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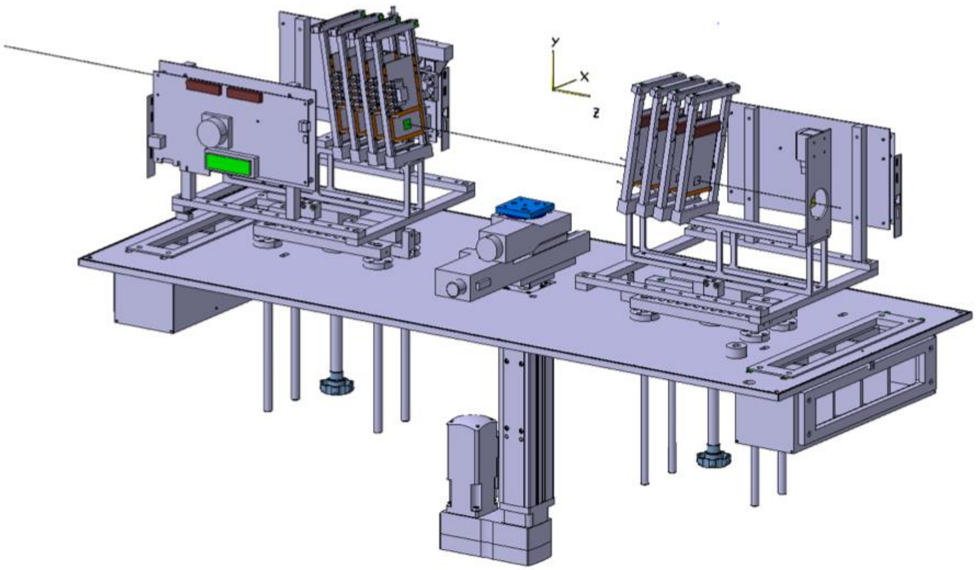
Advanced UK Instrumentation Training 2024



◆ **Testbeams**

Prof. Jaap Velthuis

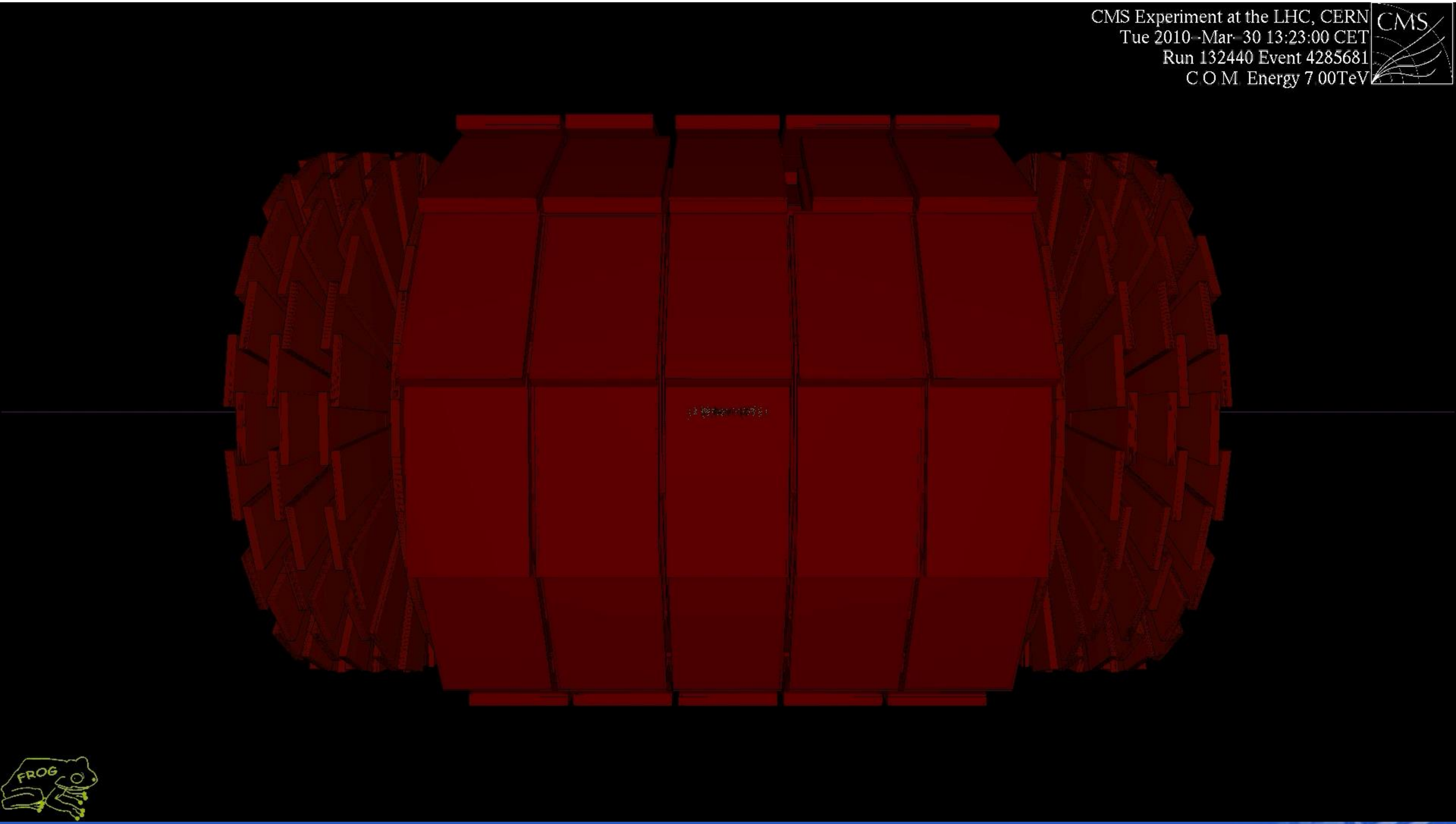
Testbeams

- Why testbeams?
- The key underlying issues of a testbeam
  - Efficiency & Purity
  - Error on the predicted position

- Different facilities and their good and bad points
- Experimental issues

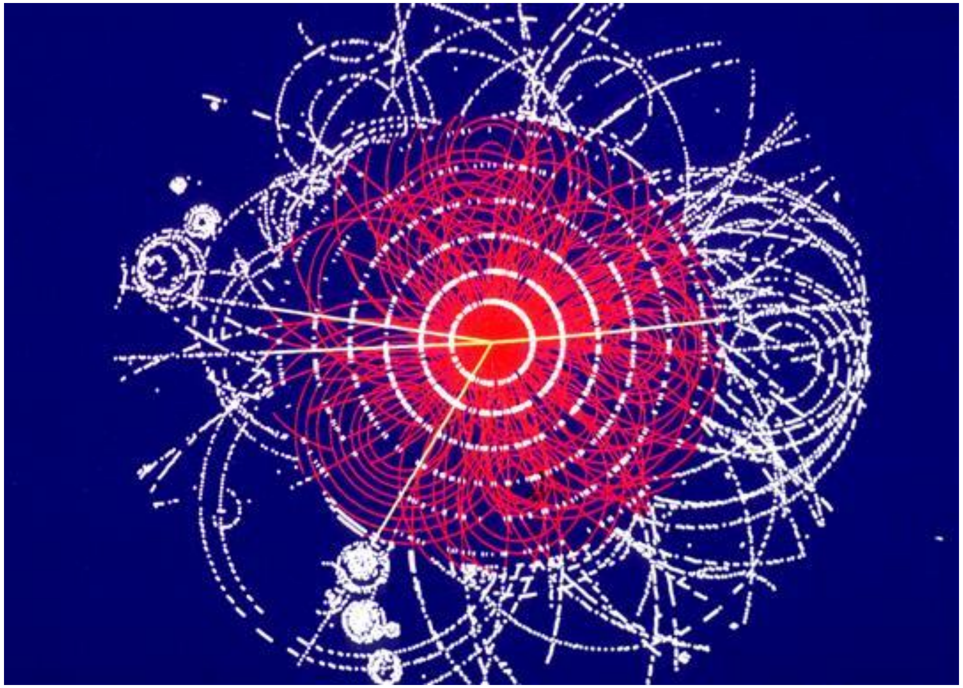
- Lecture block after this is on hit and track reconstruction, so will not go in detail into algorithms here.

Let's start at the end…



What did you see?

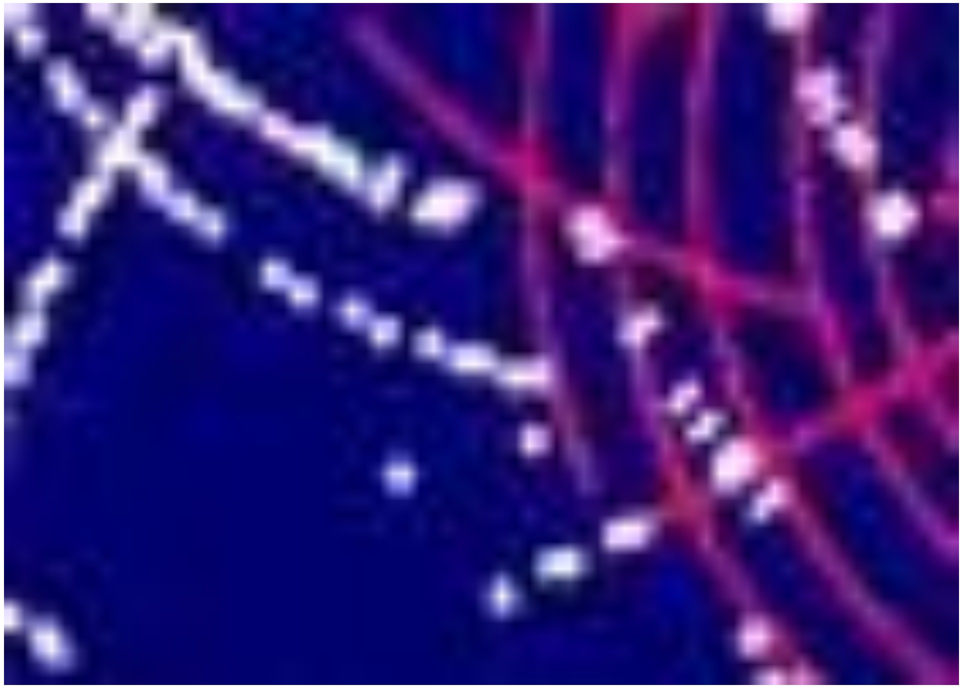
- You see dots lighting up.
  - Sometimes due to noise
  - Sometimes due to traversing particles



What did you see?

- You see dots lighting up.
  - Sometimes due to noise
  - Sometimes due to traversing particles
- Then you connect the dots and you are doing particle physics….

- Key question to ask
  - Did the dot light up due to a particle or noise?
- Secondary question
  - How certain are you of the hit position?



Hit or noise?

- Need to understand signal and noise
- Many ways to test this
  - Laser
  - Radio-active sources
  - Cosmics
  - Test charges/pulses
- All come with issues
  - Was there actually a particle or input pulse?
  - Where on the sensor?
  - Are the input charges representative of actual particles?

- It is all about efficiency and purity.

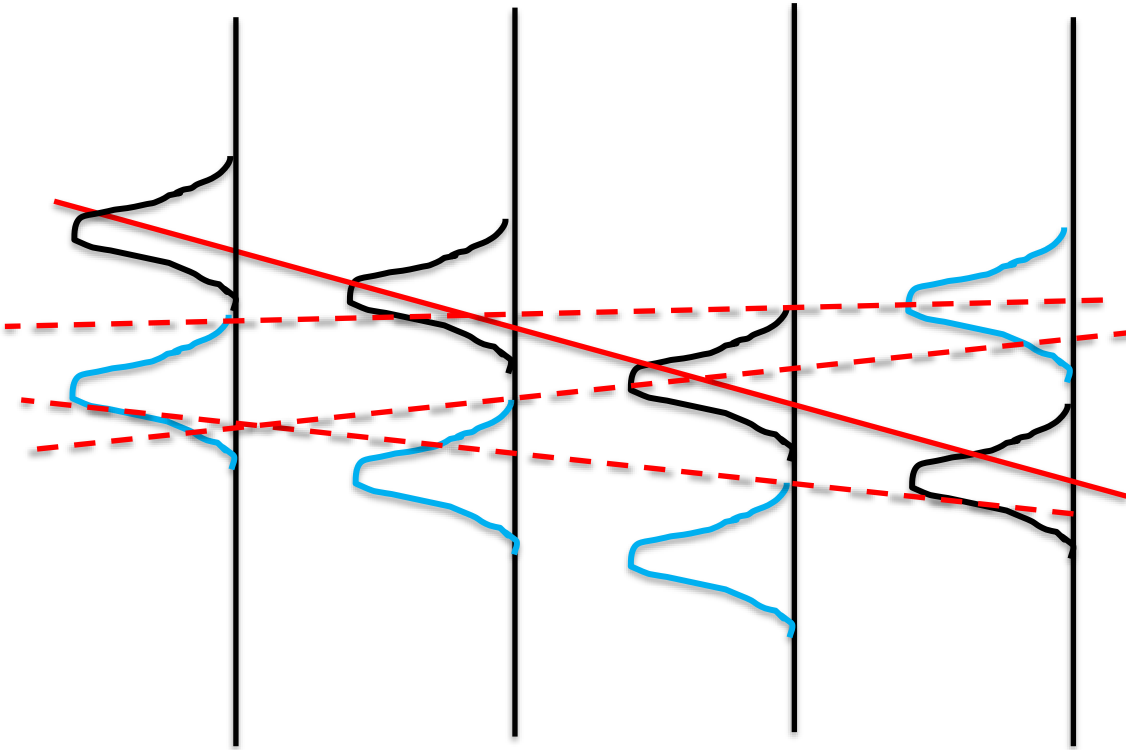
Efficiency & Purity

- Efficiency
  - If a particle traverses your detector, do you see it?
- Purity
  - If you see a hit, was it a particle?

- Getting efficiency & purity right is VITAL for experiments.
  - The job of a tracker is to reconstruct tracks.
  - Only few layers available (~<10). Track has 3 parameters.
  - Many tracks close to each other; large scope for confusion.

Tracking

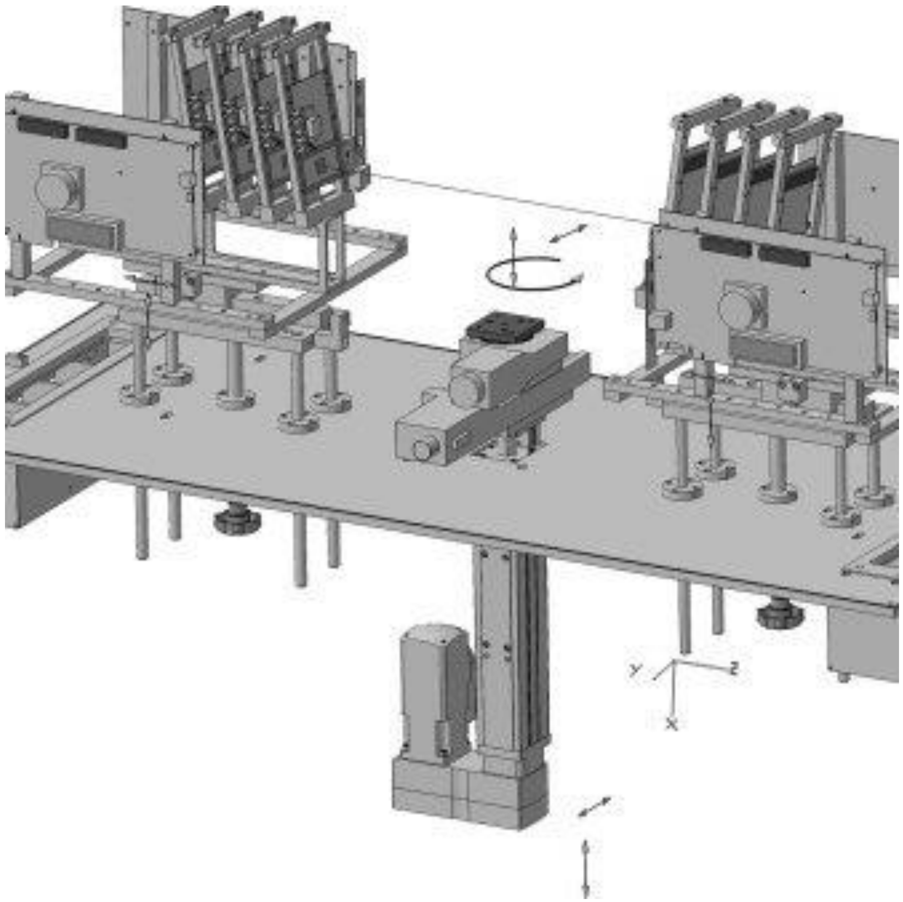
- Good efficiency and high purity means easy tracking.
- Good efficiency and bad purity make tracking difficult.
- Bad efficiency and good purity make tracking difficult.
- Bad efficiency and bad purity make it impossible.
- Do you notice that I can live with bad purity? This allows to use a low threshold and thus improve the efficiency. The track fit will clean things up.



Why a testbeam program?

- Measure efficiency & purity
- Fire particles at the sensor under test
- Reconstruct the incoming particle position with other detectors (a telescope).

