The heavy-ion program at the upgraded Baryonic Matter at Nuclotron Experiment at NICA

Petr Parfenov
NRNU MEPhI, INR RAS
for the BM@N Collaboration

Infinite and Finite Nuclear Matter (INFINUM-2023)
02.03.2023, Dubna, Russia

EOS for high baryon density matter

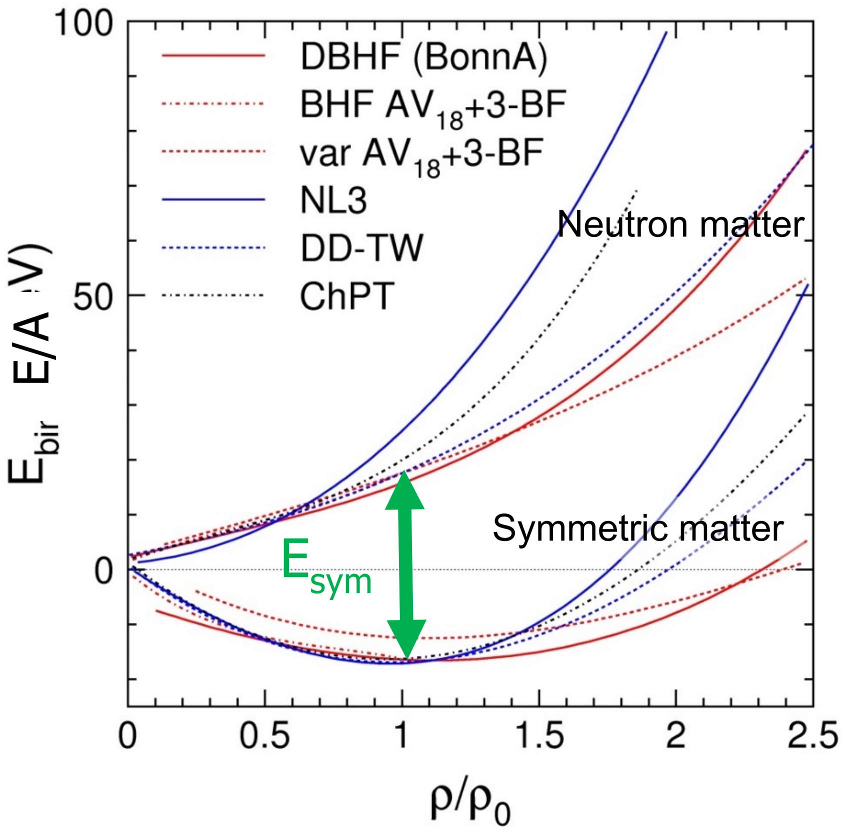
The binding energy per nucleon: $E_A(\rho,\delta) = E_A(\rho,0) + E_{sym}(\rho)\delta^2 + O(\delta^4)$

Isospin asymmetry:

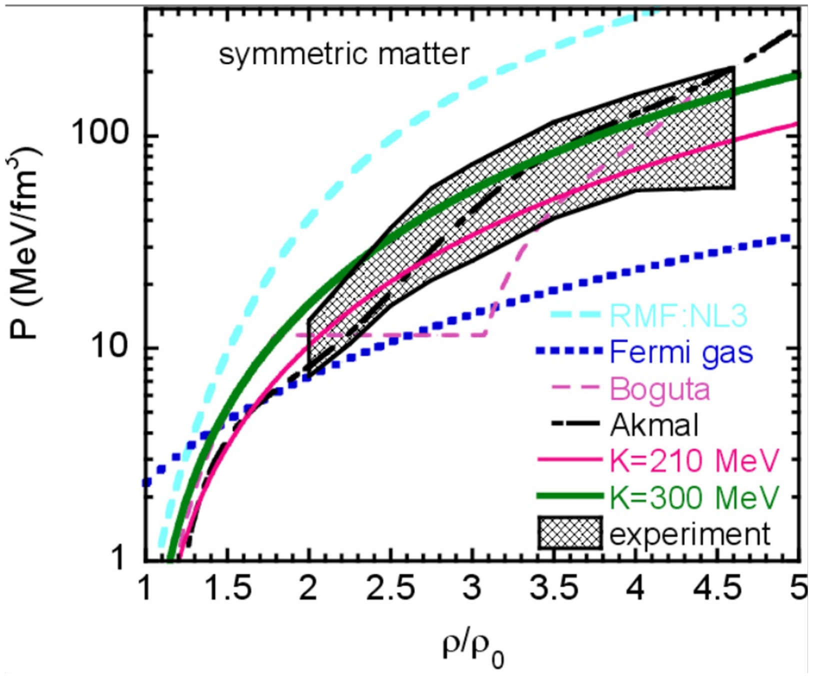
$\delta = (\rho_n - \rho_p)/\rho$

Symmetric matter

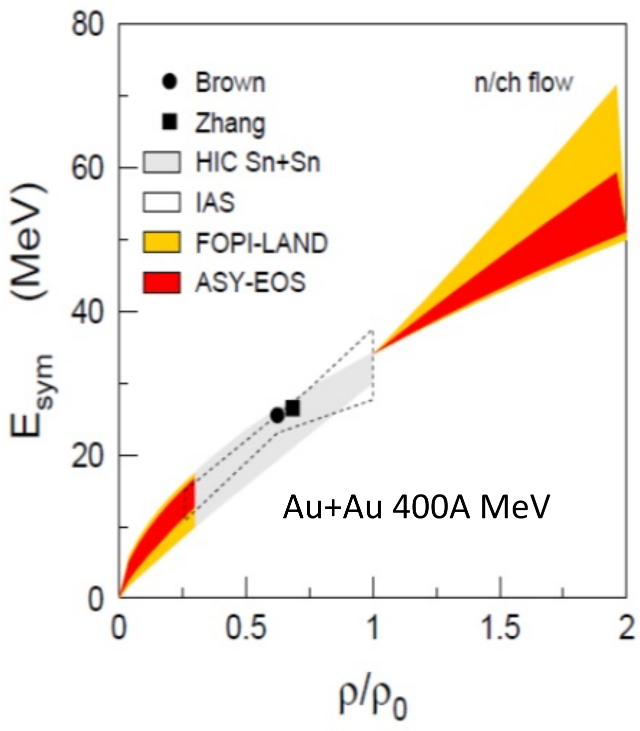
Symmetry energy



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



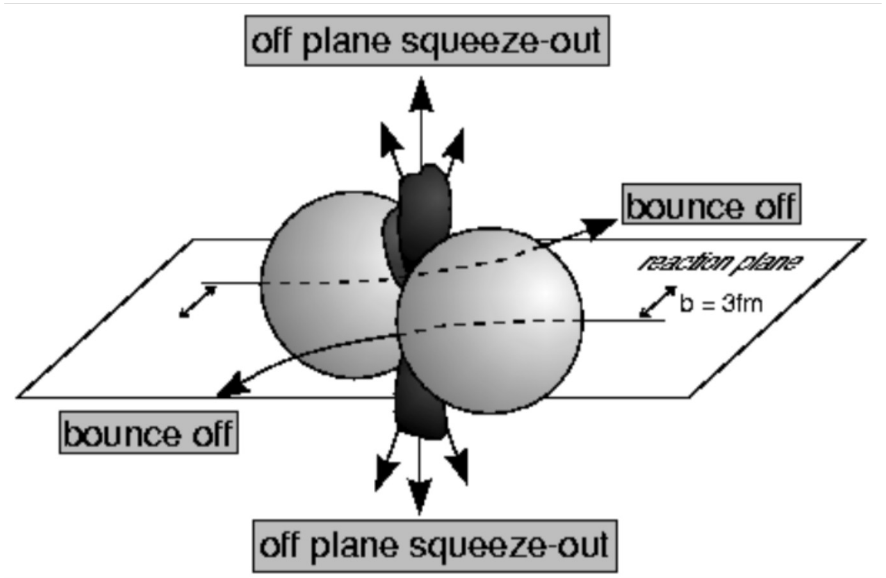
E895: elliptic flow of protons
P. Danielewicz, R. Lacey, W.G. Lynch, Science 298 (2002) 1592



ASY-EOS: Elliptic flow of neutrons/charged particles

P. Russotto et al.,
Phys. Rev. C 94 (2016) 034608

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

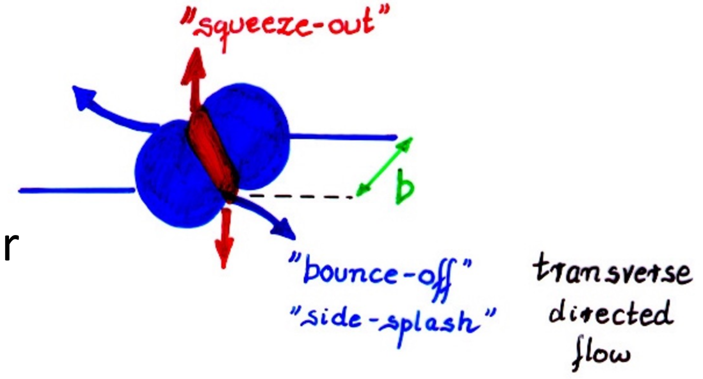
$$v_n = \langle \cos\left[n(\varphi - \Psi_{RP})\right]\rangle$$

v_1 is called directed and v_2 is called elliptic flow

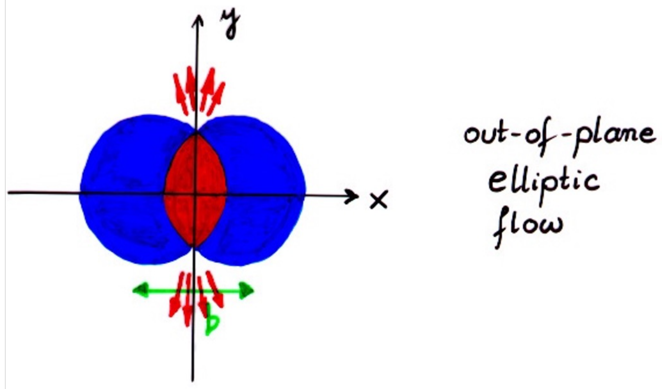
Collective flow is sensitive to:

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

Bounce-off

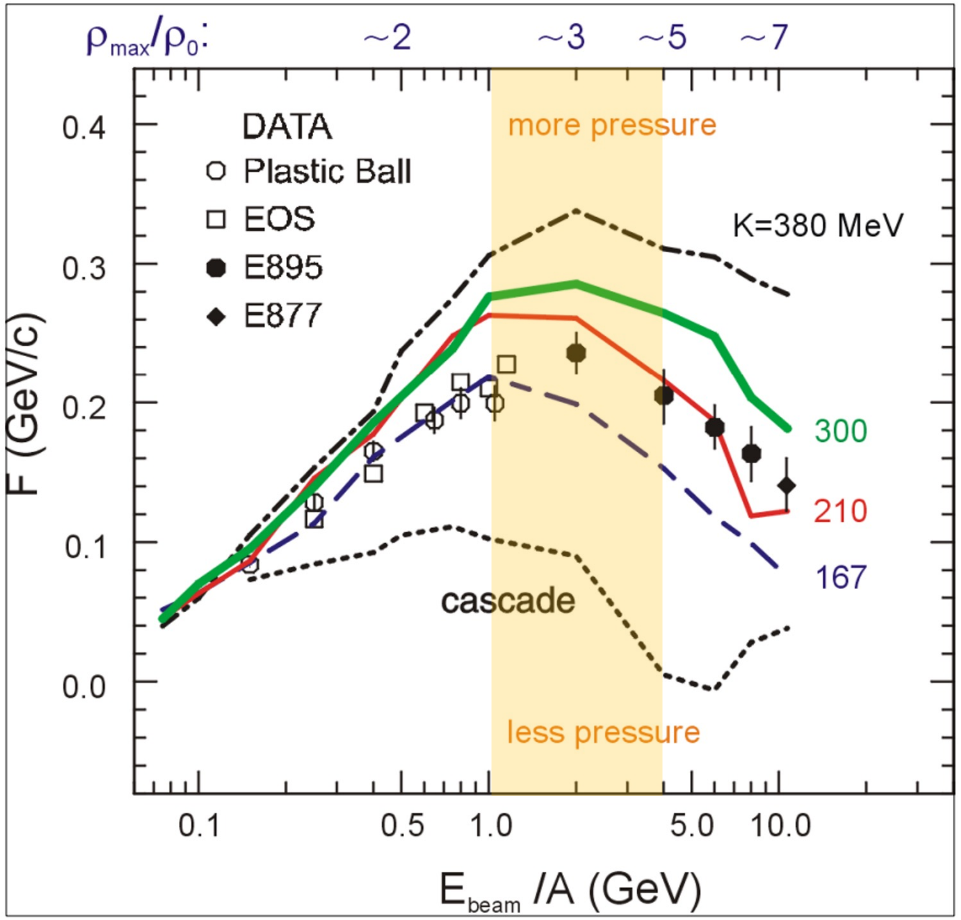


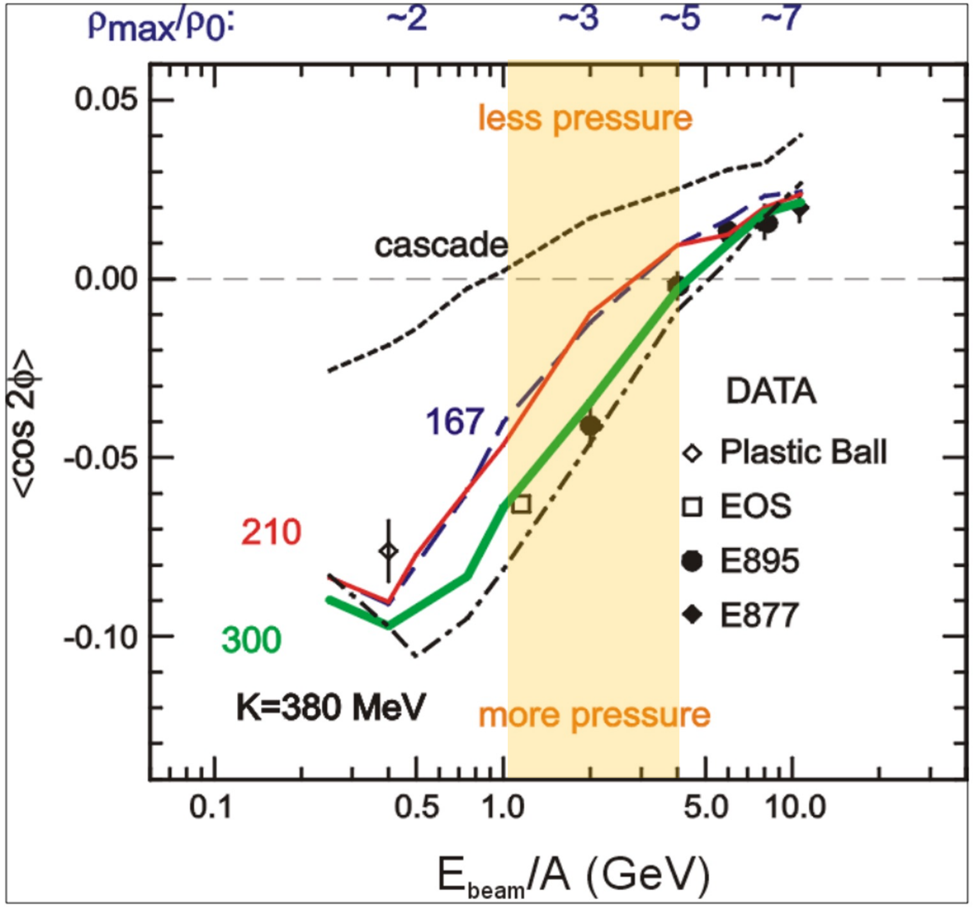
Squeeze-out



Interpretation of the previous flow data

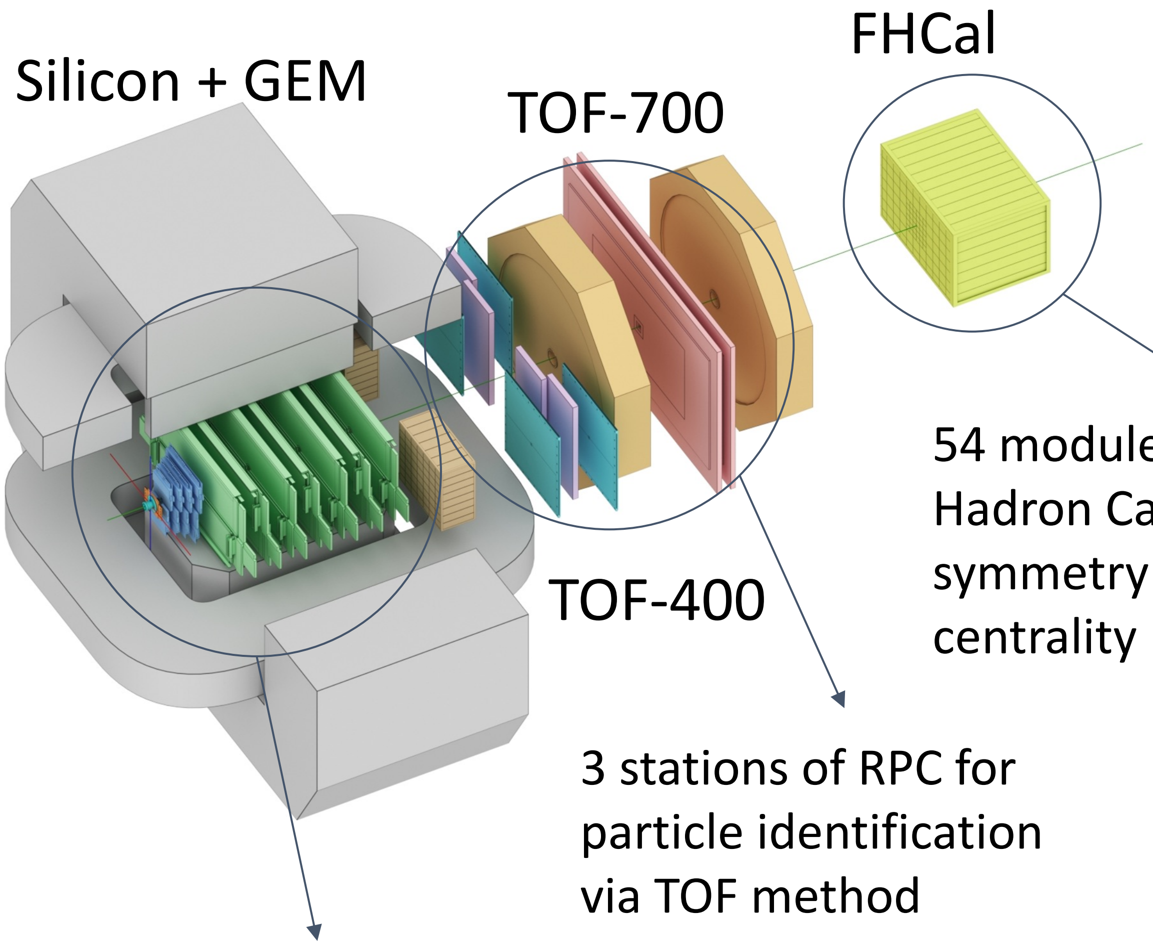
P. DANIELEWICZ, R. LACEY, W. LYNCH
10.1126/science.1078070





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

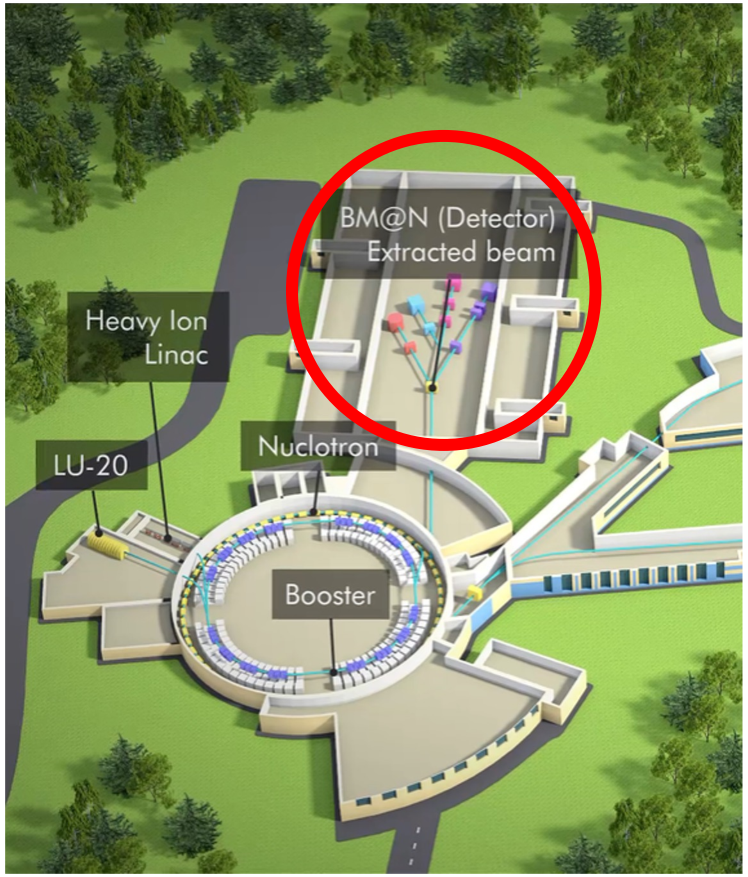
The BM@N experiment (JINR, Dubna)



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

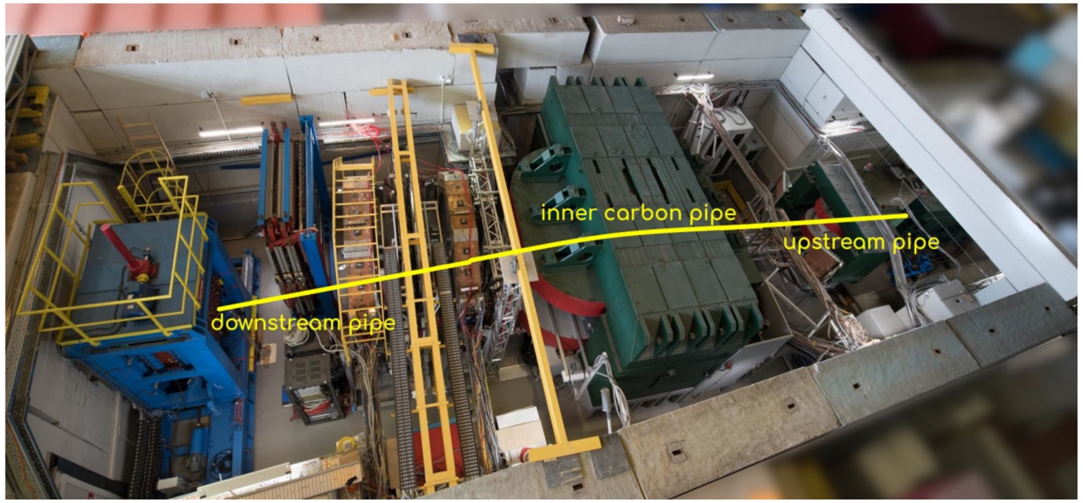


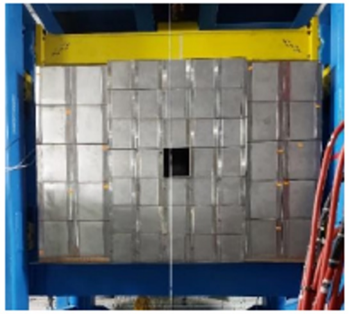
Nuclotron beam:

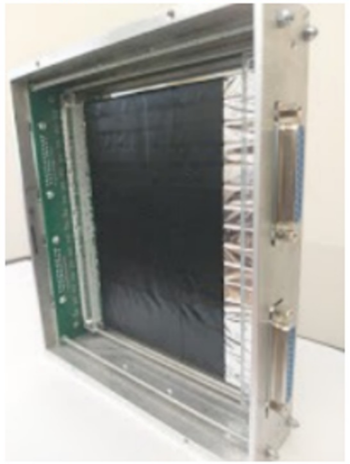
- from p to Au
- heavy ion energy 1- 3.8 GeV/n
- Au intensity ~ few 10^6 Hz

BM@N setup during the physical run Xe+Cs(I)

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







Previous runs:

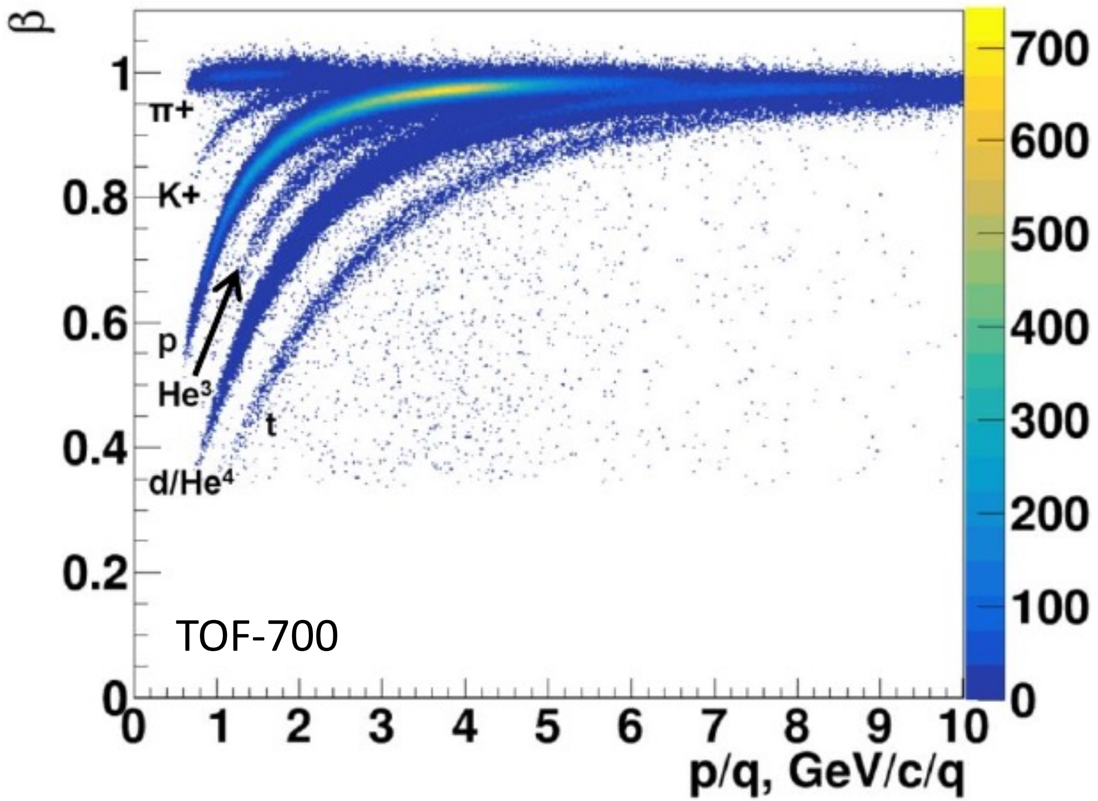
- C+C, C+Al, C+Cu @ 4 AGeV

First physical run:

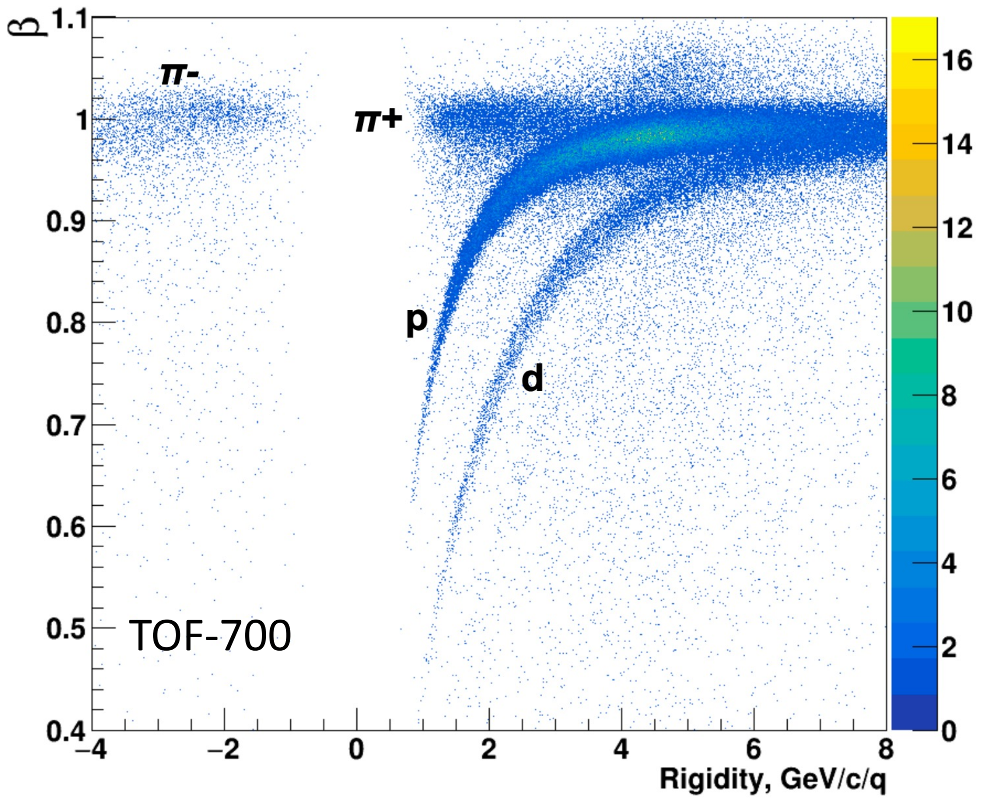
- **Xe+Cs(I)**
    - **3.8 AGeV: 500 M events**
    - **3 AGeV: 50 M events**

TOF-700 data from Ar+A and Xe+Cs(I) runs

Ar+A @ 3.2 AGeV (2018)



Xe+Cs(I) @ 3.8 AGeV (2023)

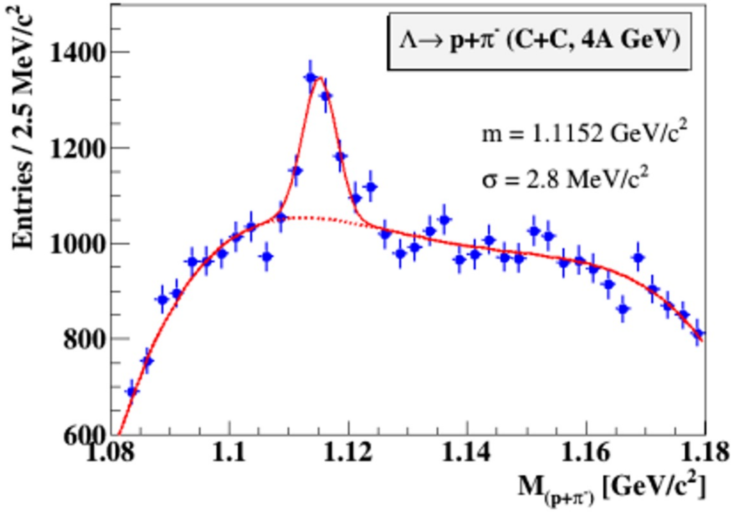


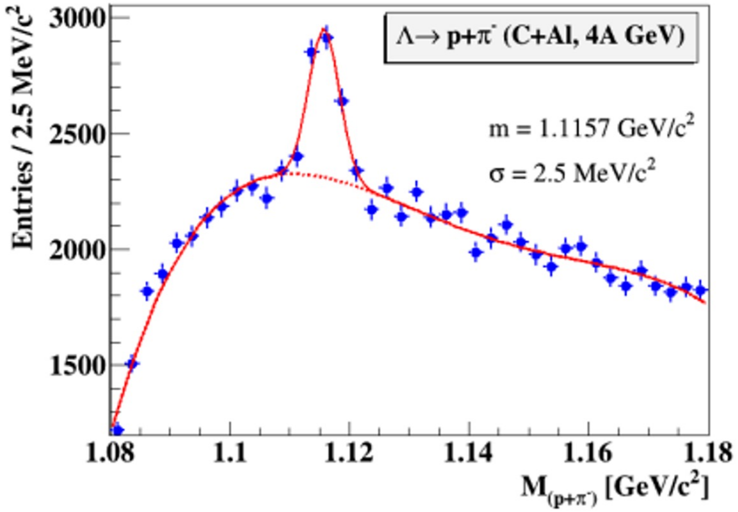
Raw online data
Without dedicated ToF calibration

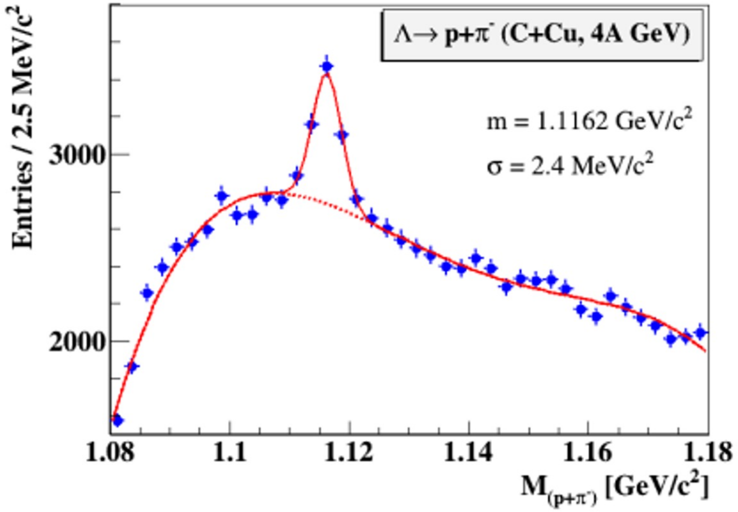
Good PID capabilities

Hyperon extraction performance

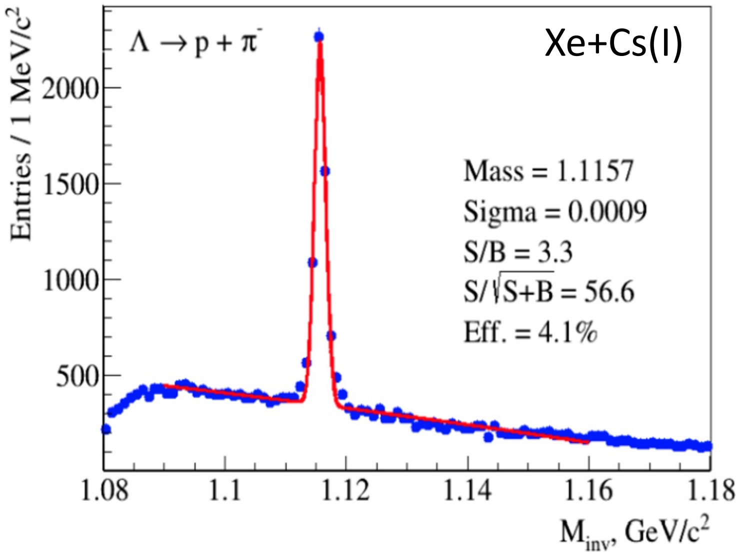
Data from 2018 run

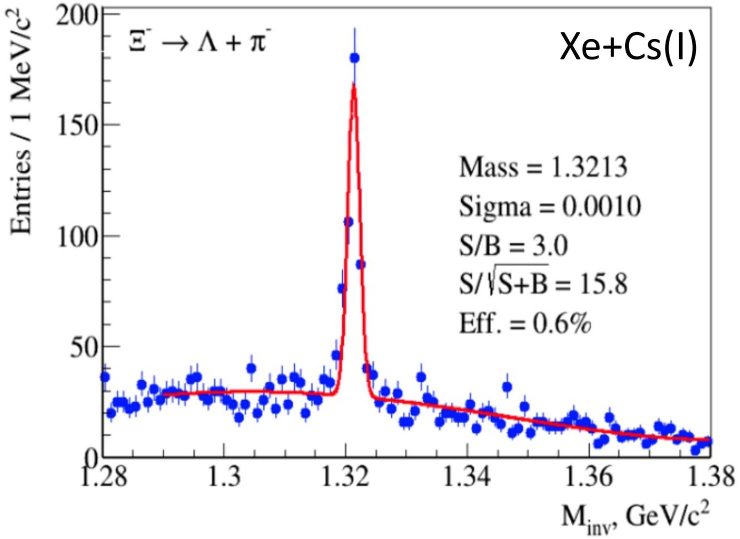


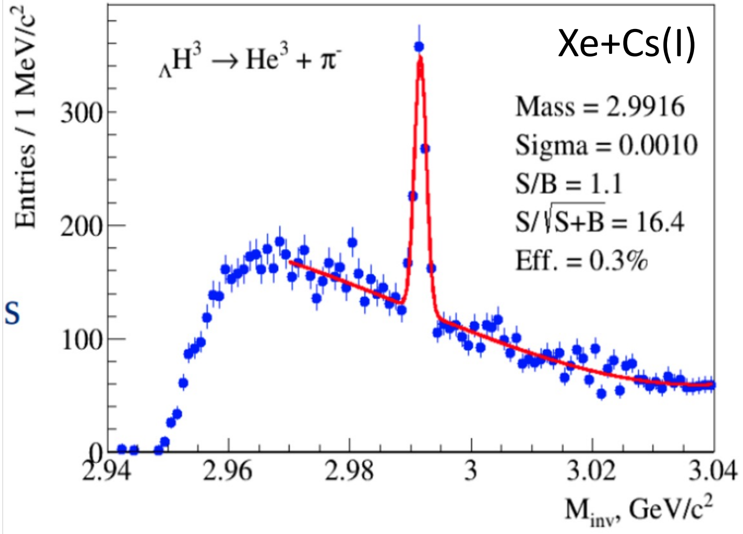




Xe+Cs(I) performance

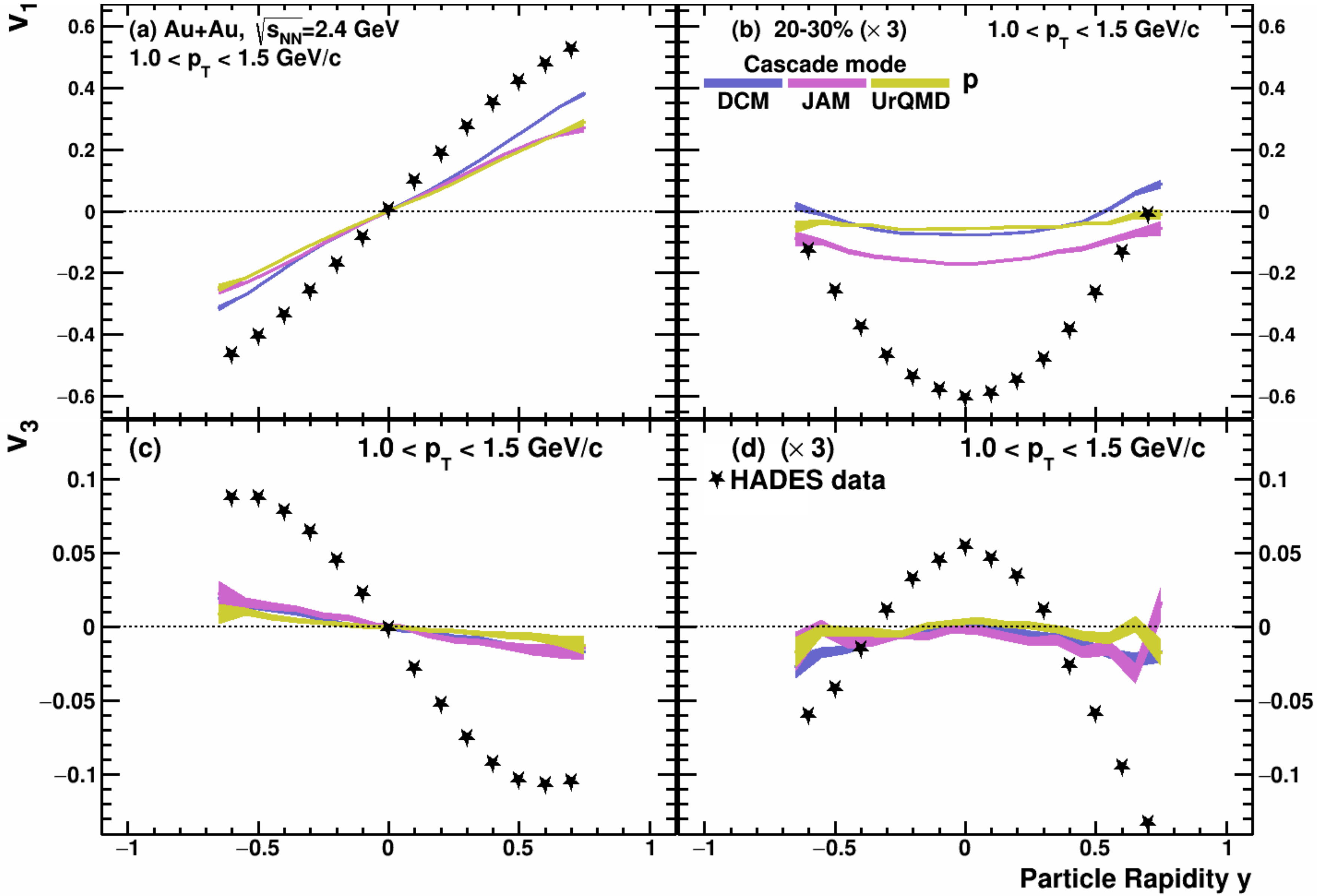






Improved performance for hyperon measurements is expected for the new Xe+Cs(I) run

$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: cascade models

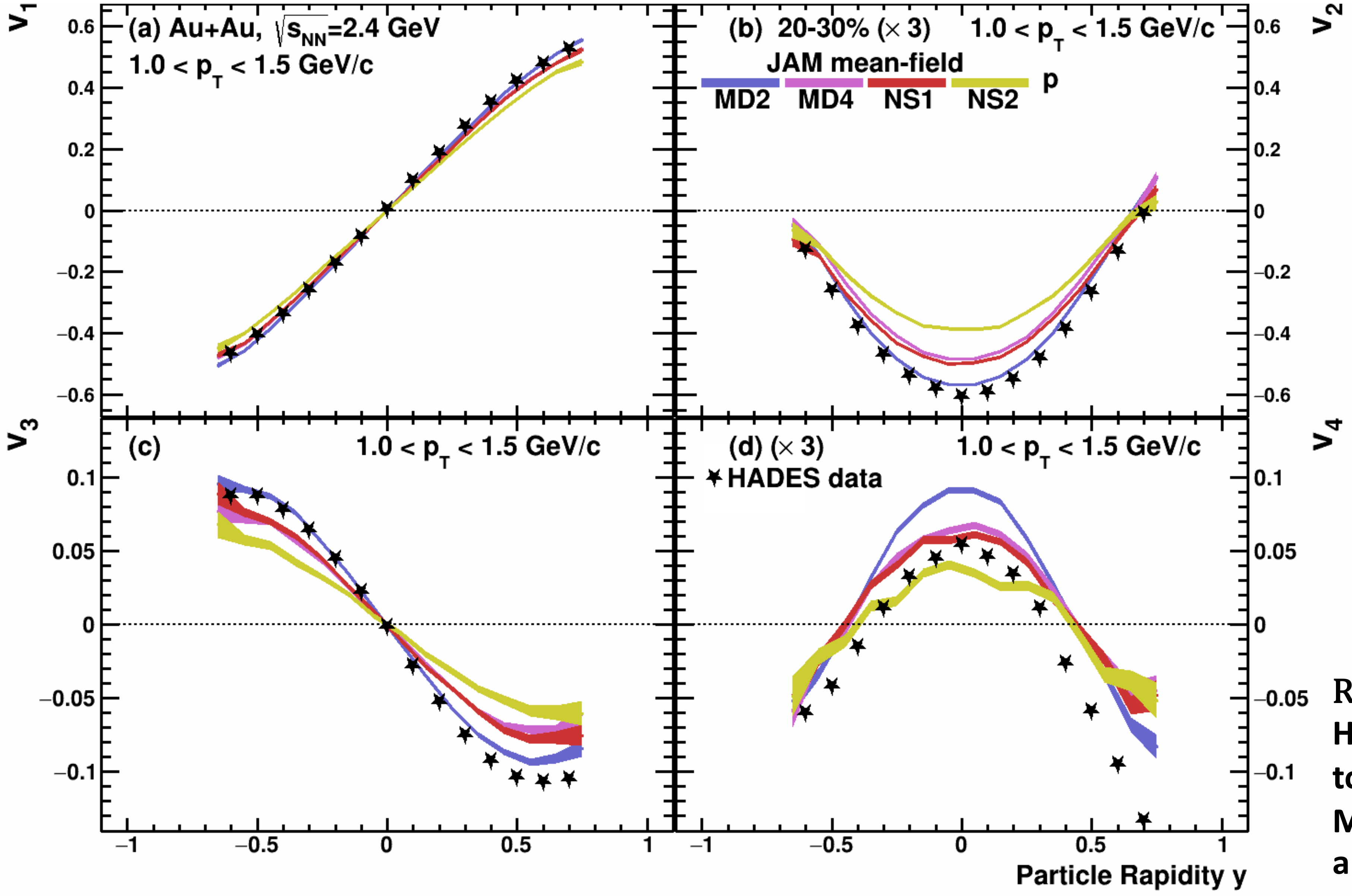


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c
$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

Cascade models fail to reproduce HADES experimental data

$v_n(y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data



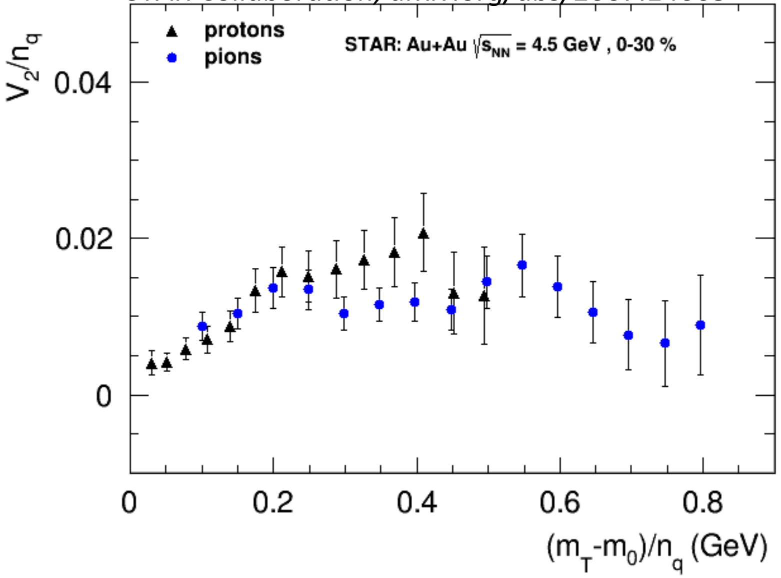
Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}$(y): 1.0 < pT < 1.5 GeV/c
$V_{2,4}$(y): 1.0 < pT < 1.5 GeV/c

