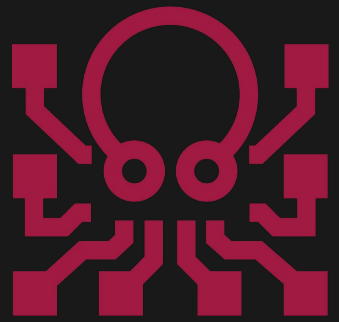
TPSCo 65nm – Limits of Spatial Resolution

How Much Charge Information Do We Need?

Finn King on behalf of the OCTOPUS project

4th DRD3 week on Solid State Detectors R&D

Geneva
11th November 2025



HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

The Question

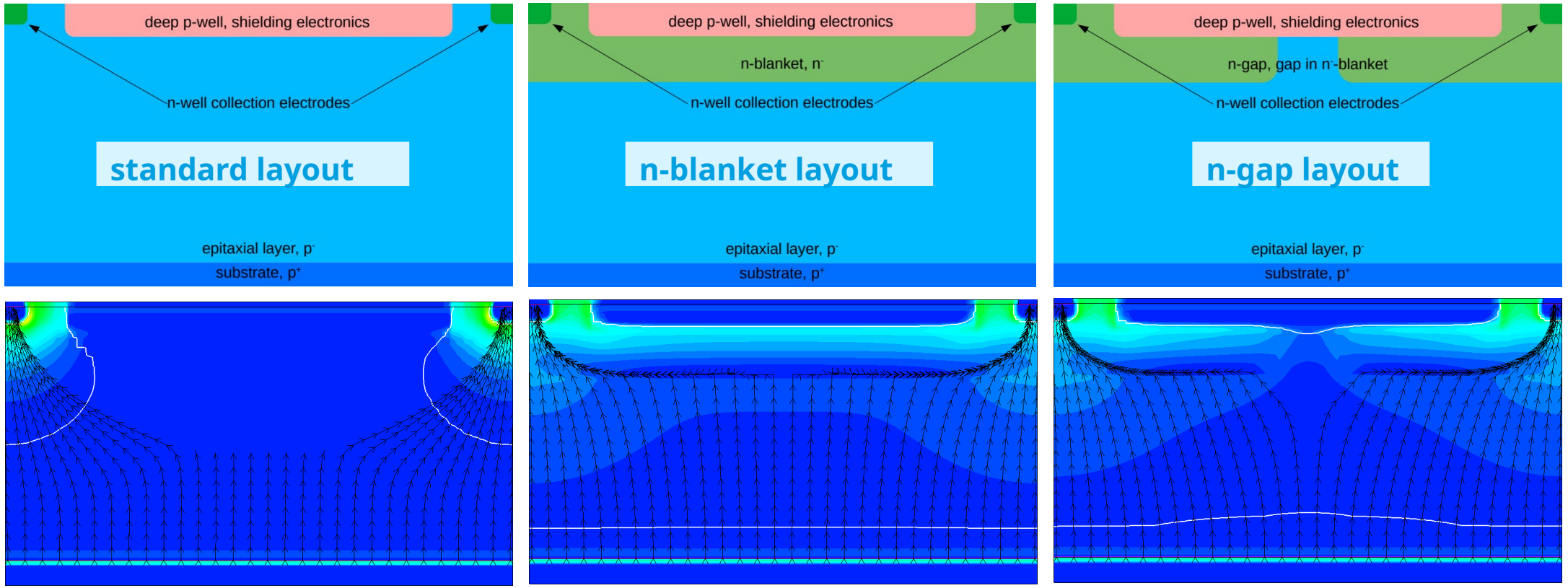
To Motivate the Design of a Pixel Sensor for a Future Lepton Collider

Key questions concerning spatial resolution

- What are the limits achievable with a certain design (standard, n-blanket, n-gap)?
- How do these limits depend on the pixel pitch and threshold?
- What is the potential for improvements that charge information offers?
  - How many bits do we need in order to leverage this potential?
  - What about two thresholds?

Introducing Process Modifications

The Trade-Off Between Charge Collection and Spatial Resolution



charge collection, detection efficiency

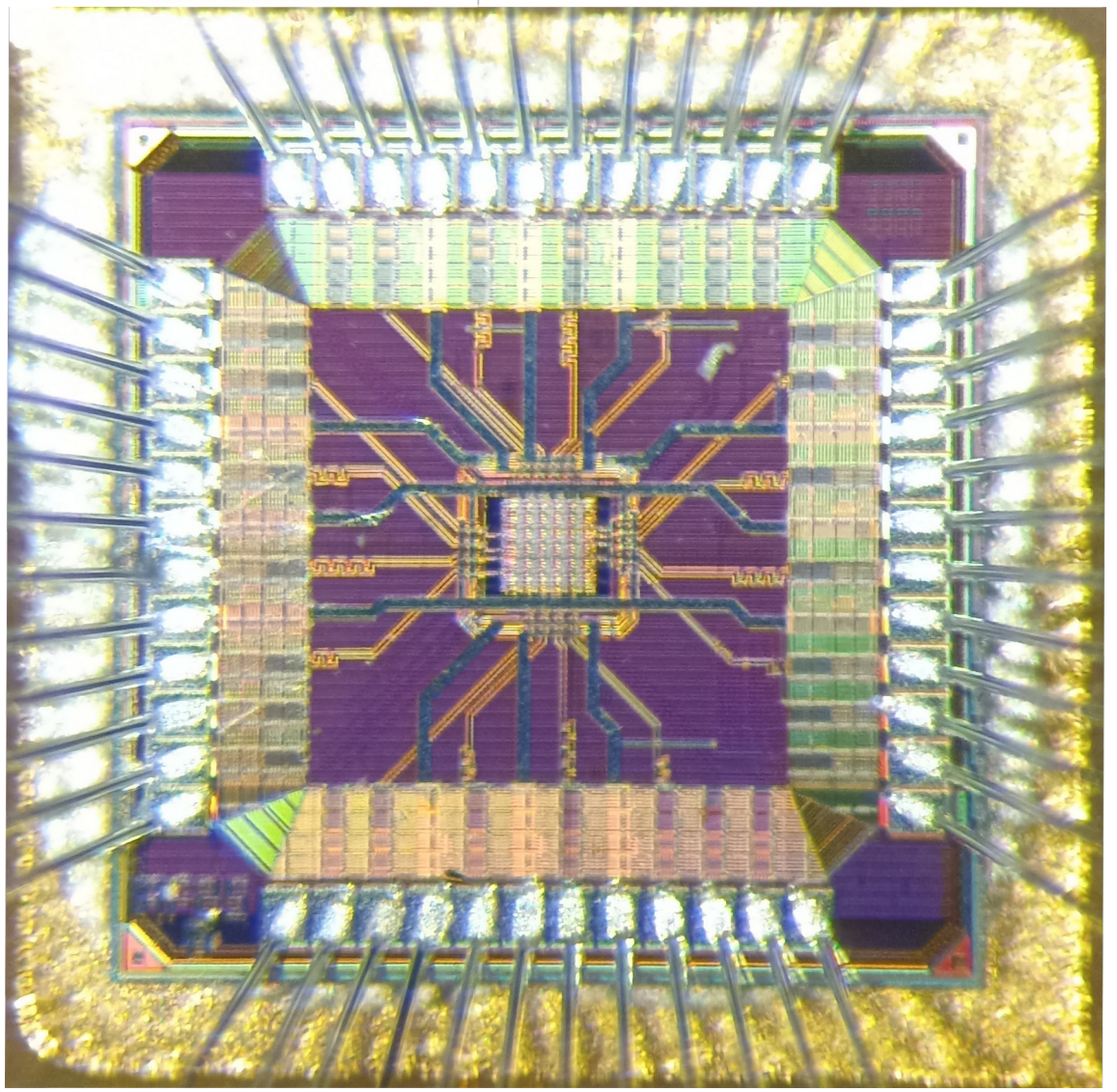
cluster size, spatial resolution

differences reinforced with decreasing thickness, increasing pitch, and increasing threshold

The Data

Test-Beam Campaign at DESY with Analog Pixel Test Structures (APTS)

- Designed by ALICE as investigator for ITS3 [ref. pub.]
  - Three design flavors (standard, n-blanket, n-gap)
  - Pitch between 10 um and 25 um
- Readout developed with CERN EP R&D using Caribou
  - “Analog” charge measurement, no online threshold
- Tested at DESY II Test-Beam Facility at about 4 GeV
- Charge calibration with ^{55}Fe
- Data analyzed with Corryvreckan
  - ClusteringAnalog: allows offline threshold scans

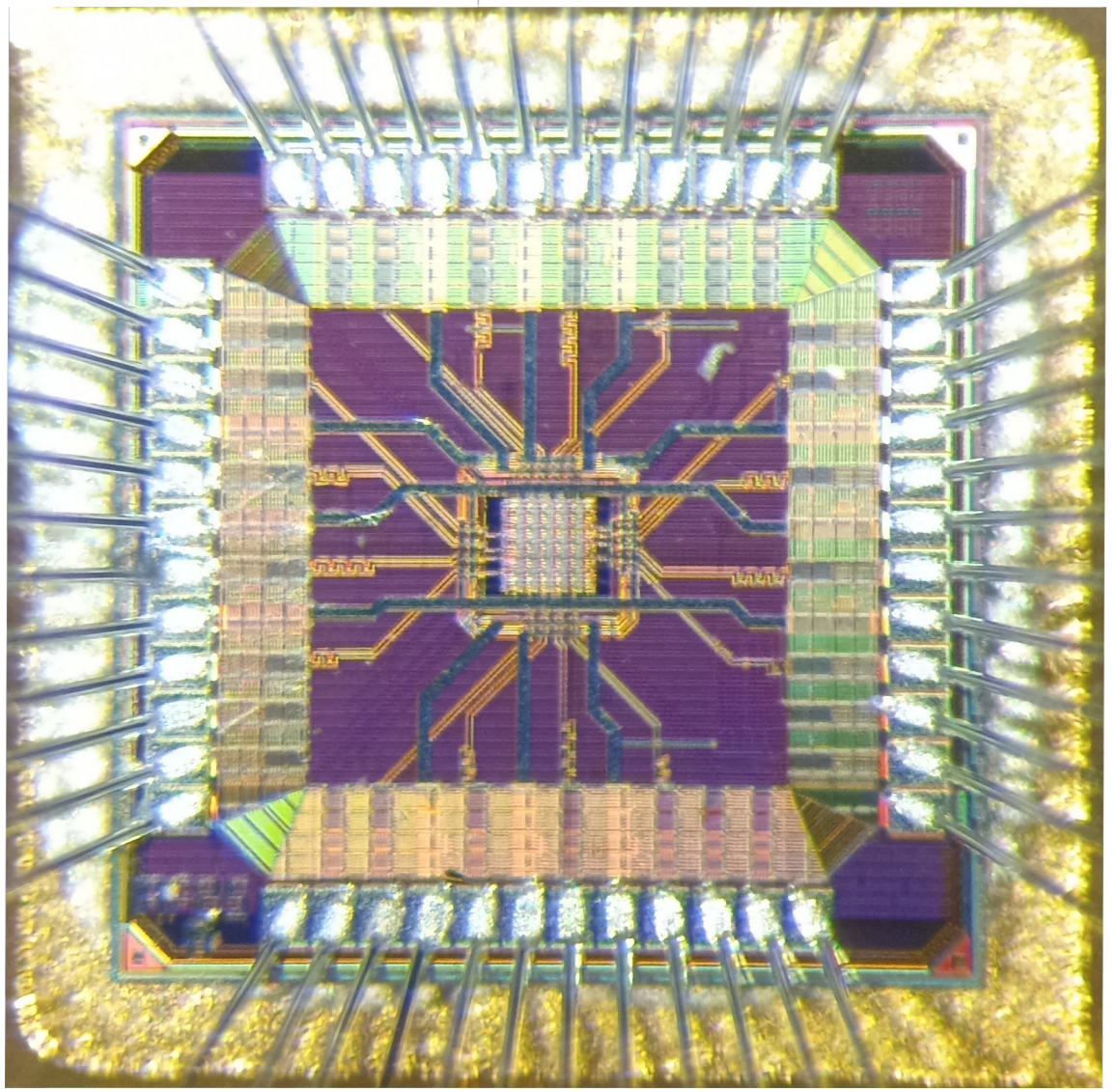


Selected Conditions

Covering Limited Parameter Range

- Use 4.8 V, if available
  - not expecting strong dependence for n-blc
- Noise below 30 electrons
- Use three thresholds if that allows efficient operation

