Heavy ion collisions

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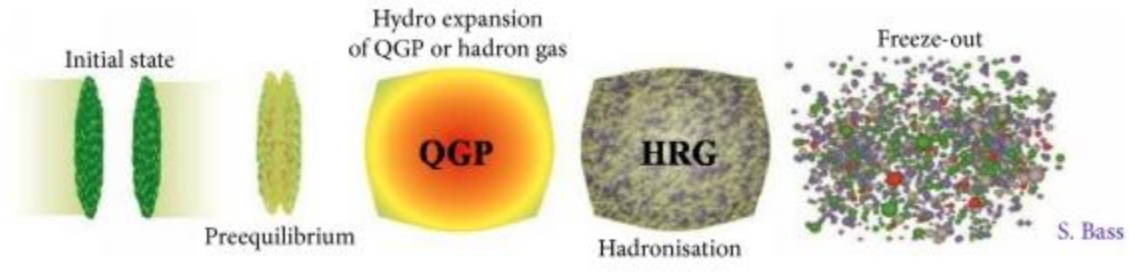
18/04/2024, Moscow, Russia

Why heavy ion collisions are of a great importance?



Within the overlap region the strongly interacting matter is produced

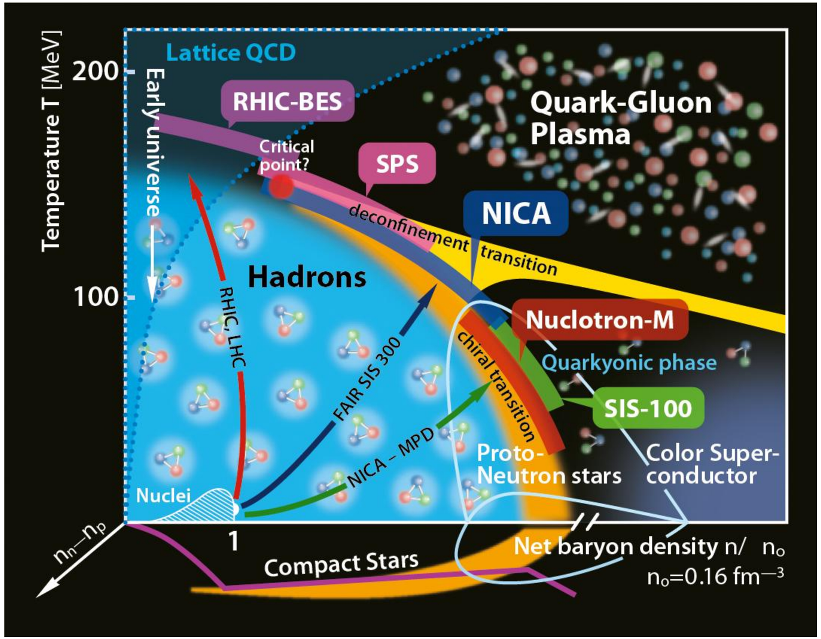
↓

Establishing the properties of the matter

↓

Linking to the astrophysical objects

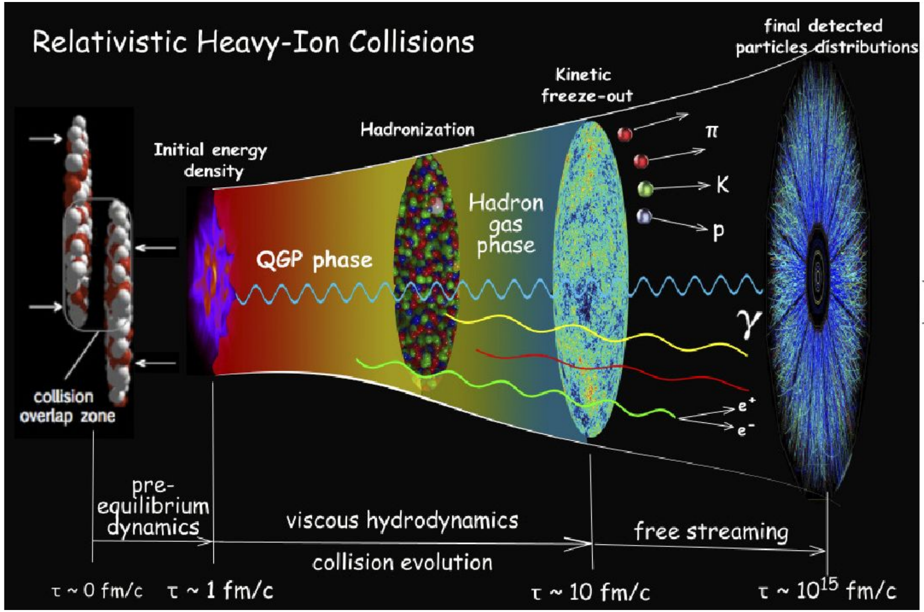
QCD Phase diagram: high baryon density region

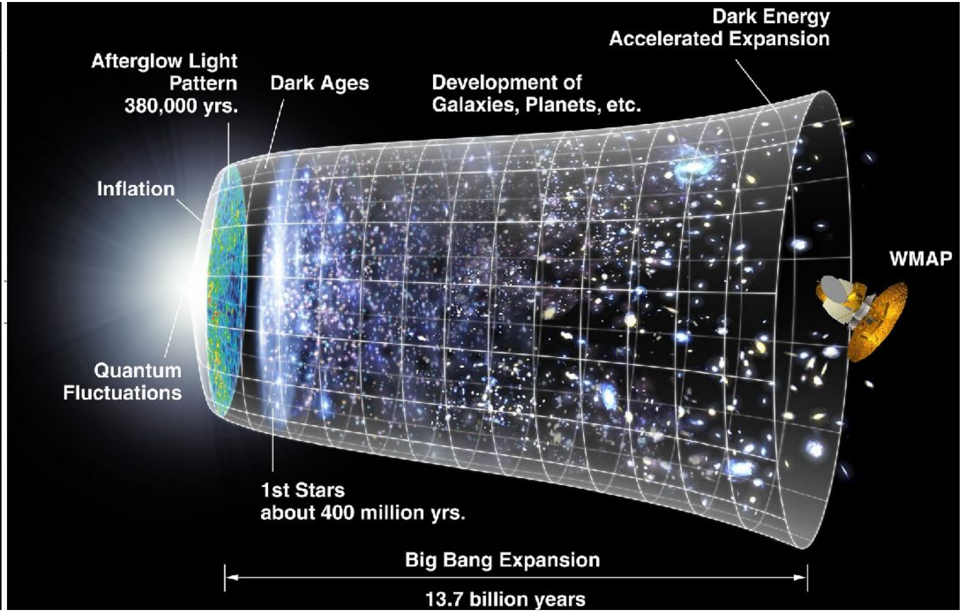


- Large Hadron Collider (LHC)
  - $\sqrt{s_{NN}}$ ~ 5 TeV
- Relativistic Heavy Ion Collider (RHIC)
  - $\sqrt{s_{NN}}$ ~ 3 - 200 GeV
- SIS-18
  - $\sqrt{s_{NN}}$ ~ 2.5 GeV
- Nuclotron
  - $\sqrt{s_{NN}}$ ~ 2-4 GeV

Varying the energy of the collision one can achieve different properties of strongly interacting matter

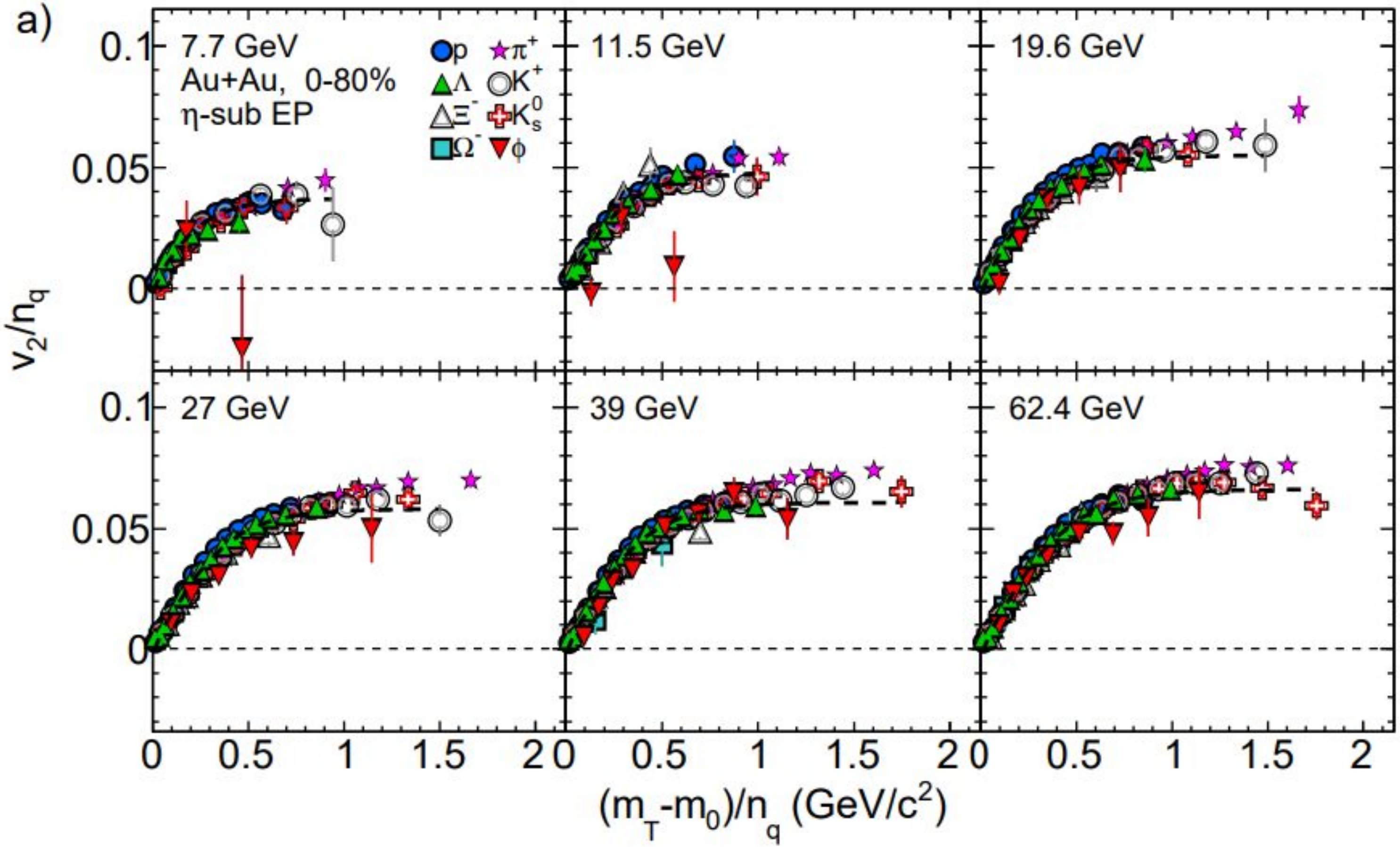
High energy heavy ion collisions





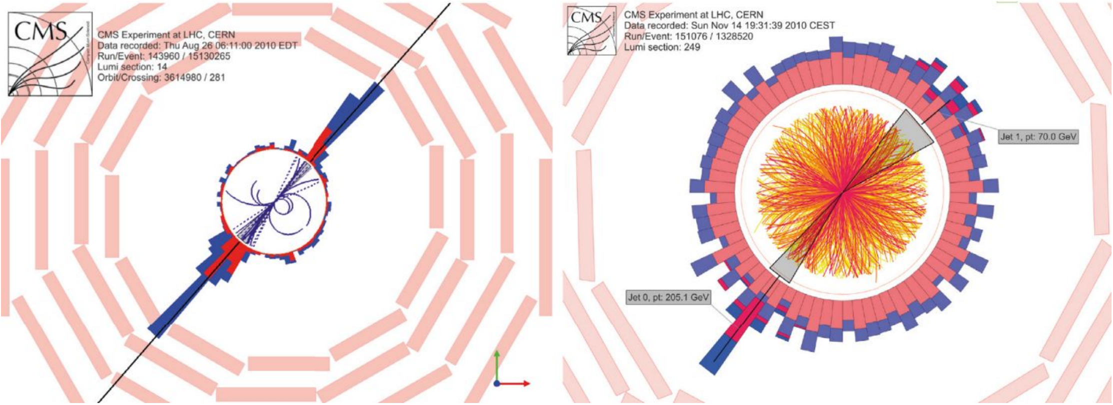
In heavy ion collisions the conditions achieved similar to the early universe: μ_B~0, T~150 Mev

