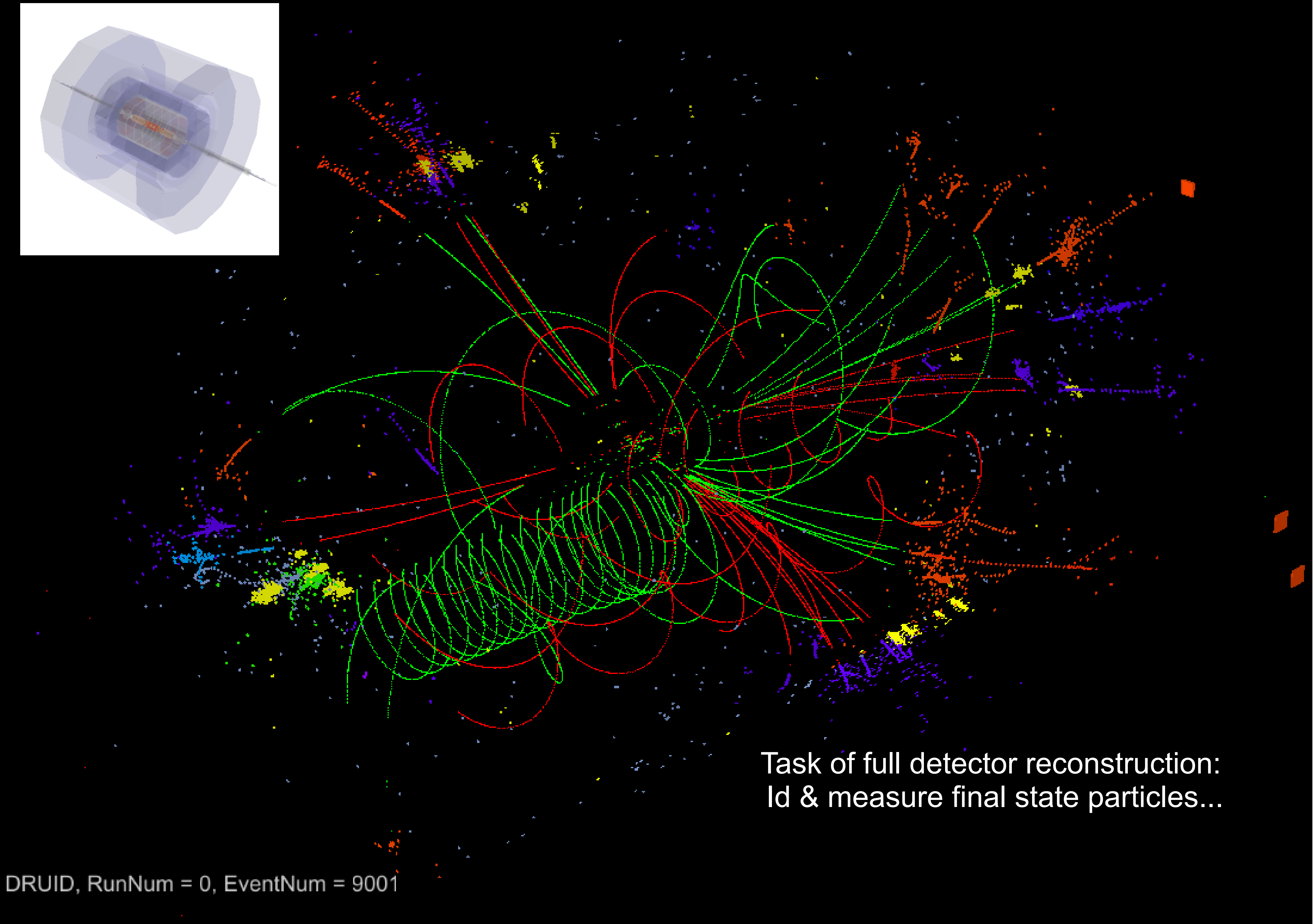
ÉCOLE POLYTECHNIQUE ParisTech

Fractal dimension analysis in a highly granular calorimeter

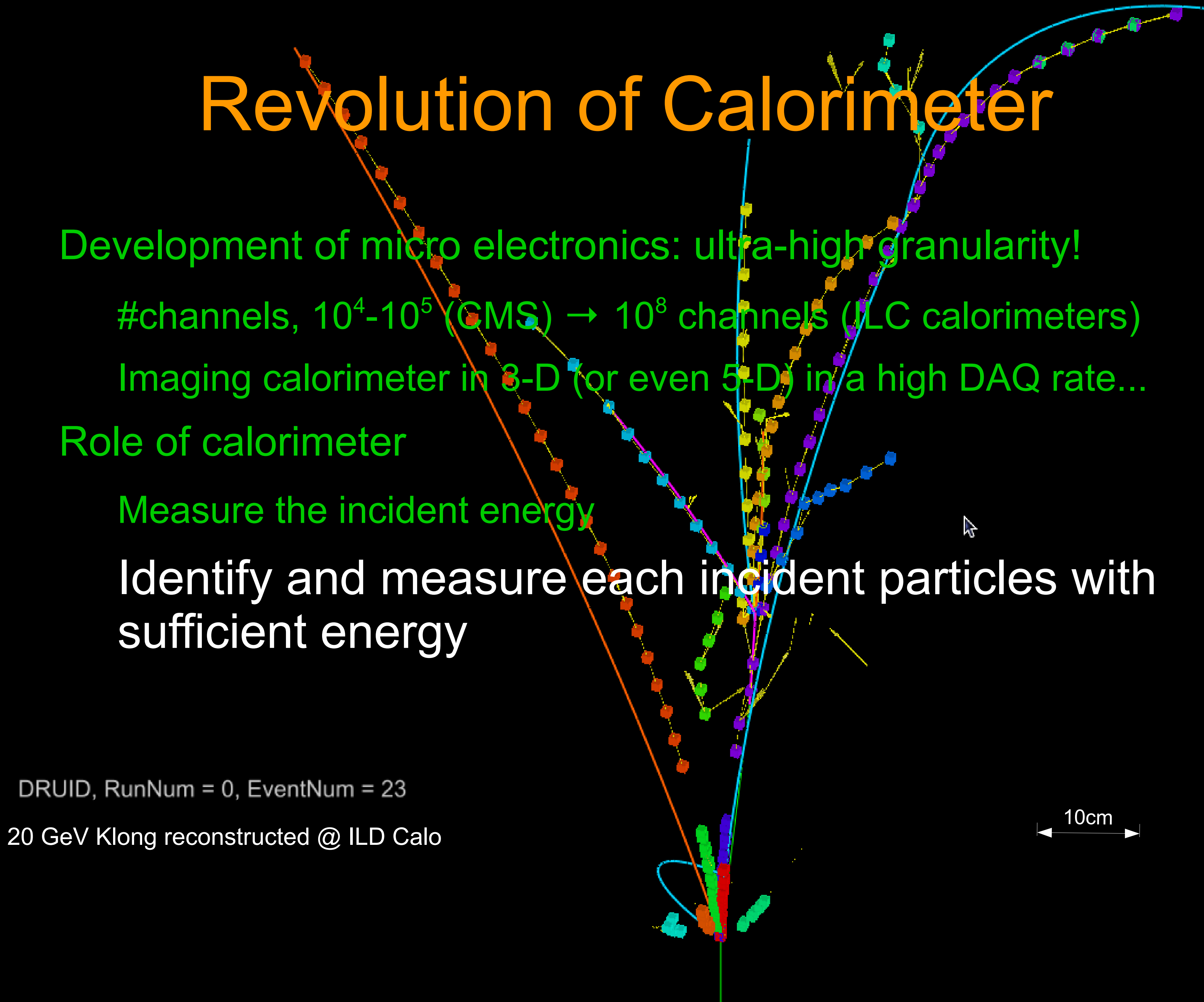
Manqi RUAN



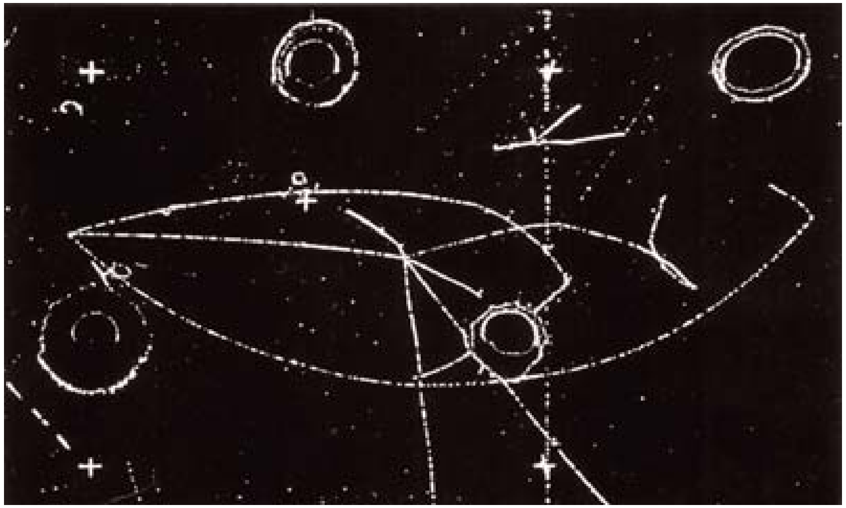
Task of full detector reconstruction:
Id & measure final state particles...

