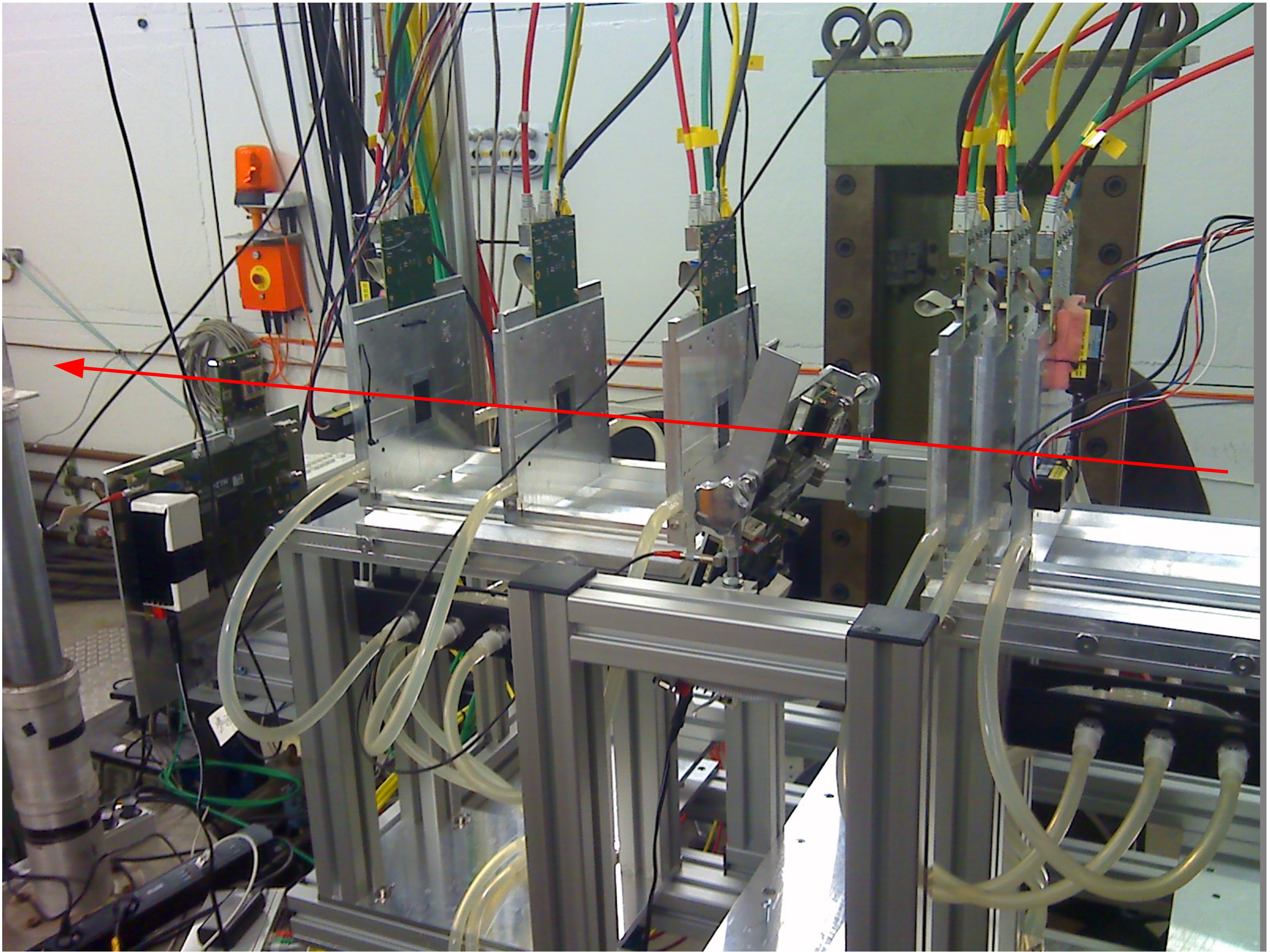
Tracking at the test beam

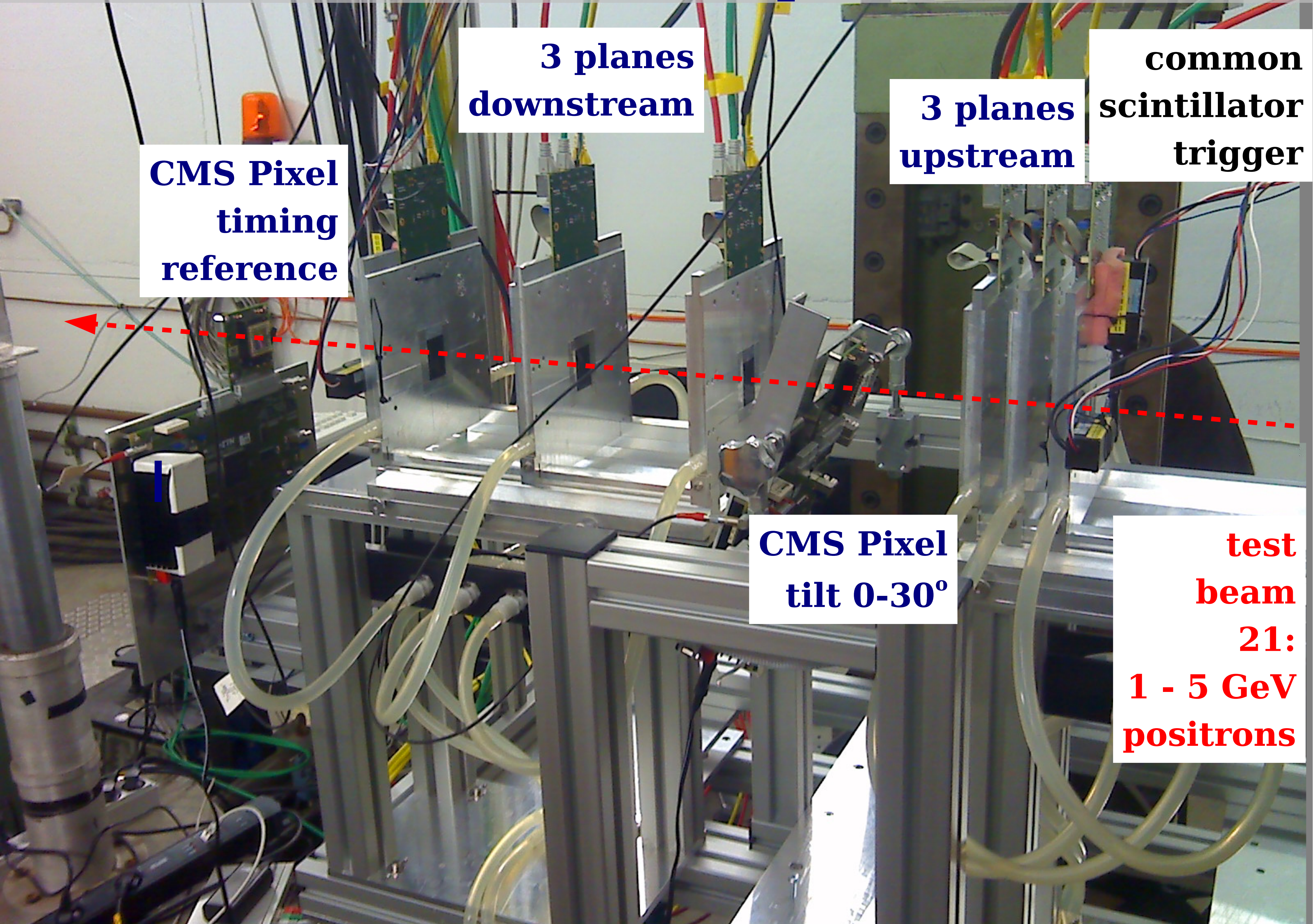
Daniel Pitzl, DESY

Test beam meeting, 2.4.2012

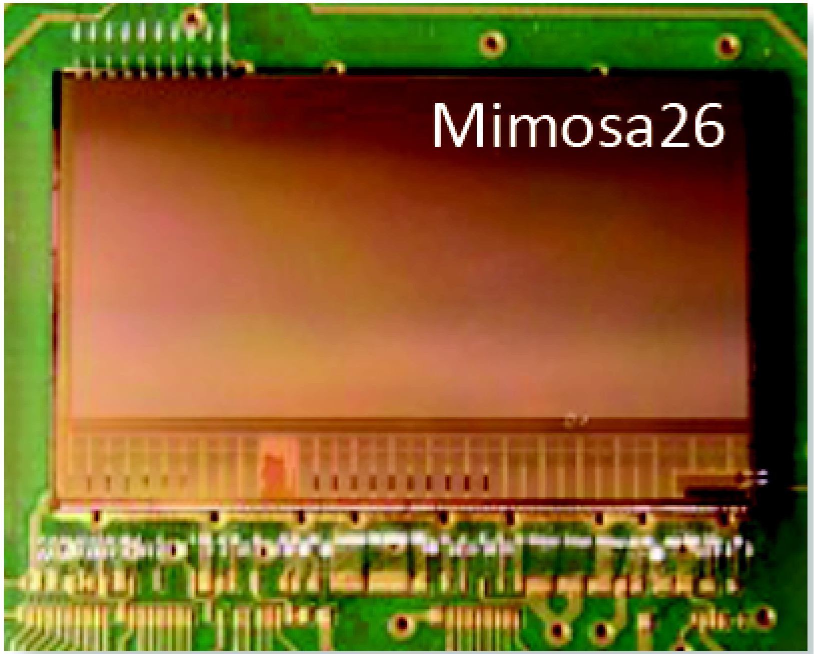


- Triplets
- General Broken Lines
- Resolution

EUTelescope



Mimosa26 pixel chip



PCB has opening underneath sensor

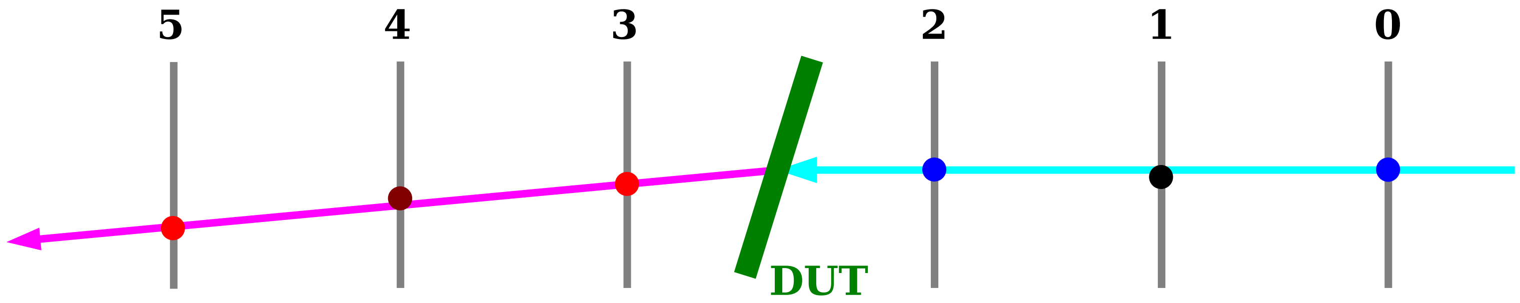
- Mimosa26 monolithic active pixel sensors (Strasburg, 2009):
- thinned to 50 μm,
- 0.05% X_0 per plane,
- $18.4 \times 18.4\ \mu m^2$ pixel size,
- $1152 \times 576 = 663k$ pixels,
- $10.6 \times 21.2\ mm^2$ active area,
- binary readout,
- integration time 115 μs.
  - 0.5 – 5 pile-up tracks, depending on beam rate.

EuTelescope software in Marlin

step		output.format	constants
0. EUDAQ data taking: 900s		**native.bin,** e.g. 200 MB 500k triggers	
1. convert, find hot pixels: 70s		**raw.lcio,** e.g. 200 MB	**hotpixel.db**
2. clustering: 240s		**clusters.lcio,** e.g. 400 MB	**offset.db**
3. hits, coarse align: 250s		**hits.lcio,** e.g. 600 MB	**pre-align.db**
4. Millepede alignment: 12s	**GBL**	**pede.bin,** e.g. 120 MB	**align.db**
5. track fitting: 270s	**GBL**	**tracks.lcio,** e.g. 25 MB	

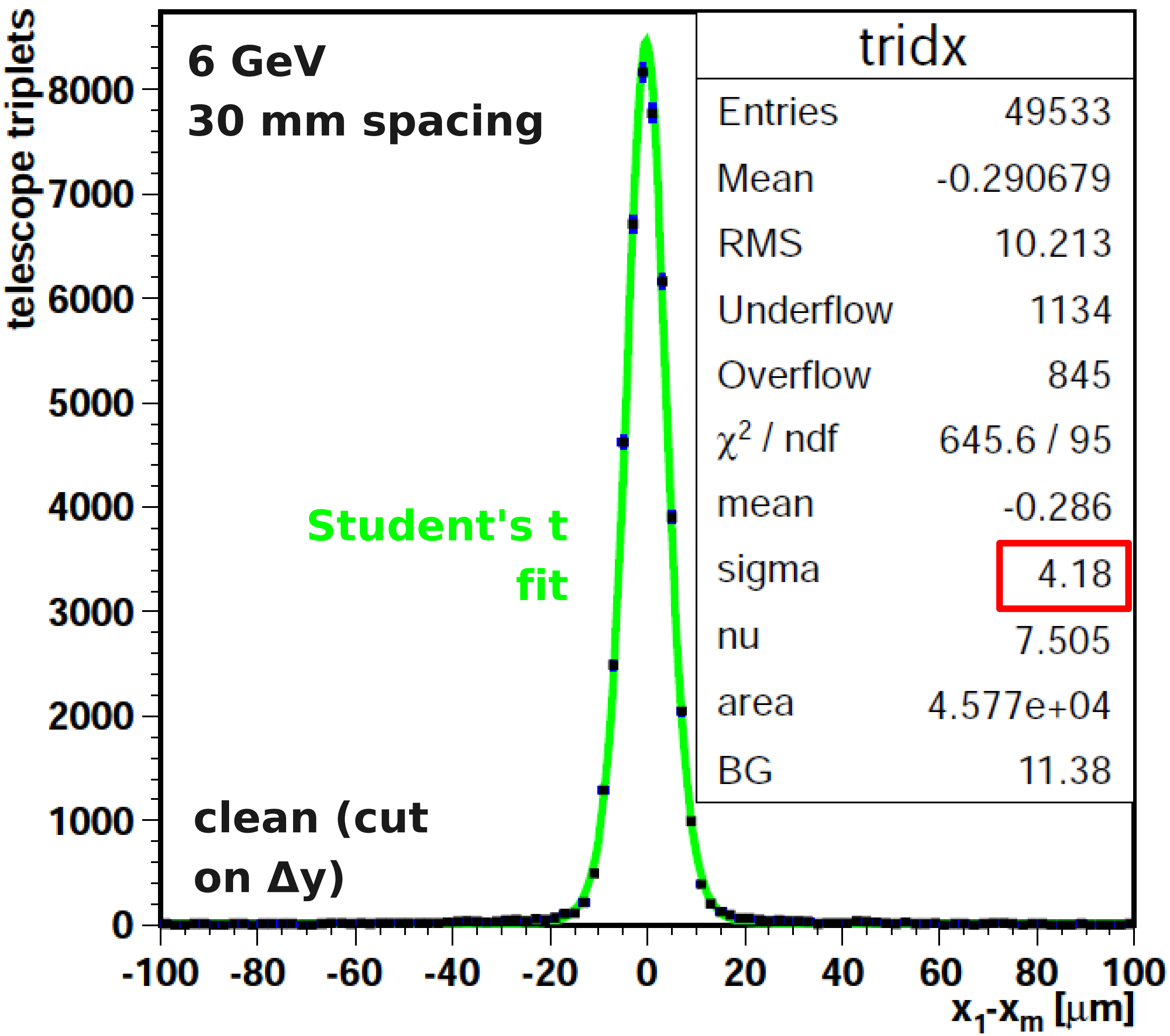
All steps produce ROOT histograms for monitoring

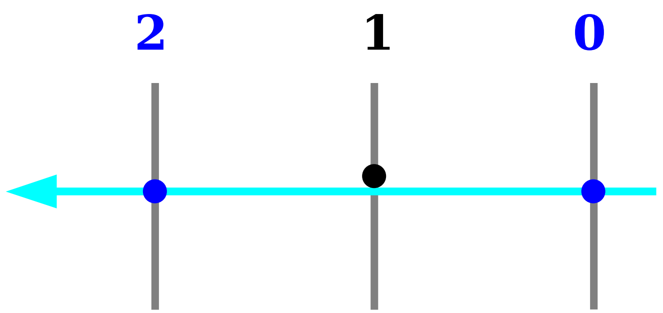
track finding with triplets



- Sort (pre-)aligned hits along z
- Upstream triplet search:
  - Double loop over planes 0 and 2, form all vectors t_{02}
  - loop over plane 1, calculate *residual* = $hit_1 - t_{02}$, cut, store
- Repeat for downstream triplet:
  - Double loop over planes 3 and 5, form all vectors t_{35}
  - loop over plane 4, calculate residual = $hit_4 - t_{35}$, cut, store
- Match upstream and downstream triplets at DUT, cut
- Refit all 6 hits with General Broken Lines, or include DUT

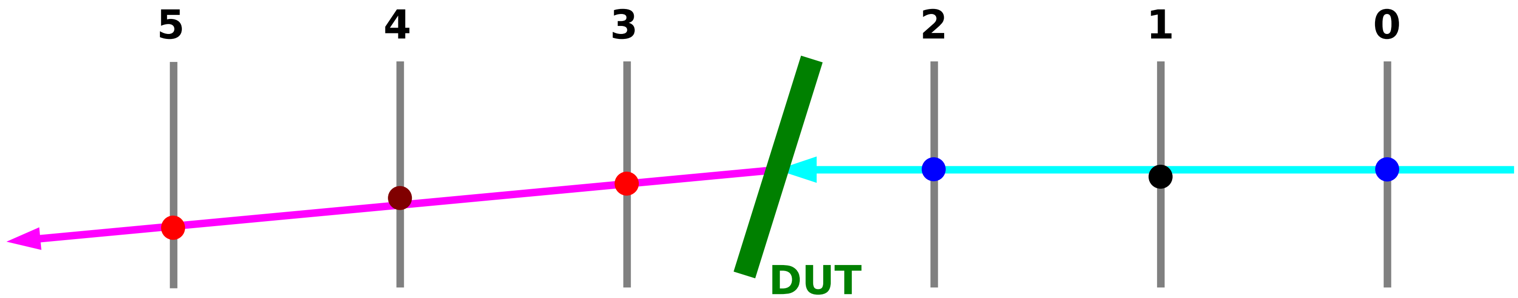
Telescope resolution from triplets

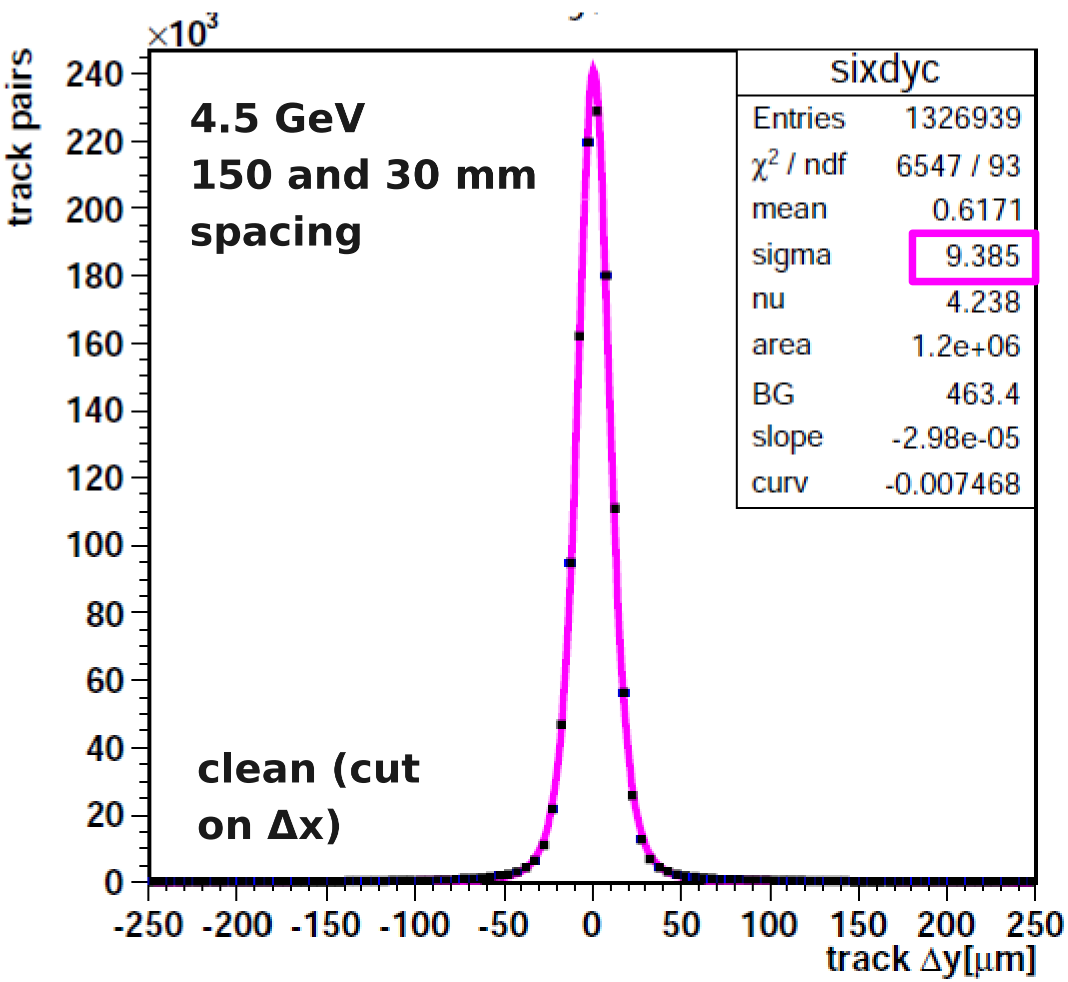




- **Triplet residuals:**
  - **hits in plane 0 and 2 form vector,**
  - **residual to hit in middle plane 1,**
  - **σ_r = 4.2 μm**
  - **$\sigma_r = \sigma_i \sqrt{(3/2)}$**
  - **σ_i = 3.4 um intrinsic telescope resolution**

triplet matching at the DUT





- **Triplet matching:**
  - **extrapolate both triplets to the DUT**
  - $\sigma_\Delta = 9.4\ \mu m$
  - $\sigma_\Delta = \sigma_{ex} \sqrt{2}$
  - $\sigma_{ex} = 6.6\ um$
  - **allows clean selection of tracks**
  - **allows DUT mapping with 7 μm steps**

General Broken lines

Track model: broken line from V. Blobel, generalized by C. Kleinwort.
Takes multiple scattering and intrinsic resolution into account.
Covariance matrix of track parameters is calculated.
The General Broken Line fit is equivalent to a Kalman filter, but faster, exploiting the bordered band matrix structure of the problem.
GBL solves the entire track fit in one step; outlier rejection requires iteration.

