DIGMAPS: a standalone tool to study digitization

an overview of a digitizer strategy for CMOS/MAPS sensors

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thanks to A.Geromitsos and J.Baudot

- Motivations for a CMOS sensor digitizer, task list.
- DIGMAPS: presentation of the tool. Example.
- Summary and outlook

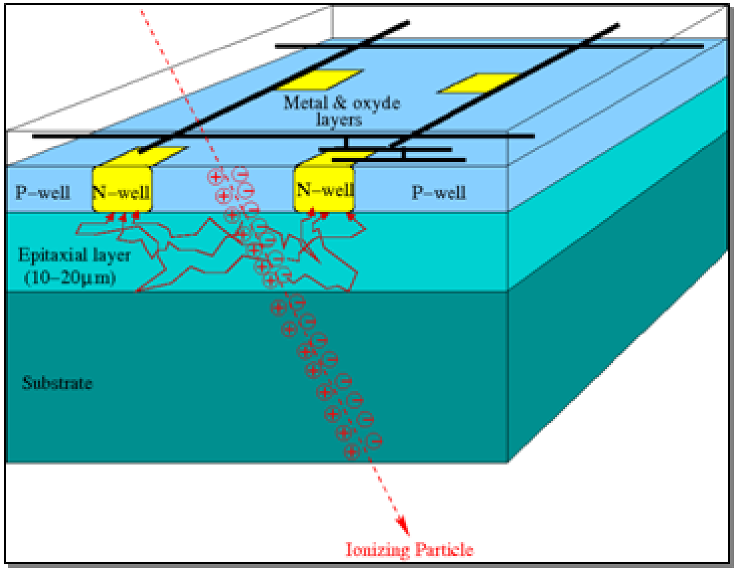
Why a digitizer tool for MAPS ?

- 2 mains motivations
  - Beeing able to foresee the response of a future chips
    - ➢ Help to optimize a design for a given application, e.g.
      N bits of ADCs, Discriminator thresholds, occupancy, hit separation, Pitch, number of layers, zero suppression stage, etc.
  - Test model for simulation
    - ➢ Goal: being able to provide models/algorithms easily transportable in real experiment
      e.g. fast or full simulation for STAR-HFT
    - ➢ Other experiments/projects will/may need also a digitizer
      CBM, AIDA, ILC, ALICE upgrade, superB, etc.

- 1 local long term goal
  - Get a full simulation chain for alignment studies
    - ➢ AIDA project (European project « Advanced Infrastructures for Detectors and Accelerators)
    - ➢ W.P.9.3: Build a telescope + target + vertex detector sector
    - ➢ Geant 4 + digitizer + tracking/alignement/vertexing
- 1 road map
  - Build a data driven model
    - ➢ to take advantage of our knowledge coming from ~30 beam test campaigns
    - ➢ Because a pure realistic analytical model is difficult to build

What do we want to simulate ?

- Step 1: incident particle generation
  - Nature, energy spectrum, incident angle spectrum
    - ➢ Beam test, beamstrahlung spectrum for ILC, etc.
- Step 2: energy deposition ⇨ charge generation
  - Landau law (MPV = 80 e- / um)
- Step 3: charge transport up to the N-well diodes
  - Thermal diffusion ≠ depleted detectors
  - Charge sharing between pixels enhanced
  - Recombination, charge collection efficiency
  - Reflexion at the epi/substrate interface
  - Noise, fake pixels
- Step 4: digital part
  - Discriminator / ADC dynamic range
    - ➢ FPN, temporal noise.
  - Zero suppression stage
- Step 5: clustering algorithms
  - Resolution, hit separation
- Step 6: (not included) tracking, vertexing etc.



- Test Criteria:
  - Realistic performances
    - ➢ Efficiency,
    - ➢ resolution,
    - ➢ fake rate
  - Charge sharing
    - ➢ occupancy (multiplicity)
    - ➢ Hit separation

DIGMAPS: a standalone digitizer tool

- MAPS Digitizer (DIGMAPS)
  - From particle generation
  - To the digitizer
- Library running in root
  - Easy to load
  - Easy to run

```
{
  gROOT->ProcessLine(".L digaction.cxx+");
  gROOT->ProcessLine(".L digadc.cxx+");
  gROOT->ProcessLine(".L digbeam.cxx+");
  gROOT->ProcessLine(".L digplane.cxx+");
  gROOT->ProcessLine(".L digparticle.cxx+");
  gROOT->ProcessLine(".L digreadoutmap.cxx+");
  gROOT->ProcessLine(".L digcluster.cxx+");
  gROOT->ProcessLine(".L digevent.cxx+");
  gROOT->ProcessLine(".L diginitialize.cxx+");
  gROOT->ProcessLine(".L  dighistograms.cxx+");
  gROOT->ProcessLine(".L digmaps.cxx+");
  //   gROOT->ProcessLine(".L digproto.cxx+");

}
```

```
DIGMAPS  myDIGMAPS("name","title", "~/mydircode/","input.txt","~/myoutputdir","output.txt","foresee")
```

  - All output stored in Root format
    - .x Read.C ; .x Plot.C

```
Int_t myconfig = 1;
myDIGMAPS2.PrintConfigurations() ;
myDIGMAPS2.PlotAConfiguration(myconfig,1);
```

- Input data cards to compare any configurations

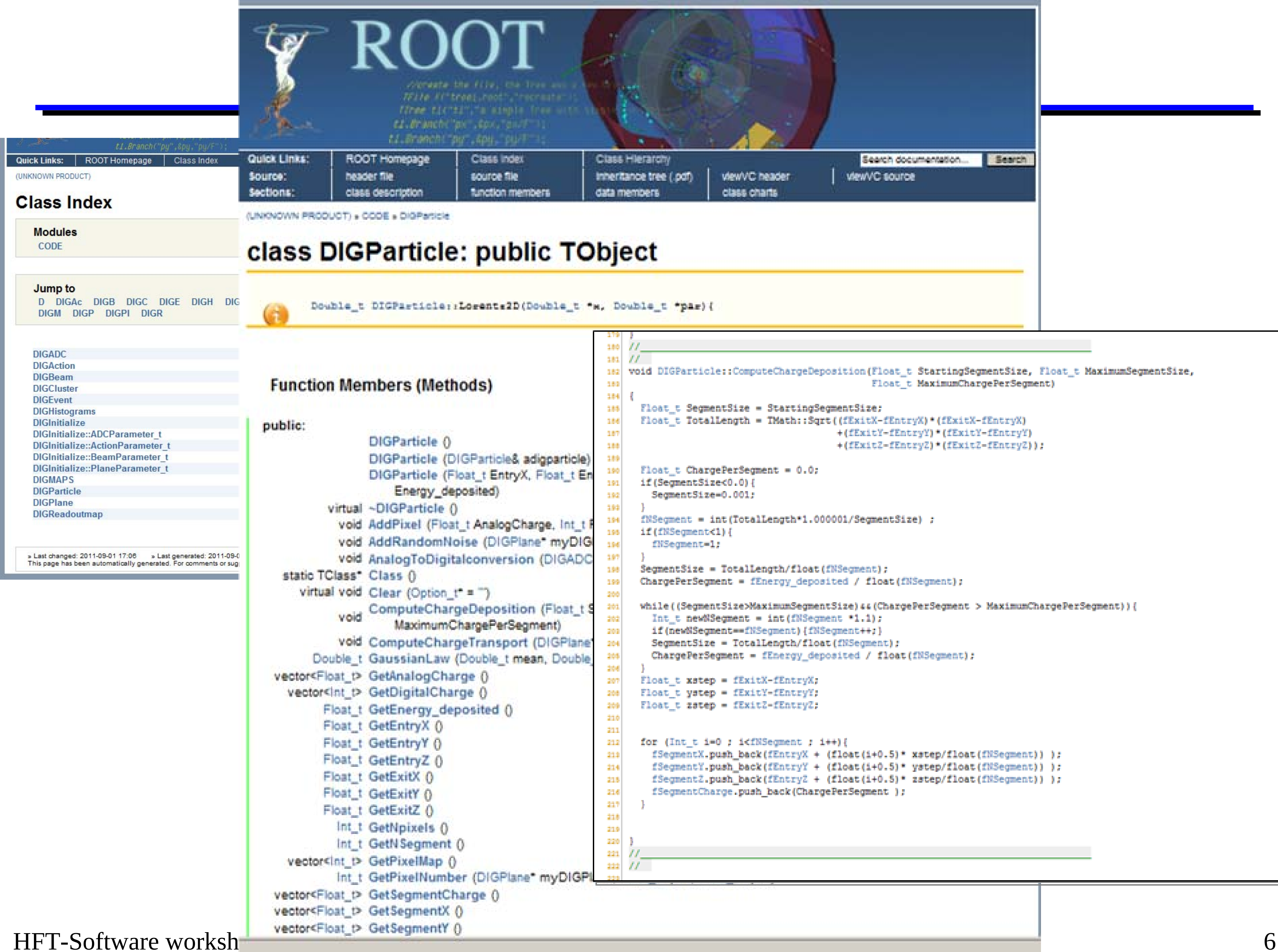
```
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
//
// This is a Configuration File for Silicon Tracking Analysis DIGMAPS Package
//
// created   -> 18/03/2011
// Author = Auguste Besson abesson@in2p3.fr
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
// ------------------- !!!! DO NOT USE Colons in Comments !!! ---
//
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
// Action Parameter
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
// chose the action -> foresee = model result ; train = adjust/fit
//  plot = fill histograms from the tree.
//Doit "foresee"
Model: "basic"

// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
// BEAM Parameter
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
RunNumber: 1000
NumberOfEvents: 10000
// Beam generation option.
//1=realistic beam with random number of particle per event
//2=1 particle per event with a hit in a central pixel
BeamOption: 2
//number of particles per mm^2 on the Plane per event (Lambda fact
ParticleDensity: 5.0
//ParticleDensityWidth 0.5
// incident angle in degrees in cylindrical coordinates (theta and
NAngles: 3
ThetaIncidentDeg 0.0 10.0 20.0
PhiIncidentDeg   0.0  0.0 45.0
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
// PLANE Parameters
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
//-----------GENERAL GEOMETRY
//---pixel pitch in X and Y in microns
NGeom: 4
PitchX:              10.00 20.00 30.00 40.00
PitchY:              10.00 20.00 30.00 40.00
//---Noise in electrons
NoiseElectrons:      10.85  9.20  9.40  9.80
//---epitaxial thickness in microns
EpitaxialThickness: 12.65 10.80  8.69  7.78
//-----------OTHER PARAMETERS
//---number of pixels
NpixelsX: 21
NpixelsY: 21
//---Chip temperature
NTemperature: 1
Temperature: 10
//-----------CHARGE TRANSPORT
//---ionization energy (eV)
IonizationEnergy: 3.6
//---Starting Segment size (in microns)
SegmentSize: 0.1
//---Maximum Segment size (in microns)
MaximumSegmentSize: 1.0
//---Maximum Charge Per Segment (in electrons)
MaximumChargePerSegment: 1.0
//---Diffusion Maximum Range in X and Y (in pitch units)
DiffusionMaximumRangeInX: 2.5
DiffusionMaximumRangeInY: 2.5
//---Reflexion Coefficient on the subtrat-epi border (1.0 means 100%) NOT USED
ReflexionCoefficient: 1.0
```

```
//-----------CHARGE TRANSPORT MODEL
//---basic model
//---sigma of the gaussian width dispersion of charge at 10 microns depth
BasicModel_SigmaTenMicrons: 10.0
//---Chose Model (1=Lorentz2D , 2=Gauss2D)
ChargeModel: 2
//---Lorentz2D model
//---C term of the Lorentz width dispersion
Lorentz2DModel_Cp0: 0.6607
Lorentz2DModel_Cp1: 0.40  //0.400664
Lorentz2DModel_RangeLimit_InPitchUnit: 2.5
//---Gauss2D Model
//sum of 2d gaussian The sigma are lineary dependant to the pitch
Gauss2DModel_sigma1_Cp0: 1.12
Gauss2DModel_sigma1_Cp1: 0.35
Gauss2DModel_sigma2_Cp0: 1.16
Gauss2DModel_sigma2_Cp1: 0.83
Gauss2DModel_weight: 0.34
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
// ADC Parameters
// -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-
// number of different ADC to test
NADC: 3
// ADC parameters
// Nbits = number of bits of the ADC. There will be (2^Nbits - 1) thresholds.
// LSB, Electron_Conversion and ADC_thresholds are in Noise multiple units (e.g. 2.0 = 2.0 t
// There are 2 different ways to set the ADC
// ----------- EITHER --------------
// 1/ ADC_linear = 1 (the response is linear, so setting the LSB and
// the Electron Conversion factor allow to compute all thresholds.
// = thresholds will be = LSB, LSB+1xElectron_conversion, LSB+2xElectron_conversion etc.
// LSB= 1.5 = threshold of the first significant bit
// Electron_Conversion= 1.5
// ADC_thresholds= -
// ----------- OR --------------
// 2/ ADC_linear = 0 (the response is not linear, so enter all the different threshold values
// LSB= -
// Electron_Conversion= -
// ADC_thresholds= 2.0 4.0 5.0 etc.
// ---ADC 1
Nbits: 1
ADC_linear: 0
LSB: -
Electron_Conversion: -
ADC_thresholds: 5.0
// ---ADC 2
Nbits: 12
ADC_linear: 1
LSB: 0.64
Electron_Conversion: 0.64
ADC_thresholds: -
// ---ADC 3
Nbits: 12
ADC_linear: 1
LSB: 0.60
Electron_Conversion:  0.60
ADC_thresholds: -
```

- Many input parameters:
  - Beam (flux, angle)
  - MAPS (pitch, noise, epi. Layer)
  - Charge transport Model
  - ADC/discri threshold
  - Etc.

(under developpment)