Pitch [um]	Type	Bias [V]	Thresholds [e]
15	std	-4.8	100, (150)
25	std	-4.8	100
25	n-blc	-1.2	100, 150
25	n-gap	-4.8	100, 150, 200



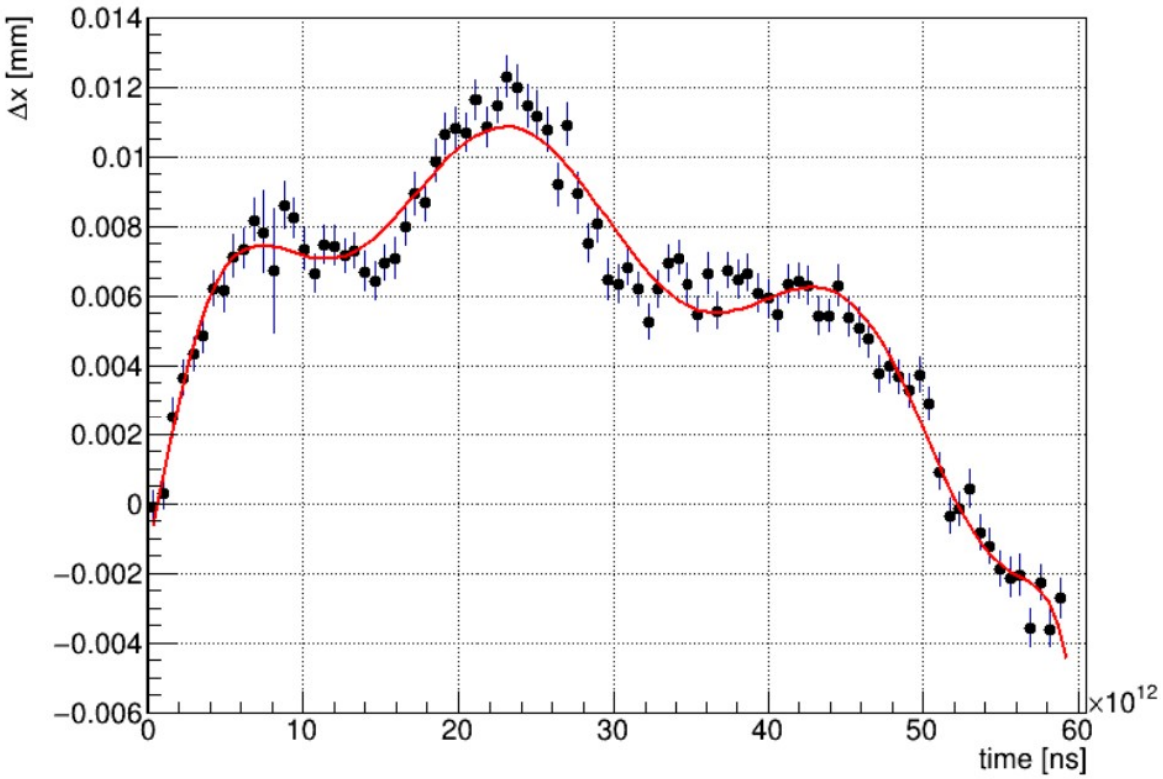
Tools and Methods

Extracting Spatial Resolutions and Comments on Systematic

- Characterizing residual width within 3σ (RMS in 99.7%)
- Need to subtract track resolution ($\sigma^2_{meas} = \sigma^2_{tel} + \sigma^2_{dut}$)
- But how to get the track resolution?

  1) Use the GBL resolution calculator
     - Probably underestimates track resolution (time dependence)

  2) Use a method similar to [Antonello] M2
     - Cut on abs(eta) = $|(c_l - c_r) / (c_l + c_r)| < 0.1$ and cluster charge < 700 e
     - Assume DUT resolution is sub-dominant (checked with simulation)
     - Potentially overestimates track resolution



- Alignment dependents on time
- Correction based on polinomial fit
- Remaining impact depends on run duration

Tools and Methods

Overview Track Resolution

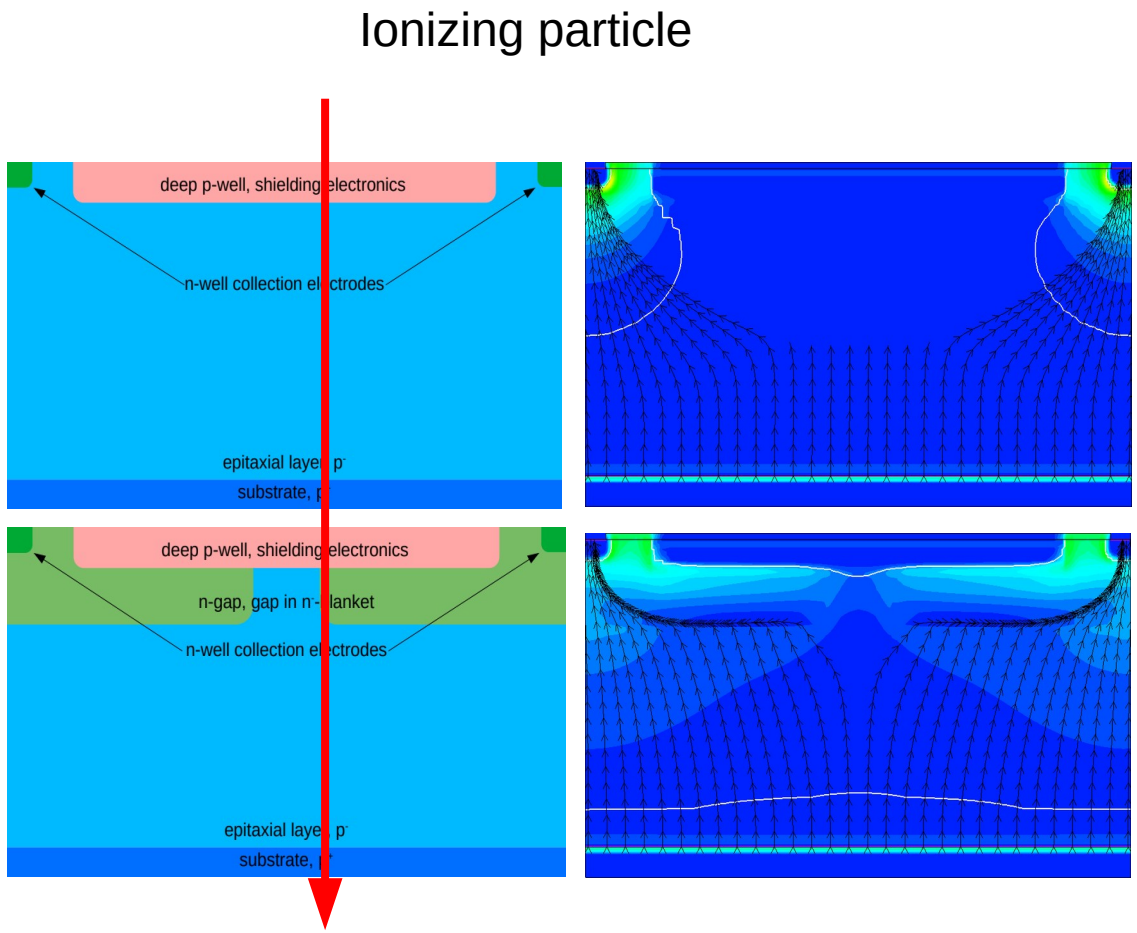
Design	Pitch [um]	Voltage [V]	σ_{track} GBL [um]	σ_{track} M2 [um]
n-gap	25	-4.8	2.5	3.7
		y	2.5	3.4
n-blc	25	-1.2	2.5	4.0
		y	2.5	4.3
std	25	-4.8	2.5	5.0
		y	2.5	4.0
std	15	-4.8	1.9	4.0
		y	1.9	4.4

Consider systematics between runs! Many conclusions can be made within a run, though!

Motivating

Eta Correction

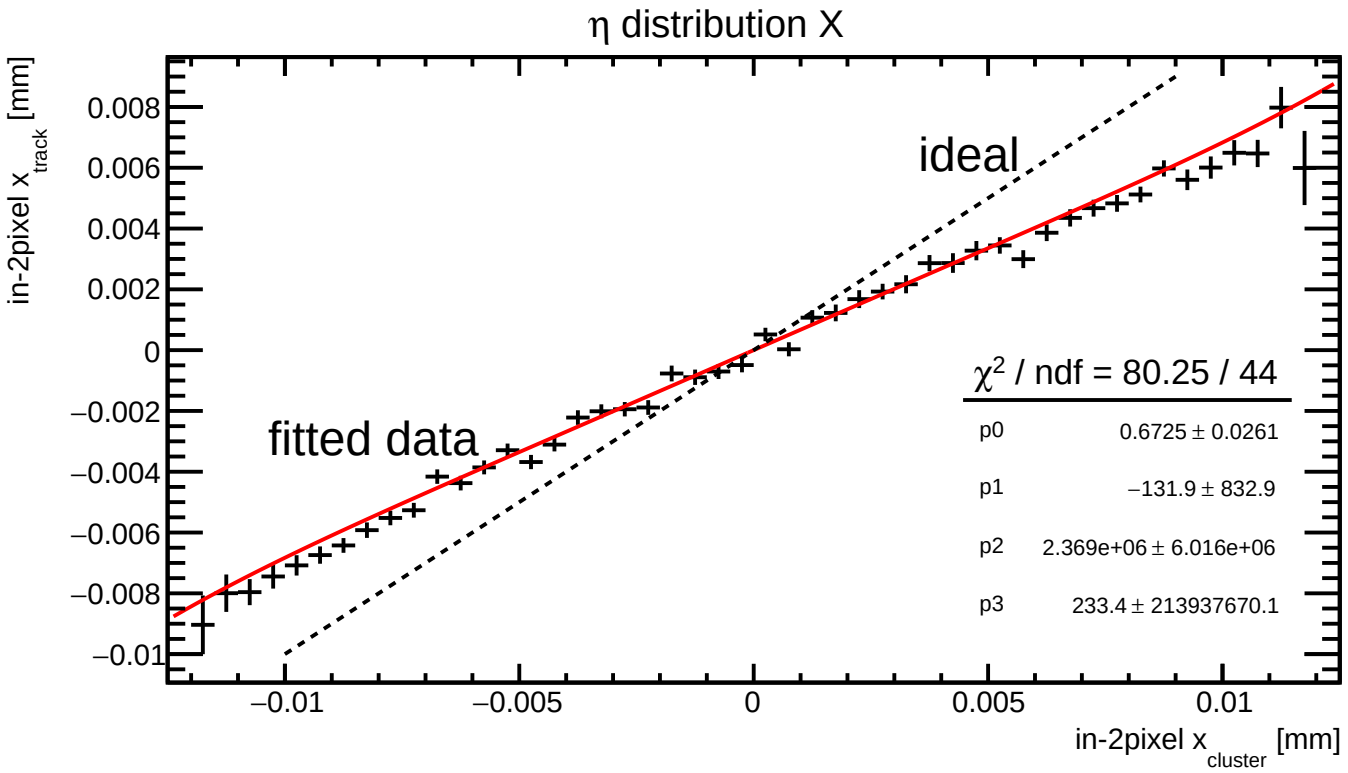
- Imagine a particle hitting our detector close to the pixel boundary
- The charge collected in each electrode depends on the electric field
  - Standard layout: low field, diffusion component, charge sharing close to 50-50
  - n-gap layout: larger field, collection by drift, charge sharing close to 0-100
- In both cases, we estimate the particle position using a charge-weighted center of gravity – this is wrong
- It is the job of the eta correction to find out how wrong this is and to correct for the effect