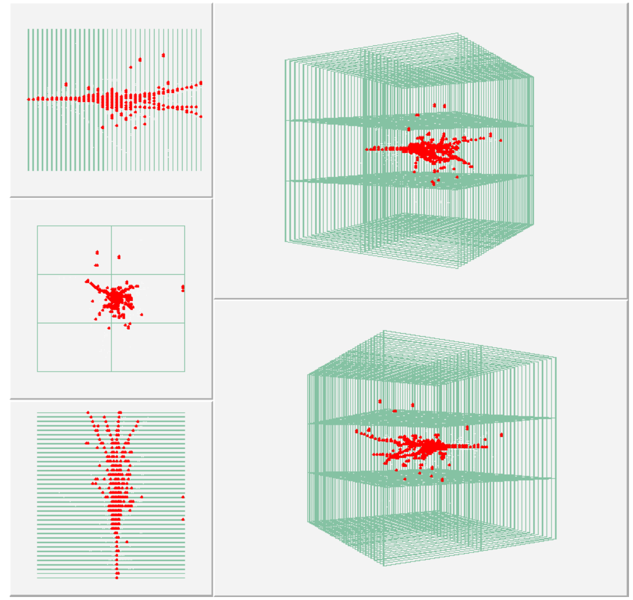
Revolution of Calorimeter

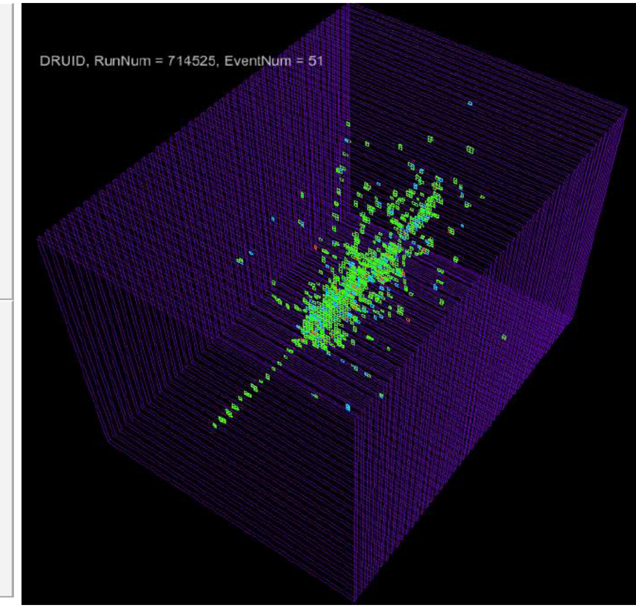
- Development of micro electronics: ultra-high granularity!
    - #channels, 10^4-10^5 (CMS) → 10^8 channels (ILC calorimeters)
    - Imaging calorimeter in 3-D (or even 5-D) in a high DAQ rate...
- Role of calorimeter
    - Measure the incident energy
    - Identify and measure each incident particles with sufficient energy

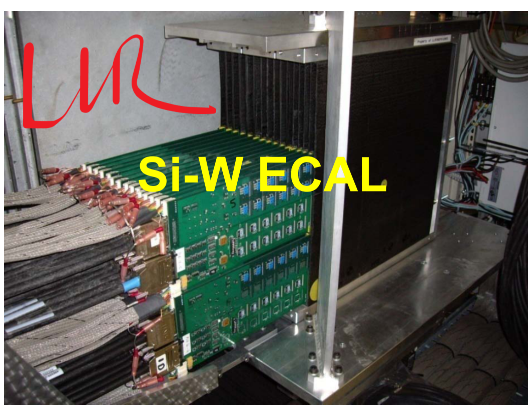


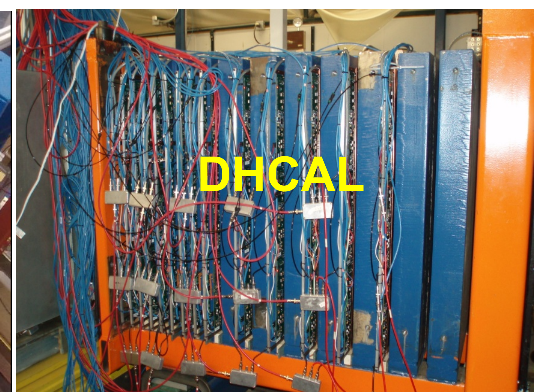
Ultra-high granularity...



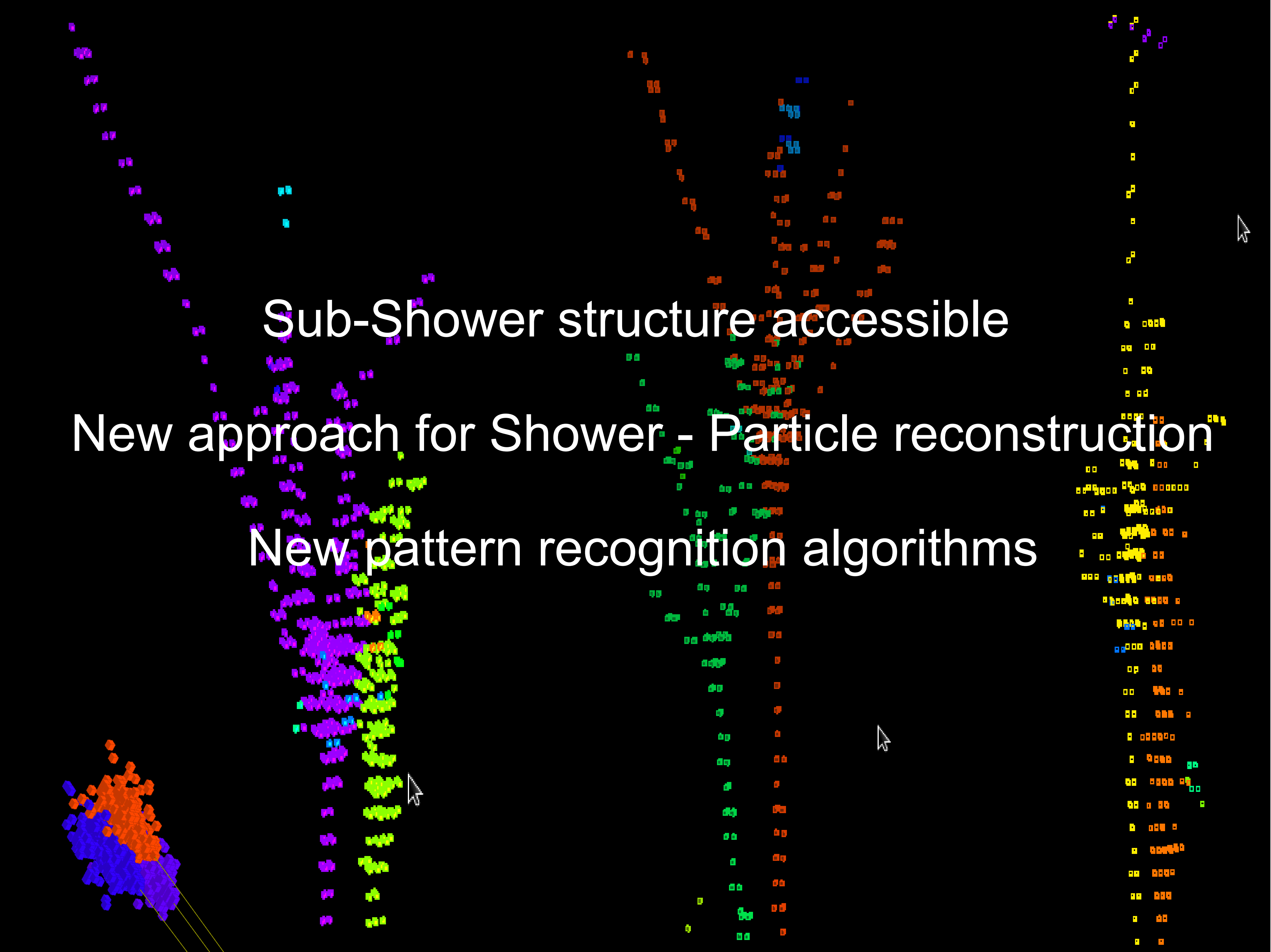








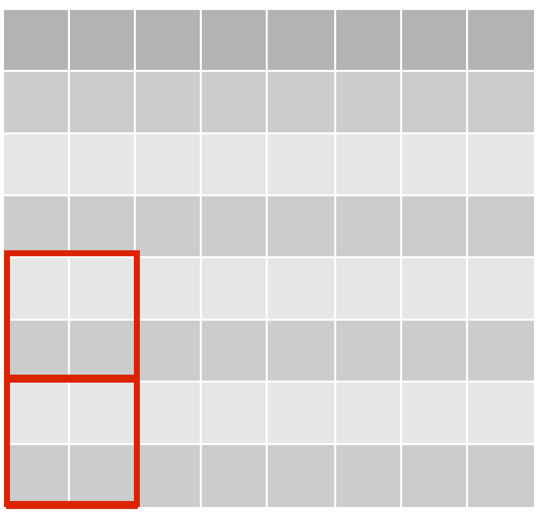
Granularity ~ 1 cm^{-3}. 3d, 4d or 5d image...


Sub-Shower structure accessible
New approach for Shower - Particle reconstruction
New pattern recognition algorithms

Fractal dimension of particle shower

$$FD_\beta = \left\langle \frac{\log(R_{\alpha,\beta})}{\log(\alpha)} \right\rangle + 1.$$

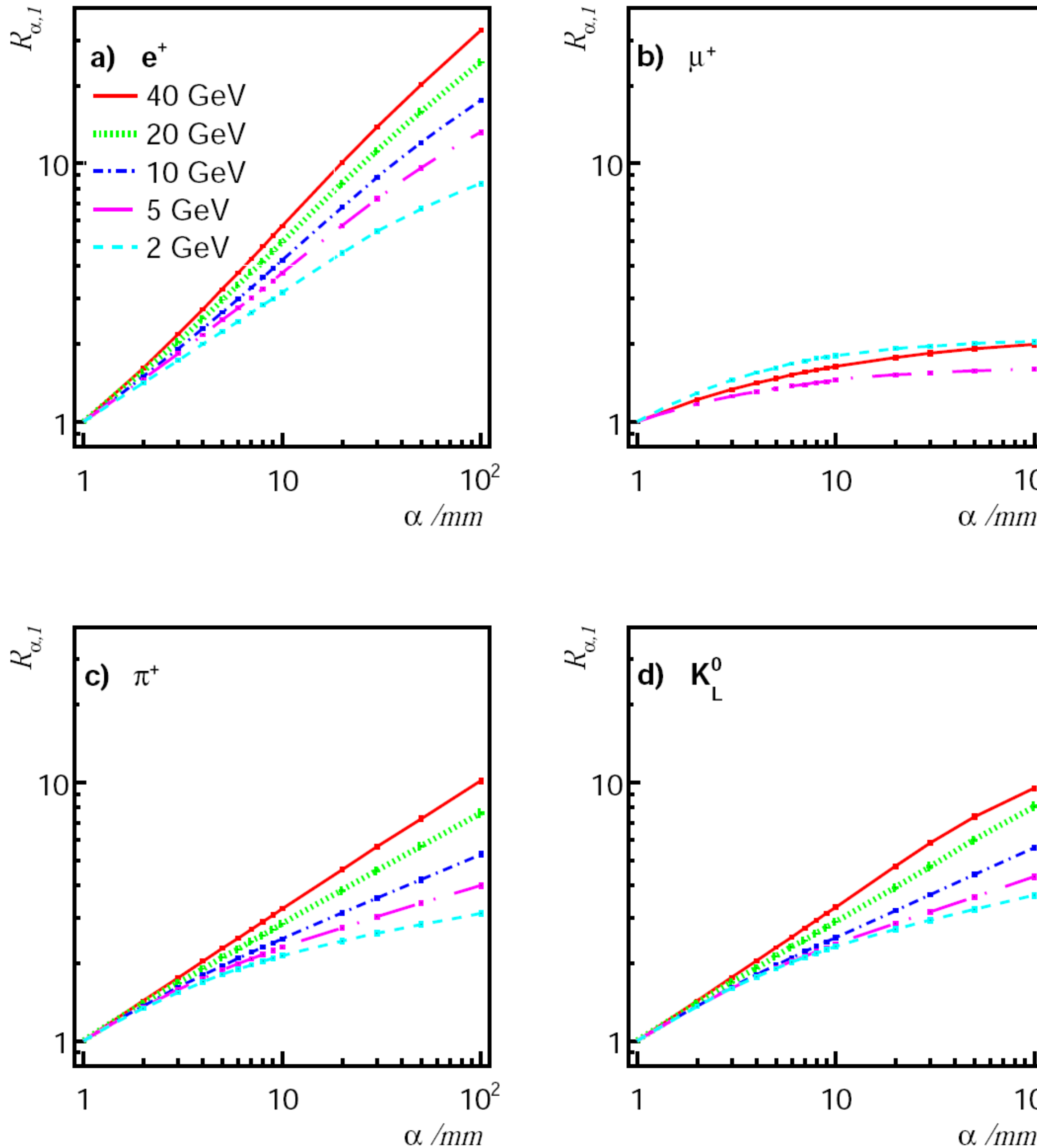
$$R_{\alpha,\beta} = N_\beta / N_\alpha.$$