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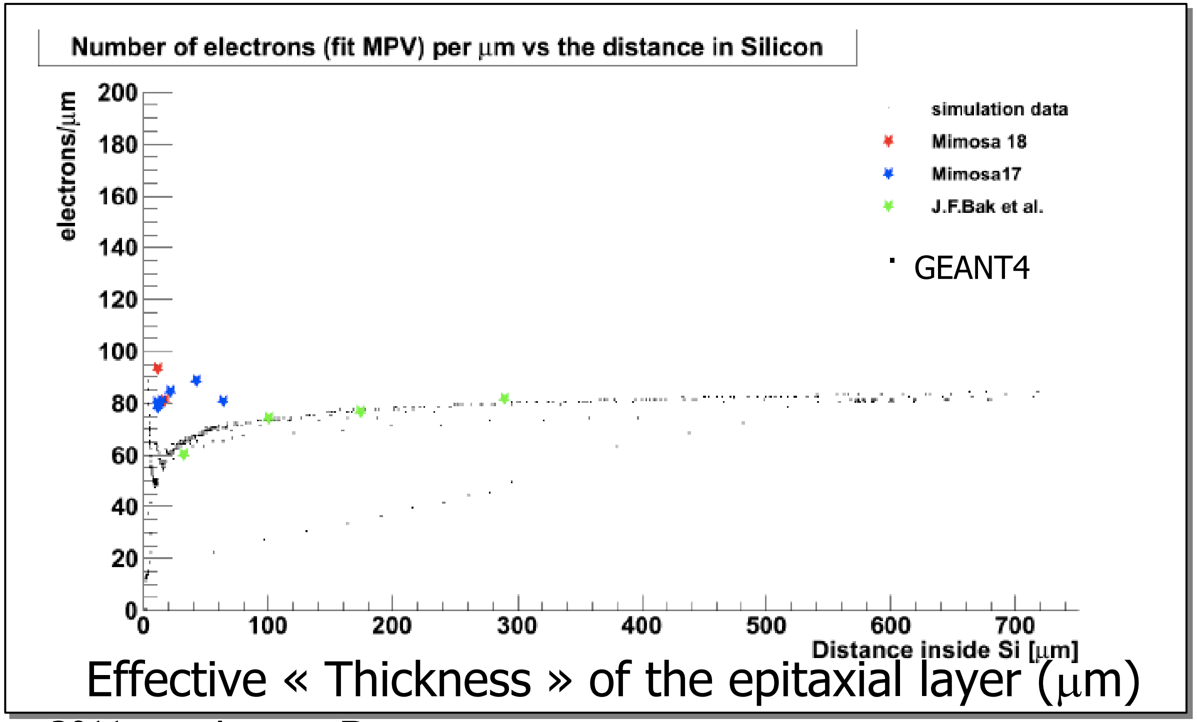
Search
(UNKNOWN PRODUCT) » CODE » DIGParticle
class DIGParticle: public TObject
Double_t DIGParticle::Lorentz2D(Double_t *x, Double_t *par){
Function Members (Methods)
public:
DIGParticle ()
DIGParticle (DIGParticle& adigparticle)
DIGParticle (Float_t EntryX, Float_t En
Energy_deposited)
virtual ~DIGParticle ()
void AddPixel (Float_t AnalogCharge, Int_t P
void AddRandomNoise (DIGPlane* myDIG
void AnalogToDigitalconversion (DIGADC
static TClass* Class ()
virtual void Clear (Option_t* = "")
void ComputeChargeDeposition (Float_t S
MaximumChargePerSegment)
void ComputeChargeTransport (DIGPlane*
Double_t GaussianLaw (Double_t mean, Double_
vector<Float_t> GetAnalogCharge ()
vector<Int_t> GetDigitalCharge ()
Float_t GetEnergy_deposited ()
Float_t GetEntryX ()
Float_t GetEntryY ()
Float_t GetEntryZ ()
Float_t GetExitX ()
Float_t GetExitY ()
Float_t GetExitZ ()
Int_t GetNpixels ()
Int_t GetNSegment ()
vector<Int_t> GetPixelMap ()
Int_t GetPixelNumber (DIGPlane* myDIGPl
vector<Float_t> GetSegmentCharge ()
vector<Float_t> GetSegmentX ()
vector<Float_t> GetSegmentY ()
}
//____
//
void DIGParticle::ComputeChargeDeposition(Float_t StartingSegmentSize, Float_t MaximumSegmentSize,
Float_t MaximumChargePerSegment)
{
Float_t SegmentSize = StartingSegmentSize;
Float_t TotalLength = TMath::Sqrt((fExitX-fEntryX)*(fExitX-fEntryX)
+(fExitY-fEntryY)*(fExitY-fEntryY)
+(fExitZ-fEntryZ)*(fExitZ-fEntryZ));
Float_t ChargePerSegment = 0.0;
if(SegmentSize<0.0){
SegmentSize=0.001;
}
fNSegment = int(TotalLength*1.000001/SegmentSize) ;
if(fNSegment<1){
fNSegment=1;
}
SegmentSize = TotalLength/float(fNSegment);
ChargePerSegment = fEnergy_deposited / float(fNSegment);
while((SegmentSize>MaximumSegmentSize)&&(ChargePerSegment > MaximumChargePerSegment)){
Int_t newNSegment = int(fNSegment *1.1);
if(newNSegment==fNSegment){fNSegment++;}
SegmentSize = TotalLength/float(fNSegment);
ChargePerSegment = fEnergy_deposited / float(fNSegment);
}
Float_t xstep = fExitX-fEntryX;
Float_t ystep = fExitY-fEntryY;
Float_t zstep = fExitZ-fEntryZ;
for (Int_t i=0 ; i<fNSegment ; i++){
fSegmentX.push_back(fEntryX + (float(i+0.5)* xstep/float(fNSegment)));
fSegmentY.push_back(fEntryY + (float(i+0.5)* ystep/float(fNSegment)));
fSegmentZ.push_back(fEntryZ + (float(i+0.5)* zstep/float(fNSegment)));
fSegmentCharge.push_back(ChargePerSegment);
}
}
//____
//

Step 2: Energy deposition

- Potential tricky issues:
  - What about charge created inside the diode ?
    - (increases locally effective epi thickness)
  - Is the Epitaxial layer thickness really known ?
    - Exact doping profile not known in principle
  - Is GEANT4 able to compute energy deposition in very thin material (10-20 um) ?

Energy deposition in thin silicon devices (A.Geromitsos)

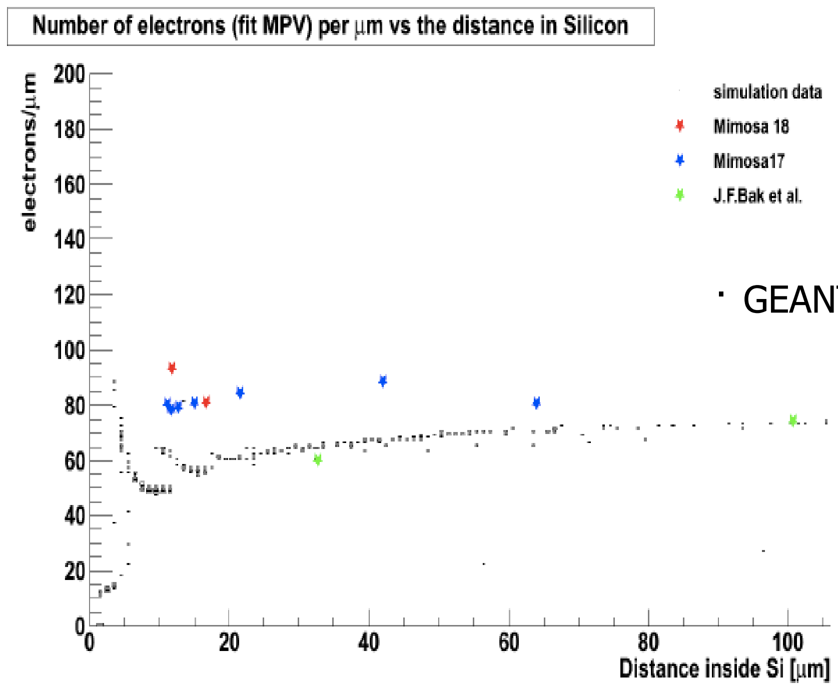
Number of e^- created per μm (MPV value)

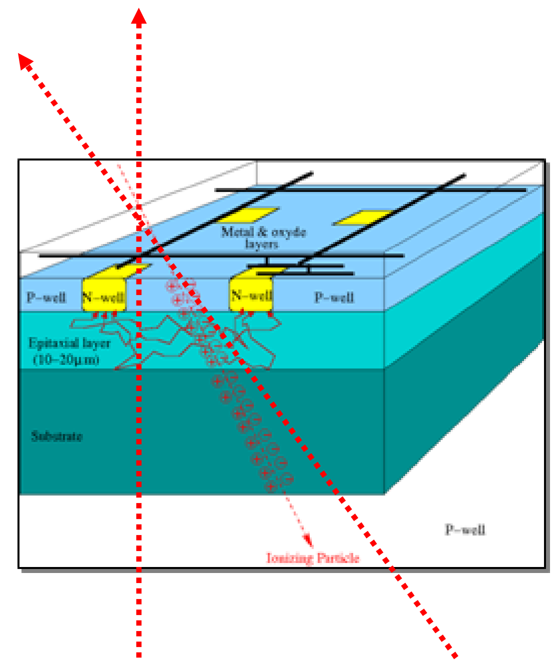


Step 2: Energy deposition in thin silicon devices (A.Geromitsos)

- (large values obtained with large incident angle)
  - GEANT4 underestimate charge creation for thin devices
    - Charge creation taken from test beam data

NOTE: No charge collection efficiency taken into account for M17 and M18

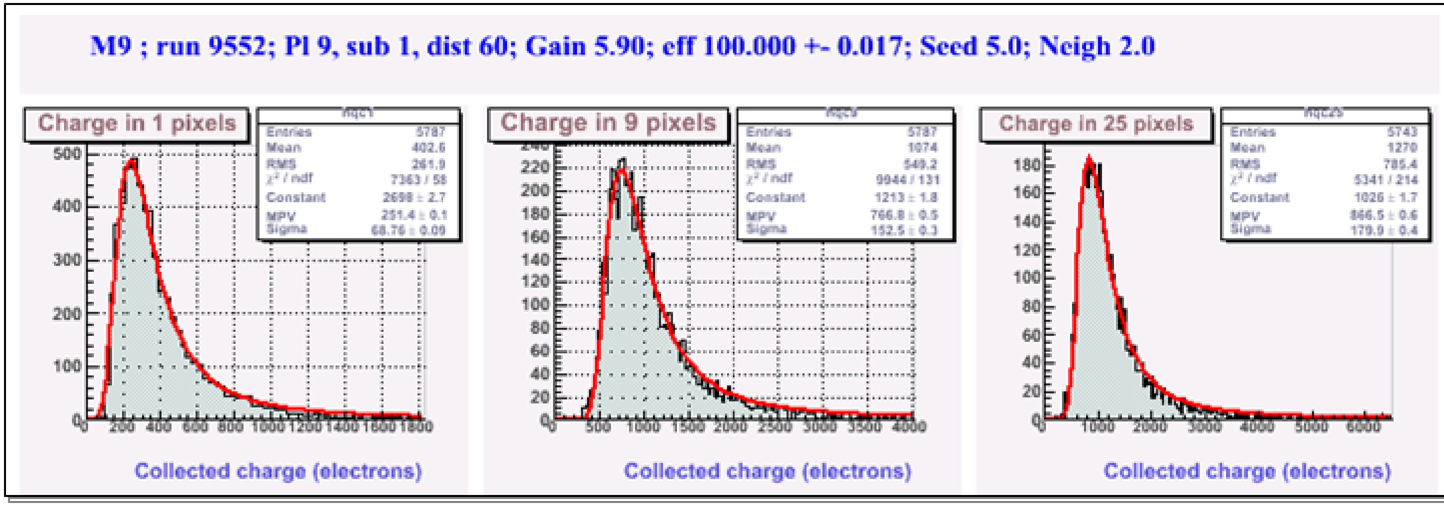


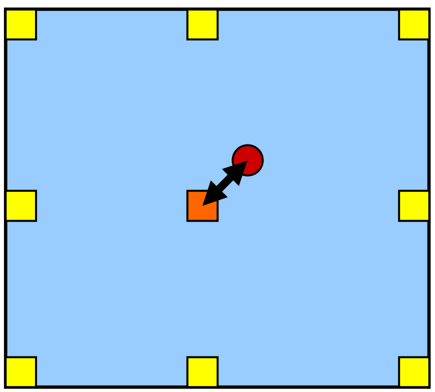


Large incident angle = increased effective thickness of the epi. layer

⇨ Chose a Landau with a MPV=80 e-/µm

Seed impact distance and charge collection



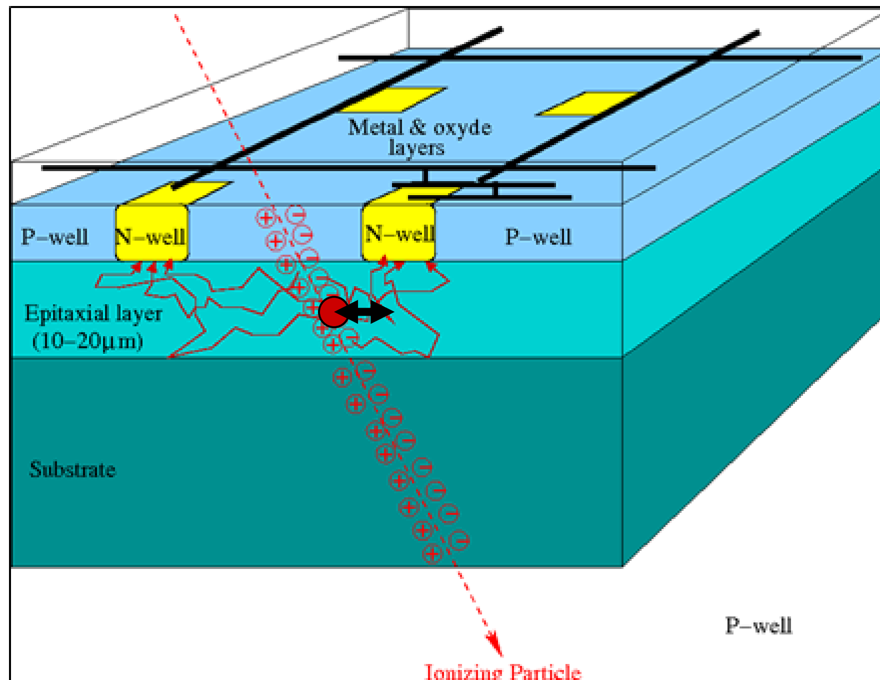


= Collecting diodes

= seed diode

= Impact position

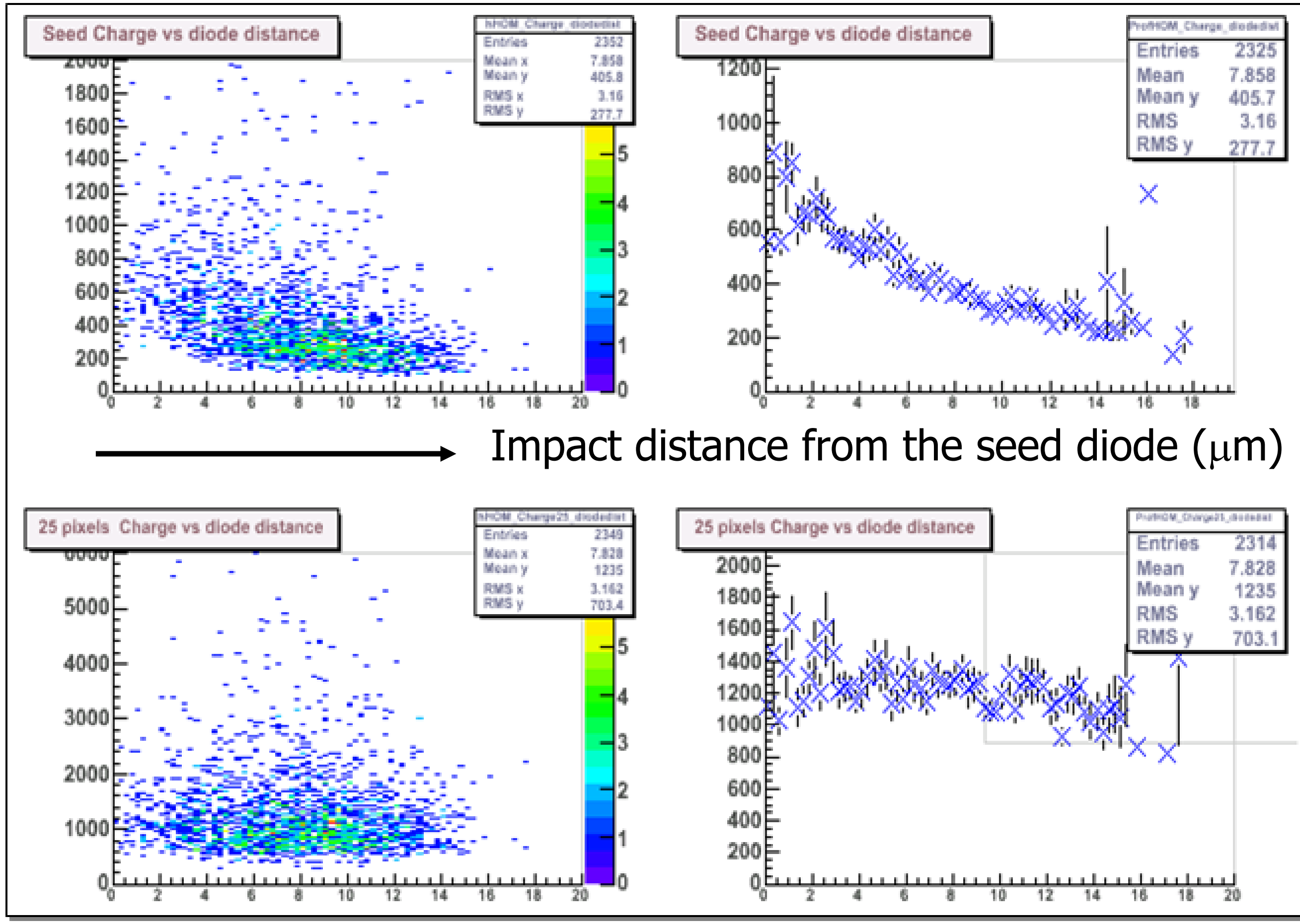
= seed-impact distance



Charge vs seed-impact distance

Collected charge (e-)
In seed pixel

Collected charge (e-)
in the whole
cluster (5x5)



- Charge in seed depends highly on impact position but total charge is « almost » constant
  - Global Charge collection efficiency is constant as a first good approximation
  - We can separate charge creation and charge collection in 2 independent steps.
  - Charge creation can be parametrized with on only one parameter = Effective epitaxial thickness for a given prototype

Step 3: Charge transport and charge collection

- Goal
  - Build a data driven model with a reasonable number of parameters
- Physical parameters:
  - Collecting charge diode (N-Well)
    - pitch
    - Surface
    - Depleted region
  - Doping profile
    - Epitaxial layer thickness
    - Epitaxial layer – Substrate interface
      Perfect reflexion of charge ?
    - Charge Collection Efficiency
      Is it constant ?

