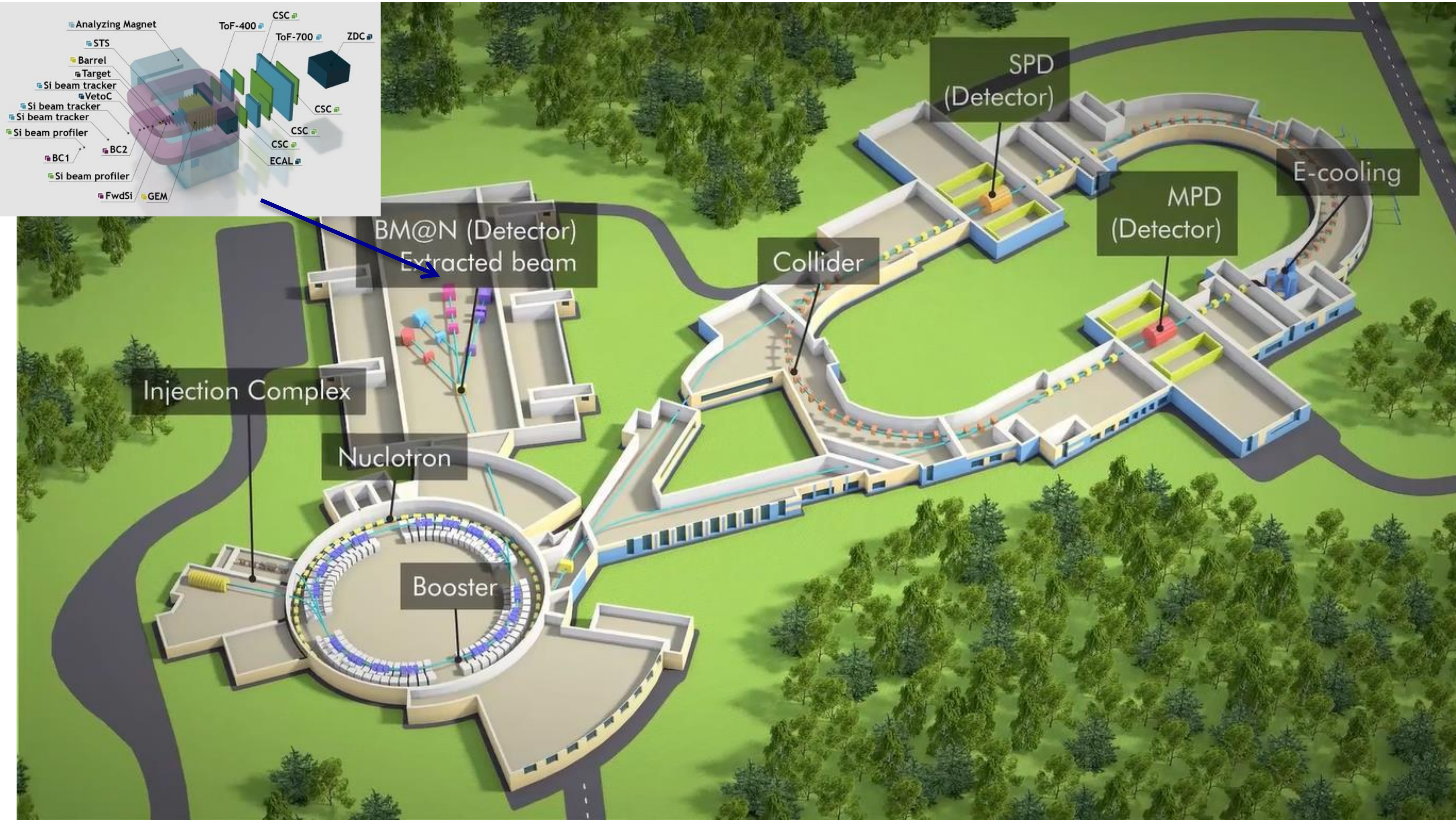
Status of the BM@N experiment at NICA/Nuclotron

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)

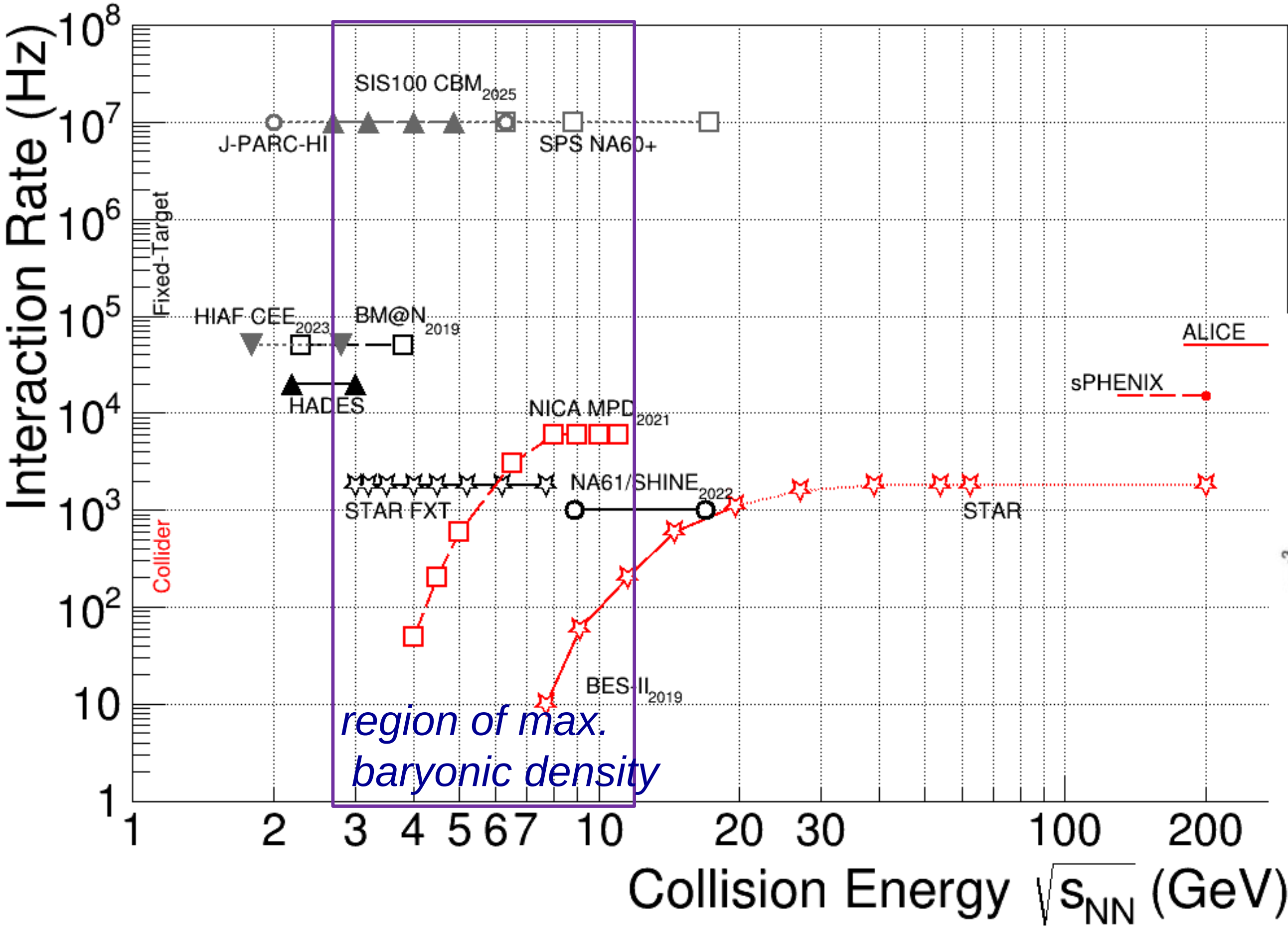


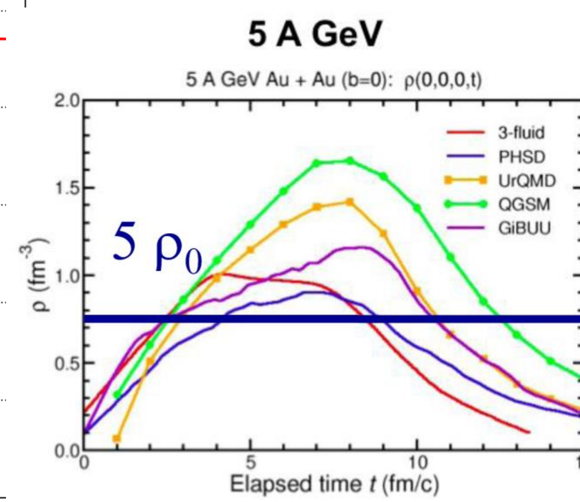
Baryonic Matter at Nuclotron (BM@N) Collaboration:

5 Countries, 13 Institutions, 214 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

Heavy Ion Collision Experiments





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

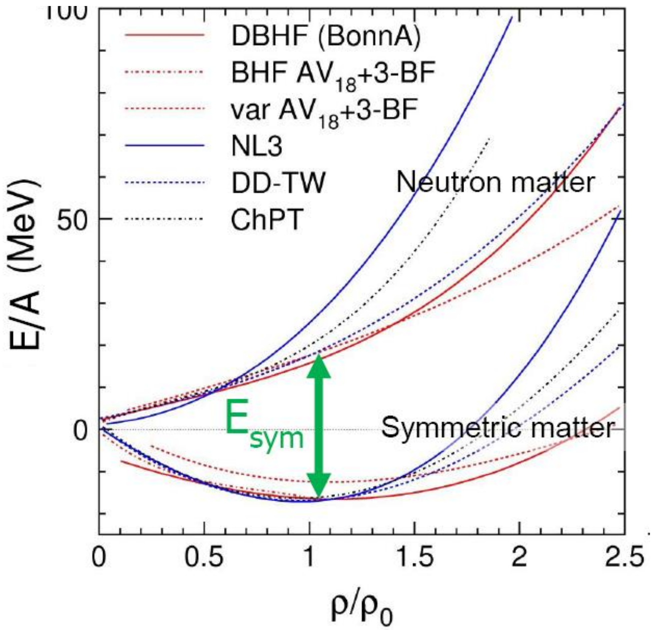
BM@N competitors:

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

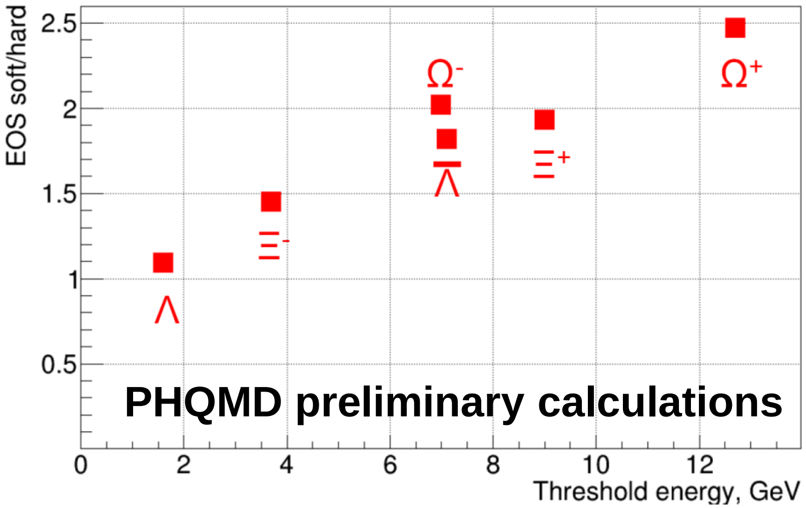
STAR BES (RHIC): Au+Au at $\sqrt{s_{NN}}$ = 3-200 GeV

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

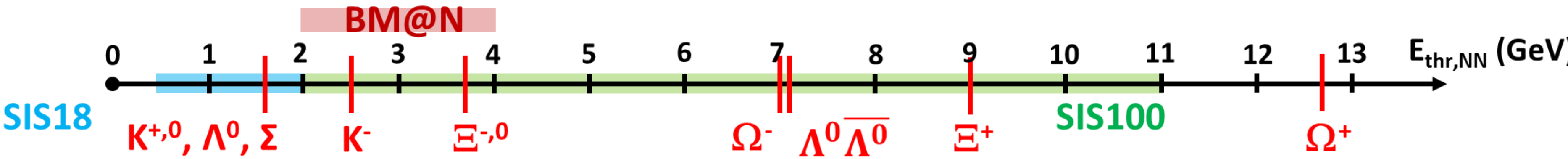
$$E_A(\rho,\delta) = E_A(\rho,0)+E_{sym}(\rho)\cdot\delta^2$$

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

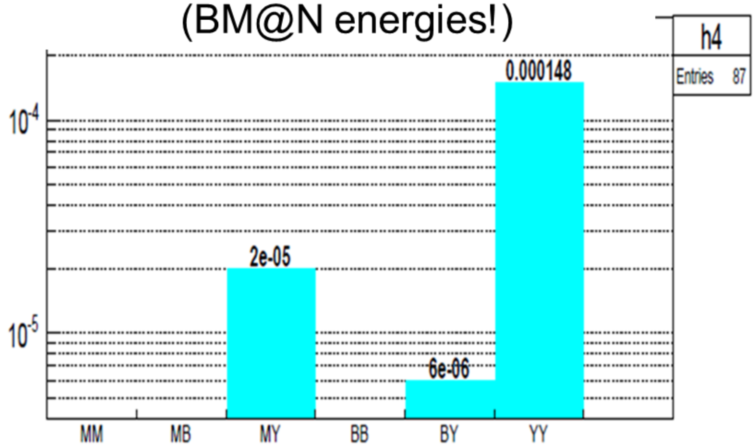
Curvature defined by nuclear incompressibility: $K = 9\rho^2\ \delta^2(E/A)/\delta\rho^2$

►Study symmetric matter EOS at $\rho=3\text{-}5\ \rho_0$
→ 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

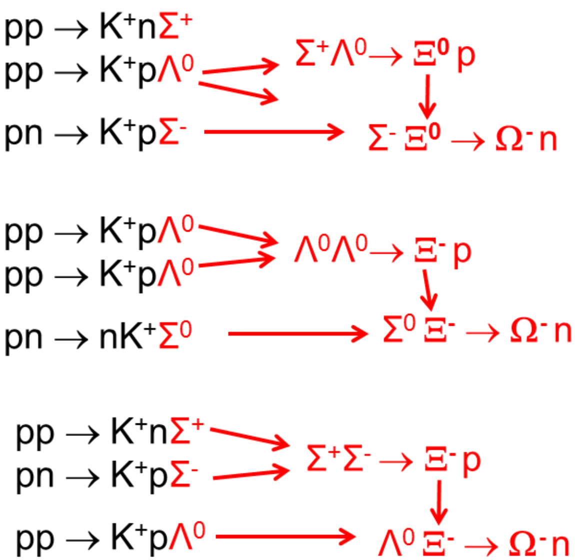
New probe of the high-density EOS: subthreshold production of multi-strange (anti-)hyperons via sequential collisions



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



HYPQGSM calculations
K. Gudima et al.



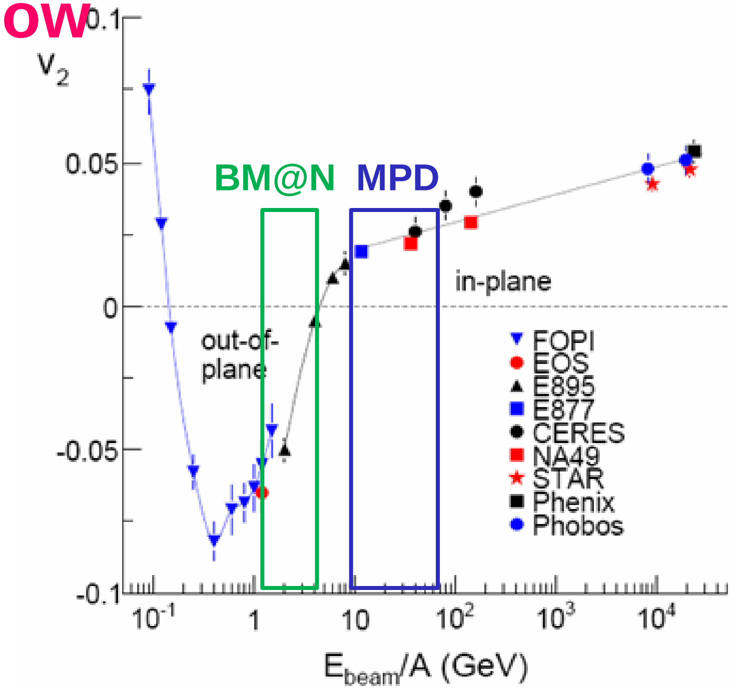
Study of EoS: Collective flow of identified particles

- 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:

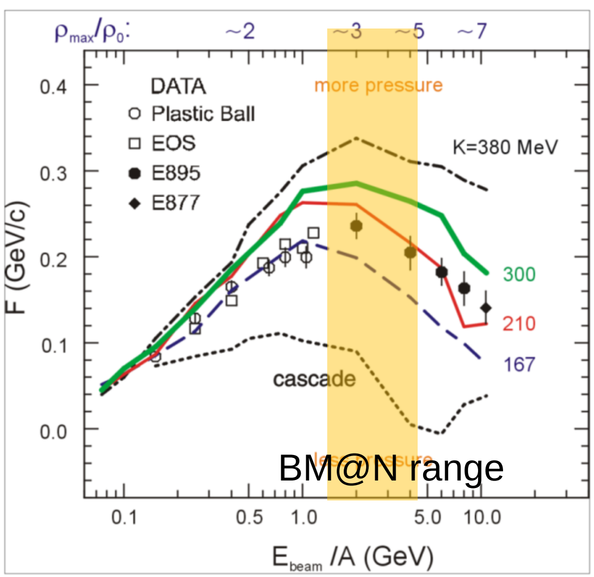
$dN/d\varphi \propto (1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi)$

