Bormio Conference

60th International Winter Meeting on Nuclear Physics

22 - 26 January 2024
Bormio, Italy

Strangeness measurements at large baryon densities

N. Herrmann, Heidelberg University

Outline

Basics/History
- Bevalac
- KaoS
- FOPI
- E895

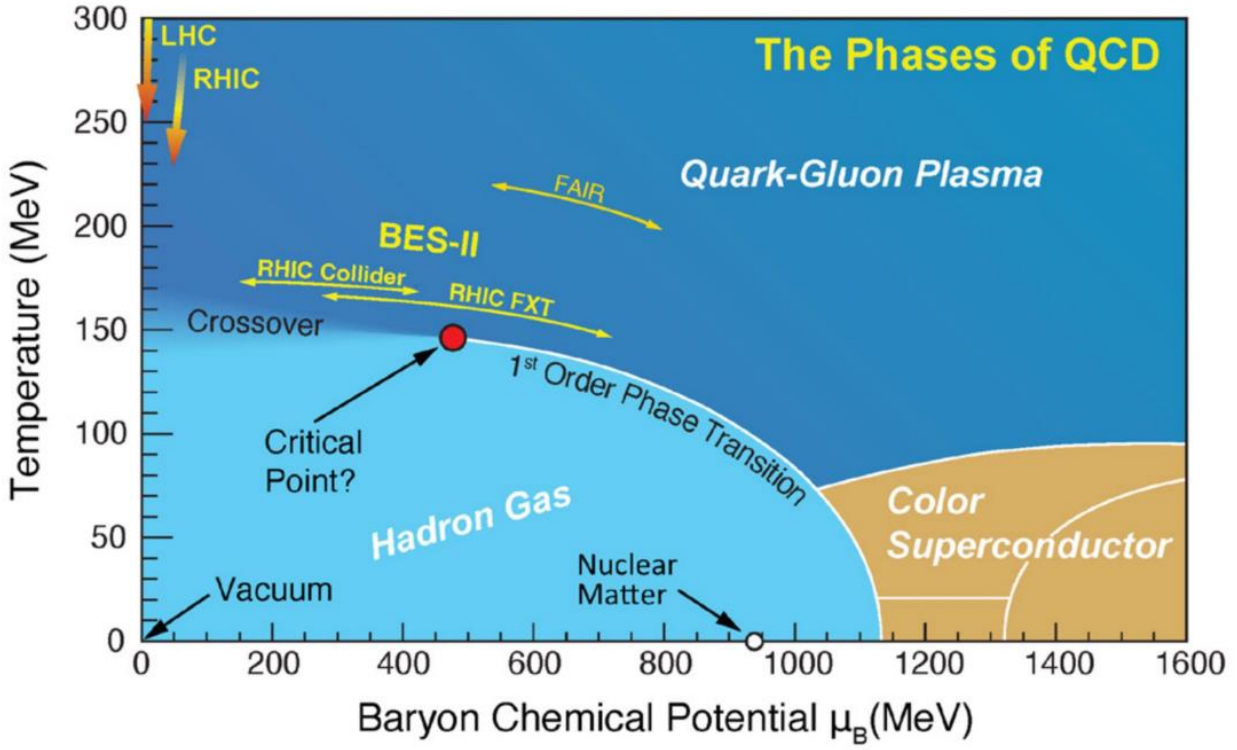
Recent results
- HADES
- STAR BES-I, BES-II

Future
- CBM
- mCBM

Conclusion

Physics cases for hyperons and hypernuclei measurements in dense baryonic matter

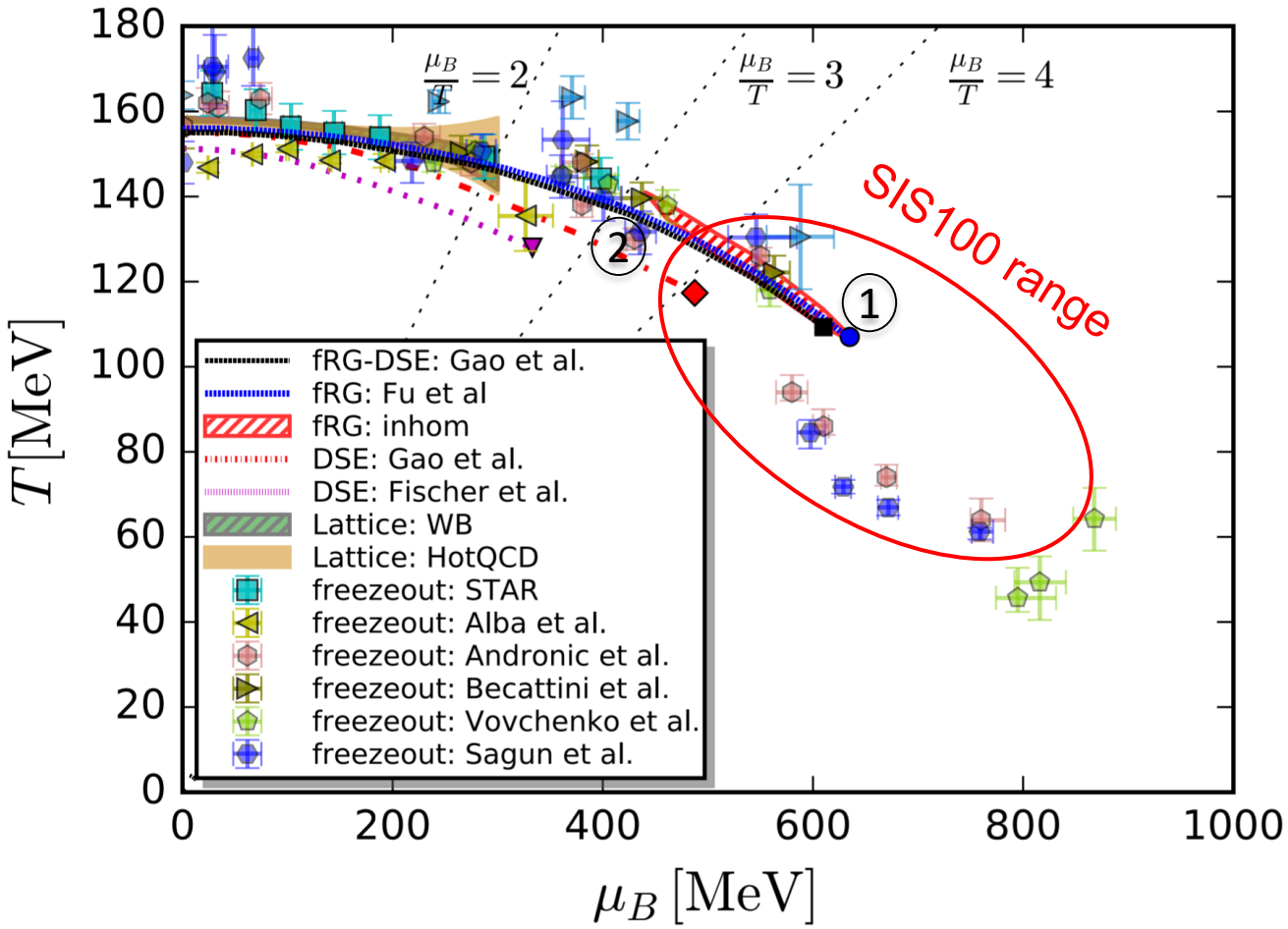
- Equation-Of-State (EOS)
- Hypernuclei existence, properties
- QCD matter at neutron star core densities



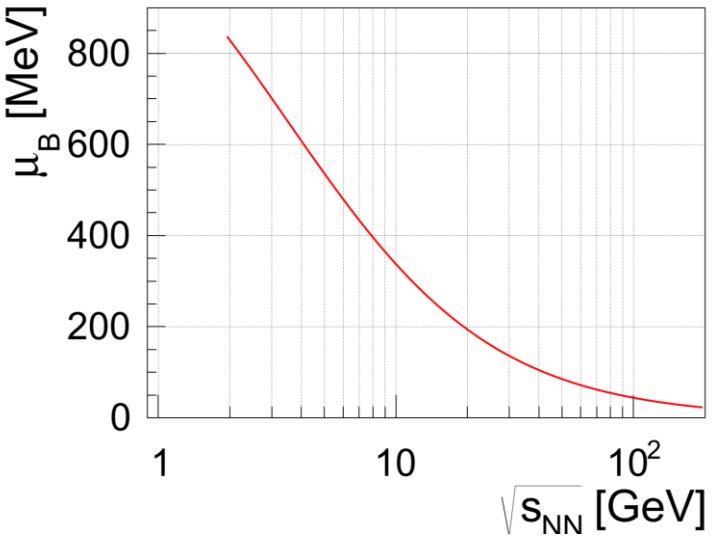
Phase structure of QCD

Location of chiral cross over

W. Fu, J. Pawlowski, F. Rennecke, *Phys.Rev.D* 101 (2020) 5, 054032, arXiv:1909.02991



A. Andronic et al., Nucl.Phys.A772:167 (2006)

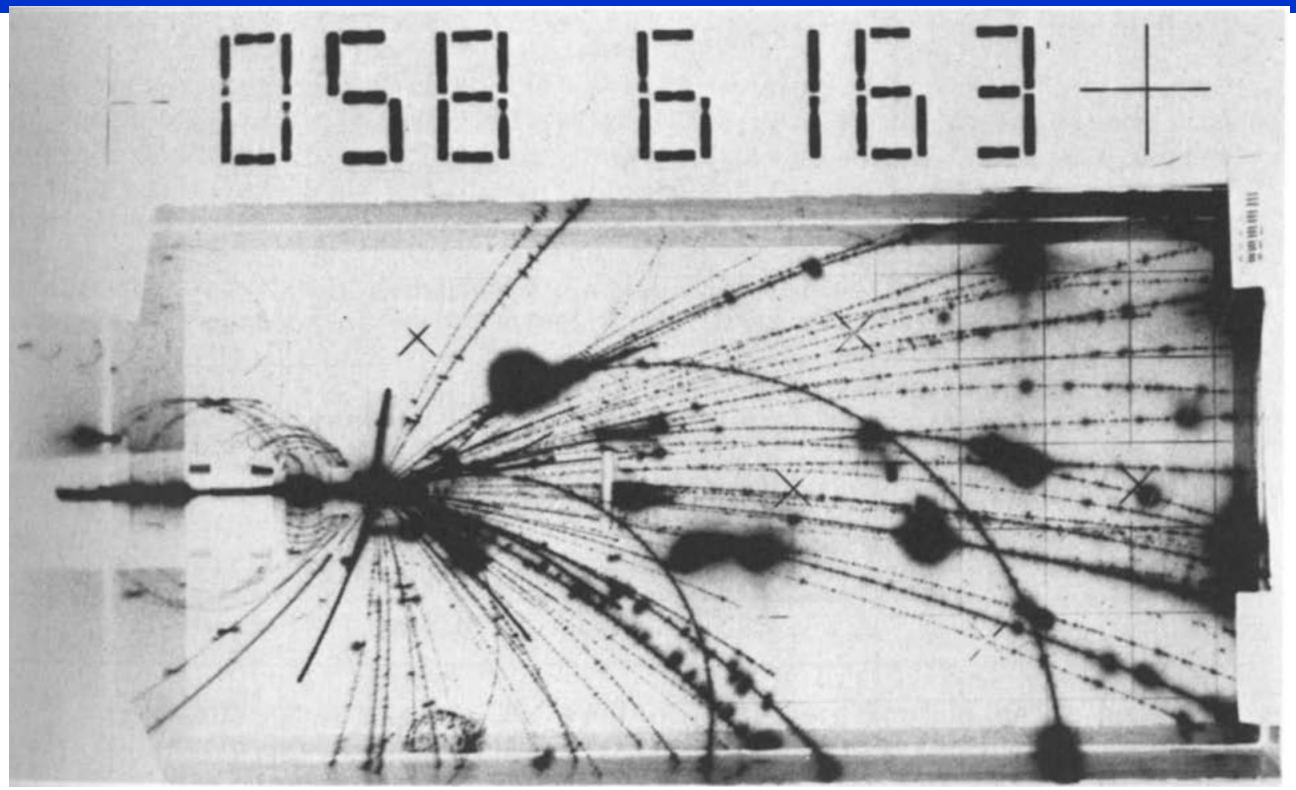


	μ_B (MeV)	$\sqrt{s_{NN}}$ (GeV)	T_{lab} (A GeV)
1	622	3.8	6.0
	500	5.2	15.0
2	400	7.8	31.5

Challenges:

Phase transition not at freeze-out line,
need probes with memory,
reaction dynamics needs to be controlled.

The Beginning



Bevalac

Λ Production Near Threshold in Central Nucleus Nucleus Collisions

J.W. Harris (Darmstadt, GSI), A. Sandoval (Darmstadt, GSI), R. Stock (Darmstadt, GSI), H. Strobele (Darmstadt, GSI), R.E. Renfordt (Philipps U. Marburg) et al. (1981)

Published in: *Phys.Rev.Lett.* 47 (1981) 229-232

Ar + KCl @ 1.8 AGeV

PRODUCTION OF K+ MESONS IN 2.1-GEV/NUCLEON NUCLEAR COLLISIONS

S. Schnetzer (LBL, Berkeley), M.C. Lemaire (LBL, Berkeley), R. Lombard (LBL, Berkeley), E. Moller (LBL, Berkeley), S. Nagamiya (LBL, Berkeley) et al. (1982)

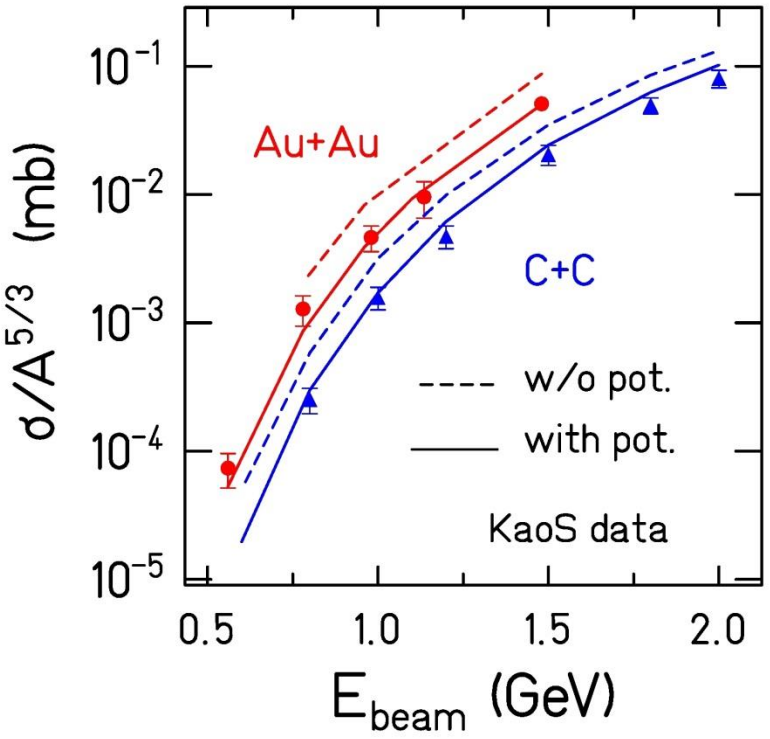
Published in: *Phys.Rev.Lett.* 49 (1982) 989-992

Ne + Pb, NaF, d, p @ 2.1 AGeV

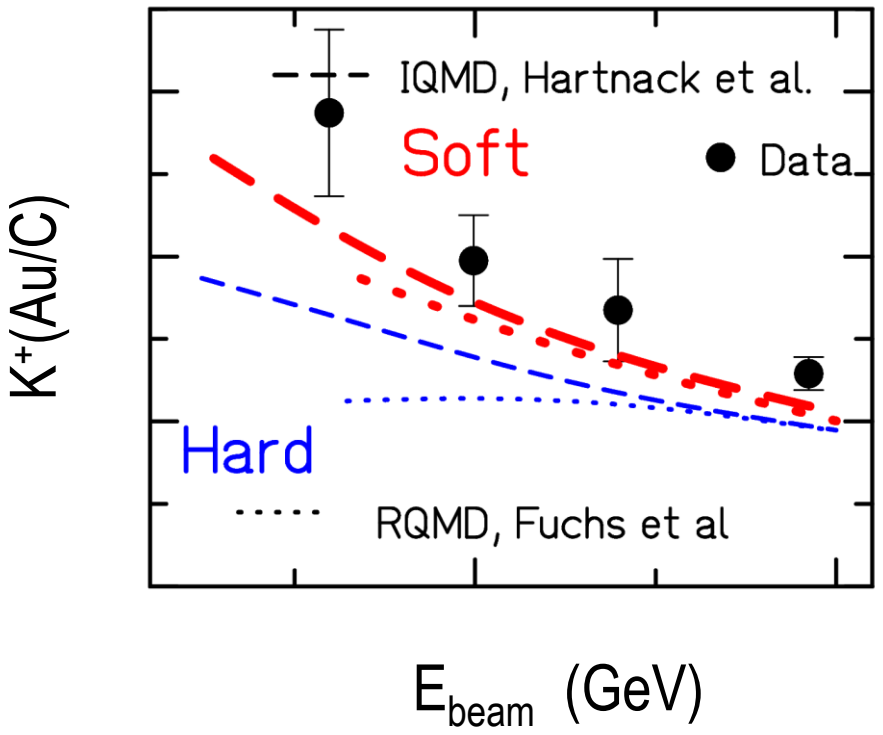
Dense hadronic matter Equation – of – state

KaoS

C.Sturm et al. (KaoS), PRL 86 (2001) 39



C. Fuchs et al., PRL 86 (2001) 1974

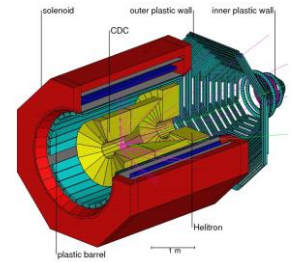


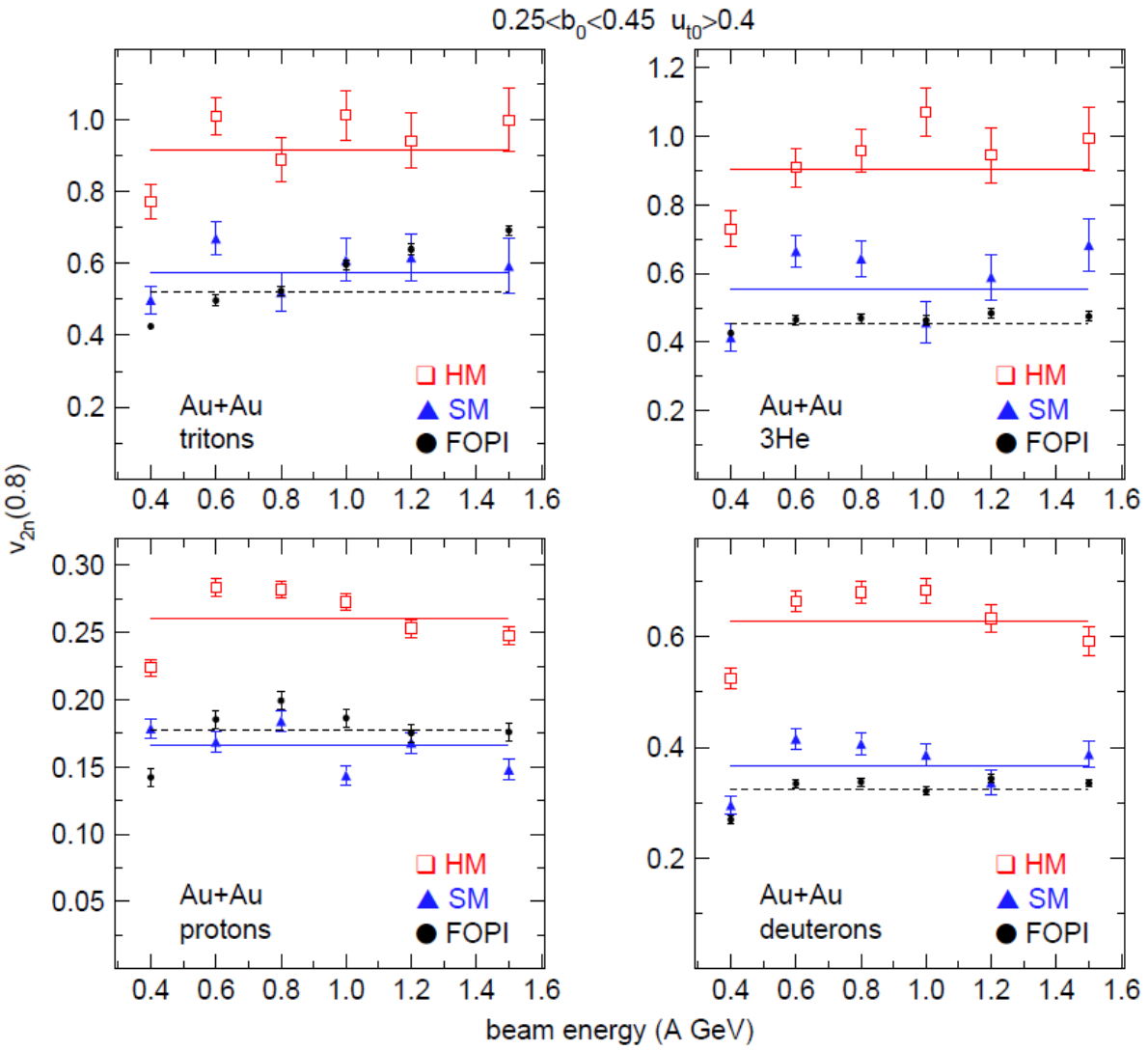
Sub-threshold kaon production

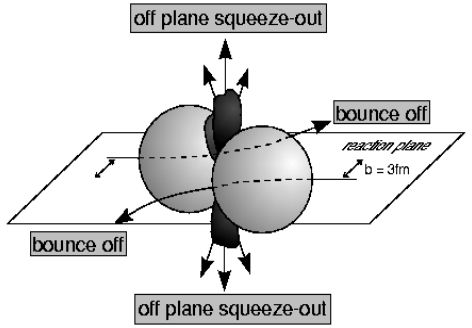
- multi-step processes, using resonances/pions as intermediate energy storage
  - strongly dependent on density
- sensitive to the stiffness of the nuclear matter equation of state

