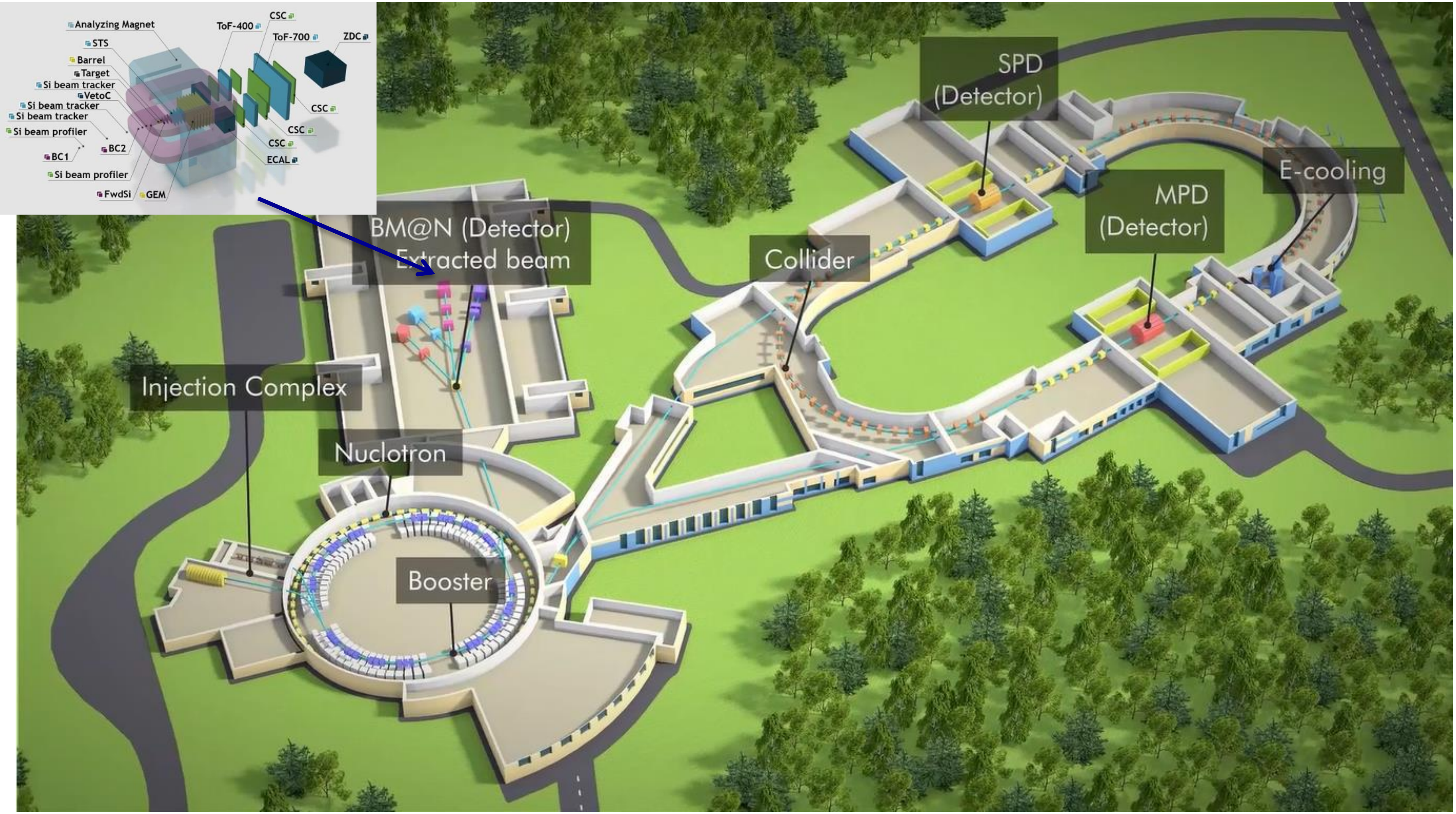
BM@N experiment at NICA/Nuclotron: scientific program and first results

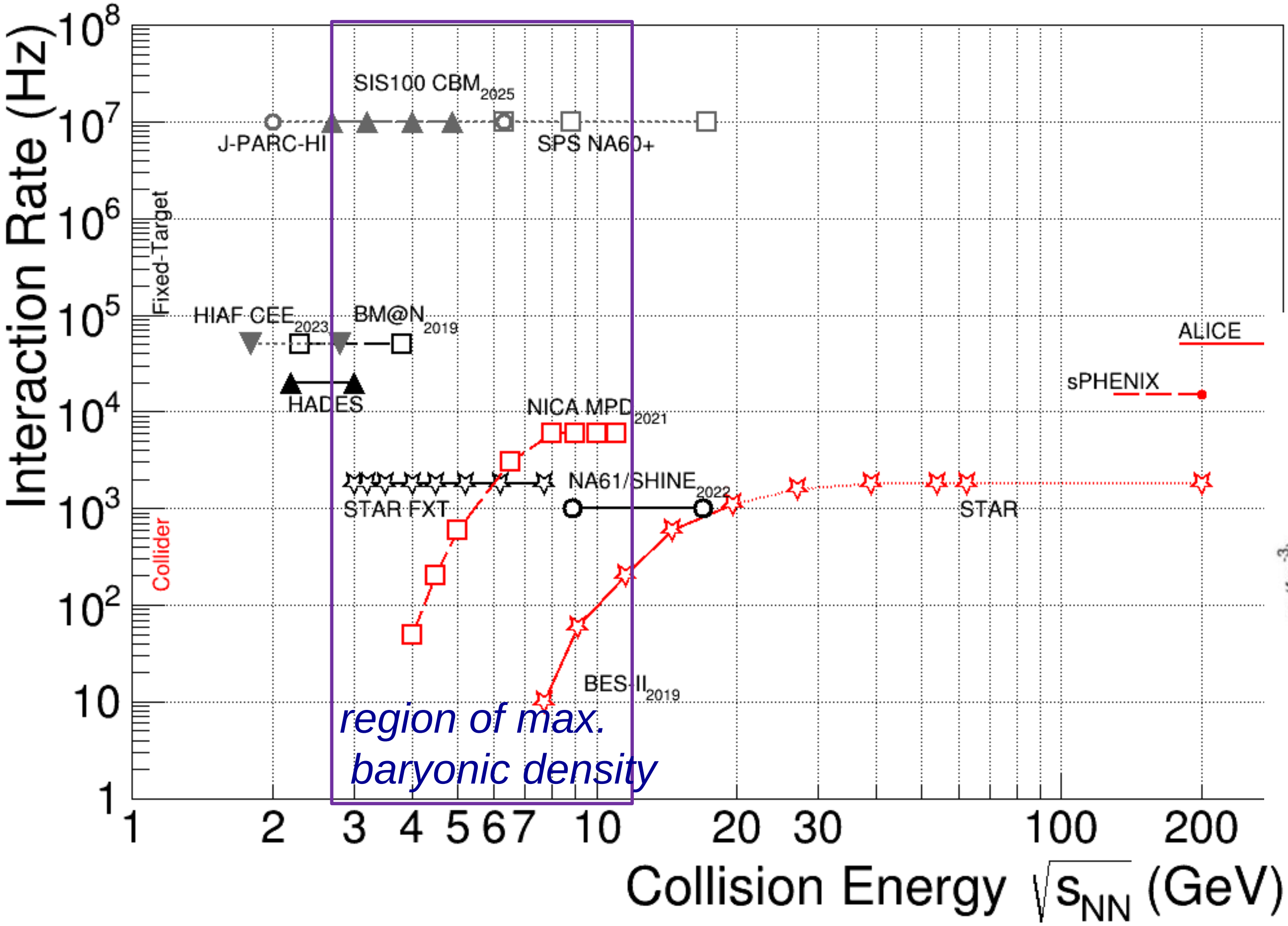
M.Kapishin

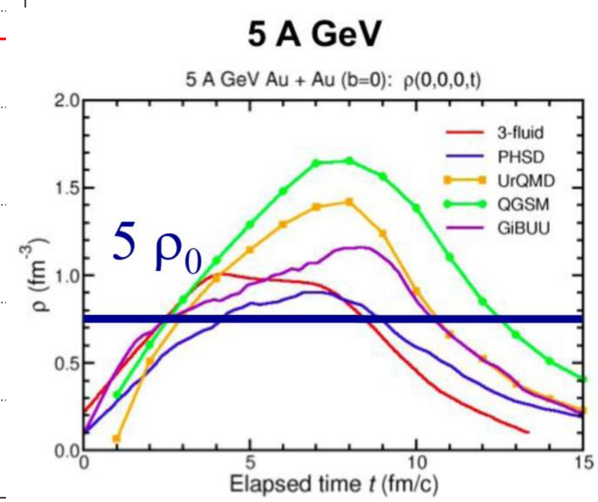
NICA Heavy Ion Complex

BM@N: heavy ion energy 1- 3.8 GeV/n, beams: d to Bi, Intensity ~few 10^6 Hz (Bi)



Heavy Ion Collision Experiments





BM@N: $\sqrt{s_{NN}}$= 2.3 - 3.3 GeV
MPD: $\sqrt{s_{NN}}$= 4 - 11 GeV

BM@N competitors:

HADES BES (SIS): Au+Au at $\sqrt{s_{NN}}$ = 2.42 GeV, Ag+Ag at $\sqrt{s_{NN}}$ = 2.42 GeV, 2.55 GeV.

STAR BES (RHIC): Au+Au at $\sqrt{s_{NN}}$ = 3-200 GeV

Fixed target (BM@N) vs Collider experiment (MPD)

$\sqrt{s} \sim \sqrt{2m(E_{beam}+m)}$ → measurements at low and middle energies

Higher acquisition rate ~ capacity of FEE electronics and DAQ

Cover beam fragmentation and part of central range, no target fragmentation

Limited reaction plane resolution

Various combinations of beam and target nuclei

Easy access to detectors

$\sqrt{s} = 2E_{beam}$ → measurements at high energies

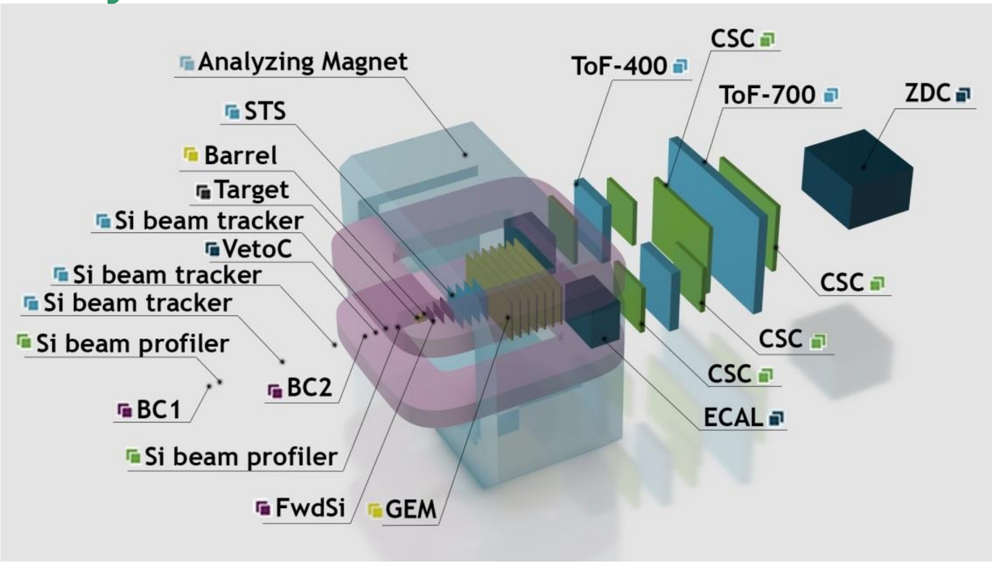
Limited acquisition rate ~ Luminosity of colliding beams

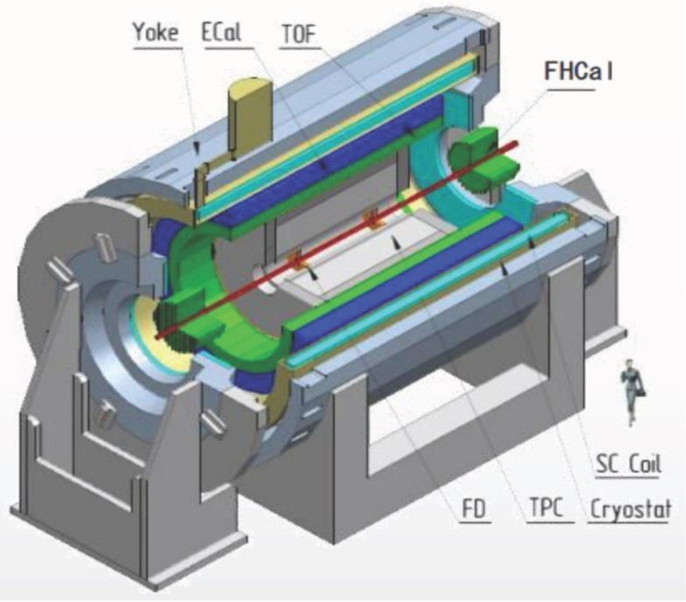
Cover central and part of fragmentation range of colliding beams

