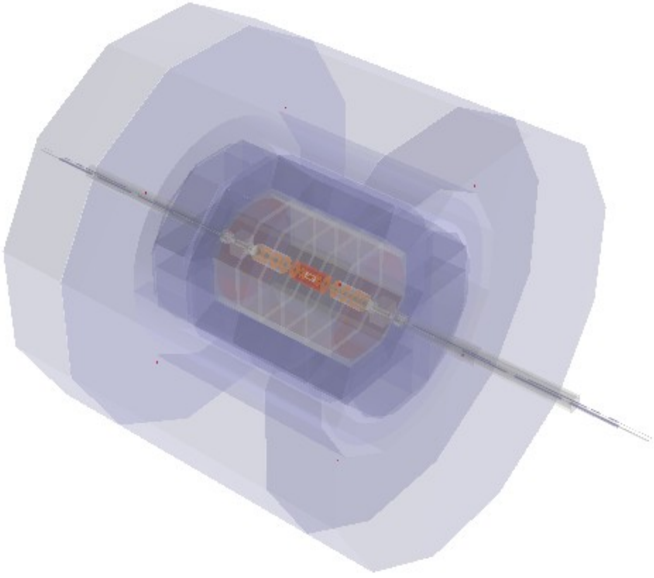
# Arbor & Shower Fractal Dimension

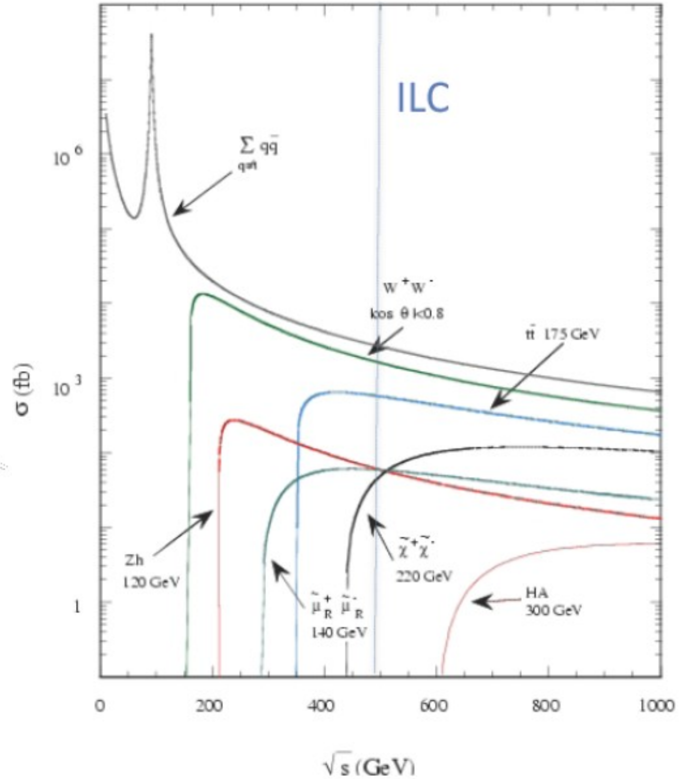
*- advanced shower reconstruction at a highly granular calorimeter*

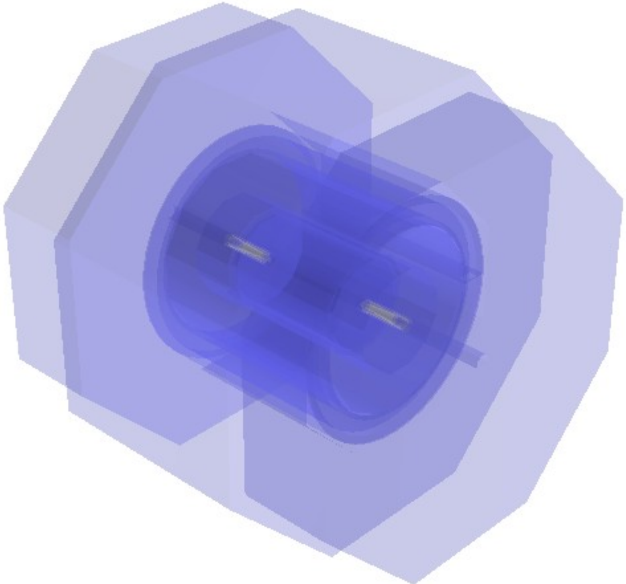
Manqi RUAN

Laboratoire Leprince-Ringuet (LLR)
Ecole polytechnique
91128, Palaiseau

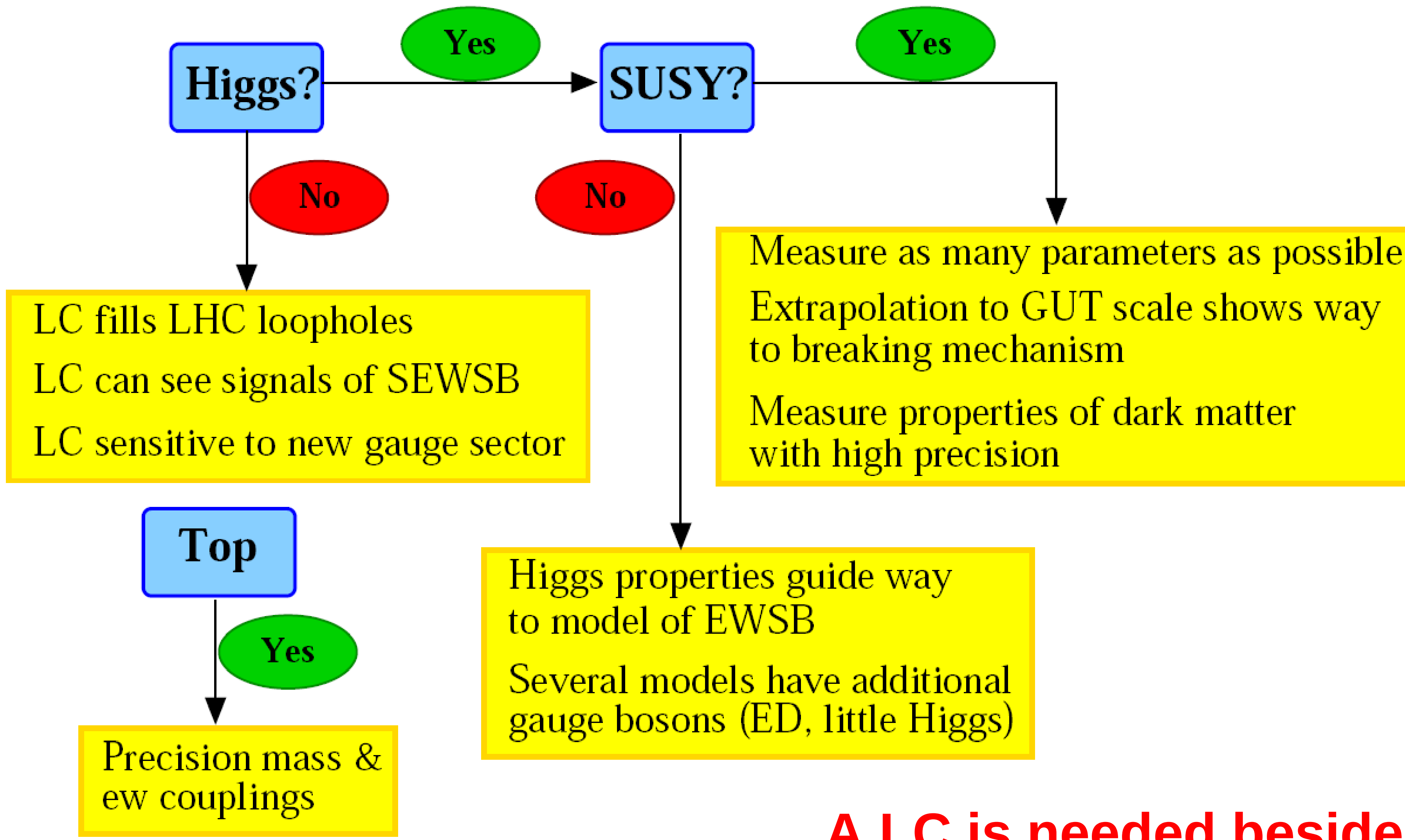
# Part I: Physics @ LC & Highly Granular Calorimeter





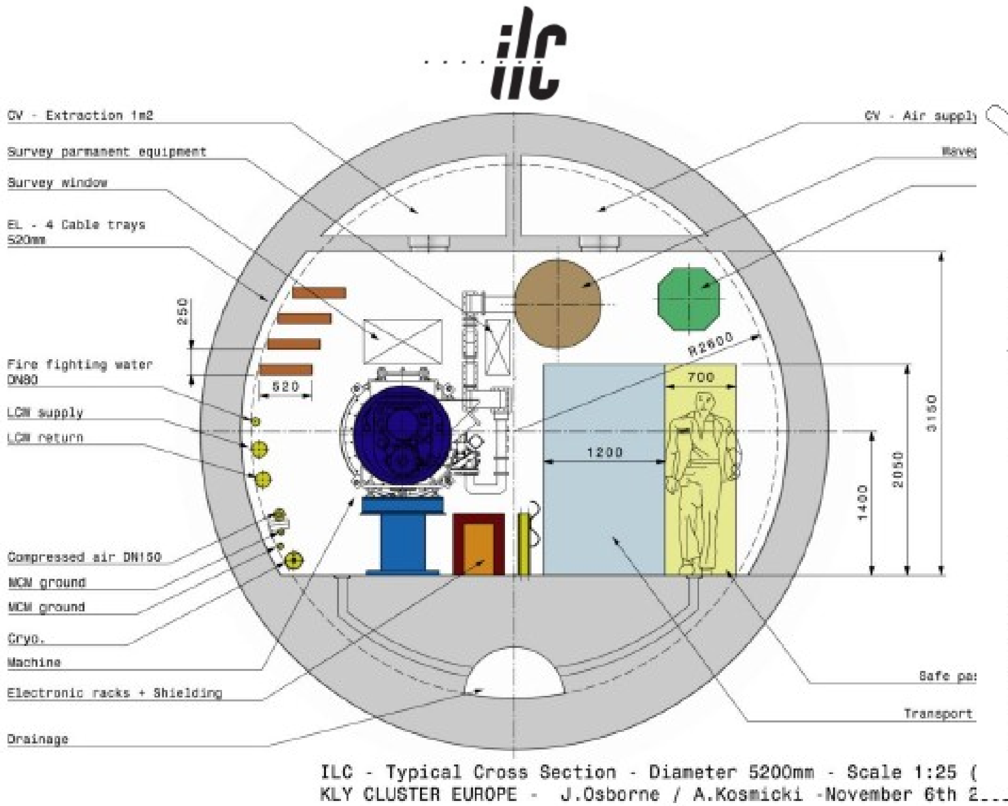
# Physics @ LC

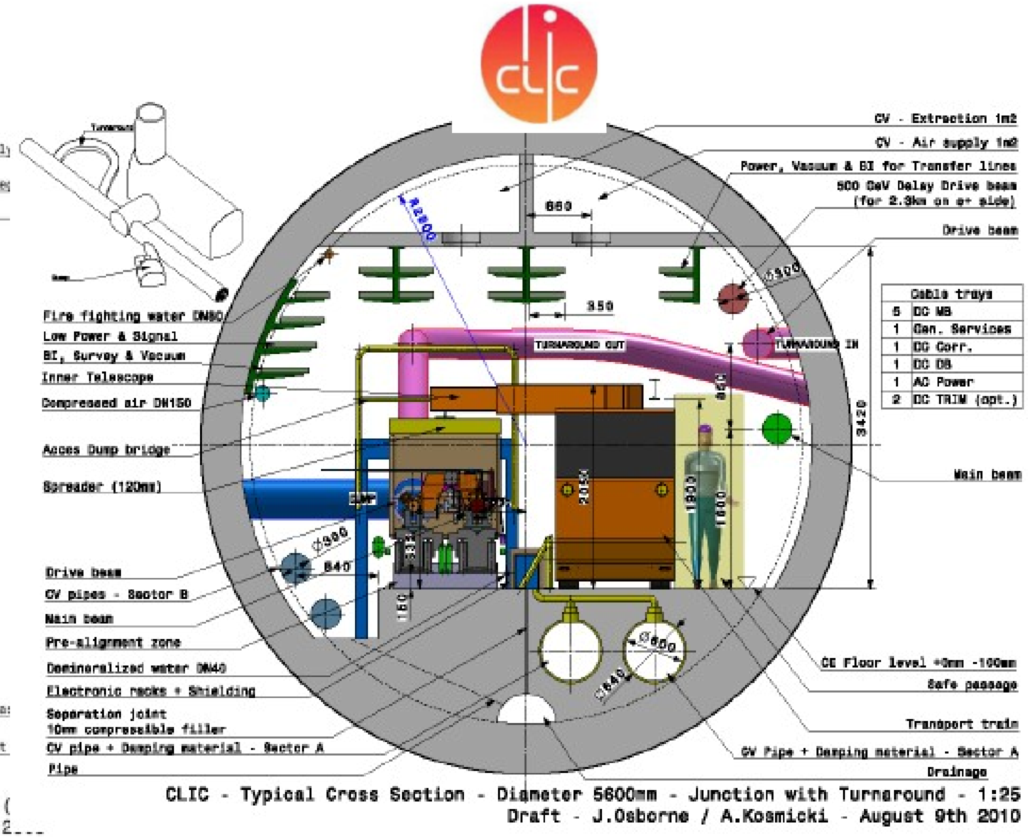



*Klaus Moenig: Physics potential of LC*

**A LC is needed besides the LHC in any case**

# Candidate Linear Collider




- CLIC: Compact Linear Collider, center-of-mass energy: 0.5 - 3 TeV. Warm technology (Room temperature & gradient ~ 100MV/m, small bunch spacing).
- ILC: International Linear Collider, center-of-mass energy: 0.5 - 1.0 TeV. Cold technology (2K & low gradient ~ 31.5 MV/m, large bunch spacing)
- CLIC & ILC: very different accelerators with similar detectors.

# Jet resolution & PFA

## Particle Flow Algorithm:

Measure jets as collections of particles, in the best suited subdetectors

$E_{jet} = E_{charged\ tracks} + E_{\gamma} + E_{h^0}$

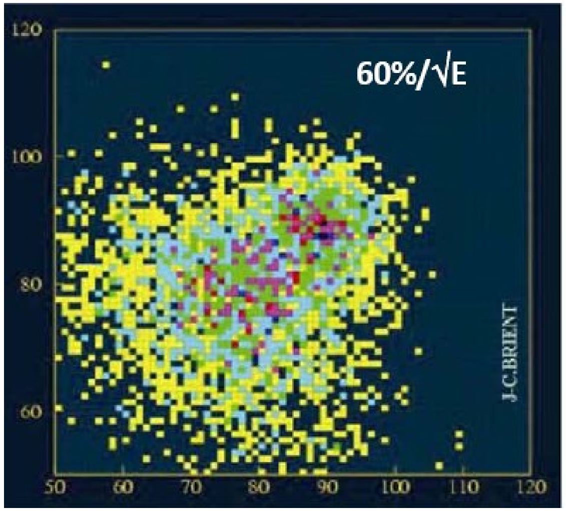
fraction 65% 26% 9%

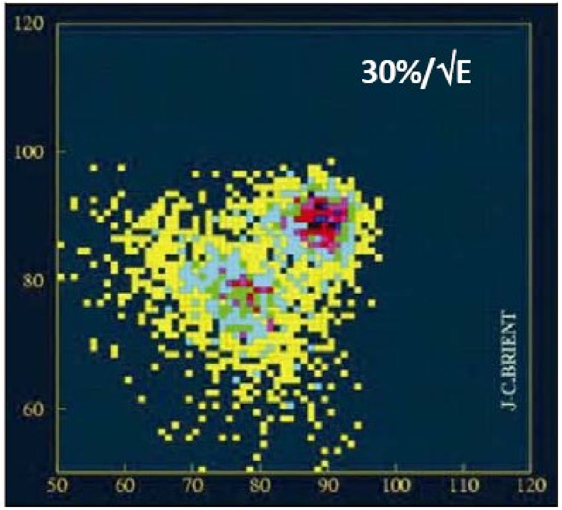
Charged Particle – Tracker:
$\Delta(1/p) \sim 2*10E\text{-}5$ (1/GeV)
Photon – ECAL:
$\Delta E/\mathrm{sqrt}(E) \sim 15\%$
Neutron Hadron – HCAL:
$\Delta E/\mathrm{sqrt}(E) \sim 50\%$

**Final states in e+e- interaction up to 1 TeV c.m.s**

| Multi bosons | Multifermions + Boson(s) |
|---|---|
| ZH | $e^+e^-$ H , e+e- Z |
| WW | νν H , νν Z |
| ZZ | ttH |
| ZHH | e ν W |
| ZZZ | νν WW, νν ZZ |
| ZWW | ttbar |

*Di-jet mass for WWνν & ZZνν @ 500GeV*




J-C. Brient - IWLC 2010

If perfectly reconstructed:

$$\sigma^2 \text{jet} = \sigma^2 \text{ch.} + \sigma^2 \gamma + \sigma^2 h^0 \quad \text{gives about} \quad (0.14)^2 E_{jet}$$

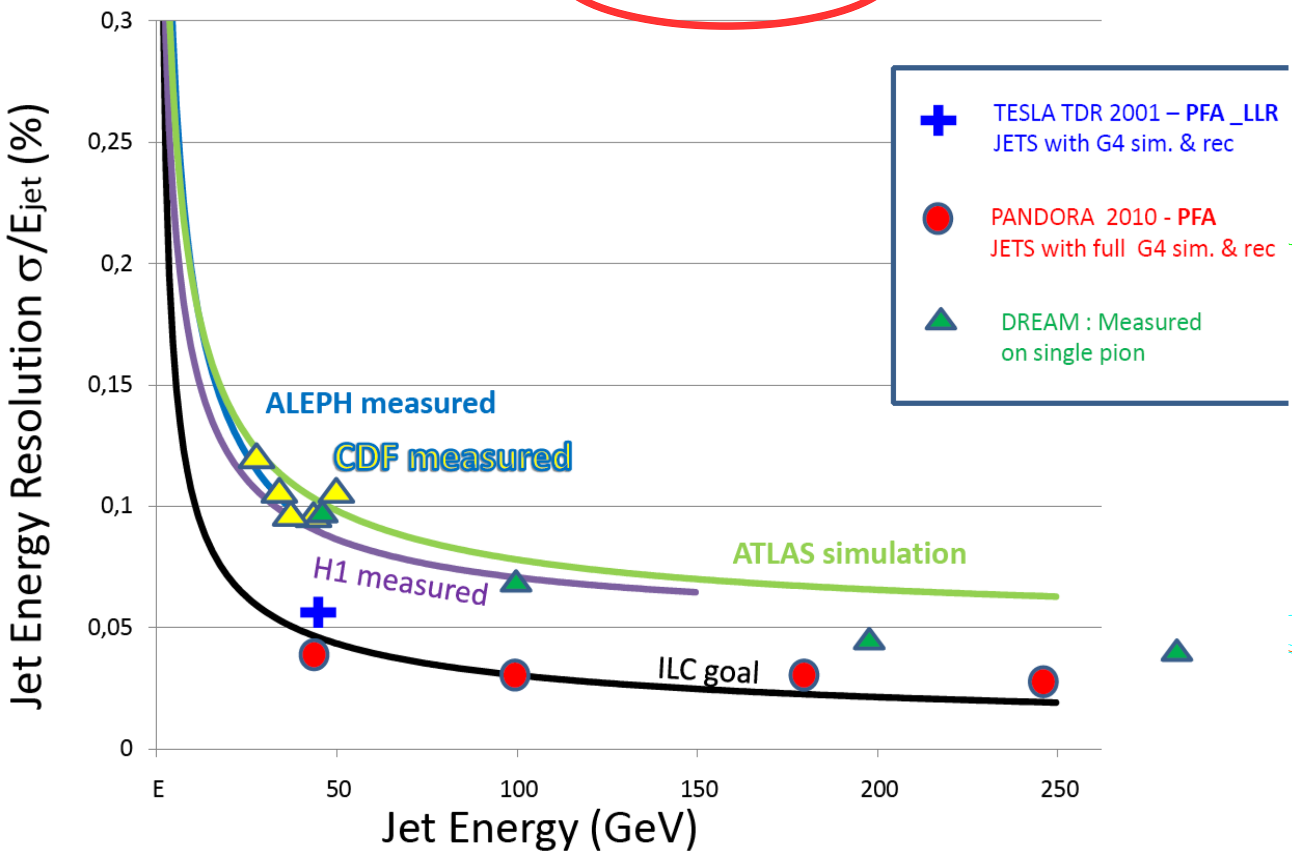
# Resolution & Confusion

Real life and real detector

$\sigma^2$threshold → Energy threshold to be rec. (depends on species)

