

Emmy
Noether-
Programm

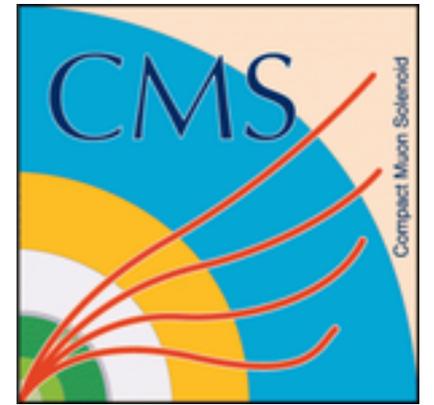
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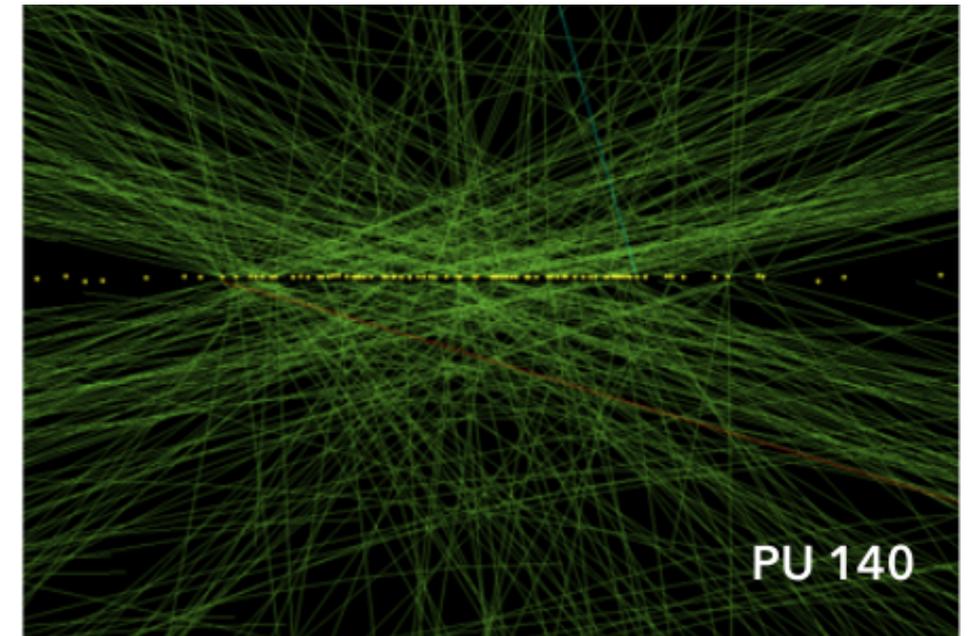
Spatial resolution measurements with planar pixel sensors for the CMS Phase-2 Upgrade

Aliakbar Ebrahimi, Finn Feindt, Erika Garutti, Paolo Gunnellini, Andreas Hinzmann,
Caroline Niemeyer, Daniel Pitzl(*), Georg Steinbrück, Jörn Schwandt, **Irene Zoi**

HL-LHC and the CMS Phase-2 Pixel Upgrade

HL-LHC

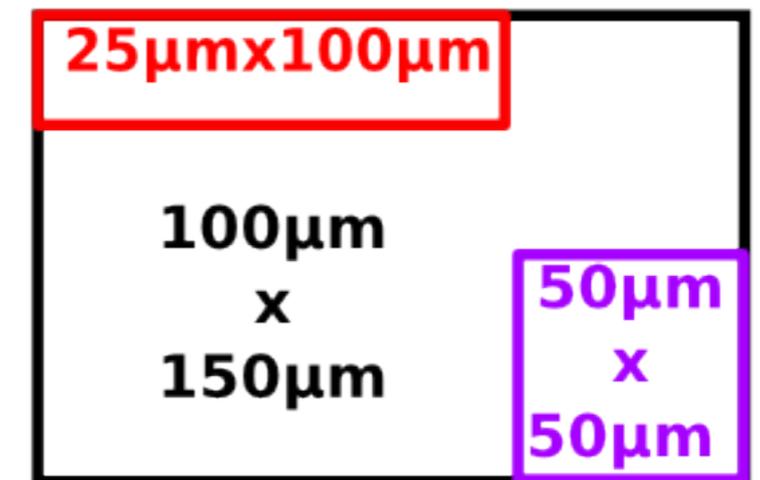
- ▶ Instantaneous peak luminosity: $5-7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- ✓ Increase Standard Model measurements precision
- ✓ Increase discovery potential
- ✓ Search for rare decays
- ✗ Increase radiation dose
- ✗ Increase pile up till 200 events/25 ns bunch crossing



Need to discriminate between interesting events and background
&
maintain detector performance

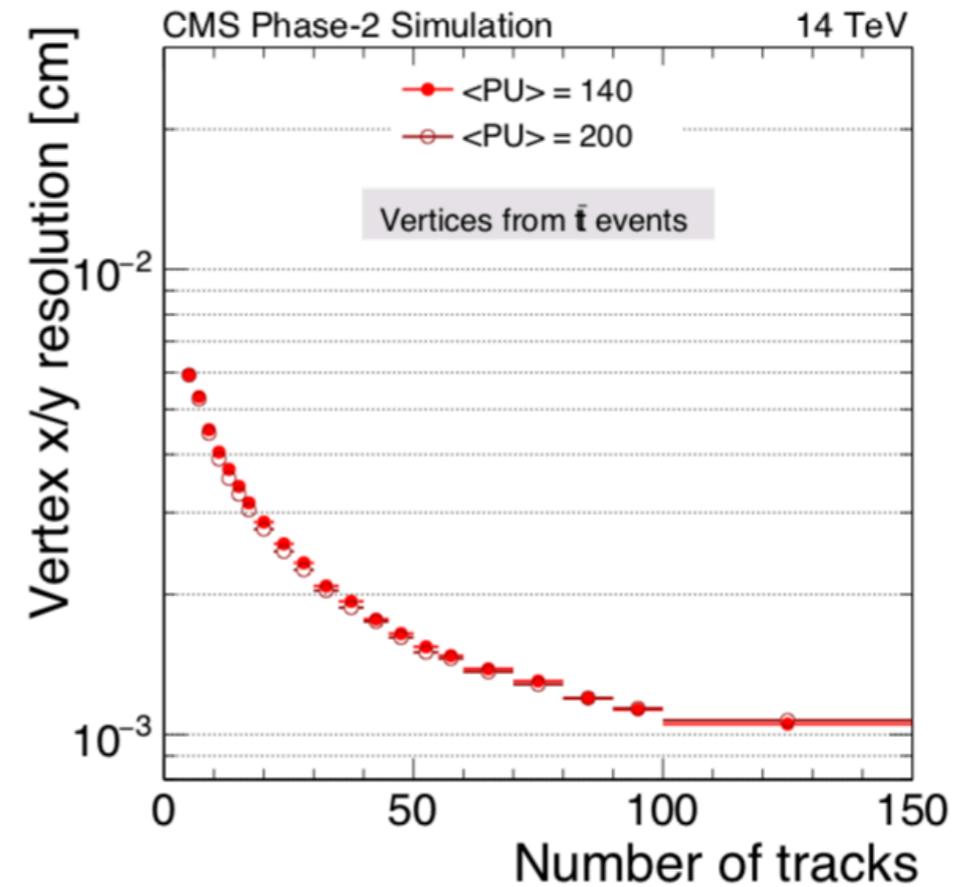
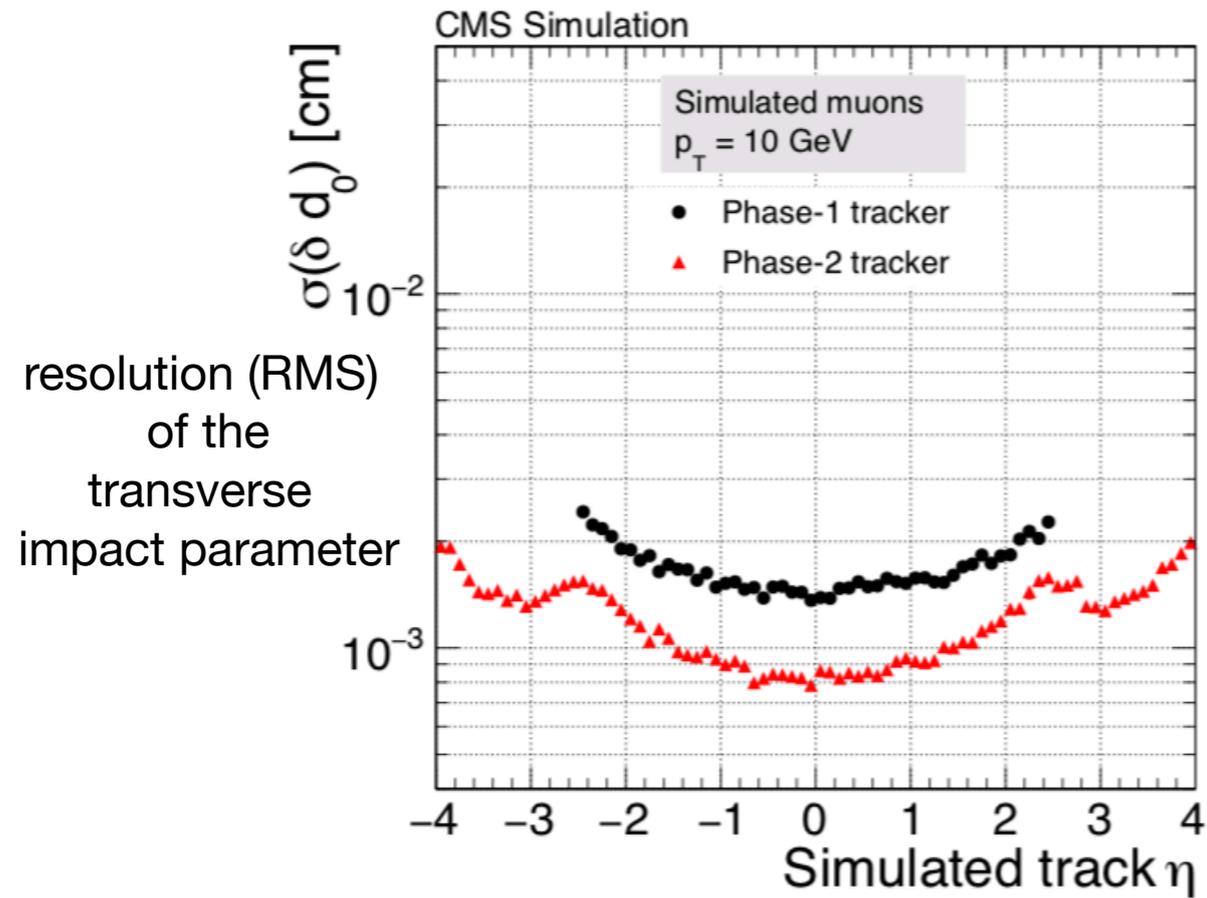


- ▶ The Phase-2 Pixel detector
- ▶ Radiation hard
- ▶ Increased pseudo-rapidity coverage
- ▶ Increased granularity



- Current CMS pixel size
- **Small pitch under test**
- **Small pitch under test**

Motivation for resolution studies

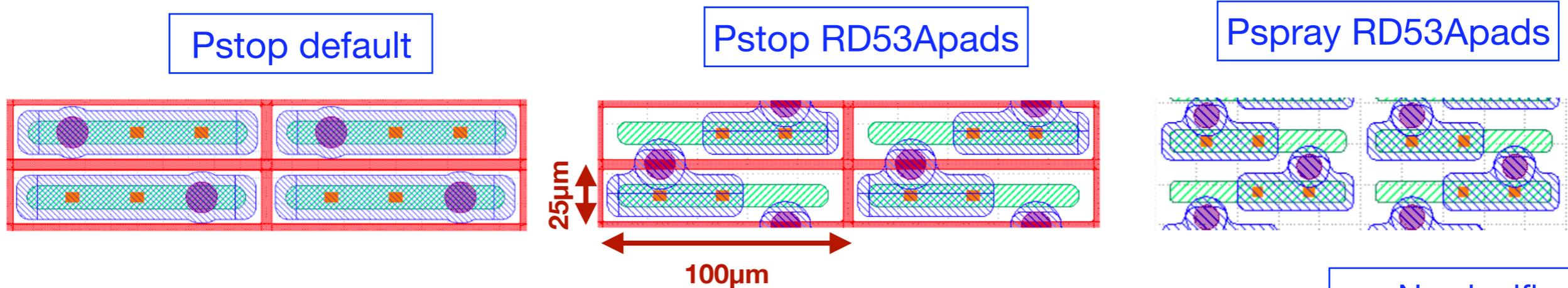


- What is the **resolution** of the **small pitch** pixel sensors?
- Does **resolution** degrade with **radiation damage**?

Tested CMS Phase-2 Prototype

- ▶ n+p-pixel sensors
- ▶ 150 μm thicknesses
- ▶ Focus on $100 \times 25 \mu\text{m}^2$
- ▶ Different geometries & pixel isolation schemes
- ▶ All samples are bump bonded to a PSI ROC4SENS analogue readout chip
 - ▶ No zero suppression but low rate (120 Hz)
 - ▶ Region of interest based data taking

More details given
in F. Feindt talk



- ▶ Sensors irradiated at CERN PS @ $3.3 \times 10^{15} \text{ p/cm}^2$ ($\phi_{\text{eq}} = 2 \times 10^{15} \text{ cm}^{-2}$)

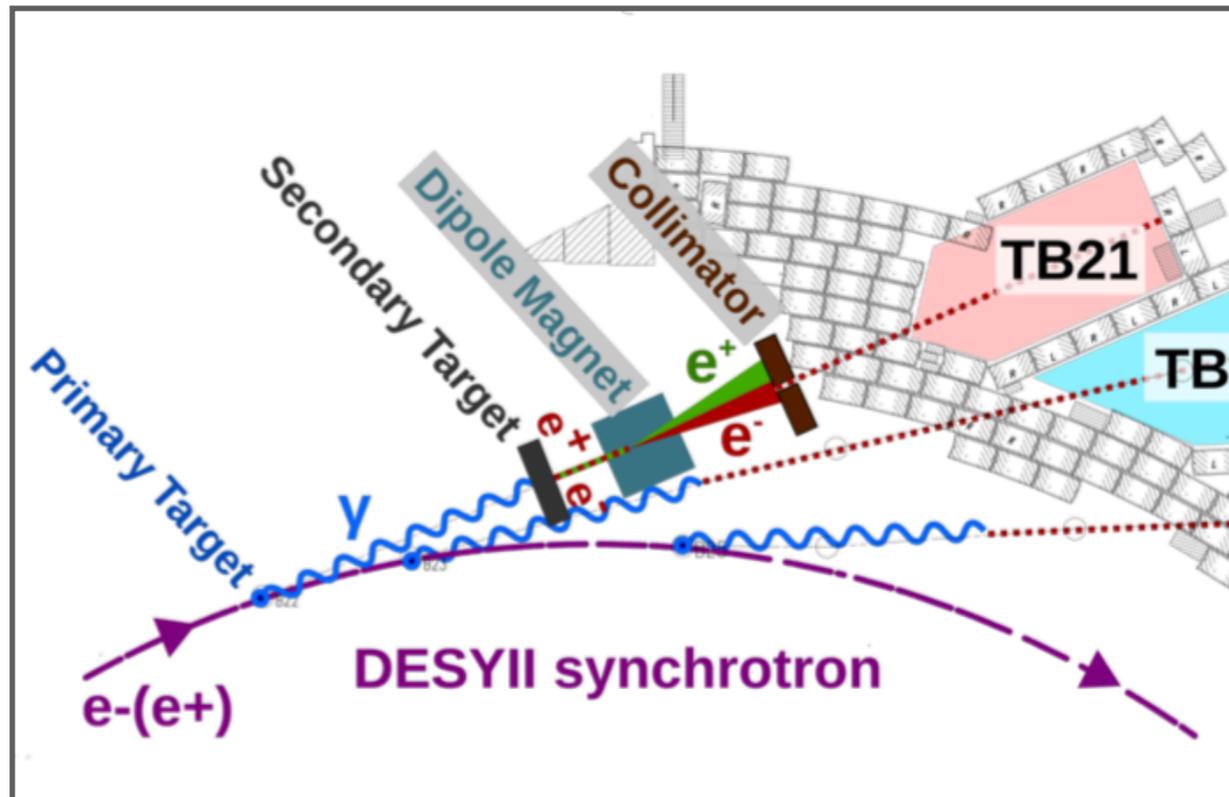
No significant
differences have
been observed in the
resolution

All the measurements shown were taken at a bias voltage of:

- ▶ **120V** for **non irradiated** sensors
- ▶ **800V** for **irradiated** sensor, temperature **-22 °C**

More details
in backup

The DESY Test Beam



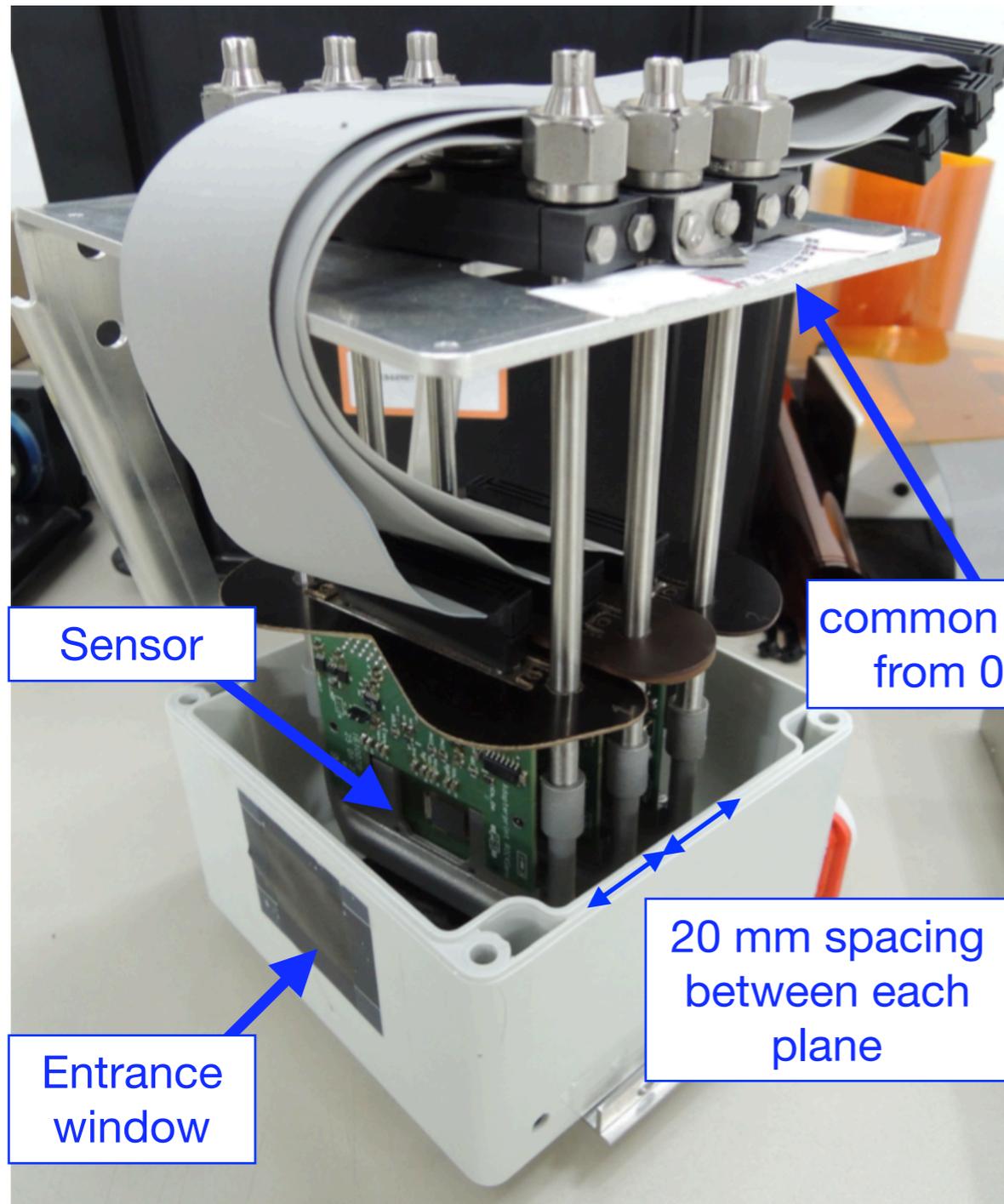
- ▶ **e⁺/e⁻** with momenta **1-6 GeV**
- ▶ useful for **resolution measurements**

No Telescope but: **“DREIMASTER”**

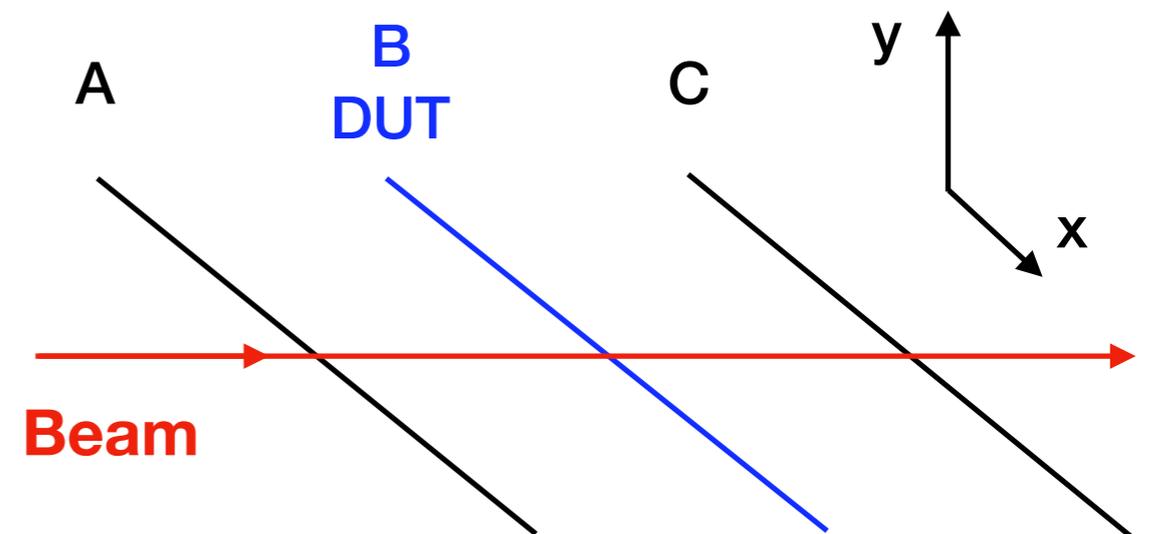
- ▶ Datura Telescope mean intrinsic resolution $(3.24 \pm 0.09) \mu\text{m}$
- ▶ We can do better!



The “Dreimaster”

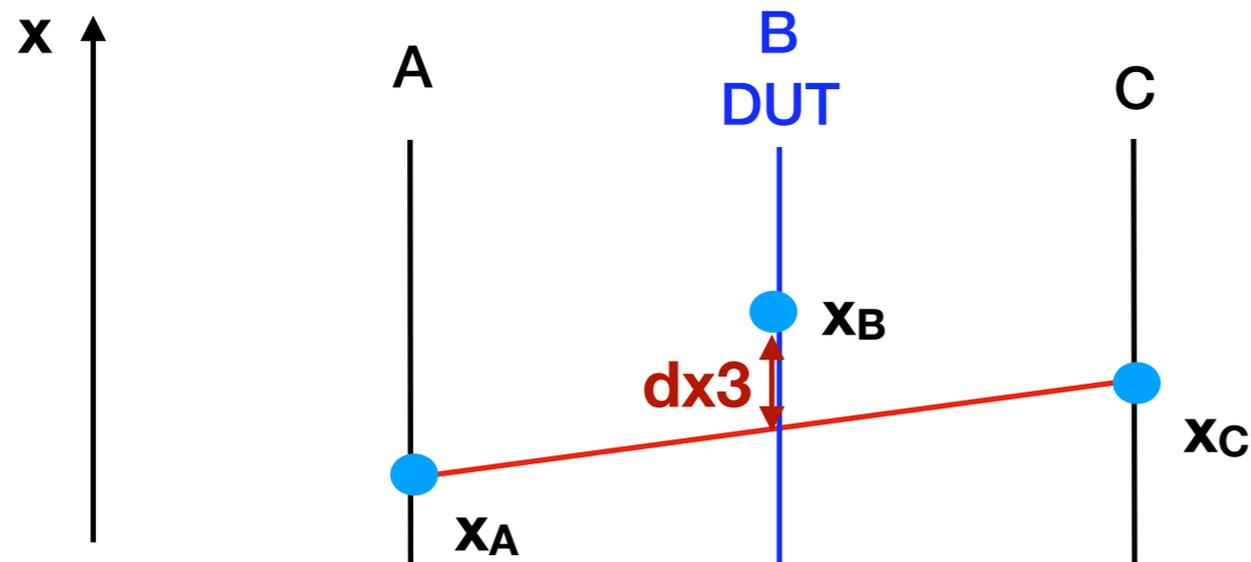


- ▶ Uses **three parallel planes of sensors**
- ▶ Does **not** rely on an **external reference tracking detector** → **intrinsic resolution**
- ▶ **Resolution** measurement by the **triplet method**



designed and produced by C. Muhl (DESY)

Resolution measurements with the Dreimaster



Triplet residual

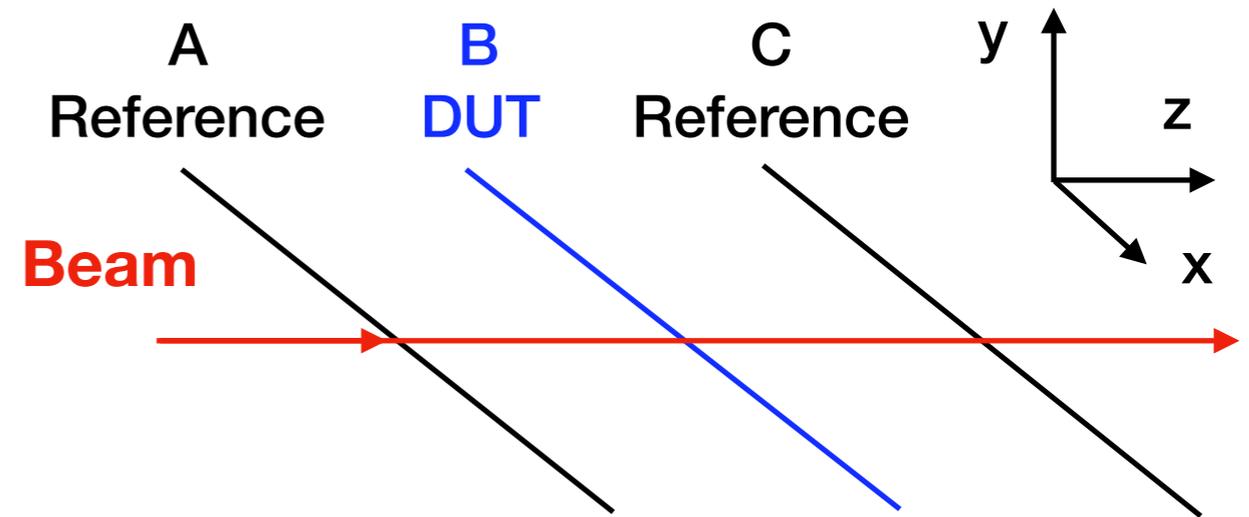
$$dx3 = x_B - \frac{x_A + x_C}{2}$$

1. Recursive track finding & alignment
2. Obtain the dx3 residual distribution
3. Evaluate the RMS of the dx3 to estimate the resolution
 - ▶ Considering the 95% of the events
4. Extraction of the single hit resolution

1. Alignment

► Assumptions:

- Average straight beam along z
- Parallel Dreimaster planes



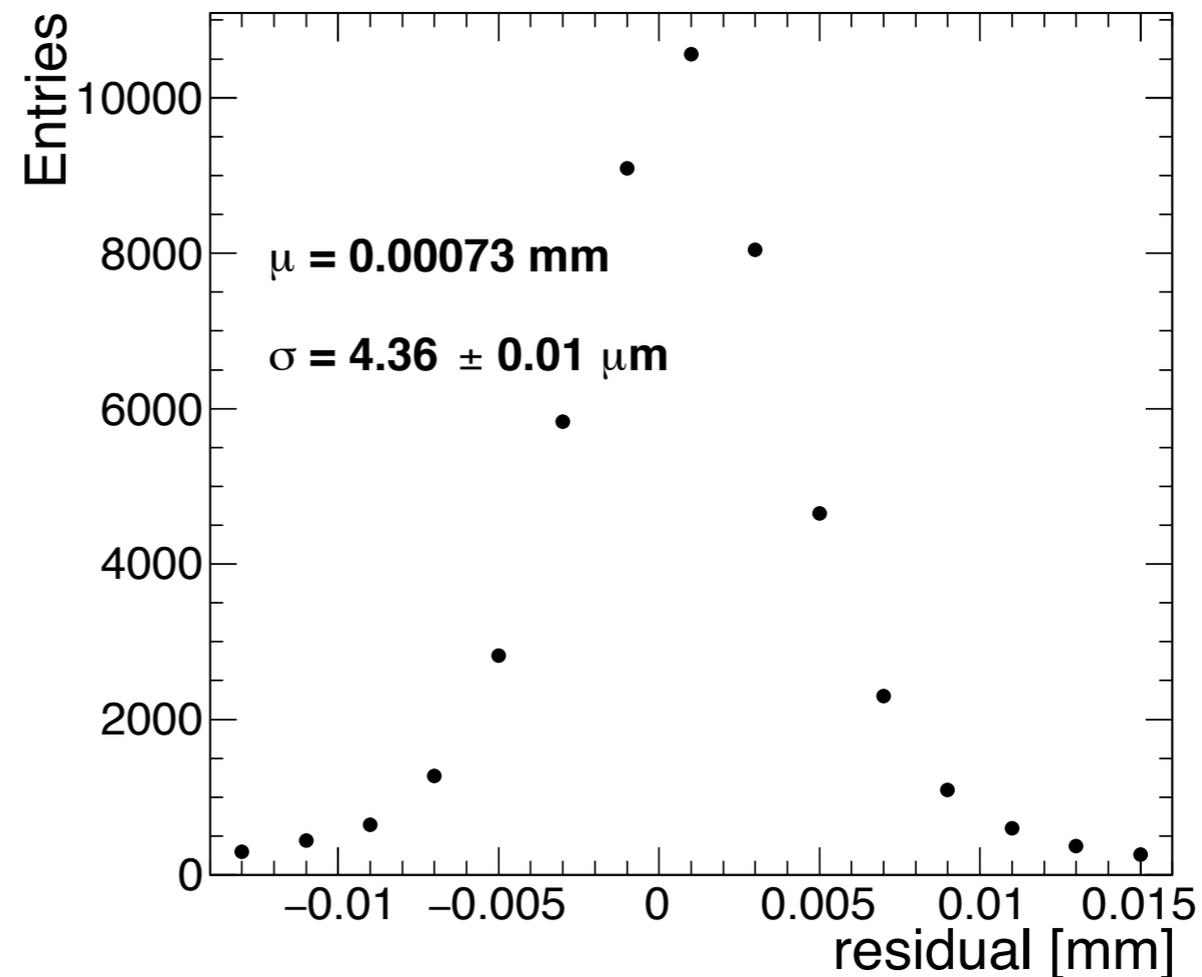
► Alignment parameters take into account:

- The relative position in x and y of the dut and the external reference planes
- Rotation around the beam axis
- Correction for rotation around the y axis

More details
in backup

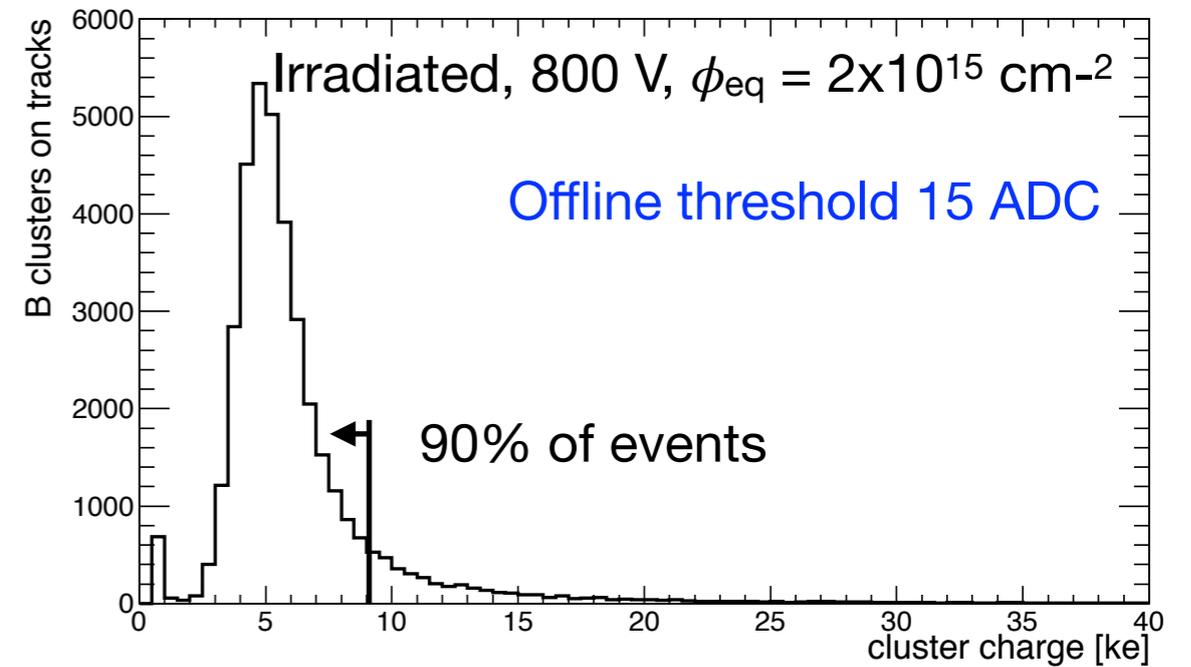
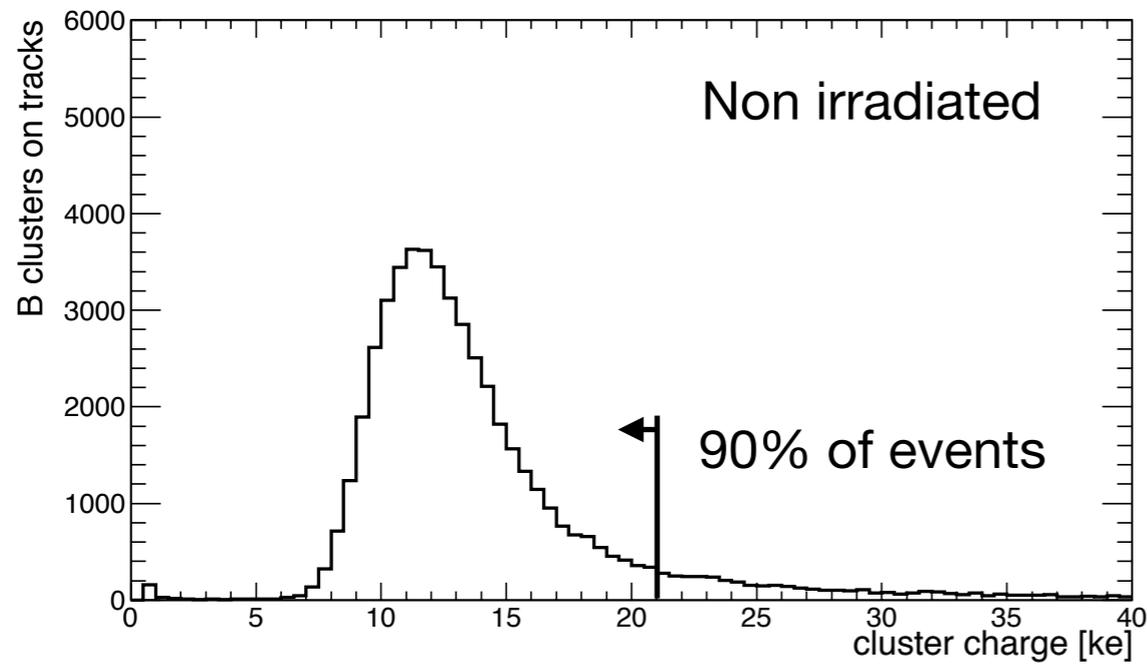
Iterative alignment

$$dx3 = x_B - \frac{x_A + x_C}{2}$$

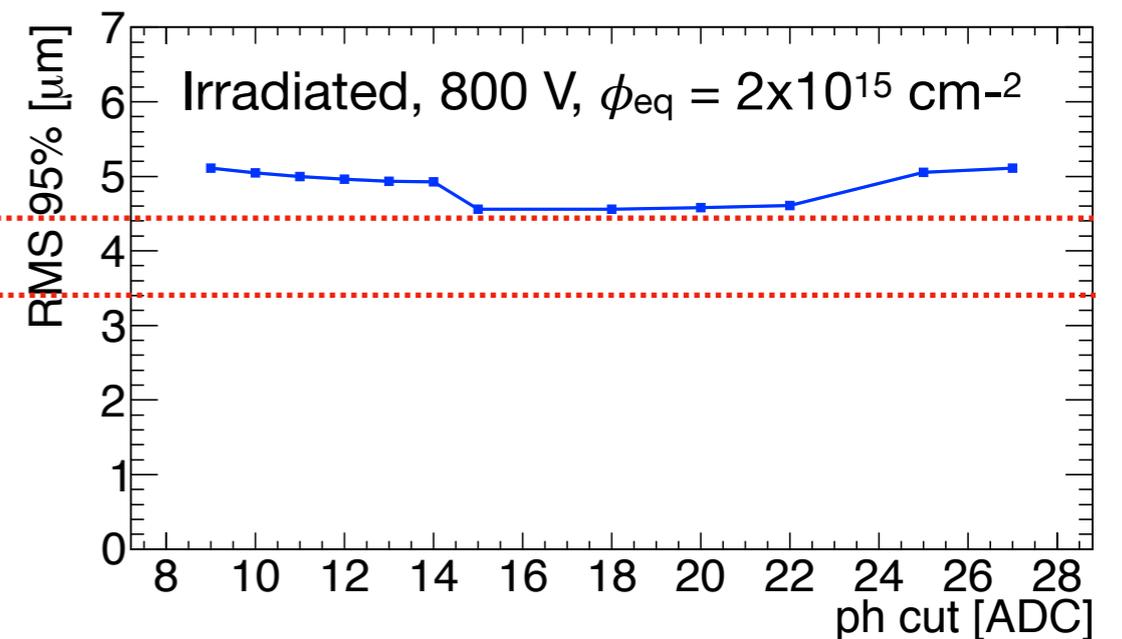
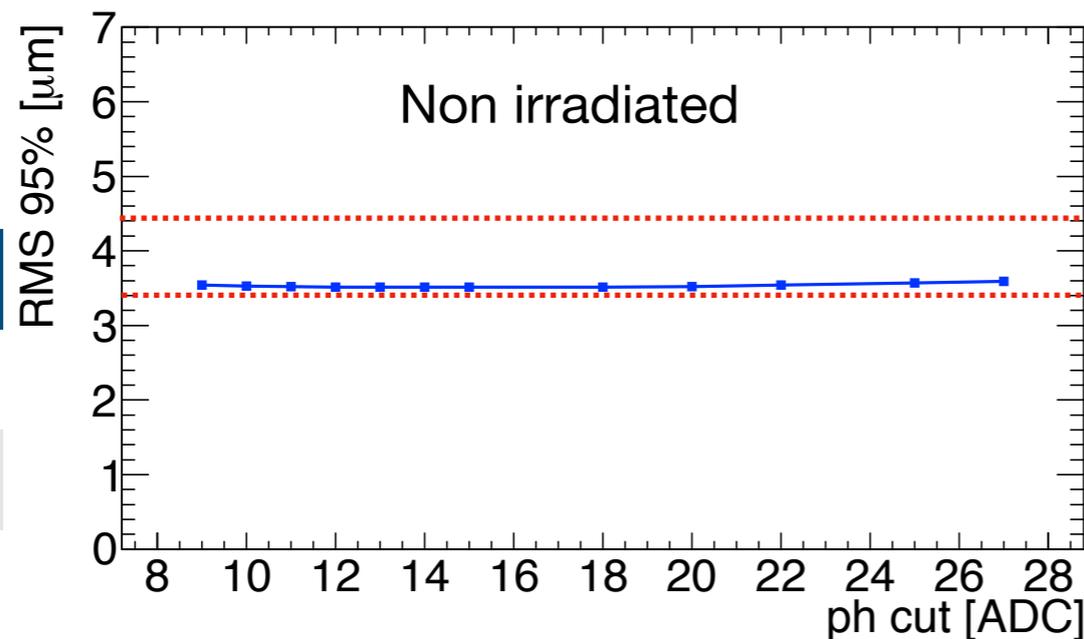


2. Obtain the dx3 residual distribution

- Require the clusters to be isolated on all the 3 planes
- Use the 90 % of the events in the Landau distribution (excluding delta rays tails) on all the three planes

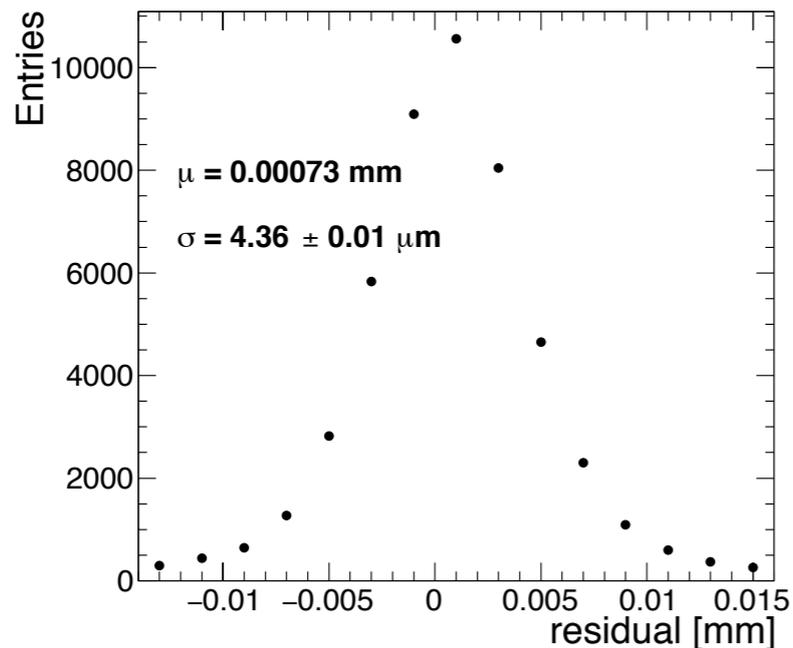


► Threshold scan



Sensors	Noise [ADC]
Non irradiated	4
$2 \times 10^{15} n_{eq}/\text{cm}^2$	6

3. & 4. Extraction of the single hit resolution from the RMS of the dx3



$$dx3 = x_B - \frac{x_A + x_C}{2}$$

residual = $dx3$
rms95% = Δ_{dx3}

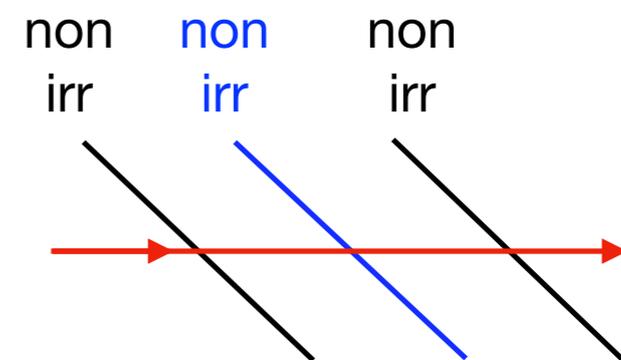
From the **uncertainty propagation**:

- ▶ Consider the uncertainty on the **single hit** Δ_{XB} independent from Δ_{XC} and Δ_{XA}
- ▶ For **non irradiated** sensors $\Delta_{XB} = \Delta_{XC} = \Delta_{XA} = \Delta_X$

$$\Delta_{dx3} = \sqrt{\frac{3}{2} \Delta_X^2}$$

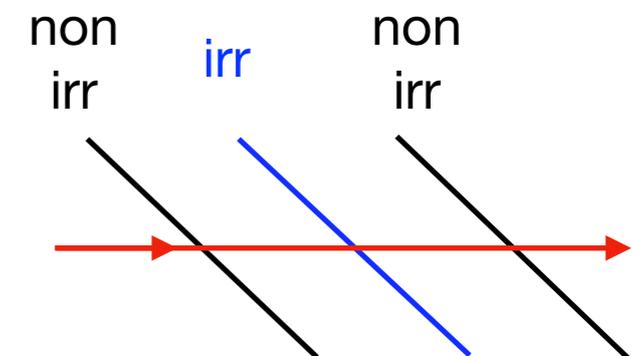


$$\Delta_X = \sqrt{\frac{2}{3}} \Delta_{dx3}$$



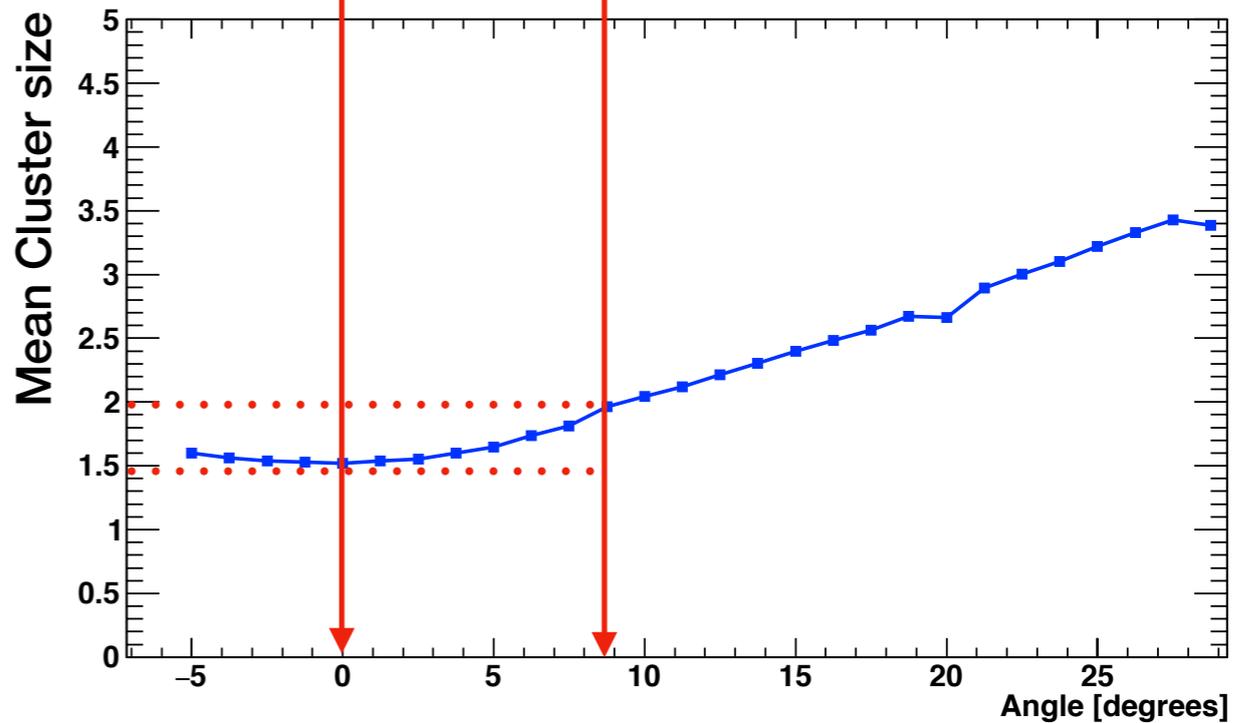
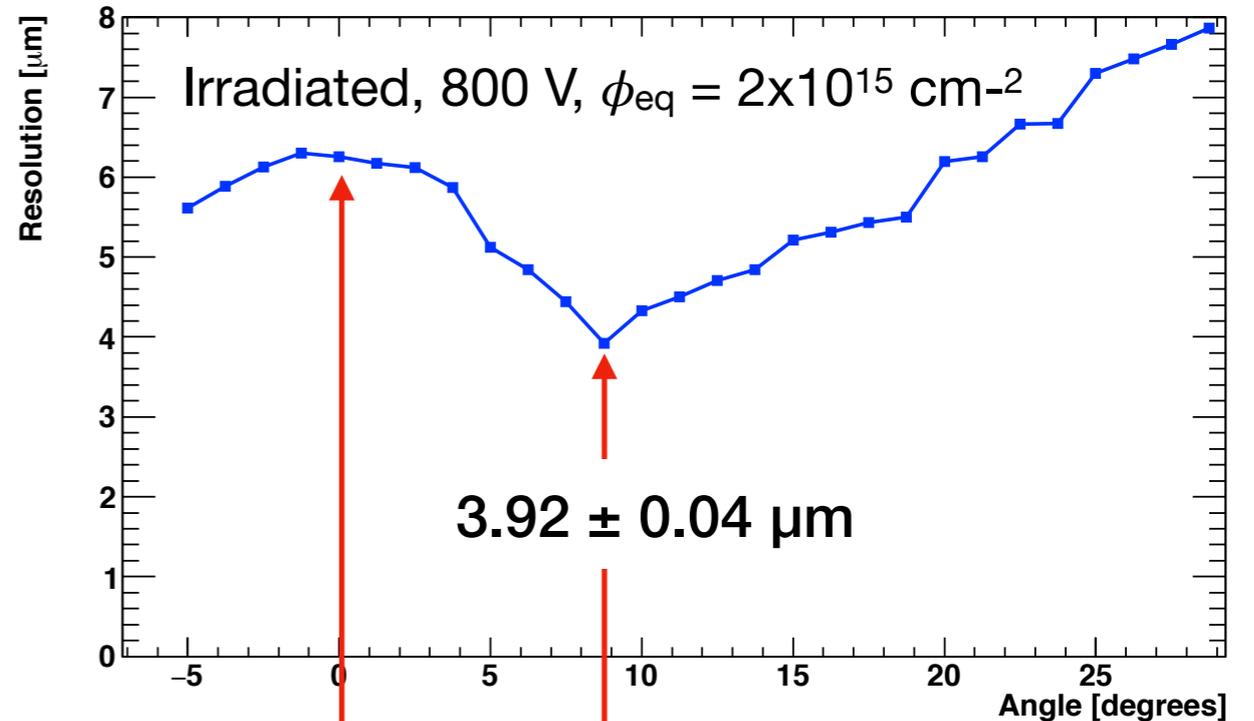
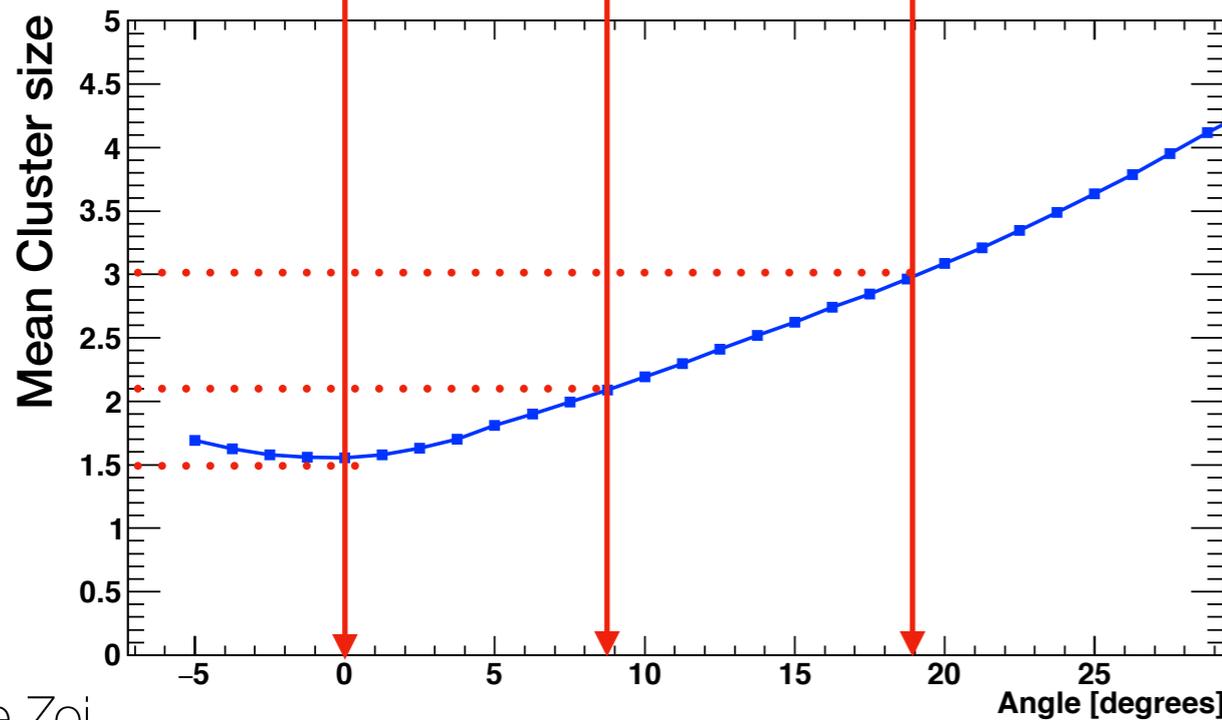
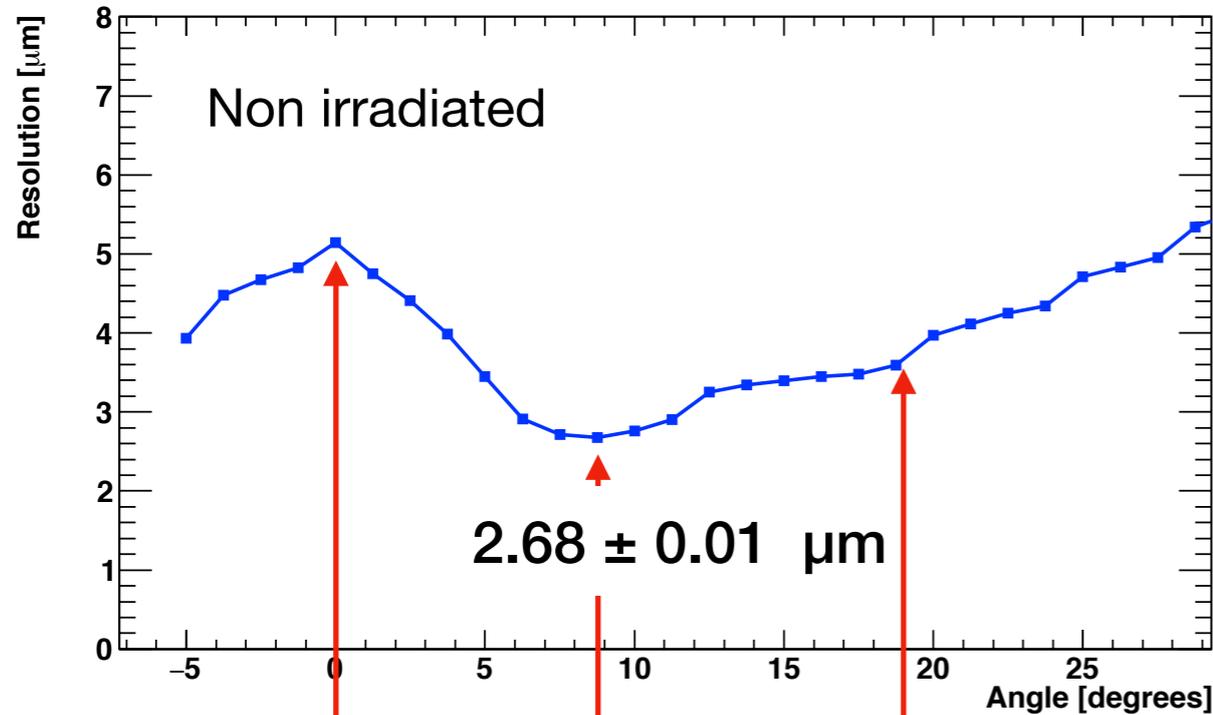
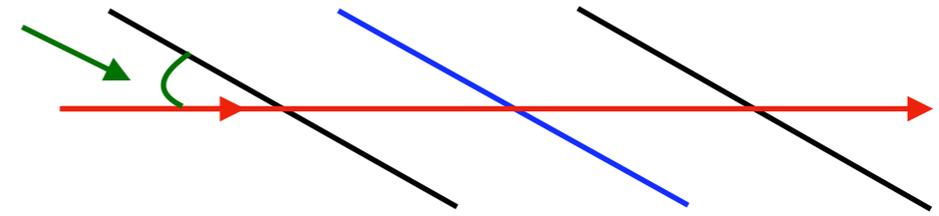
- ▶ For **irradiated** sensors $\Delta_{XB} \neq \Delta_{XC} = \Delta_{XA} = \Delta_X$

