COMPRESSED BARYONIC MATTER AT FAIR

CONSTRUCTION PROGRESS AND PROTOTYPE BEAM-TEST RESULTS

ALBERICA TOIA

UNI. FRANKFURT & GSI

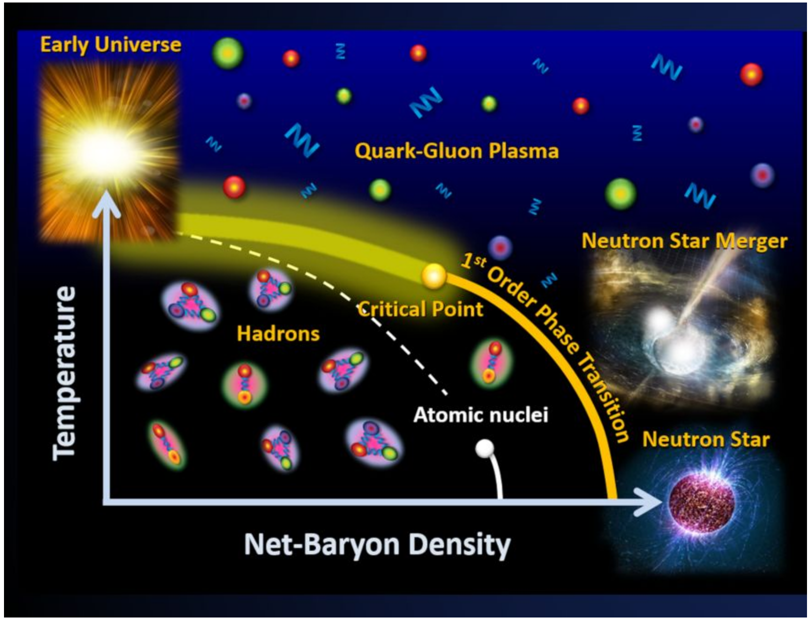
FOR THE CBM COLLABORATION

OUTLINE

- Exploring cosmic matter in the laboratory
  - the high-density nuclear matter equation-of-state
  - the QCD phase diagram
- The Facility for Antiproton and Ion Research
- The Compressed Baryonic Matter (CBM) experiment
  - physics potentials
  - construction progress
  - prototype beam-test results

62ND INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO, 19-23 JANUARY 2026

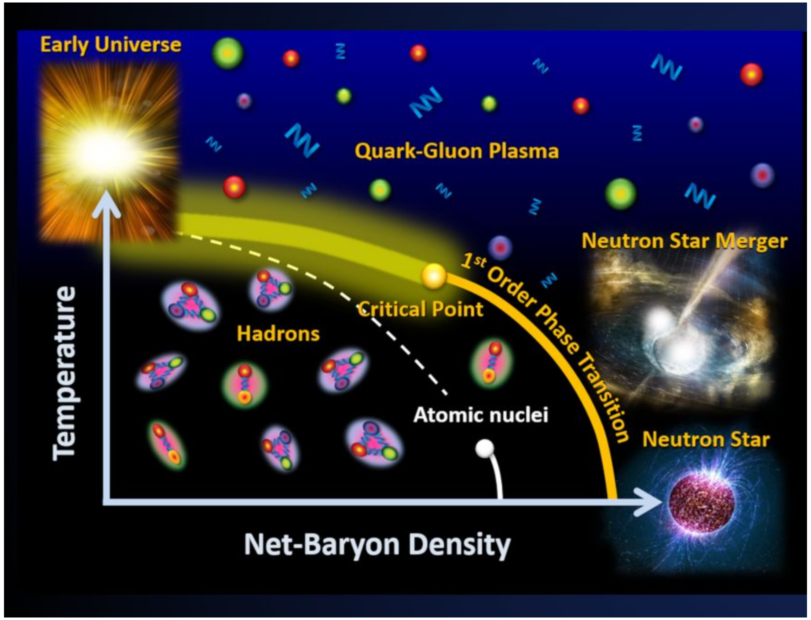
STRONGLY INTERACTING MATTER UNDER EXTREME CONDITIONS



Motivation and scope

- Strongly interacting matter, governed by **QCD**, exhibits qualitatively different phases at extreme **temperature (T)** and **baryon density (μ_B)**
- Fundamental questions:
  - Relevant degrees of freedom (hadrons ↔ quarks and gluons)
  - Restoration of chiral symmetry
  - Transport and thermodynamic properties
- These conditions occur naturally:
  - In the **early Universe** (high T, low μ_B)
  - In compact **neutron stars** and their **mergers** (low T, high μ_B)
- Heavy-ion collisions provide a unique experimental access under controlled laboratory conditions

THE QCD PHASE DIAGRAM



Organizing principle of nuclear matter and open questions

- QCD matter is commonly represented in the T–μ_B phase diagram, encoding its thermodynamic behavior

- Different regions correspond to distinct phases and degrees of freedom
- At low μ_B:
  - Smooth crossover from hadronic matter to Quark–Gluon Plasma

- At high μ_B:
  - Largely unexplored region
  - Possible first-order phase transition
  - Hypothesized QCD critical point

Key open questions at high μ_B:

- Order of the phase transition between hadronic and partonic matter
- Existence and location of a **QCD critical point**

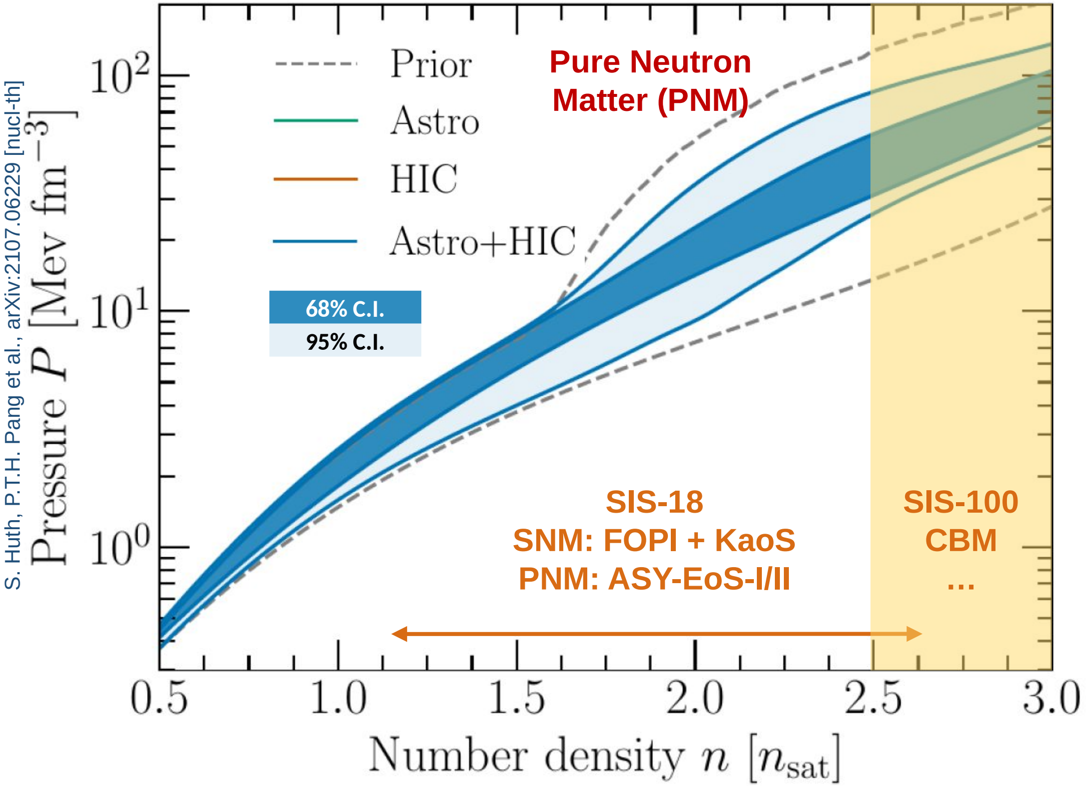
Phase boundaries and critical phenomena are reflected in:

- Discontinuities or softening of thermodynamic quantities
- Enhanced fluctuations and correlations

“While the phase diagram tells us where different forms of QCD matter exist...”

EQUATION OF STATE: FROM QCD TO ASTROPHYSICS

"... the equation of state tells us how matter responds when it is compressed, heated, or driven across phase boundaries."



From the phase diagram to observables

- The **Equation of State (EoS)** provides the quantitative thermodynamic input underlying the phase diagram
- It specifies how pressure, energy density and baryon density evolve across the diagram
- Determines key properties of dense matter

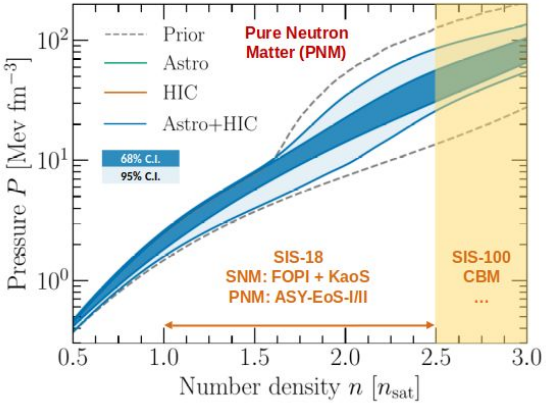
- **Phase transitions and critical phenomena manifest as:**
  - Changes in compressibility and speed of sound
  - Softening or stiffening of the EoS

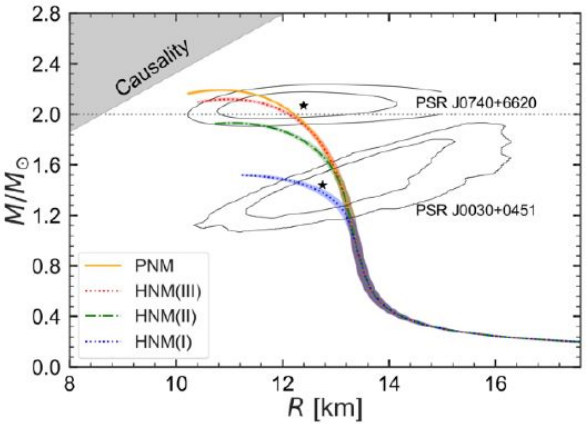
- **The same EoS governs:**
  - The evolution of heavy-ion collisions
  - The internal structure of neutron stars
  - The dynamics of neutron star mergers

- Constraining the EoS at high μ_B is therefore essential to connect QCD theory, experiments and astrophysical observations

FOPI:	Nucl. Phys. A 945, 112 (2016)	ASY-EOS-I:	Phys. Rev. C 94, 034608 (2016)
AGS, BEVALAC:	Science 298, 1592 (2002)	SπRIT:	Phys. Rev. Lett. 126, 162701 (2021)
KaoS:	Phys. Rev. Lett. 86, 39 (2001)		
	J. Phys. G 28, 1615 (2002)		

CONSTRAINING EQUATION OF STATE: NEUTRON STARS



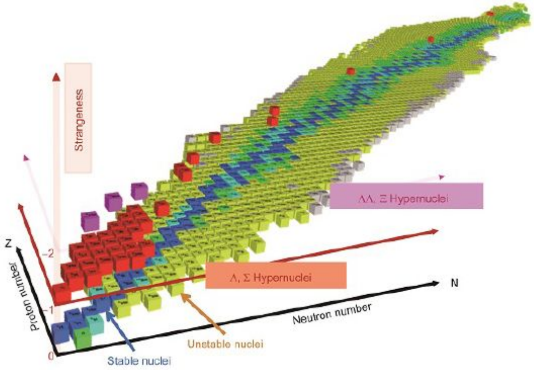


Mass and radius of neutron stars → constraints on the EoS

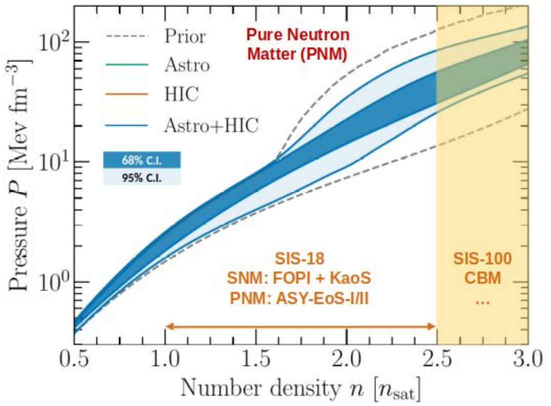
- Observations of neutron stars with masses of ≈ 2 M☉ place strong constraints on the stiffness of the Equation of State (EoS)
- At the densities reached in neutron-star cores (several times nuclear saturation density):
  - The appearance of hyperons (Y) is energetically favored
  - Conversion of nucleons (N) into hyperons reduces the Fermi pressure
- **Hyperon puzzle:**
  - Presence of hyperons softens the EoS
  - Softer EoS leads to a reduced maximum neutron-star mass
  - This is **in tension with the observed 2M☉ neutron stars**

Open question:
  - Can hyperons be present in neutron stars and still be consistent with observations?

