The upgrade program of the BM@N experiment at NICA

Peter Senger

Outline:

- Mission: Investigating nuclear matter at neutron star core densities
  - Probing the high-density equation-of-state
  - Searching for the onset of deconfinement
  - Exploxing the role of hyperons in neutron stars
- Upgrading the BM@N detector system

9th International Conference on New Frontiers in Physics (ICNFP 2020), 1. - 2. October 2020, Kolymbari, Crete, Greece

FAIR GSI

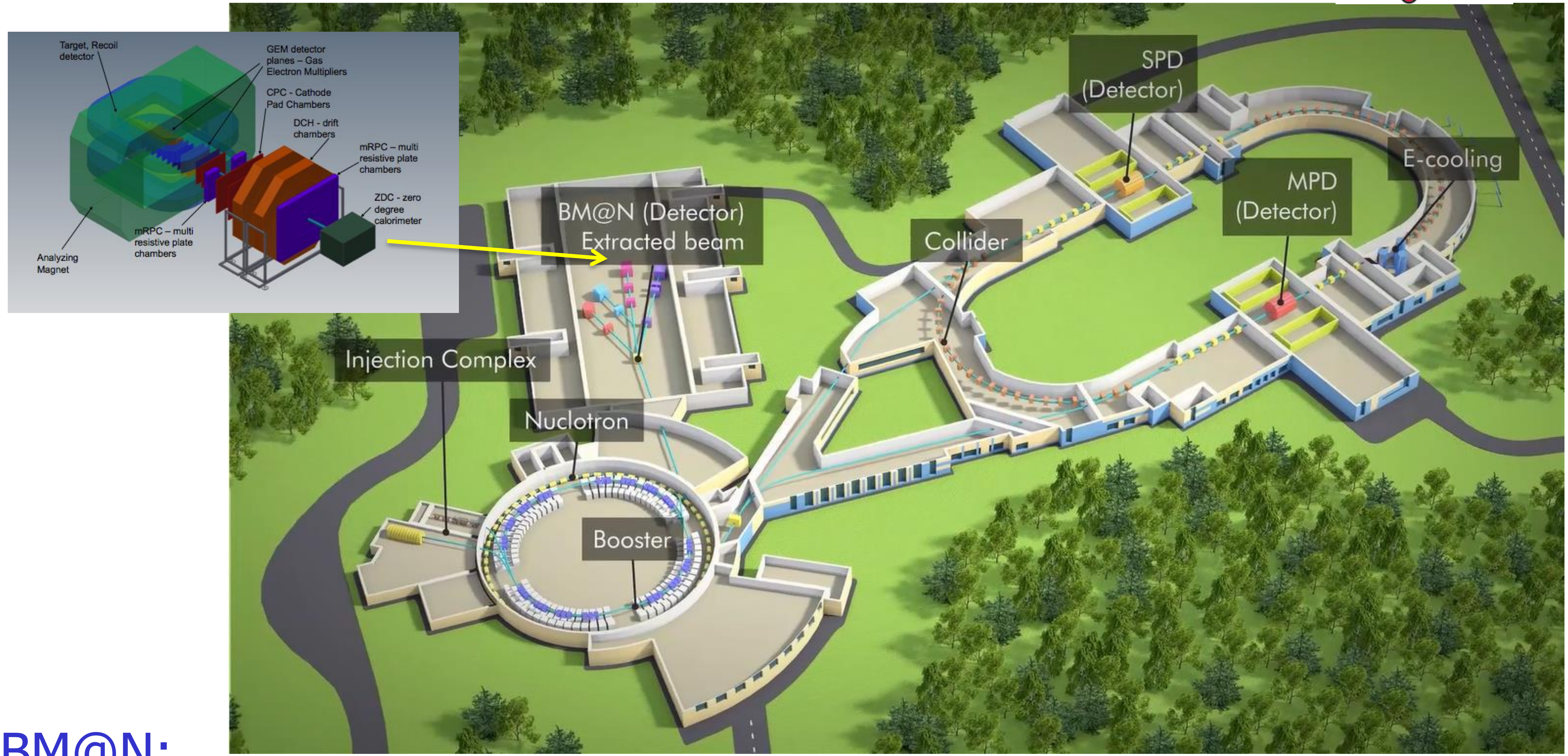
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

MEPhI

CREMLIN PLUS
Connecting Russian and European Measures for Large-scale Research Infrastructures

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

NICA Heavy Ion Complex

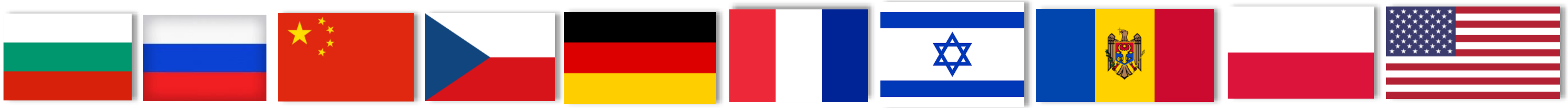


BM@N:

beams from p to Au, heavy ion energy 1- 3.8 GeV/n (17 kG Nuclotron magnets), Au intensity ~ few 10^6 Hz

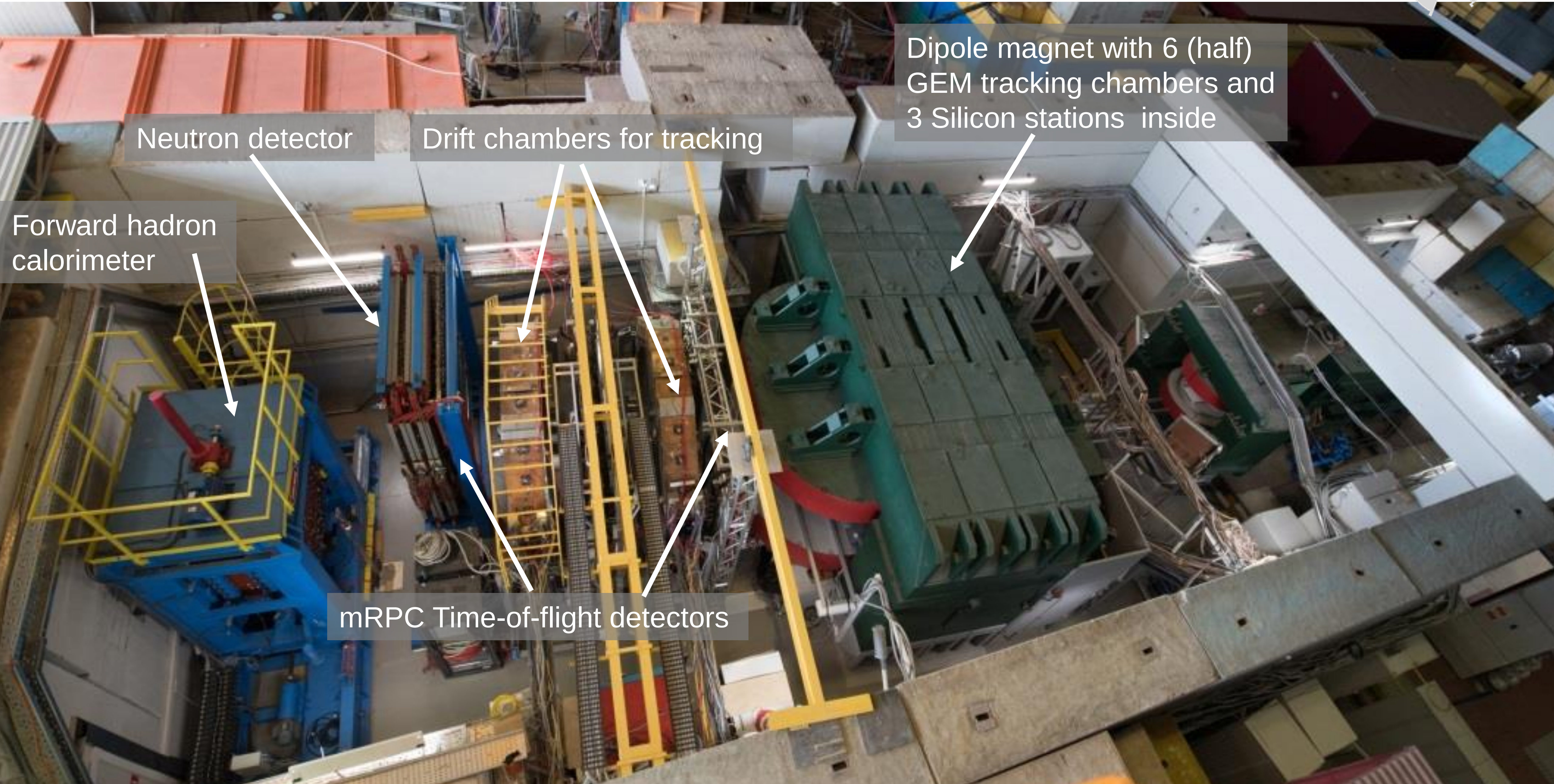
Baryonic Matter at Nuclotron (BM@N) Collaboration

10 Countries, 20 Institutions, 246 participants

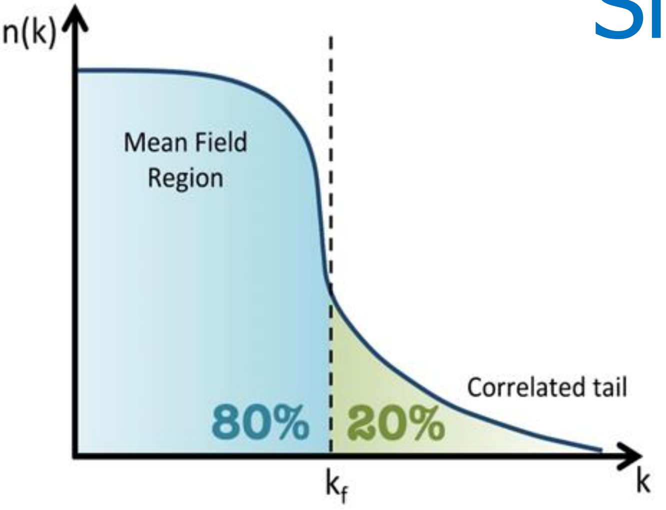


- University of Plovdiv, Bulgaria;
- Shanghai Institute of Nuclear and Applied Physics, CFS, China;
- Tsinghua University, Beijing, China;
- Nuclear Physics Institute CAS, Czech Republic;
- CEA, Saclay, France;
- TU Darmstadt & GSI Darmstadt, Germany;
- Tubingen University, Germany;
- Tel Aviv University, Israel;
- Joint Institute for Nuclear Research;
- Institute of Applied Physics, Chisinev, Moldova;
- Warsaw University of Technology, Poland;
- St Petersburg University, Russia;
- University of Wroclaw, Poland;
- Institute of Nuclear Research RAS, Moscow, Russia
- NRC Kurchatov Institute, Moscow;
- Institute of Theoretical & Experimental Physics, NRC KI, Moscow, Russia;
- Moscow Engineer and Physics Institute, Russia;
- Skobeltsin Institute of Nuclear Physics, MSU, Russia;
- Moscow Institute of Physics and Technics, Moscow, Russia;
- Massachusetts Institute of Technology, Cambridge, USA.

Baryonic Matter at Nuclotron (BM@N) Experiment

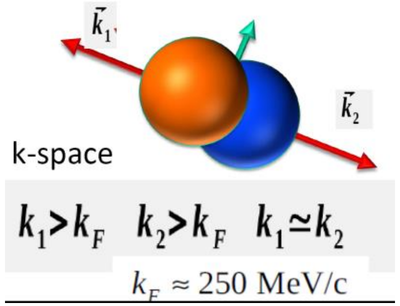


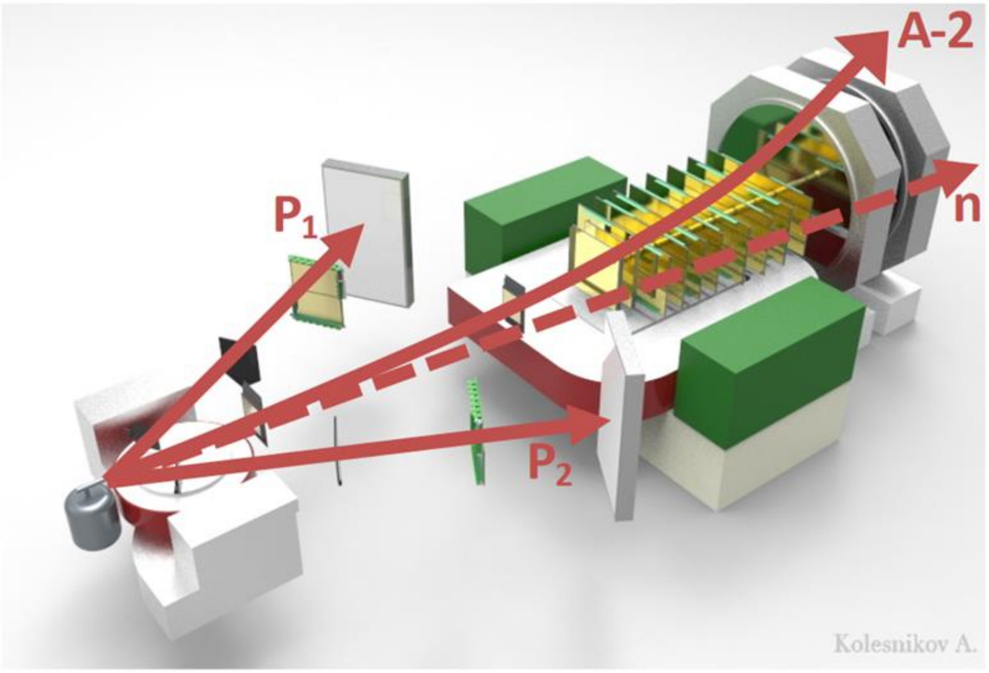
Experiments performed at BM@N: Short-Range Correlations (SRC)



$k<k_F$ Mean field region: Single nucleons

$k>k_F$ High momentum region: Correlated pairs of nucleons, which are close together in space with a high relative momentum, but a low c.m. momentum compared to the Fermi momentum k_F. SRC probe nucleonic and partonic degrees-of-freedom in nuclear systems.

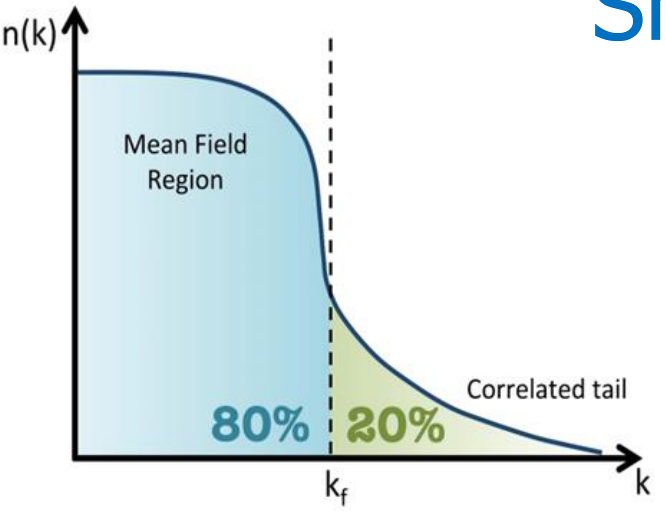




Experiment at BM@N with a 4A GeV C-beam:
First fully exclusive measurement in inverse kinematics probing the residual A-2 nuclear system!

$$^{12}C + p \rightarrow 2p + {}^{10}_{5}B + n \quad (np\ SRC)$$
$$^{12}C + p \rightarrow 2p + {}^{10}_{4}Be + p \quad (pp\ SRC)$$

Experiments performed at BM@N: Short-Range Correlations (SRC)



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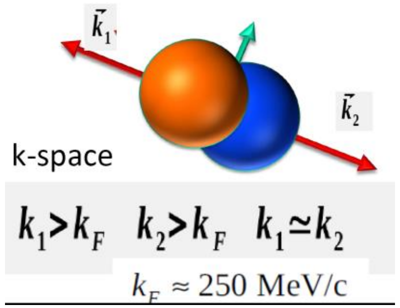
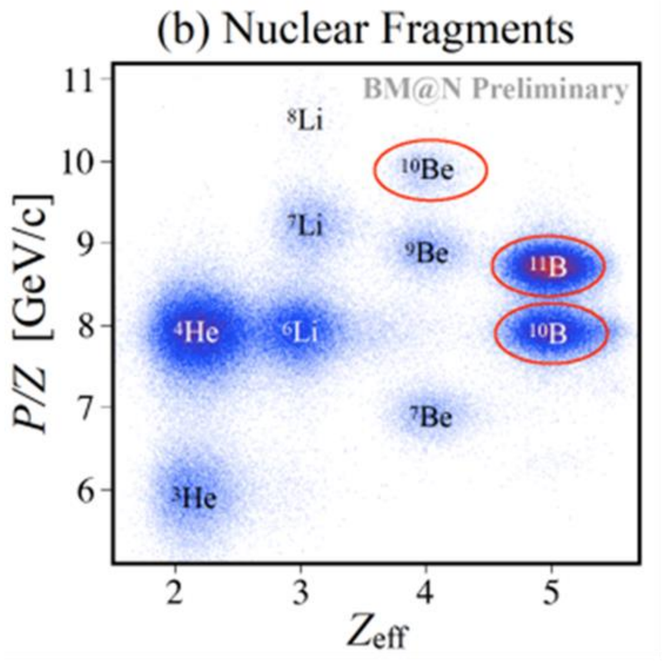


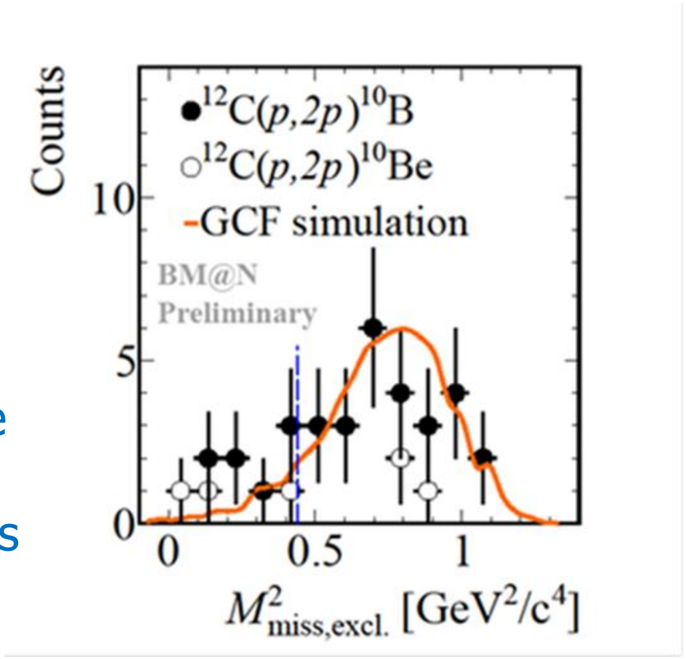


Key features of the experiment:

