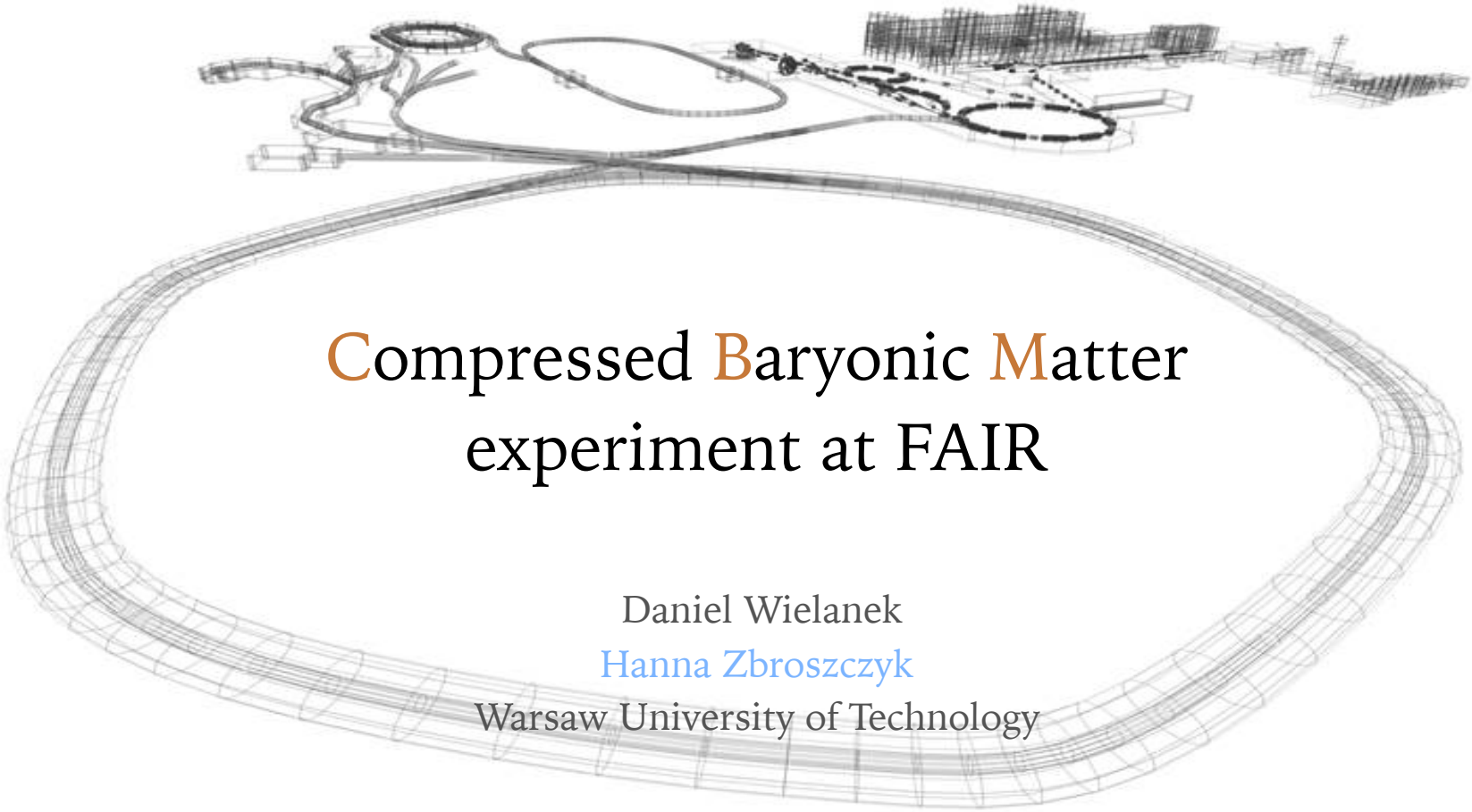


Compressed Baryonic Matter experiment at FAIR

Daniel Wielanek
Hanna Zbroszczyk
Warsaw University of Technology

XVII Polish Workshop on Relativistic Heavy-Ion Collisions, Warsaw 14-15, December 2024

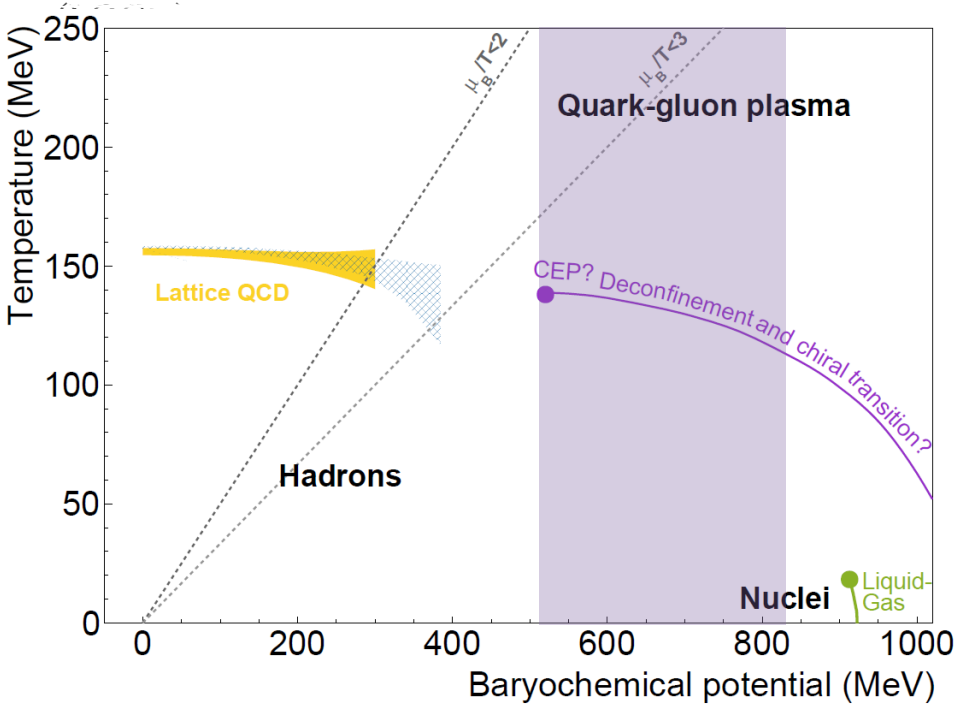
Road map

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 $\mu_B/T < 3$

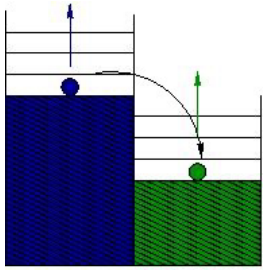


High μ_B, low T:

- 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



$M_{NS} \approx 1 \div 2\ M_\odot$

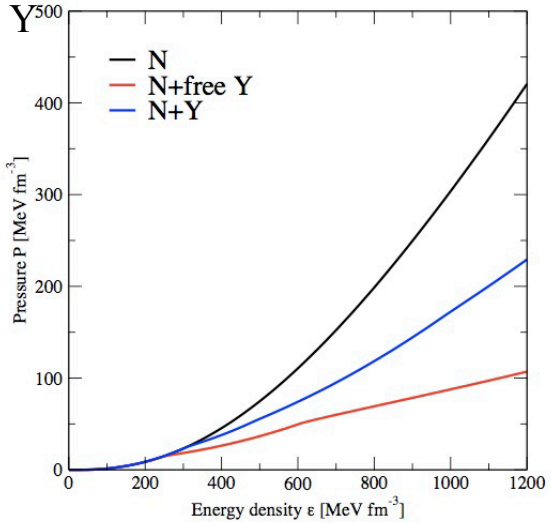
$R \approx 10\text{-}12$ km

$\rho \approx 3 \div 5\ \rho_0$

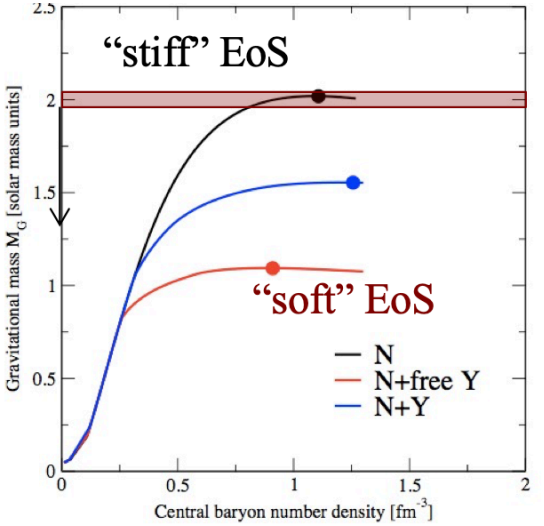
$\rho_0 \approx 2.8 \times 10^{14}$ g/cm^3

- 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?

N Y



- **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)



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

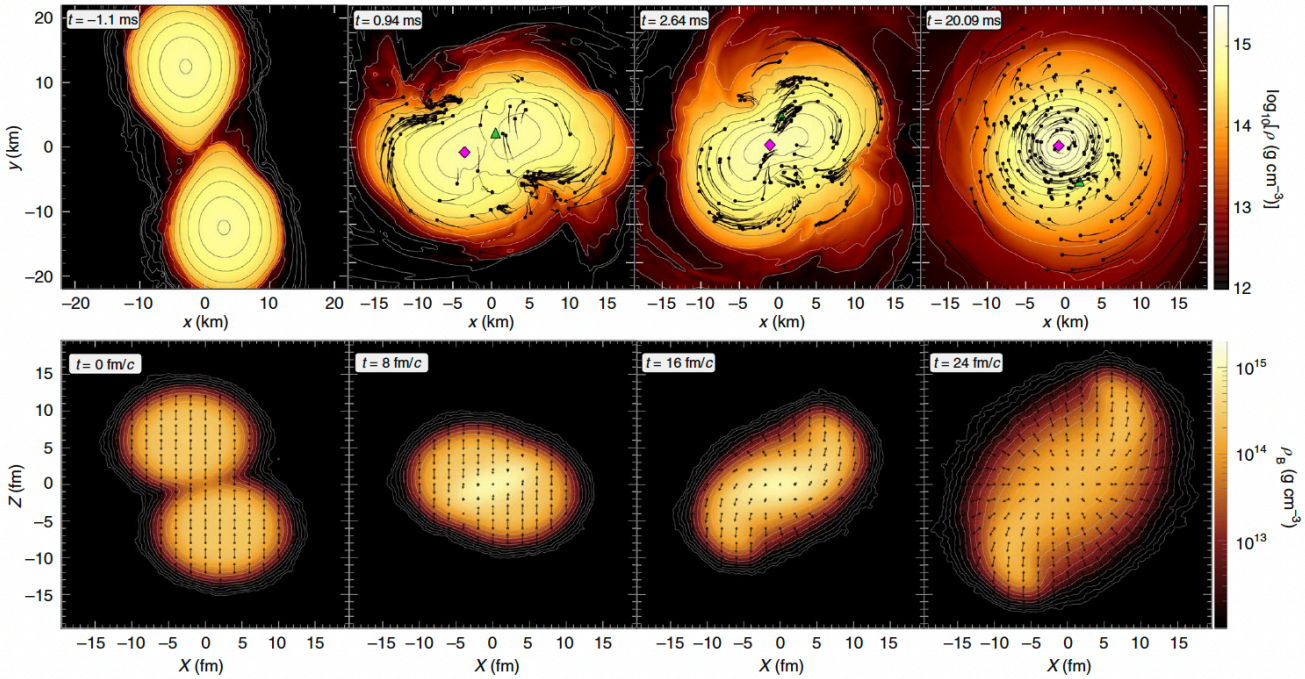
- max. temperature
- max. density

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)