Tools and Methods

Correcting Bias of Spatial Residuals – Eta Correction

- Using modules **`EtaCalculation`** and **`EtaCorrection`**
- The idea is simple
  - Plot the intercept of an associated track as a function of the reconstructed position (both in-pixel, modulo the pitch)
  - This reveals the bias of the reconstruction (deviation from diagonal)
  - Fit appropriate function (polynomial with 4 odd terms)
  - Use the fit to correct for the bias (in a next iteration over the run)
- Not stable if the number of charge bins is small

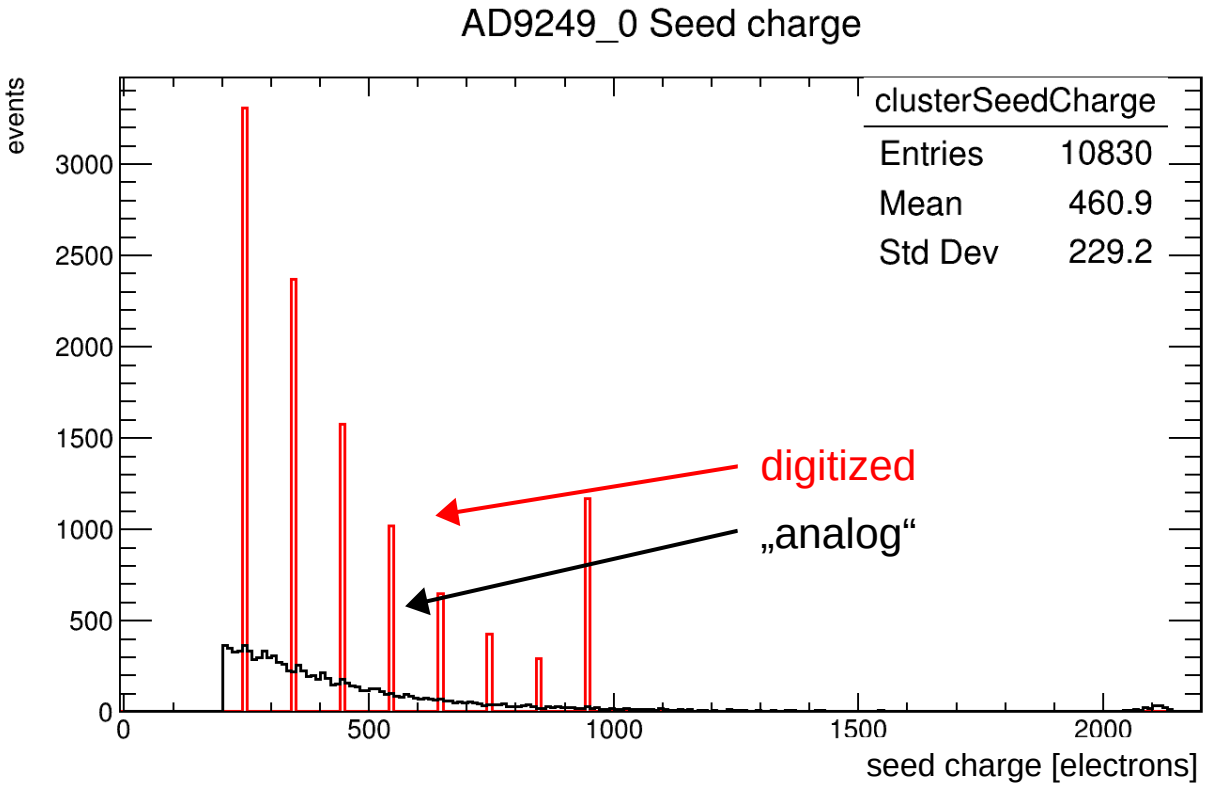


Example, eta correction for n-gap at 100 e

Tools and Methods

Offline Digitization

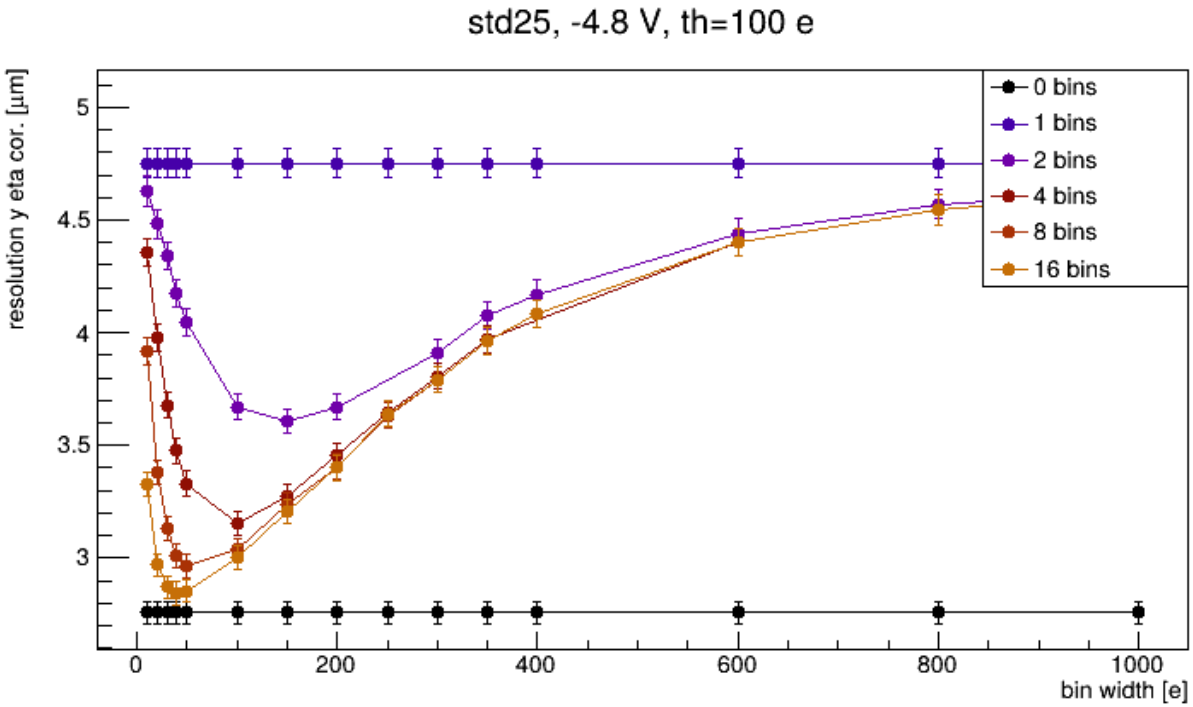
- Our analysis chain makes use of **`ClusteringAnalog`**
- This allows easy **offline threshold emulation**
- Added **digitization** feature with two parameters
  - `digitizerBinWidth`; example 100 e
  - `digitizerBinNumber`; example 8 bins
- Scanning
  - Bin width from 10 e to 1000 e (increasing step size)
  - Number of bins 0 (analog), 1(binary), 2, 4, 8, 16
- Challenge – need eta-correction for 810 conditions
  - Charge weighting will not yield optimal resolution
  - Need to apply eta correction for all studied cases



Effect of Digitization Parameters

An Example

- Straight lines for the extreme cases
  binary (1 bin) and infinite (0 bins) charge granularity
- The bin width matters
  - Choosing bins too small or too large close to binary
  - Optimal when the dynamic range
    covers ~50% of the MPV
- „Two threshold" approach (1 bin)
  - Levers 50% of the achievable improvement
- Eta-correction makes little difference
  - Either linear charge sharing or small cluster size

