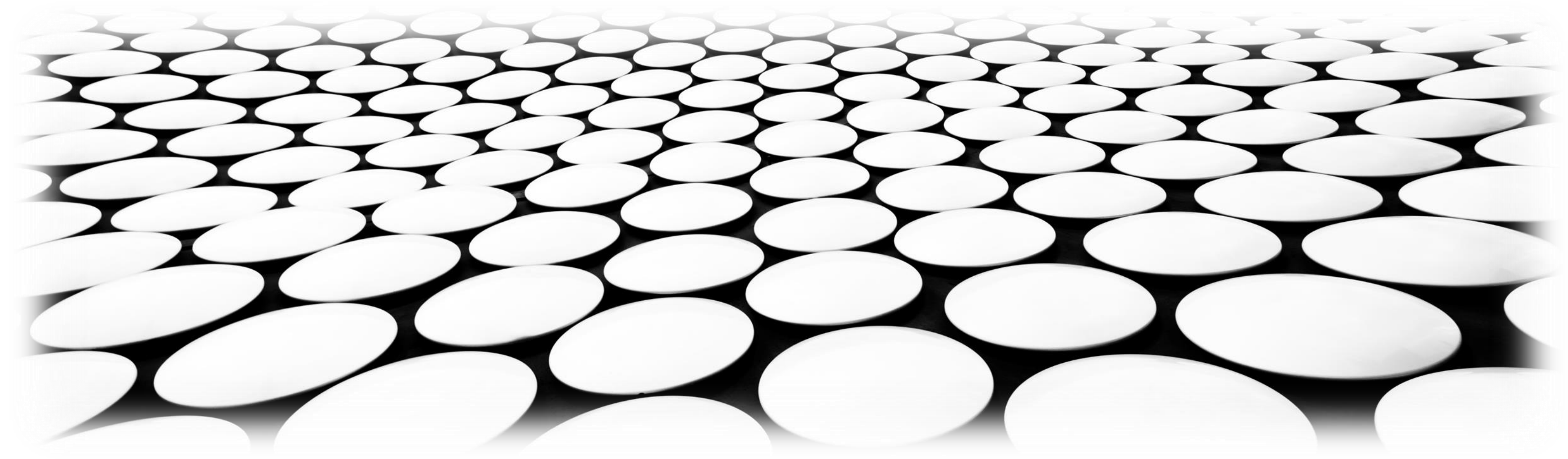
IMPROVING TIME RESOLUTION OF SILICON PIXEL DETECTORS USING CORRECTION ALGORITHMS

ANDREJ SARNATSKIY

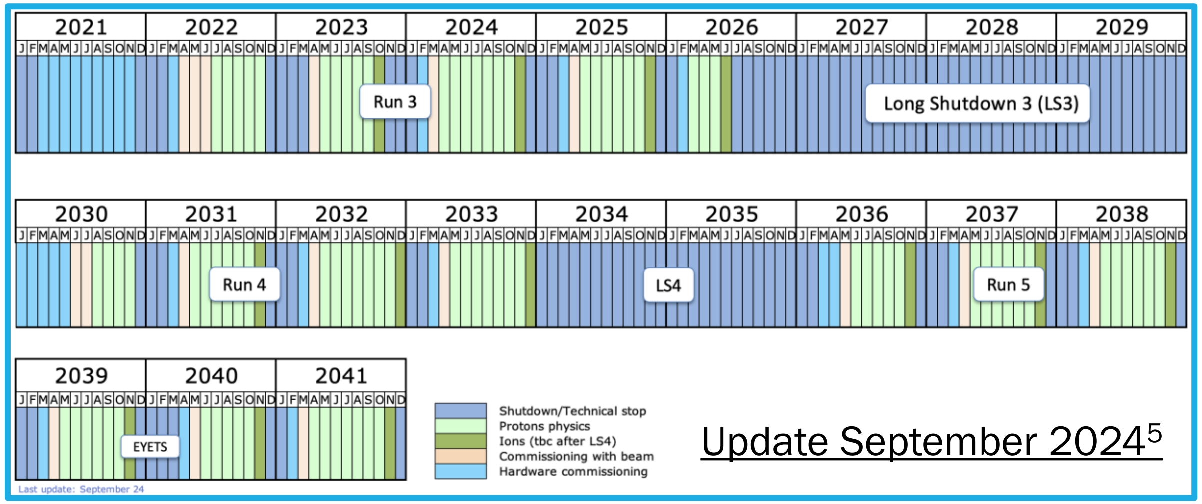


NNV Fall meeting

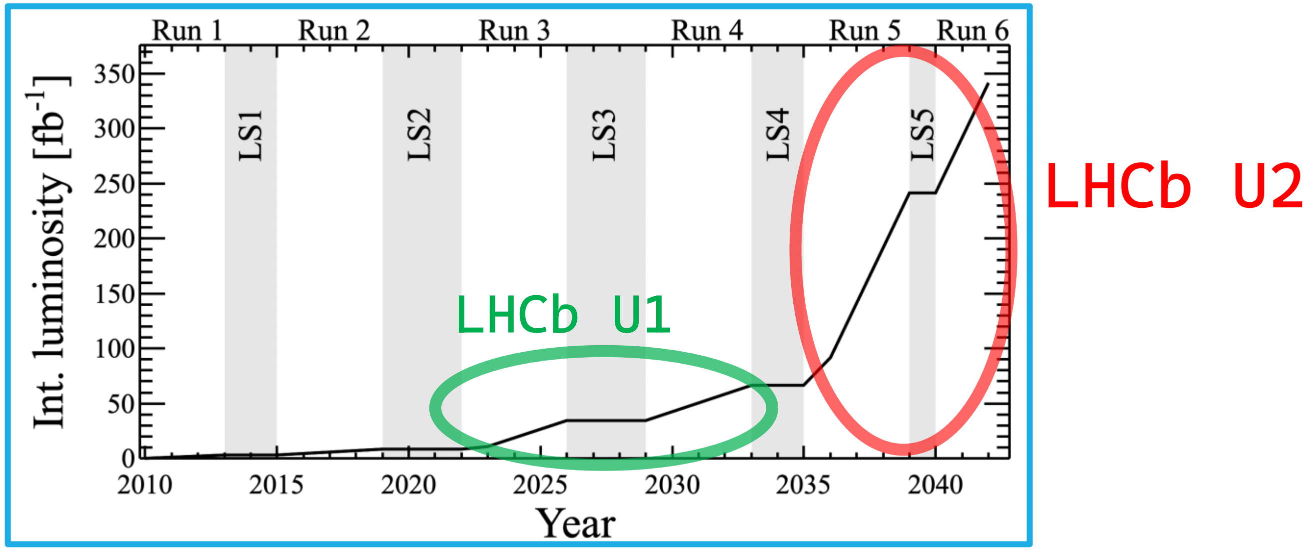
(subatomic/astro) particle physics

MOTIVATION

- LHCb U1 (Upgrade 1) running successfully now
- During LS3 the LHC and other experiments[1,2,3] get a high-luminosity upgrade.
- Higher luminosity → more collisions → more statistics
- LHCb next upgrade[4] installed during LS4 (2034)



Update September 2024[5]



(Projected) Integrated luminosity of the LHCb[6]

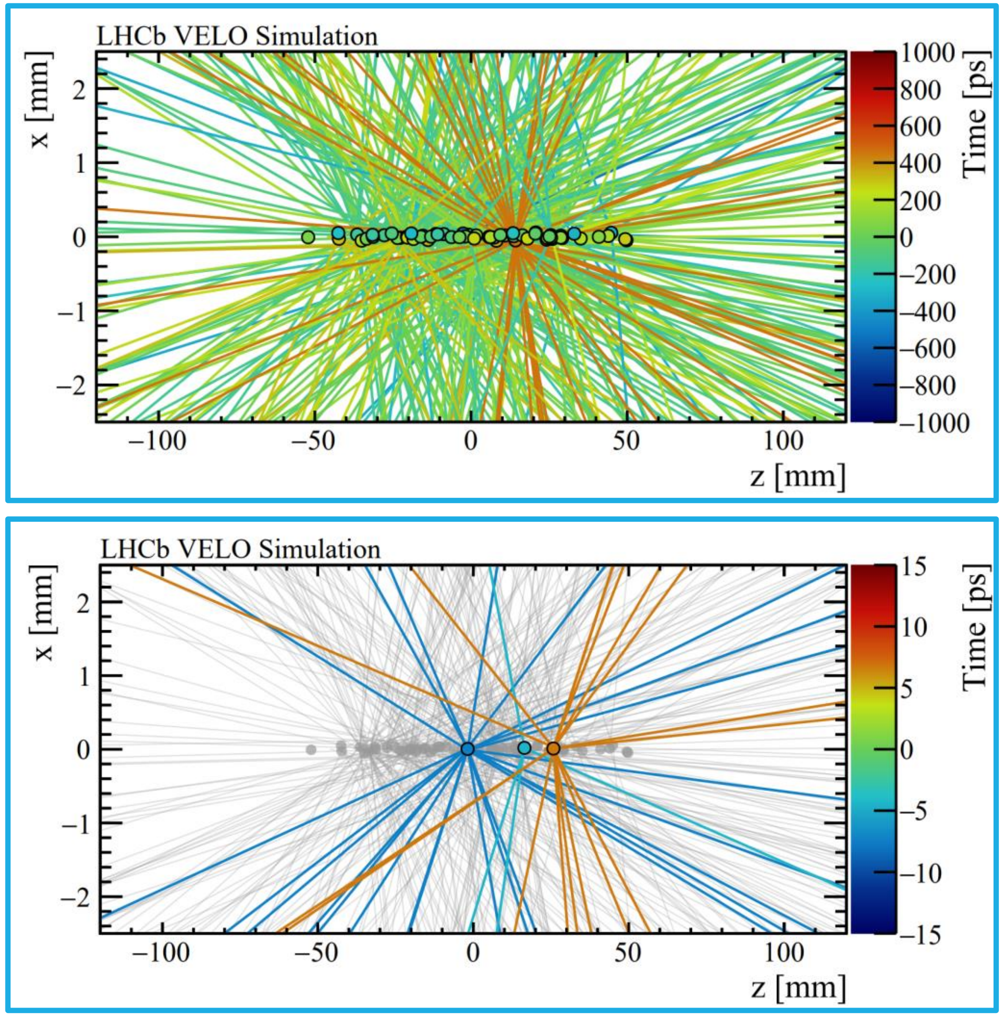
MOTIVATION

~ 5 – 40 collisions

- Silicon tracking: challenges to get data from chips to reconstruction
  - Decrease data **rate** (compression)
  - Distinguish PV events during high pile-up and associate first hits in tracking (timing)
  - Apply **corrections** as soon as possible for improved reconstruction
- **What** corrections can be applied and **where** ?

~ 2 Pbps

$\sigma_T \sim 30$ ps



Courtesy: R. E. Geertsema

VELO UPGRADE

32 bits

Timepix3

64 bits

Timepix4

64-72 bits ?

Picopix

LHCb U1

Velopix

LHCb U2

Velopix2 ?

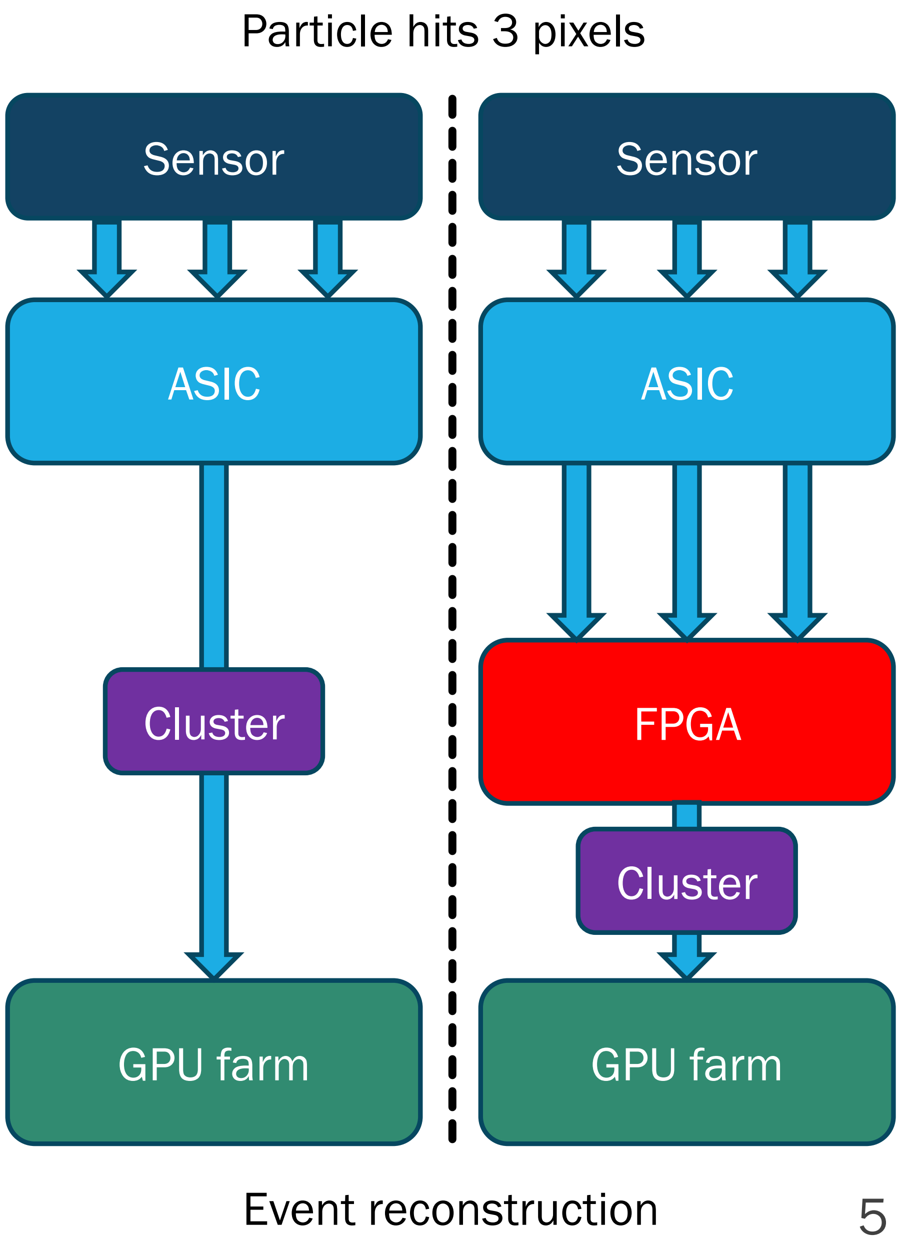
- Binary hit map in a package
- No internal timing information
  - LHC clock determines timing

$f = 40$ MHz $\rightarrow$ $\sigma_T \sim 25$ ns

- $\sigma_T \sim 30$ ps required
- Send data packages for every hit and process afterwards
  - Will be challenging due to bandwidth and resources
- ... or combine information on chip