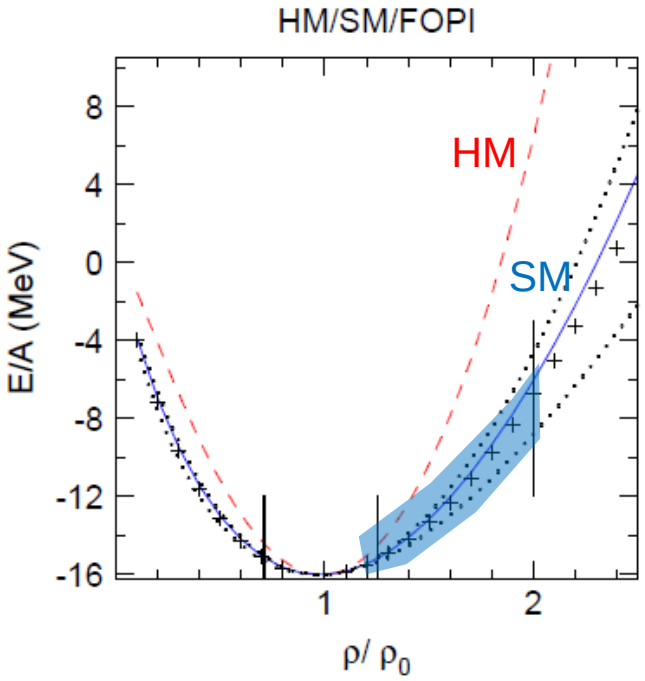
EOS determination from elliptic flow

A. Le Fevre , Y Leifels, W. Reisdorf, J. Aichelin, Ch. Hartnack, NPA A945 (2016) 112, arXiv:1501.02546



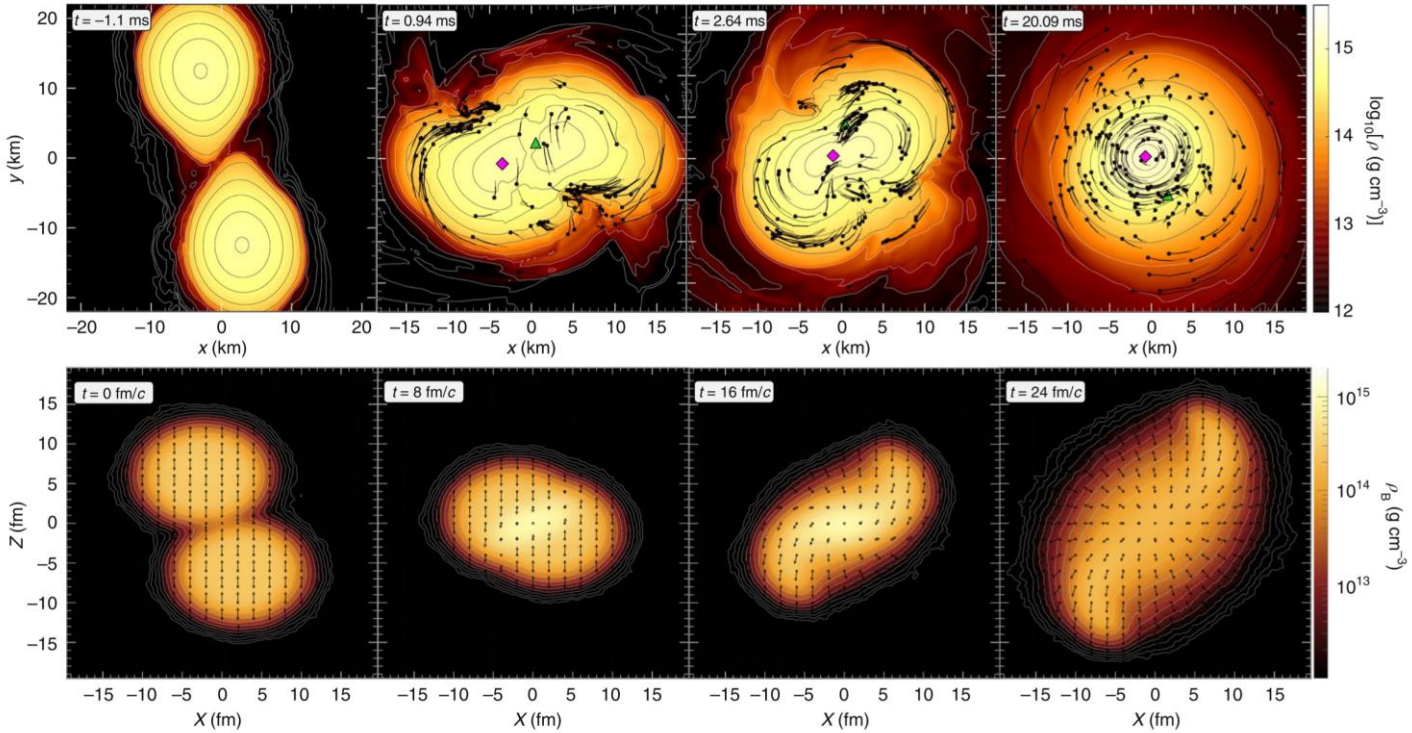




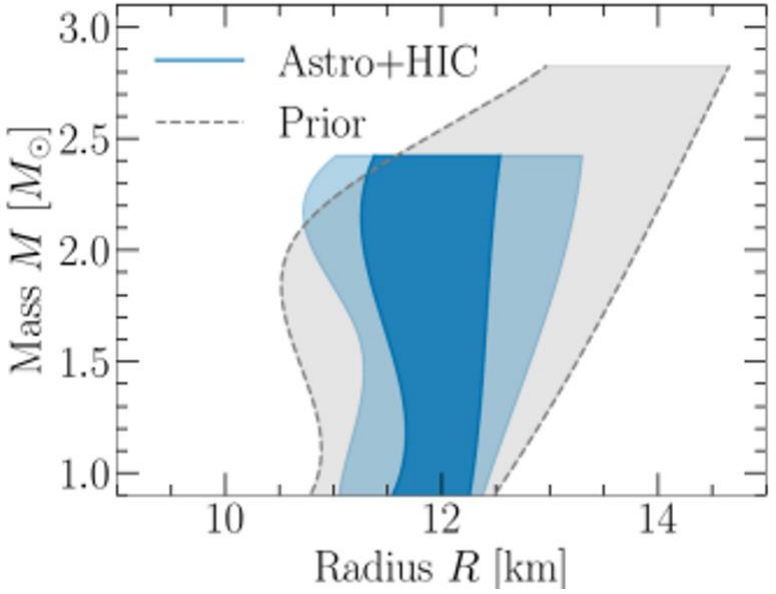


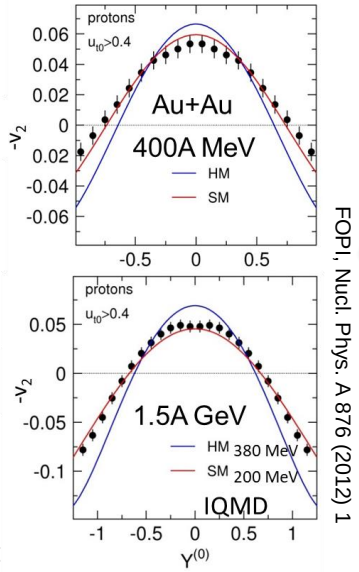
Equation of State

HADES, Nature Phys. 15 (2019) 10, 1040-1045

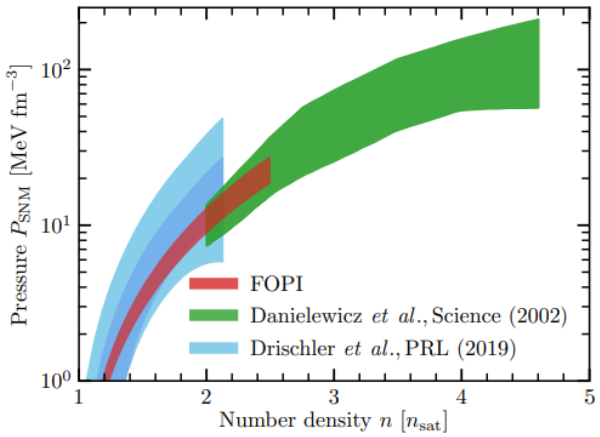


S. Huth et al., Nature 606 (2022) 276





FOPI, Nucl. Phys. A 876 (2012) 1



Multi-messanger signals from Neutron Star mergers and HI collisions are complementary tools to study EOS.

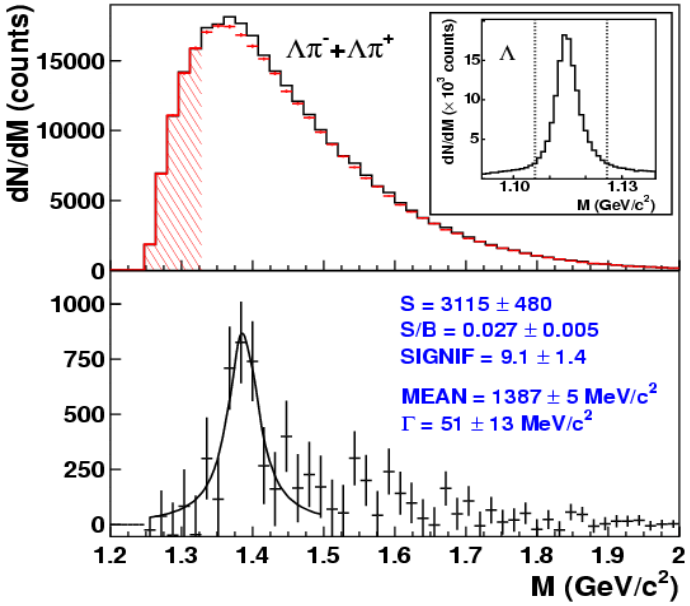
High quality collective flow data needed.

Reconstruction of short lived resonances in HI

Subthreshold production

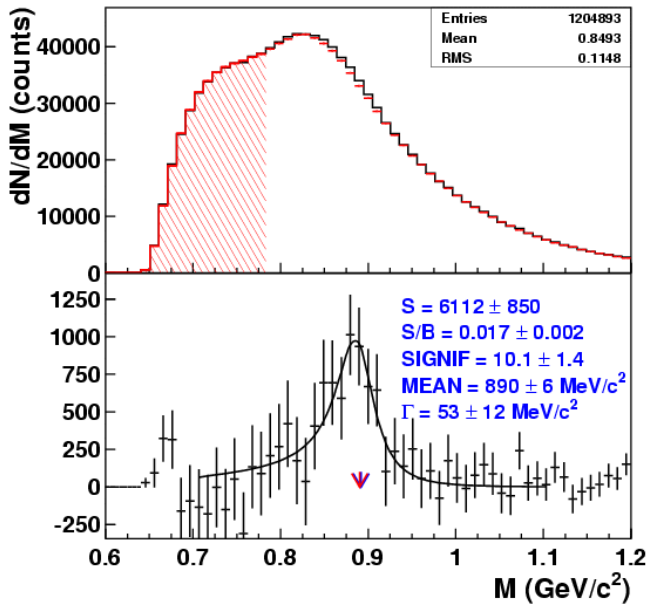
$\Sigma^* \rightarrow \Lambda + \pi$ (87± 2%)
Γ = 39.4 MeV
$c\tau$ = 5 fm
E^{thr}_{NN}=2.33 GeV

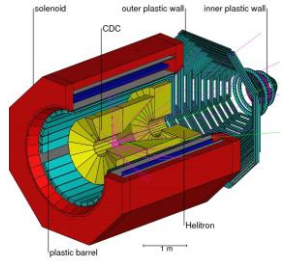
X. Lopez et al. (FOPI), PRC 76, 052203(R) (2007)



$K^* \rightarrow K + \pi$ (100%)
Γ = 50.7 MeV
$c\tau$ = 4 fm
E^{thr}_{NN}=2.75 GeV

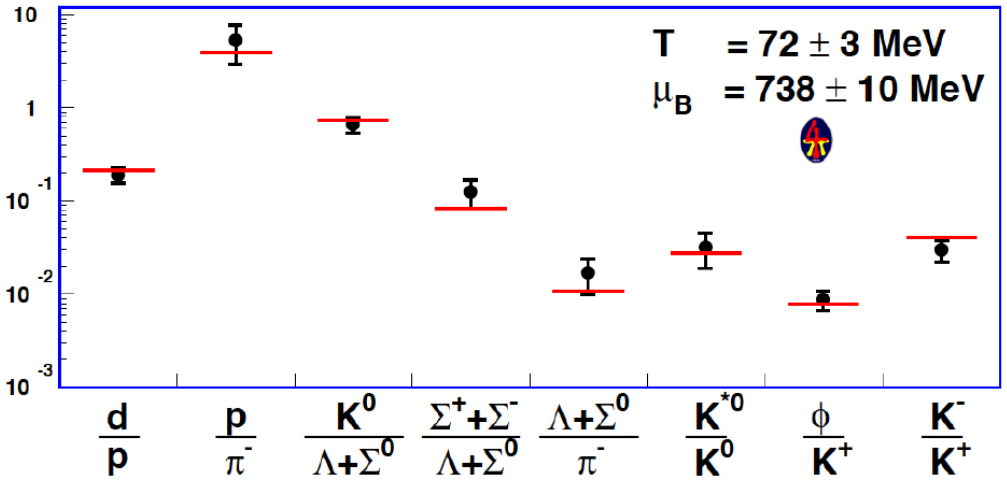
X. Lopez et al. (FOPI), PRC 81, 061902 (2010)





Exp. Conditions:
Al+Al at 1.92 AGeV,
21 d running (Aug 2005)
$5 \cdot 10^8$ recorded events
10 TByte raw data

$$P_{det} \approx 10^{-5}$$

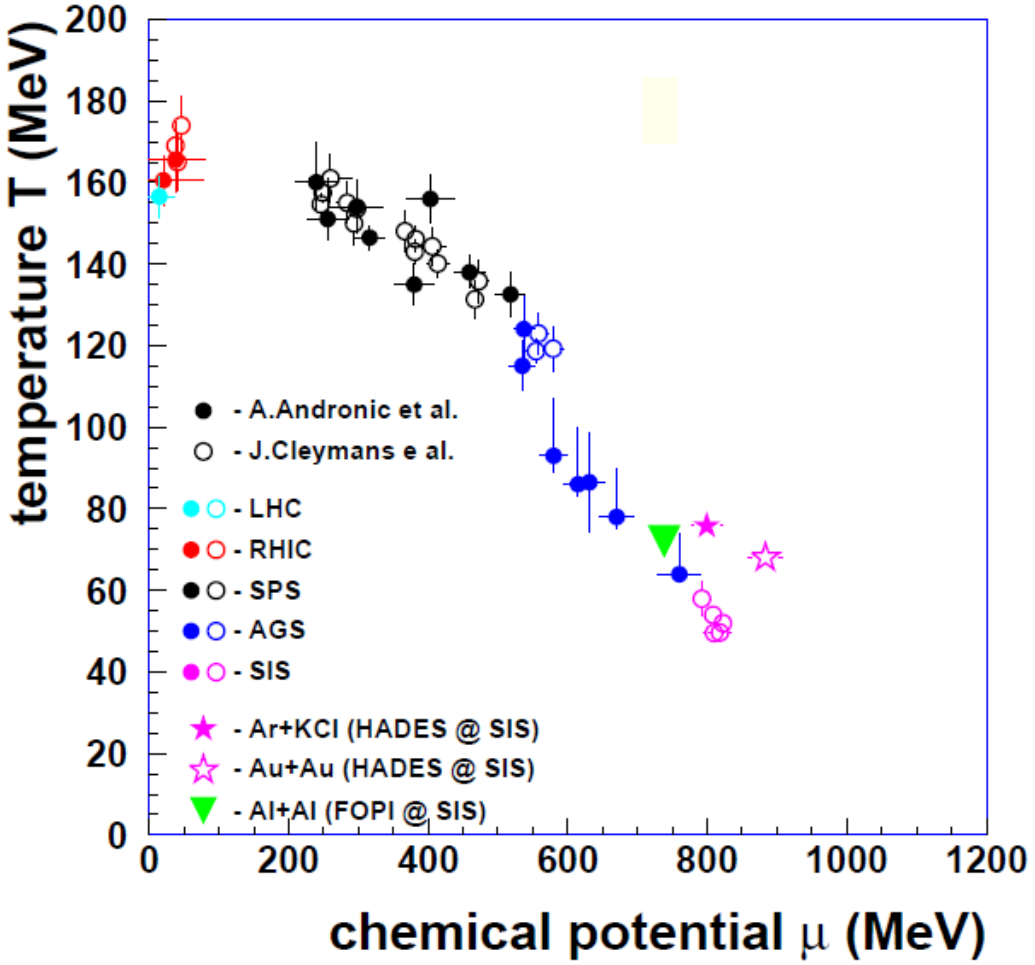


Masses and widths of Σ^* and K^* consistent with PDG values.

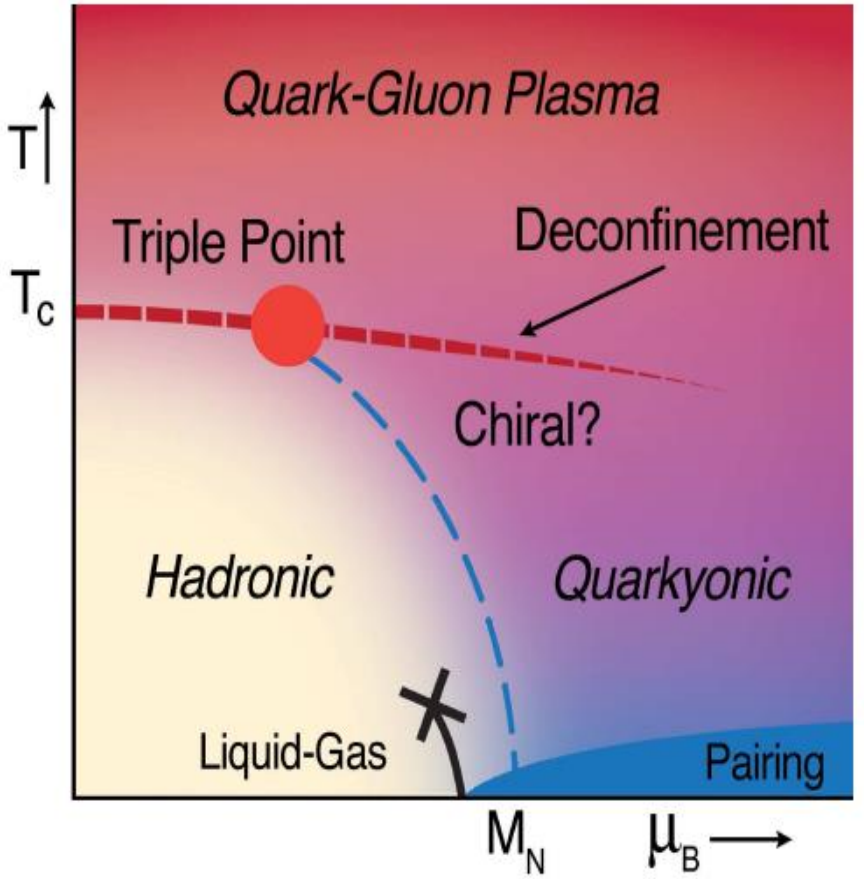
Particle ratios can be described by thermal model.

