COSMIC MATTER IN THE LABORATORY – THE CBM EXPERIMENT AT FAIR

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for the CBM Collaboration

Győrfi András: Az úton (On the road)

OUTLINE

- The Facility for Antiproton and Ion Research
- Exploring cosmic matter in the laboratory
  - the high-density nuclear matter equation-of-state
  - the QCD phase diagram
- The Compressed Baryonic Matter (CBM) experiment

"I just won't sleep," I decided. There were so many other interesting things to do."

— Jack Kerouac, On the Road

Zimanyi School 2019
Winter Workshop on heavy ion physics
2-6 December 2019
Budapest, Hungary

Cosmic Matter

Supernova explosion

Young stars are made of hydrogen, and the nuclear reaction converts
H → He → C → O → Si → Fe (+ radiation)
Radiation balances gravity. Nuclear fusion stops at iron.
Eventually, the massive core collapses to form a NS. The outer layers of the star fall in and bounce off the neutron core which creates a shock wave that blows the outer layer outward. This is the supernova explosion.

+ emission of light and neutrinos

Neutron Star

densest and tiniest stars in the universe:
~1.4 M, R = 10-16 km
Protons and electrons melt into each other to form neutrons and more...

Neutron Star Merger

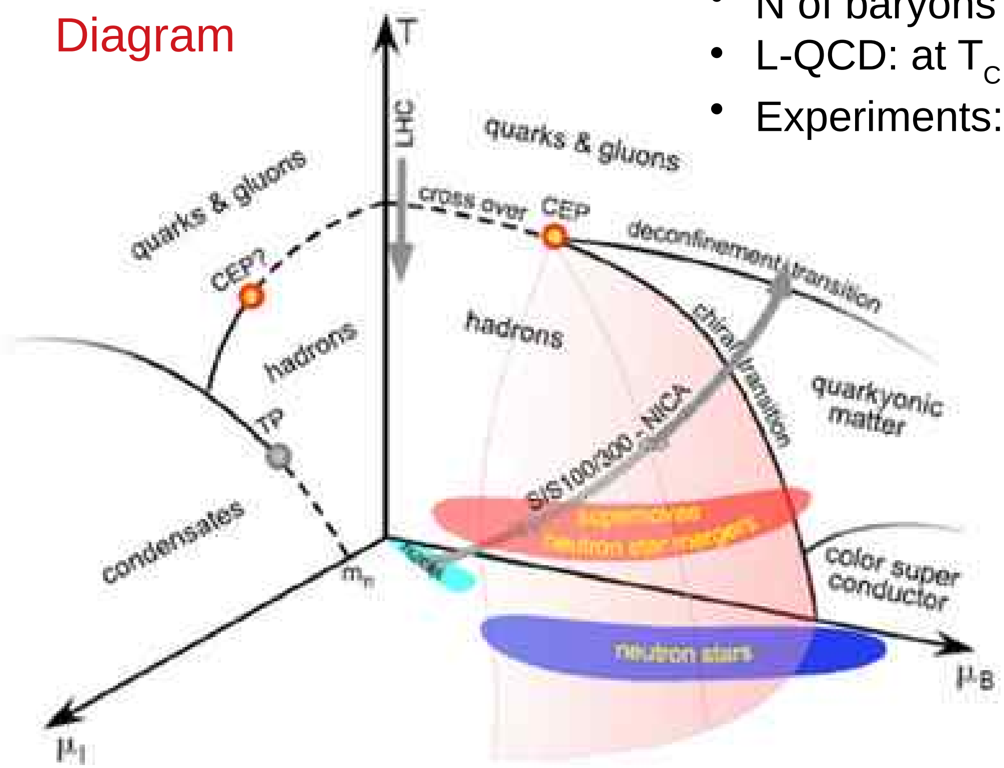
Stellar collision: two NS orbit each other closely → merger leads to creation of more massive NS or black hole;
also produces a magnetic field + short γ-ray bursts

Kilonovae

+ kilonovae (transient sources of isotropic longer wave em radiation due to radioactive decay of heavy nuclei produced and ejected during the merger)

Phase diagram of QCD Matter

Phase Diagram



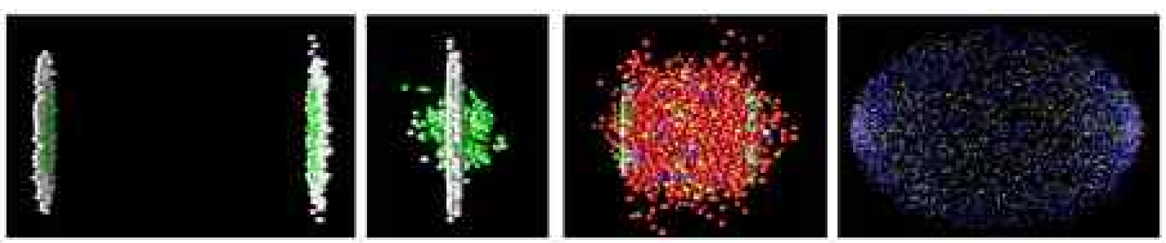
At very high temperature:

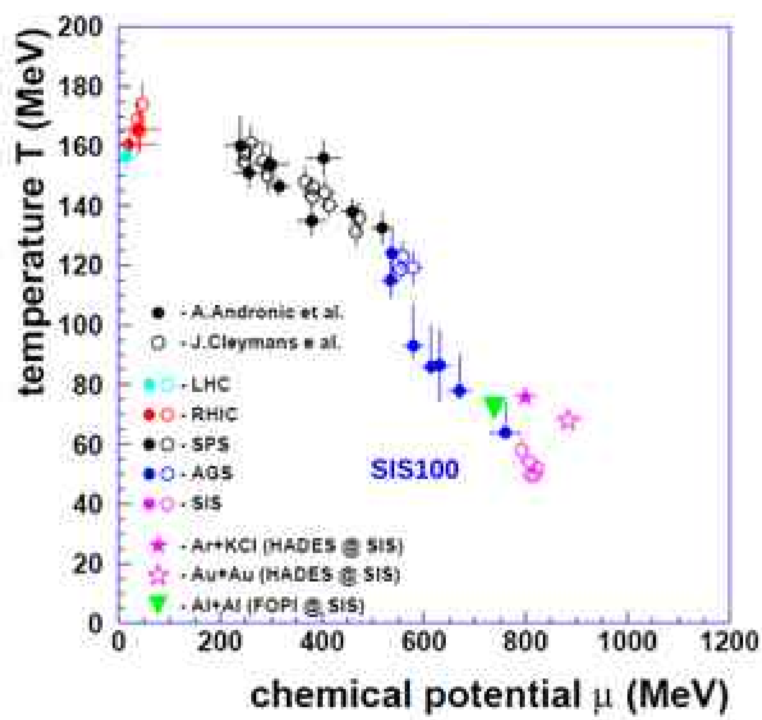
- N of baryons = N of antibaryons, situation similar to early universe
- L-QCD: at T_C ~155 MeV crossover transition hadronic matter → QGP
- Experiments: ALICE, ATLAS, CMS (LHC). STAR, PHENIX (RHIC)

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
  Experiments: BES (RHIC), NA61 (CERN SPS), CBM (FAIR), MPD/BM@N (NICA)

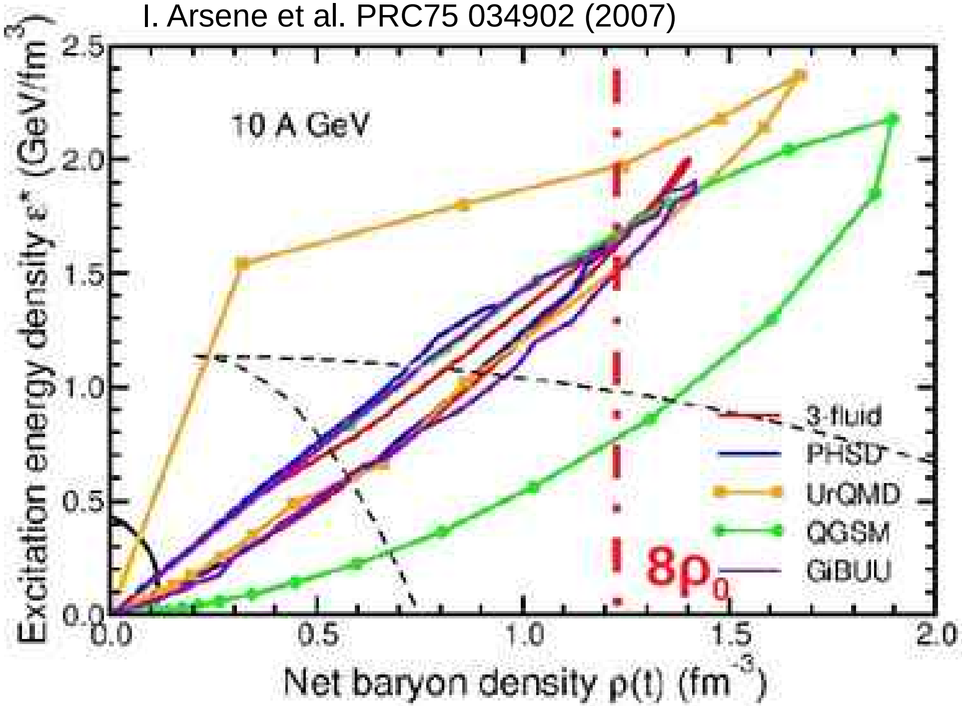
Heavy ion collision



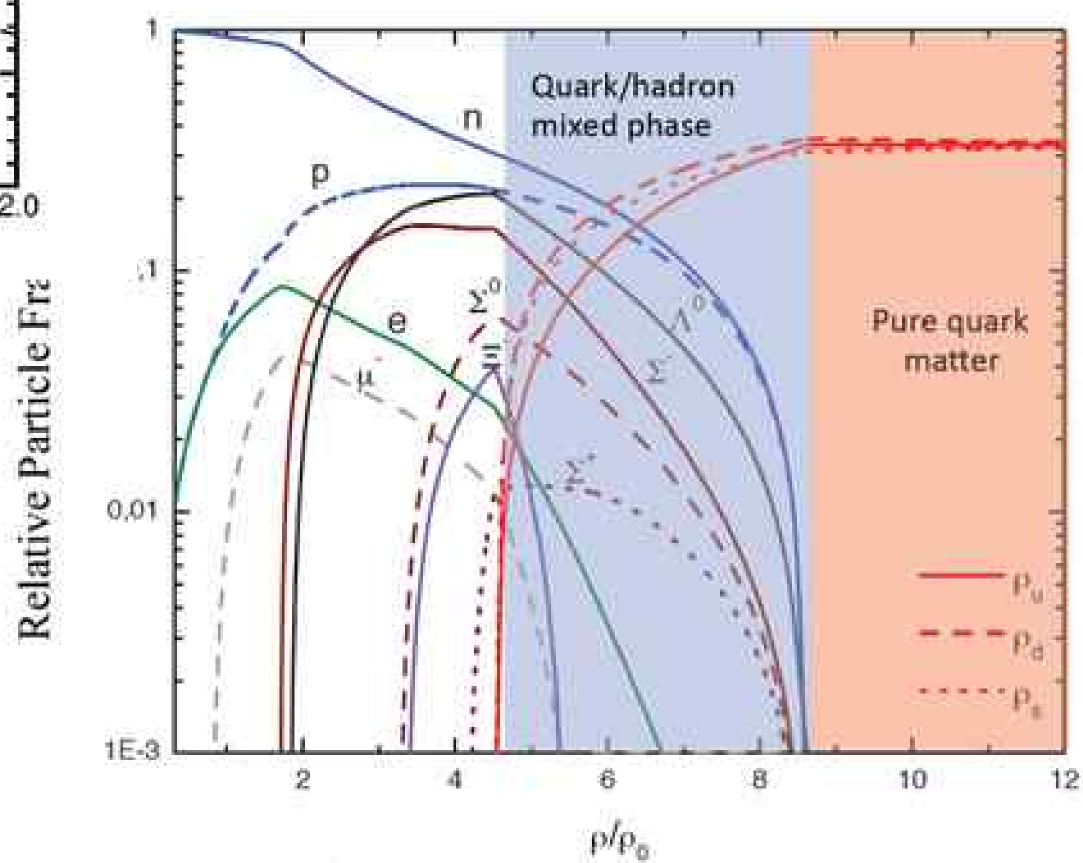


Baryon densities at SIS100

I. Arsene et al. PRC75 034902 (2007)



Net-baryon density reaches a value 5-15 times of the normal matter (ρ_0= 0.17fm^{-3}): experimentally access the region of mixed / quarkyonic phase