Quark deconfinement in higher energy collisions

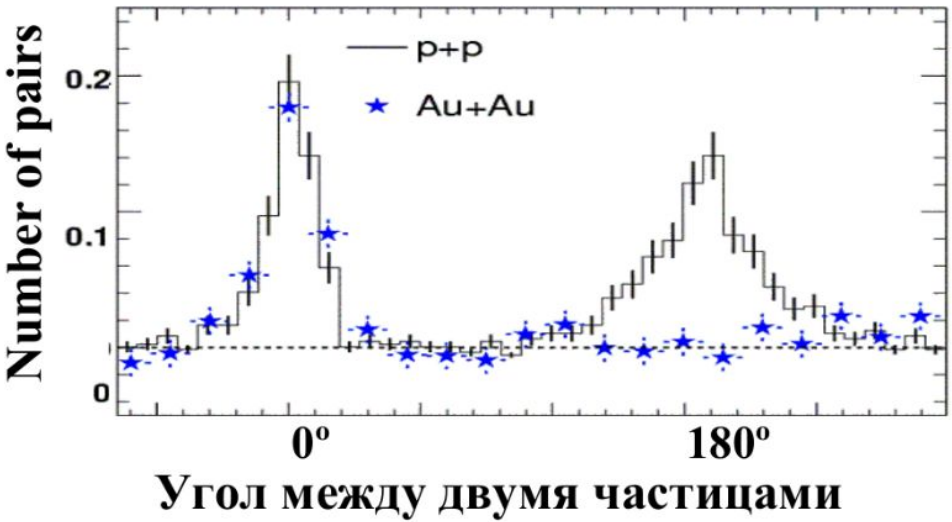


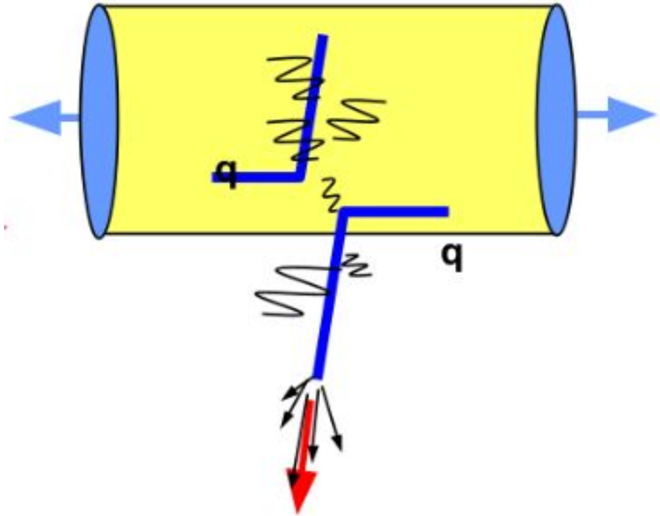
Number of quark scaling suggests that free quarks started to fly-out of the overlap region

Suggested properties of the Quark-Gluon Matter



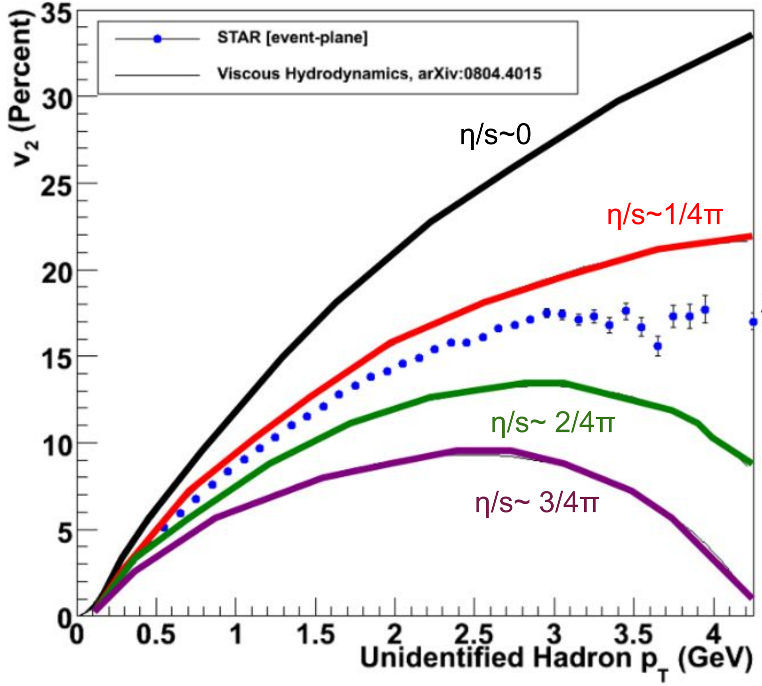
- In p-p collisions two produced particles fly back-to-back
- In A+A collisions the second jet is suppressed by the medium of strongly interacting matter

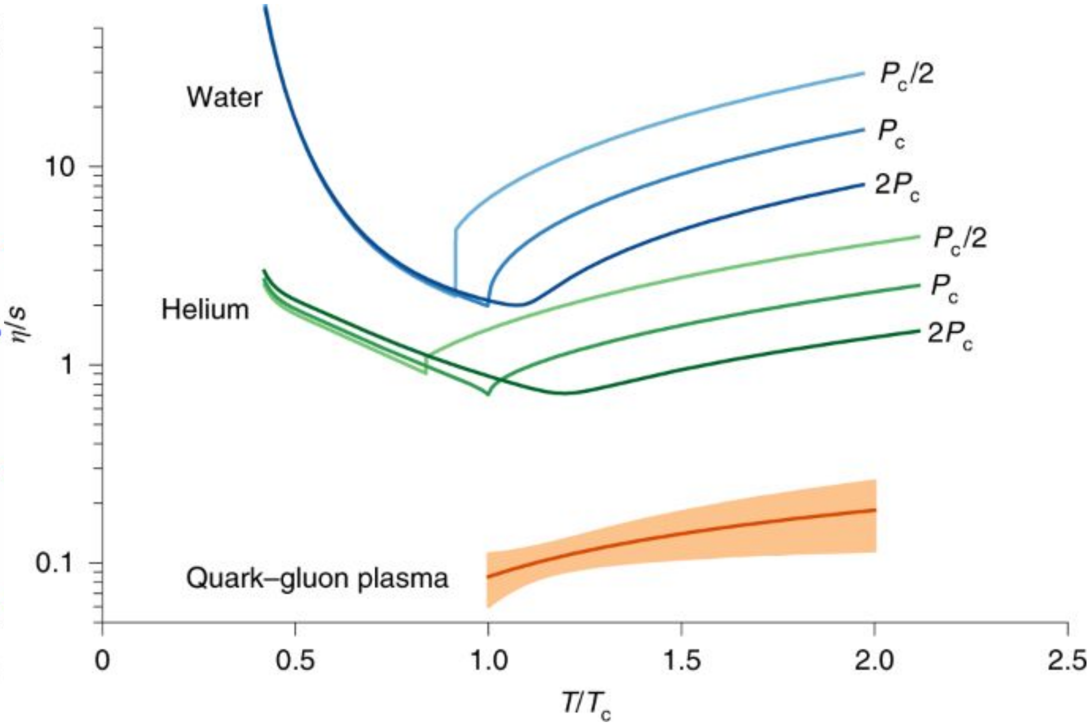




The lowest viscosity fluid

Nature Physics volume 15, pages 1113–1117 (2019)





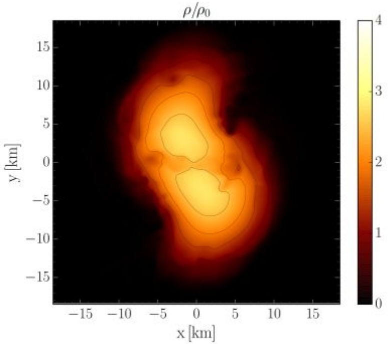
Comparing the experimental data from STAR with hydrodynamic predictions it was established that QGM possesses lowest known viscosity

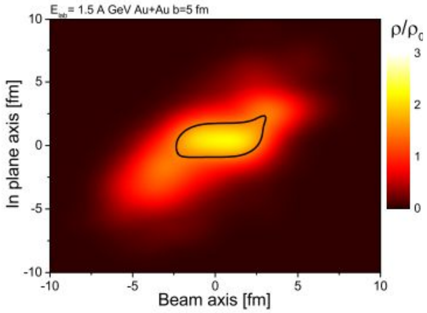
Heavy ion collisions at lower energies

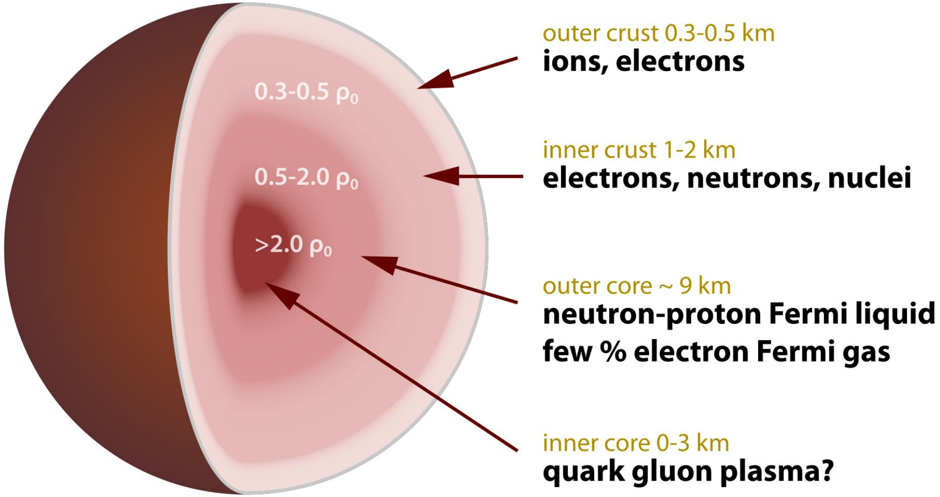
Nuclotron energies: $\sqrt{s_{NN}}$= 2.3-3.5 GeV
Achievable Net Baryon densities: ~3-5ρ_0
ρ_0 is nuclear saturation density

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

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

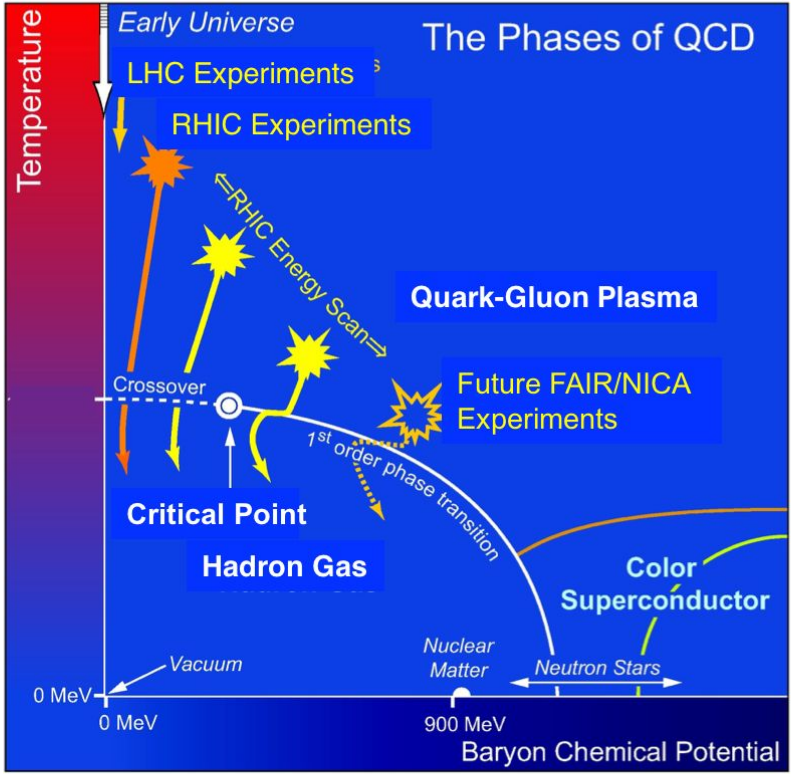




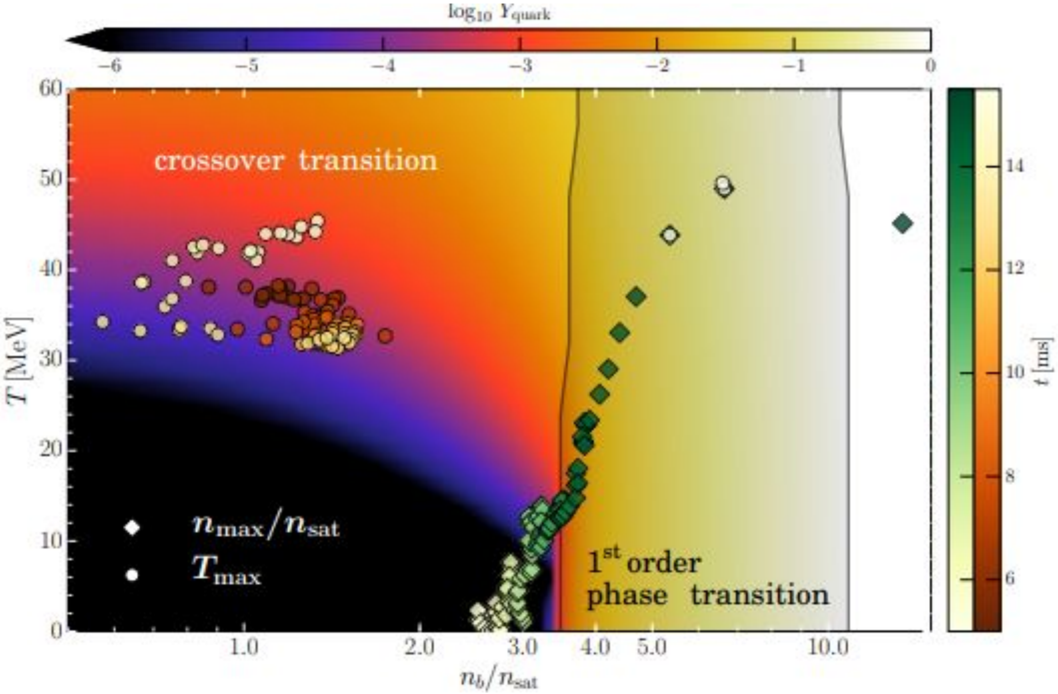


Conditions achieved are similar to those in compact stars except for the isospin asymmetry