$\sigma^2$efficiency → loss of particles (not reconstructed)

$\sigma^2$confusion → Mixing between particles in the calorimeter



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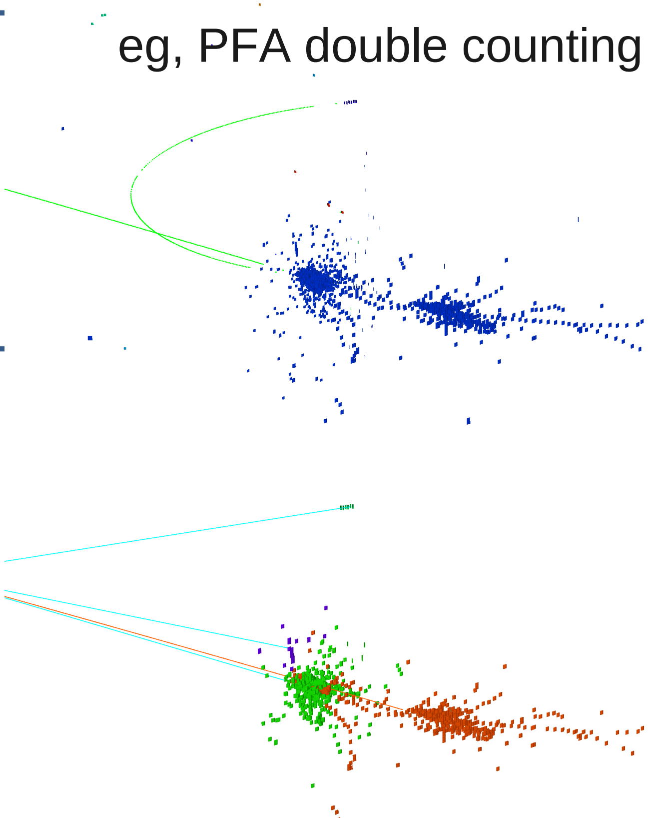
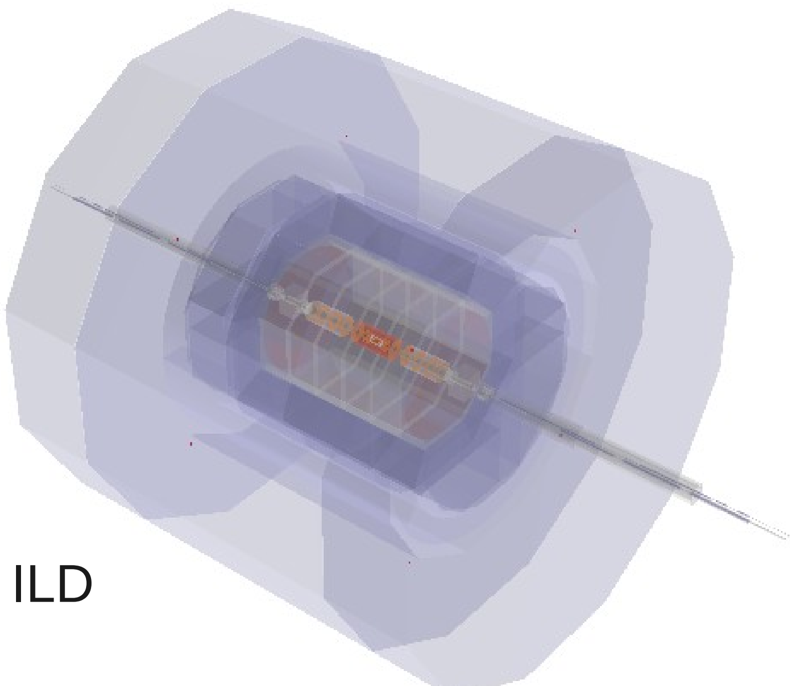
eg, PFA double counting



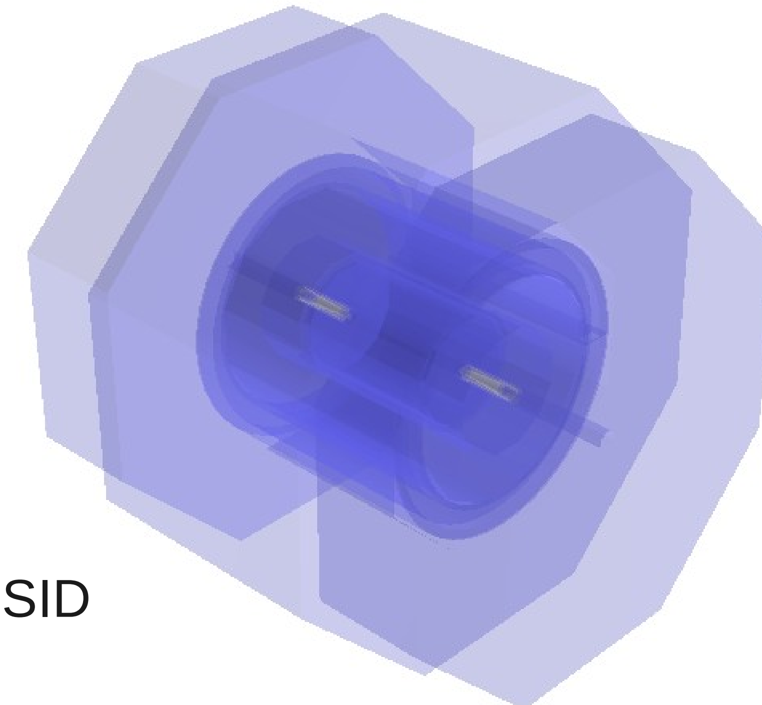
*The worst enemy:* ***confusion***

# PFA Oriented LC detectors

- PFA: less confusion ~ good separation:
  Granularity > Energy Resolution for the Calorimetry...



ILD

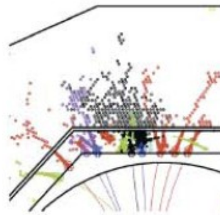


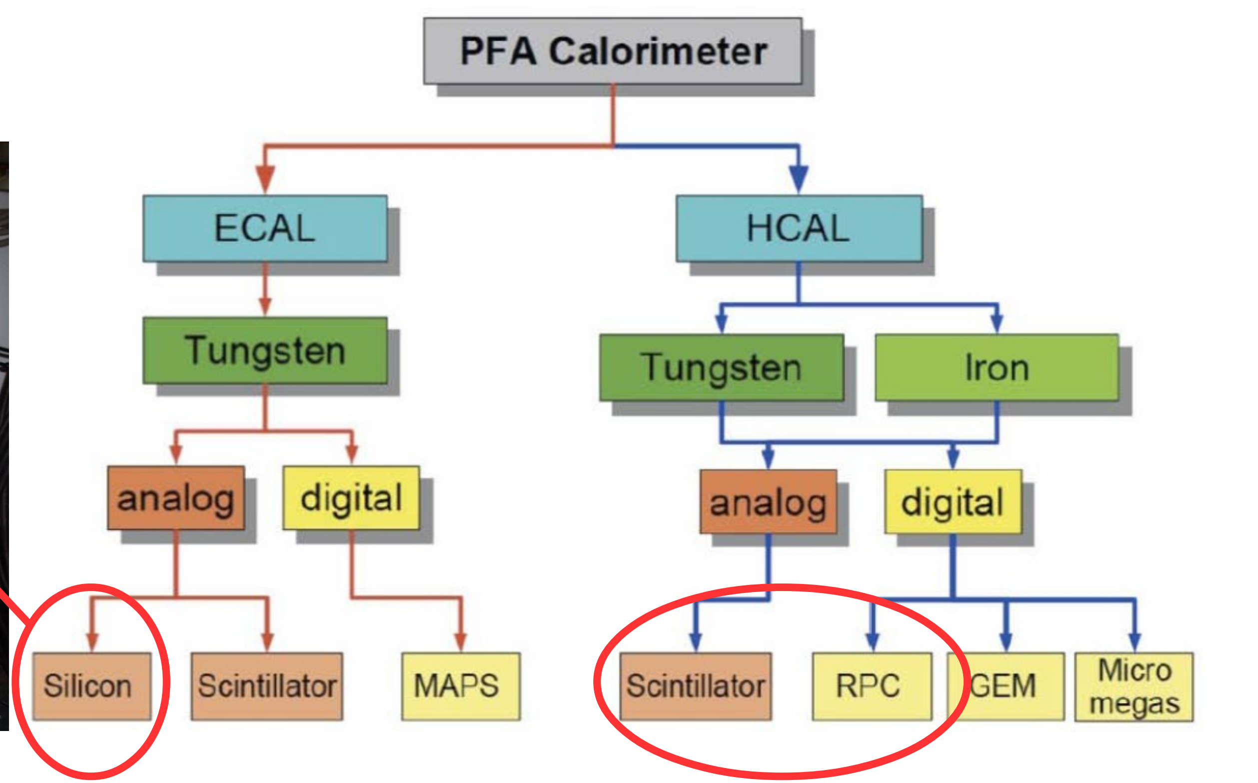
SID

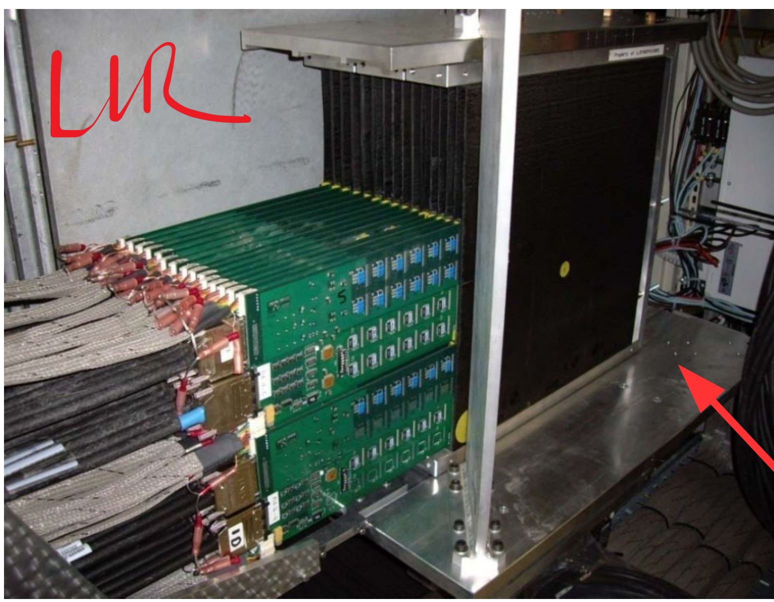
- PFA Oriented detector ( both have ILC/CLIC Versions ):
  - ILD (International Large Detector, mostly European + Asia): TPC + Silicon inner detectors tracking with B = 3.5T/4T
  - SiD (Silicon Detector, mostly in US): Silicon tracking with B = 5T

# CALICE: PFA Oriented Calorimeter

*eg: ECAL Prototype, 10k channels in a cube of 18 cm side ~ 1/8 of CMS ECAL*



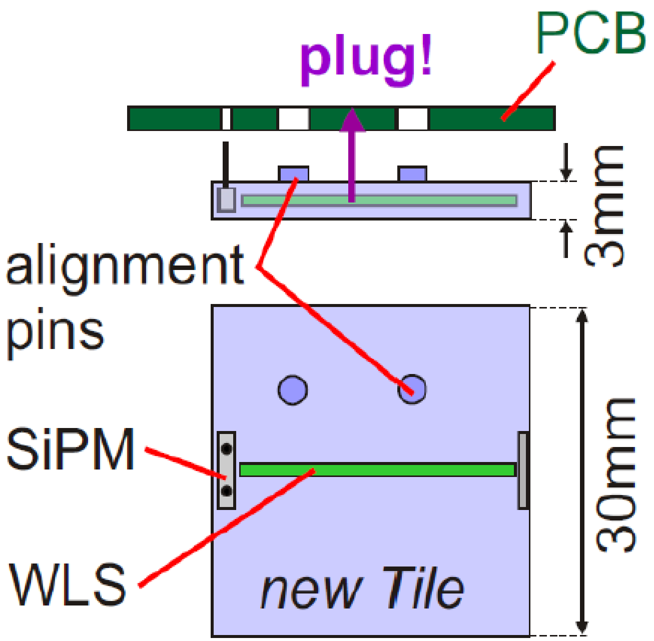


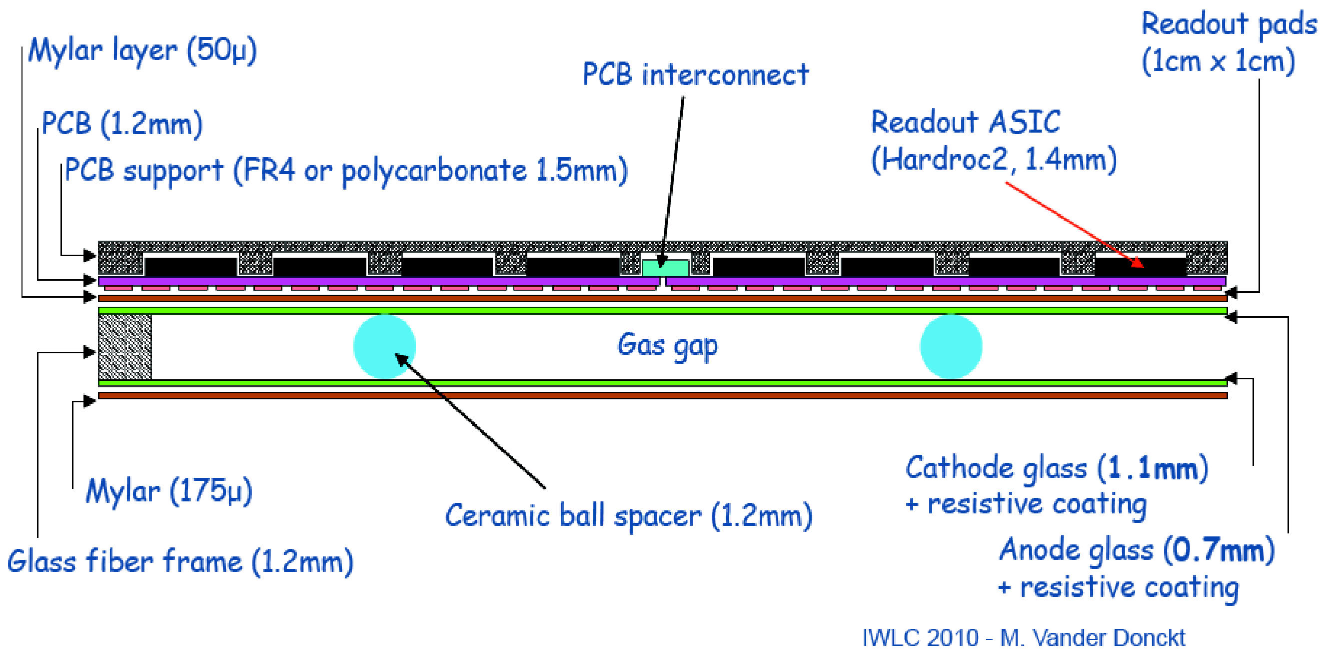




Scintillator AHCAL with 3 * 3 cm² cell @ DESY

2 GRPC Digital HCAL with 1 * 1 cm² cell: SDHCAL @ EU et al and DHCAL @ US

# HCAL: Gas Vs Scintillator



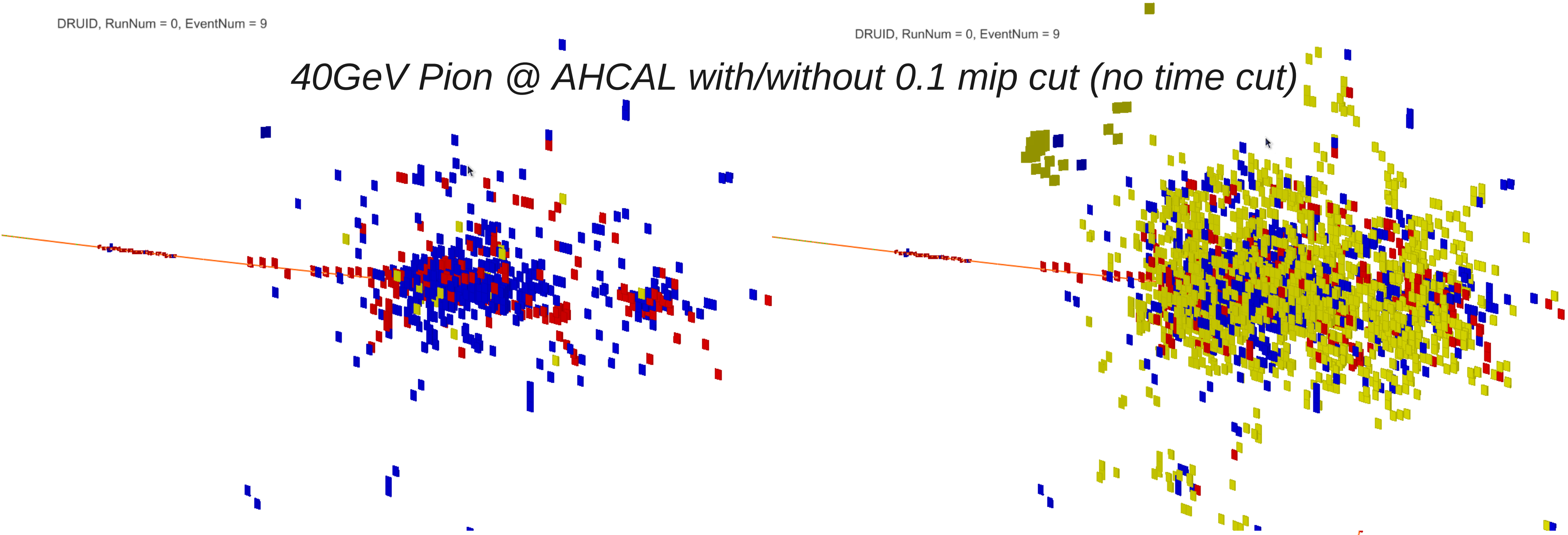

## Scintillator:

3*3*0.3 $cm^3$ cell size and analogy readout

## Gas:

- High granularity (1*1*0.12 $cm^3$ or smaller)
- RPC: high efficiency, homogeneous, robust...
- Low cost: digital or Semi-digital ( channel coded in 1 or 2 bits ) readout...
- Free of direct neutron hits

