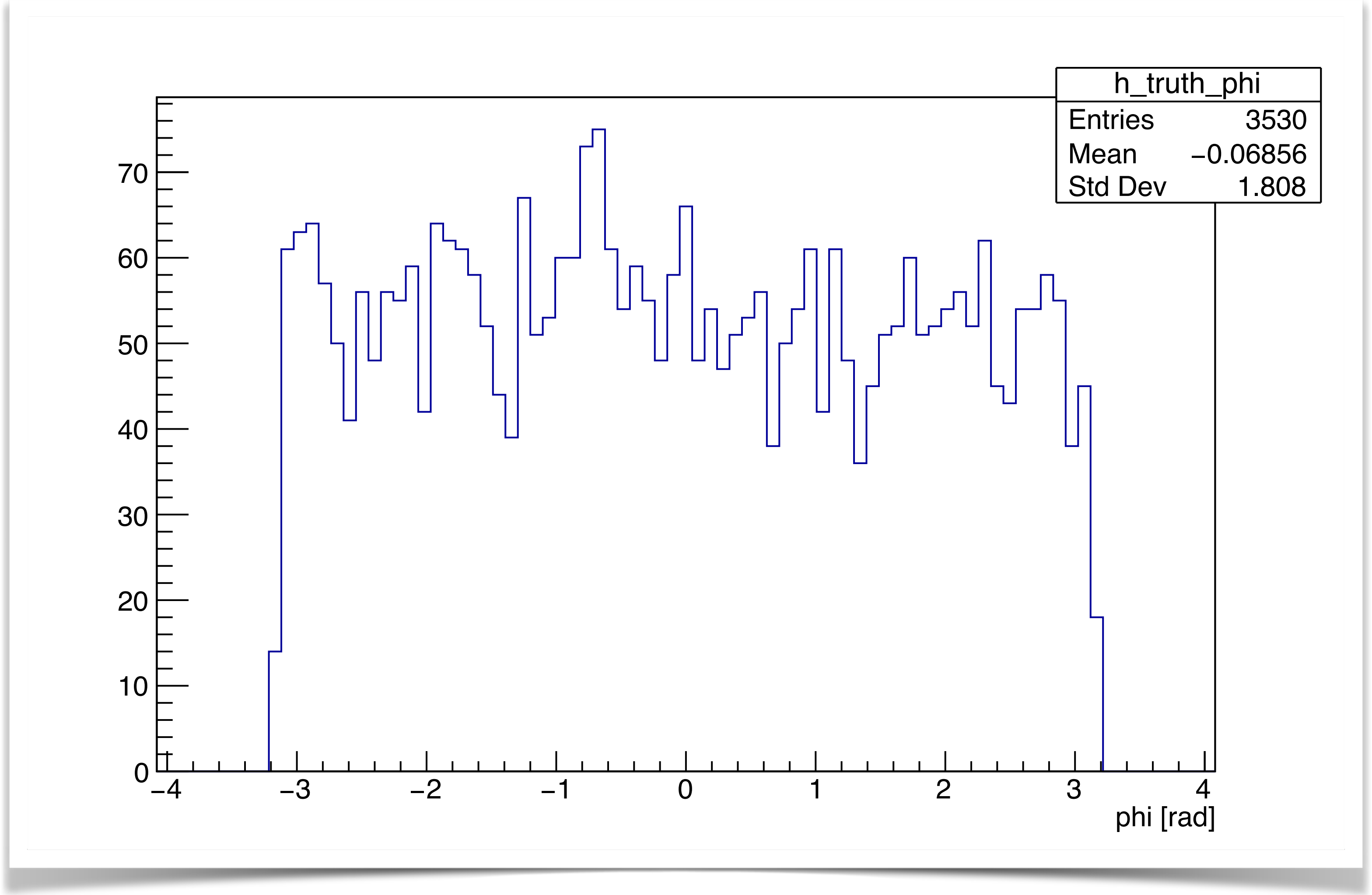
All events used (#10000)

- Position and energy collected in the scintillating (S) **and** Cerenkov (C) fibres in 10000 events **simulating** impinging electrons of uniform energy, in the range [0-125] GeV, and uniform angular distributions