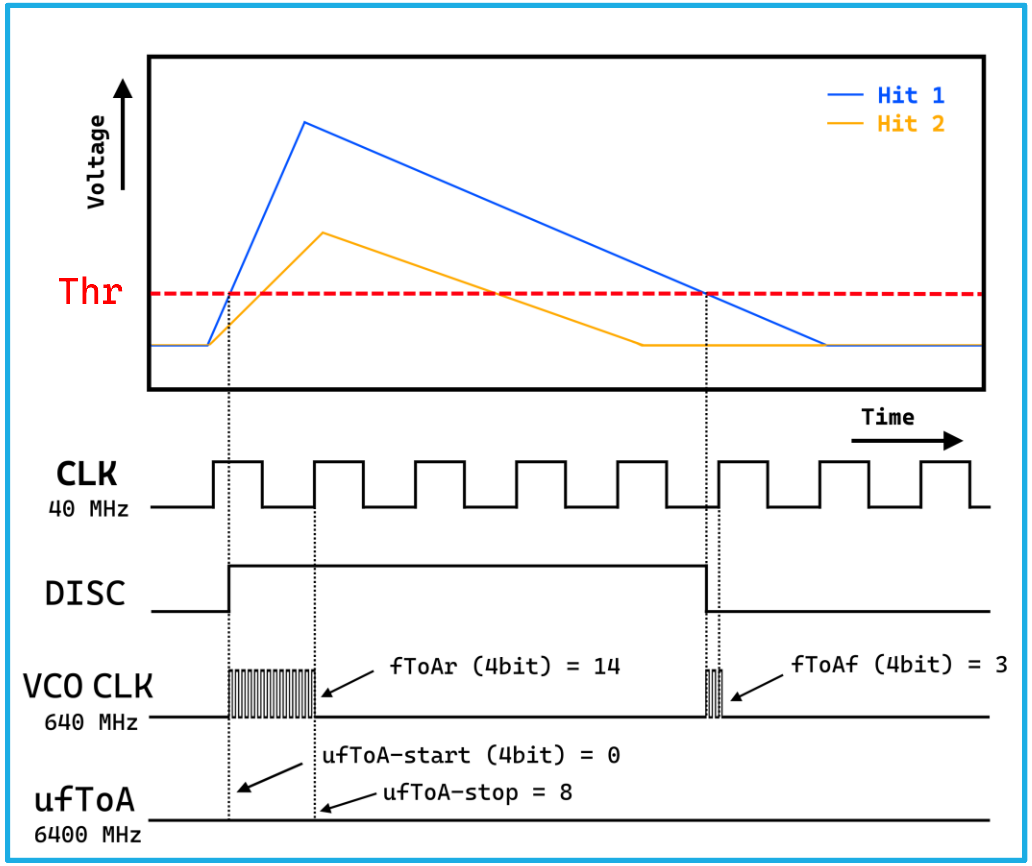
DATA REDUCTION

- **Picopix:** Attempt to reduce data rate in the ASICs
  - Cluster hits and compile information into a single data package
- The alternative is to apply corrections down the road @ FPGA or GPU
  - Possibility of **combining** and **correcting** pixel hit to clusters
  - Firmware is flexible and adjustable



CORRECTIONS

- For $\sigma_T \sim$ 30 ps additional effects need to be taken into account and appropriate corrections are necessary



Velopix [7,8]

6 bits	7 bits	9 bits	8 bits
yADDR	xADDR	ToA	hitmap

30 bits

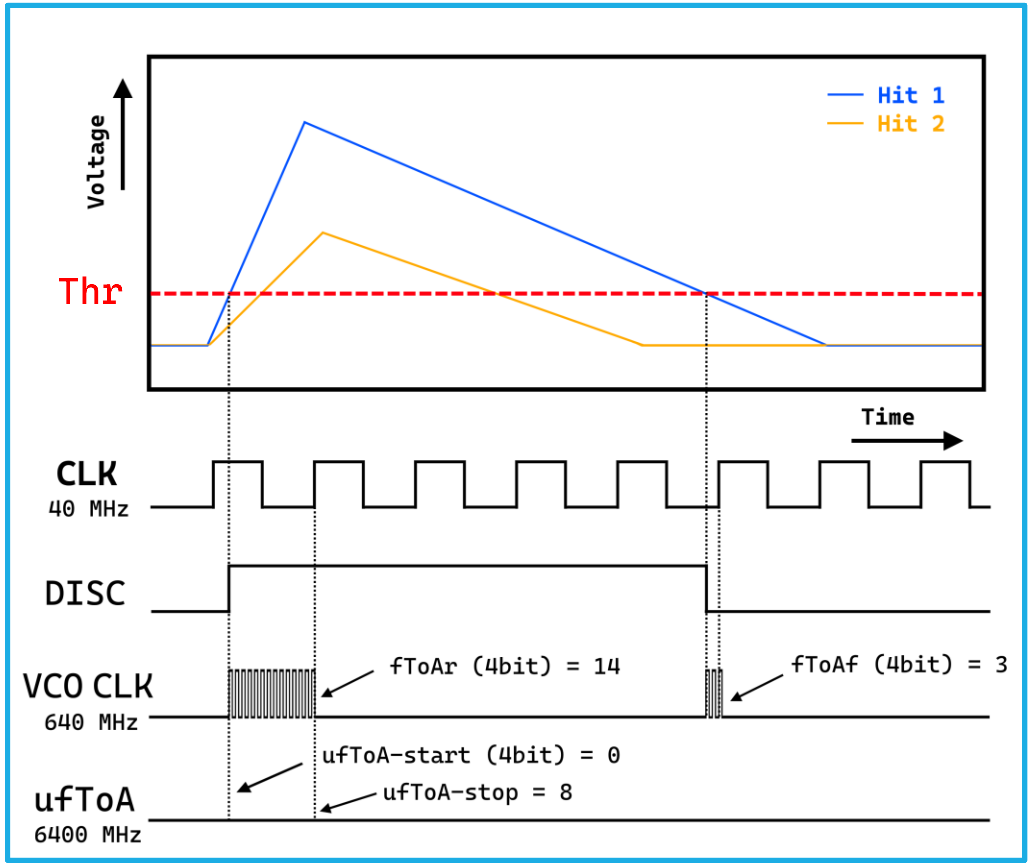
Timepix4 [9,10]

9 bits	9 bits	11 bits	16 bits	10 bits	8 bits	1 bit
yADDR	xADDR	ToT	ToA	fToA	ufToA	pileup

64 bits

CORRECTIONS

- For $\sigma_T \sim 30$ ps additional effects need to be taken into account and appropriate corrections are necessary.
- E.g. timewalk can be corrected.
  - Total charge collected is proportional to Time-over-Threshold (ToT).
  - ToT is correlated with timewalk.



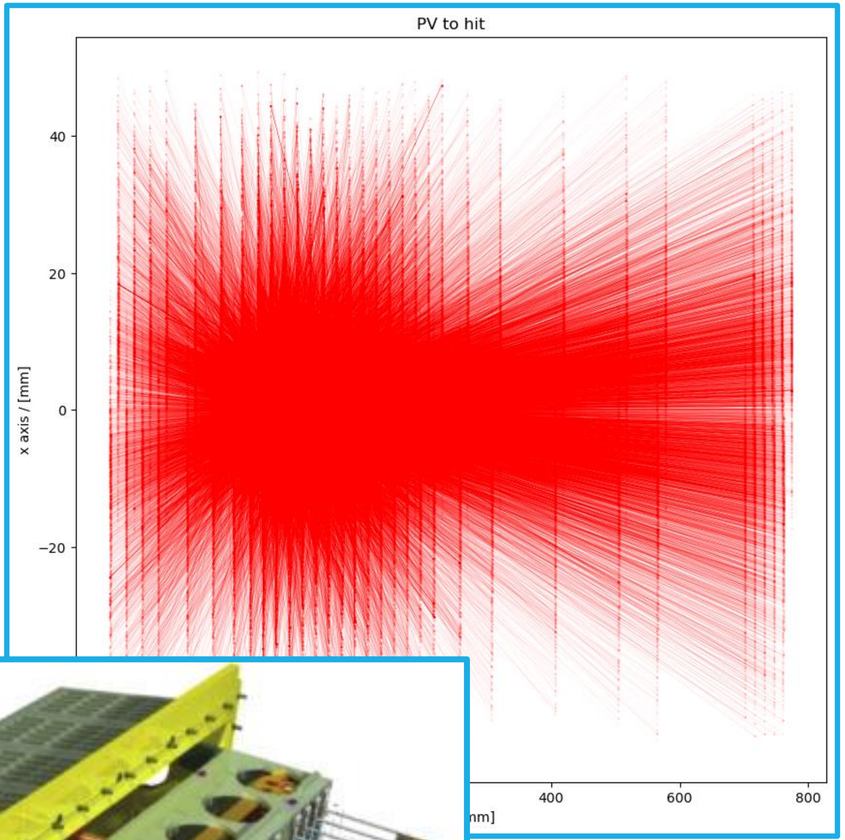
Timepix4 [9,10]

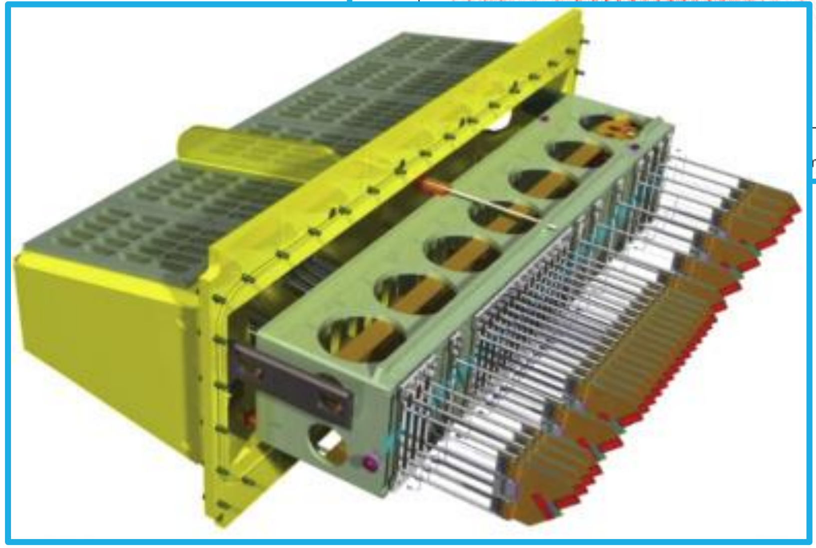
9 bits	9 bits	11 bits	16 bits	10 bits	8 bits	1 bit
yADDR	xADDR	ToT	ToA	fToA	ufToA	pileup

64 bits

LHCB UPGRADE 2 SIMULATION

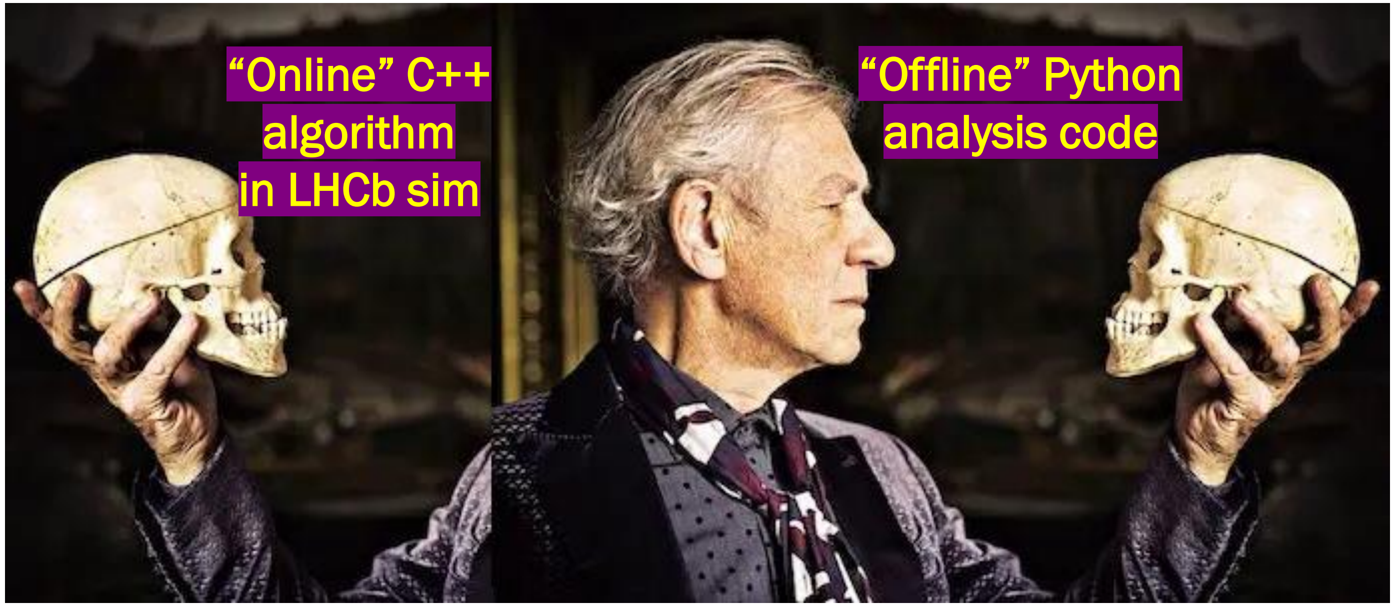
- Using LHCb simulation to analyse impact of algorithms
- What is the consequence of clustering?
- What bit allocation is optimal?





STRUGGLE OF DUALITY

- Either run the LHCb simulation once, then do the analysis
- … or implement additional code in the simulation



CLUSTERING INTERPOLATION

- Three methods tested:
  - **CoG:**

    $$(\bar{x},\bar{y})_{CoG} = \frac{1}{N}\sum_{i}^{N} q_i \cdot (x_i, y_i)$$

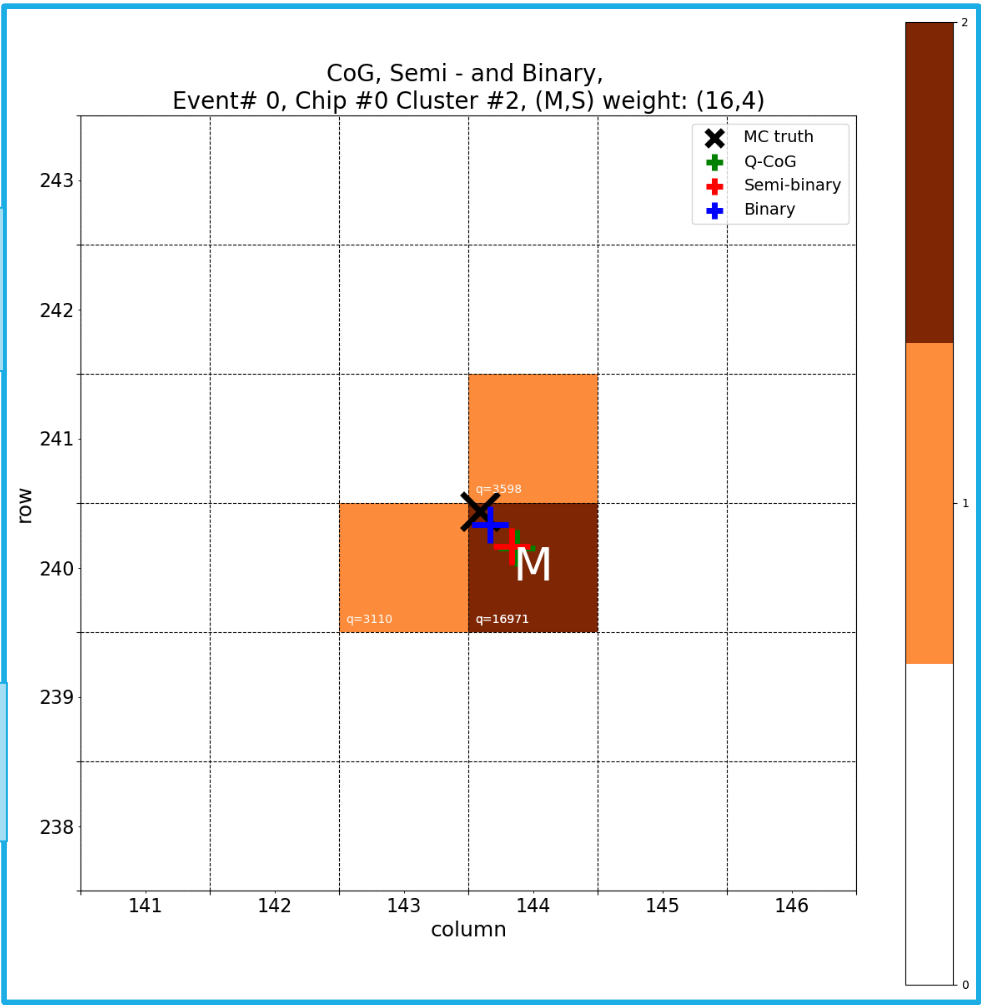
    charge weighted Center of Gravity
  - **Binary:**

    $$(\bar{x},\bar{y})_{bin} = \frac{1}{N}\sum_{i}^{N} (x_i, y_i)$$

    Every pixel in cluster has equal weight.
  - **Semi-binary:**

    $$(\bar{x},\bar{y})_{sbin} = \frac{1}{M+S}\left(M \cdot (x,y)_{main} + S \cdot \sum_{i}^{spec} (x_i, y_i)\right)$$

    Pixel with highest collected charge is Main pixel (M), others are Spectators (S). Different ratio’s (M/S) tested.