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



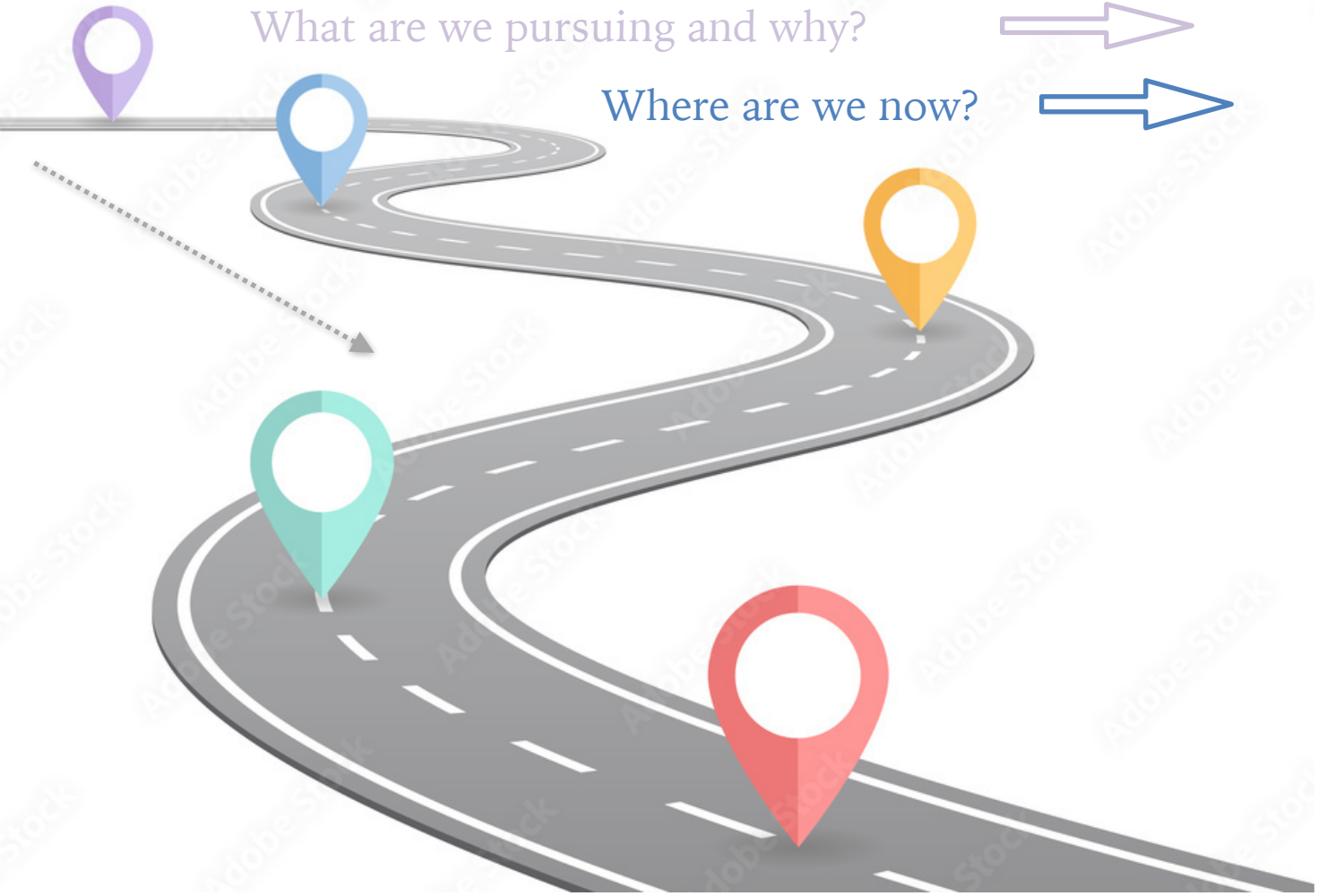
Space and **time** scales vastly contrasting (**km**-NS / **fm**-HIC - 18 orders of magnitude; **duration** - 20 orders of magnitude)

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

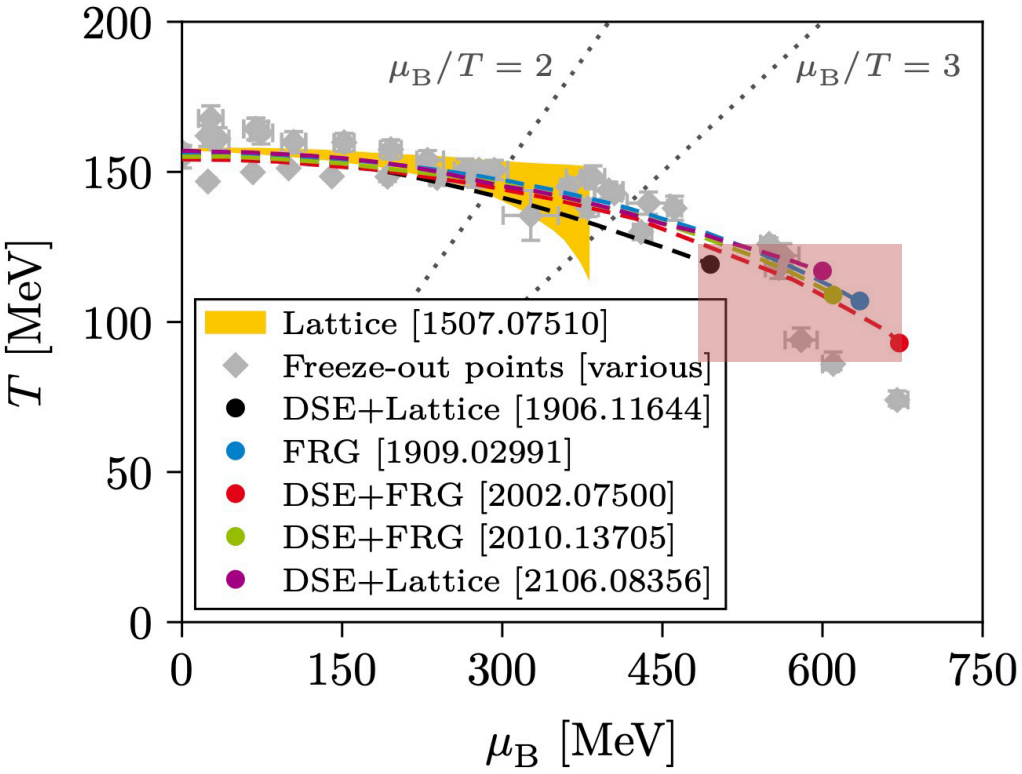
Road map

What are we pursuing and why? ⇒ Physics motivation

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



Critical point predictions

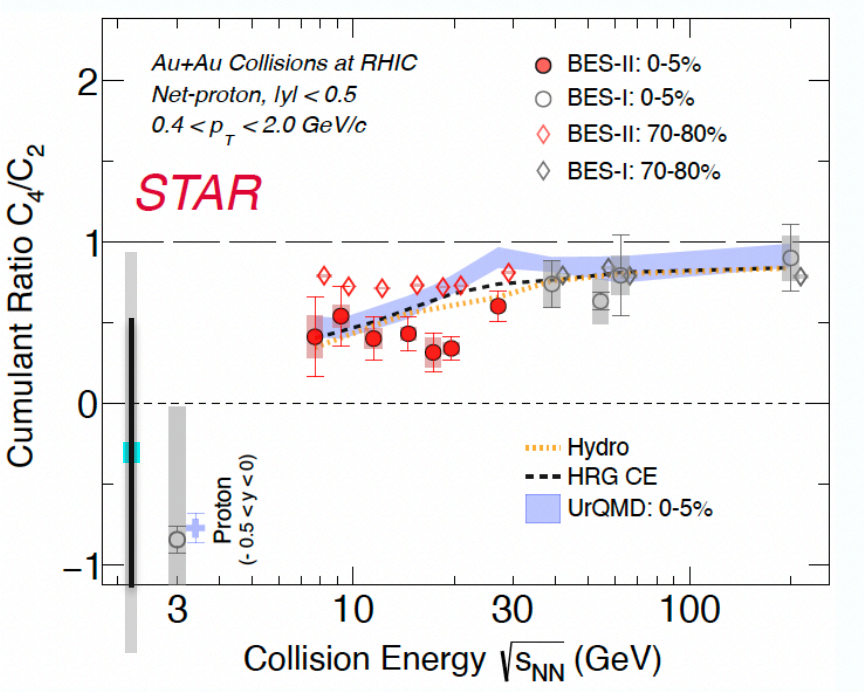


- LQCD frowns upon the location of the critical point at $\mu_B/T < 3$
- Effective QCD and lattice-based theories estimate its location at $T \sim 90 - 120$ MeV and $\mu_B \sim 500 - 650$ MeV
- This corresponds to heavy-ion collisions at $\sqrt{s_{NN}} \sim 3 - 5$ GeV

- 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

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

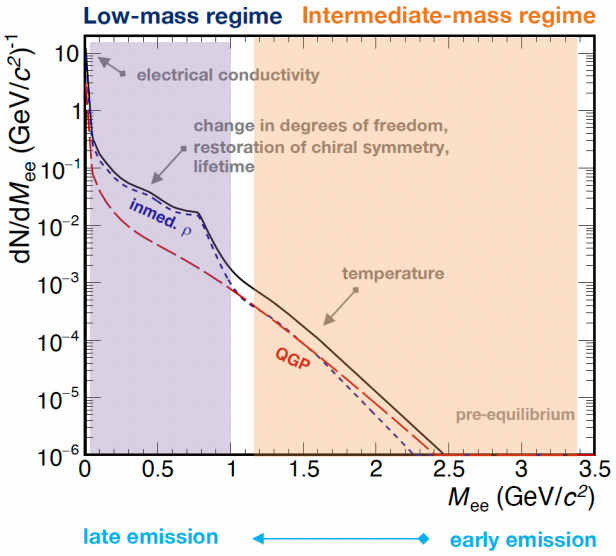
κ_n experimentally measured

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

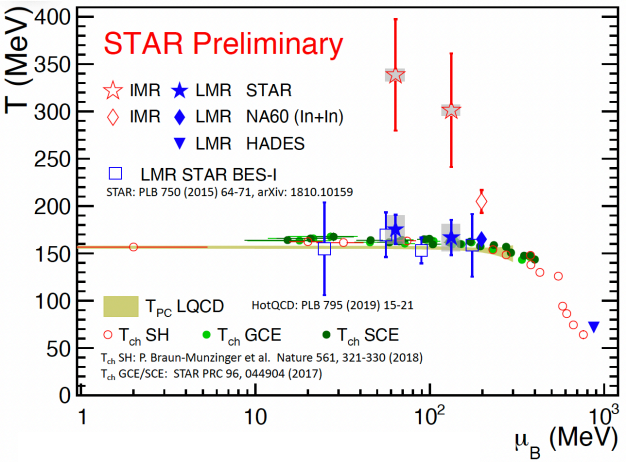
- Non-monotonic trend in κ_4/κ_2 of net-proton multiplicity distributions suggested as a **signature** of the **critical point**
- STAR collider program conducted comprehensive studies at $\sqrt{s_{NN}} > 7.7\ GeV$
- STAR fixed-target data investigation ongoing
- Sensitivity to the features of the QCD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



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



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

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: $S_{eff} \sim R\frac{S}{B}$

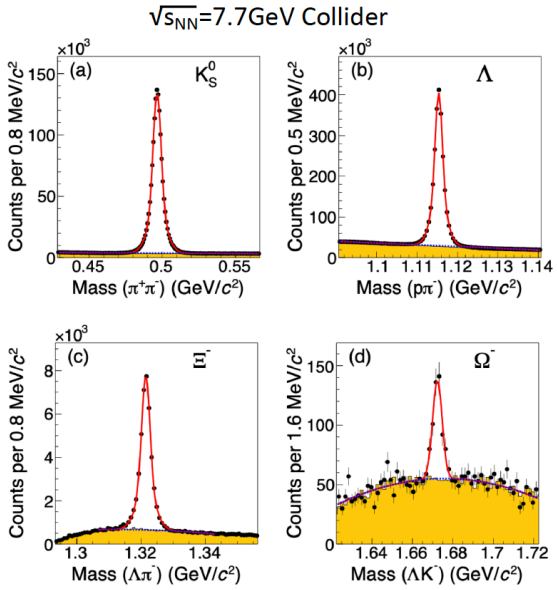
R - interaction rate
S - signal
B- combinatorial background

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)

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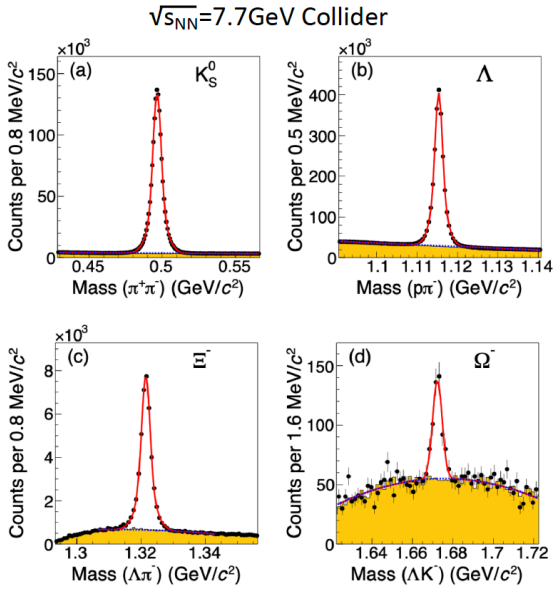
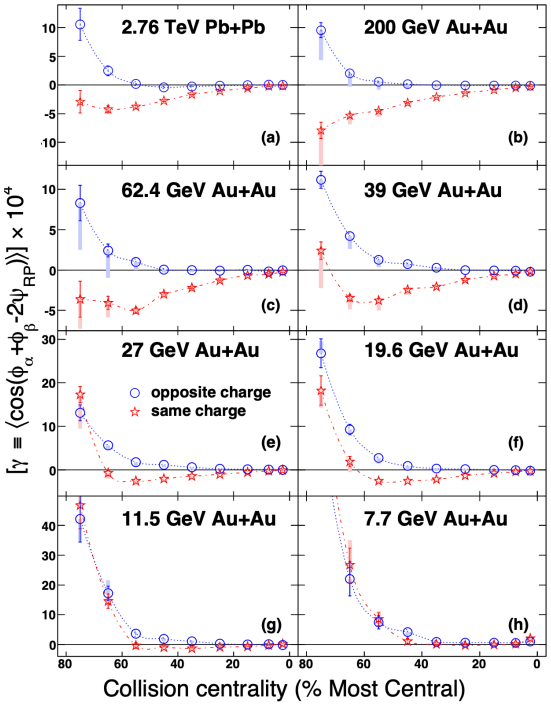