- Ultimate test of a sensor system
  - Puts down a clear marker that the system works!
  - Know where particle hits the sensor
  - “Only” way to measure efficiency & purity



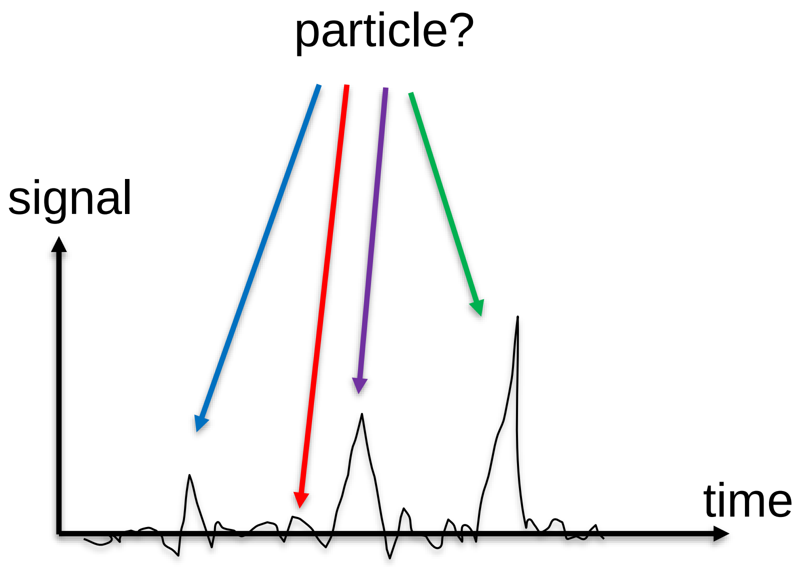
Main aims of a testbeam

- Measure key parameters of sensors
  - **Efficiency & Purity**
  - Signal to noise ratio
  - Position resolution
    - Optimize position reconstruction algorithms
  - Cluster sizes
  - Charge sharing
  - In-pixel variations
  - …
- And debug DAQ systems
  - Some groups even built their entire detector by testing all modules in the beam test

Efficiency and purity

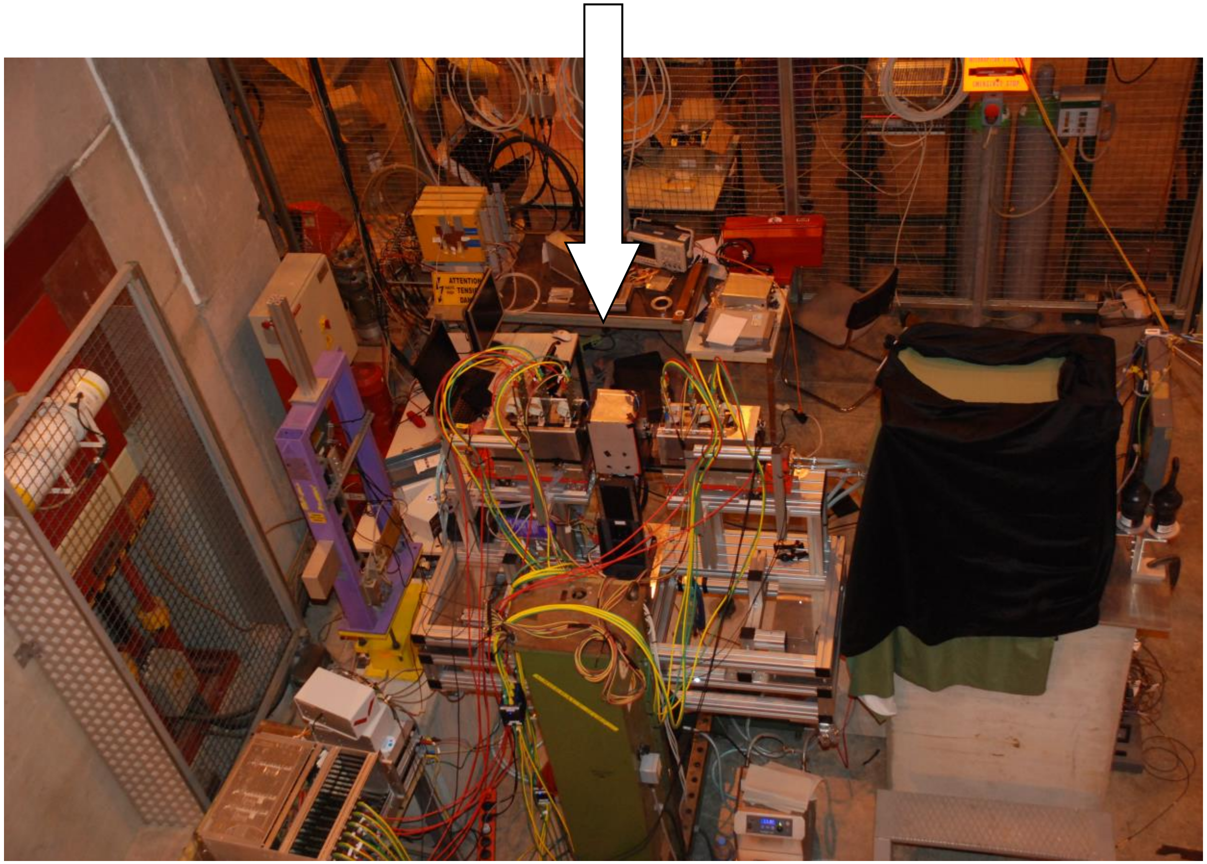
- Efficiency and purity are the **MOST important** parameters for a detector.
  - Efficiency: if a particle goes through a detector, does the detector record it?
  - Purity: if a detector records a particle, was it actually a particle?
- Which arrow points at a particle?
  - How can you tell?

- You cannot! It is a statistical thing: you can evaluate the probability.



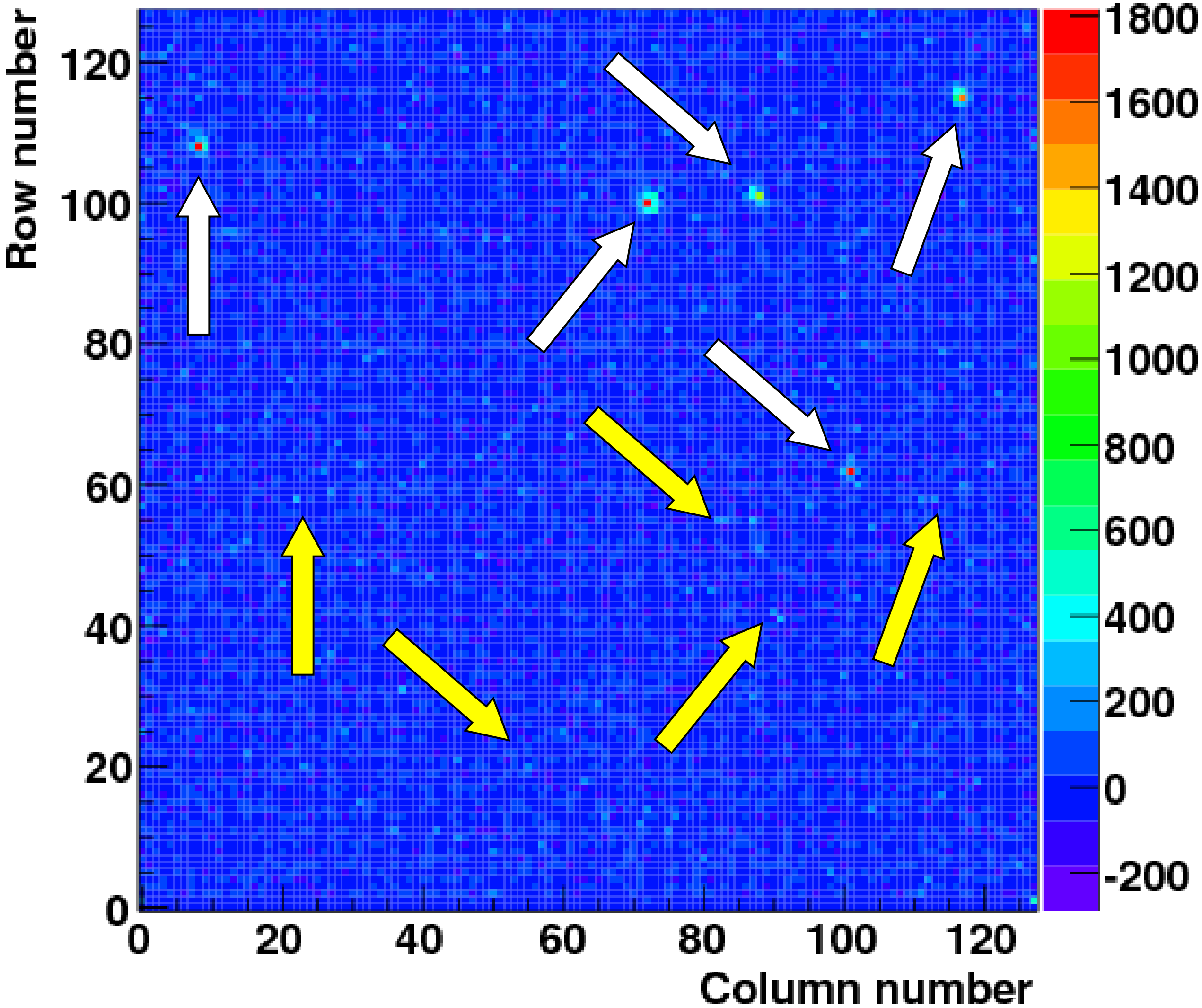
An example: FORTIS

- We fire particles and measure where they go.
  - pion beam



An example: FORTIS

- Here you see an event
- Do you think we see hits?
- And what about those?

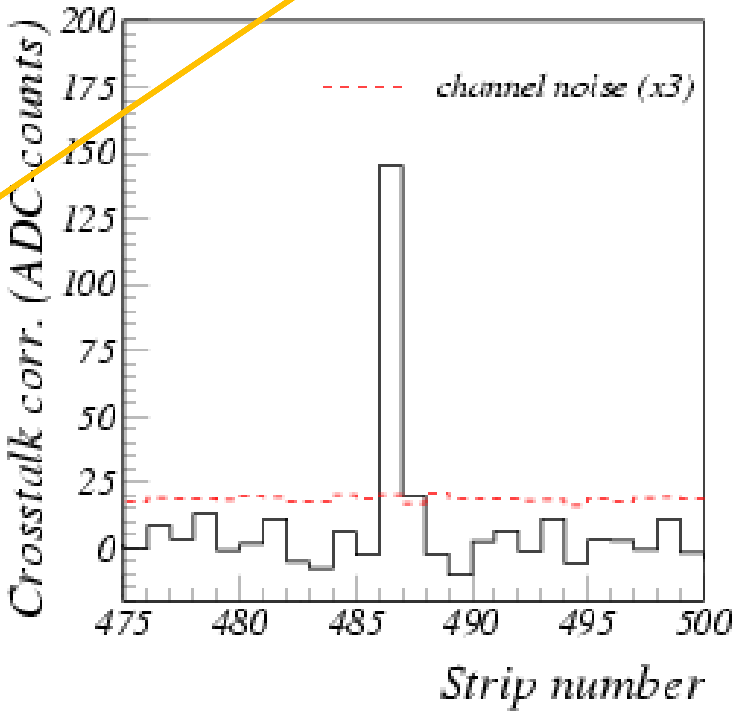


Raw data reconstruction

event *i*
channel *k*

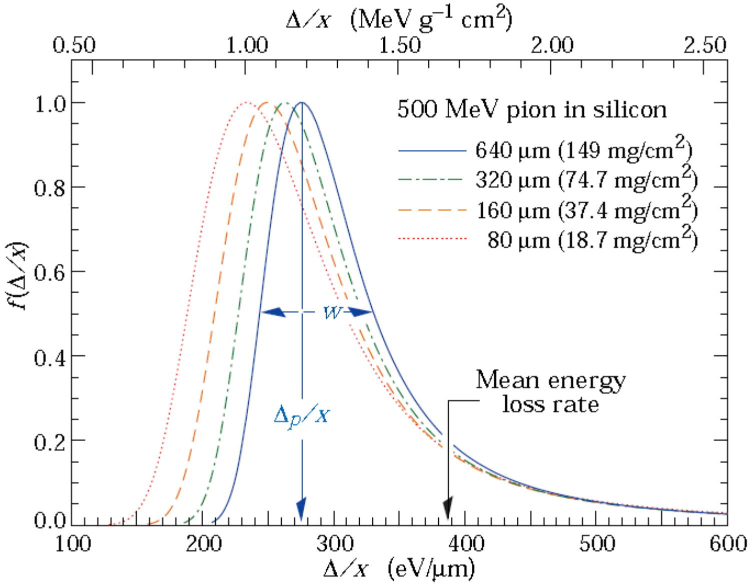
$$raw(i,k) = ped(k) + n_{random}(i,k) + n_{common}(i,k) + q(i,k)$$

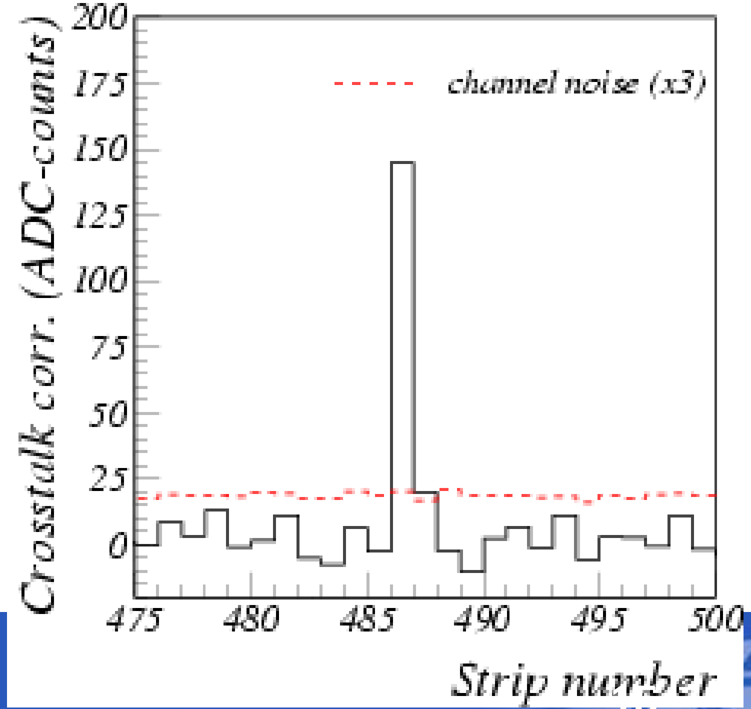
- Every channel has own offset (pedestal) and gain.
- Due to fluctuations in ground voltage, all channels show common behaviour in each event (common mode)
- Each channel own random noise
- Some channels carry signal



Cluster language

- The signal from a minimum ionizing particle follows a Landau distribution.
  - Gaussian with a tail to the right.
- The signal is shared between neighboring strips (or pixels) and some gets lost.
  - Seed strip (pixel) is the signal with the highest signal.
  - Neighbors are all other pixels that are part of the cluster.





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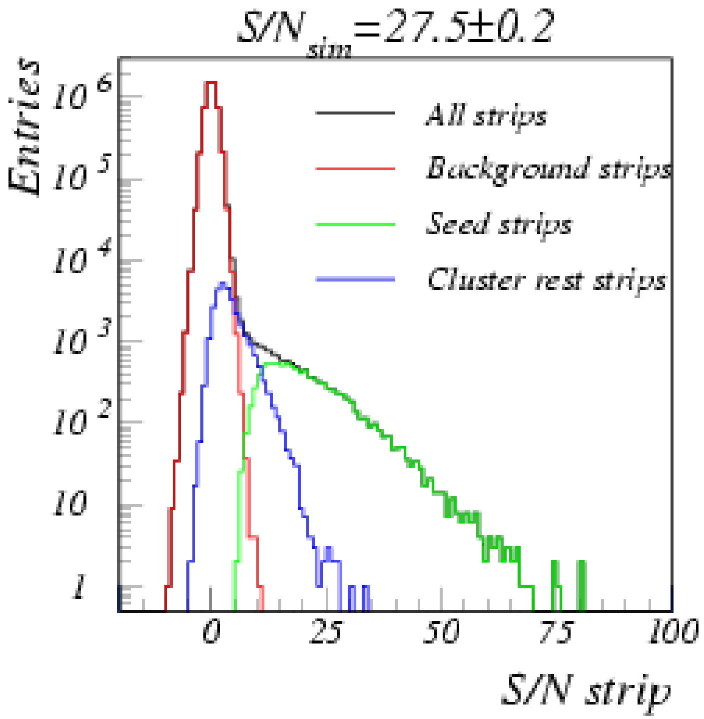
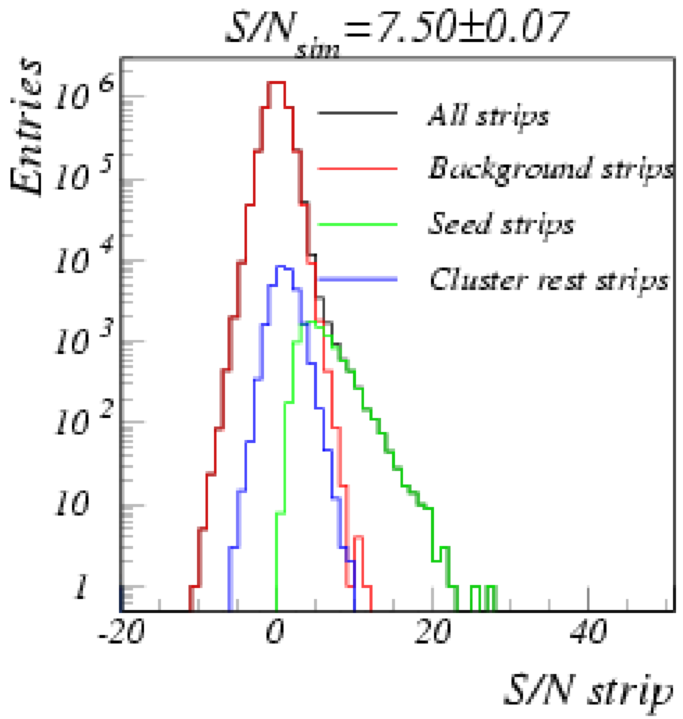
Signal or noise?

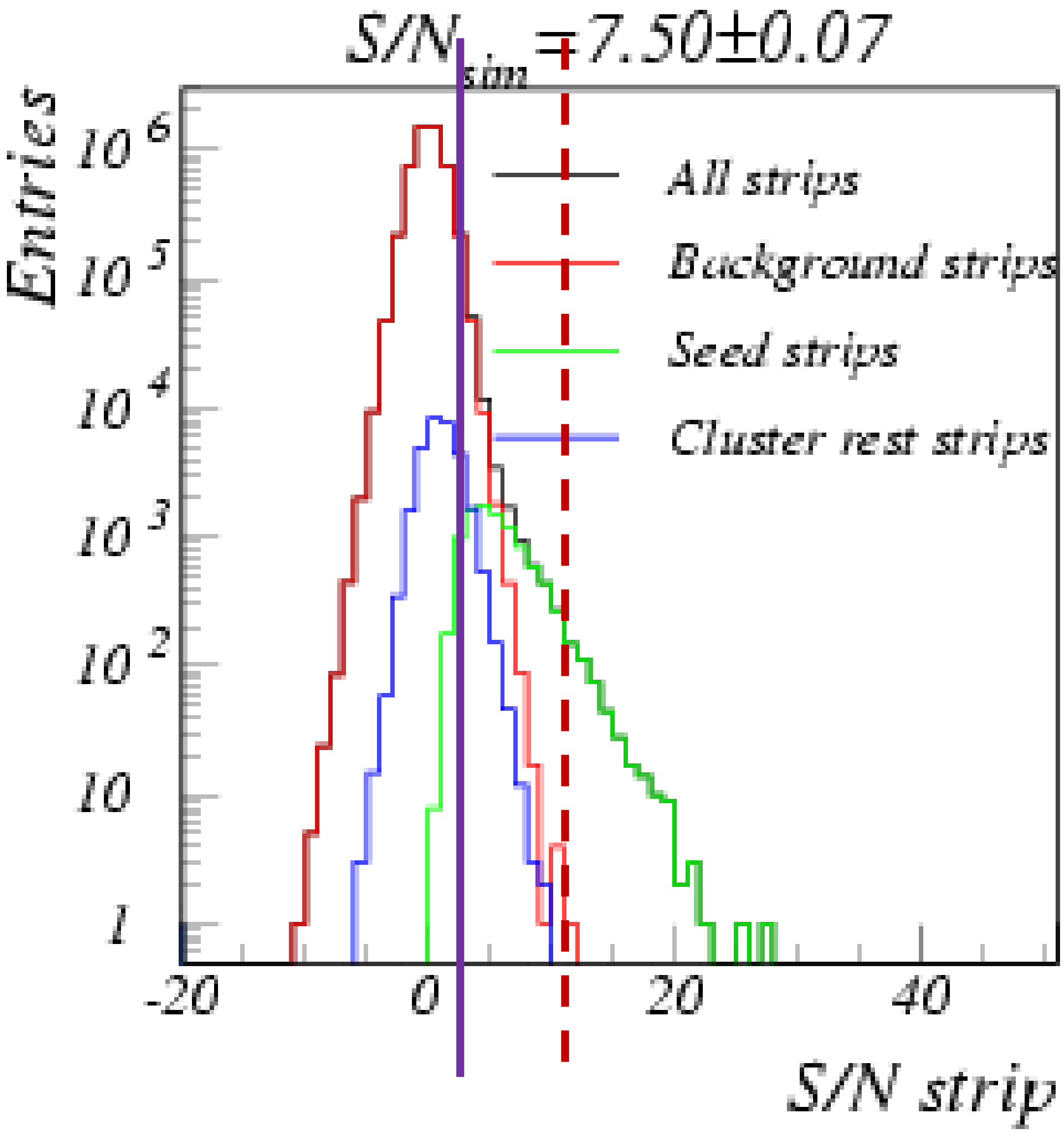
- Hits are selected based on either signal or signal/noise.
- Need to set a threshold. E.g. S/N_{seed} > 5noise.
- Defines how many real hits and how many fakes are found.