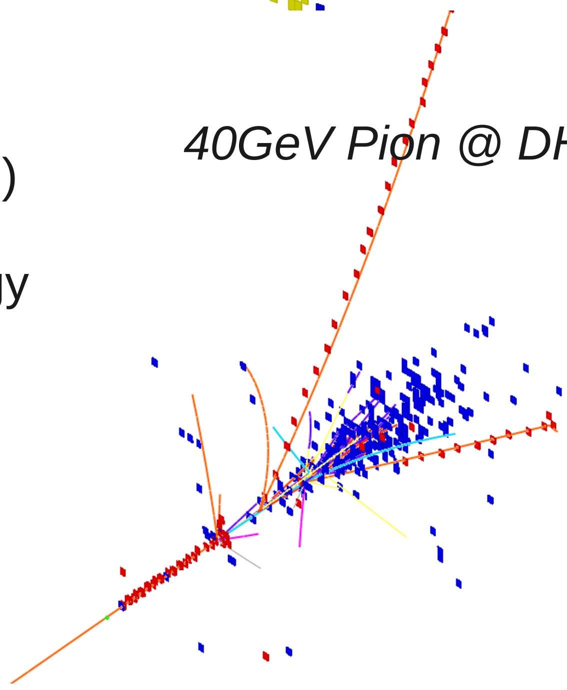
# Neutron hits




*40GeV Pion @ AHCAL with/without 0.1 mip cut (no time cut)*

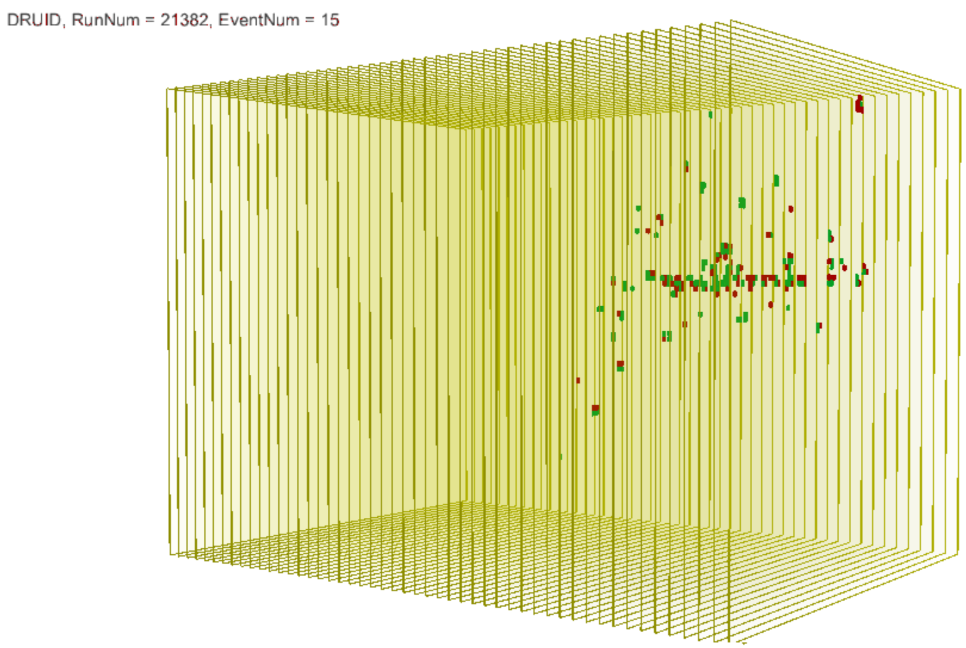
Hit Colour: EM (blue), Neutron (yellow) or hadronic (red)

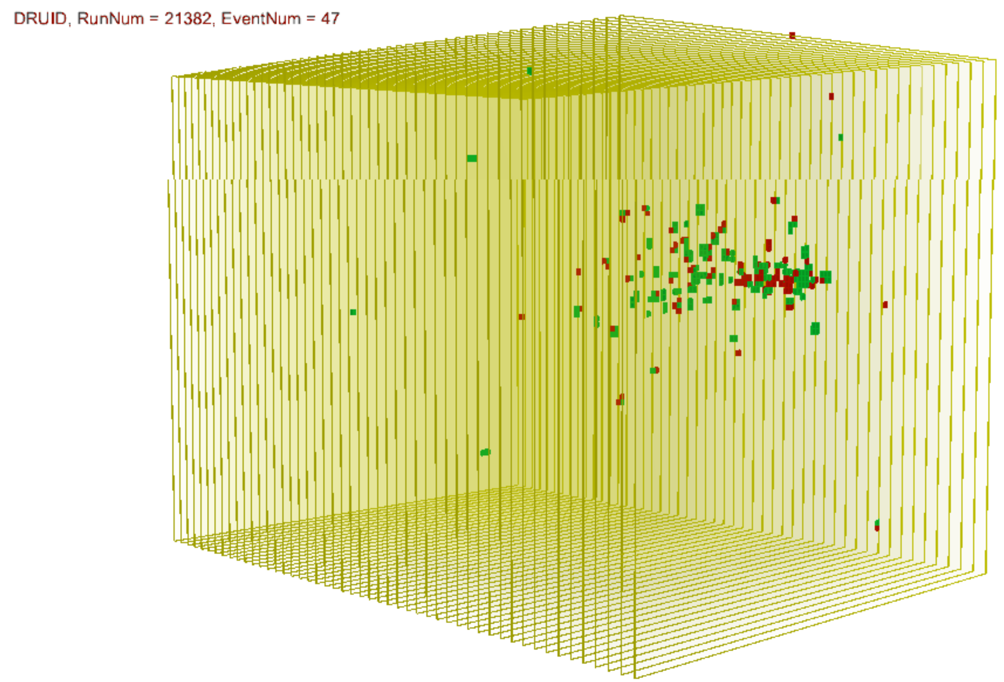
- AHCAL: Shower center surrounded by lots of low energy neutron hits
- Need careful analysis: Confusion & Energy resolution

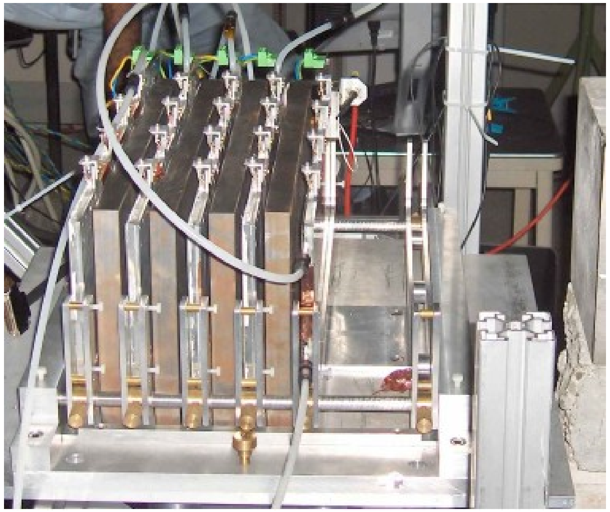


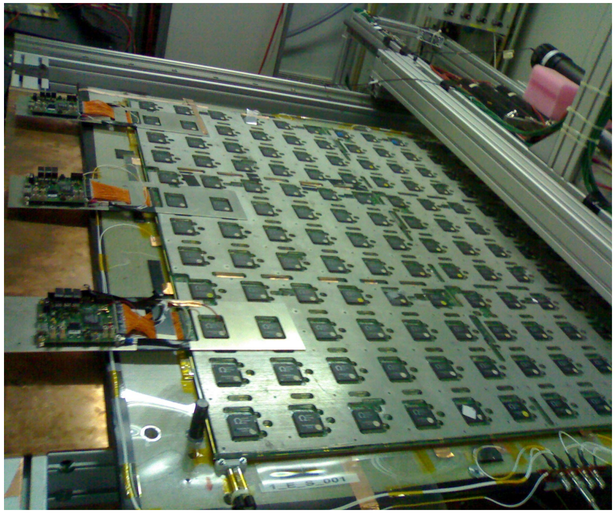
*40GeV Pion @ DHCAL*

# SDHCAL Prototype @ EU



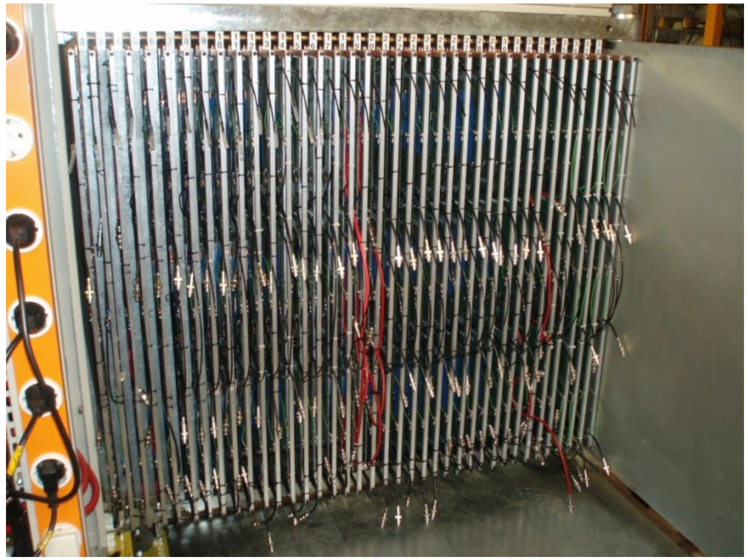



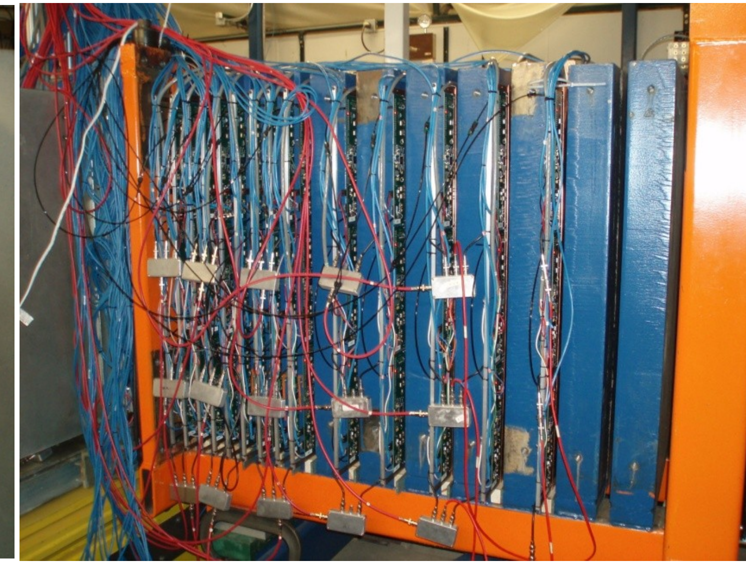


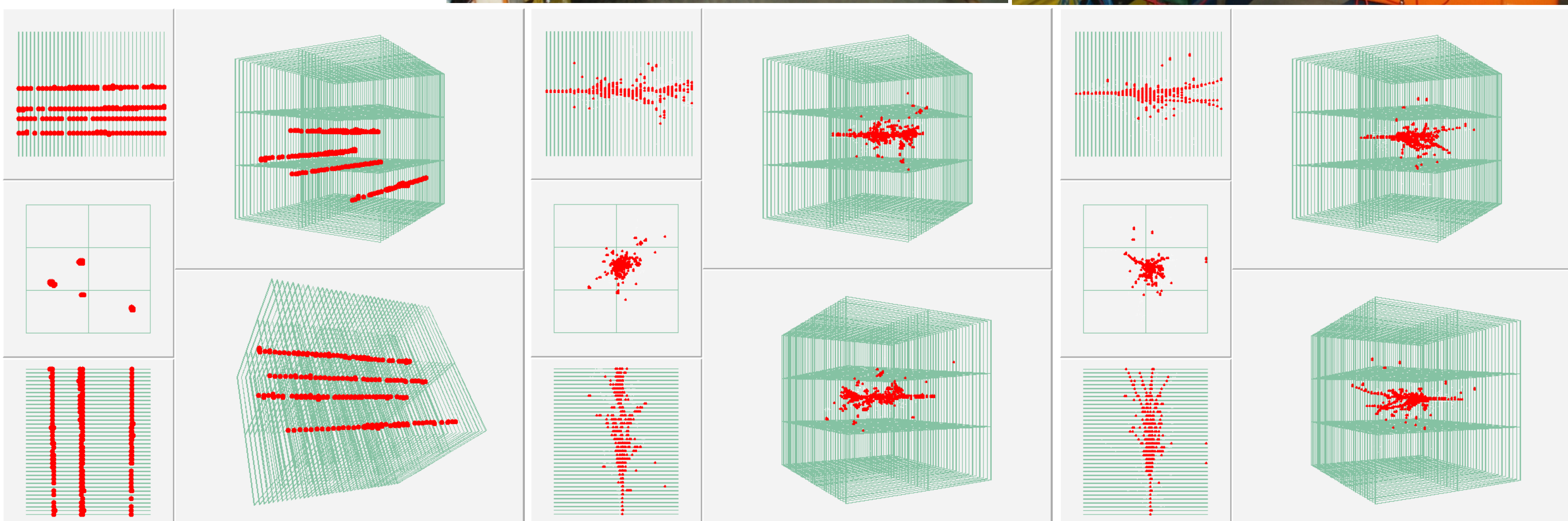
**1k** channels → **10k** channels → **~500k** channels!

# DHCAL Prototype @ US

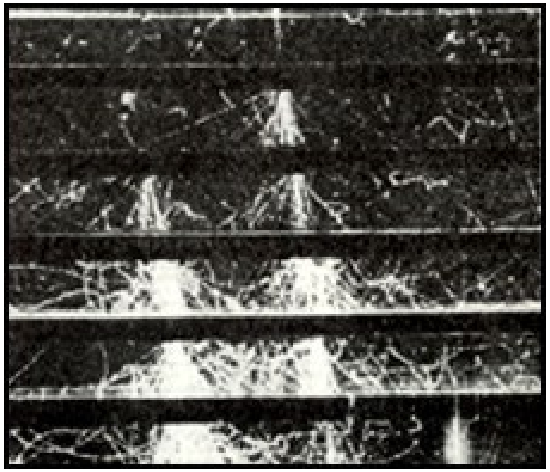
Cubic meter prototype
with 40+ layer:
480k channels!

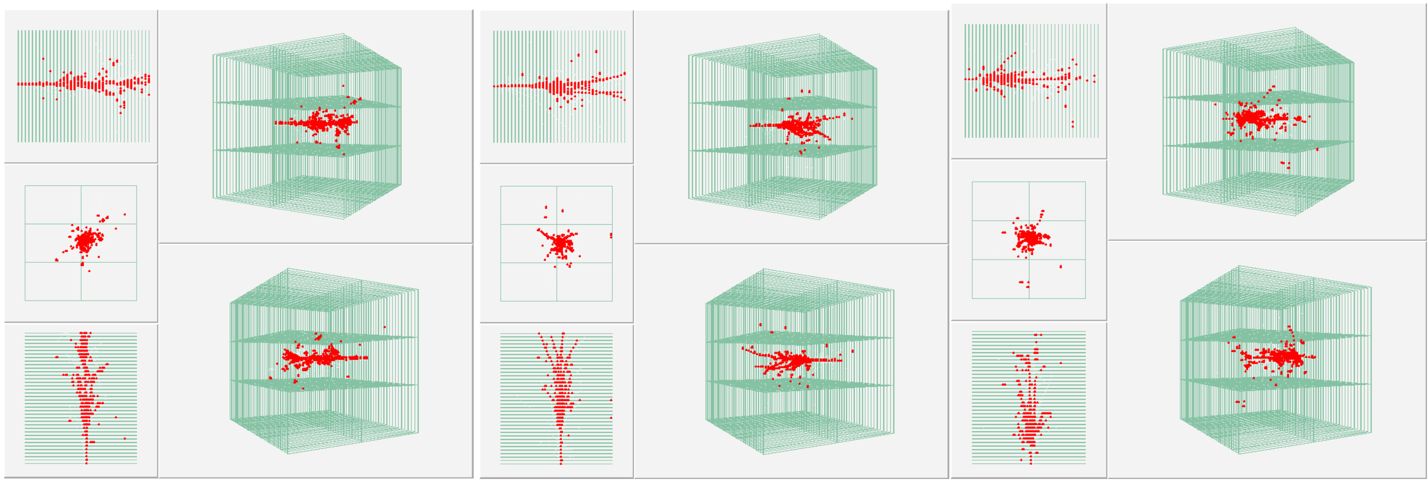


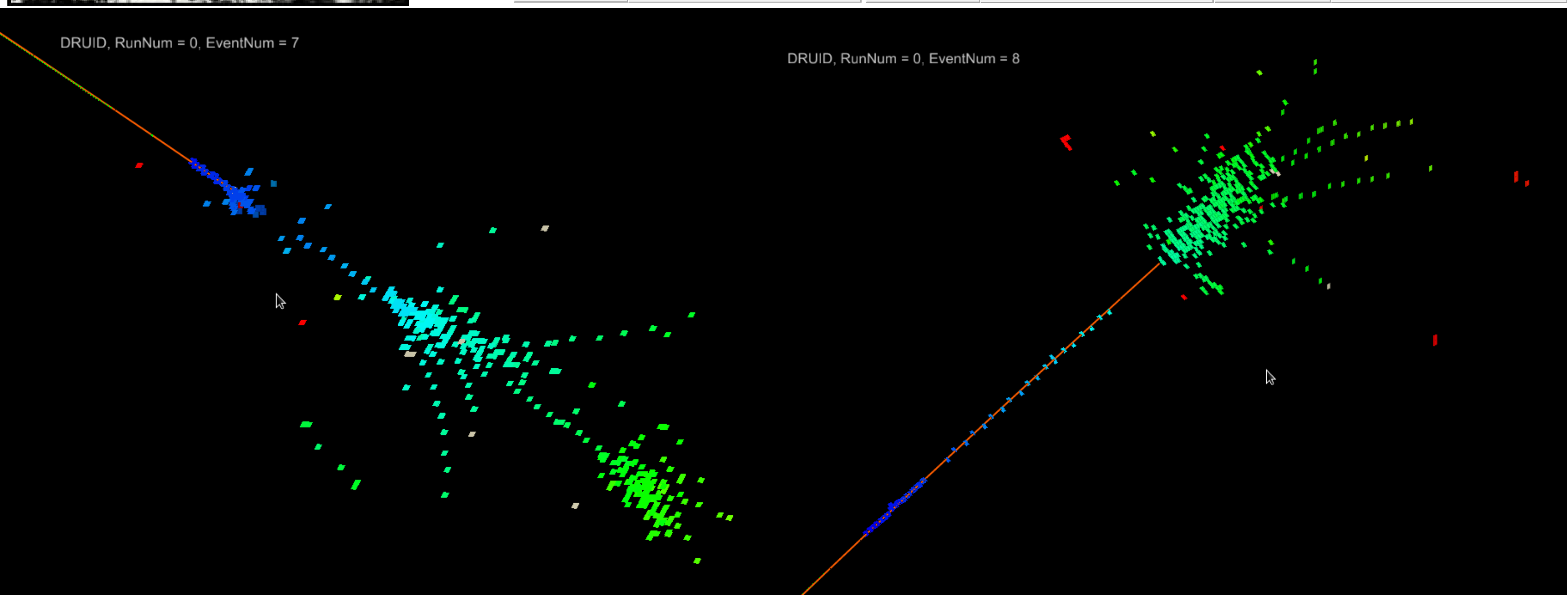




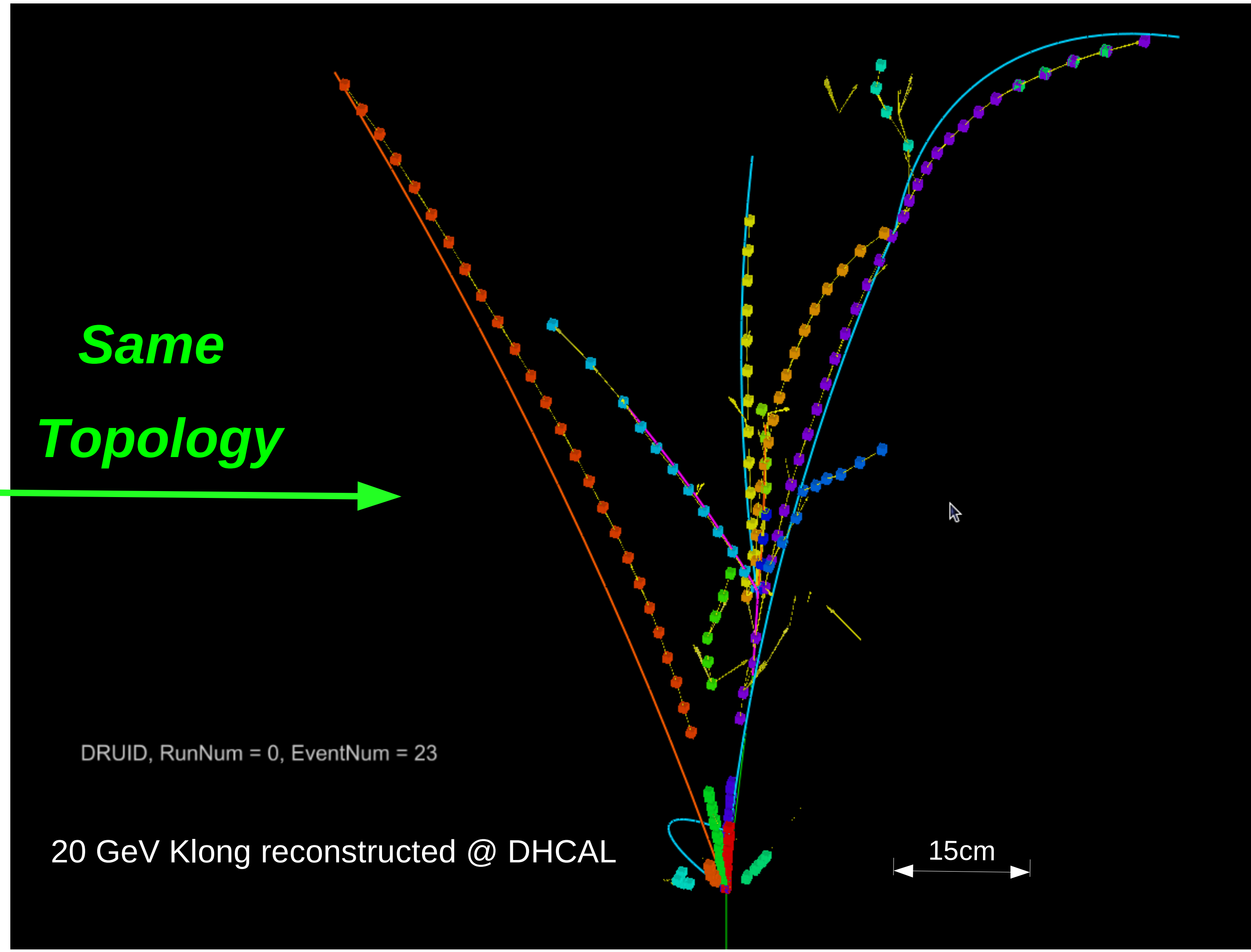
# Part II: Shower Reconstruction at an Imaging Calorimetry