Dumper Algorithm output







Truth level Variables

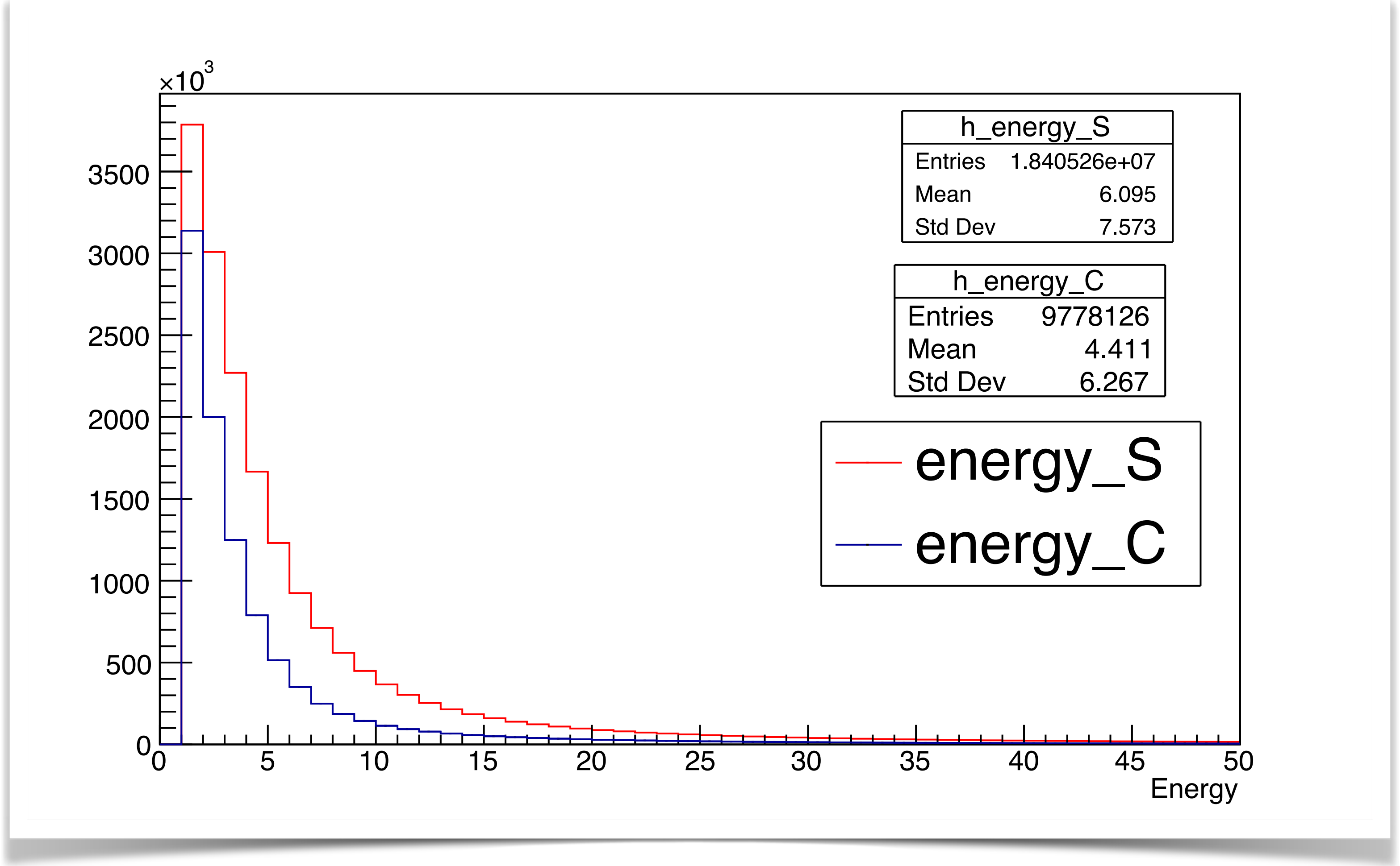
ParticleFlow Project - Status Report

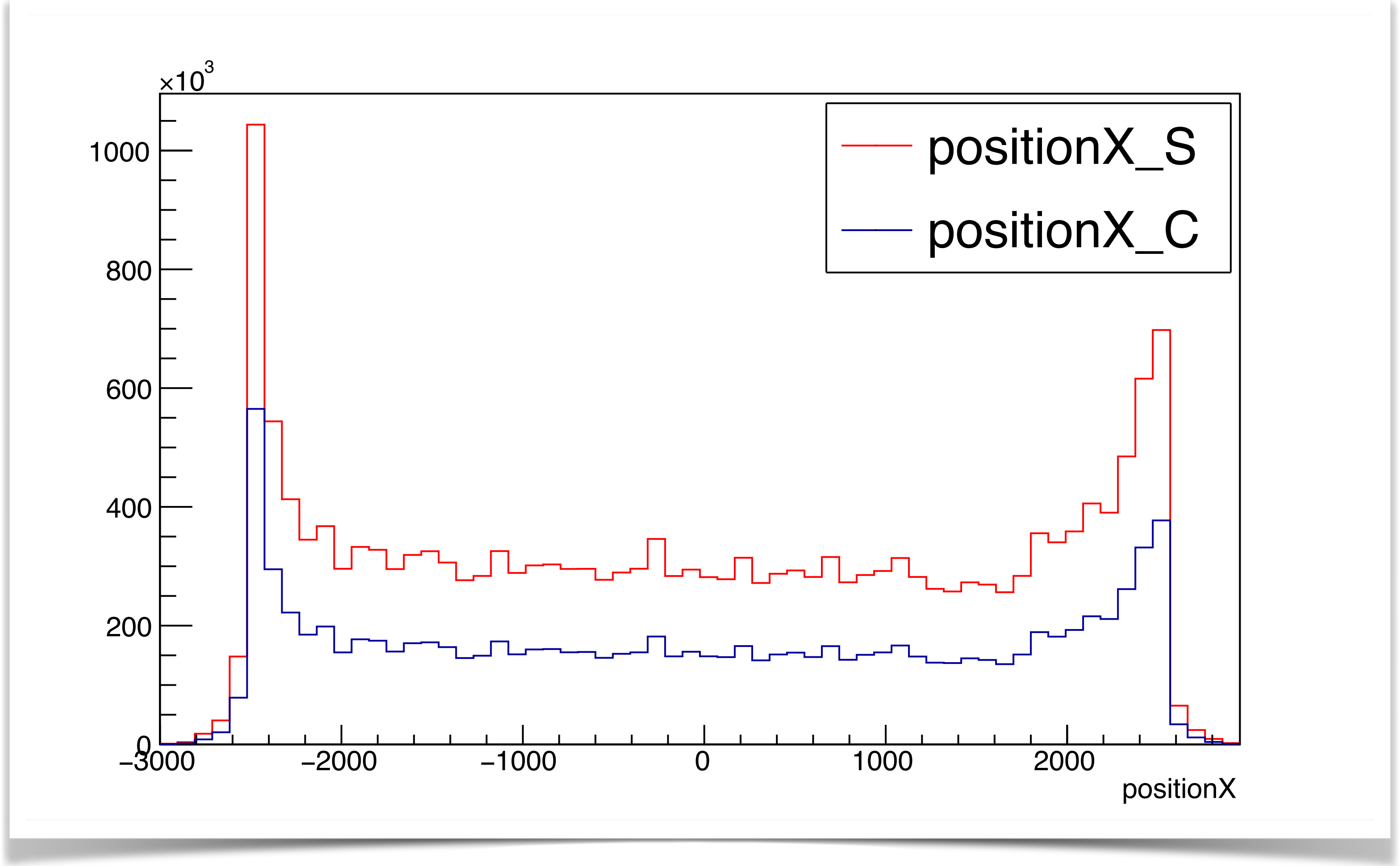
Kinematic distributions - Electrons

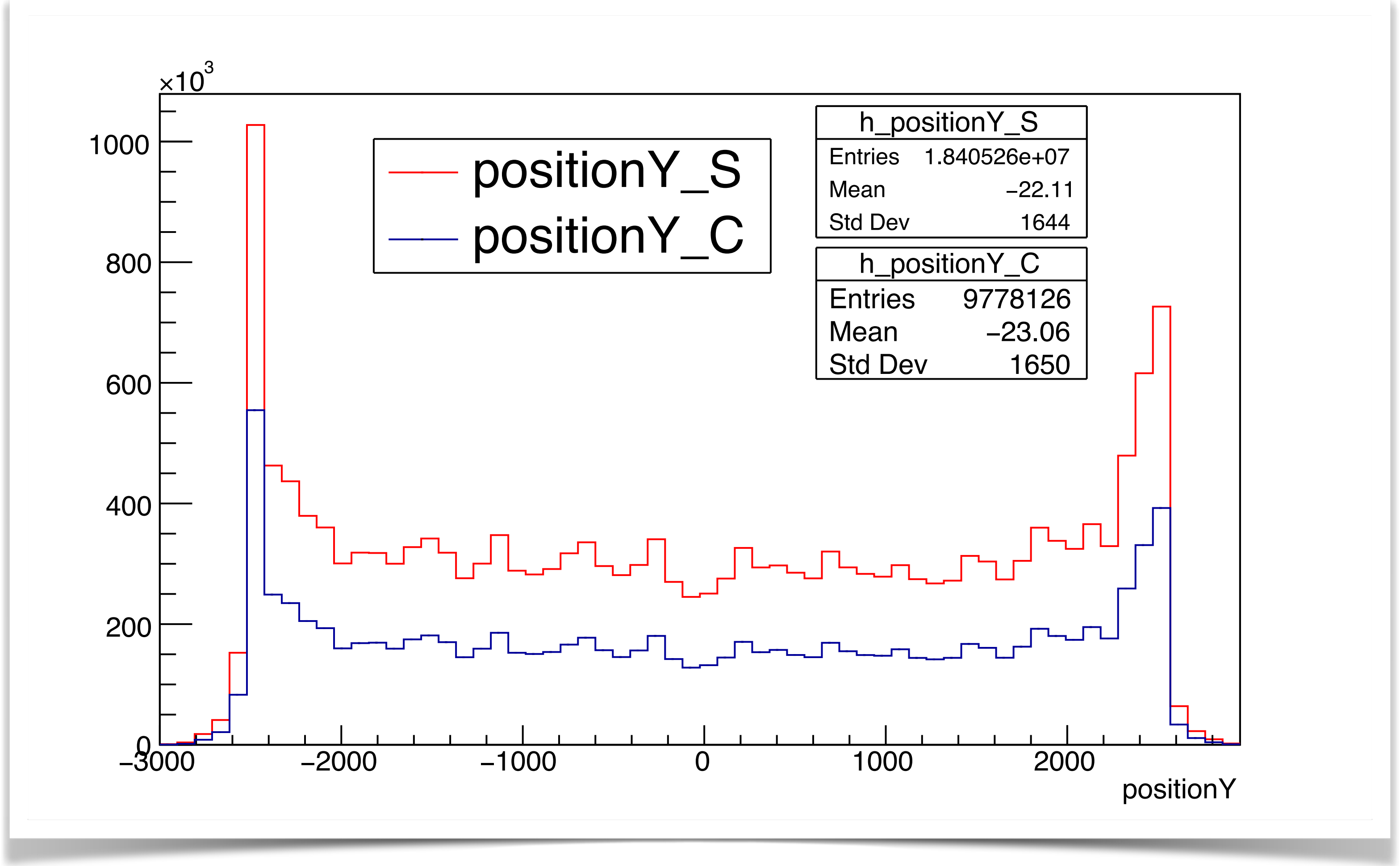
All events used (#10000)