HIC-matter evolution



NS-merger matter evolution



EOS for high baryon density matter

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

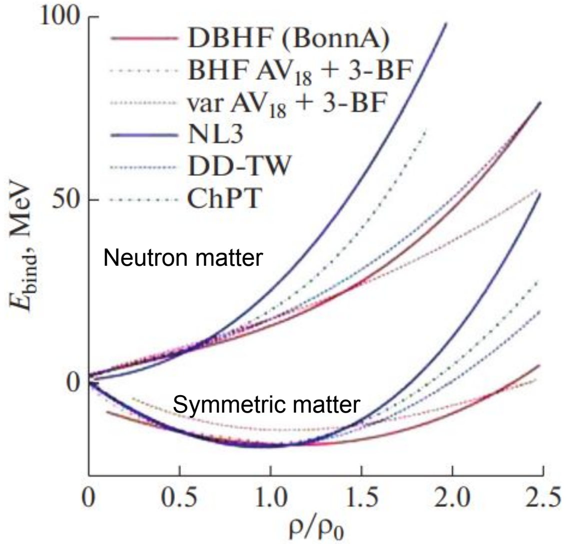
$$E_A(\rho,\delta) = \boxed{E_A(\rho,0)} + \boxed{E_{sym}(\rho)}\delta^2 + O(\delta^4)$$

Energy for symmetric system   Symmetry energy

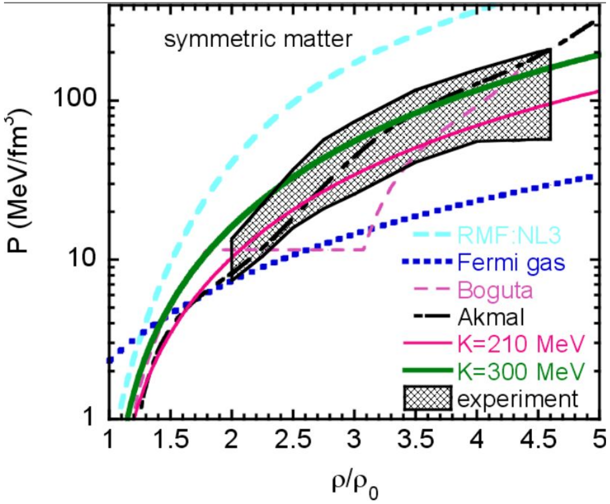
Isospin asymmetry is described as:

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

Observables from heavy ion collision experiments constrain the EOS



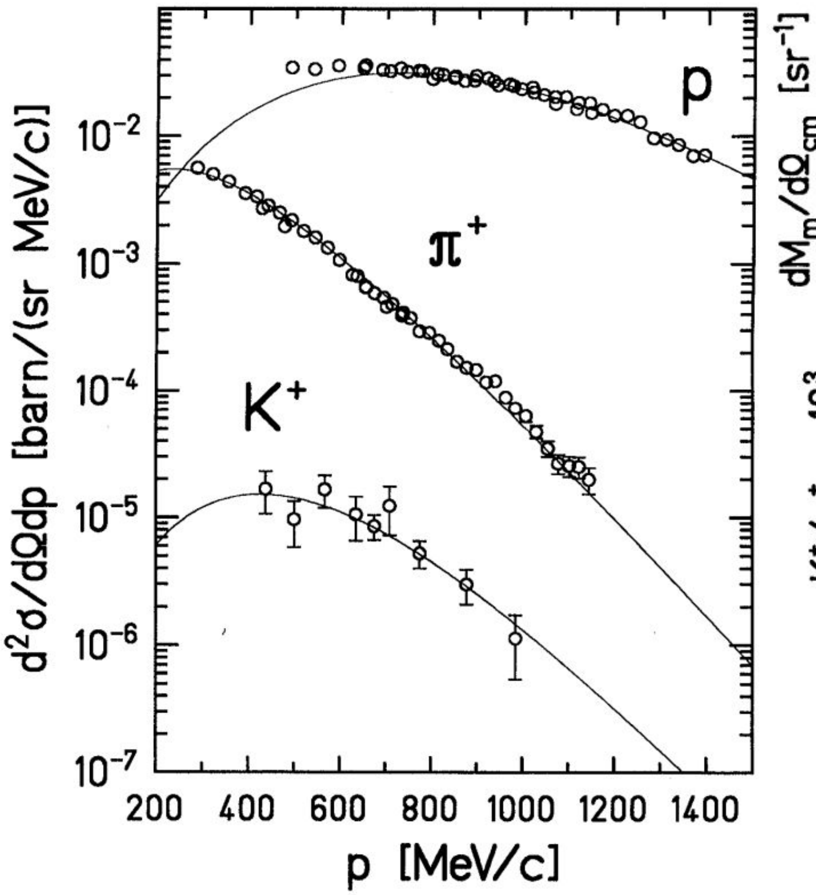
Science 298 (2002) 1592-1596

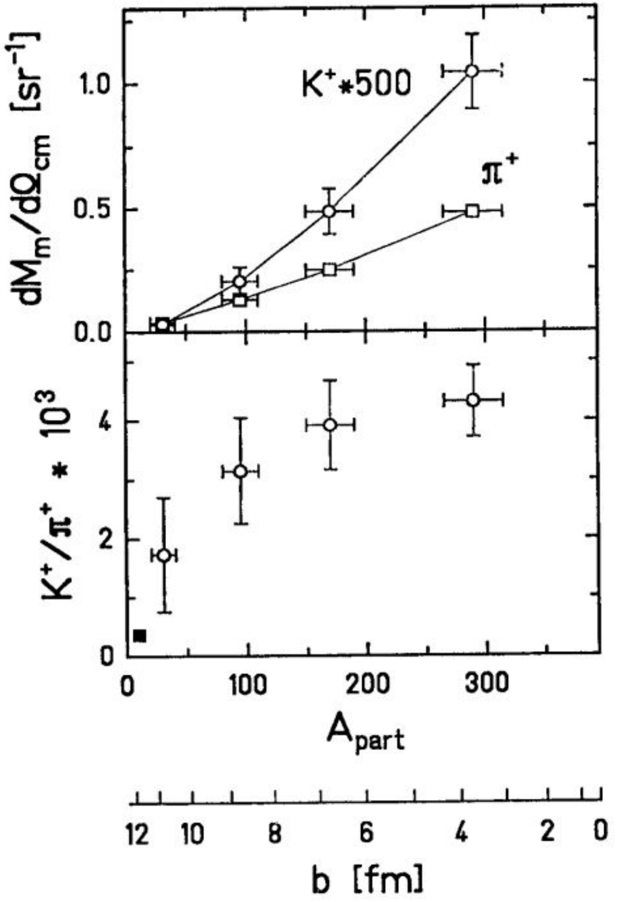


Eur. Phys. J. A 30, 5–21 (2006)

Sub-threshold strangeness production

Phys. Rev. Lett. **72**, 3650



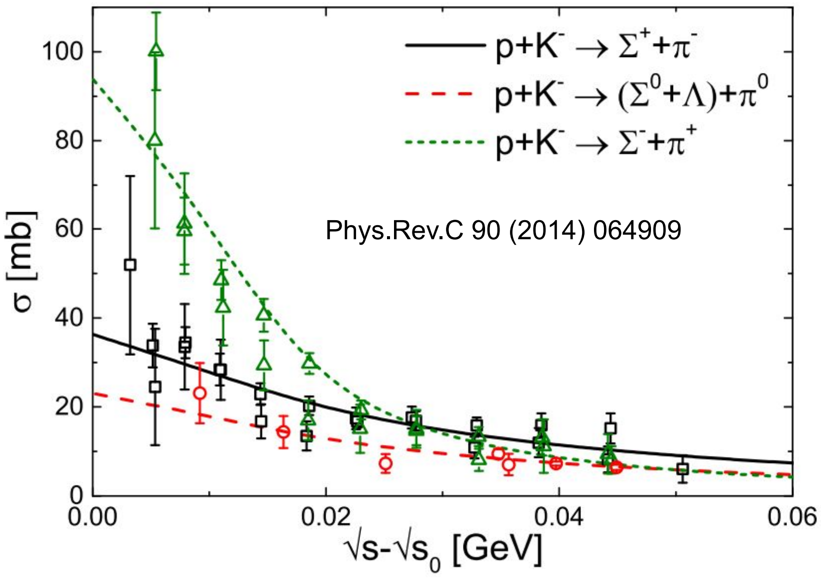


π/K ratio is sensitive to the pressure built within the overlap region

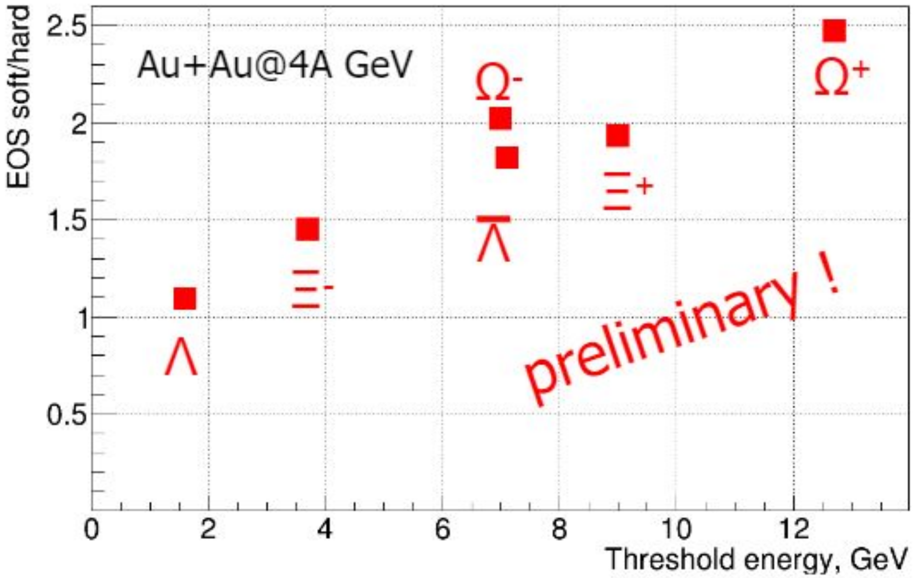
Enhanced production in central collisions suggests higher pressure

Sub-threshold multi-strange hyperons production

Kaon-nucleon strangeness exchange cross sections in URQMD



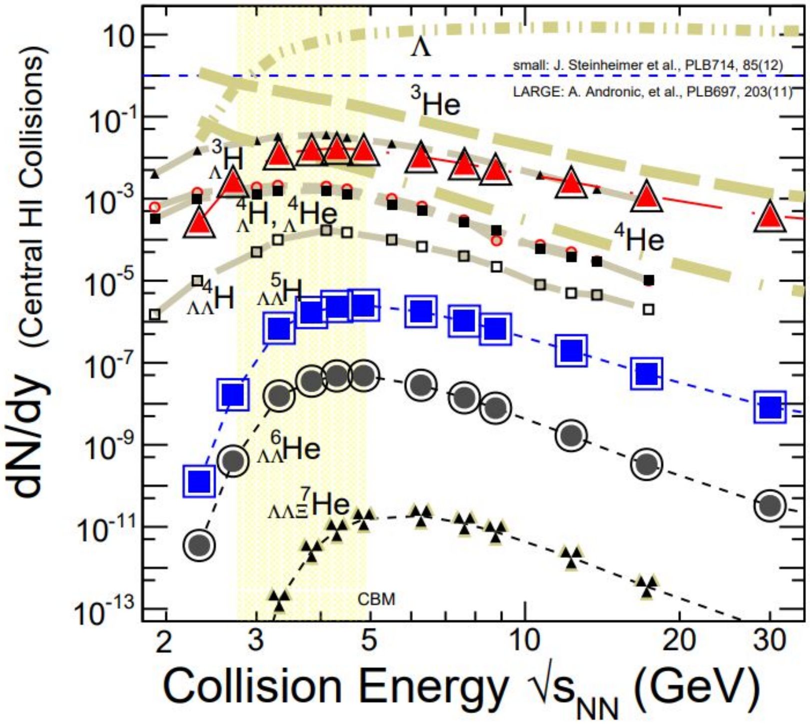
PHQMD: J. Aichelin et al., Phys. Rev. C 101 (2020) 044905