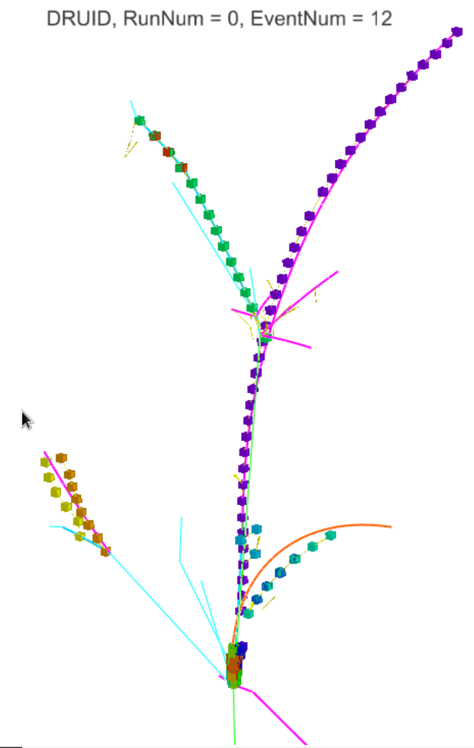
# Arbor: shower ~ tree



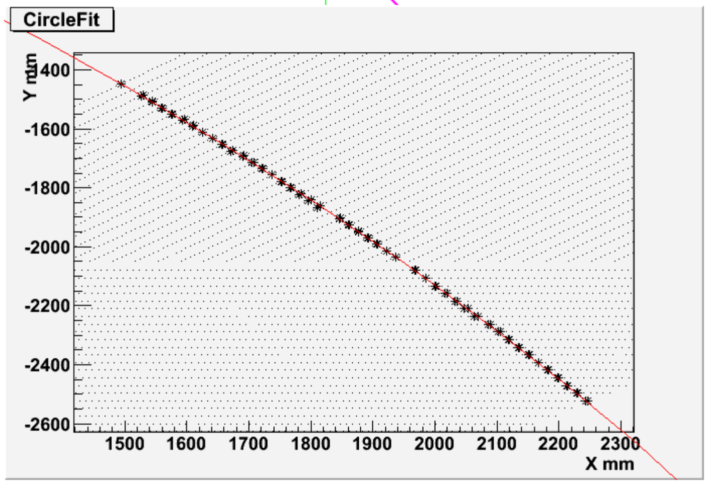

- *Start from Mirco structures: Full usage on high granular information*
- *Original idea from Henri Videau, in hadronic shower reconstruction @ ALEPH*

# Reconstruction of branches

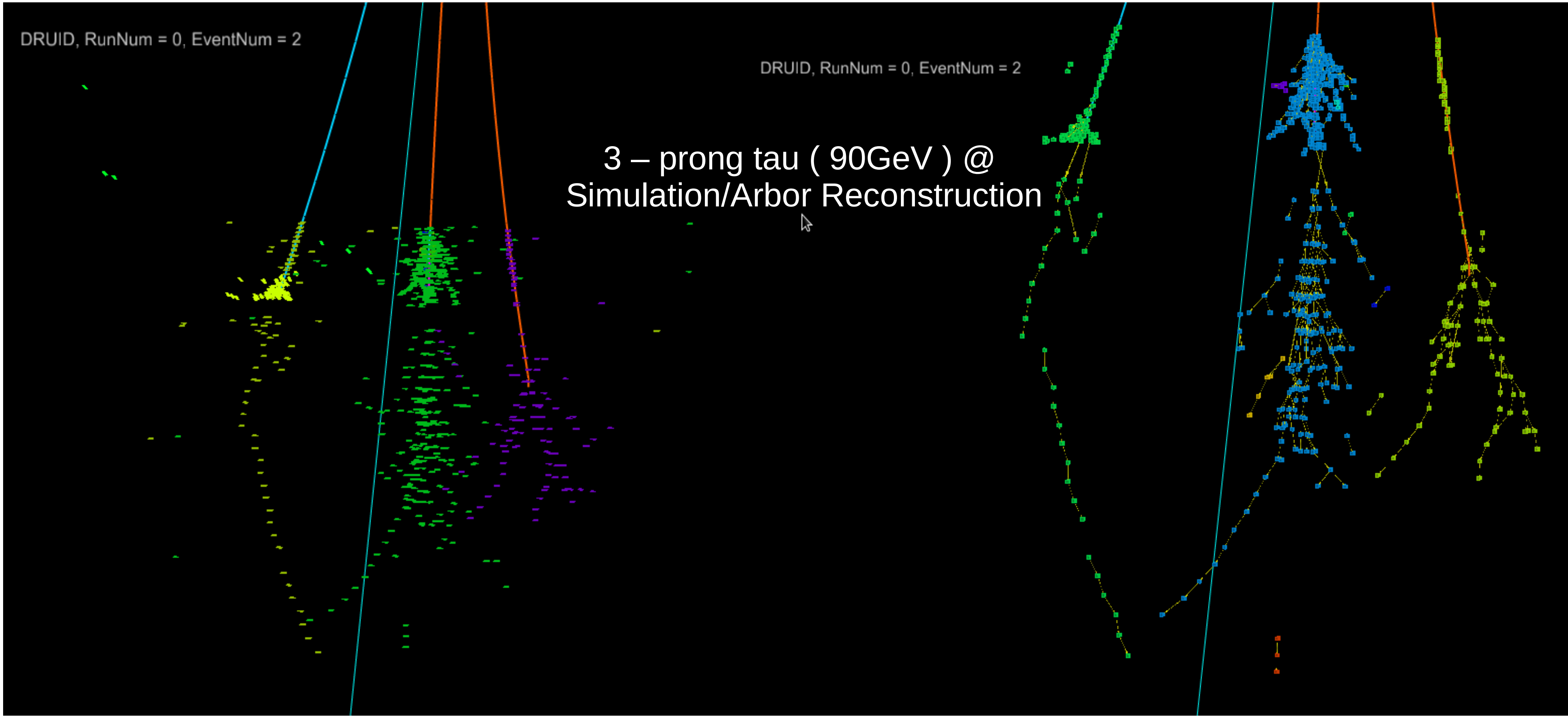
- Arbor: Promising branch tagging, with lots of potential applications
  - In situ Calibration/Stability monitoring
  - Kink & Pre interaction tagging
  - Track – Cluster linking
  - Calo Tracks Measurement:
    - Energy Estimation ~ Leakage correction
    - EM/Had hits tagging
  - ...




- Momentum reconstruction with Fit (J. Sniff, Princeton/LLR)
  - Using Pratt fit method + error calculation
  - ~10% resolution on MIP track in the barrel & leakage correction using 1 $cm^2$ DHCAL cells

