HELMHOLTZ ASSOCIATION

DESY

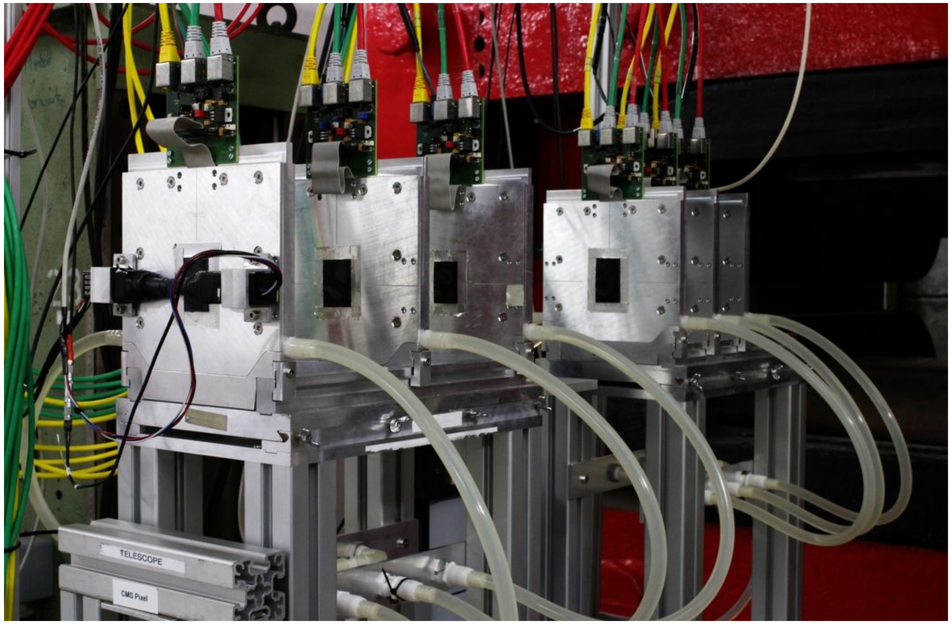
Resolution studies with the DATURA beam telescope

An iterative pull analysis

Hendrik Jansen

The DATURA beam telescope

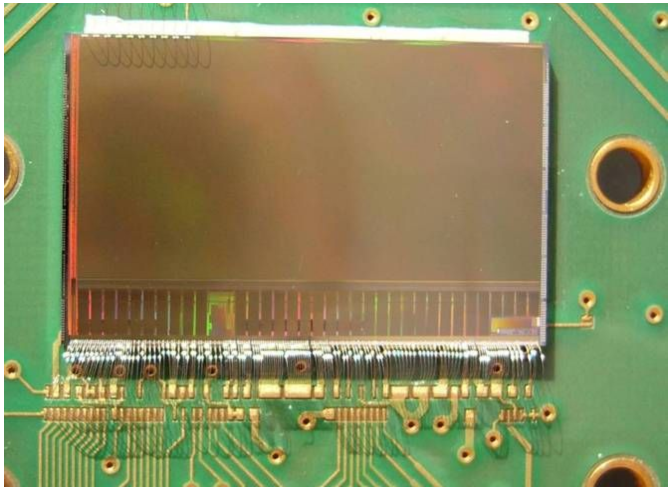
- Usually used in sensor R&D
- Located at DESY TB hall 21
- 6 Mimosa26 sensors
- NI-based DAQ system
- EUDET Trigger Logic Unit
  - Input: 4 scintillators
  - Output: Trigger to DAQ systems



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

→ Measure the *intrinsic resolution* of Mimosa26 themselves
→ Predict/Optimise set-up dependent track resolution

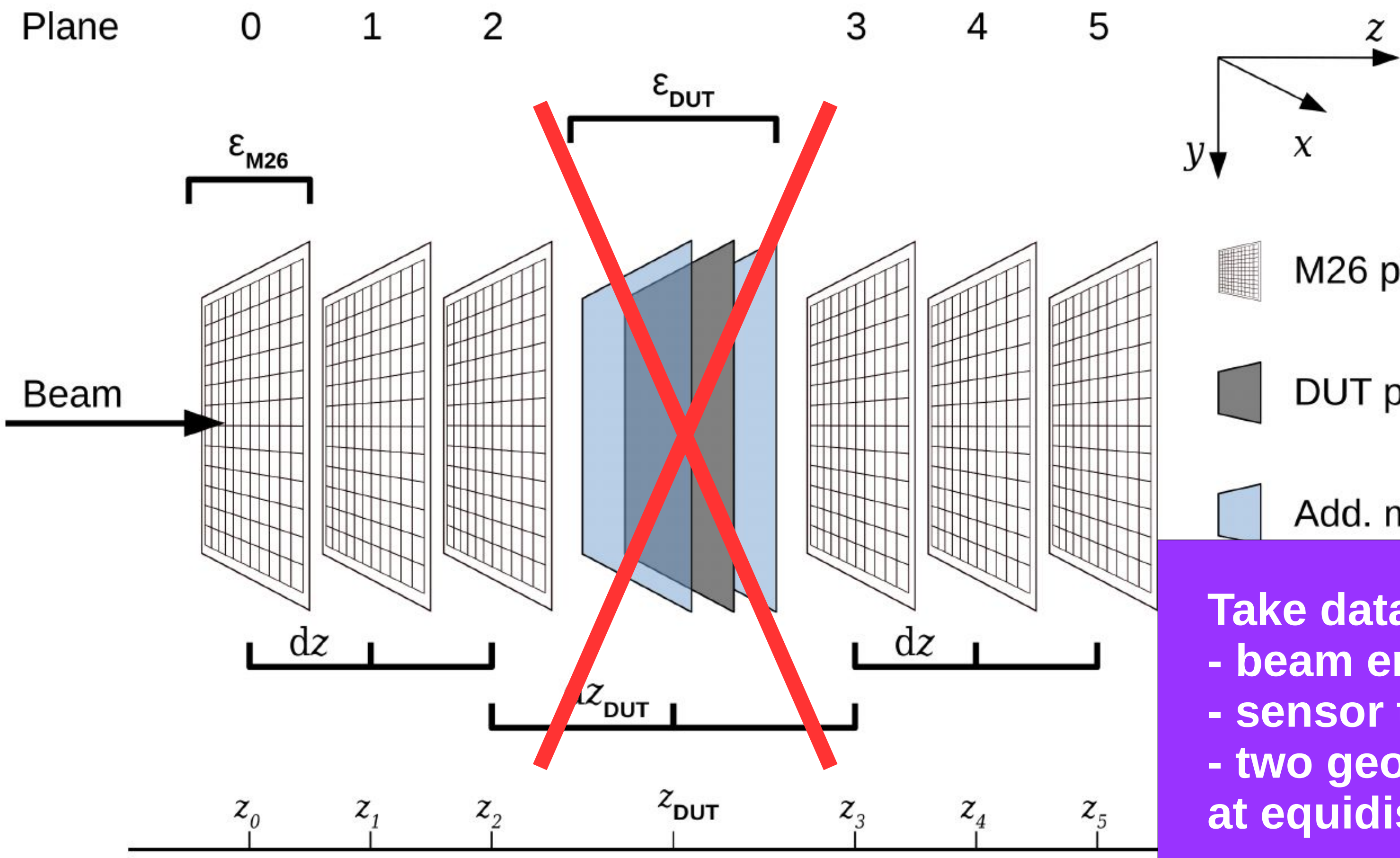
Mimosa 26 pixel sensors



- AMS 350 nm CMOS
- 18.4 um x 18.4 um
- 1152 x 576 pixels
- Roughly 10 mm x 20 mm
- Thickness: specs 50 um, measurement (55 ± 3) um
- HR epitaxial layer of 20 um thickness
- Binary resolution 5.3 um, improved by charge sharing
- Protected by 25 um Kapton on each side
- Material budget of sensor plus Kapton: ε = 7.5e-4

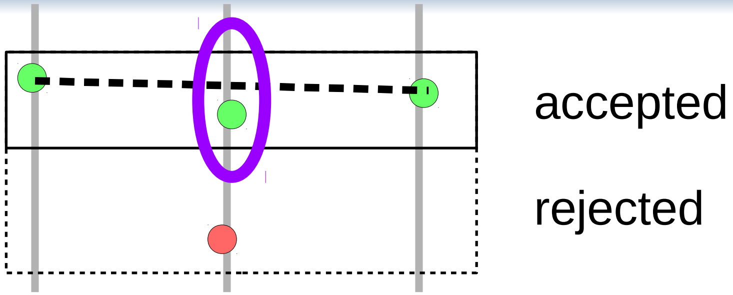
Measurement geometries

- Plane spacing dz = 20 mm (narrow) or 150 mm (wide)
- Total material budget: 4.8e-3 and 7.0e-3, respectively