Reasonable agreement for $v_n(y)$
Higher harmonics are more sensitive to different EOS than v_1
More JAM results with different EOS are needed

NCQ scaling: hybrid and cascade models

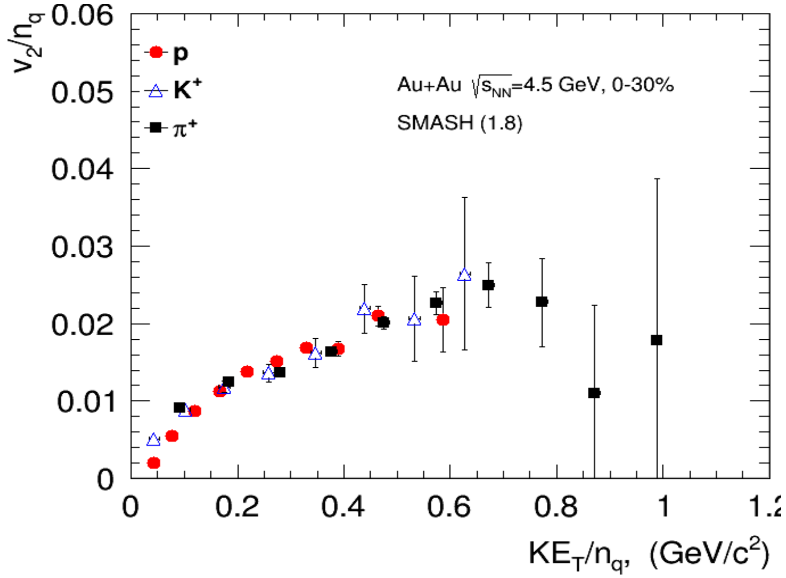
STAR Collaboration, arxiv.org/abs/2007.14005

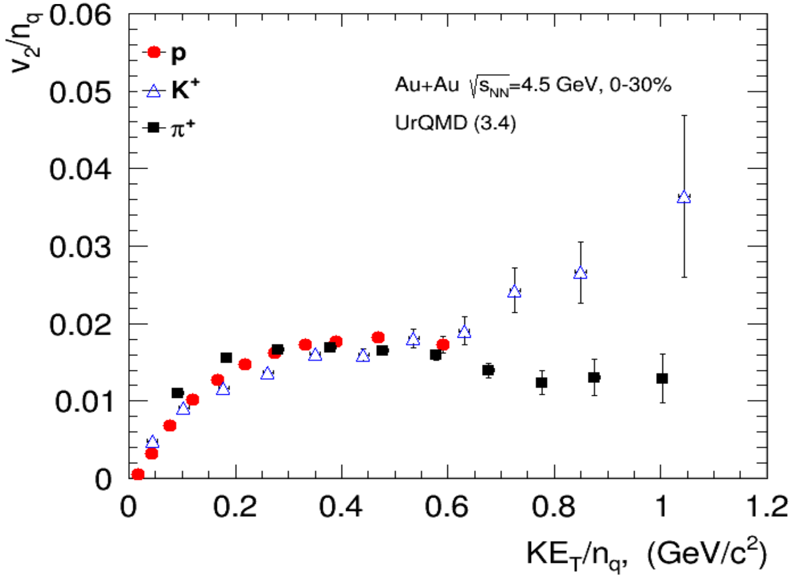


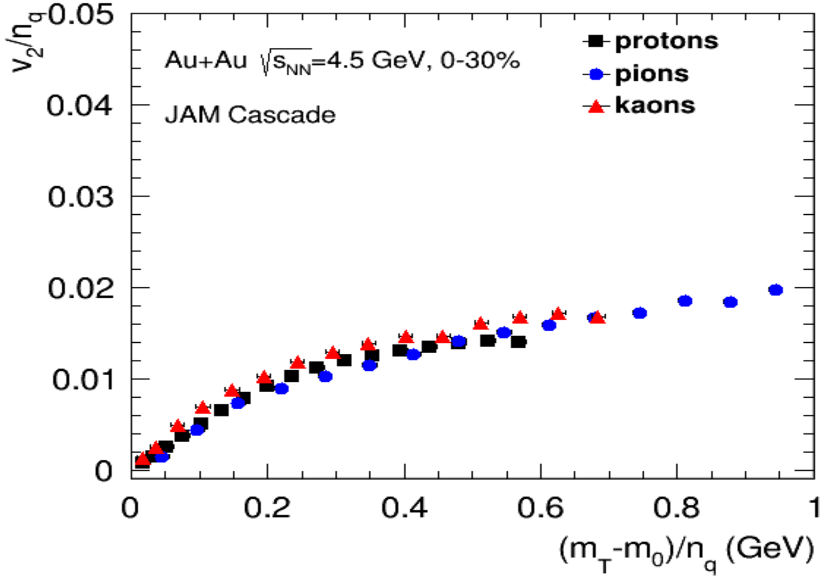
NCQ scaling: $\boldsymbol{v_n(p_T) \to v_n/n_q^{n/2}\left(\frac{KE_T}{n_q}\right)}$ $n_q = \begin{cases} 2 \text{ for mesons} \\ 3 \text{ for baryons} \end{cases}$ $KE_T = \sqrt{m^2 + p_T^2} - m$

- Scaling holds up at 4.5 GeV in STAR data and pure string/hadronic cascade models (without partonic d.o.f.)

$\boldsymbol{KE_T/n_q}$ scaling at 4.5 GeV might be accidental – more careful studies should be performed

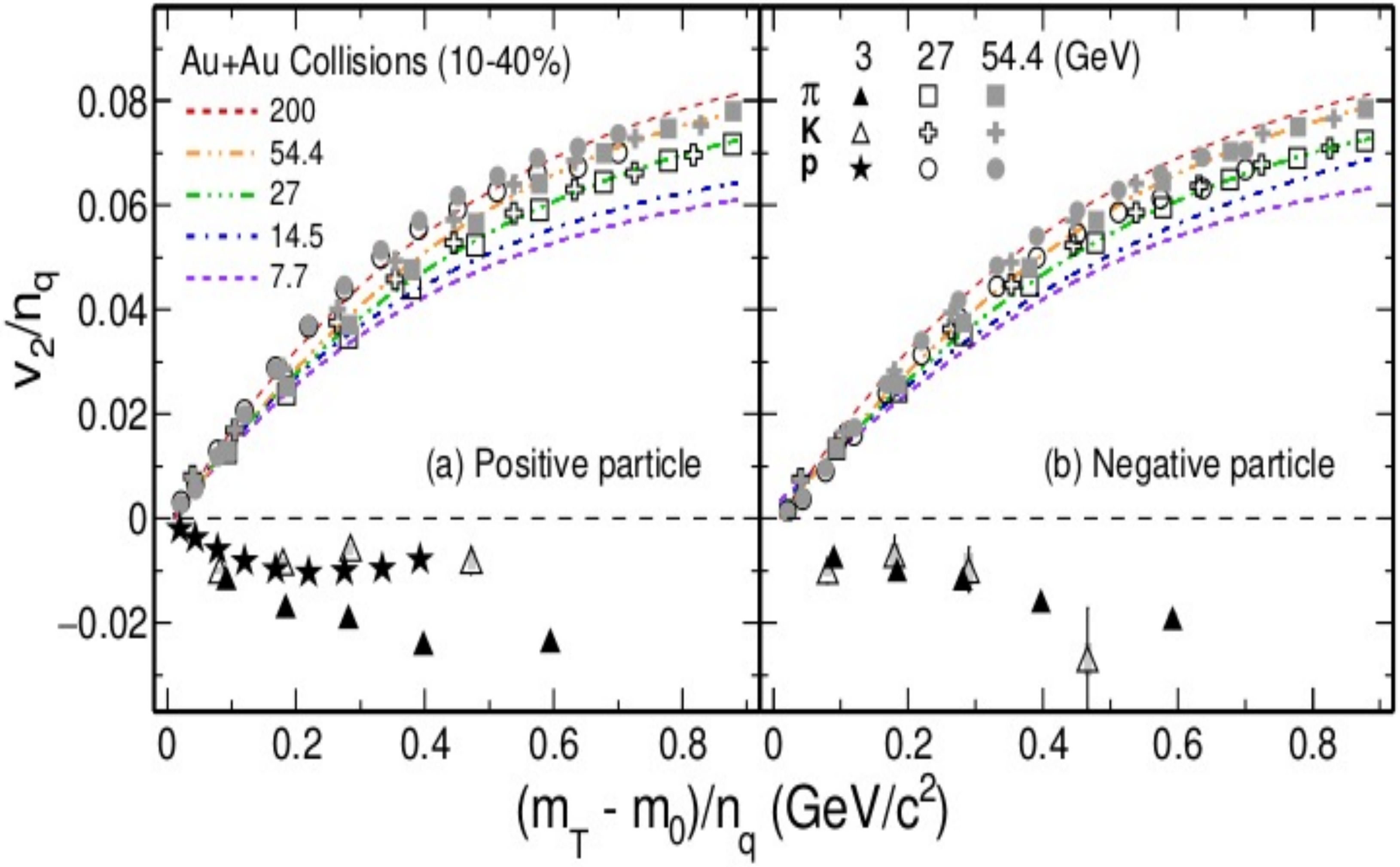






Dissapearence of partonic collectivity in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions at RHIC

Phys. Lett. B 827, 137003 (2022)



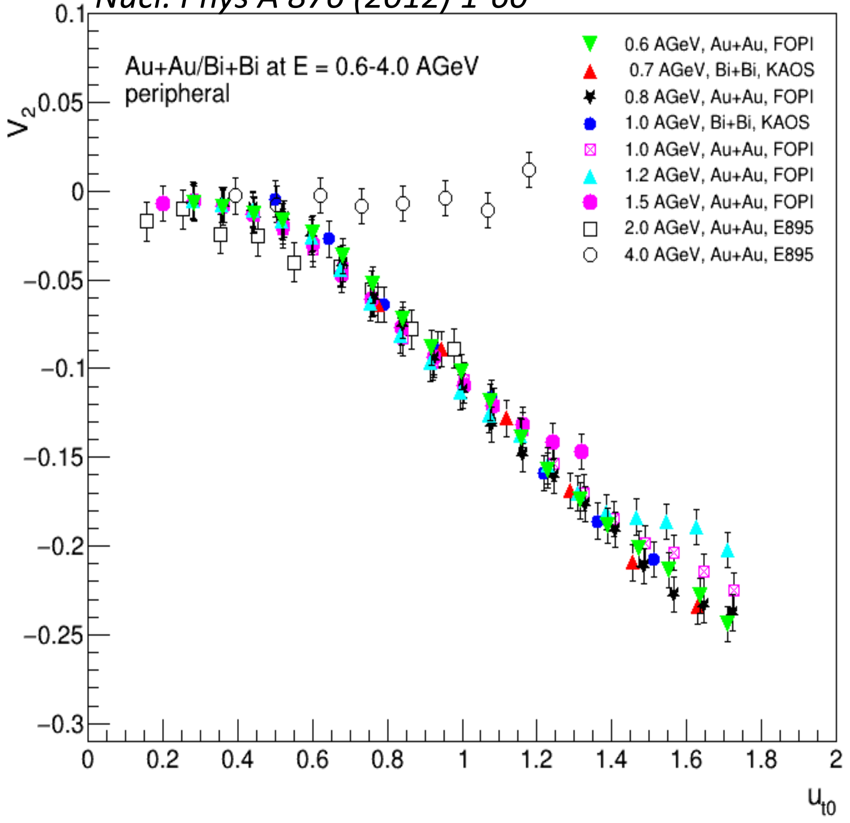
Breaking of NCQ scaling at 3 GeV

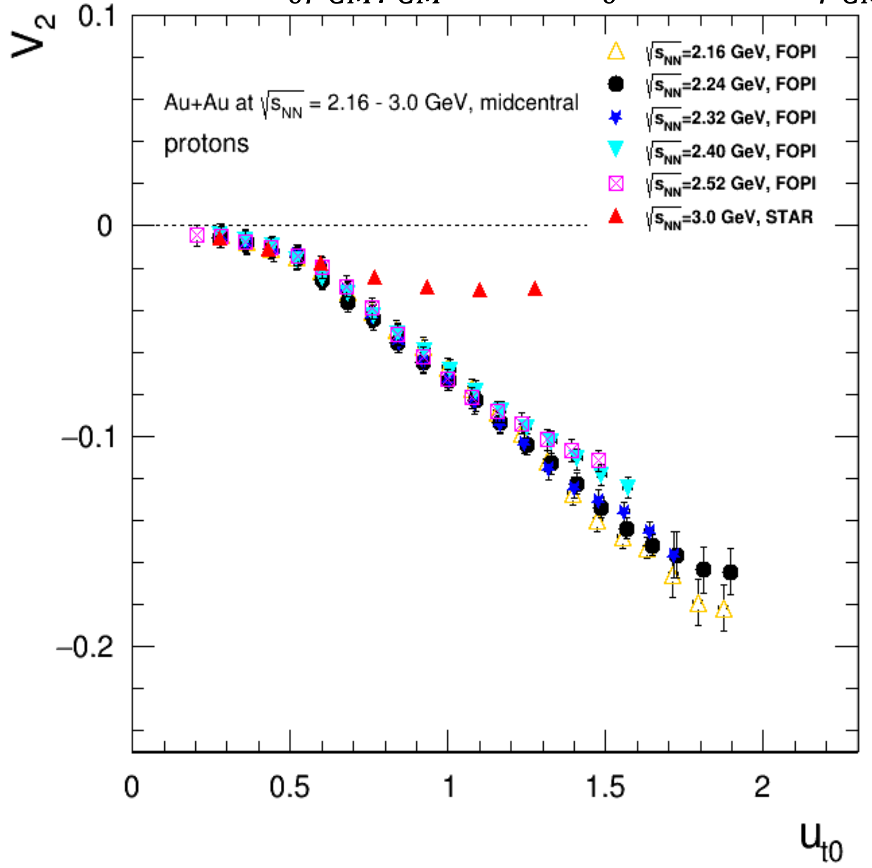
"imply the vanishing of partonic collectivity and a new EOS, likely dominated by baryonic interactions in the high baryon density region"

Scaling relations at SIS – scaling with passage time

$$u_{t0} = \frac{p_T}{m_0 \beta_{CM} \gamma_{CM}} \equiv \frac{p_T t_{pass}}{2R m_0} \quad t_{pass} = \frac{2R}{\beta_{CM}\gamma_{CM}}$$

Nucl. Phys A 876 (2012) 1-60

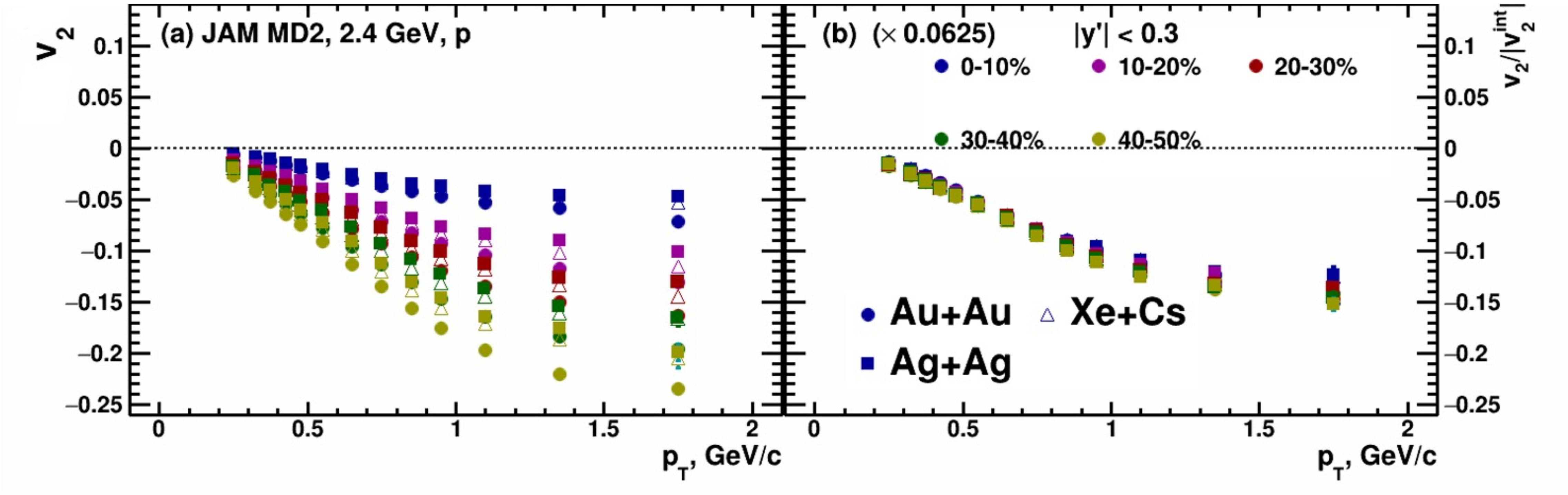




- The rather good scaling observed suggests that c_s does not change significantly over beam energy range $E_{kin} = 0.4 - 2$ AGeV ($\sqrt{s_{NN}} = 2 - 2.7$ GeV)
- Scaling breaks at $E_{kin} = 2.9$ AGeV ($\sqrt{s_{NN}} = 3$ GeV)

$\left|v_n^{int}\right|$ scaling: JAM MD2 model – Nuclotron energies

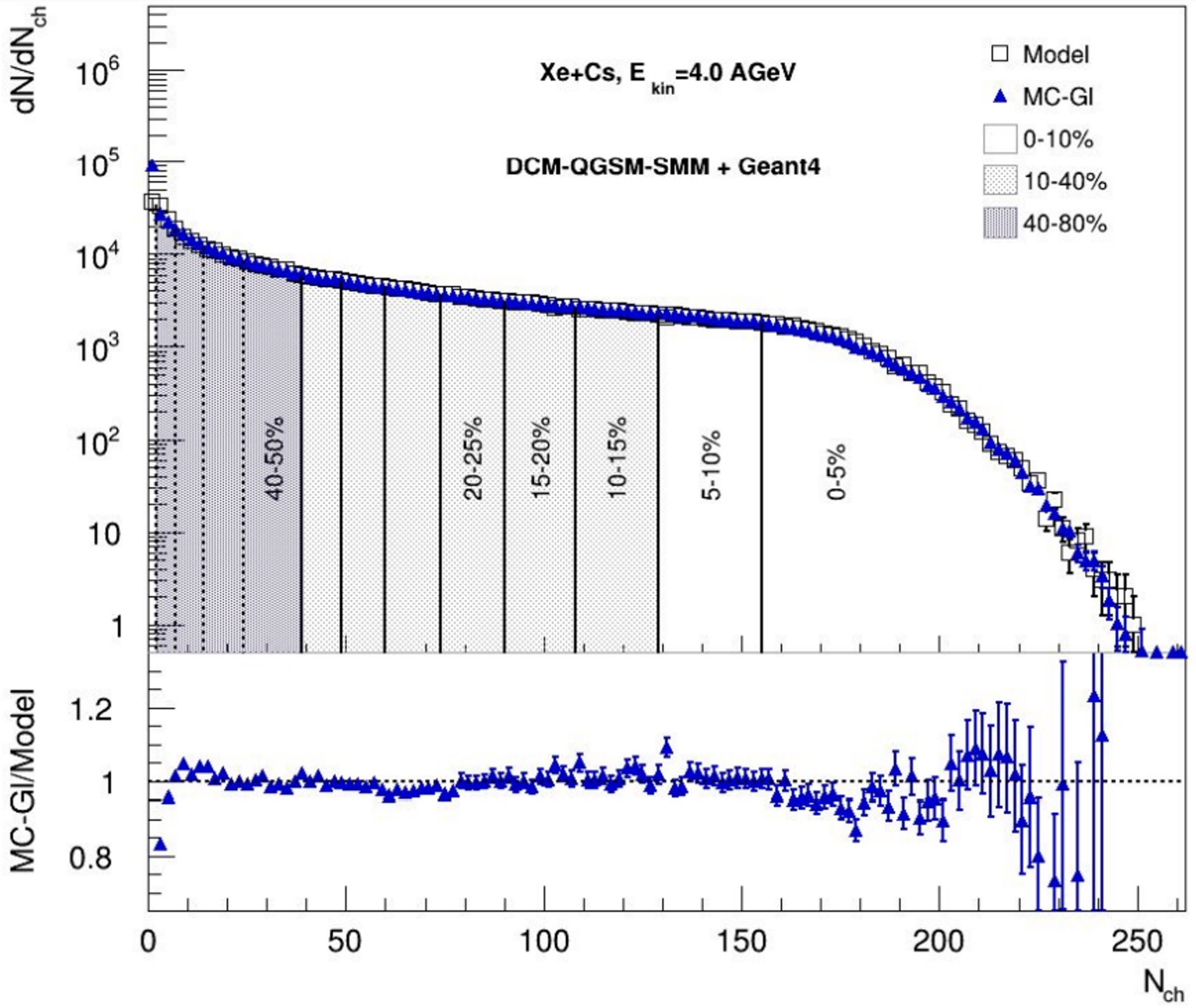
$$\left|v_n^{int}\right| = \left|\langle v_n(p_T, y, \text{centrality}, \text{PID})\rangle_{p_T,y}\right|$$

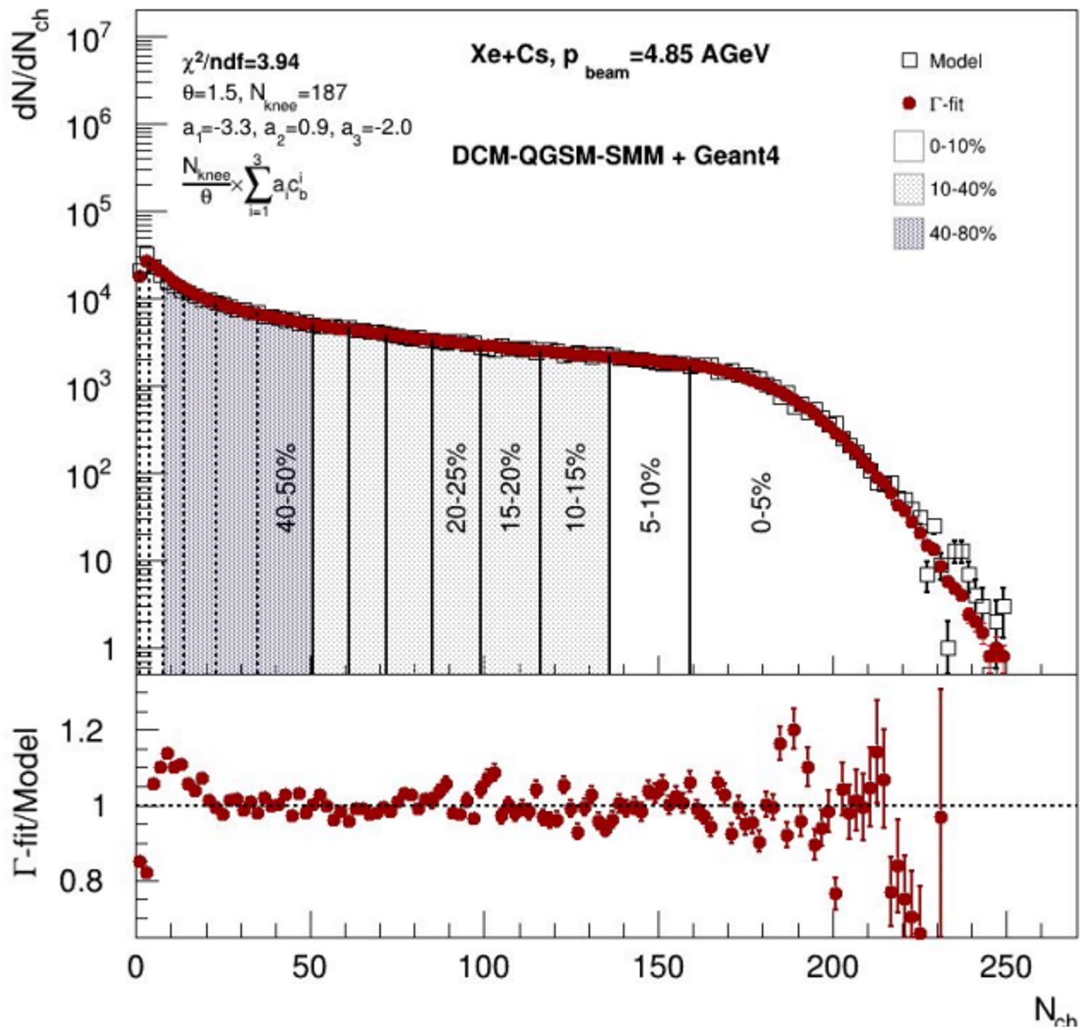


Scaling works for JAM model at $\sqrt{s_{NN}} = 2.4$ GeV for Au+Au, Xe+Cs and Ag+Ag collisions

