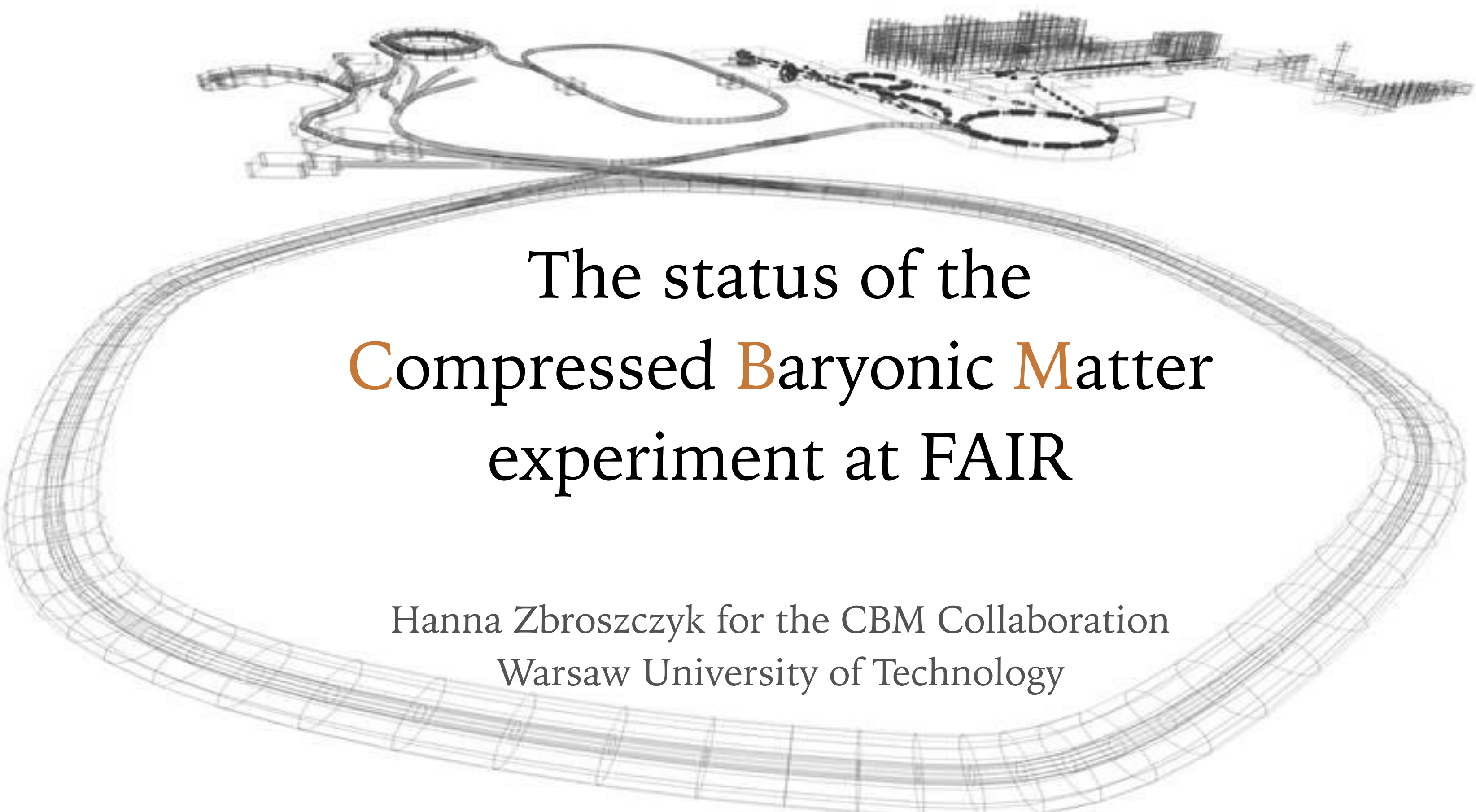


The status of the Compressed Baryonic Matter experiment at FAIR

Hanna Zbroszczyk for the CBM Collaboration
Warsaw University of Technology

New Trends in High-Energy and Low-x Physics, September 1-5, 2024, Sfantu Gheorghe, Romania

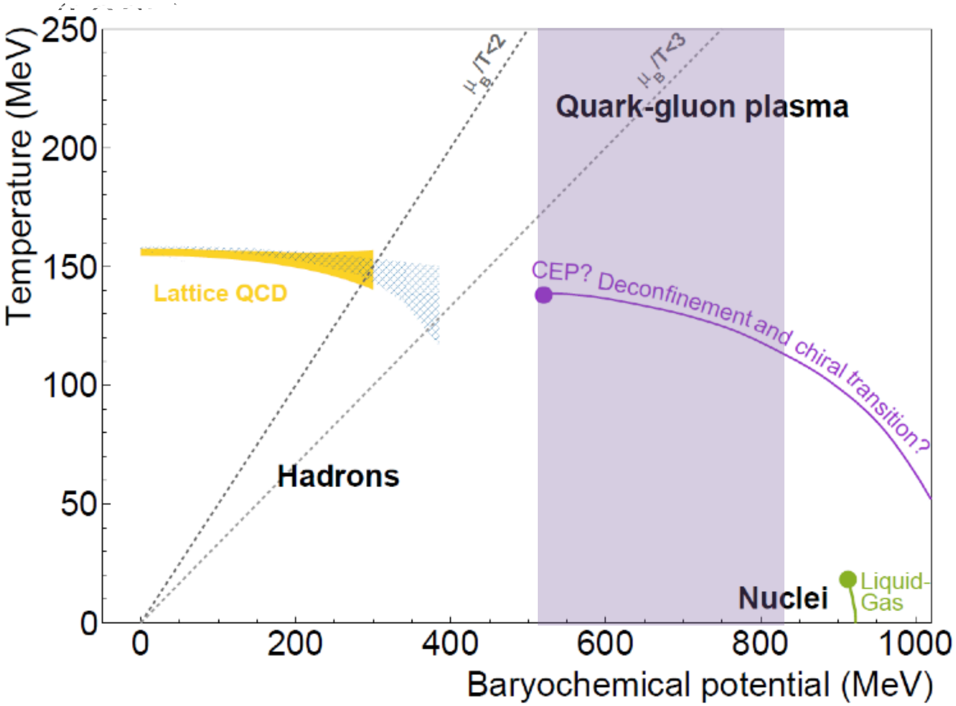
Road map

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 $\mu_B/T < 3$

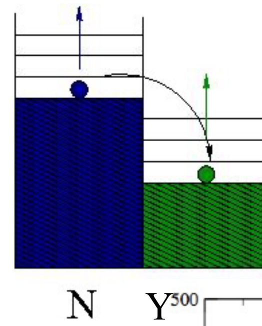


High μ_B, low T:

- 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**)

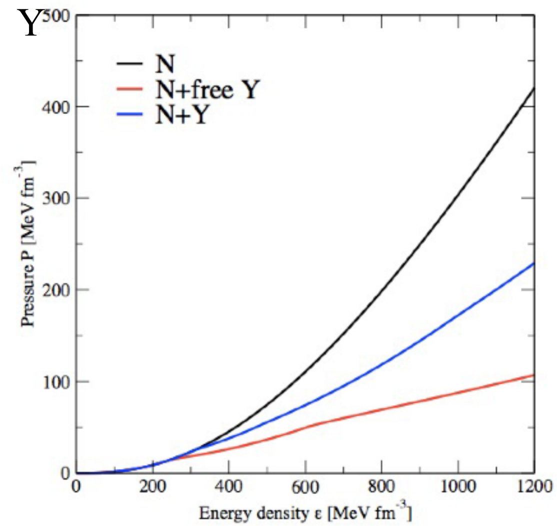
Bazavovet al.[HotQCD], PLB 795 (2019) 15-21
Dinget al., [HotQCD], PRL 123 (2019) 6, 062002
Borsanyiet al., PRL125(2020)5,052001
Isserstedt et al. PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584

NS puzzle

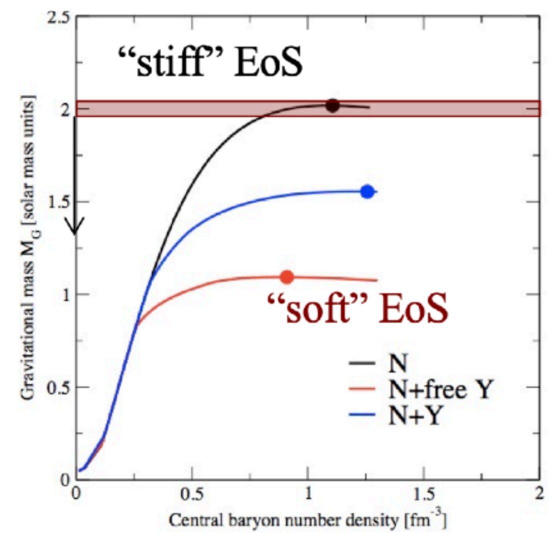


$M_{NS} \approx 1 \div 2\ M_{\odot}$
$R \approx$ 10-12 km
$\rho \approx 3 \div 5\ \rho_0$
$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

- Observation of **NS** indicates their **mass** $\sim 2M_{\odot}$
  (Shapiro-delay: Post-Keplerian parameters of orbits)
- **Hyperons:** Expected in core of NS, the conversion of N into Y is energetically favorable
- **Appearance of Hyperons:** The presence of Y alleviates Fermi pressure, resulting in a EoS and a reduction in NS mass (inconsistent with observations)
  Can they still be considered as components of NS?

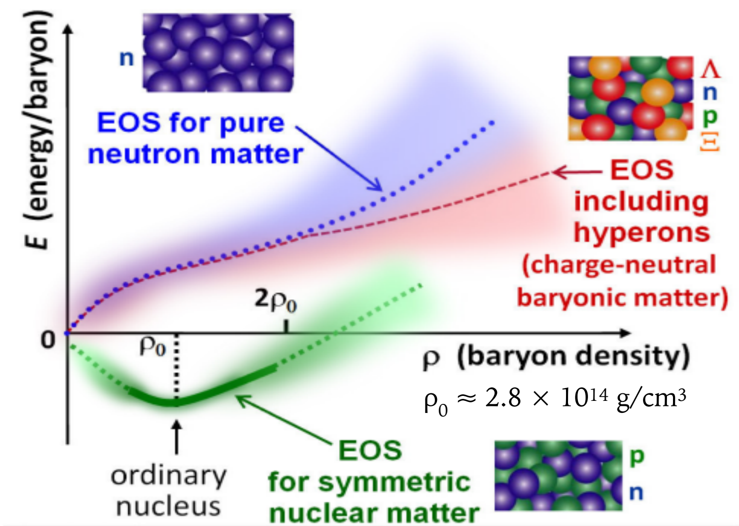


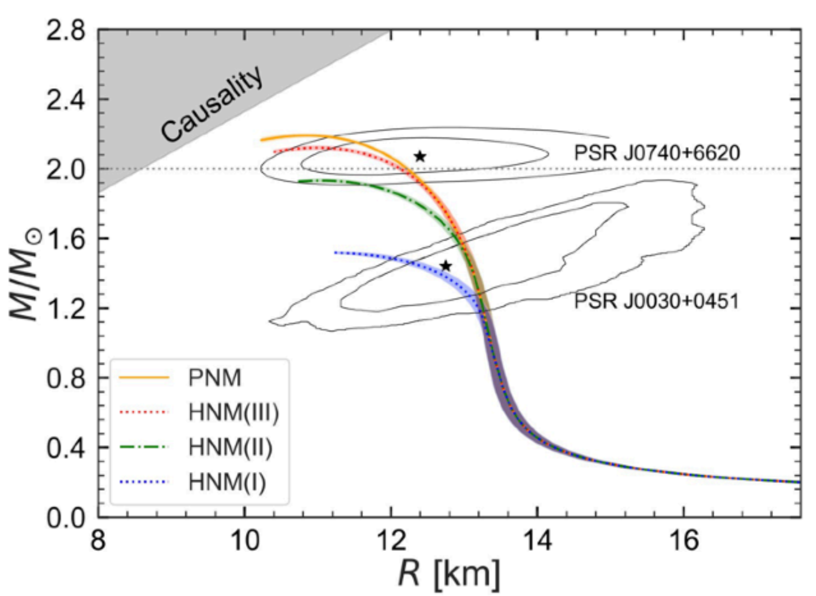
- **Proposed Solution:** A mechanism that provides additional pressure to ensure a stiffer EoS
  One emergent mechanism involves many-body interactions, such as YN, YY, NNY, NYY
  (Other: hypersonic three-body forces, Quark Matter Core - a transition to deconfined phase below hyperon threshold in density)



Neutron star (NS) puzzle

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

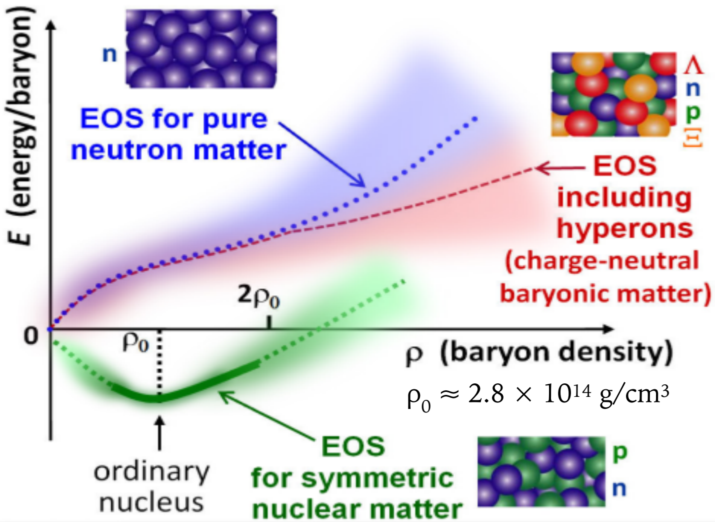


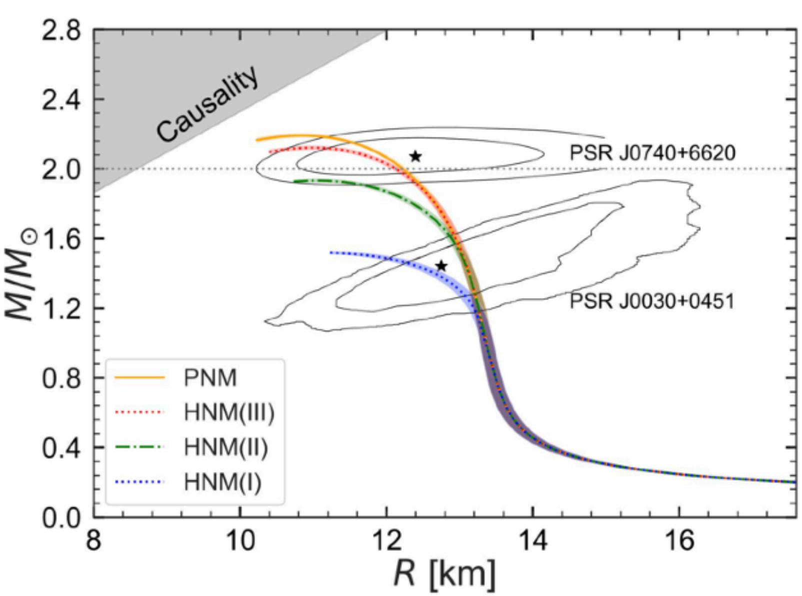


„To establish the EoS applicable to the neutron star has been one of the most important subjects in nuclear physics for a long time but has not been achieved yet." T. Hamura