PRC 102 (2020) 34909 (STAR)



PRL 113 (2014) 52302

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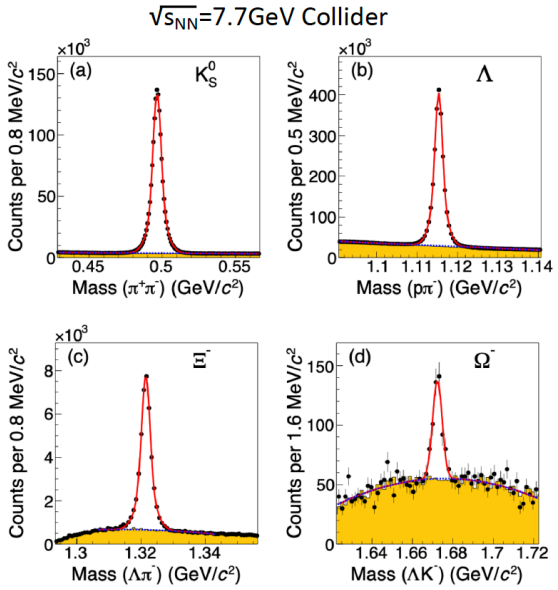
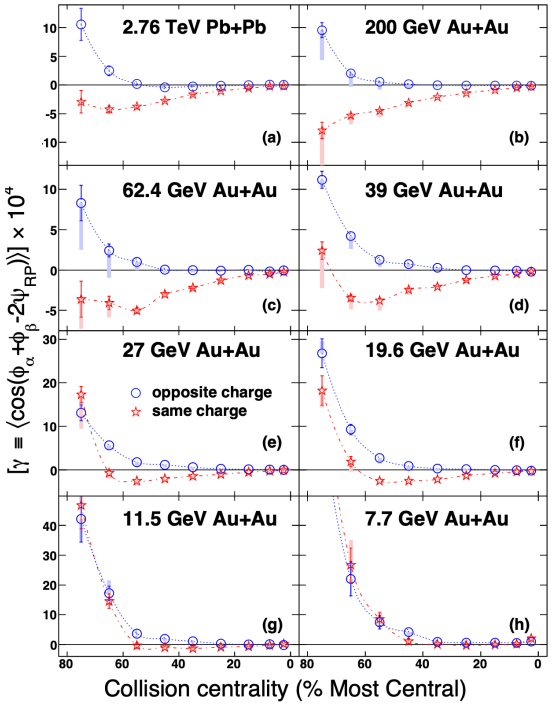
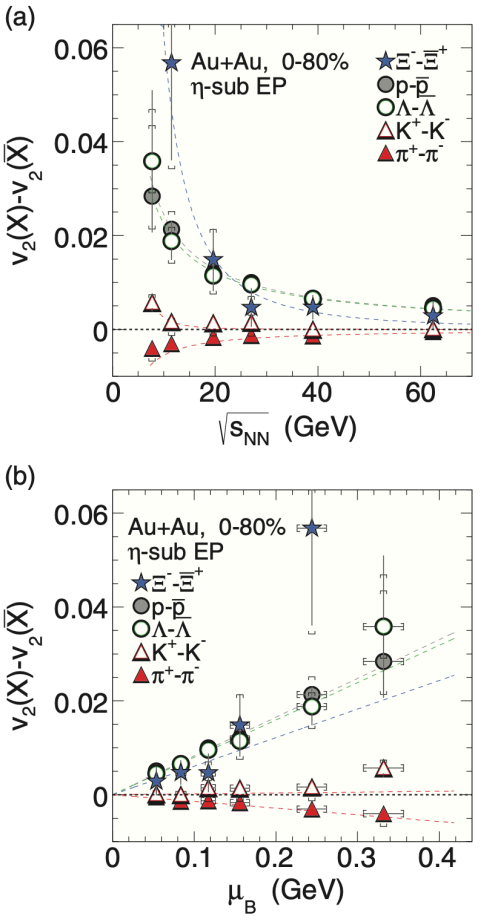


PRC 102 (2020) 34909 (STAR)



PRL 113 (2014) 52302



PRC 93 (2016) 14907 (STAR)

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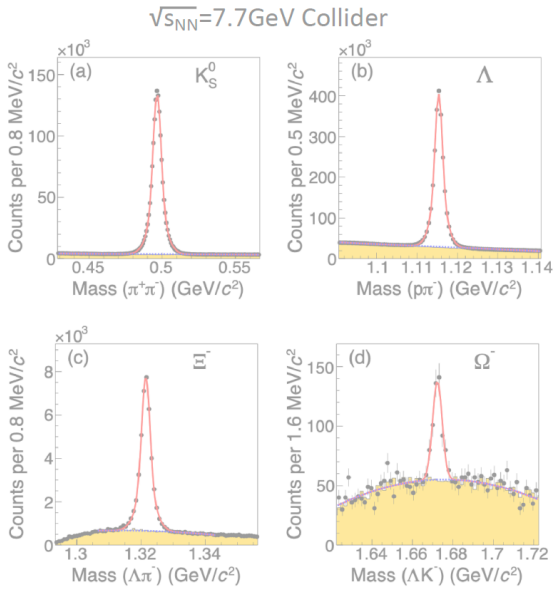
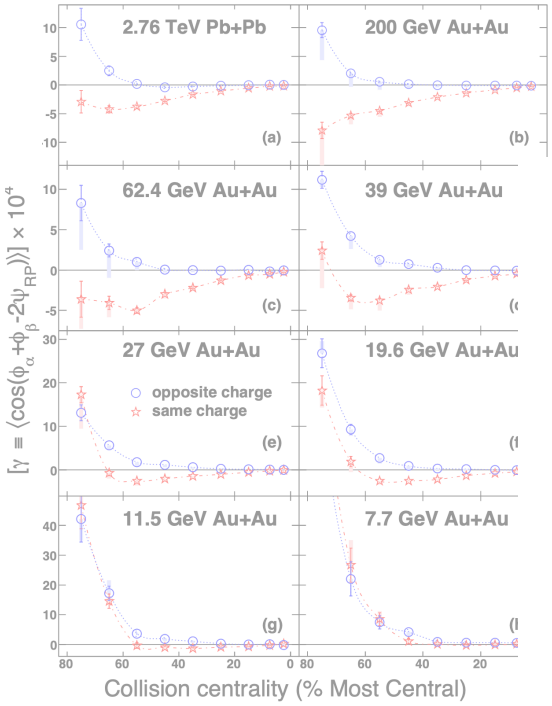


PRC 102 (2020) 34909 (STAR)



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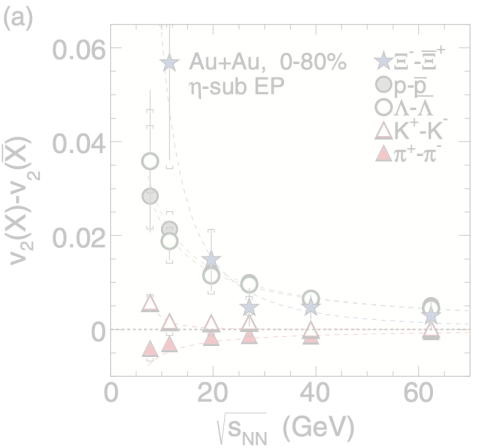
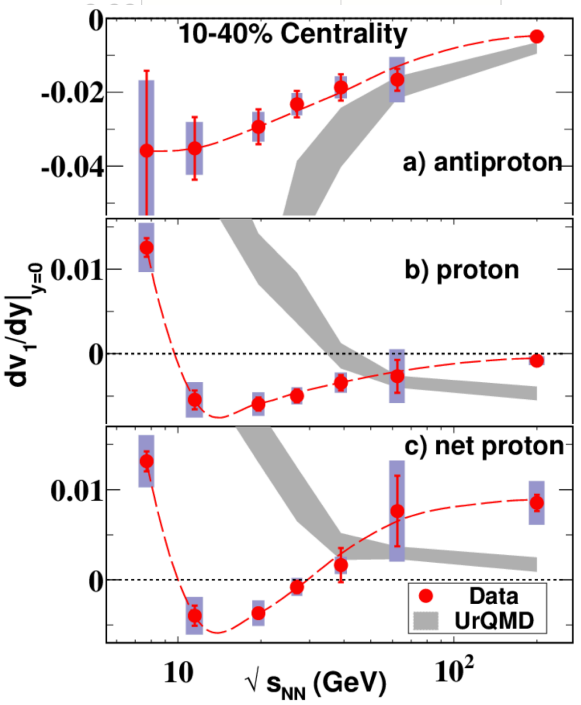


STAR, PRL 112, 162301 (2014)



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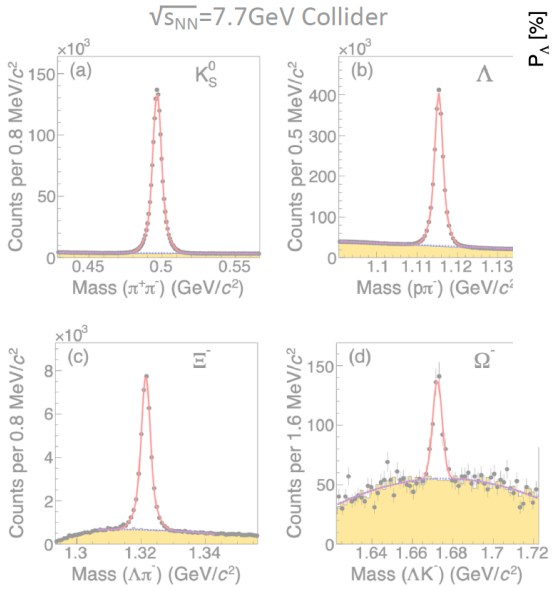
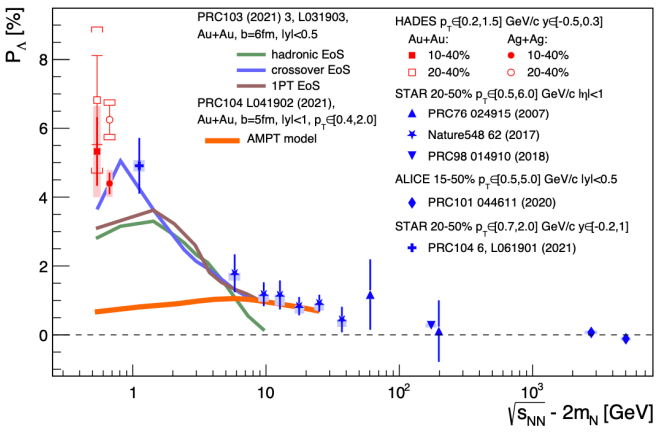
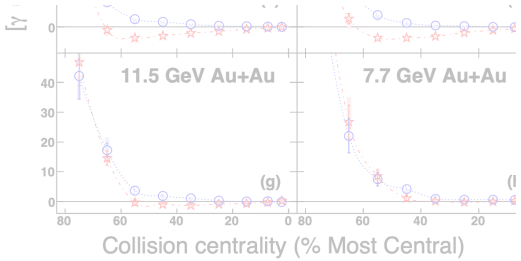


PRC 102 (2020) 34909 (STAR)

PLB 835, 137506 (2022)





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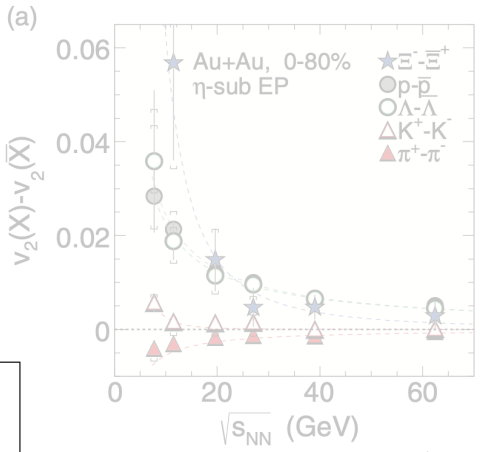

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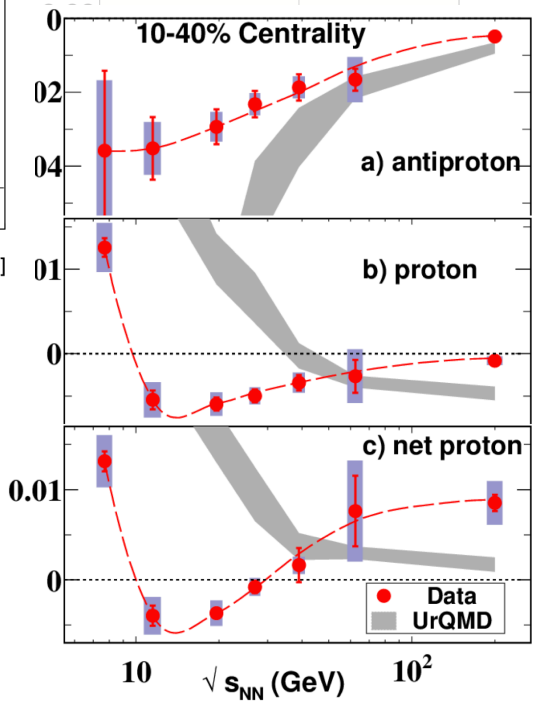

