Scattering studies with the DATURA beam telescope

Probing Highland & applications

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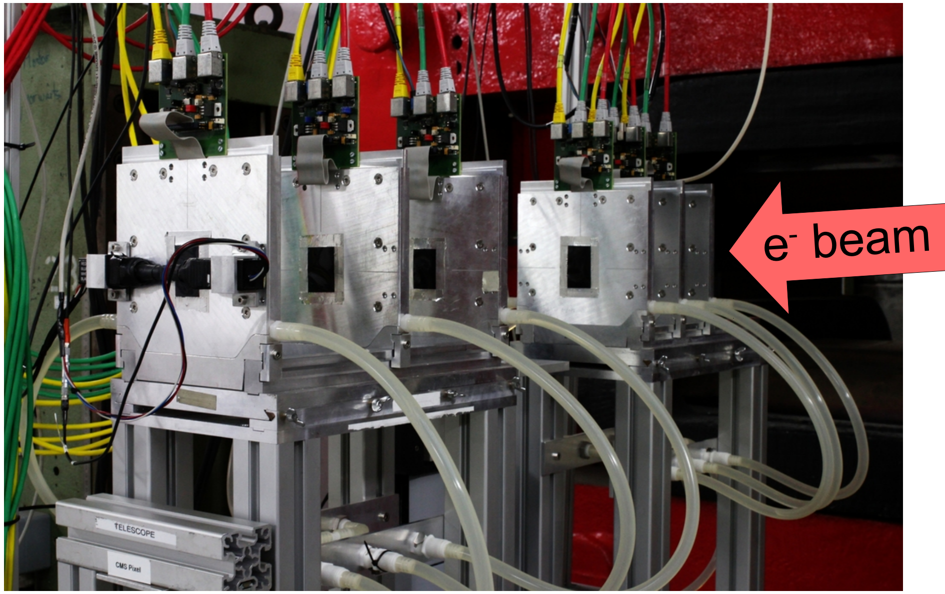
HELMHOLTZ ASSOCIATION

DESY

The DATURA beam telescope

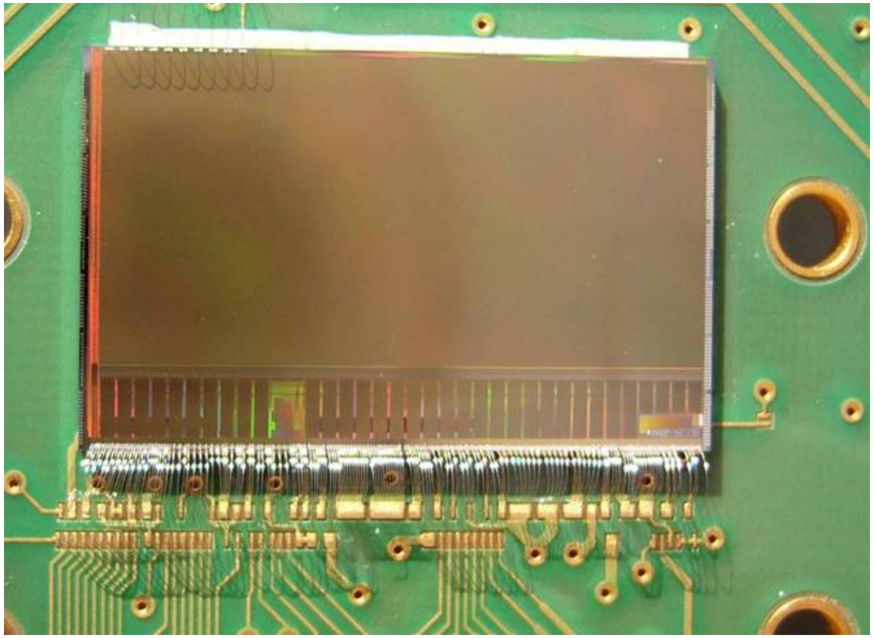
- Used extensively in sensor R&D
- Located at DESY TB hall 21
- Six Mimosa26 sensors
- NI-based DAQ system
- EUDET Trigger Logic Unit
  - Input: 4 scintillators
  - Output: Trigger to DAQ systems



- Connect multiple DUTs or additional reference sensors
- Available: x-y-phi stage for Device Under Test (DUT)

Goal:
→ Measure electron tracks passing DUTs
→ Perform track fits for multitude of studies

Mimosa 26 pixel sensors

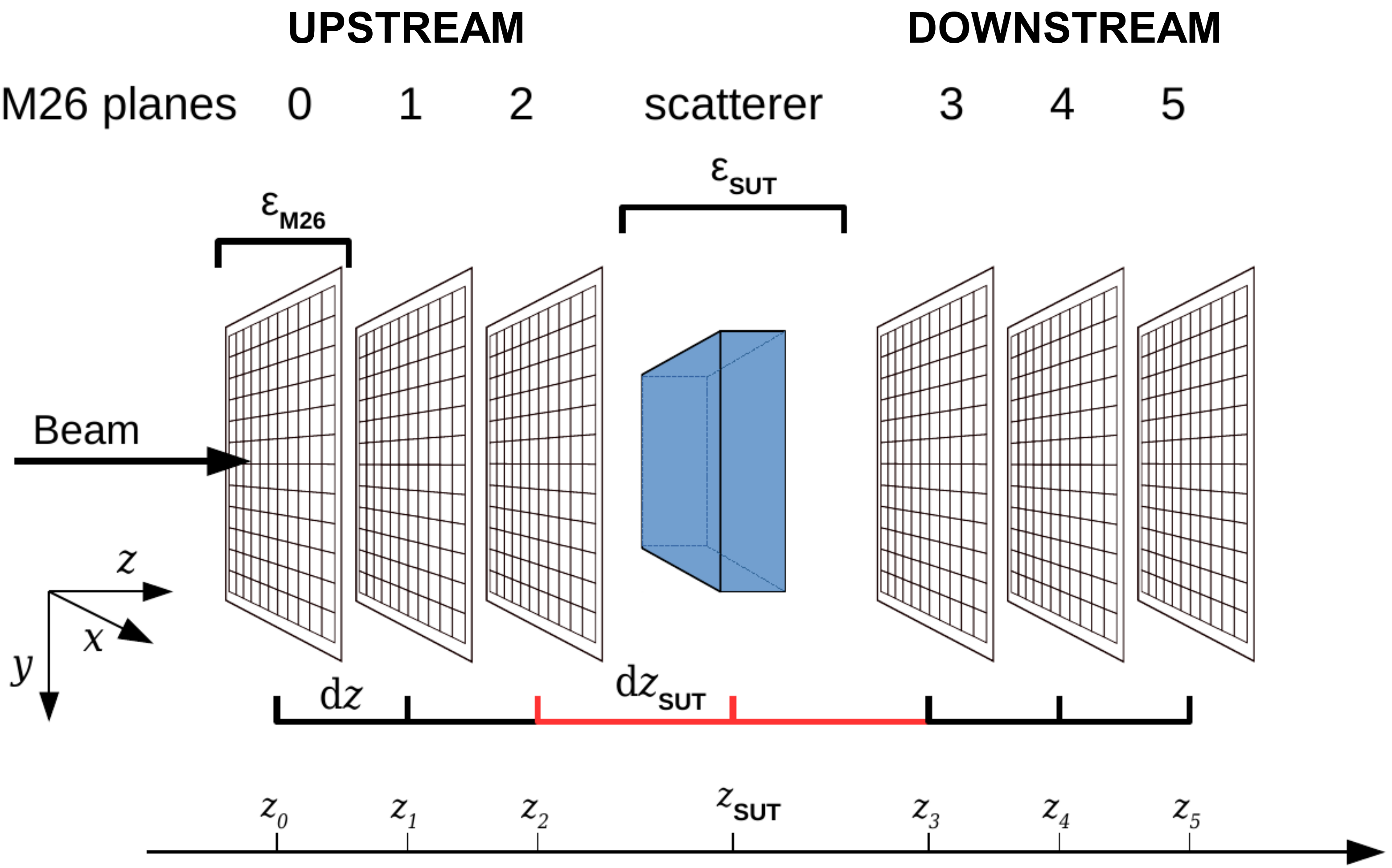


- AMS 350 nm CMOS
- Dimensions:
  - 10 mm x 20 mm / 50 um
  - 18.4 um x 18.4 um
  - 1152 x 576 pixels
- HR epitaxial layer of 20 um thickness
- Binary read-out (no charge information)
- Theoretical binary resolution: 5.3 um
- Measured intrinsic resolution: 3.24 um * (mean CS = 3.28 $)
- Protected by 25 um Kapton on each side
- Material budget of sensor plus Kapton: $\varepsilon_{M26} = x / X_0 = 7.5e\text{-}4$

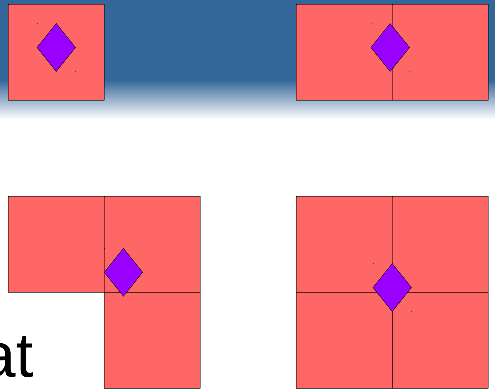
* Jansen et al., EPJ TI (2016) 3:7
$ Jansen, JINST (2016) 11 C12031

Measurement geometry

- Plane spacing dz = 20 mm, dz_{SUT} = 15 mm
- Total material budget telescope: ε(M26 + air) = 4.8e-3

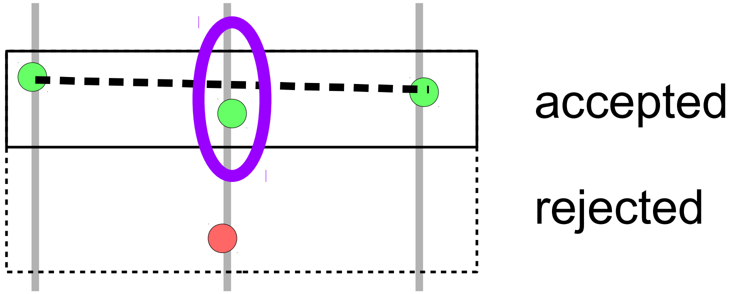


Data analysis flow

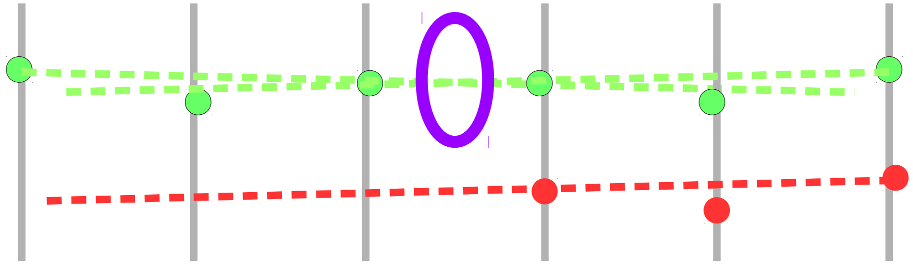


Analysis done with EUTelescope *

- Conversion of Mimosa26 raw data to LCIO format
- Hot pixel search
- Cluster formation, remove clusters with hot pixels
- Construct triplets for up- and downstream plane
- Isolation cut on triplets



- Match up- and downstream triplets in the centre → *six-tuple* from physical track

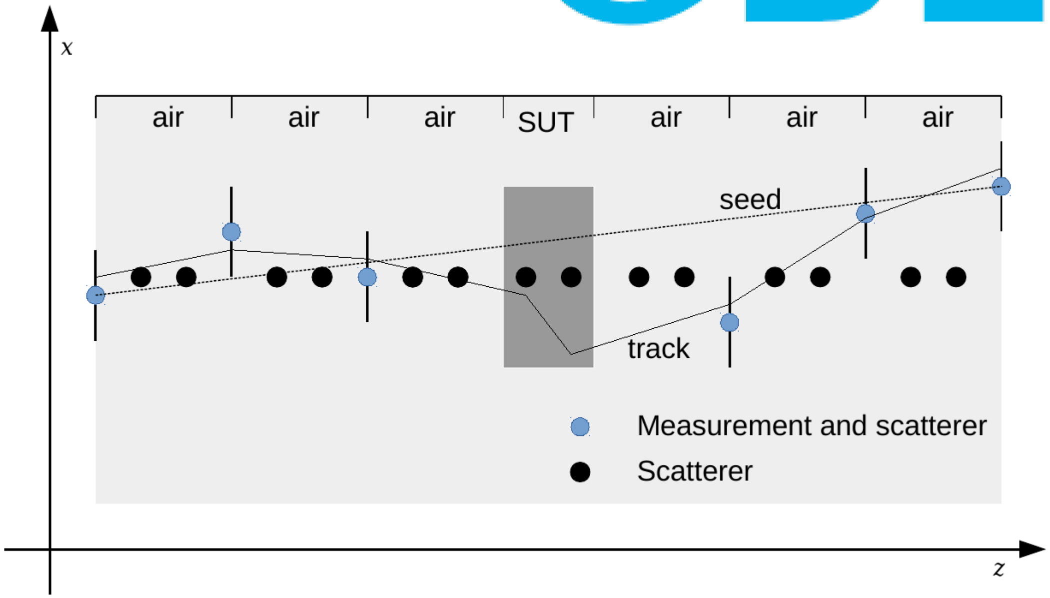


- Feed six-tuple to Millepede for alignment

* http://eutelescope.web.cern.ch/

General Broken Lines

- GBL track model allows for kinks at scatterers
- Calculating corrections to an initial simple seed track
- Perform χ^2 minimisation to find track parameters
- Simple track model:
  no bremsstrahlung, no non-Gaussian tails, no non-linear effects
- Inputs: *Measurement + error*, geometry, scattering estimate
- Outputs: residuals, residual width, kinks, track resolution



www.desy.de/~kleinwrt/GBL/doc/cpp/html/

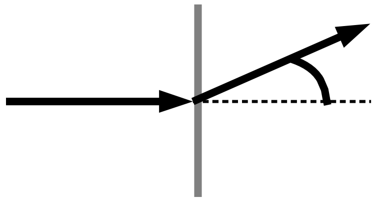
V. Blobel, C. Kleinwort, and F. Meier. Fast alignment of a complex tracking detector using advanced track models. Computer Physics Communications, 182(9):1760 – 1763, 2011.

C. Kleinwort. General broken lines as advanced track fitting method. Nucl. Instr. Meth. Phys. Res. A, 673:107–110, May 2012.

Multiple scattering

- Variance predicted by Highland at a single scatterer:

$$\Theta_0^2 = \left(\frac{13.6\ \text{MeV}}{\beta c p} \cdot z\right)^2 \cdot \varepsilon \cdot \left(1 + 0.038 \cdot \ln\left(\varepsilon\right)\right)^2$$

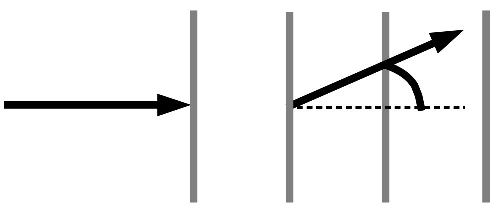


- For a composition of scatterers

$$\varepsilon = \sum \varepsilon_i$$

Highland predicts variance after ***last*** scatterer

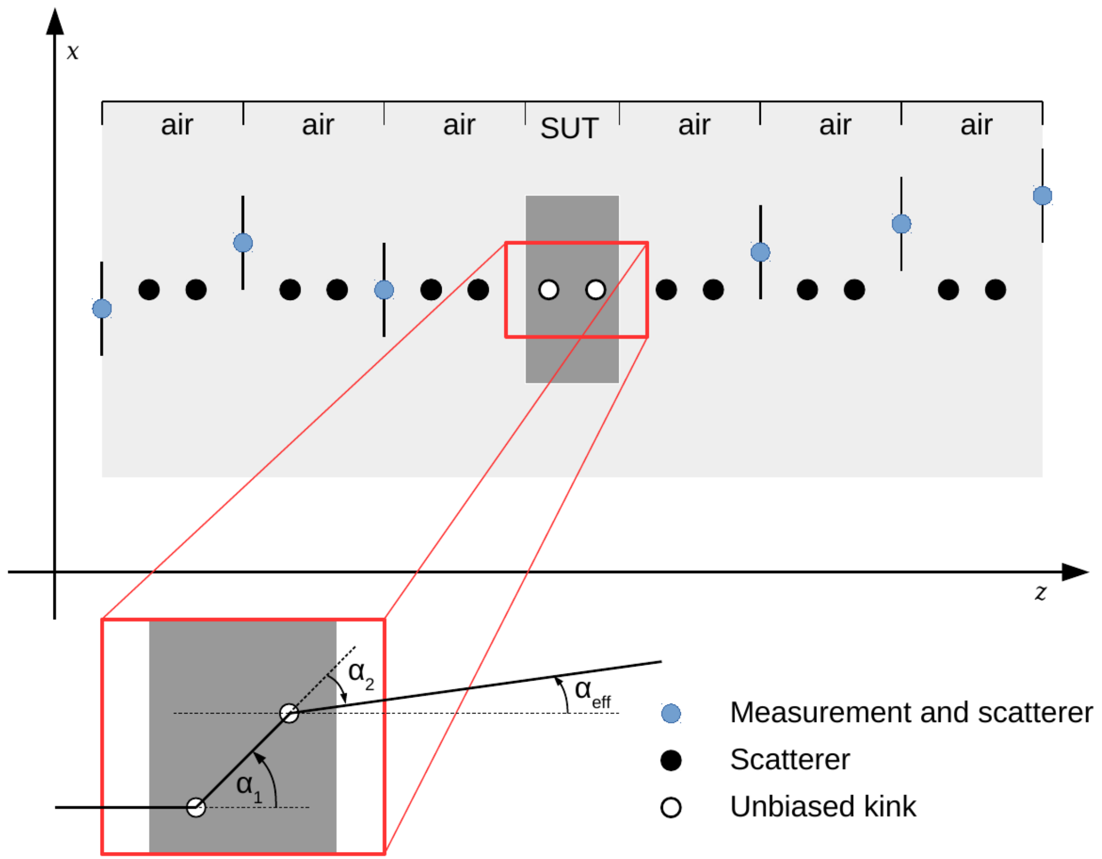
- For individual scatterer within composition:



$$\Theta_{0,i}^2 \equiv \frac{\varepsilon_i}{\varepsilon} \cdot \Theta_0^2 = \left(\frac{13.6\ \text{MeV}}{\beta c p} \cdot z\right)^2 \cdot \varepsilon_i \cdot \left(1 + 0.038 \cdot \ln\left(\varepsilon\right)\right)^2$$