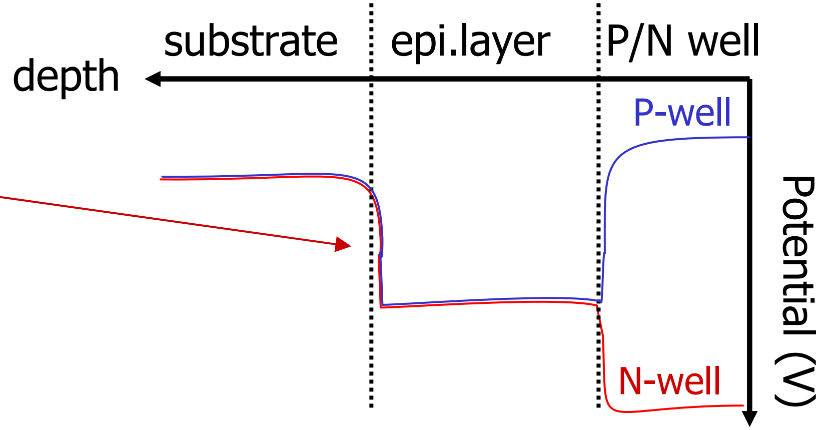
Not always known perfectly
(e.g. doping profile)

- From our data
  - Total collected charge (e^-)
  - Charge distribution between pixels
  - Noise (e^-)
  - Charge collection efficiency (>~90-95%)
    - Effective epitaxial thickness
  - ADC gain and dynamic range

Measurable from
lab and beam test
(easier with analog ouput !)

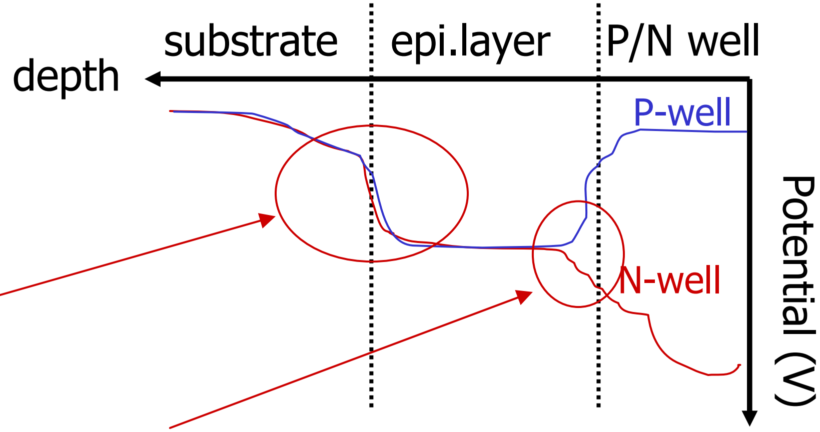
Step 3: Potential profile

- Schematical profile
  - Ideal case



➢ Measure an effective epitaxial layer

For each prototype

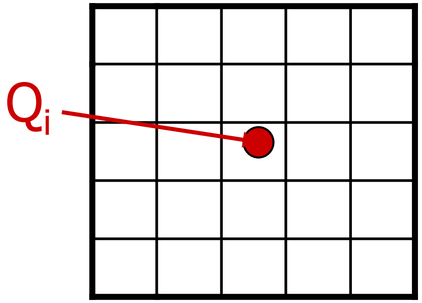


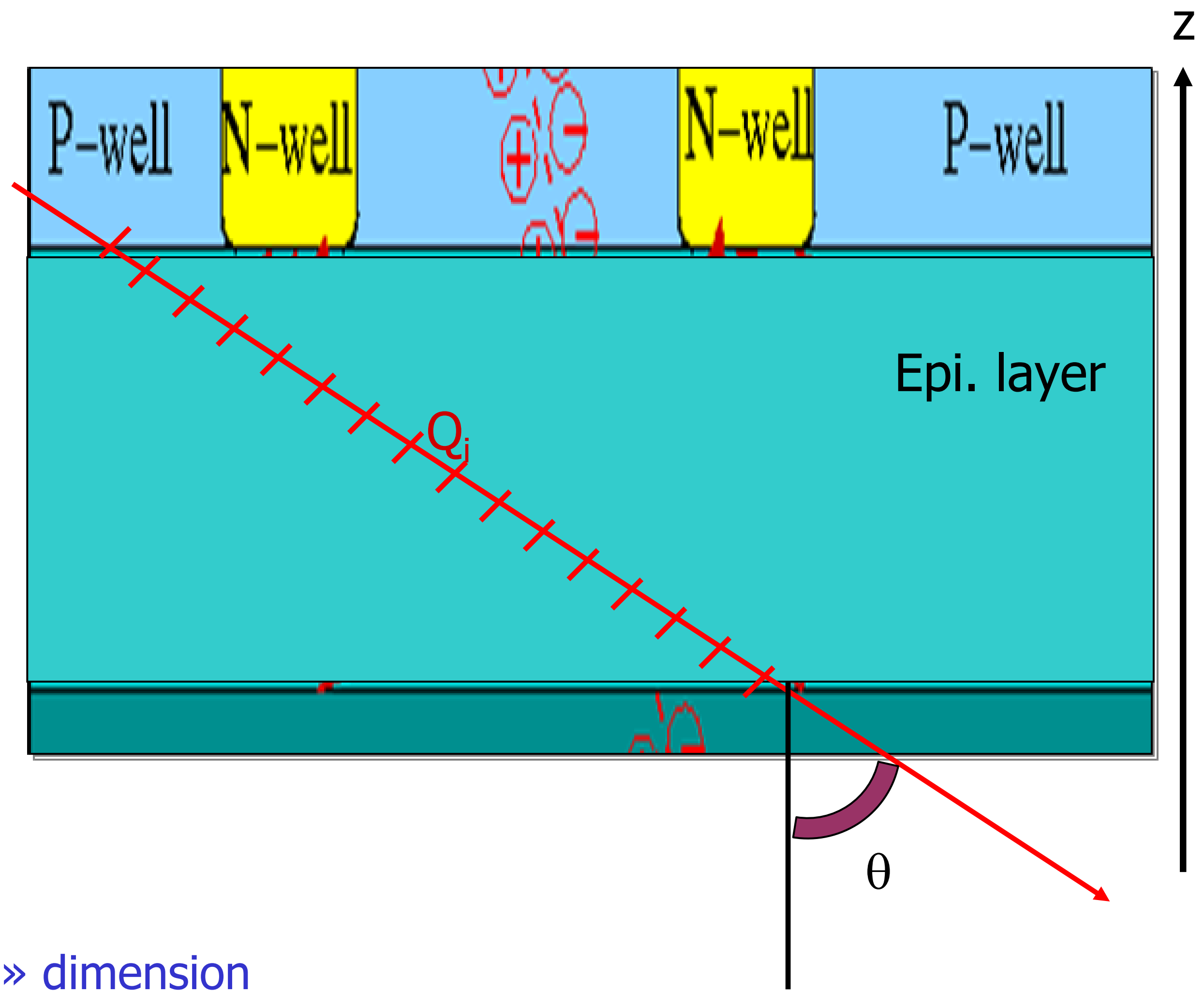
Not so sharped region

depleted region

Step 3: segmentisation

- Divide the track
  - N segments i
  - Q_i = Qtot /N
- Q_i can be as low as 1 e-
  - More CPU
  - More detailed
  - Option assumed in the following slides
- compute 25 probabilities of Charge Qi to reach pixel j(1,25)





- Model independant of « z » dimension
  - But able to deal with tracks having $\theta \neq 0$

Step 3: What we know/observe from our data

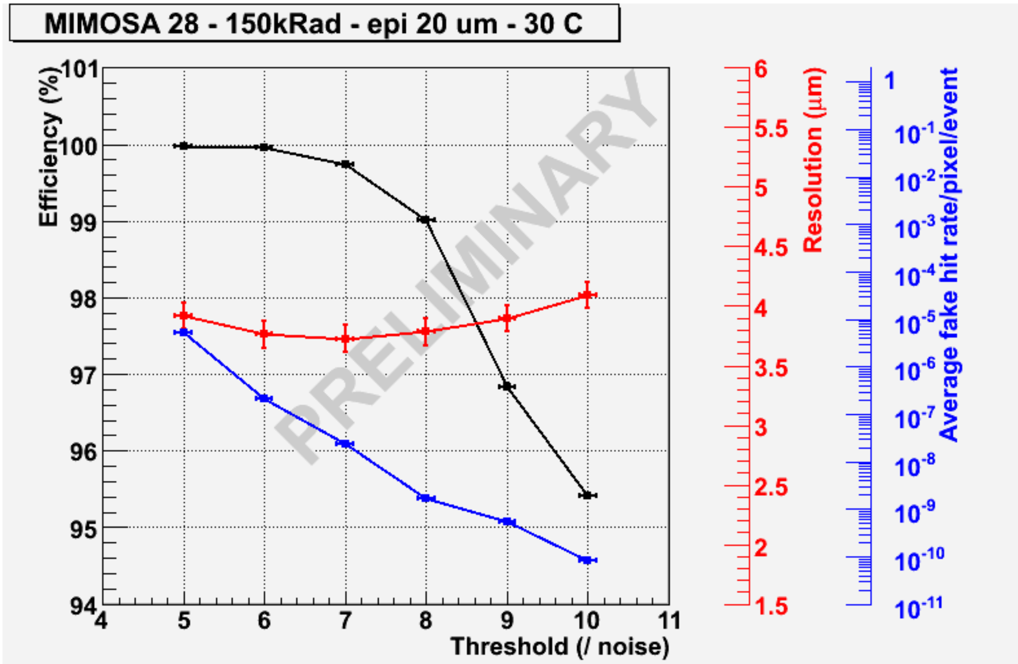
- Results taken from Mimosa 9/18 chips
  - (AMS-opto 0.35, not HR)
  - Analog output (actually 12bits ADC)
  - 10,20,30,40 um pitch
- Informations provided by beam test/lab test
  - Gain (e-/ADC)
  - Charge collection efficiency
  - Effective epitaxial layer thickness
    - ➢ Obtained from cluster total charge
  - Performances
    - ➢ S/N, efficiency, fake rate, resolution, multiplicity, etc.

What about chips with digital output ?

- Ultimate sensor for STAR HFT:
  - No charge recorded but threshold scans are available.
  - Test beam already performed
- Benchmarks
  - Efficiency/fake rate vs discriminator threshold
  - Multiplicity distribution vs discriminator threshold
  - Resolution
- Goal:
  - realistic occupancy, resolution, fake rate, efficiency, double hit separation.
  - Avoid if possible a deterministic response of the digitizer.

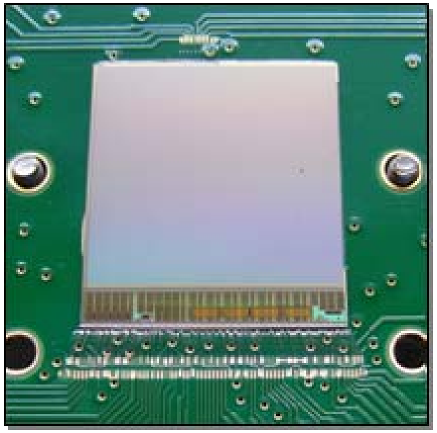
STAR – Ultimate : Performances

- Test Beam @ CERN-SPS (July 2011), 120 GeV pion beam
  - Goal: approach STAR running conditions
    - ➢ T = 30 ^{o}C
    - ➢ Chip irradiated @ 150 kRad
    - ➢ Read-out time = 198 μs
- Results
  - Efficiency ≥~99.9% with a ~<10^{-6} fake rate
  - Spatial resolution ~ 3.7 μm
  - Uniformity checked



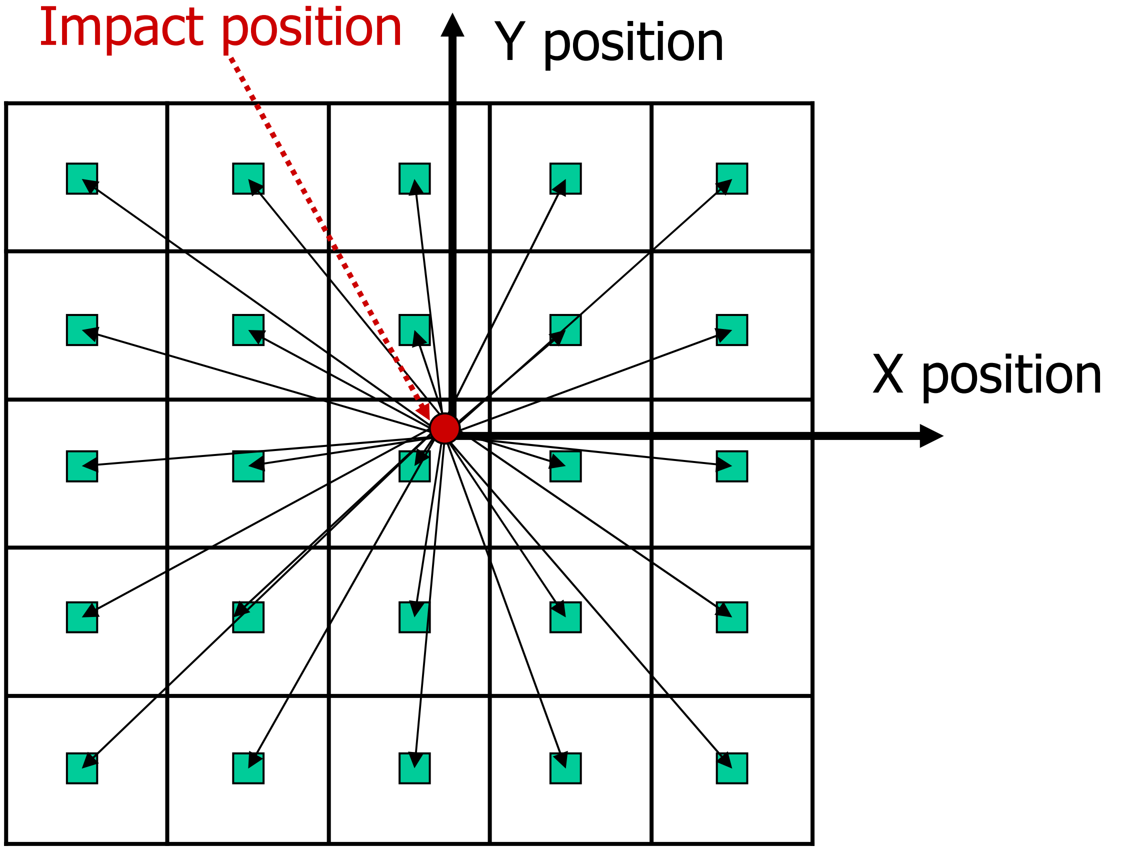
- Under study / to be done
  - Fluence of > $3x10^{12}$ n_{eq}/cm^2 (already tested with previous prototype M26)
  - Large incident angle

Ultimate sensor fulfilling STAR requirements demonstrated



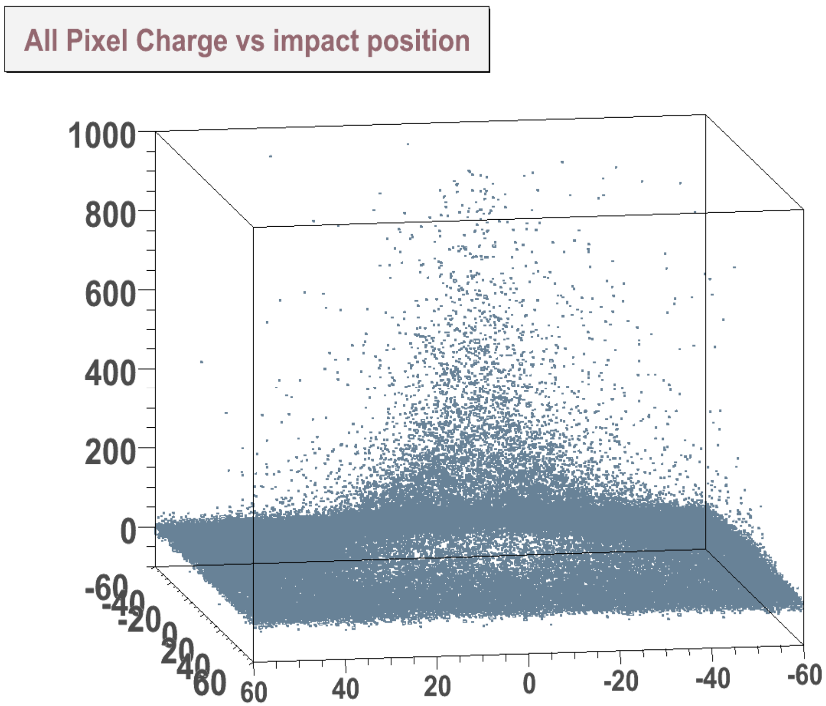
Collected charge vs impact position (analog output case)