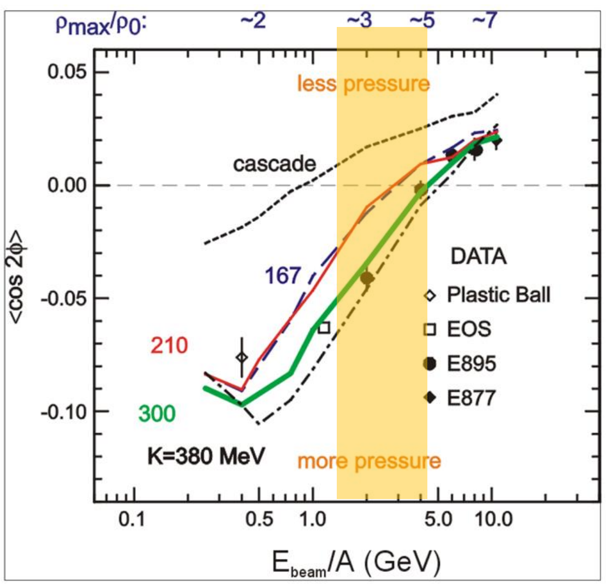


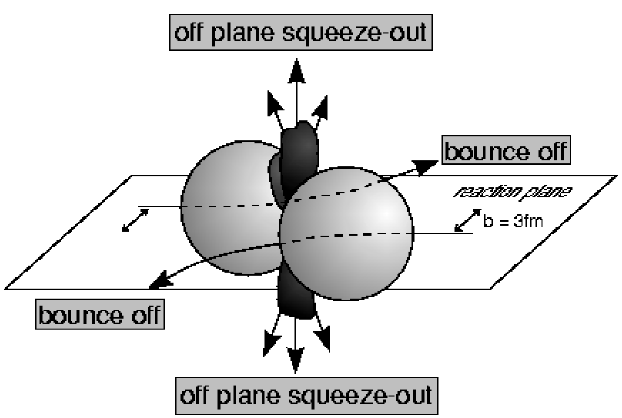
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592

Proton flow in Au+Au collisions

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

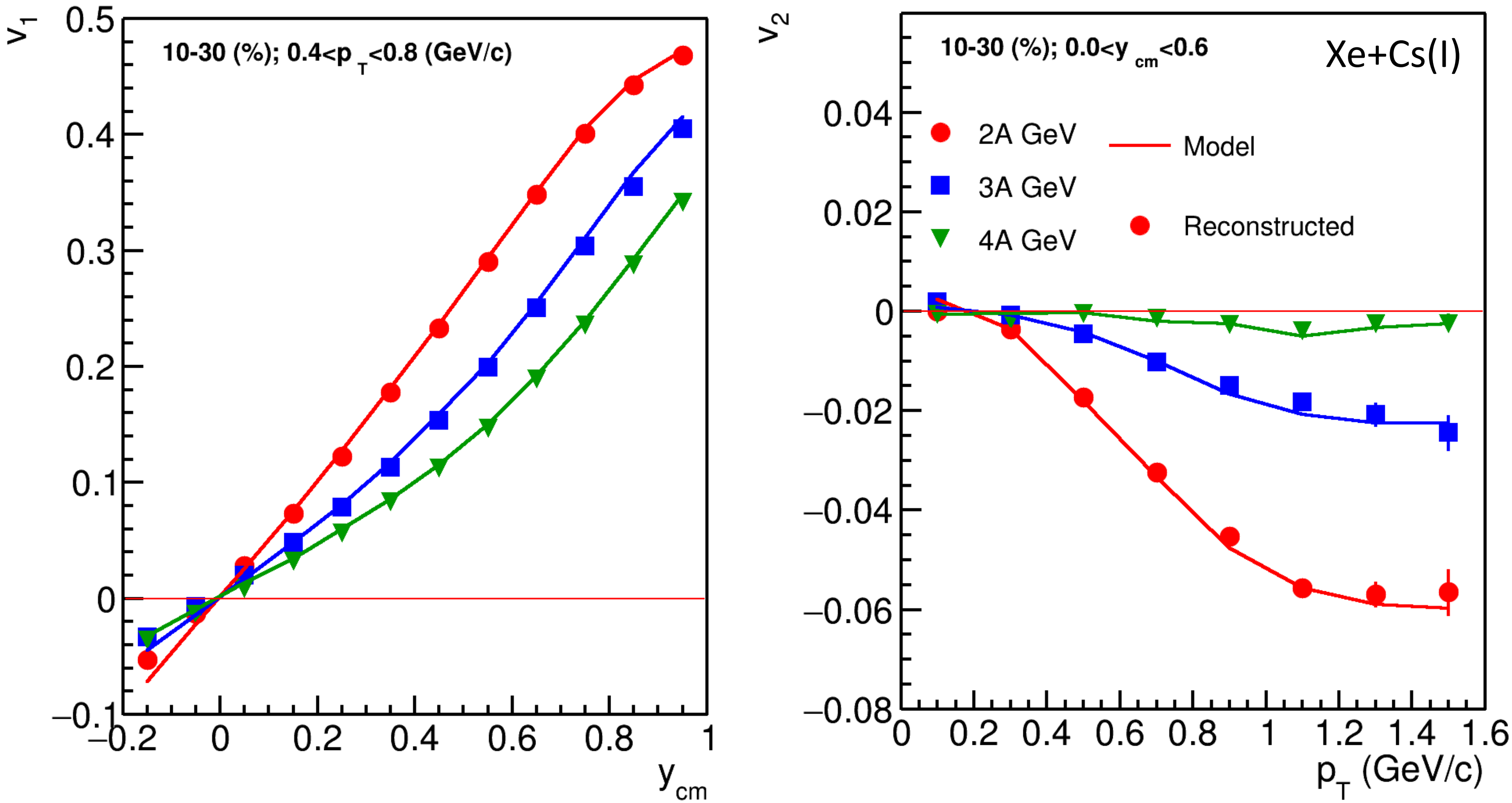






M.Kapishin BM@N experiment

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

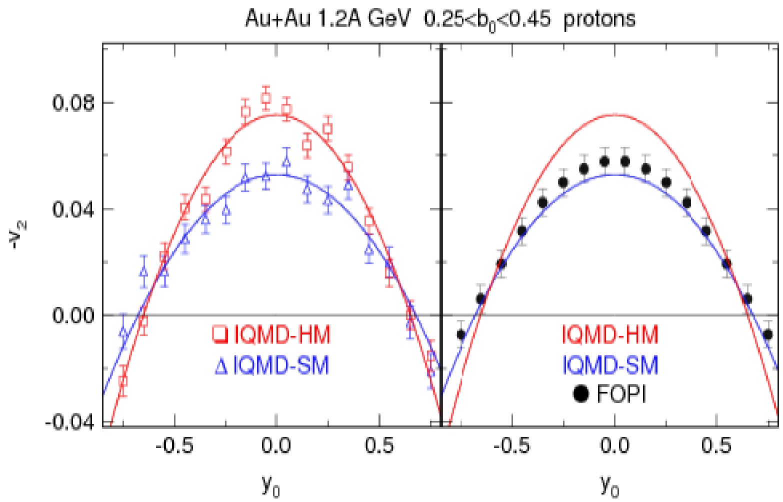
Rapidity dependence of v2 vs EOS

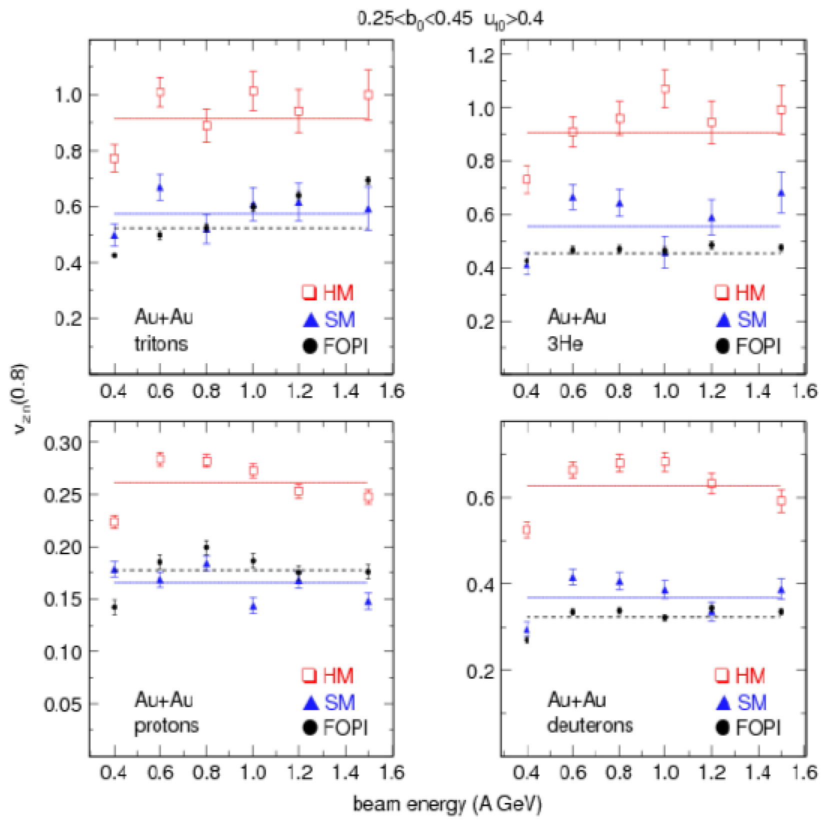
Rapidity dependence of v2 for protons and fragments is sensitive to EOS

FOPI data : Nucl. Phys. A 876 (2012) 1

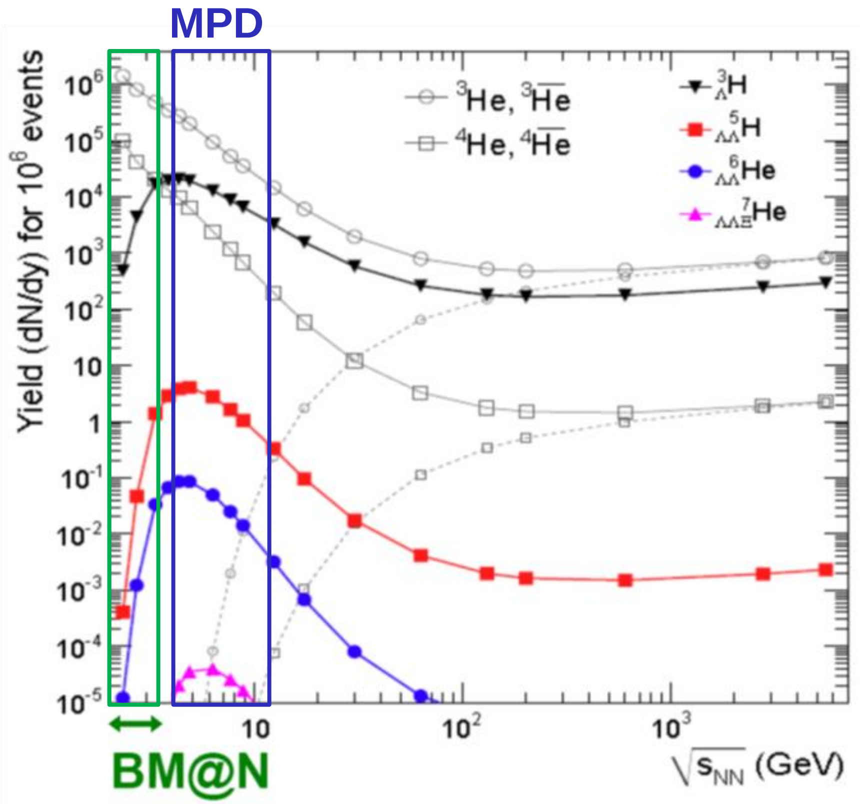
IQMD : Nucl Phys. A 945 (2016)

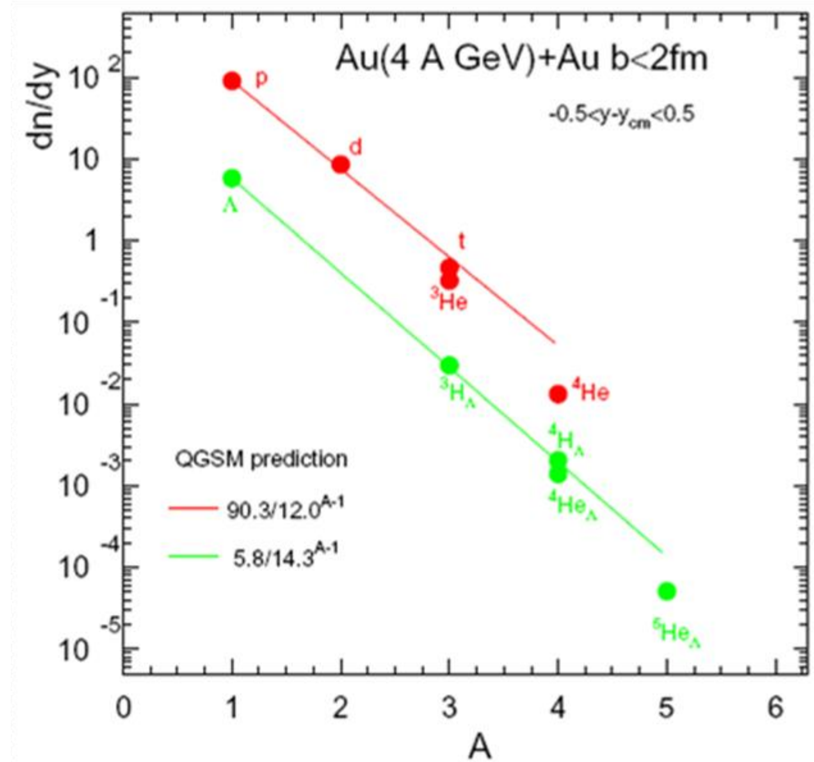
HM – hard EOS, K=376 MeV
SM – soft EOS, K= 200 Mev





Heavy-ions A+A: Hypernuclei production

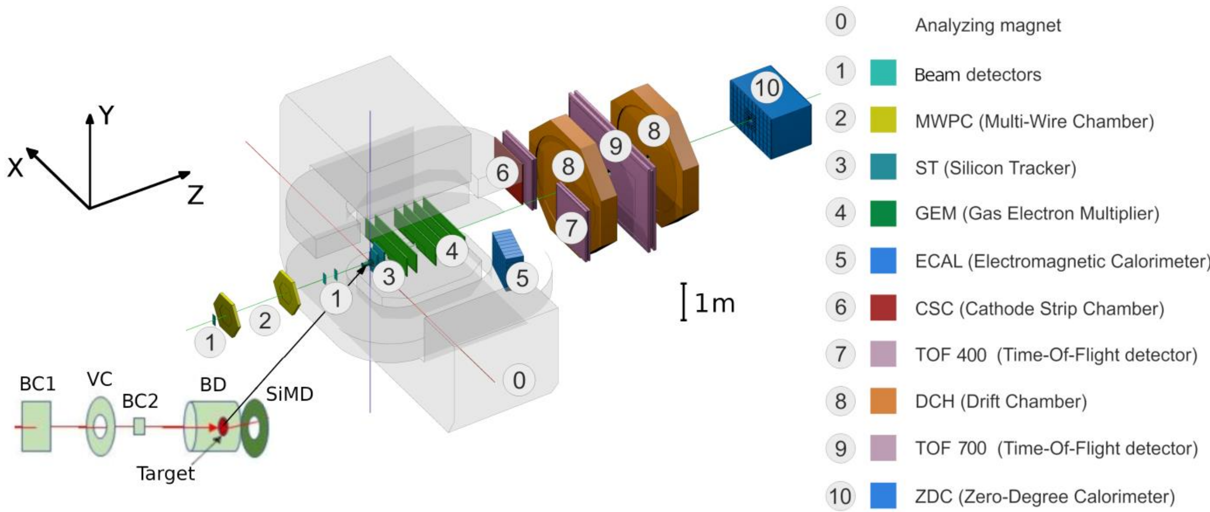


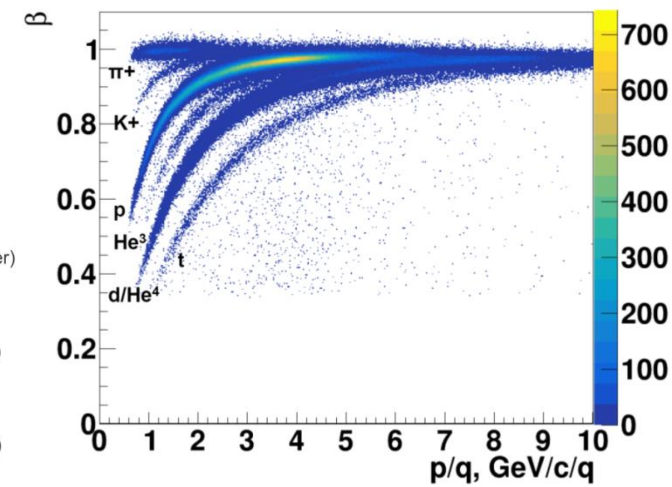


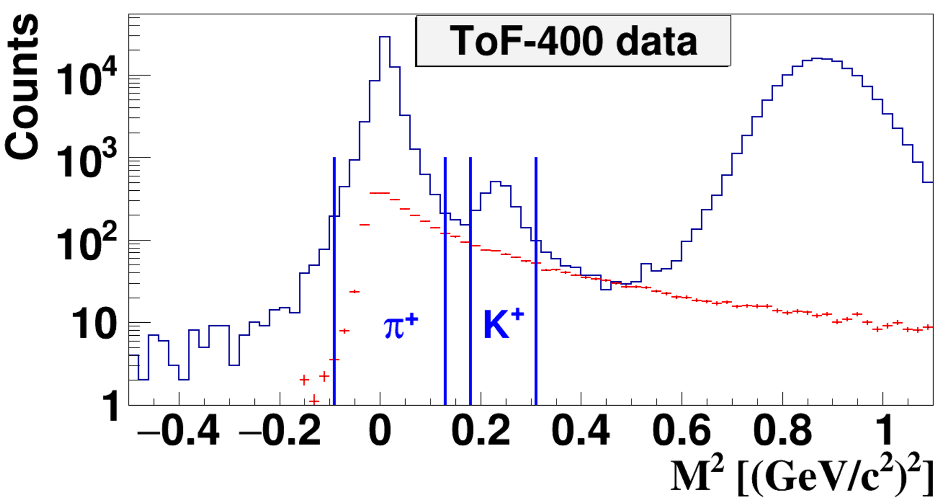
- **In heavy-ion reactions:** production of hypernuclei through coalescence of Λ with light fragments enhanced at high baryon densities
- **Maximal yield** predicted for √s=4-5A GeV (stat. model) (interplay of Λ and light nuclei excitation function)

