Baryonic Matter @ Nuclotron: Upgrade and Physics Program Overview

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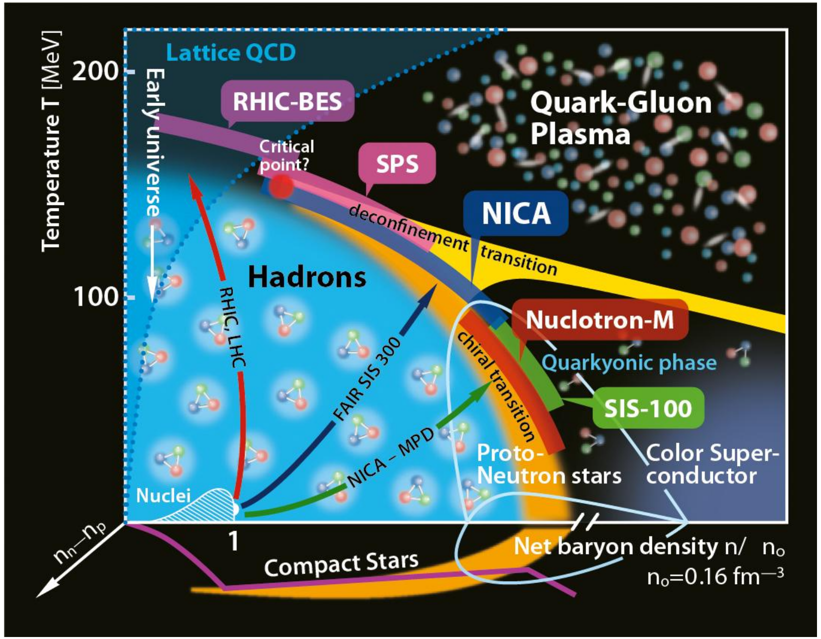
for the BM@N Collaboration

The 6th International Conference on Particle Physics and Astrophysics (ICPPA-2022)
02/12/2022, Moscow, Russia

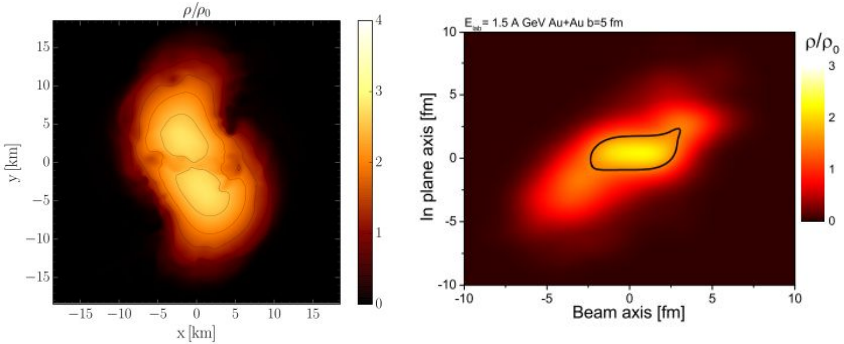
QCD Phase diagram: high baryon density region



Nuclotron energies: $\sqrt{s_{NN}}$= 2.3-3.5 GeV
Achievable Net Baryon densities: ~3-5ρ_0
ρ_0 is nuclear saturation density

The conditions are similar to those in the core of neutron stars

M. Hanauske et al., J. Phys.: Conf. Ser. 878 012031



The energy regime of the Nuclotron will test the region of the possible QCD phase transition

EOS for high baryon density matter

EOS relates the properties of the matter (pressure, temperature, etc.)
The binding energy per nucleus:

$$E_A(\rho,\delta) = \boxed{E_A(\rho,0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$$

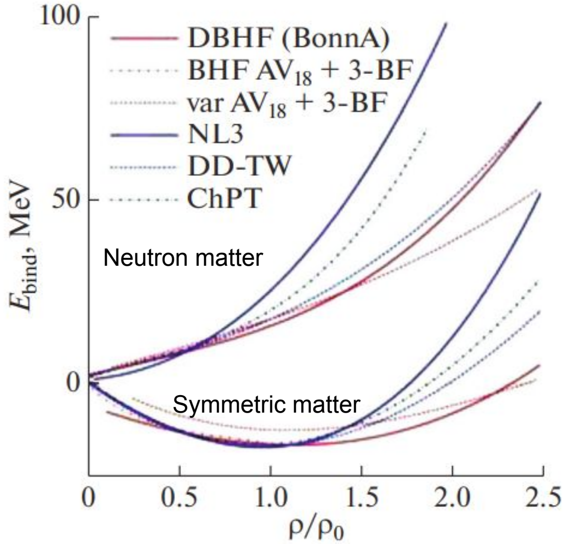
Energy for symmetric system

Symmetry energy

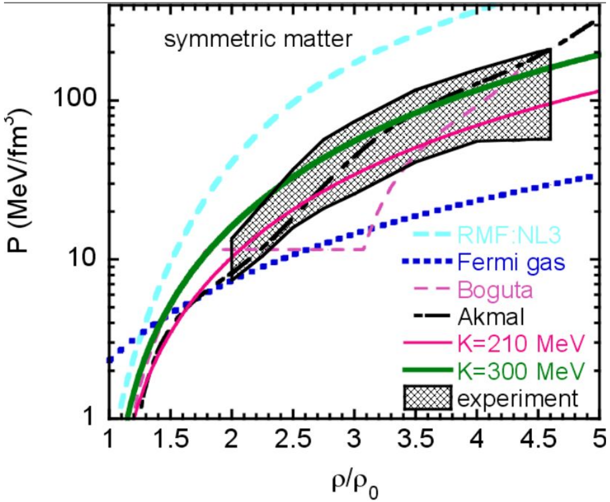
Isospin asymmetry is described as:

$$\delta = (\rho_n - \rho_p)/\rho$$

Observables from heavy ion collision experiments constrain the EOS of dense baryon matter



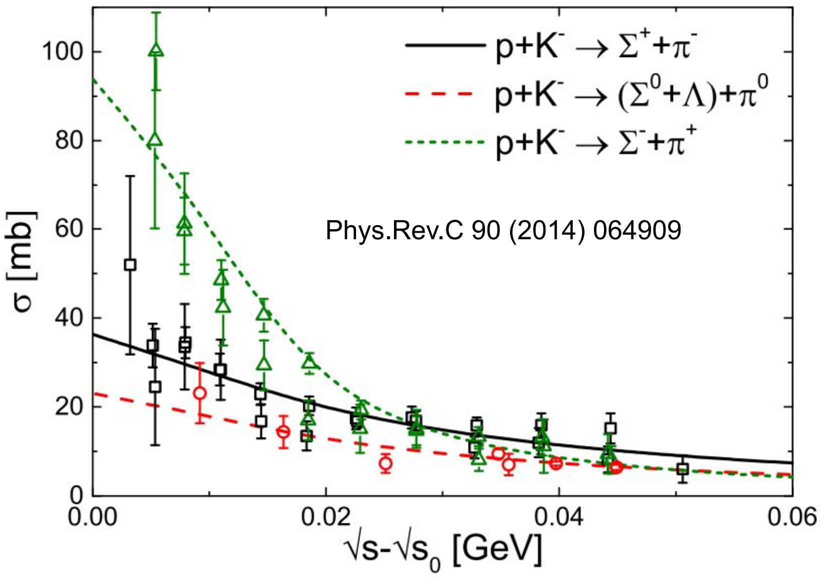
Science 298 (2002) 1592-1596



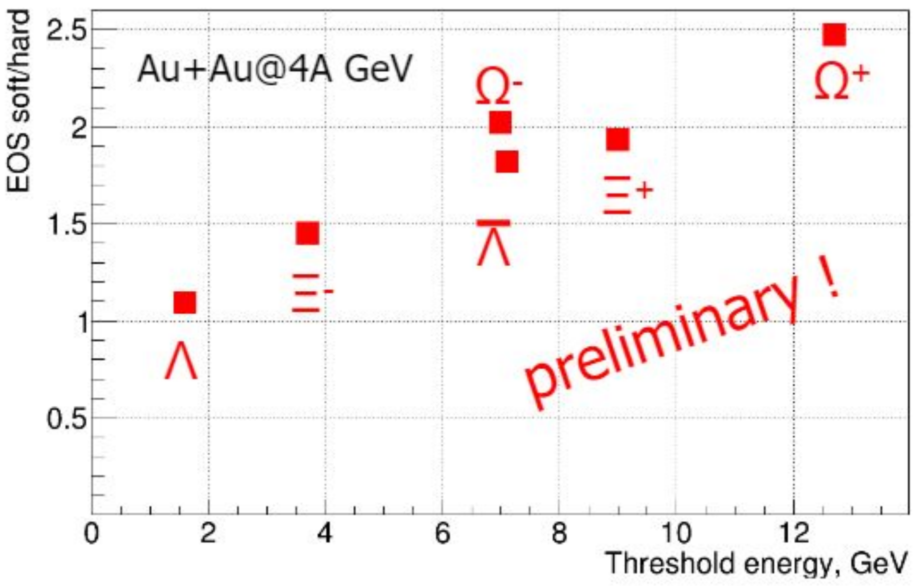
Eur. Phys. J. A 30, 5–21 (2006)