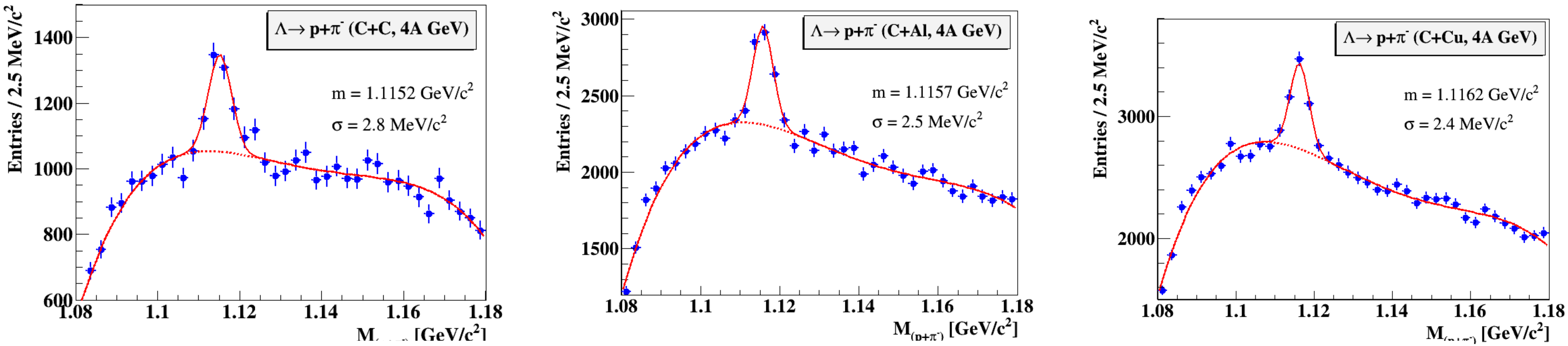
- Suppression of final-state interactions by post-selection of nuclear fragments
- Direct measurement of the SRC pair center of mass motion

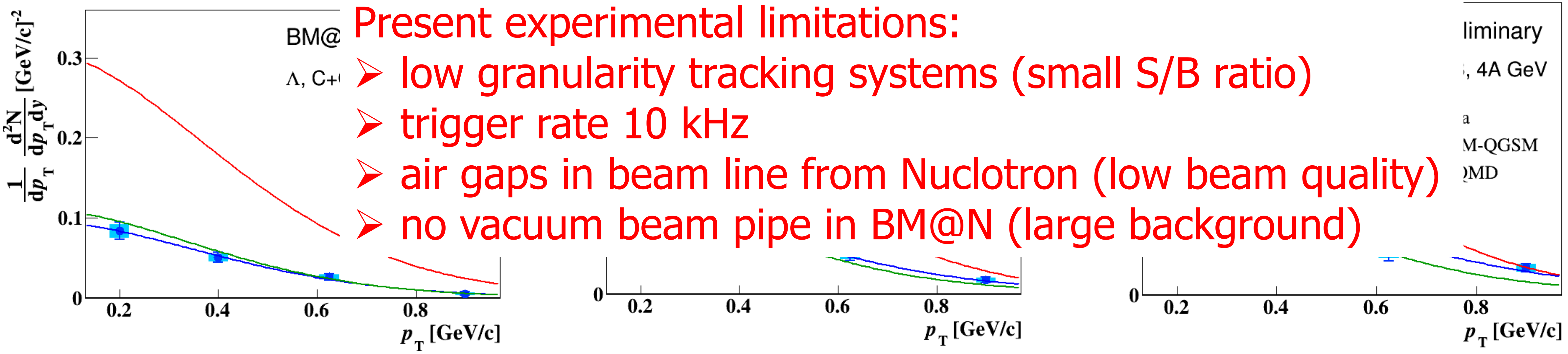
Show case:

Inverse kinematics offers the opportunity to measure SRC in short-lived neutron-rich nuclei at radioactive beam facilities, which will shed light on the properties of dense and cold matter in neutron stars.



Experiments performed at BM@N:
Lambda production in C + C, Al, Cu collisions at 4A GeV

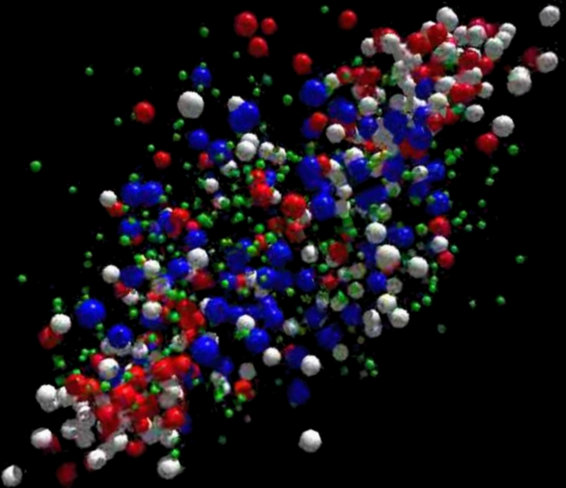


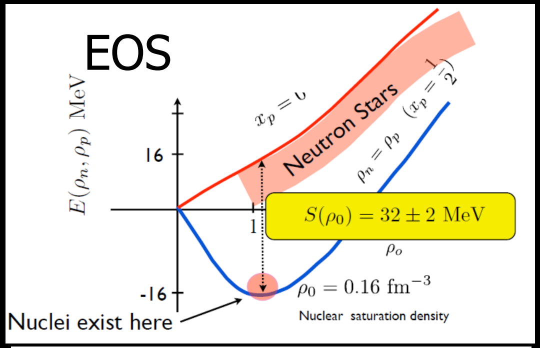


Present experimental limitations:

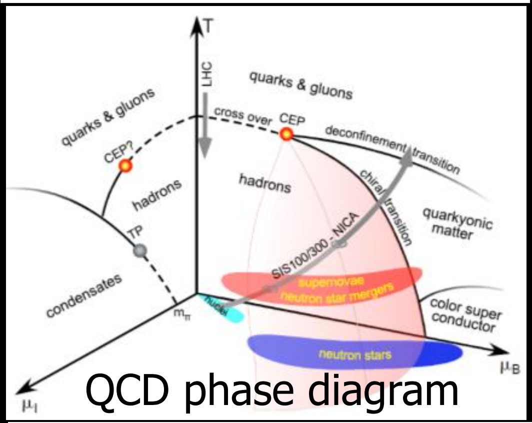
- low granularity tracking systems (small S/B ratio)
- trigger rate 10 kHz
- air gaps in beam line from Nuclotron (low beam quality)
- no vacuum beam pipe in BM@N (large background)

Upgrading the BM@N experiment:
Exploring nuclear matter at neutron star core densities

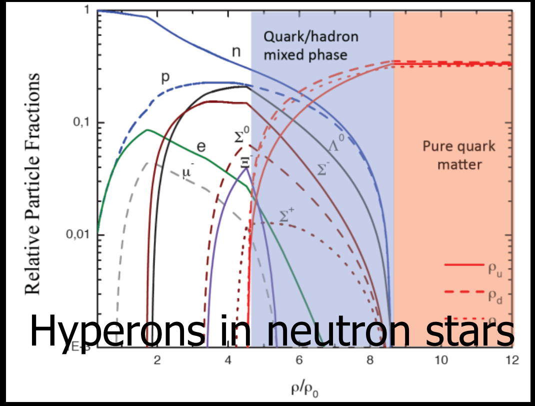




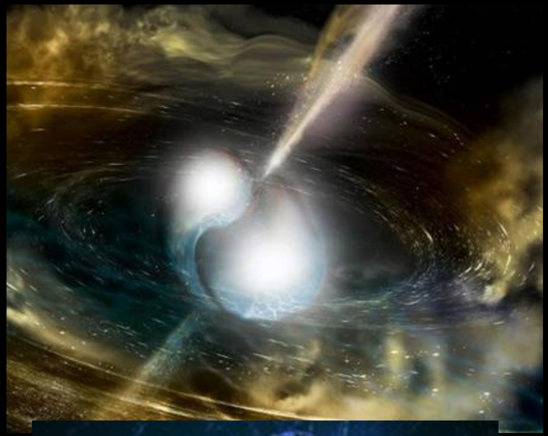
EOS

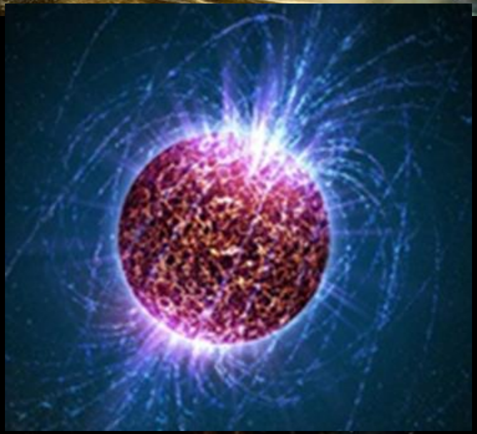


QCD phase diagram



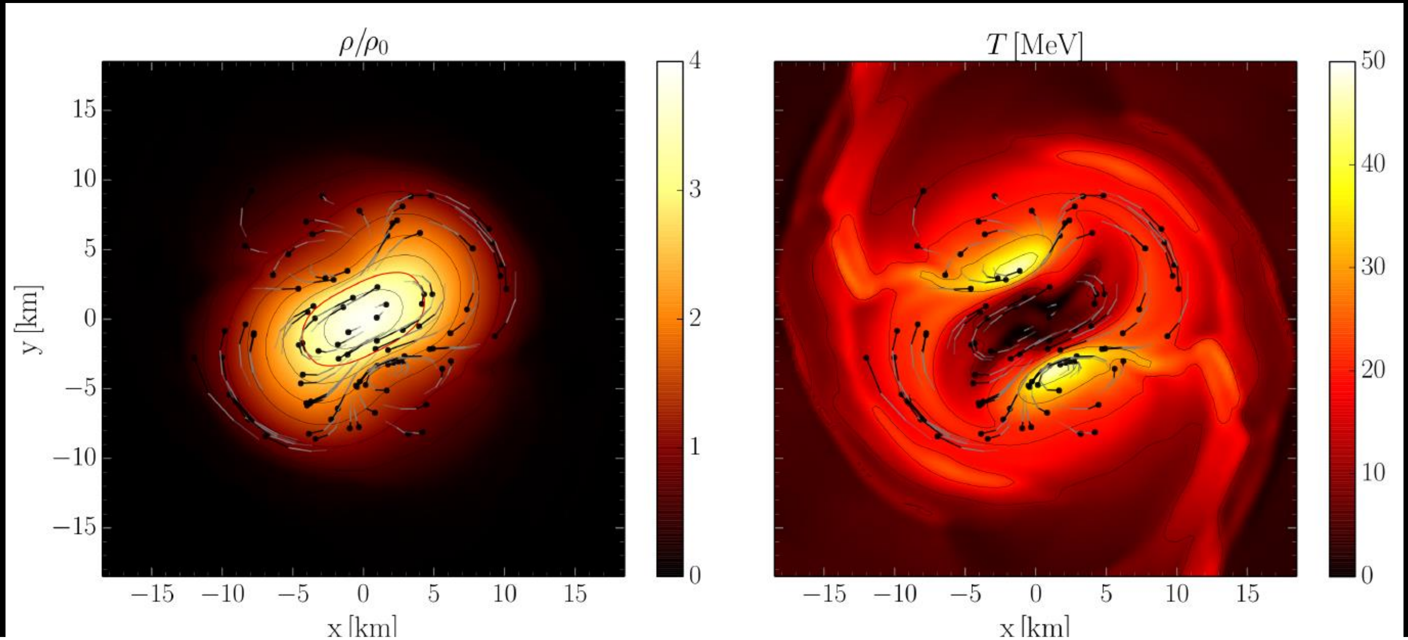
Hyperons in neutron stars





Neutron star mergers and heavy-ion collisions

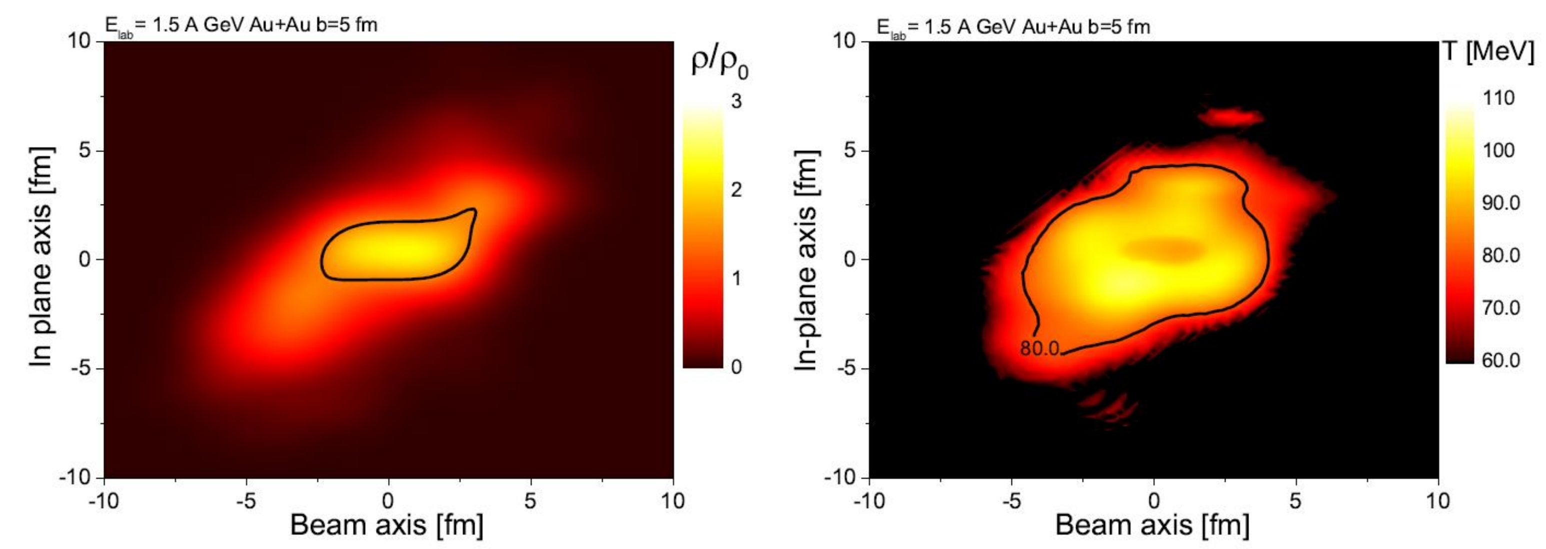
density temperature



M. Hanauske et al.,
J. Phys.: Conf. Ser.
878 012031

n-star merger

EOS



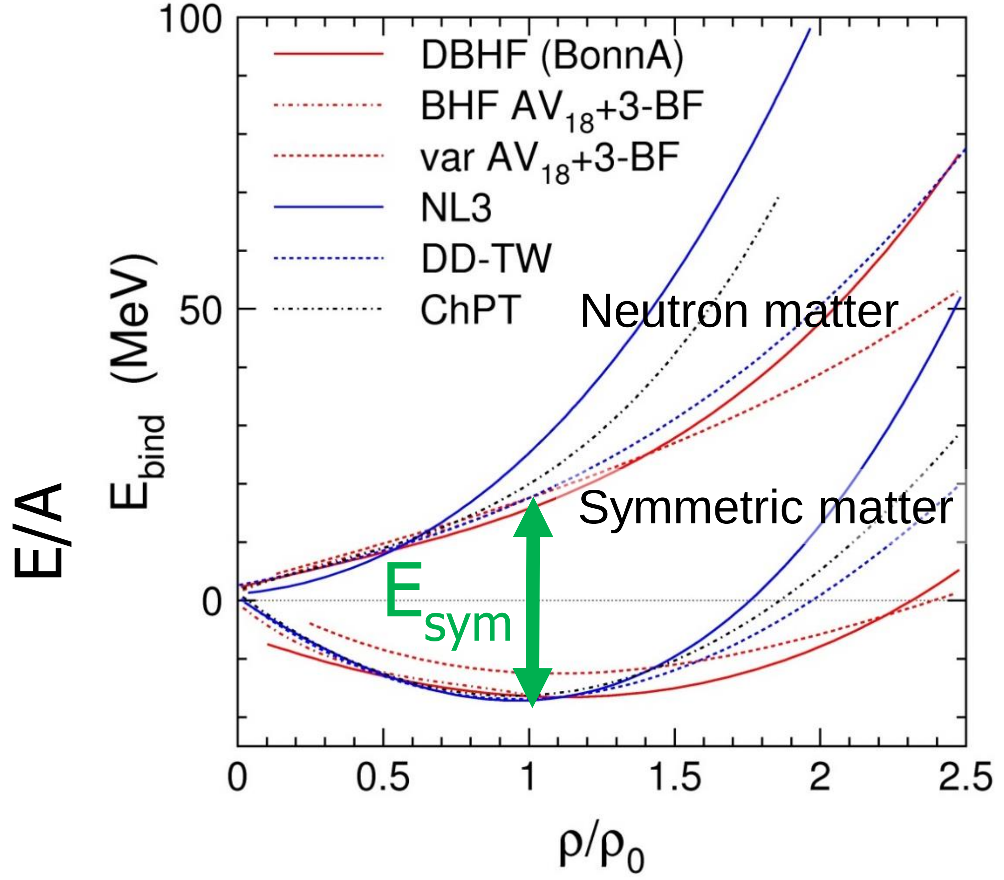
Au +Au
1.5A GeV

The nuclear matter equation-of-state

The nuclear matter equation of state (EOS) describes the relation between density, pressure, temperature, energy, and isospin asymmetry

$P = \delta E/\delta V \big|_{T=const}$
$V = A/\rho$
$\delta V/ \delta\rho = - A/\rho^2$
$P = \rho^2\ \delta(E/A)/\delta\rho \big|_{T=const}$

$E_A(\rho,\delta) = E_A(\rho,0)+E_{sym}(\rho)\cdot\delta^2$ with $\delta= (\rho_n-\rho_p)/\rho$

