Existing and future experiments at Nuclotron Based Ion Collider fAcility (NICA)

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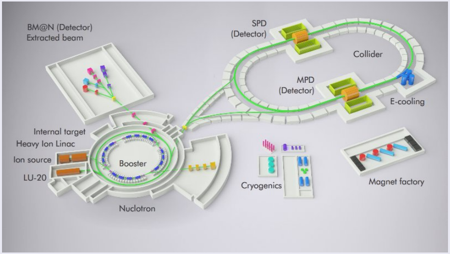
Outline:

- **The NICA complex and its general characteristics**
- **Physics to be investigated within the complex: from feasibility studies for planned experiments to first experimental results**
- **Conclusion**

NICA Complex



- Set of accelerators providing particle beams for fixed target and collider experiments
- Experimental facilities
- Line for assembling and cryogenic testing of SC-magnets
- Workshops for construction of the detector elements
- NICA innovation center

Beams - p, d **...** $^{197}Au^{79+}$
Collision energy:
$\sqrt{s_{NN}}$ = **4 - 11 GeV** E_{lab} = **1 - 6 AGeV**
Luminosity: $10^{27}\ cm^{-2}s^{-1}$ **(Au),** 10^{32} **(p)**

- 2 interaction points - **MPD** and **SPD**
- Fixed target experiment - **BM@N**

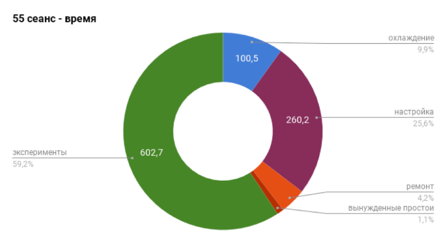
- **2018:** extracted beams of heavy ions (Ar, Kr) are available within the BM@N experiment
- **2020**: a first configuration of the MPD setup available.
- **2023**: commissioning of the fully designed NICA-complex is foreseen.

Nuclotron (in operation since 1993)

Modernized in 2010 - 2015

Parameters	Nuclotron
type	SC synchrotron
particles	↑p, ↑d, nuclei
injection energy [MeV/u]	5 (↑p, ↑d), 570-685 (Au)
max. kin. energy [GeV/u]	12.07 (↑p), 5.62 (↑d), 4.38 (Au)
magnetic rigidity [T · m]	25 - 43.25
circumference [m]	251.52
cycle for collider mode [s]	1.5-4.2 (active), 5.0 (total)
vacuum [Torr]	10^{-9}
intensity, Au [ions/pulse]	$1 \cdot 10^{9}$
spill of slow extraction [s]	up to 10

Run55: Feb - Apr, 2018



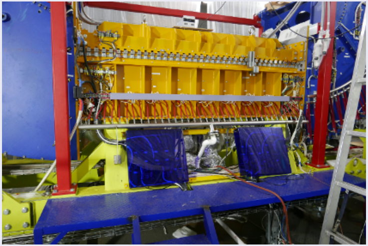
Booster

Commissioning started in 2018

Parameter	Booster
type	SC synchrotron
particles	ions $A/Z \leq 3$
injection energy [MeV/u]	**3.2**
maximum energy [MeV/u]	**600**
magnetic rigidity [T · m]	**1.6 - 25.0**
circumference [m]	**210.96**
vacuum [Torr]	10^{-11}
intensity [Au ions/pulse]	$1.5 \cdot 10^{9}$
RF range [MHz]	**0.5 - 2.53**

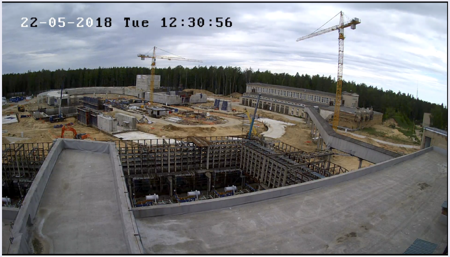
Tunnel for Booster

Electron Cooling System



Collider

NICA site online
http://nucloweb.jinr.ru/nucloserv/205corp.htm



Technical params:

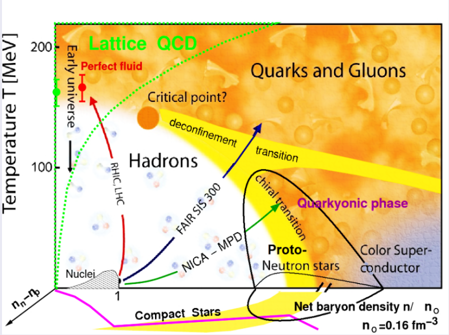
Ring circumference [m]	503.04
Number of bunches	22
$\Delta_{bunch\ length}$ [m]	0.6
Max. energy $\sqrt{s_{NN}}$ [GeV]	11
$\Delta p/p$ $[10^{-3}]$	1.6
Luminosity $[cm^{-2} \cdot s^{-1}]$	10^{27}

Main production areas:

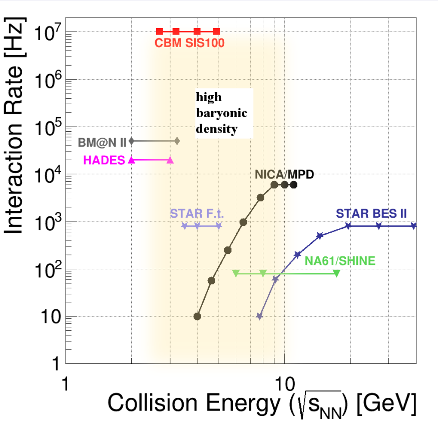
- Incoming inspection zone
- SC cable production hall
- SC coils production hall
- Area for assembling the magnets
- Area for the magnetic measurements under the room temperature
- Leakage test area
- Area for mounting the SC-magnets inside cryostats
- Cryogenic tests bench

450 magnets for NICA and FAIR projects

QCD phase diagram



Landscape of experiments exploring QCD phase diagram



High energy:

- $N_{baryons} \approx N_{antibaryons}$
- **Lattice QCD predicts crossover transition between hadronic and partonic matter**
- **ALICE, ATLAS, CMS, STAR, PHENIX**

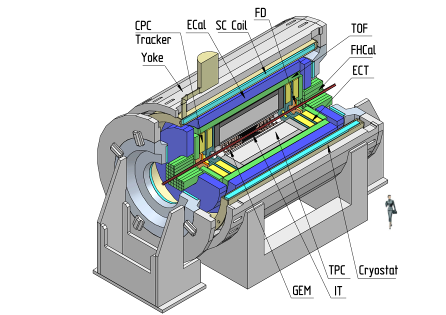
High net-baryon density:

- $N_{baryons} >> N_{antibaryons}$
- **Lattice QCD not applicable, models predict structures and exotic phases**
- **BES @ RHIC, NA61, CBM, NICA/MPD, BM@N**

Experiments in collider mode

MultiPurpose Detector (MPD) for $A + A$ collisions @ NICA

MPD Layout:



Benefits:

- Hermeticity, 2π-acceptance in azimuth
- 3D-tracking (TPC, ECT)
- Vertex high-resolution (IT)
- Powerful PID (TPC, TOF, ECAL)
  - π, K up to 1.5 GeV/c
  - K, p up to 3 GeV/c
  - γ, e from 0.1 GeV/c up to 3 GeV/c
- Precise event characterization (FHCAL)
- Fast timing and triggering (FFD)
- Low material budget
- High event rate (up to 7 kHz)

Participants:

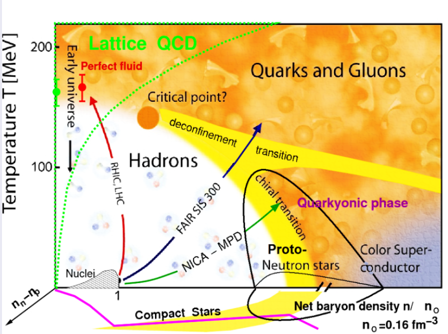
- Tsinghua University, Beijing, China
- GSI, Darmstadt, Germany
- WUT, Warsaw, Poland
- MEPhI, Moscow, Russia
- INR, RAS, Russia
- PPC BSU, Minsk, Belarus
- Dubna, JINR, Russia

Realization progress:

- TDR - completed / close to completion
- Preparation for / start of mass production
- First stage - 2019 - 2020
- Second stage and full commissioning (IT + end-cups) - 2023

MPD physics cases

QCD phase diagram



Deconfinement (chiral) phase transition at high baryonic density

enhanced strangeness production
Chiral Magnetic (vortical) effect,
Λ-polarization

Bulk properties, EOS

particle yields & spectra, ratios,
femtoscopy, flow
measure: γ, π, K, p, Λ, Ω,
(anti)-particles, light nuclei

In-Medium modification of hadron properties

onset of low-mass dilepton enhancement
measure: ρ, ω, ϕ, e^+e^-

QCD Critical Point

event-by-event fluctuations and correlations

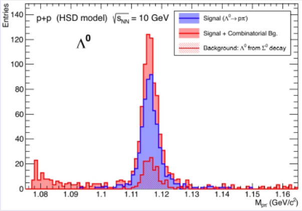
Strangeness in nuclear matter

hypernuclei

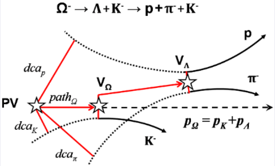
Multi-strangeness @ MPD

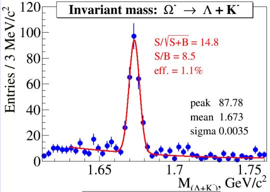
Hyperon yields for 1 week of running (Stage 1)