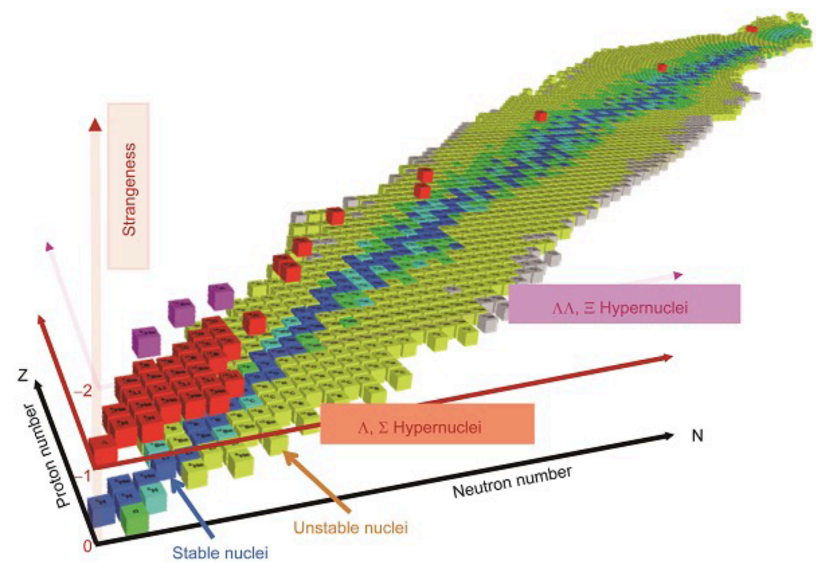
Neutron star (NS) puzzle

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



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

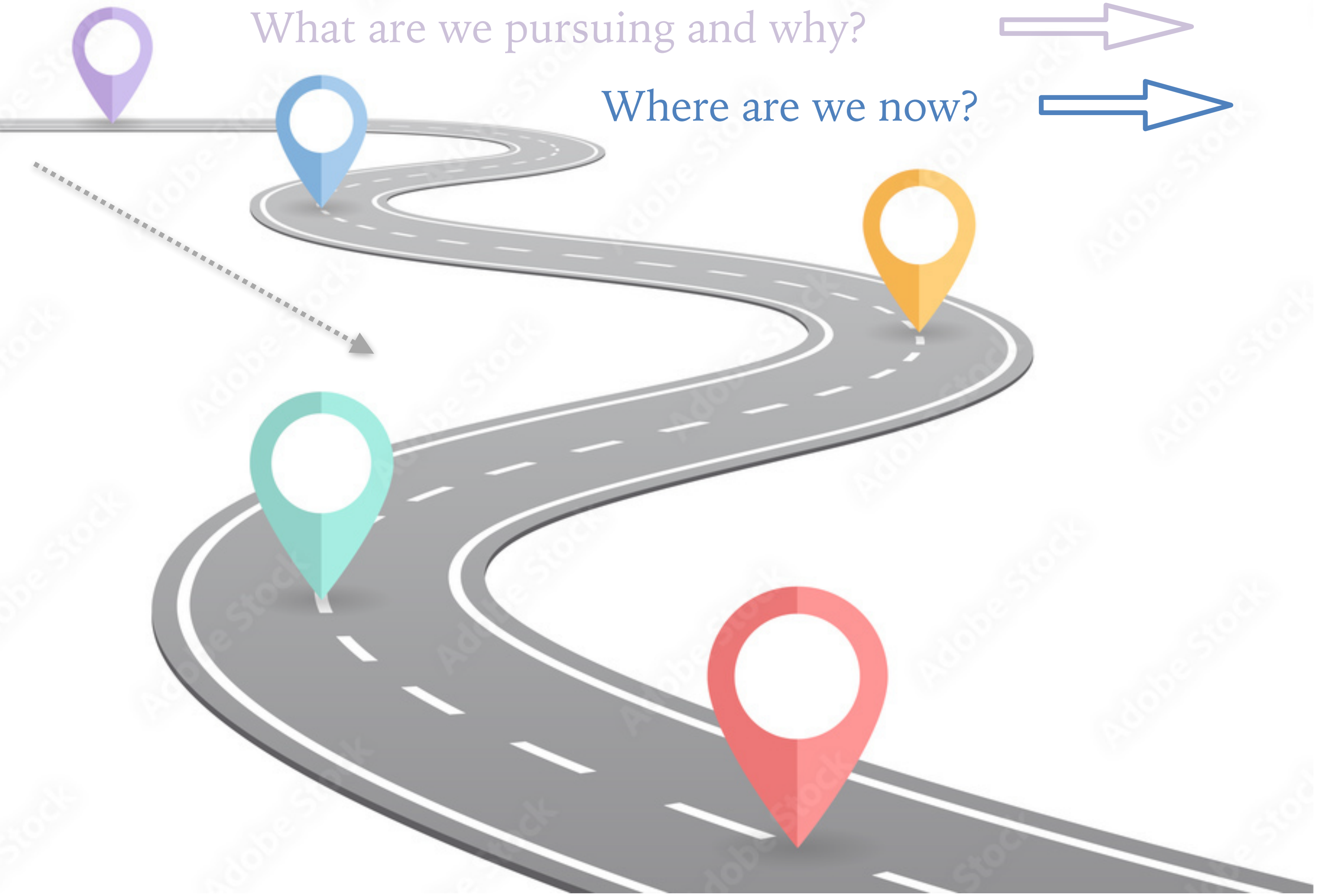
Hypernuclei are pivotal for the EoS of the NS

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

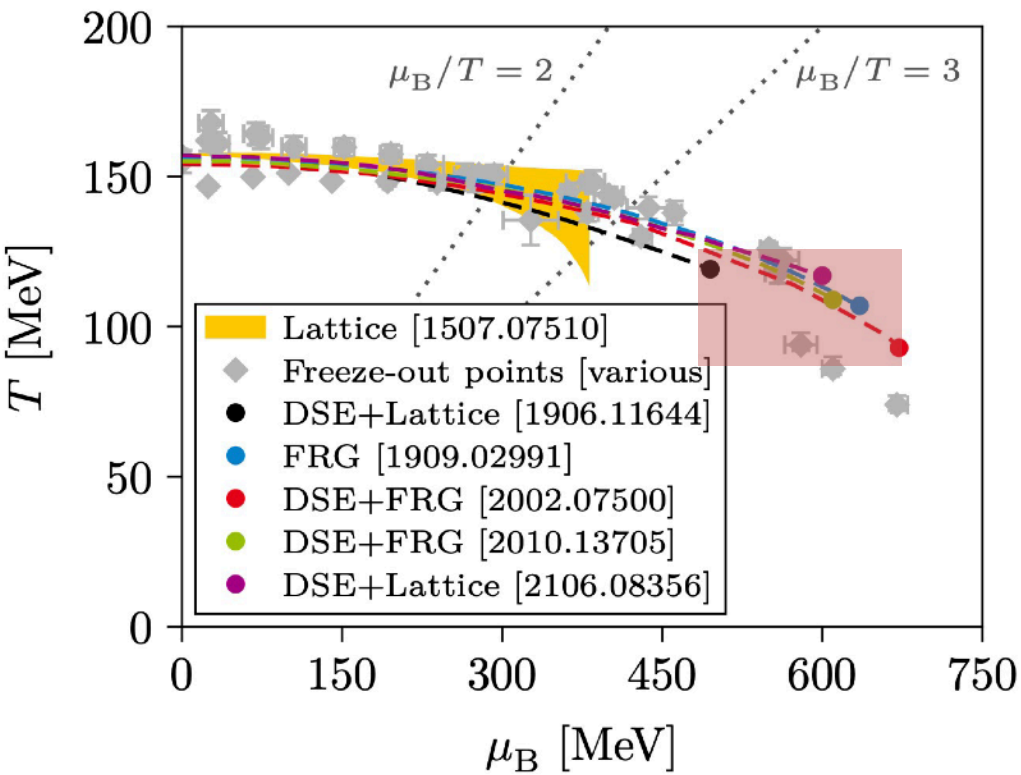
Road map

What are we pursuing and why? ⇒ Physics motivation

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



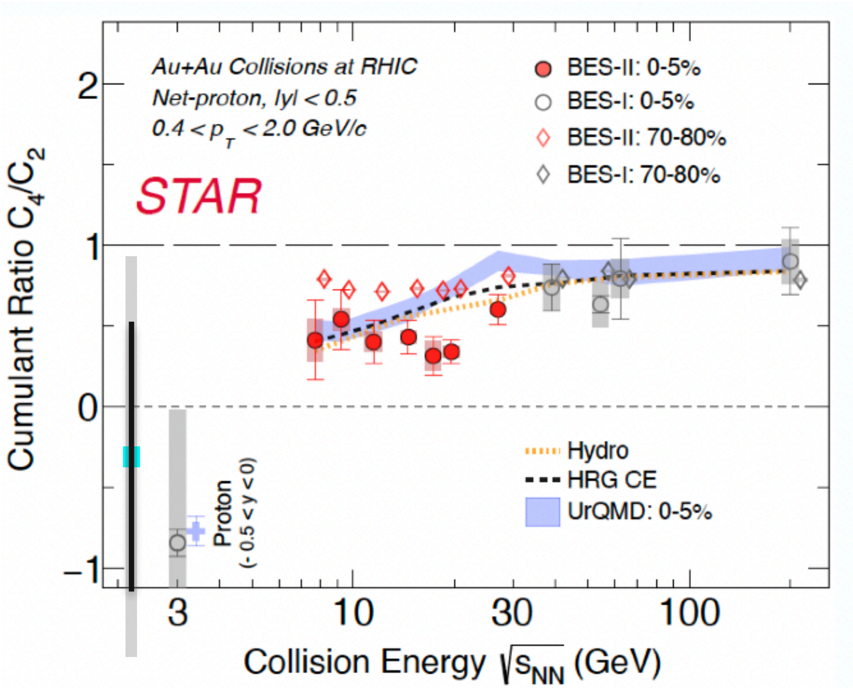
Critical point predictions



- LQCD frowns upon the location of the critical point at $\mu_B/T < 3$
- Effective QCD and lattice-based theories estimate its location at $T \sim 90 - 120$ MeV and $\mu_B \sim 500 - 650$ MeV
- This corresponds to heavy-ion collisions at $\sqrt{s_{NN}} \sim 3 - 5$ GeV
- The circumstance in which the critical point does not exist is also conceivable

DSE: Bernhardt, Fischer and Isserstedt, PLB 841 (2023)[2]
FRG: Fu, Pawlowski, Rennecke, PRD 101, 053032 (2020)[3]
BHE: Hippert et al., arXiv:2309.00579
lQCD-Pade: Basar, arXiv:2312.06952
lQCD-Pade: Clarke et al., PoS LATTICE2023 (2024),
Bazavov et al. [HotQCD], PLB 795 (2019) 15-21
Borsanyi et al. [Wuppertal-Budapest], PRL 125 (2020)
Cuteri, Philipsen, Sciarra, JHEP 11 (2021) 141
Vovchenko et al., PRD 97, 114030 (2018)

Critical point searches



STAR CPOD 2024
STAR, PRL 128 (2022) 20, 202303
HADES, PRC 102 (2020) 2, 024914

$$\frac{\kappa_n(N_B - N_{\bar{B}})}{VT^3} = \frac{1}{VT^3}\frac{\partial^3 lnZ(V,T,\mu_B)}{\partial(\mu_B/T)^n}$$

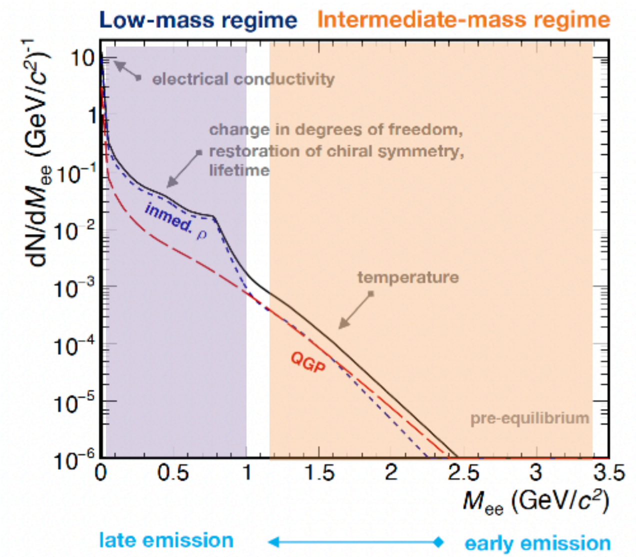
κ_n experimentally measured

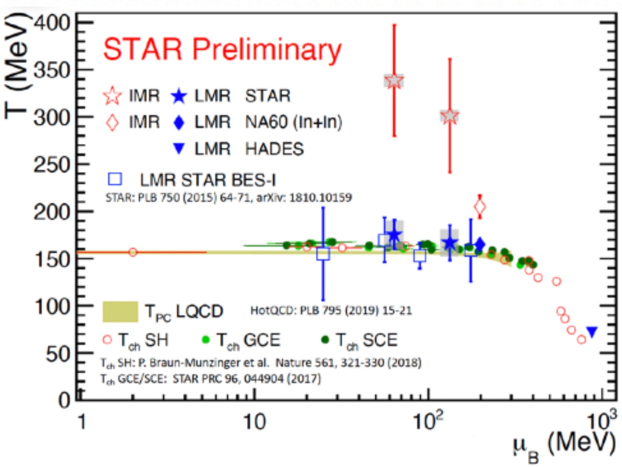
$$\kappa_n(N_B - N_{\bar{B}}) = < N_B > + (-1)^n < N_{\bar{B}} > = k_n(Skellam)$$

- Non-monotonic trend in κ_4/κ_2 of net-proton multiplicity distributions suggested as a **signature** of the **critical point**
- STAR collider program conducted comprehensive studies at $\sqrt{s_{NN}} > 7.7\ GeV$
- STAR fixed-target data investigation ongoing
- Sensitivity to the features of the QCD phase diagram increases with the order of the moment
- Higher-order moments requires prominent **statistics**

Detailed systematics studies indispensable

E-M probes access the whole collision





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

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

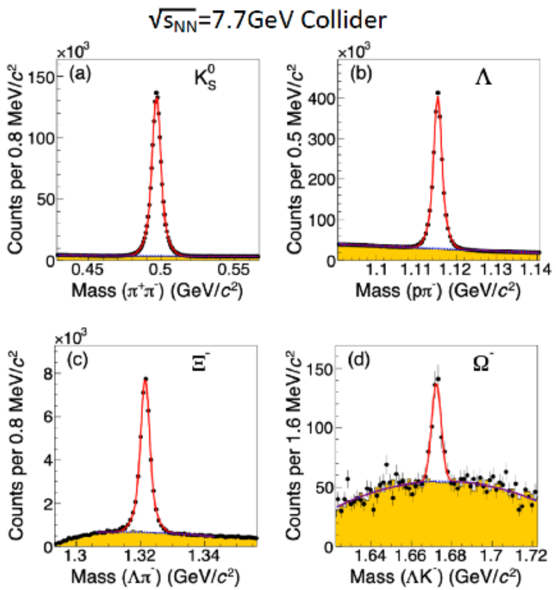
Effective size-signal: $S_{eff} \sim R\frac{S}{B}$

R - interaction rate
S - signal
B- combinatorial background

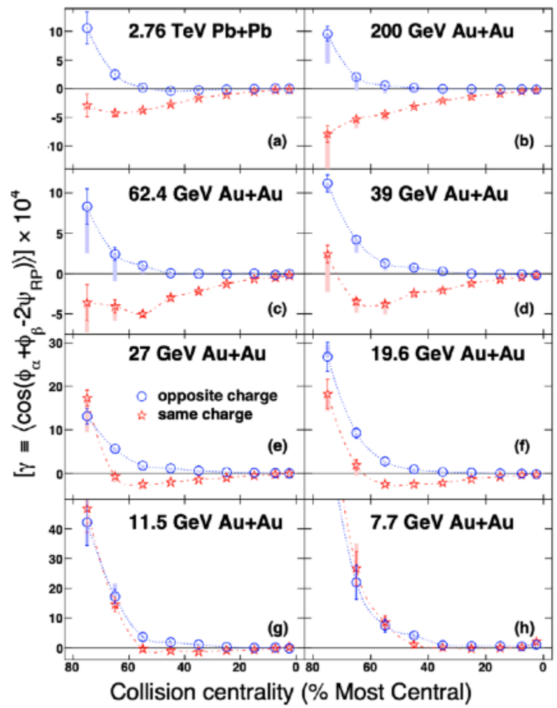
Prominent interaction rate mandatory

EoS to probe NS properties

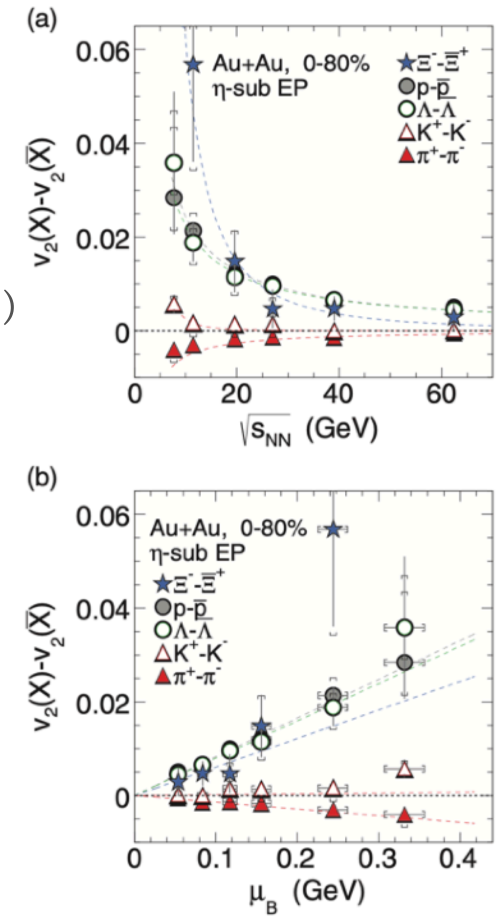
EoS investigations include vast number of measurements:
- Chemistry (strangeness, charm, hyper nuclei, …)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, …)



PRC 102 (2020) 34909 (STAR)



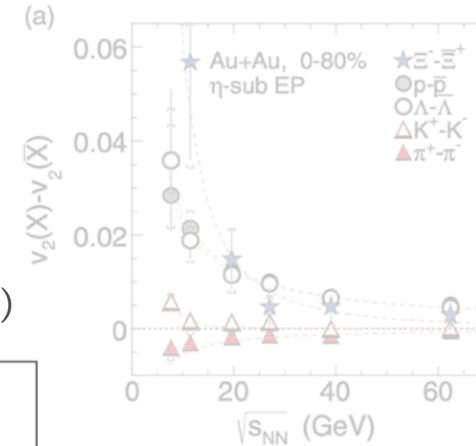
PRL 113 (2014) 52302



PRC 93 (2016) 14907 (STAR)