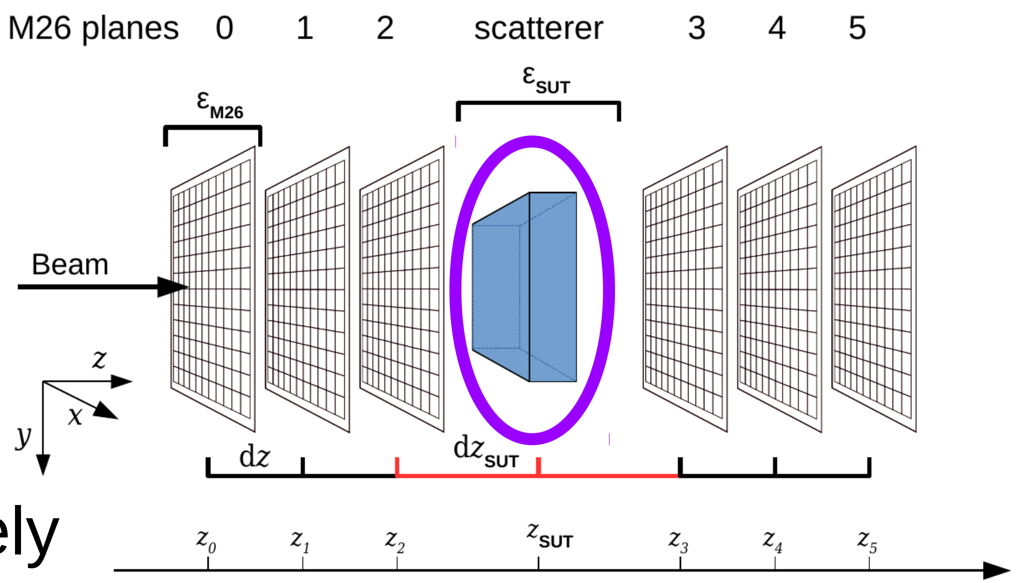
Unbiased kinks

- Last slides: scatterers of ***known*** material budget
  → constrained kink angle in χ^2 (biased)
- Goal: kink for ***unknown*** scatterer (unbiased)
  → introduce free local parameters in track model
    → dedicated track model for unbiased kinks



Targets and measurements

- Homogeneous targets
  - aluminium sheets of thicknesses:
    empty, 25 , 50 , 100, 200, 1000 um
  - energies: 1 – 5 GeV
- Inhomogeneous target
  - coaxial connector



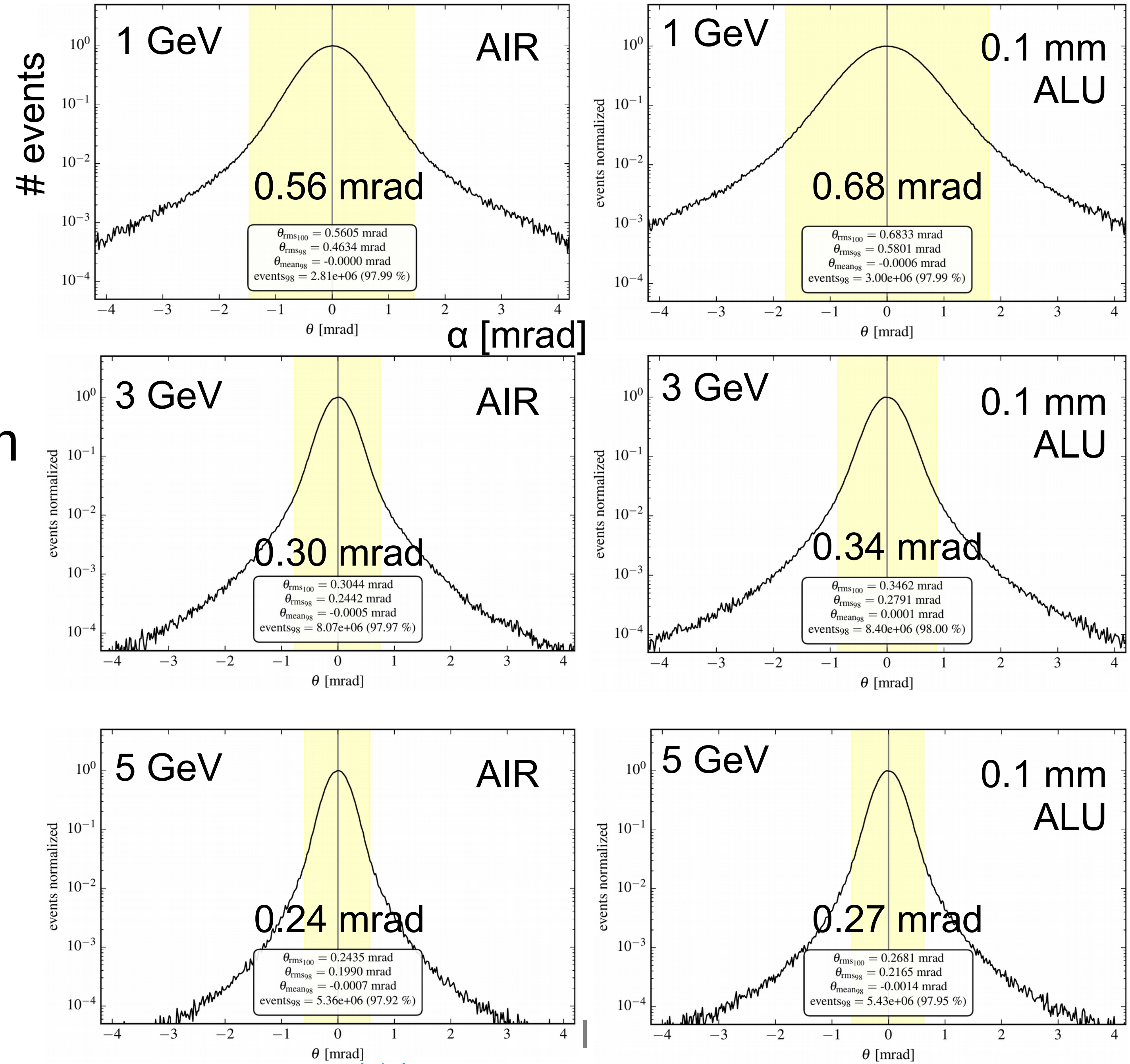
- Excellent angular resolution
  → measure kink angle precisely
    → calculate material budget
- Excellent position resolution
  → measure impact position on sample
    → position-resolved material budget

Kink angles

preliminary

- Kink angle distribution for various energies

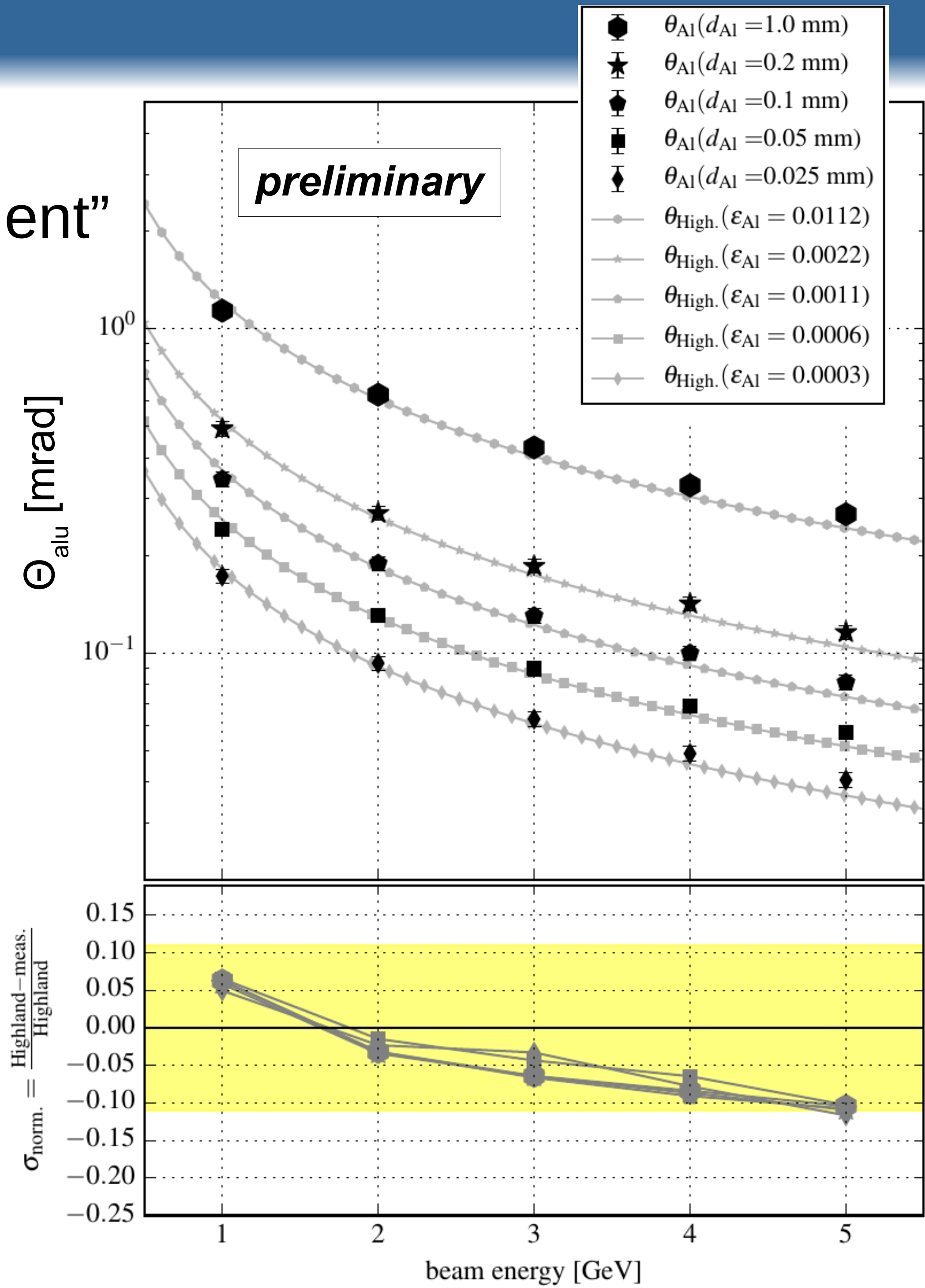
- ➔ Measurable difference for 100 um aluminium
- ➔ Clear energy-dependence
- ➔ Large statistics → populated tails



Kink angles II

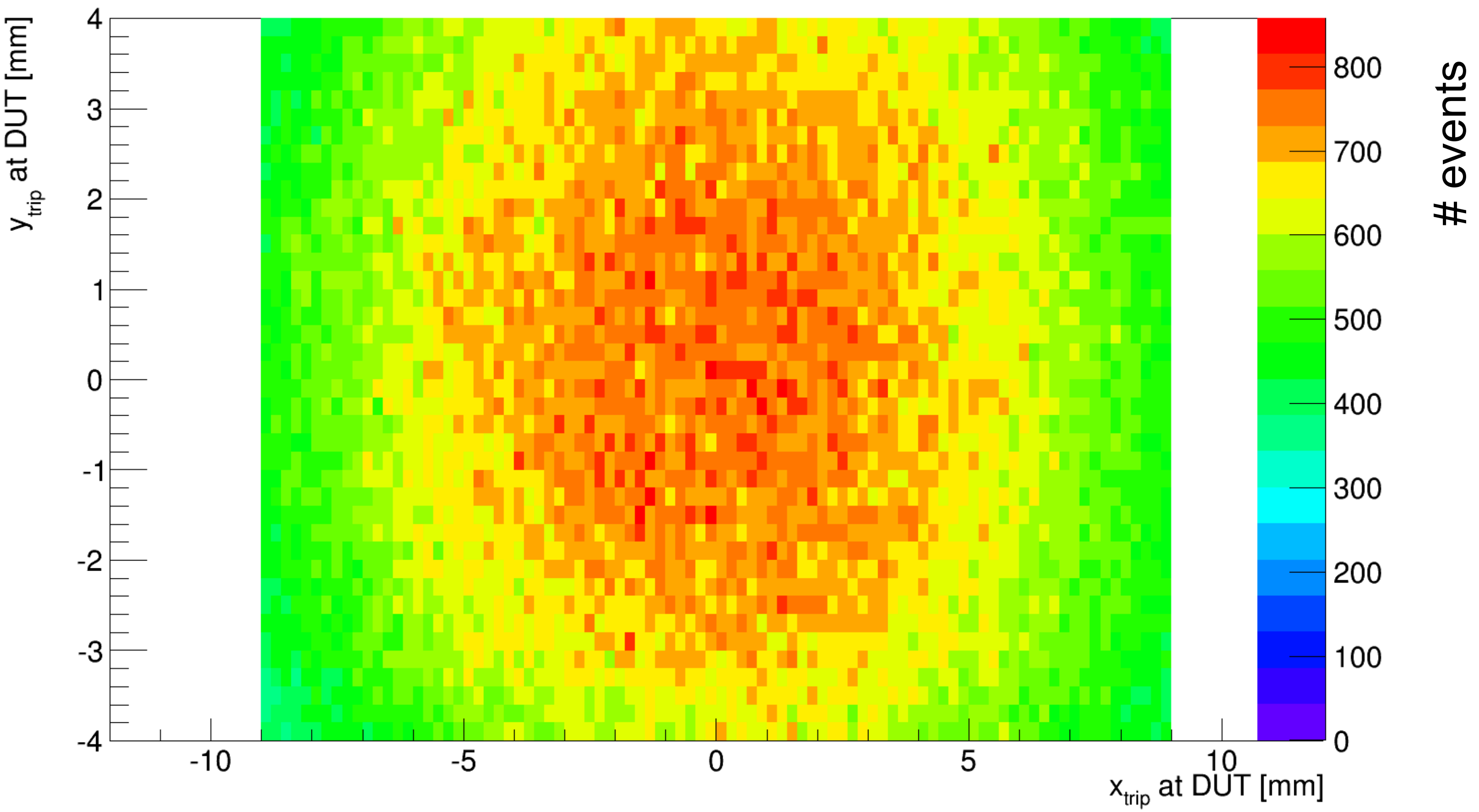
- Measurement of aluminium includes "empty measurement" → apply correction

- Results within ~10% of Highland prediction for 1 – 3 GeV
- Energy-dependence to be understood (work in progress)
- Method yields reasonable kink estimates