Provides a useful tool to make comparison of v_n results from different colliding systems

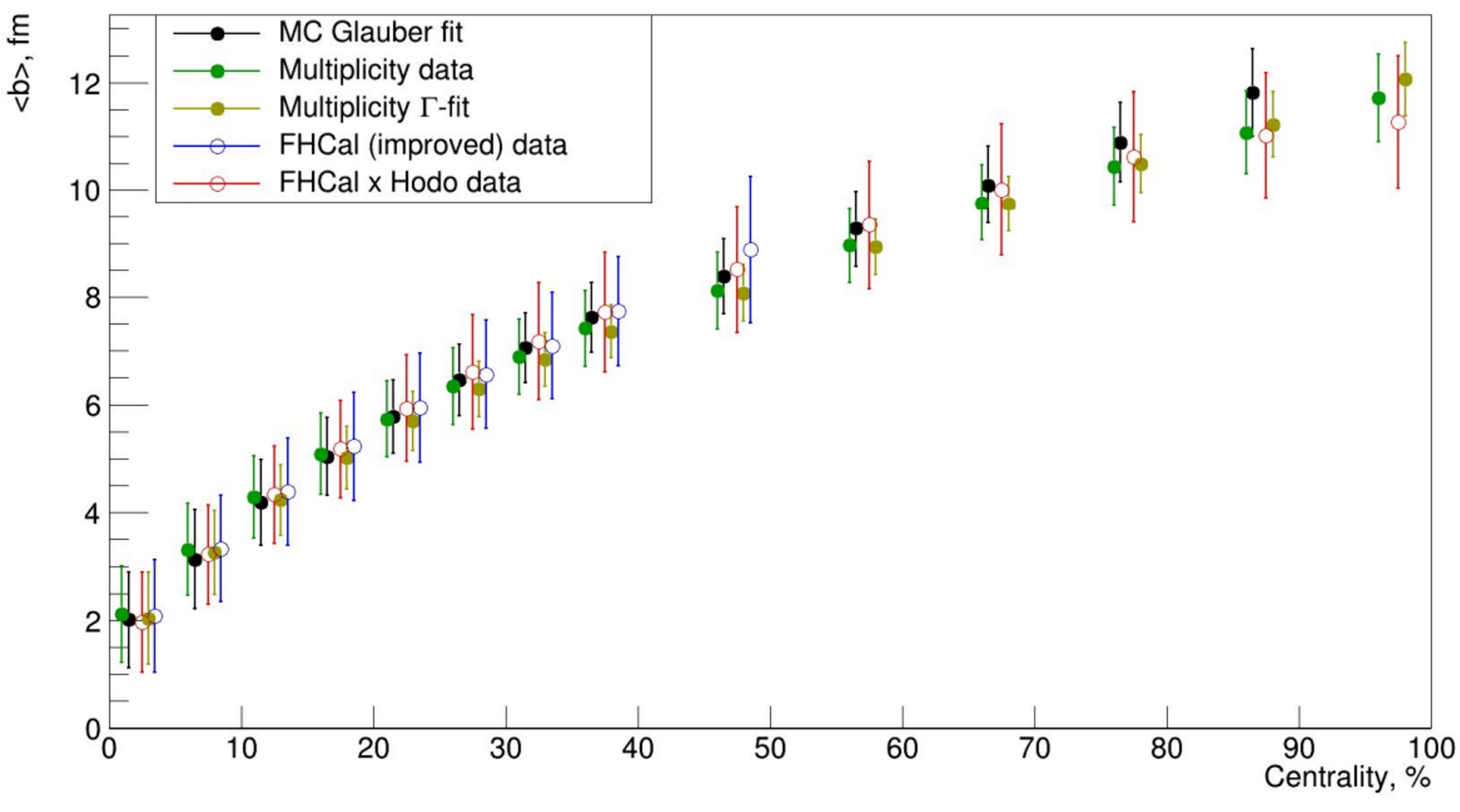
Centrality determination at BM@N





- 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

Flow vectors

From momentum of each measured particle one can define a u_n-vector in a transverse plane:

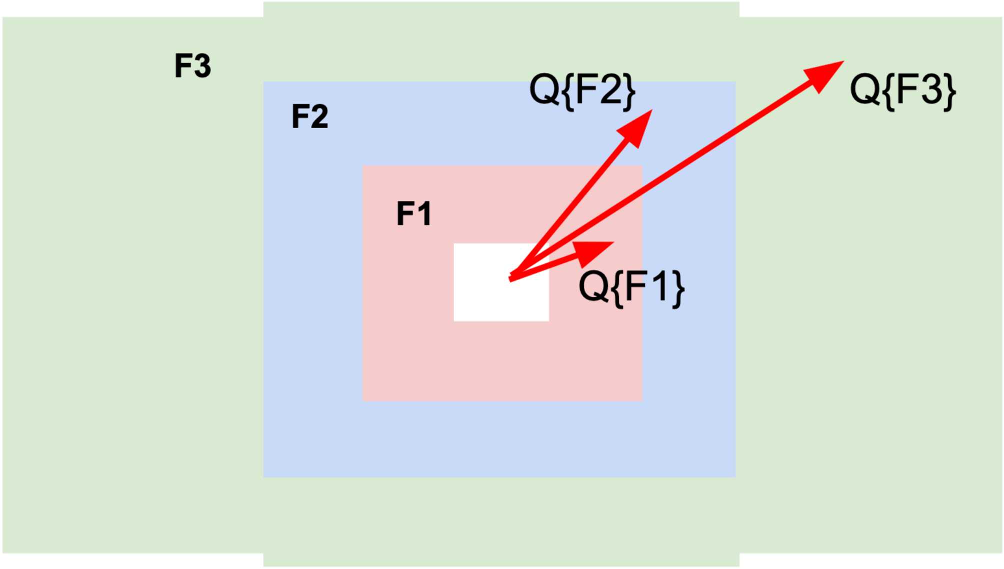
$$u_n = e^{in\varphi}$$

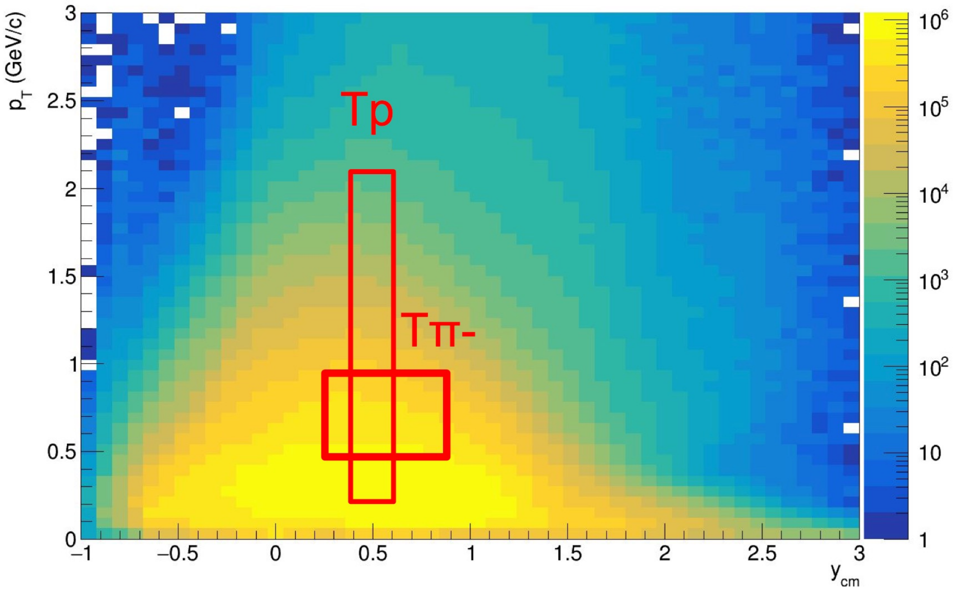
where φ is the azimuhtal angle of a particle

Q_n-vector can be defined as a sum of some group of u_n-vectors (subevent):

$$Q_n = \frac{\sum_{k=1}^{N} w_n^k u_n}{\sum_{k=1}^{N} w_n^k} = |Q_n| e^{in\Psi_n^{EP}}$$

Ψ_n^{EP} is the event plane





Additional subevents from tracks not pointing at FHCal:

Tp: p; $0.4<y<0.6$; $0.2 < pT < 2$ GeV/c; w=1/eff

Tπ: π-; $0.2<y<0.8$; $0.1 < pT < 0.5$ GeV/c; w=1/eff

T-: all negative; $1.0<\eta<2.0$; $0.1 < pT < 0.5$ GeV/c; w=1/eff

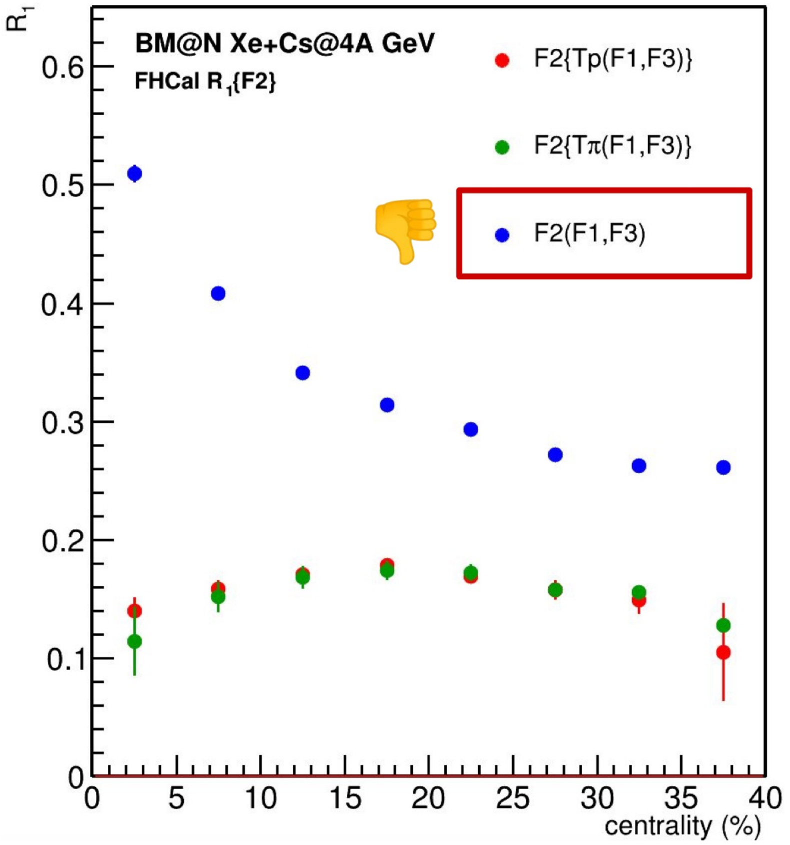
Methods for v_n calculation

Scalar product method:

$$v_1 = \frac{\langle u_1 Q_1^{F1} \rangle}{R_1^{F1}}, \qquad v_2 = \frac{\langle u_2 Q_1^{F1} Q_1^{F3} \rangle}{R_1^{F1} R_1^{F3}}$$

where R_1 is the resolution correction factor:

$$R_1 = \langle \cos(\Psi_1^{EP} - \Psi_{RP}) \rangle$$



Symbol "F2(F1,F3)" means R_1 is calculated for Ψ_1^{F2} using 3 subevents F1, F2, F3:

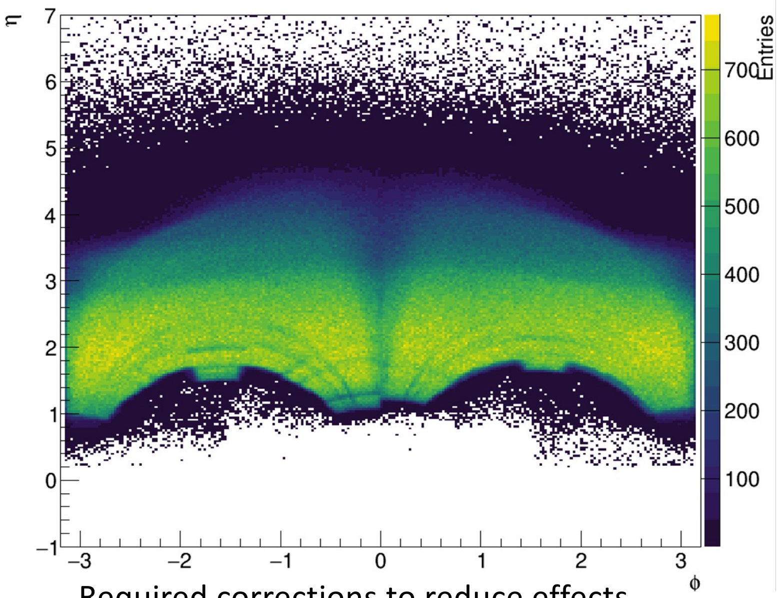
$$R_1^{F2(F1,F3)} = \frac{\sqrt{\langle Q_1^{F2} Q_1^{F1} \rangle \langle Q_1^{F2} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}$$

Symbol "F2{Tp(F1,F3)}" means R_1 is calculated for Ψ_1^{F2} using 4 subevents Tp, F1, F2, F3:

$$R_1^{F2\{Tp(F1,F3)\}} = \langle Q_1^{F2} Q_1^{Tp} \rangle \frac{\sqrt{\langle Q_1^{F1} Q_1^{F3} \rangle}}{\sqrt{\langle Q_1^{Tp} Q_1^{F1} \rangle \langle Q_1^{Tp} Q_1^{F3} \rangle}}$$

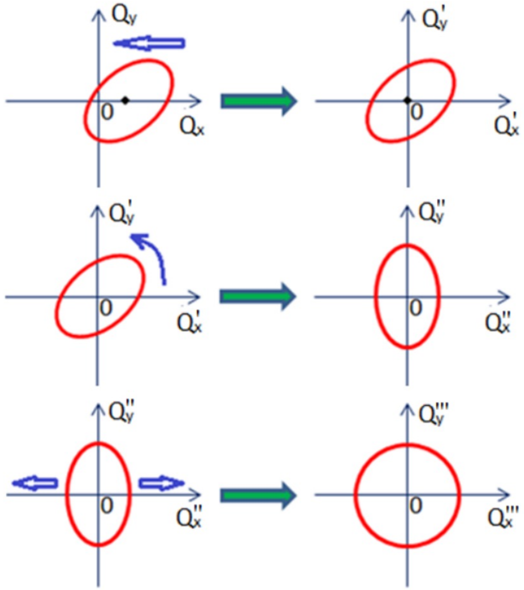
Azimuthal acceptance of the BM@N experiment

ϕ-η yield of protons

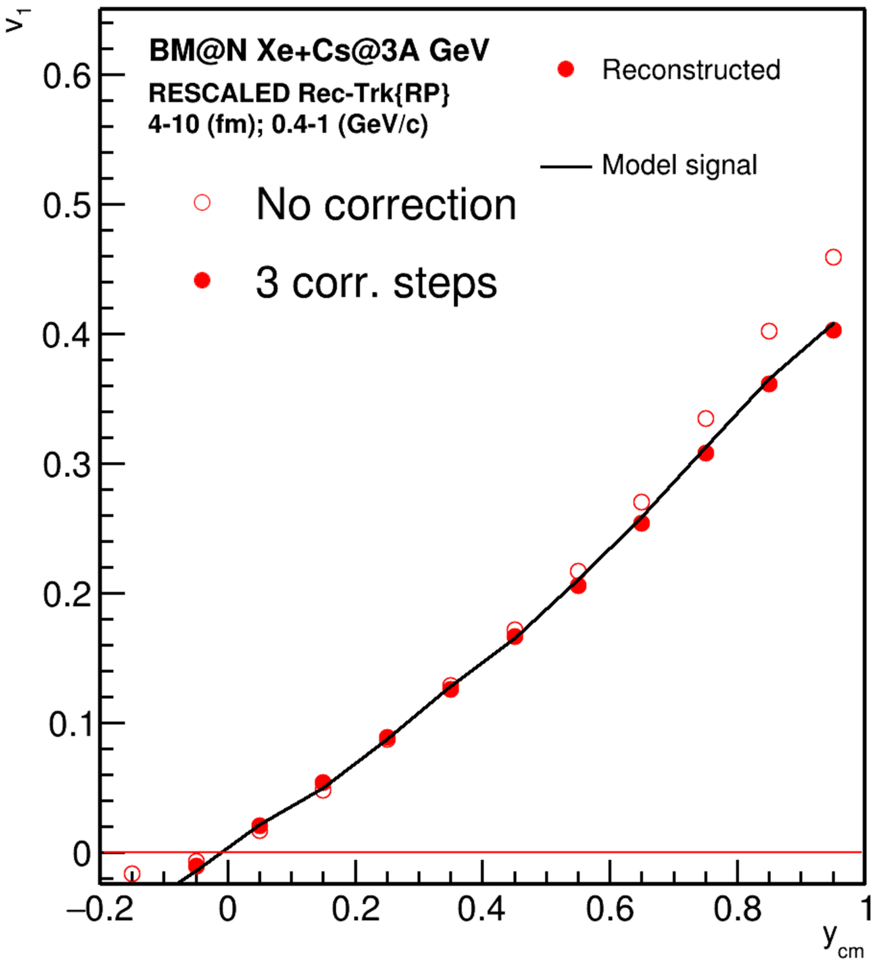


Required corrections to reduce effects of non-uniform azimuthal acceptance

1. Recentering
2. Twist
3. Rescaling

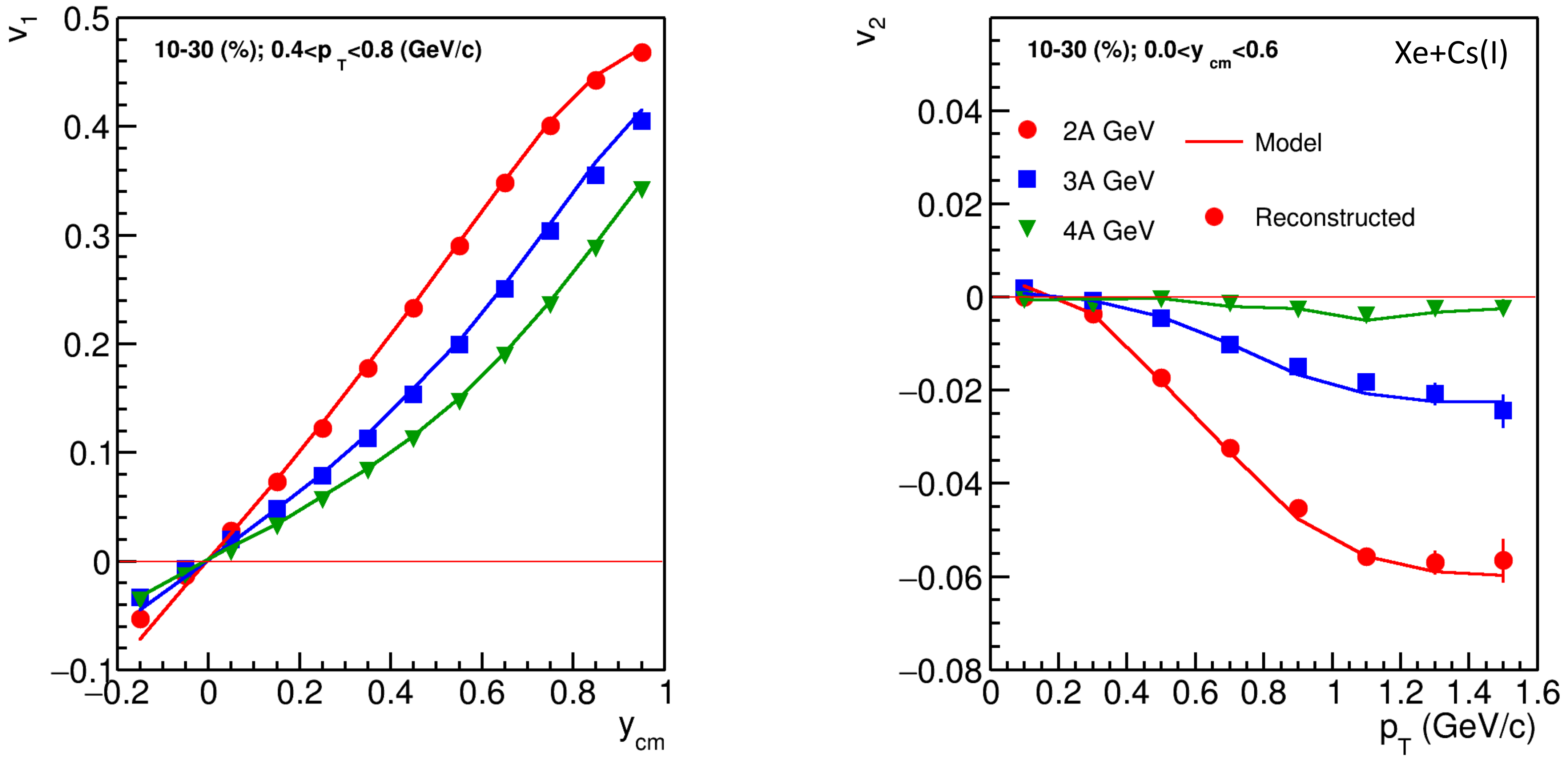


Corrections are based on method in:
I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)



Better agreement after rescaling

Directed and elliptic flow at BM@N



- 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) and recent physical run (Xe+CsI).