Freeze-out in high μ_B - region

Freeze-out data are well described by
Statistical Hadronization Model



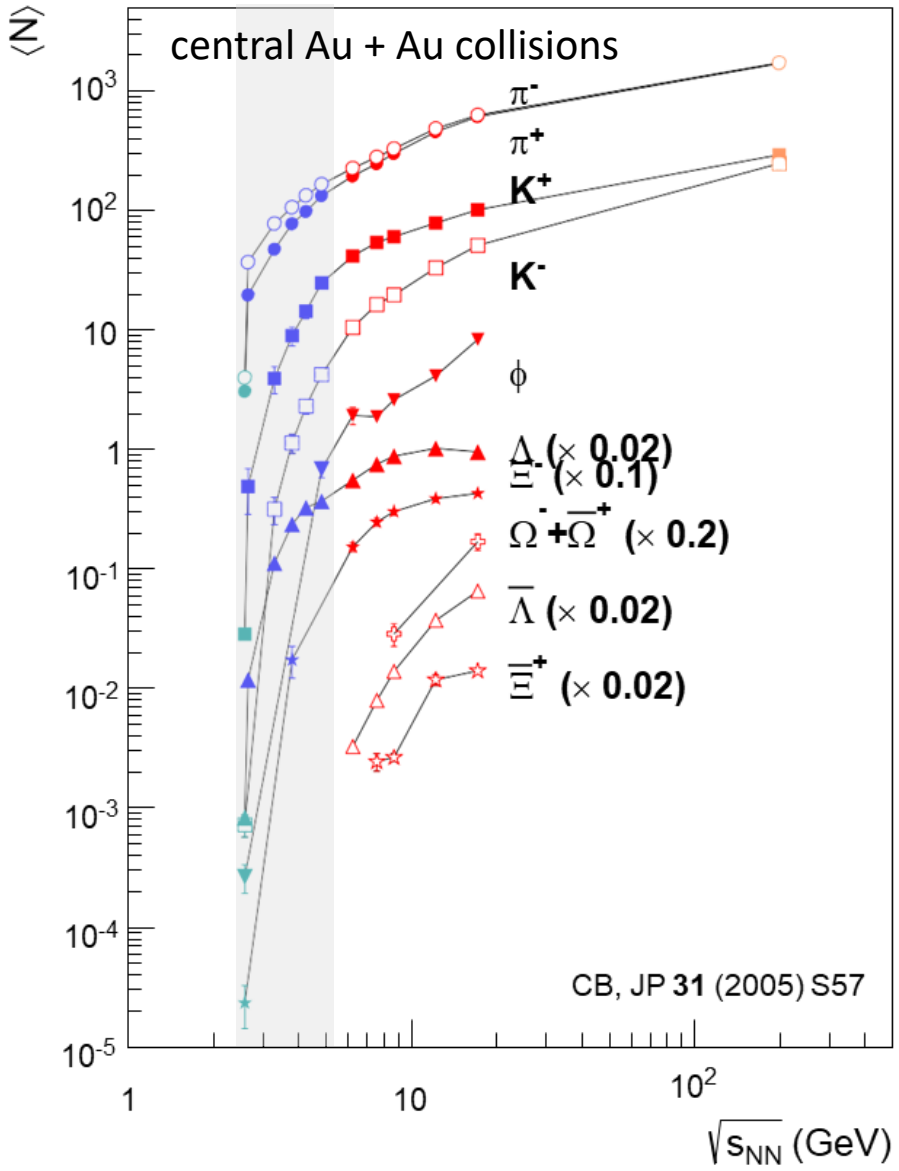
A. Andronic et al., arXiv:0911.4806



Quarkyonic Matter ?

L. McLerran and R. D. Pisarski, Nucl. Phys. A 796, 83 (2007).

Heavy Ion Physics at SIS100



C.Blume, SQM2017)

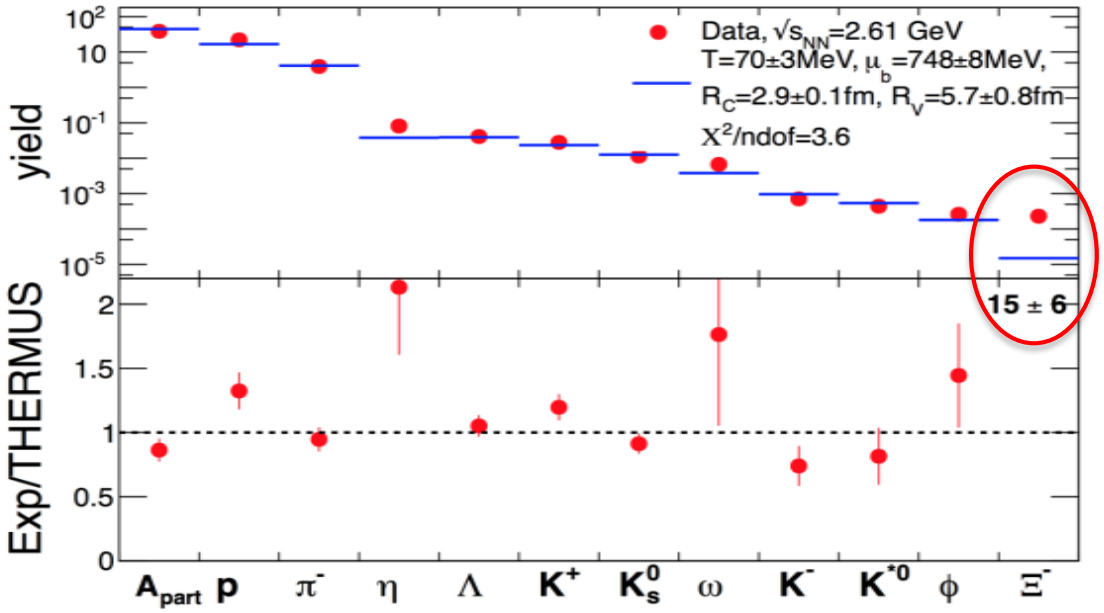
Strange and charmed particle production thresholds in pp - collisions

reaction	$\sqrt{s}$ (GeV)	T_{lab}(GeV)
$pp \rightarrow K^+\Lambda p$	2.548	1.6
$pp \rightarrow K^+K^-pp$	2.864	2.5
$pp \rightarrow K^+K^+\Xi^-p$	3.247	3.7
$pp \rightarrow K^+K^+K^+\Omega^-n$	4.092	7.0
$pp \rightarrow \Lambda\bar{\Lambda}pp$	4.108	7.1
$pp \rightarrow \Xi^-\bar{\Xi}^+pp$	4.520	9.0
$pp \rightarrow \Omega^-\bar{\Omega}^+pp$	5.222	12.7
$pp \rightarrow J/\Psi\, pp$	4.973	12.2

Deviations from Statistical Model

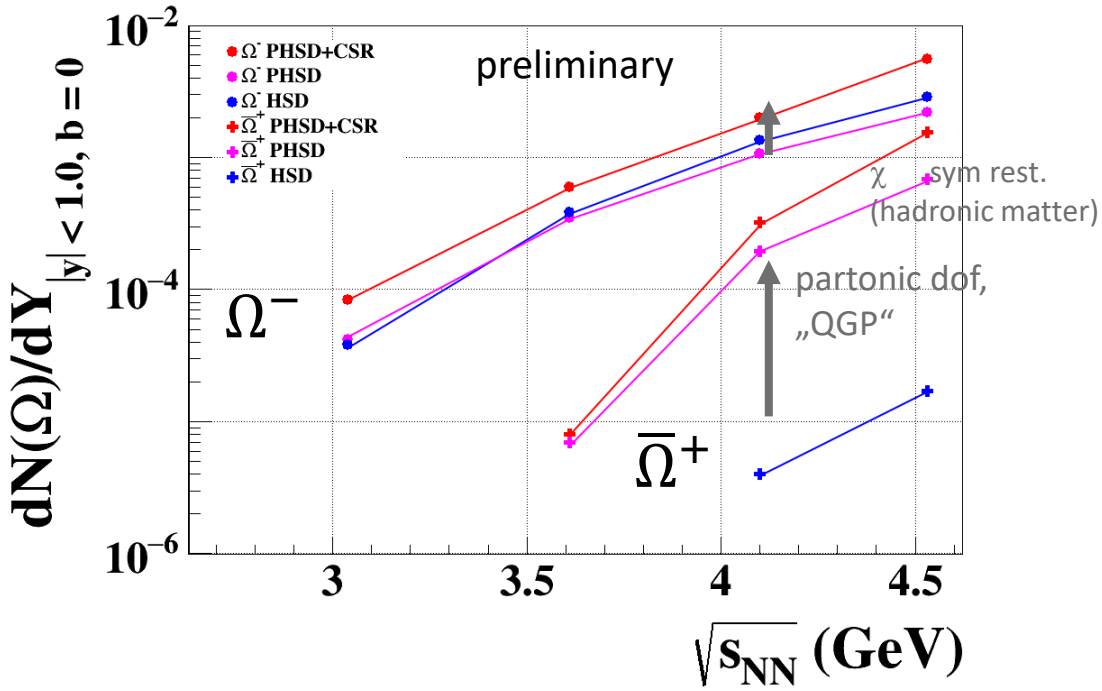
HADES data

Ar + KCl 1.76 A GeV
G. Agakishiev et al., EPJA 52 (2016) 6, 178



Transport Model Predictions

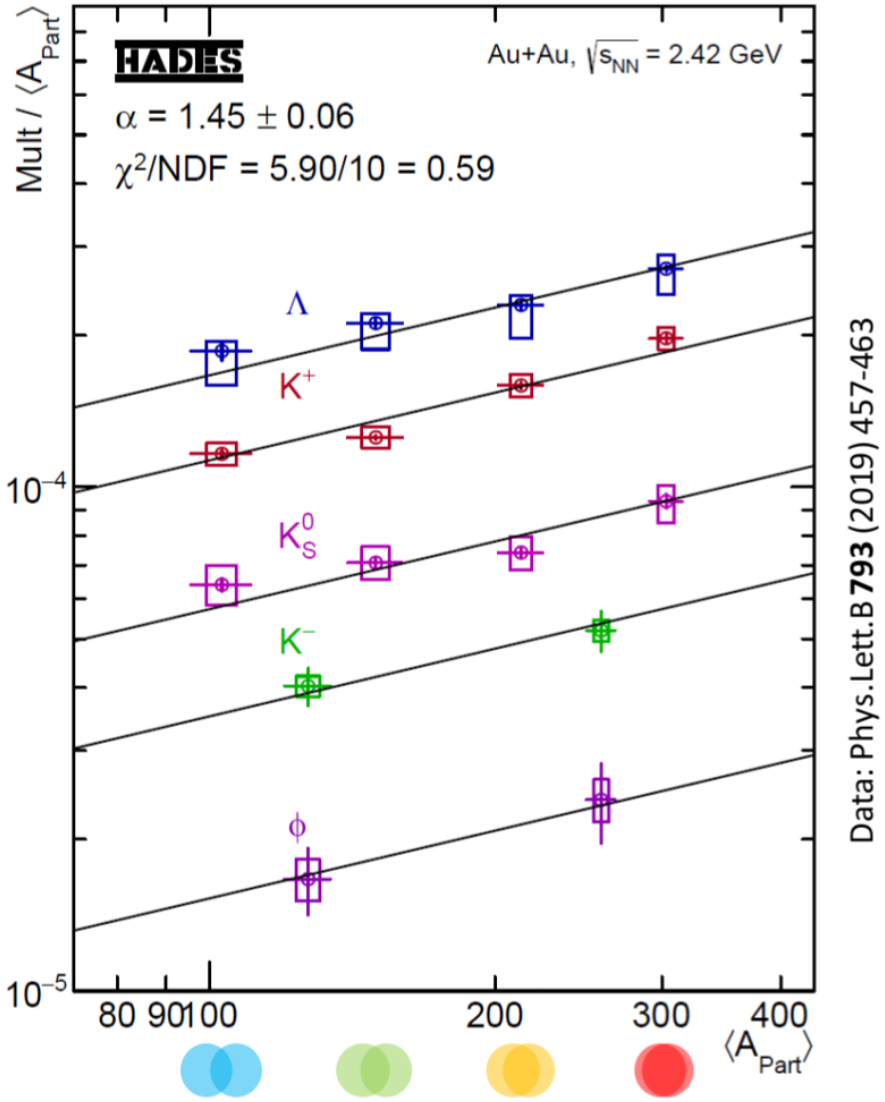
PHSD W. Cassing, E. Bratkovskaya et al., Phys.Rev. C93 (2016), 014902



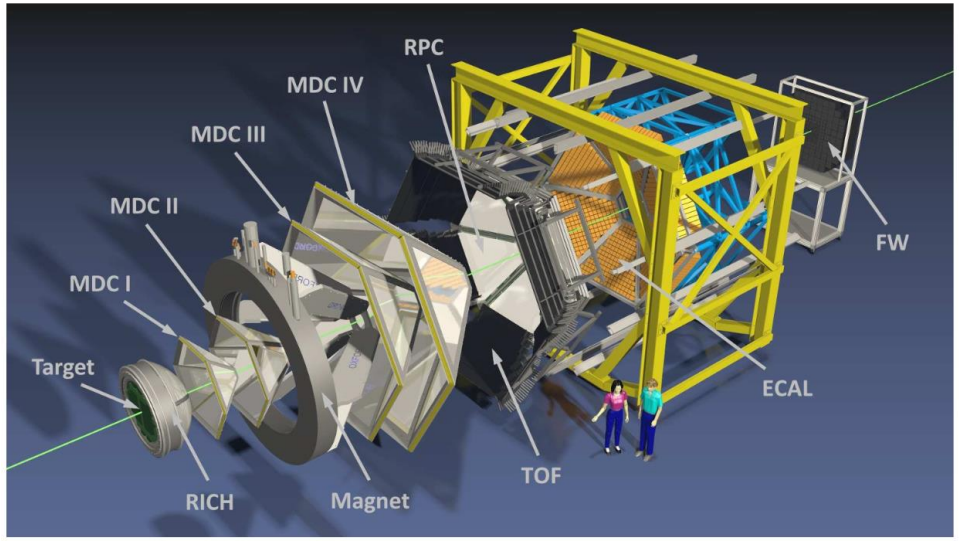
Sensitivities of subthreshold particle production

- Equation-of-state (multi step production)
- In-medium properties of hadrons
- Contributions from partonic degrees of freedom („QGP“)

Recent HADES results



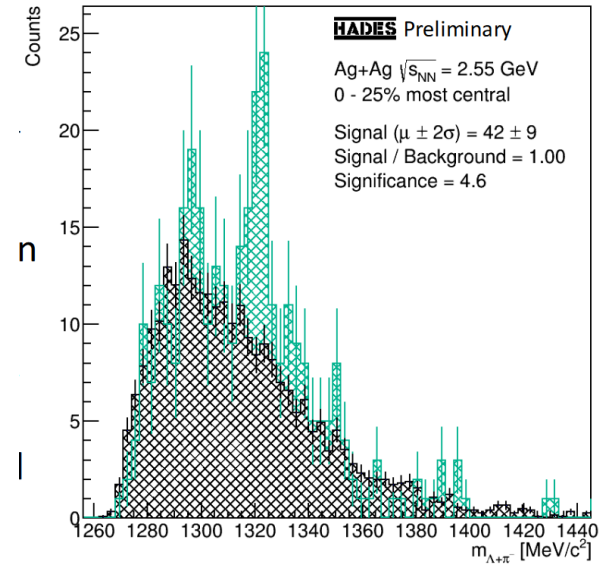
Data: Phys.Lett.B **793** (2019) 457-463



Multiplicity independent of NN production threshold

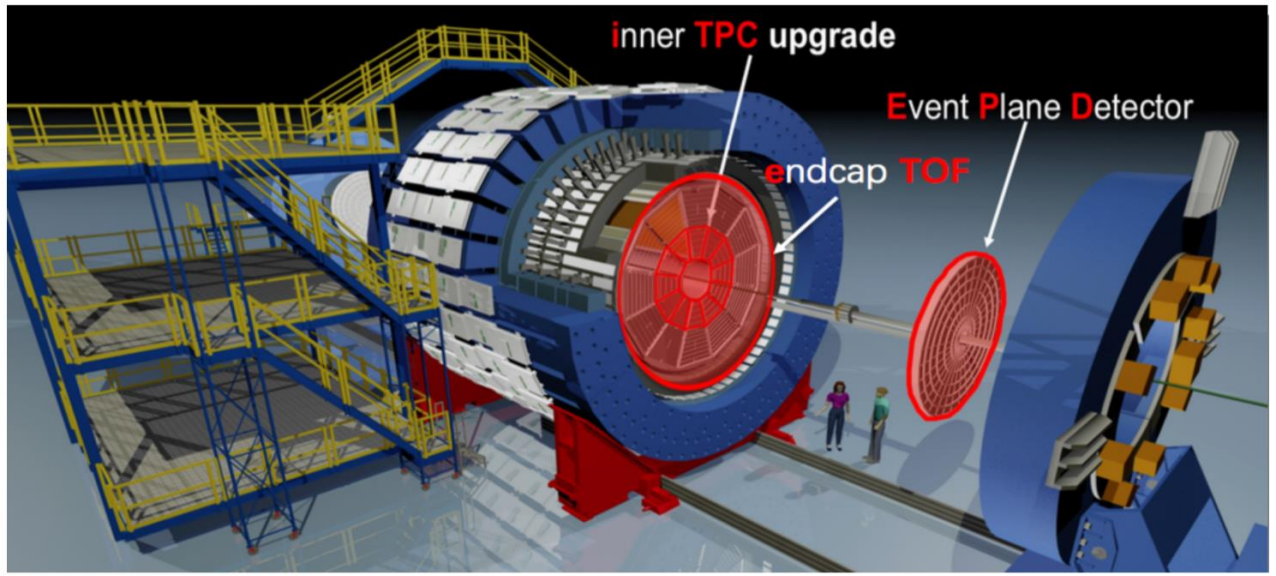
Same scaling factor α in Au+Au and Ag+Ag at different energies

