Studies of baryonic matter at BM@N

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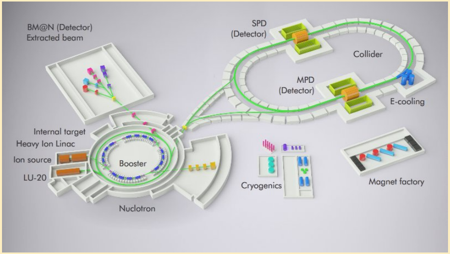
Dubna, Joint Institute for Nuclear Research

Workshop on Physics at FAIR-NICA-SPS-BES/RHIC (July 10-11, 2018)

Outline

- **Nuclotron and physics to be investigated**
- **BM@N experiment**
- **Experimental results within the BM@N experiment**
- **Short Range Correlations program as an extension to the BM@N experiment**

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**, T = **1 - 6 AGeV**
Luminosity: $10^{27}\ cm^{-2}s^{-1}$ **(Au)**, 10^{32} **(p)**

- 2 interaction points - MPD (ICNFP2018, report of V. Kolesnikov) and SPD
- Fixed target experiment - BM@N

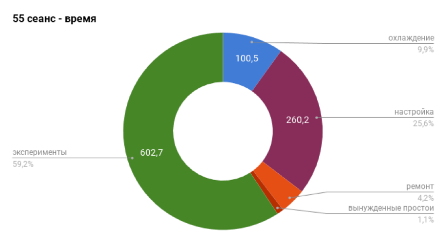
- **2018:** extracted beams of heavy ions (Ar, Kr) are available within the BM@N experiment
- **2020**: a first configuration of the MPD setup available.
- **2023**: commissioning of the fully designed NICA-complex is foreseen.

Nuclotron (in operation since 1993)

Modernized in 2010 - 2015

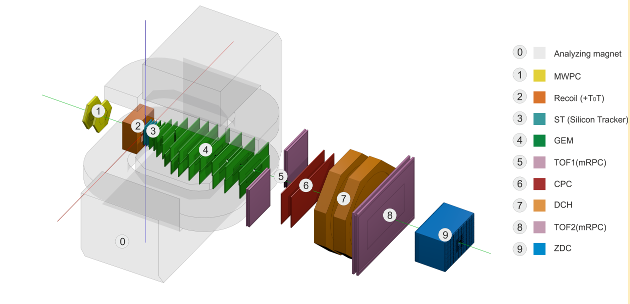
Parameters	Nuclotron
type	SC synchrotron
particles	$\uparrow$p, $\uparrow$d, nuclei
injection energy [MeV/u]	5 ($\uparrow$p, $\uparrow$d), 570-685 (Au)
max. kin. energy [GeV/u]	12.07 ($\uparrow$p), 5.62 ($\uparrow$d), 4.38 (Au)
magnetic rigidity [$T \cdot m$]	25 - 43.25
circumference [m]	251.52
cycle 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



BM@N experiment

Full setup, layout

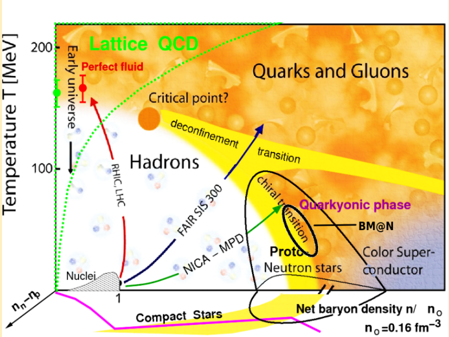


- Central tracker (Silicon tracker + GEM) inside analyzing magnet to reconstruct AA-interactions
- Outer tracker (CPC, DCH) behind magnet to link tracks from central tracker to ToF detectors
- TOF1 & TOF2 system based on mRPC and T0 detectors to identify hadrons and light nuclei
- Detectors to form T0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

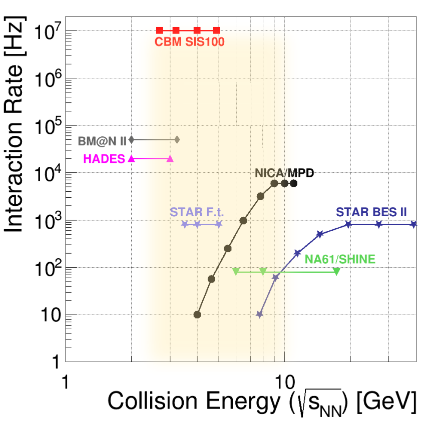
BM@N advantages:

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

QCD phase diagram



Landscape of experiments exploring QCD phase diagram

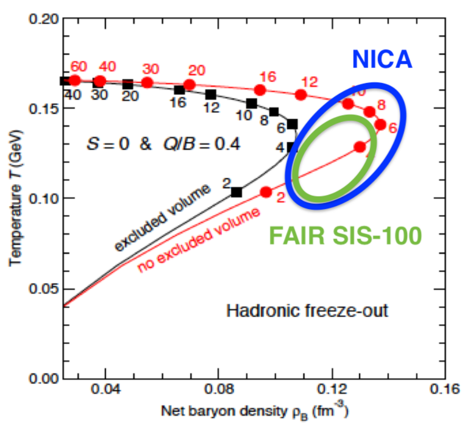


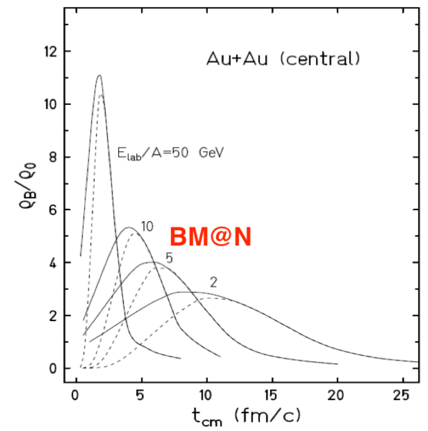
High energy:

- $N_{baryons} \approx N_{antibaryons}$
- 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





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

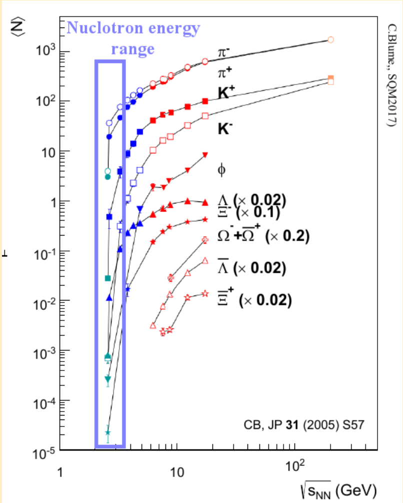
$A + A$ collisions:

- 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:

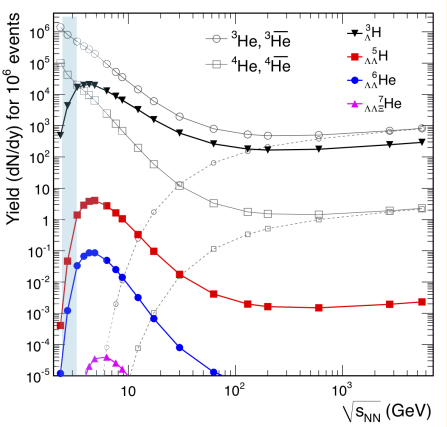
- Hadron production in elementary reactions and "cold" nuclear matter as a "reference" to determine exactly nuclear effects