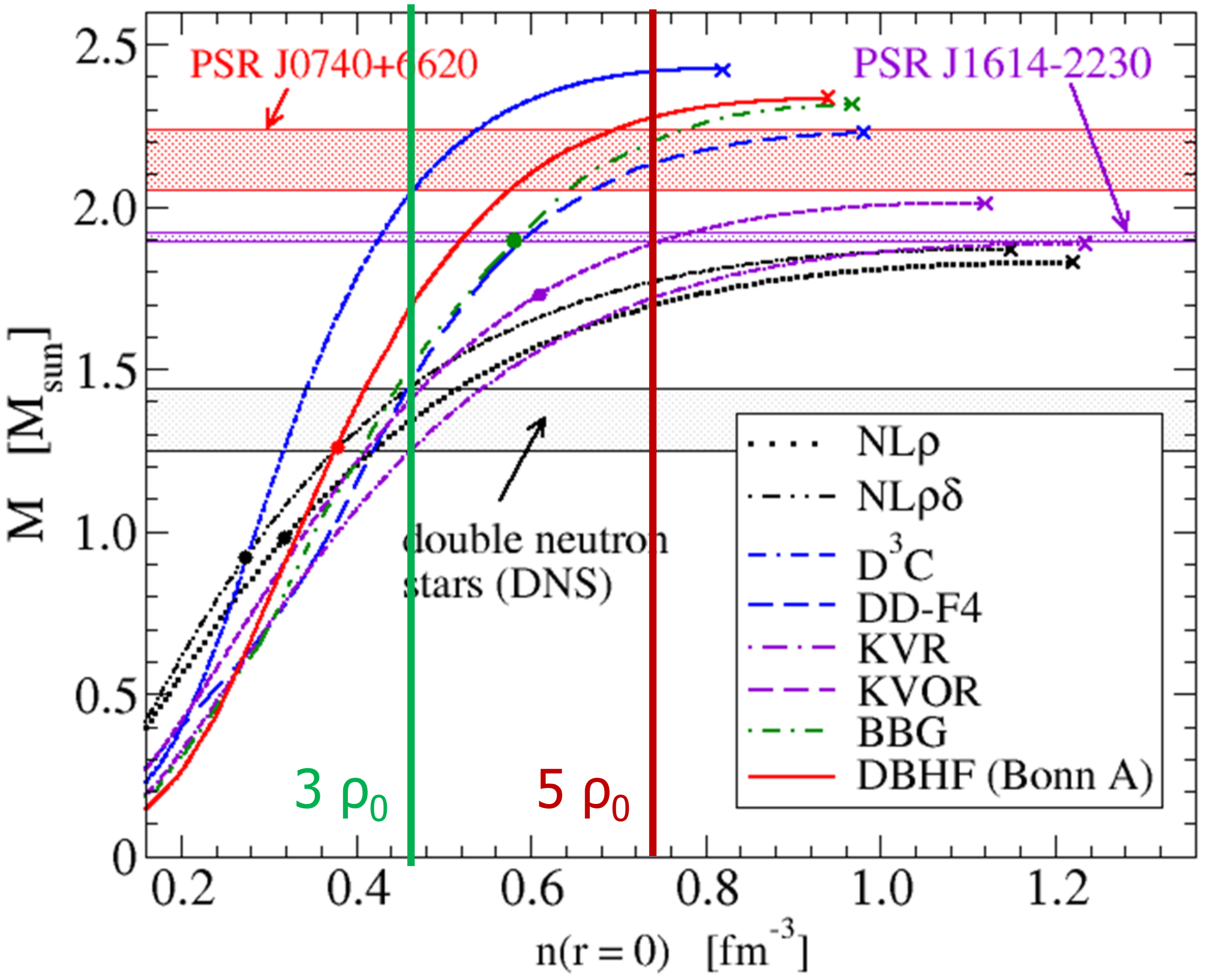


Ch. Fuchs and H.H. Wolter, EPJA 30 (2006) 5

Symmetric matter (δ=0):

- $E/A(\rho_o)$ = -16 MeV
- slope $\delta(E/A)(\rho_o)/\delta\rho = 0$
- curvature $K_{nm} = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$
  (nuclear incompressibility)

Mass-density relation of neutron stars for different EOS



PSR J0740+6620
M = 2.17±0.11 M$_{sun}$
H. Cromartie et al.,
arXiv:1904.06759 (2019)

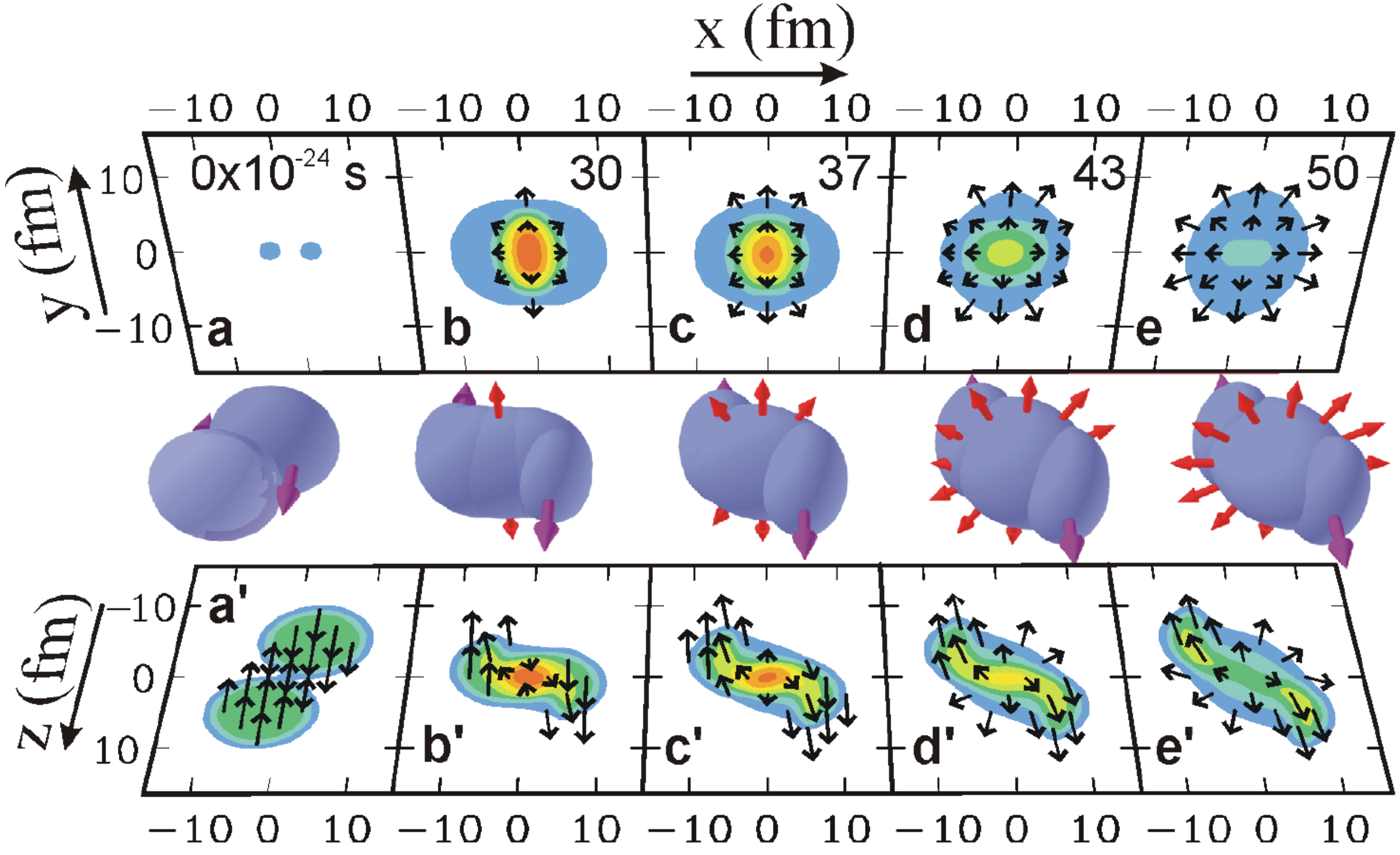
PSR J0348+0432
M = 2.01±0.04 M$_{sun}$
J. Antoniadis et al.,
Science ***340****, 6131 (2013)*

PSR J1614-2230
M = 1.97±0.04 M$_{sun}$
P. Demorest et al.,
Nature 467, 1081 (2010)

T. Klaehn et al., Phys. Rev. C74: 035802, 2006. Update by D. Blaschke, priv. comm.

Observable in heavy-ion collisions: Collective flow of nucleons

semi-central Au+Au collision at 2 AGeV

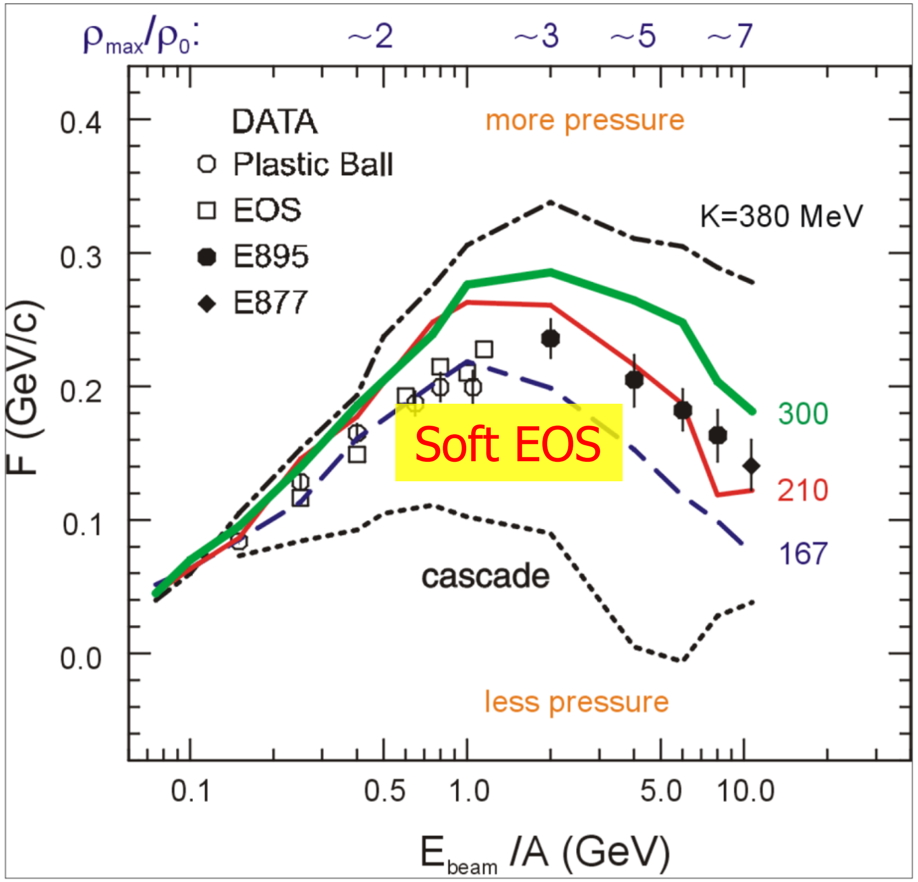


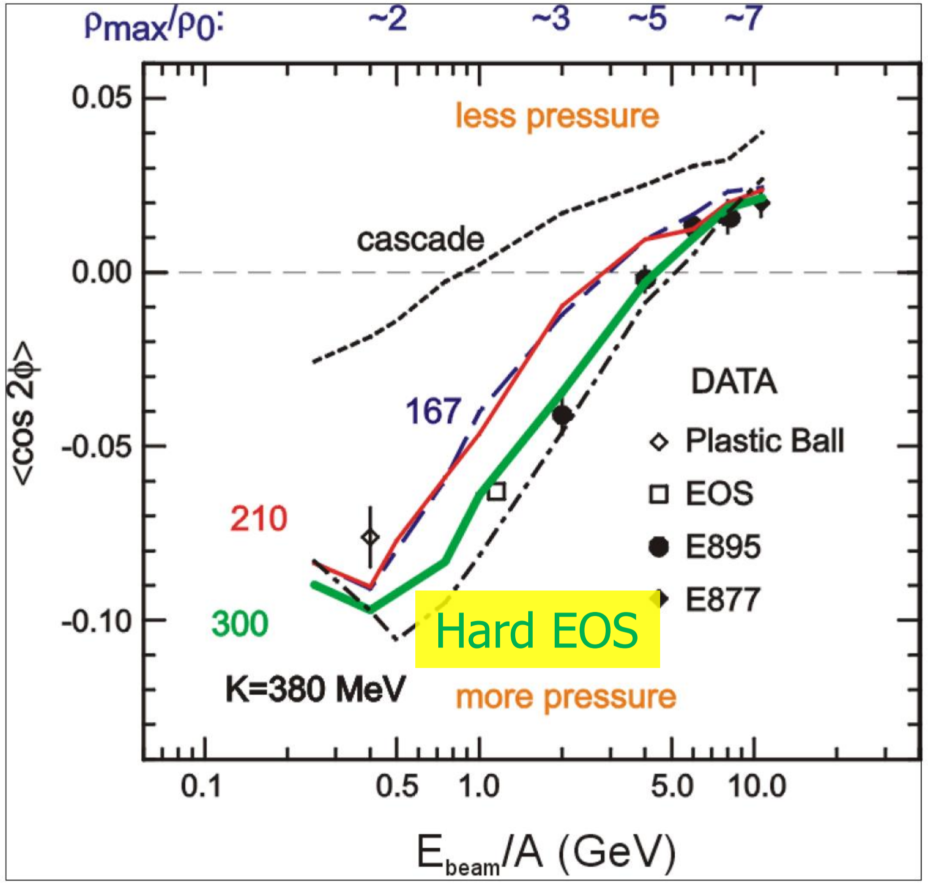
Collective flow of nucleons: driven by pressure gradient in the fireball

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Nuclear incompressibility from collective proton flow

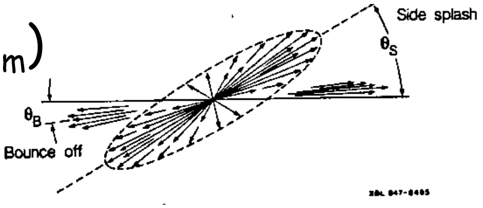
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



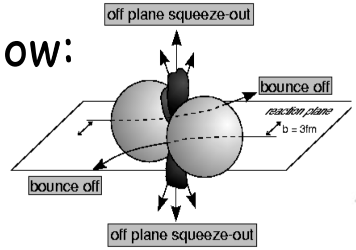


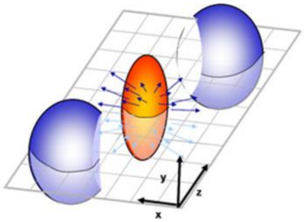
Transverse in-plane flow:

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



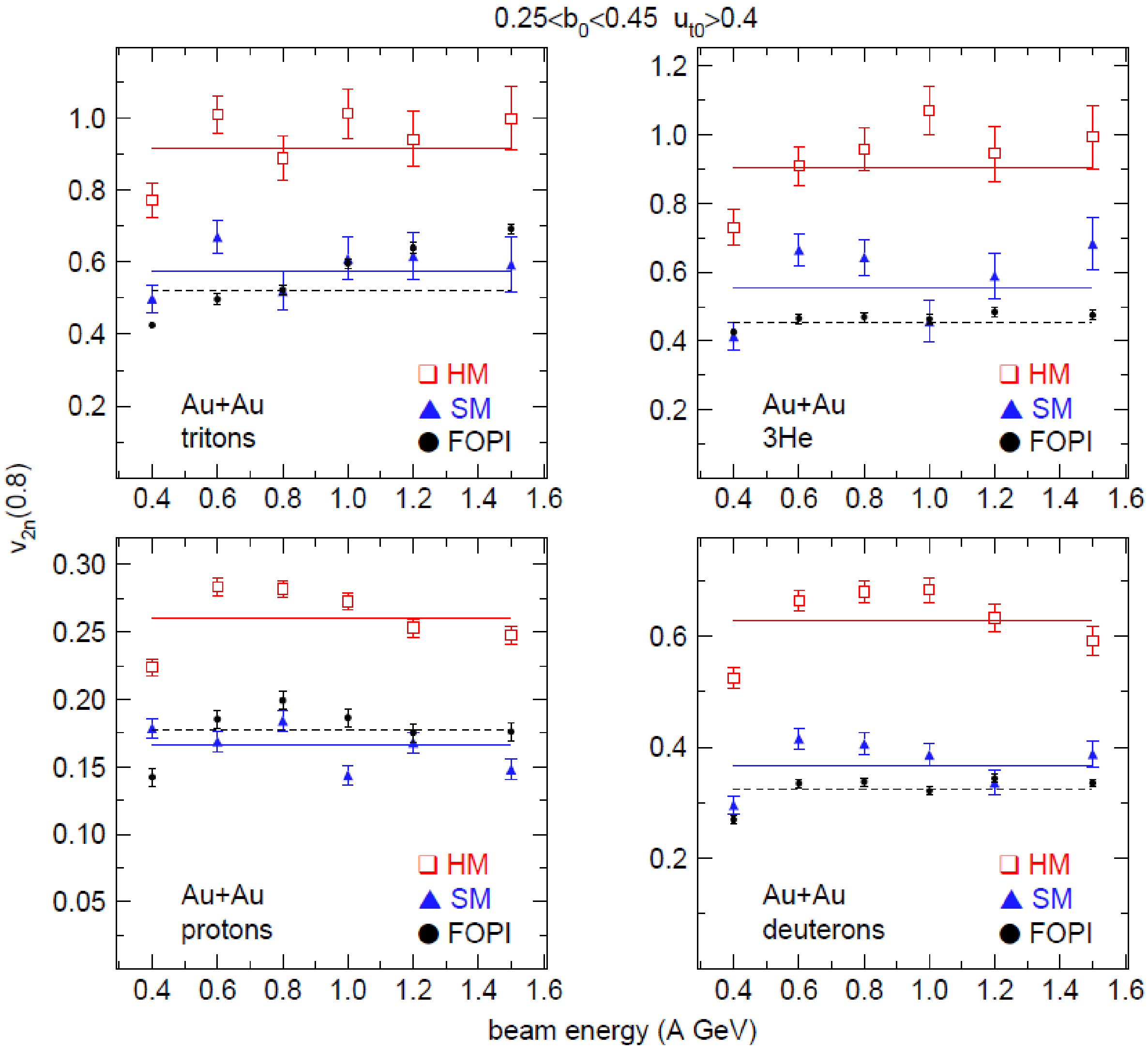
Elliptic flow:

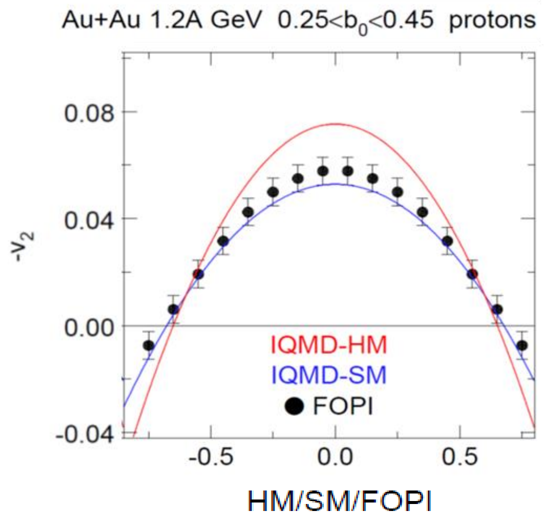




$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos 2\Phi)$

FOPI at GSI: EOS from the elliptic flow of fragments in Au+Au collisions at SIS18 energies ($\rho < 3\rho_0$)