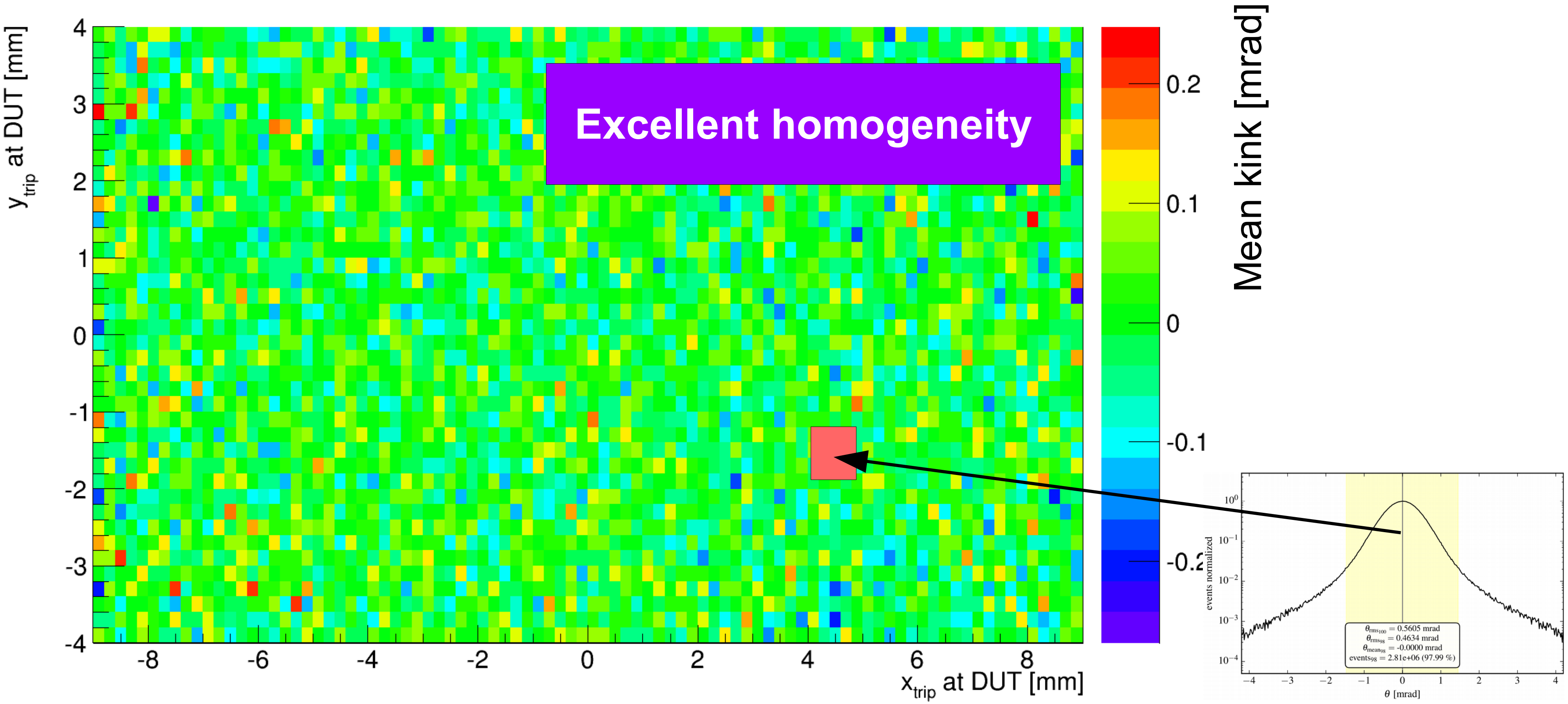
2D analysis – events

- Map of homogeneous sample 1 GeV, 1 mm alu
- ➔ Beam spot at centre of sample



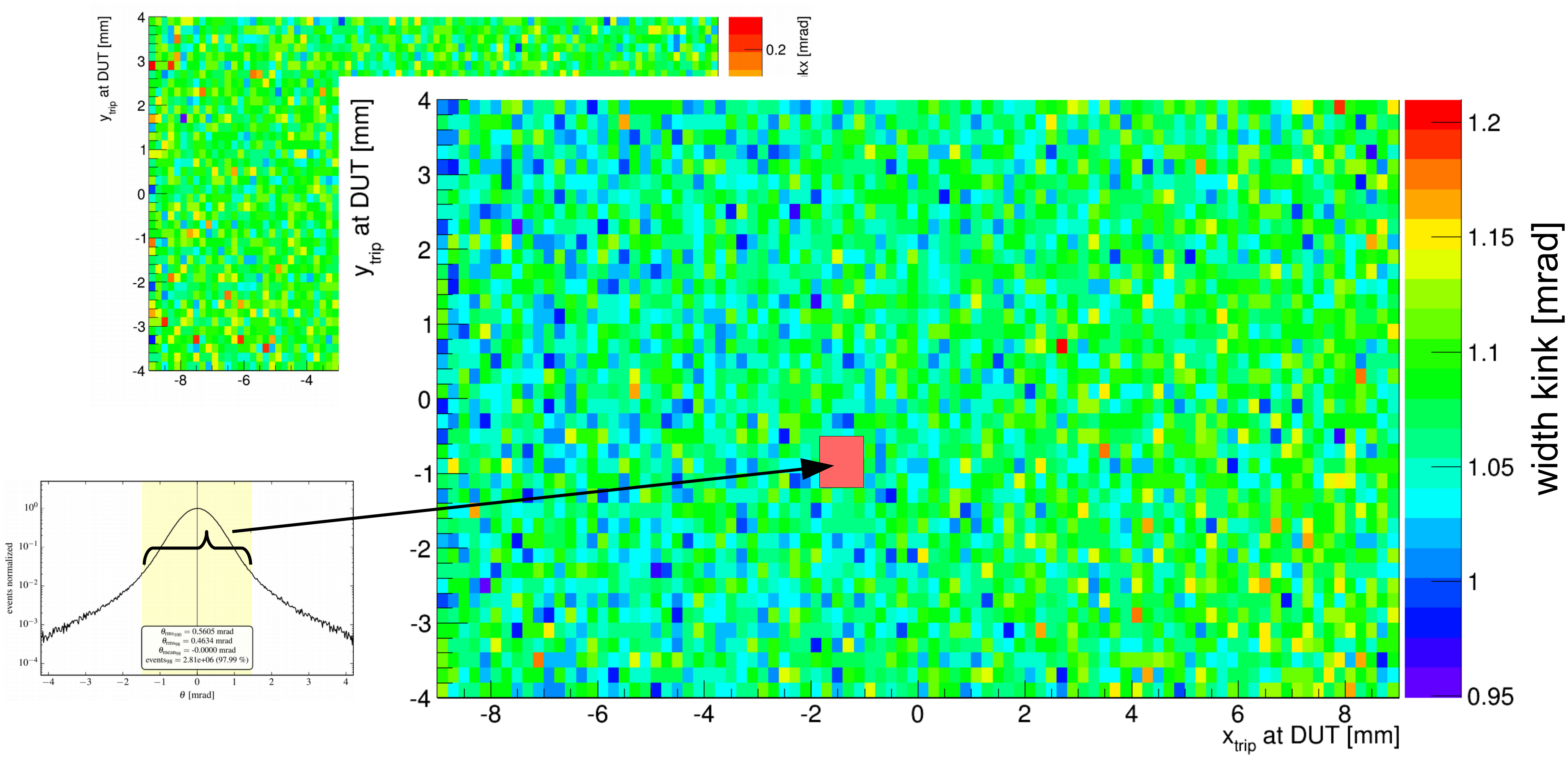
2D analysis – mean

- 2D map of homogeneous sample 1 GeV, 1 mm alu
- Mean values of bins mostly ~zero



2D analysis – width

- 2D map of homogeneous sample 1 GeV, 1 mm alu
- Mean values of bins mostly ~zero
- Widths of bins show slight trend from left → right



2D analysis – width II

- 2D map of homogeneous sample 1 GeV, 1 mm alu
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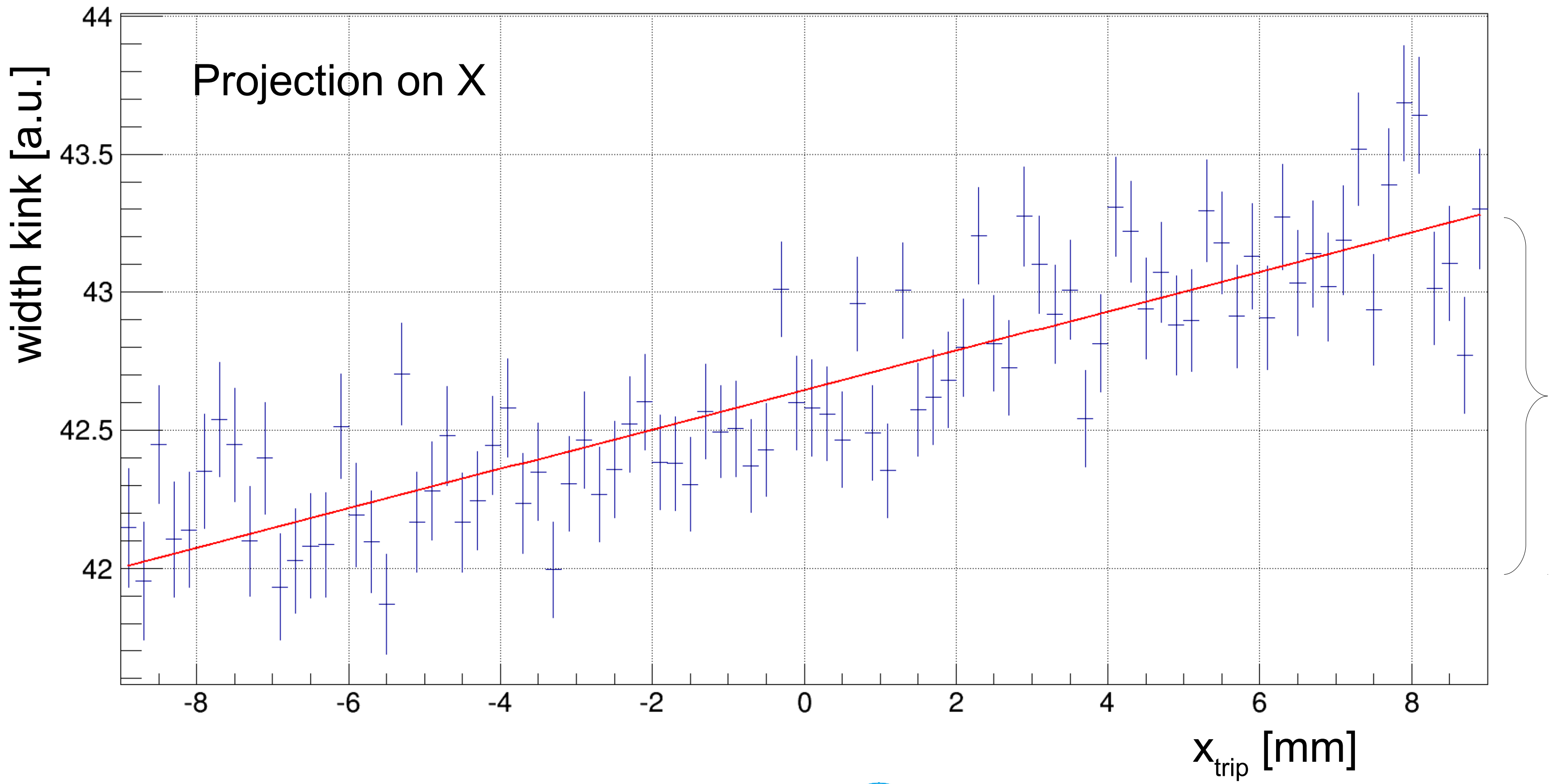
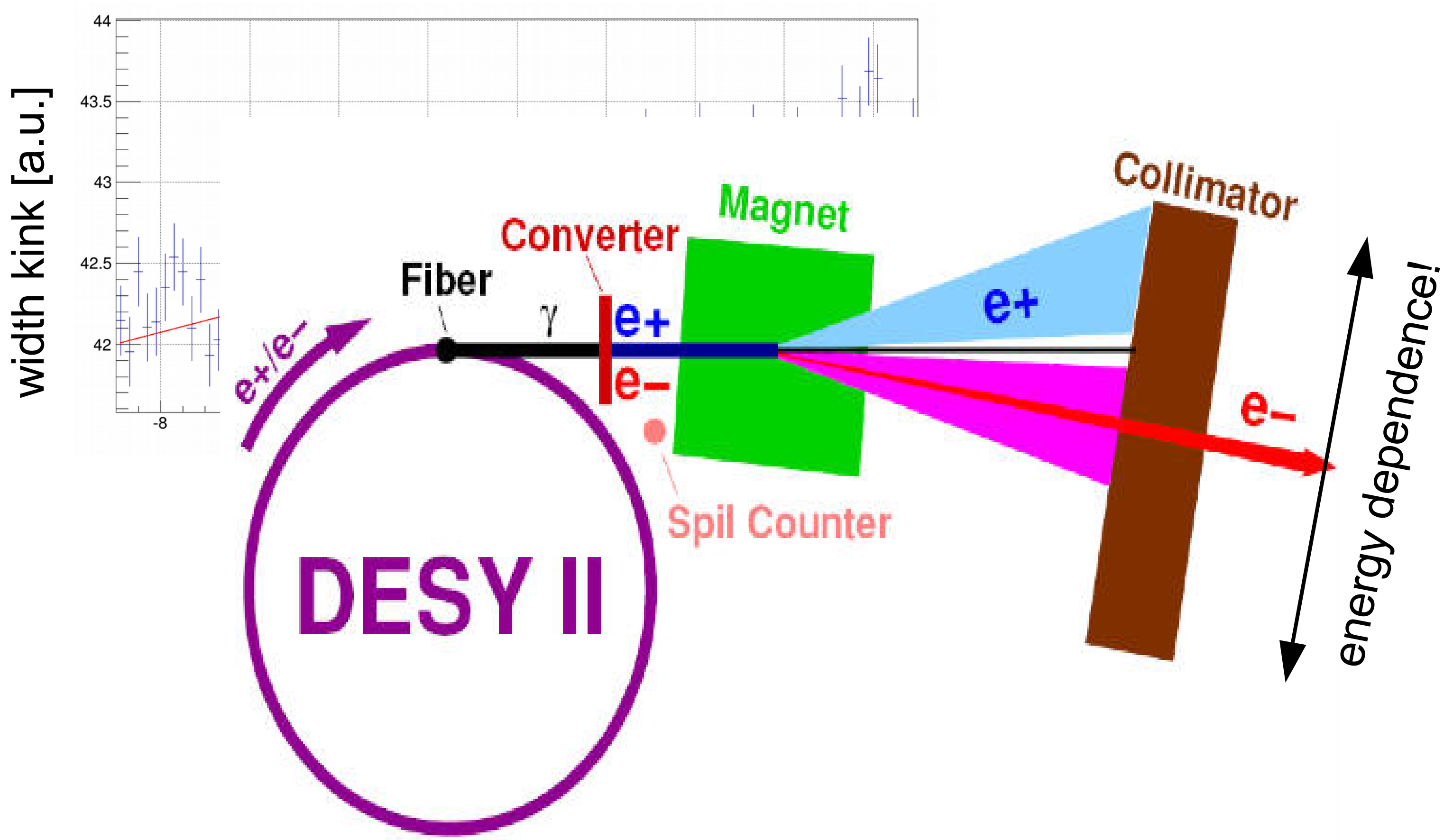


3 % over 18 mm

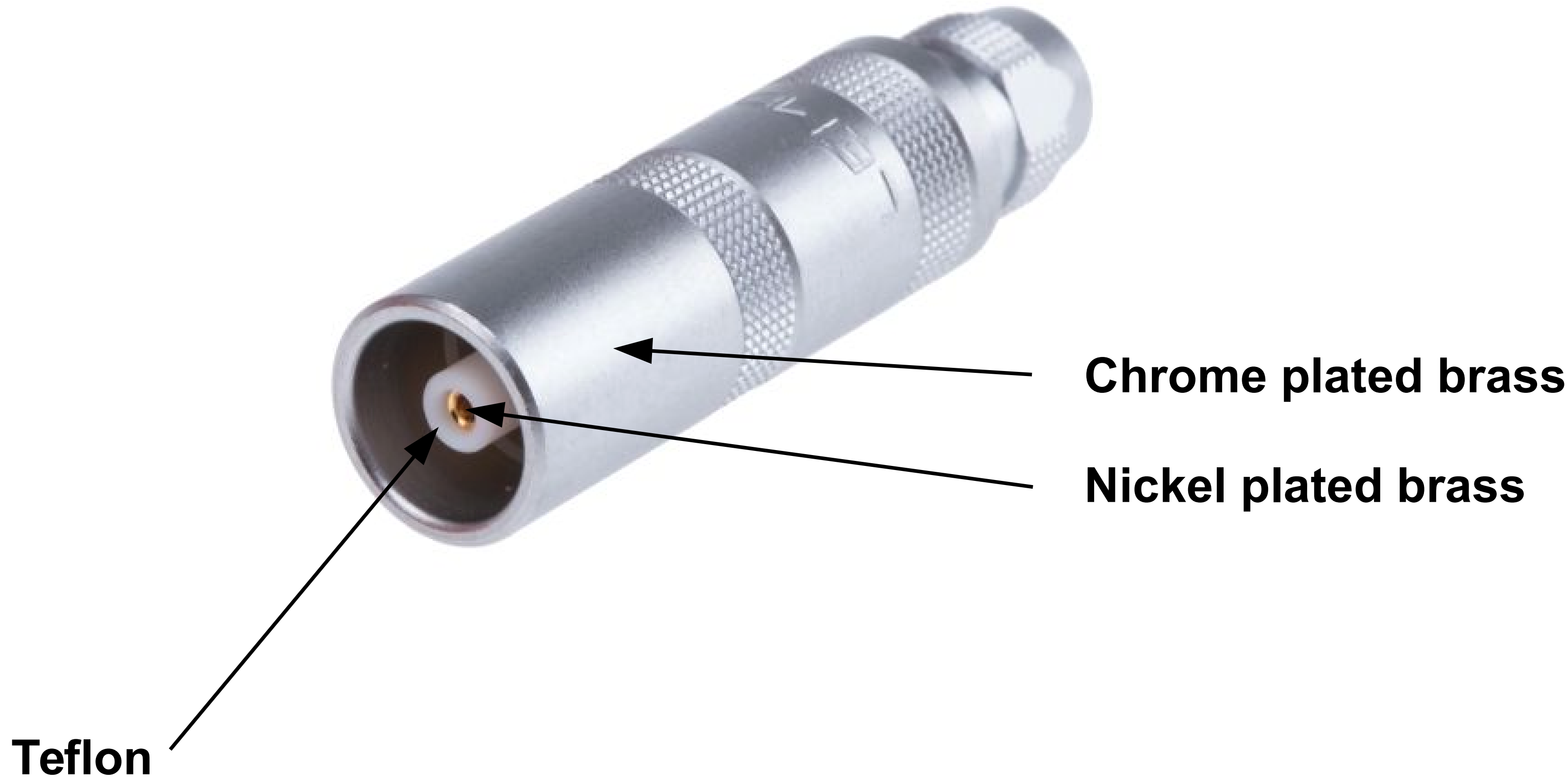
2D analysis – width II

- 2D map of homogeneous sample 1 GeV, 1 mm alu
- Mean values of bins mostly ~zero
- Widths of bins show slight trend from left → right