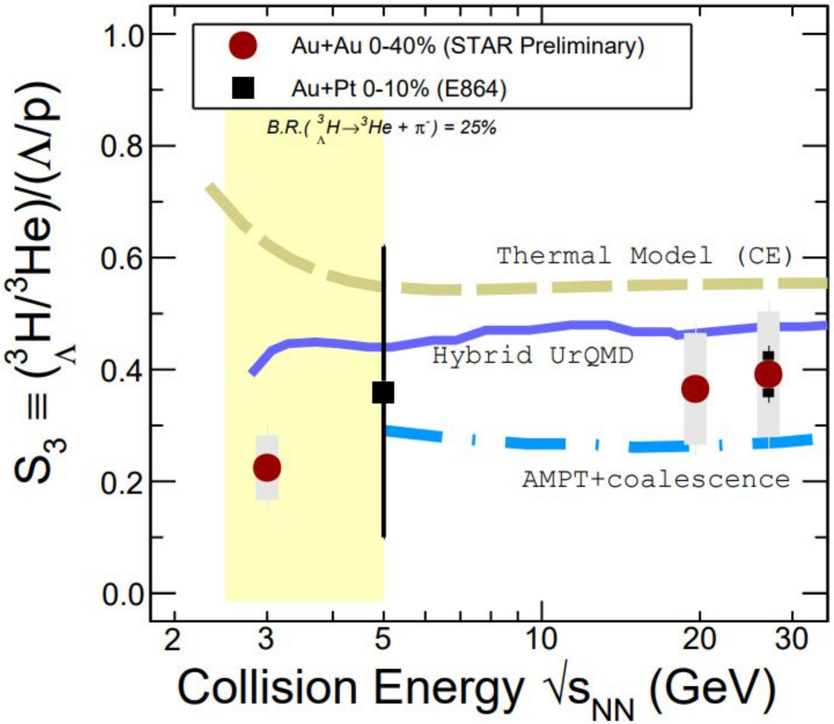


Subthreshold production of multi-strange hyperons is sensitive to the EOS

Hypernuclei production: Y-N interaction

arXiv:2209.05009v1



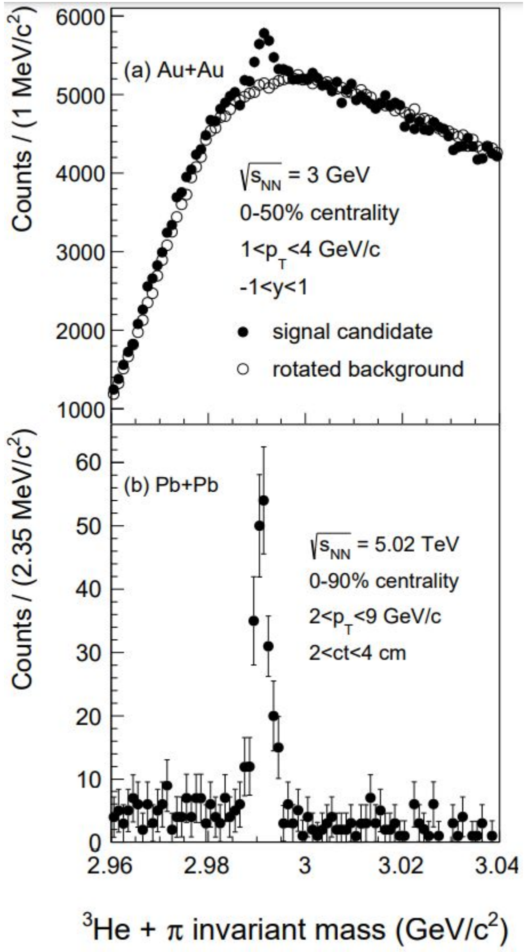


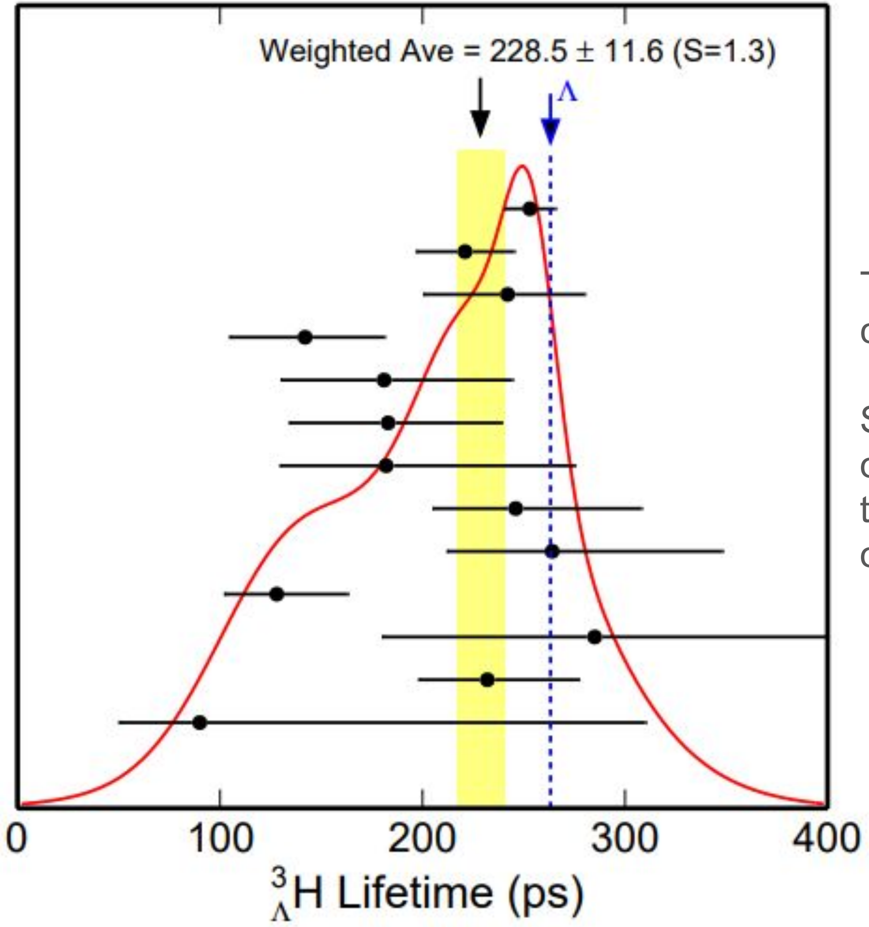
Enhanced yield of hypernuclei is expected at the beam energies of BM@N

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

Measurements of the hypernuclei on HIC

arXiv:2311.09877

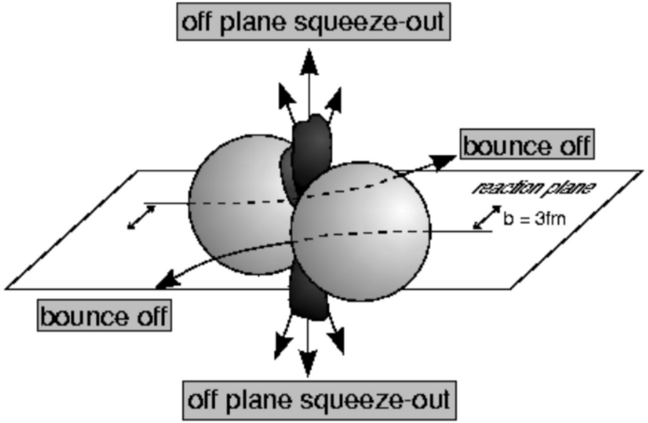




The lifetime of He3Λ is comparable to that of Λ

Studying the properties of hypernuclei may help to address the stability of heavy NS

Sensitivity of the collective flow to the EOS



Azimuthal distribution of produced particles with respect to RP:

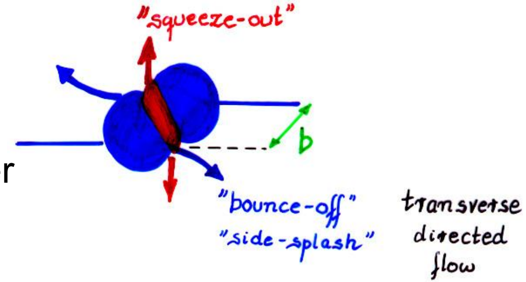
$$\rho(\varphi - \Psi_{RP}) = \frac{1}{2\pi}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_{RP})\right)$$

Coefficients of the decomposition are referred to as collective flow

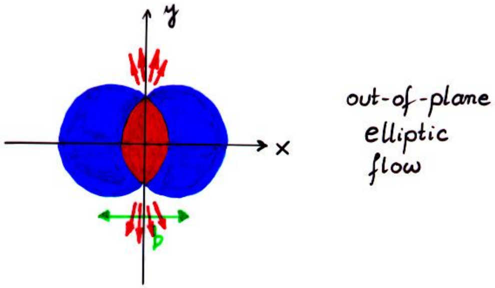
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right]\rangle$$

v_1 is called directed and v_2 is called elliptic flow

Bounce-off



Squeeze-out

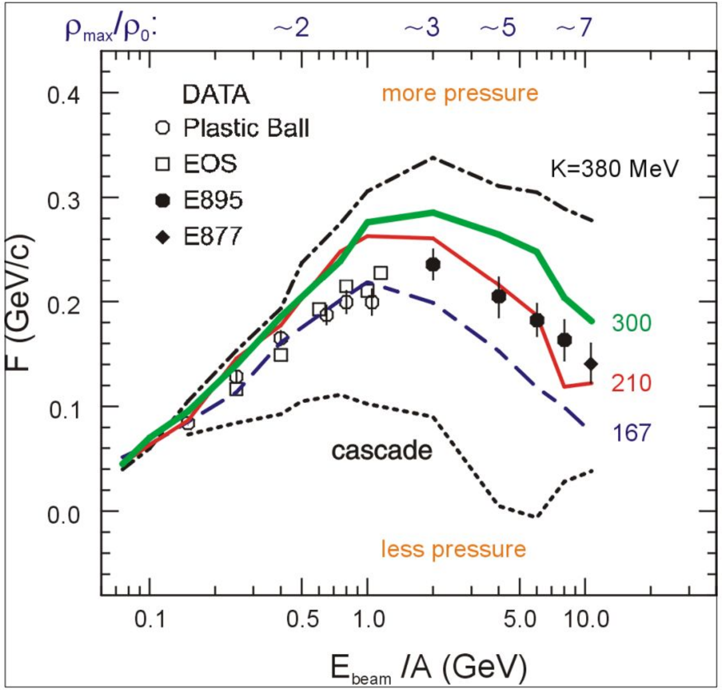


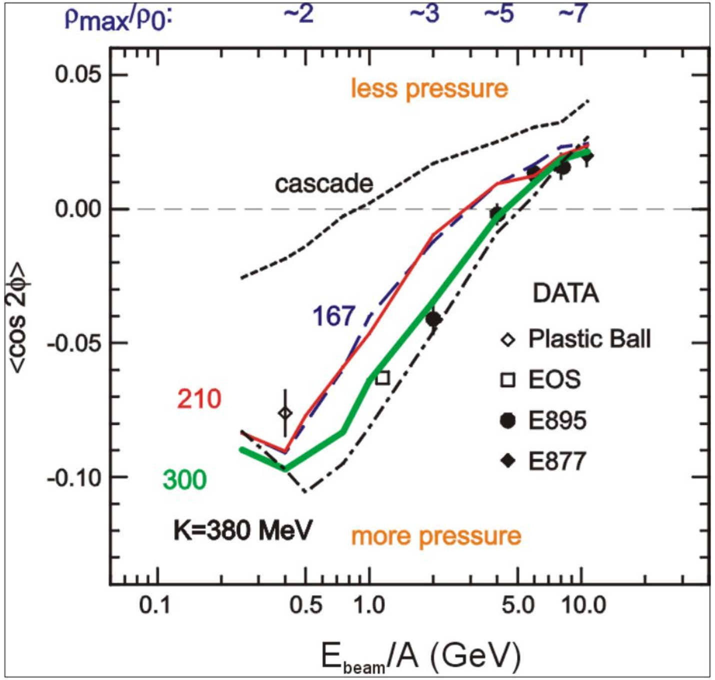
Collective flow is sensitive to:

- 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

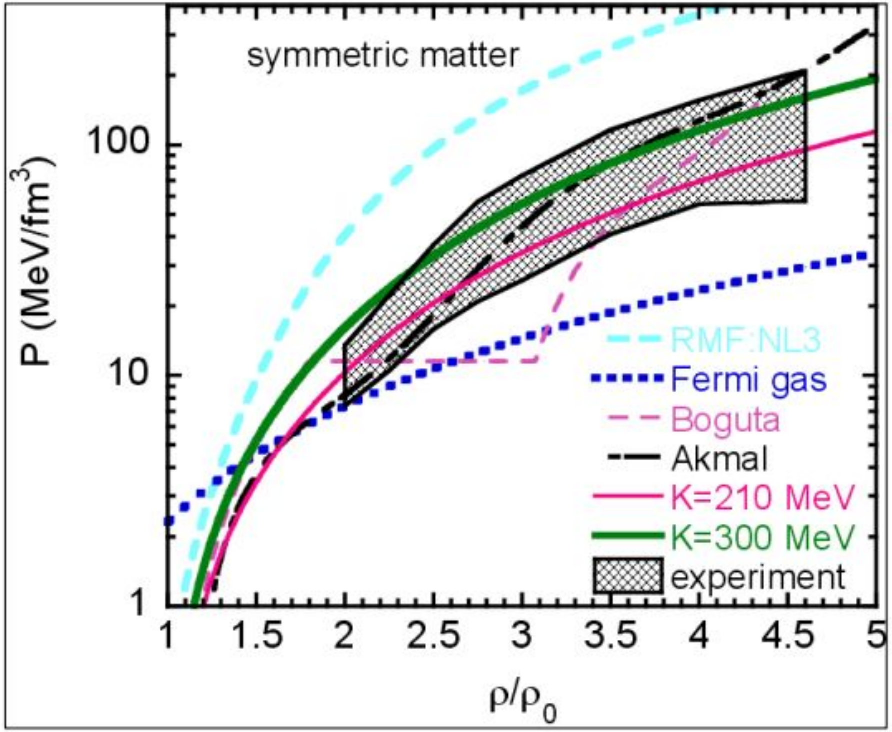




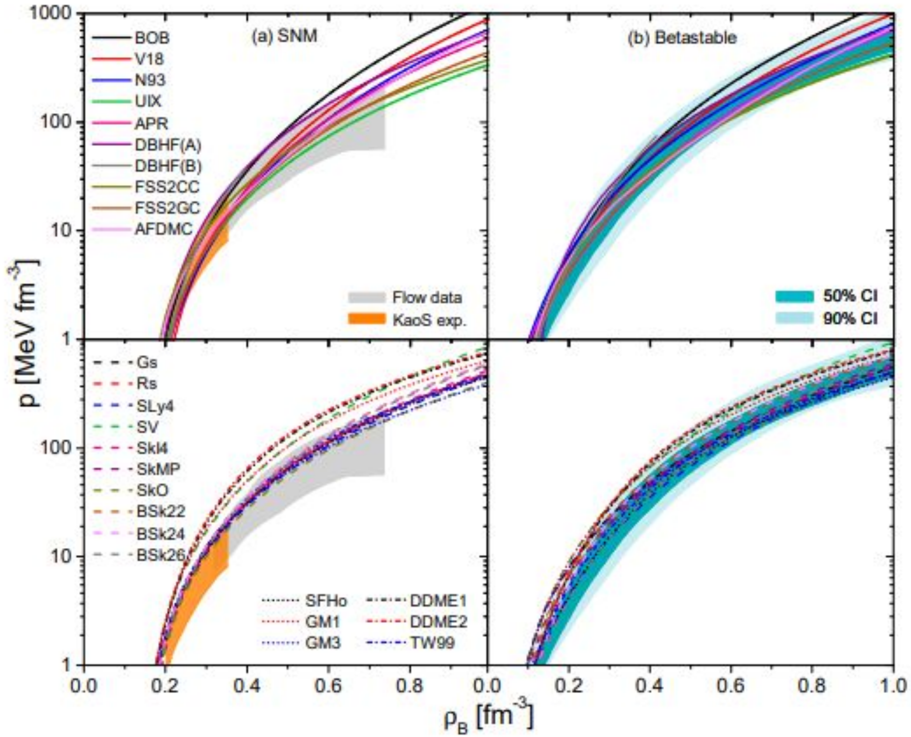
- The flow data from E895 experiment have ambiguous interpretation: v_1 suggests hard EOS while v_2 corresponds to soft EOS
  - Additional measurements are essential to clarify the previous measurements

Extracting equation of state of dense matter

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



Symmetry 2021, 13, 400

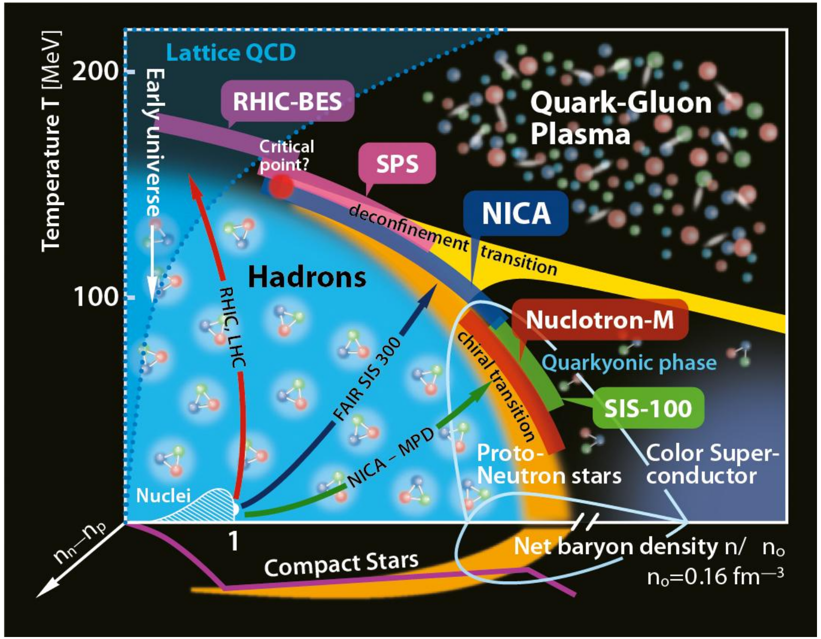


HIC-data together with the GW-data may shed lig on the properties of the dense matter within the NS-core

Summary

- The matter in heavy ion collisions at higher energies is comparable to that existed in the first moments after the Big Bang
- In the higher-energy collisions quark-deconfinement is observed
- The quark-gluon matter has the lowest viscosity among all the known matter
- Lower energy collisions probe the region of QCD-diagram with conditions similar to that of NS-core and NS-mergers
- Sub-threshold strangeness production is a sensitive probe of the pressure achieved in HIC
- Enhanced hypernuclei production in lower-energy collisions provides the possibility to study their properties
- Anisotropic flow is a sensitive probe of the conditions achieved in HIC

QCD Phase diagram: high baryon density region



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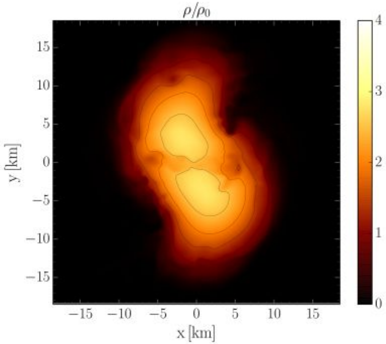
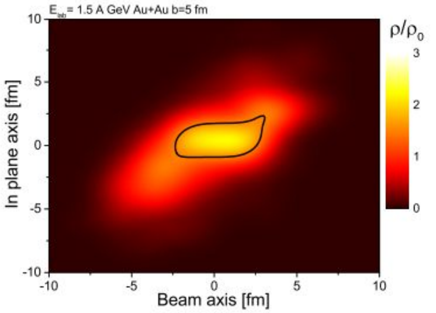
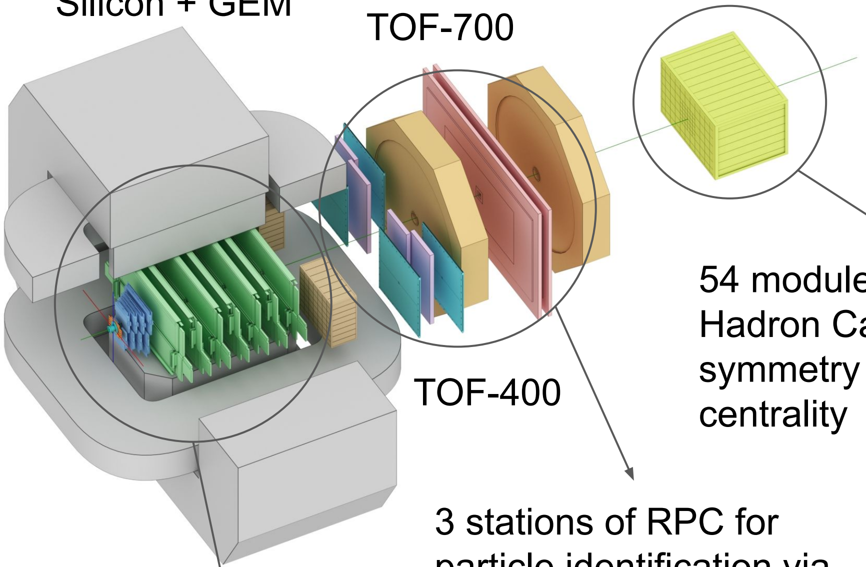
M. Hanauske et al., J. Phys.: Conf. Ser. 878 012031





Varying the energy of the collision one can achieve different properties of strongly interacting matter

The BM@N experiment (JINR, Dubna)

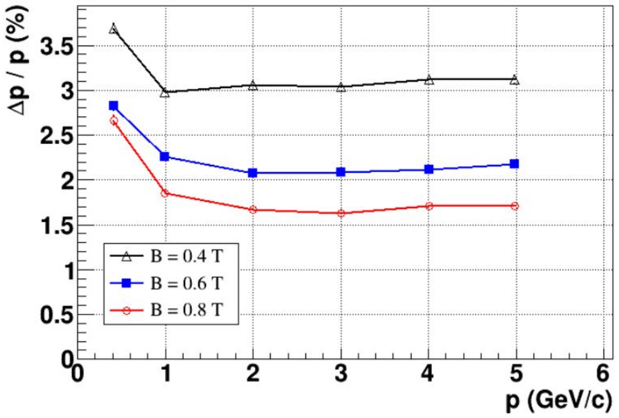


54 modules of Forward Hadron Calorimeter for symmetry plane and centrality

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)

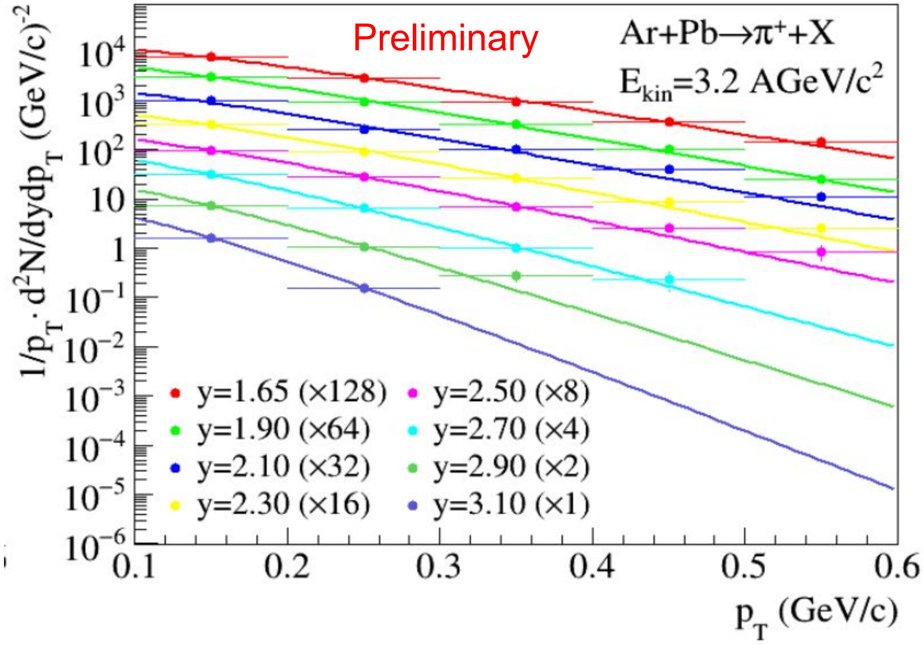
Momentum resolution

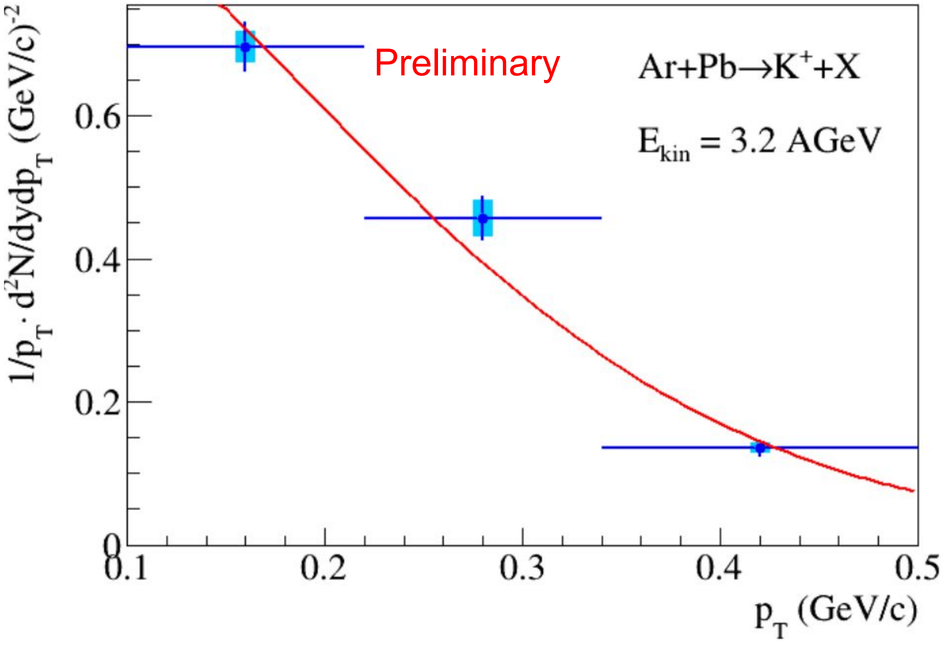


Nuclotron beam:

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

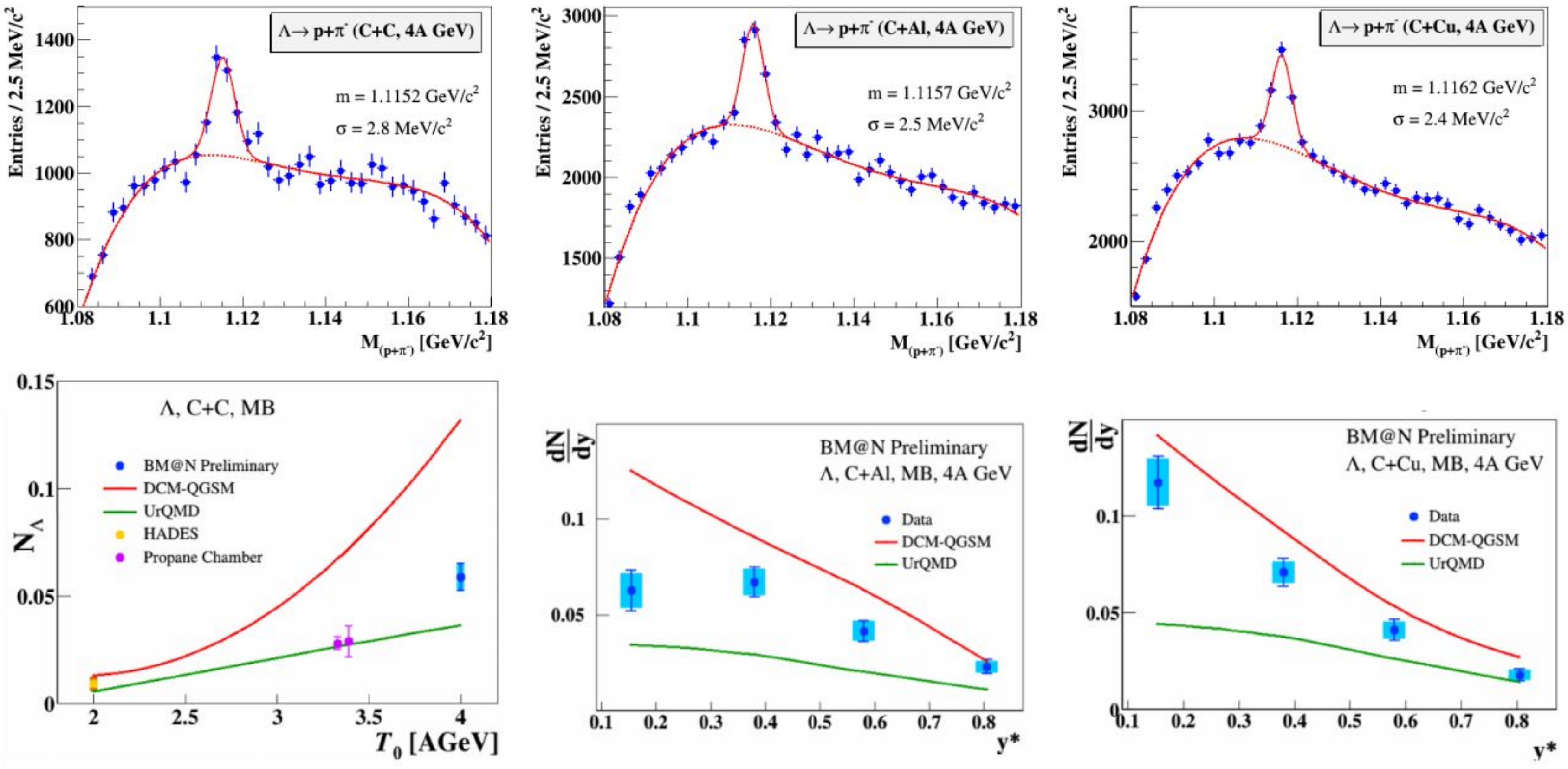
Light meson yield in technical run





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

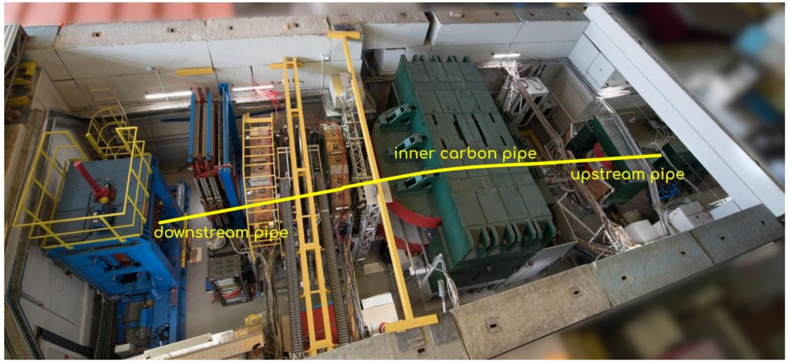
Hyperon extraction performance in technical run

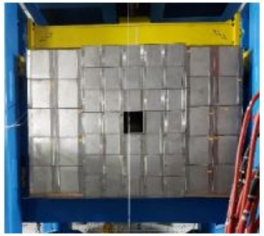


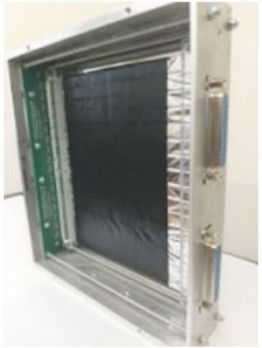
BM@N is capable of measuring the produced hyperons

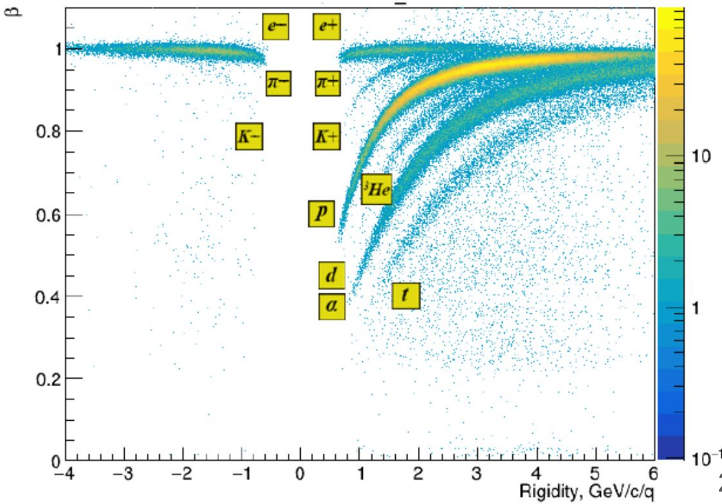
BM@N upgrade for the upcoming physical run

- 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.



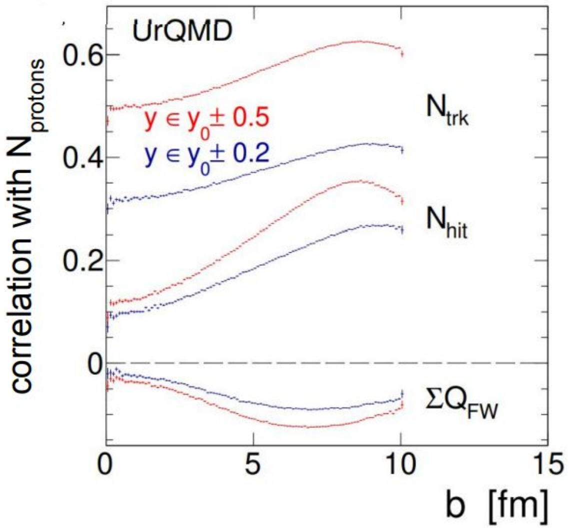


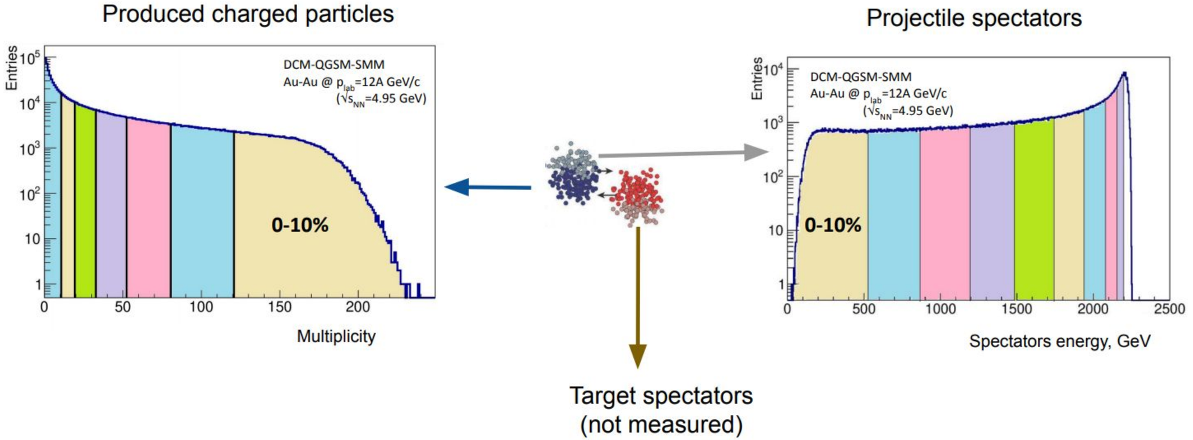




Independent centrality estimation sources

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



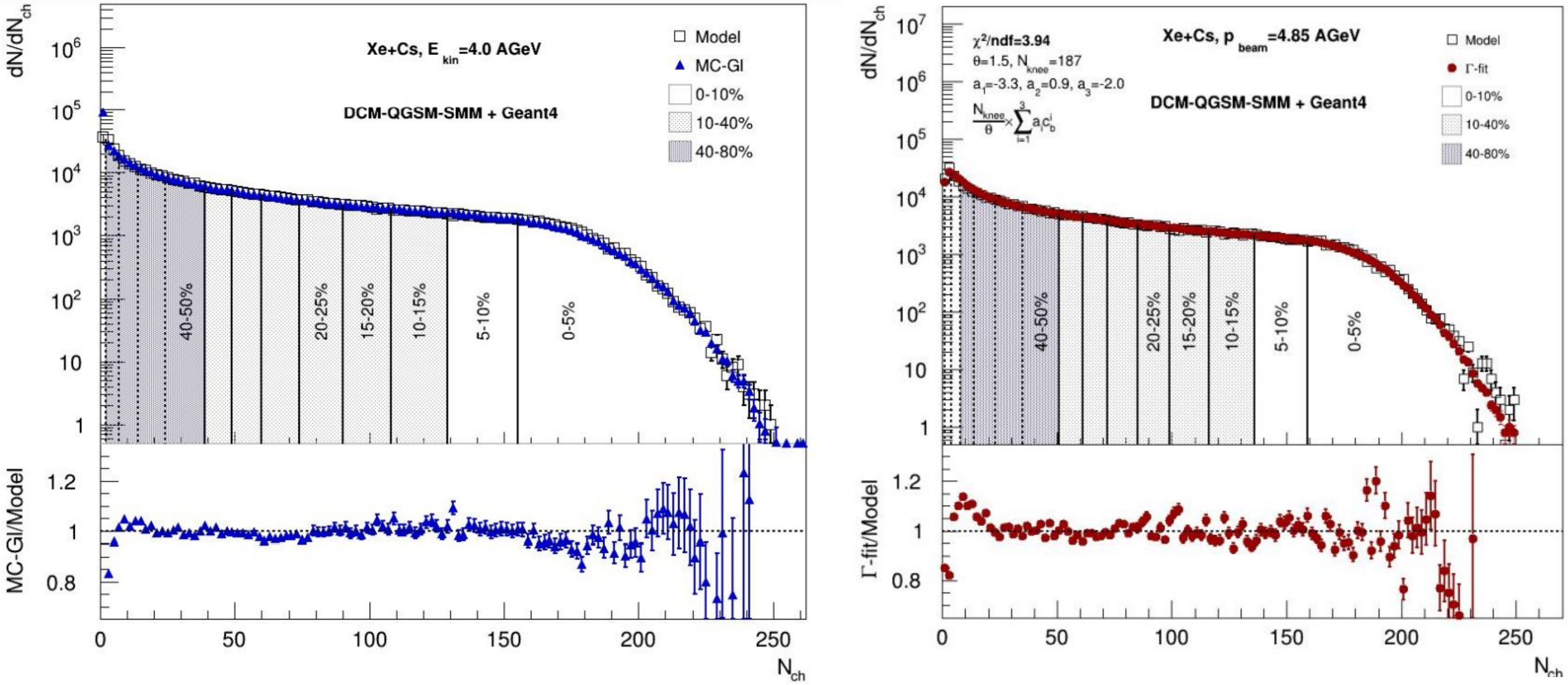


A number of produced protons is stronger correlated with the number of produced particles (track & RPC+TOF hits) than with the total charge of spectator fragments (FW)