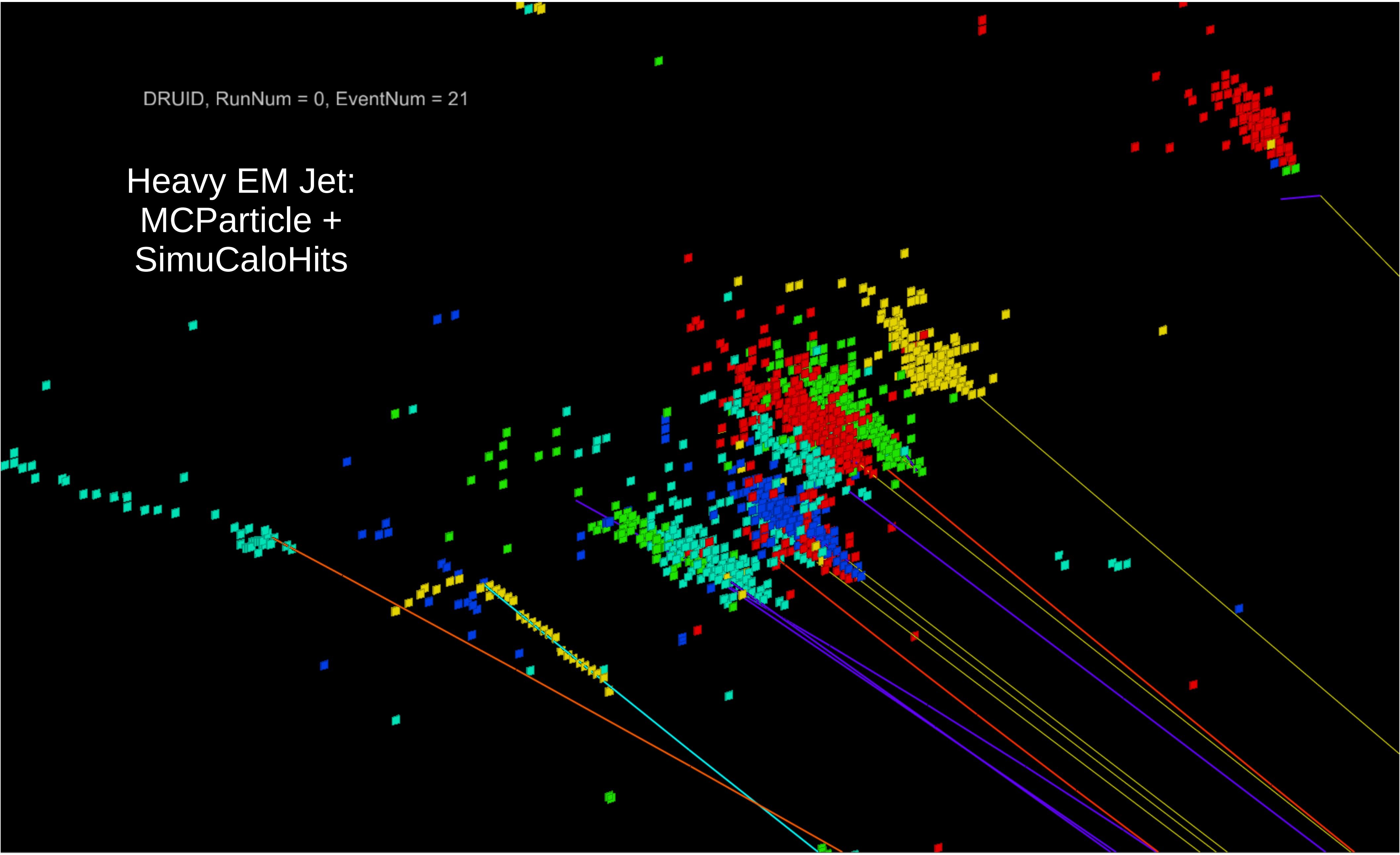


# Arbor: pion reconstruction

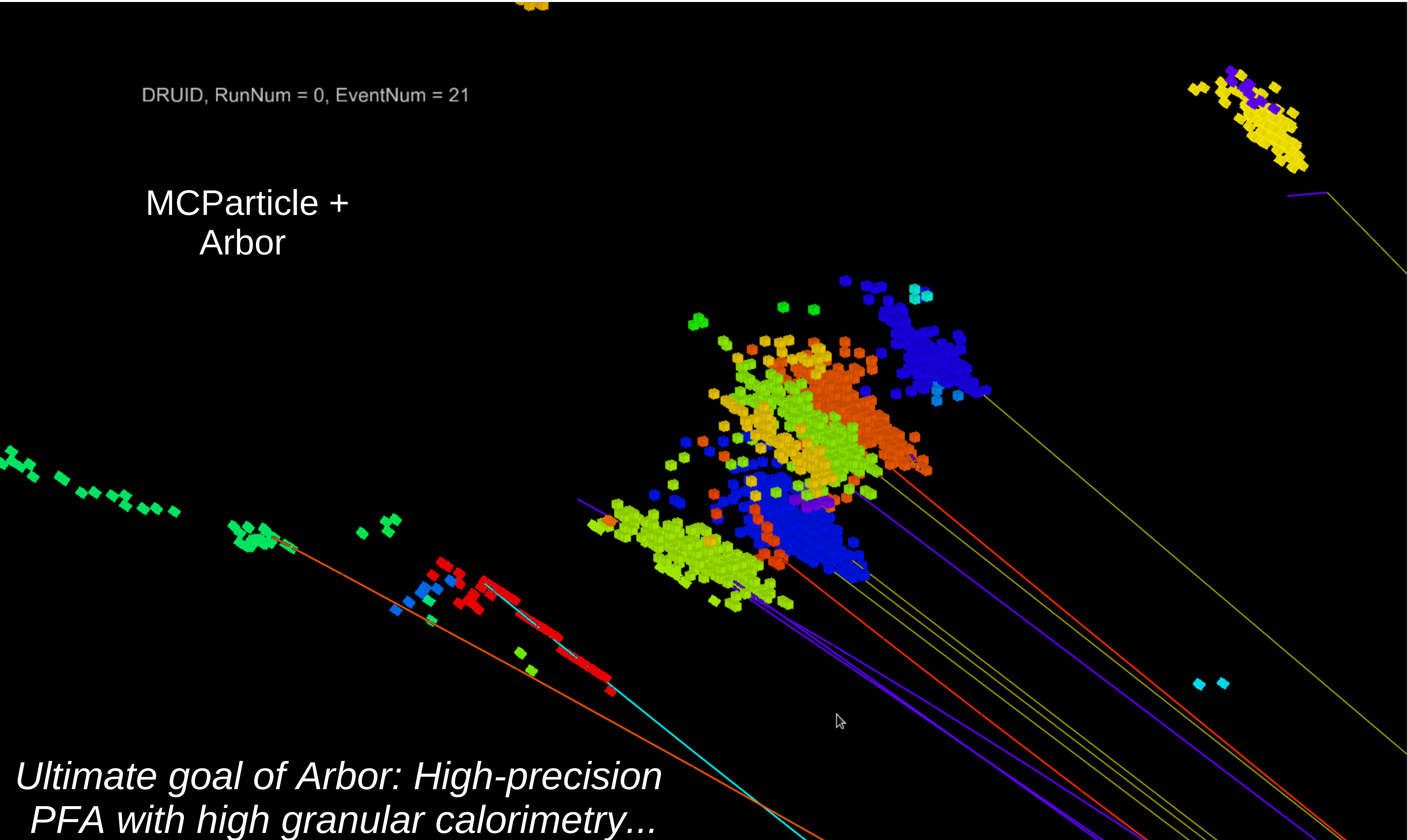



Merging Branches together : Reconstruction of Shower @ Calo

# Arbor: Separation

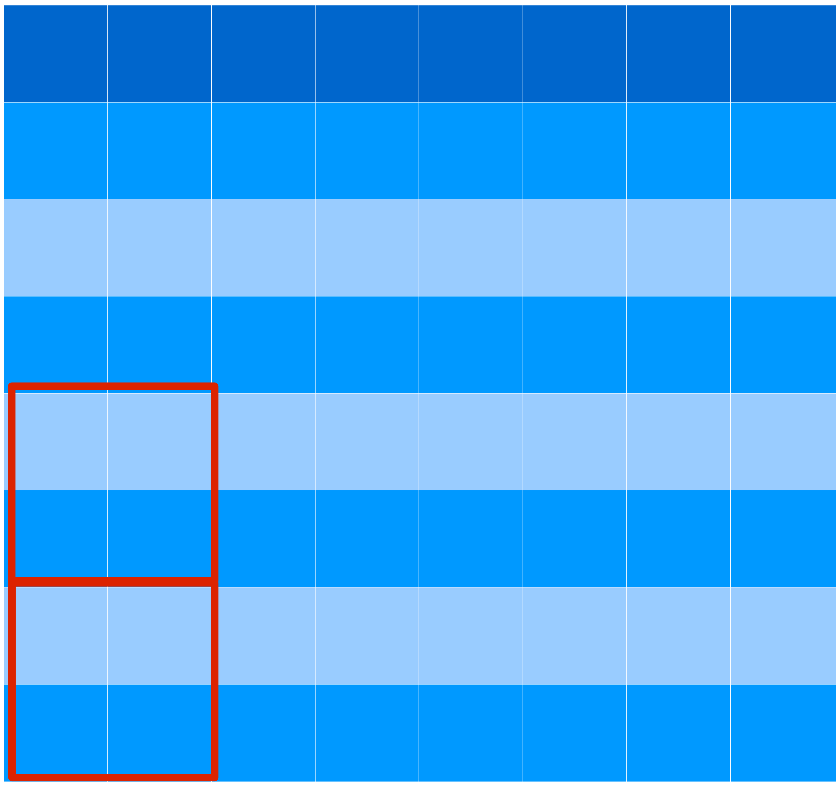


# Arbor: Separation




*Ultimate goal of Arbor: High-precision PFA with high granular calorimetry...*

# Shower particle: to interact or not



shower ~ self similar *(Mandelbrot Set)*

Measure shower Fractal Dimension (FD) at high granularity calorimeters

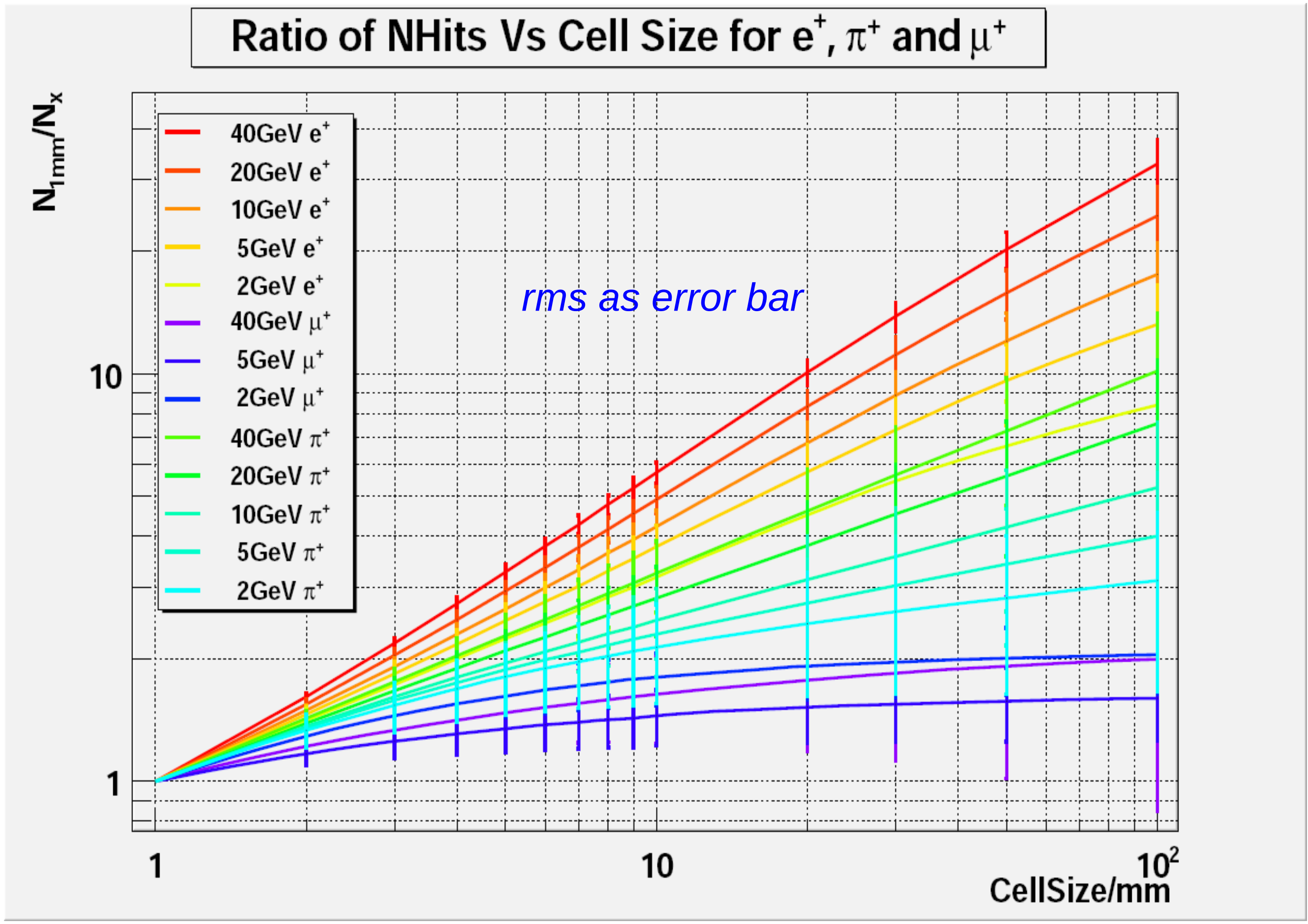
- Count Number of hits at different scale
  ( *define* $RN_x = N_{1mm}/N_{xmm}$ )
- *Varying scale by grouping neighbouring cells*

# Shower: Self Similar

- Characteristic constant based on energy/PID:

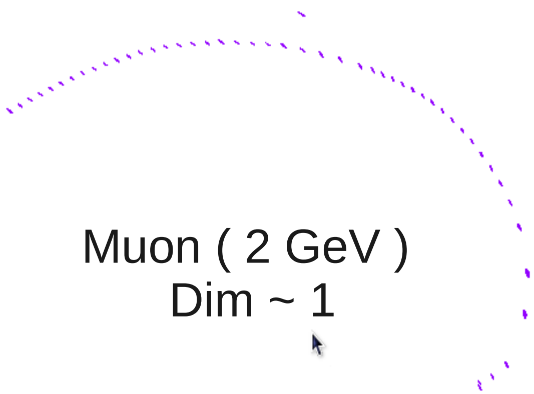
$$D = \langle \ln RN_a / \ln(a) \rangle + 1$$

  - Global parameter based on local density
  - *Cell Sizes: 2 – 10, 20, 30, 50, 60, 90, 120, 150mm.*
  - *Samples: Particles shot directly to GRPC DHCAL with only B Field*



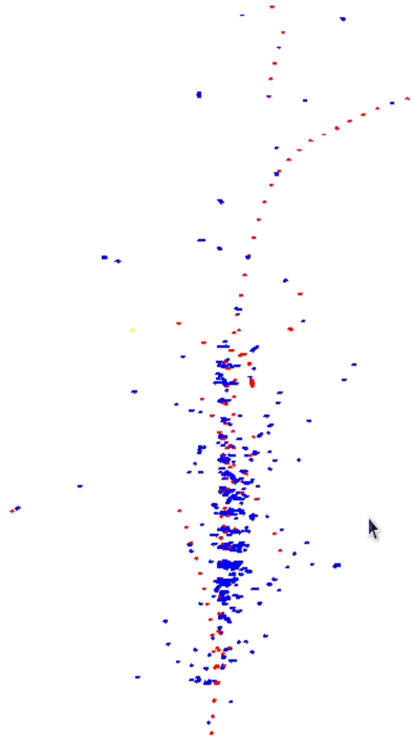

- Be observed within
  - Low scale: minimal interaction energy & sensor layer thickness ( 1.2mm )
  - High scale: full containment ~ 1 hit per layer

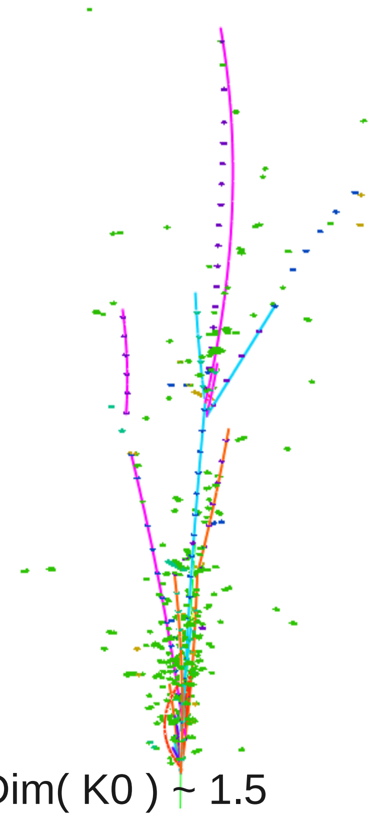
# Fractals in Nature



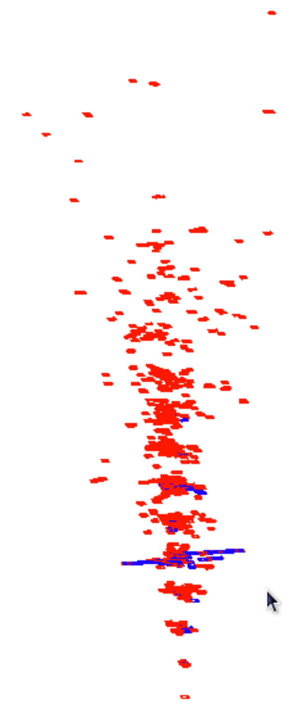
Muon ( 2 GeV )
Dim ~ 1

Curve/line:
Dim = 1

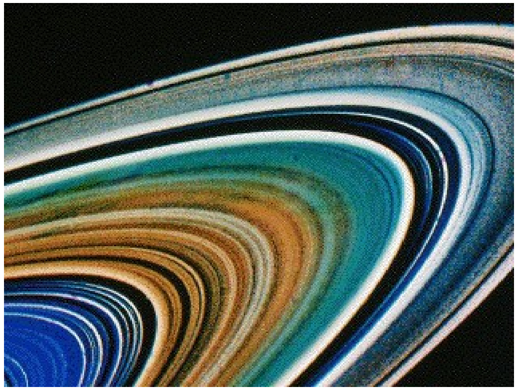




Hadrons: Dim( pi ) < Dim( K0 ) ~ 1.5

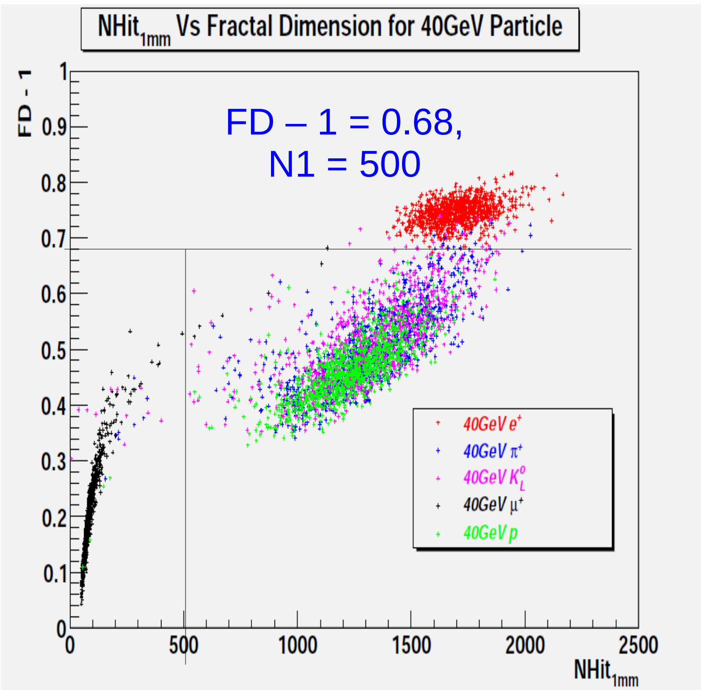


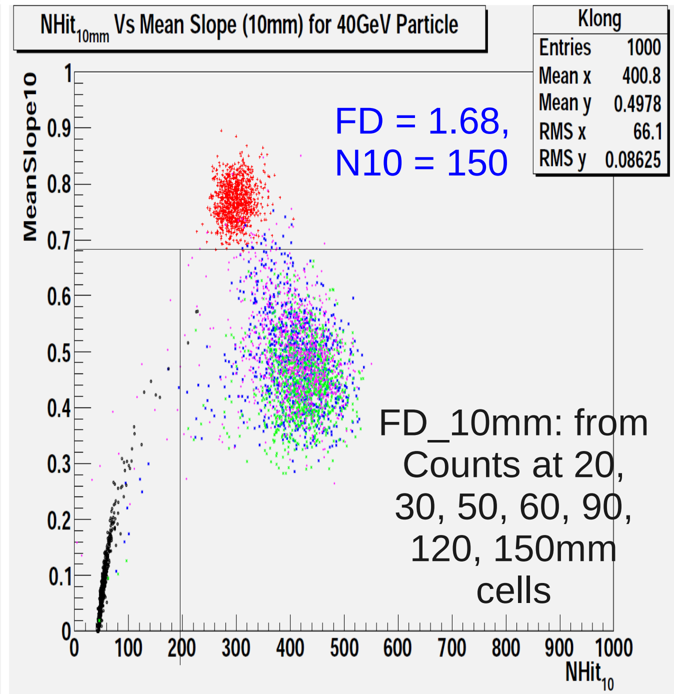
Positron ( 40GeV )
Dim ~ 1.75

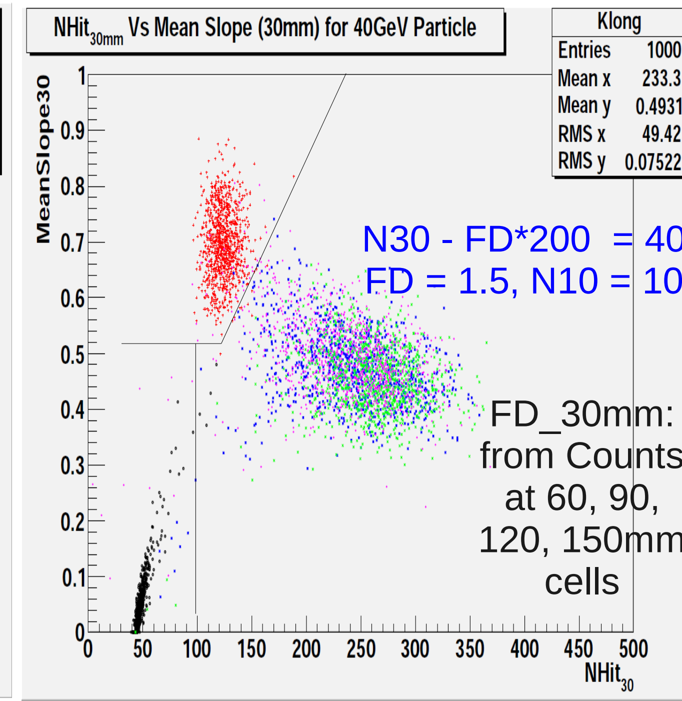


Rectangle:
Dim = 2

# Potential tool for PID




FD together with other info ( Nhits ): Clear separation at different scales

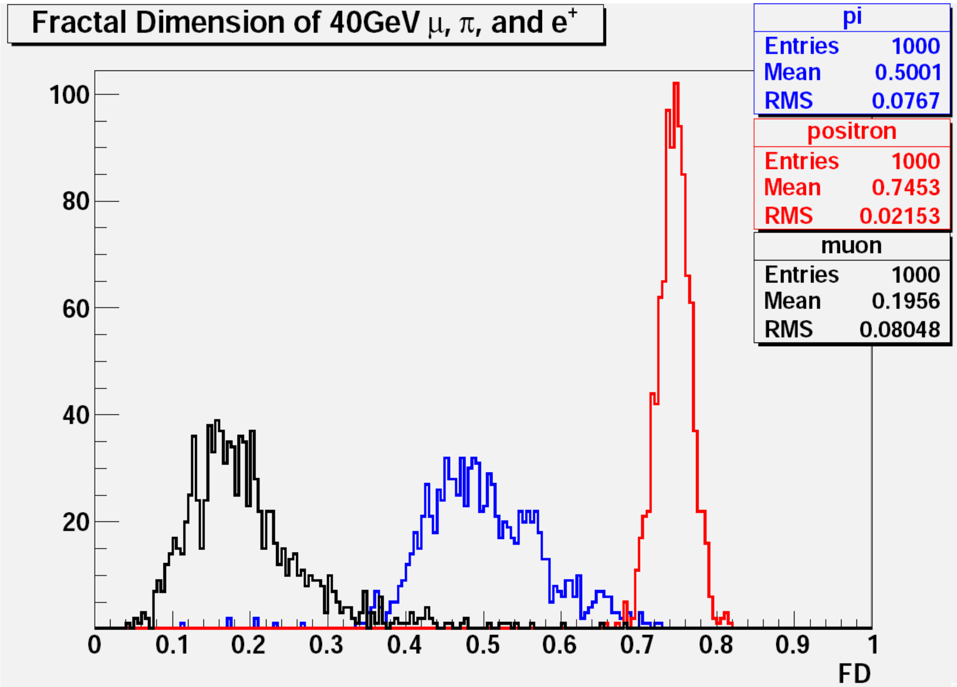
*Remark: Energy dependent Cuts, easier for charged particles*

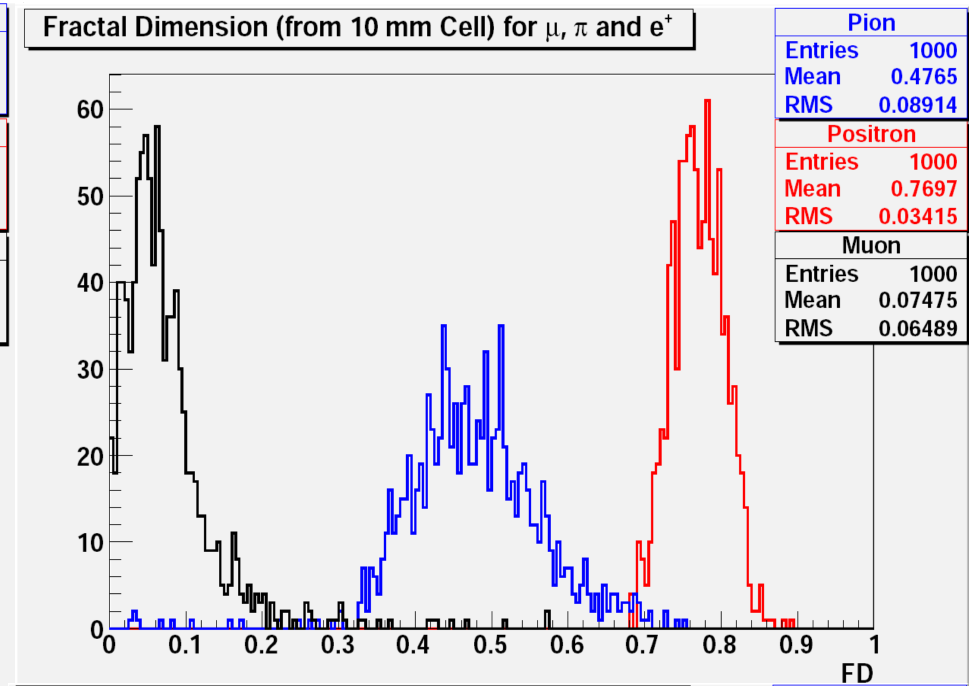
| 1mm | e+ | u | h |
|---|---|---|---|
| e+ | 998 | 0 | 2 |
| u | 1 | 994 | 5 |
| h | 15 | 14 | 971 |

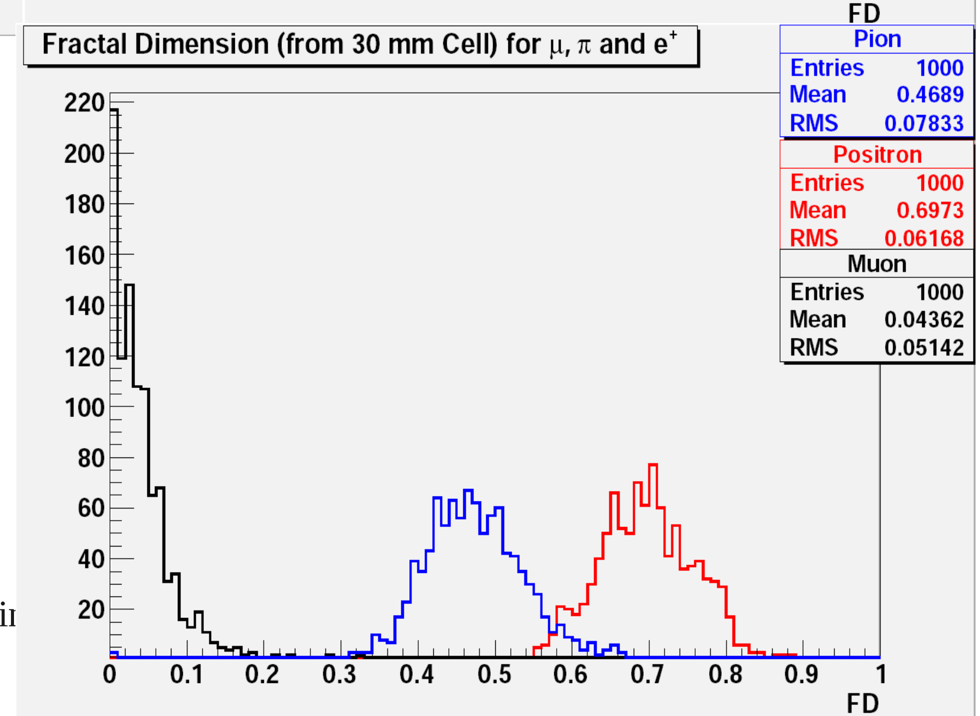
| 10mm | e+ | u | h |
|---|---|---|---|
| e+ | 1000 | 0 | 0 |
| u | 0 | 995 | 5 |
| h | 17 | 14 | 969 |

| 30mm | e+ | u | h |
|---|---|---|---|
| e+ | 1000 | 0 | 0 |
| u | 0 | 996 | 4 |
| h | 18 | 11 | 971 |