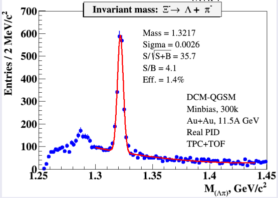
Particle	Yield
Λ^0	$3 \cdot 10^7$
$\overline{\Lambda}^0$	$3.5 \cdot 10^5$
Ξ^-	$1.5 \cdot 10^5$
$\overline{\Xi}^+$	$8.0 \cdot 10^3$
Ω^-	$7 \cdot 10^3$
$\overline{\Omega}^+$	$1.5 \cdot 10^3$



Decay topology

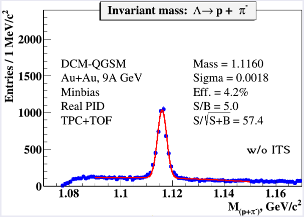


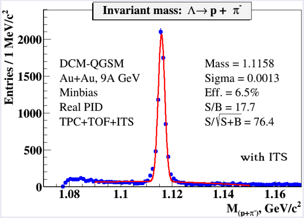




Data & Analysis

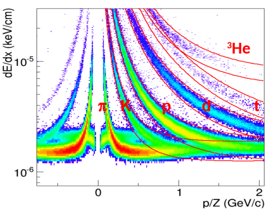
- $5 \cdot 10^5$ events, AuAu @ $\sqrt{s_{NN}} = 9$ GeV
- Λ-candidates are in inv. mass window $\pm 3\sigma$
- Topological cuts are optimized to improve significance

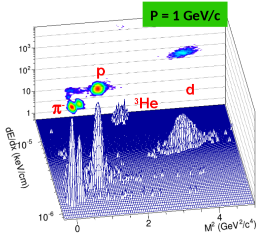




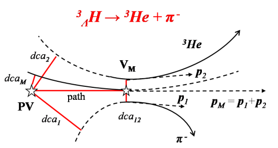
Hypernuclei @ MPD

Particle Identification





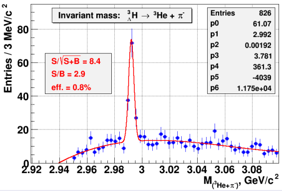
Decay topology



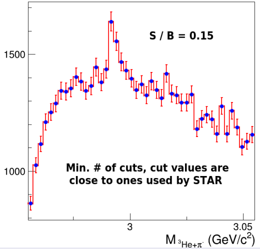
Data & Analysis

- Particles are selected within $\pm 3\sigma$-cuts in dE/dx or $dE/dx - M^2$
- V_0 finding is done with quality cuts for max. significance

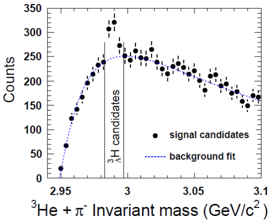
"Strong" cuts



"Soft" cuts

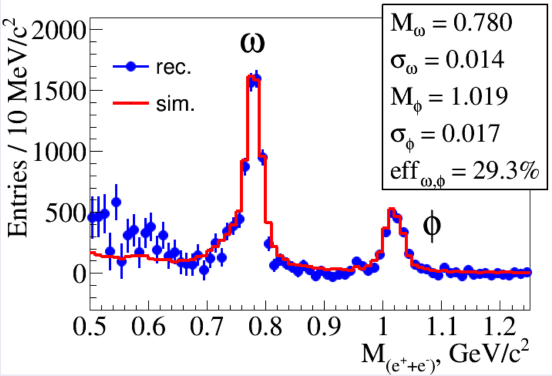


STAR preliminary



Dileptons @ MPD

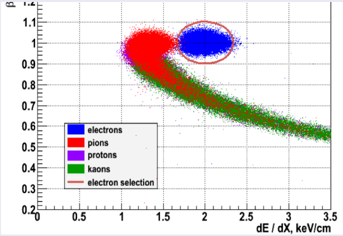
Invariant mass of dileptons (background subtracted): red - MC, blue - reco



Yield, decay modes ... for dileptons

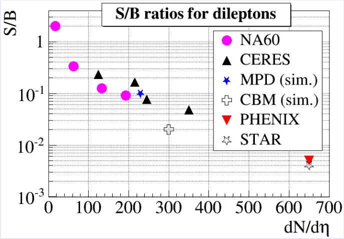
Particle	Yield		Decay mode	BR	Eff. [%]	Yield [per 1 week]
	4π	y = 0				
ρ	**31**	**17**	e^+e^-	$4.7 \cdot 10^{-5}$	**35**	$7.3 \cdot 10^4$
ω	**20**	**11**	e^+e^-	$7.1 \cdot 10^{-5}$	**35**	$7.2 \cdot 10^4$
ϕ	**2.6**	**1.2**	e^+e^-	$3 \cdot 10^{-4}$	**35**	$1.7 \cdot 10^4$