Proposed resolution:
  - Additional repulsive contributions at high density, e.g. **many-body interactions** or repulsive hyperon–nucleon forces, leading to a **stiffer EoS**



Constraining Equation of State: Neutron Stars Mrgers and Heavy Ion Collisions



Complementary probes of dense QCD matter

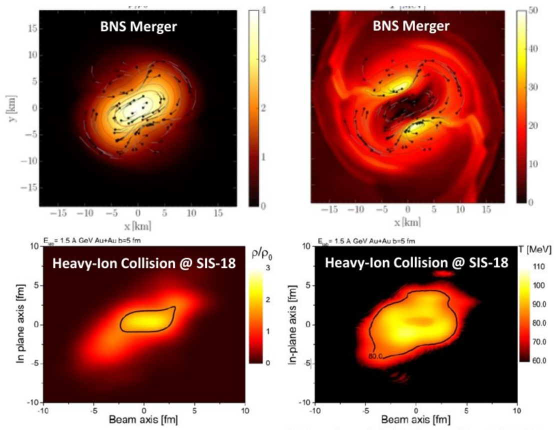
- The **Equation of State (EoS)** governs the behavior of strongly interacting matter over a wide range of **temperature** and **baryon density**
- **Neutron-star mergers** probe:
    - Very **high baryon densities**
    - Low to moderate temperatures
    - Constraints from gravitational-wave signals and post-merger dynamics

  (currently limited by statistics and model dependence)
- **Heavy-ion collisions (HIC)** probe:
    - Moderate to high baryon densities
    - Higher temperatures
    - Dynamical evolution with experimentally accessible observables

Density and temperature profile

Merger Binary System

Heavy Ion collision



M. Hanauske et al., 2017 J. Phys.: Conf. Ser. 878 012031

Current constraints on the EoS

- **Lower densities:**

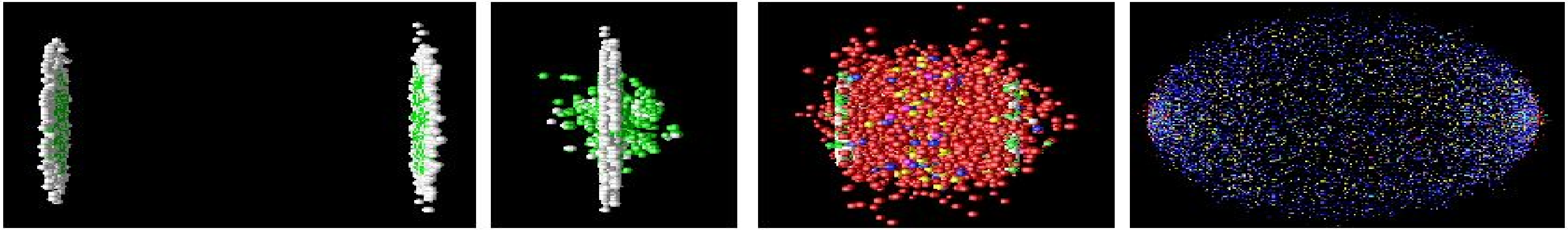
  HIC data favor a stiffer EoS
- **Higher densities:**

  Constraints mainly from astrophysics, but still limited and indirect
- **Intermediate densities:**

  HIC have large discovery potential

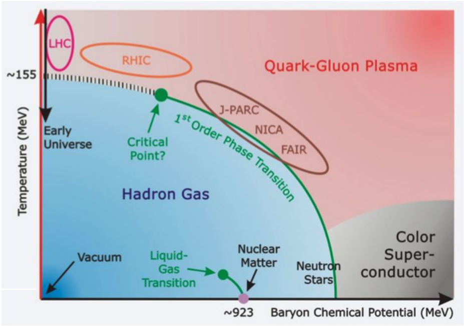
  Crucial region for phase transitions and changes in degrees of freedom

EXPERIMENTAL ACCESS TO PHASE DIAGRAM



Heavy Ion Collisions

- create hot and dense matter in the lab
- The properties of the initial state inferred from the properties of the particles in final state
- Observation: Freeze-out points map the phase diagram
- Variation of collision energy allows to study different regions



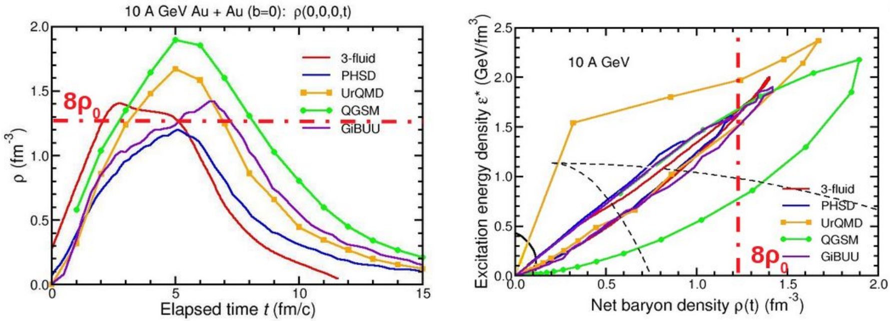
At very high temperature:

- N of baryons = N of antibaryons, similar to **early universe**
- L-QCD: at T_C ~155 MeV crossover transition hadronic matter → **QGP**
- LHC, RHIC

At high baryon density:

- N of baryons >> N of antibaryons, densities like in **neutron star cores**
- L-QCD not (yet) applicable, models predict phase transitions and exotic phases
- BES-RHIC, CERN SPS, FAIR, NICA

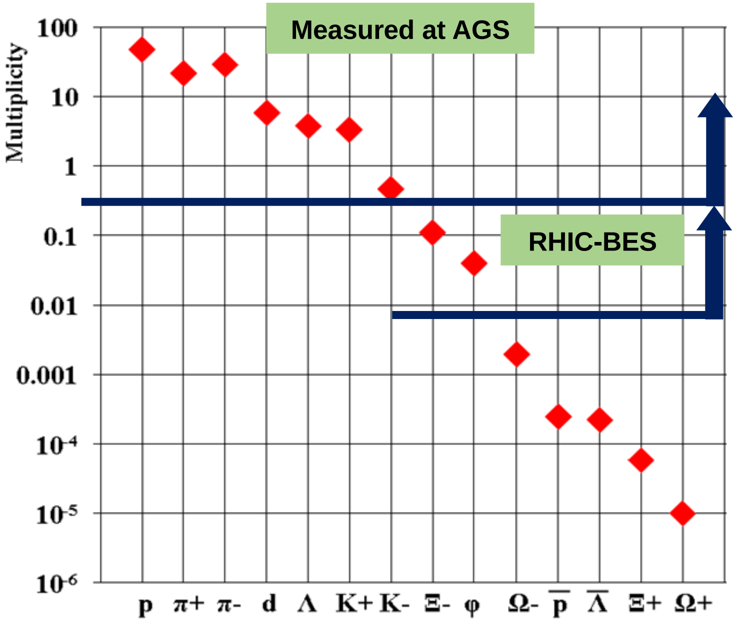
I. Arsene et al. PRC75 034902 (2007)



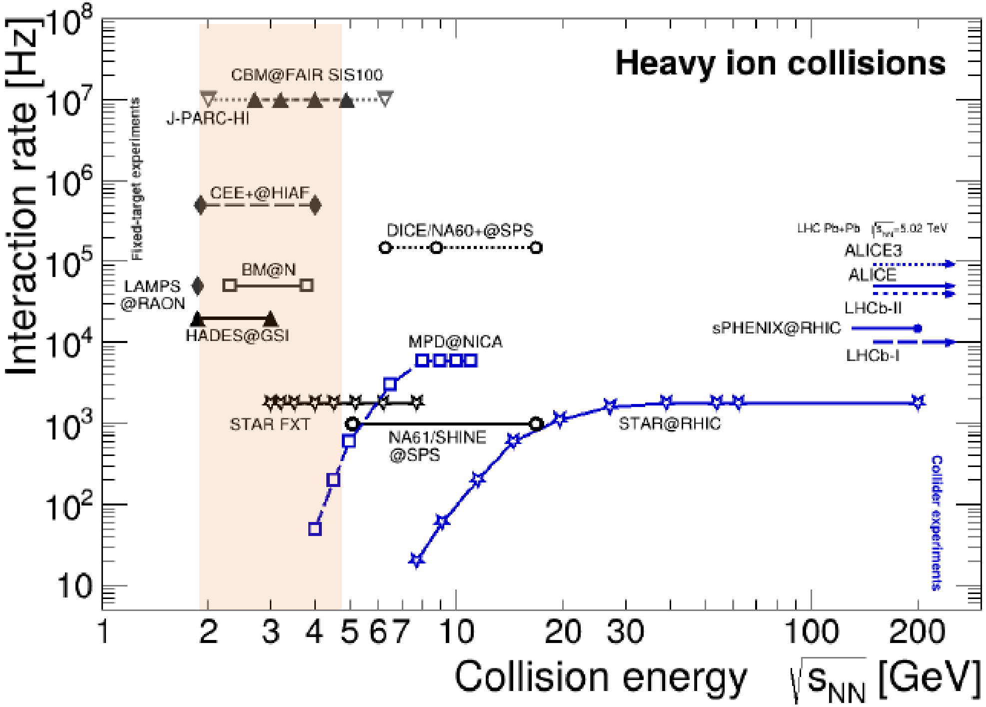
INTERACTION RATES AND EXPERIMENTAL REQUIREMENTS

Focus on high accuracy measurements of **rare/penetrating probes**
Requires high statistics/rates and excellent understanding of detector response

→ CBM‘s unique feature: **interaction rates up to 10 MHz!**



P. Senger, Phys.Scripta 96 (2021) 5, 054002

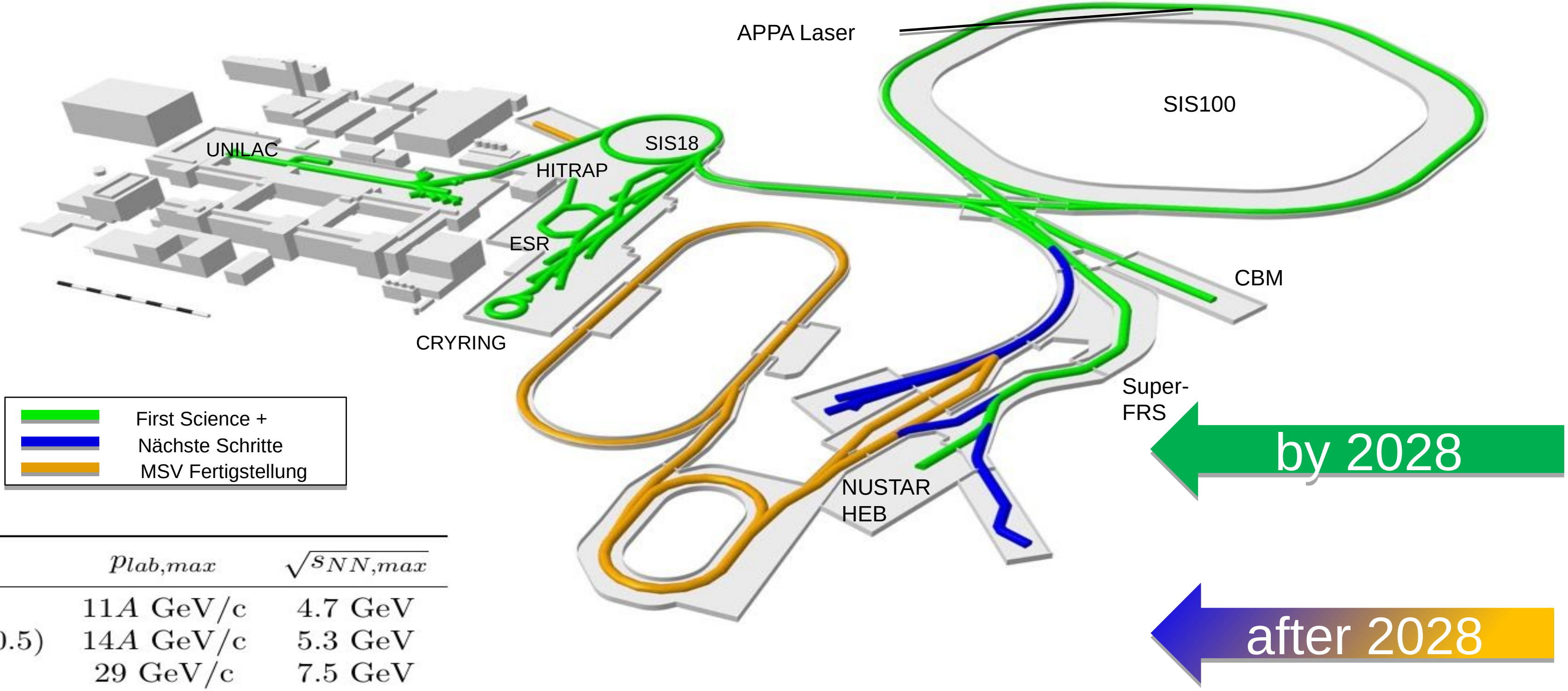


T. Galatyuk, Nucl.Phys.A 982 (2019)

FACILITY FOR ANTIPROTON AND ION RESEARCH (FAIR)

One of the largest worldwide project in fundamental science.

Forefront research in nuclear, hadron, atom, plasma, antimatter, and applied physics.



