Optimal use of charge information for HL-LHC pixel readout

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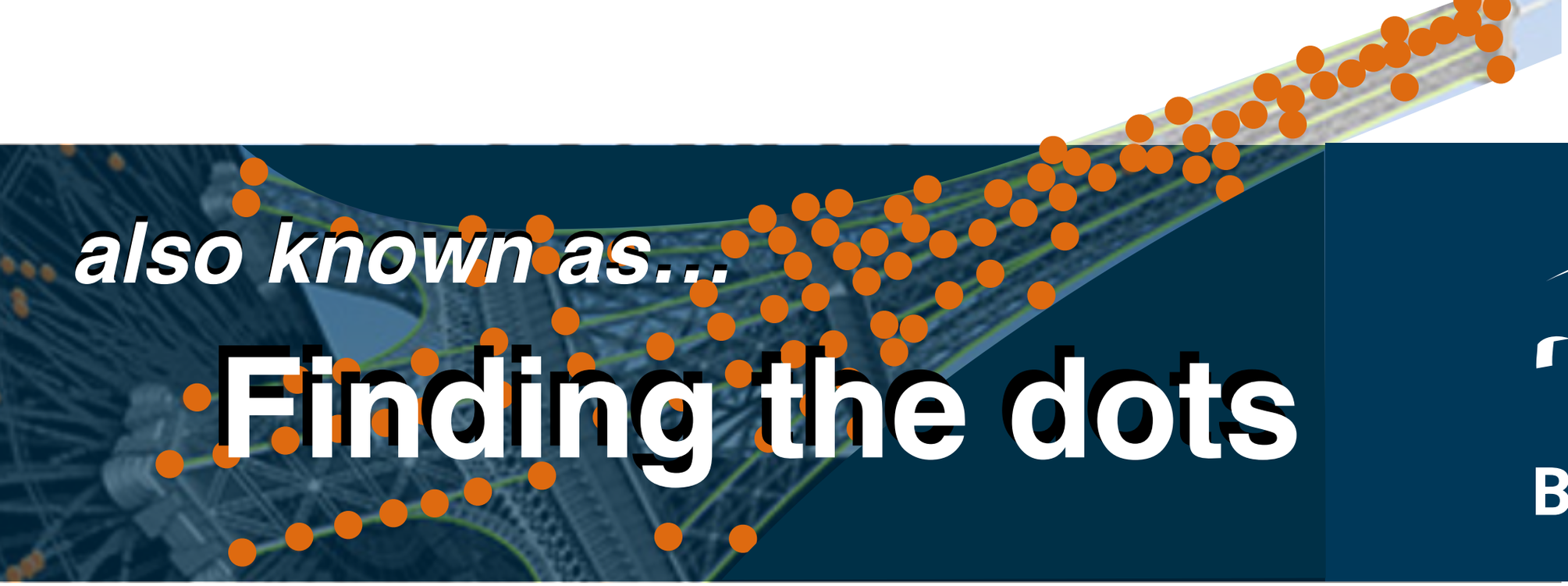
Tuesday, March 7, 2017



also known as…

Finding the dots

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The ATLAS and CMS Detectors at the LHC

are pushing the energy frontier of particle physics

At the heart of each is a **pixel detector**

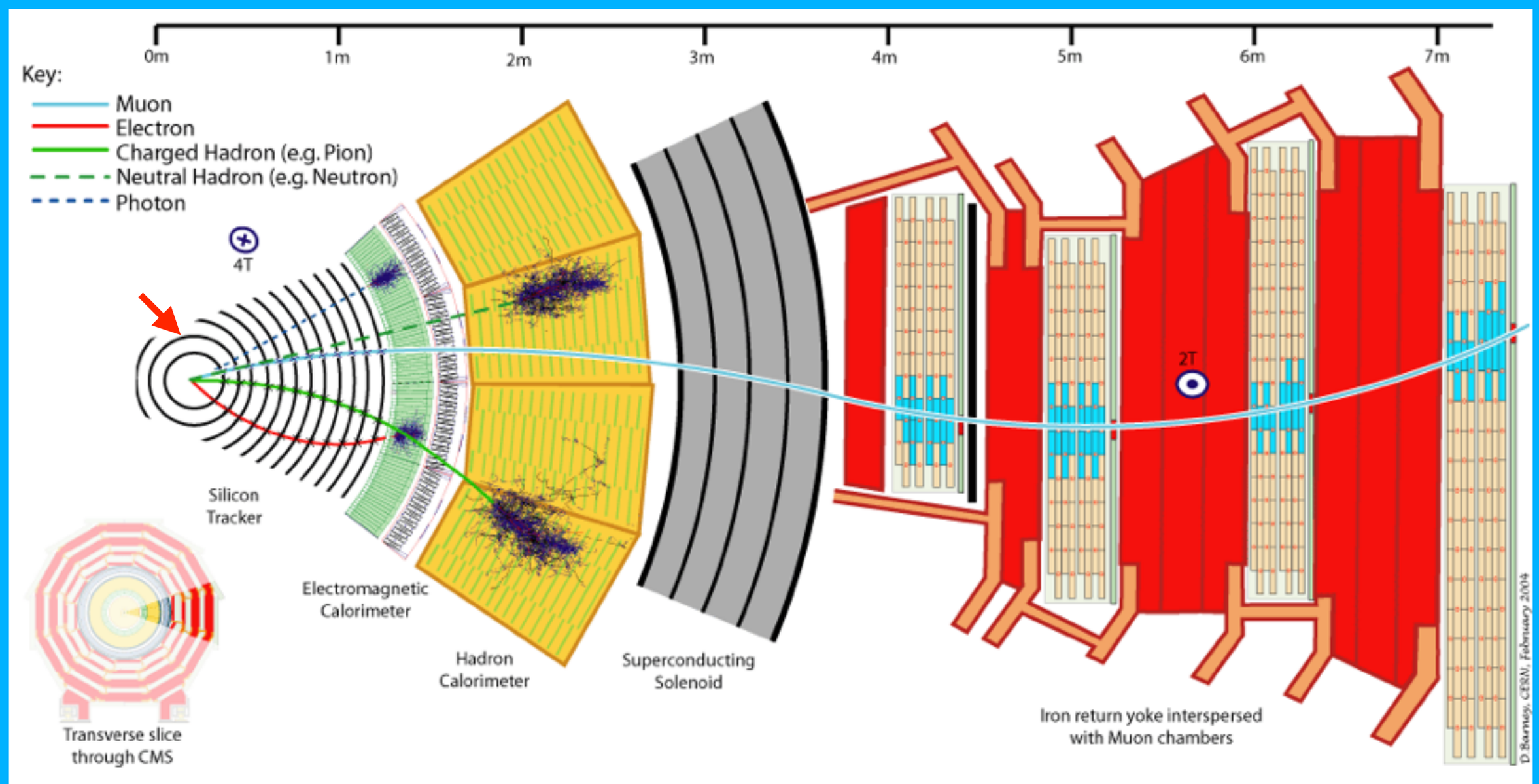
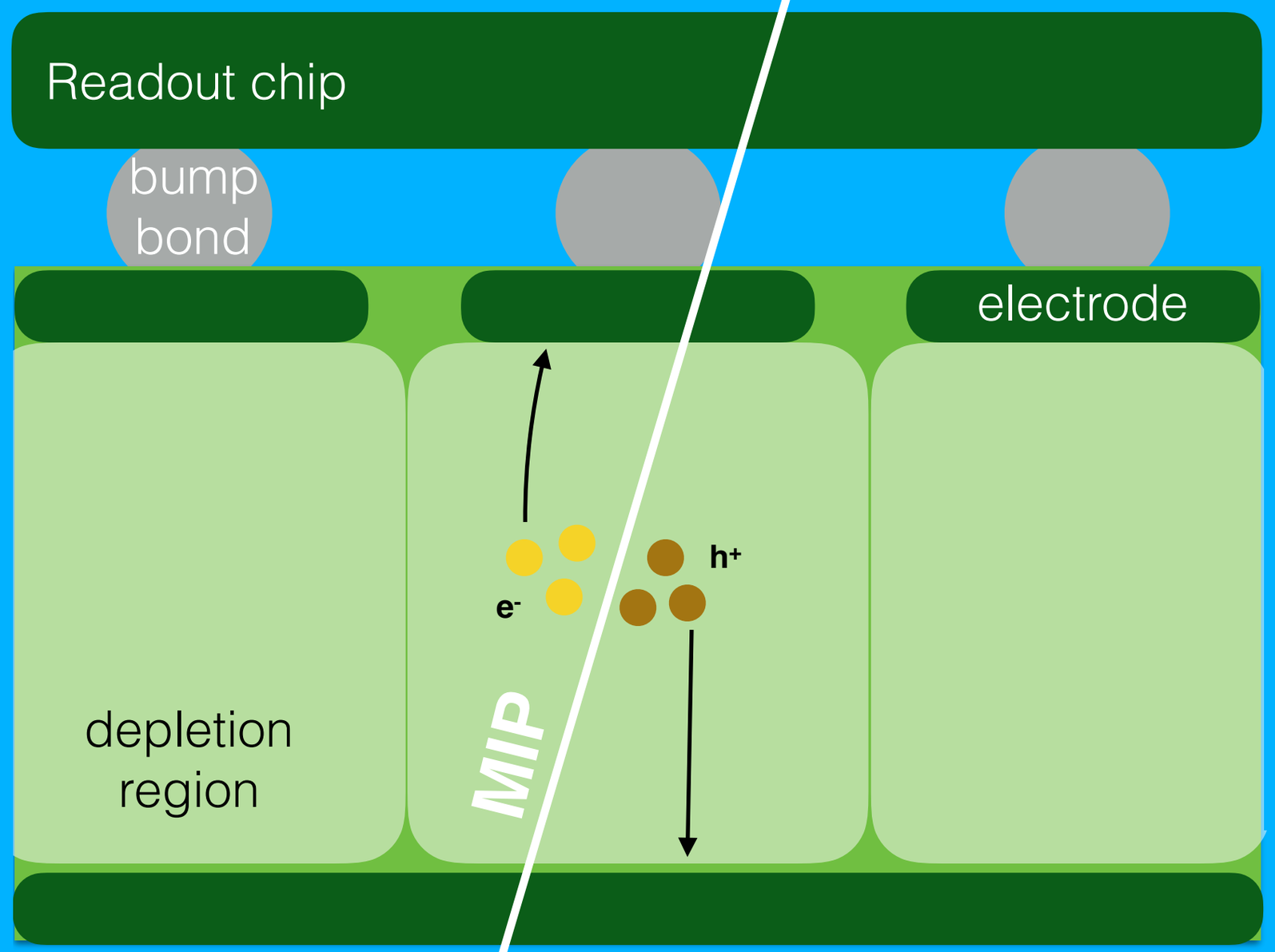


Photo Credit: http://ippog.web.cern.ch/resources/2011/cms-slice-july-2010-version

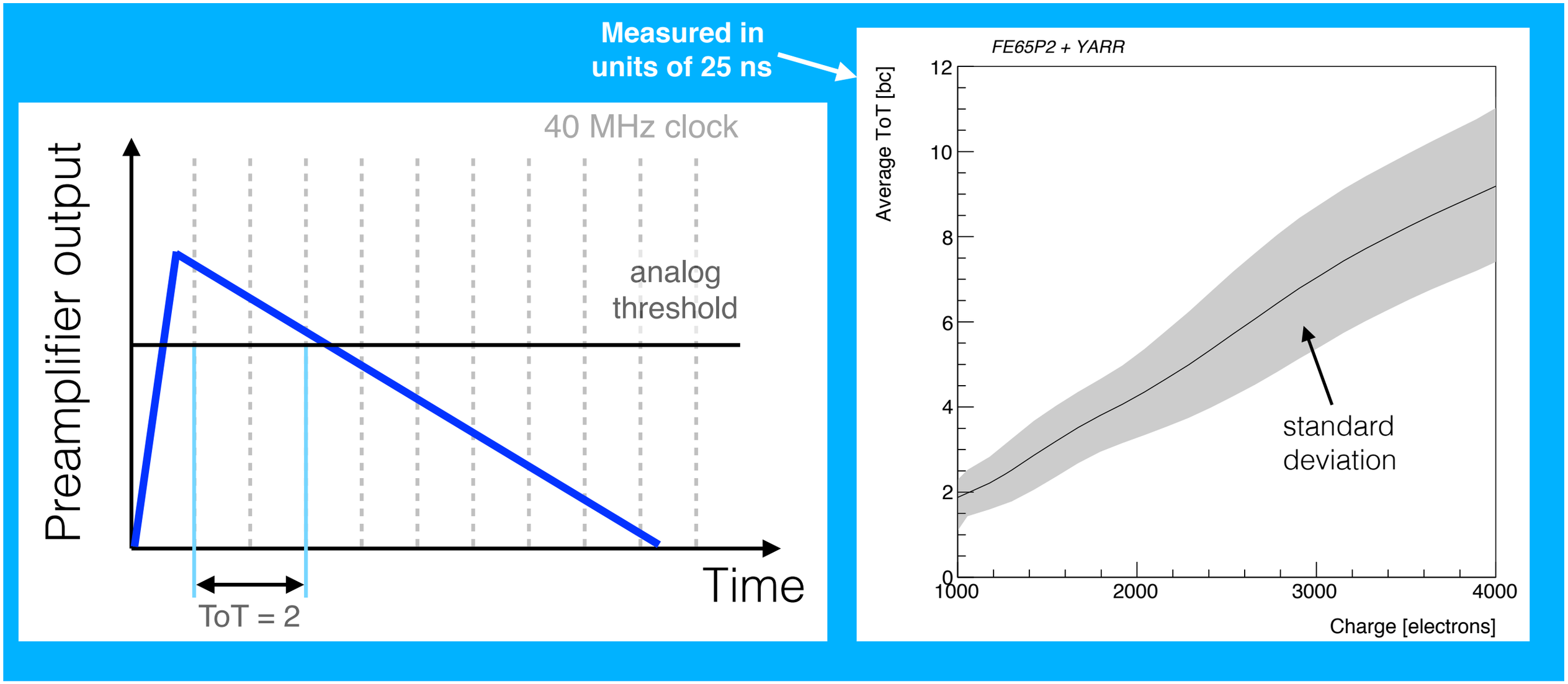
Pixel Detectors for Particle Detection

Measure deposited charge (from dE/dx)



not to scale

How we measure charge: Time over threshold (ToT)

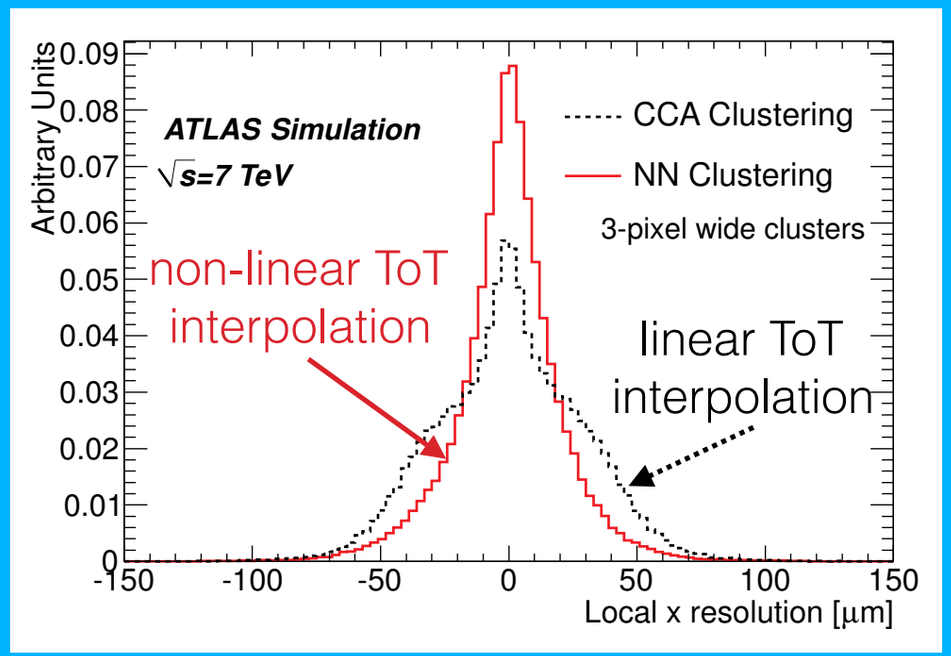


~80 electron-hole pairs per micron (MIP)

For 50 x 50 x150 sensor: $12 \text{ ke @ } |\eta| = 0 \text{ and } 4 \text{ ke @ } |\eta| \to \infty$

ToT is encoded 2^N bits; e.g. N = 4 for the ATLAS IBL modules

How have we used charge?