$$\Delta_{XB} = \sqrt{\Delta_{dx3}^2 - \frac{1}{2} \Delta_X^2}$$

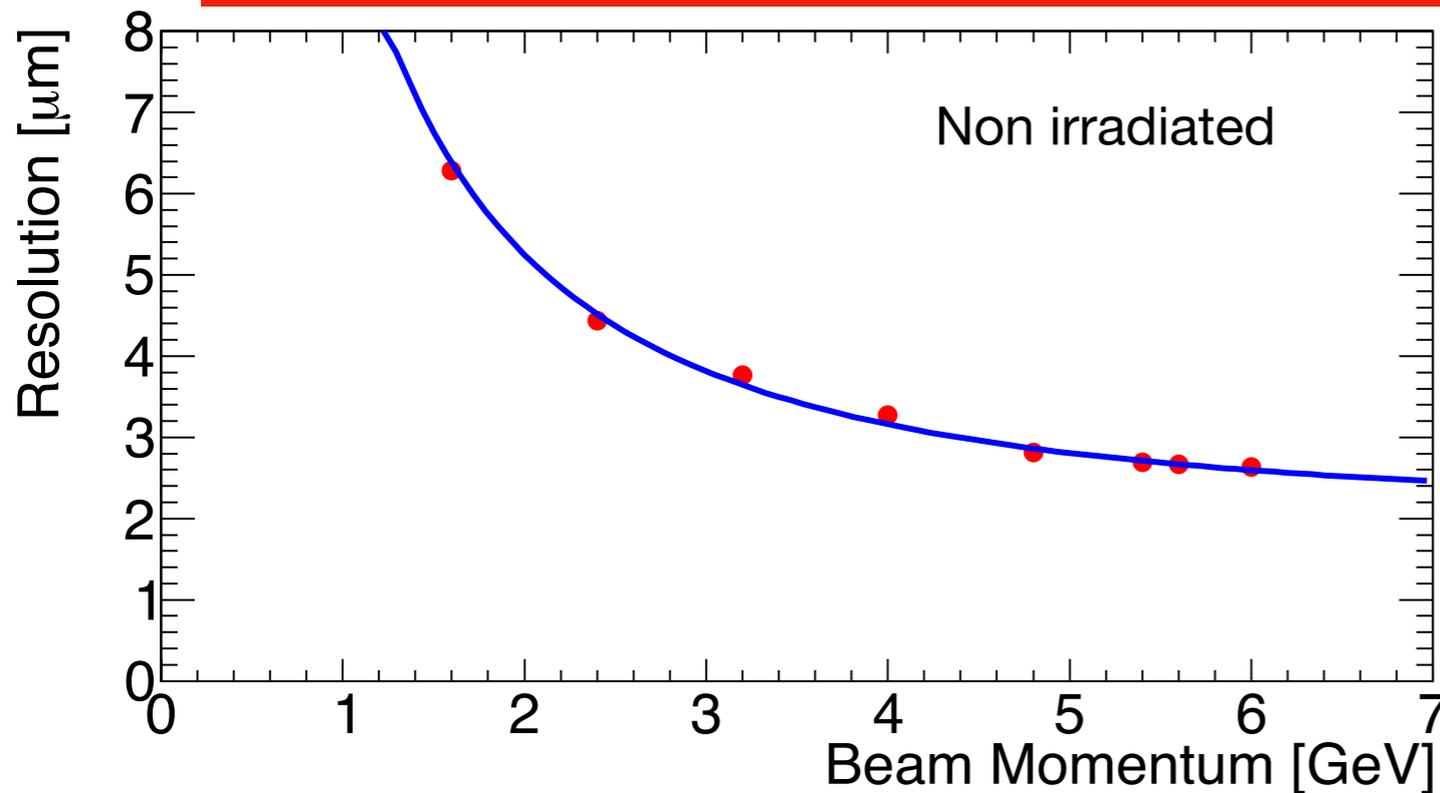


Finding the angle giving the best resolution

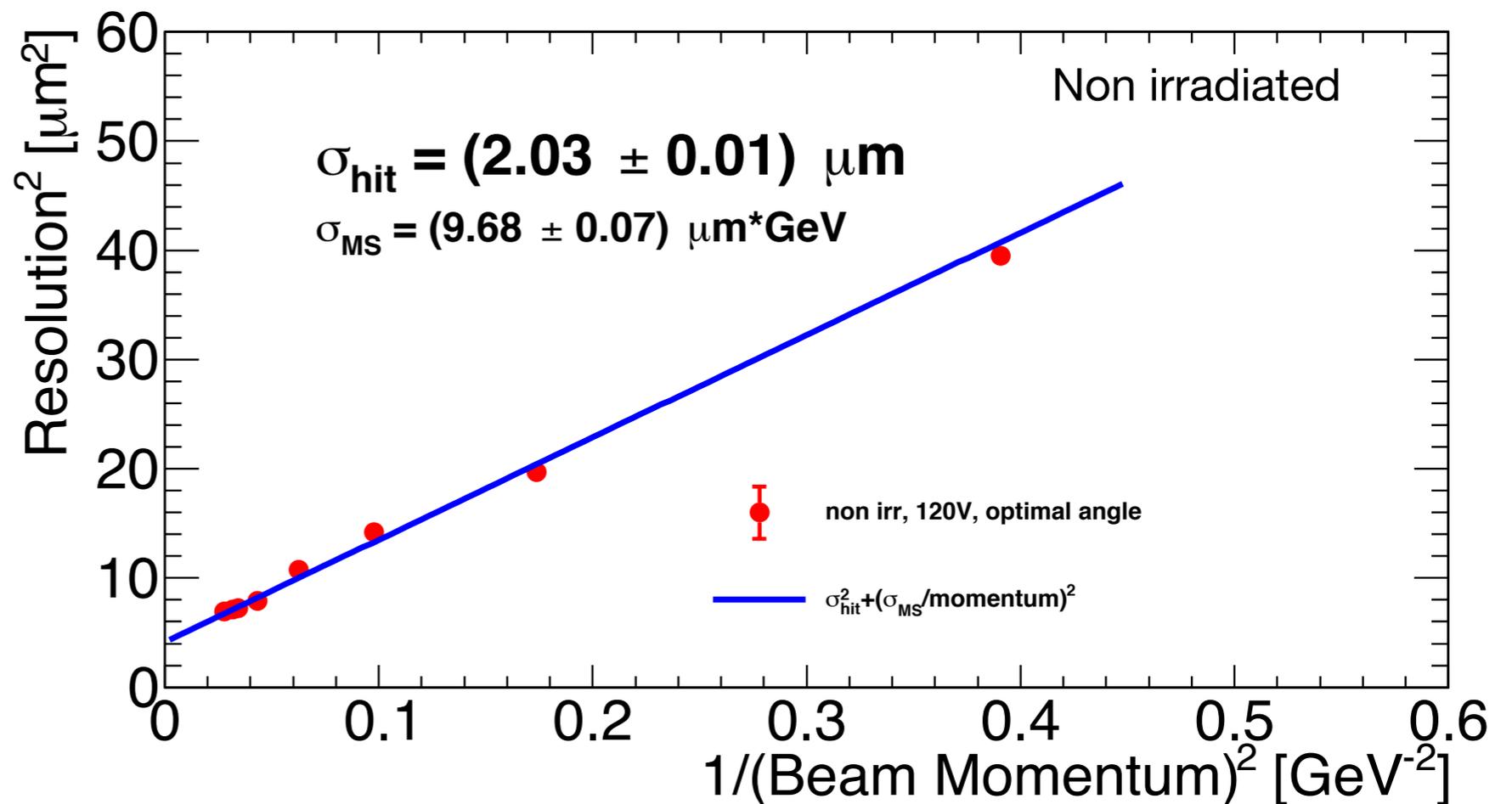
- ▶ Angle that maximises the number of clusters of size 2 for 150 μm thickness and 25 μm pitch: 9.5°
- ▶ Given the system an uncertainty of $\pm 1^\circ$ is considered
- ▶ Beam momentum 5.6 GeV



Momentum scan

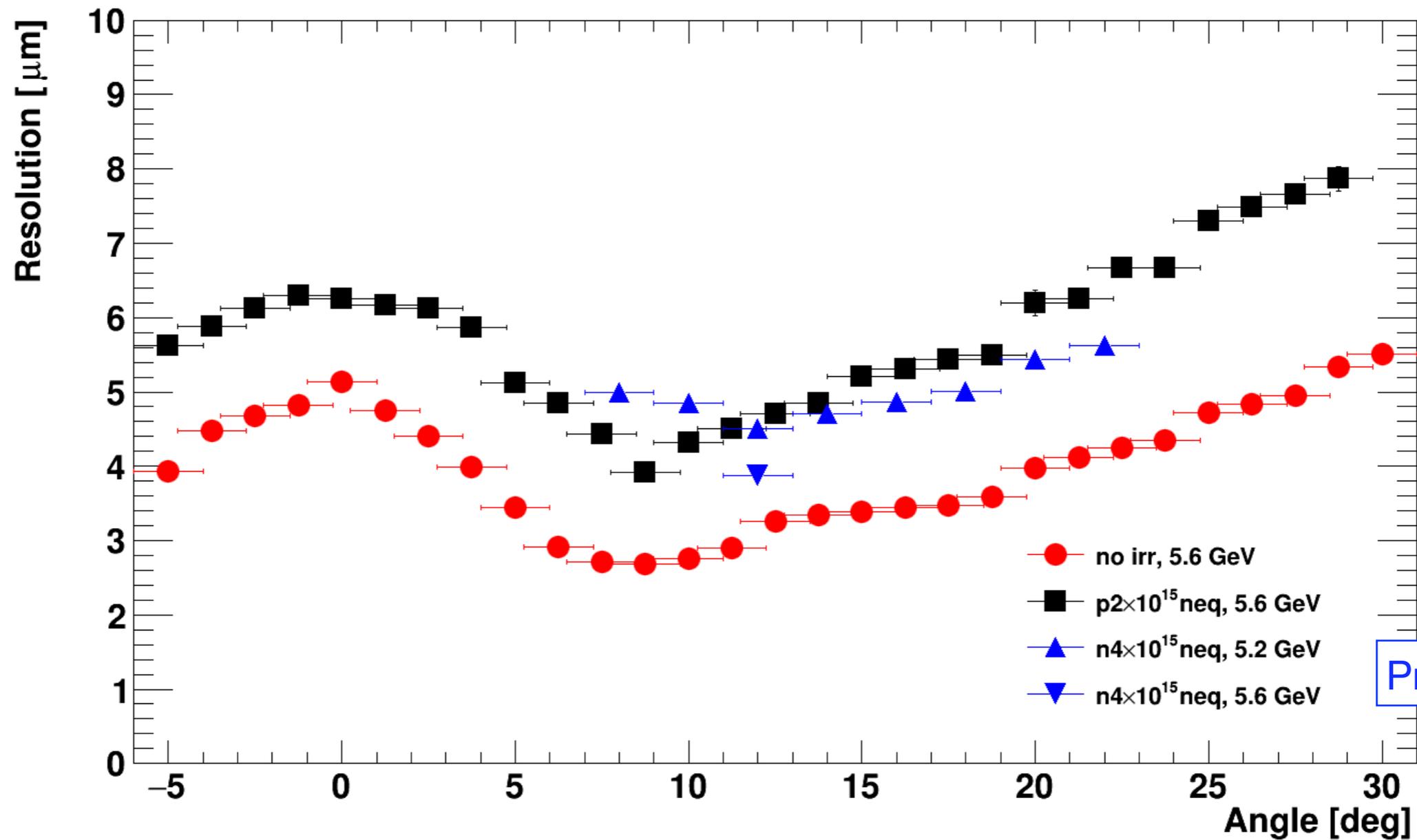


- ▶ Spatial **resolution improves** increasing the beam **energy**
 - ▶ Smaller impact of the multiple scattering
 - ▶ Extrapolation at **infinite beam momentum** gives the **intrinsic resolution**
 - ▶ **Linear** dependence of **Resolution²** vs **1/p²**



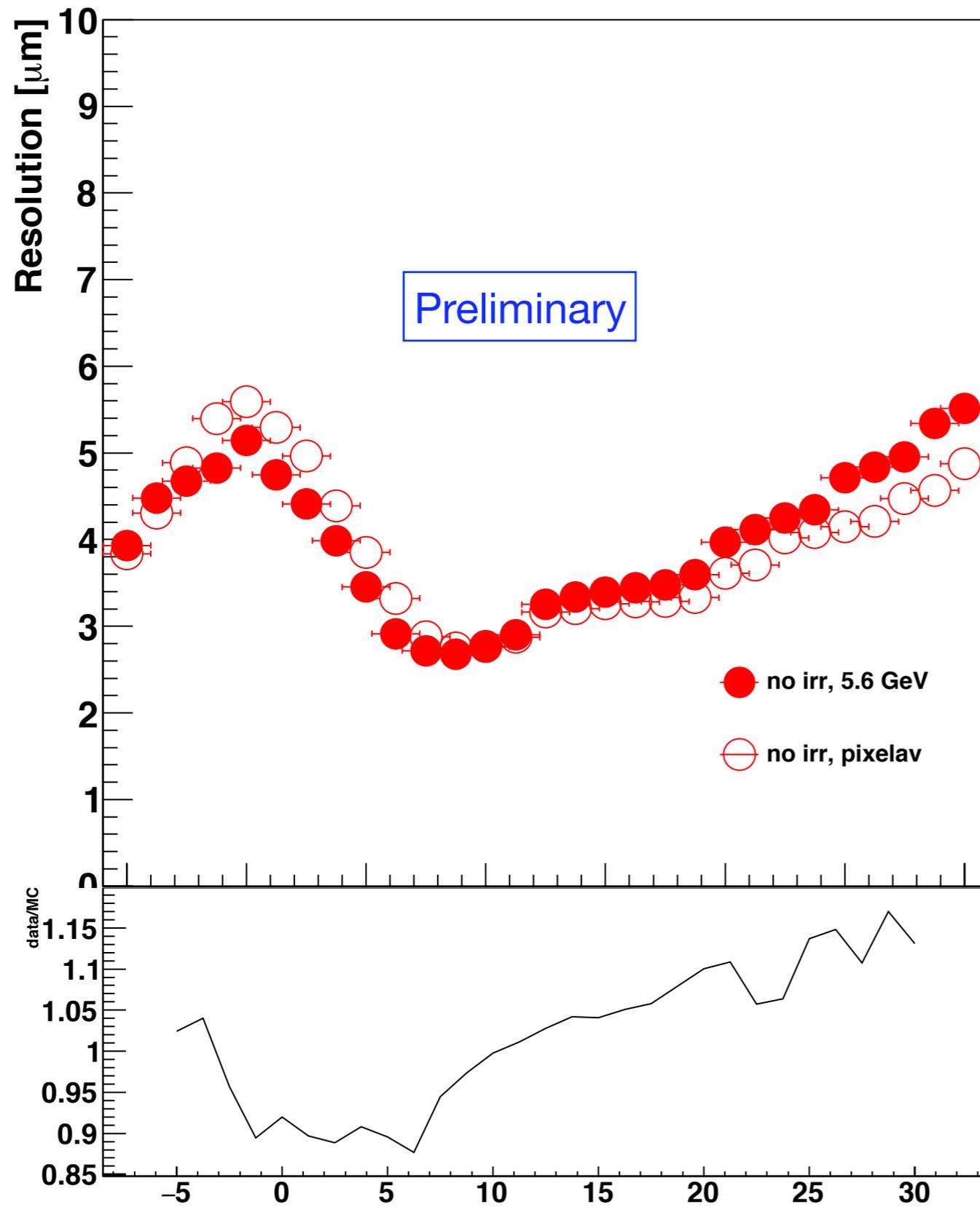
$$\text{Resolution}^2 = \sigma_{\text{hit}}^2 + \frac{\sigma_{\text{MS}}^2}{p^2}$$

Angle scans scan



- ▶ Very good resolution also after irradiation
- ▶ After neutron irradiation same resolution as with protons is achieved
 - ▶ But at a larger angle

Comparison with simulation



► Work in progress

► Threshold & thickness need to be tuned

Conclusions and outlook

- ▶ Successful use of the “**Dreimaster**” for resolution studies
 - ▶ Does **not** rely on an **external reference tracking detector**

At the **optimal angle** for charge sharing & beam **energy of 5.6 GeV** for

- ▶ n+p-pixel sensors
- ▶ 150 μm thicknesses
- ▶ **100x25 μm^2**

the measured single hit resolution is

- ▶ **< 3 μm** for a **non irradiated** sensor
- ▶ **< 4 μm** for a **proton irradiated** sensor @ $\phi_{\text{eq}} = 2 \times 10^{15} \text{ cm}^{-2}$

- ▶ **Optimal angle (@800 V) doesn't change with an irradiation up to $\phi_{\text{eq}} = 2 \times 10^{15} \text{ cm}^{-2}$,**
according to the achieved uncertainty

- ▶ **< 4 μm** for a **neutron irradiated** sensor @ $\phi_{\text{eq}} = 4 \times 10^{15} \text{ cm}^{-2}$

- ▶ **Intrinsic resolution of 2 μm** for a **non irradiated** sensor



Almost no degradation
of the resolution with
irradiation!

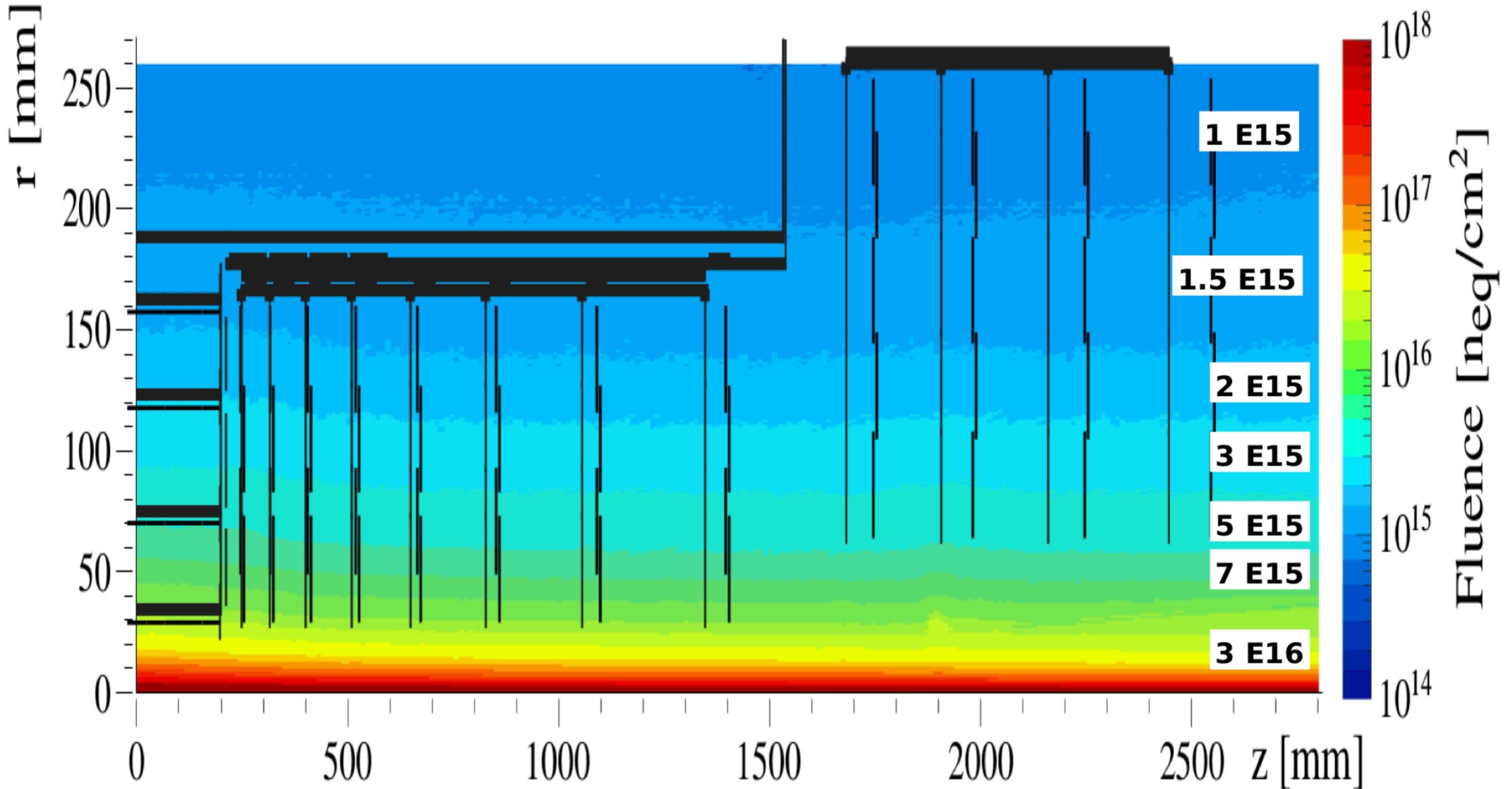
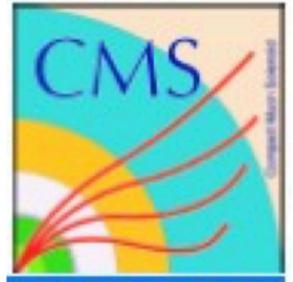
Outlook

- ▶ Improve resolution with cluster interpolation method
- ▶ Include simulation (also for irradiated sensors)
- ▶ **Dreimaster for RD53A chips**

Additional material

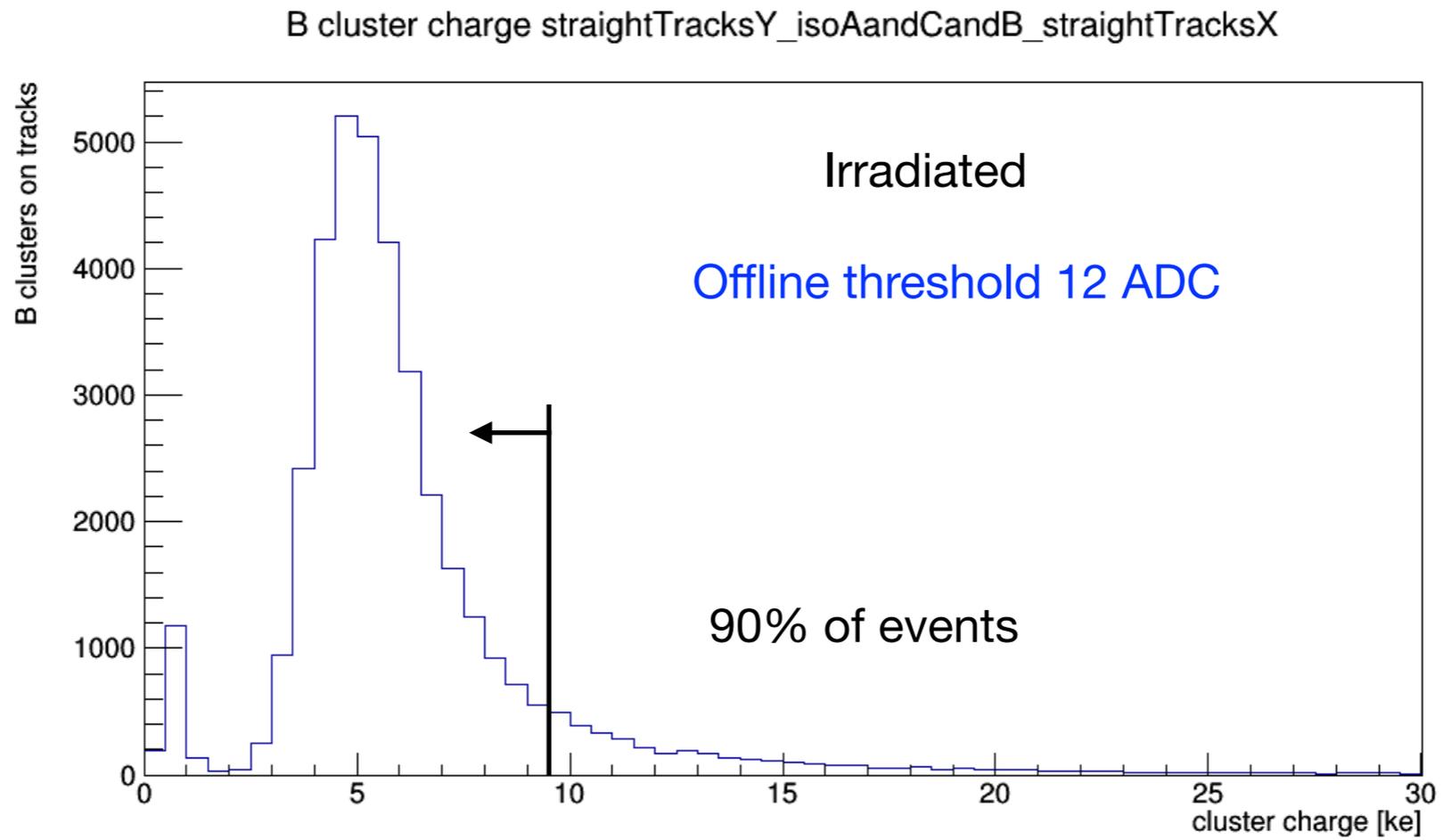
CMS expected fluence

after 3 ab^{-1} at 14 TeV



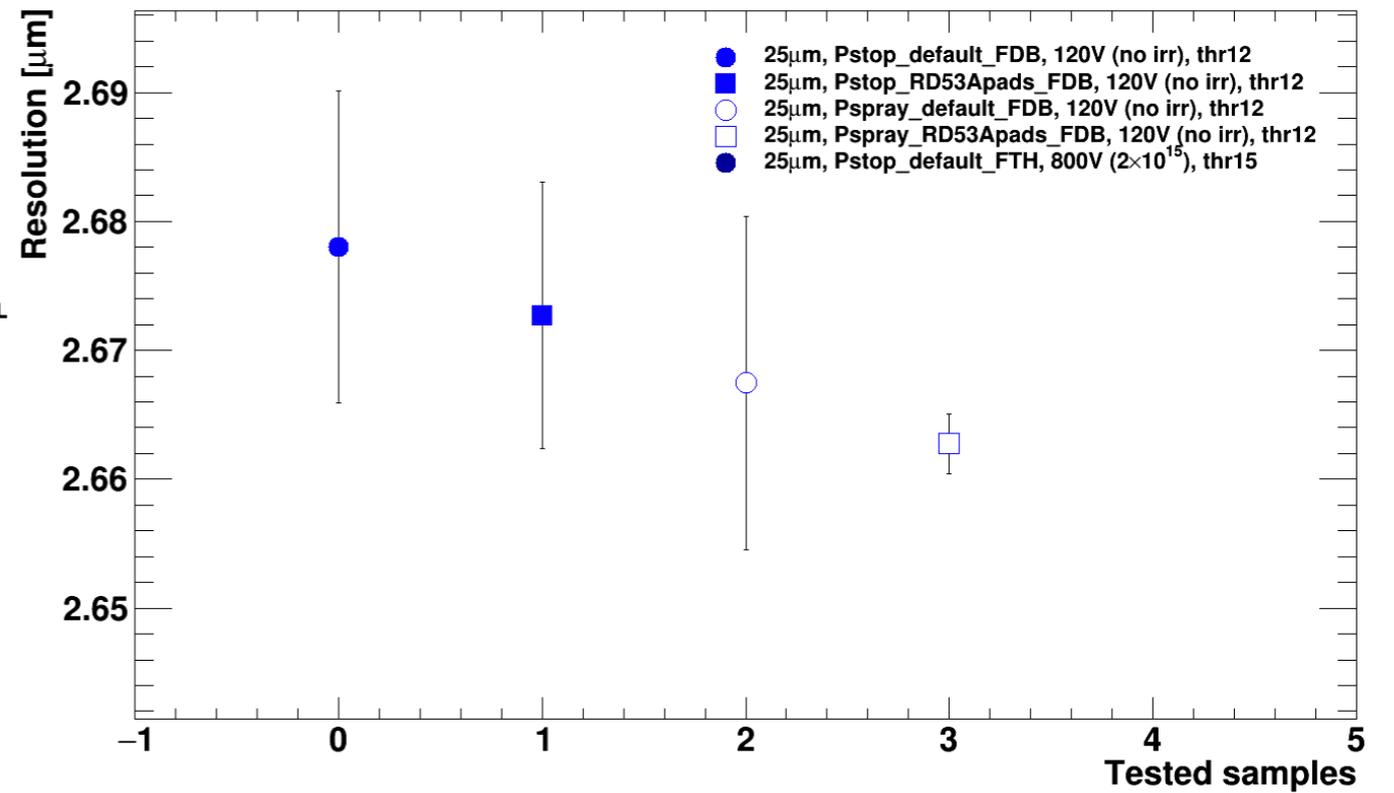
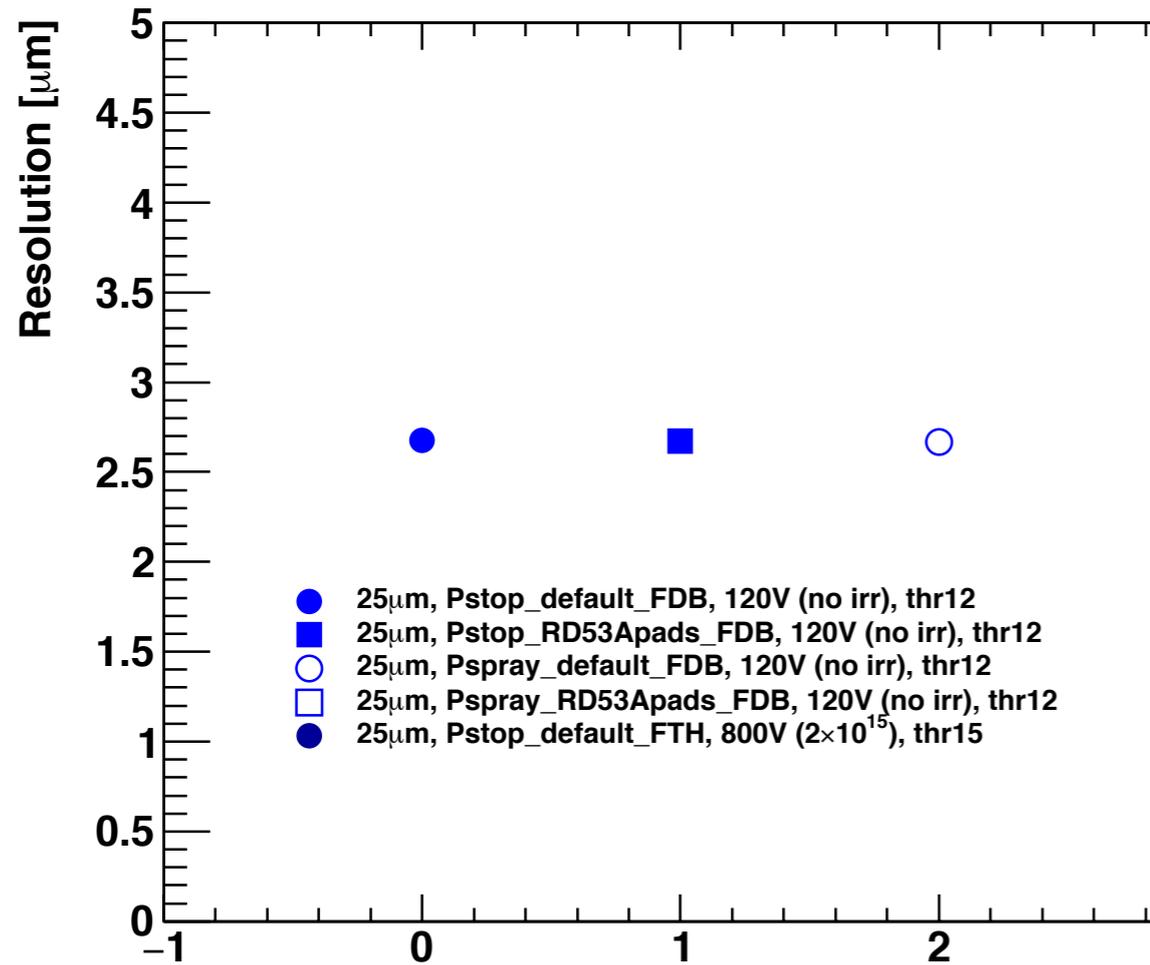
CMS Fluka 3.7.2, Phase II Tracker TDR p 148 (2017)