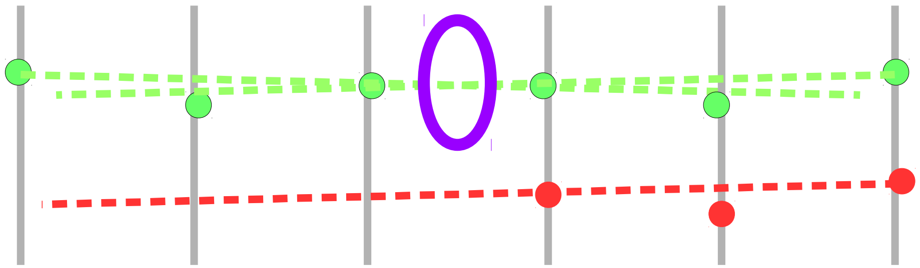


Take data with different
- beam energies,
- sensor thresholds
- two geometries
at equidistant spacing

Data analysis flow



- Analysis done with EUTelescope
- Start with Mimosa26 data
- Hot pixel search
- Cluster formation, remove clusters with hot pixels
- Track triplets built for up- and downstream plane trio
- Isolation cut on triplets
- Match up- and downstream triplets in the centre
  → *six-tuple* belonging to a physical track
- Feed six-tuple to Millepede
  for alignment using *estimates on measurement resolution*
  (multiple times if needed)

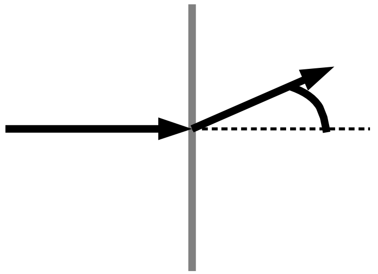


GBL tracking

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

- General Broken Lines allows for kinks at scatterers
- Calculating corrections to an initial simple seed track
- Average deflection predicted by Highland:

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



- Perform χ^2 minimisation to find track parameters
- Track model does not include bremsstrahlung, non-Gaussian tails or non-linear effects
- Inputs: *Measurement* + *error*, geometry, scattering estimate
- Outputs: residual + error, res. width estimate, kinks, track resolution

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.

Biased residuals and pulls

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

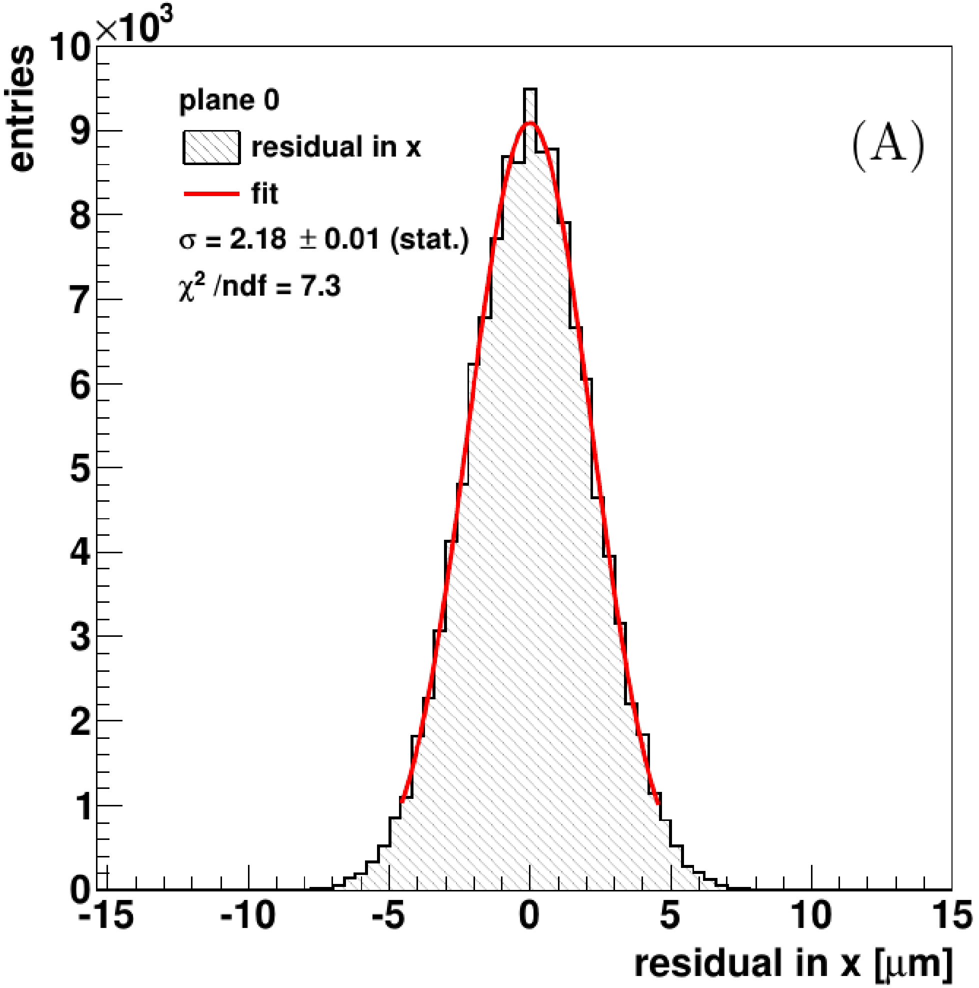
$$\mathrm{pull}_\mathrm{b} \equiv p_\mathrm{b} = \frac{r_\mathrm{b}}{\sqrt{\sigma^2_\mathrm{int} - \sigma^2_\mathrm{t,b}}}$$