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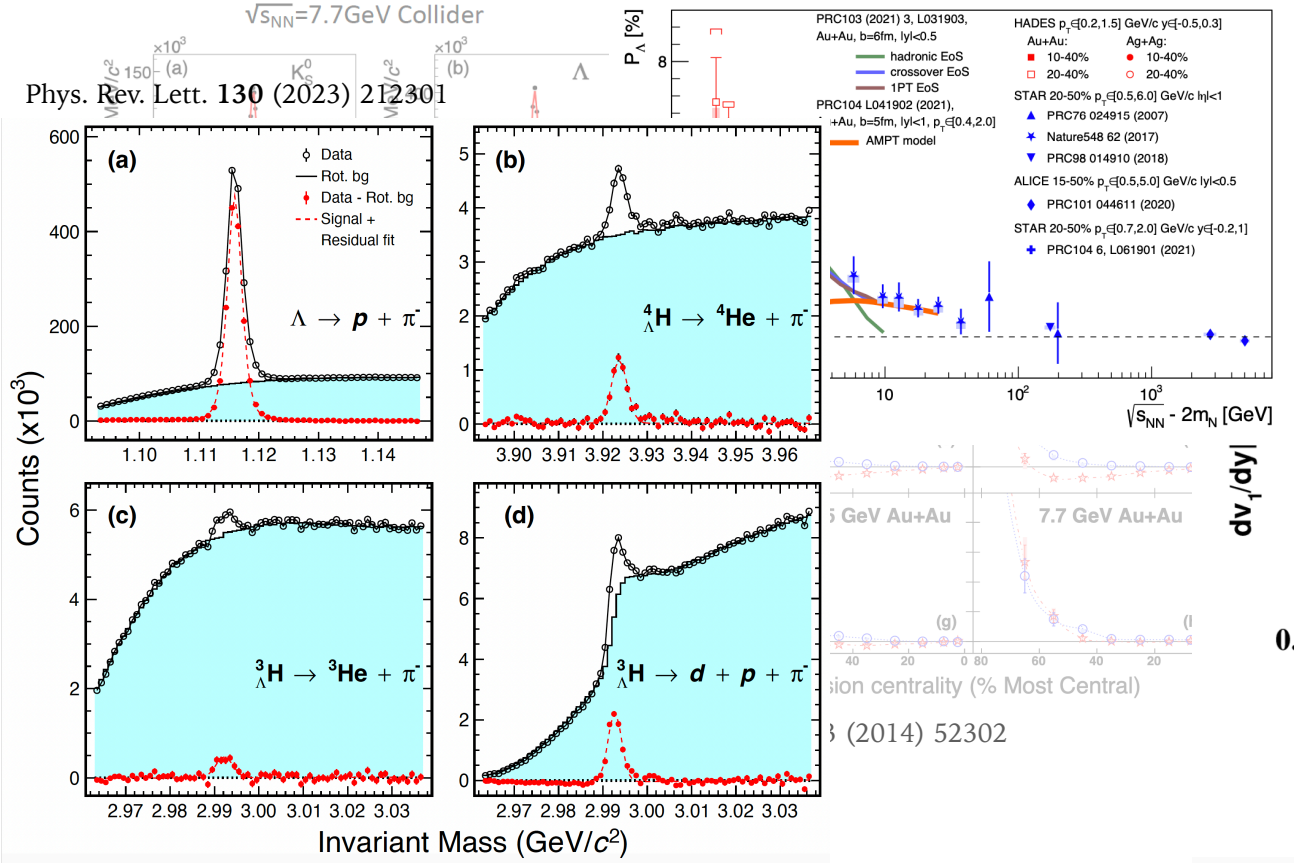

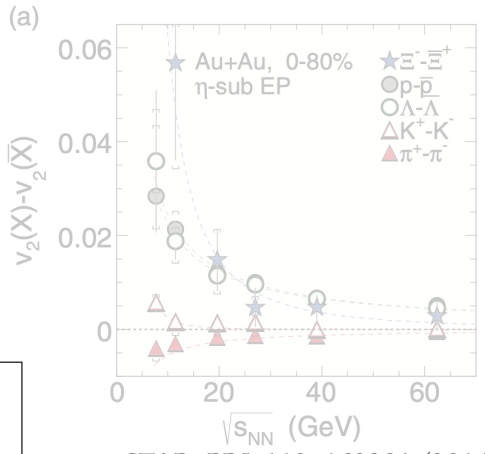

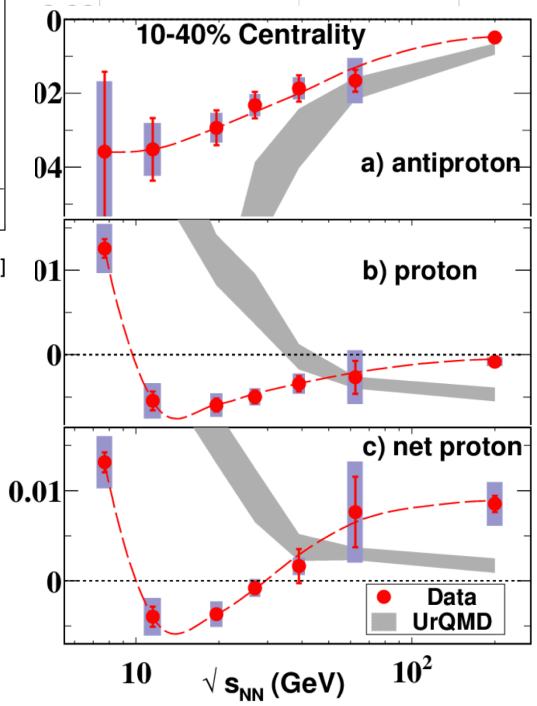

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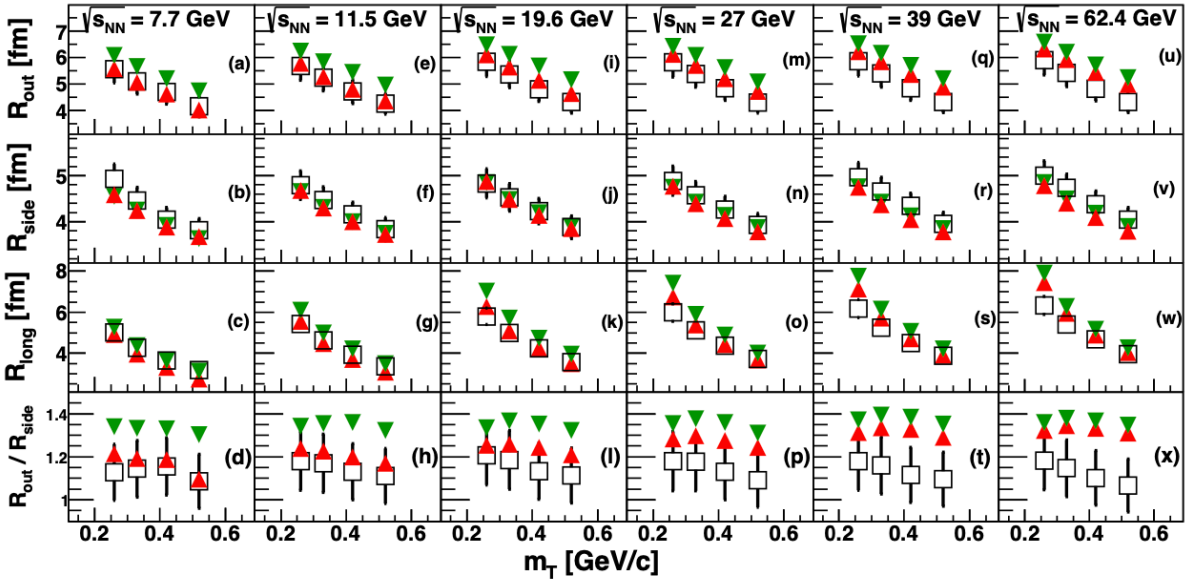
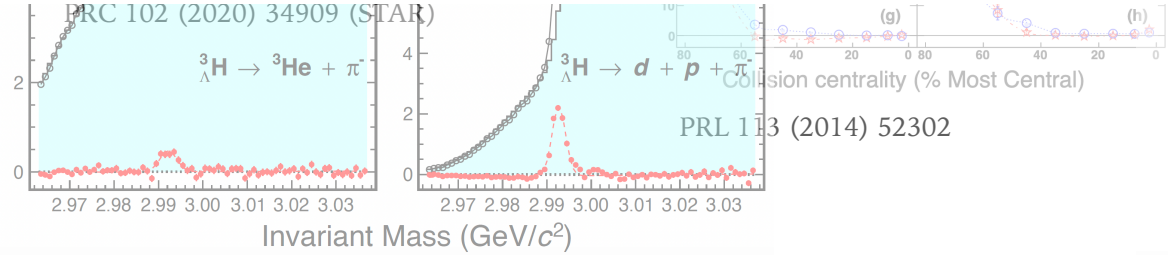
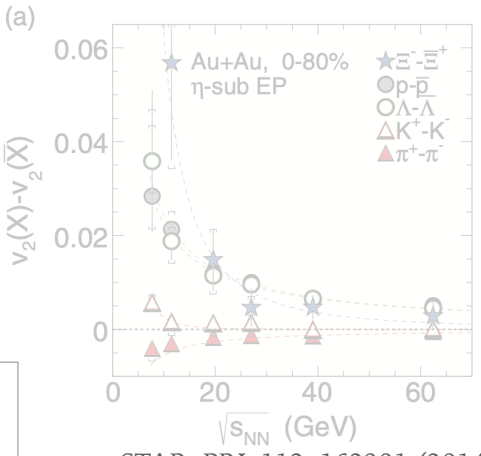
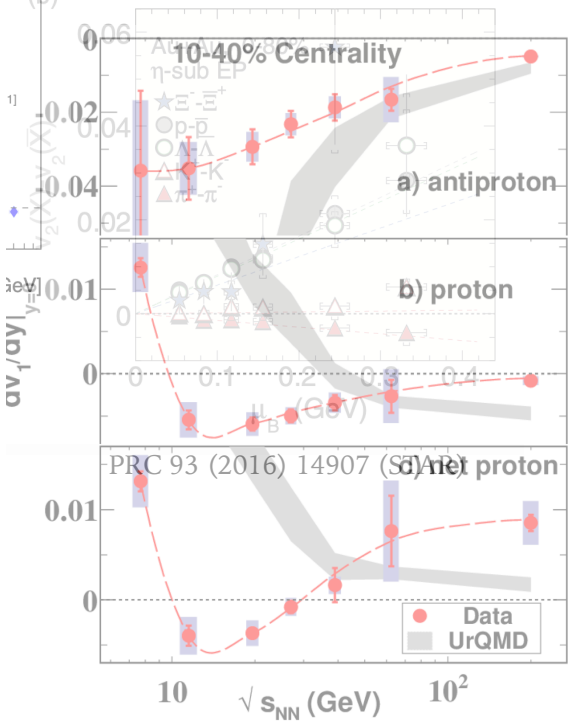
PRC 96 (2017) no.2, 024911







STAR, PRL 112, 162301 (2014)



PRC 93 (2016) 14907 (STAR)