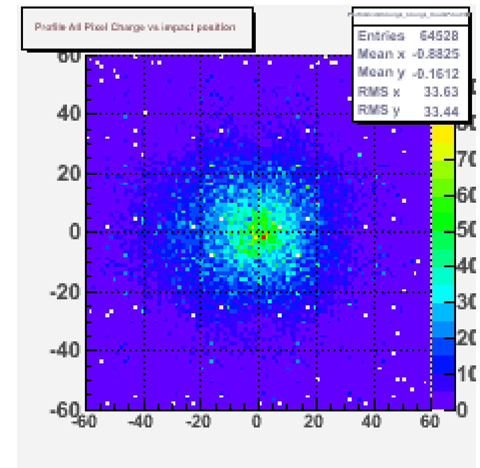
- For each event
  - Impact position from the telescope defines the origin
  - Store 25 x 3D vectors
    - {x(μm), y(μm), Q(e^-)}
- Plot all this vectors in a Single 3D plot
- All the useful information should be contained in this plot
  - Use it as a probability density function

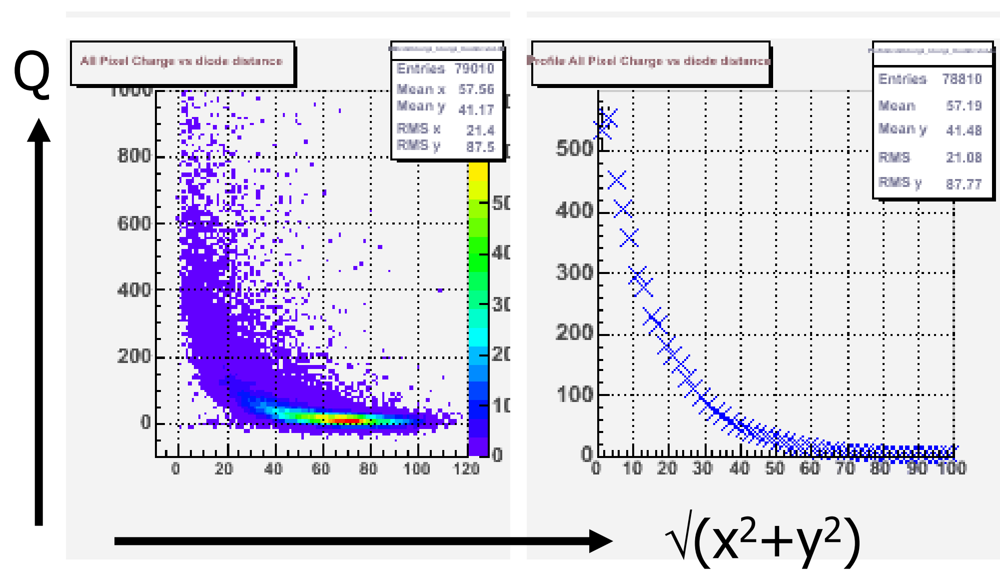


Collected charge vs impact position (2)

- Example (30 um pitch)



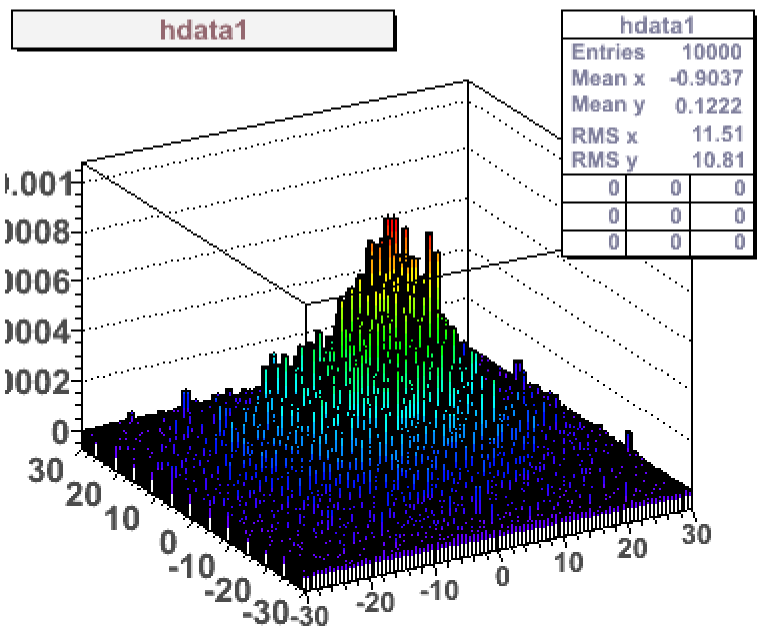


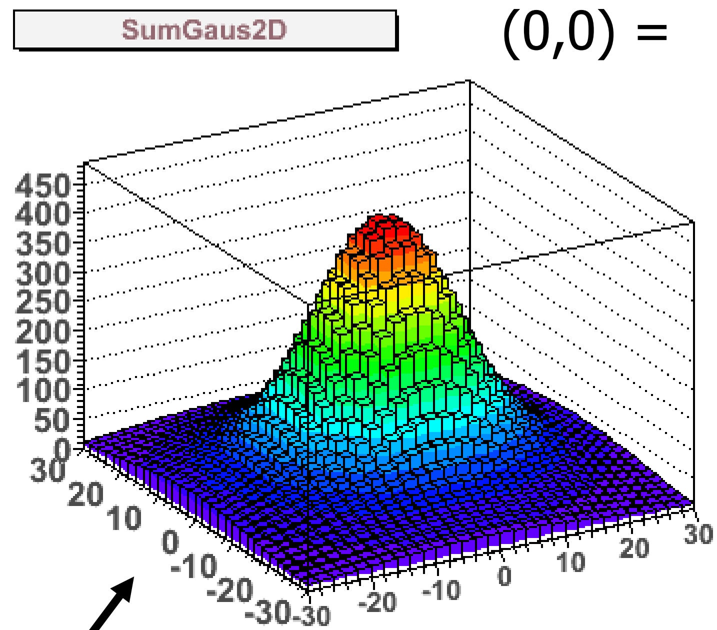


Collected charge vs impact position (4)

- Take the profile of the previous plots and fit it with
  - F(x,y) = sum of 2 x 2Dgaussian

$$\boxed{e^{-\frac{x^2+y^2}{2\sigma_1^2}} + w\times e^{-\frac{x^2+y^2}{2\sigma_2^2}}}$$



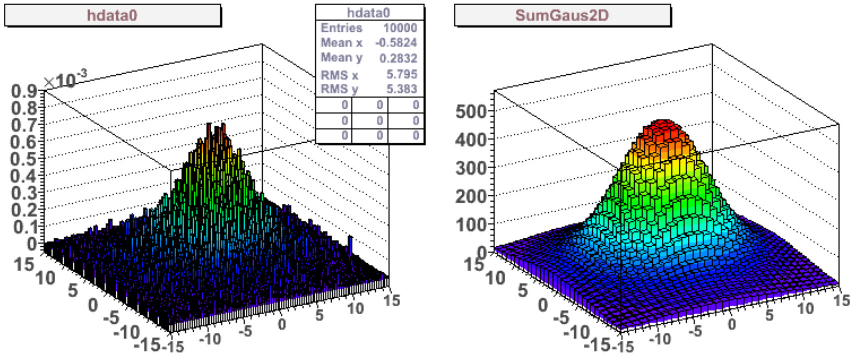


(0,0) =

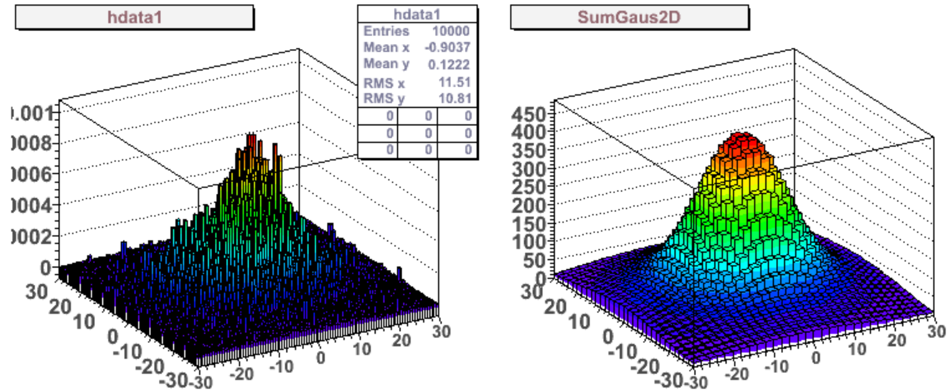
Defines a probabilty density function for charge Q_i to reach pixel j which is at (x,y) w.r.t. the impact

⇨ 25 probabilities

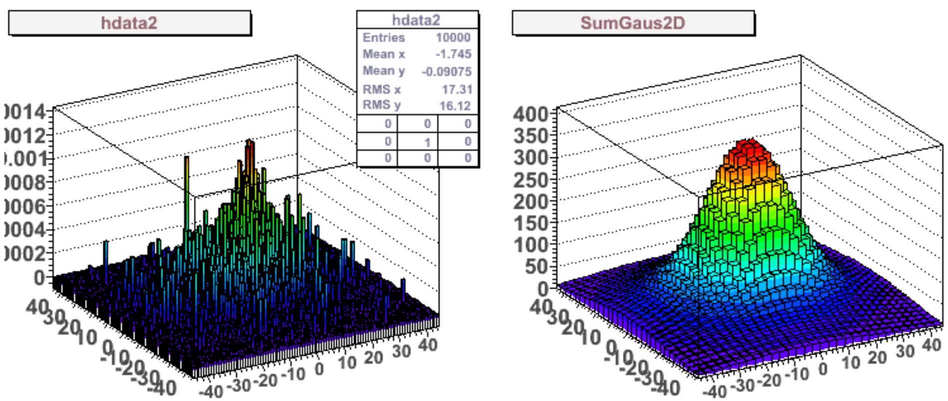
Collected charge vs impact position (3)



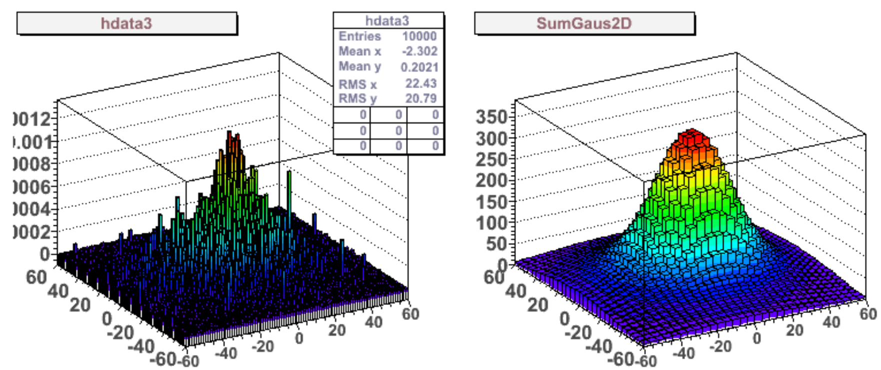
10 μm pitch



20 μm pitch



30 μm pitch

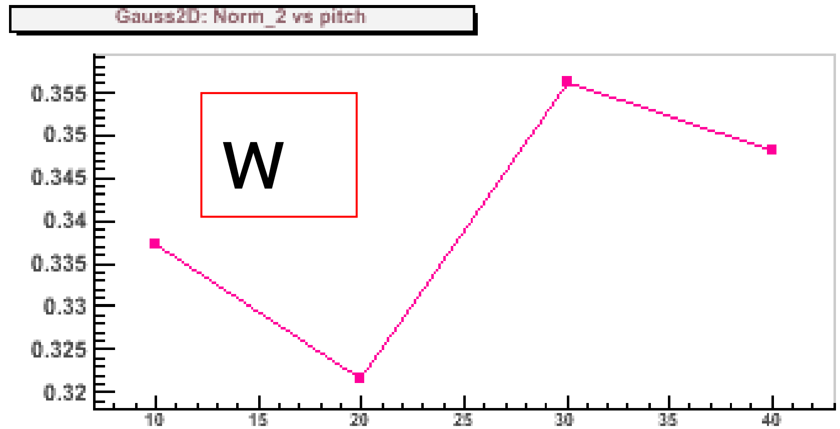


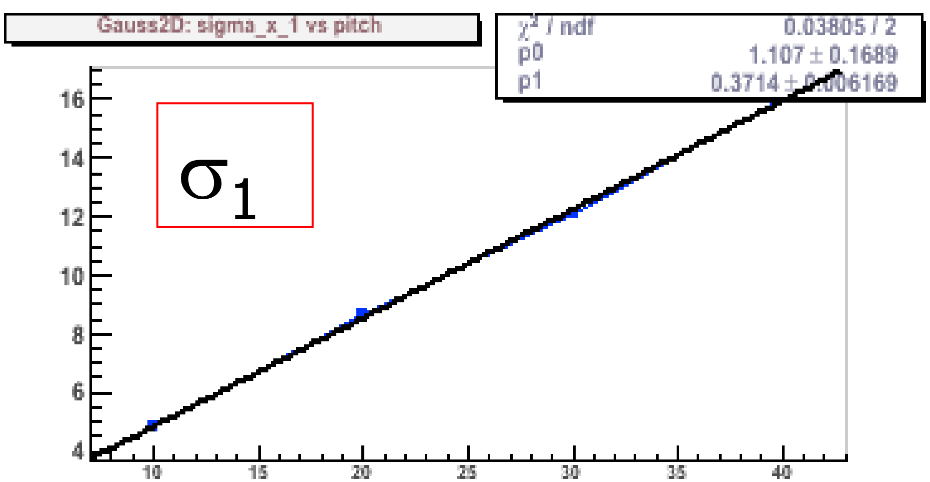
40 μm pitch

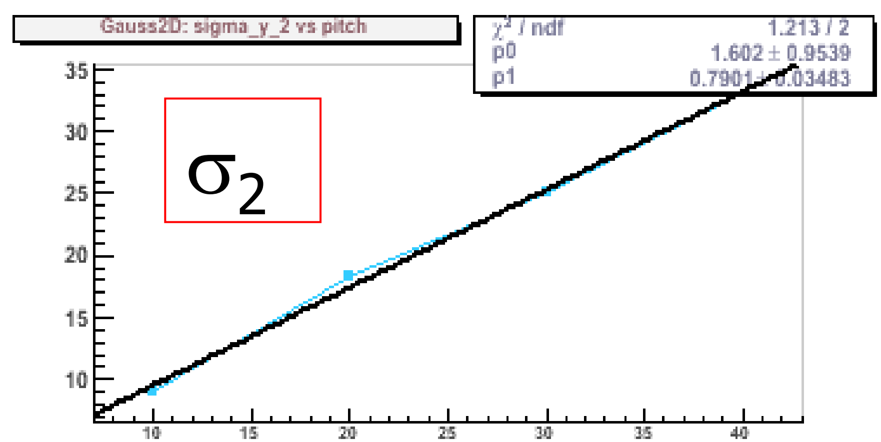
Collected charge vs impact position (5)