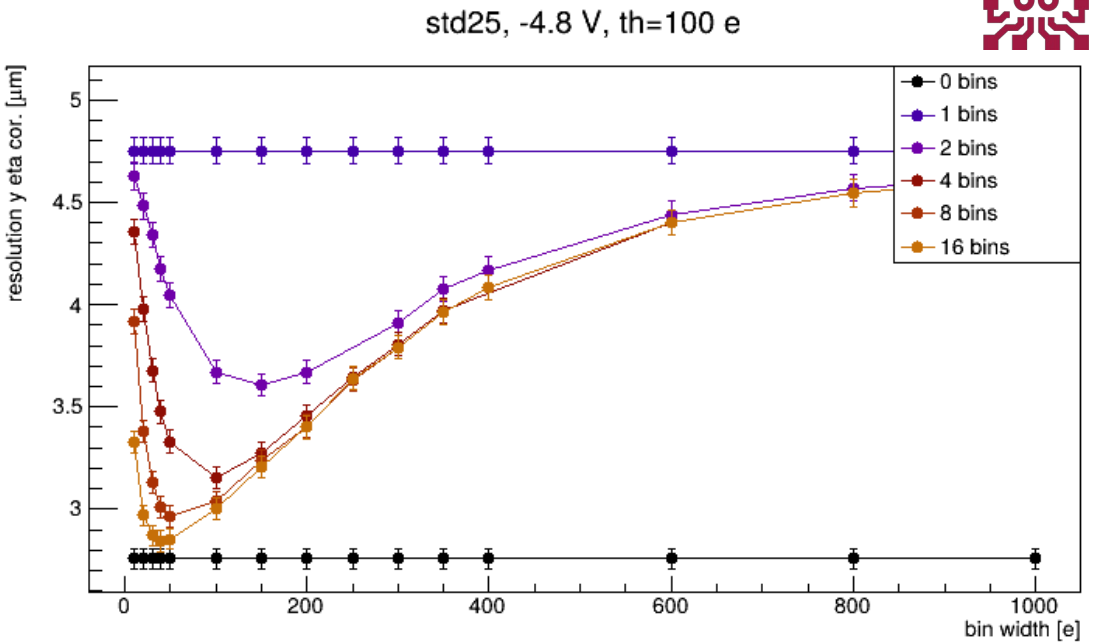


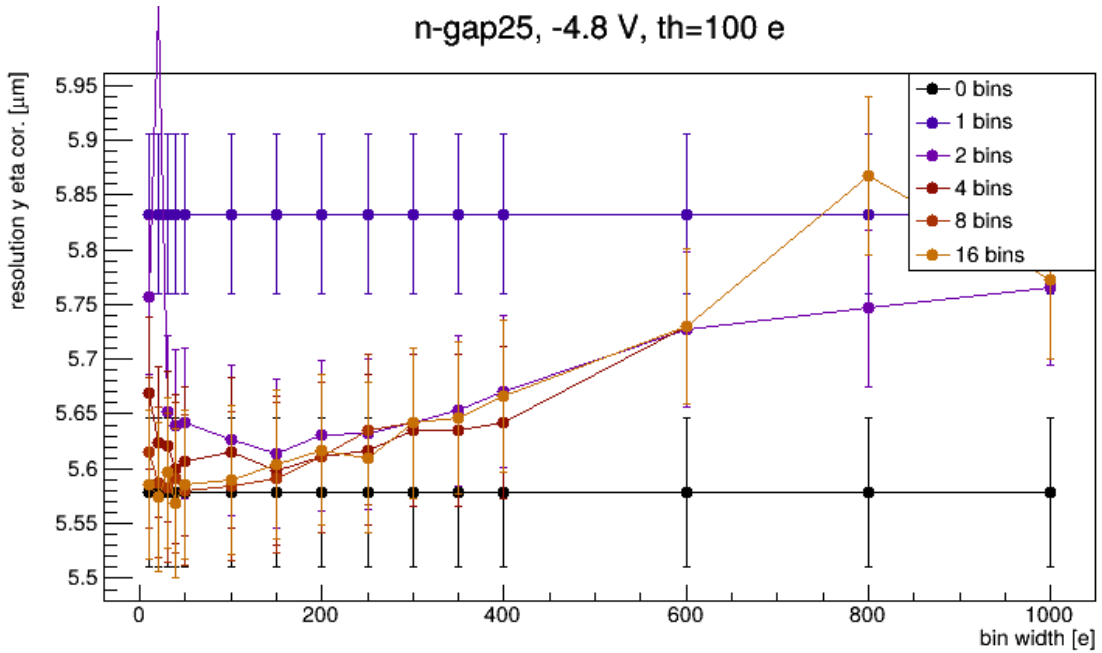
Results

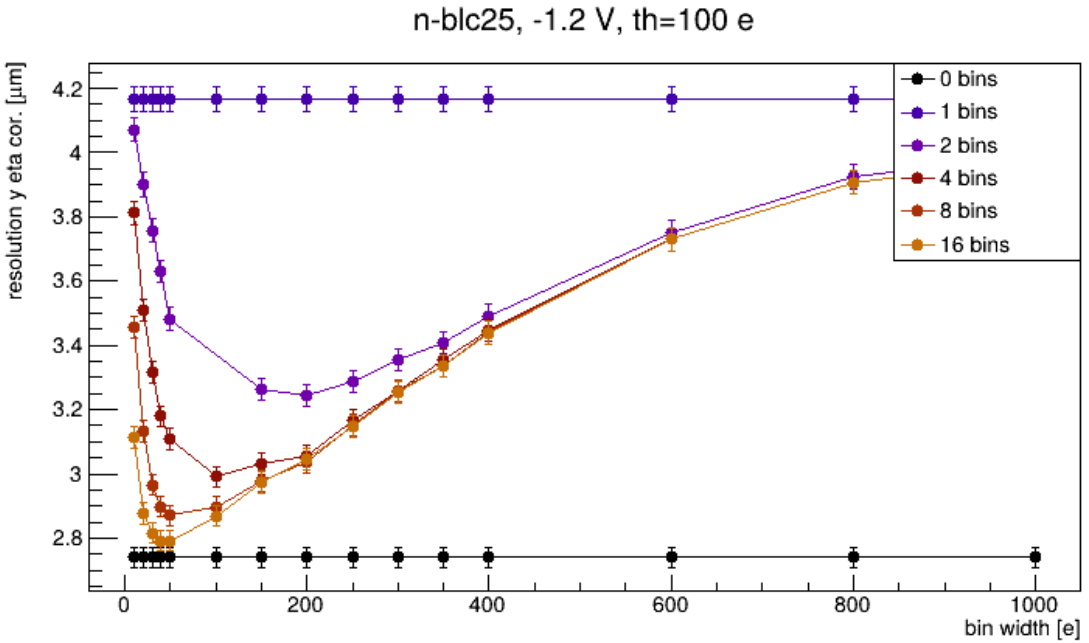
Low Thresholds

This is interesting!

- Profit from charge info, std > blc > gap
- Two bins enough to get > 50 % of the potential





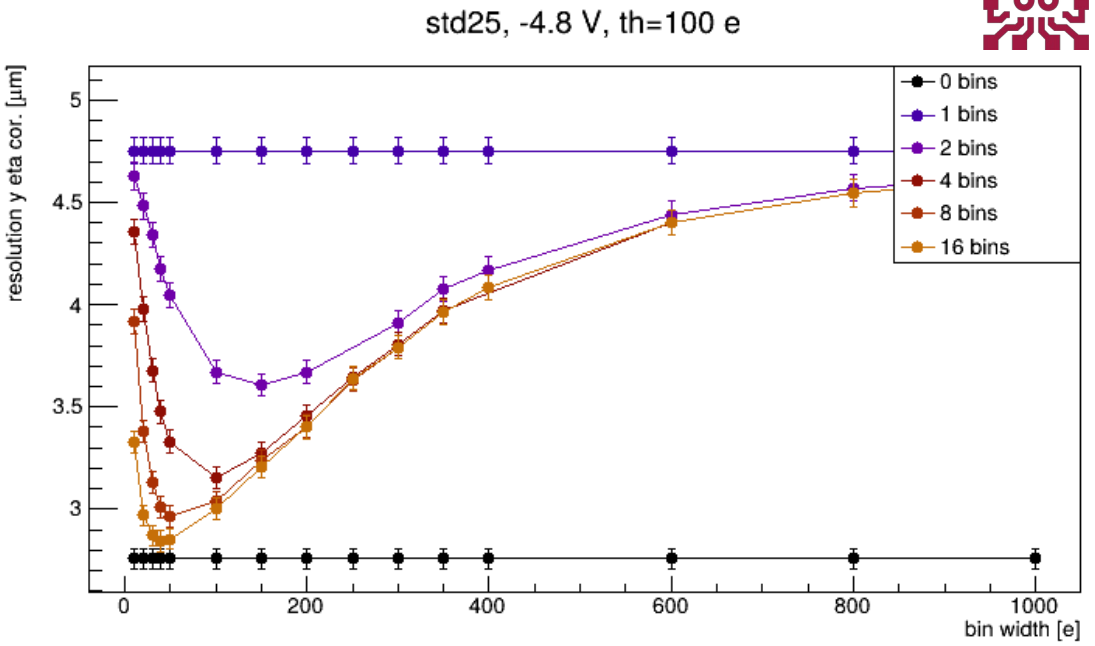


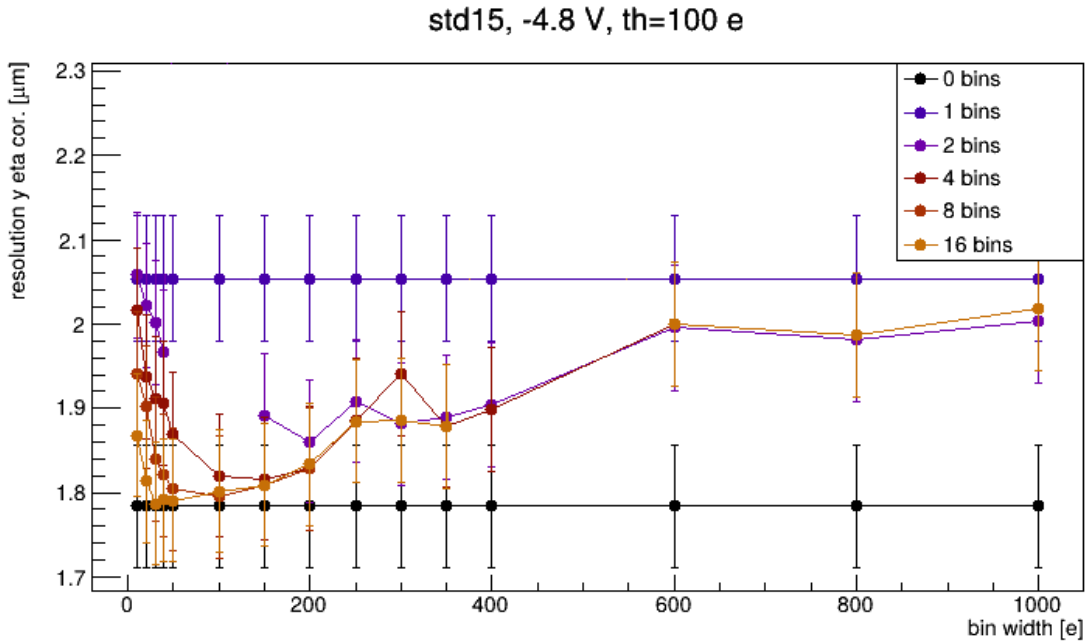
Results

Comparing Pitch

This is interesting!

- Profit from charge info, std > blc > gap
- Two bins enough to get > 50 % of the potential
- The effect of the charge info reduces with
  - Decreasing pitch
    (limited by noise?)