GBL

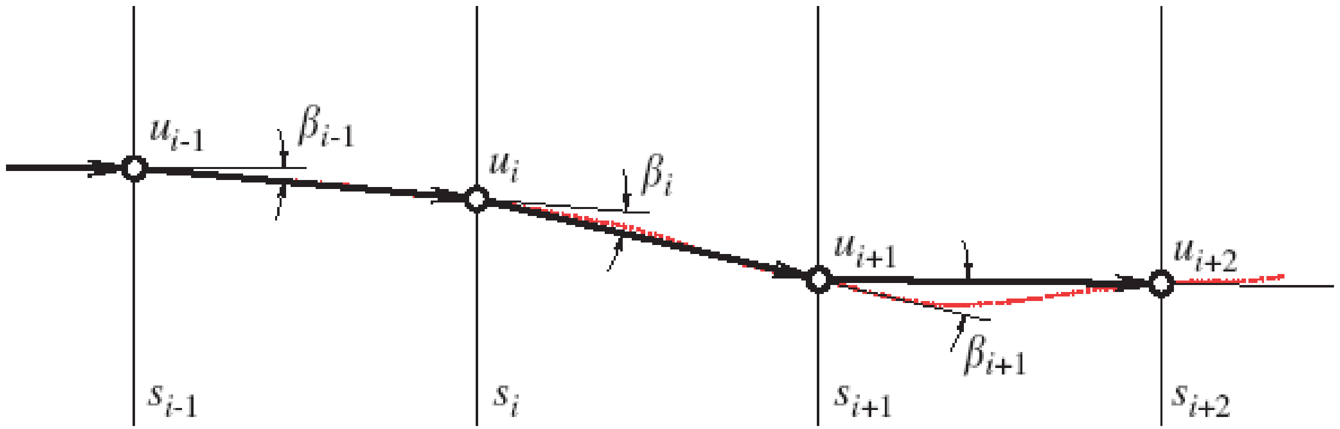
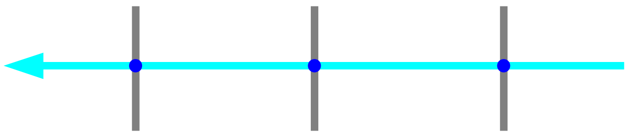


Fig. 3. Particle trajectory with fitted residuals u_i and kink angles β_i.

Volker Blobel: Software alignment for tracking detectors, NIM A566 (2006) 5-13
Volker Blobel: A new fast track-fit algorithm based on broken lines, NIM A566 (2006) 14-17
V. Blobel, C. Kleinwort, F. Meier: Fast alignment of a complex tracking detector using advanced track models, Comp Phys Comm 182 (2011) 1760-3
C. Kleinwort, F. Meier: Alignment of the CMS silicon tracker, NIM A 650 (2011) 240-4
Claus Kleinwort: General broken lines as advanced track fitting method, NIM A 673 (2012) 107-10
https://www.wiki.terascale.de/index.php/GeneralBrokenLines
http://www.desy.de/~kleinwrt/GBL/html/

multiple scattering: Si and air

- Air at NTP (20°C, 1 bar):
  - ρX_0 = 36.6 g/cm^2, ρ = 1.2 mg/cm^3
  - X_0 = 305 m (cosmic air showers!)
  - 150 mm air ≐ 0.50‰ X_0
  - approximated by 2× thin scattering

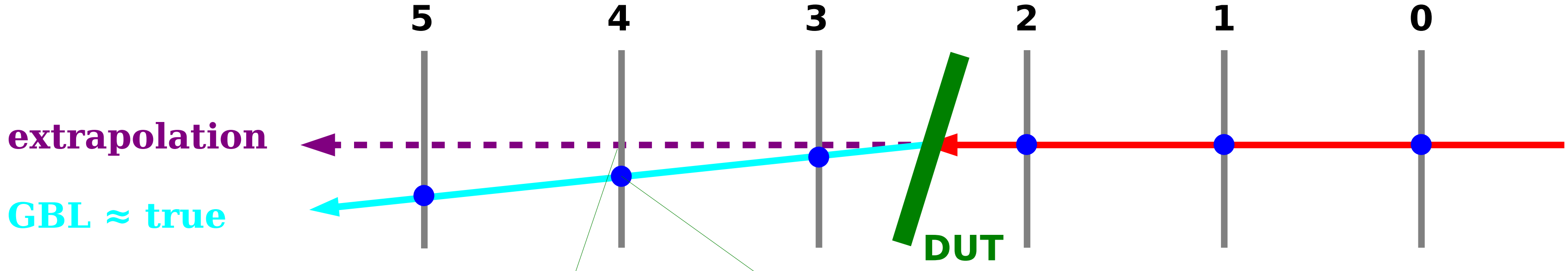


- Telescope planes:
  - 50 um Si ≐ 0.54‰ X_0
  - black Kapton foil ≈ 0.1‰ X_0
  - described by thin scatter

PDG: $$\langle\theta\rangle[rad] = \frac{0.0136}{p[GeV/c]}\sqrt{d/X_0}\left(1 + 0.038\ \ln(d/X_0)\right)$$

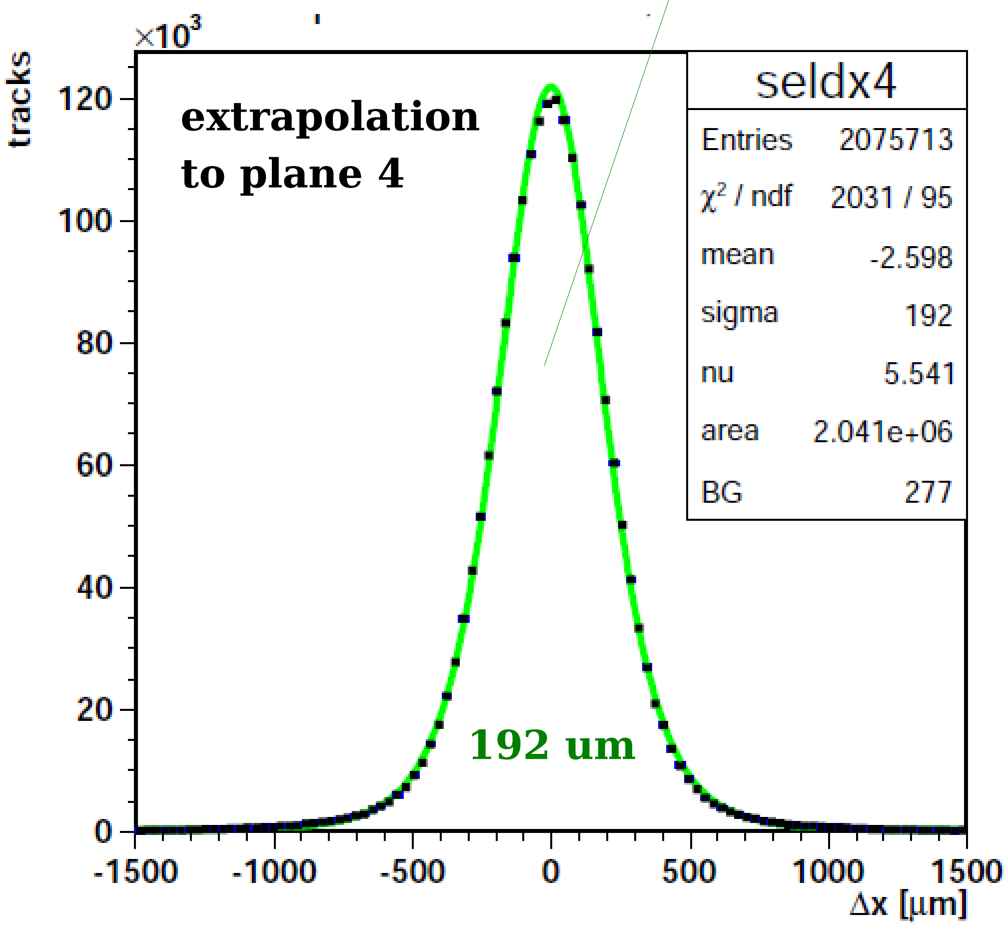
(fit to Geant simulation, 98% Gaussian core)
alternative formulae by Lynch & Dahl and Frühwirth & Regler are numerically identical in the range studied here.

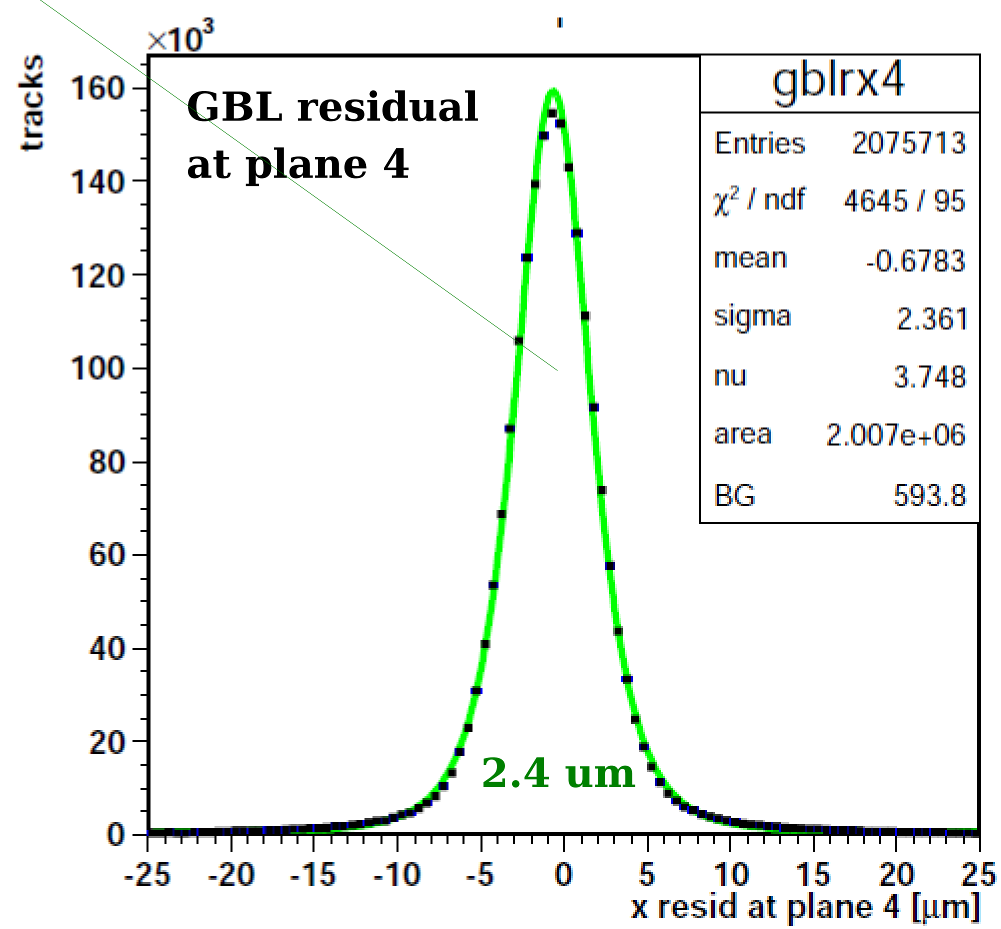
telescope tracking with GBL



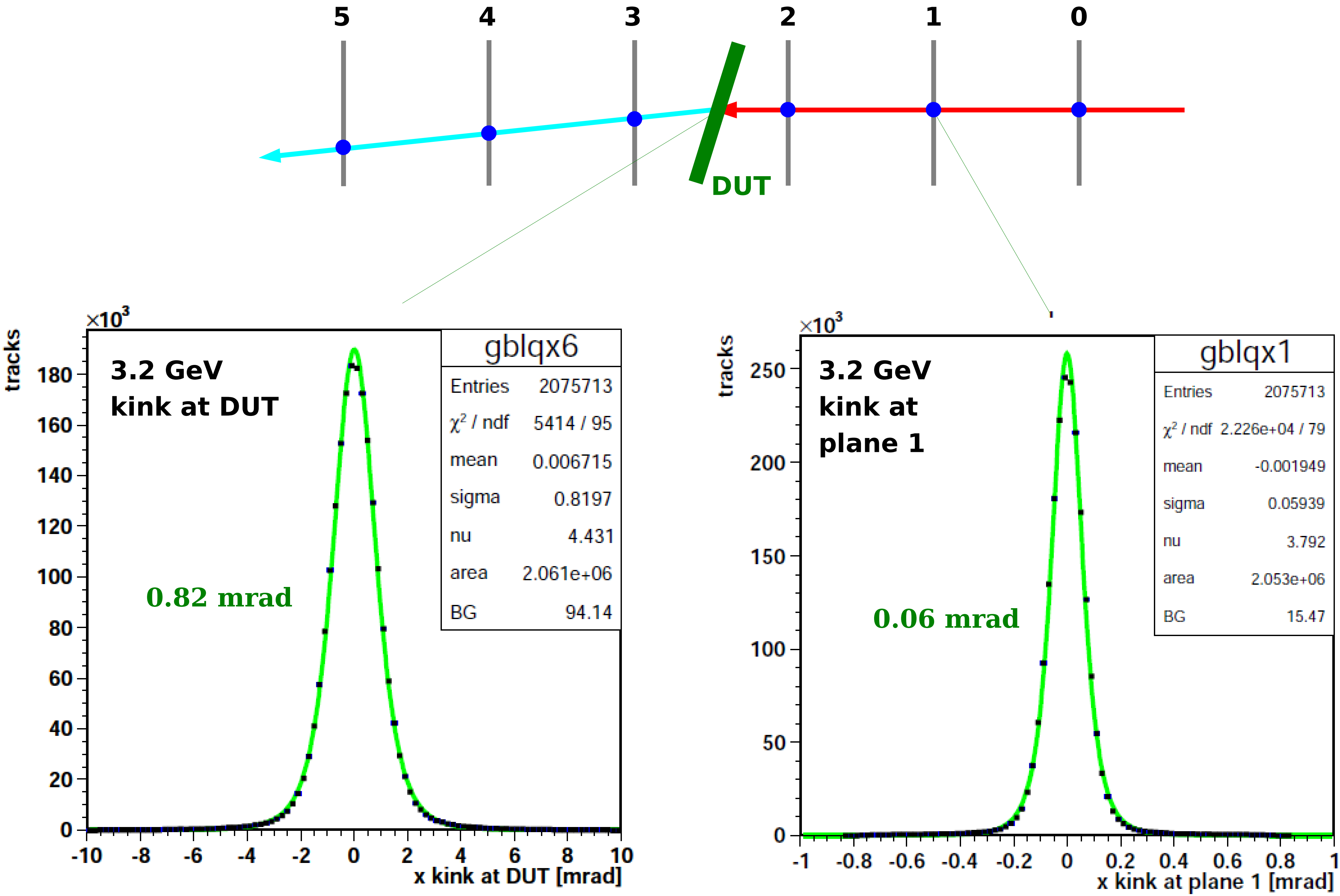
planes 2 and 0 define the reference track, verified by plane 1

run 218: 3.2 GeV, 1 mm Cu





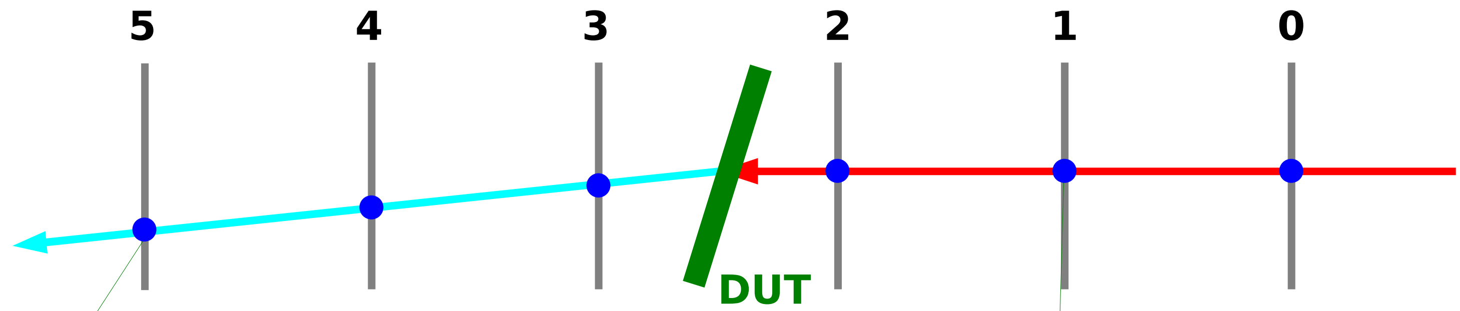
GBL kinks

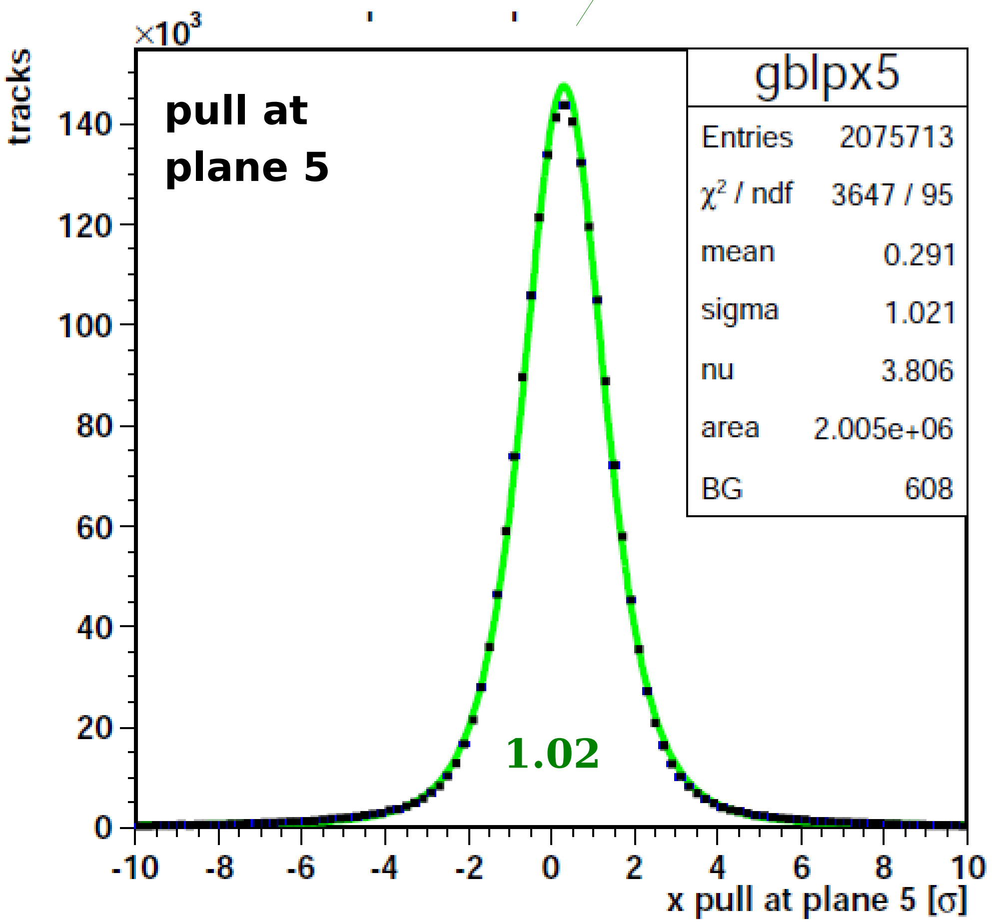

5
4
3
2
1
0
DUT
tracks
×10³
3.2 GeV
kink at DUT
0.82 mrad
gblqx6
Entries 2075713
χ² / ndf 5414 / 95
mean 0.006715
sigma 0.8197
nu 4.431
area 2.061e+06
BG 94.14
x kink at DUT [mrad]
3.2 GeV
kink at
plane 1
0.06 mrad
gblqx1
Entries 2075713
χ² / ndf 2.226e+04 / 79
mean -0.001949
sigma 0.05939
nu 3.792
area 2.053e+06
BG 15.47
x kink at plane 1 [mrad]

