Investigation into the particle identification potential of the CBM Silicon Tracking System @FAIR

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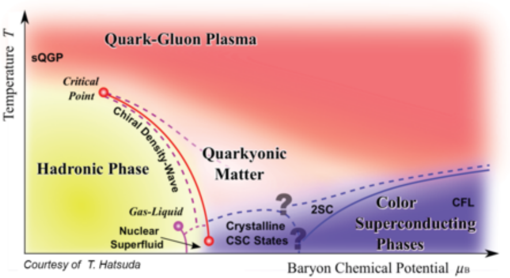
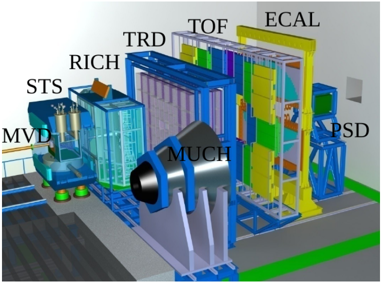
QCD WE-Heraus Physics School

September 2017, Bad Honnef, Germany

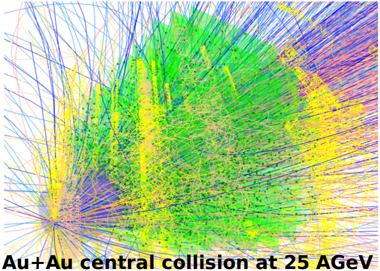
Compressed Baryonic Matter experiment @ FAIR





- QCD-diagram at moderate temperature and high density: bulk and rare probes;
- Au + Au SIS100: $2 - 11\,AGeV$, $10^5 - 10^7$ interactions/s;
- up to 700 charged particles per central collision;
- no trigger;
- first beam in $\approx$ 2022.

Silicon Tracking System (STS)



Task:

- reconstruct tracks:
  high efficiency $> 95\,\%$,
  high momentum resolution $< 2\,\%$;
- cope with hit rates $20\,\mathrm{MHz/cm^2}$.

Requirements:

- low material budget $\sim 1\%\,\mathrm{X_0/layer}$;
- high granularity;
- radiation hard: $10^{14}\,\mathrm{n_{eq}/cm^2}$.

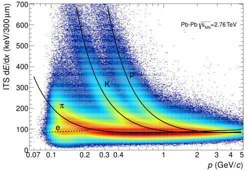
Design:

- 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^{o} stereo-angle;
- self-triggered fast read-out electronics placed outside of acceptance.

$\Delta E/E$ technique

- $\Delta E/E$: well-known technique used in nuclear/particle physics.
- Widely implemented as $\Delta E/E$: thin reference + thick absorber.
- Can be naturally implemented in tracking system as $\dfrac{dE/dx}{p/q}$:
- Sensitive to the charge ($\propto Z^2$) unlike Time-Of-Flight:
  - allows to separate particles with $m/Z = \mathrm{const}$: d, ${}_{(\Lambda)}{}^{4}\mathrm{He}$, ${}_{(\Lambda)}{}^{6}\mathrm{Li}$.
- Good separation for low momenta.

Implementation $\Delta E/p$ in other experiments

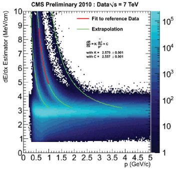


ALICE

$\Delta E/p$ inner tracking system, time projection chamber;

≤ 4 layers per track.

M. Ivanov, 2013; P. Braun-Munzinger, 2016

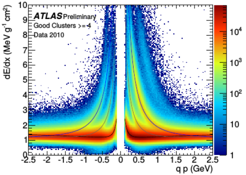


CMS

$\Delta E/p$ in silicon tracker;

≤ 20 layers per track.

L. Quertenmont, 2011



ATLAS

$\Delta E/p$ in silicon tracker, pixels;

≤ 4 layers per track.

ATLAS Note, 2011

Motivation for the STS PID

Several PID sub-systems are planned in CBM:

- **Ring Image Čerenkov detector**: for electron separation mainly;
- **Transition Radiation Detector**: $e^{\pm}/\pi^{\pm}$ discrimination;
- **Time-of-Flight**: separation of heavy hadrons and (hyper-)nuclei.

Advantages of the STS PID:

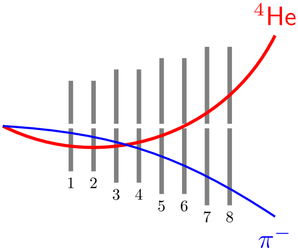
- works at highest CBM interaction rates: $10\,\mathrm{MHz}$;
- largest acceptance (after MVD): the only chance for low momentum particles with $0.1\,\mathrm{GeV}/c < p < 0.5\,\mathrm{GeV}/c$;
- closest to the target after MVD (first station at $\approx 10\,\mathrm{cm}$): the only chance for the short-lived particles $\gamma c\tau \sim 1..100\mathrm{cm}$.

Some constraints expected for the STS:

- 5-bit ADC per r/o channel;
- limited dynamic range per channel $(15\,\mathrm{fC} = 93.6\,\mathrm{ke}^{-})$.

$\Delta E/\Delta x$ measurement in the STS

- Crossing angle affects $\Delta x = 300\,\mu\mathrm{m}/\cos(\theta)$ — is taken from reconstructed track parameters.
- ΔE in each station is measured but distorted by several effects (noise, threshold, ...).



