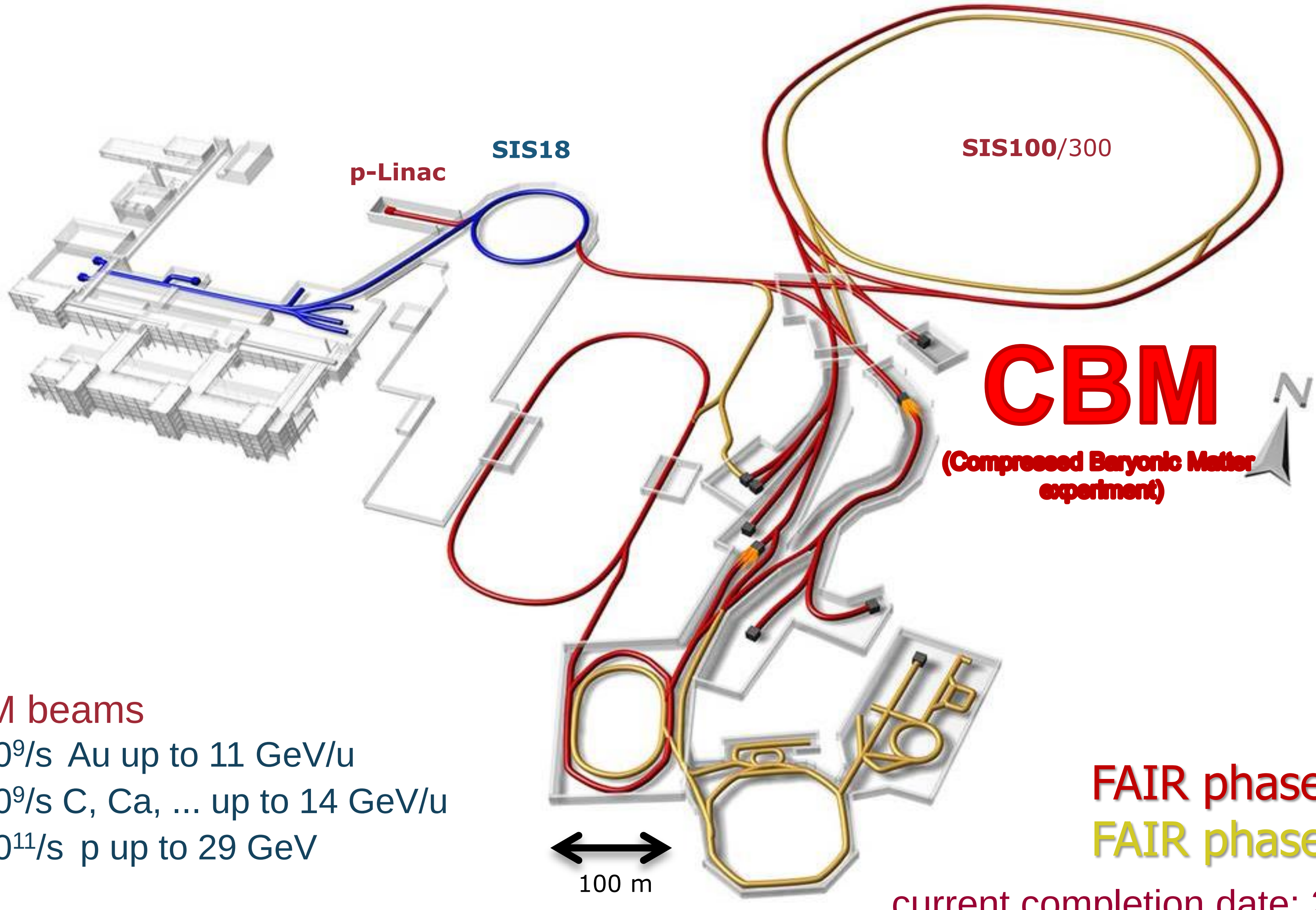
CBM´s path towards Dense Baryonic Matter

Norbert Herrmann
Univ. Heidelberg

Facility for Antiproton & Ion Research



CBM beams

- 10^9/s Au up to 11 GeV/u
- 10^9/s C, Ca, ... up to 14 GeV/u
- 10^{11}/s p up to 29 GeV

FAIR phase 1
FAIR phase 2
current completion date: 2025

CBM – Collaboration: 55 institutions, 470 members

China:
CCNU Wuhan
Tsinghua Univ.
USTC Hefei
CTGU Yichang
Chongqing Univ.

Czech Republic:
CAS, Rez
Techn. Univ. Prague

France:
IPHC Strasbourg

Germany:
Darmstadt TU
FAIR
Frankfurt Univ. IKF
Frankfurt Univ. FIAS
Frankfurt Univ. ICS
GSI Darmstadt
Giessen Univ.
Heidelberg Univ. P.I.
Heidelberg Univ. ZITI
HZ Dresden-Rossendorf
KIT Karlsruhe
Münster Univ.
Tübingen Univ.
Wuppertal Univ.
ZIB Berlin

India:
Aligarh Muslim Univ.
Bose Inst. Kolkata
Panjab Univ.
Univ. of Jammu
Univ. of Kashmir
Univ. of Calcutta
B.H. Univ. Varanasi
VECC Kolkata
IOP Bhubaneswar
IIT Kharagpur
IIT Indore
Gauhati Univ.

Korea:
Pusan Nat. Univ.

Poland:
AGH Krakow
Jag. Univ. Krakow
Warsaw Univ.
Warsaw TU

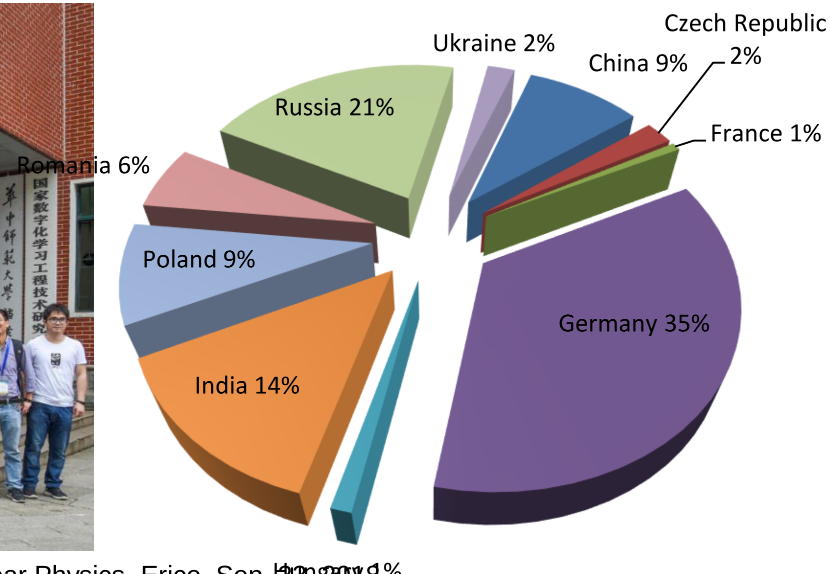
Romania:
NIPNE Bucharest
Univ. Bucharest

Hungary:
KFKI Budapest
Eötvös Univ.

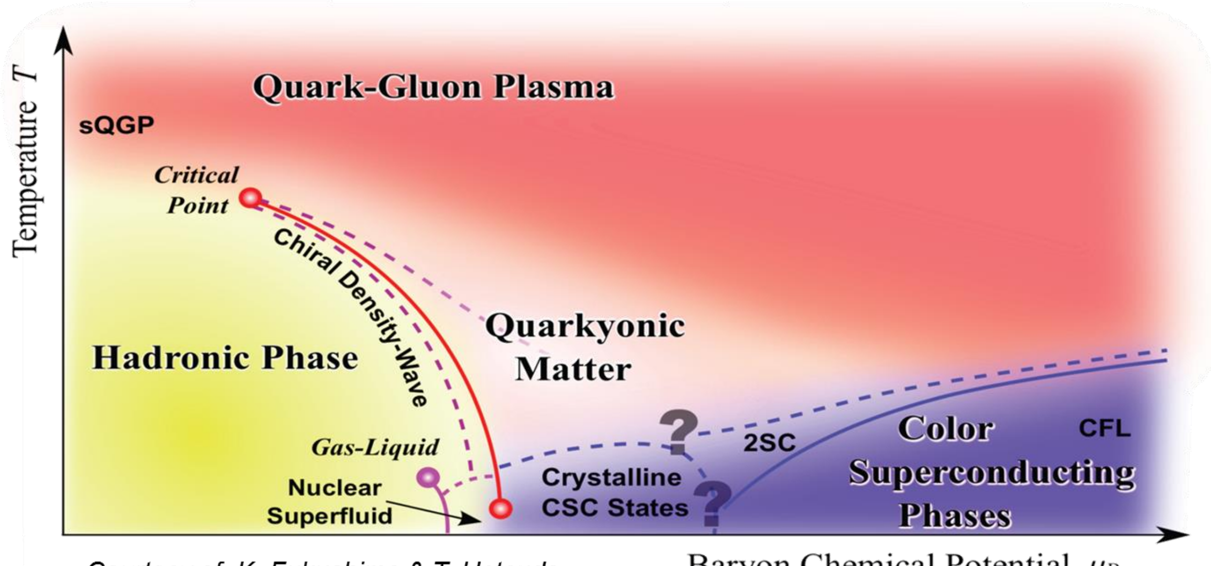
Russia:
IHEP Protvino
INR Troitzk
ITEP Moscow
Kurchatov Inst., Moscow
VBLHEP, JINR Dubna
LIT, JINR Dubna
MEPHI Moscow
PNPI Gatchina
SINP MSU, Moscow

Ukraine:
T. Shevchenko Univ. Kiev
Kiev Inst. Nucl. Research

CBM Scientists



CBM – Goals



Courtesy of K. Fukushima & T. Hatsuda

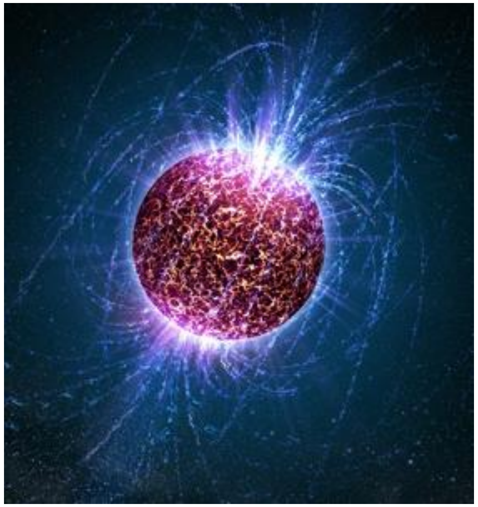
Mission:

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

Outline:

Current experimental knowledge
Experimental and theoretical expectations / predictions
Experiment setup
Planned Fair Phase-0, Day-1 and Phase-1 measurements