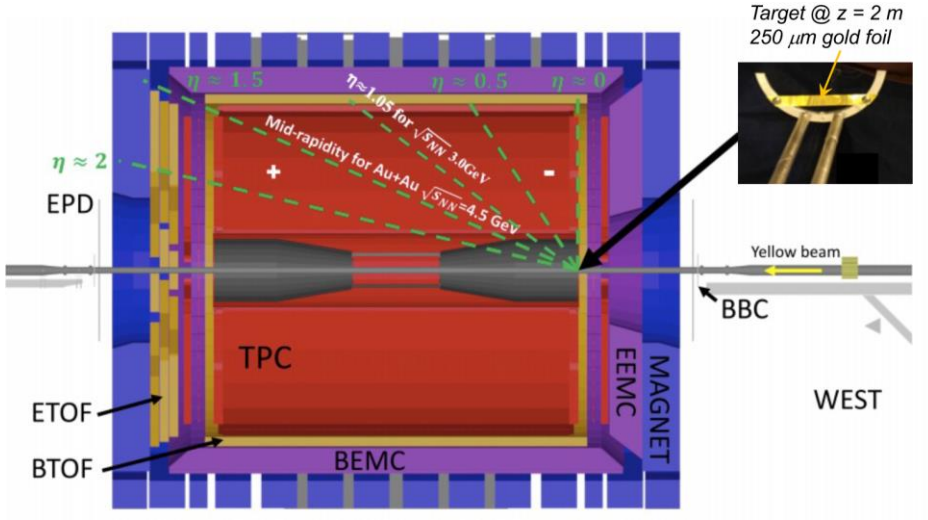
First observation of Ξ^- in Ag+Ag

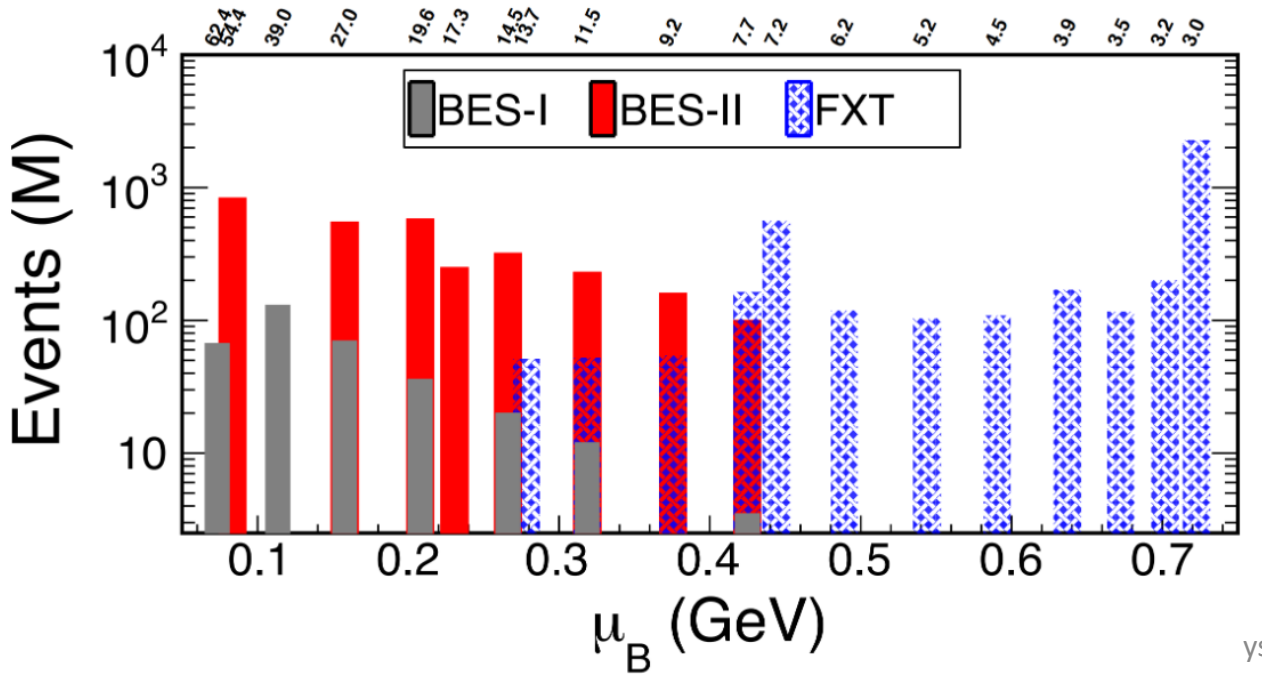


S. Spies, QM2023

STAR Beam Energy Scan







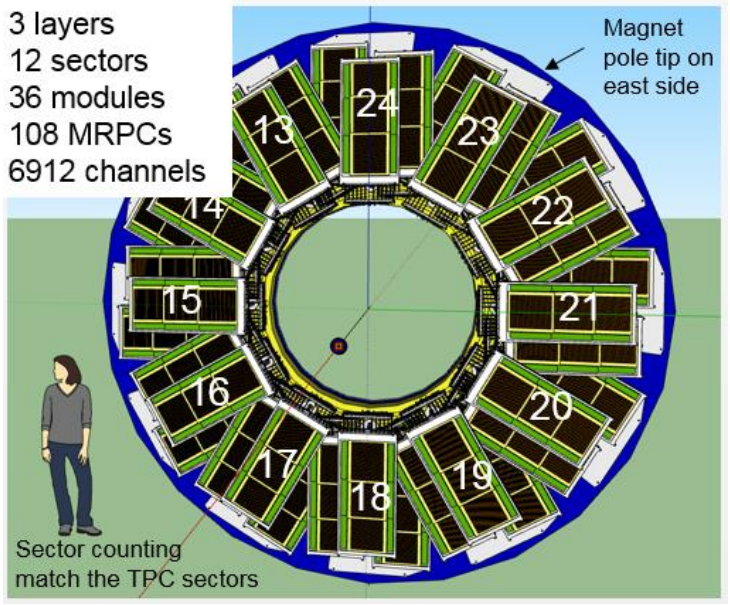
$\sqrt{s_{NN}}$

Data taking for BES-II completed in 2021

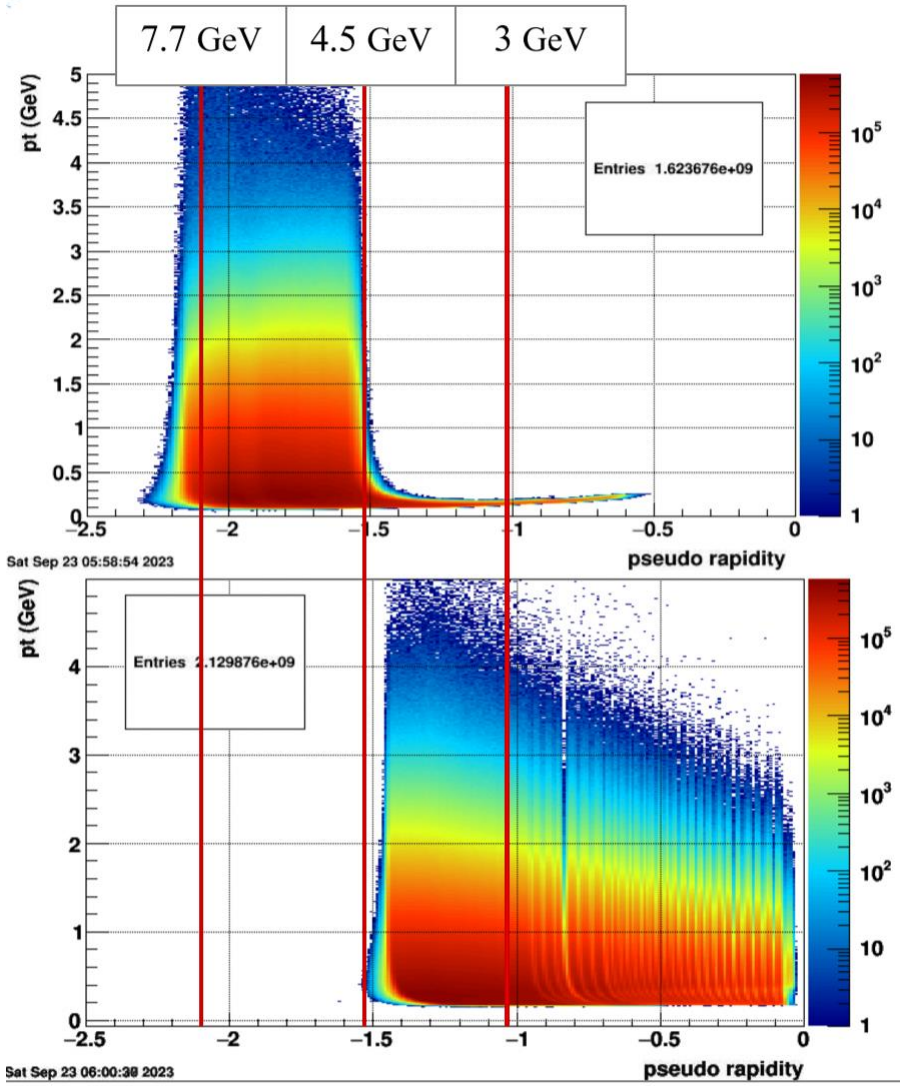
~ 100M events per energy in SIS100 range (2 G events at $\sqrt{s_{NN}}$ =3 GeV)

STAR dismantling planned for 2025

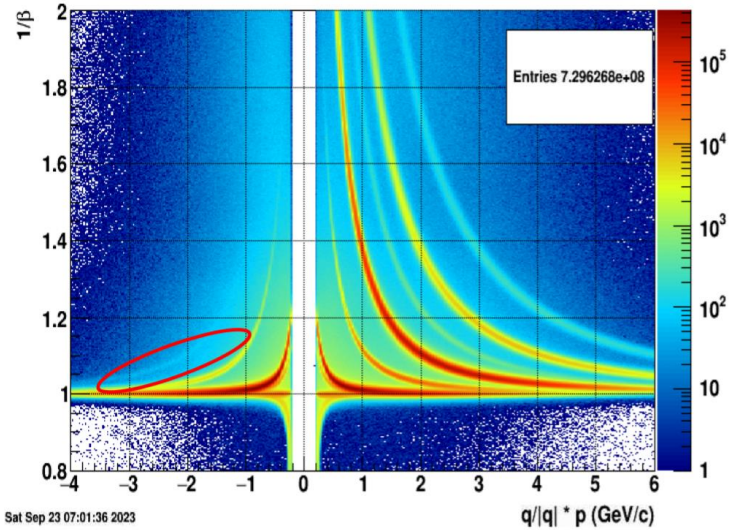
eTOF performance in STAR BES-II

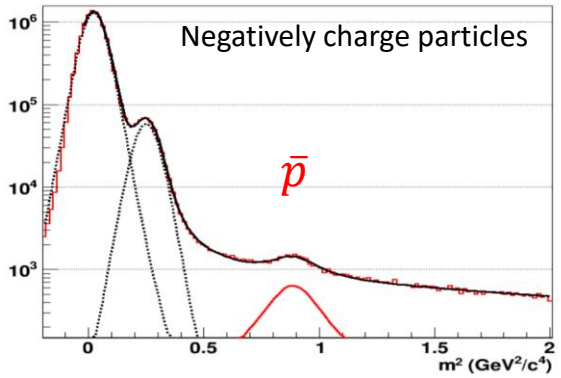


midrapidity location



Status of ETOF PID at $\sqrt{s_{NN}}$=4.5 GeV





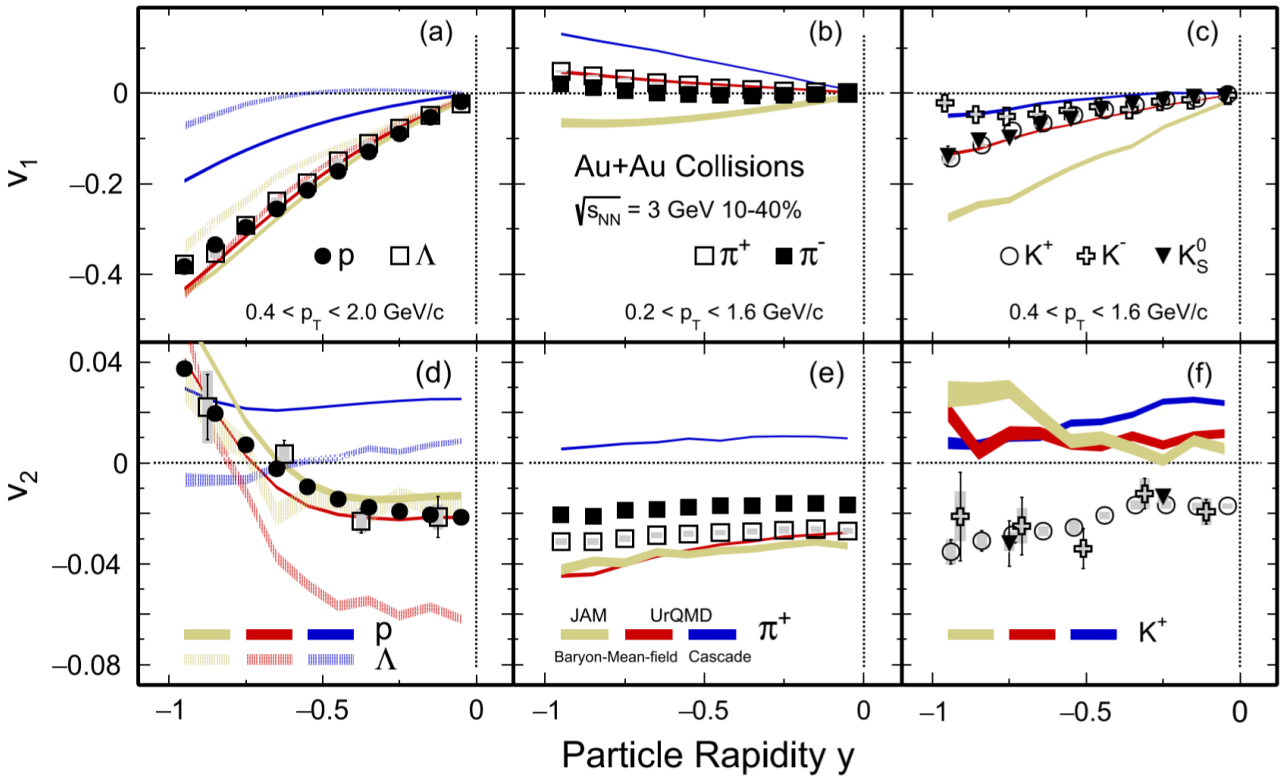
Fitted projection of m2 spectrum in the momentum range: 2.0 - 2.25 GeV
Fit function: tStudent for pions, kaons (dashed black line) and anti-protons (red line) plus exponential background (not shown)

eTOF

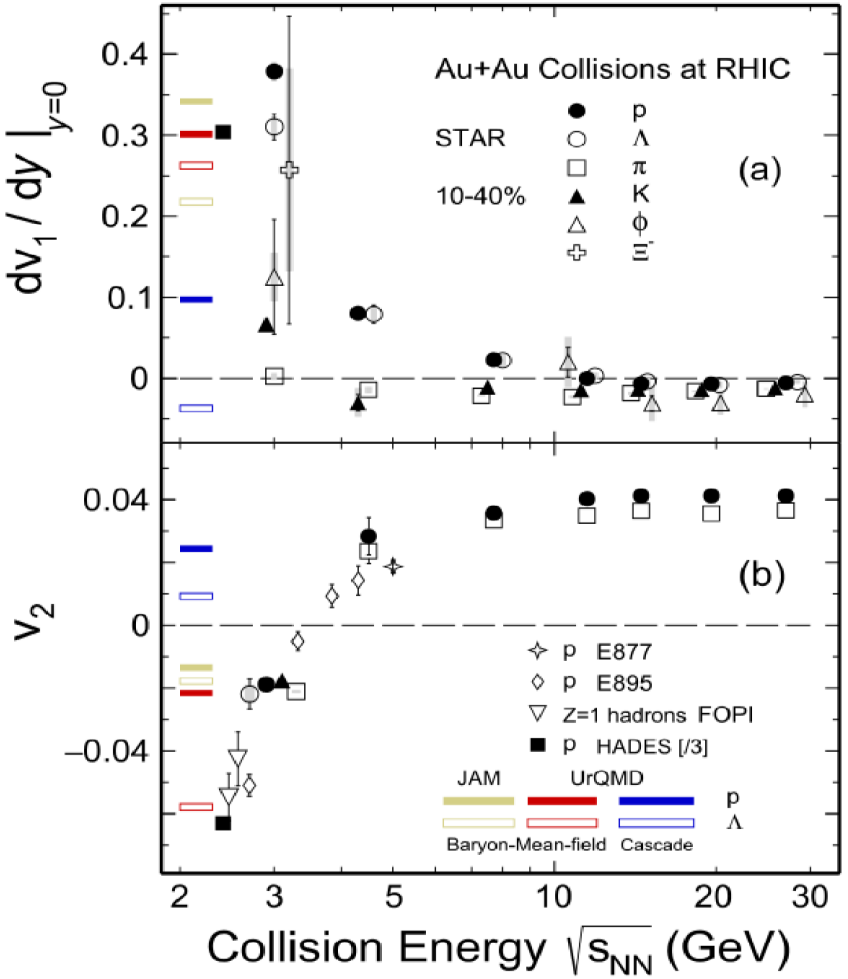
- installed in 2018
- CBM – MRPC and DAQ prototypes
- extension of STAR acceptance
- calibration and analysis ongoing

STAR BES-I results

Collective flow at $\sqrt{s_{NN}}$ = 3 GeV



STAR, Phys. Lett. B 827,137003 (2022)

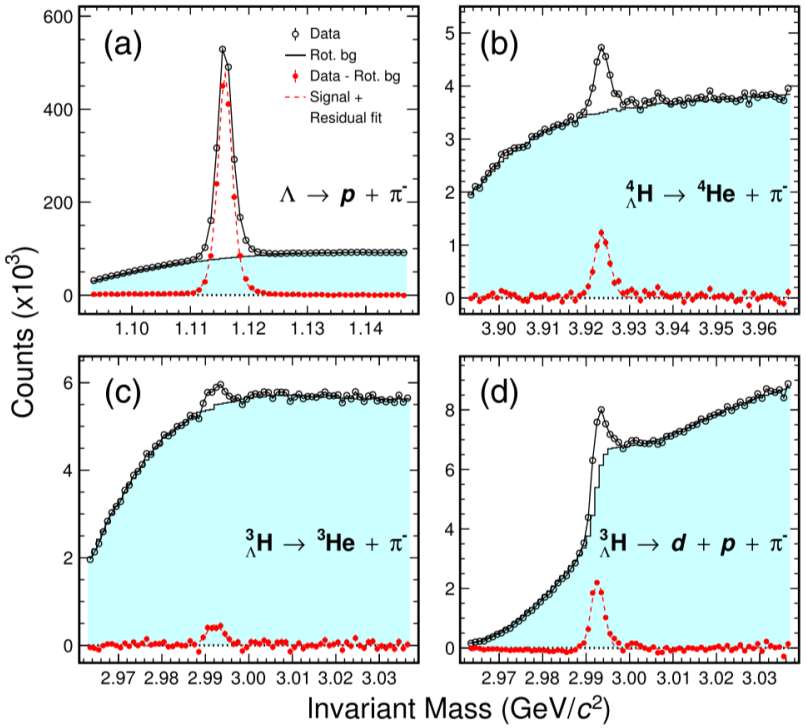


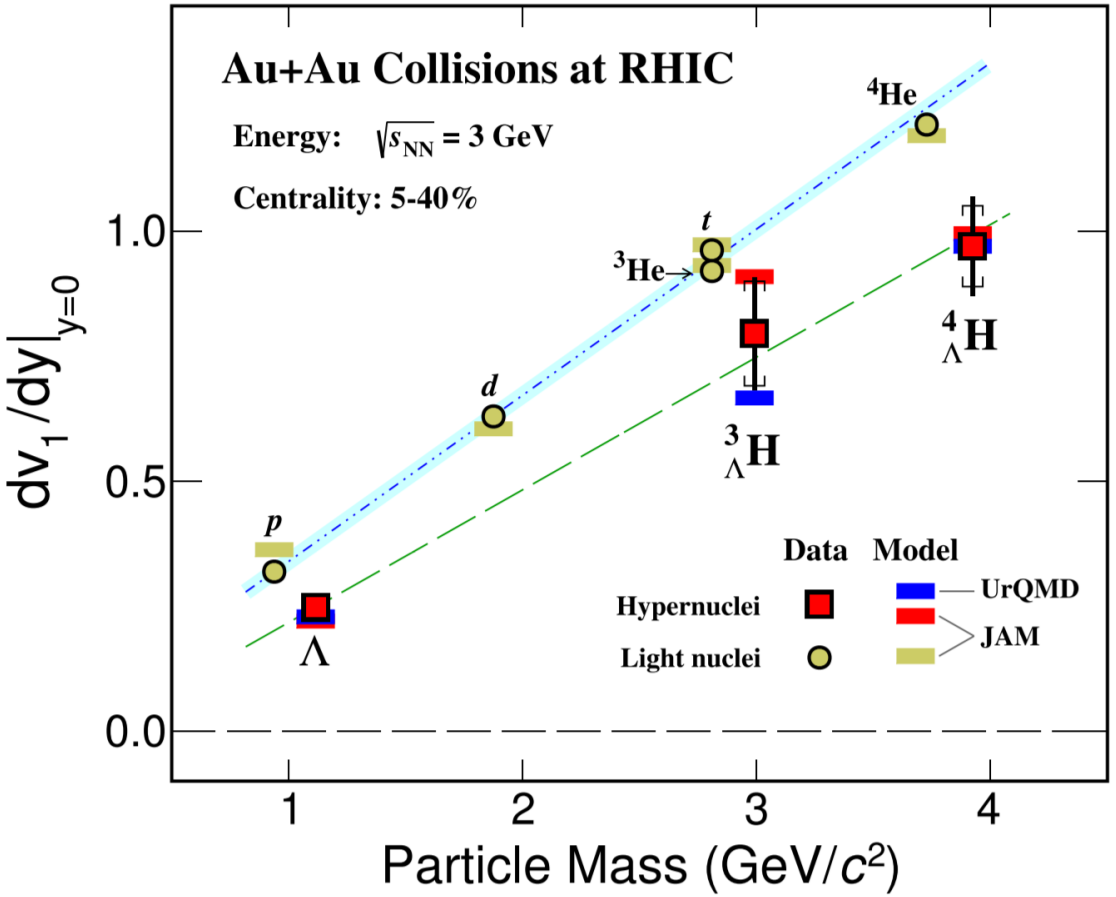
- Collective Flow shows hadronic behaviour
- Mean field necessay for proton/pion distributions
- Strange particle flows not not described by models (JAM, UrQMD)