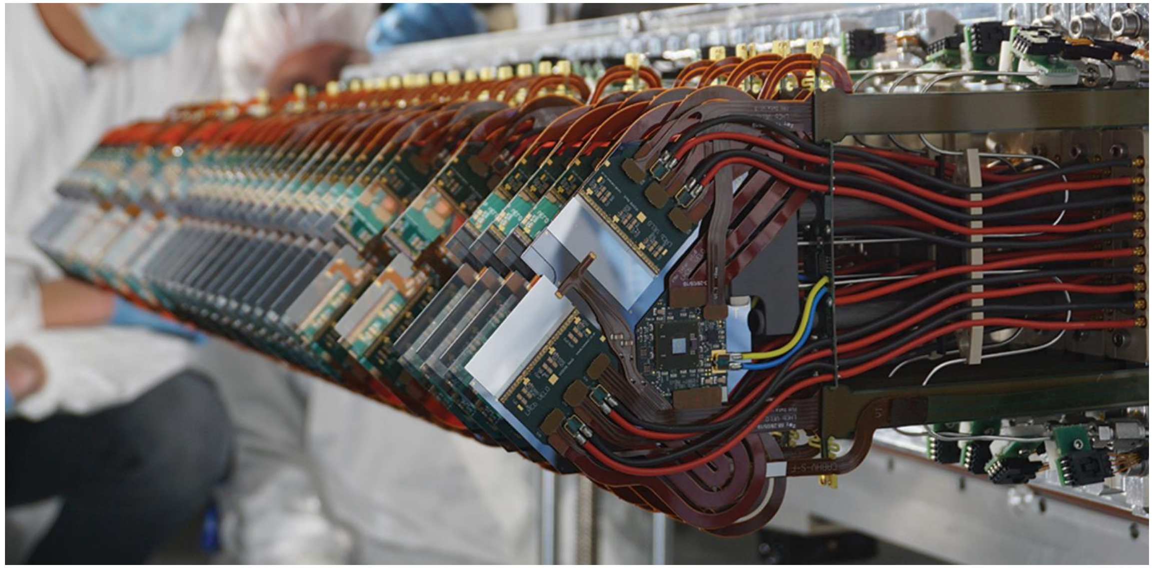


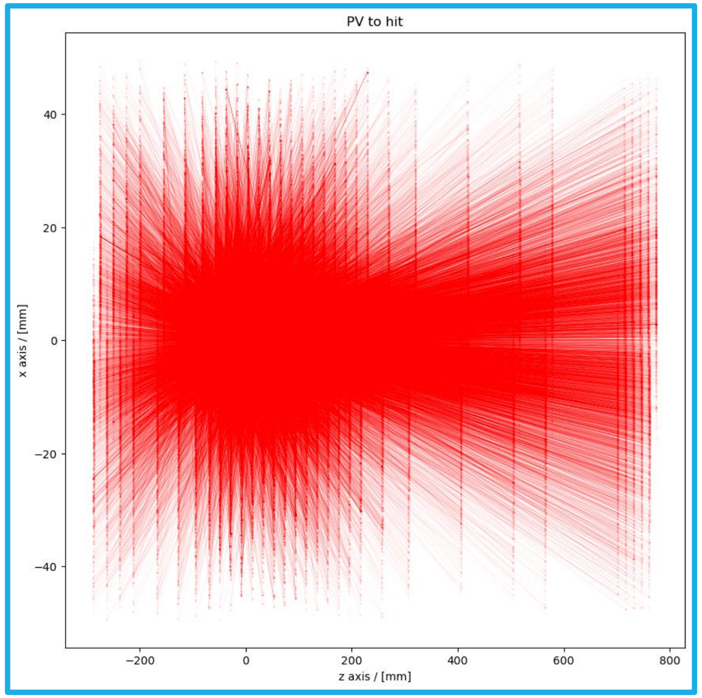
RESULTS

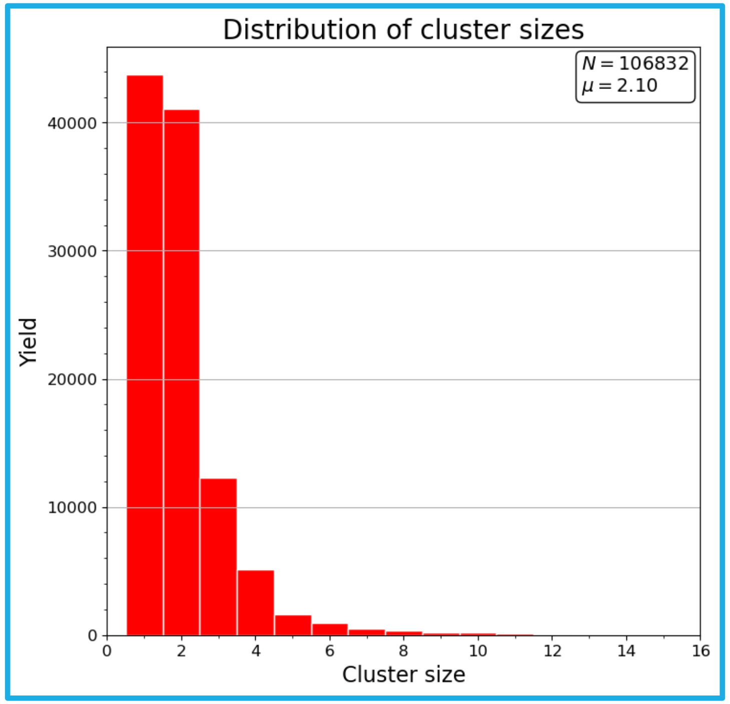
- All results are preliminary.

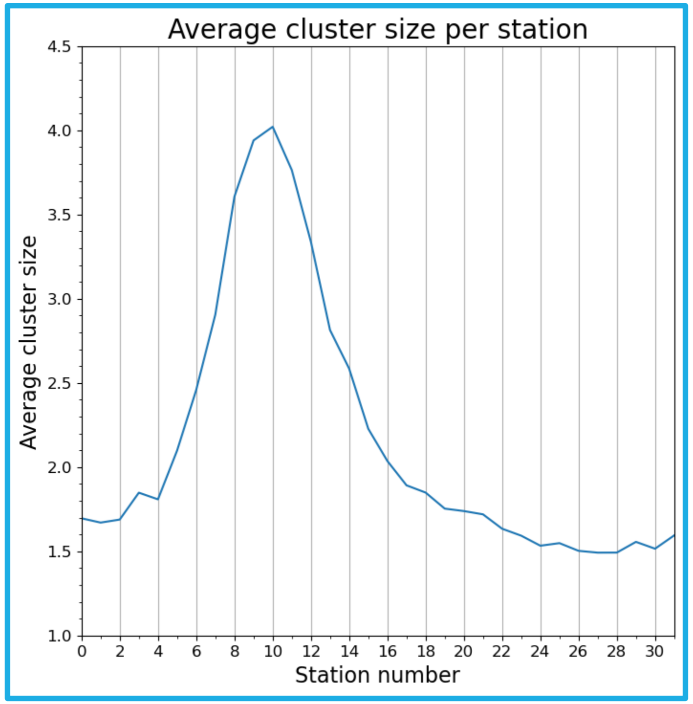
  Additional **checks** are still being made.

  Low statistic: 10 PV events, $\mathcal{O}(200{,}000)$ hits









RESULTS

- Sanity check
- Local residuals, single pixel clusters

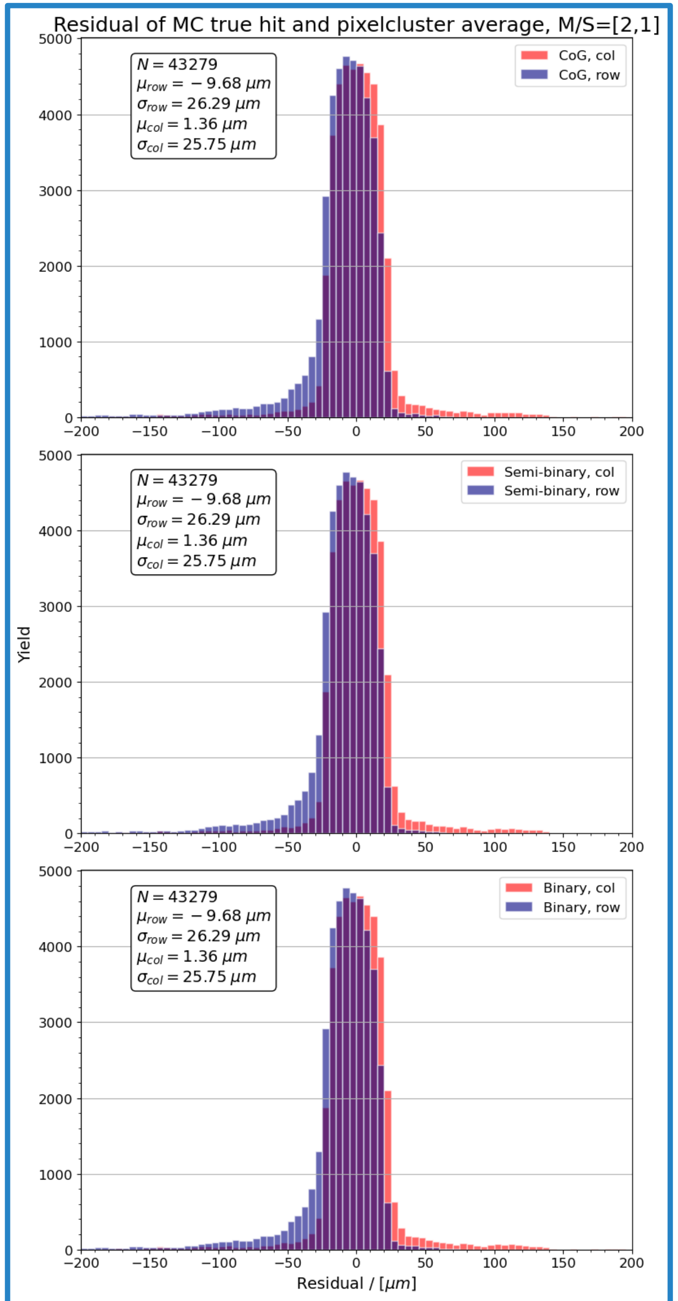
Residuals:

$$\Delta(x, y) = (\bar{x}, \bar{y}) - (x, y)_{truth}$$

Resolution:

$$\sigma_x = RMS(\Delta x)$$

$$\sigma = \sqrt{\sigma_x^2 + \sigma_y^2}$$



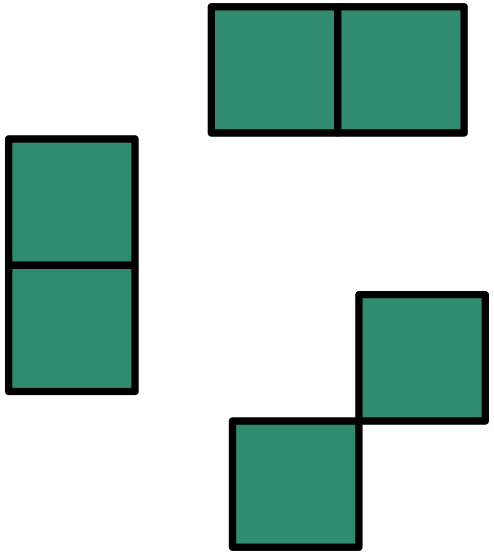
$\sigma = 36.80\ \mu m$

|res|>200um filtered

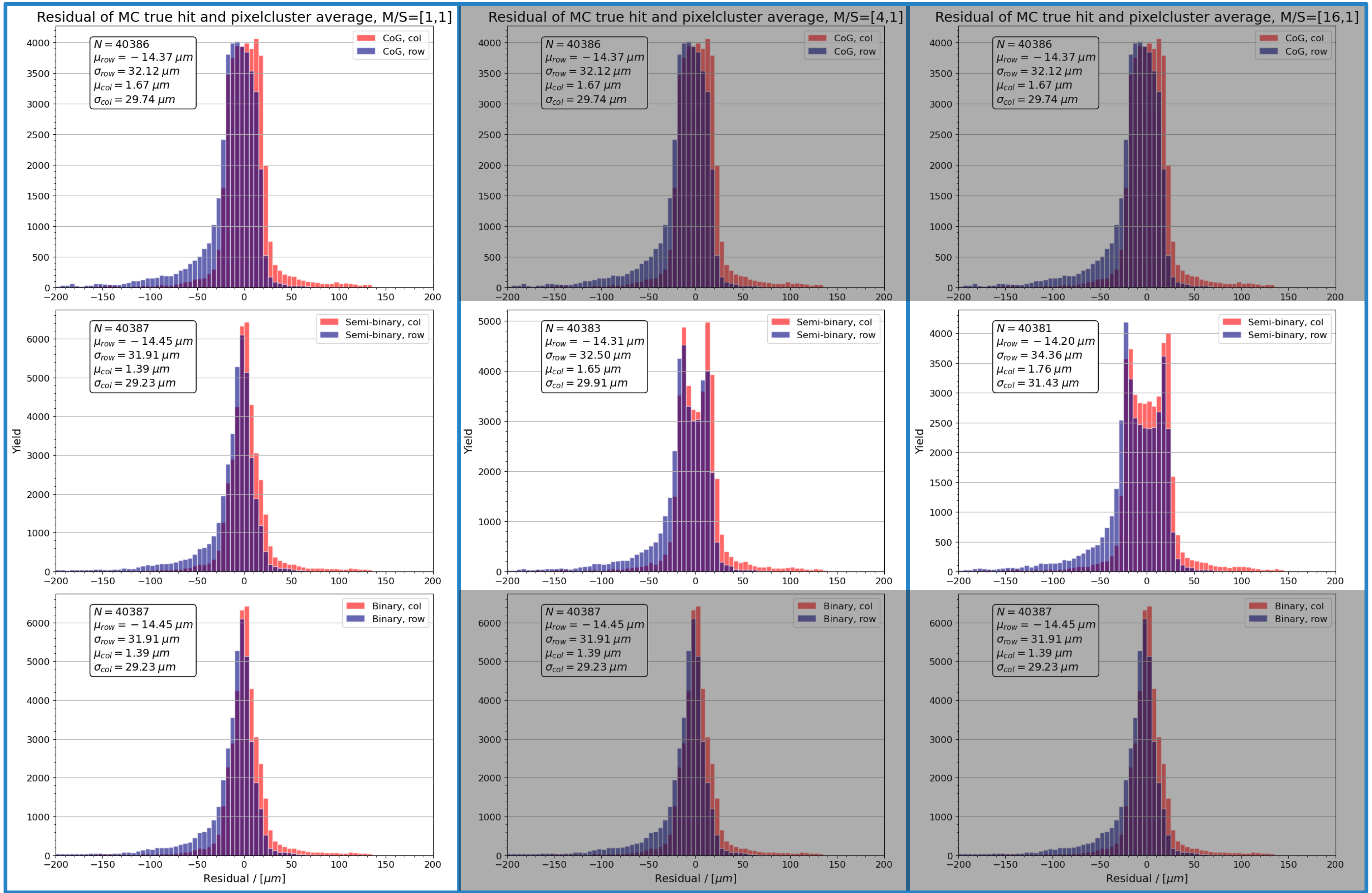
RESULTS

- Local residuals,

  double pixel clusters



[M, S] = [1, 1] [M, S] = [4, 1] [M, S] = [16, 1]