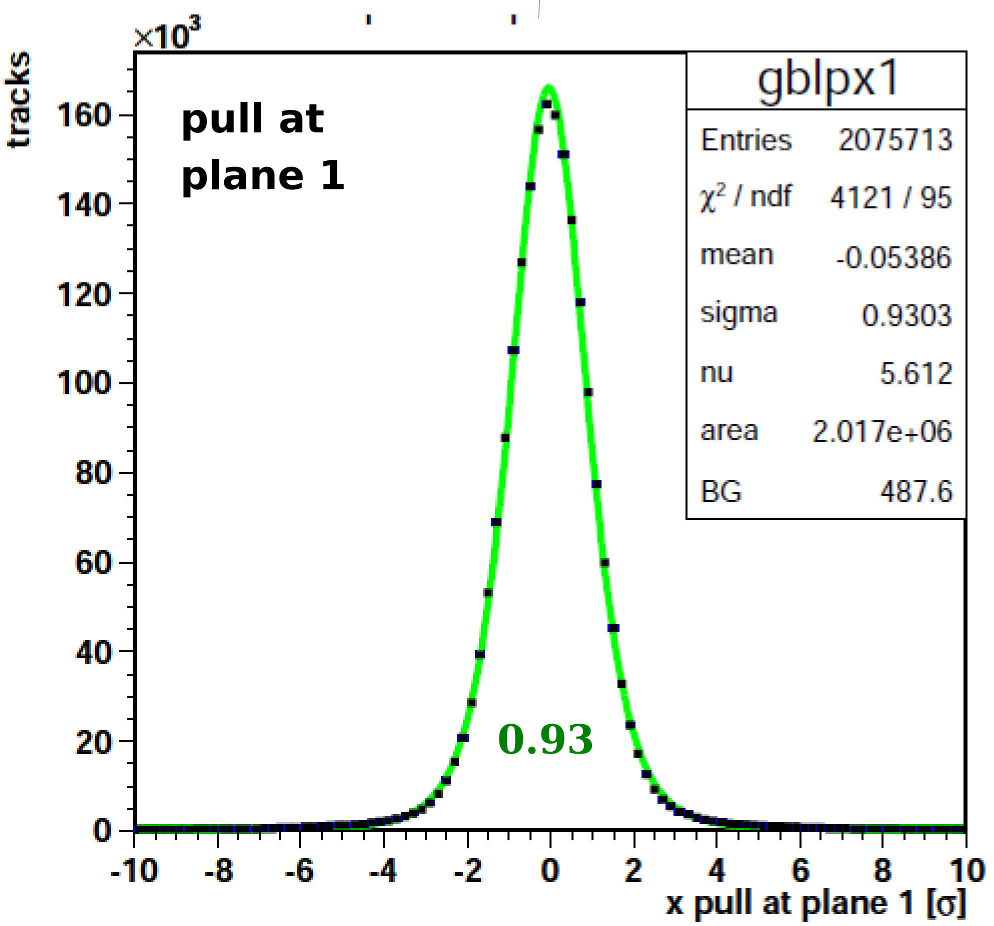
GBL pulls

$$p = \frac{\Delta}{\sqrt{\sigma_i^2 - \sigma_{fit}^2}}$$

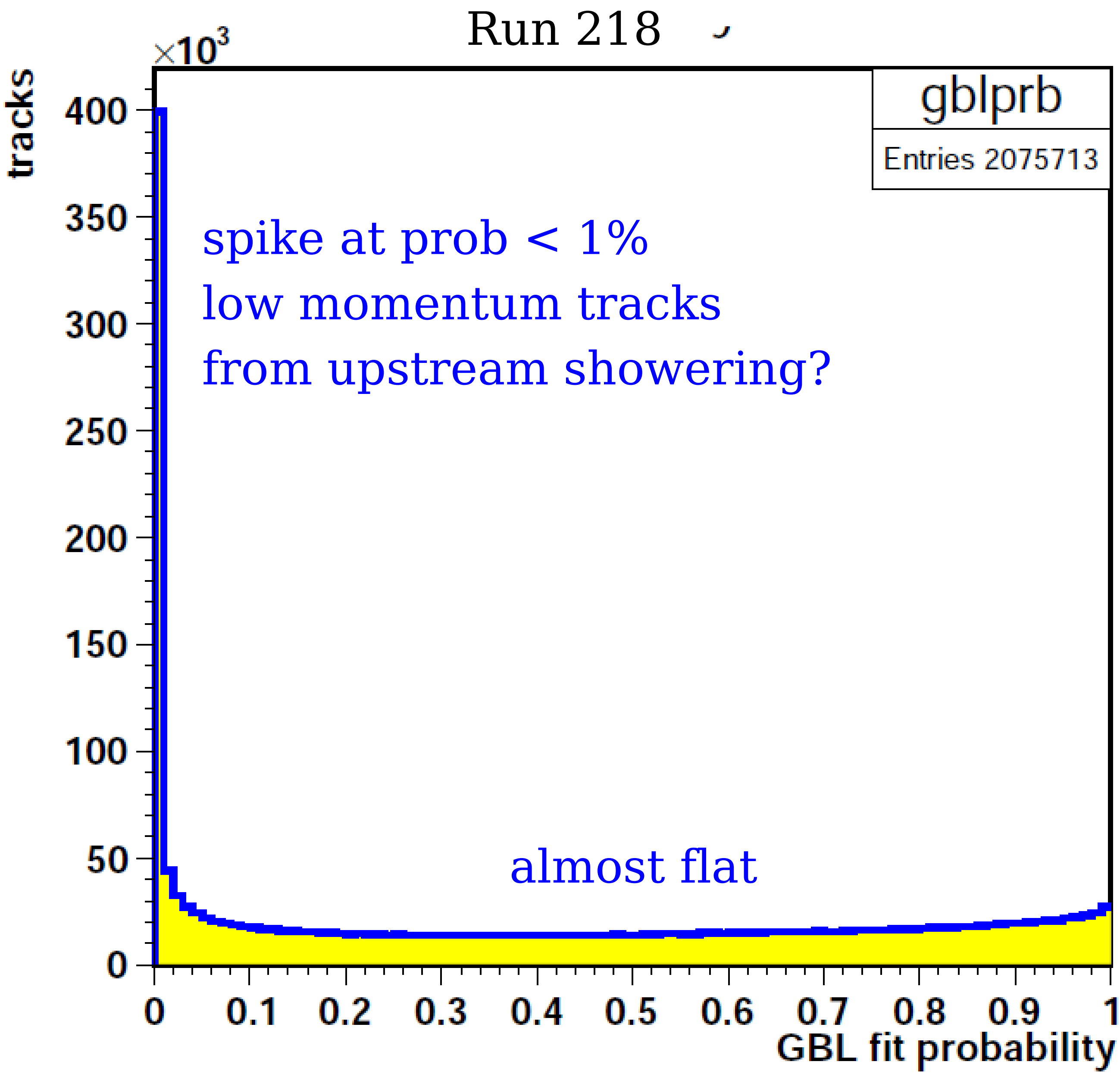
Gaussian with σ = 1







GBL fit probability



- 3.2 GeV e^+ beam.
- 6% X_0 DUT
  - adjusted (reduced) to get ~flat probability

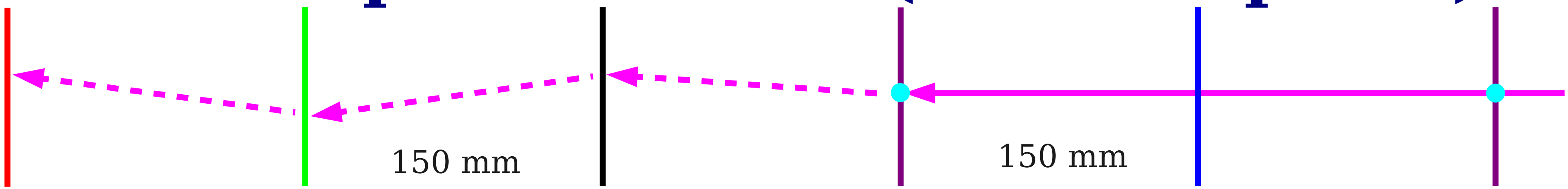
General Broken Lines for resolution study

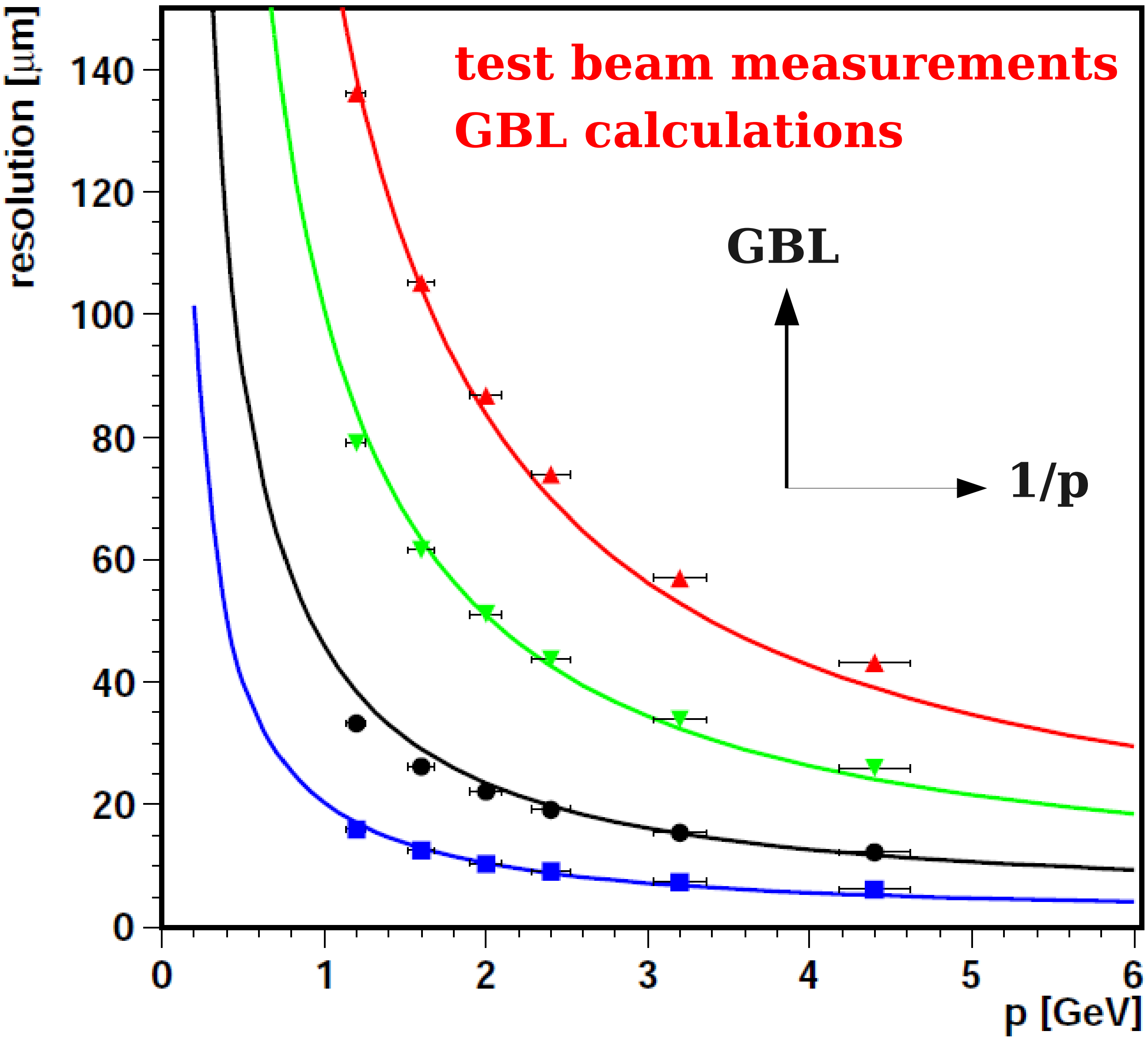
```
GblTrajectory traj(false); // curvature = false (straight line track)
double measRes = 3.5E-3; // [mm]
double p = 3.2; // [GeV]
double X0Si = 60e-3 / 94; double X0Air =  50 / 304E3; // [mm]
double tetSi = 0.0136 * sqrt(X0Si) / p * ( 1 + 0.038*log(X0Si) );
double tetAir = 0.0136 * sqrt(X0Air) / p * ( 1 + 0.038*log(X0Air) );
double step = 150; // [mm] spacing

  // Si plane 0:
  GblPoint *point = new GblPoint(jacPointToPoint);
  point->addMeasurement( unit, 0, 1/measRes/measRes );
  point->addScatterer( 0, 1/tetSi/tetSi );
  unsigned int iLabel = traj.addPoint(*point); delete point;

  // Air:
  jacPointToPoint = Jac5( 0.5*step ); // Jacobian for track parameters
  point = new GblPoint(jacPointToPoint);
  point->addScatterer( 0, 1/tetAir/tetAir );
  iLabel = traj.addPoint(*point);
  ...
// fit:
traj.fit( Chi2, Ndf, downWeight );
traj.getResults( iLabel, Corrections, Covariance );
extrapolationErrorX = sqrt(Covariance(3,3)); // [mm] traj = (k, x', y', x, y)
```

Telescope resolution (0.1% X0/plane)

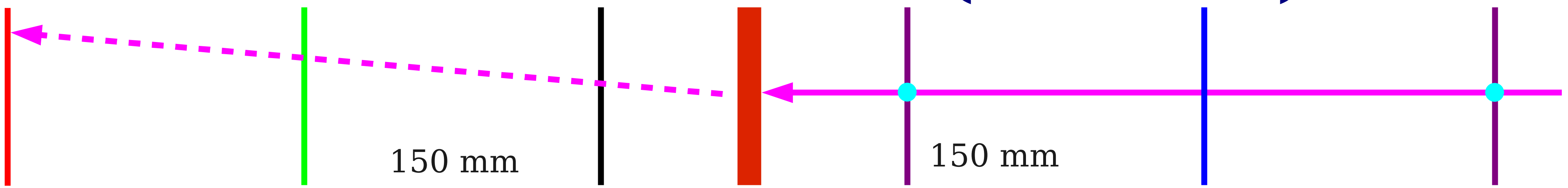


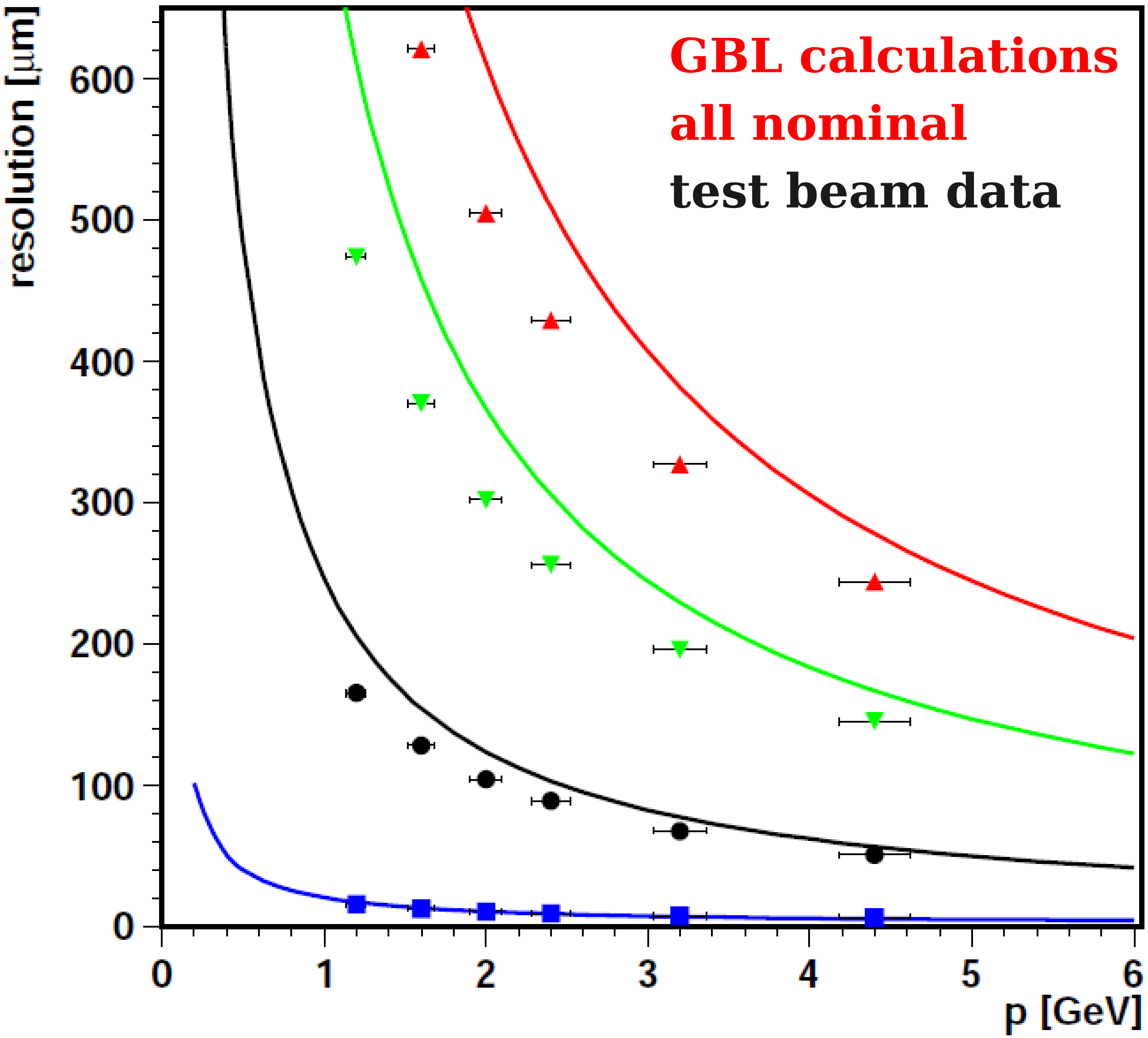


Data well described by GBL calculation using adjusted material:
65 µm Si + Kapton
2×25 mm air (?)

extrapol 3×150 mm
extrapol 2×150 mm
extrapol 1×150 mm
interpol

1 mm Cu inserted (7.0% X0)





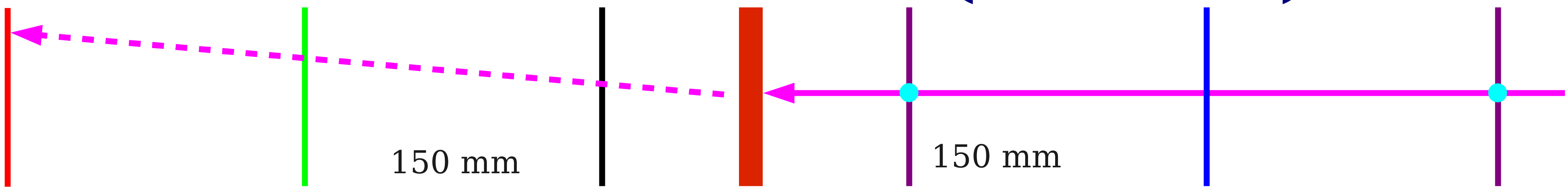
Data ~14% below the GBL calculation with nominal 1 mm Cu.
Impure Cu? No!
Momentum scale?
Fit vs RMS?
PDG formula?

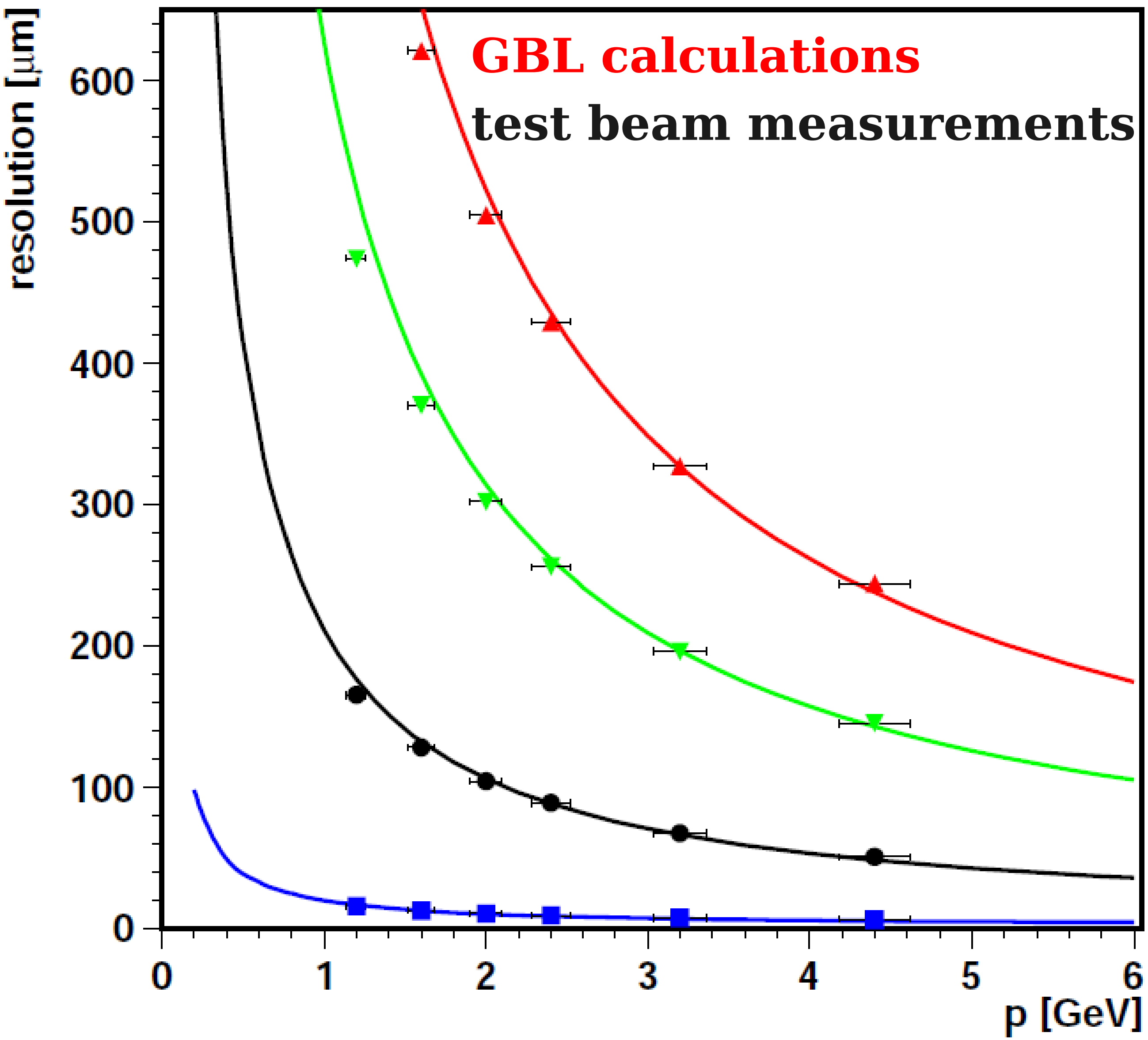
extrapol 3×150 mm

extrapol 2×150 mm

extrapol 1×150 mm
interpol

1 mm Cu inserted (7.0% X0)





Data well described by GBL calculation with reduced Cu: 0.70 instead 1.0 mm.