Good reaction plane resolution (axial symmetry)

Typically same nuclei of colliding beams

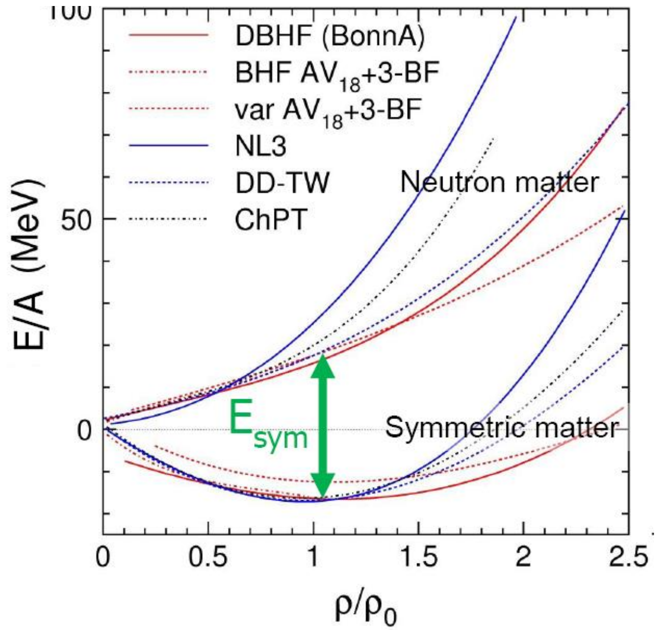
Very limited access to detectors



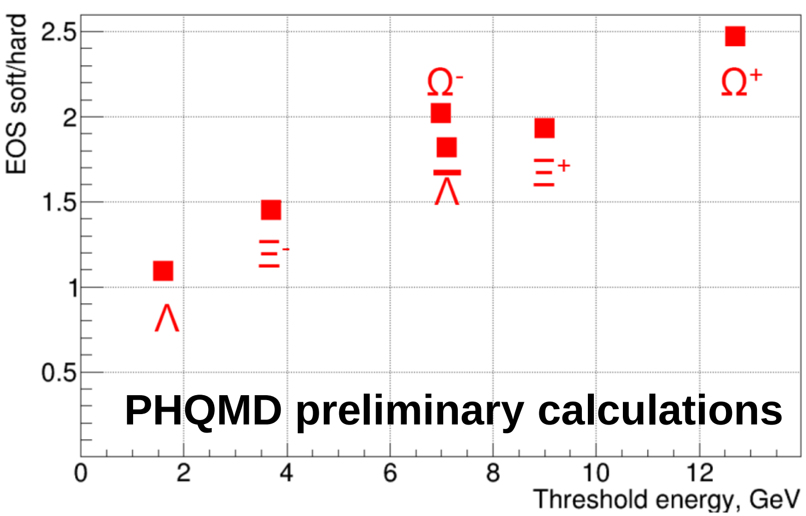


EOS of symmetric and asymmetric nuclear matter

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



Hyperon yield in 4A GeV Au+Au:
soft EOS (K=240 MeV) / hard EOS (K=350) MeV



EOS: relation between density, pressure, temperature, energy and isospin asymmetry

$$E_A(\rho,\delta) = E_A(\rho,0)+E_{sym}(\rho)\cdot\delta^2$$

with $\delta = (\rho_n-\rho_p)/\rho$ $\quad$ $E/A(\rho_o) = -16$ MeV

Curvature defined by nuclear incompressibility: $K = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$

►Study symmetric matter EOS at ρ=3-5 ρ_0
→ elliptic flow of protons, mesons and hyperons
→ sub-threshold production of strange mesons and hyperons
→ extract K from data to model predictions
►Constrain symmetry energy E_{sym}
→ elliptic flow of neutrons vs protons
→ sub-threshold production of particles with opposite isospin

BM@N physics case and observables

The QCD matter equation-of-state at high densities

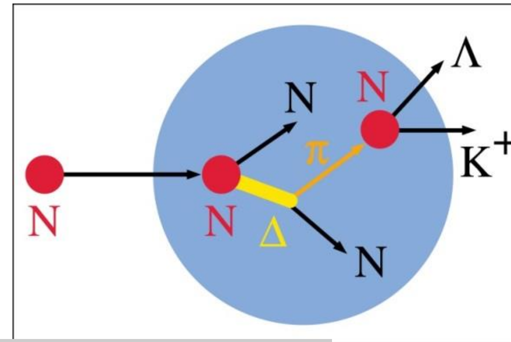
➢ particle production at (sub)threshold energies via multi-step processes

Example: subthreshold K^+ production at GSI

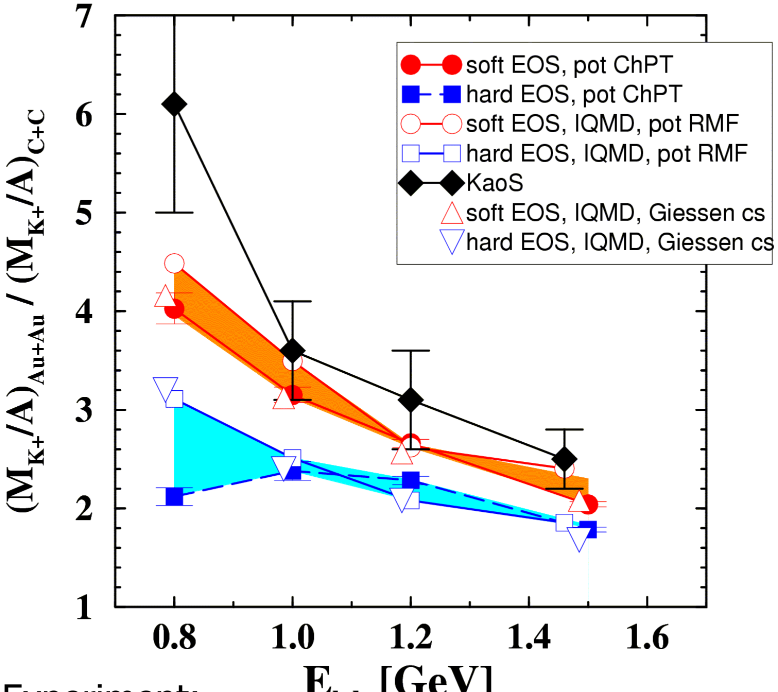
Idea: K^+ yield ∝ density ∝ compressibility

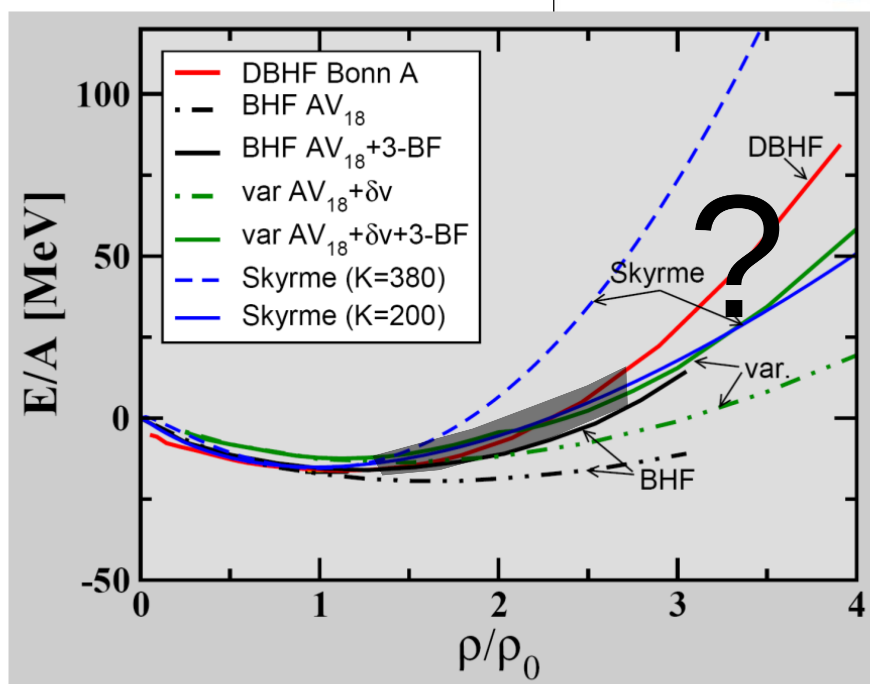
$pp \rightarrow K^+ \Lambda\, p$

$(E_{thres} = 1.6$ GeV)



K^+ from Au+Au/C+C

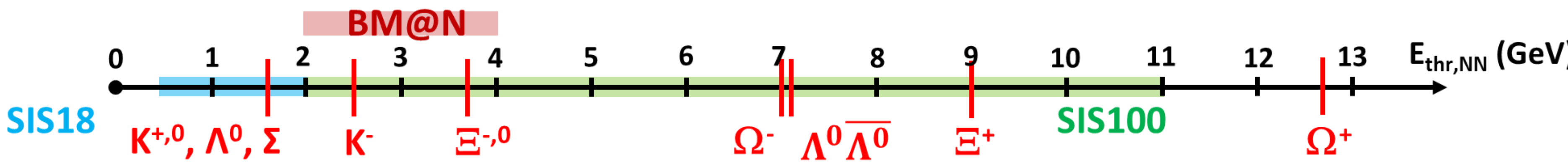




Experiment:
C. Sturm et al., (KaoS Collaboration)
PRL 86 (2001) 39

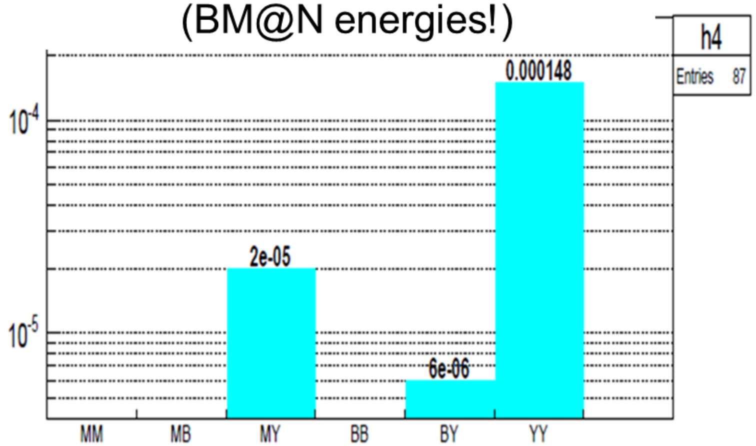
Theory: QMD: Ch. Fuchs et al., PRL86 (2001) 1974
IQMD Ch. Hartnack, J. Aichelin, J. Phys. G 28 (2002) 1649

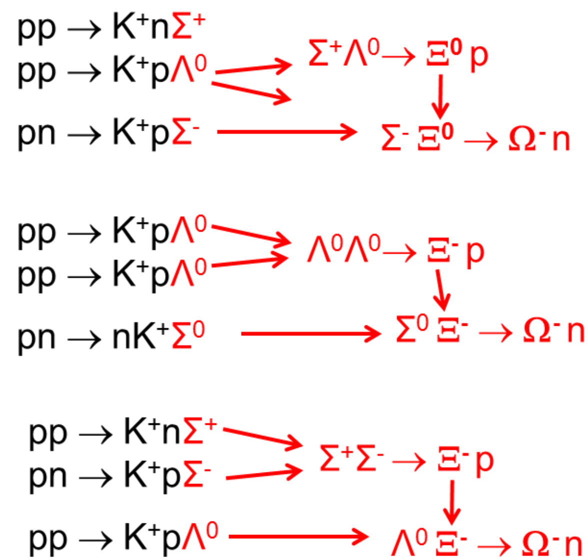
New probe of the high-density EOS: subthreshold production of multi-strange (anti-)hyperons via sequential collisions