Realistic detector response model to simulate the measured energy loss:

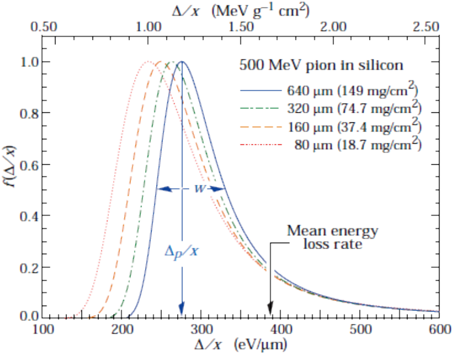
- non-uniform energy loss of particle within sensor thickness (the Urban method);
- diffusion of the created charge carriers;
- influence of the magnetic field (the Lorentz shift);
- cross-talk via interstrip capacitances;
- noise (150% of simulated ENC for chip + routing lines + sensor) and threshold (3ENC).

$\Delta E/\Delta x$ measurement in the STS

Charged particle crosses from 3 to 8 stations to be registered: several measurements of $\Delta E/\Delta x$ for one particle — equivalent number, **"mean" value**, to compare vectors $\Delta E/\Delta x$ measurements for different particles is required.

Energy loss in $300\,\mu\mathrm{m}$ of Si $p(\Delta E)$:

- can be partially expressed as the **Landau distribution**;
- mean is not equal to most probable value $\langle \Delta E \rangle \neq \Delta_p$;
- $\Delta_p/\Delta x = f(\Delta x)$;
- long tail towards higher ΔE.



Properties of mean values of distributions

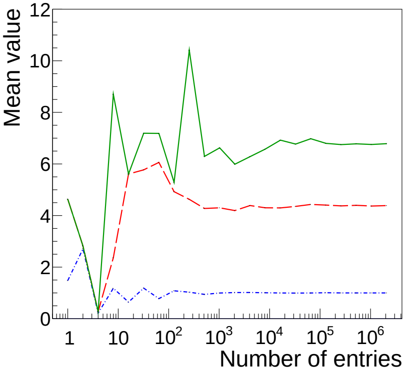
Arithmetic mean

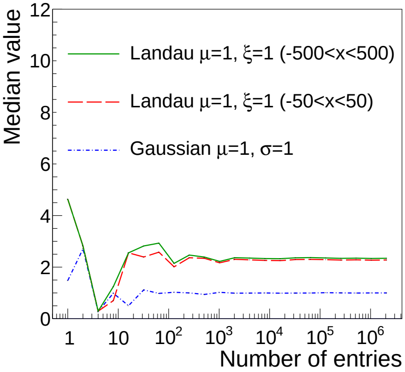
$$\bar{x}_1 = \frac{1}{n}\sum_{i=1}^{n} x_i$$

diverges for the Landau distribution.

For a set $x_1 \ldots \leq x_i \ldots \leq x_n$, **median**

$$\bar{x}_{\mathrm{M}} = \begin{cases} x_{(n-1)/2} & n \text{ is even} \\ 1/2 \cdot (x_{n/2} + x_{n/2+1}) & n \text{ is odd} \end{cases}$$





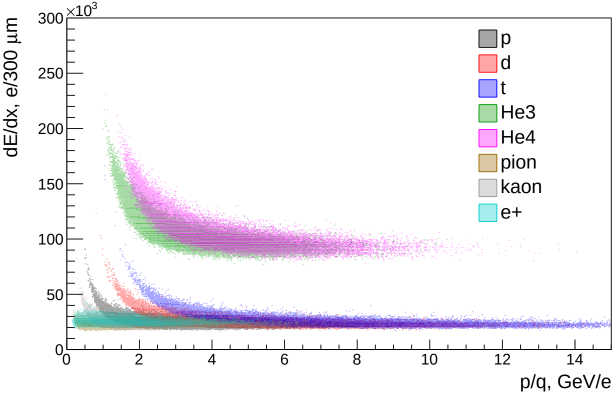
Mean estimation chosen for the STS

As a first approach:

- double-sided sensors — two clusters for each hit — two measurements of $\Delta E/\Delta x$ for each hit;
- strips with the charge $> 15\,\mathrm{fC}$ (dynamic range of ADC) go to the last ADC channel — cluster with overflow;
- clusters with overflow do not give precise measurement of ΔE — excluded from analysis;
- average over two clusters in a hit;
- median over all hits in a track.

Test of the method

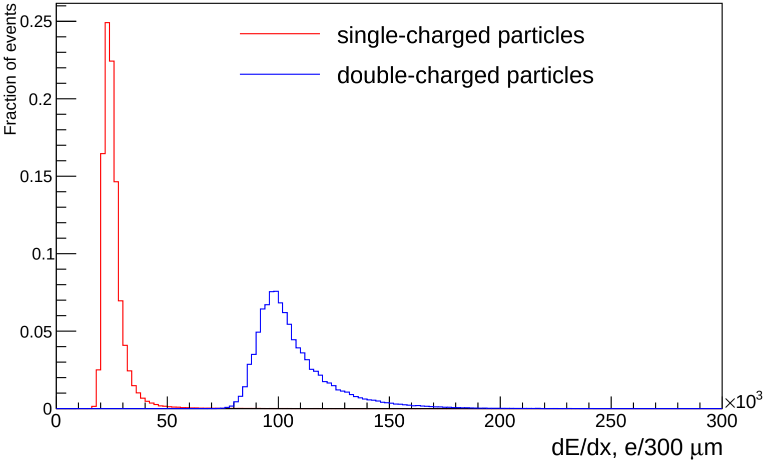
10^5 of each particle generated for Au+Au @ $10\,\mathrm{AGeV}$:



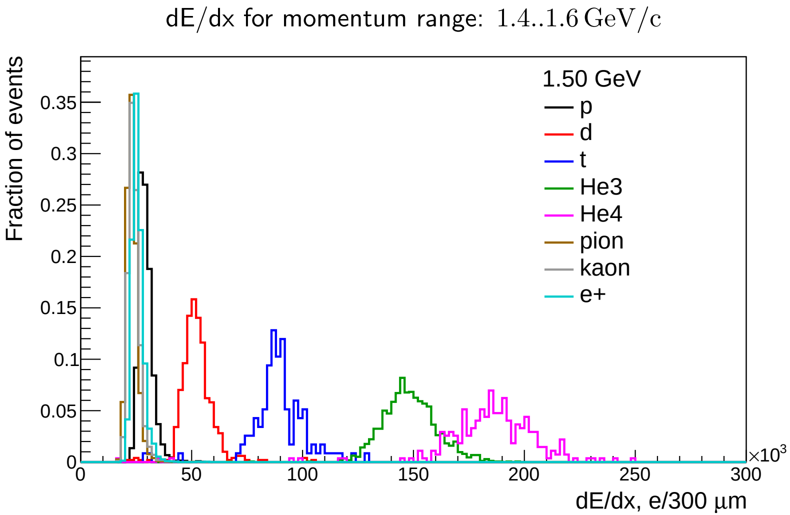
- perfect separation between single- and double-charged particles for the whole momentum range;
- separation between p/d/t up to 2.5 GeV/c.

Separation m/q=const, $10\,\mathrm{AGeV}$

Integral over the whole momentum range

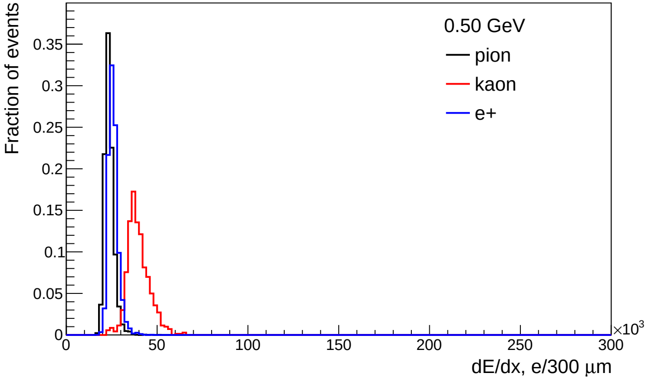


Separation of other particles, $10\,\mathrm{AGeV}$



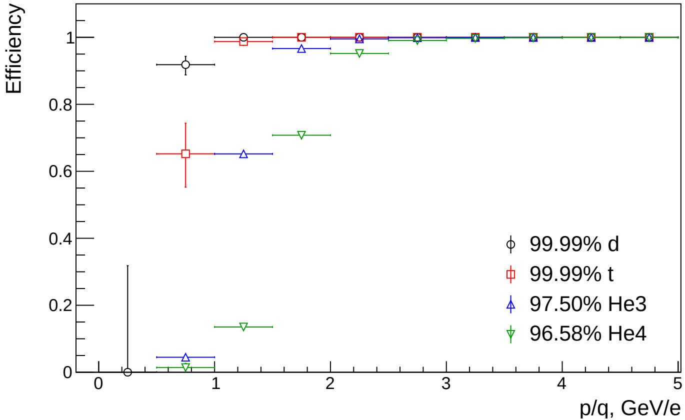
Kaon separation, $10\,\mathrm{AGeV}$

dE/dx for momentum range: $0.4..0.6\,\mathrm{GeV/c}$



- Kaon separation works up to 0.5 GeV/c.

Efficiency of dE/dx calculation for fragments, $10\,\mathrm{AGeV}$



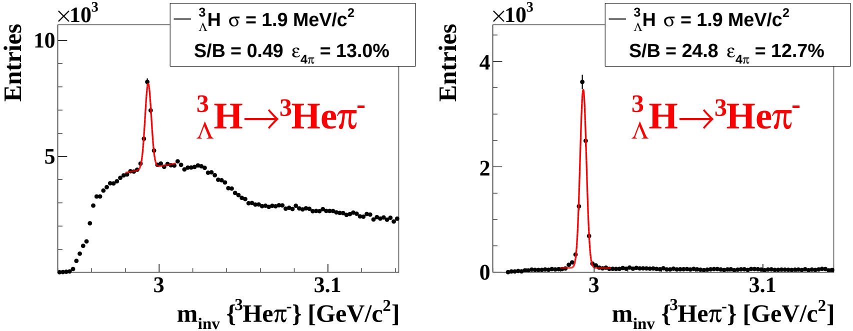
- Reason for inefficiency: high fraction of clusters with overflow for low-momentum fragments.
- Efficiency for lighter particles $100.0\,\%$.