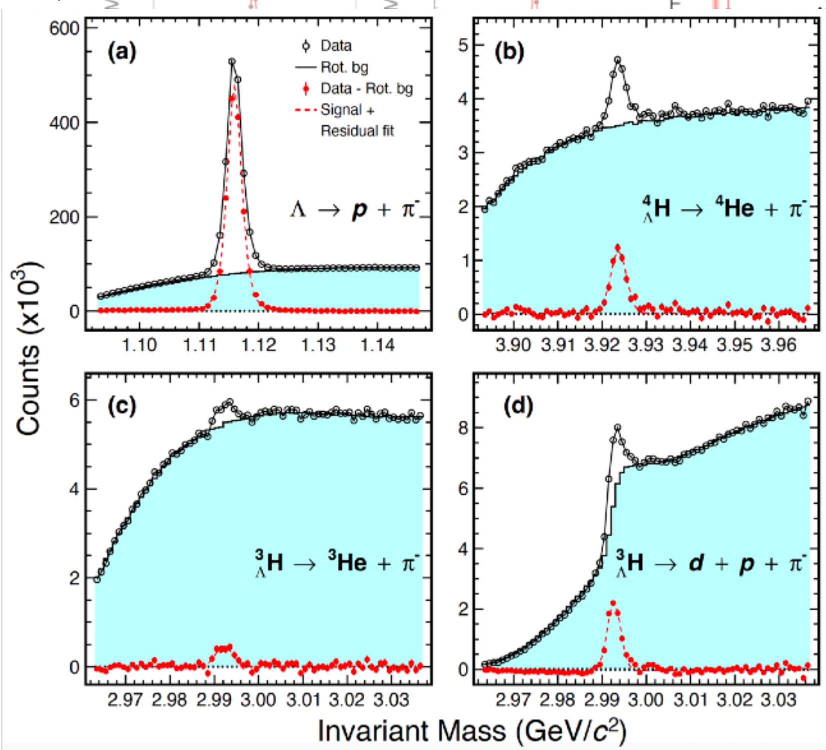
EoS to probe NS properties

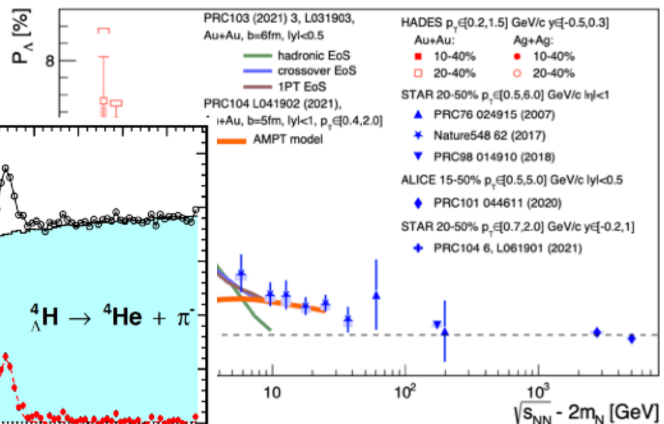
EoS investigations include vast number of measurements:
- Chemistry (strangeness, charm, hyper nuclei, …)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, …)

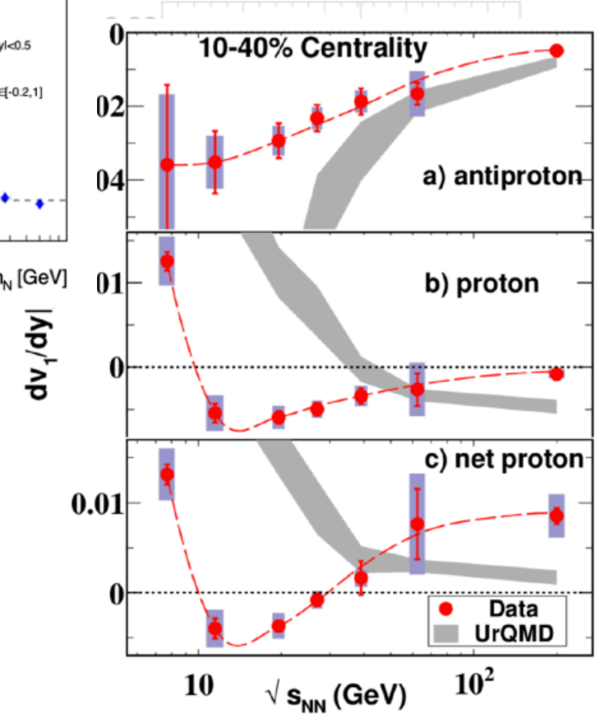


STAR, PRL 112, 162301 (2014)

Phys. Rev. Lett. **130** (2023) 212301







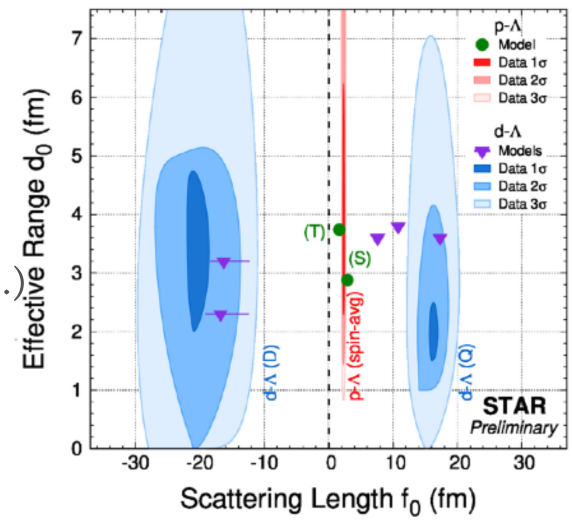
3 (2014) 52302

EoS to probe NS properties

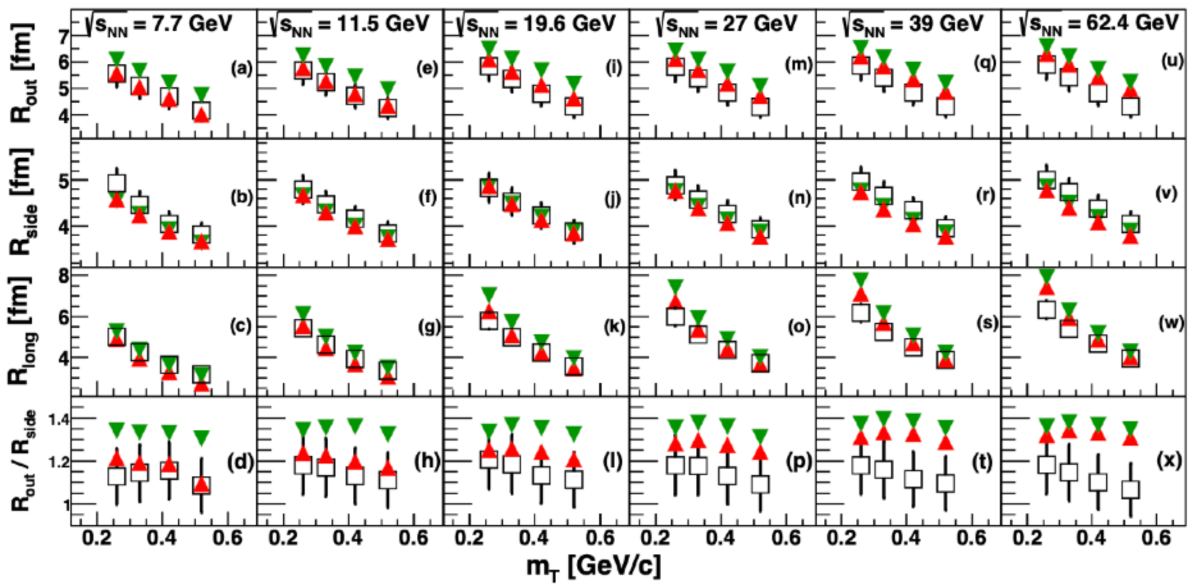
EoS investigations include vast number of measurements:

- Chemistry (strangeness, charm, hyper nuclei, …)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, …)

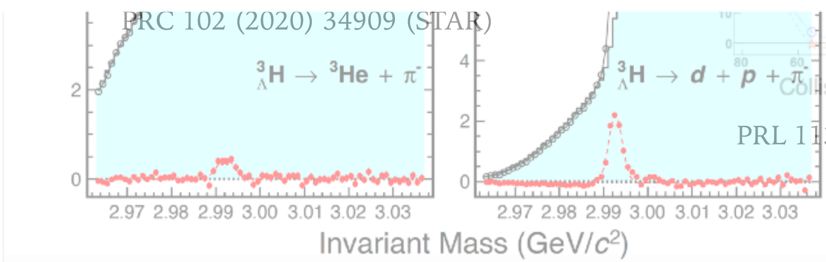
QM2024, Nucl. Phys. A 259, (2024)

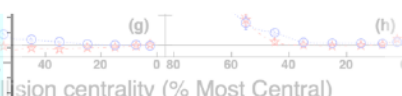


PRC 96 (2017) no.2, 024911

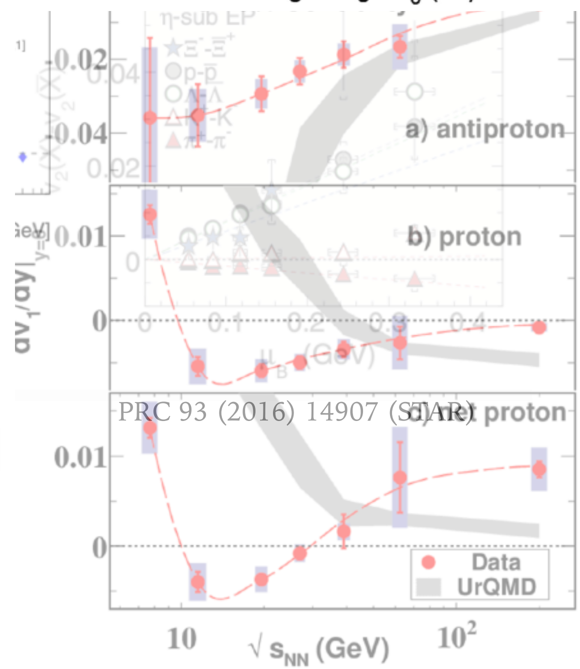


PRC 102 (2020) 34909 (STAR)





PRL 113 (2014) 52302



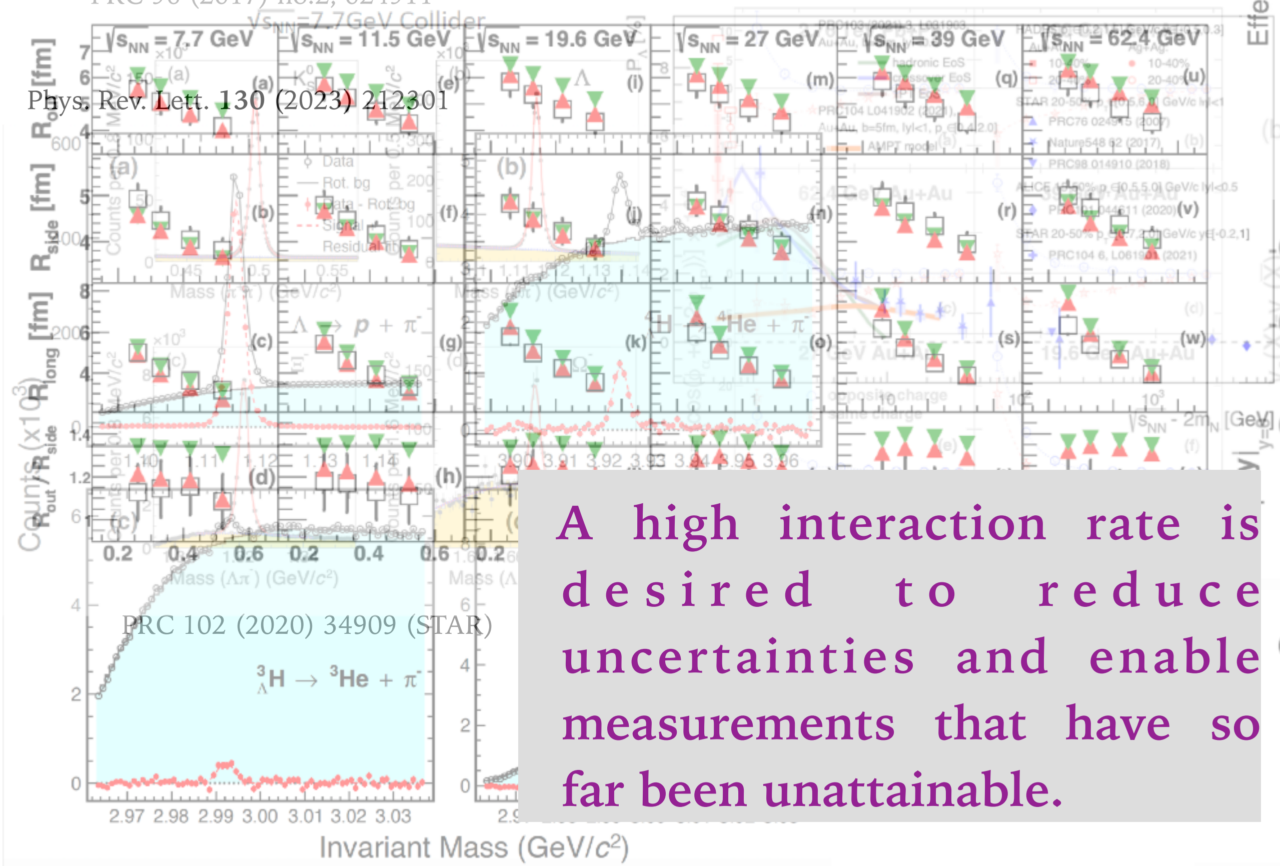
PRC 93 (2016) 14907 (STAR)

EoS to probe NS properties

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, …)

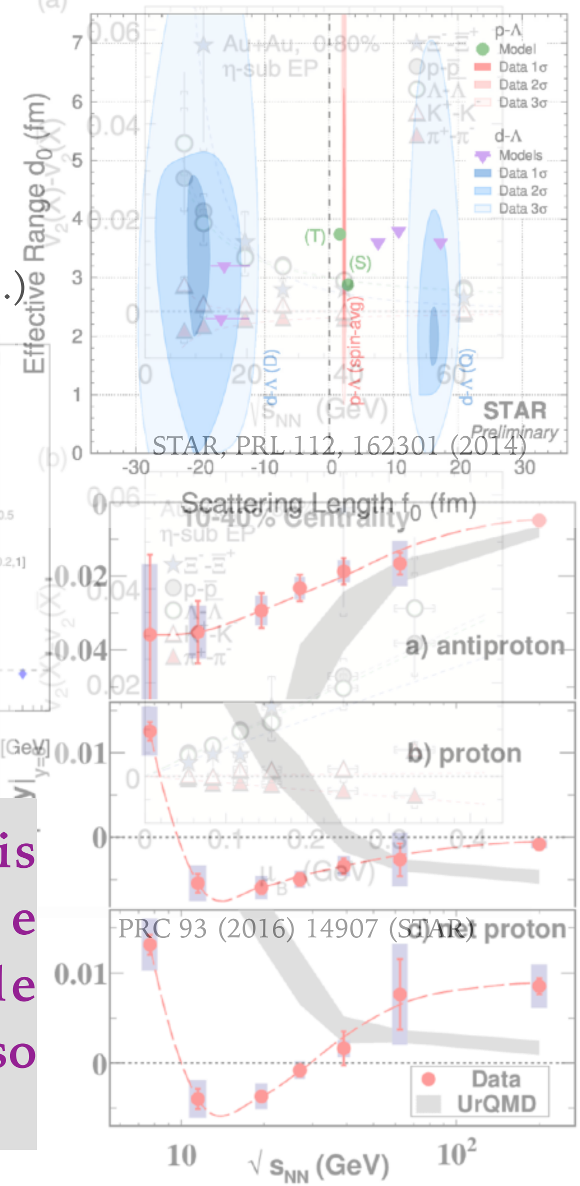
PRC 96 (2017) no.2, 024911

Phys. Rev. Lett. 130 (2023) 212301



PRC 102 (2020) 34909 (STAR)

QM2024, Nucl. Phys. A 259, (2024)



STAR, PRL 112, 162301 (2014)

PRC 93 (2016) 14907 (STAR)

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

Road map

What are we pursuing and why? ⇒ Physics motivation

Where are we now? ⇒ Current status

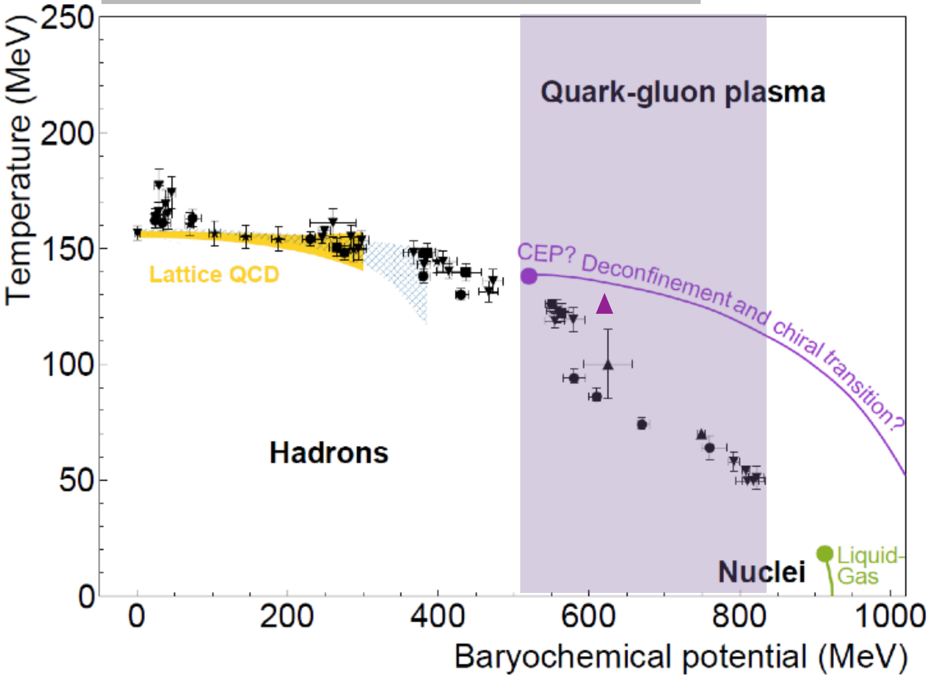
Who is involved?