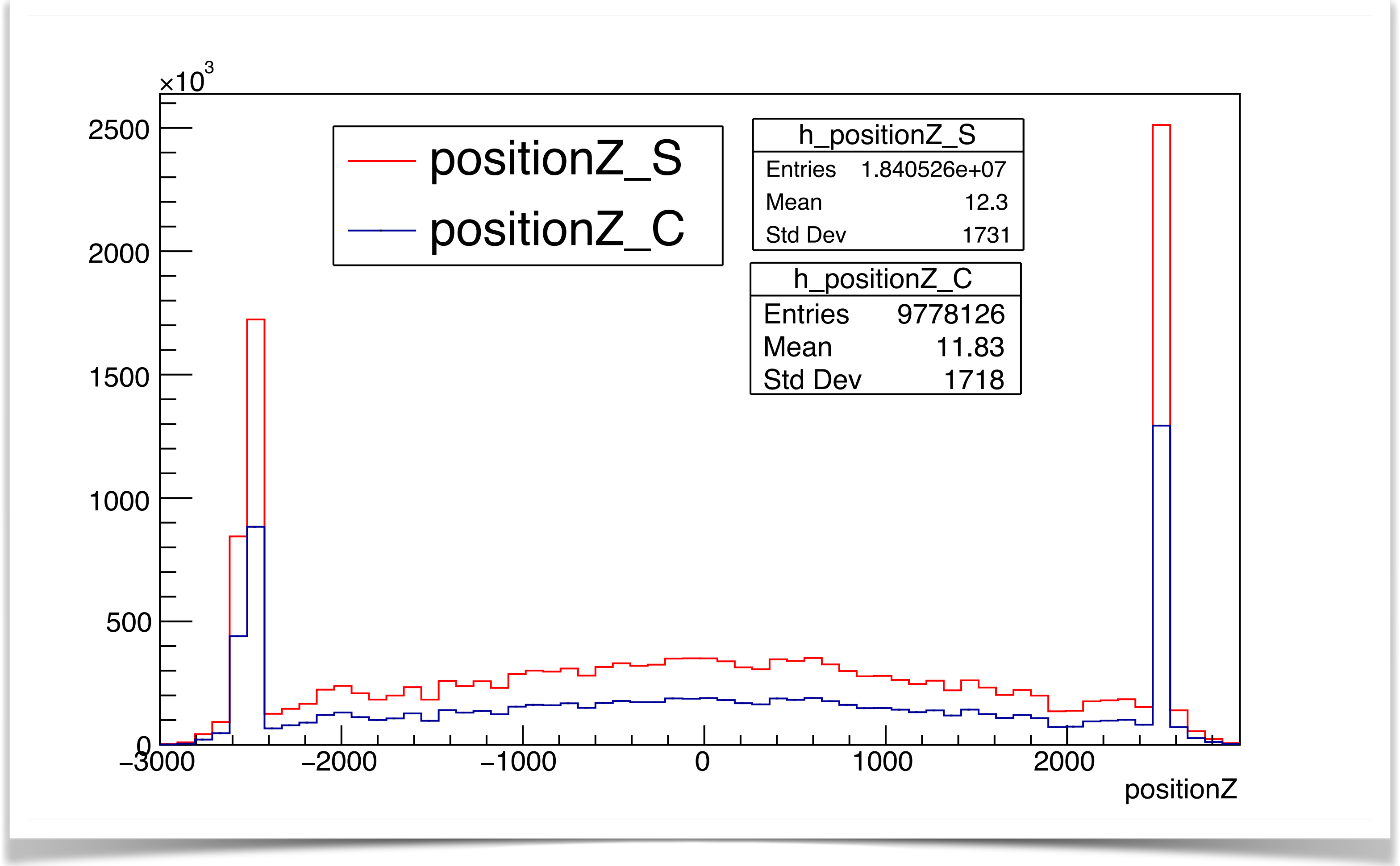
- Position and energy collected in the scintillating (S) **and** Cerenkov (C) fibres in 10000 events **simulating** impinging electrons of uniform energy, in the range [0-125] GeV, and uniform angular distributions

