The status of the Compressed Baryonic Matter experiment at FAIR

Andrej Kugler for the CBM Collaboration
Nuclear Physics Institute Czech Academy of Sciences, Rez

Compact Stars in the QCD Phase Diagram, October 7-11, 2024, Kyoto

EUROPEAN UNION
European Structural and Investment Funds
Operational Programme Research, Development and Education
MINISTRY OF EDUCATION, YOUTH AND SPORTS
CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE
Nuclear Physics Institute of the CAS public research institution
The Czech Academy of Sciences

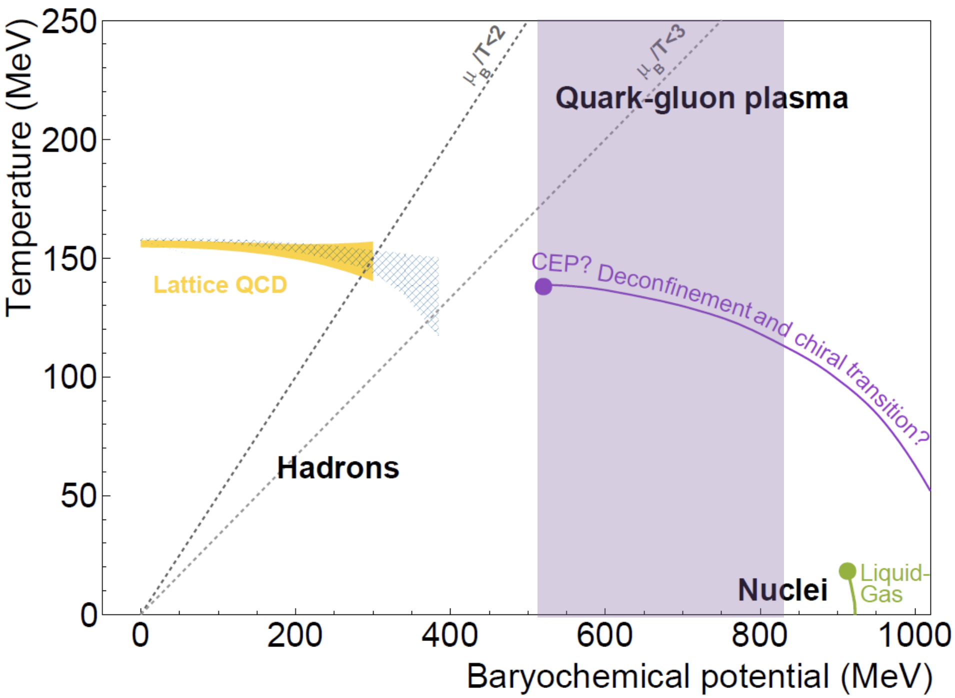
Road map

What are we pursuing and why? ⟹ **Physics motivation**

QCD phase diagram

Low μ_B, hight *T*:

- **Cross-over** transition from hadronic to quark matter - comprehensive studies of **QGP** properties
- No **critical point** anticipated for $\mu_B/T < 3$ (LQCD)



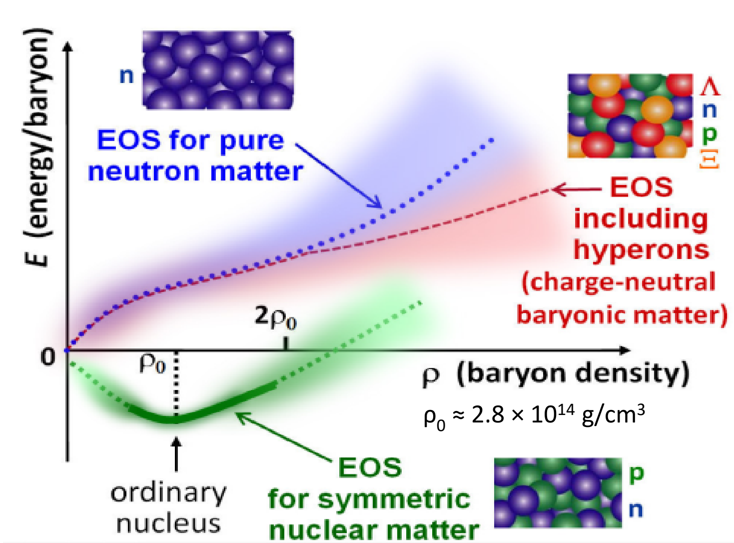
High μ_B, low *T*:

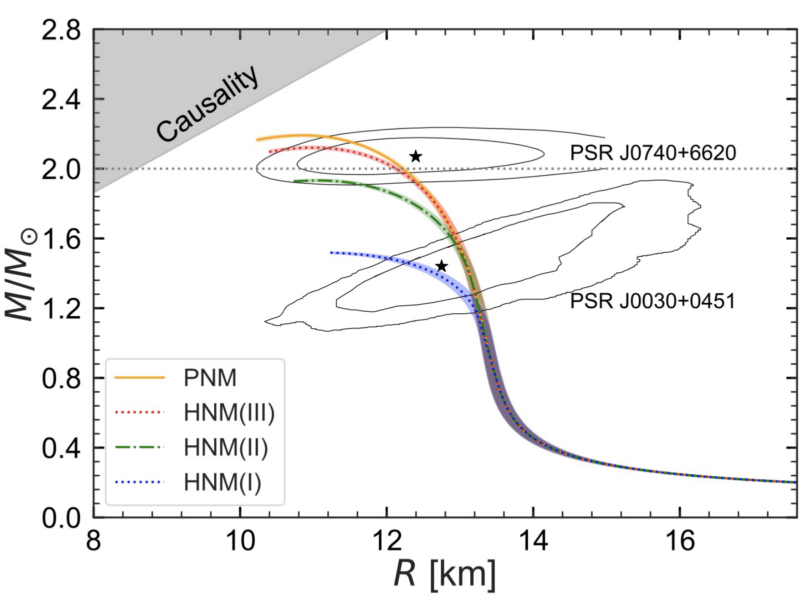
- Unknown **phase structure** (first-order phase transition, critical point possible, mixed phases, new phases, …)
- Properties of matter to determine
- Characteristics of hadrons
- Equation of State (**EoS**) to establish
- Neutron Star (**NS**)

Bazavovet al.[HotQCD], PLB 795 (2019) 15-21
Dinget al., [HotQCD], PRL 123 (2019) 6, 062002
Borsanyiet al., PRL125(2020)5,052001
Isserstedt et al. PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584

Neutron star (NS) puzzle

H.Tamura, JPS Conf. Proc. , 011003 (2014)





„To establish the EoS applicable to the neutron star has been one of the most important subjects in nuclear physics for a long time but has not been achieved yet." T. Hamura

Neutron star (NS) puzzle

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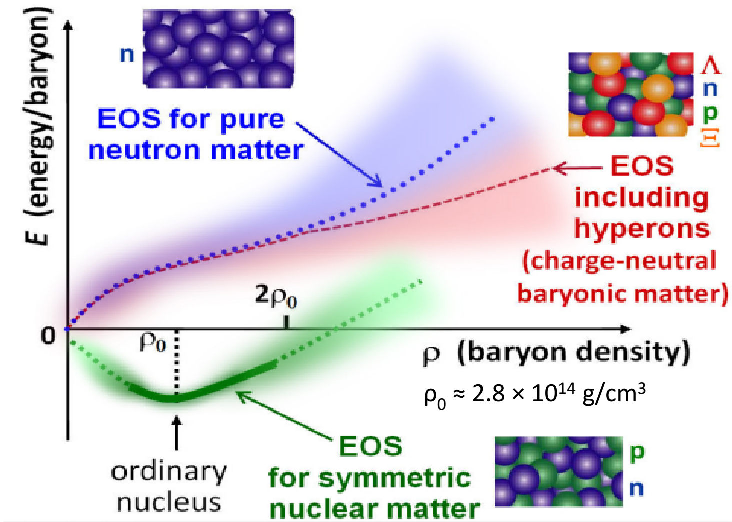