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

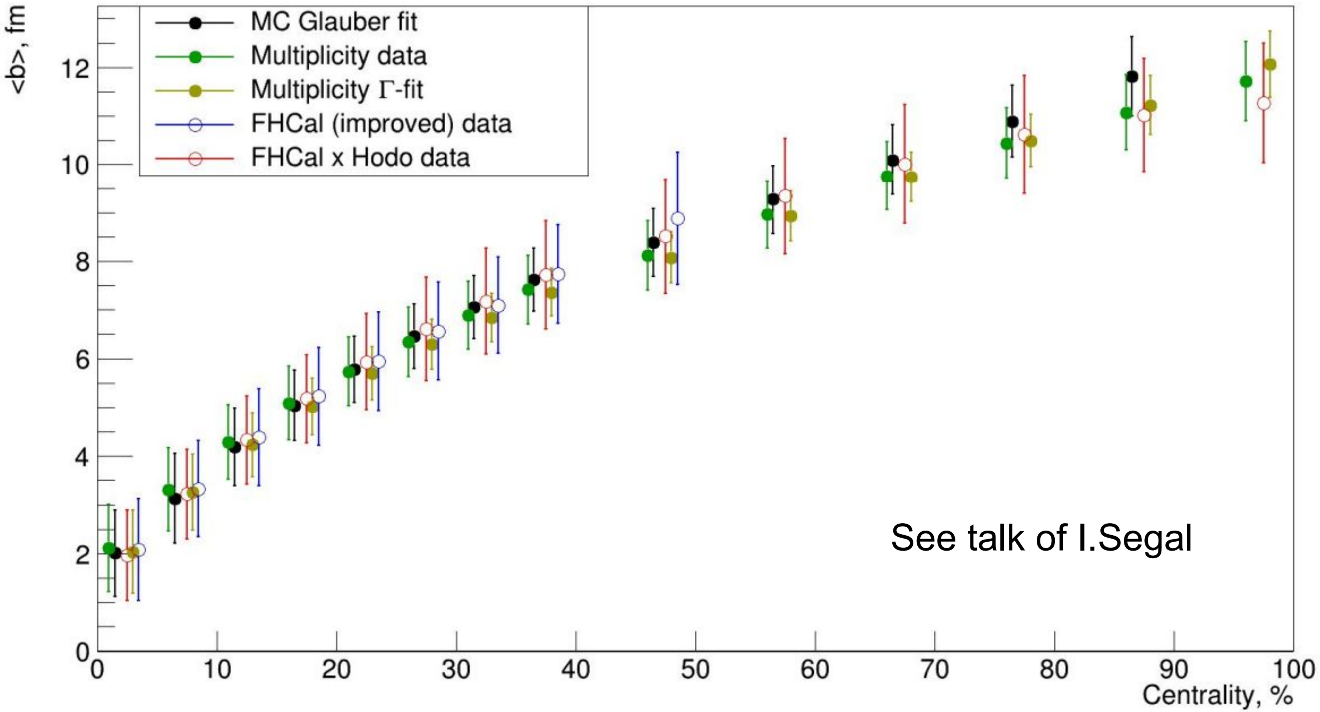
Centrality determination at BM@N

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



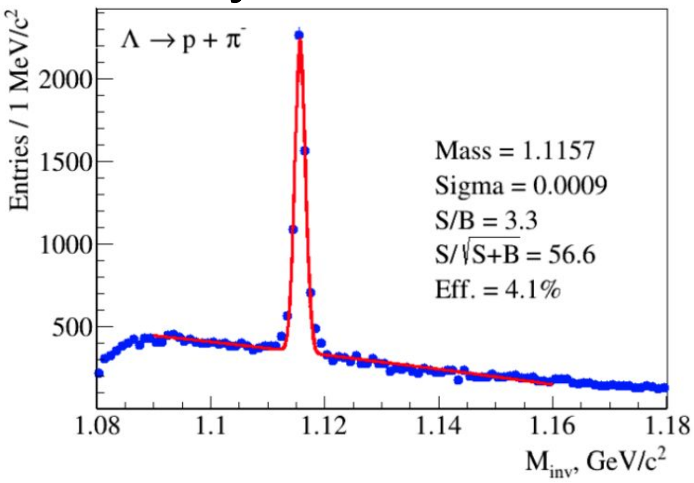
- Impact parameter distributions in different centrality classes are similar for different centrality classes
- The distributions for spectators energy are wider because of the width of b and energy correlation

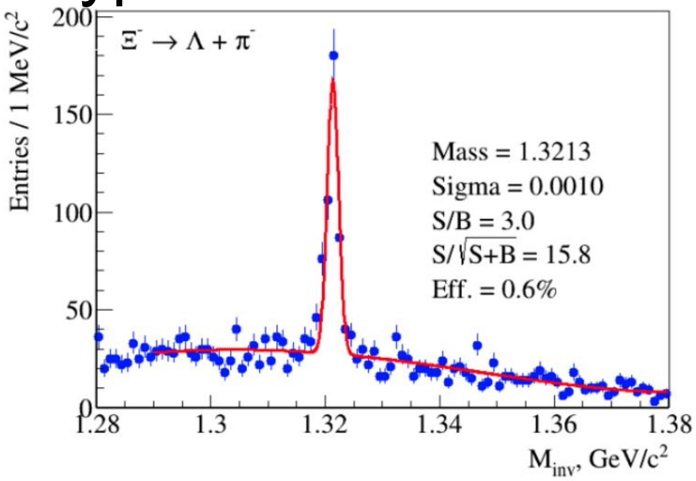
Comparison of the HADES, STAR FXT and BM@N data

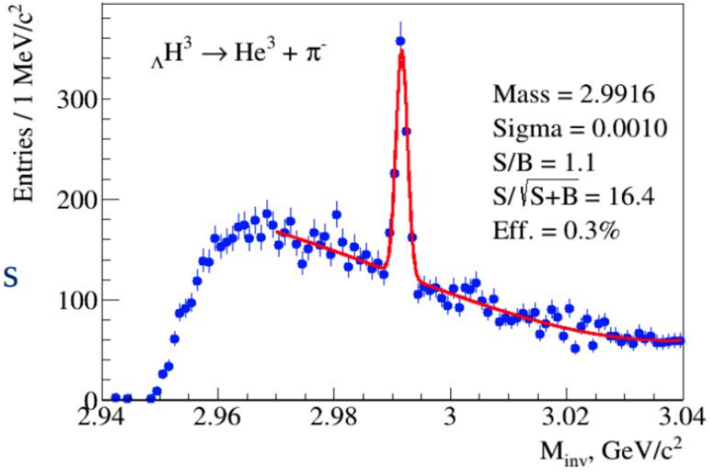
Exp.	year	A+A	E_{kin} AGeV	Statistics	Ξ^-	Ω^-	Hypernuclei
HADES	2012	Au+Au	1.23	$7 \cdot 10^9$	✗	✗	✗
HADES	2019	Ag+Ag	1.58	$1.4 \cdot 10^{10}$	✗	✗	$800\ ^3_\Lambda$H
STAR FxT	2018	Au+Au	2.9	$3 \cdot 10^8$	10^4	✗	$10^4\ ^3_\Lambda$H $6 \cdot 10^3\ ^4_\Lambda$H
STAR FxT	2021	Au+Au	2.9	$2 \cdot 10^9$	$7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







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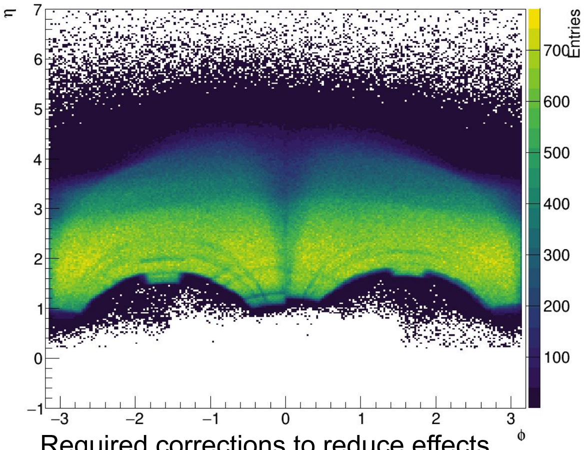
- High statistics will enable for multidifferential measurements of (multi-) strange particles and hypernuclei
- Colliding different system may shed light on the mechanisms of strangeness production in the region of large baryon densities

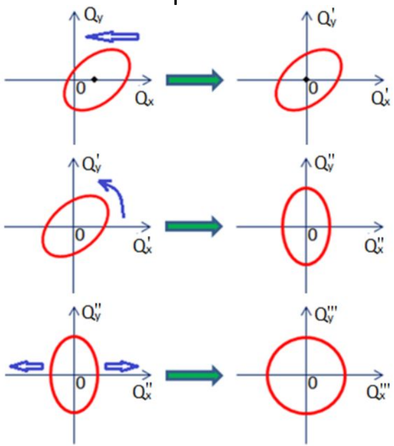
Azimuthal acceptance of the BM@N experiment

