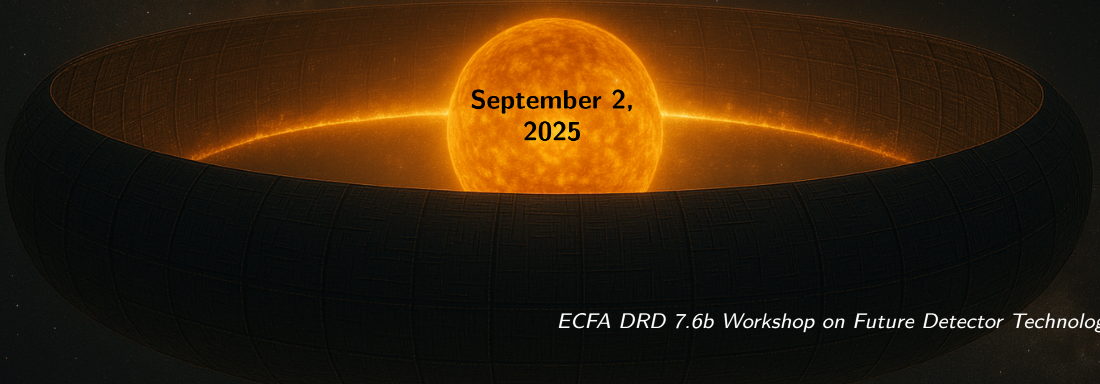
Upgrade of the CBM Tracker and Future Requirements

Maksym Teklishyn for the CBM Collaboration

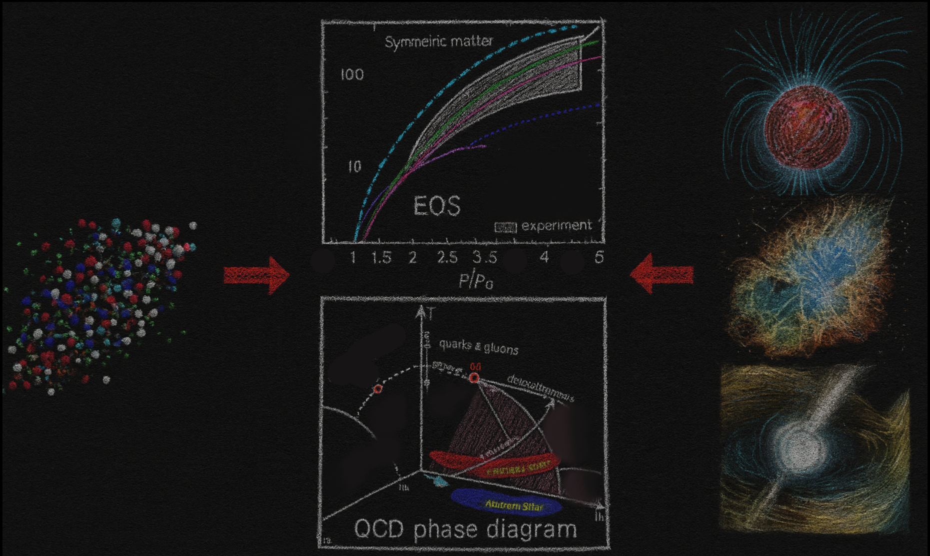
GSI Helmholtzzentrum für Schwerionenforschung GmbH (Germany)



September 2, 2025

ECFA DRD 7.6b Workshop on Future Detector Technologies

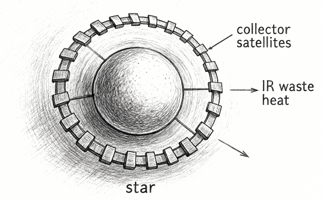
Nuclear matter at neutron star density



Compressed Baryonic Matter: a neutron star in the lab

Kardashev scale classifies civilisations by usable power P (in watts)
N. S. Kardashev, Soviet Astronomy 8 (1964) 217. :

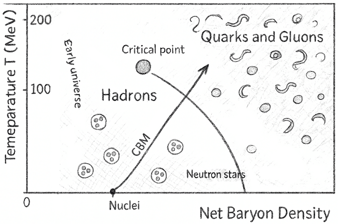
- **Type I** Planetary scale $\sim 10^{16} - 10^{17}$ W
- **Type II** Stellar scale $\sim 10^{26}$ W
  Dyson sphere F. J. Dyson, Science 131 (1960) 1667.
  - complex piece of engineering
  - captures most stellar output



- **Type III** Galactic scale $\sim 10^{36}$ W

Neutron star–like matter with heavy-ion collisions:

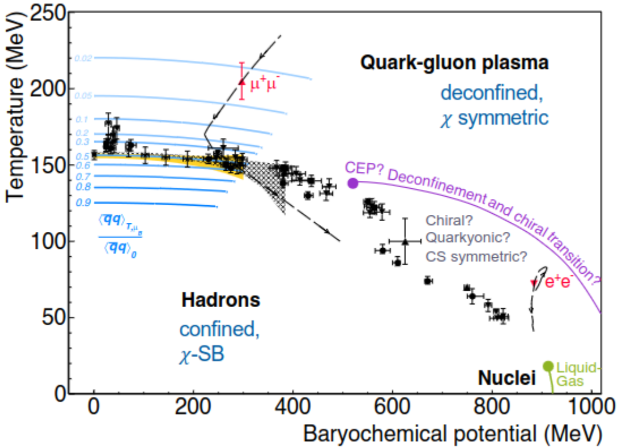
- CBM @ SIS100 at FAIR for high baryon density



- Rare probes:
  - charm, dileptons, multi-strange hyperons

- "Dyson sphere" to catch them all — CBM detector

Searching for landmarks of the QCD matter phase diagram



T. Galatyuk CPOD 2024

Experimental challenges:

- Isolate unambiguous signals of new phases of QCD matter, order of phase transitions, conjectured QCD critical point
- Probe microscopic matter properties

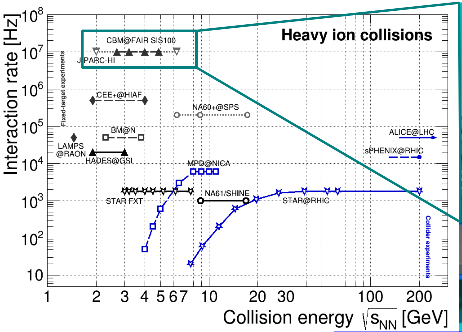
Measure with utmost precision:

- Light flavour (chemistry, vorticity, flow)
- Event-by-event fluctuations (criticality)
- Dileptons (emissivity)
- Charm (transport properties)
- Hypernuclei (interaction)