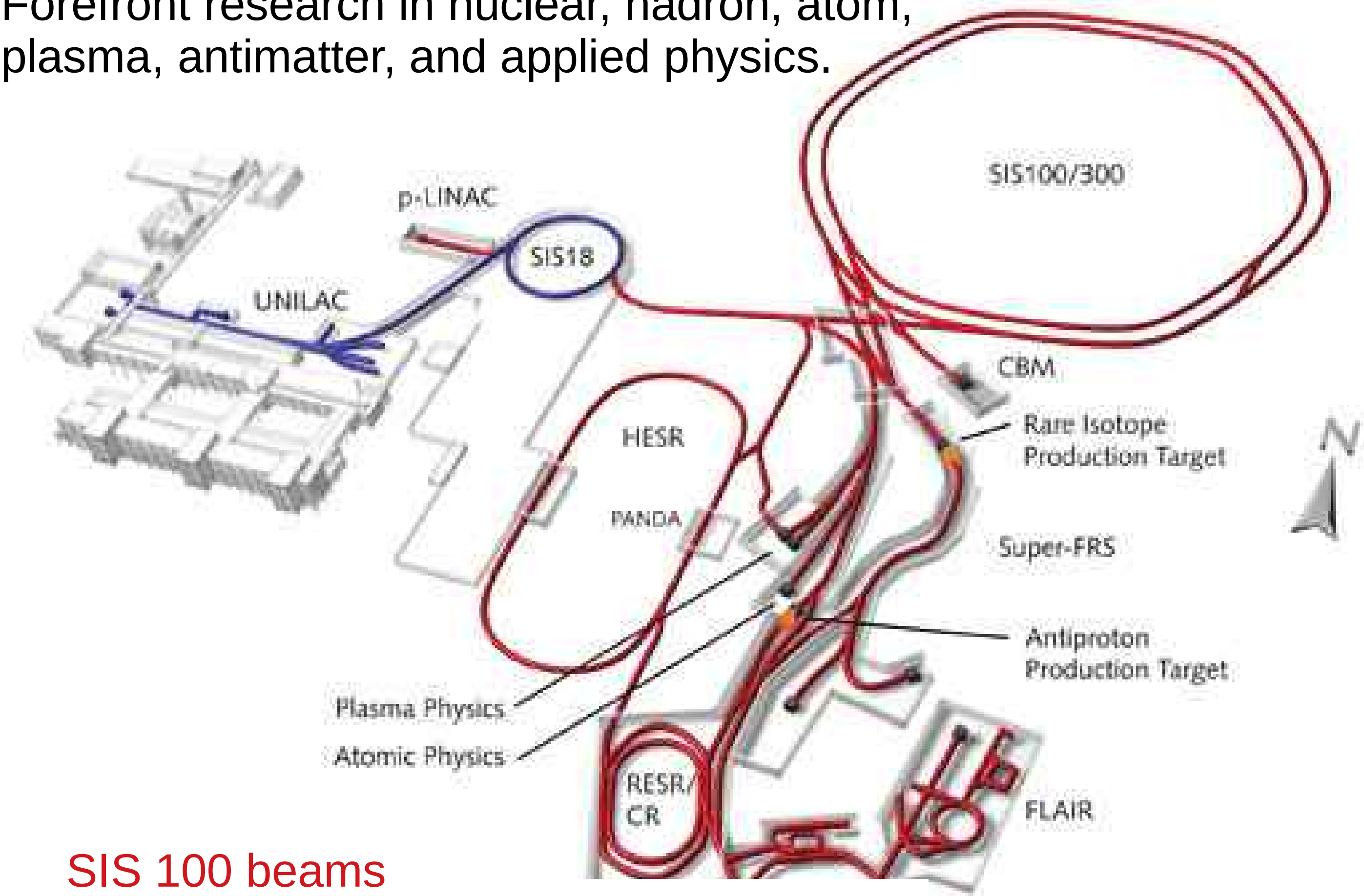


Quark matter equation-of-state at high baryon densities,coexistence (quarkyonic) & partonic phases:
- Hadron yields, collective flow, correlations, fluctuations
- (Multi-)strange hyperons (K, Σ, Λ, Ξ, Ω) production at (sub)threshold energies

Facility for Anti-proton and Ion Research (FAIR)

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

July 2017:
- Start of excavation and trench sheeting

January 2018:
- Civil construction north area awarded (SIS tunnel, CBM building)

July 2018:
- Start of shell construction

2022:
- Buildings completed (including CBM cave)

2025:
- Completion of full facility and start of operations

Financing: Germany 60%, Hessen 10%, partner countries 30%

~ 3000 users per year.

Member states: Germany, Russia, India, Poland, Romania, France, Finland, Sweden, Slovenia, Great Britain.

FAIR Project Status

Comprehensive civil construction plan: completion of all buildings by 2022

Full integrated planning for construction and commissioning of the entire project: Completion of the full FAIR facility by 2025.

2014: 1350 pillars 60 m deep

Ground breaking - 4 July 2017

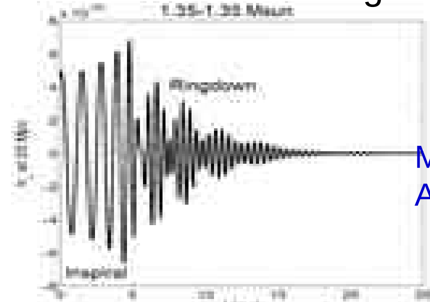
million cubic meters of earth to be excavated (5000 houses)
00,000 cubic meters of concrete to be used (8 soccer stadiums)
5,000 tons of steel to be utilized (9 Eiffel Tower)


FAIR

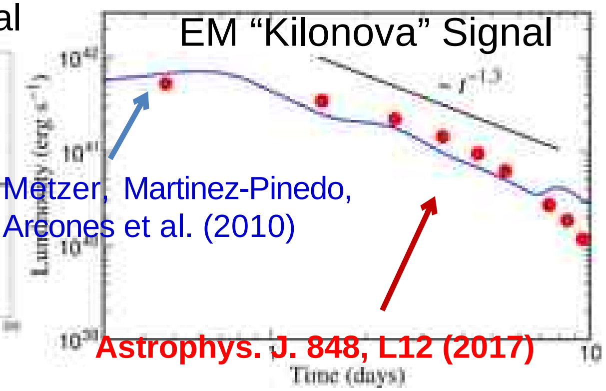
A broad experimental program

- Electromagnetic "Kilonova" theoretically predicted by GSI scientists in 2010.
- Confirmation by recent astronomical observations after gravitational wave detection from GW170817 (August 2017).
- Source of heavy elements including gold, platinum and uranium.

Gravitational Wave Signal

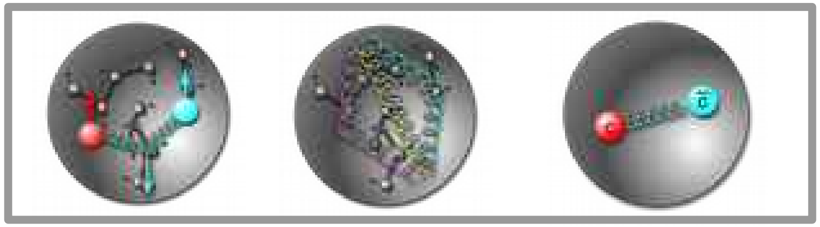


A. Bauswein

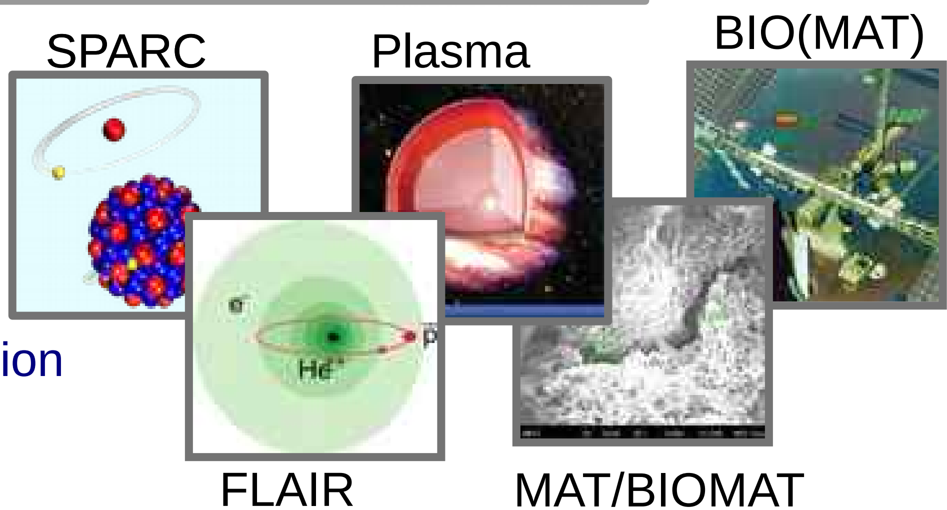


NUSTAR: Rare Isotope beams
-Nuclear structure
-Nuclear astrophysics: Origin of elements in universe?
→ Measurements in the laboratory: Mass, lifetime, decay channels, structure of very rare instable nuclei

- PANDA
  Hadron physics with Anti-protons
  - Gluonic excitations
  - Charmonium states
  - Time-like form factors, nucleon structure
  - In-medium mass modifications (charm)
  - Nuclear chart: double hypernuclei



- APPA (Atomic Physics, Plasma & Applied Sciences)
  - Strong field research (fundamental laws)
  - Anti-matter
  - State of matter in planetary interiors
  - Material Science: radiation hardness, modifications
  - Aereospace engineering: shielding of cosmic radiation
  - Biophysics: tumor therapy