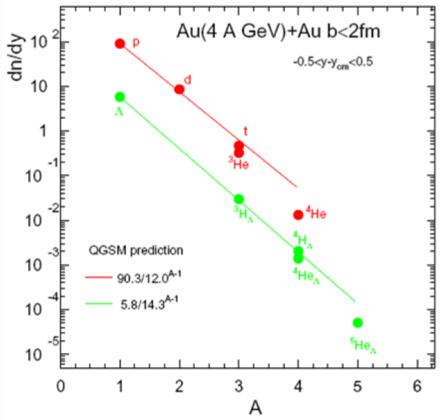
AGS NA49 BRAHMS



Heavy ions $A + A$: Hypernuclei production

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

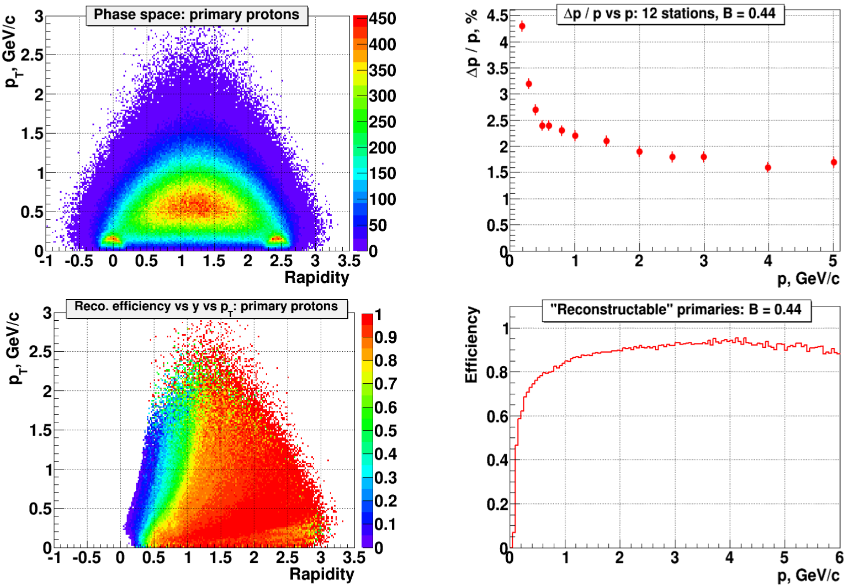




BM@N energy range is suited for the search of (double) hypernuclei

- **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)

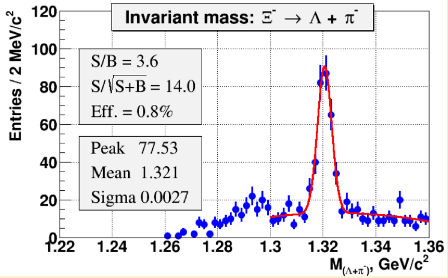
Acceptance for primary photons, mom. resolution, det. efficiency

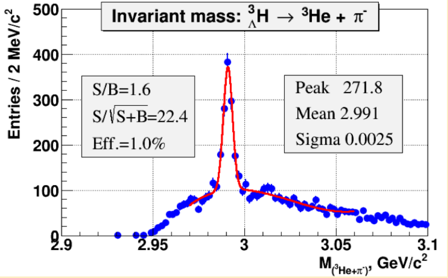


Simulation: UrQMD & DCM-QGSM, Au+Au, T = 4.5 AGeV

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

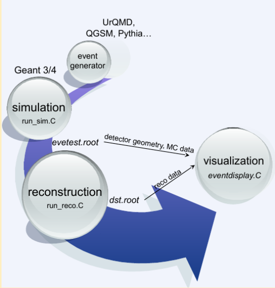


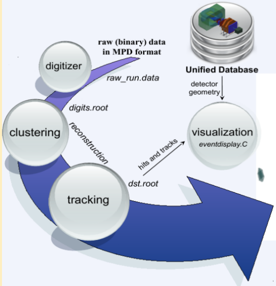


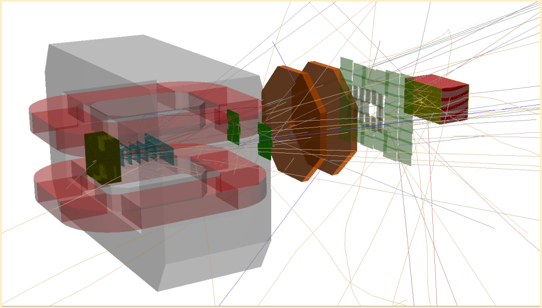
The feasibility study indicates reliable reconstruction of cascades and hypernuclei of order of 10 millions per month

Data processing for offline Event Display

Sim & Reco



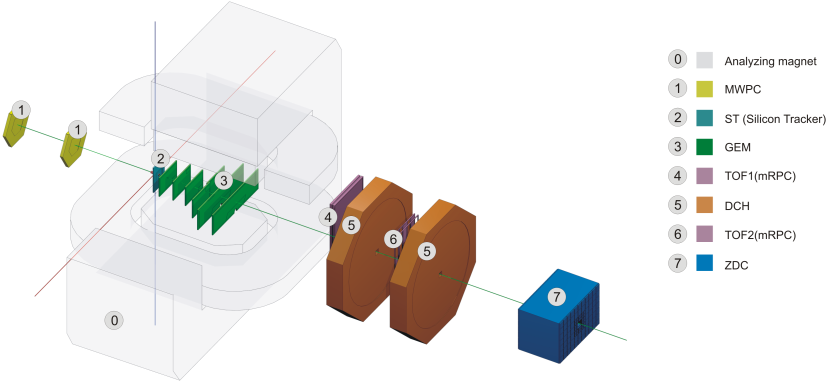




- The Event Display has been developed for graphical representations of the NICA experiments in offline as well as online mode and integrated into the BmnRoot software.
- The visualization system gives an opportunity to visually check the developed algorithms for reconstruction and physical analysis of data.