PID



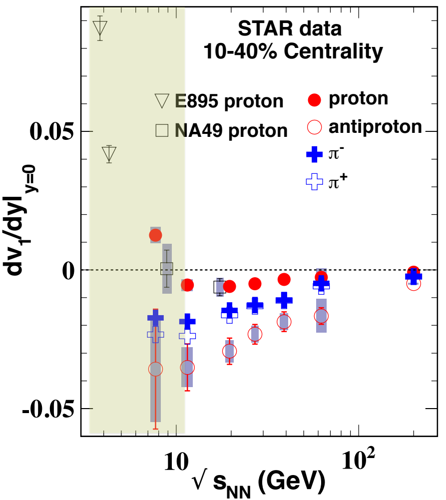
MPD

$0.2 < M_{(e^+e^-)} < 1.1 GeV/c^2$



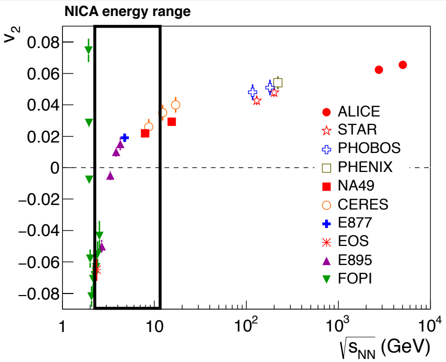
Flow @ MPD

Direct flow



Slope of v_1 changes sign in the NICA energy range

Elliptic flow

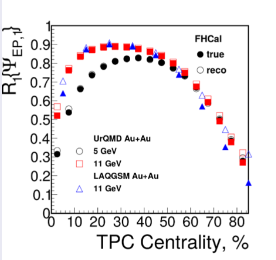


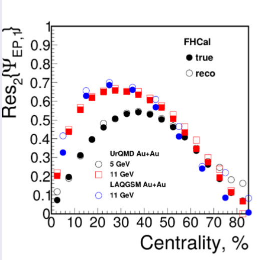
v_2 becomes very close to zero in the NICA energy range

- Large uncertainties in existing experimental data in the NICA energy range
- Non-monotonic $|dv_1/dy|_{y=0}$ behavior could be a signature of phase transition
- More differential (centrality classes) measurements required

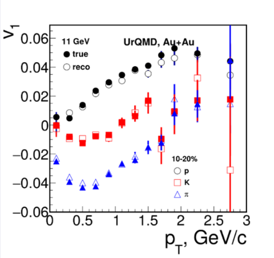
Flow performance @ MPD: v_n of charged hadrons

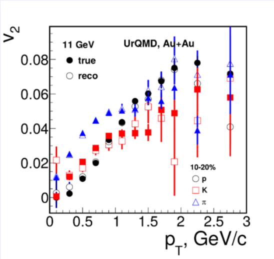
Ev. plane resolution





Flow harmonics





Azimuthal flow coefficients:

$$v_n = \frac{\langle \cos[n(\phi - \Psi_{EP,1})] \rangle}{R_{\Psi_{EP,1}}}$$

$\Psi_{EP,1}$ **- event plane angle**

$R_{\Psi_{EP,1}}$ **- resolution correction factor**

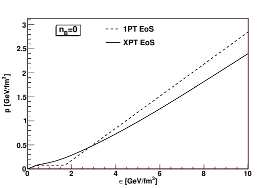
ϕ **- azimuthal angle of produced particles**

Centrality with TPC estimator

Results indicate good precision of reaction plane reconstruction and sufficiently good reproducibility of generated events in a wide range of transverse momentum p_T

Femtoscopy @ MPD with vHLLE+UrQMD

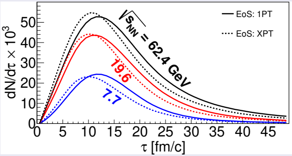
Thermodynamic pressure as a function of energy density



Parameters τ_0, $R_\perp$, R_η and η/s adjusted using basic observables in the RHIC BES region.

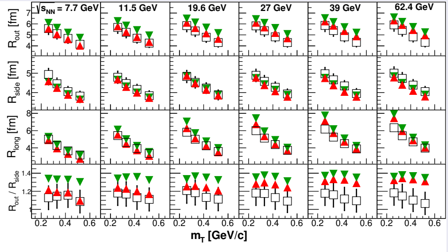
$\sqrt{s_{NN}}$ [GeV]	τ_0 [fm/c]	$R_\perp$ [fm]	R_η [fm]	η/s
7.7	3.2	1.4	0.5	0.2
8.8 (SPS)	2.83	1.4	0.5	0.2
11.5	2.1	1.4	0.5	0.2
17.3 (SPS)	1.42	1.4	0.5	0.15
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08
200	0.4	1.0	1.0	0.08

Pion emission times at the last interaction



Phys. Rev. C 96, 024911 (2017)

Comparison of extracted radii with the STAR data

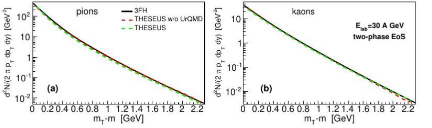


- EoS with a crossover in the fluid phase results in a quite reasonable reproduction of 3D pion femtoscopic radii measured by the STAR collaboration (empty squares).
- EoS with a first-order phase transition leads to fact that the “out” and “long” Gaussian femtoscopic radii are systematically larger if comparing with the crossover EoS; the “side” radii coincide for both types of EoS.