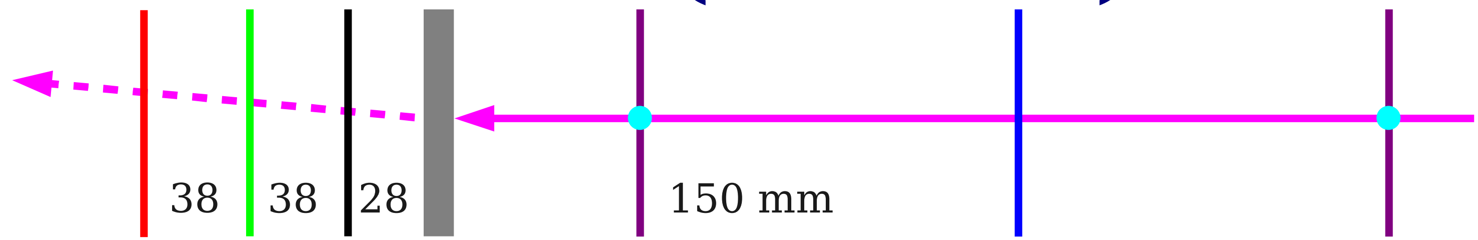
extrapol 3×150 mm

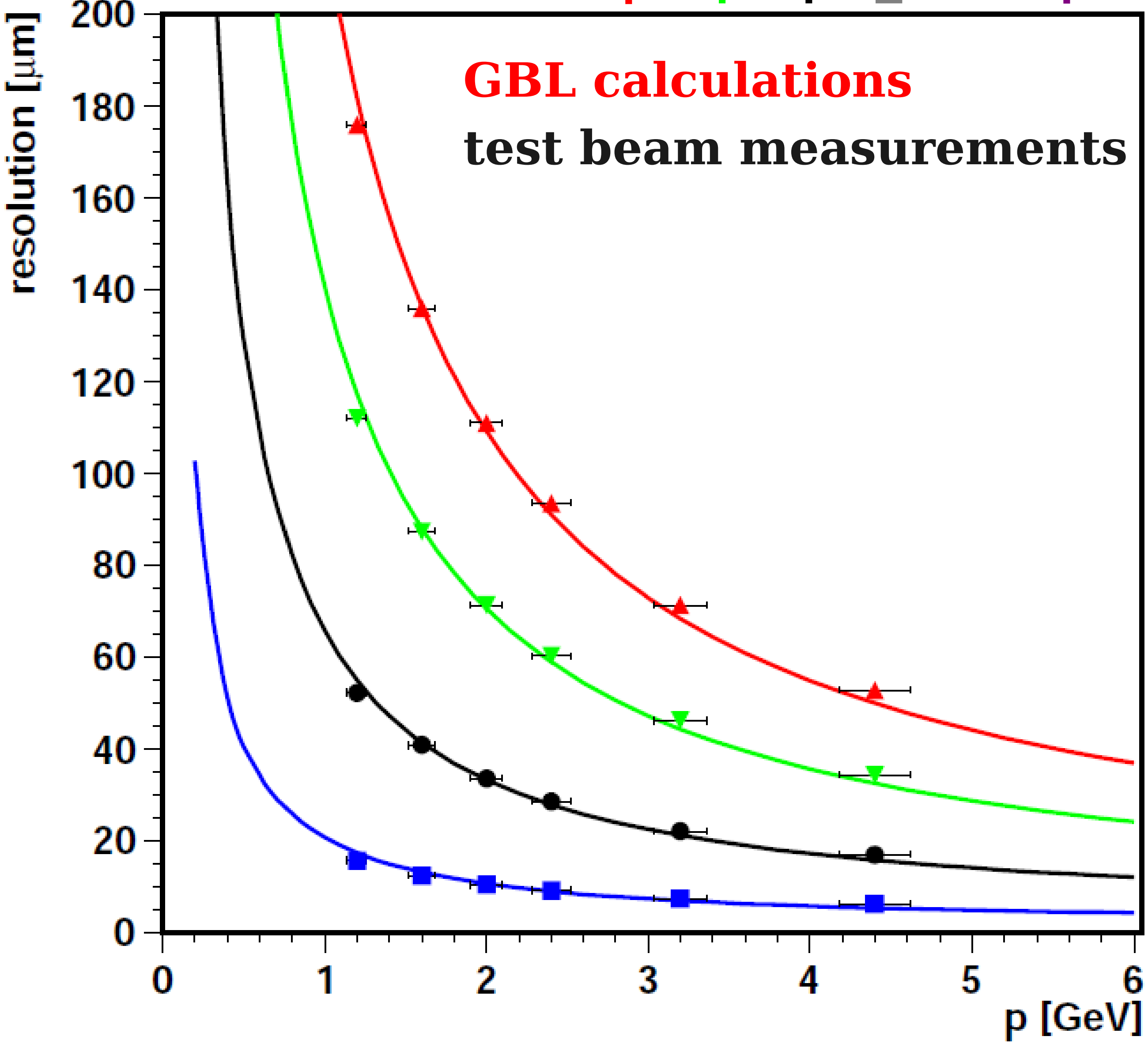
extrapol 2×150 mm

extrapol 1×150 mm

interpol

4 mm Al inserted (4.5% X0)





Data well described by GBL calculation with reduced Al: 2.6 instead 4.0 mm.

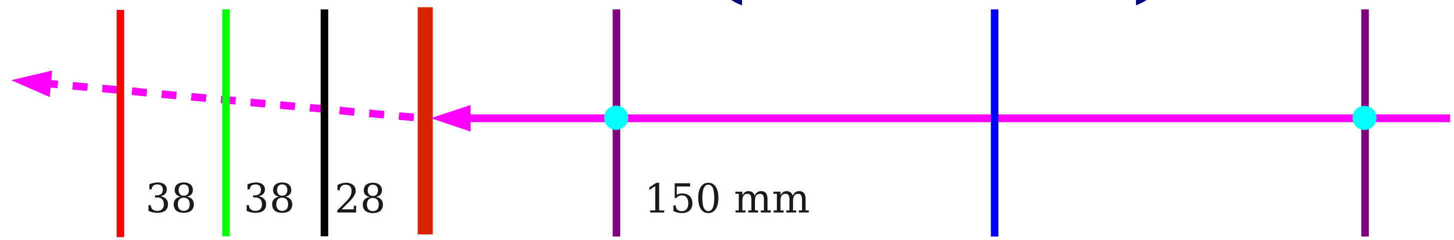
extrapol 104 mm

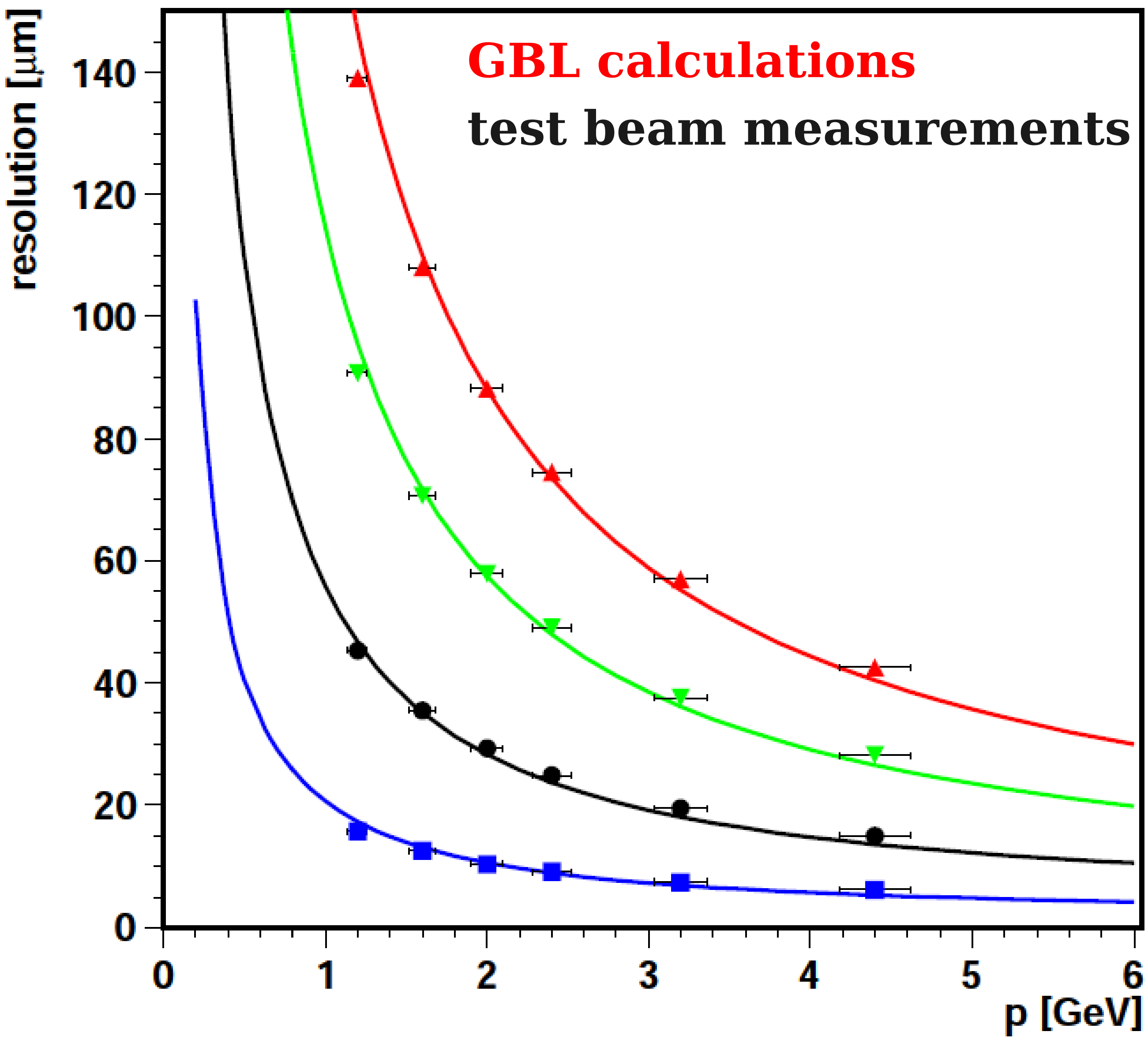
extrapol 66 mm

extrapol 28 mm

interpol

0.4 mm Cu inserted (2.8% X0)





Data well described by GBL calculation with reduced Cu: 0.27 instead 0.4 mm.

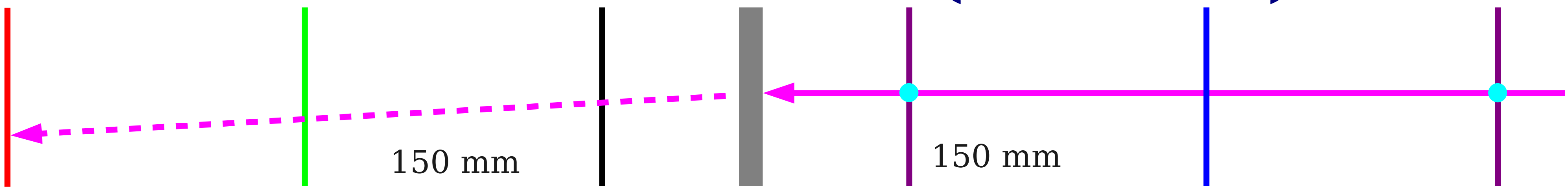
extrapol 104 mm

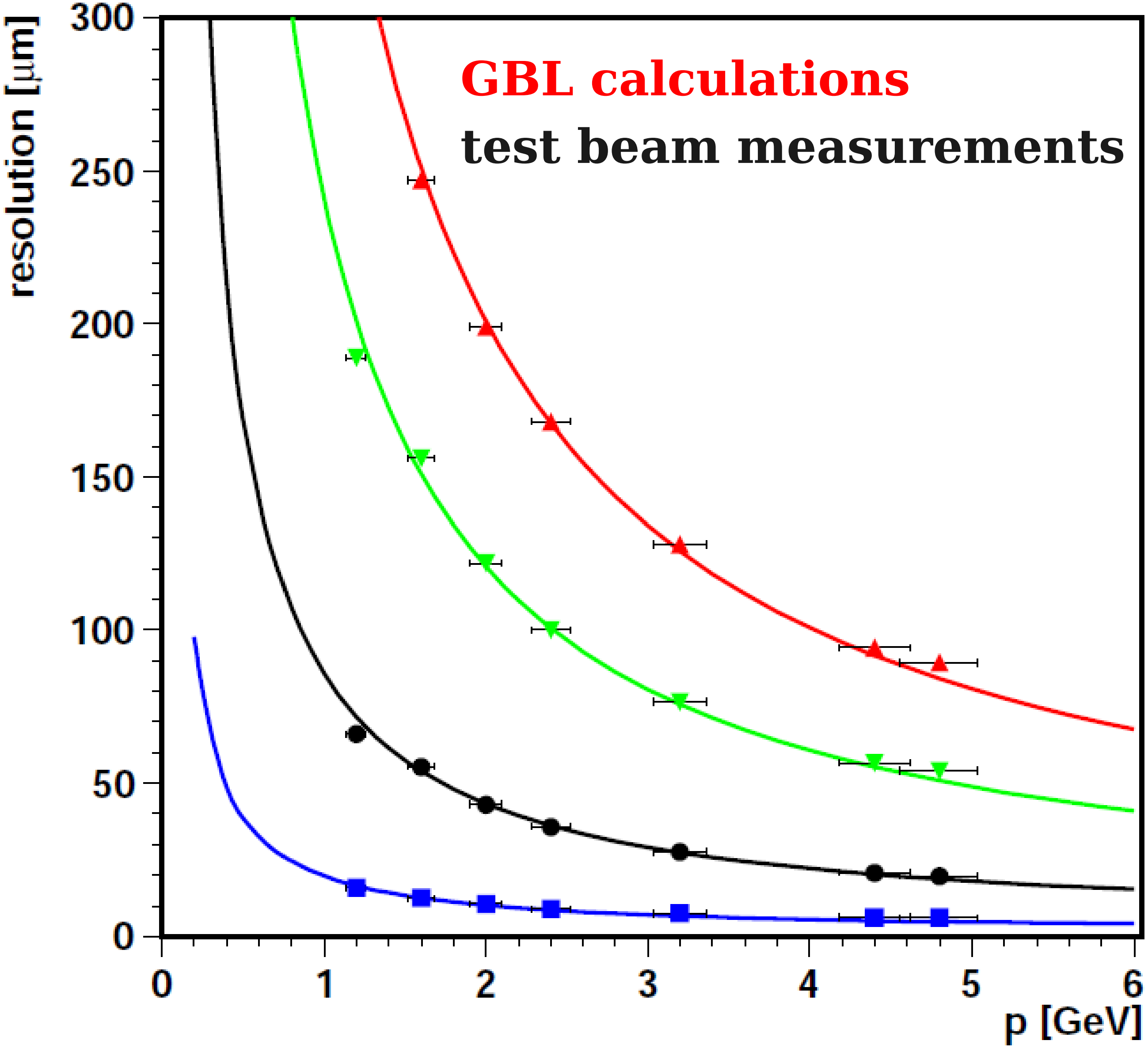
extrapol 66 mm

extrapol 28 mm

interpol

1 mm Al inserted (1.1% X0)

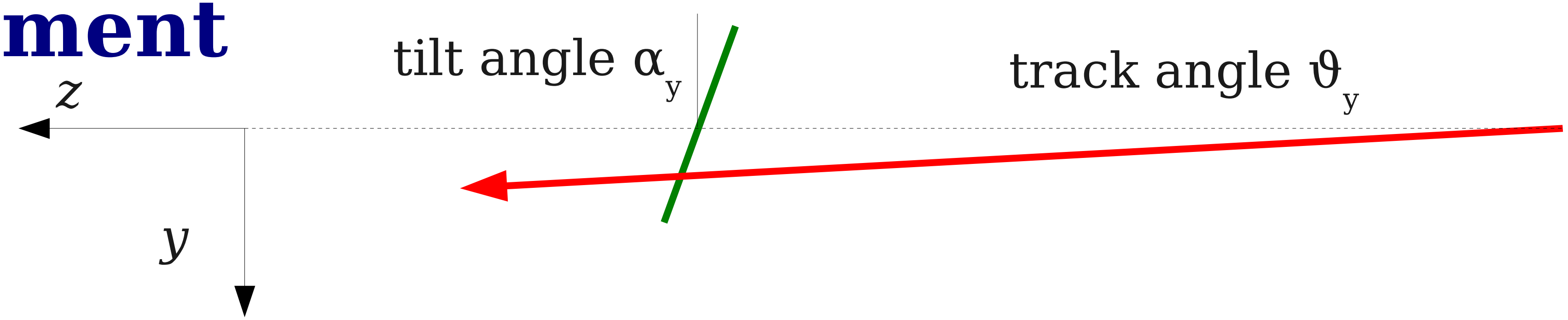




Data well described by GBL calculation with reduced Al: 0.7 instead 1.0 mm. PDG formula?

extrapol 3×150 mm
extrapol 2×150 mm
extrapol 1×150 mm
interpol

alignment



- tilted sensor: $z = z_s + y \tan\alpha$, $z_s = y$ of sensor at $y = 0$
- track: $y = y_0 + (z - z_0) \tan\vartheta_y$, $y_0 = y$ of track a some z_0
- track at sensor: $y_t = (y_0 + (z_s - z_0) \tan\vartheta_y) / (1 - \tan\alpha \tan\vartheta_y)$
- hit: shift and rotate around z:

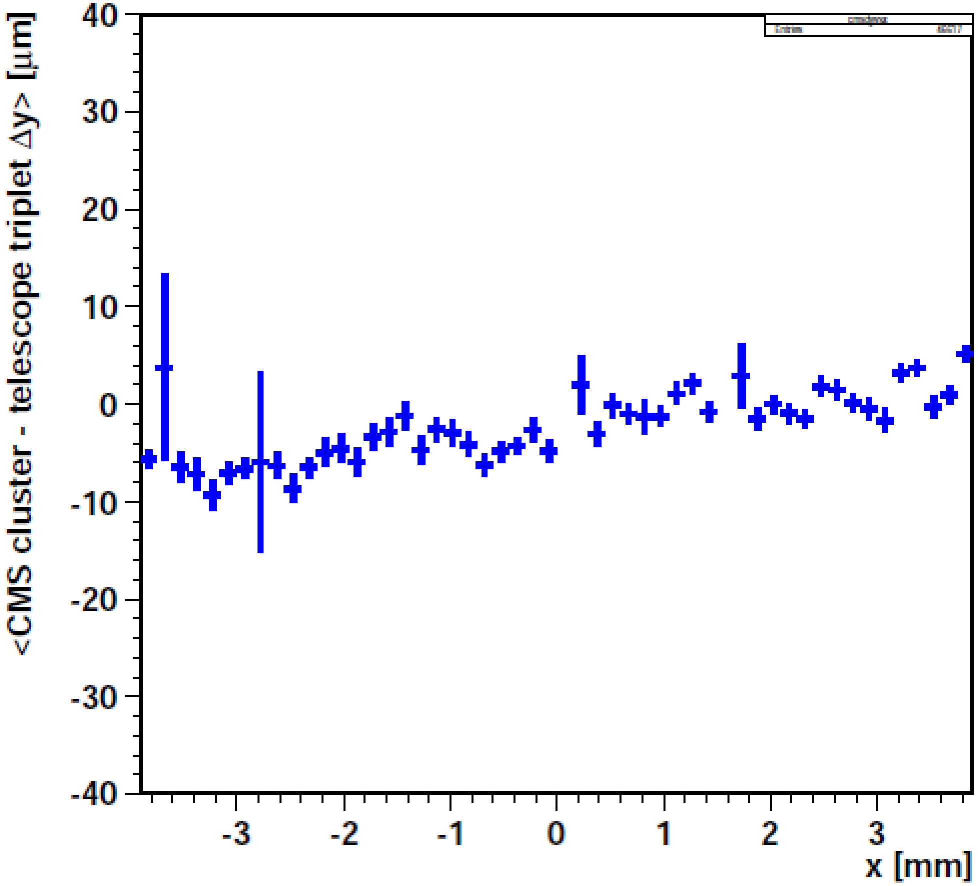
$$\begin{pmatrix} x_n \\ y_n \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} x_i \\ y_i \end{pmatrix} - \begin{pmatrix} x_s \\ y_s \end{pmatrix}$$

- hit: rotate around x: $y_r = y_n \cos\alpha_y$
- residual: $\Delta_y = y_r - y_t$
- alignment corrections: δx, δy, δz, $\delta\phi$, $\delta\alpha$
- derivatives: $\frac{\partial \Delta_y}{\partial y_s} = -1$, $\frac{\partial \Delta_y}{\partial z_s} = -\tan\theta_y$, $\frac{\partial \Delta_y}{\partial \phi} = x_i$, $\frac{\partial \Delta_y}{\partial \alpha_y} = y_n$