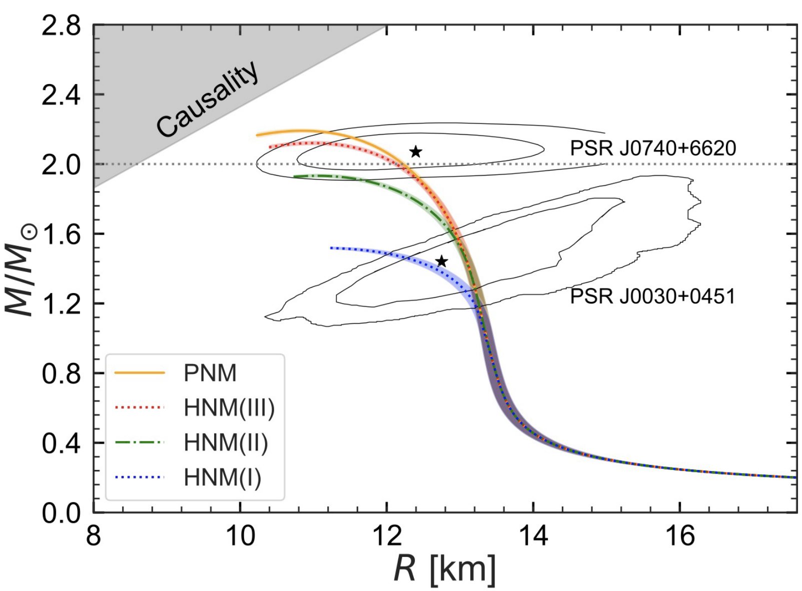

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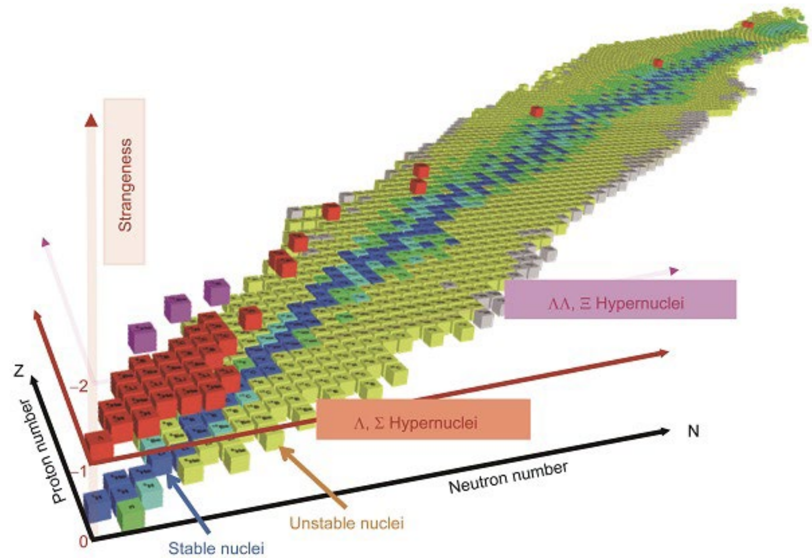


M. Kaneta, Department of Physics, Tohoku University, Japan

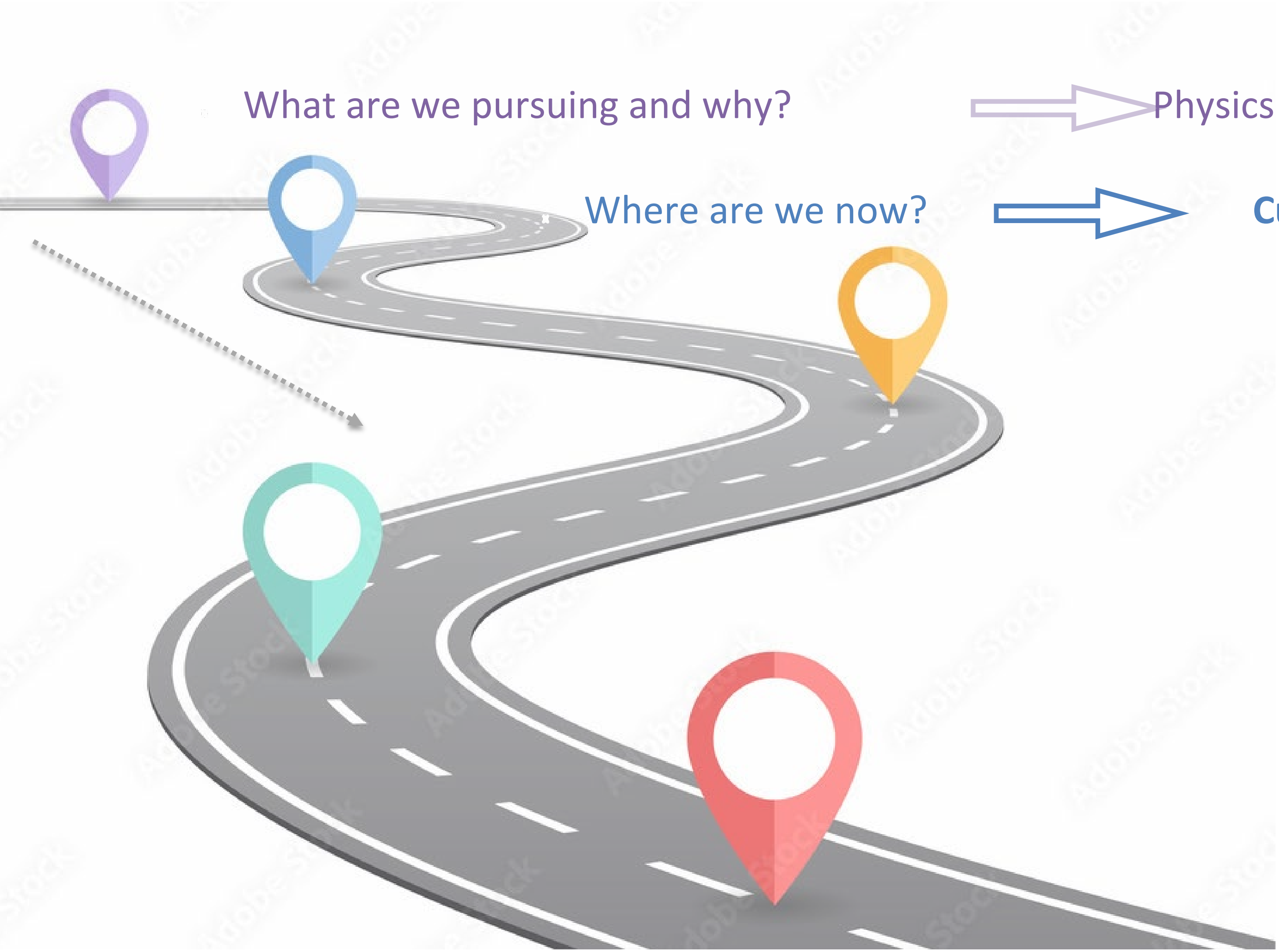
Hypernuclei are pivotal for the EoS of the NS

- How do nuclei and hyper-nuclei form?
- What are their characteristics?
- How do nuclei (N) and hyperons (Y) interact?

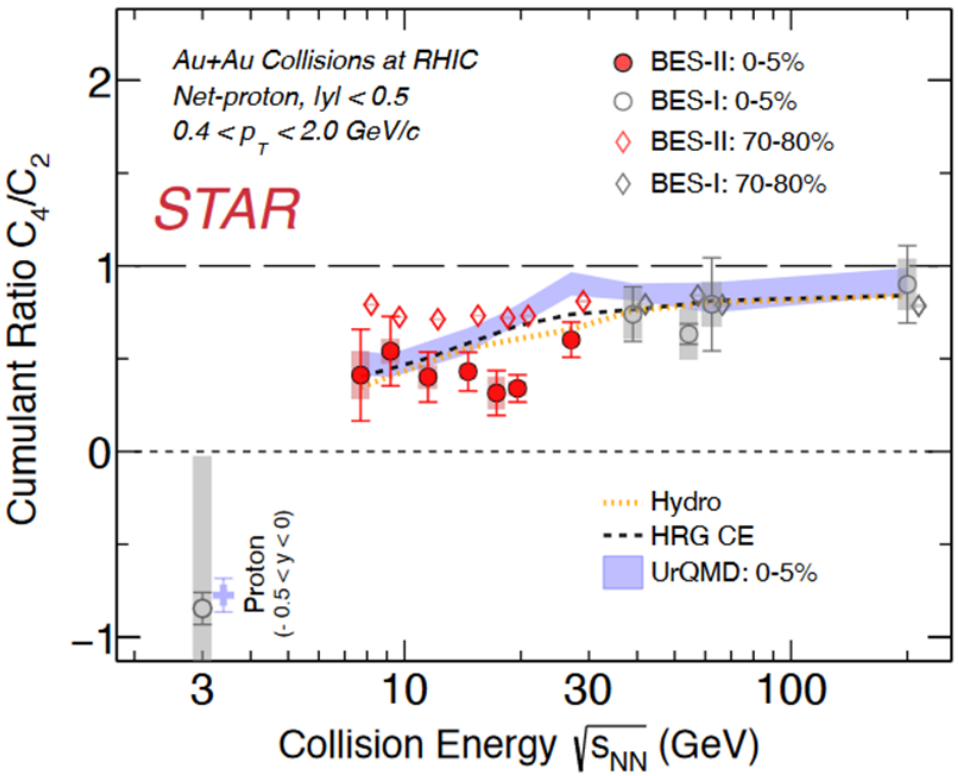
Road map

What are we pursuing and why? → Physics motivation

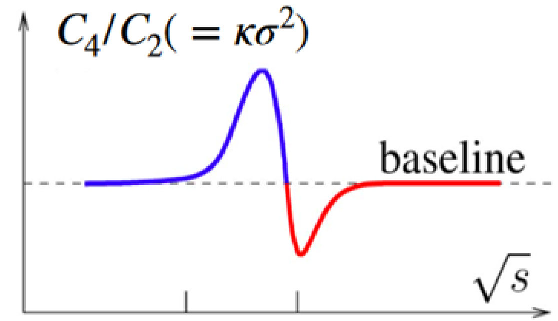
Where are we now? → **Current status**



Search for signatures of Critical End Point: Fluctuations?



