

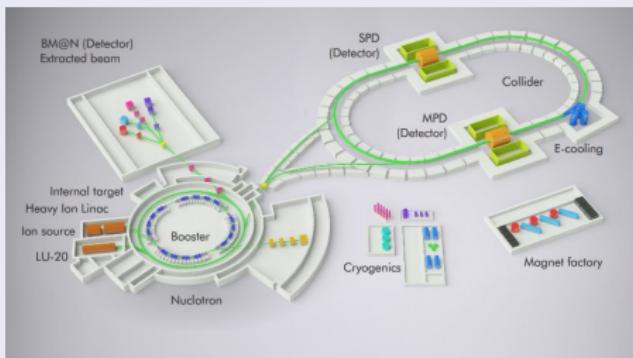


Existing and future experiments at Nuclotron Based Ion Collider fAcility (NICA)

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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 - $p, d \dots {}^{197}Au^{79+}$

Collision energy:

$$\sqrt{s_{NN}} = 4 - 11 \text{ GeV} \quad E_{lab} = 1 - 6 \text{ AGeV}$$

Luminosity: $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ (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
- 2020-2021: 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	$\uparrow p$, $\uparrow d$, nuclei
injection energy [MeV/u]	5 ($\uparrow p$, $\uparrow d$), 570-685 (Au)
max. kin. energy [GeV/u]	12.07 ($\uparrow p$), 5.62 ($\uparrow d$), 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



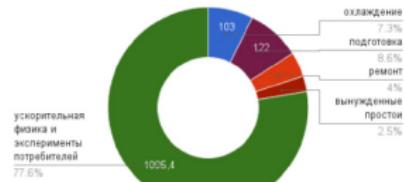
- The project approved in **1986**
- Commissioning & first beam, **March 1993**
- Slow extraction in **2000**

Ions from p to Xe
(C, Mg, Fe, Ar, Kr)
Polarized p & d beams

Nuclotron

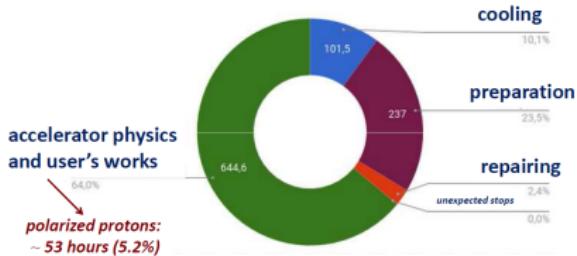
Run № 53, 1450 h, the longest one

53 сеанс - время



Run № 54, 1150 h

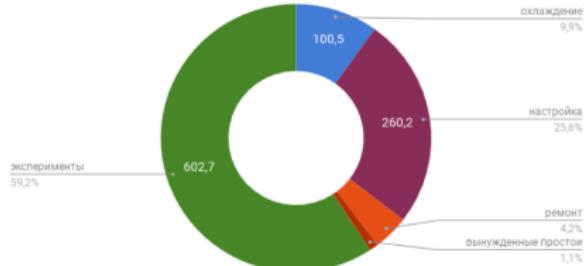
The total run duration: ≈ 1008 hours



Run55: Feb - Apr, 2018

- **Run53** - Polarized, unpolarized deuterons, maximum energy of extracted beam 4.6 GeV/u
- **Run54** - Carbon beam
- **Run55** - Argon & Krypton beams

55 сеанс - время



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



- Fabrication of the magnetic system is completed.
- Start of assembly - September 2018.
- First (technological) run - May 2019.
- Commissioning - end of 2020

First magnet was installed on 19 September 2018!

Line for assembling and cryogenic testing of SC-magnets

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

All of the Booster magnets are produced & tested



450 magnets for NICA and FAIR projects

KRION 6T - heavy ion source

Used during Nuclotron RUN №55



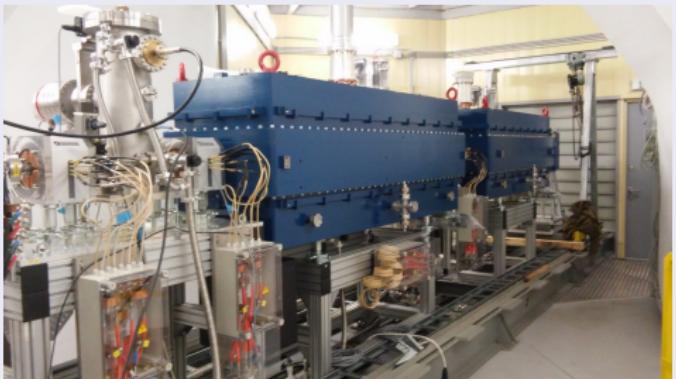
- Cryogenic heavy ion source KRION - Electron String Ion Source (ESIS) - provides up to $2.5 \cdot 10^9$ Au^{31+} ion / cycle at repetition frequency up to 10 Hz

Linacs

LU-20



HILAC



- **LU-20** - JINR, INR, ITEP, MEPhI (Commissioning - **May 2016**)
- **HILAC** - BEVATECH OHG (Commissioning - **October 2018**)

	LU-20	HILAC (NEW!)
Mass to charge ratio A/Z	1-3	1-6
Injection energy [keV / a.m.u.]	150 for A/Z 1-3	17
Extraction energy [MeV / a.m.u.]	5 (A/Z 1-3)	3.24 ($A/Z = 6$)

Collider as the main ingredient of the kitchen:)

Collider construction: Official start up
of the construction is **25 March 2016**



Collider

NICA site online

[http://nucloweb.jinr.ru/
nucloserv/205corp.htm](http://nucloweb.jinr.ru/nucloserv/205corp.htm)

22-05-2018 Tue 12:30:56

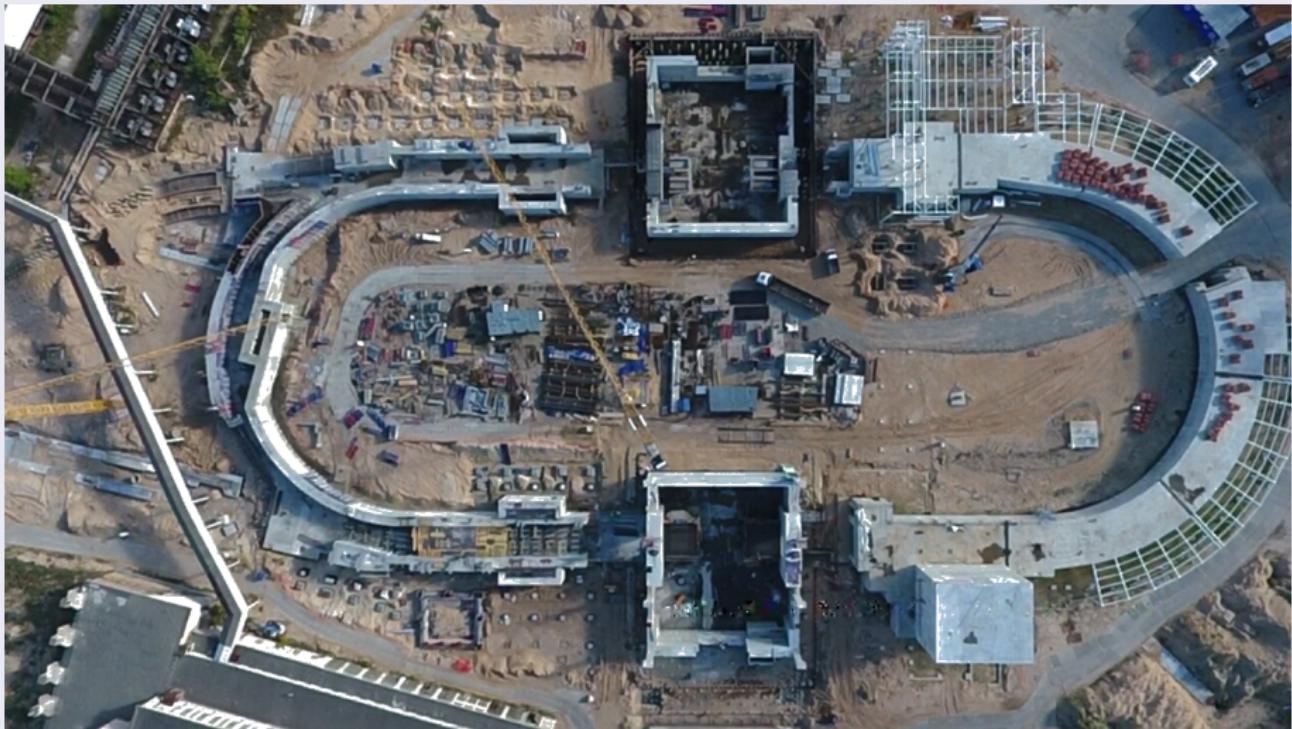


Technical params:

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}

Collider

September 2018



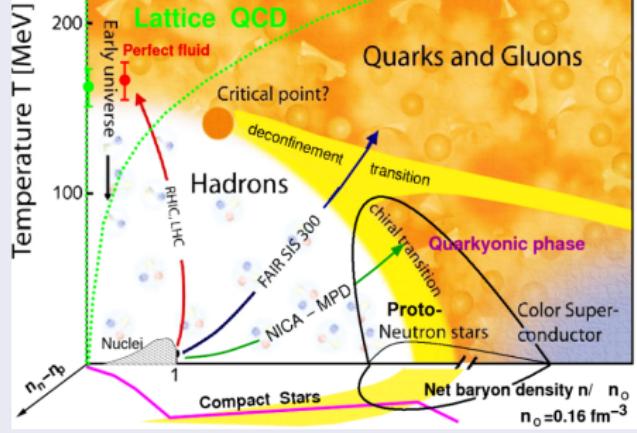
Cryogenic facility

New helium liquefier (1000 L/H)