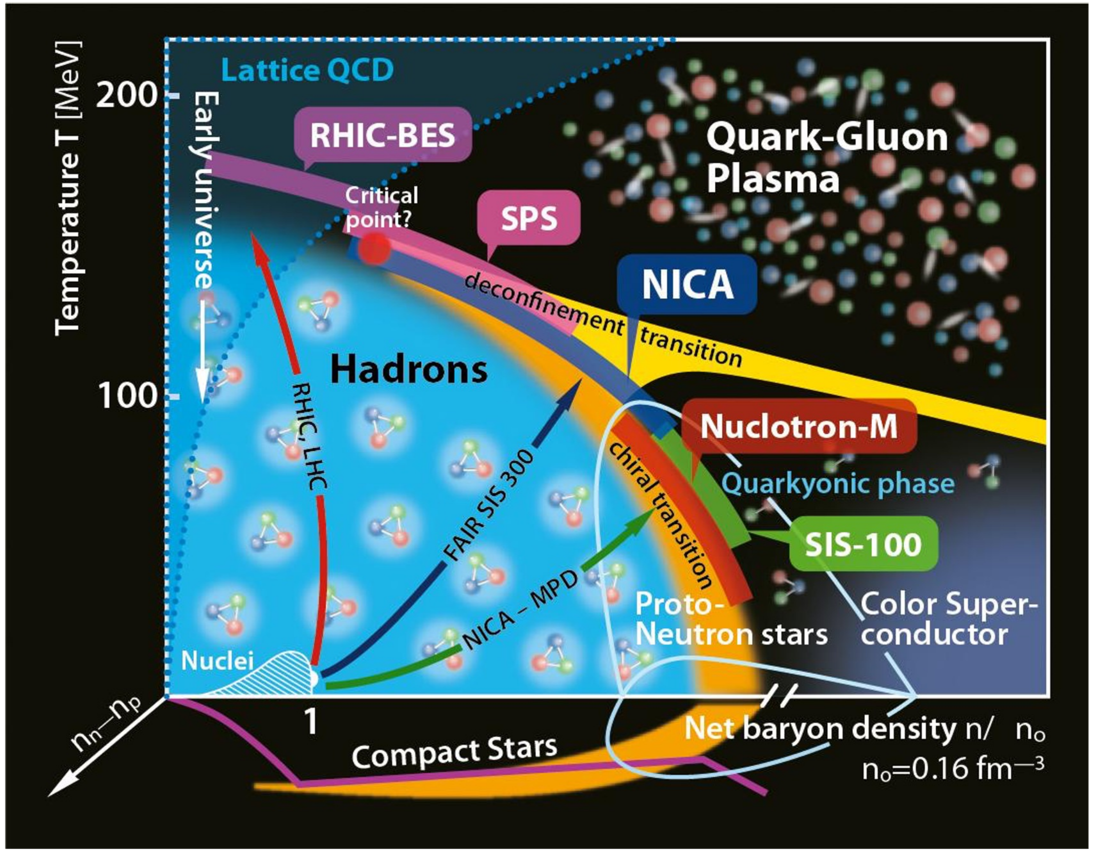
Physics analysis of the data is in its active phase, results expected to be published.

Preparation for the next experimental runs as well as the data processing from the first physical run (calibrations, physics feasibility studies ...) are ongoing.

Thank you for your attention!

Backup slides

QCD Phase diagram: high baryon density region

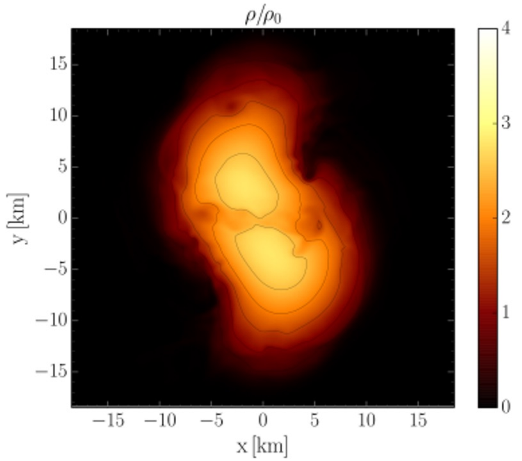


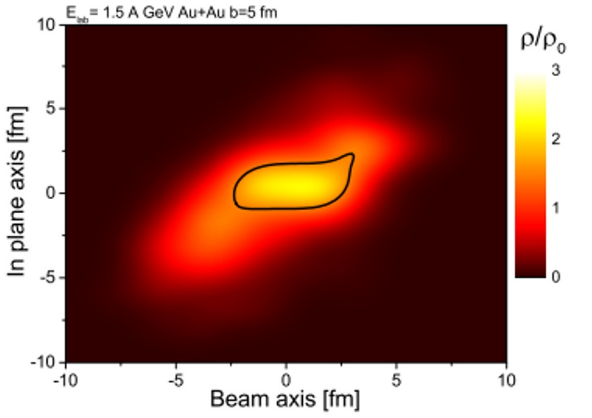
The energy regime of the Nuclotron will test the region of the possible QCD phase transition

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

Experimental data from BM@N can provide further constraints on the symmetric matter at similar densities

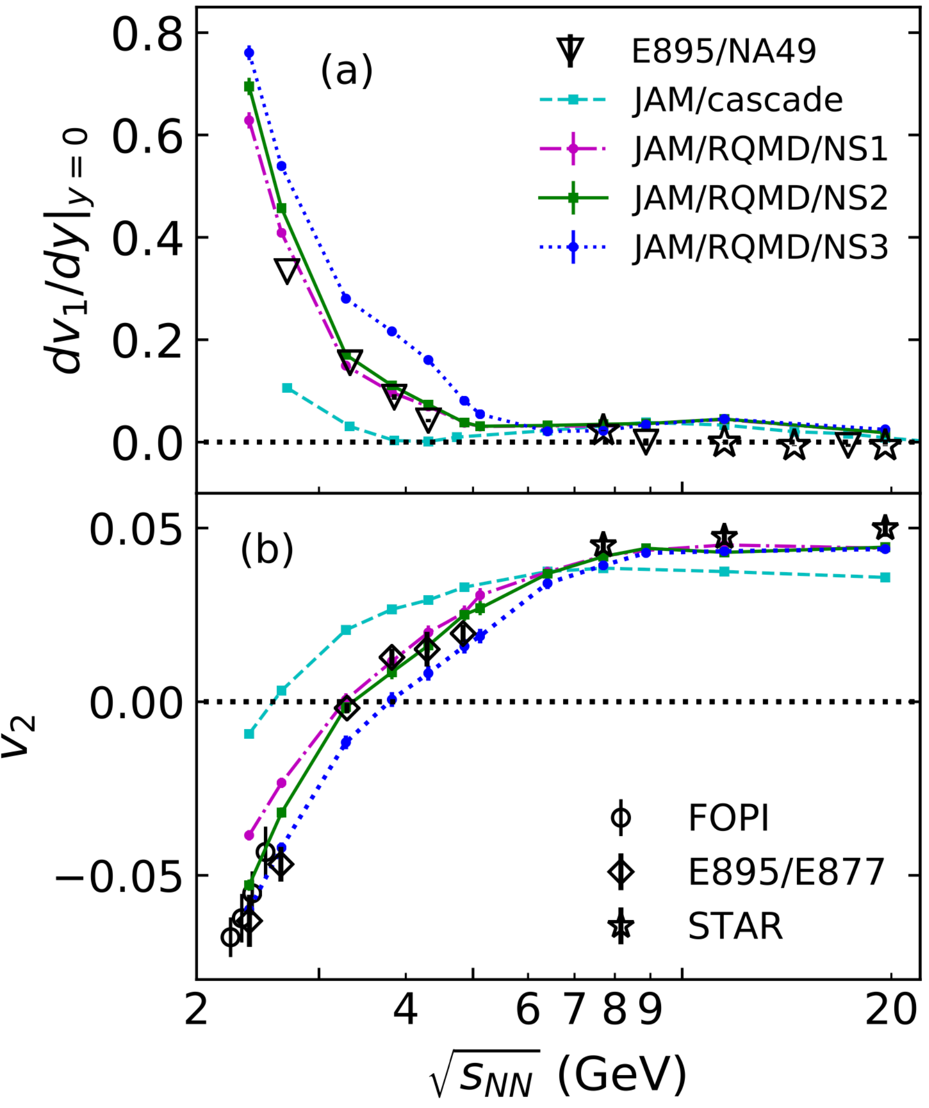
M. Hanauske et al., J. Phys.: Conf. Ser. 878 012031





Anisotropic flow study at $\sqrt{s_{NN}}$=2-4 GeV with JAM model

Y.Nara, et al., Phys. Rev. C 100, 054902 (2019)



To study energy dependence of v_n, JAM microscopic model was selected (ver. 1.90597)

NN collisions are simulated by:

- $\sqrt{s_{NN}}$<4 GeV: resonance production
- 4<$\sqrt{s_{NN}}$<50 GeV: soft string excitations
- $\sqrt{s_{NN}}$>10 GeV: minijet production

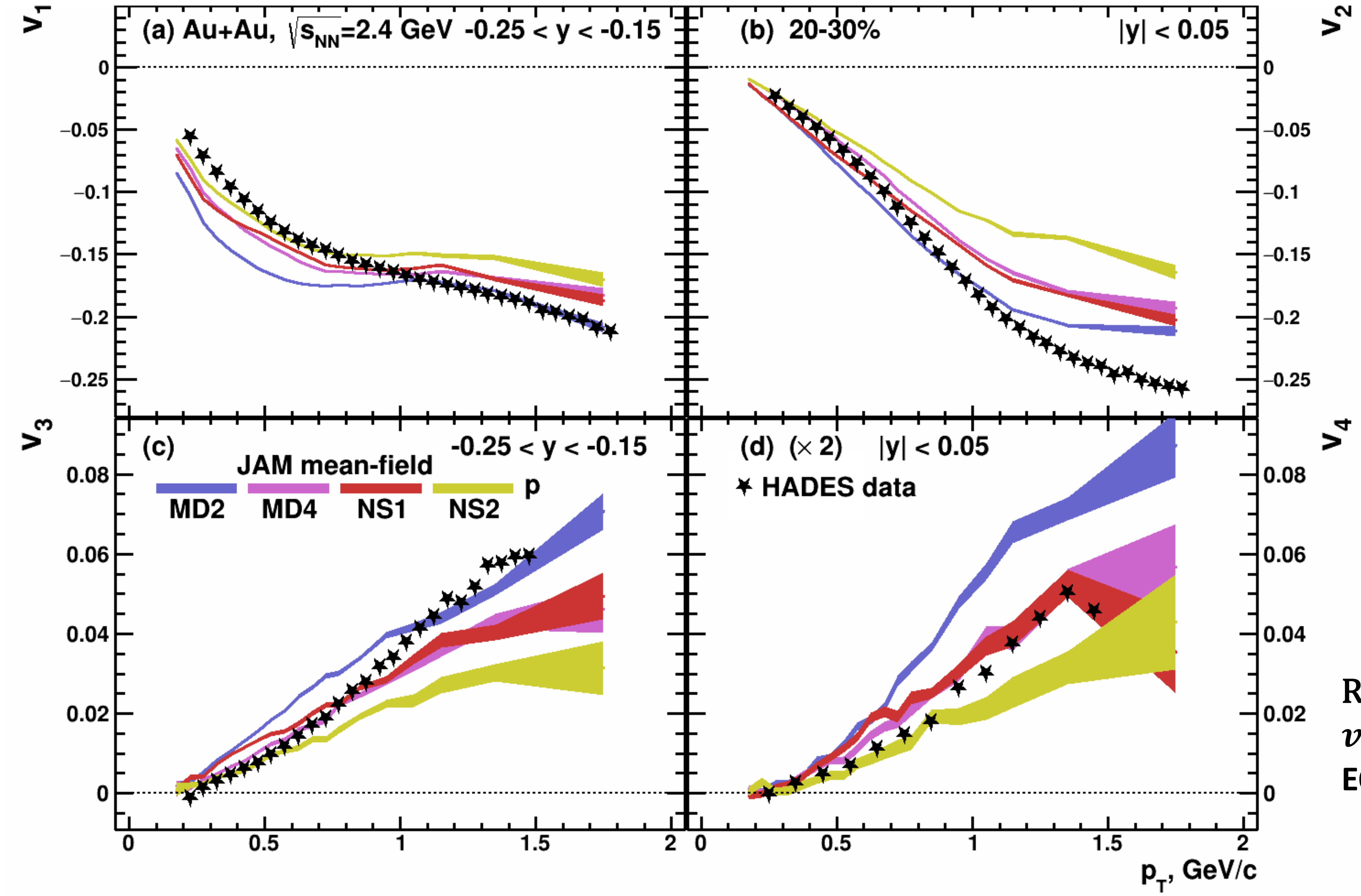
We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

Different EOS were used:

- **MD2** (momentum-dependent potential): K=380 MeV, m^*/m=0.65, $U_{opt}(\infty)$=30
- **MD4** (momentum-dependent potential): K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=67
- **NS1**: K=380 MeV, m^*/m=0.83, $U_{opt}(\infty)$=95
- **NS2**: K=210 MeV, m^*/m=0.83, $U_{opt}(\infty)$=98

Y.Nara, T.Maruyama, H.Stoecker Phys. Rev. C 102, 024913 (2020)
Y.Nara, H.Stoecker Phys. Rev. C 100, 054902 (2019)

$v_n(p_T)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data

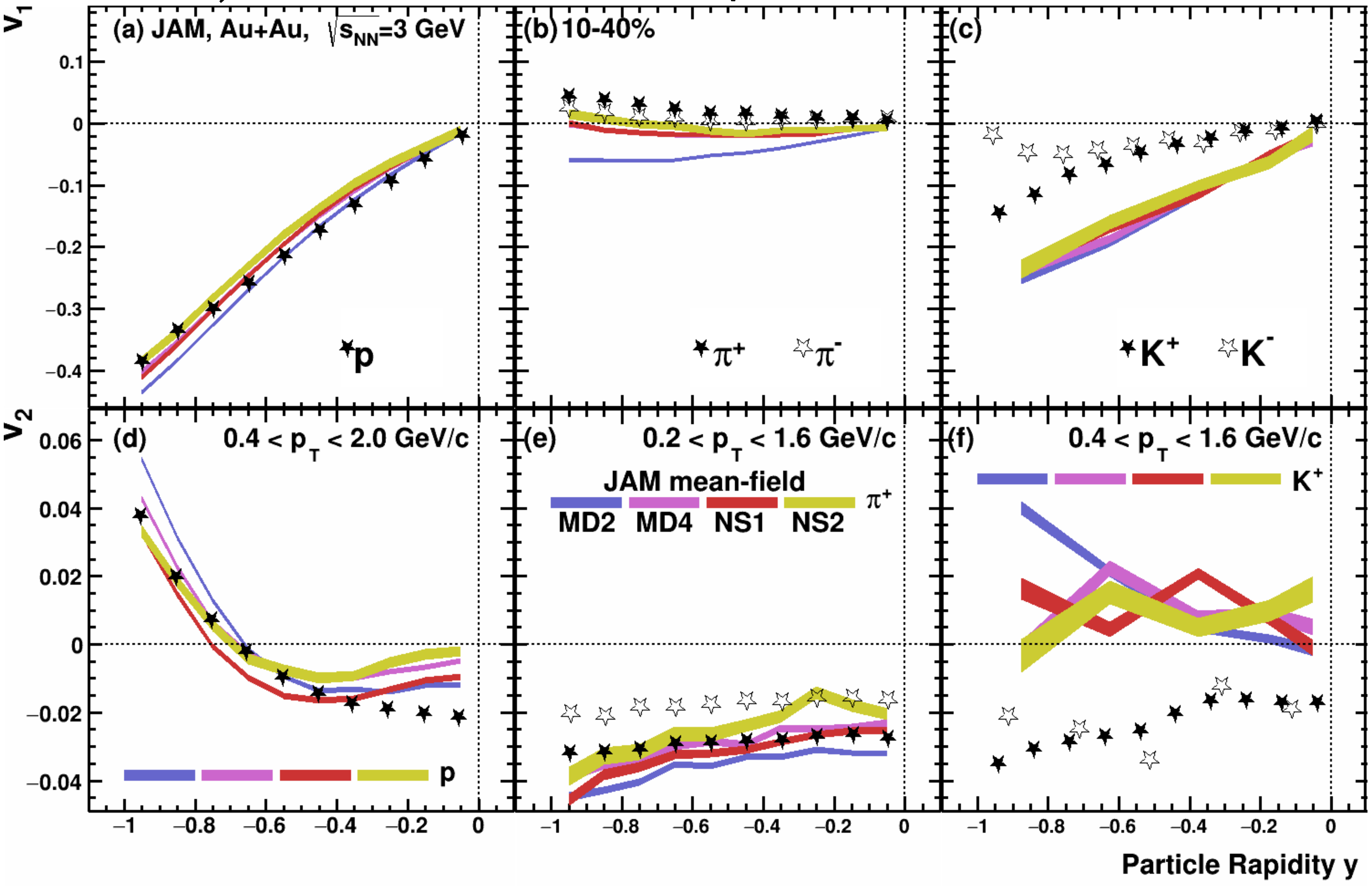


Experimental data points:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{2,4}(p_T)$: -0.05 < y < 0.05

Reasonable agreement for $v_n(p_T)$
$v_{3,4}$ are more sensitive to different EOS than v_1

$v_{1,2}(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data

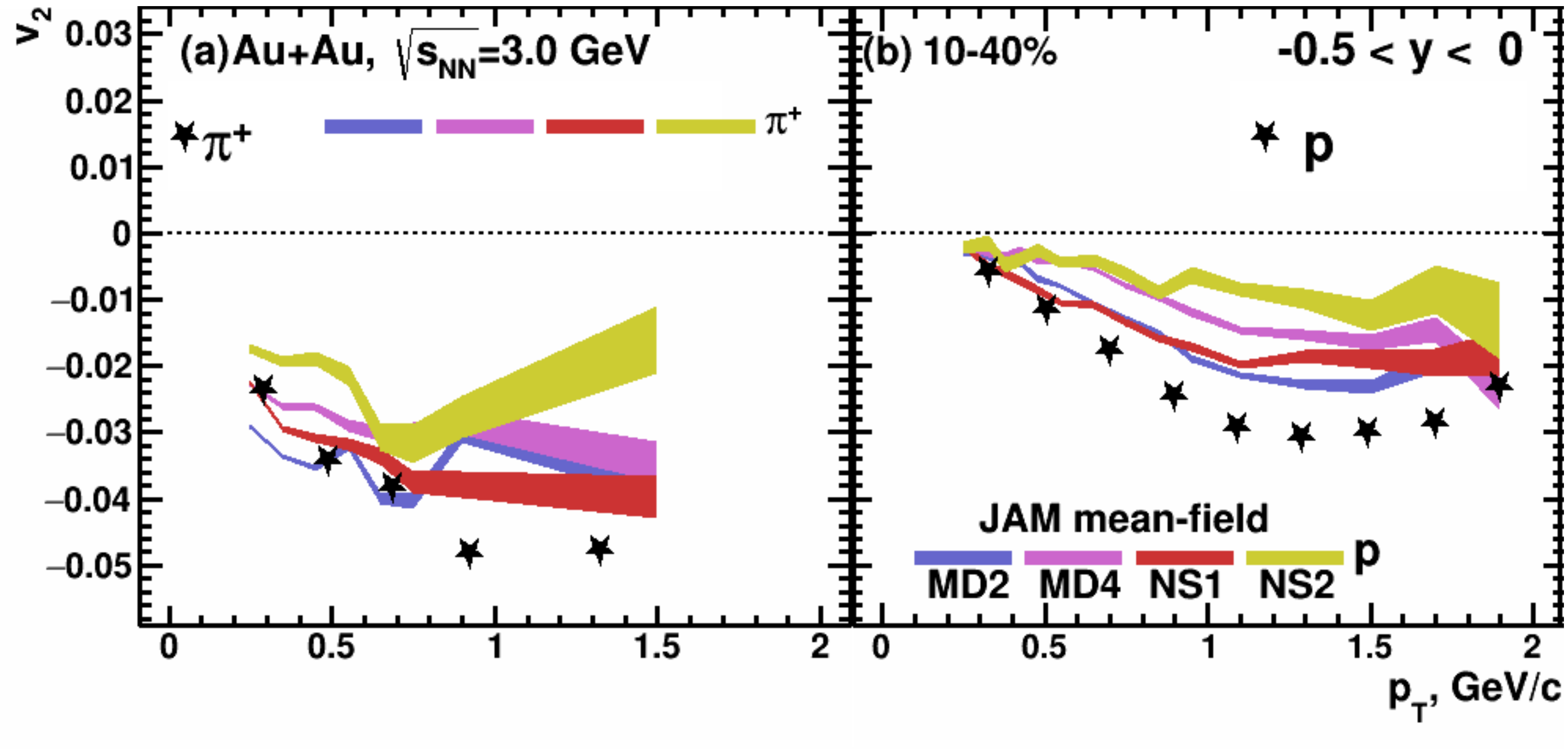


Experimental points are taken from:

M. Abdallah et al. [STAR Collaboration] *Phys.Lett.B* 827 (2022) 137003

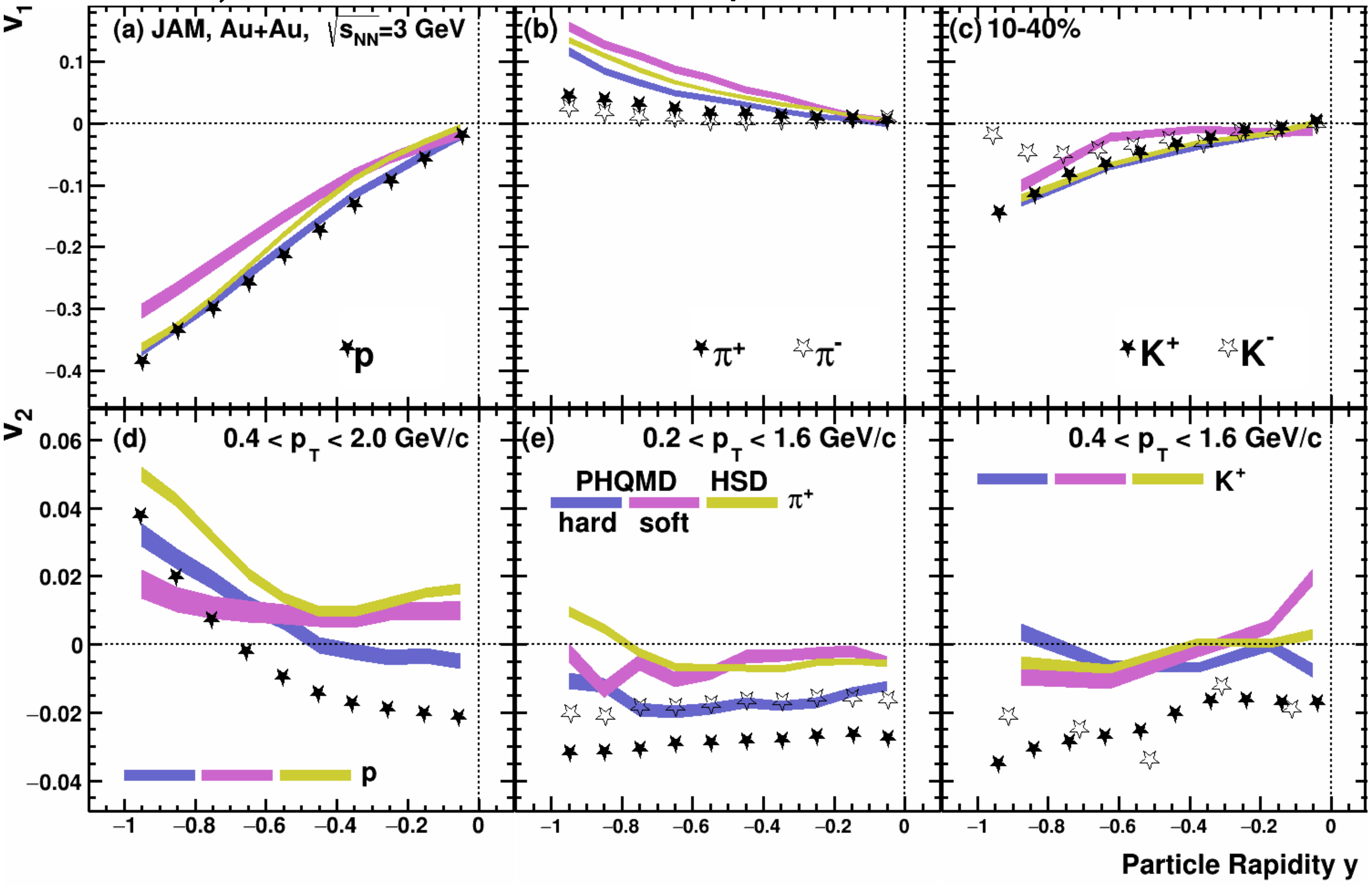
JAM does not describe all particle species equally well
v_1 of pions is most sensitive to different EOS

