Arbor & Shower Fractal Dimension

- advanced shower reconstruction at a highly granular calorimeter

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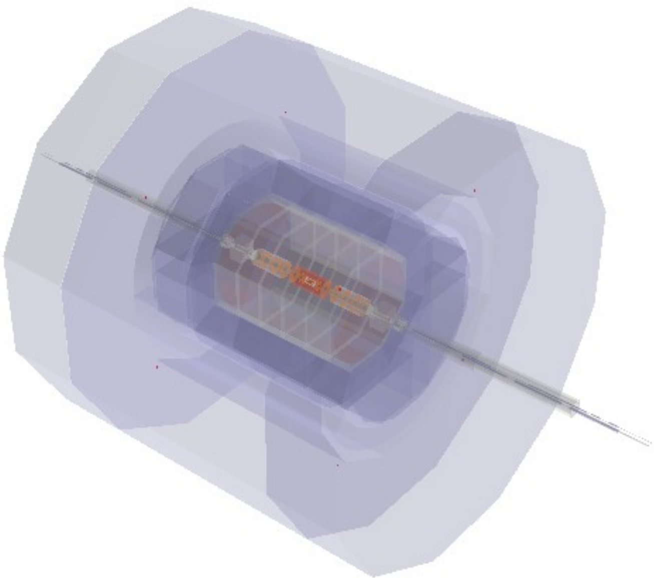
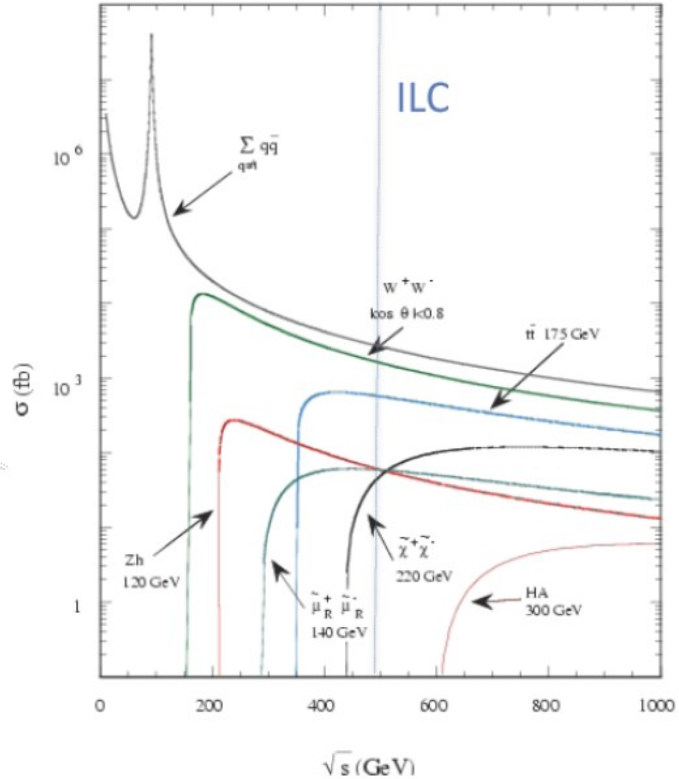
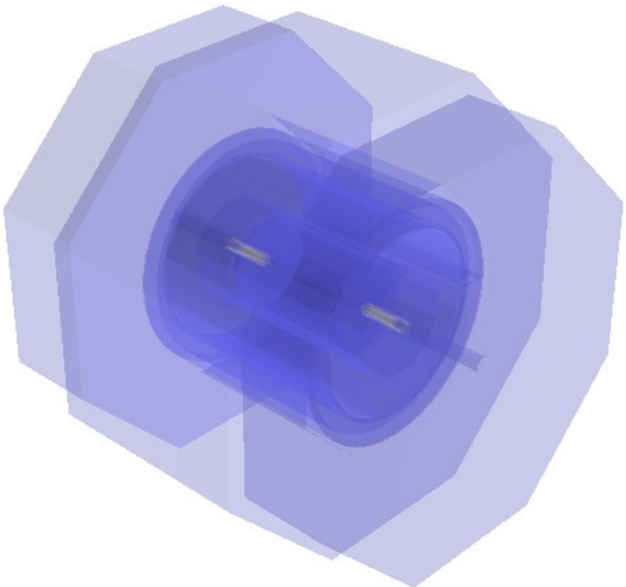
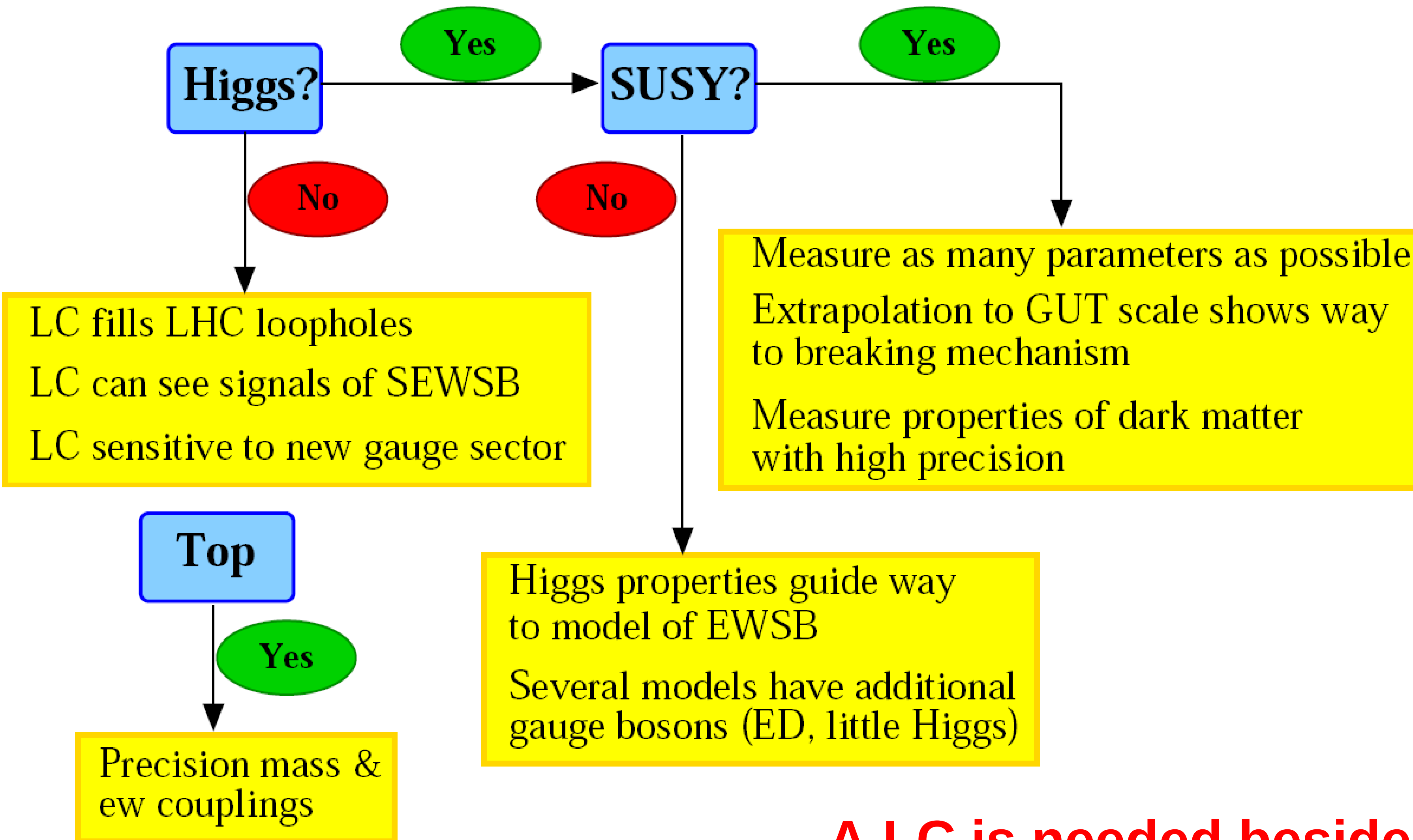
Part I: Physics @ LC & Highly Granular Calorimeter







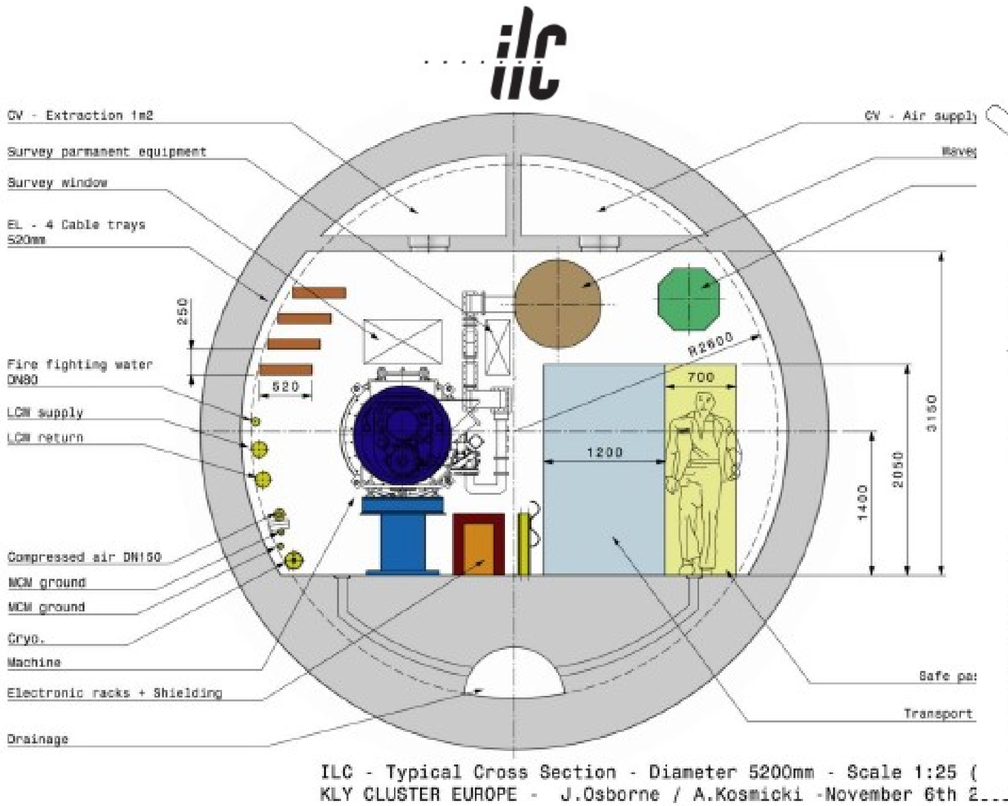
Physics @ LC

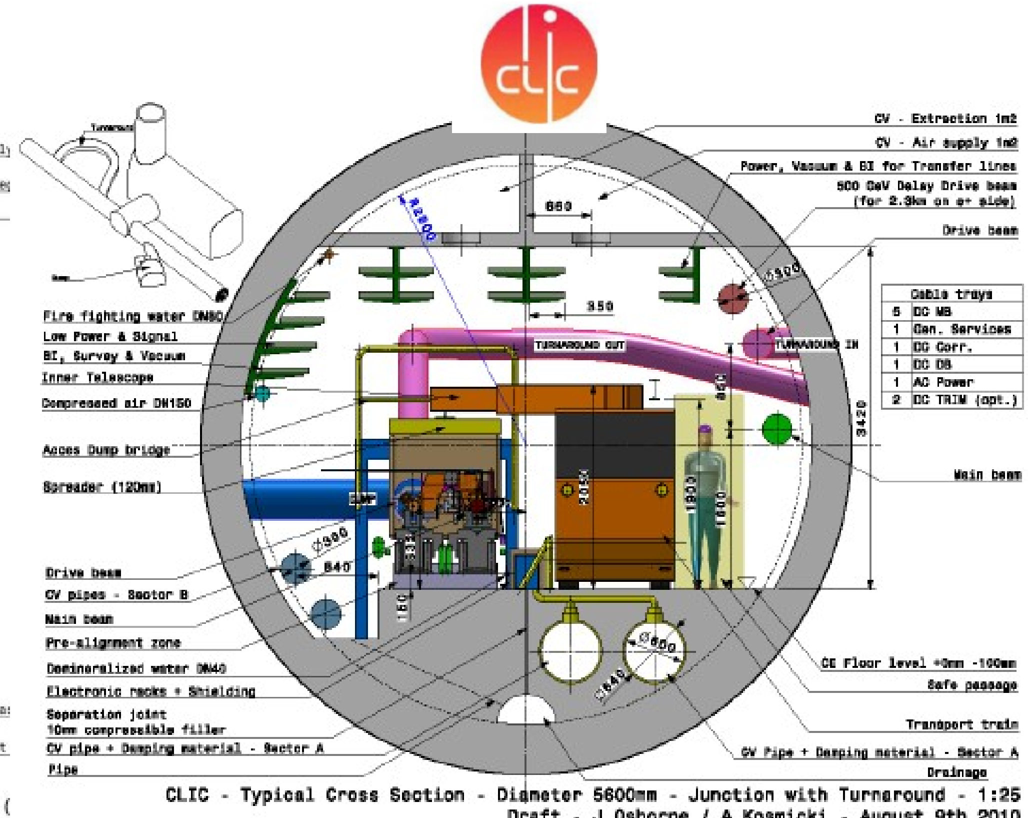


Klaus Moenig: Physics potential of LC

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:

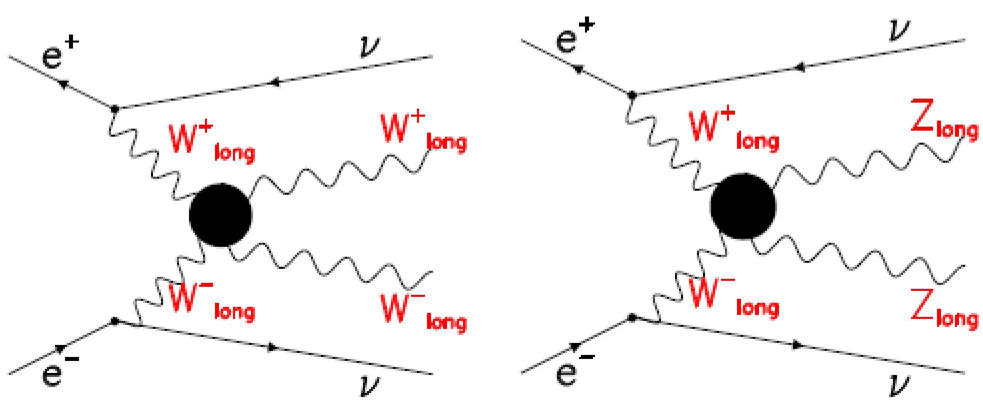
Idea (originally from ALEPH):
Measure jets as collections of particles, in the best suited sub detectors

$$\underset{\text{fraction}}{E_{jet}} = \underset{65\%}{E_{\text{charged tracks}}} + \underset{26\%}{E_{\gamma}} + \underset{9\%}{E_{h^0}}$$

Charged Particle – Tracker:
Δ(1/p) ~ 2*10E-5 (1/GeV)
Photon – ECAL:
ΔE/sqrt(E) ~ 15%
Neutron Hadron – HCAL:
ΔE/sqrt(E) ~ 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



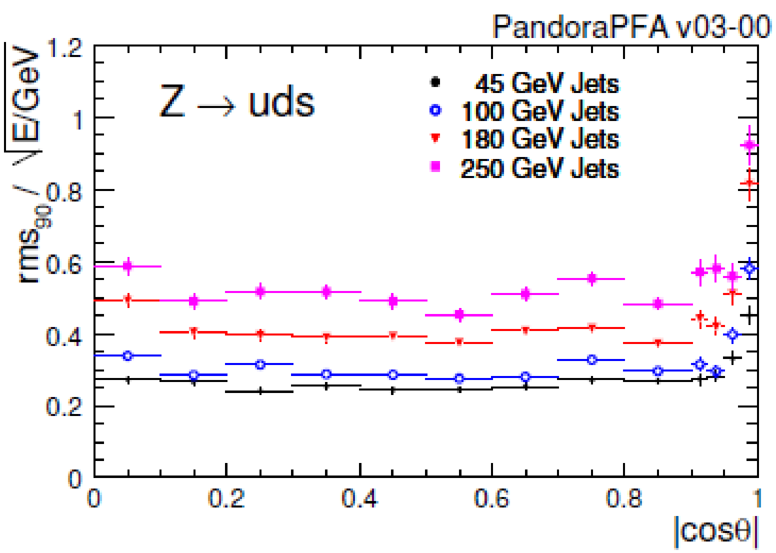
To separate WWvv & Zzvv: Jet energy resolution: 30%/sqrt(E)

If perfectly reconstructed:

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

PandoraPFA @ LC

Initial goal: Achieved



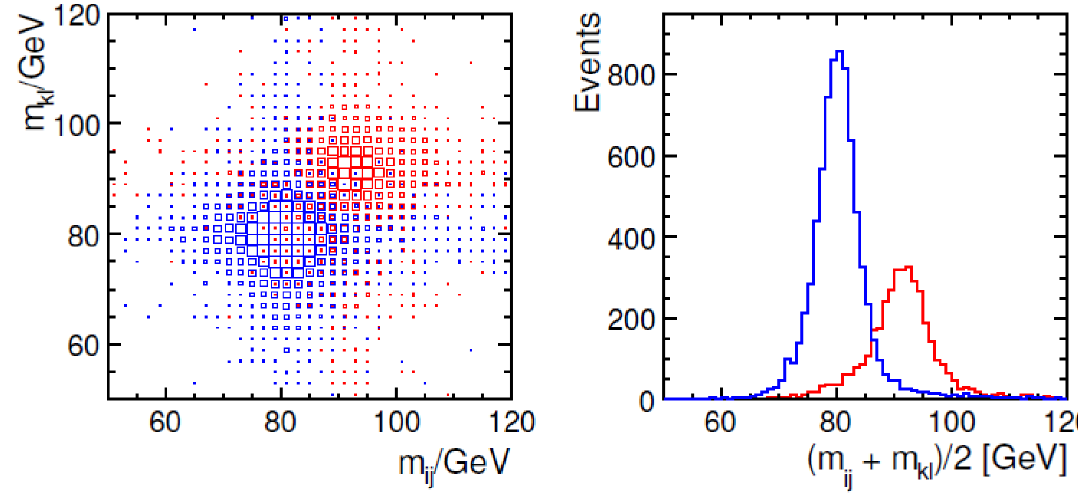


FIGURE 3.3-14. a) The reconstructed di-jet mass distributions for the best jet-pairing in selected $\nu_e\bar{\nu}_e WW$ (blue) and $\nu_e\bar{\nu}_e ZZ$ (red) events at $\sqrt{s} = 1\,TeV$. b) Distributions of the average reconstructed di-jet mass, $(m_{ij} + m^B_{kl})/2.0$, for the best jet-pairing for $\nu_e\bar{\nu}_e WW$ (blue) and $\nu_e\bar{\nu}_e ZZ$ (red) events.