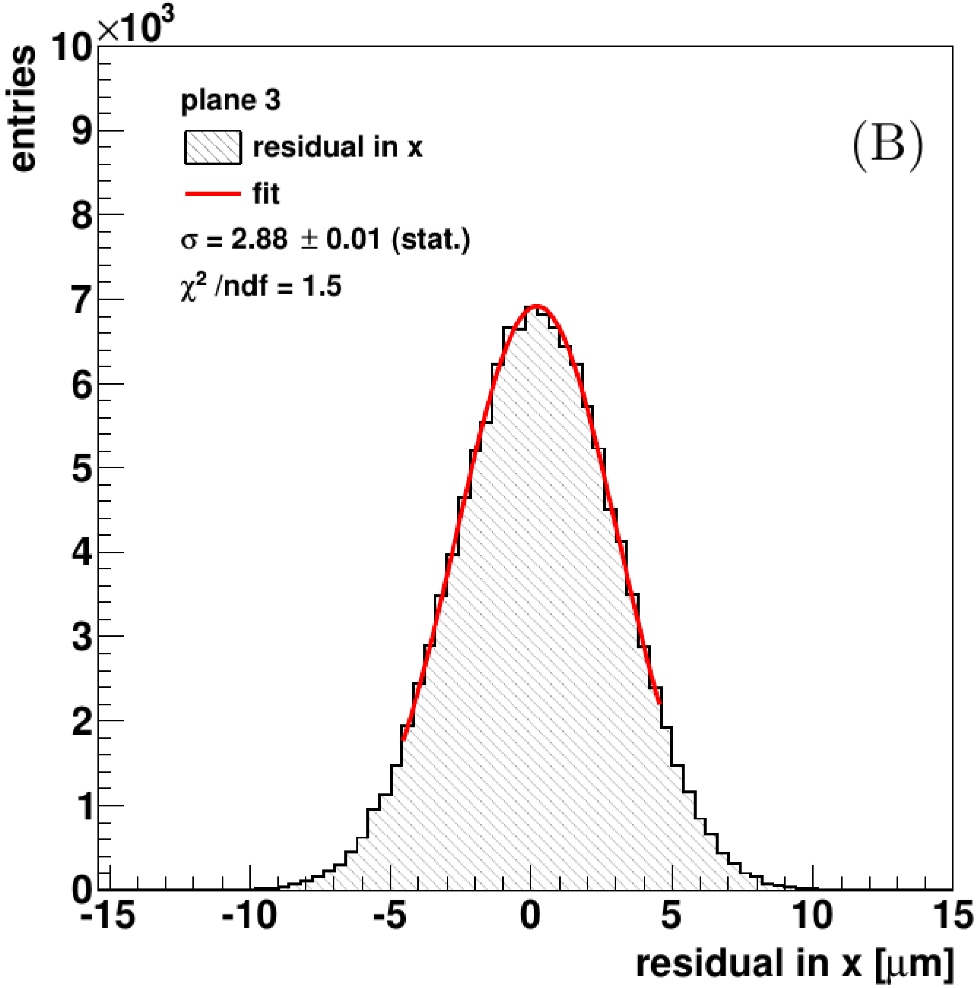
Predict using GBL

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

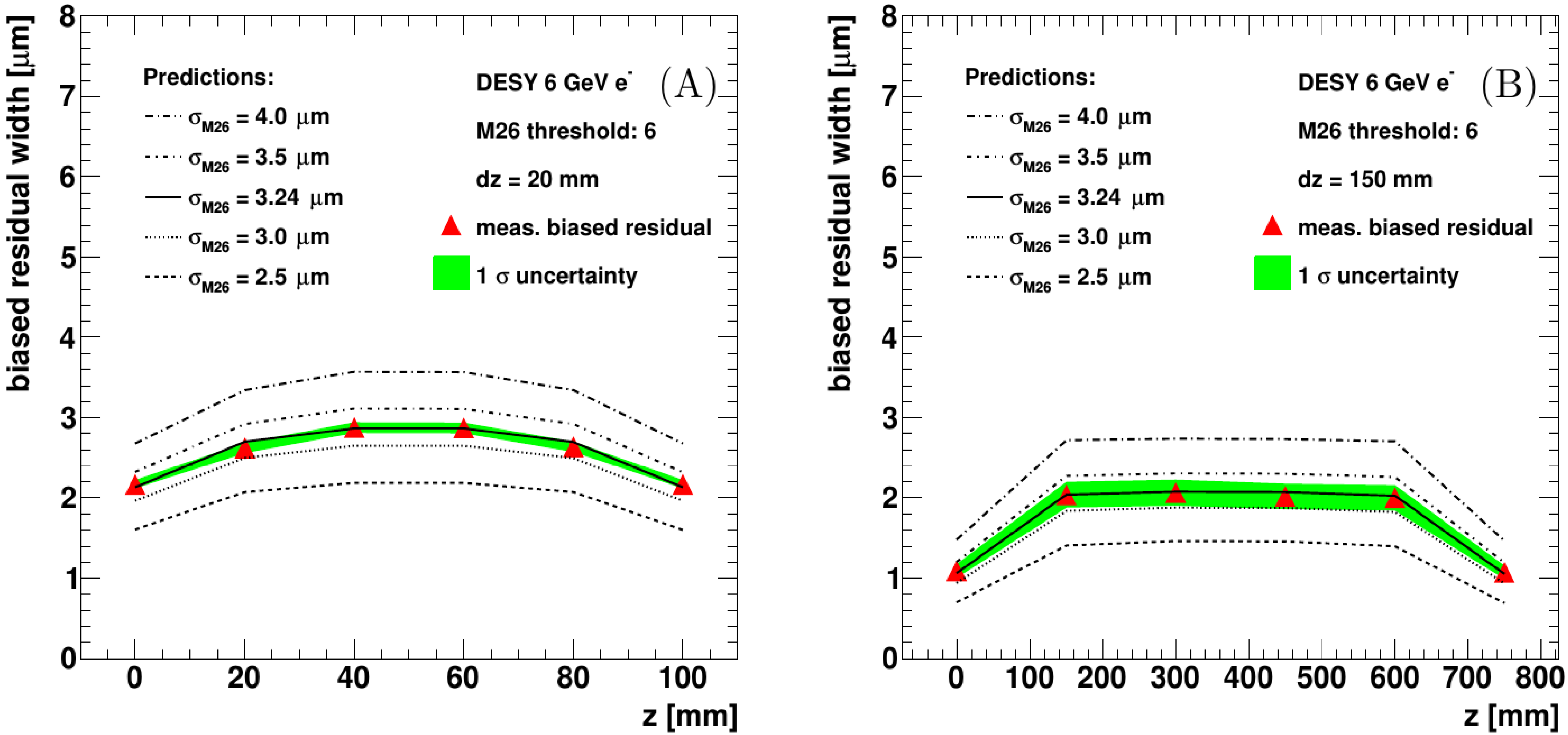
→ **Iterate** track fit with updated σ_{int} and $\sigma_{t,b}$ using the pull width
→ pull_b → N(0,1) and σ_{int} converges against true value
→ Use results from narrow and wide set-up for cross validation

Biased residuals II





Biased residuals III



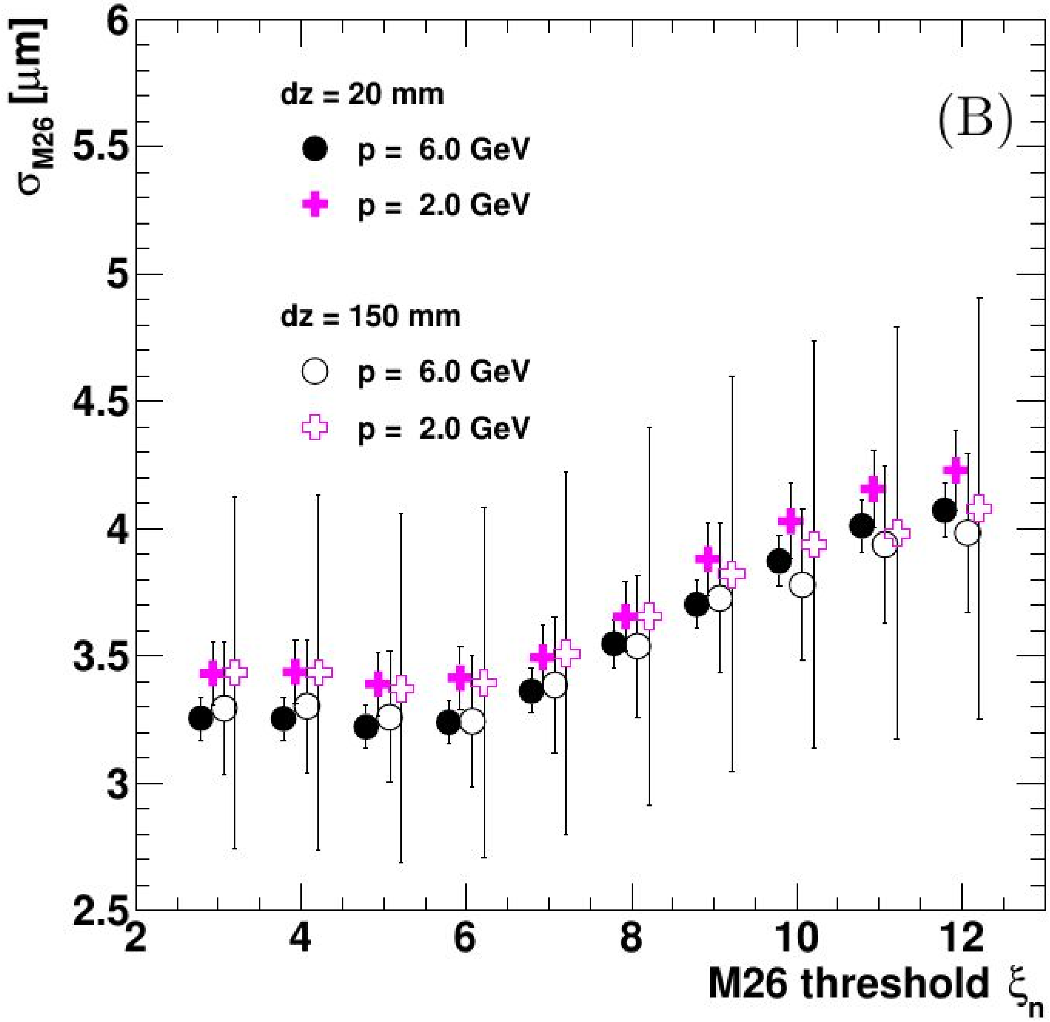
→ **Average intrinsic resolution:** $\sigma_{\mathrm{M26}} = (3.24 \pm 0.09)\ \mu\mathrm{m}$

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 $\pm 5\,\%$	Θ_0 $\pm 3\,\%$	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



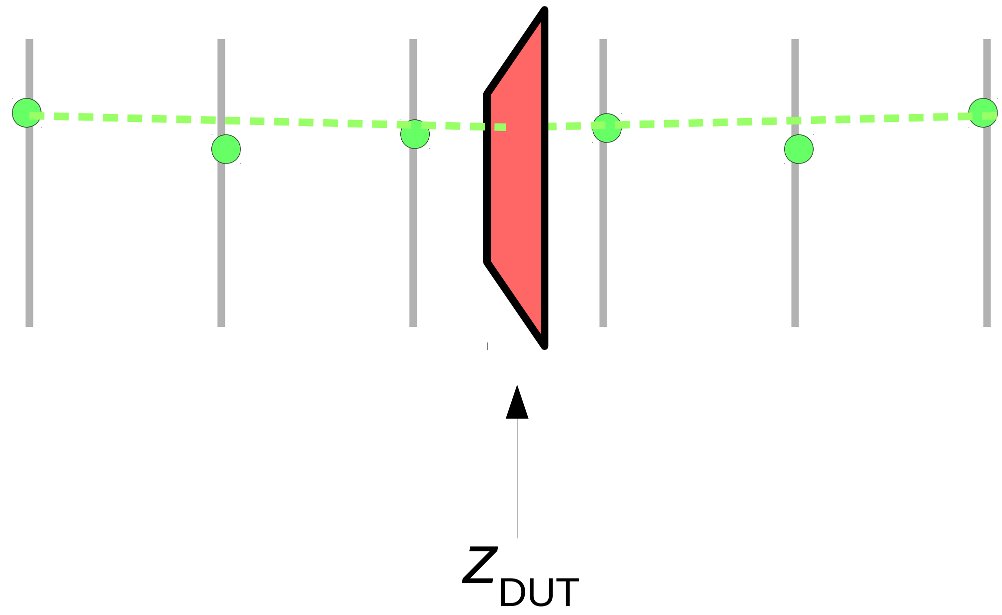
Towards higher threshold:
→ cut signal
→ smaller clustersize
→ worse resolution