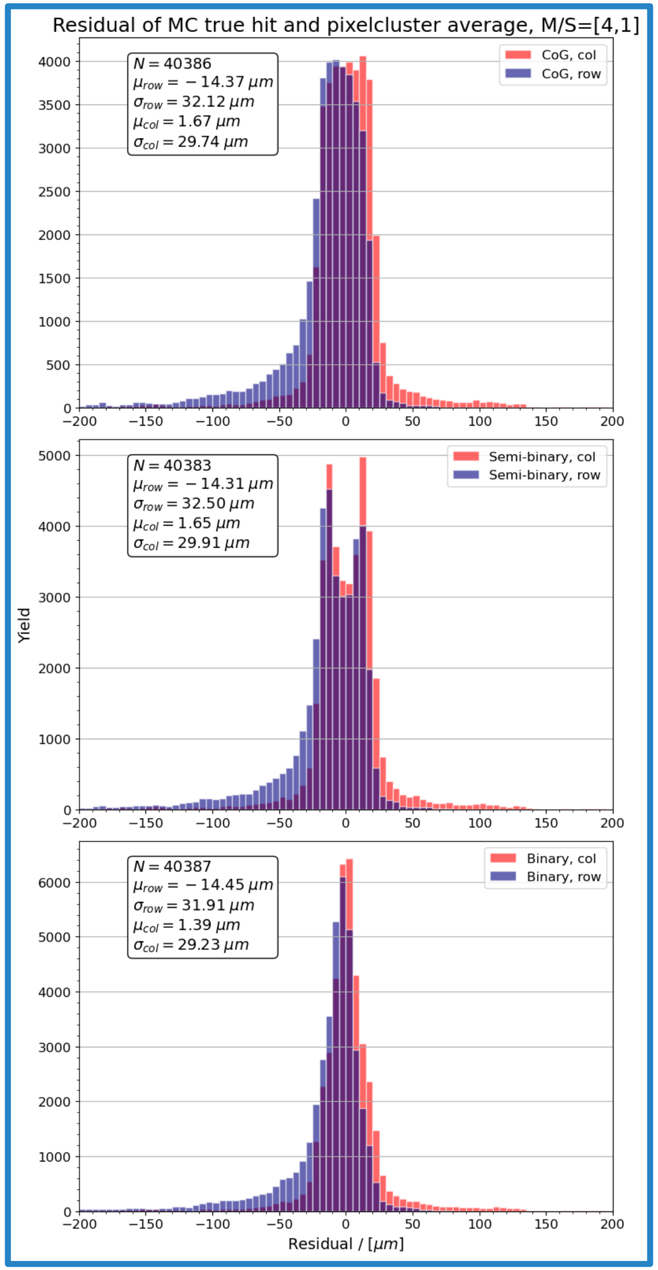


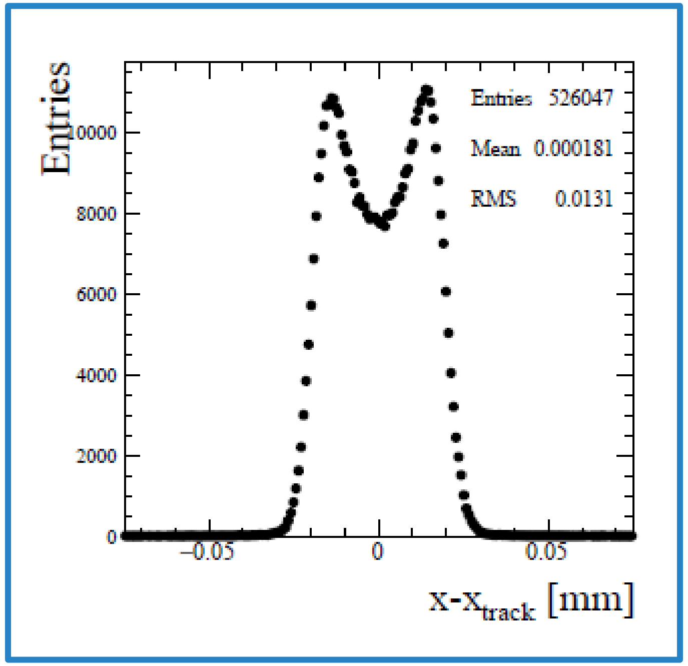
|res|>200um filtered

RESULTS

- Local residuals,

  double pixel clusters





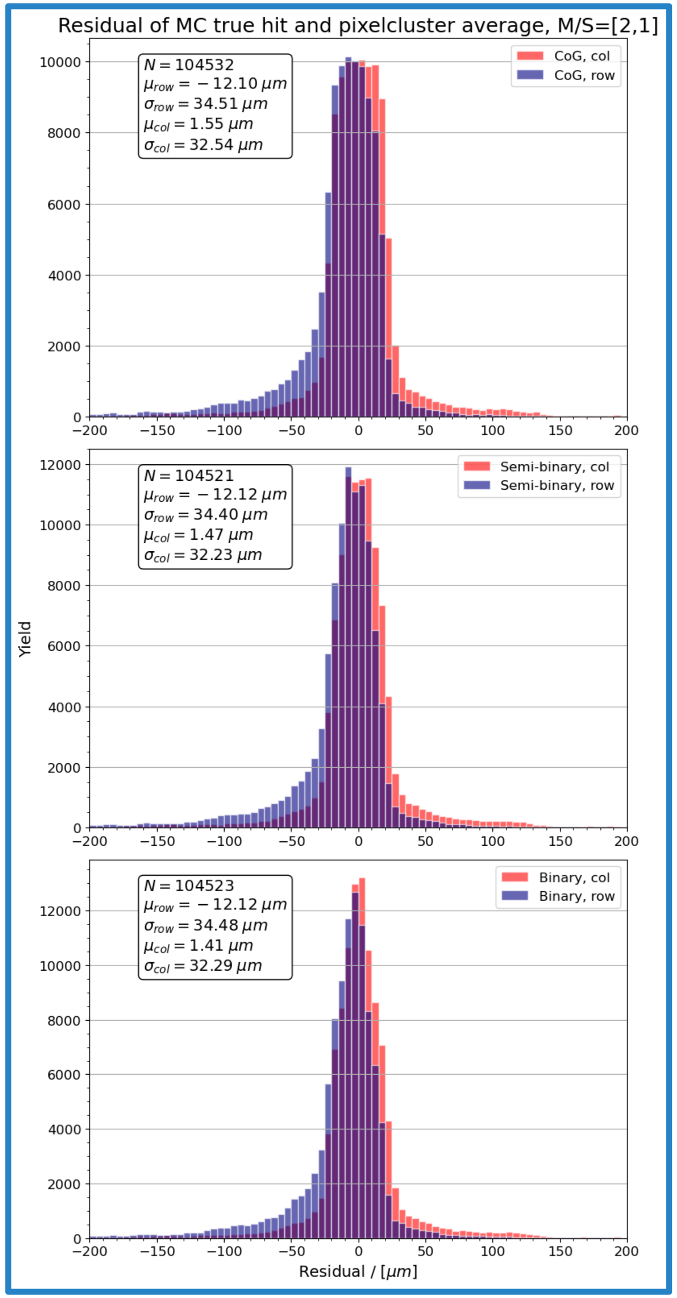
Testbeam resolution studies for LHCb upgrade I with binary readout[11]

|res|>200um filtered

RESULTS

- Local residuals, all clusters,

  N = 104,532



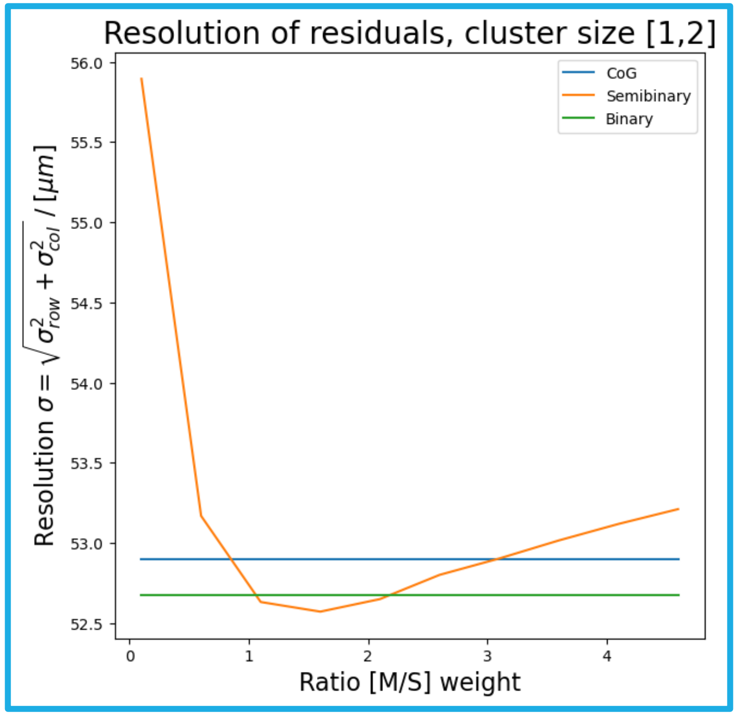
- CoG: σ = 47.43
- Semi-binary: σ = 47.14
- Binary: σ = 47.24

|res|>200um filtered

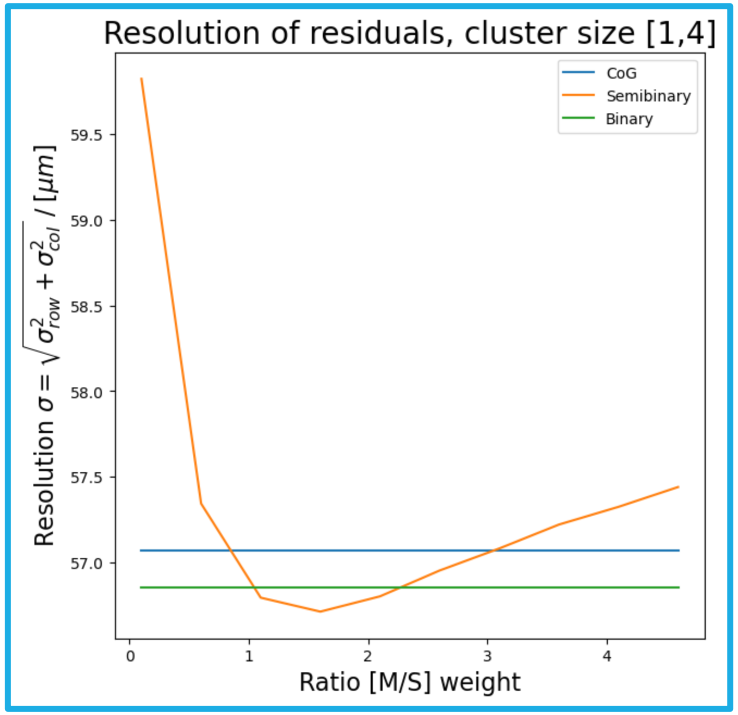
RESULTS

- Different (M/S) ratio’s tested, for different cluster size’s:

Cluster size = 1 - 2



Cluster size = 1 - 4

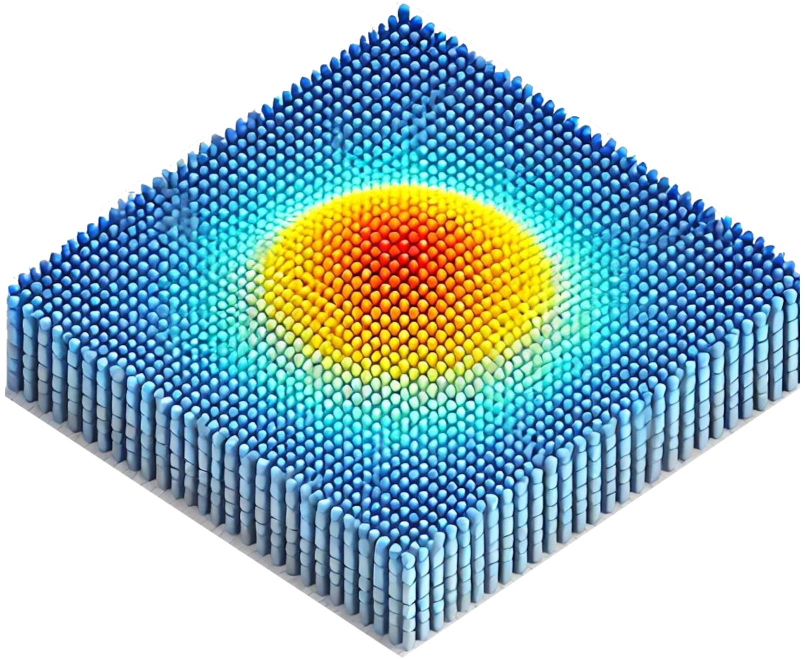


Cluster size = 1 - 999

|res|>300um filtered

CAVEATS

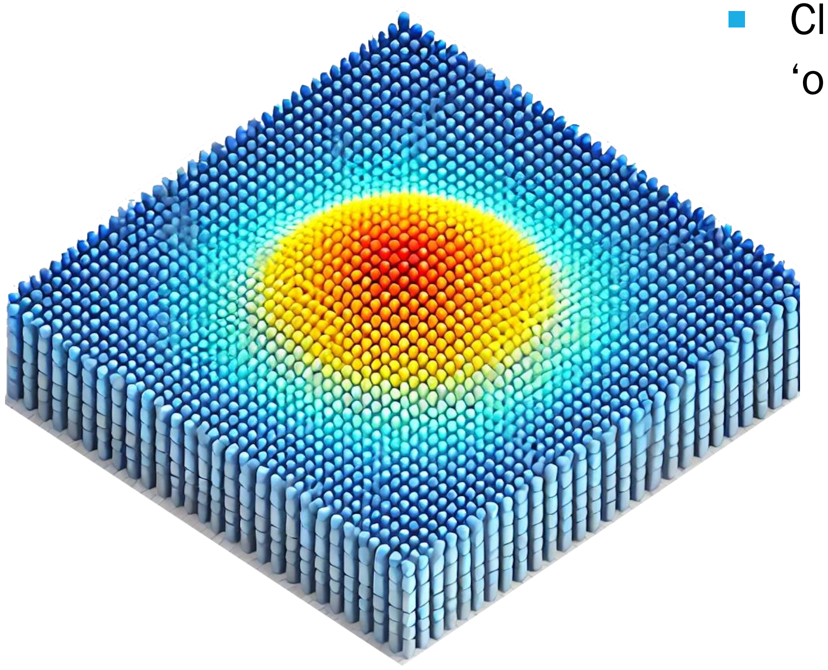
- These results depend on the way pixel hits are – and charge sharing is simulated. The smearing applied can impact the resolution.