SIS 100 beams

Beam	$p_{lab,max}$	$\sqrt{s_{NN,max}}$
heavy ions (Au)	11A GeV/c	4.7 GeV
light ions ($Z/A = 0.5$)	14A GeV/c	5.3 GeV
protons	29 GeV/c	7.5 GeV

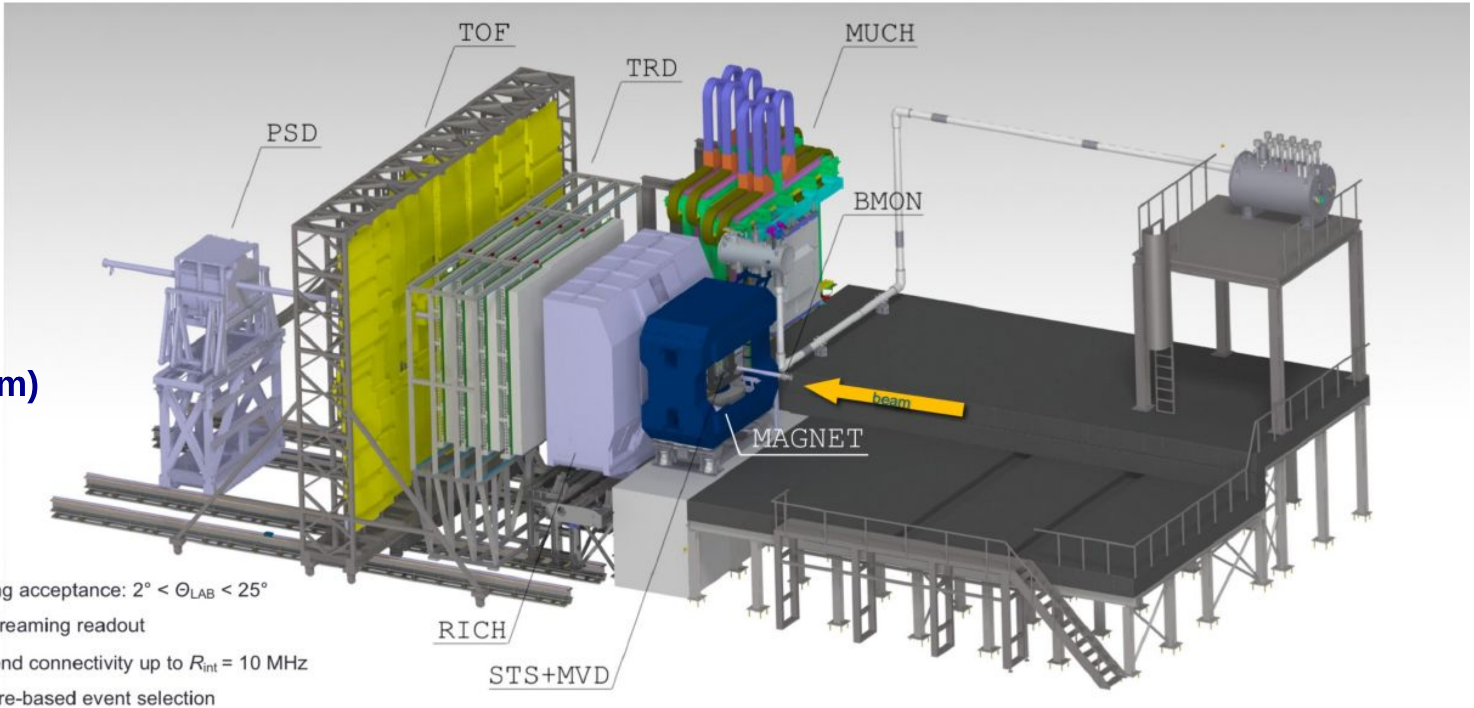
THE CBM DETECTORS

Fixed target experiment
- Polar coverage 2° < θ_{Lab} < 25°

full φ coverage
- Mid-rapidity coverage for all energies, down to low pt

Versatile detector systems
- Electron and muon setup

Superconducting Dipole Magnet (1Tm)
MVD
Micro Vertex Detector
STS
Silicon Tracking System
MuCh
Muon Chamber System
RICH
Ring Imaging Cherenkov Detector
TRD
Transition Radiation Detector
ToF
Time-of-Flight Detector
PSD/FSD
Forward Spectator Detector



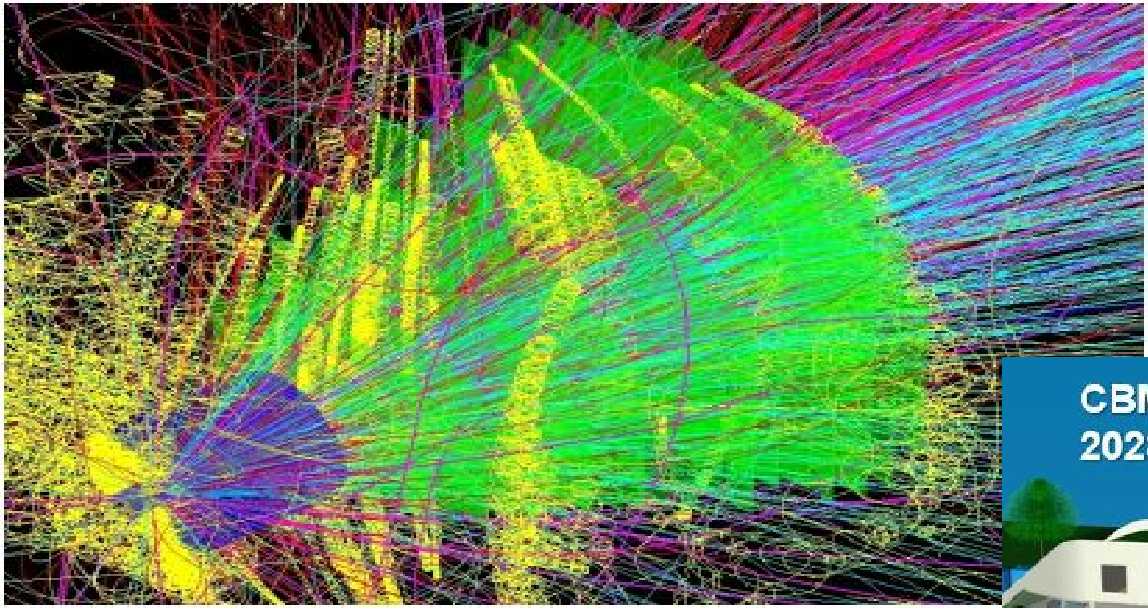
Tracking acceptance: 2° < Θ_{LAB} < 25°
Free streaming readout
Front-end connectivity up to R_{int} = 10 MHz
Software-based event selection

315 full members from 10 countries
47 full member institutions
10 associated member institutions

FLES
First Level Event Selector

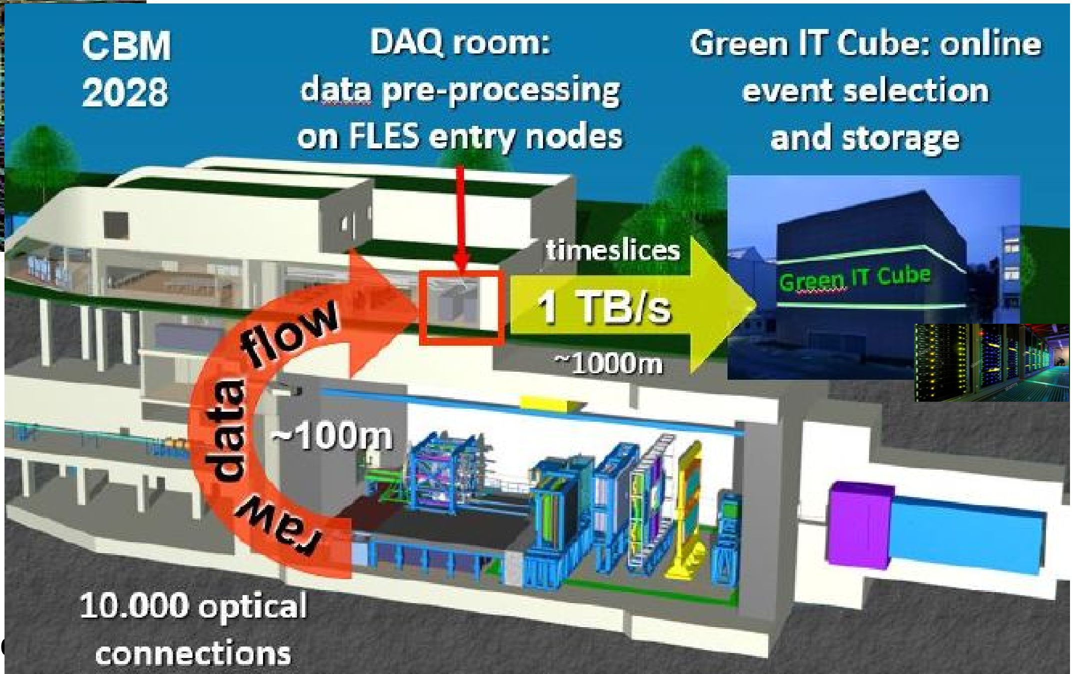
CHALLENGE OF HIGH EVENT RATE

central Au+Au collision @ 10A GeV/c



First Level Event Selector
- Online event reconstruction up to the software trigger decision
- Reconstruction in **4D (space, time)**
- Decay topology reconstruction

Online reduction of the raw data:
~2 orders of magnitude necessary

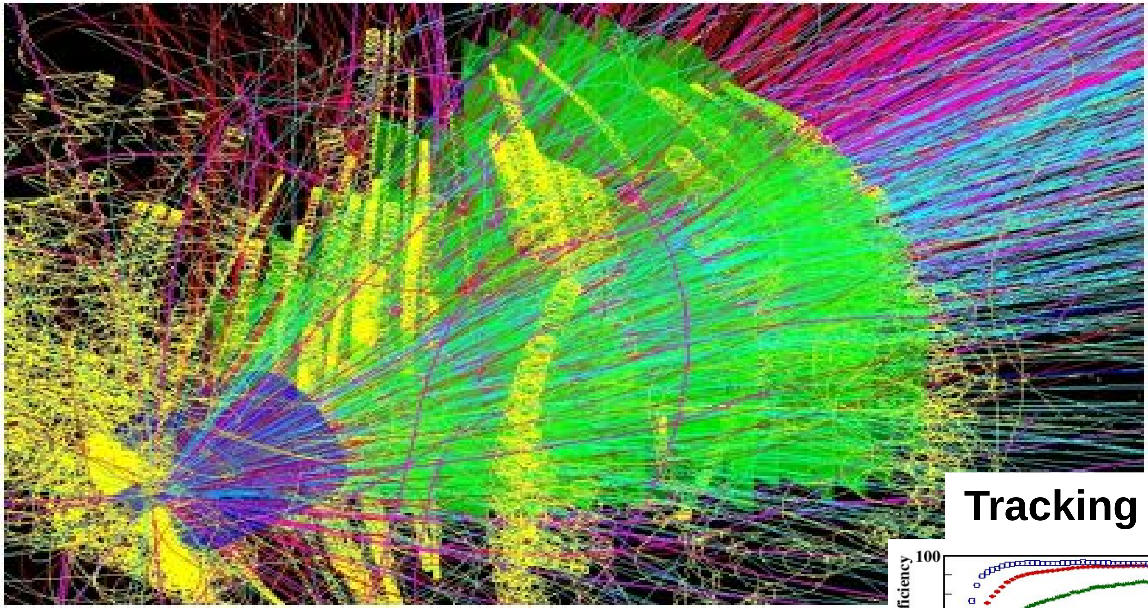


High multiplicity collisions
→ 500 particles / event in Au+Au
High interaction rate (10 MHz) implies:
- Raw data rates

10^7 ev/s x 5 10^2 ptc/ev x 50 signal/ptc x 4 Byte/signal
→ up to **1.0 TB/s**
- Events in the selected time window (time slice) will overlap in time

TRACKING AND EVENT RECONSTRUCTION

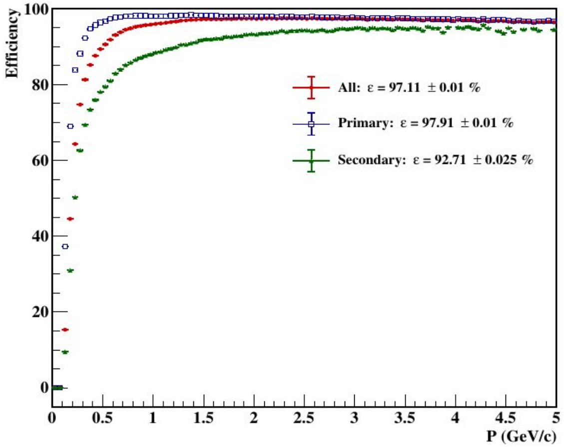
central Au+Au collision @ 10A GeV/c



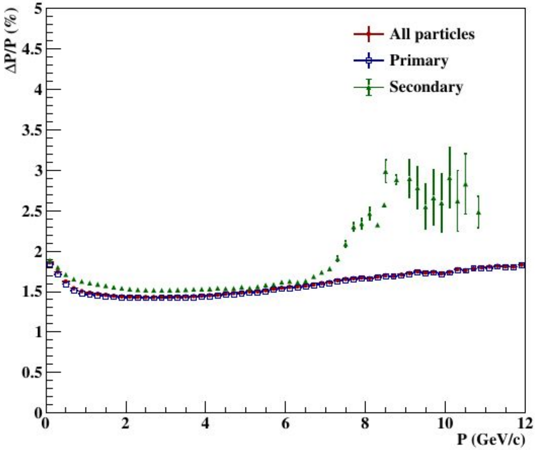
Detector requirements
• Fast and radiation hard detectors and FEE
Electronics requirements
• FEE of all CBM detectors autonomous and **free streaming** self-triggered, delivers time-stamped hit messages
Online reconstruction (tracking) requirements
• High granularity
• High efficiency ~97% for p_T > 1 GeV/c
• Excellent momentum resolution <2%

High multiplicity collisions
→ 500 particles / event in Au+Au
High interaction rate (10 MHz) implies:
• Raw data rates
10^7 ev/s x 5 10^2 ptc/ev x 50 signal/ptc x 4 Byte/signal
→ up to **1.0 TB/s**
• Events in the selected time window (time slice) will overlap in time