Dense Baryonic Matter



Neutron stars

Temperature
$T < 10$ MeV

Density
$\rho < 10\ \rho_0$

Lifetime
T ~ infinity

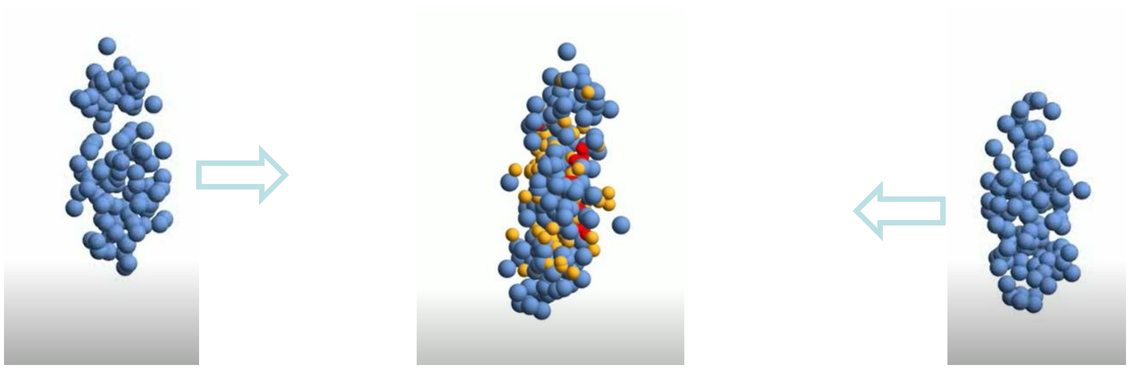
Neutron star merger

Temperature
$T < 50$ MeV

Density
$\rho < 2 - 6\ \rho_0$

Reaction time
(GW170817)
T ~ 10 ms

Heavy ion collisions at SIS100



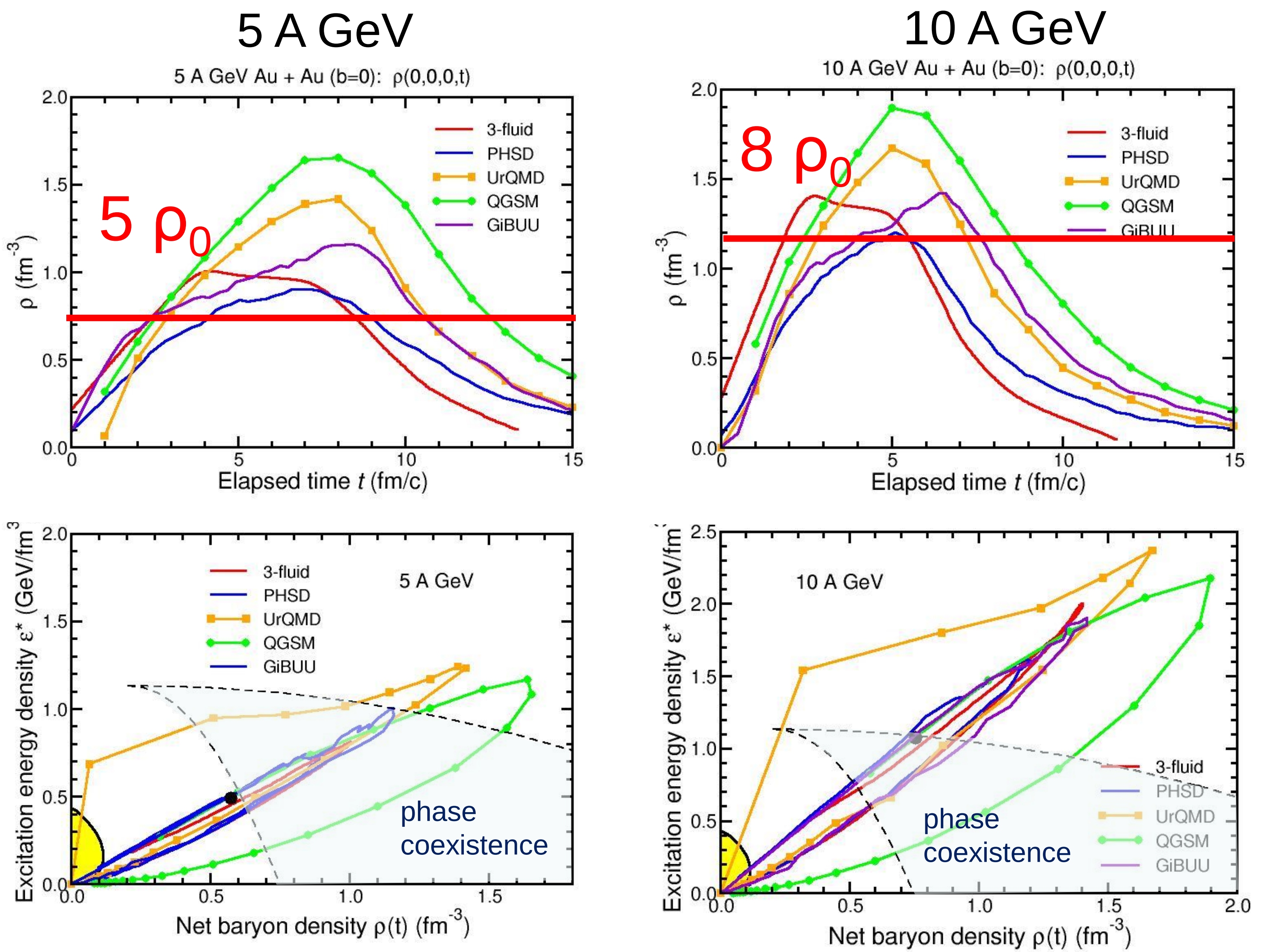
Compressed Baryonic Matter

Temperature
$T < 120$ MeV

Density
$\rho < 8\rho_0$

Reaction time
$t \sim 10^{-23}$ s

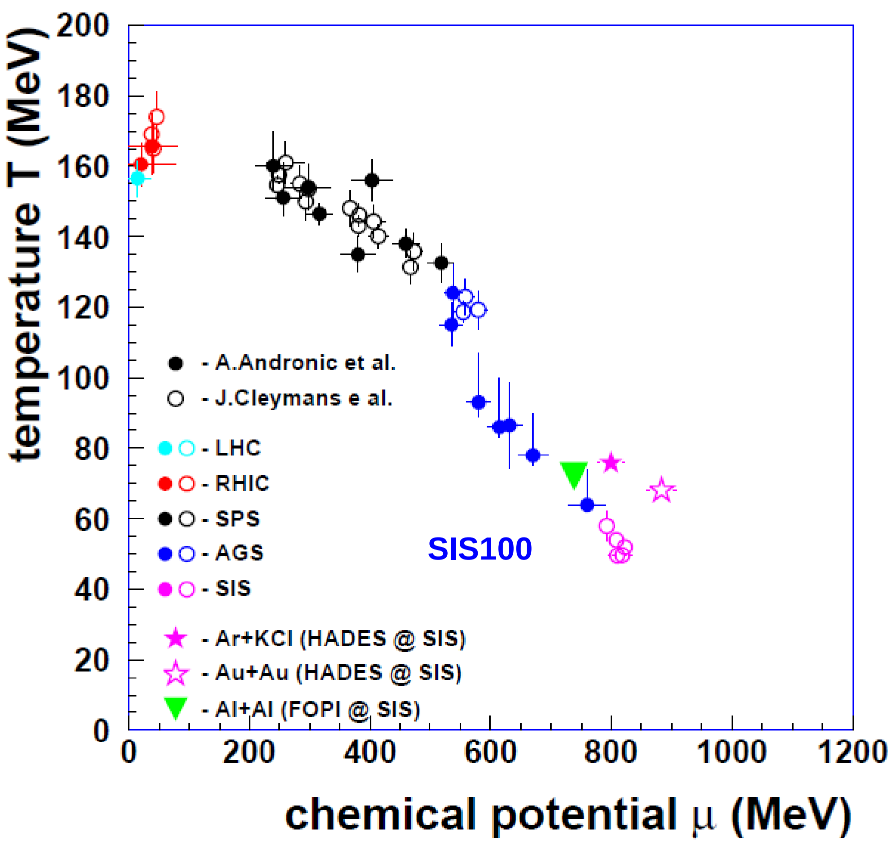
Baryon densities in central Au+Au collisions



I.C. Arsene et al., Phys. Rev. C 75, 24902 (2007)

Chemical Freeze-out data

Analyses in framework of Statistical Hadronisation Model



High energies:

grandcanonical ensemble

$$n_i(\mu,T)=\frac{N_i}{V}=-\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu}=\frac{g_i}{2\pi^2}\int\frac{p^2dp}{e^{\frac{E_i-\mu_i}{T}}\pm 1}$$

$$\mu_i=\mu_B B_i+\mu_S S_i+\mu_{I_3} I_{3,i}$$

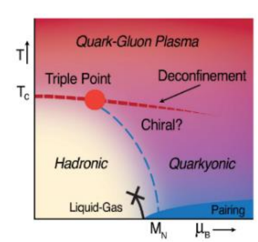
Lower energies / small systems:

canonical ensemble,
strangeness suppression factor γ_S

Equilibrium achieved in small systems?

Equilibrium as signature for phase transition?

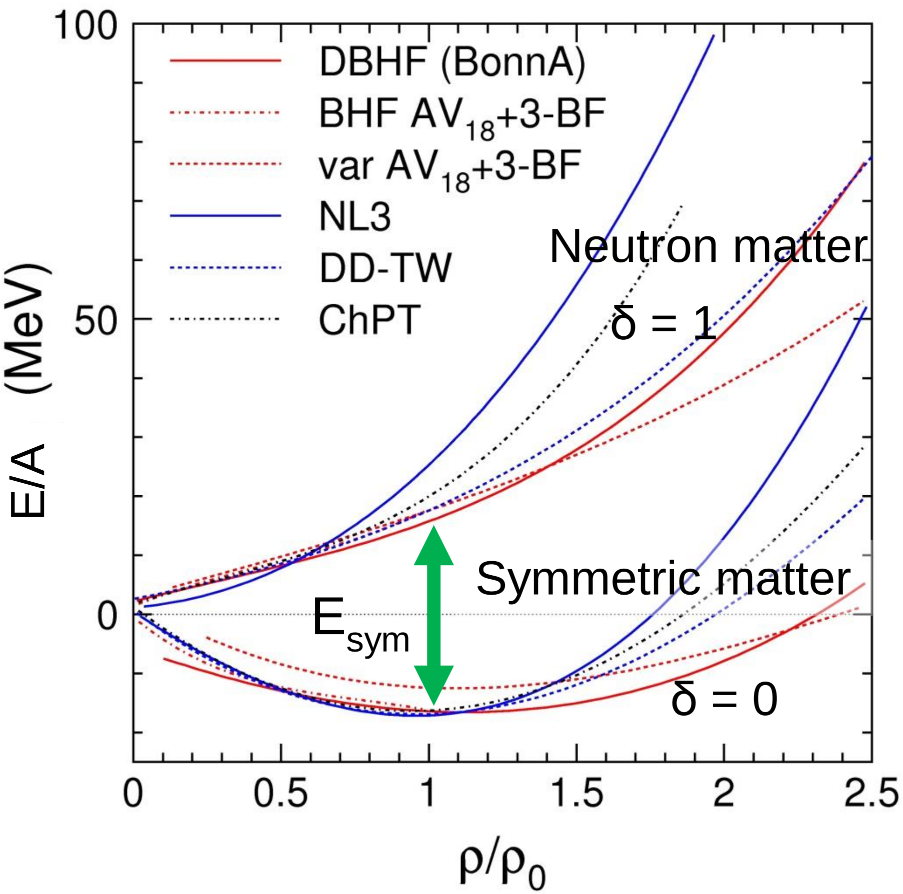
Freeze-out line at large baryon densities as phase boundary to quarkyonic matter ?



A. Andronic et al.,
Nucl. Phys. A837 (2010) 65

Equation Of State of nuclear matter

Fuchs and Wolter, EPJA 30 (2006)



EOS in thermodynamics pressure P = P(ρ,T)

$$P = \rho^2 \left. \frac{\partial\, E/A}{\partial \rho} \right|_{T=const}$$

Nuclear physics EOS:

$$\frac{E}{A} = \left. E/A(\rho) \right|_{T=0}$$

Nuclear incompressibility K

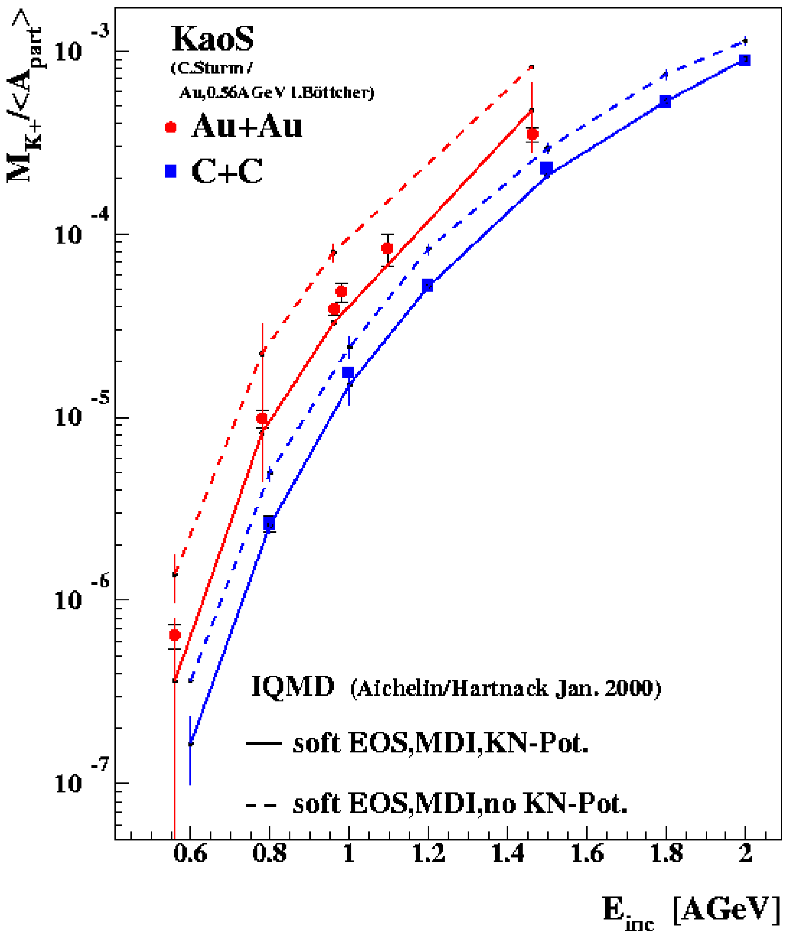
$$\mathrm{K} = 9\,\rho^2 \left. \frac{\partial^2\, E/A}{\partial^2 \rho} \right|_{\rho=\rho_0}$$

Asymmetry parameter δ

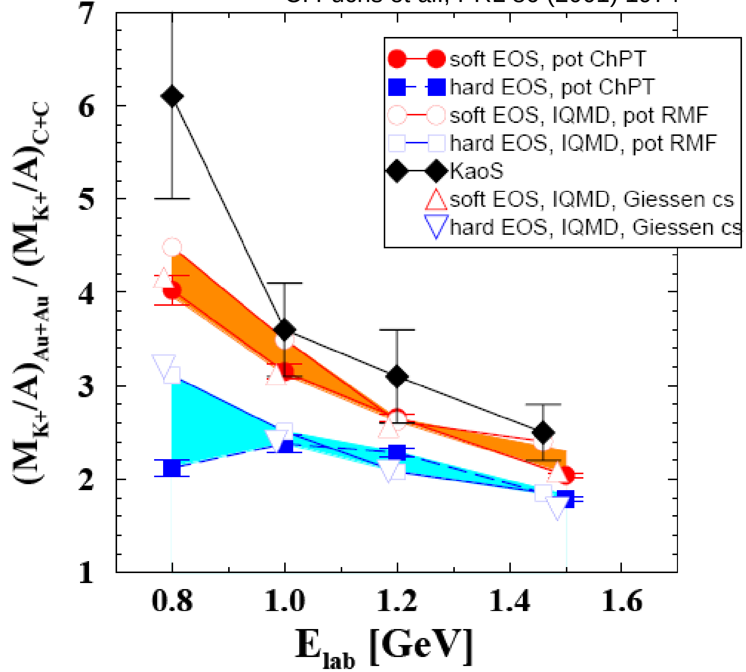
$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Subthreshold Kaon – measurements at SIS18

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



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

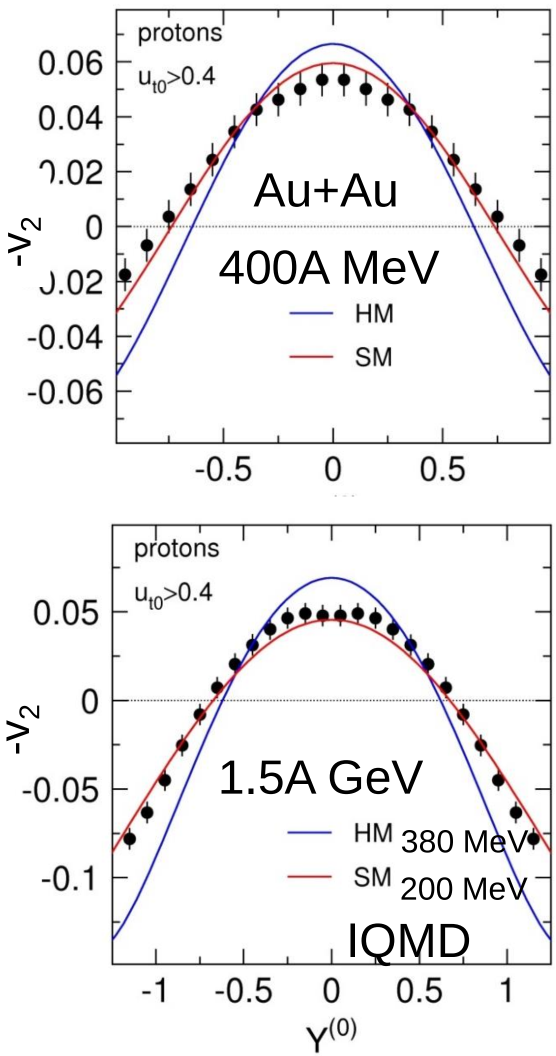


Strong sensitivity to Equation Of State
due to multistep production
(formation of nucleon resonances)
=> soft EOS (K=200 MeV)

EOS determination from elliptic flow

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

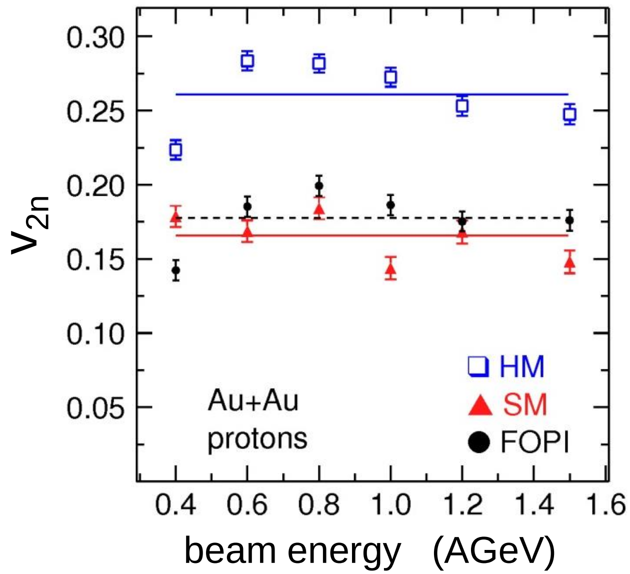
W. Reisdorf et al.,Nucl. Phys. A 876 (2012) 1