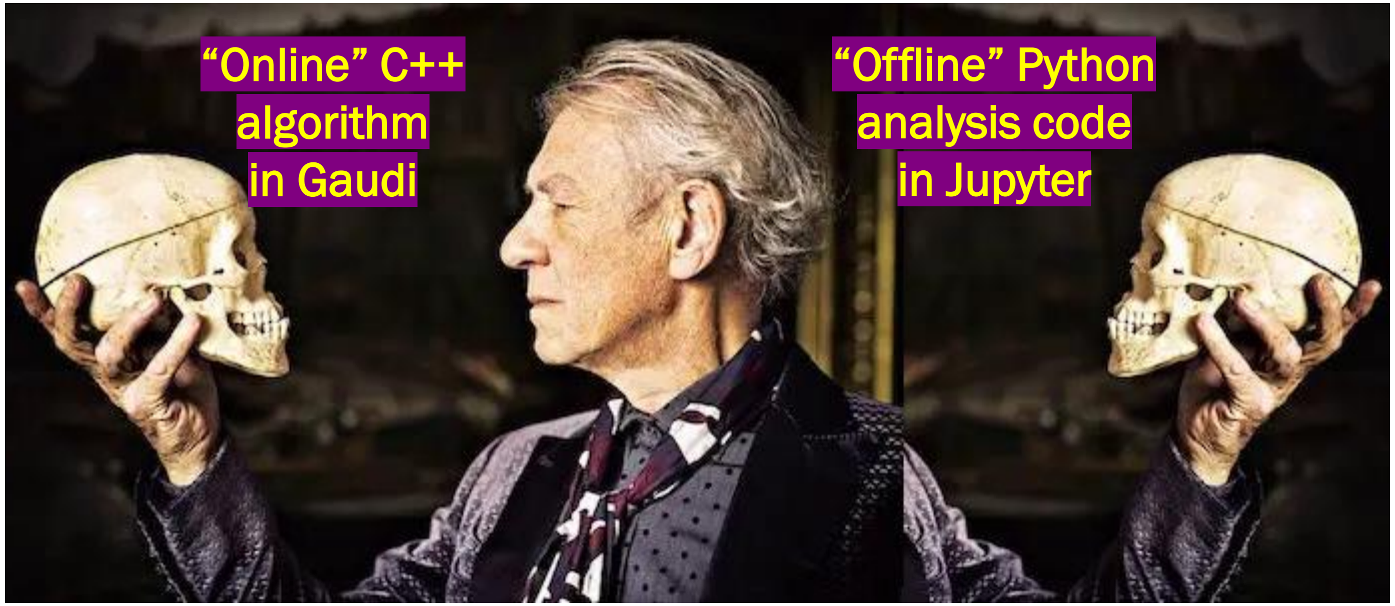
ChatGPT's interpretation of Gaussian smearing in pixel detectors.

CAVEATS

- These results depend on the way pixel hits are – and charge sharing is simulated. The smearing applied can impact the resolution.
- Clear indication that additional code needs to be developed and needs to run 'online' for timing analysis.



ChatGPT's interpretation of Gaussian smearing in pixel detectors.



OUTLOOK

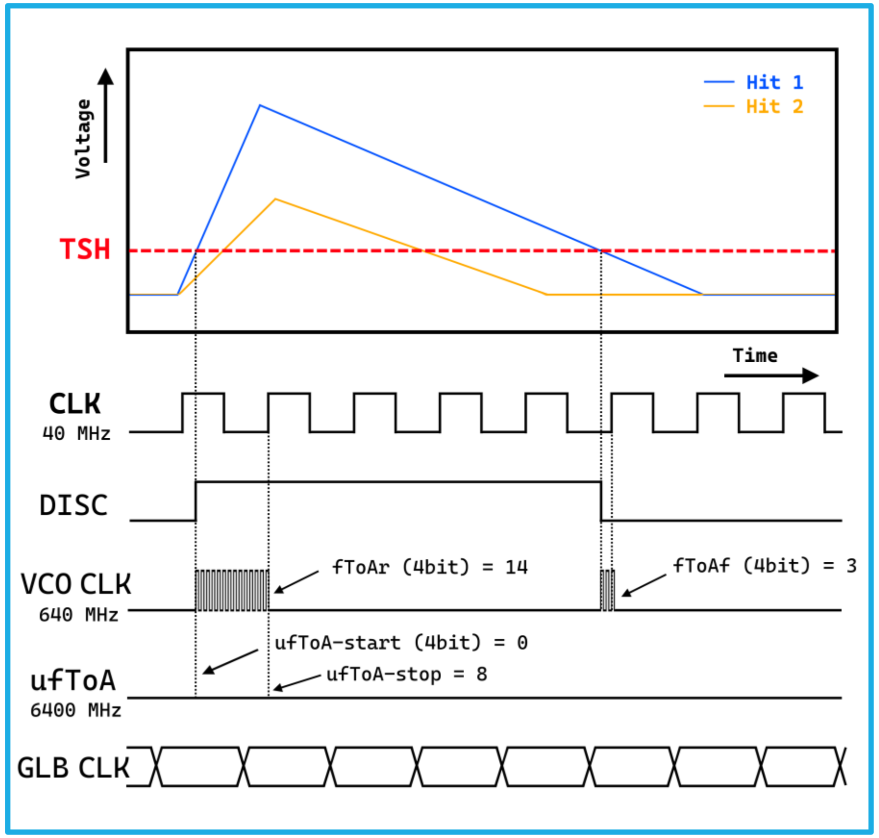
- Implement detailed timing and charge sharing in simulation

  → time-weighted clustering

- Can timing information improve spatial resolution, or vice versa?

- Investigating impact of digitization (bit allocation),

  e.g. in LHCb simulation and/or Allpix2



OUTLOOK

- Track reconstruction information can be fed back to cluster calculation to improve resolution.

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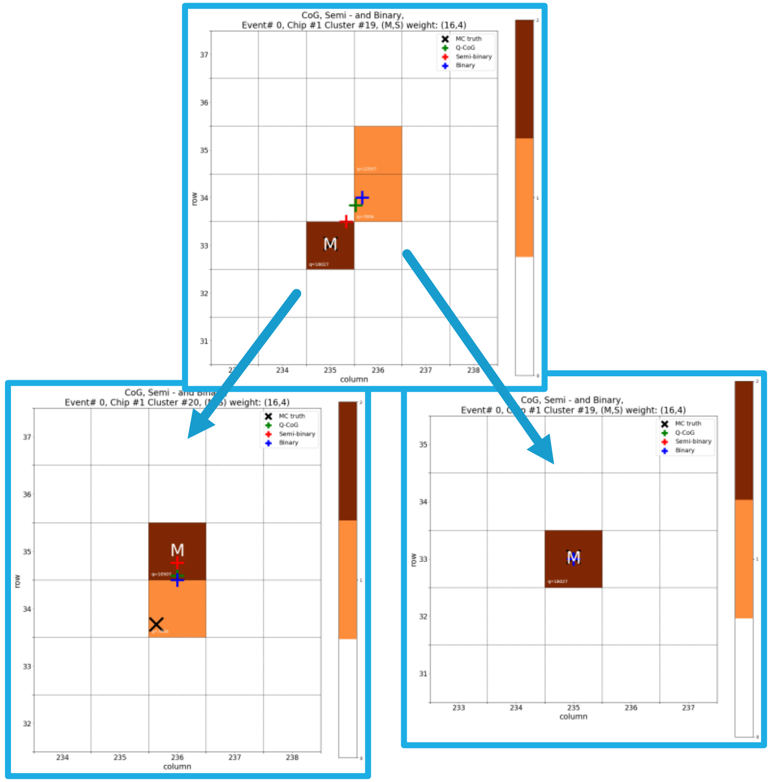
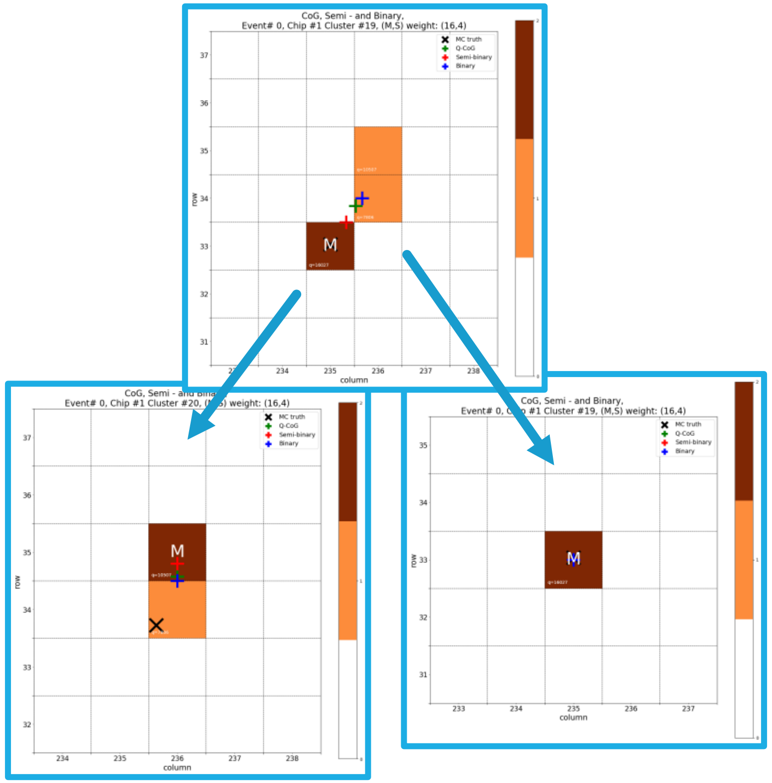
- Track reconstruction information can be fed back to cluster calculation to improve resolution.

- Possibility of checking fake clustering



OUTLOOK

- Track reconstruction information can be fed back to cluster calculation to improve resolution.
- Possibility of checking fake clustering
- Cross check simulation with data from test beam.
- Develop firmware to test algorithms during test beam.



THANK YOU
FOR YOUR TIME AND ATTENTION

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- [3] P.D. Bunin, CMS Collaboration. "Upgrade of the Compact Muon Solenoid (CMS) Detector". *Phys. Part. Nuclei* **54**, 493–499 (2023). https://doi.org/10.1134/S1063779623030085
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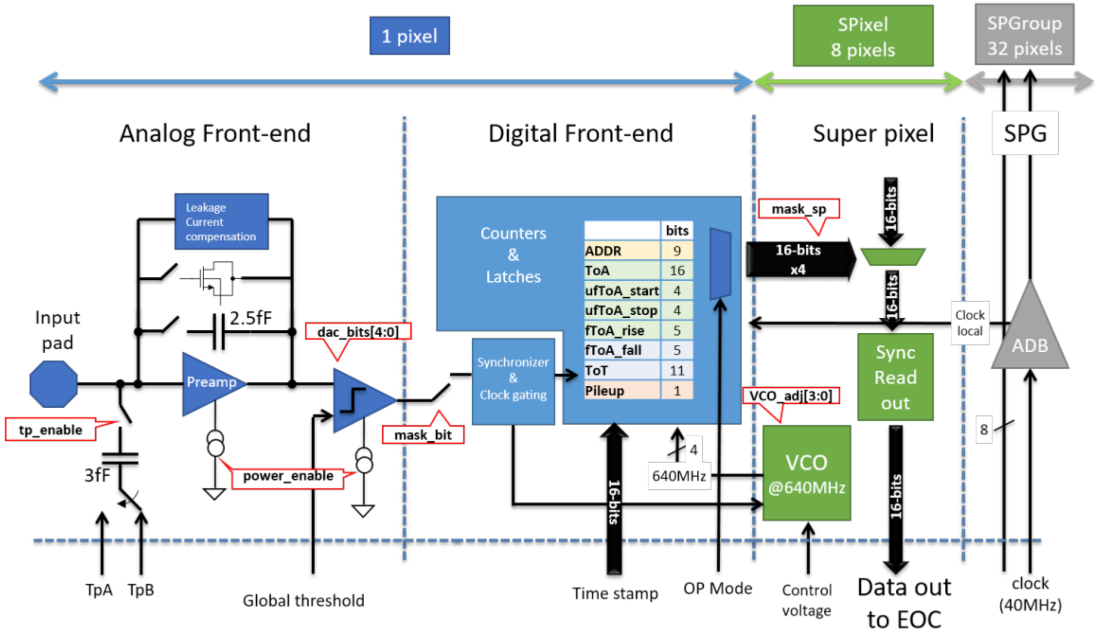
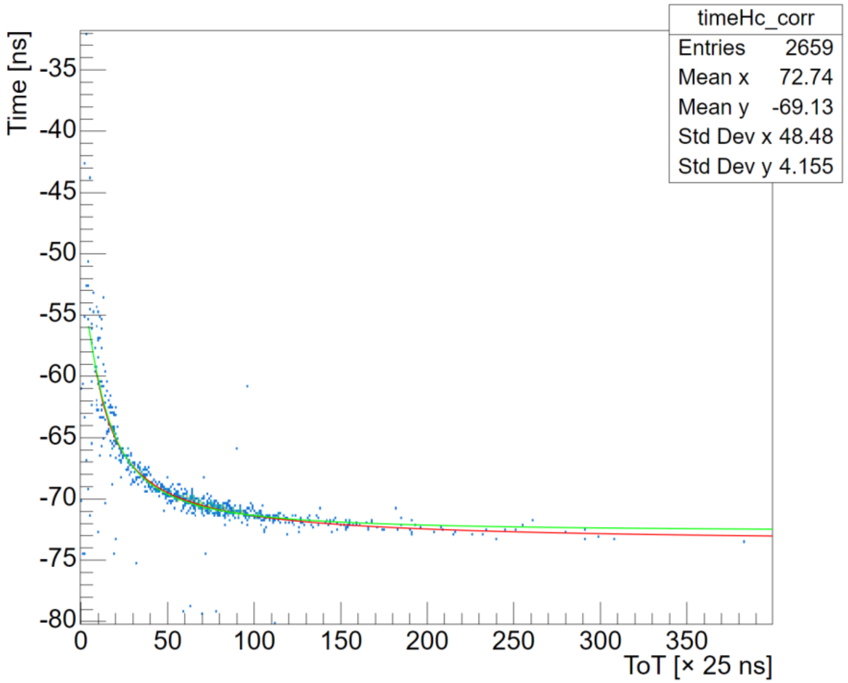
- [9] X. Llopart, *et al*. "Timepix4, a large area pixel detector readout chip which can be tiled on 4 sides providing sub-200 ps timestamp binning". *JINST* 17 (2022) C01044. https://iopscience.iop.org/article/10.1088/1748-0221/17/01/C01044
- [10] K. Heijhoff. "When and Where: Precision Time Measurements with Hybrid Silicon Pixel Detectors". *10 Feb 2023*
- [11] E. Buchanan. "Spatial Resolution Studies for the LHCb VELO Upgrade". *23 Jan 2019*

ADDITIONAL SLIDES

TIMING AND TIMEPIX

$$\Delta t_{tw} = \frac{b}{(\Delta T_{ToT} + c)^d} + a$$





Courtesy: E. Rodríguez[2]

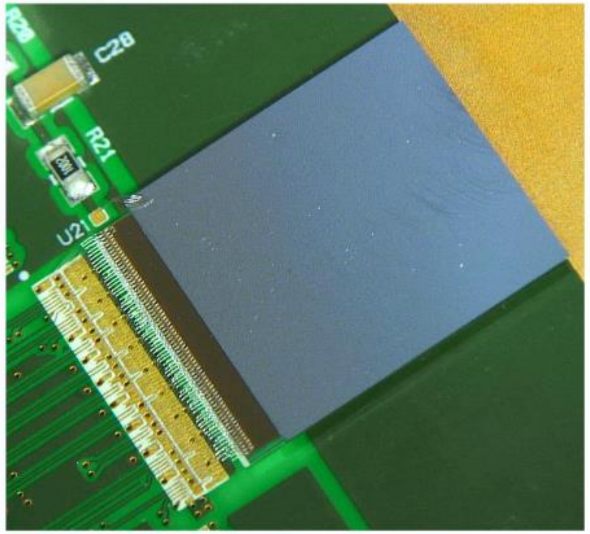
https://indico.cern.ch/event/1223972/contributions/5262141/attachments/2601194/

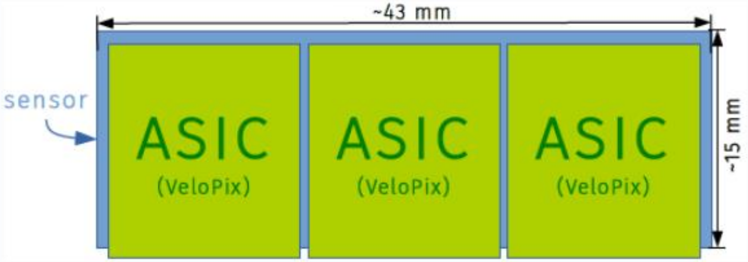
TIMING AND TIMEPIX

VeloPix ASIC design

- Derived from Timepix3 and dedicated to LHCb.