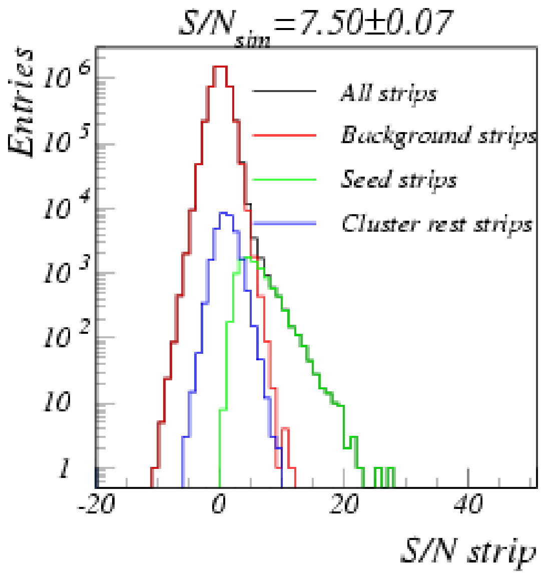


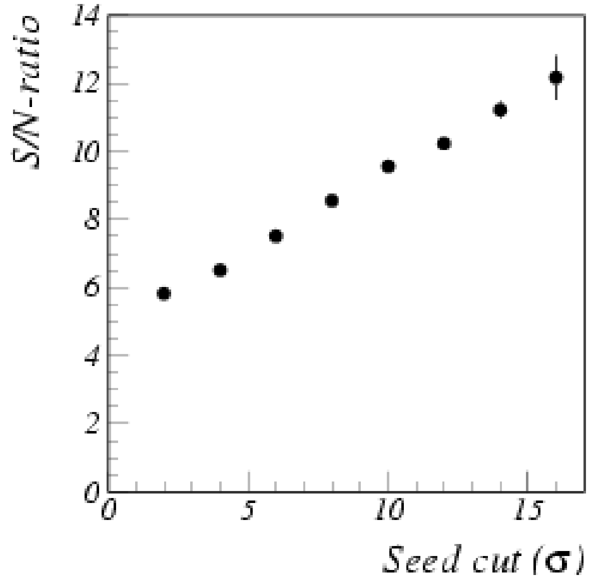
Signal or noise?

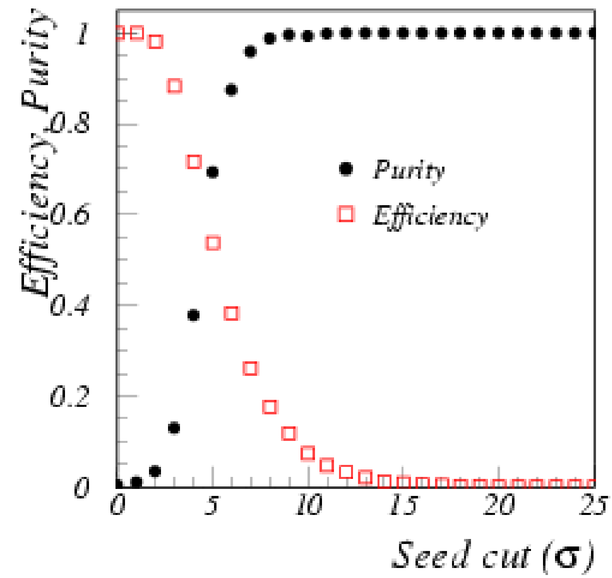
- Hit selection cut defines how many real hits and how many fakes are found.
- For dotted line
  - hardly any fake hits left, so excellent purity, but missing lots of real seeds, so bad efficiency.
- For solid line
  - Lots of fake hits left, so bad purity, but found almost all real seeds so excellent efficiency.



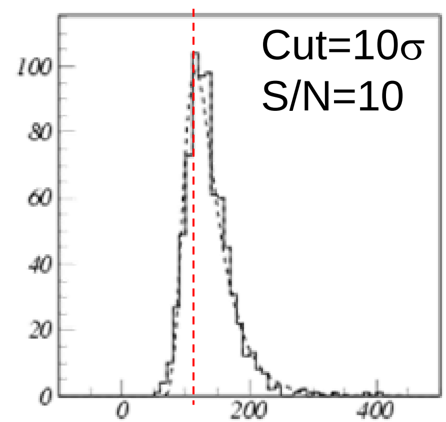
Signal or noise?

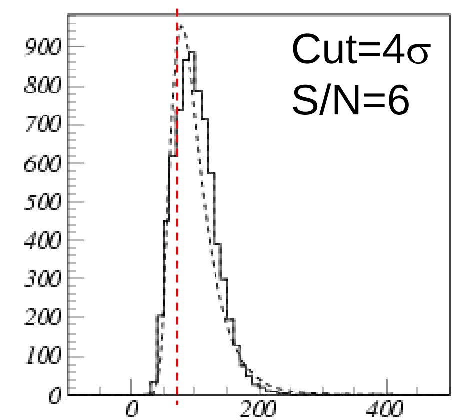






- Seed cut is compromise between efficiency and purity.
- It also affects measured properties like S/N and position resolution!
  - Can fabricate excellent performance by selecting a bad seed cut.





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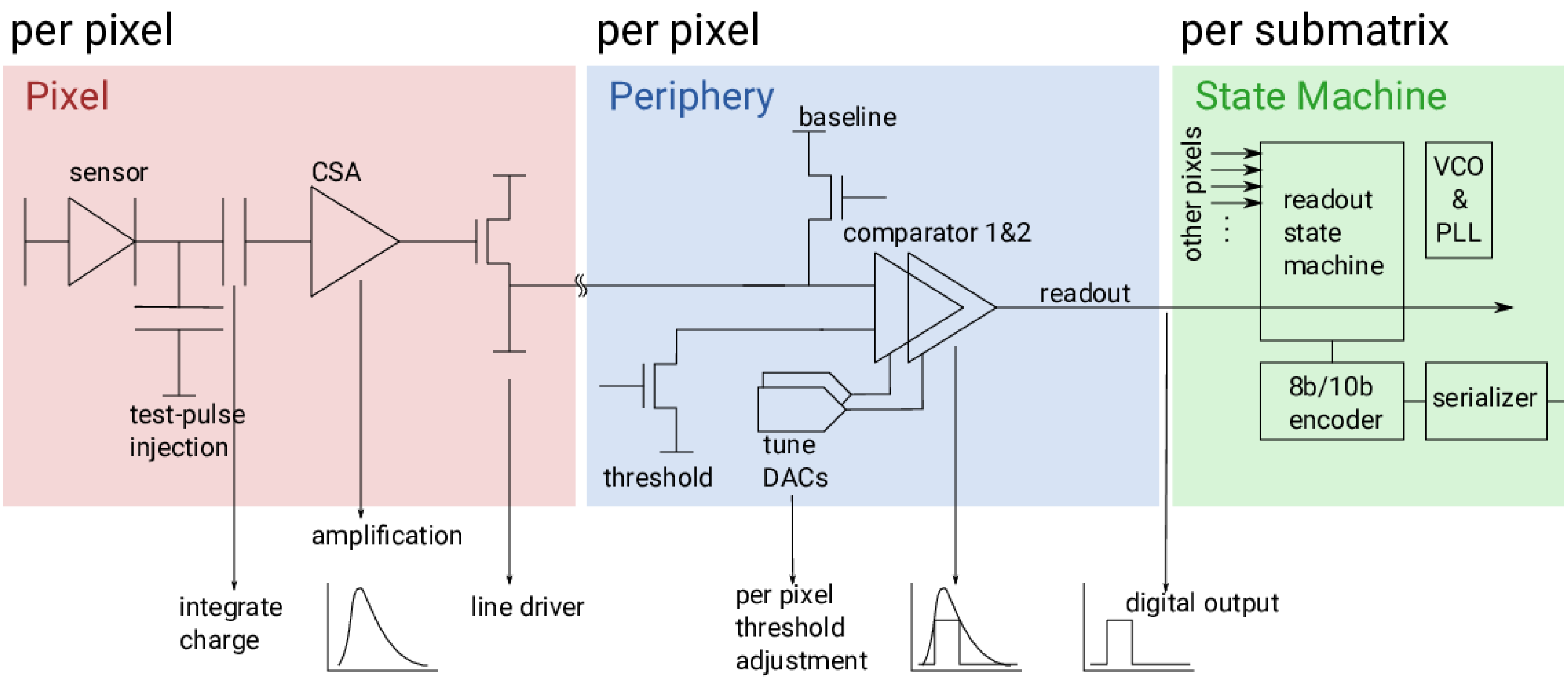
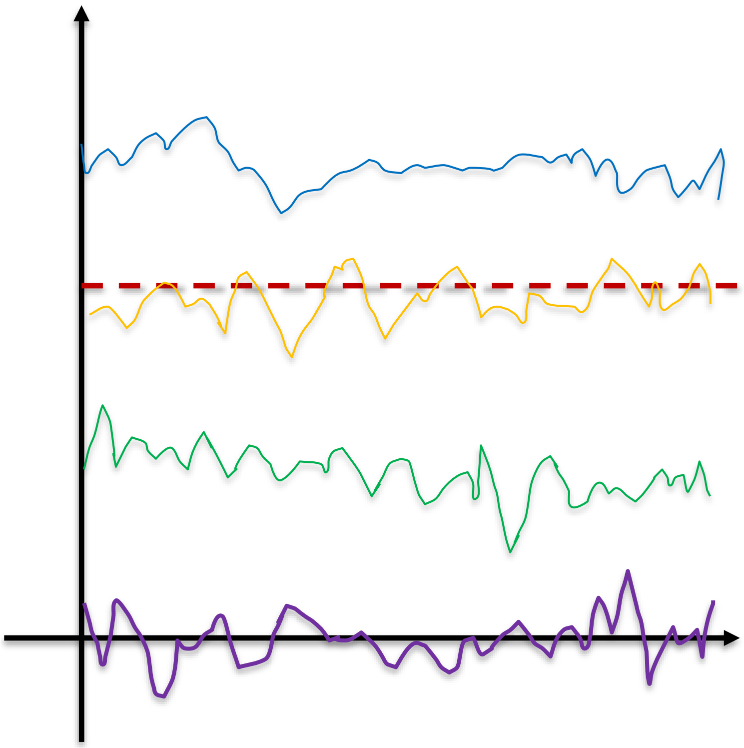
Binary or ToT sensors

- Binary or ToT sensors
  - have a similar frontend
  - signal components the same but only read out if a hit is registered
    - every pixel has a discriminator that needs to be tuned



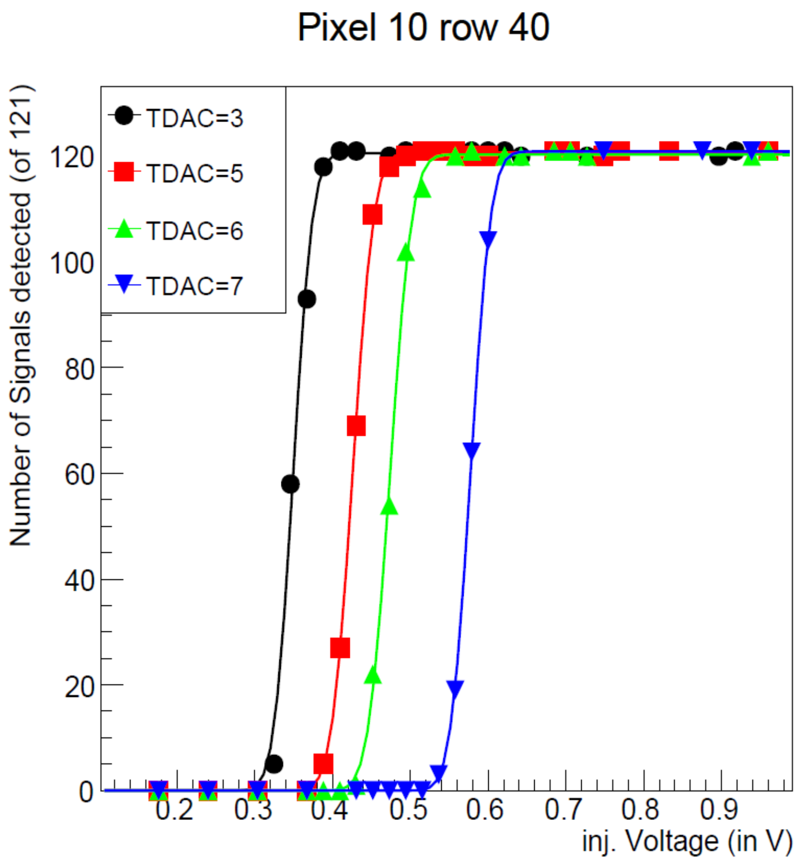
Binary or ToT sensors

- The threshold is fixed but there is a channel by channel offset.
  - This needs to be tuned, similar to seed cut.
- Tuning
  - Insert fixed number of test pulses and change amplitude of the pulses.
  - Count how many over threshold.
  - Repeat for different offset
- The counting integrates the noise.



Binary or ToT sensors

- Integrated random noise gives an error function.
  - Fit to extract the noise
- Now decide your operating point
  - What efficiency do you want for what input signal?
  - Same principle as the offline seed cut, you just cannot directly see it.



Measuring Efficiency & Purity

- Key issue: need to define what is a good hit
  - Track needs to point at it
  - Need to define what a good track is and how close the match needs to be.
    - Will get back to that.

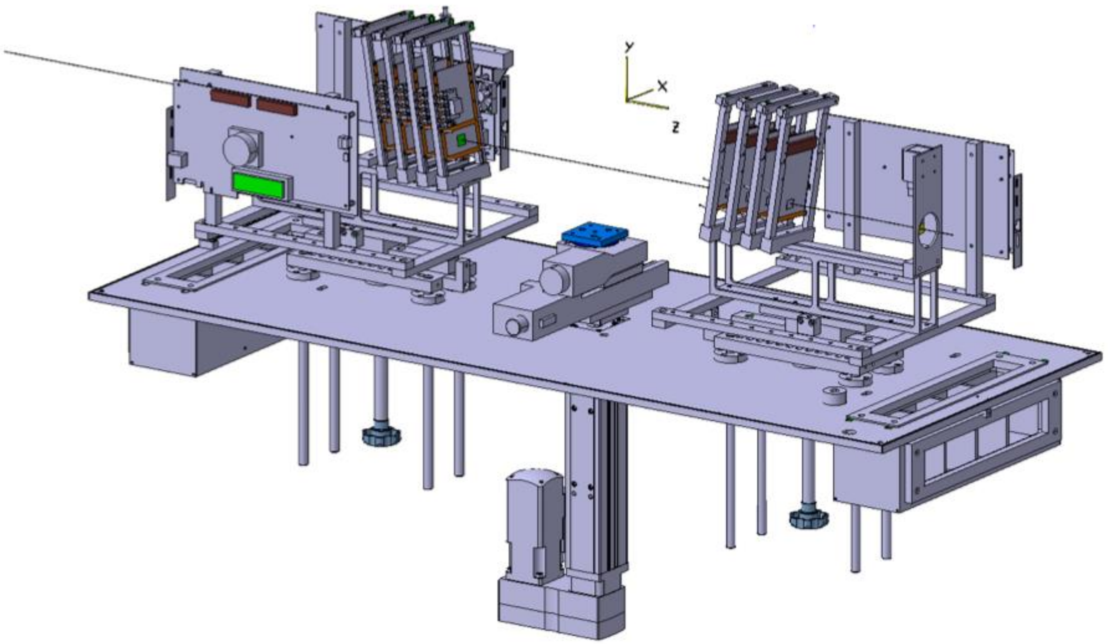
$$\text{Eff} = \frac{\text{Registered hits}}{\text{All incoming particles}}$$

$$\text{Pur} = \frac{\text{All real registered hits}}{\text{All registered hits}}$$

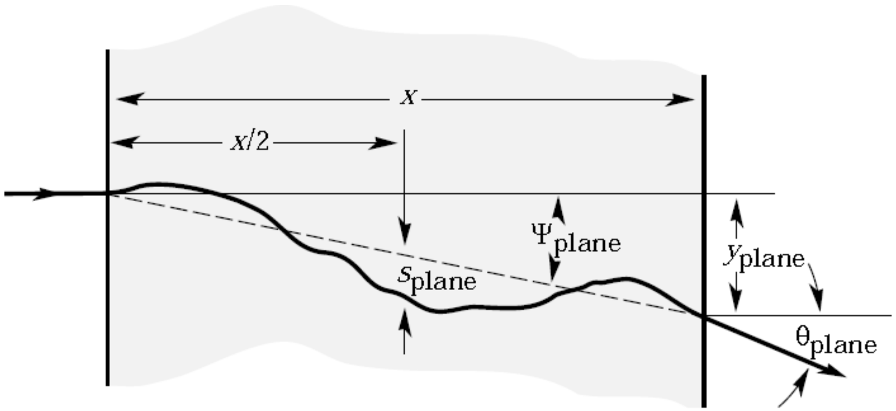
- Efficiency without Purity is useless

Track reconstruction

- Telescope consists of reference detectors.
  - Can be the same or different detectors.
- Hits are reconstructed in all planes and tracks are reconstructed. The track is extrapolated on to the device under test.
  - It is key to accurately predict the track position.



Multiple scattering



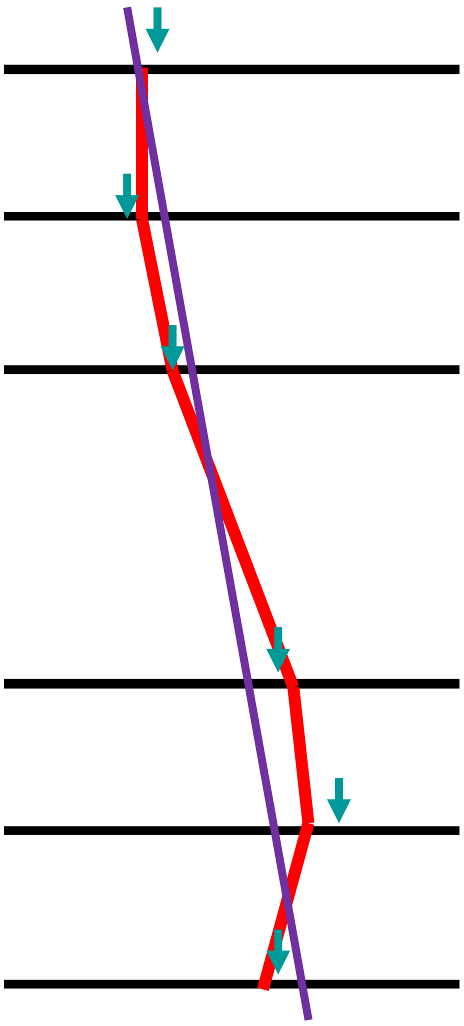
- When a charged particle enters a material, it encounters the electric fields of the electrons and nuclei.
- In the Coulomb interactions it loses energy and changes direction.
- The particle exits under an angle θ. The spectrum is almost Gaussian

$$\sigma_\theta = \frac{13.6\ MeV}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln\left(x/X_0\right)\right]$$

- Where X_0 radiation length is the mean distance over which a high-energy electron loses all but 1/e of its energy by bremsstrahlung.
- Note that:
  - most particles go straight on
  - want high momentum beam
  - thin detectors

Multiple scattering

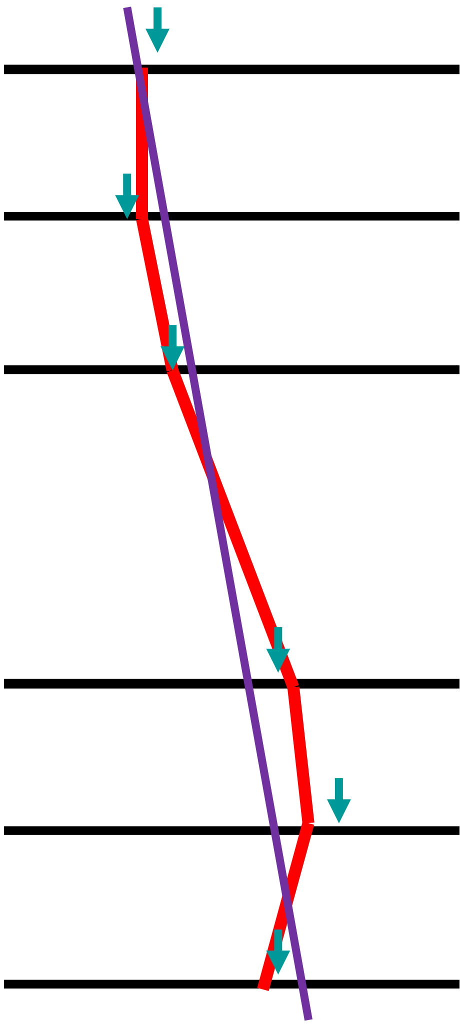
- We always assume that the particle went on a straight line.
- That is not true!
  - Particle undergoes multiple scattering.
  - The hit positions are also reconstructed imperfectly.
- You see that the reconstructed position is wrong.
- There is an uncertainty on the predicted position.