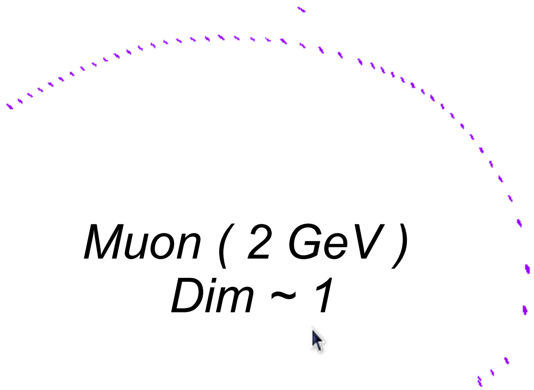
Ultimate cell size: 1mm

Resize cell: 2 – 10, 20, 30, 50, 60, 90, 120, 150 mm.

Sample: particle gun events at ILD SDHCAL

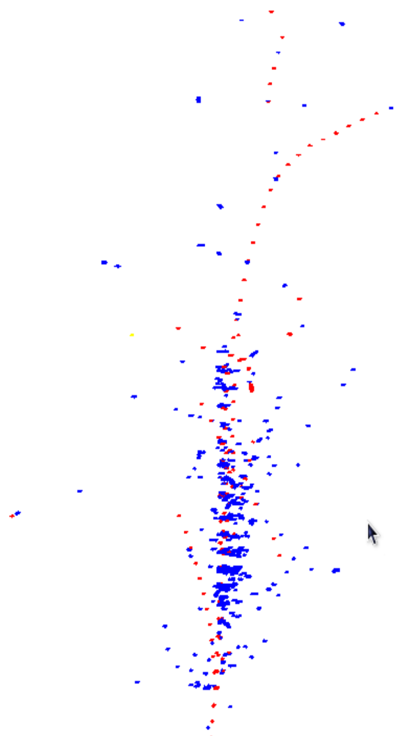


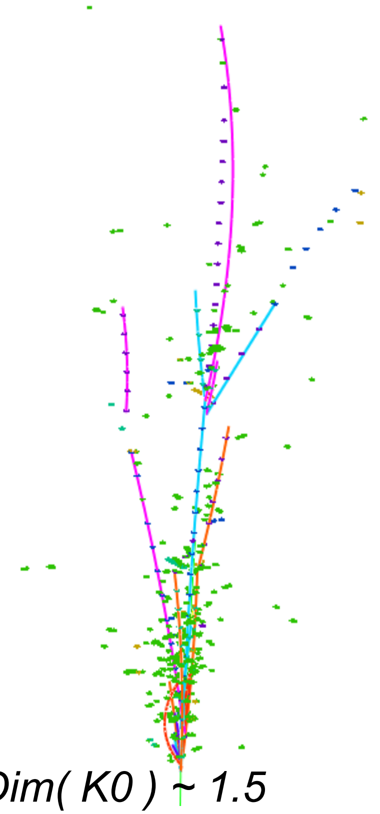
Fractals in Nature



Muon (2 GeV)
Dim ~ 1

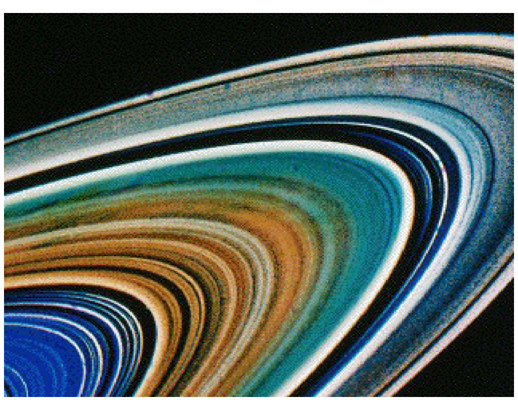
Straight line:
Dim = 1





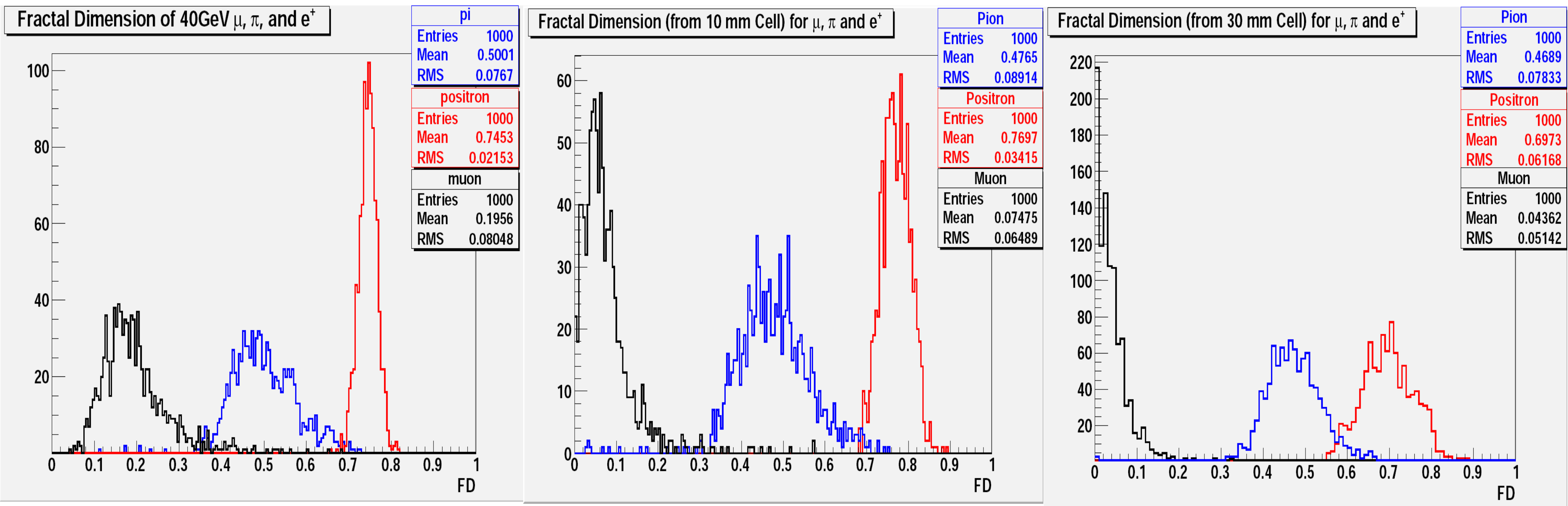
Hadrons: Dim(pi) < Dim(K0) ~ 1.5

Positron (40GeV)
Dim ~ 1.75



Rectangle:
Dim = 2

FD @ different size



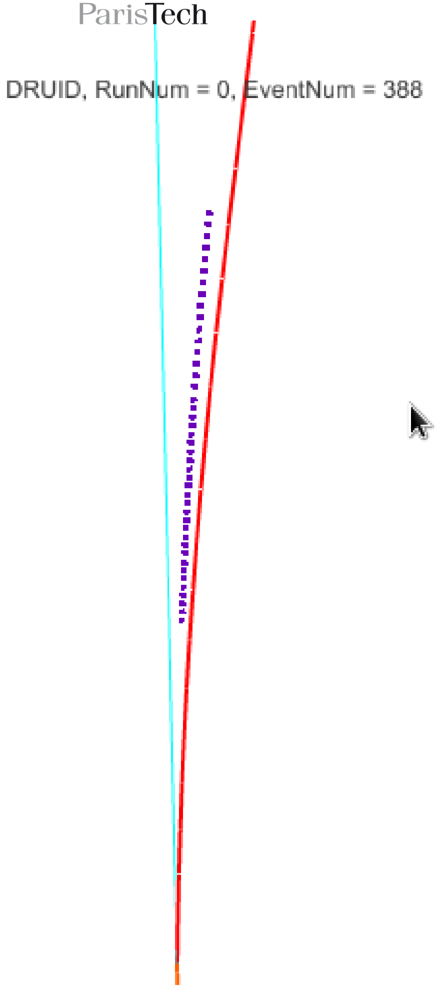
From FD(1mm) to FD(10/30mm):