Inhomogeneous sample

- Can we resolve structured samples?
  → electron-illuminated a coax connector



Inhomogeneous sample

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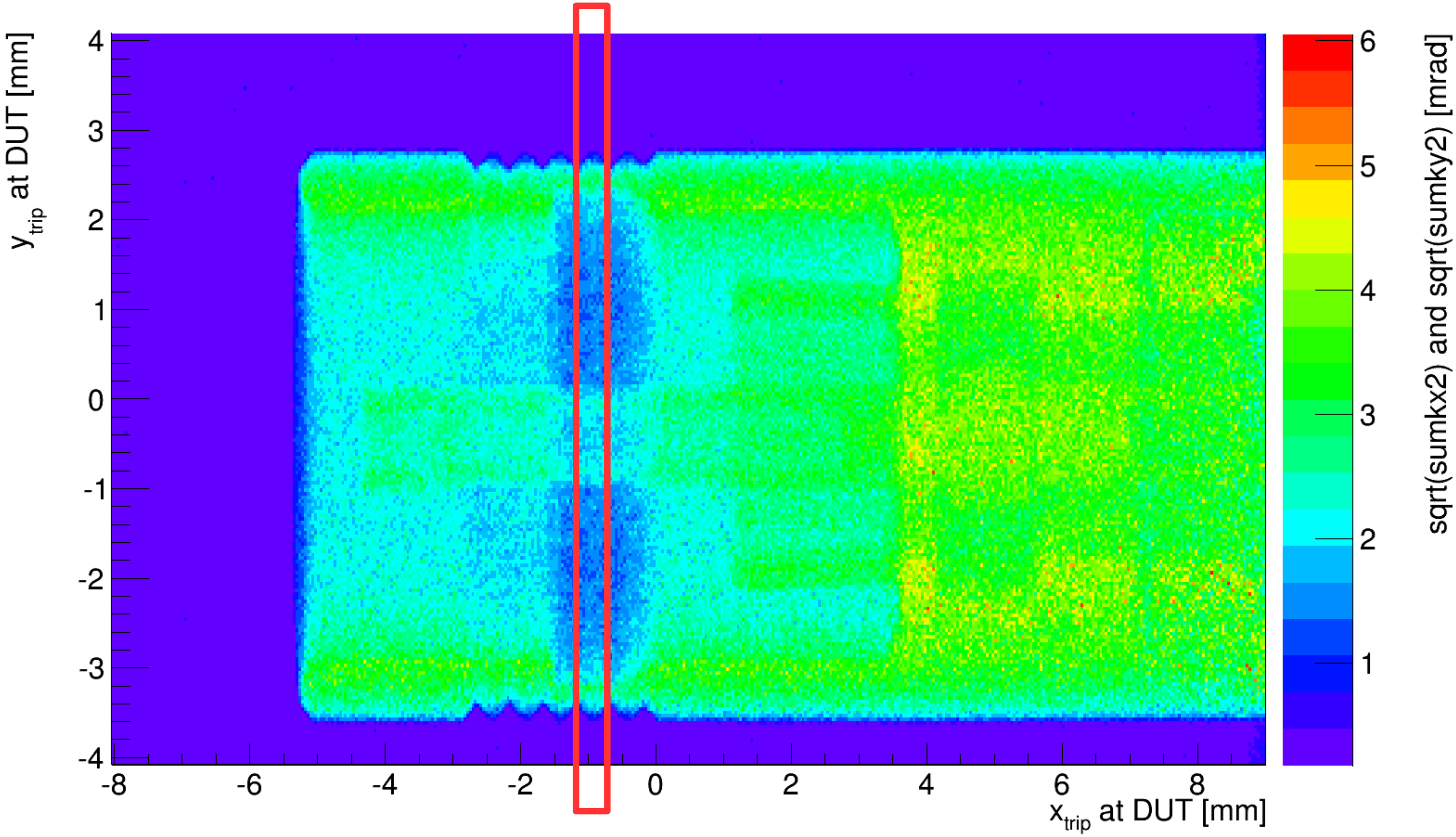
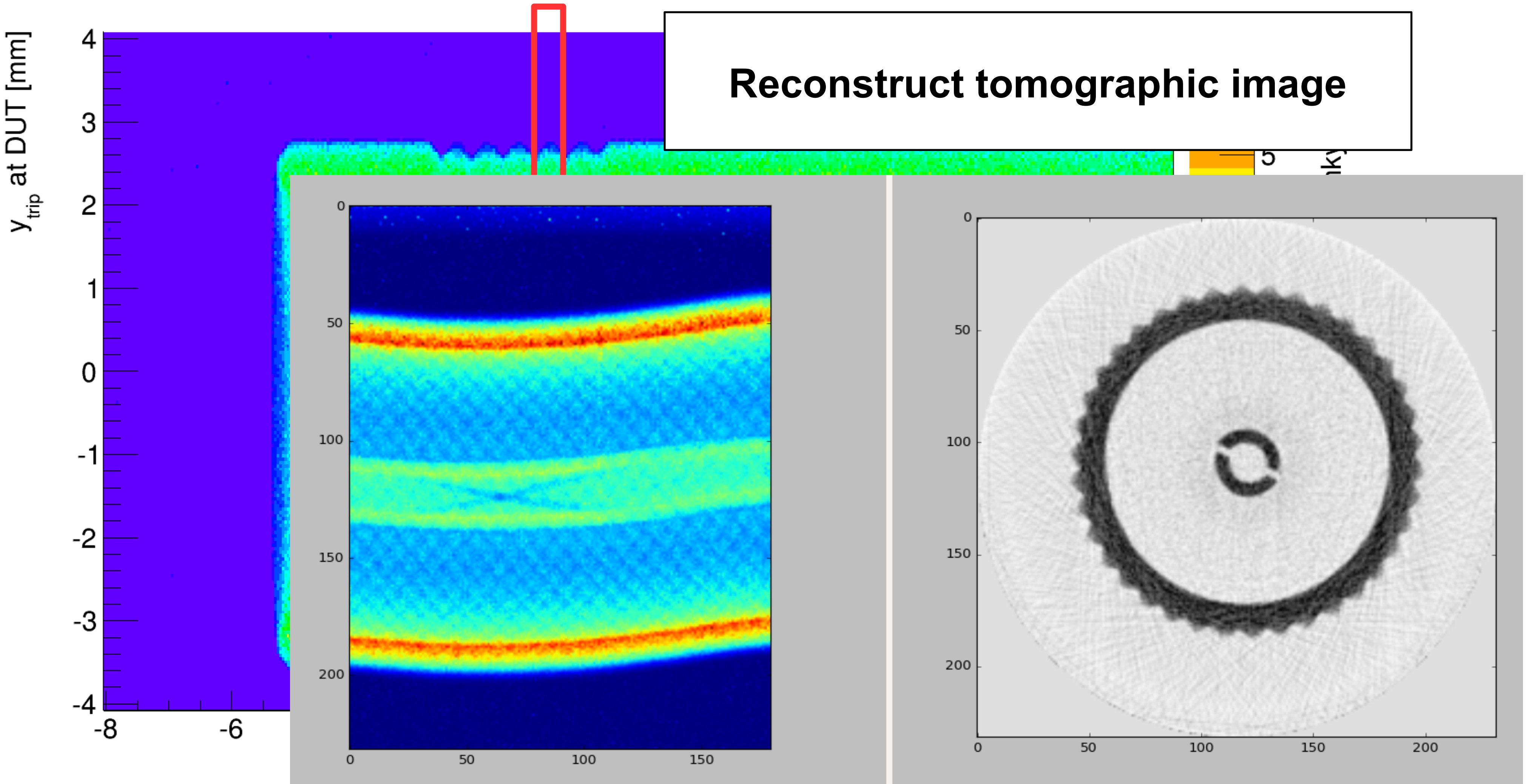


Inhomogeneous sample

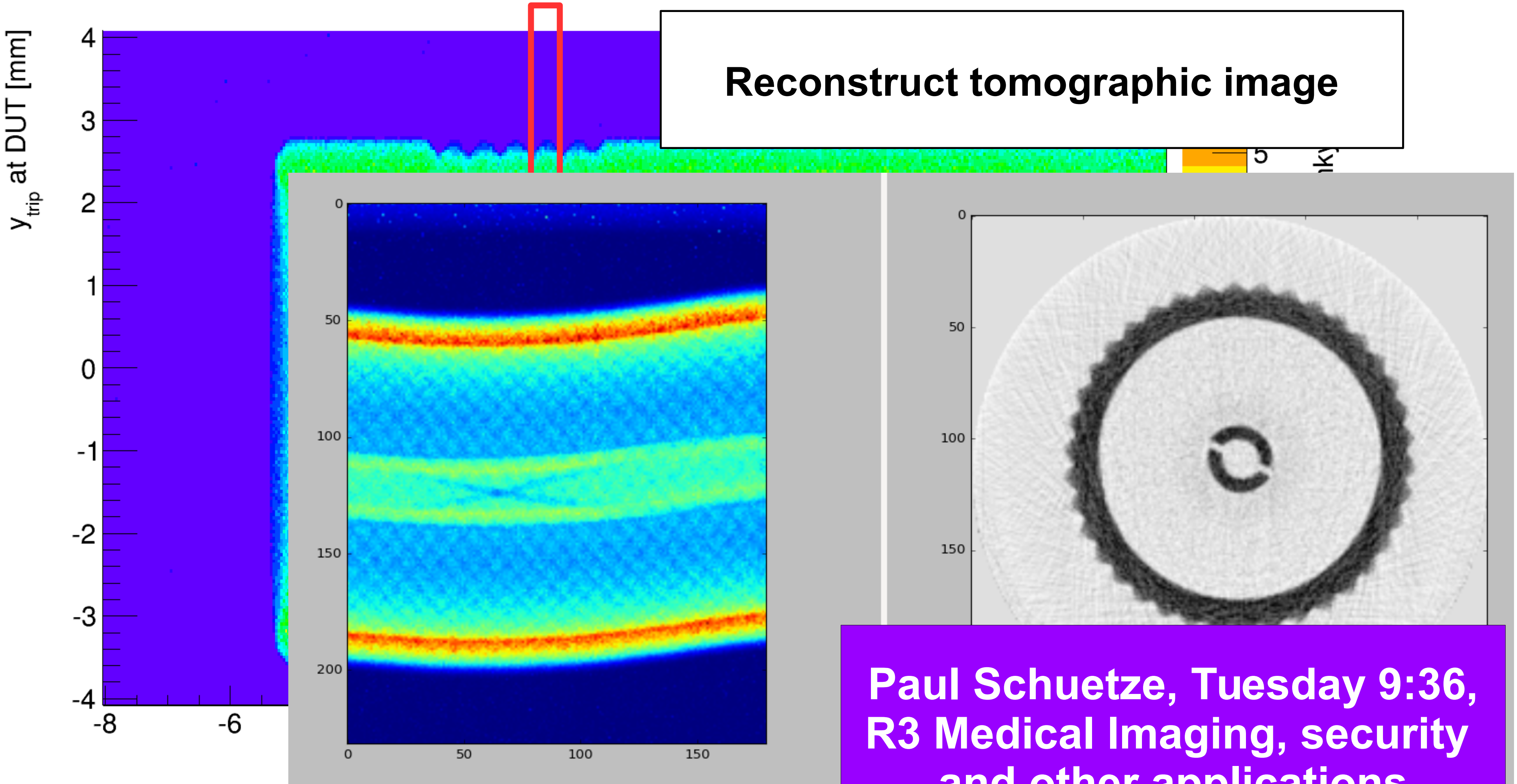
- Can we resolve structured samples?
  → electron-illuminated a coax connector

Reconstruct tomographic image



Inhomogeneous sample

- Can we resolve structured samples?
  → electron-illuminated a coax connector



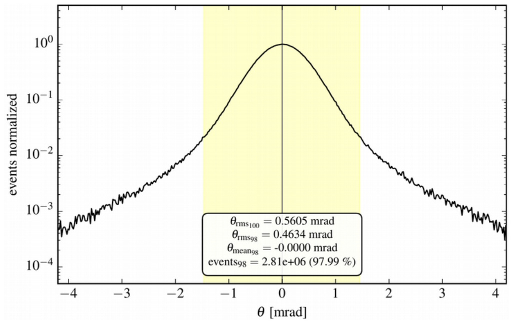
Reconstruct tomographic image

Paul Schuetze, Tuesday 9:36, R3 Medical Imaging, security and other applications

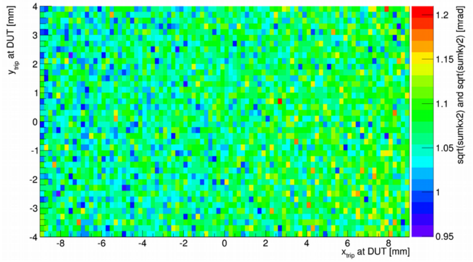
Potential

$$\Theta_0^2 = \left(\frac{13.6\,\mathrm{MeV}}{\beta c p}\cdot z\right)^2 \cdot \varepsilon \cdot \left(1 + 0.038 \cdot \ln(\varepsilon)\right)^2$$

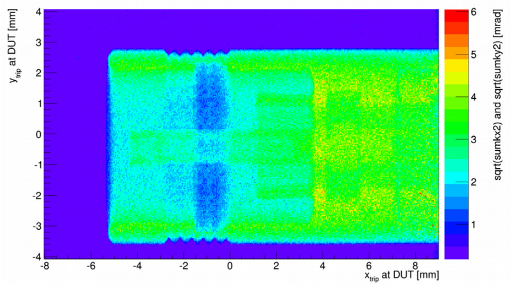
- **For known thickness, homogeneous sample**
  - measure kink width
  - → for known E → calculate X_0 from Highland
  - → for known X_0 → measure beam E to %-level



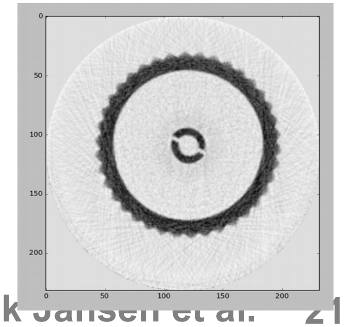
  - measure position-resolved kink width
  - → probe homogeneity of measurement for corrections



- **For inhomogeneous sample**
  - measure position-resolved kink width
  - → material budget map



- **For sample with `internal structure'**
  - measure position-resolved kink width
  - repeat for different sample angles
    - → Tomography



Conclusion

- Performed scattering study with DATURA beam telescope
- Precise tool:
  - few um track resolution
  - few tens urad angular resolution of kinks
- Implemented GBL tracking with dedicated track model for unbiased kink angle
- Measure position-resolved material budget
- Large range of applications

Dedicated BTTB workshop for test beam users

If you publish your analysis with a EUDET-type beam telescope, please cite:
Hendrik Jansen, et al., "Performance of the EUDET-type beam telescopes", EPJ Techn Instrum (2016) 3: 7, https://doi.org/10.1140/epjti/s40485-016-0033-2

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6th Beam Telescopes and Test Beams Workshop

Zurich, Switzerland

January 16th – 19th, 2018

cern egroup:
BeamTelescopesAndTestBeams-Announcements@cern.ch

bttb-ws@desy.de

Back-up

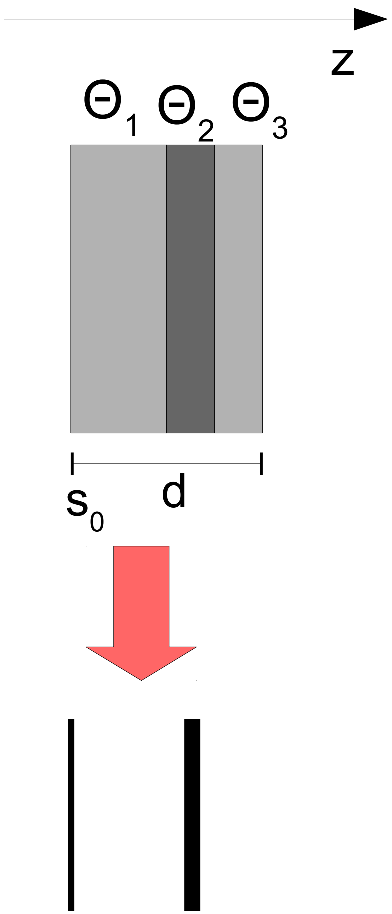
A word on thick scatterers

- Assume a non-homogeneous scatterer along z
- Describe with three parameters:
  length s, mean $\bar{s}$, variance Δs2

$$\theta^2 = \sum_i \theta_i^2, \quad \bar{s} = \frac{1}{\theta^2}\sum_i s_i \theta_i^2, \quad \Delta s^2 = \frac{1}{\theta^2}\sum_i (s_i - \bar{s})^2 \theta_i^2$$

- Find a toy scatterer composed of two thin scatterers resembling the thick scatterer;
  s_1, s_2, Θ_1, Θ2.
  - e.g. for homogeneous scatterer
    - $s_1 = \bar{s}$ – d/sqrt(12)
    - $s_2 = \bar{s}$ + d/sqrt(12)
    - $\Theta_1 = \Theta_2 = \Theta/2$
  - e.g. for inhomogeneous scatterer