Irradiated Landau at lower threshold



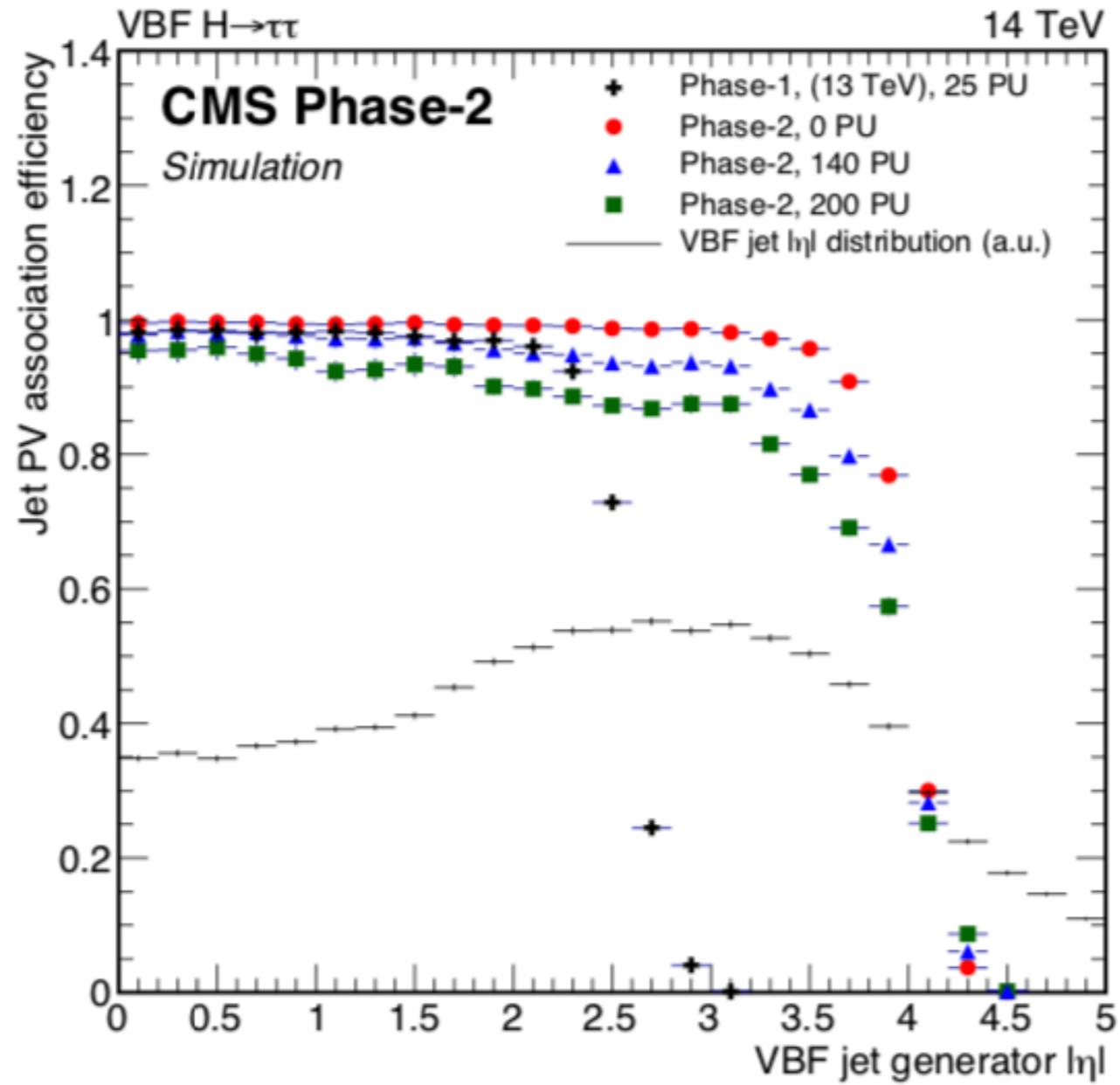
- ▶ Sensors irradiated at CERN PS @ 3.3×10^{15} p/cm² (2×10^{15} n_{eq}/cm²)
- ▶ $\phi_{eq} = 2 \times 10^{15}$ cm⁻²

Resolution comparison



All data taken @ 5.6 GeV
&
best angle

Comparison of Phase-1 and Phase-2 performance with PU



Cluster size at different angles

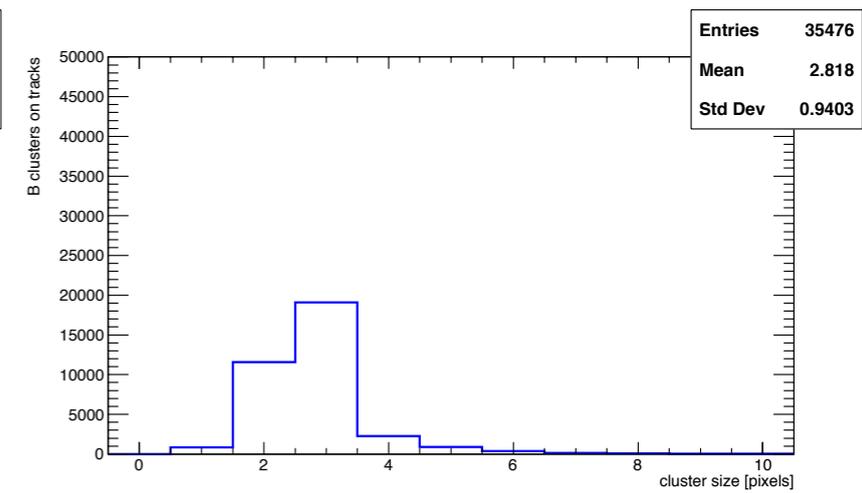
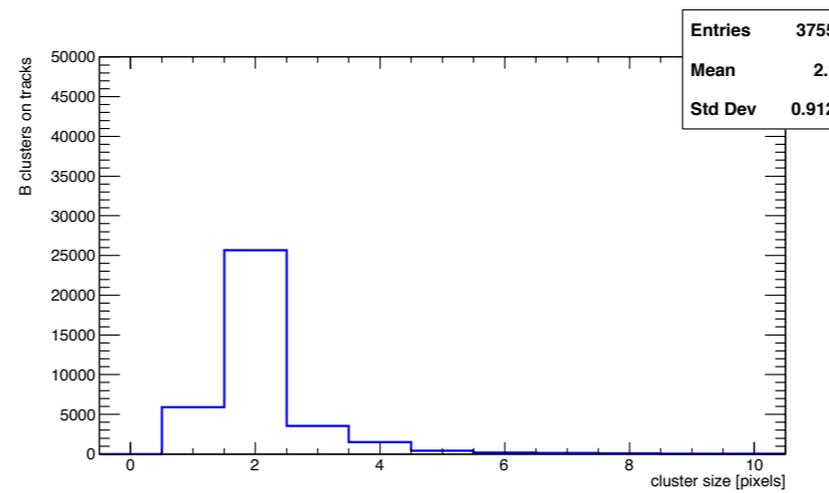
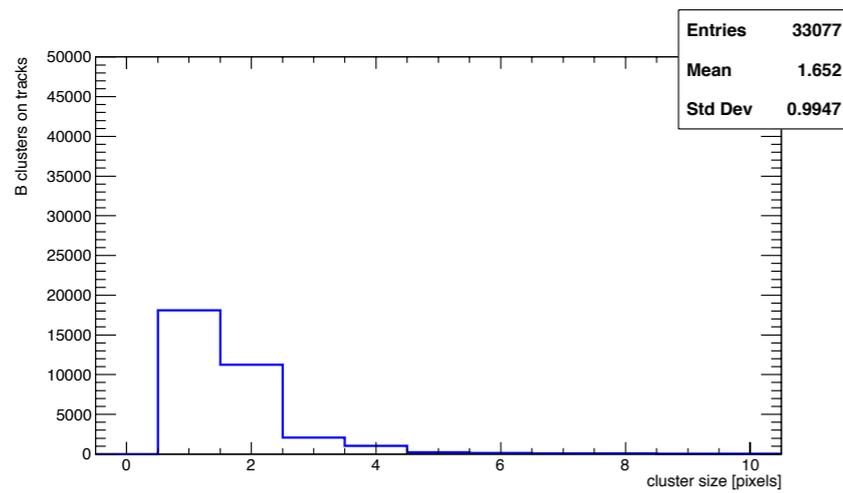
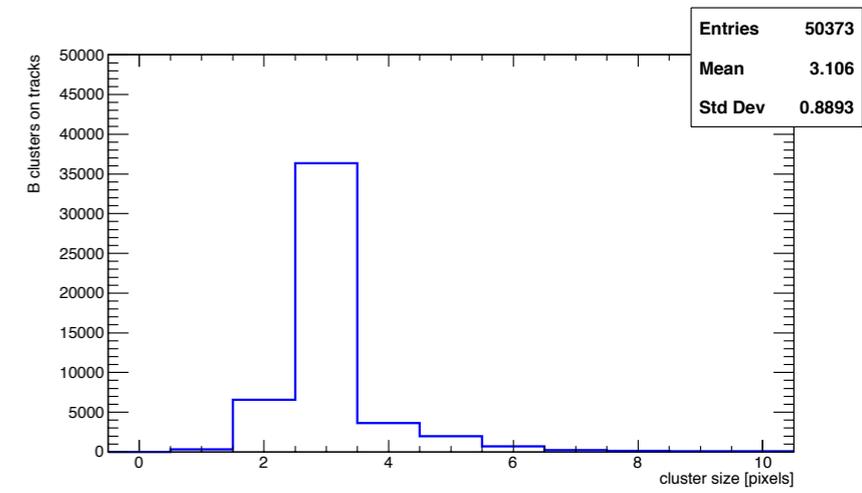
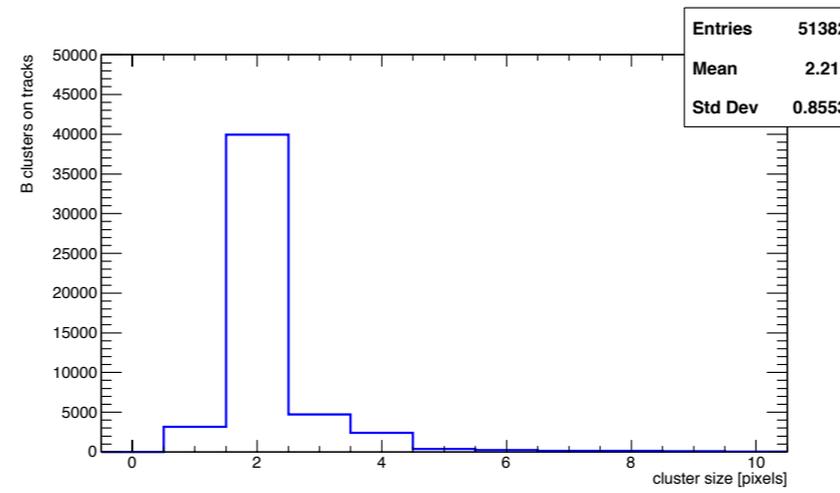
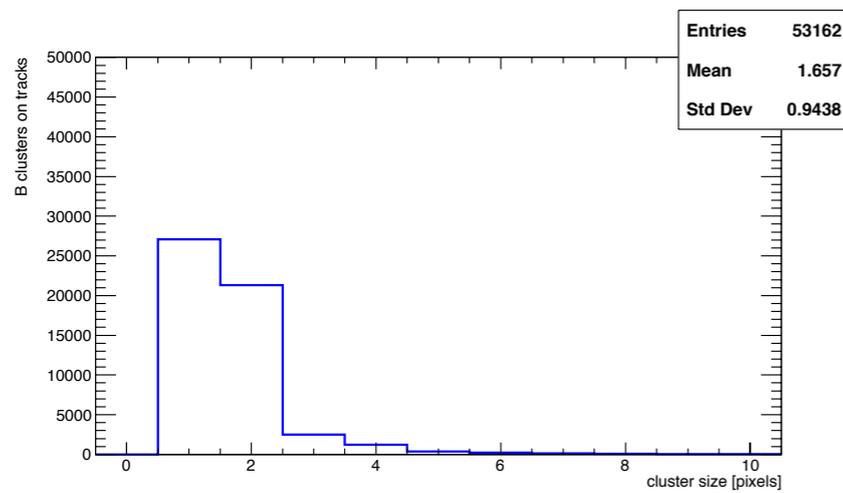
Vertical incidence

Best angle

Second local minimum

Non irradiated

Irradiated



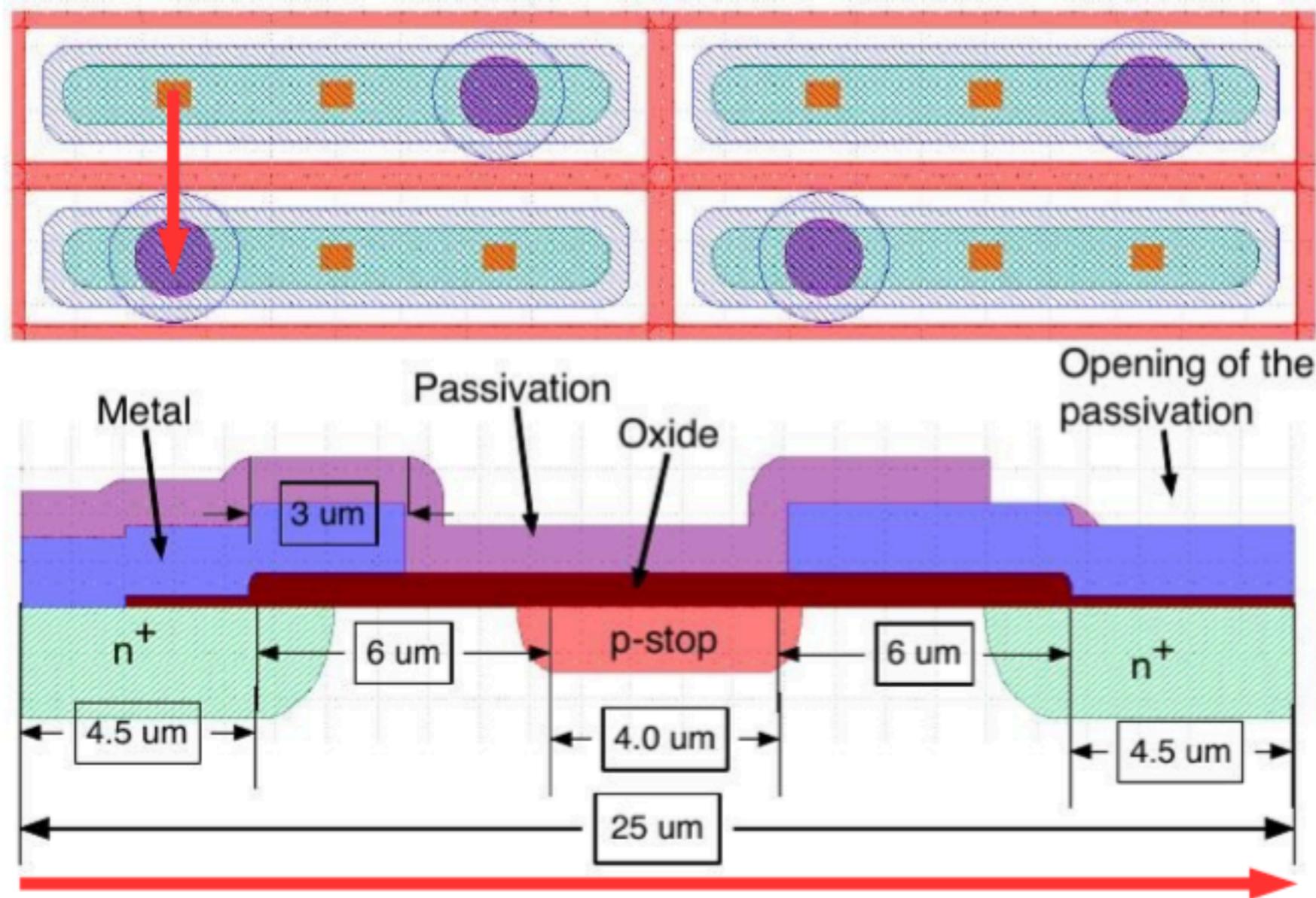
3M measurements overview

	sensor	irr[10 ¹⁵ n _{eq}]	pitch[μm]	bias[v]	Sensor type	thr[ADC]	3M (150V)
Angle Scan	c120i	2	25	800	Pstop_default_FTH	20	A=148 (Pstop_RD53Apads FDB), C=163 (Pspray_RD53Apads_FDB)
	c150	0	25	120	Pstop_default_FDB	12	A=148 (Pstop_RD53Apads FDB), C=163 (Pspray_RD53Apads_FDB)
Angle Scan	c148	0	25	120	Pstop_RD53Apads_FDB	12	A=109 (Pstop default FTH), C=110 (Pstop bdot large FTH)
	c146	0	25	120	Pspray_default_FDB	12	A=163 (Pspray_RD53Apads_FDB), C=148 (Pstop_RD53Apads FDB)
Mom Scan	c163	0	25	120	Pspray_RD53Apads_FDB	12	A=148 (Pstop_RD53Apads FDB), C=150 (Pstop_default FDB)

sensor	irr[10 ¹⁵ n _{eq}]	pitch[um]	bias[v]	short	thr[ADC]	3M (150V)
c152	0	50	120	Pstop_default_FDD	12	A=158 (FDD), C=159 (FDB)
c160	0	50	120?	Pstop_bdotwigggle_FDB	12	A=152 (FDD), C=159 (FDB)

Sensor design

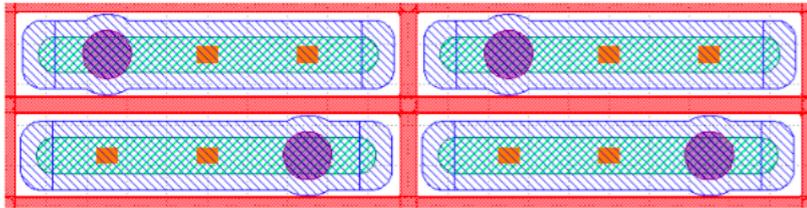
Top view 100x25 μm^2 default design



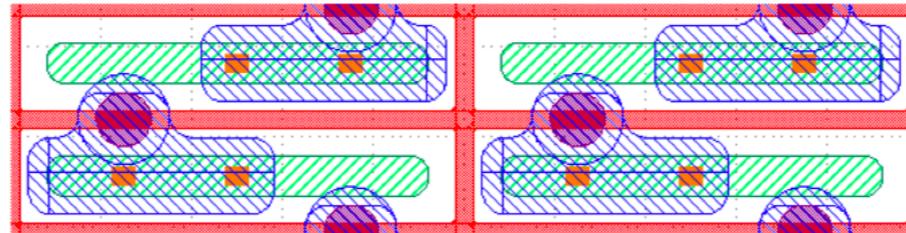
Cut image along **red arrow**

Sensor design

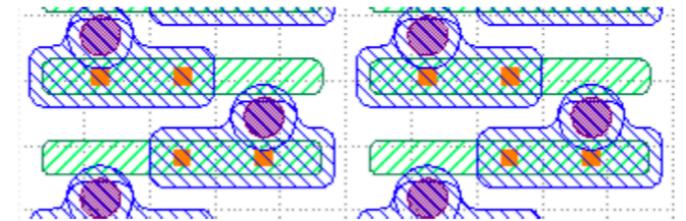
Pstop default



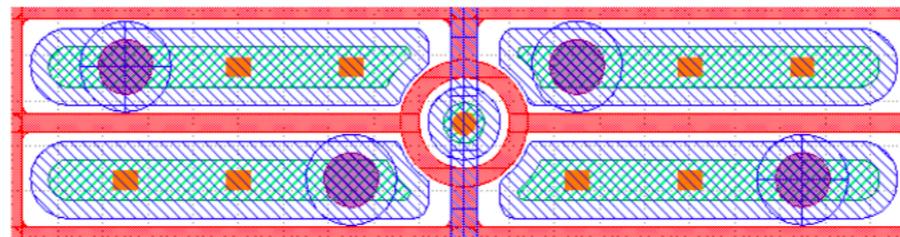
Pstop RD53Apads



Pspray RD53Apads



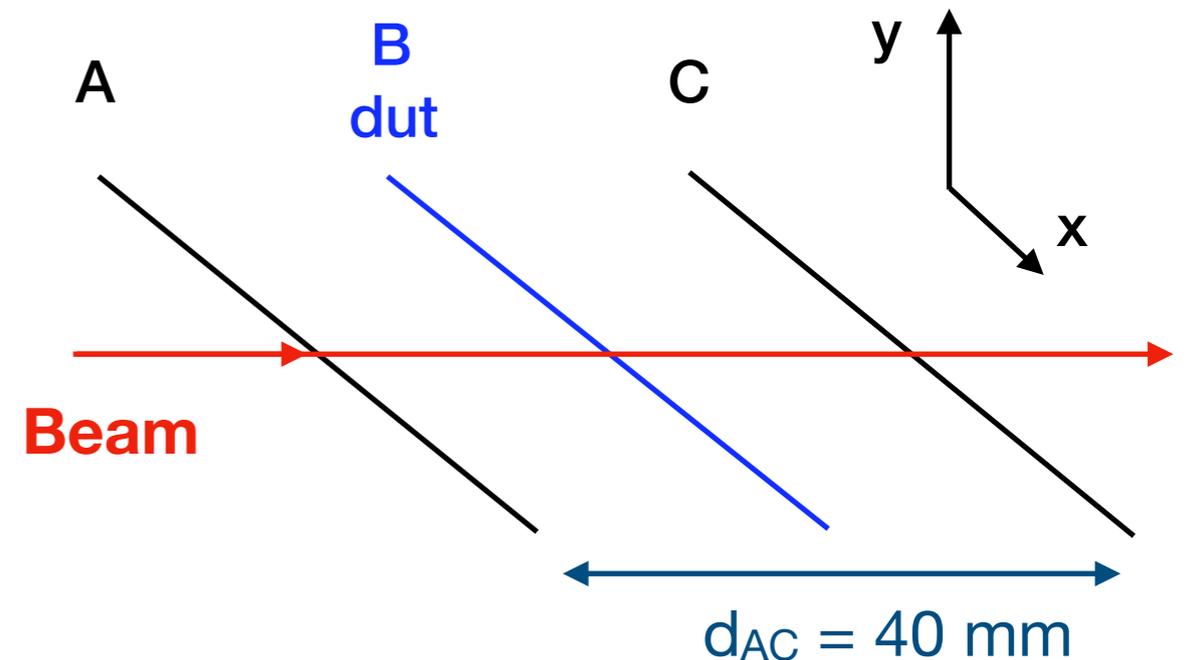
Pstop B dot large



1. Alignment

- **Assumptions:**

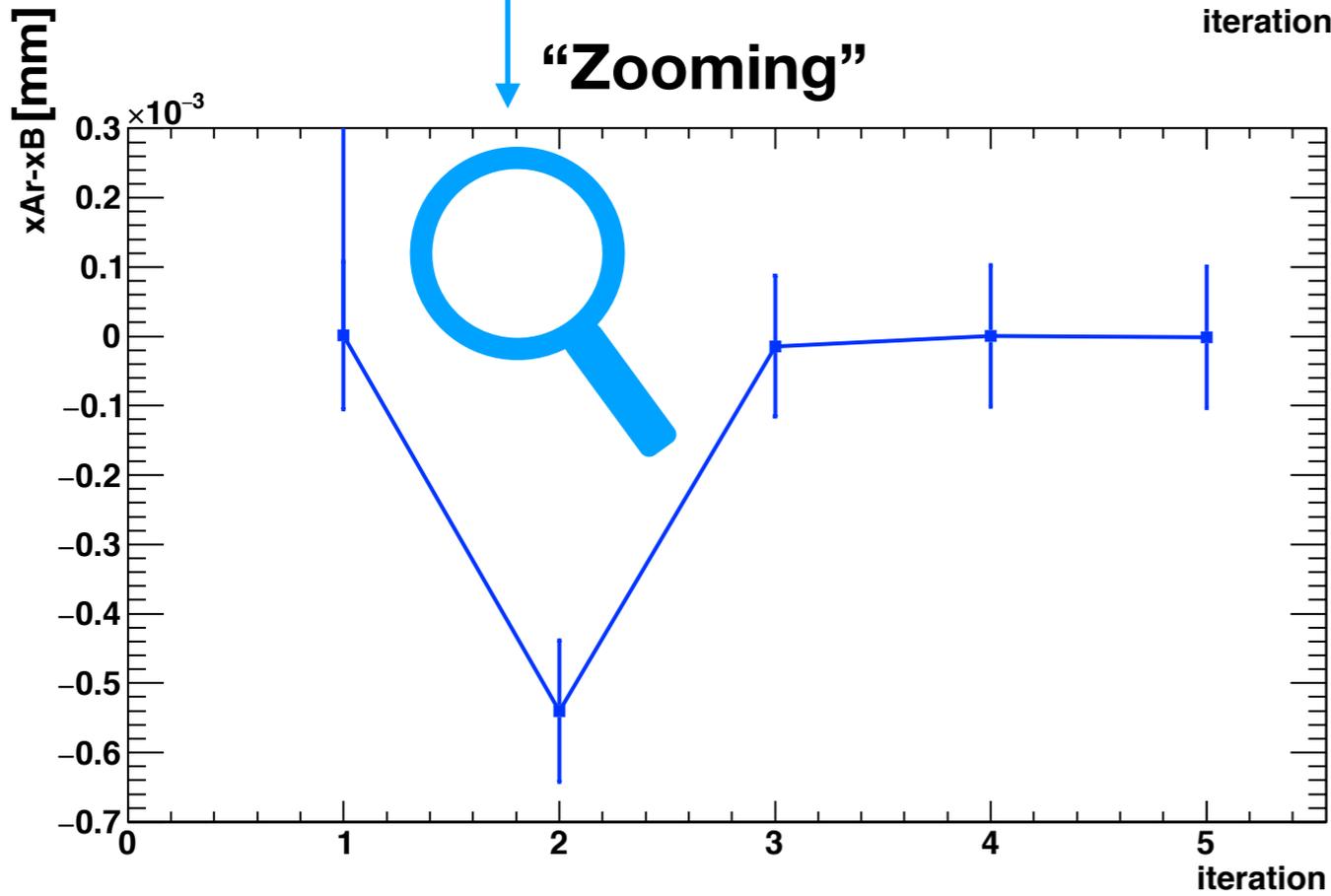
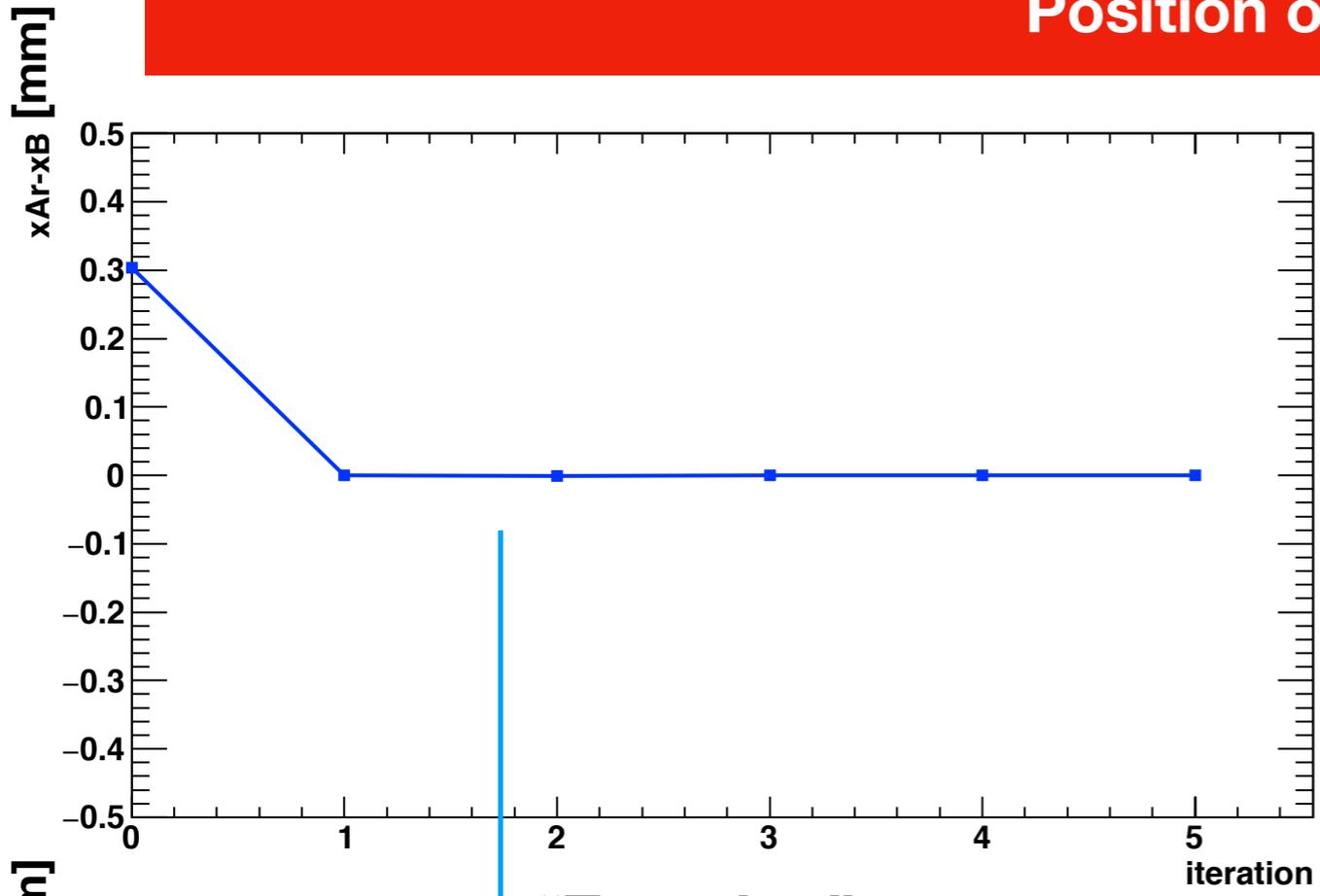
- Straight beam
 - $|dy|$ & $|dx| < d_{AC} * 1 \text{ mrad} * 3 * 5/E_{\text{beam}}$
- Parallel Dreimaster planes