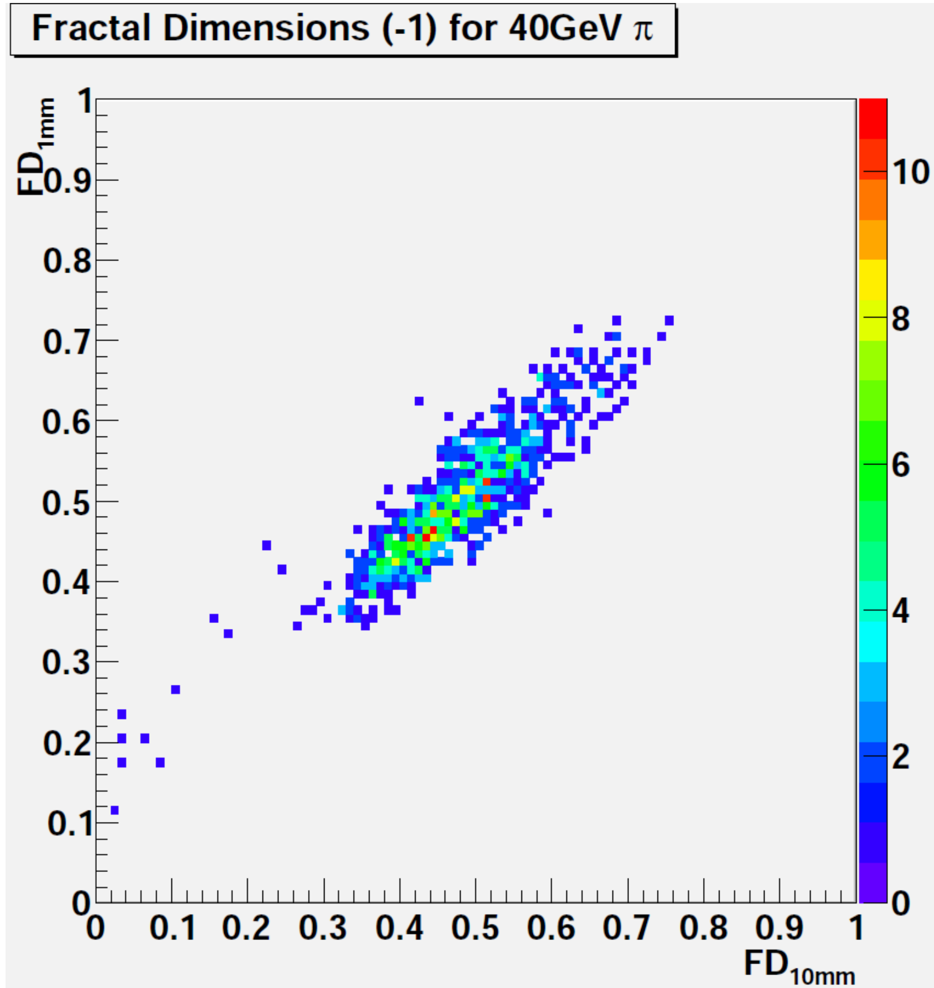
Positron Peak Smeared

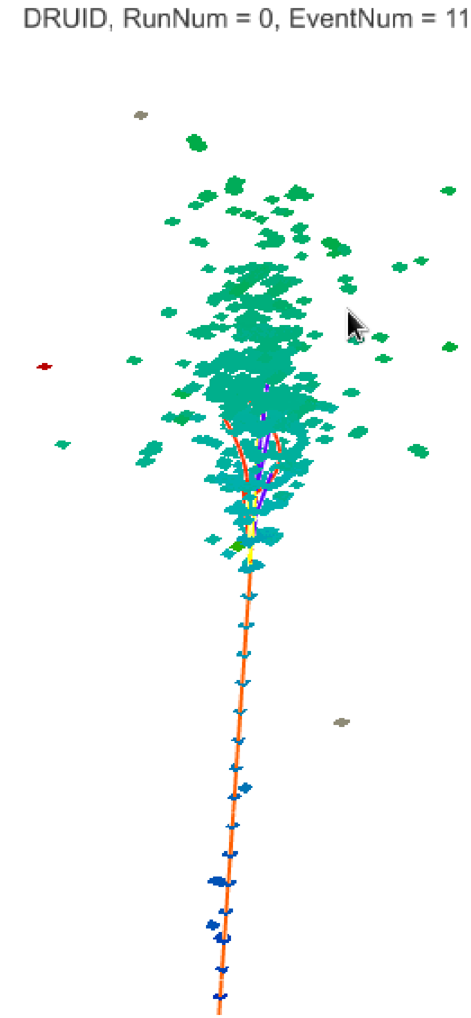
Better μ – h separation: μ acts more like a line (FD = 1); (Anyhow *we can create large cells from small ones...*)

Hadronic shower: continuous distribution between MIP and EM shower

Extreme Cases: Pion





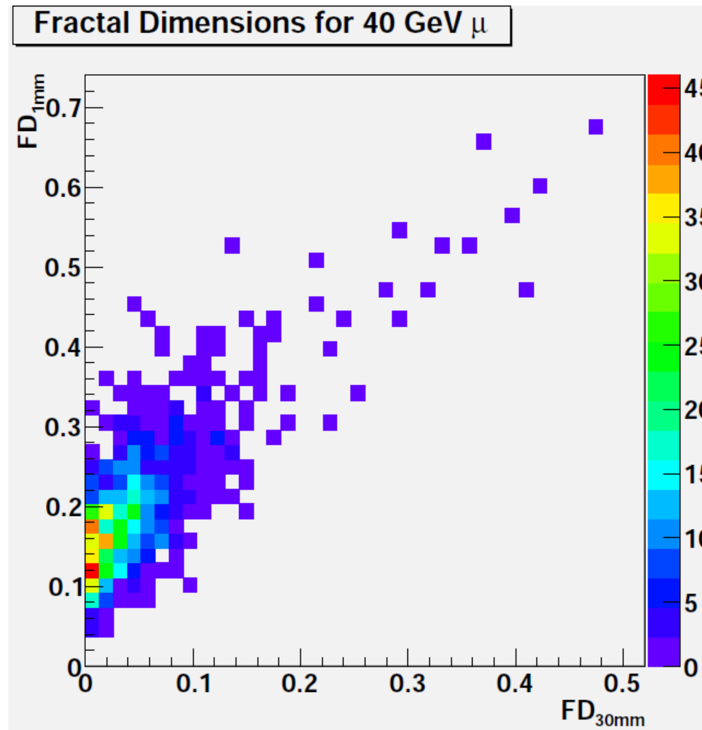


- Pion: MIP, Pion decay;
- EM interaction (pi + N = P + pi0); partially identified by interaction point tagging

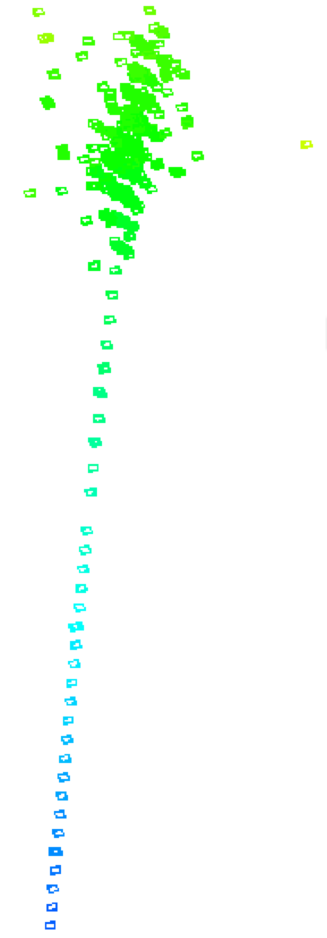
Extreme Cases: Muon

DRUID, RunNum = 0, EventNum = 535

DRUID, RunNum = 0, EventNum = 547

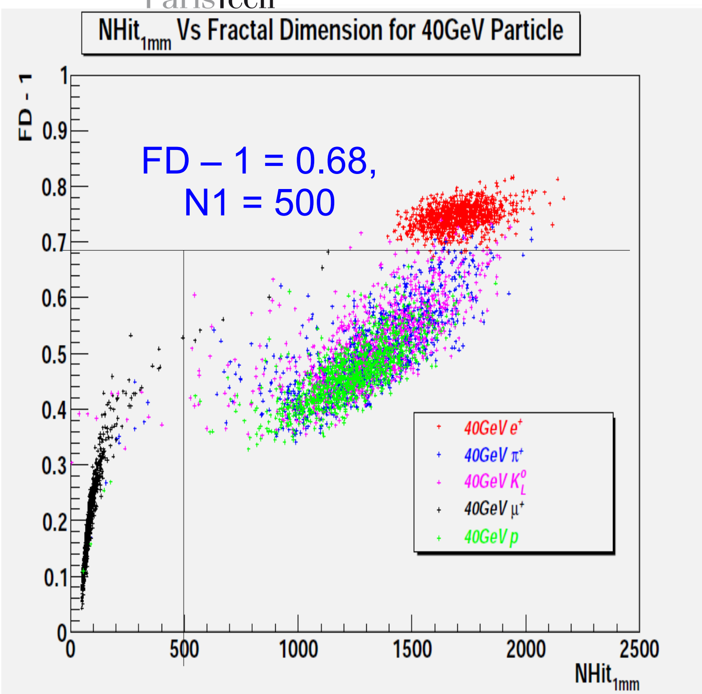


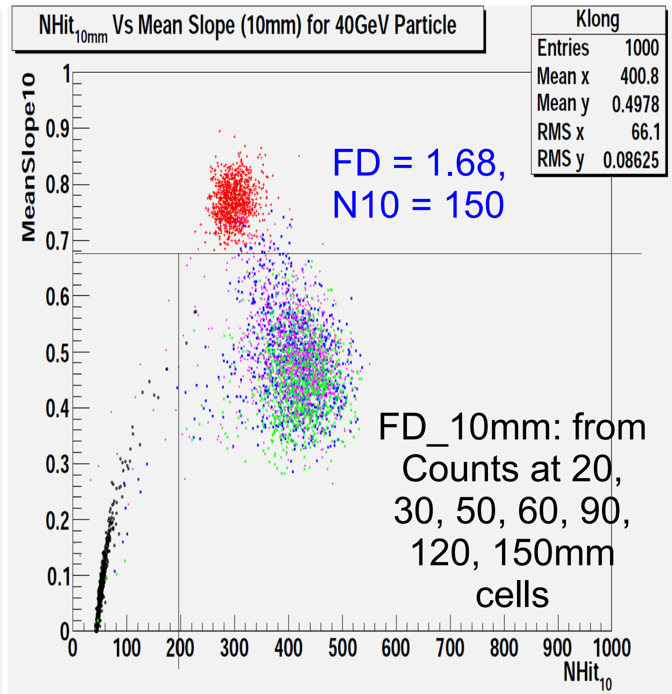
DRUID, RunNum = 0, EventNum = 367

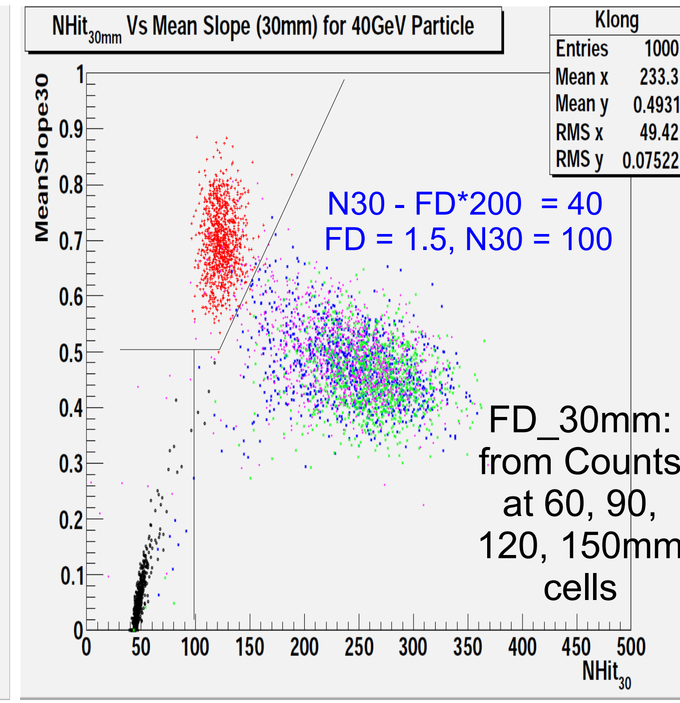


Together with Nhit information: to identify Muon radiation & String noise...