Error on the predicted position

- The error on the predicted position is the difference between the red line and the purple one.
- It depends on the
  - position of the Device Under Test (DUT)
  - position resolution telescope modules
  - energy of the particles
  - thickness of the detectors

$$\sigma_\theta = \frac{13.6\ MeV}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln\left(x/X_0\right)\right]$$

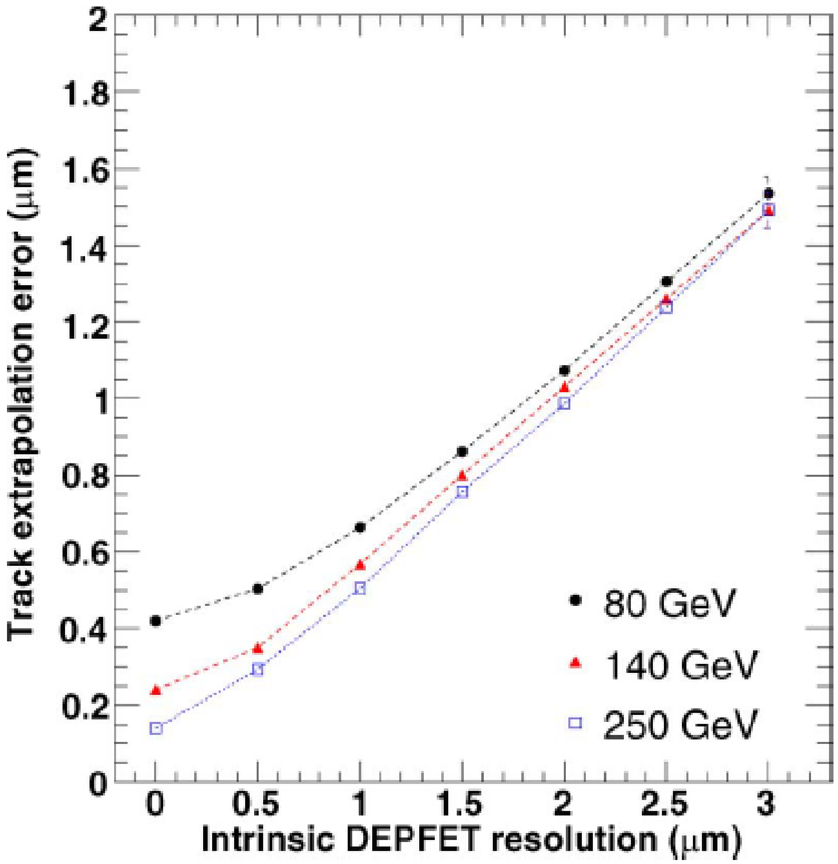


Error on the predicted position

- It is very important to quantify the error on the predicted position.
- Plays a key role in determining what a matching track is.
- Determines in what detail you can study the sensor.
- It is a component of the resolution measurement

$$\sigma^2_{raw} = \sigma^2_{intrinsic} + \sigma^2_{pred.pos}$$

- You get this from a Monte Carlo simulation.
  - Or measure it by making a beam energy scan.



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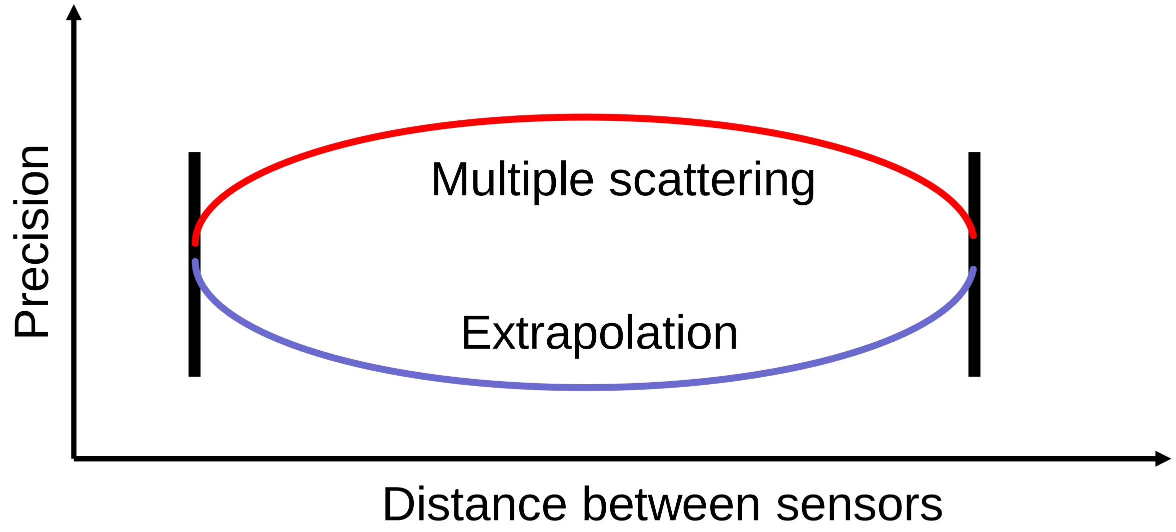
Error on the predicted position

- Telescope's key role is to provide precise tracking.
- Ideal spacing depends on beam energy, hit precision, spacing and detector material.
  - Extrapolation relies on the position of multiple detectors and thus improves further away from one detector plane.
  - Multiple scattering gives a random deviation of a straight line, therefore gets worse in between two telescope planes.



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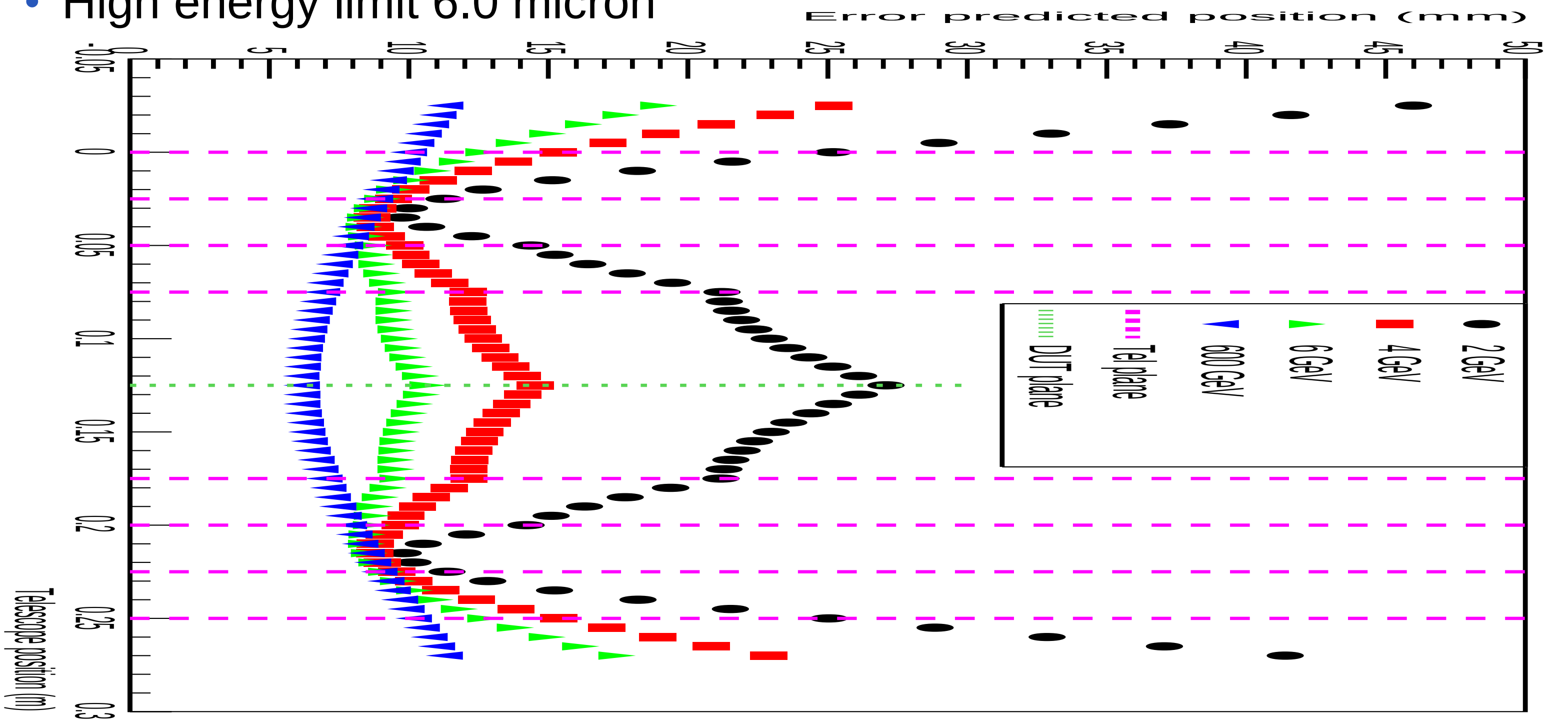
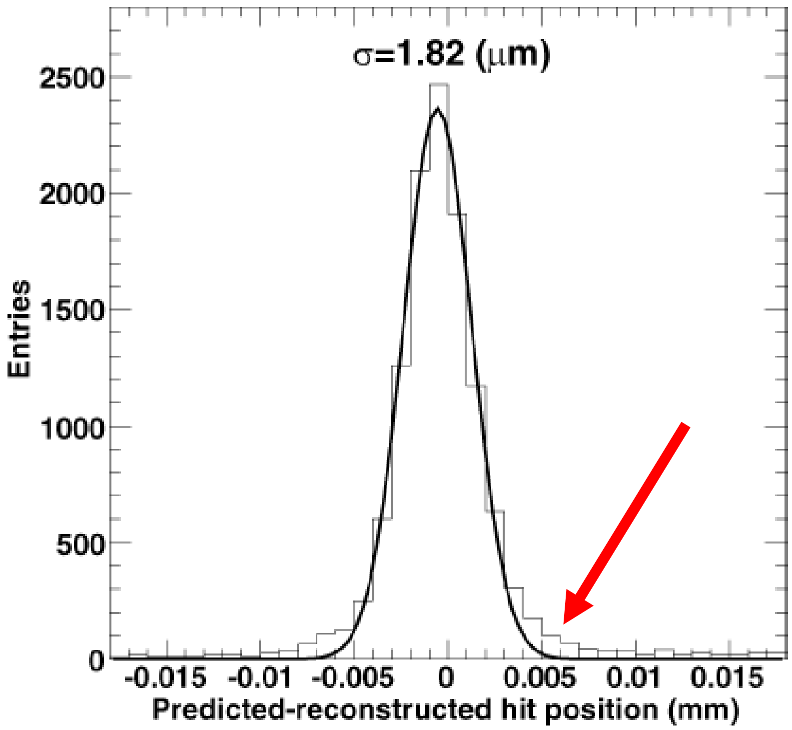
Error on the predicted position

- Simple MC for our CEPC testbeam at DESY
  - 500 micron thick detectors, 17 micron resolution for telescope planes.
  - 2.5cm between planes, DUT not in fit, 5cm DUT spacing.
  - 6 GeV electrons give 10.6 micron precision on DUT.
  - High energy limit 6.0 micron



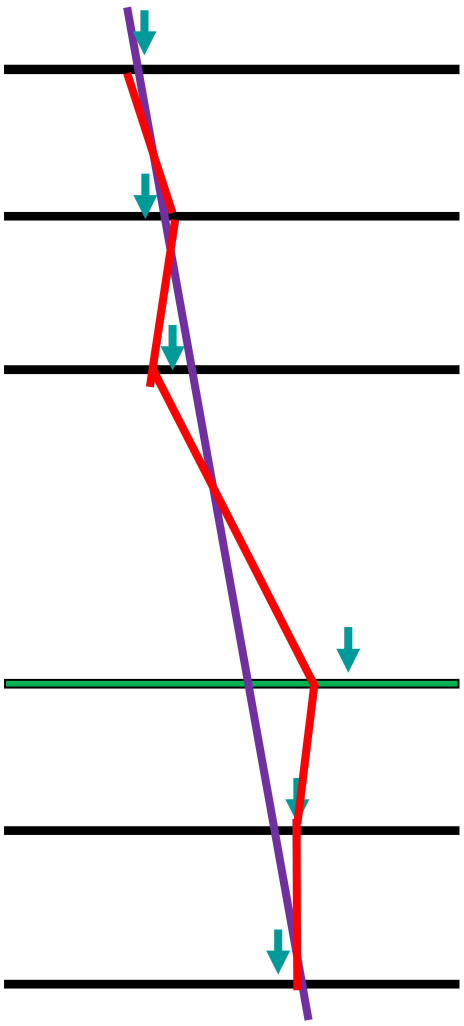
Good tracks and matching hits

- A good track is defined by a χ^2-cut. Can include a time as well as spatial coordinates.
  - Not strictly correct. We do not know the error on the hit position and residual distribution is non-Gaussian
    - Will get back to that.
- The χ^2-cut is arbitrary. You pick it. It mainly affects your spatial resolution and efficiency & purity results.
  - Some of the outliers are due to “weird” tracks. Can cut them out, but is it fair?
  - If you make the χ^2-cut extremely tight, you also exclude events where a big scatter happened in the DUT. These typically have worse resolution.



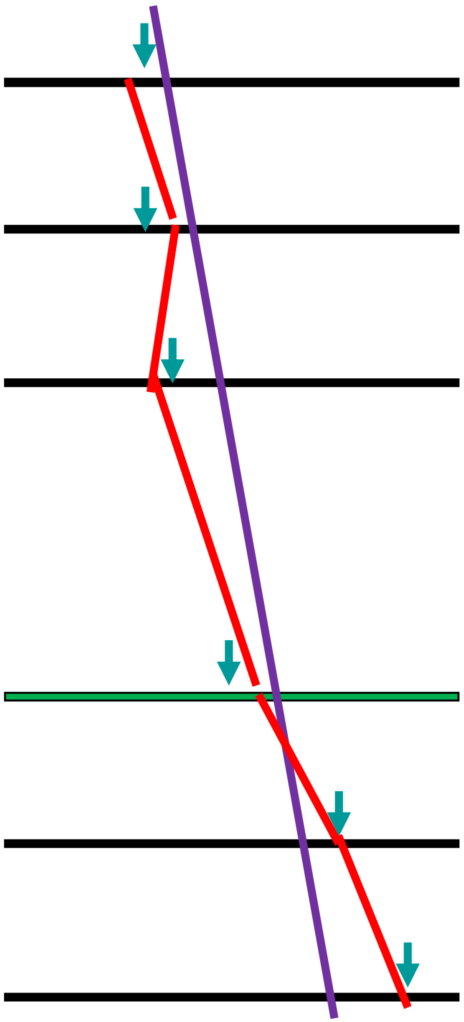
Problematic cases

- Here there was a big scatter on the track, but χ^2-cut would leave the track in.
  - If you cut it, your efficiency drops and your purity gets worse.
  - If you keep it, your position resolution gets worse.



Problematic cases

- Here there was a big scatter in the DUT, χ^2-cut would cut it.
  - If it scatters, the path gets longer so signal increases.
  - If you cut it, your S/N drops



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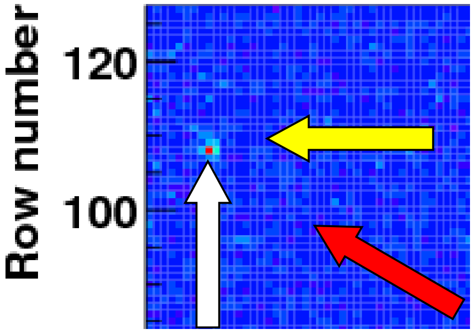
Good tracks and matching hits

- For efficiency and purity it matters whether you accept a track as matching or not.
- Error on the efficiency is

$$\sigma_\epsilon^2 = \frac{\varepsilon(1-\varepsilon)}{n}$$

- Now you can define a criterium whether a hit matches the track or not.
- Do you accept the white, yellow, red as a match?
- You can evaluate the probability that a hit is part of the residual distribution or not and tension that against the uncertainty of the efficiency.
  - Tricky because residual distribution is not Gaussian



Position reconstruction

- The most reported parameter is the position resolution
- Many algorithms exist
  - Binary $\sigma = P/\sqrt{12}$
    - Pick largest signal
  - Digital
    - Use 1 threshold, average positions
  - Centre-of-Gravity
  - η-algorithm
  - HT-algorithm (angled tracks)
  - …
- Will not go in details here. That's for the next block.