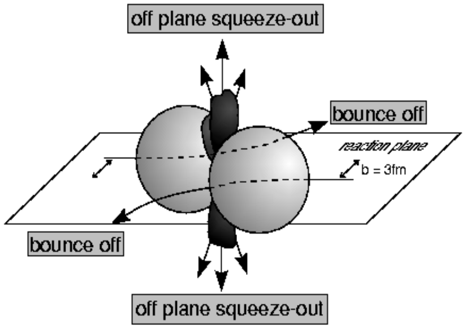
Parametrization:

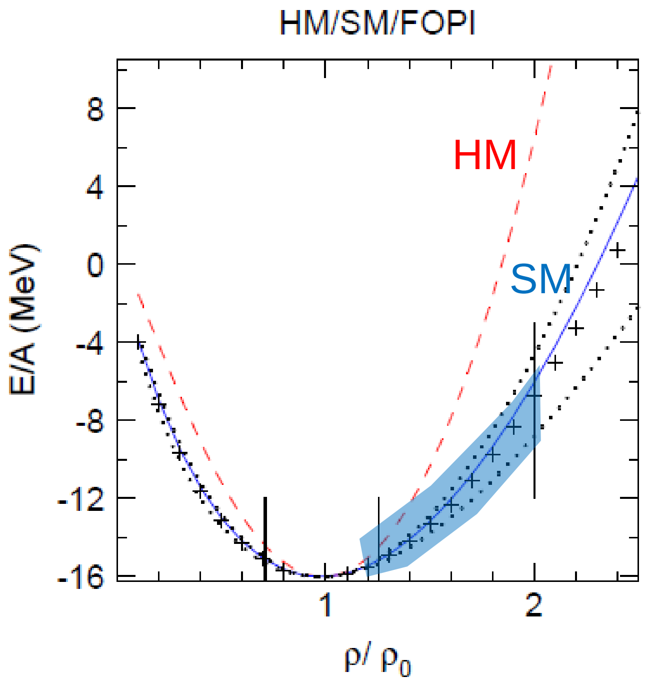
$$v_2(Y^{(0)}) = v_{20} + v_{22} \cdot Y^{(0)2}$$

$$v_{2n} = |v_{20}| + |v_{22}|$$



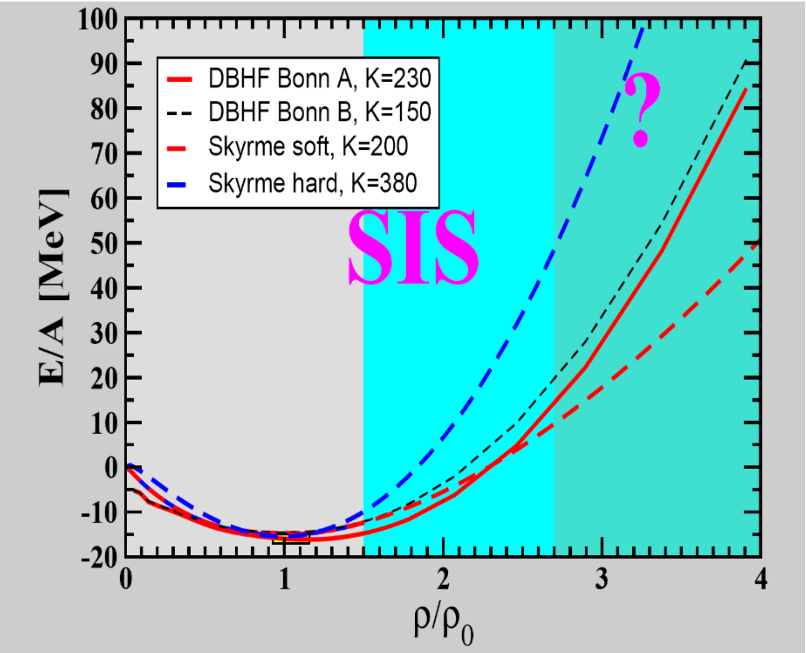
Result:
K=190±30 MeV



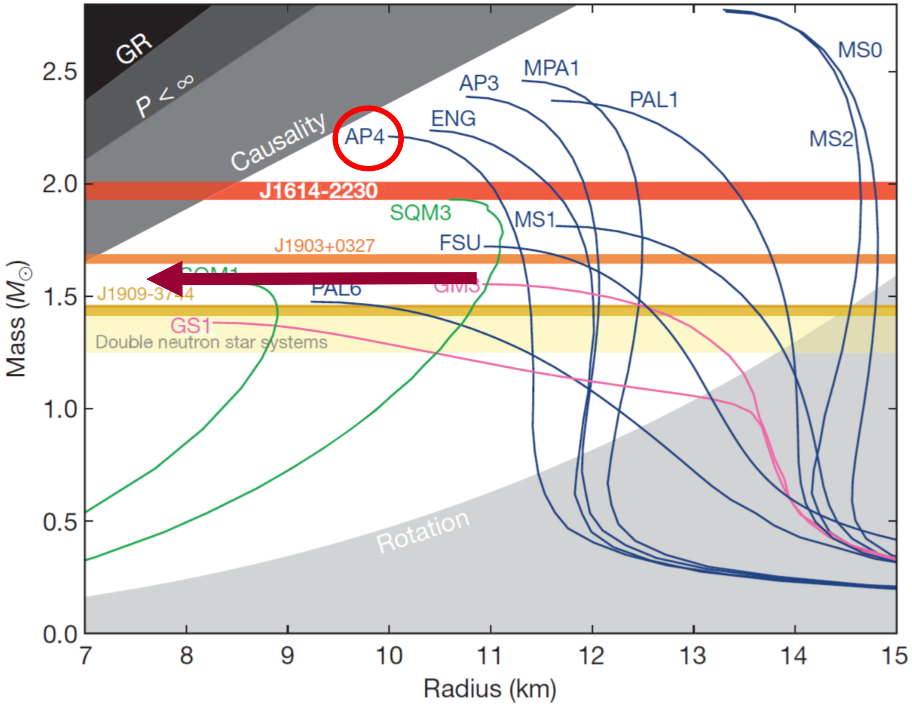


Equation of State & Neutron stars

C. Fuchs,
Prog. Part. Nucl. Phys. 56 (2006) 1



P.B. Demorest (2010)
doi:10.1038/nature09466



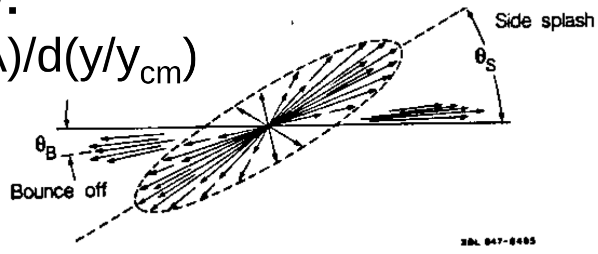
- Soft EOS (Skyrme, K = 200 MeV) does not to allow for a neutron star with 2 $M_{\odot}$.
- „DBHF BONN A“ (AP4) is stiff enough, however, does not contain strange baryons.
- Stiffening of EOS must occur in the SIS100 energy range.
- Isospin asymmetry must be explored.
- New constraints coming from GW170817, excluded NS radius range.

EOS from collective proton flow

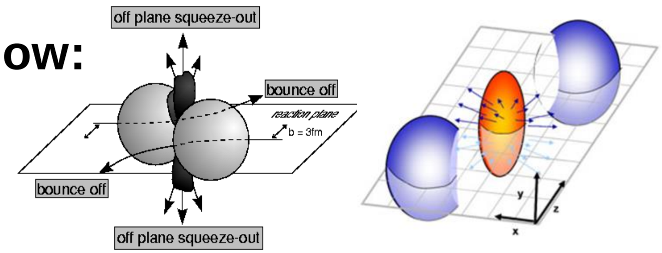
P. Danielewicz, R. Lacey, W.G. Lynch,
nucl-th/0112006 (2001), Science 298 (2002) 1592

Side flow:

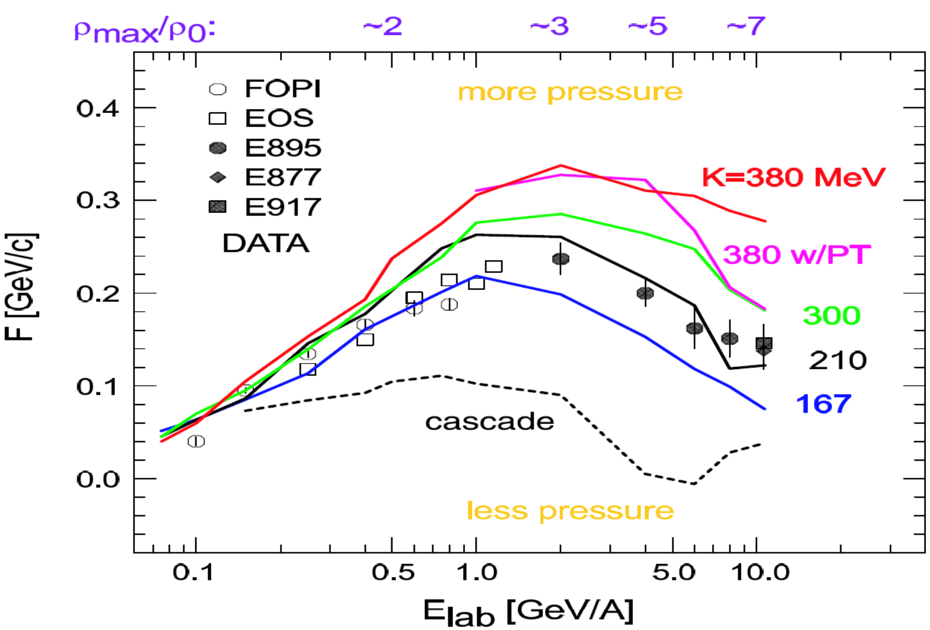
$F = d(p_x/A)/d(y/y_{cm})$

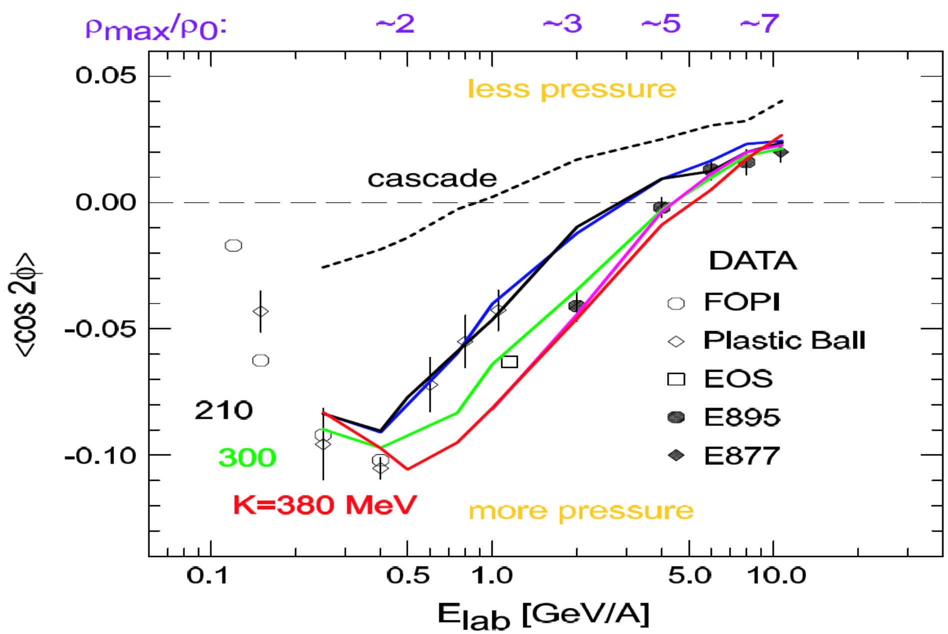


Elliptic flow:



$dN/d\phi \propto (1 + 2\, v_1 \cos\phi \; + 2\, v_2 \cos 2\phi)$





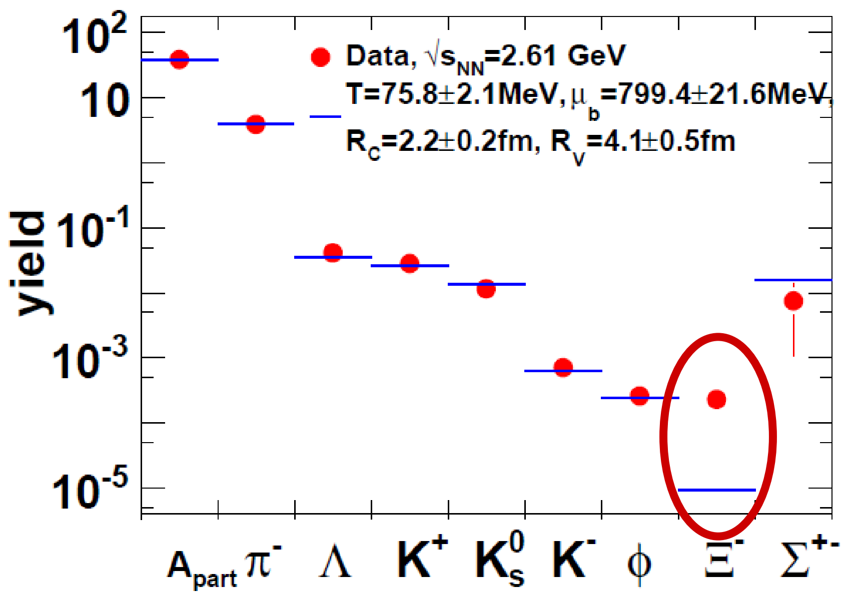
- **No consistent data available yet.**

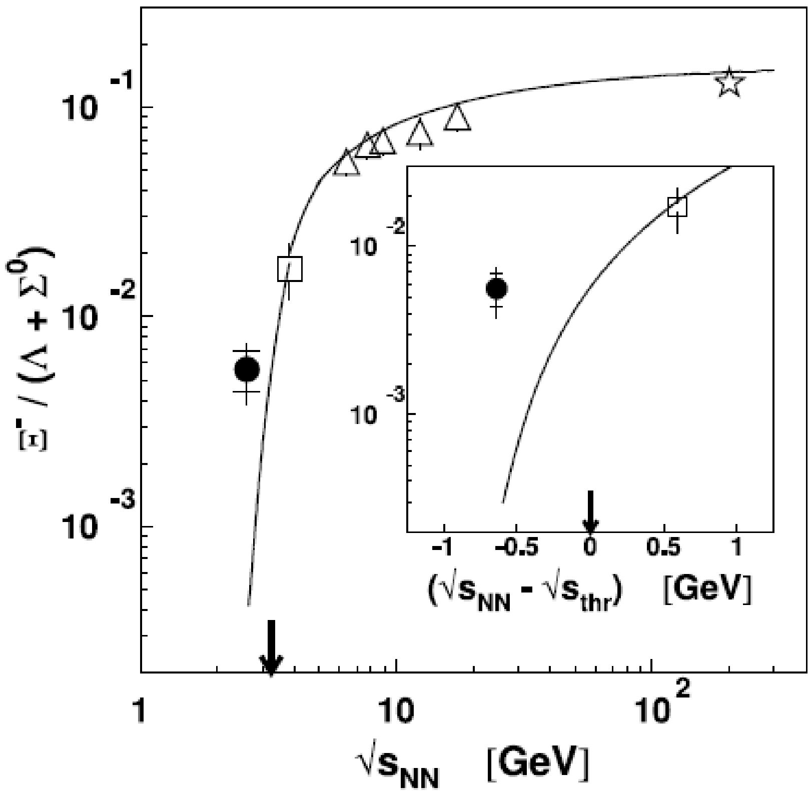
HADES: Sub-threshold Ξ^- - production

Ar+KCl reactions at 1.76A GeV

- Ξ^- yield by appr. factor 15 ± 6 higher than thermal yield

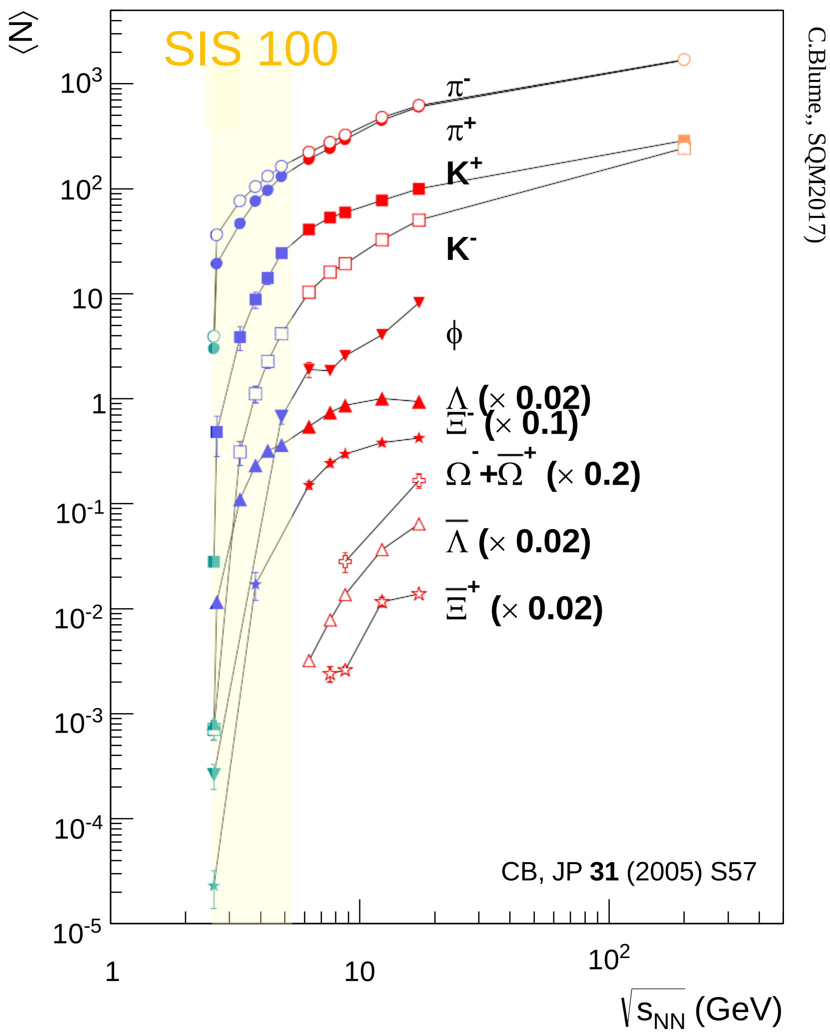
G. Agakishiev et al. (HADES), PRL103, 132301, (2009)





Final state particle abundance

Particle yields from central Au + Au collisions



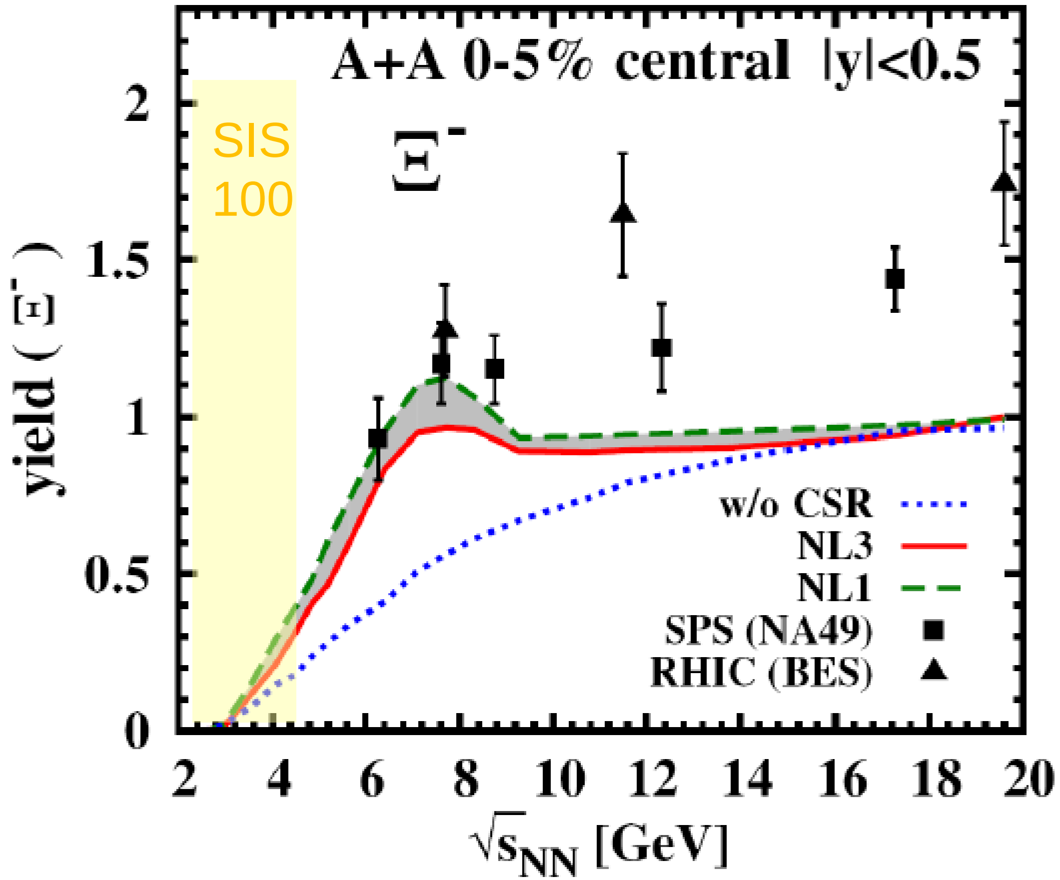
Strange and charmed particle production thresholds in pp - collisions

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

Hyperons as probes of dense matter

PHSD interpretation of Ξ^- - production

A. Palmese et al. Phys.Rev. C94 (2016) no.4, 044912



Predicted sensitivities of production yields:

strong dependence on Chiral Symmetry Restoration (CSR)

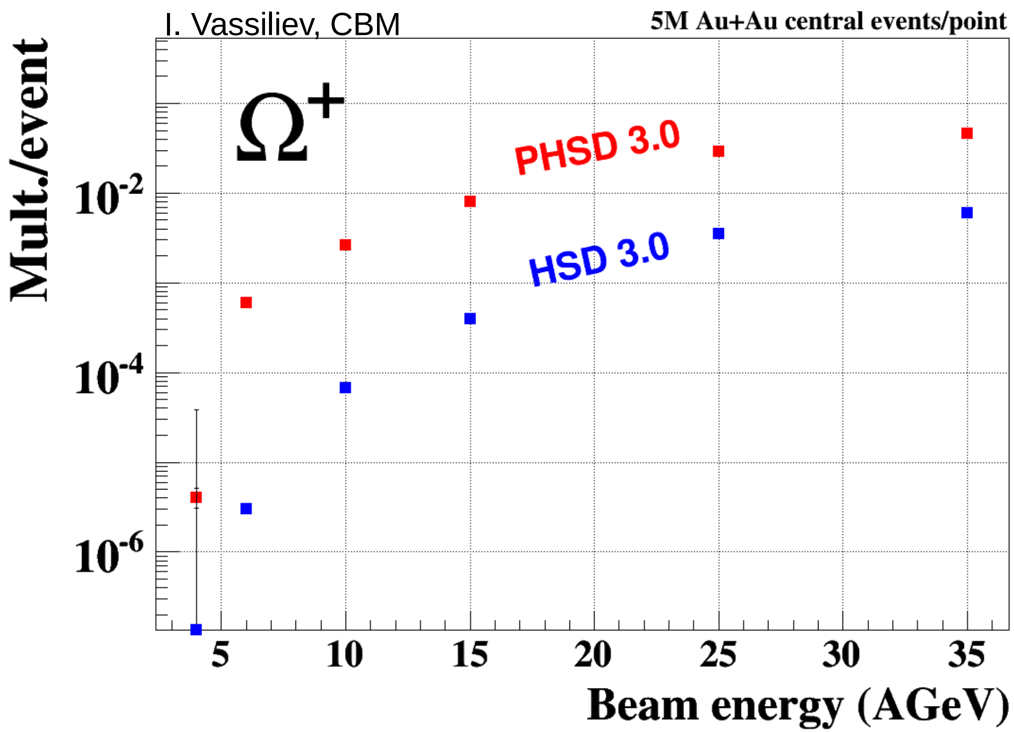
Measurable dependence on Equation of State (NL1, NL3)

Alternative explanation (URQMD): Tuned resonance parameter

J. Steinheimer, M. Bleicher, J.Phys. G43 (2016), 015104

Antihyperon – production

Prediction of PHSD transport model
(E. Bratkovskaya, W. Cassing)

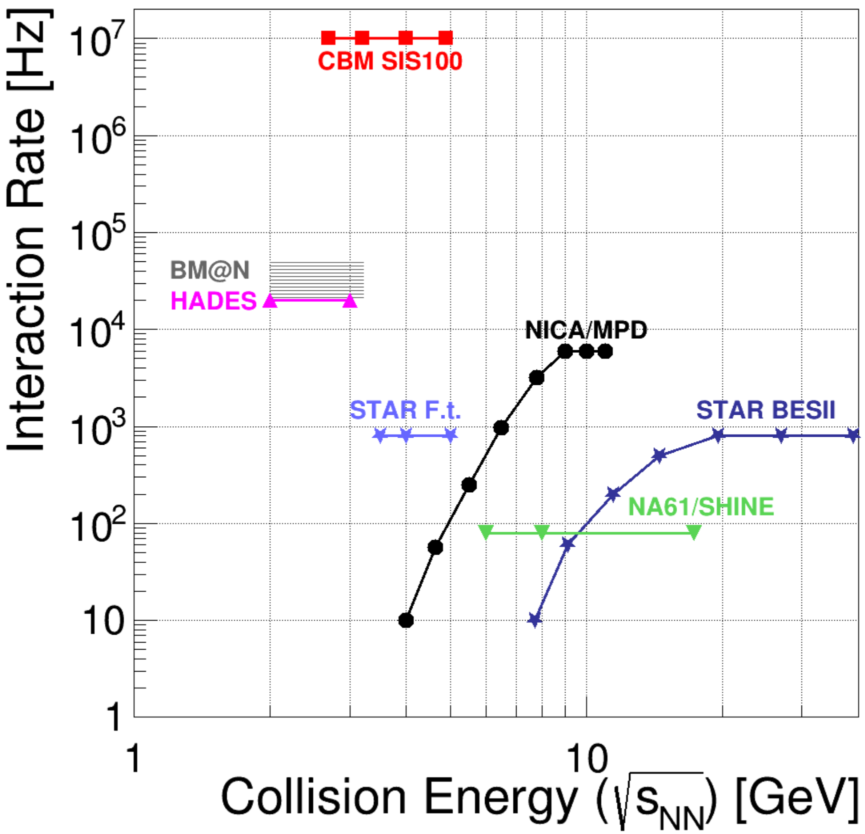


Large sensitivity to

partonic degrees of freedom
in SIS100 energy range
(deconfinement phase transition)

Mapping out the phase structure
requires systematic measurements.

CBM – Strategy

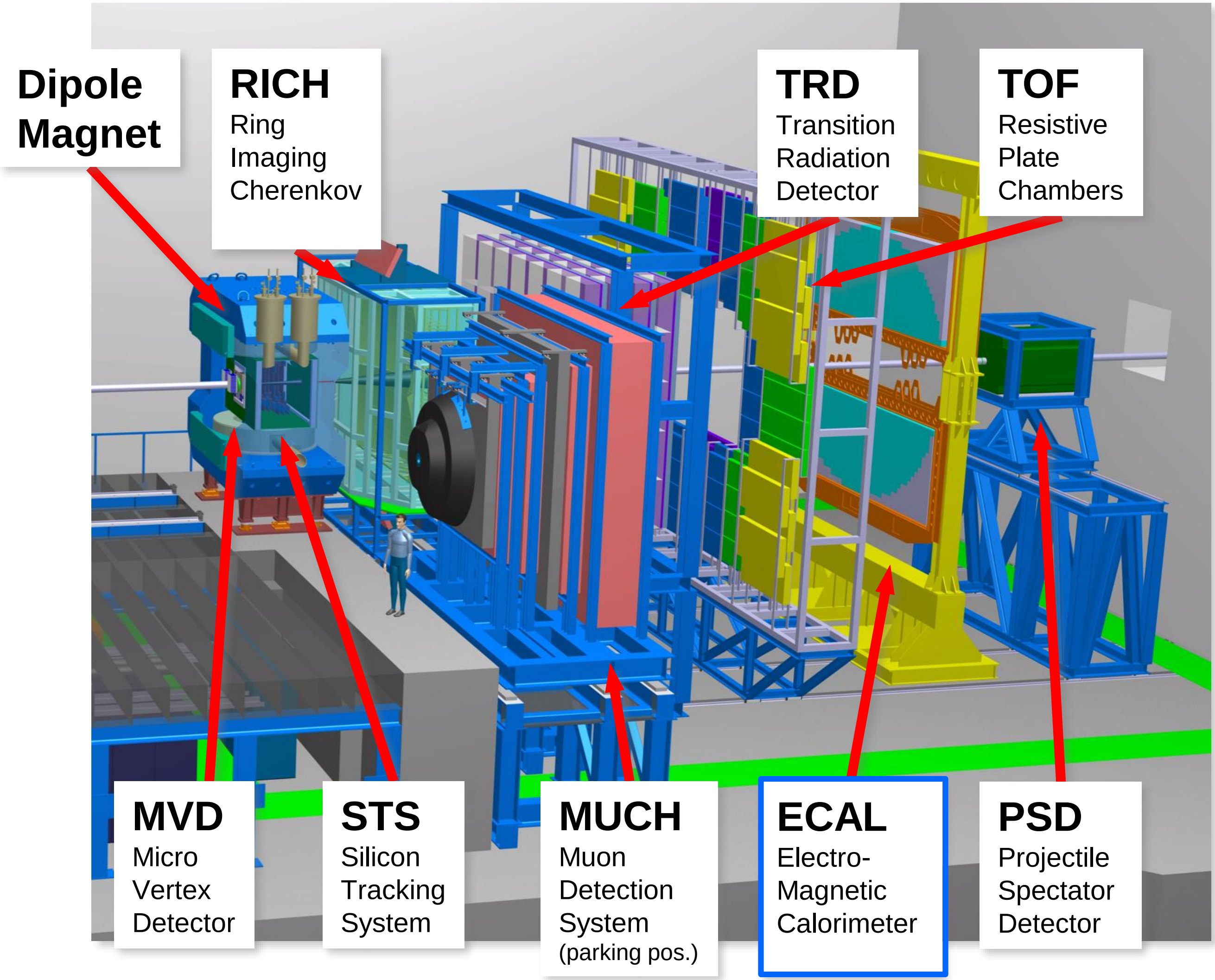


Exploration of QCD phase diagram as international effort:

NA61	@ SPS / CERN
BM@N	@ Nuclotron/JINR
STAR (F.t.)	@ RHIC/BNL
MPD	@ NICA / JINR

CBM's unique feature
High statistics measurement of rare probes

CBM experimental setup (day-1)



- Tracking acceptance: $2^o < \theta_{lab} < 25^o$
- Free streaming DAQ
- R_{int} = 10 MHz (Au+Au)

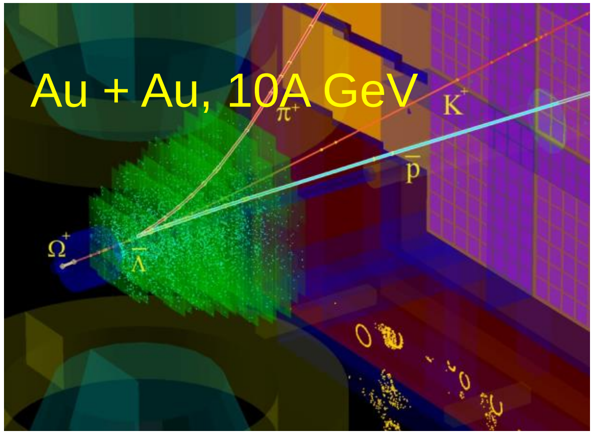
  $R_{int} \approx$ 0.5 MHz
  full bandwith:
  Det. – Entry nodes
  reduced bandwidth
  Entry nodes – Comp. farm

  with
  R_{int} (MVD)=0.1 MHz
- Software based event selection

Day-1 setup = MSV setup – Compute Performance - ECAL
Phase-1 = Day1 with full Compute Performance + ECAL

Day-1 funding:
~ 90% secured

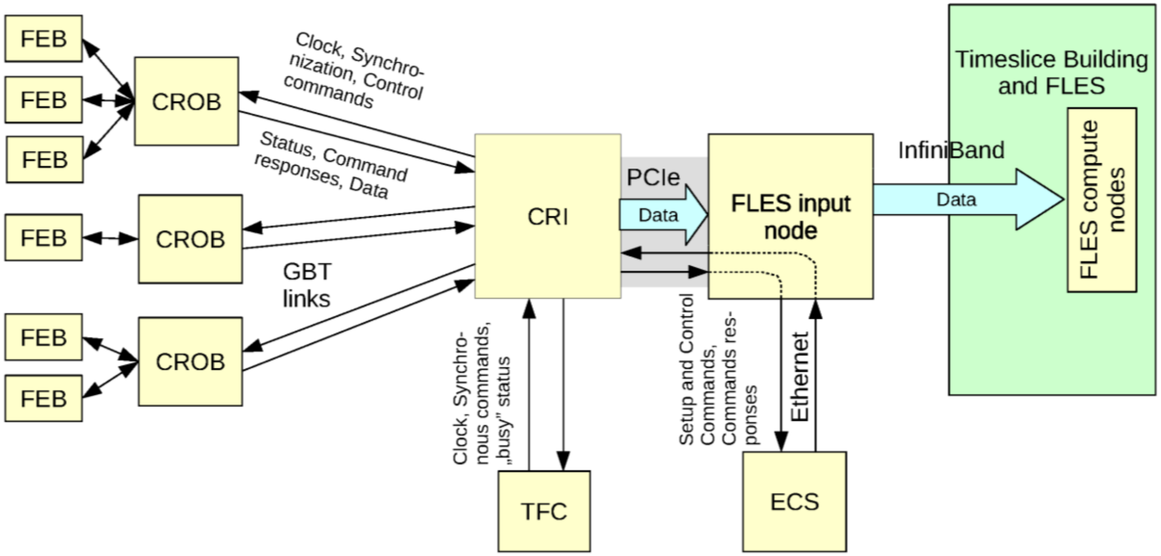
CBM data processing system



Reaction rate Au + Au:

10^7 collisions per second

Data rate: ~ 1 TB/s



Main features:

- radiation tolerant detectors and front-end electronics
- free streaming (triggerless) data with time stamps,
- software based event selection

CBM physics and observables

Eur.Phys.J. A53 (2017) 60

QCD equation-of-state
- collective flow of identified particles
- particle production at threshold energies

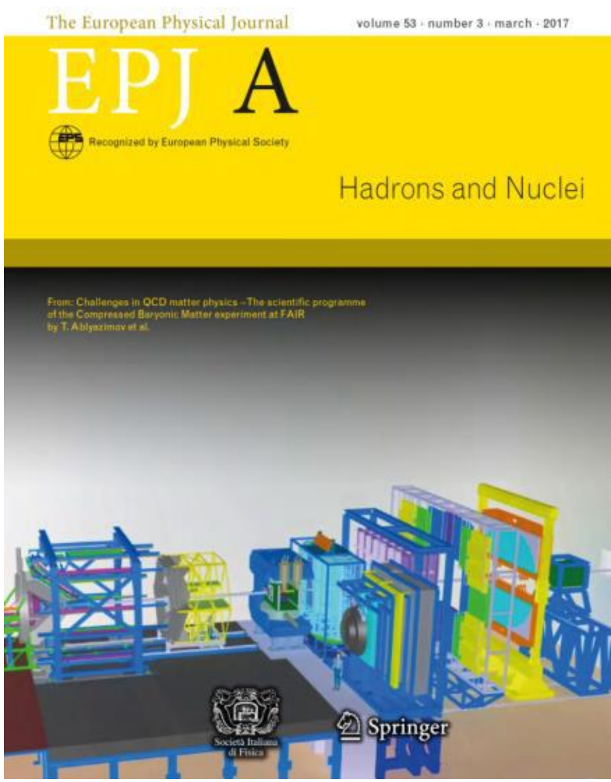
Phase transition
- excitation function of hyperons
- excitation function of LM lepton pairs

Critical point
- event-by-event fluctuations of conserved quantities

Chiral symmetry restoration at large ρ_B
- in-medium modifications of hadrons
- dileptons at intermediate invariant masses

Strange matter
- (double-) lambda hypernuclei
- Search for meta-stable objects (e.g. strange dibaryons)

Heavy flavour in cold and dense matter
- excitation function of charm production

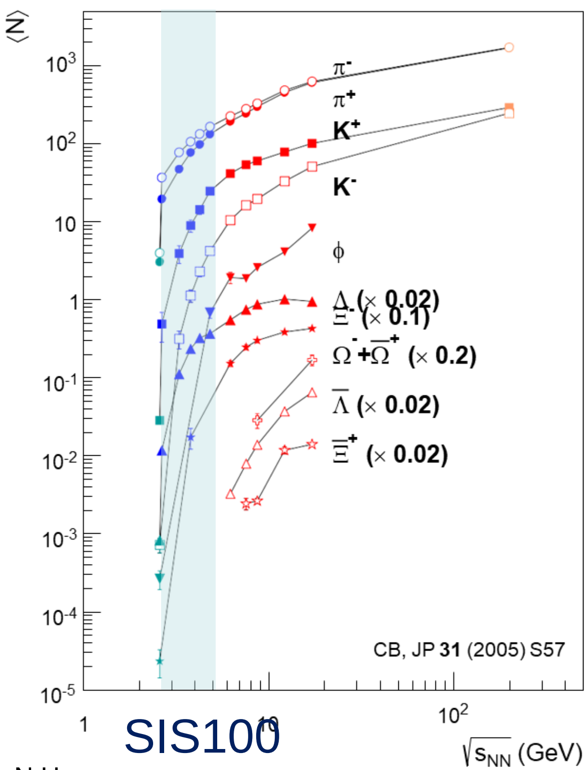


CBM day-1 – program

Observables: Strangeness and Dileptons

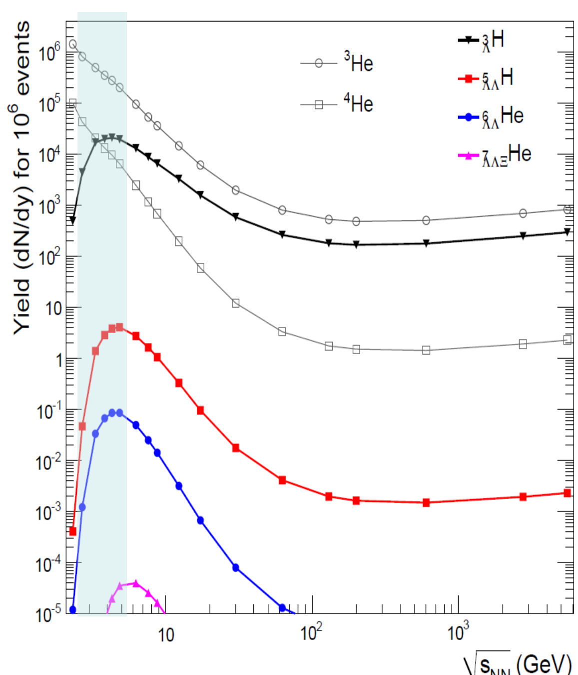
Excitation function of yields and phase-space distributions of
multi-strange hyperons and
lepton pairs in AA (C+C, Au+Au) collisions from 2-11 A GeV.
Search for hypernuclei (no data available in this energy range).

multi-strange hyperons



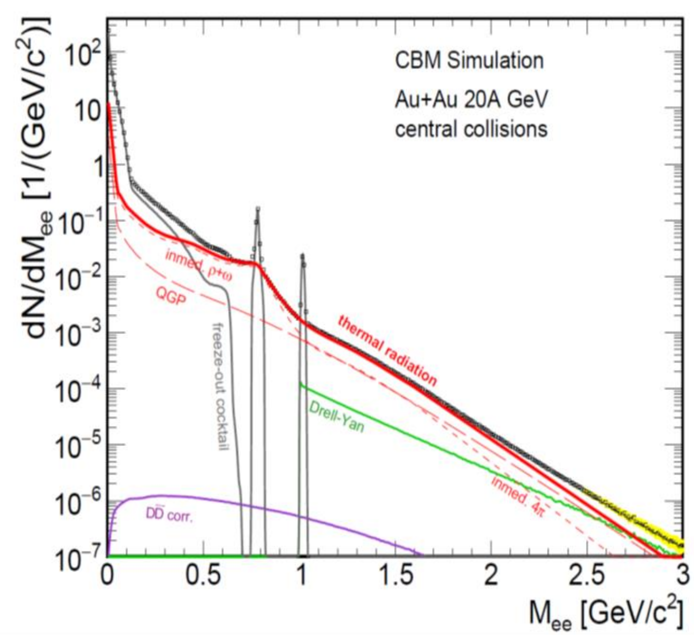
SIS100

hypernuclei



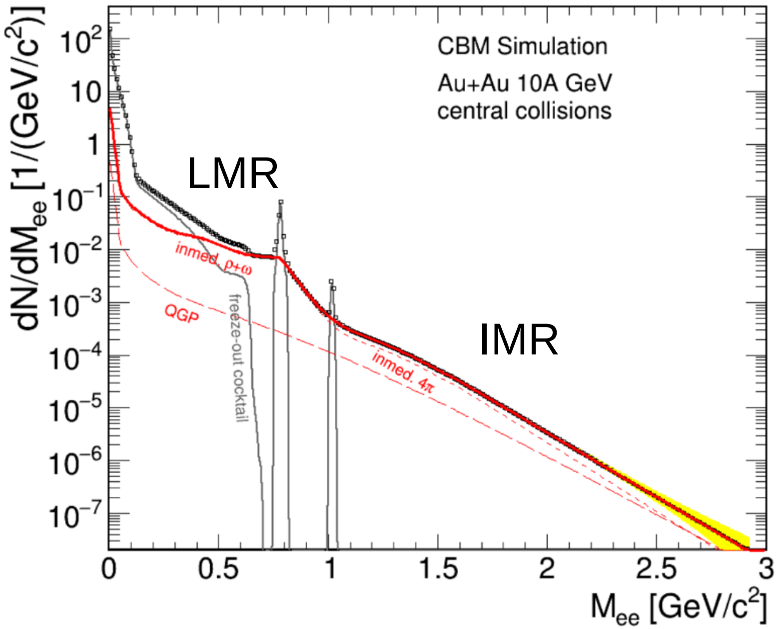
SIS100

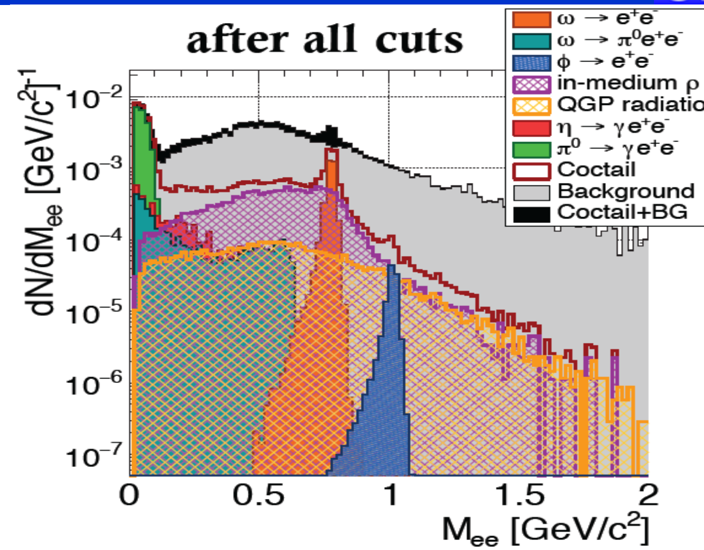
dilepton invariant mass



Dileptons as probes for dense matter (Day 1)

[R. Rapp, H. v.Hees, PLB 753 (2016) 586]



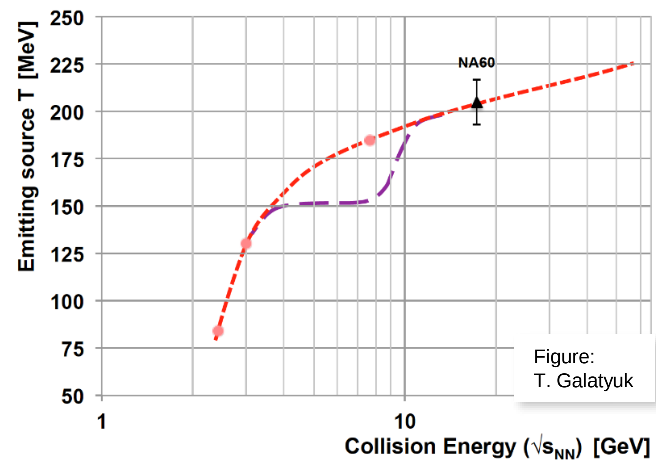


- 1M Au+Au (b=0 fm), 8A GeV
- IMR: S/B > 1/100
- Statistical accuracy of 10% requires ~ 3 weeks of beamtime