STAR BES-I results

Collective flow of hypernuclei at $\sqrt{s_{NN}}$ = 3 GeV

STAR, Phys.Rev.Lett. 130,212301(2023)



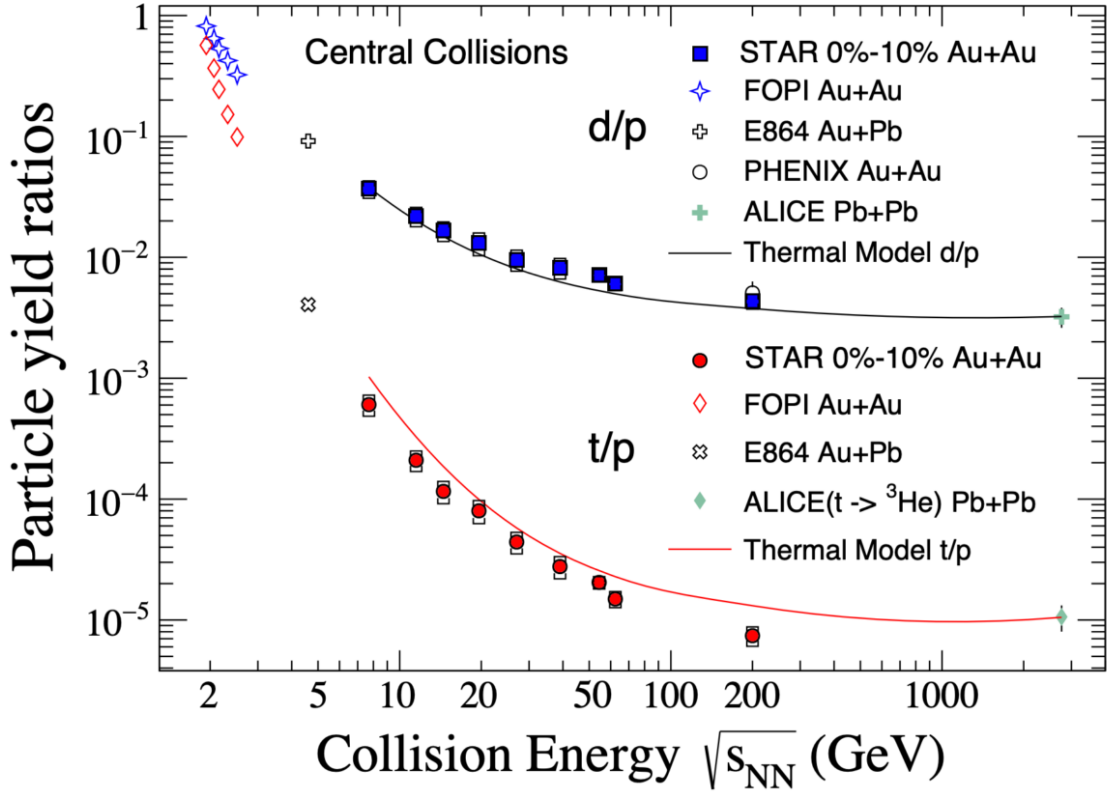


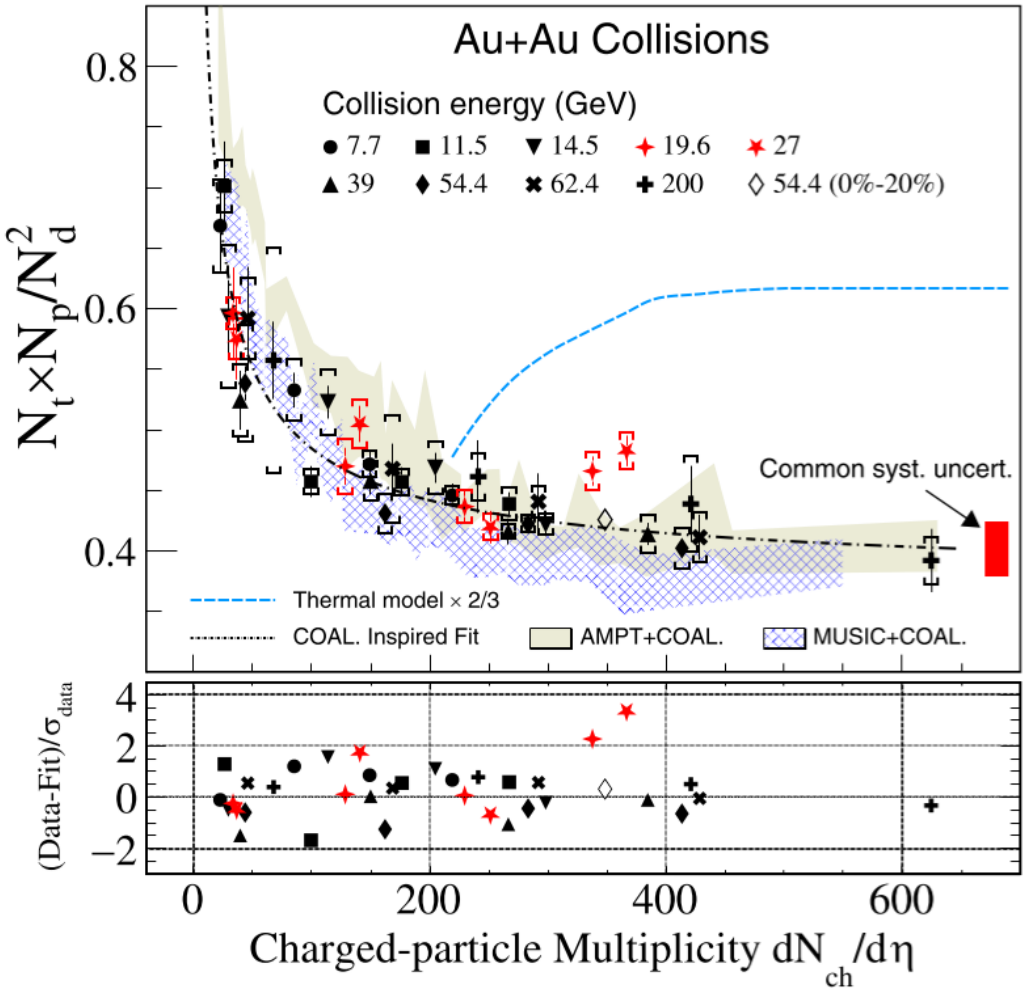
- Directed flow follows trend of non-strange hadrons
- Reduced strength in agreement with Λ - flow

STAR BES-I: cluster formation

Yield ratio $\frac{t \times p}{d^2}$ sensitive to baryon density fluctuations and production mechanism

STAR, Phys. Rev. Lett. 130 (2023) 202301





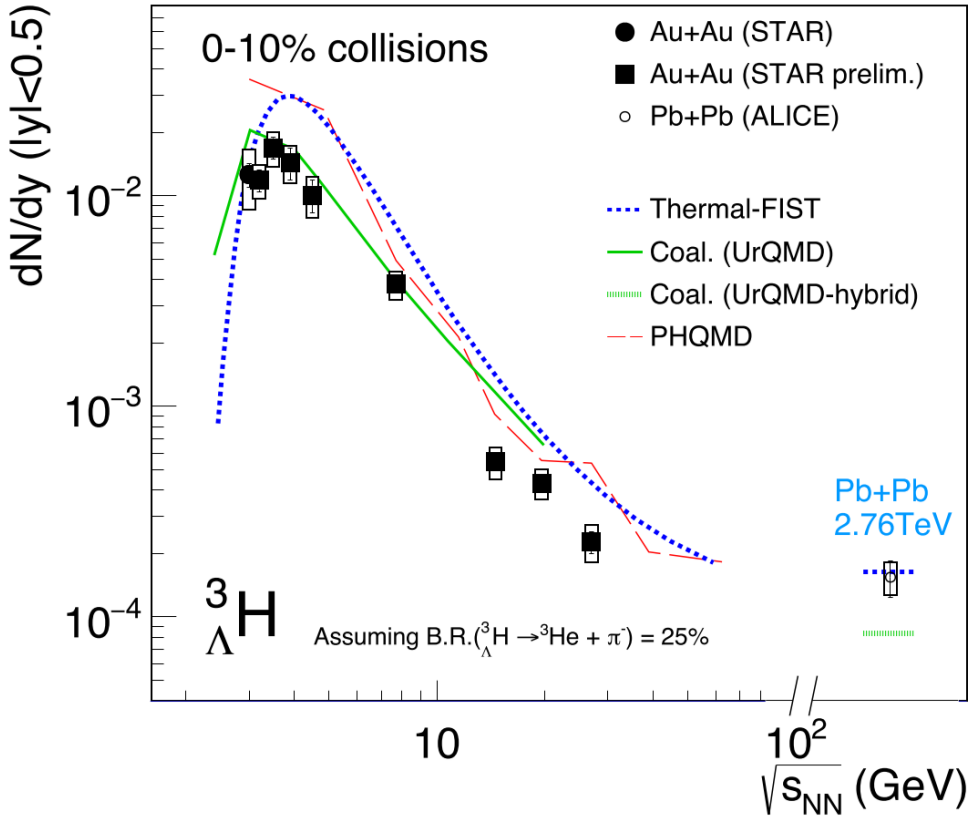
- d/p fairly well described by thermal model, t/p is overestimated
- yield ratio exhibits approx. scaling behavior with $dN_{ch}/d\eta$
- yield ratio deviates strongly from thermal model (with feed-down)

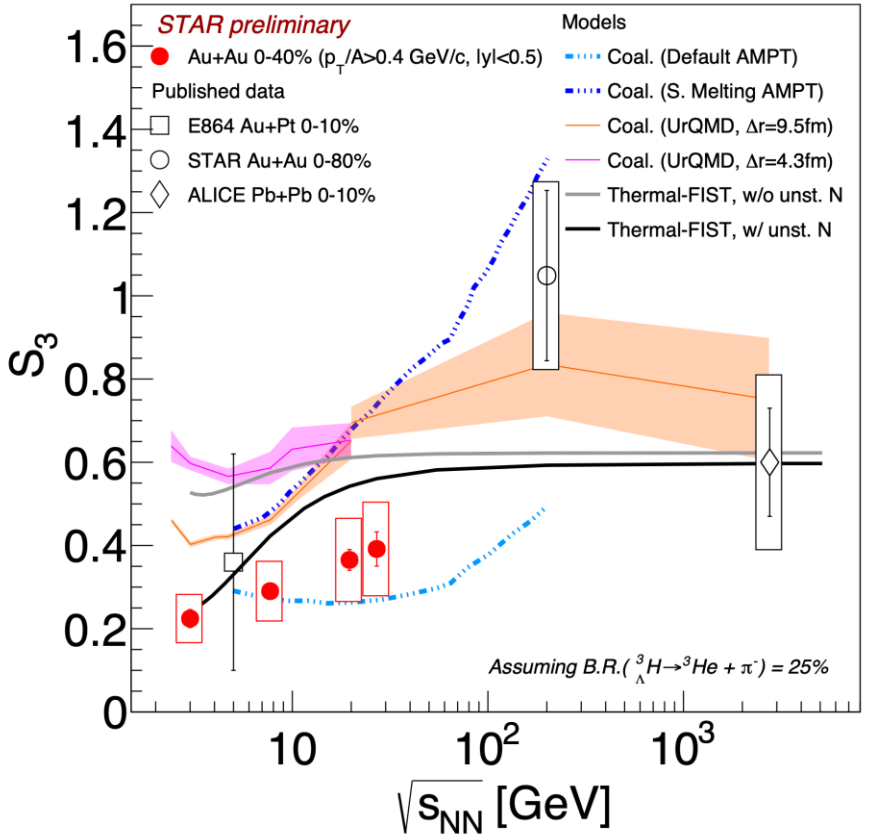
Hypertriton excitation function

Hypernuclei as probe of strangeness – baryon density fluctuations ?
Production mechanism

$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}_{\Lambda}\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$

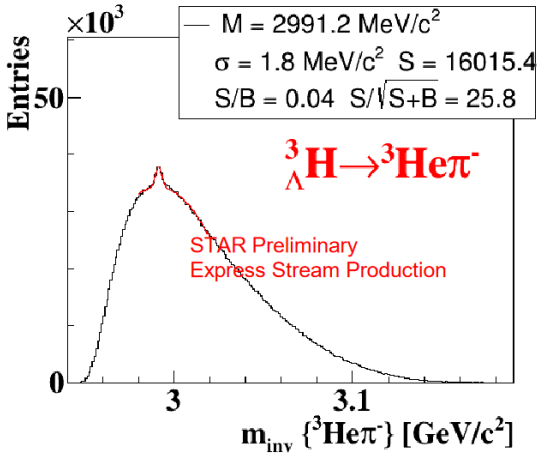
STAR preliminary

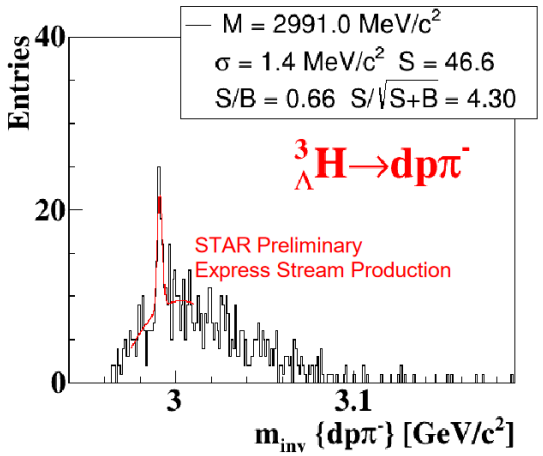


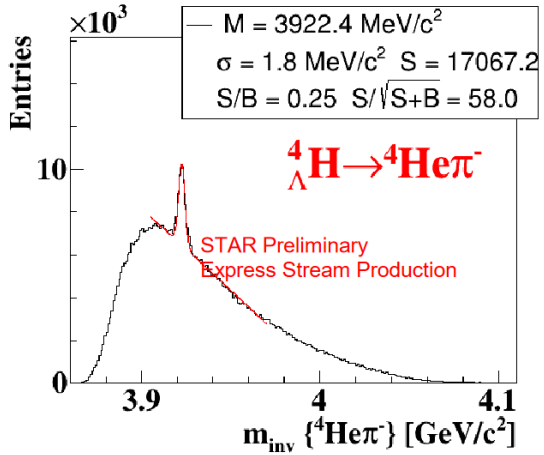


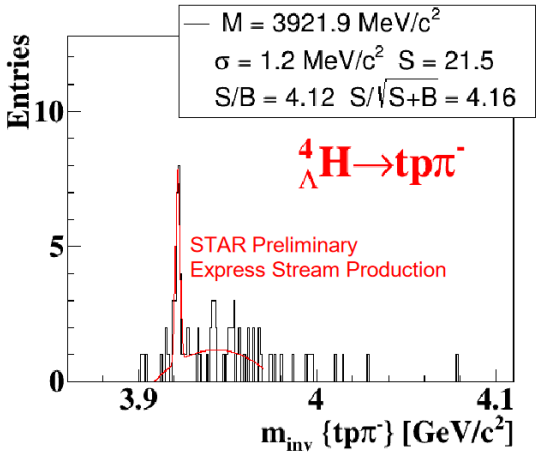
- $^{3}_{\Lambda}$H yield described well by coalescence at high baryon densities

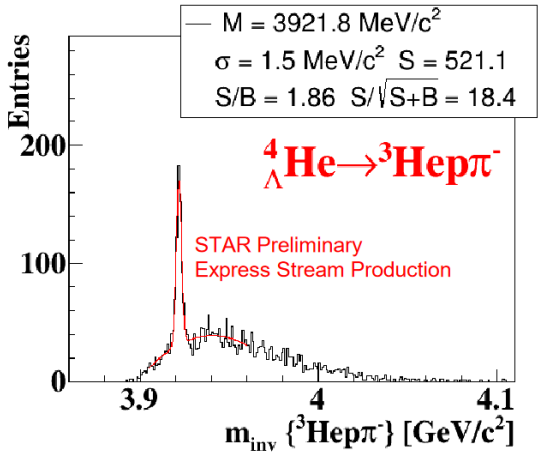
Preview: Hypernuclei from Express Stream Production

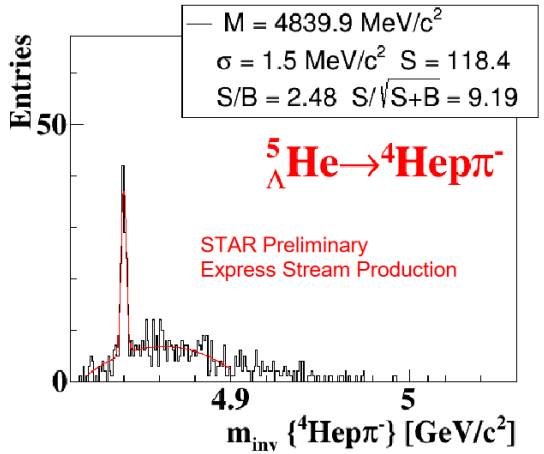












I. Vassiliev, Hadron2023

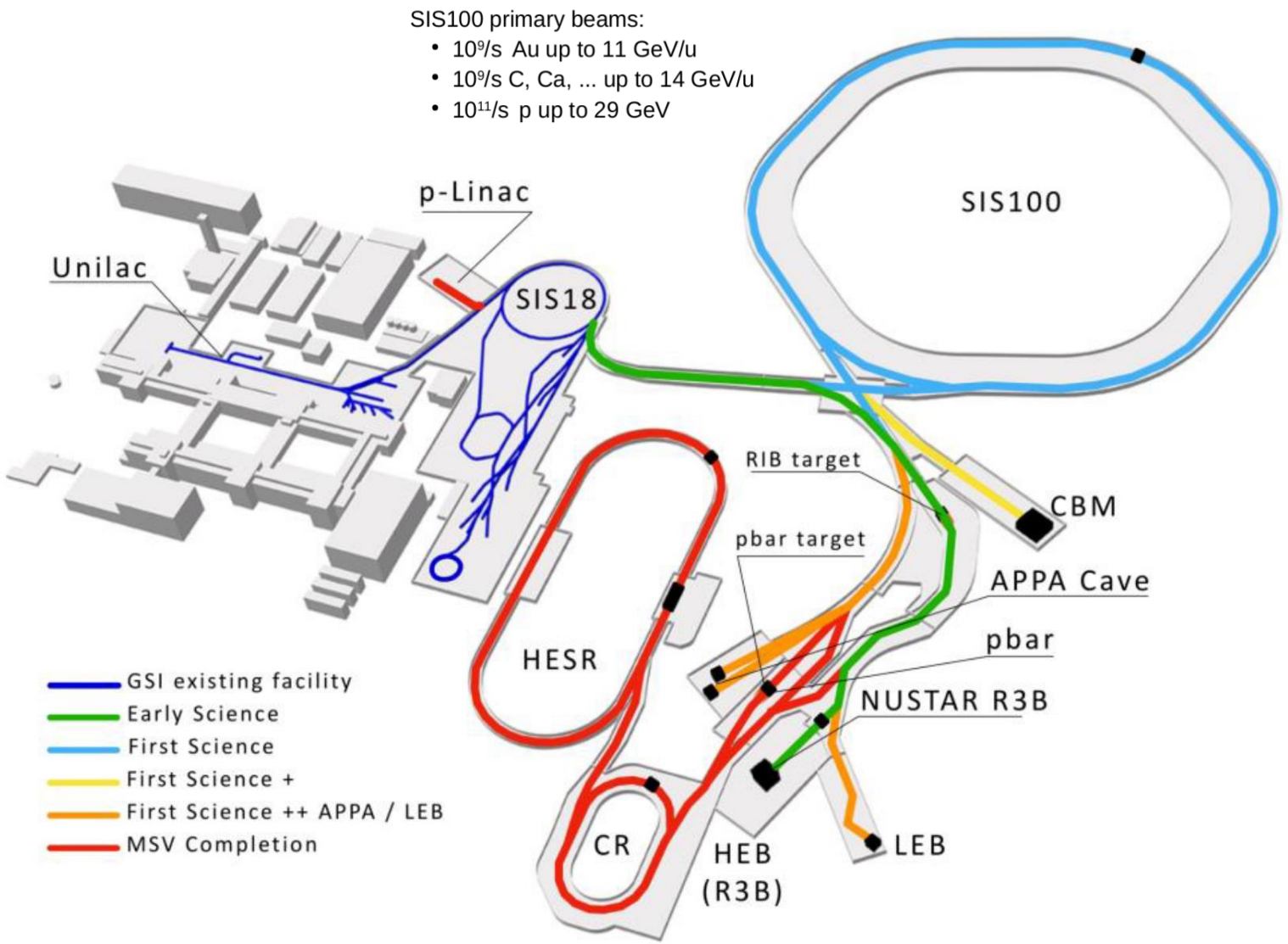
437M HLT events at $\sqrt{s_{NN}}$ =3 GeV (BES-II data)