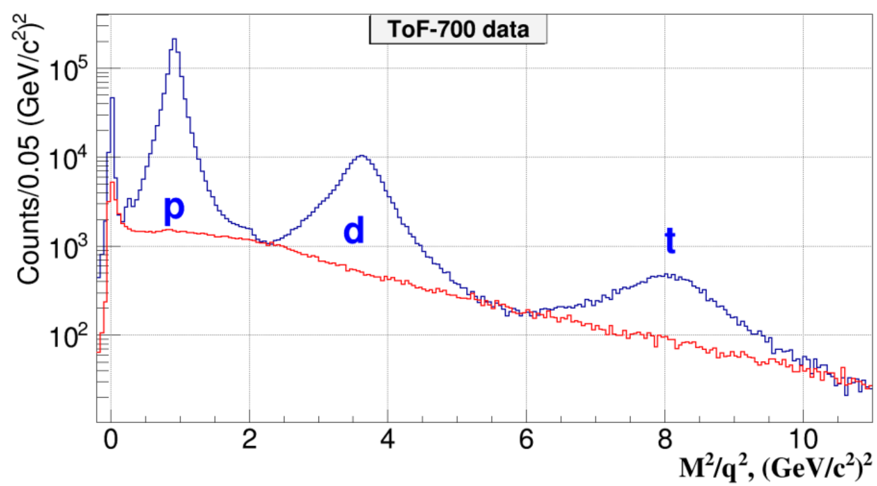
► **BM@N** energy range is **suited** for search of hyper-nuclei

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





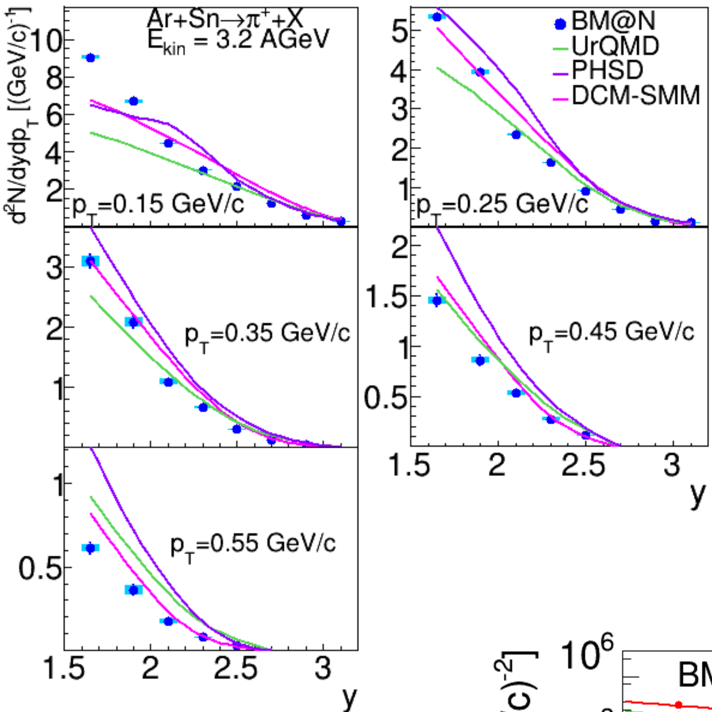


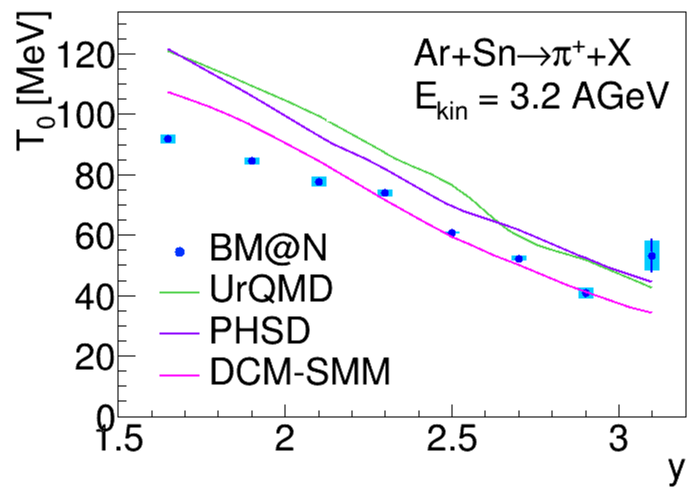


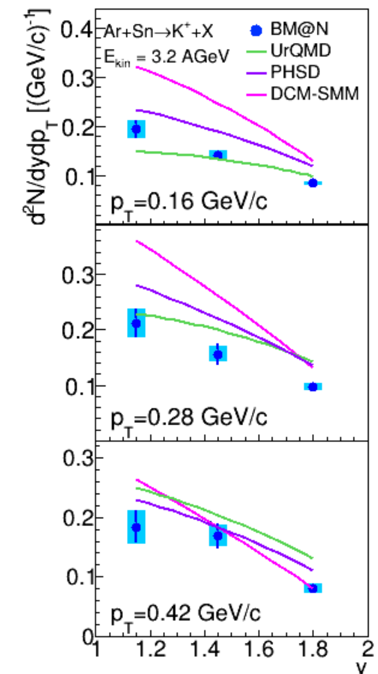
Production of π^+ and K^+ mesons in 3.2 AGeV argon-nucleus interactions