Finally the cooling power should be doubled from
4 kW to 8 kW @ 4.5K

QCD phase diagram



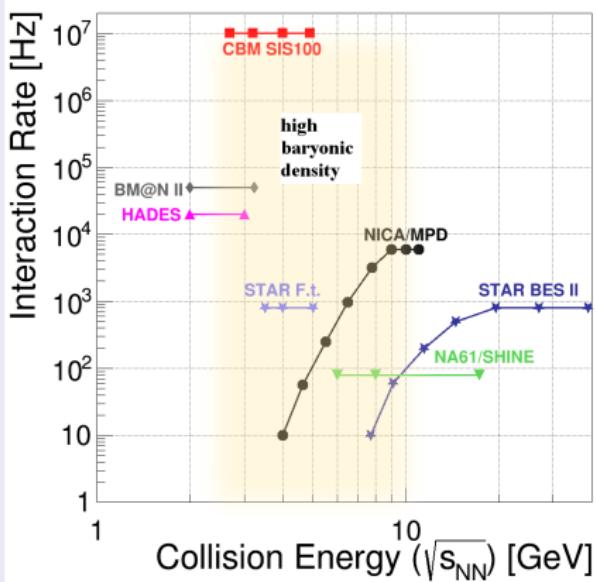
High energy:

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

High net-baryon density:

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

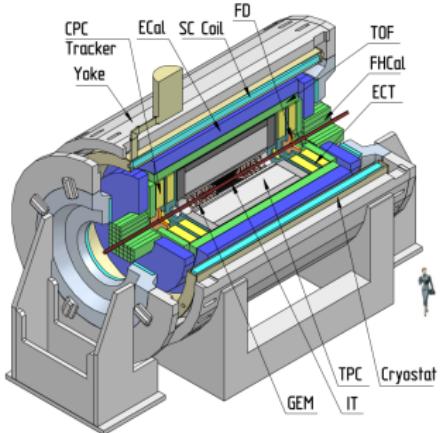
Landscape of experiments exploring QCD phase diagram



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:

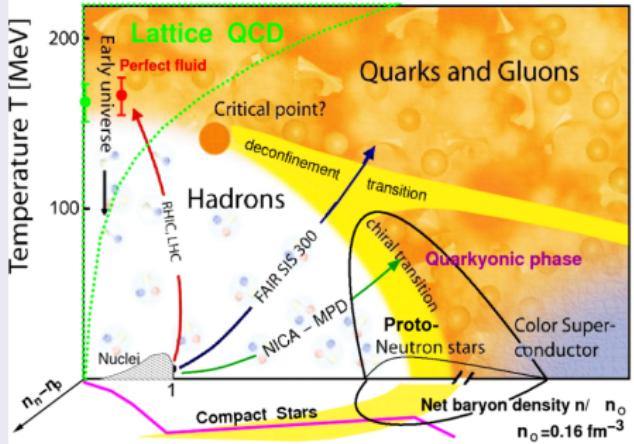
- Tsinghua University, Beijing, China
- GSI, Darmstadt, Germany
- WUT, Warsaw, Poland
- MEPhI, Moscow, Russia
- INR, RAS, Russia
- PPC BSU, Minsk, Belarus
- Dubna, JINR, Russia

Realization progress:

- TDR - completed / close to completion
- Preparation for / start of mass production
- First stage - **2020 - 2021**
- 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: $\gamma, \pi, K, p, \Lambda, \Omega, (\text{anti})\text{-particles}, \text{light nuclei}$

In-Medium modification of hadron properties

onset of low-mass dilepton enhancement

measure: $\rho, \omega, \phi, e^+e^-$

QCD Critical Point

event-by-event fluctuations and correlations

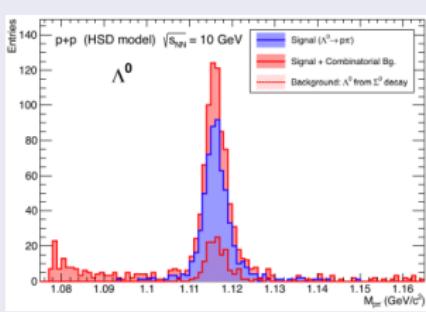
Strangeness in nuclear matter

hypernuclei

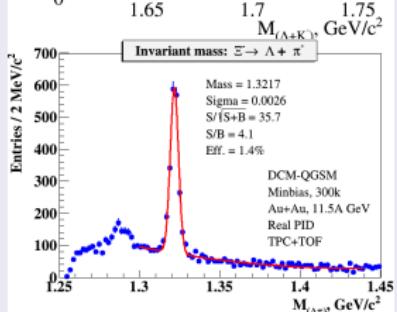
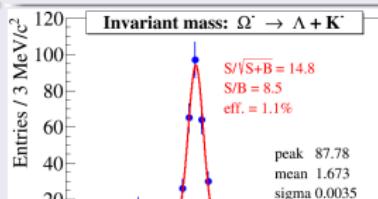
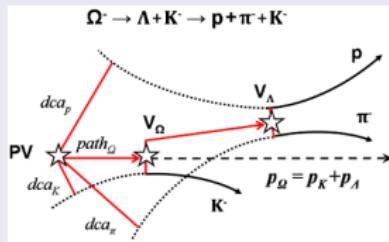
Multi-strangeness @ MPD

Hyperon yields for 1 week
of running (Stage 1)

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

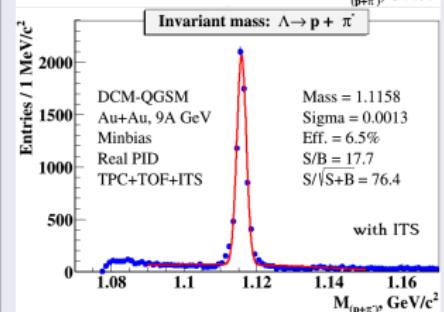
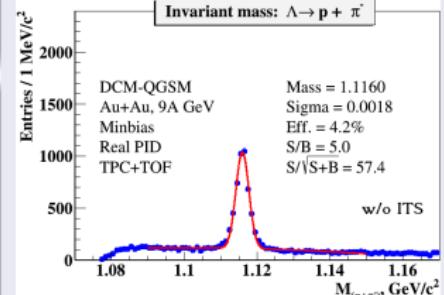


Decay topology



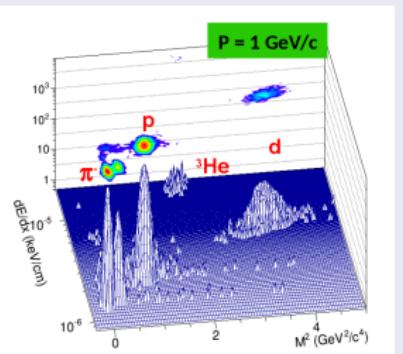
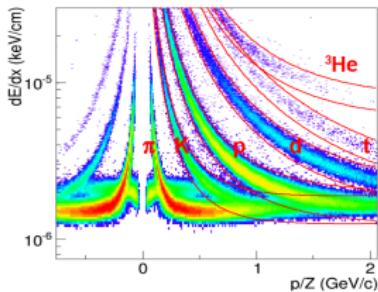
Data & Analysis