Tracking efficiency

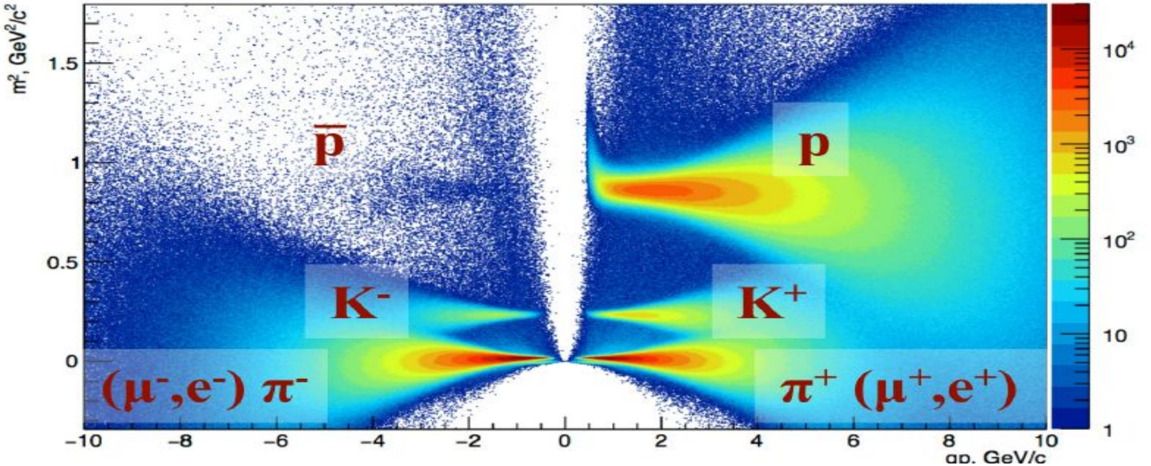


Momentum resolution

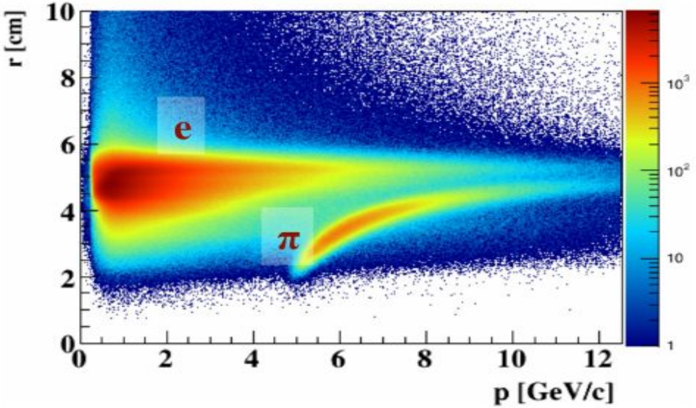


PARTICLE IDENTIFICATION

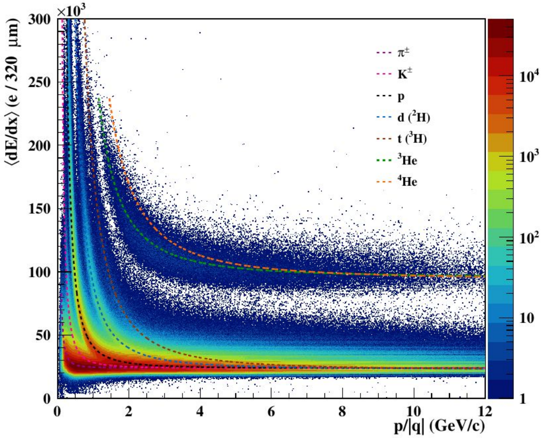
central Au+Au collision @ 10A GeV/c



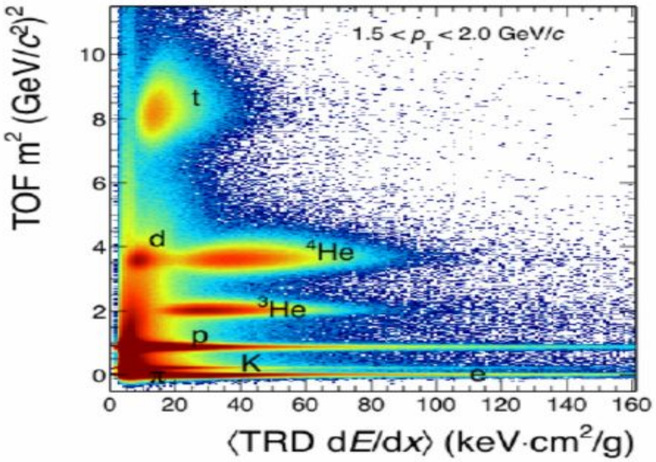
+ RICH / TRD
pions, electrons, and light nuclei



STS+ToF
High purity identification of charged protons, pions and kaons



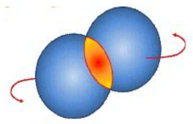
+ dE/dx in STS
distinguish heavy fragments



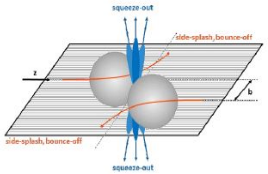
COLLECTIVE BEHAVIOR

STAR Collaboration, arXiv:2007.14005

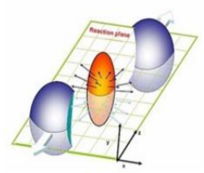
Collective flow quantifies the collective behavior of the matter, as it reflects how pressure gradients - set by the **EOS** - convert initial geometry → collective motion of the produced matter



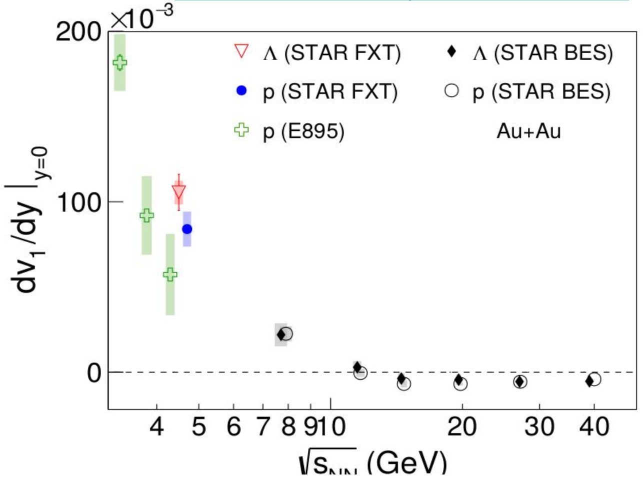
v_1 deflection of matter in the RP (signal of the phase transition?)
Paech *et al.*, NPA 681 (2001)

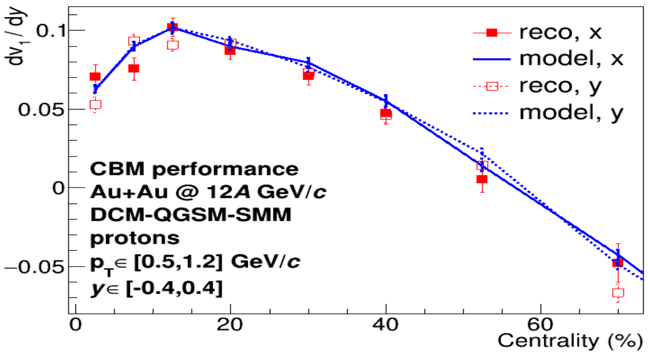


$v_2 < 0$ long spectator passing time $\tau_{passing} \approx \tau_{expansion} \Rightarrow$ "squeeze-out"



$v_2 > 0$ when spectators pass faster than fireball expands

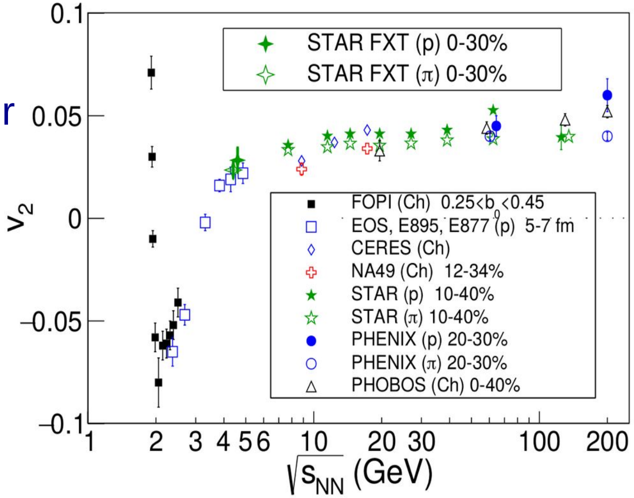




Anisotropic flow v_n is quantified via Fourier decomposition of azimuthal distribution of produced particles relative to the reaction plane Ψ_{EP}

Fourier coefficients of the distribution

$$\frac{dN}{d(\phi-\Psi_{EP})} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi-\Psi_{EP}))$$



CRITICAL FLUCTUATIONS

In strong interactions, baryon (B), electrical charge (Q) and strangeness (S) are conserved
At **critical point** or when crossing a 1st order phase transition: density fluctuations / jump in density
→ **discontinuities / fluctuations of conserved quantities**

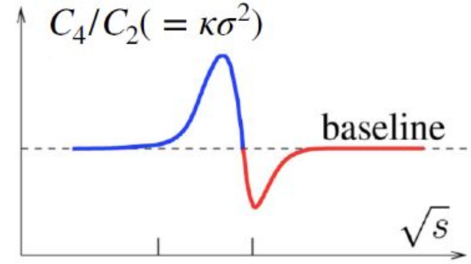
Higher order cumulants describe the shape of measured distributions and quantify fluctuations

Variance $\kappa_2 = \langle(\delta N)^2\rangle = \sigma^2$

Skewness $\kappa_3 = \langle(\delta N)^3\rangle$

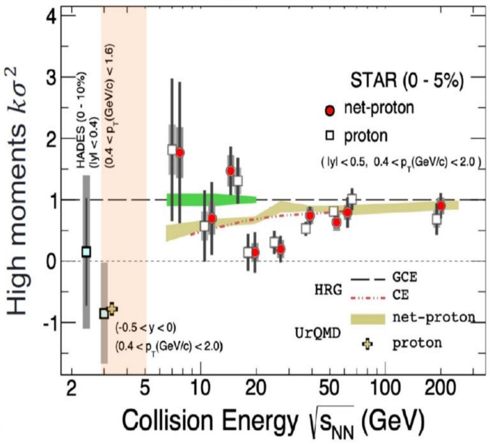
Kurtosis $\kappa_4 = \langle(\delta N)^4\rangle - 3\langle(\delta N^2)\rangle^2$

QCD **susceptibilities** are defined as derivatives of the pressure w.r.t. the corresponding chemical potentials: variance, skewness, kurtosis, …
Experimentally, event-by-event **cumulants** of B, Q, S are proportional to these susceptibilities
At critical point they can show **discontinuities**.

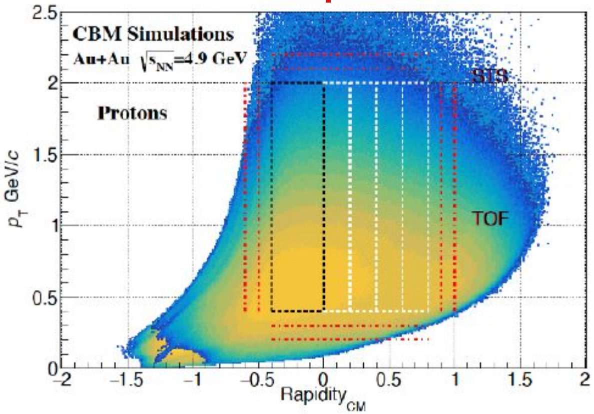


M. A. Stephanov, PRL 107 (2011) 052301

STAR, PRL 128 (2022) 202303
HADES, PRC 102 (2020) 024914

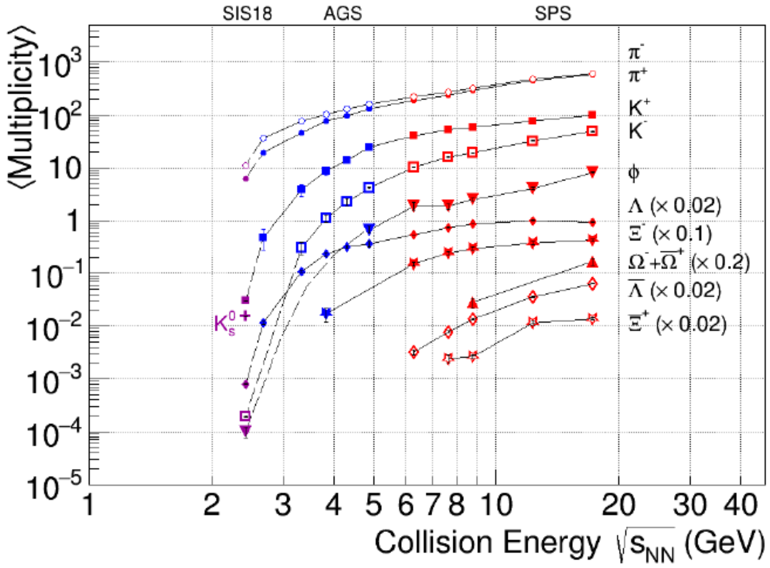


CBM acceptance



STRANGENESS

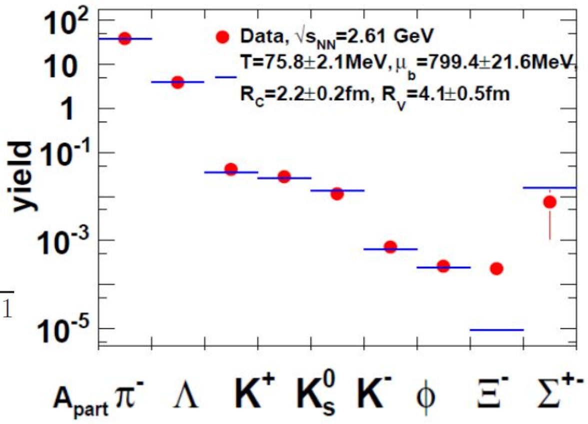
Yield at sub-threshold energies ~ multi-step collisions ~ density → EOS
Are (multi-) strange hadrons equilibrated at lower collision energies?
Clear deviation from thermal yield observed by HADES for Ξ...