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

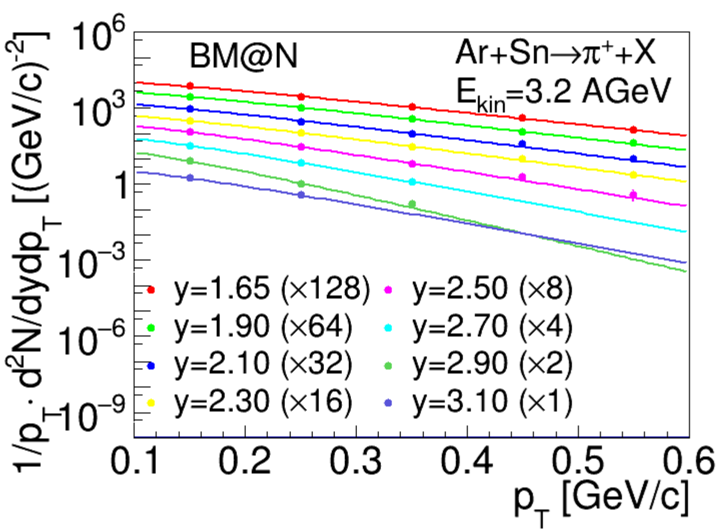
Published in JHEP 07 (2023) 174

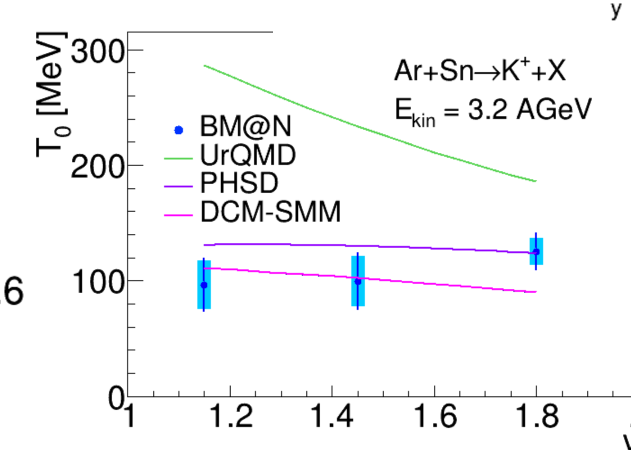




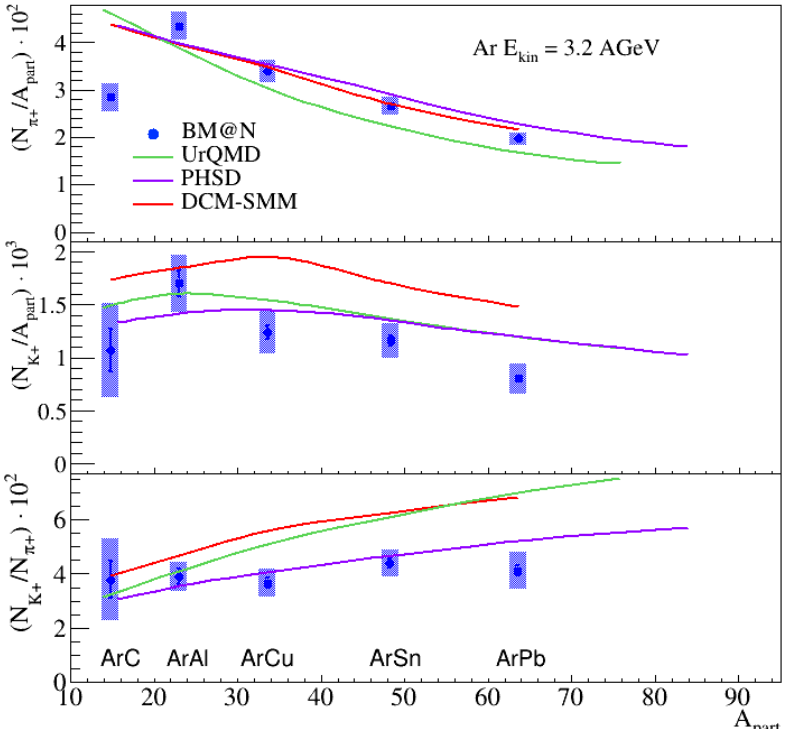


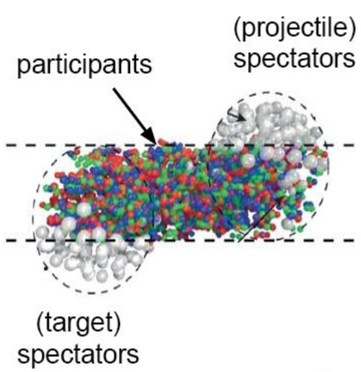
Full centrality range

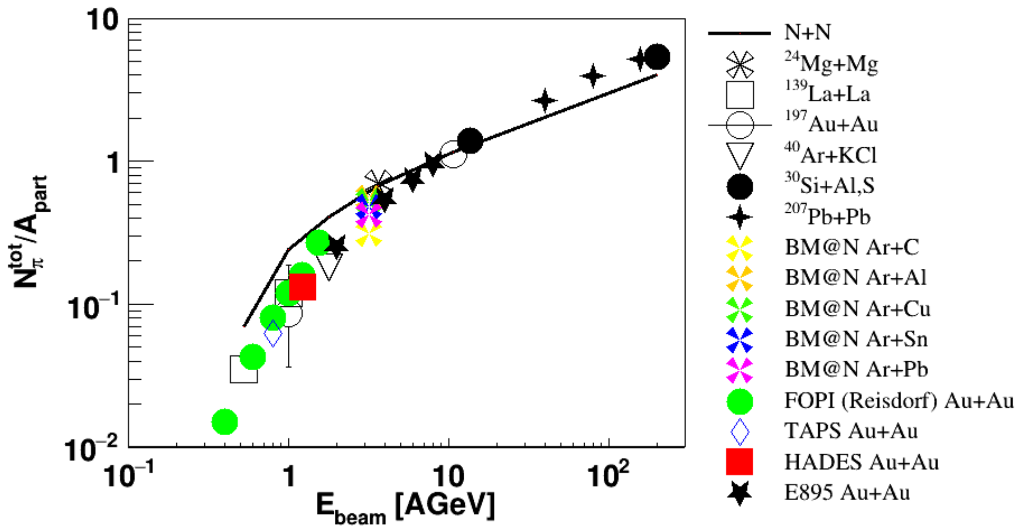


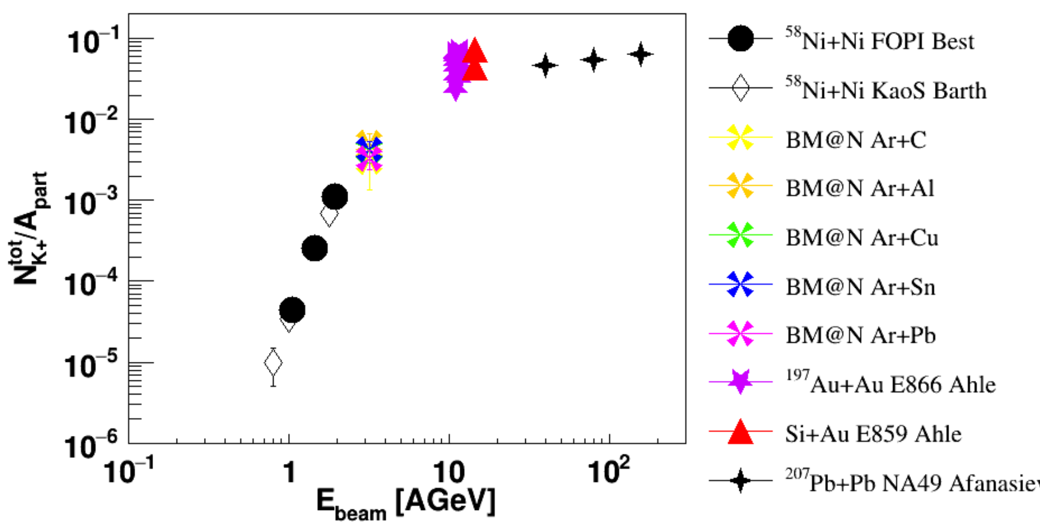


Production of π^+ and K^+ mesons in 3.2 AGeV argon-nucleus interactions



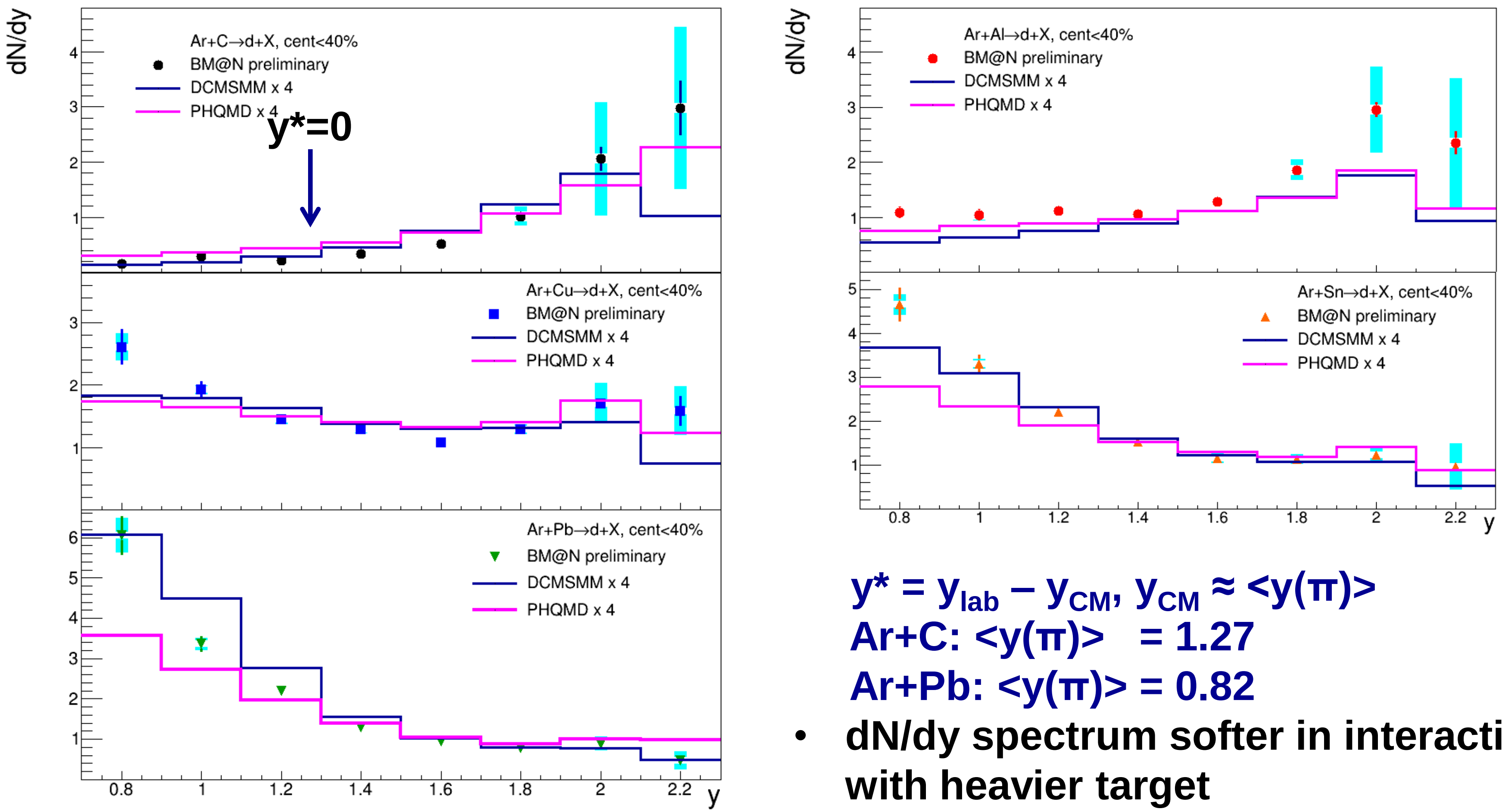






Deuterons in 3.2 AGeV argon-nucleus interactions: dN/dy dependence on y

Centrality 0-40%



$y^* = y_{lab} - y_{CM}$, $y_{CM} \approx \langle y(\pi)\rangle$

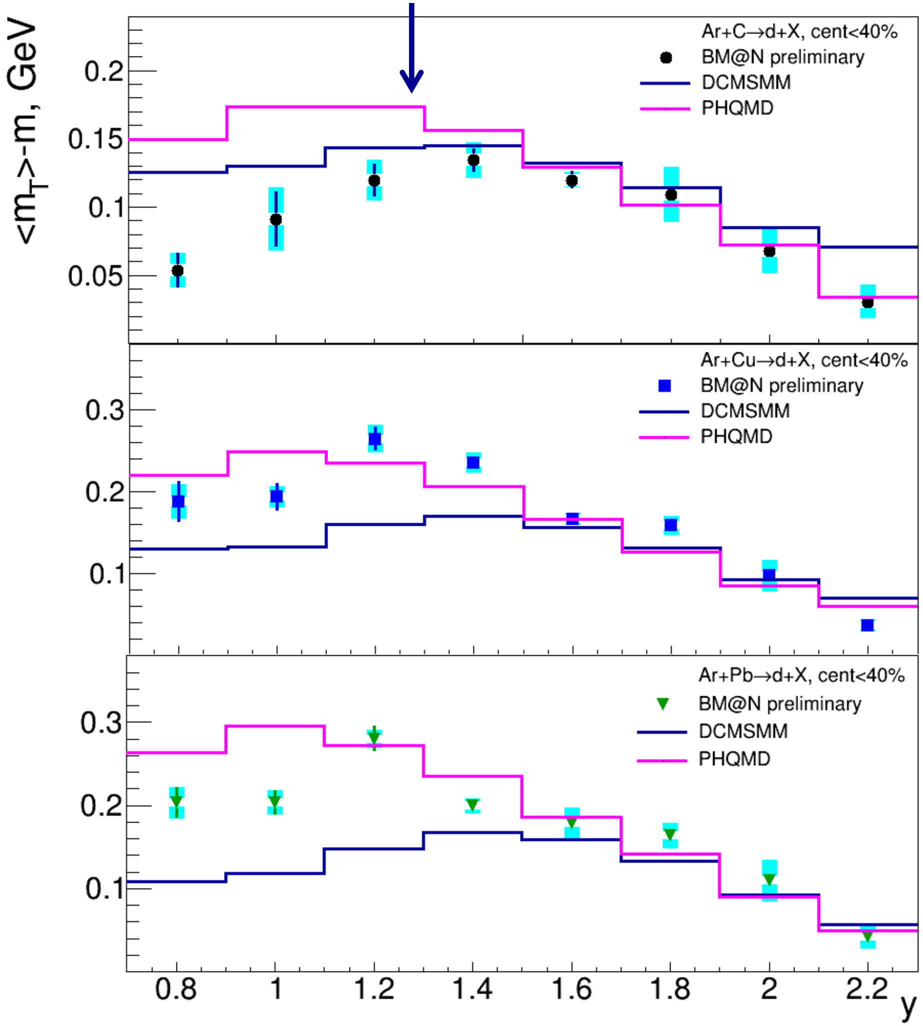
Ar+C: $\langle y(\pi)\rangle$ = 1.27

Ar+Pb: $\langle y(\pi)\rangle$ = 0.82

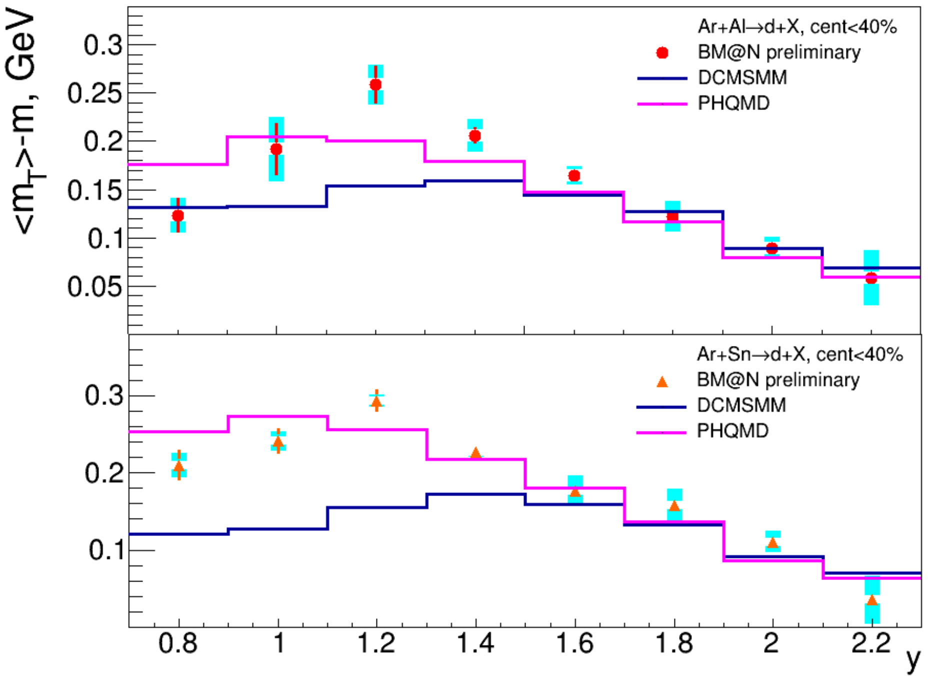
- **dN/dy spectrum softer in interactions with heavier target**
- **DCM-SMM and PHQMD models describe data shape, but are lower in normalization by factor 4**

Deuterons: $\langle m_t \rangle$ dependence on y

y*=0



Centrality 0-40%



$y^* = y_{lab} - y_{CM}$, $y_{CM} \approx \langle y(\pi) \rangle$

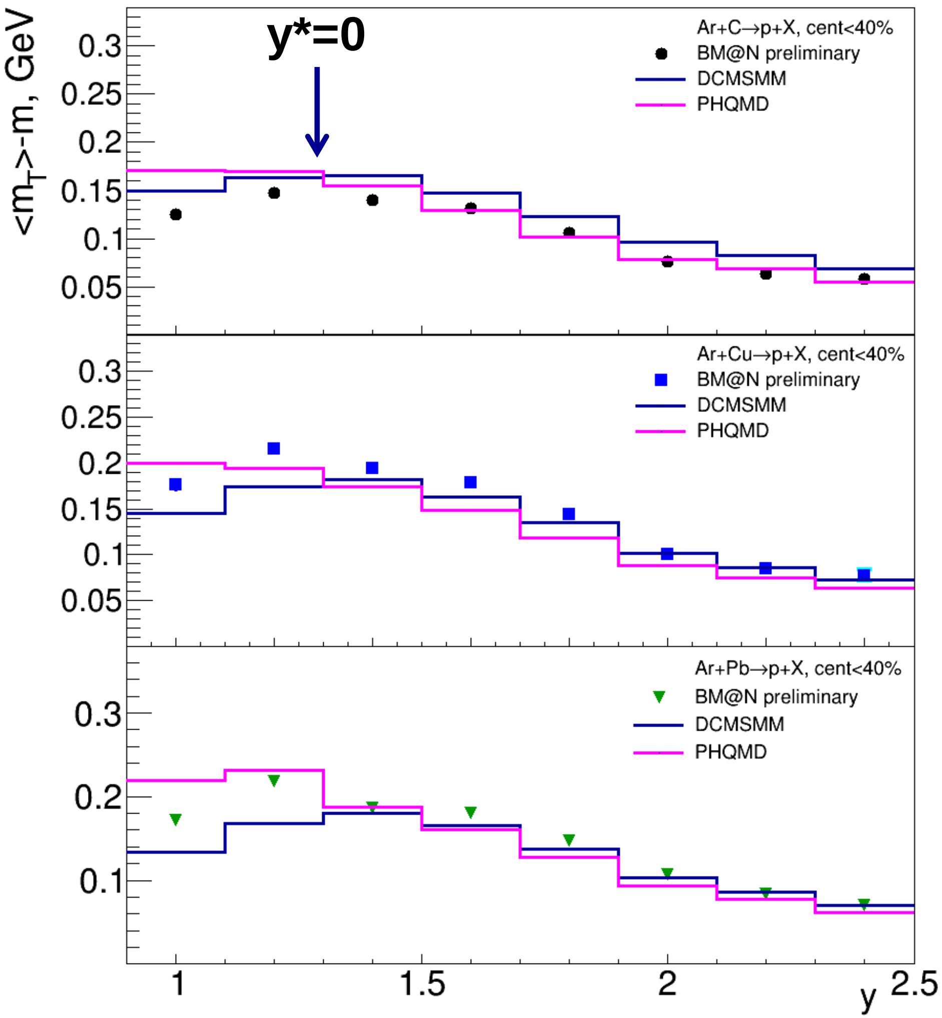
Ar+C: $\langle y(\pi) \rangle = 1.27$

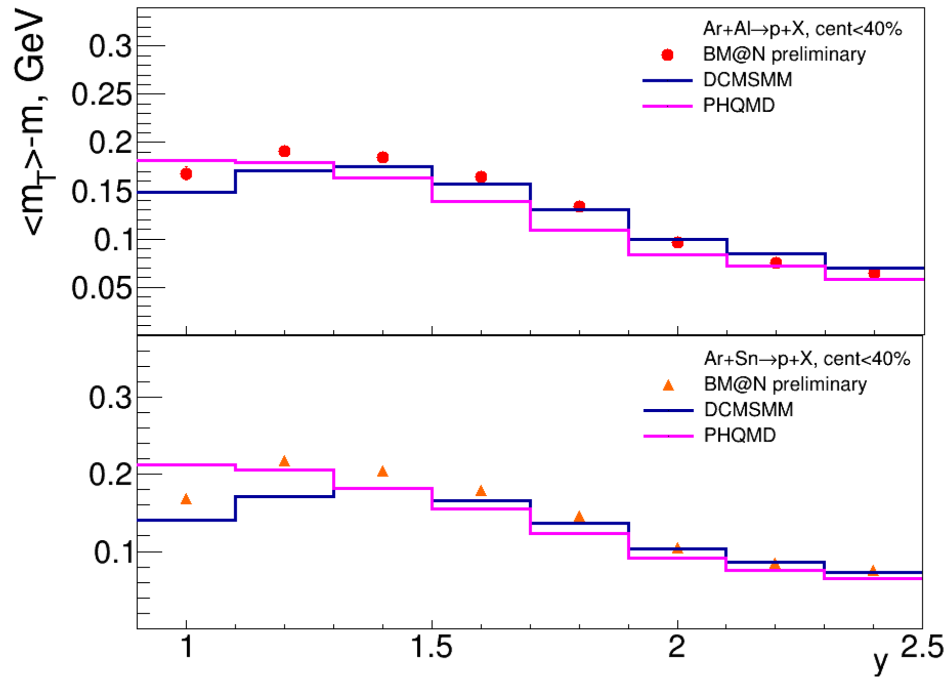
Ar+Pb: $\langle y(\pi) \rangle = 0.82$

- **Maximum $\langle m_t \rangle$ at mid-rapidity y***
- **PHQMD model is in better agreement with data at mid-rapidity than DCM-SMM**

Protons: <m_t> dependence on y

Centrality 0-40%





$y^* = y_{lab} - y_{CM}$, $y_{CM} \approx \langle y(\pi)\rangle$
Ar+C: <y(π)> = 1.27
Ar+Pb: <y(π)> = 0.82

- **Maximum <m_t> at mid-rapidity y***
- **DCM-SMM and PHQMD models describe <m_t> dependence on y**

Coalescence factors B_2 and B_3

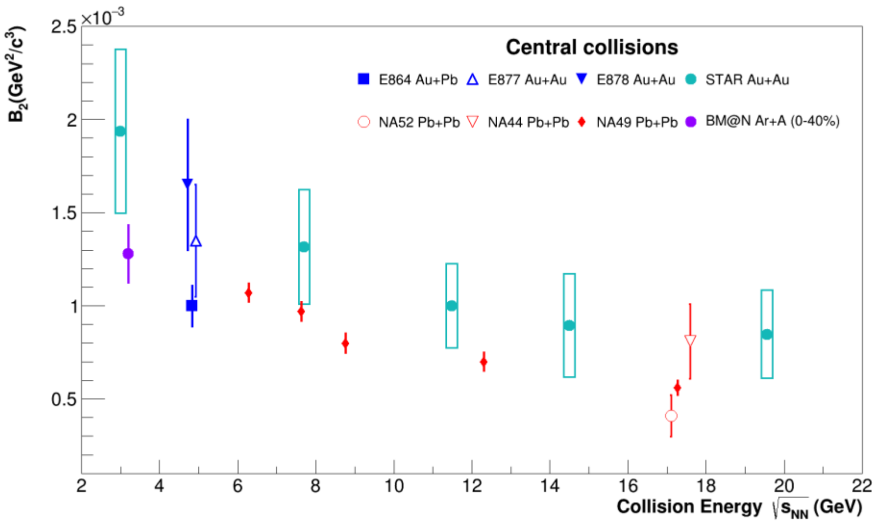
$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^Z \left(E_n \frac{d^3N_n}{dp_n^3}\right)^{A-Z} \approx B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^A,$$

$$\rightarrow B_A = d^2N_A/2\pi p_T dp_T(A)dy \;/\; [d^2N_p/2\pi p_T dp_T(p)dy)]^A,\; A=2(d),\; 3(t)$$

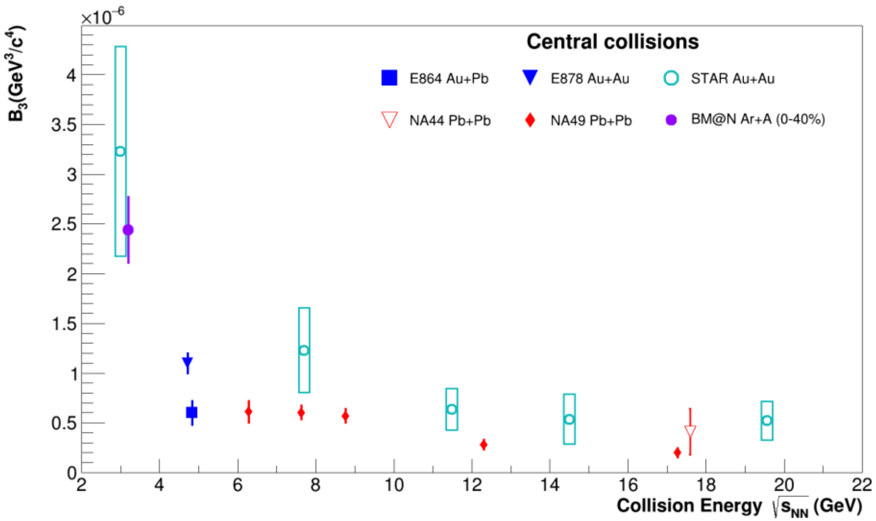
B_A is the coalescence parameter that characterizes the probability of nucleons to form nucleus A.

Coalescence parameter B_A depends on the nucleus mass number A, collision system, centrality, energy, and transverse momentum

B_2 for deuterons



B_3 for tritons



$N_p \cdot N_t / N^2_d$ ratio

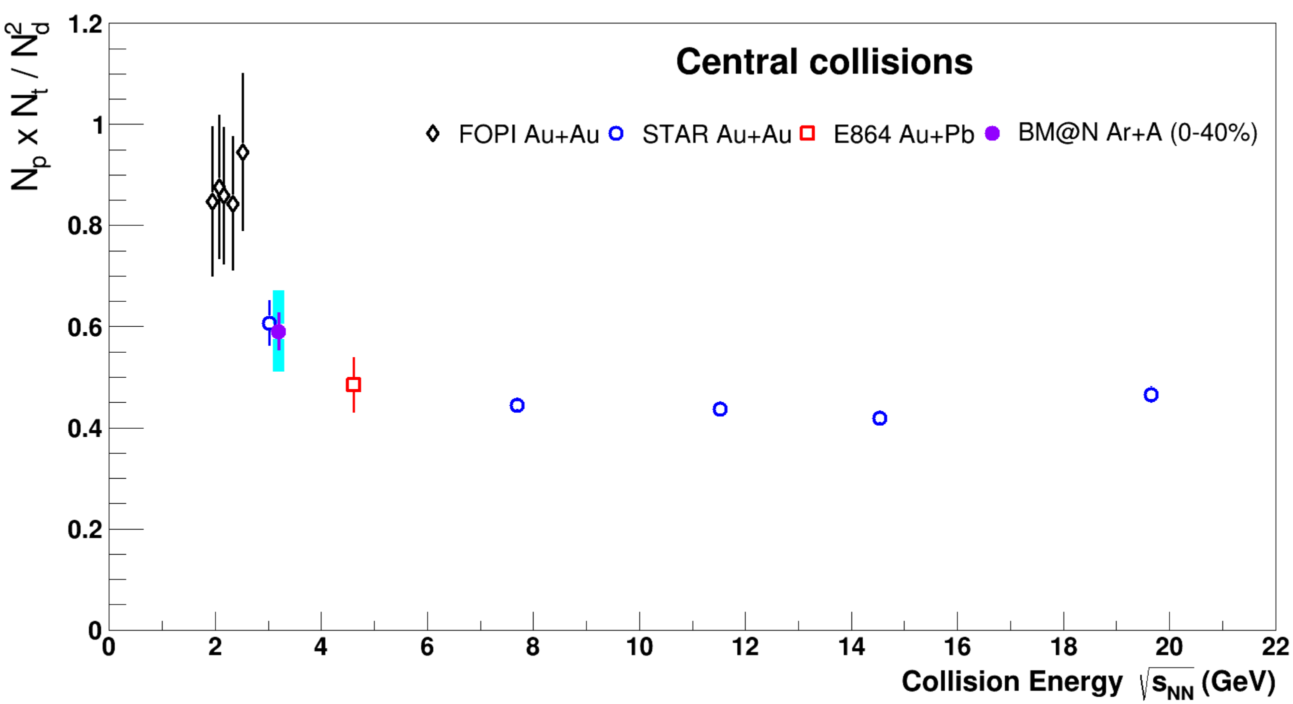
Reaction	Ar+C	Ar+Al	Ar+Cu	Ar+Sn	Ar+Pb
$N_p \cdot N_t / N^2_d$	0.53 ± 0.10	0.55 ± 0.09	0.69 ± 0.11	0.60 ± 0.07	0.59±0.06

Centrality 0-40%, use dN/dy for *p,d,t* in -0.18 < y* < 0.62

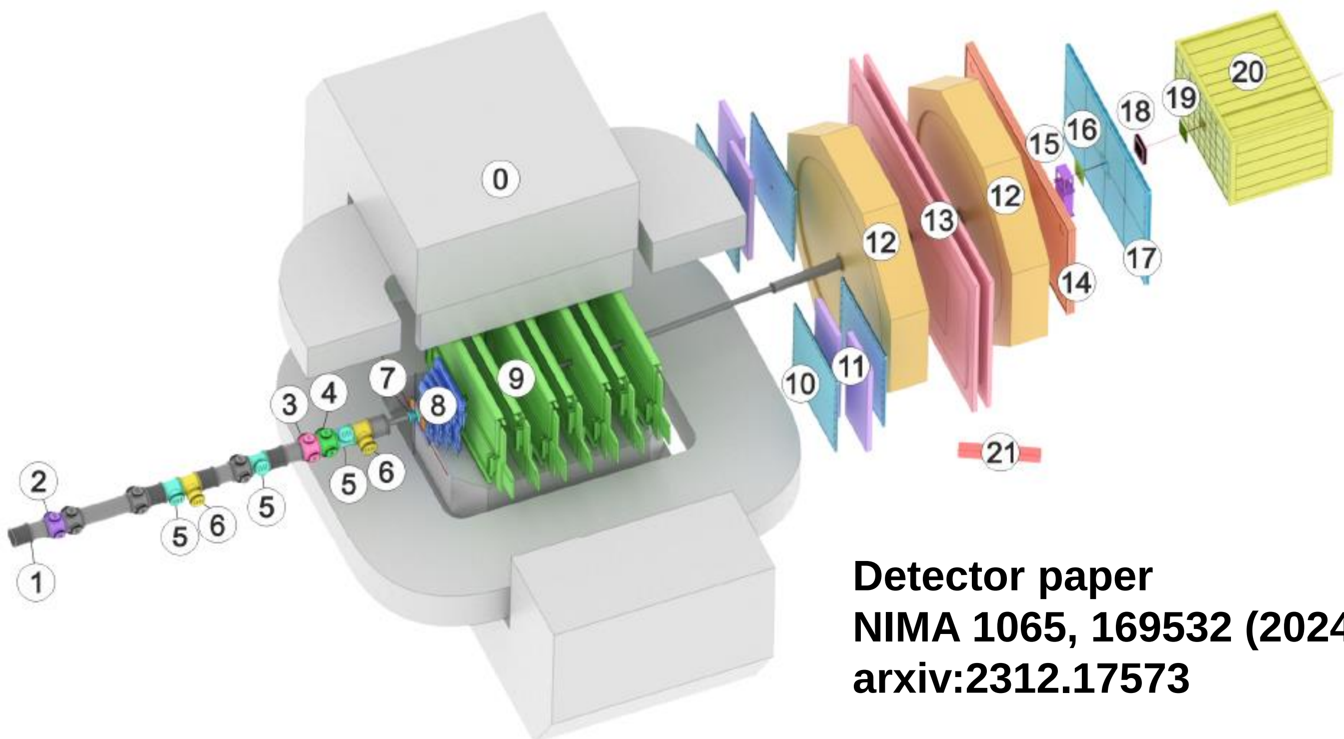
$$\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta\rho_n}{(1 + C_{np})^2}$$