Sub-threshold multi-strange hyperons production

Kaon-nucleon strangeness exchange cross sections in URQMD



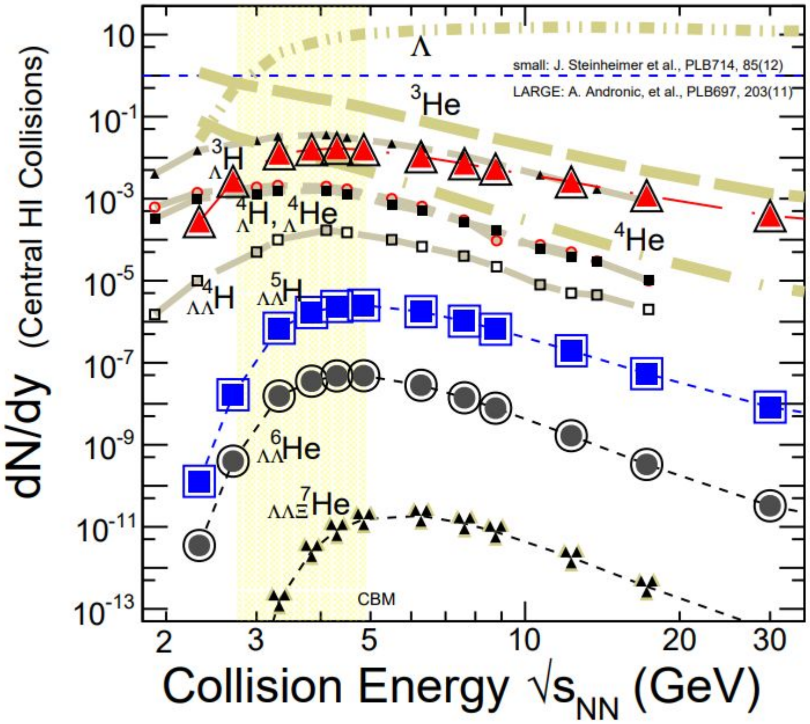
PHQMD: J. Aichelin et al., Phys. Rev. C 101 (2020) 044905

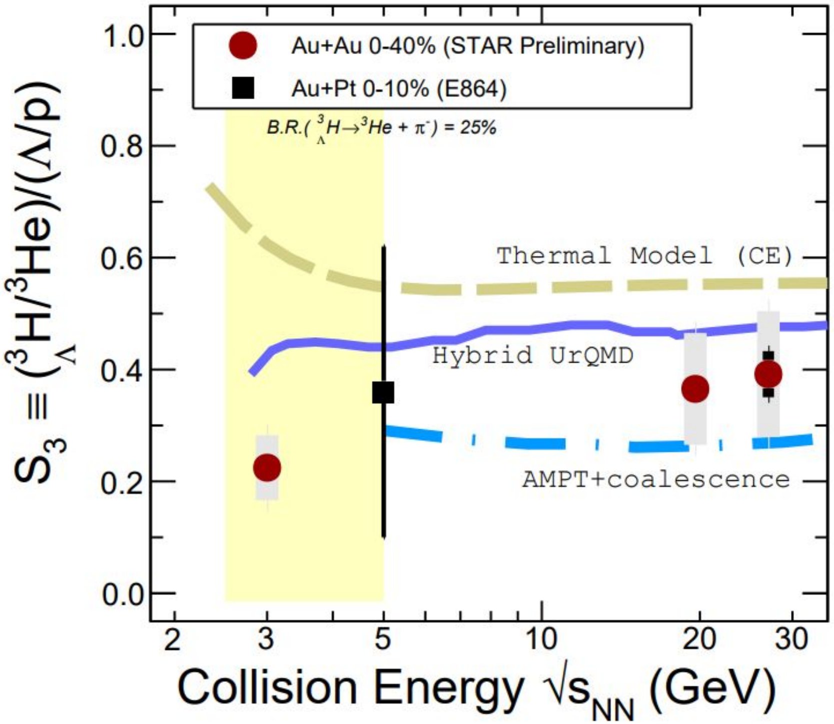


Subthreshold production of multi-strange hyperons is sensitive to the EOS

Hypernuclei production: Y-N interaction

arXiv:2209.05009v1

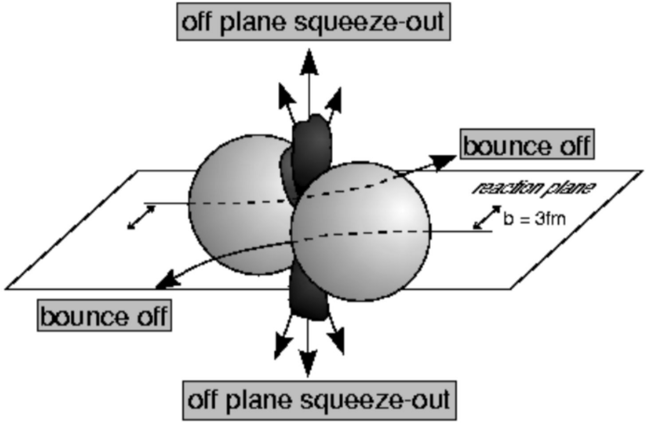




Enhanced yield of hypernuclei is expected at the beam energies of BM@N

Studying the Y-N interactions may help to establish the properties of dense matter

Sensitivity of the collective flow to the EOS



Azimuthal distribution of produced particles with respect to RP:

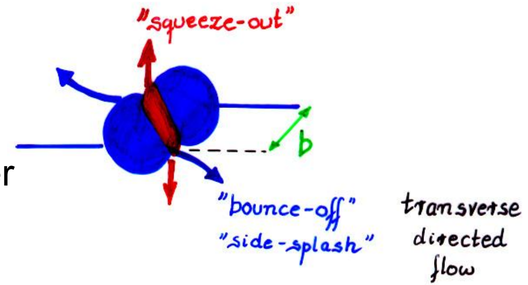
$$\rho(\varphi - \Psi_{RP}) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_{RP})\right)$$

Coefficients of the decomprosition are refered to as collective flow

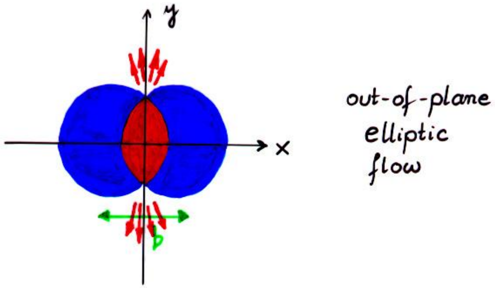
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right]\rangle$$