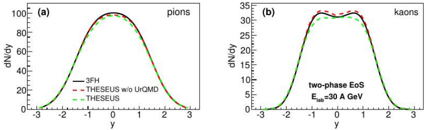
Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions (THESEUS)

3FH → PARTICLIZATION → UrQMD CASCADE

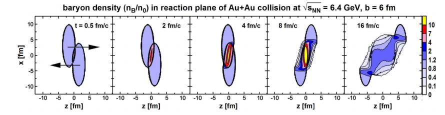
p_T-spectra:



Rapidity distribution:



3FH-model (see Phys. Rev. C 94, 044917 (2016)):



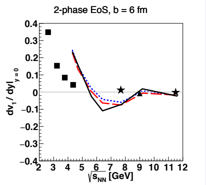
Very high baryon densities are reached in the central region of the colliding system

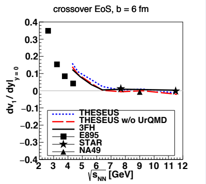
UrQMD hadronic rescattering:

- leads to a slight steepening of the pion p_T-spectrum.
- smears the double-peak structure in the kaon rapidity spectrum.

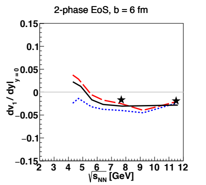
Observables @ MPD with THESEUS

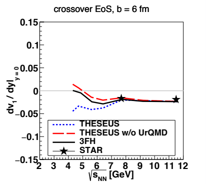
$|dv_1/dy|_{y=0}$ protons



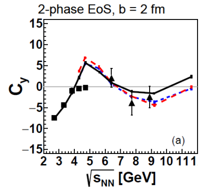


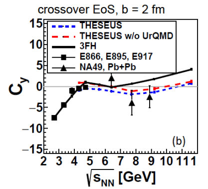
$|dv_1/dy|_{y=0}$ pions



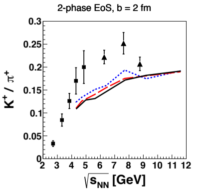


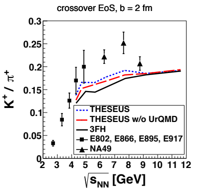
Curvature of net-proton rapidity distribution





The "horn" effect?





- Hadronic cascade has a small effect on dv_1/dy for protons
- Hadronic cascade changes flow to antiflow for pions at low energies. The effect becomes weaker with the collision energy rise.

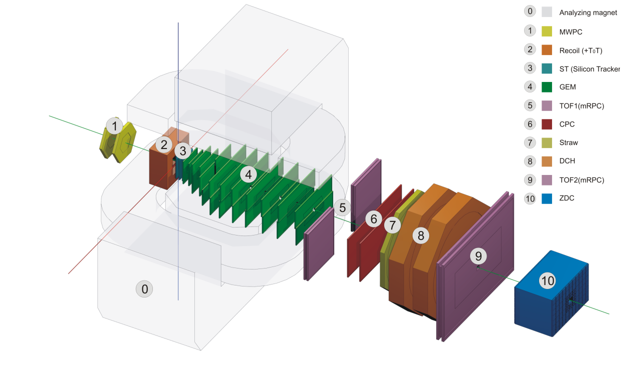
- The "wiggle" as a feature for the EoS with a 1-st order phase transition is robust against hadronic FSI.

- Turning the hadronic cascade on does not influence the kaon to pion ratio.

Experiments in fixed-target mode

BM@N experiment

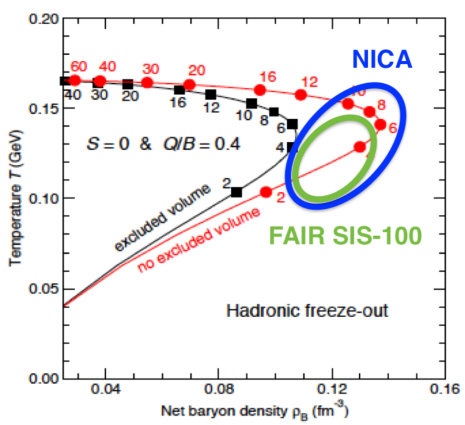
Full setup, layout

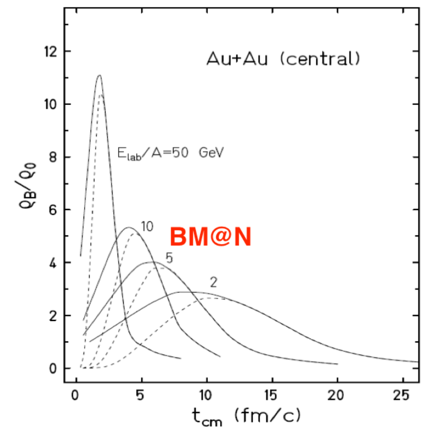


- Central tracker (Silicon tracker + GEM) inside analyzing magnet to reconstruct AA-interactions
- Outer tracker (CPC, DCH) behind magnet to link tracks from central tracker to ToF detectors
- TOF1 & TOF2 system based on mRPC and T0 detectors to identify hadrons and light nuclei
- Detectors to form T0 and beam monitors
- ZDC calorimeter to measure centrality of AA-collisions
- Electromagnetic calorimeter for γ, e^+, e^-