Some experimental results from deuteron and carbon runs

Setup & Experimental program to be performed



Input beams:

Deuteron beam (d),
$T = 4.0, 4.6$ **AGeV**
Carbon beam (C),
$T = 3.5, 4.0, 4.5$ **AGeV**

Aims:

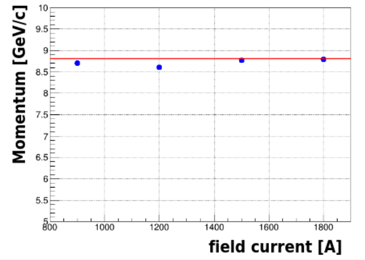
- **Focus on tests and commissioning of central tracker inside analyzing magnet → GEM detectors and forward Si detector for tracking**
- **Test / calibrate ToF, trigger detectors, calorimeters**

Program:

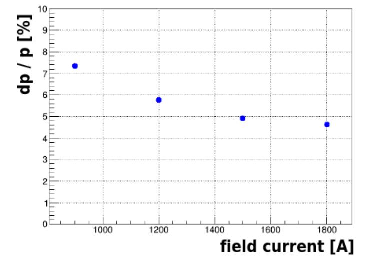
- **Trace beam through detectors, align detectors, measure beam momentum in mag. field of 0.3 - 0.85 T**
- **Measure inelastic reactions d (C) + target → X with deuteron and carbon beam energies of 3.5 - 4.6 GeV/n on targets CH_2, C, Al, Cu, Pb**

Beam momentum measured with GEM tracker in carbon run

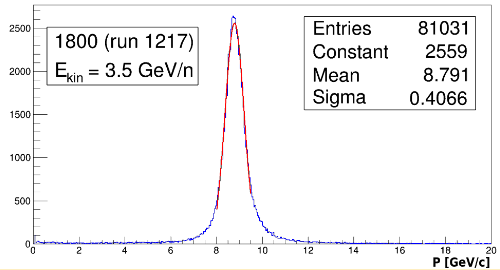
p vs. field current



$\Delta p/p$ vs. field current



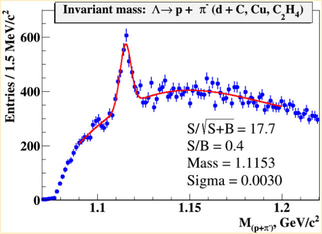
- Reconstruction of carbon beam trajectory and momentum in GEM detectors at different values of magnetic field
- Gas mixture: Ar + CO_2 (70:30)
- Carbon beam run, T = 3.5 AGeV



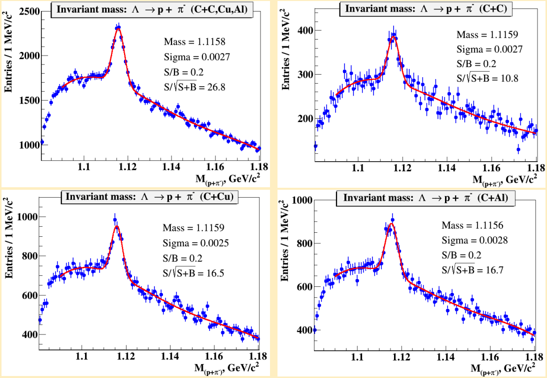
Λ^0 in deutron and carbon runs

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

Deuteron run



Carbon run, T = 4 AGeV



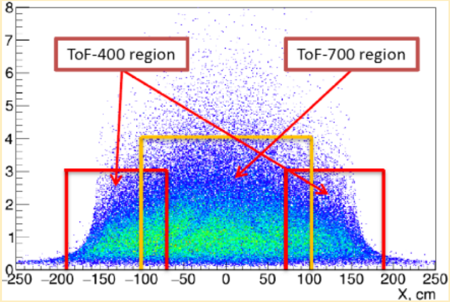
PEPAN Lett., v.15, p.136, 2018(2): First results from BM@N technical run with deuteron beam

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

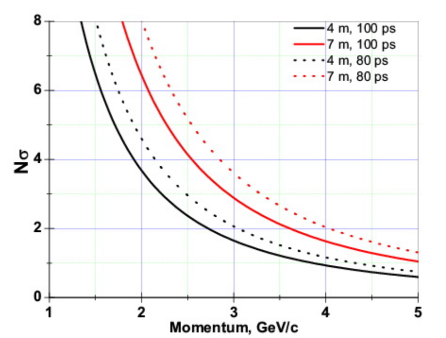
- **Need few planes of forward Silicon detectors $\rightarrow$ 3 planes used in last run**
- **Need more GEM planes to improve track momentum reconstruction**