$v_2(p_T)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



v_2 of pions and protons is more sensitive to different EOS than v_1

$v_{1,2}(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data

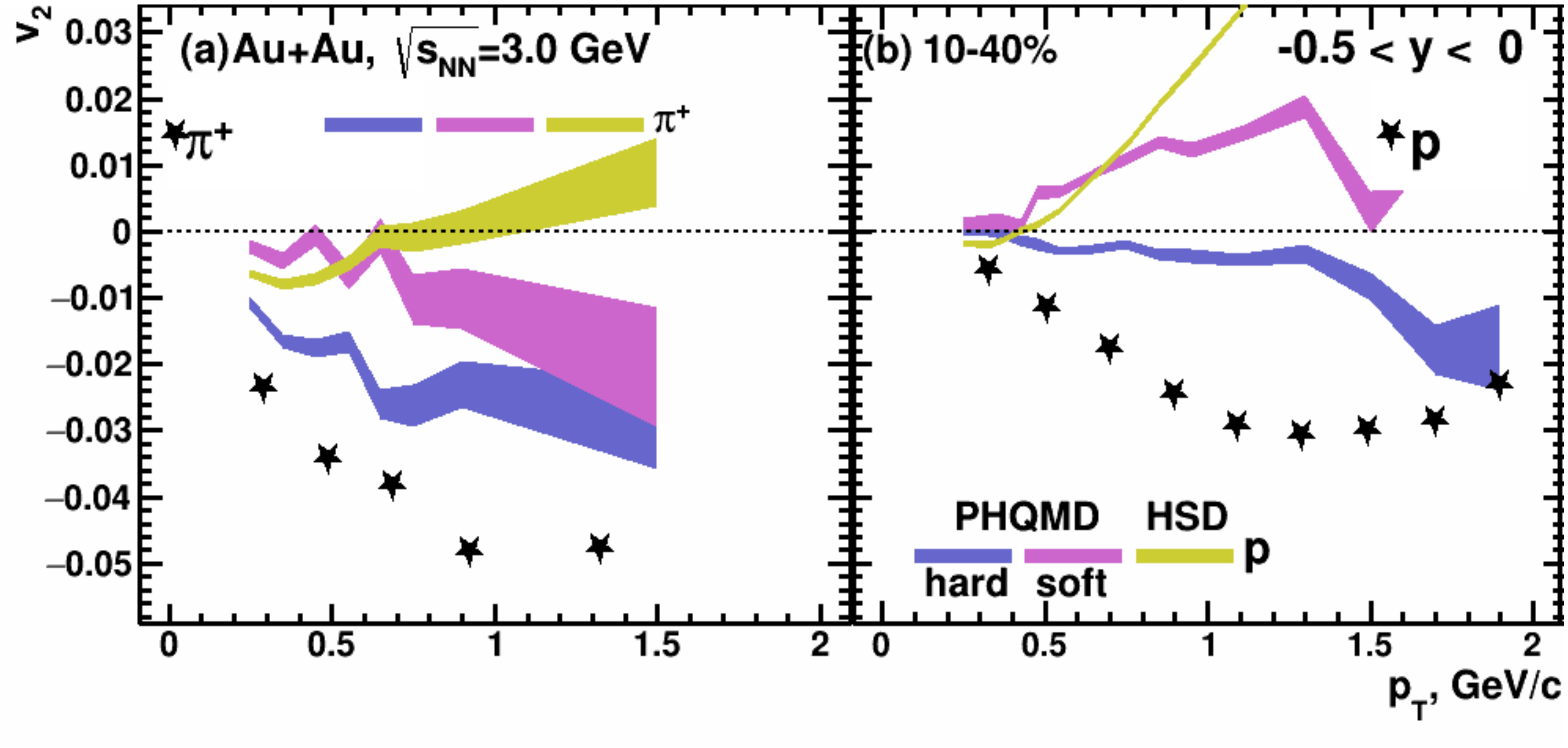


Experimental points are taken from:

M. Abdallah et al. [STAR Collaboration] *Phys.Lett.B* 827 (2022) 137003

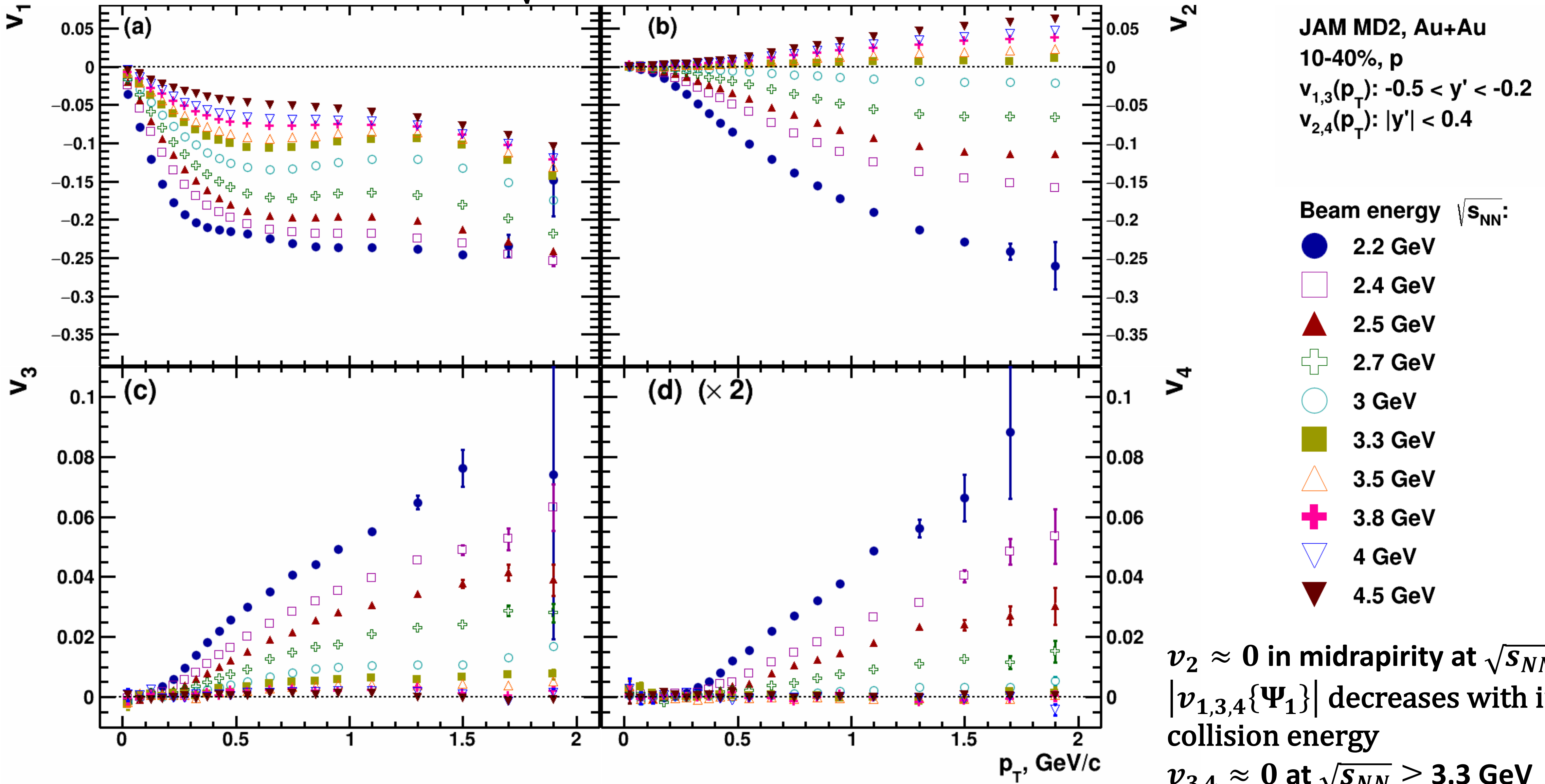
Both PHQMD and HSD cannot reproduce v_2 signal

$v_2(p_T)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data



PHQMD/HSD models cannot reproduce $v_2(p_T)$ of protons

$v_n(p_T)$ Au+Au $\sqrt{s_{NN}}$=2.4-4 GeV: JAM MD2

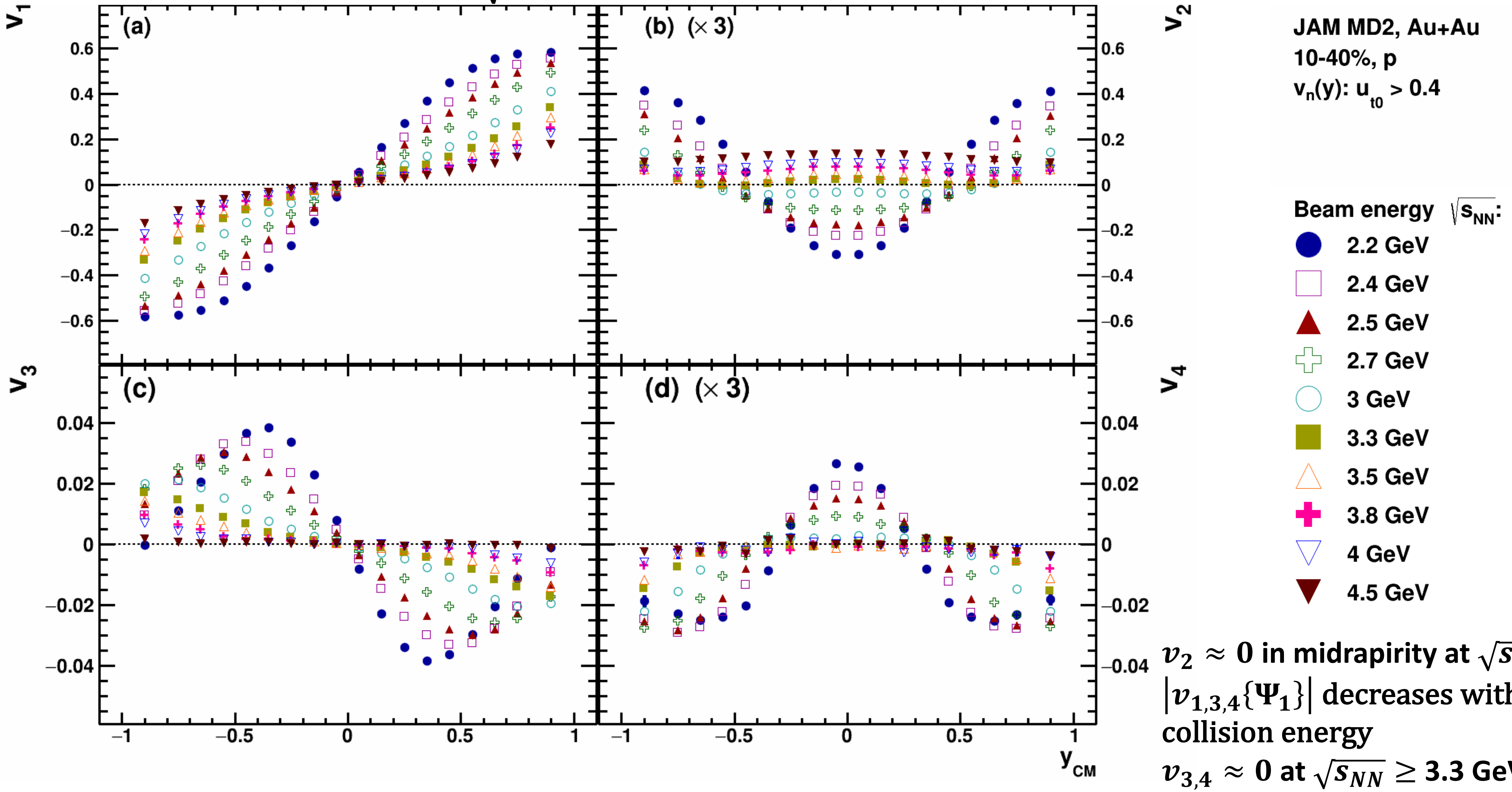


$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV

$|v_{1,3,4}\{\Psi_1\}|$ decreases with increasing collision energy

$v_{3,4} \approx 0$ at $\sqrt{s_{NN}} \geq 3.3$ GeV

$v_n(y)$ Au+Au $\sqrt{s_{NN}}$=2.4-4 GeV: JAM MD2

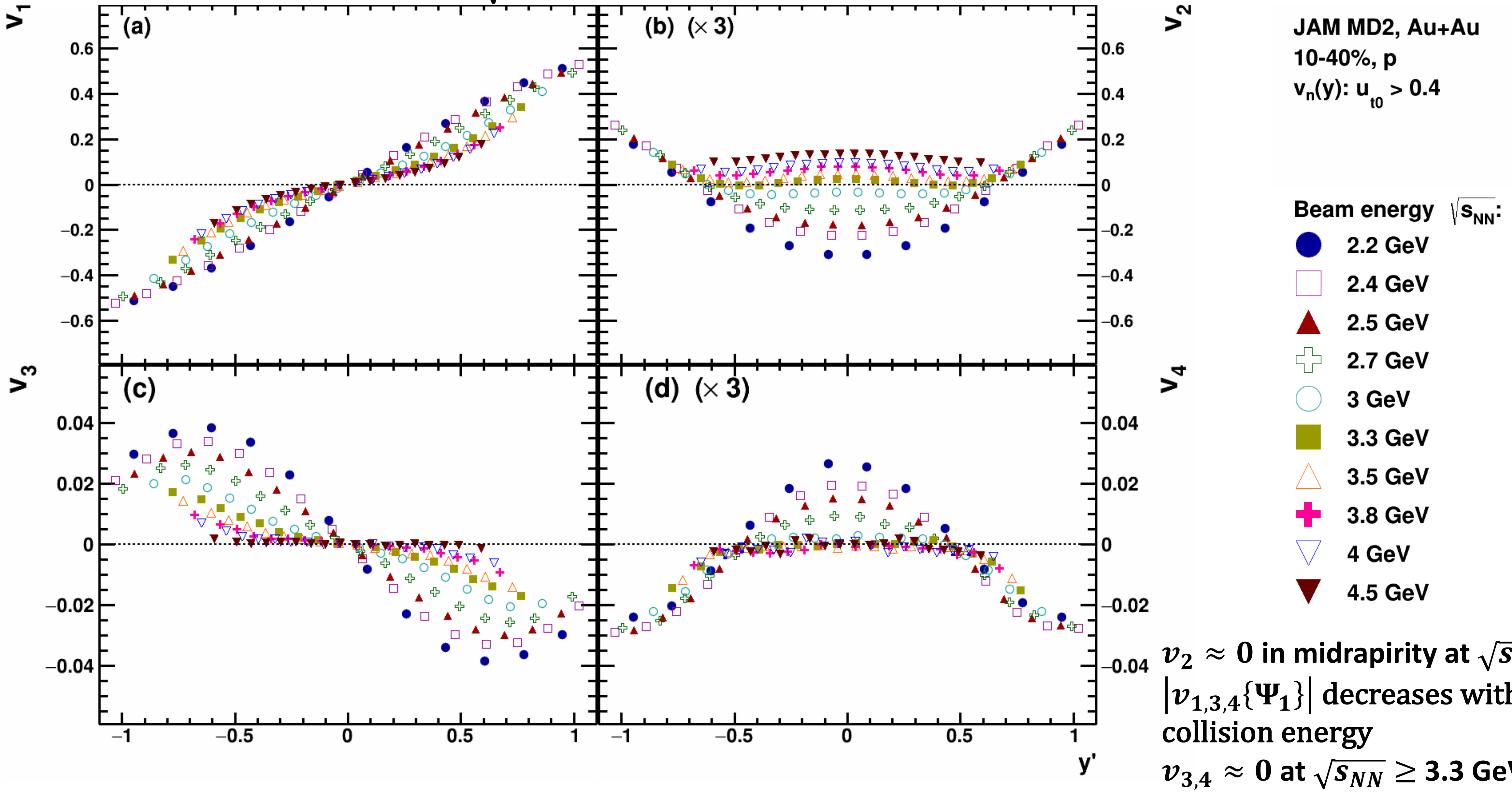


$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV

$|v_{1,3,4}\{\Psi_1\}|$ decreases with increasing collision energy

$v_{3,4} \approx 0$ at $\sqrt{s_{NN}} \geq 3.3$ GeV

$v_n(y)$ Au+Au $\sqrt{s_{NN}}$=2.4-4 GeV: JAM MD2

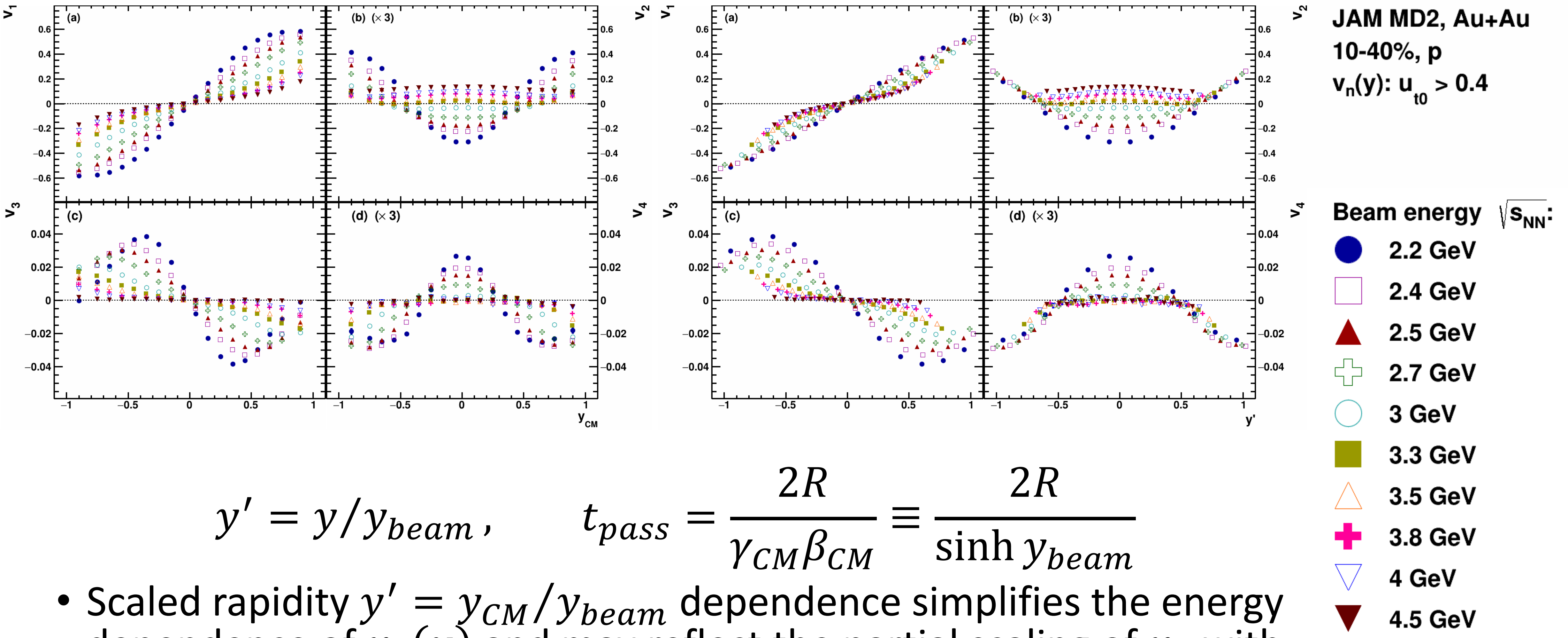


$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV

$|v_{1,3,4}\{\Psi_1\}|$ decreases with increasing collision energy

$v_{3,4} \approx 0$ at $\sqrt{s_{NN}} \geq 3.3$ GeV

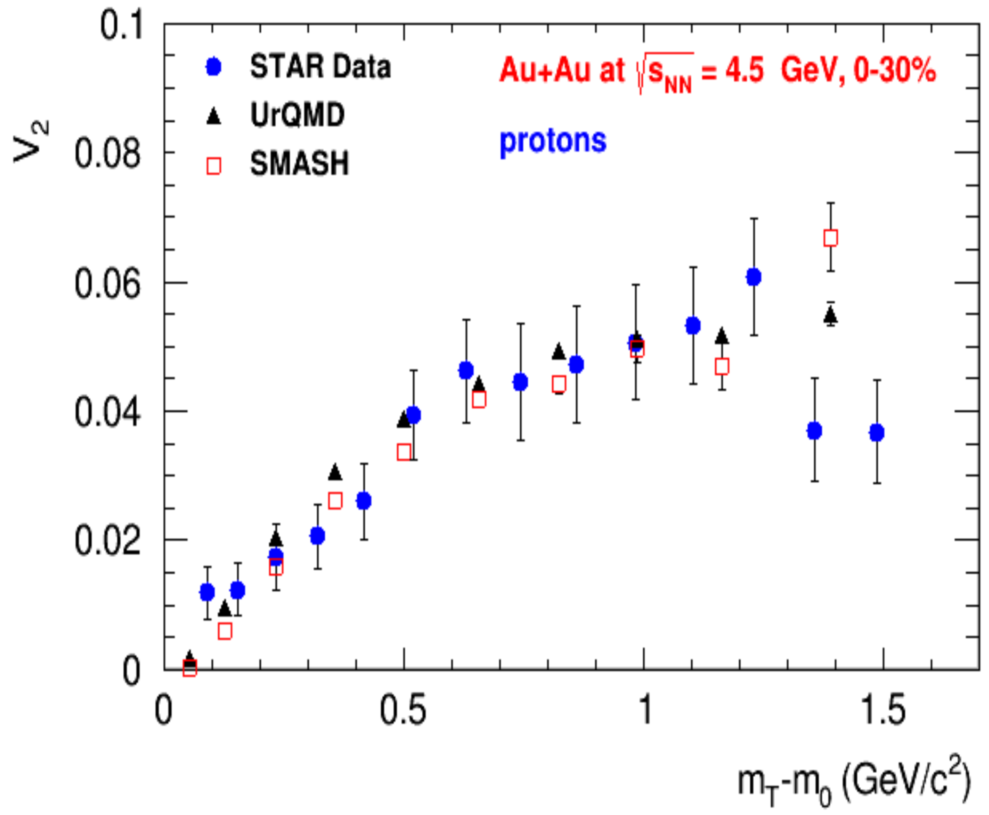
y' scaling: mean-field models



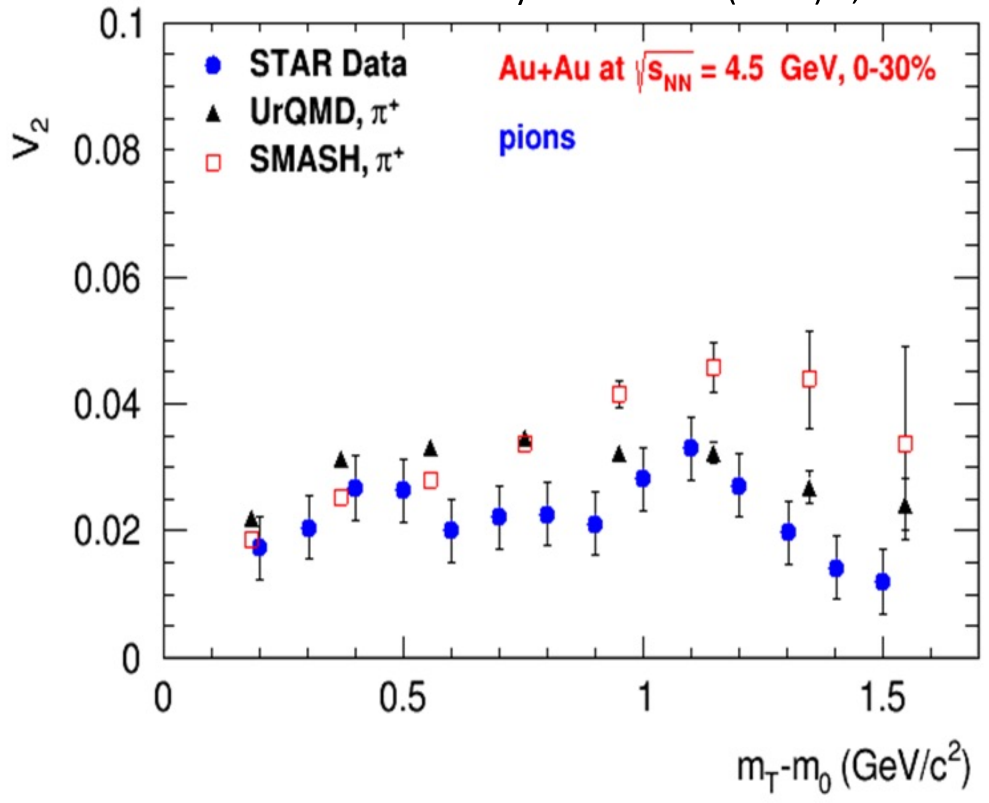
$$y' = y/y_{beam}, \qquad t_{pass} = \frac{2R}{\gamma_{CM}\beta_{CM}} \equiv \frac{2R}{\sinh y_{beam}}$$