Centre-of-Gravity

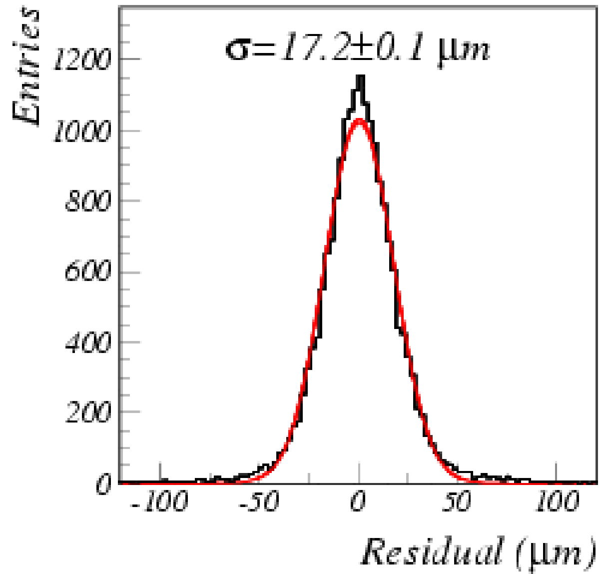
- CoG is most often used algorithm

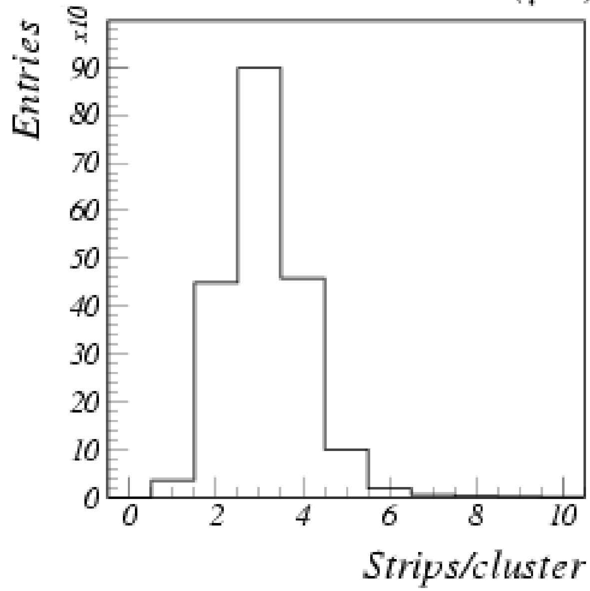
$$x_{CoG} = \frac{\sum Q_i x_i}{\sum Q_i}$$

- Expected resolution

$$\sigma^2_{CoG} = \frac{N^2}{S^2} \sum \left(x_i - x_{CoG} \right)^2$$

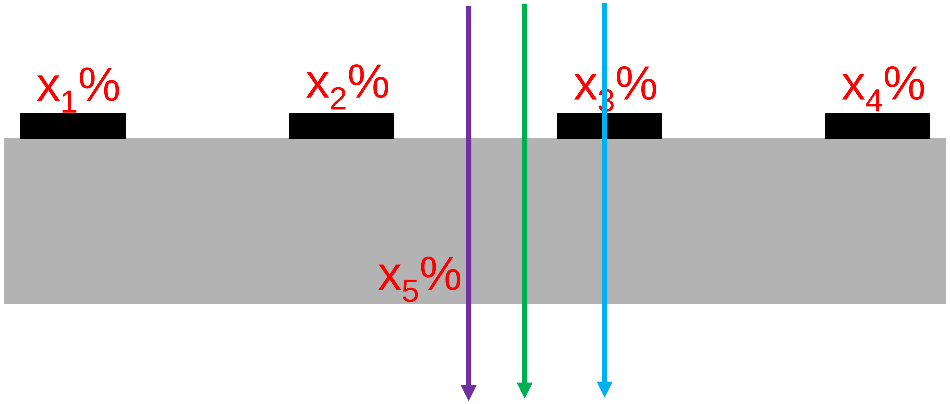
- Note: $\sigma \propto (S/N)^{-1}$
- Centre-of-Gravity assumes linear charge sharing
  - Resolution gets bad due to large clusters with non-linear charge sharing
  - The weight for the strips at the end of the cluster, who have the lowest S/N, is very high.

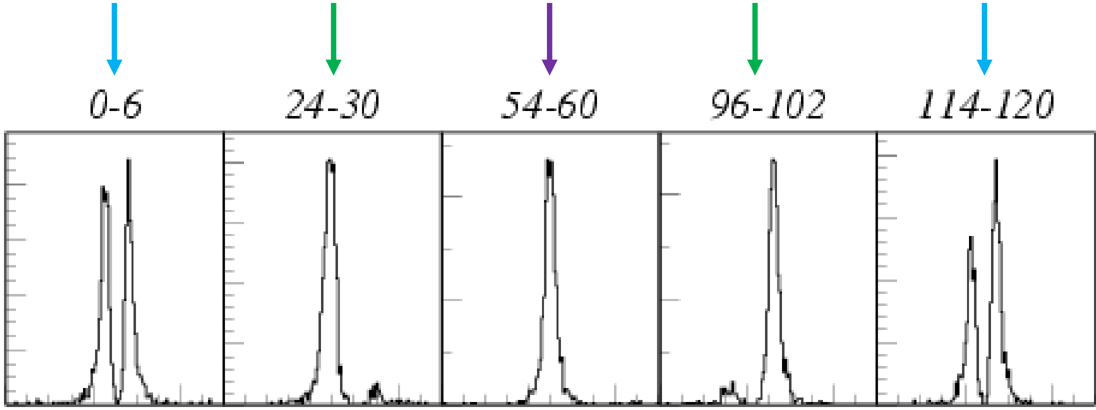




Position resolution depends on hit position

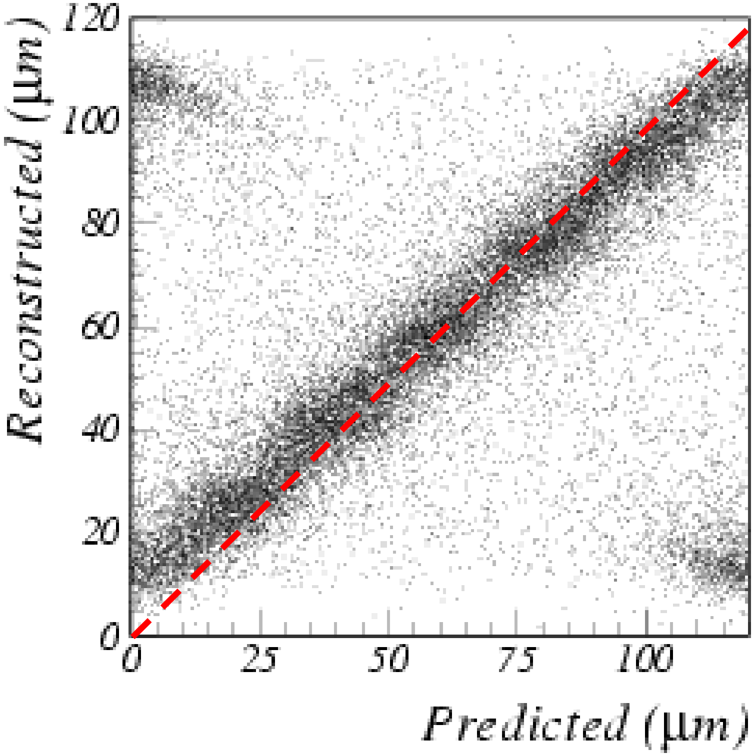
- The non-linear charge sharing leads to different position resolutions at different positions between strips or in-pixel.
- If you hit in the middle between the readout strips, the charge is evenly shared between the strips.
  - $x_2 \approx x_3$ and x_1 and x_4 are small
  - $x_2 < x_3$ and x_1 and x_4 are small and x_5 comes in play
  - x_3 is large and $x_2 \approx x_4$ and x_1 is small
- For the resolution add up all distributions. Not a proper Gaussian.





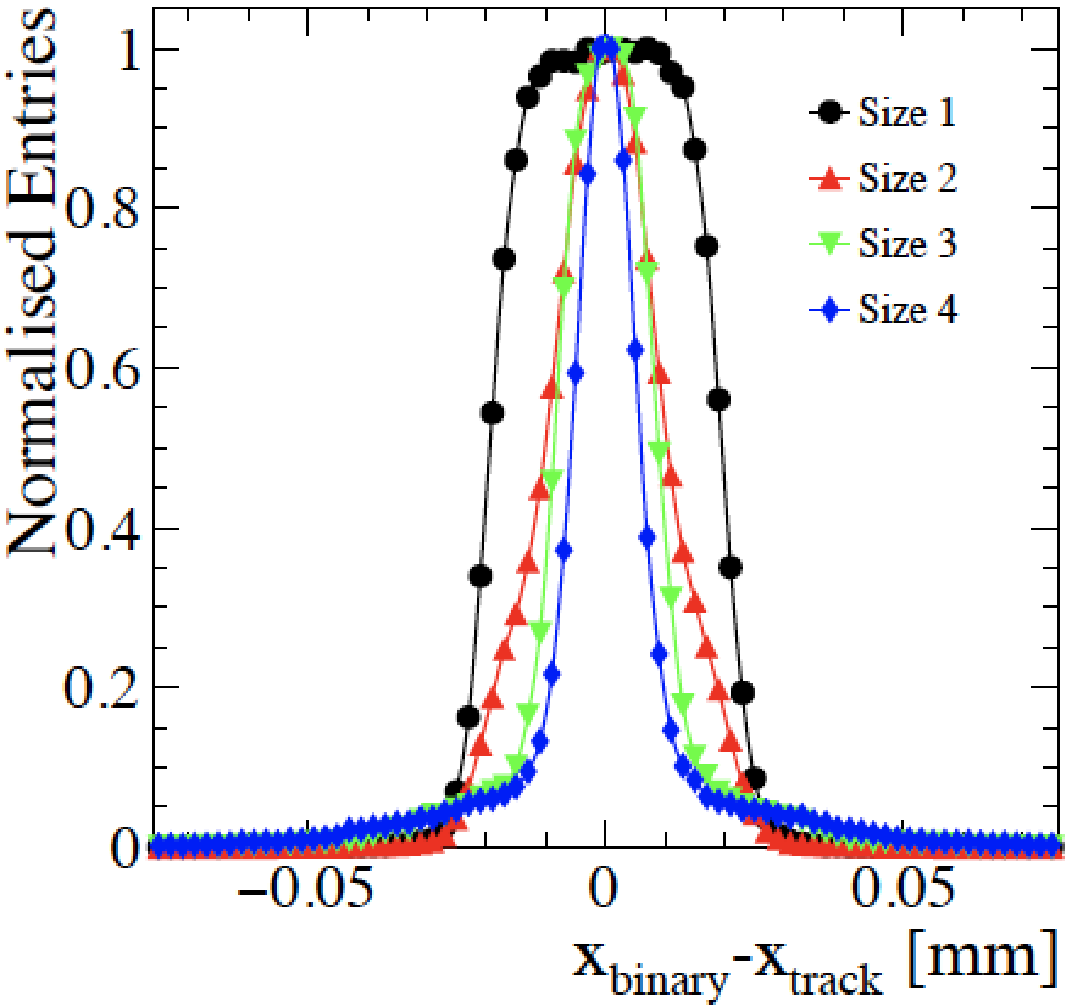
Position resolution depends on hit position

- Here you see a scatter plot of the predicted and the reconstructed position for a strip detector.
- You notice that the charge sharing is not linear.
- This yields different resolution between the strips.
- Therefore, we cannot calculate the actual χ^2 of the track until we know where it has hit the sensors.



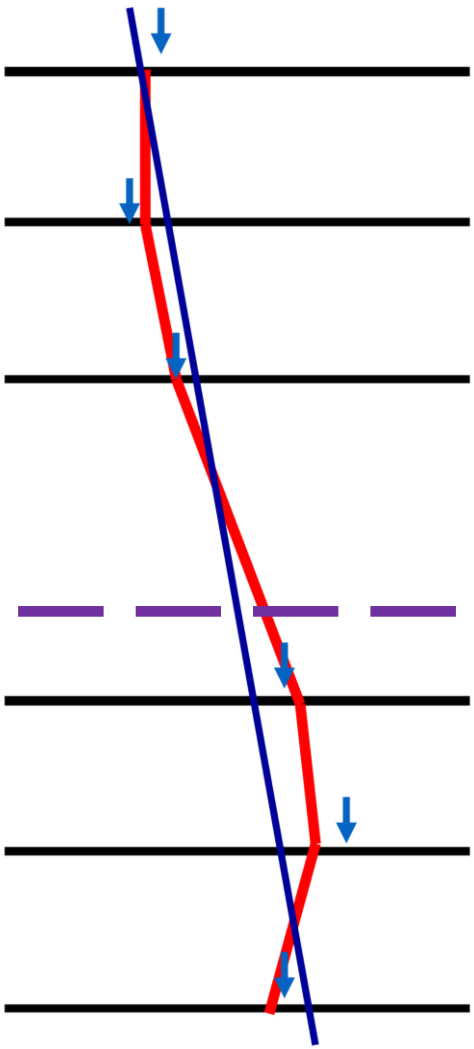
Position resolution depends on hit position

- Charge sharing in the TimePix3.
- Large pixels wrt charge cloud.
  - Huge area of single pixel clusters
  - Along the edges 2 pixel clusters
  - In the corners 3 and 4 pixel clusters
- For each area expect a resolution of the area/√12



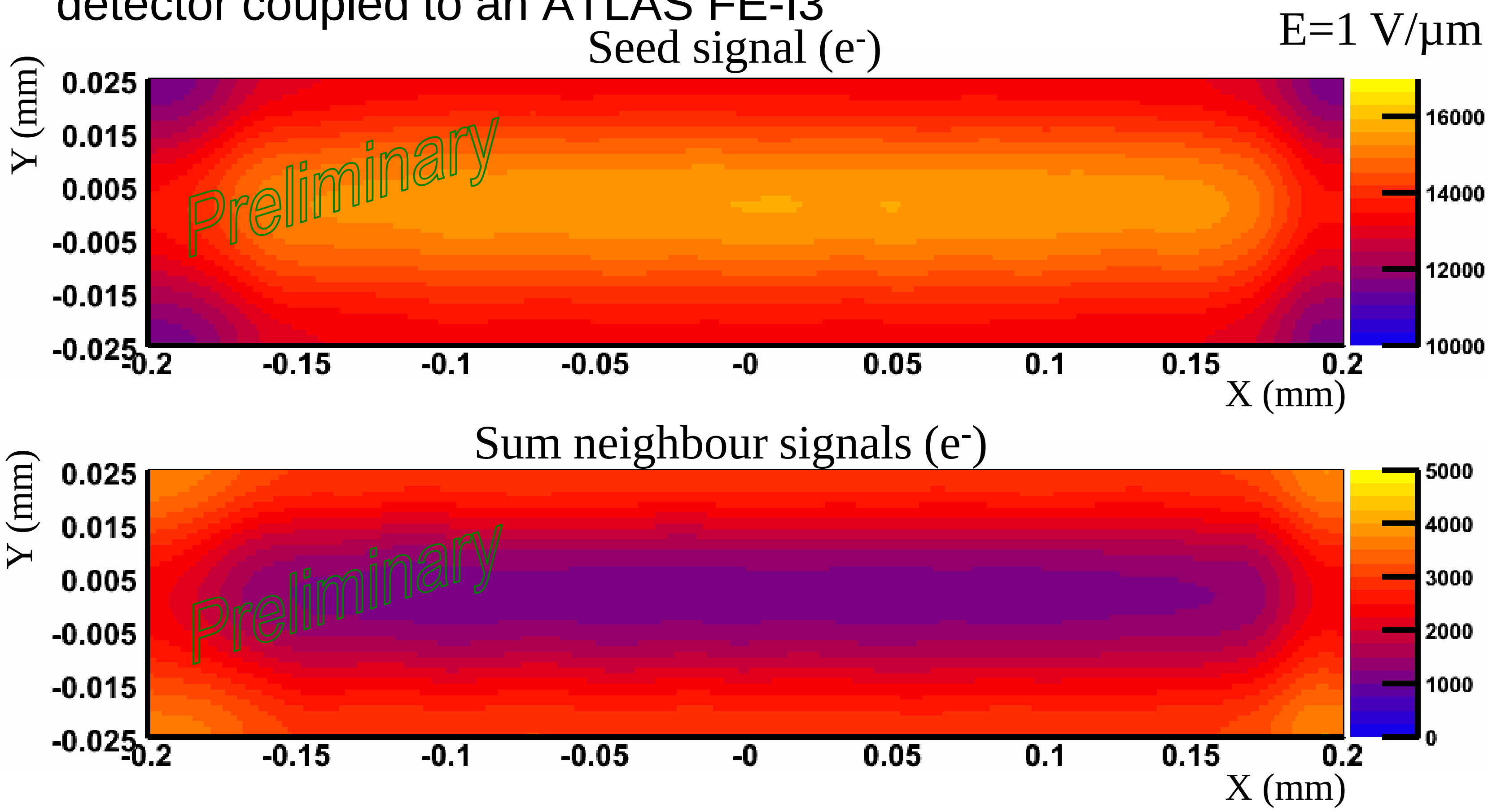
In-pixel variations

- You want to measure the variation of many properties inside a pixel or between strips.
- Scale is set by the error on the predicted position.
- It makes no sense to bin smaller than ~2x2$\sigma_{pred.pos}$
  - Your in-bin purity will be poor and thus you smooth out the results.



Charge division

- Example of an in-pixel study of the collected signal in a diamond detector coupled to an ATLAS FE-I3