LMR: ρ – chiral symmetry restoration
fireball space – time extension

IMR: access to fireball temperature
ρ-a_1 chiral mixing

Measurement program:
e.g. excitation function of IMR – slope
full performance, uses MVD (100 kHz)

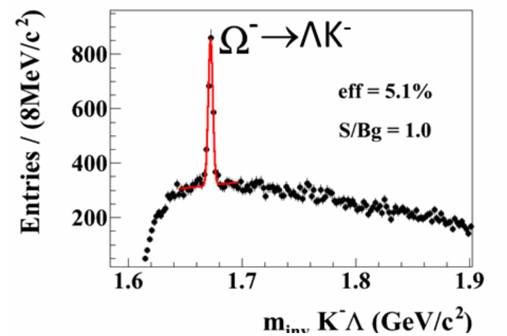


CBM Day 1 – further unique measurements

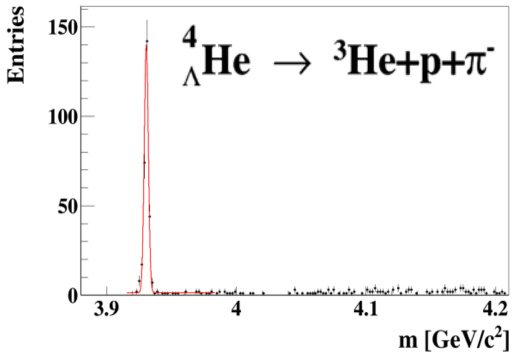
Hyperon measurements:

Au+Au at 10A GeV, ε_{duty} = 50%

Particle	Multi-plicity	BR	ε (%)	yield (s^{-1})	yield in 1 week
Ω^- (1672)	$5.6 \cdot 10^{-3}$	0.68	5	1.64	$5 \cdot 10^5$
$^4_\Lambda$He (3930)	$1.9 \cdot 10^{-3}$	0.32	14.7	0.87	$3 \cdot 10^5$



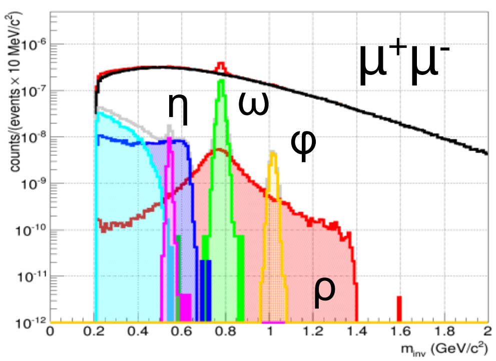
Hypernuclei measurement:



Di-Muon

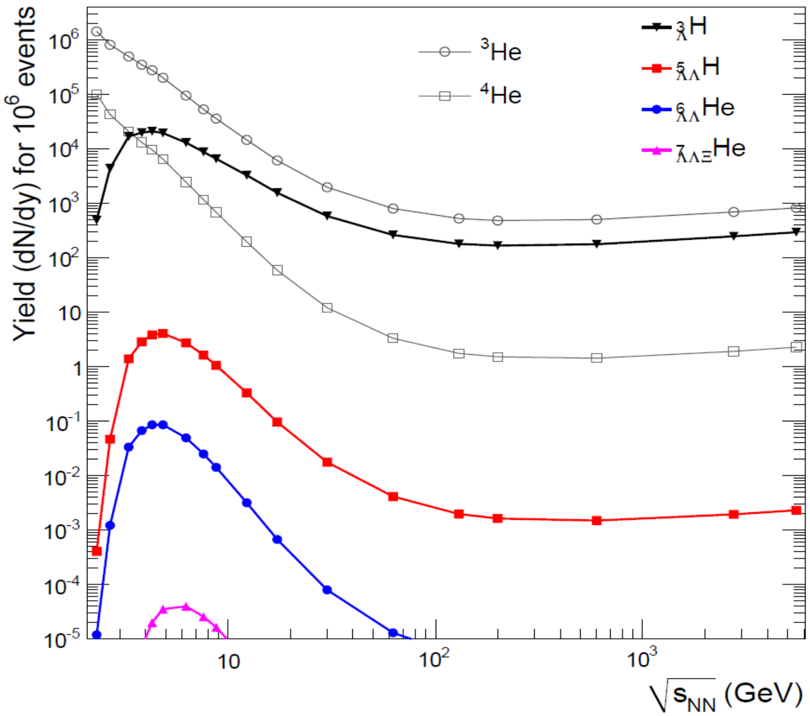
LM measurement at 8A GeV

complementary measurement to e^+e^- with different systematic errors

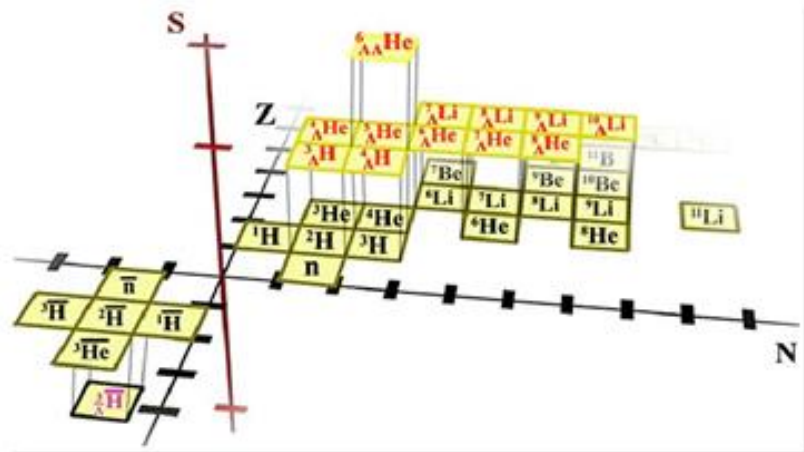


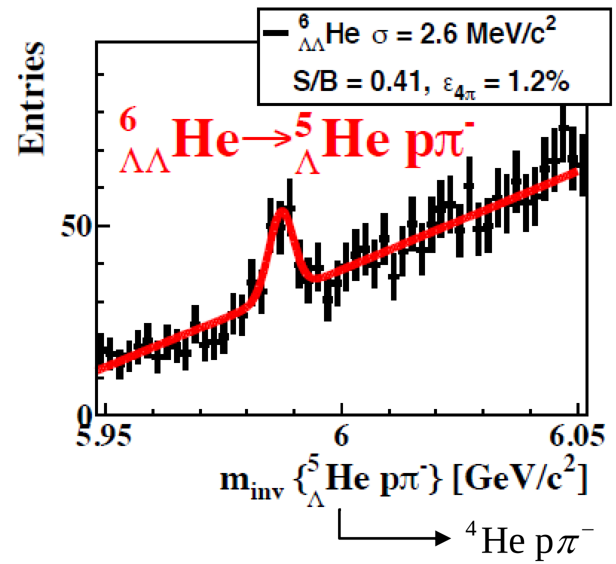
CBM – Phase 1 example: ΛΛ - Hypernuclei

Thermal model prediction



A. Andronic, et al., Phys. Lett. B697 (2011) 203



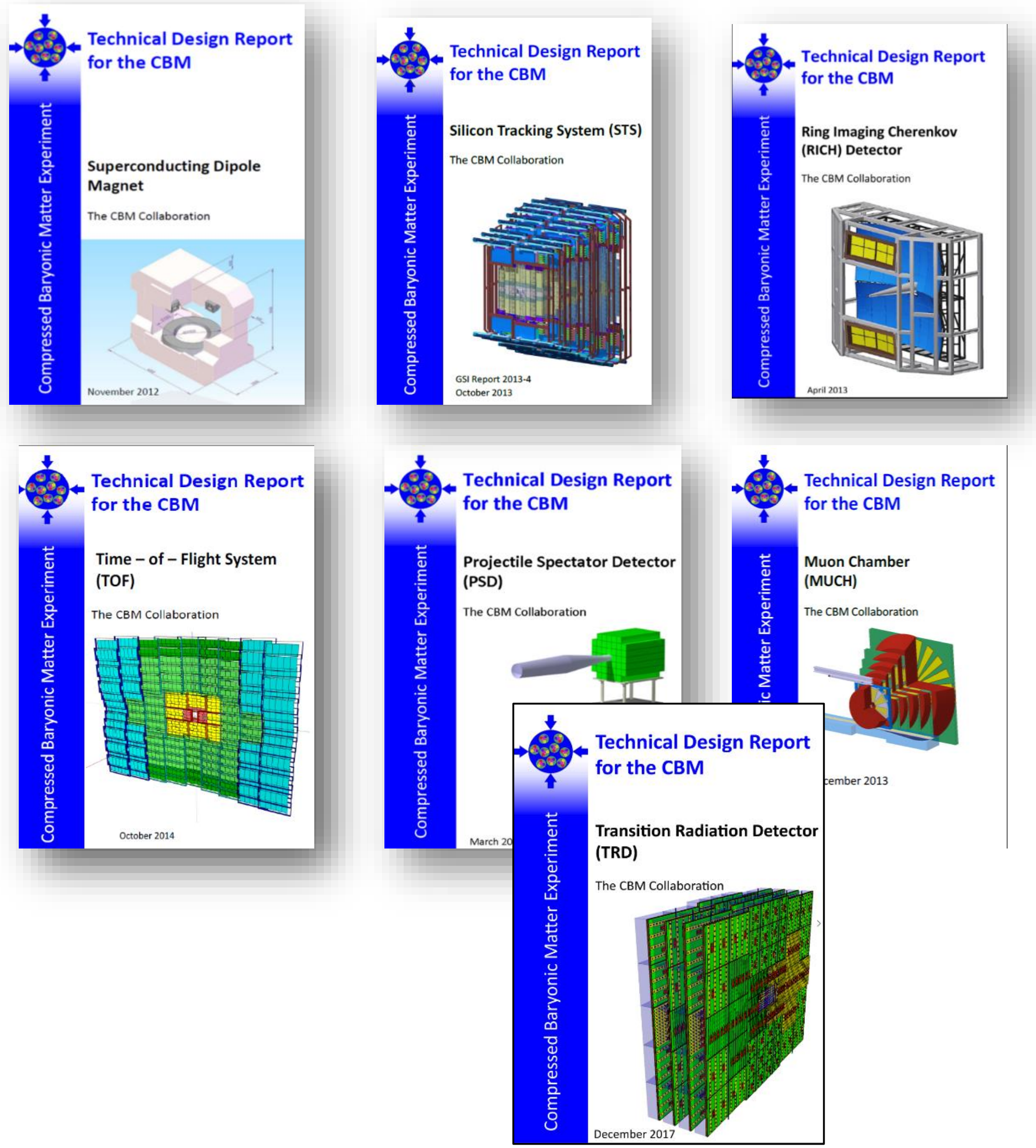


Simulation:
Au+Au collisions at 10 AGeV,
Background scaled to 10^{12} central events, TOF PID

~ 7 days of running at max. luminosity

Technical Design Reports

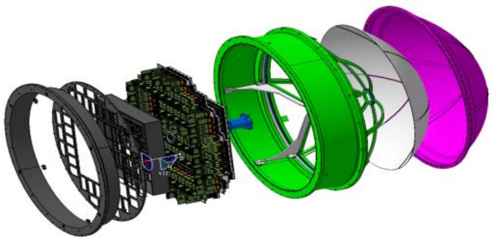
#	Project	TDR Status
1	Magnet	approved 2013
2	STS	approved 2013
3	RICH	approved 2014
4	TOF	approved 2015
5	MuCh	approved 2015
6	PSD	approved 2015
7	TRD	submitted 2017
8	MVD	submission 2018
9a	Online Systems: DAQ	submission 2018
9b	Online Systems: FLES	submission 2020
10	ECAL	submission t.b.d.



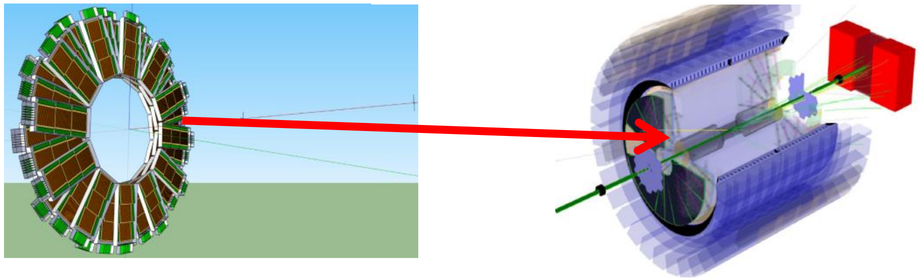
Day-1 target date: summer 2024

CBM – FAIR Phase 0 projects (2018 – 2022)

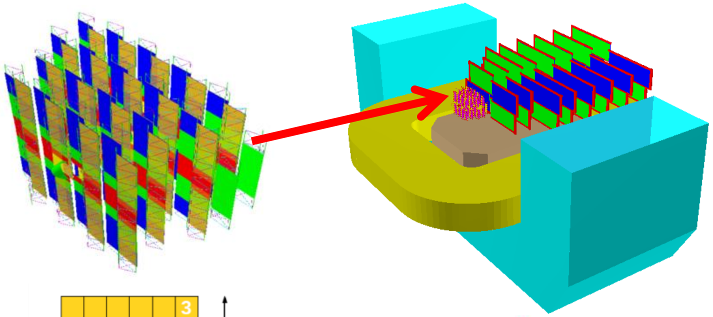
1. Install, commission and use 430 out of 1100 CBM RICH multi-anode photo-multipliers (MAPMT) including FEE in HADES RICH photon detector



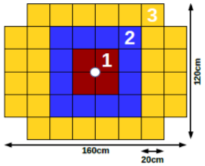
2. Install, commission and use 10% of the CBM TOF modules including read-out chain at STAR/RHIC (BES II 2019/2020)



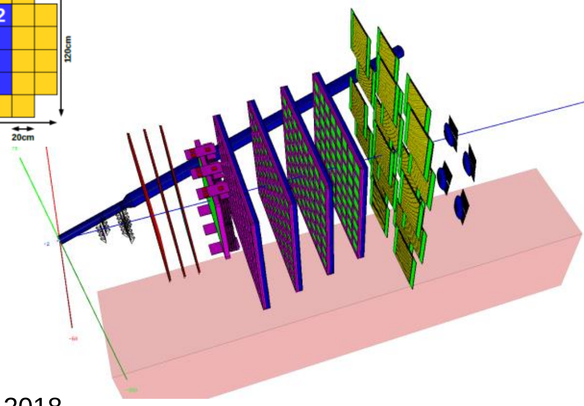
3. Upgrade BM@N experiment with 4 Silicon stations of CBM/STS design in the BM@N experiment at the Nuclotron JINR/Dubna (Au-beams in late 2020)