Compressed Baryonic Matter (CBM) Physics Case and Observable

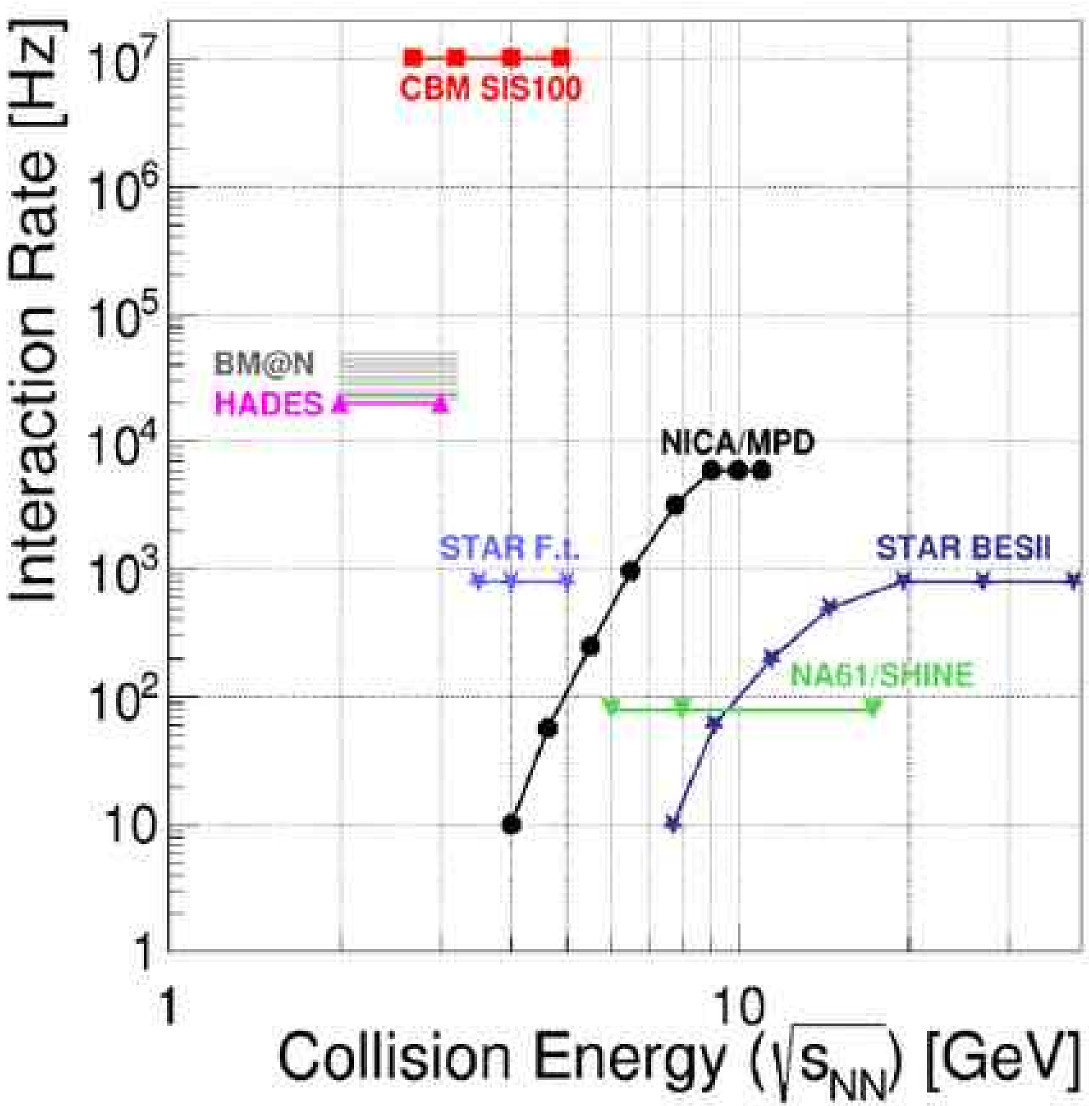
The collision of atomic nuclei at high speeds can simulate the conditions inside supermassive objects.

Exploration of QCD phase diagram at high baryon densities is an international effort:

- NA61 @ SPS / CERN
- BM@N @ Nuclotron/JINR
- STAR (BES I - II, F.t.) @ RHIC/BNL
- MPD @ NICA / JINR

CBM's unique feature:
interaction rates up to 10 MHz!
→ High statistics measurement of rare probes becomes possible

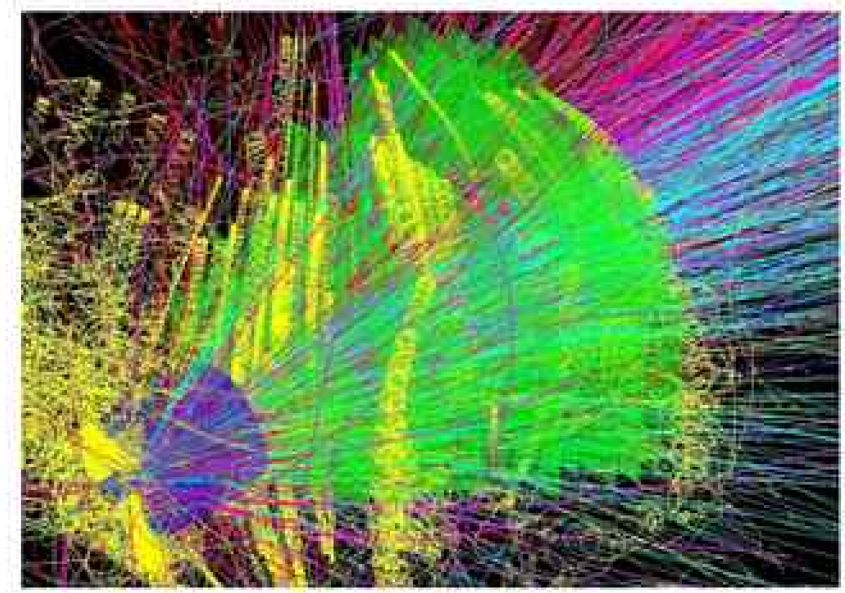
- (multi)strange hyerons
- Hypernuclei
- Charm
- Dileptons



CBM Coll., arXiv:1607.01487

Experimental requirements

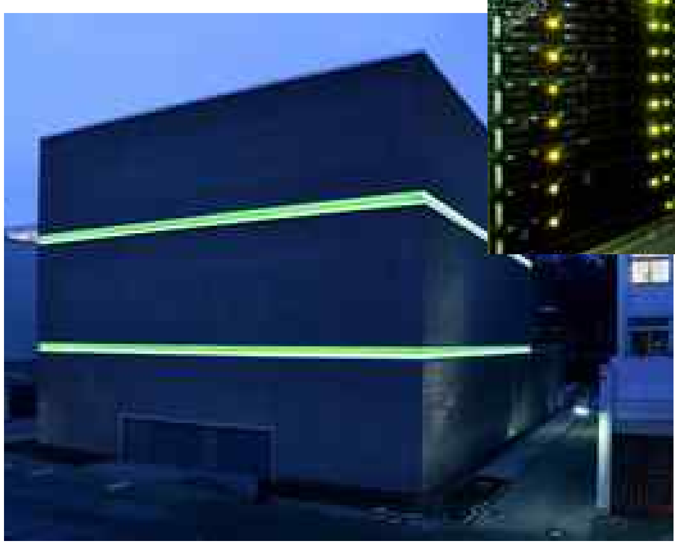
central Au+Au collision @ 10A GeV/c



Au+Au collisions
10^5 - 10^7 Au+Au reactions/sec
- require fast and radiation hard detectors and FEE
- but cannot be taped (~ 1 TB/s)

Needs online event selection
based on the desired physics observables
This requires
- determination of displaced vertices ($\sigma \approx 50$ μm)
- identification of leptons and hadrons

Green Cube (GSI)

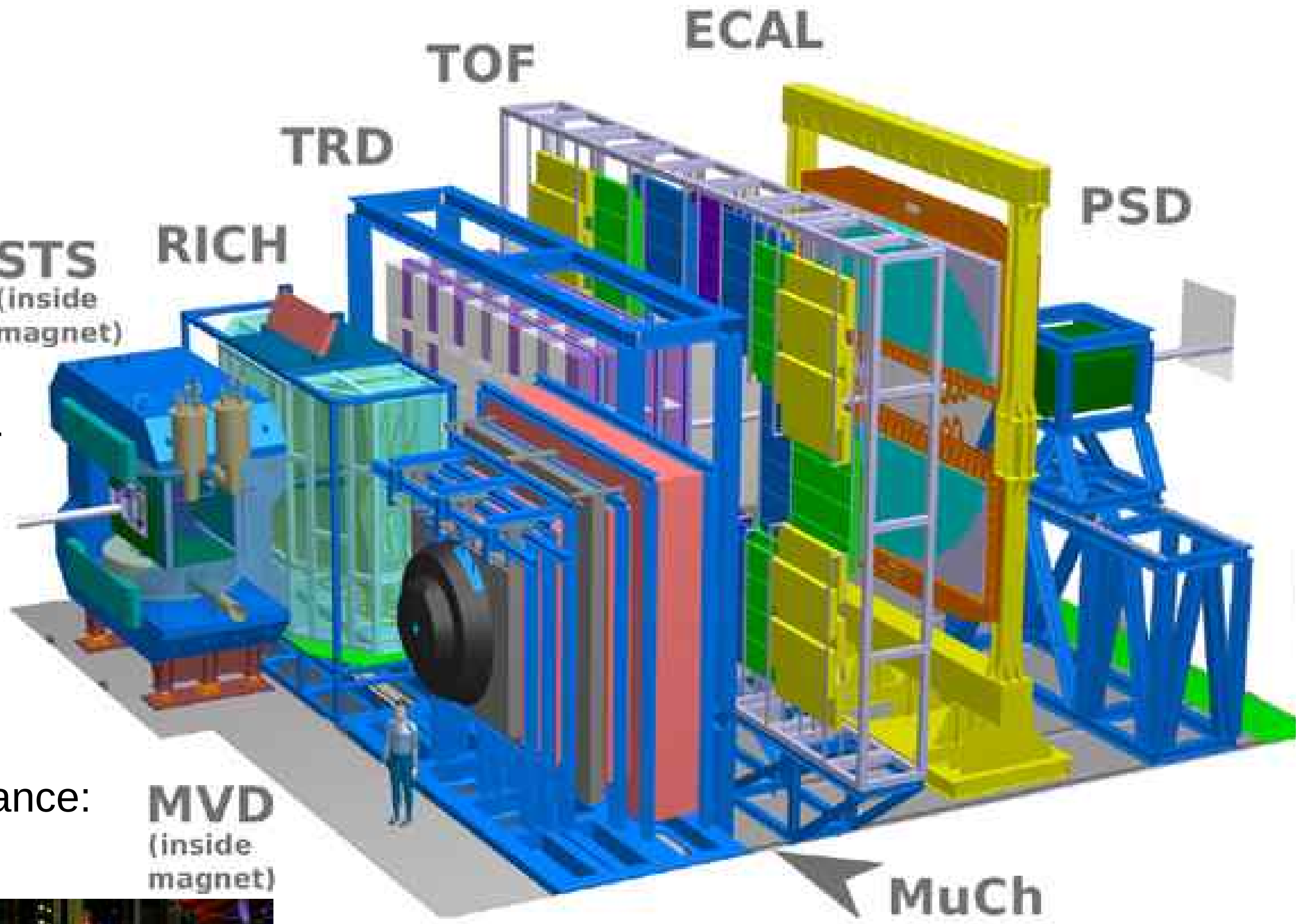


Therefore CBM operates
free streaming readout electronics
- high speed data acquisition
- high performance computer farm

for online event selection
→ 4-D (x,y,z,t) event reconstruction

The CBM detectors

Dipole Magnet
MVD
Micro Vertex Detector
STS
Silicon Tracking System
MuCh or RICH
Muon Chamber System /
Ring Imaging Cherenkov
Detector
TRD
Transition Radiation Detector
ToF
Time-of-Flight Detector
ECal
Electromagnetic Calorimeter
PSD
Projectile Spectator Detector