- Linearity vs pitch ⇨ 5 parameters for all pitches

$$e^{-\frac{x^2+y^2}{2\sigma_1^2}} + w \times e^{-\frac{x^2+y^2}{2\sigma_2^2}}$$







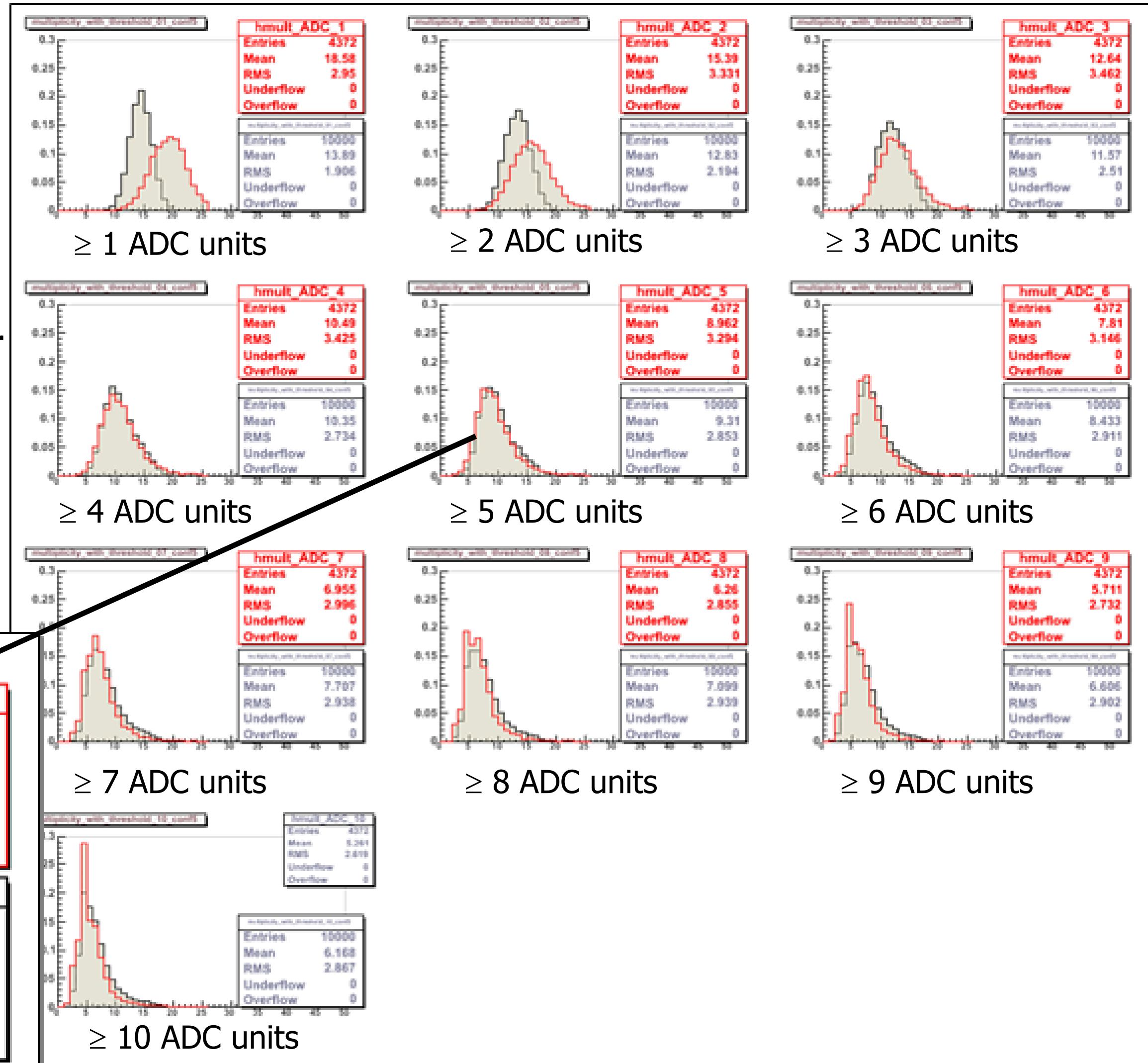
Pitch (μm)

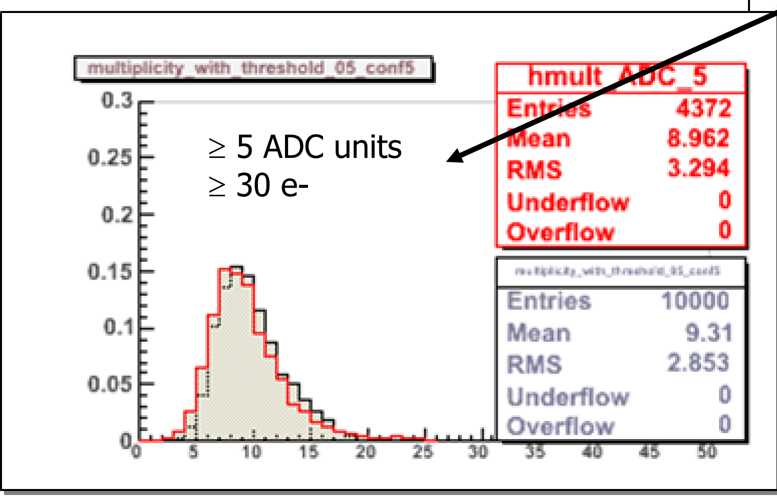
Are results close to real data ?

DIGMAPS: Some preliminary results (20 um pitch)

- Nothing optimized !
  - DIGMAPS model
  - DATA
- Mulitiplicity distribution
  - Number of pixels in cluster
  - For different ADC cuts

1 ADC unit ~ 5.9 e-
(Noise = 9.2 e-)



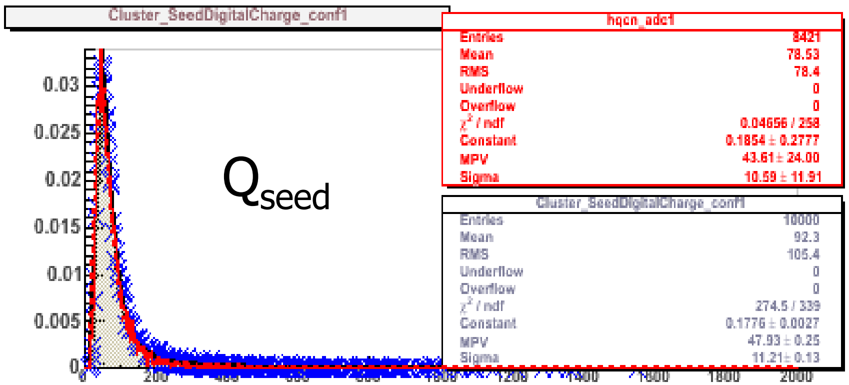


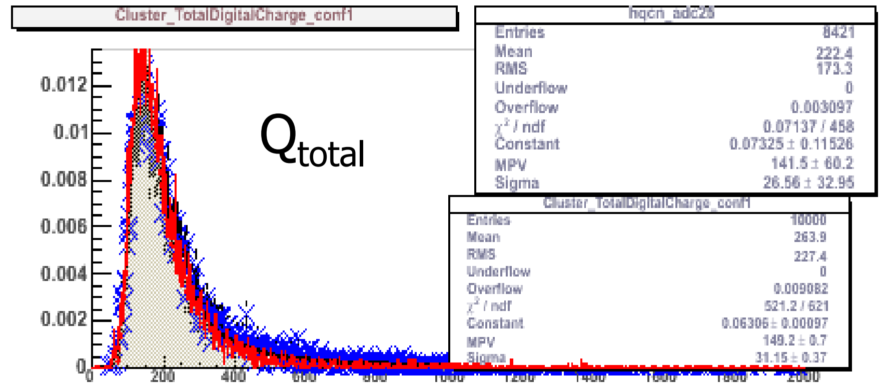
⇨

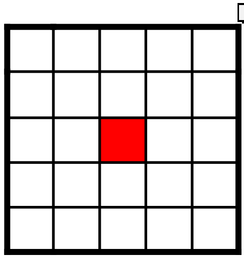
DIGMAPS model

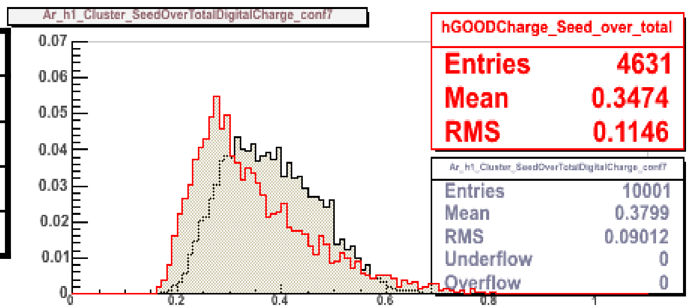
DATA

M18 (10μm pitch)

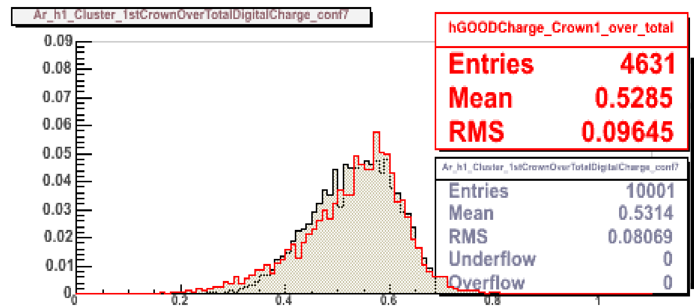




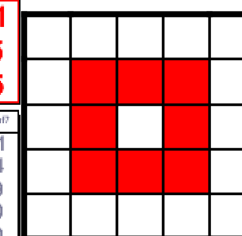


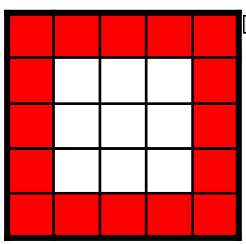


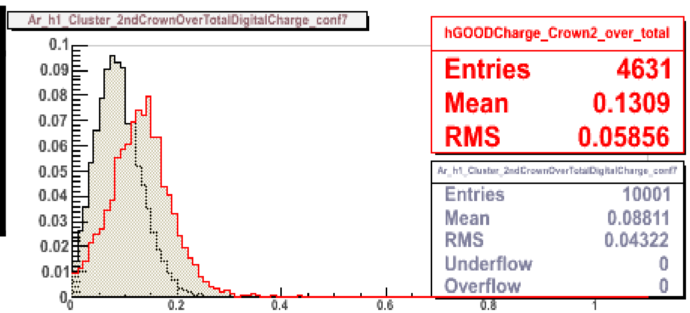
Q_{Seed}/Q_{total}



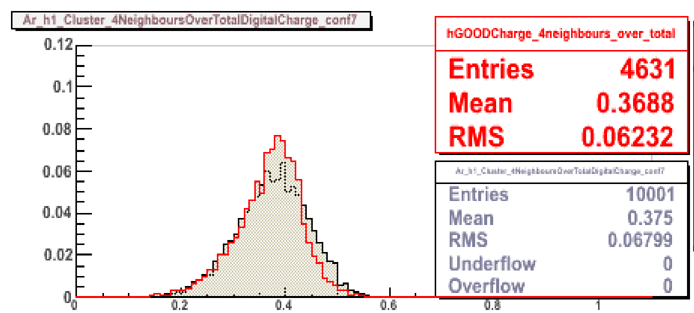
$Q_{1stcrown}/Q_{total}$



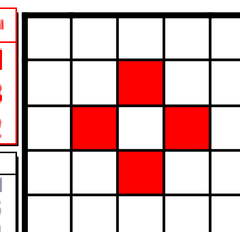




$Q_{2ndcrown}/Q_{total}$

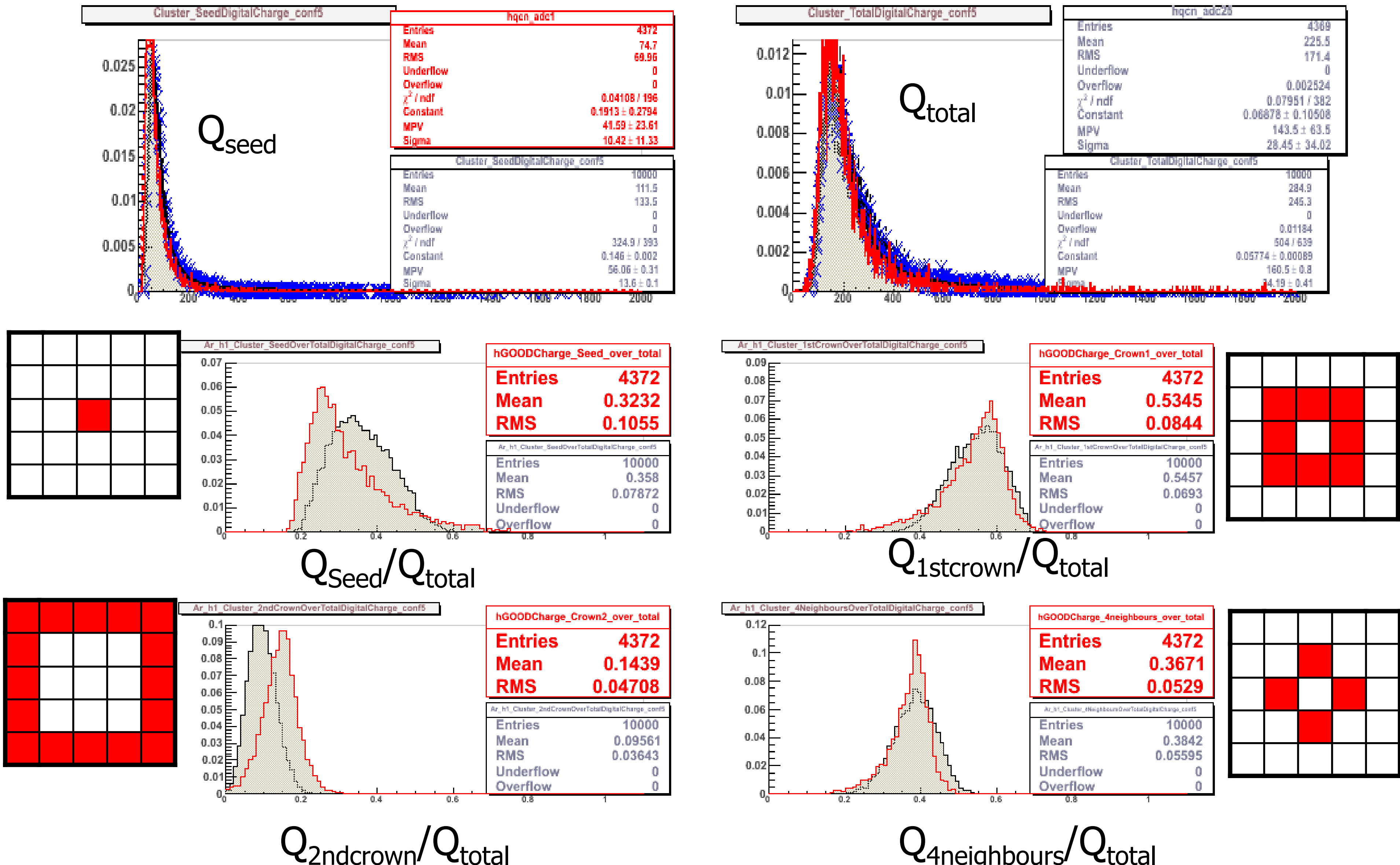


$Q_{4neighbours}/Q_{total}$



DIGMAPS model
DATA

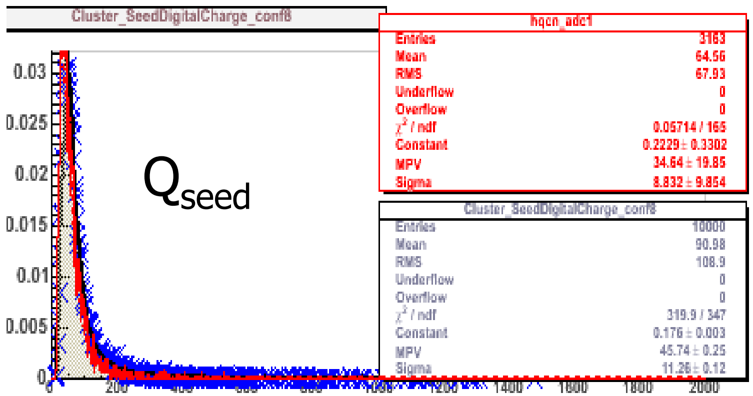
M9 (20μm pitch)