Dumper Algorithm output









Reco level Variables

Energy deposits - Electrons

Dumper Algorithm output

Electron deposits

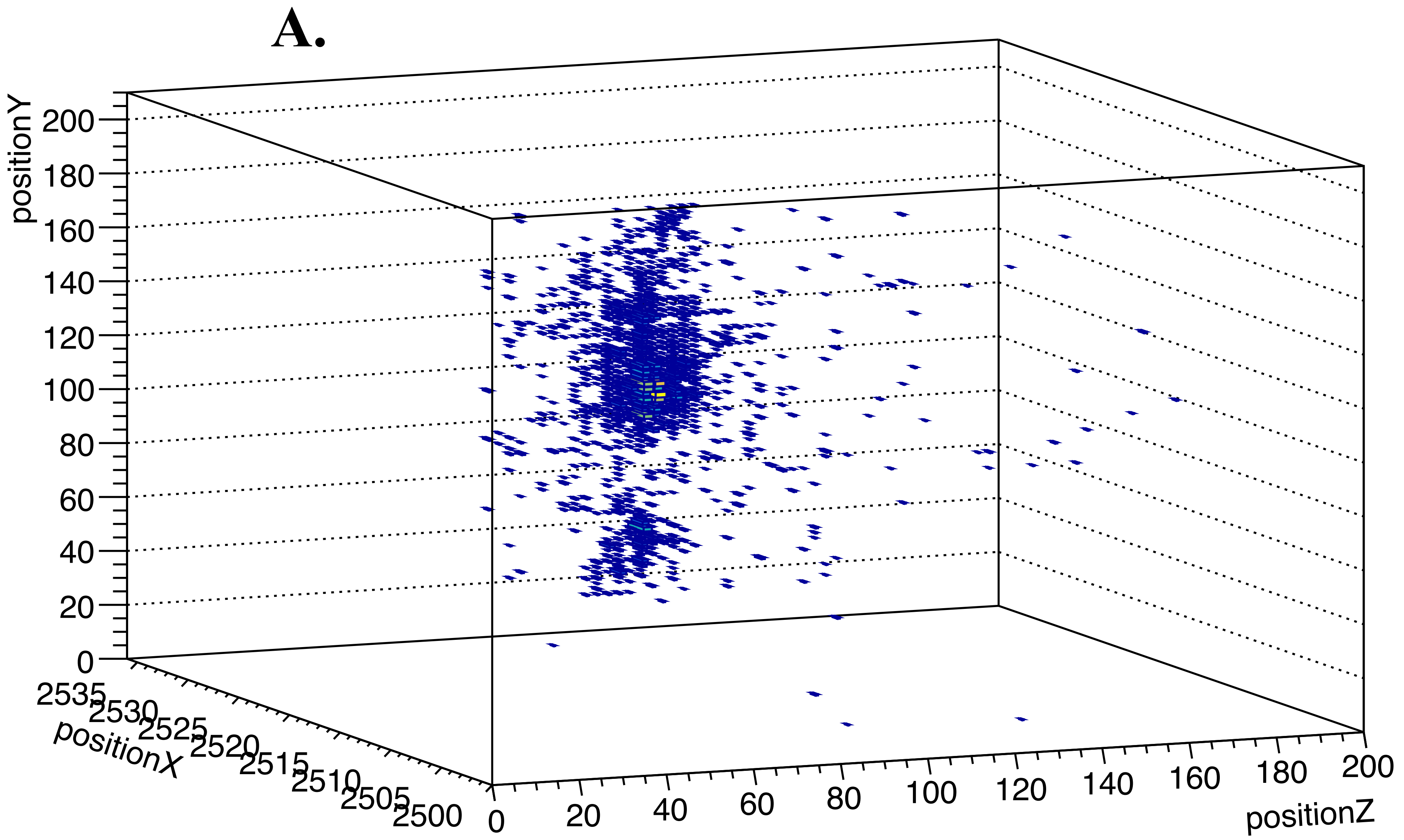
- Energy collected in the scintillating (S) **and** Cherenkov (C) fibres in 100 events **simulating** impinging electrons of 20 GeV

A. Energy deposited in the detector, projected in the *(x,y,z)* space —> combined fibres

B. Energy deposited in the scintillating fibres, polar coordinates

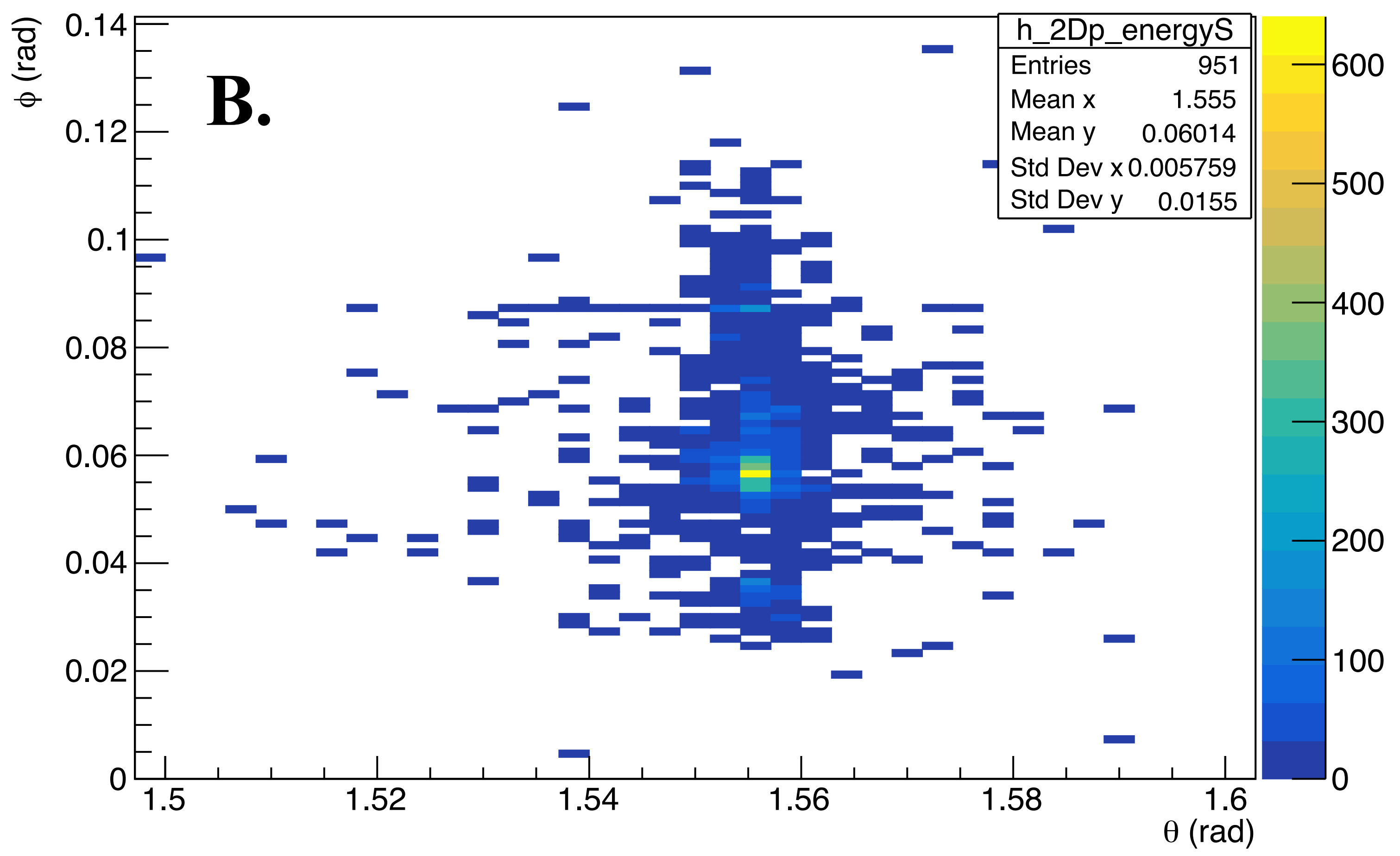
C. Energy deposited in the Cherenkov fibres, polar coordinates