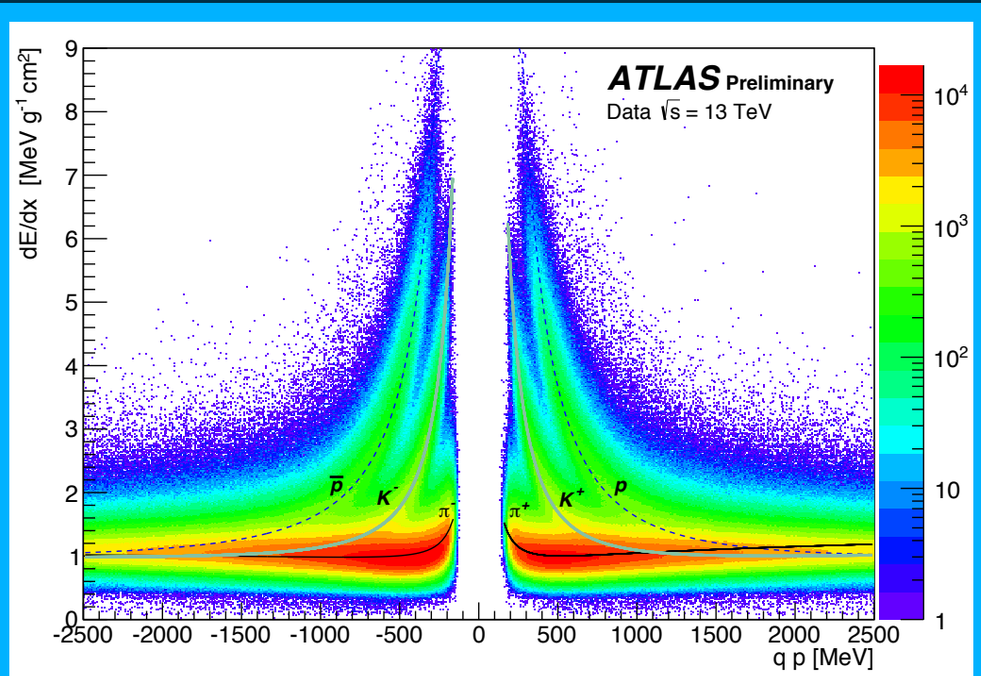


JINST 9 (2014) P09009

Resolution

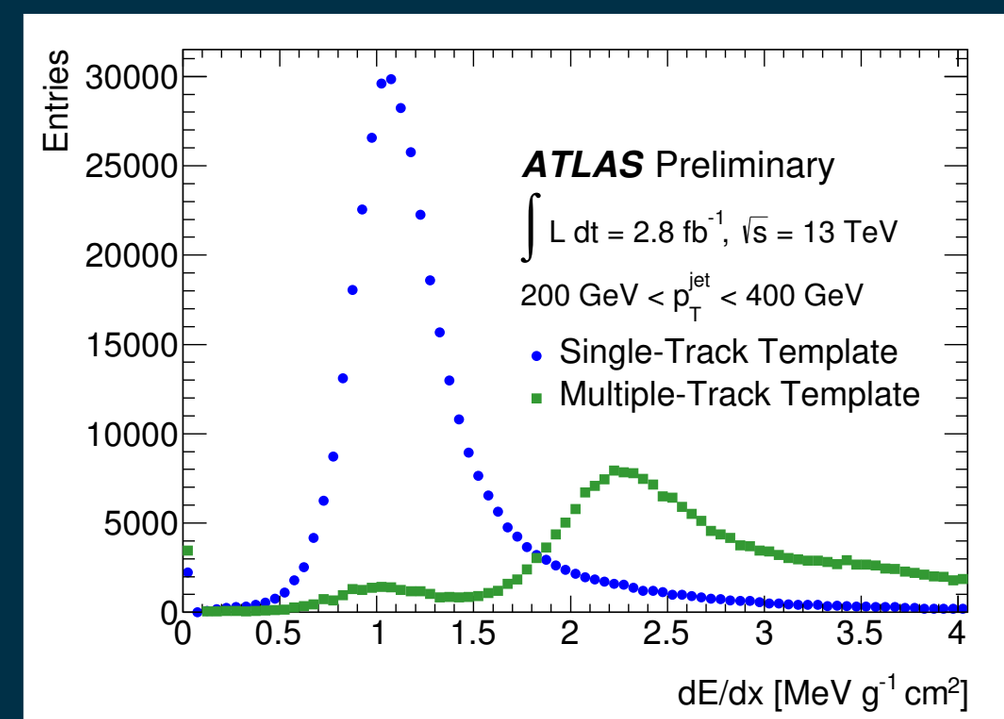
Less path length = less charge; can be used to improve residual

Split merged clusters using charge distribution



ATLAS-PIX-2015-002

Classification

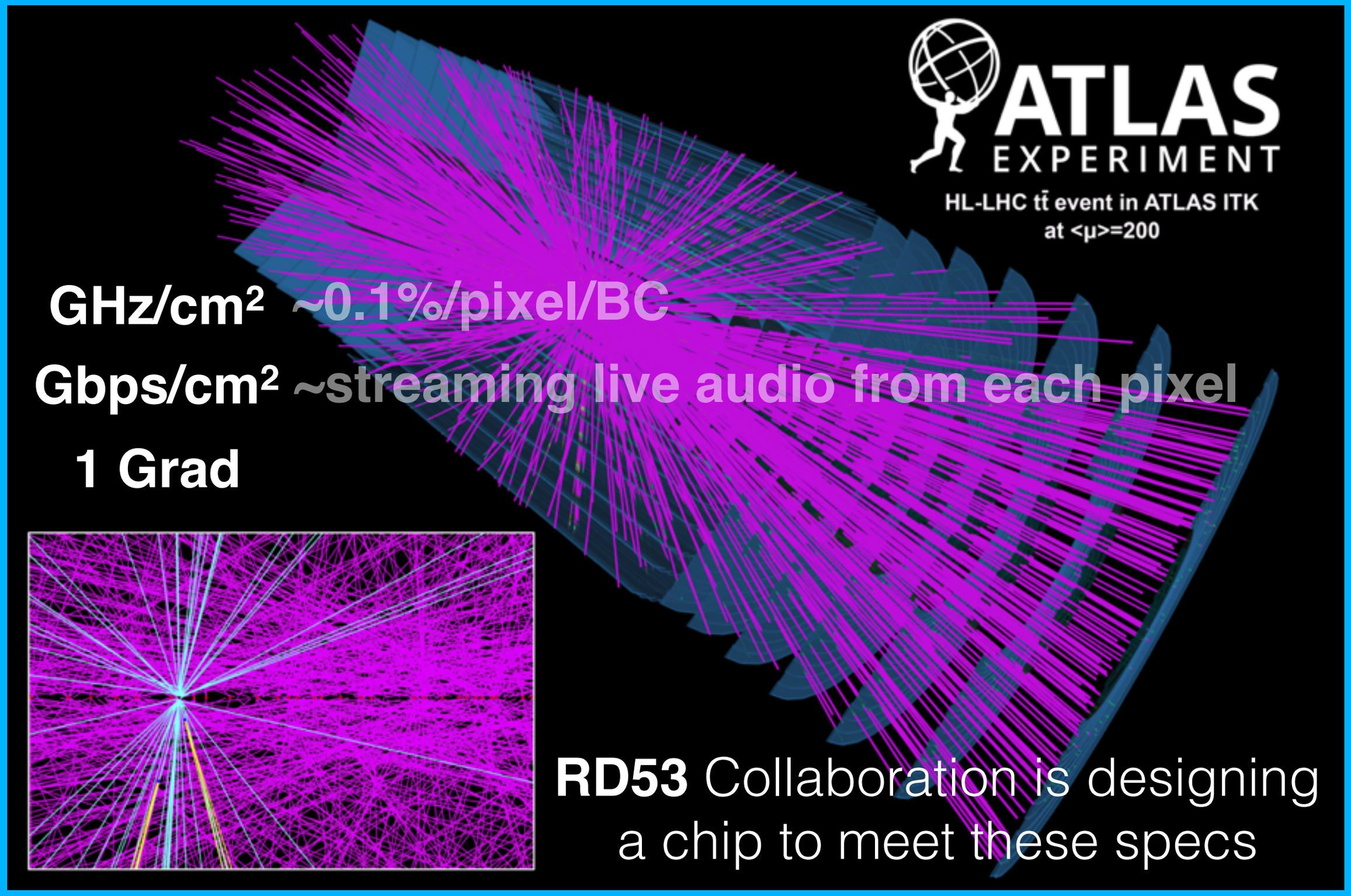


ATL-PHYS-PUB-2016-007

Particle Identification (PID)

Sensitive to heavy long lived particles beyond the SM

The future: Higher bandwidth, hit rate, radiation damage



GHz/cm² ~0.1%/pixel/BC

Gbps/cm² ~streaming live audio from each pixel

1 Grad

RD53 Collaboration is designing a chip to meet these specs

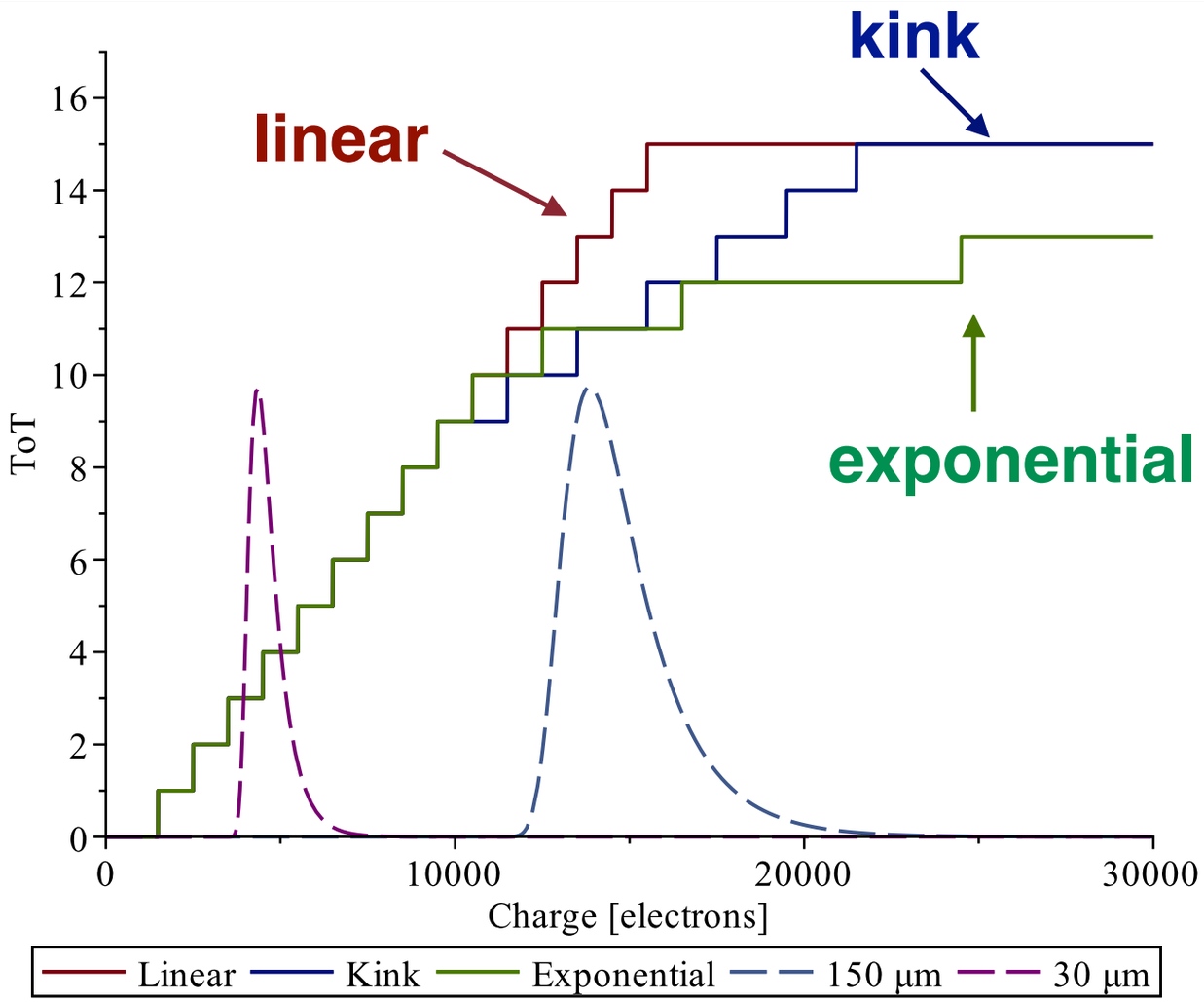
How can we optimize future use of charge?

Parameters

Digitize N bits, store (in buffer) M ≤ N bits.

One unit of ToT = f(Q|α)

Q = charge
α is the *tuning*



Metrics

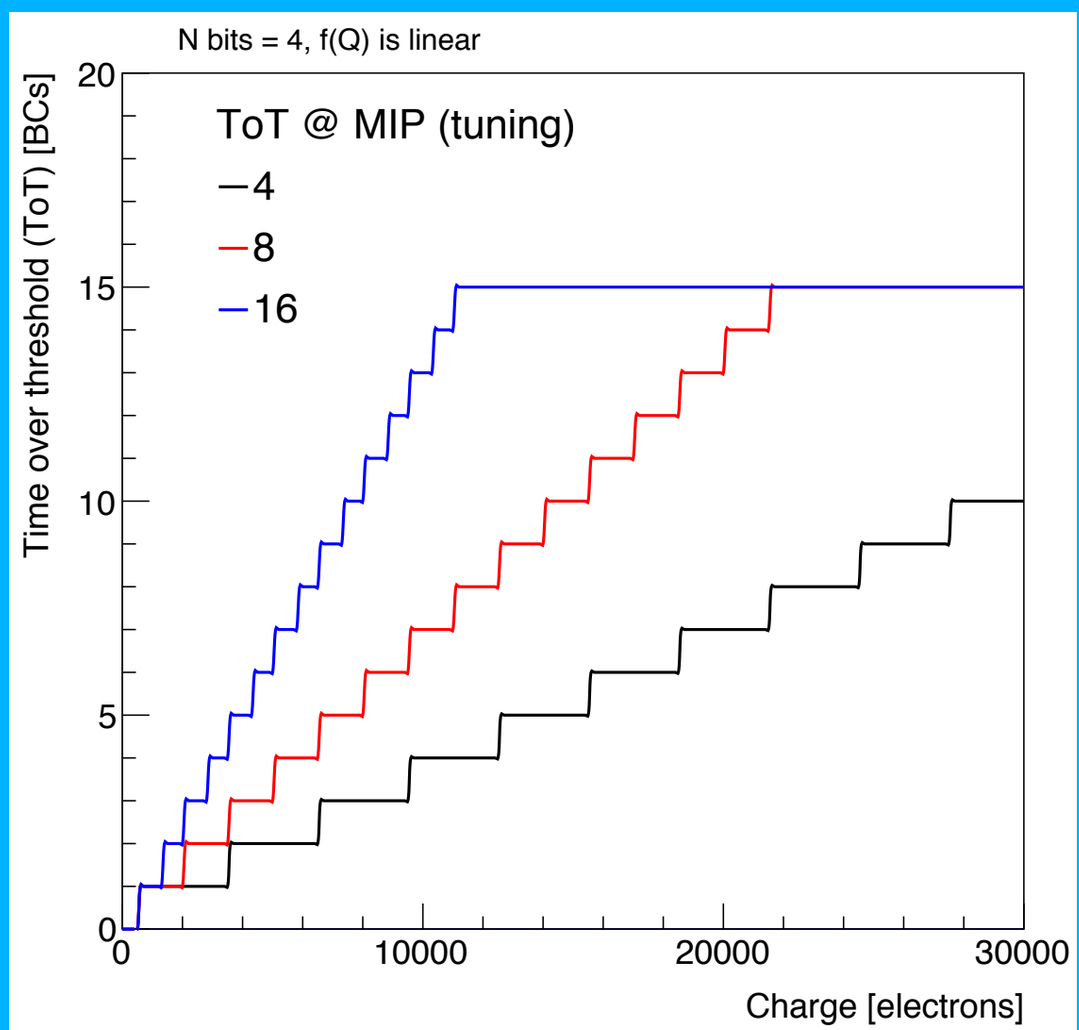
Efficiency	in-pixel pileup
Classification	how many particles deposited charge?
Resolution	cluster position
Particle Identification	δ-rays, soft SM particles, long-lived BSM

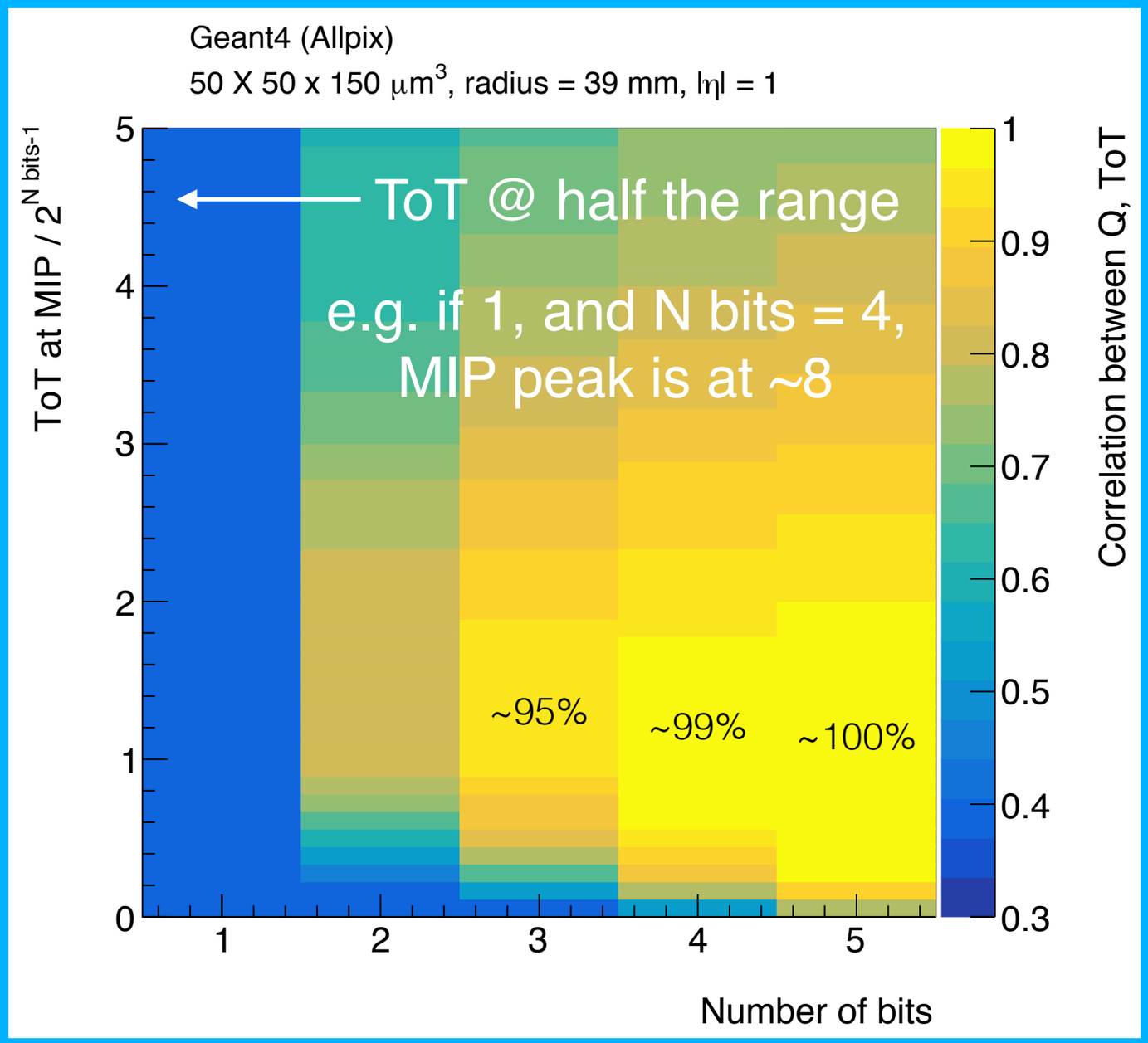
Example: Linear Conversion (~what is in ATLAS now)