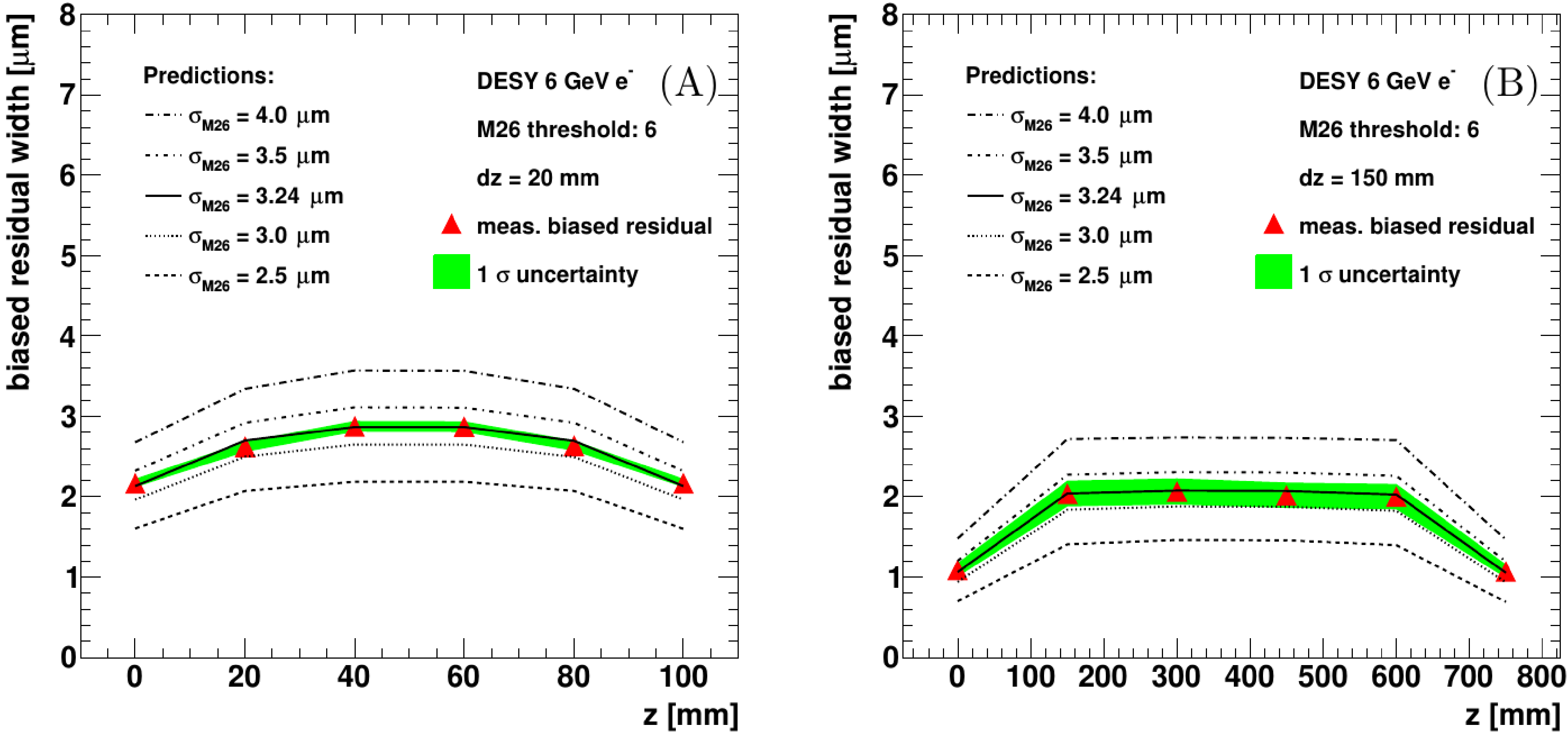
$$s_1 = s_0, \quad s_2 = \bar{s} + \frac{\Delta s^2}{\bar{s} - s_1}, \quad \theta_1^2 = \theta^2 \frac{\Delta s^2}{\Delta s^2 + (\bar{s} - s_1)^2}, \quad \theta_2^2 = \theta^2 \frac{(\bar{s} - s_1)^2}{\Delta s^2 + (\bar{s} - s_1)^2}$$



Offline analysis and reconstruction

- EUTelescope is based on the ILCSoft framework:
  - generic data model (LCIO)
  - geometry description (GEAR)
  - central event processor (Marlin)
- Marlin allows for modular composition of analysis chain
- Build-in job submission framework
- Steering of analysis via XML files loaded at runtime
- EUTelescope provides processors for full track reco including:
  - Alignment with Millepede-II
  - General Broken Lines track fitter
  - many more

Biased residuals III

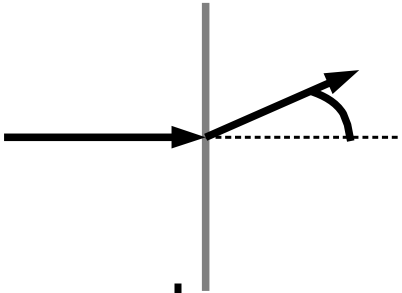


→ **Average intrinsic resolution:** $\sigma_{\mathrm{M26}} = (3.24 \pm 0.09)\ \mu\mathrm{m}$

Multiple scattering

- Average deflection predicted by Highland

$$\Theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} \cdot z\sqrt{\varepsilon} \cdot \left(1 + 0.038 \ln\left(\varepsilon\right)\right)$$



- Literature offers other models, too, HL most popular
- Distribution assumed to be Gaussian centrally
- Non-Gaussian tails
- MS and intrinsic resolution defines *track resolution*, i.e. uncertainty in space of a track along the track

Biased residuals and pulls

- Biased residual = (measurement – fit) including all 6 planes
- Normalise residual by expected residual width

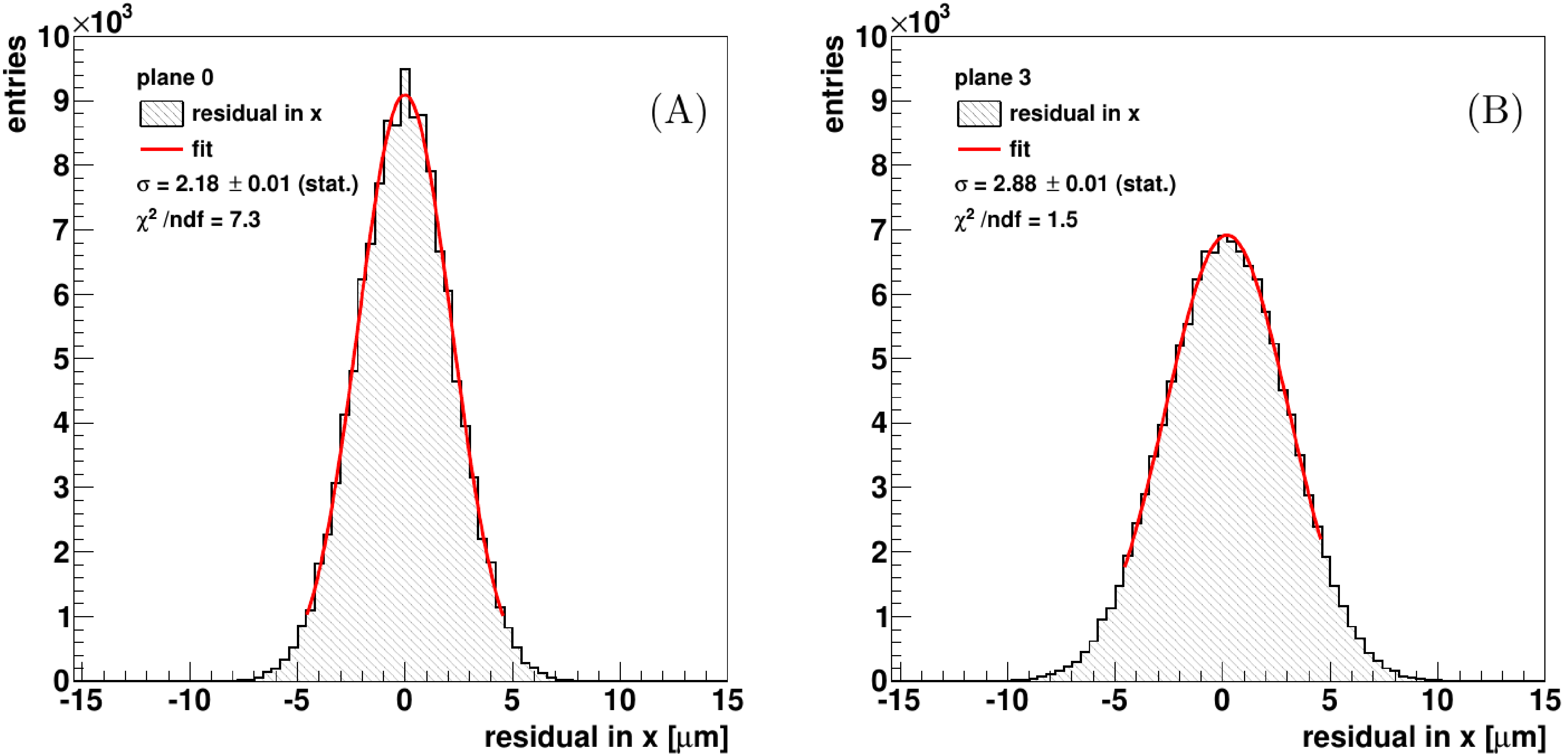
$$\mathrm{pull_b} \equiv p_\mathrm{b} = \frac{r_\mathrm{b}}{\sqrt{\sigma^2_\mathrm{int} - \sigma^2_\mathrm{t,b}}}$$

Prediction from GBL

- Pull is N(0,1) if
  - estimate for intrinsic resolution matches true value
  - material budget and scattering is accurately described

→ **Iterate** track fit with updated σ_{int} and $\sigma_{t,b}$ using the pull width
→ $\mathrm{pull_b}$ → N(0,1) and σ_{int} converges against true value
→ Use results from narrow and wide set-up for cross validation

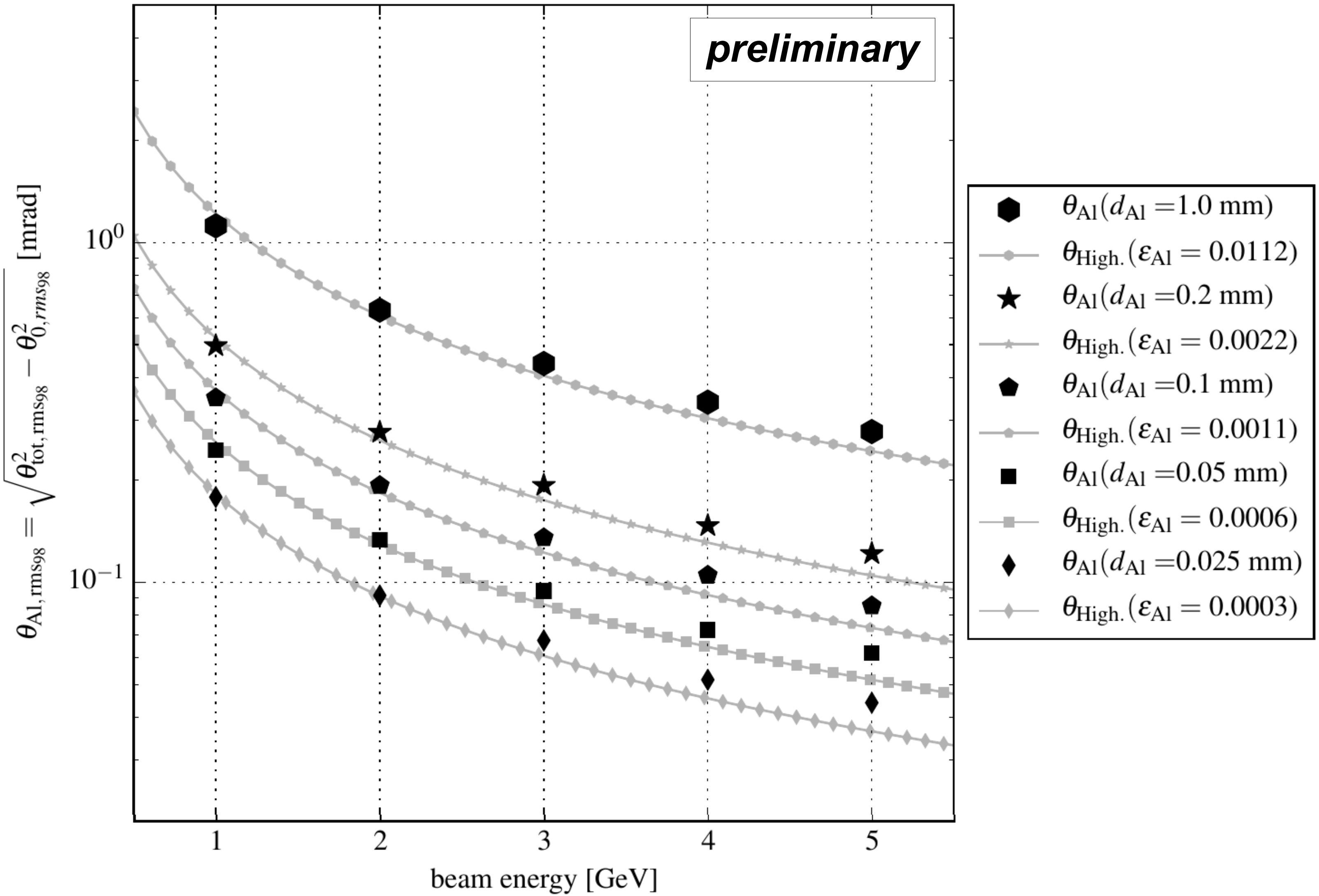
Biased residuals



Quoted is a Gaussian width (95%), but actually RMS is within 1% of this value

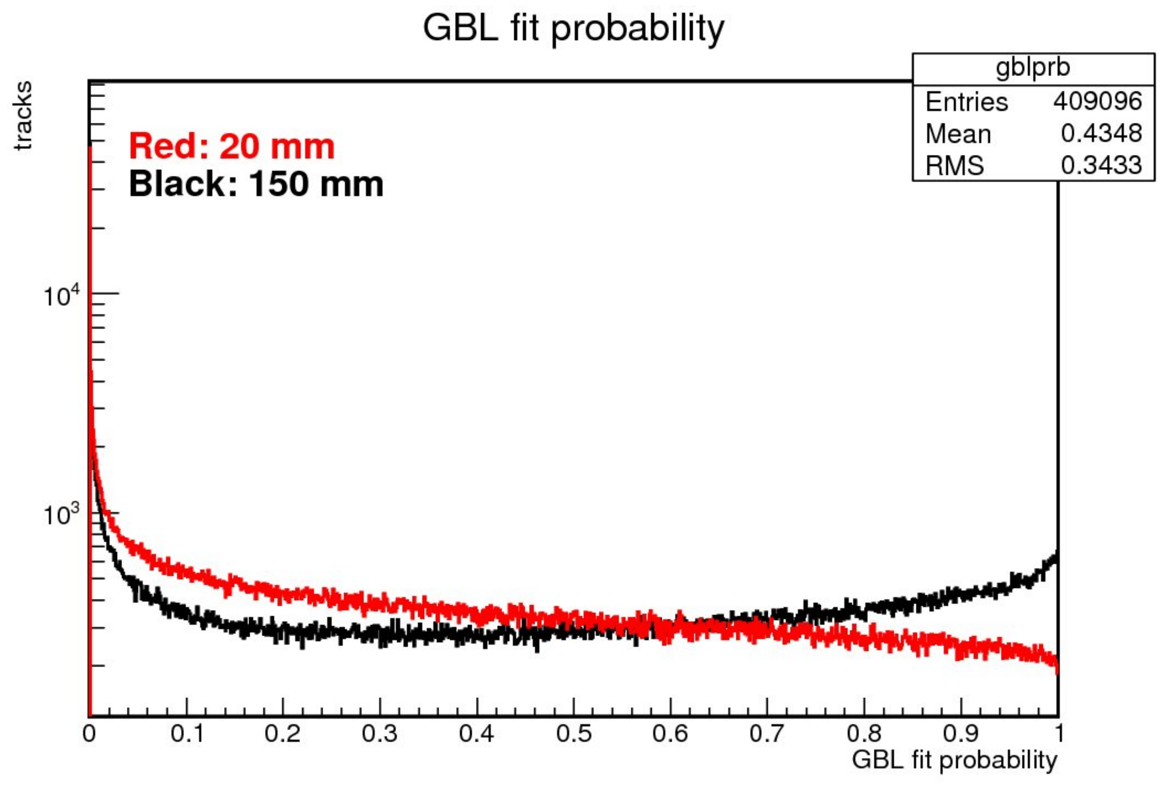
Kink angles II

- Measurement of aluminium includes “empty measurement” → apply correction

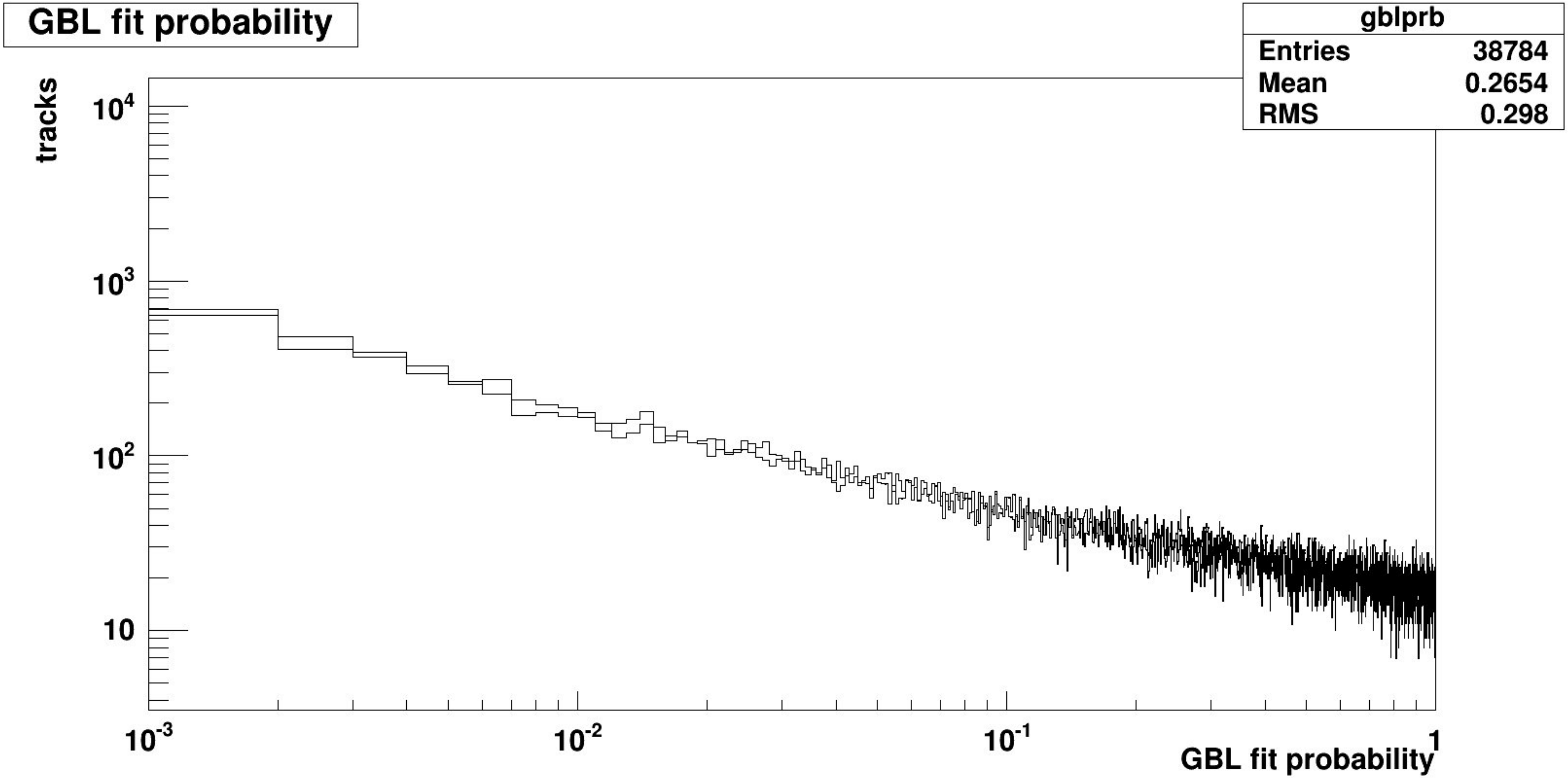


Track cleaning

- Cut on tracks: prob < 0.01 (0.1) for 20 mm (150 mm)
  - model less valid for larger amount of material budget
- Use robust statistics (down-weighting of out-layers) only if you don't have enough data (and if you know what you are doing)
- If track collection is not cleaned, “bad” tracks affect the measured intr. reso.