Combined fibres

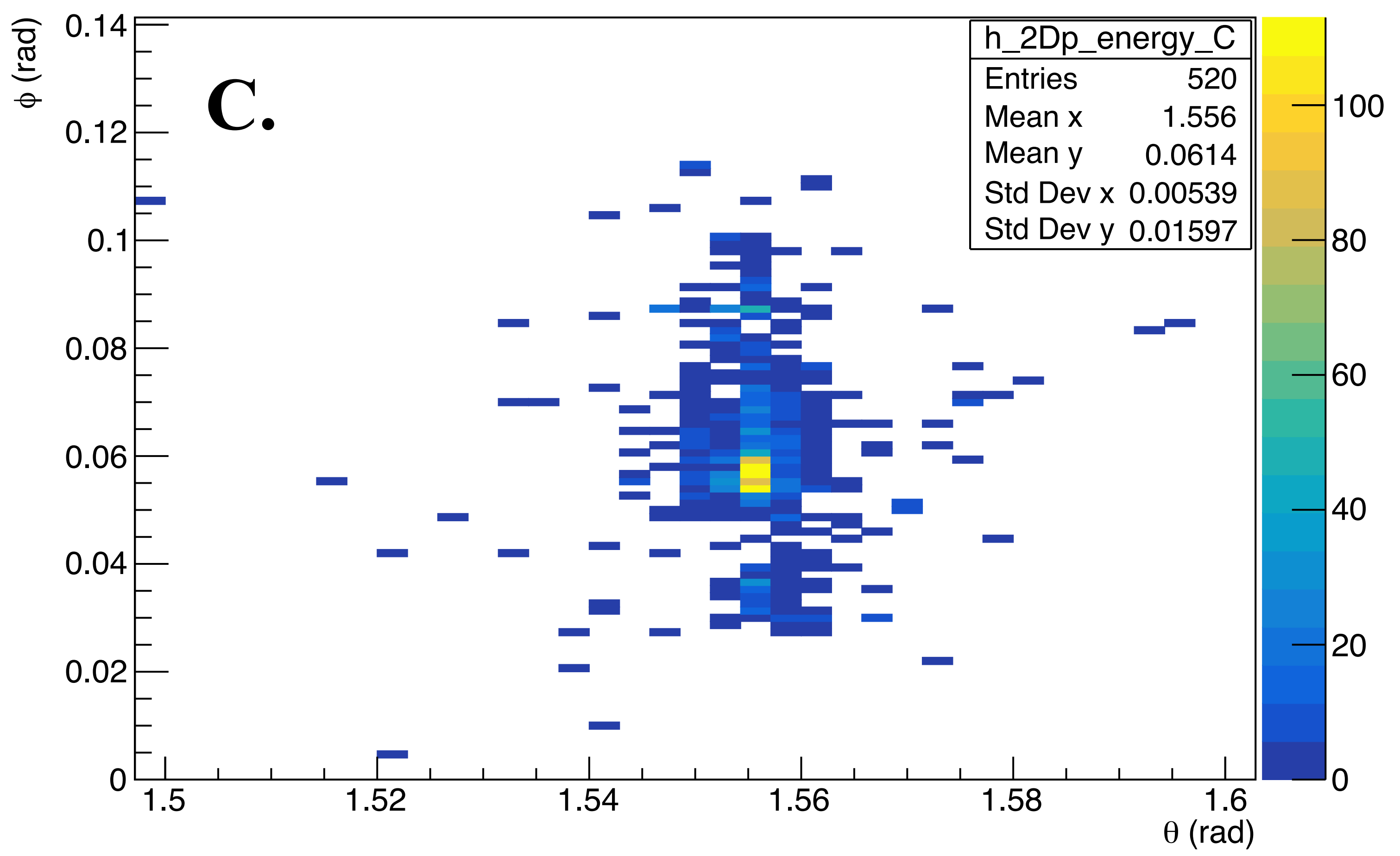


3D plot, cartesian coordinates

Scintillating fibres

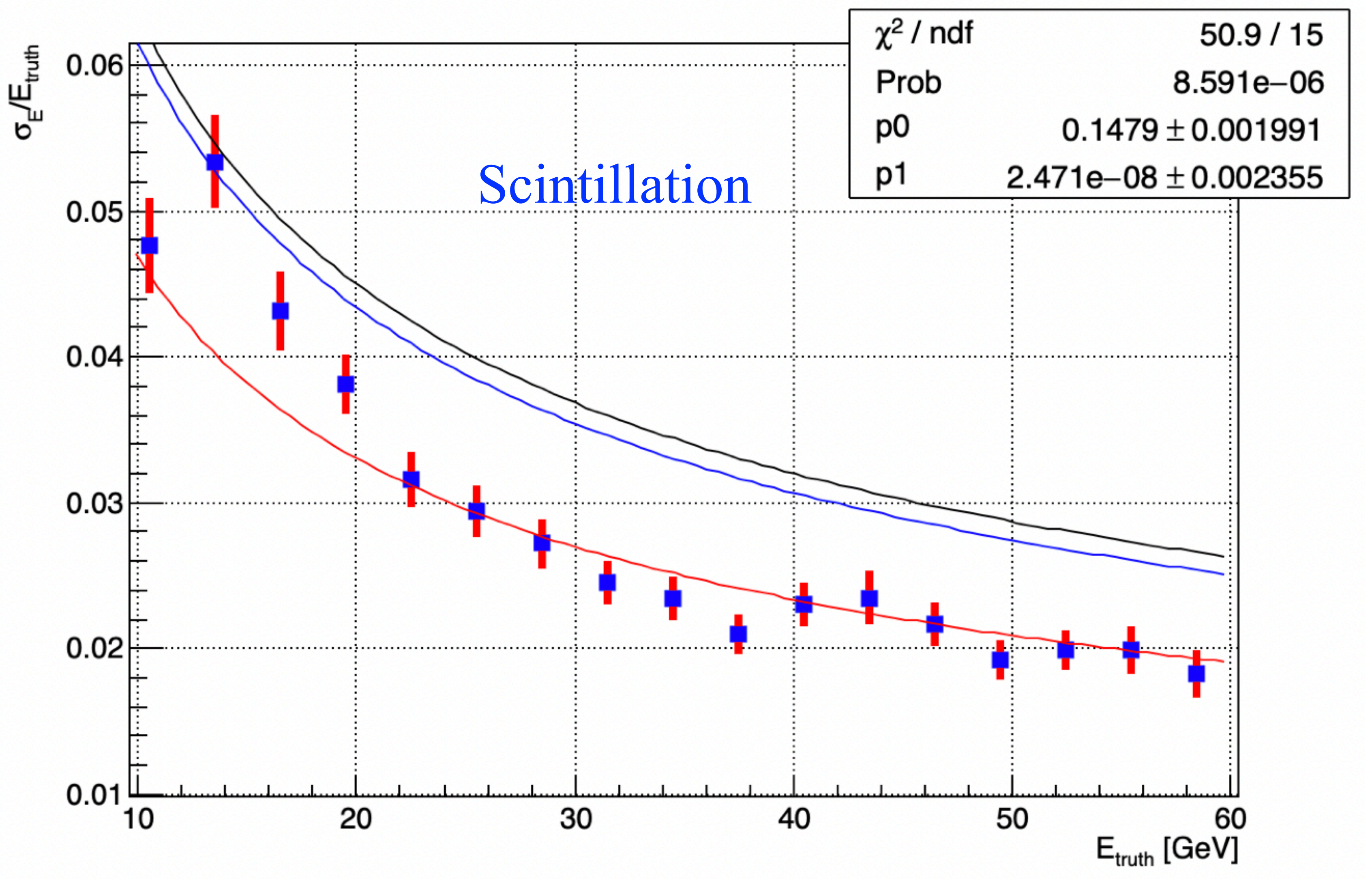


Cherenkov fibres