- Scaled rapidity $y' = y_{CM}/y_{beam}$ dependence simplifies the energy dependence of $v_n(y)$ and may reflect the partial scaling of v_n with t_{pass}

Elliptic flow at NICA energies: Models vs. Data comparison

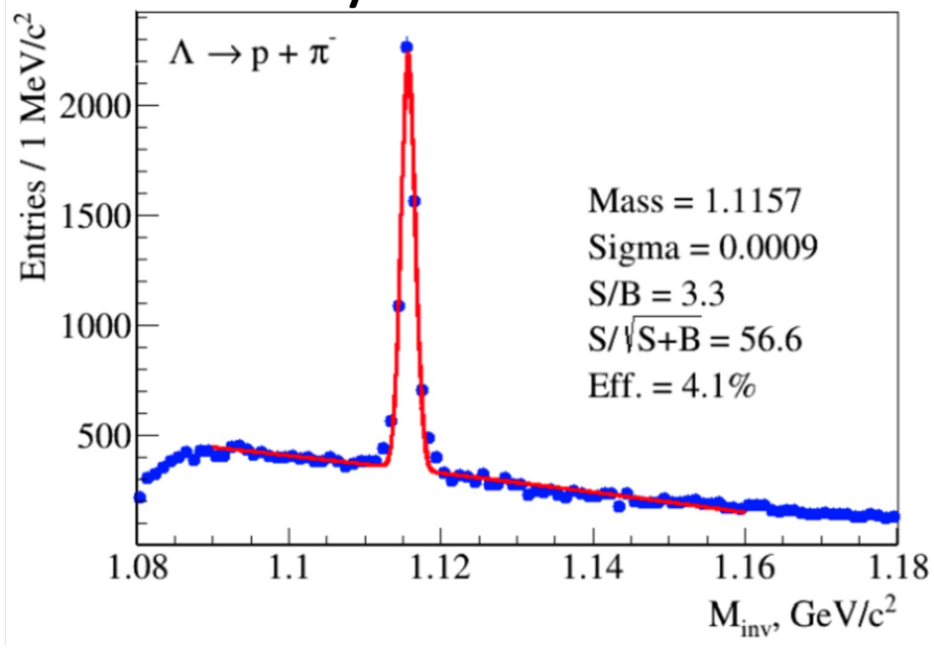


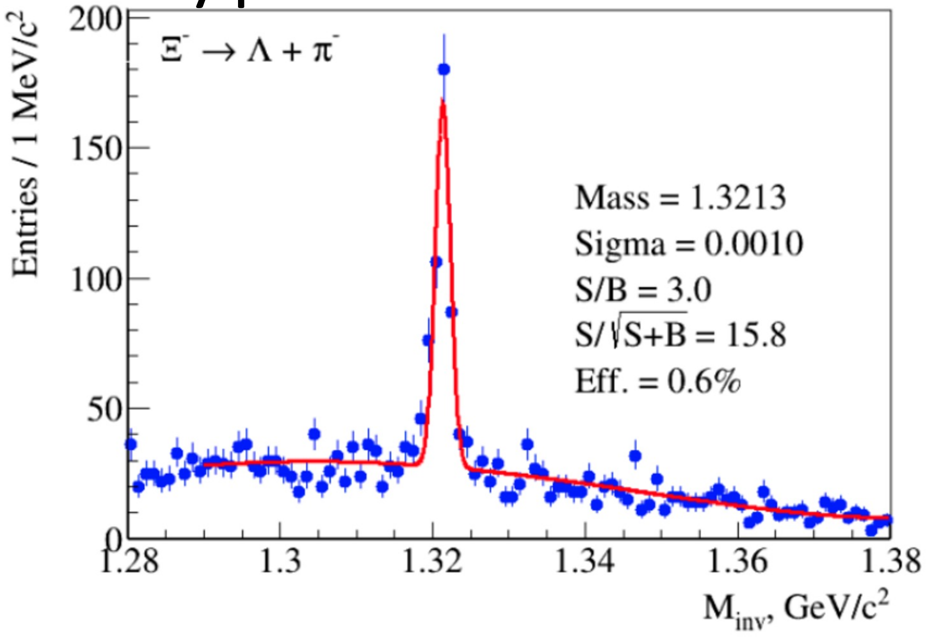
Phys. Rev. C 103 (2021) 3, 034908

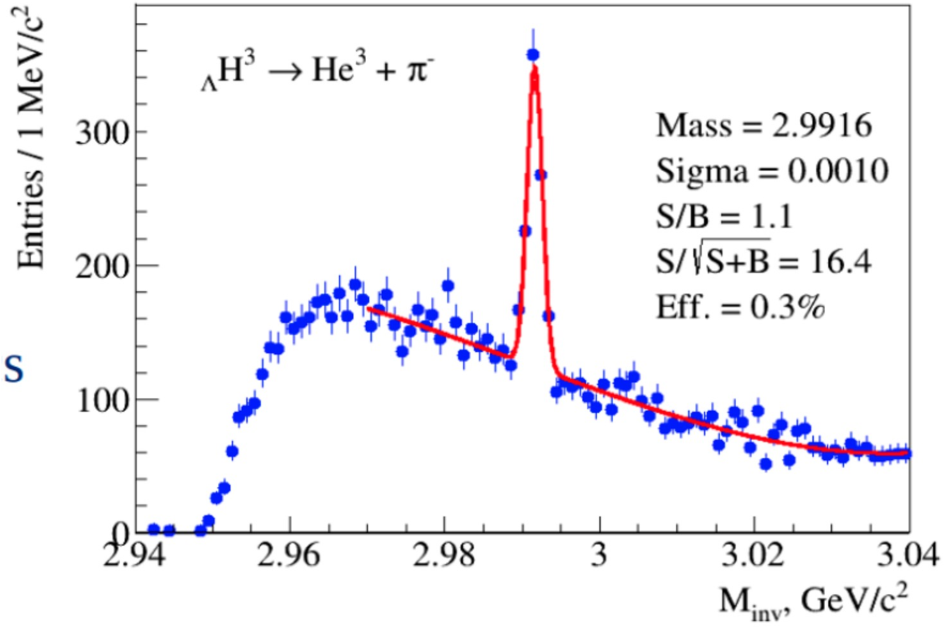


Pure String/Hadronic Cascade models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$ =4.5 GeV

Feasibility studies towards hyperon reconstruction





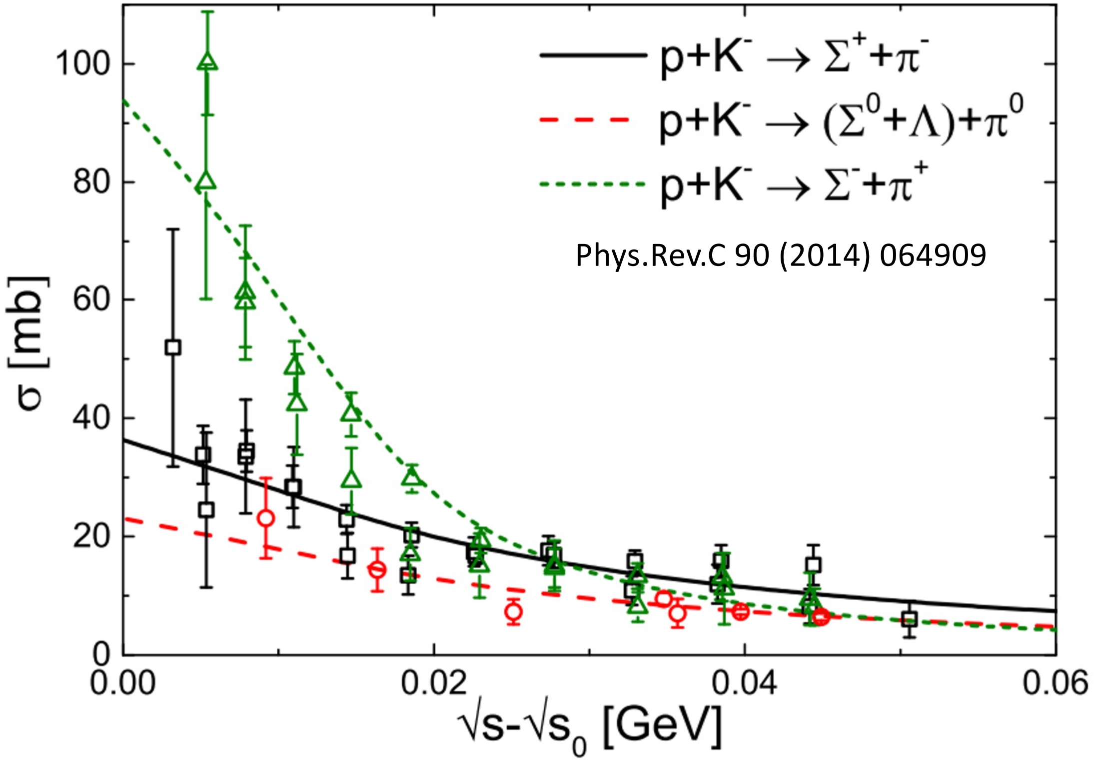


S

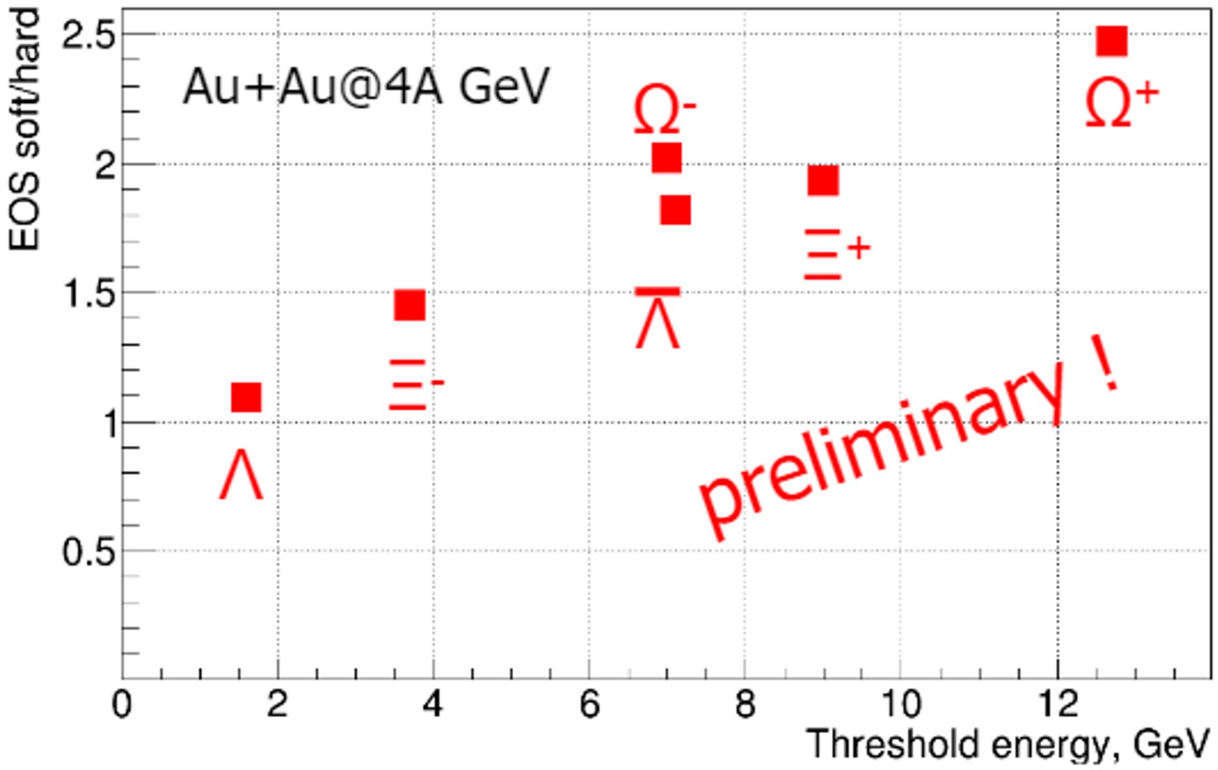
- High statistics will enable for multidifferential measurements of (multi-) strange particles and hypernuclei
- Colliding different systems may shed light on the mechanisms of strangeness production in the region of large baryon densities

Sub-threshold multi-strange hyperons production

Kaon-nucleon strangeness exchange cross sections in UrQMD



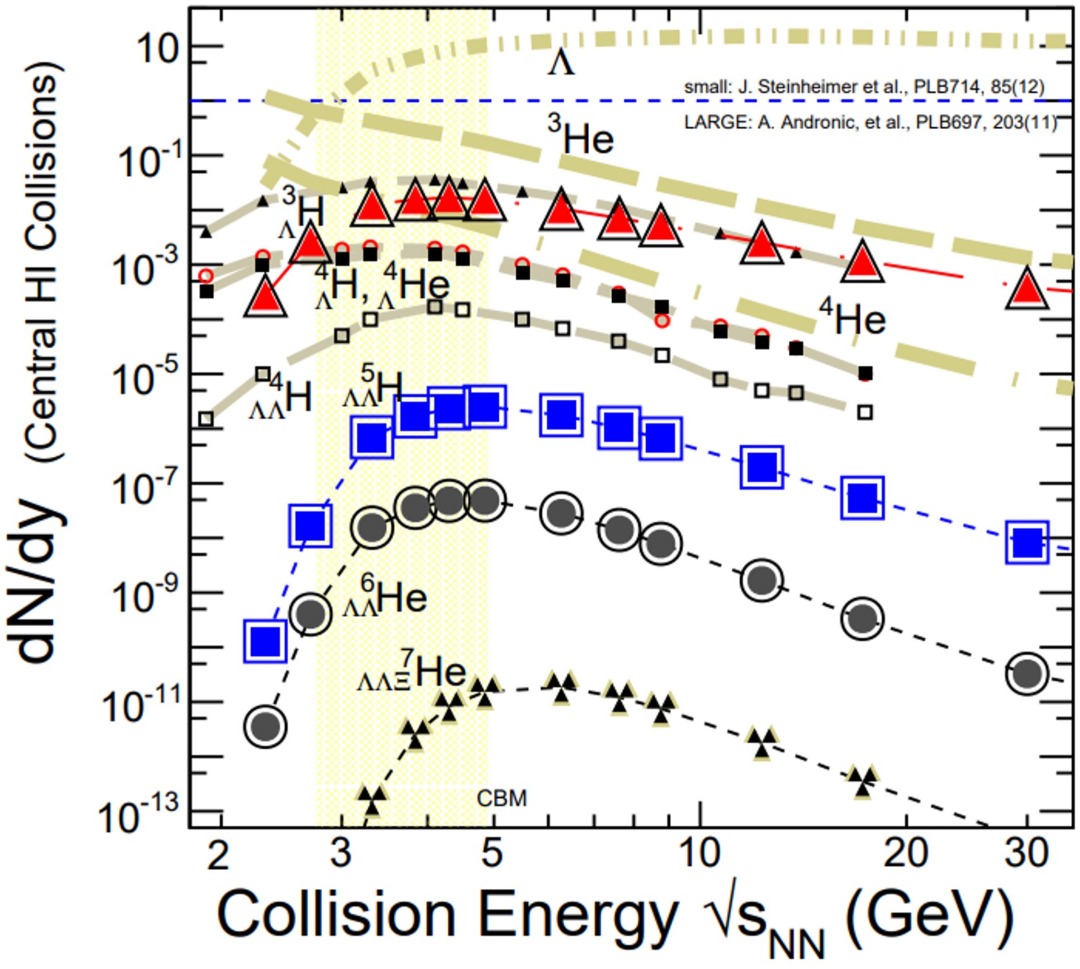
PHQMD: J. Aichelin et al., Phys. Rev. C 101 (2020) 044905

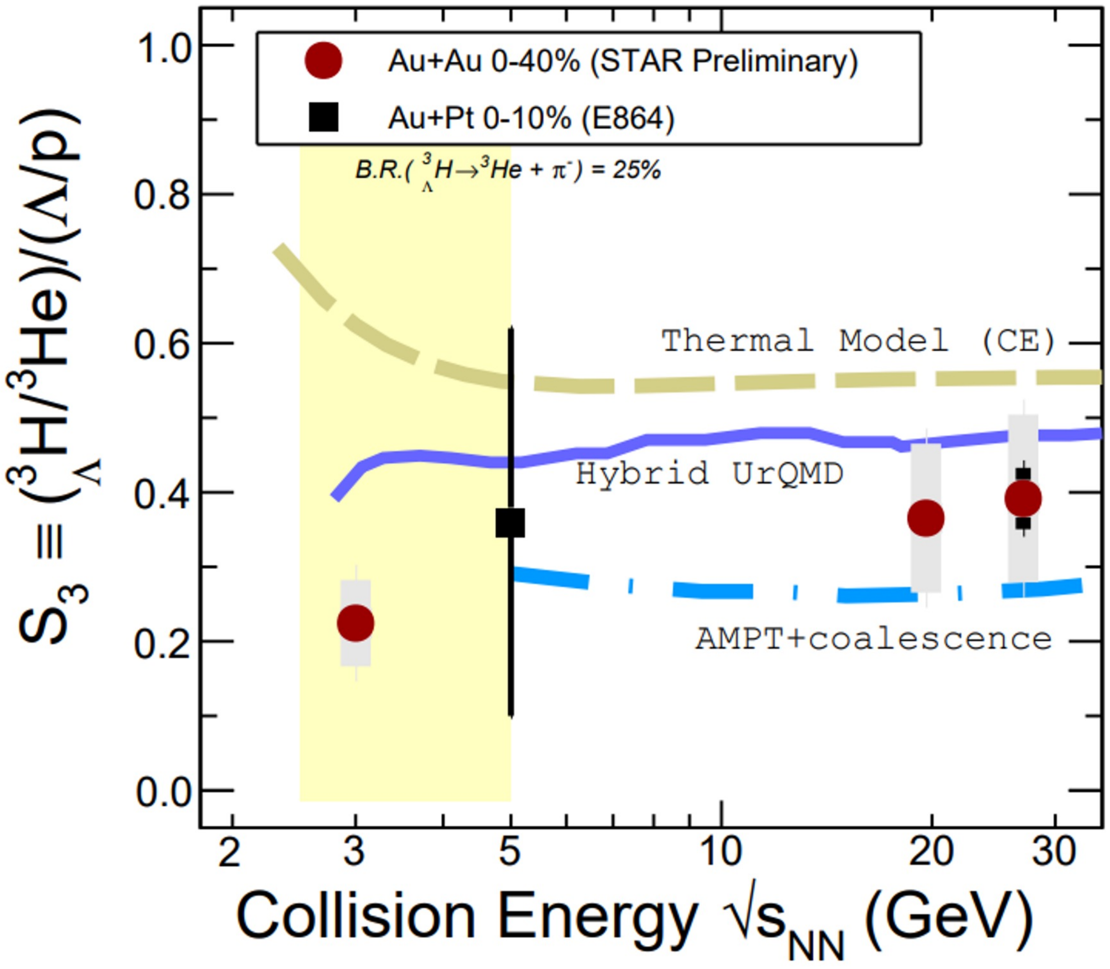


Subthreshold production of multi-strange hyperons is sensitive to the EOS

Hypernuclei production: Y-N interaction

arXiv:2209.05009v1



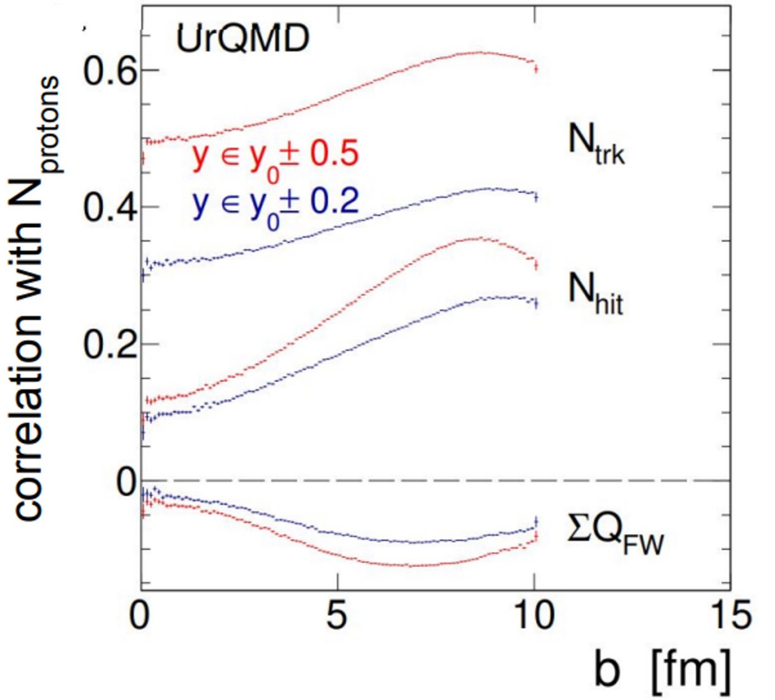


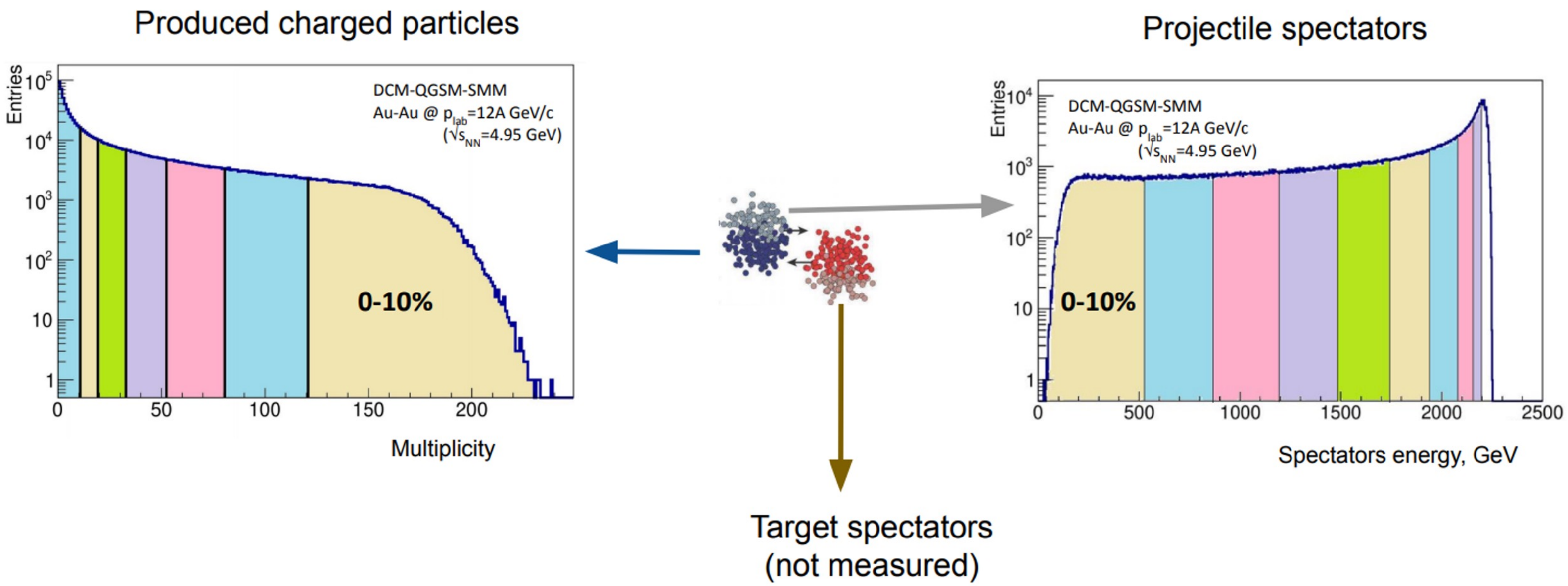
Enhanced yield of hypernuclei is expected at the beam energies of BM@N