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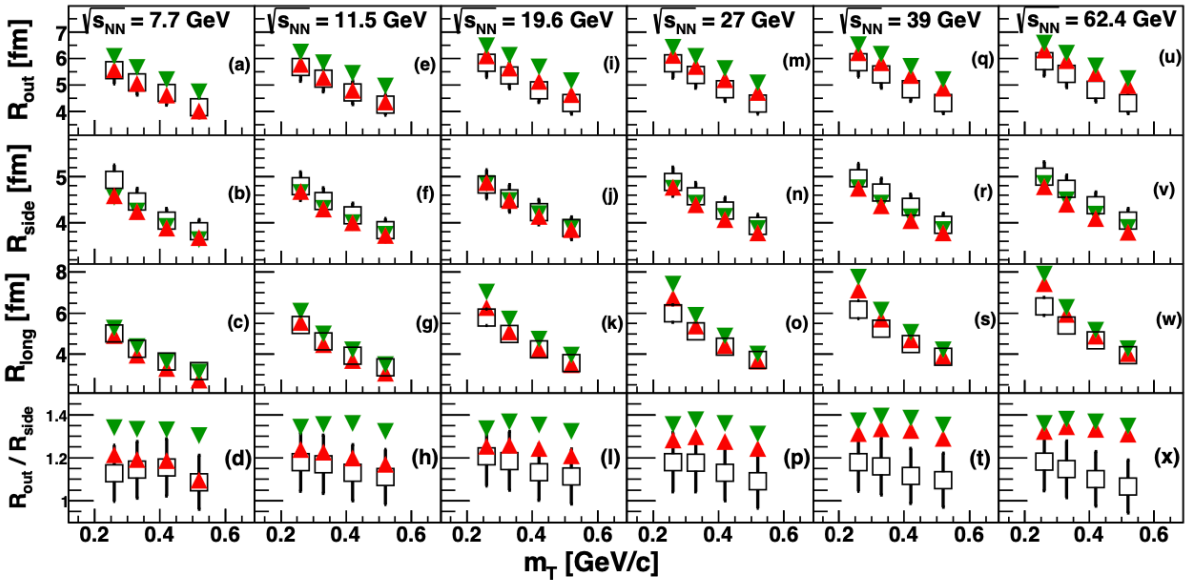
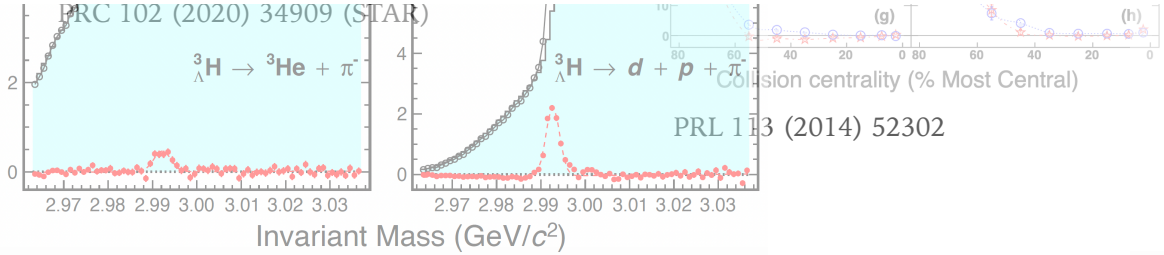
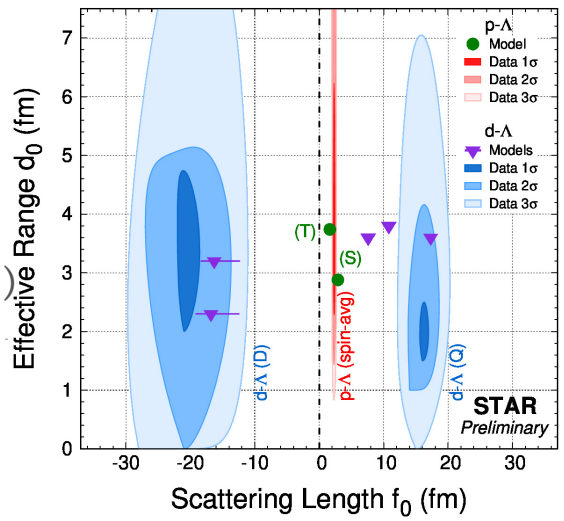
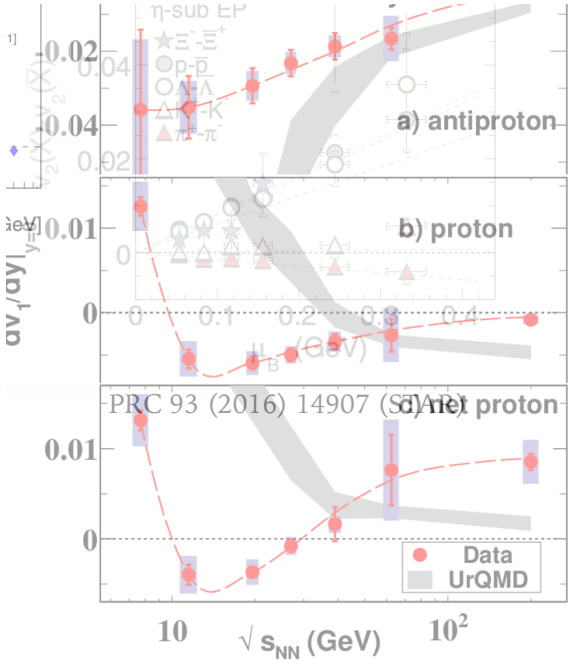
PRC 96 (2017) no.2, 024911





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





PRC 93 (2016) 14907 (STAR)

Road map

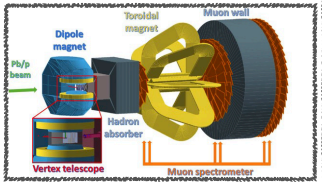
What are we pursuing and why? → Physics motivation

Where are we now? → Current status

Who is involved? → **Experimental facilities**

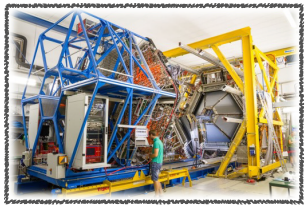
High μ_B facilities

NA60@SPS(>2030)



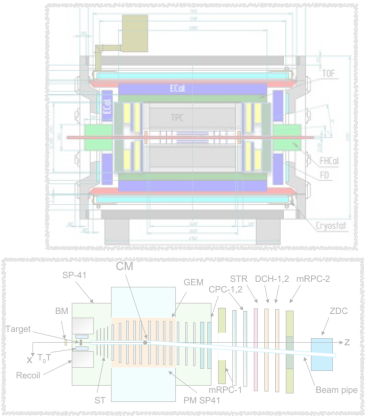
NA61/SHINE@SPS

HADES@SIS18

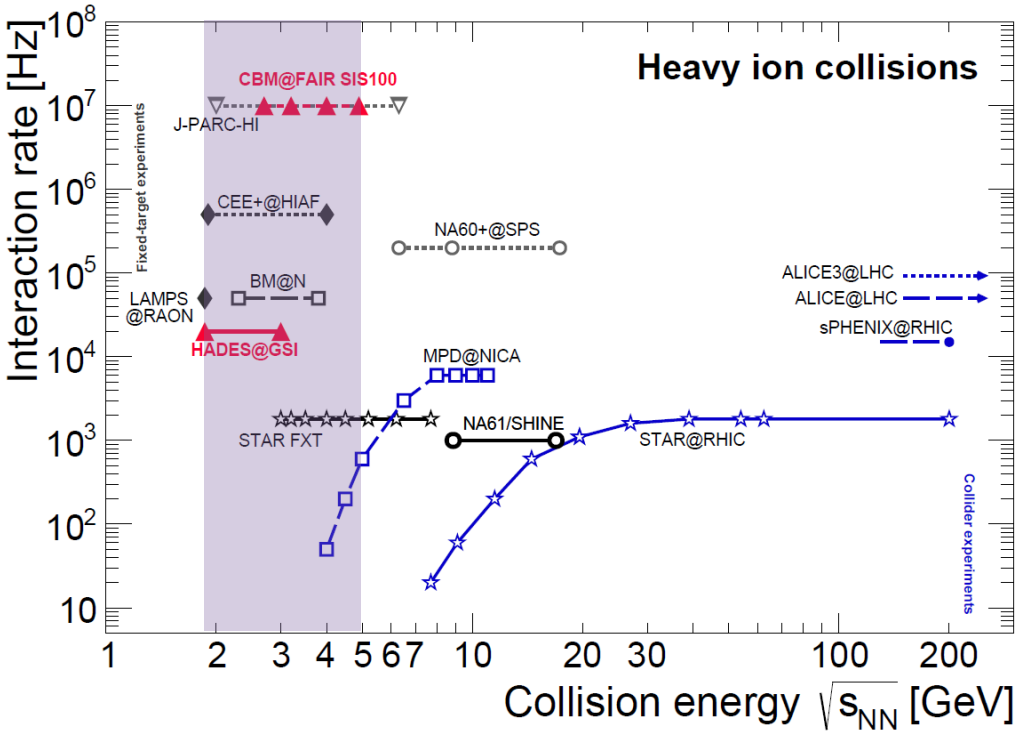


CBM / HADES@ SIS100 (>2028)

MPD, BM@N@NICA



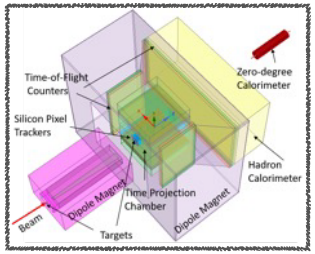
STAR@RHIC



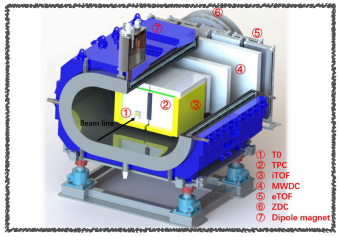
CBM / HADES: operations at $\sqrt{s_{NN}} \sim 2-5\ GeV$

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

J-PARC-HI



CEE@HIAF (>2027)



Road map

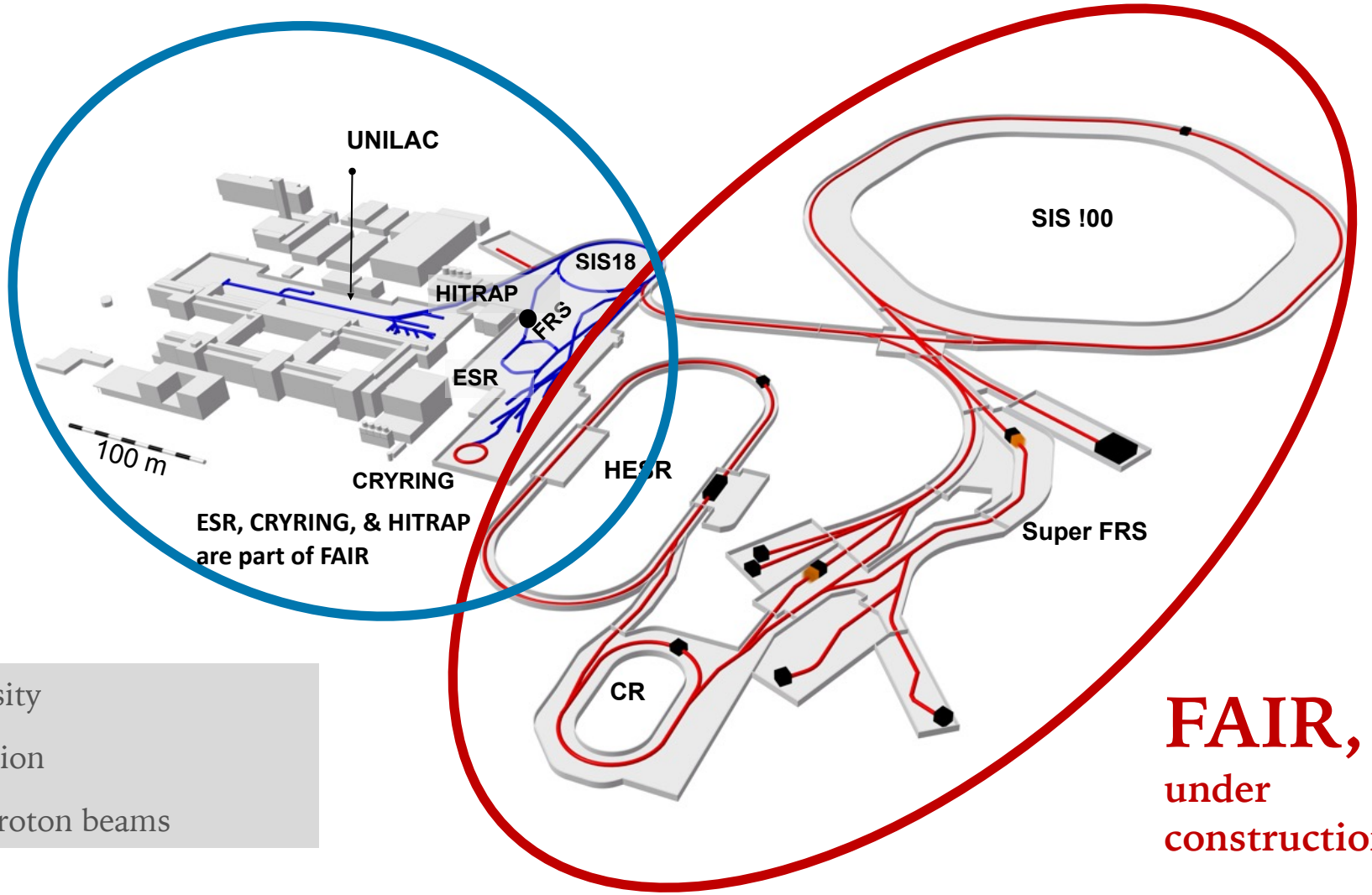
What are we pursuing and why? → Physics motivation