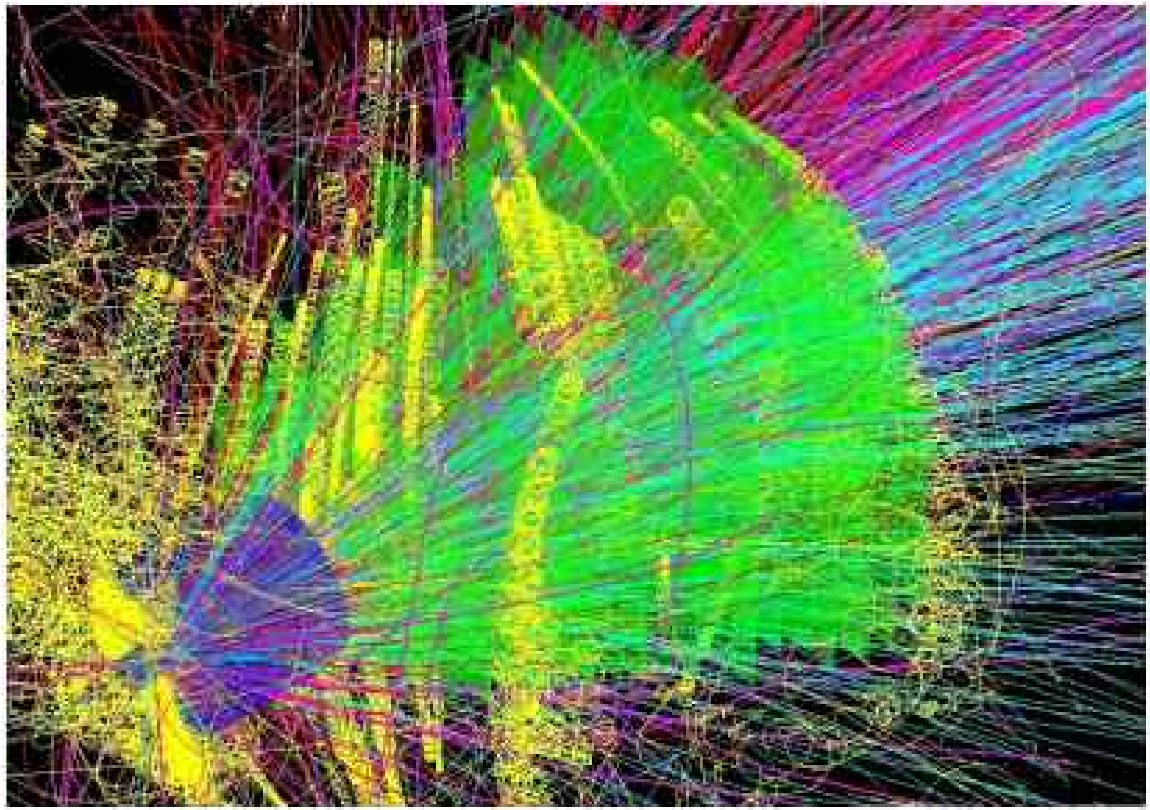
Tracking acceptance:
$2^o < \theta_{lab} < 25^o$

FLES
First Level Event Selector

Equation-of-state
Phase transitions
Hypernuclei

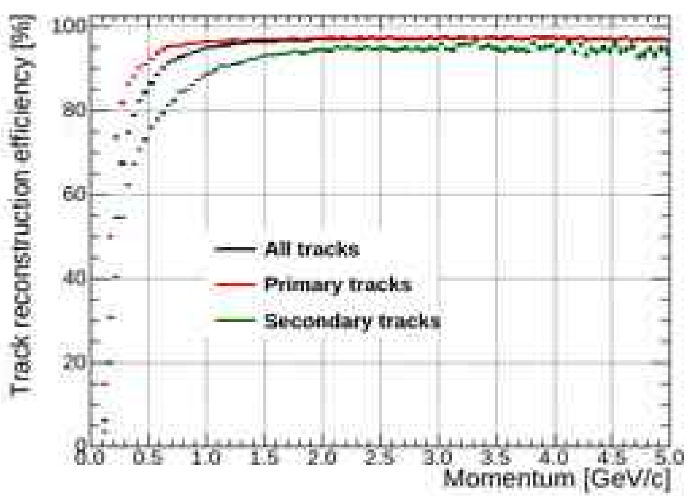
Tracking and event reconstruction

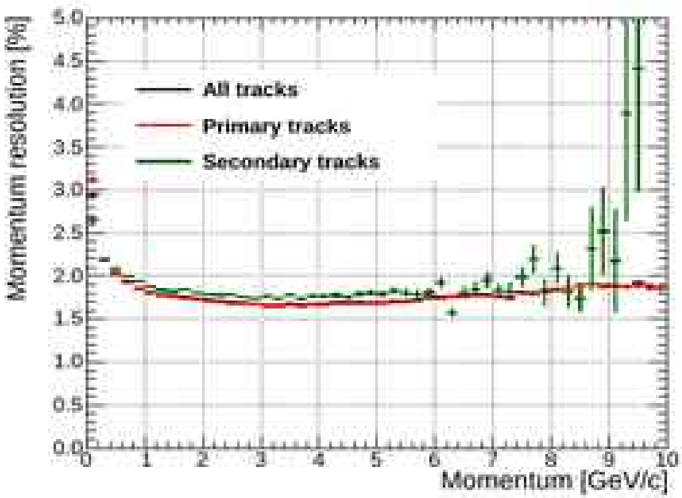
central Au+Au collision @ 10A GeV/c



High multiplicity collisions
→ almost 1000 particles
- High efficiency ~97% for p_T > 1 GeV/c
- Excellent momentum resolution <2%

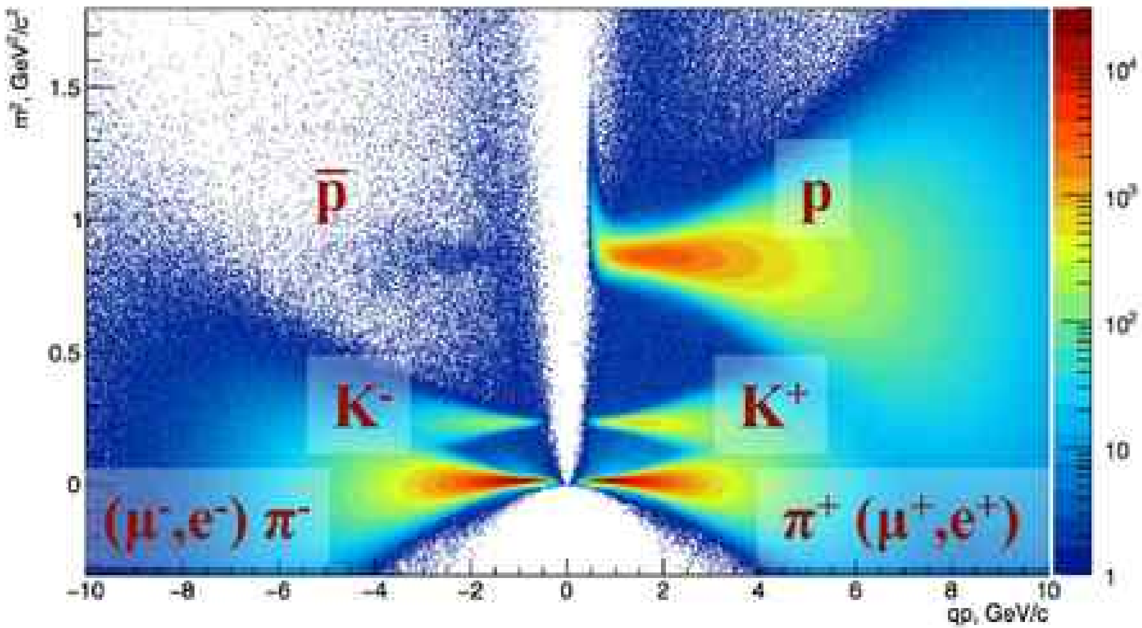
High interaction rate implies:
- Events in the selected time window (time slice) will overlap in time
- reconstruction in 4D (space, time)
- Decay topology reconstruction