- **Parameters:**

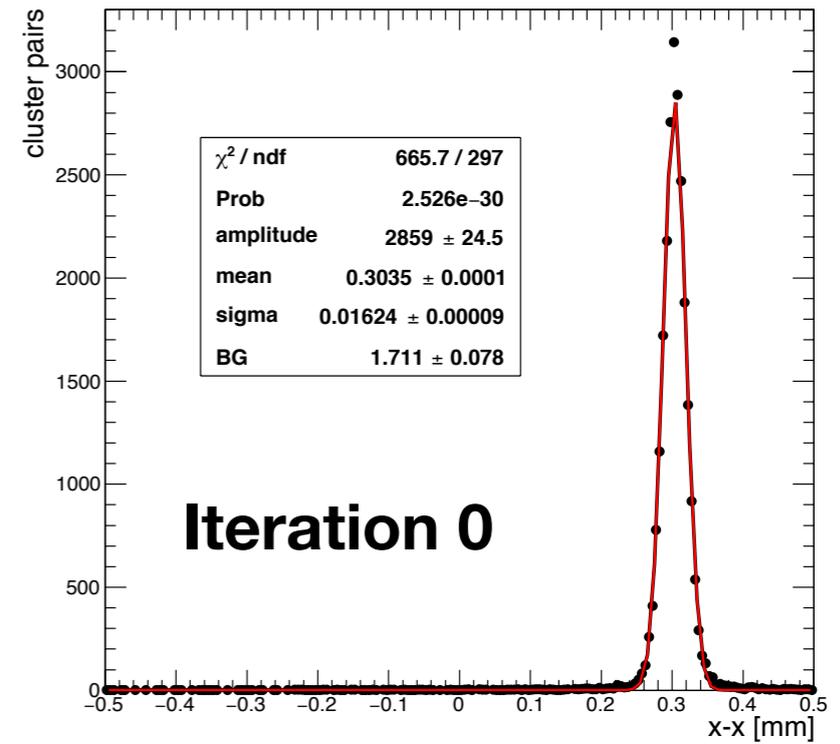
- Position of $x_B - x_A$ & $x_B - x_C$
- Position of $y_B - y_A$ & $y_B - y_C$
- Slope of
 - $x_B - x_A$ vs y_B
 - $x_B - x_C$ vs y_B } Takes into account rotation around the beam axis
 - dx_3 vs x_B } Takes into account rotation around the y axis (mechanics)

Position of xB-xA

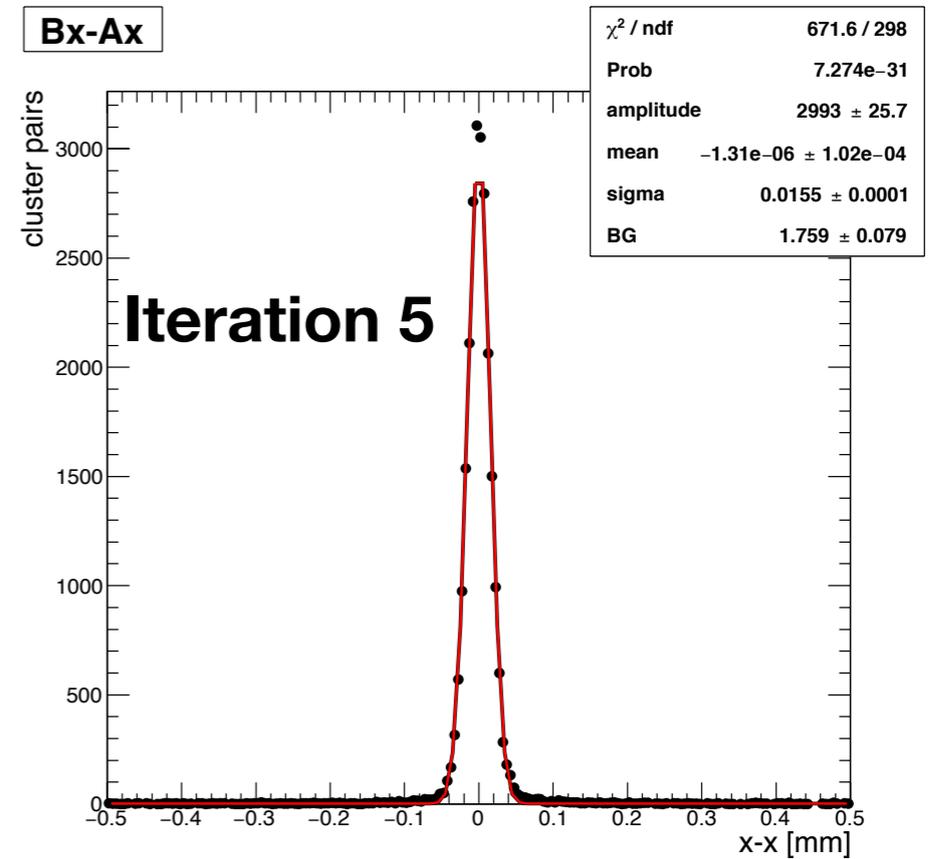


“Zooming”

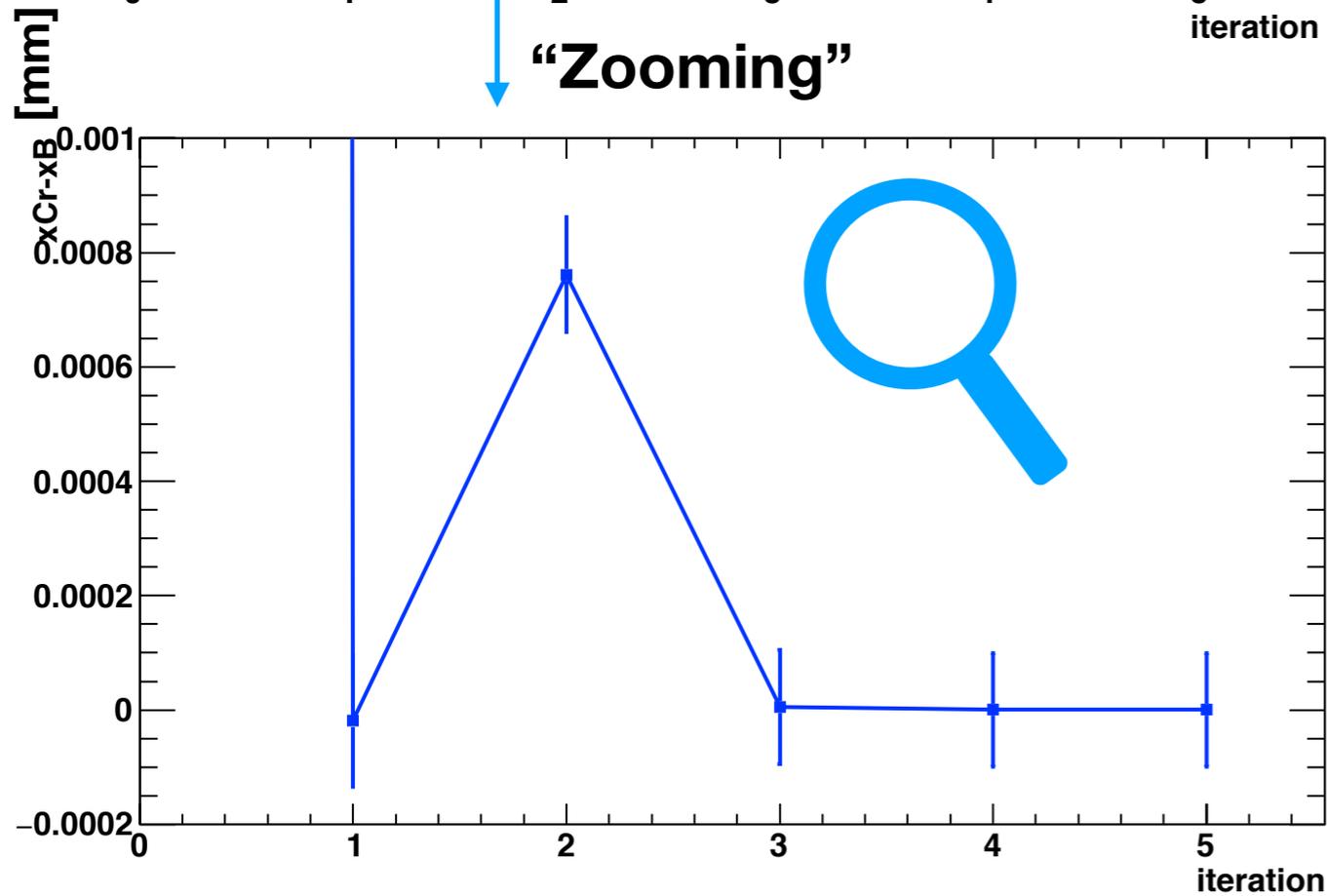
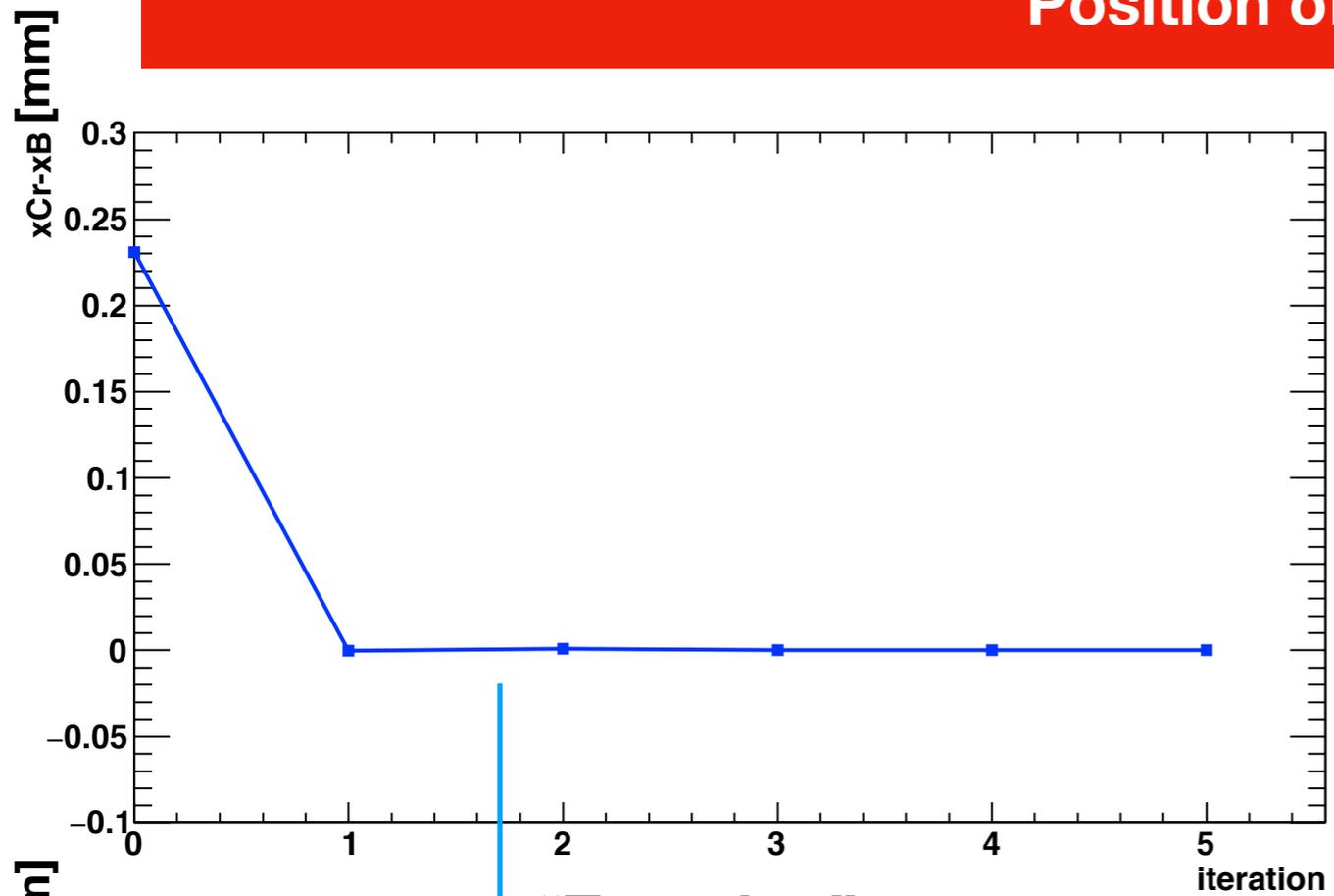
Bx-Ax



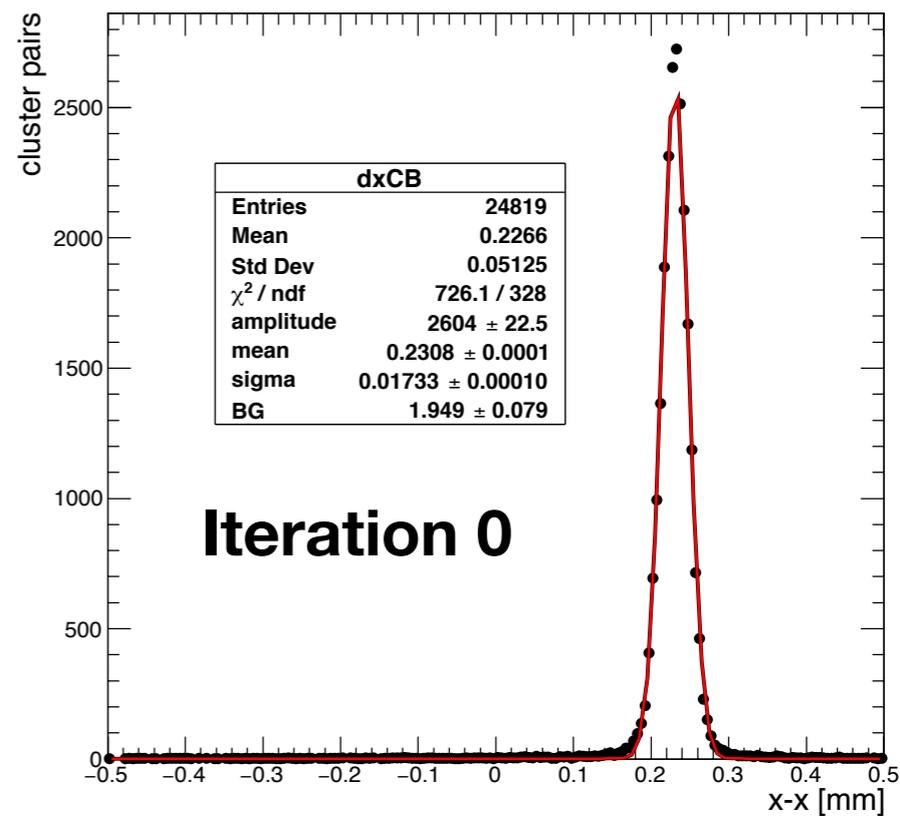
Bx-Ax



Position of xB-xC

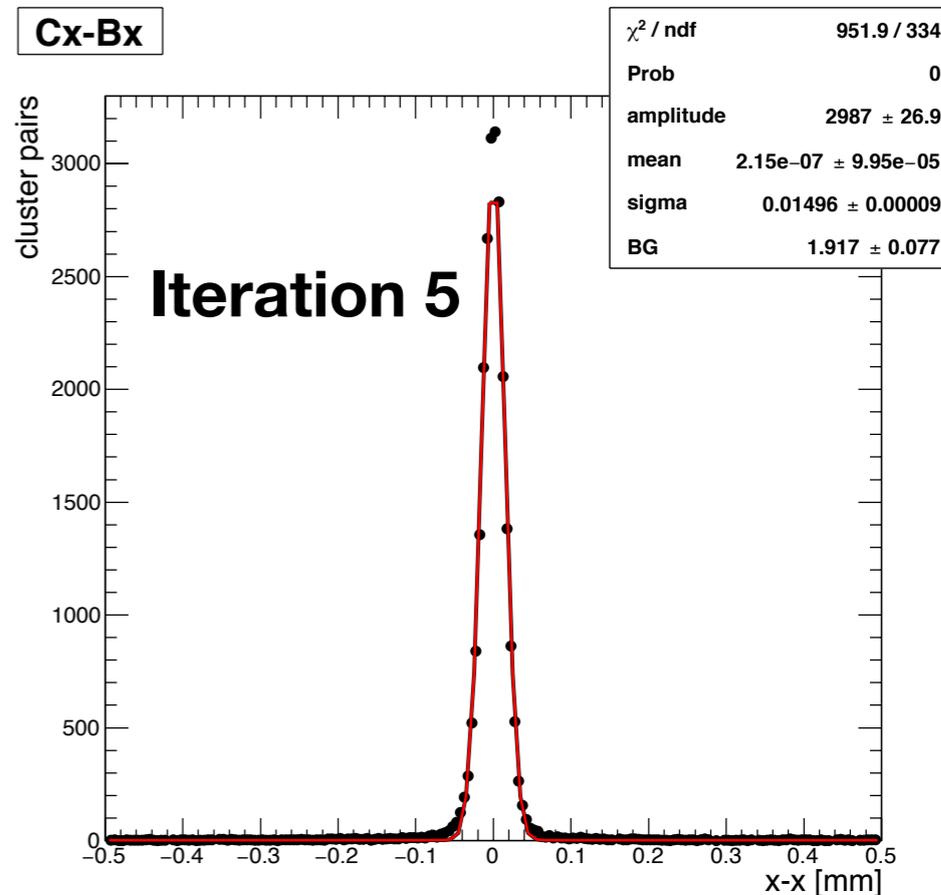


Cx-Bx



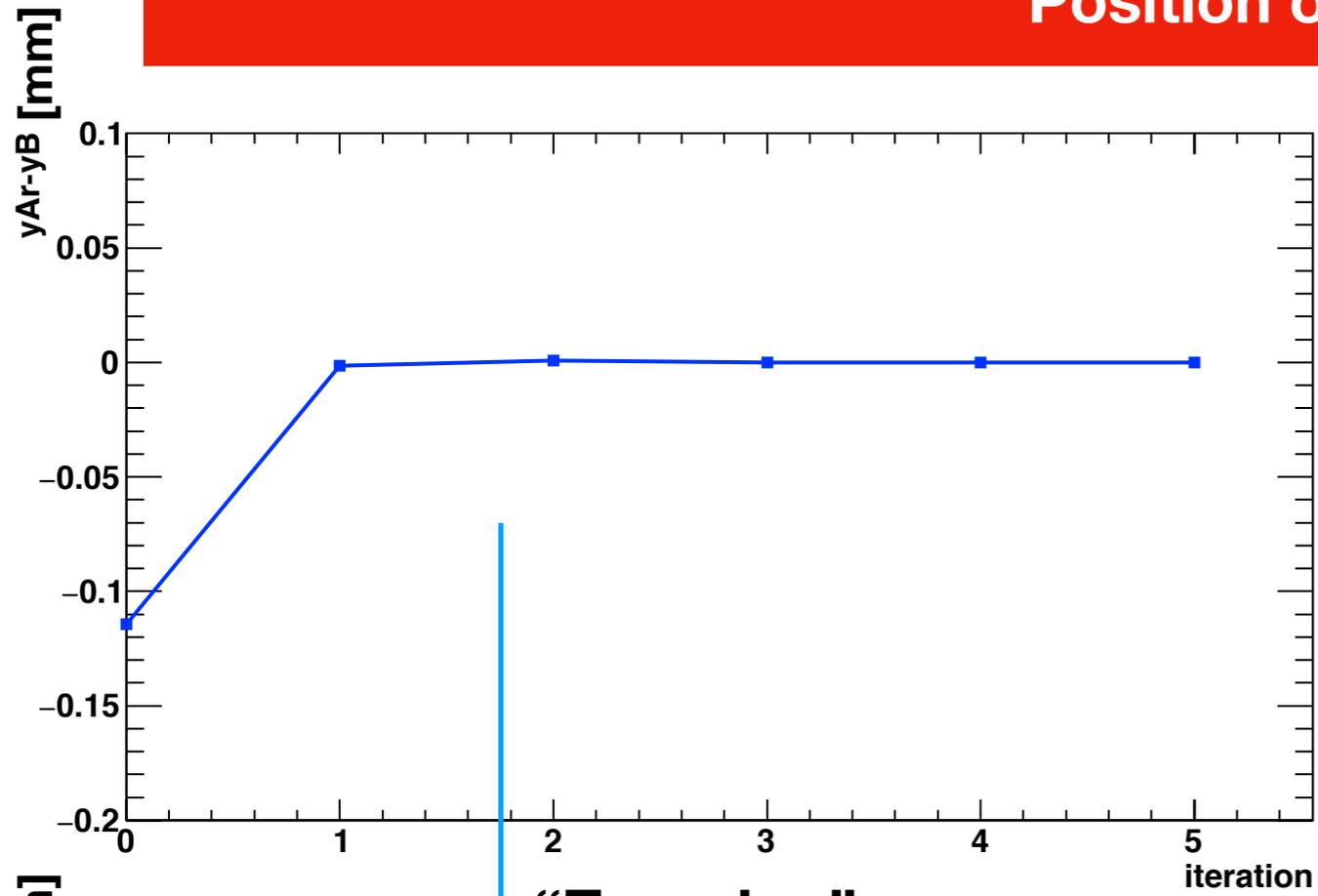
Iteration 0

Cx-Bx

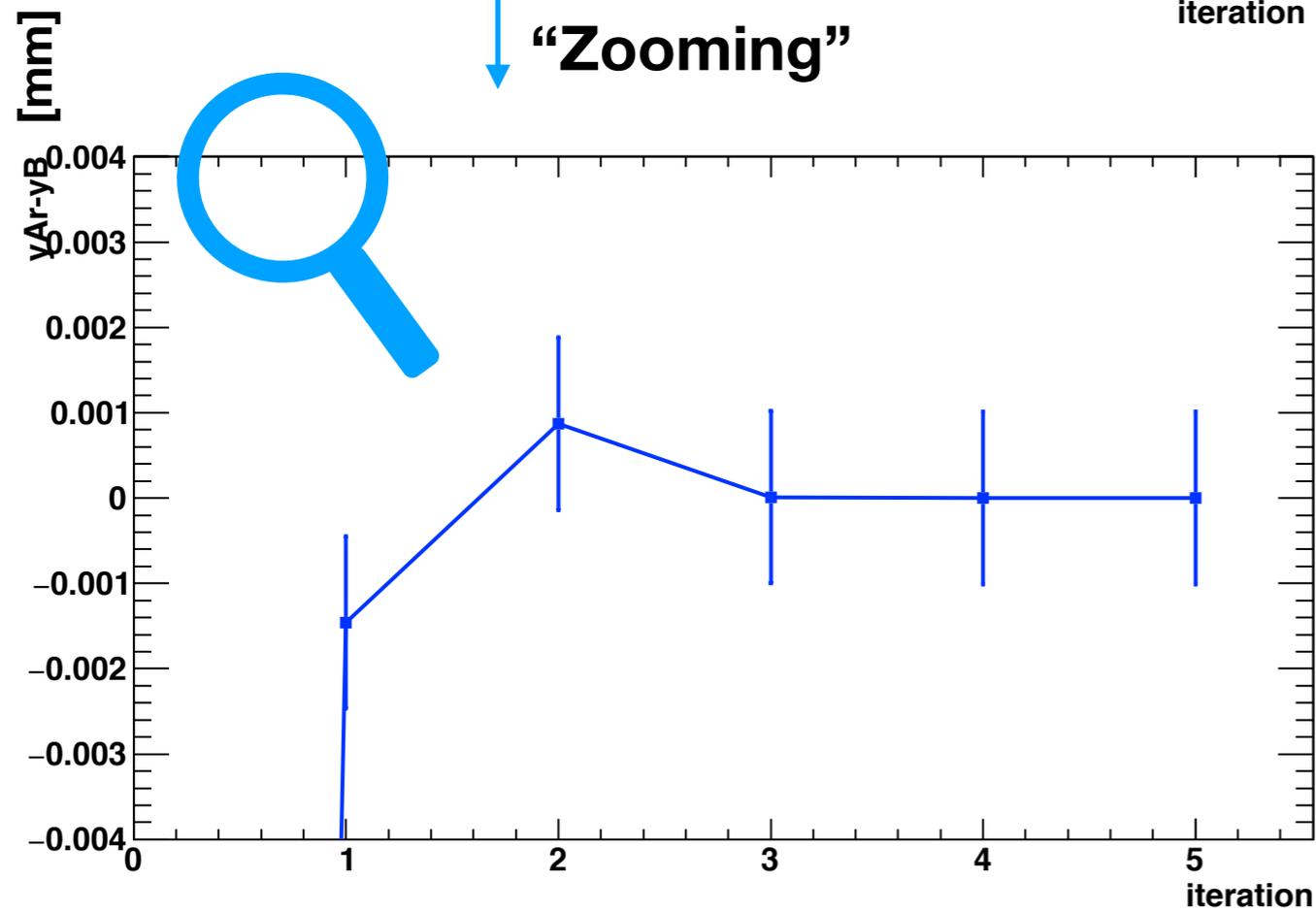


Iteration 5

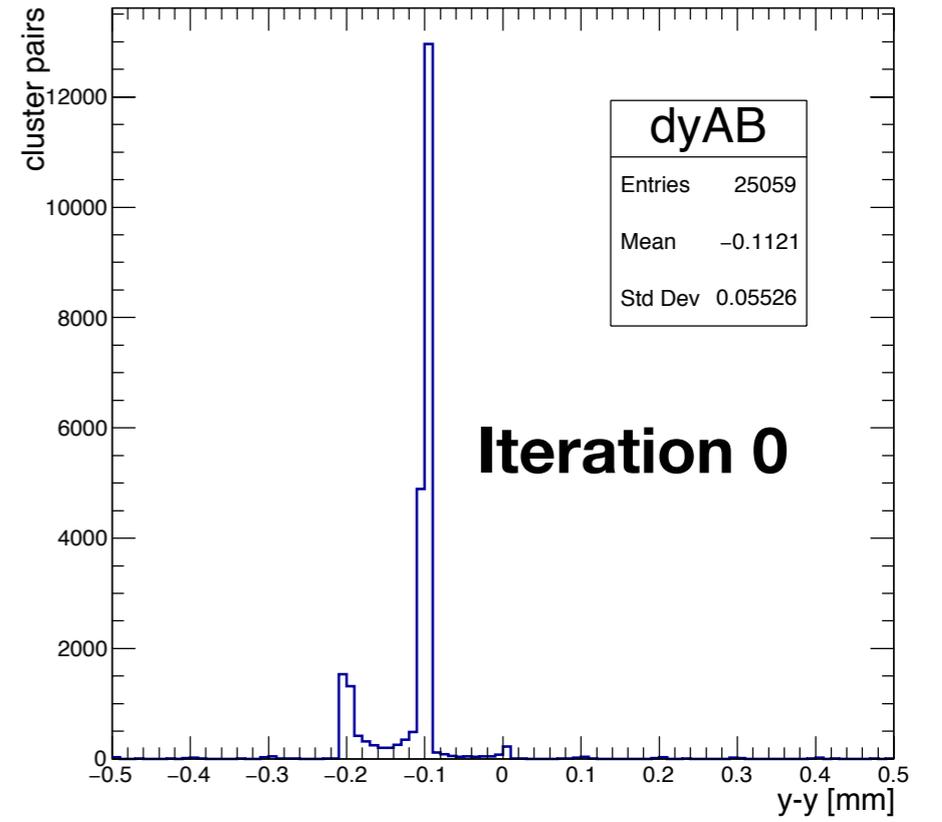
Position of yB-yA



“Zooming”

