Hit reconstruction in the CBM Silicon Tracking System

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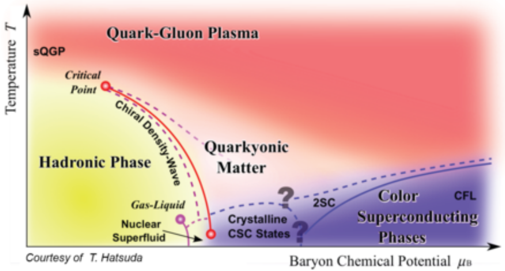
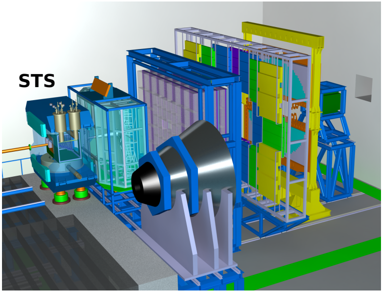
MT student retreat, Darmstadt, January 2017

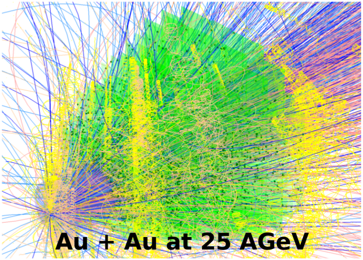
Compressed Baryonic Matter experiment @ FAIR





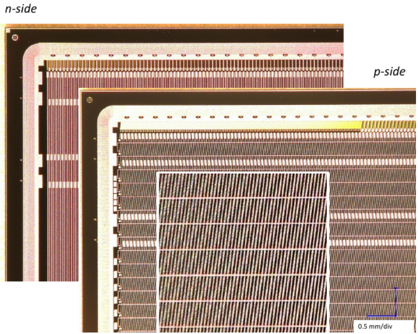
- QCD-diagram at moderate temperature and high baryonic density;
- extensive physical program: rare probes, complex trigger signatures:
  - high interaction rate: $10^5..10^7$ interactions/s;
  - no hardware trigger;
- Au + Au SIS100 - SIS300: $2..45\ AGeV$.

Silicon Tracking System (STS) – main tracking detector system



Requirements:

- momentum resolution $\lesssim 1.5\%$;
- high reconstruction efficiency;
- hit rates up to $20\,\mathrm{MHz/cm^2}$;
- no hardware trigger.



Design:

- 8 tracking stations in a $1\,\mathrm{T}$ dipole magnet;
- double-sided micro-strip Si sensor: $\sim 300\,\mu\mathrm{m}$ thickness, $58\,\mu\mathrm{m}$ strip pitch, 7.5° stereo-angle;
- radiation hard: $10^{14}\,1\,\mathrm{MeV}\,\mathrm{n_{eq}/cm^2}$;
- fast free-streaming read-out electronics out of the acceptance.

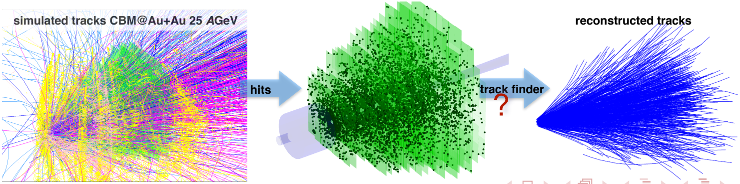
Reconstruction chain

0. **Digitization:** modelling the relevant processes from a particle track within a sensor up to a digital signal in each read-out channel (`digi`);

Reconstruction:

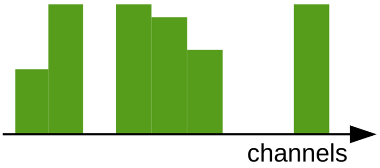
1. several (neighbouring) digis from one side of sensor combine to `cluster`;
2. combine 2 clusters from opposite sides of sensor to `hit`;
3. 4-8 hits from different layers of sensors (stations) combine to `track`.

- No hardware trigger → no events → time slices ($\sim 100..1000$ events) → time coordinate for every stage — **time-based reconstruction**;
- Do not store all data (1 TB/s) → software trigger: on-line event reconstruction and selection → fast algorithms.

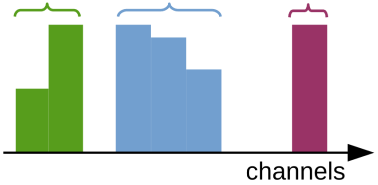


Cluster finding

Fired channels:



Clusters:



- Neighbouring digis (which presumably originate from the same incident particle) combine to a cluster;
- Additionally, analyse time difference before adding a digi into the cluster;
- Estimate cluster centre using measured charges q_i.