$$\mathrm{ToT}(Q) = Q \times \frac{\mathrm{ToT@MIP}}{Q\mathrm{@MIP}}$$

MIP := 80 e/μm at perp. incidence

~Will focus on this example for the rest of the talk~



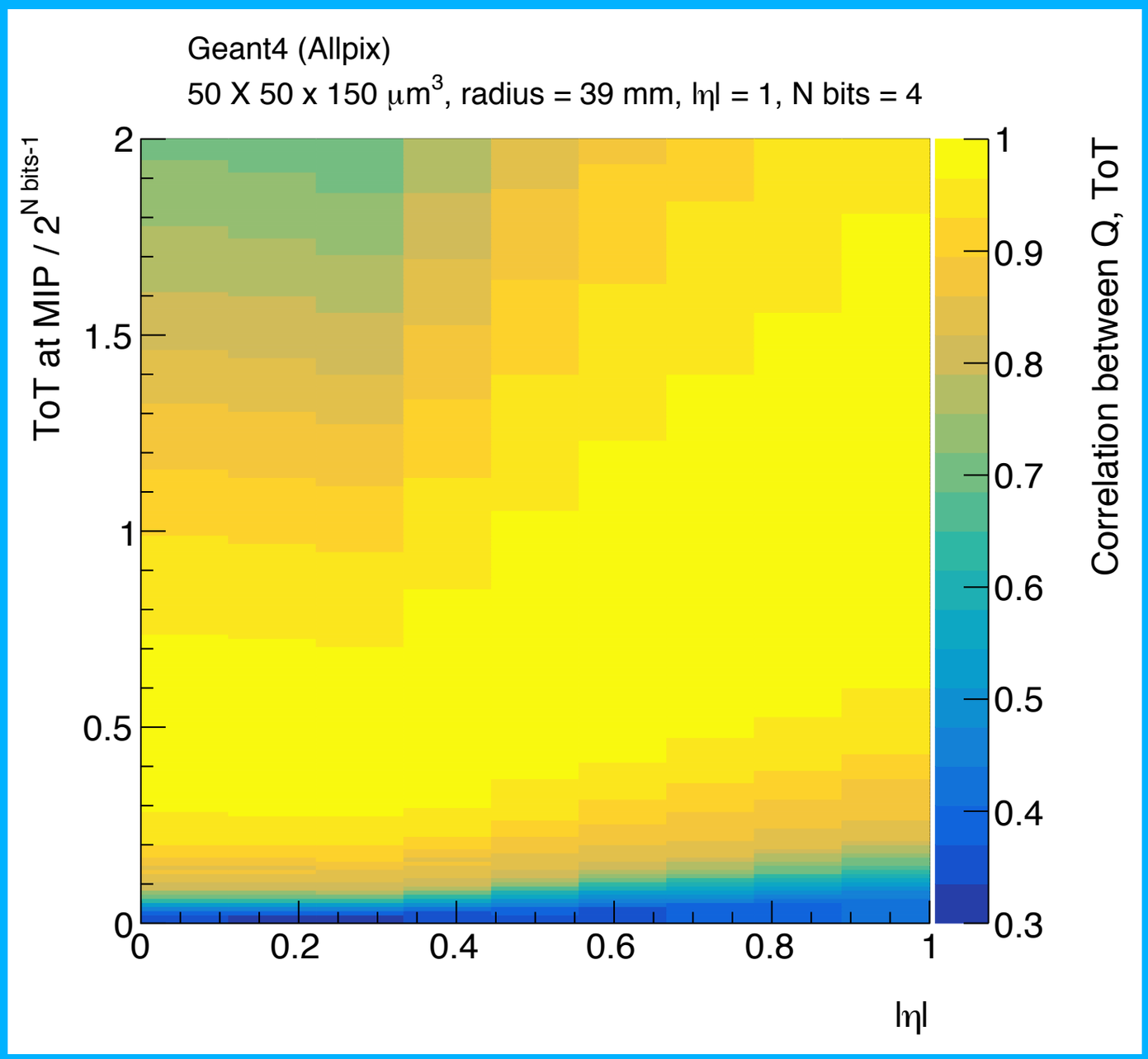


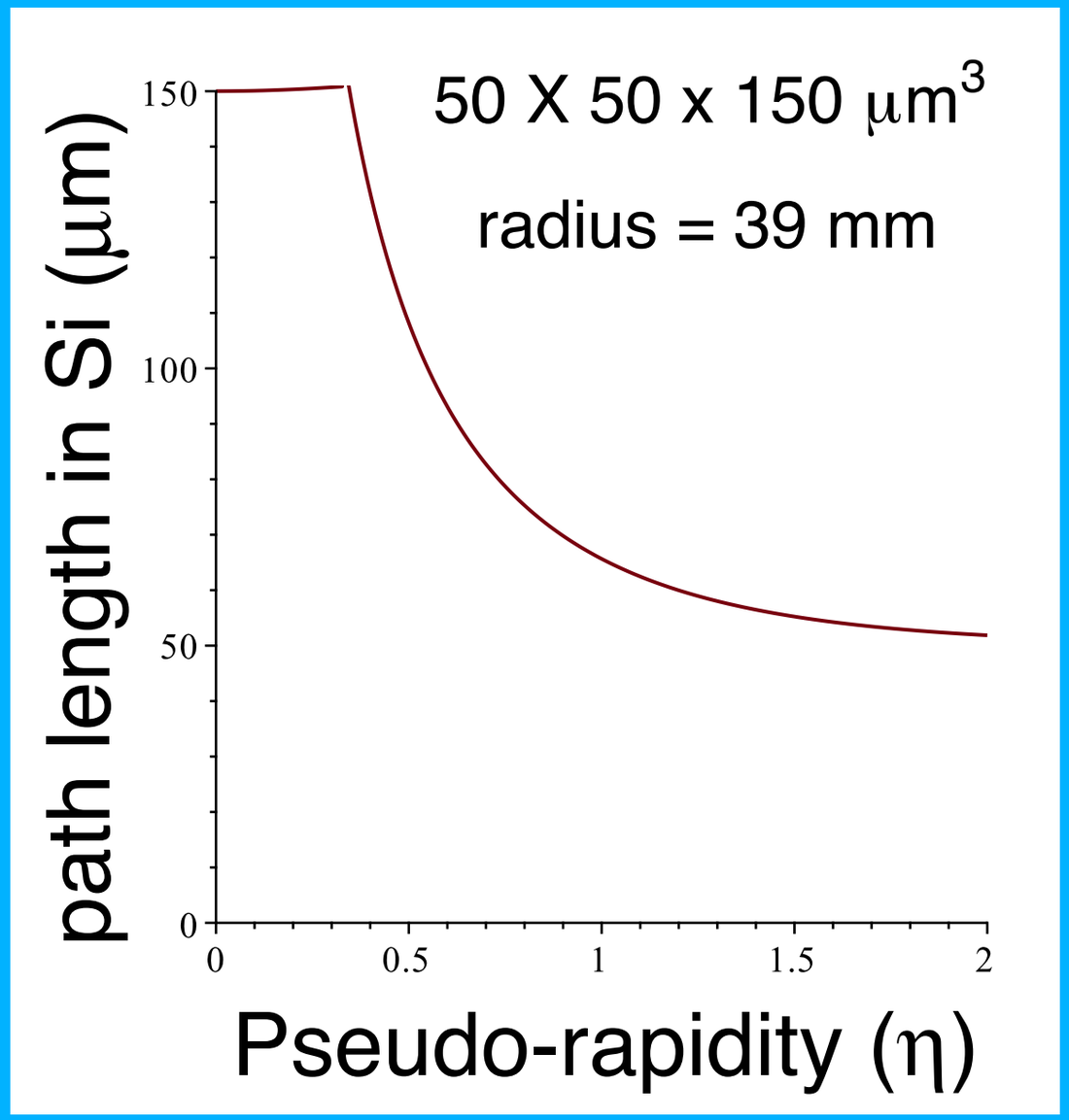
N.B. linear correlations don't tell the whole story! Need to check the various use-cases.

Optimizing the use of charge

Tuning should depend on angle!

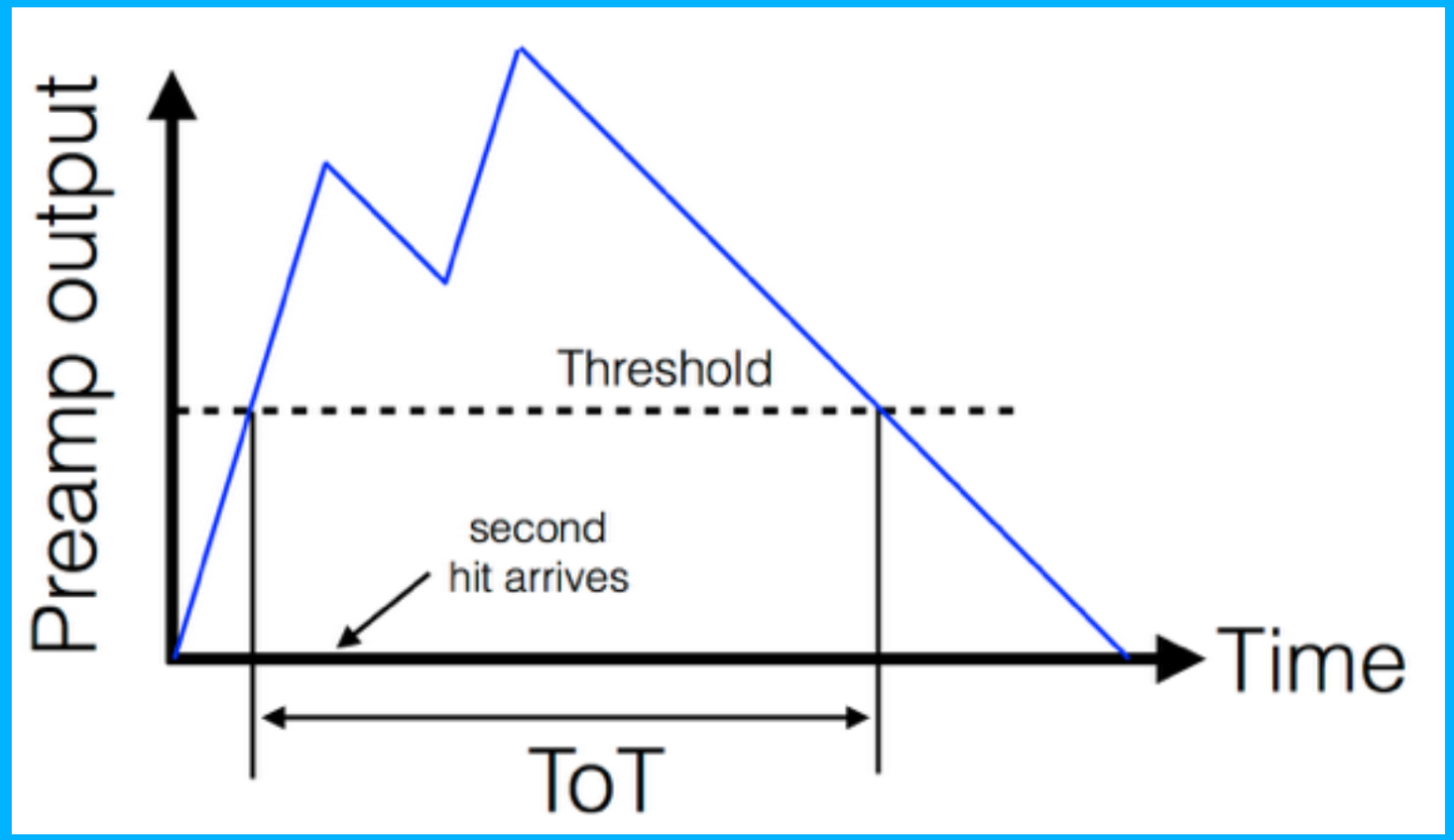
charge $\propto$ *path length*





(not the best metric, since over-emphasizes the high tail)

Efficiency



Counting longer increases precision but also **in-pixel pileup**

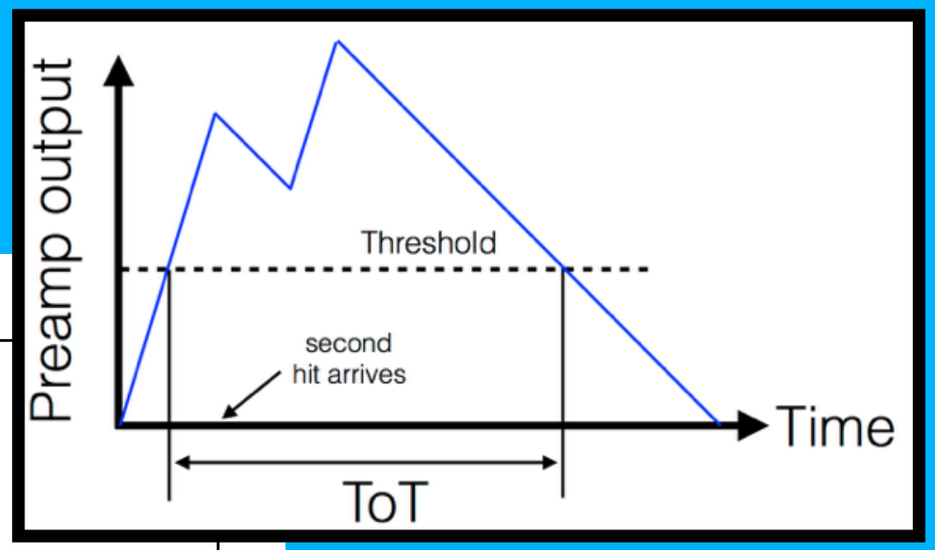
Could mitigate by counting faster than 40 MHz, but if fixed:

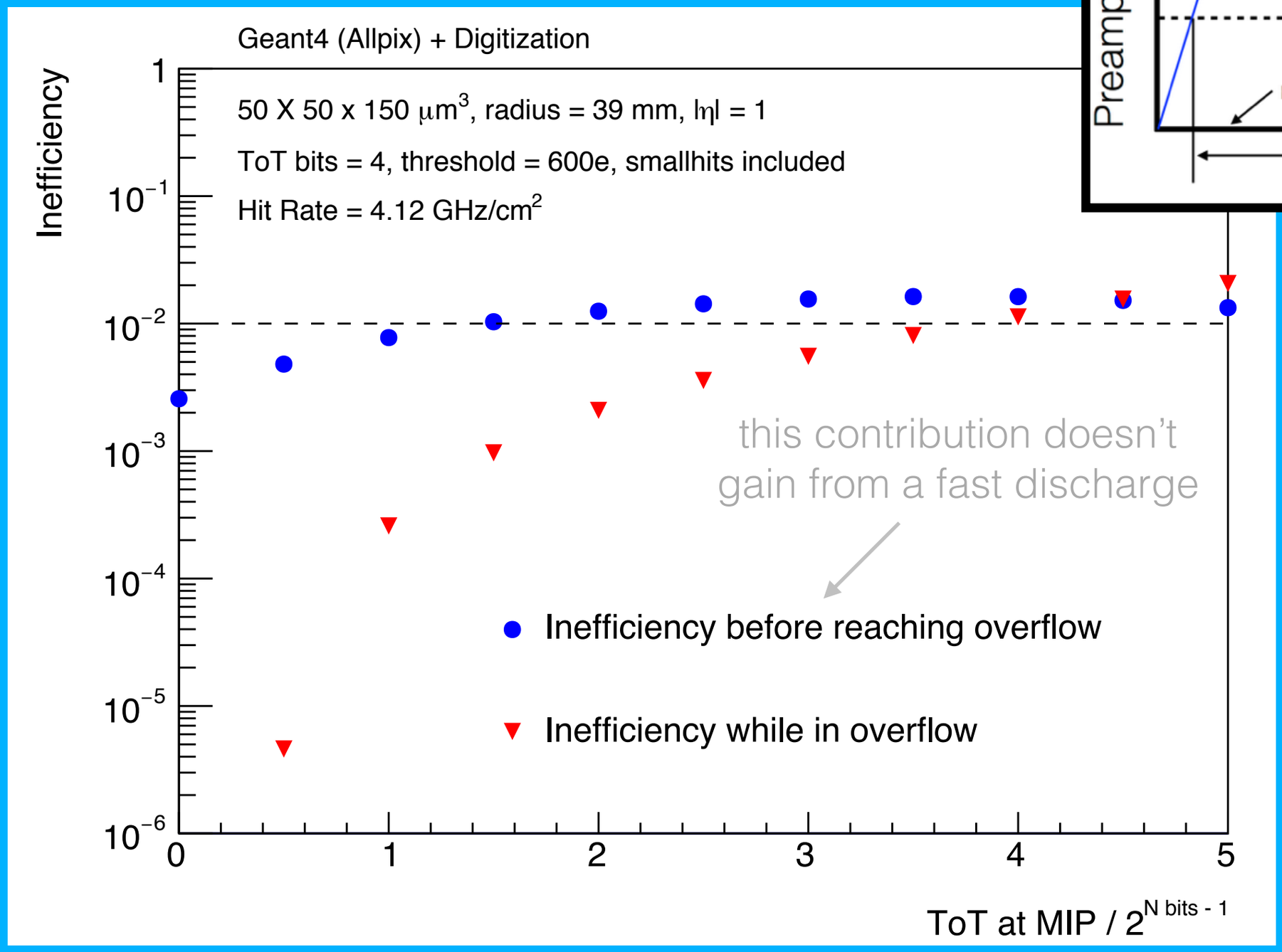
there is a tradeoff between dynamic range
(charge / ToT + N bits) and efficiency

N.B. can't just reduce N bits - still need to discharge overflow!

Fast (analog) discharge

What if you could ~instantly remove charge when the counter reached $2^N - 1$?