Dependence on Detector Parameters and Jet energy:

$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left(\frac{R}{1825\,\mathrm{mm}}\right)^{-1.0} \left(\frac{B}{3.5\,\mathrm{T}}\right)^{-0.3} \left(\frac{E}{100\,\mathrm{GeV}}\right)^{0.3} \%.$$

From ILD Letter of Intent

PFA @ LHC

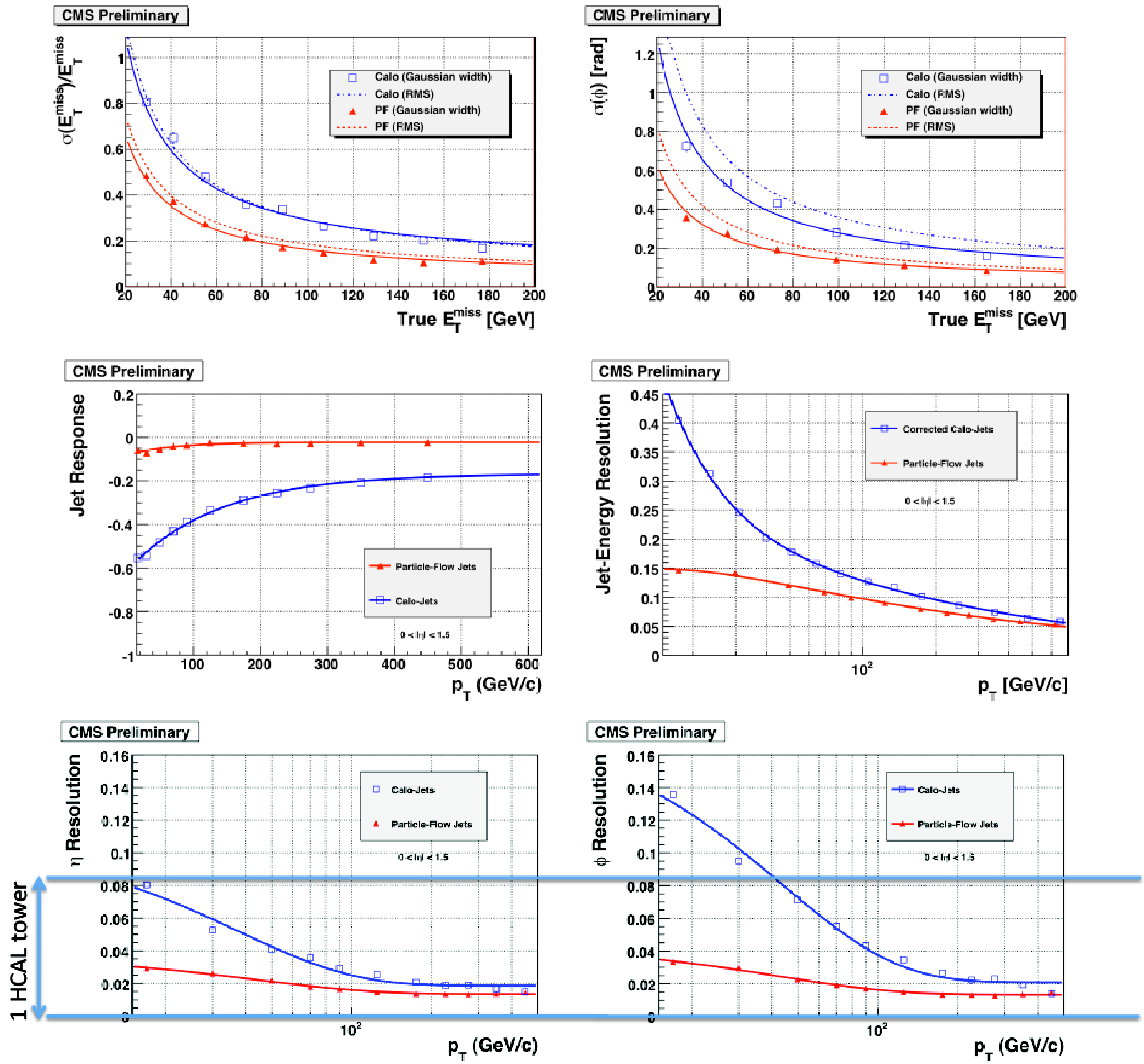
Energy Flow @ CMS

Improves significantly:

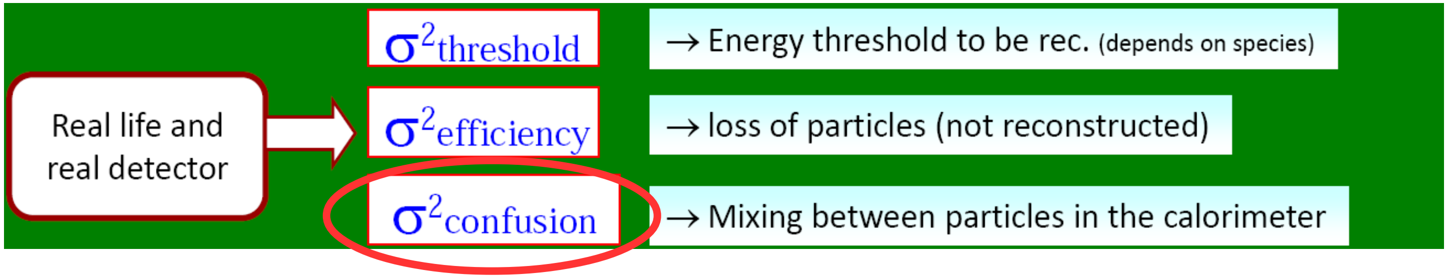
Missing Transverse Momentum, energy & Direction (φ)

Jet momentum resolution: energy & direction (η, φ)

Lepton identification

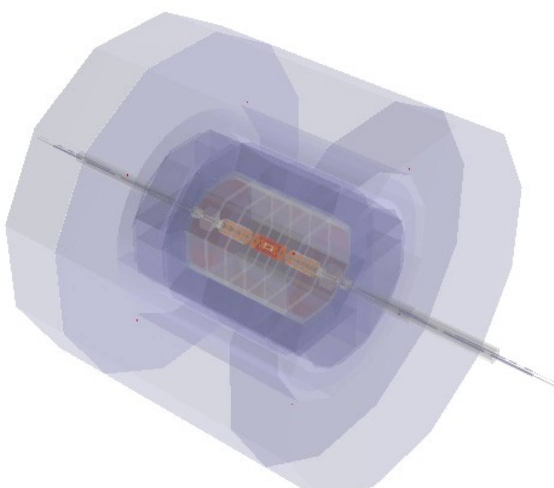


PFA Oriented LC detectors



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

ILD



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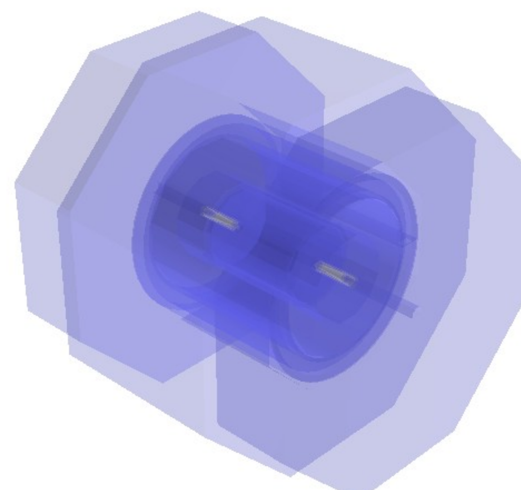
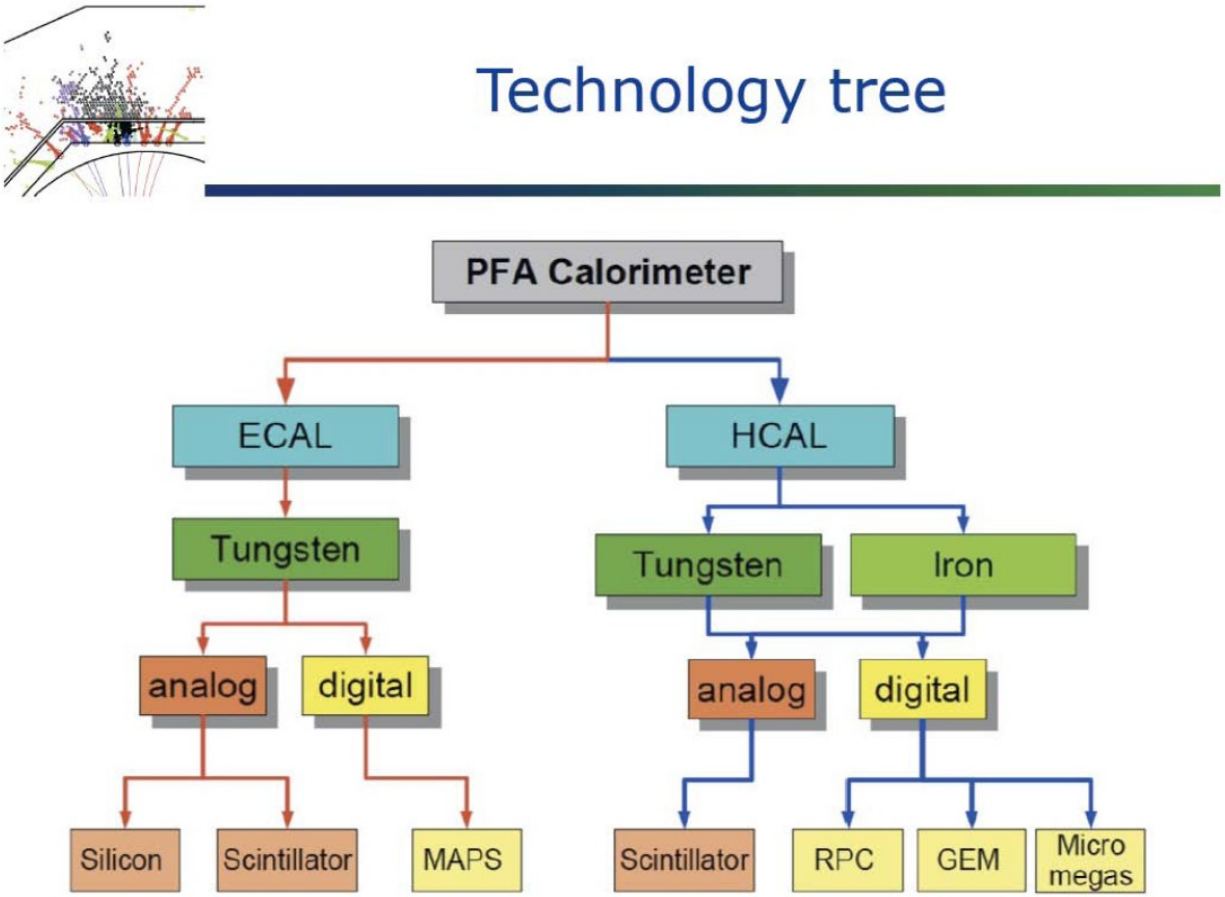
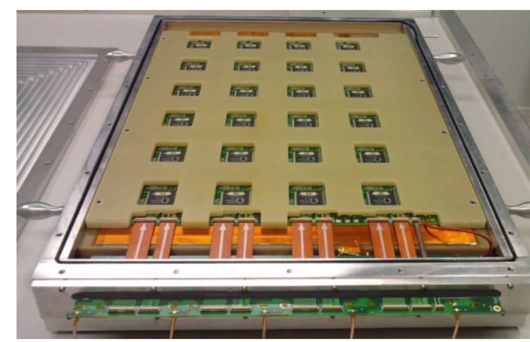
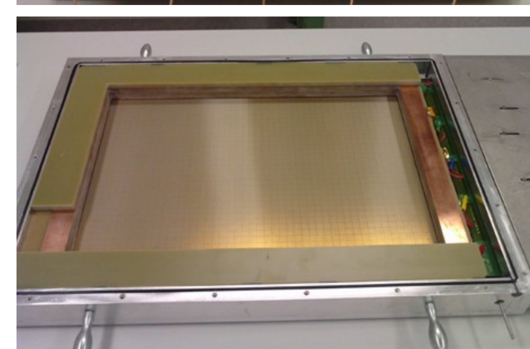


- PFA Oriented detector (both have ILC/CLIC Versions):
  - ILD (International Large Detector, mostly European + Asia): TPC + Silicon inner detectors tracking with B = 3.5T/4T
  - SiD (Silicon Detector, mostly in US): Silicon tracking with B = 5T

CALICE: PFA Oriented Calorimeter







Up right: Si-W ECAL prototype, 10k channels in a cube of 18 cm³ ~ 1/8 of CMS ECAL