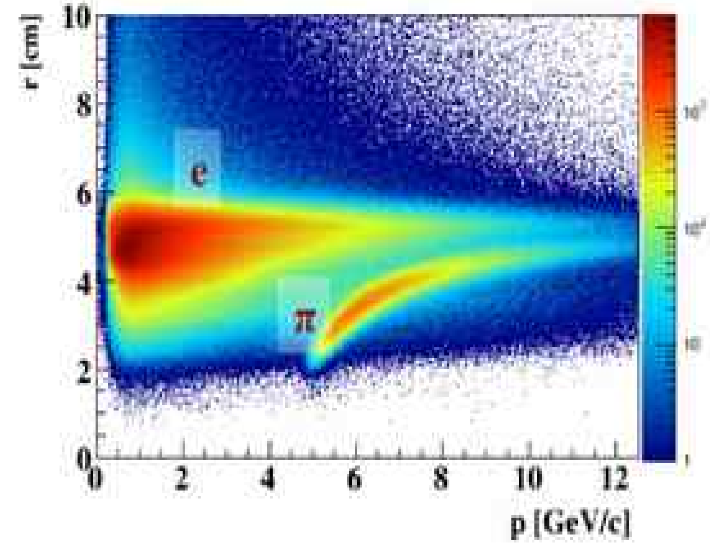
Particle Identification

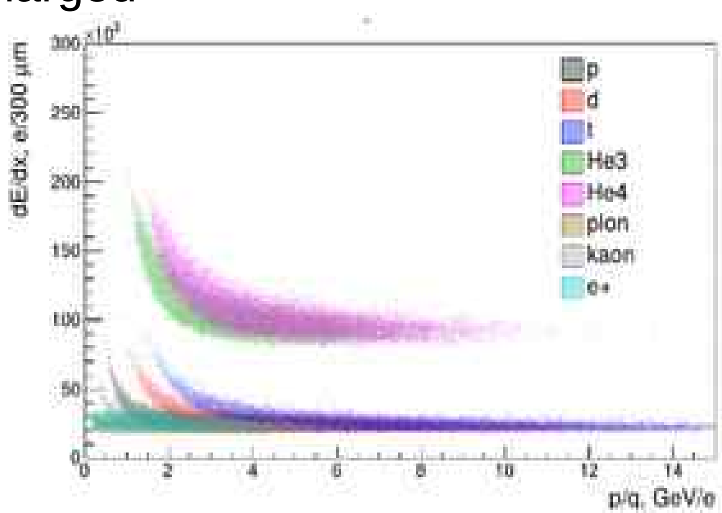
central Au+Au collision @ 10A GeV/c

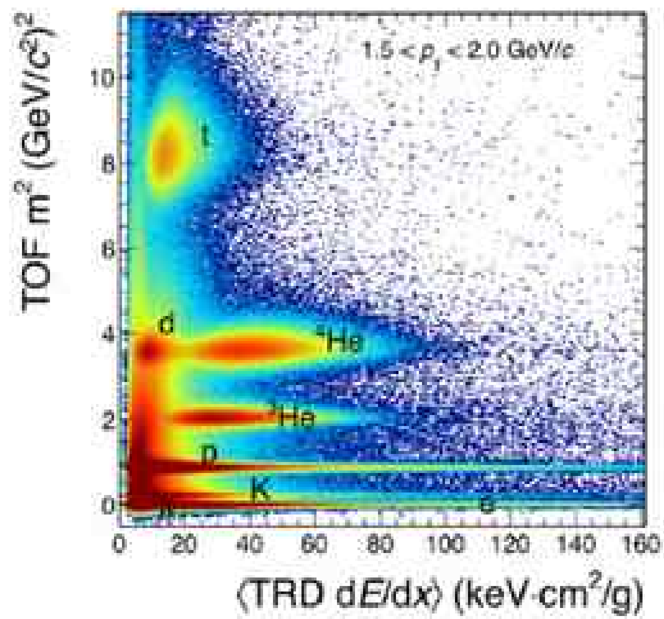


STS+ToF
High purity identification of charged protons, pions and kaons

+ RICH / TRD
pions, electrons, and light nuclei







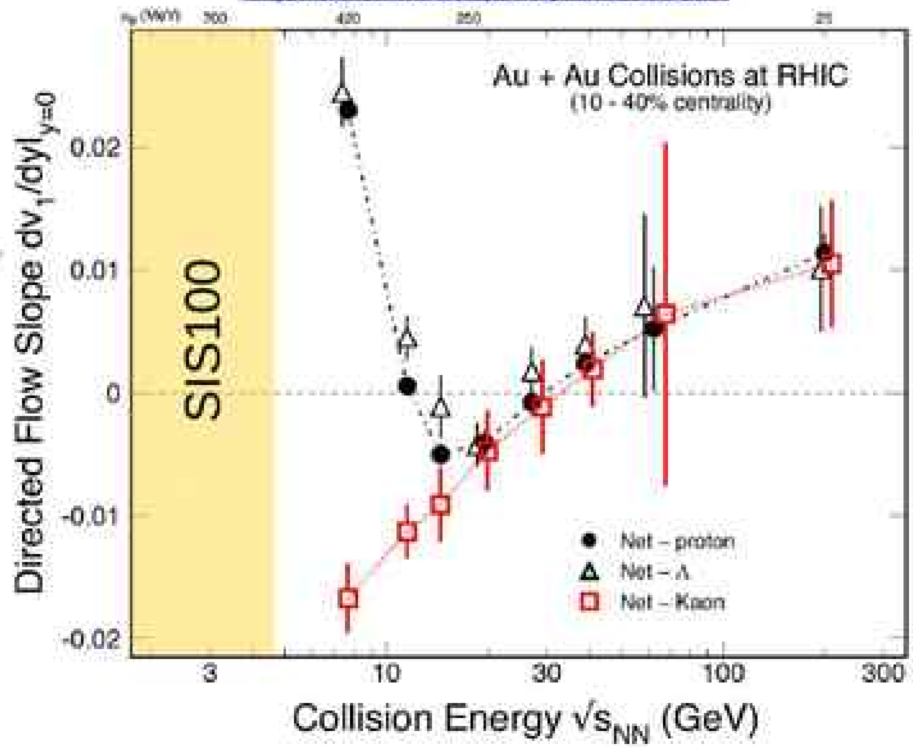
+ dE/dx in STS
distinguish heavy fragments

Flow

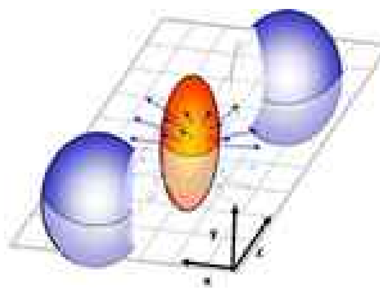
EOS of symmetric matter extracted from collective proton flow
→ driven by the pressure gradient in the early fireball

Au+Au collisions measured at AGS for beam energies from 2 to 11A GeV: → „The heavy-ion constraint“

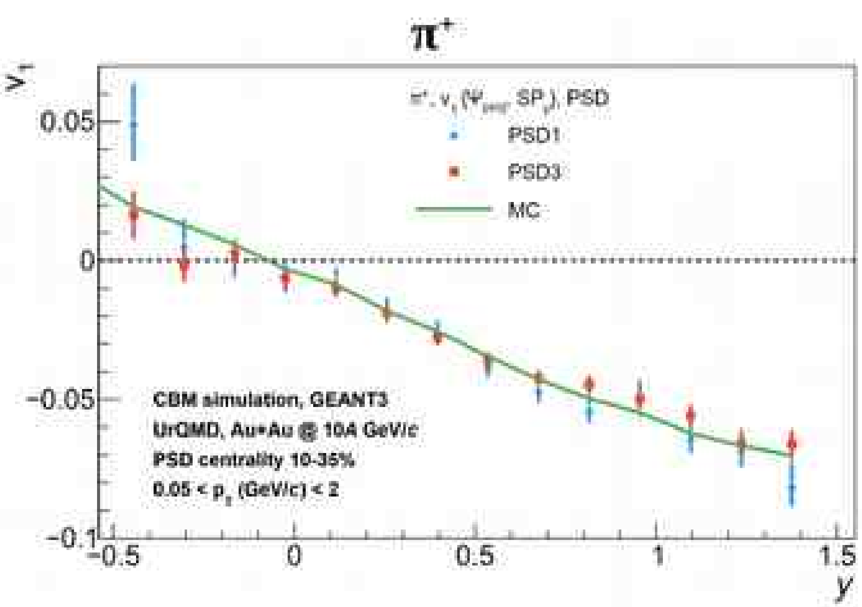
STAR Collaboration:
Phys.Rev.Lett. 120 (2018) no.6, 062301



Anisotropic flow v_n is defined via Fourier decomposition of azimuthal (φ) distribution of produced particles relative to the reaction plane Ψ_{RP}



$dN/d\varphi = C\,(1 + v_1 \cos(\varphi-\Psi_{RP}) + v_2 \cos(2\varphi-\Psi_{RP}) + \ldots)$



“input” model v_1 is recovered using “data-driven” method

Multi-strange hadrons

Ξ and **Ω** yield at subthreshold energies ~ multi-step collisions ~ density → EOS

Strangeness production:

pp → $K^+\Lambda^0 p$ (E_{thr} = 1.6 GeV)

pp → $K^+K^- pp$ (E_{thr} = 2.5 GeV)

multi-strange hyperon production:

pp → $\Xi^- K^+K^+ p$ (E_{thr} = 3.7 GeV)

pp → $\Omega^- K^+K^+K^0 p$ (E_{thr} = 7.0 GeV)

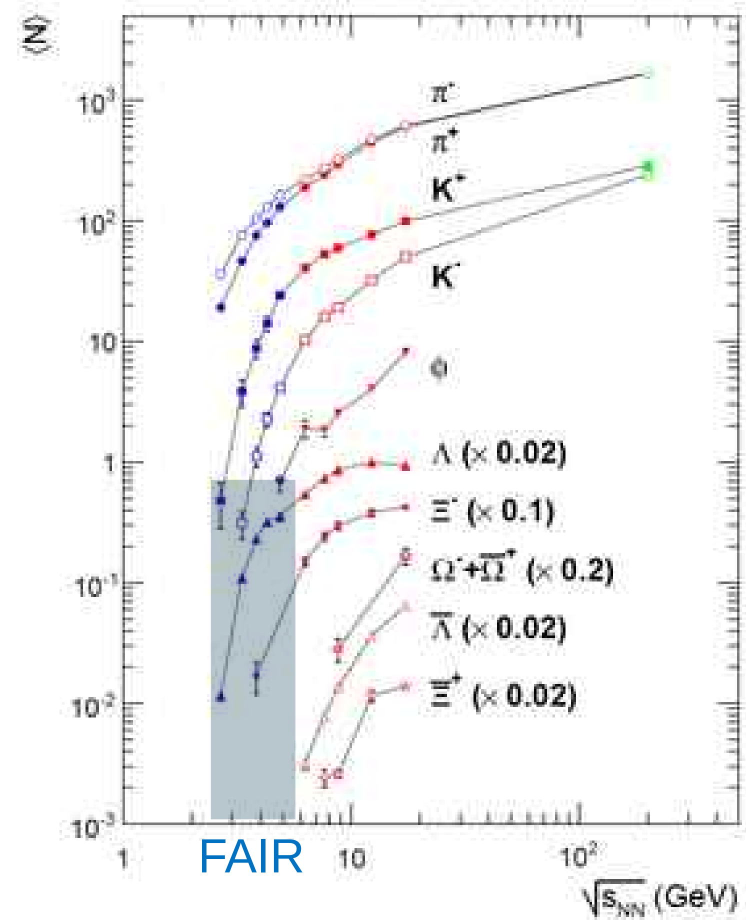
pp → $\overline{\Lambda}^0\Lambda^0$ pp (E_{thr} = 7.1 GeV)

pp → $\Xi^+ \Xi^-$ pp (E_{thr} = 9.0 GeV)

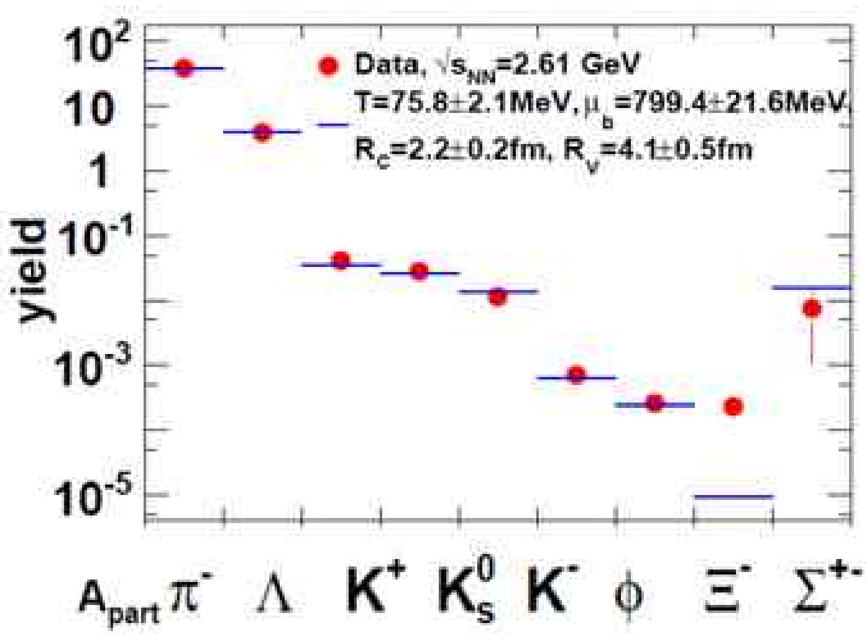
pp → $\Omega^+ \Omega^-$ pp (E_{thr} = 12.7 GeV