BM@N advantages:

- large aperture analyzing magnet
- sub-detector systems are resistant to high multiplicities of charged particles
- PID: "near to magnet" (TOF1), "far from magnet" (TOF2)





Nuclotron is well suited to study high density (dominantly baryonic) matter since at that energies baryon-dominated system exists comparatively long lifetime

Physics possibilities at the Nuclotron

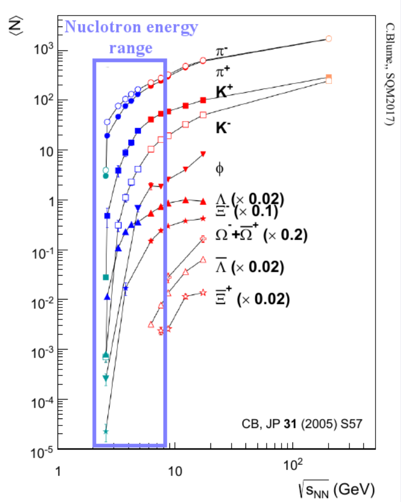
$A + A$ collisions:

- strangeness at threshold
- Need more precise data for strange mesons, hyperons and hypernuclei, multi-variable distributions, unexplored energy range

$p+p$, $p+n$, $p+A$ collisions:

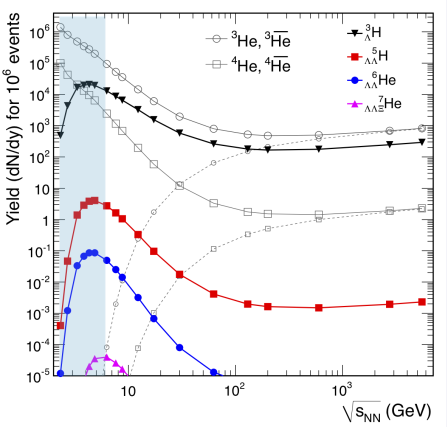
- Hadron production in elementary reactions and "cold" nuclear matter as a "reference" to determine exactly nuclear effects

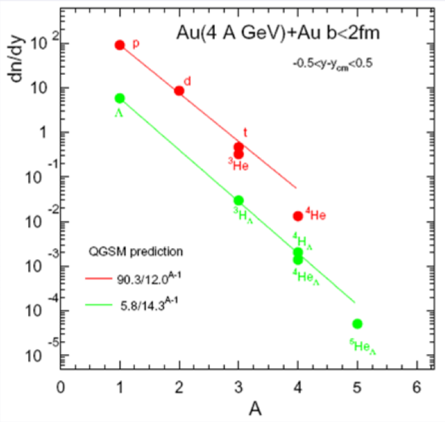
AGS NA49 BRAHMS



Heavy ions $A + A$: Hypernuclei production

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





BM@N energy range is **suited** for the search of (double) hypernuclei

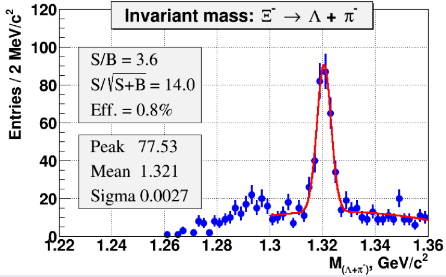
- **In heavy-ion collisions:** production of hypernuclei through coalescence of Λ with light fragments enhanced at high baryon densities
- **Maximal yield** predicted for $\sqrt{s_{NN}} =$ 4 - 5 AGeV (stat. model)

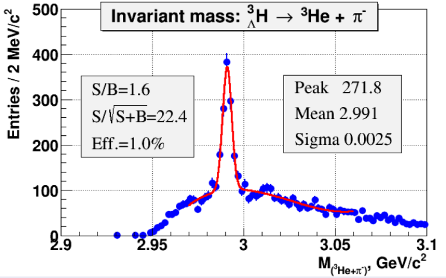
BM@N feasibility study

Simulation: UrQMD & DCM-QGSM, Au+Au, T = 4.5 AGeV

900k central events,
7.5M Ξ^- in 1 month
20 kHz trigger

2.6M central events,
8.5M $^3_\Lambda H$ in 1 month
20 kHz trigger

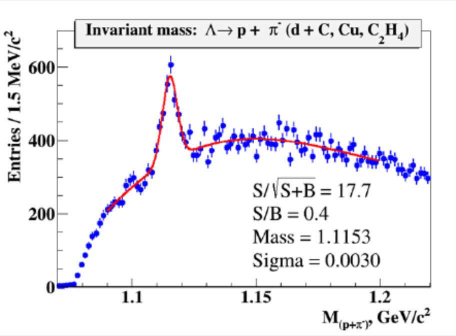




The feasibility study indicates reliable reconstruction of cascades and hypernuclei of order of 10 millions per month