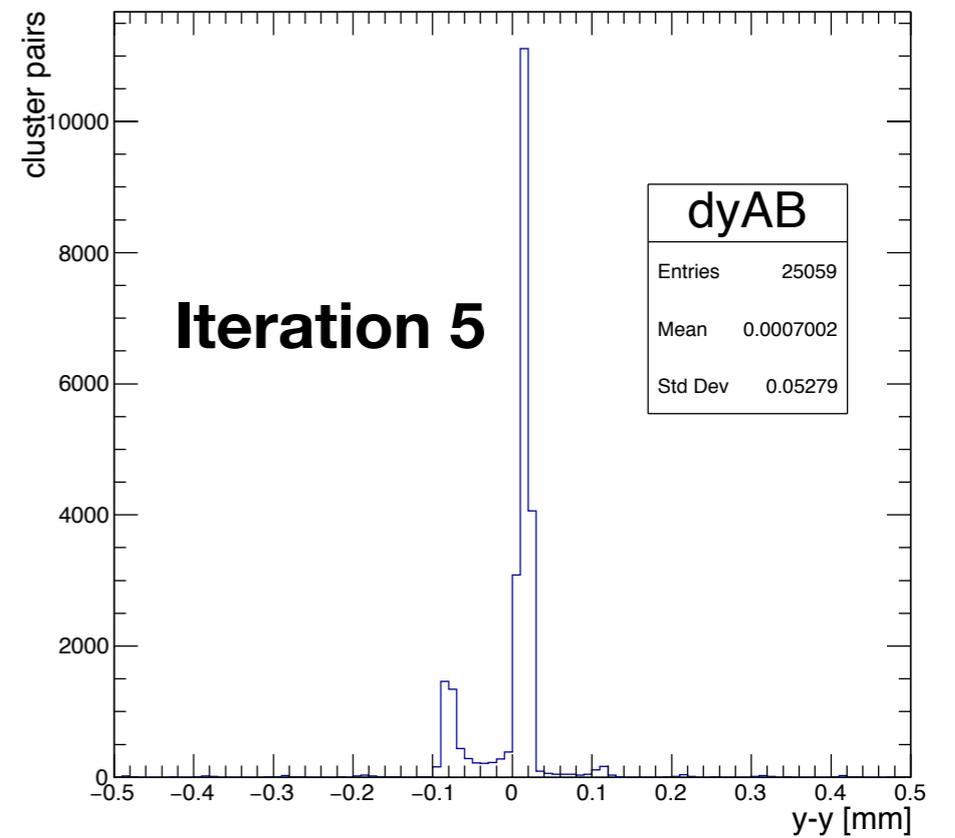


By-Ay



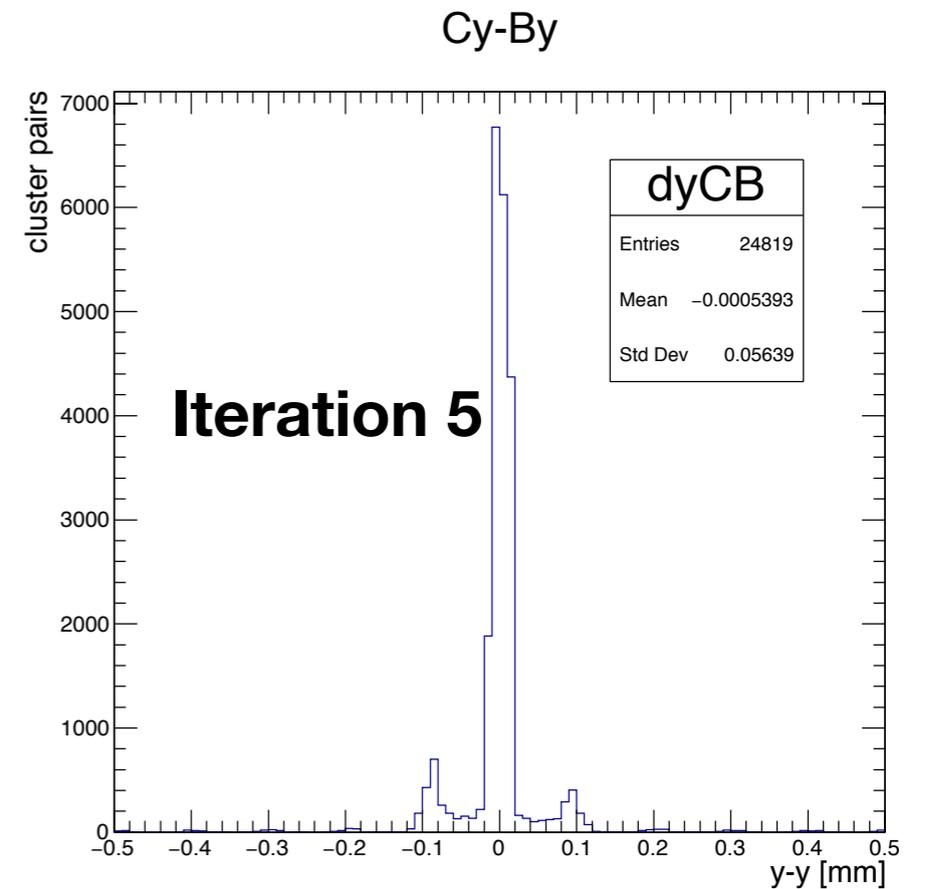
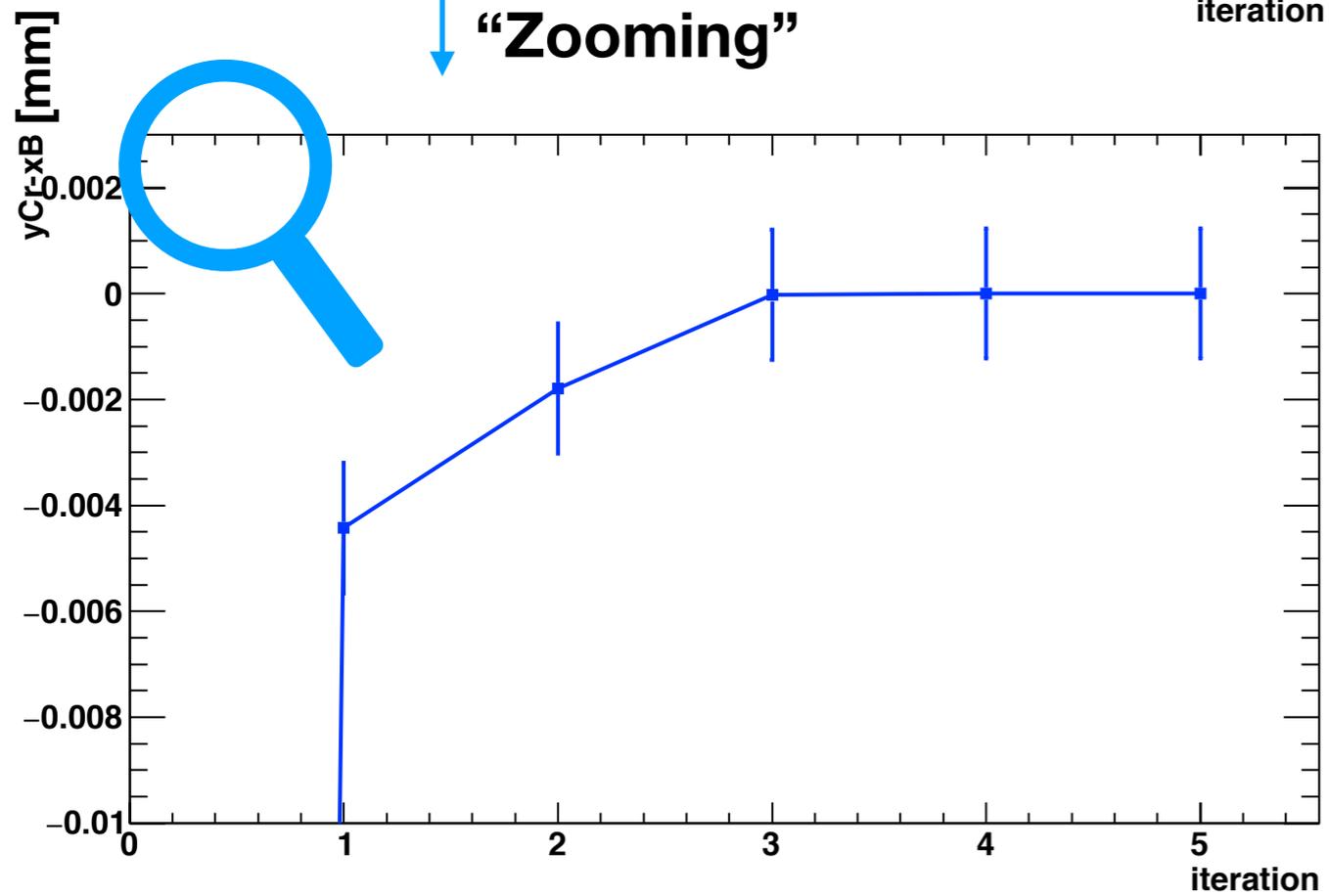
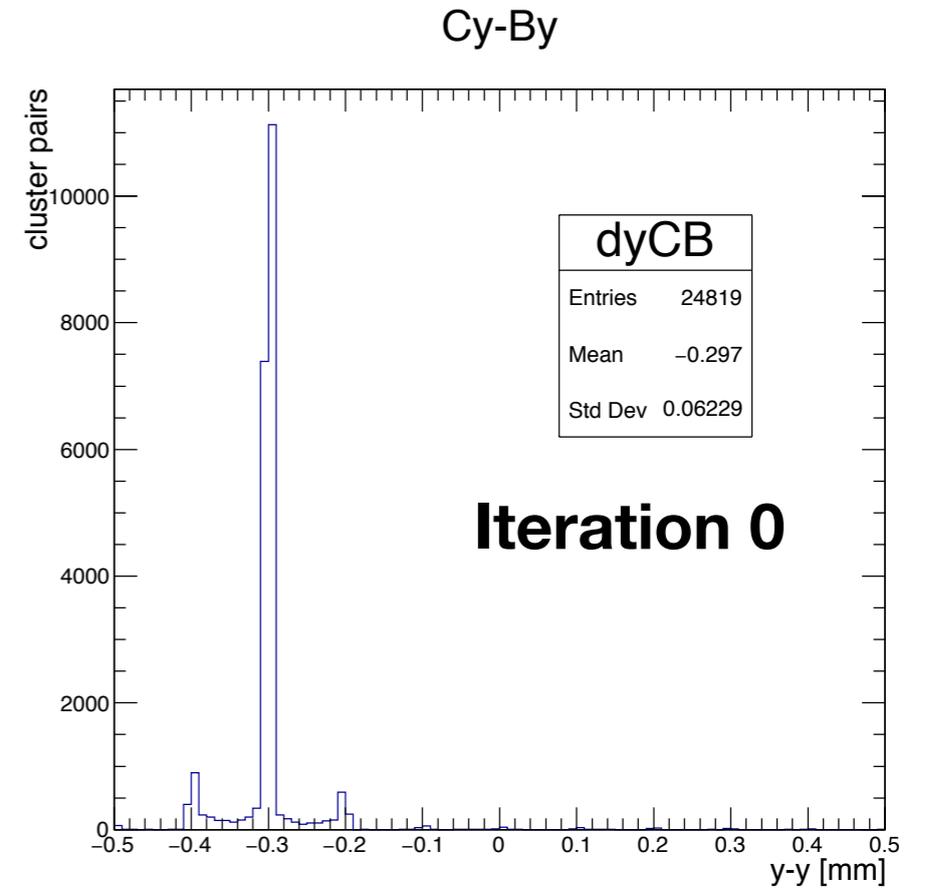
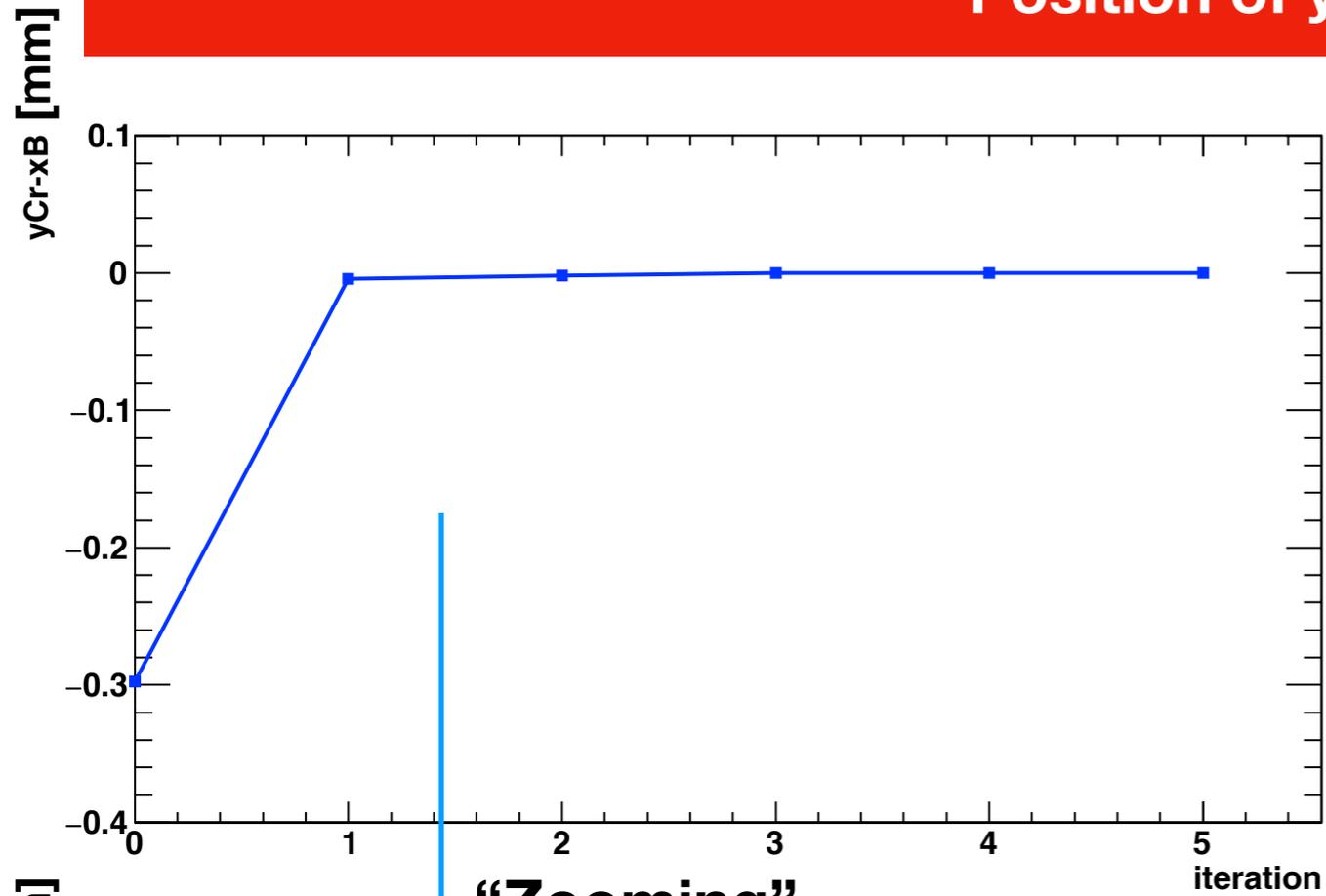
Iteration 0

By-Ay

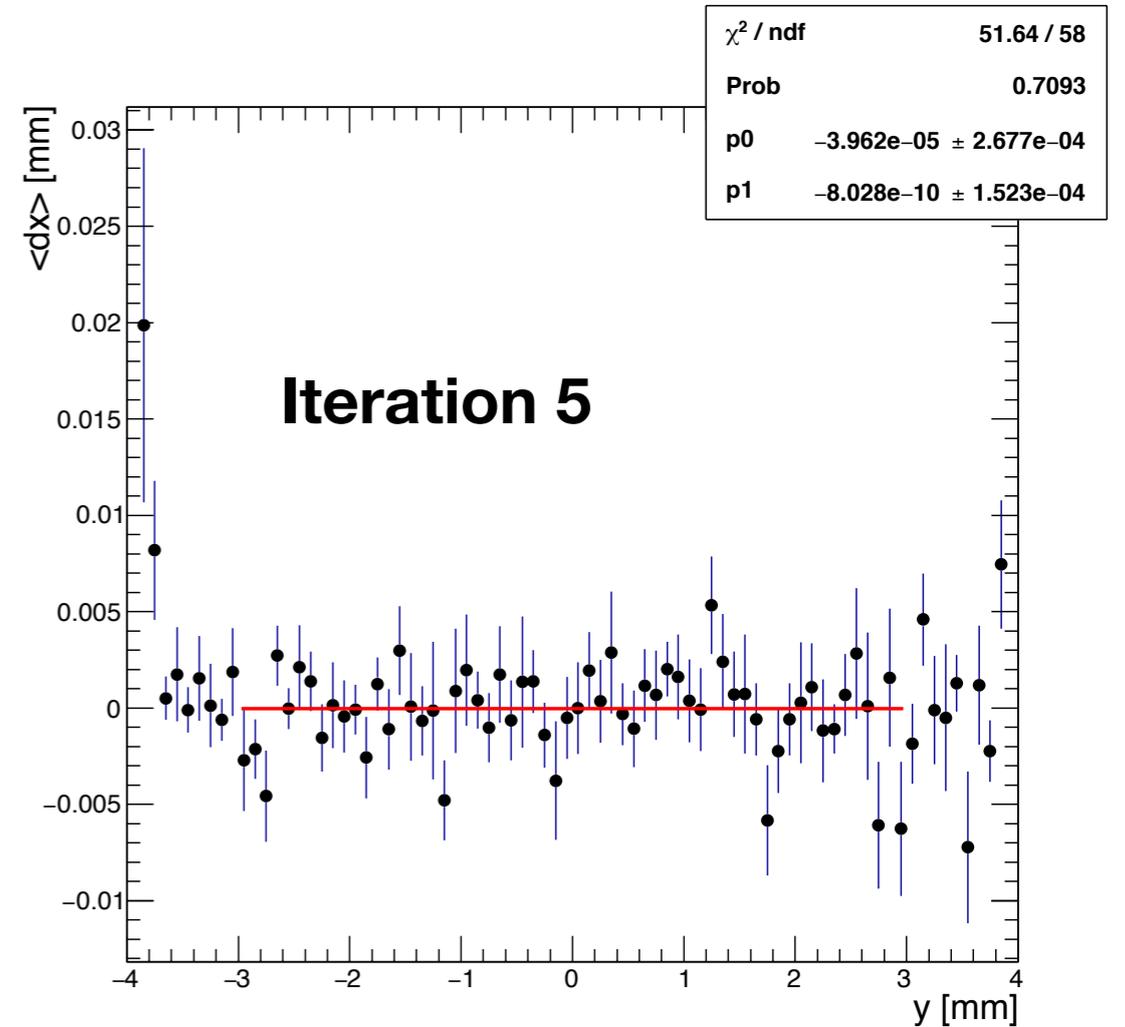
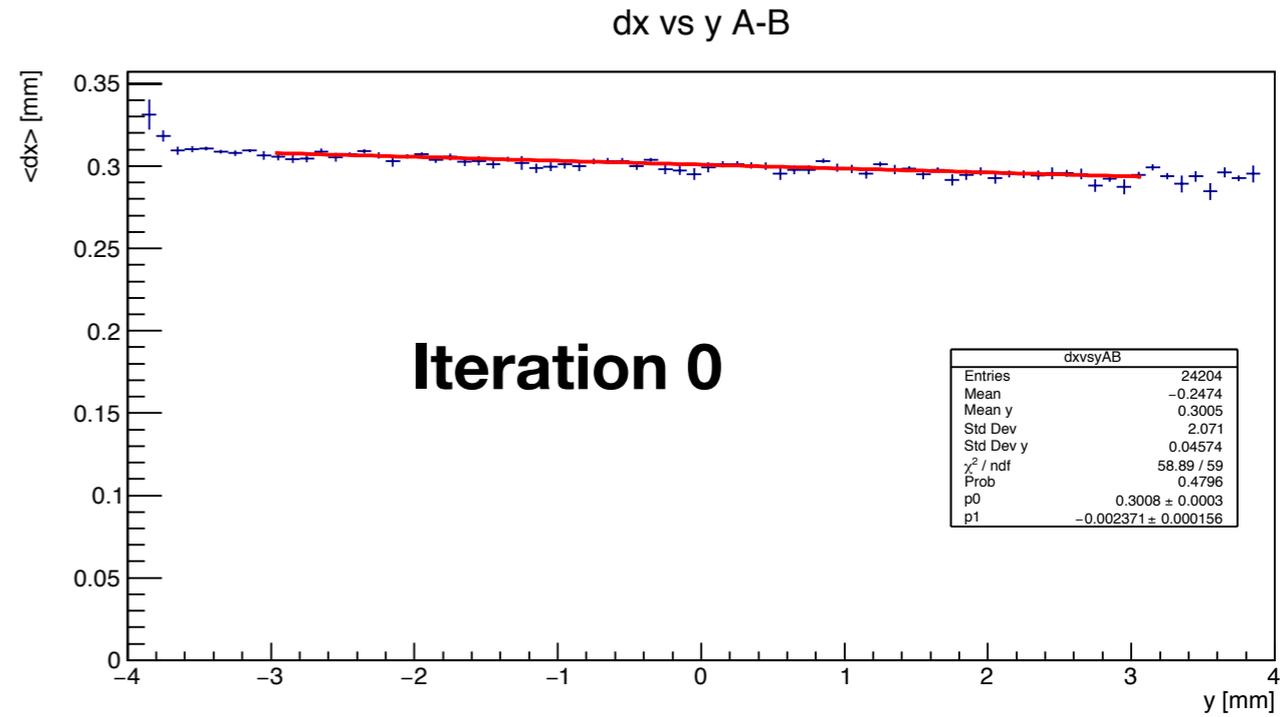
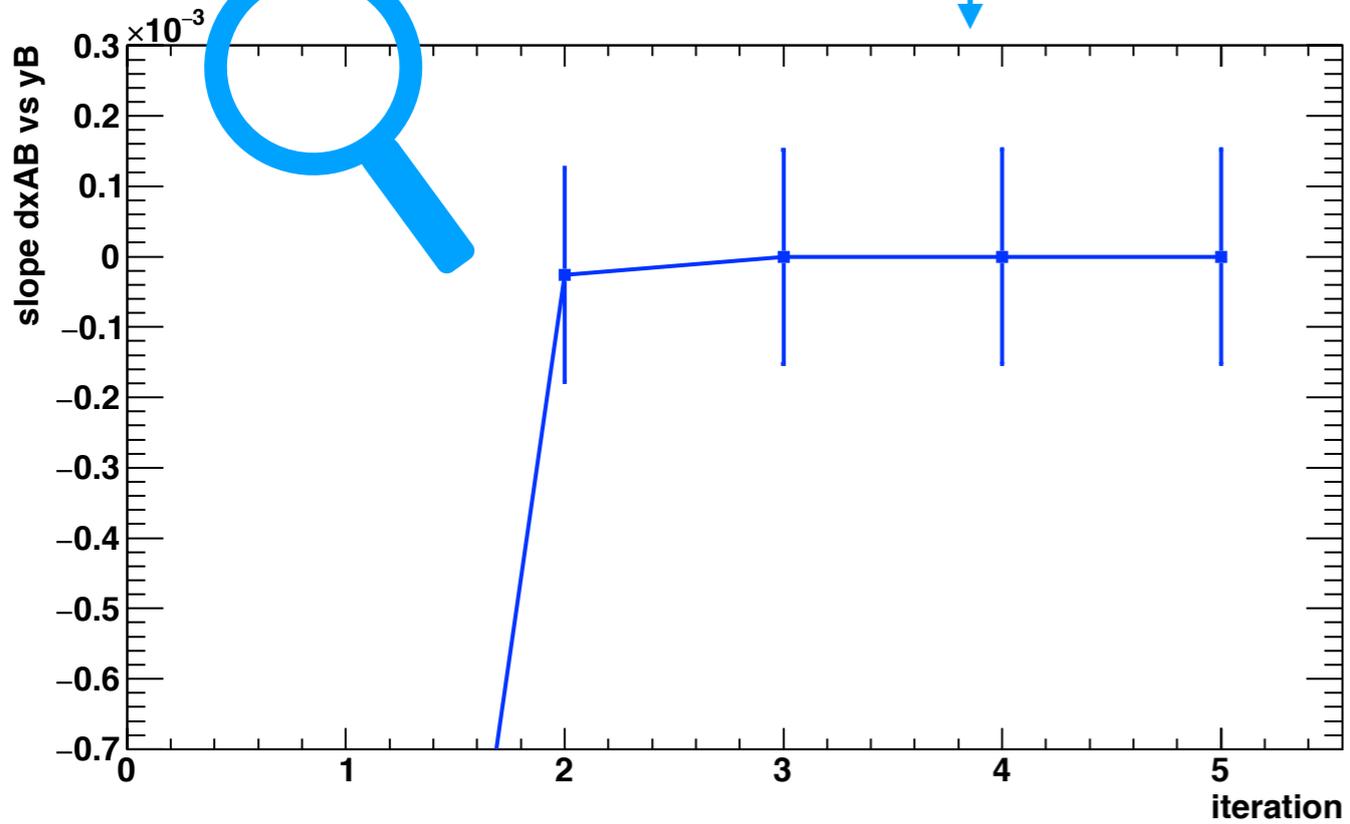
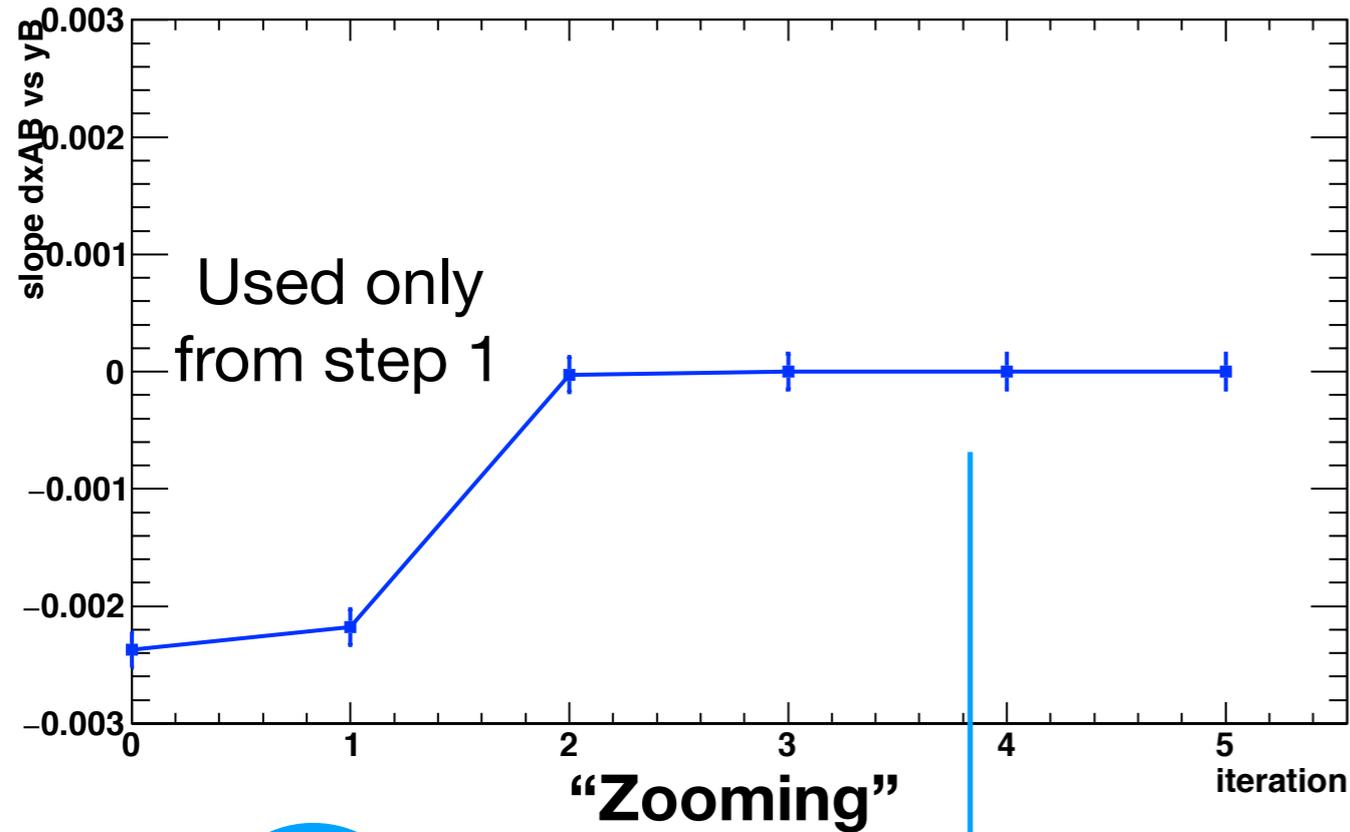