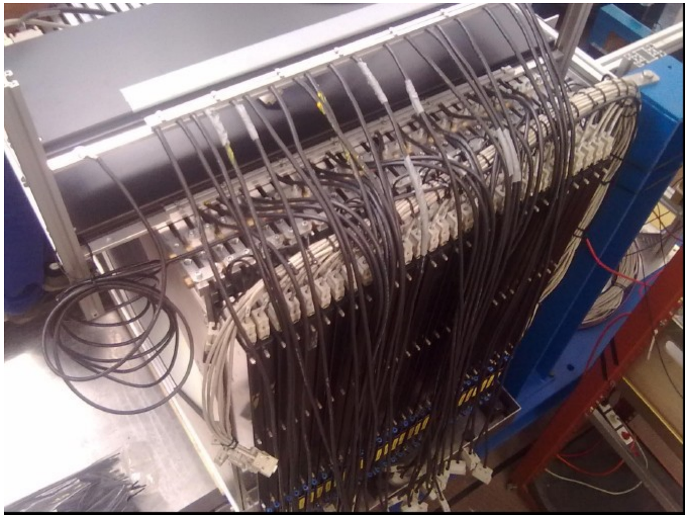
Lower right: Micromegas m² prototype

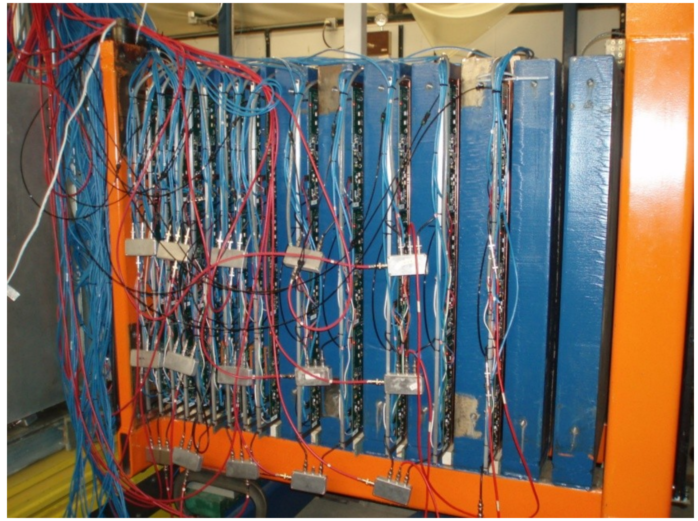
m³ HCAL Prototypes

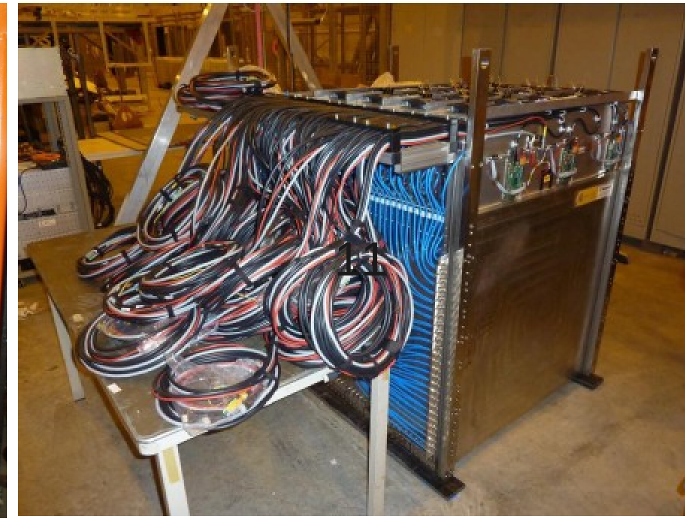
AHCAL@DESY

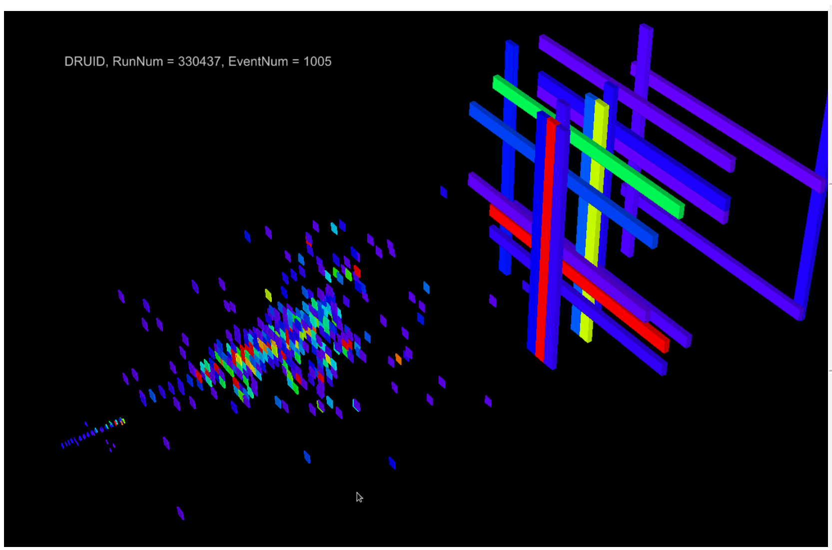
DHCAL@US

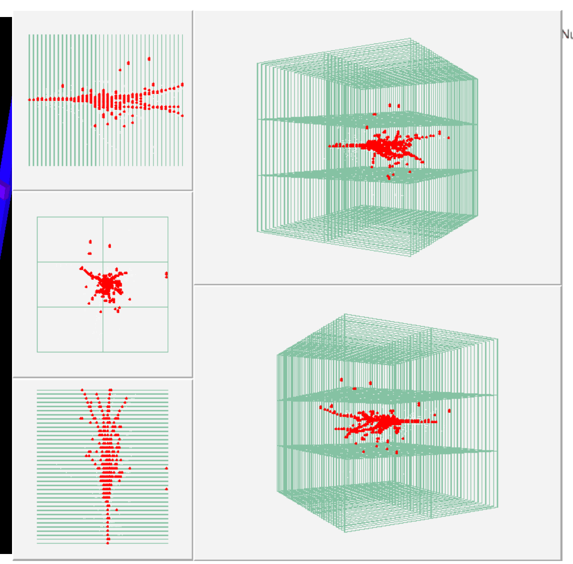
SDHCAL@EU

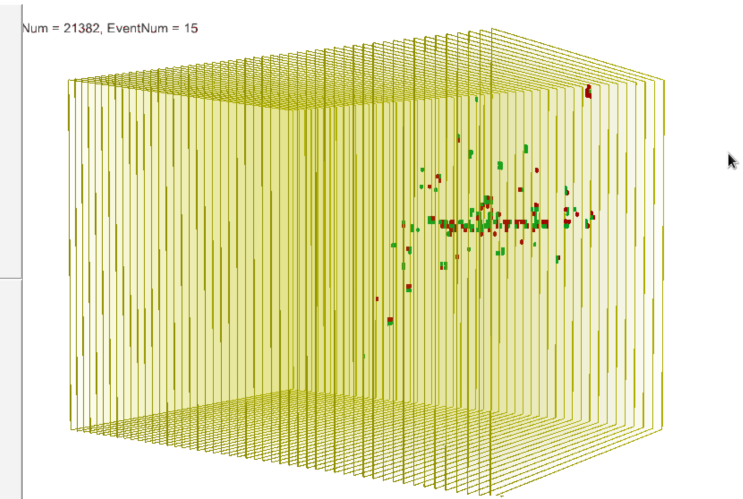








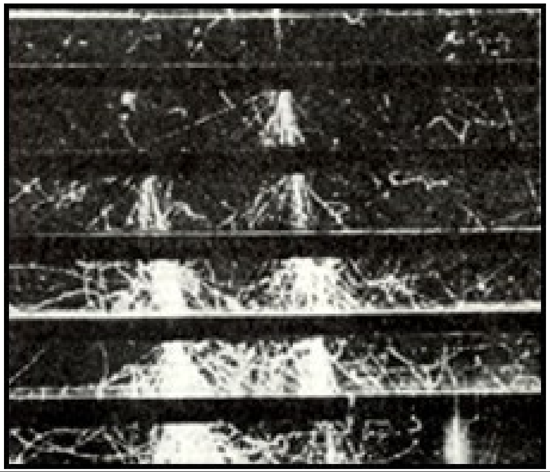


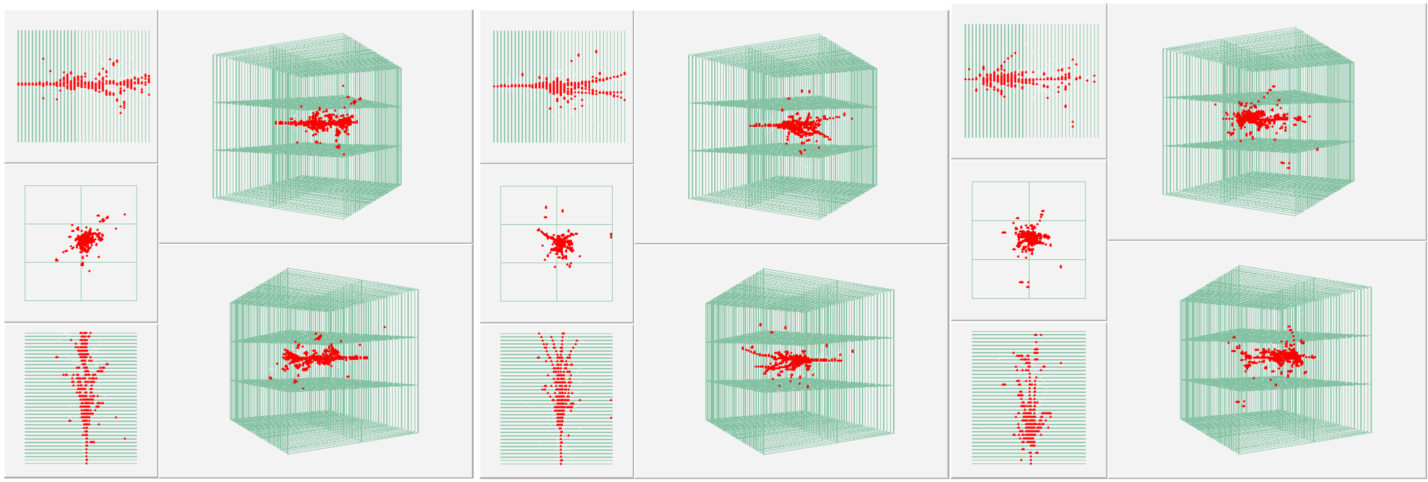


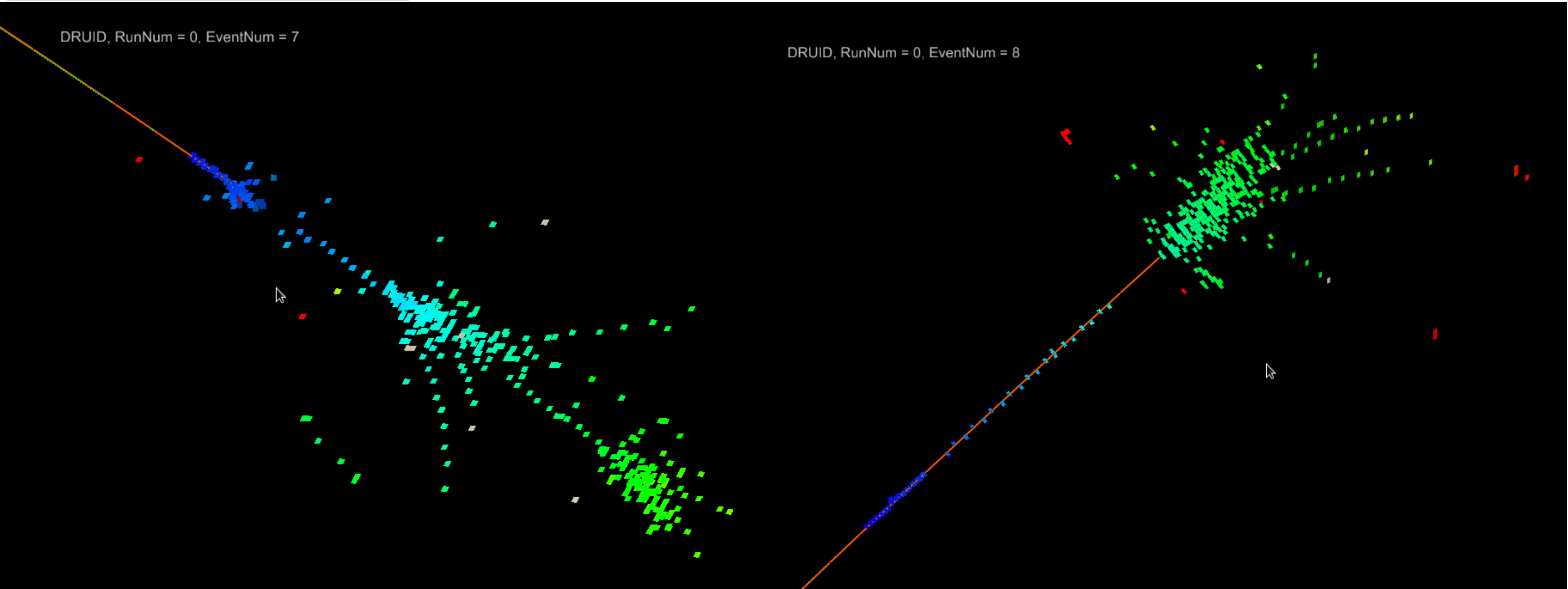
*Scintillator + 3*3 cm cells*

*GRPC + 1*1 cm cells: ~ 500k channels*

Part II: Shower Reconstruction at an Imaging Calorimetry



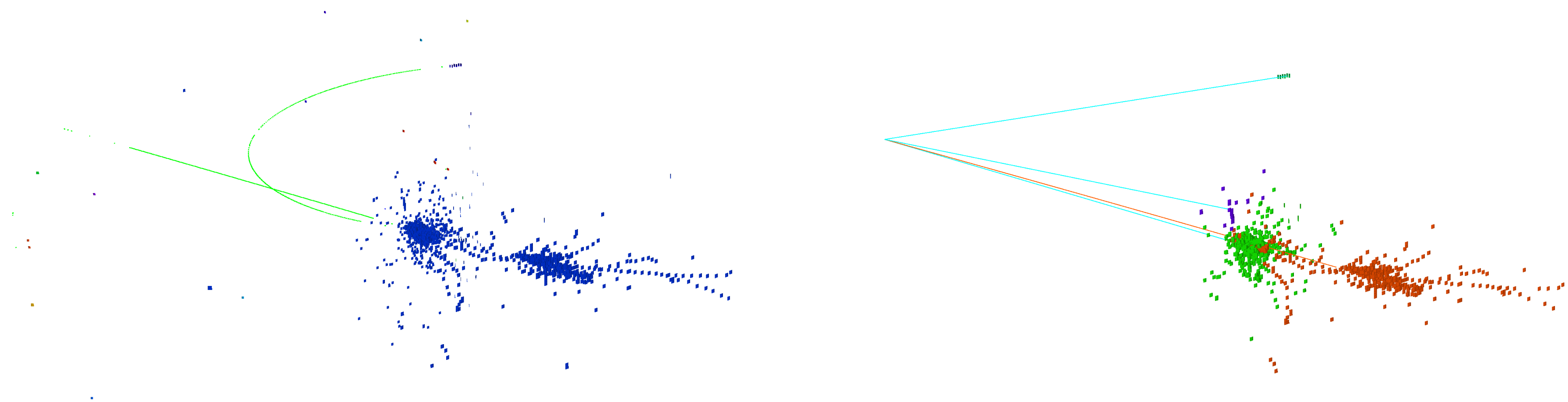




PFA: Potential to improve

PandoraPFA: Promising performance.

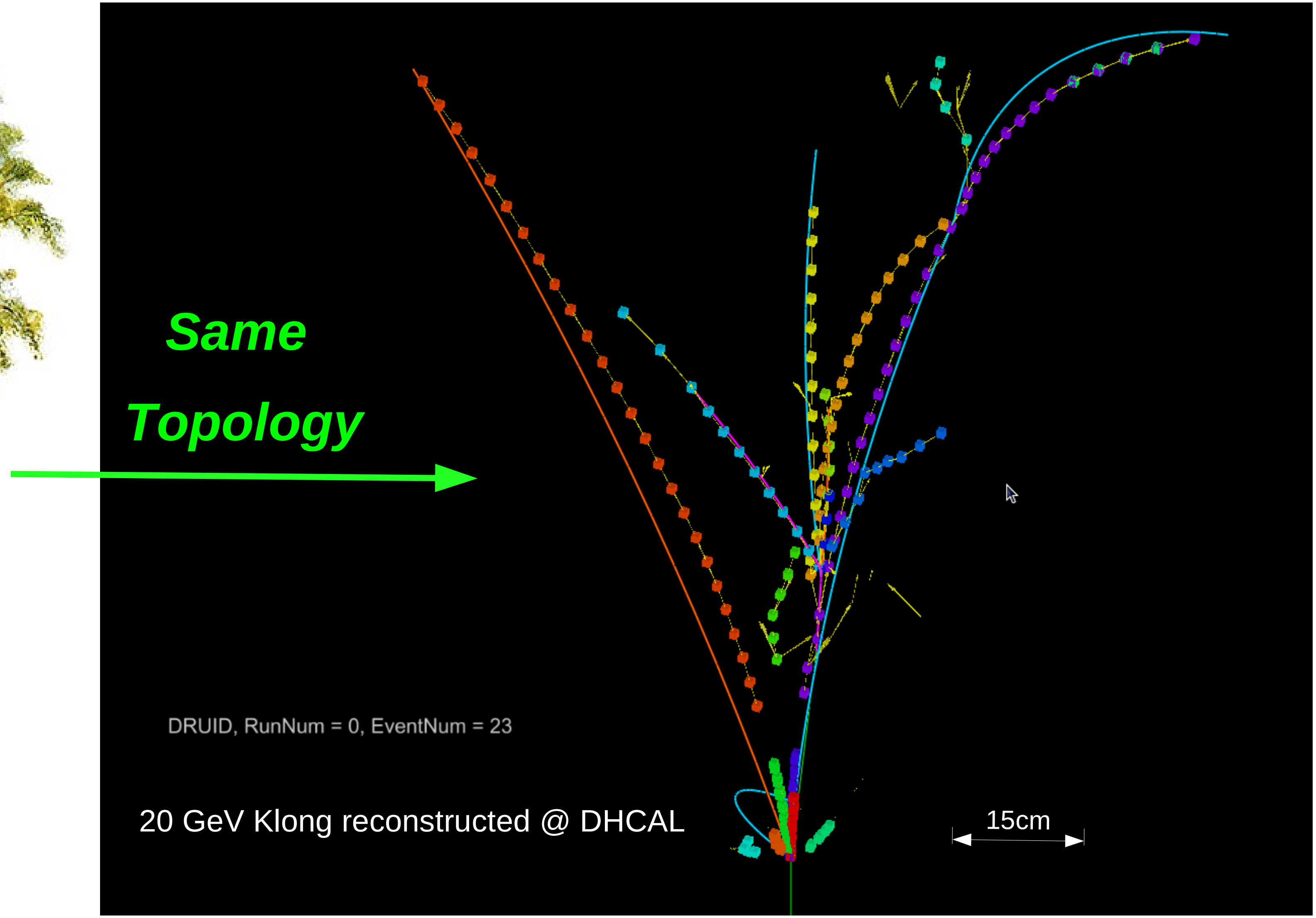
- But:
- Optimized for AHCAL with 3 * 3 cm cells, while DHCAL has 1 * 1 cm cell!
- Confusion not negligible (worse at higher energy):
  - eg, ~10% of pions affected by PFA double counting



To improve:

- Better pattern recognition based on shower geometry
- Better Measurement: more dedicate estimators

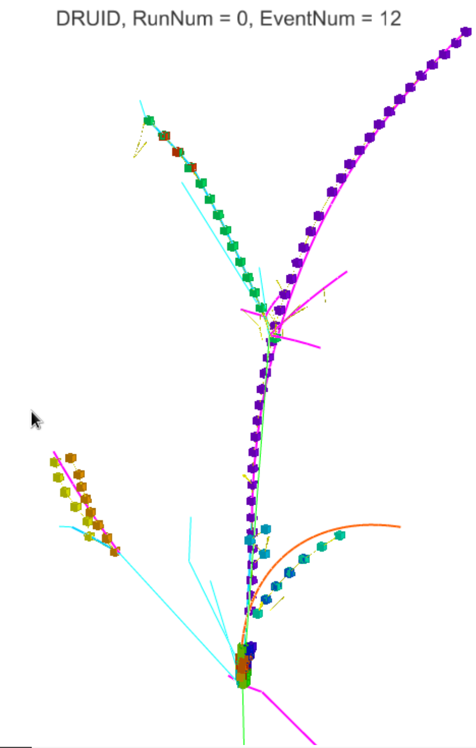
Arbor: shower ~ tree



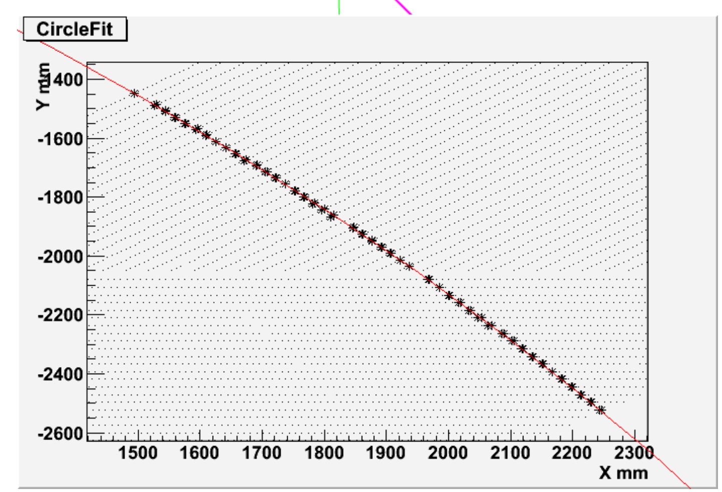
- *Start from Mirco structures: Full usage on high granular information*
- *Original idea from Henri Videau, in hadronic shower reconstruction @ ALEPH*

Reconstruction of branches

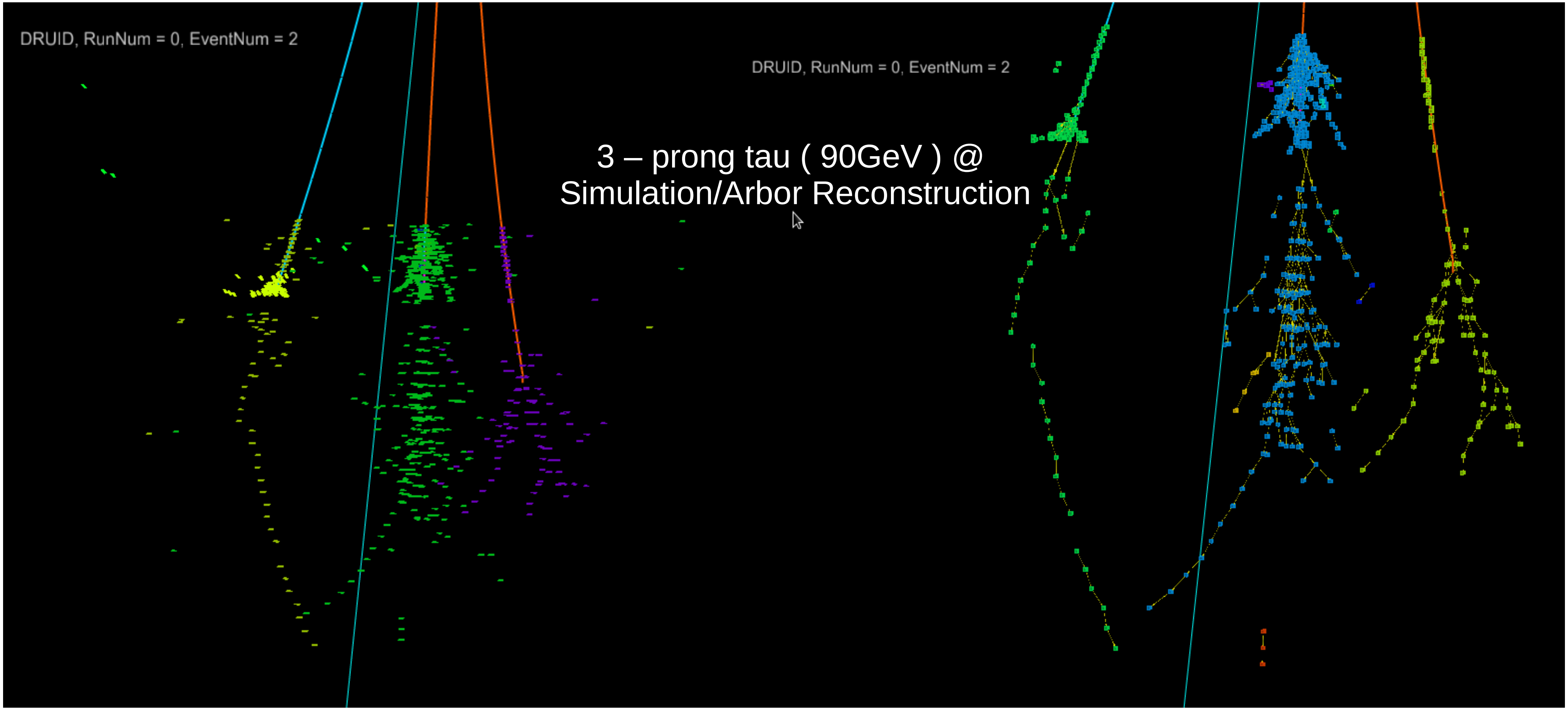
- Arbor: Promising branch tagging, with lots of potential applications
  - In situ Calibration/Stability monitoring
  - Kink & Pre interaction tagging
  - Track – Cluster linking
  - Calo Tracks Measurement:
    - Energy Estimation ~ Leakage correction
    - EM/Had hits tagging
  - ...