Where are we now? → Current status

Who is involved? → Experimental facilities

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

GSI, 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

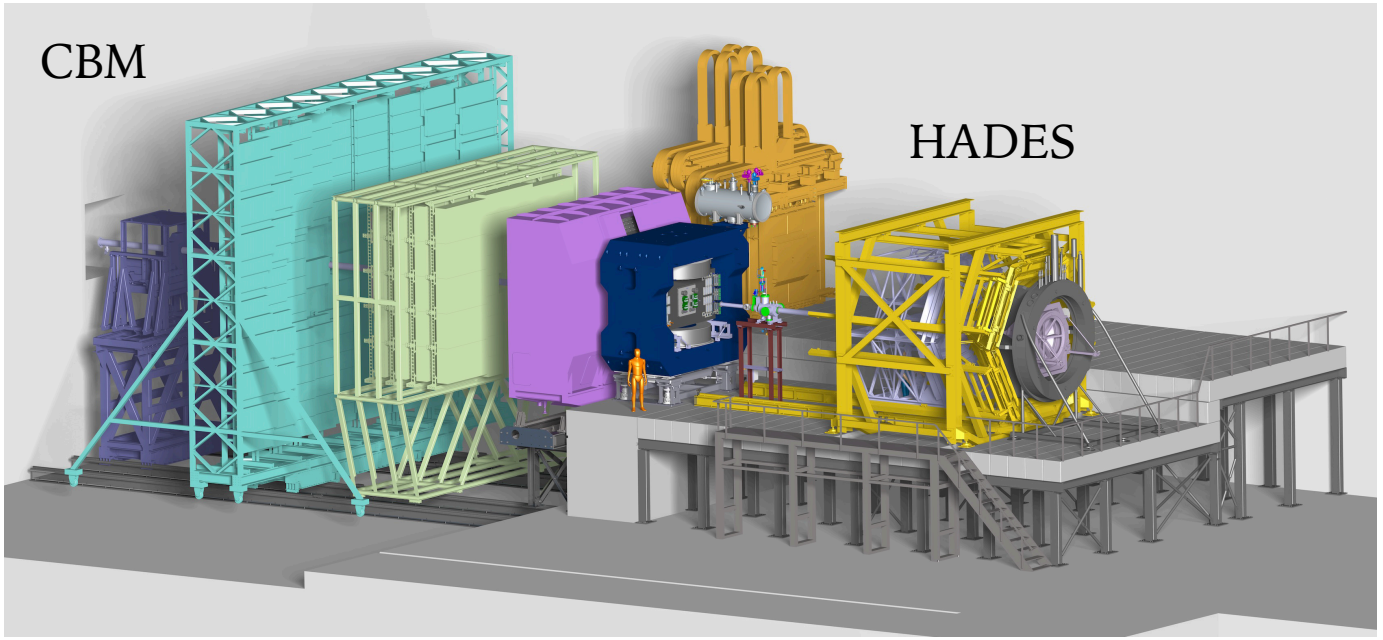
Compressed Baryonic Matter experiment

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

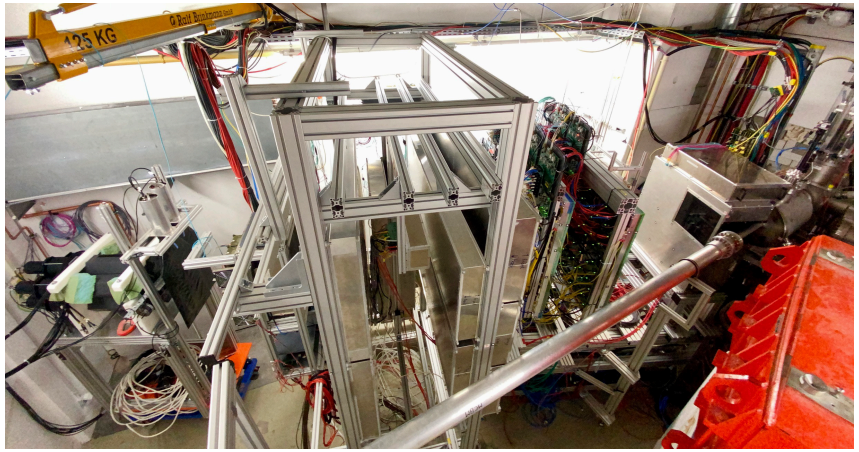
Years 1-3: first energy scan, improved statistical uncertainties of factor 10 with respect to STAR

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

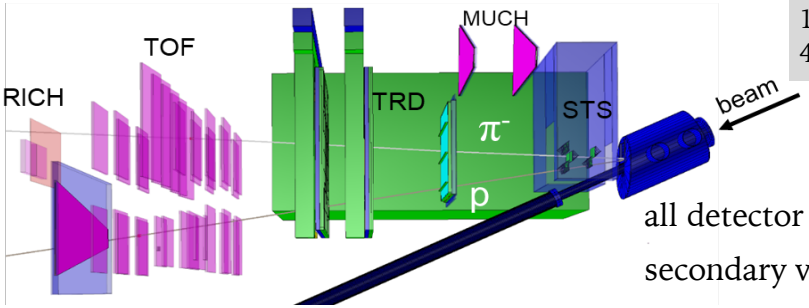
Λ baryons in Ni+Ni at 1.0 - 1.93 AGeV

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

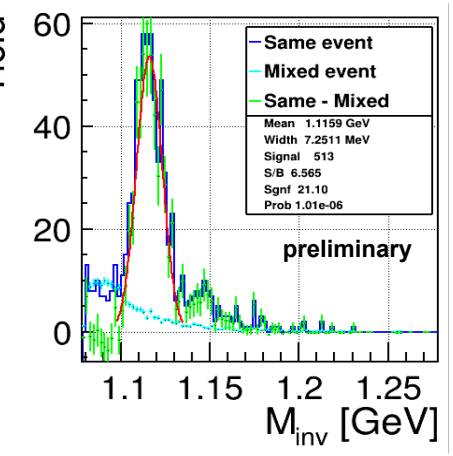


Ni+Ni 1.93 AGeV
run 2391 (May '22):
10^9 collisions, 1:57h
400 kHz av. coll. rate

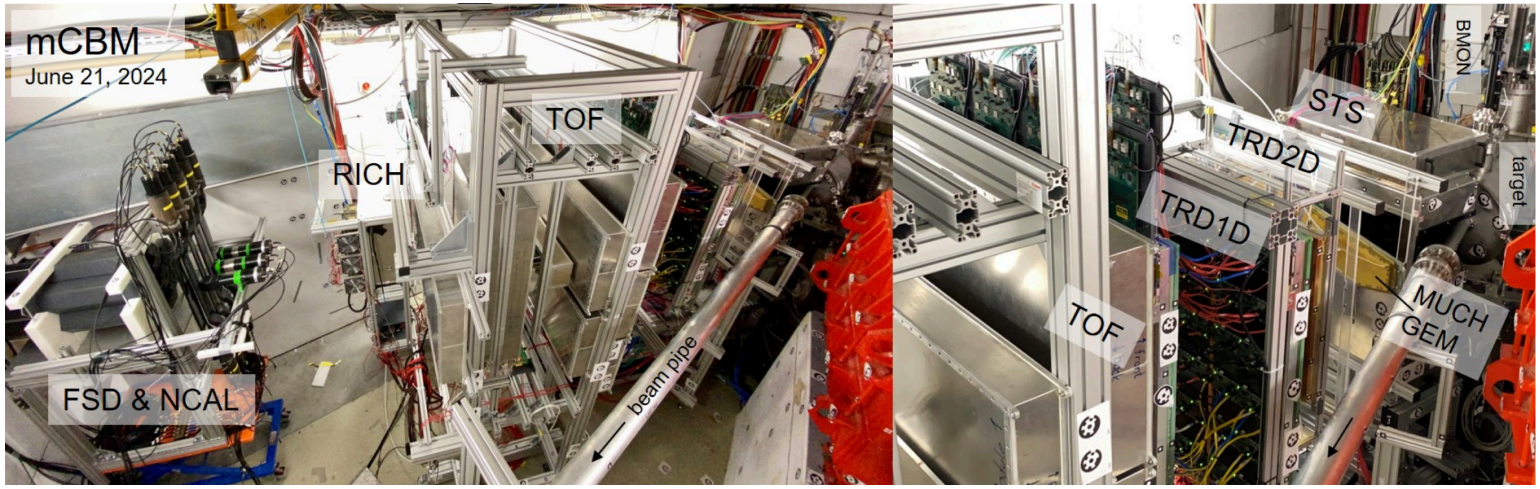
all detector systems involved

secondary vertex

velocity windows for p and π⁻ candidate



mCBM

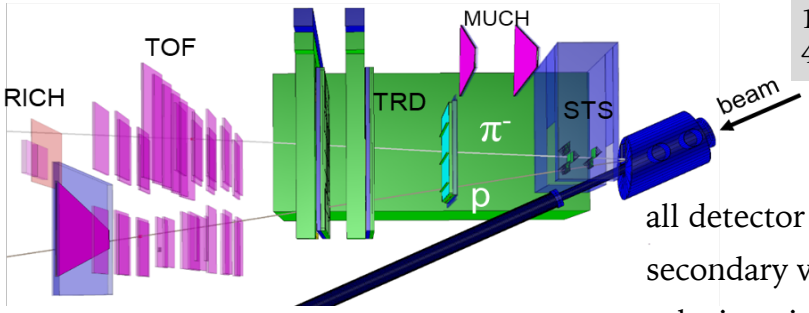


Free-streaming CBM data transport

Pre-series productions of all CBM detector systems

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

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



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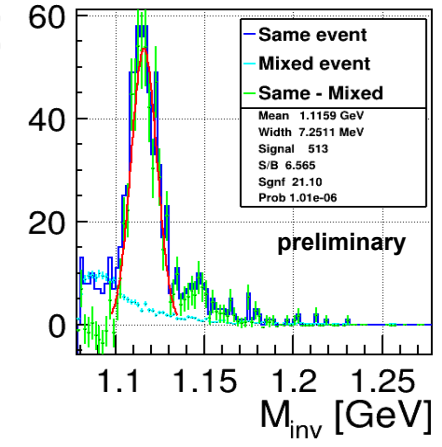

Campaign 2024:

high-rate studies

online reconstruction and selection

Λ baryons in Ni+Ni at 1.0 - 1.93 AGeV

Road map

What are we pursuing and why? → Physics motivation

Where are we now? → Current status

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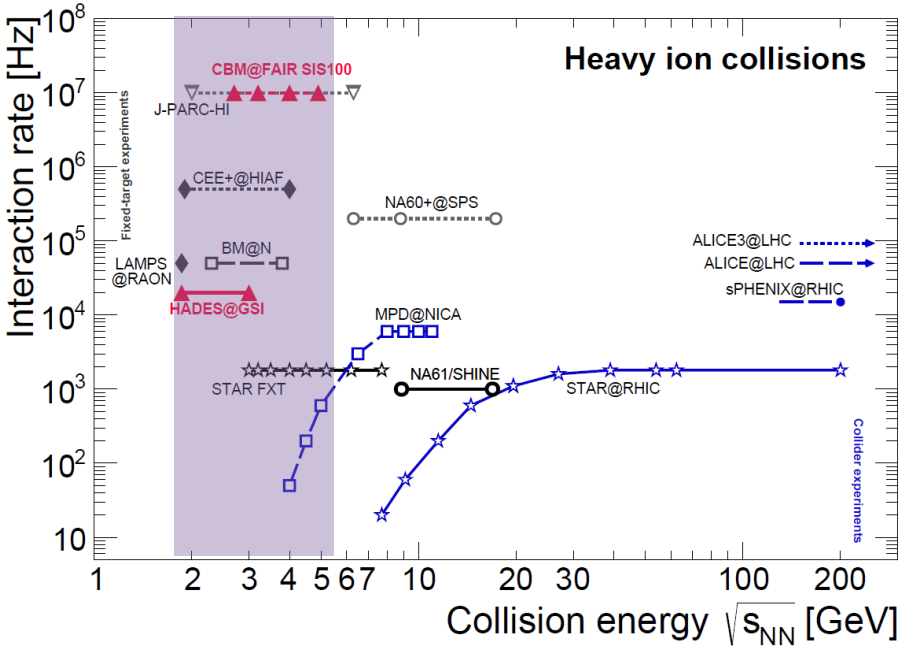
How to achieve the goal? → Compressed Baryonic Matter