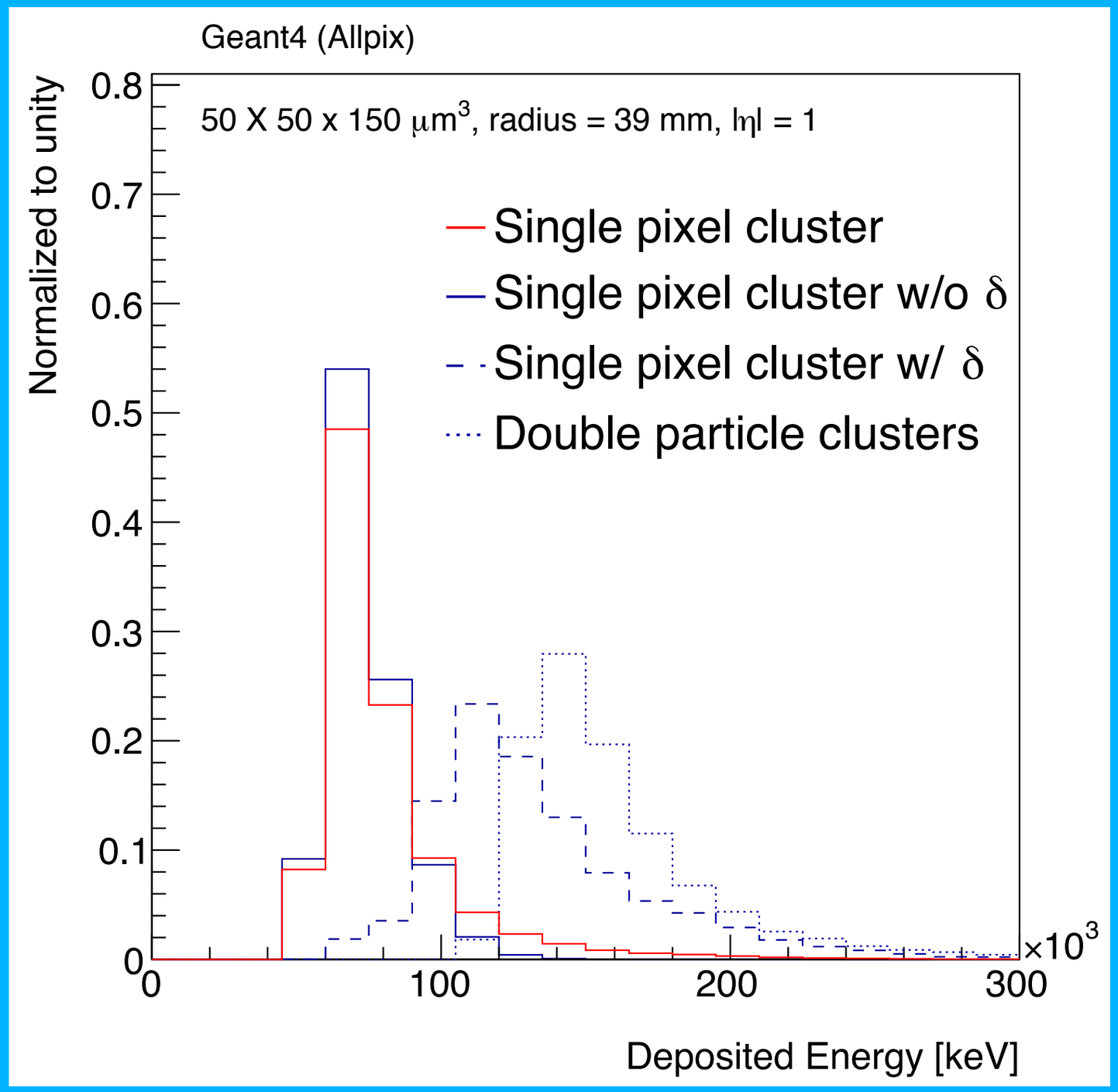


$$\sum_{\mathrm{ToT}=2^N-1}^{\infty} \mathrm{Pr}(\mathrm{ToT}) \times \mathrm{Pr}(2^{\mathrm{nd}}\ \mathrm{hit\ at\ or\ before\ ToT\ BC's})$$

$$\|$$

$$\sum_{\mathrm{ToT}=2^N-1}^{\infty} \mathrm{Pr}(\mathrm{ToT}) \times (1 - e^{-\mathrm{ToT} \times r})$$

Classification

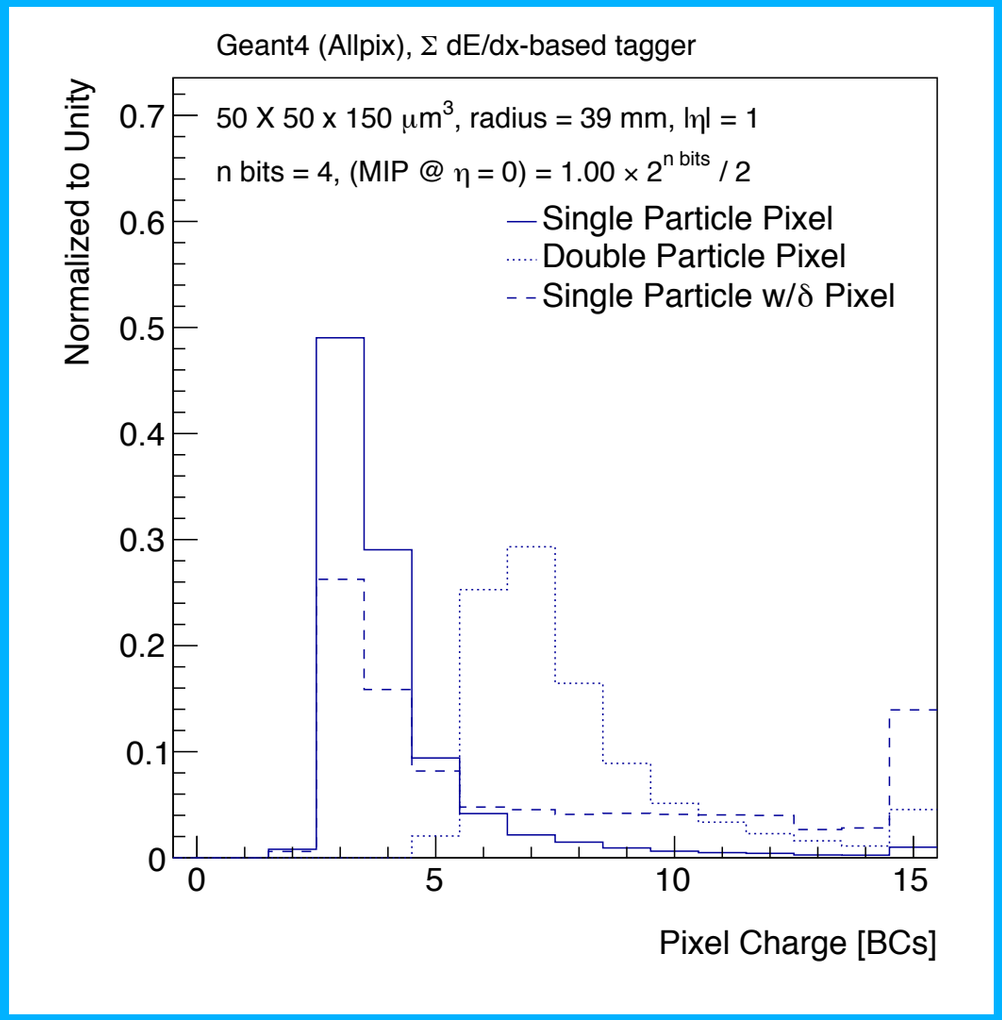


Inside dense environments (jets/τ), **clusters can merge**

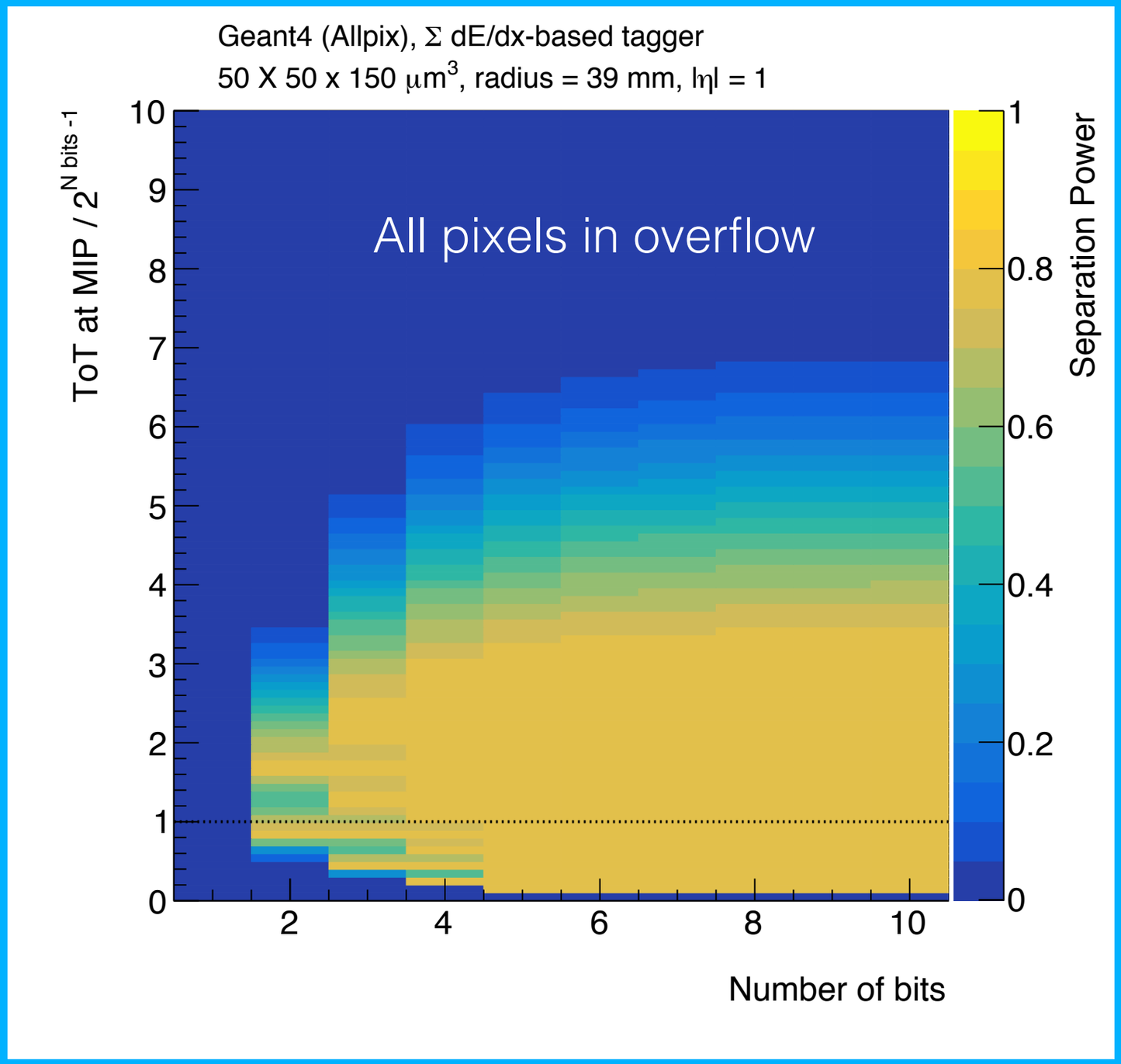
Merged clusters can result in **lost tracks** and poor track parameter estimation

It is therefore critical for high p_T physics to be able to **split clusters**

Classification



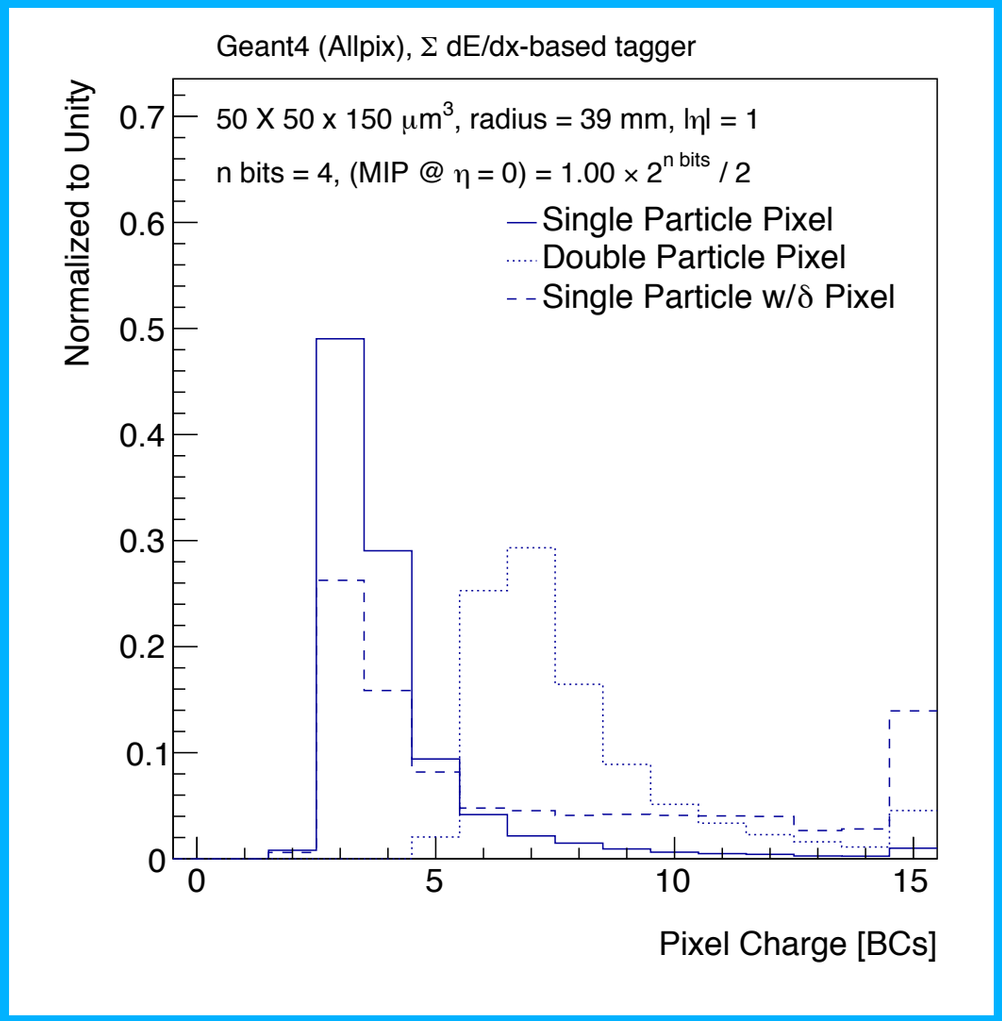
Single pixel classification, using only charge



Separation power

$$= \frac{1}{2}\int dx \frac{(p_1(x)-p_2(x))^2}{p_1(x)+p_2(x)}$$

Classification



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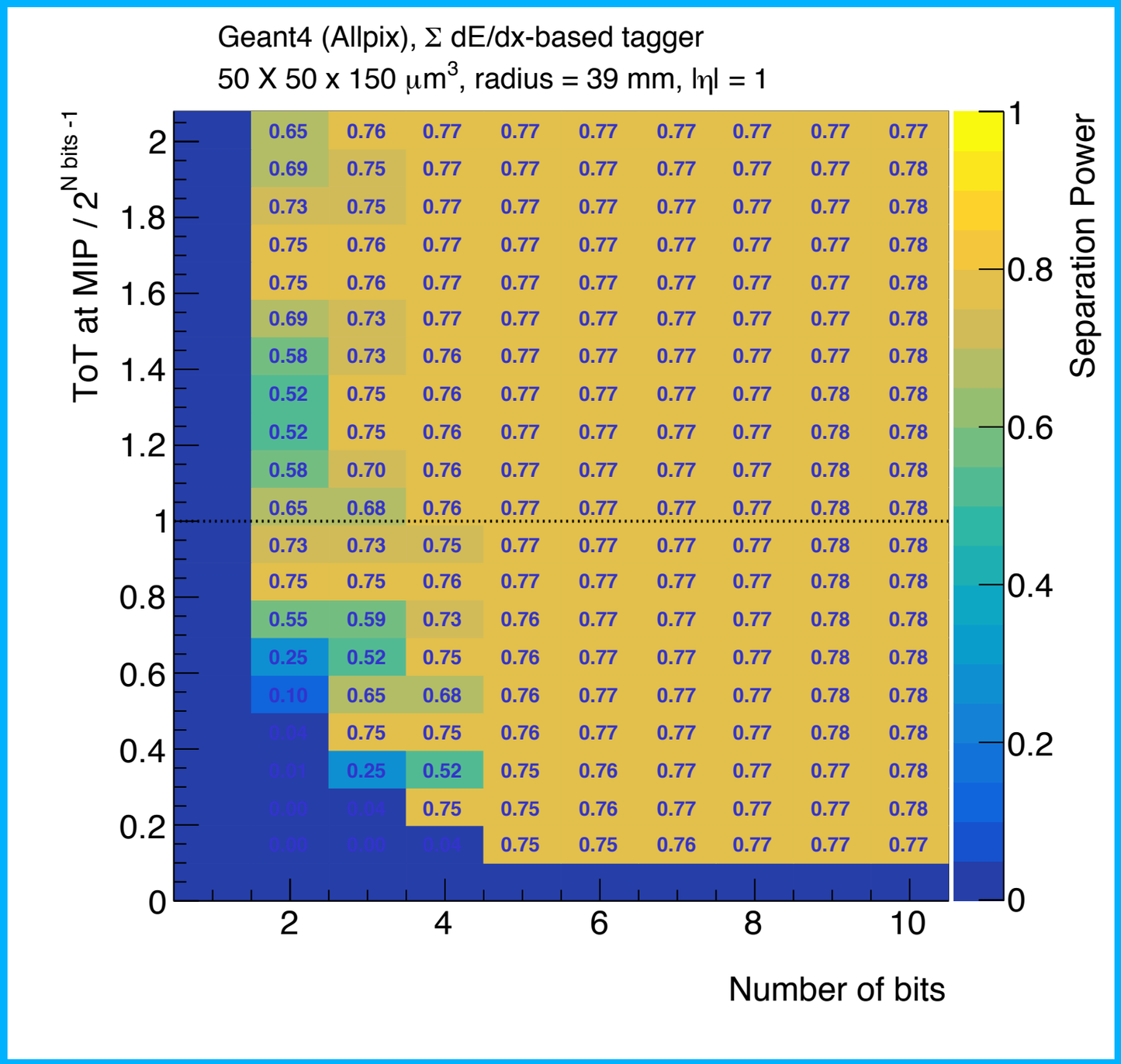
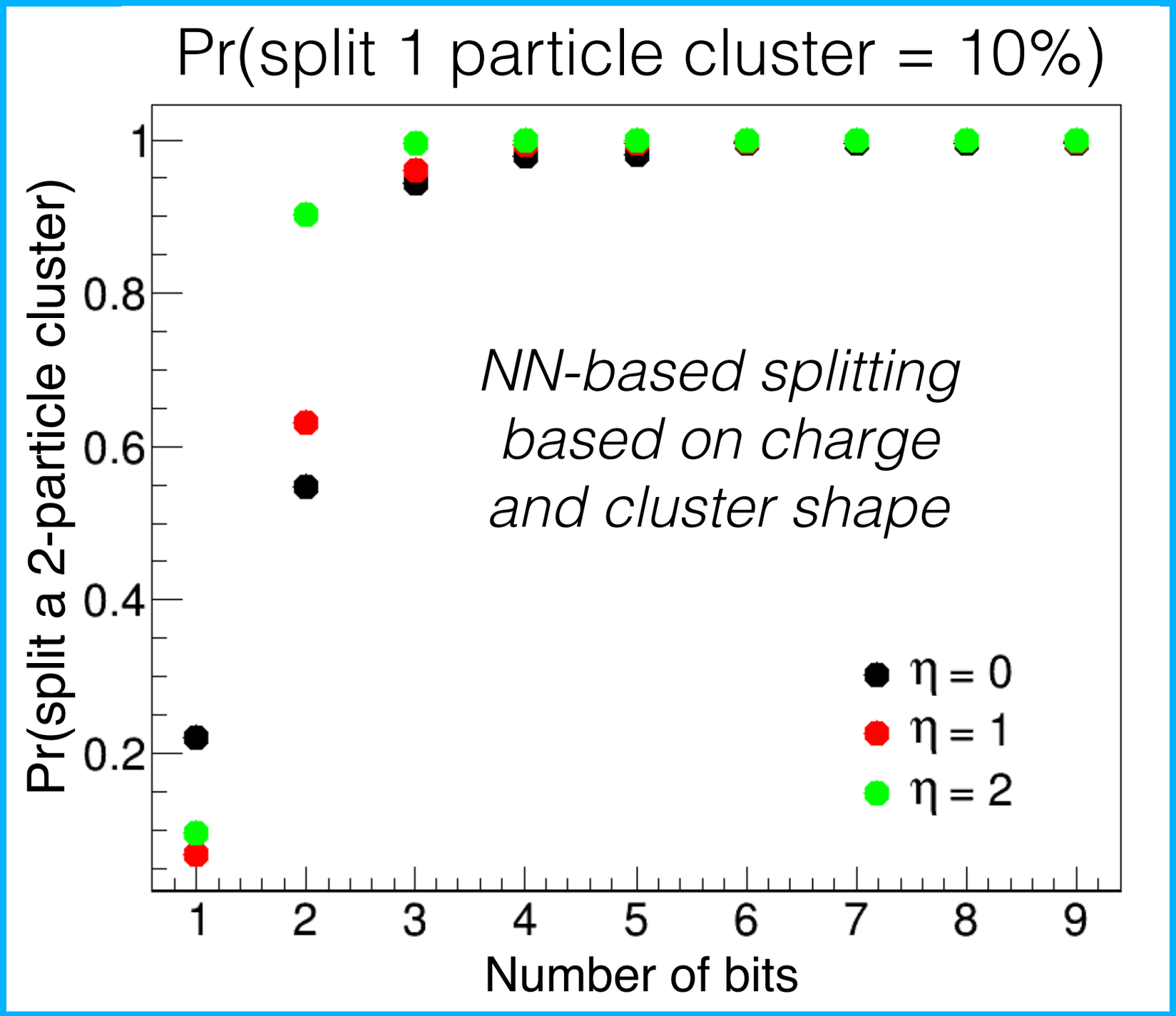
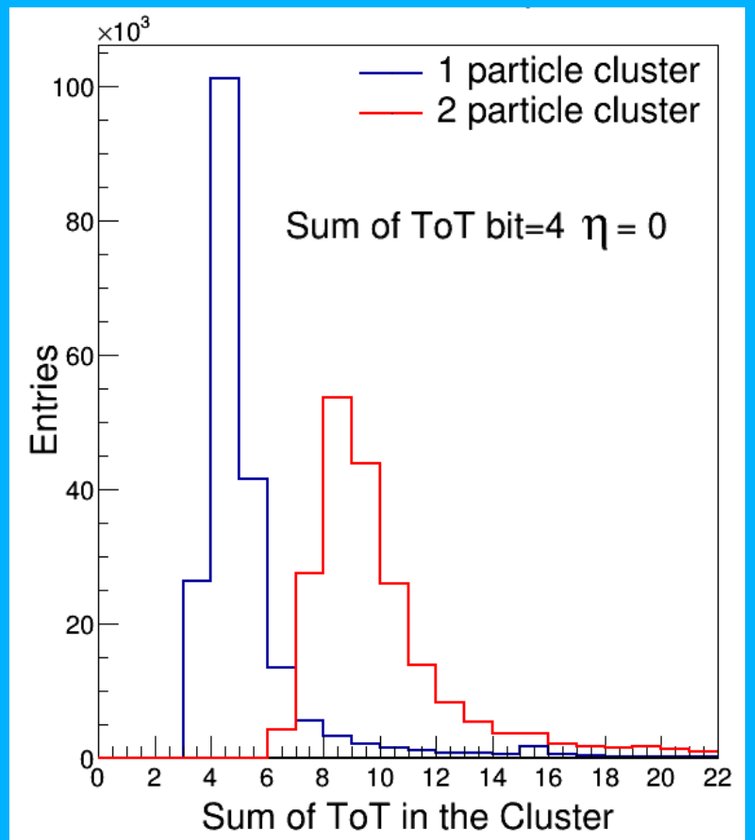