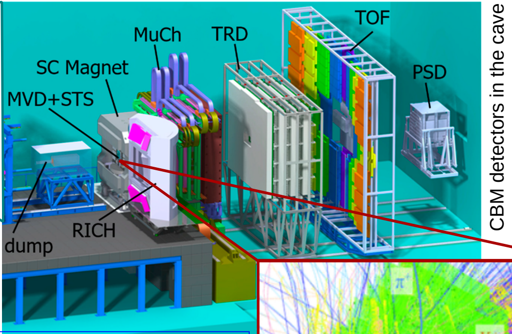
Almost unexplored (not accessible) so far in the high μ_B region

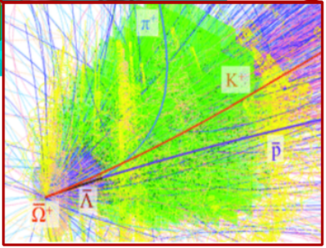
CBM detector

N. Herrmann EPJ Web Conf. 259 (2022)



T. Galatyuk, NPA 982 (2019), update 2022

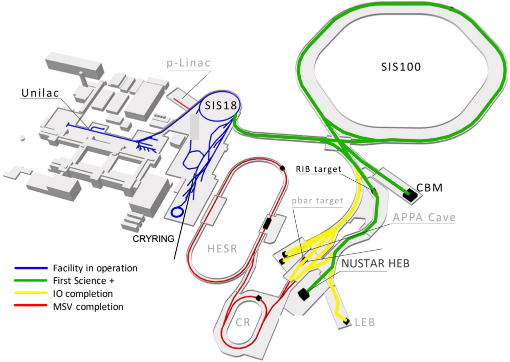


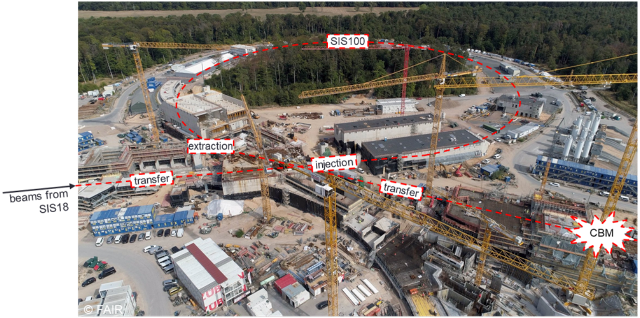


- CBM aims for precision measurement of rare and penetrating probes
- Unprecedented beam-target interaction up to $10\,\mathrm{MHz}$
- Challenges for detectors:
  - hundreds tracks in aperture /interaction, high occupancy
  - low momenta $\rightarrow$ low material budget

Facility, accelerator, and infrastructure

Facility for Antiproton and Ion Research: exploring new frontier



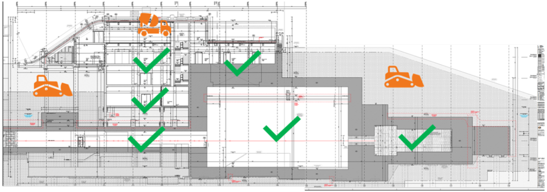


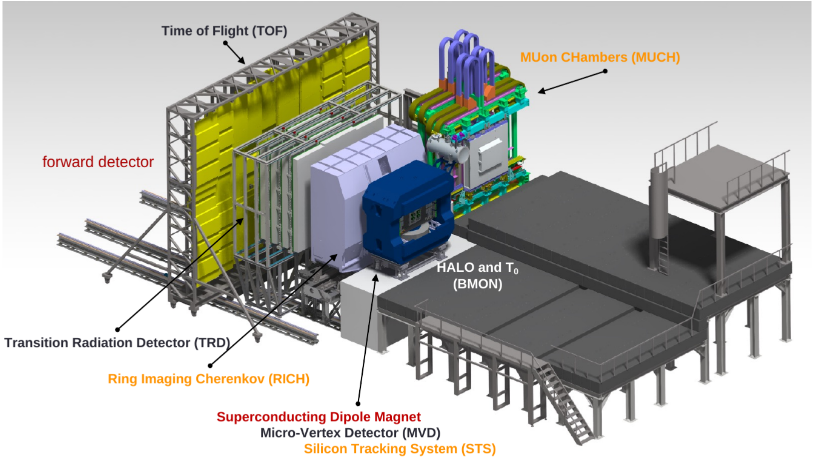
- Located in Darmstadt, Germany, FAIR is one of the largest projects for basic research in physics worldwide.
- The facility will provide particle beams with unprecedented intensity and quality.
- Research at FAIR will cover areas such as nuclear structure, nuclear astrophysics, hadron physics, and atomic physics.
- International collaboration with scientists from more than 50 countries.

Compressed Baryonic Matter experiment

- Heavy-ion experiment, first at the beam line: CBM
  - CBM stands for Compressed Baryonic Matter
  - It is designed to explore the properties of nuclear matter at high densities.
  - The experiment aims to study the behavior of matter under extreme conditions, similar to those in neutron stars
- Relativistic heavy-ion beams: gold up to $11\,A$GeV, lighter ions up to $14\,A$GeV
  - gold ions are used because they provide a large number of nucleons for collision experiments
  - lighter ions provide complementary information
- Beam intensity up to 10^9 ions/s
  - high beam intensity allows for the exploration of rare processes