Cluster position finding algorithm

Centre-Of-Gravity algorithm (COG):

$$x_{\rm rec} = \frac{\Sigma x_i q_i}{\Sigma q_i}$$

x_i – the coordinate of ith strip,
q_i – its charge,
$i = 1..n$ – the strip index in the n-strip cluster.

COG is biased: $\langle x_{\rm true} - x_{\rm rec}\rangle \equiv \langle \Delta x\rangle \neq 0$ for $n \geq 2$ at fixed q_2/q_1.

An **unbiased algorithm**:
2-strip clusters:

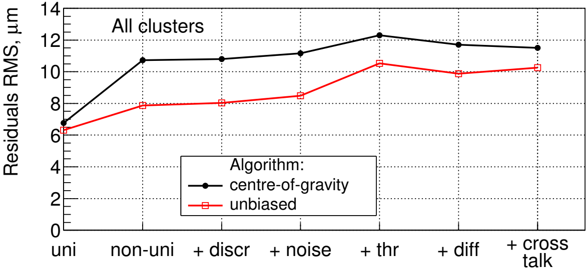
$$x_{\rm rec} = 0.5\,(x_1 + x_2) + \frac{p}{3}\frac{q_2 - q_1}{\max(q_1, q_2)}, \quad p \text{ – strip pitch;}$$

n-strip clusters (Analog head-tail algorithm[1]):

$$x_{\rm rec} = 0.5\,(x_1 + x_n) + \frac{p}{2}\frac{\min(q_n, q) - \min(q_1, q)}{q}, \quad q = \frac{1}{n-2}\sum_{i=2}^{n-1} q_i$$

[1] R. Turchetta, "Spatial resolution of silicon microstrip detectors", 1993

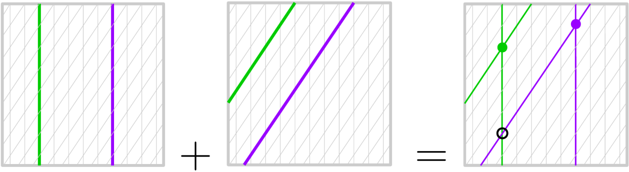
Residuals comparison for COG and the unbiased algorithms



500 minimum bias Au+Au events at 10 AGeV are simulated with the realistic STS geometry.

- Non-ideal effects make the performance comparable;
- The unbiased algorithm is faster and simplifies the hit position error estimation.

Hit reconstruction



- number of fakes can be estimated as: $(n^2 - n)\tan\alpha$, where α is stereo-angle between strips;
- smaller stereo-angle leads to worse spatial resolution;
- analysis of time difference between clusters allows to keep fake hits rate low for the time-based reconstruction.

	Event-based	Time-based
Efficiency	98 %	97 %
True hits	55 %	53 %

Event-based: minimum bias events Au+Au @ 25 GeV;
Time-based: time slices of 10 μs, interaction rate 10 MHz.

Hit position error: basic ideas

Why care: A reliable estimate of the hit position error $\Rightarrow$
get proper track χ^2 $\Rightarrow$
discard ghost track candidates $\Rightarrow$
improve the signal/background and keep the efficiency high.

Method: Calculations from first principles and independent of:
simulated residuals;
measured spatial resolution.

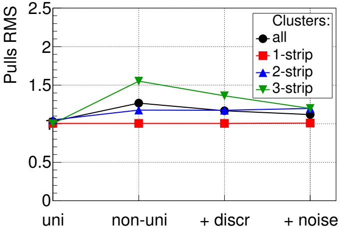
$$\sigma^2 = \sigma_{\text{alg}}^2 + \sum_i \left(\frac{\partial x_{\text{rec}}}{\partial q_i}\right)^2 \sum_{\text{sources}} \sigma_j^2,$$

σ_{alg} – an error of the cluster position finding algorithm;
σ_j – errors of the charge registration at one strip, among them already included:

- $\sigma_{\text{noise}} = \text{Equivalent Noise Charge};$
- $\sigma_{\text{discr}} = \dfrac{\text{dynamic range}}{\sqrt{12}\ \text{number of ADC}};$
- $\sigma_{\text{non-uni}}.$