φ-η yield of protons

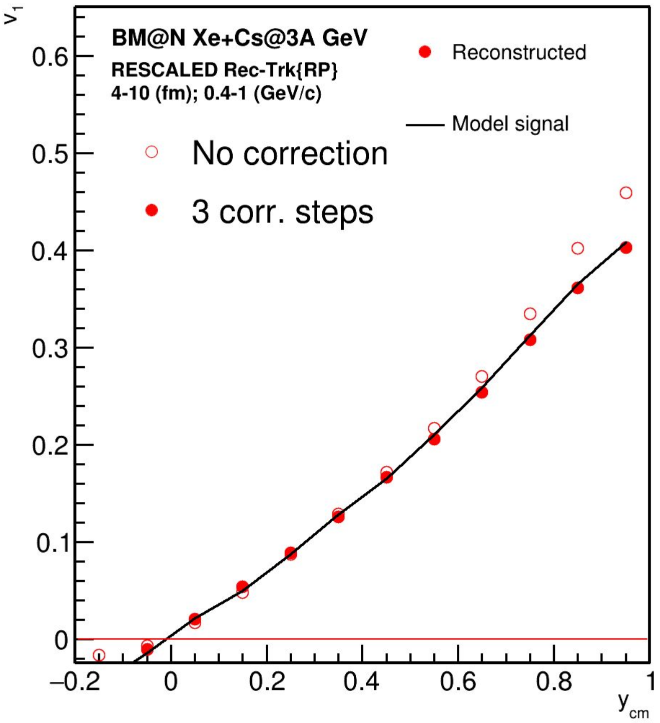


Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

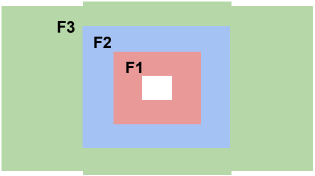


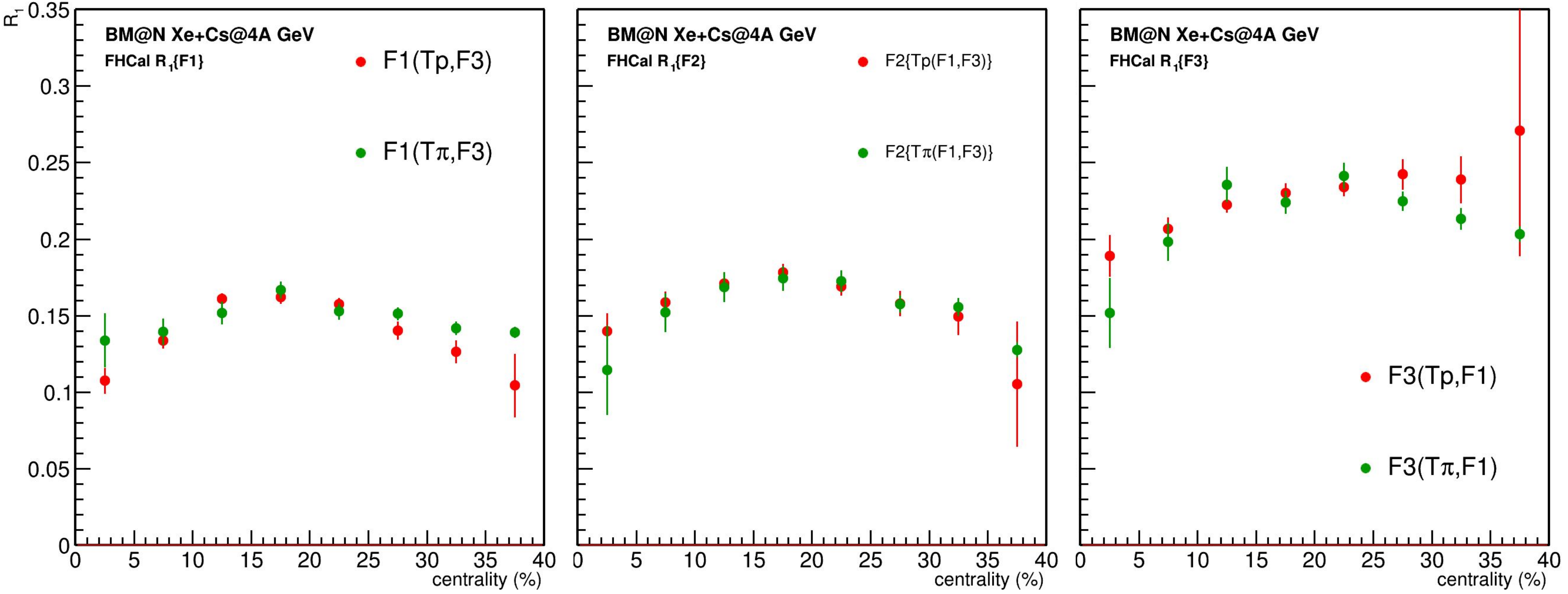
Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



Better agreement after rescaling

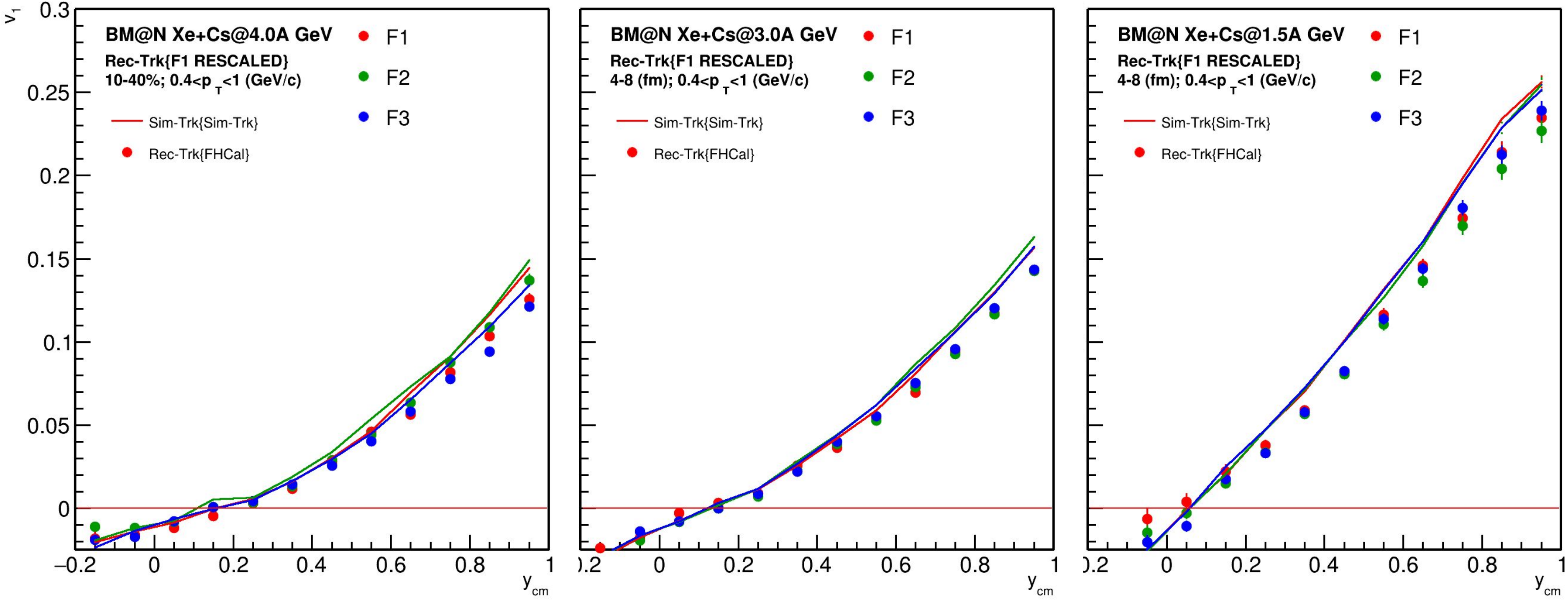
Rec R1: DCMQGCM-SMM Xe+Cs@4A GeV





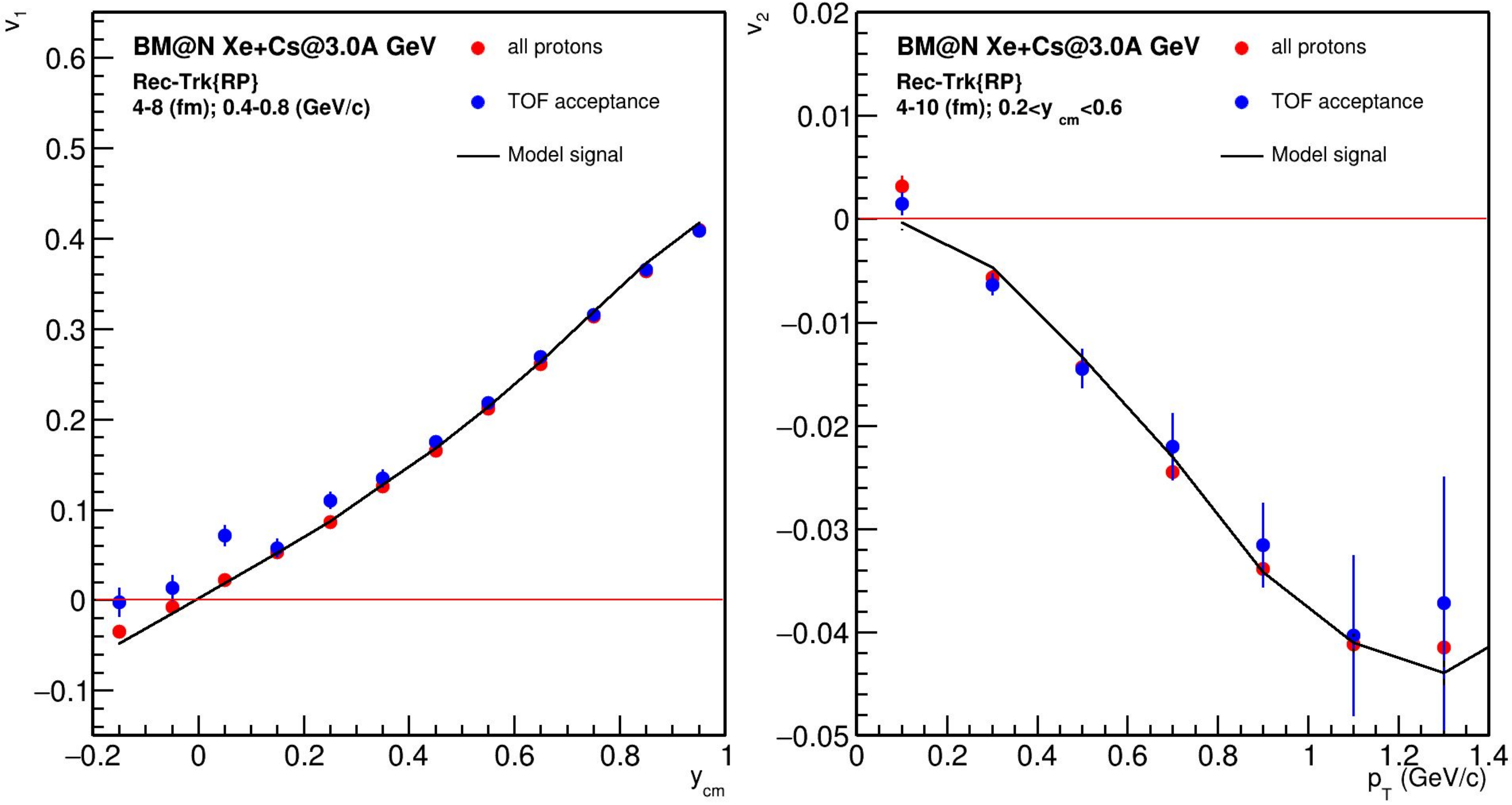
Using the additional sub-events from tracking provides a robust combination to calculate resolution

v_1: DCMQGCM-SMM Xe+Cs



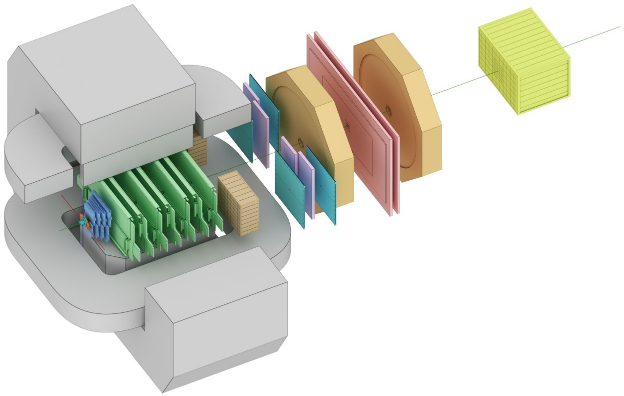
Reasonable agreement between model and reconstructed data

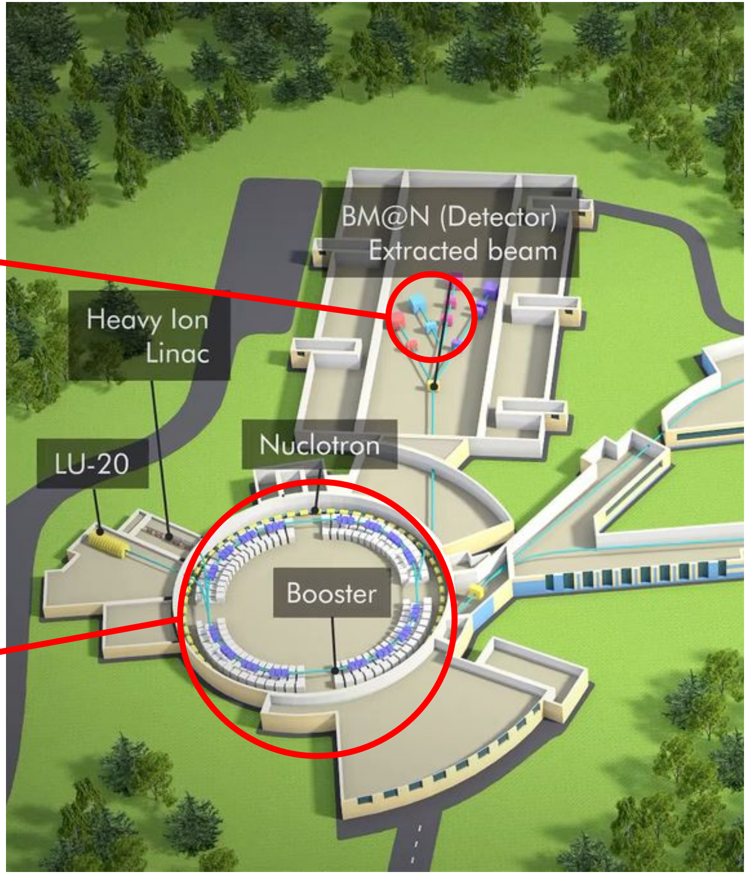
Directed and elliptic flow in Xe+Cs@3A GeV (JAM)



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

Nuclotron ion accelerator facility JINR, Dubna





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