Using dE/dx technique for hypernuclei reconstruction

5 M central Au+Au events at 10 AGeV.

Time-Of-Flight

Time-Of-Flight + STS



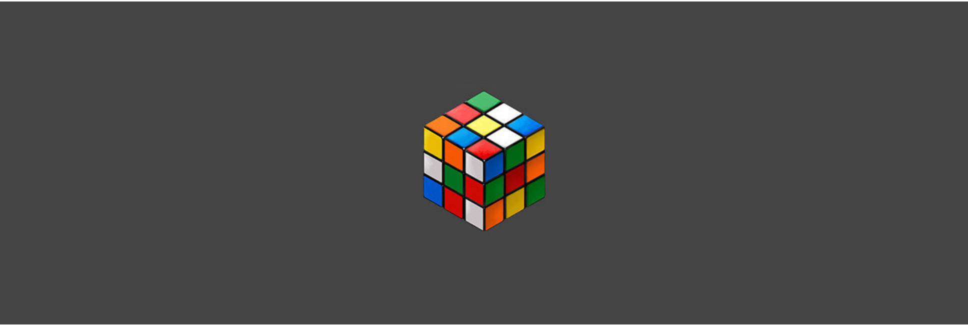
Maksym Zyzak, Iouri Vassiliev

Summary and outlook

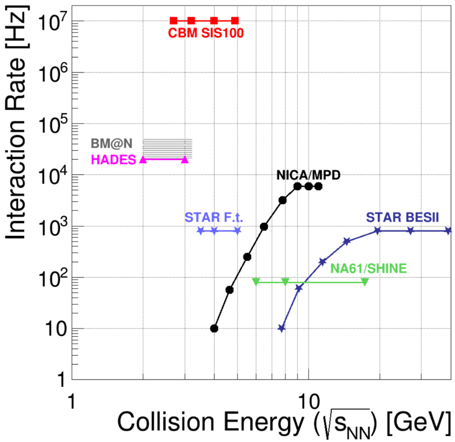
- STS is promising tool for PID of single- and double charged particles: perfect separation for the whole momentum range.
- Efficiency of the dE/dx calculation is $96.6\,\%$ for He4 and $99.99\,\%$ for t and lighter particles.
- STS involving into PID increase S/B for $^{3}_{\Lambda}H$ in 50 times(!) in comparison with TOF only;
- STS can be involved in PID for K/p/d/t for low momenta up to $2.5..3\,\mathrm{GeV}/c$.

- other estimation for “mean” to be studied;
- develop treatment for clusters with overflow to increase efficiency for low-momentum fragments;
- test for low-momentum particles ($< 1\,\mathrm{GeV}/c$) and for short-lived particles.

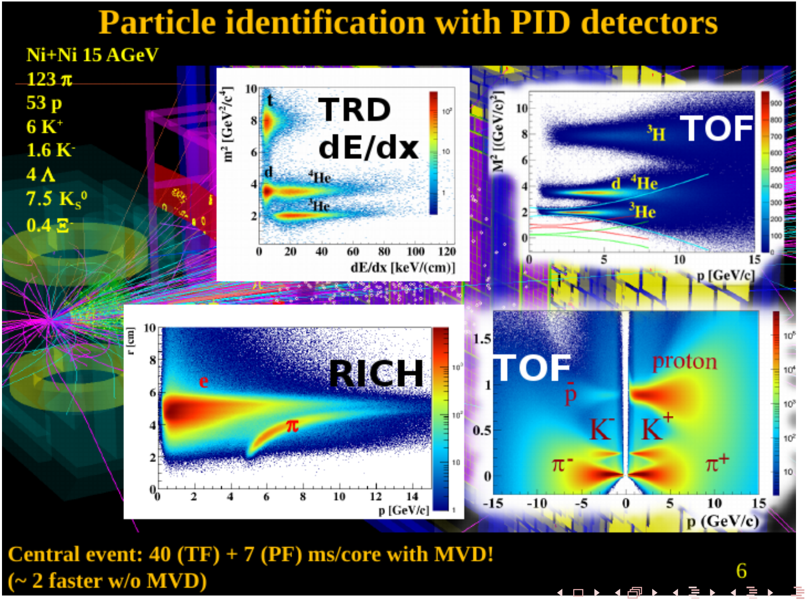
Back-up slides



Other experiments explore QCD diagramm



After upgrade in 2018, Pb+Pb:
ALICE and CMS max rate: $50\,\mathrm{kHz}$.
Mostly limited by readout electronics.


Particle identification with PID detectors
Ni+Ni 15 AGeV
123 π
53 p
6 K+
1.6 K-
4 Λ
7.5 Ks0
0.4 Ξ-
TRD dE/dx
m² [GeV²/c⁴]
dE/dx [keV/(cm)]
t
d
4He
3He
TOF
M² [(GeV/c)²]
p [GeV/c]
3H
d 4He
3He
RICH
r [cm]
p [GeV/c]
e
π
TOF
p̄
proton
K-
K+
π-
π+
p (GeV/c)
Central event: 40 (TF) + 7 (PF) ms/core with MVD!
(~ 2 faster w/o MVD)
6

Particle yields in CBM

Expected particle yields Au+Au @ 6, 10 AGeV

Particle (mass MeV/c²)	Multi-plicity 6 AGeV	Multi-plicity 10 AGeV	decay mode	BR	ε (%)	yield (s^{-1}) 6AGeV	yield (s^{-1}) 10AGeV	yield in 10 weeks 6AGeV	yield in 10 weeks 10 AGeV	IR MHz
$\bar{\Lambda}$ (1115)	$4.6\cdot10^{-4}$	0.034	$\bar{p}\pi^+$	0.64	11	1.1	81.3	$6.6\cdot10^{6}$	$2.2\cdot10^{8}$	**10**
Ξ^- (1321)	0.054	0.222	$\Lambda\pi^-$	1	6	$3.2\cdot10^{3}$	$1.3\cdot10^{4}$	$1.9\cdot10^{10}$	$7.8\cdot10^{10}$	**10**
Ξ^+ (1321)	$3.0\cdot10^{-5}$	$5.4\cdot10^{-4}$	$\bar{\Lambda}\pi^+$	1	3.3	$9.9\cdot10^{-1}$	17.8	$5.9\cdot10^{6}$	$1.1\cdot10^{8}$	**10**
Ω^- (1672)	$5.8\cdot10^{-4}$	$5.6\cdot10^{-3}$	ΛK^-	0.68	5	17	164	$1.0\cdot10^{8}$	$9.6\cdot10^{8}$	**10**
Ω^+ (1672)	-	$7\cdot10^{-5}$	$\bar{\Lambda}K^+$	0.68	3	-	0.86	0	$5.2\cdot10^{6}$	**10**
${}^3_\Lambda H$ (2993)	$4.2\cdot10^{-2}$	$3.8\cdot10^{-2}$	${}^3He\pi^-$	0.25	19.2	$2\cdot10^{3}$	$1.8\cdot10^{3}$	$1.2\cdot10^{10}$	$1.1\cdot10^{10}$	**10**
${}^4_\Lambda He$ (3930)	$2.4\cdot10^{-3}$	$1.9\cdot10^{-3}$	${}^3He p\pi^-$	0.32	14.7	110	87	$6.6\cdot10^{8}$	$5.2\cdot10^{8}$	**10**
${}^5_{\Lambda\Lambda}He$(5047)		$5.0\cdot10^{-6}$	${}^3He2p2\pi$	0.01	1		$5\cdot10^{-3}$		$3\cdot10^{4}$	**10**
${}^6_{\Lambda\Lambda}He$(5986)		$1.0\cdot10^{-7}$	${}^4He2p2\pi$	0.01	1		$1\cdot10^{-4}$		600	**10**