TOF1 and TOF2 based on mRPC

AuAu @ T = 3.4 AGeV, $\pi^{\pm}$, 4m from target



Separation of π/K for different time resolution and bases



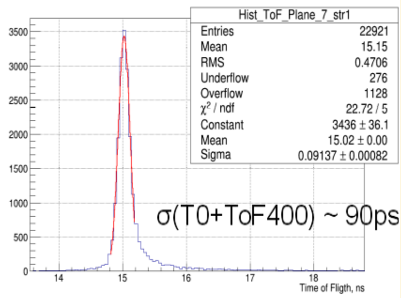
Requirements to TOF system:

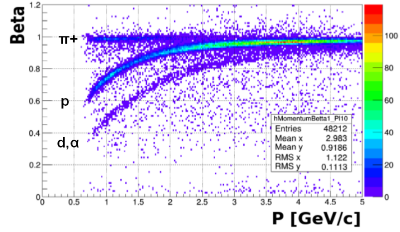
- high granularity to keep the overall system occupancy below 15% and minimize efficiency degradation due to double hits
- operation at high particle flux
- time resolution better then 80 ps
- high combined geometrical and detection efficiency (better than 95%)

TOF1 and TOF2 performance in carbon run

T = 3.5 GeV/n, C + Al → X

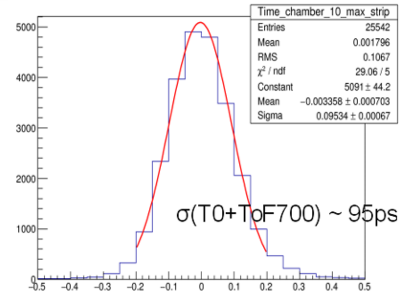
Includes inf. from GEM tracking

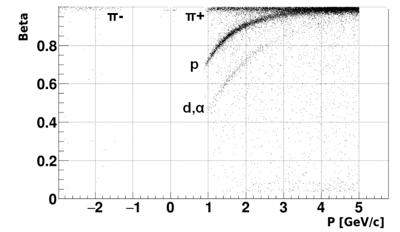




T = 4.5 GeV/n, C + Cu → X

Includes inf. from GEM and DCH trackings

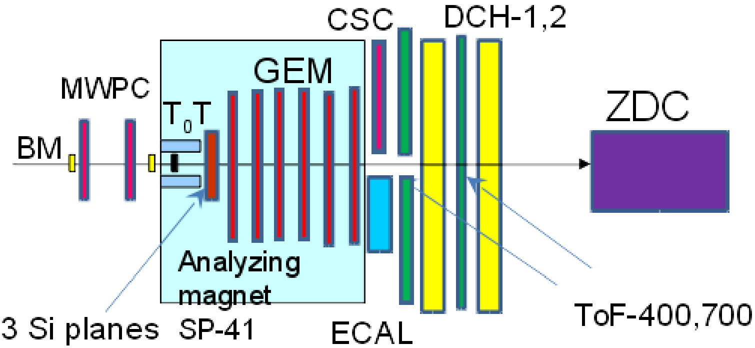




And what about the last run on March 2018?

Data analysis is in progress, but nevertheless...

Setup & experimental program to be performed



Input beams:

Ar beam, $T = 3.2$ AGeV
Kr beam,
$T = 2.4, 3.0$ AGeV

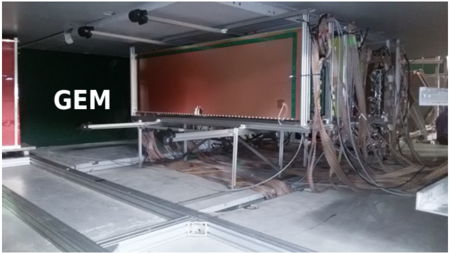
Aims:

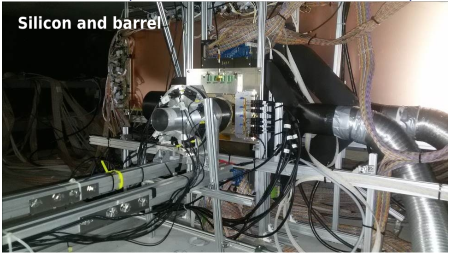
- Central tracker inside analyzing magnet → 6 GEM detectors $163 \cdot 45 cm^2$ and forward Si strip detectors for tracking
- Test ToF system, trigger detectors, hadron and EM calorimeters, outer tracker supplemented by CSC