Charge division

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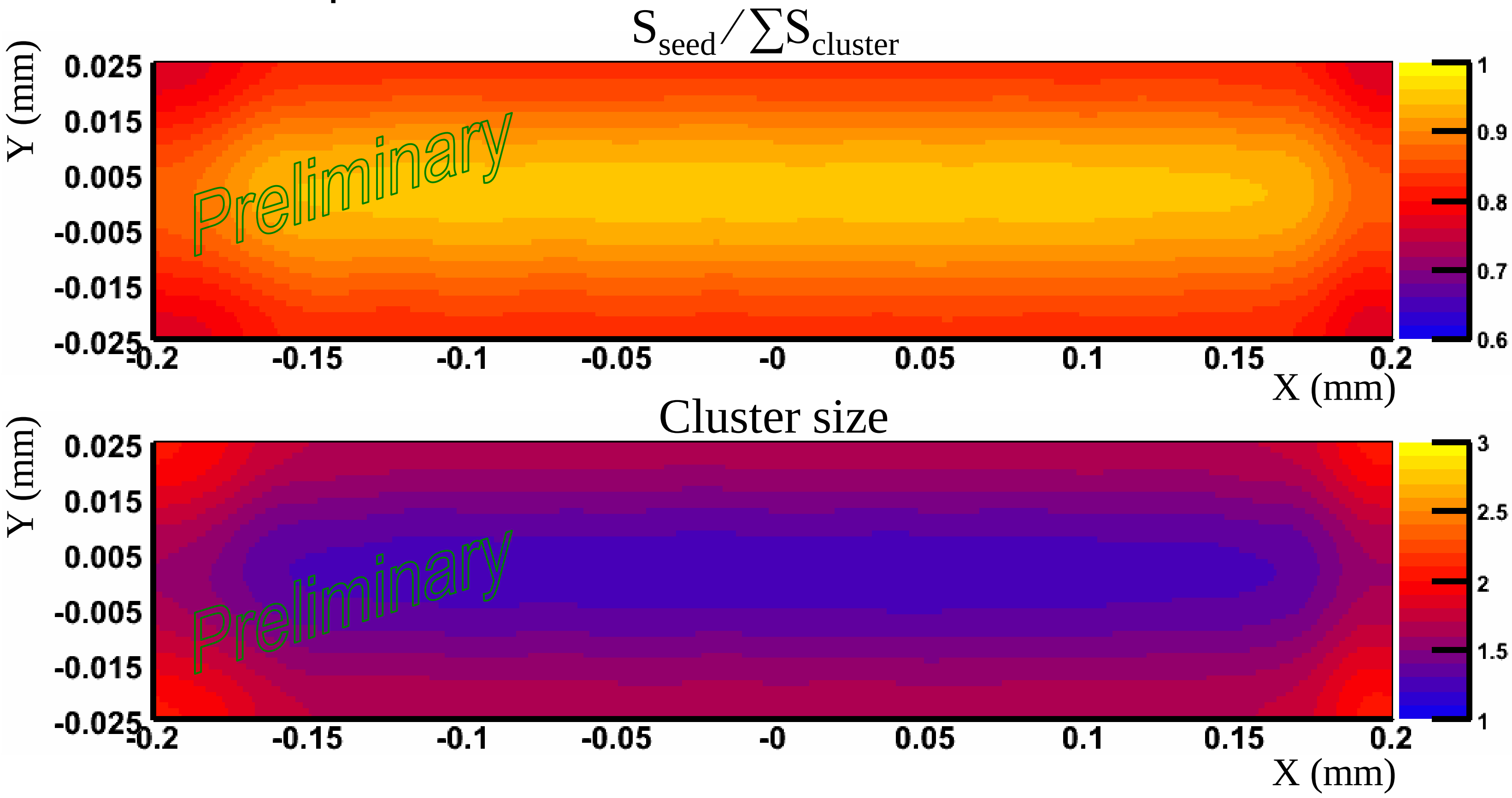
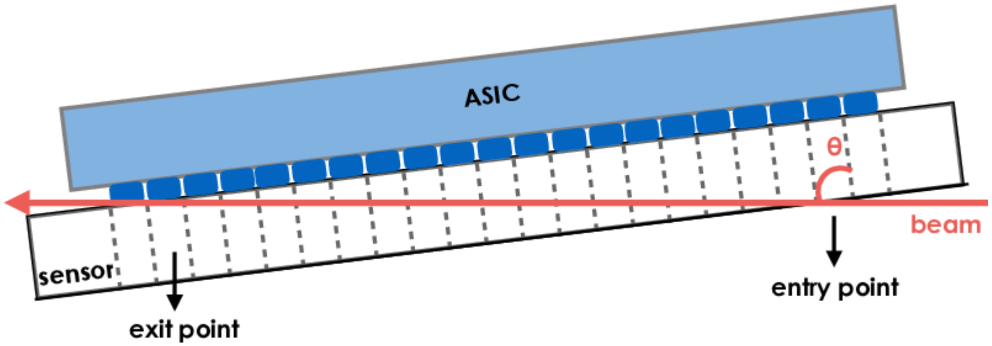
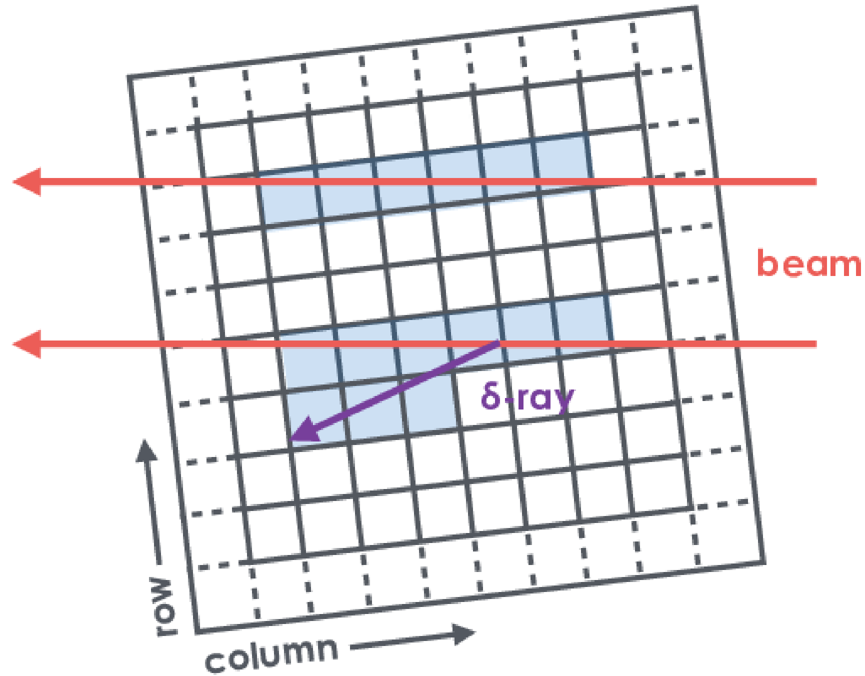


Telescope free testbeam: grazing angle

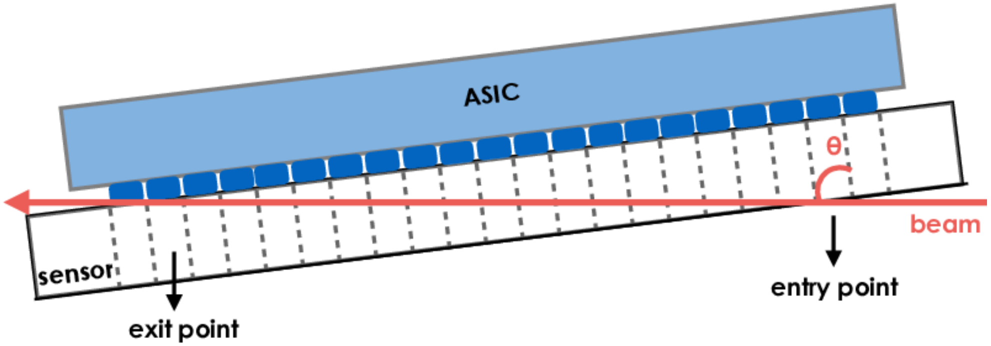
- Most testbeams are using perpendicular beams.
- Here they use a grazing angle, i.e. almost parallel to the sensor.
  - gives long tracks in the detector.
- Now you can use your own detector as a telescope and DUT at the same time.

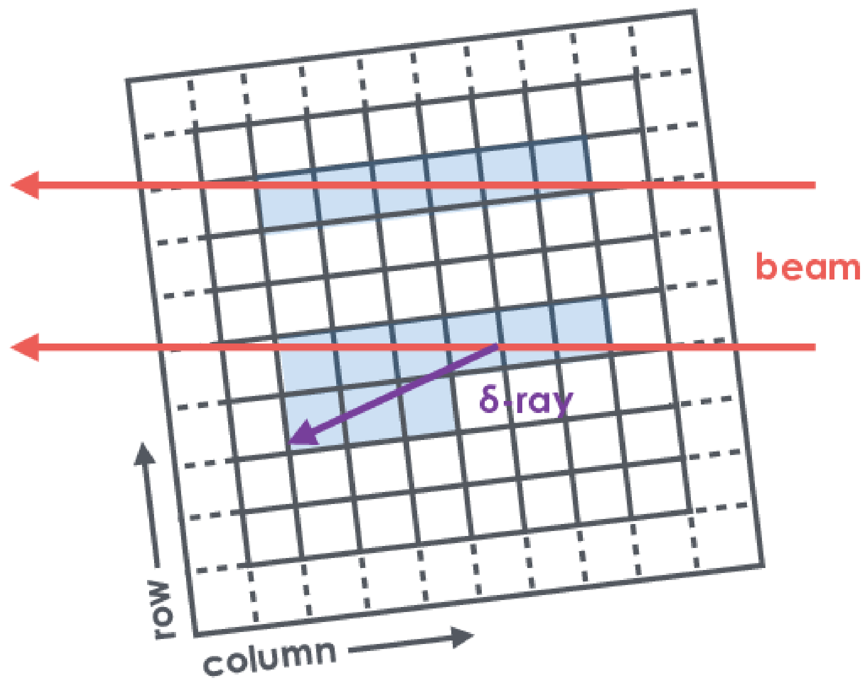




Telescope free testbeam: grazing angle

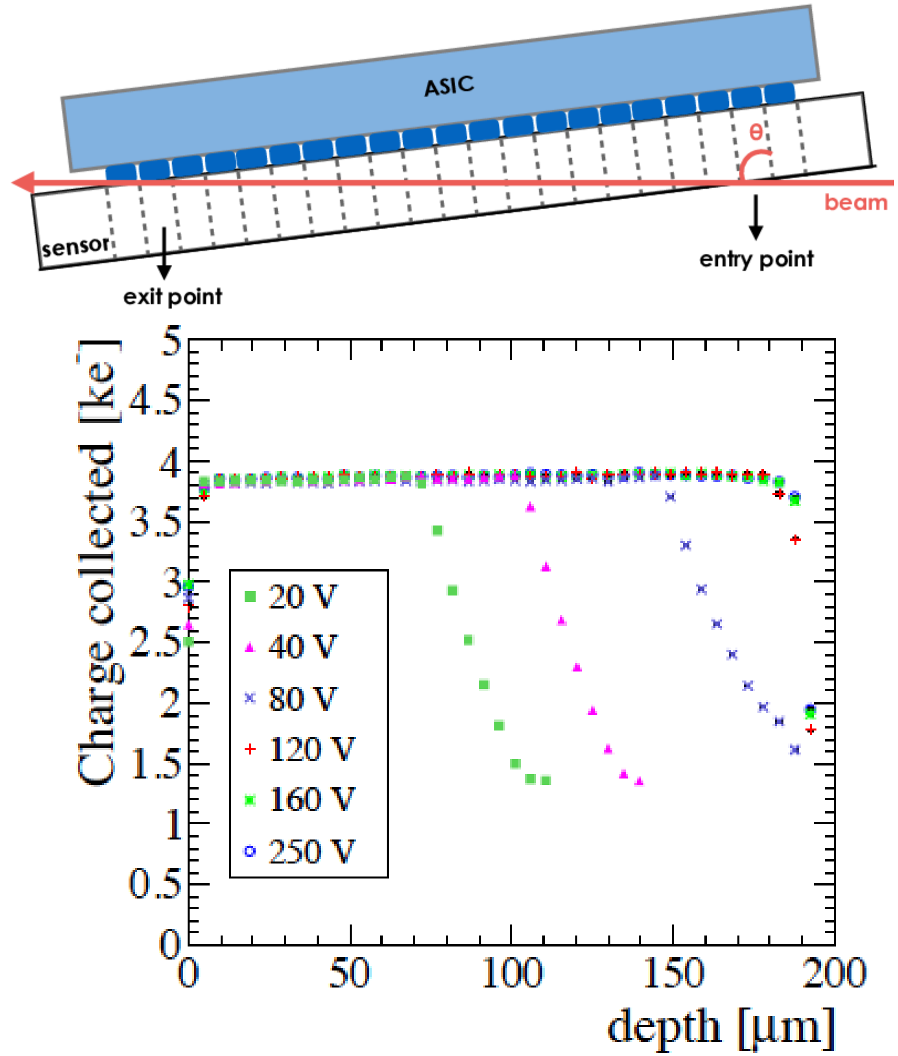
- For unirradiated sensors all depths contribute the same amount until depletion depths.
  - carrier lifetime >> collection time
- Can see this using grazing angle method.
  - Expect 3.8ke MPV per pixel at this angle.
- Signal drops really quick at depletion edge.
  - Charge is collected due to generated charge diffusing into depleted area.
  - (In this analysis will always measure at least 1500e)





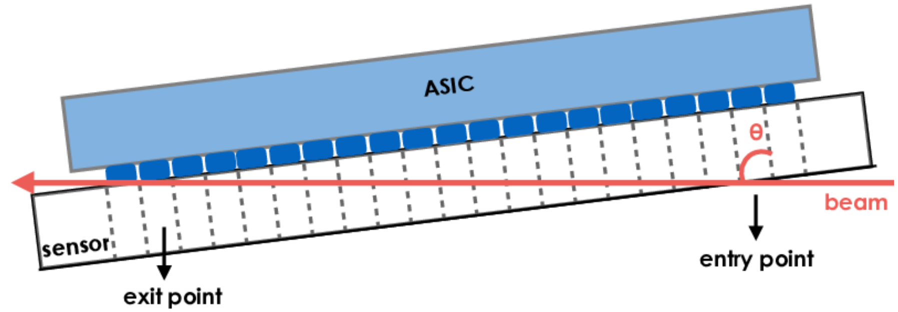
Telescope free testbeam: grazing angle

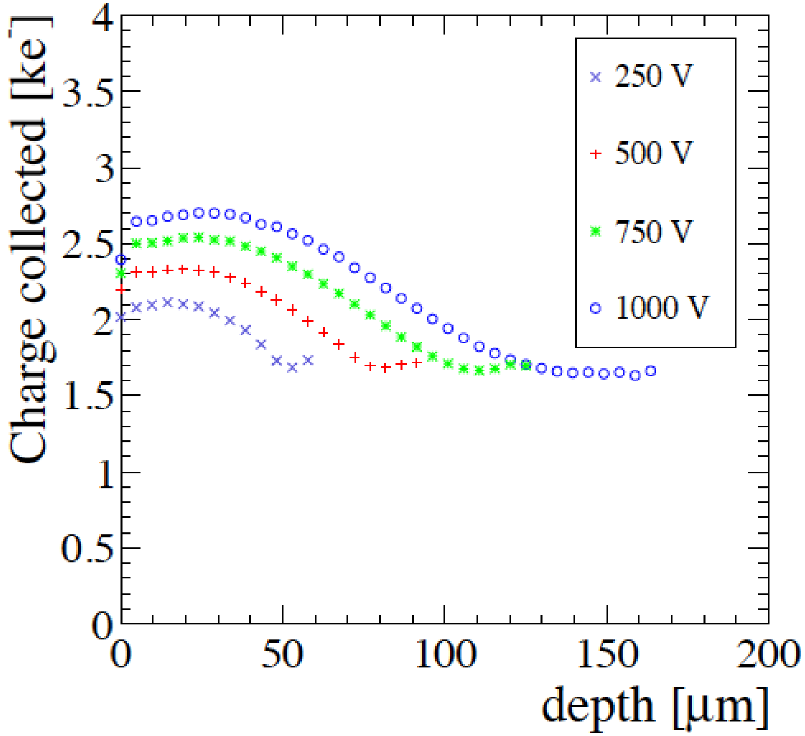
- It also allows to study from how deep in the sensor your charge is collected.
- Here you see a partially depleted detector.
  - If the bias voltage is not high enough parts of the sensor do not contribute to the signal.



Telescope free testbeam: grazing angle

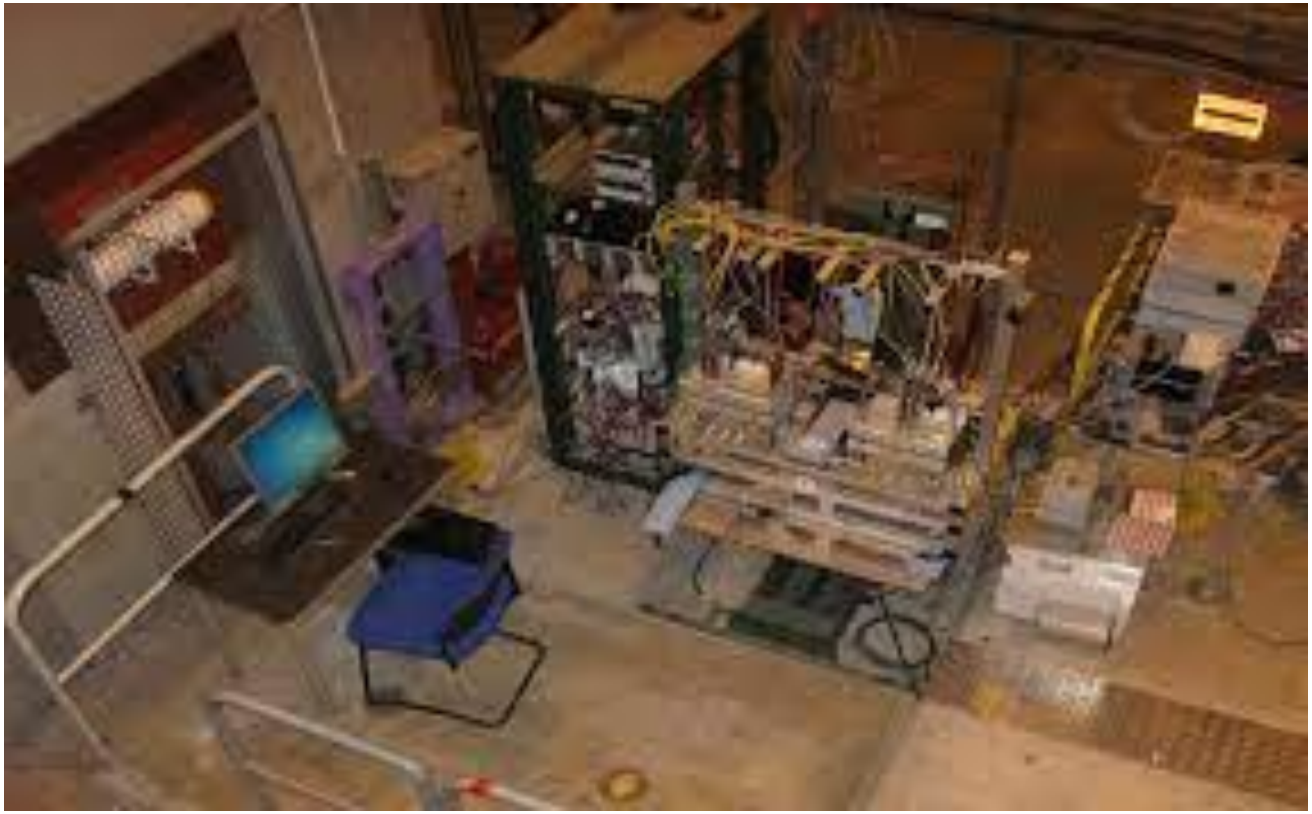
- It also allows to study from how deep in the sensor your charge is collected.
- Here you see a partially depleted detector.
  - If the bias voltage is not high enough parts of the sensor do not contribute to the signal.
  - This gets worse with radiation.





Test beam facilities

- There are many places where you can go for a test beam.
  - CERN
    - SPS
    - PS
  - Fermilab
  - DESY



CERN-SPS

- Best place for testbeams
- Can get protons and pions
- Highest energy available
  - 20-400 GeV protons/pions
  - minimizes multiple scattering
- Beam specs
  - spill duration approx. 5 seconds
  - usually every 14s
  - 2×10^8 per spill

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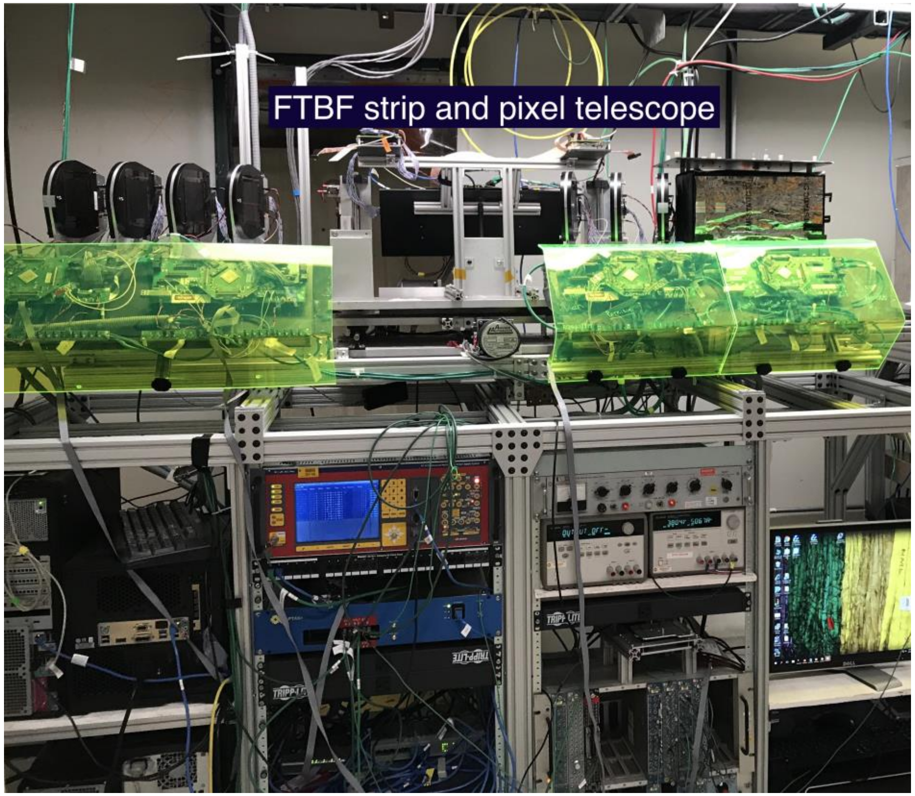
CERN-PS

- 15 GeV protons
  - 2×10^8 per spill
  - 1 spill every 33.6 s

Fermilab

- 120 GeV protons
- one 4.2 s spill per minute with about 100,000 protons.
- The beam is bunched at 53MHz, so lots of particles close together in time.