Potential tool for PID







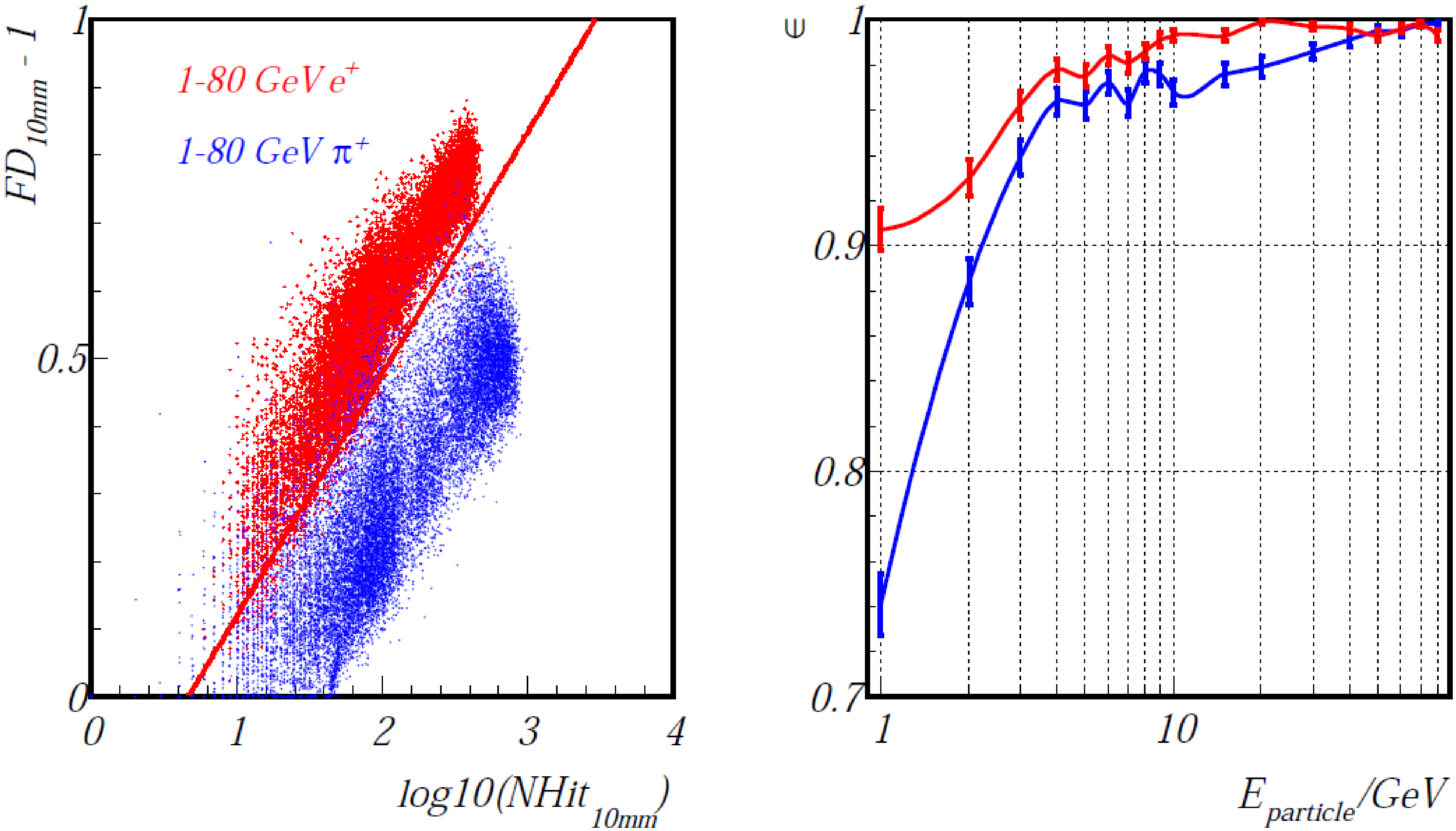
FD together with hit counts: Clear separation at different scales

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

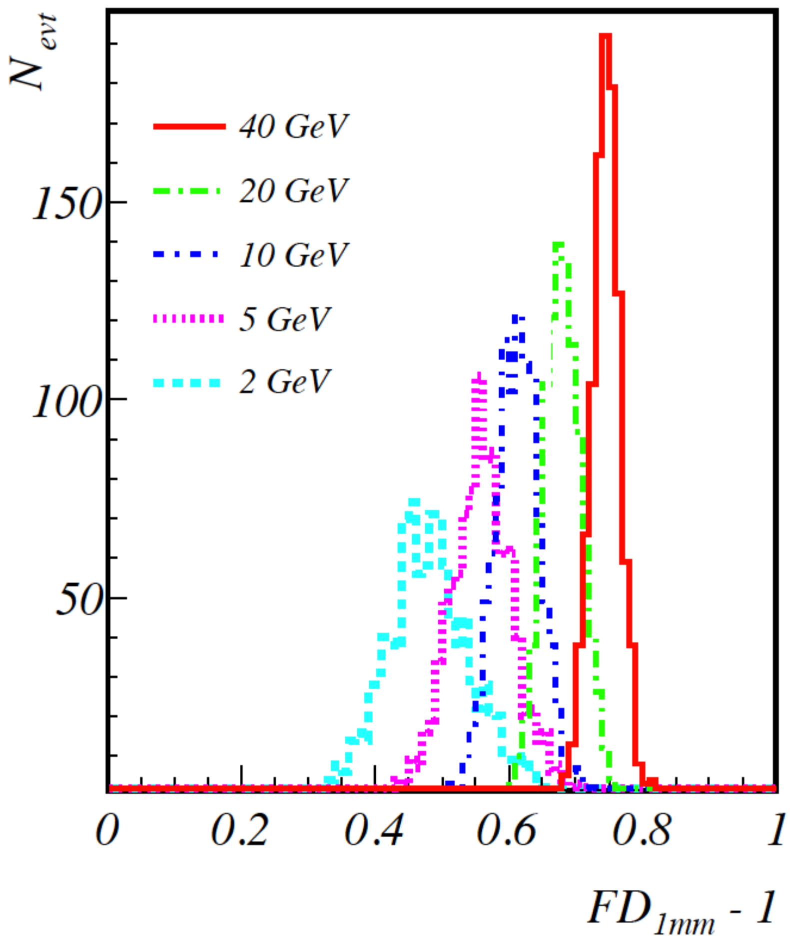
Without knowing energy information

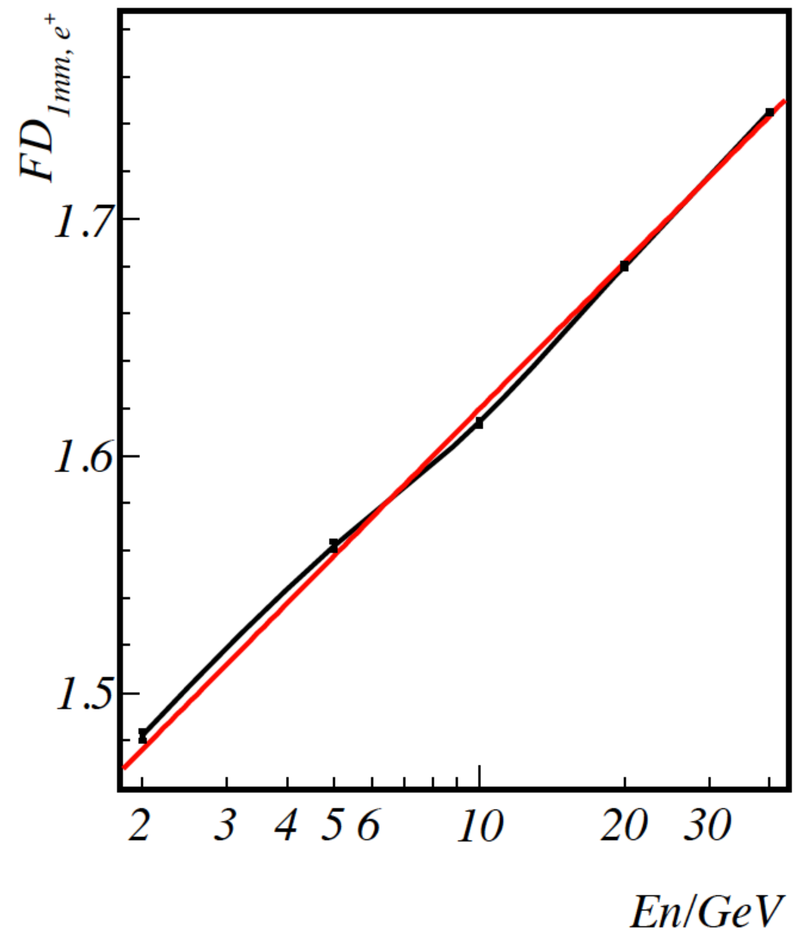


Remark: FD is only the transverse shower information...