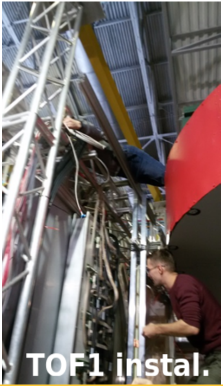
Program:

- Measure inelastic reactions Ar (Kr) + target → 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)



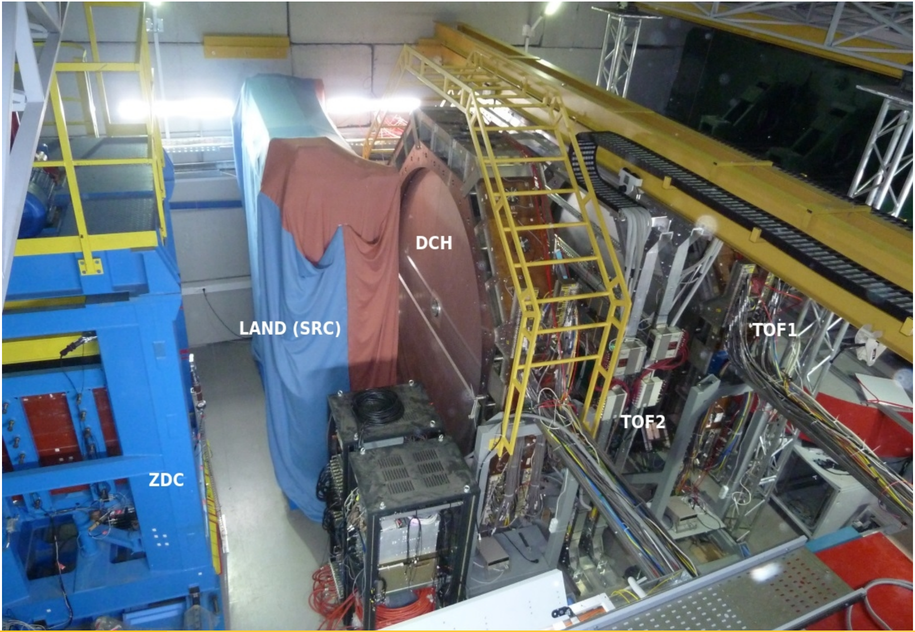




New detector components:

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

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



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

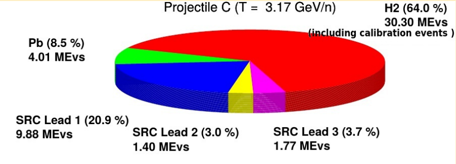
SRC:

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

BM@N:

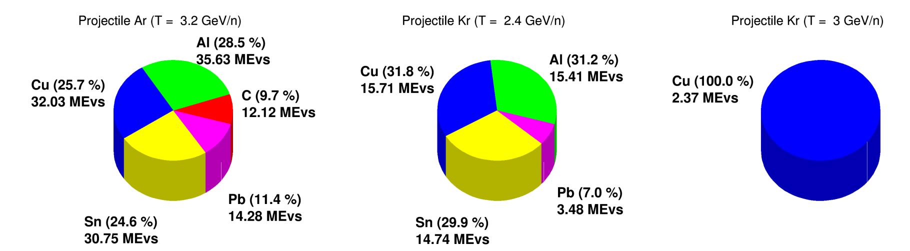
- One beam energy available for Ar-beam and three - for Kr-beam
- Wide set of targets used (C, Al, Cu, Sn, Pb)

SRC



Data analysis is in progress ...