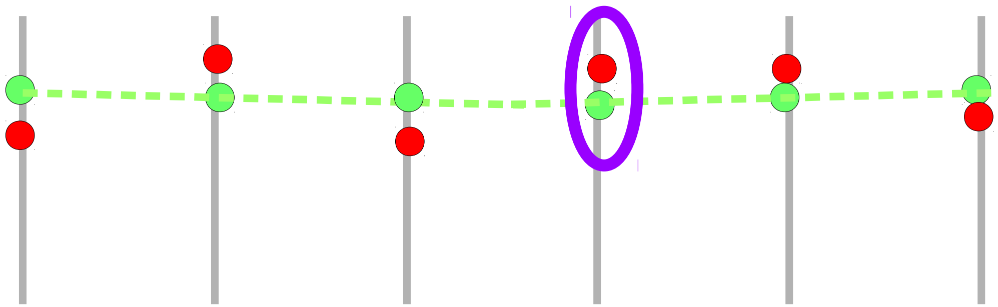


Prob biased vs unbiased



Residuals

- Residual = Measurement - Fit
- Biased (use all measurements) and unbiased (leave one out) tracks are different!



- Use track fits for residual and pull distribution

$$r_{\mathrm{b}}^2(z) = \sigma_{\mathrm{int}}^2(z) - \sigma_{\mathrm{t,b}}^2(z)$$
$$r_{\mathrm{u}}^2(z) = \sigma_{\mathrm{int}}^2(z) + \sigma_{\mathrm{t,u}}^2(z)$$

Different!

Pulls

- Normalise residual by expected residual width

$$\text{pull}_\text{b} \equiv p_\text{b} = \frac{r_\text{b}}{\sqrt{\sigma^2_\text{int} + \sigma^2_\text{t,b}}}$$

- Pull is N(0,1) if
  - estimate for intrinsic resolution matches true value
  - material budget and scattering is accurately described

→ **Iterate** track fit with updated σ_{int} using the pull width
→ pull_b → N(0,1) and σ_{int} converges against true value
→ Use results from narrow and wide set-up for cross validation

Pulls and track resolution

- Normalise residual by expected residual width

$$\mathrm{pull}_u \equiv p_u = \frac{r_u}{\sqrt{\sigma_{\mathrm{int}}^2 + \sigma_{\mathrm{t},u}^2}}$$

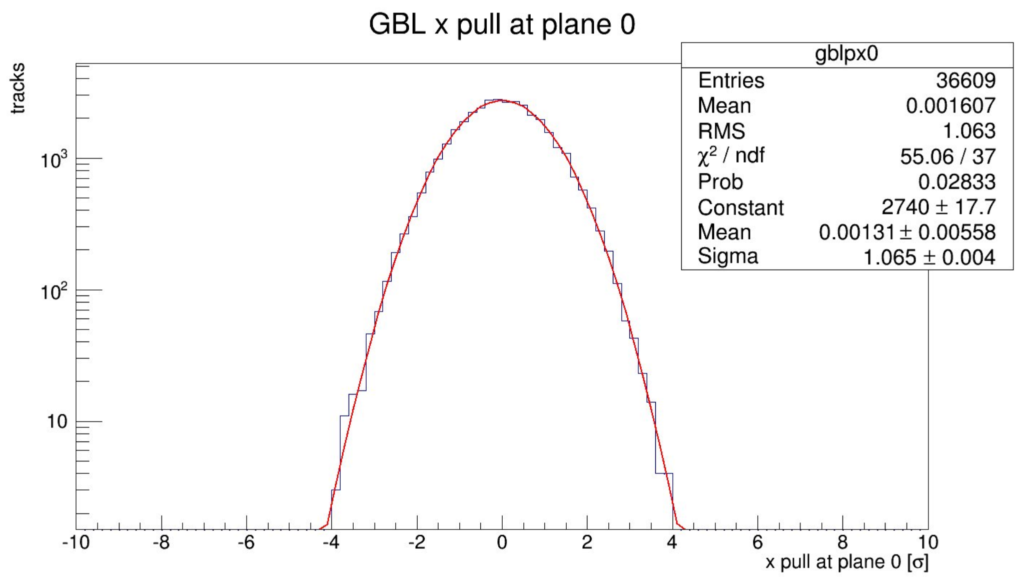
Pull is N(0,1) if
- estimate for intrinsic resolution matches true value
- material budget is accurate
- deflection due to multiple Coulomb scattering is accurately described

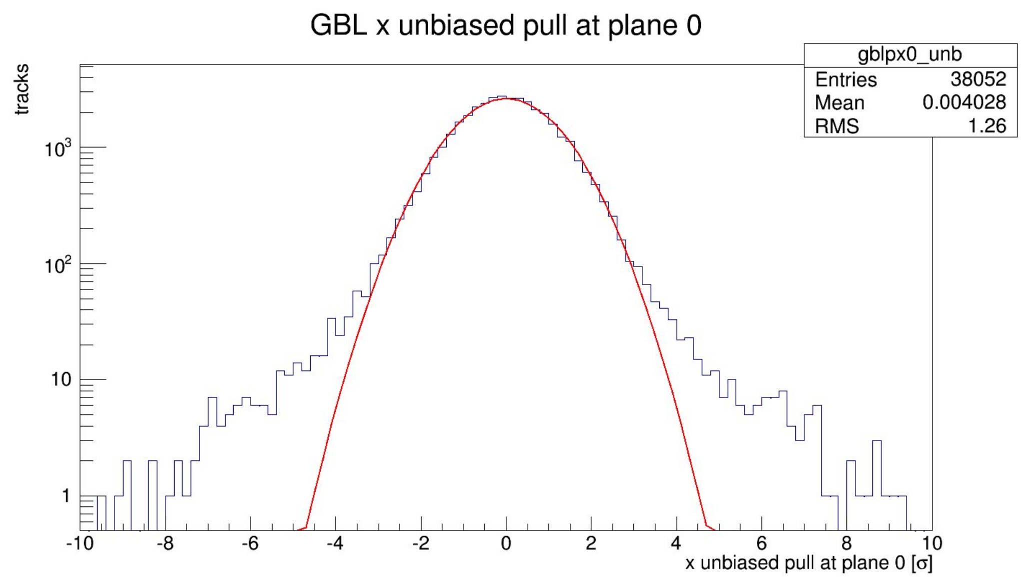
→ repeat track fit varying σ_{int} by pull width
→ pull → N(0,1) and σ_{int} converges

Pulls and track resolution II

- One example of an iteration step:

BIASED **UNBIASED**

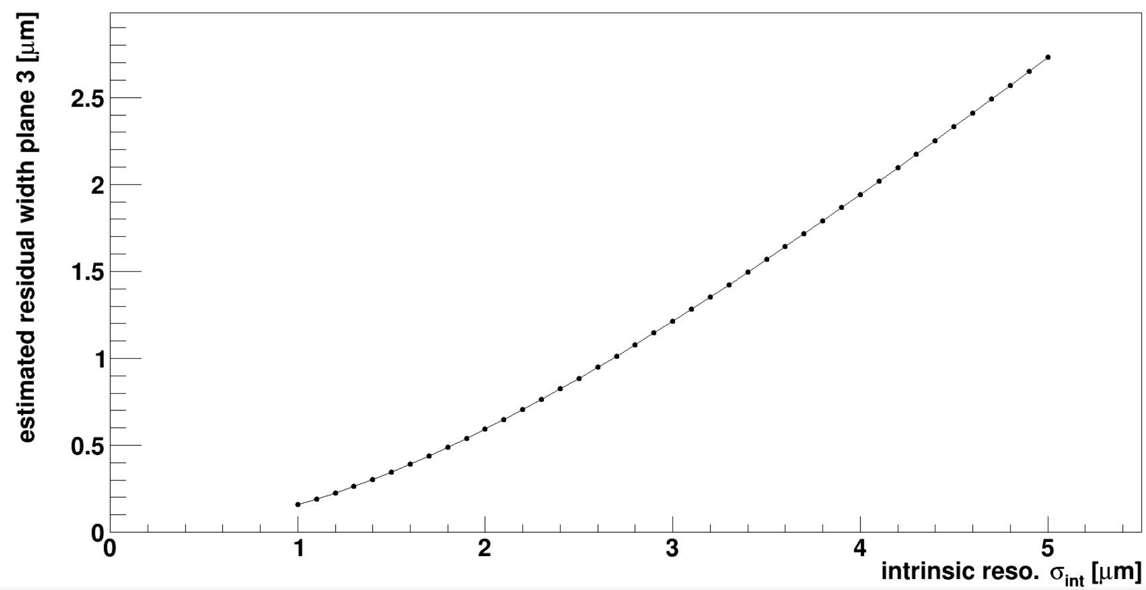




→ Increase σ_{int} by 6%, re-fit the tracks

Pulls and track resolution III

- Residual estimate as function of intr. resolution:



- Systematics affect unbiased track reso. relatively equal
- But $\sigma_{t,b} < \sigma_{t,u}$

$$\mathrm{pull}_\mathrm{b} \equiv p_\mathrm{b} = \frac{r_\mathrm{b}}{\sqrt{\sigma_\mathrm{int}^2 - \sigma_\mathrm{t,b}^2}}$$

→ absolute error smaller
→ what about the residual?

Intrinsic resolution

- The iterative method converges i.e. estimator for σ_{int} converges against the true value
- We find energy independent value of

$$\sigma_{int} = 3.24 \text{ +- } 0.5\% \text{ (stat.) +- } 3\% \text{ (syst.)}$$ (cf.last slide)

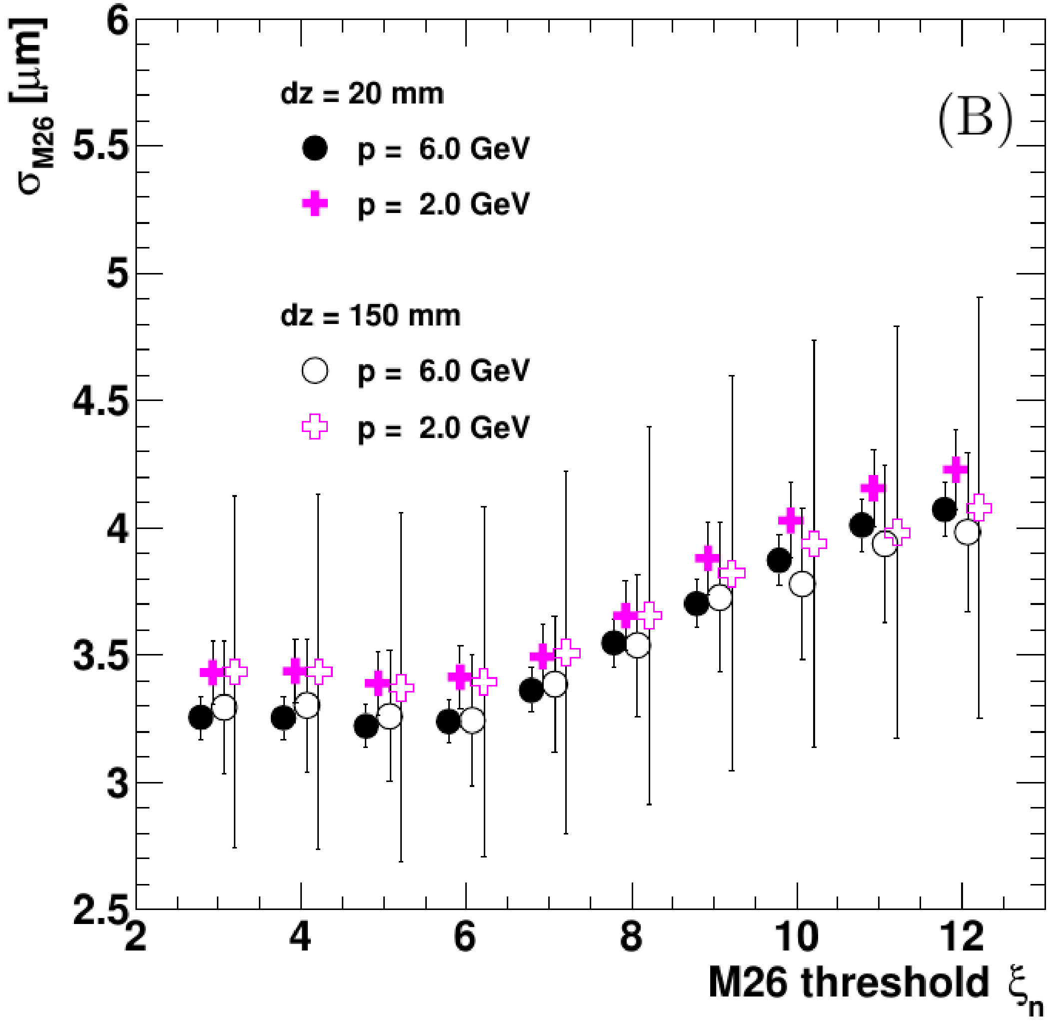
- Control sys. uncert. further by comparing set-ups
- Increases for lower thresholds (more noise hits)
- Increases for higher thresholds (smaller clusters)
- Optimum is 5 – 6, probably a tune of 5.5

Systematics

- Estimate systematic uncertainties of intrinsic resolution based on the input uncertainties

			$\sigma_{\sigma_{\mathrm{int}}}$ in %				
			per plane			all planes	$\sqrt{\sum(x_i)^2}$
			E ±5 %	Θ_0 ±3 %	fit range ±1 std.	rms(p_{b})	
6 GeV	20 mm	biased	−0.34 +0.21	+0.08 −0.28	+1.76 −1.27	1.57	2.6
		unbiased	−0.43 +0.71	+0.44 −0.25	−0.93 −1.00	1.23	1.8
	150 mm	biased	−3.5 +2.9	+1.95 −2.60	+6.4 −5.4	1.51	7.9
		unbiased	−4.80 +5.43	+2.97 −4.13	−5.29 +3.11	0.75	8.7
2 GeV	20 mm	biased	−1.56 +1.13	+0.65 −1.22	+0.23 +0.33	3.1	3.7
		unbiased	−1.67 +1.21	+0.92 −1.10	−2.15 +1.35	1.94	3.1
	150 mm	biased	−10.5 +15.7	+10.2 −6.59	+8.0 +0.82	0.82	20.3
		unbiased	−17.5 +24.9	+14.9 −15.2	−23.9 +25.1	1.03	38.5

Threshold dependency



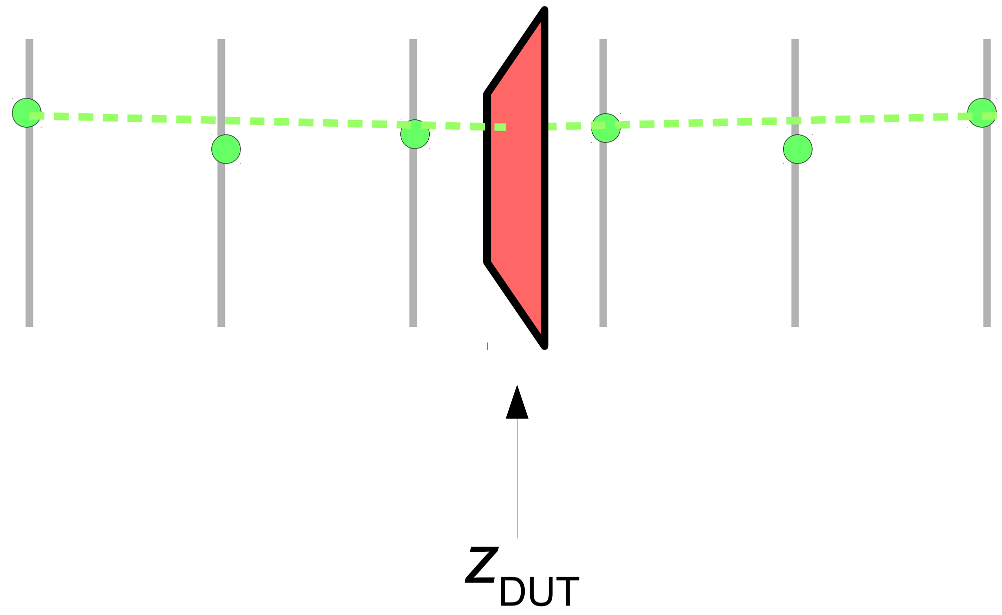
Towards higher threshold:
→ cut signal
→ smaller clustersize
→ worse resolution