Verification: hit pull distribution

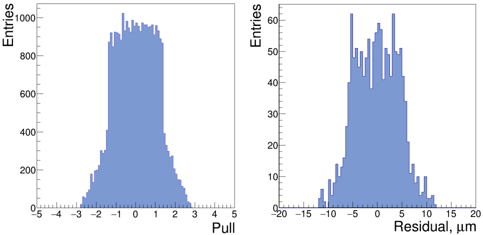
Width



500 mbias events Au+Au @ 10 AGeV

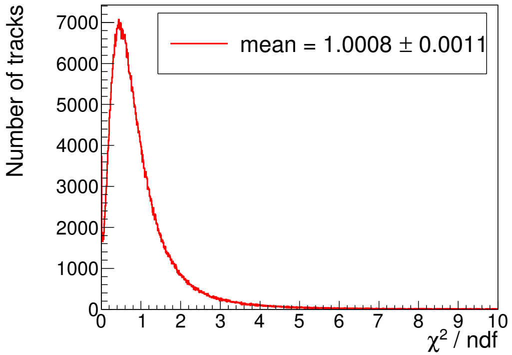
- $\text{pull} = \dfrac{\text{residual}}{\text{error}}$;
- pull distribution width must be ≈ 1;
- pull distribution shape must reproduce residual shape.

Shape



Ideal detector, 2-strip clusters, residuals at fixed: $\dfrac{|q_2 - q_1|}{\max(q_1, q_2)}$.

Verification: track χ^2 distribution



10 000 minimum bias events Au+Au @ 10 AGeV

- χ^2 distribution for tracks: mean value must be ≈ 1.

Summary

- Wide physical program of the CBM experiment: rare probs and complex trigger signatures
  - high interaction rate, no hardware trigger $\Rightarrow$ free-streaming electronics and time-based reconstruction.
- Two **cluster position finding algorithm** were implemented for the STS: Centre-Of-Gravity and the unbiased. The last
  - gives similar residuals as the Centre-Of-Gravity algorithm;
  - simplifies position error estimation.
- Developed method of **hit position error estimation** yields correct errors, that was verified with:
  - hit pulls distribution (width and shape);
  - track χ^2/ndf distribution.
- **Time-based reconstruction** algorithms show sufficient reconstruction quality and time performance.

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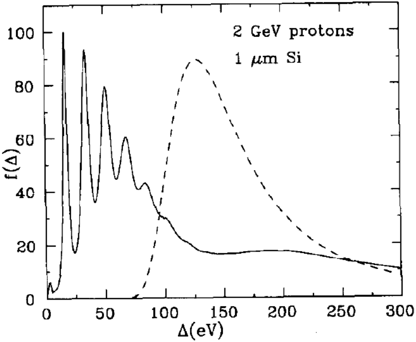
Thank you for your attention!

Detector response model:

- non-uniform energy loss in sensor: *divide a track into small steps and simulate energy losses in each of them using Urban model*[1]*;*
- drift of created charge carriers in planar electric field
- movement of e-h pairs in magnetic field (Lorentz shift)
- diffusion
- cross-talk due to interstrip capacitance
- modeling of the read-out chip

[1] K. Lassila-Perini and L. Urbán (1995)

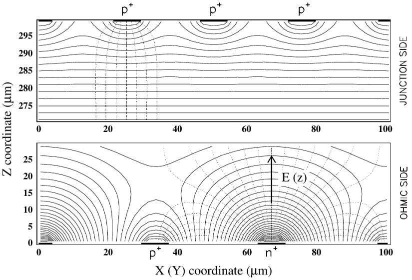


Energy losses of $2\,\mathrm{GeV}$ *protons in* $1\,\mu\mathrm{m}$ *of Si (solid line)*[2].

[2] *H. Bichsel (1990)*

Detector response model:

- non-uniform energy loss in sensor
- drift of created charge carriers in planar electric field:
  non-uniformity of the electric field is negligible in 90% of the volume;
- movement of e-h pairs in magnetic field (Lorentz shift)
- diffusion
- cross-talk due to interstrip capacitance
- modeling of the read-out chip

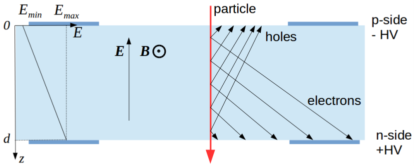


Calculated electric field for sensors with strip pitch $25.5\,\mu\mathrm{m}$ *on the p-side and* $66.5\,\mu\mathrm{m}$ *on the n-side*[1].