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



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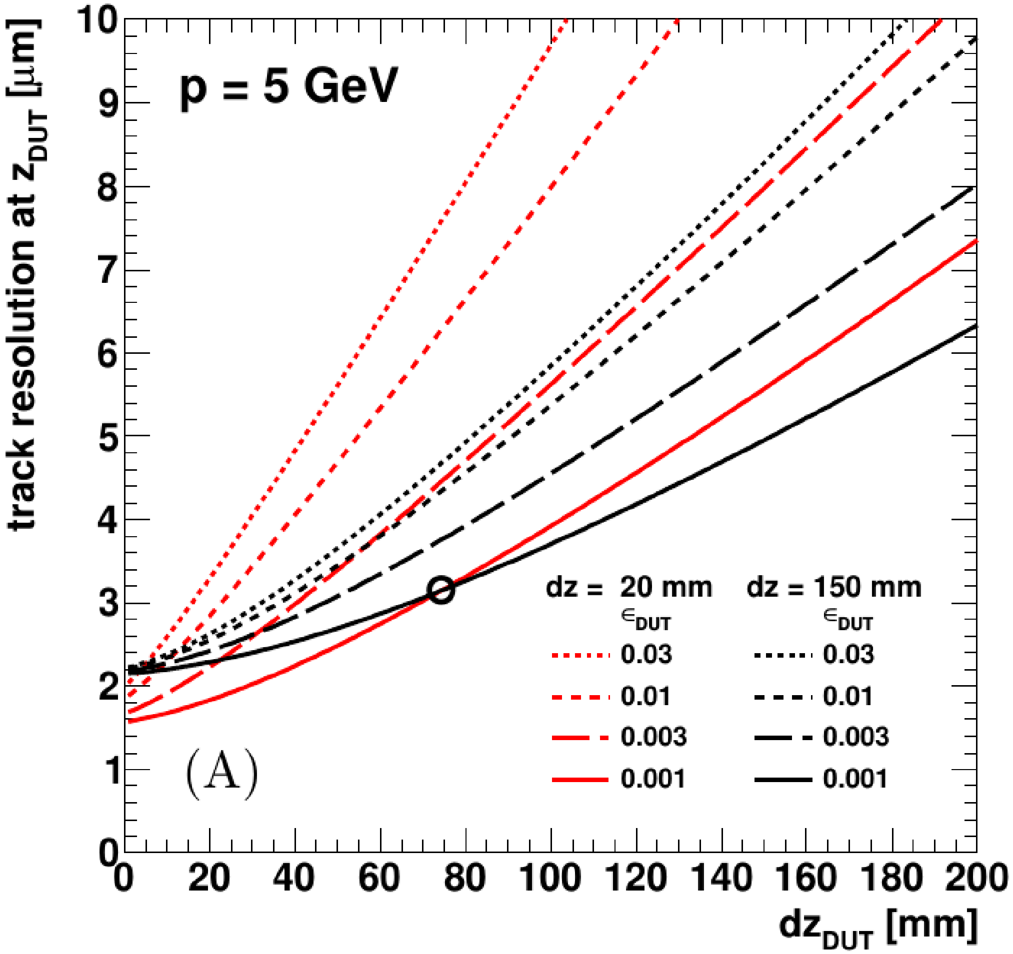
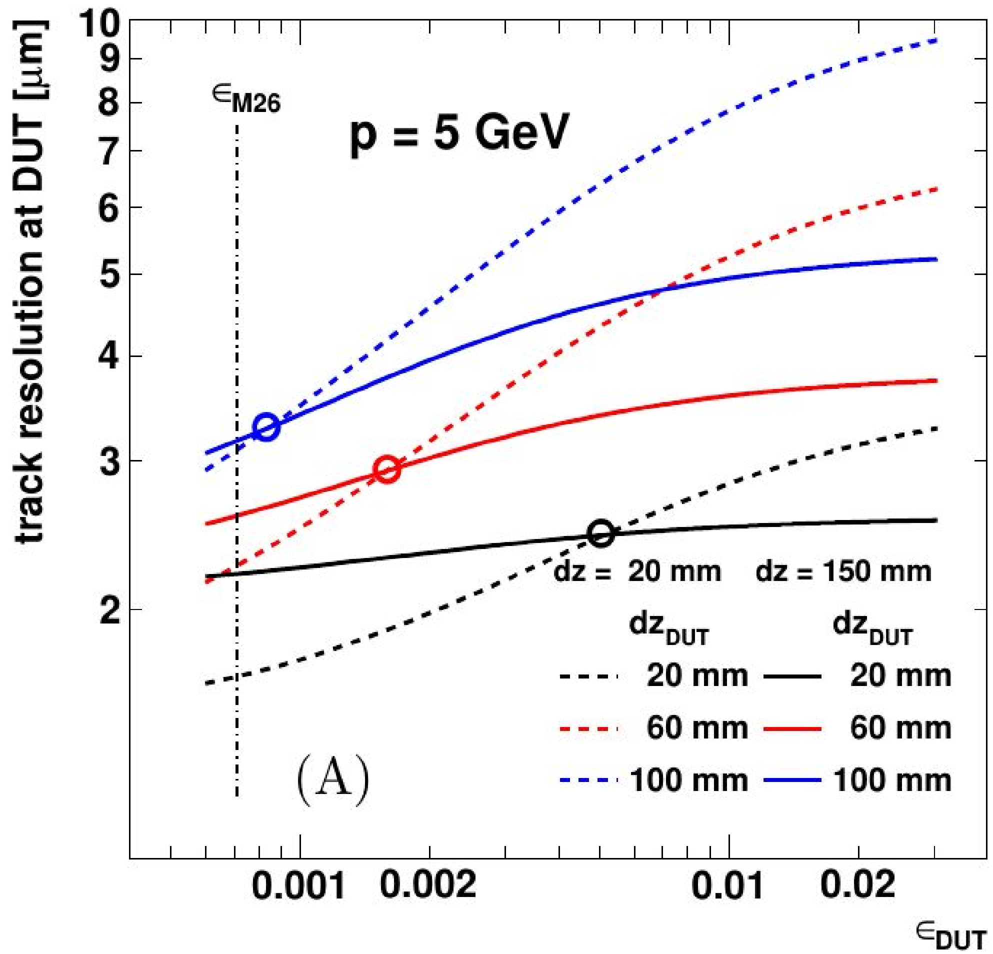


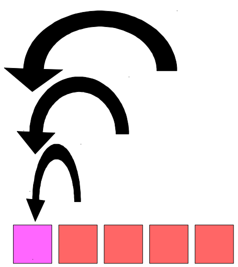


→ dz_{DUT} as small as possible

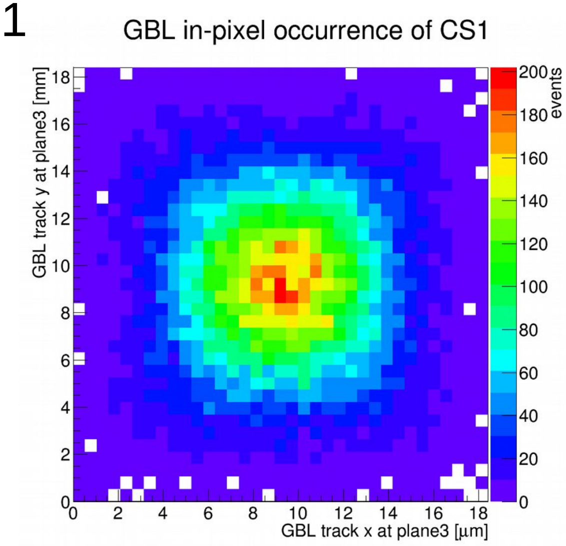
→ Thick DUT: use wide set-up
Thin DUT: use narrow set-up

Looking even closer ...

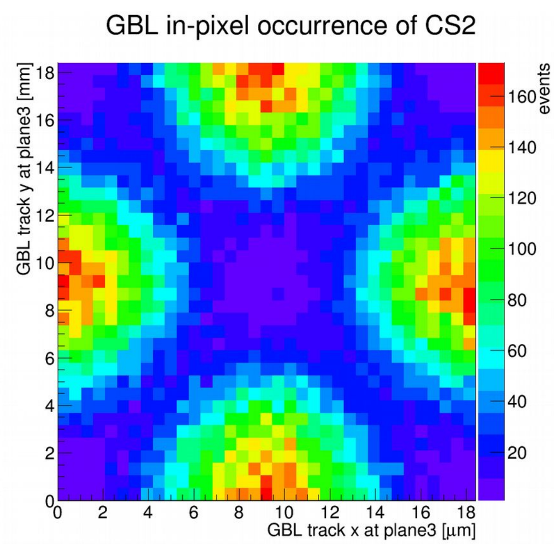
Fold occurrence into one pixel for intra-pixel studies