Promising PID over full energy range

Logarithmic dependence on particle energy



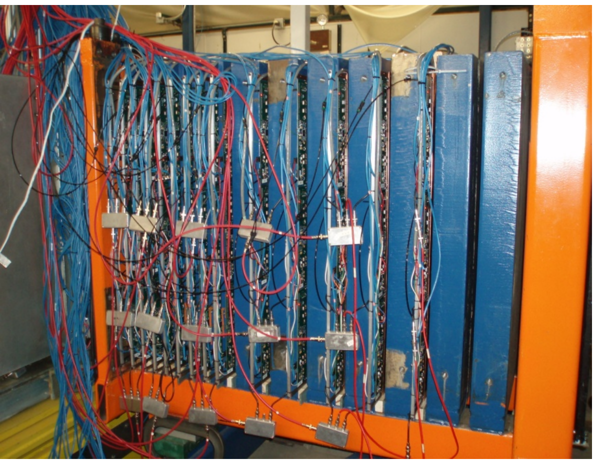


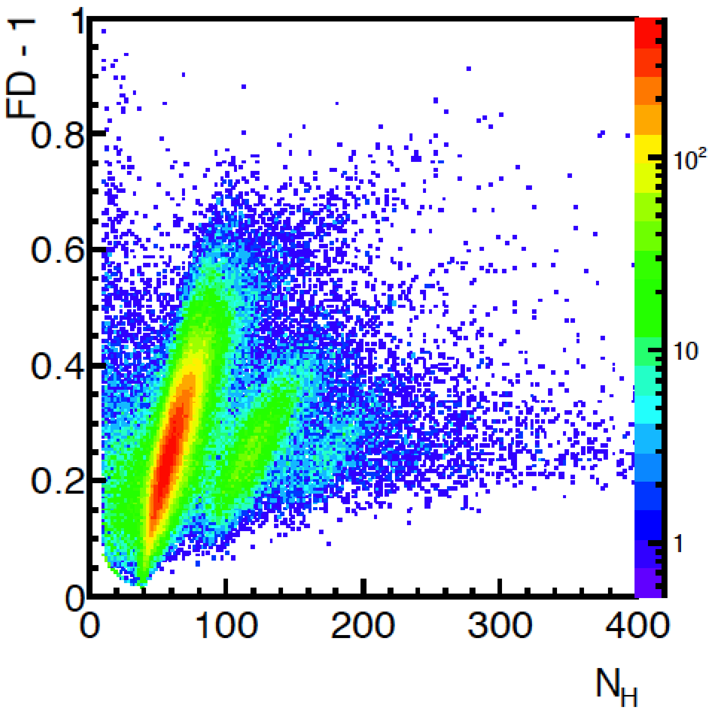
$$FD^{em}_{1\mathrm{mm}}(E) = 1.41 + 0.21 \times \log_{10}(E/\mathrm{GeV})$$

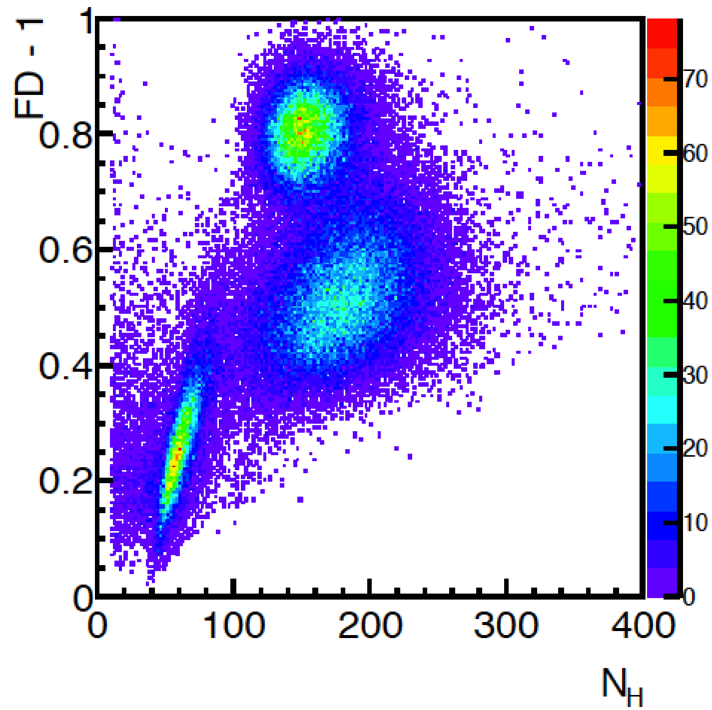
$$FD^{had}_{1\mathrm{mm}}(E) = 1.24 + 0.15 \times \log_{10}(E/\mathrm{GeV})$$

$$FD^{mip}_{1\mathrm{mm}}(E) = 1.2$$

In Real data?

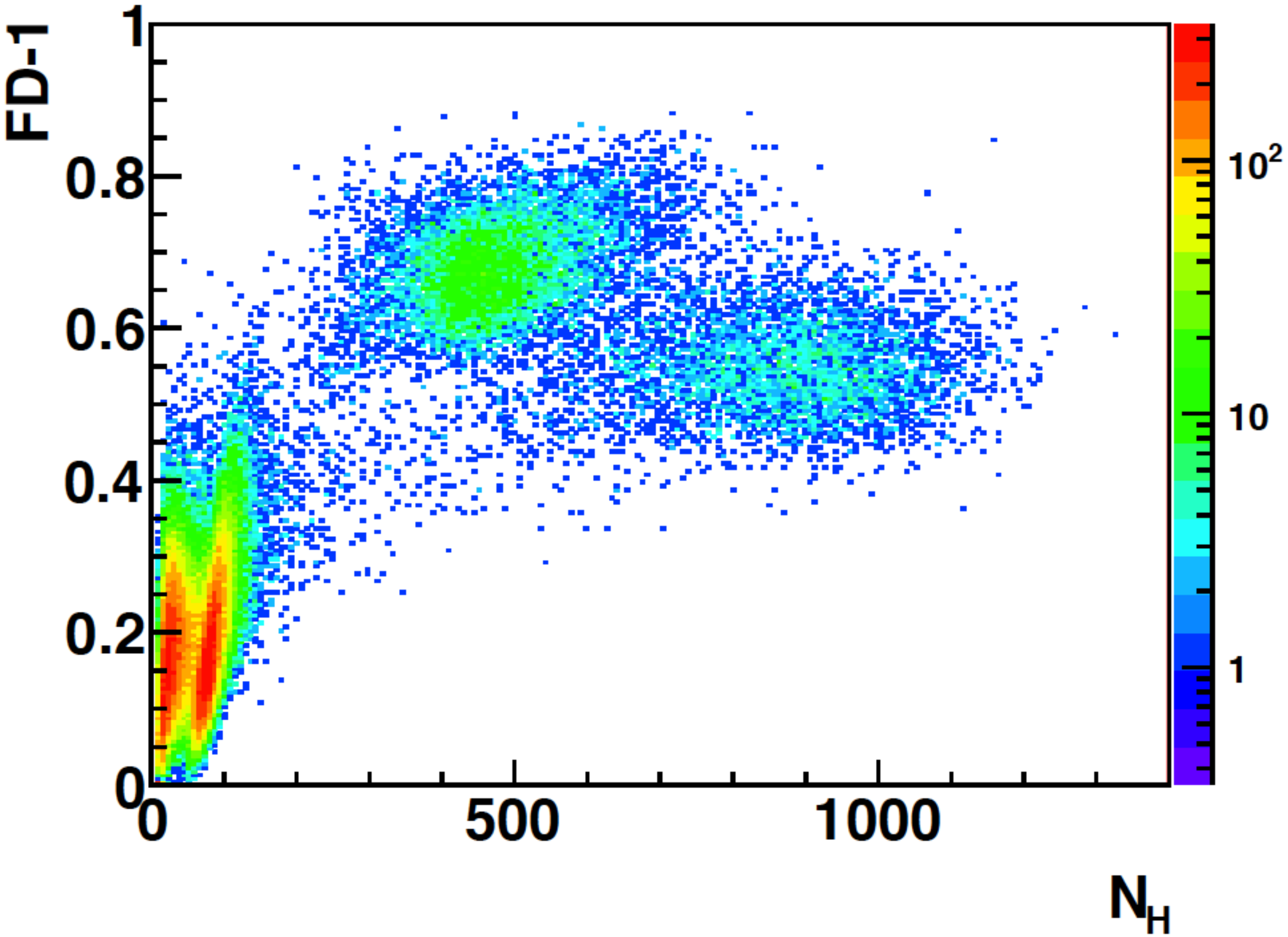


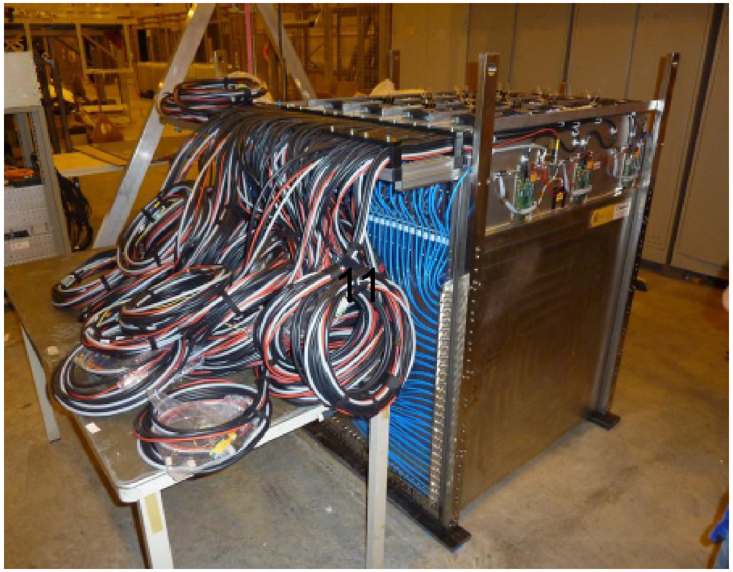




Fermi lab test beam, multiple muon events
Signal triggered by pairs of scintillator tile located in the front/end of the prototype.

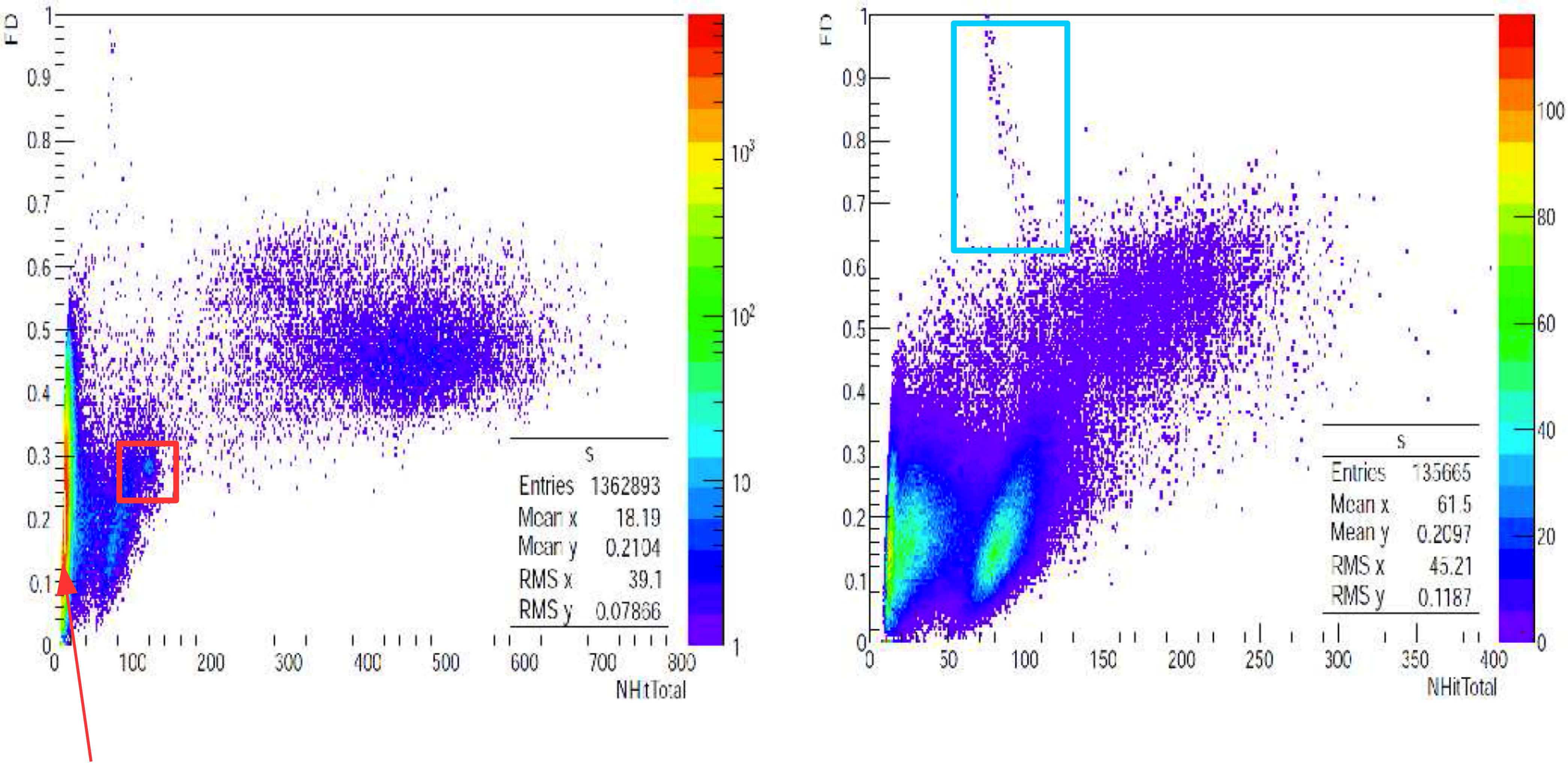
In Real data?