[1] *S. Straulino et al. (2006)*

Detector response model:

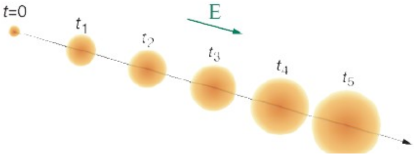
- non-uniform energy loss in sensor
- drift of created charge carriers in planar electric field
- movement of e-h pairs in magnetic field (Lorentz shift):
  taking into account the fact that Lorentz shift depends on the mobility, which depends on the electric field, which depends on the z-coordinate of charge carrier;
- diffusion
- cross-talk due to interstrip capacitance
- modeling of the read-out chip



Lorentz shift for electrons and holes in Si sensor.

Detector response model:

- non-uniform energy loss in sensor
- drift of created charge carriers in planar electric field
- movement of e-h pairs in magnetic field (Lorentz shift)
- diffusion:
  integration time is bigger than the drift time: estimate the increase of the charge carrier cloud during the whole drift time using Gaussian low;
- cross-talk due to interstrip capacitance
- modeling of the read-out chip



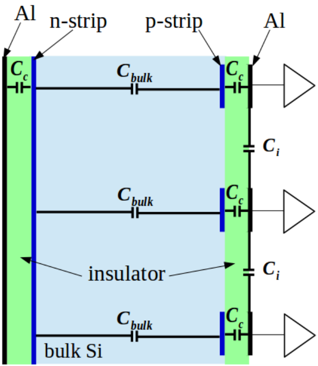
Increasing of charge cloud in time.

Detector response model:

- non-uniform energy loss in sensor
- drift of created charge carriers in planar electric field
- movement of e-h pairs in magnetic field (Lorentz shift)
- diffusion
- cross-talk due to interstrip capacitance:

$$Q_{\text{neib strip}} = \frac{Q_{\text{strip}} C_{\text{i}}}{C_{\text{c}} + C_{\text{i}}};$$

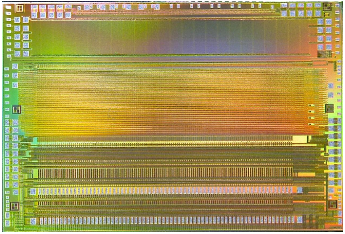
- modeling of the read-out chip



Simplified double-sided silicon microstrip detector layout.

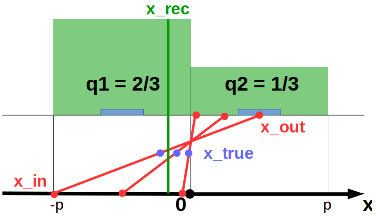
Detector response model:

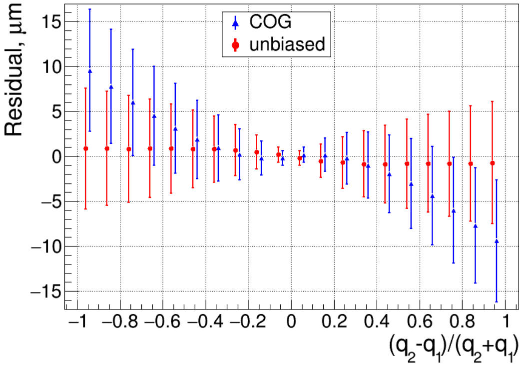
- non-uniform energy loss in sensor
- drift of created charge carriers in planar electric field
- movement of e-h pairs in magnetic field (Lorentz shift)
- diffusion
- cross-talk due to interstrip capacitance
- modeling of the read-out chip:
  - *noise: + Gaussian noise to the signal in fired strip;*
  - *threshold;*
  - *digitization of analog signal;*
  - *time resolution;*
  - *dead time.*



STS-XYTER read-out chip for the CBM Silicon Tracking System.

Residuals comparison for 2 CPFAs: 2-strip clusters





Ideal detector model & uniform energy loss.
Error bars: RMS of the residual distribution.
$q_{1,2}$ – measured charges on the strips.