⇒ **Experimental facilities**

Current coverage of the QCD phase diagram

CBM / HADES 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

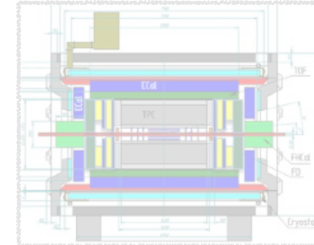
A. Andronic, P. Braun- Munzinger, K. Redlich and B. J . Stachel, Nature 561, no. 7723, 321 (2018)

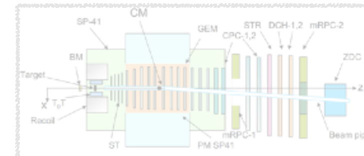
High μ_B facilities

High μ_B facilities

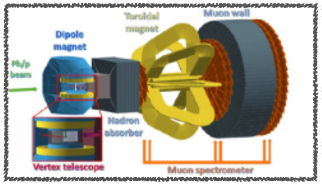
CBM / HADES@ SIS100 (>2028)

MPD, MB@N@NICA



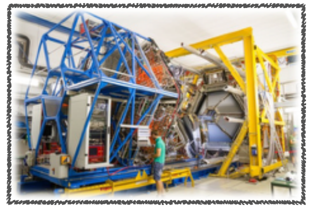


NA60@SPS(>2030)



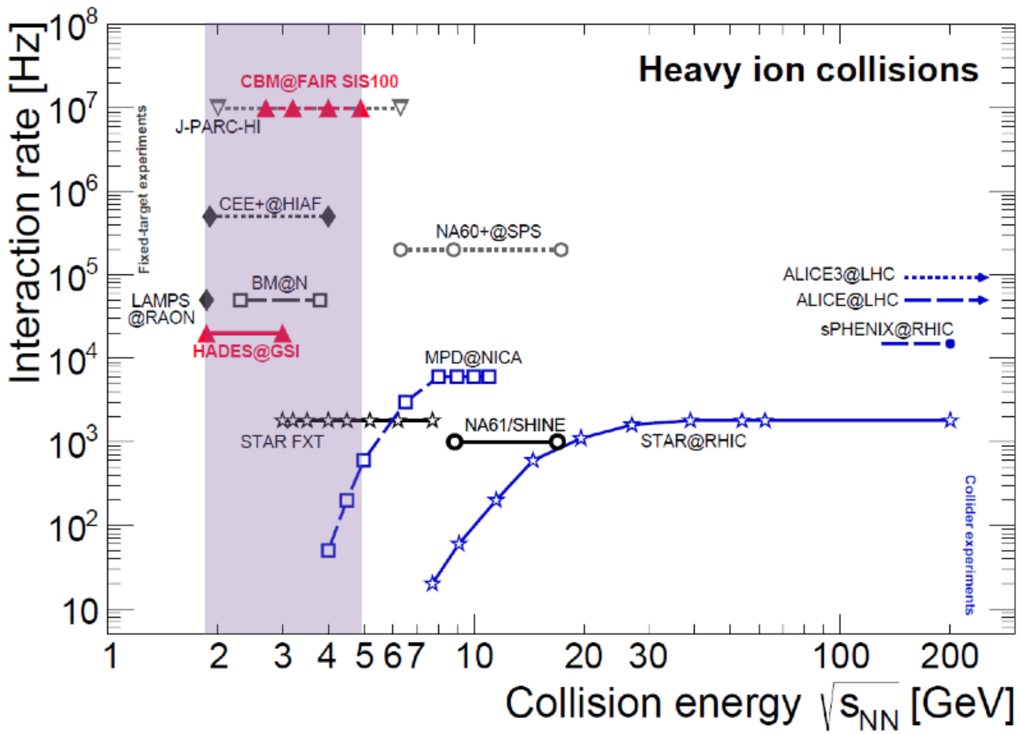
NA61/SHINE@SPS

HADES@SIS18



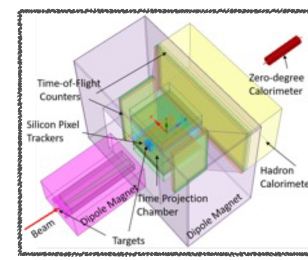
STAR@RHIC

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

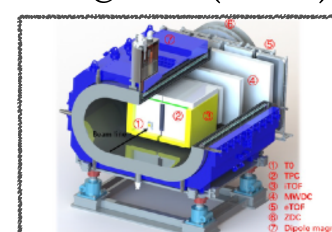


T. Galatyuk, NPA 982 (2019), update 2024 https://github.com/tgalatyuk/interaction_rate_facilities
CBM, EPJA 53 3 (2017) 60

J-PARC-HI



CEE@HIAF (>2027)



Road map

What are we pursuing and why? ⇨ Physics motivation

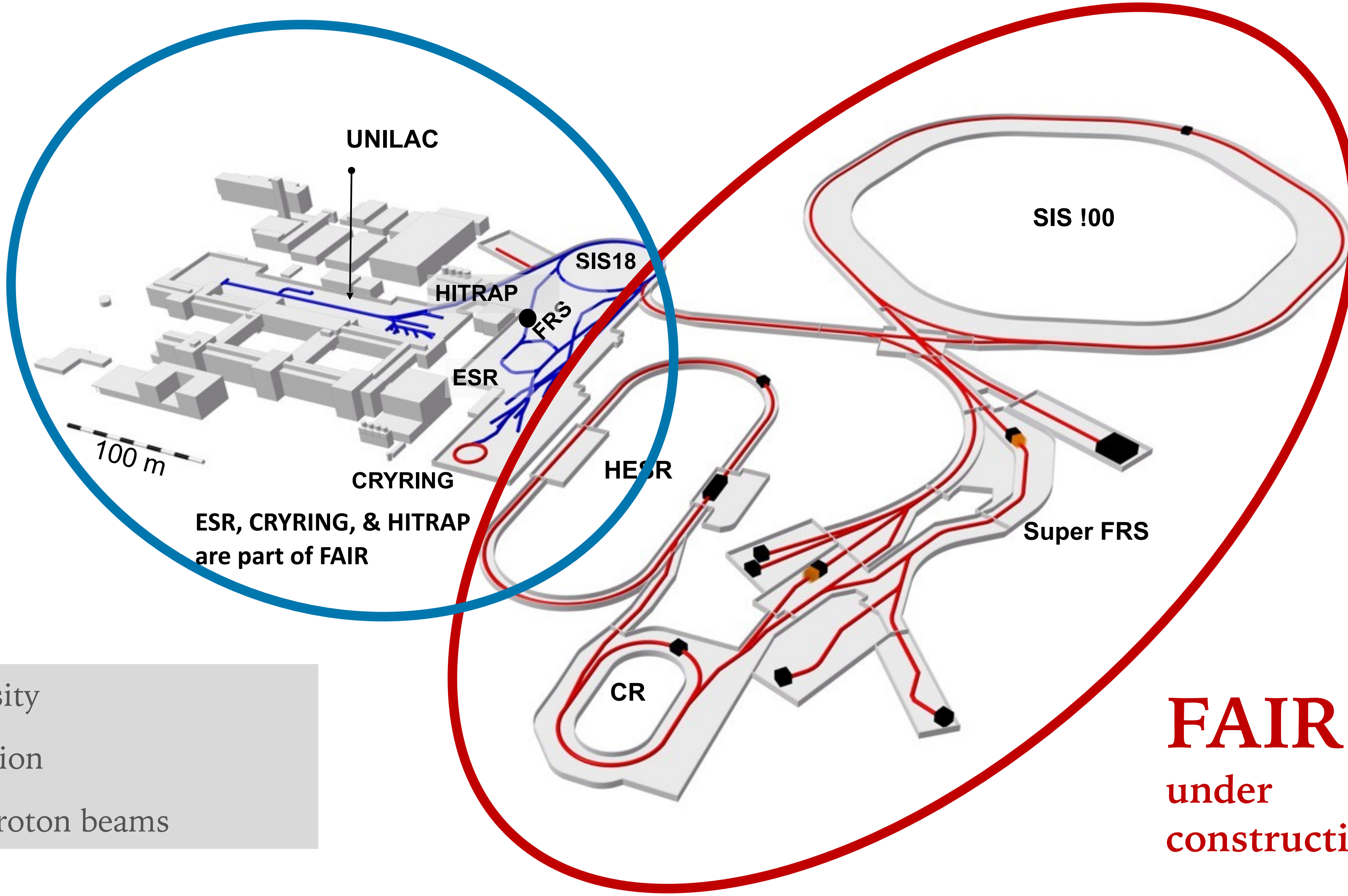
Where are we now? ⇨ Current status

Who is involved? ⇨ Experimental facilities

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

GSI GmbH – Helmholtzzentrum für Schwerionenforschung
FAIR GmbH – Facility for Antiproton and Ion Research

GSI, existing (upgraded to integrate with FAIR)

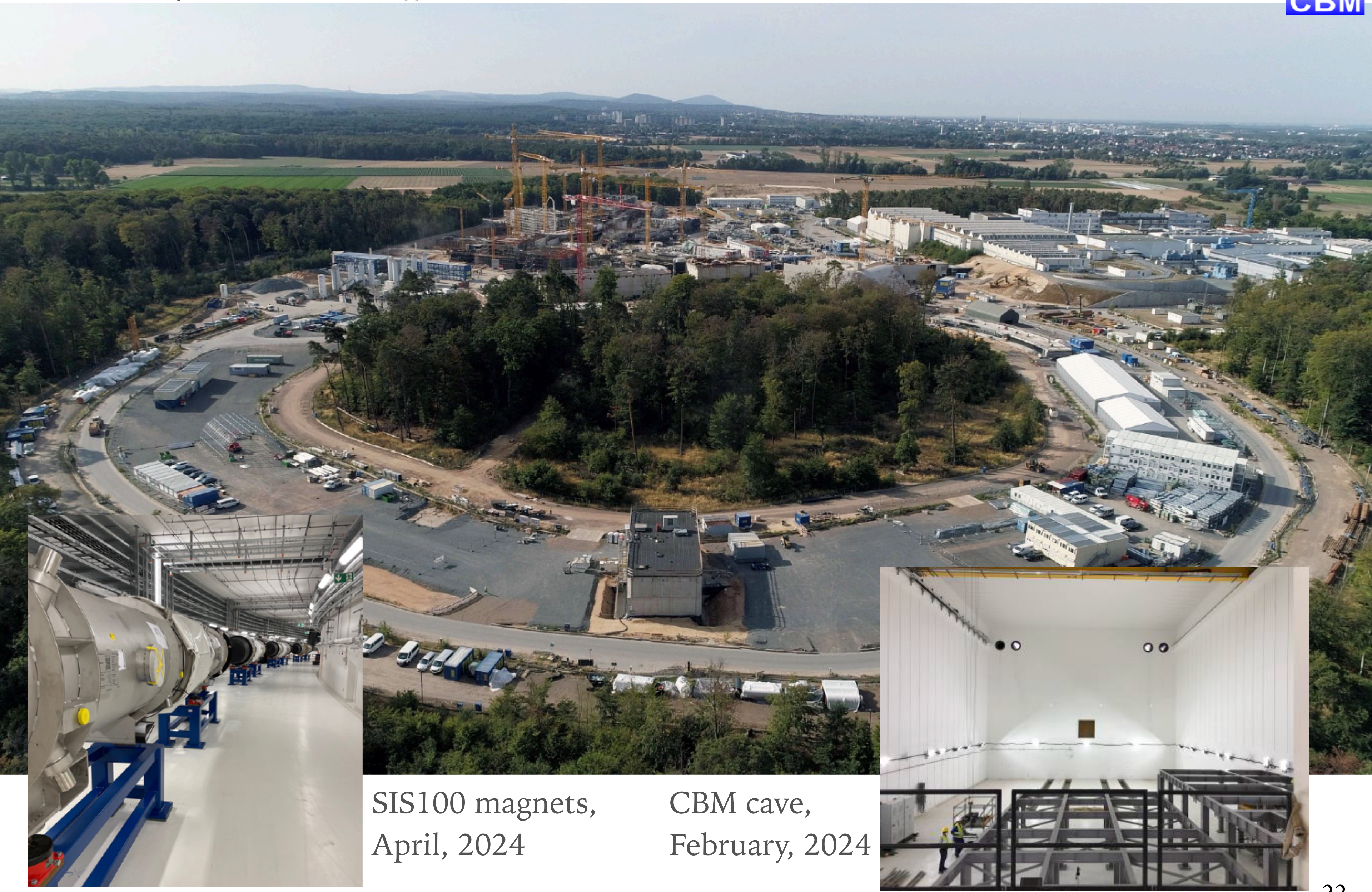


- Intensity
- Precision
- Antiproton beams

FAIR, under construction

Facility for Antiproton and Ion Research

Facility for Antiproton and Ion Research



SIS100 magnets,
April, 2024

CBM cave,
February, 2024

Facility for Antiproton and Ion Research

NuPECC LRP2024 Executive Summary

https://nupecc.org/lrp2024/Draft_Executive_Summary_LRP2024.pdf

Introduction

What does nuclear physics stand for?

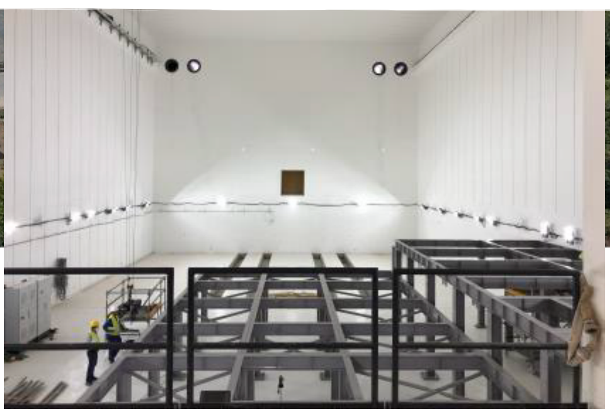
Nuclear physics is the study of the atomic nucleus, its constituents, structure, reactions and the properties of strongly interacting matter in its various forms. It is a key basic scientific field that investigates the properties of matter at the subatomic level. This domain of research affects not only our fundamental understanding of nature but also has many peaceful applications in all areas of modern life. Nuclear physics research originally started in Europe in the late 19th century. Now, in the 21st century, Europe is still at the forefront of nuclear physics research and applications. This leading European role is due to a rich and diverse landscape of research institutions and infrastructures in all European countries.
The present Long Range Plan for European nuclear physics summarises progress in the field in the last decade, provides an outlook on expected developments in the next decades, and presents recommendations for scientific institutions, policymakers, and research funding organisations.

Recommendations for Nuclear Physics Infrastructures

The NuPECC Long Range Plan 2024 resulted in the following main recommendations for infrastructures of importance for nuclear physics:

- The first phase of the international **FAIR** facility is expected to be operational by 2028, facilitating experiments with SIS100 using the High-Energy Branch of the Super-FRS, the CBM cave and the current GSI facilities. Completing the full facility including the **APPA**, **CBM**, **NUSTAR** and **PANDA** programs will provide European science with world-class opportunities for decades and is highly recommended.

SIS100 magnets, April, 2024



CBM cave, February, 2024

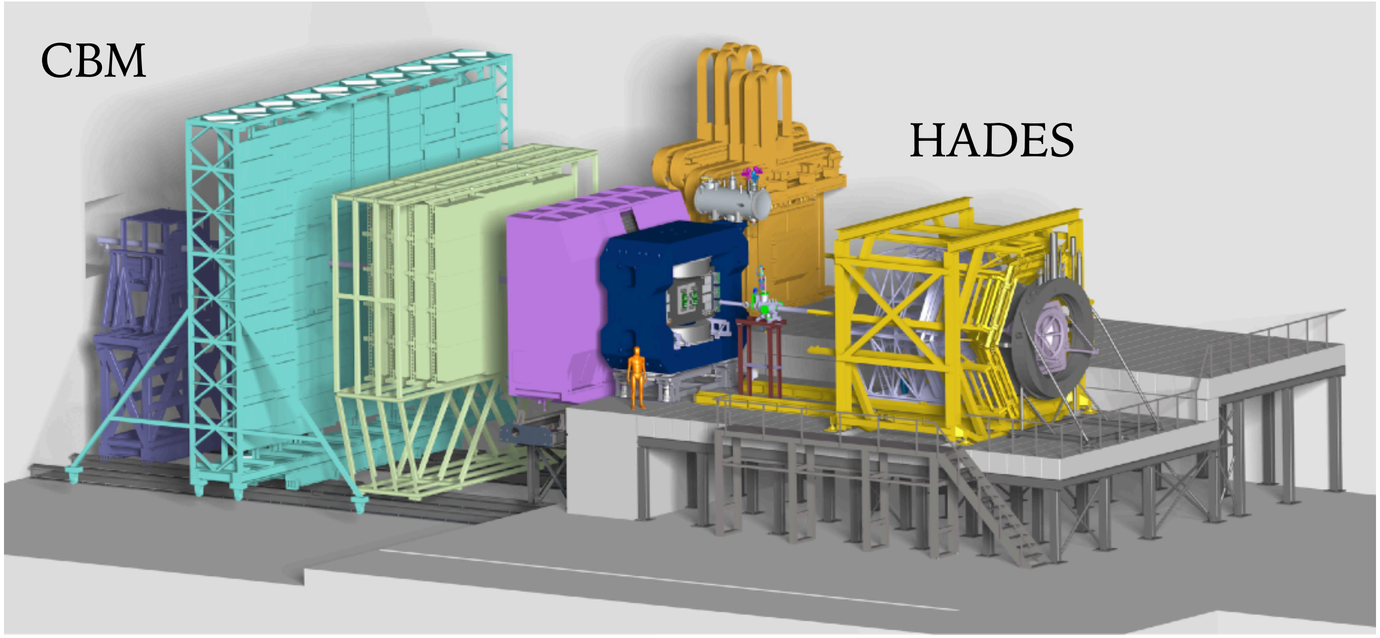
Compressed Baryonic Matter experiment

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



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

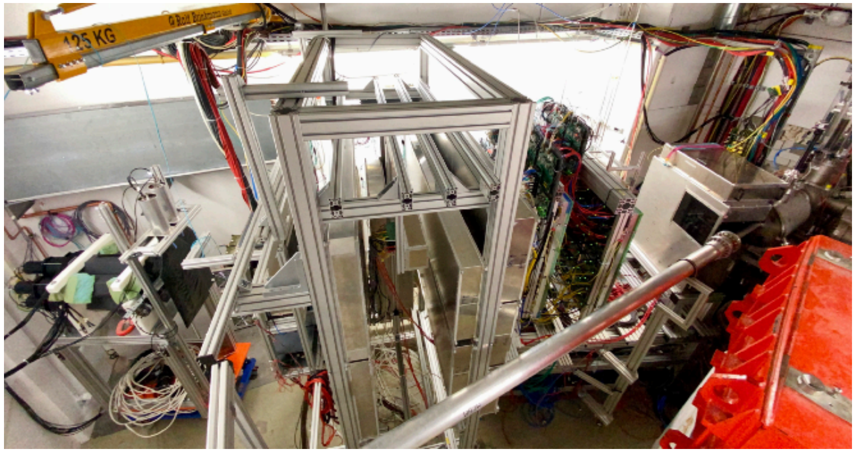
mCBM

Campaign 2024:

high-rate studies

online reconstruction and selection

Λ baryons in Ni+Ni at 1.0 - 1.93 AGeV

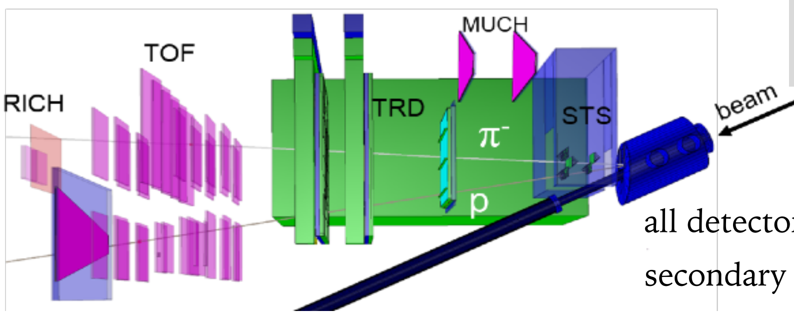


Free-streaming CBM data transport

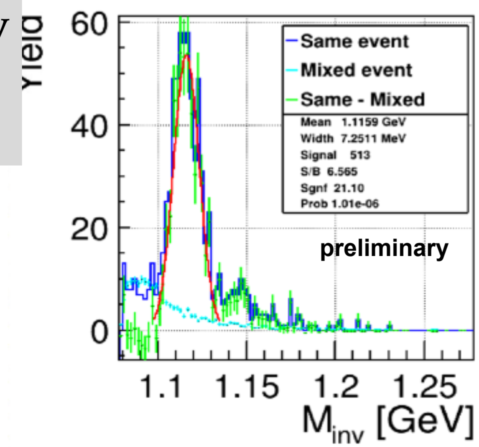
Pre-series productions of all CBM detector systems