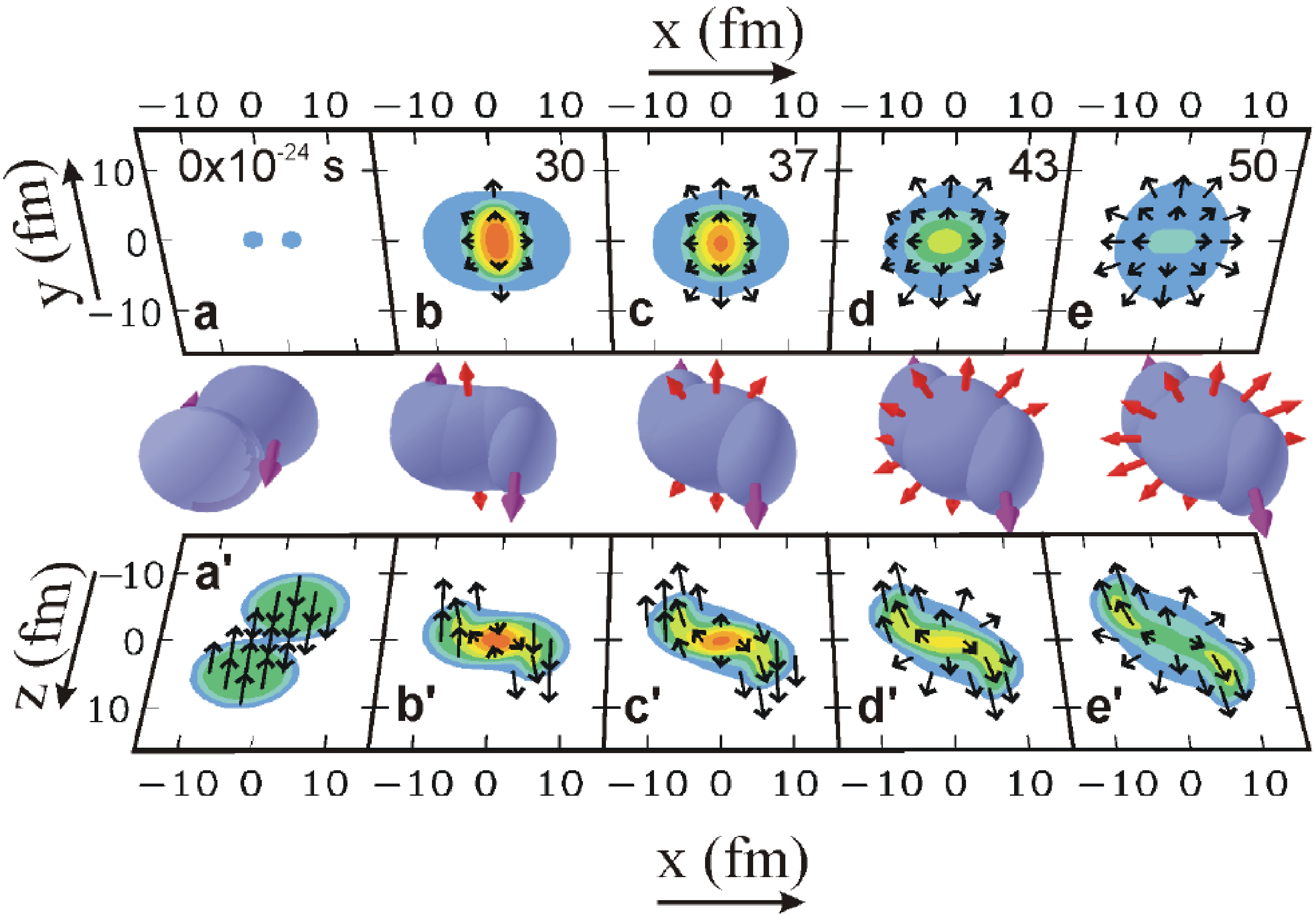
Ω^- production in 4 A GeV Au+Au (BM@N energies!)

HYPQGSM calculations
K. Gudima et al.





Time (x axis) , transverse (y axis) and longitudinal (z axis) dynamics of Au+Au collision



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

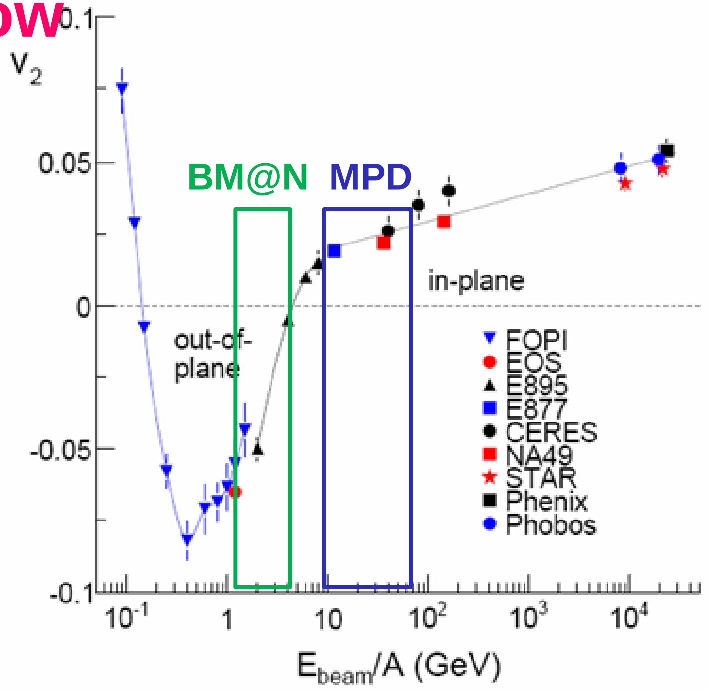
Study of EoS: Collective flow of identified particles

➢ collective flow of identified particles (π,K,p,Λ,Ξ,Ω,...) driven by the pressure gradient in the early fireball

→ Nuclear incompressibility: $K = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$

Azimuthal angle distribution:

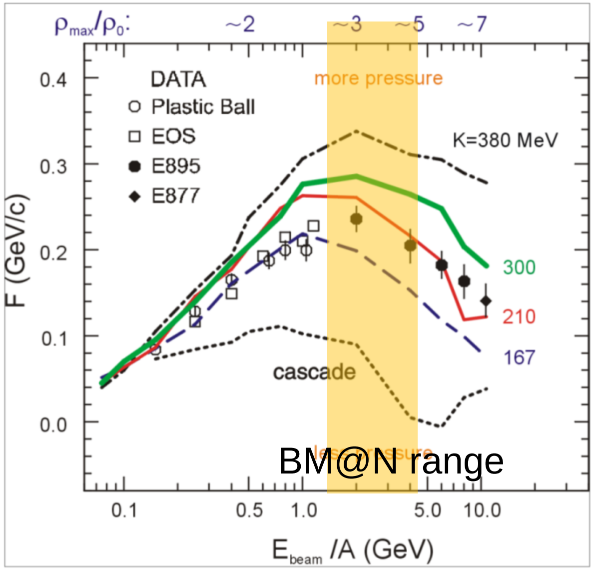
$dN/d\varphi \propto (1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi)$

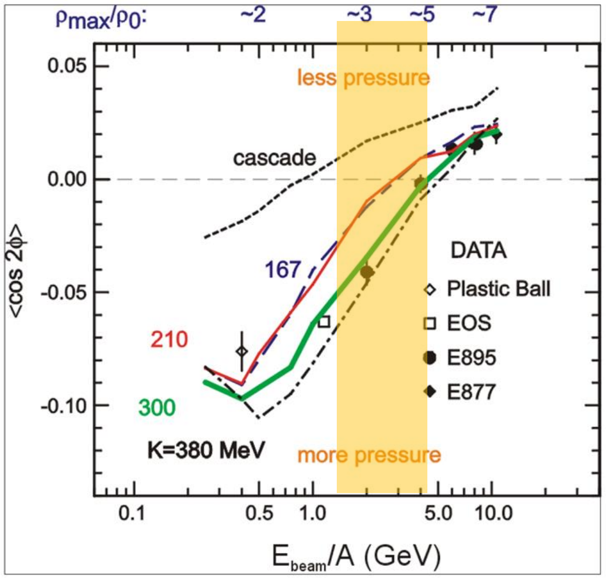


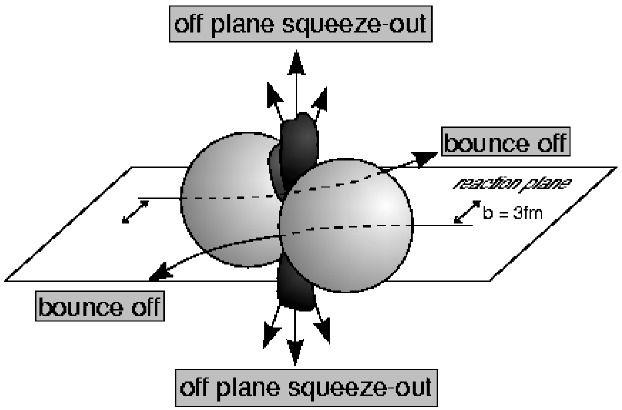
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Proton flow in Au+Au collisions

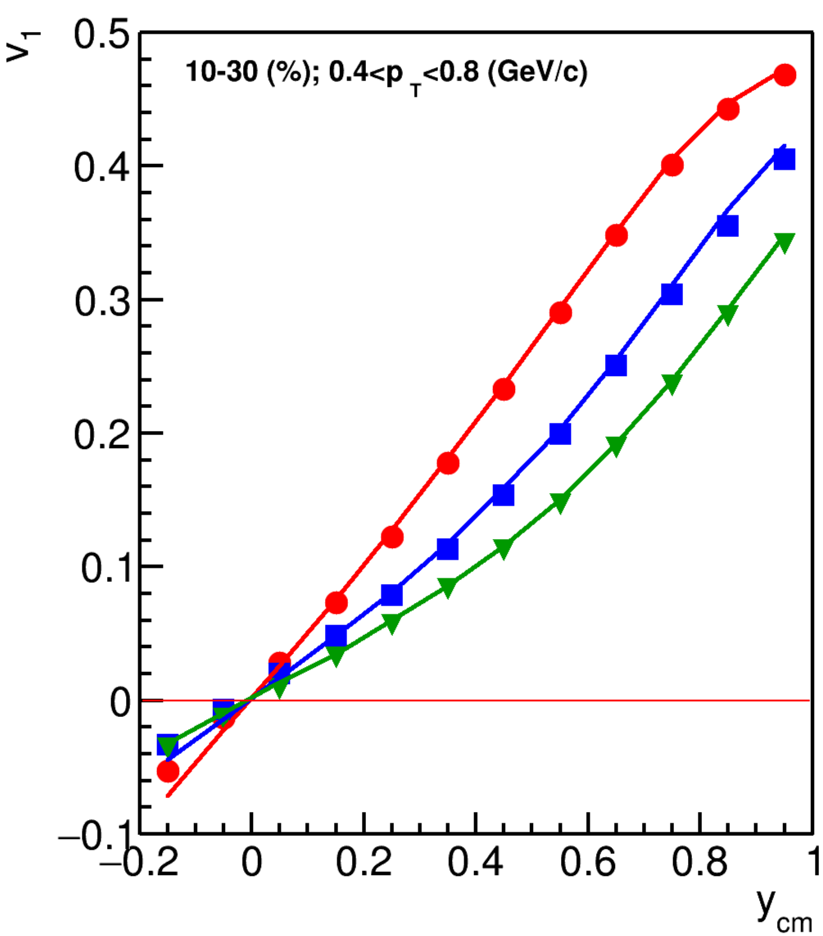
in-plane flow ~ v_1 out-of-plane flow v_2