Blume, Markert, PPNP 66 (2011)
see also yield ratios for Si+Au Braun-Munzinger, Stachel, Wessels, Xu, PLB 344 (1995)

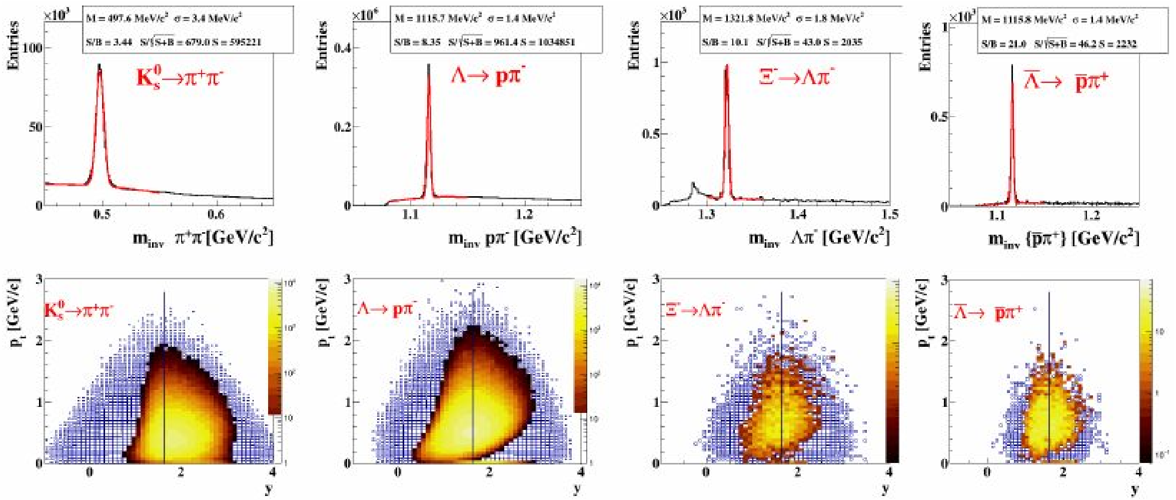
Particle yields and thermal model fits

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i-\mu_i)/T] \pm 1}$$

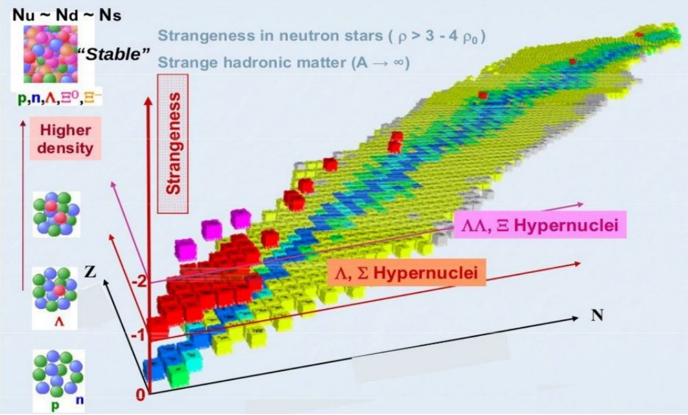


HADES Eur.Phys.J. A47 (2011) 21

CBM simulation
UrQMD, Au+Au @ 10A GeV/c, centra
5M events

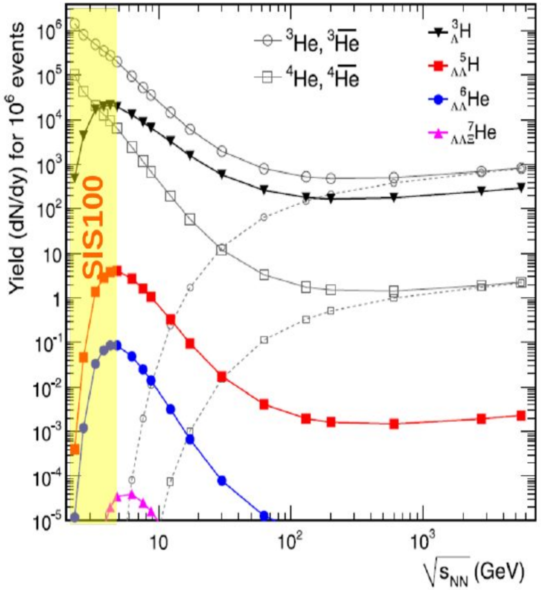


HYPERNUCLEI



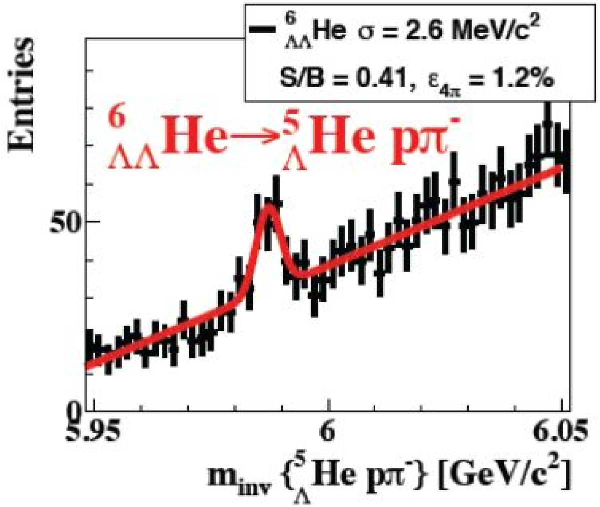
- **Nuclei with at least one hyperon** (besides protons and neutrons)
- Produced by a **nucleus capturing a Λ or K** meson and boiling off neutrons or by direct **strangeness exchange reaction**.
- Λ-Hypernuclei live long enough to have sharp nuclear energy levels → study nuclear spectroscopy and reaction mechanism
- Hyperon has non-zero strangeness quantum number → **not restricted by Pauli exclusion principle** → can share space and momentum coordinates with the usual four nucleon states
- The strength of the **Λ-N strong interaction** may be extracted

A. Andronic, PLB697 203 (2011)

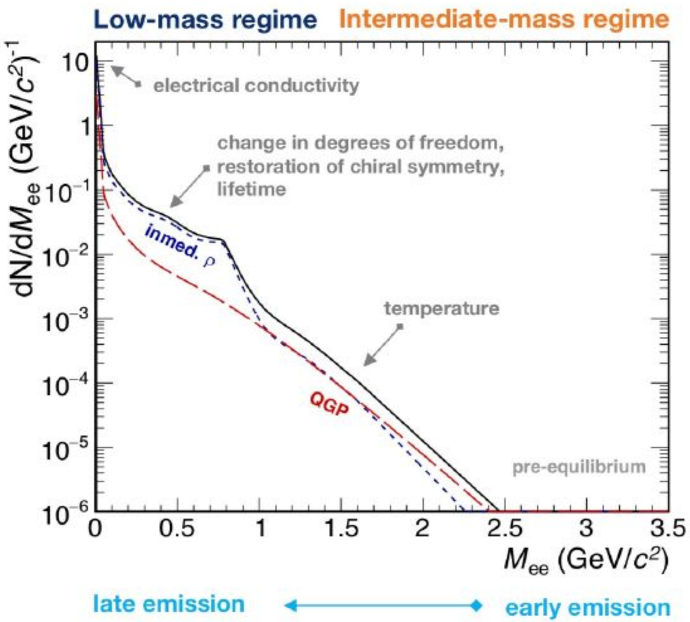


At CBM:
- **Highest production cross section**
- **Complex topology** of decays
- Reliable identification of decay particles

CBM simulation
Au+Au @ 10A GeV/c, 10^{12} events



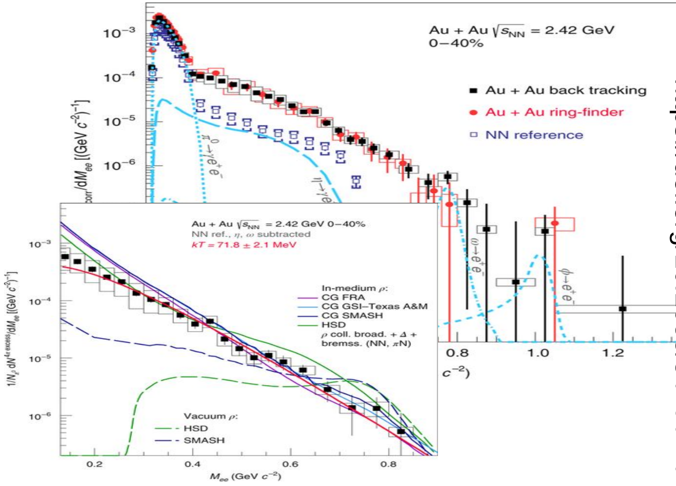
EM RADIATION



Unlike hadrons, leptons trace the entire evolution of the fireball.
Rich information:
- **temperature**
- **density**
- **lifetime**

Difficult measurement due to abundant background

Can be measured with **electrons and muons**

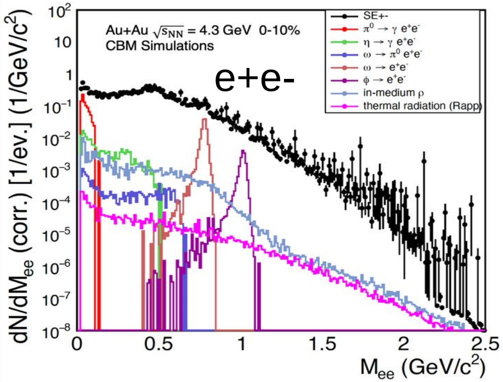


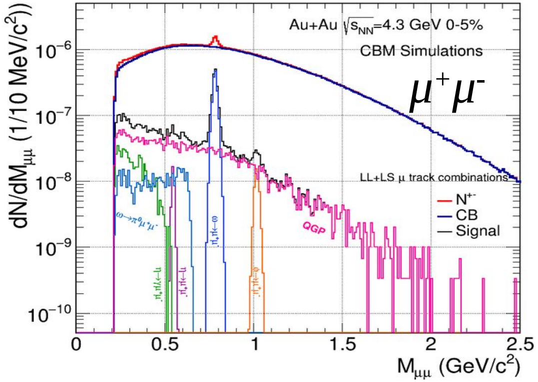
HADES, Nature Physics 2019, https://doi.org/10.1038/s41567-019-0583-8

Here: “caloric curve”:
flattening as signal of phase transition?

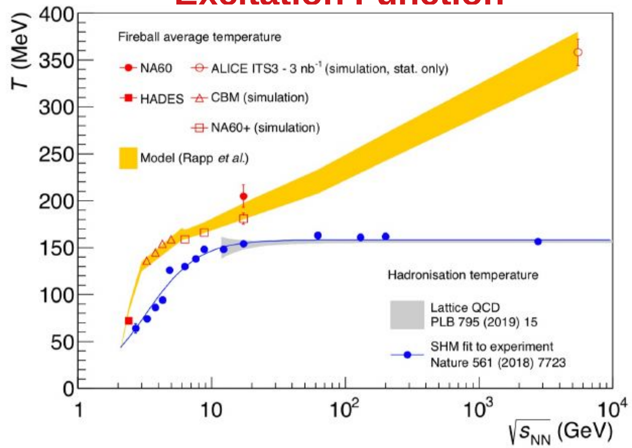
CBM simulations

central Au+Au collision @ 10A GeV/c





Excitation Function



Toia

A COMPREHENSIVE QCD PROGRAM WITH SIS100 PROTON BEAM

• Opening new realm: **proton energy range 4.7 GeV (SIS18) – 29 GeV (SIS100)**
- production, spectroscopy and interactions of double and triple strangeness
- charm production and interactions close to production threshold
- significant increase in production yield of hyperons

• Important new insight into hadron structure (hyperon spectrum, study intrinsic charm component of the hadron wave function)

• Competitive and complementary program to other facilities world-wide

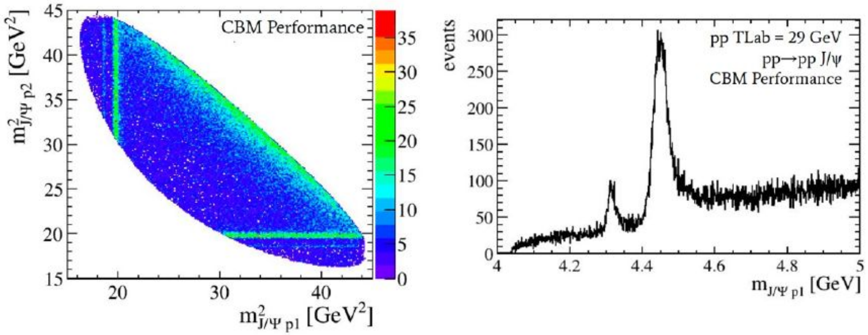
QCD at FAIR

Physics opportunities with proton beams at SIS100 Workshop Wuppertal, Feb 2024
https://indico.gsi.de/event/18475/overview

QCD at FAIR workshop, Nov 11-14, 2024,
https://indico.gsi.de/event/20301/

White-paper preparation

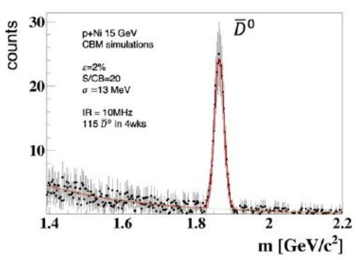
Reconstructed Dalitz plot with pentaquarks

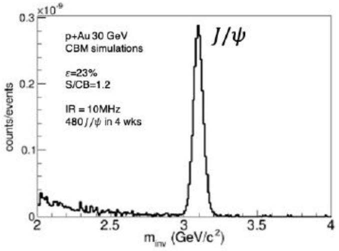


• **Charm in pp / pA / AA**
- CBM is well adapted to the pp exclusive channels program
    - high-rate capabilities and free-streaming DAQ’s
    - excellent mass resolution (~2%)
    - excellent coverage for exclusive channels

• pp/pA collisions to establish baseline and to study cold nuclear matter effects

• AA (light ions) probe in-medium QCD force
- how is the fundamental QCD force screened at μB > 0?
- consequences for heavy-quark transport





FAIR PROJECT STATUS

FAIR staged realization plan
- 2023: Buildings completed
- 2024: Installation started
- 2025: Start FAIR commissioning
- **2028: CBM ready for beam**