- 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

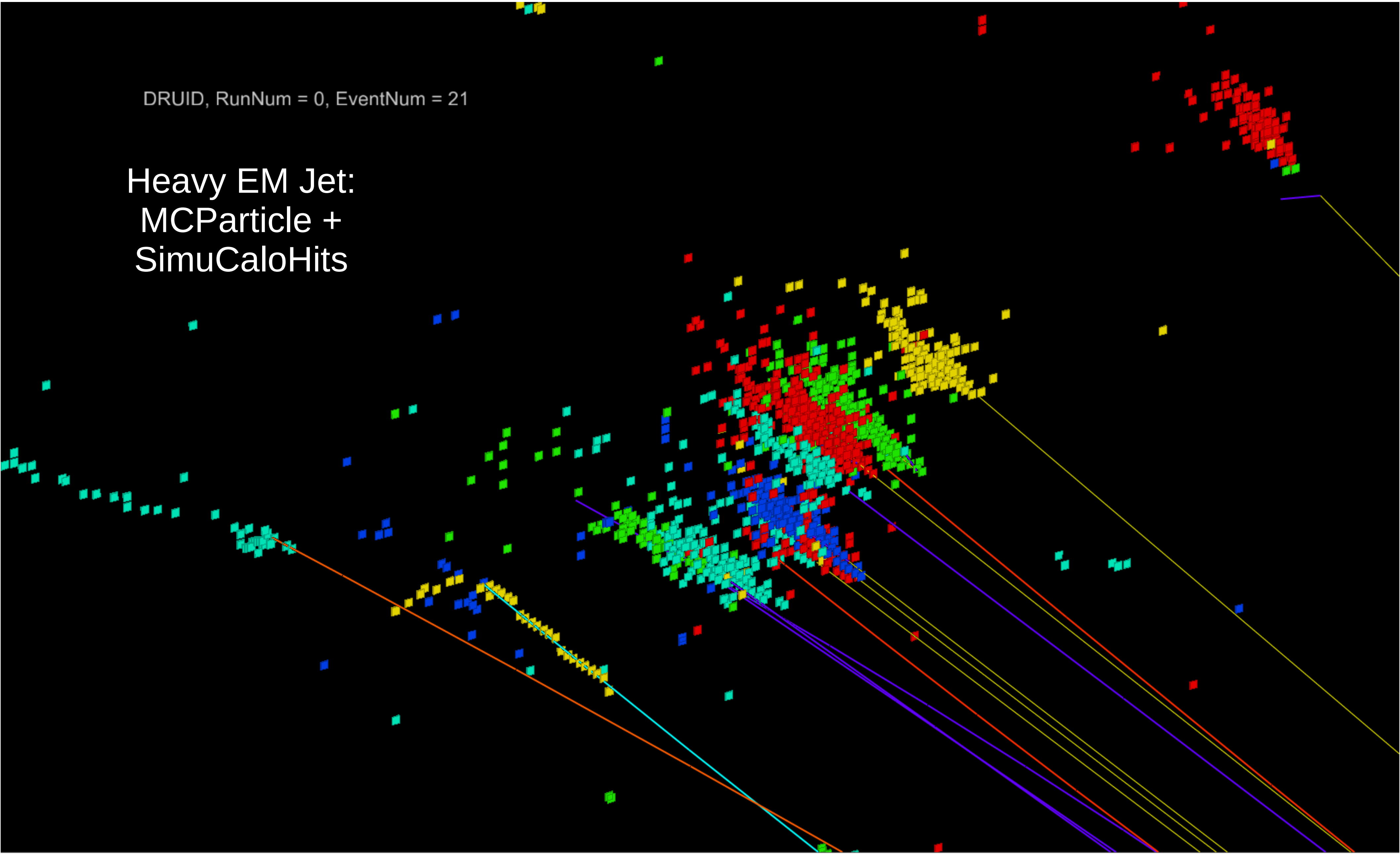


Arbor: pion reconstruction

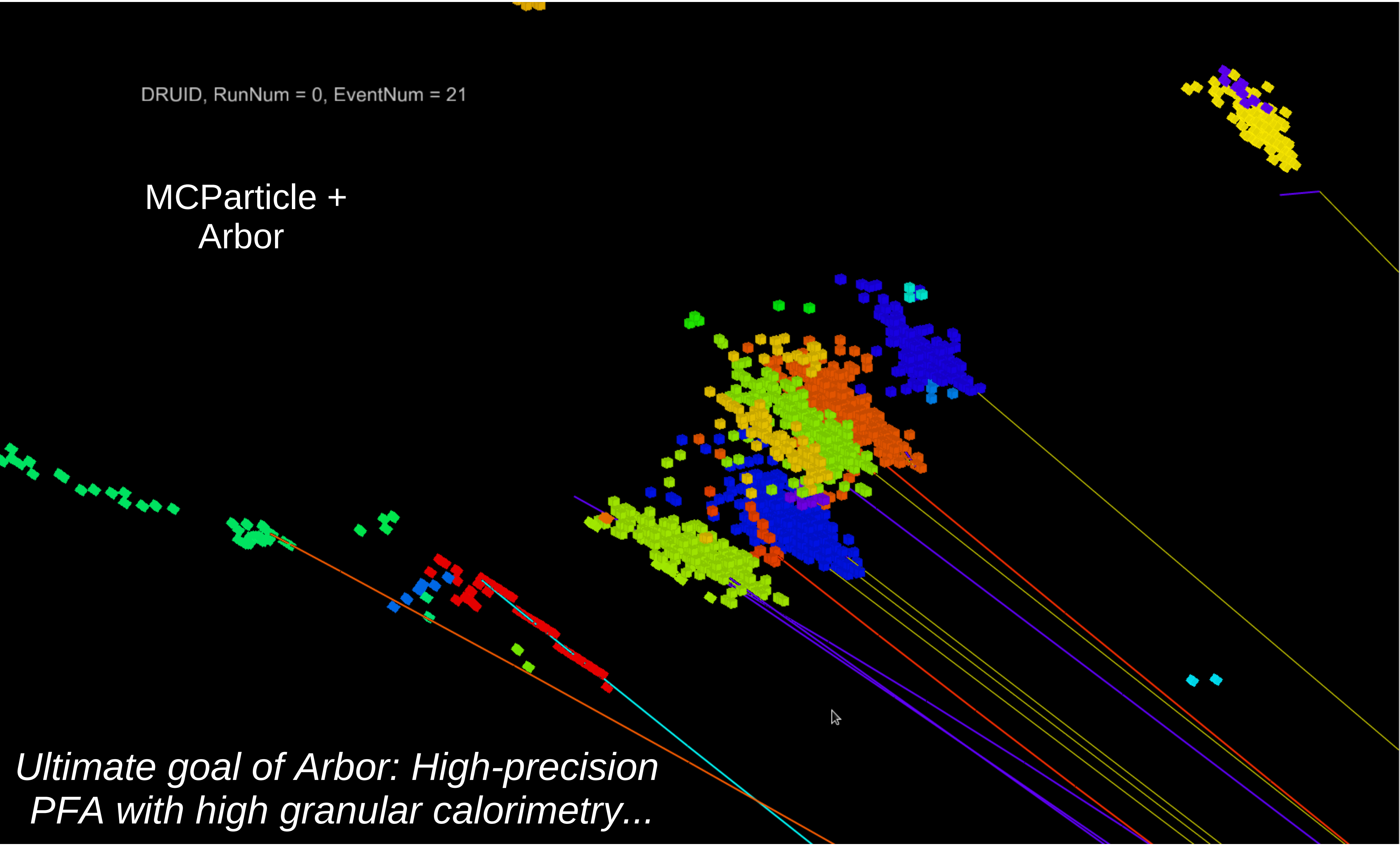


Merging Branches together : Reconstruction of Shower @ Calo

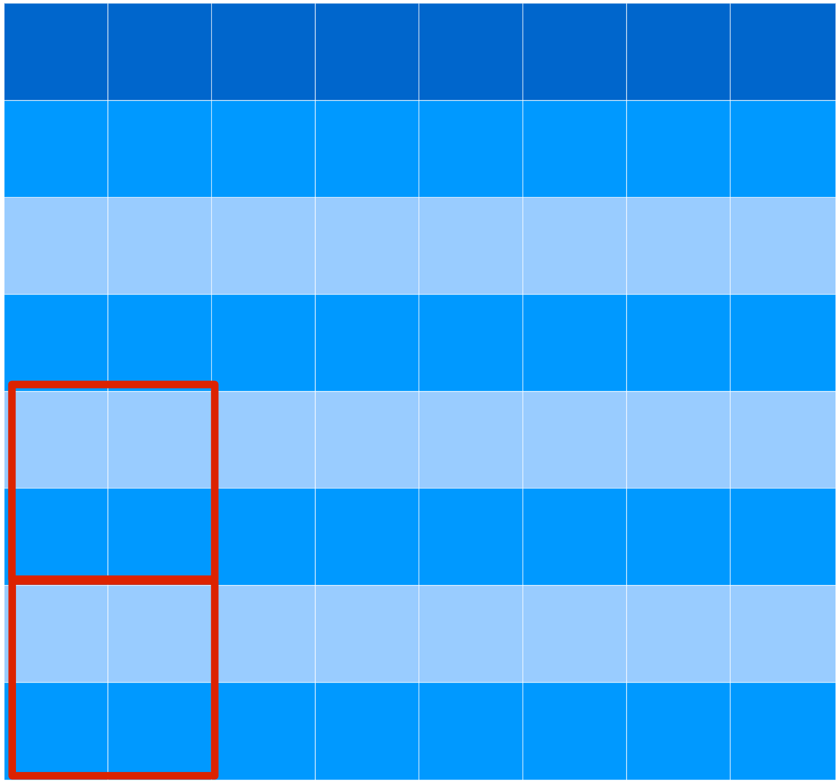
Arbor: Separation



Arbor: Separation



Shower particle: to interact or not



shower ~ self similar *(Mandelbrot Set)*

Measure shower Fractal Dimension (FD) at high granularity calorimeters

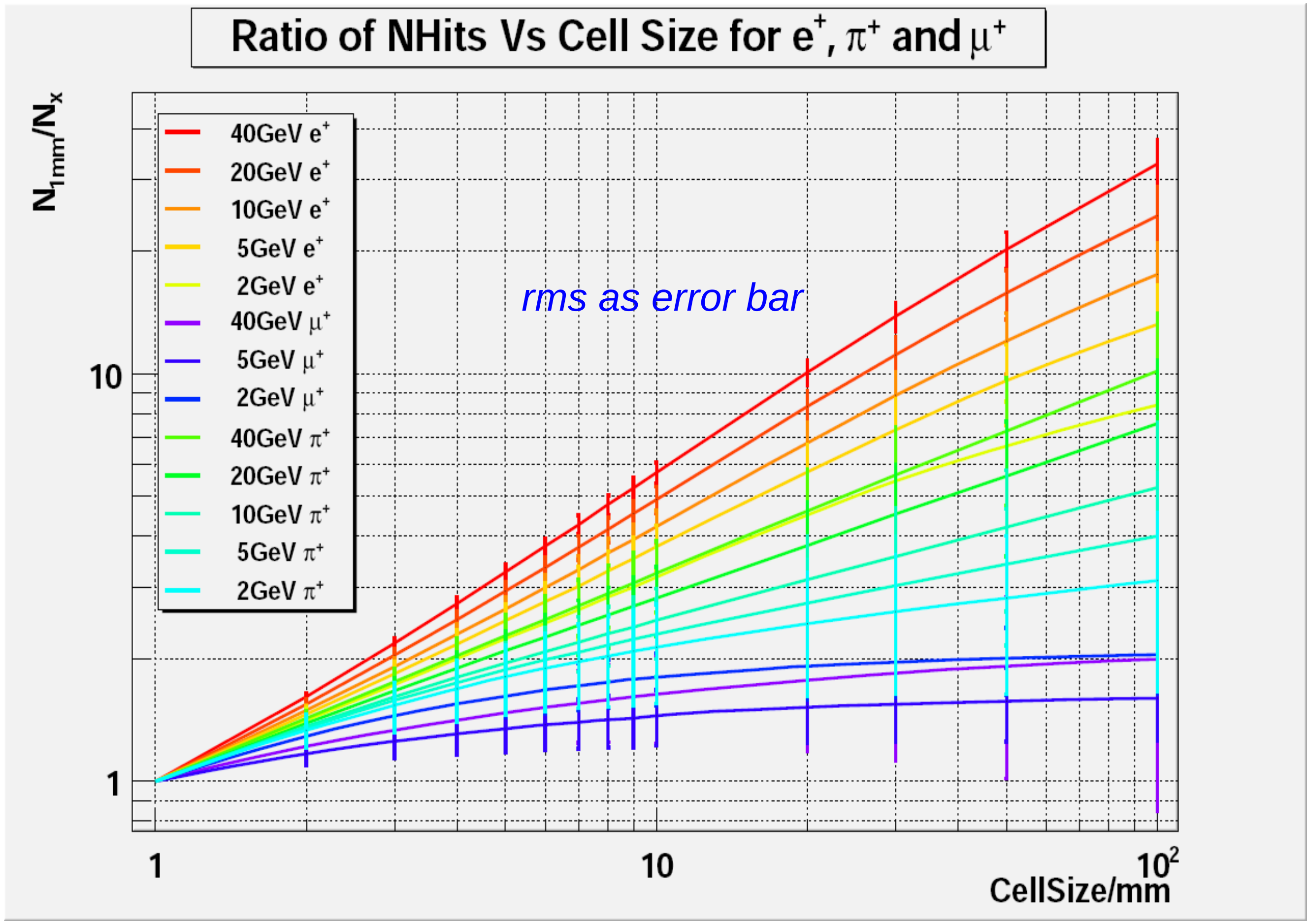
- Count Number of hits at different scale
  (define $RN_x = N_{1mm}/N_{xmm}$)
- *Varying scale by grouping neighbouring cells*

Shower: Self Similar

- Characteristic constant based on energy/PID:

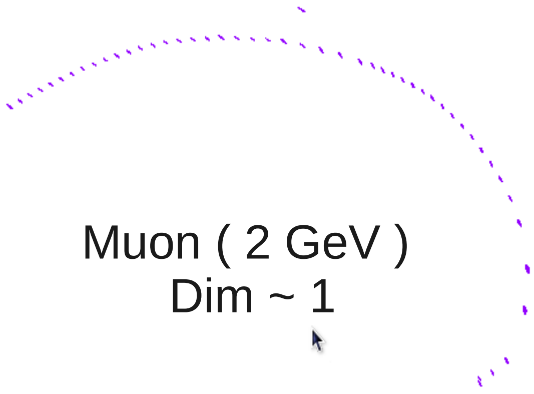
FD = < lnRN$_a$/ln(a) > + 1

  - 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*



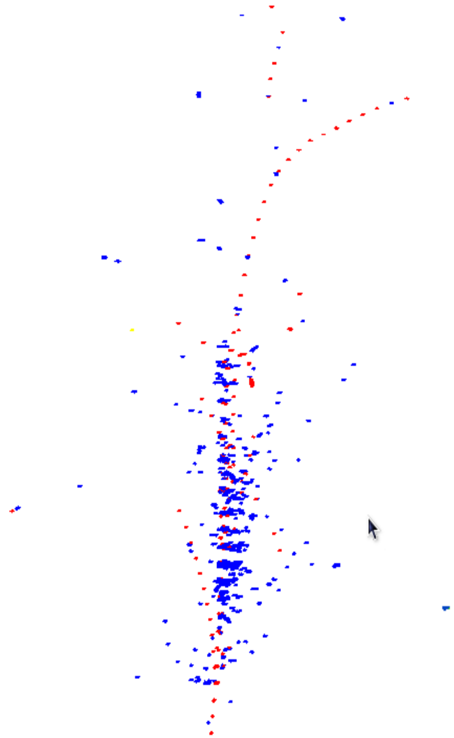
- Be observed within
  - Low scale: minimal interaction energy & sensor layer thickness (1.2mm)
  - High scale: full containment ~ 1 hit per layer

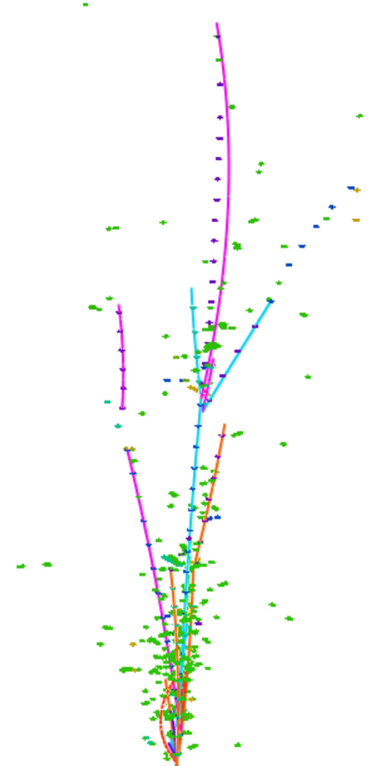
Fractals in Nature



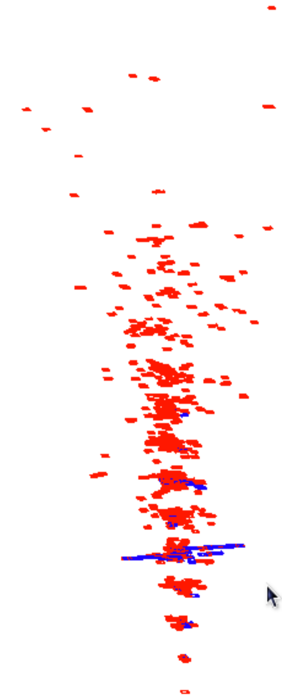
Muon (2 GeV)
Dim ~ 1

Curve/line:
Dim = 1

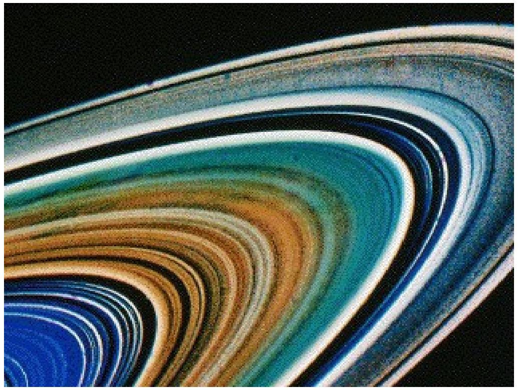




Hadrons: Dim(pi) < Dim(K0) ~ 1.5

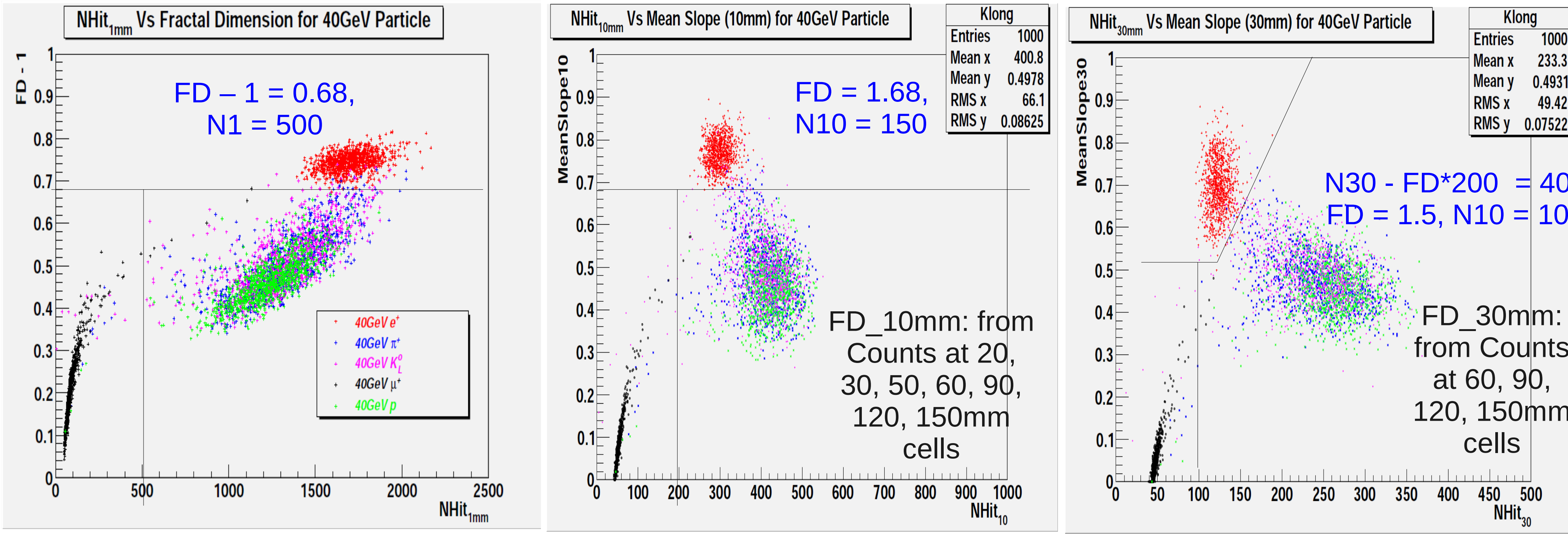


Positron (40GeV)
Dim ~ 1.75



Rectangle:
Dim = 2

Potential tool for PID



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

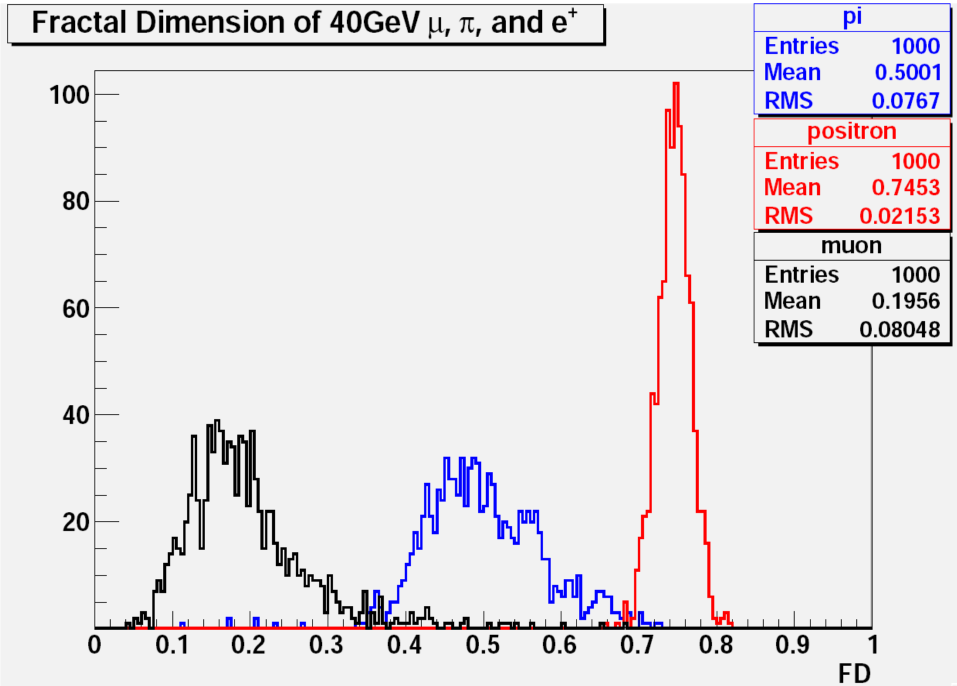
Remark: Energy dependent Cuts, easier for charged particles

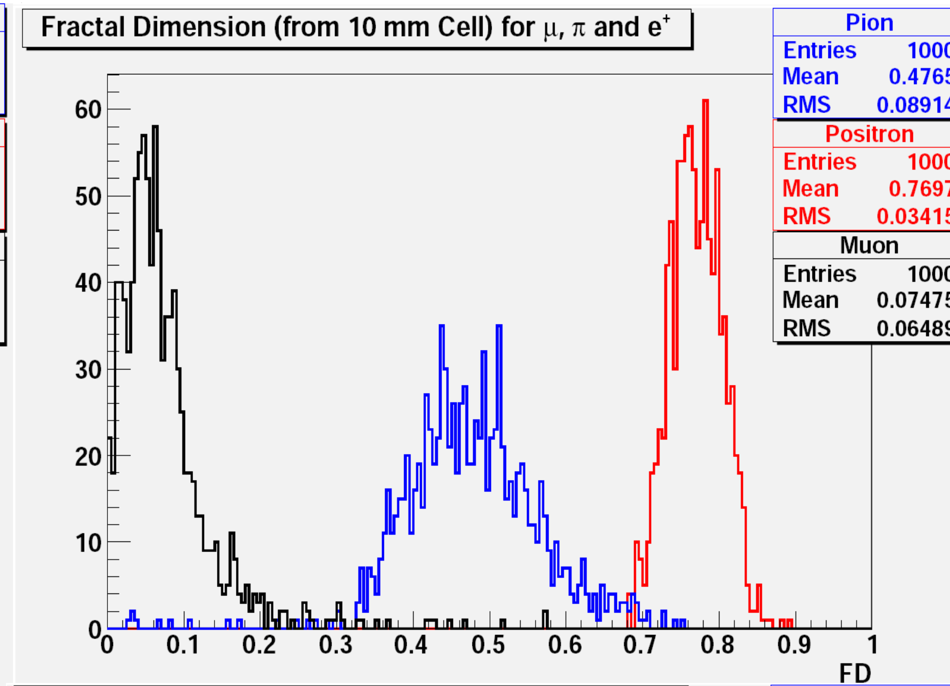
1mm	e+	u	h
e+	998	0	2
u	1	994	5
h	15	14	971

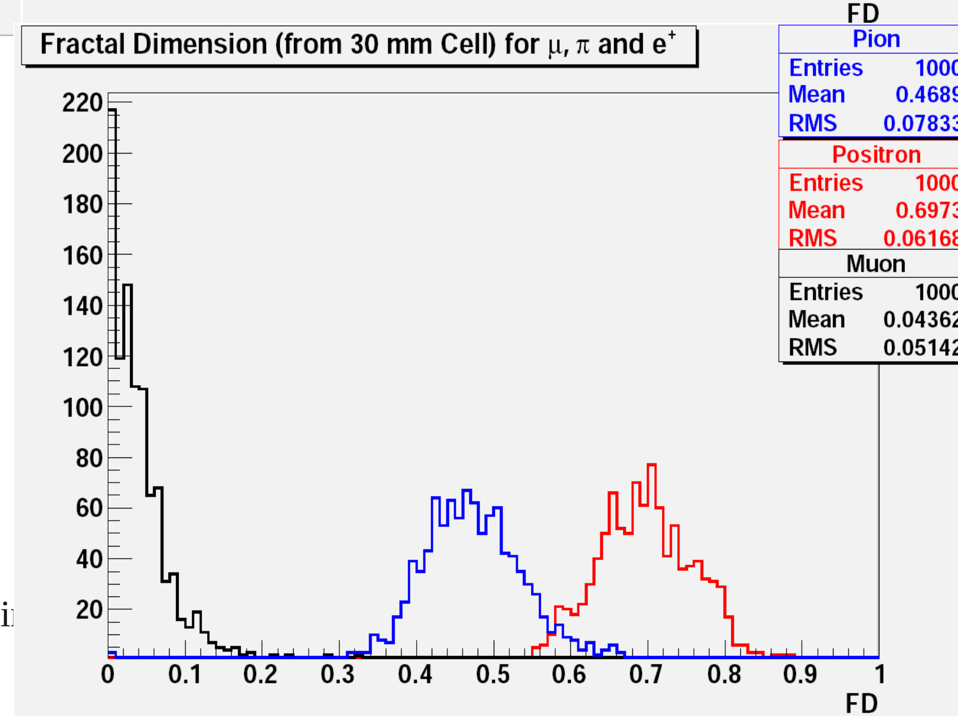
10mm	e+	u	h
e+	1000	0	0
u	0	995	5
h	17	14	969

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

FD @ different size







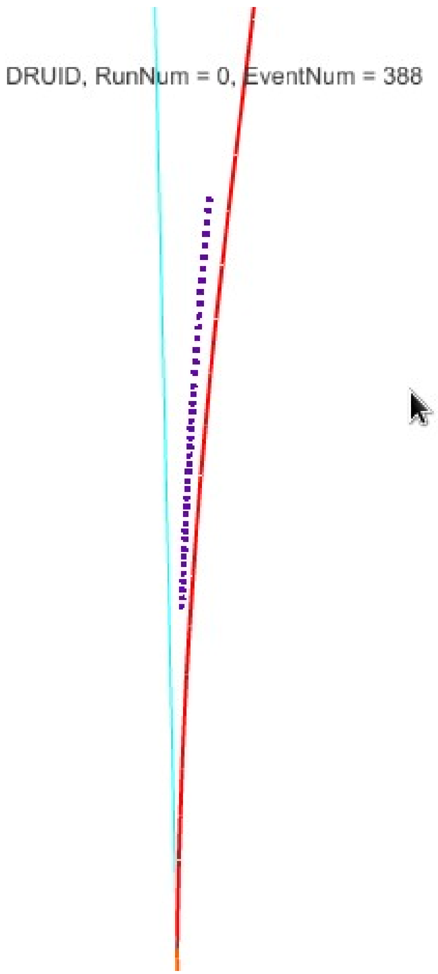
From FD(1mm) to FD(10/30mm):

