System Size/Rapidity Scan - MPD

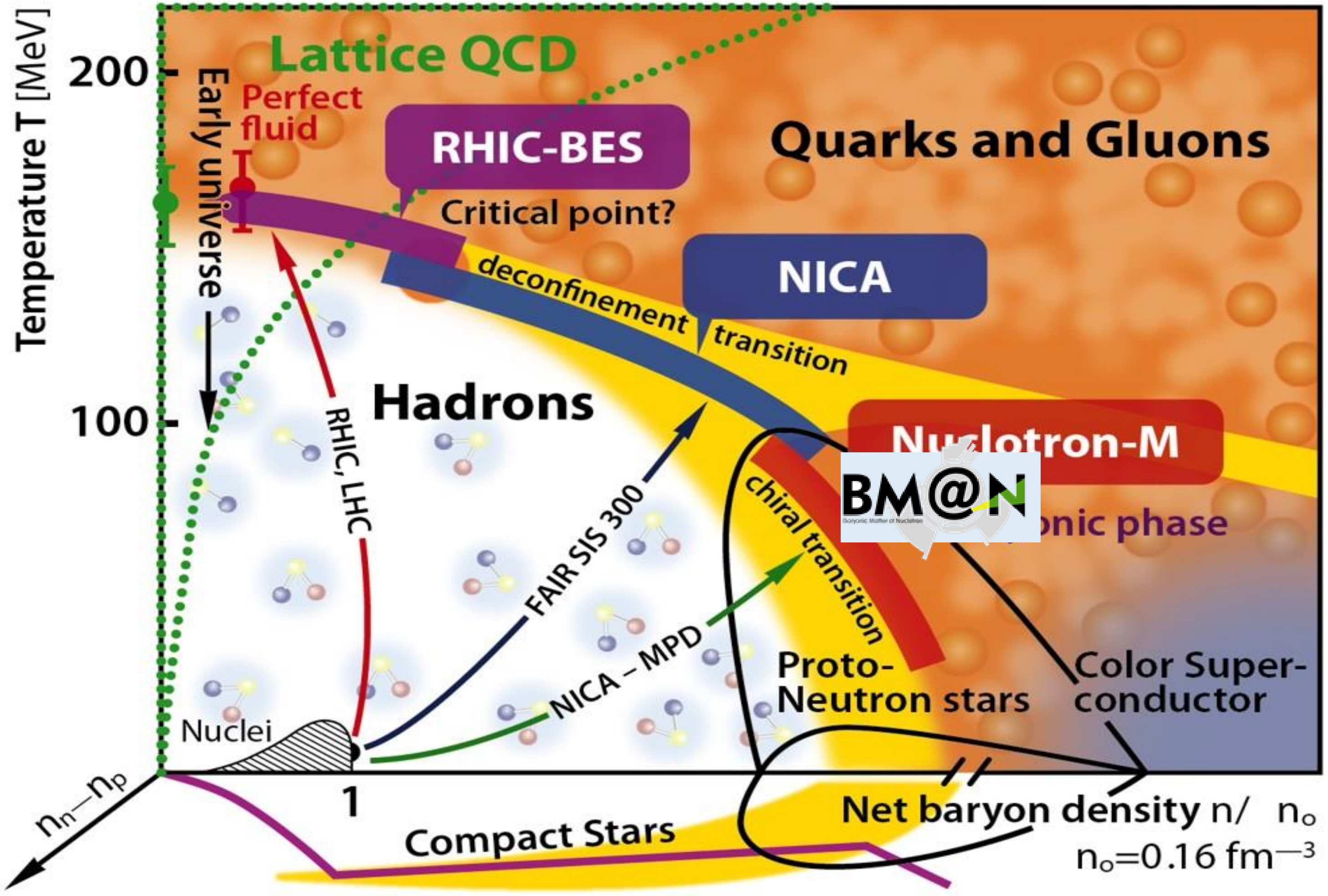
Arkadiy Taranenko
(NRNU MEPhI, JINR)