- light hypernuclei are well measurable in STAR BES-II acceptance with limited statistics
- 3-body decays offer opportunities to investigate internal structure

October 2023

FAIR facility

Recent developments at FAIR

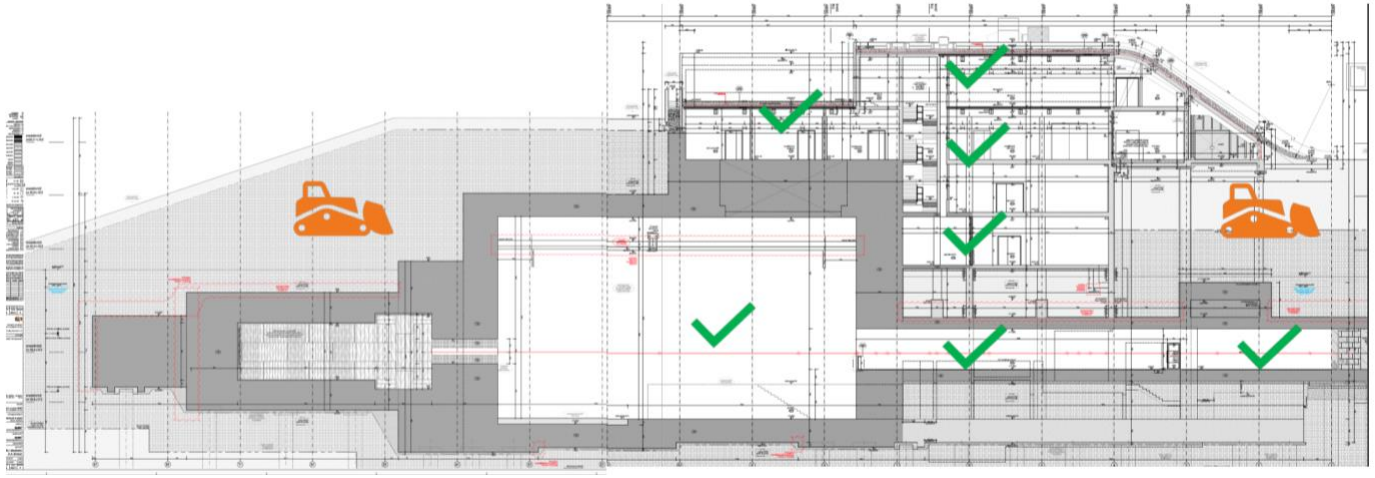


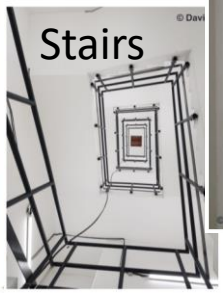
https://www.gsi.de/fileadmin/oeffentlichkeitsarbeit/fair/FAIR-report_221025.pdf

- Science evaluation in 2022
  (chairs: R. Heuer, R. Tribble)
  3/10 years
- FAIR council committed to build MSV
- Available budget is driver for decisions
- FAIR project execution strategy:

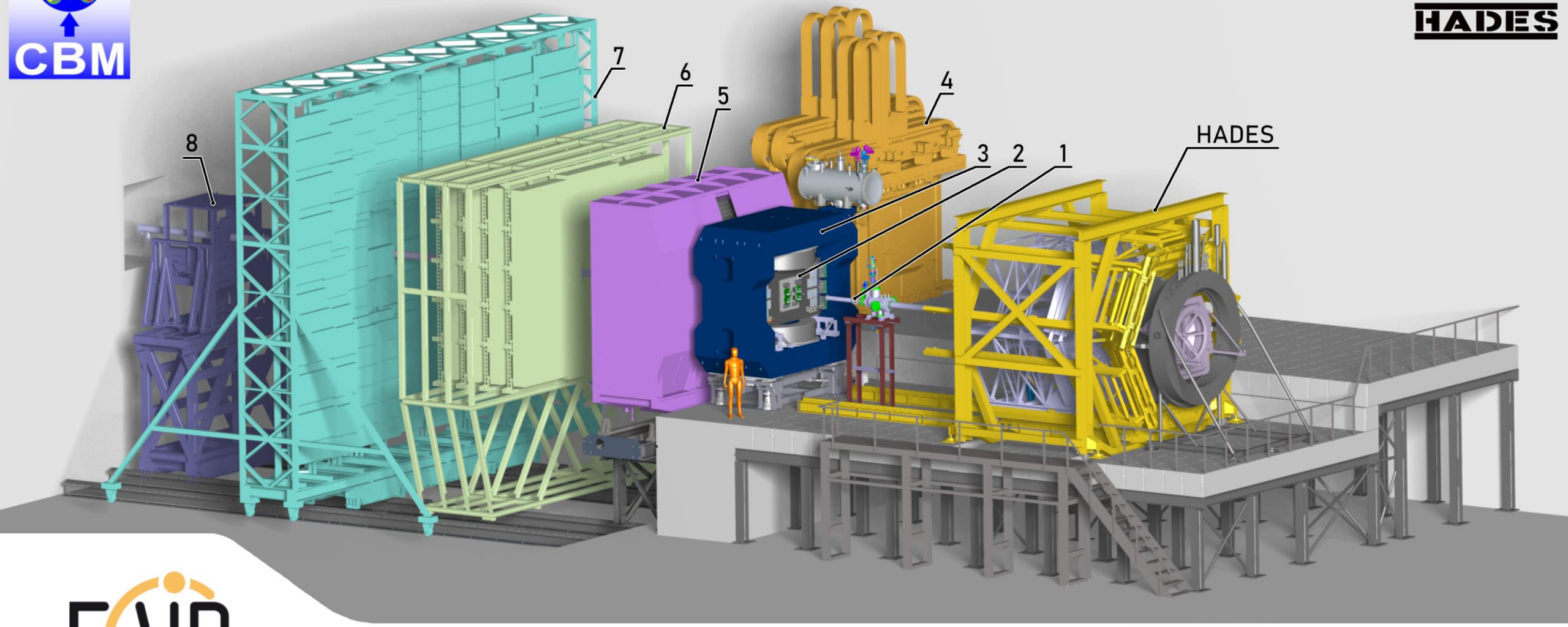
  start with FAIR2028
  ES, FS, FS+
- Priority given by sequence
  ES in 2027
  FS in 2028
  \+ in 2028

CBM – Building



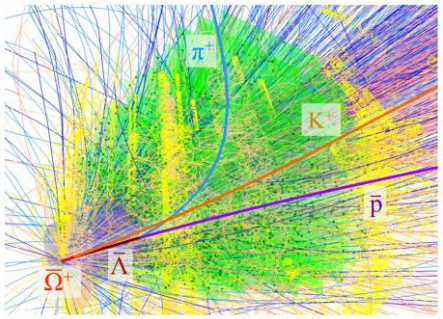


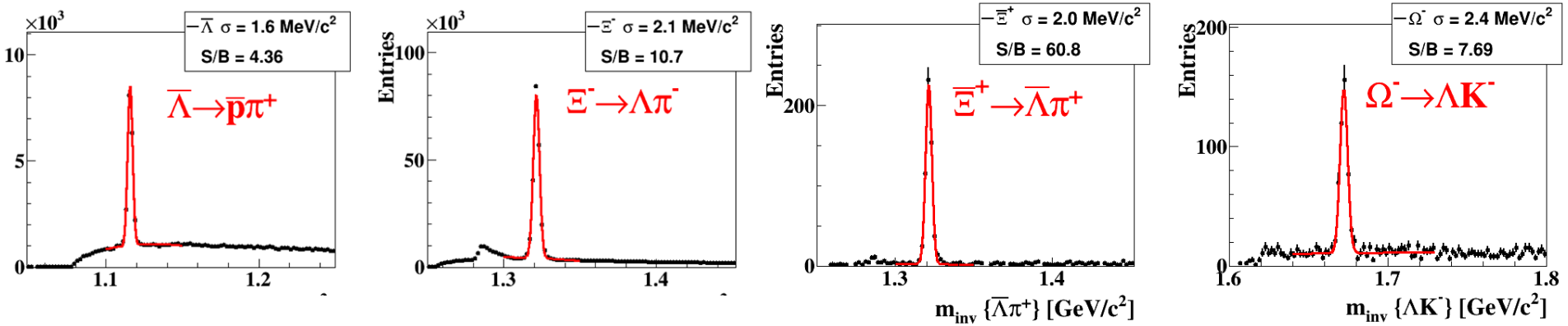
Compressed Baryonic Matter



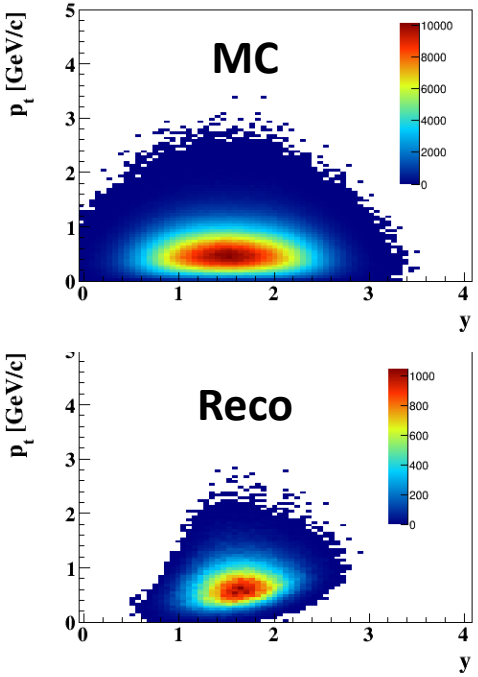
1: Time-Zero Detector & Beam Diagnostics
2: Silicon Tracking System / Micro Vertex Detector
3: Superconducting Dipole Magnet
4: Muon Chambers
5: Ring Imaging Cherenkov Detector
6: Transition Radiation Detector
7: Time of Flight Detector
8: Forward Spectator Detector

Production yields of strange hadrons





Au + Au, central, 10AGeV, Ξ⁻



Eventwise reconstruction of UrQMD events with **KFParticle** package

Particle (mass MeV/c²)	Multi-plicity 6 AGeV	Multi-plicity 10 AGeV	decay mode	BR	ε (%)
Λ (1115)	$4.6 \cdot 10^{-4}$	0.034	$p\pi^+$	0.64	11
Ξ^- (1321)	0.054	0.222	$\Lambda\pi^-$	1	6
Ξ^+ (1321)	$3.0 \cdot 10^{-5}$	$5.4 \cdot 10^{-4}$	$\Lambda\pi^+$	1	3.3
Ω^- (1672)	$5.8 \cdot 10^{-4}$	$5.6 \cdot 10^{-3}$	ΛK^-	0.68	5
Ω^+ (1672)	-	$7 \cdot 10^{-5}$	ΛK^+	0.68	3

Improvements possible by Machine Learning.

Statistics estimation at R_{int}=0.1 MHz for Ω^- at T=10 AGeV

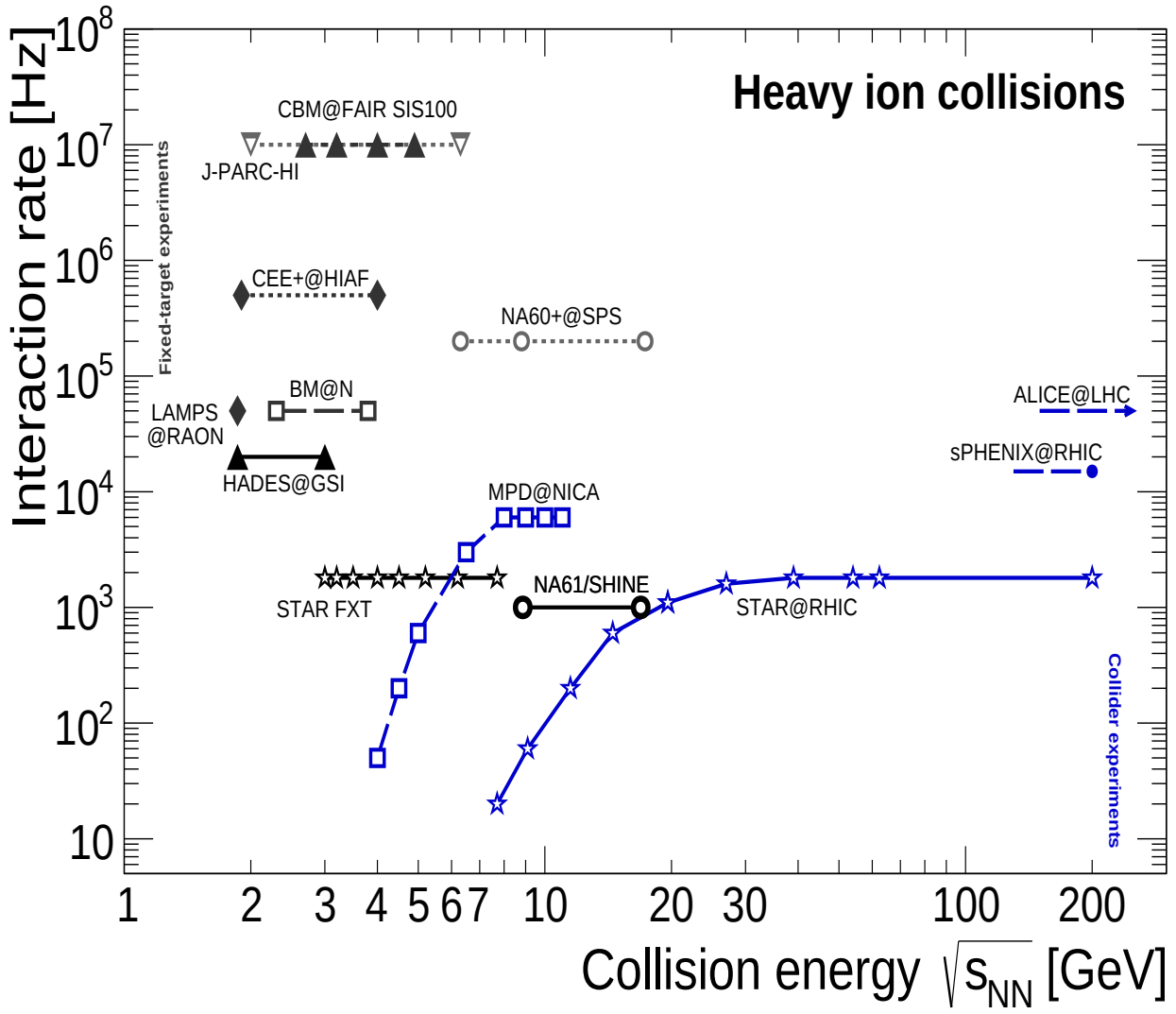
Signal counts per week:

$S_w = R_{av} * \varepsilon_{duty} * P_{prod} * f_{mb/cen} * BR * \varepsilon_{reco} * \Delta T$
$= 1\ 10^5 * 0.7 * 5\ 10^{-3} * 0.25 * 0.68 * 0.05 * 6\ 10^5$
$= 1.800.000$

Statistics sufficient for YN correlation studies (femtoscopy)

CBM – Technological Goal

T. Galatyuk, https://github.com/tgalatyuk/interaction_rate_facilities, 2022

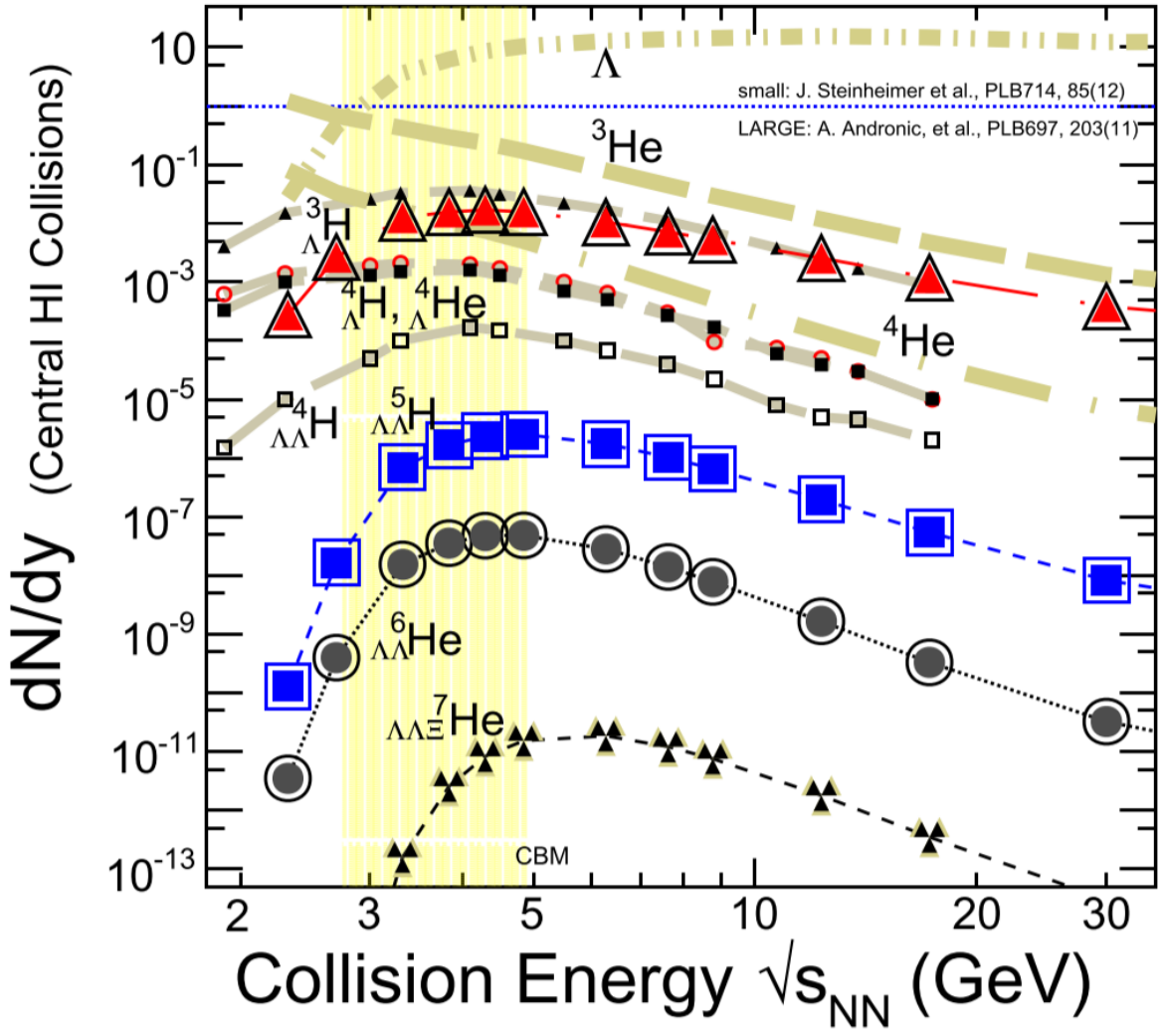


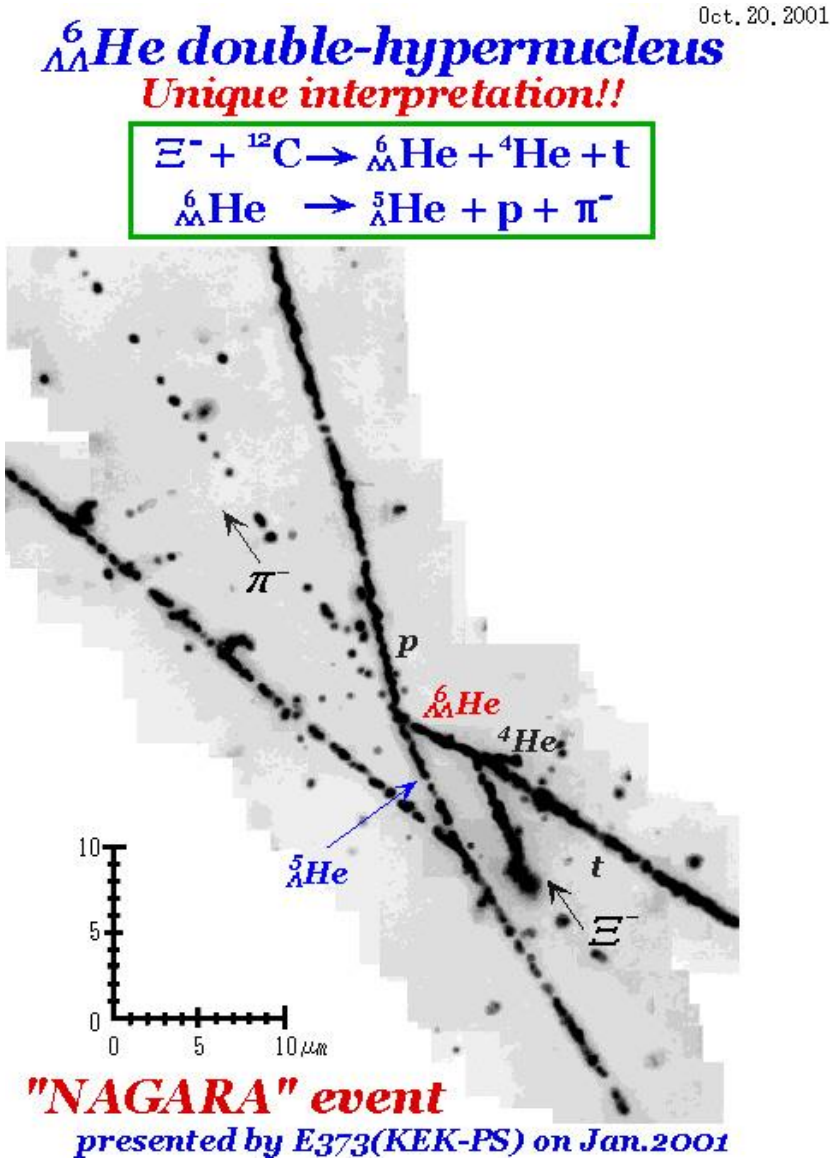
Mission:
Systematically explore QCD matter
at large baryon densities
with high accuracy and rare probes.