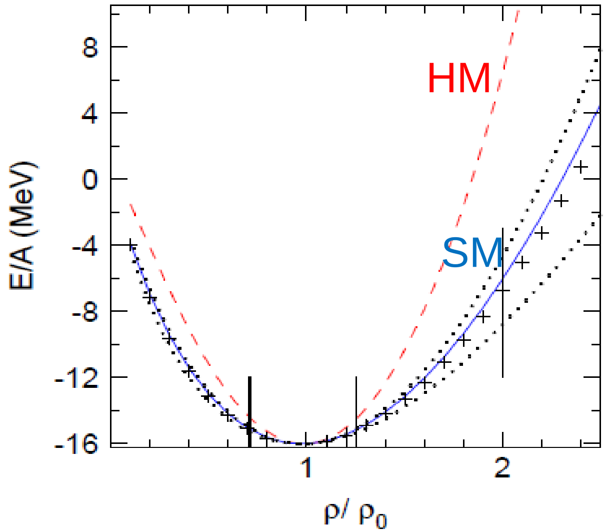


Hard Momentum-dependent

HM: K = 380 MeV

Soft Momentum dependent

SM: K_0 = 200 MeV



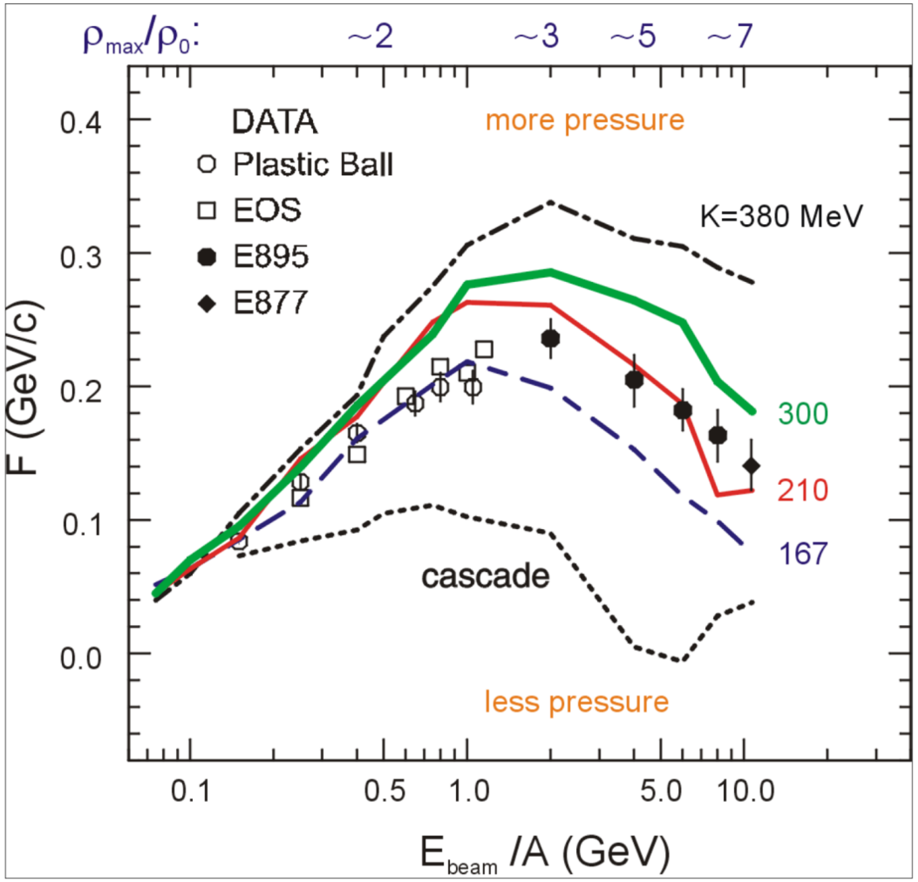
Nuclear incompressibility

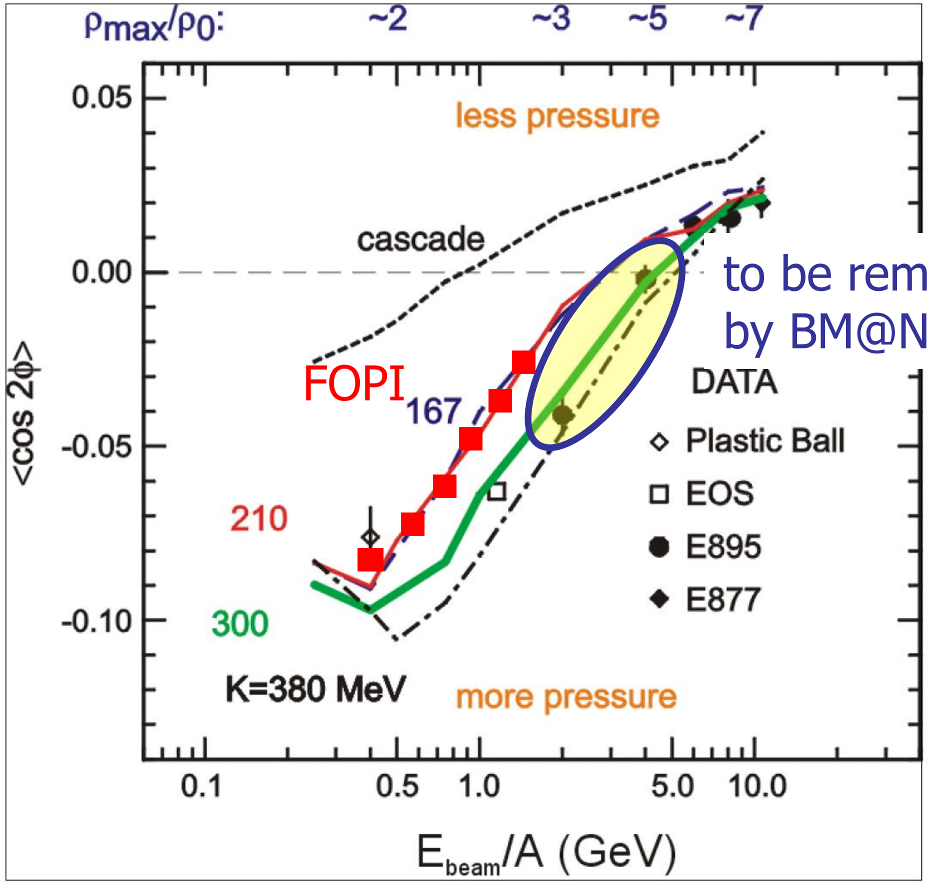
K_0=190 ±30 MeV

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

Nuclear incompressibility from collective proton flow

P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

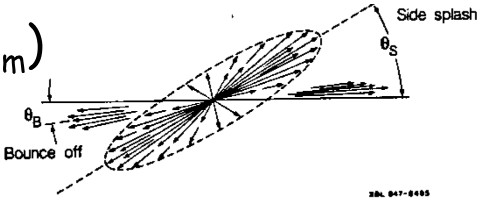




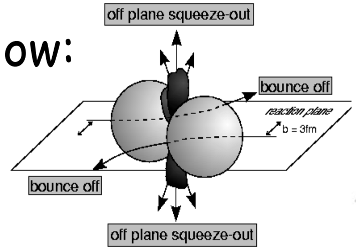
to be remeasured by BM@N

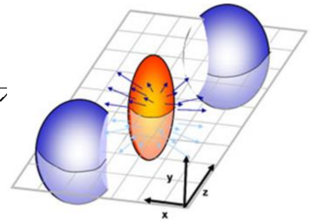
Transverse in-plane flow:

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



Elliptic flow:





$dN/d\Phi \propto (1 + 2v_1 \cos\Phi + 2v_2 \cos2\Phi)$

Exploring the EOS with subthreshold strangeness production

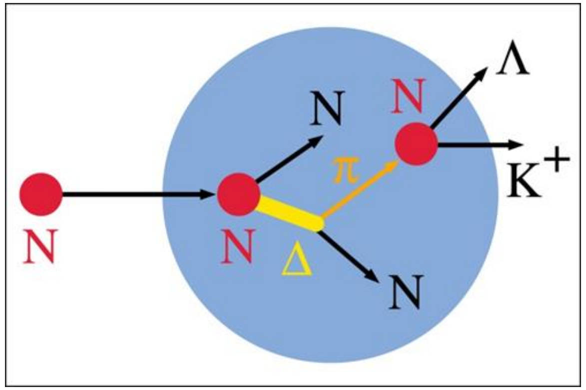
Experiment: C. Sturm et al., (KaoS Collaboration) Phys. Rev. Lett. 86 (2001) 39

Theory: QMD Ch. Fuchs et al., Phys. Rev. Lett. 86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

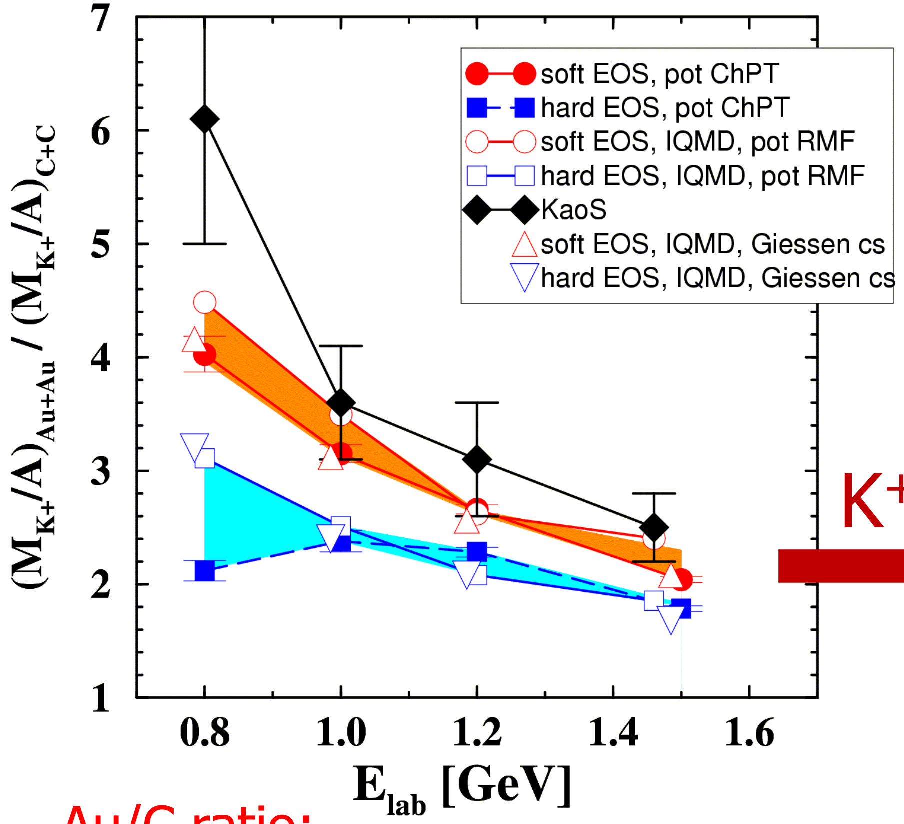
K^+ meson production in Au+Au and C+C collisions at 0.8 – 1.5A GeV

$pp \to K^+ \Lambda p$
(E_{thres}= 1.6 GeV)

subthreshold production:
density dependent

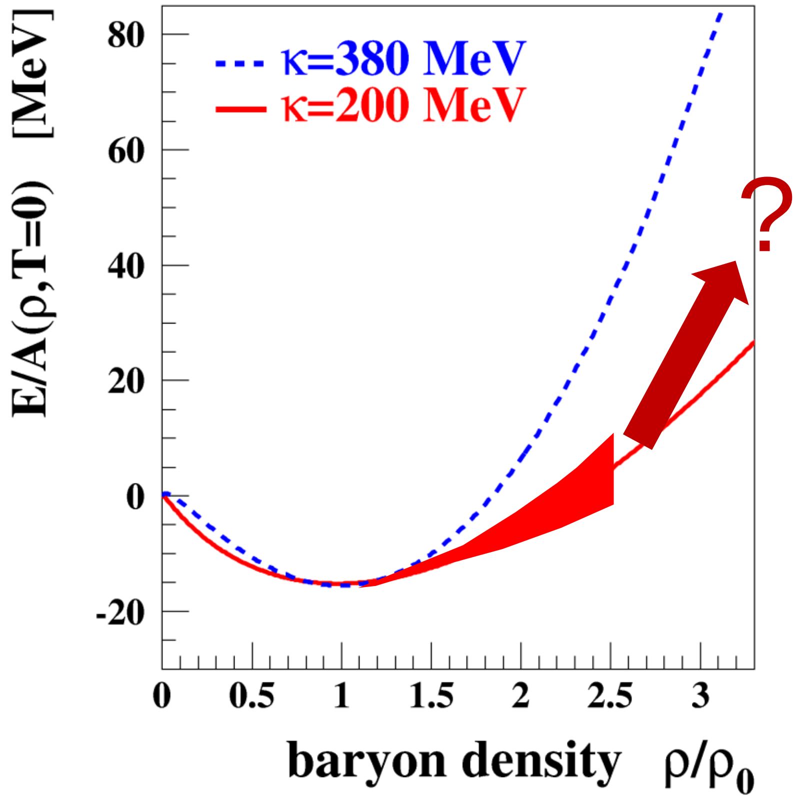


Au+Au: strong EOS effect,
C+C: no EOS effect



Au/C ratio:
cancellation of systematic errors
both in experiment and theory

K^+ → ?



Soft equation-of-state: κ ≤ 200 MeV
Confirmation of flow measurements

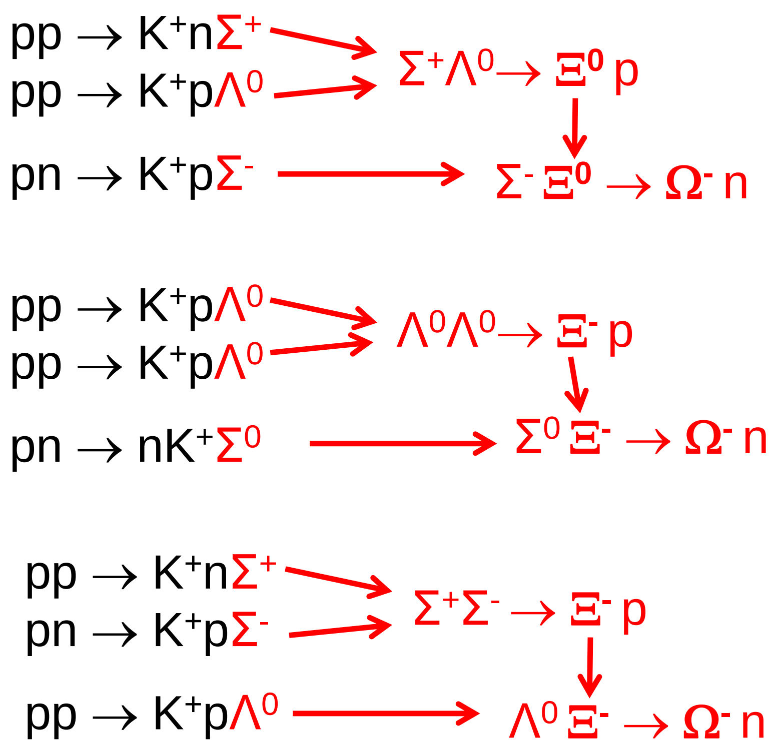
Probe of the high-density EOS:
subthreshold production of multi-strange hyperons

Idea: Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density → EOS

Strangeness production:

$pp \rightarrow K^+\Lambda^0 p$	(E_{thr} = 1.6 GeV)
$pp \rightarrow K^+K^- pp$	(E_{thr} = 2.5 GeV)
$pp \rightarrow \Xi^- K^+K^+ p$	(E_{thr} = 3.7 GeV)
$pp \rightarrow \Omega^- K^+K^+K^0 p$	(E_{thr} = 7.0 GeV)
$pp \rightarrow \bar{\Lambda}^0\Lambda^0 pp$	(E_{thr} = 7.1 GeV)
$pp \rightarrow \Xi^+ \Xi^- pp$	(E_{thr} = 9.0 GeV)
$pp \rightarrow \Omega^+ \Omega^- pp$	(E_{thr} = 12.7 GeV

Hyperon production via multiple collisions



$pp \rightarrow K^+ n \Sigma^+$
$pp \rightarrow K^+ p \Lambda^0$
$\Sigma^+\Lambda^0 \rightarrow \Xi^0 p$
$pn \rightarrow K^+ p \Sigma^-$
$\Sigma^- \Xi^0 \rightarrow \Omega^- n$

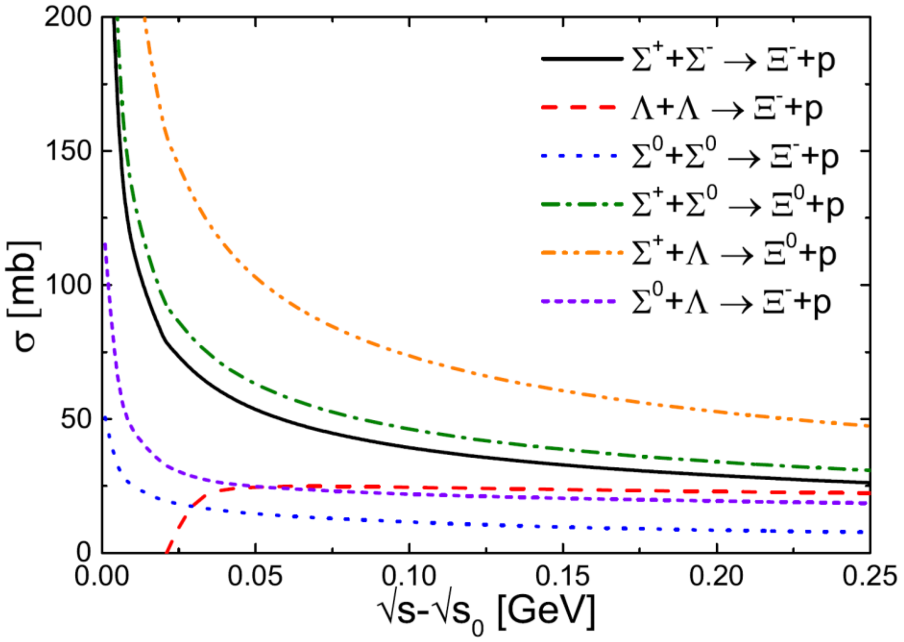
$pp \rightarrow K^+ p \Lambda^0$
$pp \rightarrow K^+ p \Lambda^0$
$\Lambda^0\Lambda^0 \rightarrow \Xi^- p$
$pn \rightarrow n K^+ \Sigma^0$
$\Sigma^0 \Xi^- \rightarrow \Omega^- n$

$pp \rightarrow K^+ n \Sigma^+$
$pn \rightarrow K^+ p \Sigma^-$
$\Sigma^+\Sigma^- \rightarrow \Xi^- p$
$pp \rightarrow K^+ p \Lambda^0$
$\Lambda^0 \Xi^- \rightarrow \Omega^- n$