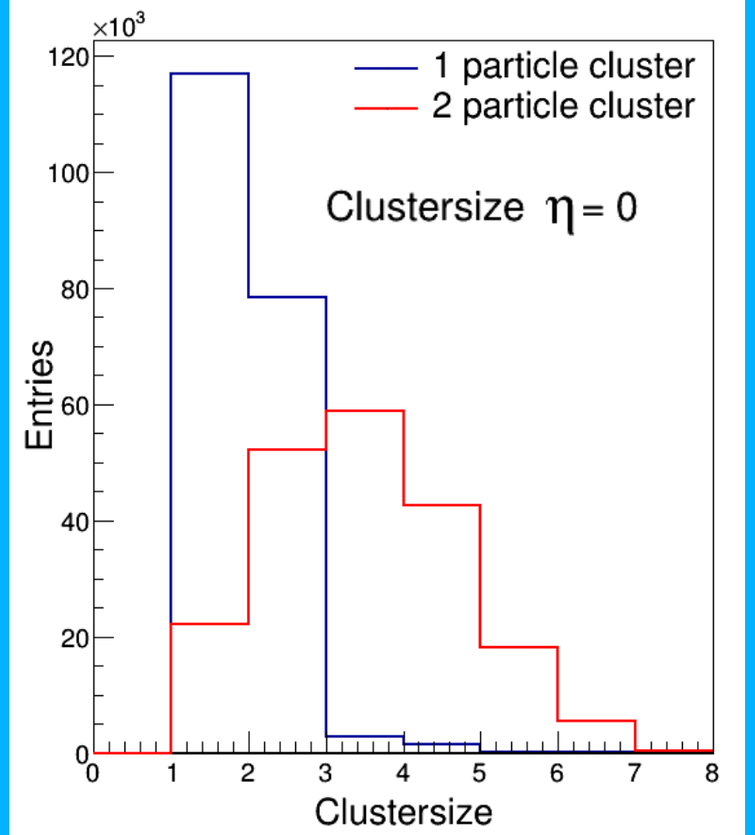
Separation power

$$= \frac{1}{2} \int dx \frac{(p_1(x) - p_2(x))^2}{p_1(x) + p_2(x)}$$

Classification

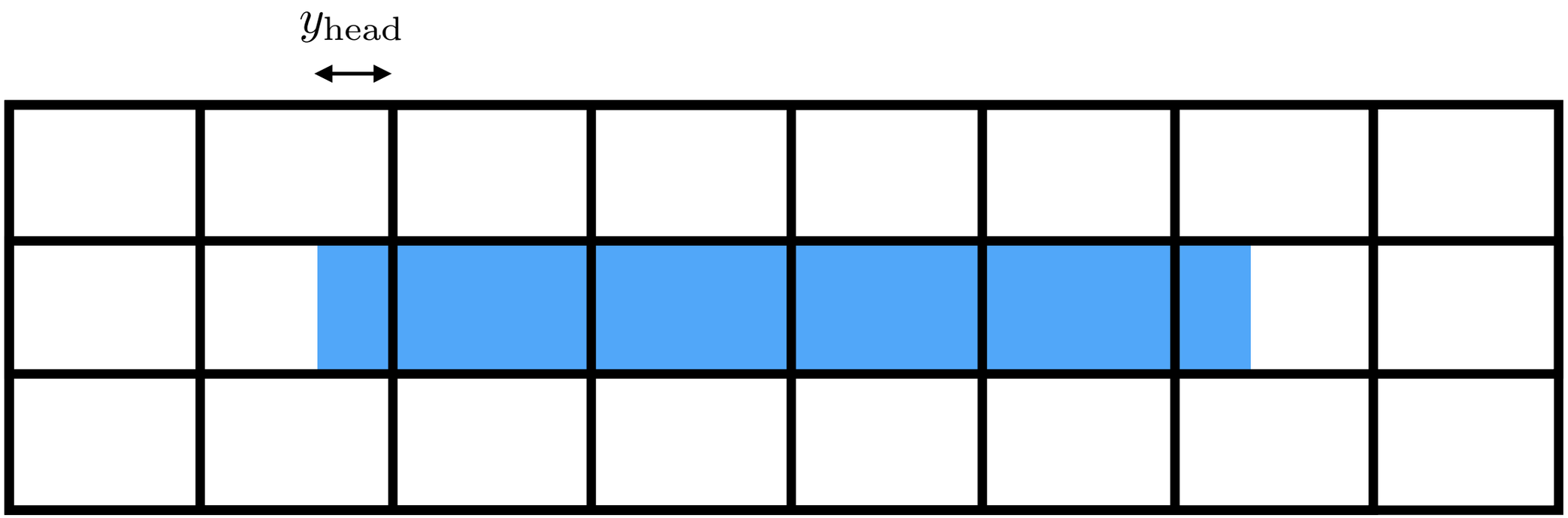






Resolution: one-particle clusters

one-particle @ a cluster has 4 parameters: x,y,θ,ϕ

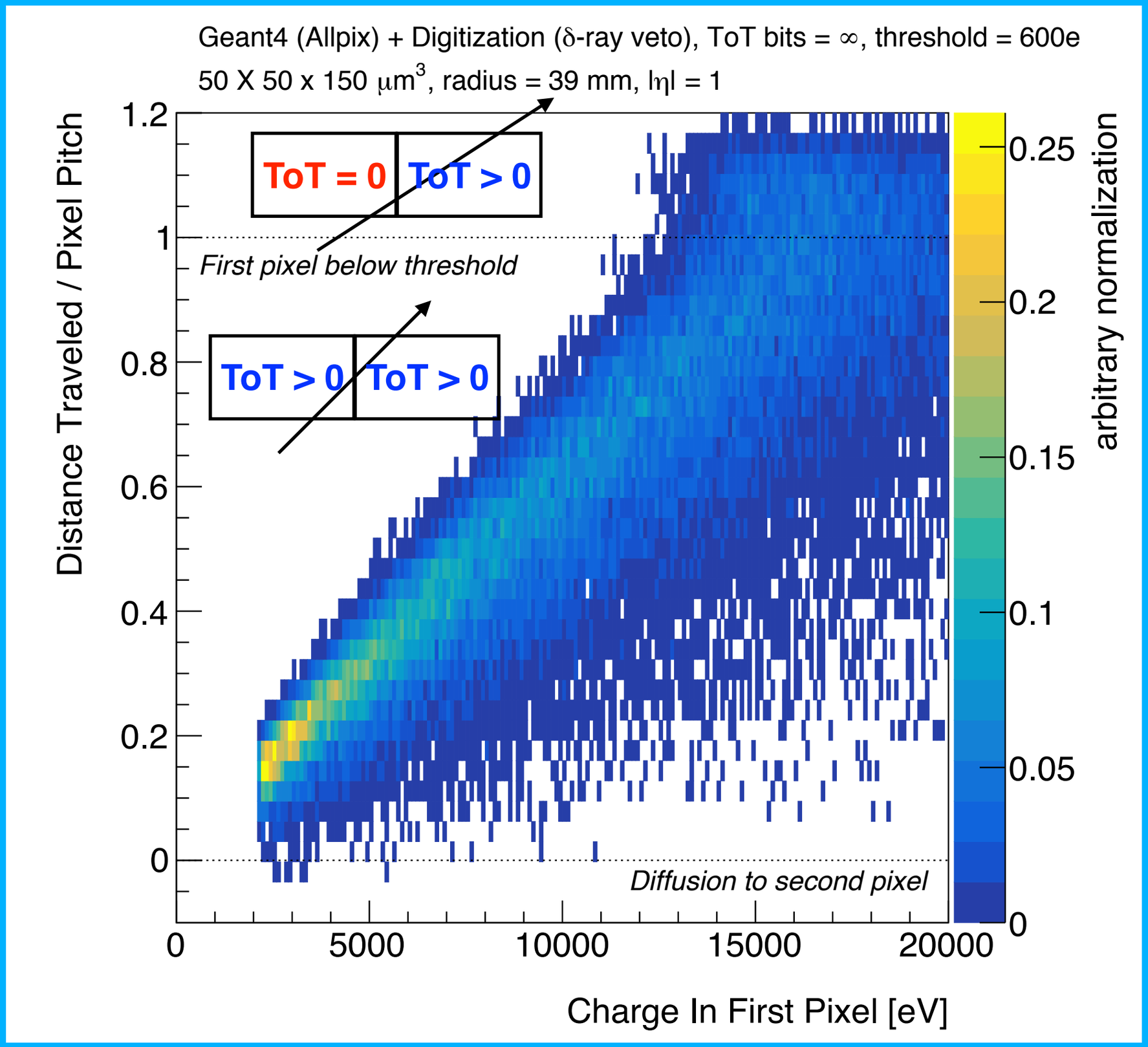


θ is determined by the cluster length; θ and y resolution set by how well we can resolve the two ends:

$$y_{\mathrm{cluster}} = \frac{1}{2}(y_{\mathrm{head}} + y_{\mathrm{tail}}) \rightarrow \sigma_{y_{\mathrm{cluster}}} = \sigma_{y_{\mathrm{head}}}/\sqrt{2}$$

$$L_{\mathrm{cluster}} = y_{\mathrm{head}} - y_{\mathrm{tail}} \rightarrow \sigma_{L_{\mathrm{cluster}}} = \sqrt{2}\sigma_{y_{\mathrm{head}}}$$

Resolution: one-particle clusters



Optimal resolution:

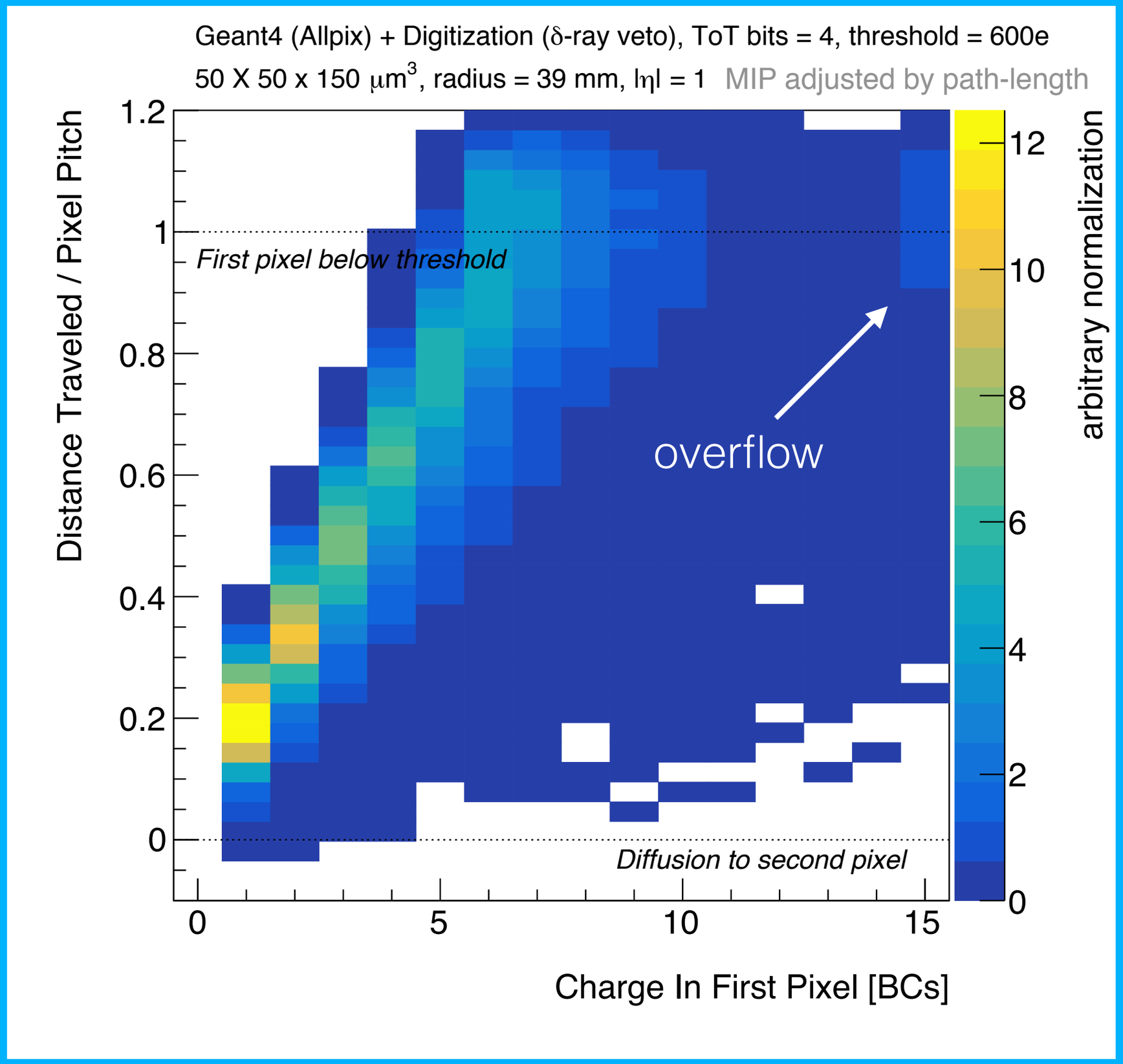
$$\min_f (f(y) - y)^2$$

$$\implies f(y) = \langle y|Q\rangle$$

Near the MIP, not much sensitivity

Ideally: as much low charge as possible!