CBM Cave

CBM building is accessible by road
30-ton crane installed and commissioned

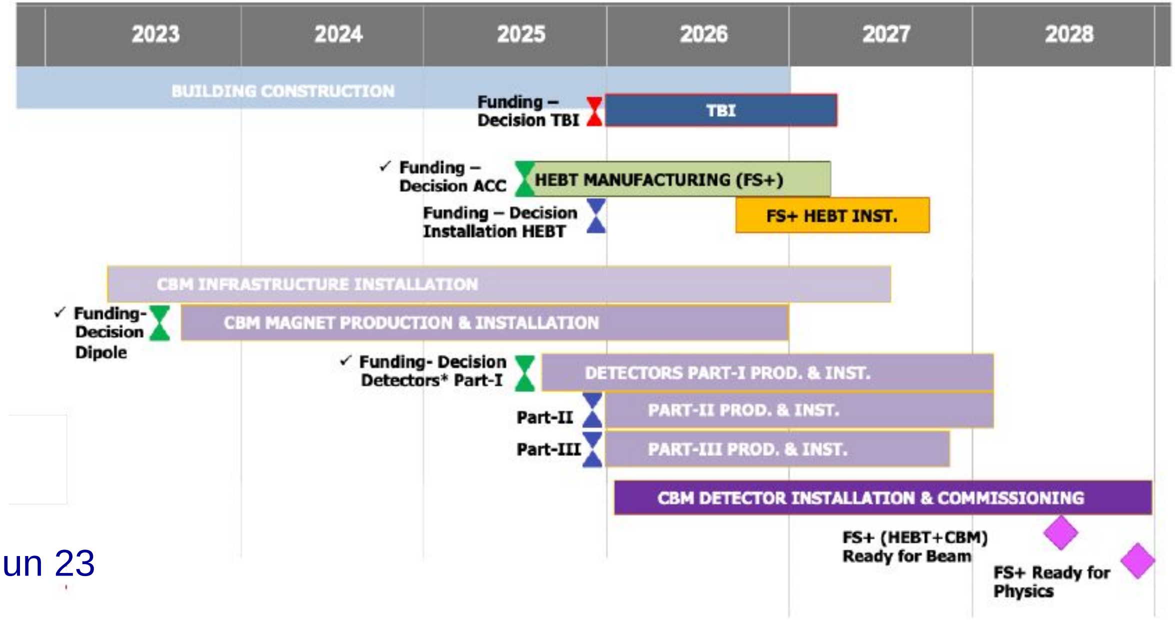
Dipole and quadrupole power converters

Cryo Plant and cooling water system

Central Transfer Building

SIS100 accelerator tunnel

CBM TIMELINE AND PLANS



CBM Cave
- a dedicated cave with a massive beam dump for high-intensity, high-energy beams
- CBM cave/building shell completed, road, crane
- Technical Building Infrastructure in 2026/2027

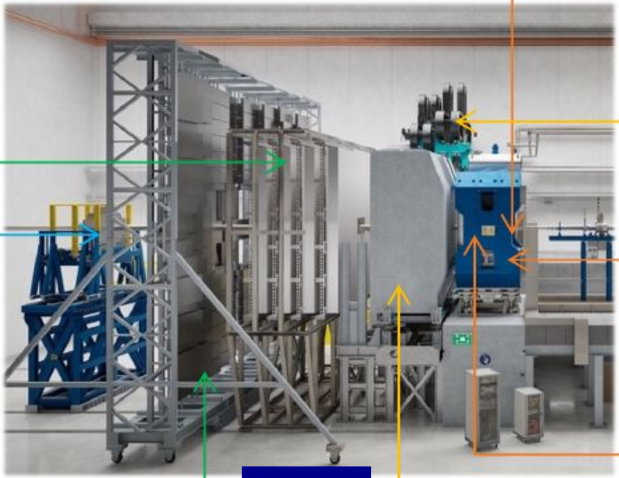
CBM Phase-0
- pre-commissioning of sub-detectors in different facilities

CBM Installation
- CBM installation activities (platform), started in Jun 23
- CBM ready for beam by 2028

First 3 years scenario: focus on beam energy scan
− 60 days / year beam on target
− different detector configurations
− subject to a reshaping depending on findings (e.g. long run at maximum energy with MUON setup)

Setup	Included subsystems	Average day-1 interaction rate
ELEHAD	MVD,STS,RICH,TRD,TOF,FPW	0.1 MHz
MUON	STS,MUCH,TRD,TOF,FPW	1 MHz
HADR	STS,TRD,TOF,FPW	0.5 MHz

CBM IN CONSTRUCTION



TRD

Transition Radiation Detector

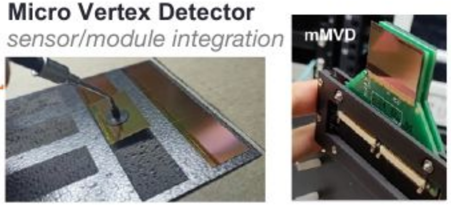
pre-production modules of 1D and 2D options ready

Pre-prod finalize

MVD

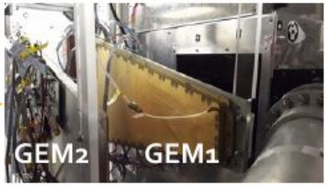
Micro Vertex Detector

sensor/module integration



Prod. Readiness MIMOSIS-3

MUCH



Prod. Readiness GEM r/o

Superconducting dipole magnet

Magnet support factory acceptance test

FSD

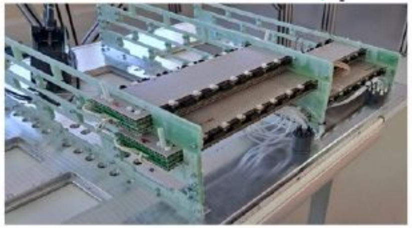
Forward Spectator Detector

3x3 FSD test module

TDR in Jan.

TOF

Time of flight detector



20% counters assembled, module pre-production ongoing successful operation of mToF in 2025

>30% MRPC prod.

RICH

Ring Imaging Cherenkov detector

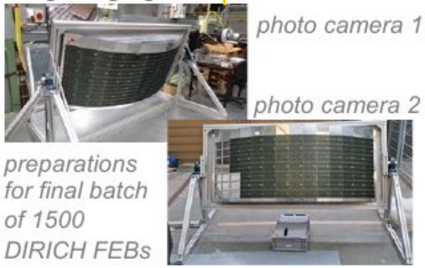


photo camera 1

photo camera 2

preparations for final batch of 1500 DIRICH FEBs

2 cameras ready
Prod. Readiness mirror wall

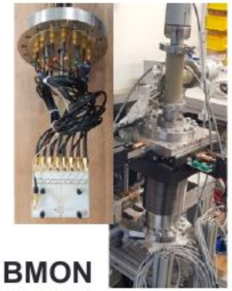
STS

Silicon Tracking System

STS half-unit assembly and Integration

>80% modules
>20% ladders

BMON



BMON

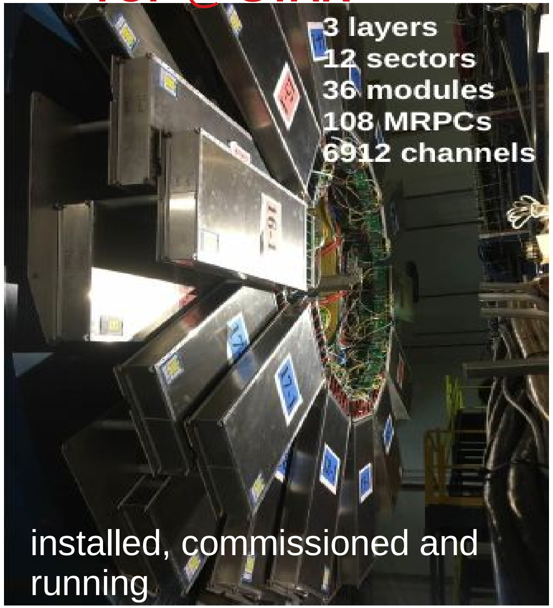
T0 manipulator X/Y/Z Vacuum test – done

pcCVD sensor ready

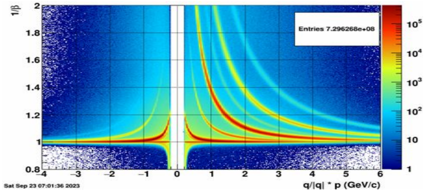
CBM PHASE-0 PROGRAM

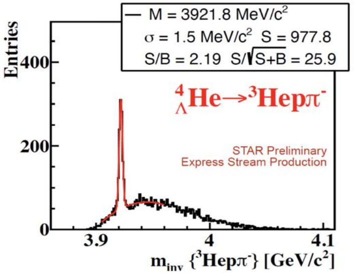
BEFORE OPERATION IN 2028

TOF @ STAR



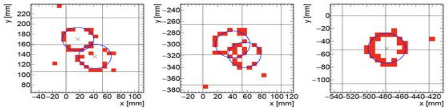
Hypernuclei reconstruction in STAR, eTOF data for PID

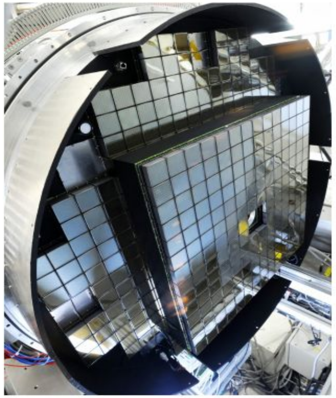




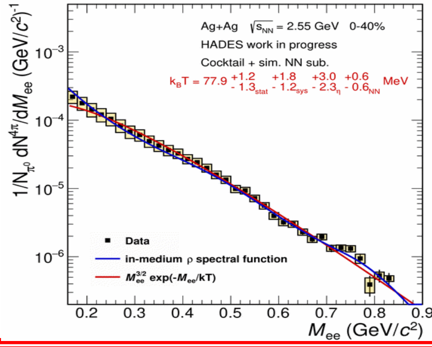
RICH @ HADES

Use 430 out of 1100 CBM RICH multi-anode photo-multipliers in HADES



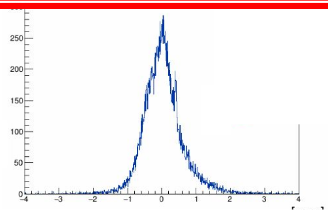


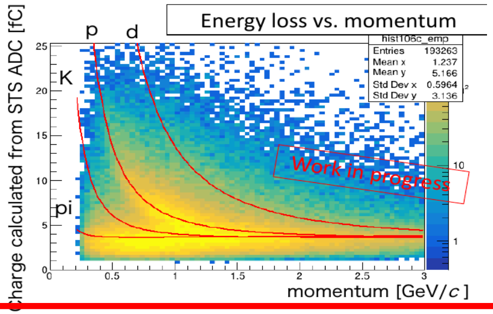
Thermal dilepton radiation from HADES RICH photodetector upgrade employing CBM technology

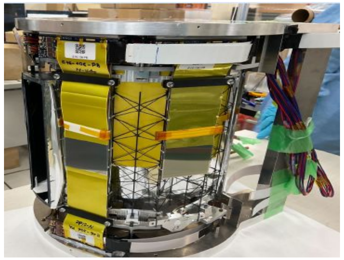


STS @ E16

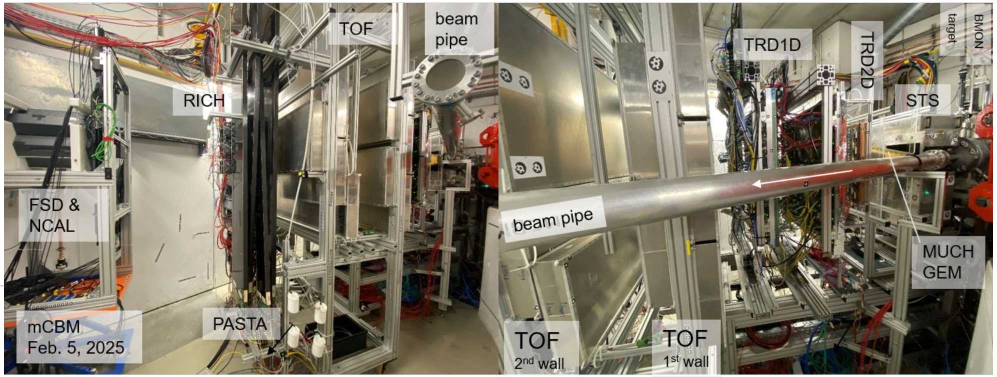
10 pre-series STS modules as innermost tracking layer in E16 @ J-PARC