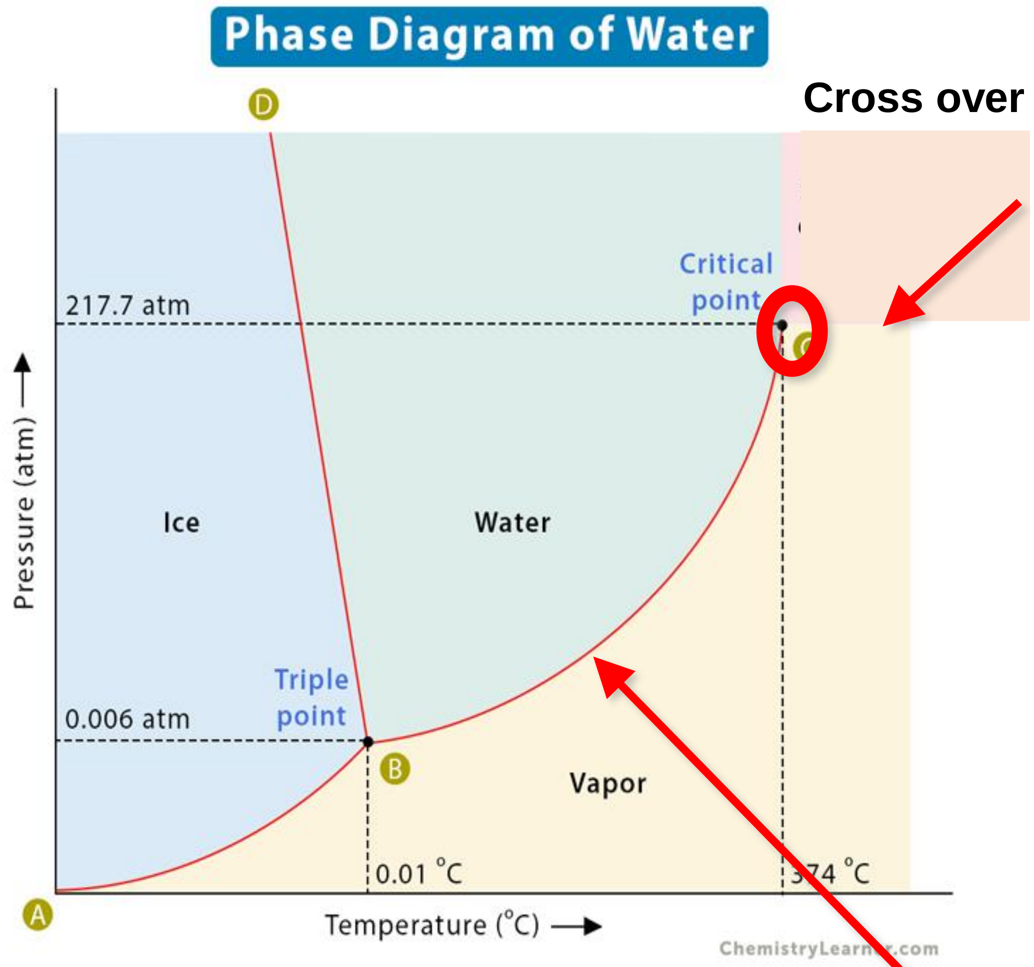
15th MPD Collaboration Meeting
15-17 Apriil 2025, JINR

Relativistic Heavy-Ion Collisions and QCD Phase Diagram

Critical Temperature
$T_c \approx$ **156 +/- 9 MeV**

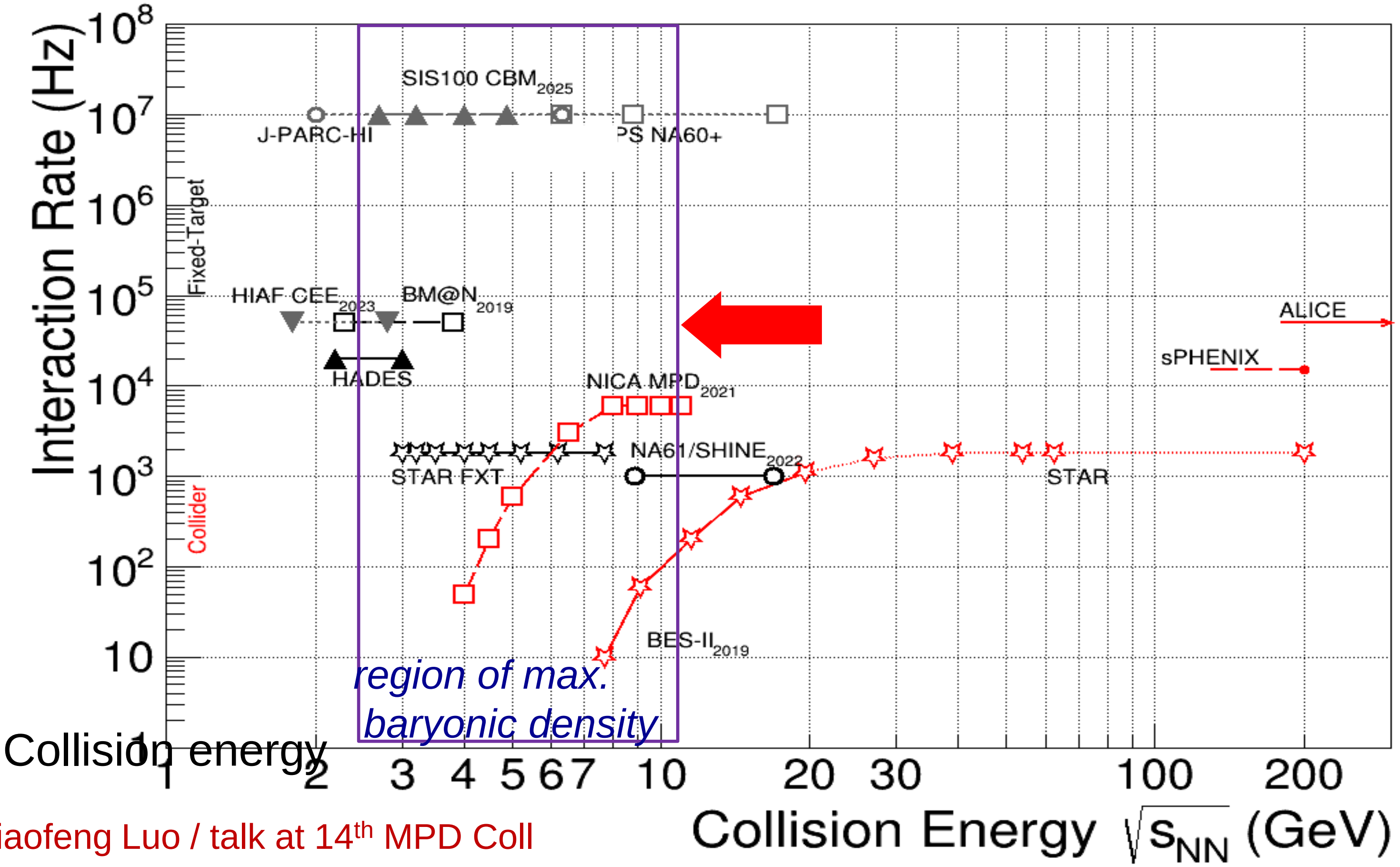
[PRD 90 094503 (2014)]





Smooth *transition from hadronic degrees of freedom to quark-gluon degrees of freedom at zero baryonic density*

Relativistic Heavy Ion Collision Experiments



Collision energy

Xiaofeng Luo / talk at 14th MPD Coll

MPD competitors:

Present:

RHIC/STAR (USA) 3-200 GeV
SPS/NA61 (CERN) 5.1-17.3 GeV

Future:

HIAF/CEE (China) 2.1-4.5 GeV (2026-?)
FAIR/CBM (Germany) 2.4-4.9 GeV (2029-?)
JPARC-HI (Japan) 2-5 GeV (2030-?)