High-rate studies up to 10 MHz coll. rate in A+A 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

Road map

What are we pursuing and why? ⇒ Physics motivation

Where are we now? ⇒ Current status

Who is involved? ⇒ Experimental facilities

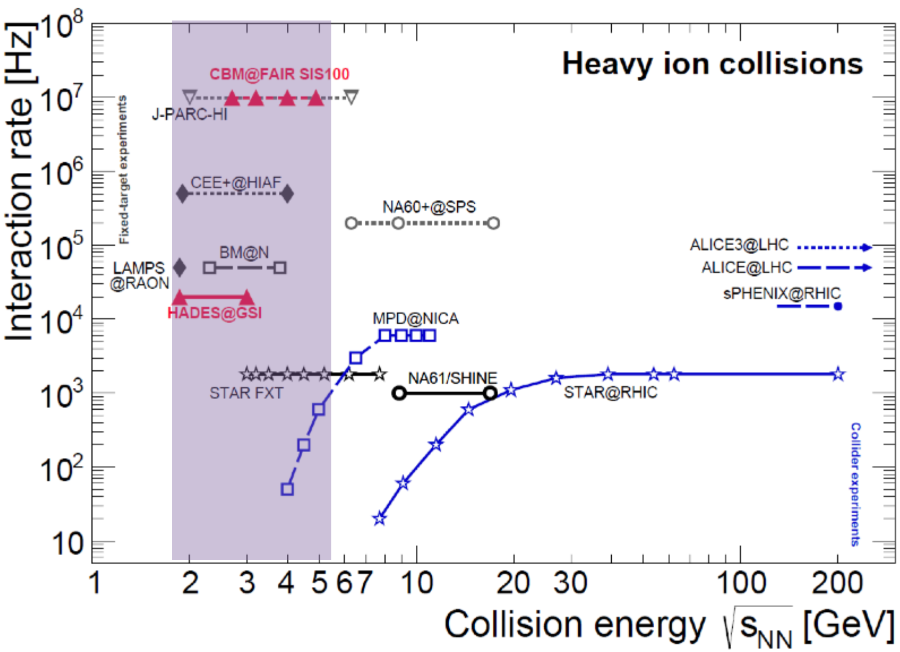
How to achieve the goal? ⇒ Compressed Baryonic Matter

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

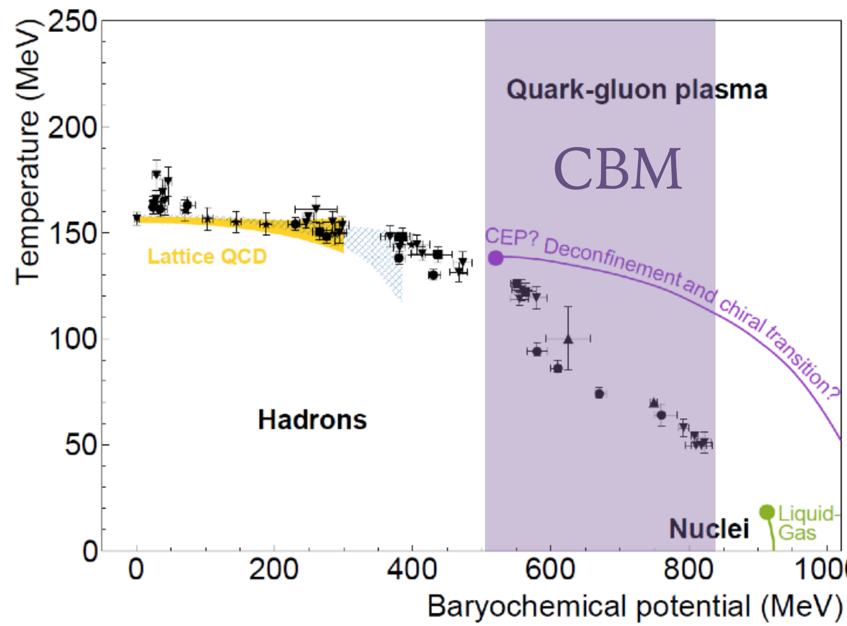
Key observables

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



T. Galatyuk, NPA 982 (2019), update 2023
https://github.com/tgalatyuk/interaction_rate_facilities

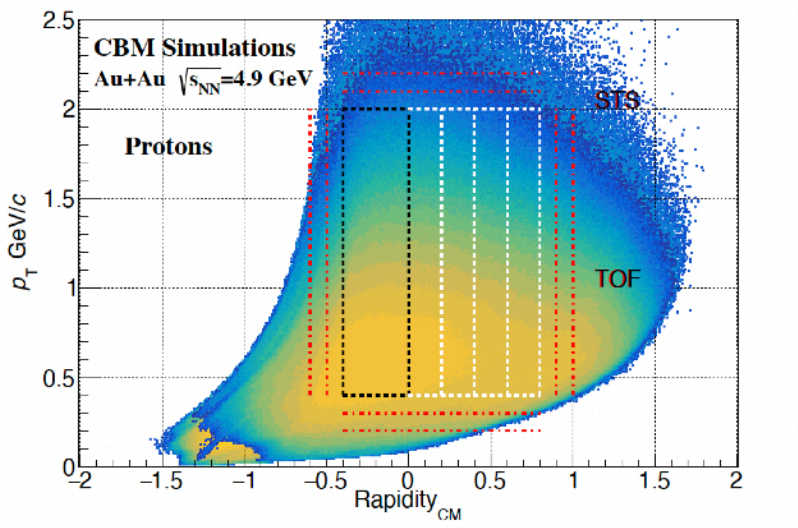


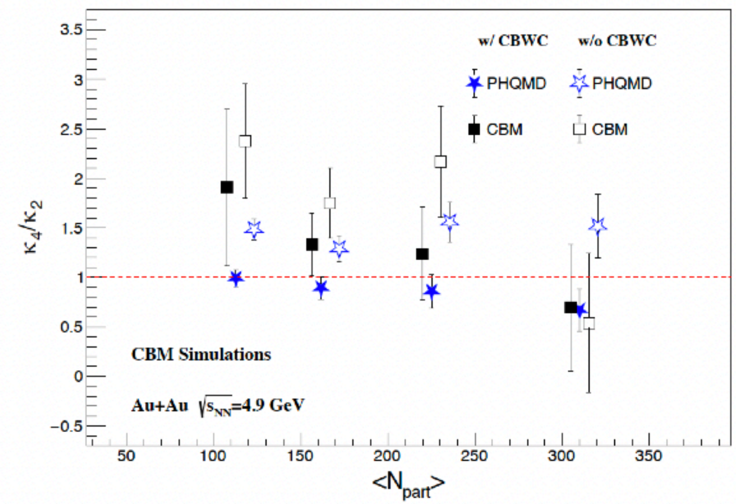
HADES; Nature Physics 15 (2019) 10, 1040-1045

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

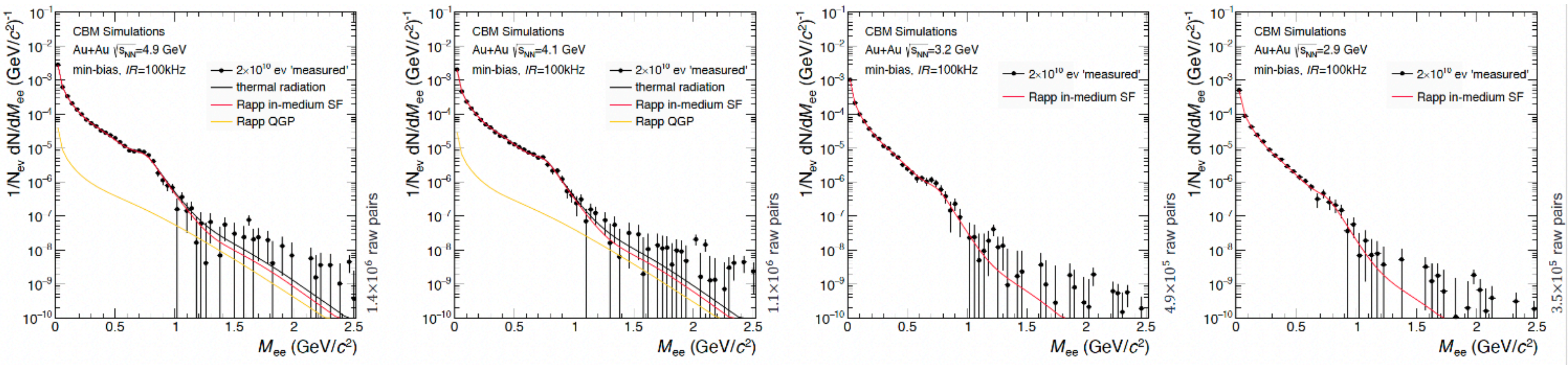
Electron thermal radiation, corrected for acceptance and efficiency,

Dominated by ρ contribution at LMR,

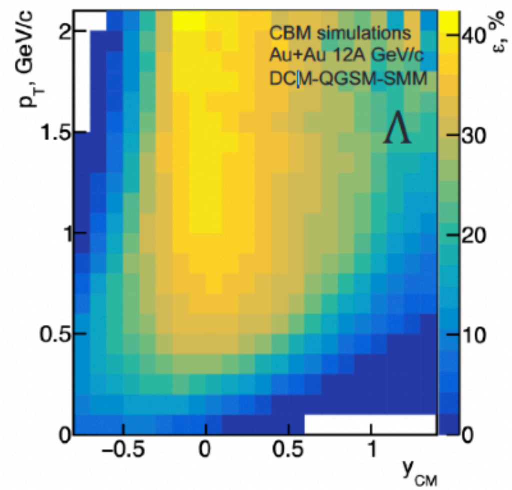
Can be reconstructed with 1.5-4.5% of precision,

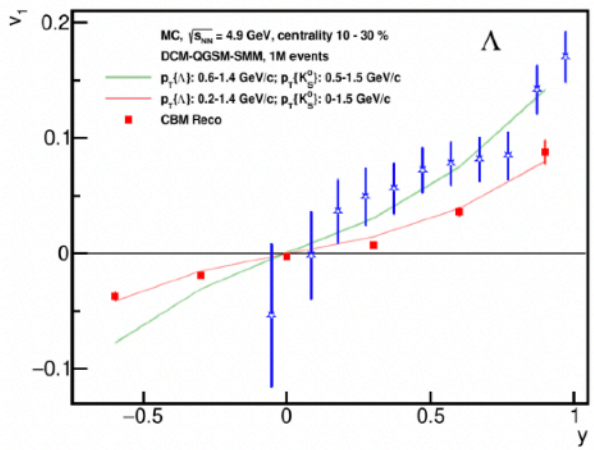
Gives access to to the fireball lifetime and electrical conductivity (transport properties)

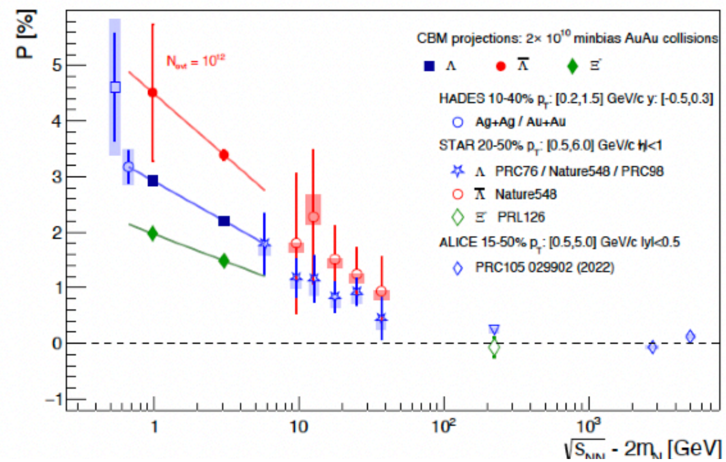
T vs. baryon density effects from partonic to hadronic fireballs