A. Pandav for the STAR Collaboration at CPOD 2024



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

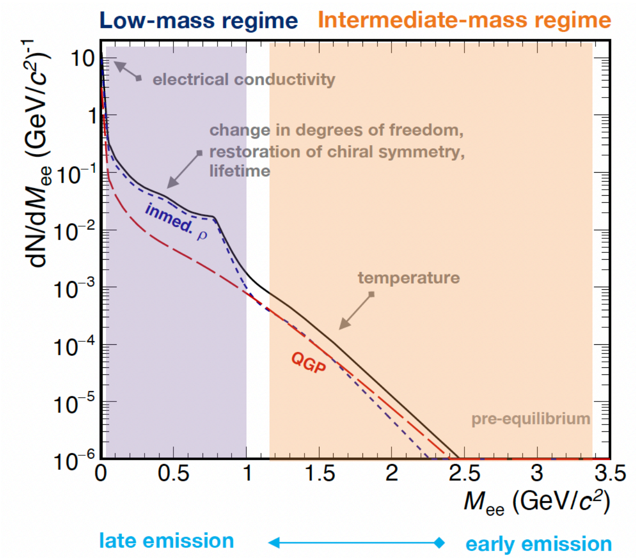
"….. Usual caveats apply: other (nontrivial) contributions to moments which do not behave singularly at the critical point can turn out to be relatively large. These include initial geometry fluctuations, jets, and other nonequilibrium effects. In addition, charge conservation effects may impose constraints on certain observables, such as total charge fluctuations. It is beyond the scope of this Letter to estimate these effects….."

→ Correction of reaction volume fluctuations using mixed events or pion multiplicites, see arXiv:2403.03598
R. Holzmann, A. Rustamov, V. Koch, J. Stroth

Higher-order moments requires prominent statistics

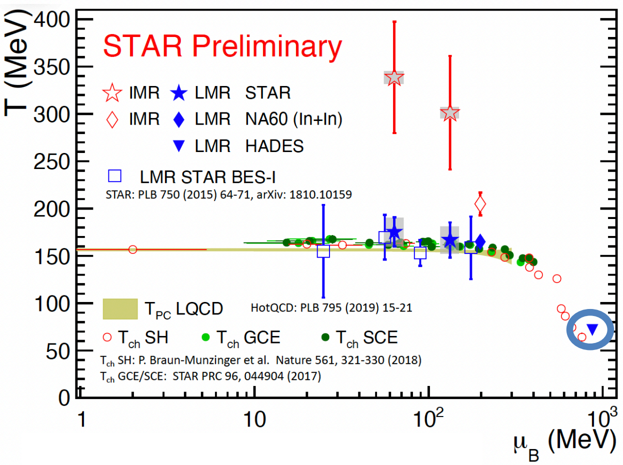
Detailed systematics studies indispensable

E-M probes access the whole collision



Inscribes matter properties enabling estimation:

- degrees of freedom of the medium
- fireball's lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry



Thermal dileptons in **LMR**:

- T close to T_{ch} and T_{pc}
- dominantly emitted around phase transition

Thermal dileptons in **IMR**:

- T is higher than T_{pc}
- Emitted fom QGP phase

Effective size-signal: $S_{eff} \sim R\frac{S}{B}$

R - interaction rate

S - signal

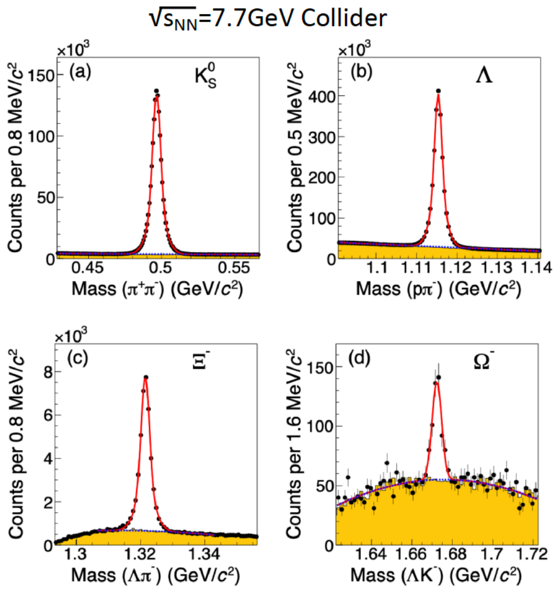
B- combinatorial background

Prominent interaction rate mandatory

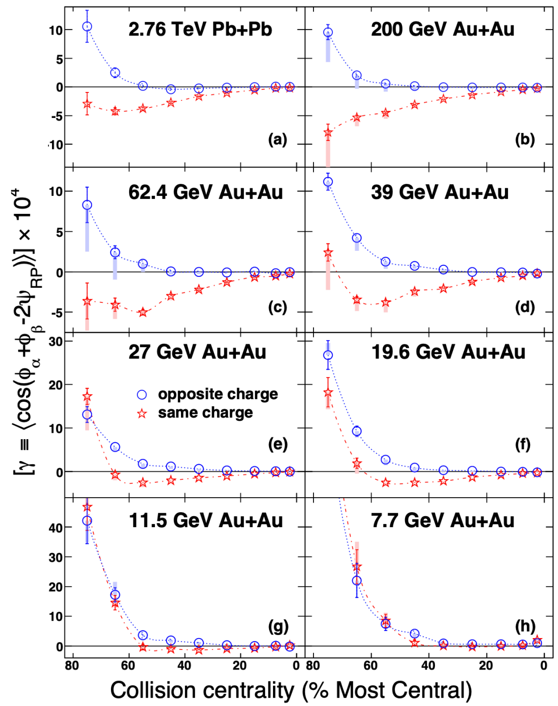
EPJC (2009) 59 607-623
Nature Physics 15, 1040-1045 (2019)
JPS Conf.Proc. 21 (2020) 010079

Flow of strange particles

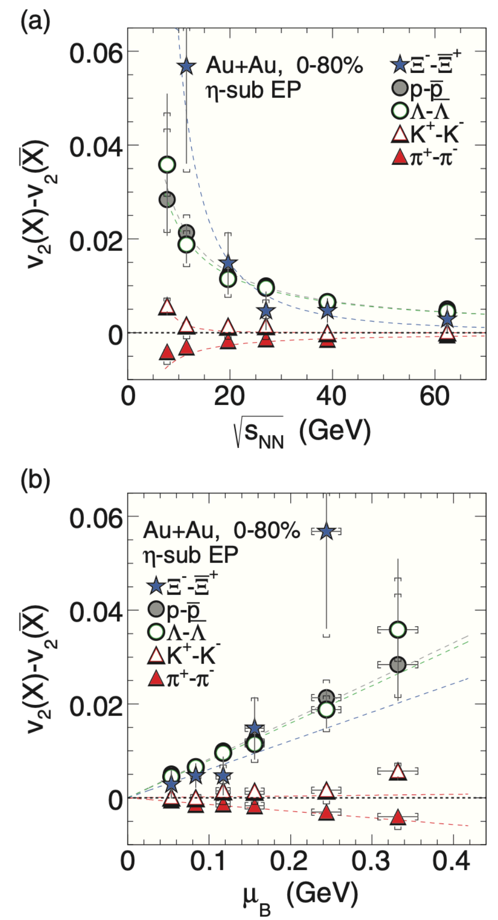
EoS investigations include vast number of measurements:
- Chemistry (strangeness, charm, hyper nuclei, …)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, …)



PRC 102 (2020) 34909 (STAR)



PRL 113 (2014) 52302



PRC 93 (2016) 14907 (STAR)

Road map

What are we pursuing and why? ⇨ Physics motivation

Where are we now? ⇨ Current status

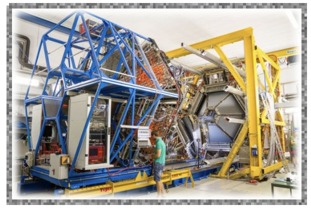
Who is involved?