Λ^0 in deutron (RUN5) and carbon (RUN6) beams

RUN5

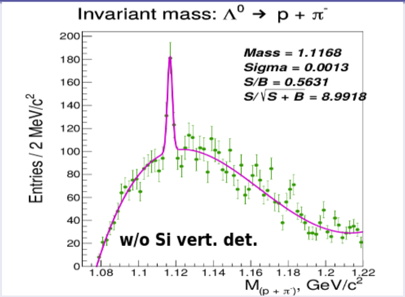


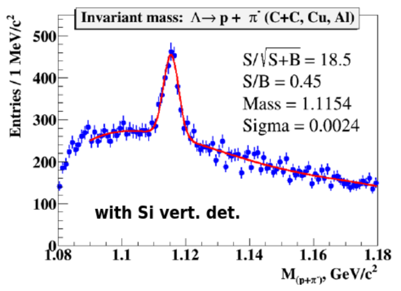
RUN5 and 6 are considered as technical ones!

To improve vertex and momentum resolution and reduce background:

- Need a few planes of forward Si vertex detector (vertex precision)
- Need more GEM planes (mom. resolution precision)

RUN6

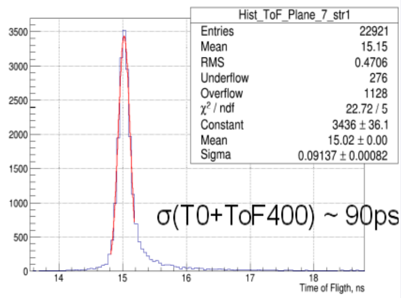


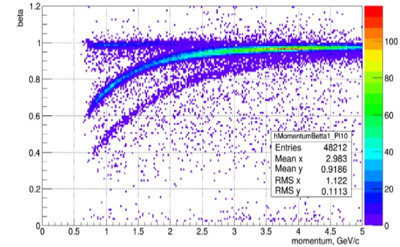


TOF1 and TOF2 performance in RUN6

$T = 3.5$ GeV/n, $C + Al \to X$

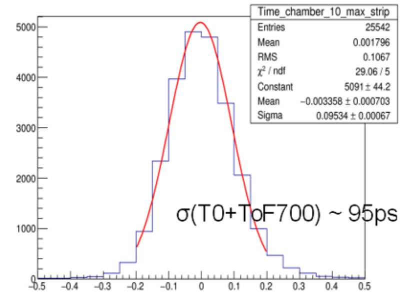
Includes inf. from GEM tracking

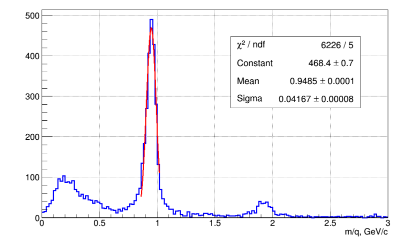




$T = 4.5$ GeV/n, $C + Cu \to X$

Includes inf. from GEM and DCH trackings

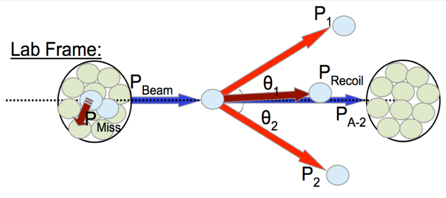




Short Range Correlation (SRC) programme as an extension to the BM@N experiment

How to study SRC?

Inverse kinematics



$$^{12}_{6}\mathrm{C} \rightarrow 2\mathrm{p} + {}^{10}_{5}\mathrm{B} + \mathrm{n}\ (\mathrm{np\ SRC})$$
$$^{12}_{6}\mathrm{C} \rightarrow 2\mathrm{p} + {}^{10}_{4}\mathrm{Be} + \mathrm{p}\ (\mathrm{pp\ SRC})$$

Participants

- JINR: BM@N
- Israel: Tel Aviv University
- Germany: TUD and GSI
- USA: MIT
- France: CEA

Super exclusive measurement!