PDF of the energy losses

- Energy losses obey Landau-Vavilov distribution:

$$p \propto \varphi(\Delta E,\, \Delta_p,\, \xi) \otimes e^{-\dfrac{\Delta E^2}{2\delta_2}},$$

where

$$\Delta_p = \xi \times \left(\ln \frac{2 m_e c^2 \beta^2 \gamma^2}{I} + \ln \frac{\xi}{I} + 0.2 - \beta^2 \right),$$

$$\xi = 17.8 \times Z^2 x[\mu\mathrm{m}]/\beta^2 \mathrm{eV},$$

$\delta_2 = \frac{8}{3}\xi \sum_i I_i f_i \ln \dfrac{2 m_e \beta}{I_i}$, for thin sensors ($\lesssim 300\mu\mathrm{m}$) $\sqrt{\delta_2} \sim \xi$

- The Landau distribution:

$$\varphi(x) = \frac{1}{\pi} \int_0^\infty e^{-t \log t - xt} \sin(\pi t)\, dt, \qquad x = \frac{\Delta E - \Delta_p}{\xi}$$

S. Meroli, D. Passeri and L. Servoli, JINST **6** (2011) P06013.
S. Hancock, F. James, J. Movchet, P. G. Rancoita and L. Van Rossum, Phys. Rev. A **28** (1983) 615
K. A. Olive *et al.* [Particle Data Group], Chin. Phys. C **38** (2014) 090001
H. Bichsel, Rev. Mod. Phys. **60** (1988) 663.

Generalised mean

- **Power mean** or Hödler mean:

$$\bar{x}(m) = \left(\frac{1}{n} \cdot \sum_{i=1}^{n} x_i^m \right)^{\frac{1}{m}}$$

  - various of mean can be obtained:

$m \to \infty$ maximum of x_i
$m = 2$ quadratic mean
$m = 1$ arithmetic mean
$m \to 0$ geometric mean
$m = -1$ harmonic mean
$m \to -\infty$ minimum of x_i

- f-mean as more general approach:

$$\bar{x} = f^{-1} \left(\frac{1}{n} \cdot \sum_{i=1}^{n} f(x_i) \right)$$

- Weighted mean

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i \cdot x_i}{\sum_{i=1}^{n} w_i}$$

- Truncated mean
uses a part of a sub set

$$x_1, \cdots x_k, x_{k+1}, \cdots x_{k+l}, \cdots x_n$$

  - robust against outliers
  - largest and smallest values are ignored

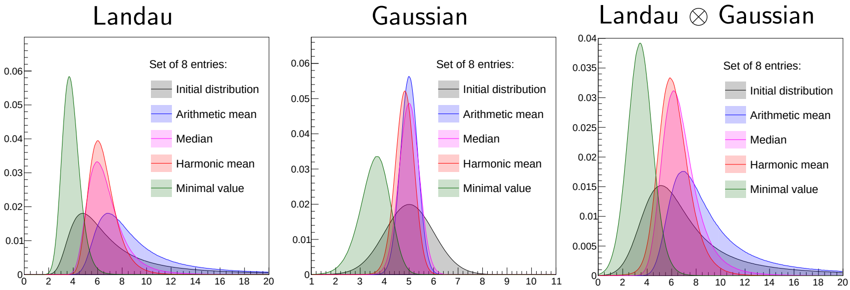
- Interquartile mean

$$\bar{x} = \frac{2}{n} \sum_{i=(n/4)+1}^{3n/4} x_i$$

- **Median**

Mean and median estimation

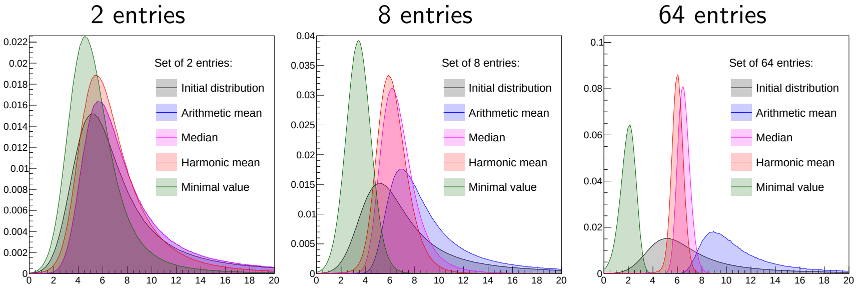
number of measurements $n = 8$



- 10^7 randomly generated numbers
- Position parameters $\mu = 5$, scale parameters $\sigma = \xi = 1$
- $p_{\bar{x},\,n}(\bar{x})$ differs a lot for Gaussian and Landau
  - higher orders m of $p_{\bar{x},\,m}(\bar{x})$ are more sensitive to larger values of x_i
  - median and harmonic mean appear to be universally reliable
  - minimal value gives the sharpest PDF for Landau

Mean and median estimation

Landau $\otimes$ Gaussian



- 10^7 randomly generated numbers, $n = 2,\ 8,\ 64$
- Landau most probable value $\mu = 5$, scale parameters $\sigma = \xi = 1$
- $p_{\bar{x},\,m}(\bar{x})$ highly depend on the number of measurement n
  - there may be an optimum for m depending on n
  - median and harmonic mean still are universally reliable
  - minimal value shifts and smears on higher n

Mean estimation in other silicon trackers

ALICE inner tracker:

4 measurements per track.
Truncated mean for each track:

- **4** measurements: average of lowest 2 points;
- **3** measurements: a weighted sum of the lowest (w=1) and the second-lowest points (w=1/2).