	Timepix3 (2013)	VeloPix (2016 v1 & 2018 v2)
Pixel arrangement	256 x 256	
Pixel size	55 x 55 μm^2	
Peak hit rate	80 Mhits/s/ASIC	800 Mhits/s/ASIC 50 khits/s/pixel
Readout type	Continuous, trigger-less, TOT	Continuous, trigger-less, binary
Timing resolution/range	1.5625 ns, 18 bits	25 ns, 9 bits
Total Power consumption	<1.5 W	< 2 W
Radiation hardness		400 Mrad, SEU tolerant
Sensor type	Various, e- and h+ collection	Planar silicon, e- collection
Max. data rate	5.12 Gbps	20.48 Gbps
Technology	130 nm CMOS	



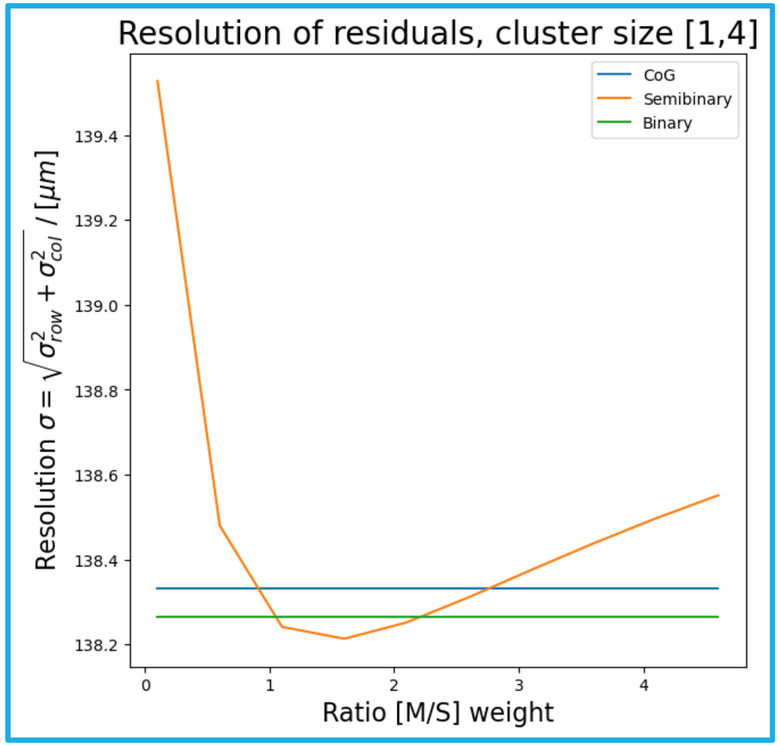


RESULTS

- Different (M/S) ratio's tested:
  - For different cluster size's

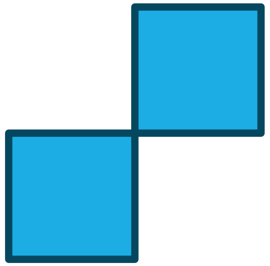
Some residuals are of order ~ 2000um

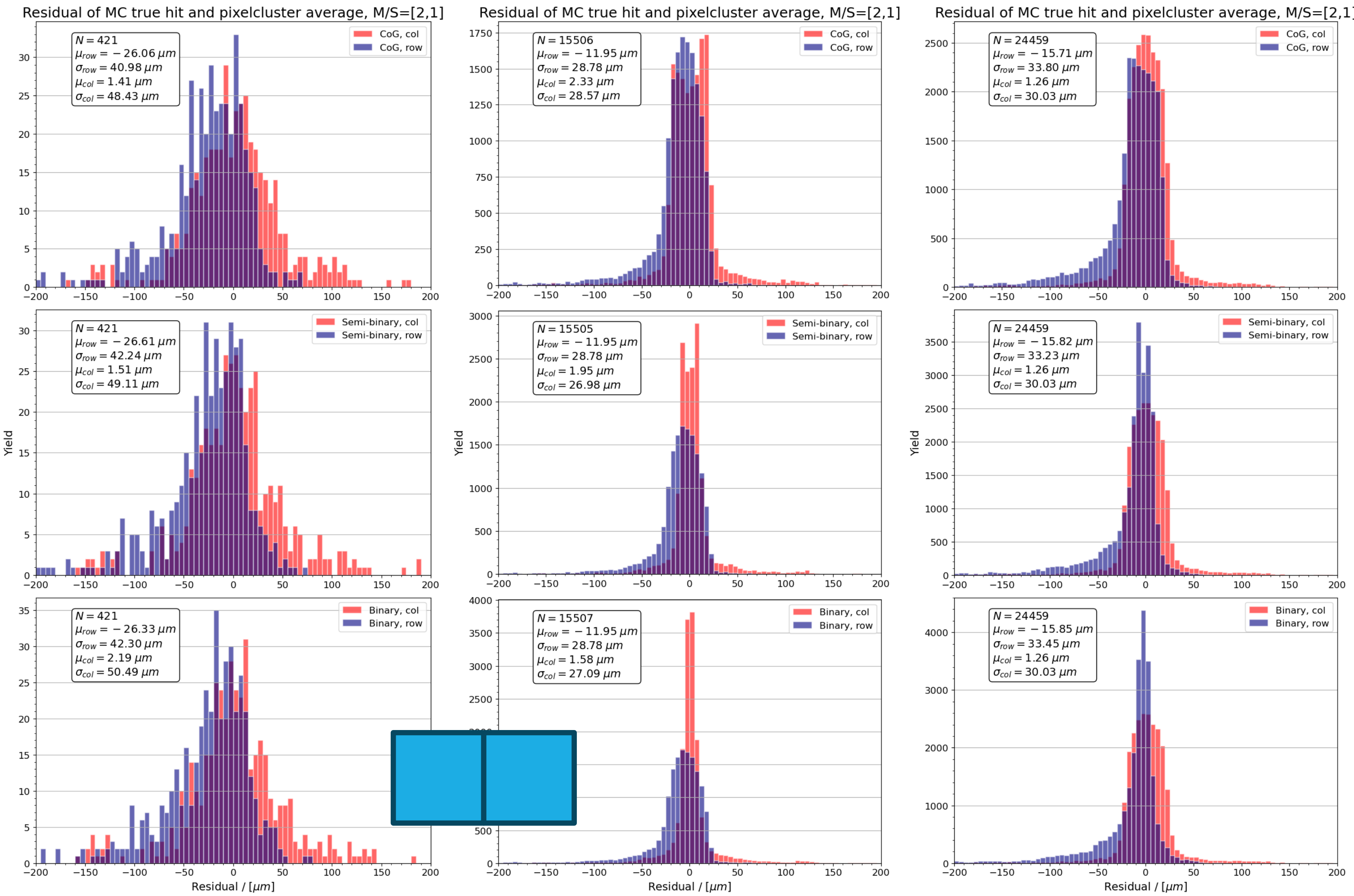
Caused either by the alignment or huge clusters

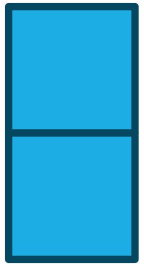


RESULTS

- Local residuals, two pixel clusters

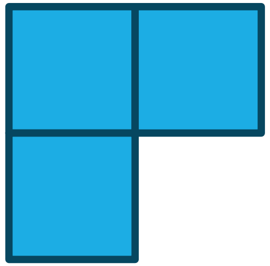


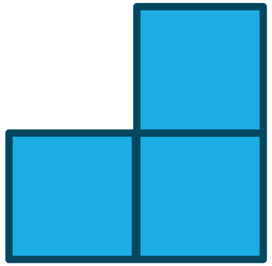


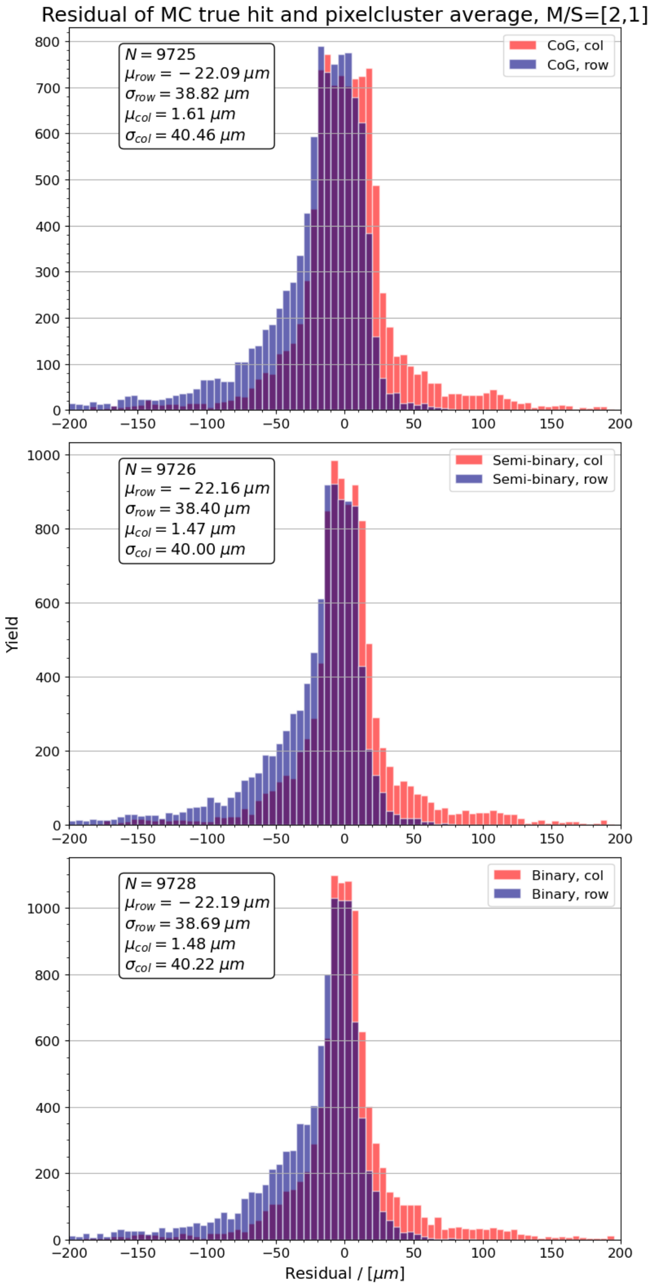


RESULTS

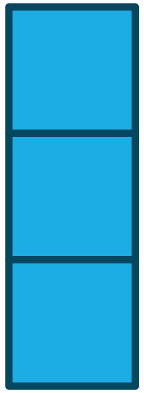
- Local residuals, 3 pixel hits, within 2x2

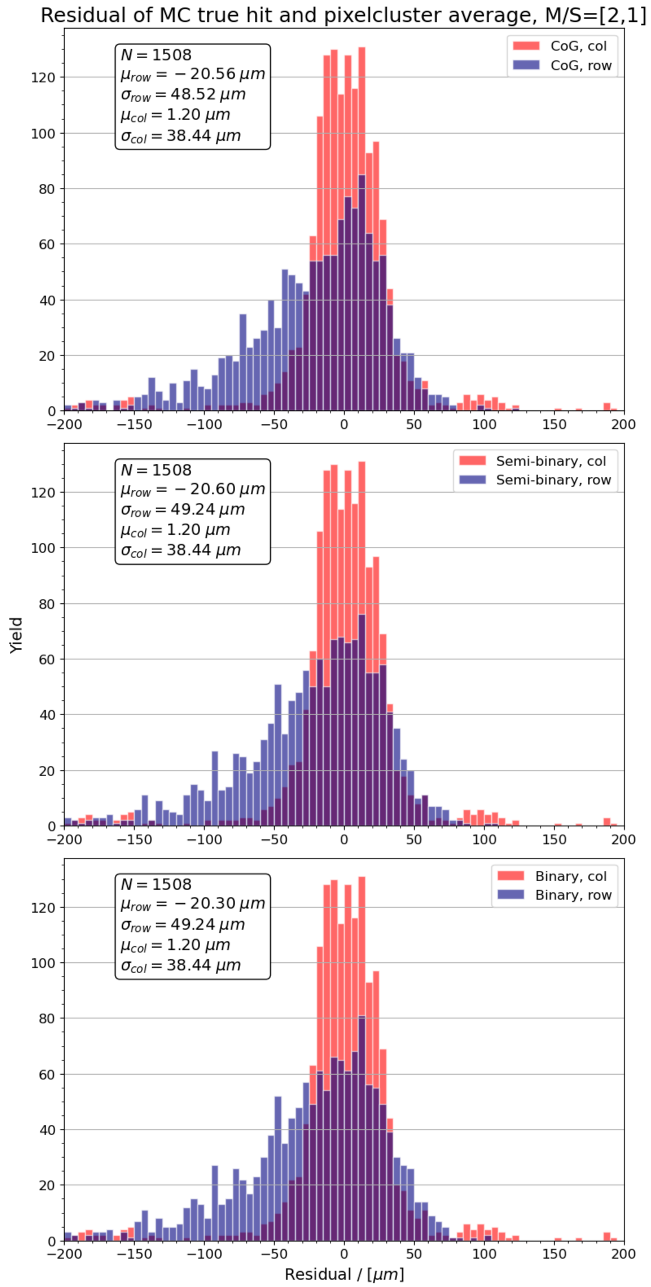






3 pixel hits, within 1x3



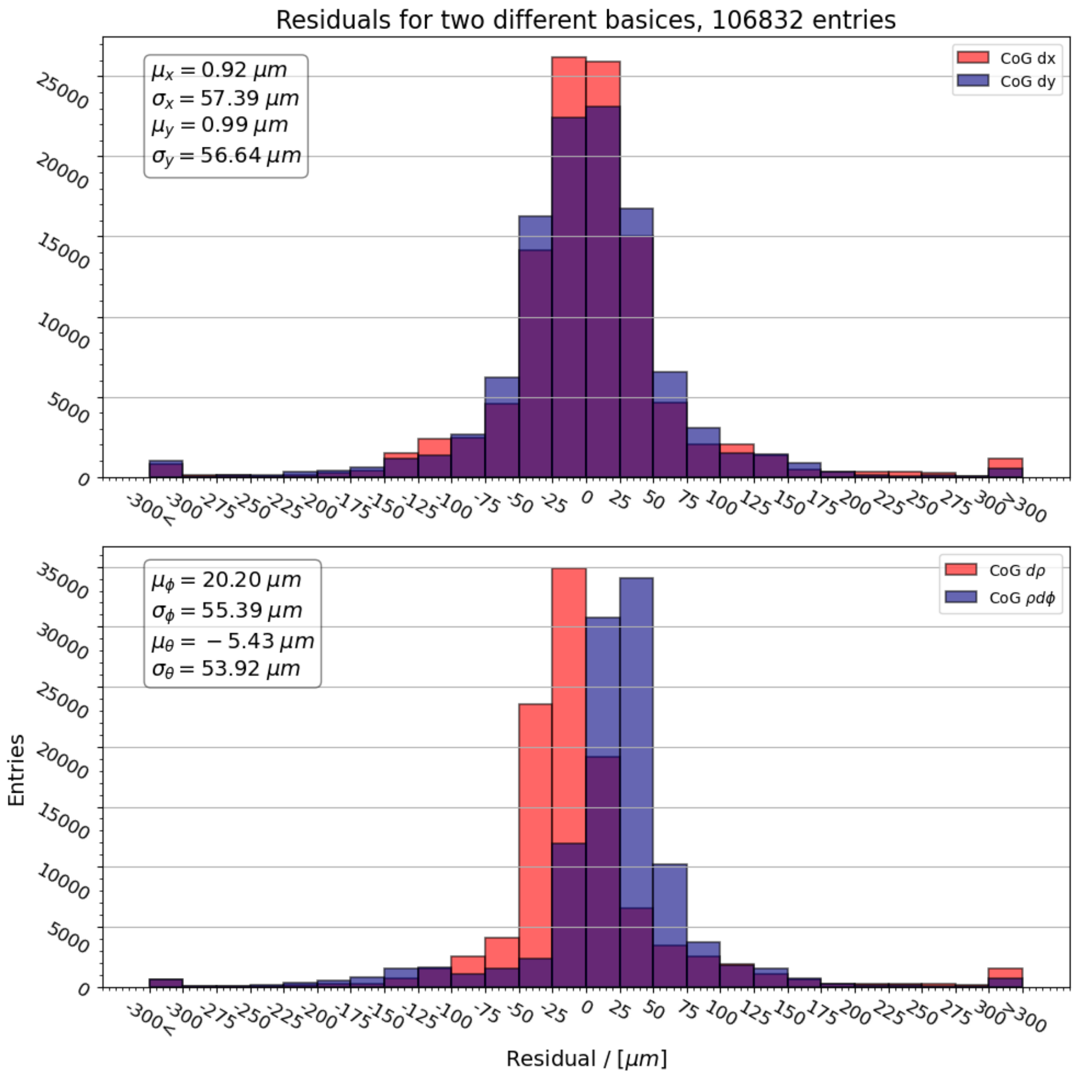


RESULTS

- Also angular residuals are considered: $(rd\theta, rd\phi)$
  - Residuals calculated as projections on the chip:
    - $rd\theta$ is approximated as $d\rho$
    - $rd\phi$ is approximated as $\rho d\phi$