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
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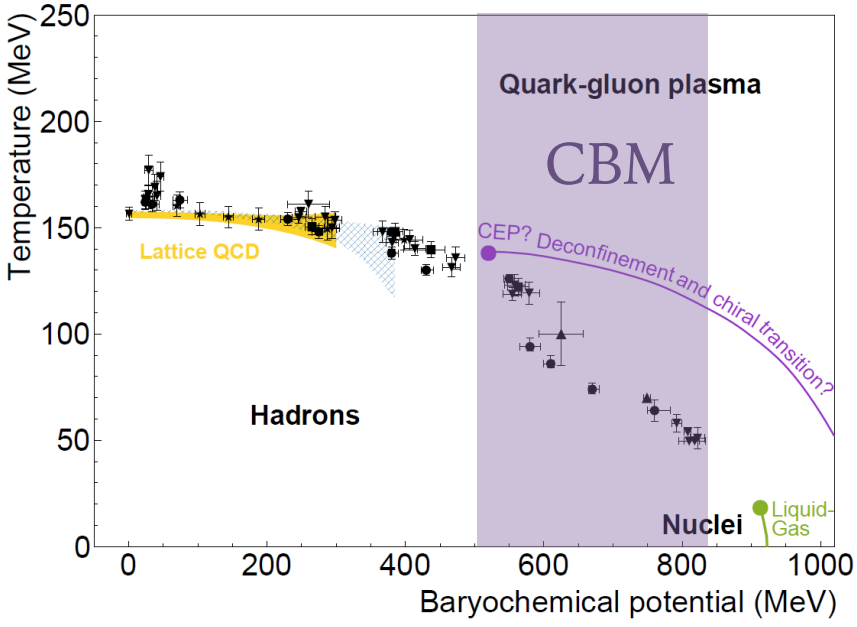
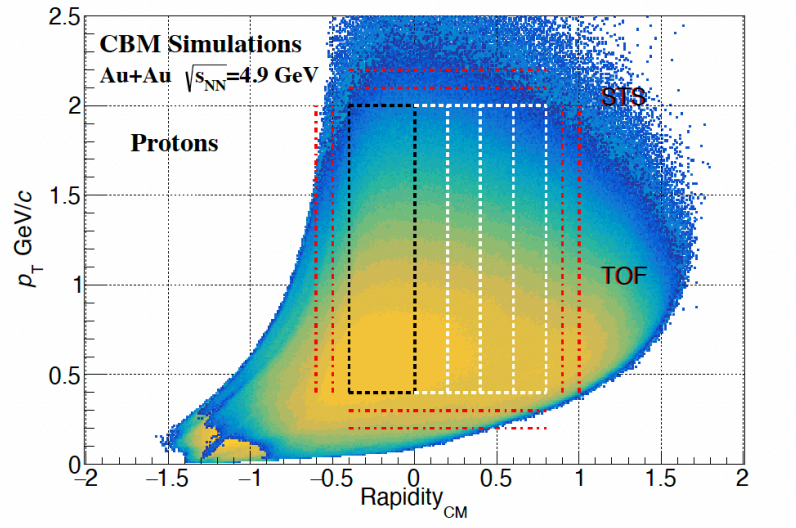


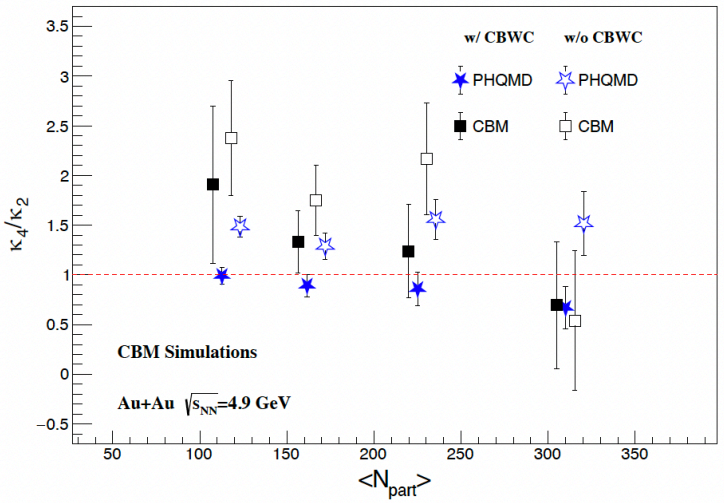
HADES; Nature Physics 15 (2019) 10, 1040-1045

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

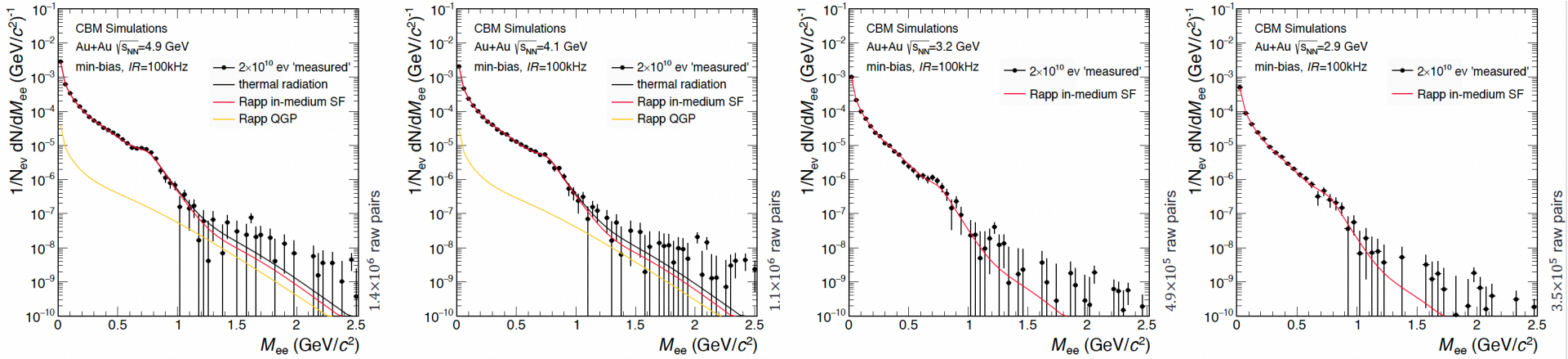
Electron thermal radiation, corrected for acceptance and efficiency,

Dominated by ρ contribution at LMR,

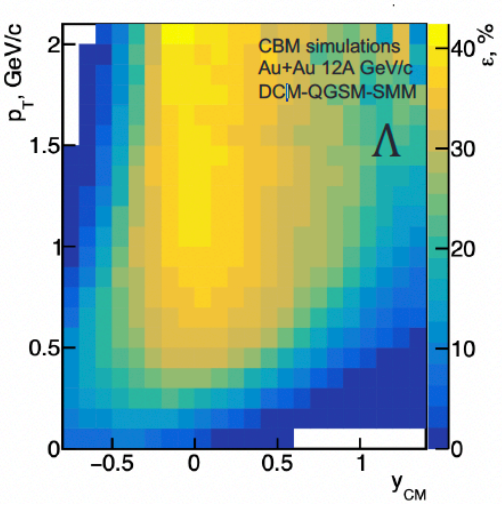
Can be reconstructed with 1.5-4.5% of precision,

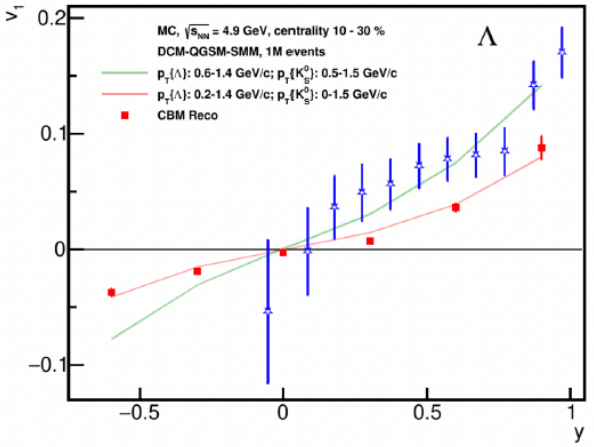
Gives access to to the fireball lifetime and electrical conductivity (transport properties)

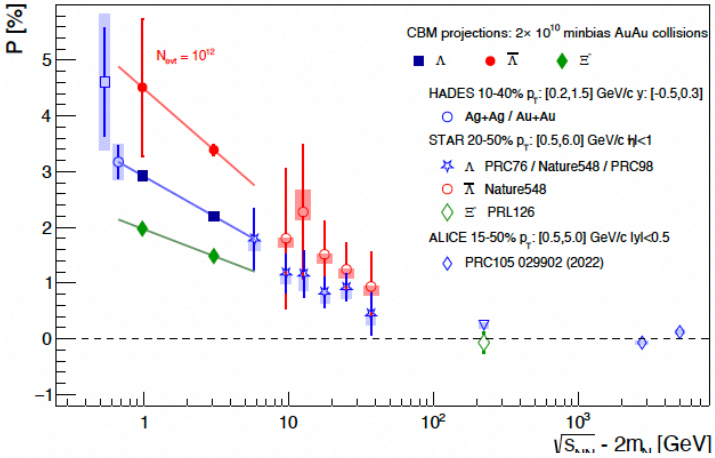
T vs. baryon density effects from partonic to hadronic fireballs



Flow, polarization, correlations

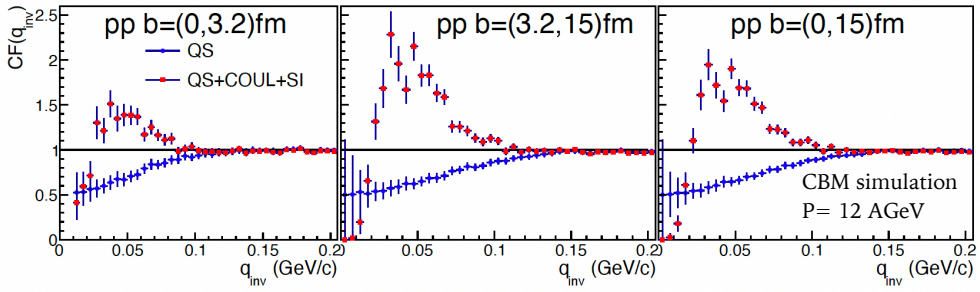




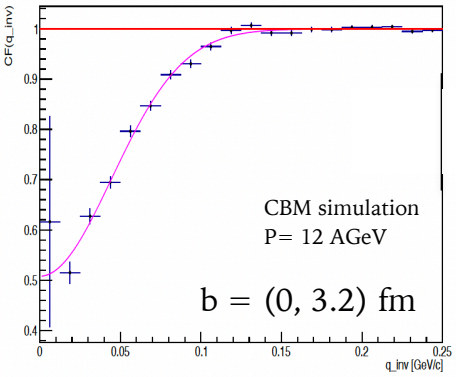


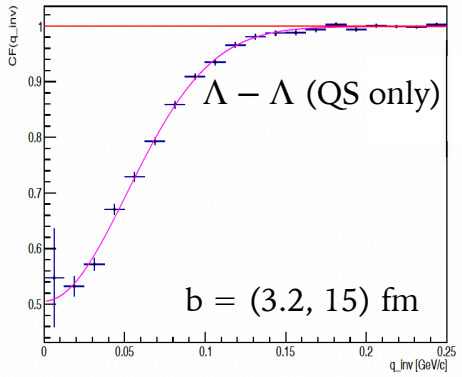
Excellent acceptance coverage

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

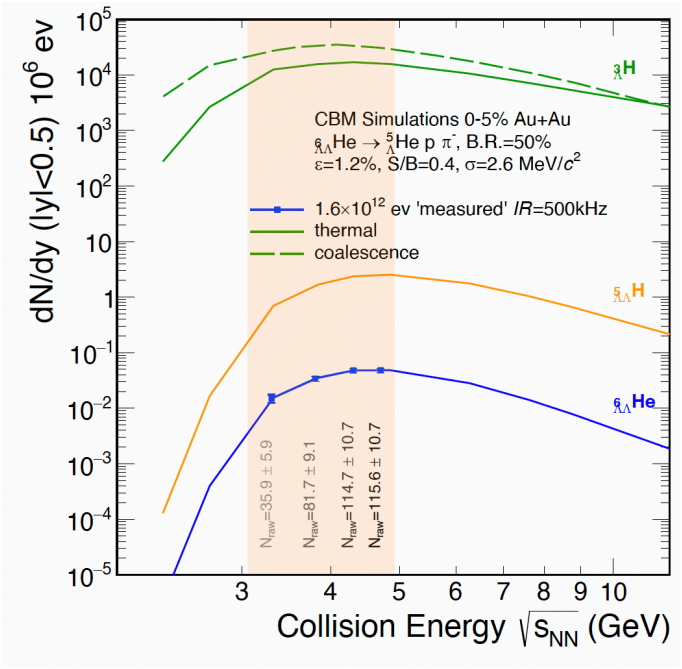




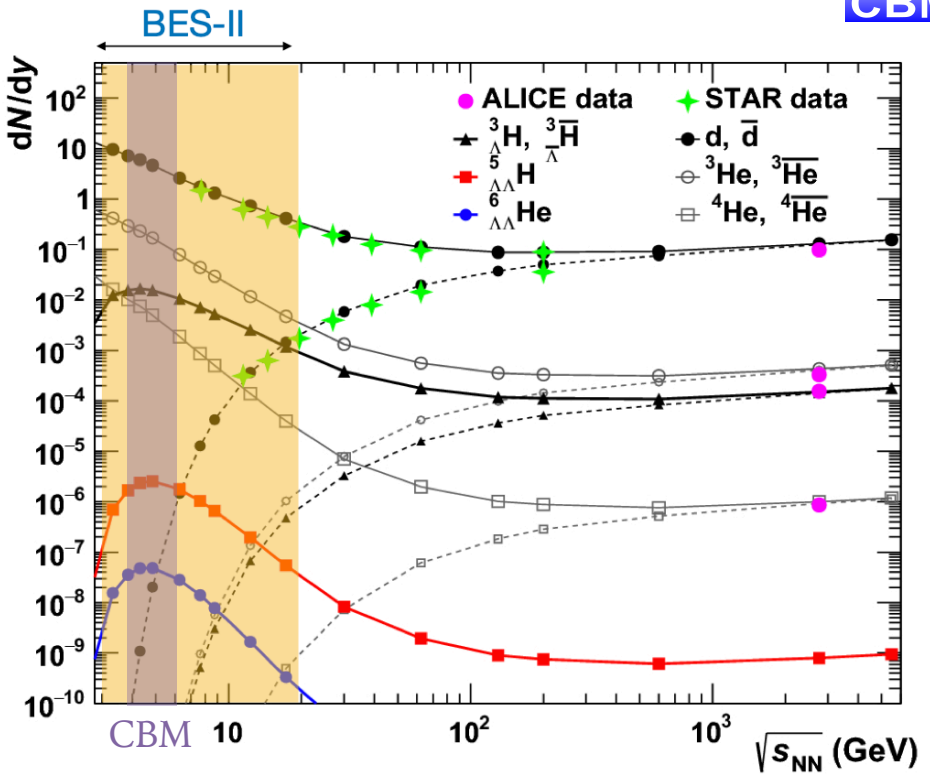
Interactions: hyper-nuclei, bound-states