BM@N

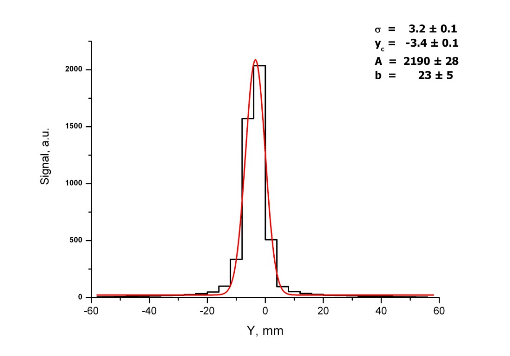


BM@N beam profile

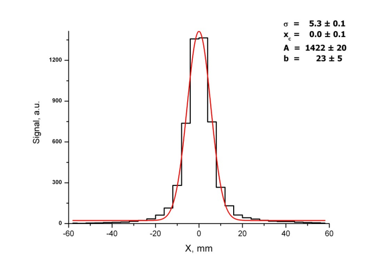
Beam profiles measured by beam group

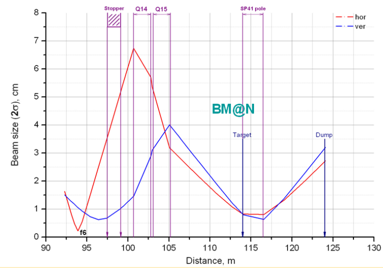
	C, Spring 2017	Ar, Spring 2018	Kr, Spring 2018
$\sigma_x[mm]$	6	5	5.3
$\sigma_y[mm]$	4.9	5	3.2

Kr beam, Y-profile

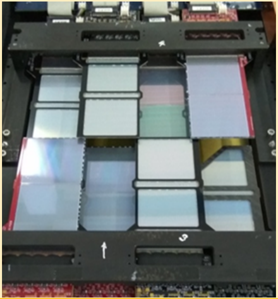


Kr beam, X-profile

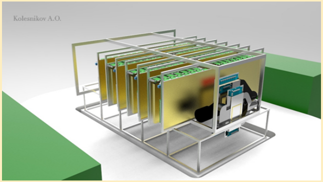




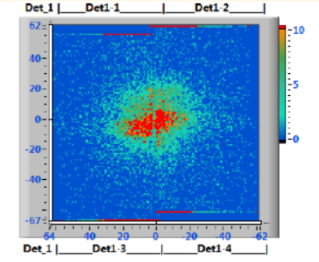
Forward silicon strip detectors



Central tracker (GEM + SI) in Argon/Krypton run



Kr beam fragments in silicon vertex detector



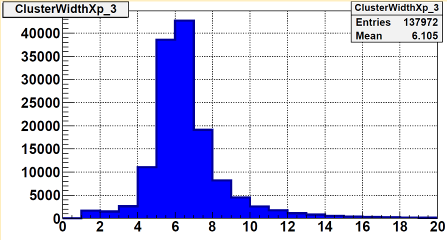
- Two-coordinate Si detector with strip pitch of $95/103\mu m$, full size of $25 \cdot 25 cm^2$
- Detector consists of 4 sub-detectors located around beam
- 2 smaller vertex detectors (March 2018)

New Cathode Strip Chamber (CSC) as Outer tracker

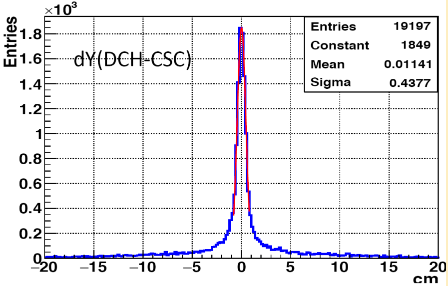
Argon (krypton) run:

CSC chamber installed in front of TOF1 to check its performance as Outer tracker for heavy ions

Average cluster size:



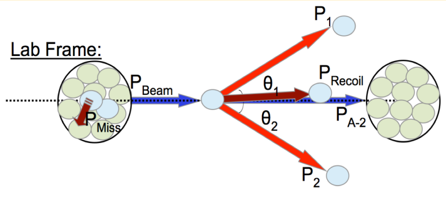
Matching between CSC and DCH:



Short Range Correlations (SRC) @ BM@N

How to study SRC?

Inverse kinematics



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

Participants

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

Super exclusive measurement!

Four particles detected:

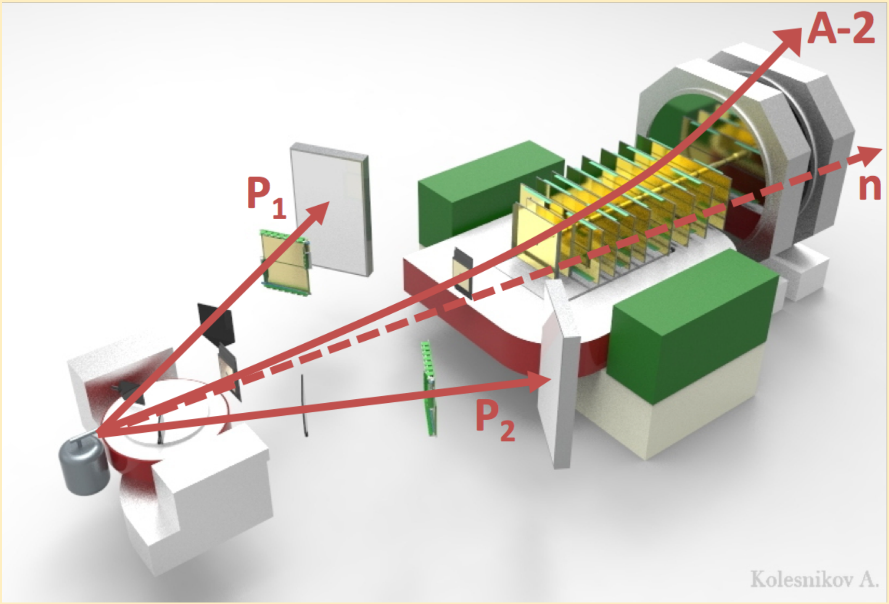
- scattered probe
- knocked-out nucleon
- recoil
- (A-2)-fragment system

Objectives

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

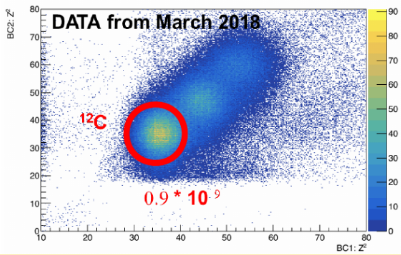
First BM@N SRC program run in March 2018: $\sim$ 30 MEvents collected

Experimental setup

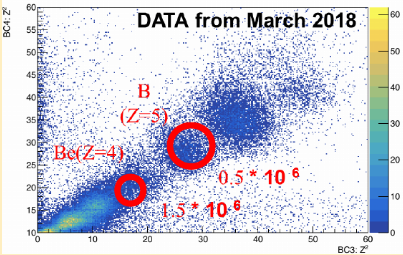


Counter analysis (A - 2) identification

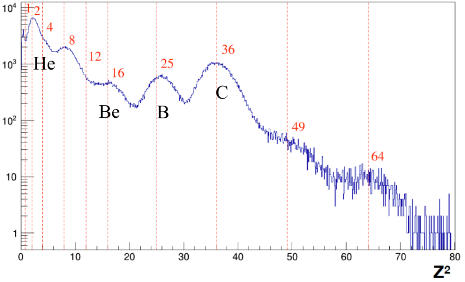
Before target:

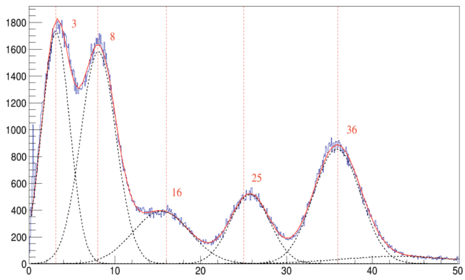


After target:



Nuclear fragment identification





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

Conclusion:

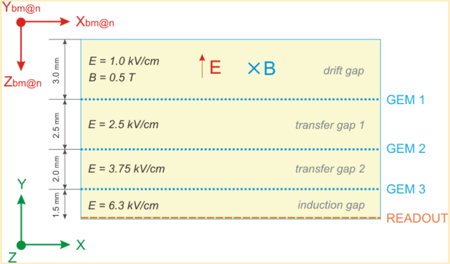
- **BM@N experiment has recorded experimental data with carbon, argon and krypton beams at several energies and on several targets.**
- **Minimum bias interactions have been analyzed aimed to reconstruct tracks, primary and secondary vertices using central GEM and Si tracking detectors.**
- **Reconstructed signals of Λ^0 and K_s^0 are visible in proton-pion and pion-pion invariant mass spectra.**
-

Towards realistic simulation of GEM tracker

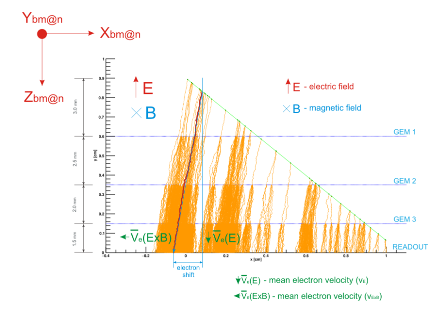
Simulation of GEM response: Garfield++

- 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)