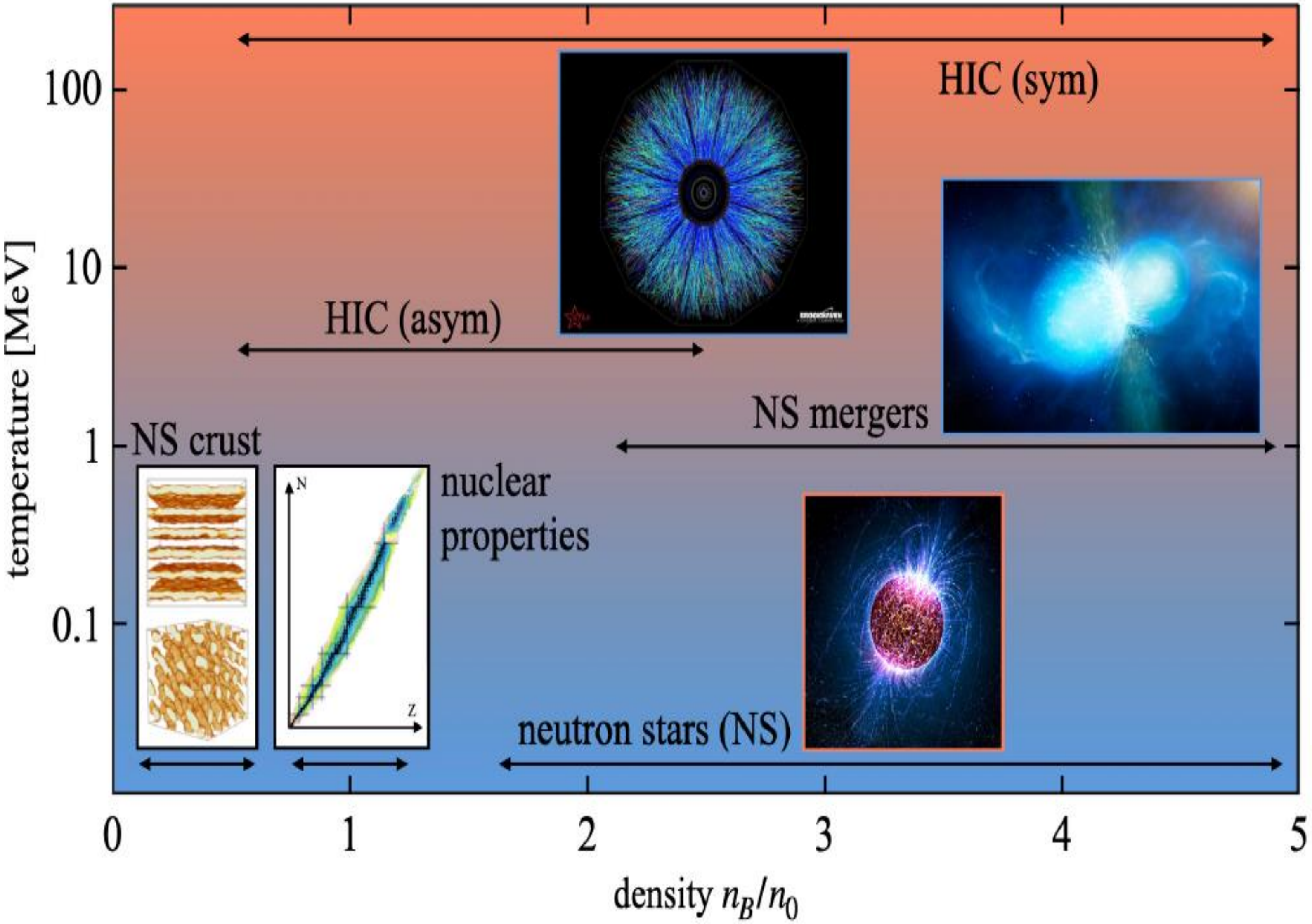
BM@N: $\sqrt{s_{NN}}$ = 2.3 - 3.3 GeV
MPD: $\sqrt{s_{NN}}$ = 4 - 11 GeV

Method	μ_c (MeV)	T_c (MeV)
Holography + Bayesian	560 - 625	101 - 108
FRG/DSE	495 - 654	108 - 119
Lee-Yang edge singularities	500 - 600	100 - 105
Lattice QCD	$\mu_c/T_c > 3$	F. Karsch et al.
Summary	**495 - 654**	**100 - 119**