4. Install, commission and use the Project Spectator Detector at the BM@N experiment

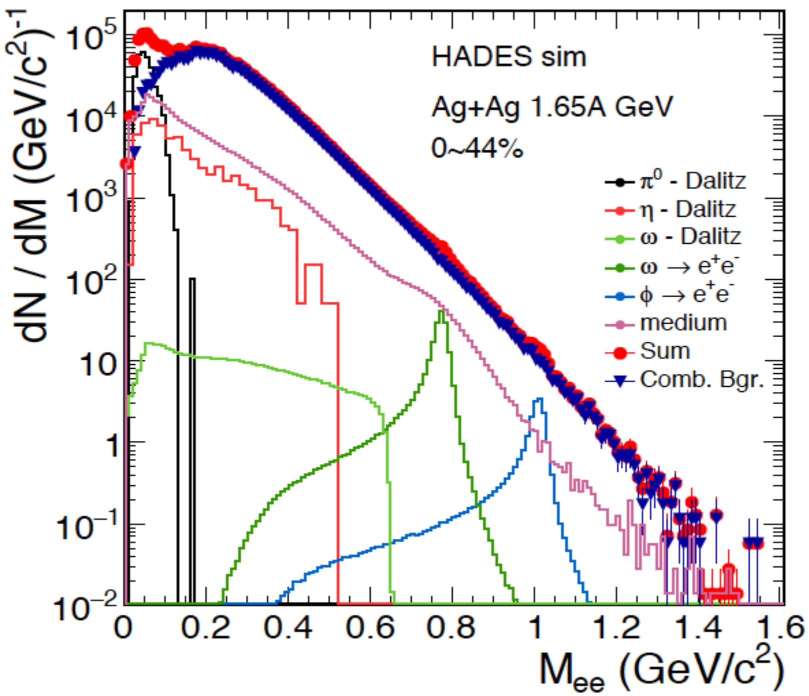


5. mini CBM (mCBM@SIS18) demonstrator for full CBM data taking and analysis chain



Ag+Ag, 1.65*A* GeV @ SIS18

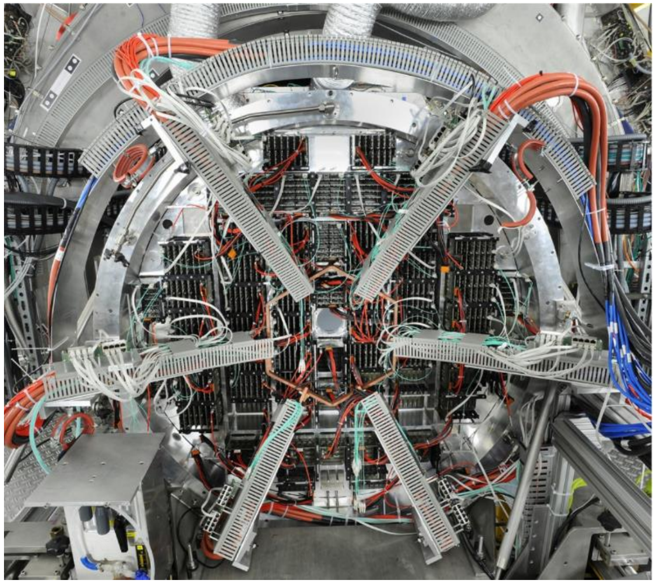
Expected **dielectron** invariant mass spectra expected after 4 weeks of Ag+Ag running.



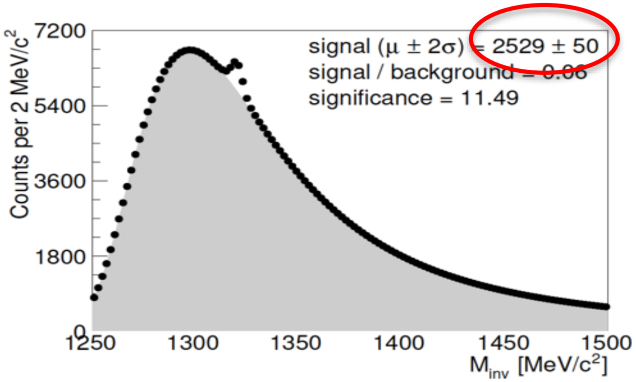
- Access for the first time at this collision energies intermediate mass range

CBM groups:

- GSI Darmstadt,
- Univ. Giessen,
- Univ. Wuppertal

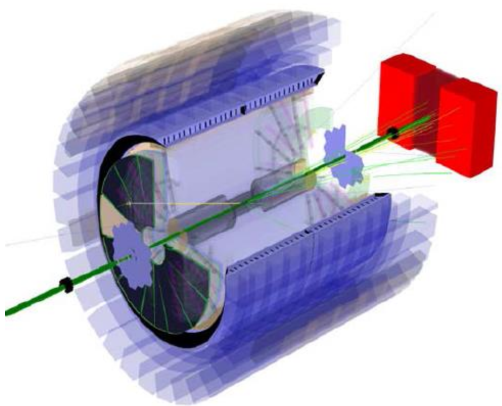


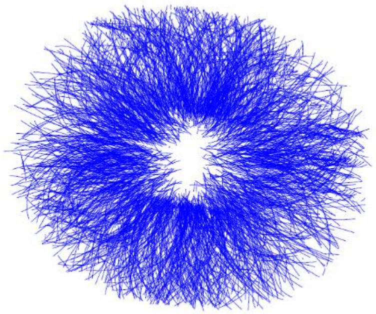
(Multi)-Strangeness in Ag+Ag.
Understanding of the Ξ^- excess.



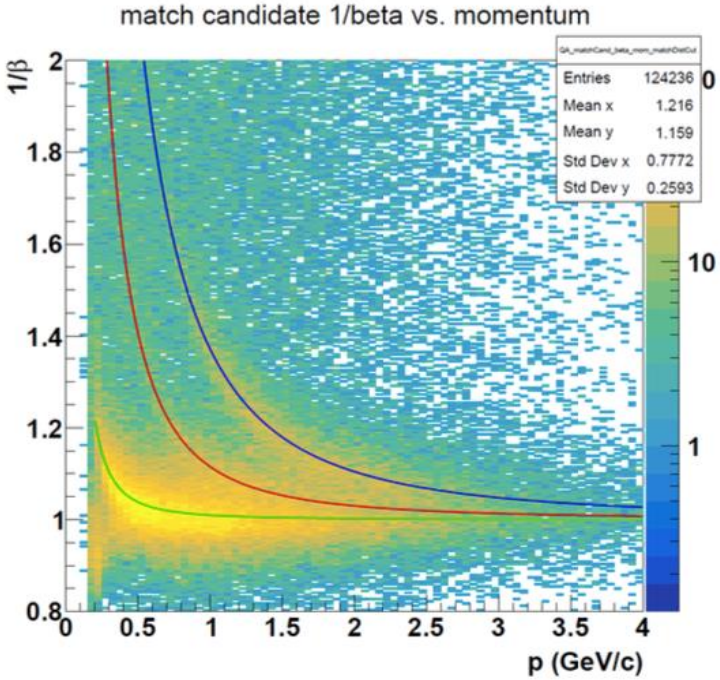
2018, 4 weeks of beam time approved.
4.5×10^9 events, 10 kHz trigger rate

eTOF & HPC software in STAR at RHIC (BNL)





Correlation:
CBM-eTOF
with STAR TPC
from Run18



CBM groups:

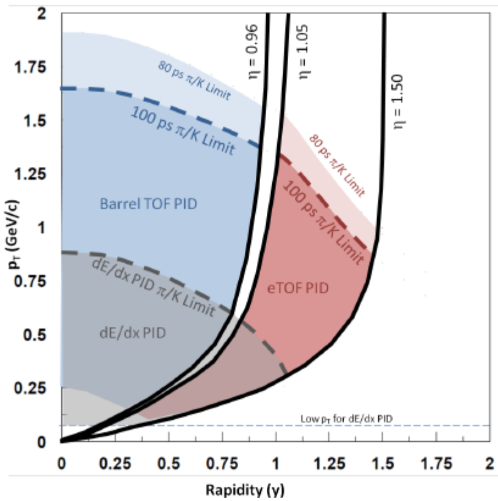
- Tsinghua Univ. Beijing
- GSI Darmstadt
- TU Darmstadt
- Univ. Frankfurt
- Univ. Heidelberg
- USTC Hefei
- CCNU Wuhan

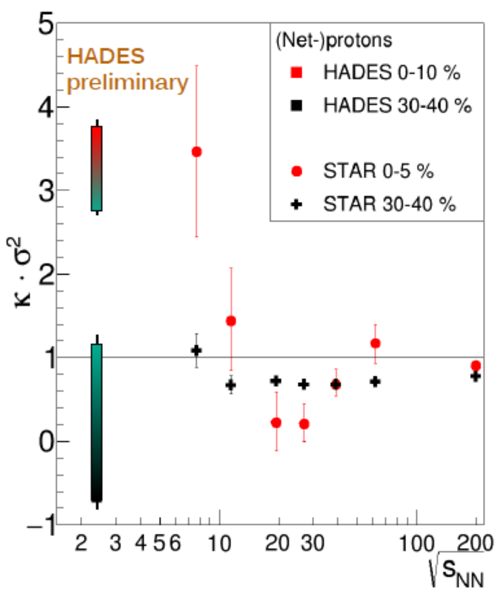
Test module operational	(Oct. 2016)
STAR DAQ interface	(Jan. 2017)
Full sector test	(Spring 2018)
Wheel installation	(Fall 2018)
BES II data taking	(2019/2021)
Transfer of modules to FAIR	(2022/23)

STAR – BES II physics program

arXiv:1609.05102v1 [nucl-ex]

Physics Program for the STAR/CBM eTOF Upgrade



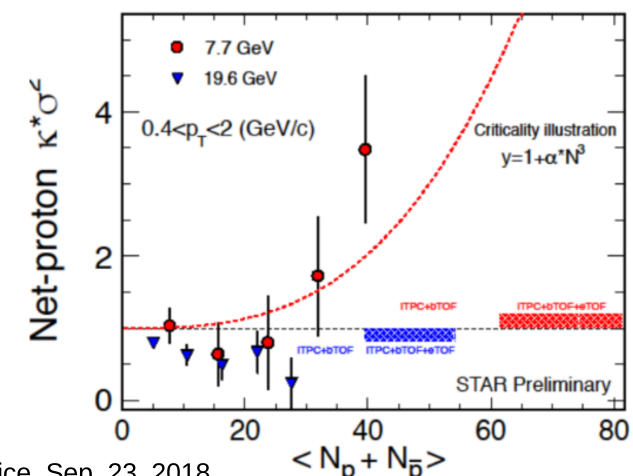


HADES: M. Lorenz, QM 2017
STAR: X. Luo et al, CPOD 2014

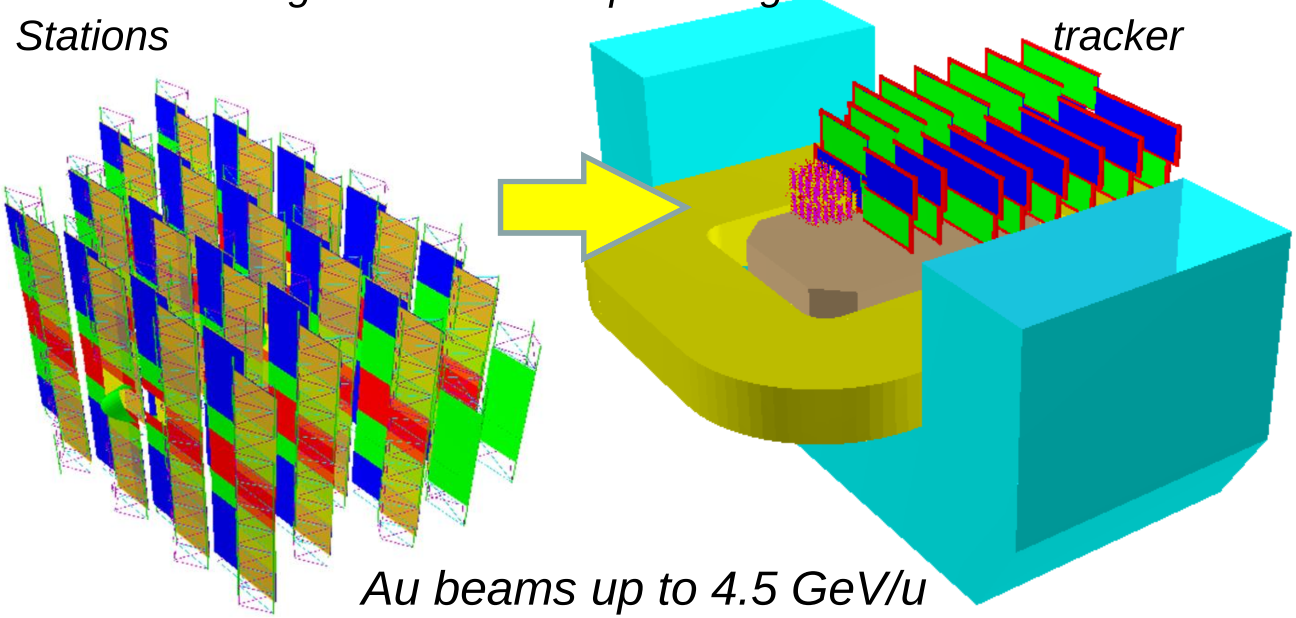
Topics to be studied with extended acceptance in energy range $\sqrt{s_{NN}} = 3 – 62$ GeV:

- Excitation function and phase-space distributions of hyperons, hypernuclei, anti-protons, ...
  → Equilibration, phase transitions
- Collective Flow (v_1, v_2)
  → Equation-of-State, phase transitions
- Dilepton yields
  → Chiral symmetry restoration
- **Fluctuations of conserved quantum numbers** (baryon, charge, strangeness)
  → Critical point

Expected increase in signal strength:

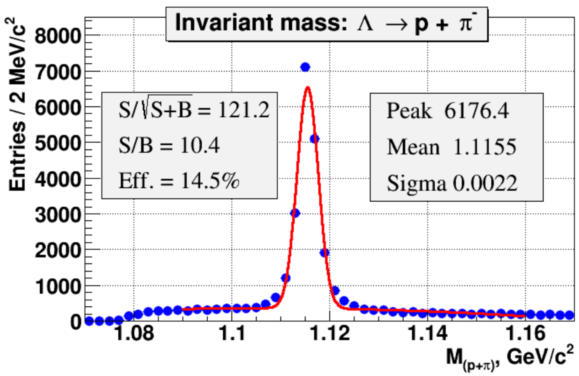


STS & PSD in BM@N (JINR)



PSD calorimeter

Improvement in efficiency & signal / backrgound



BM@N timeline: NICA white paper
(Eur. Phys. J. A (2016) 213

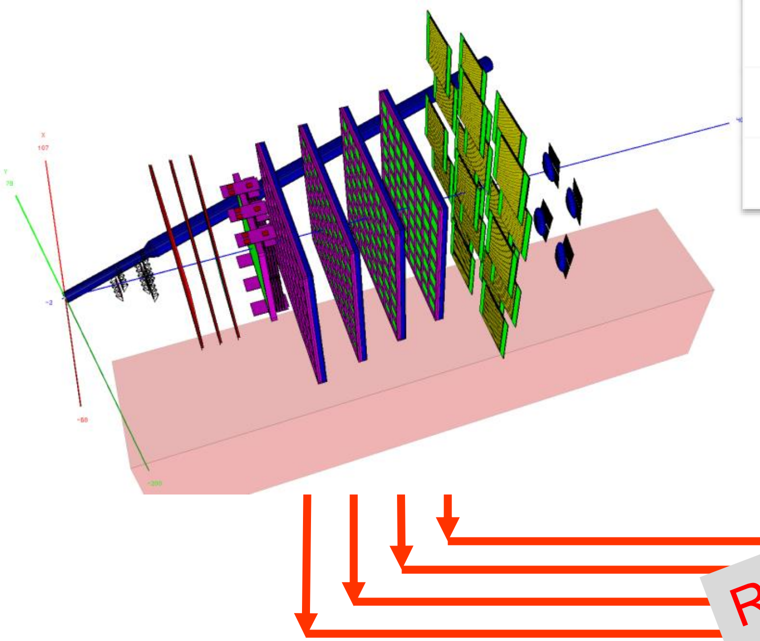
2018	Installation of PSD detector (MoU signed)
2019	Au beams from Nuclotron
2020	Installation of 4 Si Tracking Stations (MoU signed)