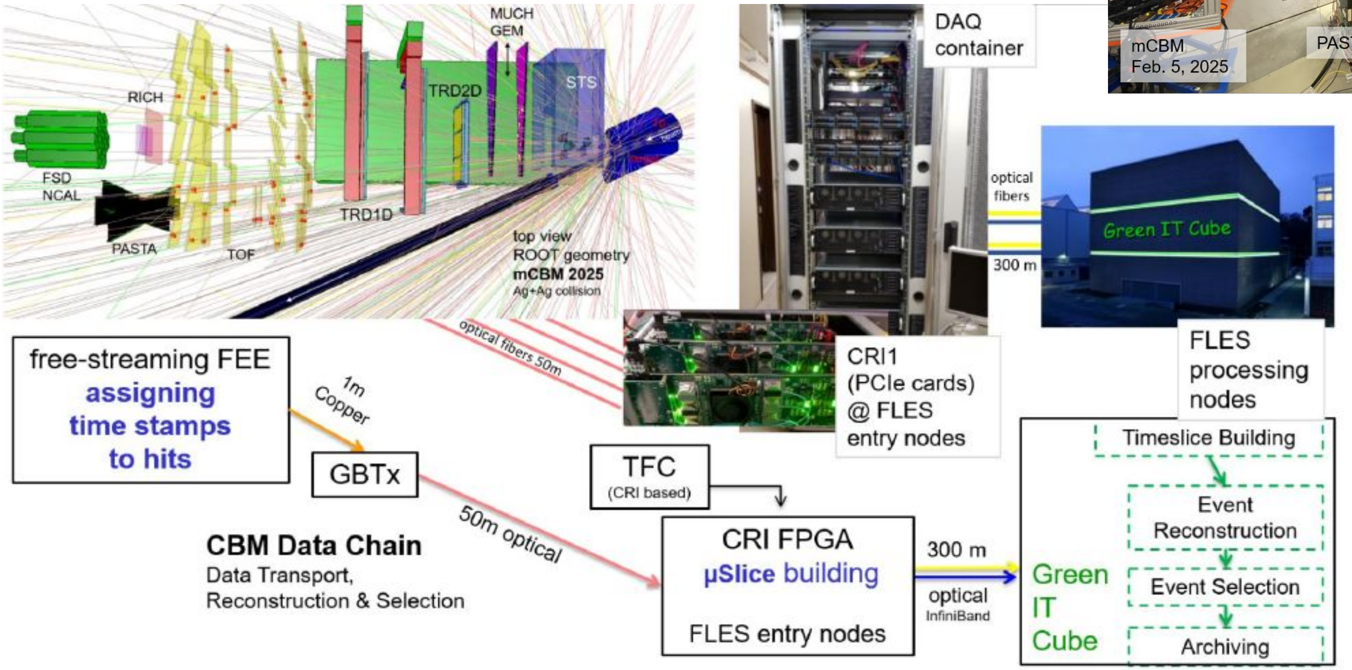




TESTING TO SCALE: MINI-CBM @ SIS18



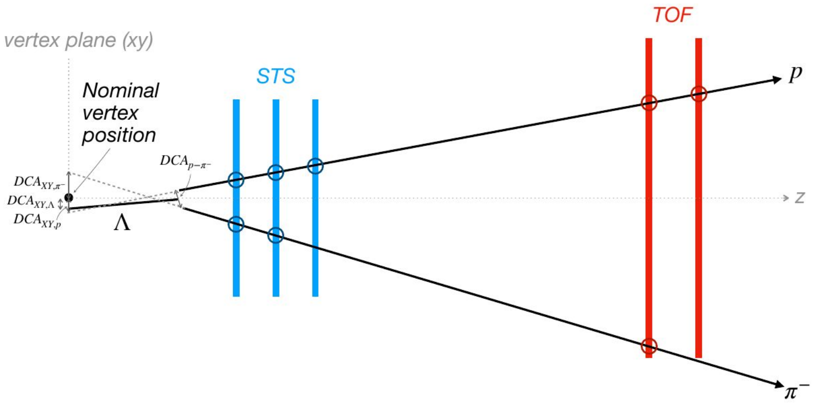
miniCBM Setup

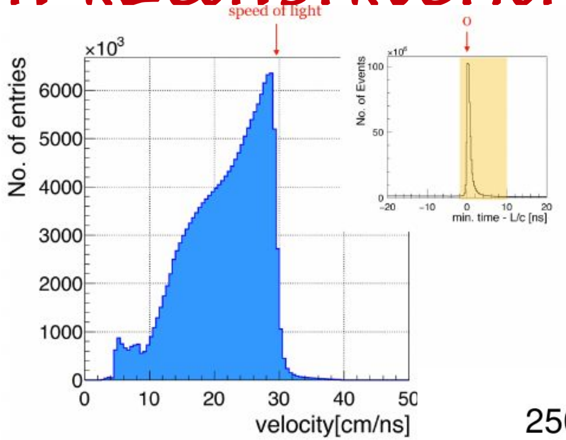


Full system test with SIS18 beam

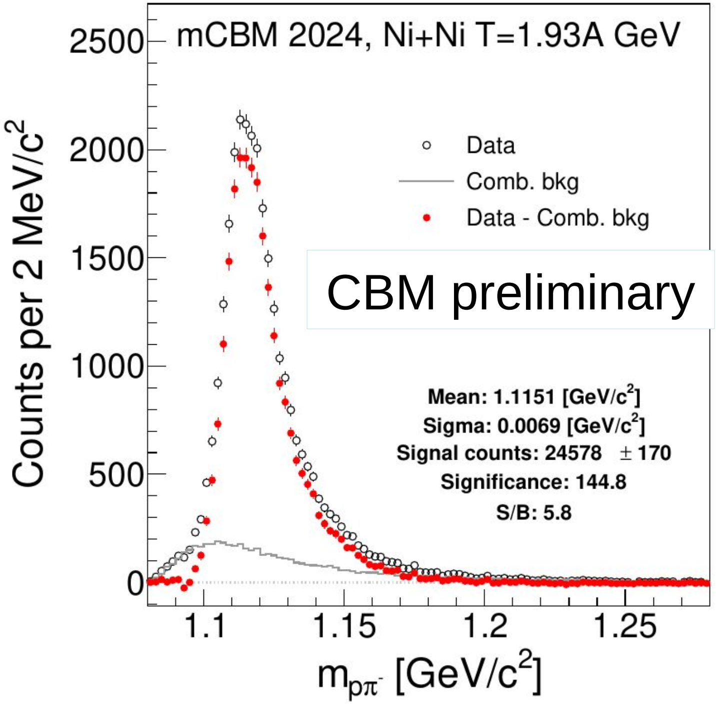
- Detector pre-series modules
- Free-streaming readout implemented and commissioned
- Data transport scheme and hardware close to the final CBM DAQ
- High-rate detector studies
- Scalable towards full CBM
- Reconstruction of rare signals (Λ hyperon)

Λ HYPERON RECONSTRUCTION





CBM PAPER
in preparation (NIM)



Common data readout/transport + software developments

Λ baryon: rare probe at SIS18

w/o magnetic field:

- Tracks defined by STS-TOF correlations
- Alignment of individual detector elements
- CA tracking + KFParticleFinder Package
- TOF hit time adjusted to speed of light
- particle mass assignment (p, π-) based on track impact par.

→ pair reconstructed with topological cuts

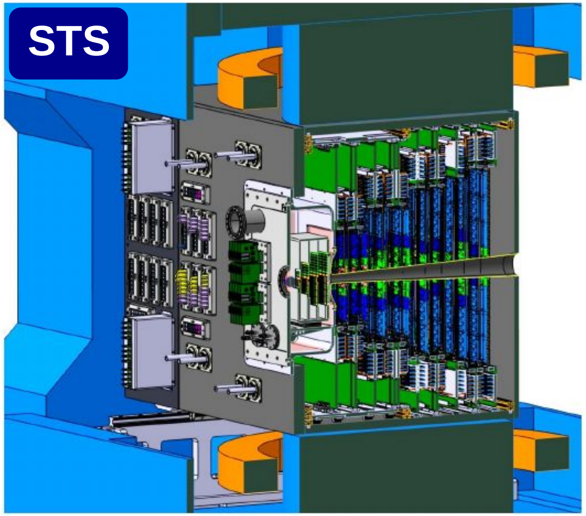
- CBM detector and readout concept verified at miniCBM

- Gained experience in operations, calibration and alignment

→ speed up of commissioning of full CBM

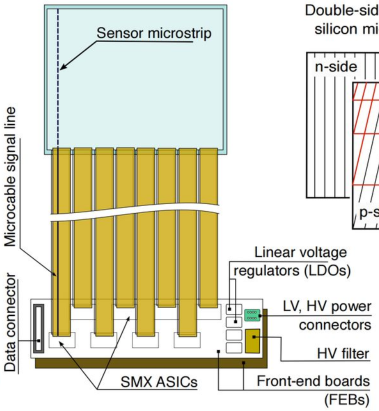
THE SILICON TRACKING SYSTEM

STS



Main tracking detector

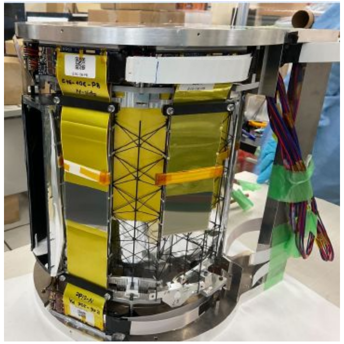
- 8 tracking stations, 4 m^2 of Si strip sensors



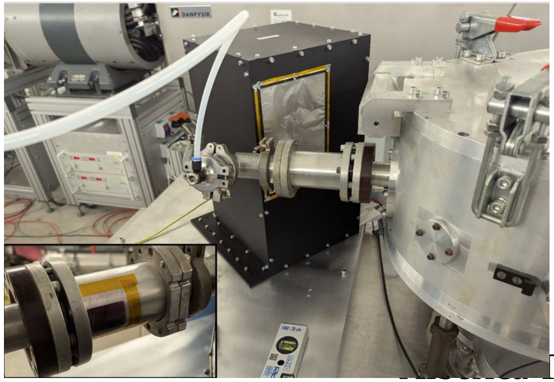
- **Light-weight:** 0.4% – 1.4% X_o per station
- High-rate collision **10^7 Hz Au+Au**
- Hit spatial resolution: 25 μm
- Time resolution: 5 ns
- Δp/p: 1.8%
- Track reconstruction efficiency: 96%

Employed also at:

STS in E16 @ J-PARC



Clinical test @ Cologne



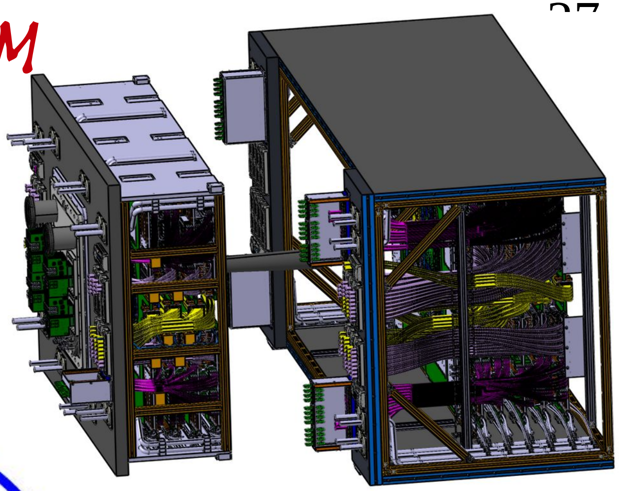
MODULE

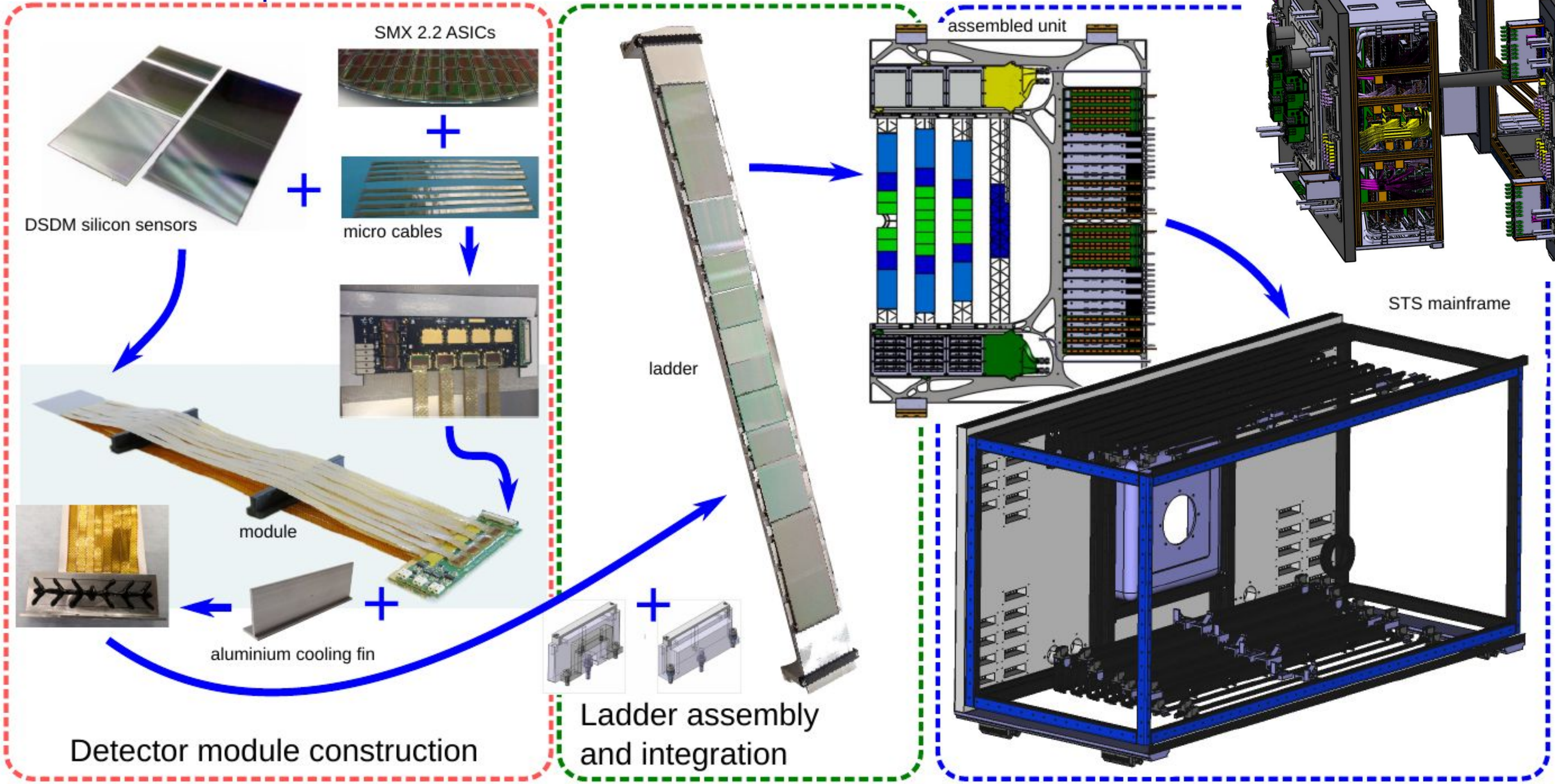
- Large area **double-sided Si sensors**:
  - 1024 strips/side, 58 μm pitch
  - Thickness:~320 μm, Strip length 2/4/6/12 cm
  - 7.5° stereo angle for p-side strips
  - Radiation tolerance: 10^{14} neq (1 MeV) /cm^2
- **2 Front-end boards** carrying 16 SMX **ASICs**
  - Self-triggered signal, dual path processing:
  - Timing comparator (< 5ns resolution)
  - 5 bit flash ADC (15 fC dynamic range)