Hyperon production via multiple collisions

pp → $K^+p\Lambda^0$ →
pp → $K^+p\Lambda^0$ → $\Lambda^0\Lambda^0$ → Ξ^- p
pp → $K^+p\Lambda^0$ → $\Lambda^0 \Xi^-$ → Ω^- n



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



Particle yields and thermal model fits

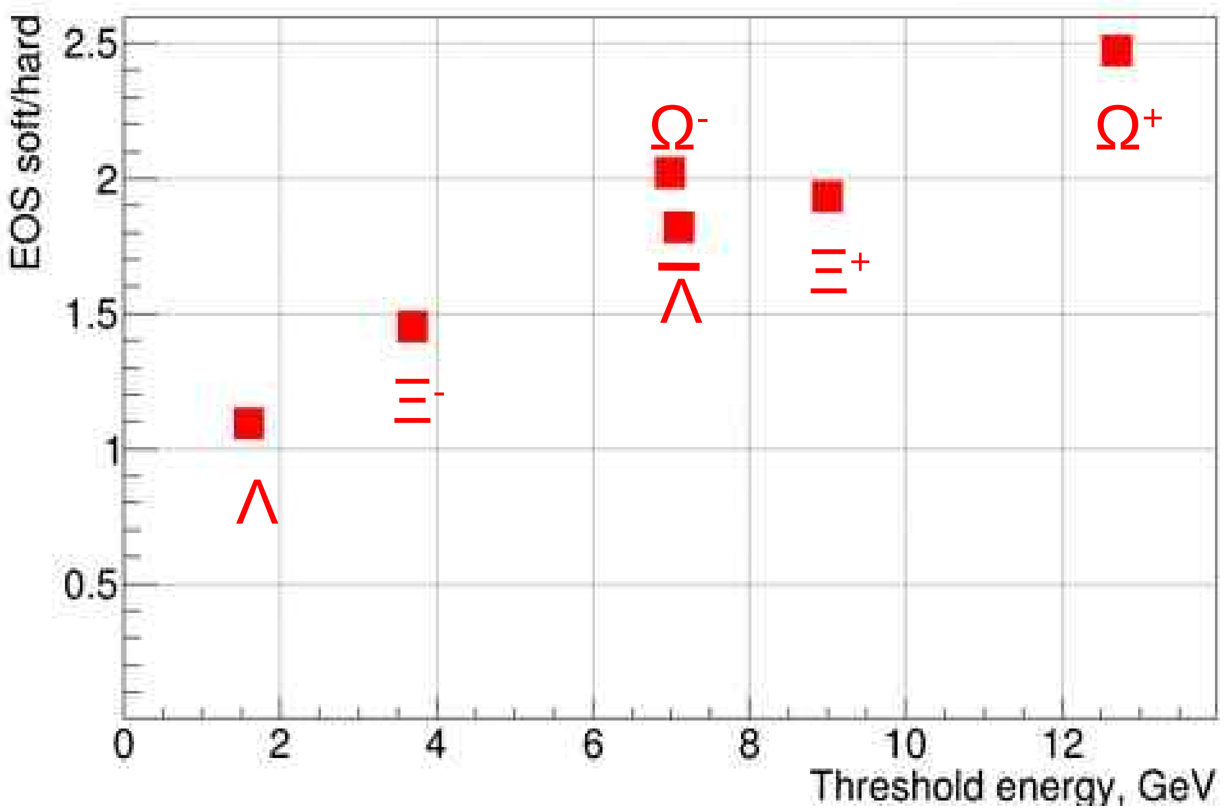
$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 dp}{\exp[(E_i-\mu_i)/T] \pm 1}$$

Multi-strange hadrons

Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density → EOS

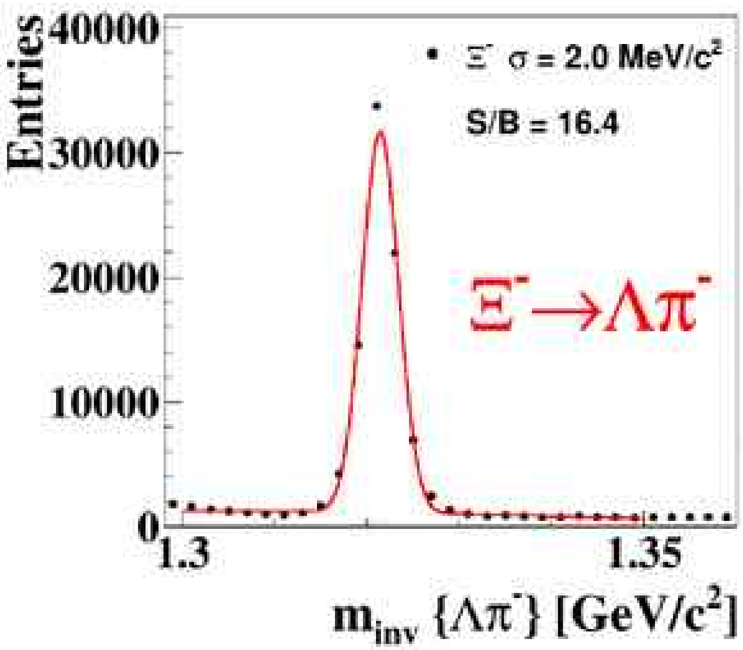
Excitation function of strangeness: Ξ^-(dss),Ξ^+(dss),Ω^-(sss),Ω^+(sss)
→ chemical equilibration at the phase boundary ?
sensitivity to EoS

Hyperon yield in 4A GeV Au+Au:
soft EOS / hard EOS



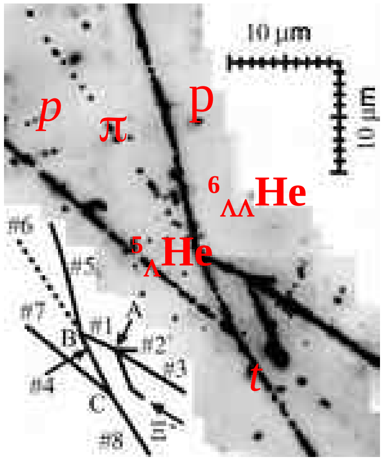
PHQMD calculations , J. Aichelin, E. Bratkovskaya, V. Kireyeu et al., priv. comm.

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

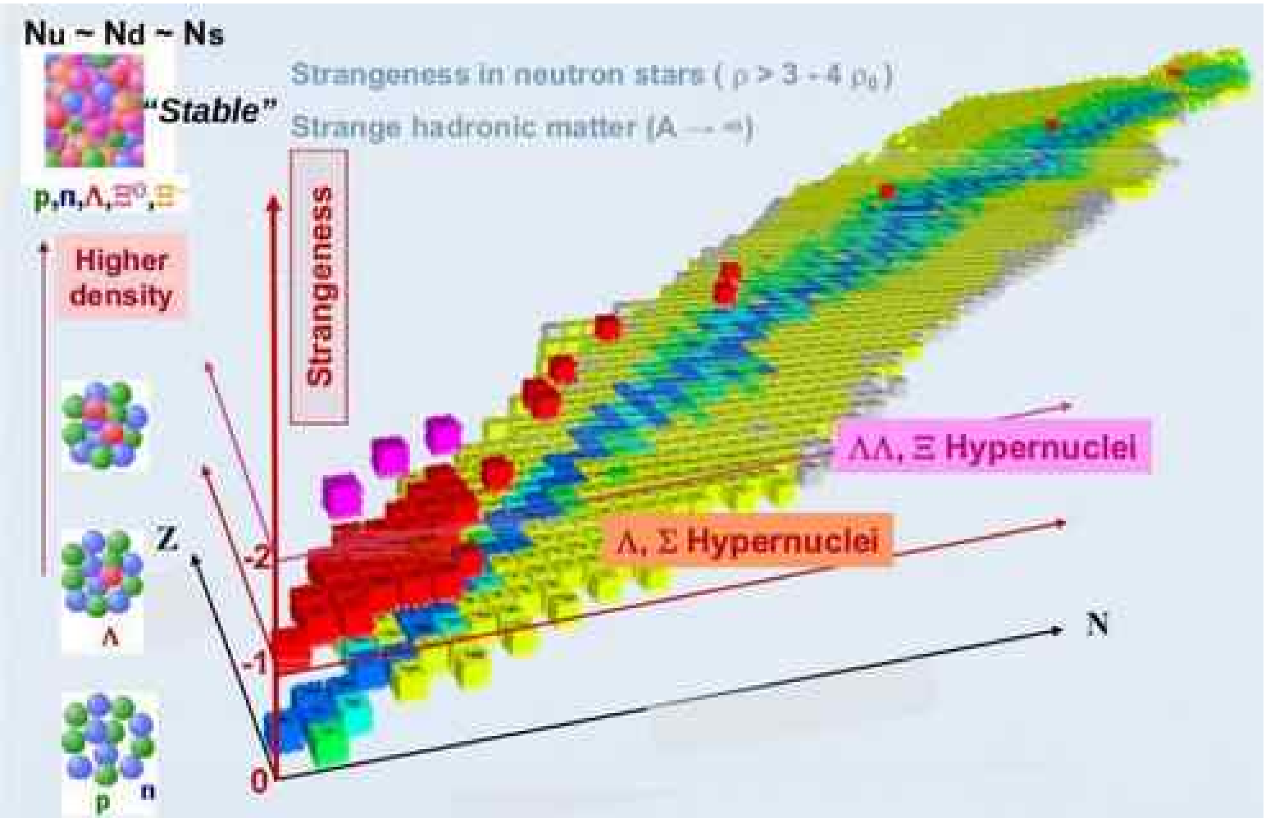


Hypernuclei

• Nuclei with at least one hyperon in addition to the normal 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