⇨ **Experimental facilities**

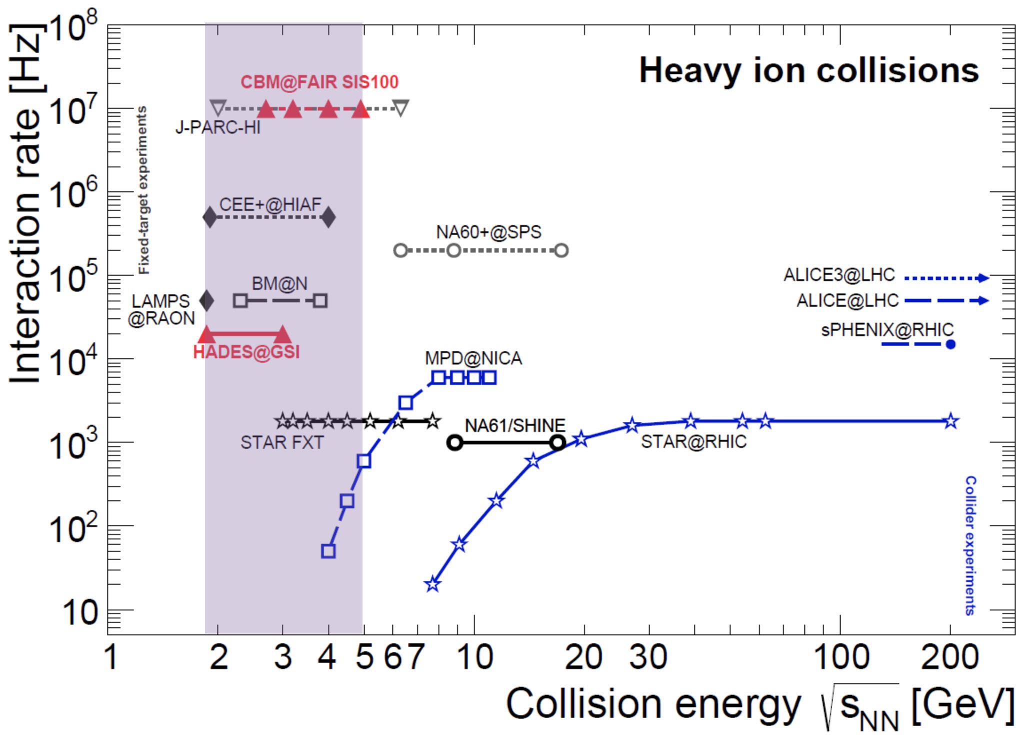
High μ_B facilities

NA61/SHINE@SPS

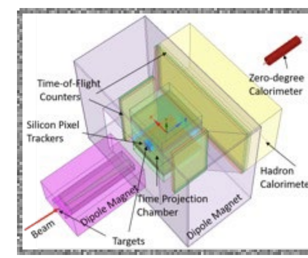
HADES@SIS18



STAR@RHIC



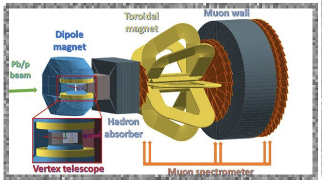
J-PARC-HI



T. Galatyuk, NPA 982 (2019), update 2024
https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

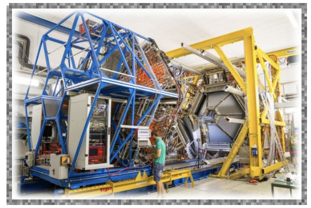
High μ_B facilities

NA60@SPS(>2030)



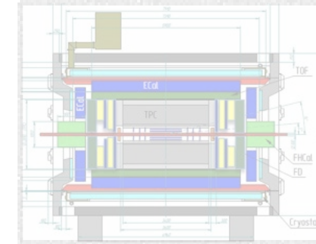
NA61/SHINE@SPS

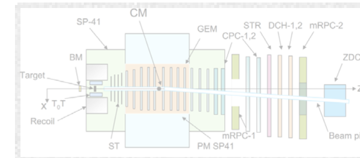
HADES@SIS18



CBM / HADES@ SIS100 (>2028)

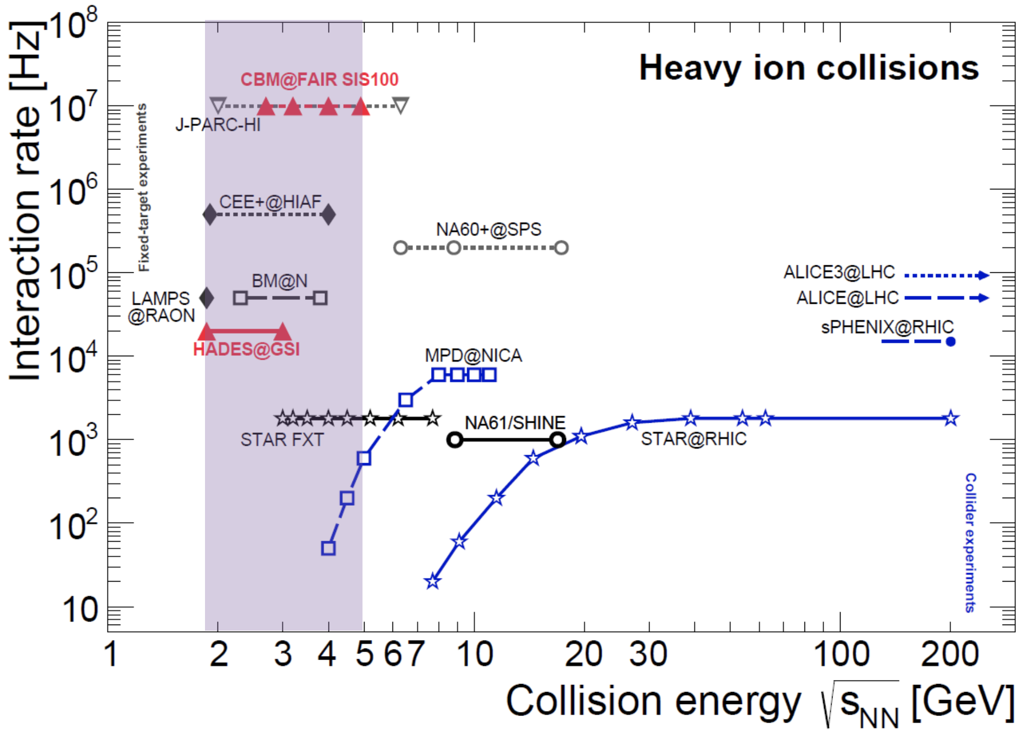
MPD, MB@N@NICA





STAR@RHIC

CBM / HADES: operations at $\sqrt{s_{NN}} \sim 2-5$ *GeV*



T. Galatyuk, NPA 982 (2019), update 2024
https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

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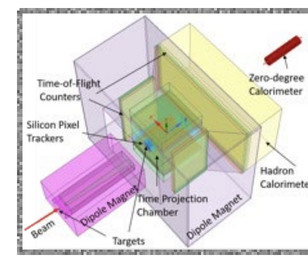
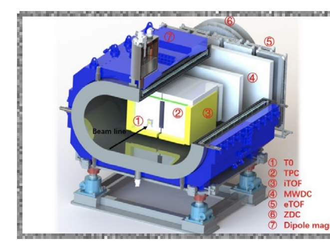


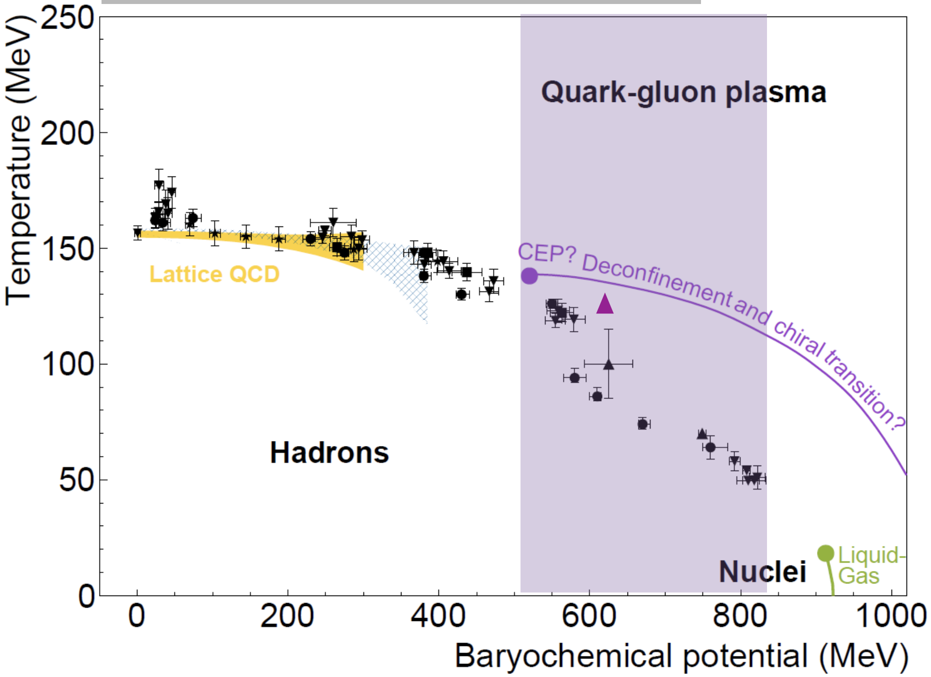
CEE@HIAF (>2027)



Coverage of the QCD phase diagram

CBM / HADES @ SIS100 experimental exploration of the region $\mu_B \sim 520 - 830\ MeV$