The Silicon Tracking System

The **STS** Silicon Tracking System

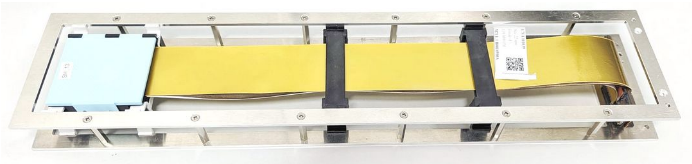
… and its components

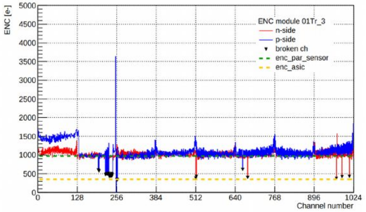




STS CONSTRUCTION STATUS

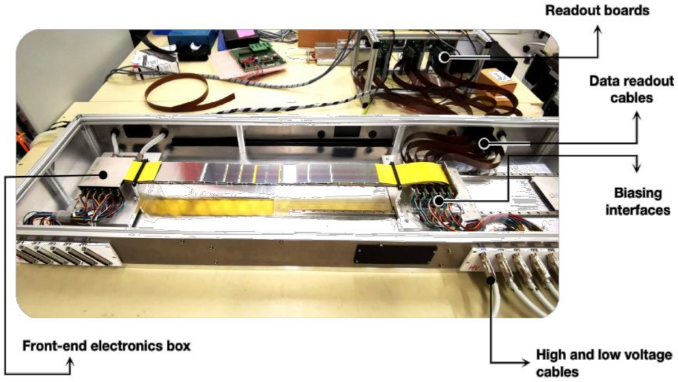
876 x MODULES



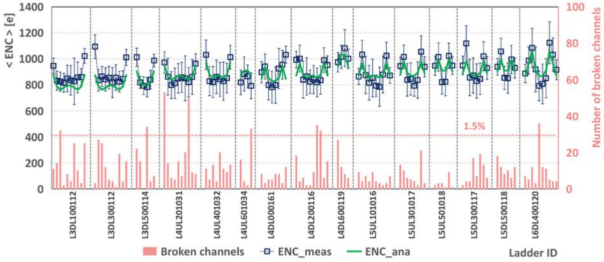


Elementary functional component assembled, tested, calibrated

106 x LADDERS

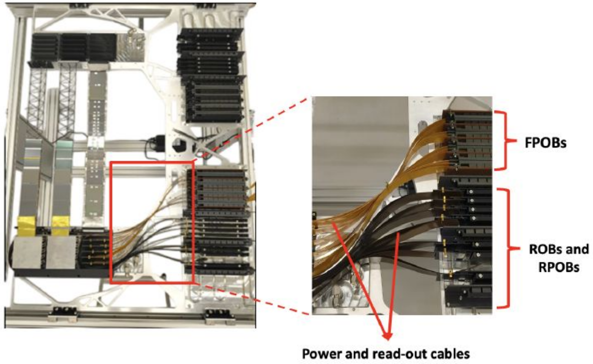


Hosts up to 10 modules



Assembled characterized functional tested

20 x HALF-UNITS

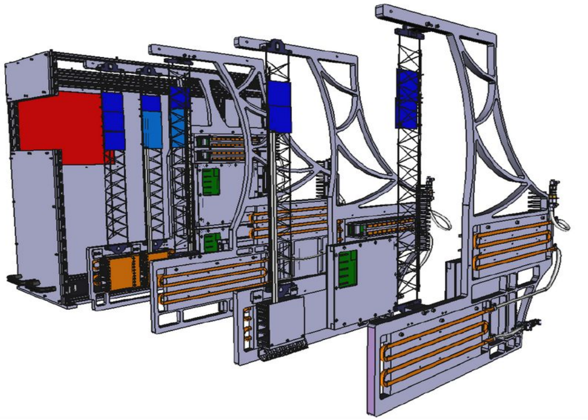


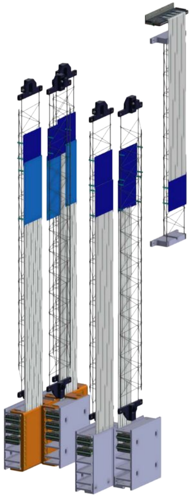
First half-unit being assembled right now!

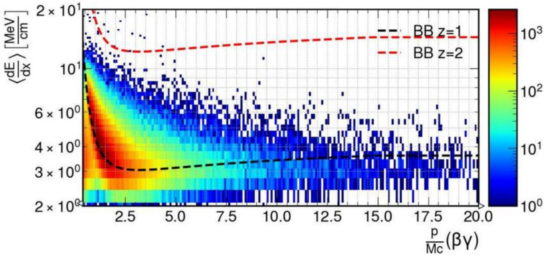
ASSEMBLY STATUS
15.01.2026

- ☑ MODULES: 758
- ☑ M. Testing: 693
- ☑ LADDERS: 26
- ☑ L. Testing: 19

PERFORMANCE OF STS







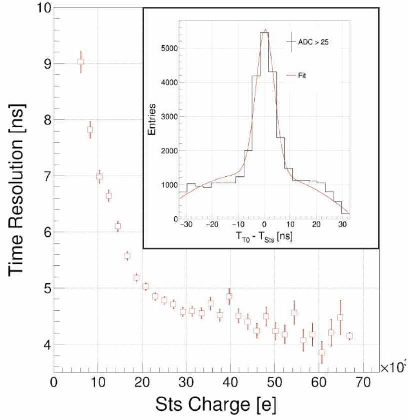
miniSTS Setup:

Three Stations Telescope built with 12 modules

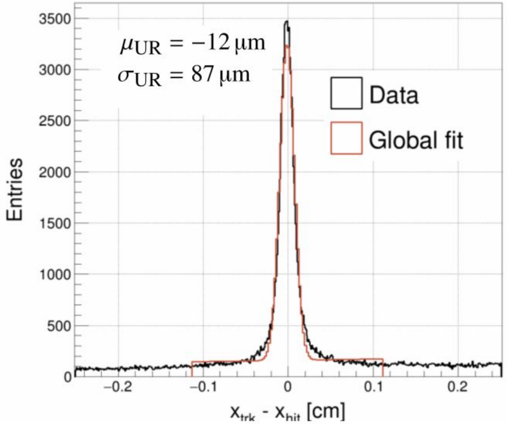
Performance observed so far shows that targeted STS system can be constructed in line with expectations

- **time resolution: 5ns**
- **space resolution: 25 μm**
- **hit reconstruction efficiency 98%**
- **sustained rates up to expected in CBM**

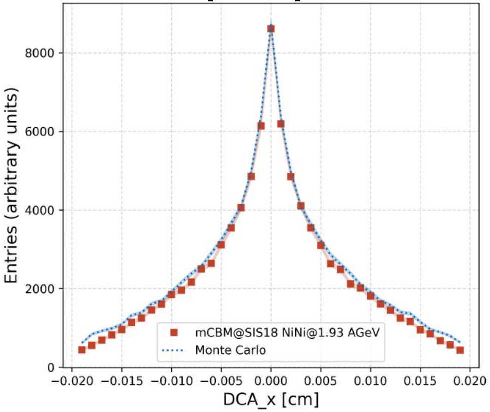
Time Resolution < 5ns



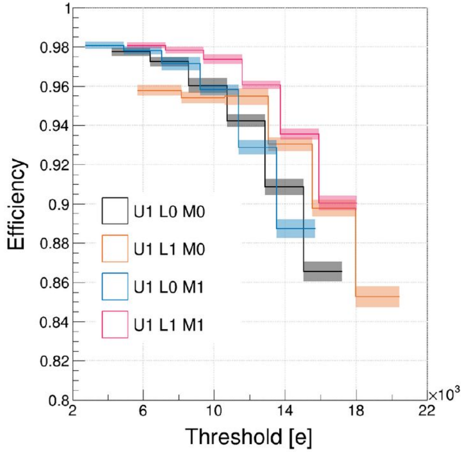
Space Resolution ~ 25μm



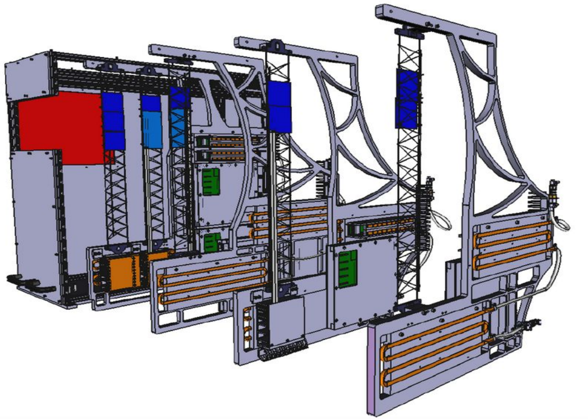
Track Impact parameter



Hit Reconstruction Efficiency ~98%



PERFORMANCE OF STS

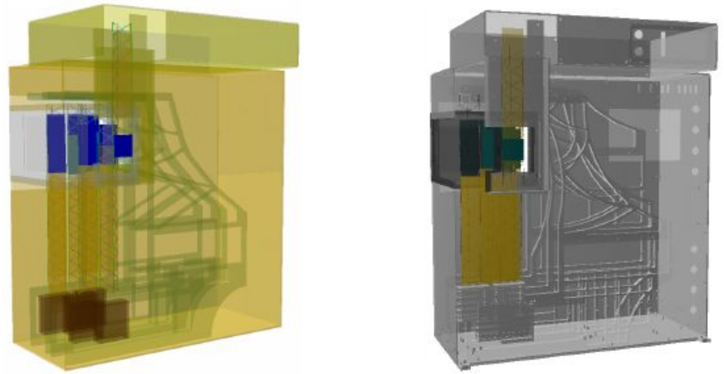


miniSTS Setup:

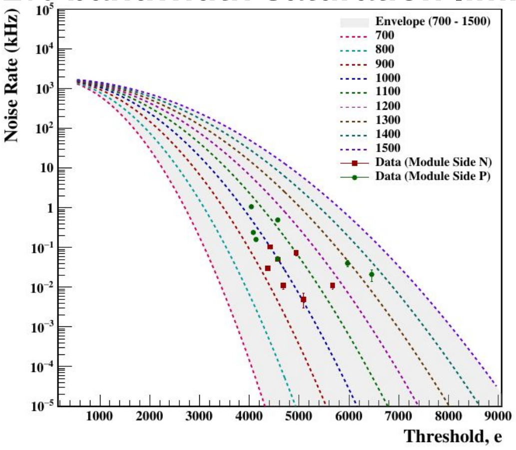
Three Stations Telescope built with 12 modules

Geometry:

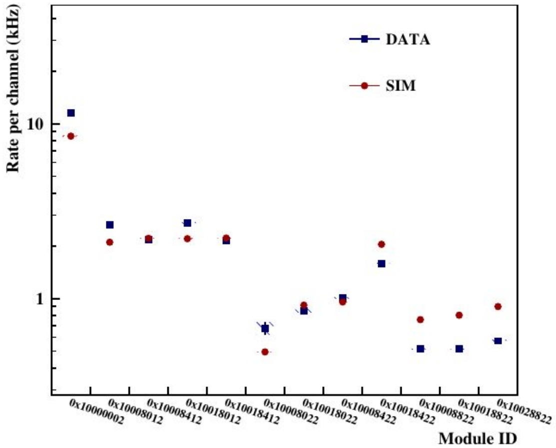
detailed comparison Primitive vs Tessellated CAD-to-ROOT



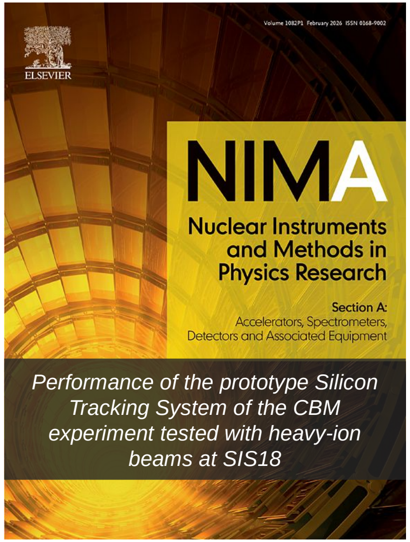
Dark rate (noise): 0.5 kHit/s/channel
< 1% bandwidth saturation limit



Data rate ~ time-based Sim. Rate
Time-based Sim: Urqmd + Beam



1st CBM PAPER
arXiv:2505.20517
https://doi.org/10.1016/j.nima.2025.171059
NIM A 1082, 171059, 2026



SUMMARY

CBM physics program at SIS100:
● Precision study of the QCD phase diagram in the region of extreme high net-baryon densities. Discovery potential!

Unique measurements of rare diagnostic probes with CBM:
● High-precision multi-differential measurements of hadrons for different beam energies and collision systems.
- collective effects
- event-by-event fluctuations
- multistrange hyperons
- hypernuclei
- dileptons

Key experimental requirements:
● high-rate capability of detectors and DAQ
● online event reconstruction and selection

Status of CBM experiment preparation:
● Extensive performance studies for many physics observables
● Detector construction steadily progressing
● Intermediate FAIR phase-0 program: testing components and analysis methods

45. CBM Collaboration Meeting

GSI, Darmstadt 16-21 February 2025

- 47 full member institutions
- 10 associated member institutions
- from 10 countries, 315 full members