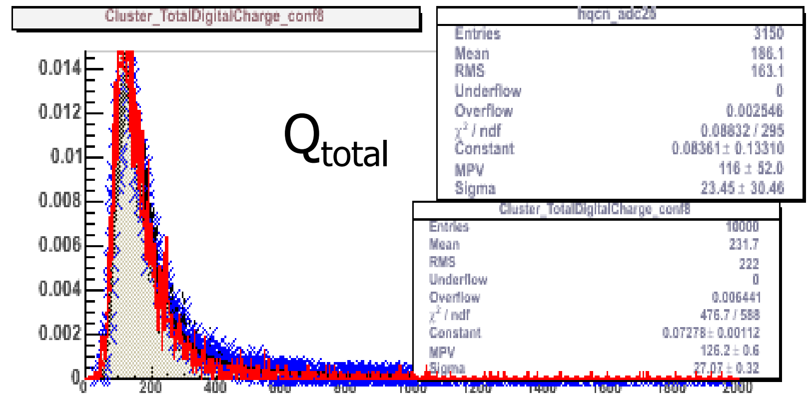


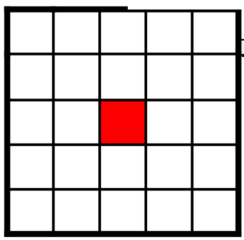
DIGMAPS model

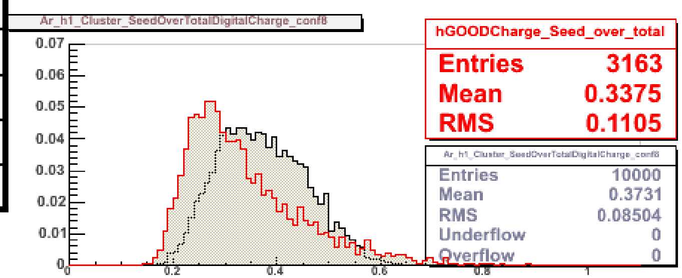
DATA

M9 (30μm pitch)

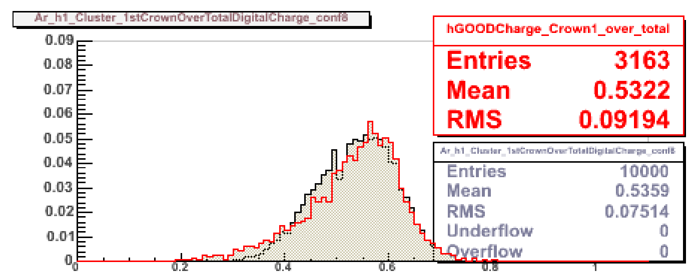


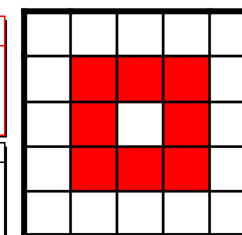




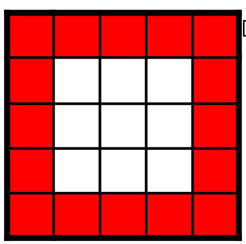


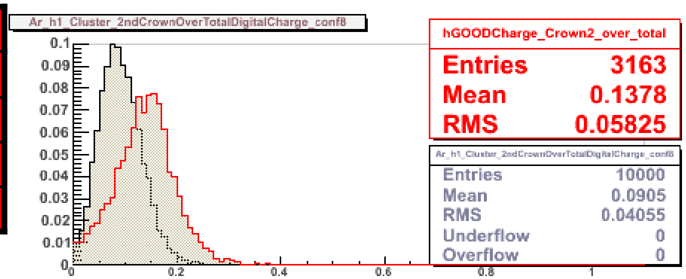
Q_{Seed}/Q_{total}

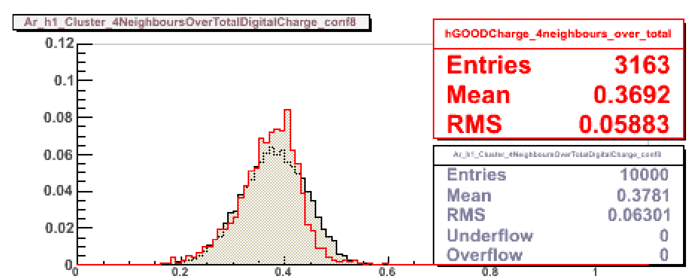


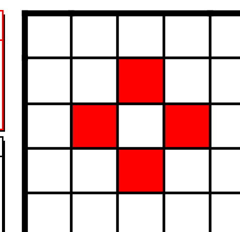


$Q_{1stcrown}/Q_{total}$







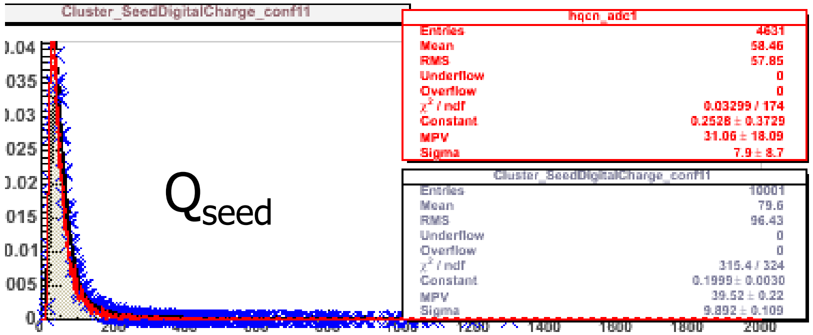


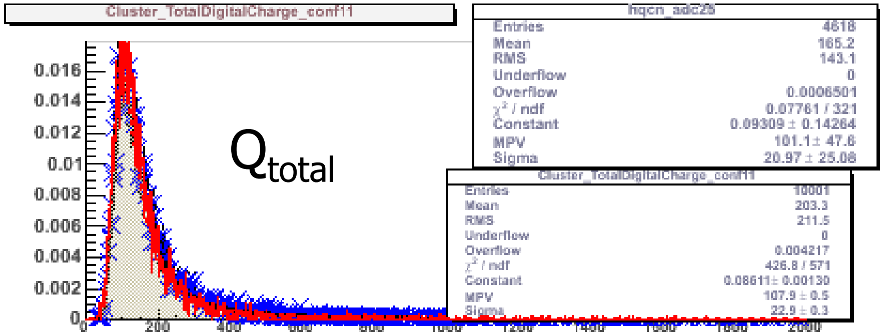
$Q_{2ndcrown}/Q_{total}$ $Q_{4neighbours}/Q_{total}$

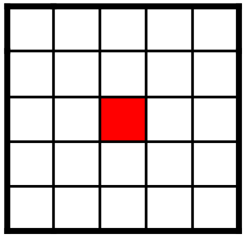
DIGMAPS model

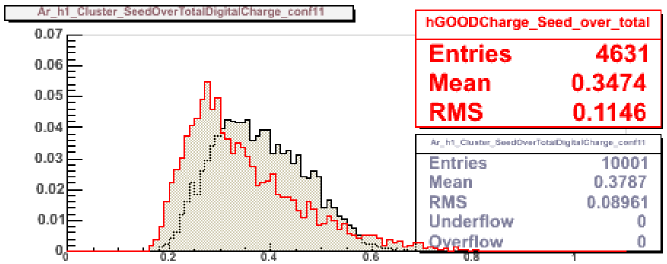
DATA

M9 (40μm pitch)

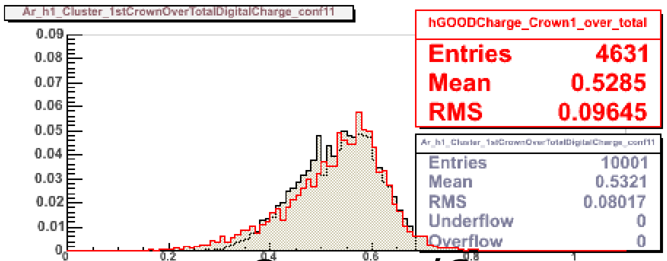


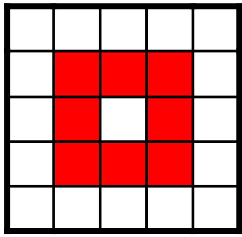




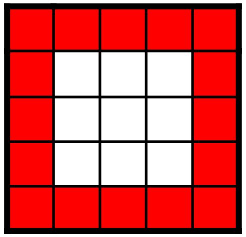


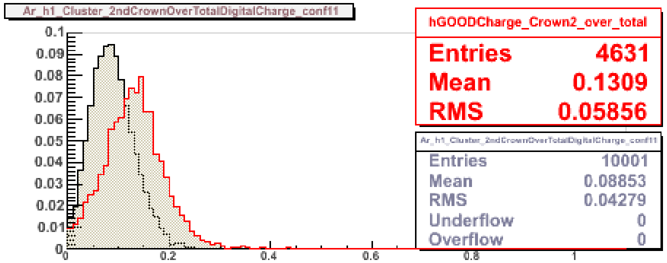
Q_{Seed}/Q_{total}

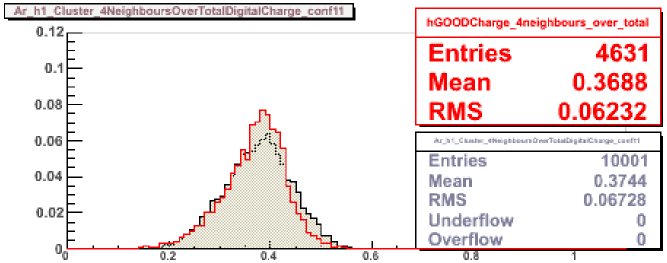


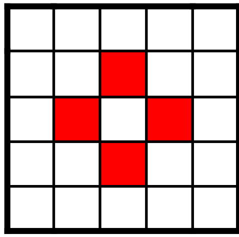


$Q_{1stcrown}/Q_{total}$





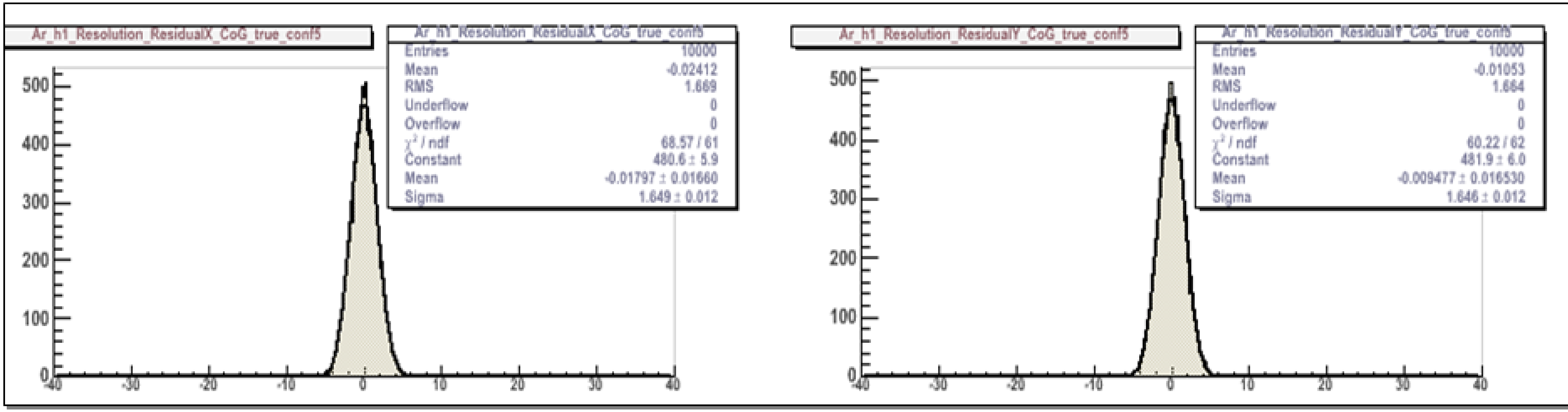




$Q_{2ndcrown}/Q_{total}$ $Q_{4neighbours}/Q_{total}$

Resolution (μm)

- E.g. M9, 20 um pitch



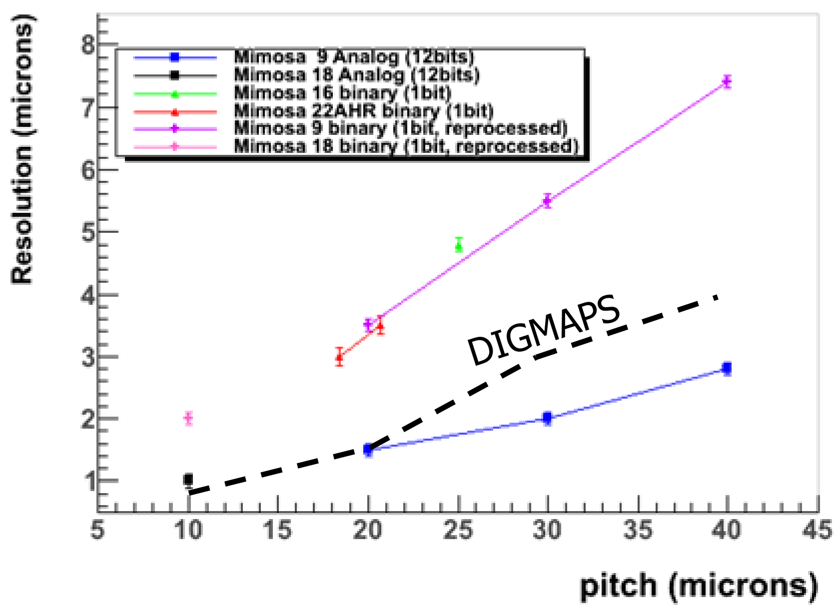
DIGMAPS model

$\sigma_{(CenterofGravity)} \sim 1.7\ \mu m$

DATA

$\sigma_{(CenterofGravity)} \sim 1.8\ \mu m$

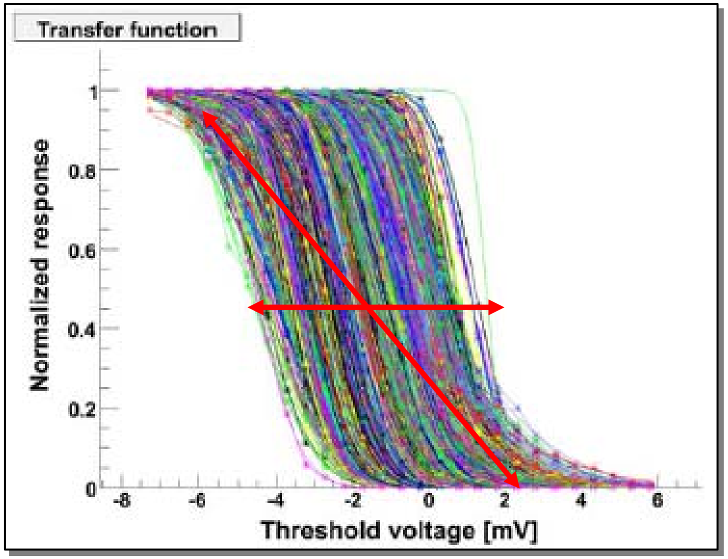
Not so good agreement for larger pitch…



Step 4/5 (ADC and cluster algorithms)

- Under development
  - Only perfect clustering at the moment
  - Only perfect ADC/discri.
    - ➢ Realistic Noise treatment to be added

      FPN + Temporal Noise
    - ➢ Zero suppression to be added



FPN / Temporal Noise

Performances: summary

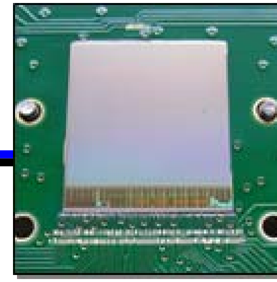
- Fit / model not optimized
  - Address more carefully the weight of 2nd crown pixels
    - ➢ small number of entries ⇨ uncertainty underestimated
    - ➢ Reduce range of the 2D fit ?
  - Focus should me made on the response of the 8 neighbouring pixels
    - ➢ Determines multiplicity (particularly for digitized chips)
    - ➢ Determines resolution
    - ➢ Determines hit separation performances
  - Global response is already encouraging
    - ➢ Limited number of parameters (Noise, epitaxial layer + 2D double gaussian)
    - ➢ Multiplicity can be reproduced
    - ➢ Still many optimization to be done
  - Model could be simplified
    - ➢ each Q_i of a given segment has to be randomly adressed to one pixel
    - ➢ Option: suppress random part and charge only with PDF values.