Flow, polarization, correlations

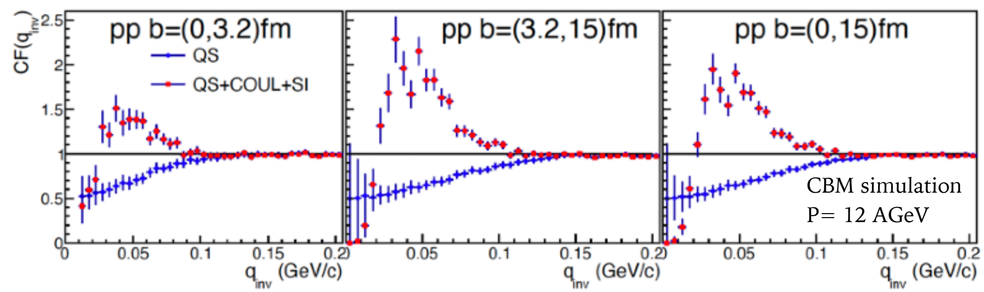




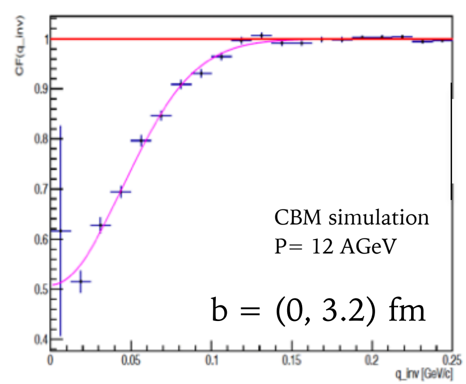


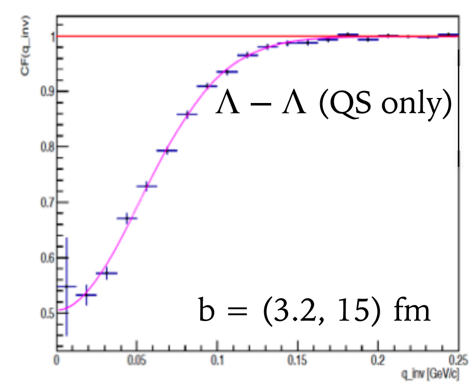
Excellent acceptance coverage

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

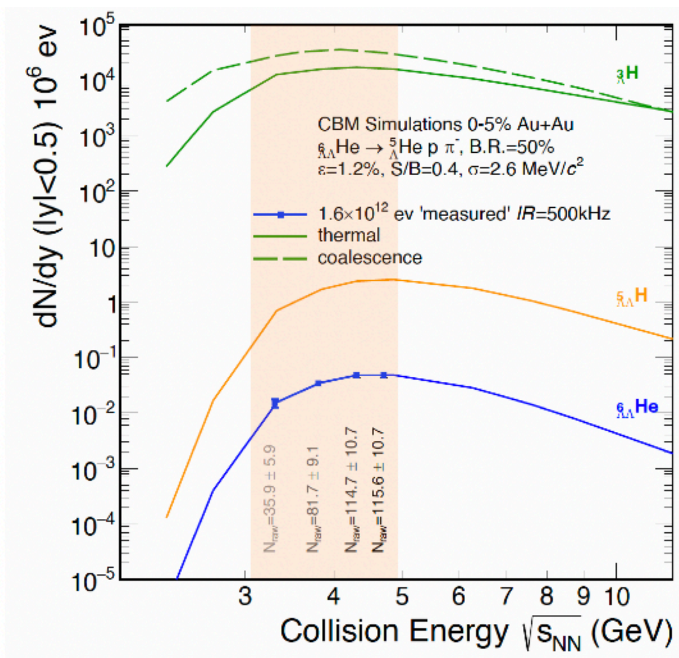


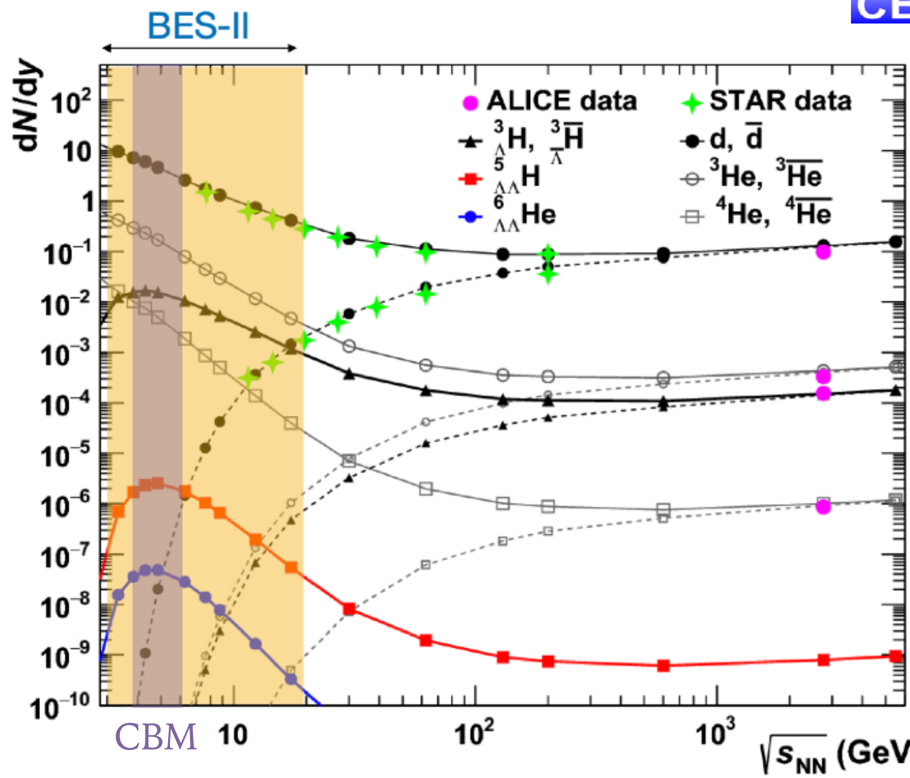


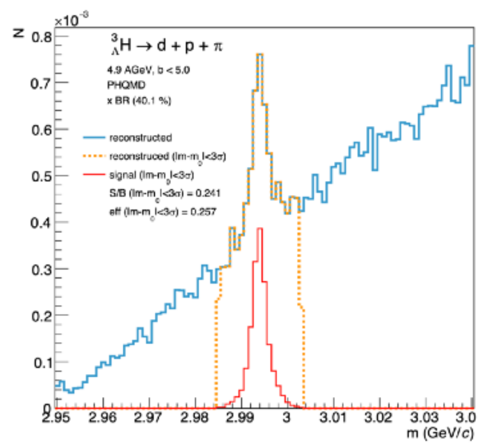
Interactions: hyper-nuclei, bound-states

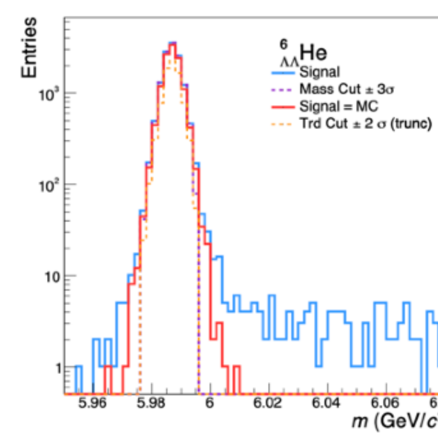
The most abundant production of hyper-nuclei anticipated at $\sqrt{s_{NN}} \sim 2-5$ GeV

Prominent interaction rates and excellent particle identification will facilitate to search for multi-strange hyper-nuclei

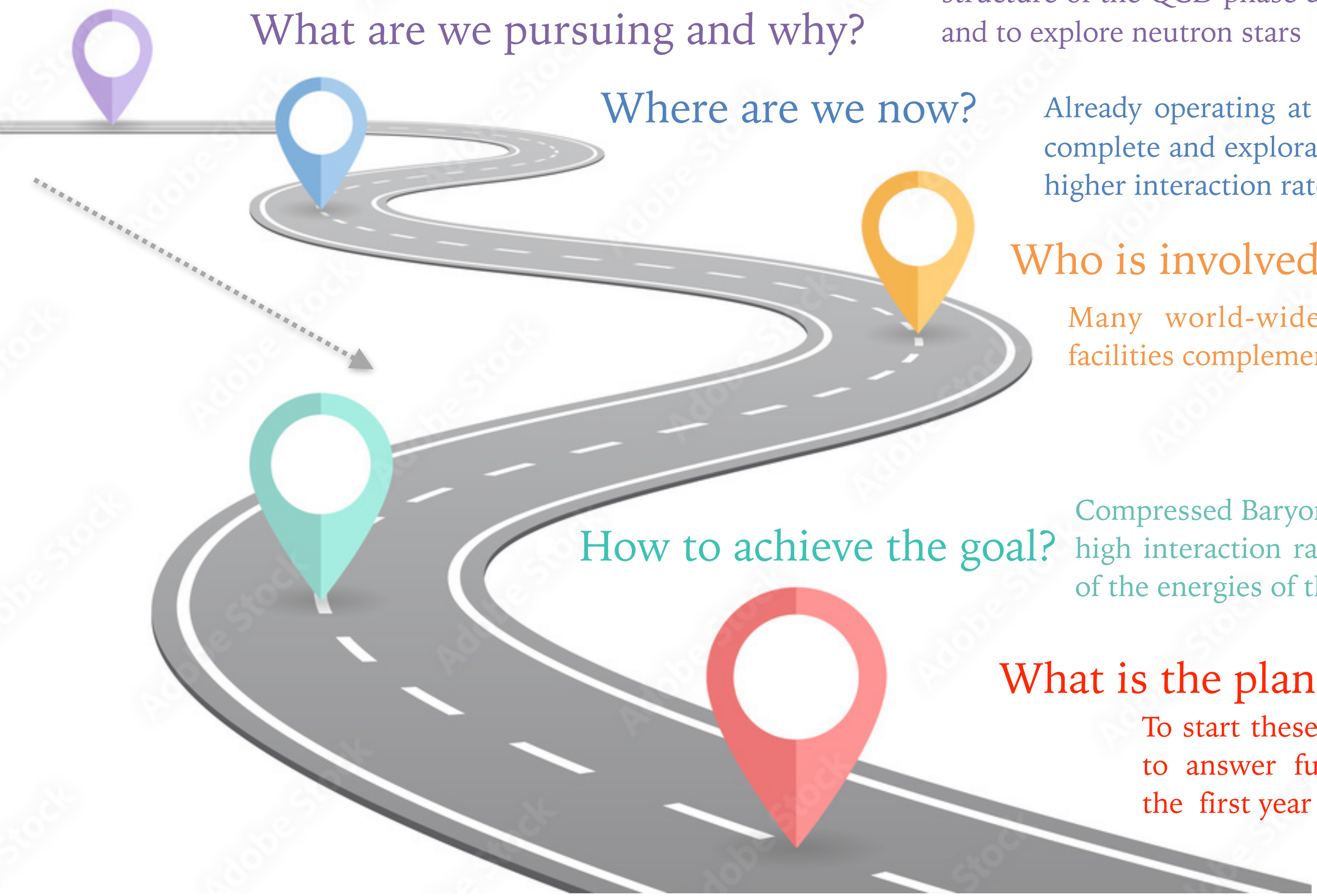








Andronic et al., PLB 697 (2011)
Steinheimer et al., PLB 714 (2012)



What are we pursuing and why?

To answer fundamental questions about the structure of the QCD phase diagram at high μ_B and to explore neutron stars

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

What are we pursuing and why?

To answer fundamental questions about the structure of the QCD phase diagram at high μ_B and to explore neutron stars

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

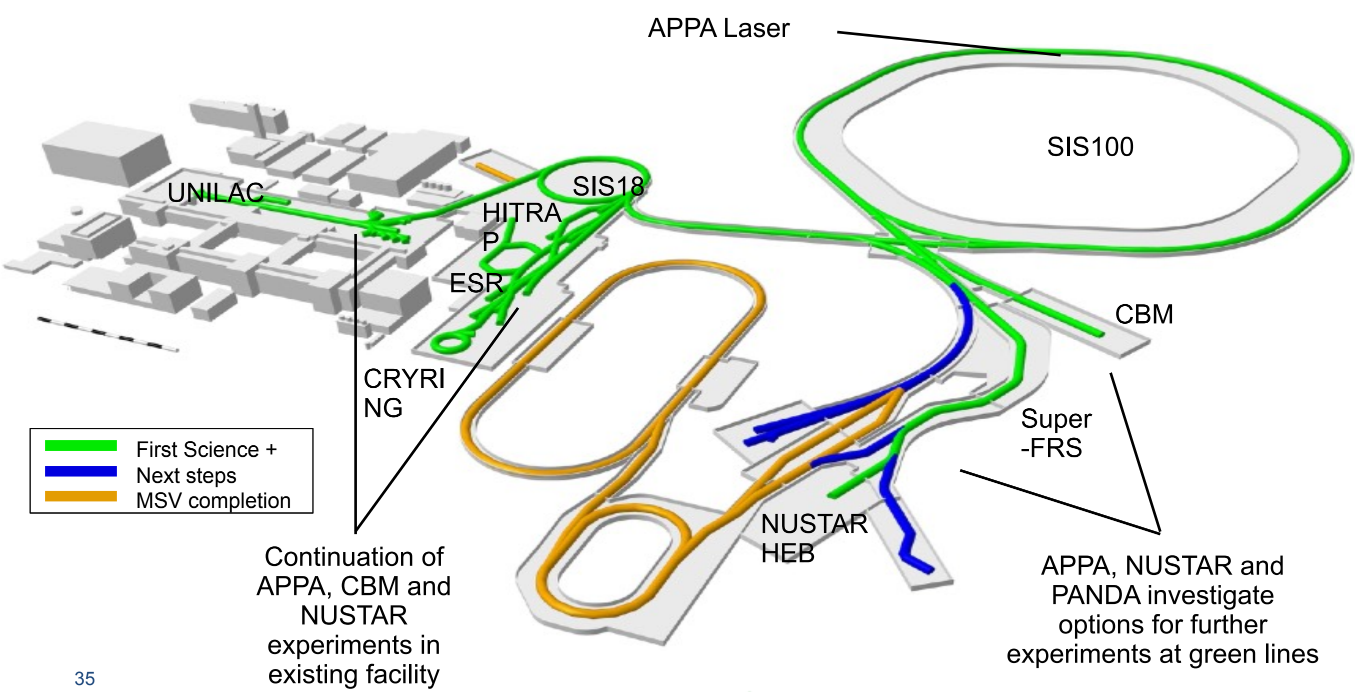
The Future is Bright

Be the light

CBM is open for new participation

Current prospects and timeline

FAIR



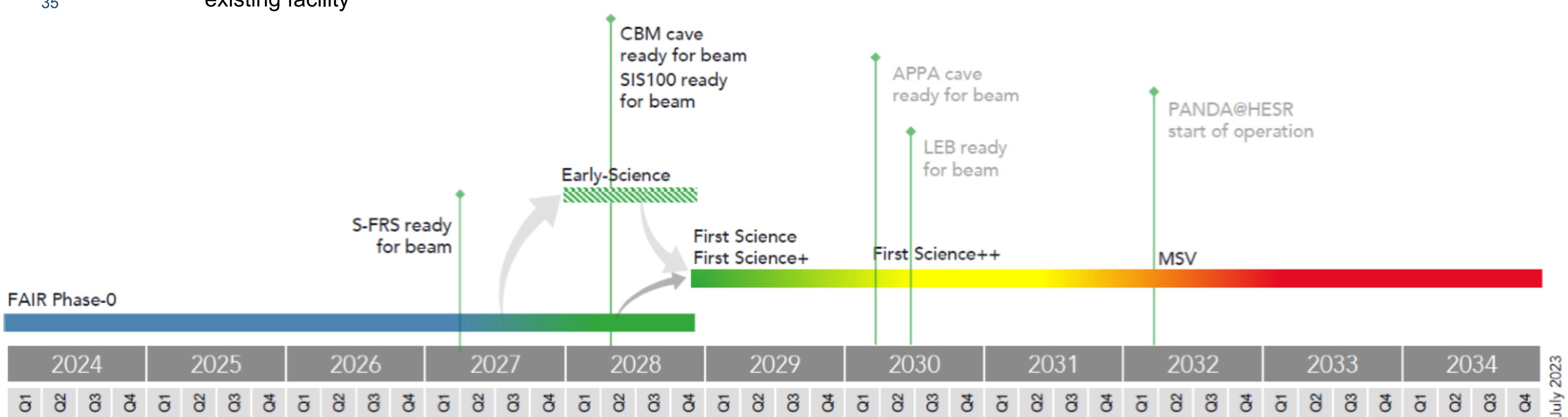
until 2028

FAIR Phase-0

after 2028

Staged implementation recommended by the Heuer/Tribble Commission's report (2022) with the First Science stage endorsed by the FAIR Council as "the most appropriate starting scenario to achieve world-leading science."

35



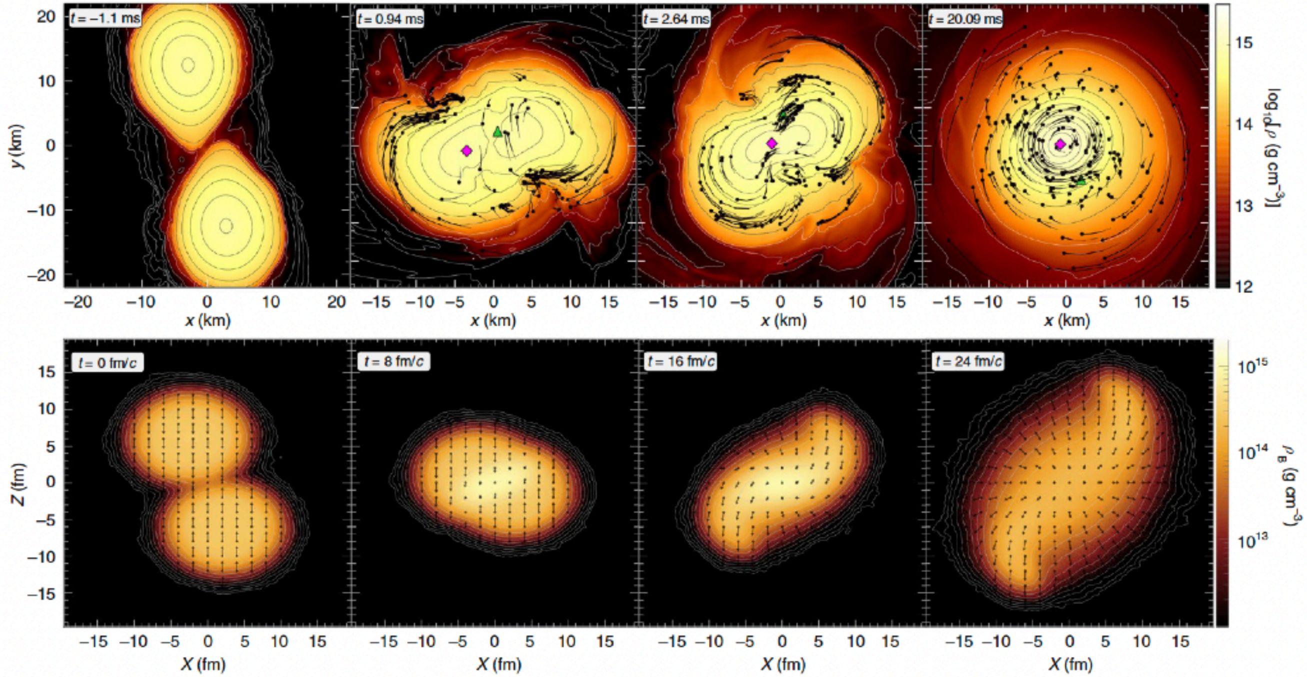
NSM and HIC

Top row: simulation of **NS mergers (NSM)**
2 NSs of 1.35 M⊙ each,
merging into a single object (2R ~ 10 km, $n \sim 5n_0$, $T \leq 20$ MeV).
Overlap region: $t \sim 20$ ms, $n \sim 2n_0$, $T \sim 75$ MeV
- max. temperature
- max. density

Artist's depiction of a neutron star collision after inspiral, NASA/Swift/Dana Berry

Bottom row: non-central **Au+Au collision** at $\sqrt{s_{NN}} = 2.42$ GeV
$n \simeq 3n_0$, $T \simeq 80$ MeV

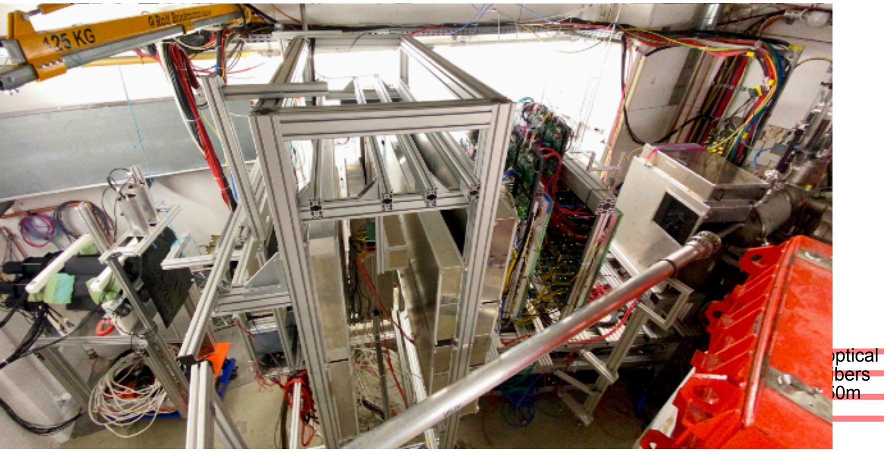
HADES, Nature Phys. 15, 1040–1045 (2019)