Disclaimer:
not all measurements benefit from the highest possible rates.

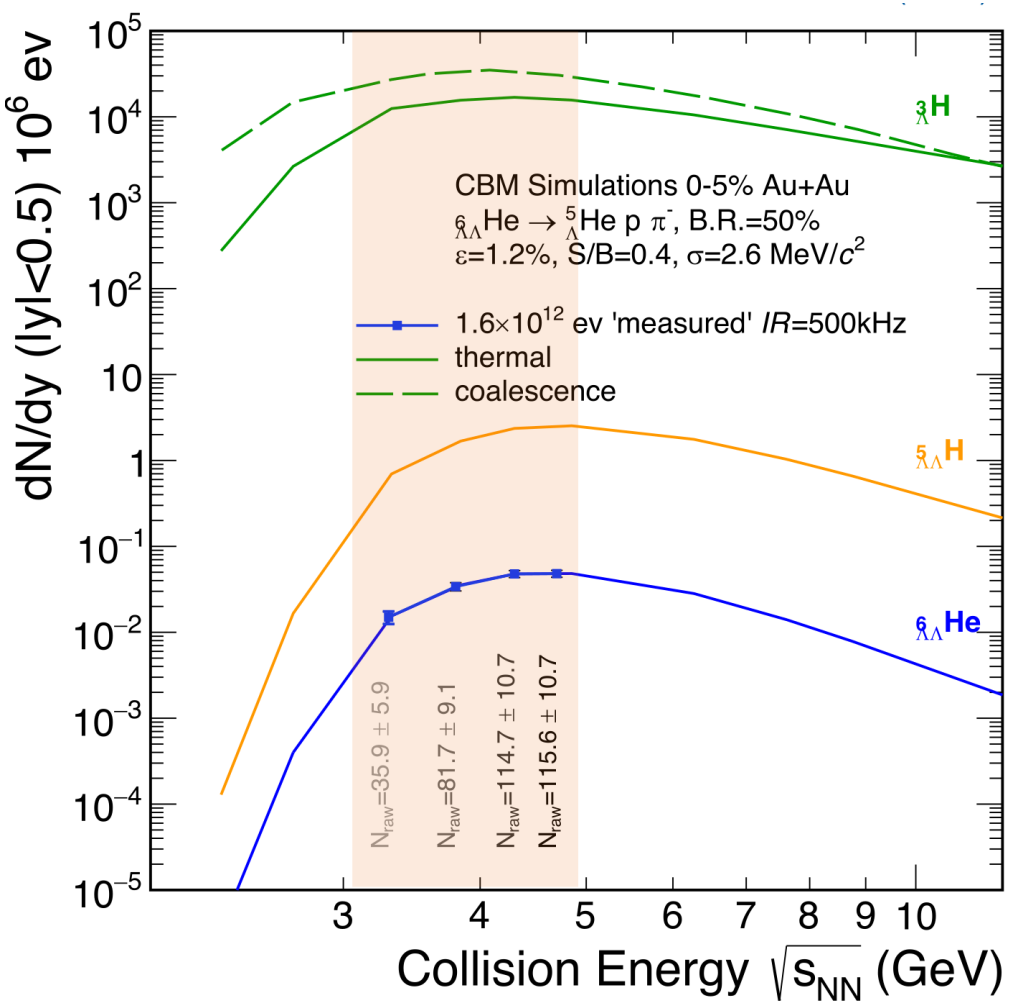
Hypernuclei production

US white paper, arXiv:2209.05009v1 [nucl-ex]





Hypernuclei measurements with CBM



Projection for 1.6 x 10^{12} events:

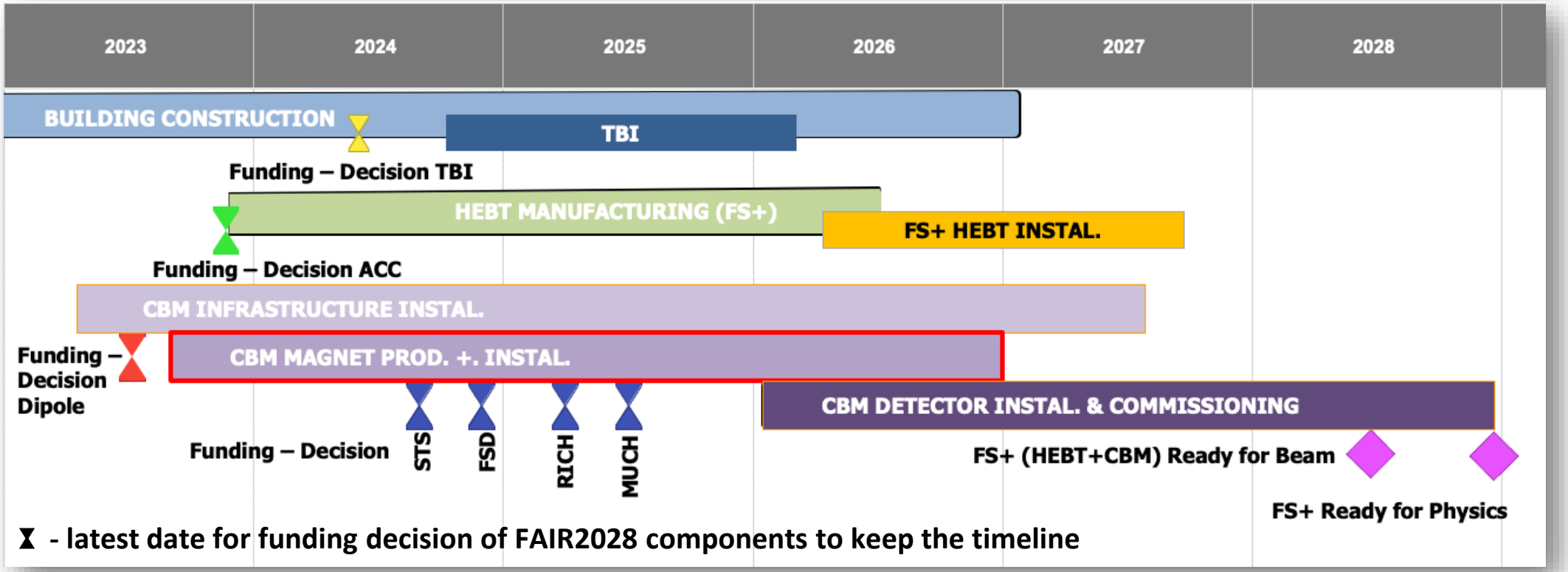
IR (MHz)	Runtime (days)
0.5	220
5	22

Production cross section, binding energy and branching fraction measurements are feasible with hadron setup down to thermal yields of ${}^{6}_{\Lambda\Lambda}He$.

Data set will contain all hypernuclei with larger production cross section

Needed run time for ~ 100 ${}^{6}_{\Lambda\Lambda}He$:
3 weeks at peak rate 10 MHz

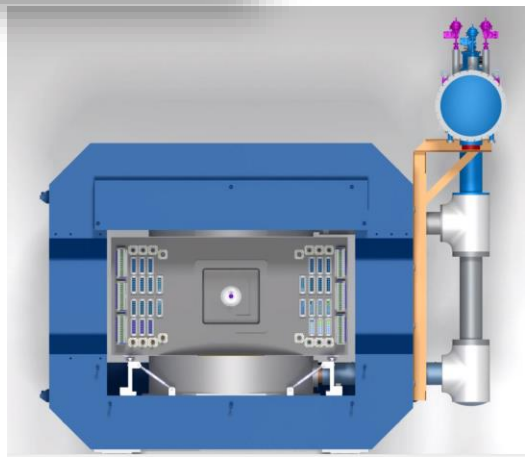
CBM status after June2023 Council



FS+ currently not fully funded.
Current strategy: get subprojects approved step by step
magnet contract signed by FAIR management ✓
next step: HEBT to CBM cave (due Dec. 2023)

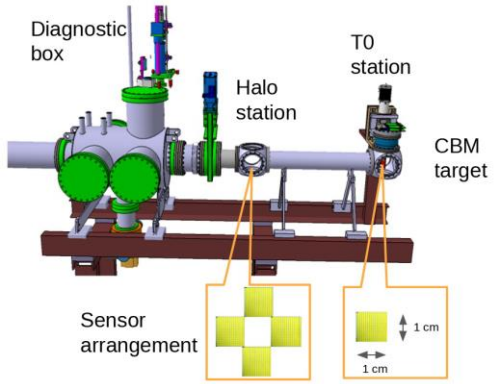
All scientific committees very supportive for CBM in FAIR2028.

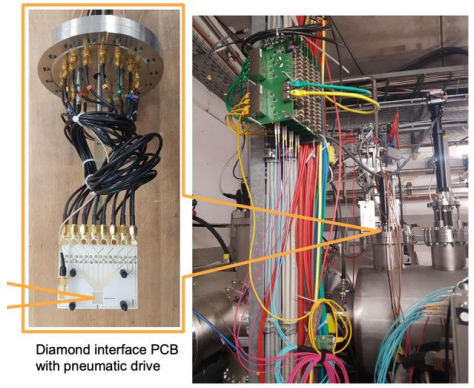
Designation	Estimated Date
Award of contract	12/23
Preliminary Design Review (PDR)	06/24
Conceptional Design Review (CDR)	12/24
Final Design Review (FDR)	06/25
Final Acceptance Test FAT	12/26
Shipment incl. documentation	03/27
Site Acceptance Test (SAT)	06/27
Final Acceptance	09/27
Magnetic field mapping	12/27



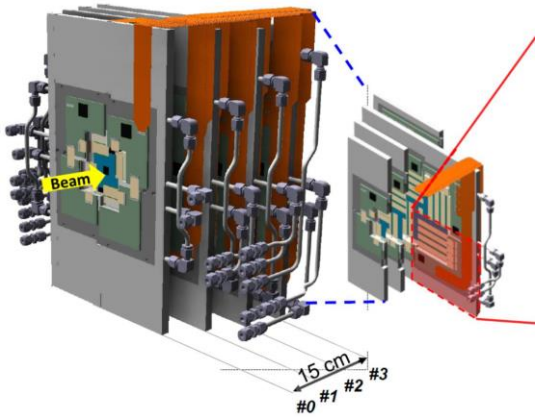
Status of CBM detector systems

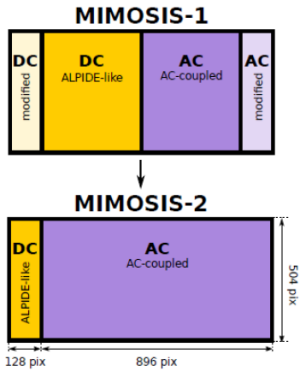
Beam Monitor (BMON)
- T0 high purity pcCVD diamond demonstrator successfully tested in mCBM 2022 runs
- novel sensor technologies (LGAD, SiC) under investigation

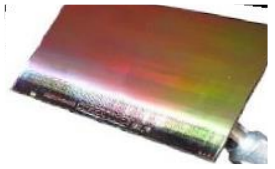




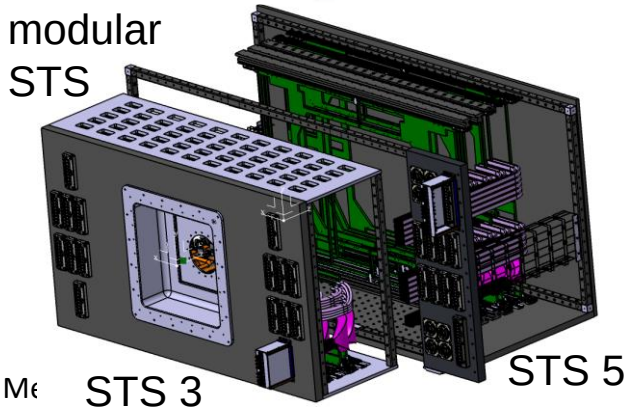
Micro Vertex Detector (MVD)
- Intensive test campaigns of full-size MAPS prototype MIMOSIS-1
- → MIMOSIS-2 needs re-submission
- Preproduction quadrant in preparation

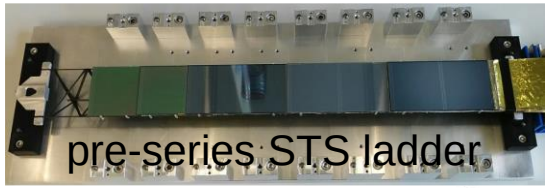




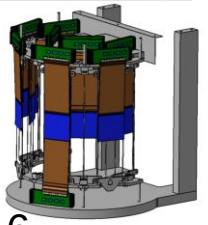


Silicon Tracking System (STS)
- Revised modular design with 3+5 stations
- Ladder preproduction will be deployed in J-PARC E16
- Design of FEB8-2 and FEB8-5 finished
- Module pre-production ongoing

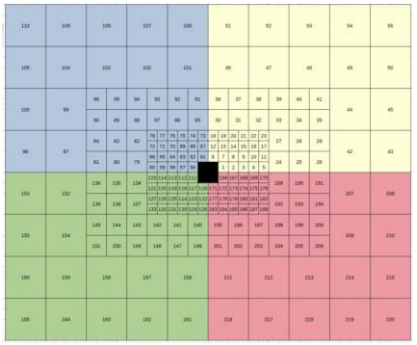


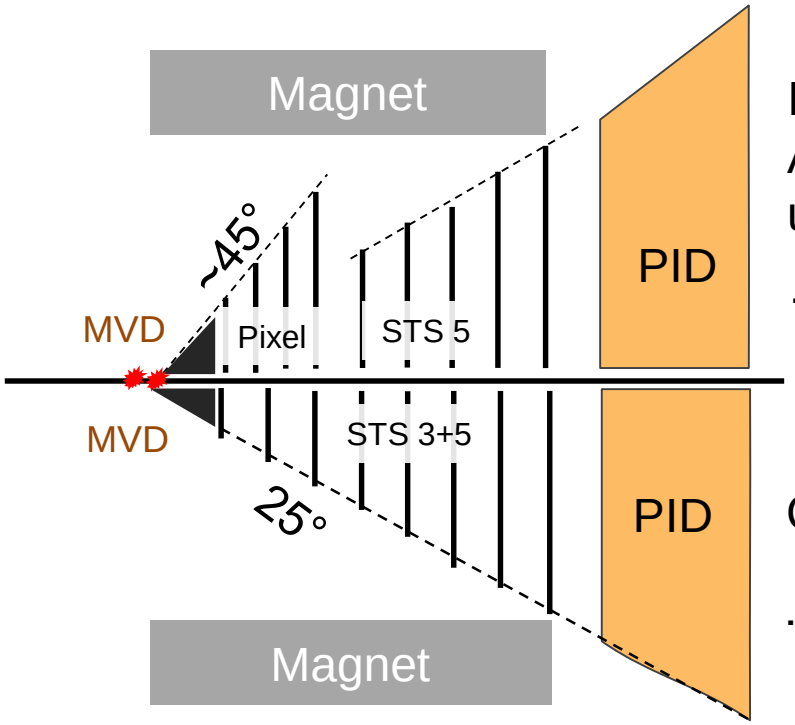


STS ladder pre-series production deployed in J-PARC E16



CBM developments





Inner tracker Acceptance upgrade.

…

CBM 2028

…

Forward Spectator Detector (FSD)

- New design, likely based on ZnS scintillators and LYSO crystals for central part
- Read-out via SiPM
- Readout electronics based on existing solutions
- Alternate readout by PMT under investigation
- PWG input mandatory

Upgrade to Forward Spectrometer (?)