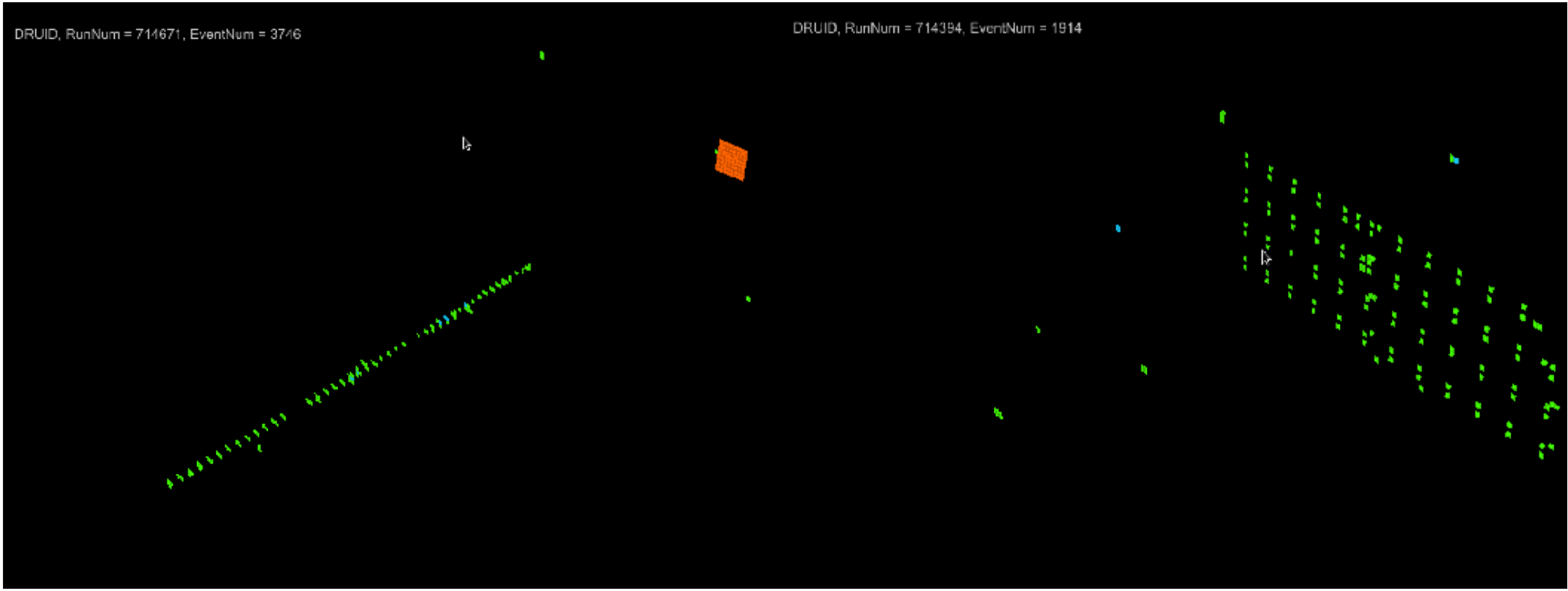
CERN SPS Test beam experimental data
Extremely low noise rate - triggleless mode: Significant cosmic ray component

In Real data?



NOISE PATTERN...

In Real data?


DRUID, RunNum = 714671, EventNum = 3746
DRUID, RunNum = 714394, EventNum = 1914

Source code...

```
int NHScaleV2( LCCollection *inputHit, std::vector<CalorimeterHit*> clu0, int RatioX, int RatioY, int RatioZ )
{

        int ReScaledNH = 0;
        int NumHit = clu0.size();
        int tmpI = 0;
        int tmpJ = 0;
        int tmpK = 0;
        float tmpEn = 0;
        int NewCellID0 = 0;

        CellIDDecoder<CalorimeterHit> idDecoder(inputHit);      //Input Hits here refer to AllCleanHits collection

        std::map <double, float> testIDtoEnergy;

        for(int i = 0; i < NumHit; i++)
        {
                CalorimeterHit *hit = dynamic_cast<CalorimeterHit*>( clu0[i]);

                tmpI = idDecoder(hit)["I"]/RatioX;
                tmpJ = idDecoder(hit)["J"]/RatioY;
                tmpK = (idDecoder(hit)["K-1"]+1)/RatioZ;
                tmpEn = hit->getEnergy();

                NewCellID0 = (tmpK<<24) + (tmpJ<<12) + tmpI;

                if(testIDtoEnergy.find(NewCellID0) == testIDtoEnergy.end() )
                {
                        testIDtoEnergy[NewCellID0] = tmpEn;
                }
                else
                {
                        testIDtoEnergy[NewCellID0] += tmpEn;
                }
        }

        ReScaledNH = testIDtoEnergy.size();

        return ReScaledNH;
}
```

/afs/ihep.ac.cn/users/m/manqi/Analysis/Arbor/ArborF1/src/ArborTool.cc

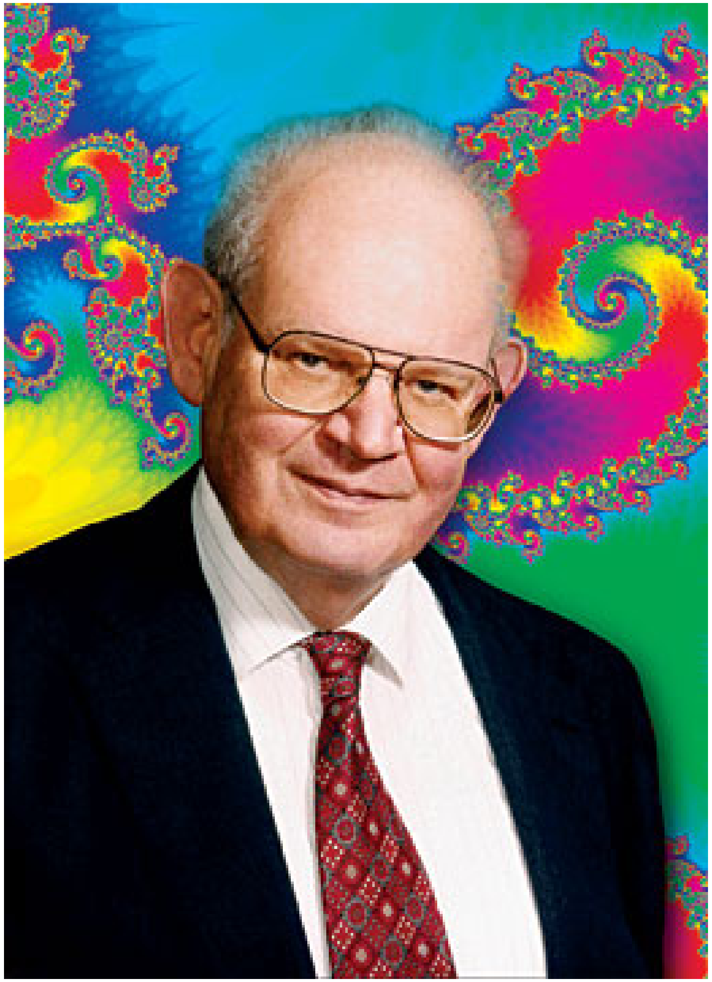
Source code...