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

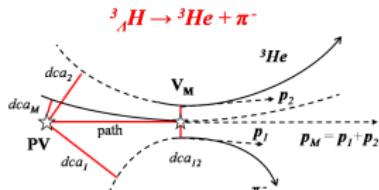


Hypernuclei @ MPD

Particle Identification



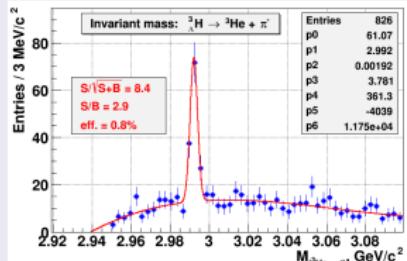
Decay topology



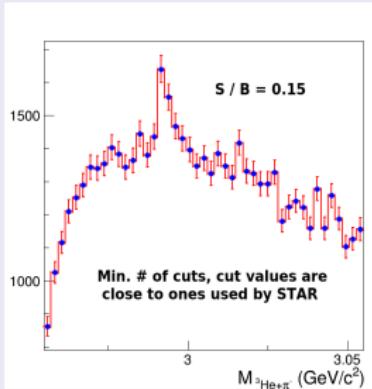
Data & Analysis

- 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

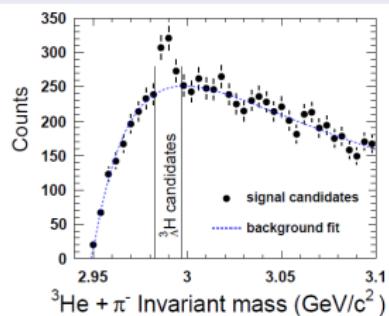
“Strong” cuts



“Soft” cuts

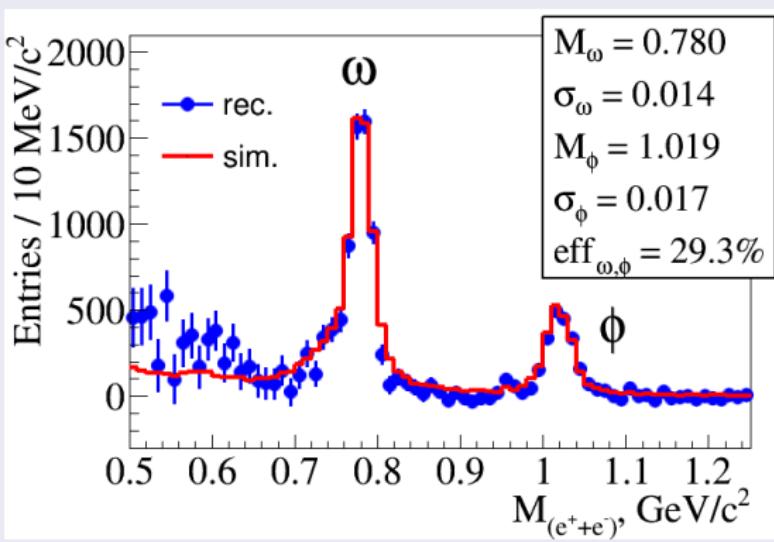


STAR preliminary



Dileptons @ MPD

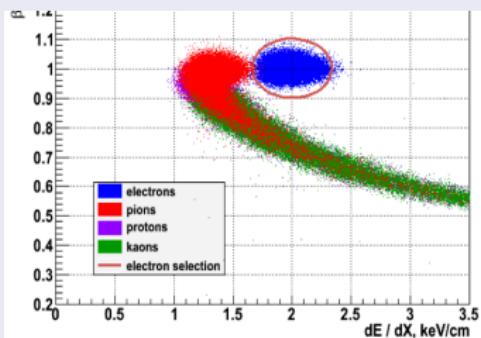
Invariant mass of dileptons (background subtracted): red - MC, blue - reco



Yield, decay modes ... for dileptons

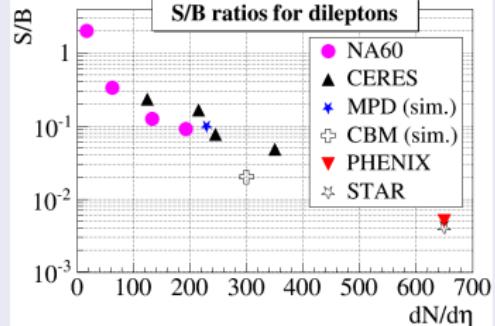
Particle	Yield		Decay mode	BR	Eff. [%]	Yield [per 1 week]
	4π	$y = 0$				
ρ	31	17	e^+e^-	$4.7 \cdot 10^{-5}$	35	$7.3 \cdot 10^4$
ω	20	11	e^+e^-	$7.1 \cdot 10^{-5}$	35	$7.2 \cdot 10^4$
ϕ	2.6	1.2	e^+e^-	$3 \cdot 10^{-4}$	35	$1.7 \cdot 10^4$

PID



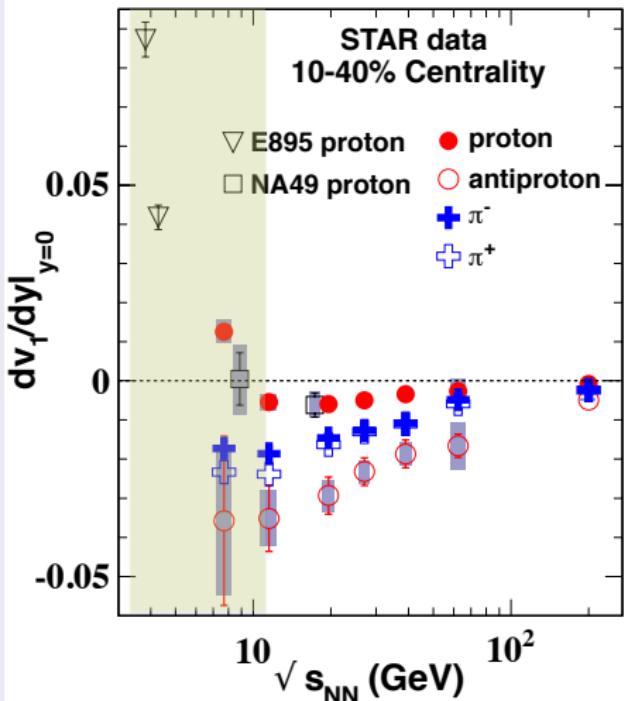
MPD

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



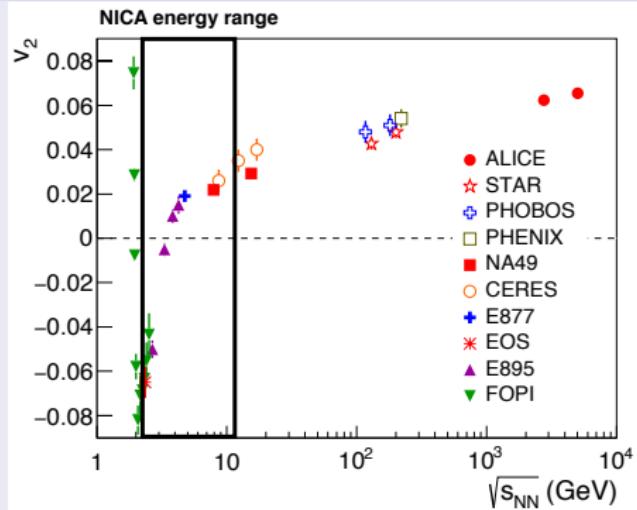
Flow @ MPD

Direct flow



Slope of v_1 changes sign in the NICA energy range

Elliptic flow

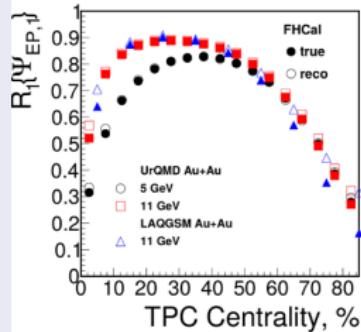


v_2 becomes very close to zero in the NICA energy range

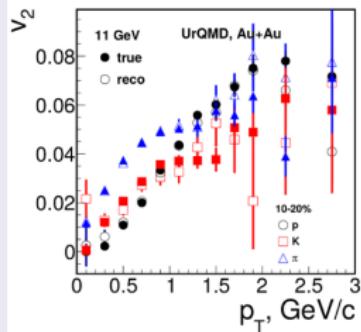
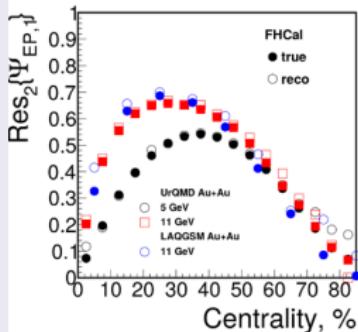
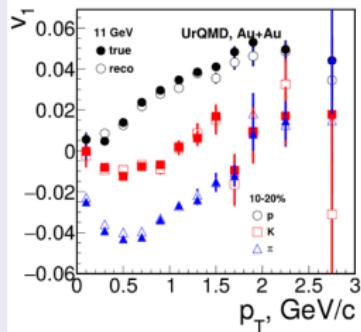
- Large uncertainties in existing experimental data in the NICA energy range
- Non-monotonic $|dv_1/dy|_{y=0}$ behavior could be a signature of phase transition
- More differential (centrality classes) measurements required

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

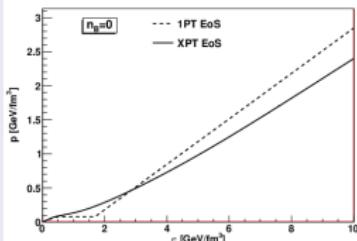
ϕ - azimuthal angle of produced particles

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

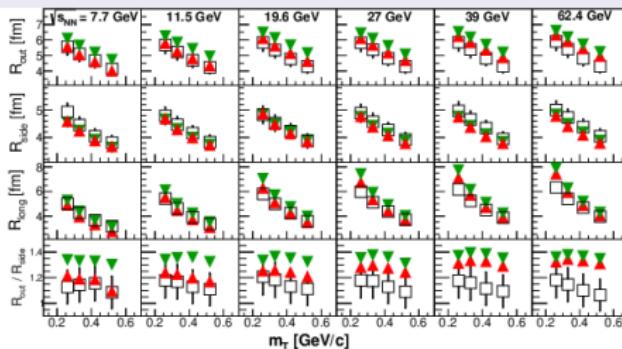
Thermodynamic pressure as a function of energy density



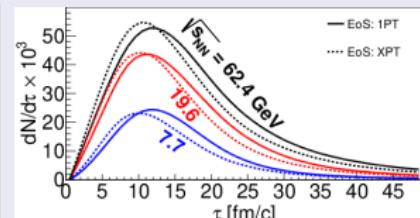
Parameters τ_0 , R_\perp , R_η and η/s adjusted using basic observables in the RHIC BES region.