Probe of the high-density EOS: subthreshold production of multi-strange hyperons

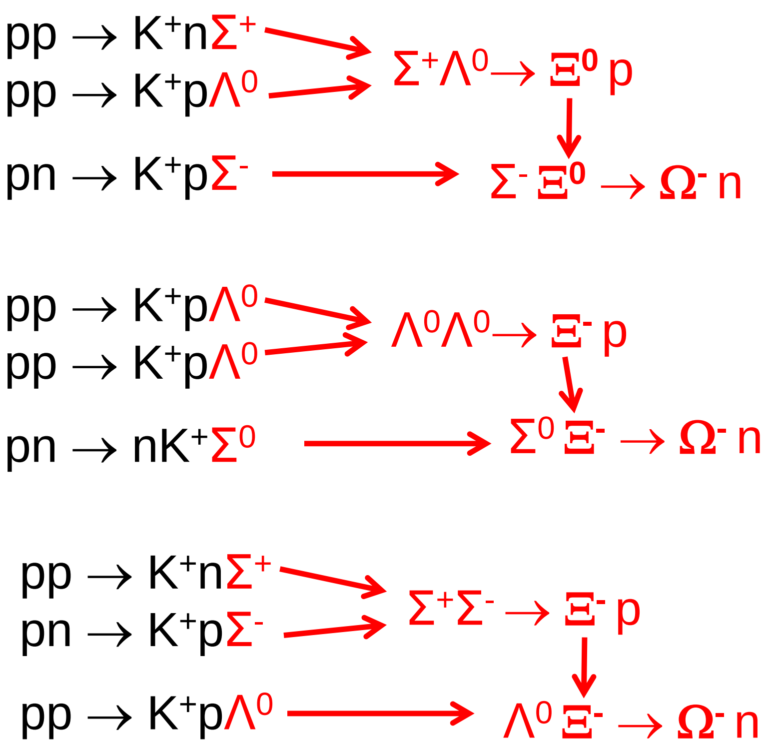
Idea: Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density → EOS

Isospin-dependent strangeness-exchange cross sections in UrQMD



G. Graef, J. Steinheimer, F. Li, M. Bleicher, Phys. Rev. C 90, 064909 (2014)

Hyperon production via multiple collisions



$pp \rightarrow K^+ n \Sigma^+$

$pp \rightarrow K^+ p \Lambda^0$

$\Sigma^+ \Lambda^0 \rightarrow \Xi^0 p$

$pn \rightarrow K^+ p \Sigma^-$

$\Sigma^- \Xi^0 \rightarrow \Omega^- n$

$pp \rightarrow K^+ p \Lambda^0$

$pp \rightarrow K^+ p \Lambda^0$

$\Lambda^0 \Lambda^0 \rightarrow \Xi^- p$

$pn \rightarrow n K^+ \Sigma^0$

$\Sigma^0 \Xi^- \rightarrow \Omega^- n$

$pp \rightarrow K^+ n \Sigma^+$

$pn \rightarrow K^+ p \Sigma^-$

$\Sigma^+ \Sigma^- \rightarrow \Xi^- p$

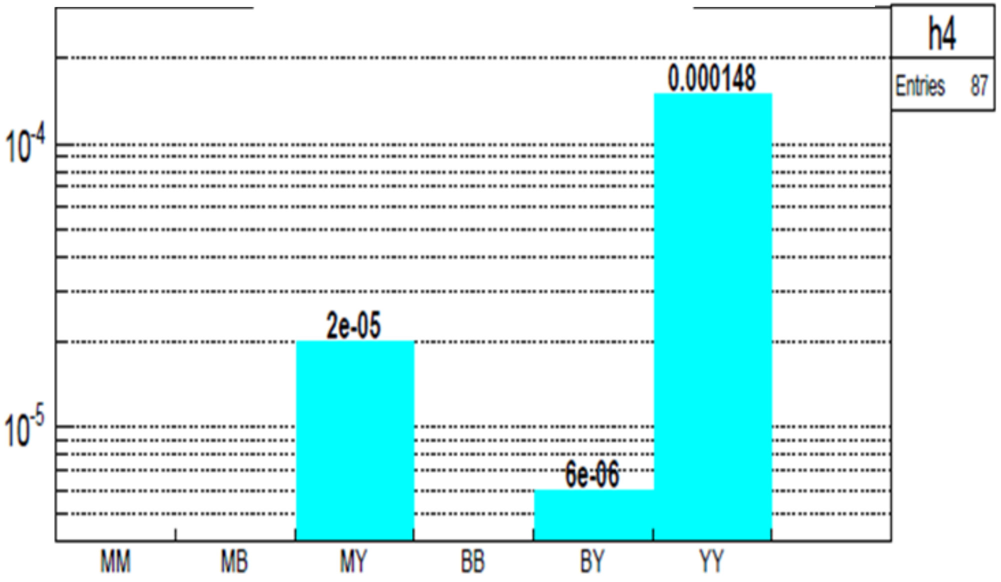
$pp \rightarrow K^+ p \Lambda^0$

$\Lambda^0 \Xi^- \rightarrow \Omega^- n$

Probe of the high-density EOS: subthreshold production of multi-strange hyperons

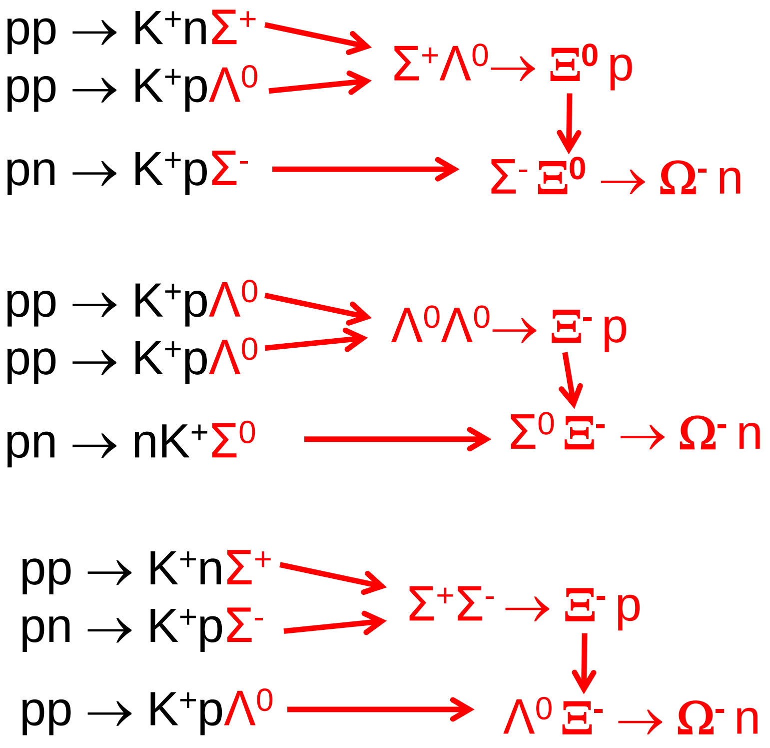
Idea: Ξ and Ω yield at subthreshold energies ~ multi-step collisions ~ density → EOS

Ω^- production in 4 A GeV Au+Au
(BM@N energies!)



HYPQGSM calculations , K. Gudima et al.

Hyperon production via multiple collisions



$pp \to K^+ n \Sigma^+$

$pp \to K^+ p \Lambda^0$

$\Sigma^+ \Lambda^0 \to \Xi^0 p$

$pn \to K^+ p \Sigma^-$

$\Sigma^- \Xi^0 \to \Omega^- n$

$pp \to K^+ p \Lambda^0$

$pp \to K^+ p \Lambda^0$

$\Lambda^0 \Lambda^0 \to \Xi^- p$

$pn \to n K^+ \Sigma^0$

$\Sigma^0 \Xi^- \to \Omega^- n$

$pp \to K^+ n \Sigma^+$

$pn \to K^+ p \Sigma^-$

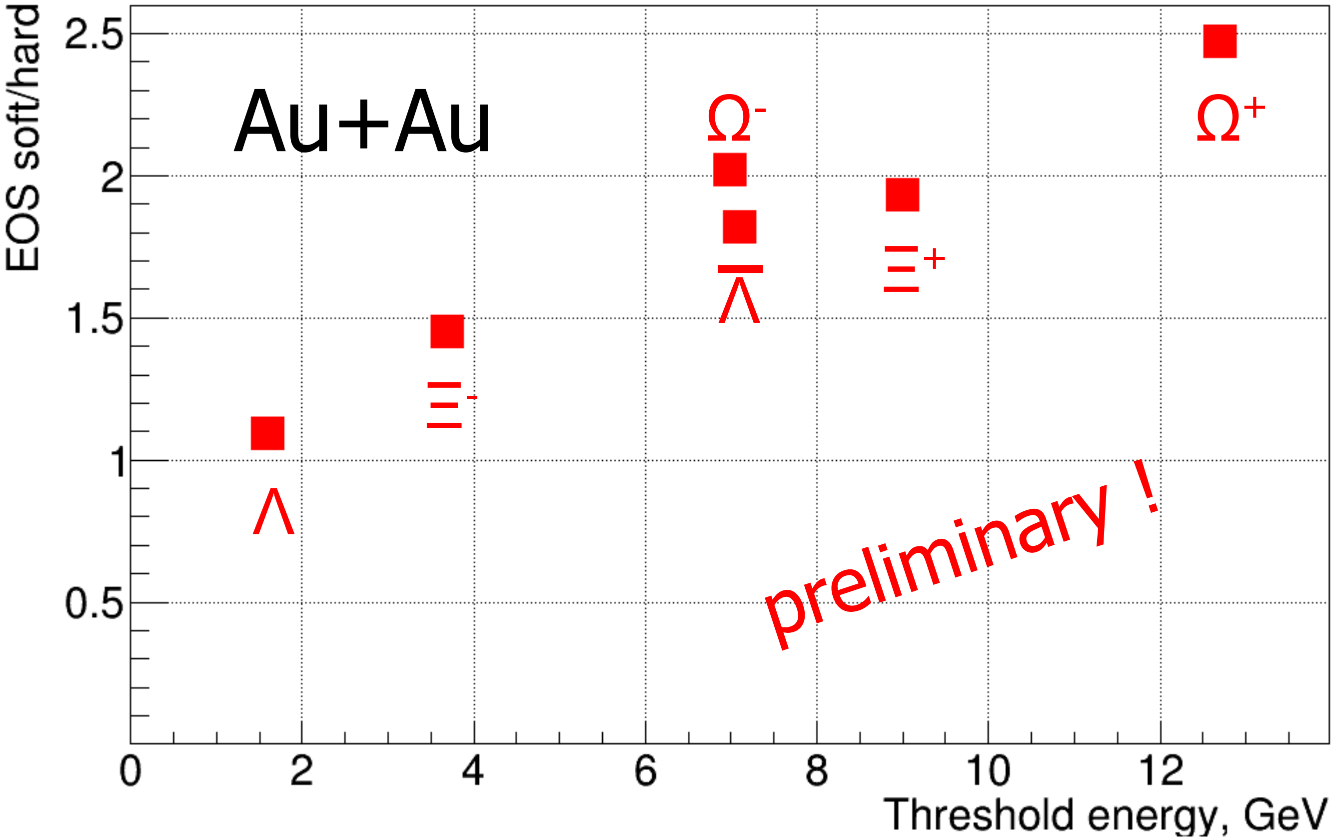
$\Sigma^+ \Sigma^- \to \Xi^- p$

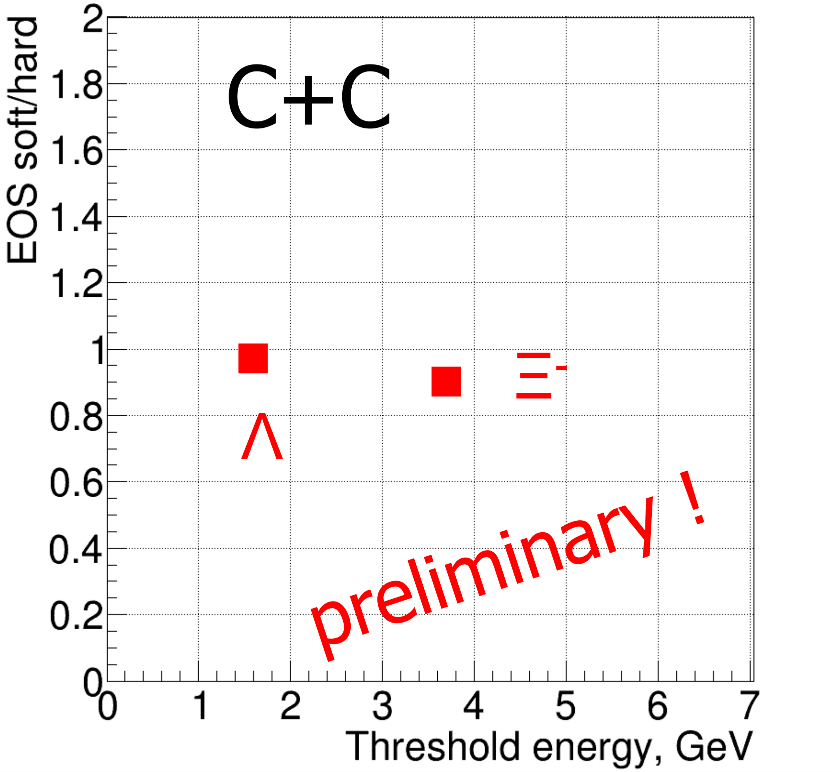
$pp \to K^+ p \Lambda^0$

$\Lambda^0 \Xi^- \to \Omega^- n$

Multi-strange hyperons: promising observables for the EOS of symmetric matter at Nuclotron beam energies

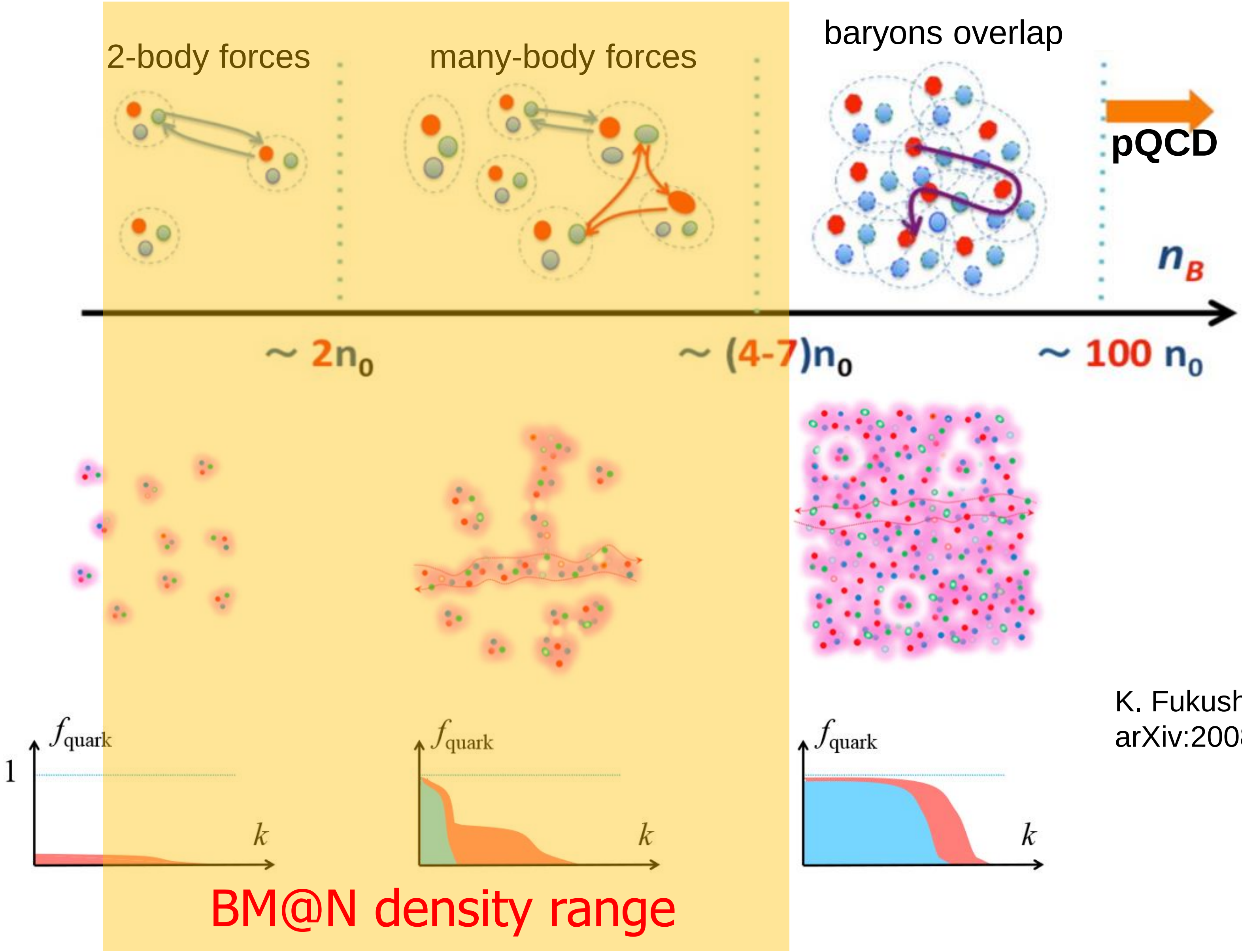
Hyperon yield in heavy ion collisions at 4A GeV (BM@N energies):
soft EOS (K=240 MeV) / hard EOS (K=350) MeV





PHQMD calculations , J. Aichelin, E. Bratkovskaya, V. Kireyeu et al., priv. comm.