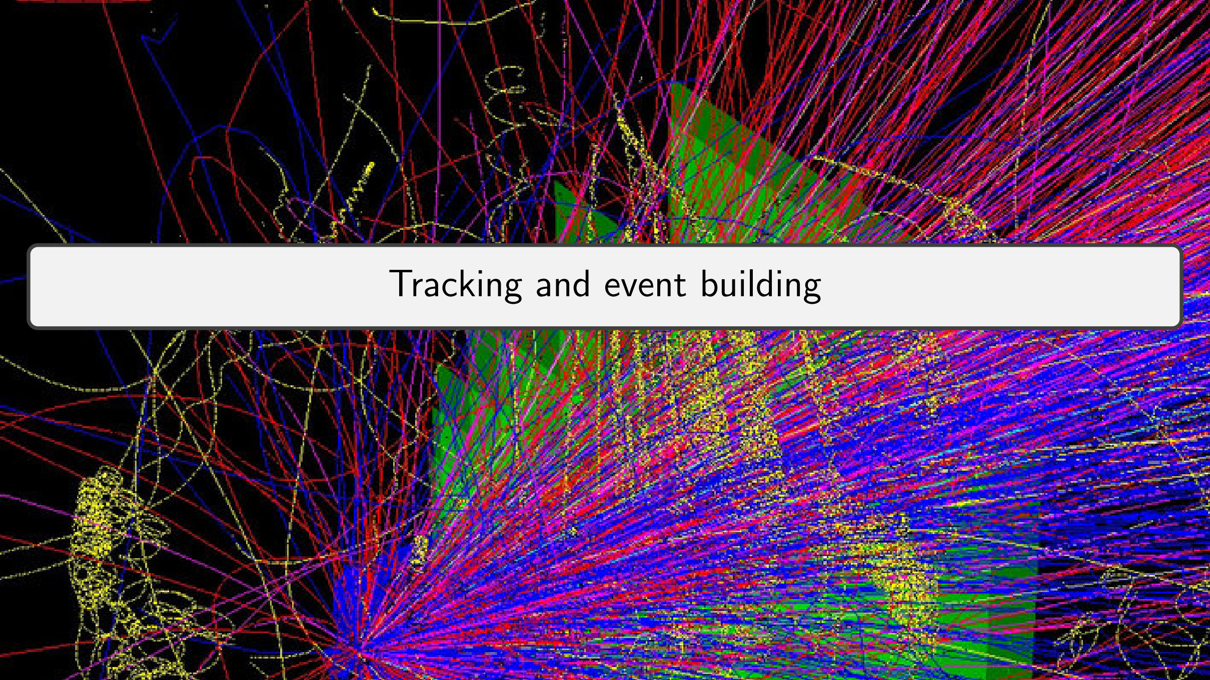


Experimental complex and infrastructure: cave, magnet, mechanics

Tracking and vertexing: Silicon Tracking System and Micro-Vertex Detector

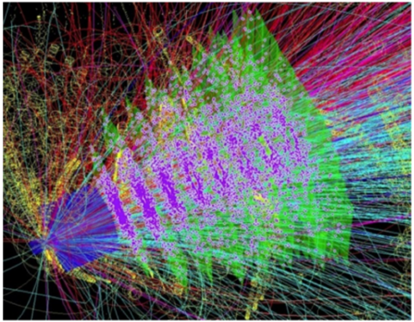
Event geometry determination: forward detector

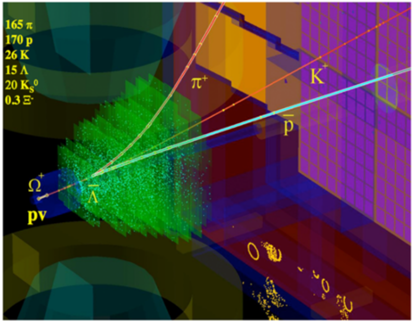
Global tracking and particle identification: RICH, TRD, ToF, MUCH



Tracking and event building

Challenging reconstruction and tracking environment

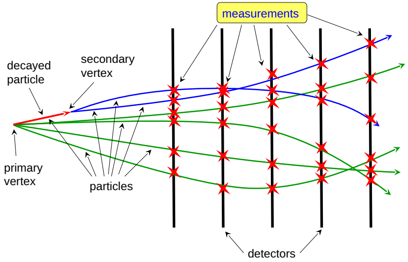


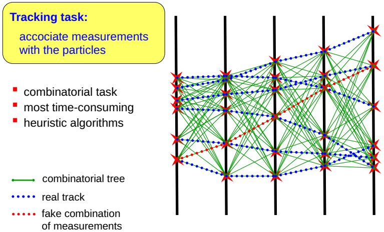


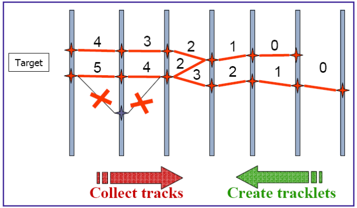
- $\lesssim 700$ charge particle tracks in the detector per $11\,A\mathrm{GeV}$ Au-Au collision
- Continuous beam, free-streaming detector operation
- Complex decay chains within the tracker

  Ω decay examples: $\Omega^+ \to \bar{\Lambda}(\to \pi^+ \bar{p})K^+$,
  $\Omega^+ \to \bar{\Xi}^0(\to \pi^+ \bar{\Lambda})\pi^+ \ldots$
- On-line event reconstruction and selection: data being fed non-stop to the computing farm

Tracking task: consequences for the tracker design



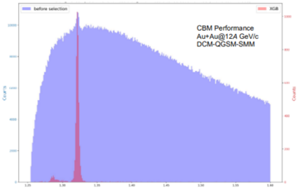




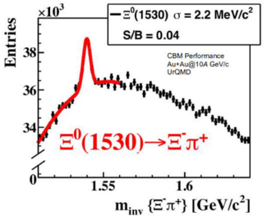
- Challenging track reconstruction in dense environment
  - high granularity, timing information
  - robust algorithms, online reconstruction
- Complex decay chains within the tracker
- Light detector $\not\Leftrightarrow$ fast read-out

On-line reconstruction algorithms for the CBM and ALICE experiments, S. Gorbunov

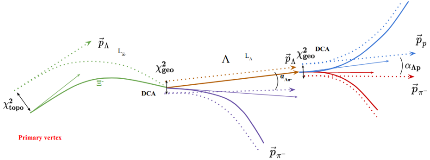
Reconstruction of complex topologies



invariant mass of Ξ⁻ candidates

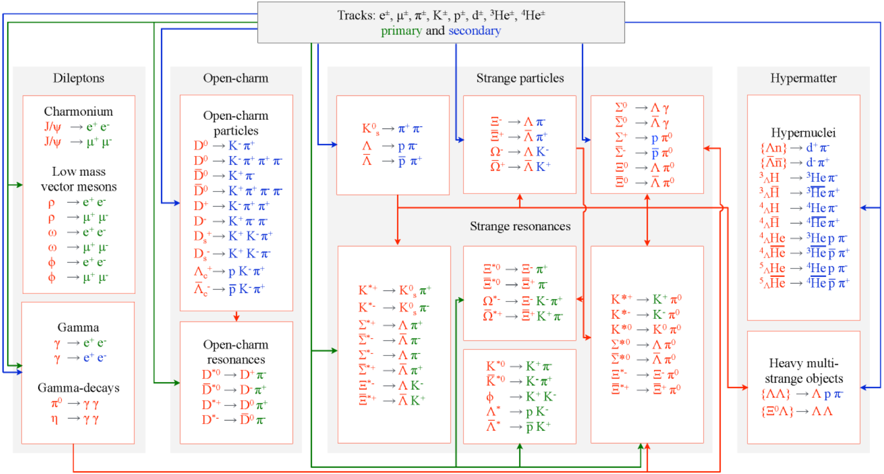


M. Zyzak, PhD thesis @ UFra, 2016



- Global tracking covering extended decays (MVS/STS $\longrightarrow$ MUCH/TRD $\longrightarrow$ ToF)
- Particle identification: electrons (RICH, TRD), hadrons (ToF), muons (MUCH)