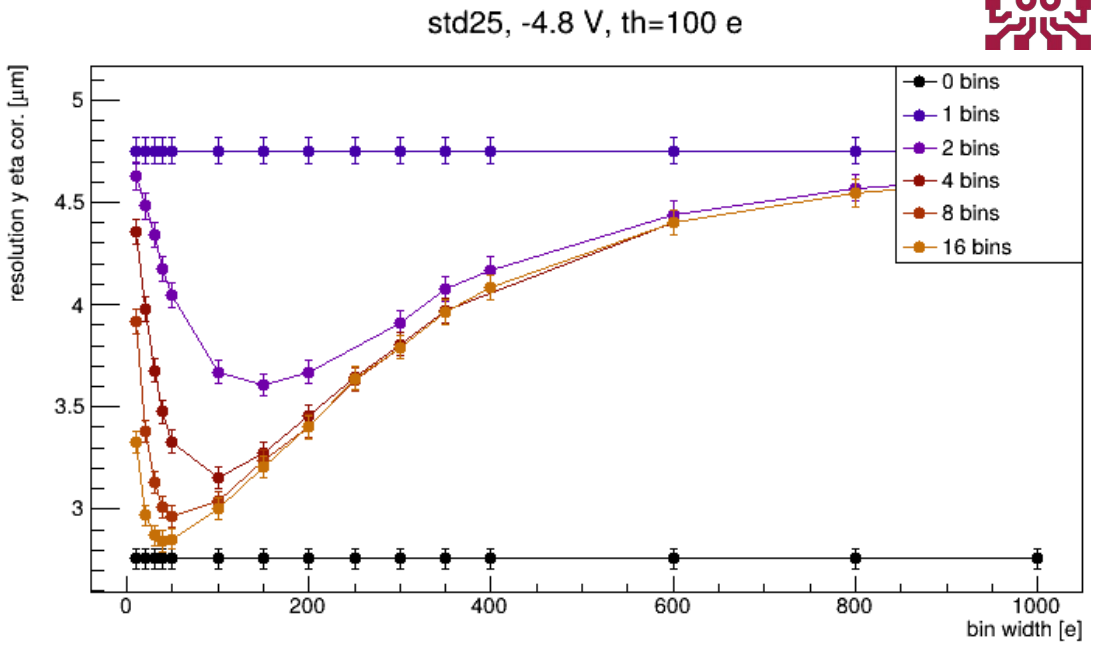


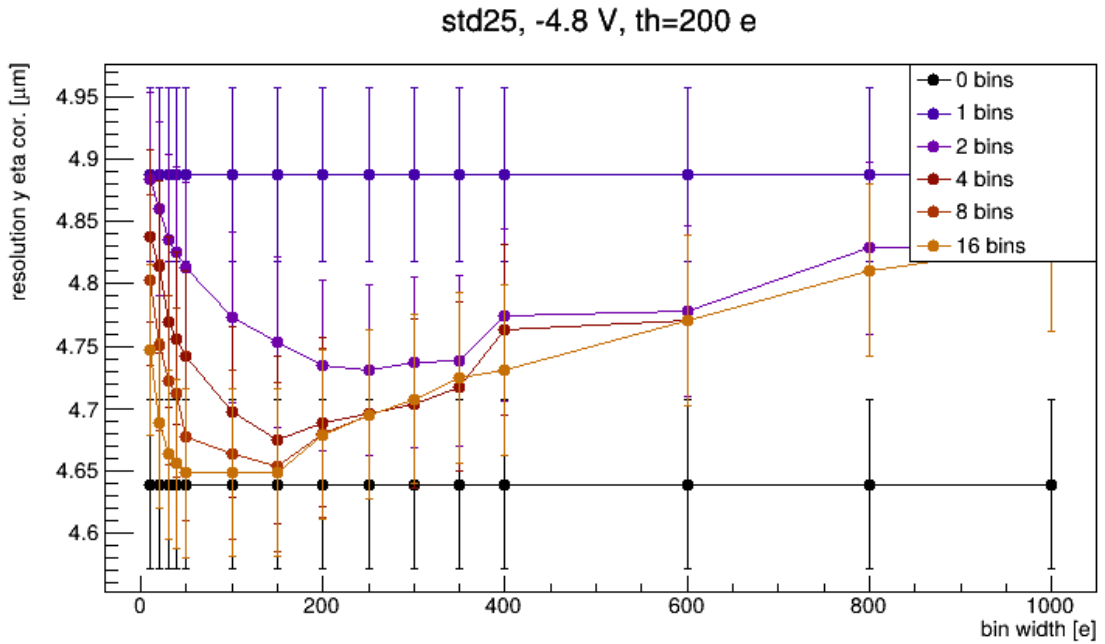
Results

Comparing Thresholds

This is interesting!

- Profit from charge info, std > blc > gap
- Two bins enough to get > 50 % of the potential
- The effect of the charge info reduces with
  - Decreasing pitch
    (limited by noise?)
  - Increasing threshold
    cluster size (efficiency) decreases

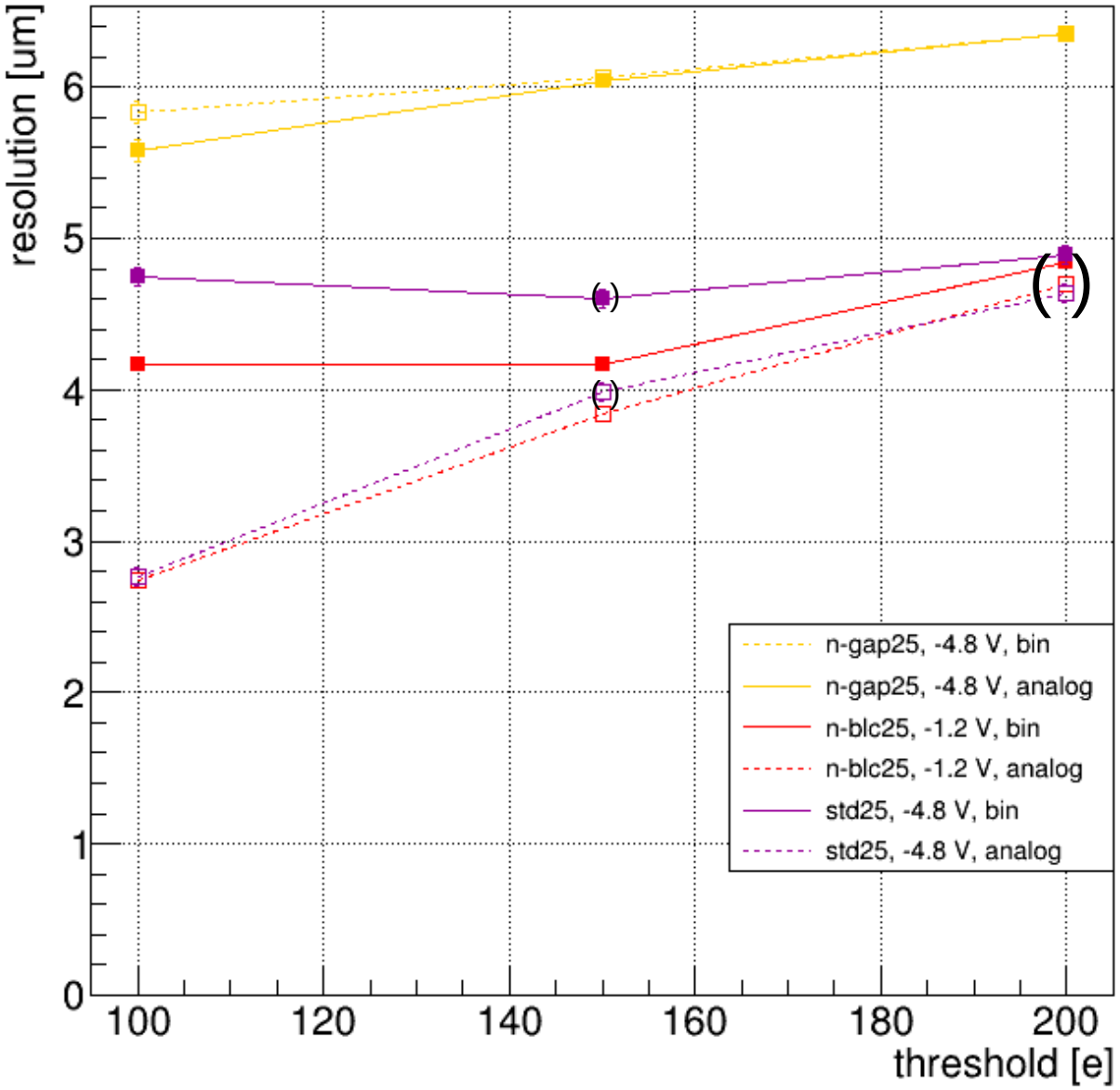




Results

Threshold Dependence

- Caveats
  - Points in () are below 99% efficiency
  - Systematic uncertainties between designs (telescope resolution)
- Threshold has comparably large impact
  - n-gap: resolution gains from threshold larger thank resolution gains from charge info
  - n-blanket and standard: need low threshold to profit from charge info



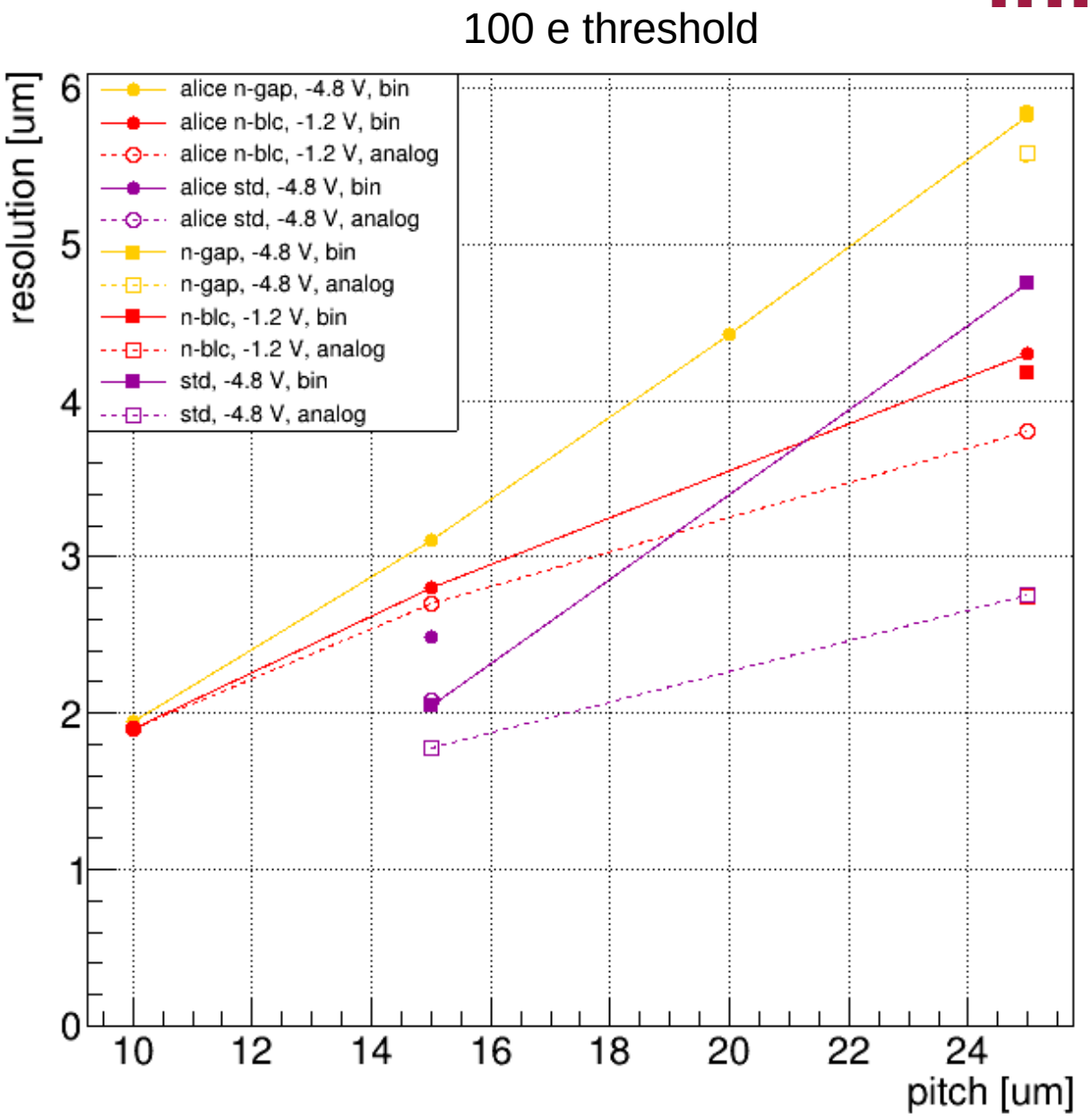
Results

Pitch Dependence

- Alice data is from APTS [ref. pub.]
  - Pitch has clear, strong, linear impact on spatial resolution for n-gap and n-blanket design
  - Alice results indicate lower impact of charge info
    - Especially n-blanket 25 um
- Data for standard layout is a bit scarce/ confusing
  - 15 um: small tension between Alice and us
  - 25 um, binary: this is unexpectedly bad

To achieve a resolution better than 3 um:

- Pitch and design are crucial, threshold too
- Impact of charge info might make difference



The Answers

To Shape the Design of a Pixel Sensor for a Future Lepton Collider

Key questions concerning spatial resolution

- What are the limits achievable with a certain design (standard, n-blanket, n-gap)?
- How do these limits depend on the pixel pitch and threshold?