Searching for the onset of deconfinement



schematic
3-stage
model

nucleons with
hard core and
pion cloud

quark occupation
function with localized
(red) and delocalized
(blue) modes

BM@N density range

Courtesy of T. Kojo

K. Fukushima,T. Kojo, W. Weise,
arXiv:2008.08436

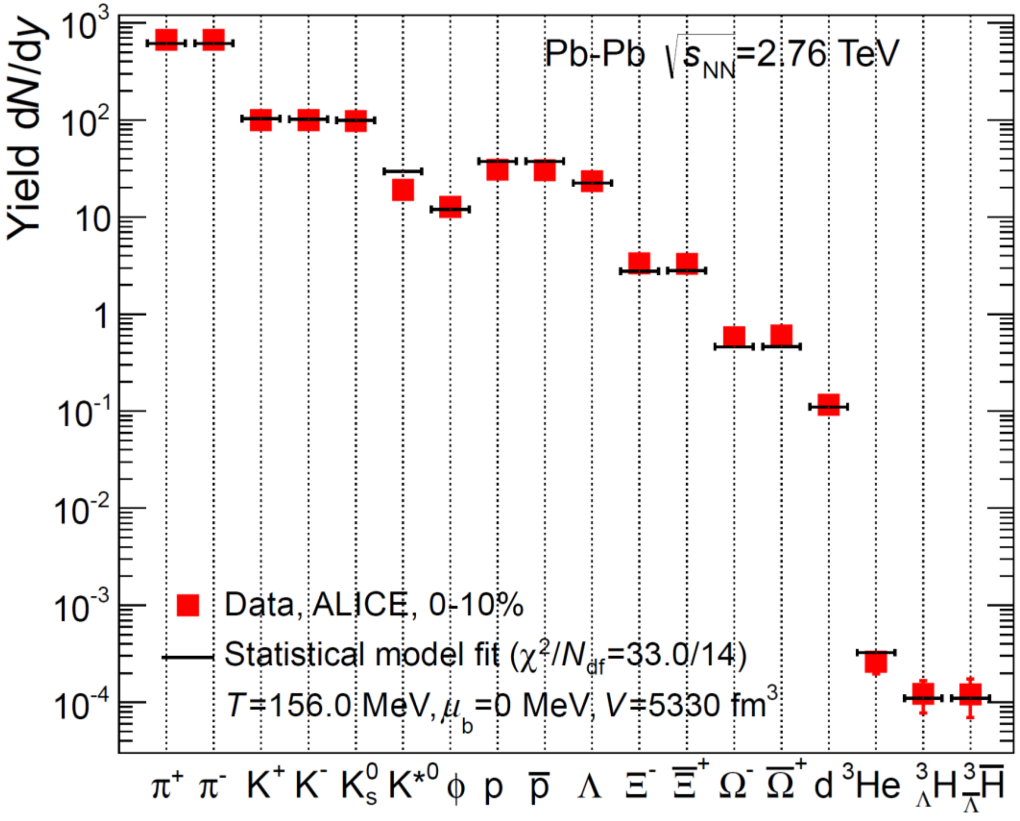
Searching the onset of deconfinement with multistrange hyperons

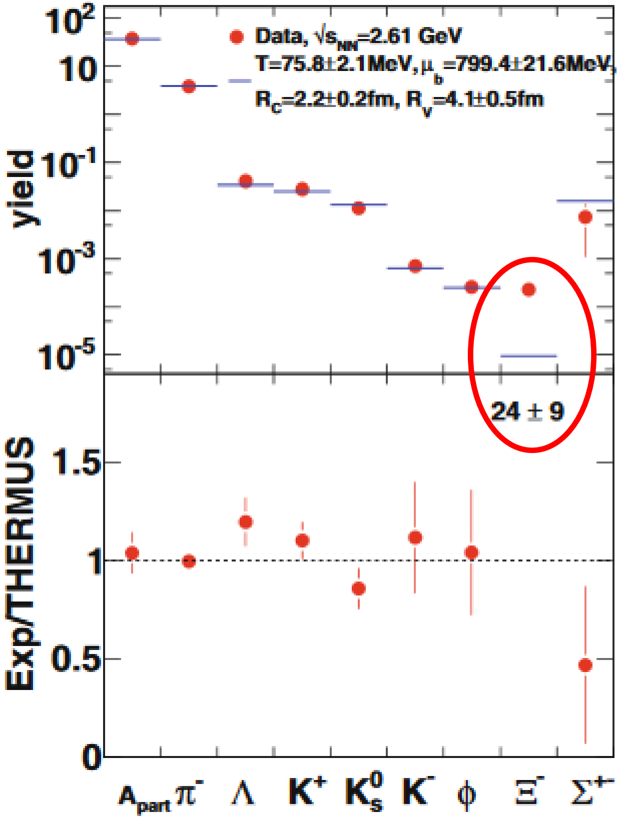
Excitation function of strangeness: Ξ^-(dss),Ξ^+($\overline{\text{dss}}$),Ω^-(sss),Ω^+($\overline{\text{sss}}$)
→ chemical equilibration at the phase boundary ?

Particle yields and thermal model fits

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i-\mu_i)/T] \pm 1}$$

A. Andronic et al., Jour. Phys. G38 (2011)





HADES:
Ar + KCl 1.76 A GeV
G. Agakishiev et al.,
Eur. Phys. J. A 47 (2011) 21

Searching the onset of deconfinement with multistrange hyperons

Excitation function of strangeness: Ξ^-(dss),Ξ^+($\overline{dss}$),Ω^-(sss),Ω^+($\overline{sss}$)
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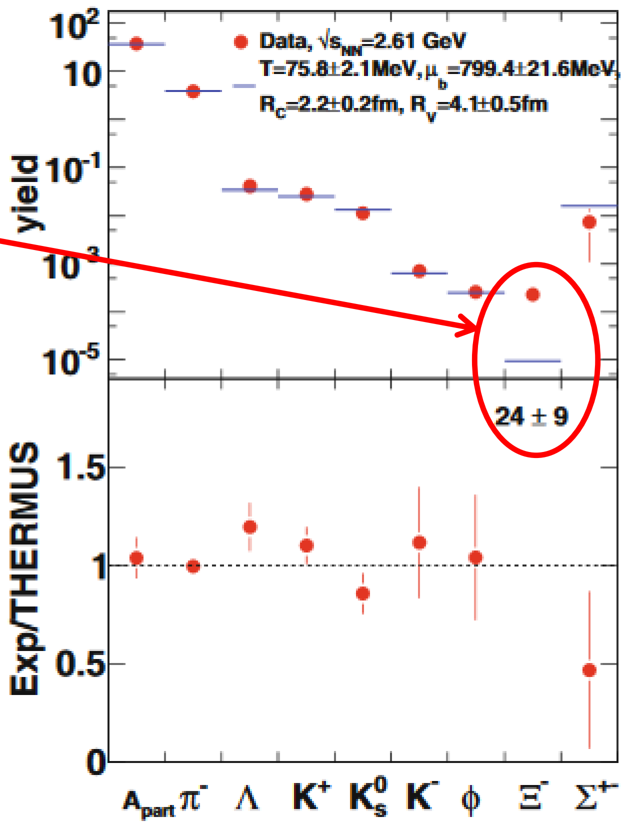
- ➢ Ξ^- production by multiple collisions including strangeness exchange
- ➢ No thermal equilibration in hadronic environment because of small hyperon-nucleon cross sections



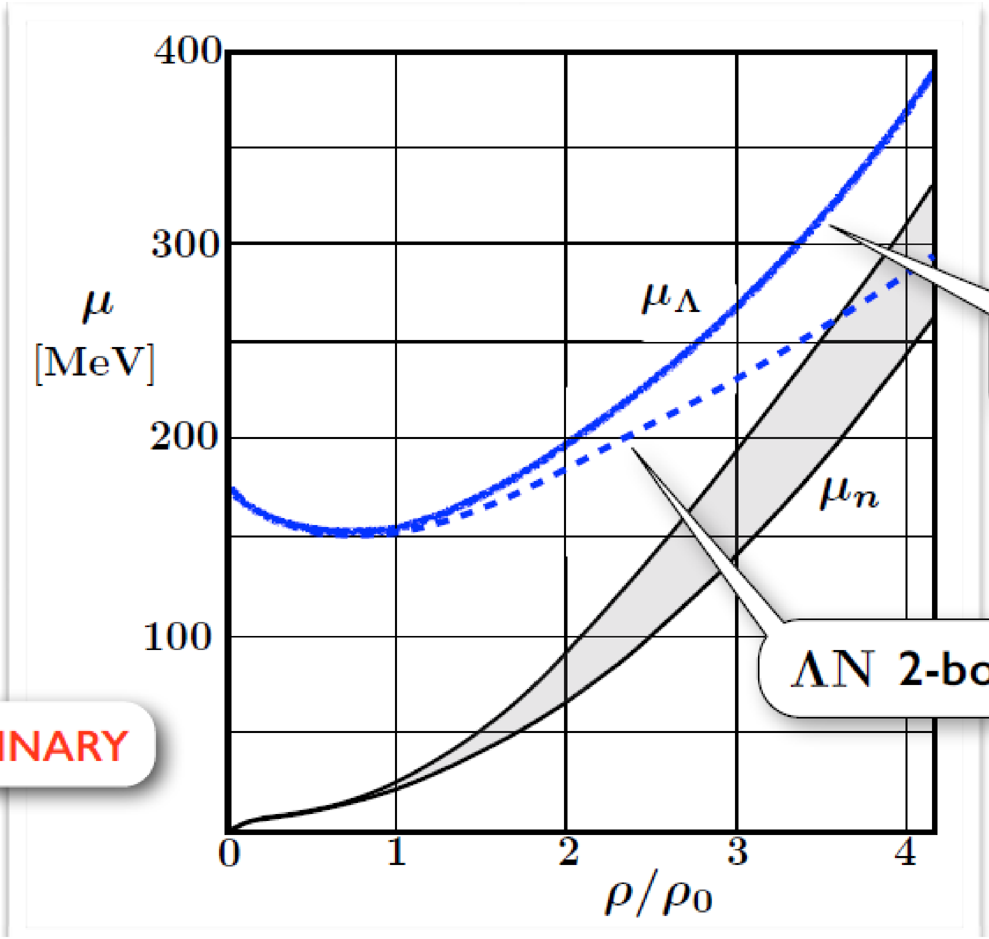
HADES:
Ar + KCl 1.76 A GeV
G. Agakishiev et al.,
Eur. Phys. J. A 47 (2011) 21

Strategy:
measure excitation function of Ξ and Ω production.
The beam energy, where thermal equilibration is reac
(or disappears), indicates onset of deconfinement

Hyperons in massive neutron stars?

chemical potentials

$$\mu_i = \frac{\partial \mathcal{E}}{\partial \rho_i}$$



$$\mu_\Lambda = \mu_n$$

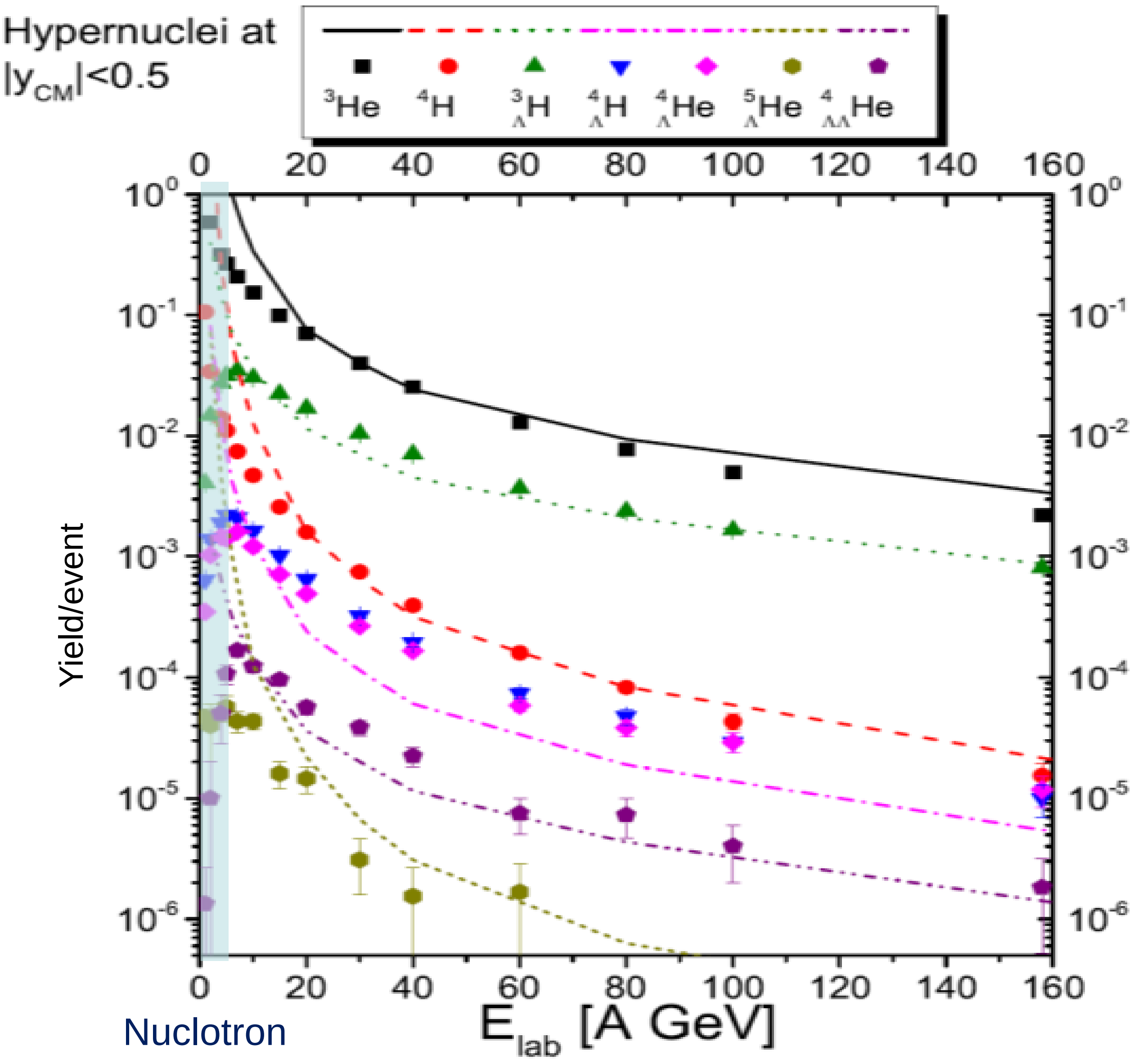
Both the chemical potentials of nucleons μ_n and hyperons μ_Λ increase with increasing baryon density.

If $\mu_n > \mu_\Lambda$, the EOS softens, and prevents the existence of massive neutron stars.

Measure ΛN, ΛNN, and ΛΛN interactions !

W. Weise, arXiv:1905.03955v1, to appear in JPS Conf. Proc
(Lambda single particle potential in neutron star matter from Chiral SU(3) EFT interactions)

Hypernuclei production in heavy-ion collisions



central Pb+Pb/Au+Au collisions

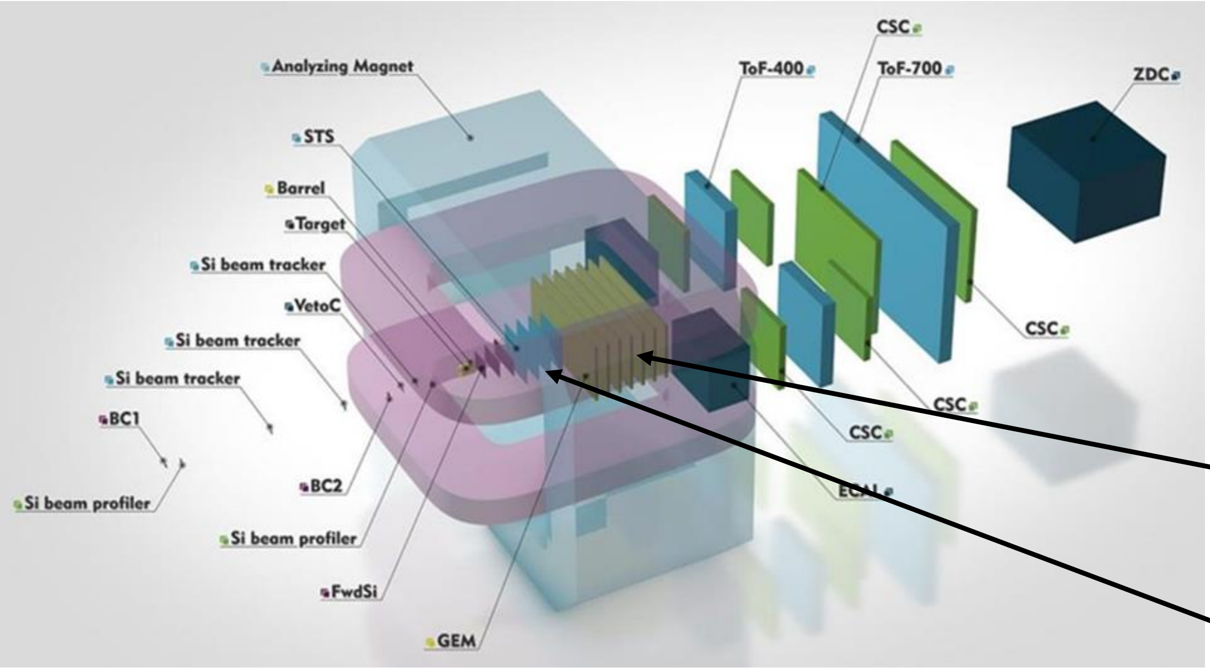
Lines:
Thermal production
(UrQMD-hydro hybrid model)

Symbols:
Coalescence results
(Dubna Cascade Model, DCM-QGSM)

The discovery of hypernuclei and the precise mearurement of their life times will shed light on the ΛN, ΛNN, and ΛΛN interactions

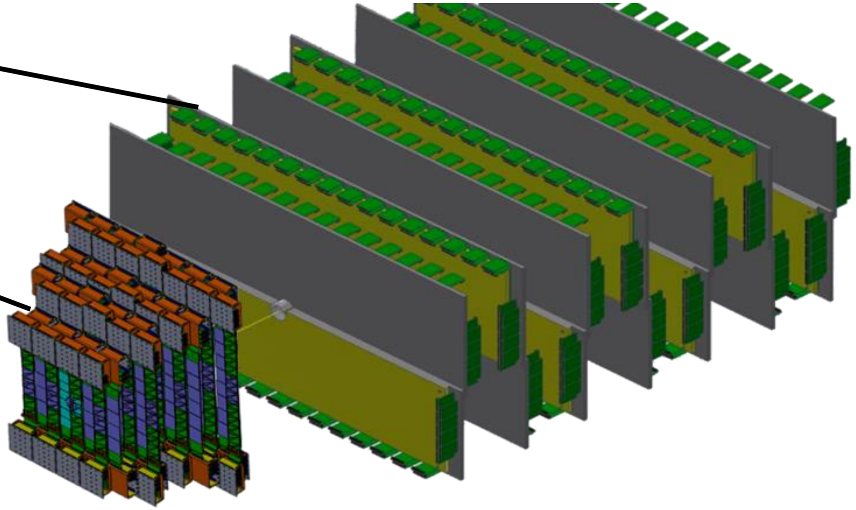
J. Steinheimer et al., Phys. Lett. B 714 (2012) 85