→ related to fluctuations of neutron density

- BM@N observe $N_p \cdot N_t / N^2_d$ ~0.59 ± 0.07 for Ar + C,Al,Cu,Sn,Pb interactions
- Compare BM@N with STAR, SIS-18 and AGS results for Au+Au



Configuration of BM@N detector in Xe+CsI run



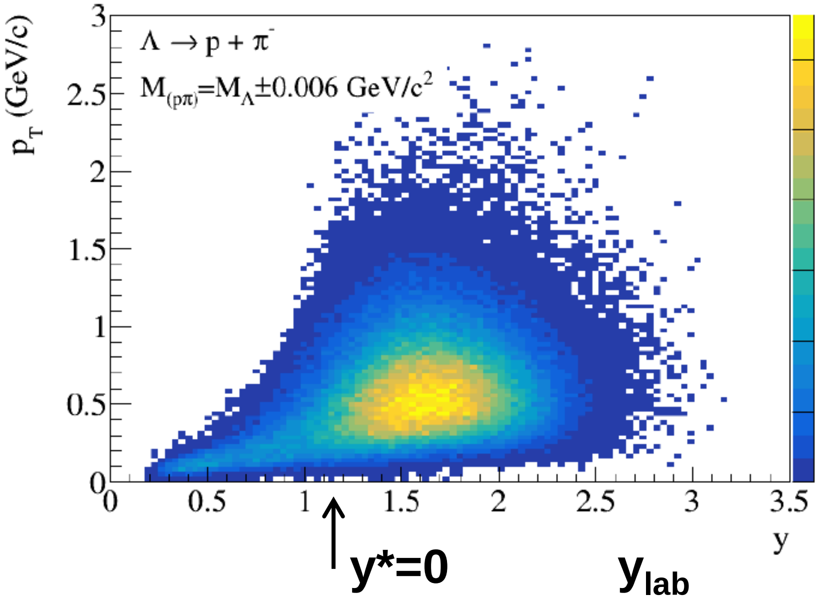
- Magnet SP-41 (0)
- Vacuum Beam Pipe (1)
- BC1, VC, BC2 (2-4)
- SiBT, SiProf (5, 6)
- Triggers: BD + SiMD (7)
- FSD, GEM (8, 9)
- CSC 1x1 m² (10)
- TOF 400 (11)
- DCH (12)
- TOF 700 (13)
- ScWall (14)
- FD (15)
- Small GEM (16)
- CSC 2x1.5 m² (17)
- Beam Profilometer (18)
- FQH (19)
- FHCal (20)
- HGN (21)

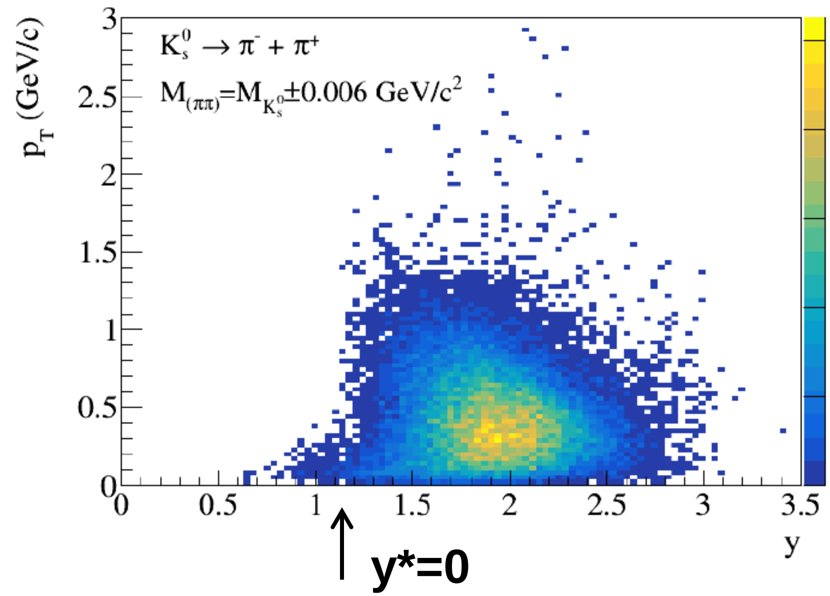
Detector paper
NIMA 1065, 169532 (2024)
arxiv:2312.17573

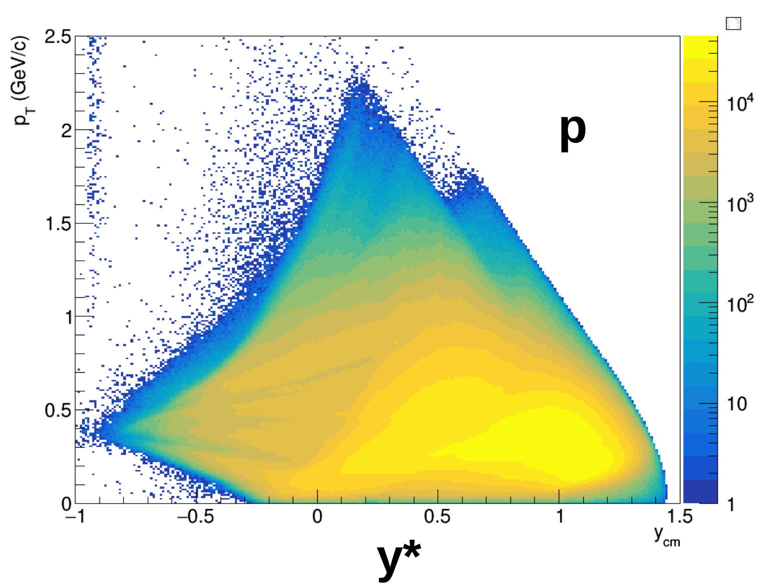
Xe^{124} + CsI interactions:
main trigger cover centrality < 70-75% (85% events)
min bias trigger (7% events), beam trigger (3% events)

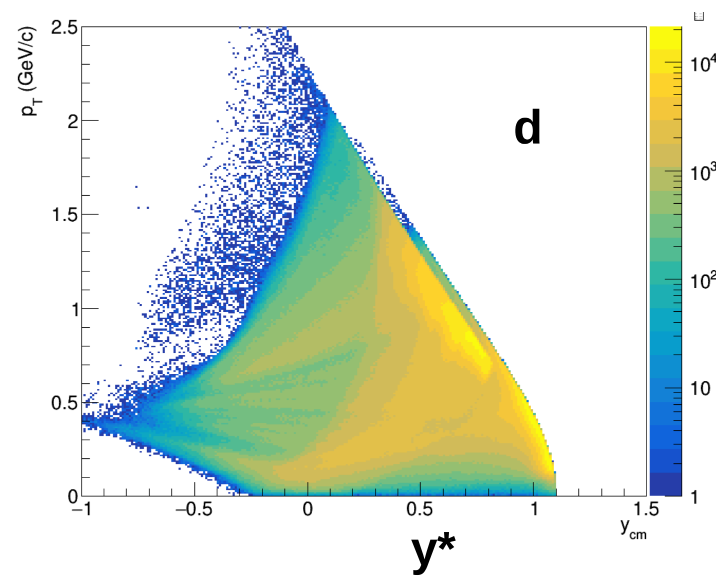
→ Collected >500M events at 3.8 AGeV, 50M events at 3.0 AGeV

BM@N acceptance for Λ, K^0_s , identified p, d

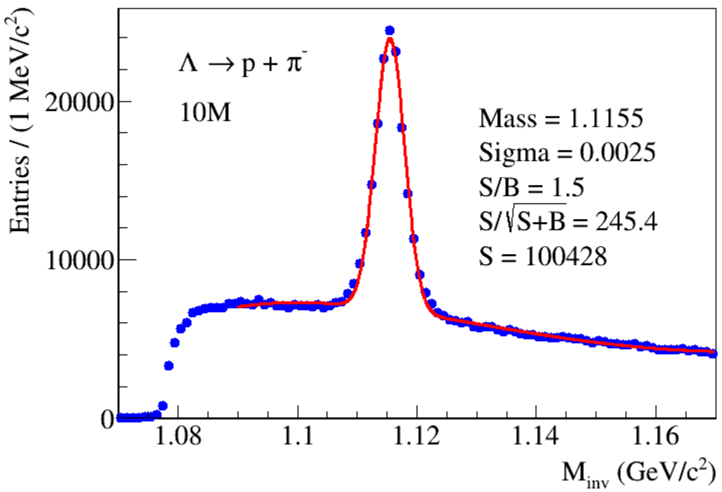


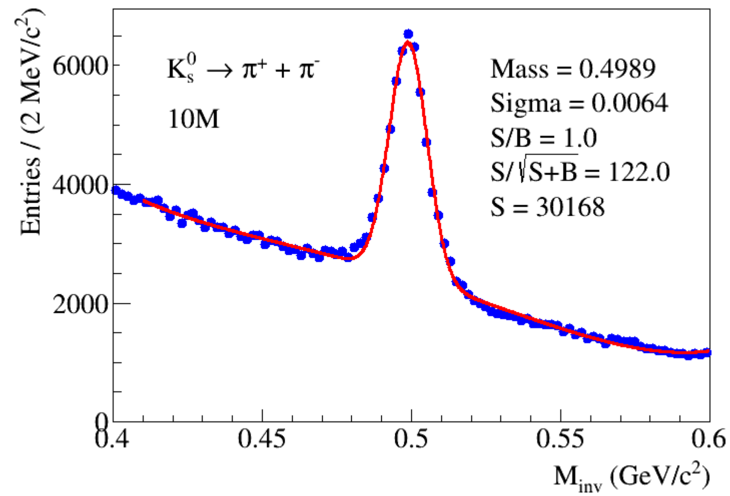




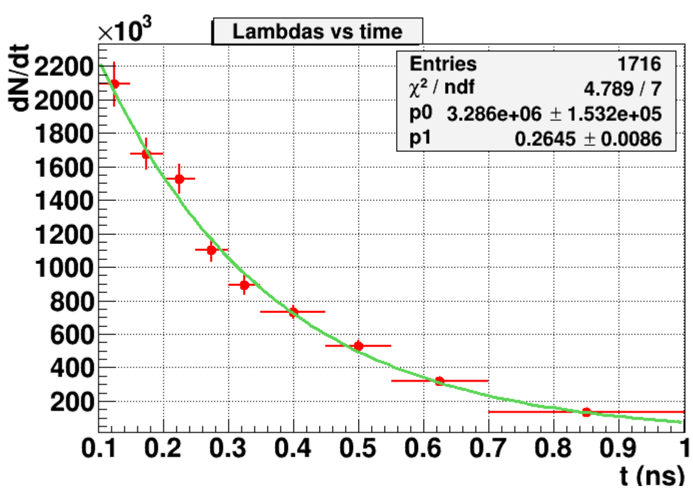


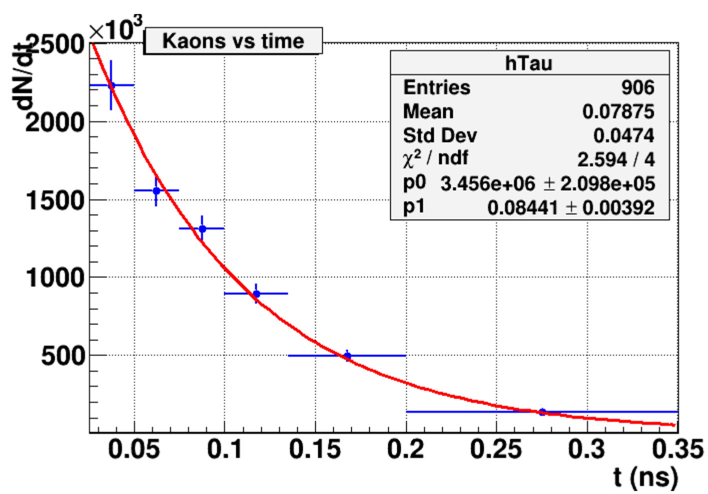
Λ and K^0_s production in Xe+CsI interactions





In 500M events expect: 4M Λ, 1.2M K^0_S



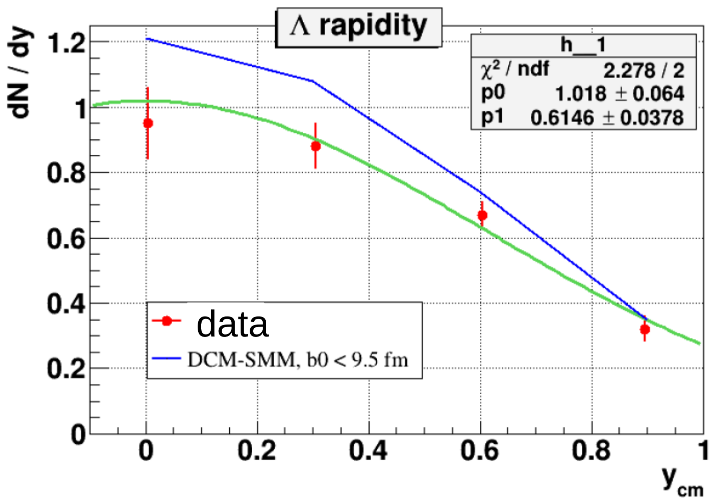


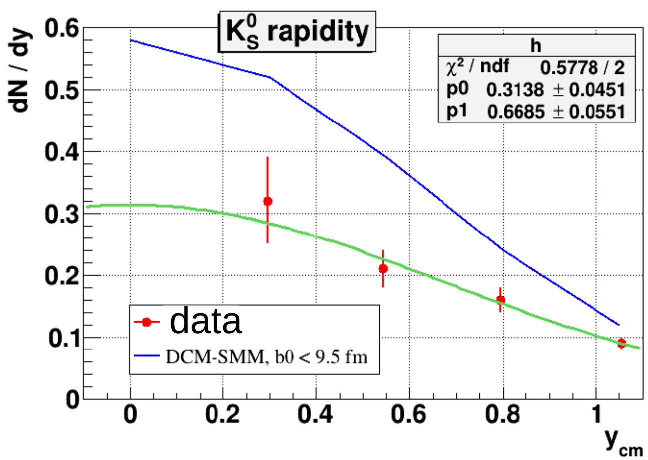
Life time is in agreement with PDG values: 0.2632 ns for Λ, 0.0895 ns for K^0_s

Λ and K^0_s production in Xe+CsI interactions

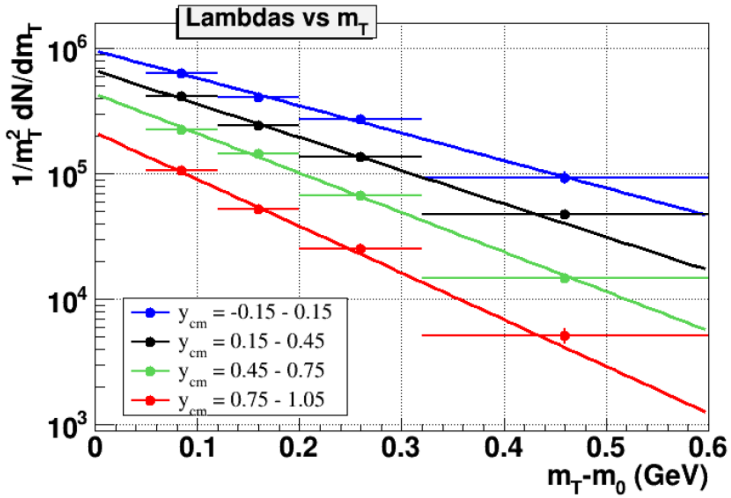
→ not official BM@N result yet

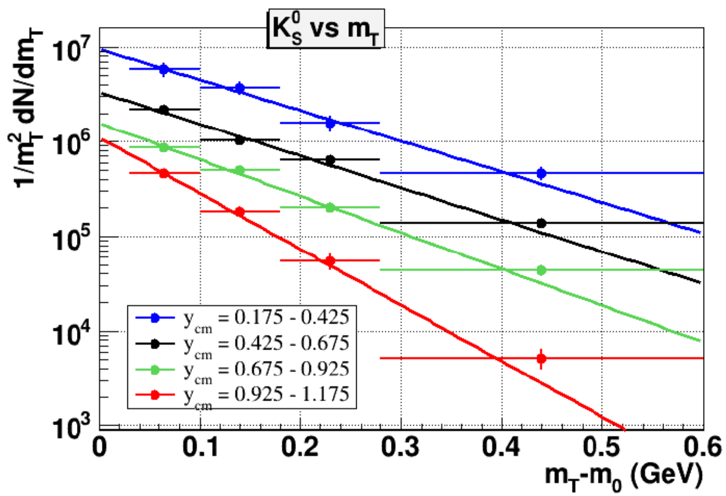
Rapidity distribution of Λ and K^0_s compared with DCM-SMM model