CBM groups: GSI Darmstadt, Univ. Tübingen, JINR Dubna

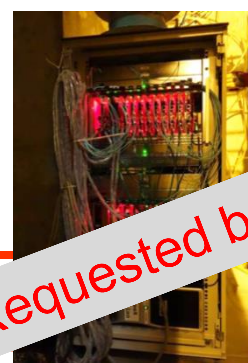
mCBM setup @ SIS18

Schedule

10/2017	cave & beam line: reconstruction started, procurement started
11/2017	μDAQ test stand @ Heidelberg operational
12/2017	beam dump mounted
03/2018	cave reconstruction completed
04/2018	mFLES cluster @ Green IT Cube installed
05/2018	beam line installed and commissioned
05/2018	installation of detector stations
09/2018	start commissioning w/o beam
Q1/2019	first system high rate test



Requested beamtime was fully granted by G-PAC

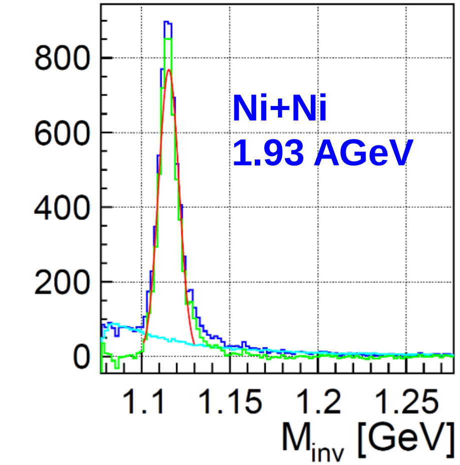


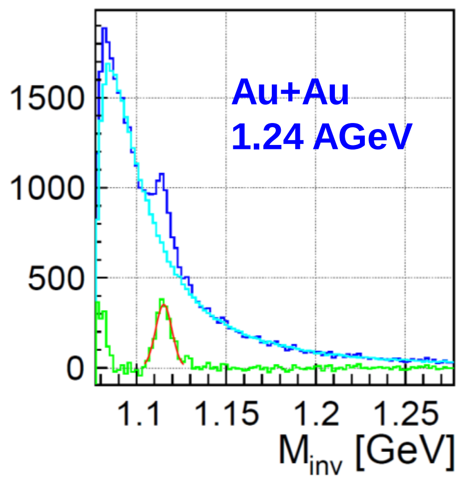
mCBM status (Sep. 2018)

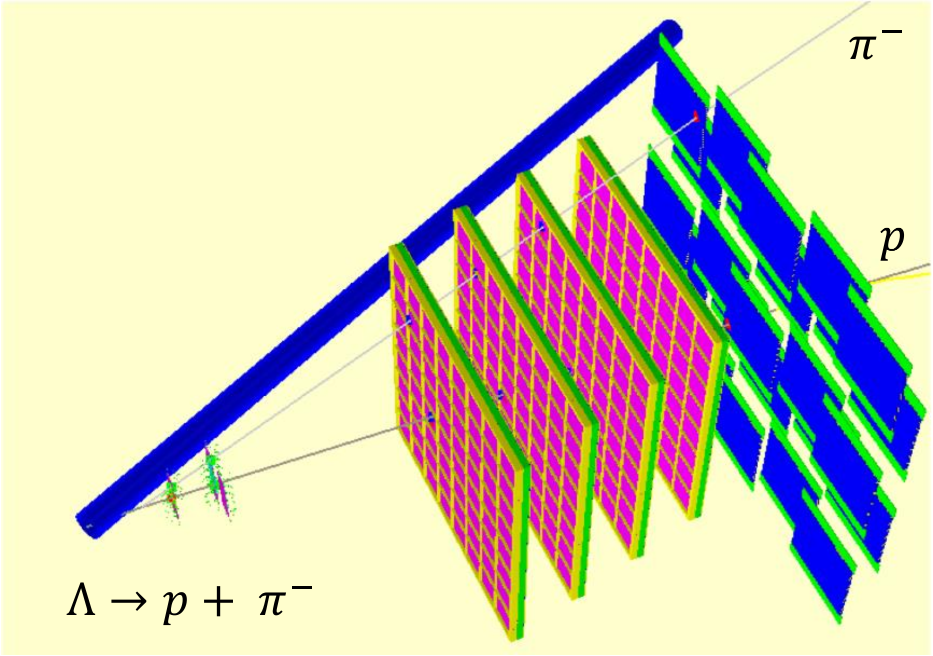
mCBM performance benchmark

(Sub)threshold Λ – baryon reconstruction.

Event based MC simulation of 10^8 events
(equivalent measurement time: 10 s)



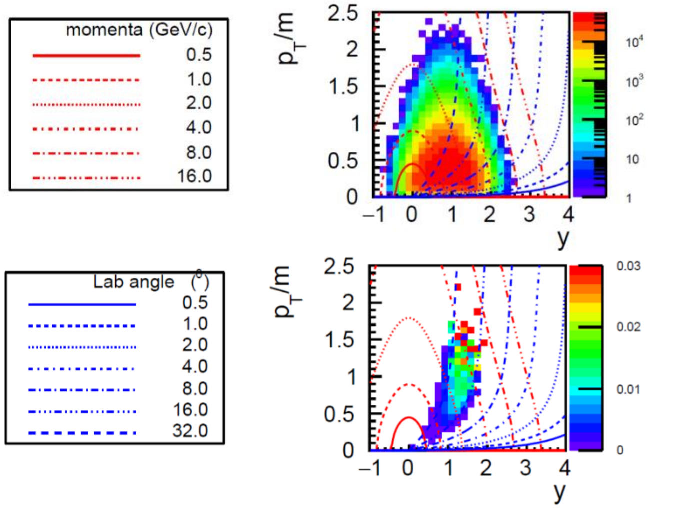




Acceptance

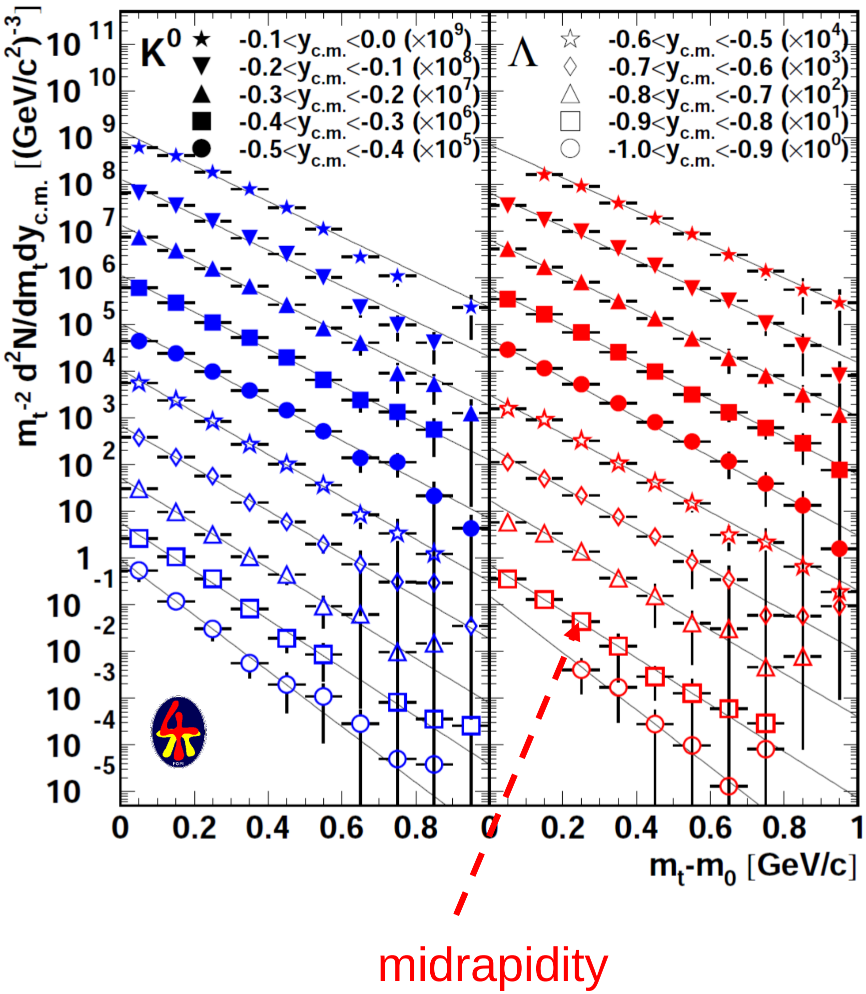
&

Efficiency



Reference data for Λ – production

M. Merschmeyer et al. (FOPI), PRC 76, 024906 (2007)



Reaction:

$^{58}Ni + ^{58}Ni$ at 1.93 AGeV

Centrality:

350 mb (most central)

$$\frac{\sigma_{cen}}{\sigma_{geo}} \leq 0.13$$

Data taking period:

17.1.2003 – 3.2.2003

Statistics:

~ 60.000 reconstructed Λ

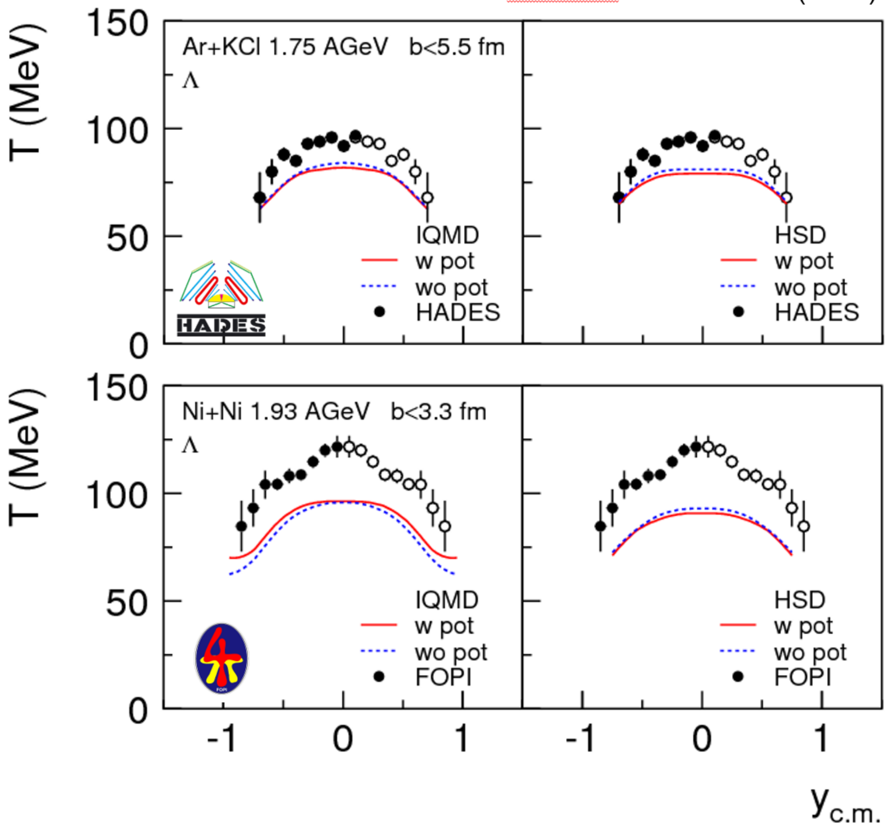
Derived quantities:

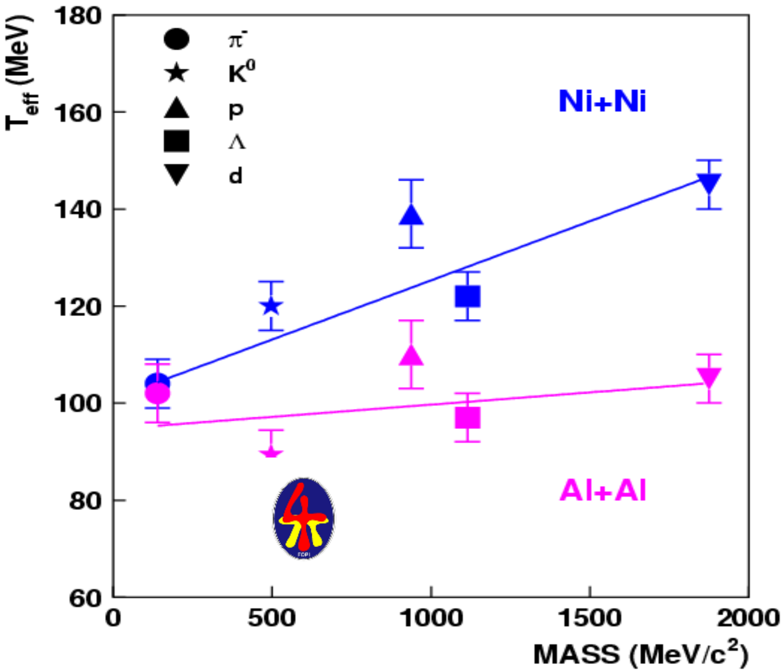
slope parameter

integrated yield

Physics of the benchmark observable

C. Hartnack et al. PR 510 (2012)





Λ - slope parameter:

- smaller than proton
- not explained by transport models
- reason unclear:
  - rescattering cross section
  - repulsive potential

Summary / Conclusion

CBM scientific program at SIS100 is unique

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

CBM day-1 setup allows start of program with significant discovery potential

- excitation function of hyperons production
- excitation function of di-lepton production
- study of hypernuclei

CBM Phase 0 activities targeted towards usage and understanding of major components & production of physics results with CBM devices

CBM – RICH sensors & readout	in HADES at SIS18
CBM – TOF and HPC software	in STAR at RHIC/BNL
CBM – PSD and CBM - STS	in BM@N at Nuclotron/JINR
Integration of all subsystems & FLES	in mCBM at SIS18

CBM collaboration is open for contributions from additional groups.

Acknowledgements

CBM

Bundesministerium für Bildung und Forschung

GSI

FAIR

HIC for FAIR Helmholtz International Center

HELMHOLTZ GEMEINSCHAFT

ROSATOM

IFIN-HH www.ifin.ro

प ऊ वि DAE

FRRC FAIR-Russia Research Center FAIR

MŠMT MINISTRY OF EDUCATION YOUTH AND SPORTS

Cremlin Connecting Russian and European Measures for Large-scale Research Infrastructures

CSIR Council of Scientific and Industrial Research

विज्ञान एवं प्रौद्योगिकी विभाग DEPARTMENT OF SCIENCE & TECHNOLOGY

सत्यमेव जयते

ifa

Ministry of Science and Higher Education Republic of Poland

विश्वविद्यालय अनुदान आयोग University Grants Commission quality higher education for all

中华人民共和国科学技术部 Ministry of Science and Technology of the People's Republic of China

NSFC 国家自然科学基金委员会 National Natural Science Foundation of China