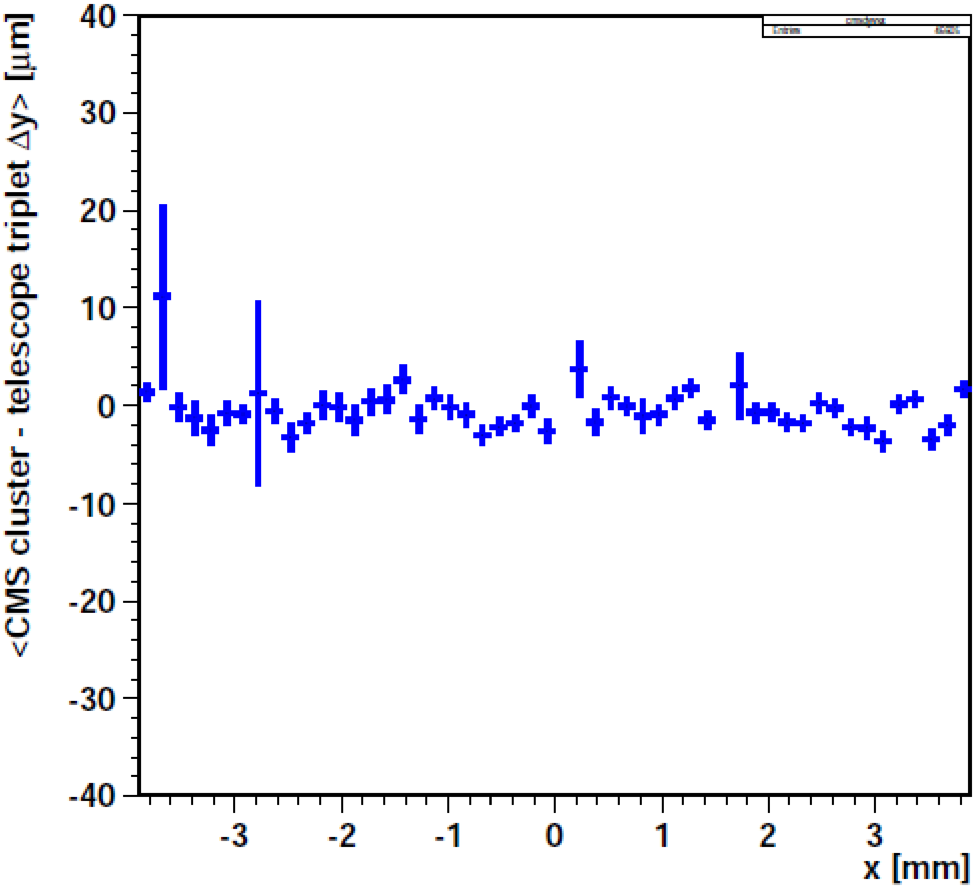
rotate pixel around *z*

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

ϕ = 20 mrad



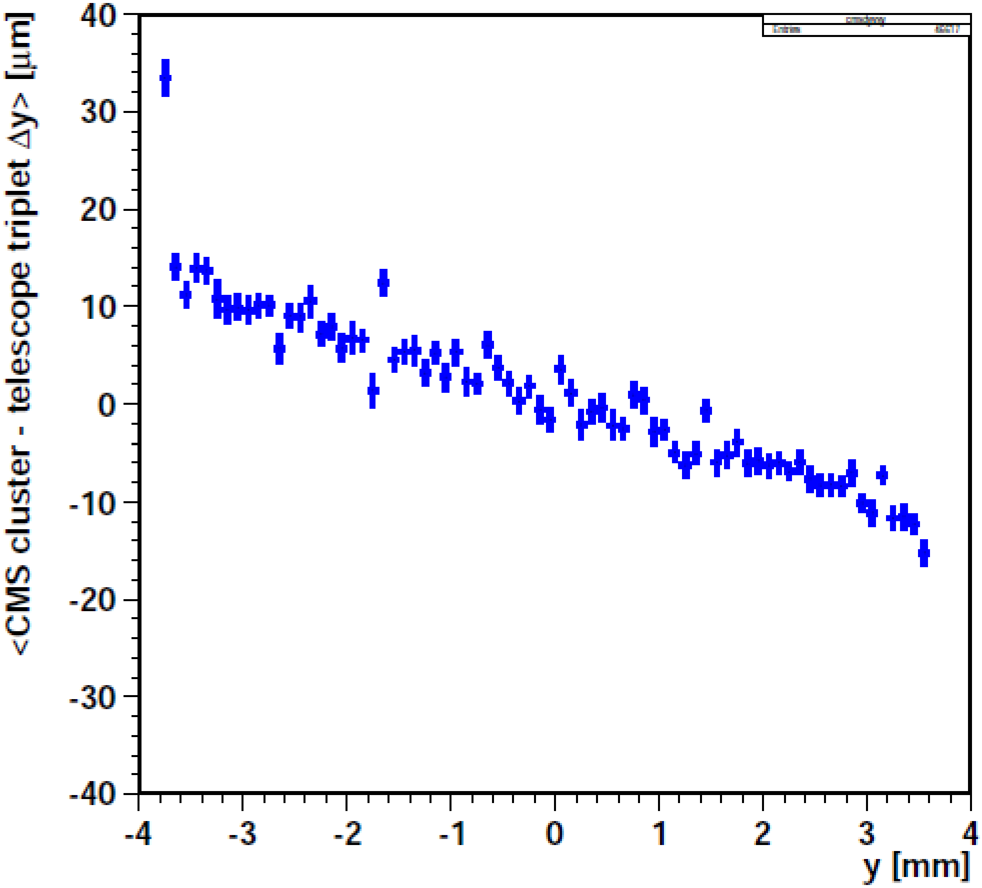
ϕ = 30 mrad



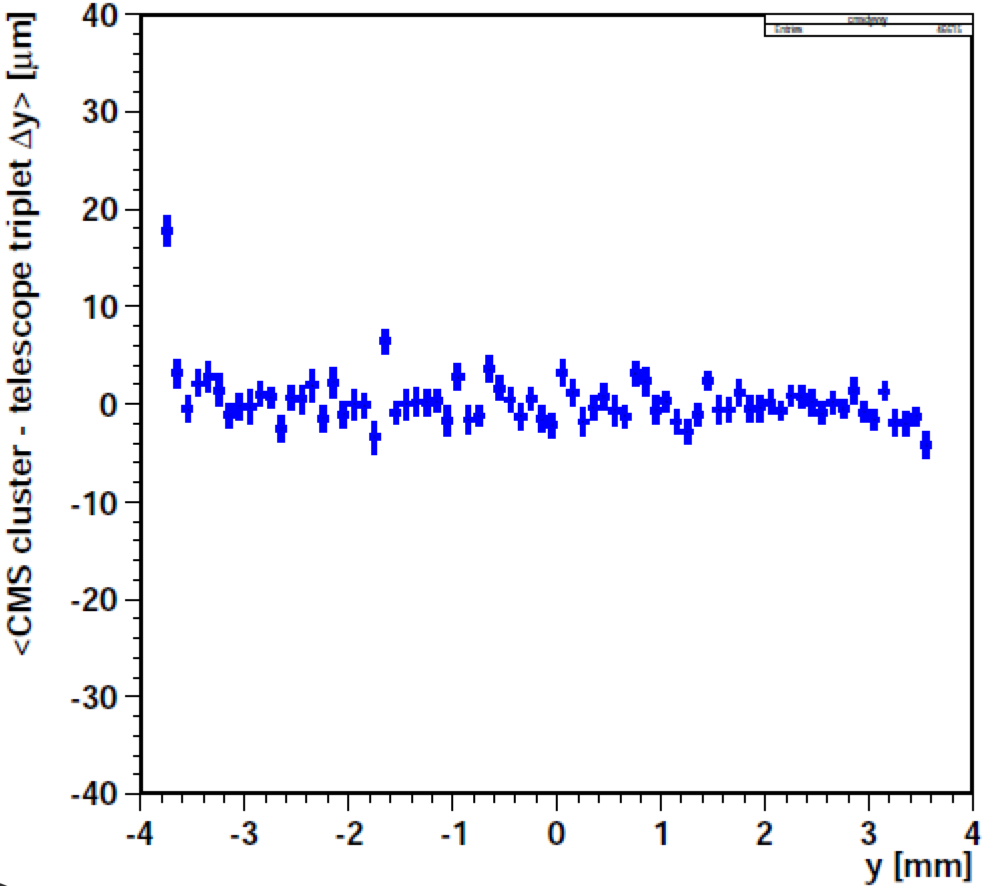
- monitored by mean Δ*y* vs *x*

tilt angle

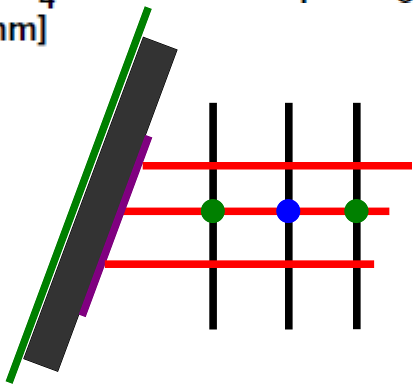
α = 20.5°



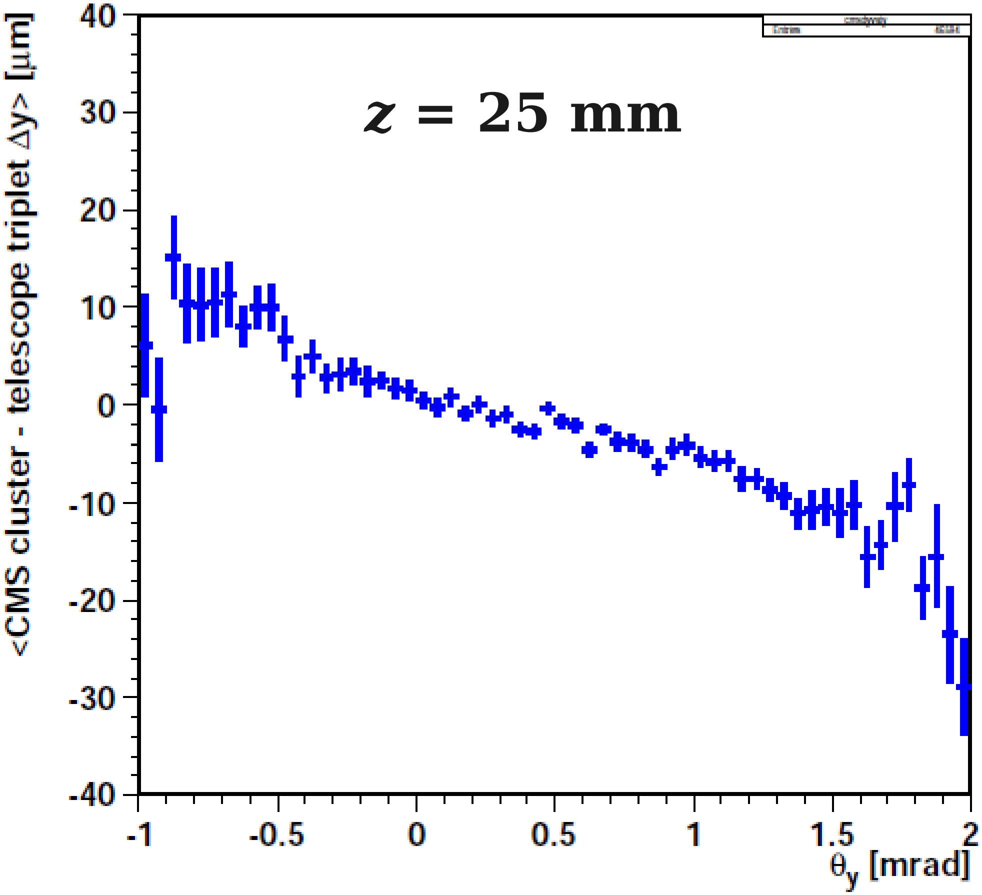
α = 20.0°

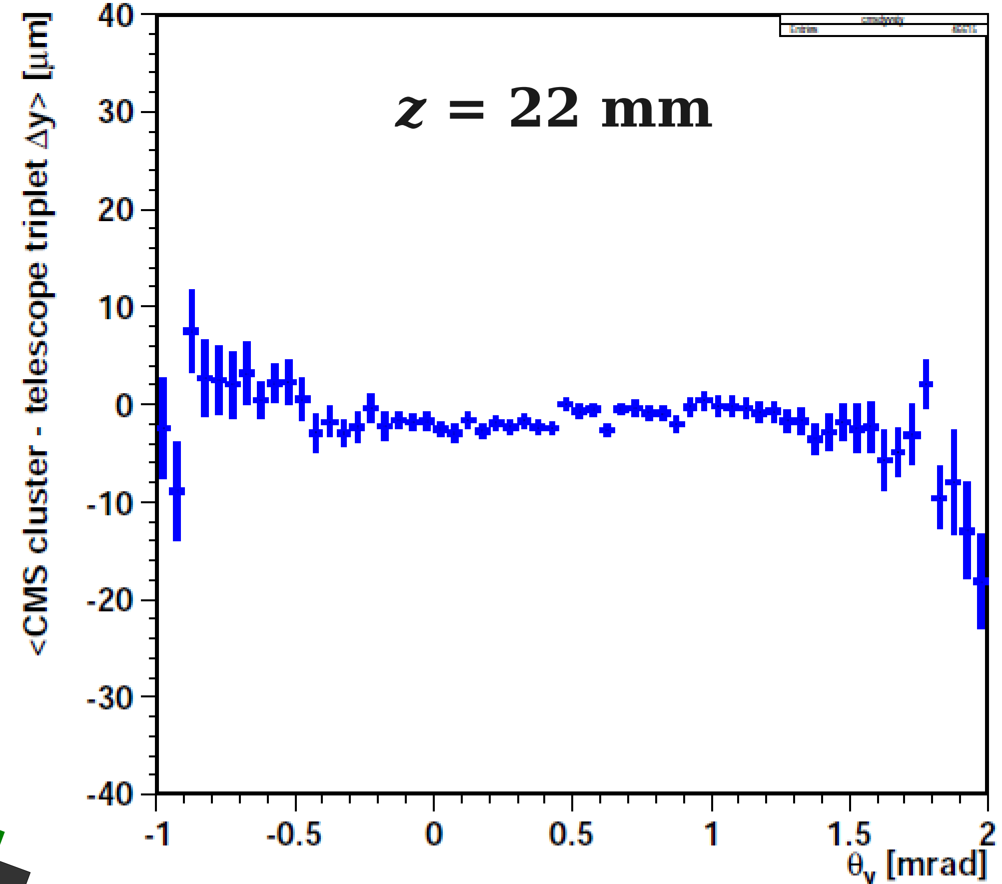


- monitored by mean Δ*y* vs *y*

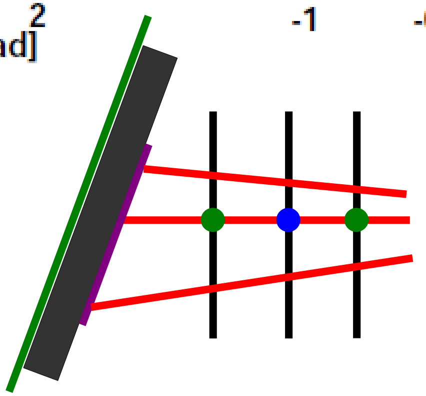


z shift





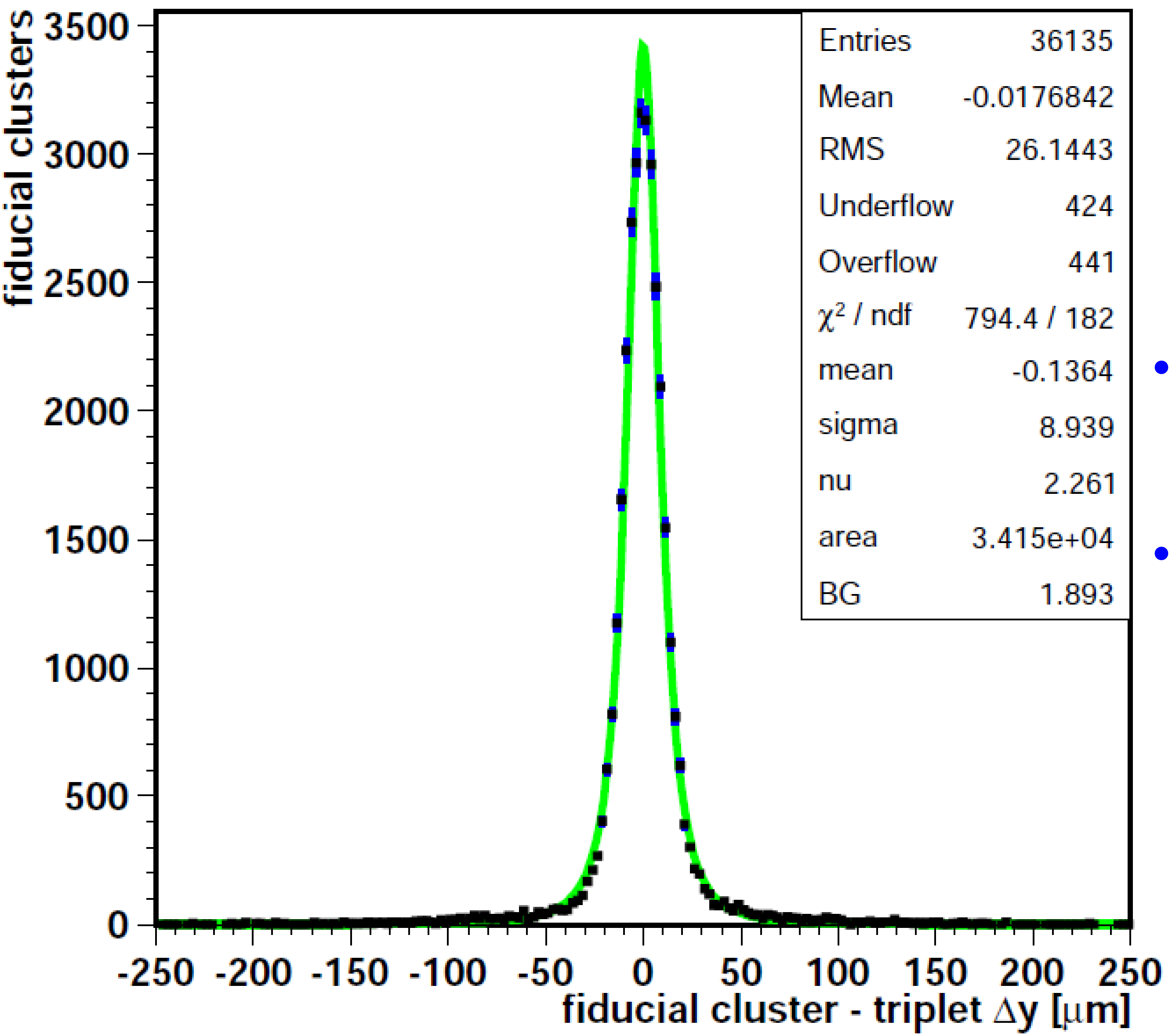
- monitored by mean Δ*y* vs ϑ_y

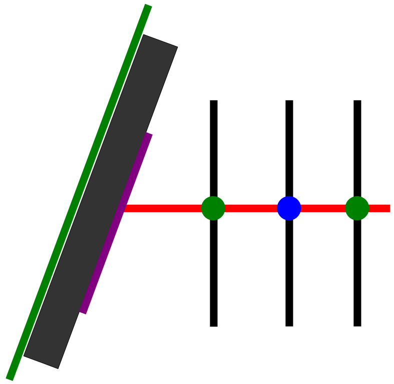


beam has ~1 mrad divergence

CMS pixel row resolution

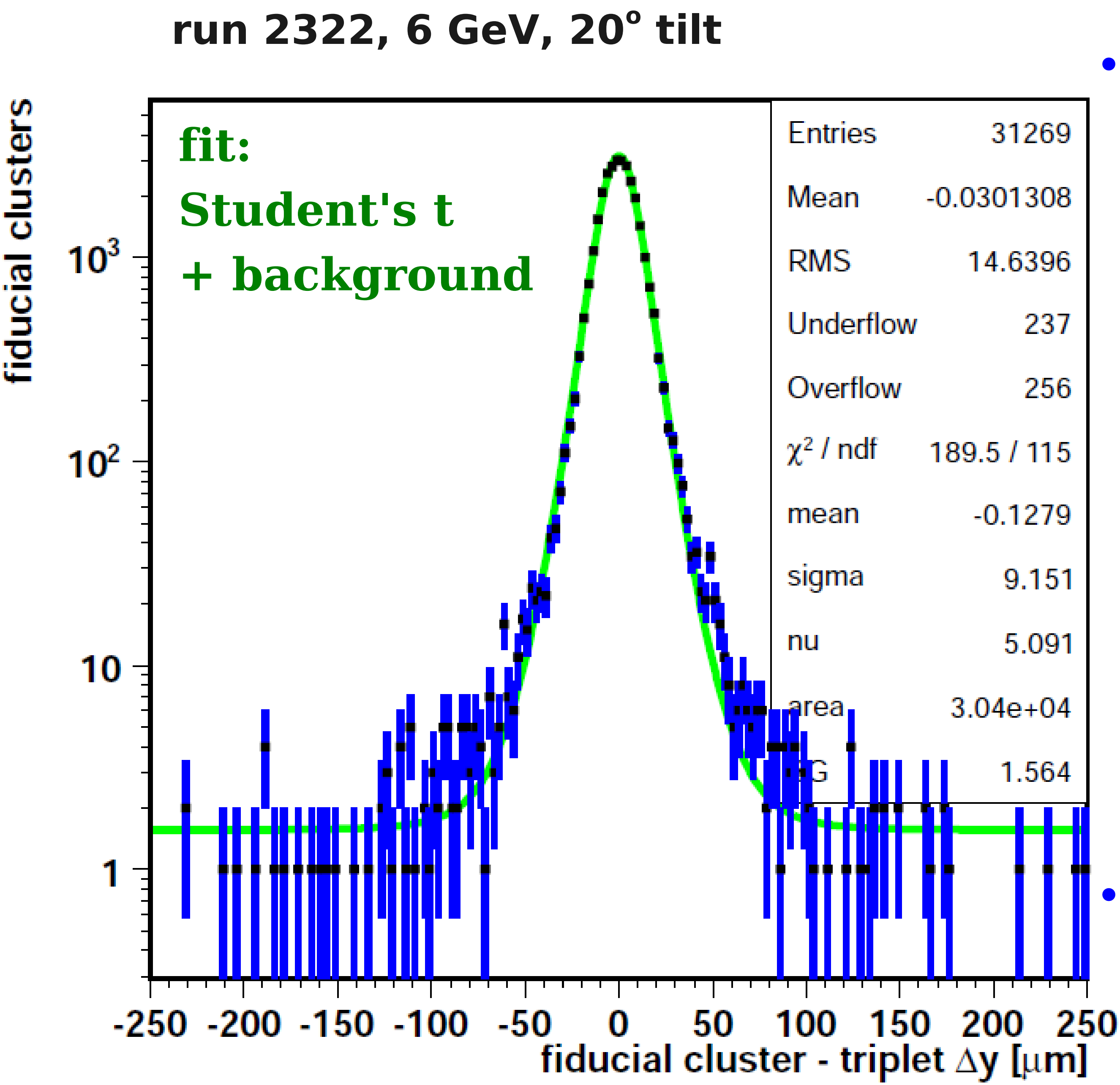
run 2322, 6 GeV, 20° tilt





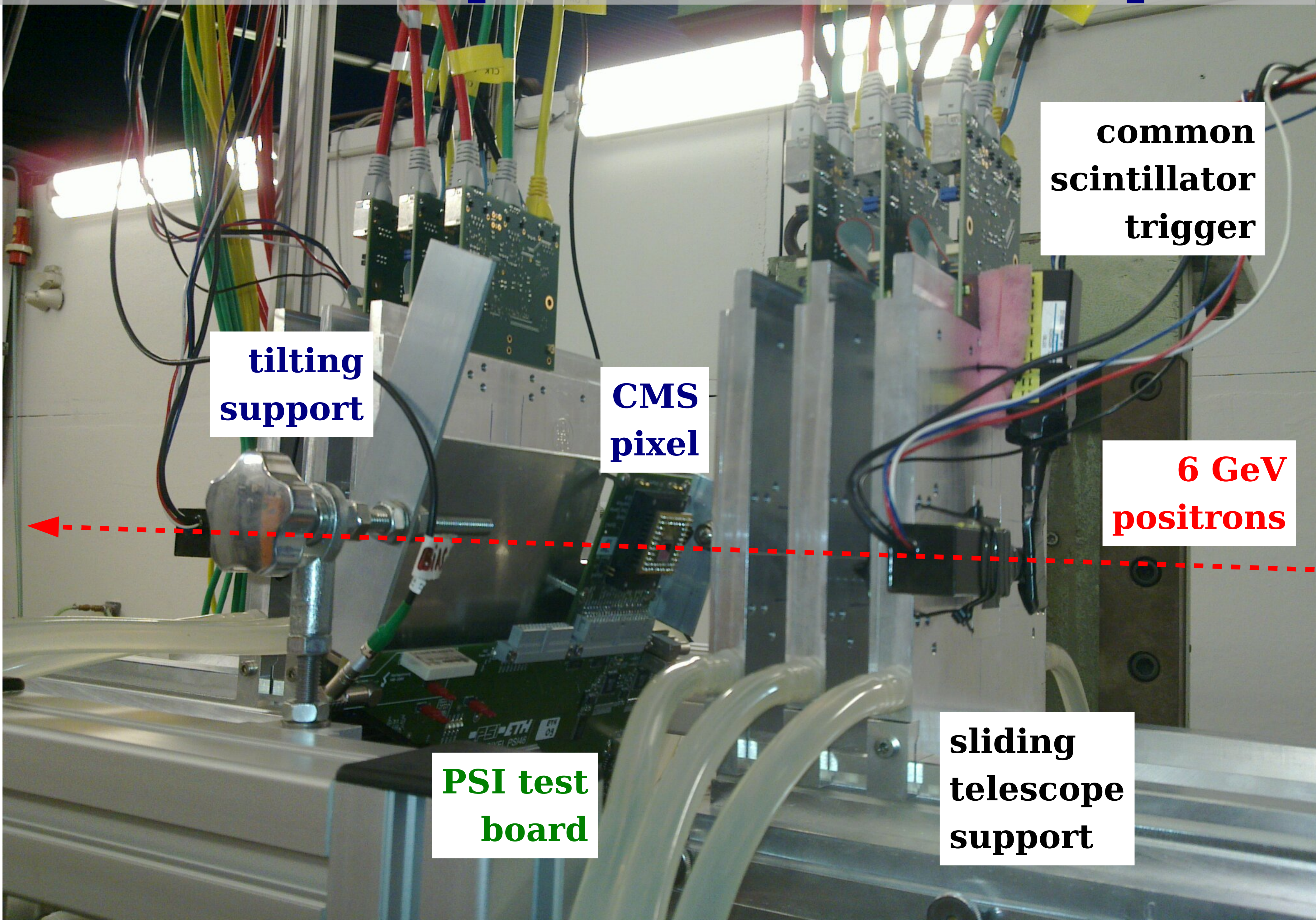
- Vertical = rows
  - CMS pixel = 100 μm.
- Residual:
  - σ = 9 μm,
  - telescope extrapolation: 4.5 μm,
  - **CMS resolution: 8 μm.**