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

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

MC-Glauber based centrality framework

MC Glauber data

Evaluate N_a:
$N_a = fN_{part}+(1-f)N_{coll}$

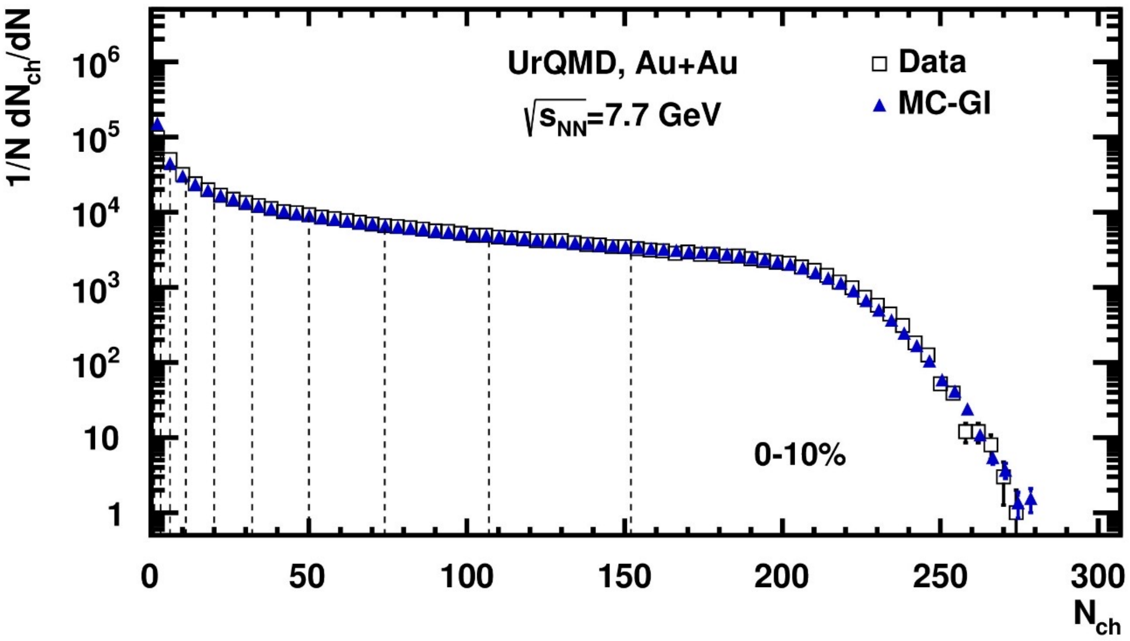
Call
NBD(μ,k) x N_a

Evaluate χ^2

Build multiplicity fitting function

Input multiplicity distribution

Minimize χ^2 to find f, μ, k



NBD – negative binomial distribution
Parameters of the fit:

- **f** – fraction of the production from the soft component
- **μ** – mean multiplicity value
- **k** – width of the multiplicity distribution, can be connected to the fluctuations

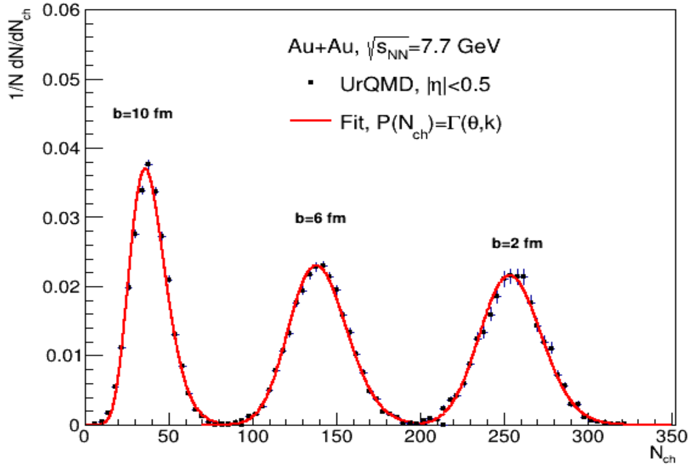
This centrality procedure was used in CBM, NA49, and NA61/SHINE:
I. Segal, et al., J.Phys.Conf.Ser. 1690 (2020) 1, 012107
Implamentation for MPD and BM@N:
https://github.com/FlowNICA/CentralityFramework
P. Parfenov, et al., Particles. 2021; 4(2):275-287

The Bayesian inversion method (Γ-fit): main assumptions

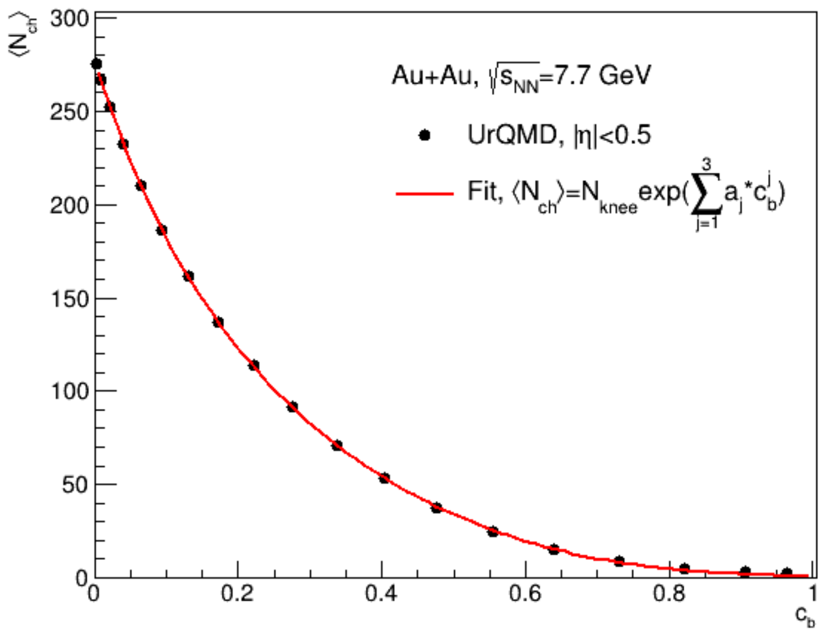
- Relation between multiplicity N_{ch} and impact parameter b is defined by the fluctuation kernel:

$$P(N_{ch}|c_b) = \frac{1}{\Gamma(k(c_b))\theta^k} N_{ch}^{k(c_b)-1} e^{-n/\theta}$$

$$c_b = \int_0^b P(b')db' \simeq \frac{\pi b^2}{\sigma_{inel}}$$ – centrality based on impact parameter



The results of fitting the multiplicity distribution for a fixed impact parameter



The dependence of the average value of multiplicity on centrality and the results of its fit

$$\frac{\sigma^2}{\langle N_{ch}\rangle} = \theta \simeq const$$

$$\langle N_{ch}\rangle = N_{knee}\exp\left(\sum_{j=1}^{3} a_j c_b^j\right), \quad k = \frac{\langle N_{ch}\rangle}{\theta}$$

Five fit parameters N_{knee}, θ, a_j

R. Rogly, G. Giacalone and J. Y. Ollitrault, Phys.Rev. C98 (2018) no.2, 024902

Reconstruction of *b*

- Normalized multiplicity distribution $P(N_{ch})$

$$P(N_{ch}) = \int_0^1 P(N_{ch}|c_b)dc_b$$

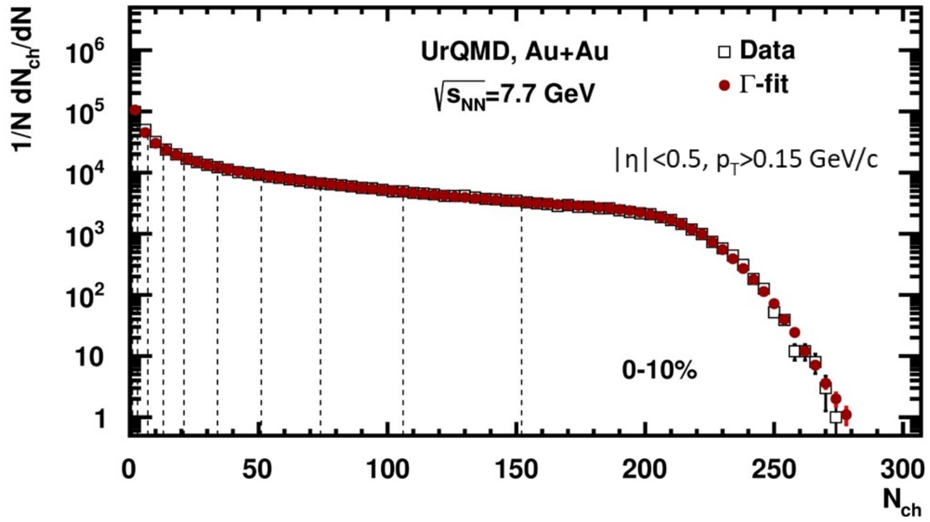
- Find probability of *b* for fixed range of N_{ch} using Bayes' theorem:

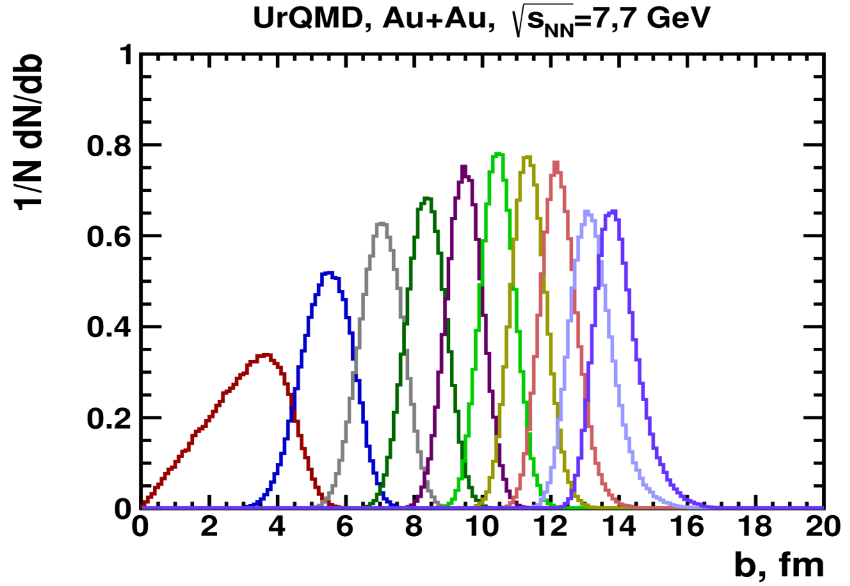
$$P(b|n_1 < N_{ch} < n_2) = P(b)\frac{\int_{n_1}^{n_2} P(b|N_{ch})dN_{ch}}{\int_{n_1}^{n_2} P(N_{ch})dN_{ch}}$$

- **The Bayesian inversion method consists of 2 steps:**

–Fit normalized multiplicity distribution with $P(N_{ch})$

–Construct $P(b|N_{ch})$ using Bayes' theorem with parameters from the fit

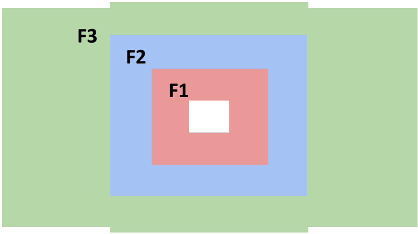


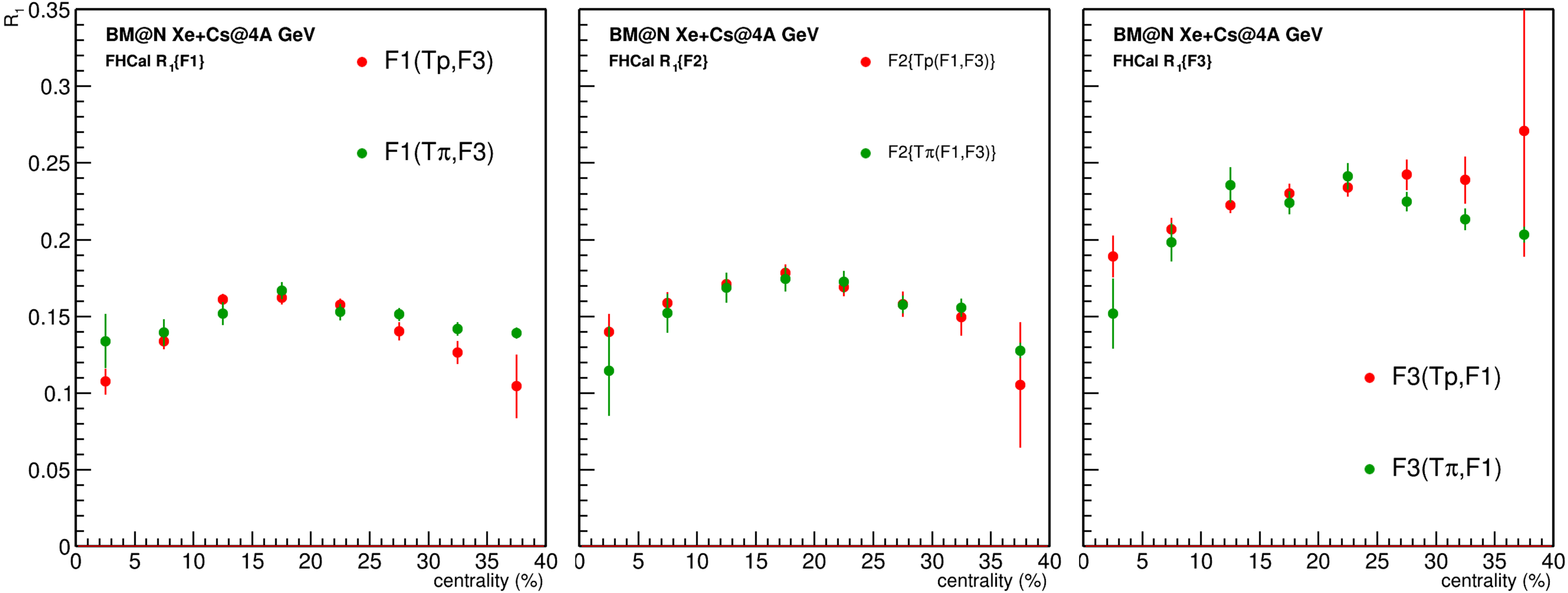


Parfenov, P., Idrisov, D., et. all. Relating Charged Particle Multiplicity to Impact Parameter in Heavy-Ion Collisions at NICA Energies. (2021) PARTICLES, 4(2), 275-287.

Implementation in MPD and BM@N: https://github.com/Dim23/GammaFit

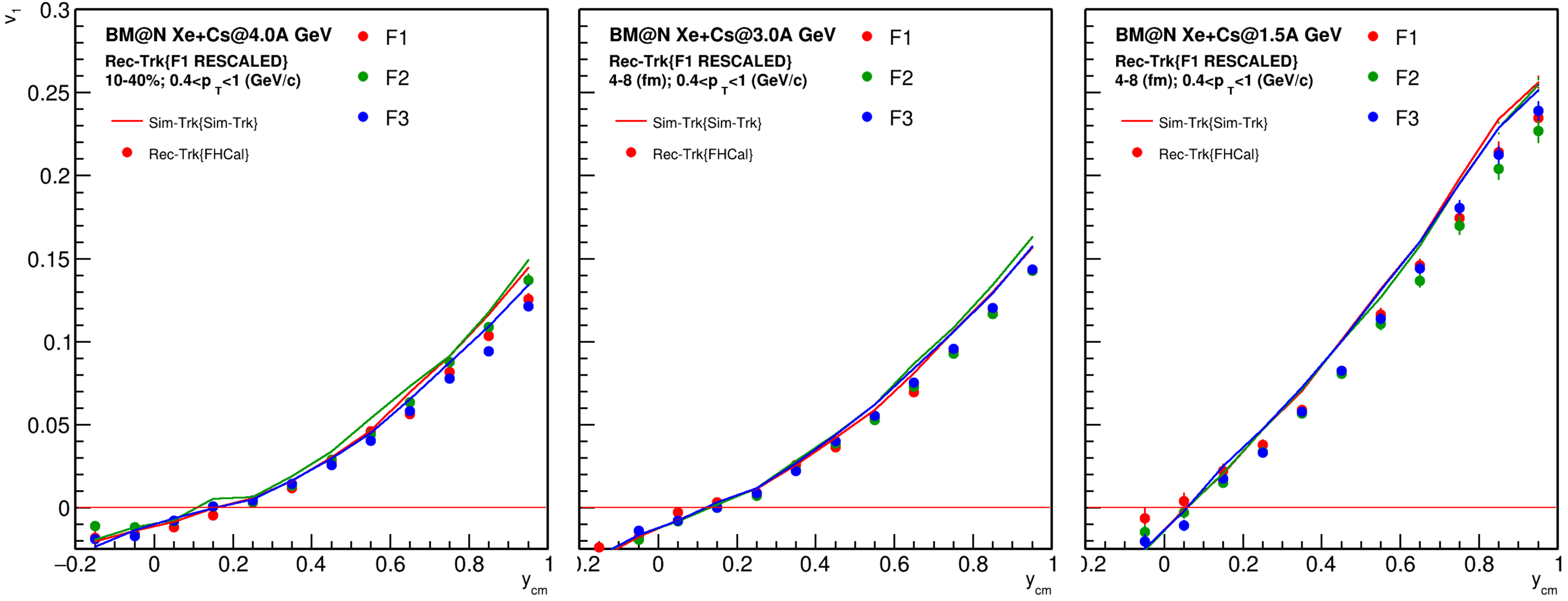
Rec R1: DCMQGCM-SMM Xe+Cs@4A GeV





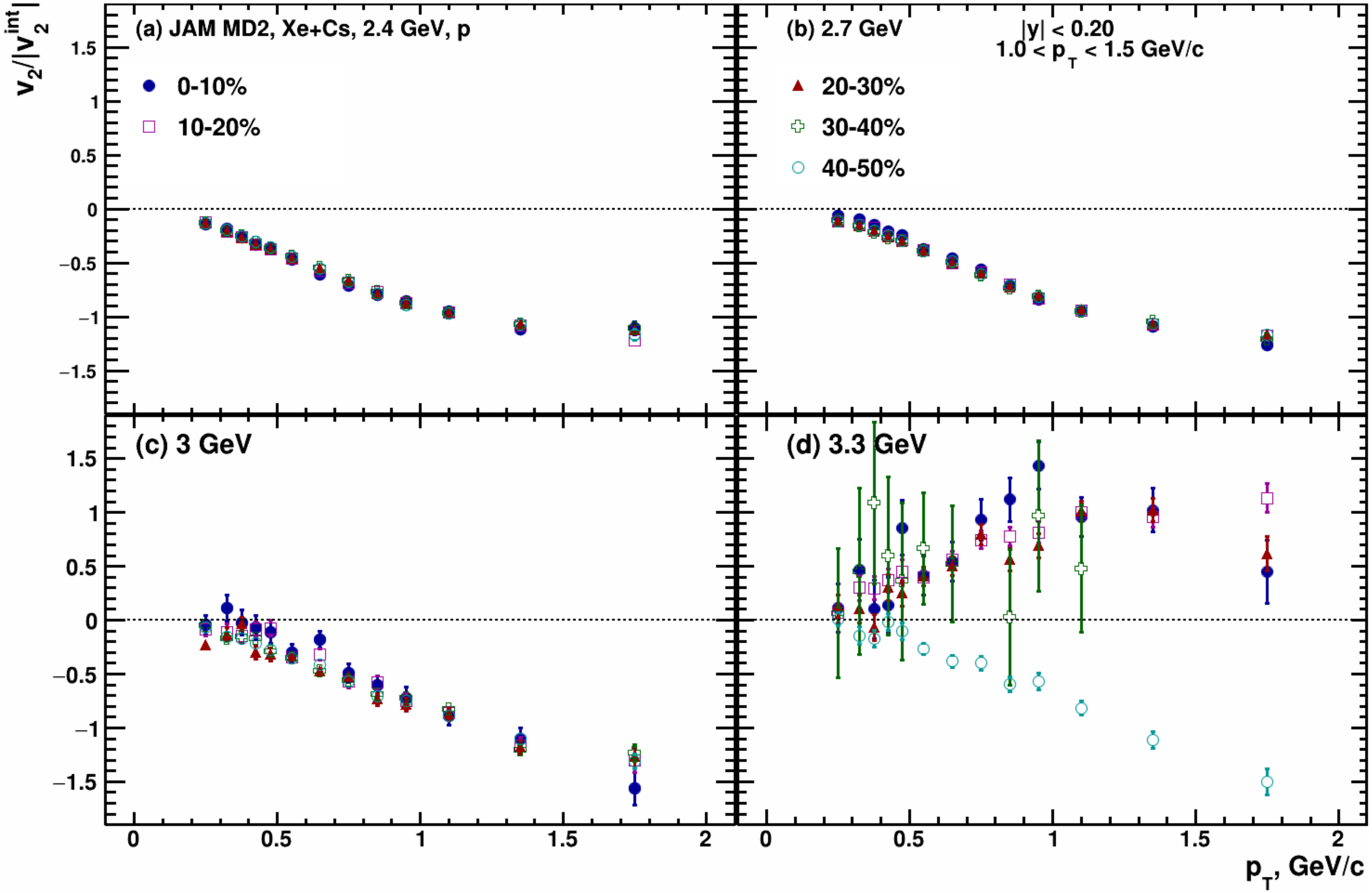
Using the additional sub-events from tracking provides a robust combination to calculate resolution

v_1: DCMQGCM-SMM Xe+Cs



Reasonable agreement between model and reconstructed data

$|v_2^{int}|$ scaling: JAM MD2 model – Nuclotron energies



Scaling works for energy range $\sqrt{s_{NN}} = 2.4 - 3$ GeV and breaks at $\sqrt{s_{NN}} = 3.3$ GeV where v_2 changes sign