# FD @ different size



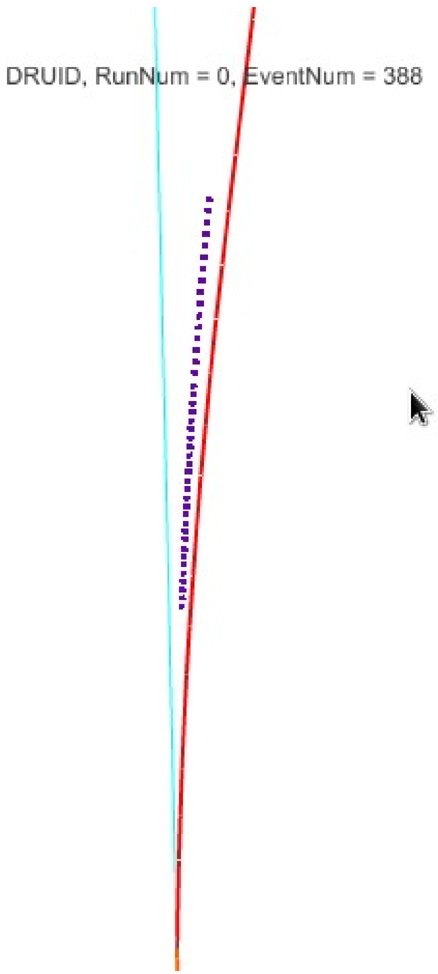

From FD( 1mm ) to FD( 10/30mm ):

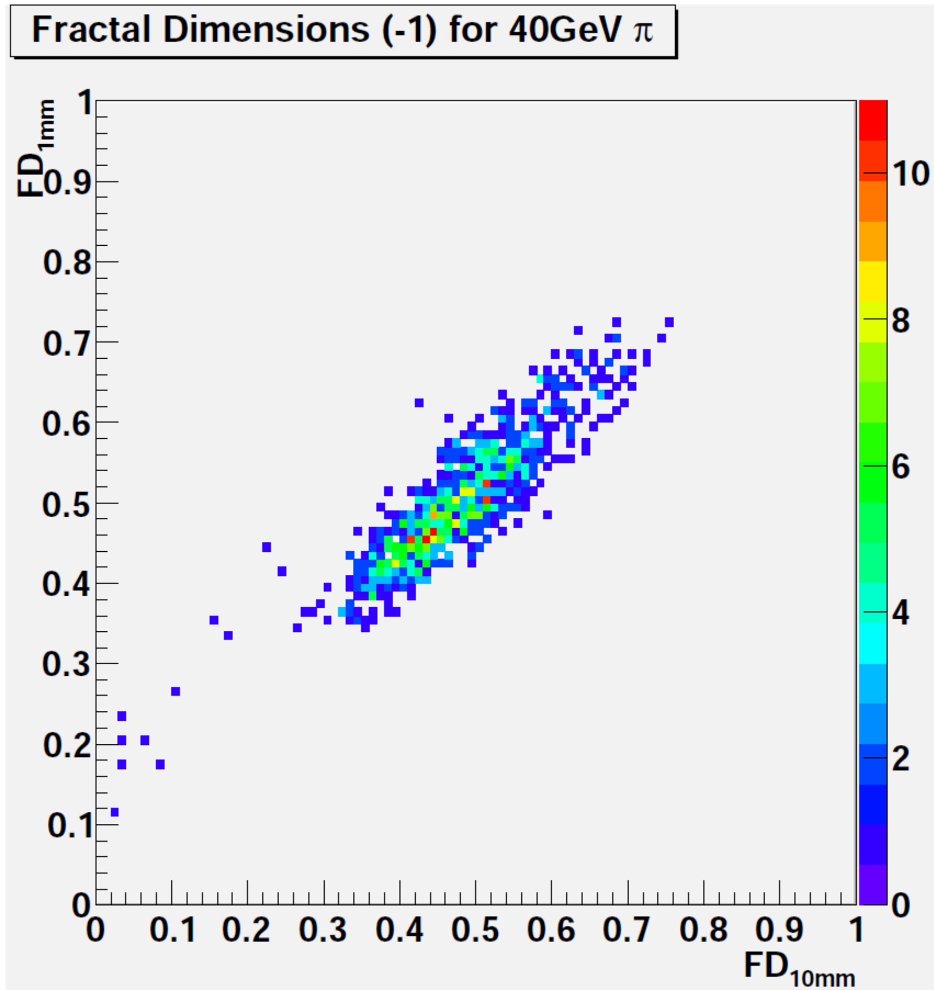
Positron Peak Smeared

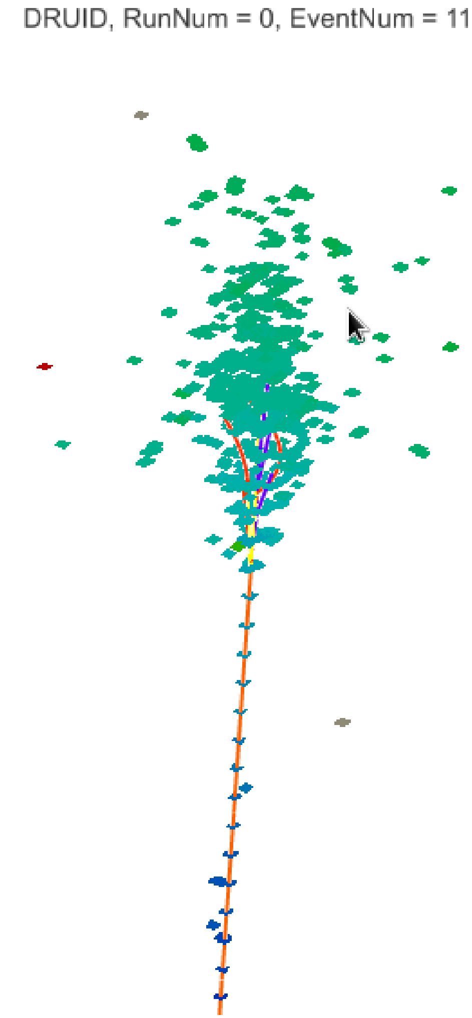
Better μ – h separation: μ acts more like a line ( FD = 1 ); ( Anyhow *we can create large cells from small ones...* )

π: continuous distribution from MIP to EM

# Extreme Cases: Pion

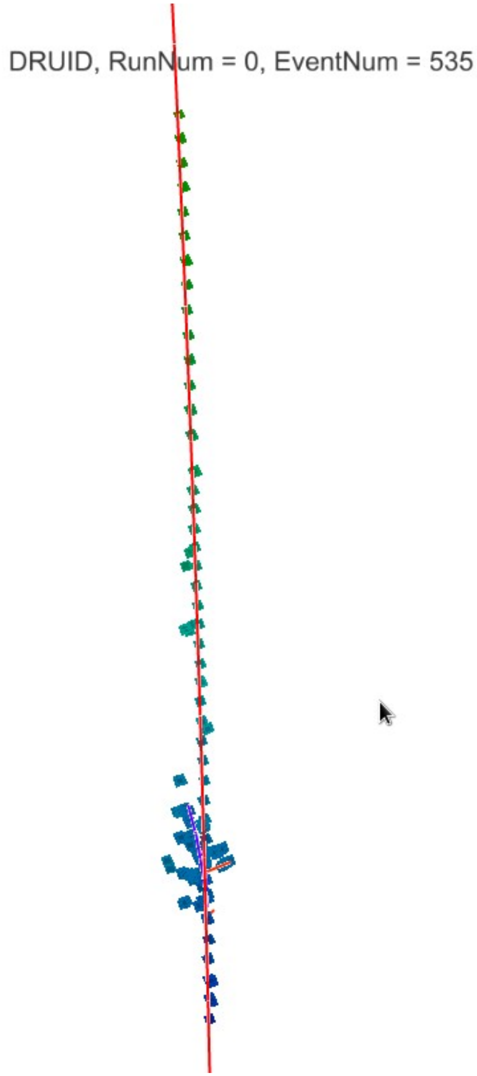


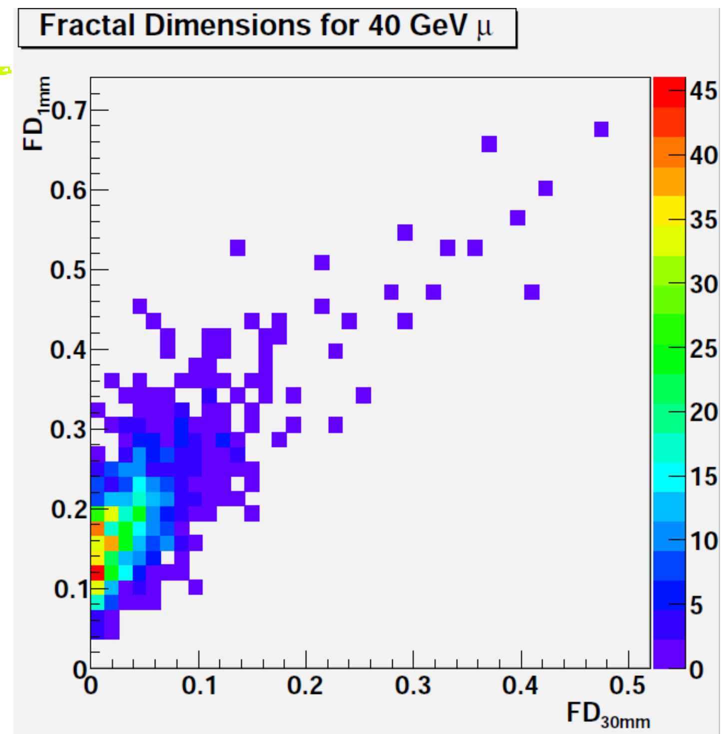



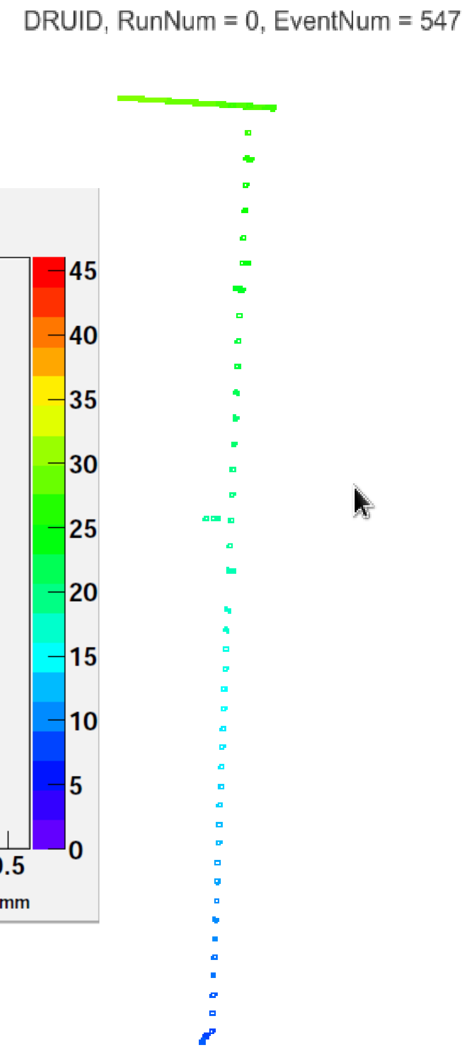

- Pion: MIP, Pion decay;
- EM interaction ( pi + N = P + pi0 ); partially identified by interaction point tagging

# Extreme Cases: Muon



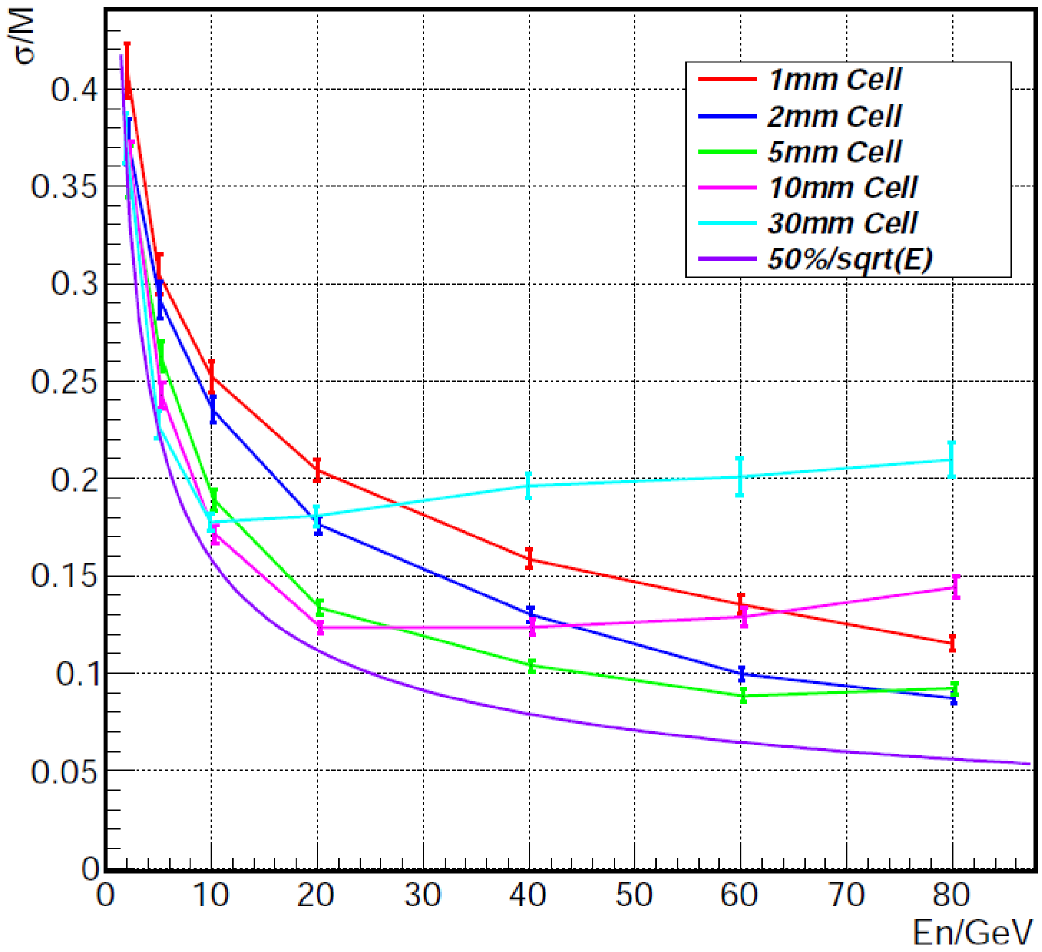


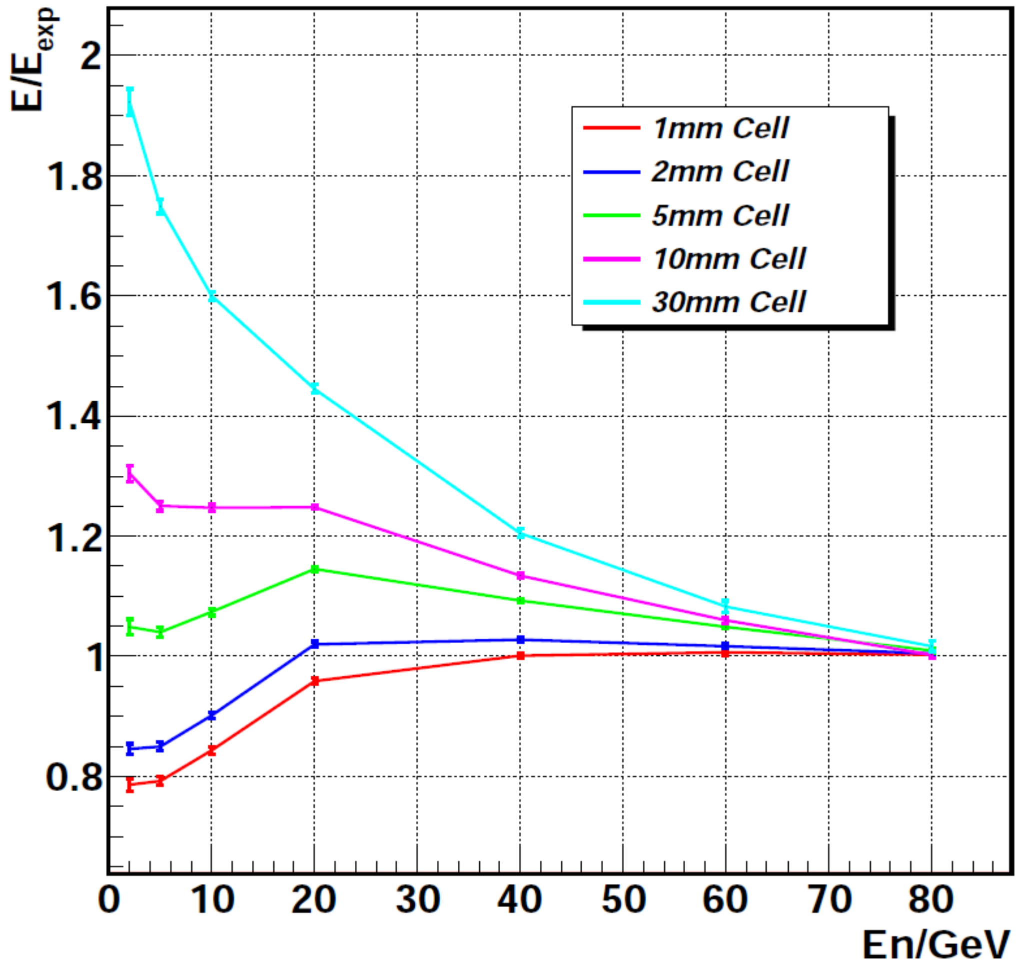



Muon radiation & String noise (electrons trapped in gas layer)...

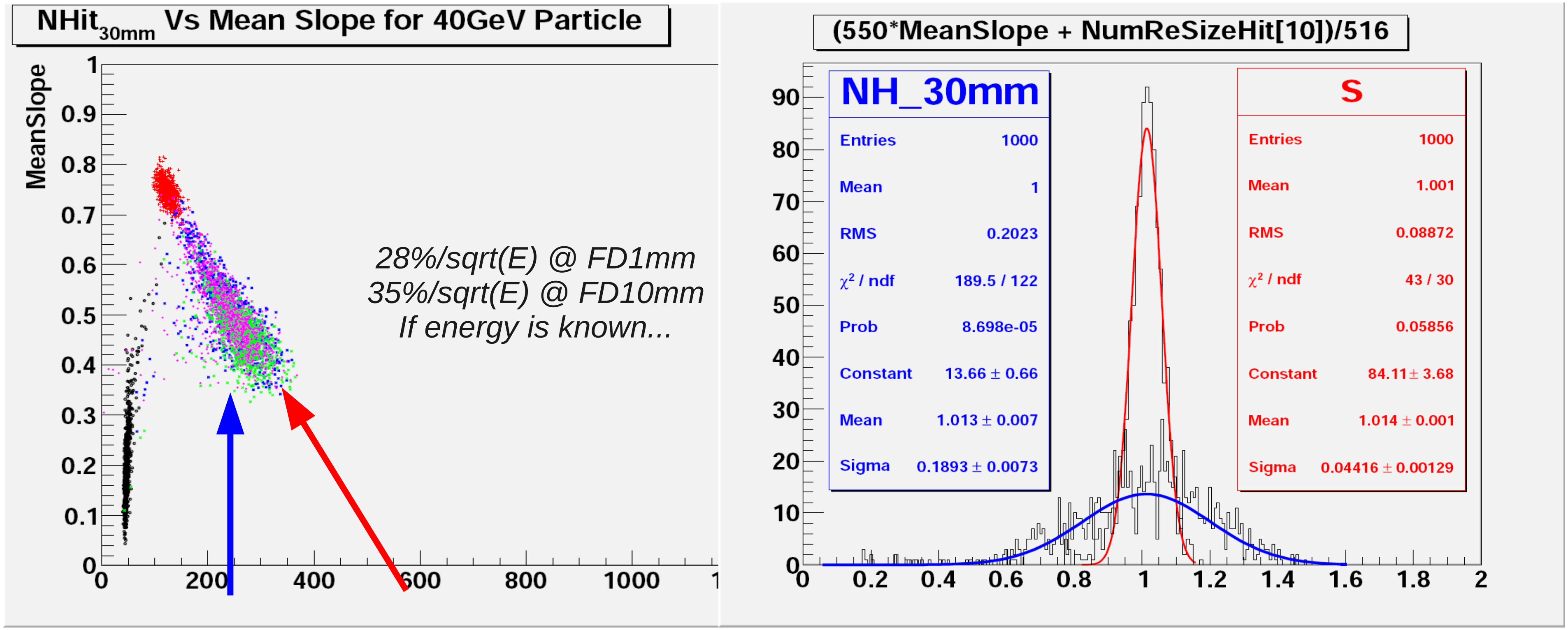
# Energy Estimation with Naive Counting




σ/M: Large cell better at low energy & Smaller cell at high energy.
Linearity: Better at 2 – 5 mm, stronger saturation effects at larger cell...
Naively: 5mm seems a nice choice...