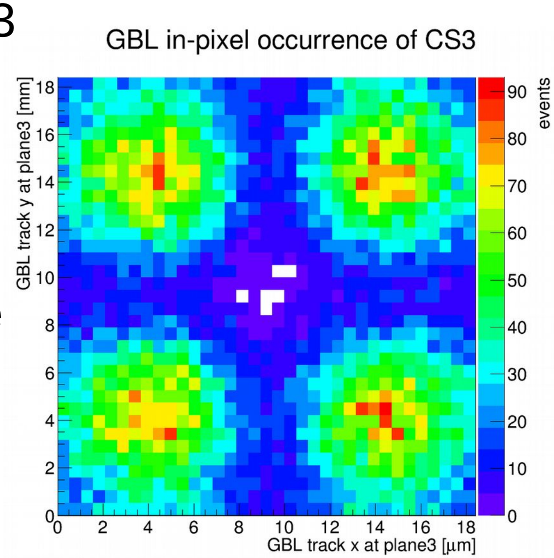
CS 1



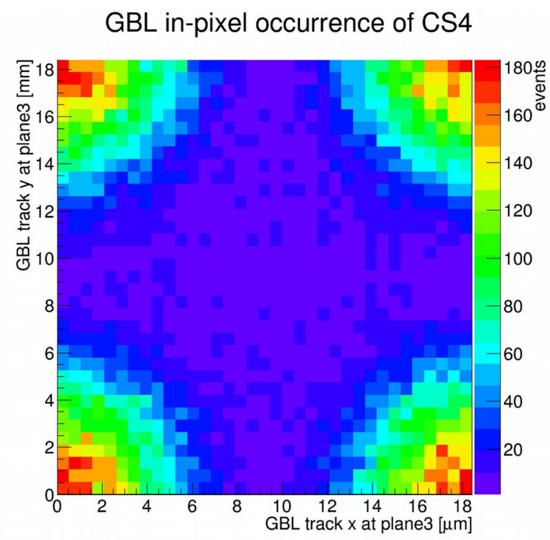
CS 2



CS 3



CS 4



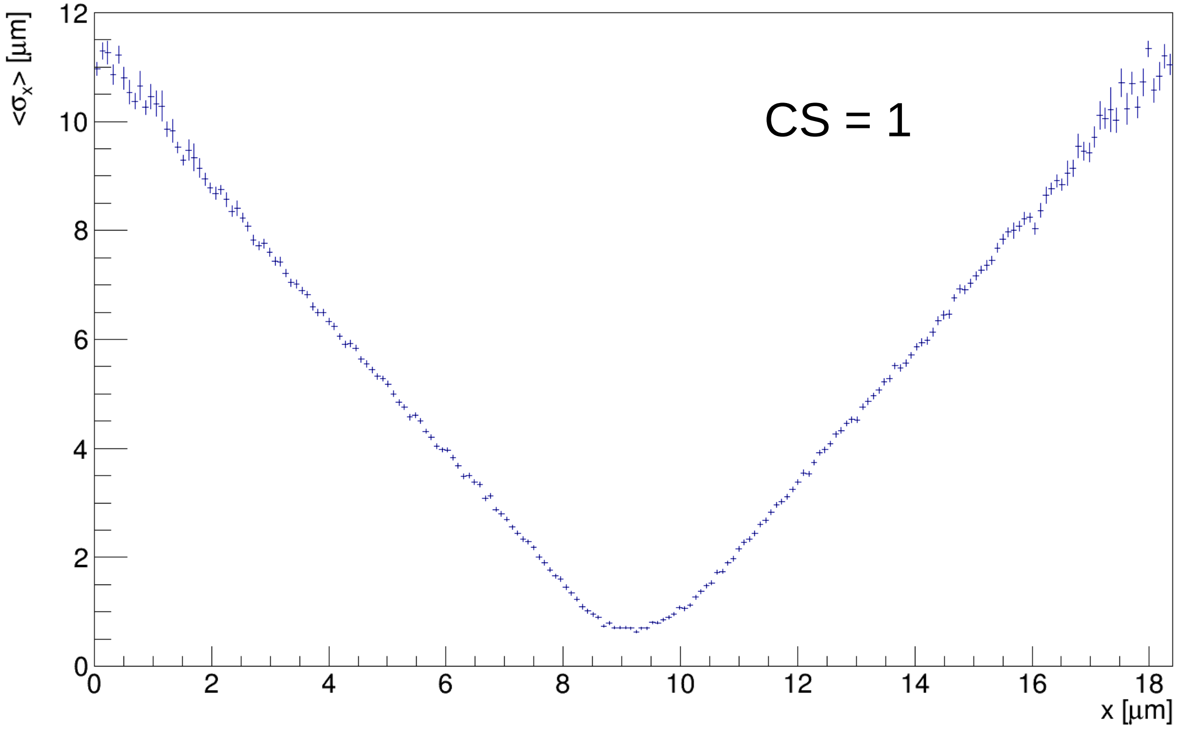
- → **Frequency of occurrence is position dependent**
- → **Populated areas differ in size**
- → **Resolution is CS dependent**
  - → **Calculate differential intrinsic resolution**

CS-dependent quantities

- Repeat iterative pull method for each clustersize
  → 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 clustersize:



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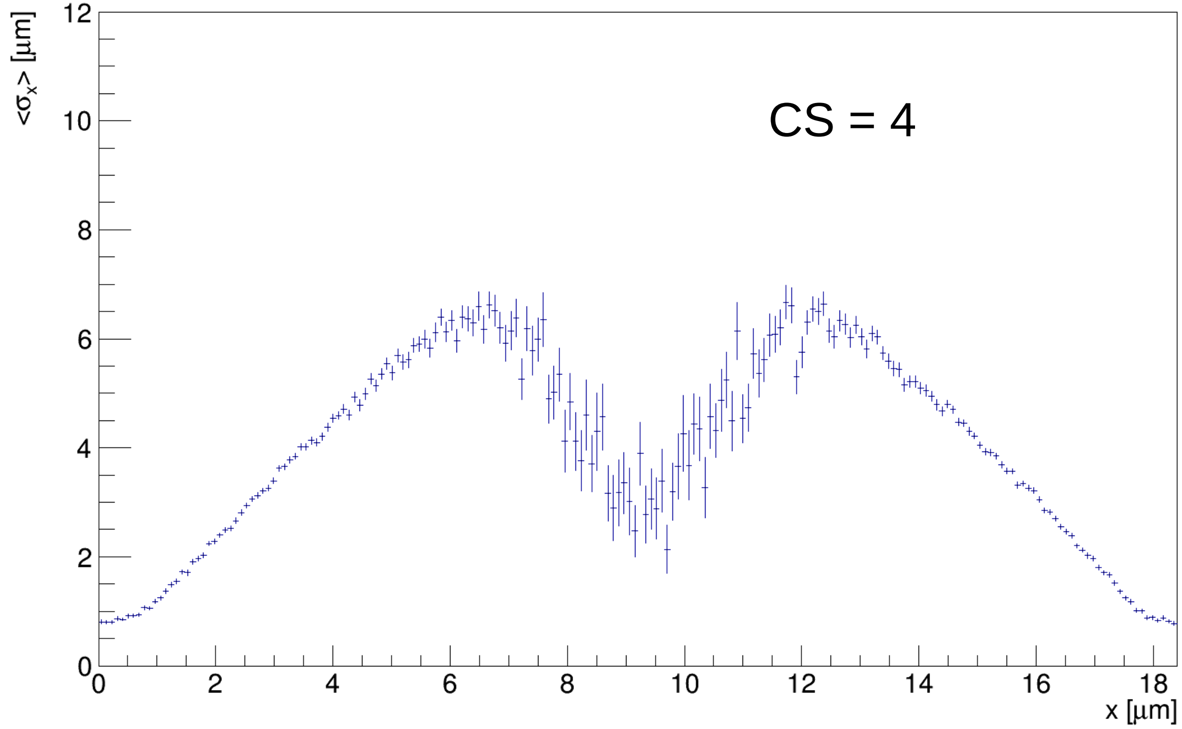

Conclusion

- Performed in-depth resolution study of DATURA
- Very precise tool (few um track res.) for sensor R&D
- Iterative pull analysis:
  → Avg. intrinsic resolution σ_{M26} = 3.24 um at threshold 6
- Repeat for different clustersizes:
  → Differential intrinsic resolution,
  can be used as CS-dependent input during tracking
- Recommendation to users:
  → Use track resolution predictions for optimisation
  of test beam set-up

Some of these results have recently been published at EPJ Techniques & Instrumentation:
Hendrik Jansen, et al., "Performance of the EUDET-type beam telescopes", in press.