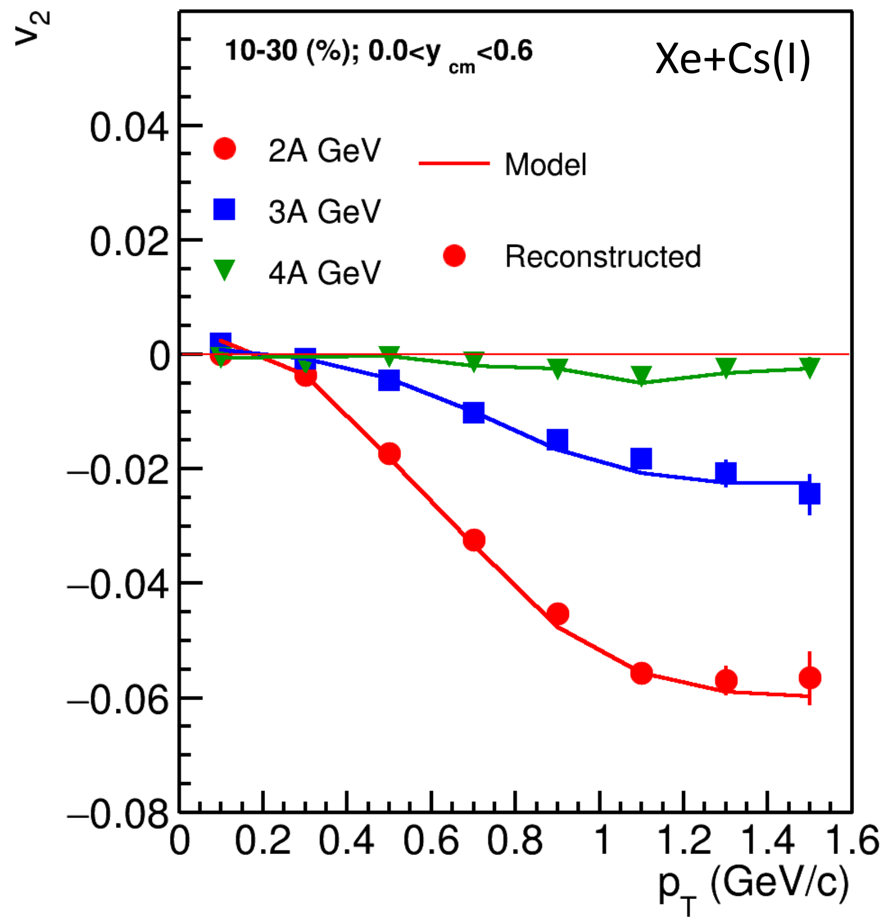






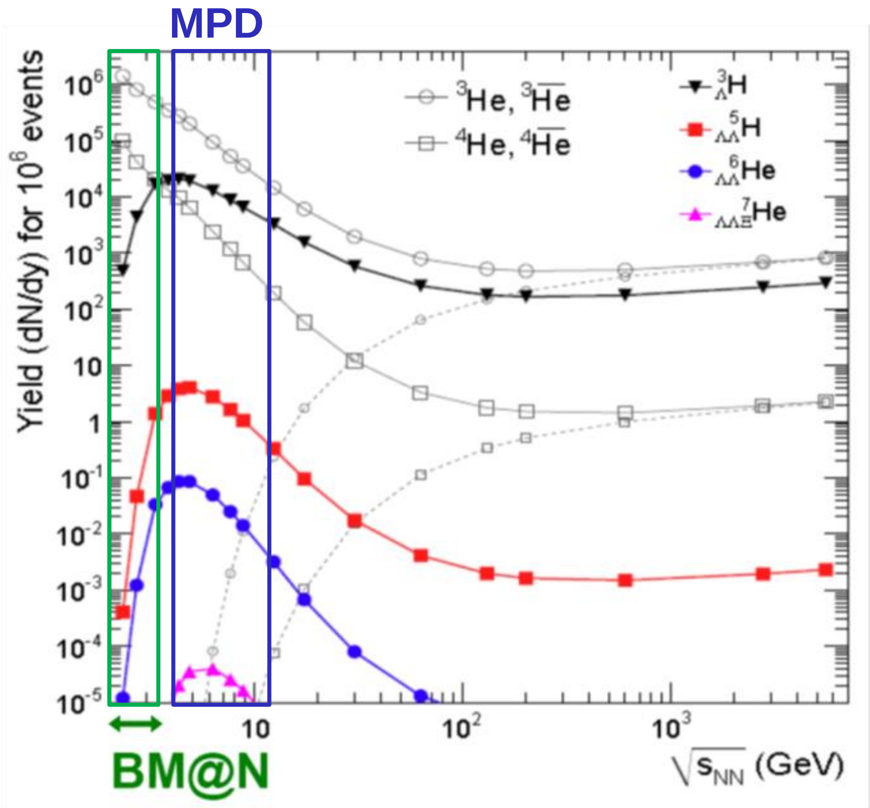
Directed and elliptic flow at BM@N

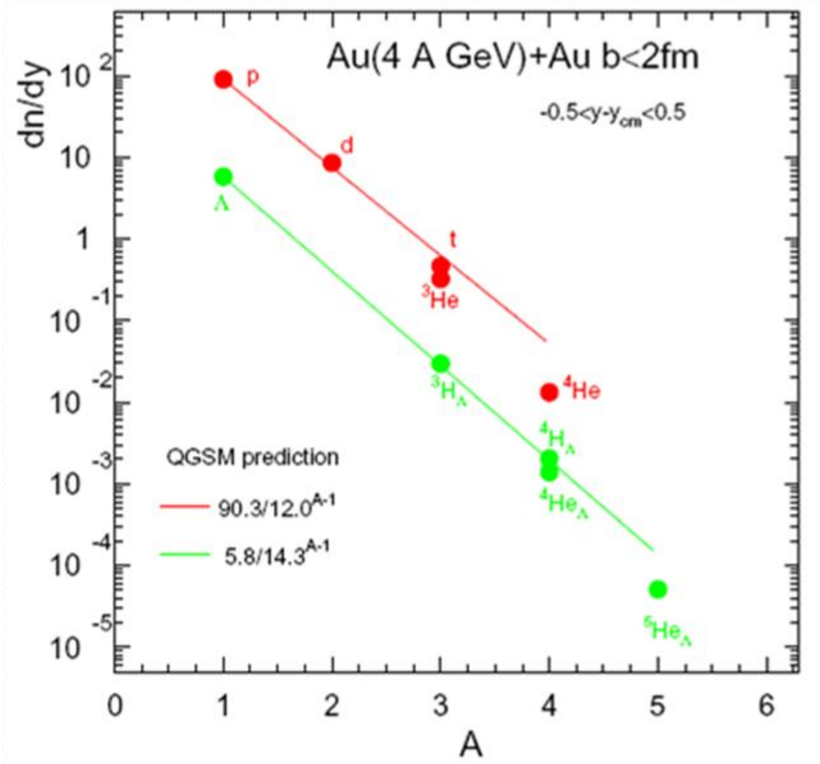




- Good agreement between reconstructed and model data
- Approximately 250-300M events are required to perform multi-differential measurements of v_n

Heavy-ions A+A: Hypernuclei production





- **In heavy-ion reactions:** production of hypernuclei through coalescence of Λ with light fragments enhanced at high baryon densities
- **Maximal yield** predicted for √s=4-5A GeV (stat. model) (interplay of Λ and light nuclei excitation function)

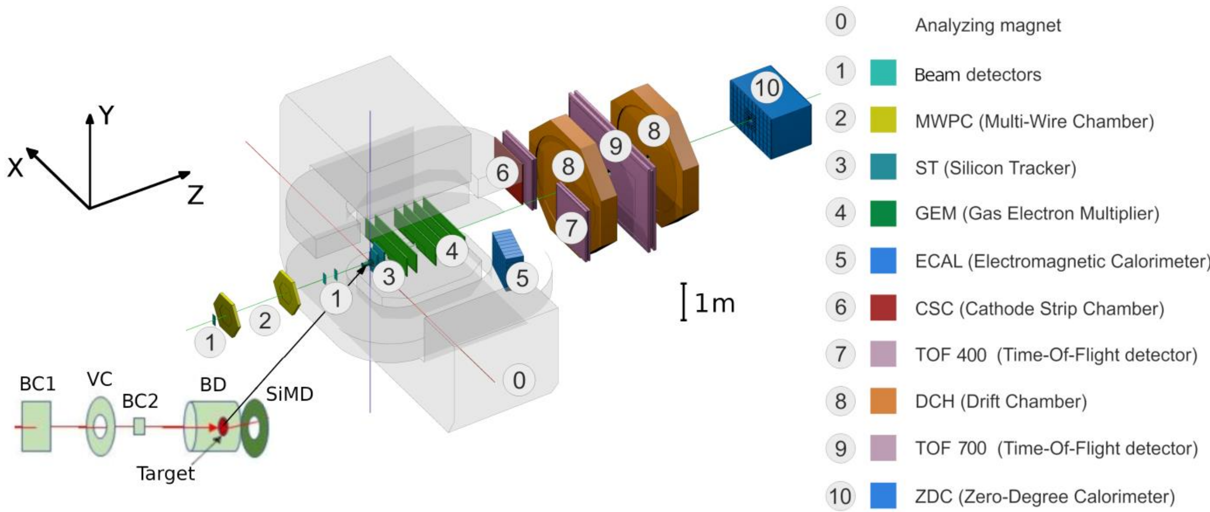
► BM@N energy range is suited for search of hyper-nuclei

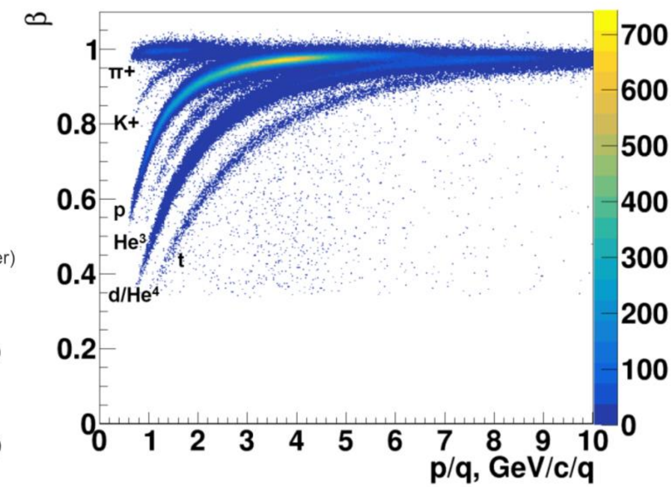
Baryonic Matter at Nuclotron (BM@N) Collaboration:

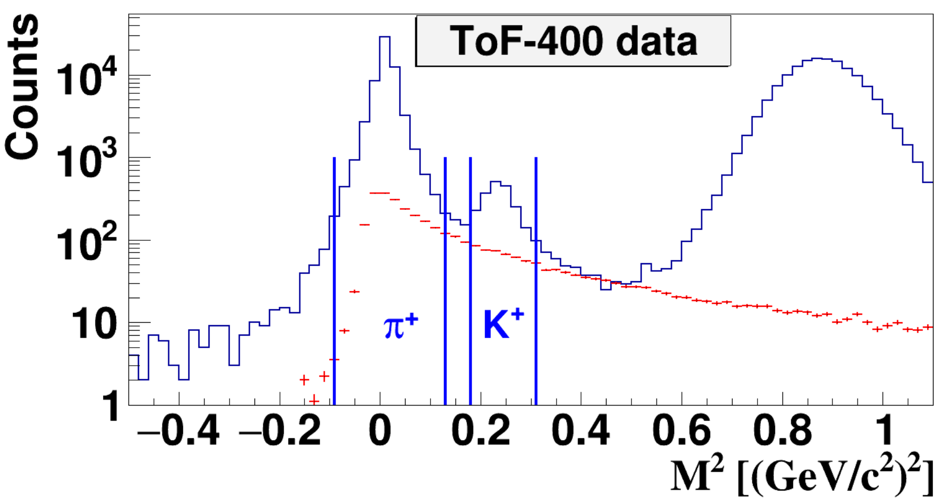
5 Countries, 13 Institutions, 217 participants

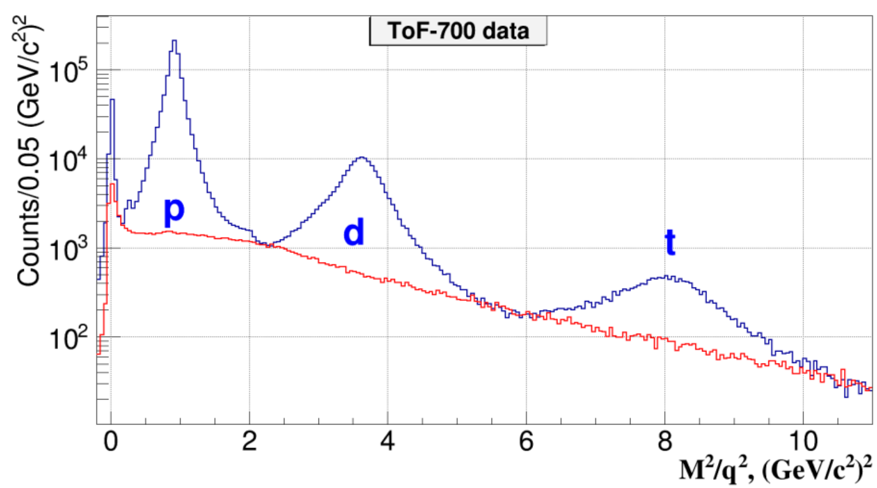
- *University of Plovdiv, Bulgaria*
- *St.Petersburg University*
- *Shanghai Institute of Nuclear and Applied Physics, CFS, China;*
- *Joint Institute for Nuclear Research;*
- *Institute of Nuclear Research RAS, Moscow*
- *NRC Kurchatov Institute, Moscow combined with Institute of Theoretical & Experimental Physics, NRC KI, Moscow*
- *Moscow Engineer and Physics Institute*
- *Skobeltsyn Institute of Nuclear Physics, MSU, Russia*
- *Moscow Institute of Physics and Technics*
- *Lebedev Physics Institute of RAS, Moscow*
- *Institute of Physics and Technology, Almaty*
- **Physical-Technical Institute Uzbekistan Academy of Sciences, Tashkent**
- **High School of Economics, National Research University, Moscow**

Production of π^+, K^+, p, d, t in 3.2 AGeV argon-nucleus interactions at the Nuclotron