v_1 is called directed and v_2 is called elliptic flow

Bounce-off



Squeeze-out

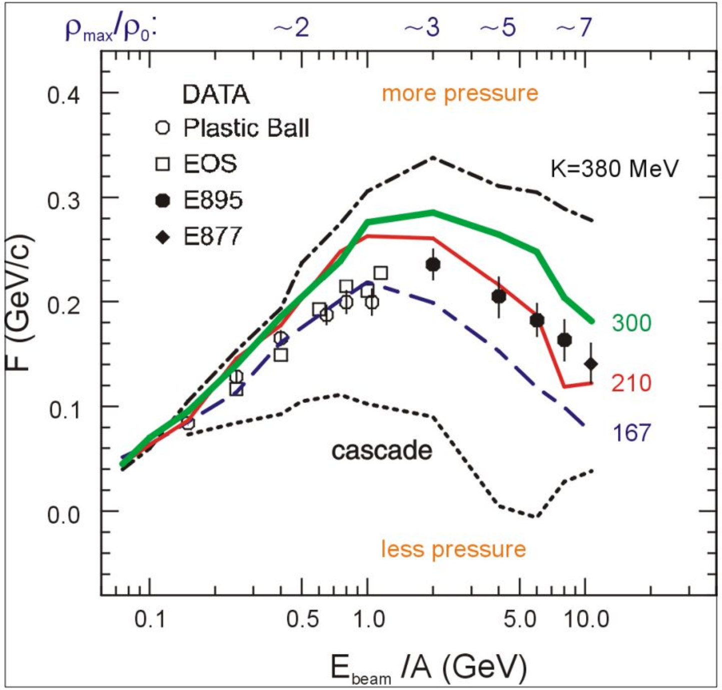


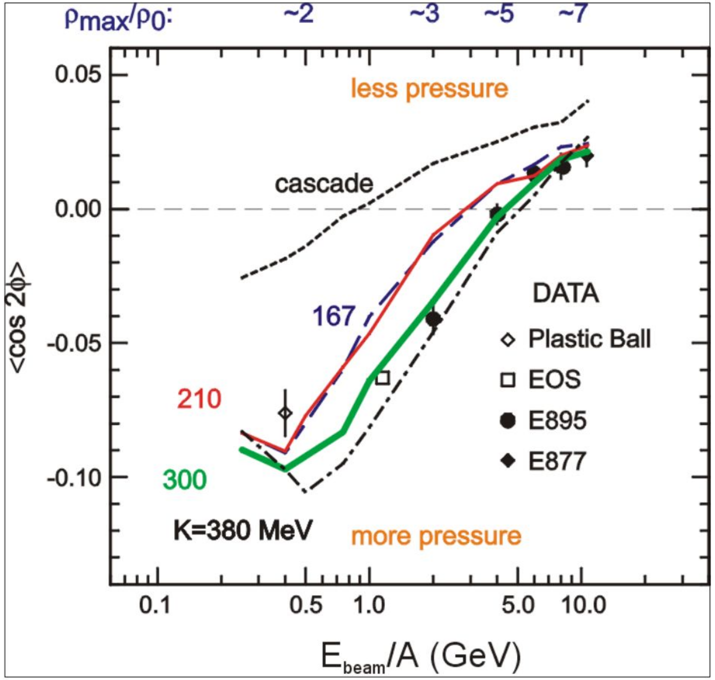
Collective flow is sensitive to:

- Compressibility of the created in the collision matter
- Time of the interaction between the matter within the overlap region and spectators

Interpretation of the previous flow data

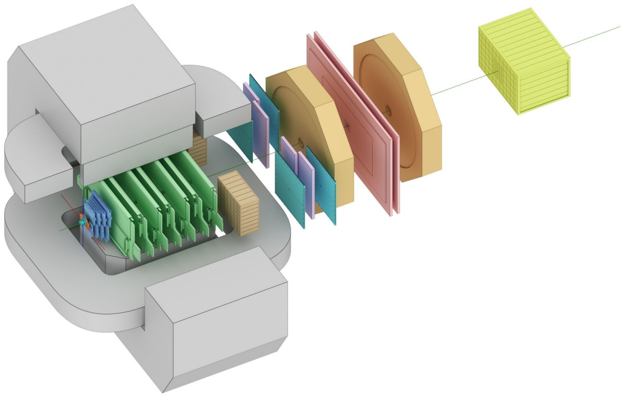
P. DANIELEWICZ, R. LACEY, W. LYNCH
10.1126/science.1078070

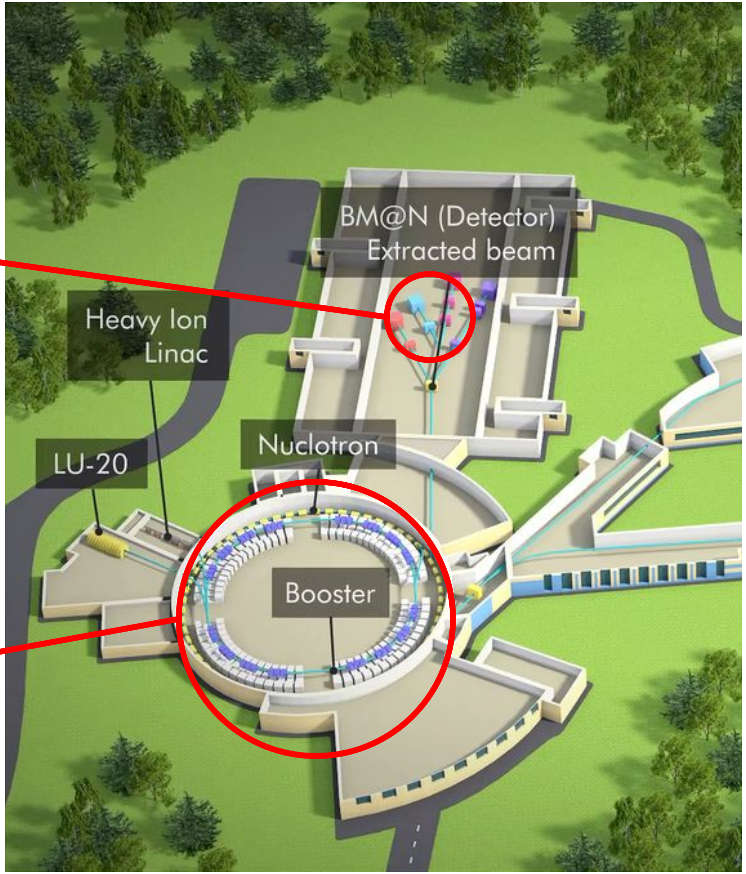




- The flow data from E895 experiment have ambiguous interpretation: v_1 suggests hard EOS while v_2 corresponds to soft EOS
  - Additional measurements are essential to clarify the previous measurements

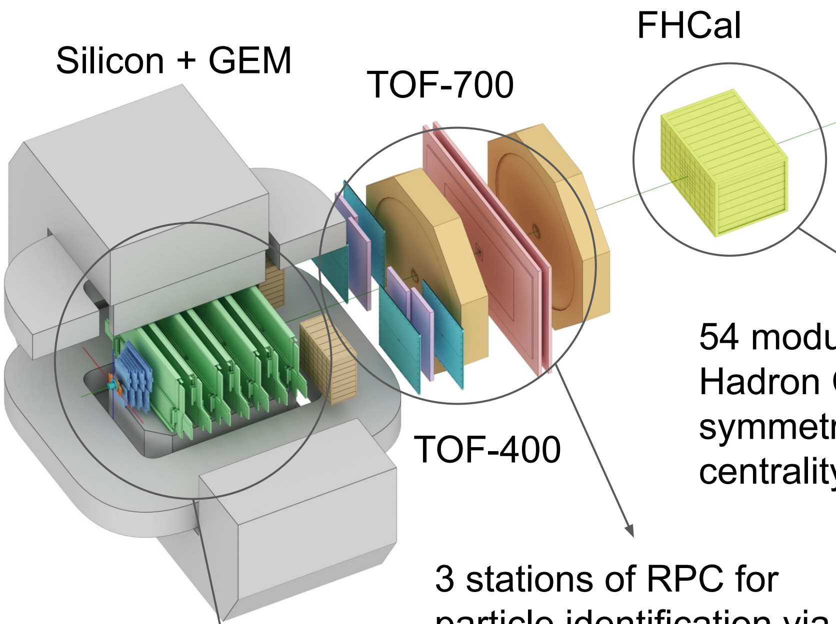
Nuclotron ion accelerator facility JINR, Dubna





- Various Collision systems
- $\sqrt{s_{NN}}$=2.3-3.5A GeV
- Upcoming high statistics Xe+CsI run

The BM@N experiment (JINR, Dubna)

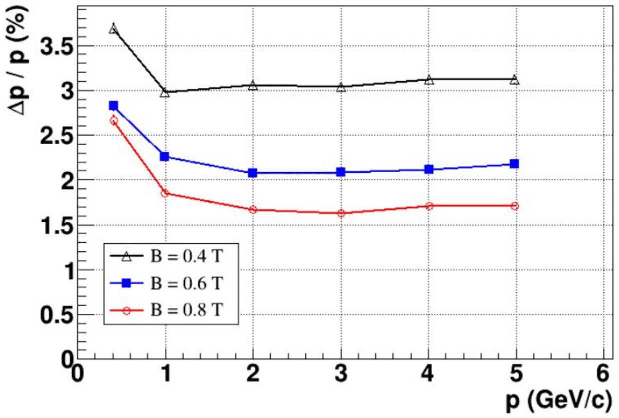


54 modules of Forward Hadron Calorimeter for symmetry plane and centrality

3 stations of RPC for particle identification via TOF method

4 silicon stations + 7 GEM stations within magnetic field for charged particles trajectories reconstruction
(see talk of A. Galavanov)