CMS pixel residual distribution

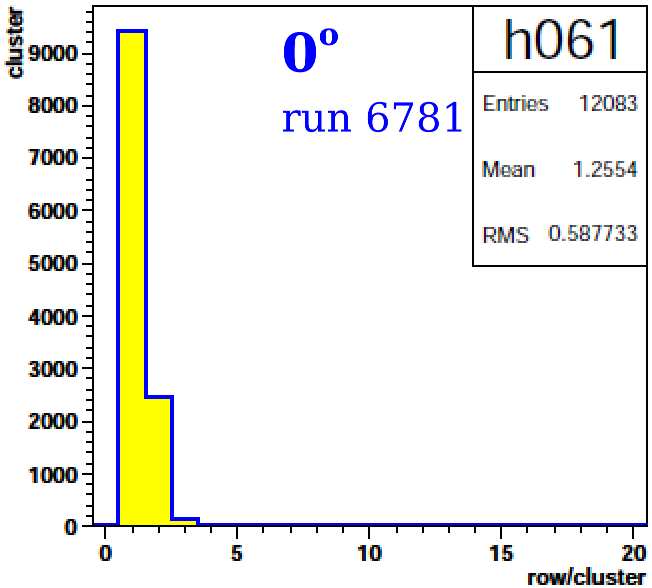


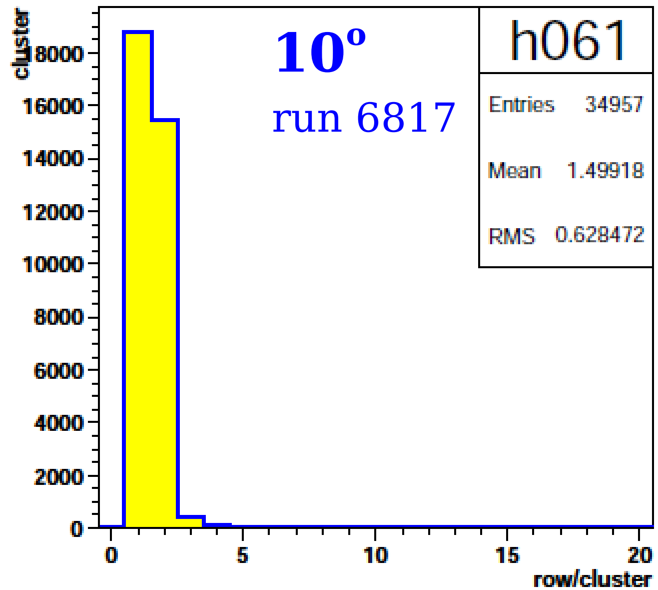
- cleaning cuts:
  - cluster one pixel away from edges and dead columns,
  - $|\Delta x| < 0.15$ mm,
  - only 1- and 2-row clusters (against δ-rays)
  - cluster charge > 18 ke (against wrong timing),
  - | track angle | < 2 mrad (against scattering).
- Result:
  - less tails, more Gaussian

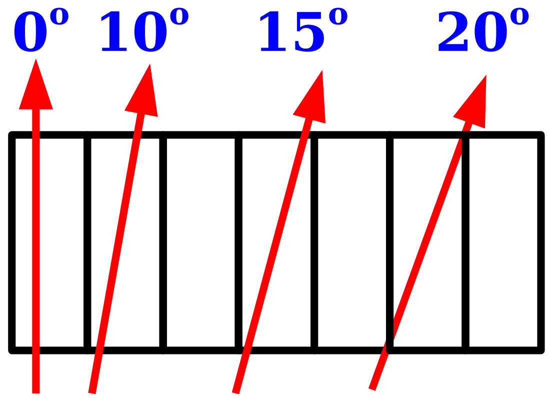
Tilted CMS pixel in the EuTelescope



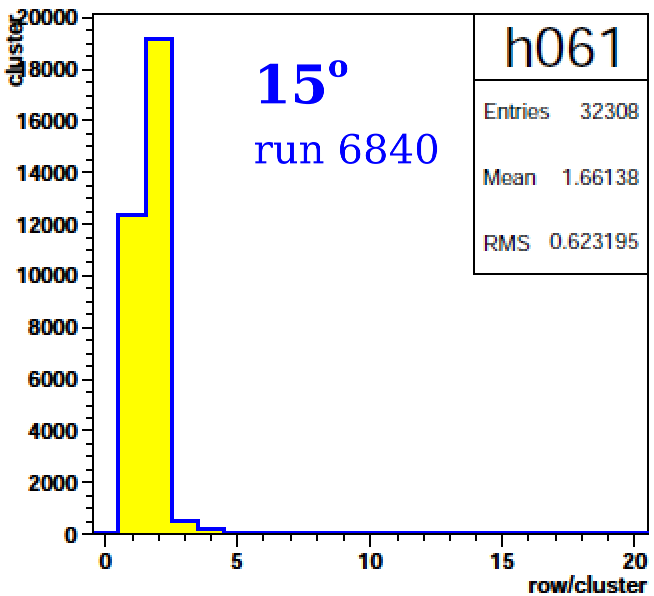
cluster size vs tilt angle

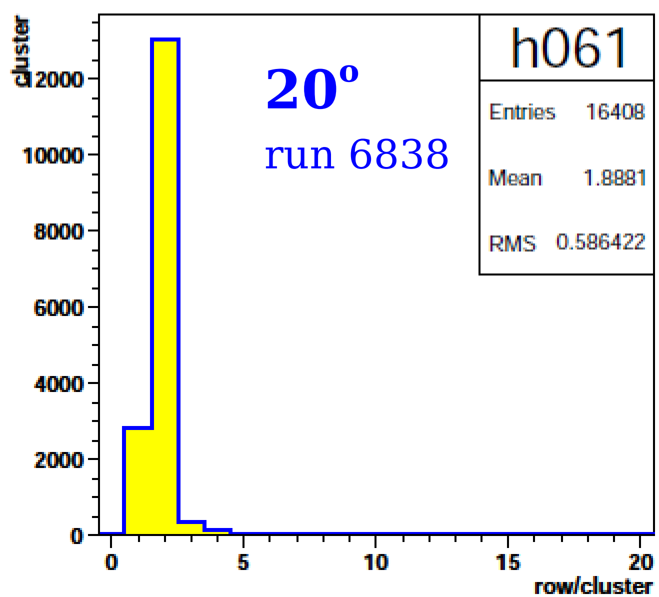


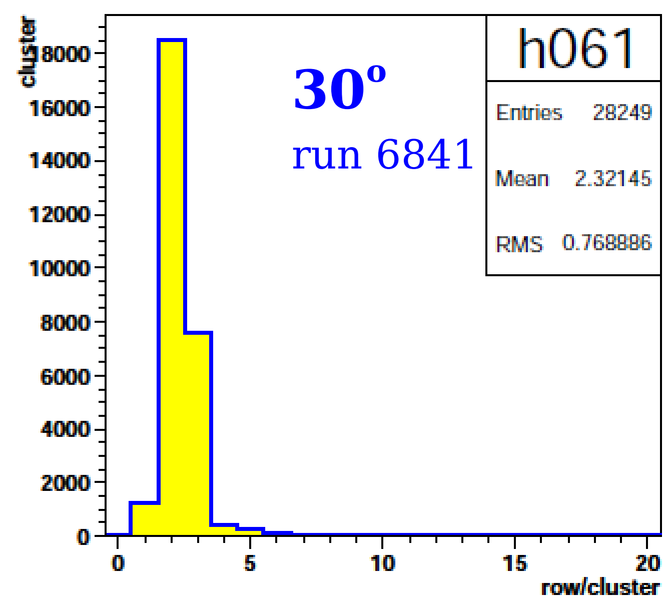




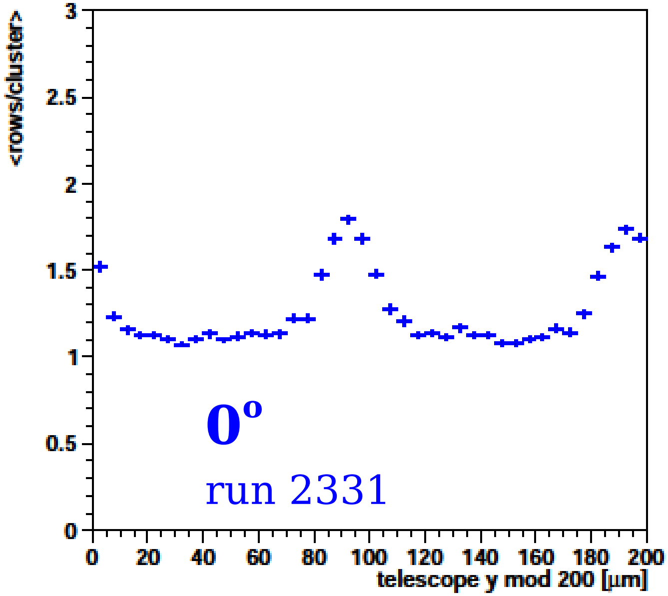
atan(100/285) = 19.3°

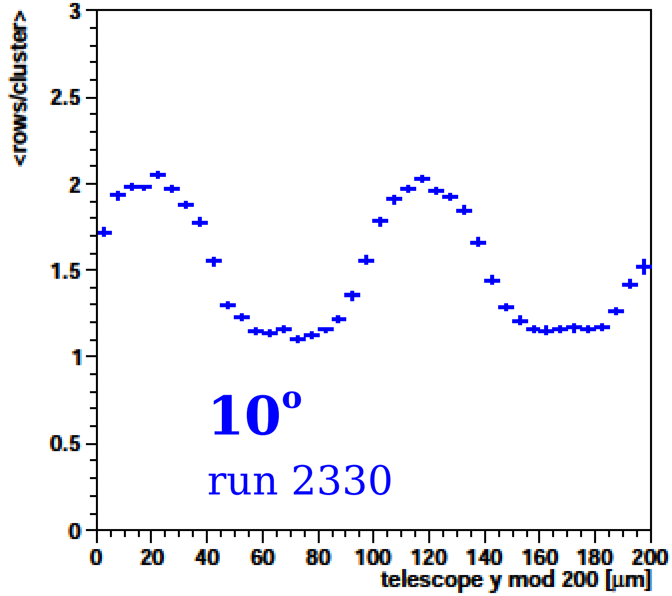


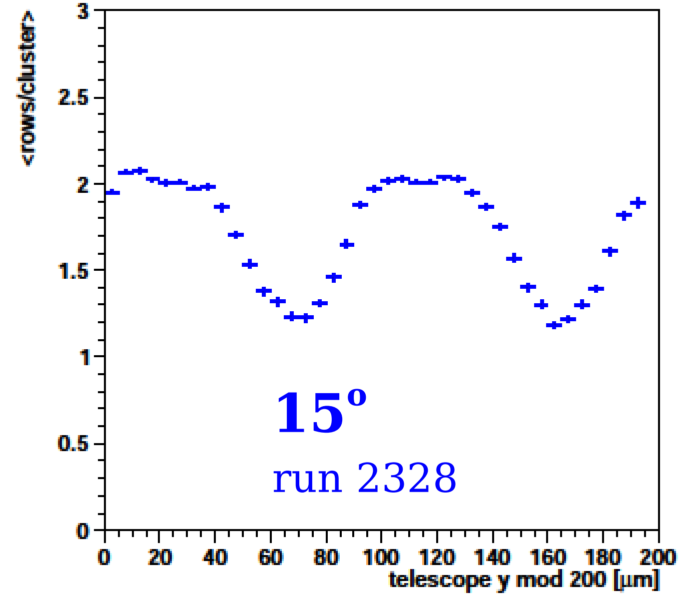




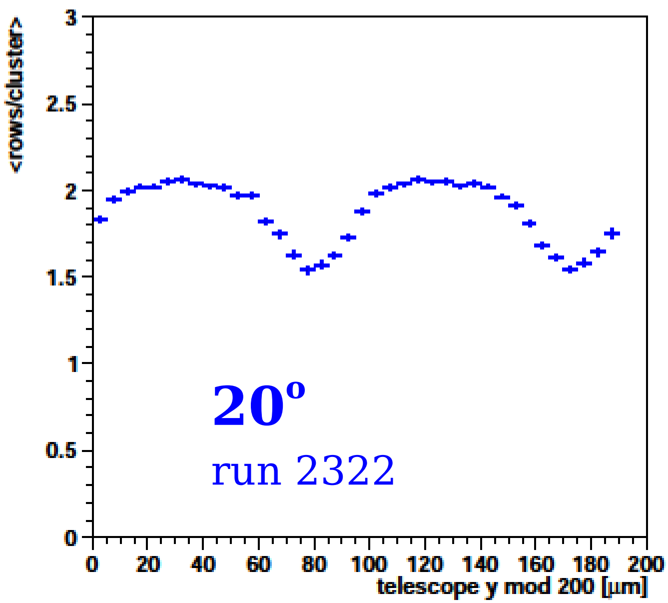
cluster size vs impact point and tilt angle

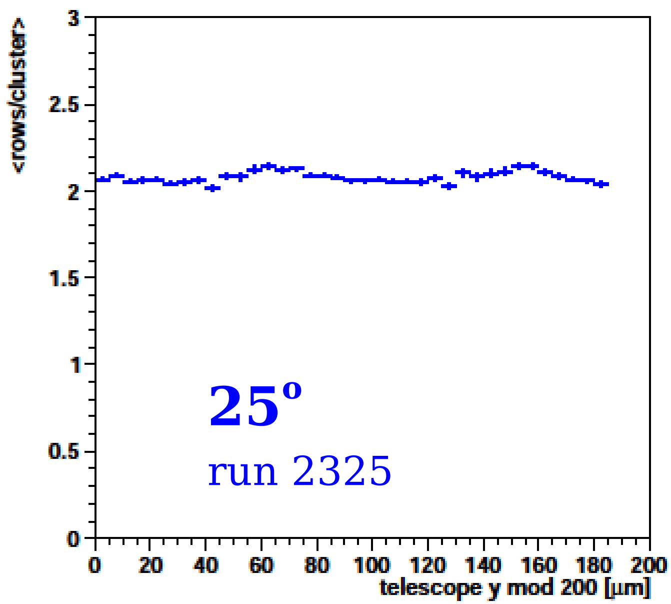


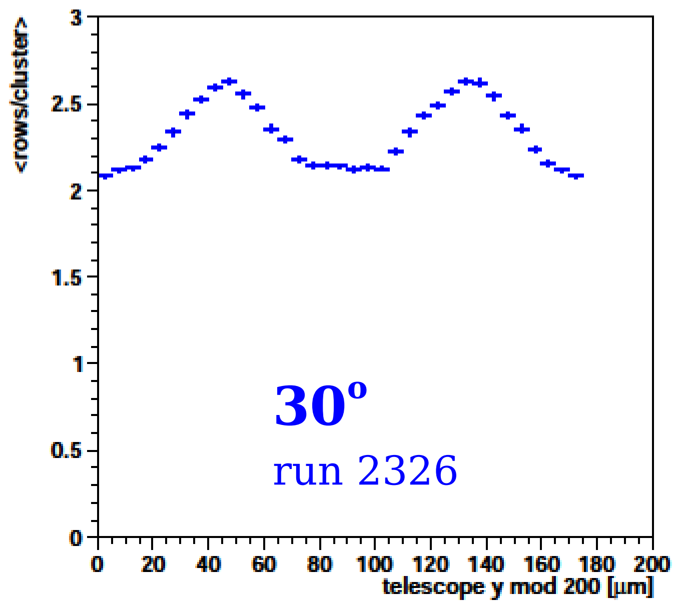




y_{impact} mod 200 µm: 2 pixels

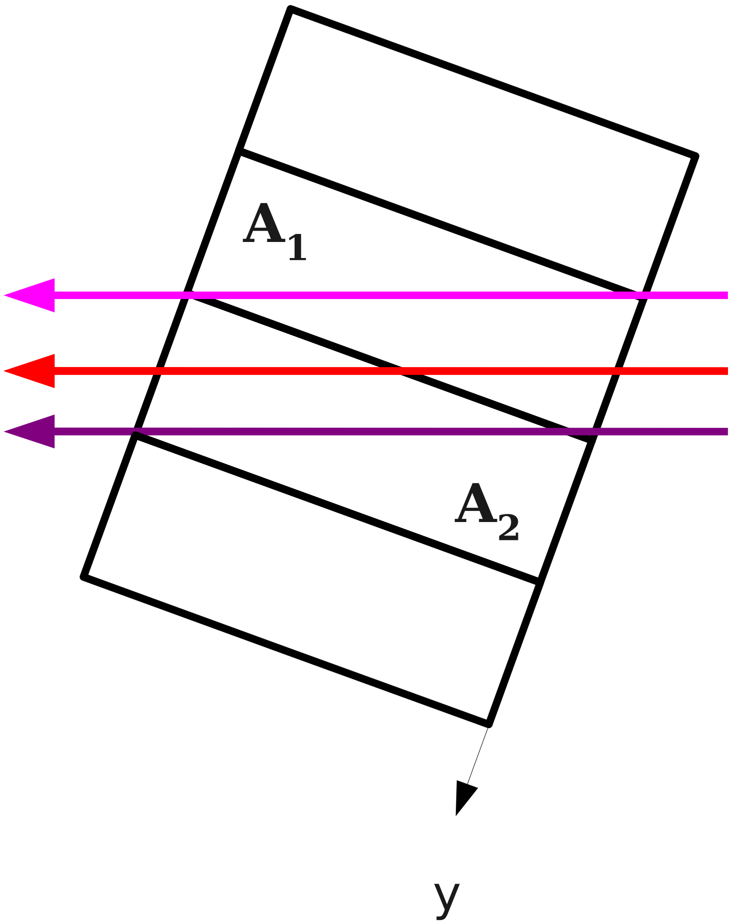






charge sharing: η

at 20°:



$\eta = (A_1 - A_2) / (A_1 + A_2)$

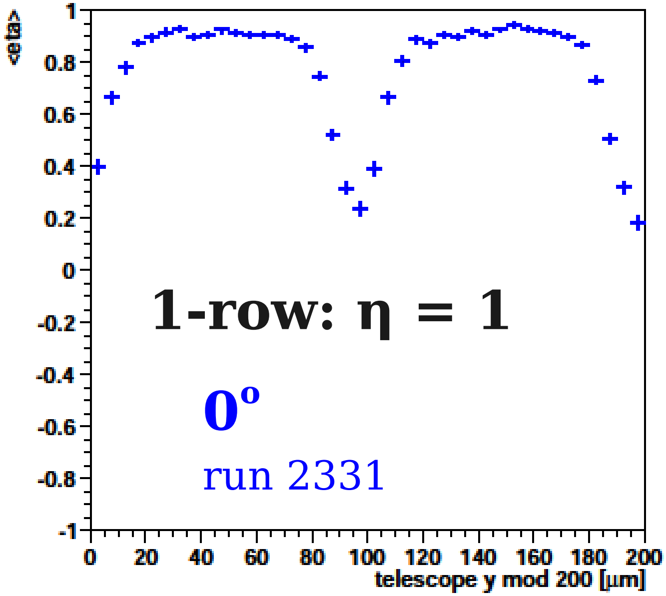
1.0
0.0
(-1.0)

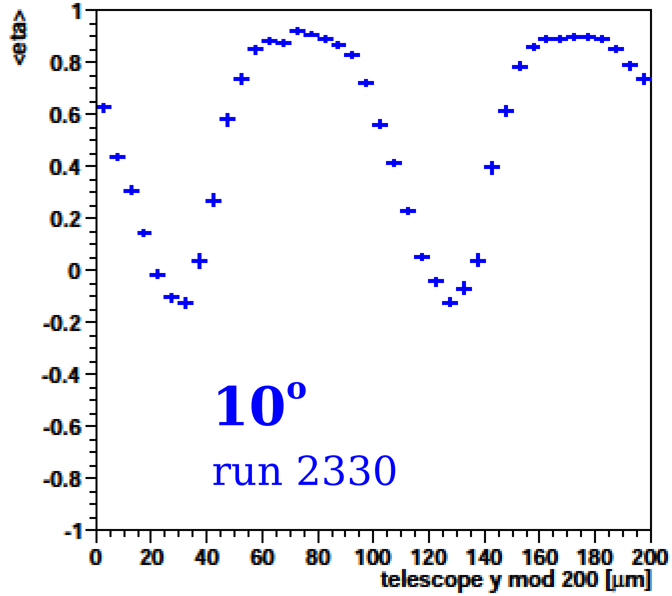
1-row clusters have η = 1.