$\sqrt{s_{NN}}$ [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

Comparison of extracted radii with the STAR data



Pion emission times at the last interaction



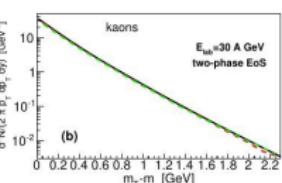
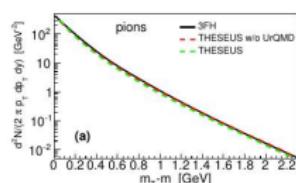
Phys. Rev. C 96, 024911 (2017)

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

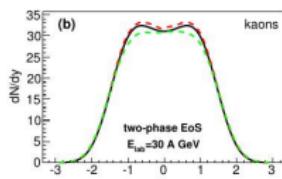
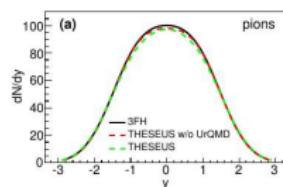
Three-fluid Hydrodynamics-based Event Simulator Extended by UrQMD final State interactions (THESEUS)



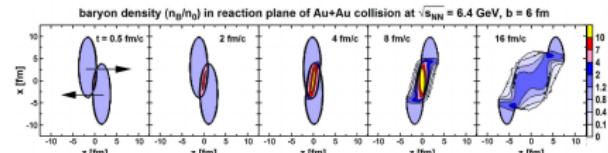
p_T -spectra:



Rapidity distribution:



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



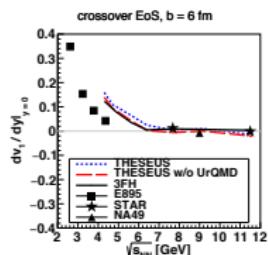
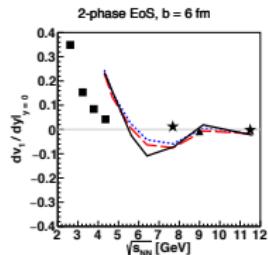
Very high baryon densities are reached in the central region of the colliding system

UrQMD hadronic rescattering:

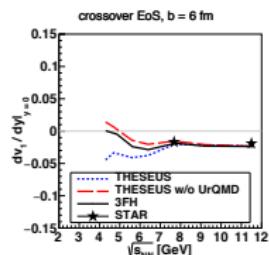
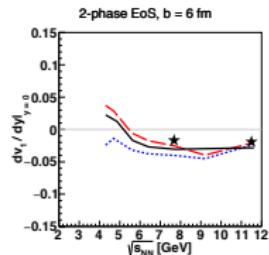
- leads to a slight steepening of the pion p_T -spectrum.
- smears the double-peak structure in the kaon rapidity spectrum.

Observables @ MPD with THESEUS

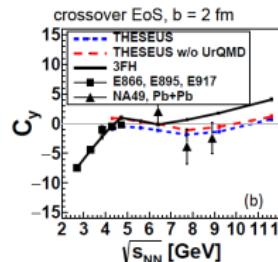
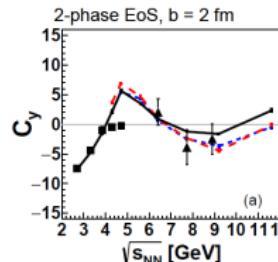
$|dv_1/dy|_{y=0}$ protons



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

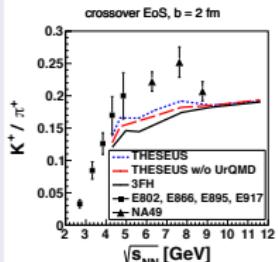
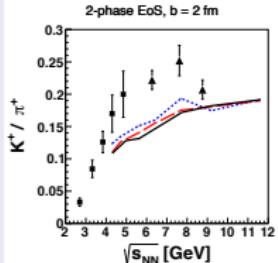


Curvature of net-proton rapidity distribution



- 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 "horn" effect?

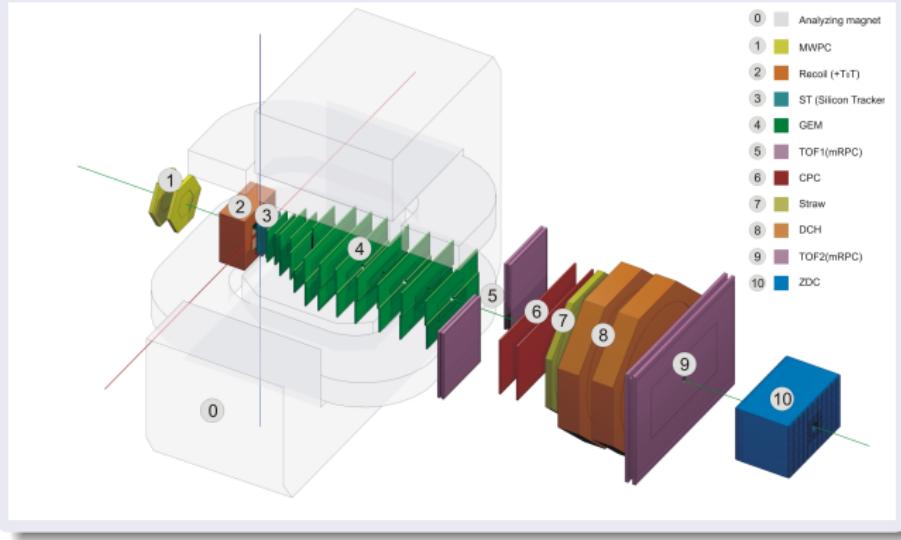


- The “wiggle” as a feature for the EoS with a 1-st order phase transition is robust against hadronic FSI.
- Turning the hadronic cascade on does not influence the kaon to pion ratio.

Experiments in fixed-target mode

BM@N experiment

Full setup, layout

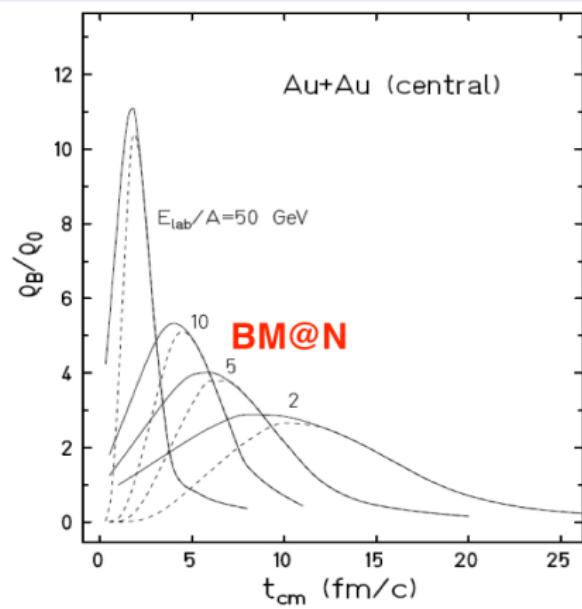
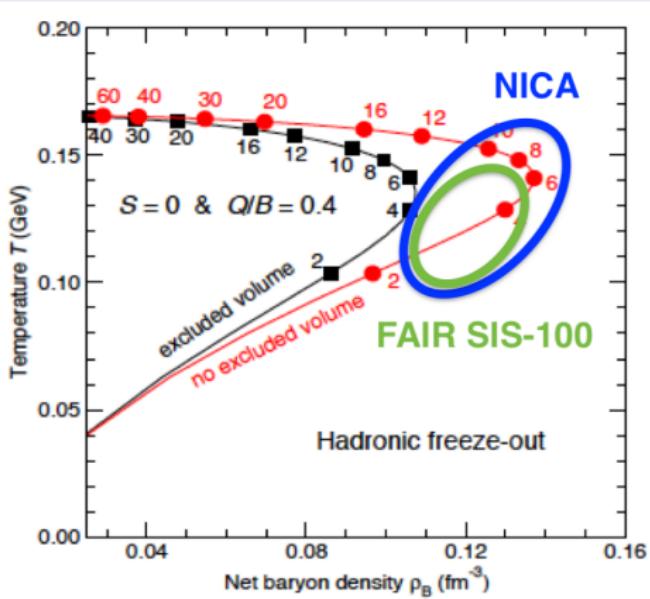


- Central tracker (Silicon tracker + GEM) inside analyzing magnet to reconstruct AA-interactions
- Outer tracker (CPC, DCH) behind magnet to link tracks from central tracker to ToF detectors
- TOF1 & TOF2 system based on mRPC and T0 detectors to identify hadrons and light nuclei
- Detectors to form T0 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)

Exploring high density baryonic matter with Nuclotron



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

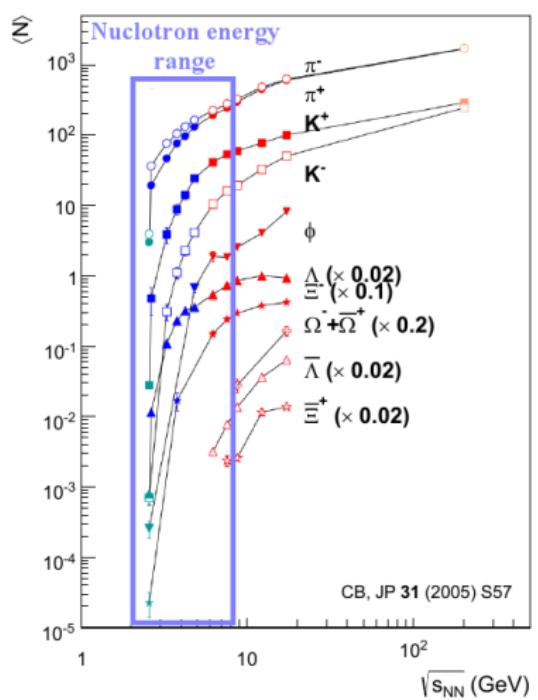
$A + A$ collisions:

- 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:

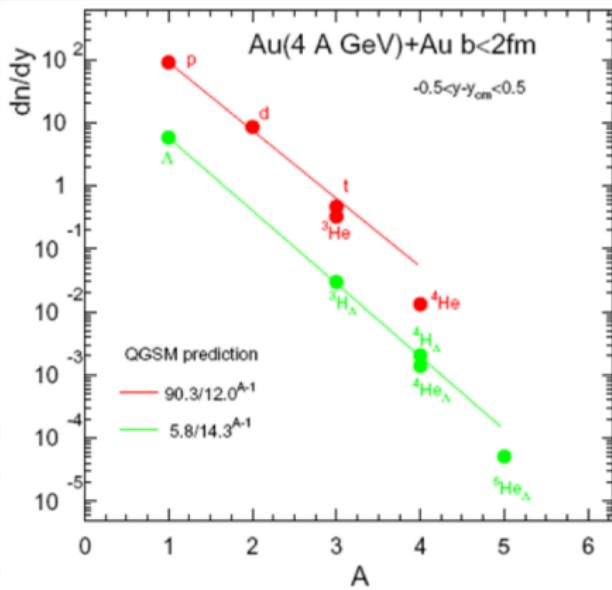
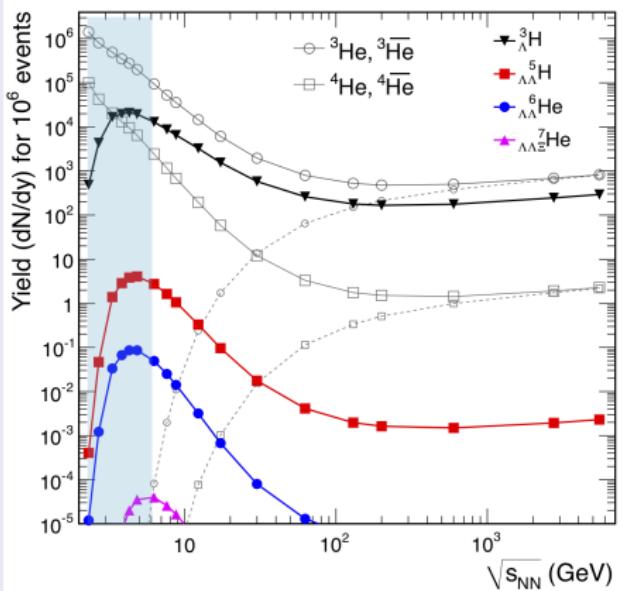
- Hadron production in elementary reactions and “cold” nuclear matter as a “reference” to determine exactly nuclear effects

AGS NA49 BRAHMS



Heavy ions $A + A$: Hypernuclei production

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



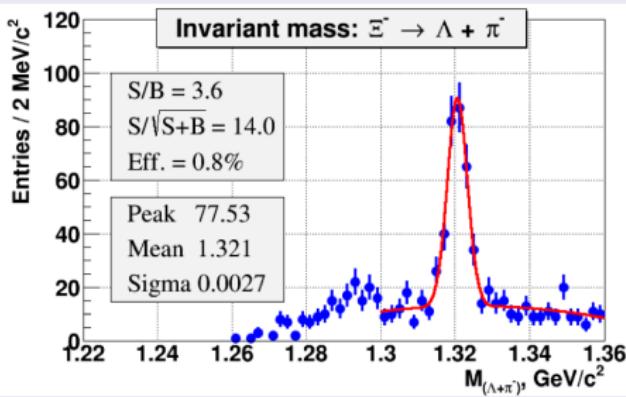
BM@N energy range is suited
for the search of (double)
hypernuclei

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

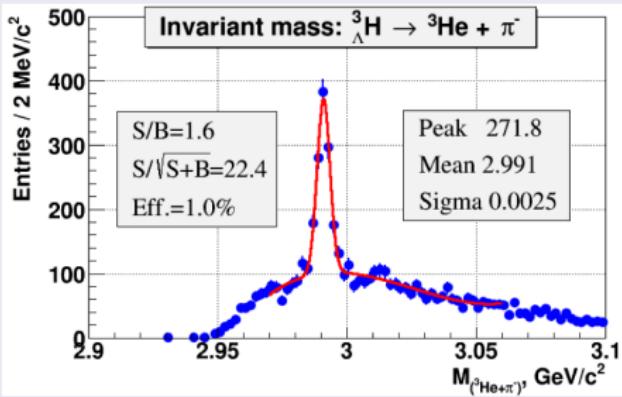
BM@N feasibility study

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 $^3\Lambda\text{H}$ in 1 month
20 kHz trigger



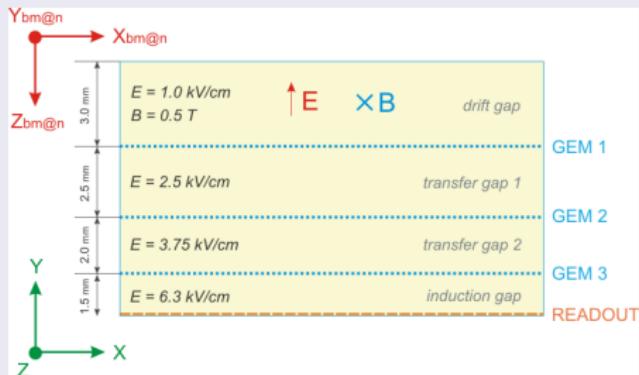
The feasibility study indicates reliable reconstruction of cascades and hypernuclei of order of 10 millions per month

Towards realistic simulation of GEM tracker

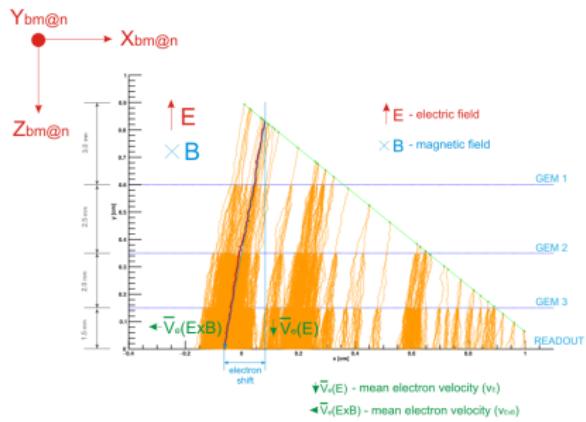
Simulation of GEM response: Garfield++

- **Garfield++** is a framework for micro-simulation of physical processes in gas detectors
- A charge particle passing through GEM chamber detecting volume ionizes electrons in gas
- Multiplayer GEM-cascades form avalanches which drift to readout-plane and fire strips

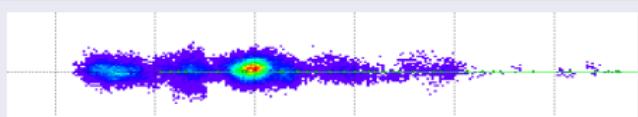
Simulation parameters in Garfield++



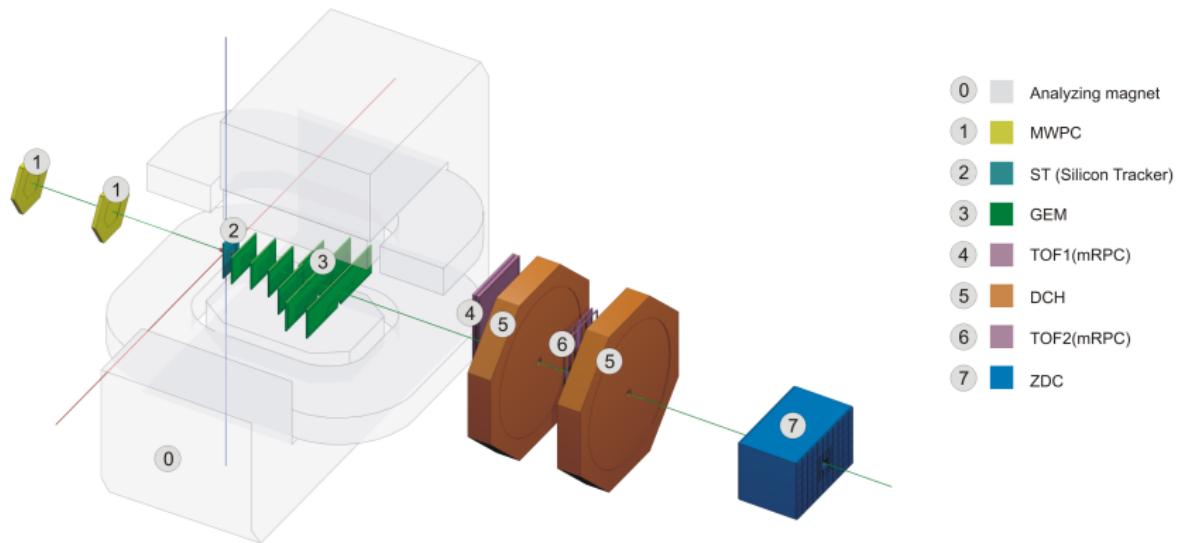
Structure of BM@N GEM chamber and simulated electron avalanches



Profile of electron avalanche at the readout-plane (cluster)