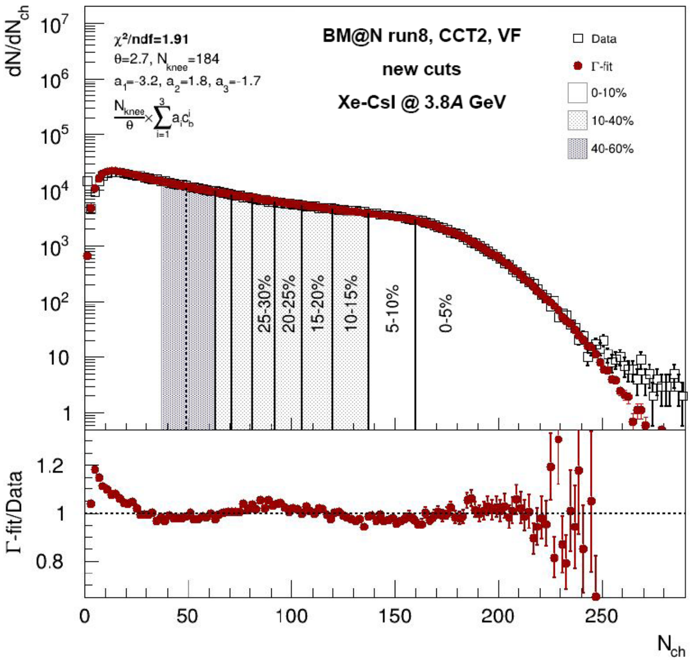


Transverse mass distribution of Λ and K^0_s





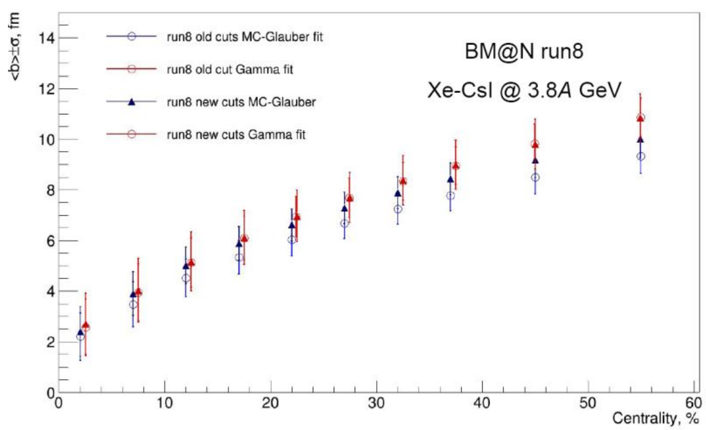
Centrality from track multiplicity and forward detectors

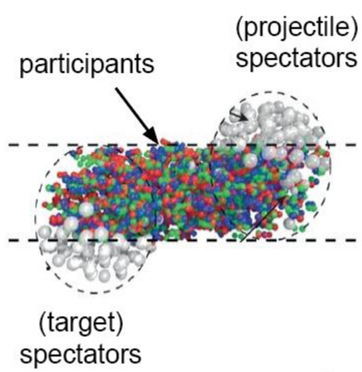


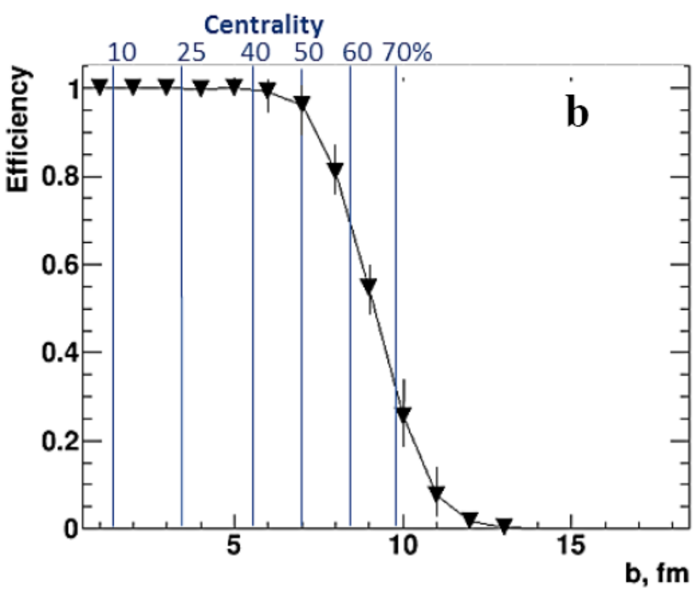
Parametrization of data track multiplicity N_{ch} by MC Glauber model or Negative Binominal Distribution (Γ-fit) with free parameters

→ Extract $P(b \mid N_{ch})$

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







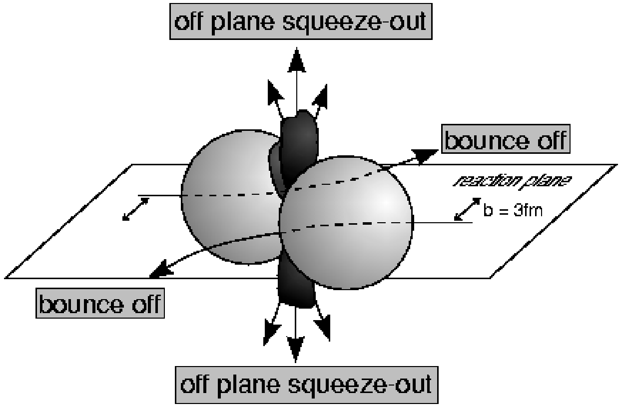
Trigger efficiency vs centrality

Collective flow of protons in Xe+CsI interactions

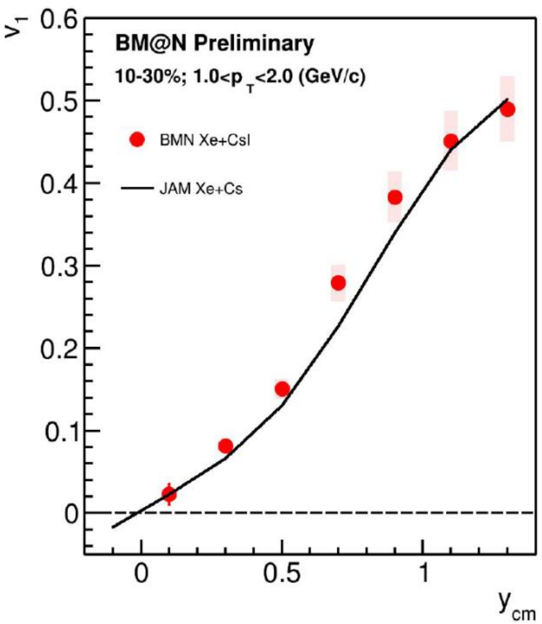
Azimuthal angle distribution:
$dN/d\varphi \propto (1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi)$

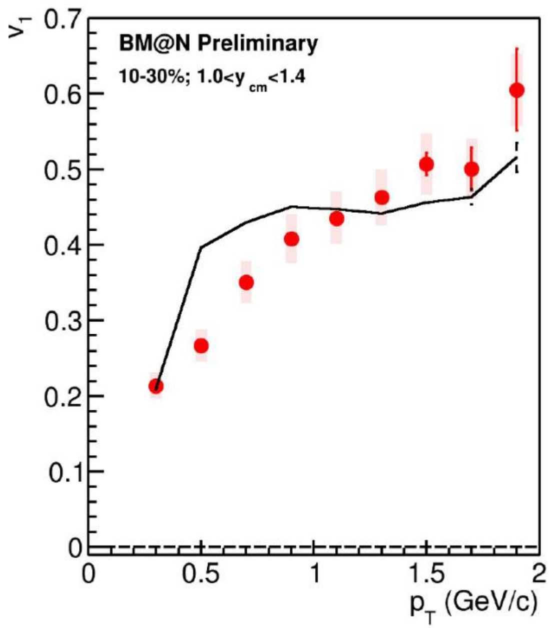
→ **Direct flow of protons as a function of rapidity, transverse momentum; compared with the JAM model**

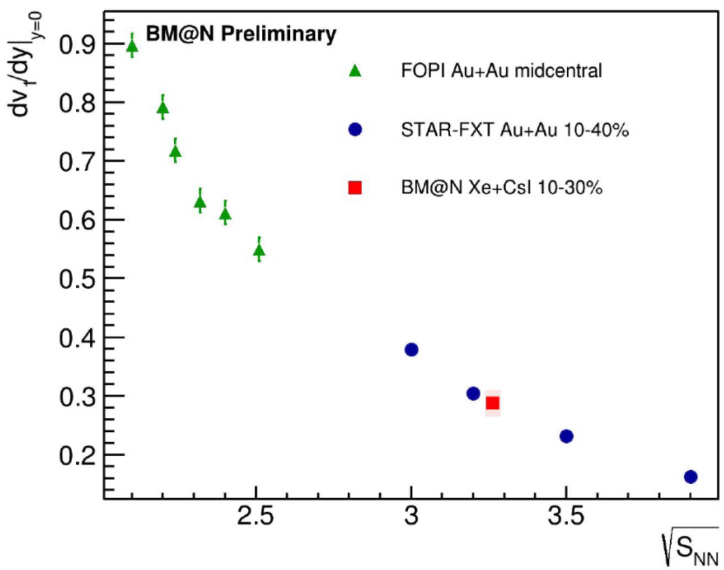
→ **BM@@N result is in line with the energy dependence of the world data**



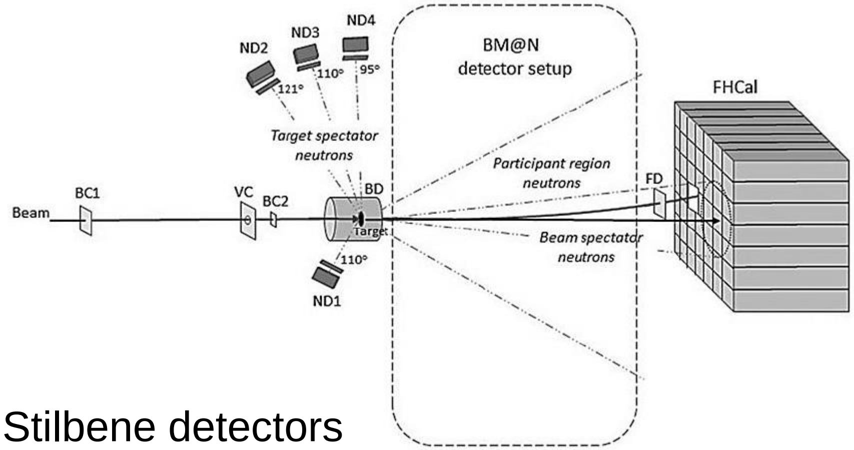
BM@N Preliminary







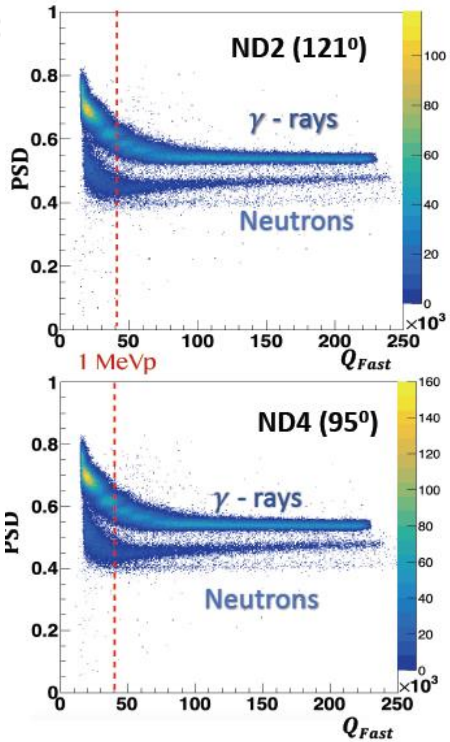
Study of neutron emission from target spectators in ^{124}Xe + CsI collisions at 3.8 A GeV



Stilbene detectors

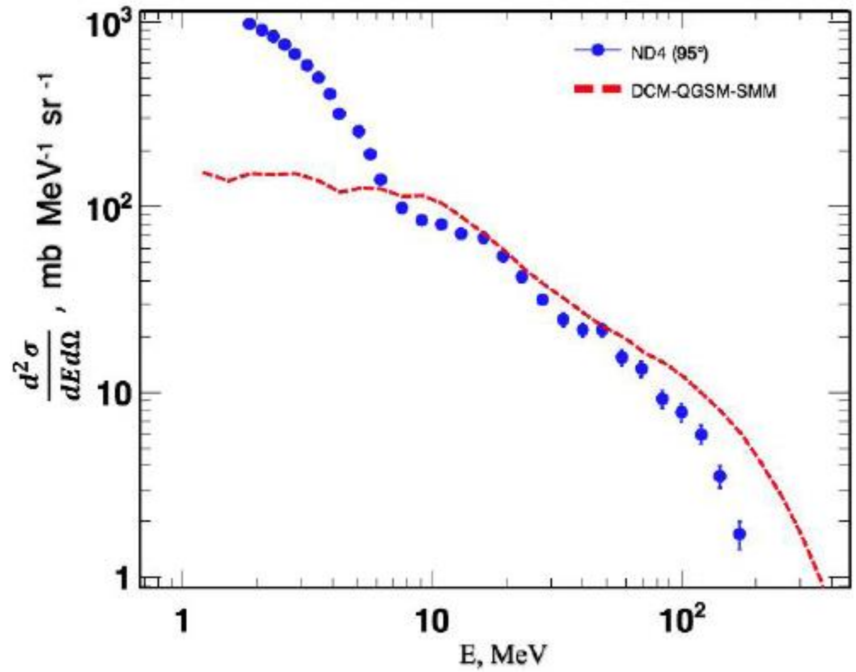
Quality of pulse shape discrimination:

$$PSD = \frac{Q_{fast}}{Q_{total}}$$

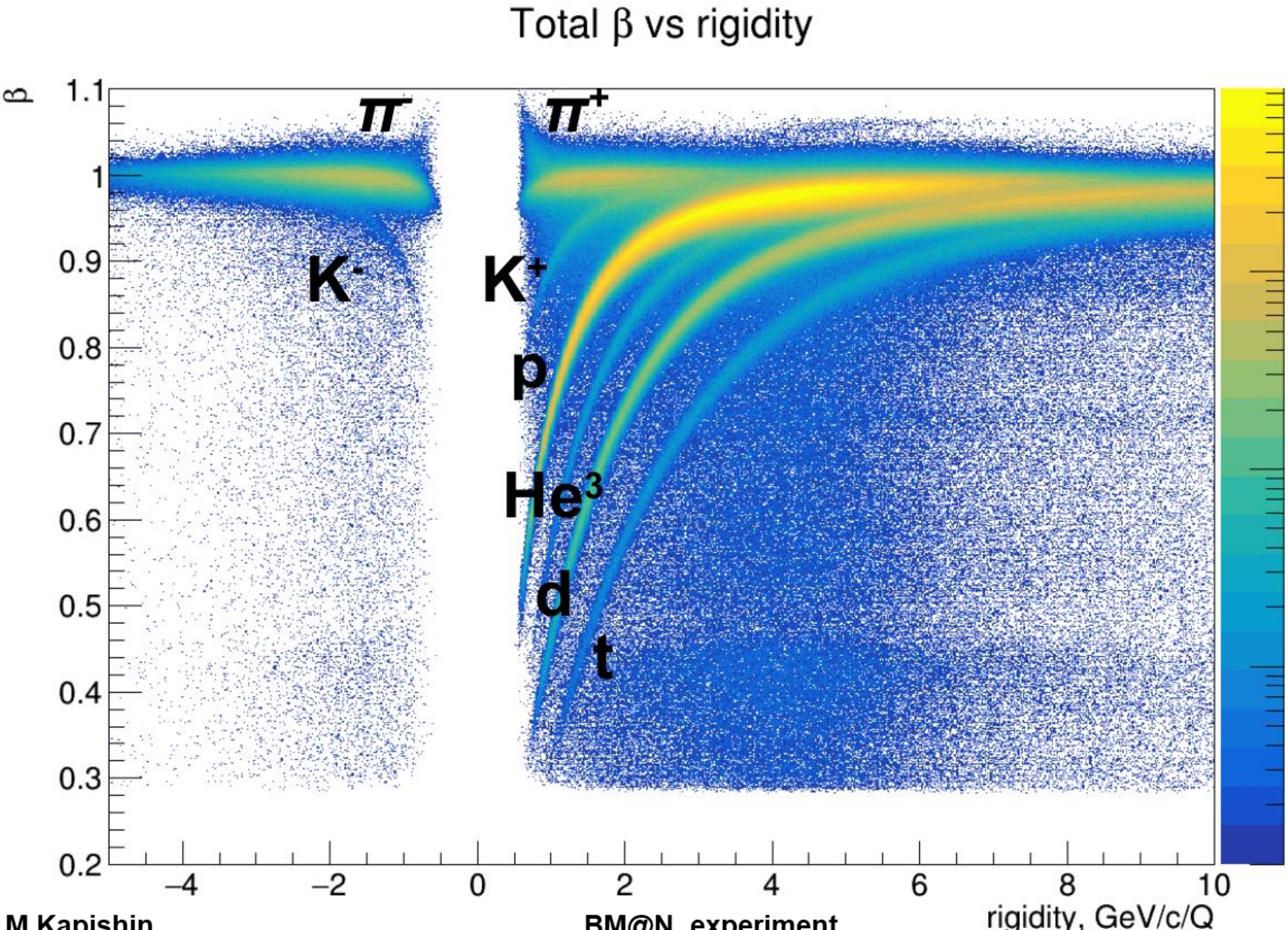


Compare spectra with DCM-SMM model

BM@N Preliminary



Xe+CsI data: π+-, K+-, p, He3, d/He4, t identification

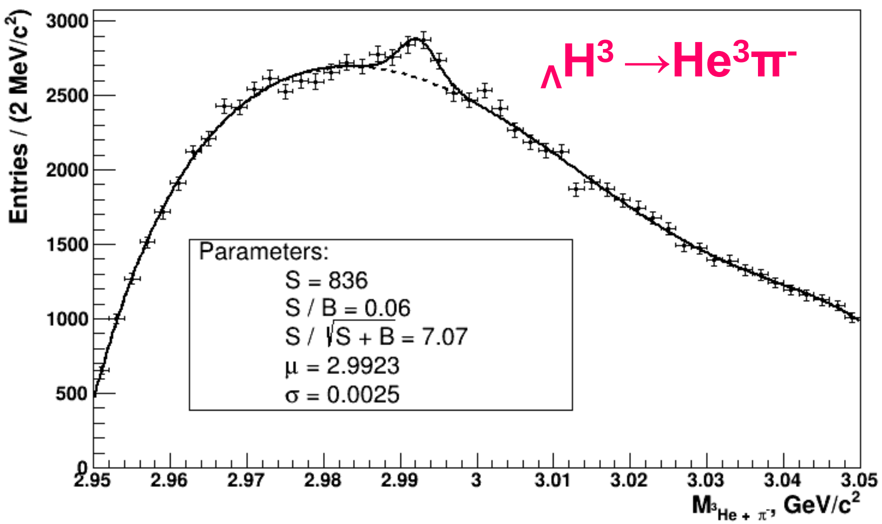


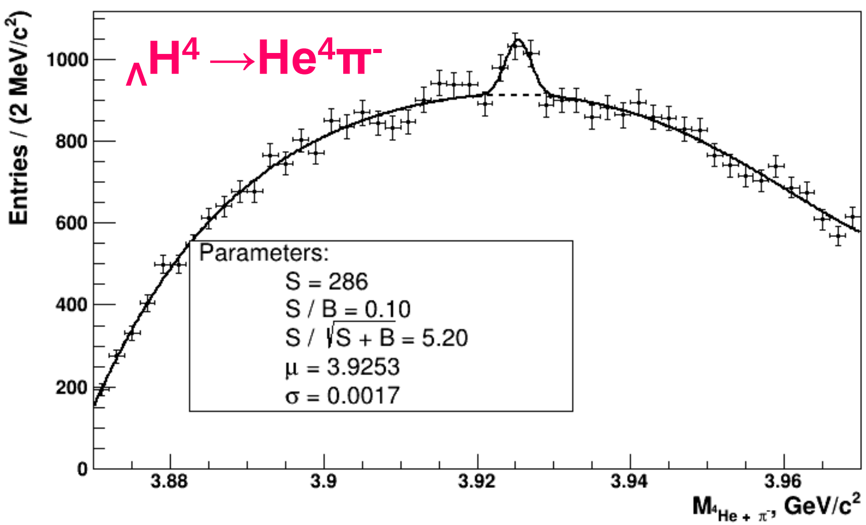
M.Kapishin

BM@N experiment

Search for $_{\Lambda}H^3$, $_{\Lambda}H^4$ in Xe+CsI interactions

First signals of $_{\Lambda}H^3$, $_{\Lambda}H^4$





Room for improvements:

- **Increase ToF-700 hit finding efficiency**
- **Improve dE/dx in GEMs for He^3, He^4 selection**

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 in Xe+CsI interactions;
- analysis of collective flow of protons, π±, light nuclear fragments
- search for light hyper-nuclei $_\Lambda H^3$, $_\Lambda H^4$

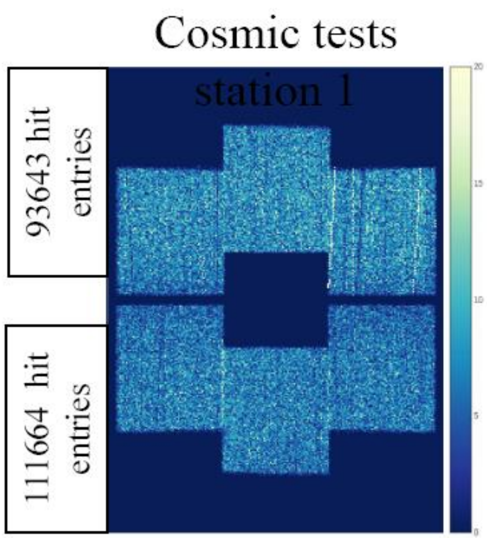
Physics run in the Xe beam in 2025

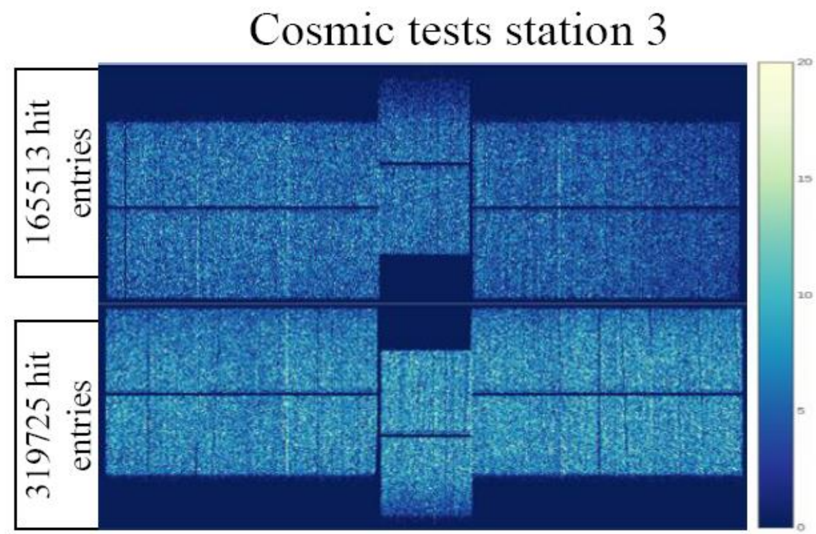
→ beam energy scan in the range of 2-3 AGeV
→ same central tracker configuration based on silicon micro-strip and GEM detectors,
→ additional 1^{st} vertex plane of silicon micro-strip detectors

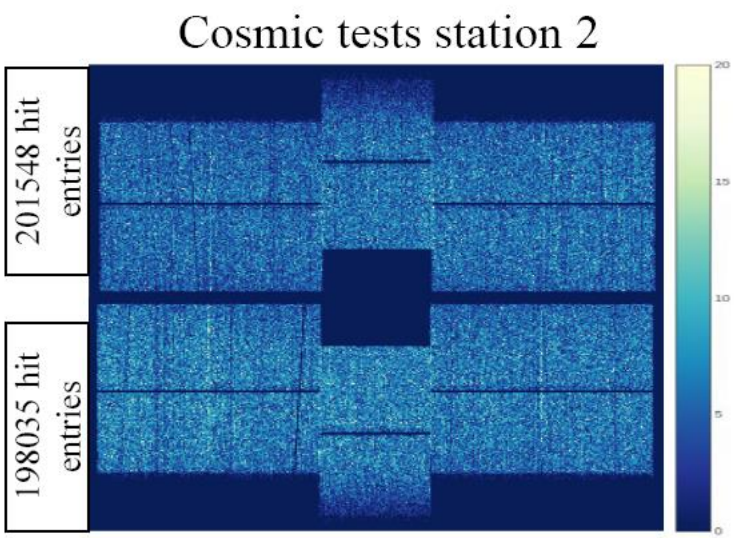
Preparations for a physics run with the Bi beam

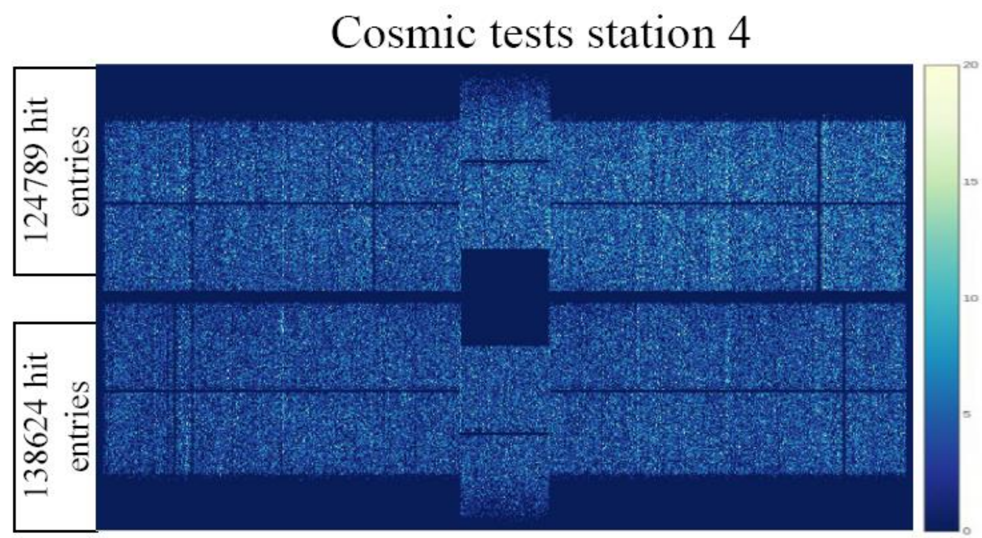
- Further development of the central tracker is foreseen: installation of additional station of silicon micro-strip detectors
- It is planned to put into operation a 2-coordinate (X/Y) neutron detector of high granularity to measure neutron yield and collective flow

Forward Silicon Detectors





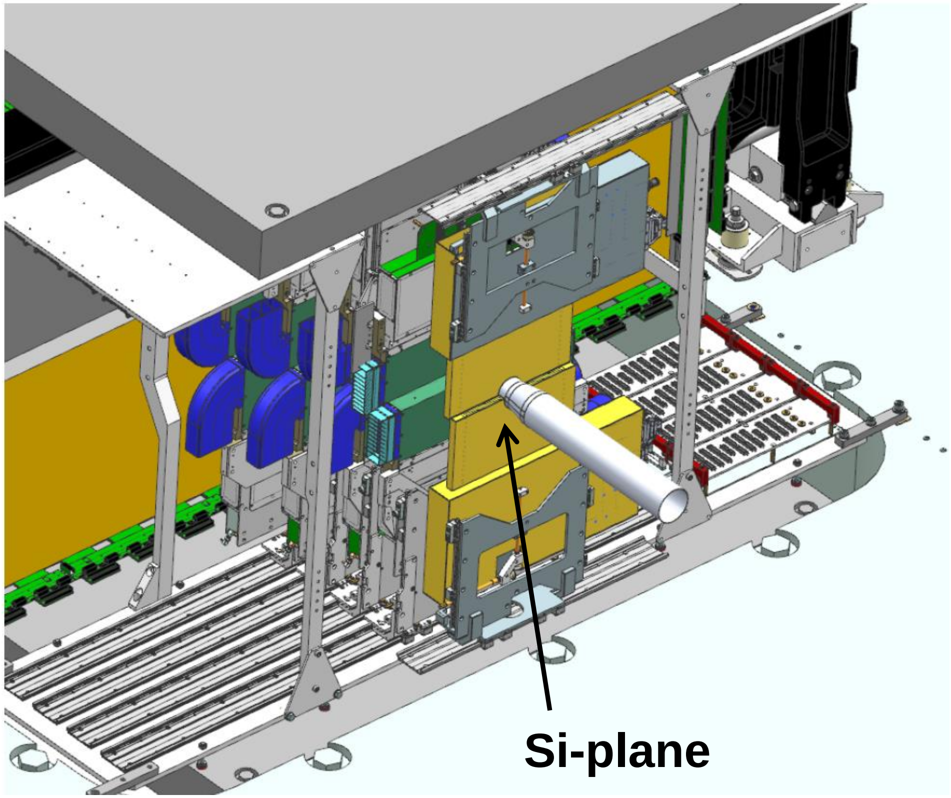


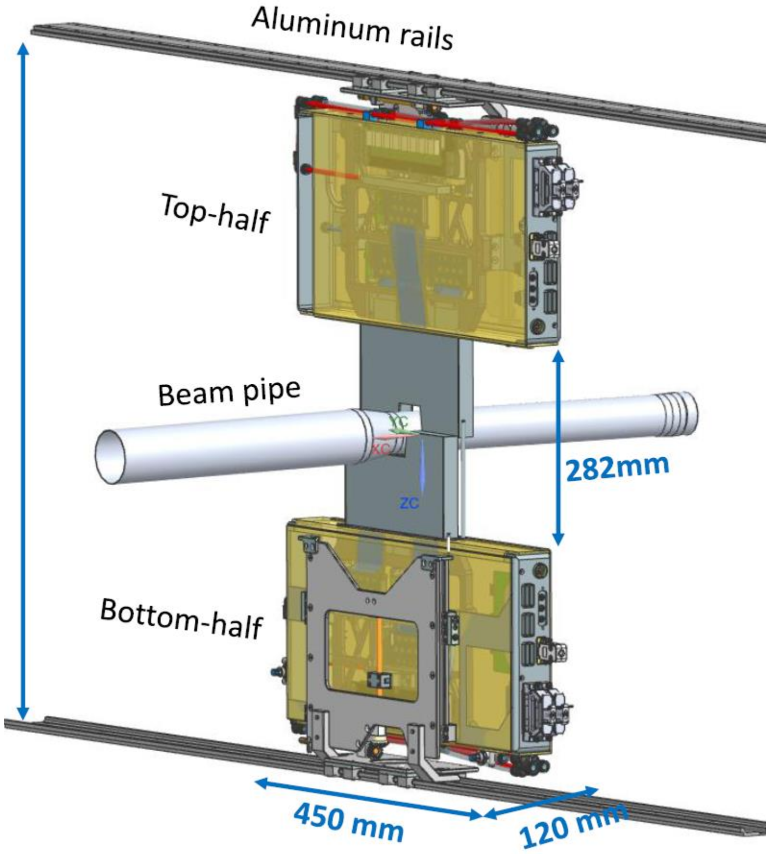


2-coordinate Si-plane based on STS modules

A new Si-plane based on STS modules to be installed between the **Target** and **Forward Si-Tracker**

Motivation: to improve track and momentum resolution for the low-momentum particles

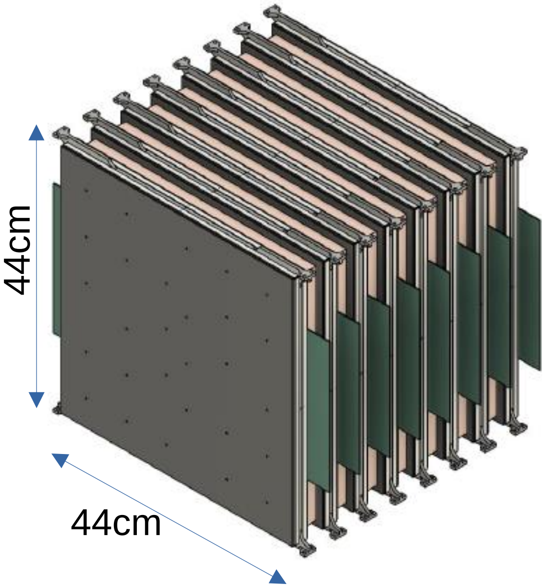




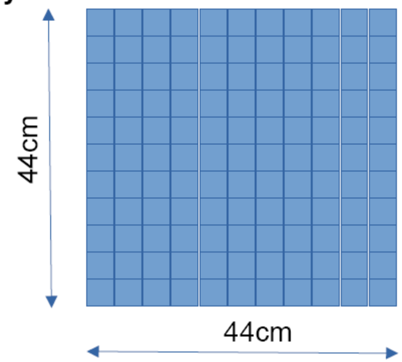
Plan to install and commission the new Si plane for the next experimental run

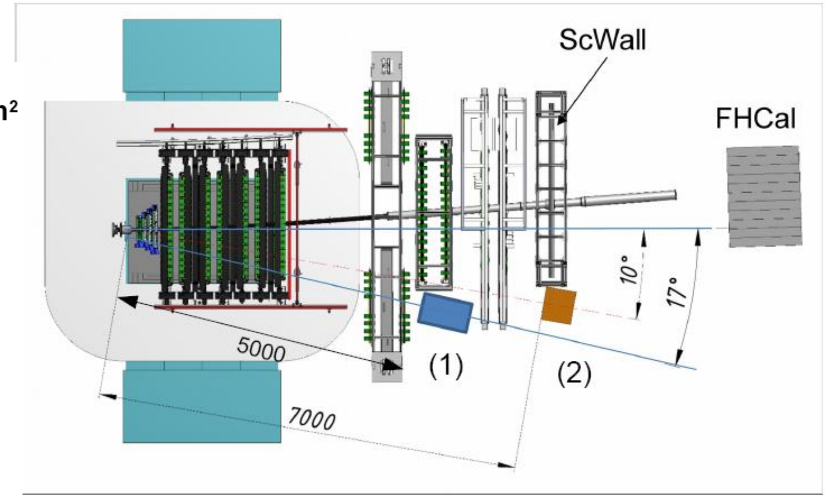
New neutron detector of high granularity

→ **plan to install in 2026**



Structure of Scint. layer:
array of 11x11 scintillator cells 4 x 4 cm²

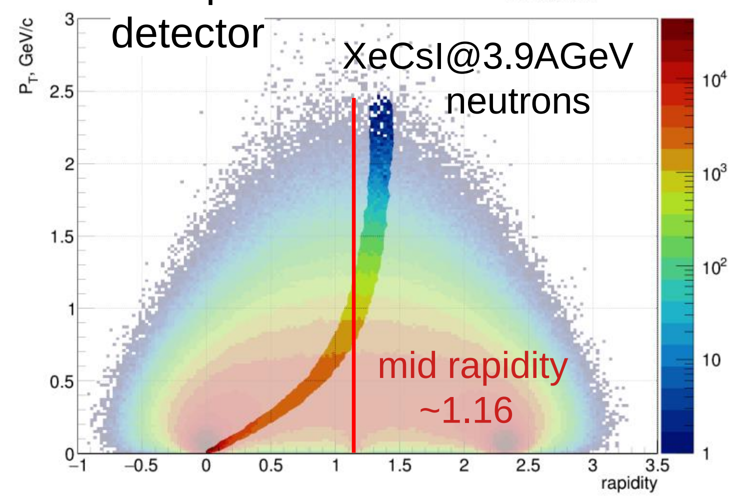




2 positions of HGN detector at BM@N: at 10º and 17º

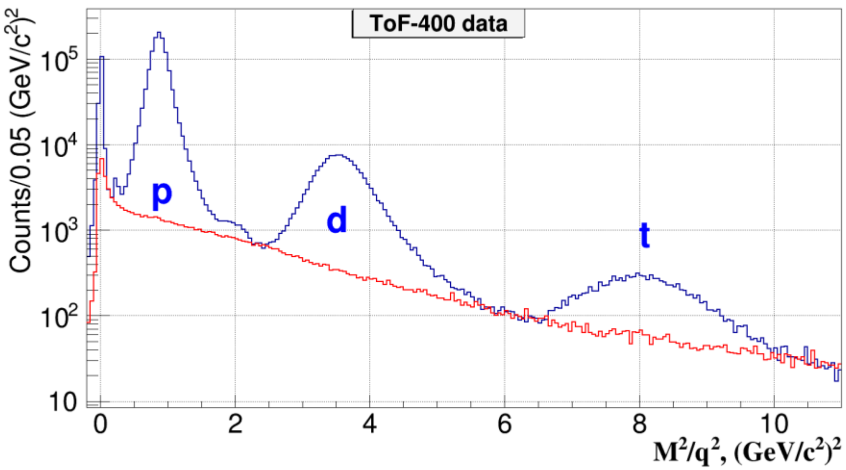
HGN detector parameters: 2 sub-detectors with 8 layers each (~1.5 λ_{int})
- 11 x 11 cells in one layer with SiPM read-out
- first layer works as VETO
- next 7 layers: 3cm Cu + 2.5cm scintillator
- FPGA based fast TDC read-out with additional ToT amplitude measurement
  - time resolution of one scint. cell ~ 120ps
  - neutron detection efficiency: > 60% @ 1GeV

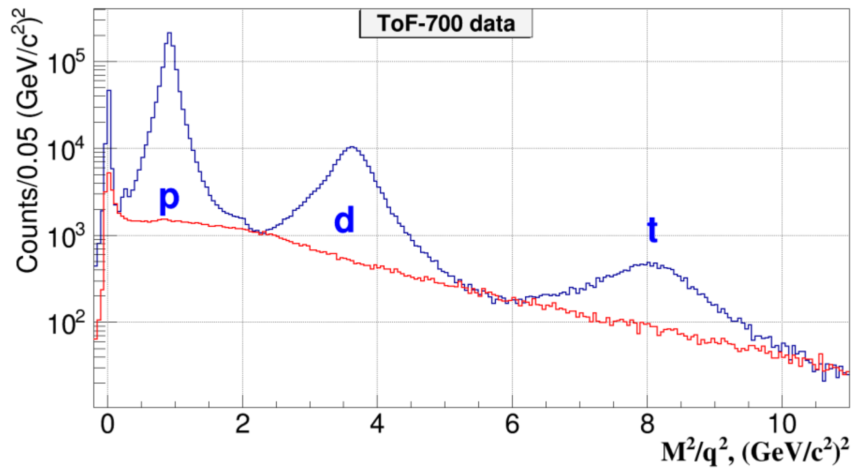
Acceptance of HGN detector



Thank you
for attention!