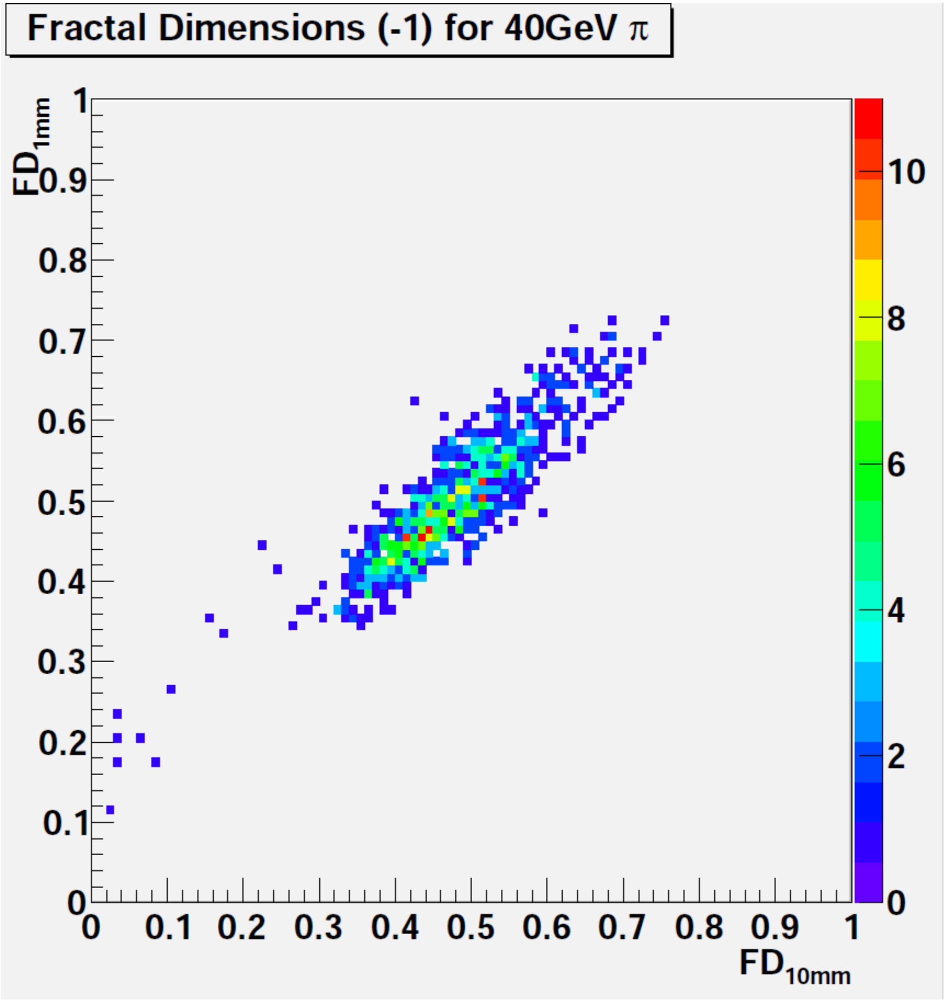
Positron Peak Smeared

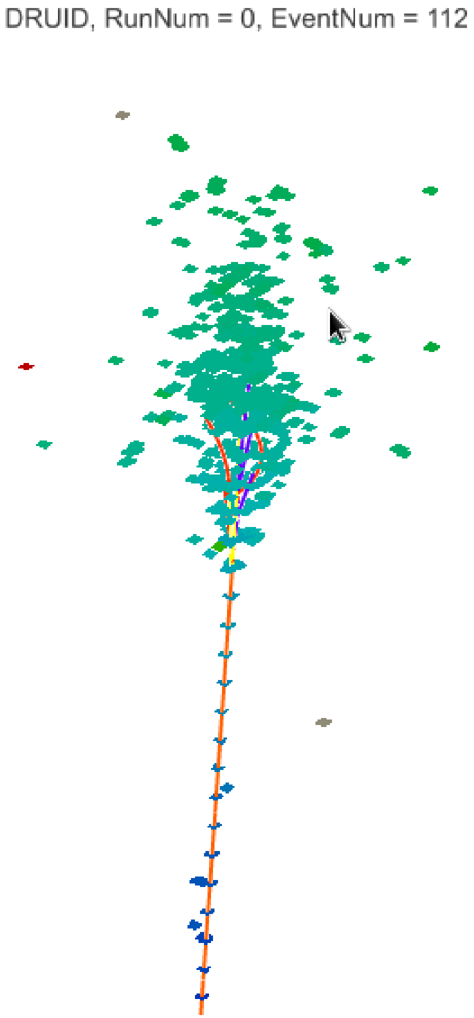
Better μ – h separation: μ acts more like a line (FD = 1); (Anyhow *we can create large cells from small ones...*)

π: continuous distribution from MIP to EM

Extreme Cases: Pion

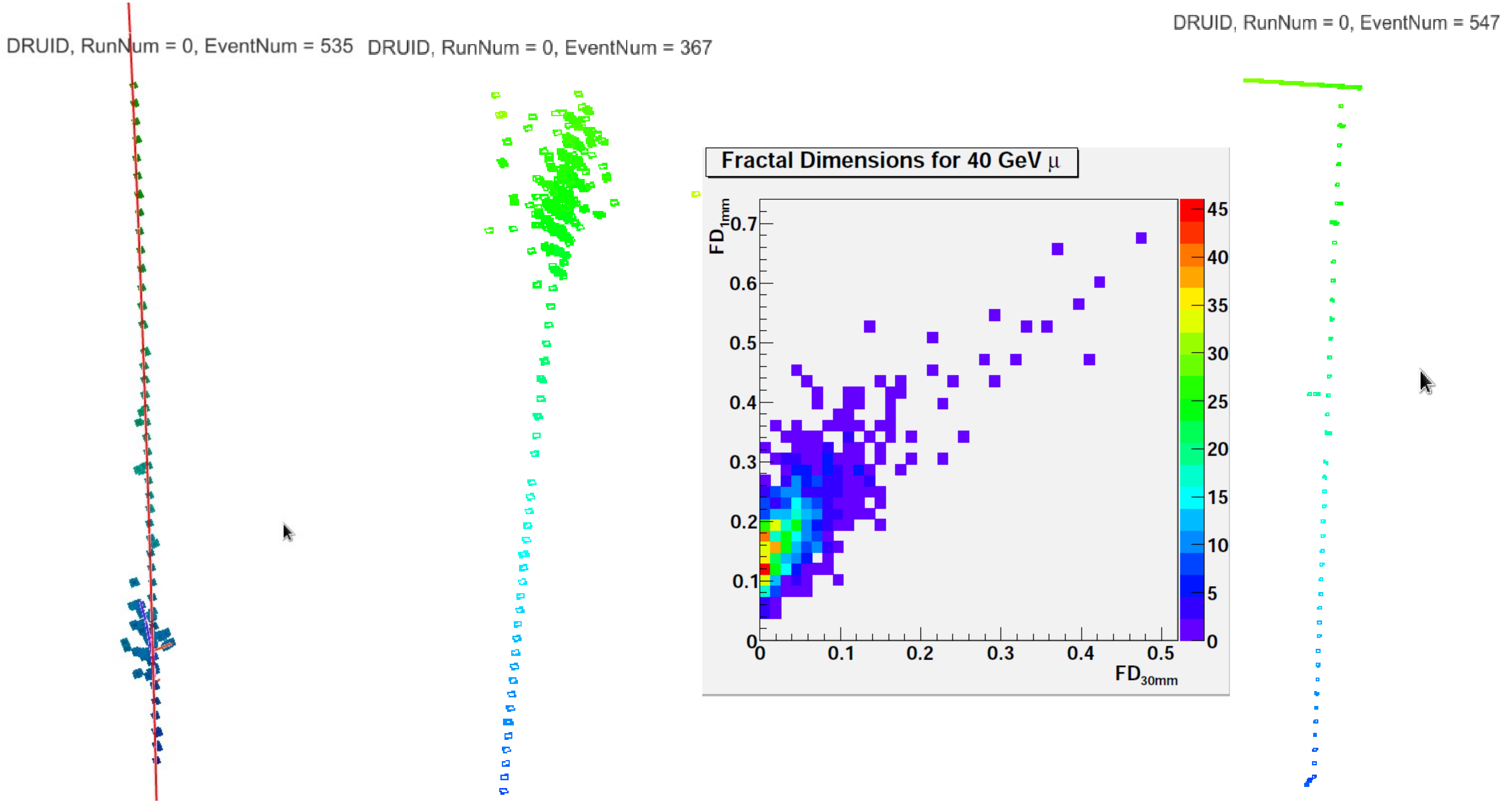






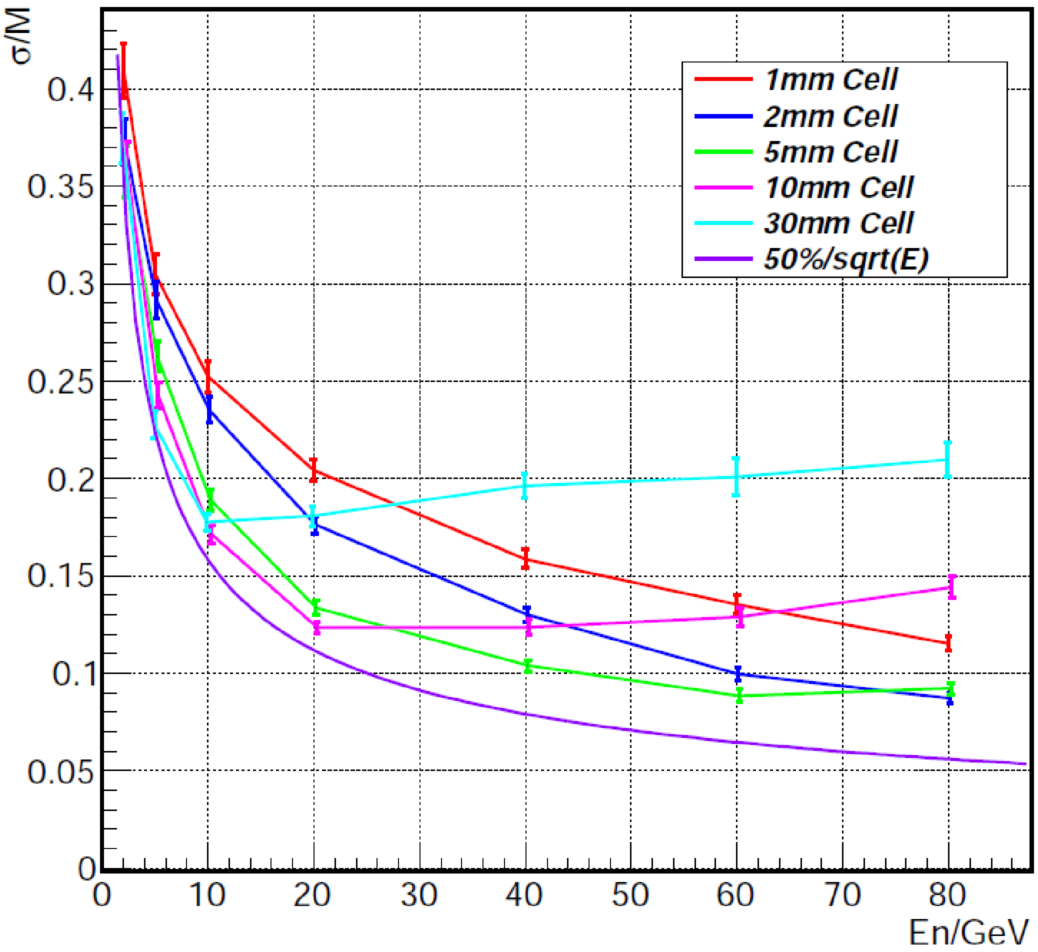
- Pion: MIP, Pion decay;
- EM interaction (pi + N = P + pi0); partially identified by interaction point tagging

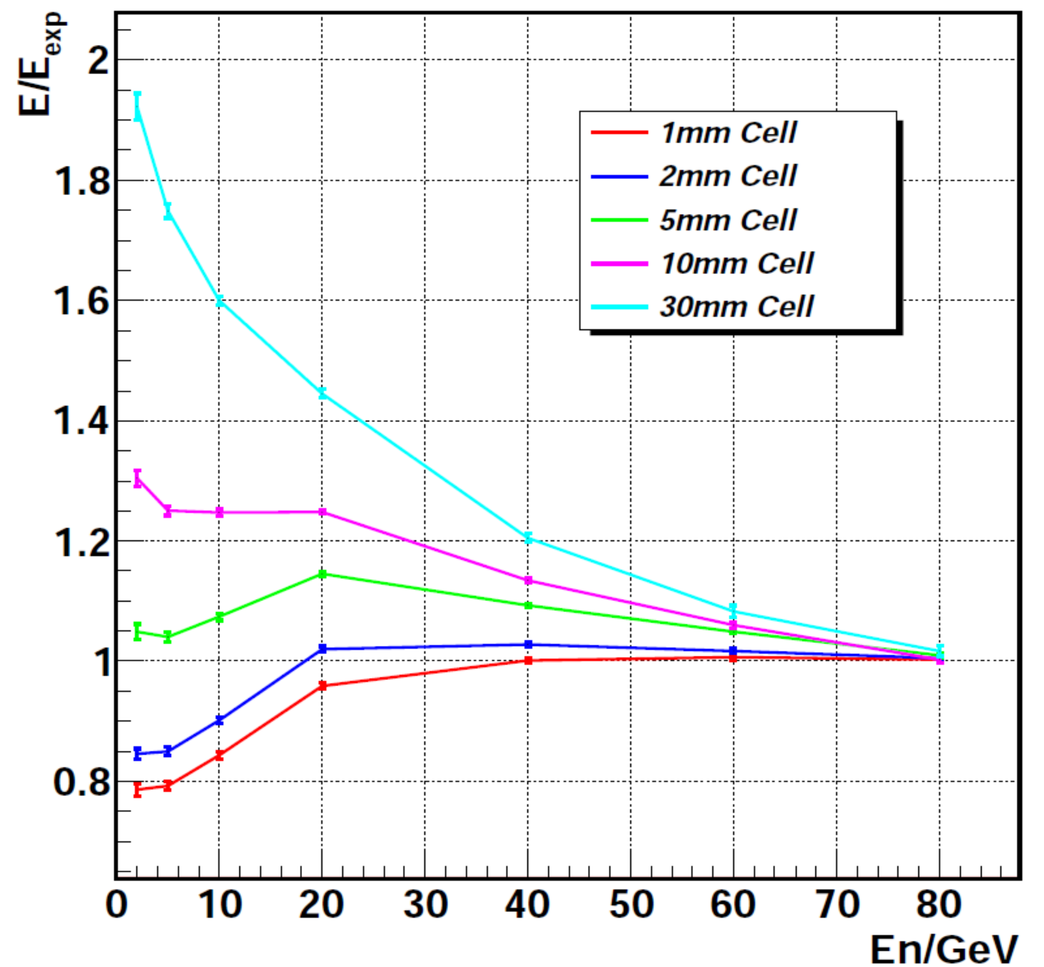
Extreme Cases: Muon



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

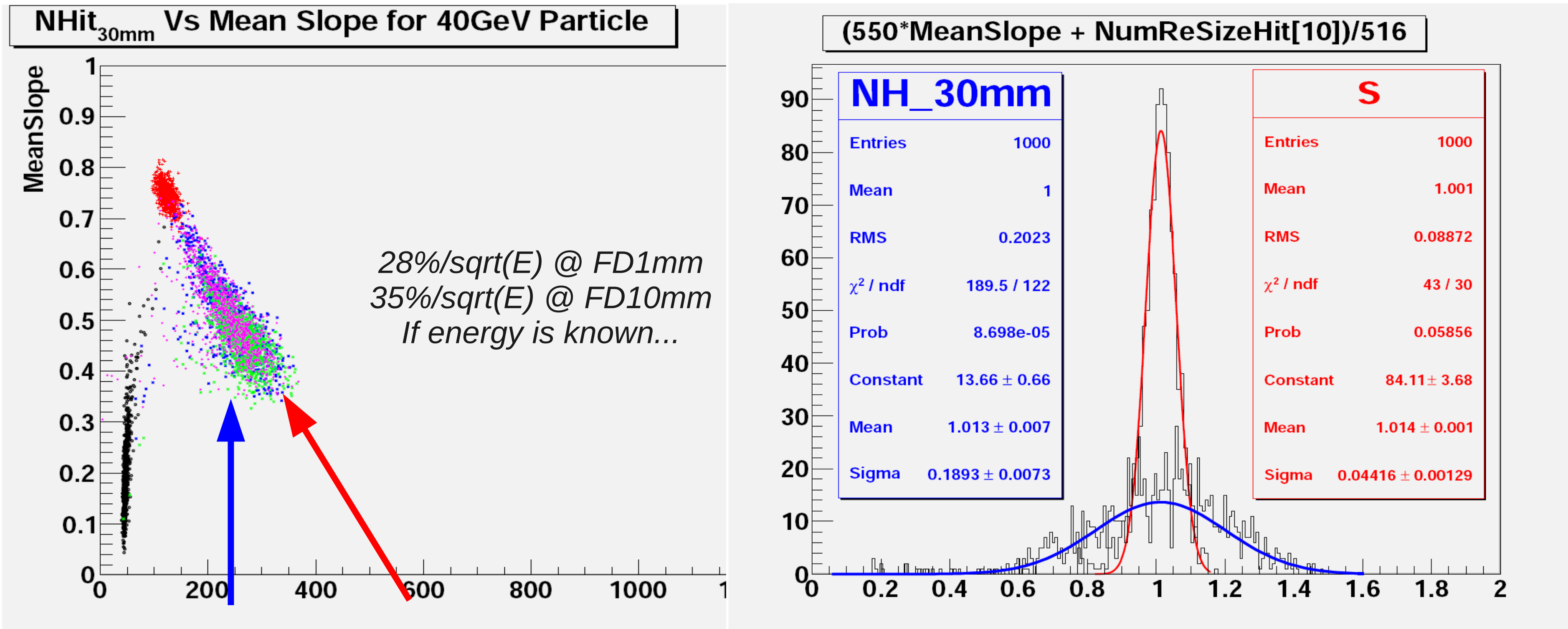
Energy Estimation with Naive Counting





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

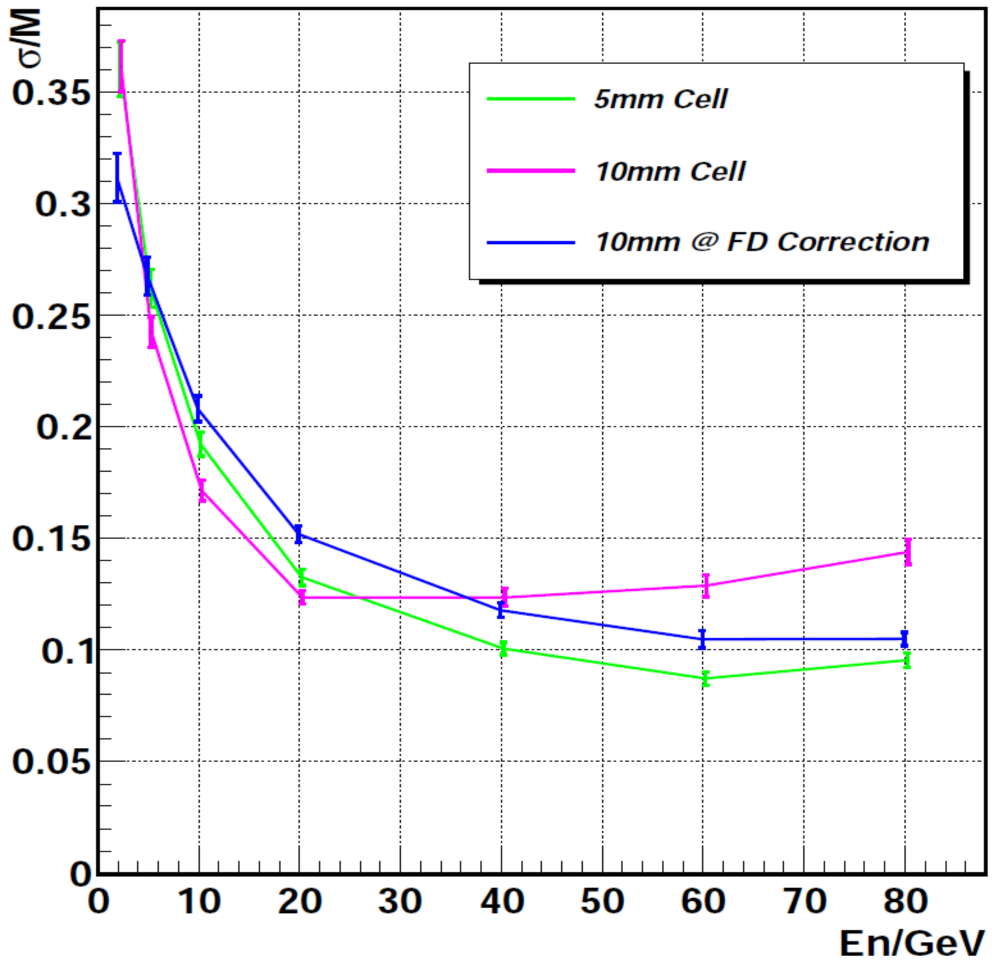


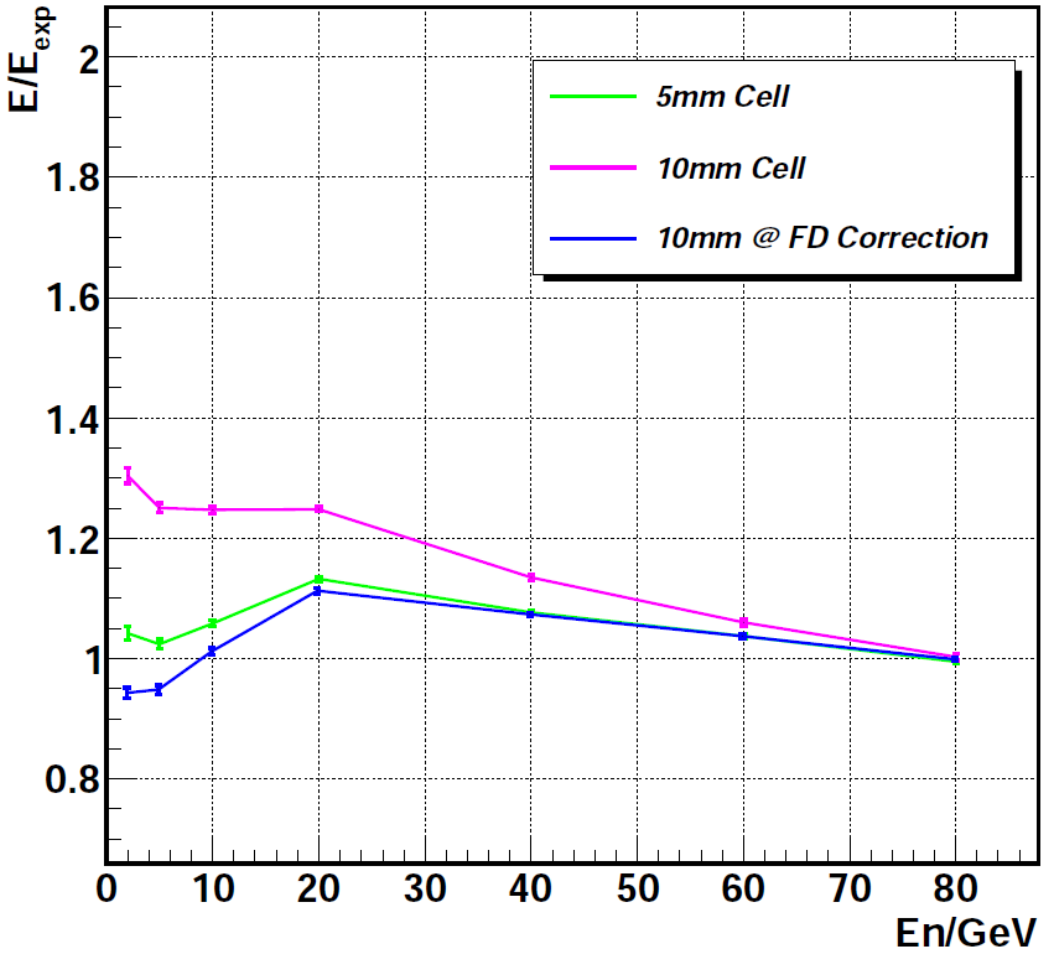
- For example: Compensation based on the correlation of NH_30mm & FD1mm:

  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

Spin-off: Gas Calorimeter Digitizer

K. BELKADHI

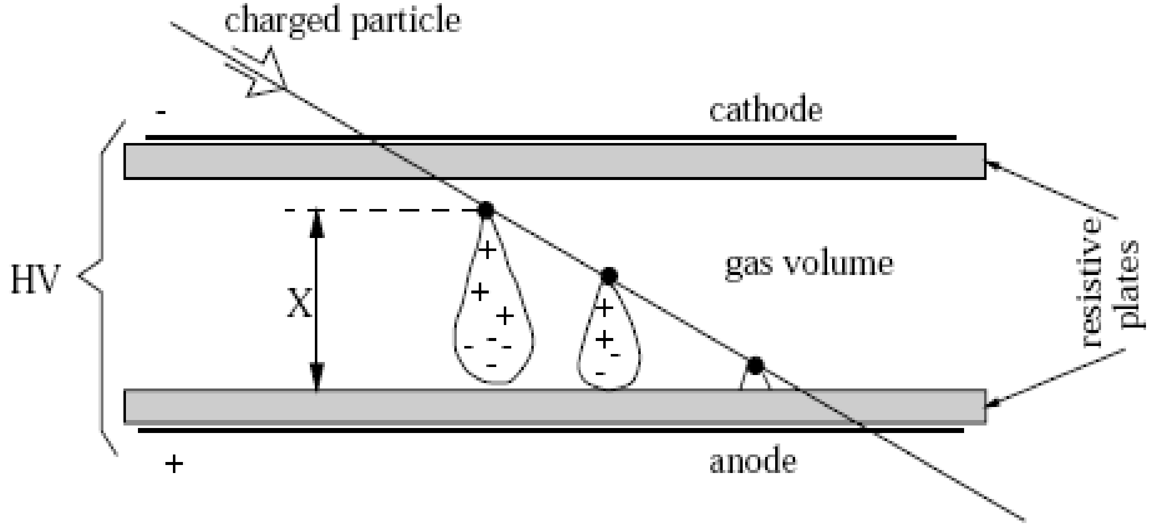
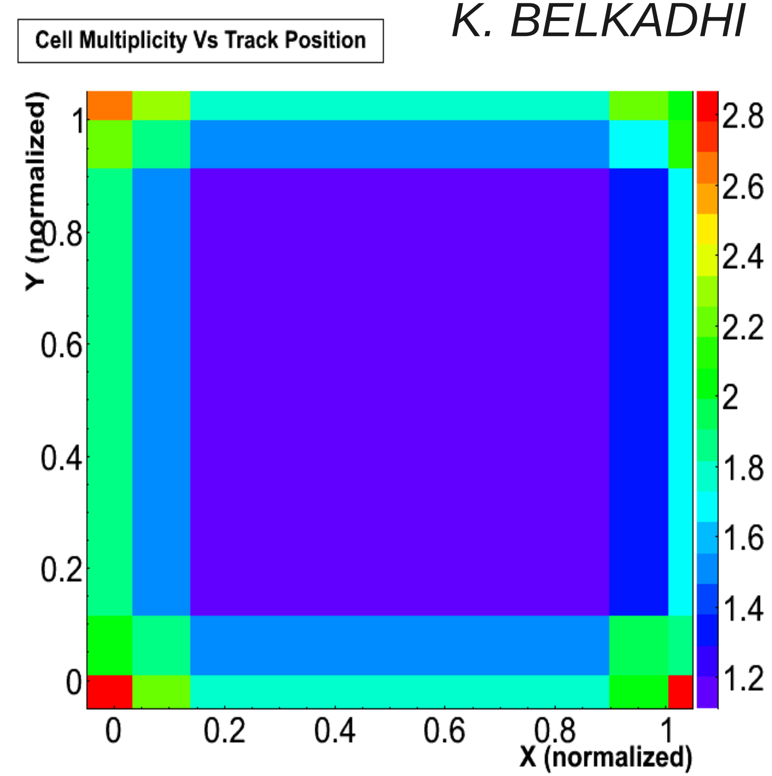


Fig. 1. Sketch of RPC gap.



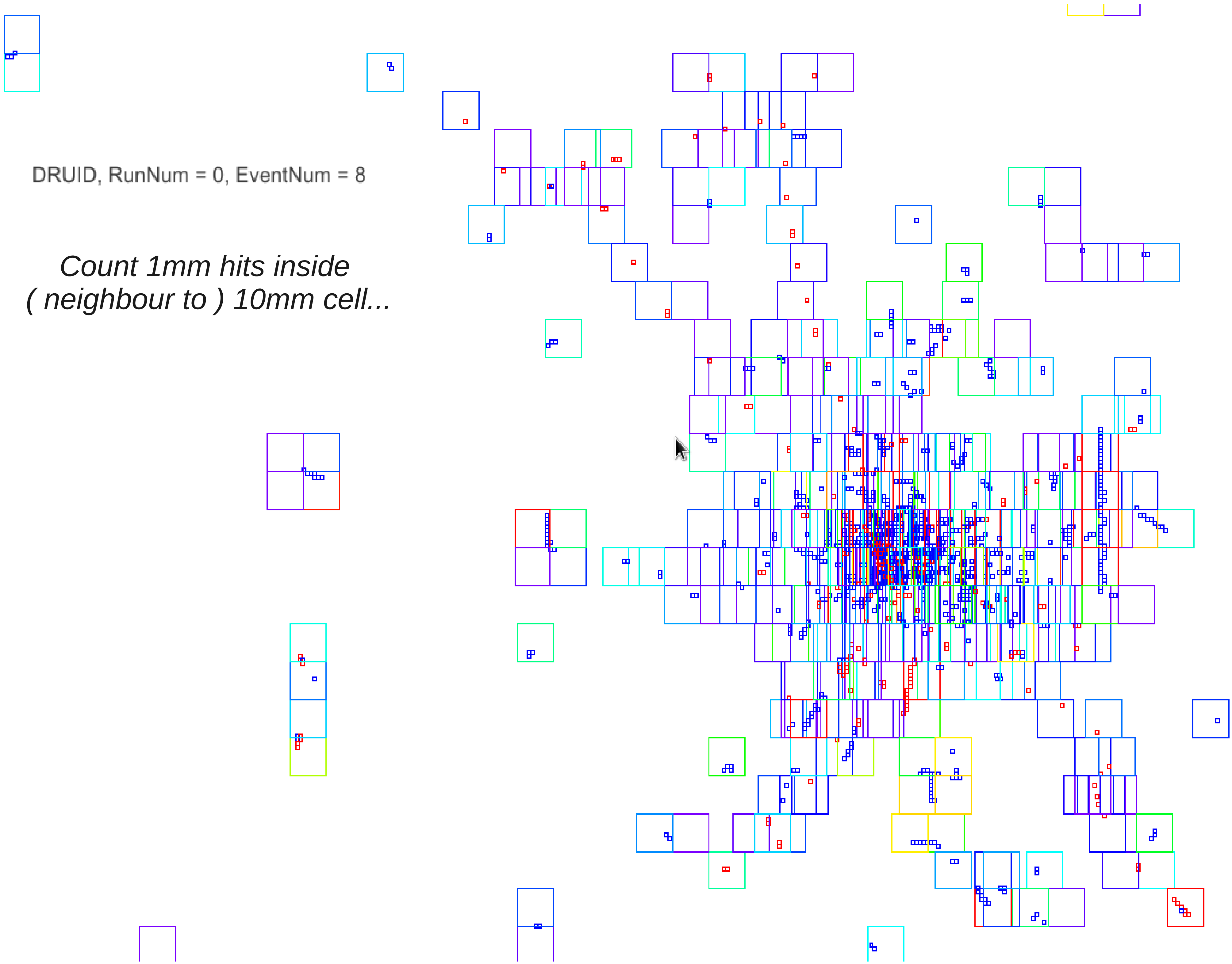
- Characteristic Parameter: from test beam data
  - Multiplicity: global ~ 1. - 2.
  - Charge Image Size (depending on resistive plates thickness) : ~ 1mm (*as convoluted with spatial resolution*)

Idea

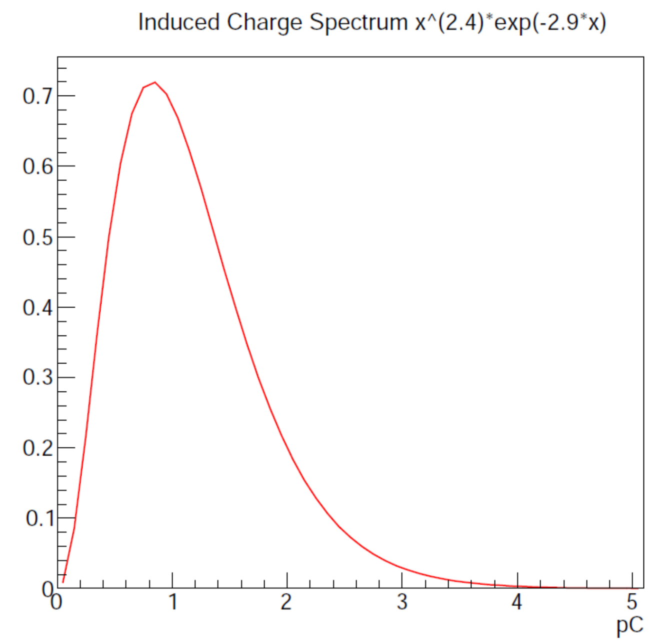
- Keep simulation level information to 1mm cells: count corresponding number of hits in/nearby 1 square cm^2
  - Advantages:
    - Natural cut off: 1mm ~ gas gap thickness ~ size of charge image
      - Self Saturation & easy to integrate other saturation effects
    - Reliable estimation of multiplicity
    - Samples: available for other analysis, like cell size optimization study
  - Cost:
    - Machine time: the same
    - Data size: increased ~ 5% (ParticleCont recorded & Nhits increased by ~ 3 times, t*est on 20GeV Klong sample*)
    - Negligible at full detector event: ***Utilize as Simulation base line?***

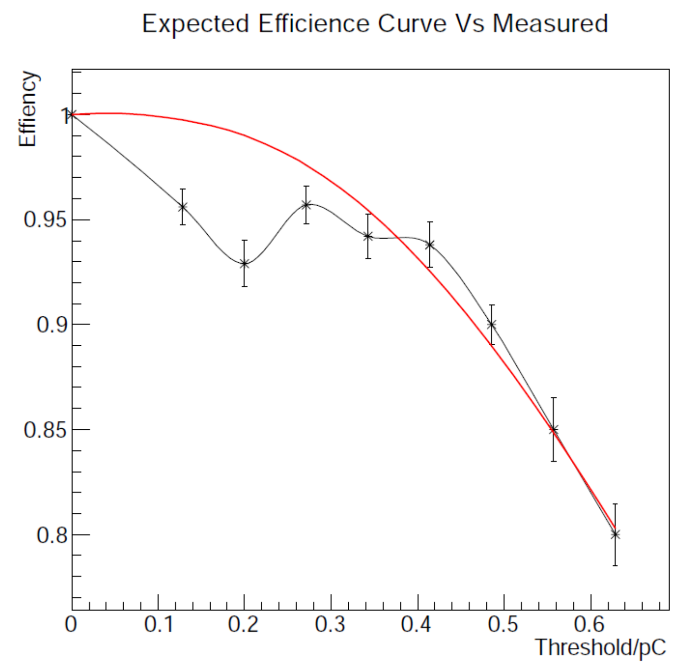
DRUID, RunNum = 0, EventNum = 8

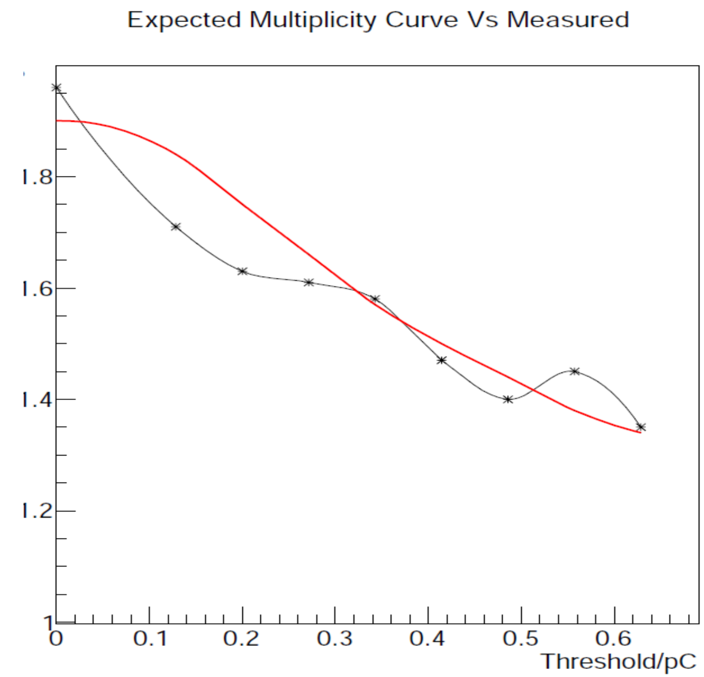
Count 1mm hits inside (neighbour to) 10mm cell...



Parametrize from TB
Test on 20GeV Muon Sample







For 1 mip ~(1 hit at 1mm cell)

Total Charge: Polya function

Spatial: distribution over 5 * 5 mm region

Efficiency & Multiplicity VS Threshold: Result repeated to the first order

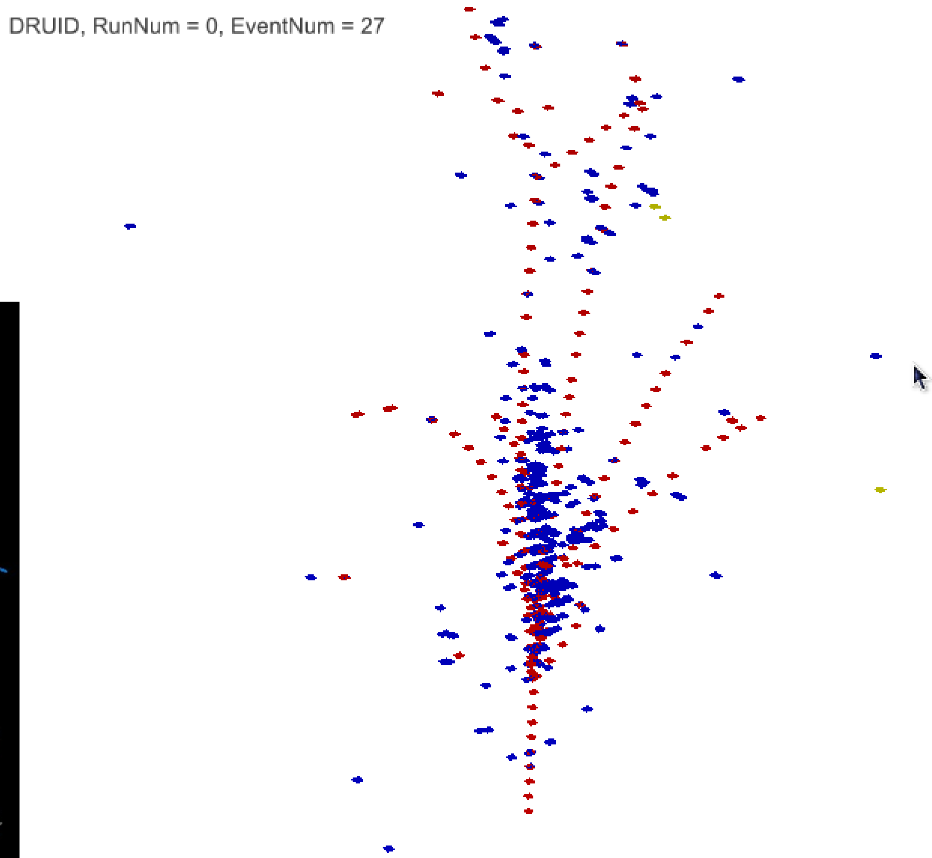
Summary

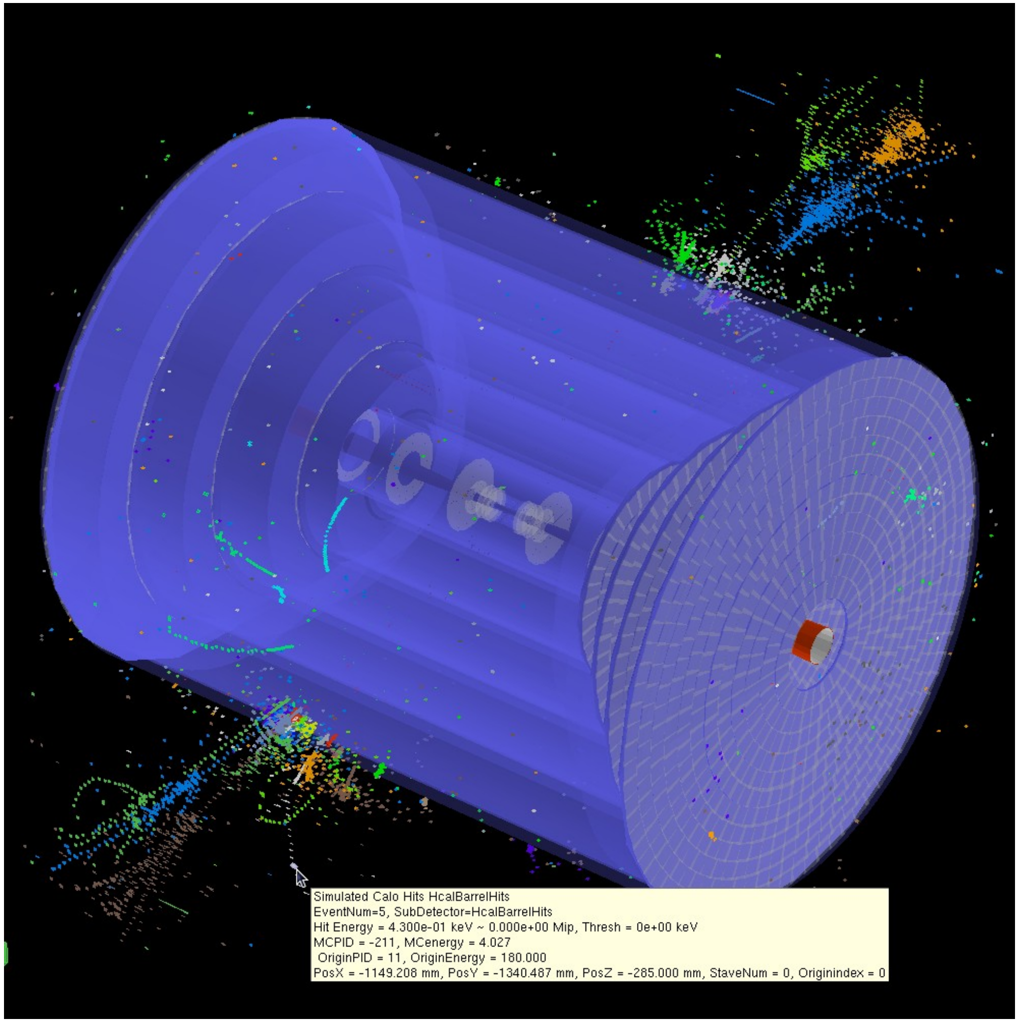
- Huge reconstruction potential at high granularity calorimeter...
  - Arbor:
    - MIP tagging with lots of potential application:
      - Energy Estimation,
      - Leakage correction
      - ...
    - Pre-mature PFA Framework: better separation, pattern recognition
  - Fractal Dimension:
    - Promising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

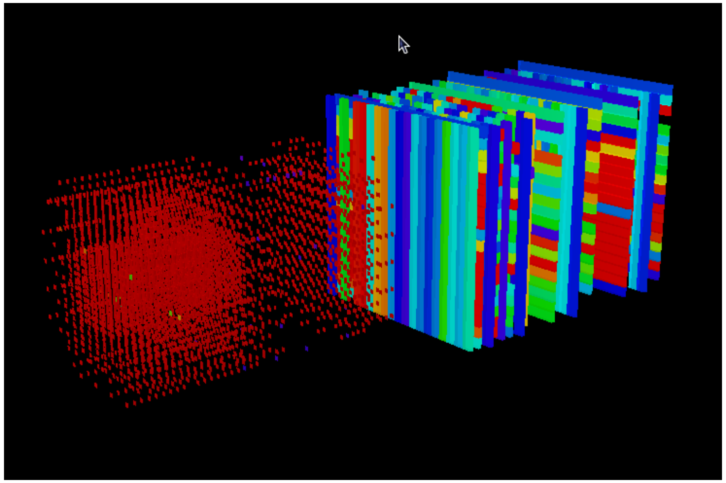
Thank you!