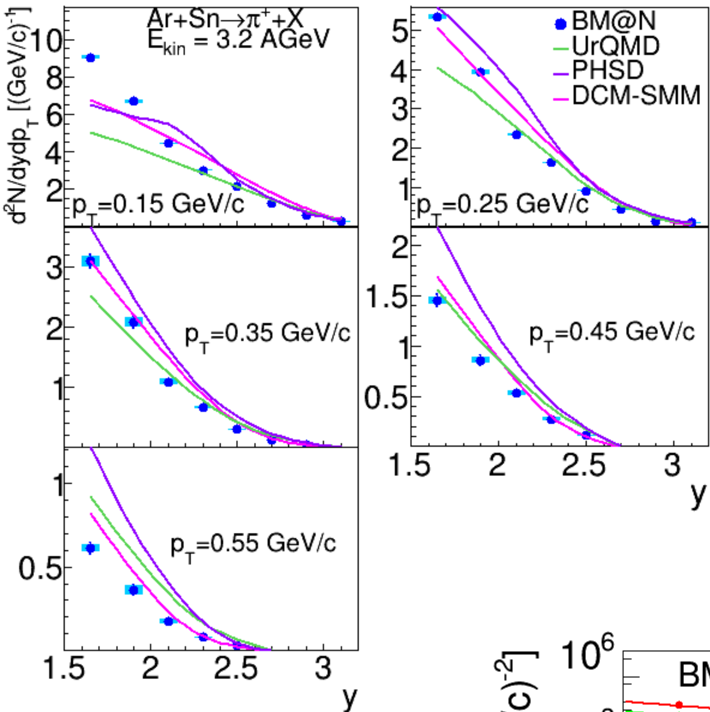


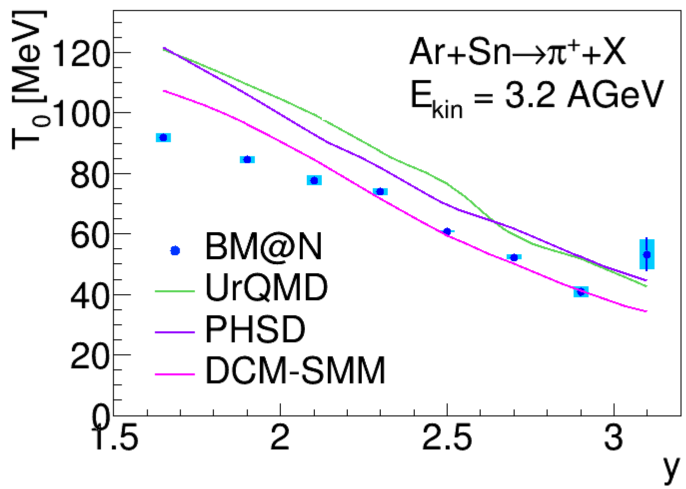


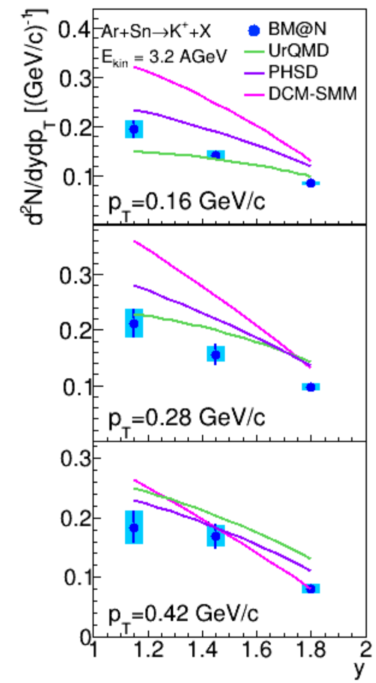
Production of π^+ and K^+ mesons in 3.2 AGeV argon-nucleus interactions at the Nuclotron