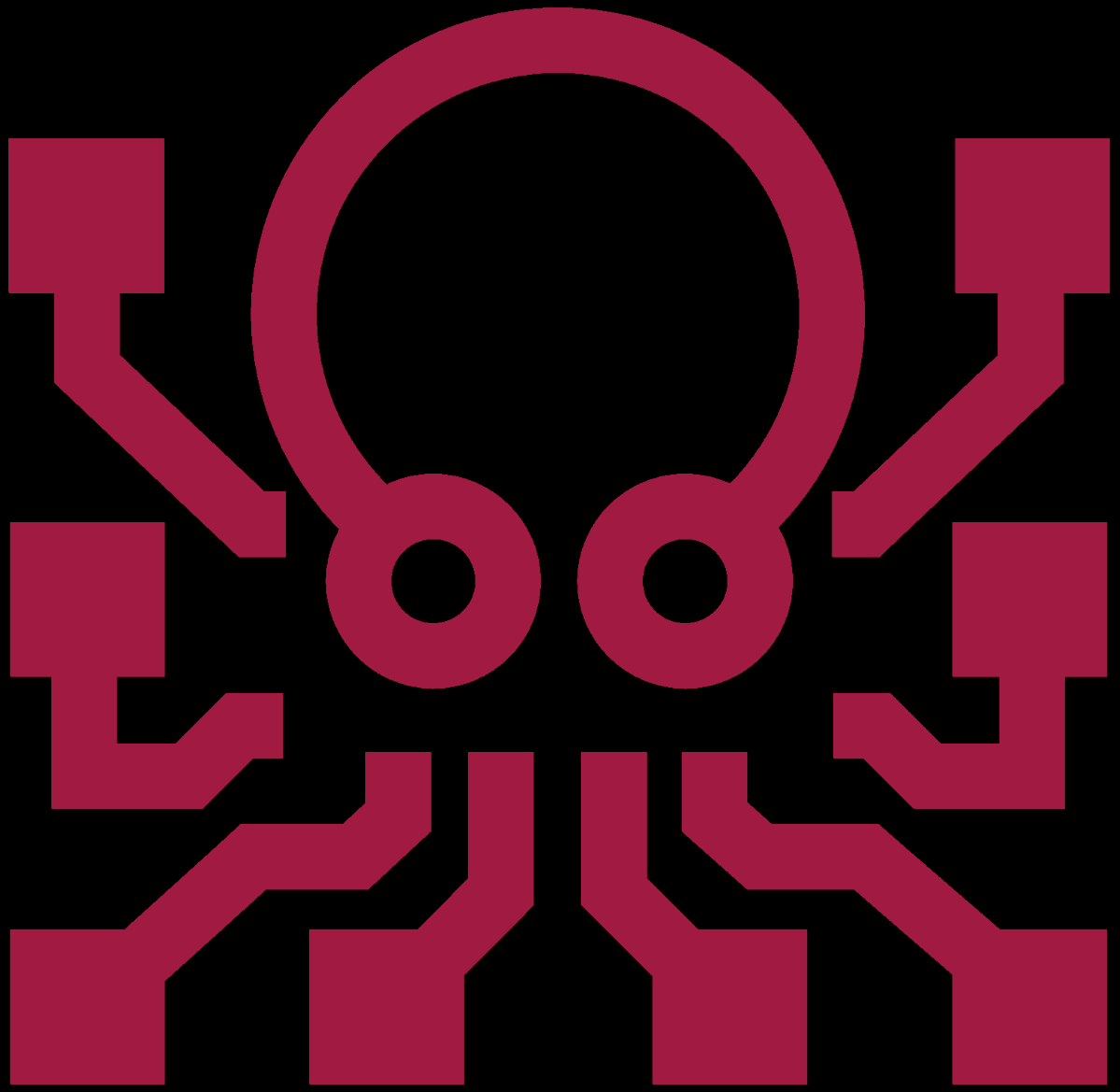
→ Campaign of simulations and literature review within OCTOPUS } Anastasiias talk

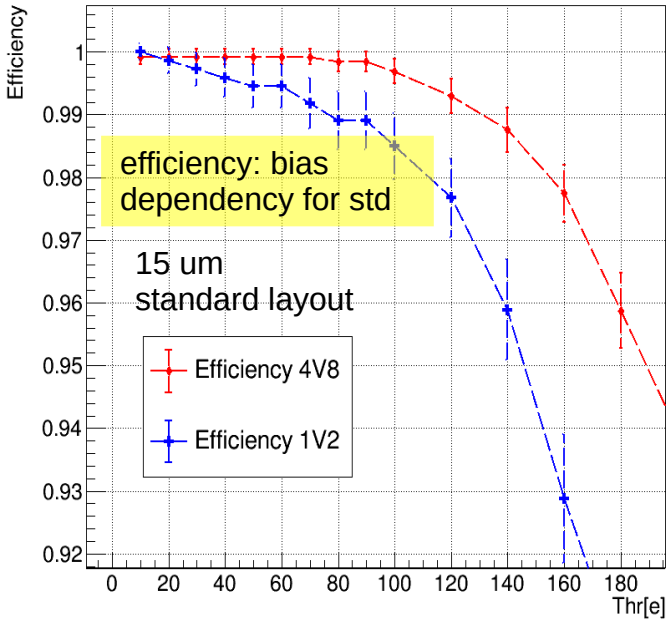
→ Pitch has a lower limit from design constrains! } Robertos talk

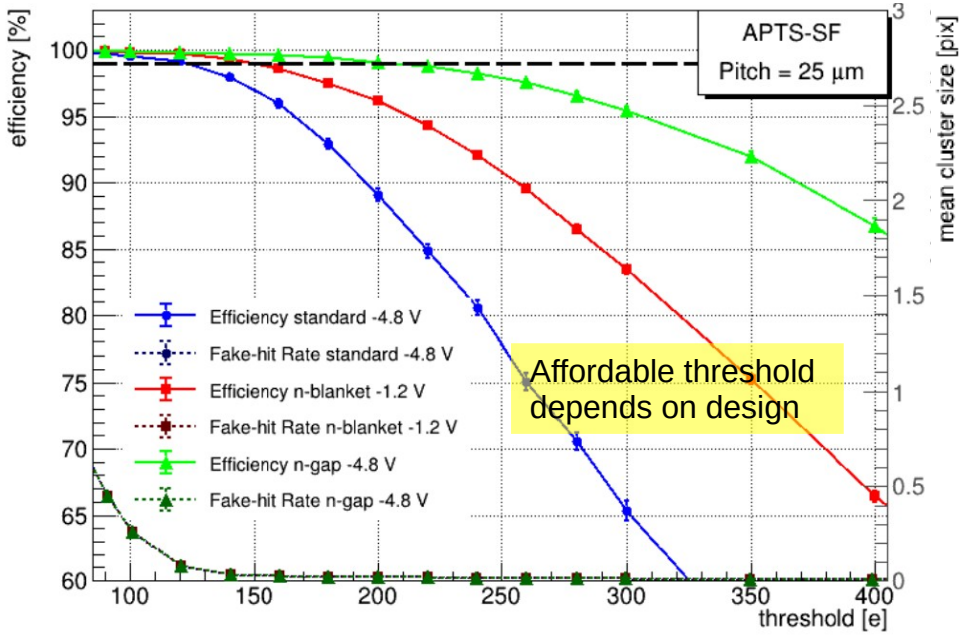
- How much potential for improvements does charge information offer?
  - How many bits do we need in order to leverage this potential?
  - What about two thresholds?

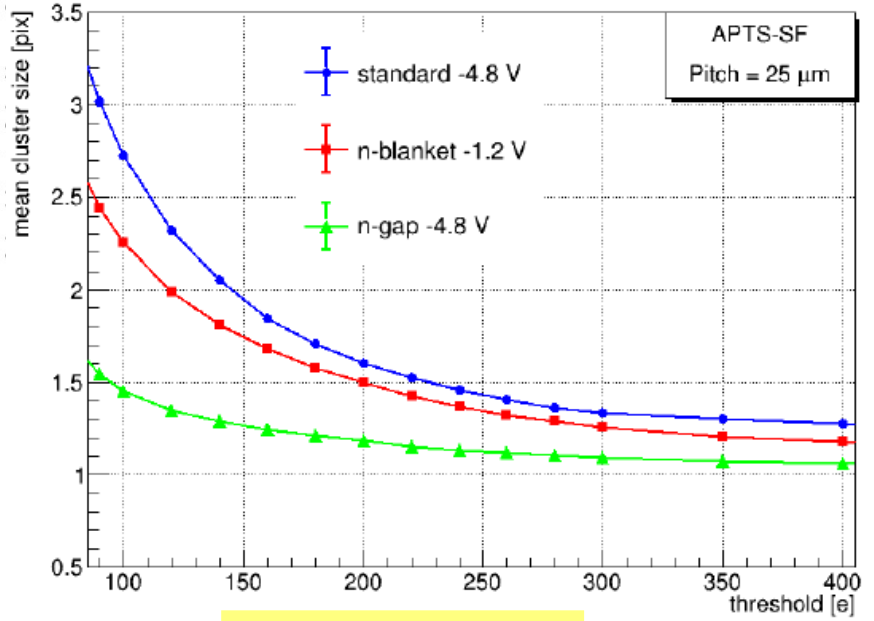
→ Spatial resolution profits most from “the first 2 bits”

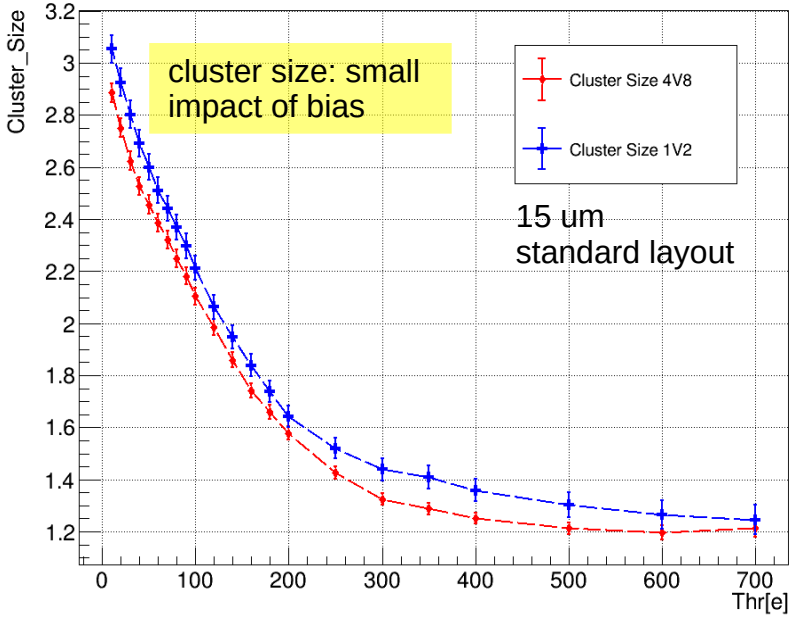
→ Temporal resolution drives the requirement on charge granularity } Robertos talk