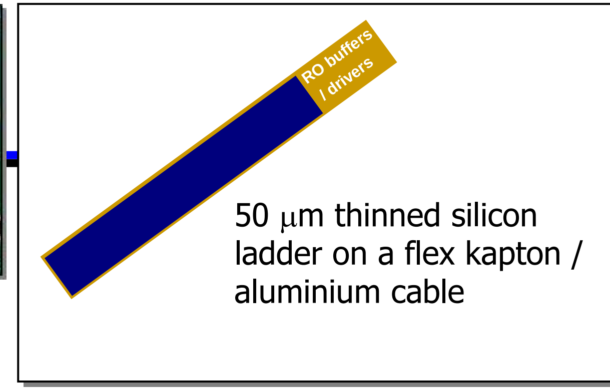
Outlook: implementing a digitizer in HFT-software

- DIGMAPS = Tool under development but allows already many studies:
  - sensor(s)/models with a digitised output
  - any other charge transport model
    - Optimize parametrized models for fast sim
  - Optimize ADCs/discris
    - N bits, dynamic range, Noise, etc.
  - clustering algorithms
    - chip occupancy
    - Hit separation performances
  - Zero suppression blocks, etc.
  - Study incident angle effects
  - CPU performances vs models
- HFT simulation (Fast/full simulation)
  - Simulating charge transport can be CPU time consuming
    - You should define which amount of complexity/computing you can afford.
  - A lot of possible algorithms/approachs
    - DIGMAPS can help to decide which precision you want
    - Multiplicity vs incident angle/charge deposition/impact position = difficult to parametrize
  - Nevertheless, building a physical model is out of reach
    - Data driven approach
    - Use test beam data as input/guideline is the key

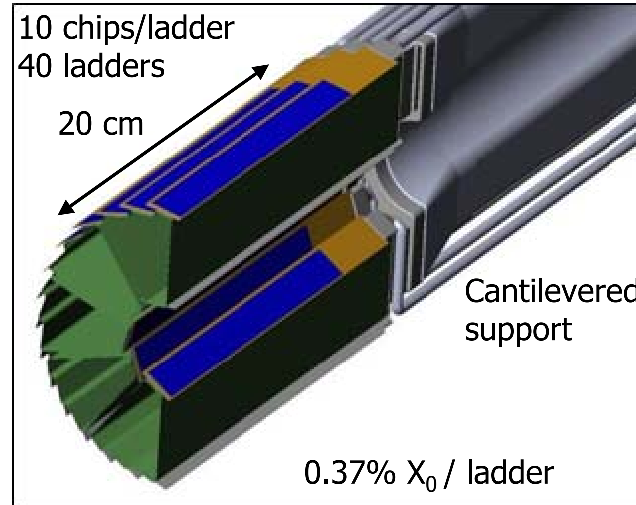
Back up

Ultimate Sensor for STAR Vertex detector (1)

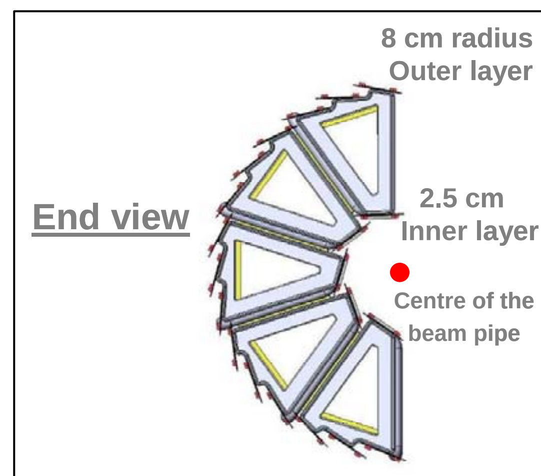




- STAR PIXL upgrade (physics run in 2014)
  - Requirements
    - ~ 150 kRad and few 10^{12} n_{eq} /cm²/year
    - Temperature 30-35 °C (air flow cooling only)
    - Power consumption ~130 mW/cm²
    - Spatial resolution < 10 µm
    - Integration time ~< 200 µs to cope with occupancy (~200 hits / 4 cm² sensor / read-out cycle)
  - Design
    - 2 layers (2.5/8 cm radius)
    - 40 ladders: 50 µm silicon, Flex kapton / aluminium cable
    - 10 Mimosa chips/ladder ⇨ 370 x 10^6 pixels
    - 0.37% X_0 per layer



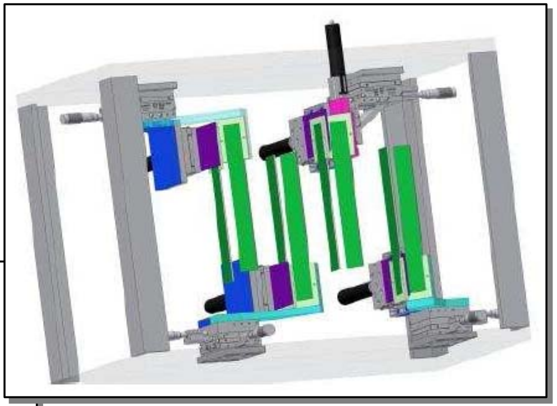
- Ultimate (alias Mimosa 28)
  - Final sensor for the upgrade of STAR pixel layers of the vertex detector
    - Design process Austria Micro System AMS-0.35 µm - OPTO, 4 metal- and 2 poly- layers
    - 15 µm thick epi. layer, High-Resistivity substrate (400 Ohm.cm)
    - Radiation tolerant structures
    - 928 (rows) x 960 (columns) pixels, 20.7 µm pitch ⇨ ~20 x 23 mm²
    - Fast binary readout, zero suppression
    - 200 µs read-out time: Suited for 10^6 part/cm²/s

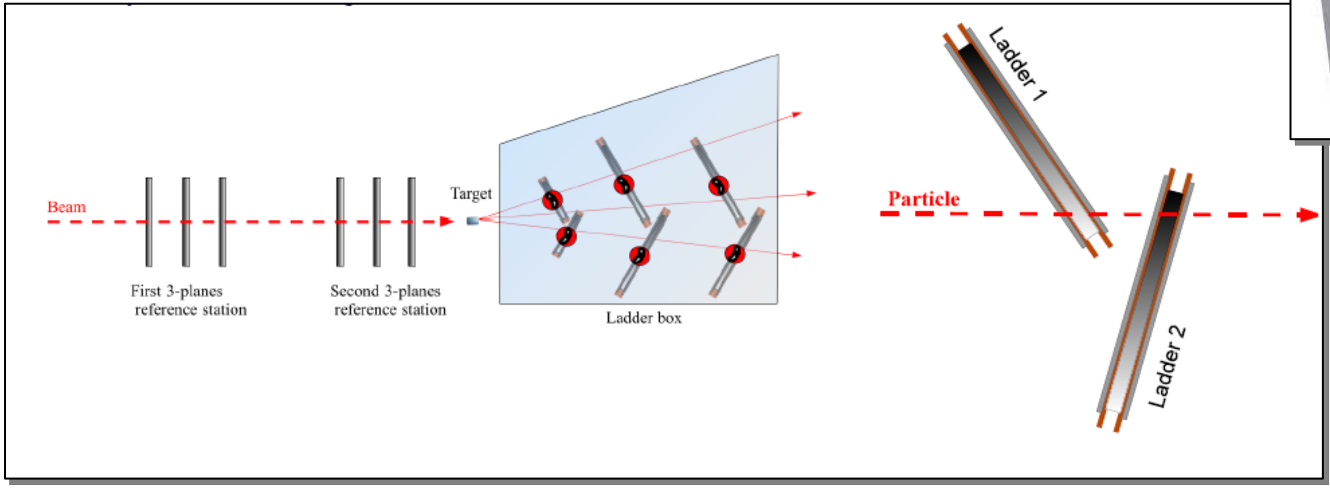


Chip delivered in spring 2011
First data taking in 2013
First vertex detector equipped with CMOS pixel sensors !

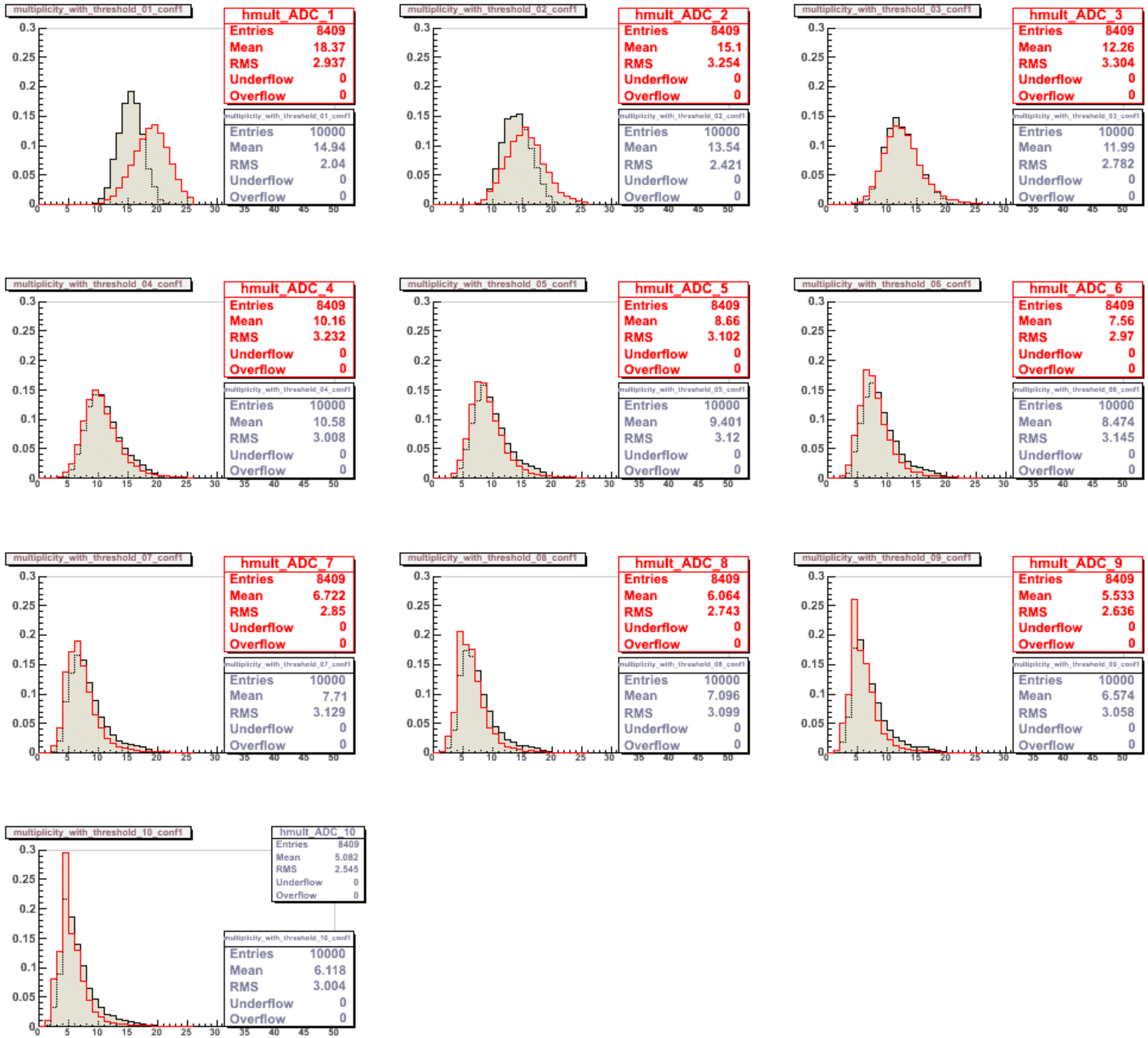
AIDA

- AIDA (EU-FP7 WP9.3) test beam infrastructure (2014)
  - Large area beam tel. (~6x4 cm2)
  - Alignment Investigation Device (AID)
    - ➢ Reproduce a VTX detector sector
    - ➢ Double sided ladders mounted on precise adjustable stages
  - Thermo-mechanical studies