BM@N, carbon run



Input beams:

Deuteron beam (d),
 $T = 4.0, 4.6 \text{ AGeV}$
Carbon beam (C),
 $T = 3.5, 4.0, 4.5 \text{ AGeV}$

Aims:

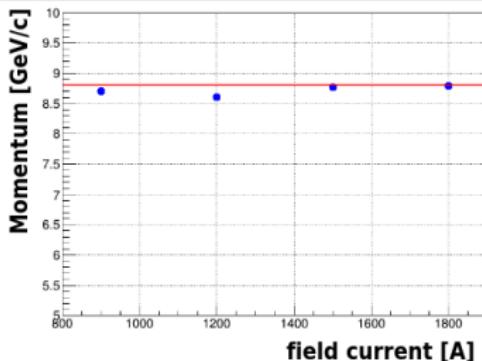
- Focus on tests and commissioning of central tracker inside analyzing magnet → GEM detectors and forward Si detector for tracking
- Test / calibrate ToF, trigger detectors, calorimeters

Program:

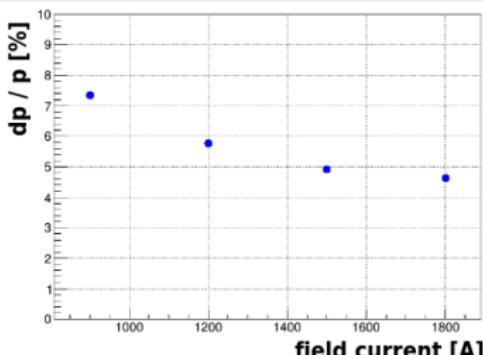
- Trace beam through detectors, align detectors, measure beam momentum in mag. field of 0.3 - 0.85 T
- Measure inelastic reactions d (C) + target → X with deuteron and carbon beam energies of 3.5 - 4.6 GeV/n on targets CH_2 , C, Al, Cu, Pb

Beam momentum measured with GEM tracker in carbon run

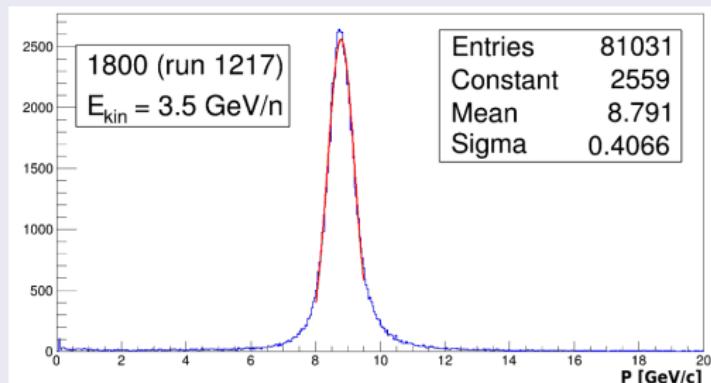
p vs. field current



$\Delta p/p$ vs. field current



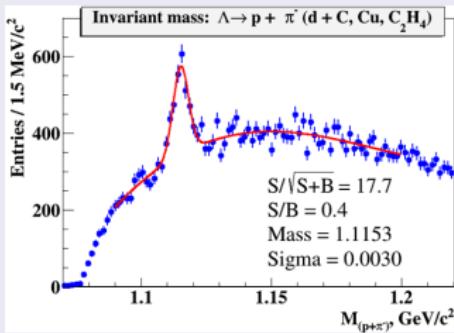
- Reconstruction of carbon beam trajectory and momentum in GEM detectors at different values of magnetic field
- Gas mixture: Ar + CO₂ (70:30)
- Carbon beam run, T = 3.5 AGeV



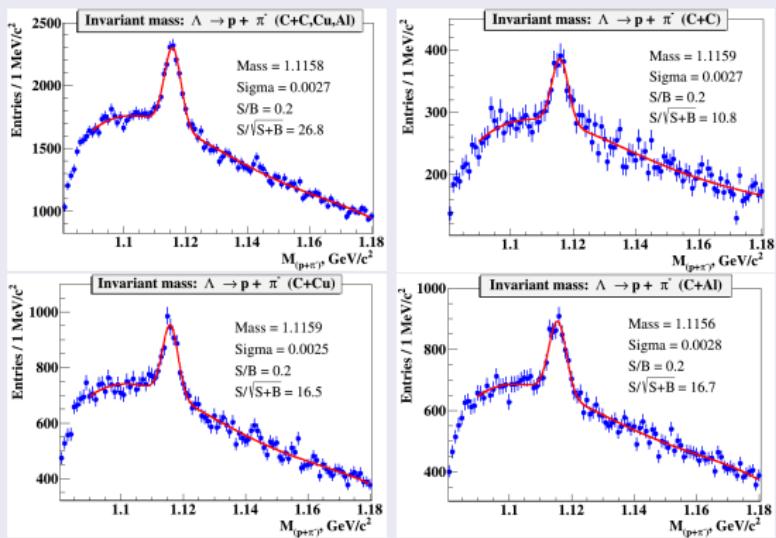
Λ^0 in deuteron and carbon runs

d (C) + target $\rightarrow X$
 Λ^0 -signal width $\sim 2.5\text{-}3$ MeV

Deuteron run



Carbon run, T = 4 AGeV



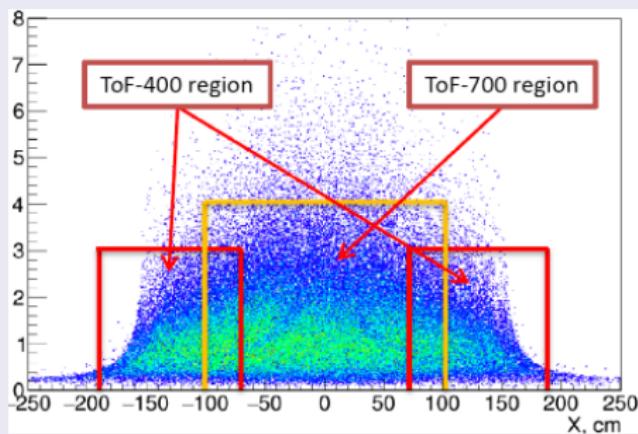
PEPAN Lett., v.15,
p.136, 2018(2): First
results from BM@N
technical run with
deuteron beam

To improve vertex and momentum resolution and reduce background under Λ^0 :

- Need few planes of forward Silicon detectors \rightarrow 3 planes used in last run
- Need more GEM planes to improve track momentum reconstruction

TOF1 and TOF2 based on mRPC

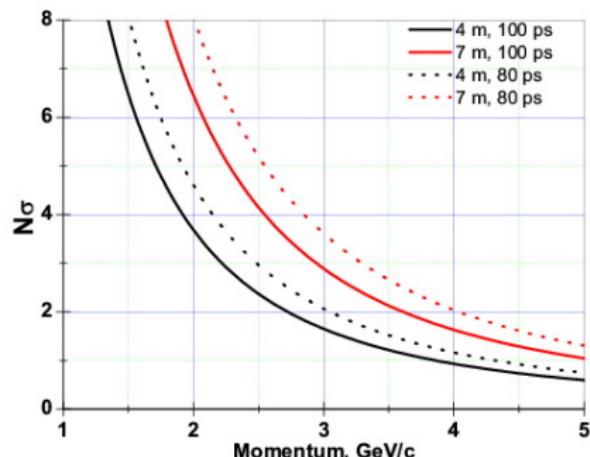
AuAu @ T = 3.4 AGeV, π^\pm , 4m from target



Requirements to TOF system:

- high granularity to keep the overall system occupancy below 15% and minimize efficiency degradation due to double hits
- operation at high particle flux

Separation of π/K for different time resolution and bases

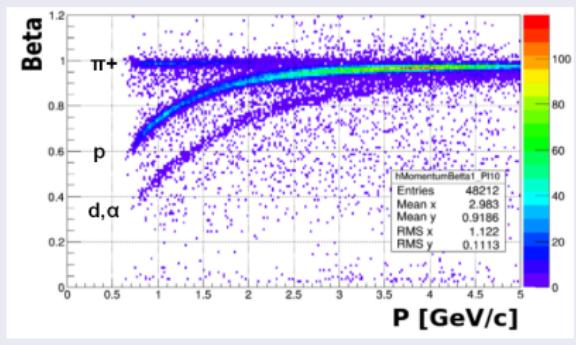
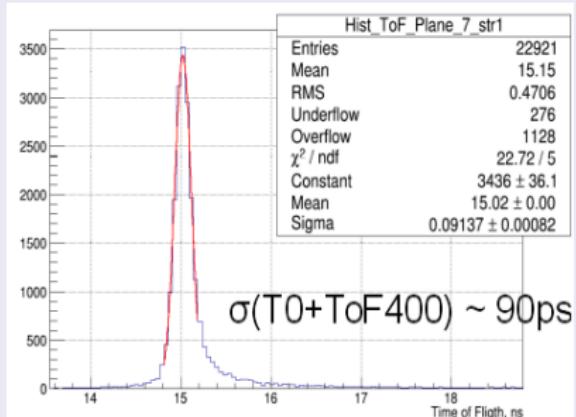


- time resolution better than 80 ps
- high combined geometrical and detection efficiency (better than 95%)