https://arxiv.org/abs/2303.16243v3

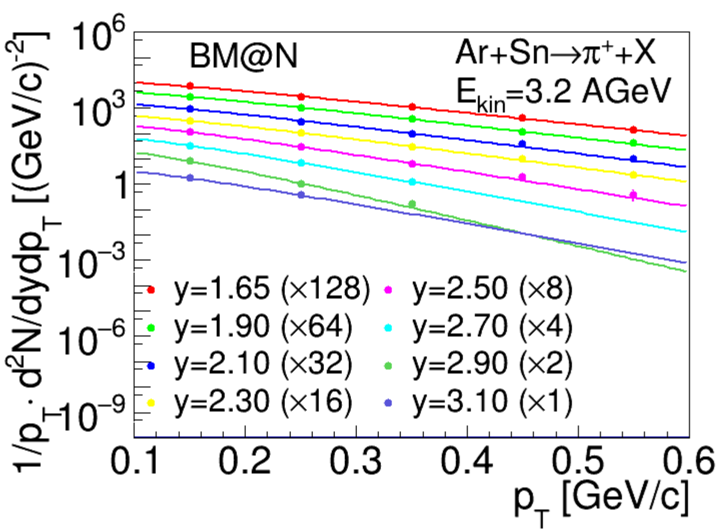
Published in JHEP 07 (2023) 174

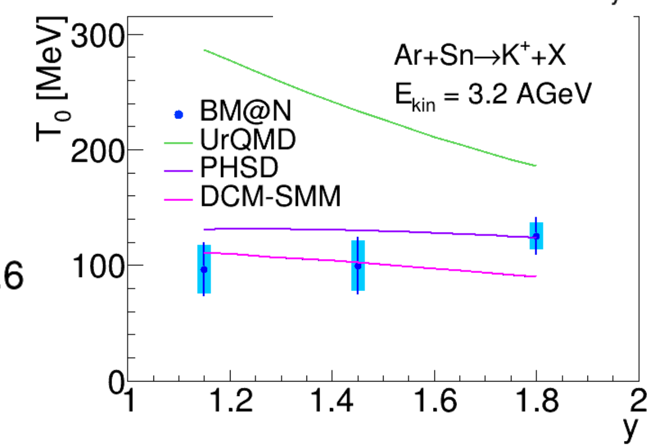






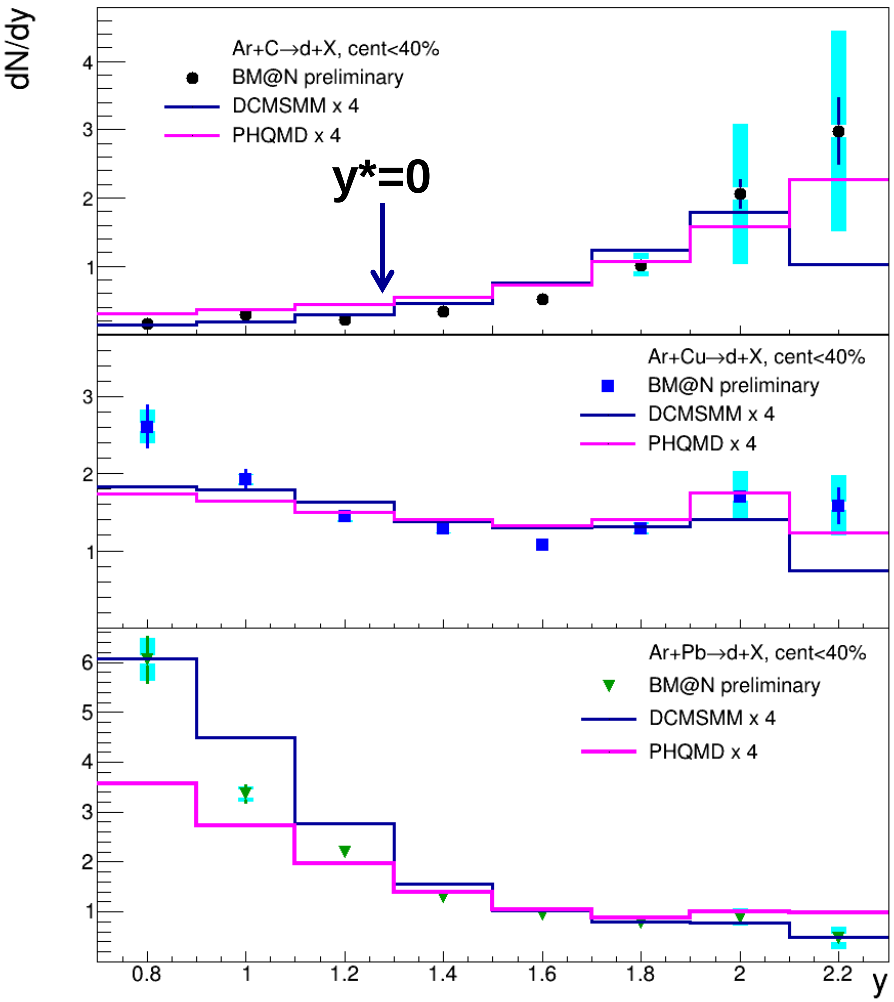
Full centrality range

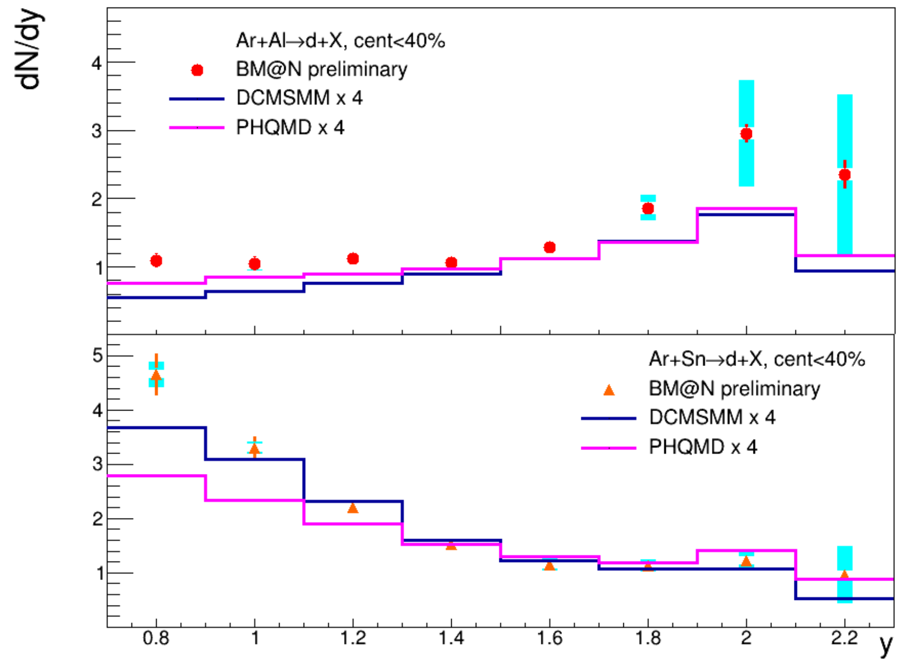




Deuterons: dN/dy dependence on y

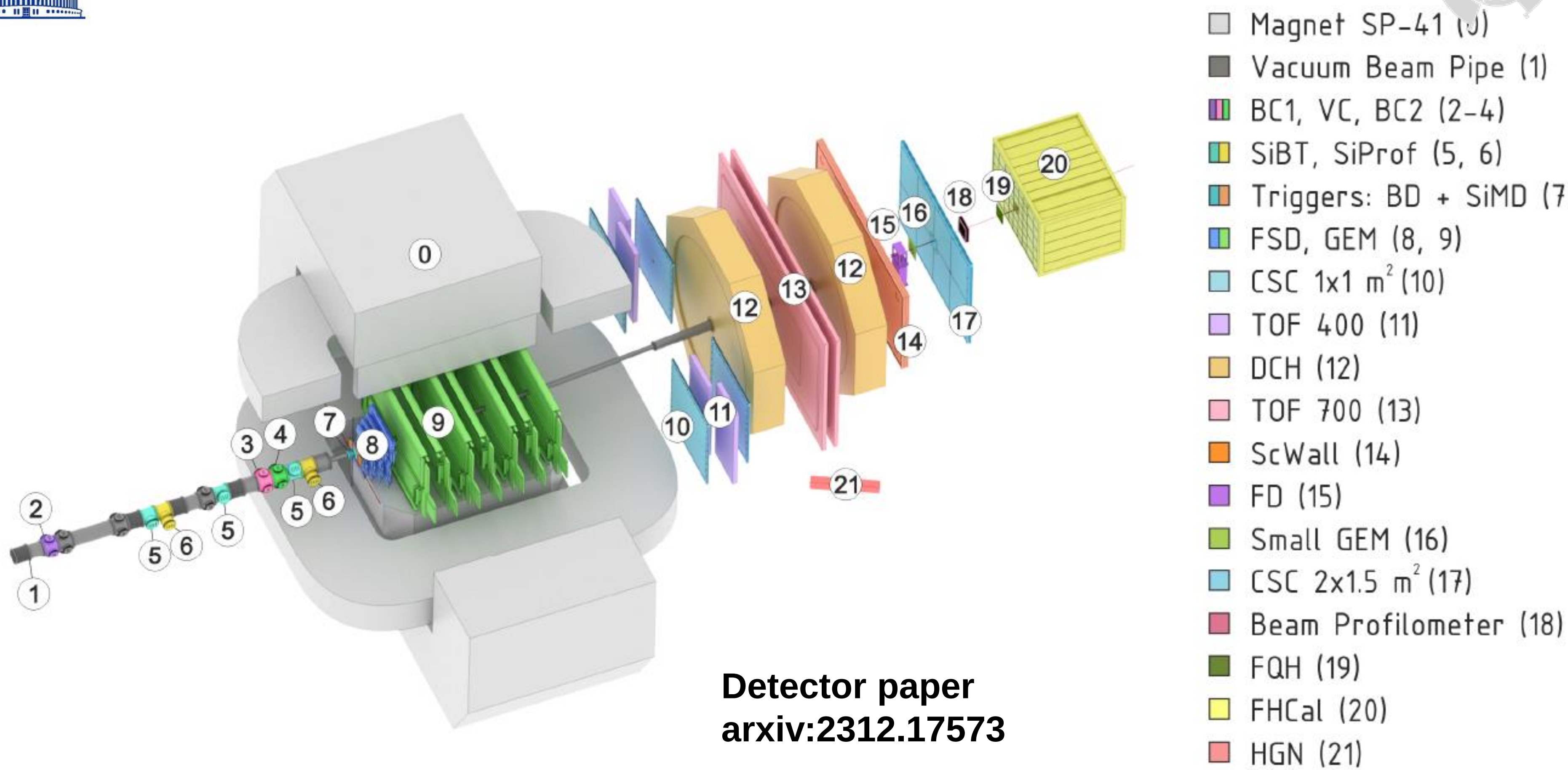
Centrality 0-40%





- **dN/dy spectrum softer in interactions with heavier target**
- **DCM-SMM and PHQMD models describe data shape, but are lower in normalization by factor 4**

Configuration of BM@N detector in Xe+CsI run



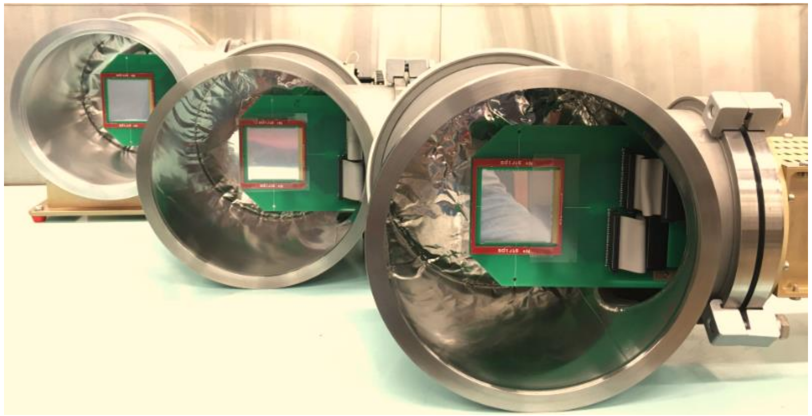
Detector paper
arxiv:2312.17573

Xe^{124} + CsI interactions:
main trigger cover centrality < 70-75% (85% events)
min bias trigger (7% events), beam trigger (3% events)

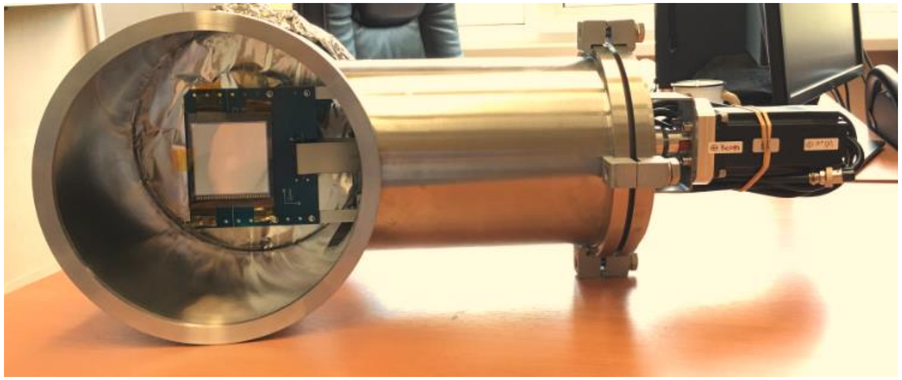
→ Collected 507M events at 3.8 AGeV, 48M events at 3.0 AGeV

BM@N detectors for Xe+CsI run

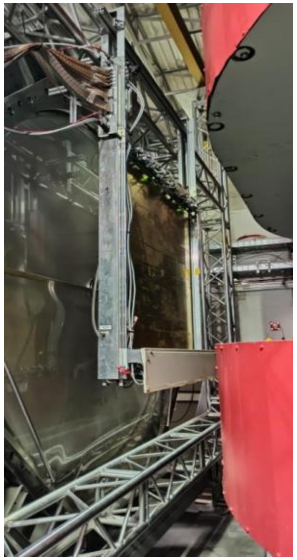
3 Silicon beam tracking detectors



Beam profile meter with Si detector and positioning mechanics



Outer tracker: Cathode Strip Chambers → 4 CSC of 106x106 cm2



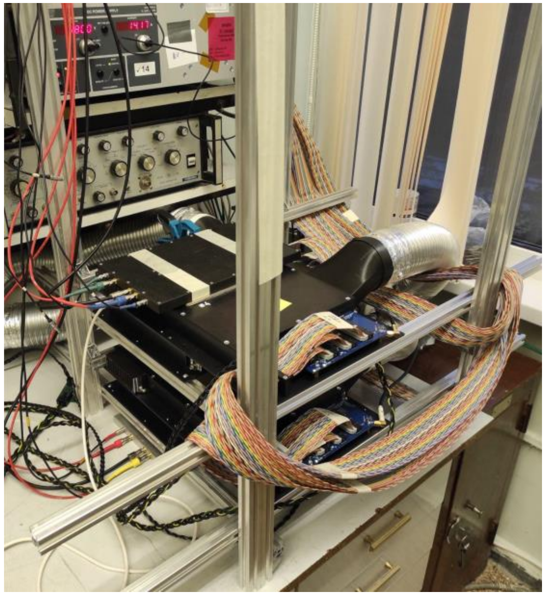
Outer tracker group

Big CSC 220x145 cm2

Forward hodoscope in front of FHCAL

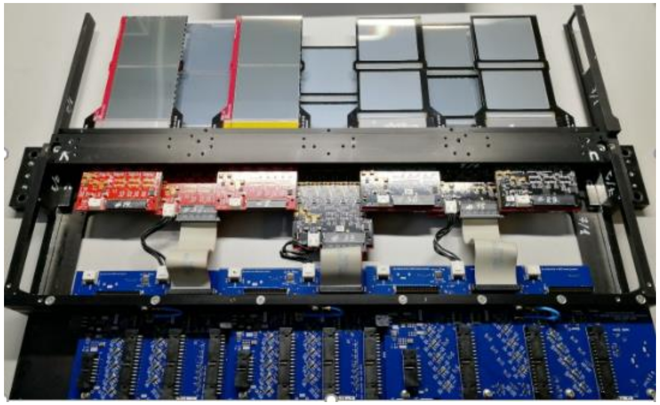
Forward Silicon Detectors for Xe+CsI run

Setup for FSD tests with cosmic rays

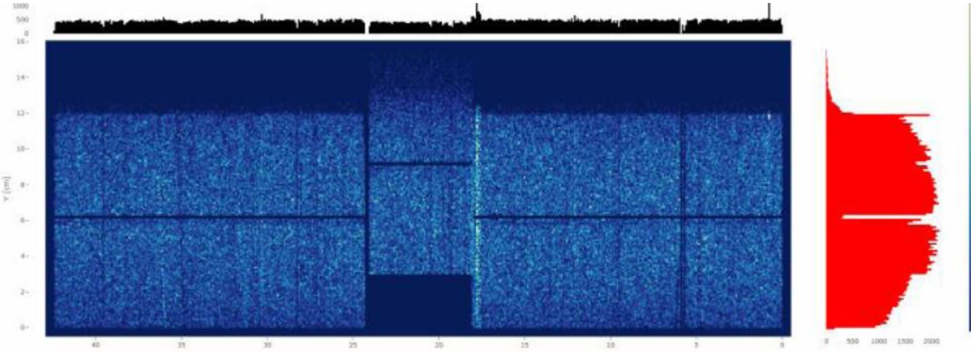


FSD support mechanics

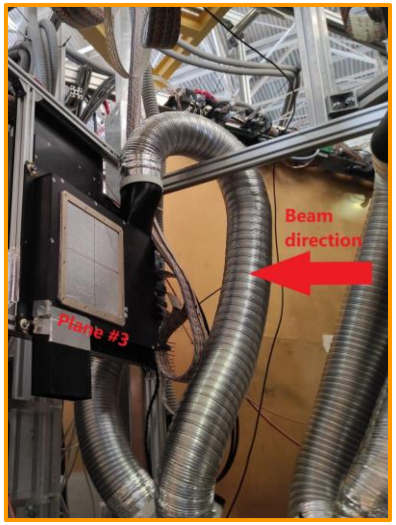
Assembled FSD half station of 7 detectors



Cosmic ray X/Y profile of FSD half station



Installed FSD module

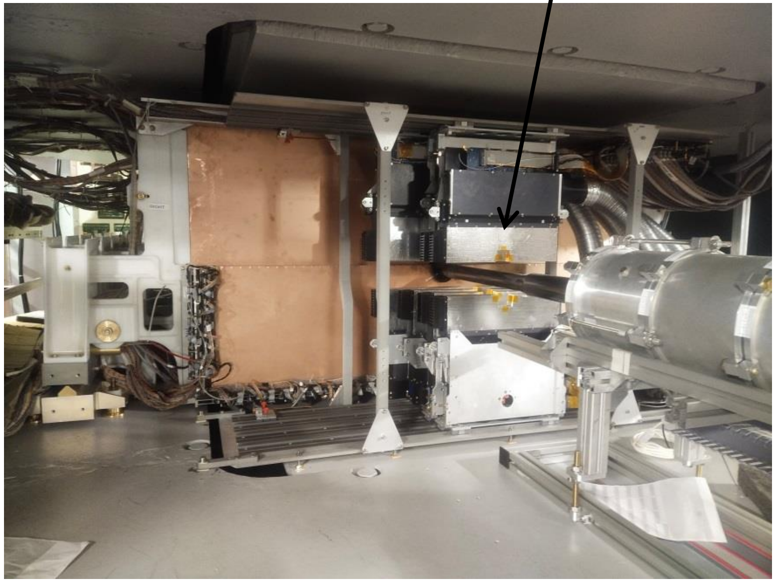


► All 48 modules and 4 FSD stations with 6, 10,14,18 modules are assembled, tested and installed