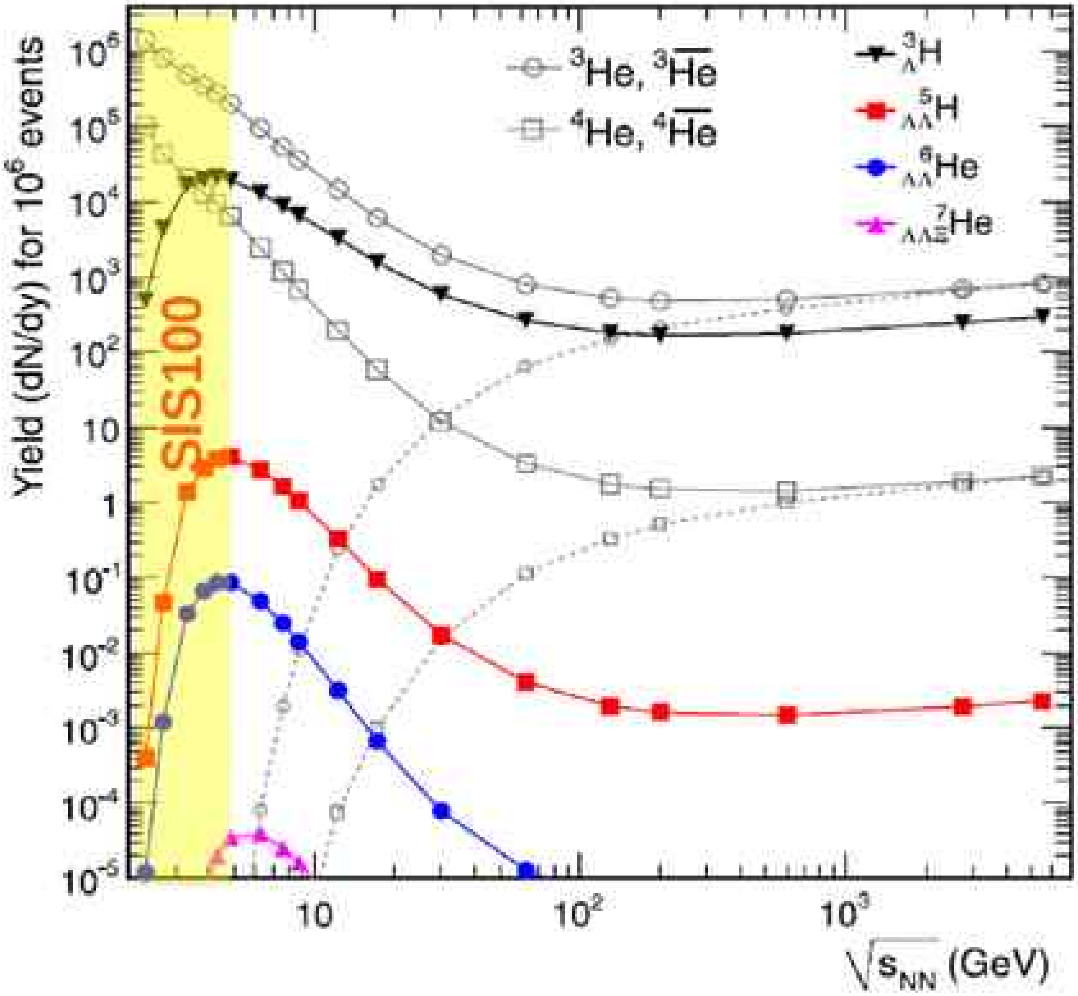


discovery by Danysz and Pniewski (1952) with nuclear emulsion technique.



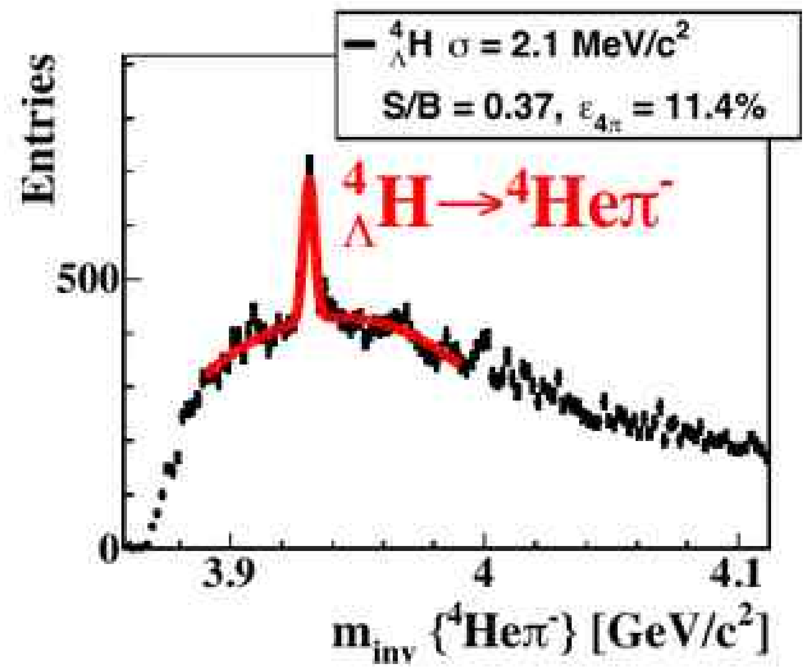
Hypernuclei in CBM

A. Andronic, PLB697 203 (2011)



•Highest production cross section
•Complex topology of decays can be easily identified
•Reliable identification of produced hypersystems.
•Access to ΛΛ-hypernuclei: high interaction rates, optimal collision energies and clean identification

CBM simulation
Au+Au @ 10A GeV/c, central, 10M events
+ thermal isotropic signal

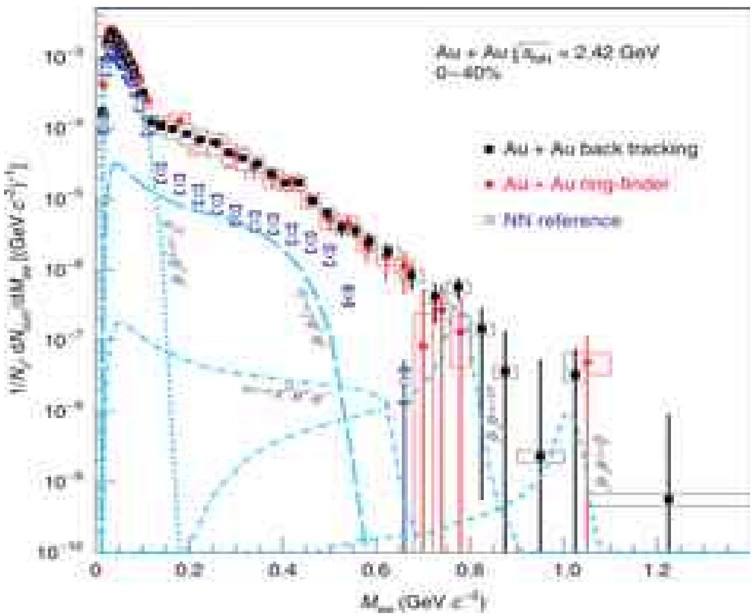


observables:

- yield
- lifetime
- collective flow

Thermal radiation

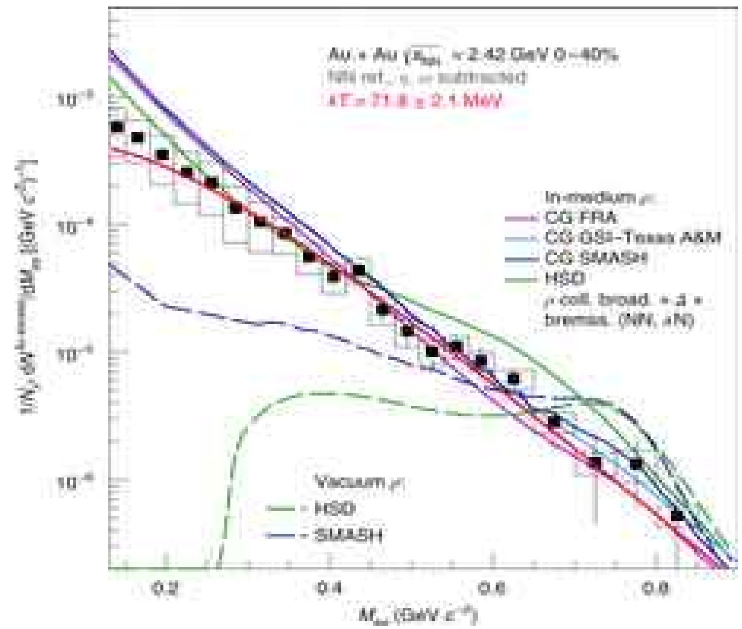
HADES @ SIS 18 has measured
Au+Au collisions at 1.25 A GeV ($\rho \leq 2.5\ \rho_0$, T ≈ 72 MeV)
excess of di-electron yield above NN reference



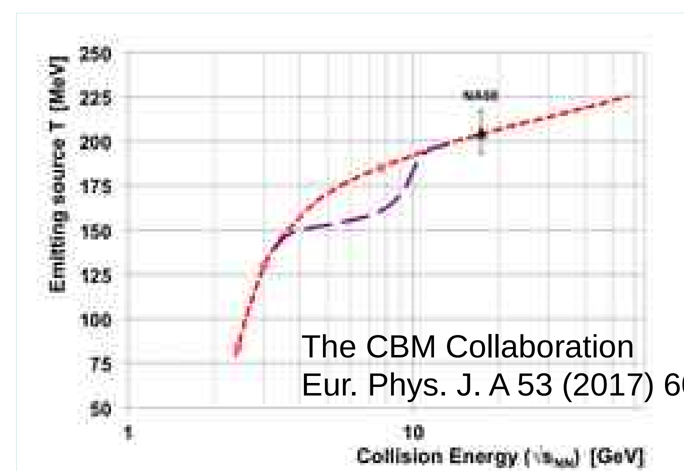
The HADES Collaboration, Nature Physics 2019,
https://doi.org/10.1038/s41567-019-0583-8

after subtraction of vector mesons

nearly exponential spectrum
→ thermal source
T ≈ 72 MeV



Slope of dilepton invariant mass spectrum 1 < M_{inv} < 2.5 GeV/c^2



The CBM Collaboration
Eur. Phys. J. A 53 (2017) 60

Invariant mass (M_{inv} > 1 GeV/c^2) of lepton pairs as function of beam energy
→ thermal radiation from fireball
→ caloric curve → phase coexistence (1st order transition)

Dileptons in CBM

Low Mass Region:

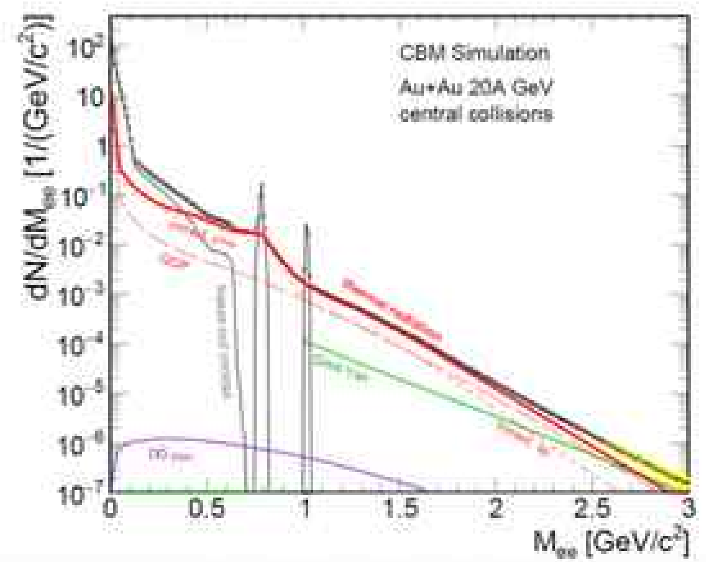
ρ – chiral symmetry restoration

fireball space – time extension

Intermediate Mass Region:

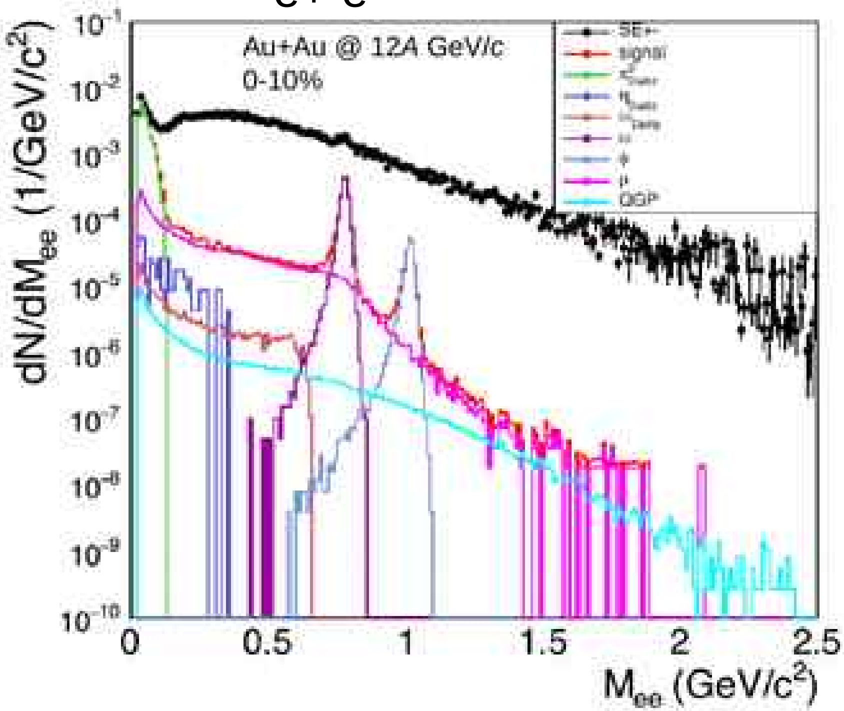
access to fireball temperature

excitation function

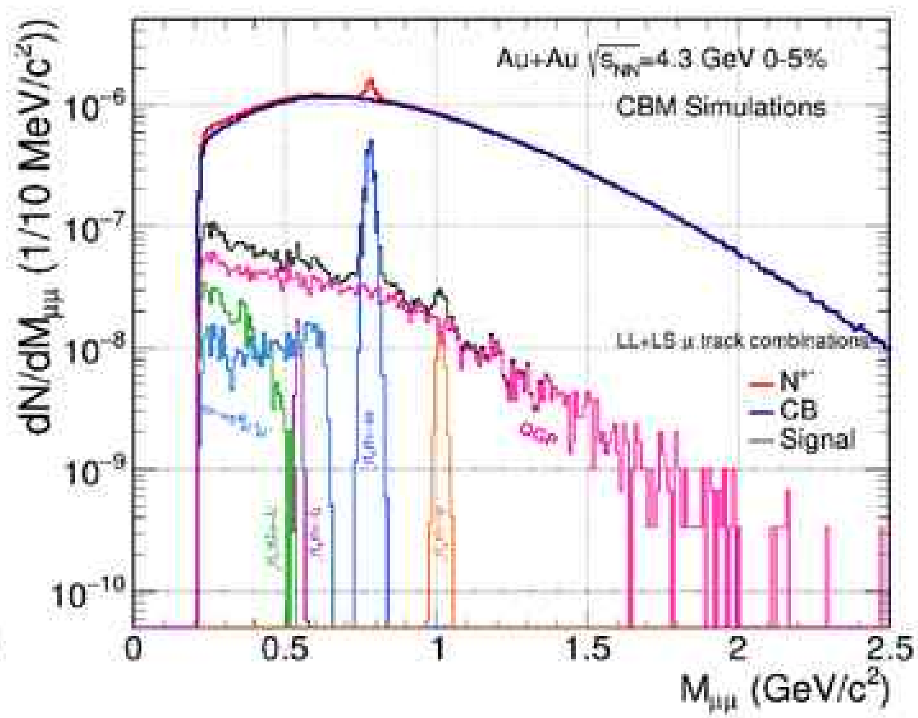


central Au+Au collision @ 8-12A GeV/c

e+ e-

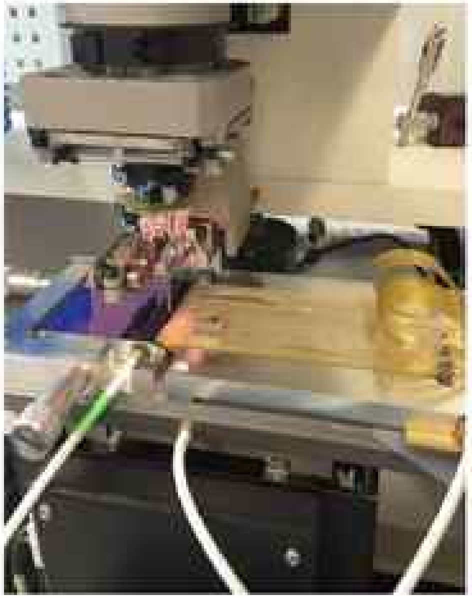


μ+ μ-



CBM Phase-0 Program

TOF @ STAR



STS @ BM@N

4 Silicon Tracking Stations in JINR (start 2020 with Au-beams up to 4.5A GeV)

BEFORE OPERATION IN 2025

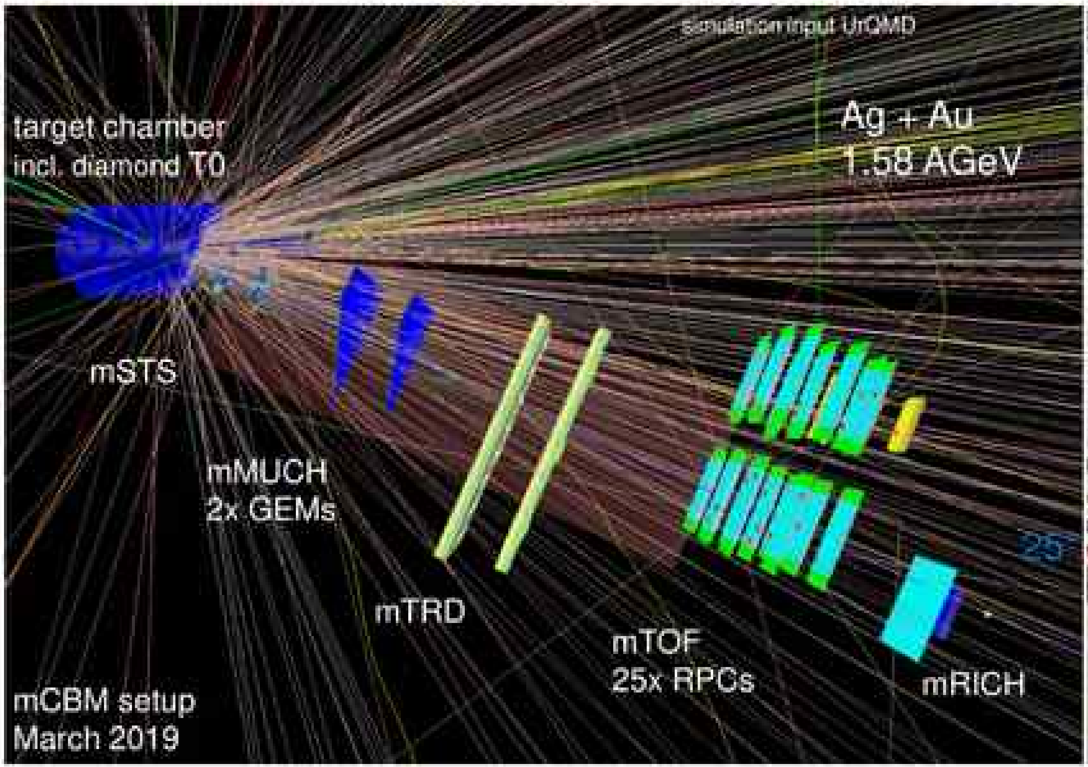
PSD @ BM@N / NA61/SHINE

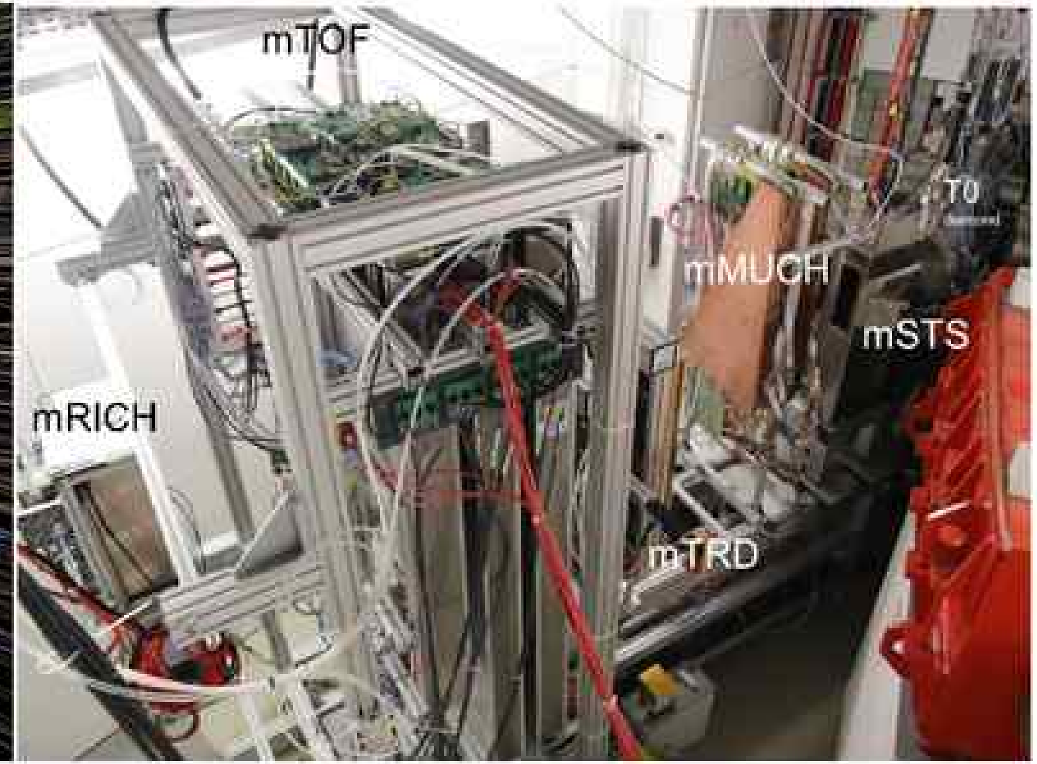
Use PSD modules @ BM@N & NA61/SHINE Tests and performance studies at the NA61/SHINE experiment @ CERN SPS

RICH @ HADES

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

mCBM @ SIS18 (GSI)





CBM full-system test for high-rate nucleus-nucleus collisions at the SIS18 facility

1st data taking 12/2018 & 03/2019, data analysis ongoing

- data transport of all subsystems in a common, synchronized data stream
- beam intensities up to 10^8 Ag ions/sec with collision rate up to 10 MHz
- peak data rate > 2.5 GByte/s

2nd data campaign: 11-12/2019 & 05/2020

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
- Dileptons
- charm
- Hypernuclei

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
● Intermediate FAIR phase-0 program: testing components and analysis methods