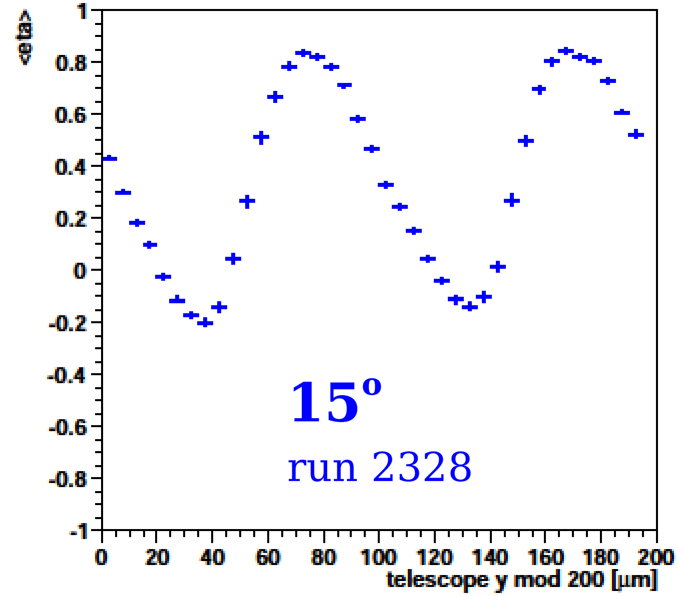
ideal:
linear η vs y
(saw tooth)

deviations:
- **diffusion**
- **thresholds**
- **trapping**
- **delta-rays**

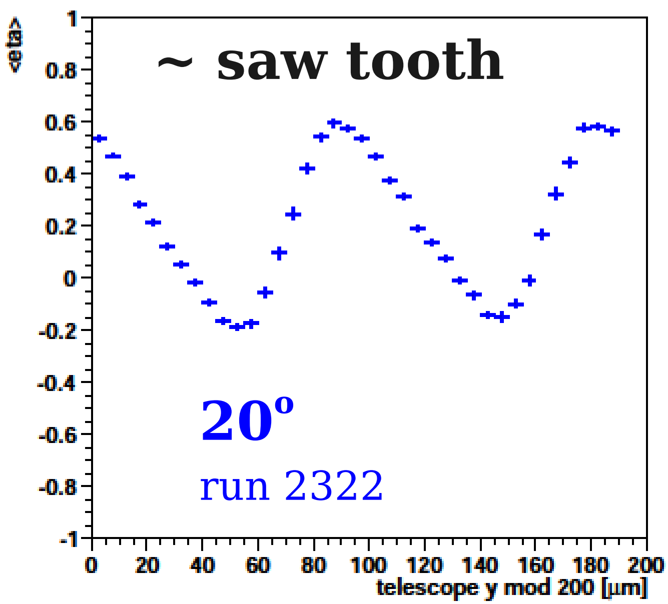
charge sharing vs tilt angle

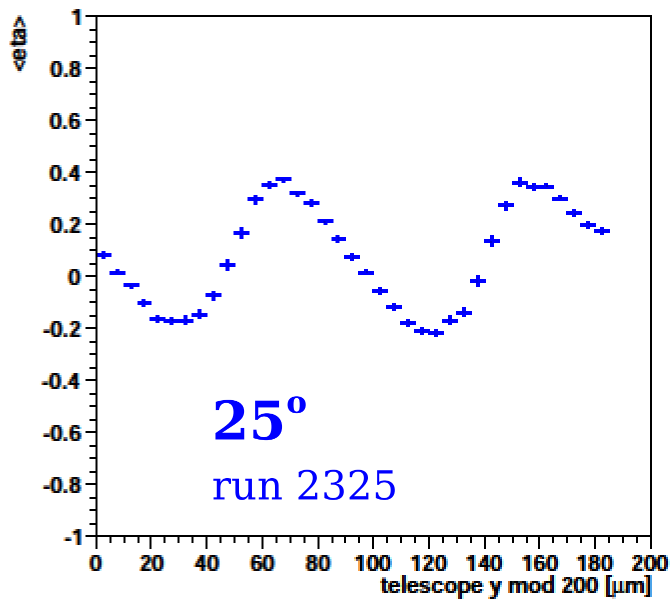


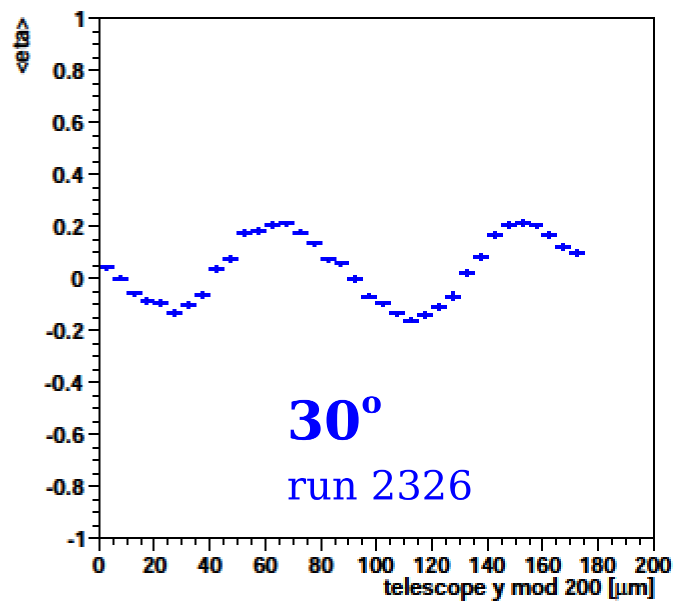




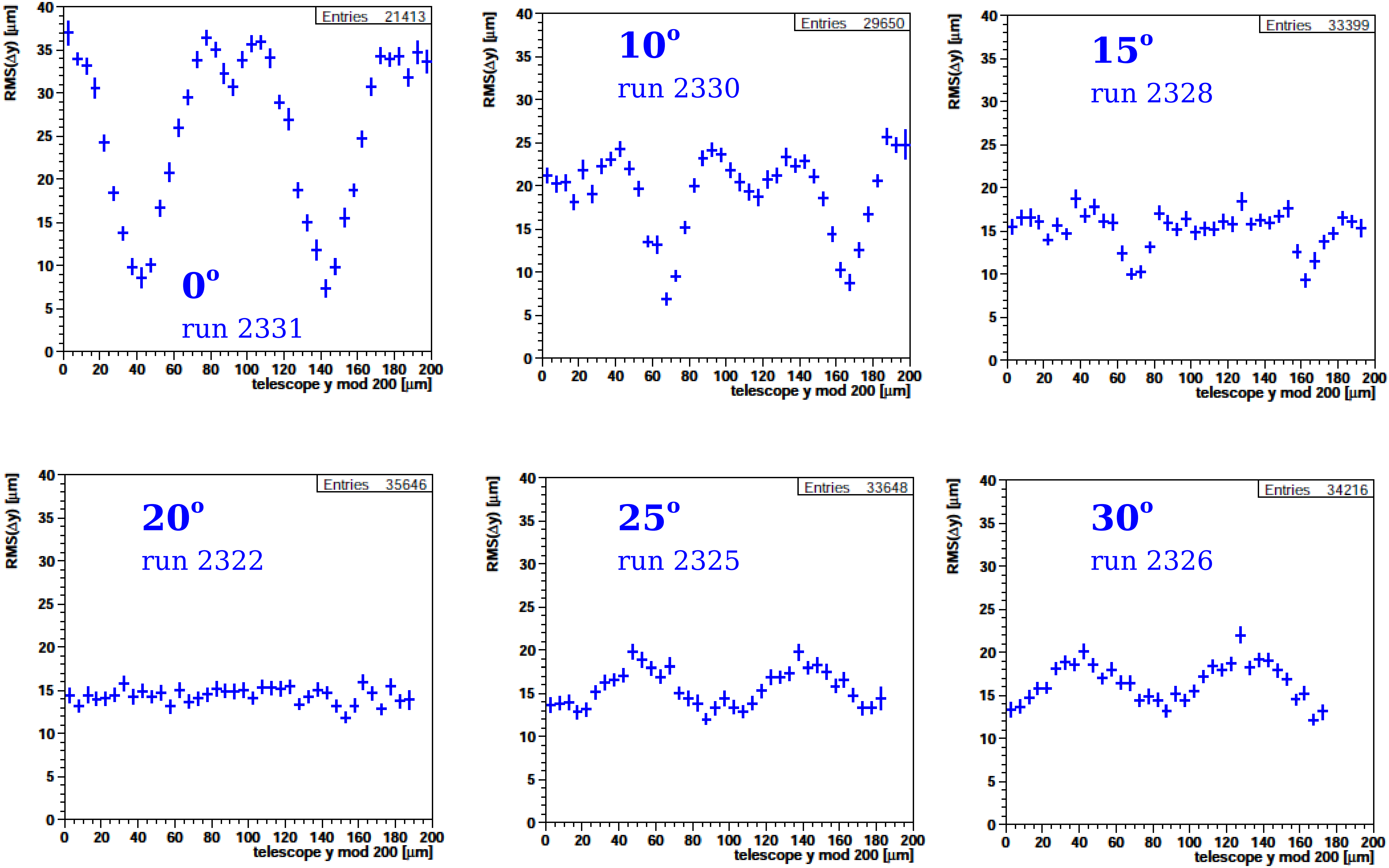
y_{impact} **mod 200 µm: 2 pixels**



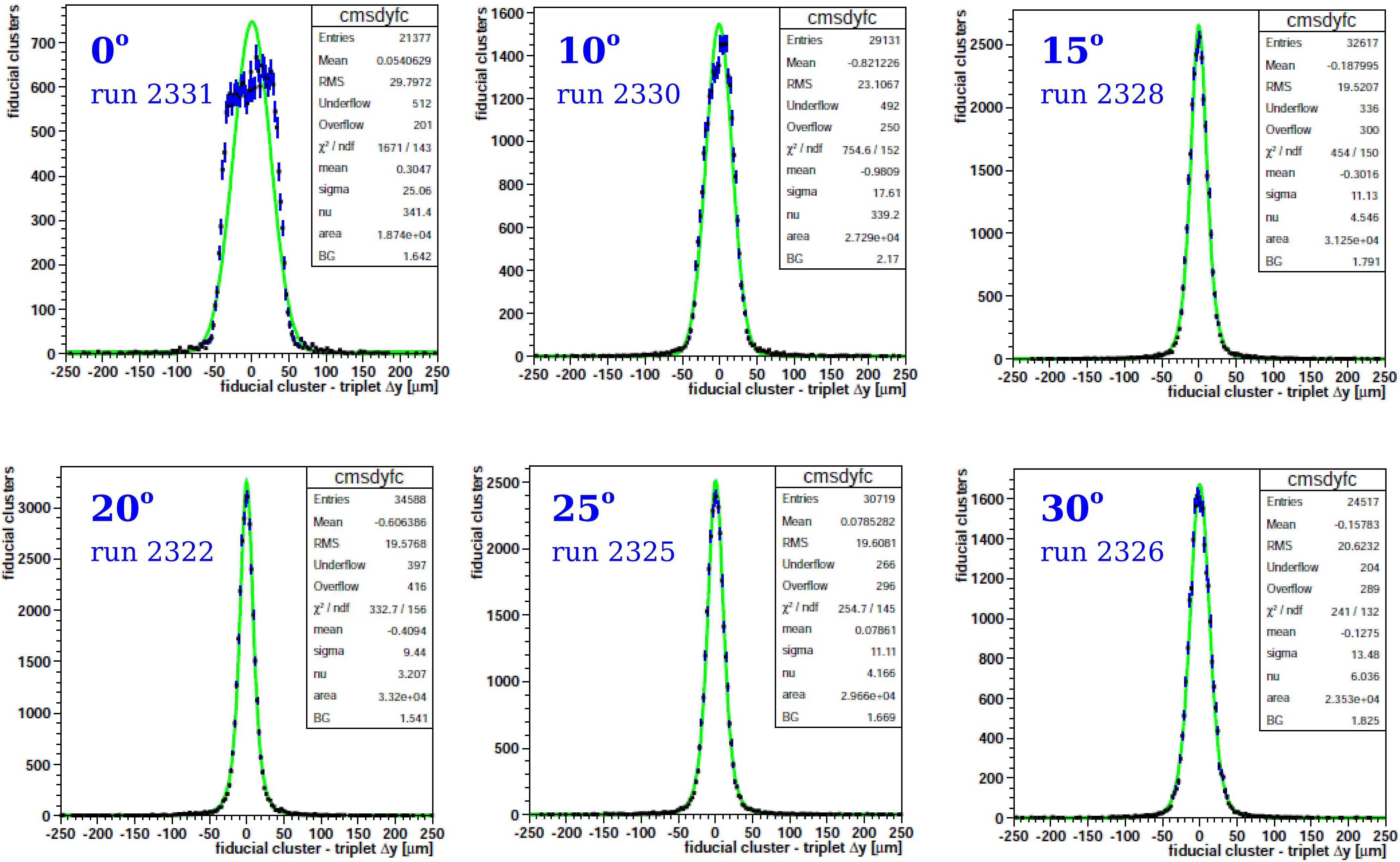




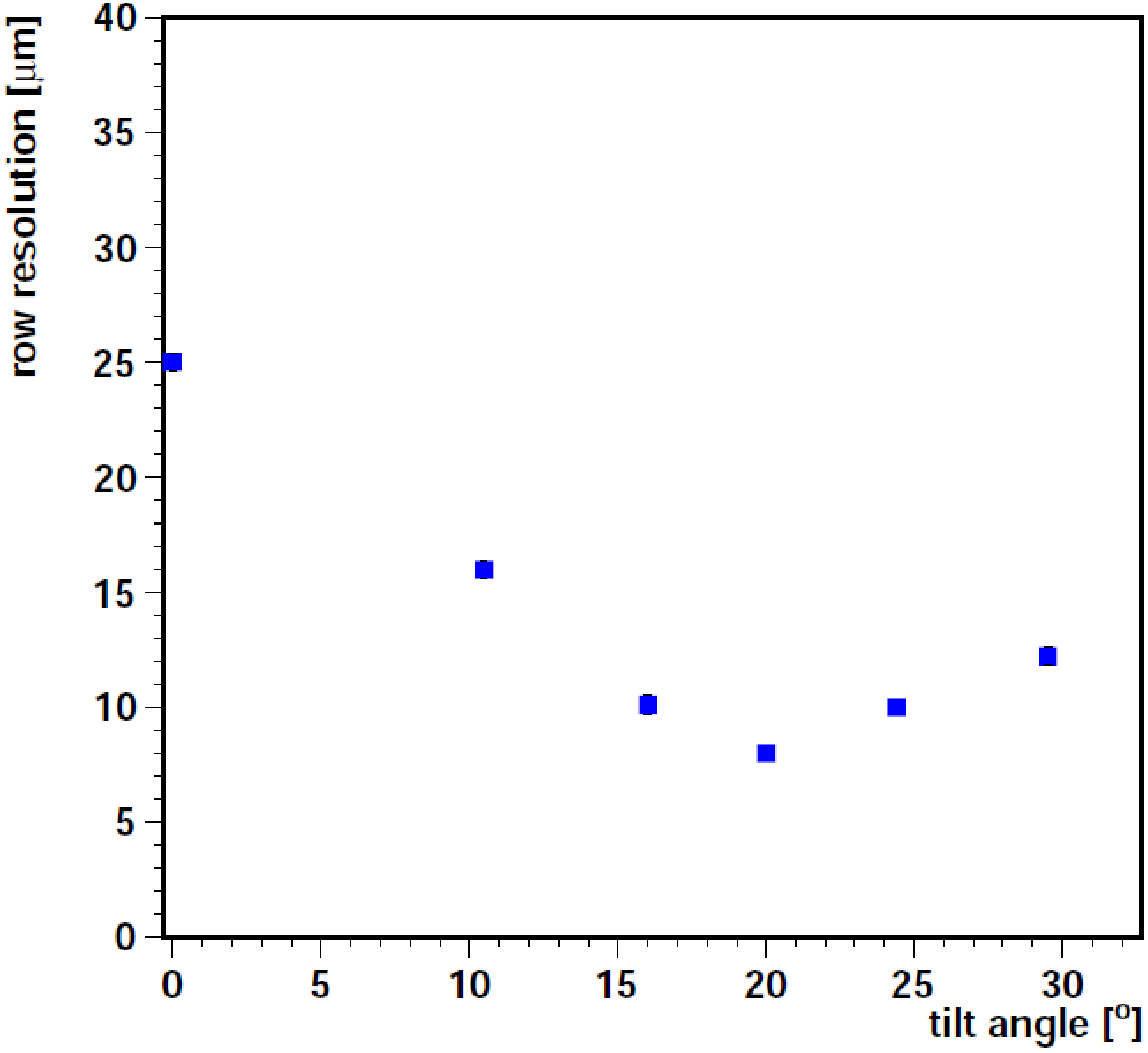
resolution profile vs tilt angle

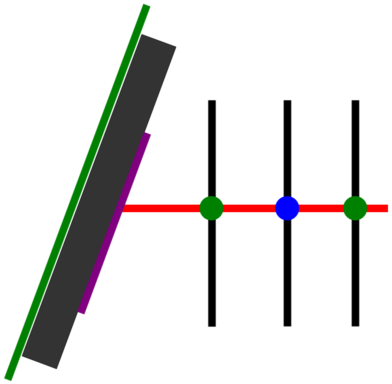


CMS pixel resolution vs tilt angle



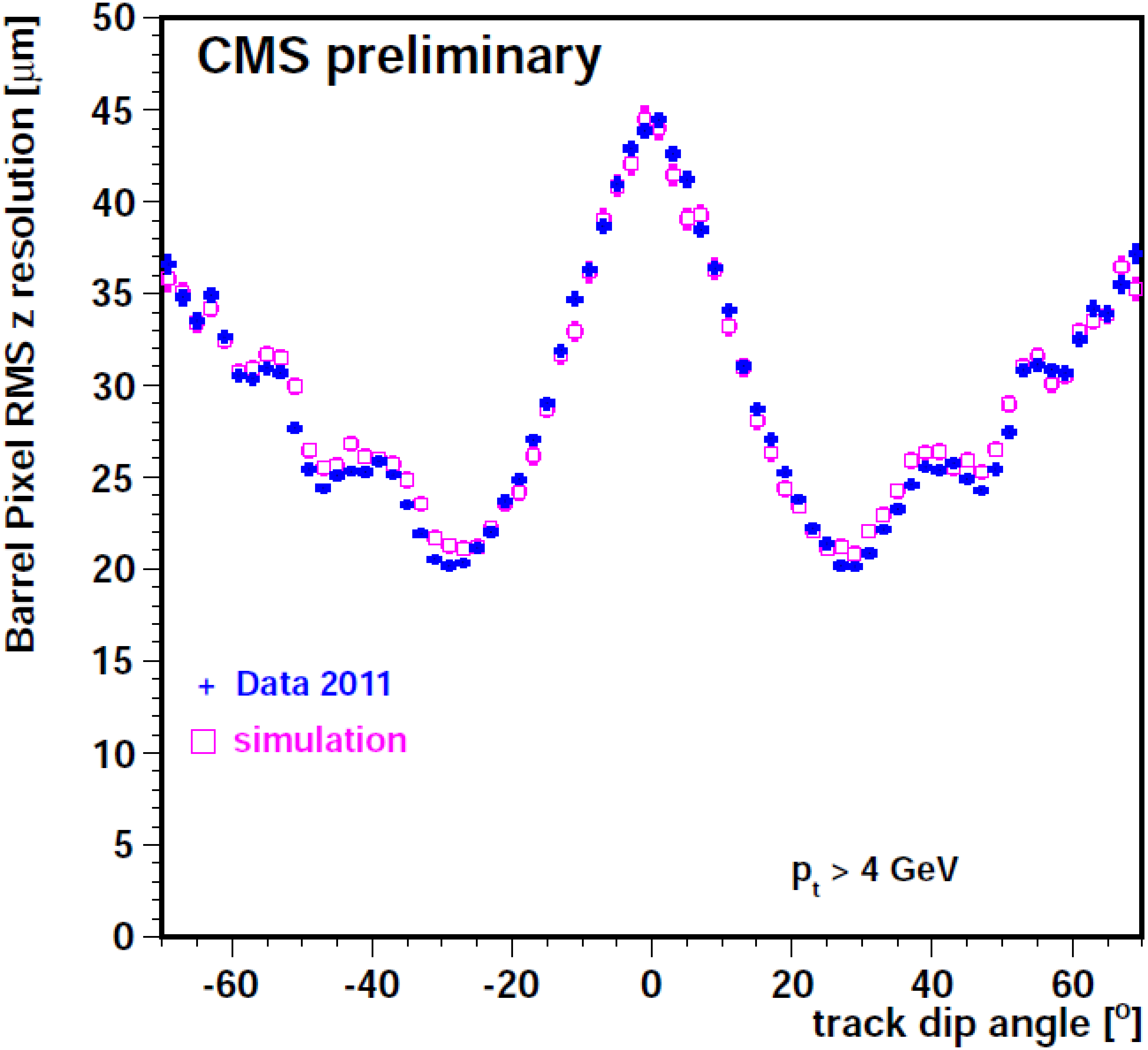
CMS pixel row resolution vs tilt angle



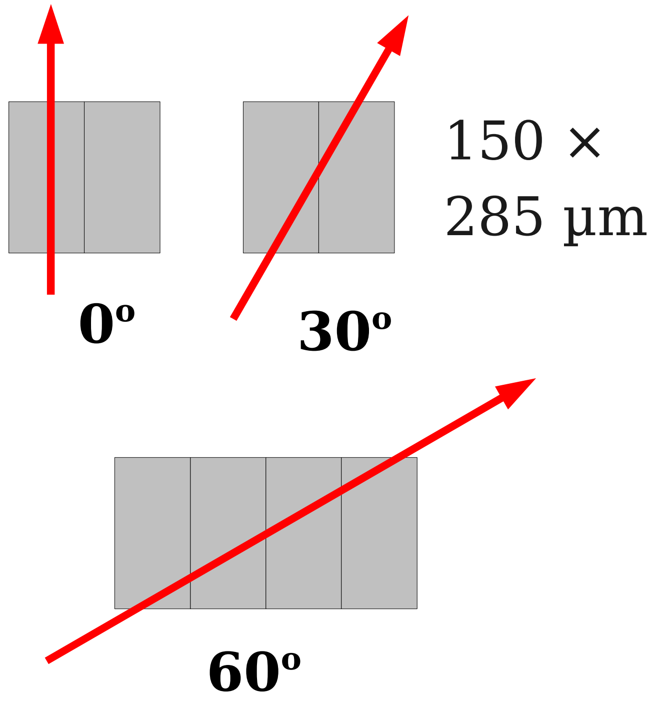


- 6 GeV, telescope extrapolation uncertainty subtracted.
- row pixels = 100 μm.
- Binary:
  - $\sigma = 100 / \sqrt{12} = 29$ μm
- Optimal angle 19°:
  - $\sigma = 8$ μm.