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Next Beam Telescope and Test Beam Workshop

BARCELONA

January 24th – 27th, 2017

cern egroup:
BeamTelescopesAndTestBeams-Announcements@cern.ch

hendrik.jansen@desy.de

Back-up

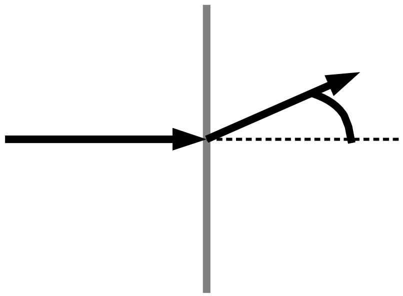
Offline analysis and reconstruction

- 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

Multiple scattering

- Average deflection predicted by Highland

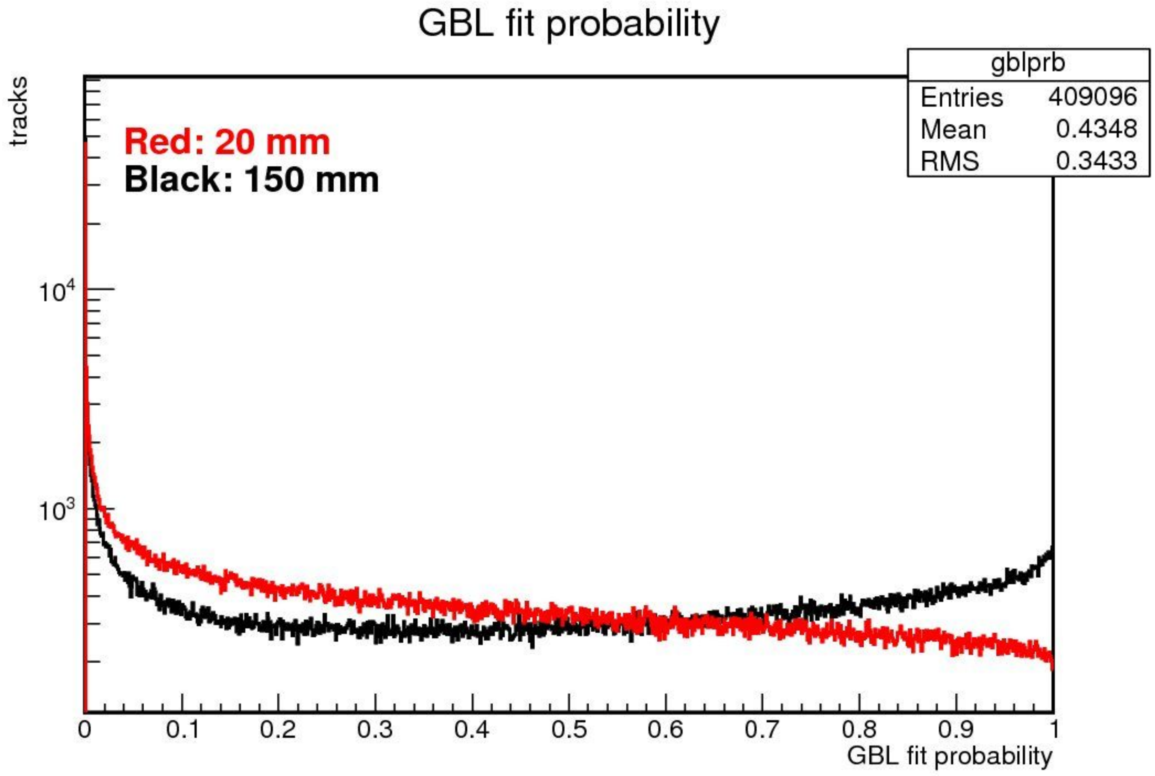
$$\Theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} \cdot z\sqrt{\varepsilon} \cdot \left(1 + 0.038 \ln\left(\varepsilon\right)\right)$$



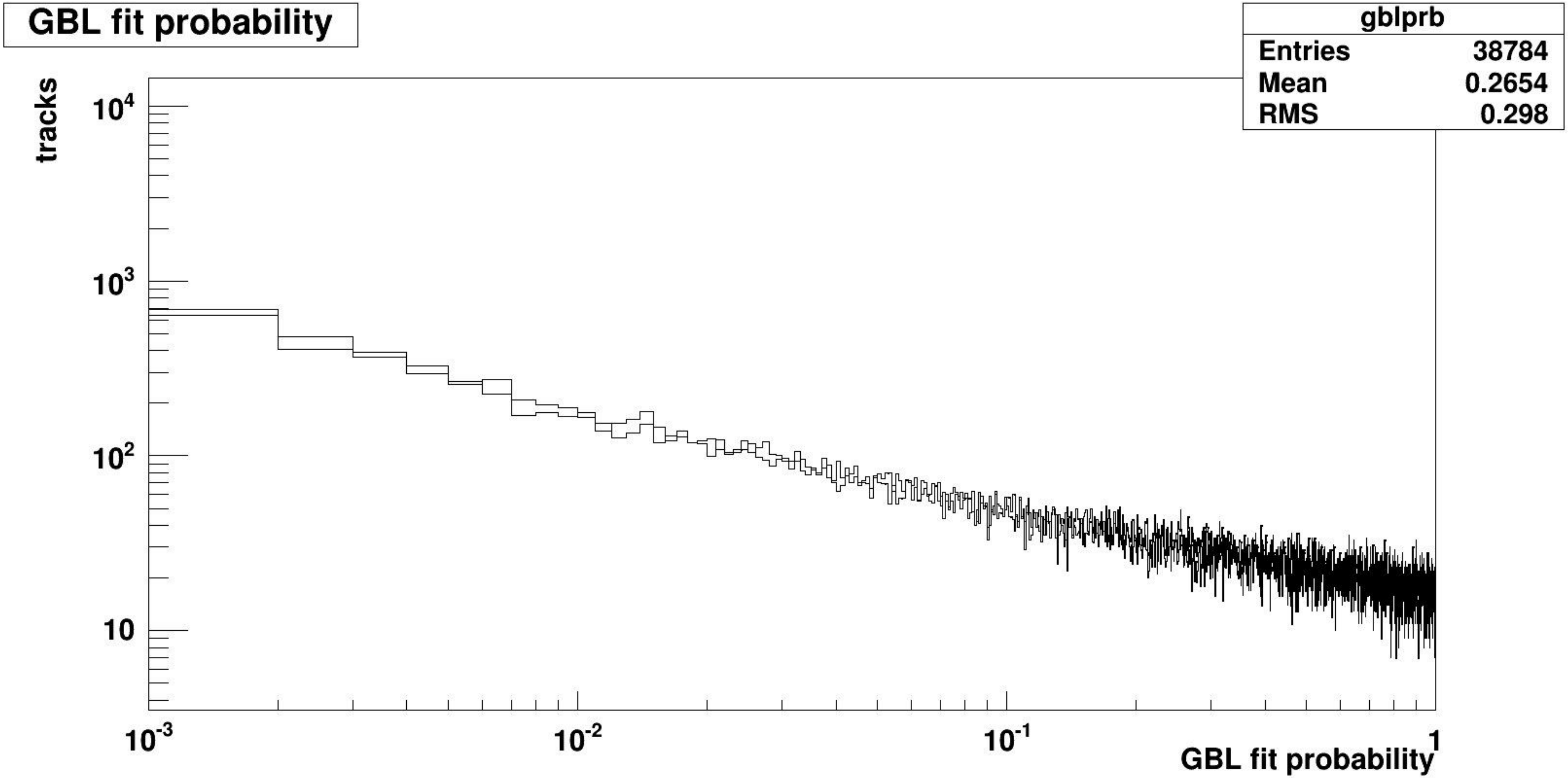
- Literature offers other models, too, HL most popular
- Distribution assumed to be Gaussian centrally
- Non-Gaussian tails
- MS and intrinsic resolution defines *track resolution*, i.e. uncertainty in space of a track along the track

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.

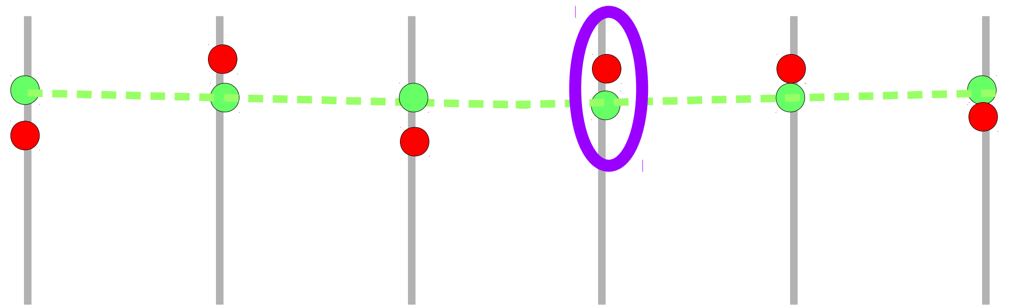


Prob biased vs unbiased



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

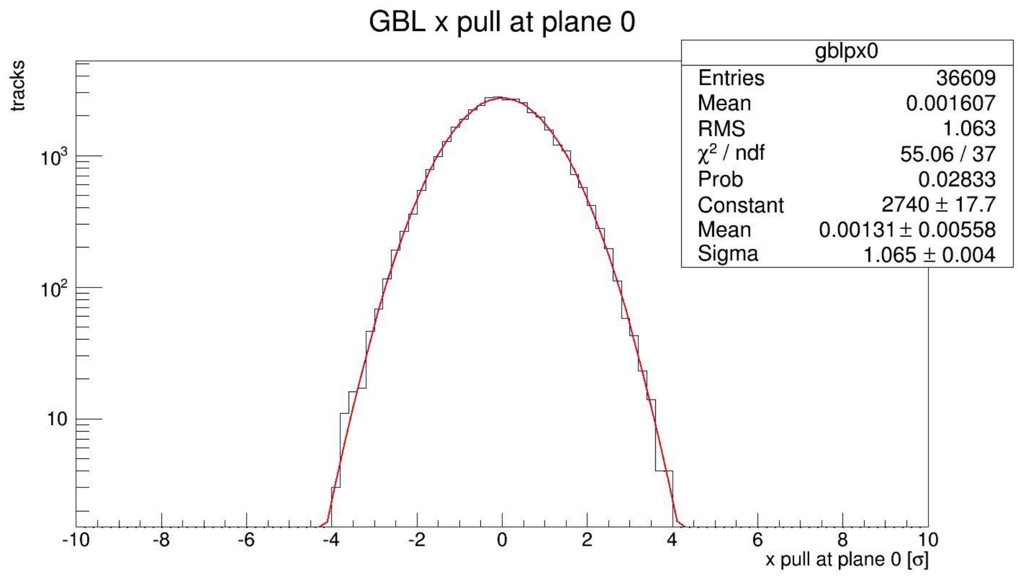
$$\mathrm{pull}_u \equiv p_u = \frac{r_u}{\sqrt{\sigma_{\mathrm{int}}^2 + \sigma_{\mathrm{t},u}^2}}$$