G. Contin, 2011

ATLAS inner tracker:

≤ 7 measurements per track, mostly 3.
Truncated mean for each track:

- **1-2** measurements: average over all points;
- **3-4** measurements: 1 highest point excluded;
- **5-...** measurements: 2 highest excluded.

ATLAS Note, 2011

CMS inner tracker:

≤ 20 measurements per track.
Several methods:

- 60% of lowest measurements;
- (favourite one) Harmonic-2:

$$\bar{x} = \left(\frac{1}{n} \cdot \sum_{i=1}^{n} x_i^{-2}\right)^{-\frac{1}{2}}.$$

L. Quertenmont, 2011

Input

- From thermal distribution of Au+Au at $2\,\mathrm{AGeV}$ and $10\,\mathrm{AGeV}$ generated:
  - particles: protons, pions, kaons, positrons, muons;
  - fragments: deuterons, tritons, He3, He4.
- The realistic digitizer for STS with: $1500\,\mathrm{e}$ noise and $4500\,\mathrm{e}$ threshold (STS-XYTER team promises $< 1000\,\mathrm{e}$ noise).
- Only STS in recostruction.

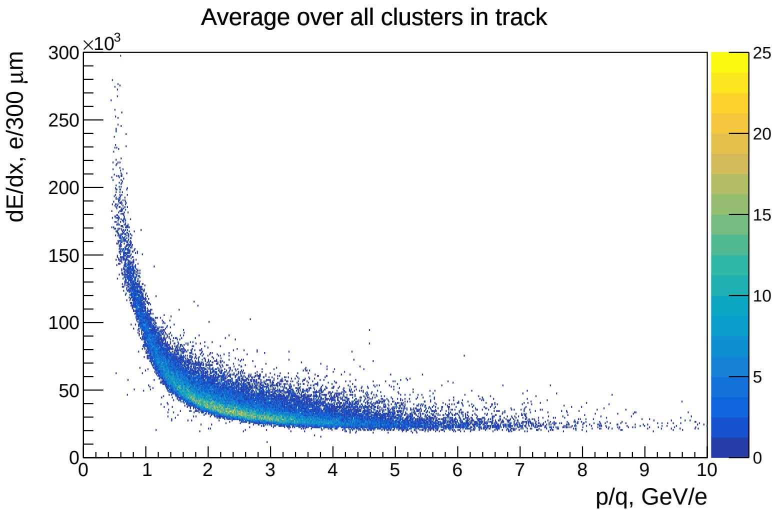
Limitation from STS-XYTER:

- dynamic range of the STS-XYTER chip is $\sim 15\,\mathrm{fC} = 93750\,\mathrm{e} \approx 4 - 5\,\mathrm{MIPs}$: digis with the charge $> 15\,\mathrm{fC}$ go to ADC channel $\#31$;
- charge resolution: 5-bit ADC corresponds to $3000\,\mathrm{e/ADC}$.

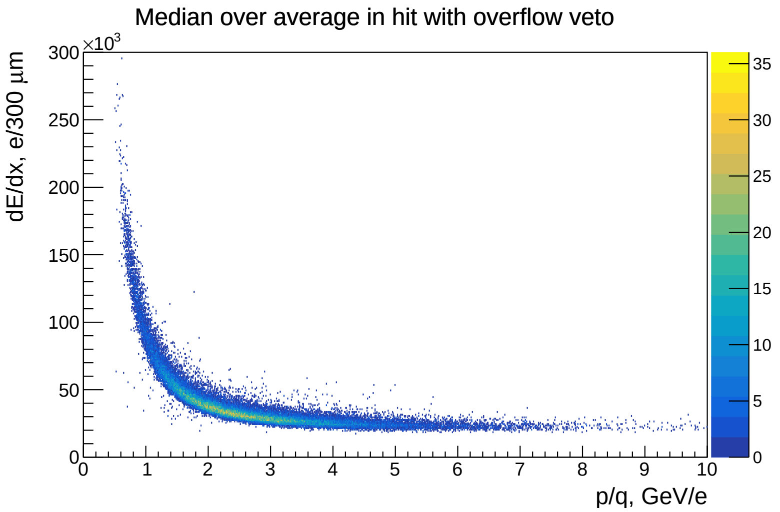
dE/dx calculation in STS

1. reconstruct a track;
2. remove clusters, which have an overflow: at least one digi in a cluster has an amplitude $31\,\mathrm{ADC}$;
3. for each remaining cluster dE is defined as a total cluster charge;
4. to estimate dx:
   4.1 track is assumed to be a straight line between the current hit and the hit in the next station;
   4.2 track inclination is calculated;
   4.3 dx is calculated from the track inclination.
5. take median value of dE/dx over remaining clusters.