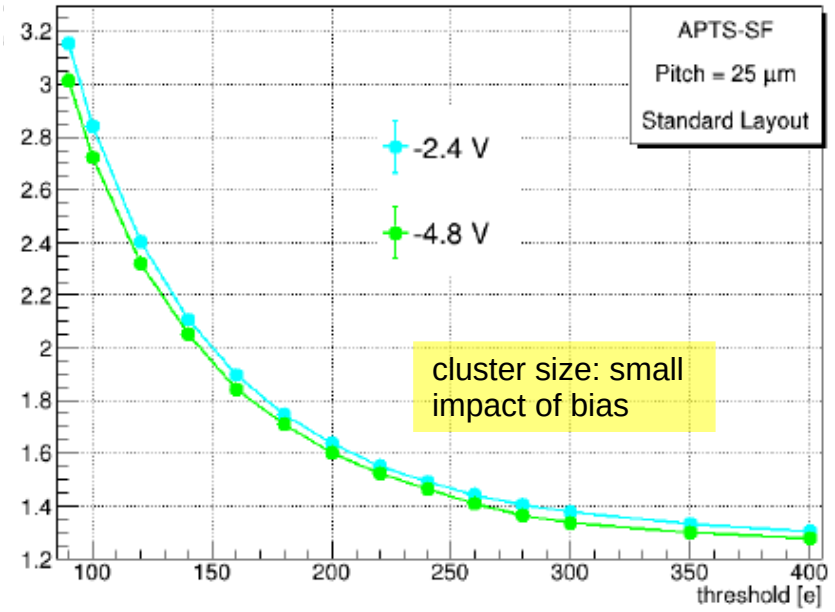




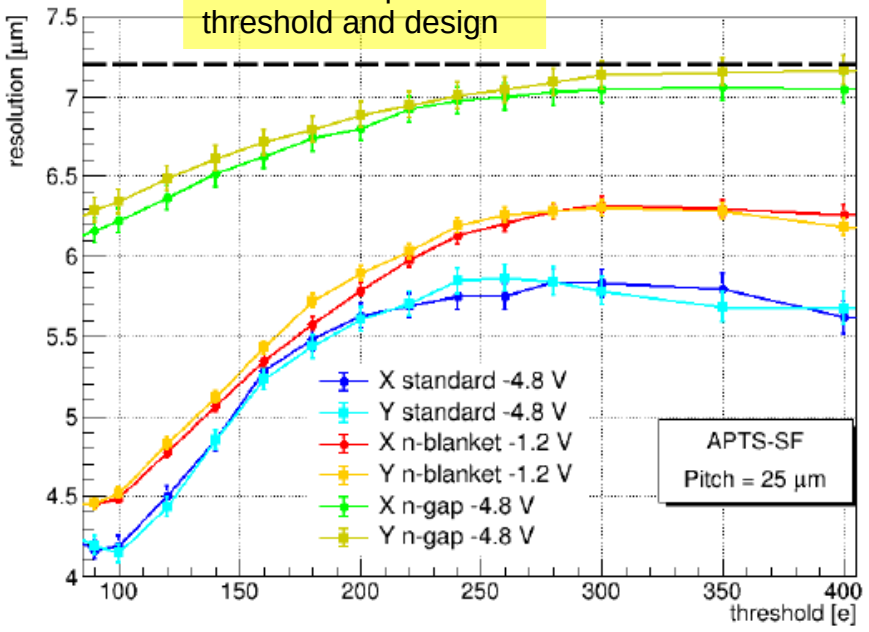






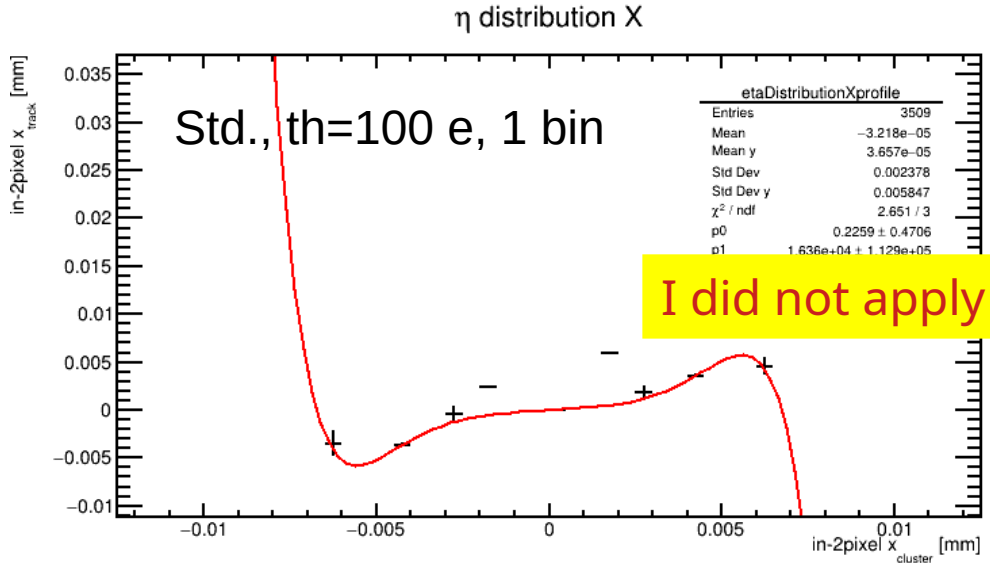


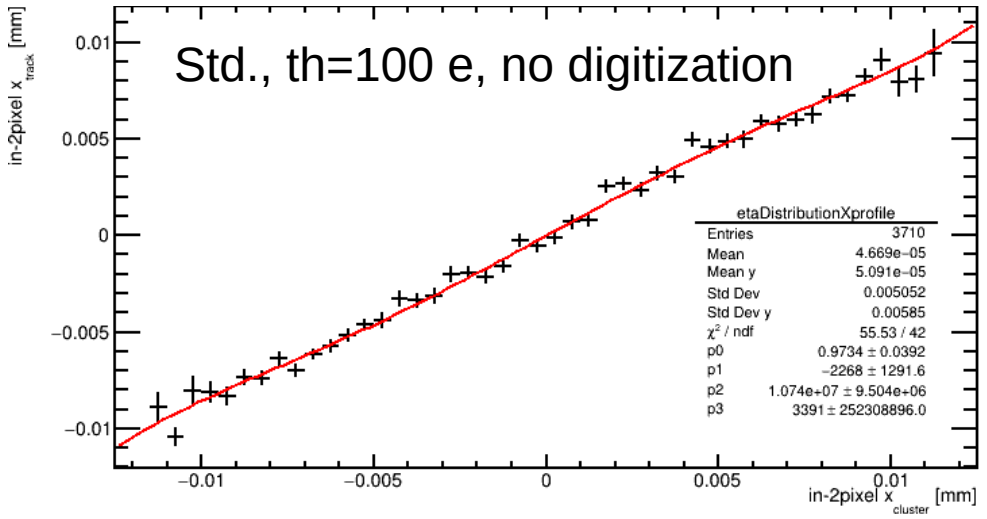
resolution depends on threshold and design



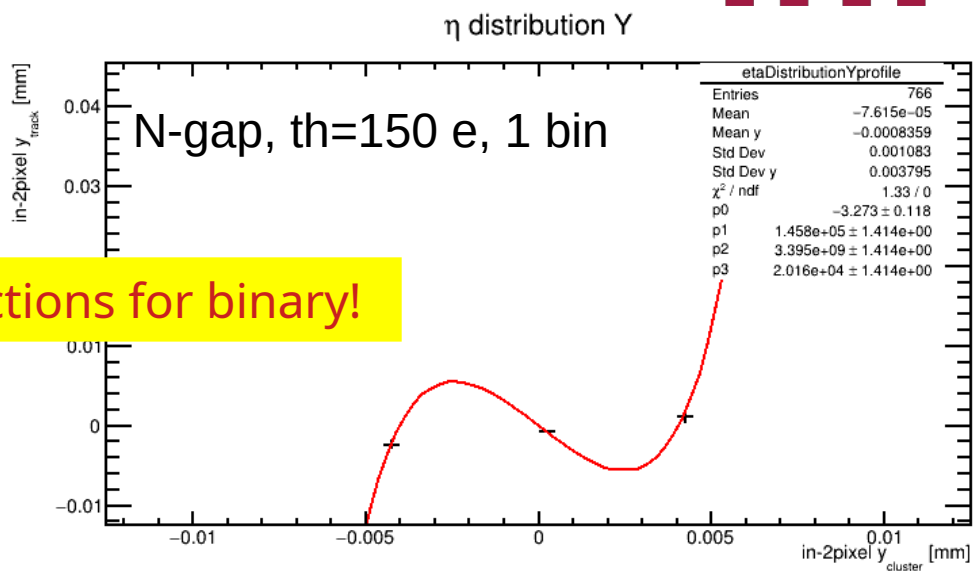
Tools and Methods

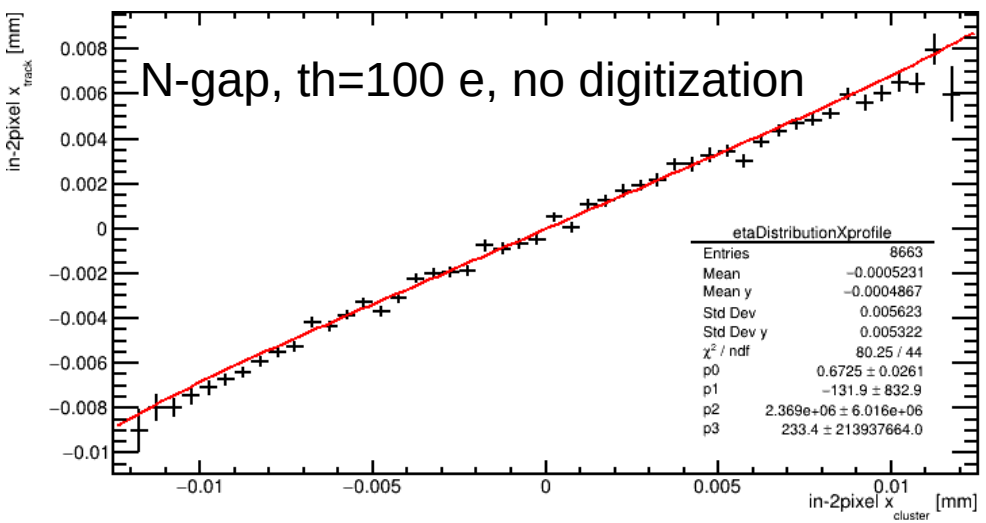
Eta Correction – Examples





I did not apply eta-corrections for binary!