Four particles detected:

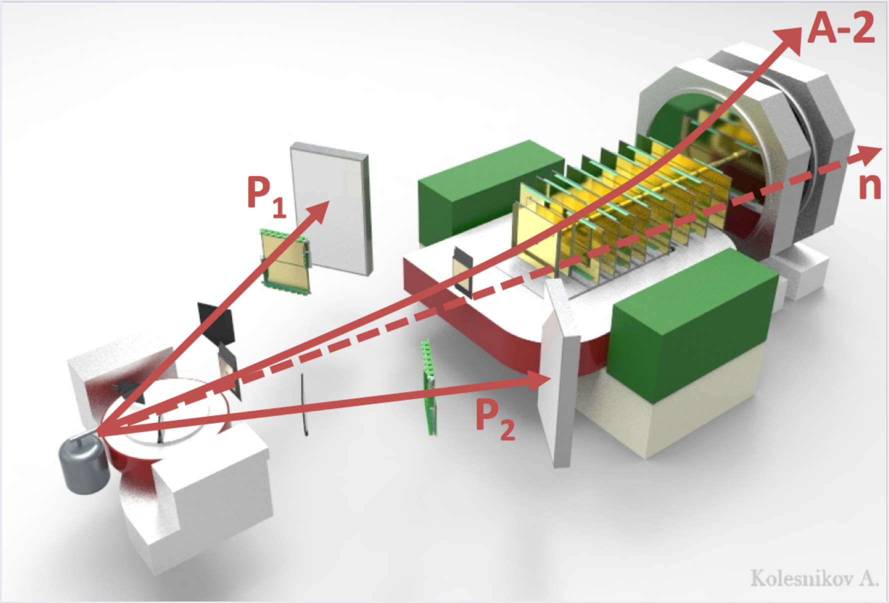
- scattered probe
- knocked-out nucleon
- recoil
- (A-2)-fragment system

Objectives

- identifying 2N-SRC events with inverse kinematics
- studying isospin decomposition of 2N-SRC
- studying (A-2) spectator nuclear system

First BM@N SRC program run in March 2018: $\sim$ 30 MEvents collected

Experimental setup



And, finally, what about collected data we have?

BM@N and SRC, data collected, RUN7 (March 23 - April 5)

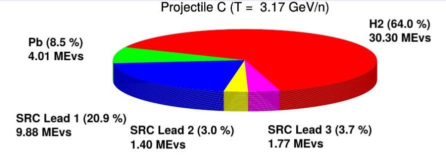
SRC:

- One beam energy available for C-beam
- More than half of the collected statistics can be used for analysis

BM@N:

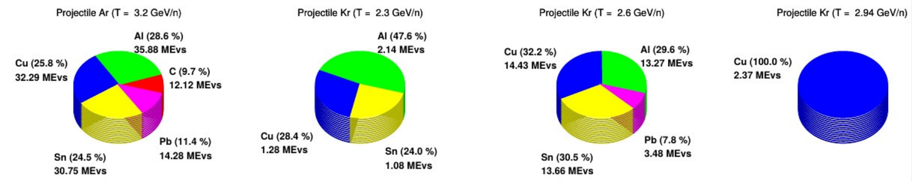
- One beam energy available for Ar-beam and three - for Kr-beam
- Wide set of targets used (C, Al, Cu, Sn, Pb)

SRC



Data analysis is in progress ...

BM@N



BM@N: past & future, status & plans

Beam parameters and setup at different stages of the experiment

Year	2016	2017	2018	2020	2021 and later
Experim. status	techn. run	techn.run	techn. run	stage 1, phys.	stage 2, phys.
Beam	d(↑)	C	Ar, Kr, C	Au	p, Au
Max. intensity [MHz]	0.5	0.5	0.5	1	10
Trigger rate [kHz]	5	5	10	10	20-50
Central tracker					
GEM	6 (half planes)	6 (half planes)	6 (half planes)	7	7
SI	-	1 (small plane)	3 (small planes)	4	4

Status:

- Technical runs with deuteron and carbon beams (T = 3.5 - 4.6 GeV/n), argon beam (T = 3.2 GeV/n) and krypton beam (T = 2.3 GeV/n) performed
- Measurement on Short Range Correlations with inverse kinematics: C + H_2-target performed
- Major sub-systems are operational, but are still in limited configurations: GEMs, forward Silicon detectors, Outer tracker, ToF, ZDC, ECAL, trigger, DAQ, slow control, online monitoring
- Algorithms for event reconstruction and analysis are being developed

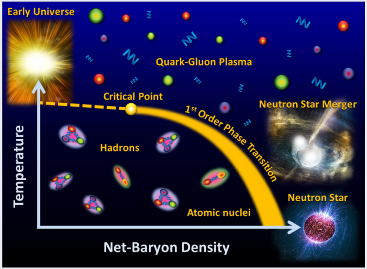
Plans:

- Collaborate with CBM to produce and install large aperture silicon detectors in front of GEM-tracker
- Extend the GEM central tracker and the CSC outer tracker to full configuration
- Implement beam detectors into vacuum beam pipe, implement vacuum / helium beam pipe through the BM@N setup

Summarising ...

NICA energy region:

- Maximum in K^+/π^+-ratio
- Maximum in Λ/π-ratio
- Maximum in the net-baryon density
- Transition from a Baryon dominated system to a Meson dominated one



- The construction of accelerator complex and both detectors BM@N & MPD are going close to the schedule
- NICA got a recognition as a part of European research infrastructure
- You are kindly invited to join the BM@N or/and MPD Collaborations