TOF1 and TOF2 performance in carbon run

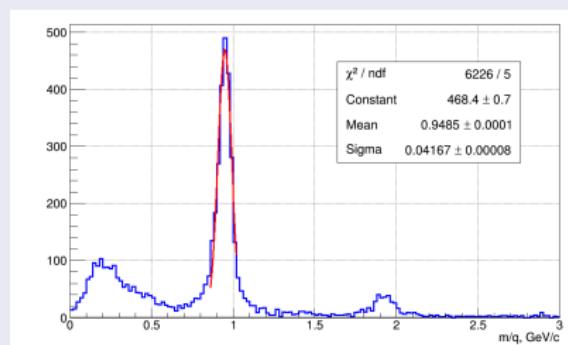
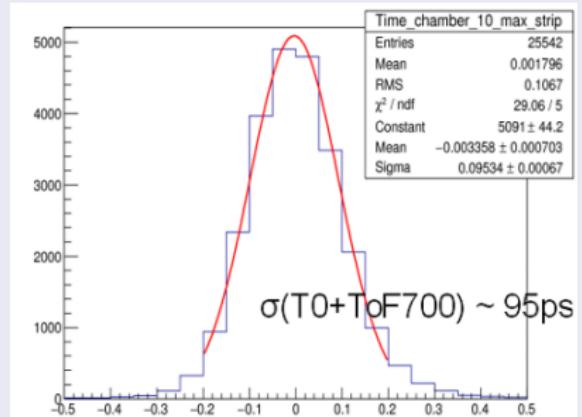
$T = 3.5 \text{ GeV/n}$, $\text{C} + \text{Al} \rightarrow \text{X}$

Includes inf. from GEM tracking

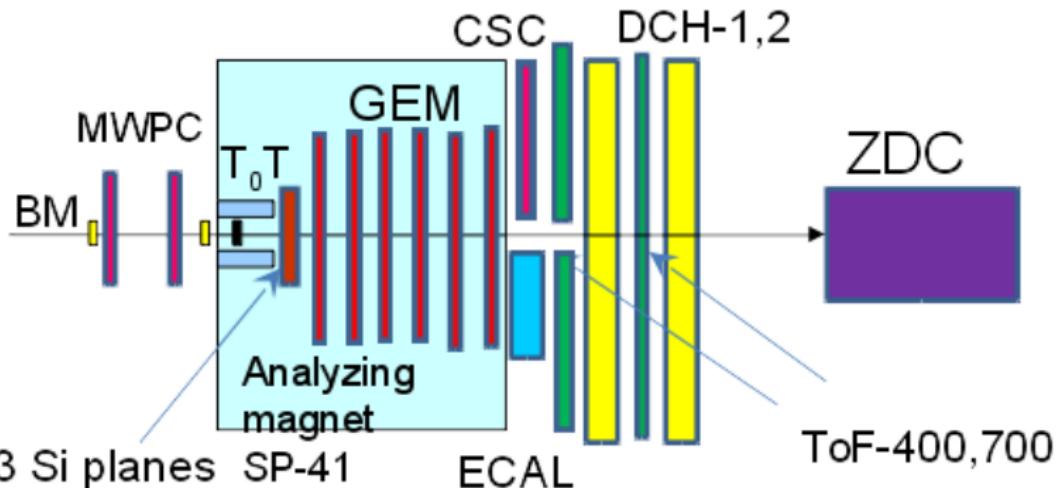


$T = 4.5 \text{ GeV/n}$, $\text{C} + \text{Cu} \rightarrow \text{X}$

Includes inf. from GEM and DCH trackings



BM@N, Argon & Krypton runs



Input beams:

Ar beam, $T = 3.2 \text{ AGeV}$
Kr beam,
 $T = 2.4, 3.0 \text{ AGeV}$

Aims:

- Central tracker inside analyzing magnet \rightarrow 6 GEM detectors $163 \cdot 45\text{cm}^2$ and forward Si strip detectors for tracking
- Test ToF system, trigger detectors, hadron and EM calorimeters, outer tracker supplemented by CSC

Program:

- Measure inelastic reactions Ar (Kr) + target $\rightarrow X$ on targets Al, Cu, Sn, Pb
- Hyperon production measured in central tracker (Si + GEM)
- Charged particles and nuclear fragments identified with ToF
- Gamma and multi-gamma states identified in ECAL

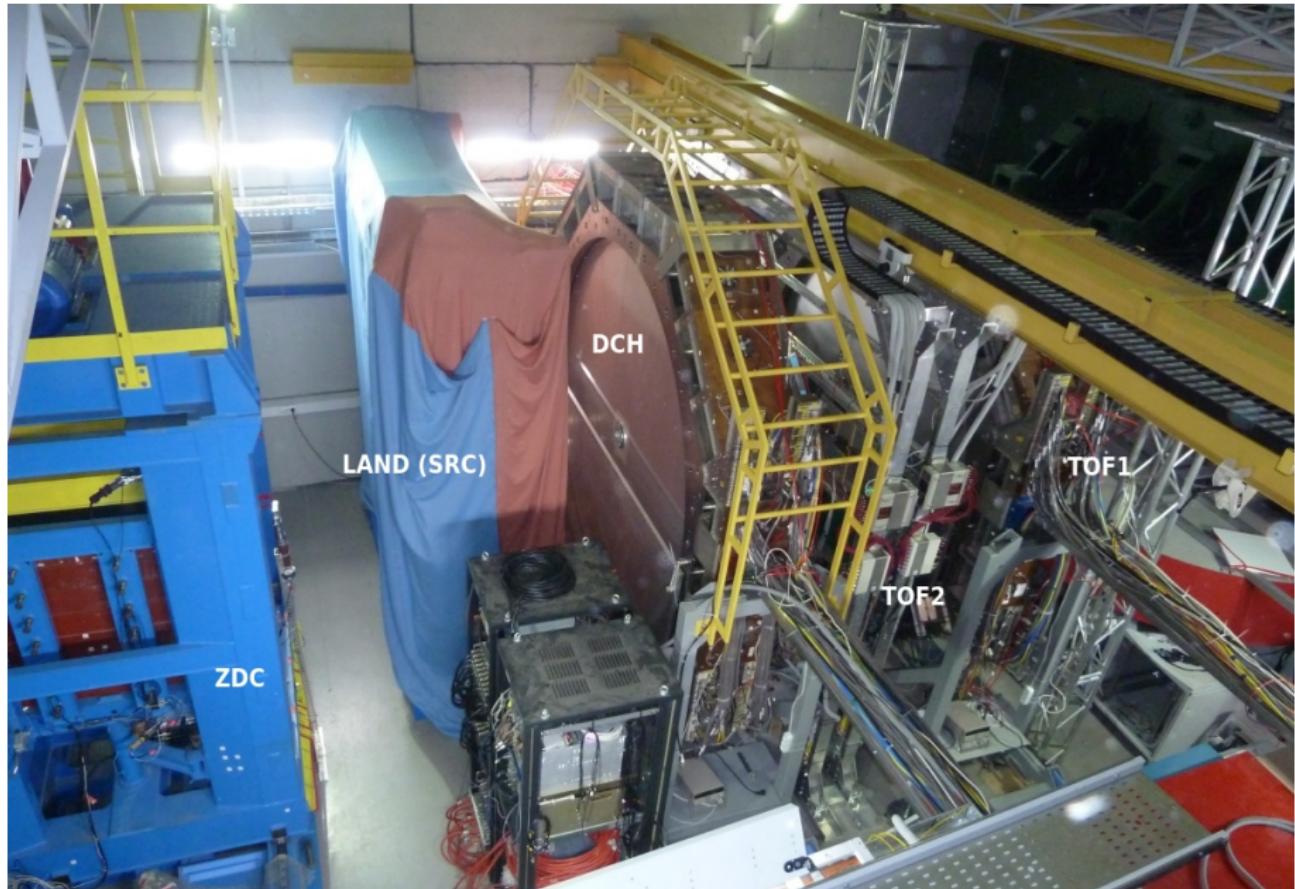
BM@N setup in the last run (before magnet)



New detector components:

- Six big GEMs
- Trigger detectors
- Three Si detectors
- CSC chamber
- Full set of TOF detectors

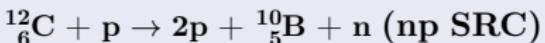
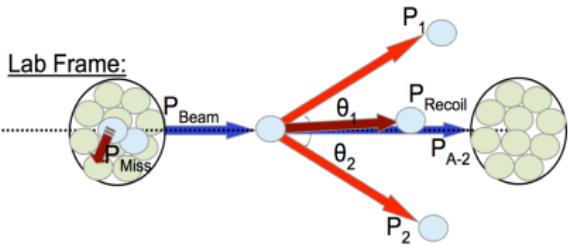
BM@N setup in the last run (behind magnet)



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

How to study SRC?

Inverse kinematics



Participants

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



Super exclusive measurement!