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

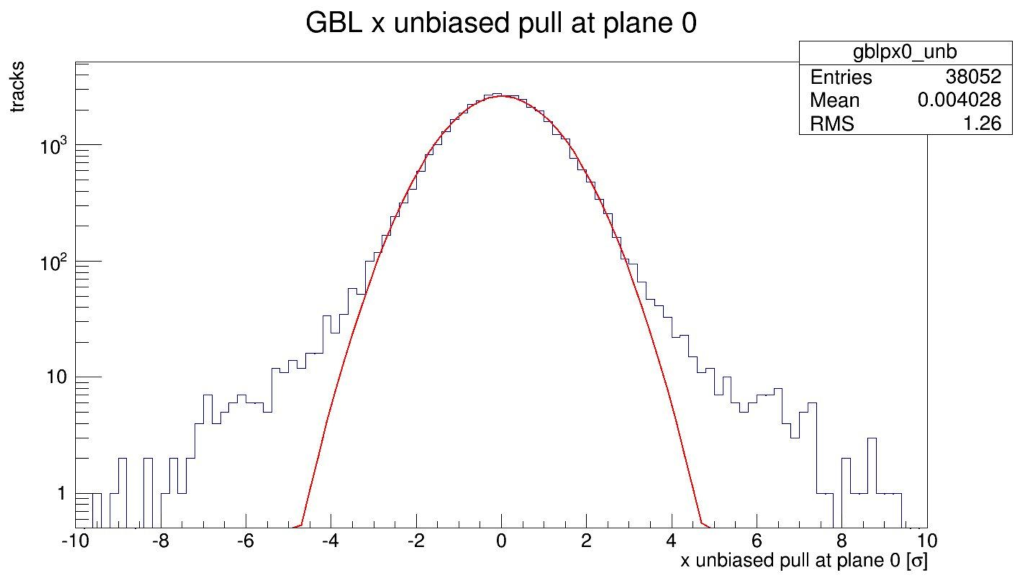
→ repeat track fit varying σ_{int} by pull width
→ pull → N(0,1) and σ_{int} converges

Pulls and track resolution II

BIASED



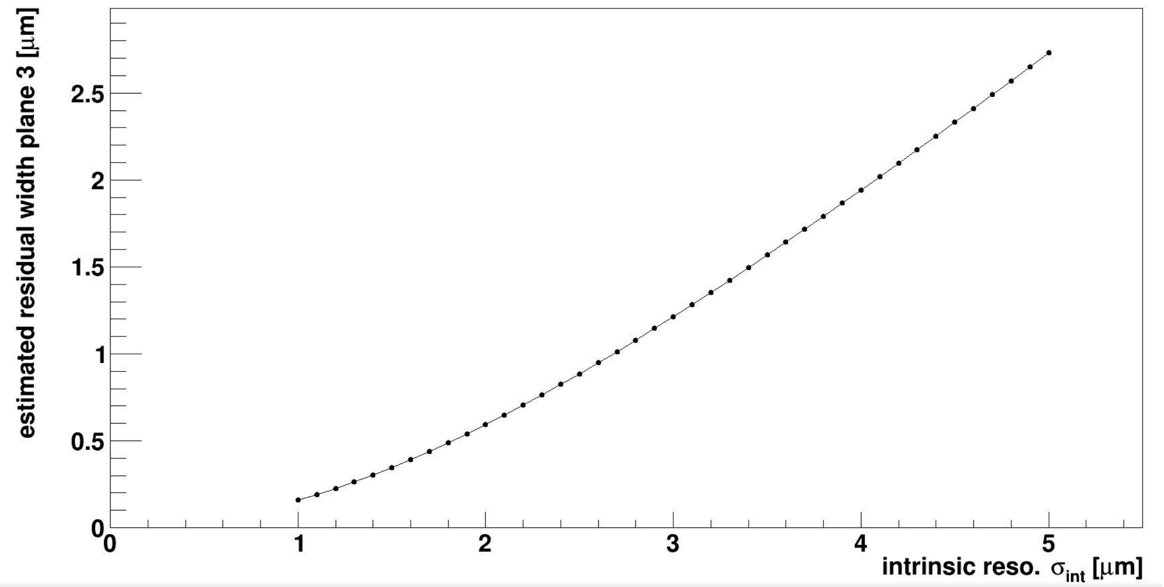
UNBIASED



→ 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 $\sigma_{t,b} < \sigma_{t,u}$

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

→ 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

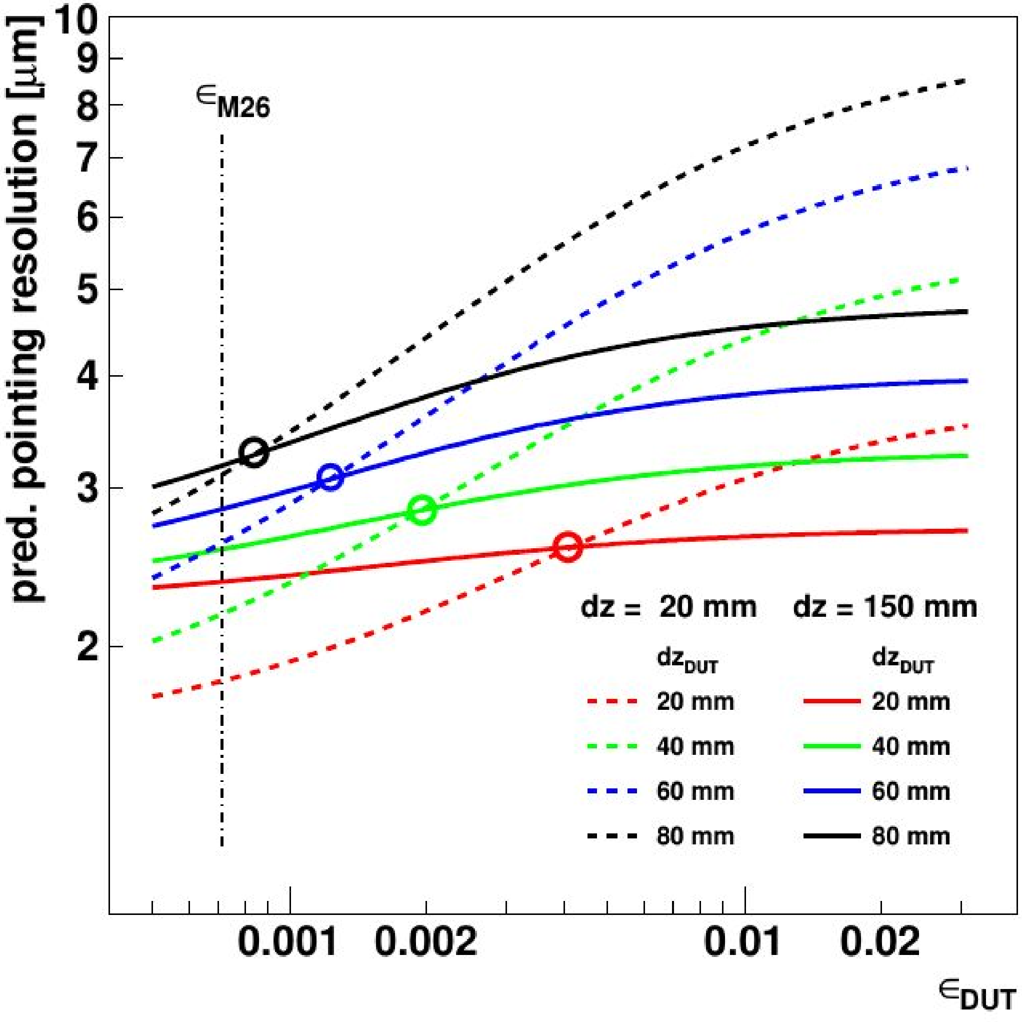
$$\sigma_{int} = 3.24 \text{ +- } 0.5\% \text{ (stat.) +- } 3\% \text{ (syst.)}$$ (cf.last slide)

- 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

Track resolution predictions

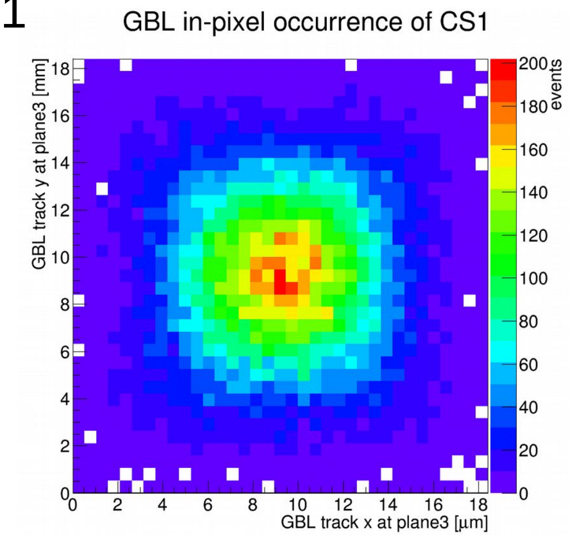
- Using 6 planes, assuming DUT in the centre
- Wide set-up offers superior track resolution with thicker DUTs and vice versa.
- Intersection is function of material budget