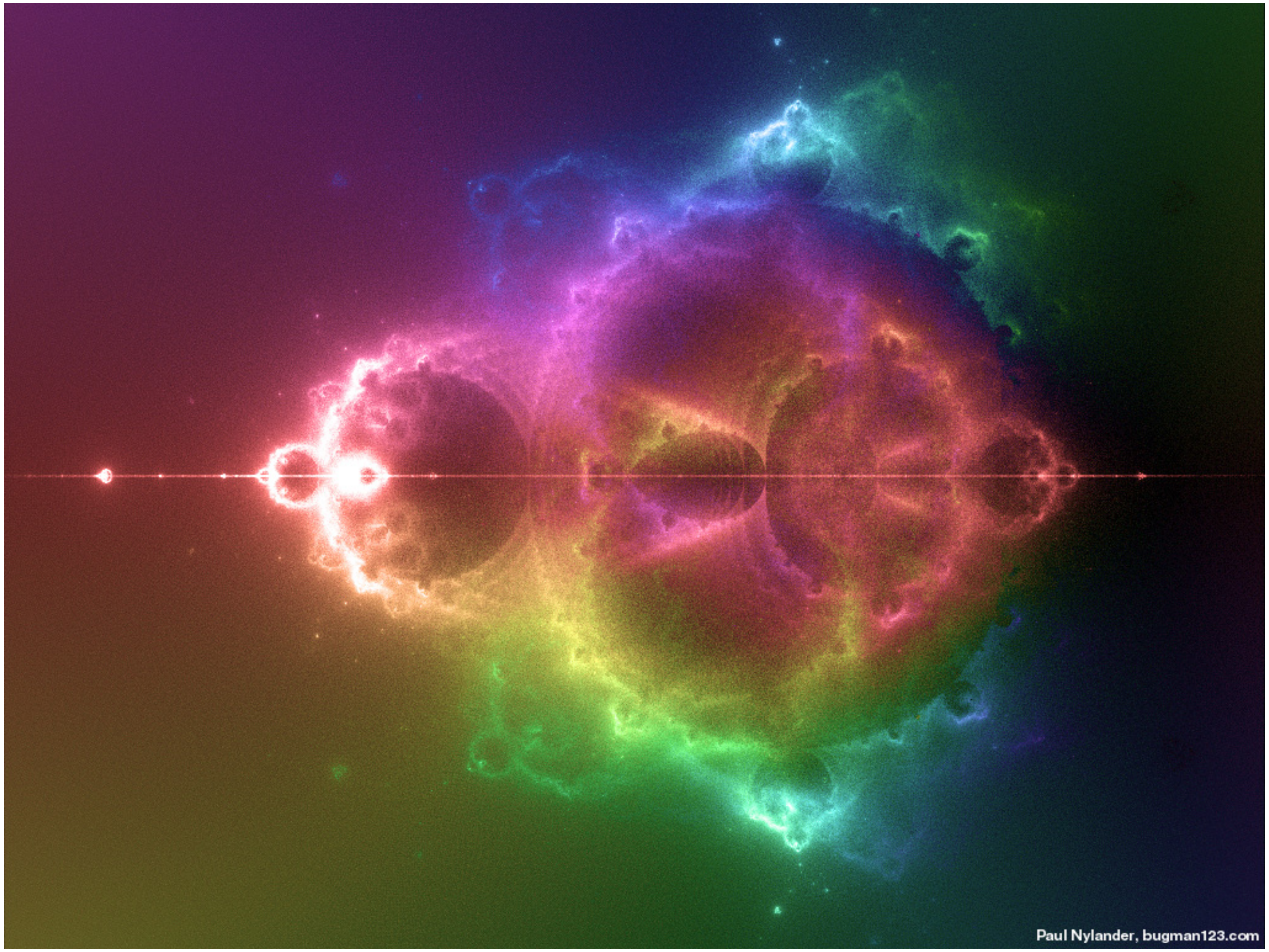
```
float FDV2( std::vector<CalorimeterHit*> clu, LCCollection *HitCollection )
{
        float FractalDim = 0;
        int NReSizeHit[10] = {0, 0, 0, 0, 0, 0, 0, 0, 0, 0};
        int Scale[10] = {2, 3, 4, 5, 6, 7, 8, 9, 10, 20};
        int OriNHit = clu.size();

        for(int j = 0; j < 10; j++)
        {
                NReSizeHit[j] = NHScaleV2(HitCollection, clu, Scale[j], Scale[j], 1);
                FractalDim += 0.1 * TMath::Log(float(OriNHit)/NReSizeHit[j])/TMath::Log(float(Scale[j]));
        }

        return FractalDim;
}
```

Summary

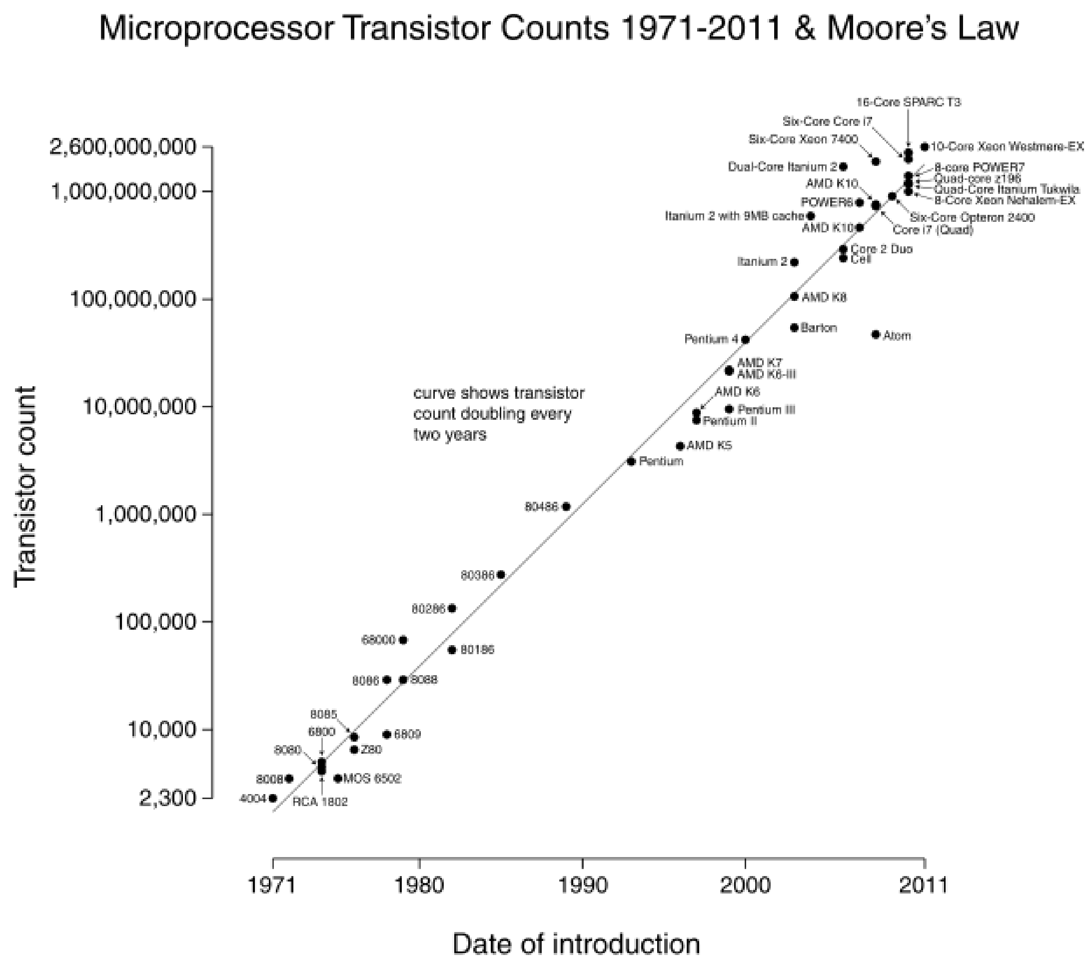
- Impaction of Moore's law: boosted granularity in future calorimeter

- Huge potential for reconstruction at high granularity
  - Shower Fractal Dimension: Highly dependent on Particle type & energy
    - Promising tool for PID
    - Investigating into sub-shower structure
    - Potentially be used for energy measurement
    - Group pattern tagging – Noise tagging
  - Dream algorithms...

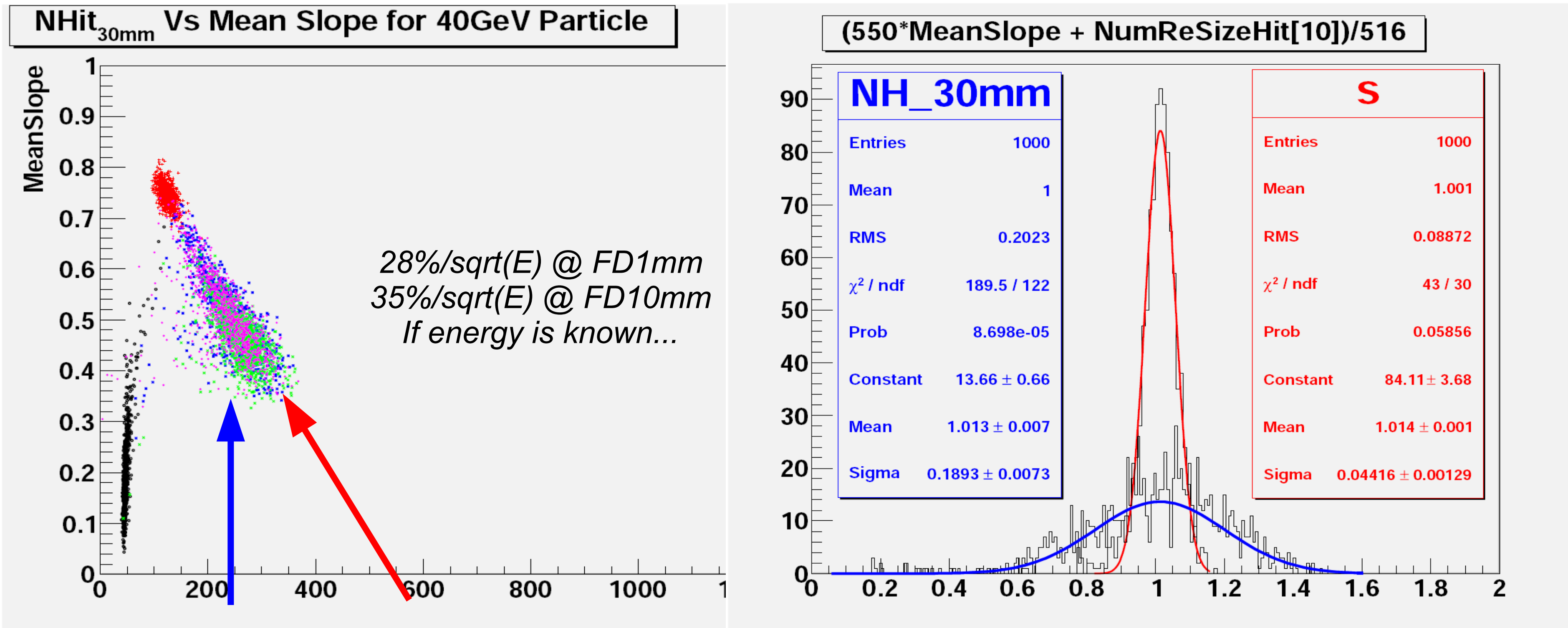




Special Thanks to ...


Microprocessor Transistor Counts 1971-2011 & Moore's Law
16-Core SPARC T3
Six-Core Core i7
Six-Core Xeon 7400
10-Core Xeon Westmere-EX
Dual-Core Itanium 2
8-core POWER7
Quad-core z196
Quad-Core Itanium Tukwila
8-Core Xeon Nehalem-EX
AMD K10
POWER6
Itanium 2 with 9MB cache
Six-Core Opteron 2400
AMD K10
Core i7 (Quad)
Core 2 Duo
Cell
Itanium 2
AMD K8
Barton
Atom
Pentium 4
AMD K7
AMD K6-III
AMD K6
Pentium III
Pentium II
AMD K5
Pentium
80486
80386
80286
68000
80186
8086
8088
8085
6800
6809
Z80
8080
8008
MOS 6502
4004
RCA 1802
curve shows transistor count doubling every two years
Transistor count
2,600,000,000
1,000,000,000
100,000,000
10,000,000
1,000,000
100,000
10,000
2,300
1971
1980
1990
2000
2011
Date of introduction

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): check matching
- A set of energy independent (LO) estimator: E = a' * NH_x/(1 – FD*b')