# FD for Energy Estimation

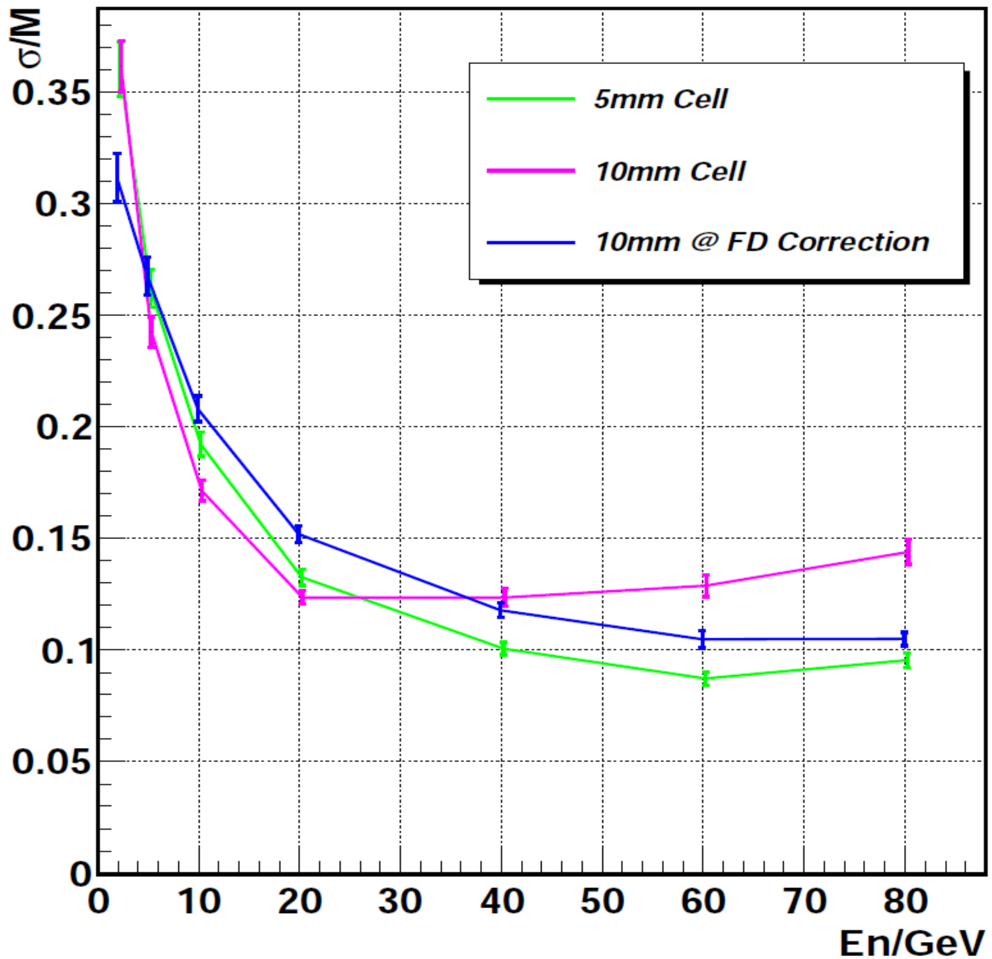


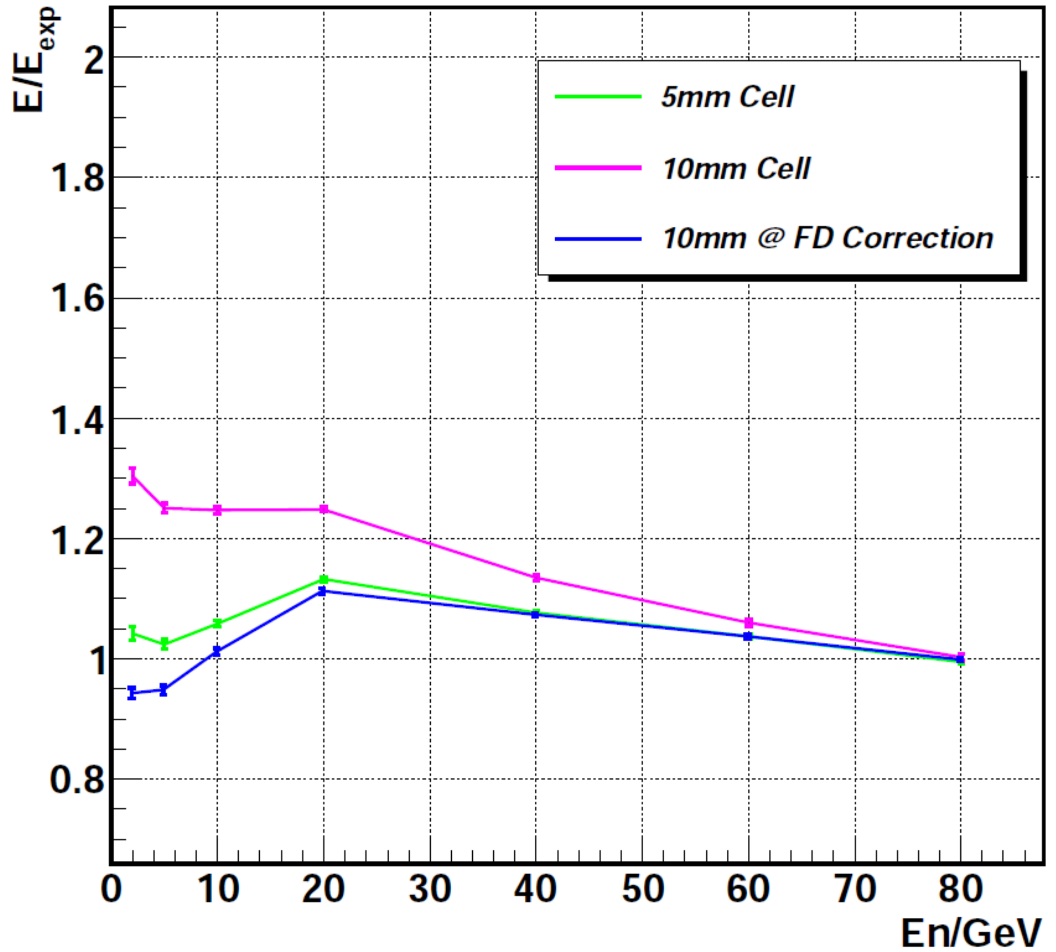

- For example: Compensation based on the correlation of NH_30mm & FD1mm:

  E = a * NH_30 + b * FD ~ 30%/sqrt(E)! But...

- Correlation coefficient depending on Energy: b ~ 0.0266*E. To measure cluster energy of charged particle (with track info): to improve track-cluster linking...
- Energy independent ( LO ) estimator: E = a' * NH_x/(1 – FD*b')

# Energy Estimation with FD Correction




Hand put Energy Estimator with FD: NH10/(1-0.65*FD10)
Energy resolution improved at high energy: ~ saturation effect correction
Linearity improved: closed to 5mm Cell

# Summary

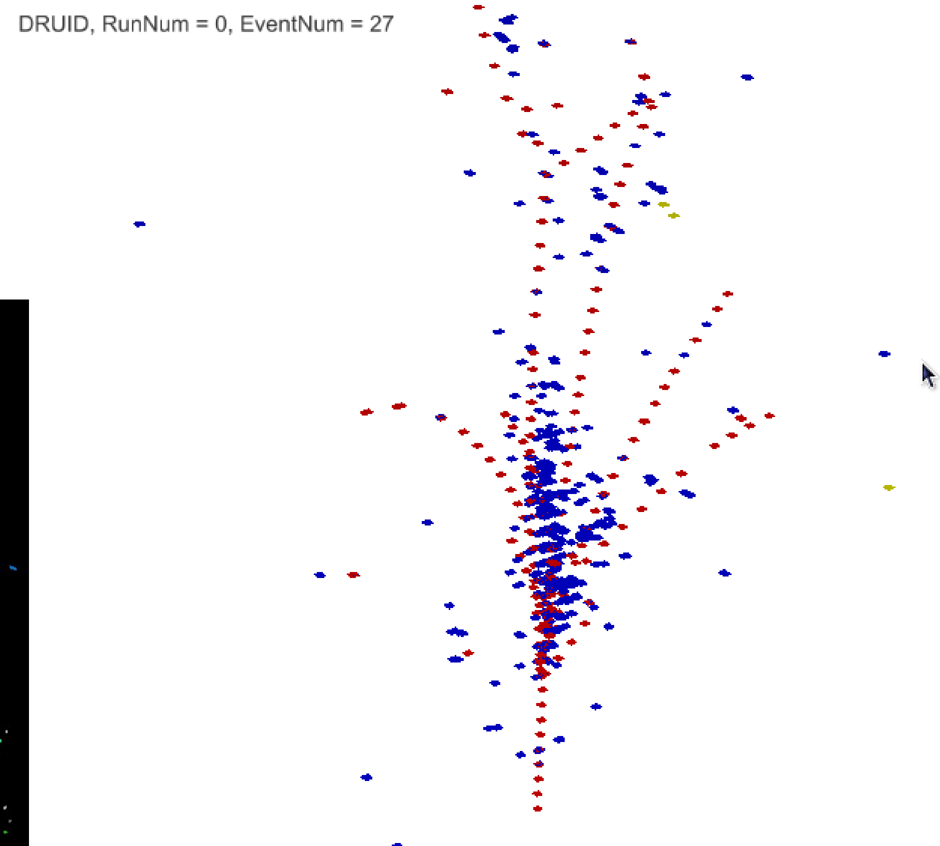
- DHCAL with extremely high granularity: Valid @ Simulation and TB data

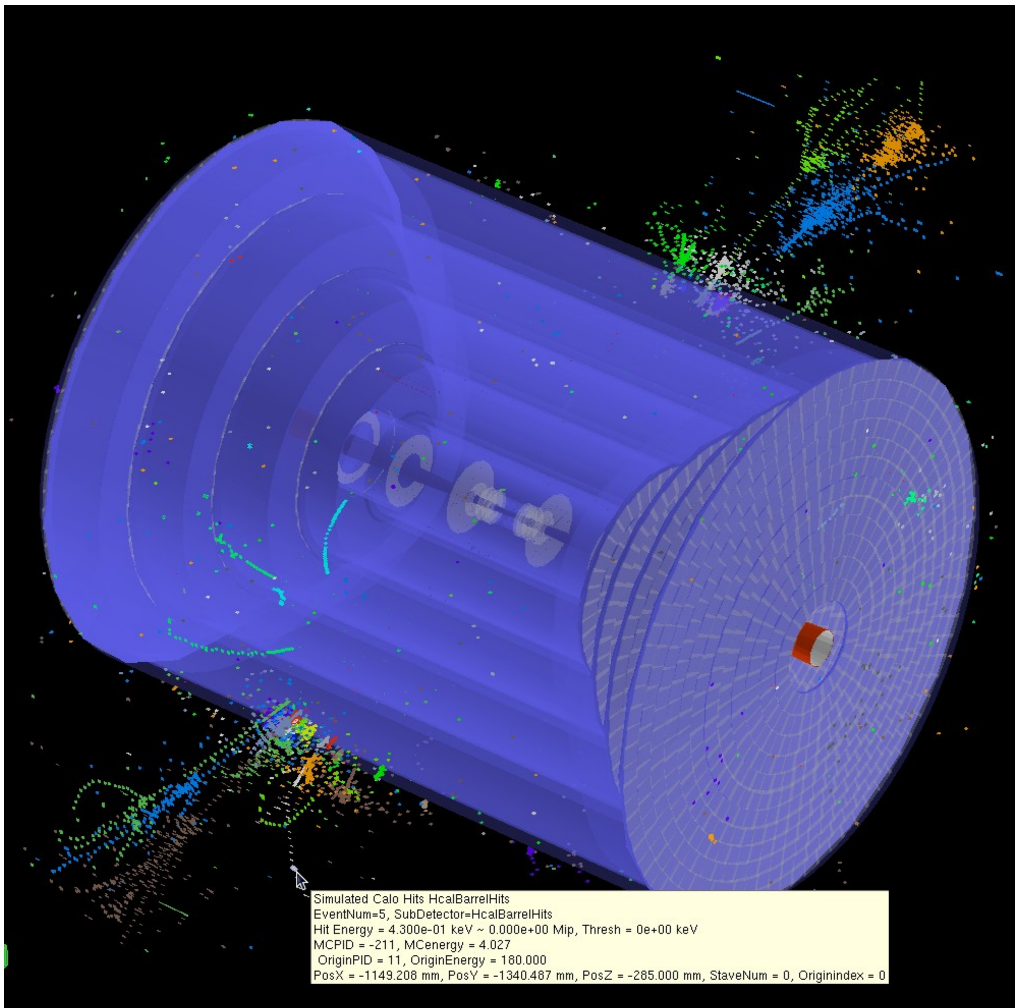
- Huge reconstruction potential at high granularity calorimeter...
  - Arbor:
    - MIP tagging with lots of potential application:
      - Energy Estimation,
      - Leakage correction
      - ...
    - Future PFA Framework: Better separation, pattern recognition
  - Fractal Dimension:
    - Promising PID
    - Track-clustering matching & energy estimation
    - Not fully investigated...
  - Your dreamed but never realised algorithms

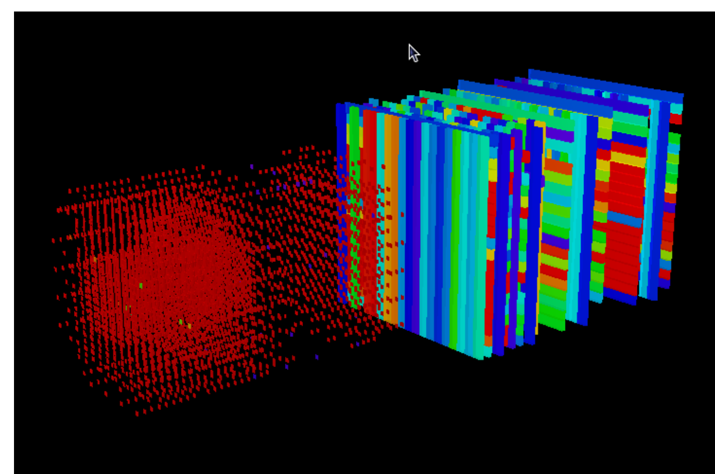
# Thank you!


Wish you a happy & fruitful Dragon's Year!

# Spare Slides

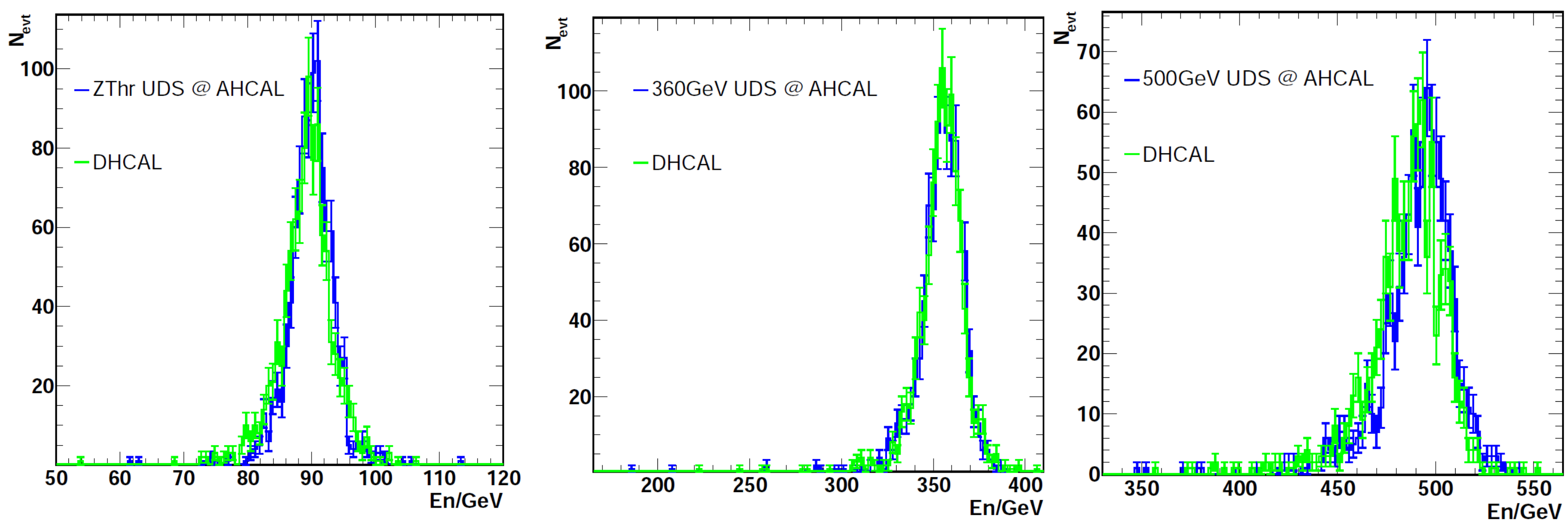


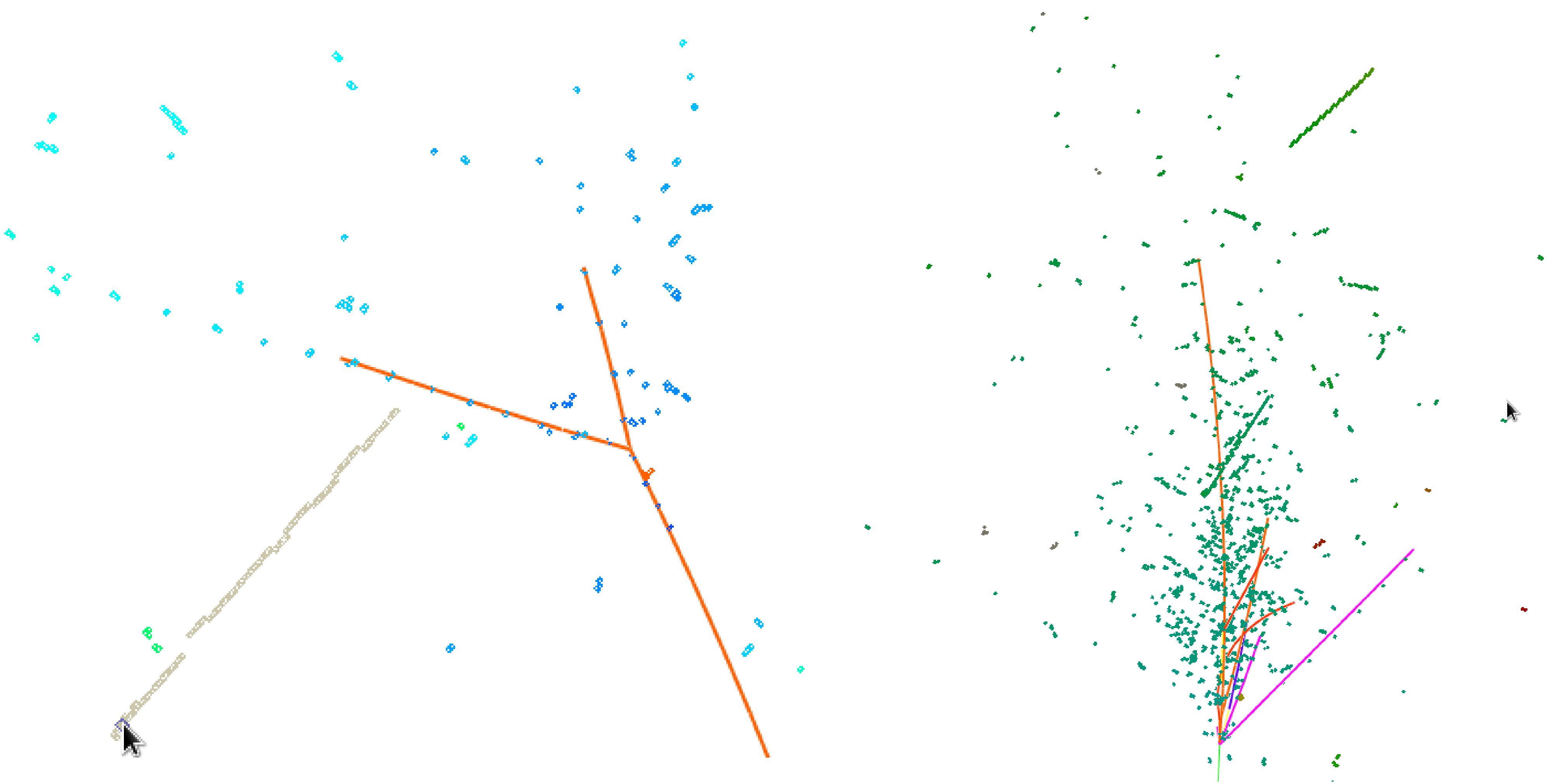
# Reconstruction Software

- Goal: develop & optimize the reconstruction chain for ILD with SDHCAL
- Status & Plans:
  - Detailed simulation and Digitization with experimental input
  - PandoraPFA ( *Currently Best PFA for the LC* ) adapted & to be optimized