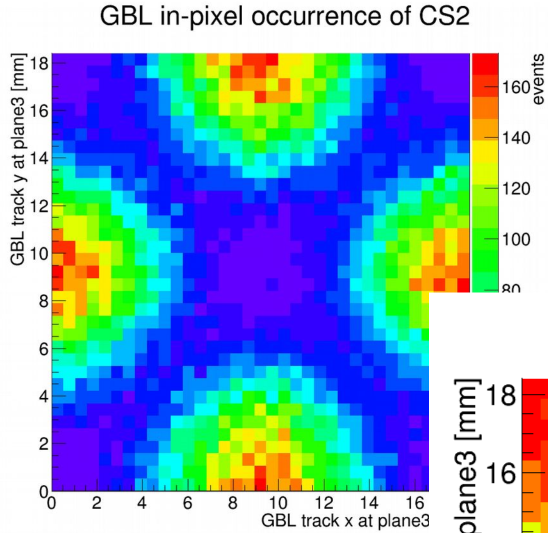
→ Optimise resolution prior to your test beam



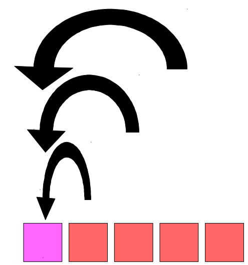
Looking even closer ...

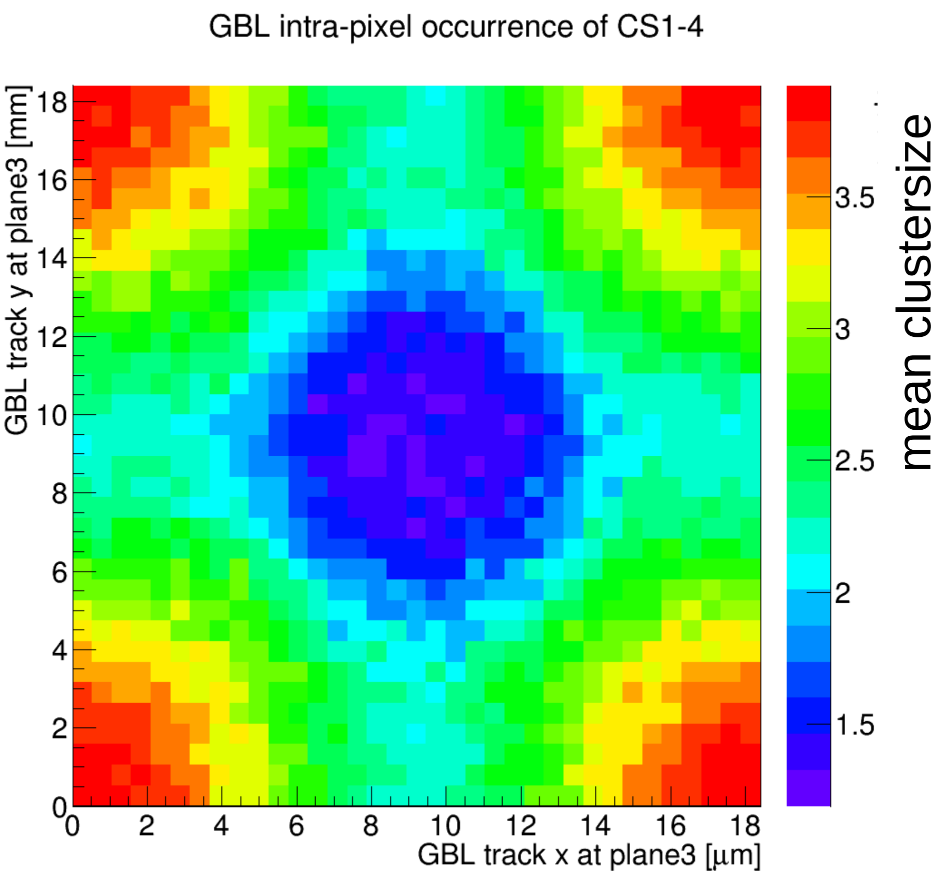
CS 1



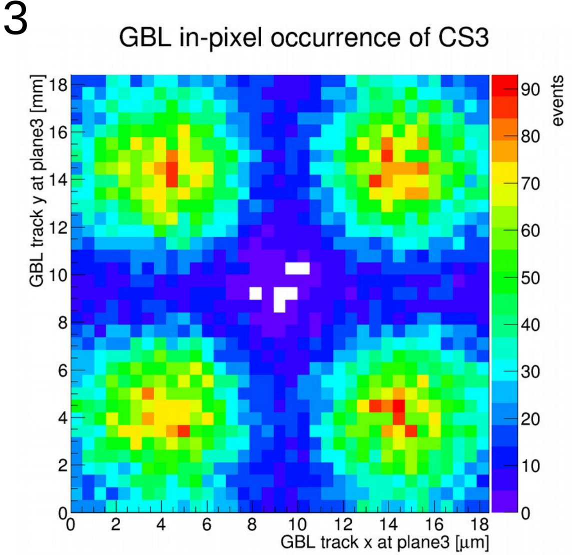


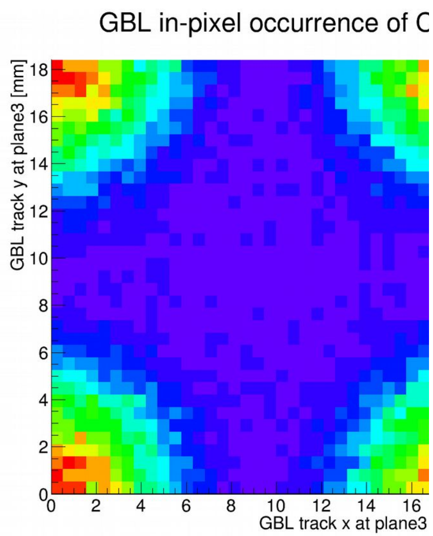
CS 2





CS 3





CS-dependent quantities

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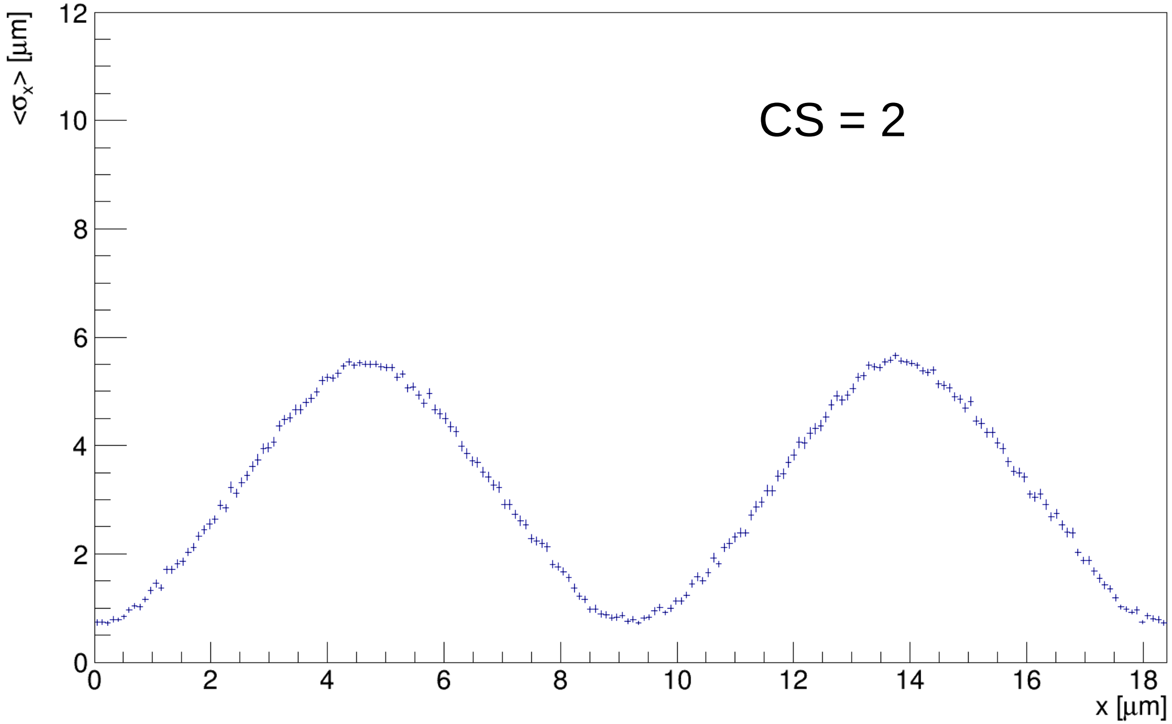

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