HADES; Nature Physics 15 (2019) 10, 1040-1045



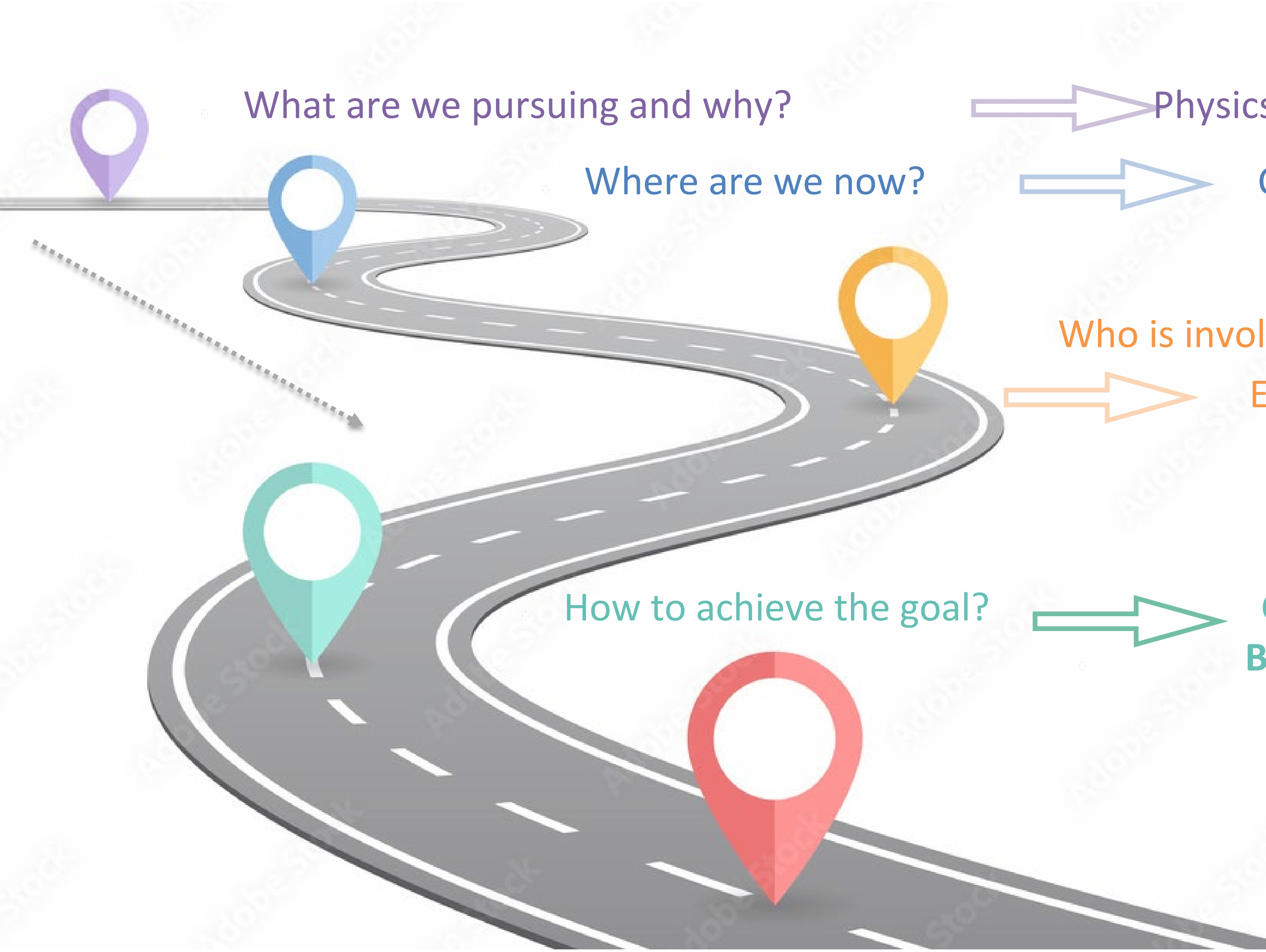
Bazavovet al.[HotQCD], PLB 795 (2019) 15-21
Dinget al., [HotQCD], PRL 123 (2019) 6, 062002
Borsanyiet al., PRL125(2020)5,052001
Isserstedt et al. PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584

Fu et al., PRD 101 (2020), 054032
Gunkel, Fischer, PRD 104 (2021) 5, 054022

	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)
HADES@SIS18	**2-2.5**	**830-760**
CBM@SIS100	**2.3-5.3**	**785-520**
NA61/SHINE@SPS	5.1-17.3	530-220
STAR-COLL@RHIC	7.7-200	400-22
STAR-FXT@RHIC	3-13.7	700-265

A. Andronic, P. Braun- Munzinger, K. Redlich and
B. J . Stachel, Nature 561, no. 7723, 321 (2018)

Road map



What are we pursuing and why? → Physics motivation

Where are we now? → Current status

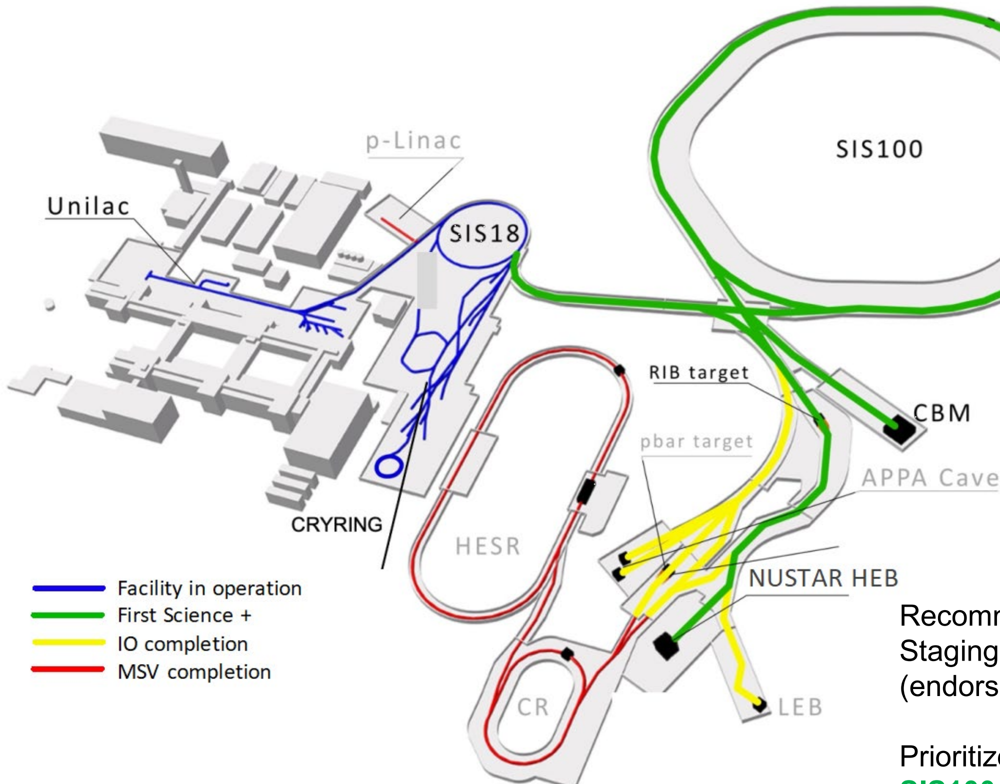
Who is involved? → Experimental facilities

How to achieve the goal? → **Compressed Baryonic Matter**

Facility for Antiproton and Ion Research

2018 start of **FAIR Phase-0**
~3 month beamtime/year

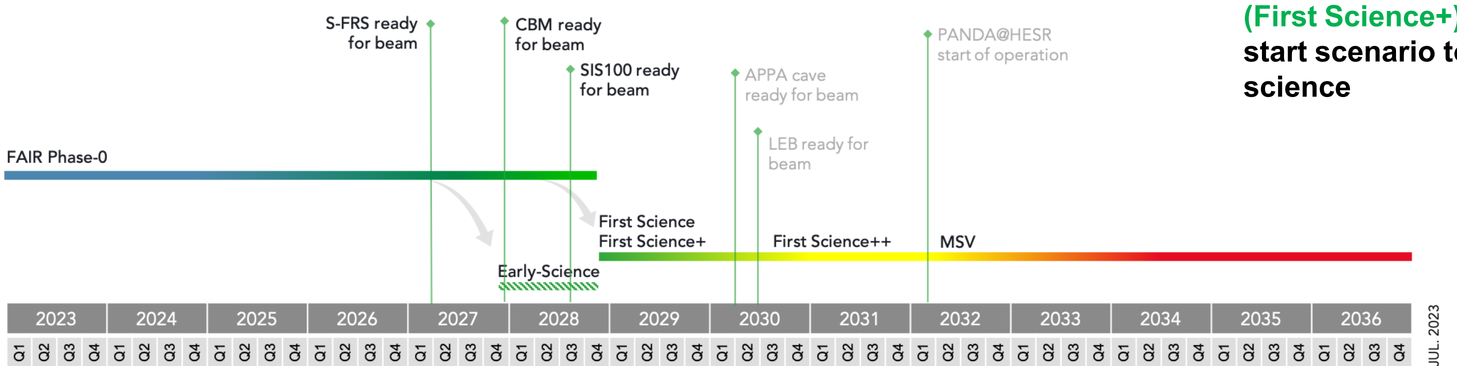
Intermediate forefront research program at GSI with improved beams and FAIR detectors



APPA, and PANDA investigate options for further experiments at green lines

Recommendation of the "First Science and Staging Review of the FAIR Project" (endorsed by the FAIR Council in Oct. 2022):

Prioritize implementation of Scenario #3: **SIS100, Super-FRS-HEB, CBM (First Science+) – the most appropriate start scenario to achieve world-leading science**