Four particles detected:

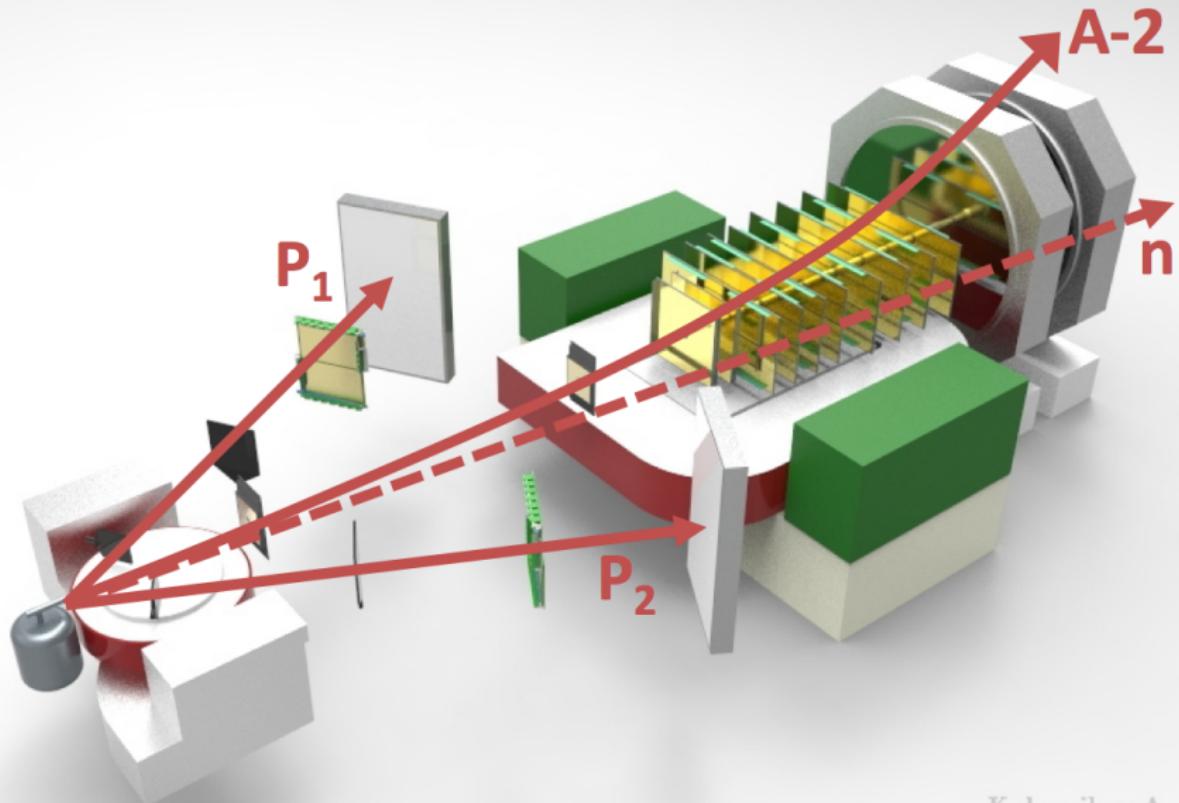
- scattered probe
- knocked-out nucleon
- recoil
- (A-2)-fragment system

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: ~ 30 MEvents collected

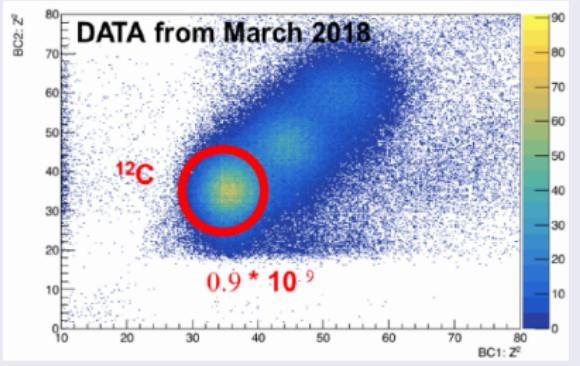
Experimental setup



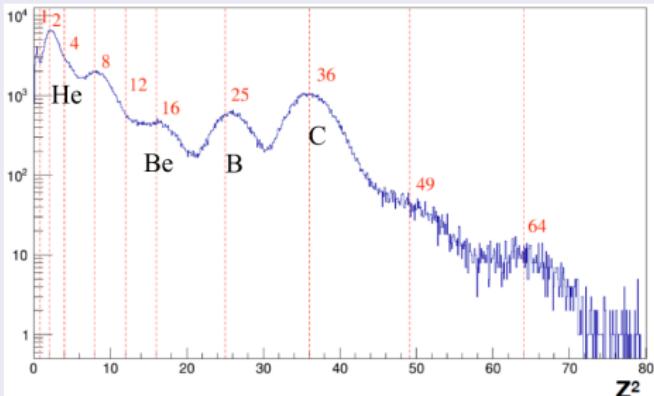
Kolesnikov A.

Counter analysis (A - 2) identification

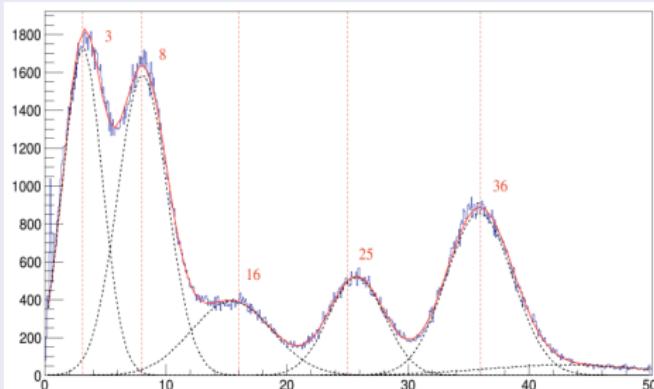
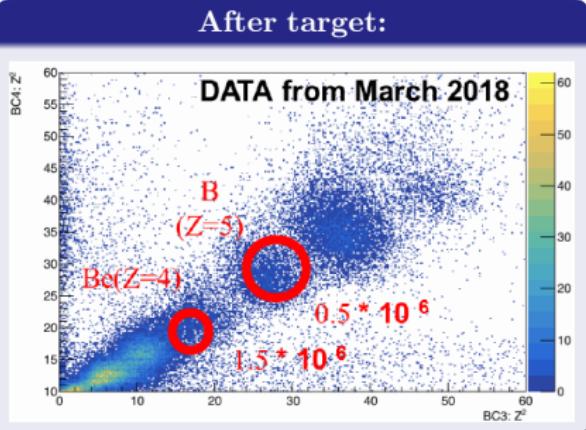
Before target:



Nuclear fragment identification



After target:



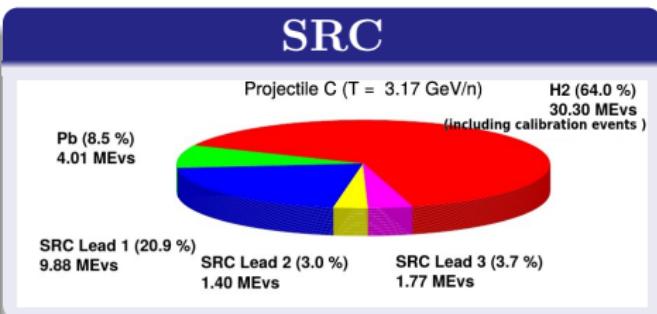
BM@N and SRC, data collected, RUN7 (March 23 - April 5)

SRC:

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

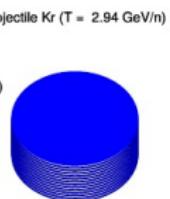
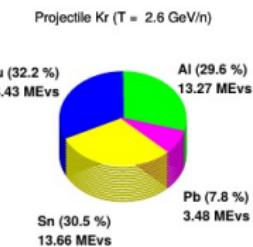
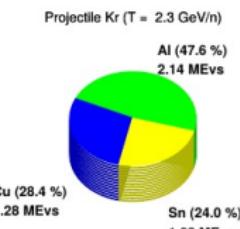
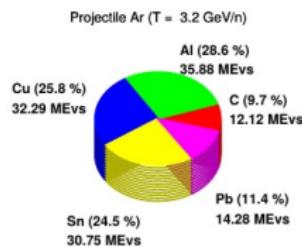
BM@N:

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



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(\uparrow)	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 ($T = 3.5 - 4.6 \text{ GeV/n}$), argon beam ($T = 3.2 \text{ GeV/n}$) and krypton beam ($T = 2.3 \text{ GeV/n}$) performed
- Measurement on Short Range Correlations with inverse kinematics: C + H₂-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

- The 1st collaboration meeting (**April, 11-13 2018**)

The 2nd collaboration meeting (**October, 29-30 2018**)



At present:

BM@N:
10 Countries,
17 Institutions,
216 Participants

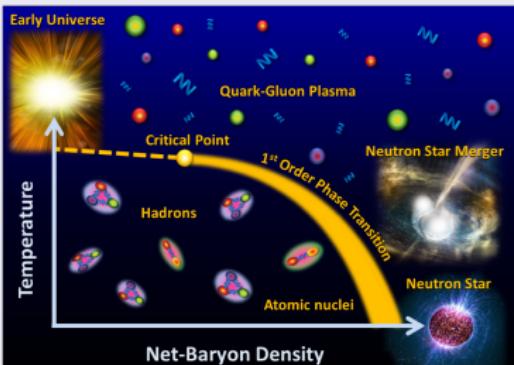
MPD:
10 Countries,
26 Institutions,
436 Participants

- N. B.: The 3rd collaboration meeting is coming
April, 16-17

Summarising ...

NICA energy region:

- Maximum in K^+/π^+ -ratio
- Maximum in Λ/π -ratio
- Maximum yield of hypernuclei
- Maximum in the net-baryon density
- Transition from a Baryon dominated system to a Meson dominated one
- Maximum of Λ -polarization
- 1st order ph. transition & mixed phase creation
- Critical end-point???



- 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