Resolution: one-particle clusters



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$$\min_f (f(y) - y)^2$$

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Near the MIP, not much sensitivity

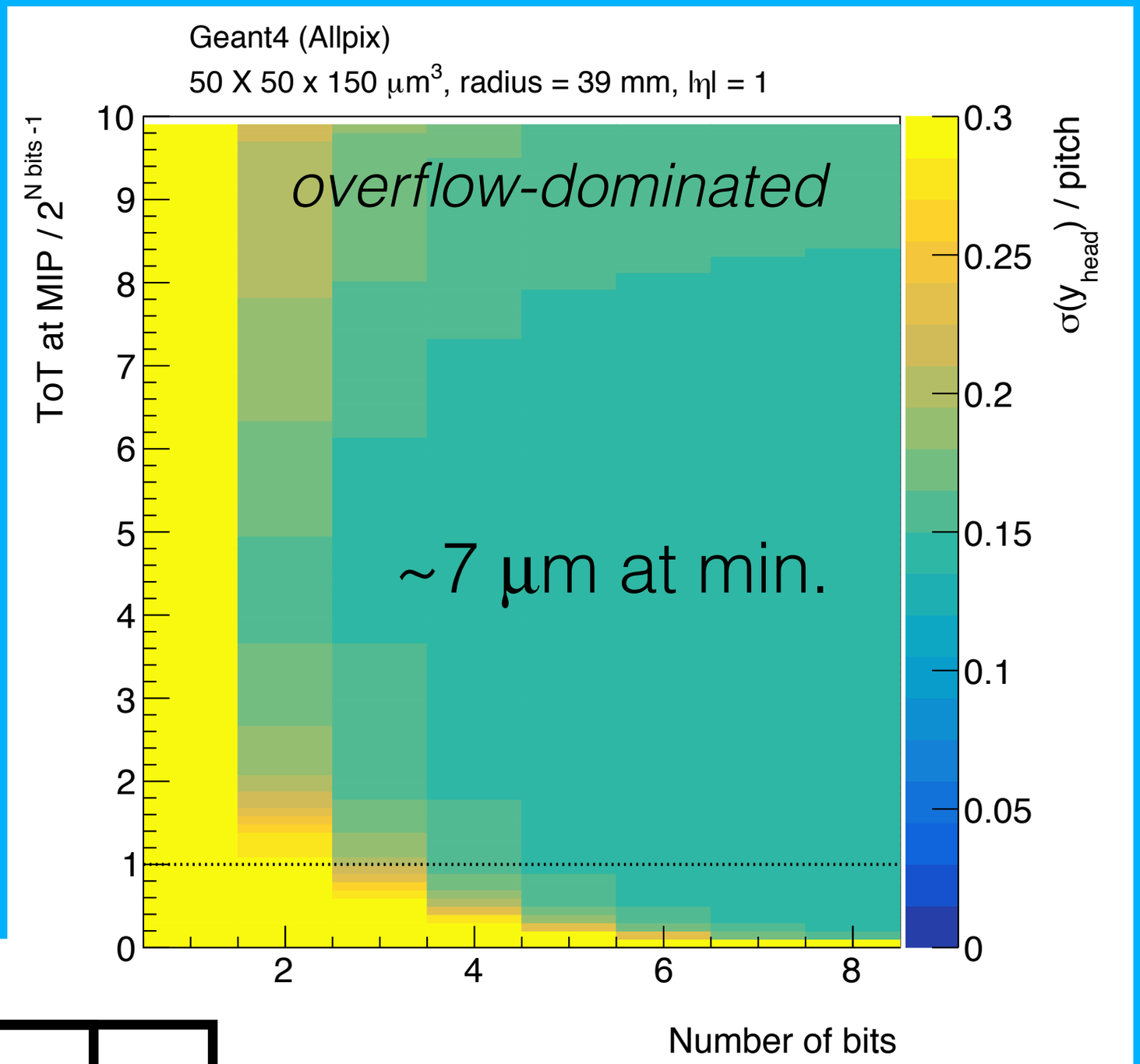
Ideally: as much low charge as possible!

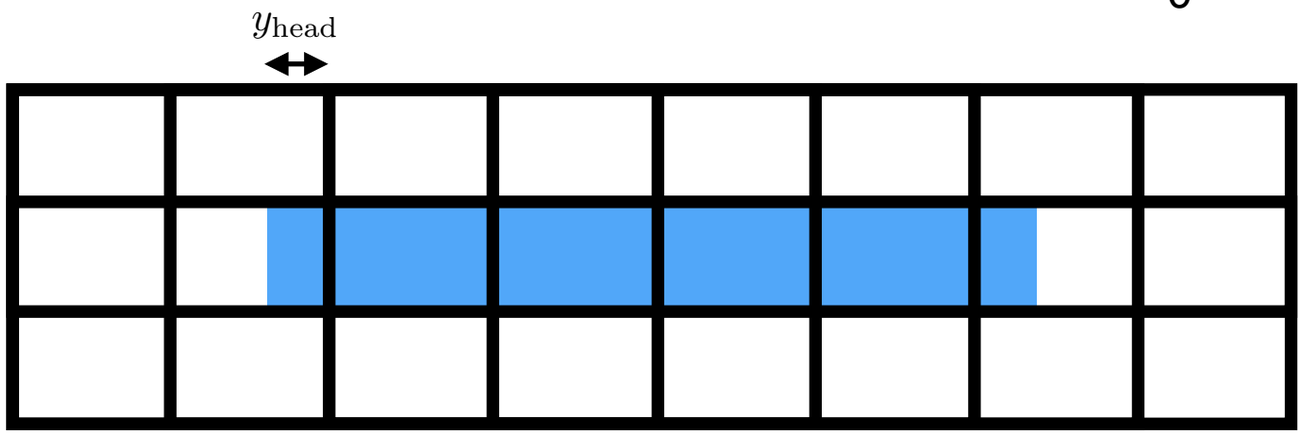
Resolution: one-particle clusters

For a fixed number of bits, prefer higher ToT @ MIP

bits	Resolution
1	0.29
2	0.19
3	0.16
4	0.15
5	0.14
infty	0.13

(for path-length corrected MIP)





ceiling: $1/\sqrt{12} \sim 0.29$

Resolution: one-particle clusters

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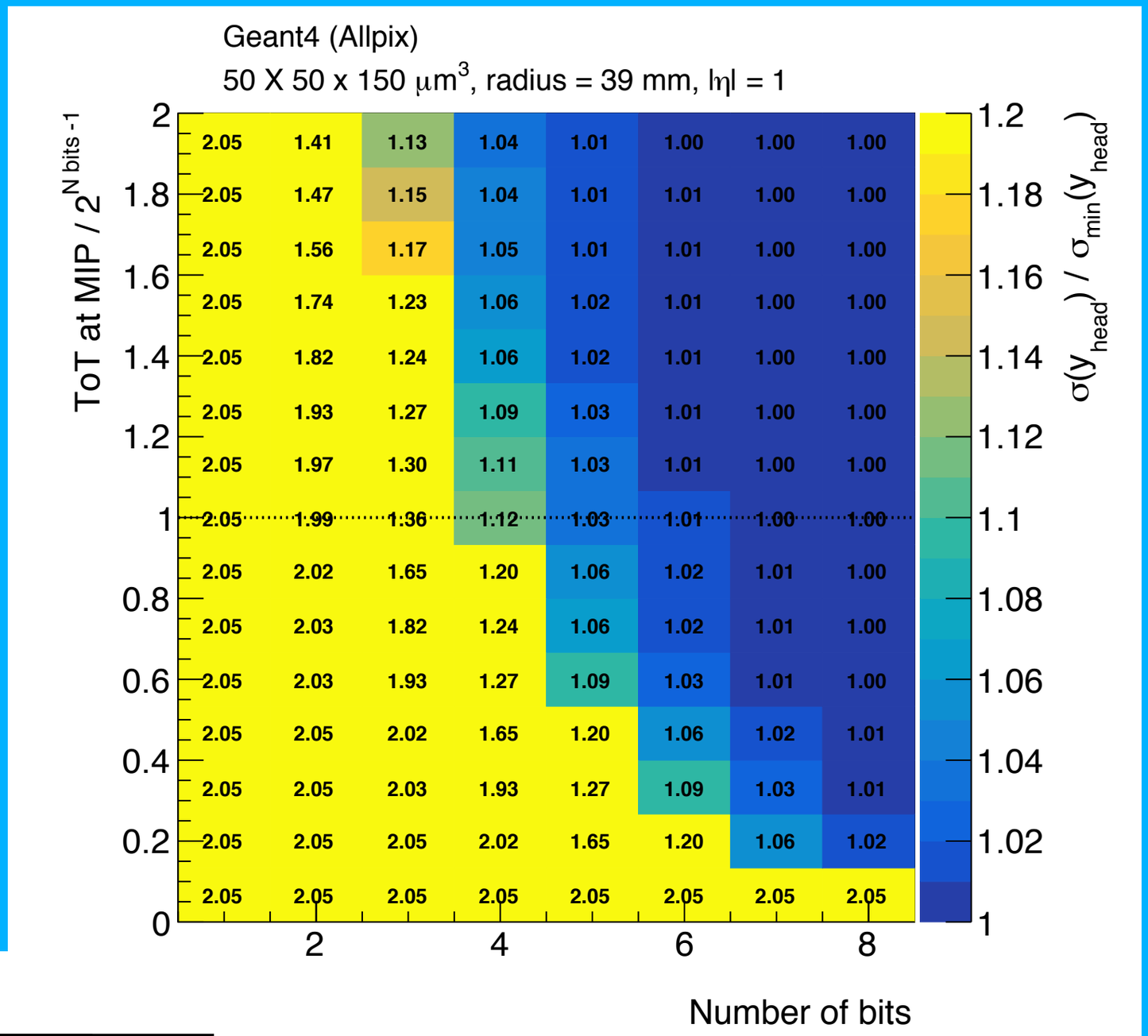
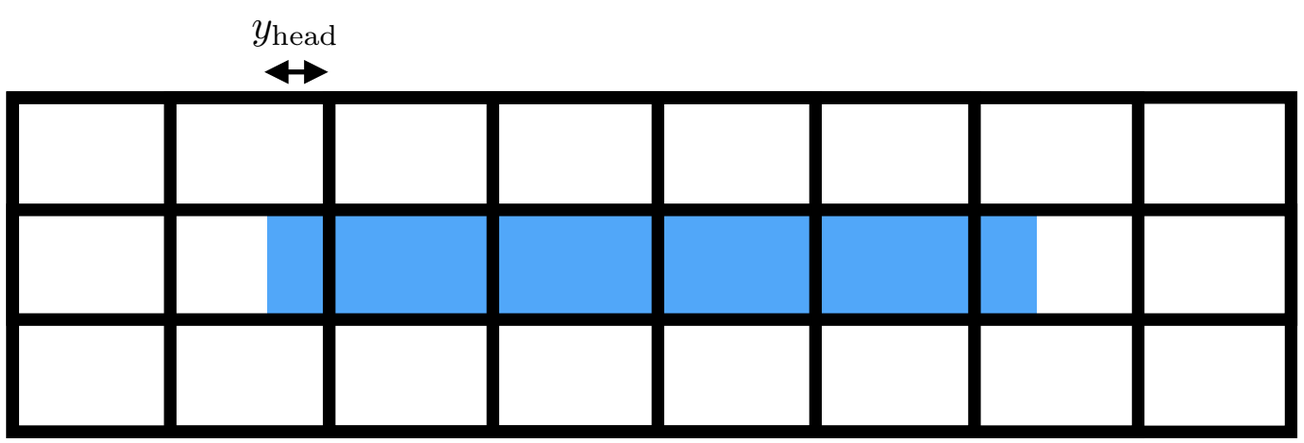
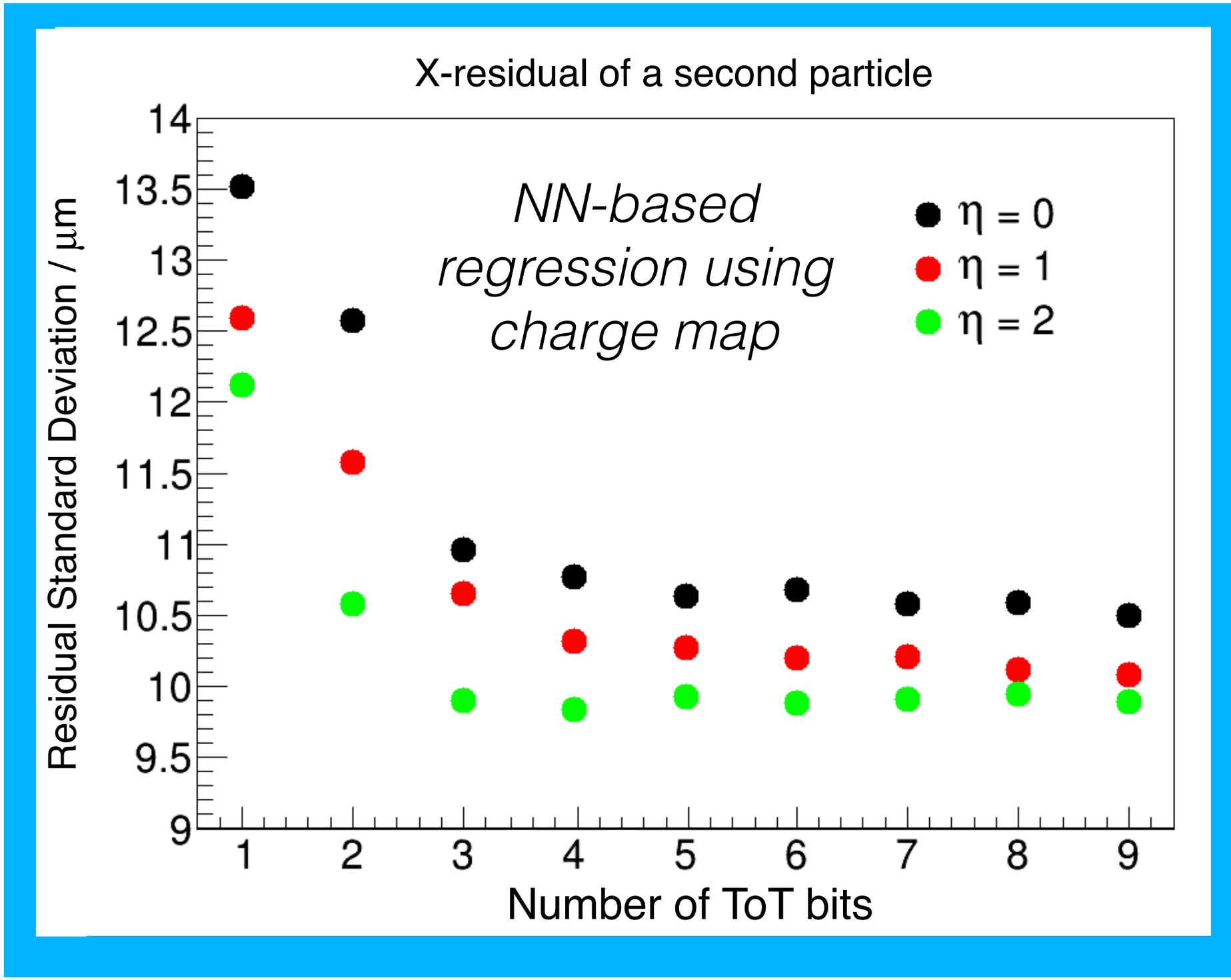




ceiling: $1/\sqrt{12} \sim 0.29$

Resolution: two-particle clusters

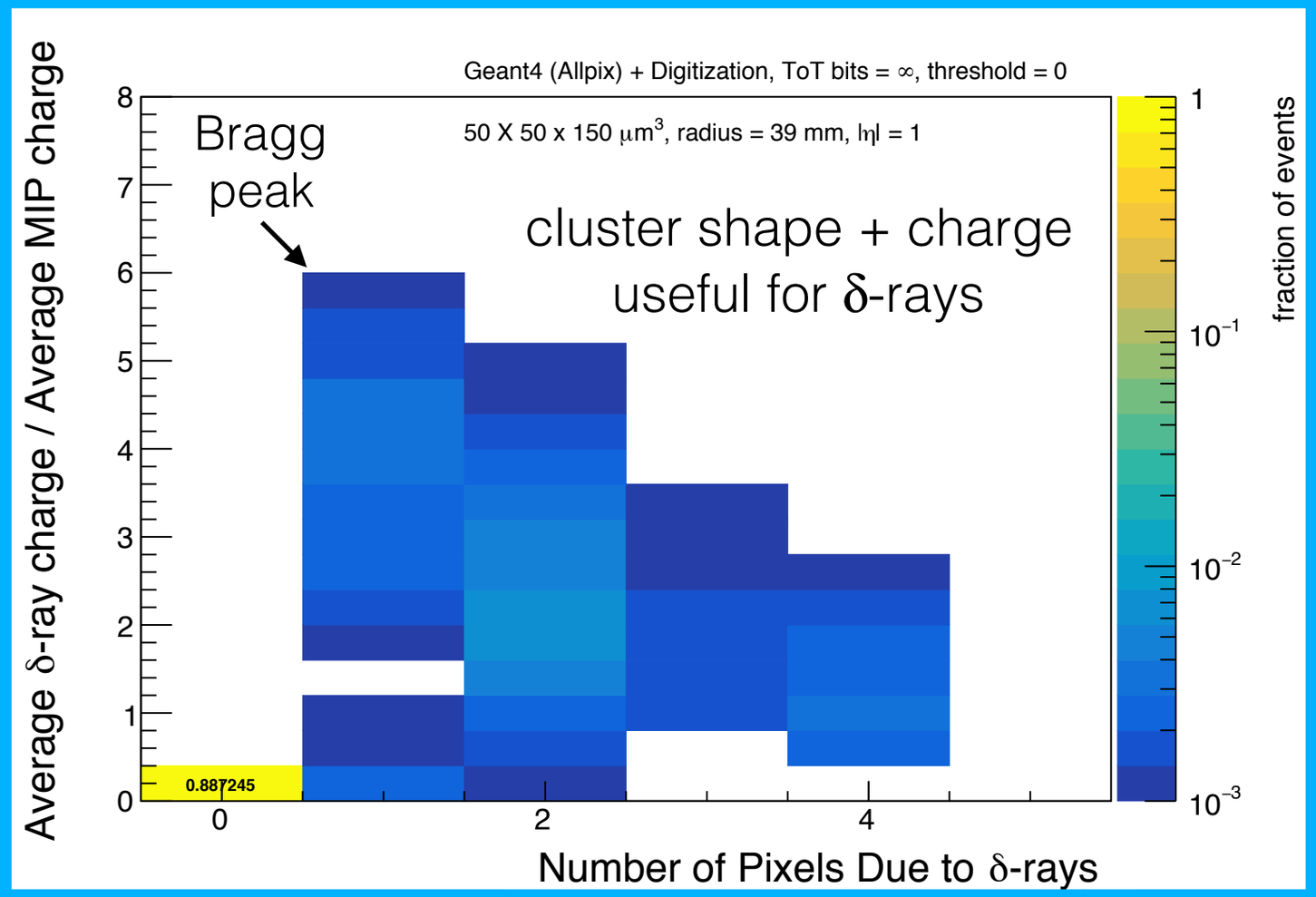
Worse than single clusters; saturates at ~3-4 bits



Particle Identification

Identifying δ-rays can improve resolution

Classifying π,p,k is interesting at low p_T



Searching for R-hadrons or other long-lived particles is a major on-going search effort