  - Huge potential to improve
    - Shower Clustering & Reconstruction: Arbor
    - PID & Energy Estimation: impaction from Shower Fractal Dimension
  - Druid ( event display ): heavily employed in algorithm development

# Noise cleaning

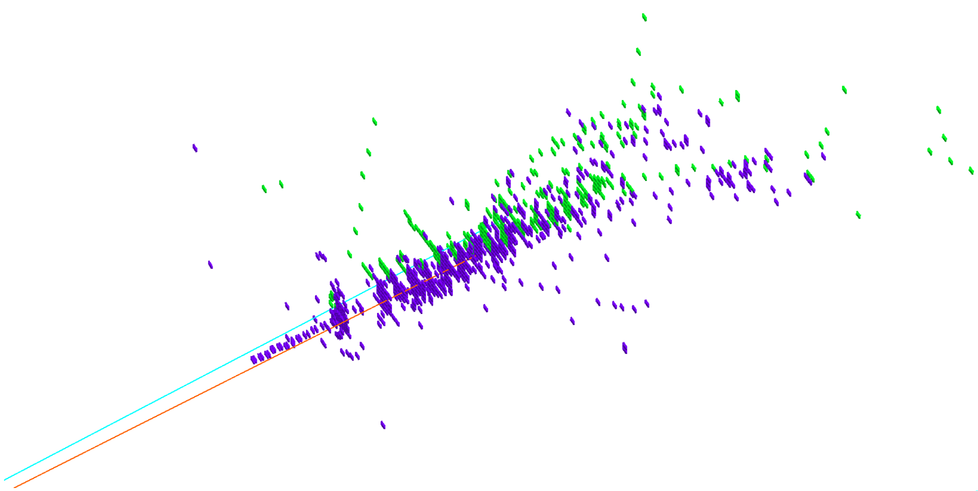


*String Noise: Typical in gaseous detector: charged particle tripped In the gas layer ( display of 1mm hits Information )*

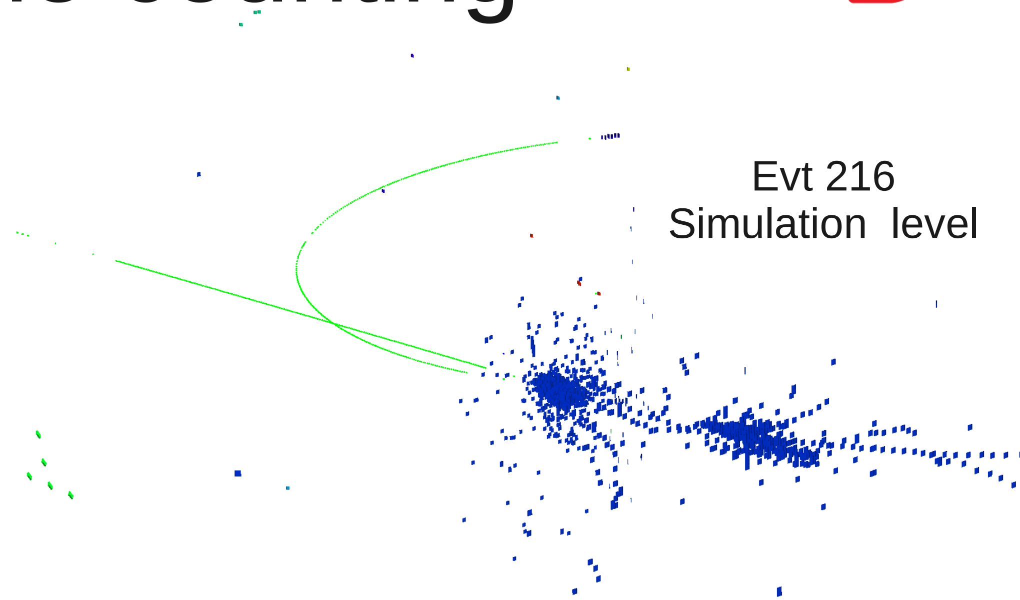
Roughly improve 5% - 10% on Energy Resolution by Cleaning

# Double counting

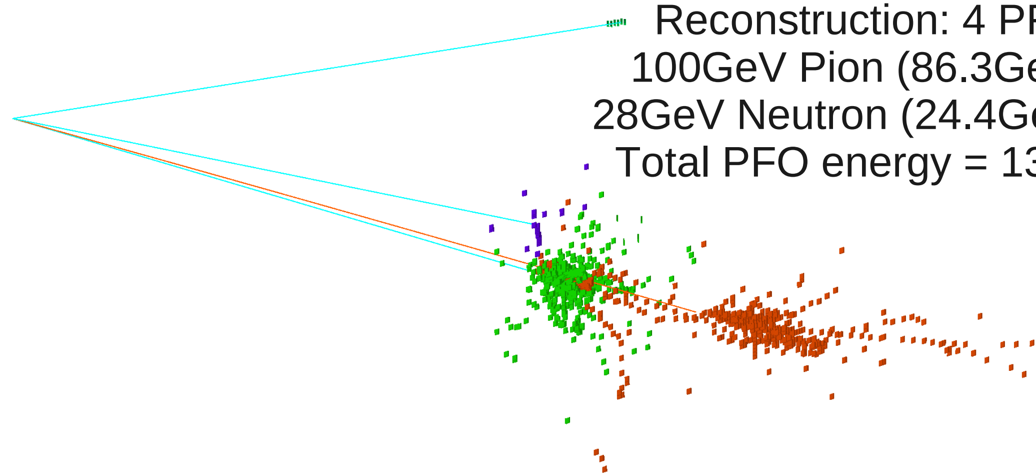
(Evt 286) 2 PFOs, Identify as
100GeV Pion (80.7GeV cluster) +
45GeV Neutron (45.4GeV)
Total PFO energy = 145GeV
Seed at deep ECAL Layer...



Evt 216
Simulation level



Reconstruction: 4 PFOs:
100GeV Pion (86.3GeV) +
28GeV Neutron (24.4GeV) + ...
Total PFO energy = 130GeV



**Clustering**
**To be improved...**

# Interaction based double counting

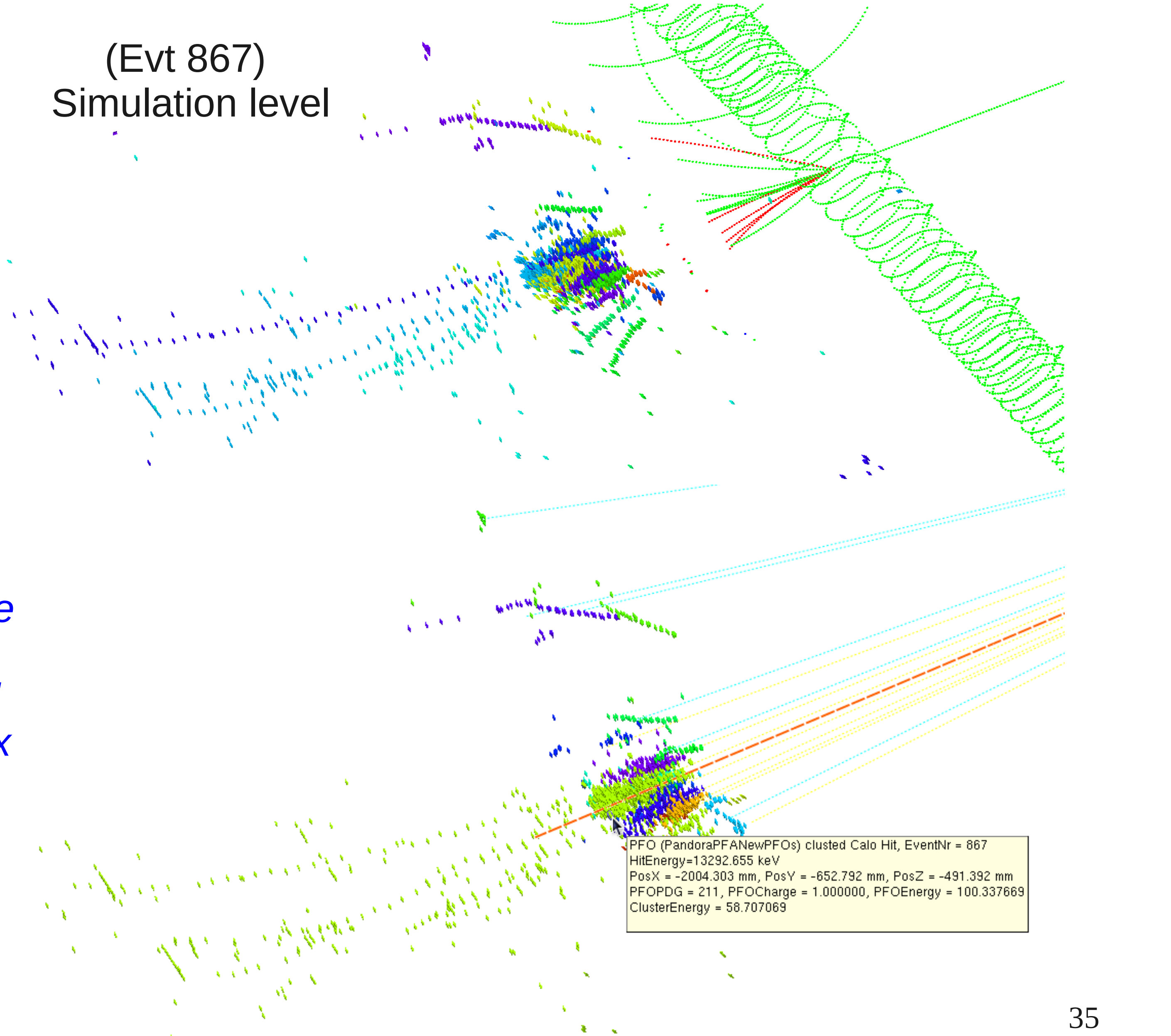
## Near the Calo

Reconstruction level:

15PFOs
Leading PFO (59GeV cluster) identified as 100GeV pion.
Others contribute to double counted 32GeV...

*To be improved by fitting the PFO position & direction... if coming from same spatial point ( besides IP ) & Vertex Reconstruction in Tracker...*

(Evt 867)
Simulation level



# Even more crazy...

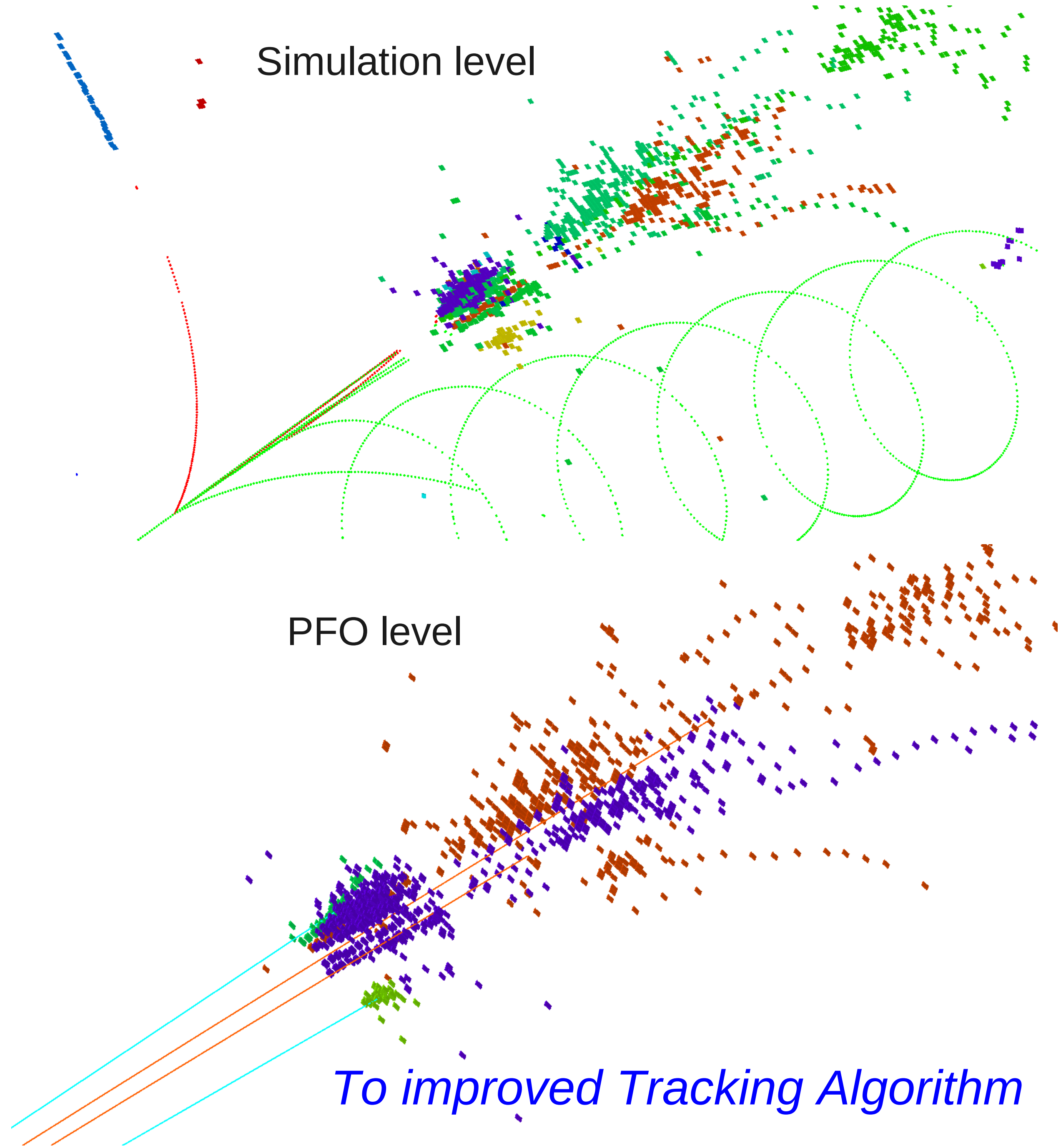
Evt 646: Interaction Inside TPC (1/3 of the radius)

Confused tracker: 3 LDCTrack found

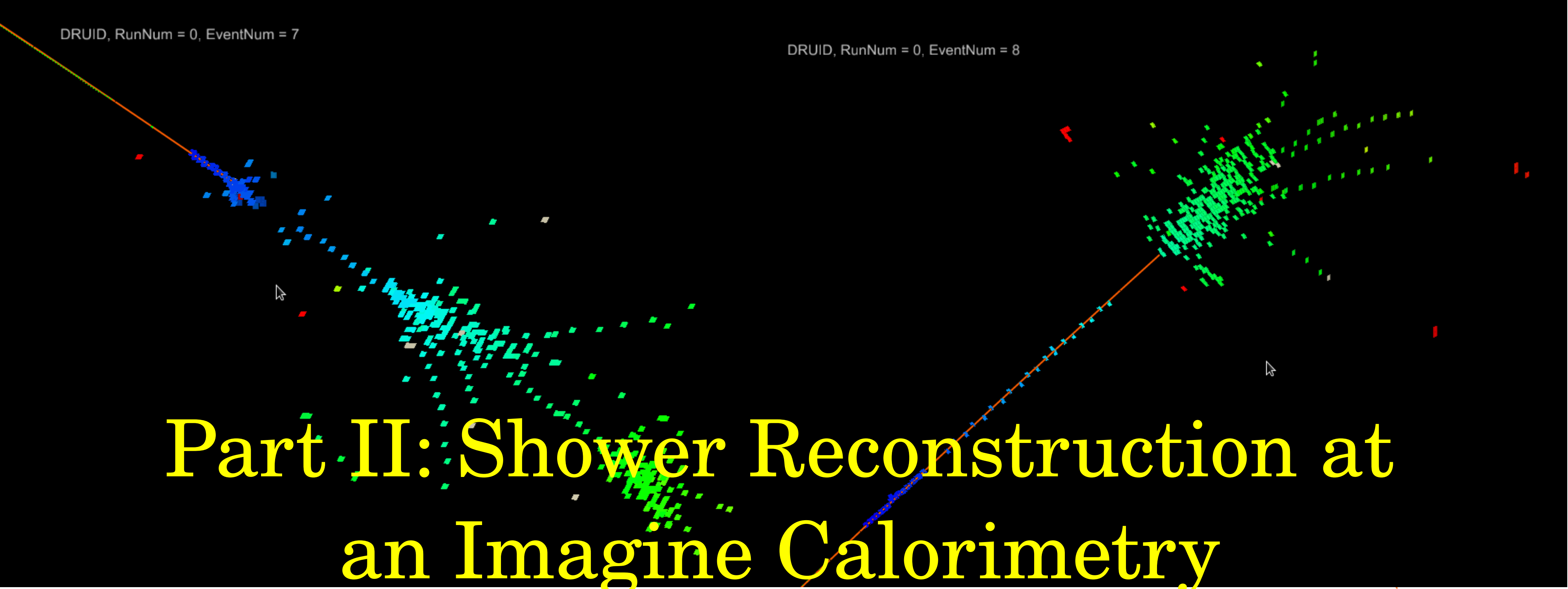
6PFOs:
2 leading PFO assigned with tracks + cluster, with energy 110GeV (40GeV cluster) and 148GeV (55GeV cluster)

Totally reconstructed energy: 264GeV

*Judgement on trk quality?*
*Flag on those kind of evts*
*Rely more on cluster info?*




*To improved Tracking Algorithm*




# Part II: Shower Reconstruction at an Imagine Calorimetry