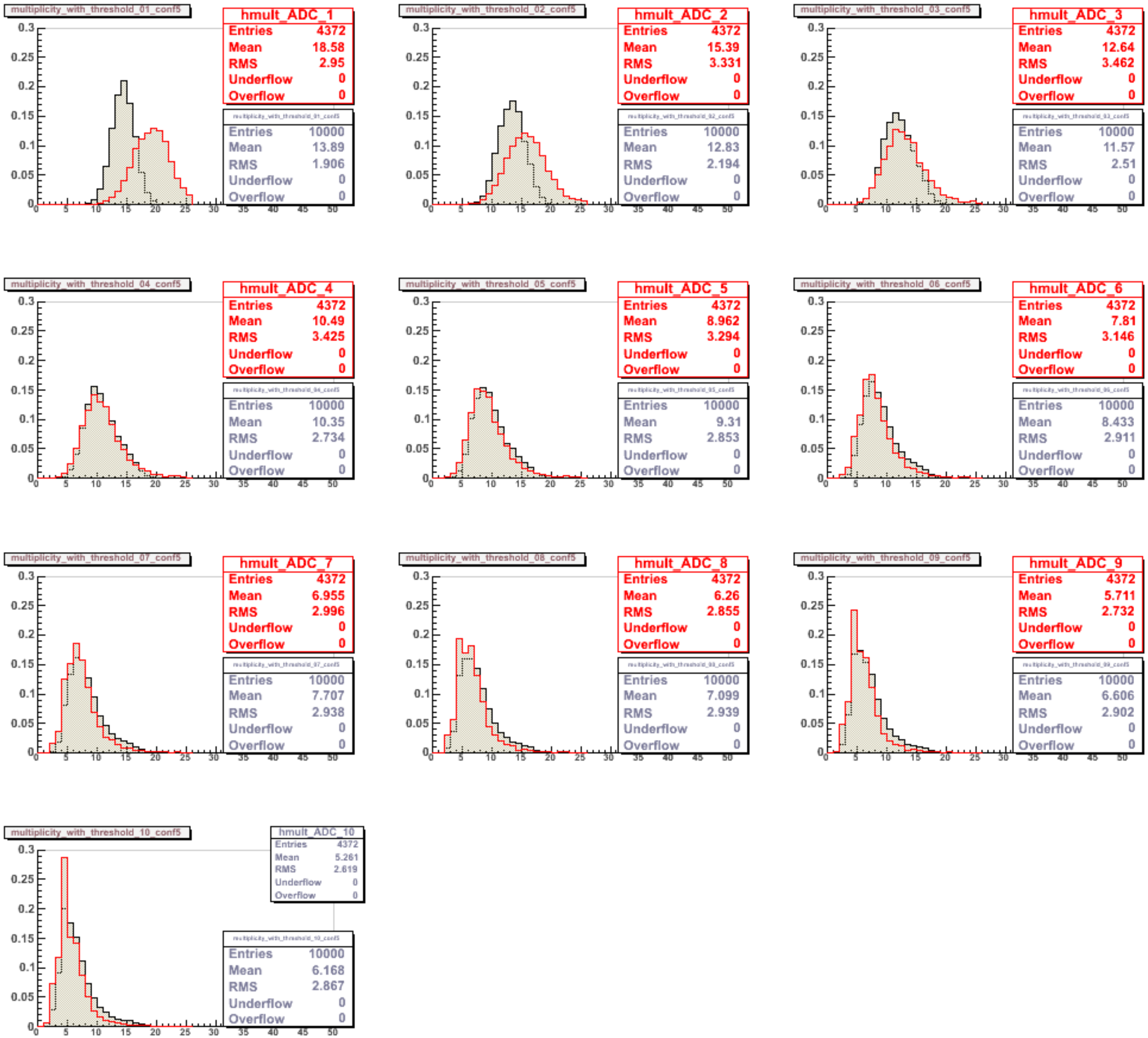




10 um pitch

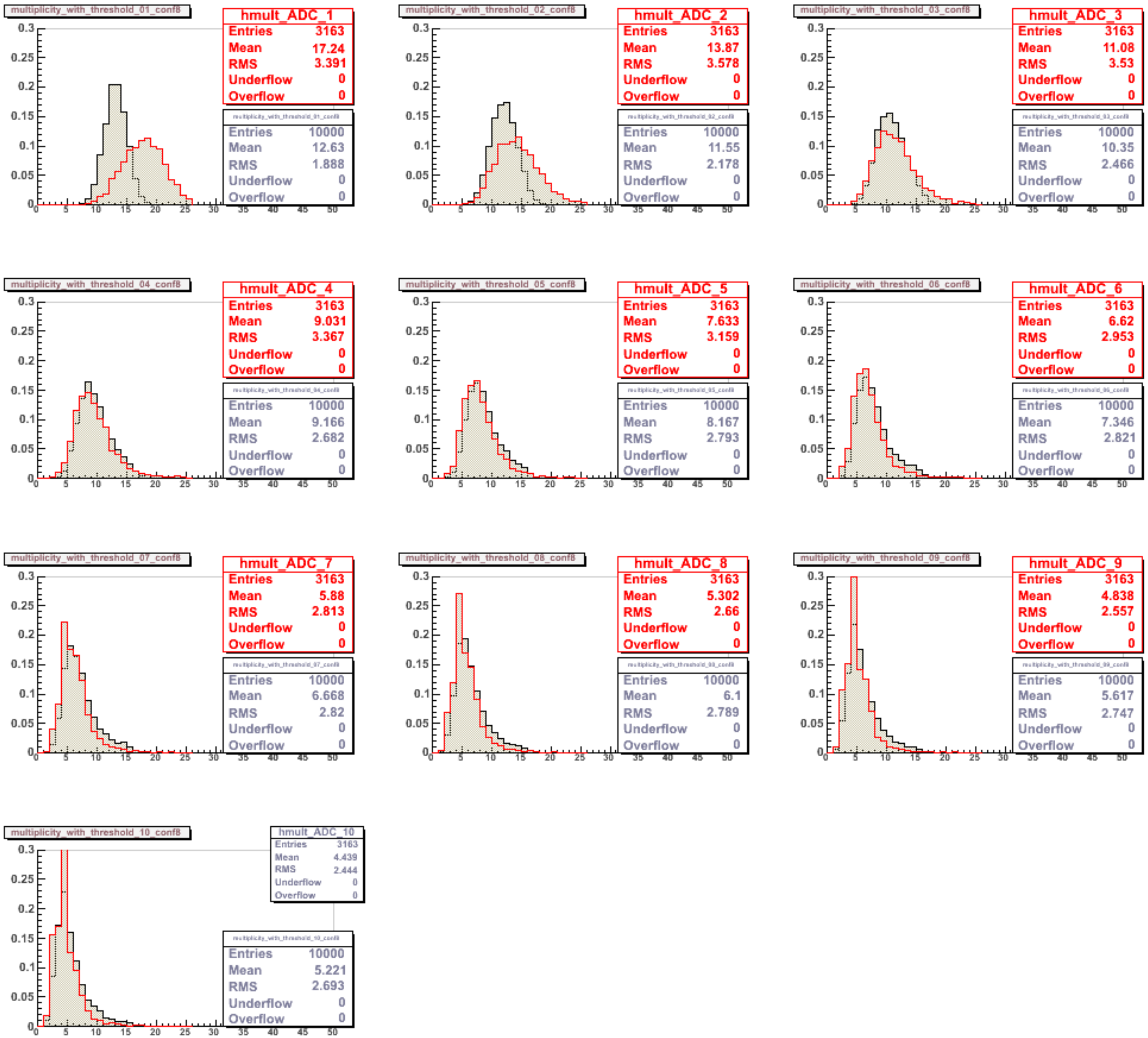

multiplicity_with_threshold_01_conf1
hmult_ADC_1
Entries 8409
Mean 18.37
RMS 2.937
Underflow 0
Overflow 0
multiplicity_with_threshold_01_conf1
Entries 10000
Mean 14.94
RMS 2.04
Underflow 0
Overflow 0
multiplicity_with_threshold_02_conf1
hmult_ADC_2
Entries 8409
Mean 15.1
RMS 3.254
Underflow 0
Overflow 0
multiplicity_with_threshold_02_conf1
Entries 10000
Mean 13.54
RMS 2.421
Underflow 0
Overflow 0
multiplicity_with_threshold_03_conf1
hmult_ADC_3
Entries 8409
Mean 12.26
RMS 3.304
Underflow 0
Overflow 0
multiplicity_with_threshold_03_conf1
Entries 10000
Mean 11.99
RMS 2.782
Underflow 0
Overflow 0
multiplicity_with_threshold_04_conf1
hmult_ADC_4
Entries 8409
Mean 10.16
RMS 3.232
Underflow 0
Overflow 0
multiplicity_with_threshold_04_conf1
Entries 10000
Mean 10.58
RMS 3.008
Underflow 0
Overflow 0
multiplicity_with_threshold_05_conf1
hmult_ADC_5
Entries 8409
Mean 8.66
RMS 3.102
Underflow 0
Overflow 0
multiplicity_with_threshold_05_conf1
Entries 10000
Mean 9.401
RMS 3.12
Underflow 0
Overflow 0
multiplicity_with_threshold_06_conf1
hmult_ADC_6
Entries 8409
Mean 7.56
RMS 2.97
Underflow 0
Overflow 0
multiplicity_with_threshold_06_conf1
Entries 10000
Mean 8.474
RMS 3.145
Underflow 0
Overflow 0
multiplicity_with_threshold_07_conf1
hmult_ADC_7
Entries 8409
Mean 6.722
RMS 2.85
Underflow 0
Overflow 0
multiplicity_with_threshold_07_conf1
Entries 10000
Mean 7.71
RMS 3.129
Underflow 0
Overflow 0
multiplicity_with_threshold_08_conf1
hmult_ADC_8
Entries 8409
Mean 6.064
RMS 2.743
Underflow 0
Overflow 0
multiplicity_with_threshold_08_conf1
Entries 10000
Mean 7.096
RMS 3.099
Underflow 0
Overflow 0
multiplicity_with_threshold_09_conf1
hmult_ADC_9
Entries 8409
Mean 5.533
RMS 2.636
Underflow 0
Overflow 0
multiplicity_with_threshold_09_conf1
Entries 10000
Mean 6.574
RMS 3.058
Underflow 0
Overflow 0
multiplicity_with_threshold_10_conf1
hmult_ADC_10
Entries 8409
Mean 5.082
RMS 2.545
Underflow 0
Overflow 0
multiplicity_with_threshold_10_conf1
Entries 10000
Mean 6.118
RMS 3.004
Underflow 0
Overflow 0
0 0.05 0.1 0.15 0.2 0.25 0.3
0 5 10 15 20 25 30 35 40 45 50

20 um pitch

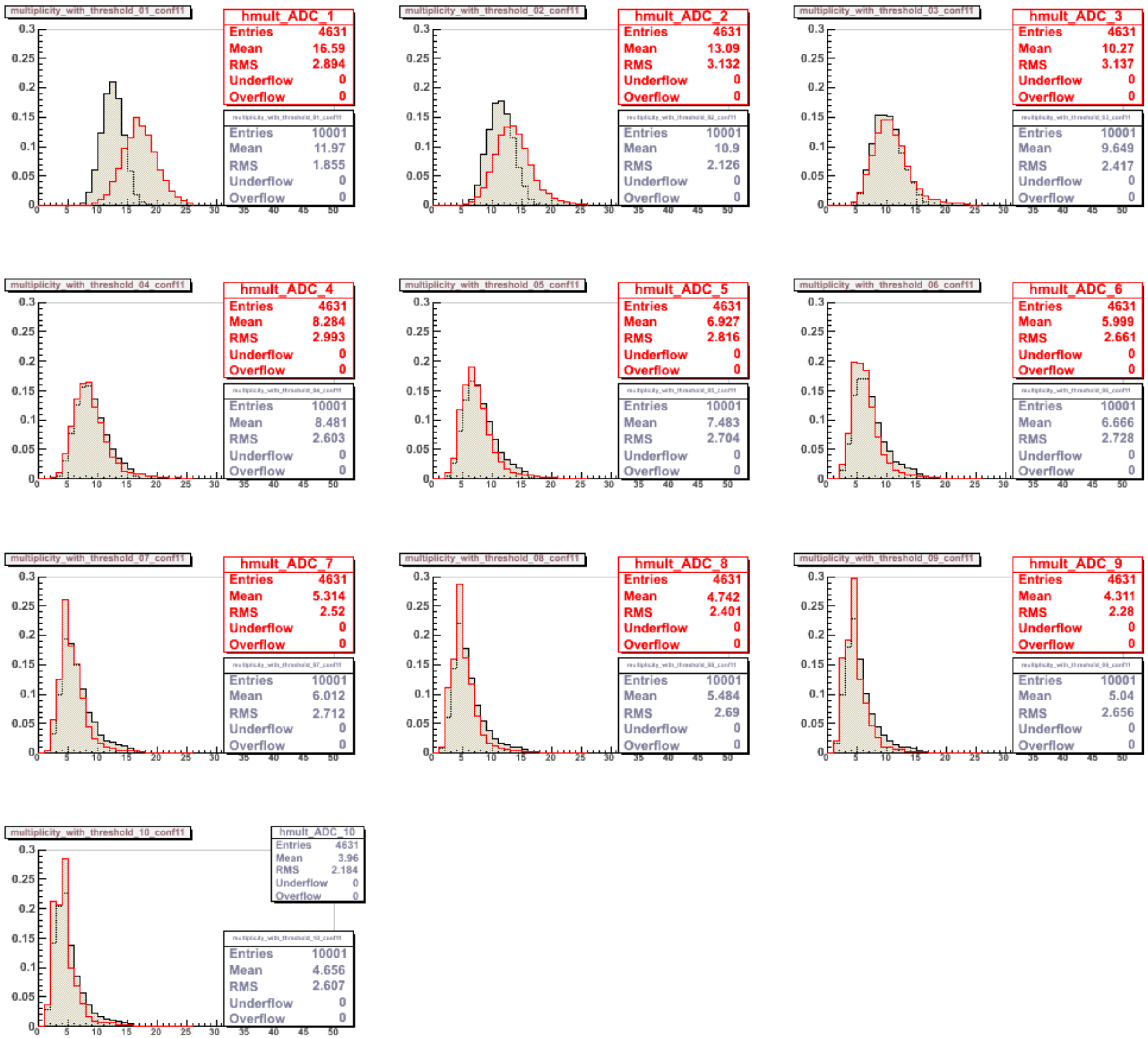


multiplicity_with_threshold_01_conf5
hmult_ADC_1
Entries 4372
Mean 18.58
RMS 2.95
Underflow 0
Overflow 0
Entries 10000
Mean 13.89
RMS 1.906
Underflow 0
Overflow 0
multiplicity_with_threshold_02_conf5
hmult_ADC_2
Entries 4372
Mean 15.39
RMS 3.331
Underflow 0
Overflow 0
Entries 10000
Mean 12.83
RMS 2.194
Underflow 0
Overflow 0
multiplicity_with_threshold_03_conf5
hmult_ADC_3
Entries 4372
Mean 12.64
RMS 3.462
Underflow 0
Overflow 0
Entries 10000
Mean 11.57
RMS 2.51
Underflow 0
Overflow 0
multiplicity_with_threshold_04_conf5
hmult_ADC_4
Entries 4372
Mean 10.49
RMS 3.425
Underflow 0
Overflow 0
Entries 10000
Mean 10.35
RMS 2.734
Underflow 0
Overflow 0
multiplicity_with_threshold_05_conf5
hmult_ADC_5
Entries 4372
Mean 8.962
RMS 3.294
Underflow 0
Overflow 0
Entries 10000
Mean 9.31
RMS 2.853
Underflow 0
Overflow 0
multiplicity_with_threshold_06_conf5
hmult_ADC_6
Entries 4372
Mean 7.81
RMS 3.146
Underflow 0
Overflow 0
Entries 10000
Mean 8.433
RMS 2.911
Underflow 0
Overflow 0
multiplicity_with_threshold_07_conf5
hmult_ADC_7
Entries 4372
Mean 6.955
RMS 2.996
Underflow 0
Overflow 0
Entries 10000
Mean 7.707
RMS 2.938
Underflow 0
Overflow 0
multiplicity_with_threshold_08_conf5
hmult_ADC_8
Entries 4372
Mean 6.26
RMS 2.855
Underflow 0
Overflow 0
Entries 10000
Mean 7.099
RMS 2.939
Underflow 0
Overflow 0
multiplicity_with_threshold_09_conf5
hmult_ADC_9
Entries 4372
Mean 5.711
RMS 2.732
Underflow 0
Overflow 0
Entries 10000
Mean 6.606
RMS 2.902
Underflow 0
Overflow 0
multiplicity_with_threshold_10_conf5
hmult_ADC_10
Entries 4372
Mean 5.261
RMS 2.619
Underflow 0
Overflow 0
Entries 10000
Mean 6.168
RMS 2.867
Underflow 0
Overflow 0

30 um pitch


multiplicity_with_threshold_01_conf8
hmult_ADC_1
Entries 3163
Mean 17.24
RMS 3.391
Underflow 0
Overflow 0
Entries 10000
Mean 12.63
RMS 1.888
Underflow 0
Overflow 0
multiplicity_with_threshold_02_conf8
hmult_ADC_2
Entries 3163
Mean 13.87
RMS 3.578
Underflow 0
Overflow 0
Entries 10000
Mean 11.55
RMS 2.178
Underflow 0
Overflow 0
multiplicity_with_threshold_03_conf8
hmult_ADC_3
Entries 3163
Mean 11.08
RMS 3.53
Underflow 0
Overflow 0
Entries 10000
Mean 10.35
RMS 2.466
Underflow 0
Overflow 0
multiplicity_with_threshold_04_conf8
hmult_ADC_4
Entries 3163
Mean 9.031
RMS 3.367
Underflow 0
Overflow 0
Entries 10000
Mean 9.166
RMS 2.682
Underflow 0
Overflow 0
multiplicity_with_threshold_05_conf8
hmult_ADC_5
Entries 3163
Mean 7.633
RMS 3.159
Underflow 0
Overflow 0
Entries 10000
Mean 8.167
RMS 2.793
Underflow 0
Overflow 0
multiplicity_with_threshold_06_conf8
hmult_ADC_6
Entries 3163
Mean 6.62
RMS 2.953
Underflow 0
Overflow 0
Entries 10000
Mean 7.346
RMS 2.821
Underflow 0
Overflow 0
multiplicity_with_threshold_07_conf8
hmult_ADC_7
Entries 3163
Mean 5.88
RMS 2.813
Underflow 0
Overflow 0
Entries 10000
Mean 6.668
RMS 2.82
Underflow 0
Overflow 0
multiplicity_with_threshold_08_conf8
hmult_ADC_8
Entries 3163
Mean 5.302
RMS 2.66
Underflow 0
Overflow 0
Entries 10000
Mean 6.1
RMS 2.789
Underflow 0
Overflow 0
multiplicity_with_threshold_09_conf8
hmult_ADC_9
Entries 3163
Mean 4.838
RMS 2.557
Underflow 0
Overflow 0
Entries 10000
Mean 5.617
RMS 2.747
Underflow 0
Overflow 0
multiplicity_with_threshold_10_conf8
hmult_ADC_10
Entries 3163
Mean 4.439
RMS 2.444
Underflow 0
Overflow 0
Entries 10000
Mean 5.221
RMS 2.693
Underflow 0
Overflow 0

40 um pitch


multiplicity_with_threshold_01_conf11
hmult_ADC_1
Entries 4631
Mean 16.59
RMS 2.894
Underflow 0
Overflow 0
Entries 10001
Mean 11.97
RMS 1.855
Underflow 0
Overflow 0
multiplicity_with_threshold_02_conf11
hmult_ADC_2
Entries 4631
Mean 13.09
RMS 3.132
Underflow 0
Overflow 0
Entries 10001
Mean 10.9
RMS 2.126
Underflow 0
Overflow 0
multiplicity_with_threshold_03_conf11
hmult_ADC_3
Entries 4631
Mean 10.27
RMS 3.137
Underflow 0
Overflow 0
Entries 10001
Mean 9.649
RMS 2.417
Underflow 0
Overflow 0
multiplicity_with_threshold_04_conf11
hmult_ADC_4
Entries 4631
Mean 8.284
RMS 2.993
Underflow 0
Overflow 0
Entries 10001
Mean 8.481
RMS 2.603
Underflow 0
Overflow 0
multiplicity_with_threshold_05_conf11
hmult_ADC_5
Entries 4631
Mean 6.927
RMS 2.816
Underflow 0
Overflow 0
Entries 10001
Mean 7.483
RMS 2.704
Underflow 0
Overflow 0
multiplicity_with_threshold_06_conf11
hmult_ADC_6
Entries 4631
Mean 5.999
RMS 2.661
Underflow 0
Overflow 0
Entries 10001
Mean 6.666
RMS 2.728
Underflow 0
Overflow 0
multiplicity_with_threshold_07_conf11
hmult_ADC_7
Entries 4631
Mean 5.314
RMS 2.52
Underflow 0
Overflow 0
Entries 10001
Mean 6.012
RMS 2.712
Underflow 0
Overflow 0
multiplicity_with_threshold_08_conf11
hmult_ADC_8
Entries 4631
Mean 4.742
RMS 2.401
Underflow 0
Overflow 0
Entries 10001
Mean 5.484
RMS 2.69
Underflow 0
Overflow 0
multiplicity_with_threshold_09_conf11
hmult_ADC_9
Entries 4631
Mean 4.311
RMS 2.28
Underflow 0
Overflow 0
Entries 10001
Mean 5.04
RMS 2.656
Underflow 0
Overflow 0
multiplicity_with_threshold_10_conf11
hmult_ADC_10
Entries 4631
Mean 3.96
RMS 2.184
Underflow 0
Overflow 0
Entries 10001
Mean 4.656
RMS 2.607
Underflow 0
Overflow 0