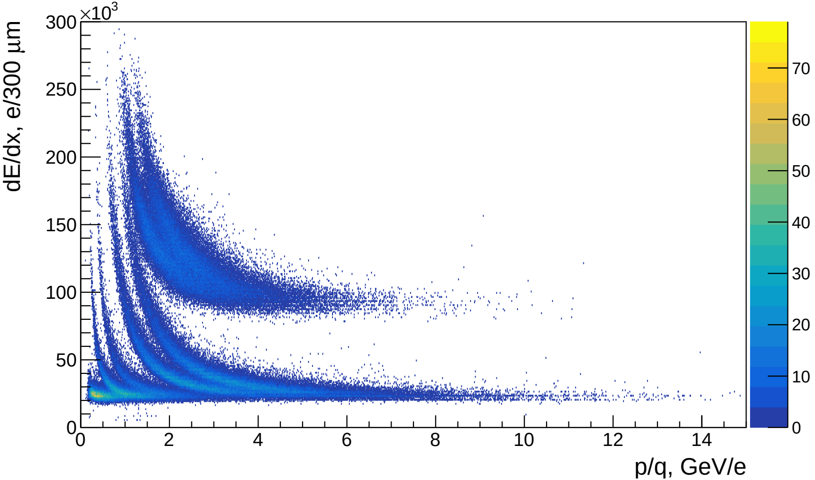
Deutrons


Average over all clusters in track
dE/dx, e/300 µm
×10^3
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
p/q, GeV/e
25
20
15
10
5
0

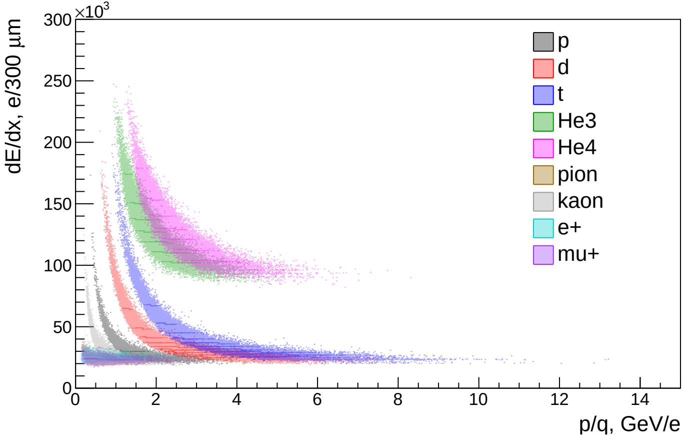
Deutrons


Median over average in hit with overflow veto
×10^3
dE/dx, e/300 µm
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
p/q, GeV/e
35
30
25
20
15
10
5
0

All particle and fragments in the same amount, $2\,\mathrm{AGeV}$



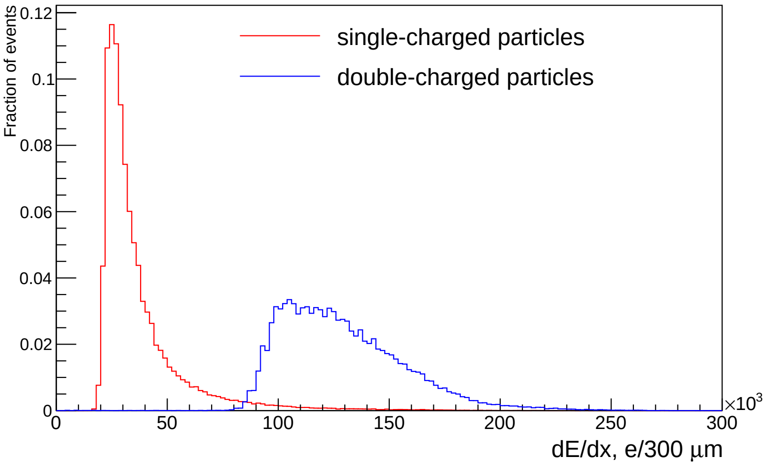
All particle and fragments in the same amount, $2\,\mathrm{AGeV}$



- perfect separation between single- and double-charged particles for the whole momentum range;
- separation between p/d/t up to 2.5/c GeV.