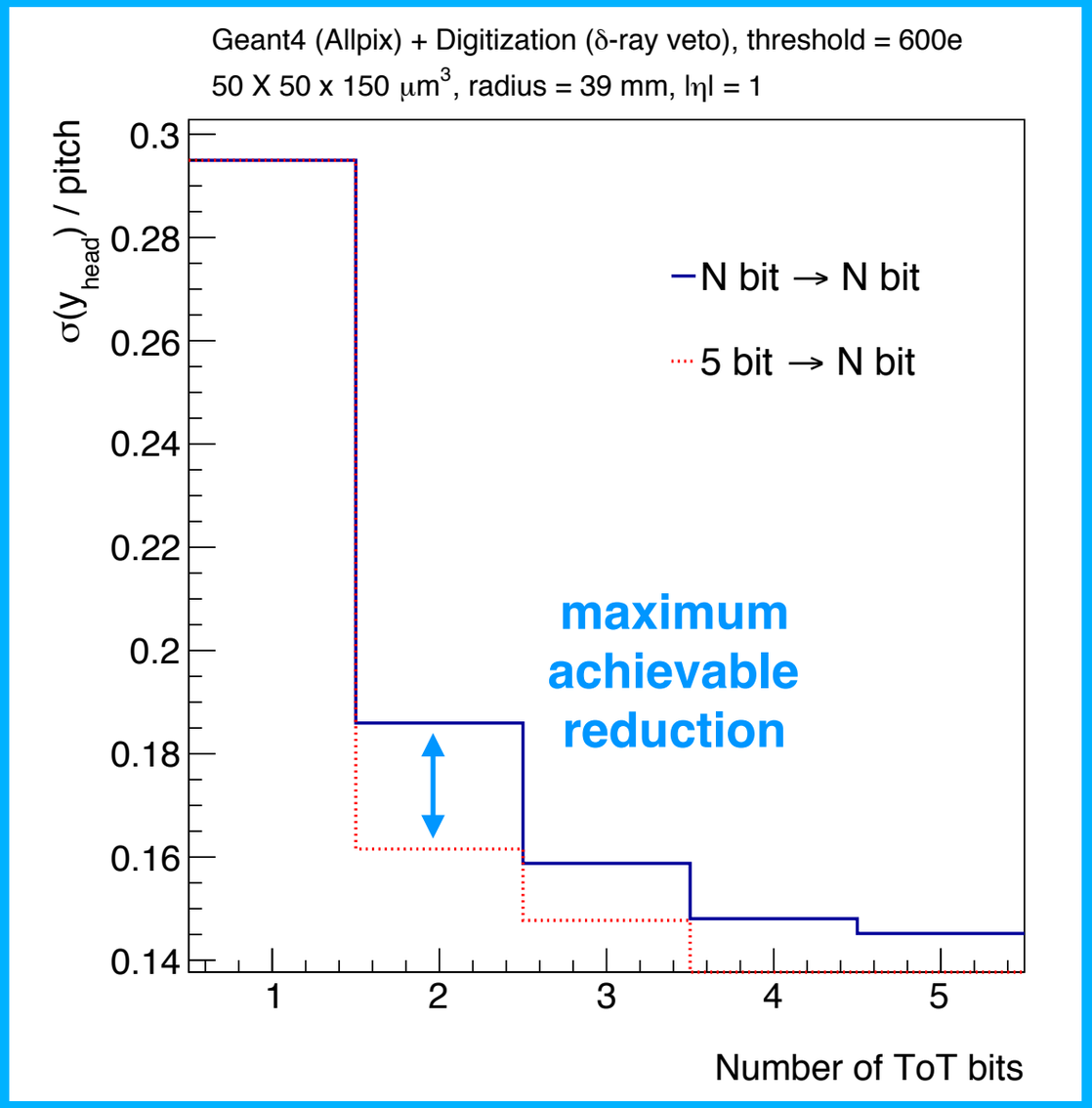
As such, need to ensure we preserve sensitivity with our choice of N bits.

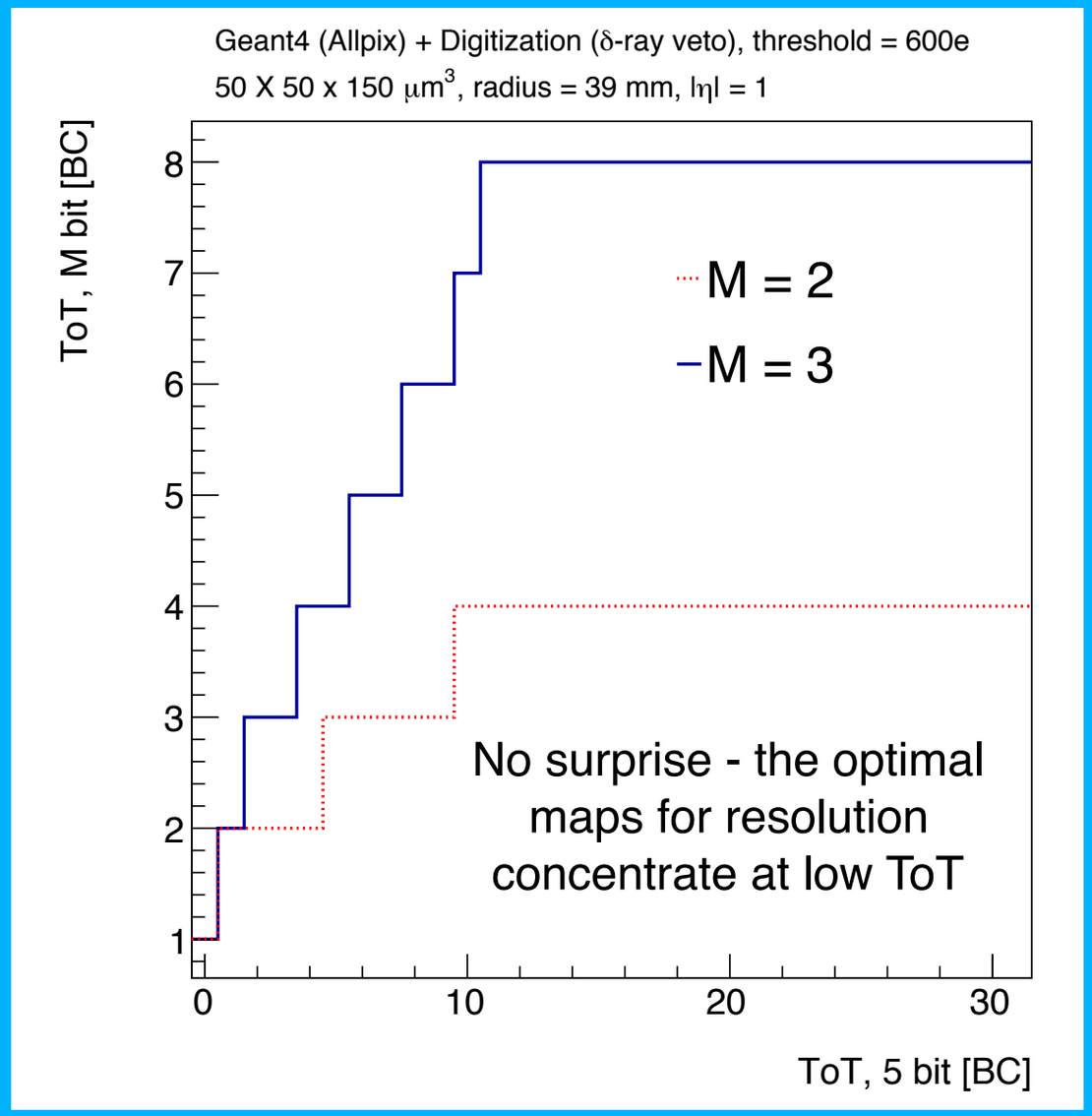
May even improve sensitivity with e.g. exponential charge to ToT scheme.

Down-sampling

Can add digital logic so that N digitized bits are stored as M ≤ N bits.

There are $\binom{2^N - 2}{2^M - 2}$ possible functions mapping N to M bits.





Additional encoding schemes

The usual paradigm is one ToT counter per pixel.

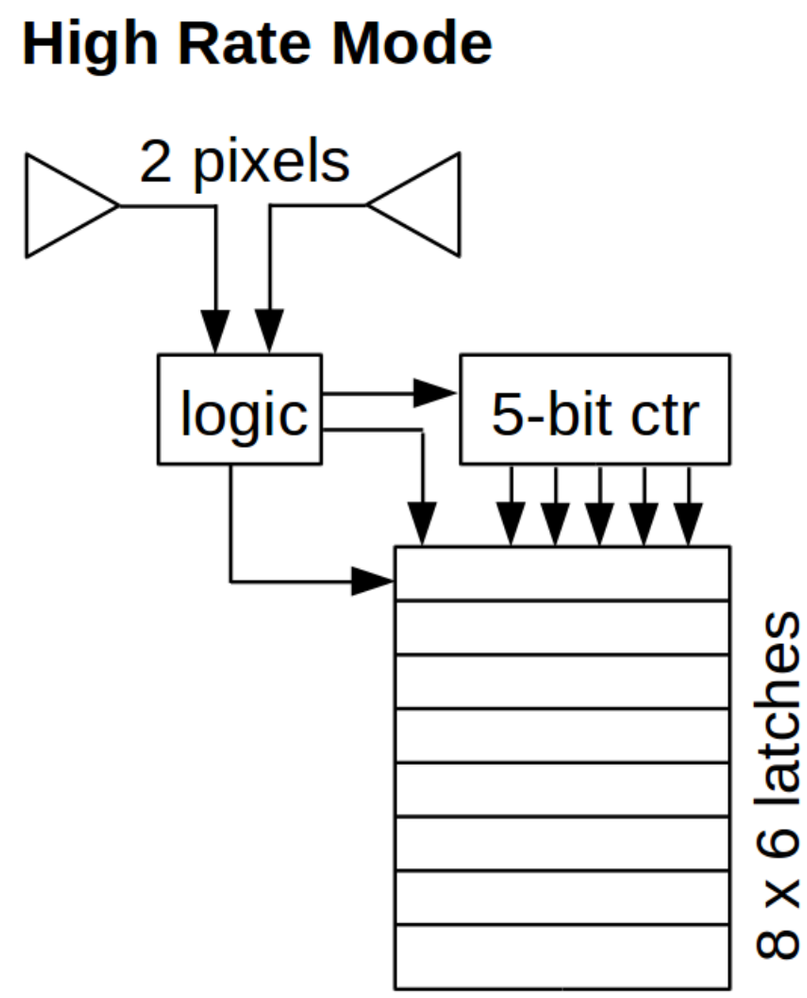
Can we save space by using one counter for two pixels?

Consider a scheme in which the sum is counted with 5 bits.

(N.B. this gives us a 1/2 bc time resolution)

In terms of ToT bits per area, this is better than the 4 bits for the ATLAS IBL and with less digital structure.

(N.B. can't separately tune 4 and 5 bit parts)



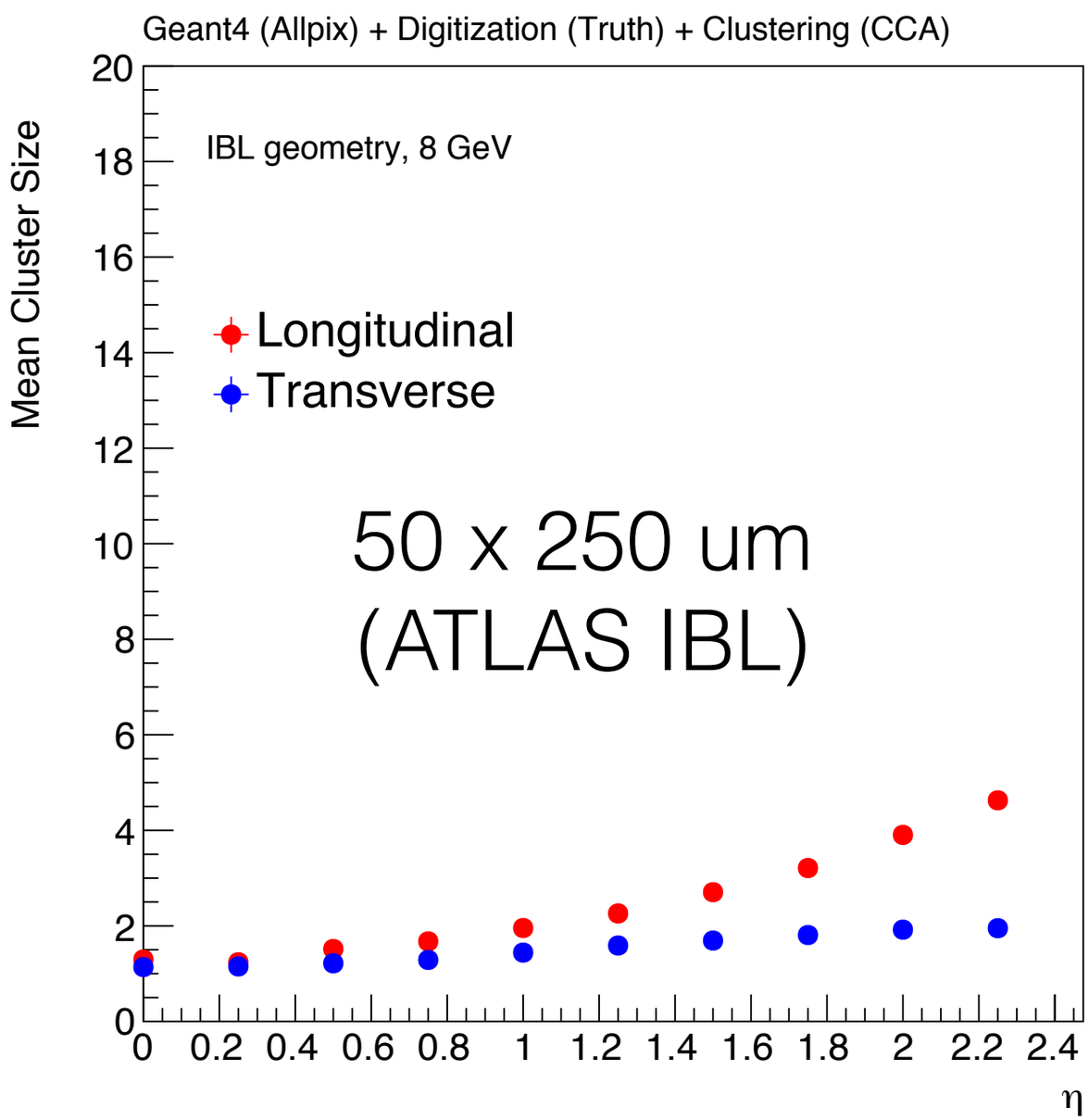
Both hit	1	5-bit ToT	
Left hit	0	0	4-bit TOT
Right hit	0	1	4-bit TOT