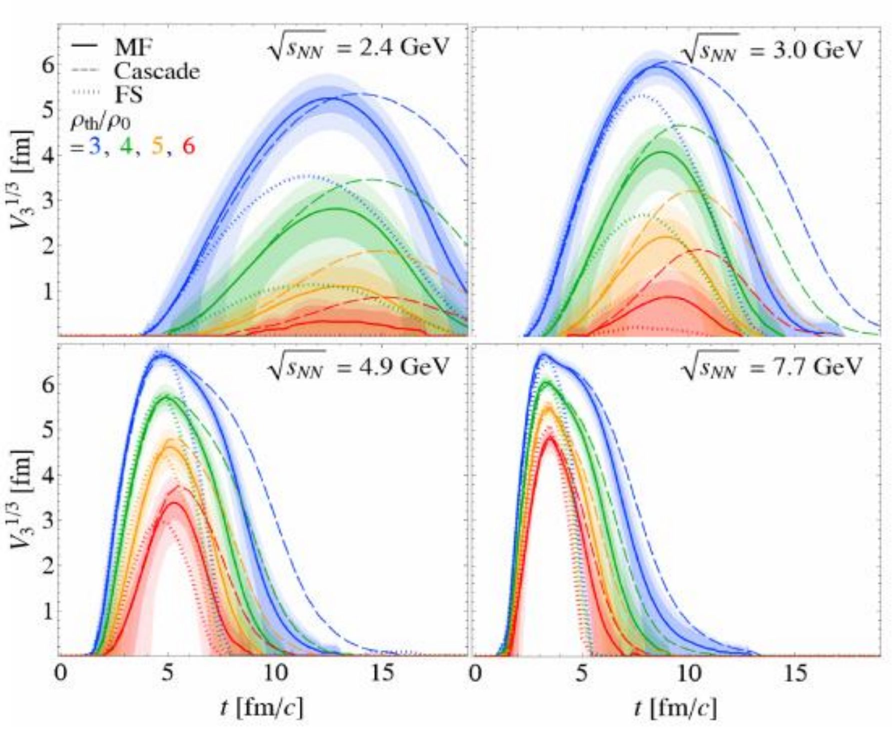
(μ_c, T_c) = (495 - 654, 100 - 119) MeV → $3.5 < \sqrt{s_{NN}} < 4.9$ GeV

BM@N and MPD are both in the collision energy range of the predicted CEP location.

Dense Nuclear Matter



J.Subatomic Part.Cosmol. 3 (2025) 100015



Relativistic heavy-ion collisions provide a unique and controlled experimental way to study the properties of nuclear matter at high baryon density.

Equation of state (EoS) for high baryon density matter

pressure *energy per nucleon*

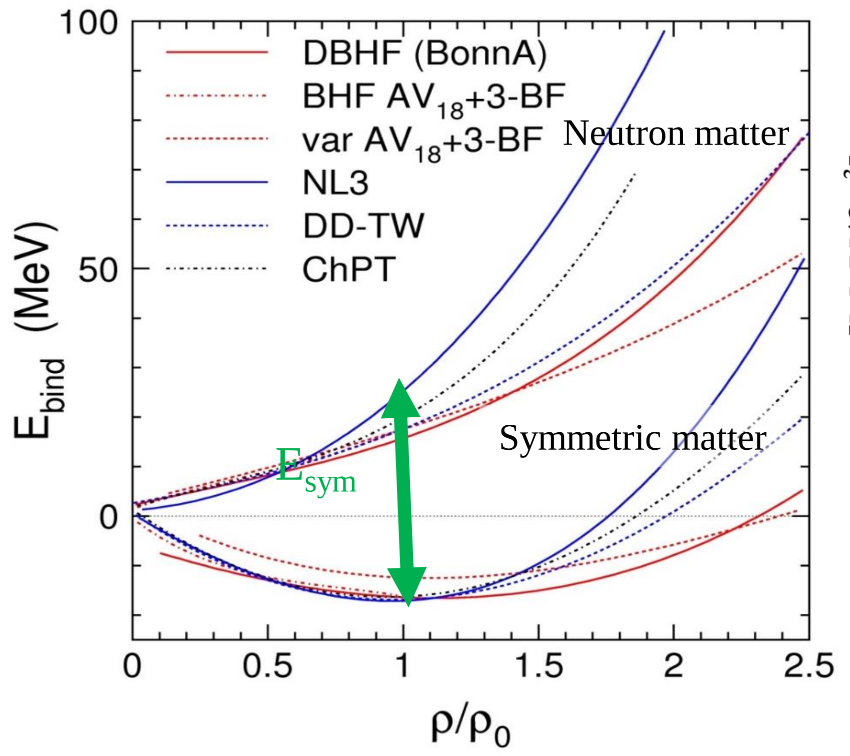
$$P = n^2 \frac{\mathrm{d}(E/A)}{\mathrm{d}n_b}$$

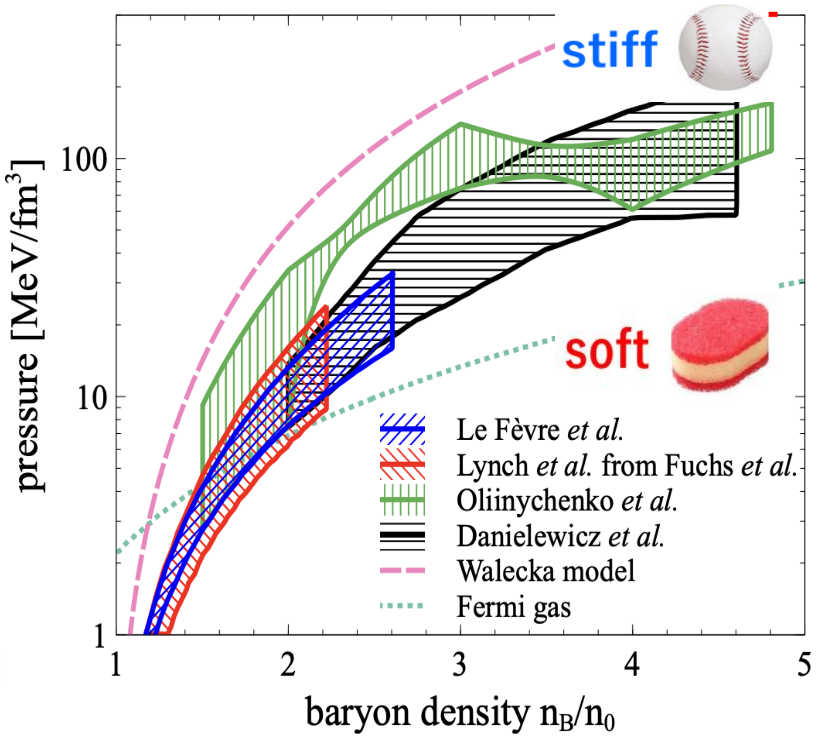
$$\frac{E}{A} = m_N + E_A(n_B) + E_{sym}(n_B)\frac{(n_p - n_n)^2}{n_B^2}$$