Wish you a happy & fruitful Dragon's Year!

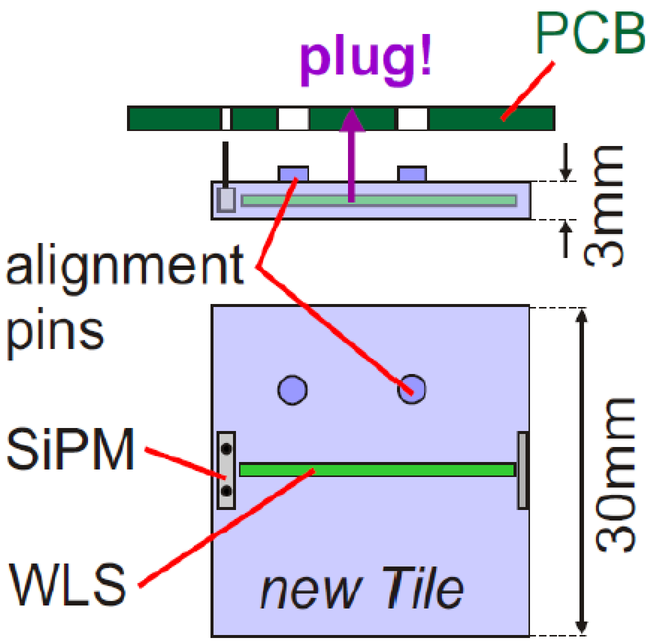
Spare Slides

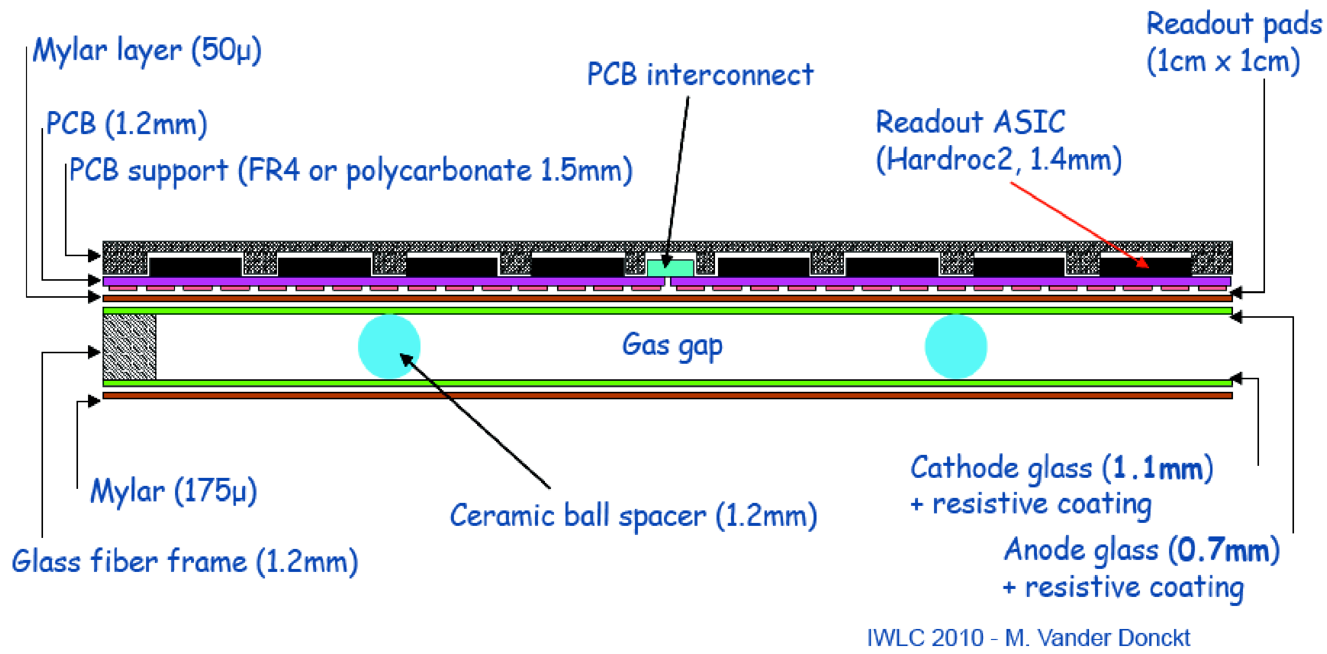






HCAL: Gas Vs Scintillator





Scintillator:

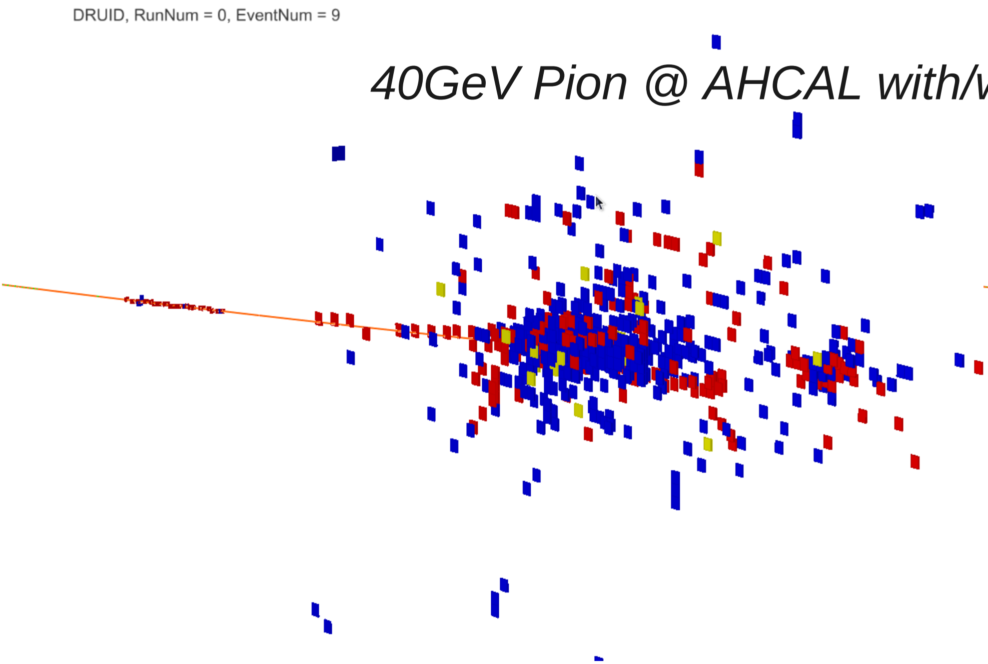
3*3*0.3 cm³ cell size & analogy readout

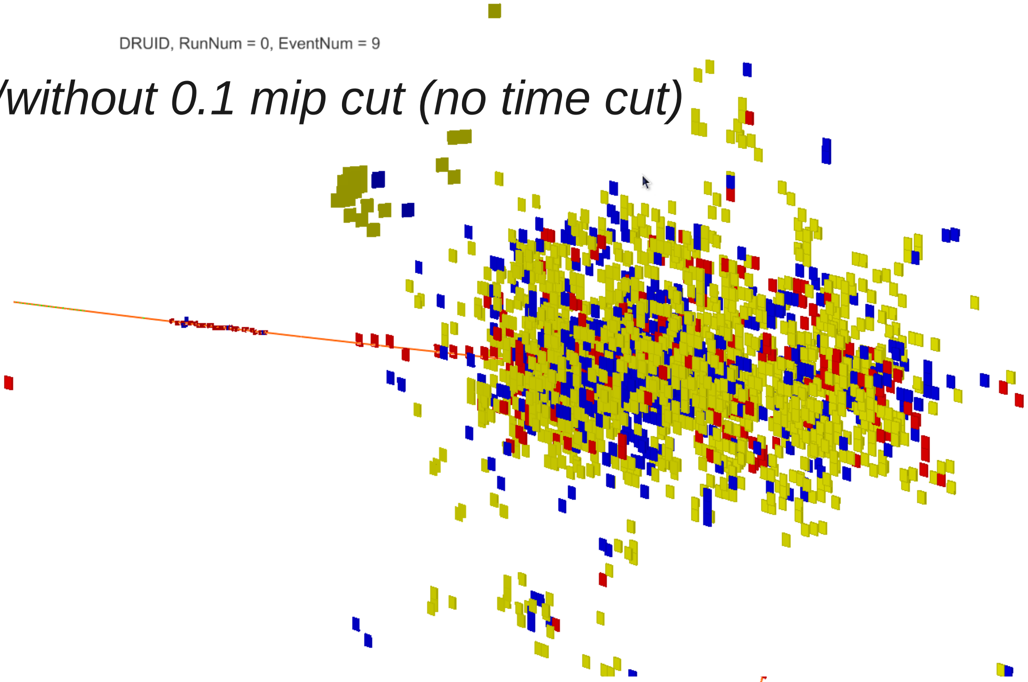
Gas:

- High granularity (1*1*0.12 cm³ 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

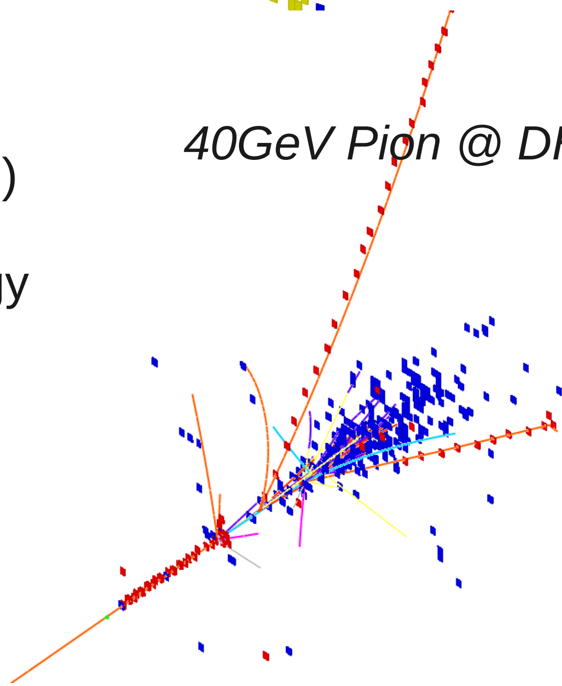
Neutron hits

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





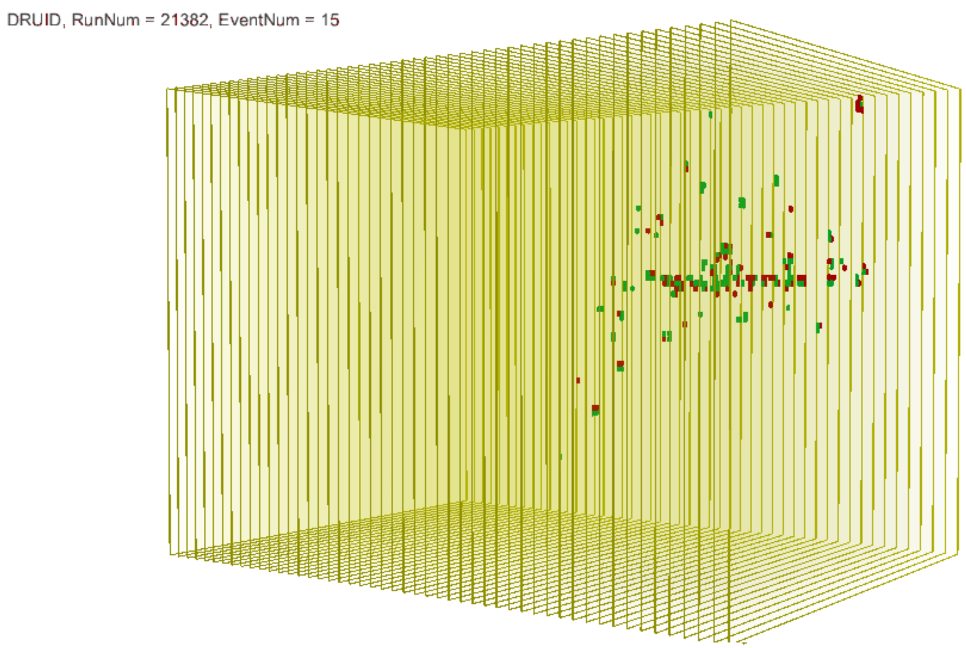
40GeV Pion @ DHCAL

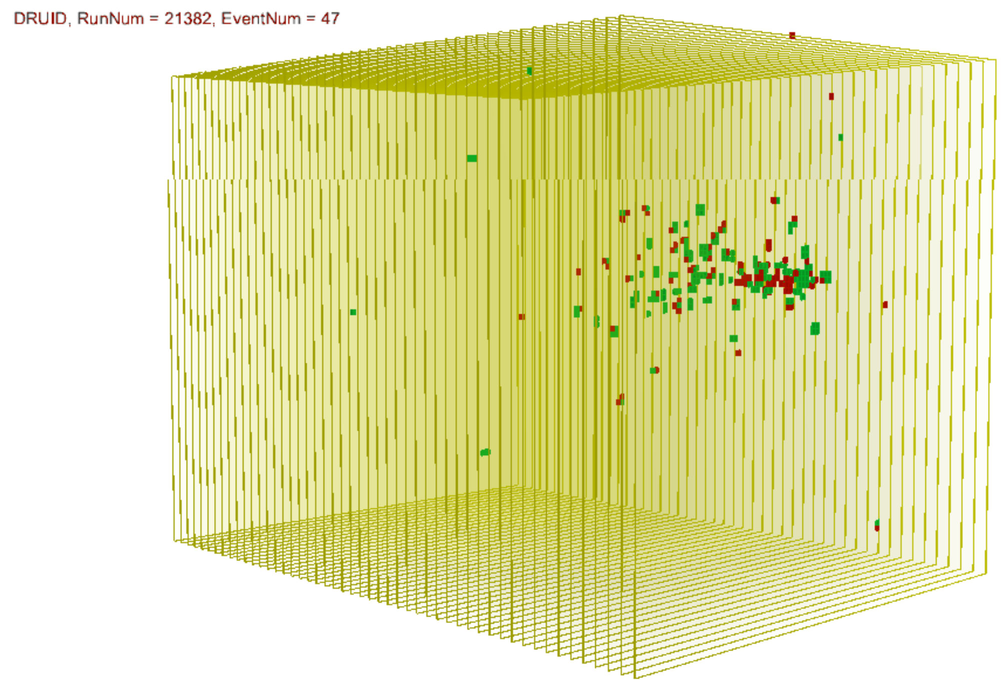


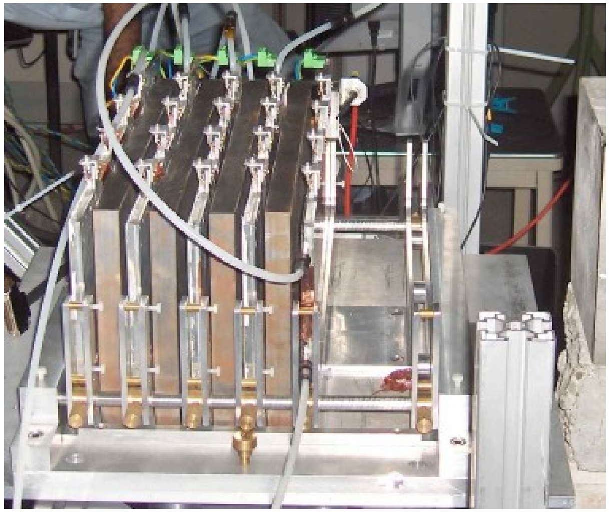
Hit Colour: EM (blue), Neutron (yellow) or hadronic (red)

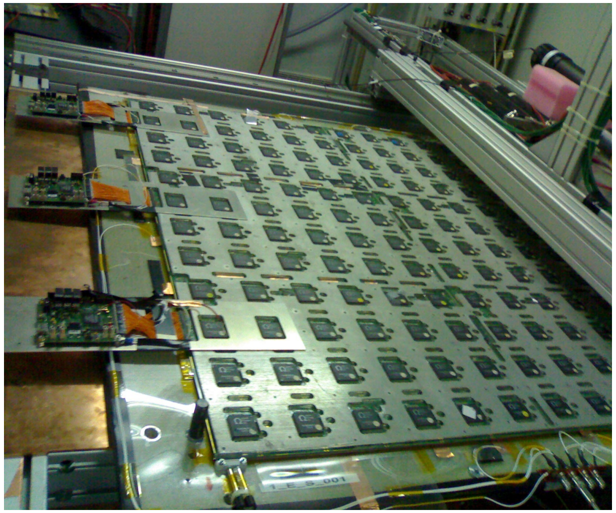
- AHCAL: Shower center surrounded by lots of low energy neutron hits
- Need careful analysis: Confusion & Energy resolution

SDHCAL Prototype @ EU





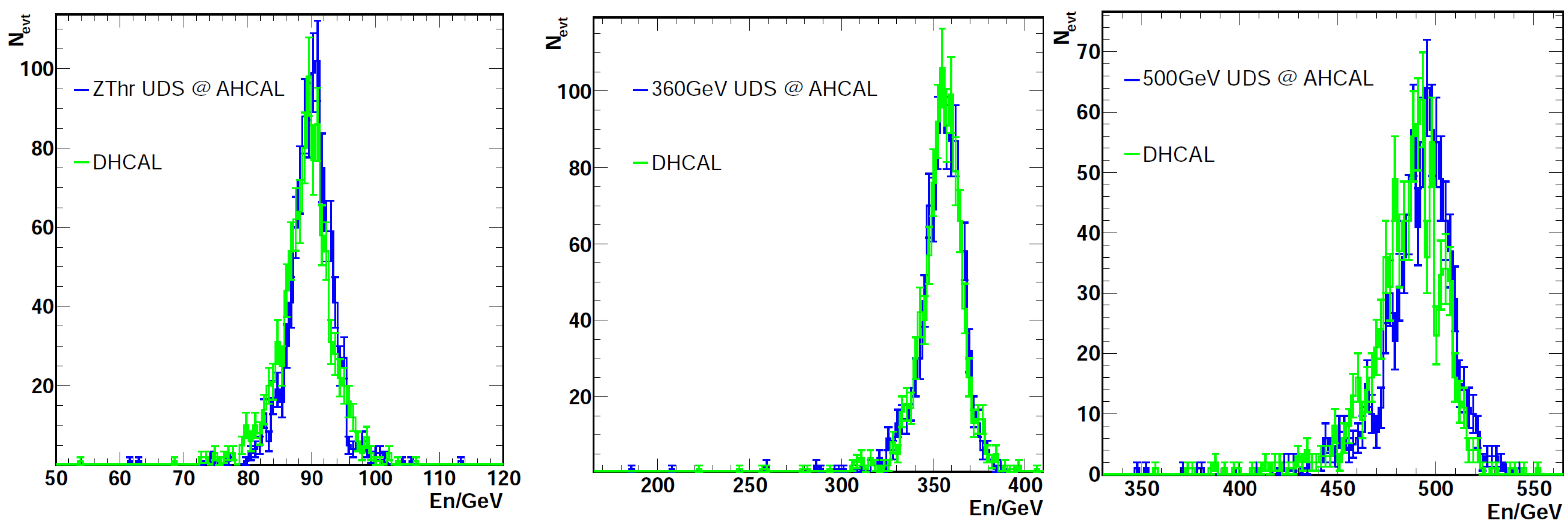




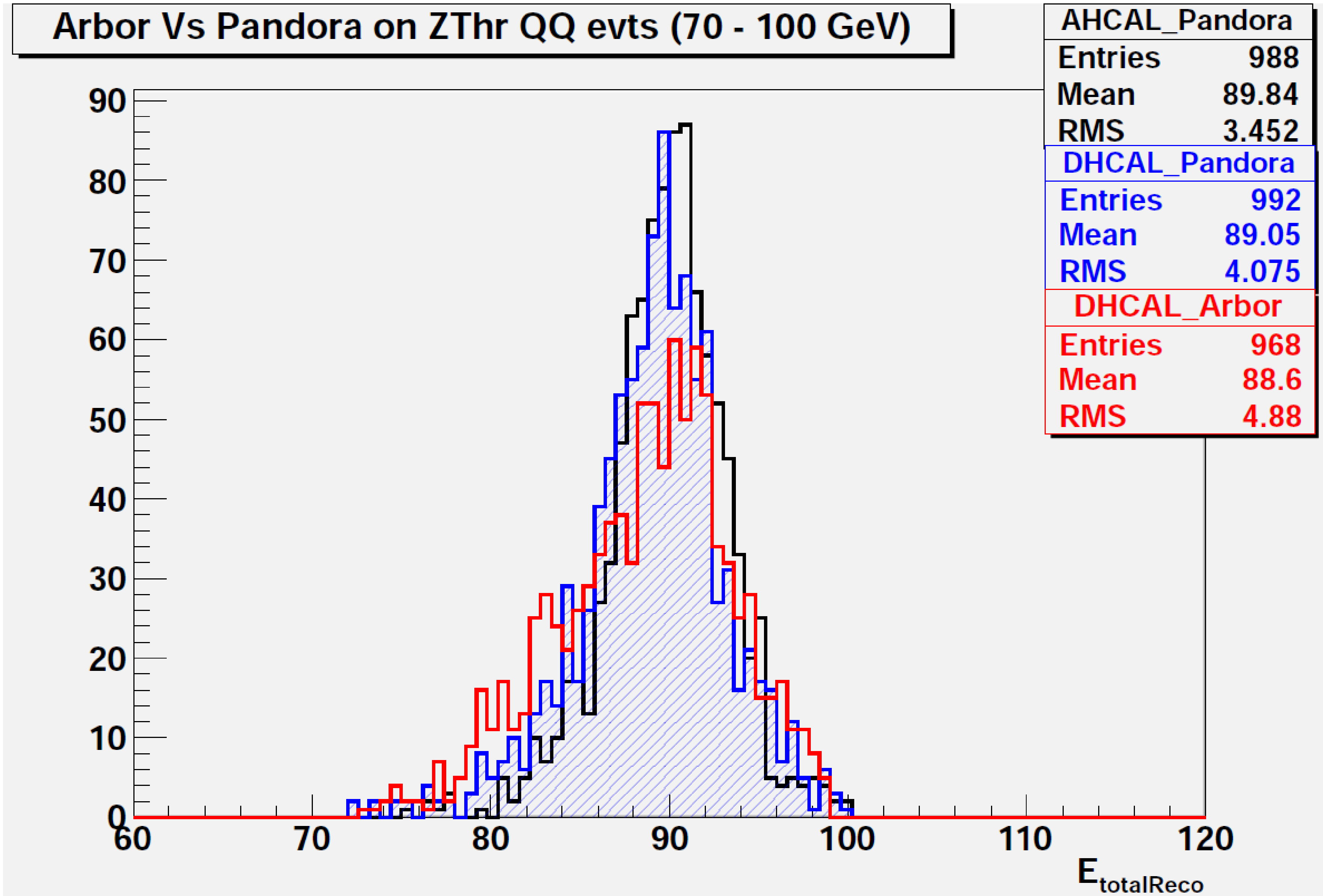
1k channels → **10k** channels → **~500k** channels!