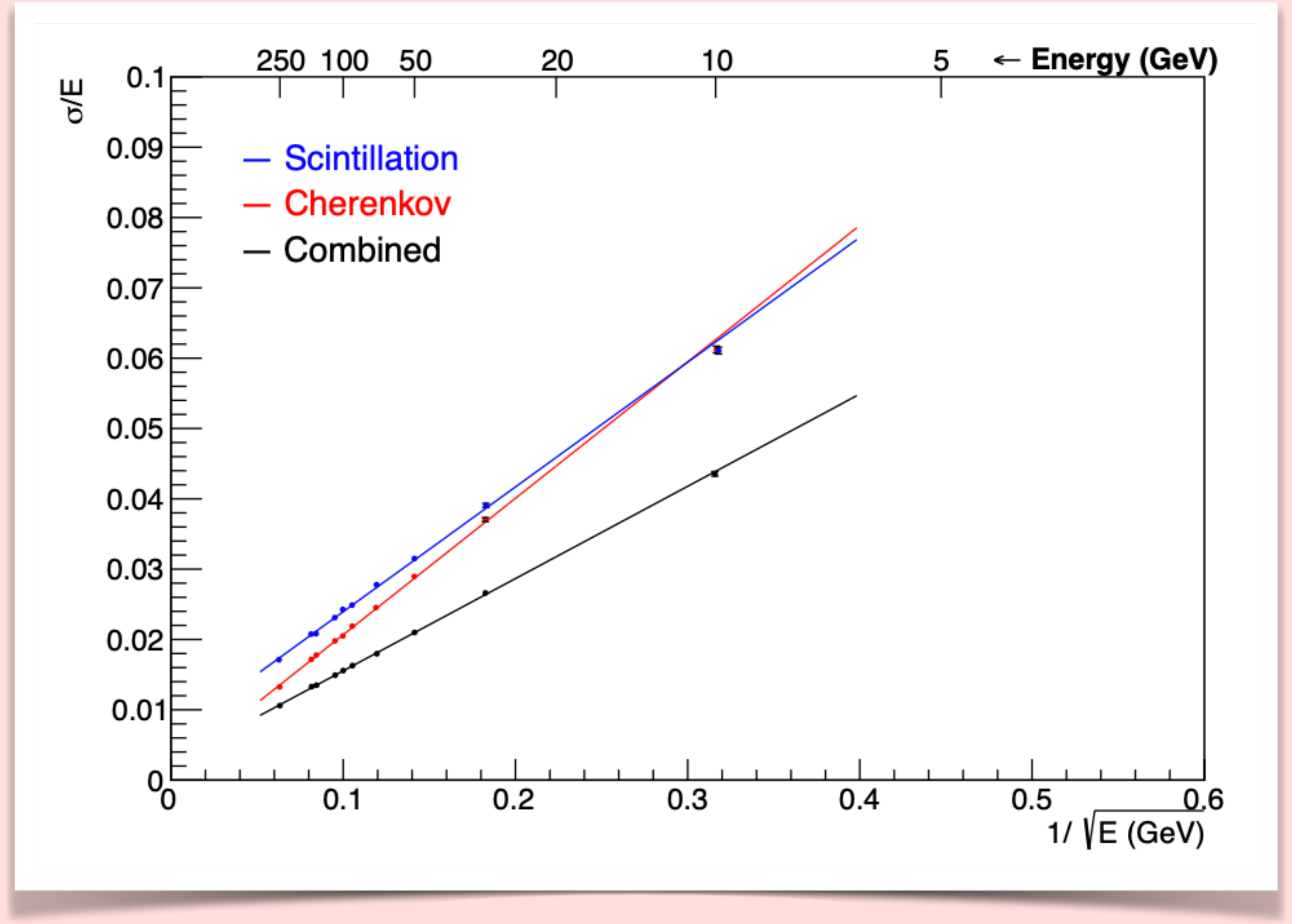
2D plots, polar coordinates

Cross-check - Using the sum of Energy



$$\frac{\sigma}{E} = \frac{\boxed{a}}{\sqrt{E}} \oplus c$$

From reference: https://inspirehep.net/literature/1861660



Cherenkov

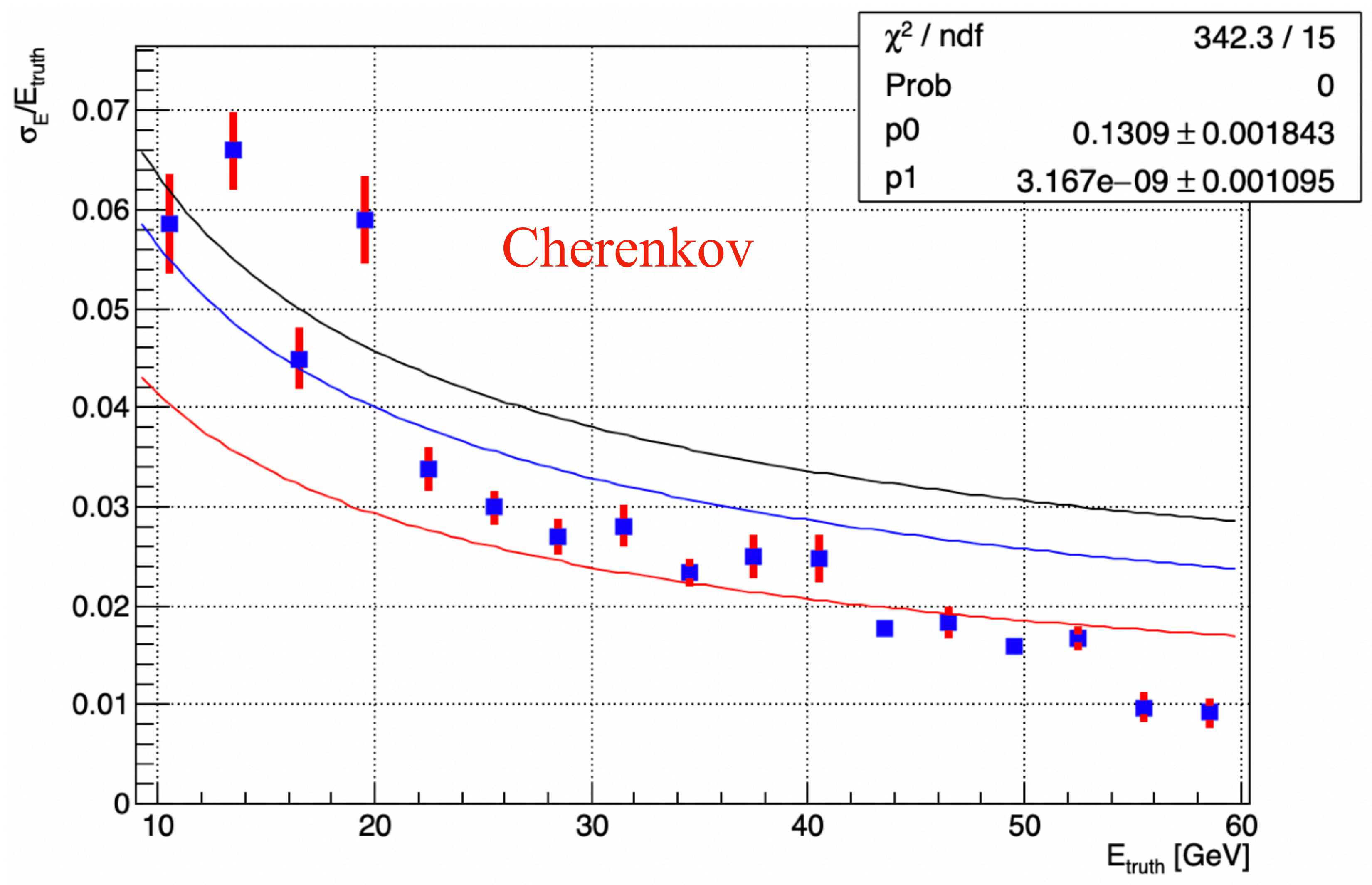
$$\frac{\sigma}{E} = \frac{17.7\%}{\sqrt{E}} + 0.6\% \text{ or, } \frac{19.6\%}{\sqrt{E}} \oplus 1.3\%$$