- Comes with telescope
  - four $100 \times 150 \mu m^2$ pixel layers and fourteen strip modules with 60μm pitch
- nominal resolution of 10–15μm



DESY

- 1-6 GeV electrons
- comes with telescope
- low momentum bad for multiple scattering.
- can extract the position resolution from energy scan.

$$\sigma^2_{\text{raw}} = \sigma^2_{\text{intrinsic}} + \sigma^2_{\text{pred. pos}}$$

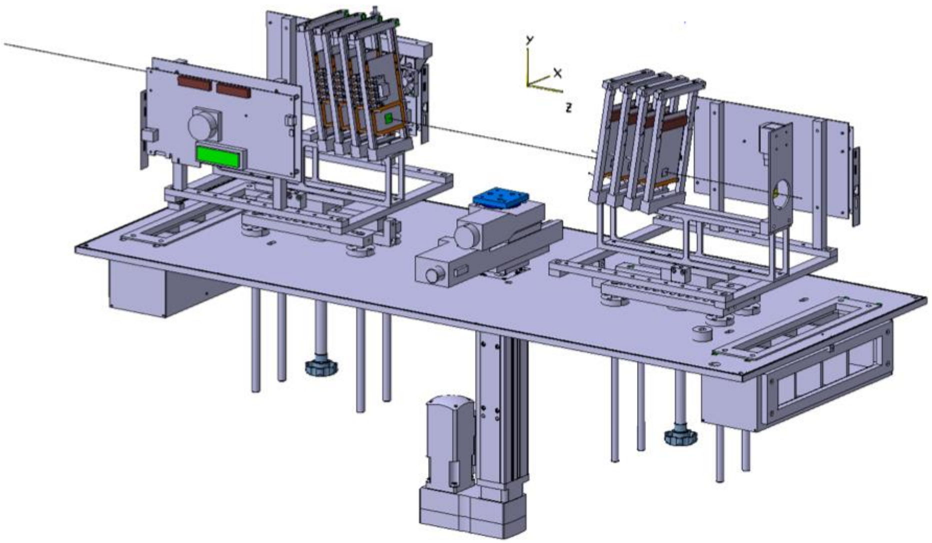
$$\sigma^2_{\text{pred. pos}} = \sigma^2_{\text{tracking}} + \sigma^2_{\text{multiple scat.}}$$

$$\sigma_\theta = \frac{13.6\ MeV}{\beta c p} z \sqrt{x/X_0}\left[1 + 0.038 \ln\left(x/X_0\right)\right]$$

- Plot resolution vs $(1/p)^2$. Gives straight line.
- Error on predicted position ~2μm for naked telescope.

The ugly truth…

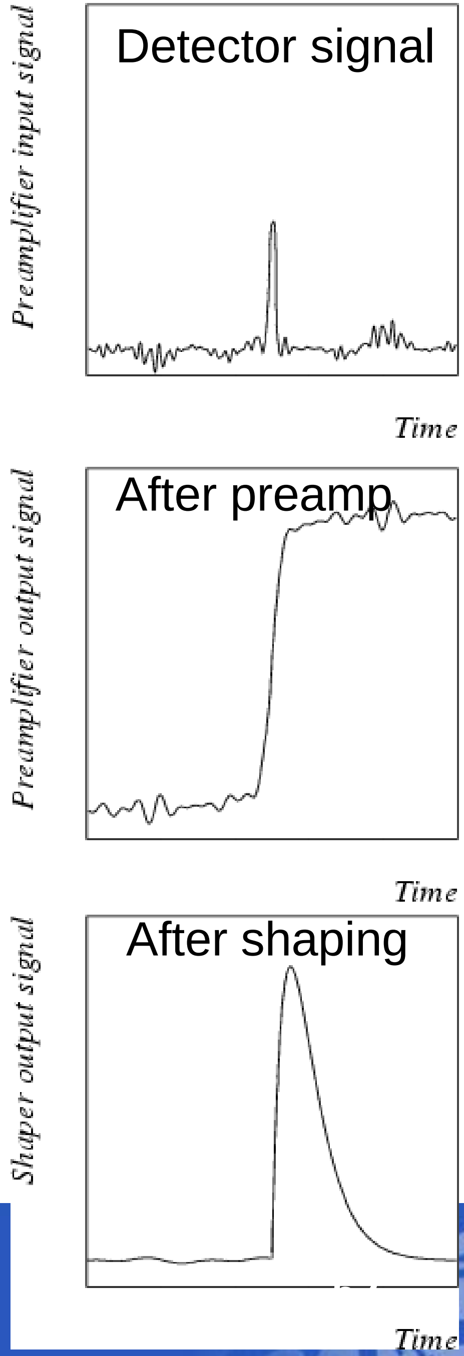
- Testbeams are very simple but there are many issues.
- Need to reconstruct the track that goes with your hit
  - Need to look at all detectors at the same time and have them all lined up.
  - Not easy!
- Most need a trigger.
  - usually provided by coincidence of scintillators



“Triggered” systems

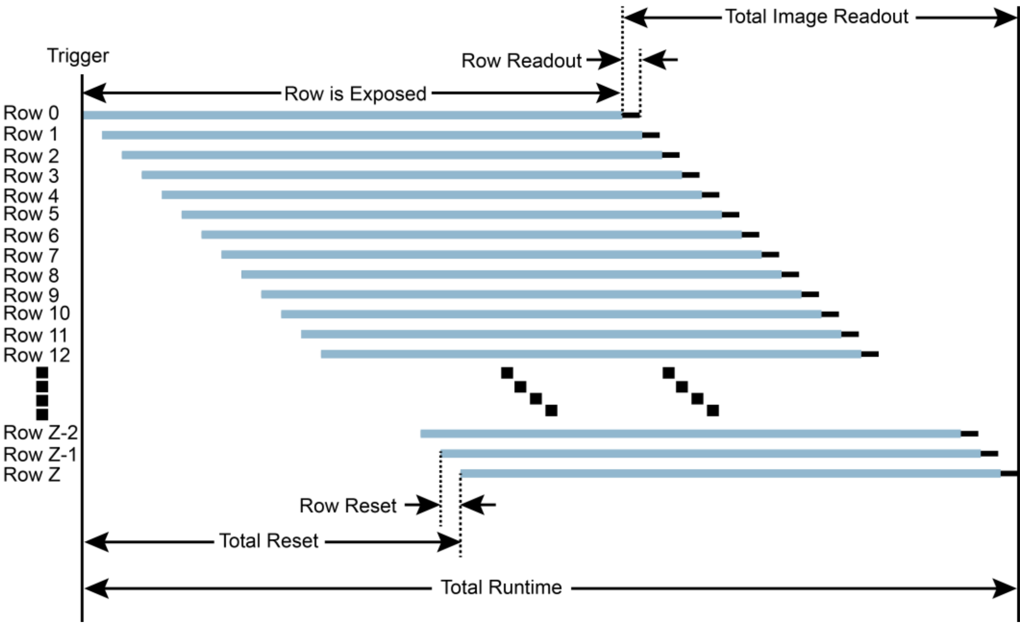
- Older systems have a preamp, shaper and sample and hold circuit.
  - Still in common use.
- Every clock the output of the shaper is stored in a pipeline.
- When a trigger occurs, one of the pipeline columns is marked for read out.
  - You need to set the correct delay to sample the correct pipeline column.
    - Can do this partly in the lab, but the correct delay depends on the DAQ system.

- Data combination is easy as long as the detector is not integrating



Rolling shutter readout

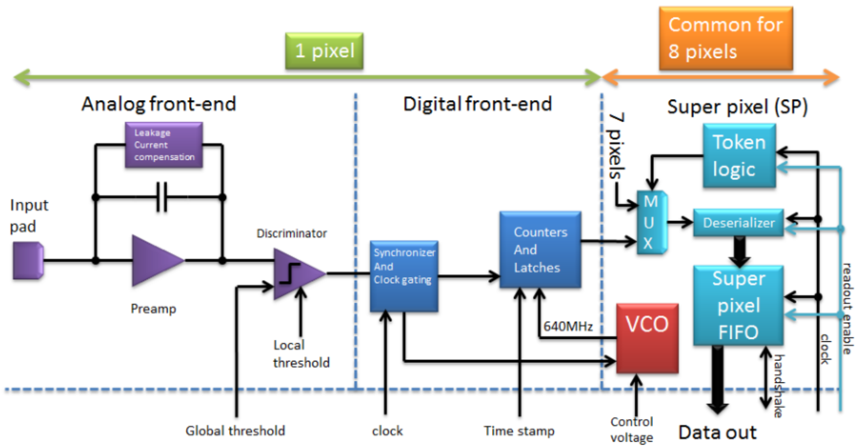
- Many monolithic active pixel sensors are traditionally read out in rolling shutter mode.
  - Row 1 is read out, reset and starts integrating.
  - Row 2 is read out, reset and starts integrating.
  - Row 3 is read out, reset and starts integrating.



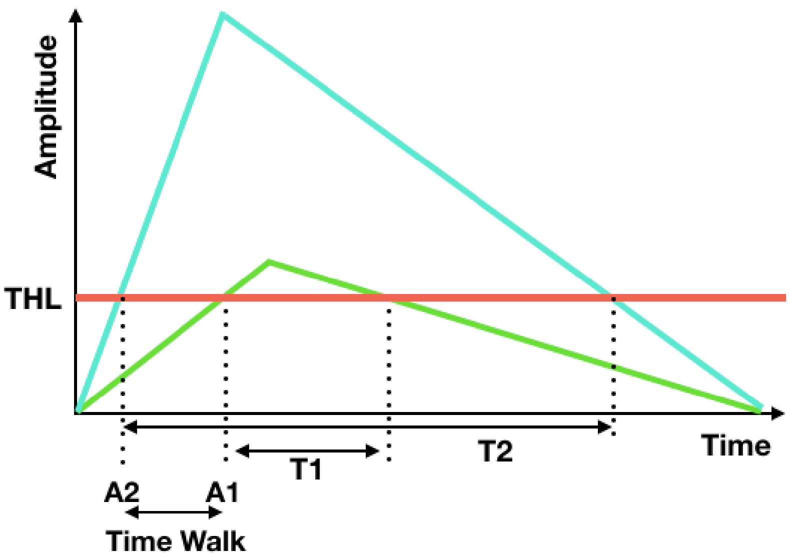
- For each row the integration start and stop time are different.
- The trigger signal is used as a tagger. From the trigger time, you know what row is read out. Need to store 2 frames to be guaranteed to reconstruct the hit.

Data-driven read out

- Some chips have a data driven mode (asynchronous).
- Each pixel has its threshold. When the shaped signal exceeds the threshold, a hit is registered.
  - Output contains:
    - Pixel address
    - Time stamp for passing threshold
    - Time over threshold

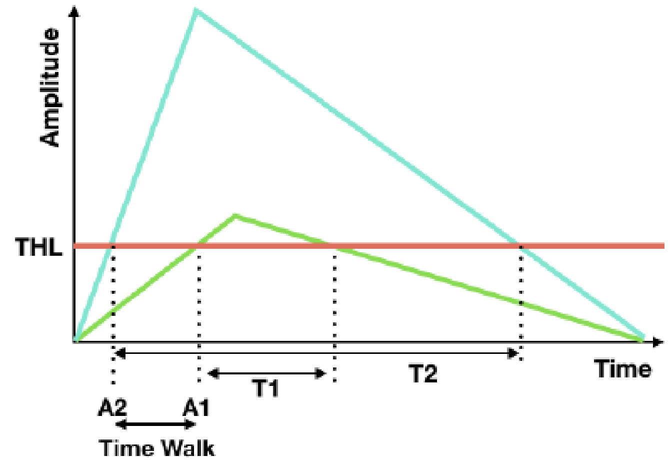


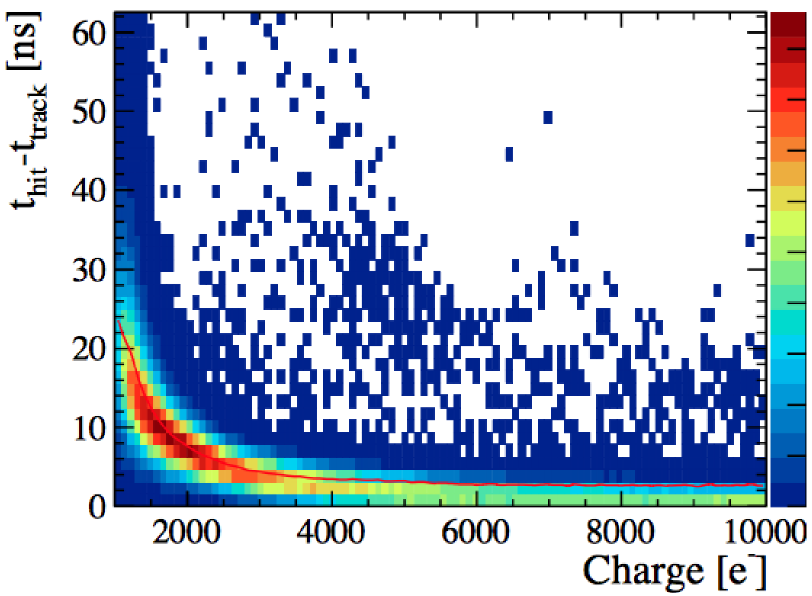
- "Simple" to combine data if you have synchronicity signal.
  - In practice, problematic because you need to read a large chunk of data and try to find same time stamps



Using multiple types of sensors

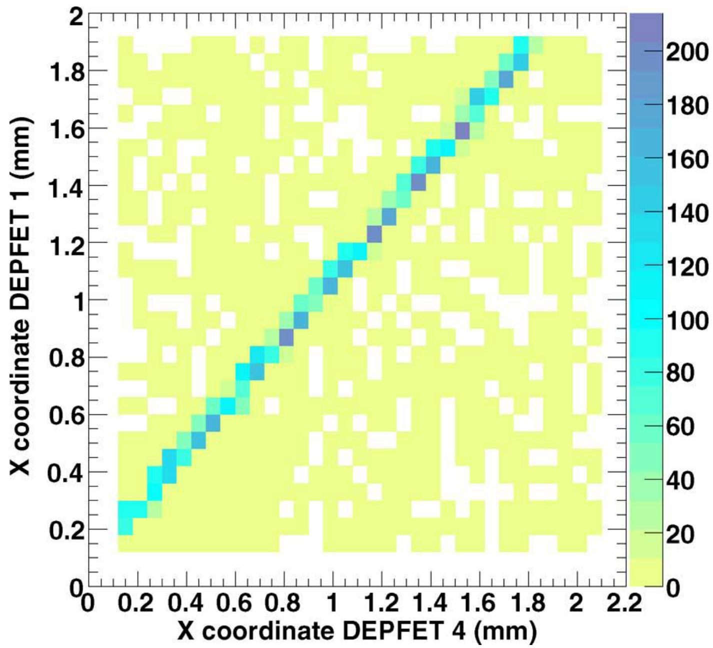
- Need to think how to make a failsafe system to combine the data.
- Difficult
  - Can block the trigger using BUSY logic for triggered systems.
  - Integrating devices will still see all the hits though.
  - How to match data? Time stamps? Trigger counting?
  - How to keep the clocks synchronous?
  - Time walk in data driven systems.
- No real solutions
  - special synchronization signals
  - short runs
  - limit the beam rate

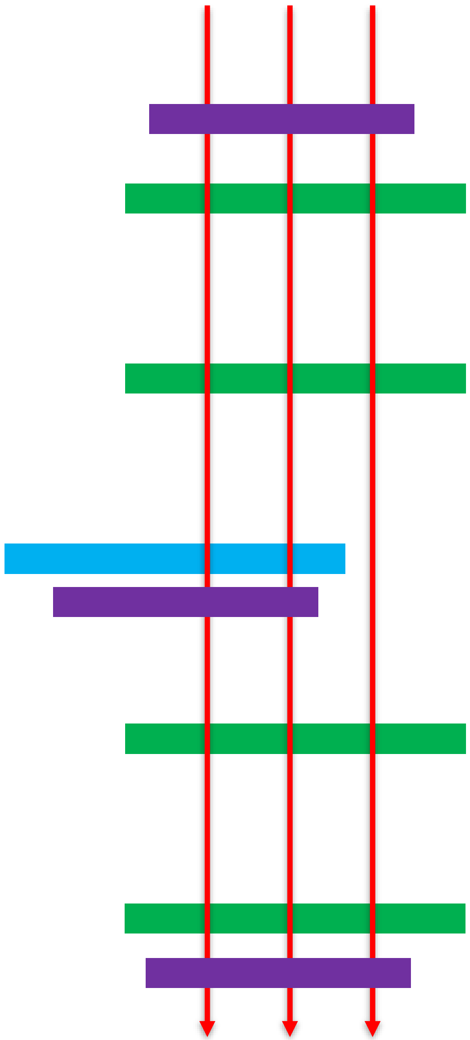




Alignment

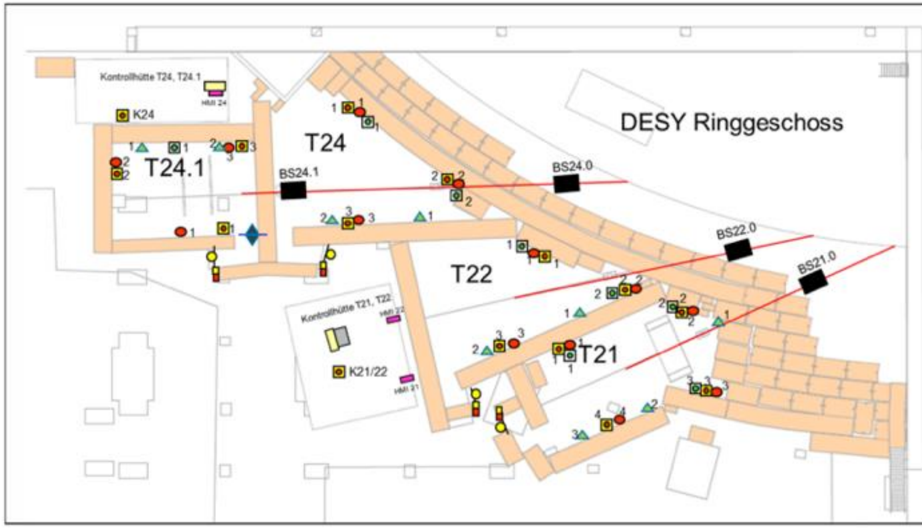
- Can fix small alignment issues offline.
- Online you might be firing the beam (partly) next to the DUT.
  - Needs online analysis!
  - Can look at hit correlations and shadow plots.
  - Can use additional scintillators