KF Particle Finder

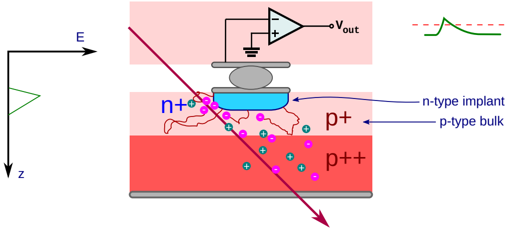


PhD thesis Maksym Zyzak

CBM Tracker construction

How to make a silicon detector

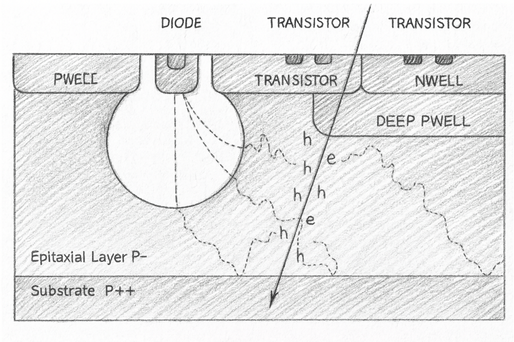
1. Take a silicon diode
2. Do few modifications as we will collect charge carriers using diffusion:
   - invert type to collect electrons in diode field
   - make it thinner, add low-ohmic p-substrate
   - smaller implant for lower capacitance



3. Add r/o electronics...

Monolithic Active Pixel Sensors (MAPS)

- R/o electronics integrated in the same chip
  - P/NWELLs needed for transistors
  - analogue and digital circuits on the same crystal



- Low material budget, easier integration, pixel size of $\mathcal{O}(10 \times 10\,\mu\mathrm{m}^2)$

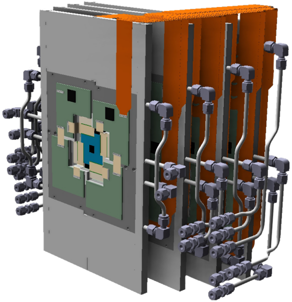
MVD: ultra-light detector for precise vertex determination

Micro Vertex Detector (MVD) for the CBM experiment at GSI/FAIR:

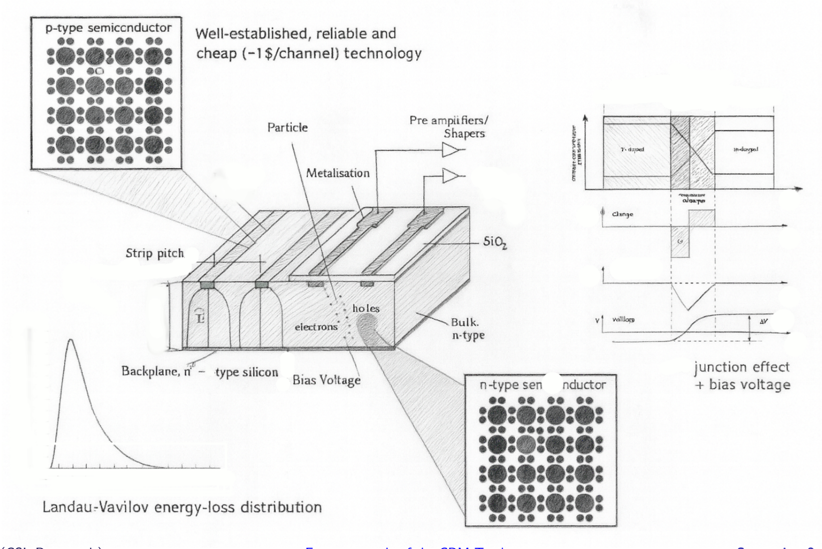
- Secondary vertex determination ($\simeq 50\,\mu\mathrm{m}$), background rejection in di-electron spectroscopy, reconstruction of weak decays
- Vacuum/magnetic field operation
- 4 stations
- $\simeq 300$ CMOS sensors
- Radiation tol* (non-ion): $> 7 \times 10^{13}\,\mathrm{neq/cm^2}$
- Radiation tol* (ionizing): $\simeq 5\,\mathrm{Mrad}$
- Power consumption: $40 - 70\,\mathrm{mW/cm^2}$

Quadrant (smallest functional unit):

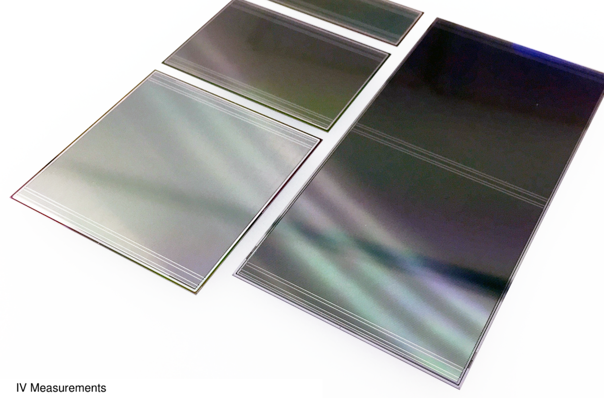
- CVD Diamond / TPG carrier for heat evacuation
- CMOS pixel sensors: $\simeq 5\mu s$ read-out
- Aluminum heat-sink (actively cooled)



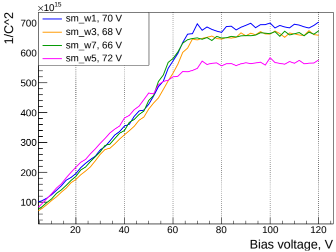
Silicon micro-strip detectors

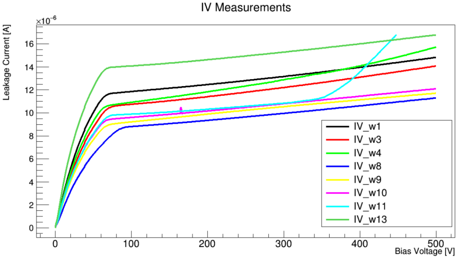


DSDM silicon micro-strip sensors



- Double sided n-type silicon sensors (XY positioning): 1024 strips each side, p-side tilted by 7.5° to the edge
- **Thickness** $320\,\mu\mathrm{m}$ $\pm 15\,\mu\mathrm{m}$
- **Pitch size** $58\,\mu\mathrm{m}$ for both sides
- $62\,\mathrm{mm} \times 22\,\mathrm{mm}$, $42\,\mathrm{mm}$, $62\,\mathrm{mm}$ or $124\,\mathrm{mm}$
- Strip coupling capacitance (n) $14.1 \pm 0.1\,\mathrm{pF/cm}$ interstrip capacitance $0.37 \pm 0.01\,\mathrm{pF/cm}$





nXYTER: ASIC that measures time and amplitude

- nXYTER was a dedicated ASIC for (ToF and Imaging) neutron detectors
  - one of applications: double-sided Silicon micro-strip detector
    (coupled to a Gadolinium neutron-converter layer)