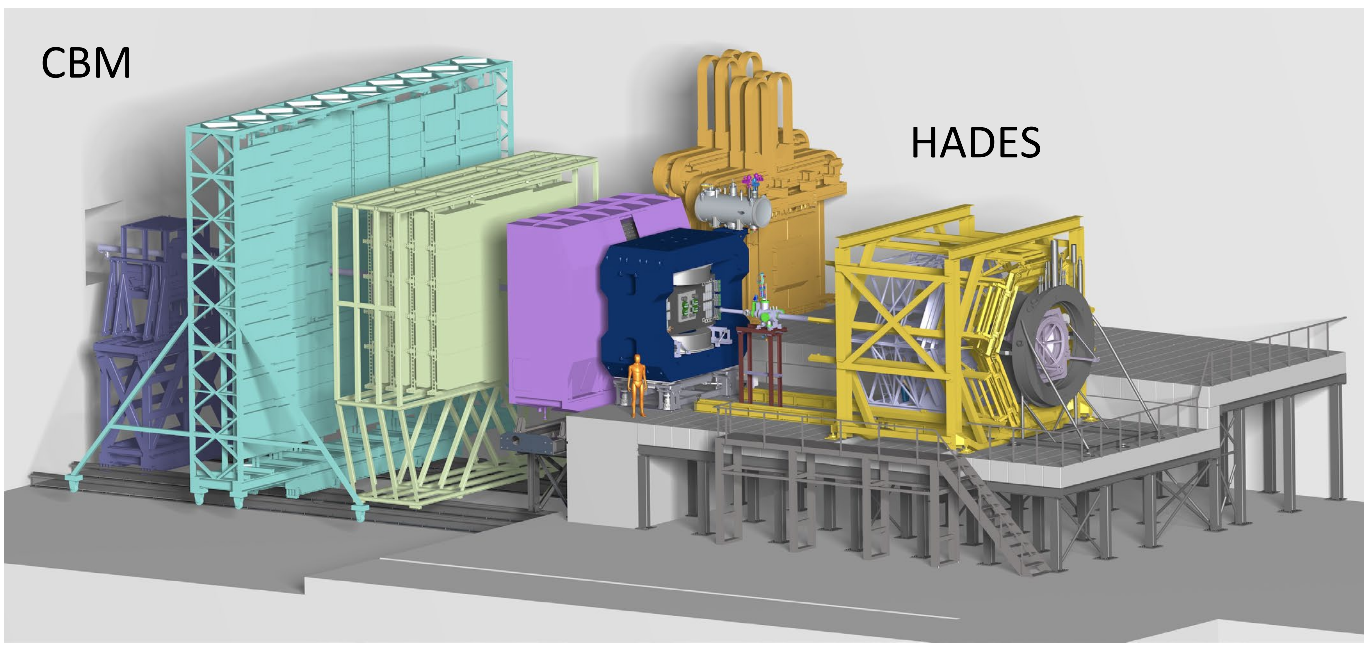
Civil Work Completed

Civil Work Completed

Compressed Baryonic Matter experiment

Fixed-target experiment → highest rates achievable
Versatile subsystems → tailored for the physics program
Silicon-based tracking → fast and precise
Free-streaming front-end-electronics (FEE) → minimal dead-time while data acquisition
Online event selection → advanced data taking focused on customized needs

First beams in 2028/2029



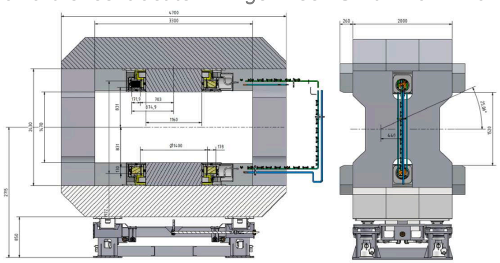
315 full members from 10 countries
47 full member institutions
10 associated member institutions

CBM subsystems are on the verge of series production

➥ pre-production is ongoing in all systems

Superconducting dipole magnet

award of contract to Bilfinger Noell GmbH 20.12.2023



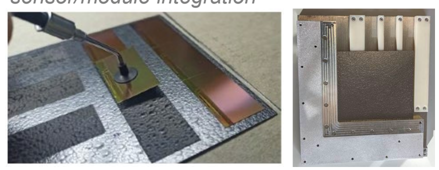
Beam monitoring system

Transition Radiation Detector

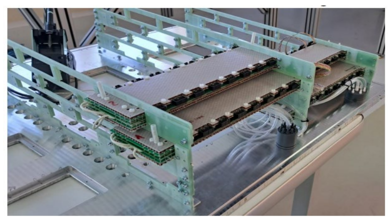
pre-production modules of 1D and 2D options ready

Micro Vertex Detector

sensor/module integration



Time of flight detector

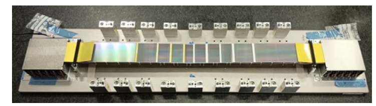


module pre-production concluded

MUon CHamber system

test of full-size GEM and RPC prototypes

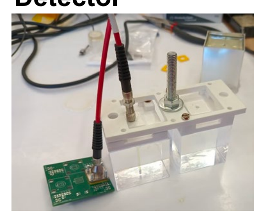
Silicon Tracking System



first STS series ladder

> 100 modules assembled

Forward Spectator Detector



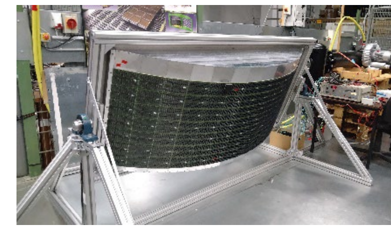
ZnS scintillators and LYSO crystals

read-out via SiPM or/and PMT

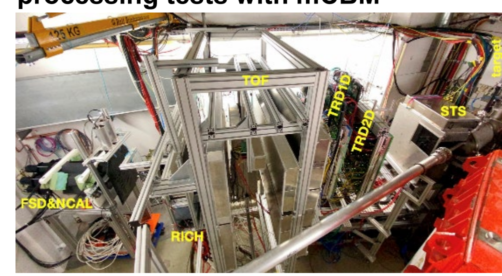
Ring Imaging Cherenkov detector

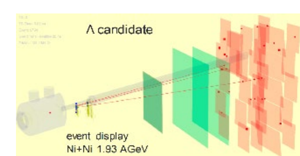
1 of 2 photo cameras ready

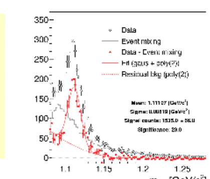
50% FEE produced



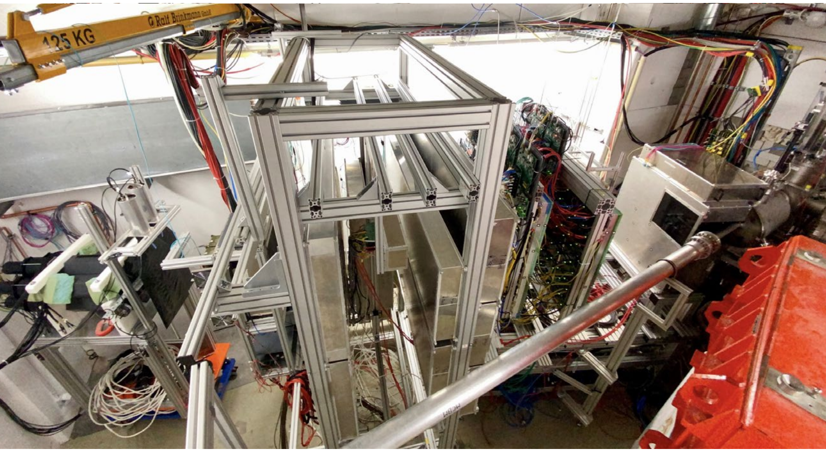
Prototype of CBM online data processing tests with mCBM





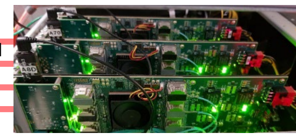


mCBM



ptical
ibers
0m

FLES entry nodes
CRI FPGA
µSlice building
(DAQ container)



optical
fibers
300 m

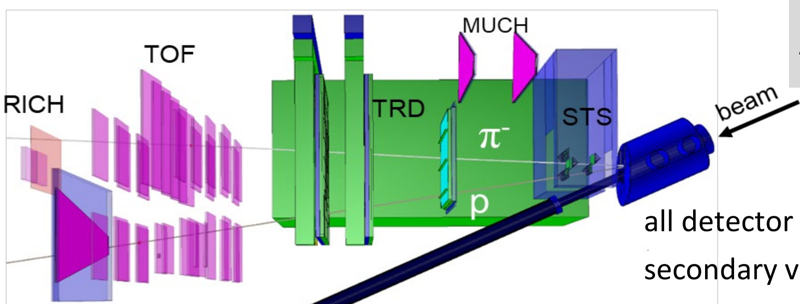
FLES processing nodes
time slice building
event reconstruction
& selection
archiving

Free-streaming CBM data transport

Pre-series productions of all CBM detector systems

High-rate studies up to 10 MHz coll. rate in nucleus-nucleus collisions

Rare signal reconstructed: $\Lambda \rightarrow p\ \pi^-$

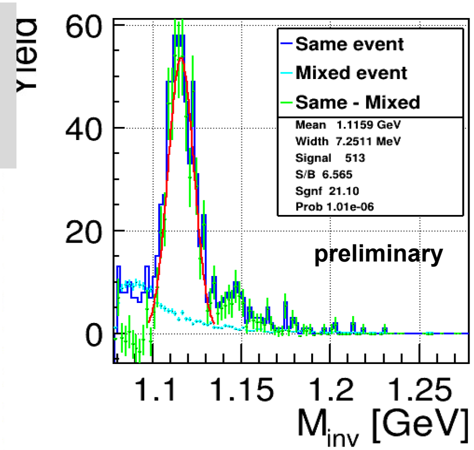


Ni+Ni 1.93 AGeV
run 2391 (May '22):
10^9 collisions, 1:57h
400 kHz av. coll. rate

all detector systems involved

secondary vertex

velocity windows for p and π^- candidate



Campaign 2024:

high-rate studies

online reconstruction and selection

Λ baryons in Ni+Ni at 1.0 - 1.93 AGeV

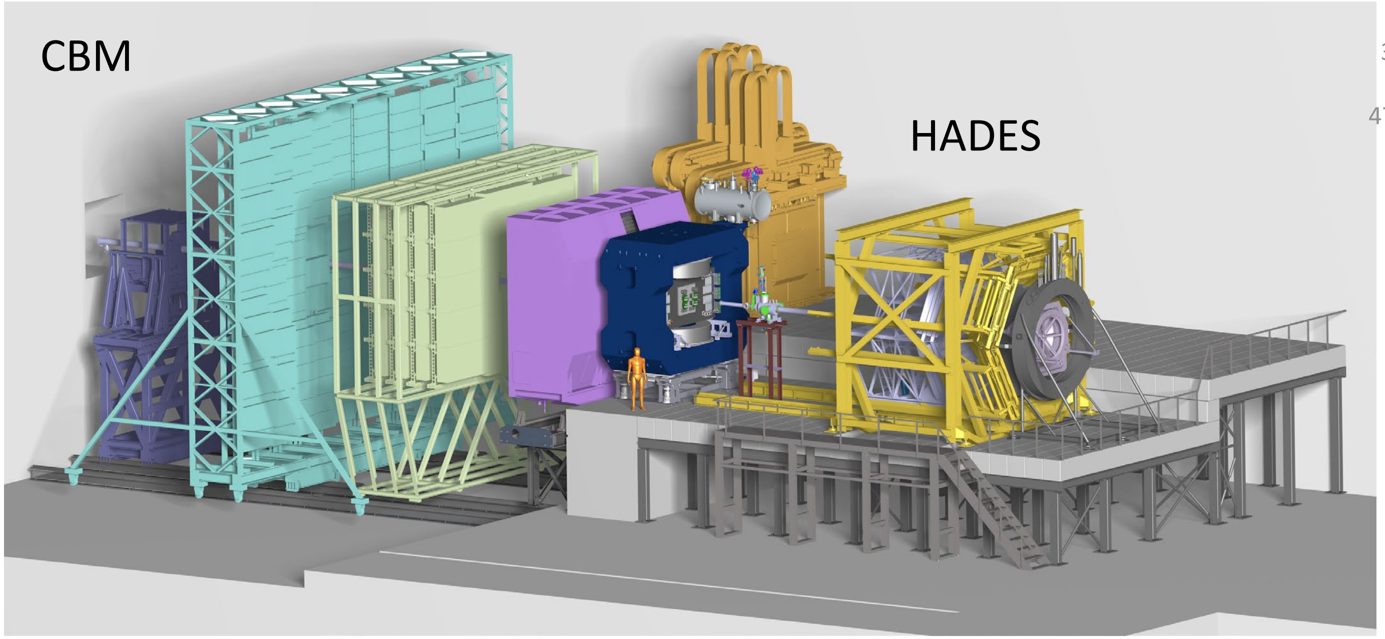
Compressed Baryonic Matter experiment

Fixed-target experiment → highest rates achievable
Versatile subsystems → tailored for the physics program
Silicon-based tracking → fast and precise
Free-streaming front-end-electronics (FEE) → minimal dead-time while data acquisition
Online event selection → advanced data taking focused on customized needs

First beams in 2028/2029

Years 1-3: first energy scan, improved statistical uncertainties of factor 10 with respect to STAR

Years 4-8: high-statistics measurements: di-lepton IMR, ultra-rare probes



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Road map

What are we pursuing and why? → Physics motivation

Where are we now? → Current status

Who is involved? → Experimental facilities

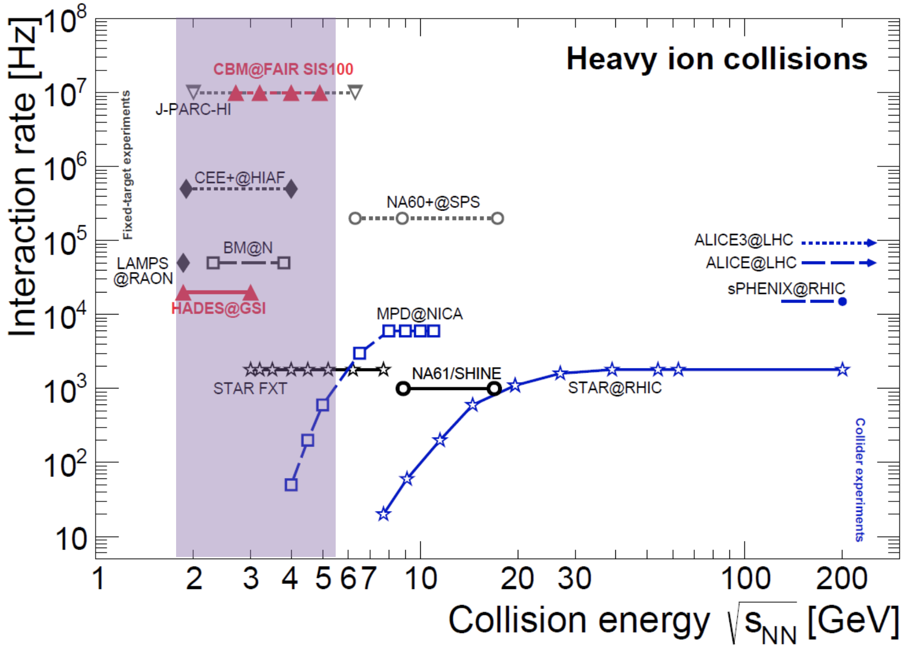
How to achieve the goal? → Compressed Baryonic Matter

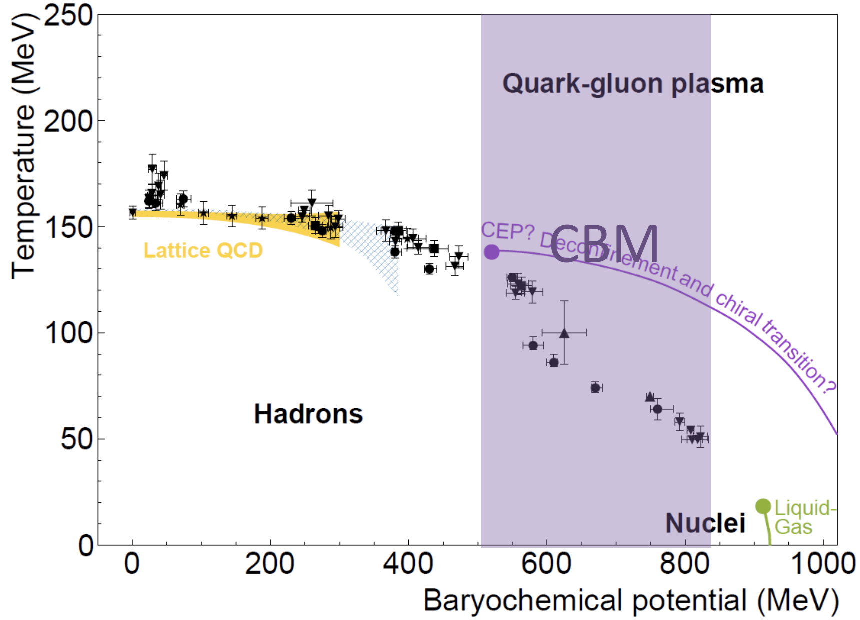
What is the plan? → **Key measurements**

Key observables

Systematic measurements:

- **Fluctuations**: System alteration through first-order phase transition, critical point
- **Dileptons** : Emissivity: system's lifetime, temperature, density, in-medium characteristics
- **Hadrons (Strangeness, Charm, Hyper-nuclei, Bound states):** EOS: vorticity, collectivity, correlations: NN, YN, YY, multi-body interactions



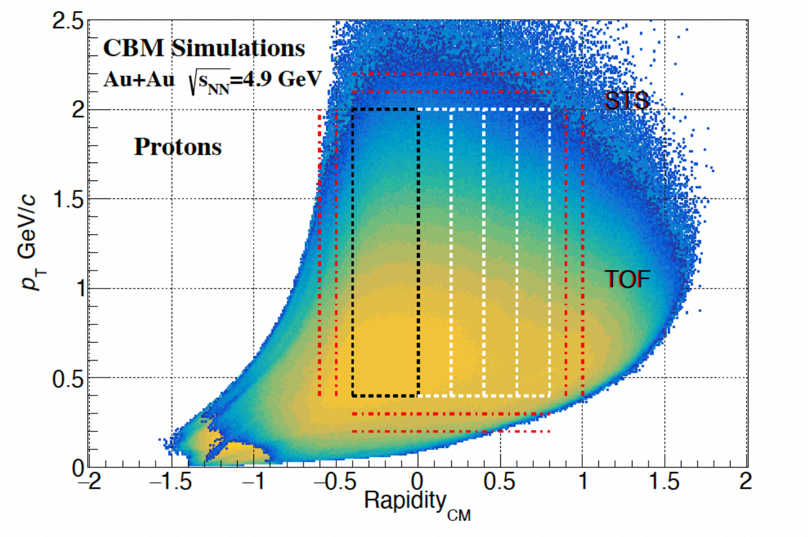


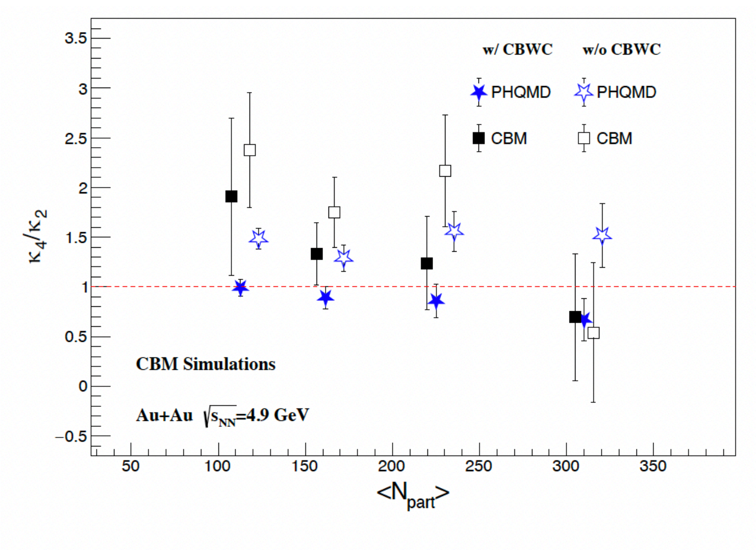
A high interaction rate is desired to reduce uncertainties and enable measurements that have so far been unattainable.