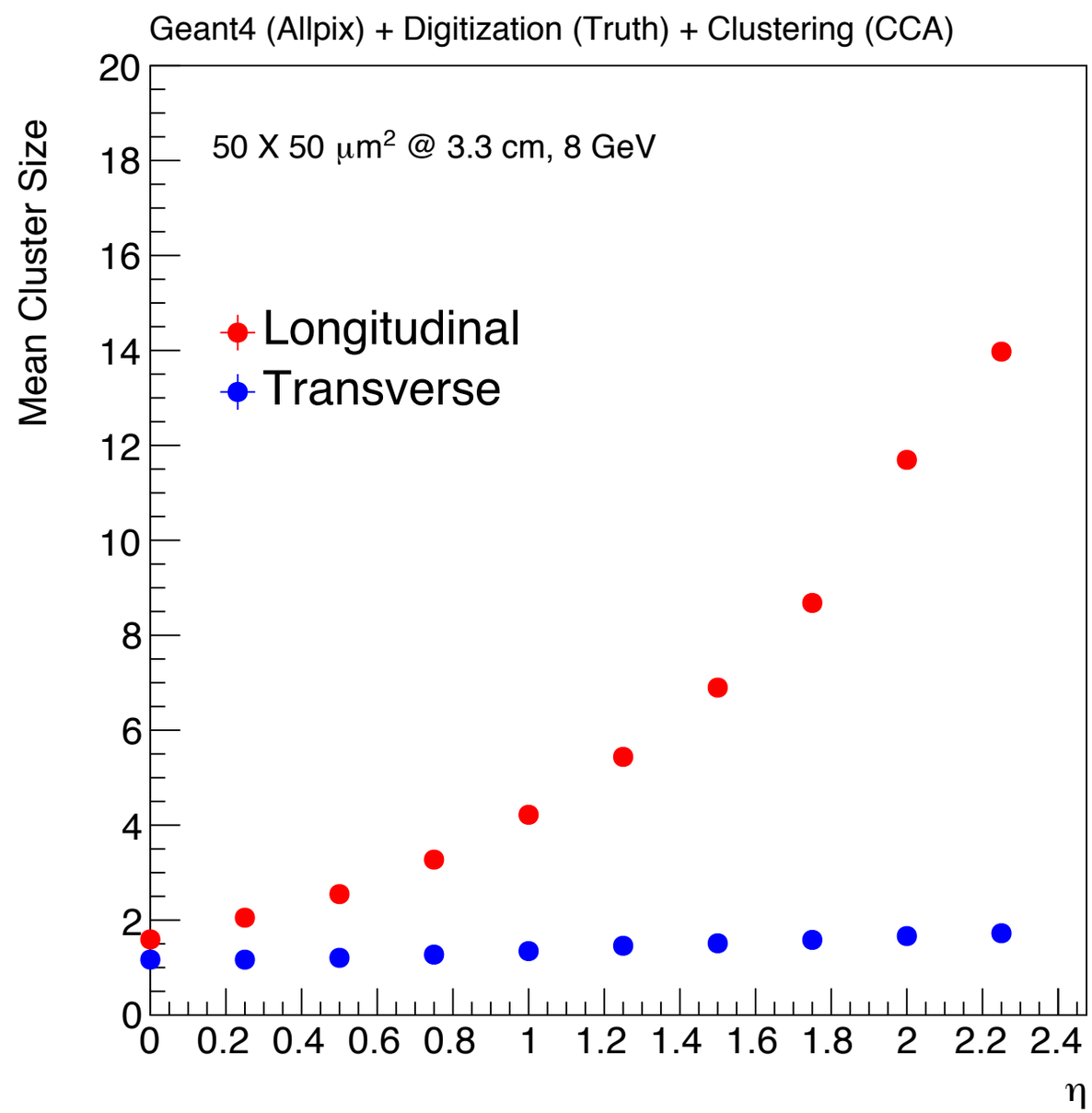
More on the theme: neighboring pixels

ATLAS currently reads out 2 x 2 regions around hit pixels

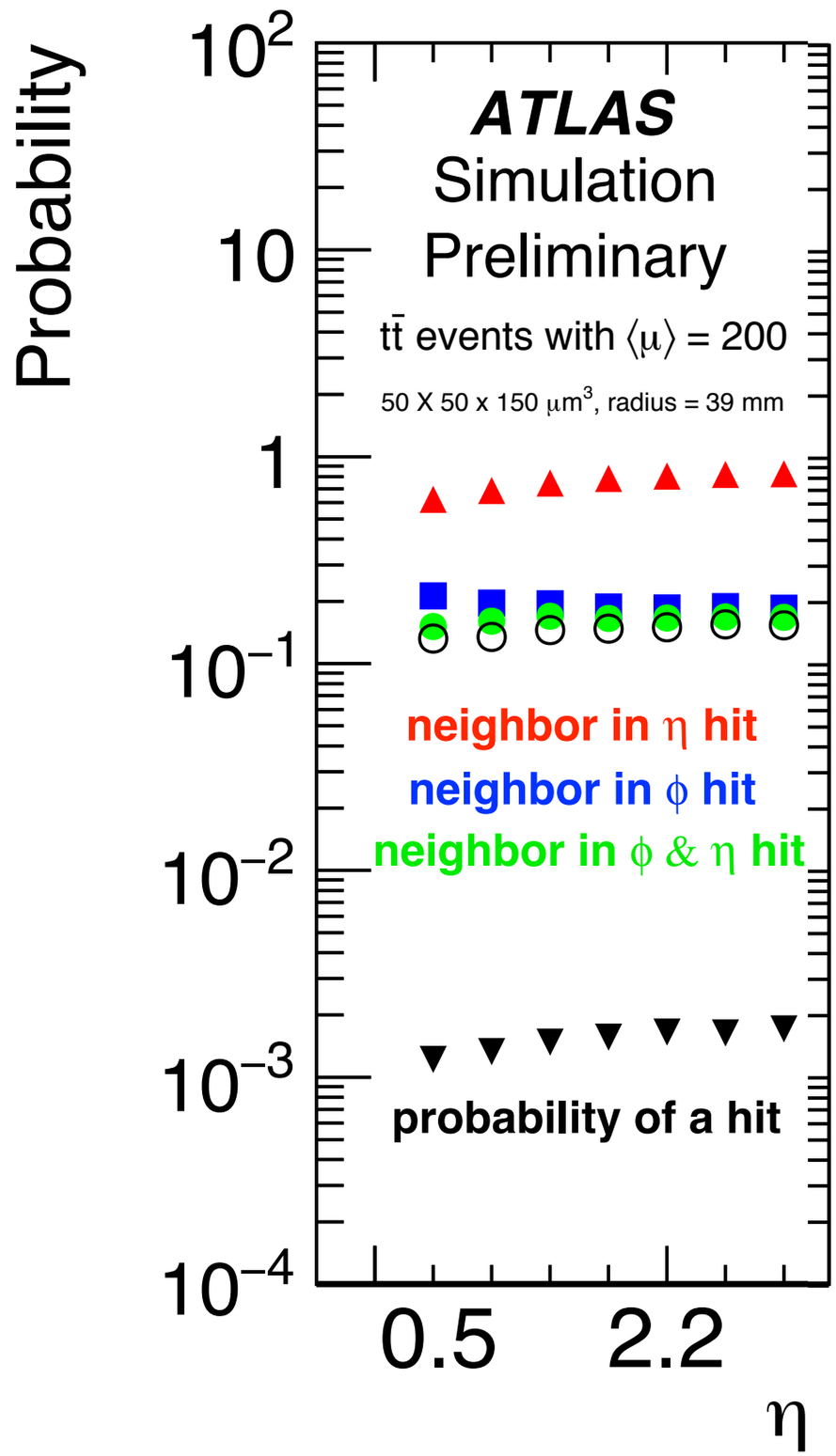
-helps recover low charge hits

Is this still optimal with smaller pixels?

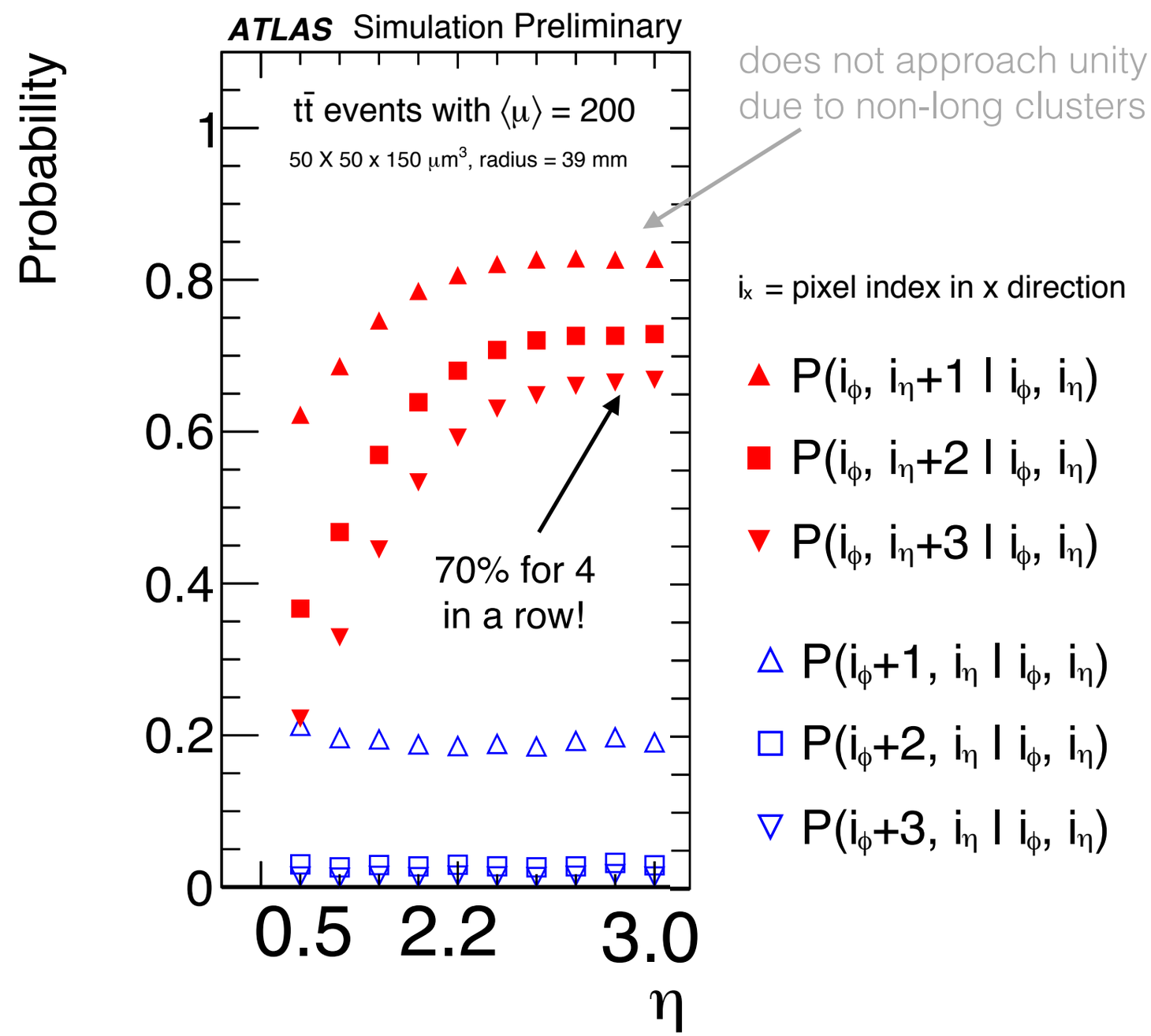




How to group hits for storage and readout



The neighbor occupancy is well above background: useful input for the hybrid ToT from earlier



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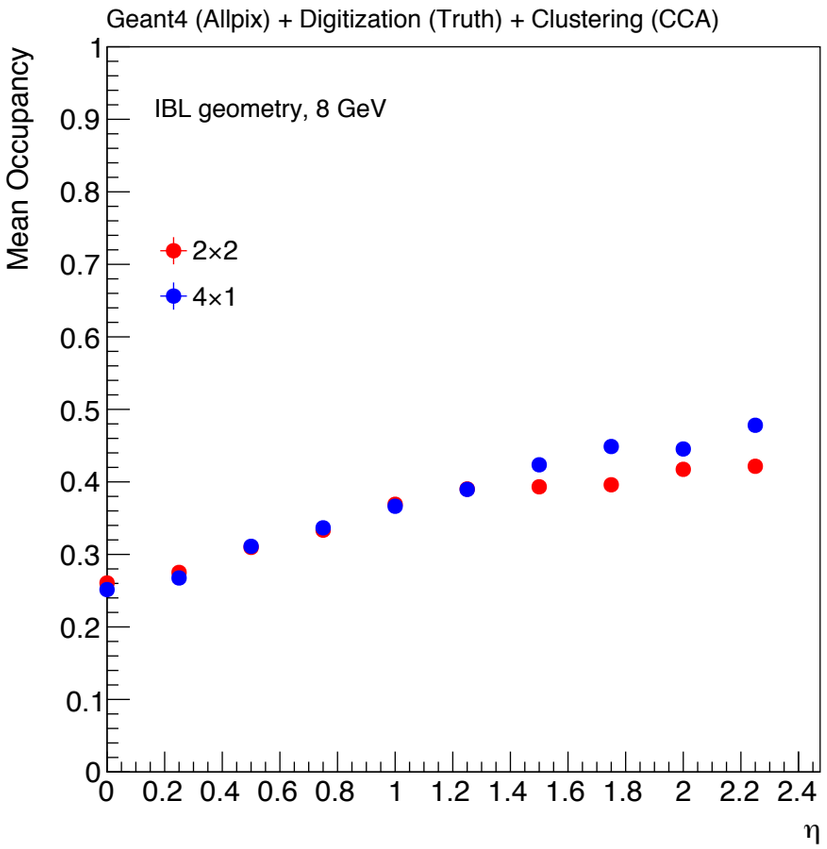
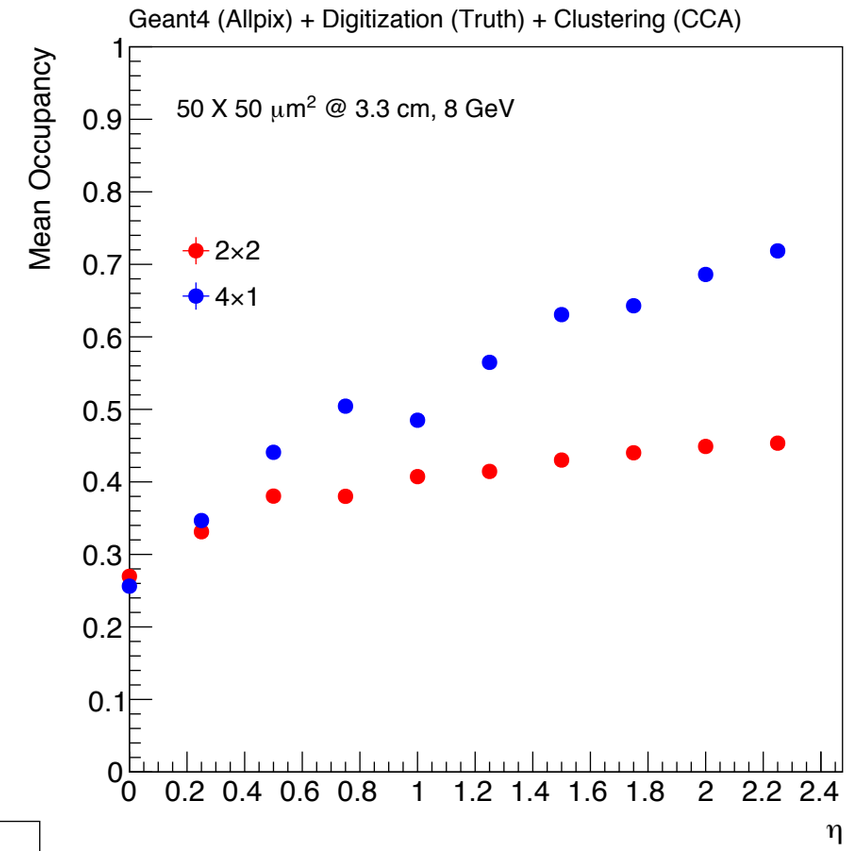
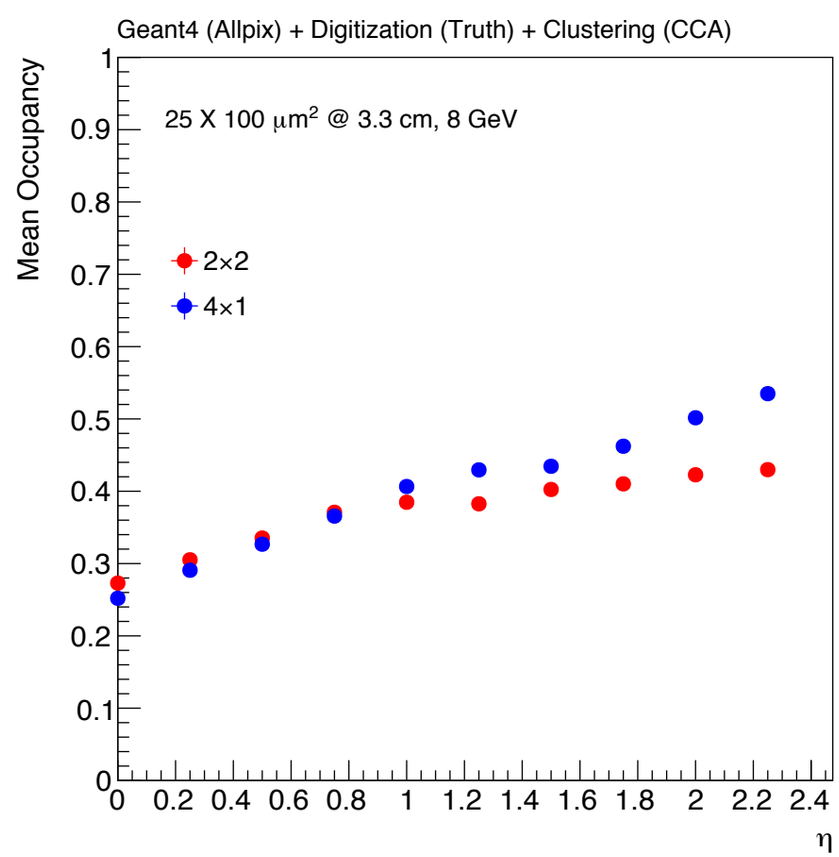


A simplified analysis
(not full physics sim)





2 x 2 fine for Run 1

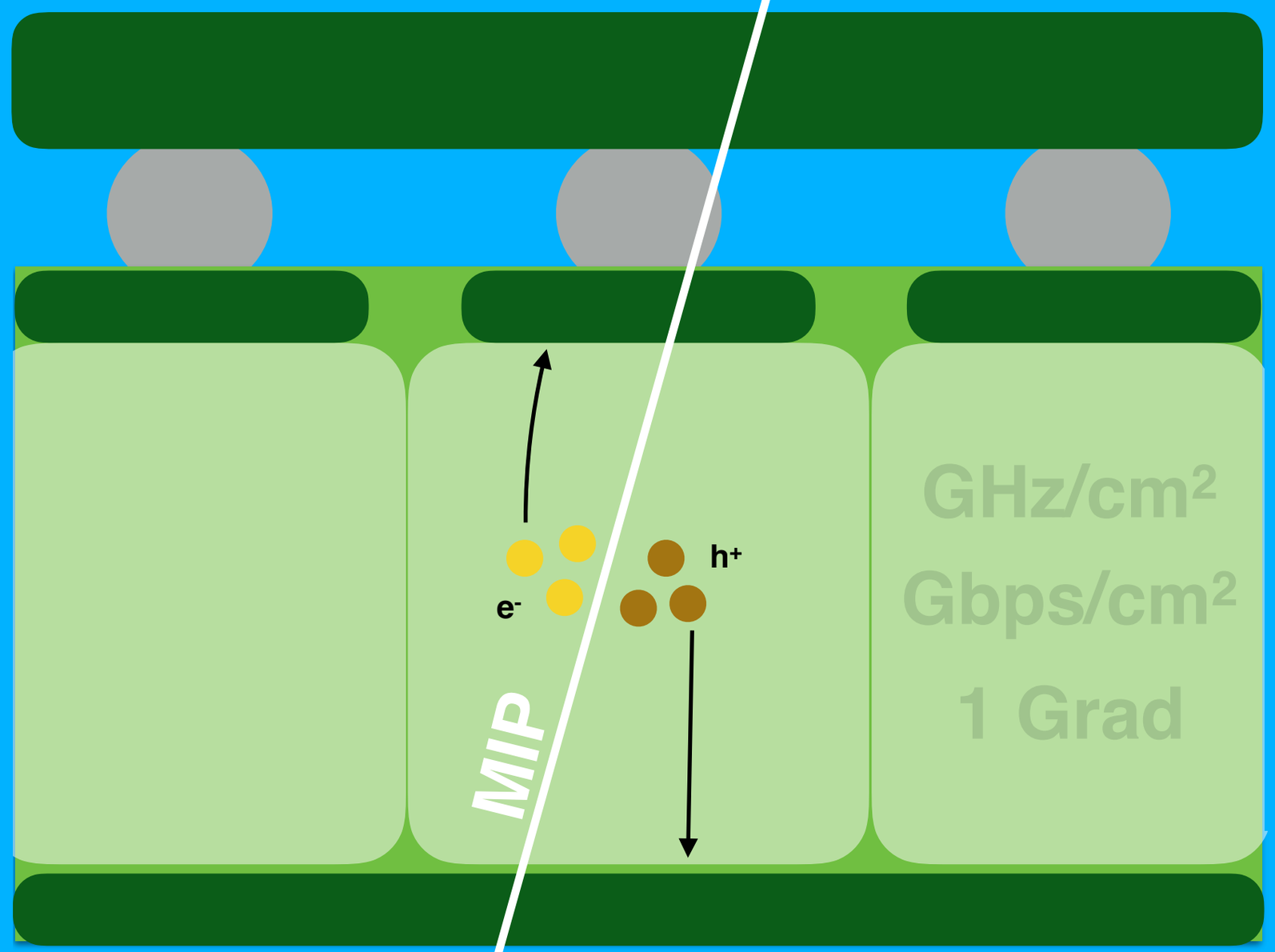
4 x 1 likely (much) better for HL-LHC (maybe even bigger?)

Conclusions / outlook

Preliminary studies suggest that **4-5 bits** is likely sufficient to maintain performance at the HL-LHC

Several studies still on-going

RD53A is currently under design, but we will iterate more; now is the time to ensure an **optimal use of charge for the HL-LHC!**



BACKUP

Gbps /cm^2 * 50 microns * 50 microns in kbps

=25 kbps

http://www.shoutcheap.com/mono-vs-stereo/