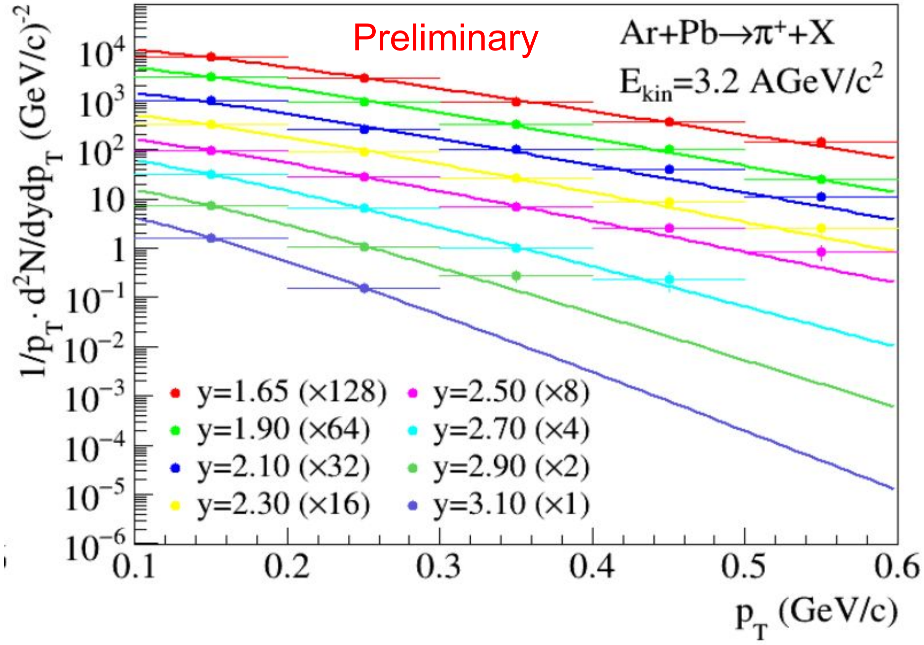
Momentum resolution

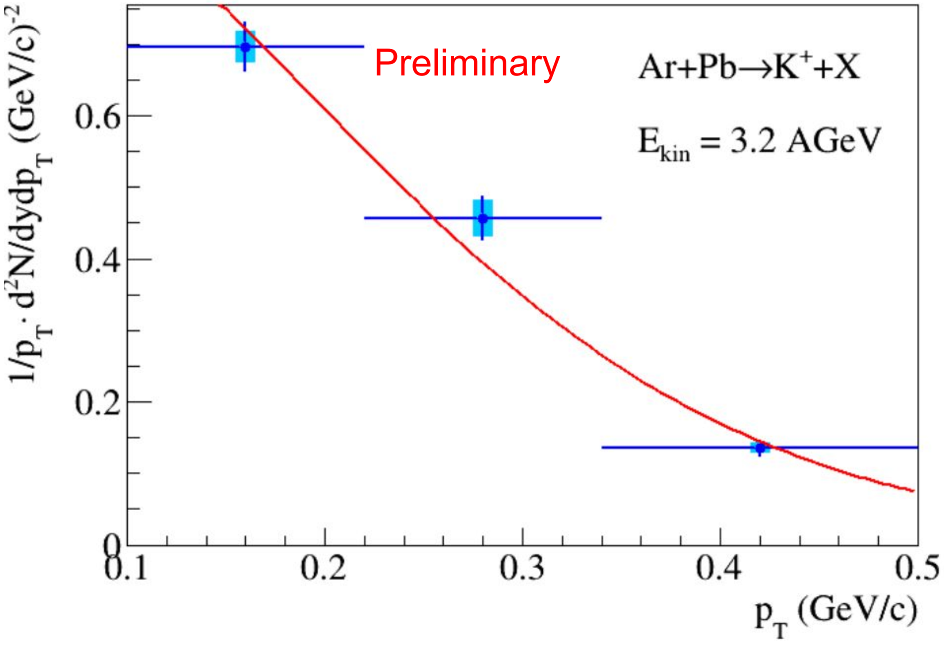


Nuclotron beam:

- from p to Au
- heavy ion energy 1- 3.8 GeV/n
- Au intensity ~ few 10^6 Hz

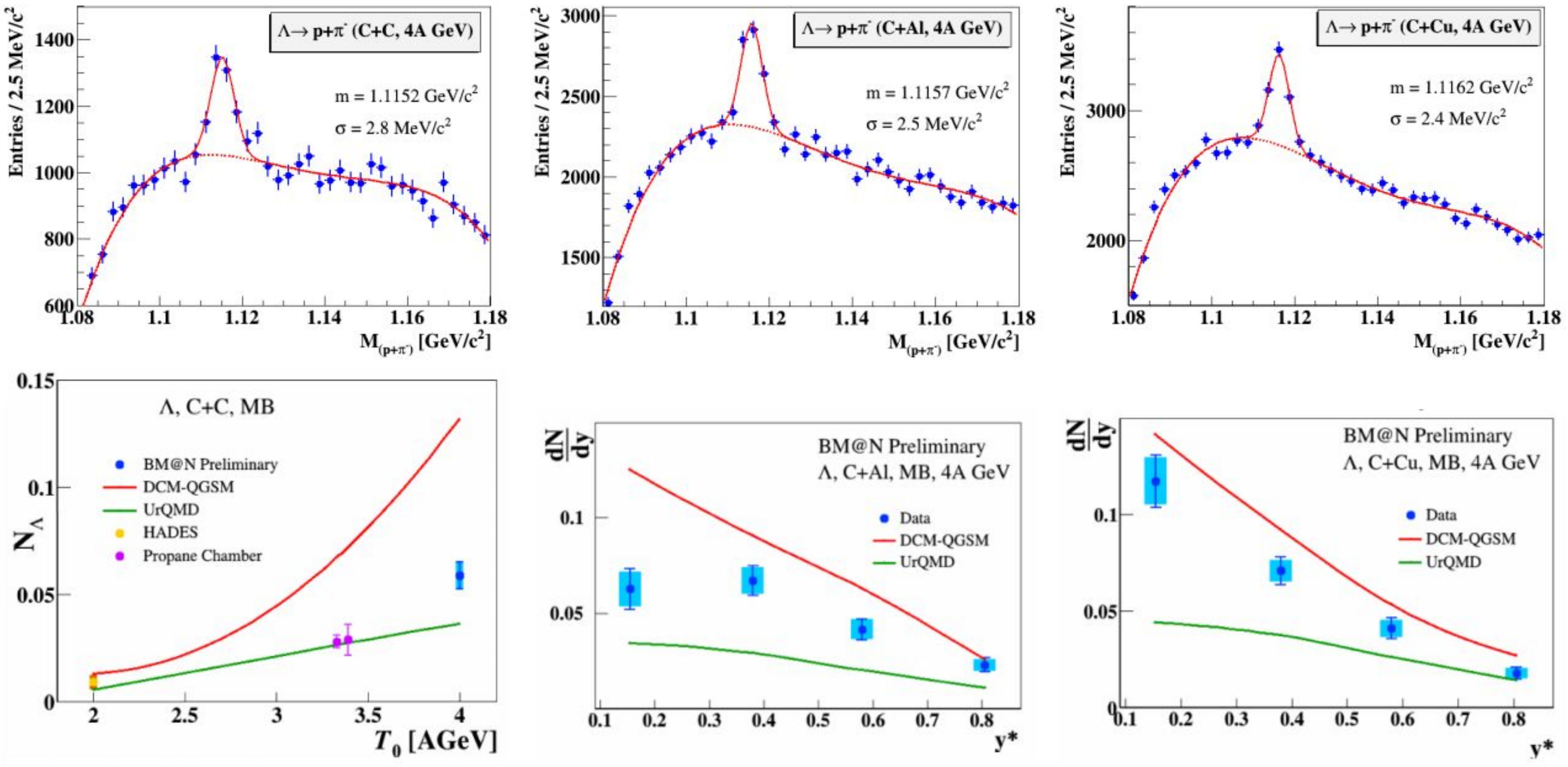
Light meson yield in technical run





BM@N is capable of extracting the yield of light mesons such as π, K

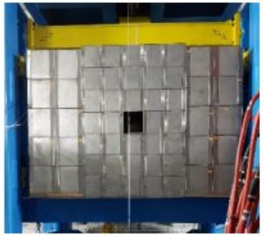
Hyperon extraction performance in technical run