Towards lower threshold:
→ more noise hits
→ worse resolution

→ Optimum at threshold 5 to 6

Track resolution predictions

- Using 6 planes, assuming DUT in the centre



Track resolution predictions

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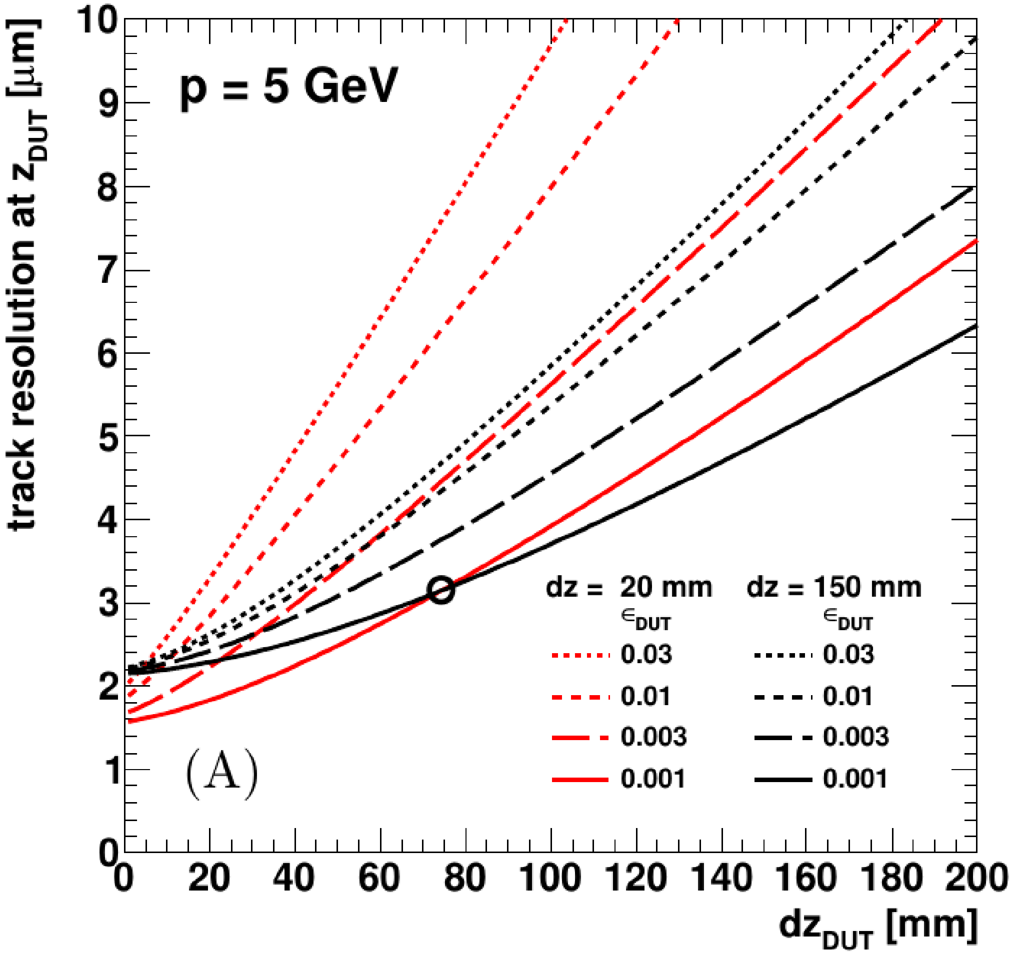
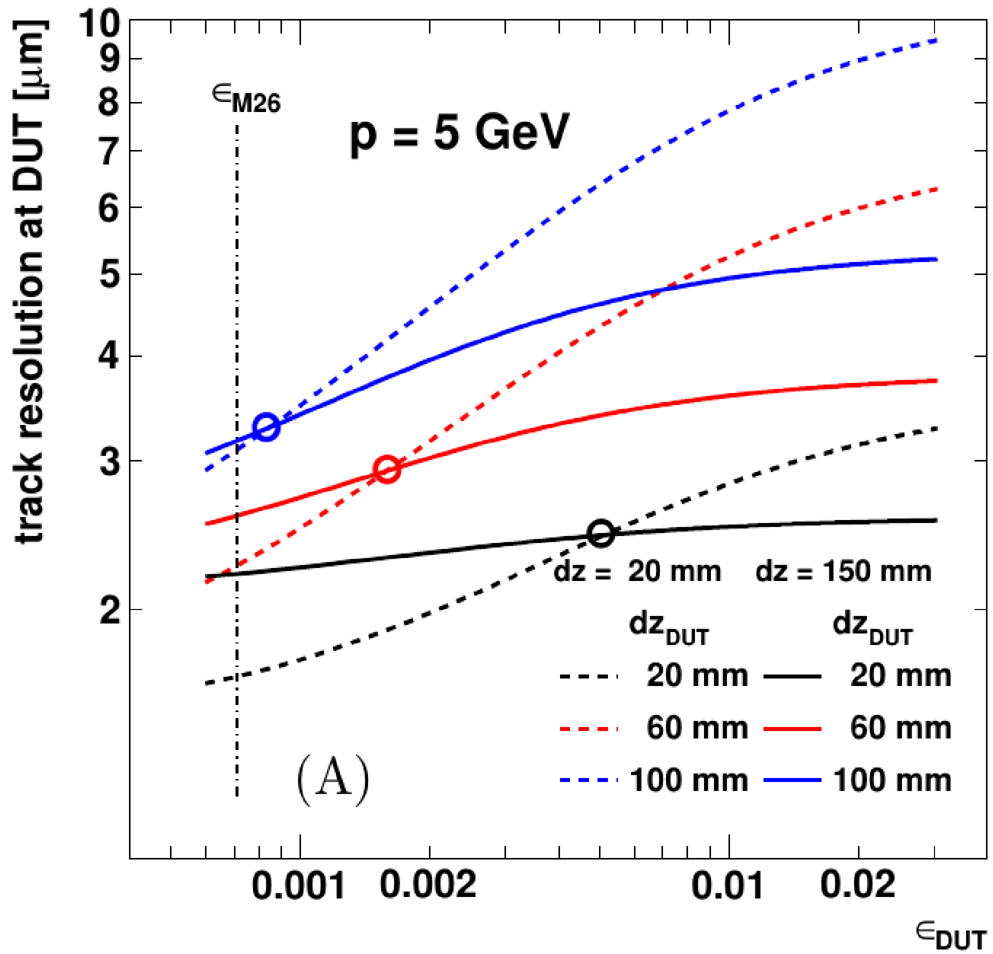




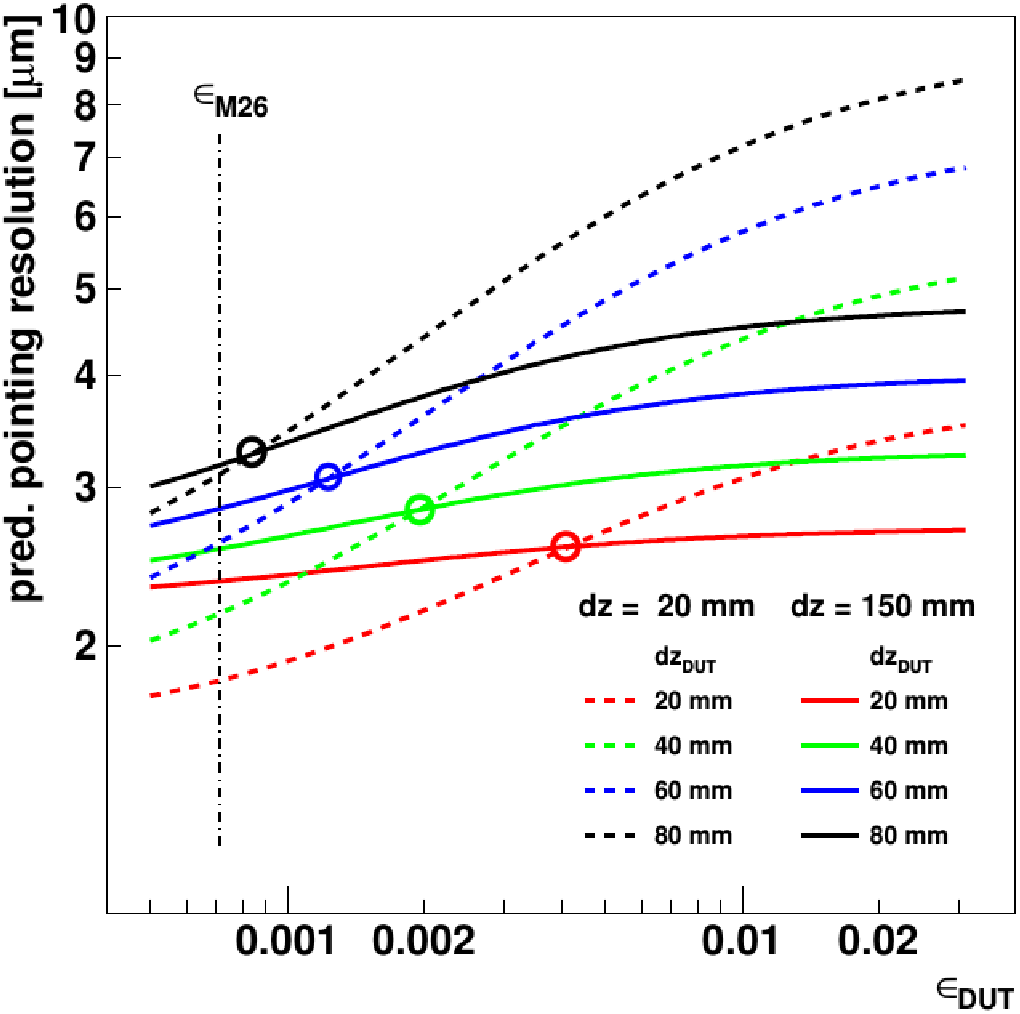
→ dz_{DUT} as small as possible

→ Thick DUT: use wide set-up
Thin DUT: use narrow set-up

Track resolution predictions

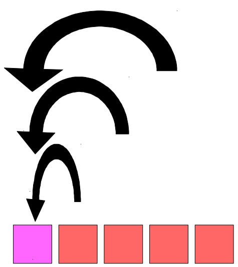
- Using 6 planes, assuming DUT in the centre
- Wide set-up offers superior track resolution with thicker DUTs and vice versa.
- Intersection is function of material budget

→ Optimise resolution prior to your test beam

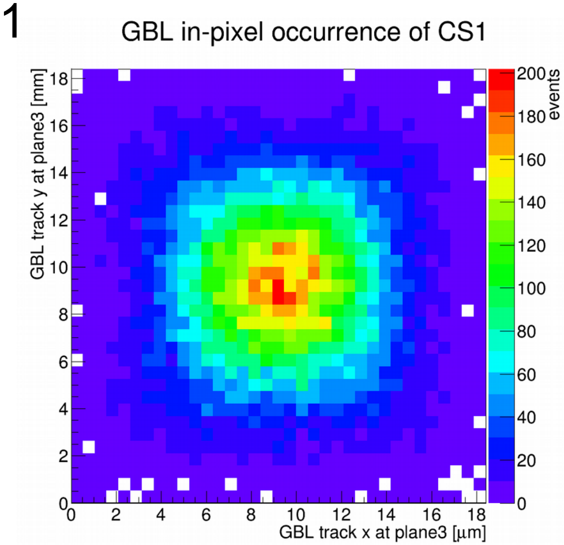


Looking even closer ...

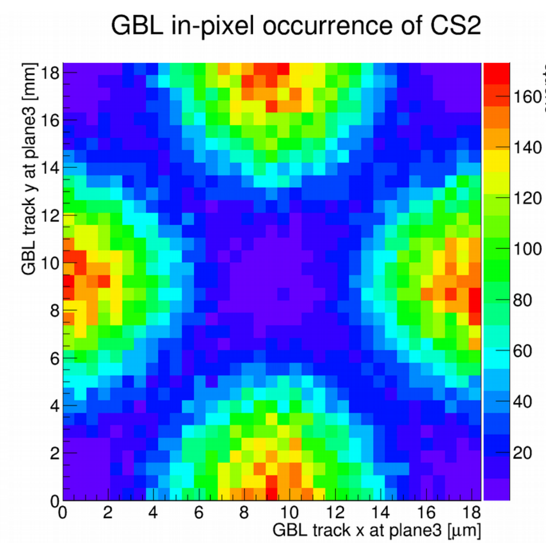
Fold occurrence into one pixel for intra-pixel studies



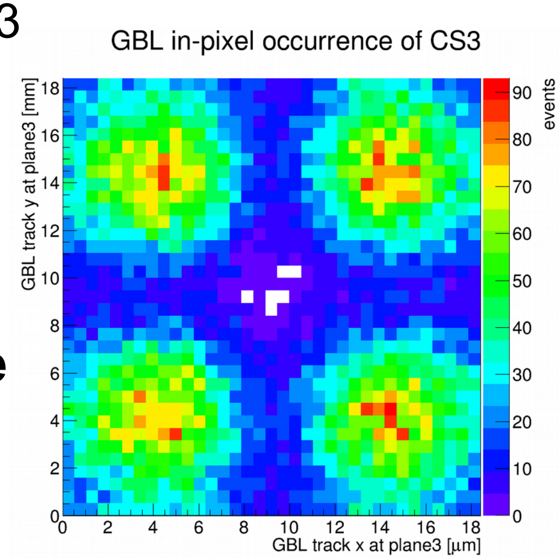
CS 1



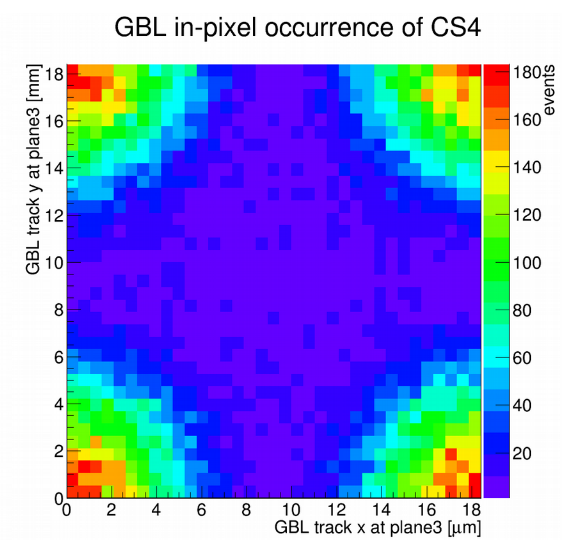
CS 2



CS 3



CS 4



→ Density of recon. track position is non-uniform, it depends on cluster size

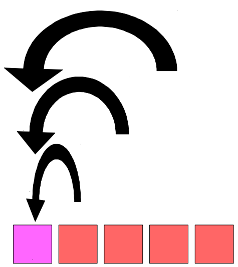
→ Populated areas differ in size

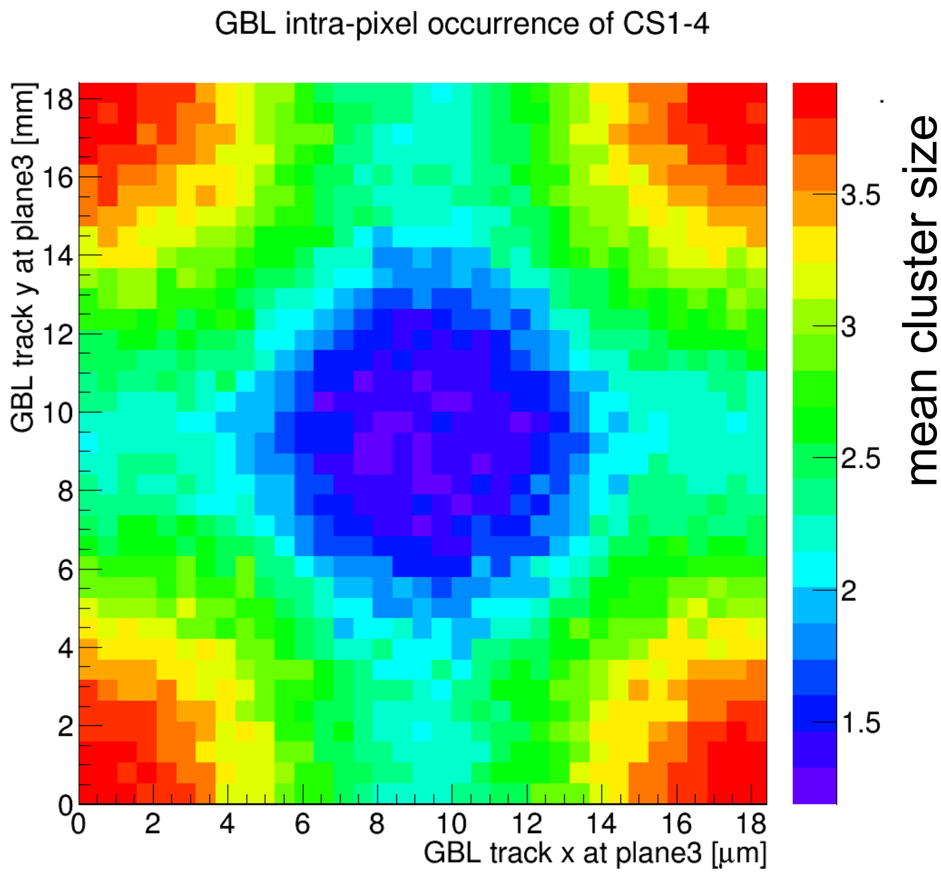
→ Resolution is CS dependent

→ Calculate differential intrinsic resolution

Looking even closer ...