Other things to think about

- Data quality monitoring essential



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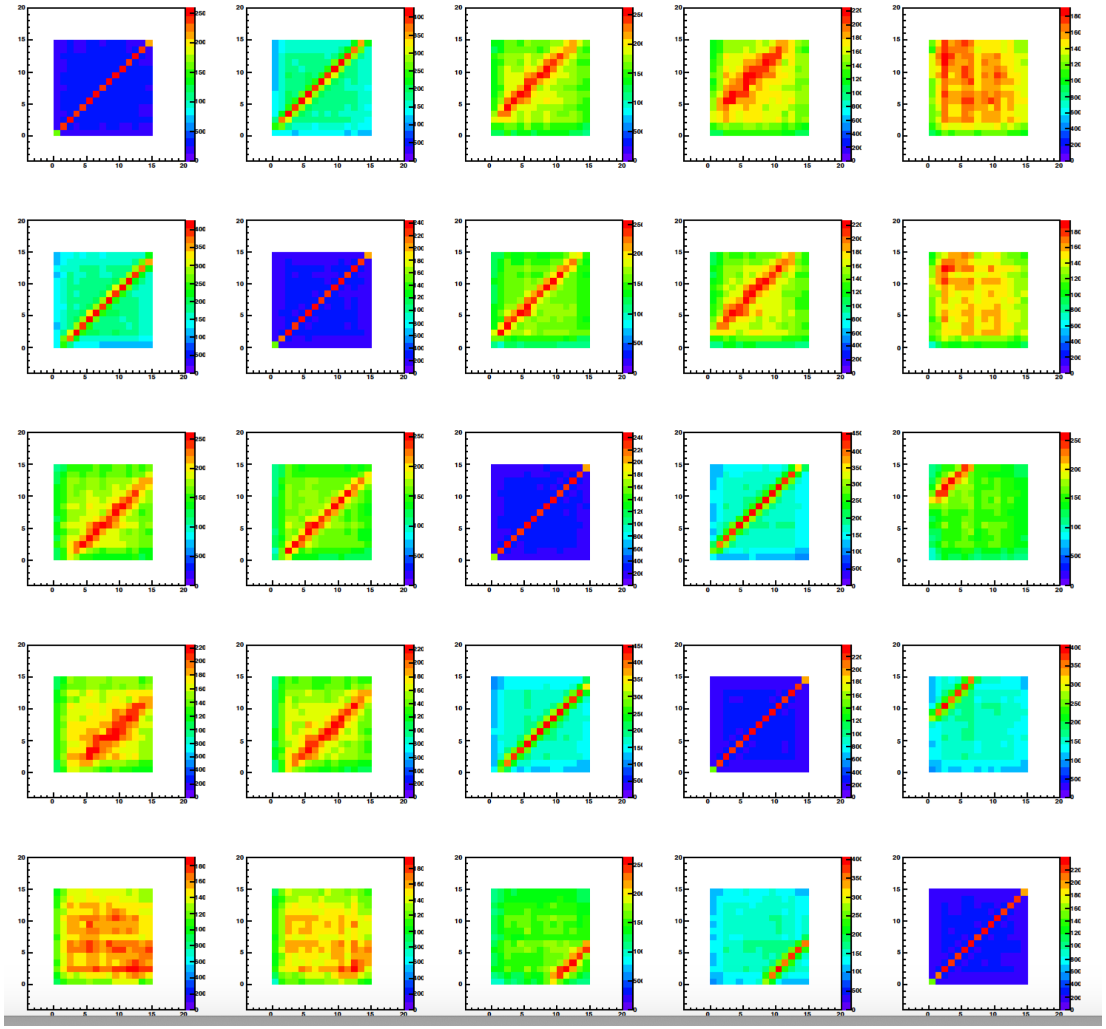
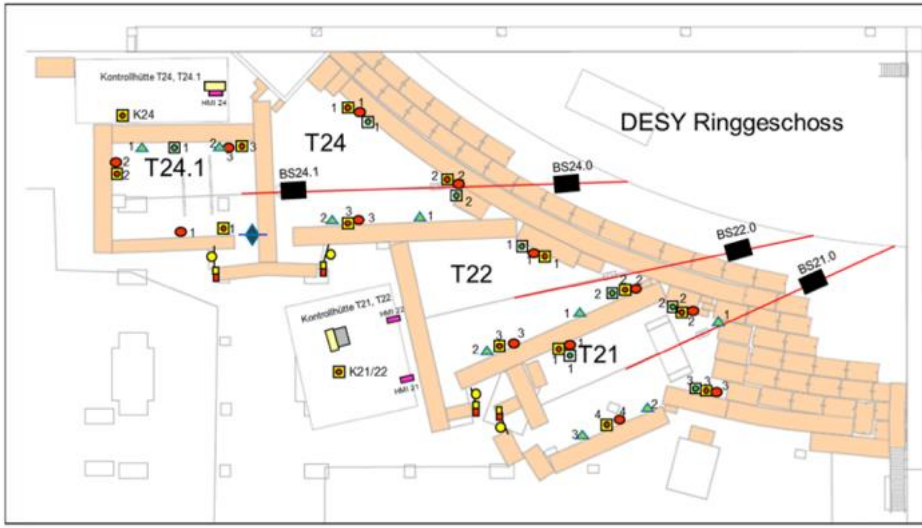
Data quality monitoring

- Make a quick version of the analysis.
- Use simple hit finder.
- Exploit all hit maps and correlations
- This HAS to look okay if you want to be successful.



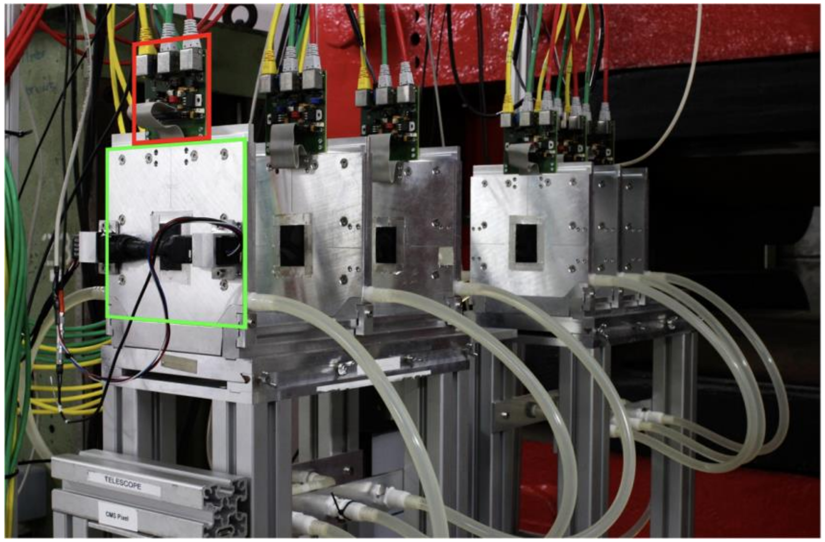
Other things to think about

- Data quality monitoring essential
- Pretest detectors and software
- Data handling
  - bring enough disks
- Bring enough computers and cables
  - got a control hut and a beam area
- Have a good test beam team
  - good leaders and good followers
  - good plan catering for various scenarios
- Power plugs
- Transport of people and equipment
- Safety courses, inspections and health certificates



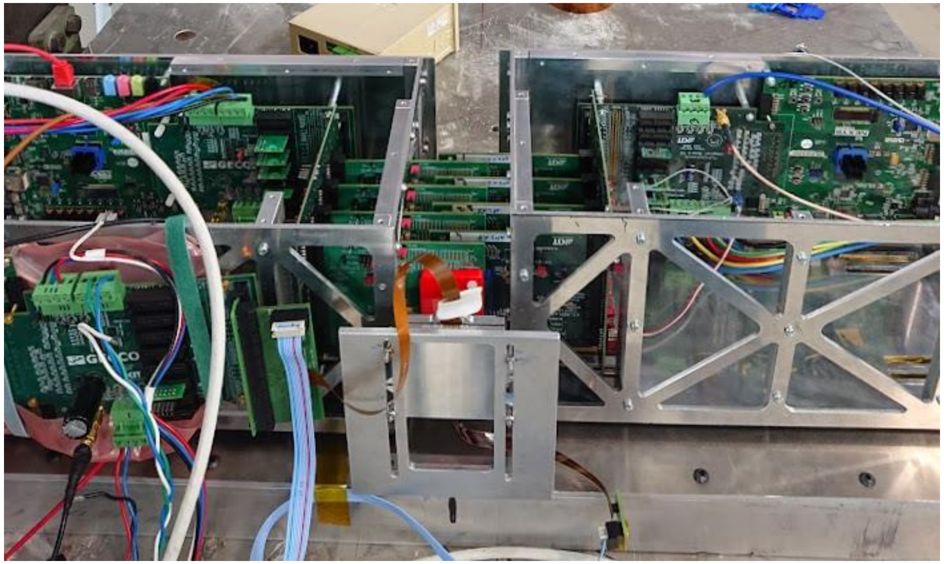
Standard telescope or bring your own

- At DESY, you get the EUDET telescope.
  - 6 MIMOSA26 MAPS with 18.4 μm × 18.4 μm pitch and total area 21.2 × 10.6 mm^2. Each 50 μm thick
  - Trigger Logic Unit (TLU) providing trigger logic, time stamp and a data acquisition system.
  - σ_{M26} = (3.24 ± 0.09) μm.
- Error on predicted position is (1.83±0.03)μm
- Disadvantage
  - Need to integrate your sensor with DAQ AND online software.
- Advantages
  - Most of the work done for you
  - Only need 1 sensor



Standard telescope or bring your own

- Our ATLASPIx3 telescope.
- Advantages
  - Same DAQ system and software as in our labs when testing with cosmics.
  - Test several sensors at once.
- Disadvantages
  - Need to write own DAQ and online analysis software.
  - Need at least 4 sensors.



Alternatives to testbeam

- Cosmics
  - You can put a stack of detectors together and measure tracks.
  - Works just as well. However, there are issues.
    - Rate is low.
    - Beam is not parallel. This makes alignment very complicated.
    - You do not know the momenta and thus the error on the predicted position.
- Laser
  - The laser spot is usually much larger than the error on the predicted position.
  - Can be difficult to get signal in the sensor due to the metallization.
- Radio-active sources
  - Can use sources but you do not know where the particles hit and how many you have.
- Test charges/pulses
  - You essentially test the electronics only.

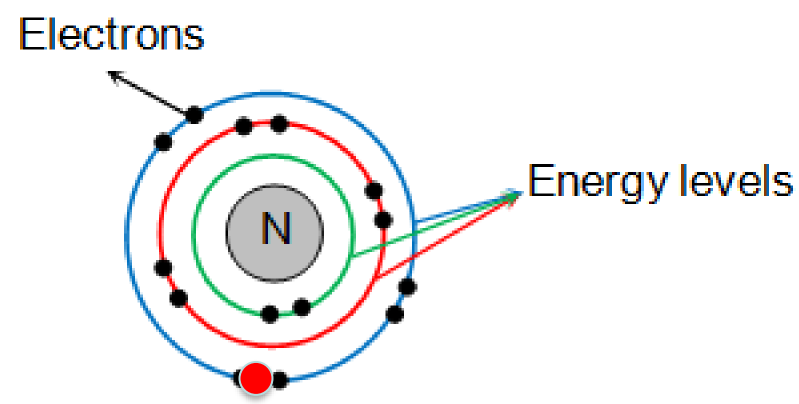
Summary

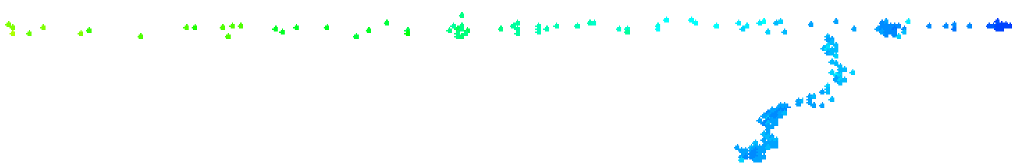
- In this lecture we discussed the basis behind test beams.
- Key issues
  - Need to understand your telescope and most importantly, the error on the predicted position.
  - Can fabricate all kinds of beautiful results if you do not report your efficiency and purity.
- Can do testbeams without a telescope using the grazing angle method.
  - There are also other alternatives that are almost just as good.
- Main places for test beam are: CERN, DESY & Fermilab.
- We discussed main complications.
  - Integration is complicated
  - Your telescope or standard one
- Good luck with your next test beam!

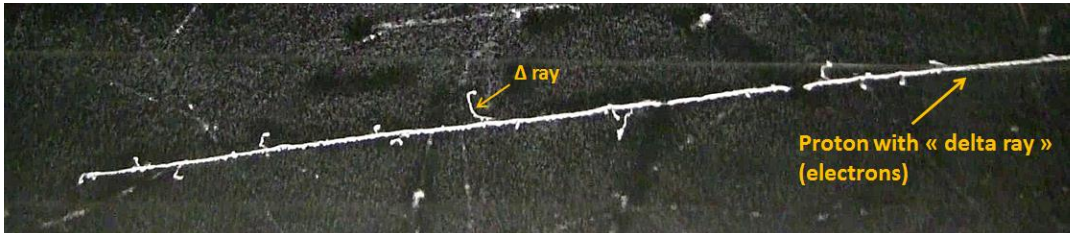
Back up

Energy loss – “remaining” electron

- If the electron gets enough energy, then it will ionize the atom.
- This electron is mobile! This is vital to our detection challenge.
- If it gets more energy, it will travel and ionize more atoms.
- These are low energy electrons so they will not travel far and deposit a lot of energy.
  - Called δ-electrons

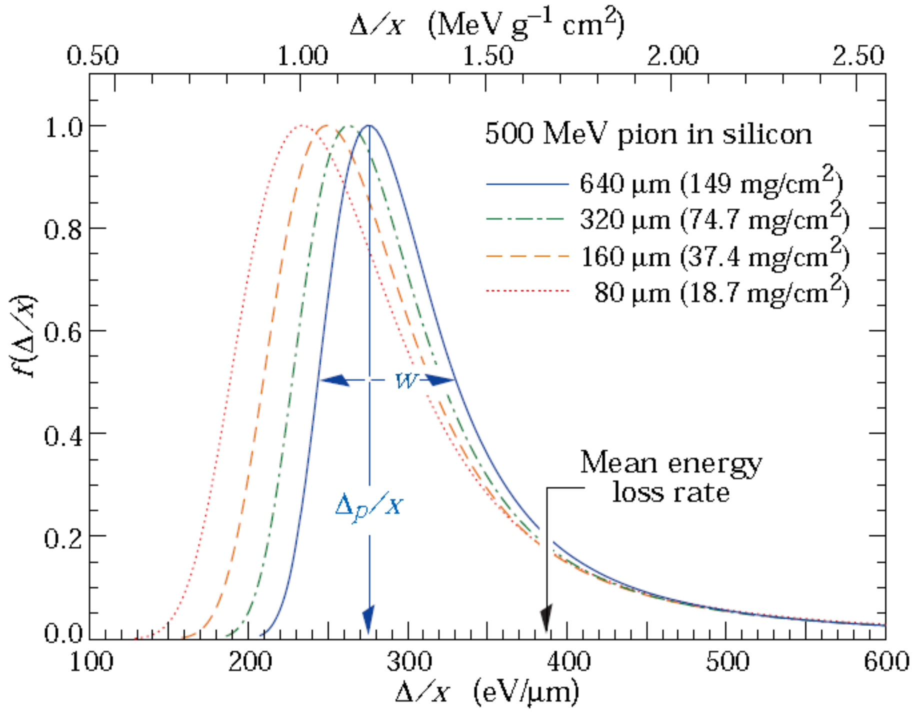






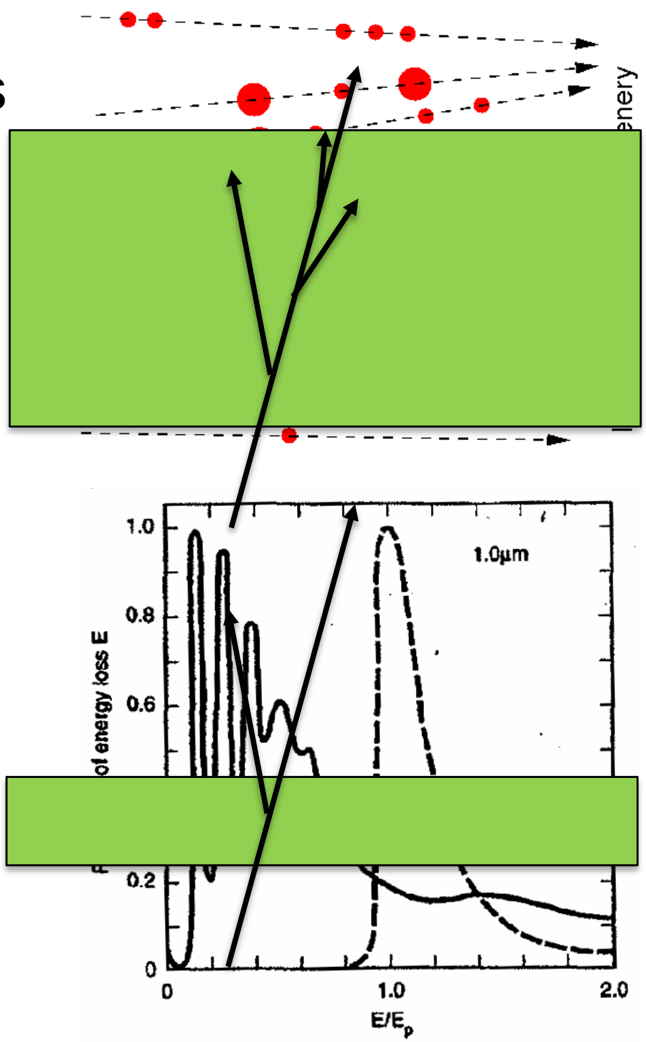
Energy loss: Landau distribution

- The amount of energy lost by a traversing particle will vary due to statistical fluctuations.
- The distribution looks like a Gaussian with a tail on the right. This is due to the δ's: some electrons get enough energy to ionise more particles.
  - δ's mostly go along the original particle direction, but can have big angles



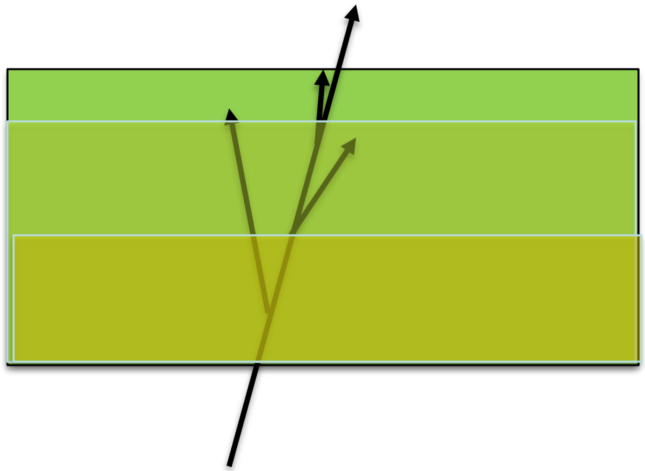
Energy loss: Landau distribution

- Landau assumed a thin detector with an infinite sea of free electrons. In practise this is not true.
- However, in practise the measured signal distributions look a lot like Landau distributions and any Gaussian with a tail signal distribution is called a Landau distribution.
- If the detectors get very thin, the distributions look very different.
- For thin detectors, thinner than say 10 or 20μm thick, there are not enough energy transfers to smooth out the distribution and the δ-rays reach the end of the detector material before they would stop.



Energy loss: Landau distribution

- The dependence on the thickness was measured.
- The plot shows that the energy loss per micron increases with increasing thickness.



- Very important when choosing detector thickness