Space and **time** scales vastly contrasting (**km**-NS / **fm**-HIC - 18 orders of magnitude; **duration** - 20 orders of magnitude)

Similar **densities** and **temperatures** achieved

mCBM



FLES entry nodes
CRI FPGA
μSlice building
(DAQ container)

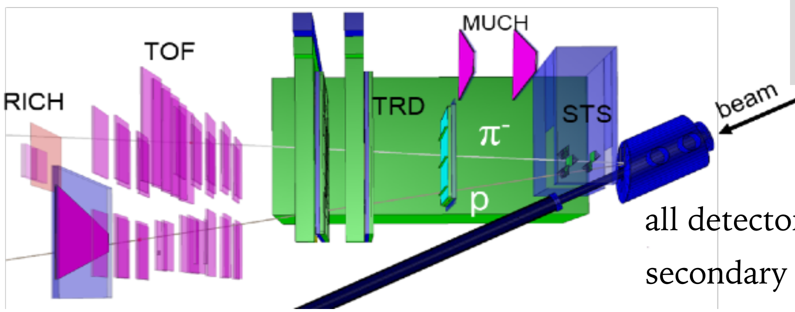
FLES processing nodes
time slice building
event reconstruction & selection
archiving

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: $\Lambda \rightarrow p\, \pi^-$

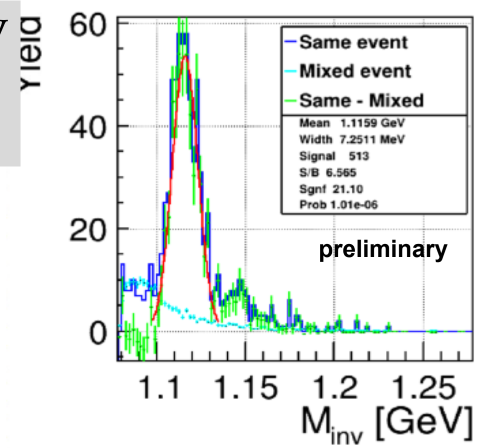


Ni+Ni 1.93 AGeV
run 2391 (May '22):
10^9 collisions, 1:57h
400 kHz av. coll. rate

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

Strange hadronic matter in the inner core

The inner core of the neutron star is totally unknown. One of the most probable scenarios is that hyperons (baryons with strange quarks) appear at a density larger than (2–3) ρ_0

Λ hyperons, being free from Pauli exclusion principle by neutrons, are allowed to stay at the bottom of the attractive nuclear potential made by neutrons. **When the kinetic energy of a neutron on the Fermi surface of the degenerate neutron matter exceeds the Λ-n mass difference of 176 MeV, it converts into a Λ hyperon via weak interaction.**

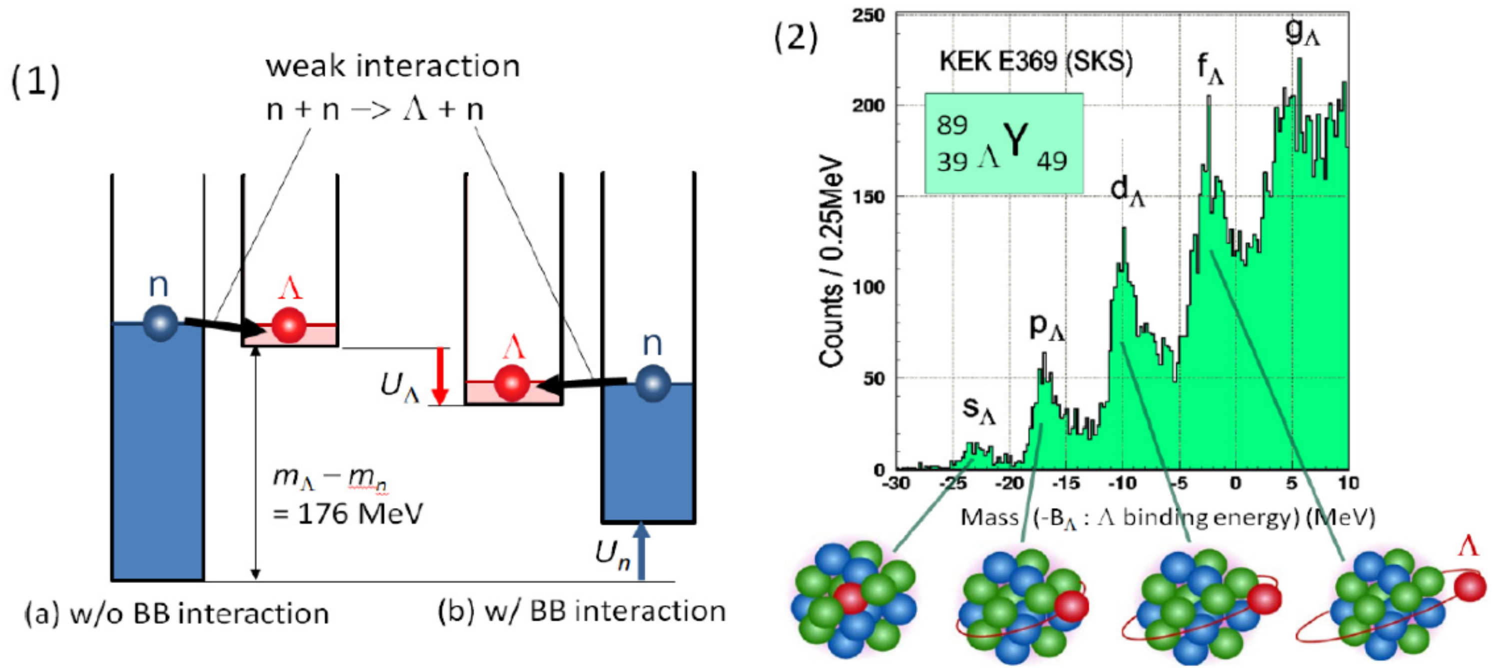


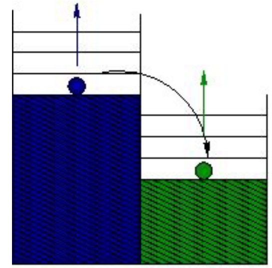
Fig. 3. (1) Energies of neutrons and Λ hyperons in high density neutron matter confined in the potential made by gravity. See text for details. (2) Excitation spectrum of a Λ hypernucleus $^{89}_{\Lambda}$Y via the (π^+, K^+) reaction on ^{89}Y target [6].

NS puzzle

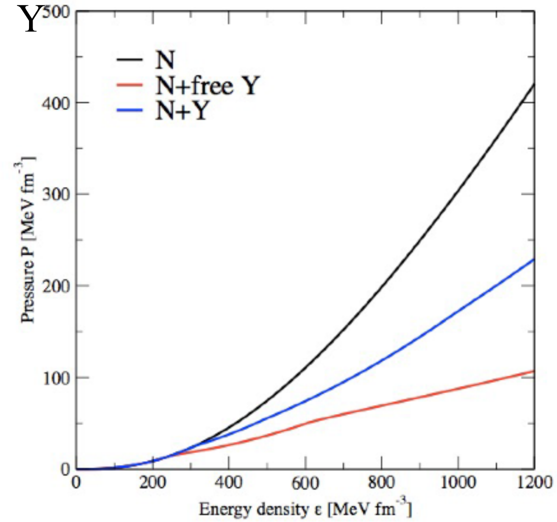
- Observation of **NS** indicates their **mass** $\sim 2M_{\odot}$
  (Shapiro-delay: Post-Keplerian parameters of orbits)
- **Hyperons:** Expected in core of NS, the conversion of N into Y is energetically favorable
- **Appearance of Hyperons:** The presence of Y alleviates Fermi pressure, resulting in a EoS and a reduction in NS mass (inconsistent with observations)
  Can they still be considered as components of NS?
- **Proposed Solution:** A mechanism that provides additional pressure to ensure a stiffer EoS
  One emergent mechanism involves many-body interactions, such as YN, YY, NNY, NYY
  (Other: hypersonic three-body forces, Quark Matter Core - a transition to deconfined phase below hyperon threshold in density)

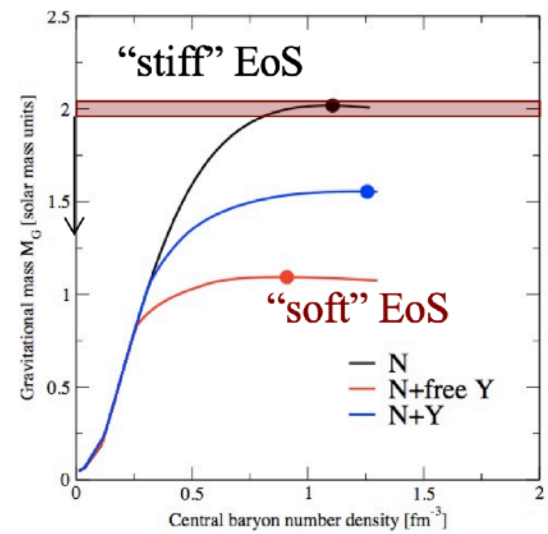
  Measuring YN and YY interactions is essential to substantial implications for the potential formation of bound states involving N and Y

  The existence of hyper-nuclei, confirmed by the attractive YN interaction, suggests the possibility of binding Y to N

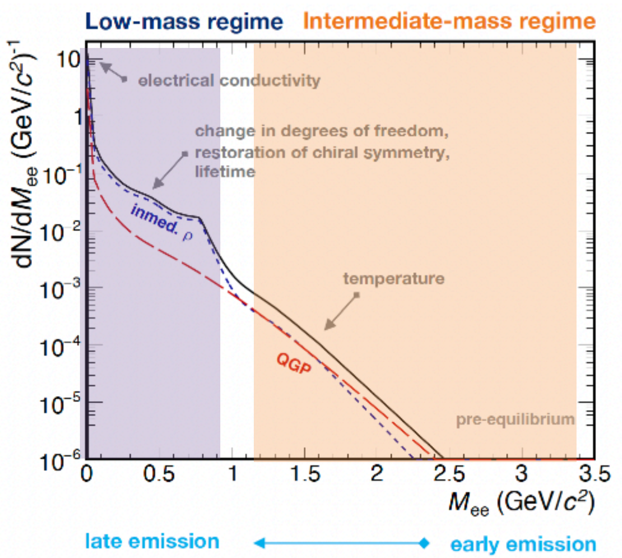


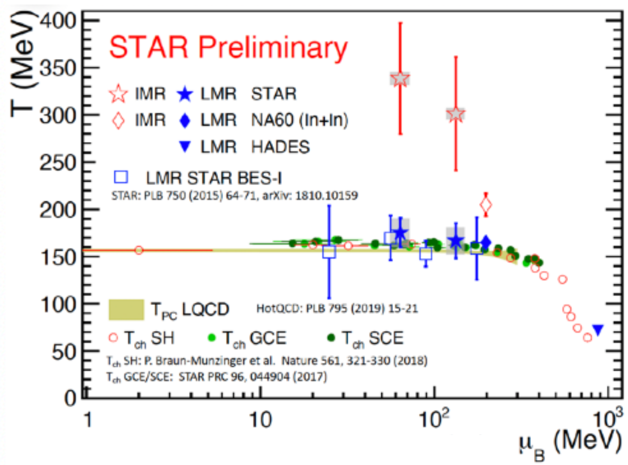
$M_{NS} \approx 1 \div 2\ M_{\odot}$
$R \approx 10\text{-}12$ km
$\rho \approx 3 \div 5\ \rho_0$
$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3





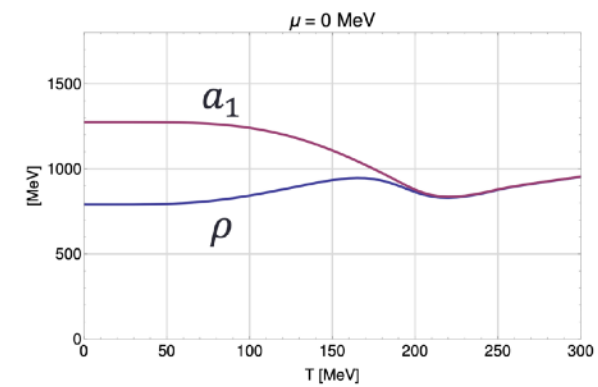
E-M probes access the whole collision





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

Inscribes matter properties enabling estimation:
- degrees of freedom of the medium
- fireball's lifetime, temperature, acceleration, polarization
- transport properties
- restoration of chiral symmetry



Hohler and Rapp, PLB 731 (2014), Jung, Rennecke, Tripolt, v. Smekal, Wambach, PRD95 (2017) 036020, Aartz, QM2022, April 2022

a_1 and ρ mesons probe chiral symmetry restoration (mixing vector and axial-vector correlators)

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

R - interaction rate
S - signal
B- combinatorial background

Prominent interaction rate mandatory

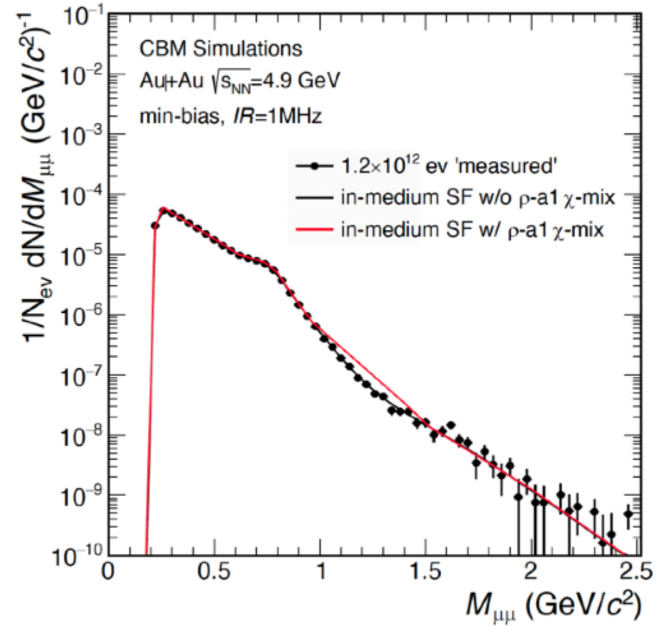
Thermal dileptons in **LMR**:
- T close to T_{ch} and T_{pc}
- dominantly emitted around phase transition

Thermal dileptons in **IMR**:
- T is higher than T_{pc}
- Emitted fom QGP phase

Dileptons

Dey, Eletsky, Ioffe, PLB252 (1990)
Rapp, Wambach, ANP 25 (2000)
Sakai et al., arXiv:2308.03305 [nucl-th]

20-30% enhancement w.r.t. no chiral mixing foreseen in the region $M \sim 0.8 - 1.5\ MeV/c^2$



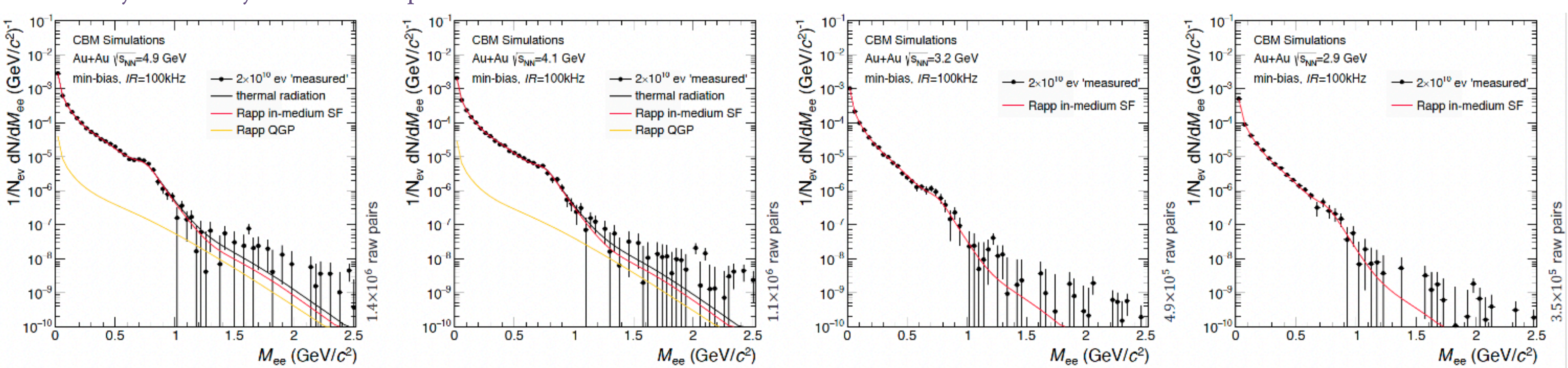
Electron thermal radiation, corrected for acceptance and efficiency,

Dominated by ρ contribution at LMR,

Can be reconstructed with 1.5-4.5% of precision,

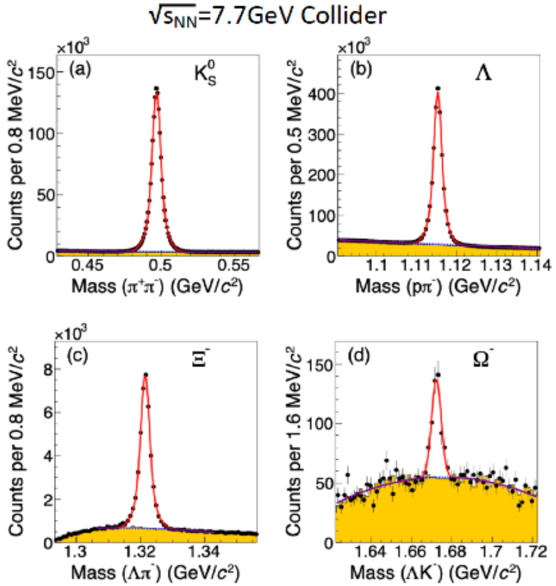
Gives access to to the fireball lifetime and electrical conductivity (transport properties)