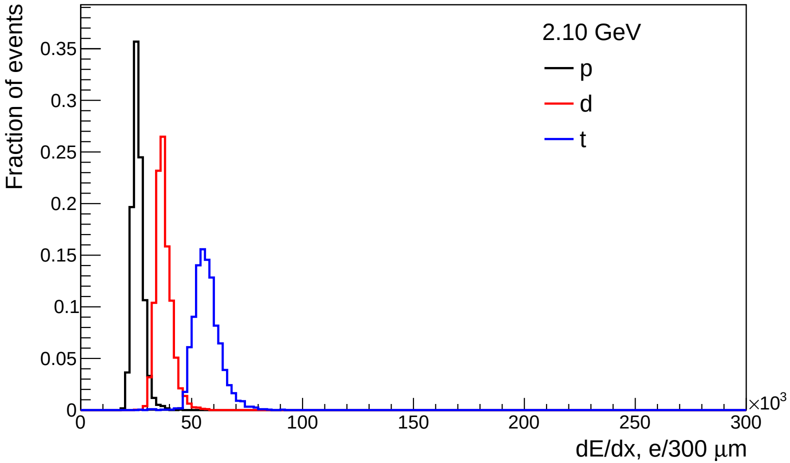
Separation m/q=const, 2 AGeV

Integral over the whole momentum range

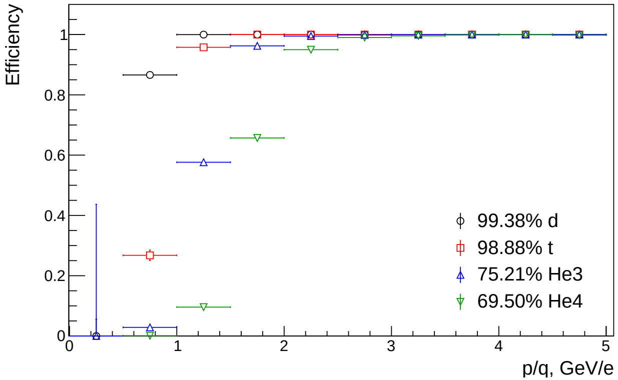


Separation p/d/t, $2\,\mathrm{AGeV}$

dE/dx for momentum range: $2.0..2.2\,\mathrm{GeV/c}$

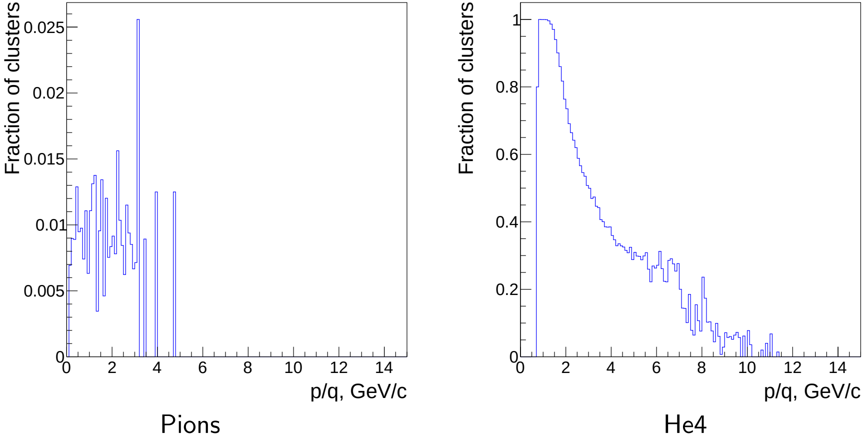


Efficiency of dE/dx calculation for fragments, $2\,\mathrm{AGeV}$

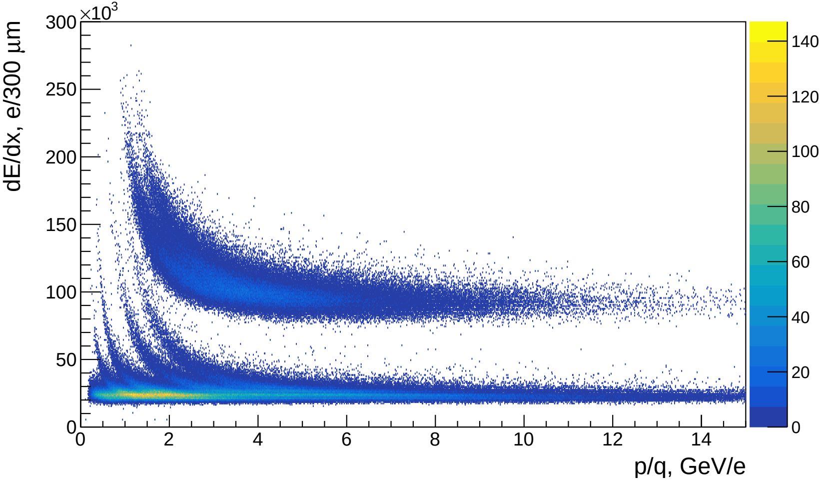


- Efficiency $\stackrel{\text{def}}{=}$ (tracks with calculated dE/dx) / (reconstructed tracks).
- Inefficiency due to clusters with overflow for heavy low-momentum particles.
- For lighter particles, efficiency = 1.

Fraction of clusters with overflow: pions vs He4, $2\,\mathrm{AGeV}$

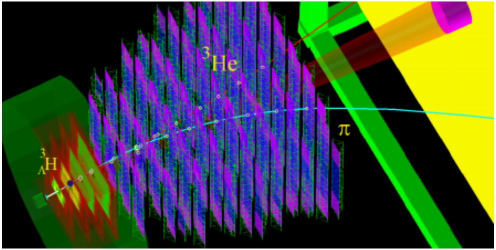


All particle and fragments in the same amount, $10\,\mathrm{AGeV}$



Using dE/dx technique for hypernuclei reconstruction

Background: 5×10^6 central Au+Au events at $10\,\mathrm{AGeV}$ generated with UrQMD.
Signal: ${}^3_\Lambda H \to {}^3He\,\pi^-$ with the thermal momentum distribution from Au+Au collisions at $10\,\mathrm{AGeV}$ normalised to 5×10^6 central Au+Au events.
$c\tau$ of ${}^3_\Lambda H$ is $5\,\mathrm{cm}$;
Signal — Gaussian, background — parabola;
S/B is calculating in $\pm 2\sigma$;
Background mainly p misidentified as He3.



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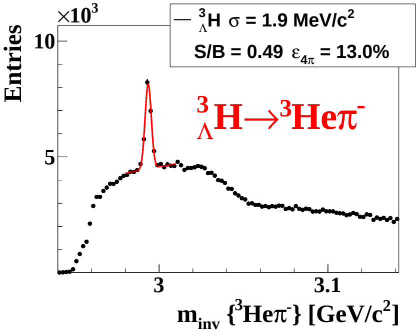
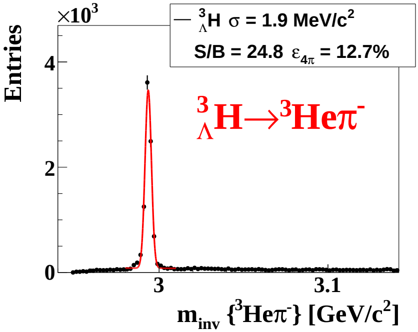
Time-Of-Flight



Time-Of-Flight + STS



Using dE/dx technique for hypernuclei reconstruction

Background: 5×10^6 central Au+Au events at $10\,\mathrm{AGeV}$ generated with UrQMD.
Signal: ${}^3_\Lambda H \to {}^3He\,\pi^-$ with the thermal momentum distribution from Au+Au collisions at $10\,\mathrm{AGeV}$ normalised to 5×10^6 central Au+Au events.