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Nuclear Instruments and Methods in Physics Research A 568 (2006) 301–308

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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N-XYTER, a CMOS read-out ASIC for high resolution time and amplitude measurements on high rate multi-channel counting mode neutron detectors

A.S. Brogna[d], S. Buzzetti[a,*], W. Dabrowski[b], T. Fiutowski[b], B. Gebauer[c], M. Klein[d], C.J. Schmidt[d], H.K. Soltveit[d], R. Szczygiel[b,e], U. Trunk[d]

nXYTER: ASIC that measures time and amplitude

- nXYTER was a dedicated ASIC for (ToF and Imaging) neutron detectors
  - one of applications: double-sided Silicon micro-strip detector
    (coupled to a Gadolinium neutron-converter layer)
  - two paths after CSA: slow (amplitude) and fast (time)

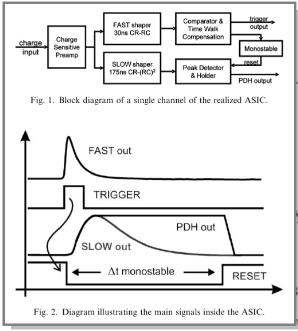
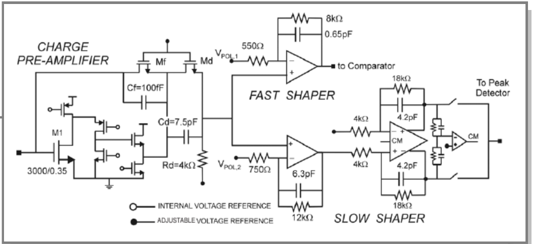
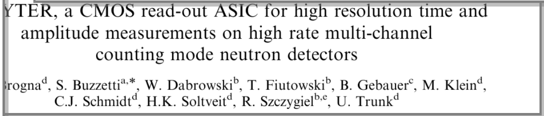


Fig. 1. Block diagram of a single channel of the realized ASIC.

Fig. 2. Diagram illustrating the main signals inside the ASIC.





YTER, a CMOS read-out ASIC for high resolution time and amplitude measurements on high rate multi-channel counting mode neutron detectors

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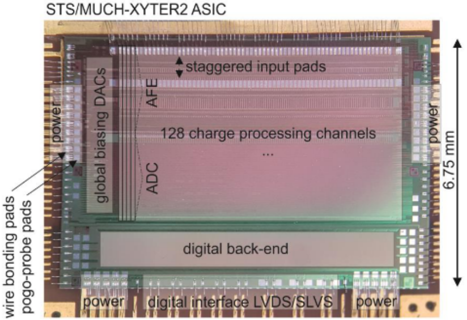
- Analogue memory, external ADC required

Latest Generation: STS-MUCH-XYTER v 2.2

Features of the ASIC:

- Low-power, self triggering AISC
- 128 channels + 2 test channels
- Time resolution $\lesssim 5\,\mathrm{ns}$
- Provides digitized hits with:
  - 5 bit energy resolution
  - 14 bit time stamp
- Linearity range up to $15\,\mathrm{fC}$ $(100\,\mathrm{fC})$
- **Flash ADC + digital buffer** integrated in ASIC



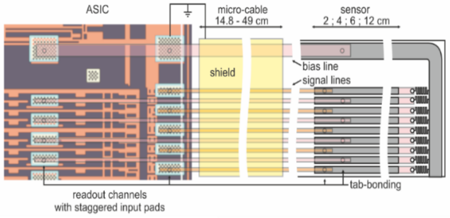
K. Kasinski *et al* Nucl.Instrum.Meth.A 908 (2018)

Current status:

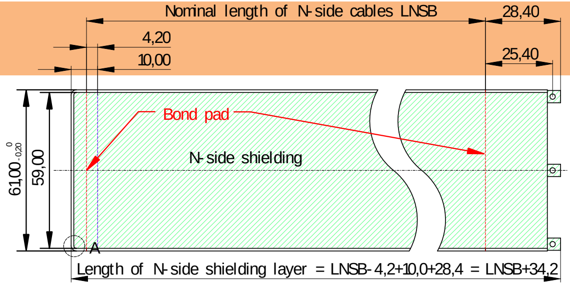
- ASIC production yield 98.5%–99.0%, chip cable yield 96%
- **production:** ~ 4000 available for series module production
- 360 dies per wafer, 100 wafers produced

Ultra-thin r/o micro cables

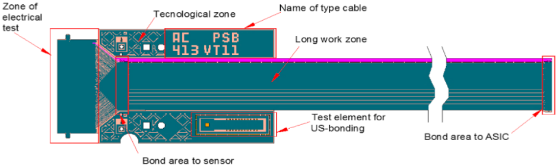
- FEE connected via micro-cable lines (64 lines/cable)

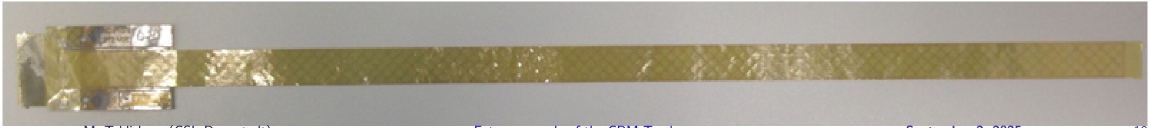


- 2×1024 ch./sensor: stack of 32 micro cables per module, 8 sub types
- Length from 160 mm to 495 mm



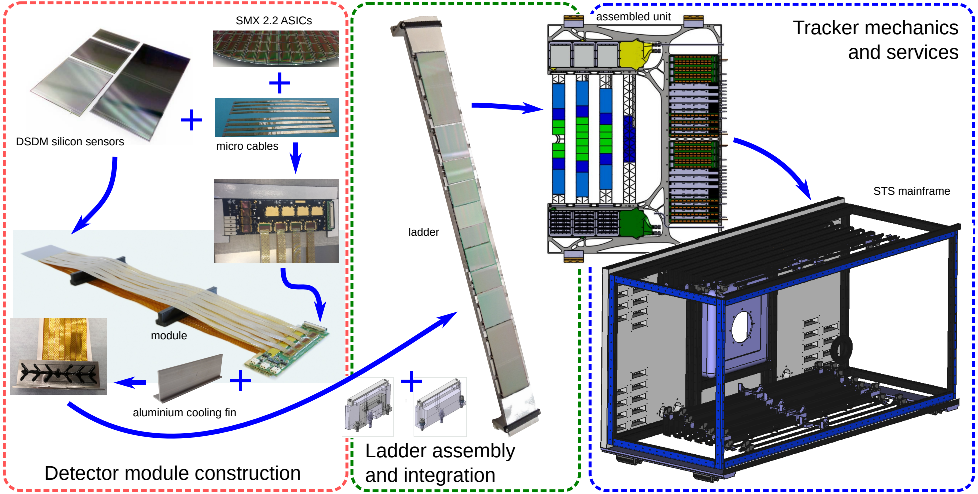
↗ Read-out lines are protected w/ shielding layers