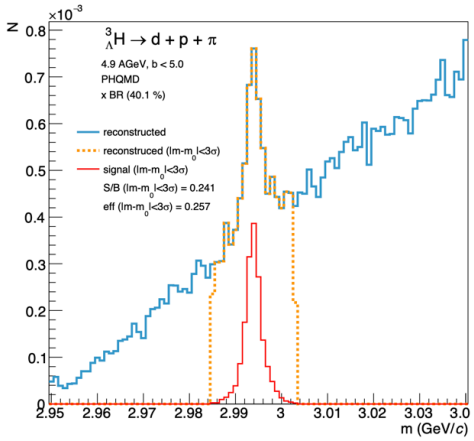
The most abundant production of hyper-nuclei anticipated at $\sqrt{s_{NN}} \sim 2-5$ GeV

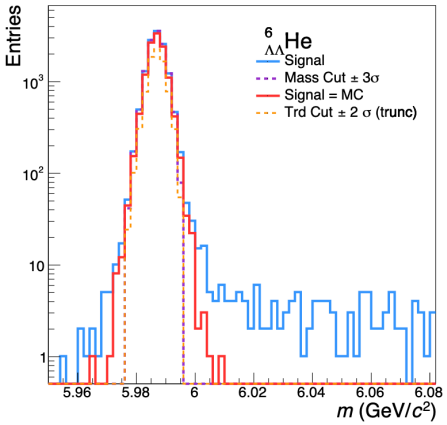
Prominent interaction rates and excellent particle identification will facilitate to search for multi-strange hyper-nuclei



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

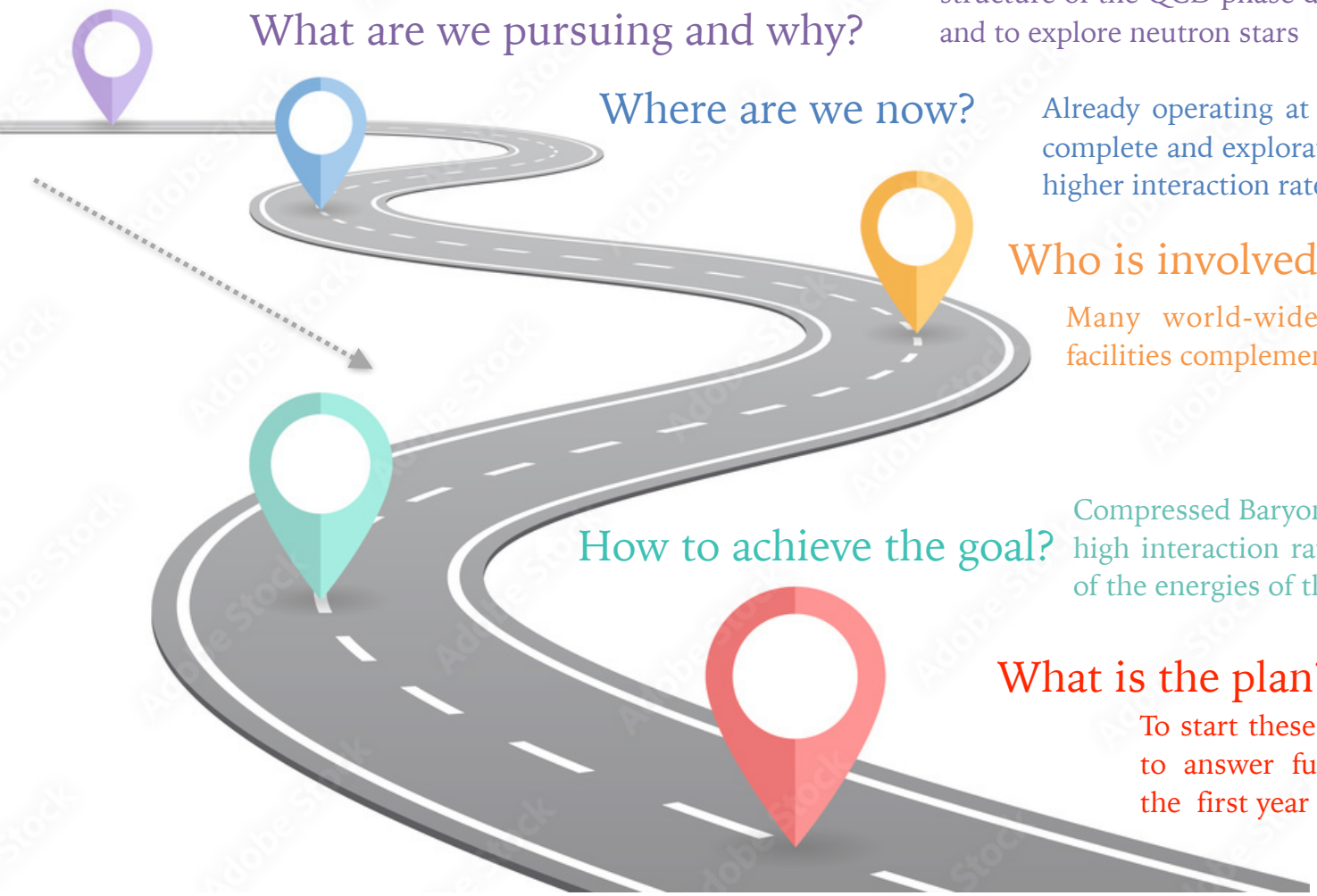






What are we pursuing and why?

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

Postdoctoral Research Associate positions in Experimental Heavy-Ion Physics

Warsaw U. of Tech. (main) • Europe

hep-ex nucl-ex PostDoc • Experiments: GSI-FAIR-CBM, BNL-RHIC-STAR

Deadline on Dec 31, 2024

https://inspirehep.net/jobs/2811921

Job description:
The Heavy-Ion Reaction Group (HIRG) at the Faculty of Physics at Warsaw University of Technology participates in the experiments STAR at BNL, CBM at FAIR, HADES at GSI, ALICE, and NA61/SHINE at CERN.

The STAR, HADES, and CBM groups specialize in two-particle femtoscopic correlation analysis measurements. We closely cooperate with the ALICE group at WUT.

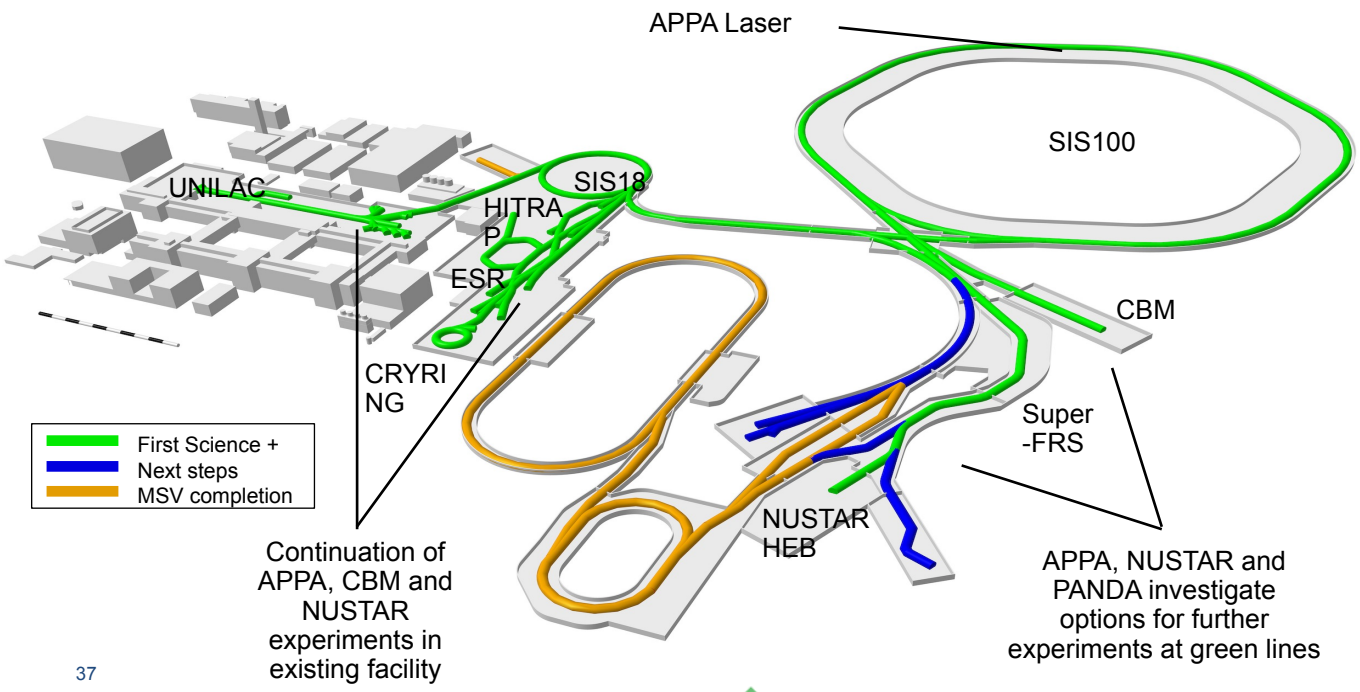
The successful candidates will work with Professor Hanna Zbroszczyk on the STAR experiment at RHIC, the HADES experiment at SIS18, or the CBM experiment at SIS100, focusing on studies of two-particle correlations. One position can relate up to 2 experiments. Responsibilities include data analysis and publication of results, collaboration service work, mentoring students, and supporting the Heavy Ion Reaction Group's research activities. Occasional travel to BNL and/or GSI will be required. The successful candidates are expected to lead studies of femtoscopic correlations in the search for STAR, HADES, or CBM experiments. The contract can be extended up to 24 months, provided a satisfactory evaluation outcome after the first 12 months.

Duties and Responsibilities:

- Taking part in the analysis of heavy-ion collision RHIC data recorded by the STAR detector to study two-particle correlations or
- Taking part in the analysis of heavy-ion collision SIS-18 data recorded by the HADES detector to study two-particle correlations or
- Taking part in the Monte Carlo data analysis for the CBM experiment
- Joining the STAR/HADES or CBM collaborations and the relevant Physics Working Group, participating in weekly deliberations and active participation in its meetings (at least every few weeks);
- Taking part in data-taking (experimental shifts);
- Presentation of results at meetings and conferences, as well as writing scientific articles and publishing papers in peer-reviewed journals;
- Maintaining close cooperation with colleagues in the PWG group will be essential for the progress of all stages of the project

- Thank you

Current prospects and timeline



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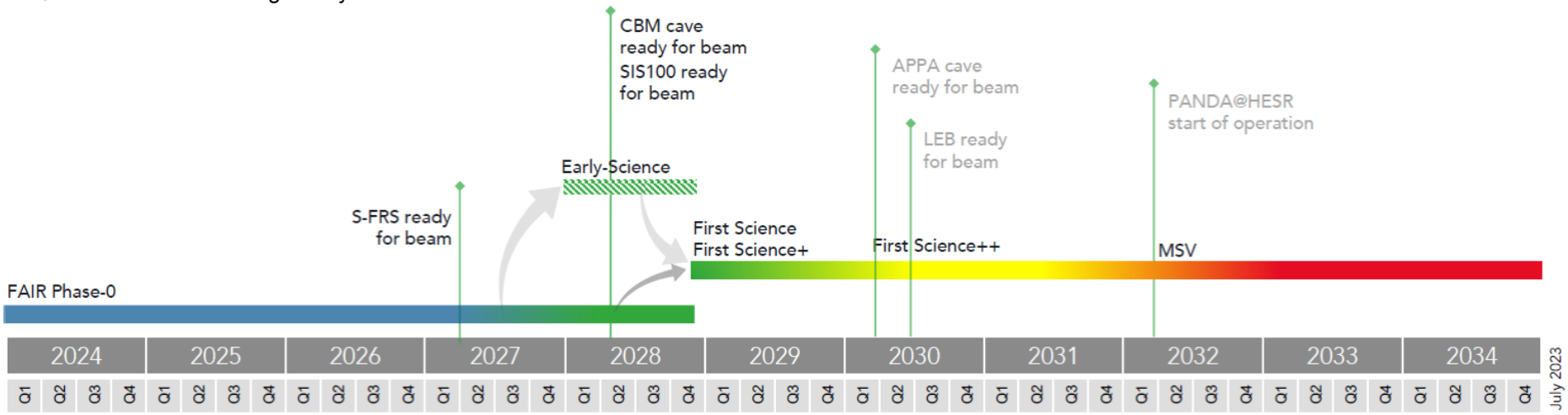
until 2028

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."