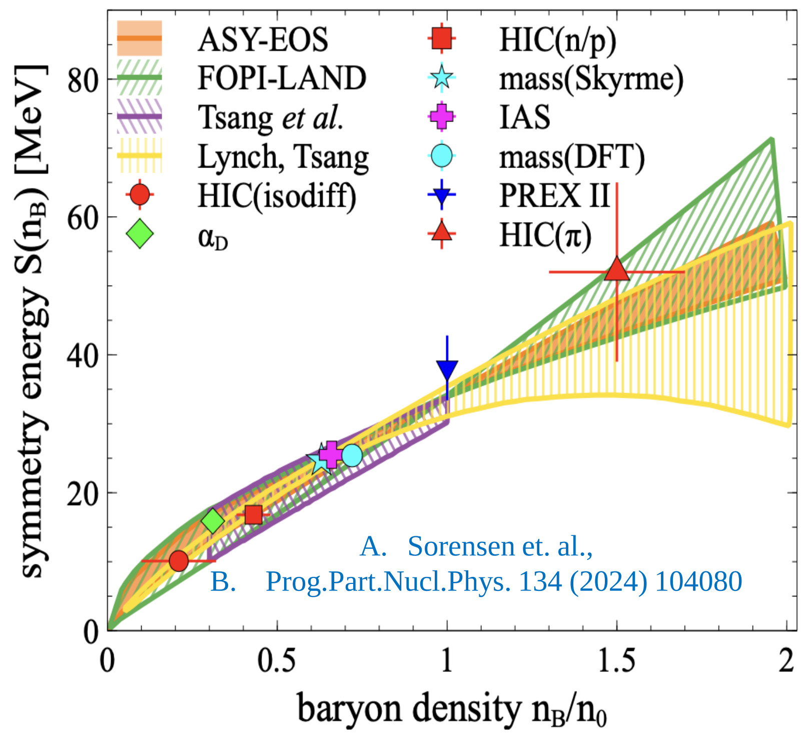
isospin asymmetry

$$n_B = n_p + n_n$$

Symmetric matter **Symmetry energy**

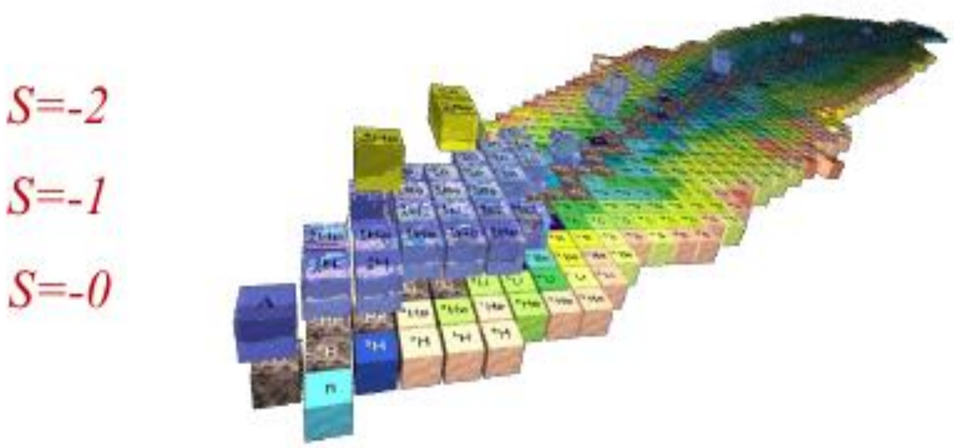


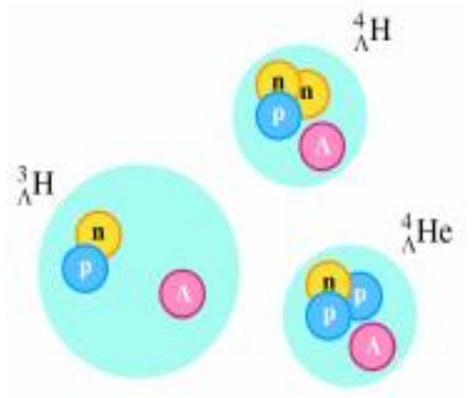


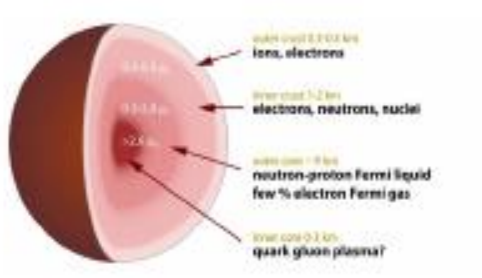


EOS describes the relation between density (n_B), pressure (P), temperature (T), energy (E), and isospin asymmetry $(n_p-n_n)/n_B$