T vs. baryon density effects from partonic to hadronic fireballs



EoS to probe NS properties

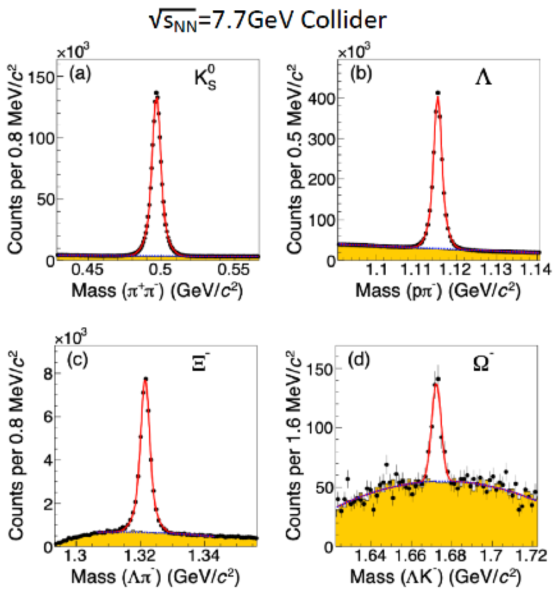
EoS investigations include vast number of measurements:
- Chemistry (strangeness, charm, hyper nuclei, …)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, …)



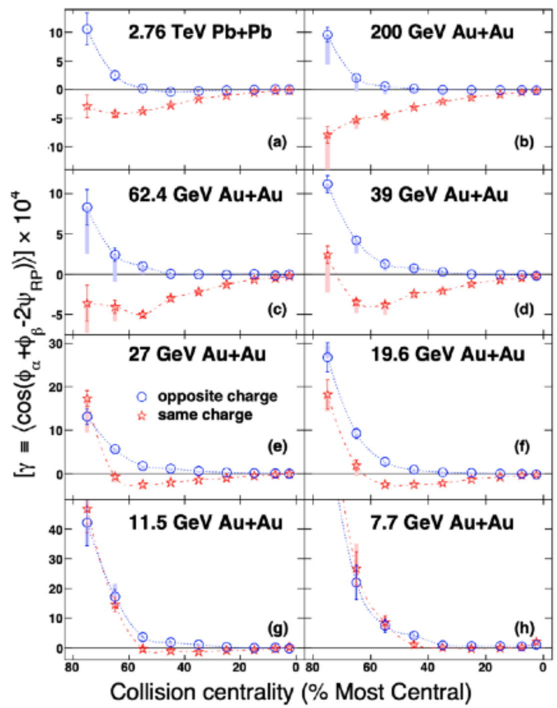
PRC 102 (2020) 34909 (STAR)

EoS to probe NS properties

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)

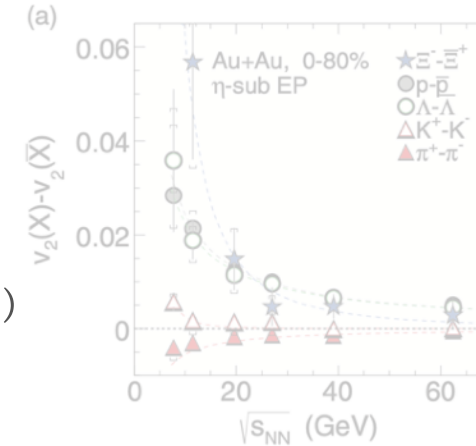


PRL 113 (2014) 52302

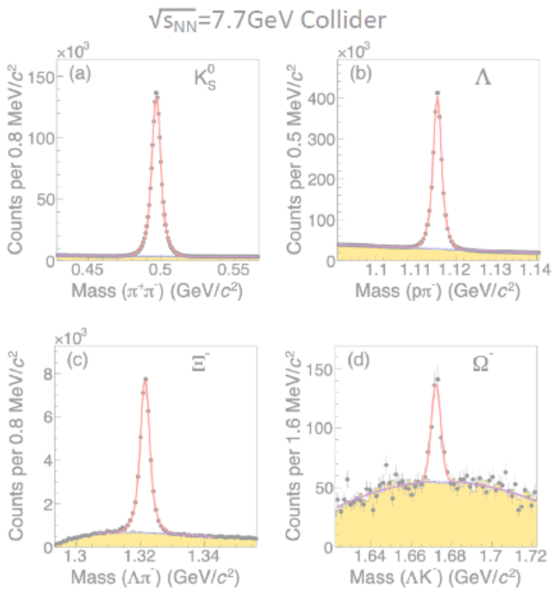
EoS to probe NS properties

EoS investigations include vast number of measurements:

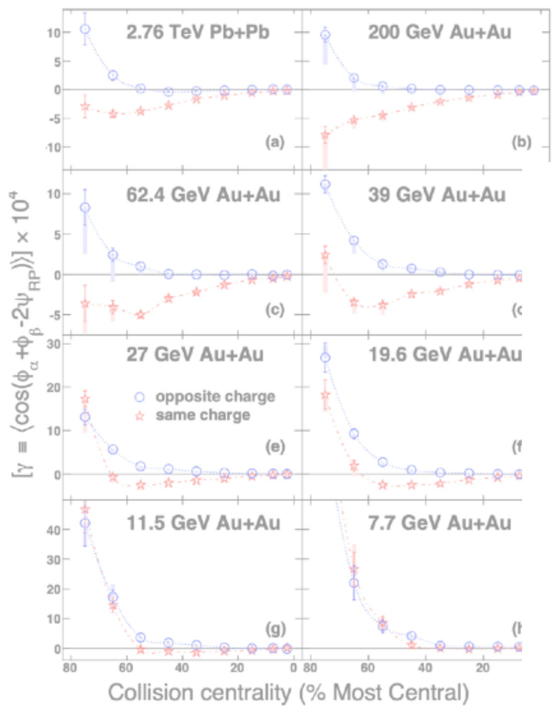
- Chemistry (strangeness, charm, hyper nuclei, ...)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, ...)



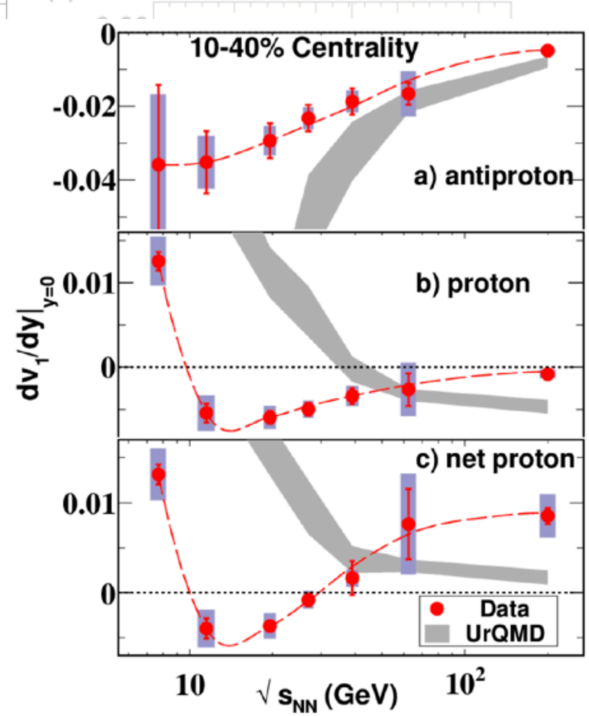
STAR, PRL 112, 162301 (2014)



PRC 102 (2020) 34909 (STAR)



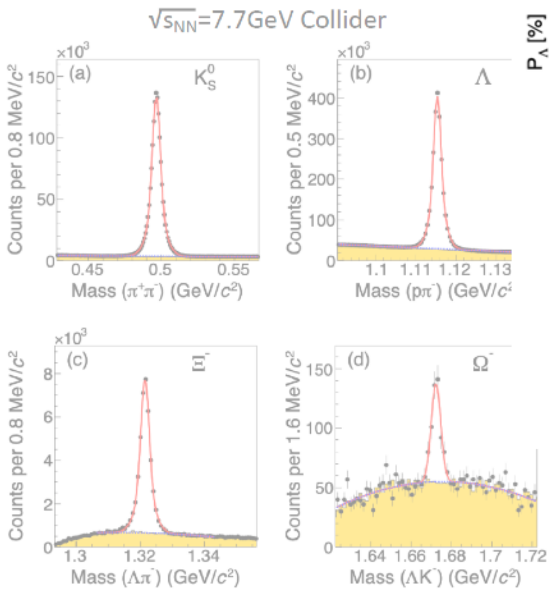
PRL 113 (2014) 52302



EoS to probe NS properties

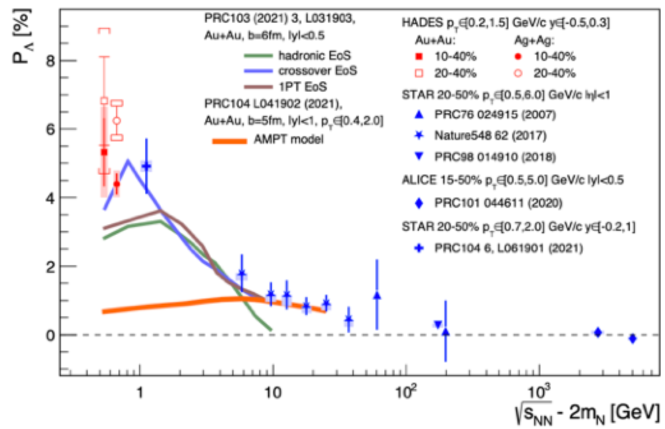
EoS investigations include vast number of measurements:

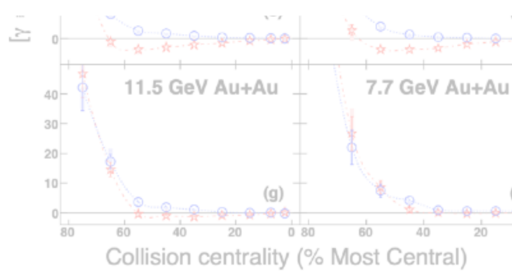
- Chemistry (strangeness, charm, hyper nuclei, …)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, …)



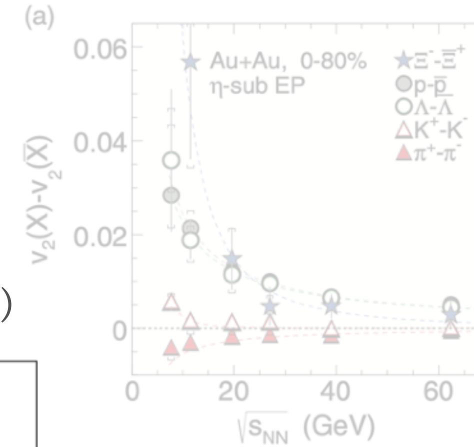
PRC 102 (2020) 34909 (STAR)

PLB 835, 137506 (2022)

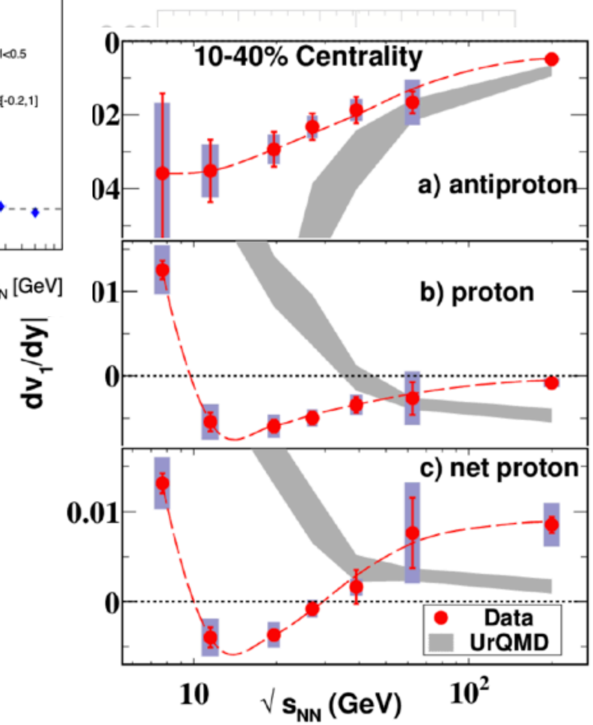




PRL 113 (2014) 52302



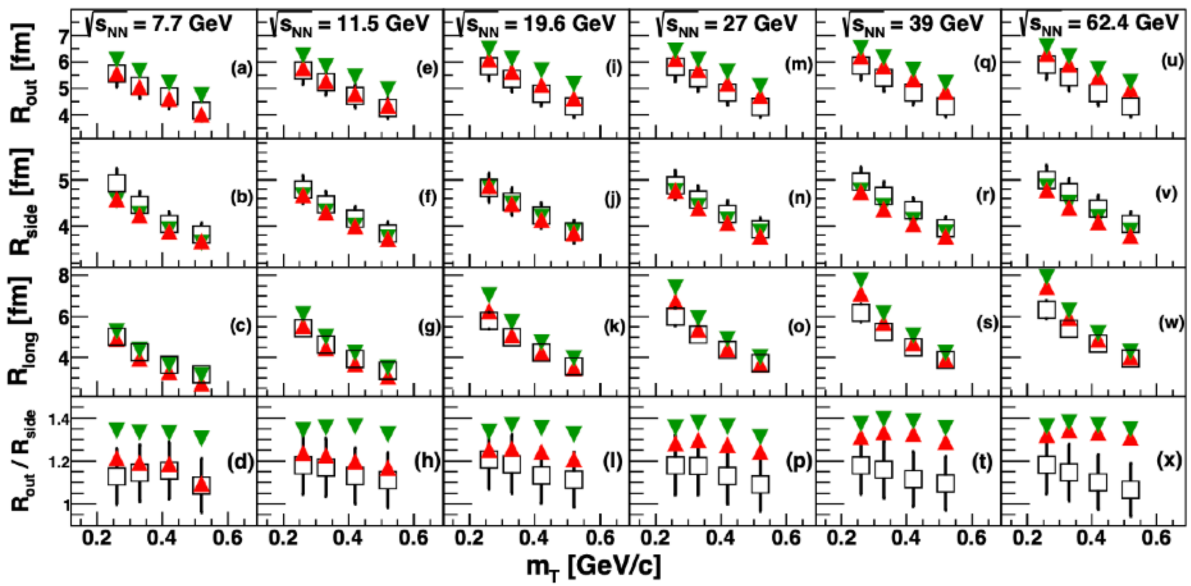
STAR, PRL 112, 162301 (2014)

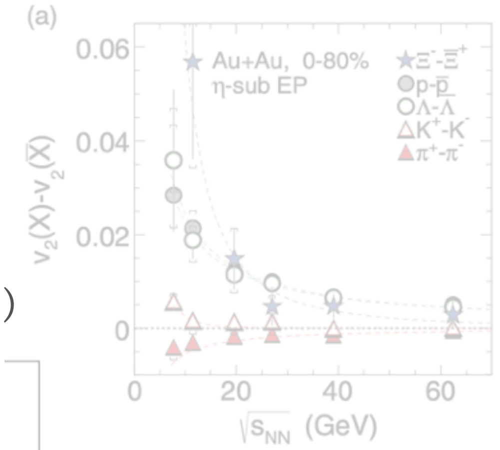


EoS to probe NS properties

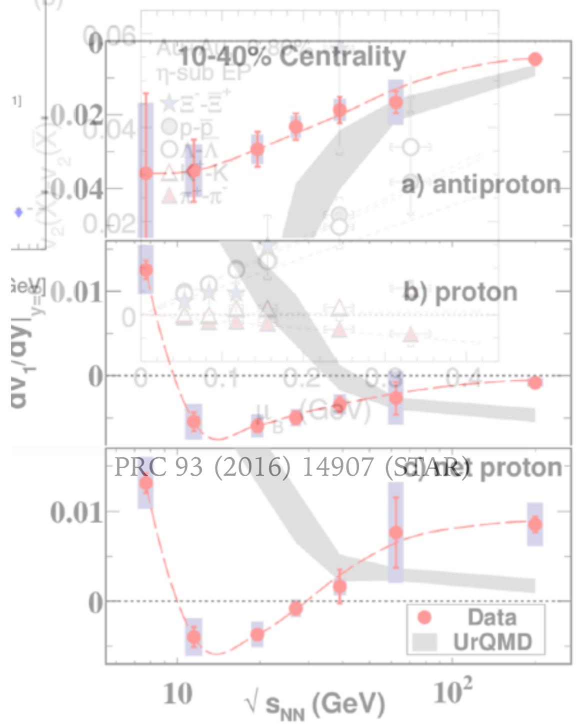
EoS investigations include vast number of measurements:
- Chemistry (strangeness, charm, hyper nuclei, …)
- Collectivity
- Vorticity
- Fluctuations and correlations
- Interactions in the final states (NN, NY, YY, many-body, hyper-nuclei, …)

PRC 96 (2017) no.2, 024911

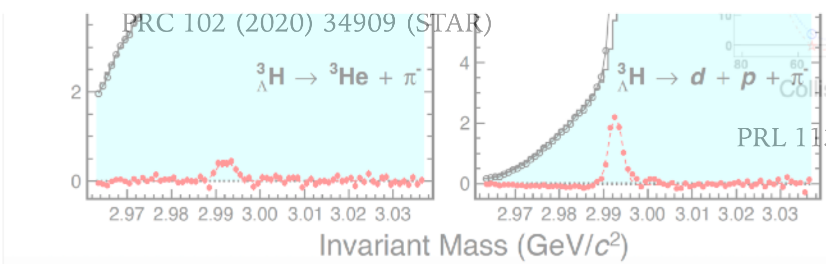




STAR, PRL 112, 162301 (2014)



PRC 93 (2016) 14907 (STAR)



PRC 102 (2020) 34909 (STAR)

PRL 113 (2014) 52302