Iteration 5

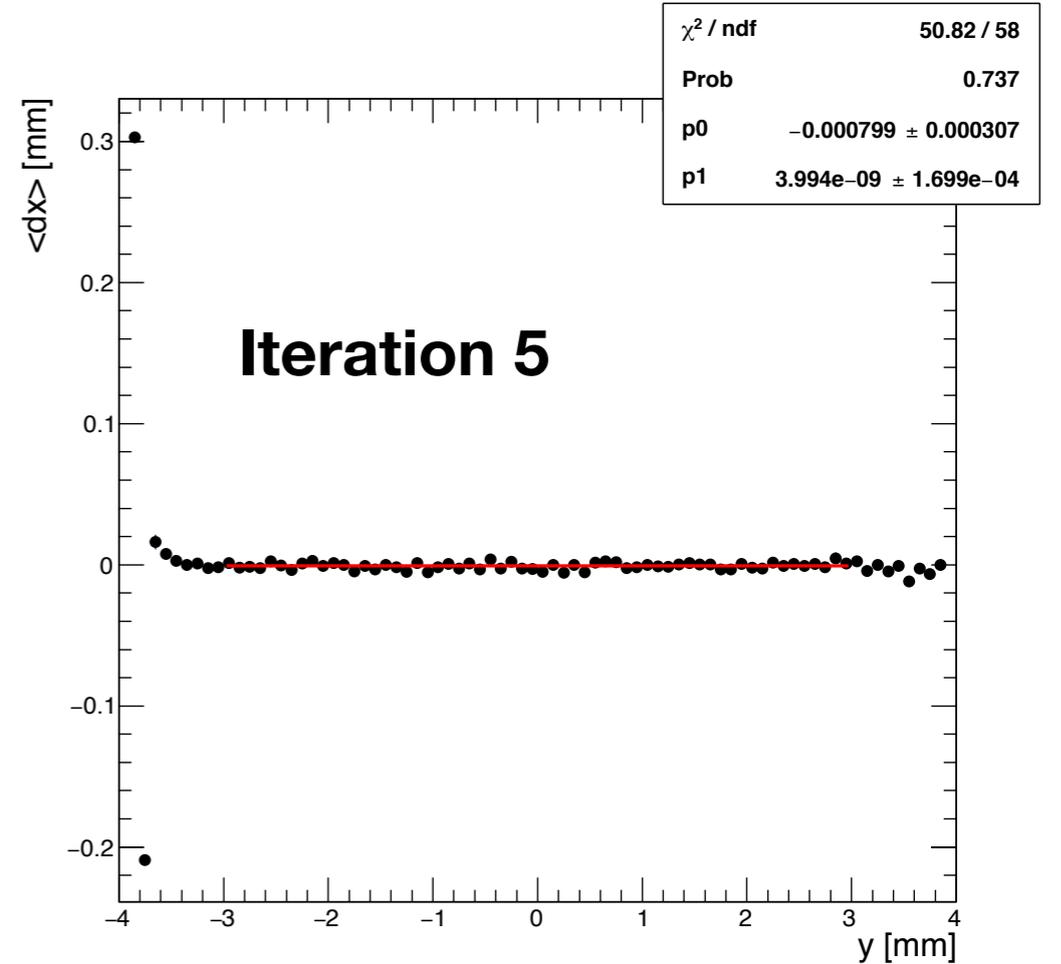
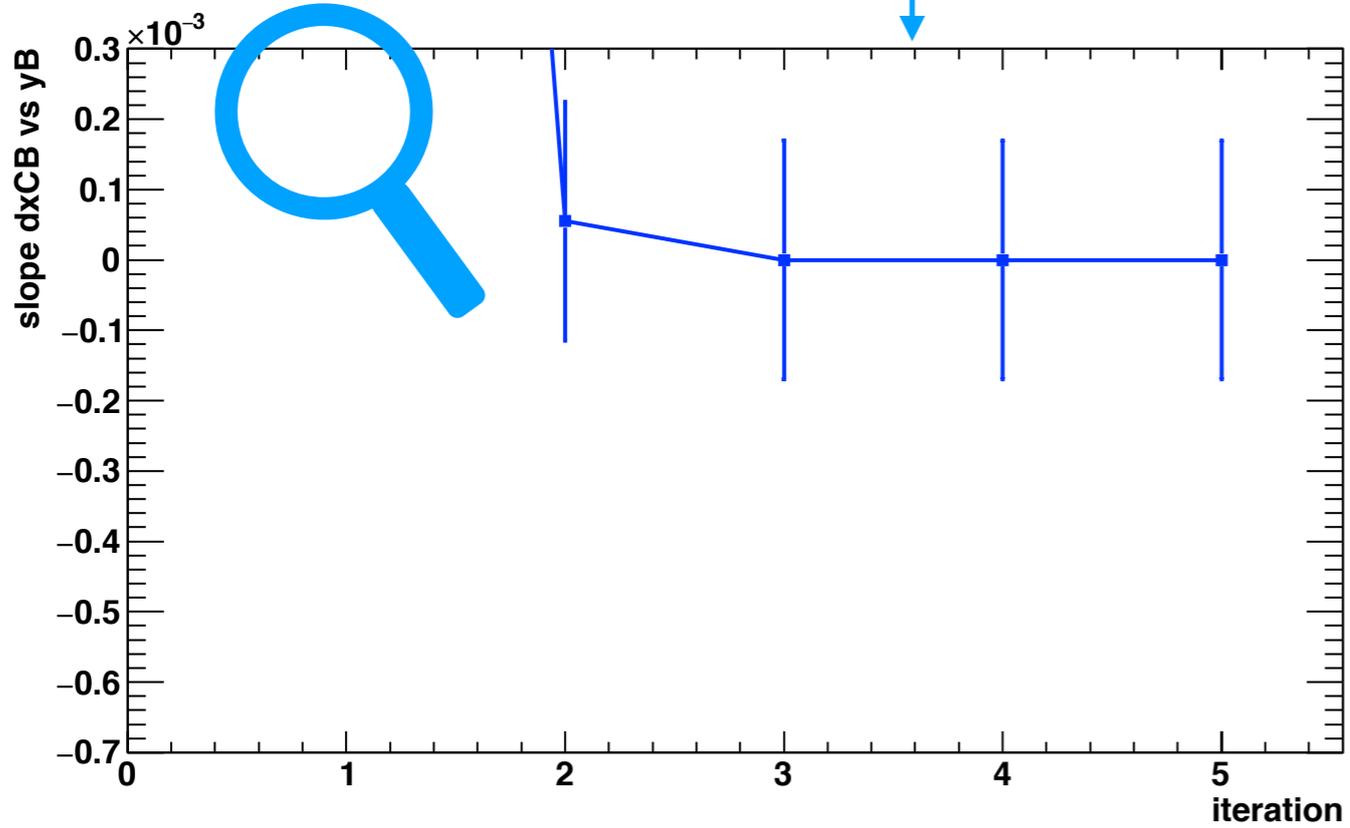
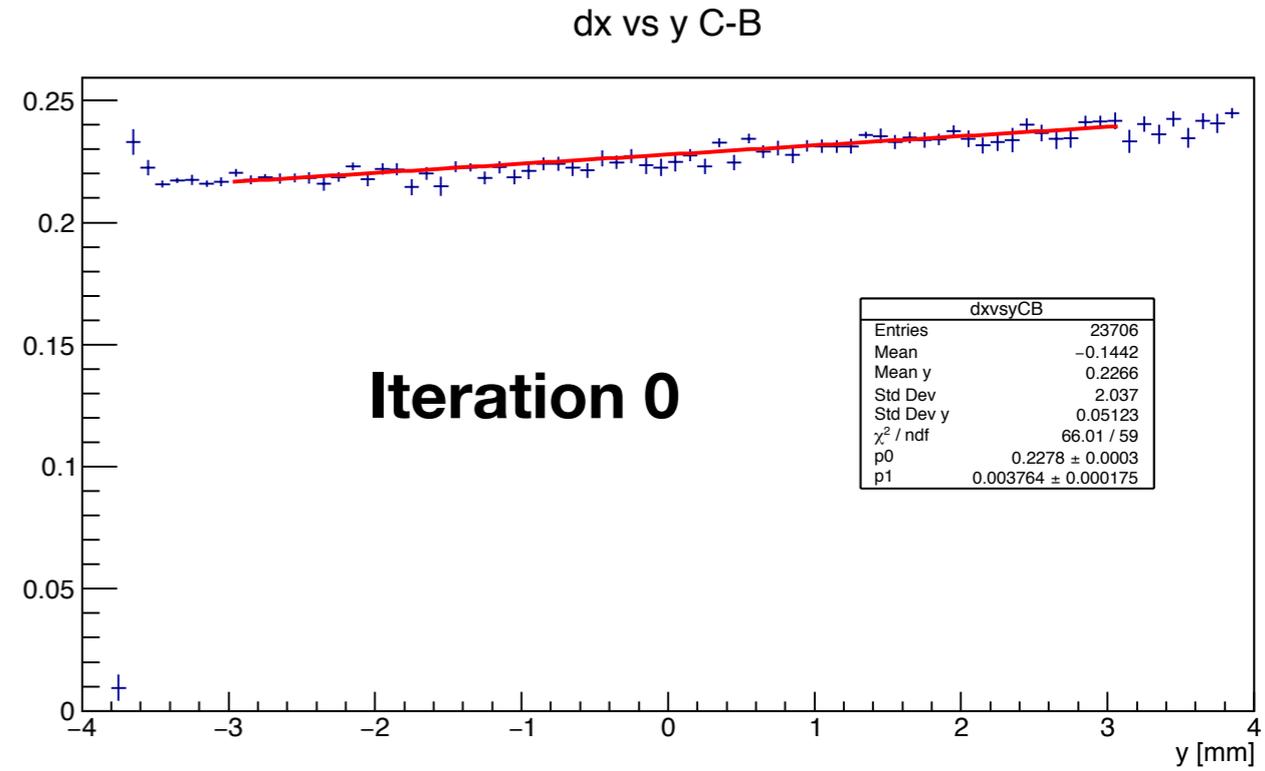
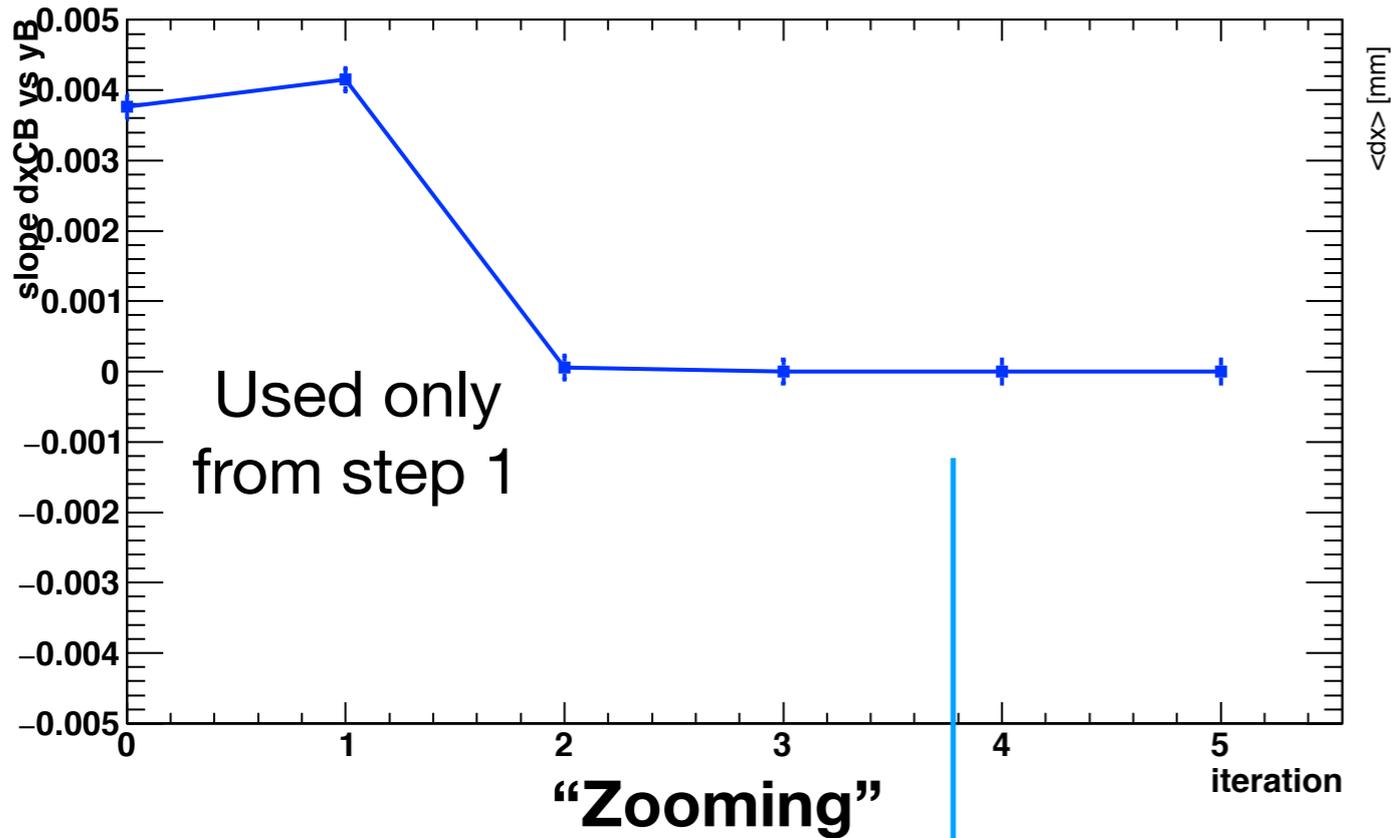
Position of yB-yC



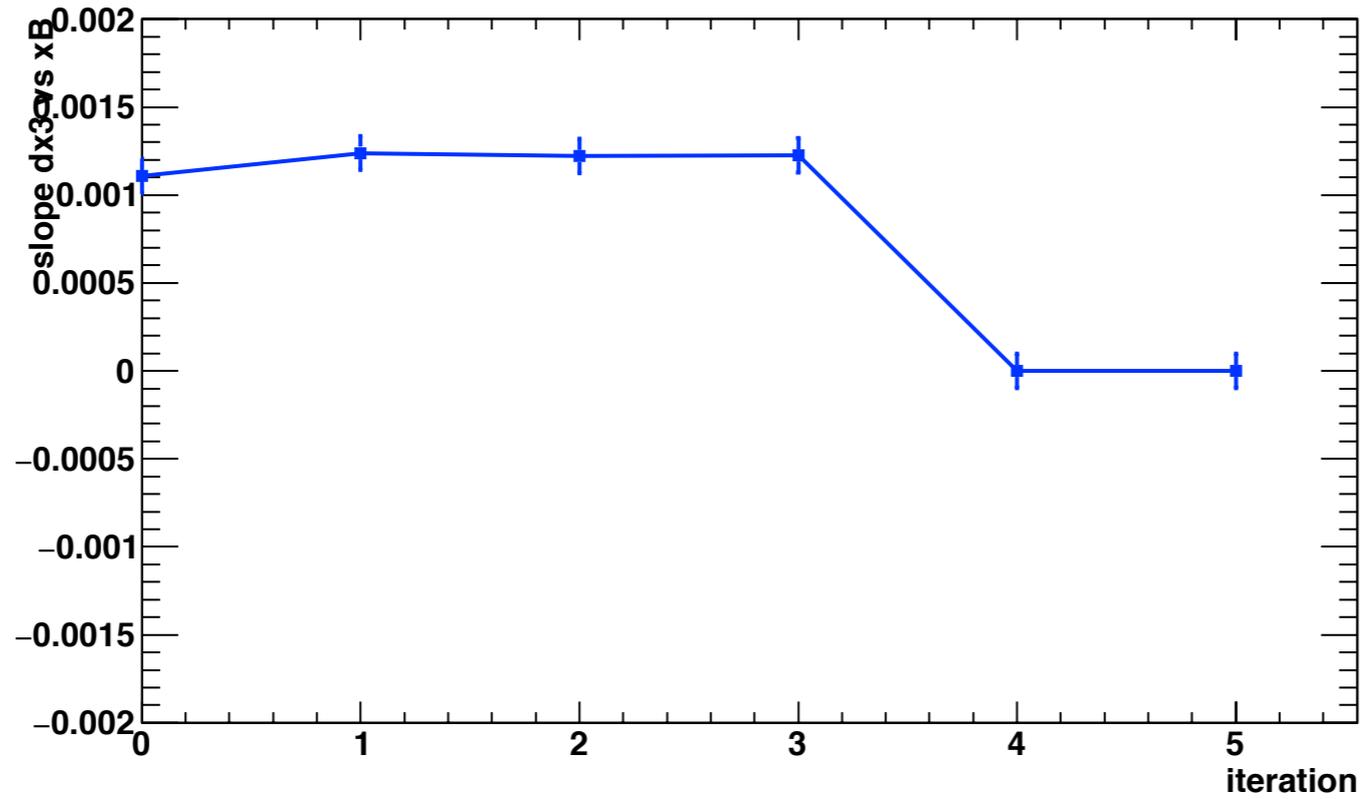
Slope of $x_B - x_A$ vs y_B



Slope of xB-xC vs yB



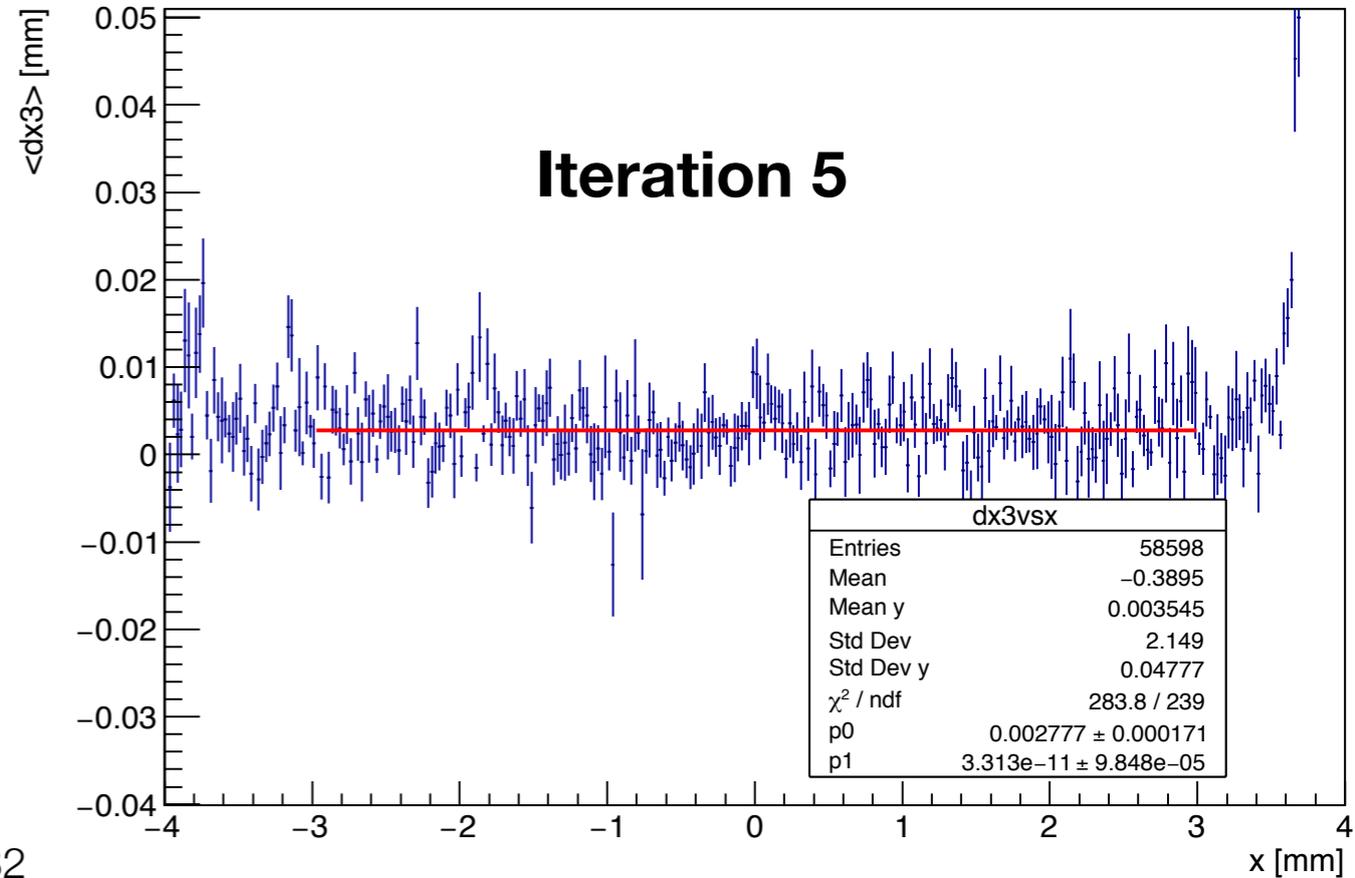
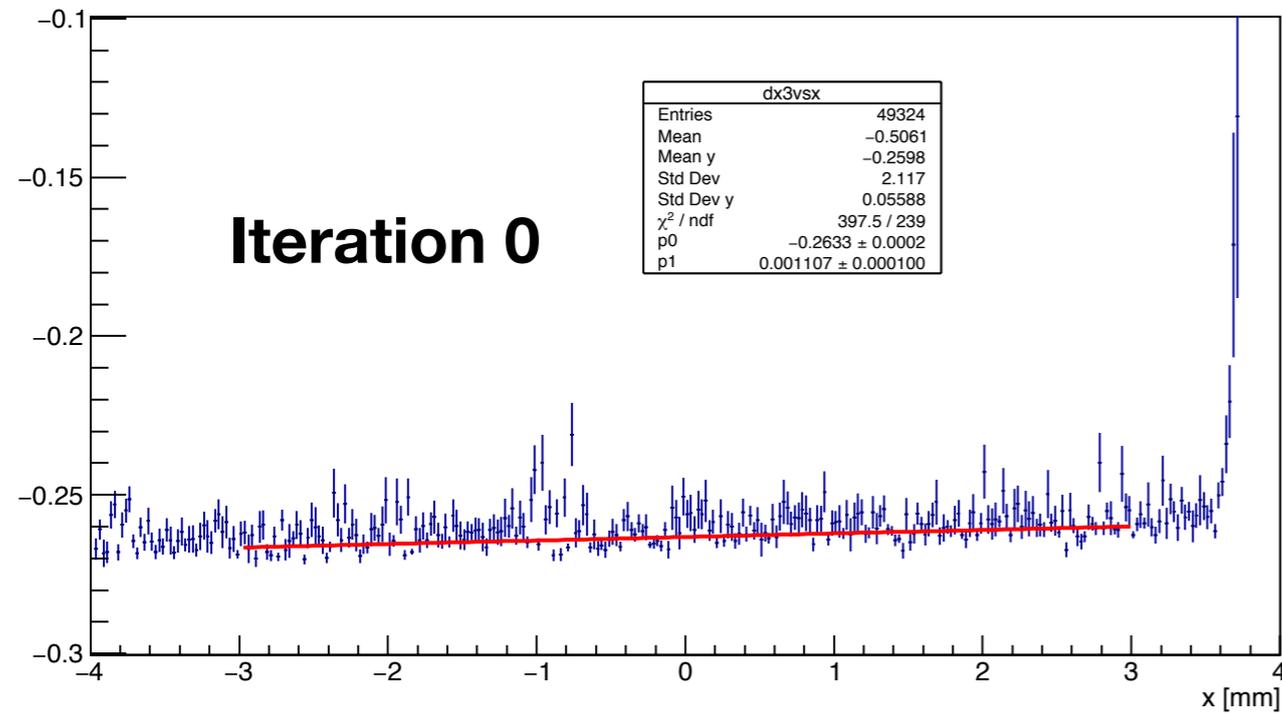
Slope of dx3 vs xB



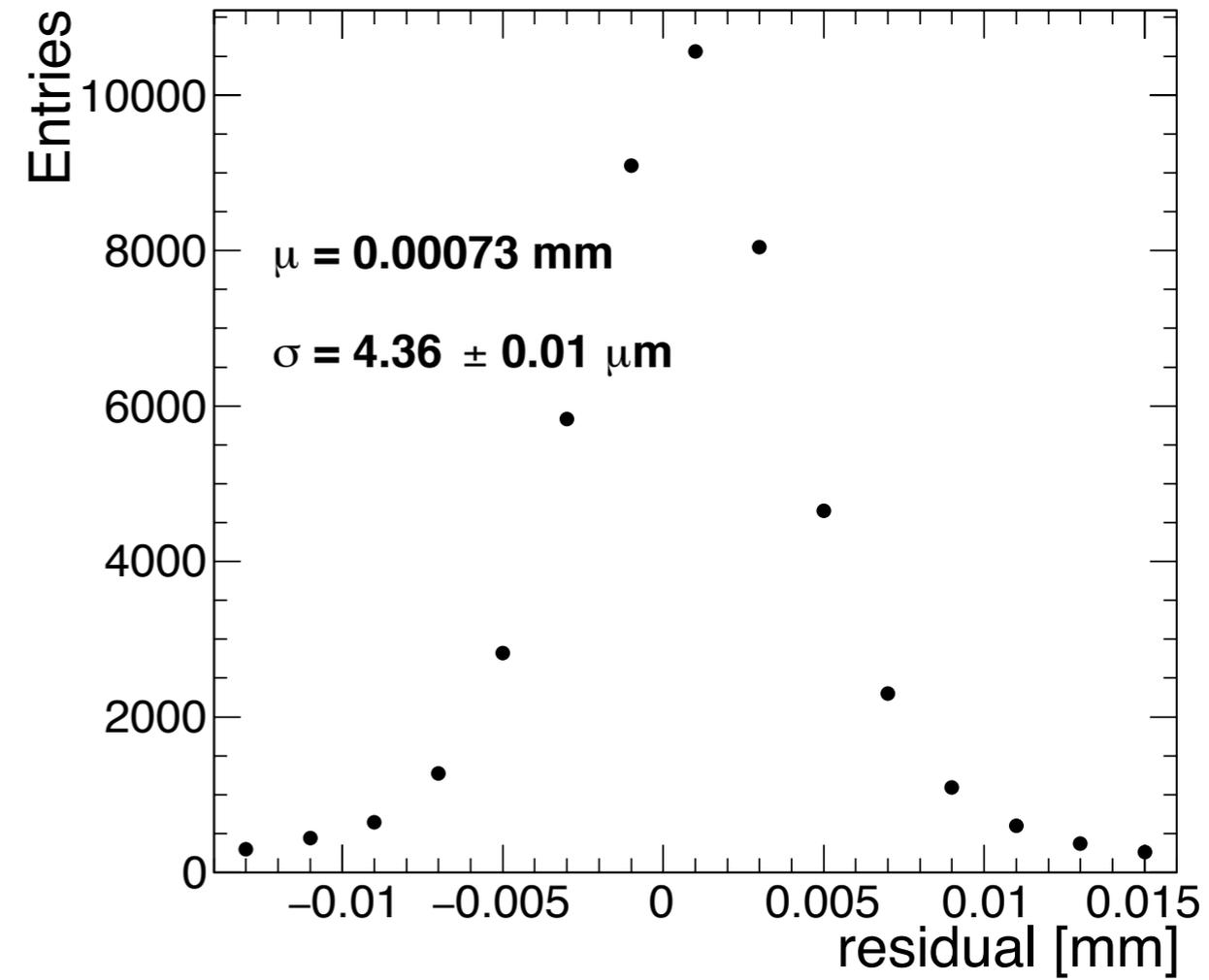
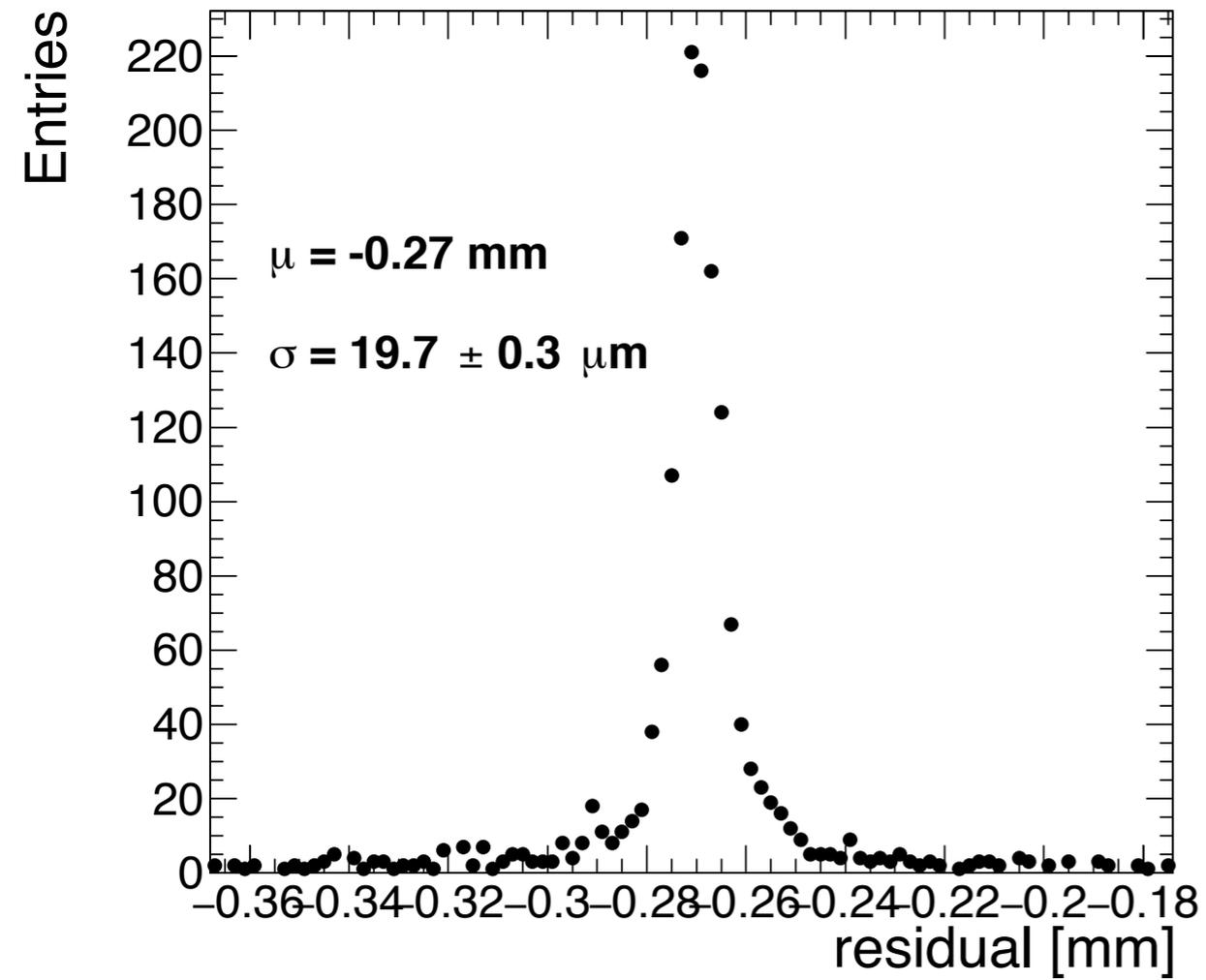
Used only
from step 4

dx vs x

dx vs x



Before alignment vs after

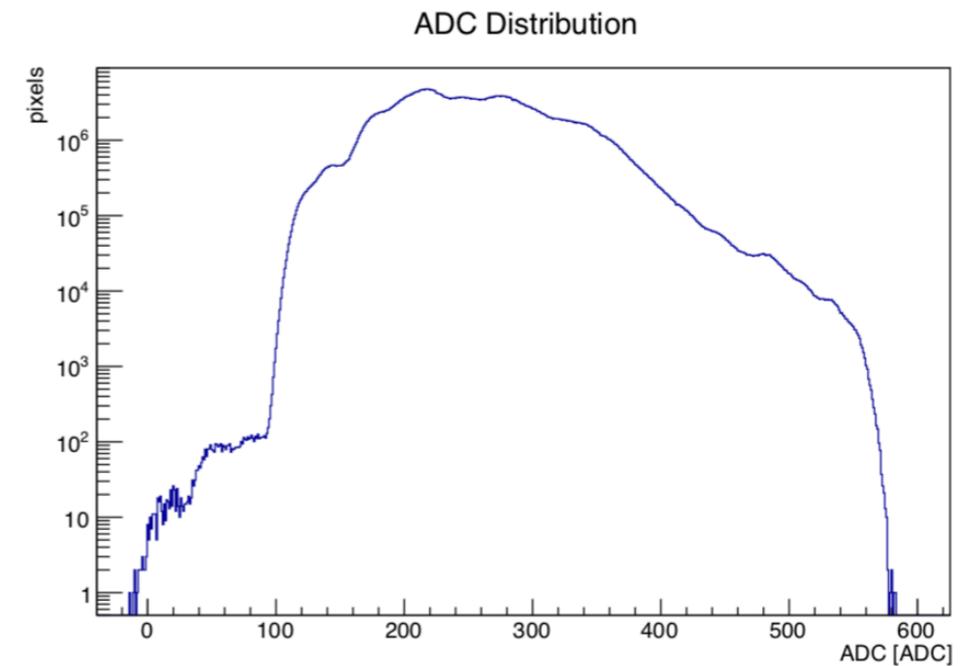


Note the different scales!