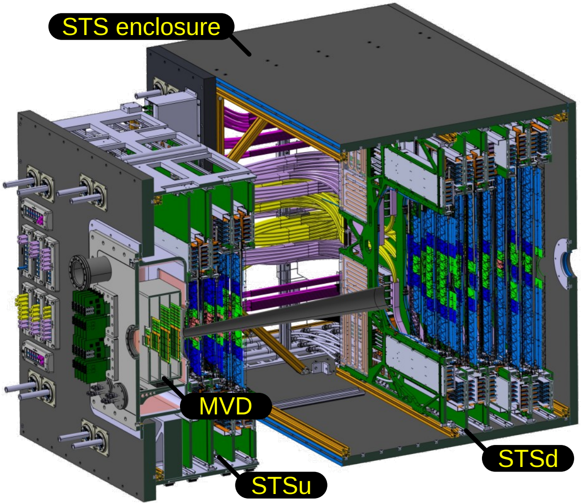


Silicon Tracking System

assembly sequence and structure



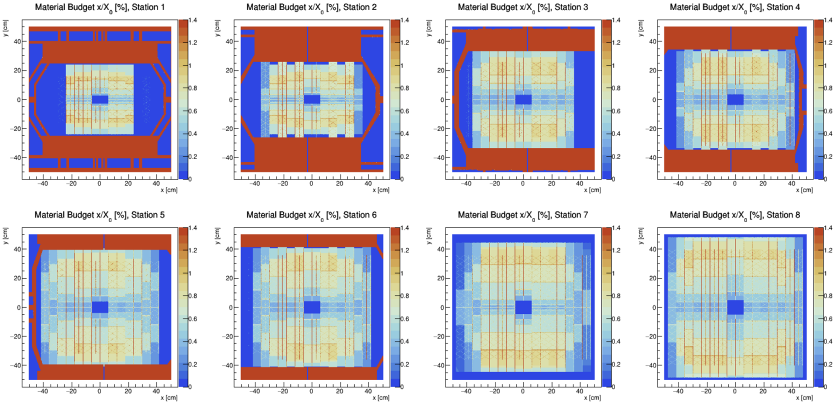
Modular design of the CBM Tracker: MVD + STSu + STSd



Simulation of the detector performance

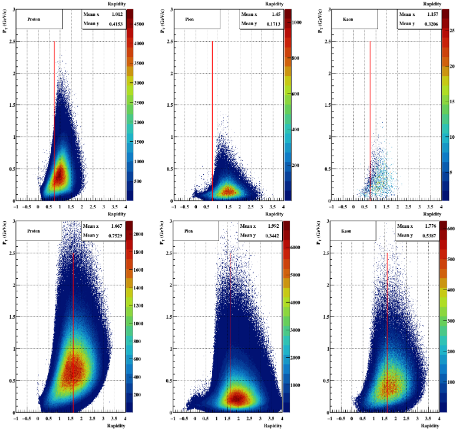
material budget

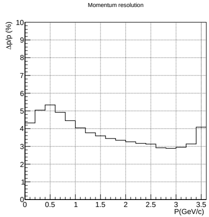
- Down to $0.3\%\,X_0$ per layer around the bending plane,
- No more than $1\%\,X_0$ at the periphery

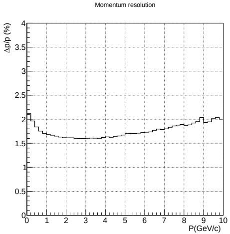


Simulation of the detector performance

acceptance and momentum resolution







- Au target with $2\,\mathrm{GeV}/c$ Au beam (upper row), $12\,\mathrm{GeV}/c$ Au beam (bottom row)

Can we do better?

considerations for the future CBM Tracker Upgrade

What's on the menu?

a better momentum resolution (in current design $\Delta p/p \approx 1.5\%$)

- precise resolution in bending plane (now $58\,\mu\mathrm{m}$ strip pitch)
- stronger magnetic field (now up to $1\,\mathrm{Tm}$)
- longer detector base (now for STS only: $(8-1) \times 105\,\mathrm{mm} = 735\,\mathrm{mm}$)
- smaller material budget to reduce the multiple scattering

b finer granularity (presently, strip length from $20\,\mathrm{mm}$ to $122\,\mathrm{mm}$)

- finer segmentation: resolution in the vertical plane (now by factor 10 worse than in the bending plane)

c more tracking stations for better tracking, complex topologies, secondary vertexes

d smaller dead time (about $300\,\mathrm{ns}$ with present FEE)

e wider acceptance: angular coverage

f better timing (now $\Delta t \approx 5\,\mathrm{ns}$)

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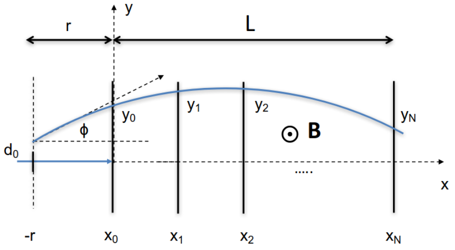
How do we achieve it?

We can do it!
(although not all of that and not at once)

Upgraded detector performance

analytical expressions for the momentum resolution

- Multiple options/configurations; what is important?
- We need to develop and intuition before extensive simulations
  - analytical expression for the simplified geometry:



$$\left.\frac{\Delta p}{p}\right|_{\text{res.}} = \frac{\sigma p}{0.3BL^2}\sqrt{\frac{720N}{(N-1)(N+1)(N+2)(N+3)}},$$

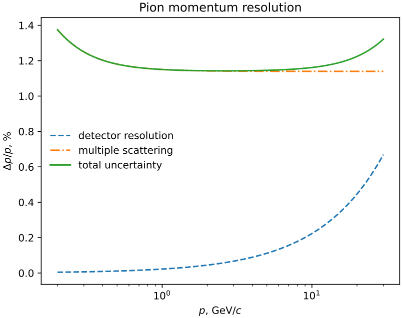
$$\left.\frac{\Delta p}{p}\right|_{\text{scat.}} = \frac{N}{\sqrt{(N+1)(N-1)}} \cdot \frac{0.0136\ \text{GeV/c}}{0.3\beta BL} \cdot \sqrt{\frac{d_{\text{tot}}}{X_0}} \cdot \left(1 + 0.038 \ln \frac{d}{X_0}\right),$$

where $\beta = \sqrt{p^2/p^2 + m^2}$

Z. Drasal, W. Riegler DOI:10.1016/j.nima.2018.08.078

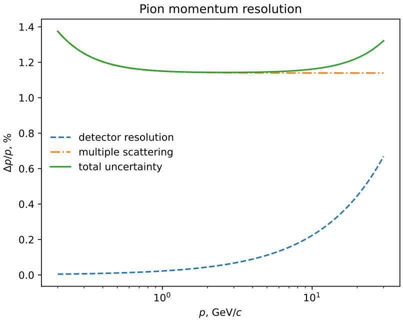
Upgraded detector performance: number of layers