Fold occurrence into one pixel for intra-pixel studies





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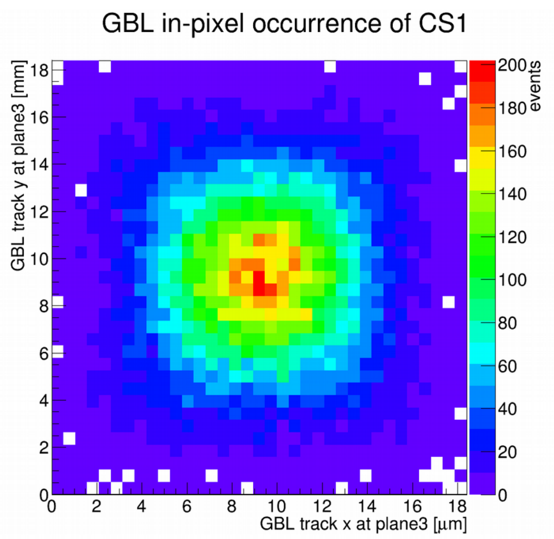
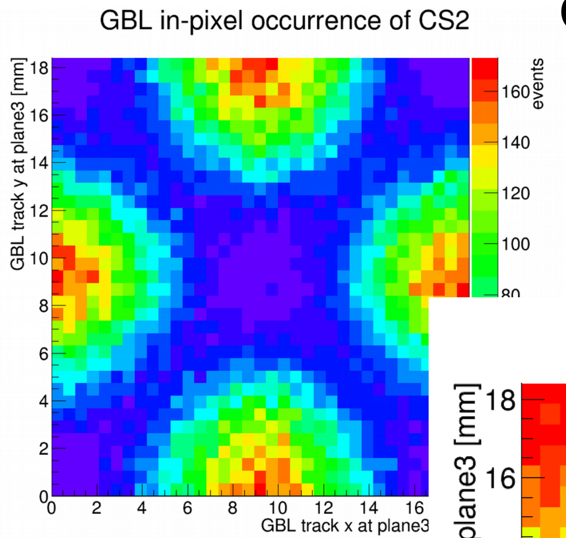
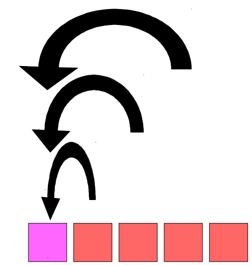
Looking even closer ...

CS 1





CS 2



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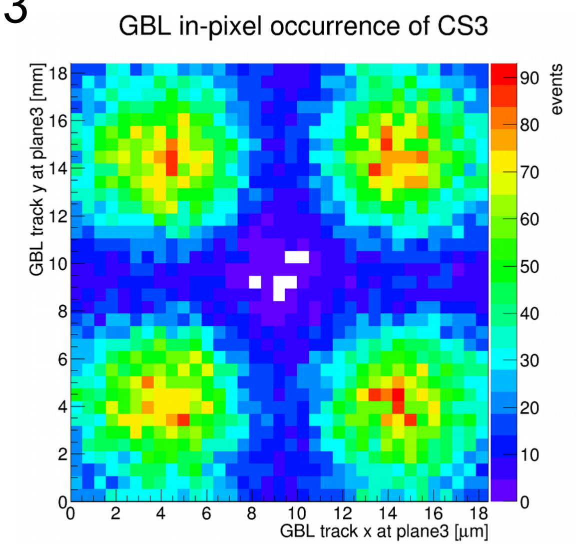
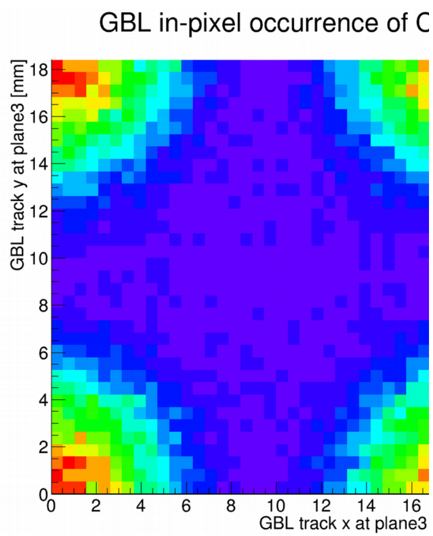
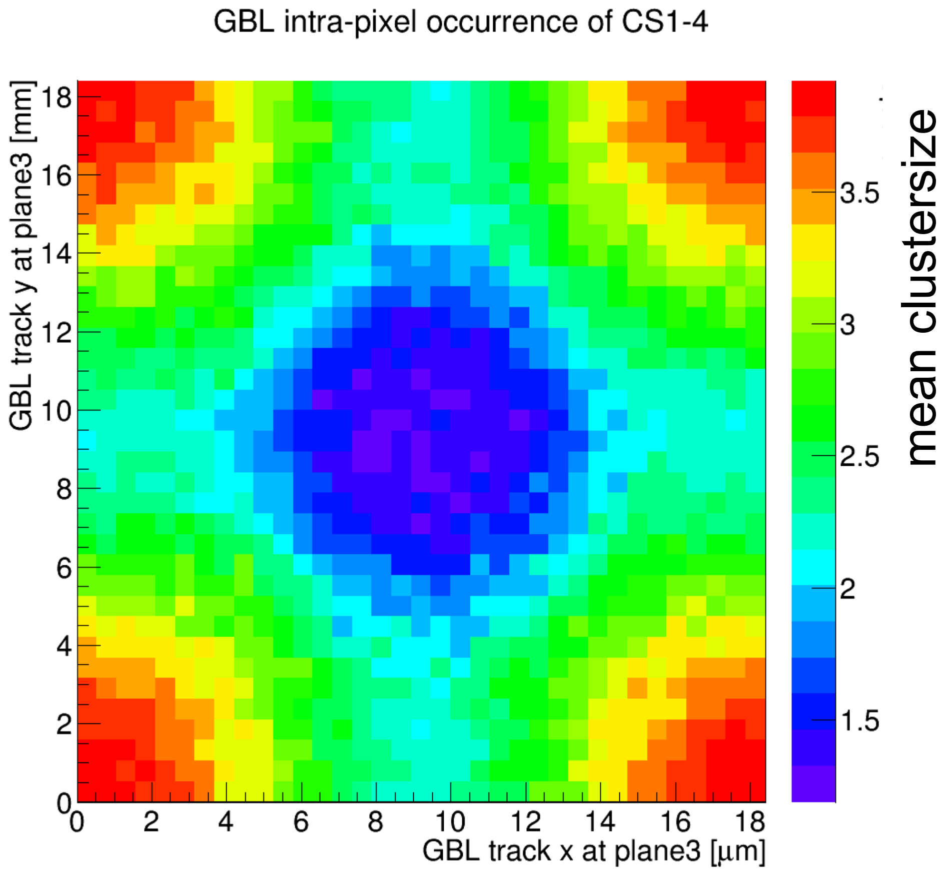




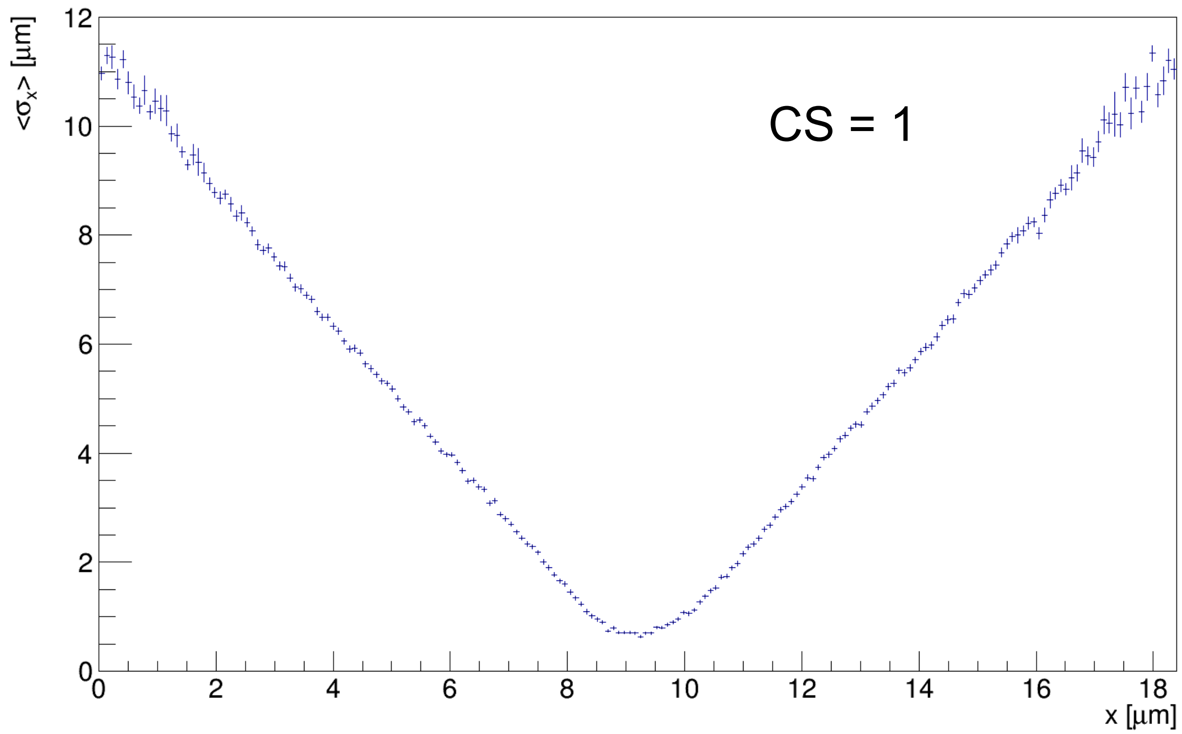


CS-dependent quantities

- Repeat iterative pull method for each cluster size
  → differential intrinsic resolution

CS1: 3.60 μm
CS2: 3.16 μm
CS3: 2.86 μm
CS4: 3.40 μm
CS5: 2.53 μm
CS6: 2.70 μm
CS>6: 4.17 μm

- Resulting σ_x vs x within a pixel per cluster size:



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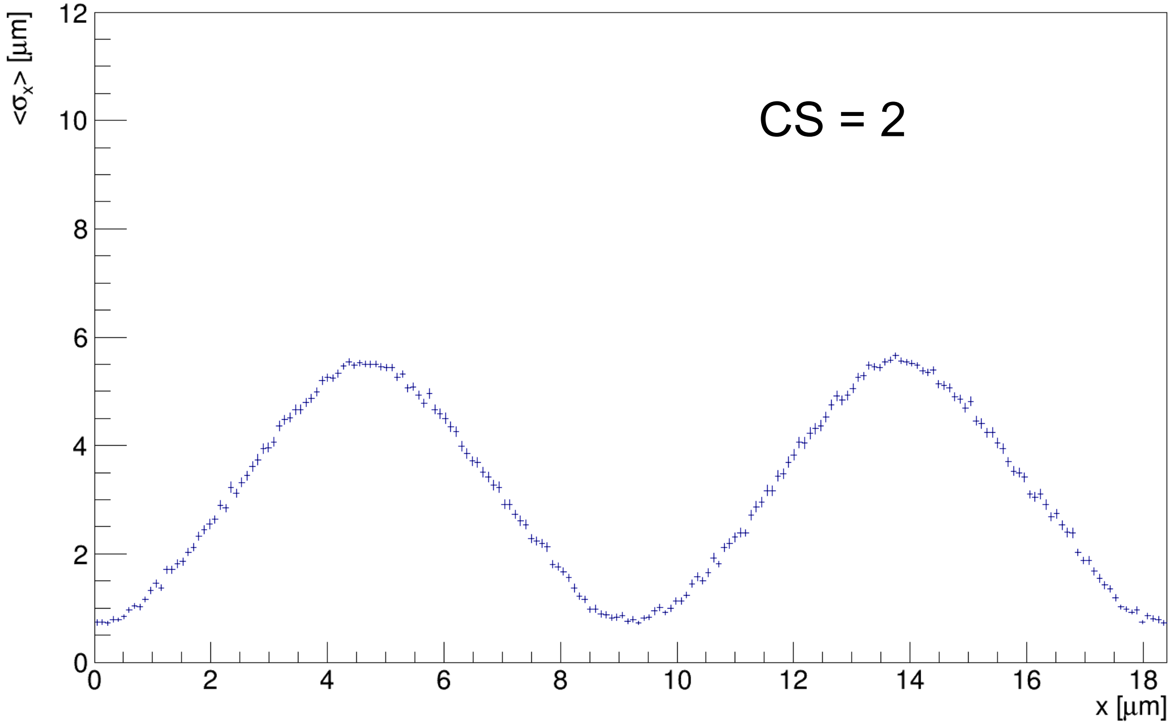

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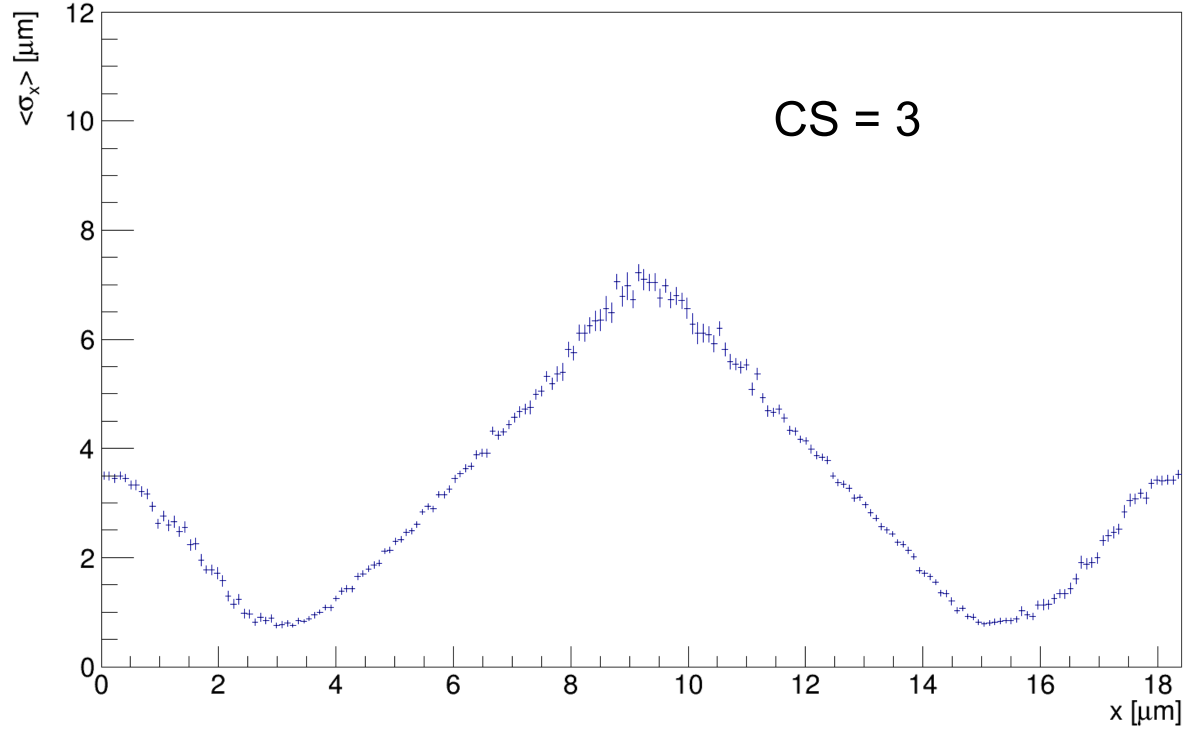

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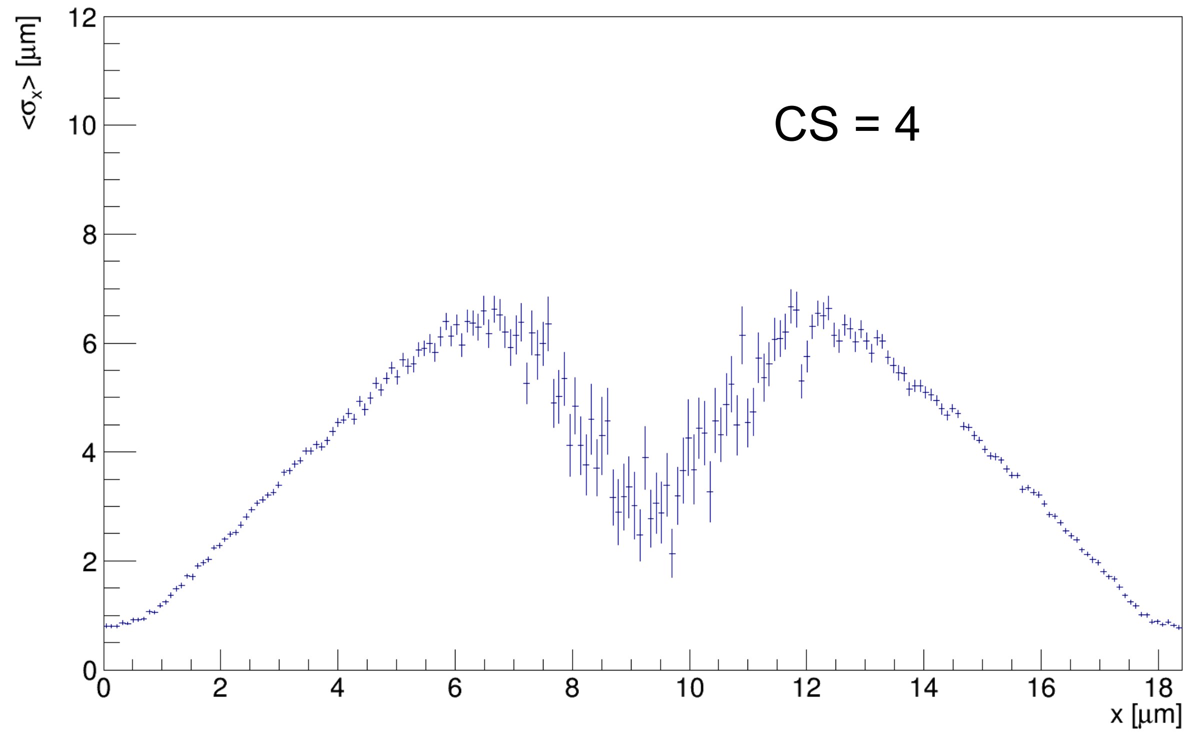

Horizontal beam spread

- After spectral magnet