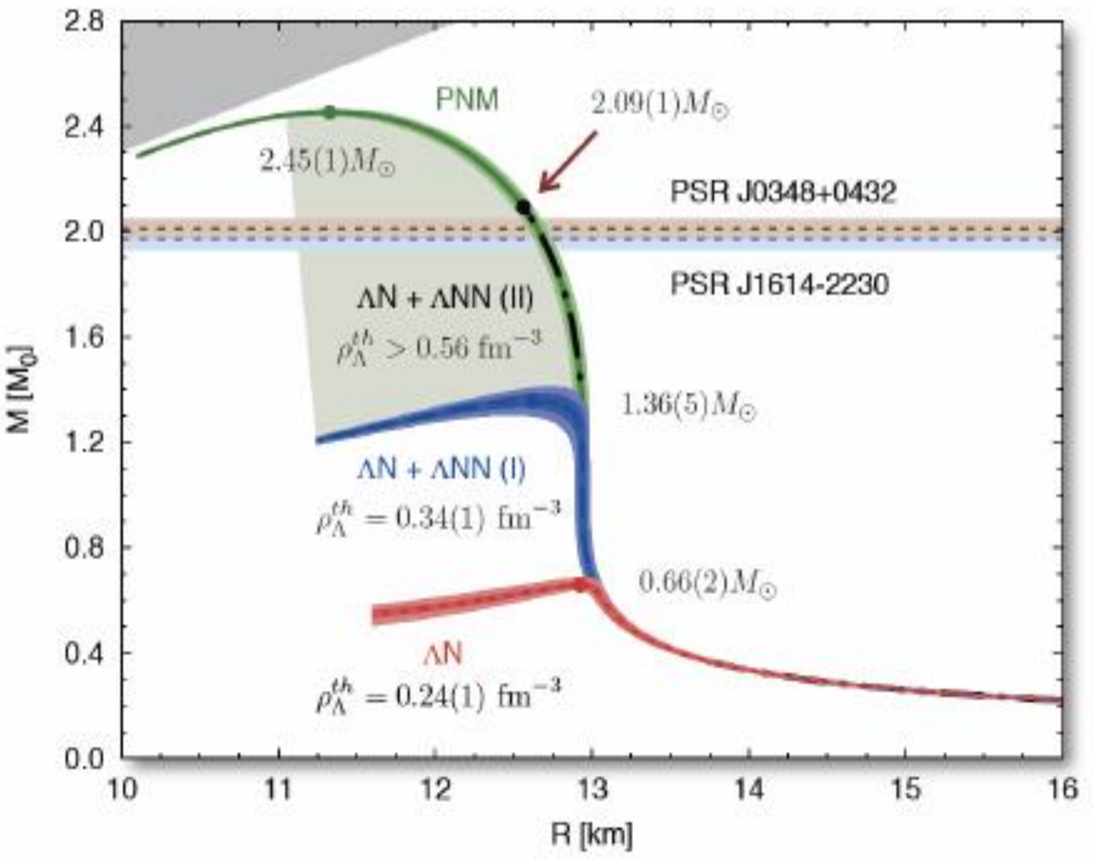
Hyperon and Hyper-Nuclei Production in Heavy-Ion Collisions and Neutron Stars







PRL**114**, 092301(2015), HYP2018, 1512.06832, 1711.07521



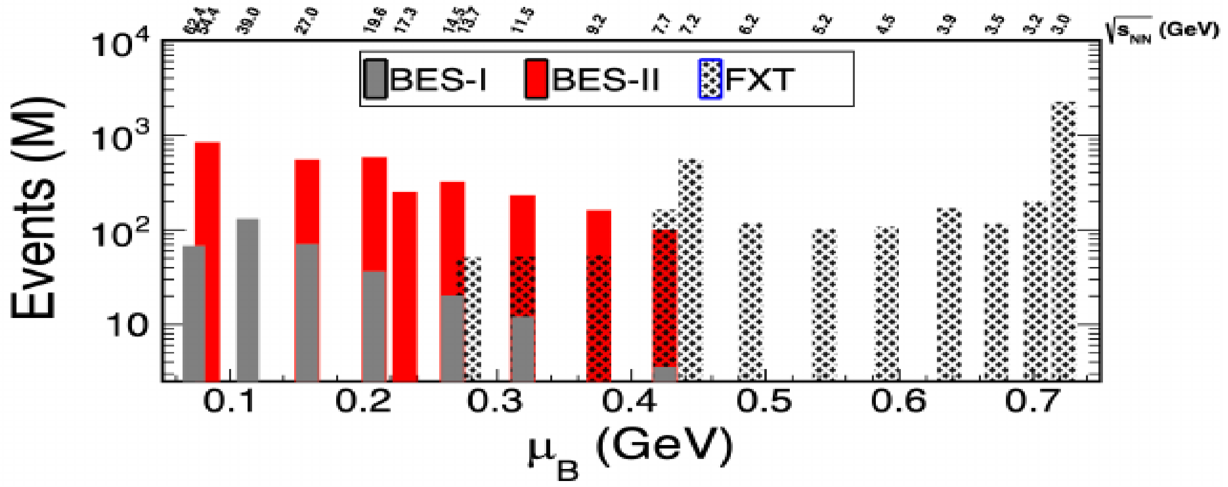
Hyperon and Hyper-Nuclei production provide access to the hyperon–nucleon interactions: NY, YNN, : key to understand the EoS at high baryon density and inner structure of neutron star.