BM@N tracking detector installation for Xe+CsI run

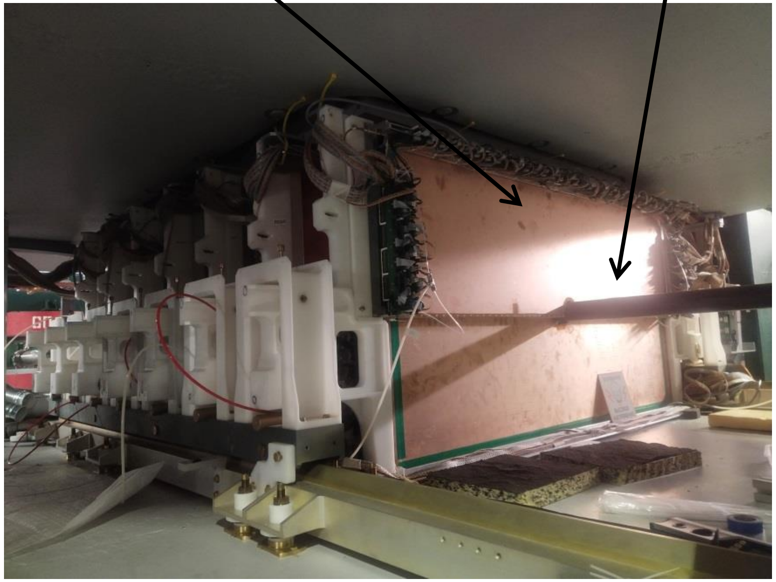
Big CSC chamber

Forward Si tracker detectors in front of GEM detectors



GEM detectors installed in magnet

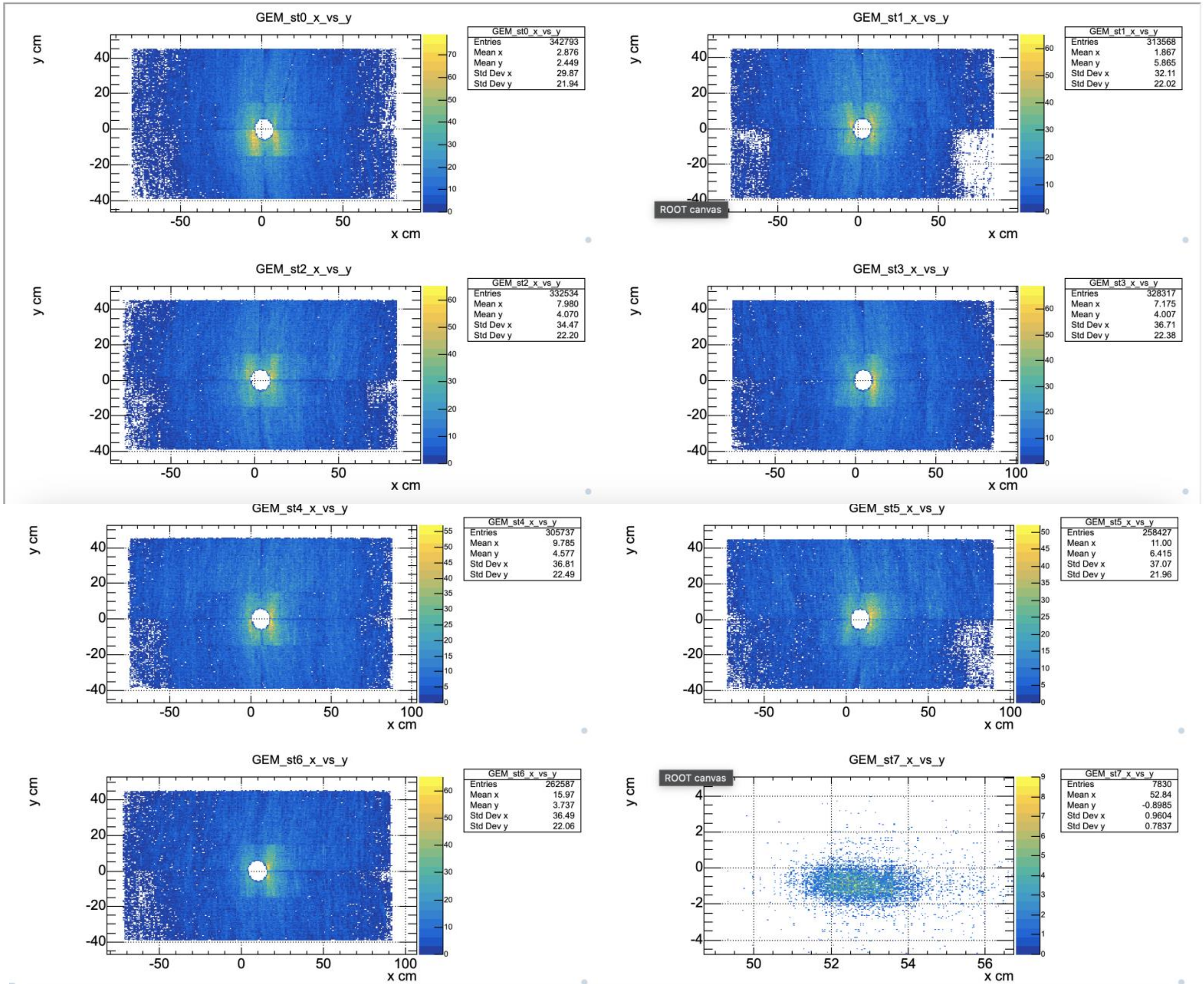
Carbon vacuum beam pipe



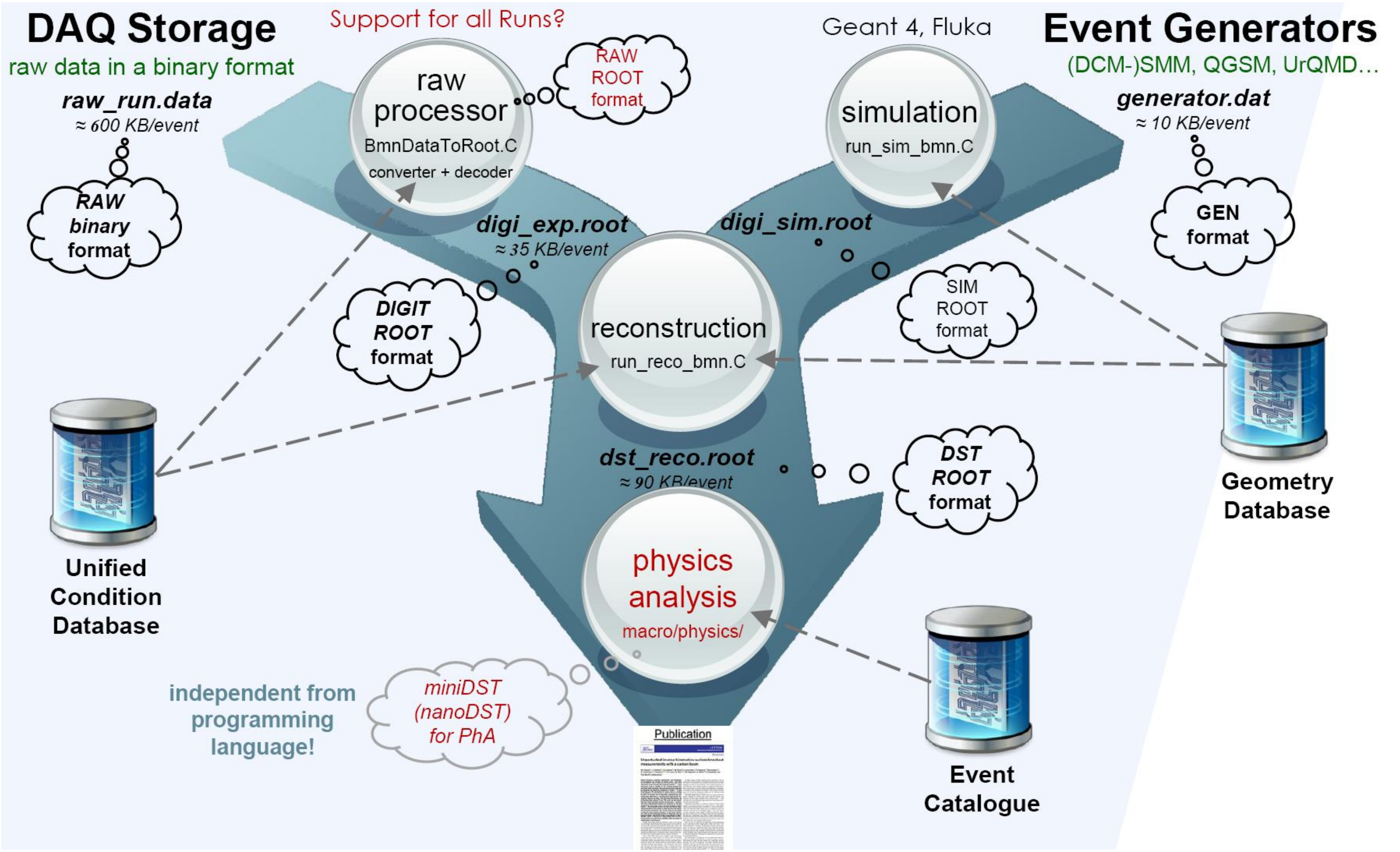
Vacuum boxes for beam detectors

GEM hit reconstruction: 7 stations + small GEM profile meter

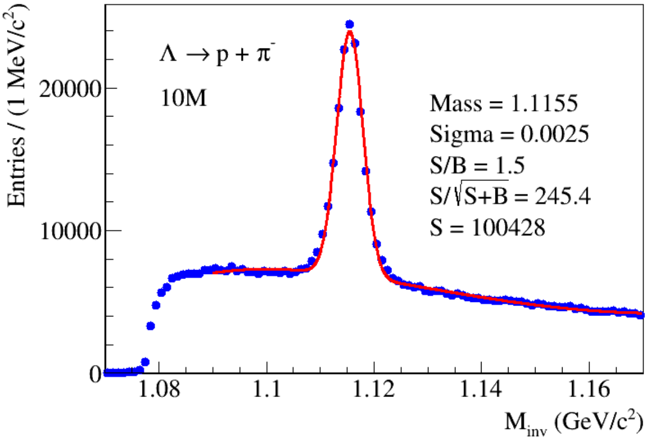
GEM Hits

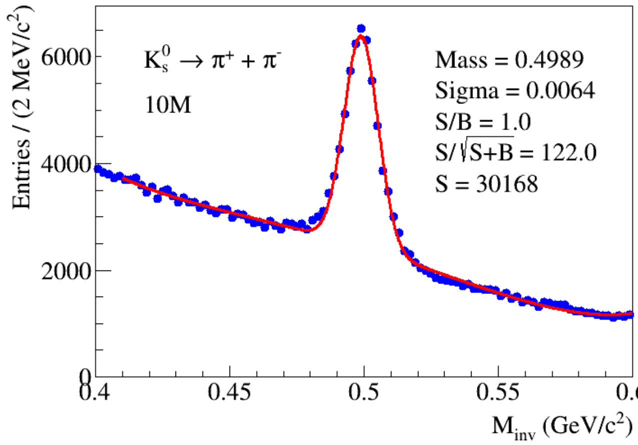


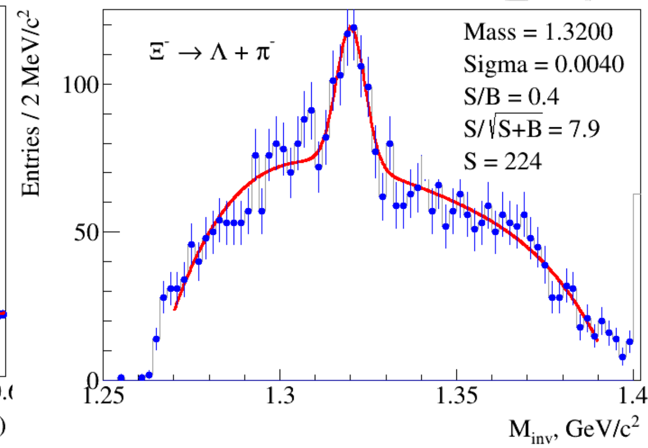
Data recording, simulation, reconstruction and analysis



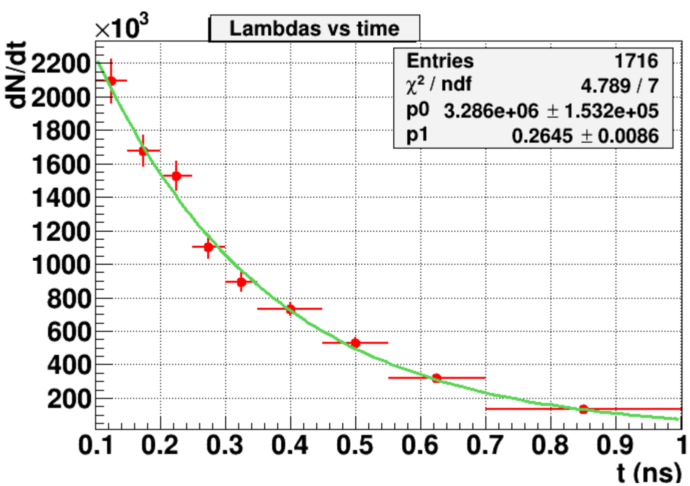
Xe+ CsI data : $\Lambda \to p\pi^-$, $K^0_s \to \pi^+\pi^-$, $\Xi^- \to \Lambda\pi^-$