- PANDA straw tube tracker
- Neutron detection

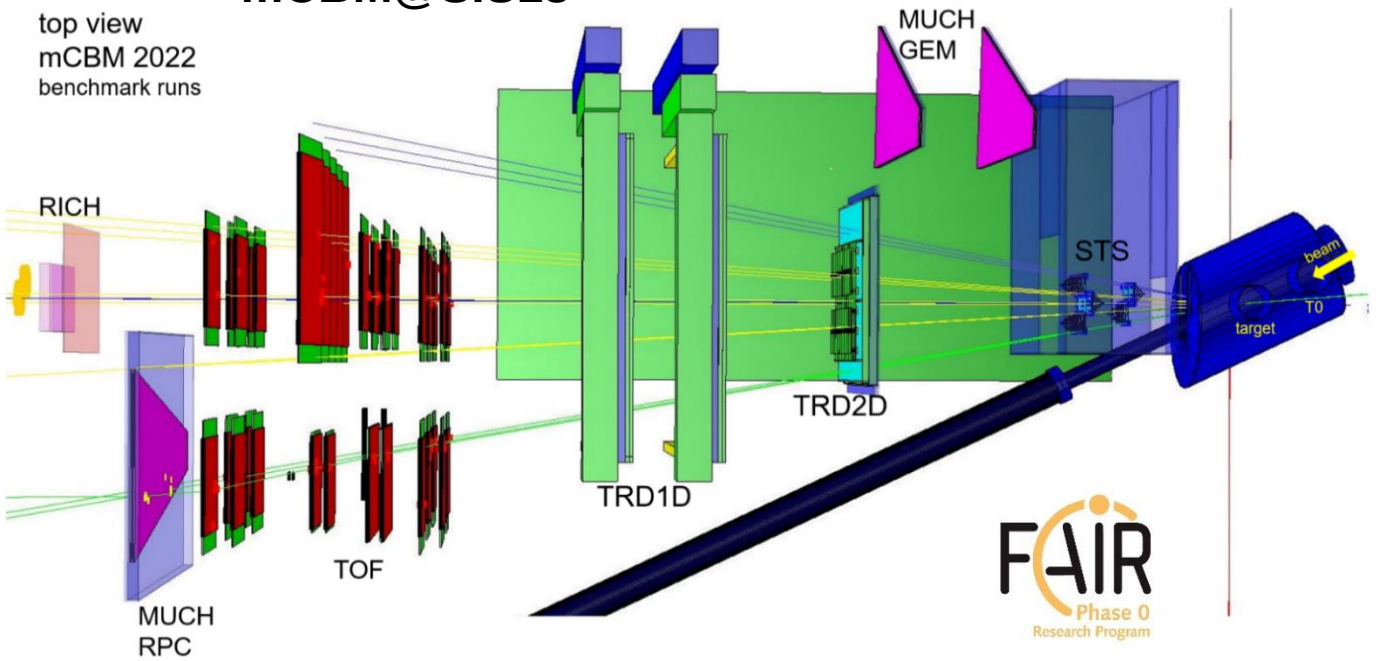
Inner Tracker (MVD/STS) performance and upgrade

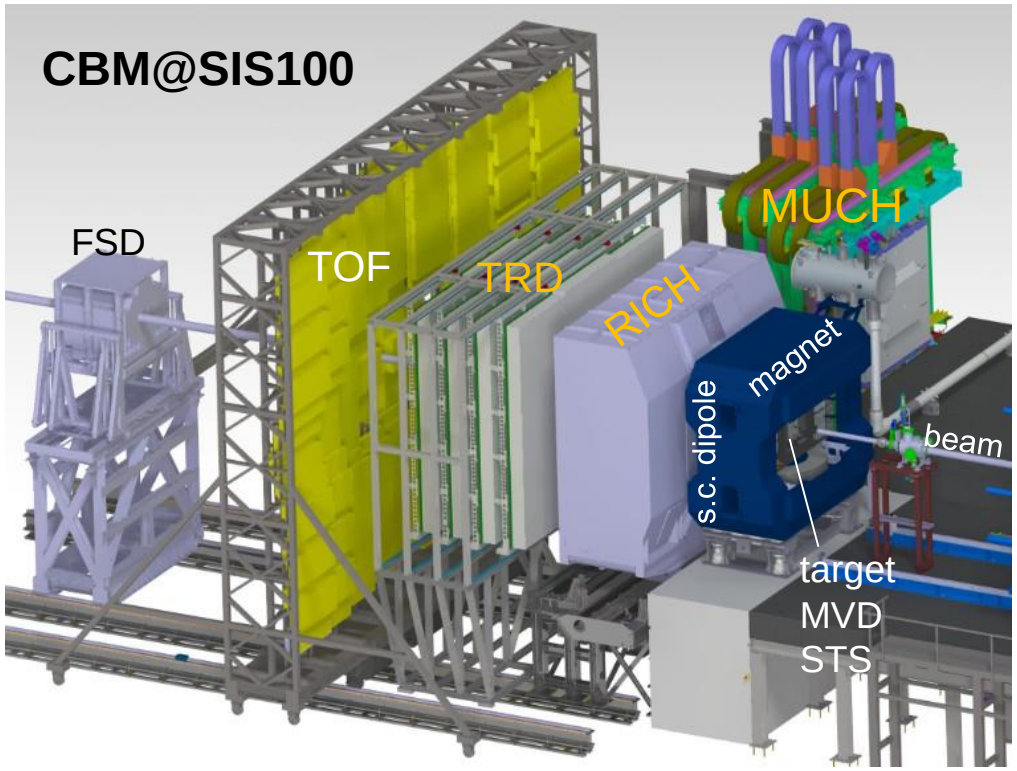
- Physics projections of measurement of excitation function (target position, material budget)
- Physics projections for strip -> pixel transition
- Pixel technology

Next step: Workshop "Prospects for complementary instrumentation in CBM“, May 2024, GSI

With mCBM towards CBM

mCBM@SIS18



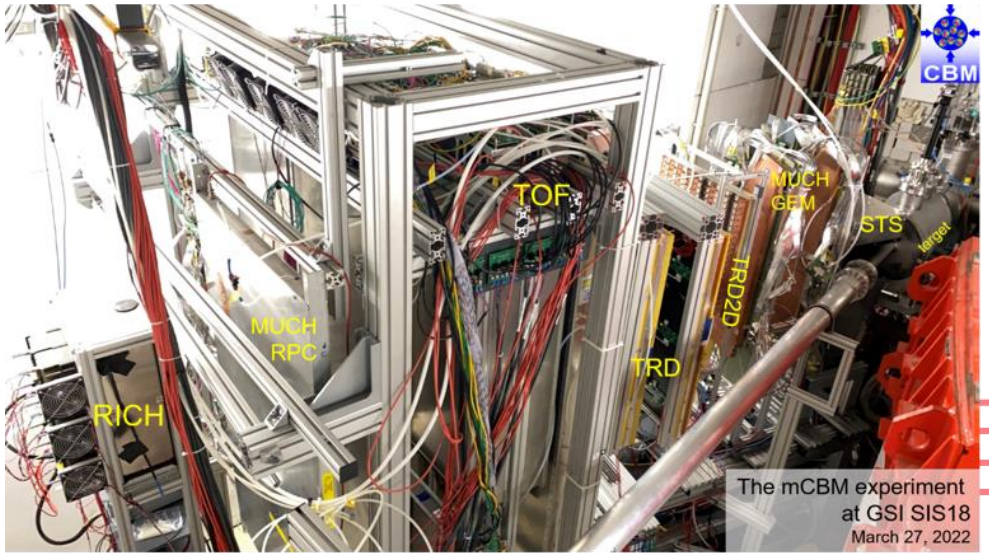


CBM full-system test setup at SIS18/GSI comprising pre-series productions of all CBM detector systems:

T0	16+16ch pcCVD diamond, 1x1cm^2, 80 µm, part of BMON
STS	11 modules, 6x6cm^2 and 6x12cm^2 double-sided silicon-strip sensors, 5 ladders on 2 stations
MUCH	2 GEMs M2 modules (MUCH 1+2), 1 RPC (MUCH 3+4)
TRD	2 MWPCs with rect. pad (TRD1D, outer region), 1 MWPC with triang. pads (TRD2D, inner part)
TOF	8 MRPCs modules in 2 stacks
RICH	2 aerogel radiators (2 20x20cm^2), 36 MAPMTs

FSD and MVD test systems in preparation

The free-streaming CBM DAQ and data processing



optical fibers 50m

CRI ≡ BNL FLX-712v2

DAQ container

CRI (PCIe) @ FLES entry nodes

optical fibers 300 m

FLES processing nodes

FAIR Phase 0 Research Program

triggerless-streaming FEE **assigning time stamps to hits**

1 m Copper

GBTx

50 m optical

TFC (CRI based)

CRI FPGA **µSlice building**

FLES entry nodes

300 m optical InfiniBand

Green IT Cube

Timeslice Building

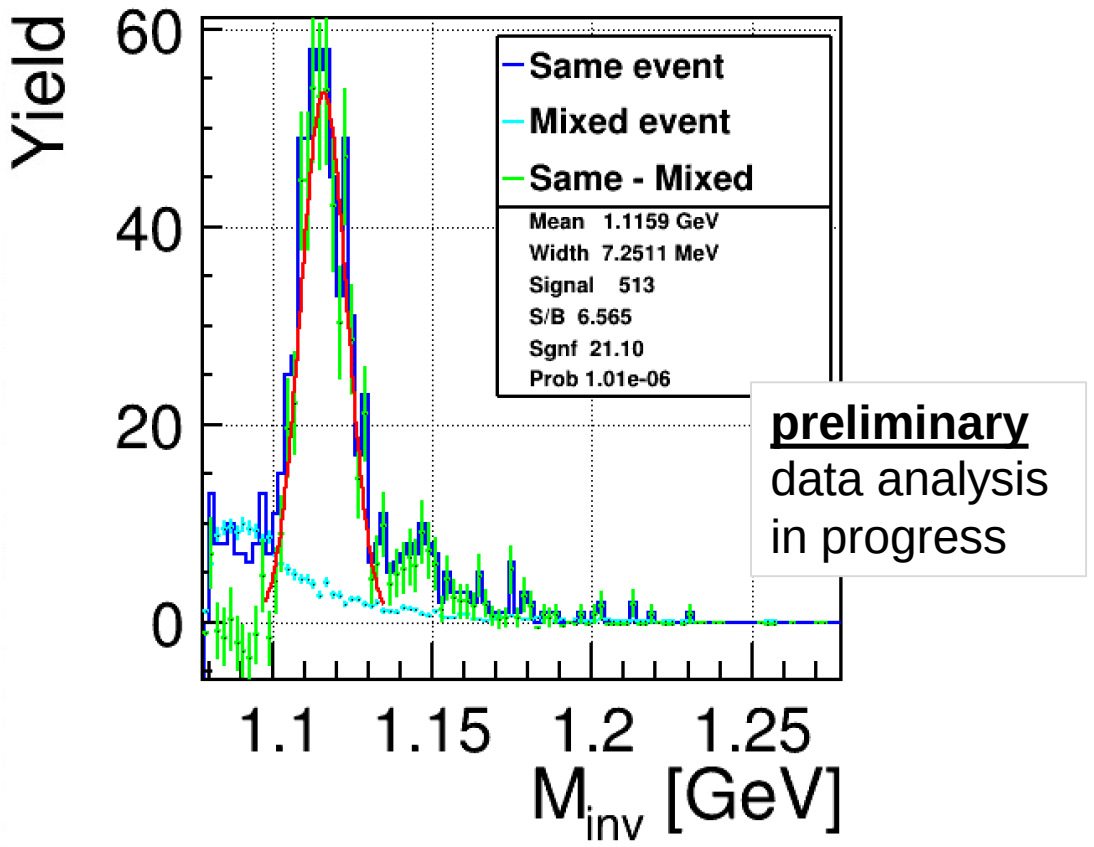
Event Reconstruction

Event Selection

Archiving

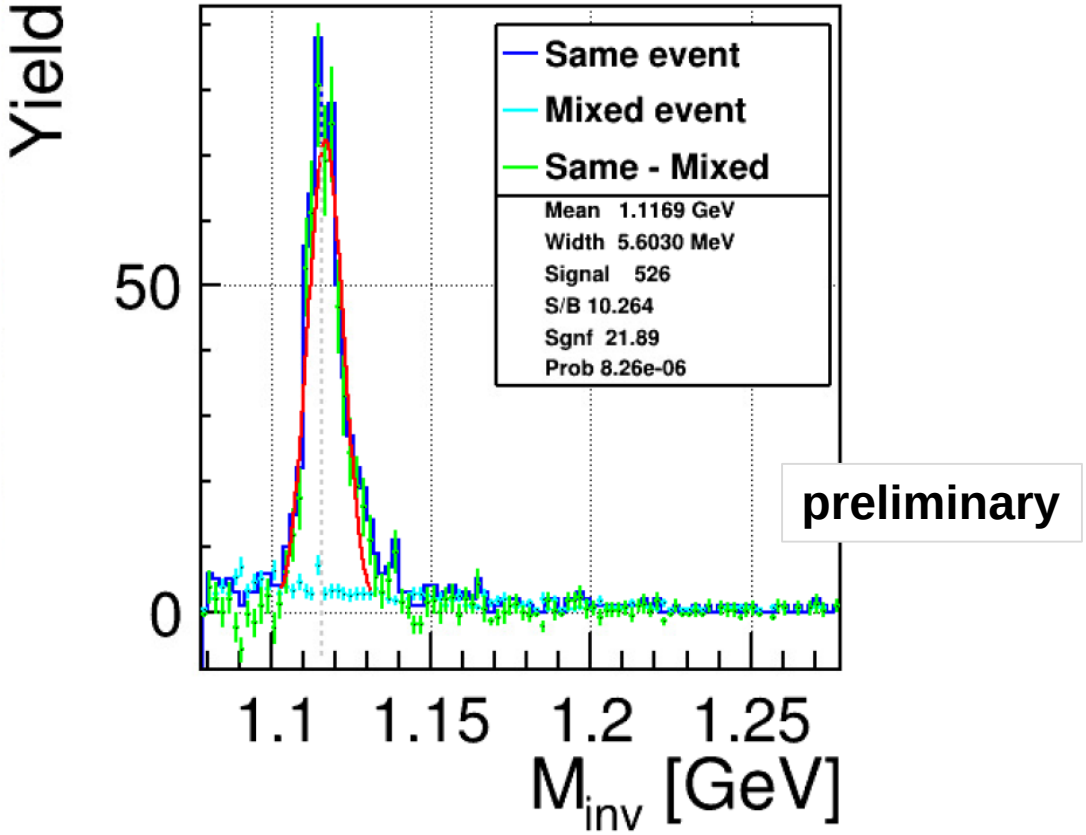
Λ reconstruction in Ni+Ni collisions at 1.93 AGeV

Data, run 2391, total run duration **1:57h**
4x to 5x10^7 ions per spill, 10s spill
400 - 500 kHz average collision rate,
500 M triggered events



preliminary
data analysis
in progress

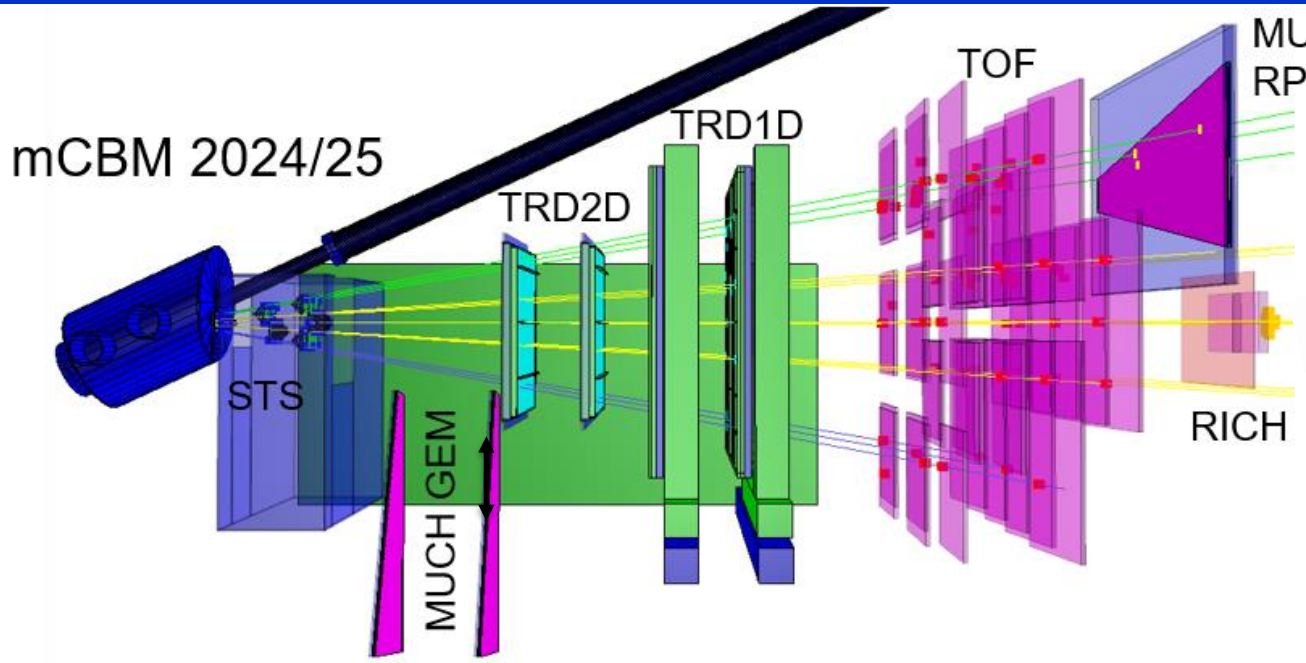
MC, similar reconstruction chain
100 M generated events
10^5 events / s
63.7 M triggered events



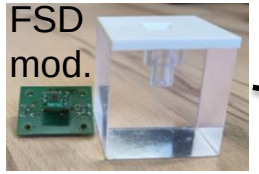
preliminary

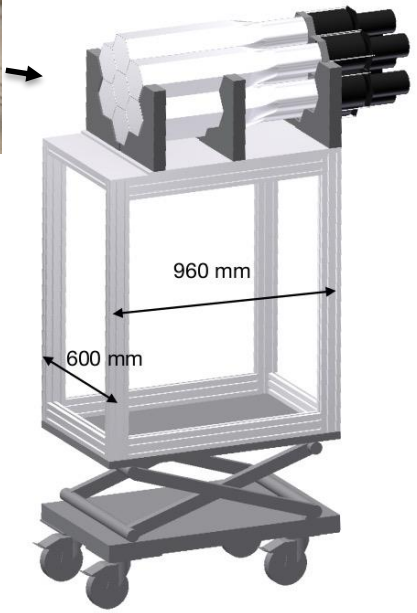
rare signal reconstructed – development of background description and efficiency corrections ongoing .

mCBM campaigne 2023 / 2024

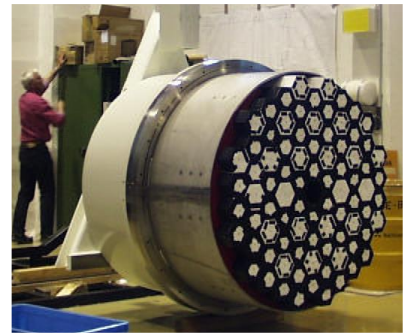


FSD & neutron det. at 25°

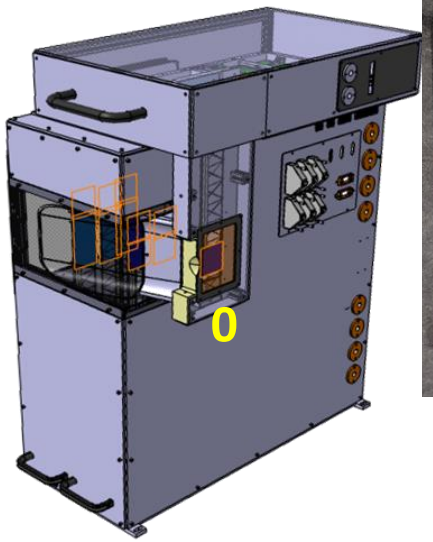




taken from Jülich TOF Calorimeter



2023, Dec. 15 - 19	High-rate TOF tests during machine engineering runs
2024, Mar. 2 - 24	Commissioning for benchmark run with Au beam
2024, May 6 - 13	Ni+Ni benchmark run Λ production excitation function at 1.93, 1.58, 1.23, 1.0 AGeV, online reconstruction and selection (events with Λ candidate)
2024, June 12 - 15	Rate scans with U beam



Conclusion

New data on strangeness production and propagation at high baryon densities

- strange particle flow at 3 GeV
- hypernuclei production at high μ_B
- density fluctuation observables

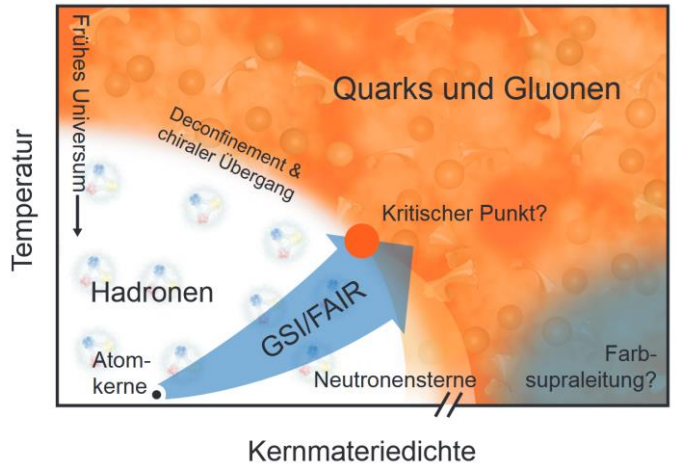
CBM scientific program at SIS100 is unique

- explore QCD matter at neutron star core densities
- employ high statistics capability
  - to achieve high-precision of multi-differential observables
  - to enable rare processes as sensitive probes

CBM prepares for start of data taking in 2028 with significant discovery potential.

- systematic study of light hypernuclei production and properties
- excitation function of hyperon production
- excitation function of proton number fluctuations
- excitation function of di-lepton production
- emerging proton beam program

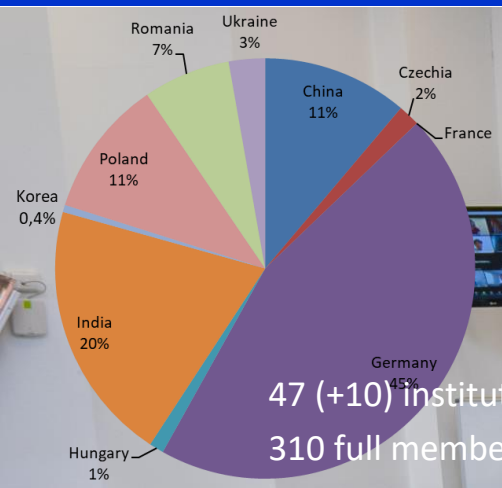
CBM collaboration is open for new ideas and new members.



Thank you!

Photo: C. Betz

CBM collaboration



47 (+10) institutes

310 full members

42nd CBM collaboration meeting, Sep. 2023, NIHAM, HPD, Bucharest