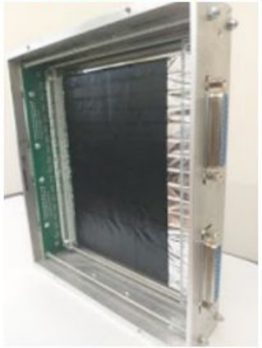


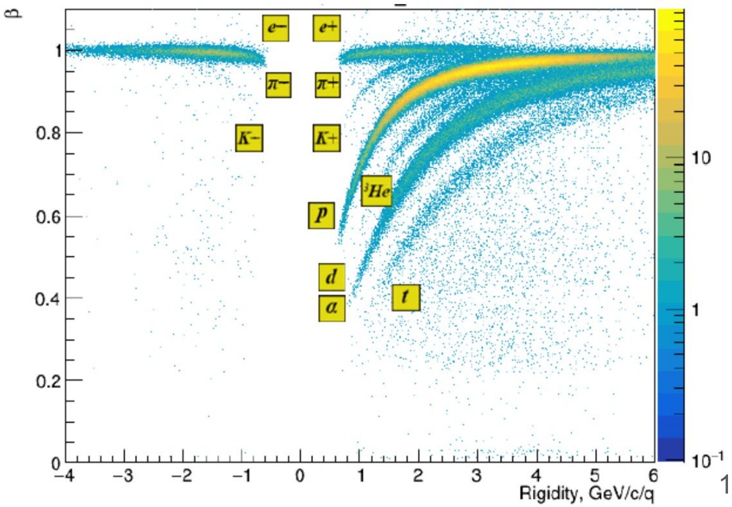
BM@N is capable of measuring the produced hyperons

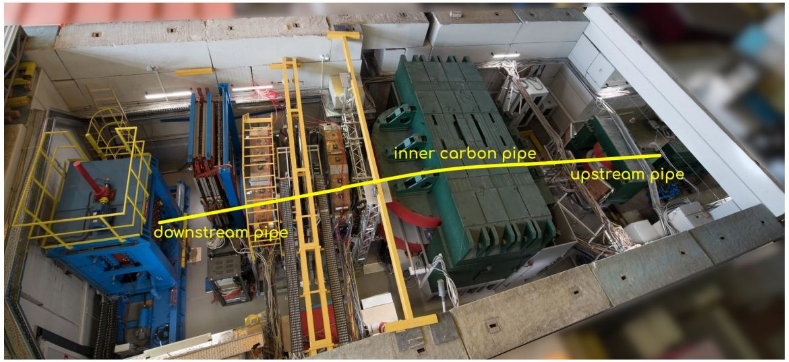
BM@N upgrade for the upcoming physical run

- The tracking system have been upgraded to cover the full available acceptance
- Scincilator wall and Silicon Hodoscope were added to the setup
- Beam pipe with vacuum up to 10^-5 Torr.