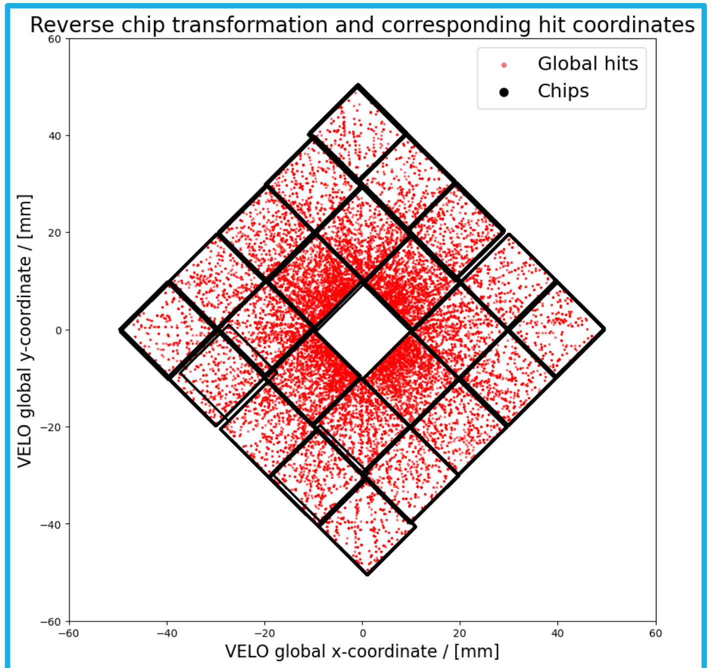
  where r is the global radius and ρ is the radius in XY-plane

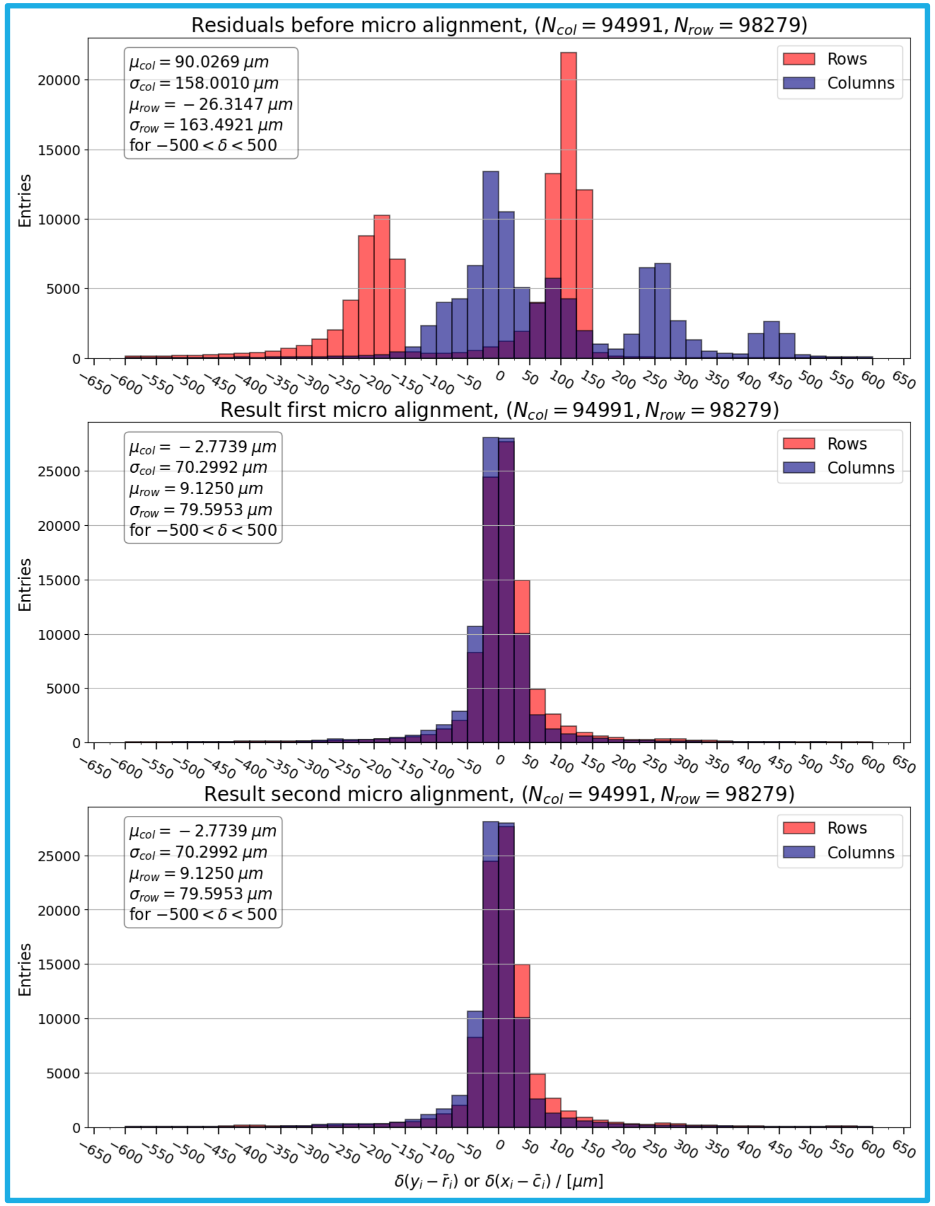
However the global coordinates are used for these residuals



MICROALIGNMENT

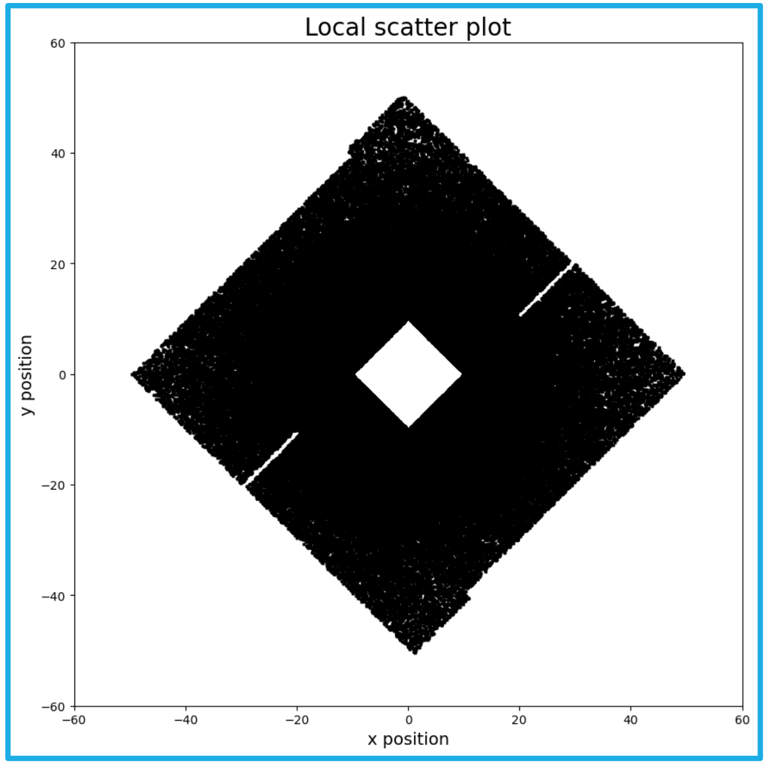
- The error is plotted between the centre of the column/row x_i, y_i and the average of hits in that column/row $\overline{c_i}, \overline{r_i}$

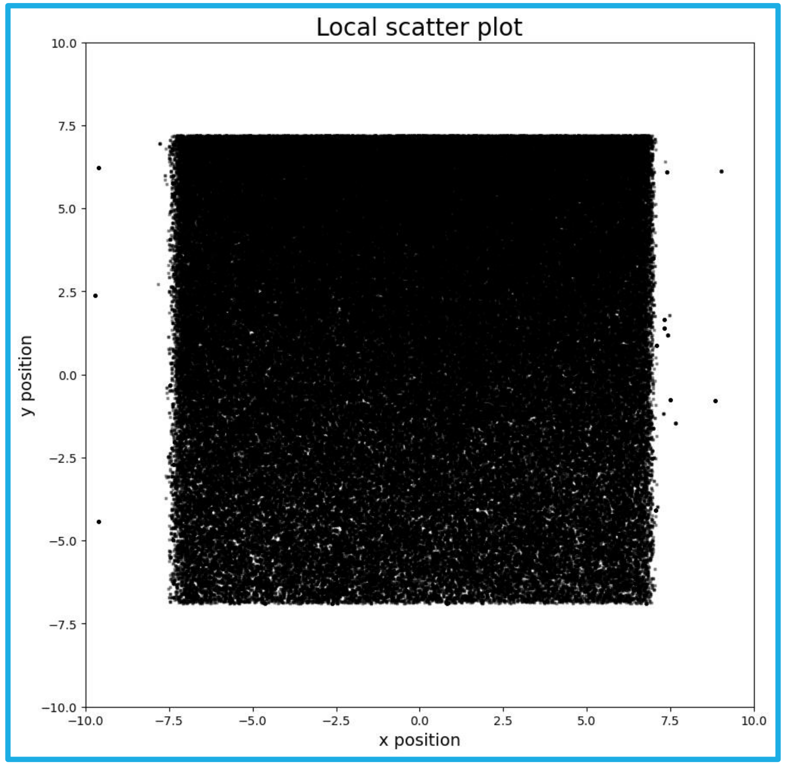




OFFLINE ANALYSIS

- Global to local mapping
- Columns and rows aligned, reflected if needed
- Additional micro alignment applied
- Source for systematic uncertainty