BM@N upgrade for Au+Au collisions up to 4.0A GeV

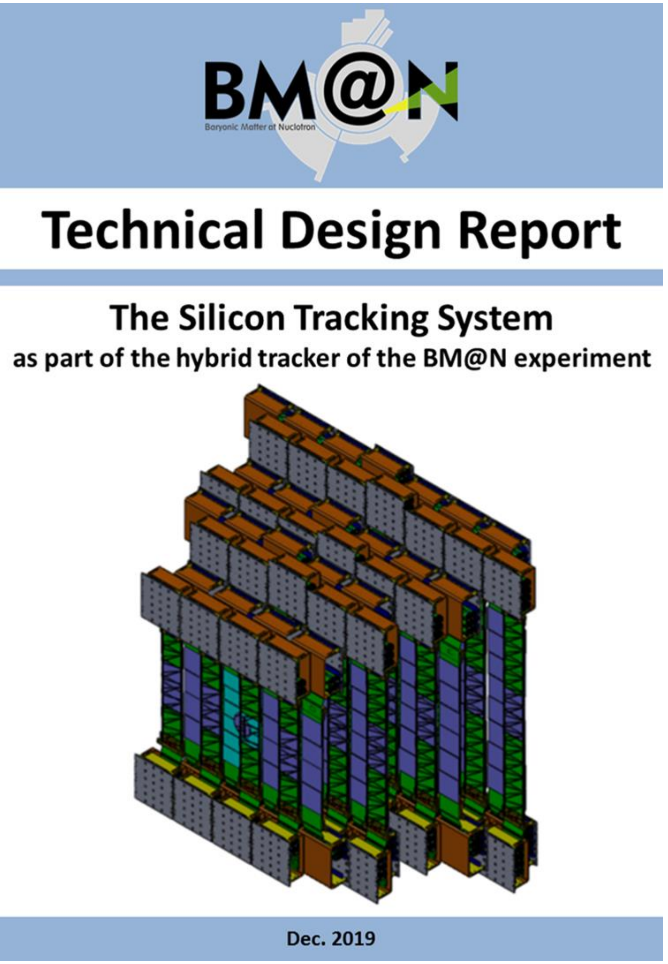


Upgrade:

- 4 stations double-sided micro-strip silicon sensors
- 7 full stations Gas-Electron-Multiplier (GEM) chambers
- Forward Hadron Calorimeter
- vacuum beam pipe from Nuclotron to BM@N
- vacuum target chamber and downstream beam pipe with low material budget



The BM@N Silicon tracking system: Based on double-sided micro-strip sensors



BM@N

Baryonic Matter at Nuclotron

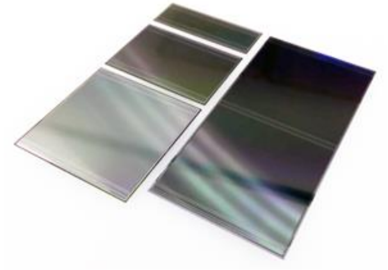
Technical Design Report

The Silicon Tracking System

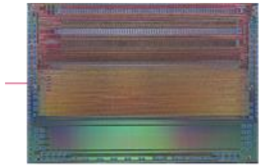
as part of the hybrid tracker of the BM@N experiment

Dec. 2019

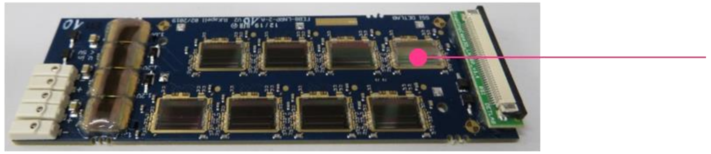
sensors



ASIC

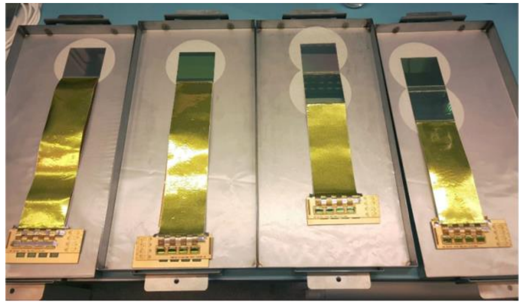


STS XYTER v.2.1



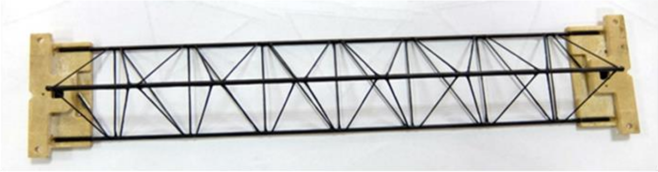
Front-end Board with 8 STS XYTER ASICs

sensors + micro cables + FEBs



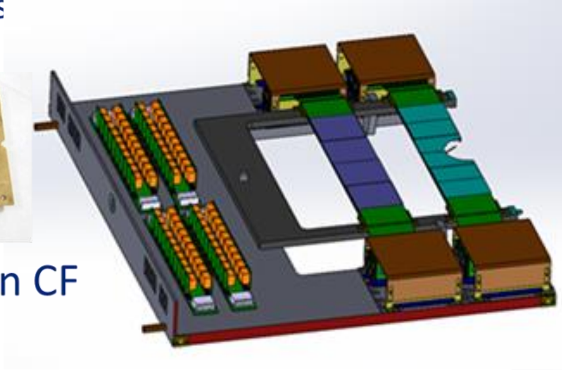
Assembled mockups of the modules

Assembled modules are covered with aluminum shielding

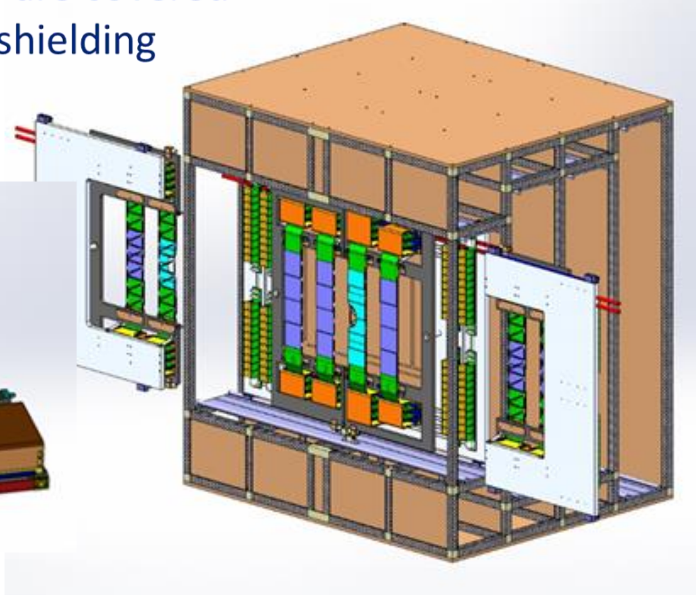


Modules are in groups installed on CF trusses with mounting blocks

half-station

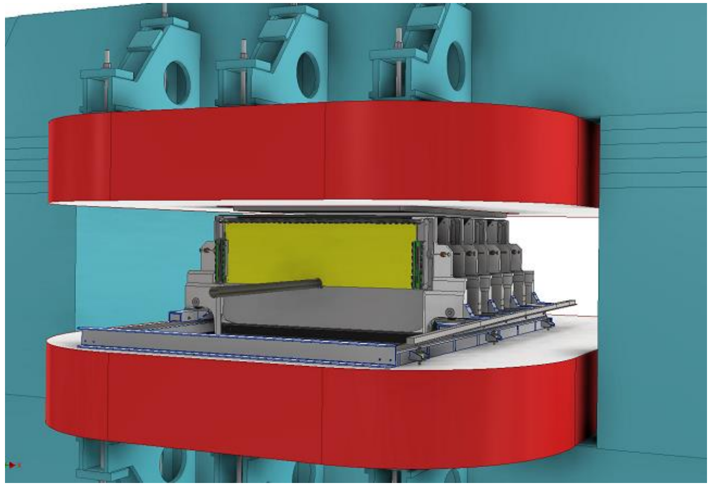


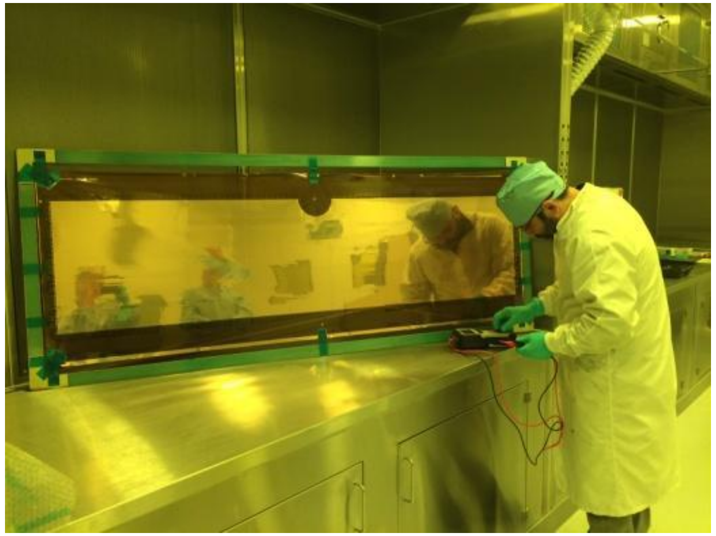
main frame

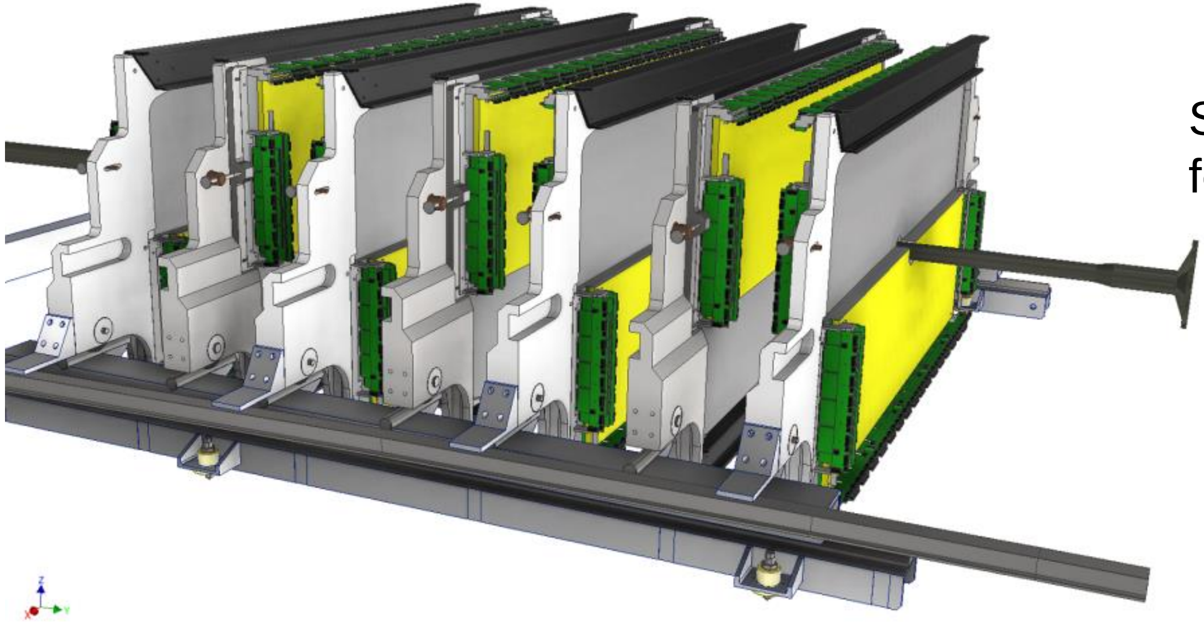


GEM central tracker for heavy ion runs

- 7 upper GEM 163x45 cm^2 chambers produced at CERN were integrated into BM@N
- 7 lower GEM 163x39 cm^2 chambers were assembled, delivered to BM@N and tested



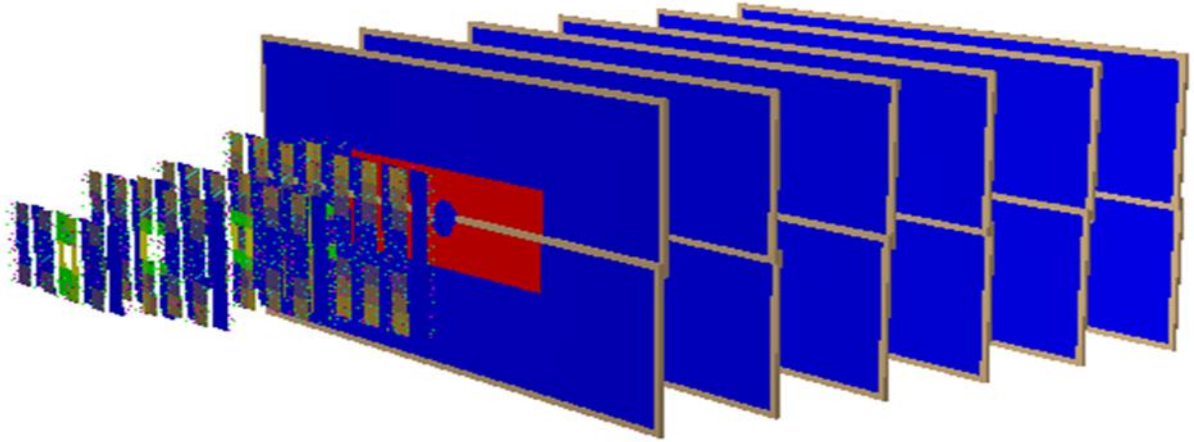




GEM 163x39 cm^2 chamber assembly at CERN

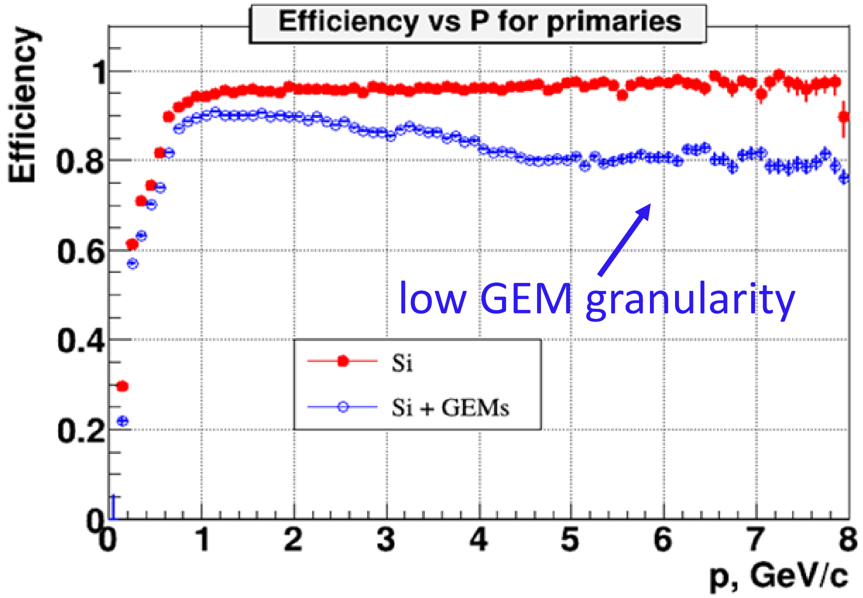
Setup of GEM detectors for cosmic tests

BM@N upgrade for Au+Au collisions



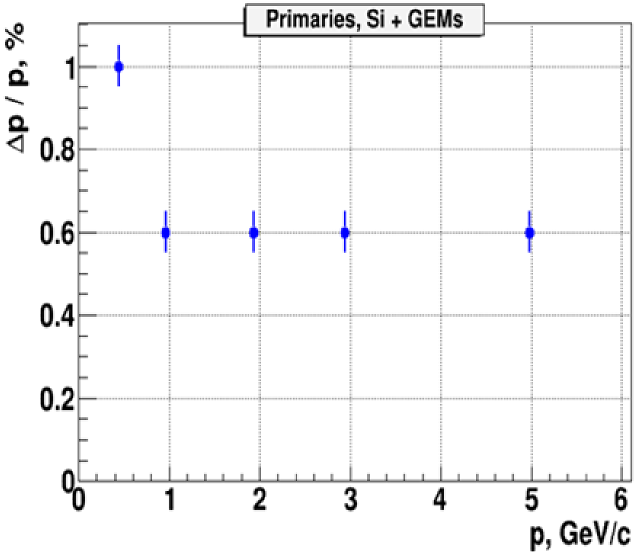
central Au+Au collisions at 4A GeV (QGSM generator)

track reconstruction efficiency



low GEM granularity

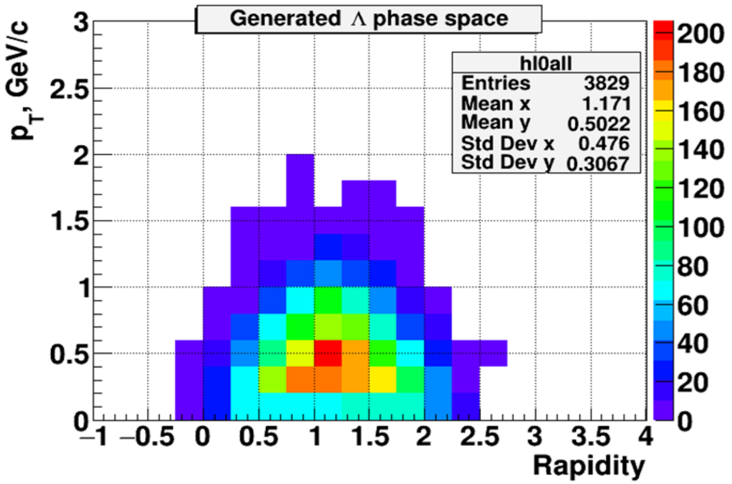
momentum resolution



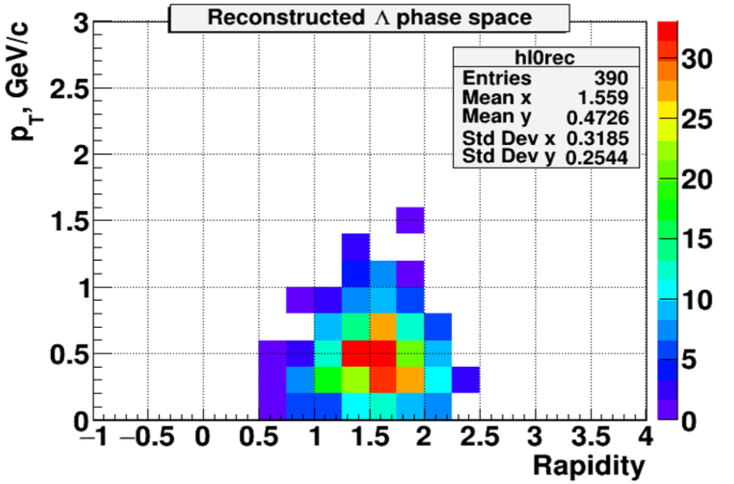
Physics performance simulations of the hybrid tracking system

Lambda reconstruction in 1000 central Au+Au 4A GeV (A. Zinchenko)

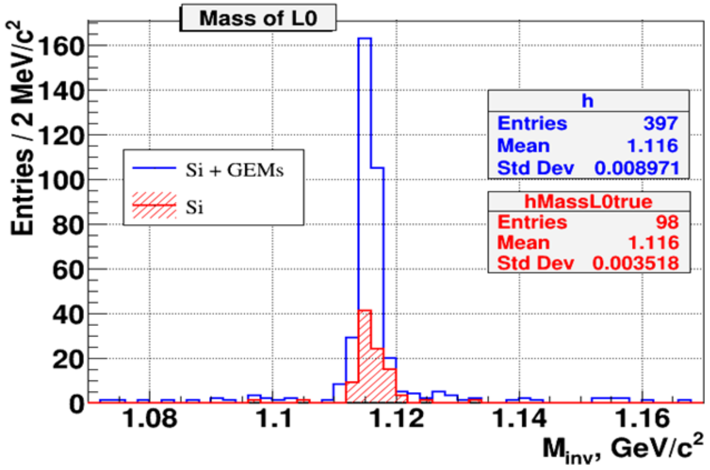
Produced Λ

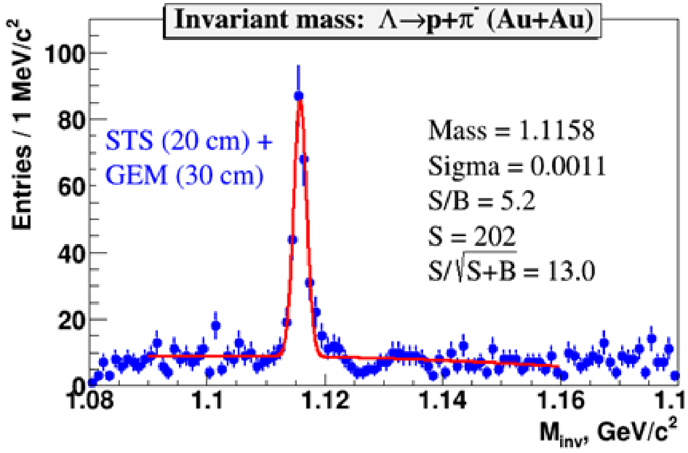


Reconstructed Λ



Much higher statistics required to see Ξ and Ω hyperons !