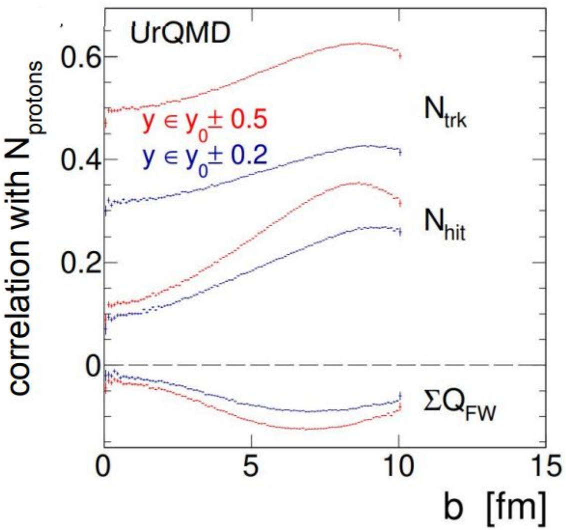


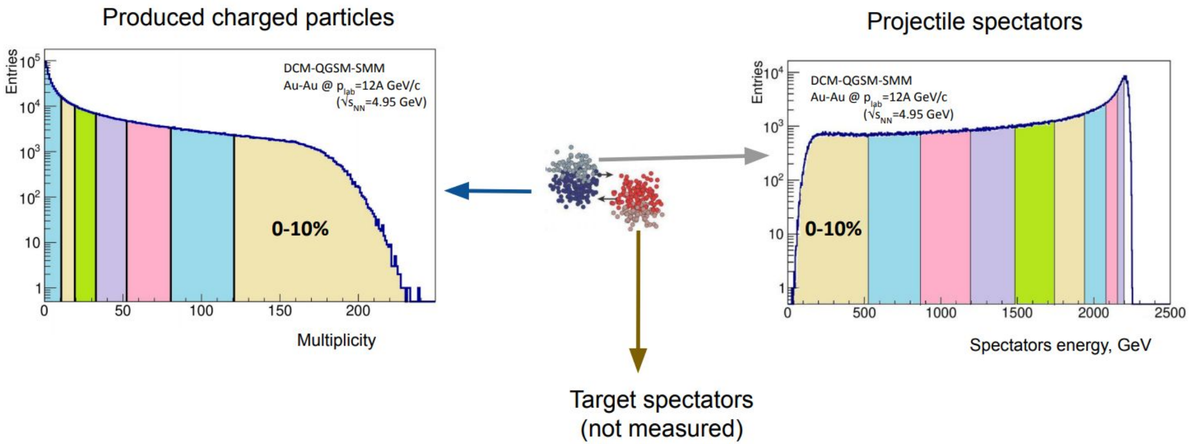




Independent centrality estimation sources

HADES; Phys.Rev.C 102 (2020) 2, 024914



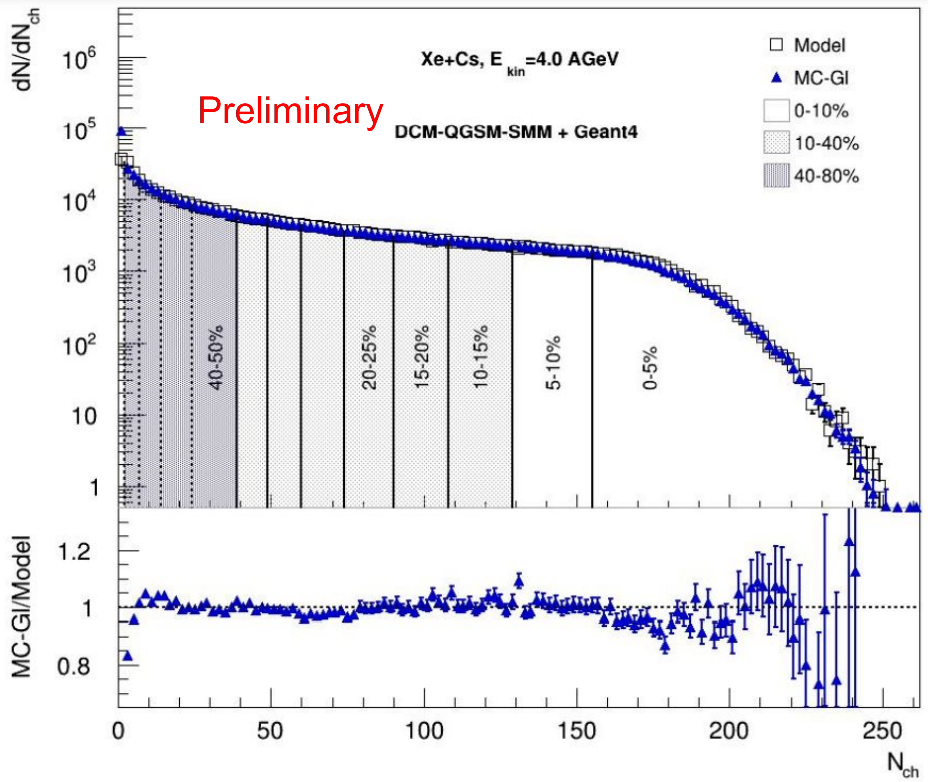


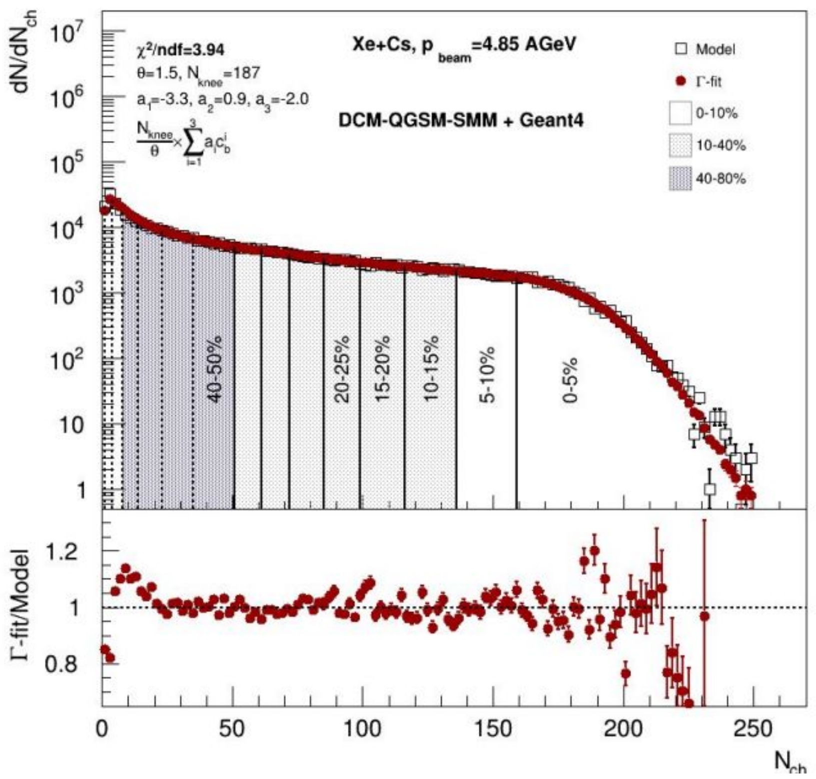
Projectile spectators can be utilized to estimate centrality independently to the multiplicity of the produced particles thus avoiding possible autocorrelations

A number of produced protons is stronger correlated with the number of produced particles (track & RPC+TOF hits) than with the total charge of spectator fragments (FW)

Centrality determination at BM@N

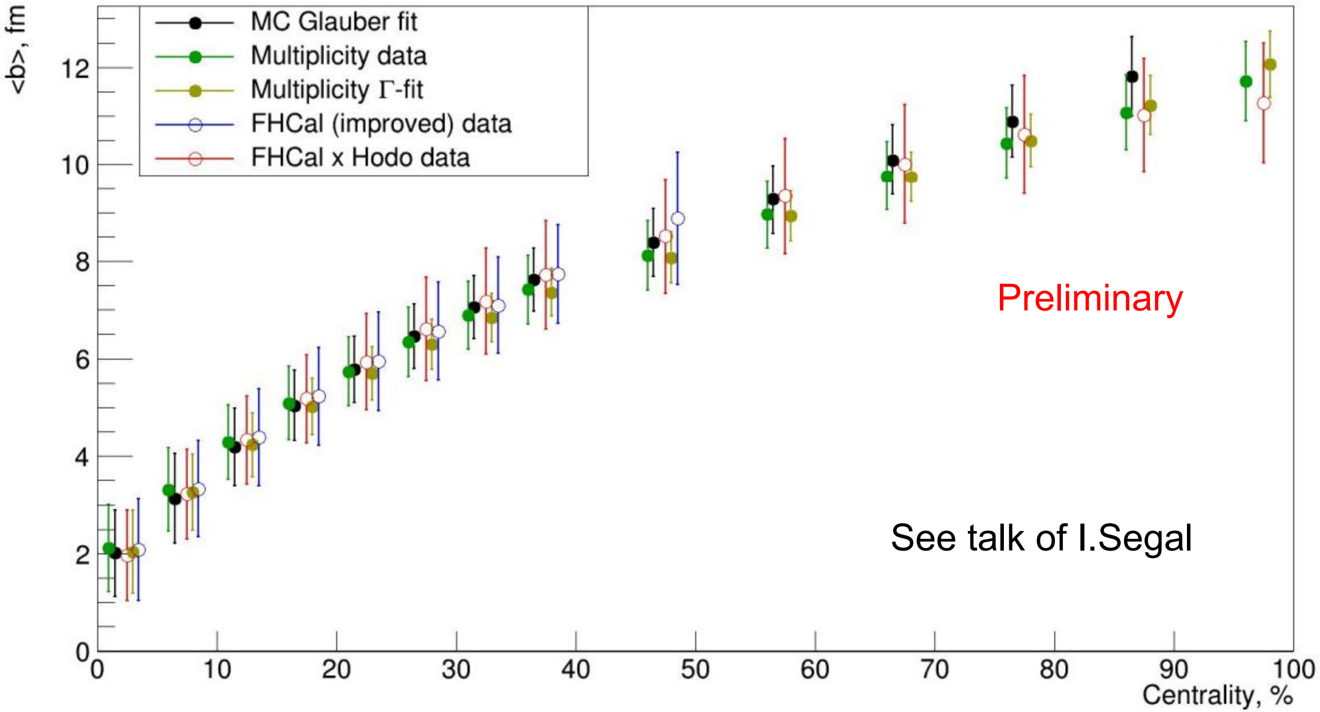
I. Segal and D. Idrisov





- Fit results are good both for MC-Glauber and Inverse Γ-fit methods
- Impact parameter distributions in centrality classes are well-reproduced

Comparison of different estimators and methods



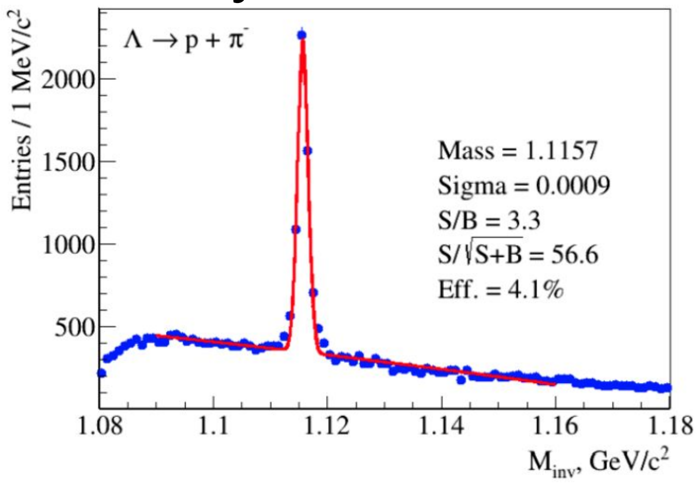
- Impact parameter distributions in different centrality classes are similar for different centrality classes
- The distributions for spectators energy are wider because of the width of b and energy correlation

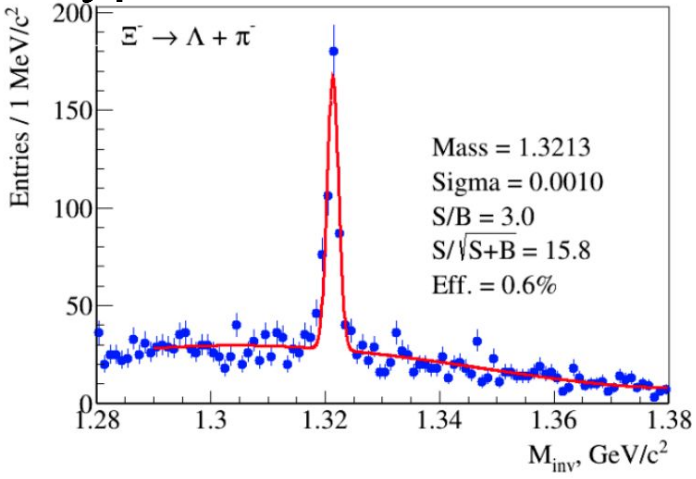
Comparison of the HADES, STAR FXT and BM@N data