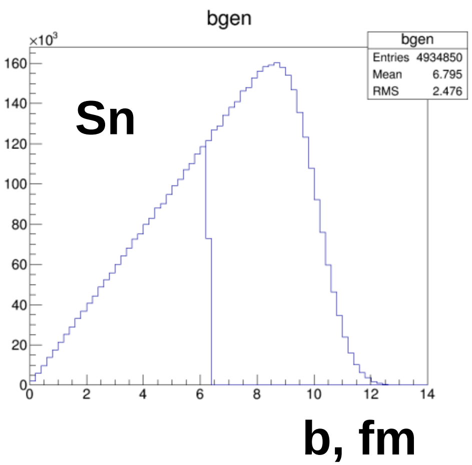
Production of *p, d, t* in 3.2 AGeV argon-nucleus interactions

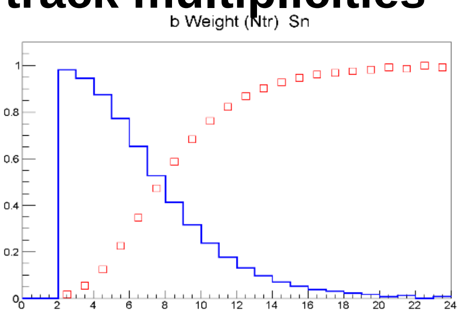


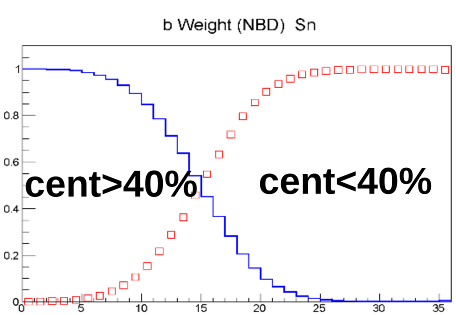


Two classes of centrality <40% and >40% based on barrel detector and track multiplicities

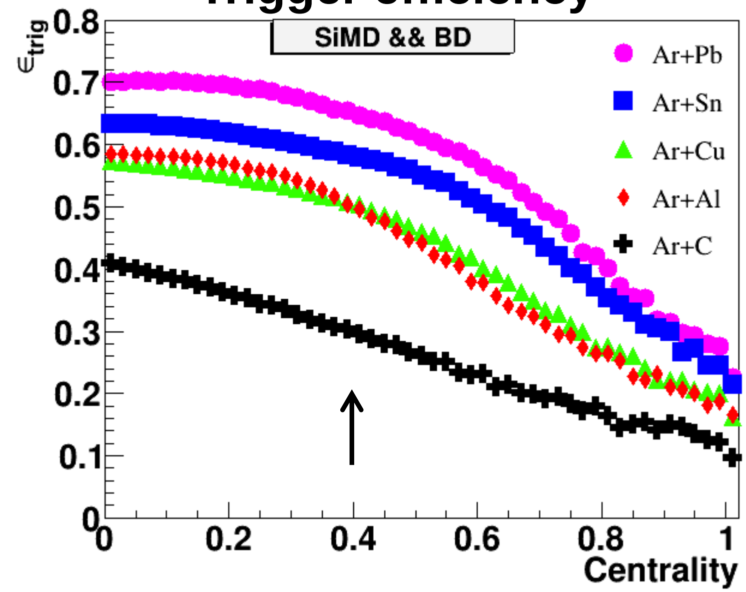
cent<40% cent>40%







Trigger efficiency



Coalescence factors B_2 and B_3

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^Z \left(E_n \frac{d^3N_n}{dp_n^3} \right)^{A-Z} \approx B_A \left(E_p \frac{d^3N_p}{dp_p^3} \right)^A ,$$

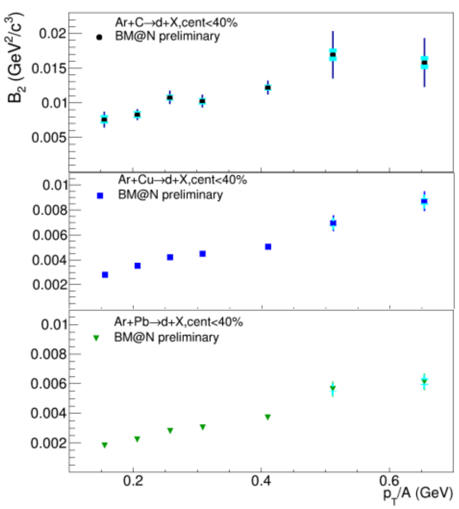
$$\rightarrow B_A = d^2N_A/2\pi p_T dp_T(A)dy \;/\; [d^2N_p/2\pi p_T dp_T(p)dy)]^A, \; A=2(d),\; 3(t)$$

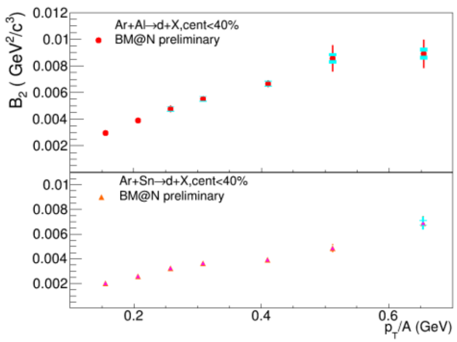
B_2 for deuterons

B_A is the coalescence parameter that characterizes the probability of nucleons to form nucleus A.

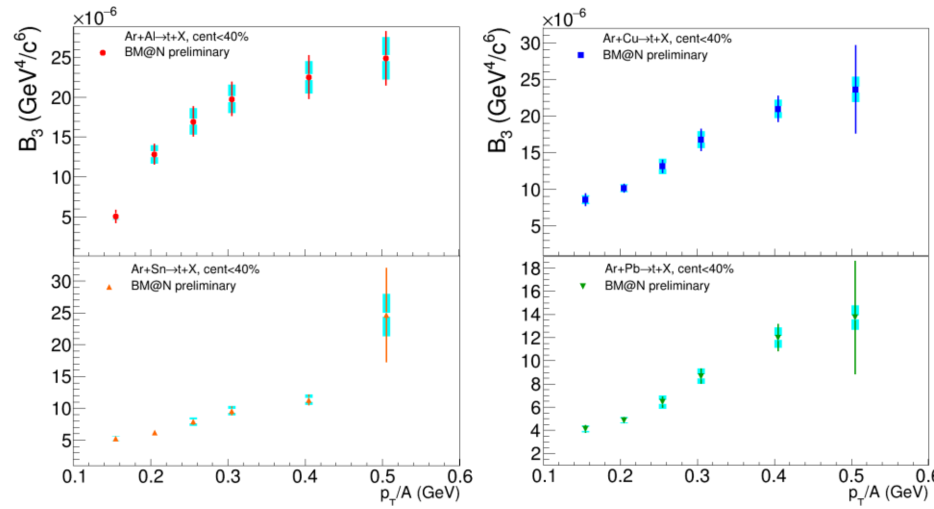
Coalescence parameter B_A depends on the nucleus mass number A, collision system, centrality, energy, and transverse momentum

B_3 for tritons





-0.18 < y* < 0.62
Centrality 0-40%

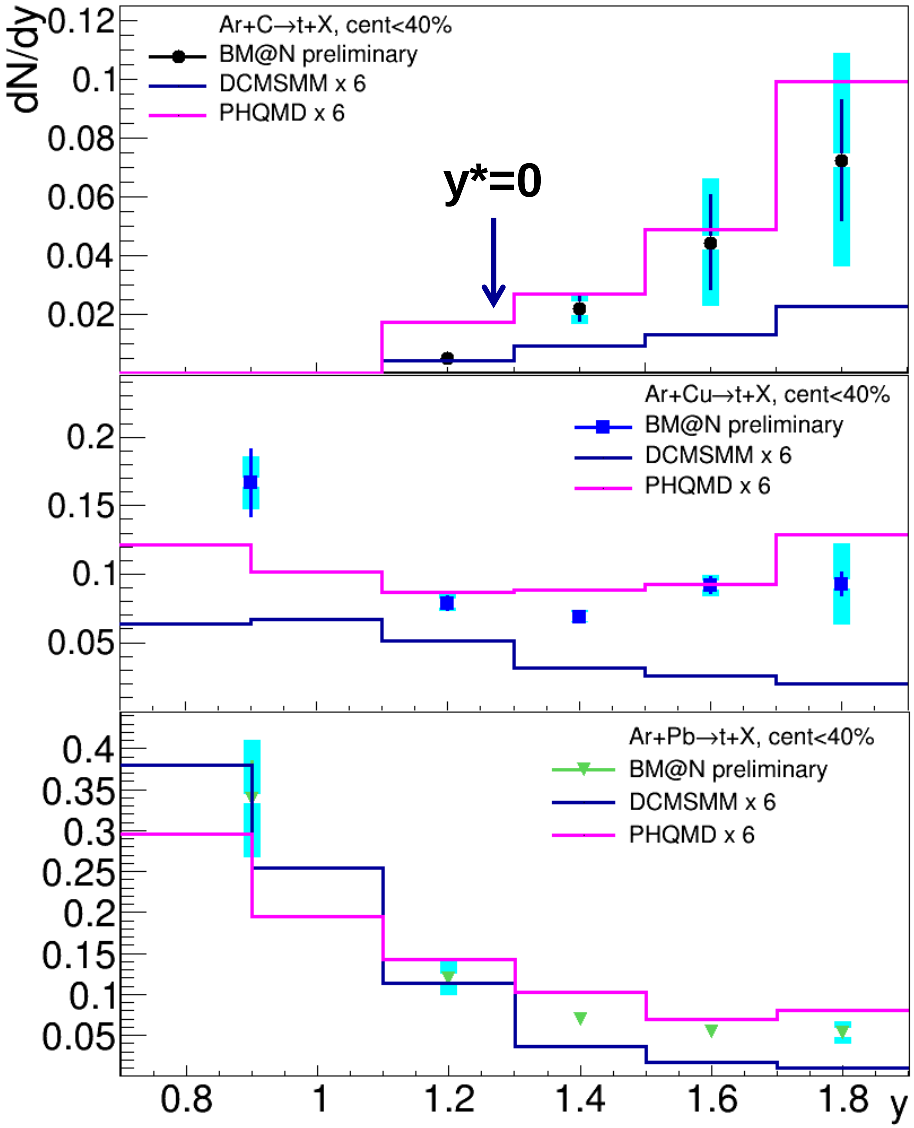


→ B_2 and B_3 rise with $p_T(A)/A$

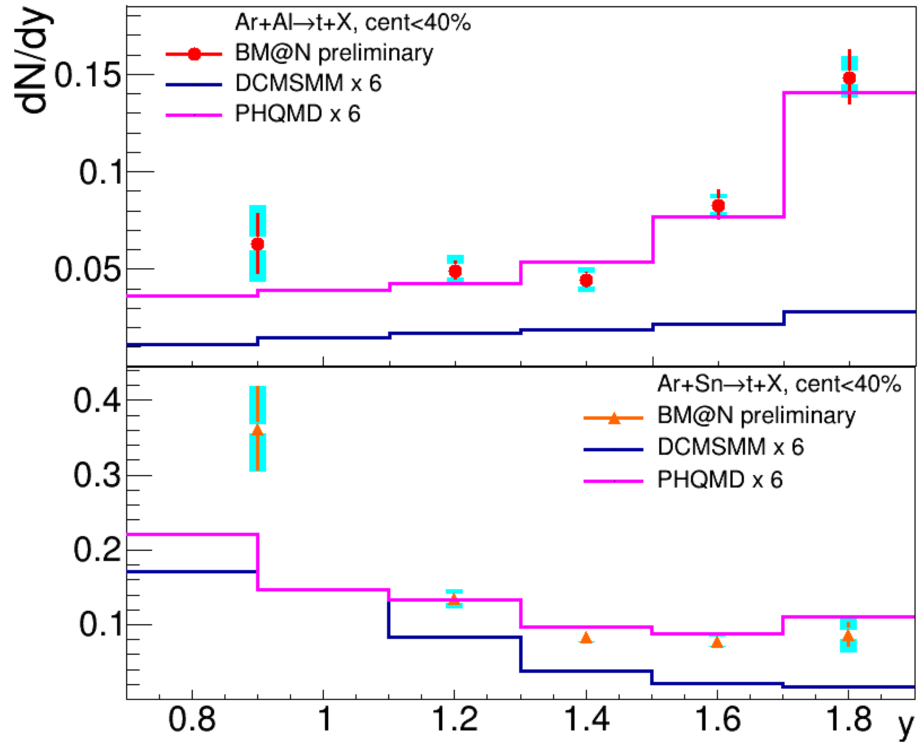
In the coalescence model B_A rises with p_T

$$B_2 = \frac{3\,\pi^{3/2}\,\langle \mathcal{C}_\mathrm{d} \rangle}{2m_t\,\mathcal{R}_\perp^2(m_t)\,\mathcal{R}_\parallel(m_t)}\, e^{2(m_t-m)\left(\frac{1}{T_\mathrm{p}^*}-\frac{1}{T_\mathrm{d}^*}\right)}$$

Tritons: dN/dy dependence on y



Centrality 0-40%



- **PHQMD model better describes data shape than DCM-SMM, but both models are lower in normalization by factor 6**

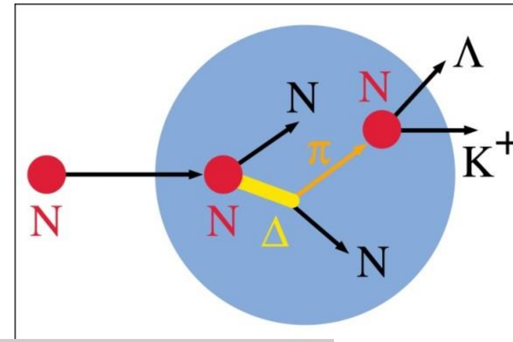
BM@N physics case and observables

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

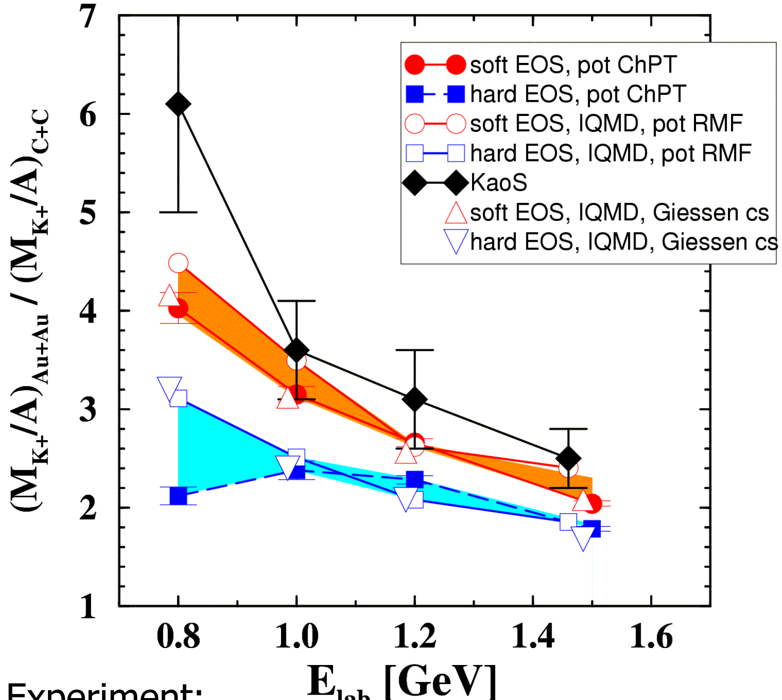
Idea: K^+ yield ∝ density ∝ compressibility

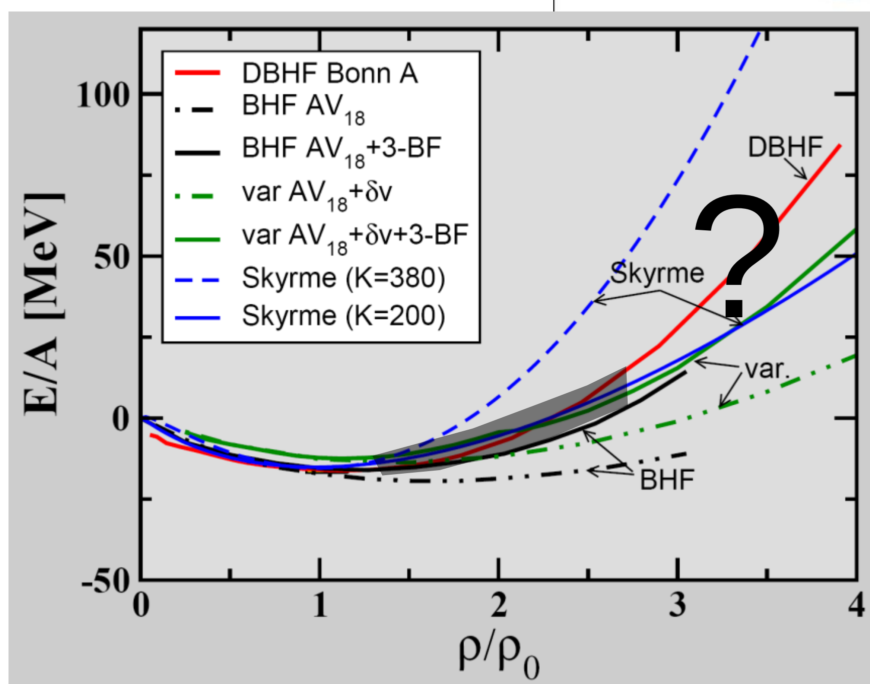


$pp \rightarrow K^+ \Lambda\, p$

(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

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