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

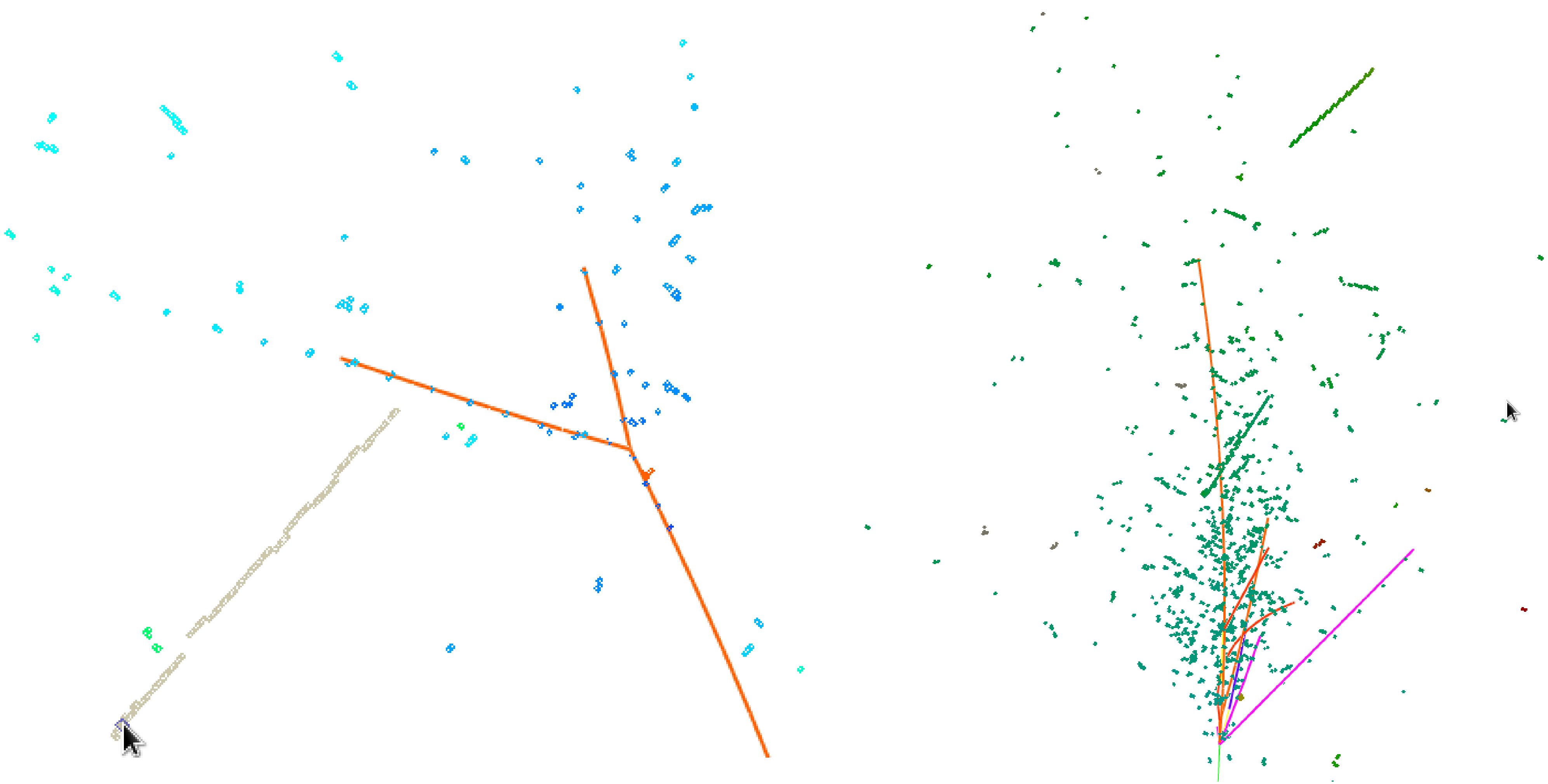


  - Huge potential to improve
    - Shower Clustering & Reconstruction: Arbor
    - PID & Energy Estimation: impaction from Shower Fractal Dimension
  - Druid (event display): heavily employed in algorithm development



Arbor Vs Pandora on ZThr QQ evts (70 - 100 GeV)
AHCAL_Pandora
Entries 988
Mean 89.84
RMS 3.452
DHCAL_Pandora
Entries 992
Mean 89.05
RMS 4.075
DHCAL_Arbor
Entries 968
Mean 88.6
RMS 4.88
0
10
20
30
40
50
60
70
80
90
60
70
80
90
100
110
120
E_totalReco

Noise cleaning

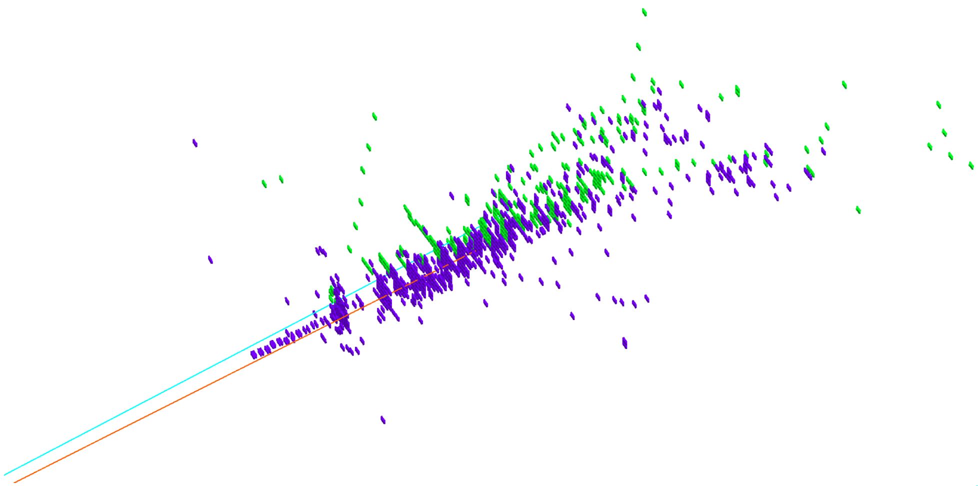


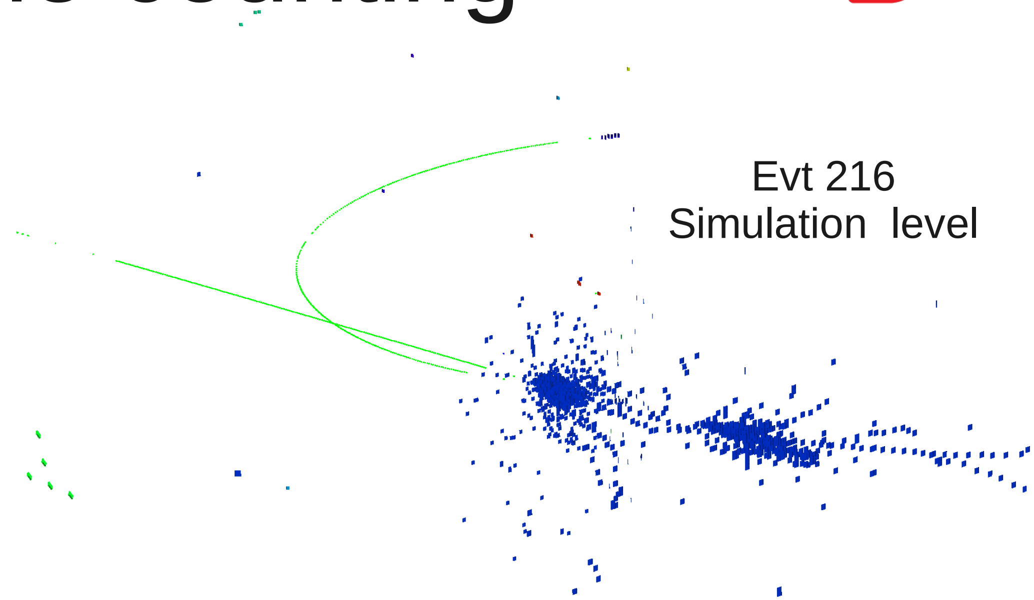
String Noise: Typical in gaseous detector: charged particle tripped In the gas layer (display of 1mm hits Information)

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

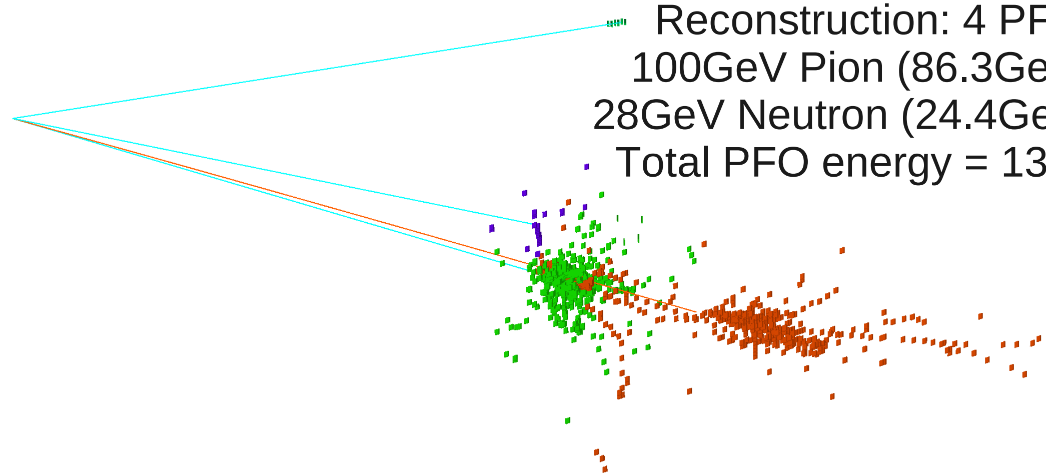
Double counting

(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

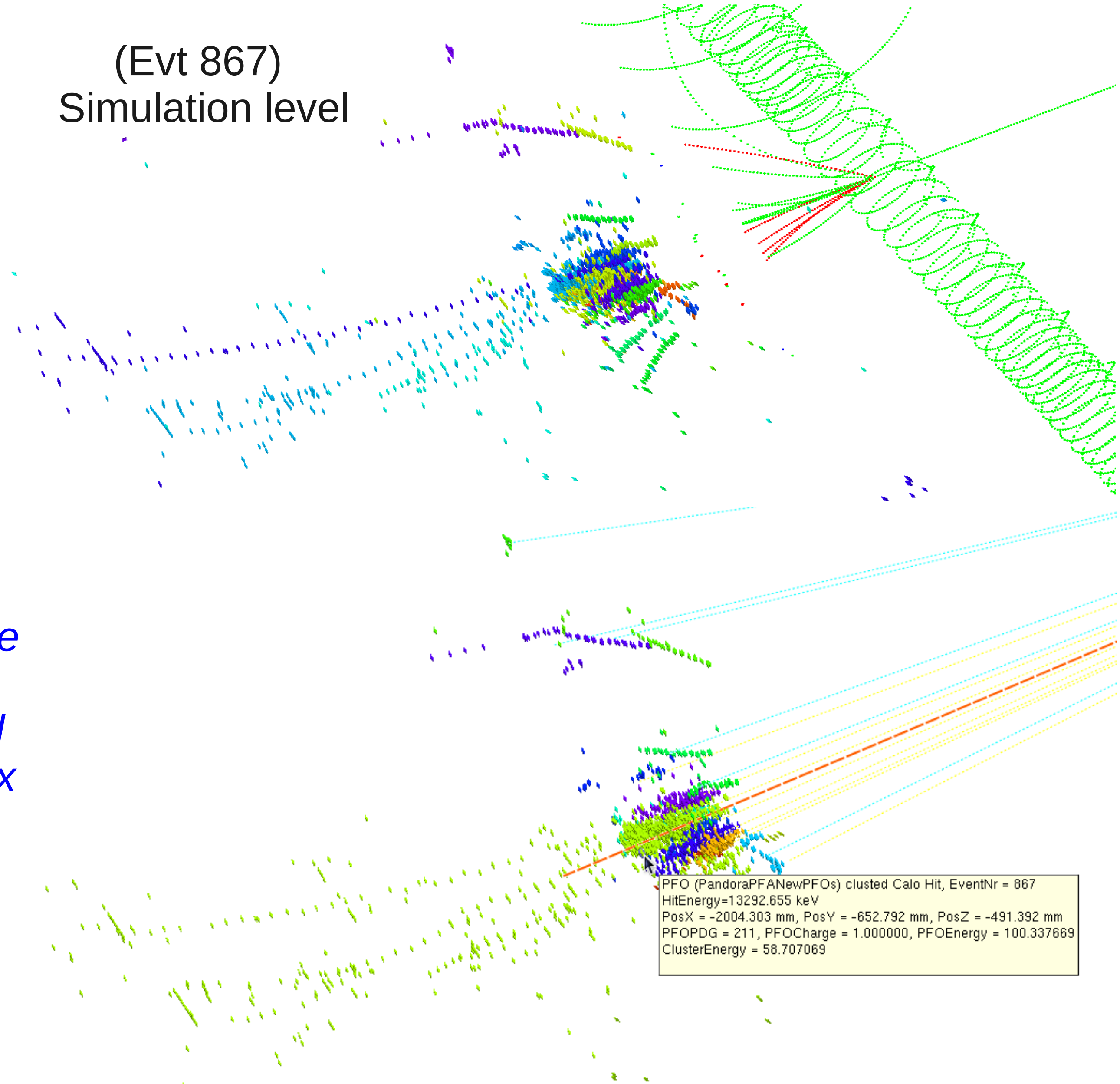
Near the Calo

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...

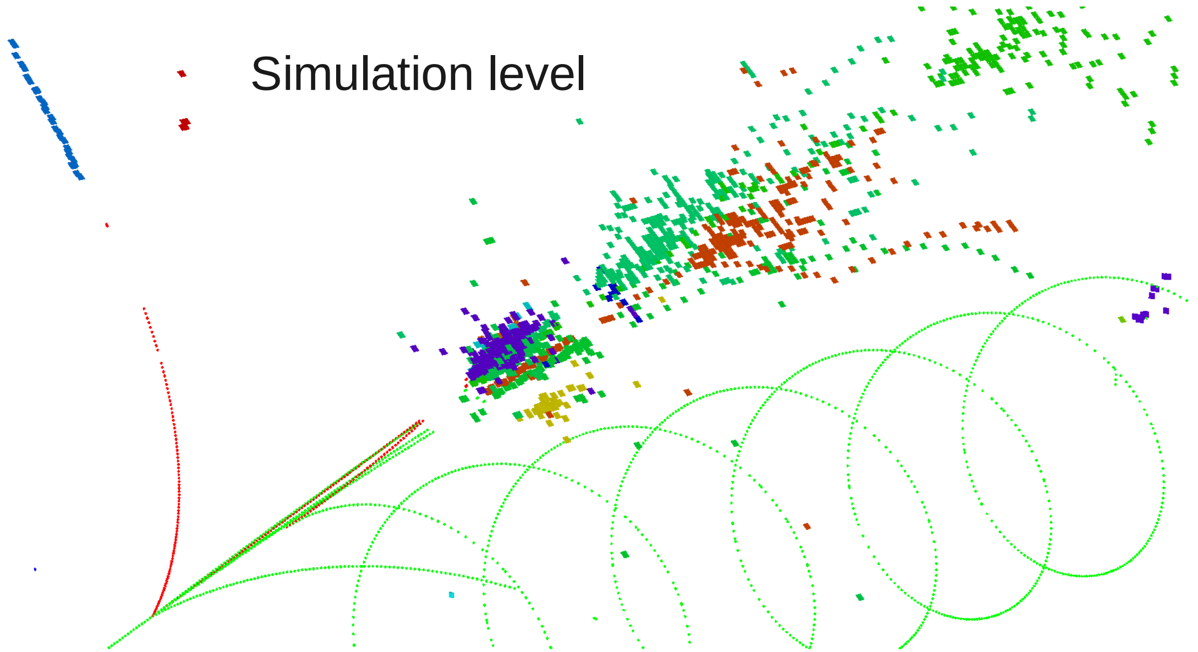
Evt 646: Interaction Inside TPC (1/3 of the radius)

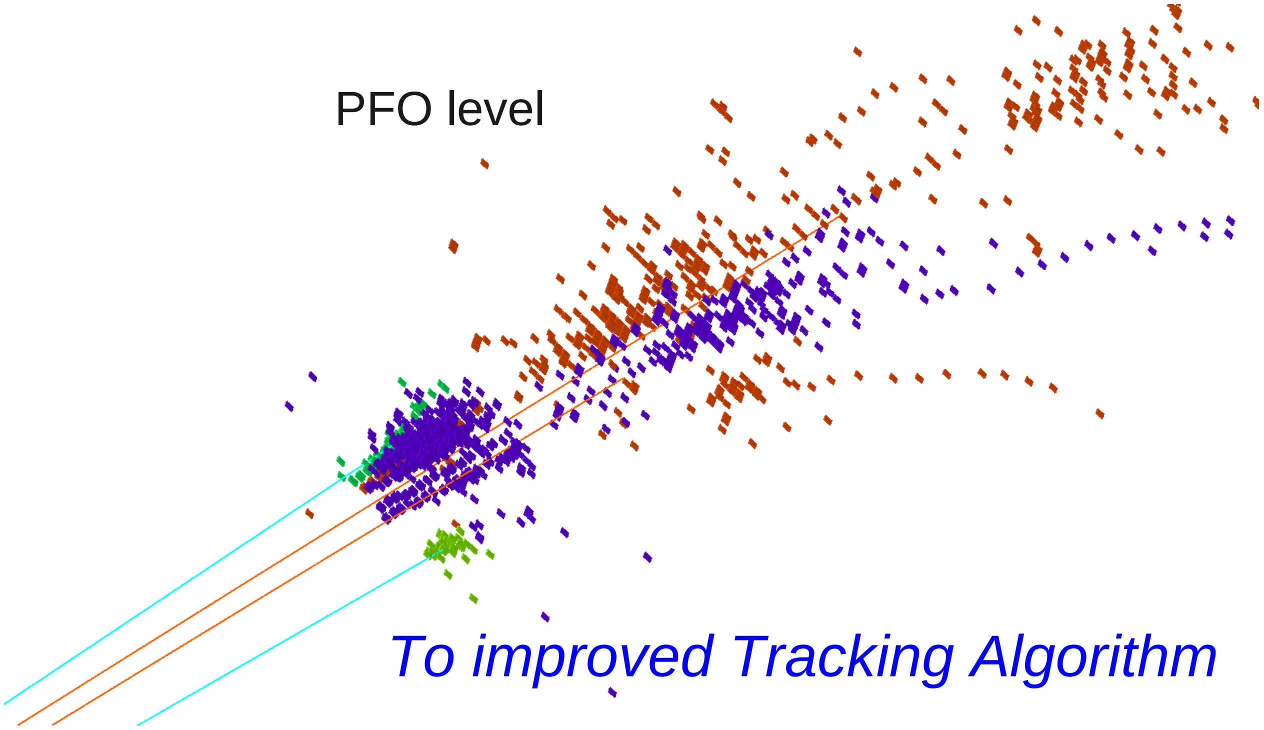
Confused tracker: 3 LDCTrack found

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