Fluctuations

Corrections for volume fluctuations and conservation laws

- Event-by-event changes of efficiency
- Proper selection of $y - p_T$ interval
- (Net-)baryons vs. protons, neutrons, nuclei





Expectations after ~3 years of running

- Full coverage of κ_4(E) for protons
- First results of κ_6
- Possible addition of strangeness: $\kappa_4(\Lambda)$

Dileptons

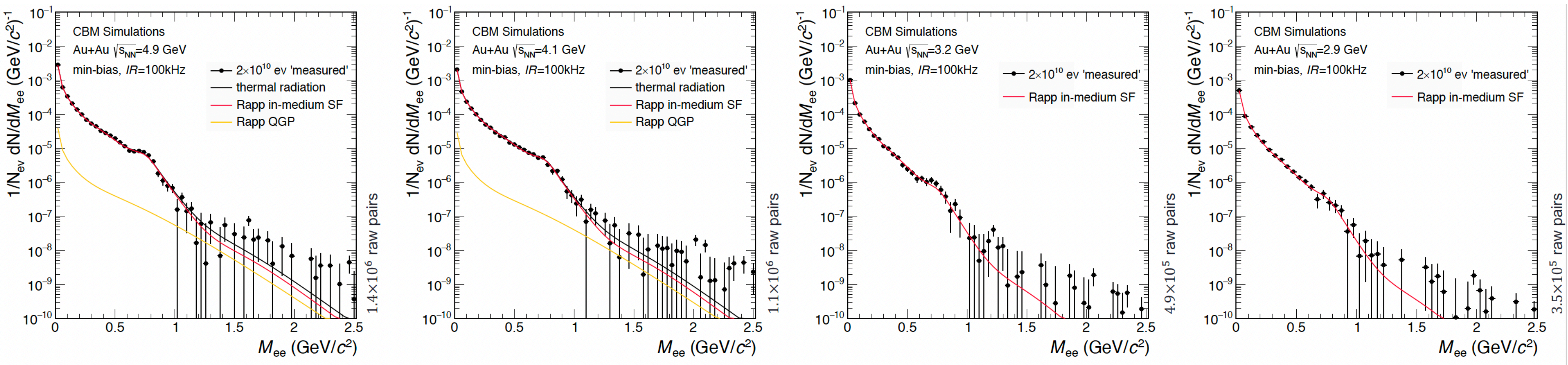
Electron thermal radiation, corrected for acceptance and efficiency,

Dominated by ρ contribution at LMR,

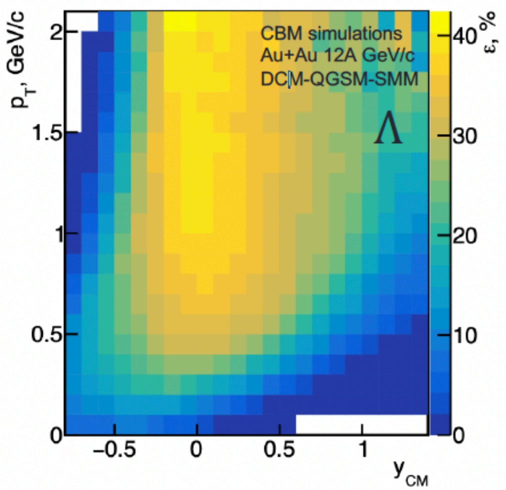
Can be reconstructed with 1.5-4.5% of precision,

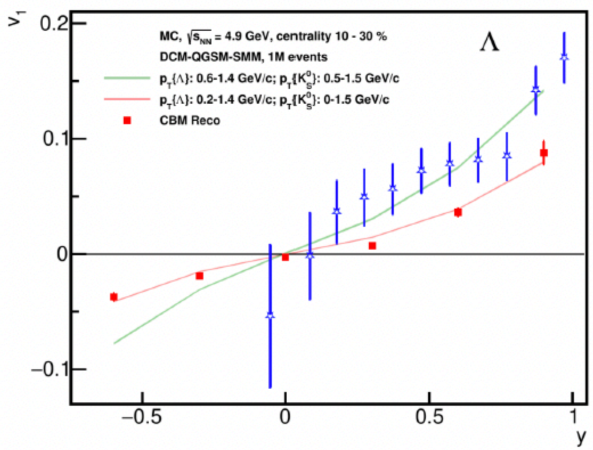
Gives access to to the fireball lifetime and electrical conductivity (transport properties)

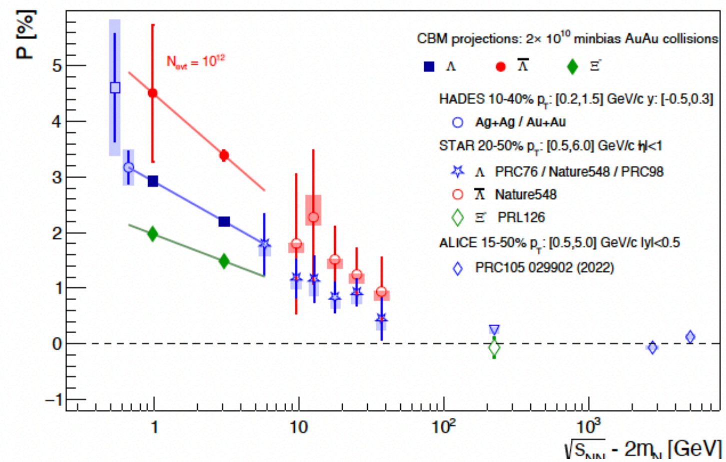
T vs. baryon density effects from partonic to hadronic fireballs



Flow, polarization, correlations

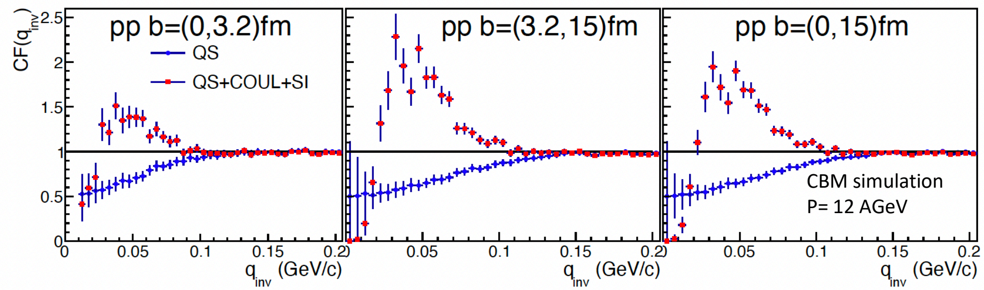




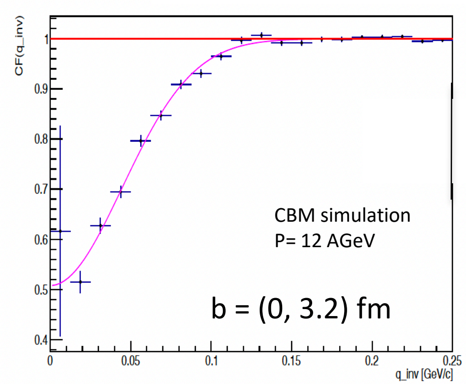


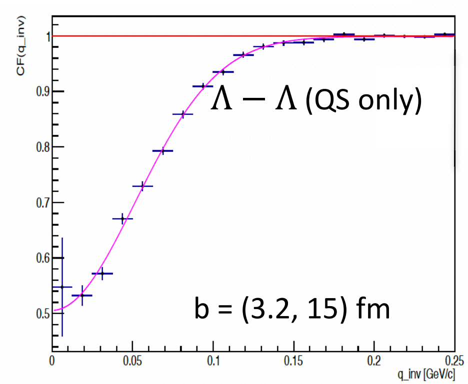
Excellent acceptance coverage

Reconstruction efficiency ~30%



- Precise measurements of flow for S=1, 2, 3
- Polarization measurement with precision of ~5%
- Thorough multi body N and Y correlations of S=1, 2, 3 achievable





What are we pursuing and why?

CBM aims to answer fundamental questions about the structure of the QCD phase diagram at high μ_B

Where are we now?

Already operating at high μ_B experiments are complete and exploration of new physics needs higher interaction rates

Who is involved?

Many world-wide existing and planned facilities complement each other programs

How to achieve the goal?

Compressed Baryonic Matter experiment with high interaction rates will explore the region of the energies of the highest importance

What is the plan?

To start these exploration in 2028 and to answer fundamental questions in the first year of CBM running

The Future is Bright

Be the light

CBM is open for new participation

Thank You for your attention