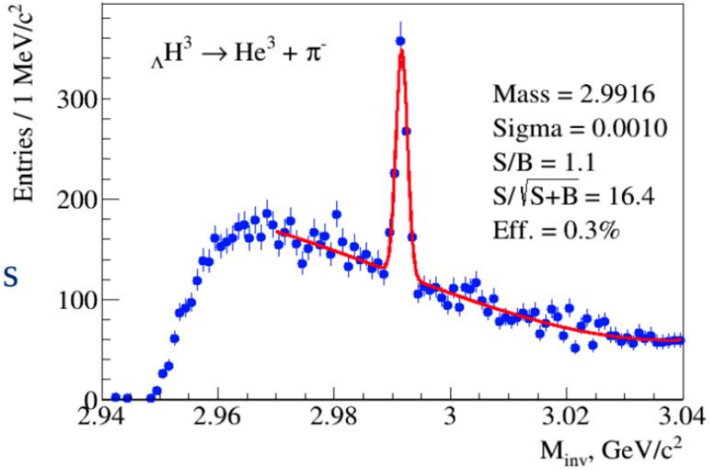
Exp.	year	A+A	E_{kin} AGeV	Statistics	Ξ^-	Ω^-	Hypernuclei
HADES	2012	Au+Au	1.23	$7 \cdot 10^9$	✗	✗	✗
HADES	2019	Ag+Ag	1.58	$1.4 \cdot 10^{10}$	✗	✗	$800\ ^3_\Lambda$H
STAR FxT	2018	Au+Au	2.9	$3 \cdot 10^8$	10^4	✗	$10^4\ ^3_\Lambda$H $6 \cdot 10^3\ ^4_\Lambda$H
STAR FxT	2021	Au+Au	2.9	$2 \cdot 10^9$	$7 \cdot 10^4$	✗	$7 \cdot 10^4\ ^3_\Lambda$H $4 \cdot 10^4\ ^4_\Lambda$H
BM@N full program	sim.	Au+Au	3.8	$2 \cdot 10^{10}$	$5 \cdot 10^6$	10^5	$10^6\ ^3_\Lambda$H $^4_\Lambda$H, $^5_\Lambda$He $^7_\Lambda$Li, $^7_\Lambda$He $10^2\ ^5_{\Lambda\Lambda}$H

- HADES and BM@N data are complementary science HADES lacks the Ω and Ξ hyperons
- Hypernuclei statistics at BM@N is expected to be ~100 times higher

Feasibility studies towards hyperon reconstruction





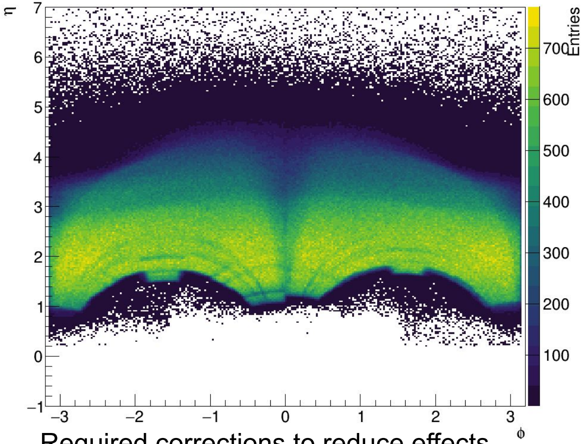


S

- High statistics will enable for multidifferential measurements of (multi-) strange particles and hypernuclei
- Colliding different system may shed light on the mechanisms of strangeness production in the region of large baryon densities

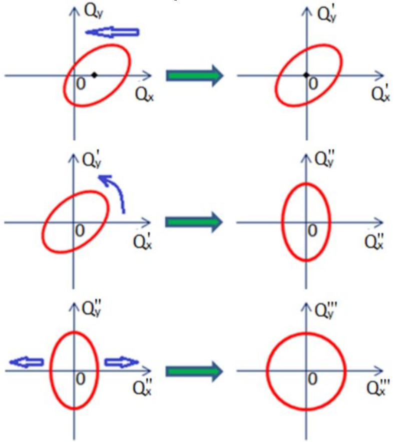
Azimuthal acceptance of the BM@N experiment