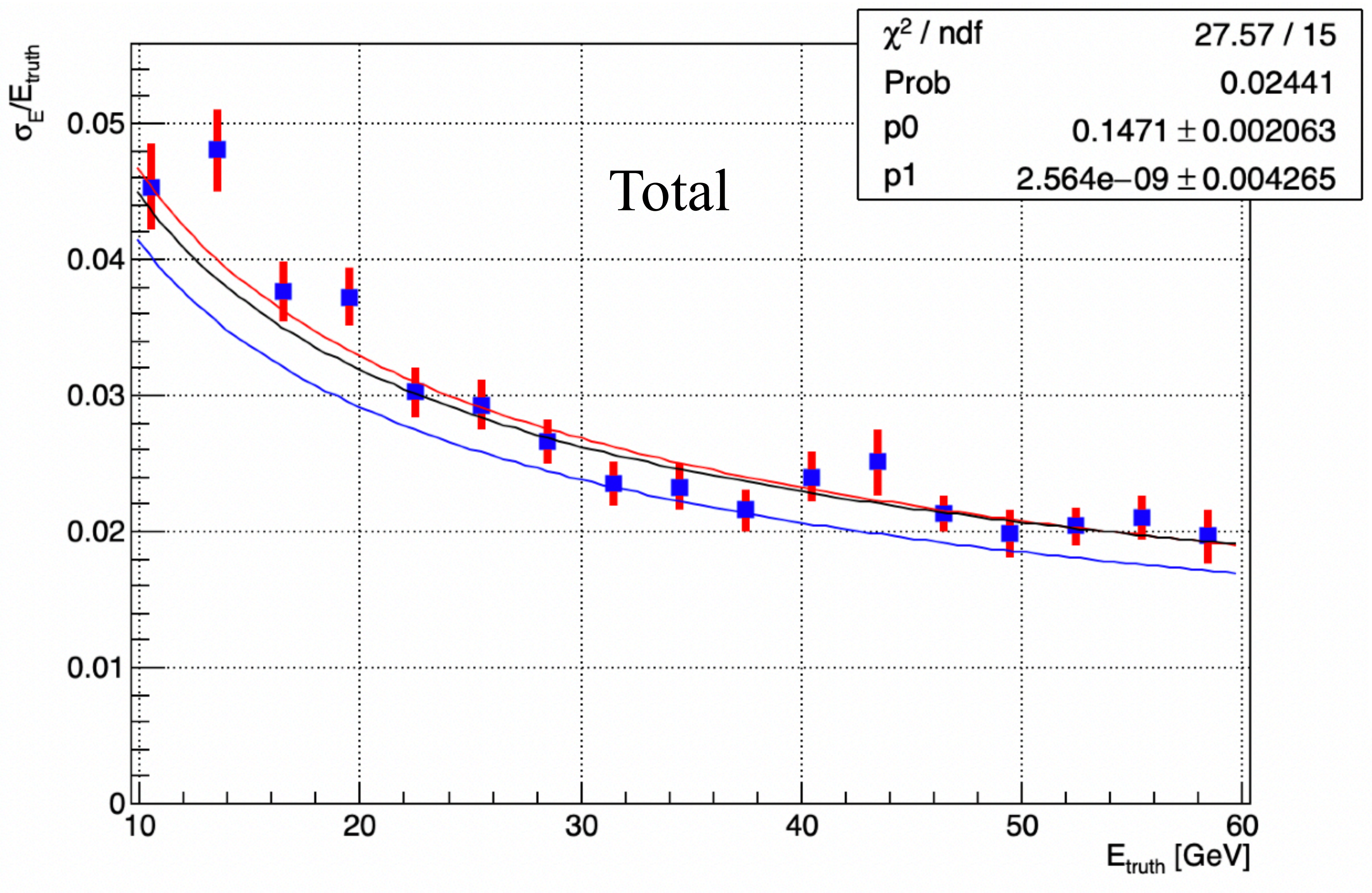
Scintillation

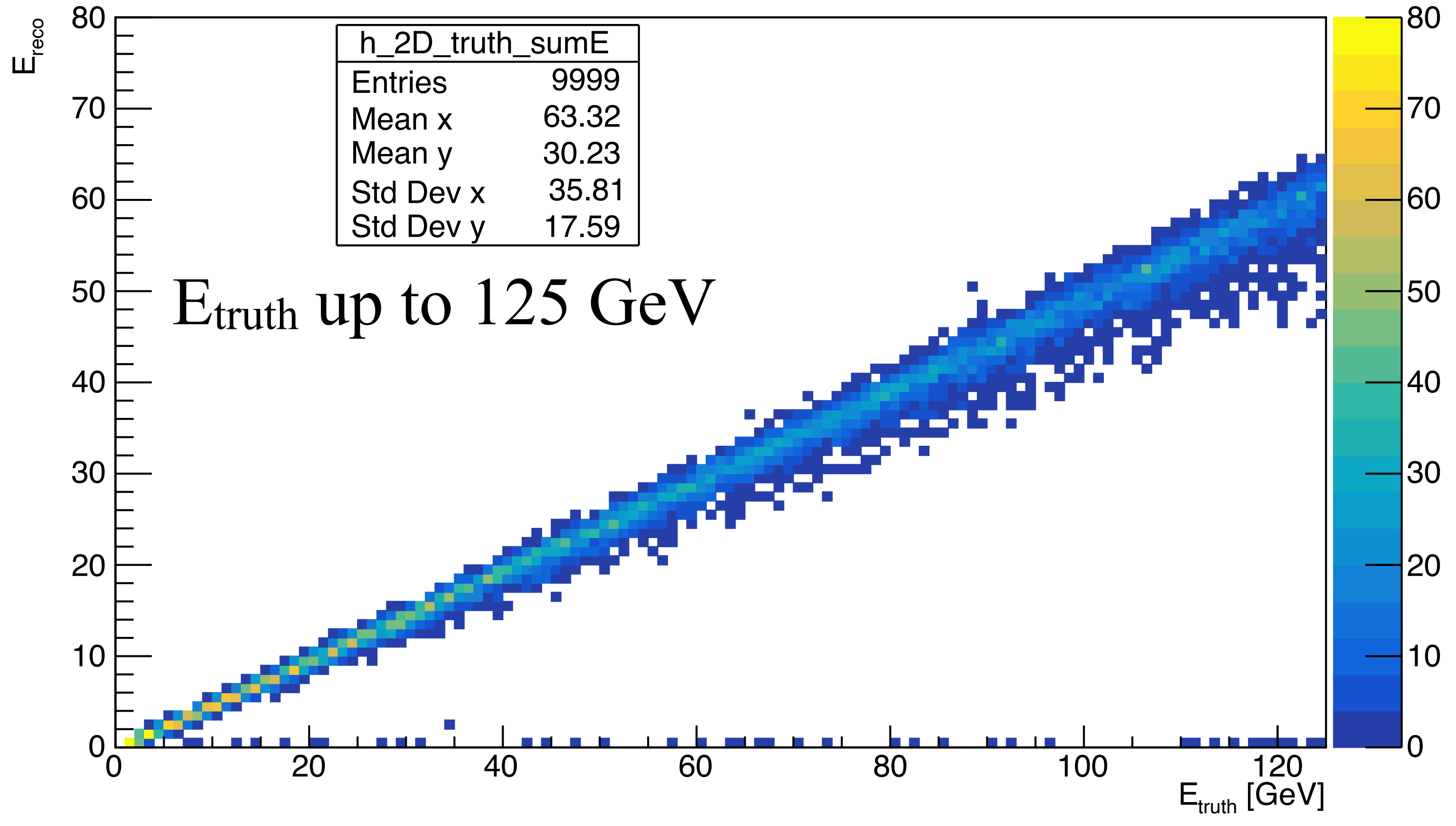
$$\frac{\sigma}{E} = \frac{19.4\%}{\sqrt{E}} + 0.1\% \text{ or, } \frac{20.0}{\sqrt{E}} \oplus 0.5\%$$

Total

$$\frac{\sigma}{E} = \frac{13.0\%}{\sqrt{E}} + 0.2\% \text{ or, } \frac{14.0\%}{\sqrt{E}} \oplus 0.6\%$$







ParticleFlow Project - Status Report