$\varepsilon(\Lambda) \approx 10\%$
without PID for p and π

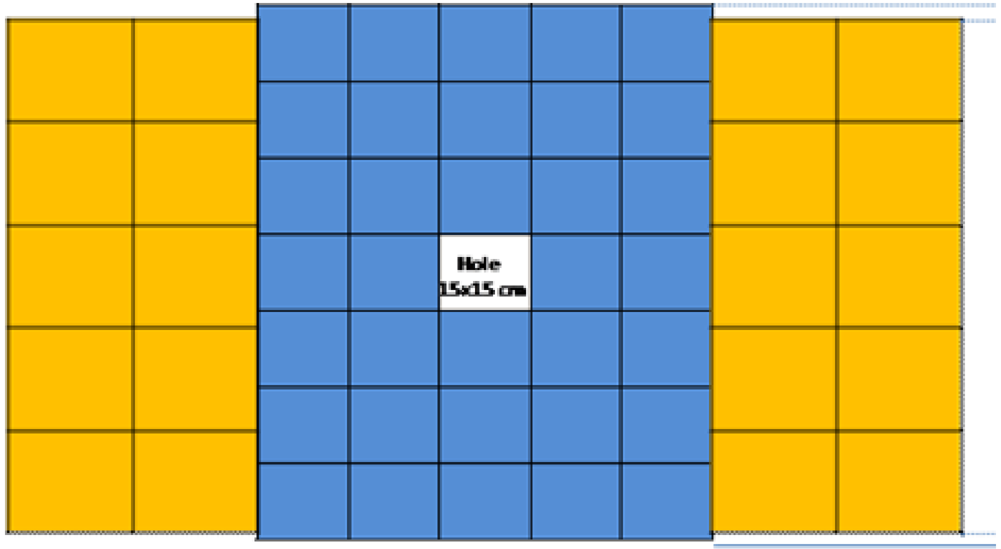
Forward Hadron Calorimeter

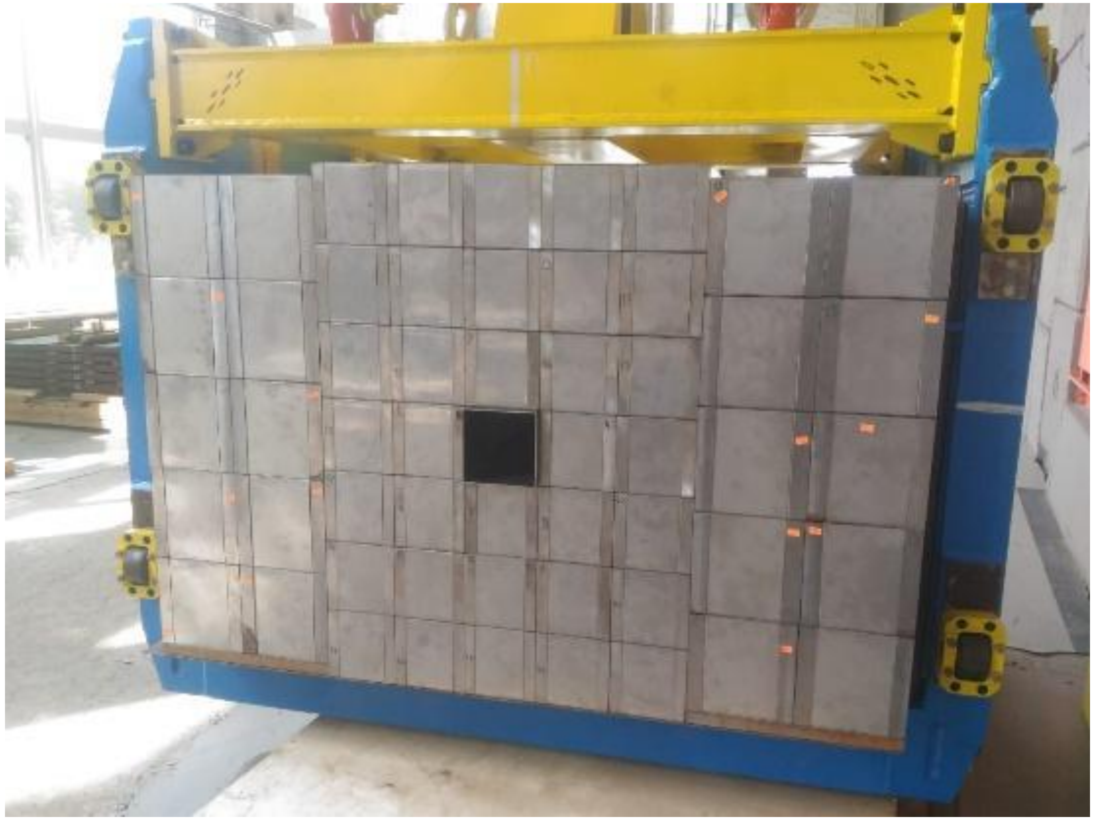
Determination of:

- Orientation of the reaction plane
- Collision centrality

- FHCAL assembled and installed into BM@N setup
- Cosmic tests are under way

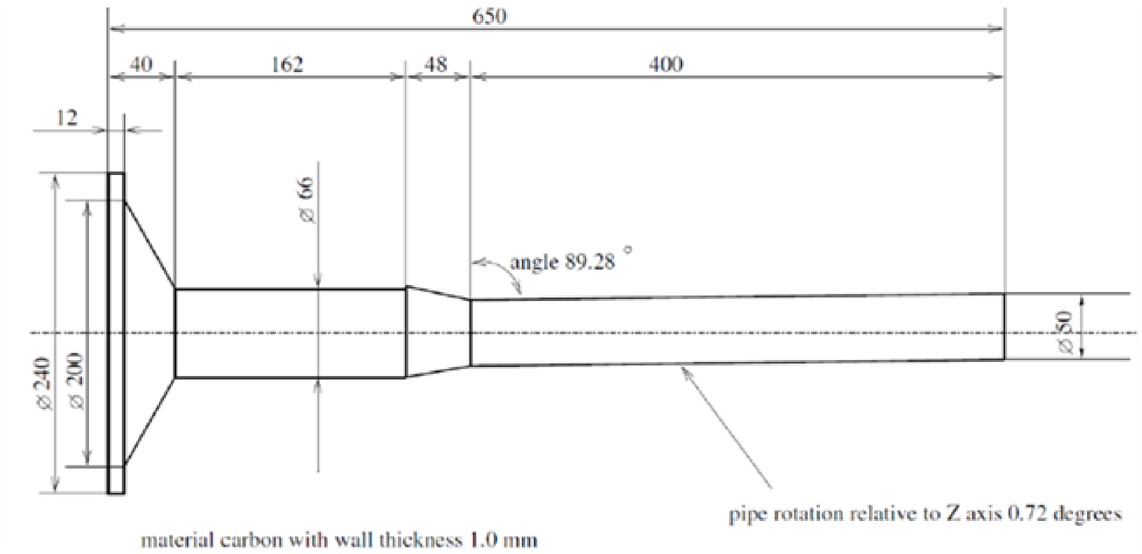
CBM modules MPD modules

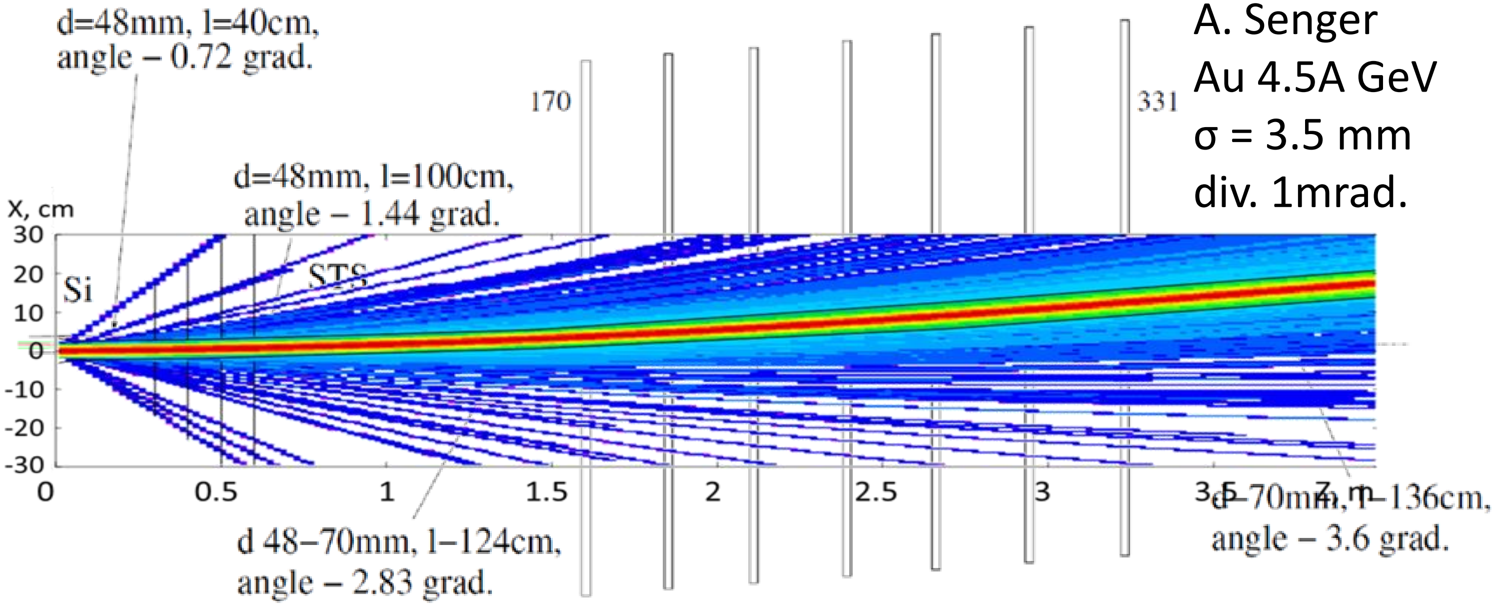




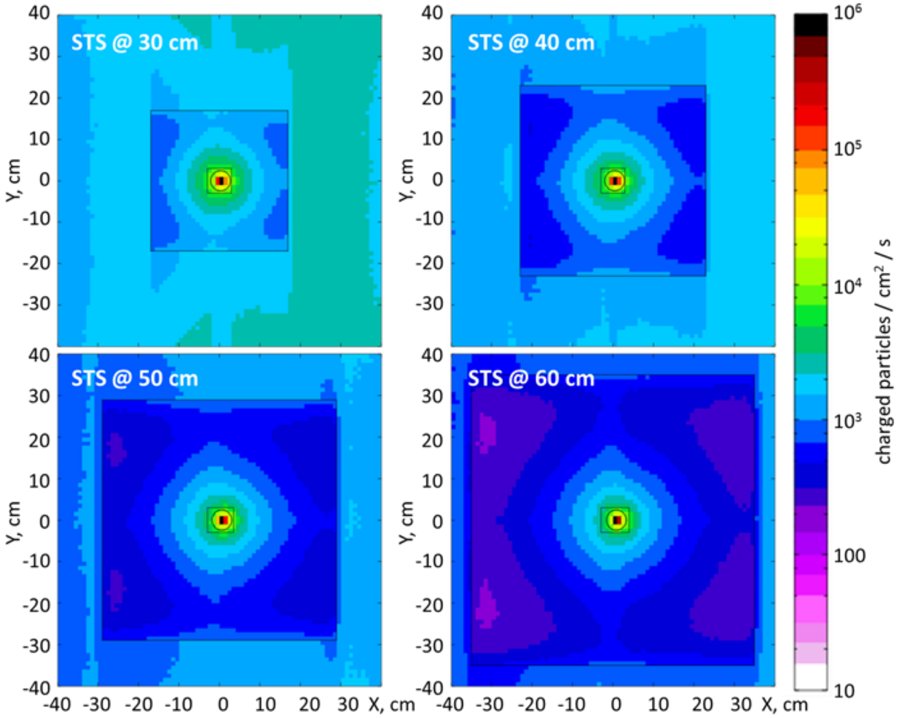
Team of INR RAS, Troitsk

Radiation environment





A. Senger
Au 4.5A GeV
σ = 3.5 mm
div. 1mrad.



max. rate 5 kHz/cm^2 (innermost sensors)
strip size 50 μm · 6 cm = 3·10^{-2} cm^2
read-out time 1 μs → occupancy 1.5·10^{-4}

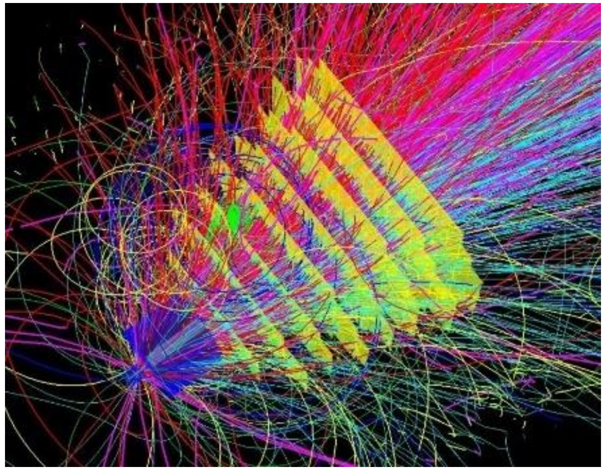
Beam parameters and setup at different stages of the BM@N experiment

Year	2016	2017 spring	2018 spring	fall 2021	2022	2023
Beam	d(↑)	C	Ar,Kr, C(SRC)	Kr,Xe	up to Au	up to Au
Max.intensity, Hz	0.5M	0.5M	0.5M	0.5M	0.5M	0.5M
Trigger rate, Hz	5k	5k	10k	10k	10k	50k
Central tracker status	6 GEM half planes	6 GEM half planes	6 GEM half planes + 3 forward Si planes	7 GEM full planes + forward Si planes	7 GEM full planes + forward Si + 2 large STS planes	7 GEM full planes + 4 large STS planes
Experimental status	technical run	technical run	technical run+physics	physics run	stage1 physics	stage2 physics

CREMLIN PLUS

Connecting Russian and European Measures
for Large-scale Research Infrastructures

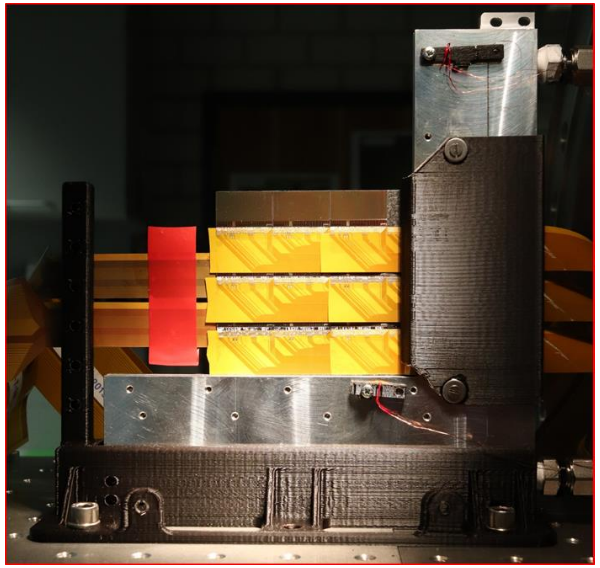
Budget 25 M€ over 4 years: 2020 - 2023
GSI/FAIR and JINR involvement in two Working Packages



WP2: Collaboration with NICA

Develop the instrumentation for NICA/BM@N and FAIR/CBM
Engineering and construction of fast detectors, and development of high rate data acquisition chain and software packages for simulation and data analysis
Total budget 4.61 M€

Participants: JINR (9 FTE), FAIR (8.5 FTE), U Tübingen (1 FTE), WUT Warsaw (2 FTE), Wigner Budapest (2 FTE), MEPhI (4 FTE) INR Moscow (1 FTE), NPI Prague (2 FTE)



WP7: Joint development of detector technologies

Develop a beyond state of the art CMOS pixel sensors (MAPS) for high-rate Silicon trackers for several particle physics and heavy-ion research communities in Europe and Russia for the potential upgrade of many experimental setups (e.g. at SCT, at NICA, at CERN-colliders), development of neutron detectors, detector school at BINP
Total budget 1.8 M€

Participants: JINR (1 FTE), FAIR (1 FTE), DESY (1 FTE), U Frankfurt (1 FTE), IPHC Strasbourg (1 FTE), KINR Kiev (1 FTE), BINP (1 FTE)

Summary

- The upgraded BM@N experiment offers the opportunity to explore nuclear matter at neutron star core densities in heavy-ion collisions at energies of up to 3.8A GeV.
- The research program includes:
  - the high-density equation-of-state
  - the onset of deconfinement
  - the role of hyperons in neutron stars
- Sensitive observables:
  - elliptic flow of charged particles
  - excitation function of multi-strange hyperons
  - hypernuclei
- First measurements with Au beams are expected in 2023.

- The new Silicon Tracking System at BM@N will be realized in closed collaboration with groups from the CBM collaboration as a prototype detector for the CBM experiment at FAIR, which is expected to take first beams in 2025.