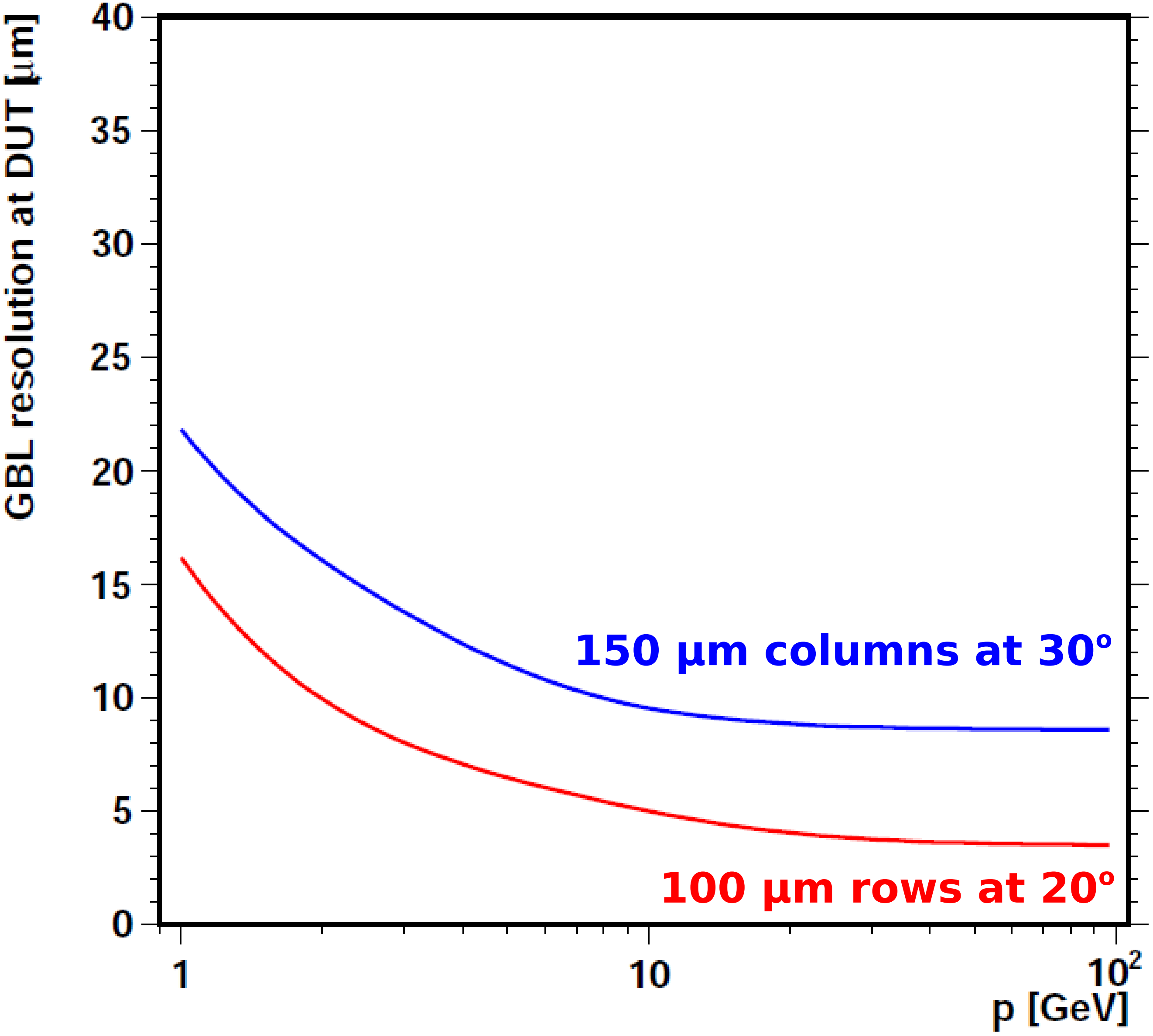
CMS pixel resolution in columns



- Column: 150 μm
- from CMS data
- dip angle:
  - $\lambda = \pi/2 - \theta$.
- optimal resolution at $\lambda = \pm 30°$:

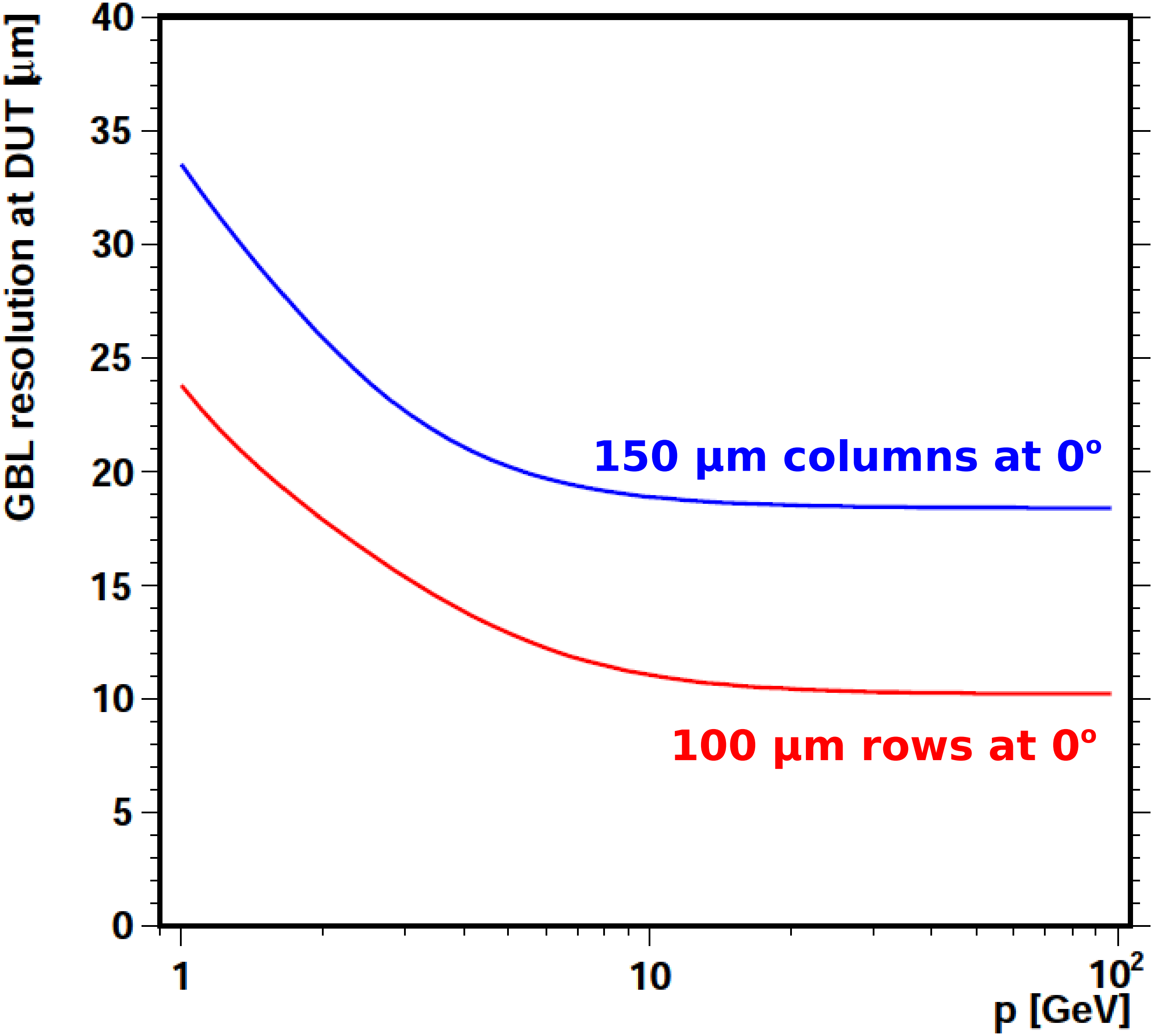


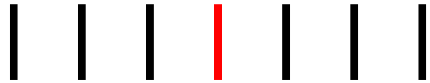
GBL prediction for a tilted CMS telescope



- GBL error propagation for CMS pixel telescope:
  - 1.1% X_0 per plane
  - σ_{col} = 21 µm at 30°
  - σ_{row} = 8 µm at 20°
  - 6 active planes
  - interpolate to DUT

GBL prediction for a flat CMS telescope



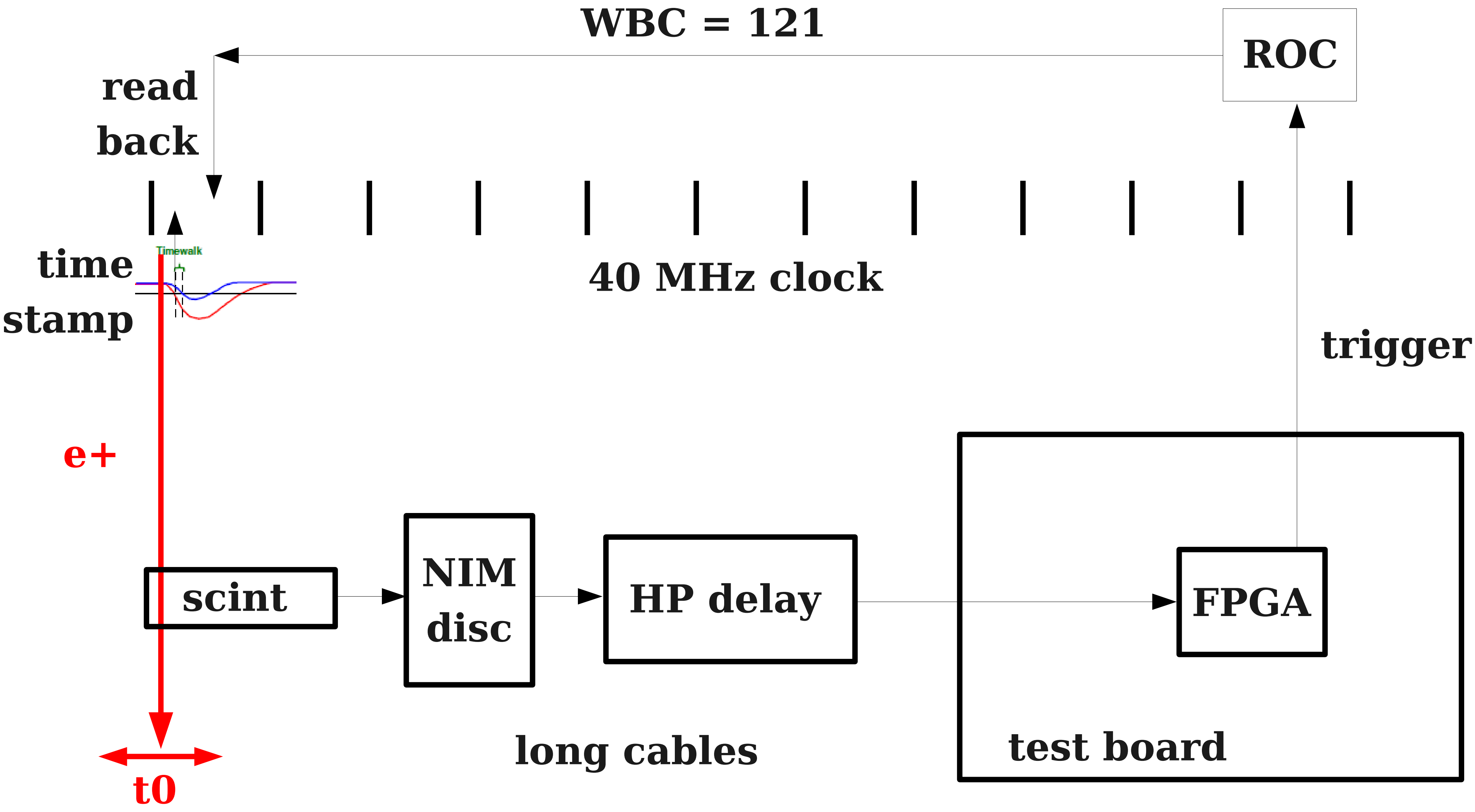


- GBL error propagation for CMS pixel telescope:
  - 1.1% X_0 per plane
  - σ_{col} = 45 µm at 0°
  - σ_{row} = 25 µm at 0°
  - 6 active planes
  - interpolate to DUT

Summary

- Track finding based on triplets:
  - interpolation is better than extrapolation
- General Broken Line fit:
  - allows rejection of presumably lower momentum tracks
  - interface to MillePede works nicely for telescope alignment
  - allows quick stand-alone resolution studies for detector design
  - nominal material thickness need adjustment (~30% reduction)
- Tilting the CMS pixel sensor by 20^{o} (rows) and 30^{o} (columns):
  - improves the resolution by a factor 2.5 compared to vertcial incidence due to charge sharing in 2×2 pixel clusters.

WBC timing needs scanning



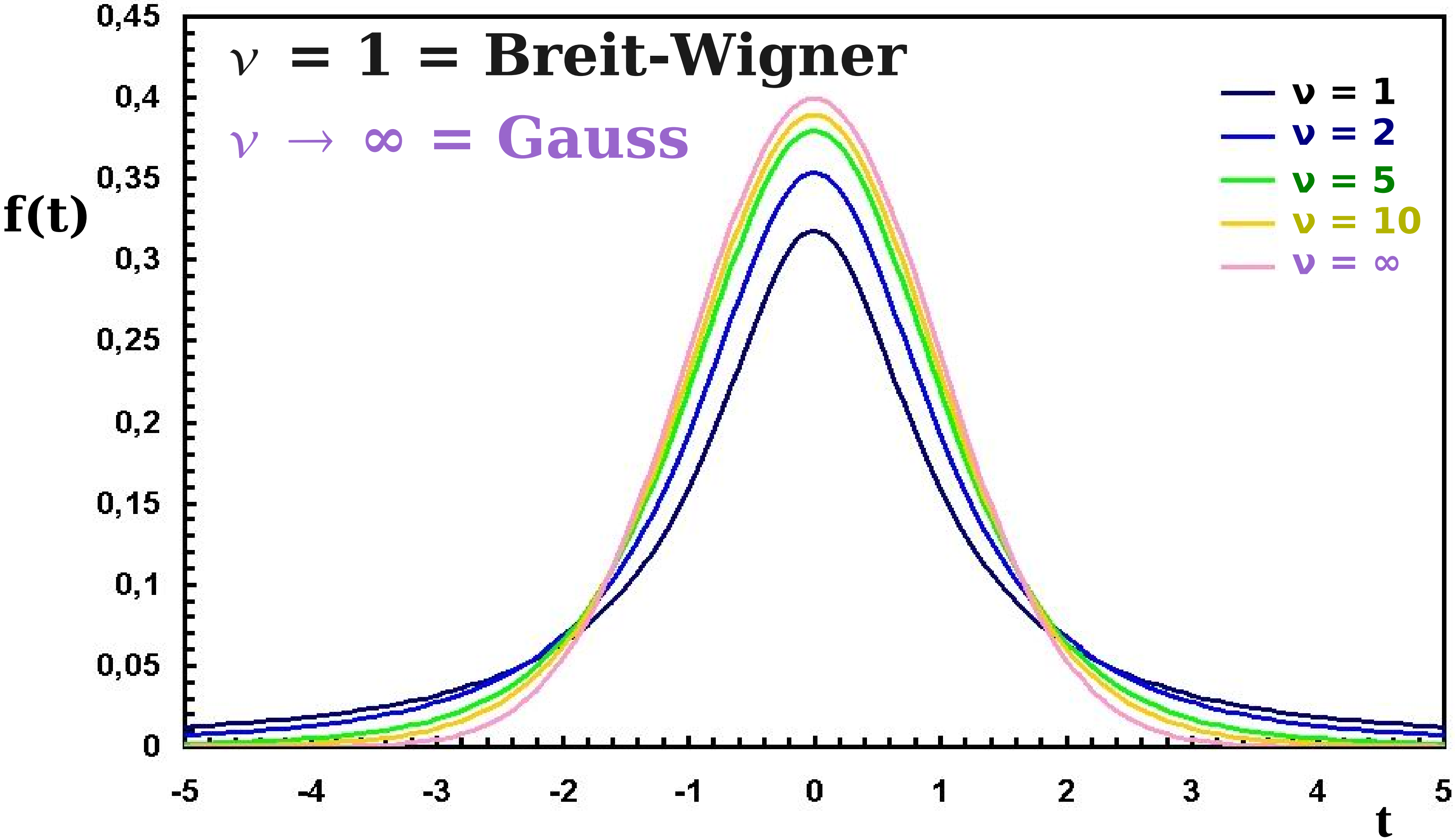
beam not synchronized to clock

Fitting peaks with Student's t

$t = (x\text{-}x_0)/\sigma$ = normalized residual.

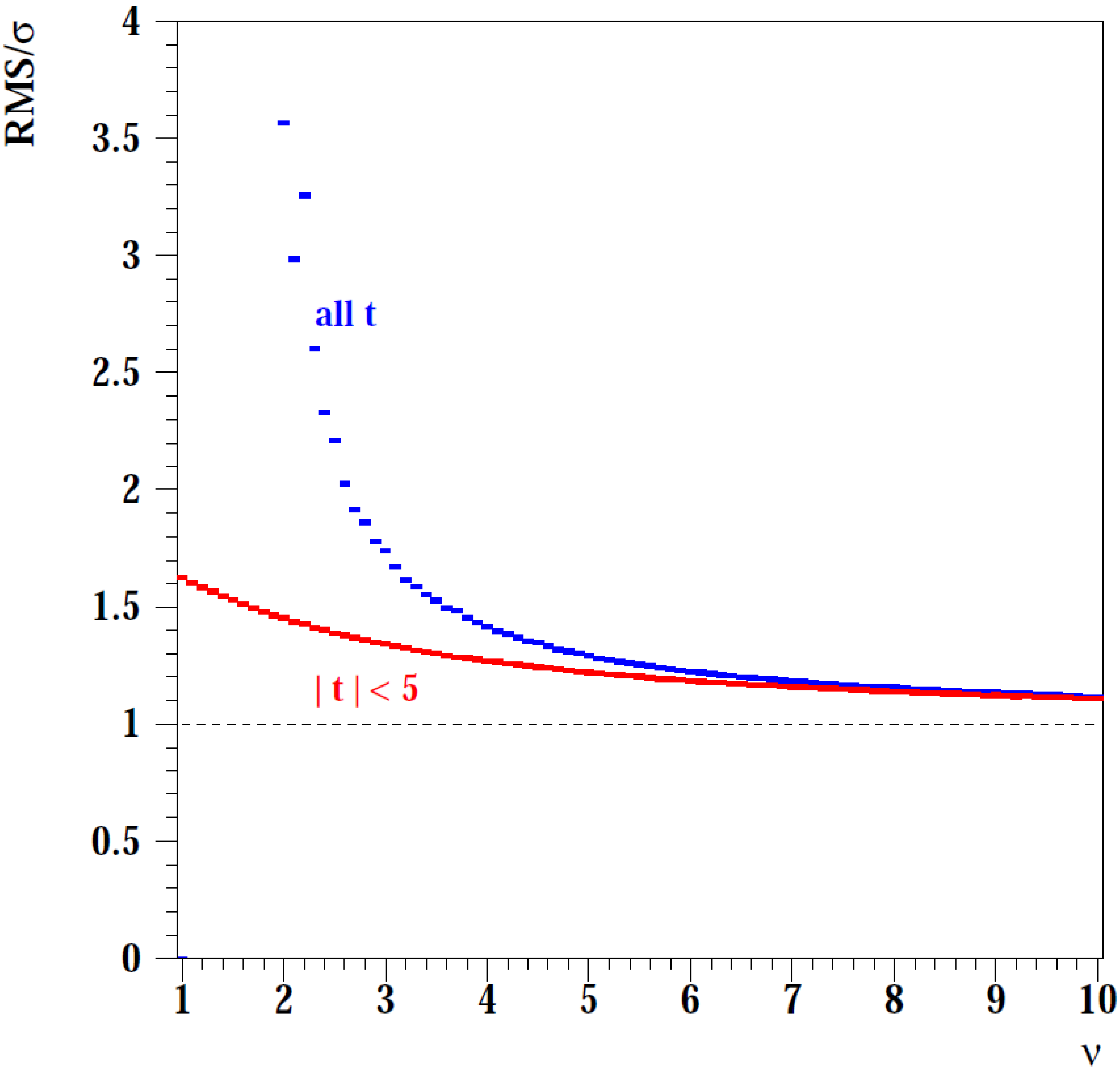
$$f(t) = \frac{\Gamma((\nu+1)/2)}{\sqrt{\nu\pi}\,\Gamma(\nu/2)}(1+t^2/\nu)^{-(\nu+1)/2}$$

f(t) is a normalized probability density.
Γ function is in PAW, ROOT.



Parameter ν interpolates between Gaussian and Breit-Wigner.

rms/σ for Student's t



Student's t parameter ν

- Generate random numbers according to Student's t for different ν (see W. Hoermann, Computing 81 (2007) 317).
- calculate rms:
  - for all t. (rms diverges for $\nu = 1$).
  - for | t | < 5. (rms stays below 1.62 for all $\nu \geq 1$).
- Asymptotic value (rms/σ = 1) slowly approached.