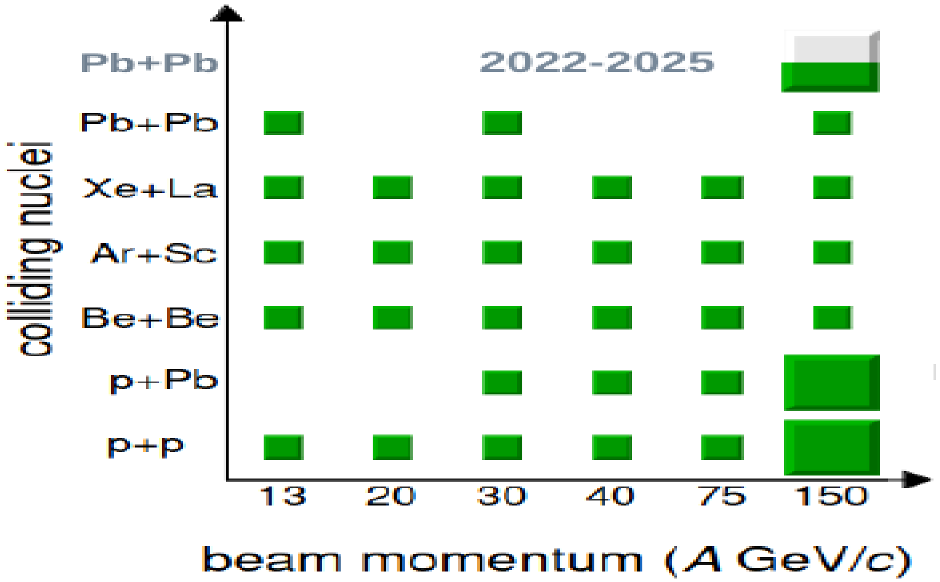
Mass-Radius relation is "unique" to the underlying EoS
- Soft EoS: low maximum mass and small radii
- Stiff EoS: high maximum mass and large radii

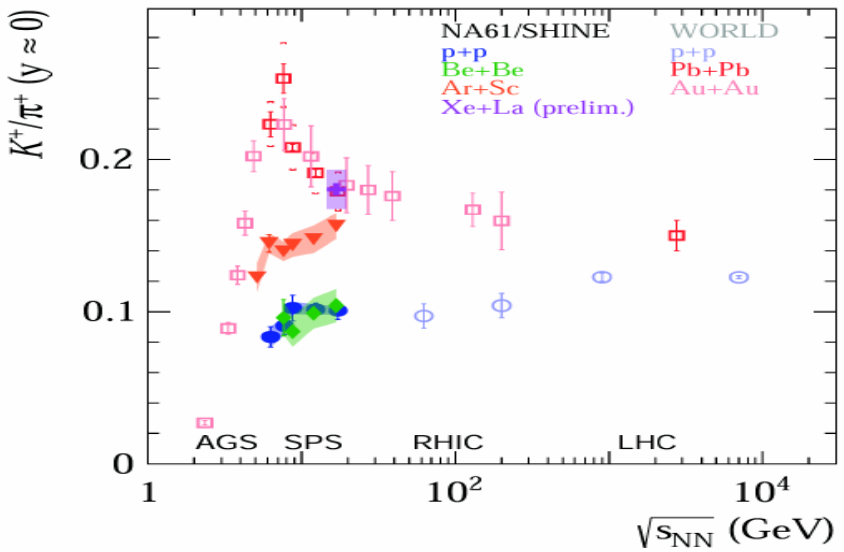
Beam Energy Scan programs

STAR at RHIC: 3 < $\sqrt{s_{NN}}$ < 200 GeV (750 < μ_B < 25 MeV)