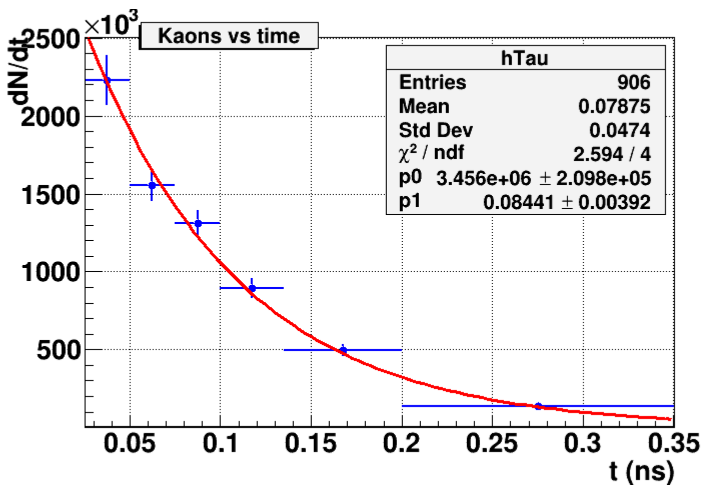






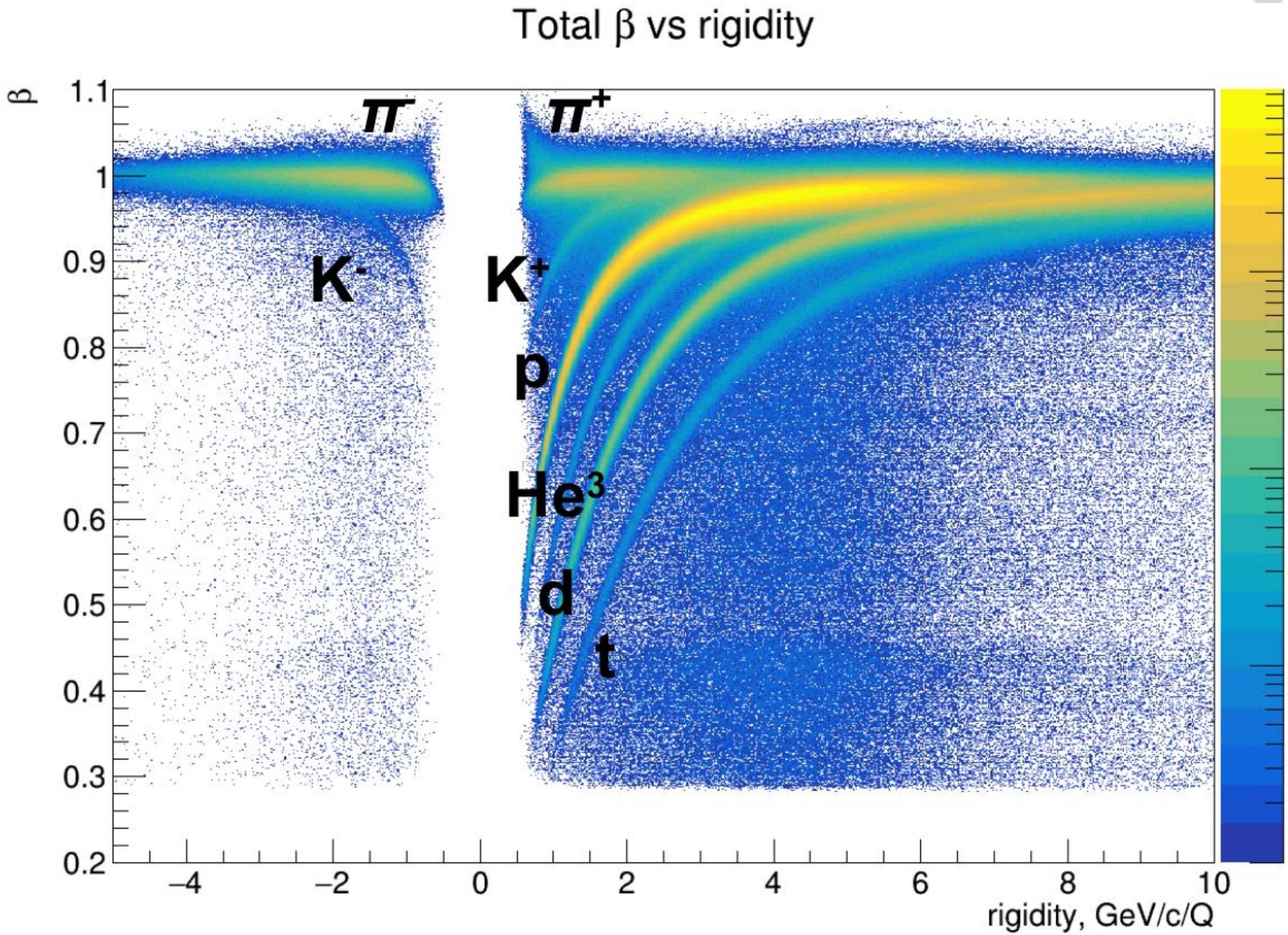
In 500M events expect: 4M Λ, 1.2M K^0_S and 8K Ξ-





Life time is in agreement with PDG values: 0.2632 ns for Λ, 0.0895 ns for K^0_s

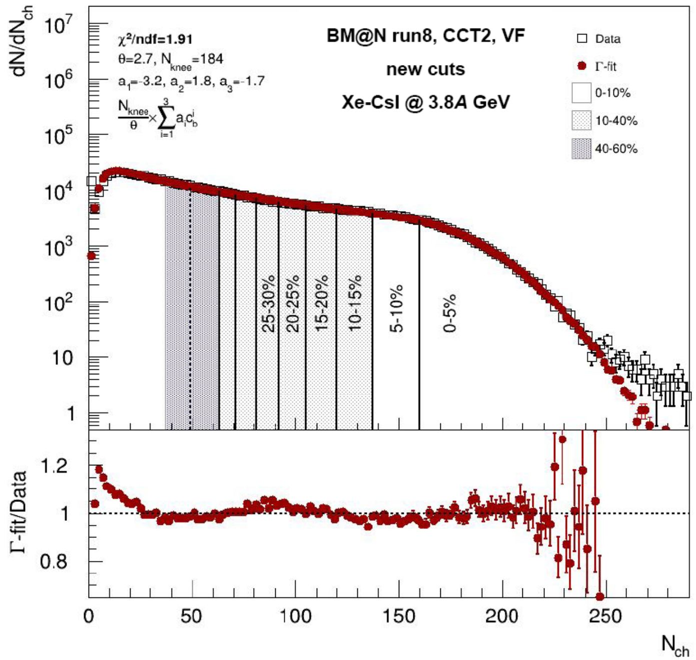
Xe+CsI data: π+-, K+-, p, He3, d, t identification



M.Kapishin

BM@N experiment

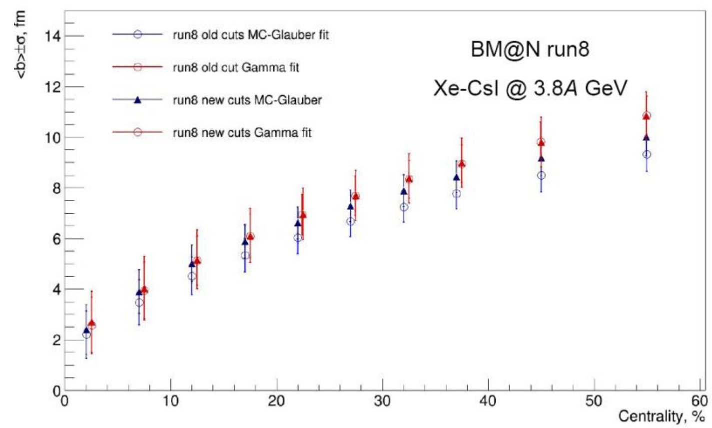
Centrality from track multiplicity and forward detectors

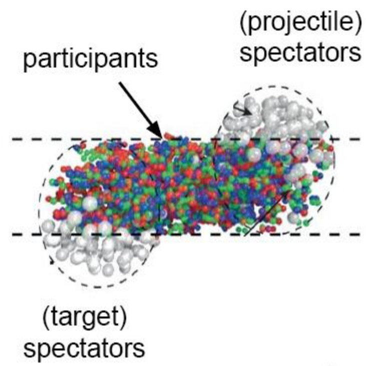


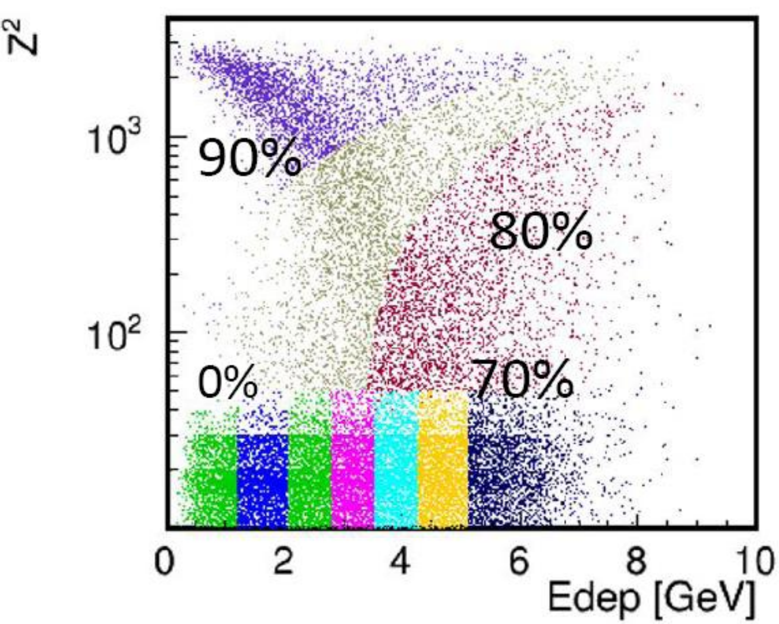
Parametrization of data track multiplicity N_{ch} by MC Glauber model or Negative Binominal Distribution (Γ-fit) with free parameters

→ Extract $P(b \mid N_{ch})$

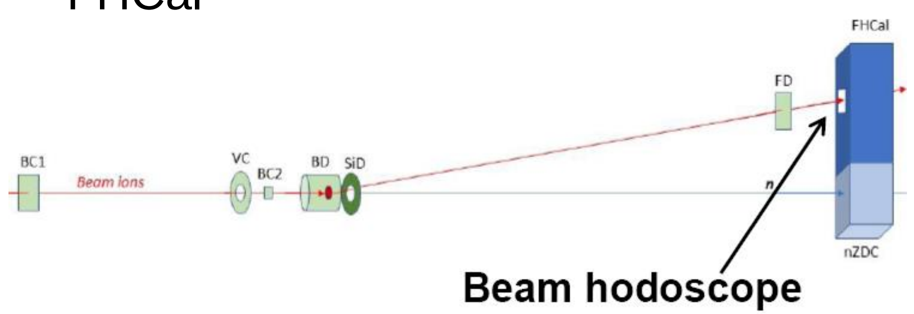
→ Γ-fit and MC-Glauber fit are in agreement







Independent method: centrality definition from Z^2 in beam hodoscope and energy in FHCal



Status of data analysis and plans for next physics runs

Topics of physics analyses:

- analysis of production of Λ, Ξ- hyperons, K^0_S , K±, π± mesons, light nuclear fragments, neutrons in Xe+CsI interactions;
- analysis of collective flow of protons, π±, light nuclear fragments
- search for light hyper-nuclei $_\Lambda H^3$, $_\Lambda H^4$

Physics run in the Xe beam in 2024-2025

→ beam energy scan in the range of 2-3 AGeV

Preparations for a physics run with the Bi beam

- Further development of the central tracker is foreseen: installation of additional stations of silicon micro-strip detectors
- It is planned to put into operation a 2-coordinate (X/Y) neutron detector of high granularity to measure neutron yield and collective flow

Possible contributions of new participants:

- Analysis of recorded Xe+CsI interactions (with perspective for publications and PhD)
- Software development (under guidance of the software coordinator)

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

Year	2016	2017 spring	2018 spring	2023	2025 and later
Beam	d(↑)	C	Ar	Xe	Bi
Max.intensity / spill	0.5M	0.5M	0.5M	1M	1.5M
Trigger rate, spill	5k	5k	8k	10k	15k
Central tracker status	6 GEM half planes	6 GEM half planes	6 GEM half planes + 3 forward Si planes	7 GEM full planes + 4 forward Si planes	7 GEM full planes + forward Si + STS planes
Experimental status	technical run	technical run	technical run+physics	stage1 physics	stage2 physics

Thank you
for attention!

BM@N heavy ion program goals and observables

1. BM@N energy range is very promising (EOS, symmetry energy, hypernuclei)
2. Sensitive probes have to be measured multi-differential (p_T, y) and as function of beam energy (2 – 4 GeV/u)

- EOS for high-density symmetric matter:
  - Collective flow of protons and light fragments in Au+Au collisions: Centrality, event plane, identification of fragments
  - Ξ^- (dss) and Ω^- (sss) hyperons: Yields, spectra, p_T vs. y from Au+Au and C+C collisions
- Symmetry energy at high baryon densities:
  - Particles with opposite isospin $I_3=\pm1$: Σ^{*+}(uus)/Σ^{*-}(dds)
  - Proton vs neutron collective flow (need highly granulated neutron detector)
- Λ-N and Λ-NN interactions
  - Hypernuclei: Yields, lifetimes, masses of ${}^3_\Lambda H$, ${}^4_\Lambda H$, ${}^5_\Lambda H$, ${}^4_\Lambda He$, ${}^5_\Lambda He$, …

- Phase transition from hadronic to partonic matter:
  - Deconfinement: excitation function of Ξ^- (dss), Ω^- (sss) (EOS observables)
  - Transition to scaling of collective flow of mesons / hyperons with number of quarks (partonic matter)
  - Critical endpoint: higher order moments of the proton multiplicity distribution