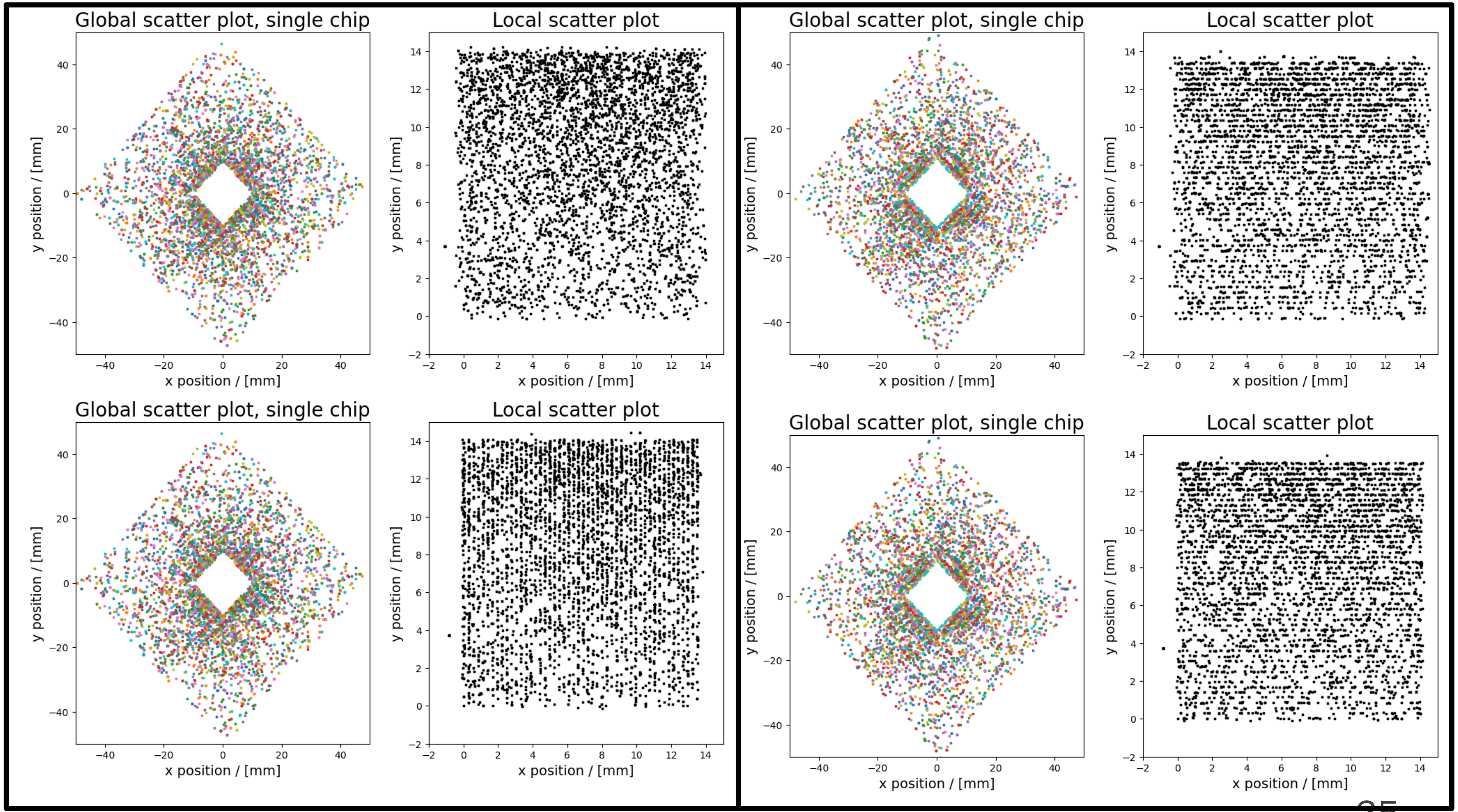


MICRO ALIGNMENT

every 5th row/column plotted

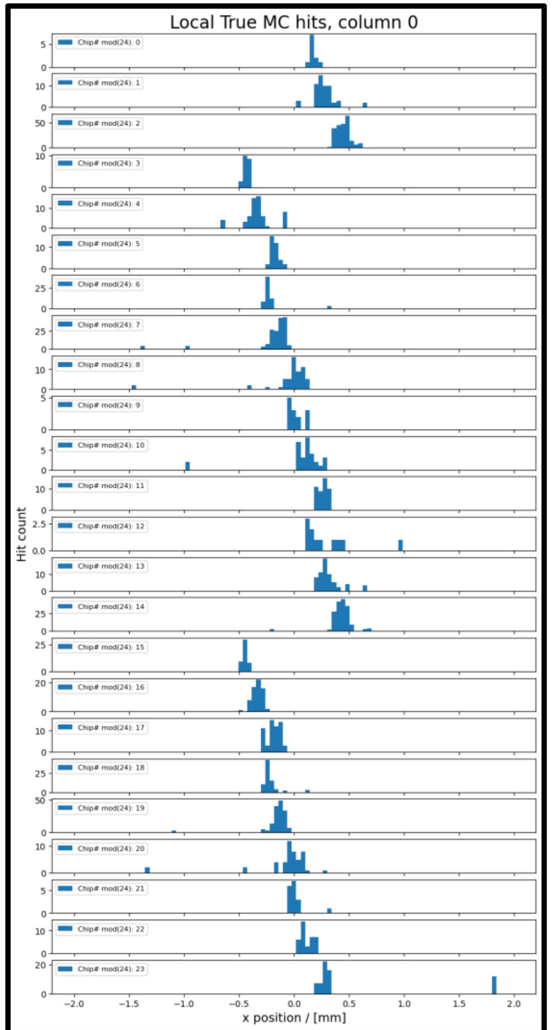
Before

After

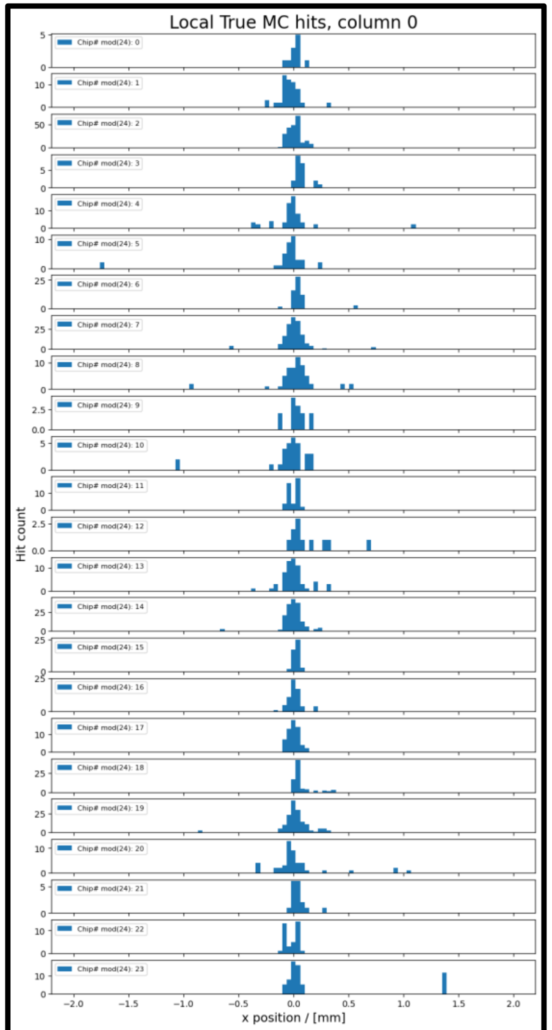


MICRO ALIGNMENT

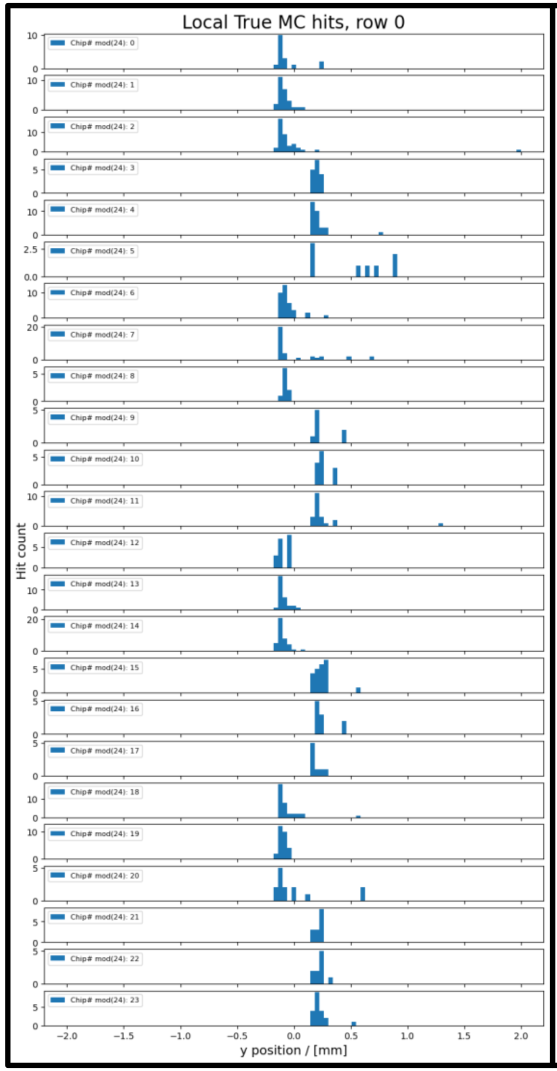
Before



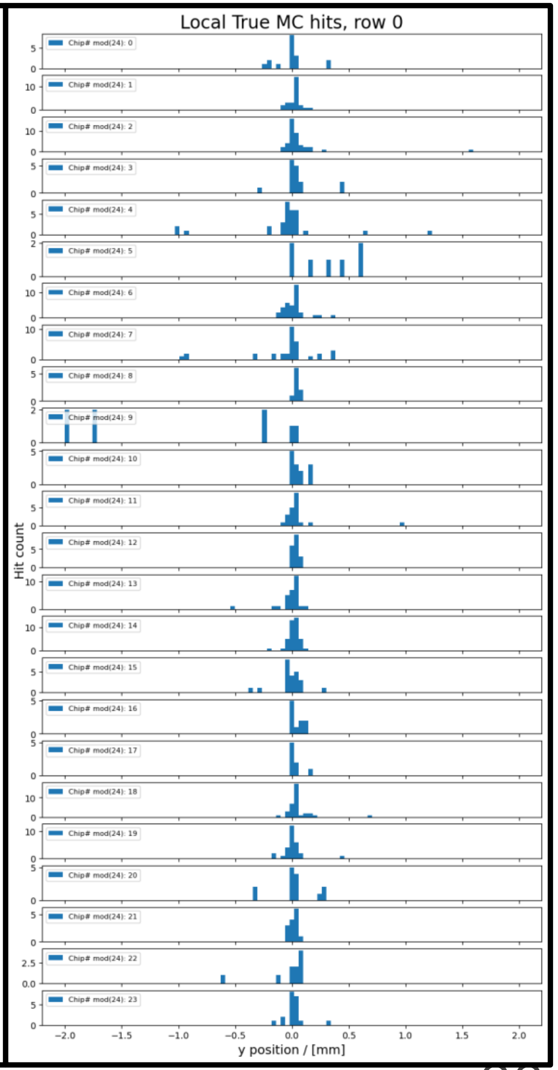
After



Before

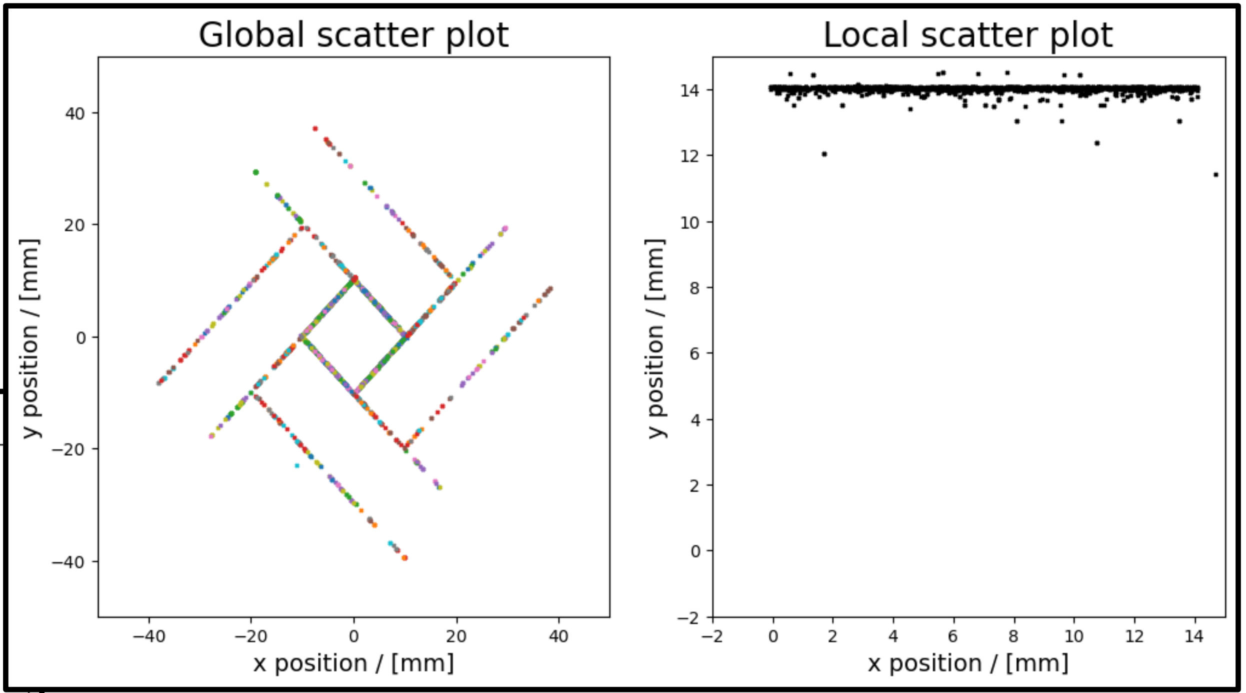


After

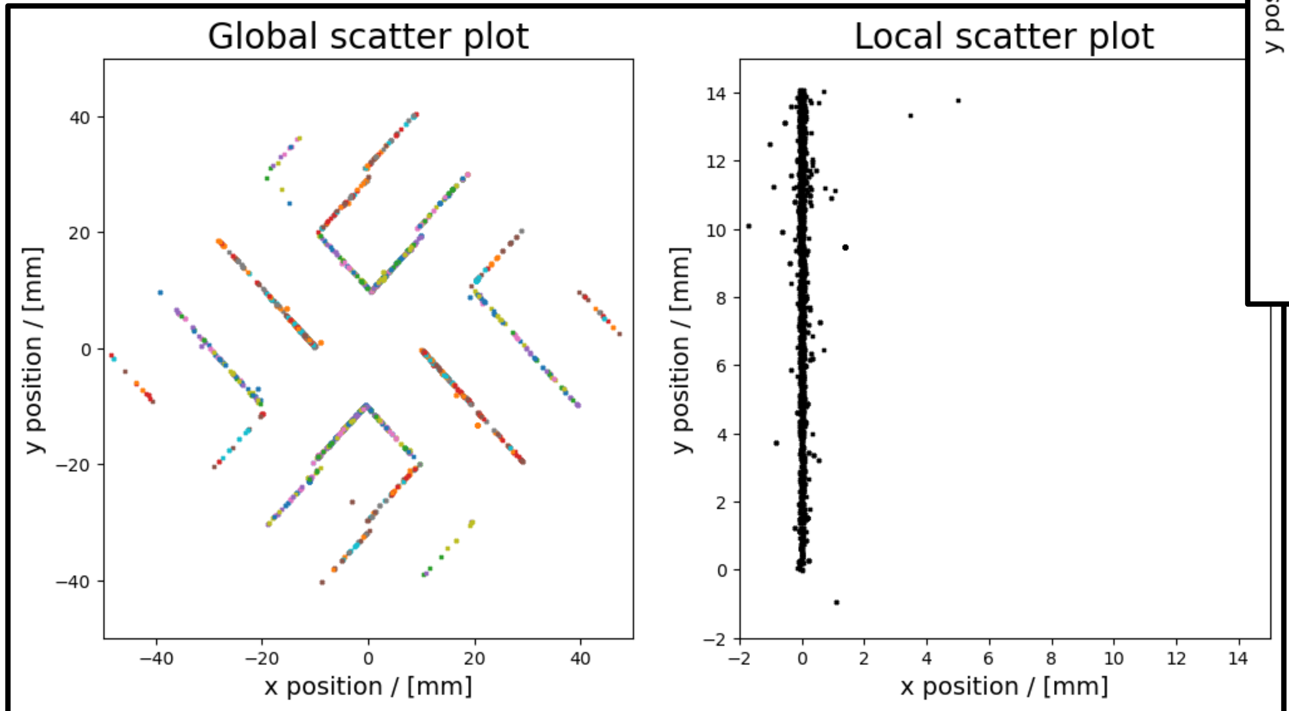


MICRO ALIGNMENT

255th row



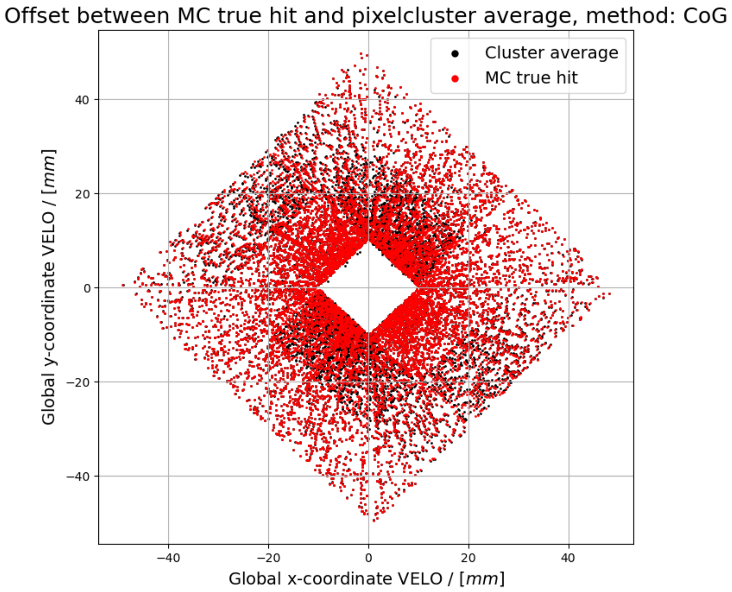
0th column

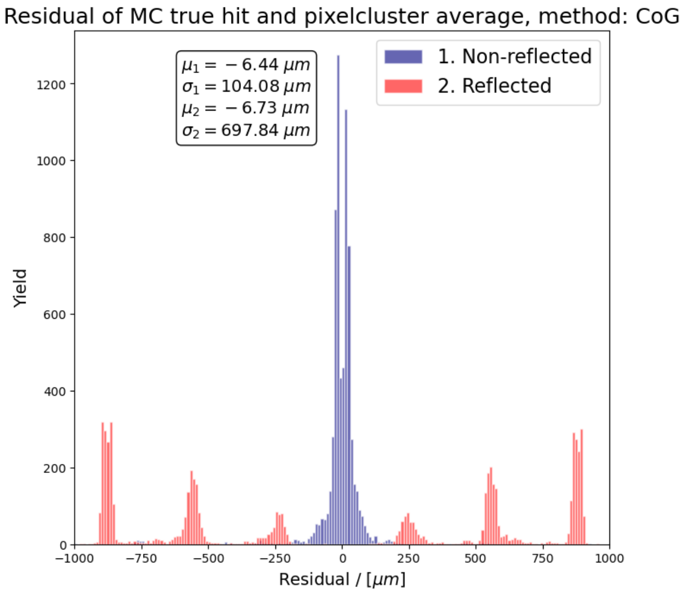


CAVEATS

- Apart from the micro alignment, additional systematic deviation found in simulation. Cause unknown.

```
Chip 0 (mod24):  [dx,dy] = [+0.1, 0]
Chip 1 (mod24):  [dx,dy] = [+0.25, 0]
Chip 2 (mod24):  [dx,dy] = [+0.40, 0]
Chip 11 (mod24): [dx,dy] = [0, -0.27]
Chip 12 (mod24): [dx,dy] = [-0.1, 0]
Chip 13 (mod24): [dx,dy] = [-0.25, 0]
Chip 14 (mod24): [dx,dy] = [-0.40, 0]
Chip 23 (mod24): [dx,dy] = [0, +0.27]
```





GLOBAL COORDINATES