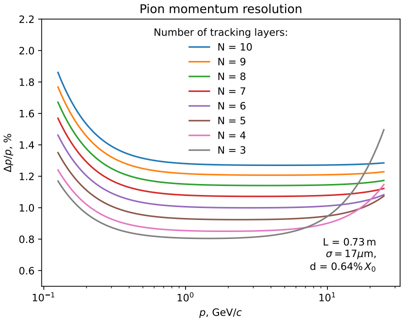
- STS momentum uncertainty is dominated by multiple scattering
  - $\propto \sqrt{d_{\text{tot}}}$ less material would help
  - $\propto 1/\beta$ more relativistic is a particle $\Rightarrow$ less it is affected by it
  - relation to the number of stations?



Upgraded detector performance: number of layers

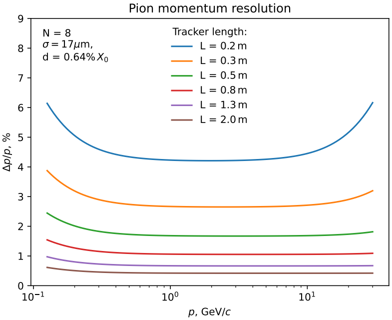
- STS momentum uncertainty is dominated by multiple scattering
  - $\propto \sqrt{d_{\text{tot}}}$ less material would help
  - $\propto 1/\beta$ more relativistic is a particle $\Rightarrow$ less it is affected by it
  - relation to the number of stations?
- More tracking stations do not help (at our energies)

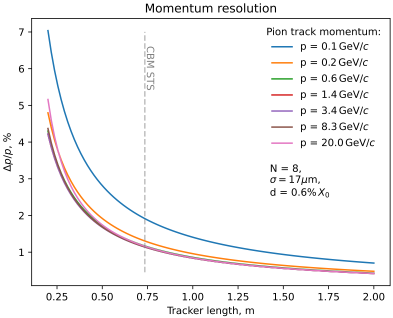




Upgraded detector performance: tracker length

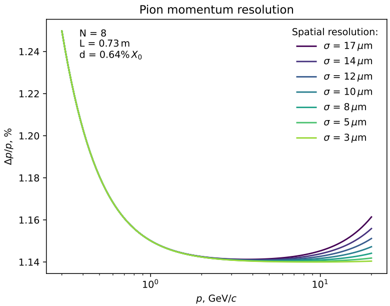
- Long tracker = good tracker
  - $\propto 1/L$ for low-momentum non-relativistic particles
  - $\propto 1/L^2$ for higher momenta
  - silicon surface $\propto L^3$ (challenge for the integration with low material)
    - number of tracking layer should also increase
- No clear benefit of making CBM Tracker longer, but clear disadvantage to make it shorter!

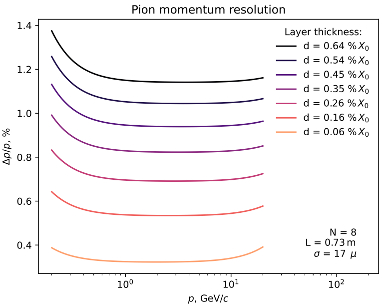




Upgraded detector performance with $N = 8$

- Limited benefit from better resolution
- Huge improvement with reduced material (integration?)

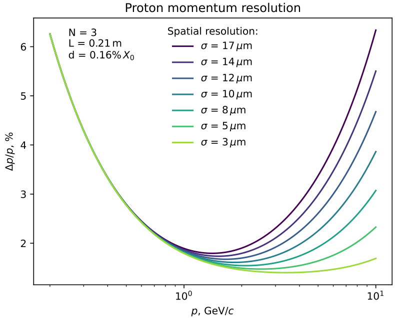


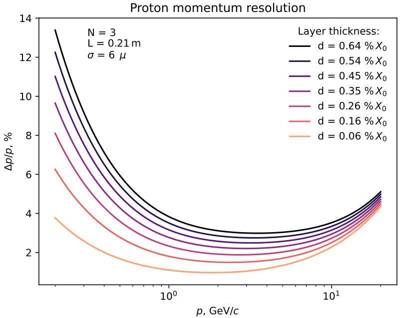


- Enormous challenge for mechanics. r/o, cooling for
  - $\mathcal{O}(1\,\mathrm{m}^2)$ layer surface
  - $\mathcal{O}(1‰)$ layer thickness

Upgraded detector performance with $N = 3$

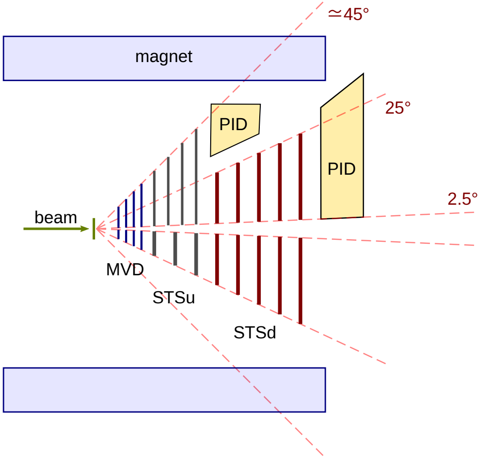
- Reduced material budget can compensate to shorter base and fewer stations
- More realistic integration in the Upstream STS (first 3 stations)?
  - ✓ easier to implement wider acceptance
  - ✓ benefit from higher granularity
  - ✓ lower momenta ⇒ less material





Vision of the Upgraded CBM Tracker

- Magnet aperture and STS enclosure are natural constraints
- Modular Tracker design allows for gradual replacement
  - staged upgrade: STSu + extra PID, MVD, STSd...
- MAPS at STSu: wider acceptance, lower material
  - search for a suitable technology
  - integration will be the main challenge
  - additional PID detectors to cover wider angles
- Better $p_T - y$ coverage for lower beam energies
- Higher granularity with MAPS, better resolution in vertical plane
  - improved rate tolerance
  - better reconstruction of cascade decays



Sensor targets for CBM upgrades

STS upgrade:

- Spatial resolution: 10 μm
- Time binning: 10 ns
- Radiation hardness: 2×10^{14} n_{eq}/cm^2, 17 Mrad/year
- Interaction rate: 10 MHz/cm^2 + margin
- Power density: 50 mW/cm^2

MVD upgrade:

- Spatial resolution: 5 μm
- Time binning: 10 ns
- Radiation hardness: 1×10^{15} n_{eq}/cm^2, 50 Mrad/year
- Interaction rate: 90 MHz/cm^2 + margin
- Power density: < 100 mW/cm^2

Community effort in DRD3 (MANTA, OCTOPUS)

- Shared R&D with ALICE, ILC/FCC, medical/industrial applications
- Versatile MAPS design configurable by slow control

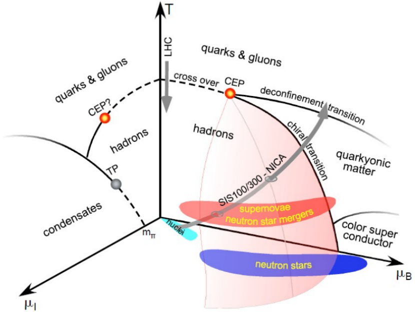
Conclusions and outlook

- CBM physics goal: explore nuclear matter at highest baryon densities
  - Laboratory access to neutron star–like conditions
  - Rare probes: charm, dileptons, multi-strange hyperons
    - light-weight, high-granularity tracker
    - reconstruction of cascade decays in the detector
- Detector upgrades essential
  - STS: extended acceptance, light MAPS stations, 10 μm / 10 ns
  - MVD: rate $\times 10$, improved time stamping, 50 μm vertexing
- Next-generation MAPS sensors are key
  - High granularity and fast timing
  - Radiation hardness up to 10^{15} n_{eq}/cm^2, 50 Mrad
  - Ultra-low material budget — advances in integration required
- Collaboration efforts are essential: DRD3, DRD7, DRD8

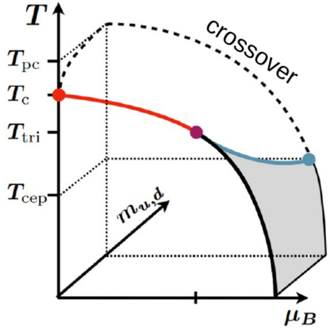
Back-up slides

Exploration of the QCD phase diagram

State of the nuclear matter depending on baryochemical potential (μ_B), isospin symmetry (μ_I) and temperature (T)



lQCD, F. Karsch, arXiv:1905.03936



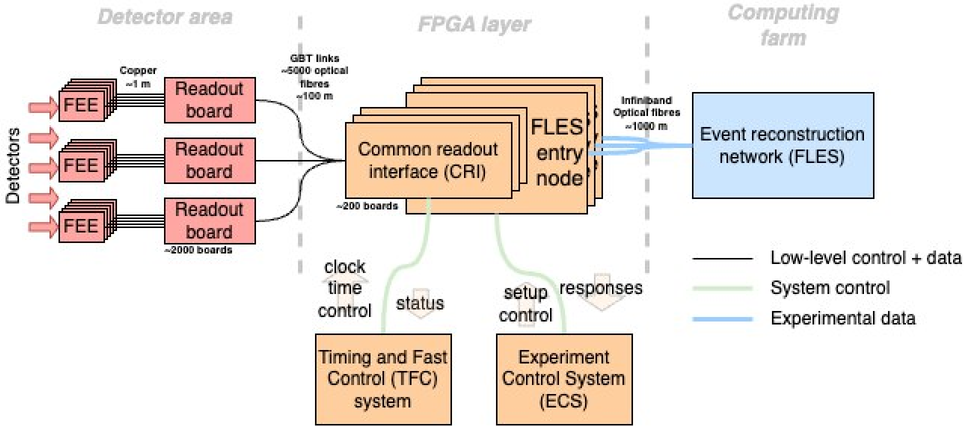
$T_{pc} = 156.5 \pm 1.5\,\mathrm{MeV}$ at $\mu_B = 0$

$T_{\text{cep}} < T_c^0 = 132^{+3}_{-6}\,\mathrm{MeV}$ (chiral limit)

Special interest: observation of the phase transition and finding the critical point

CBM DAQ chain

- CBM read-out operates with continuous beam in free-streaming mode
- Full online event processing



Momentum resolution of the tracker

Z. Drasal, W. Riegler DOI:10.1016/j.nima.2018.08.078

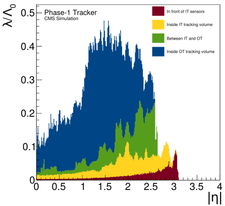
Momentum measurement precision:

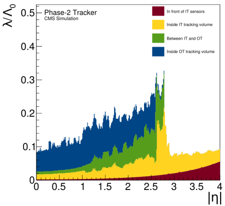
$$\left.\frac{\delta p}{p}\right|_{\text{res.}} = \frac{\sigma p}{0.3BL^2}\sqrt{\frac{720N}{(N-1)(N+1)(N+2)(N+3)}},$$

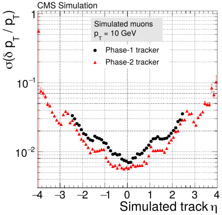
$$\left.\frac{\delta p}{p}\right|_{\text{scat.}} = \frac{N}{\sqrt{(N+1)(N-1)}} \cdot \frac{0.0136\ \text{GeV/c}}{0.3\beta BL} \cdot \sqrt{\frac{\lambda}{\Lambda_0}} \cdot \left(1 + 0.038 \ln \frac{d}{\Lambda_0}\right),$$

where $\beta = \sqrt{p^2/(p^2+m^2)}$

Example of the CMS Tracker Upgrade:

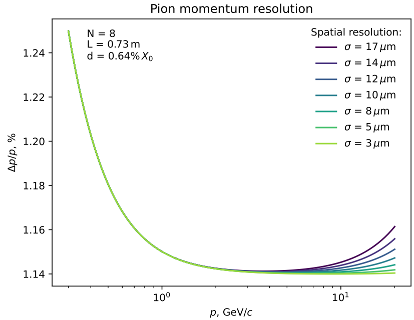


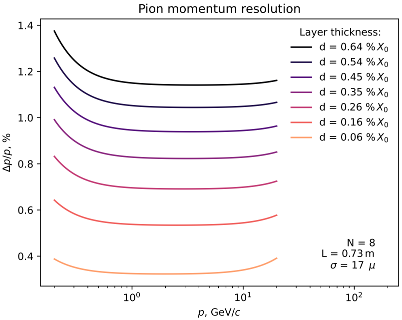




CBM Tracker momentum resolution

- Limited benefit from better resolution
- Huge improvement with reduced material (integration?)





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