Hit Finding method 1- F. Feindt

- ▶ PSI ROC4SENS analogue readout chip
 - ▶ No zero suppression but low rate (120 Hz)
 - ▶ Region of interest based data taking

- ▶ Pulse height distribution of calibration pulse
 - ▶ Broad and no signal separation



- ▶ Pedestal correction method:
 - ▶ Increase signal separation

- Initialization (on first 100)

$$PED = \sum_{i=1}^{100} \frac{ADC_i}{100}$$

- Running update

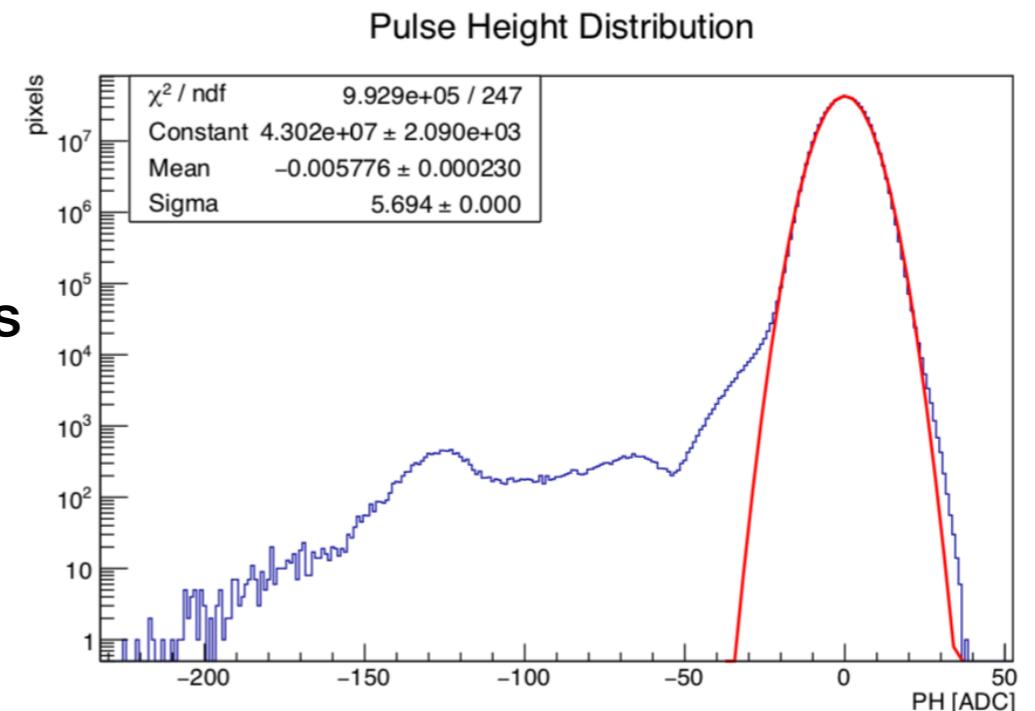
- If pixel not hit:

$$PED_i = \frac{99}{100} PED_{i-1} + \frac{1}{100} ADC_i$$

- $PH_i = ADC_i - PED_{i-1}$

- Needs first 100 events clean

Currently 200 events



Common Mode Correction

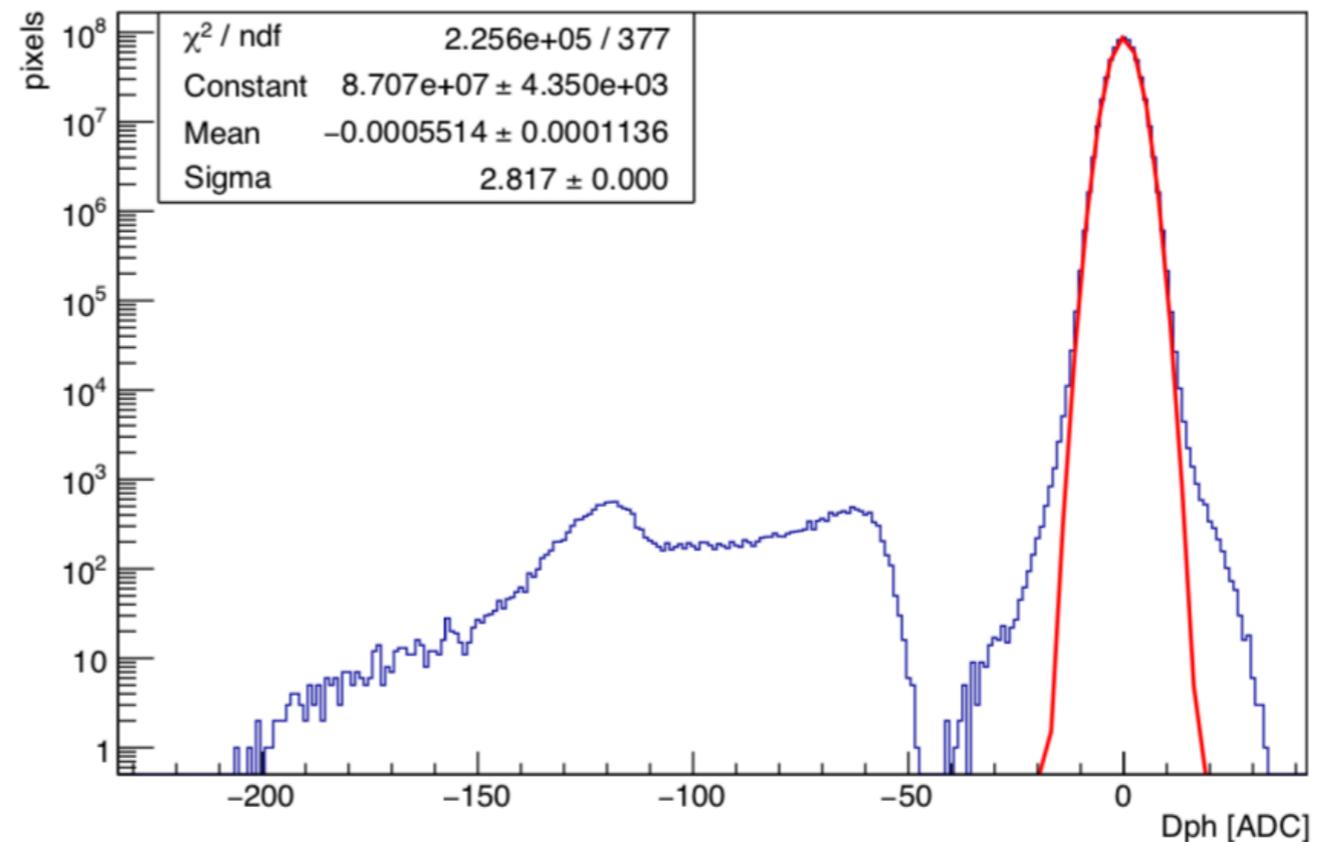
Method

- Neighbors (row) are strongly correlated
- $Dph_j = PH_j - PH_{j-1}$
($j = \text{pixel index}$)

Pulse height difference distribution

- Noise dist. gets even narrower
- Good separation of test pulses
- Use Dph for hit finding

Pulse Height Difference Distribution



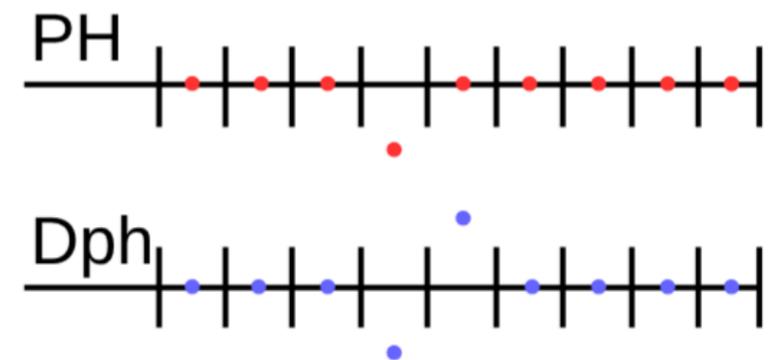
Finally!

Backup – Hit Finding Method

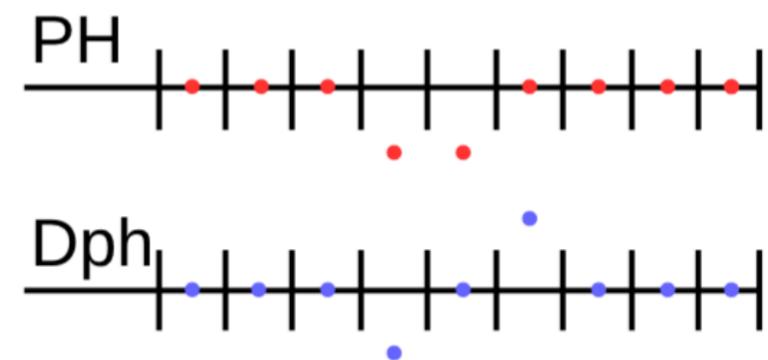
Method

- $Dph_j = PH_j - PH_{j-1}$
- $Sph_j = Dph_j / \sigma(Dph_j)$ (significance)
- Set a threshold of 4
- Pixel j marked as **hit** if $Sph_j < 4$
- Pixel $j - 1$ marked as **hit** if $Sph_j > -4$

Single hit



Double hit



Backup – Common Mode Correction

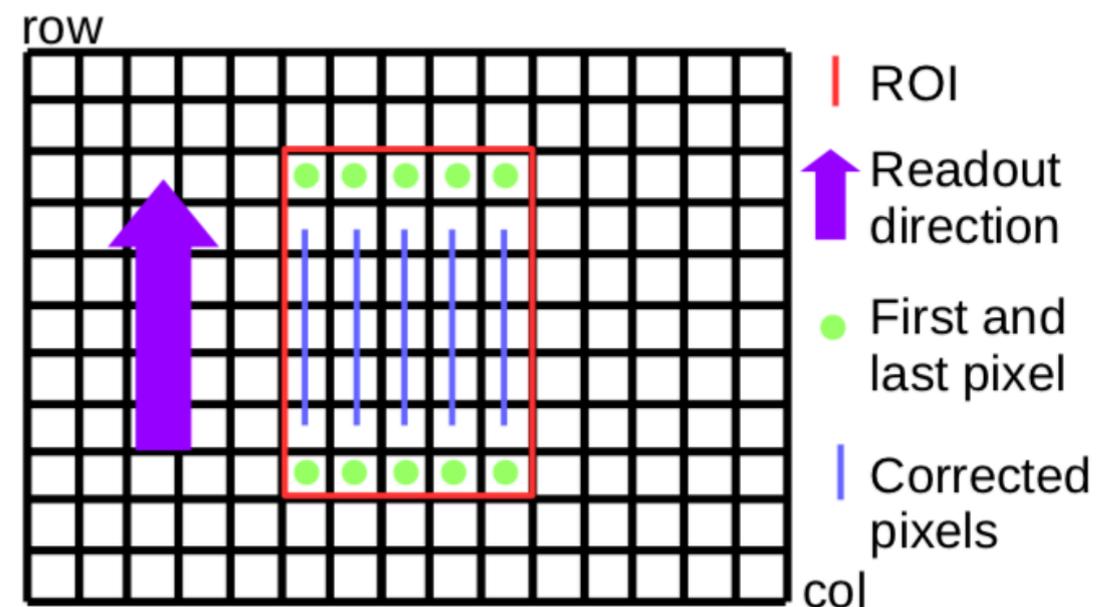
Online

- Perform pedestal correction
- Take difference of neighboring pixels Dph_j
- Calculate significance Sph_j
- Use threshold of ± 4
- Store region of interest (ROI)
- Not suitable in offline analysis

Offline

- ROI-based data
- Perform column wise correction
- Find first and last pixel of the column
Subtract average PH from those in between

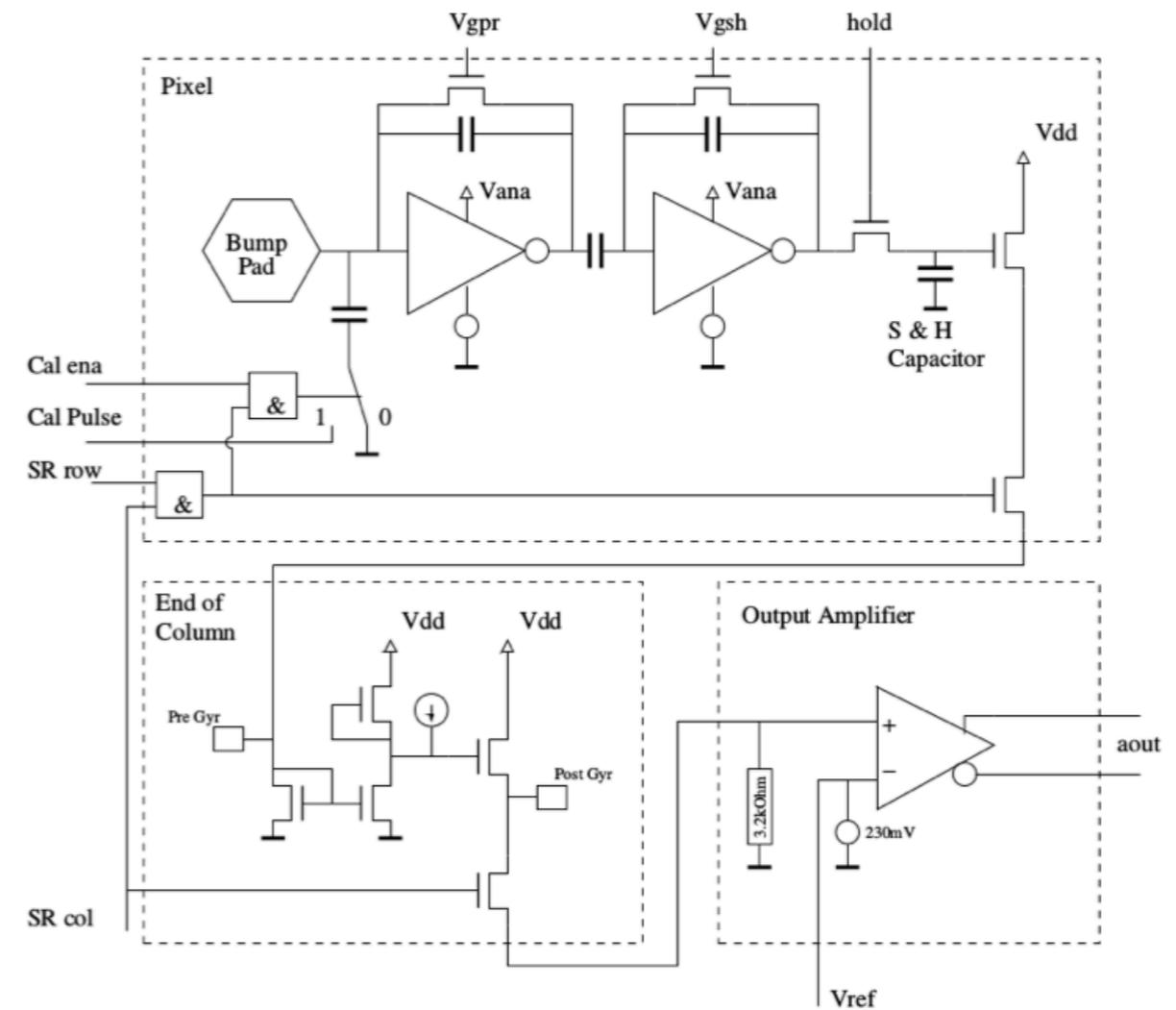
Correction Scheme



*If the first and the last pixel have the same distance we correct by the last.

Backup – ROC4SENS

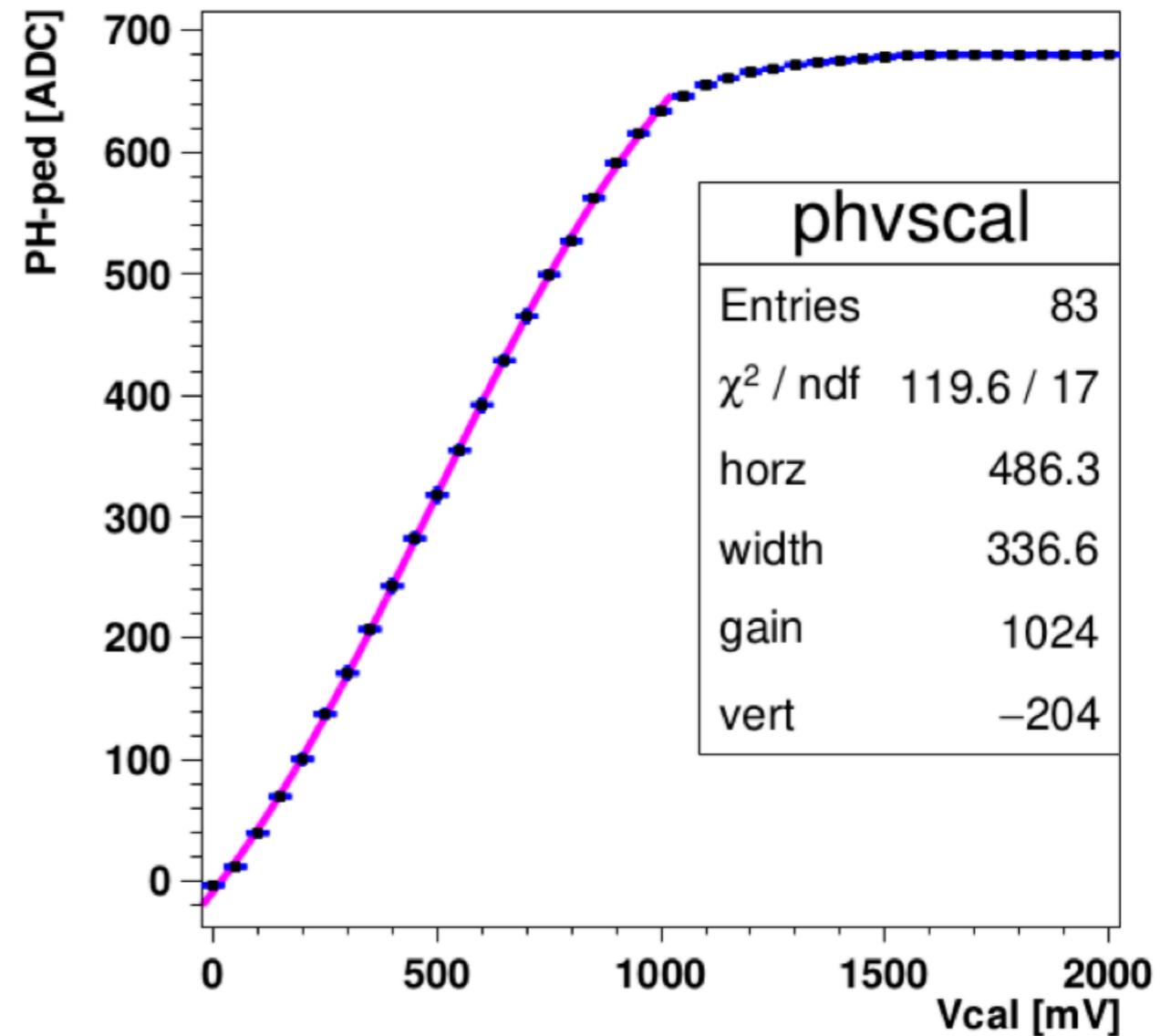
- Geometry: $50 \times 50 \mu\text{m}$ pitch
- 155×160 pixels
- Analogue readout chain:
 - **Preamplifier**
 - **Shaper**
 - Sample and hold
 - Output Amplifier
- No discriminator, no zero suppressio, no ADC: 50 kB/event
- ≈ 0.7 ms for a readout cycle (at 40 MHz)
- Operated with Pixel **Digital Test Board**



Schematic of the analogue readout chain

Take Gain Calibration

- Use internal calibrations pulses (V_{cal}) of the ROC4Sens
- Draw $PH - ped$ vs V_{cal}
- Fit by Fermi function for every pixel
$$PH - ped = p_3 + \frac{p_2}{1 + \exp(-u)}; u = \frac{V_{cal} - p_0}{p_1}$$
- Use inverse function to get the charge
$$Q(PH - ped) = V_{cal}$$
- Correction for **relative gain variations** of the pixels!
- Source calibration missing
⇒ Abs. calibration to expected charge



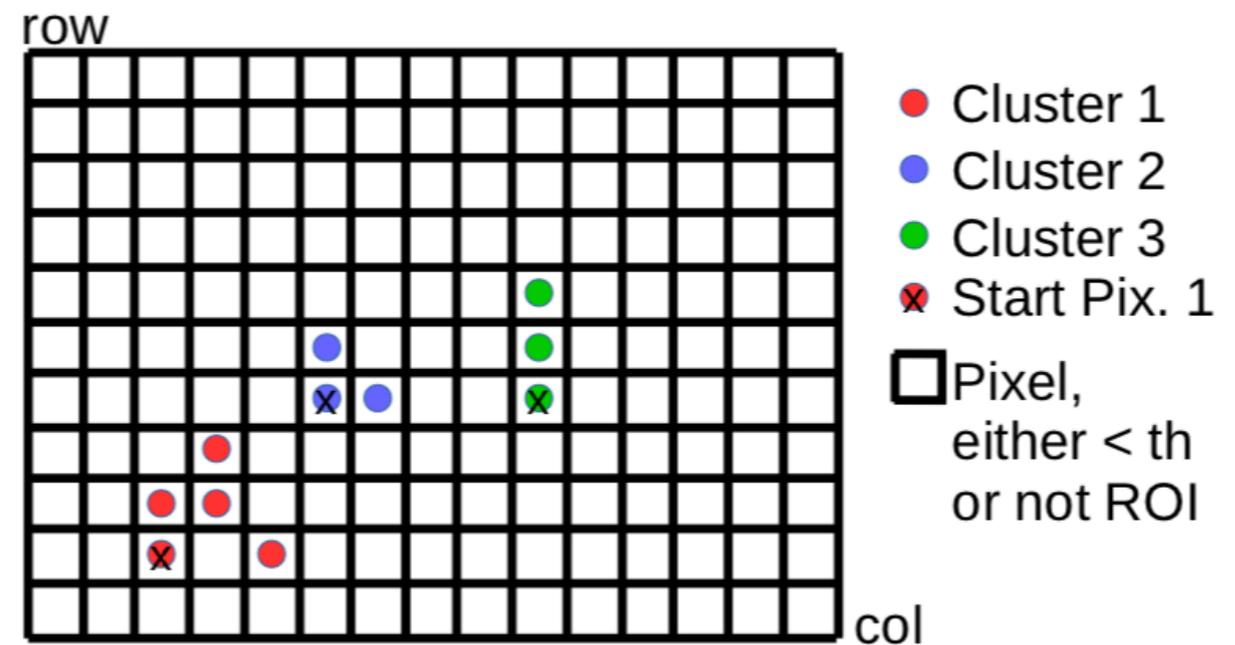
Before Clustering – DUT

- Common mode correction is applied
- Gain equalization is applied
- ROC coordinates \Rightarrow sensor coordinates

Center of Gravity Clustering – All Planes

- Take any not yet clustered pixel over threshold
- Add all neighbors to cluster
- Charge weighted average position of all pixels in the cluster \Rightarrow Cluster position
- Start next cluster

Clustering



- DUT: Threshold \approx 4 signi. cut on ΔPH
- Telescope: Binary, skip hot pixels

Main steps

- Read parameters from alignment file
- Get calibration parameter
- Read data file & assemble pixel hits
 - Skip noisy events with more than 400 hits
 - Tsunami correction
 - Common mode correction (column-wise)
 - in roc coordinates
 - we read along one column
 - a roi is 7 pixels long
 - we find the pixel with the highest and lowest row index in one column
 - we assume there is no significant charge in these pixels
 - we take the average pulse height of these two pixels and subtract it from those in between
 - $dph_i = ph_i - (ph_up + ph_low)/2$

```
# alignment for run 1840
iteration 66
alignxA -1.04171
alignyA -0.17015
alignfA -0.000243457
alignxC 0.029724
alignyC -0.02488
alignfC -0.00333106
gainA /home/cmsspx/r4sclient/B/scm148-scanca12-drei-pr650-sh630-2018-03-13-hold17.dat
gainB /home/cmsspx/r4sclient/B/scm108-scanca12-drei-2018-3-15-hold24.dat
gainC /home/cmsspx/r4sclient/C/scm109-scanca12-drei-pr650-sh630-ia125-2018-03-13-hold20.dat
keA 0.0511
keB 0.0385
keC 0.0463
beamEnergy 5.6
pitch 25
qL 9
qR 15
qLB 9
qRB 15
TsunamiA 0
TsunamiB 0
TsunamiC 0
dphcutA 30
dphcutB 40
dphcutC 30
```

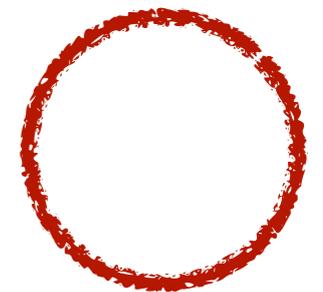
Main steps

$$\text{dph} = \text{ph4} - (\text{ph1} + \text{ph7})/2$$

online we select the seeds (center pixel triggering a roi to be stored) to be any pixel which has a **dph** which is above 4 sigma significance

- Continue analysis if **dph > dphcut**
 - for each sample we use the cut yielding the best resolution
 - 25 vs 50
 - Conversion from ADC to ke (**updated for Vcal offset correction - as Finn**)
 - **Clustering** for **events with less than 50 hits** (speeding)
 - From a seed pixel add to it all adjacent pixels with a hit
 - Evaluating the cluster isolation
- Check inside a distance of 300 μm in x and y direction, if more than 1 cluster is found, the one with the higher charge is considered

- Evaluate cluster coordinate in the sensor frame and correct for the alignment
 - requiring straight tracks: $|\text{dxCA}| < 40[\text{mm}] * 1\text{mrad} * 3 * 5/E_{\text{beam}} + 0.02$
 - requiring straight tracks: $|\text{dyCA}| < 40[\text{mm}] * 1\text{mrad} * 3 * 5/E_{\text{beam}} + 0.1$



“Historic”
After alignment,
should not matter

Alignment

- Align x_A w.r.t. B: fit with Gaussian+B the dx_{AB} distribution (same for C)
 - Peak position is the correction to the alignment
- Align y_A w.r.t. B: mean of the dy_{AB} distribution (same for C) is the correction
- Angle alignment on A: fit with a pol1 dx_{AB} vs y_B (same for C)
 - Angular coefficient is the correction

```
x = c->row*pitchr - halfSensorX - align; //align = 0 for B
double xCr = xC*cfC - yC*sfC;
double yCr = xC*sfC + yC*cfC;
```

Examples of how the alignment is applied

Residual!

```
double xavg = 0.5 * ( xAr + xCr );
double yavg = 0.5 * ( yAr + yCr );
double dx3 = xB - xavg;
dx3 -= dx3corr*xavg; // from -dx3vsx.Fit("pol1")
```