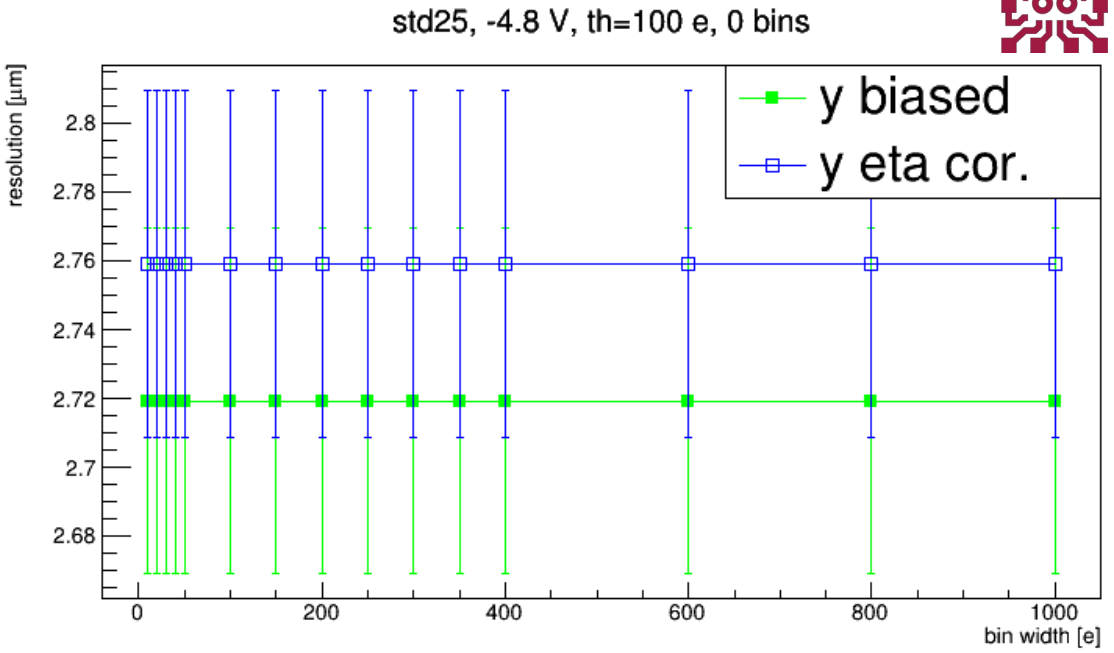


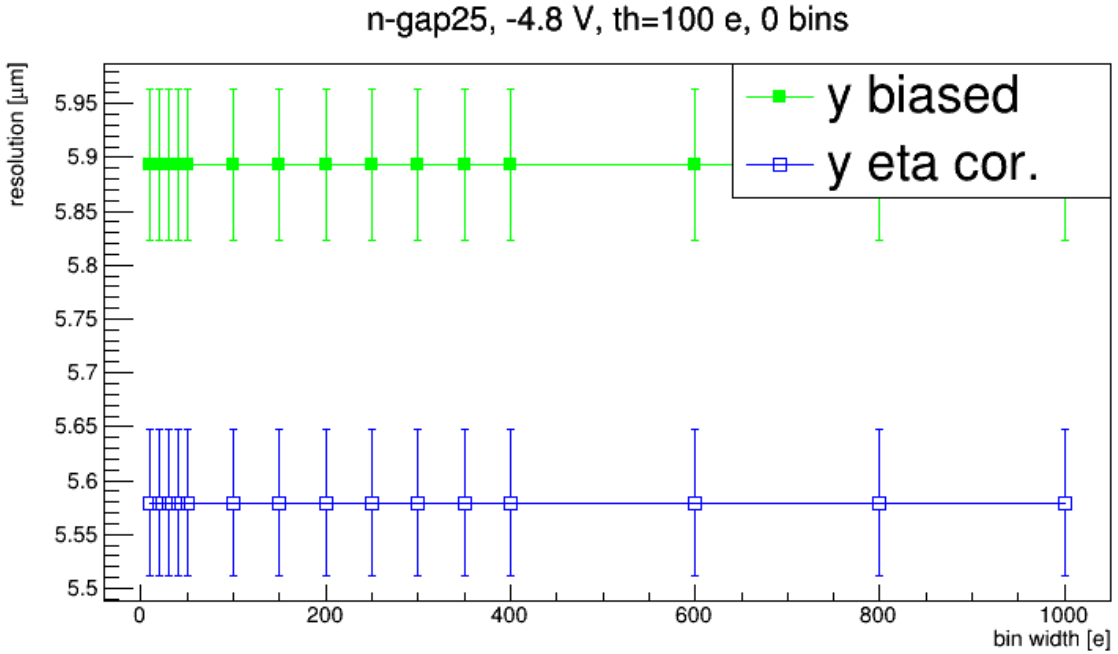


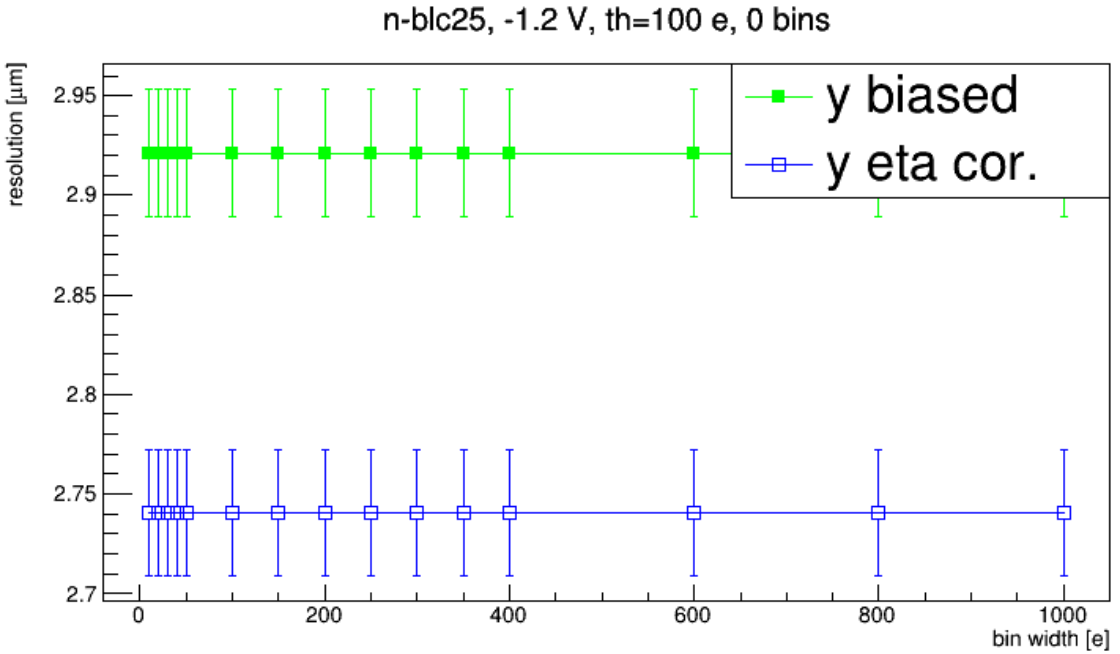
The „Eta-Potential“

How much can we gain from the Eta-Correction?*

- Especially at low thresholds
- Overall not that impressive
  - Either small cluster size (n-gap)
  - Or relatively linear charge sharing (std)
- However, this does not mean that charge info is







*questions in a title usually indicate the answer is NO!

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- Especially at low thresholds
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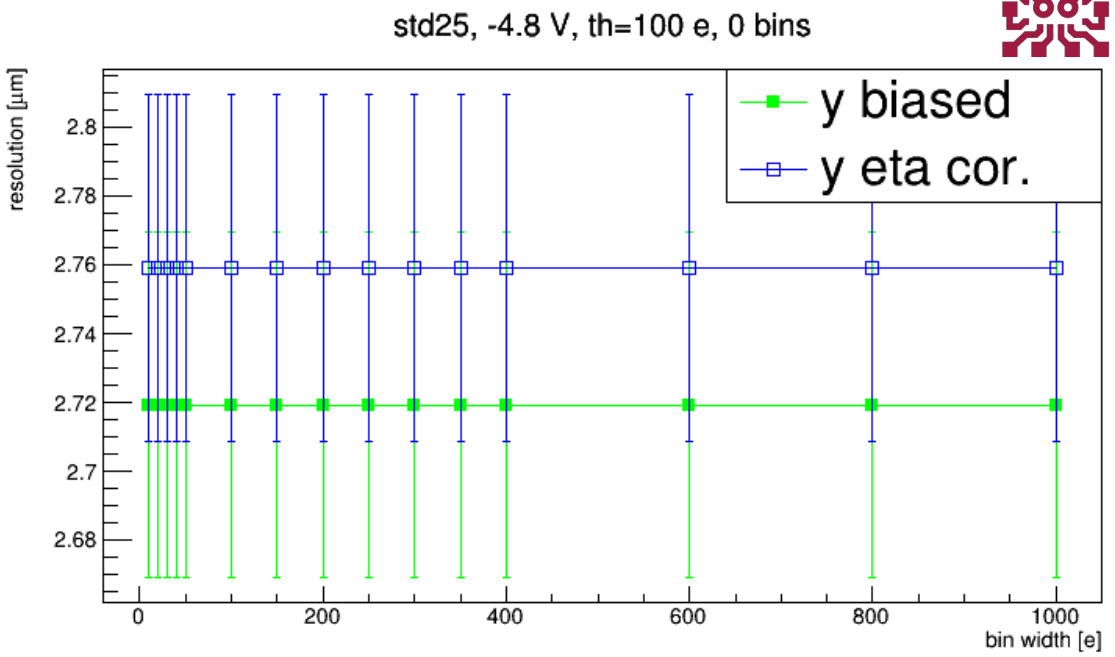
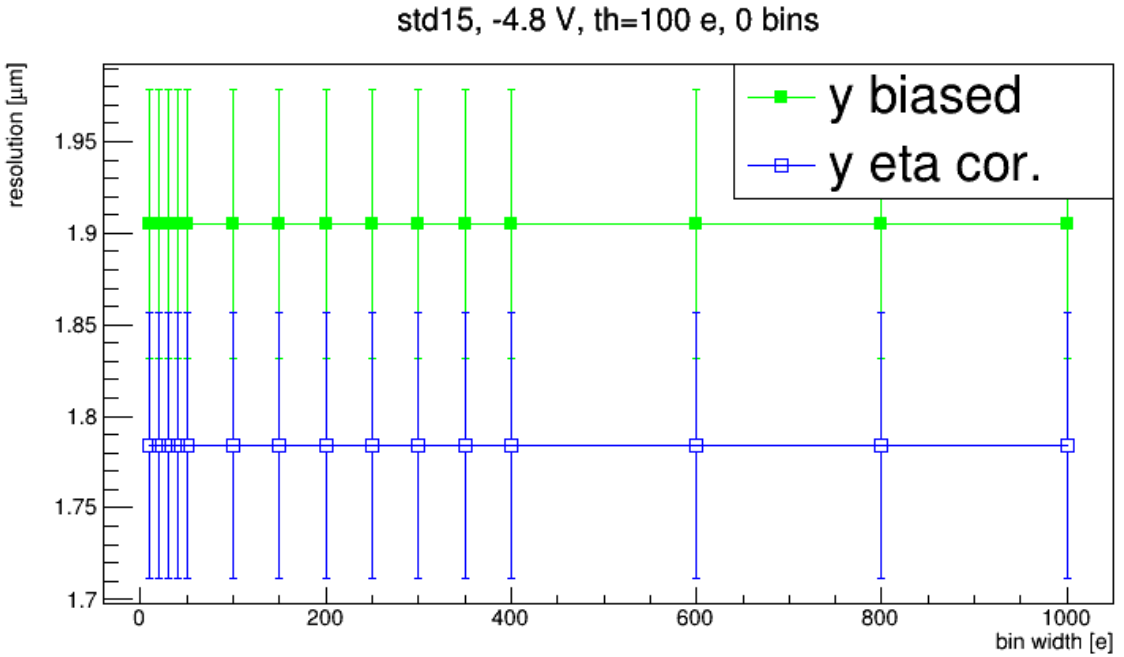
  - Either small cluster size (n-gap)
  - Or relatively linear charge sharing (std)
- However, this does not mean that charge info is useless!





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