φ-η yield of protons

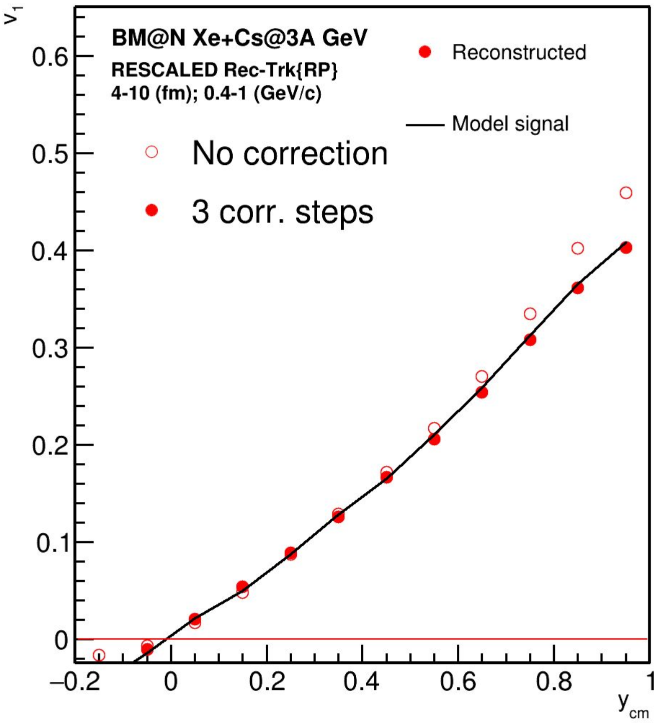


Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

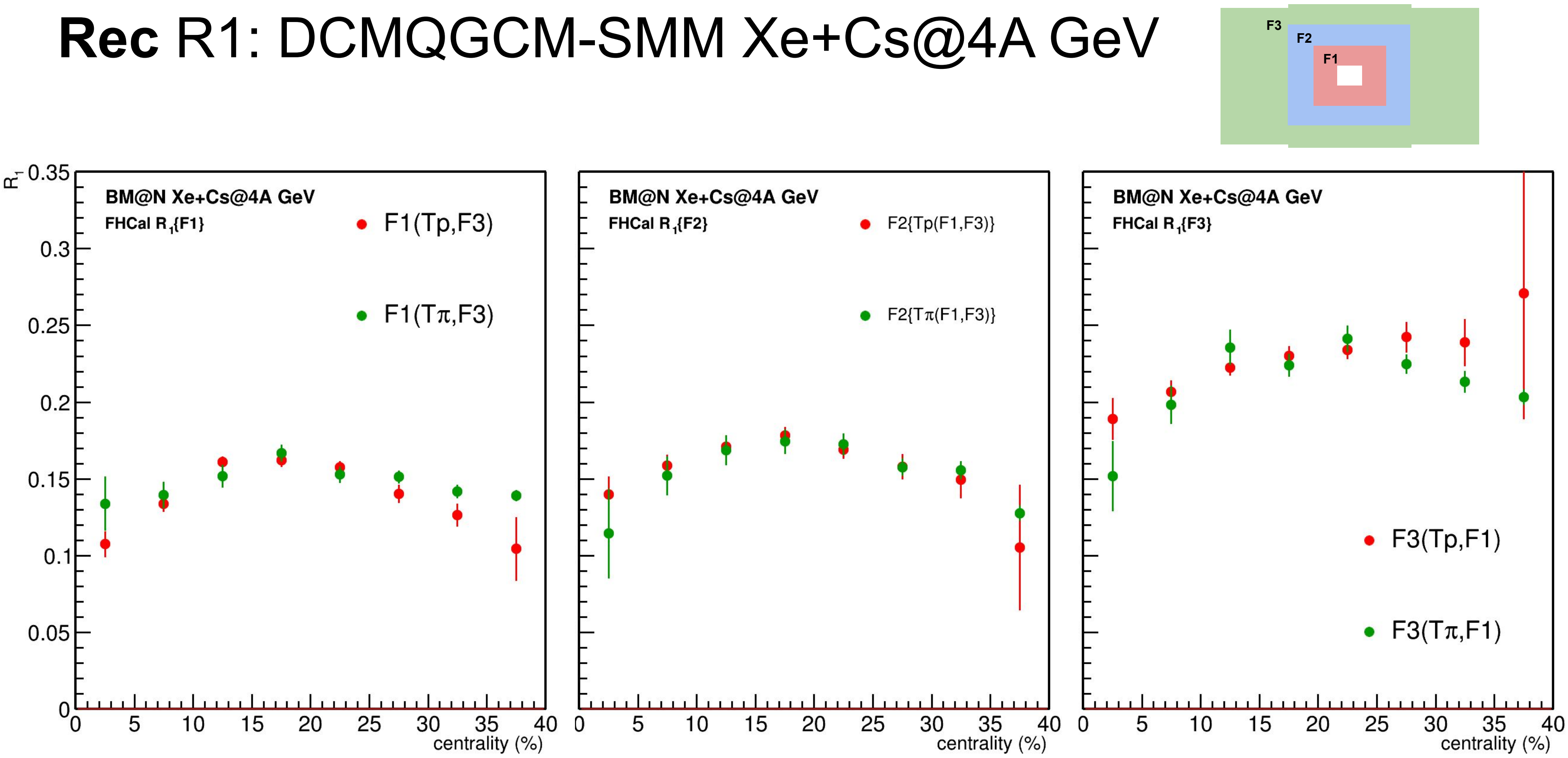


Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



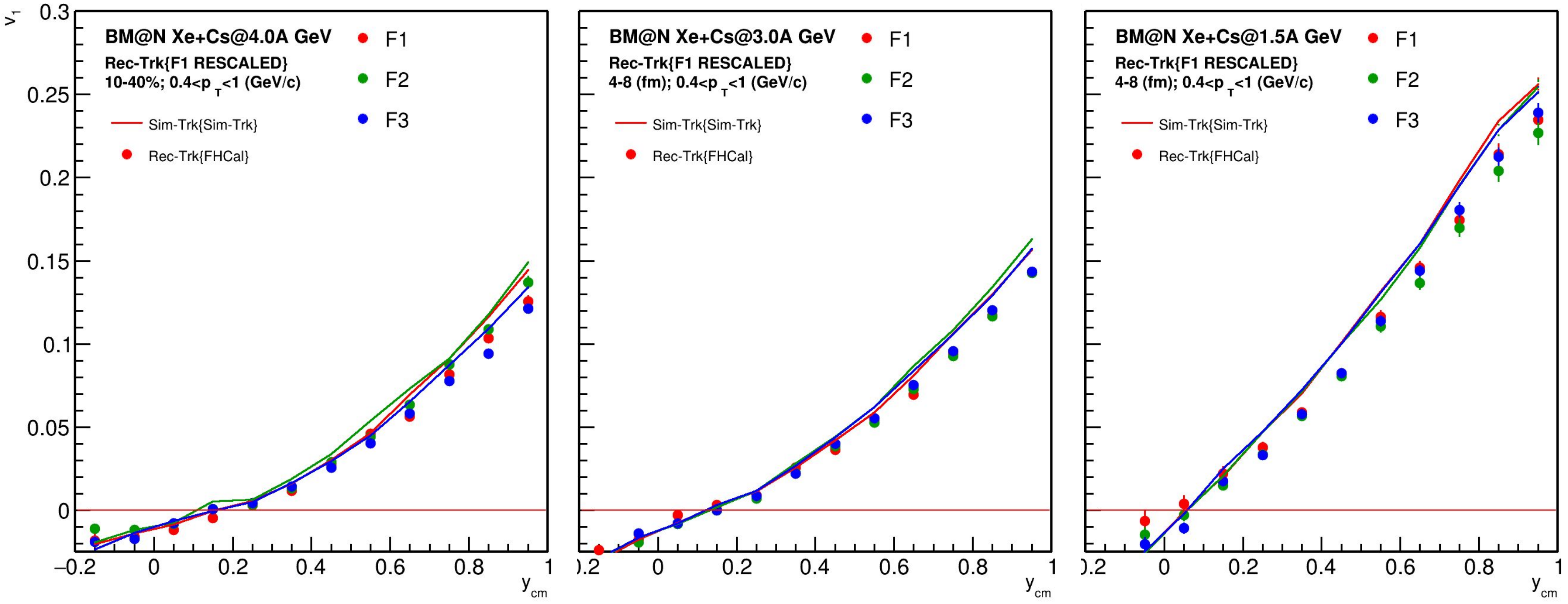
Better agreement after rescaling

Rec R1: DCMQGCM-SMM Xe+Cs@4A GeV



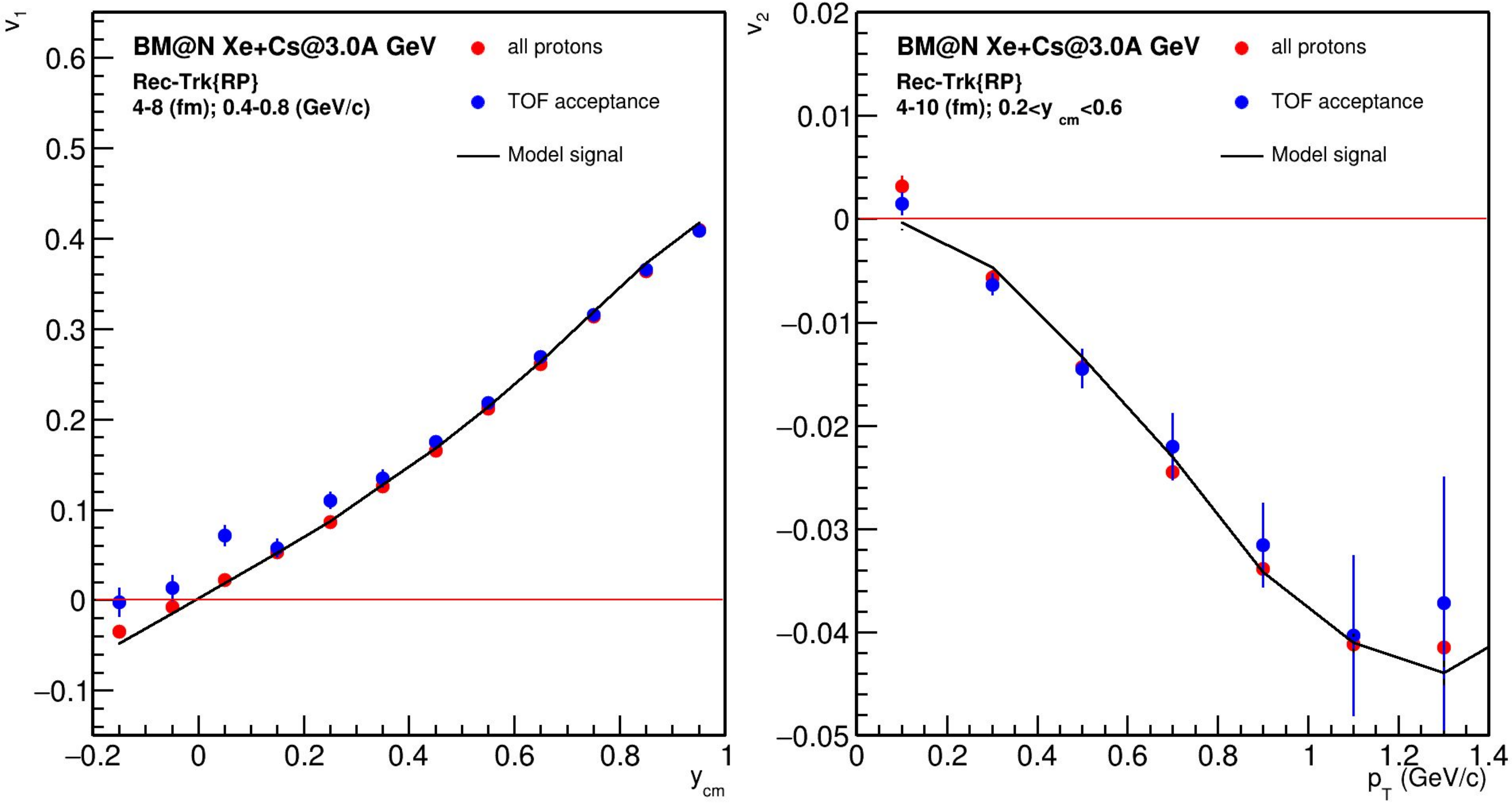
Using the additional sub-events from tracking provides a robust combination to calculate resolution

v_1: DCMQGCM-SMM Xe+Cs



Reasonable agreement between model and reconstructed data

Directed and elliptic flow in Xe+Cs@3A GeV (JAM)



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

Summary

The upgraded BM@N experiment offers the opportunity to explore nuclear matter at neutron star core densities in heavy-ion collisions at energies of up to 4A GeV. And study the EOS for high-density symmetric matter:

- Collective flow of protons and light fragments in A+A collisions
- Yields of multi-strange (anti-) hyperons from A+A collisions
- Role of hyperons in neutron stars (ΛN and ΛNN interaction): hypernuclei

BM@N already recorded experimental data from a set of technical runs (carbon, argon-krypton). Physics analysis of data is in its active phase, results expected to be published.

Preparation for next experimental runs (detector construction, physics feasibility study according to the BM@N physics program ...) is ongoing.