Unbiased cluster position finding algorithm (CPFA), n-strip clusters

formula for **unifrom** energy loss:

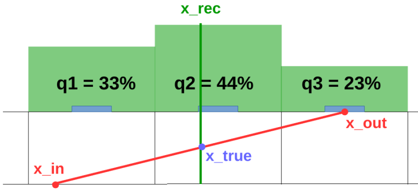
$$x_{\text{rec}} = 0.5\,(x_1 + x_n) + \frac{p}{2}\frac{q_n - q_1}{q},$$

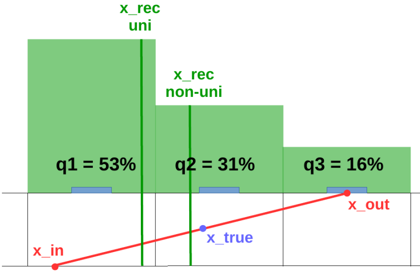
$$q = \frac{1}{n-2}\sum_{i=2}^{n-1} q_i;$$

formula for **non-uniform** energy loss (head-tail algorithm[1]):

$$x_{\text{rec}} = 0.5\,(x_1 + x_n) + \frac{p}{2}\frac{\min(q_n, q) - \min(q_1, q)}{q},$$

[1] R. Turchetta, "Spatial resolution of silicon microstrip detectors", 1993





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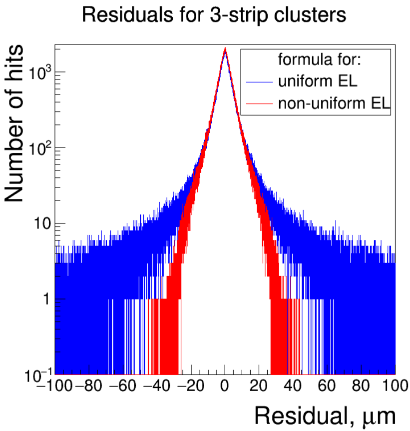

Estimation of hit position error

Hit position error: $\sigma^2 = \sigma_{\mathrm{alg}}^2 + \sum_i \left(\frac{\partial x_{\mathrm{rec}}}{\partial q_i}\right)^2 \sum_{\mathrm{sources}} \sigma_j^2,$

σ_{alg} – an error of the unbiased CPFA:

$$\sigma_1 = \frac{p}{\sqrt{24}}, \qquad \sigma_2 = \frac{p}{\sqrt{72}} \frac{|q_2 - q_1|}{\max(q_1, q_2)}, \qquad \sigma_{n>2} = 0.$$

σ_j – errors of the charge registration at one strip, among them already included:

- $\sigma_{\mathrm{noise}} = \mathrm{Equivalent\ Noise\ Charge};$
- $\sigma_{\mathrm{discr}} = \frac{\mathrm{dynamic\ range}}{\sqrt{12}\ \mathrm{number\ of\ ADC}};$
- $\sigma_{\mathrm{non-uni}}$ is estimated assuming:
  - registered charge corresponds to the most probable value of the energy loss;
  - incident particle is ultrarelativistic ($\beta\gamma \gtrsim 100$).
- σ_{diff} is negligible in comparison with other effects.

Error due to non-uniform energy loss

The contribution from the non-uniformity of energy loss is more difficult to take into account because the actual energy deposit along the track is not known. The following approximations allow a straightforward solution:

- the registered charge corresponds to the most probable value (MPV) of energy loss;
- the incident particle is ultrarelativistic ($\beta\gamma \gtrsim 100$).

The second assumption is very strong but it uniquely relates the MPV and the distribution width (Particle Data Group)

$$MPV = \xi[\mathrm{eV}] \times \left(\ln\left(1.057 \times 10^6 \xi[\mathrm{eV}]\right) + 0.2 \right).$$

Solving this with respect to ξ gives the estimate for the FWHM (S. Merolli, D. Passeri and L. Servoli, Journal of Instrumentation, Volume 6, 2011)

$$\sigma_{\mathrm{non}} = w/2 = 4.018\xi/2.$$

1-strip clusters: why not $\sigma_{method} = p/\sqrt{12}$?

In general, for **all** track inclinations:

- $N = \int\limits_{x_{in}} \int\limits_{x_{out}} P_1(x_{in}, x_{out}) dx_{in} dx_{out} = p^2$;
- $\sigma^2 = \frac{1}{N} \int\limits_{x_{in}} \int\limits_{x_{out}} P_1(x_{in}, x_{out}) dx_{in} dx_{out} \Delta x^2 = \frac{p^2}{24}$.

Particullary, for **perpendicular** tracks: $x_{in} = x_{out}$

- $N = \int\limits_{x_{in}} P_1(x_{in}, x_{out}) dx_{in} = p$;
- $\sigma^2 = \frac{1}{N} \int\limits_{x_{in}} P_1(x_{in}, x_{out}) dx_{in} \Delta x^2 = \frac{p^2}{12}$