NA61SINE at SPS: 5.1 < $\sqrt{s_{NN}}$ < 17 (27) GeV





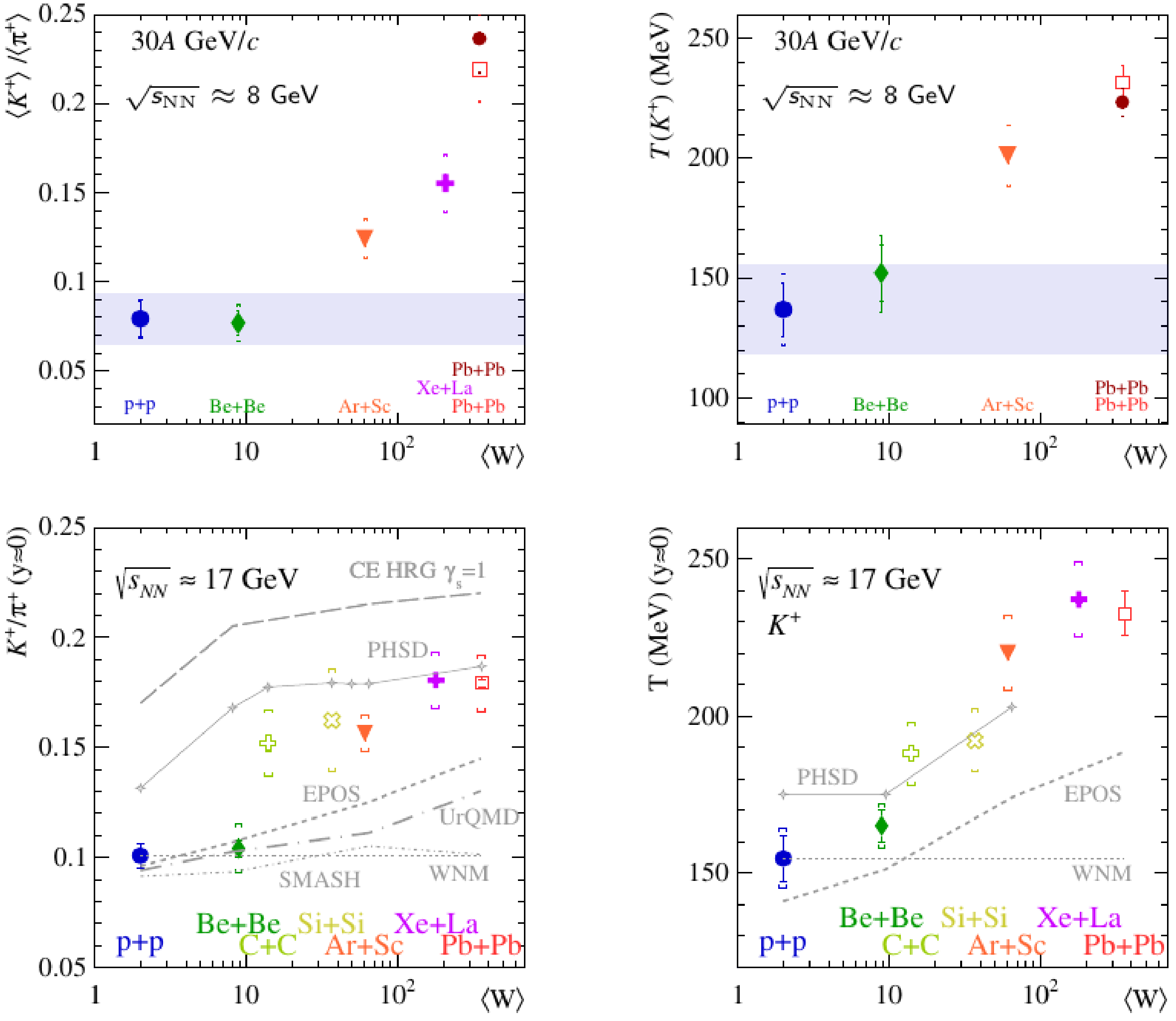


Au+Au Collisions at RHIC

Collider Runs						Fixed-Target Runs					
	$\sqrt{S_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{S_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	200	380 M	25 MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	3.0 (3.85)	2000 M	750 MeV	-1.05	Run-18, 21

System size dependence of K/π and T

- (Rapid) changes of observables when moving from small (p+p, Be+Be) to intermediate and large (Ar+Sc, Xe+La, Pb+Pb) systems
- None of the models can fully reproduce the system size dependence of K^+/π^+ and T



(p+p ≈ Be+Be) ⩽ Ar+Sc ⩽ (Xe+La ≈ Pb+Pb)

N: Event-by-event multiplicity

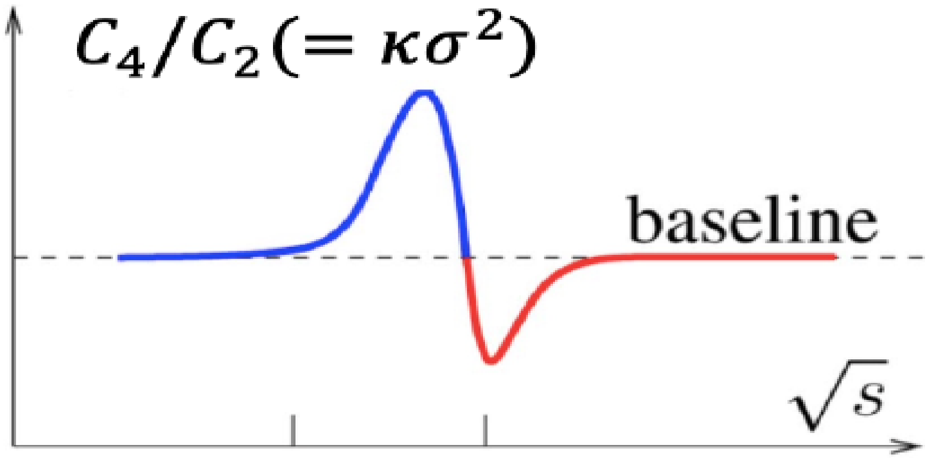
$\delta N = N - \langle N \rangle$

Cumulants

- ❑ $C_1 = \langle N \rangle$
- ❑ $C_2 = \langle \delta N^2 \rangle$
- ❑ $C_3 = \langle \delta N^3 \rangle$
- ❑ $C_4 = \langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2$

Factorial Cumulants

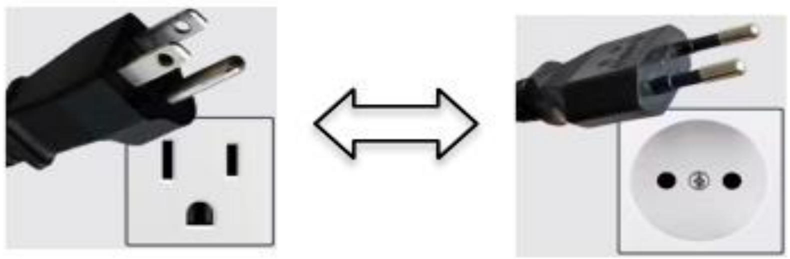
- ❑ $\kappa_1 = C_1$
- ❑ $\kappa_2 = -C_1 + C_2$
- ❑ $\kappa_3 = 2C_1 - 3C_2 + C_3$
- ❑ $\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$



Non-monotonic energy dependence of C_4/C_2 for the conserved baryon number (using protons as a proxy) indicates the existence of a critical region.[1]

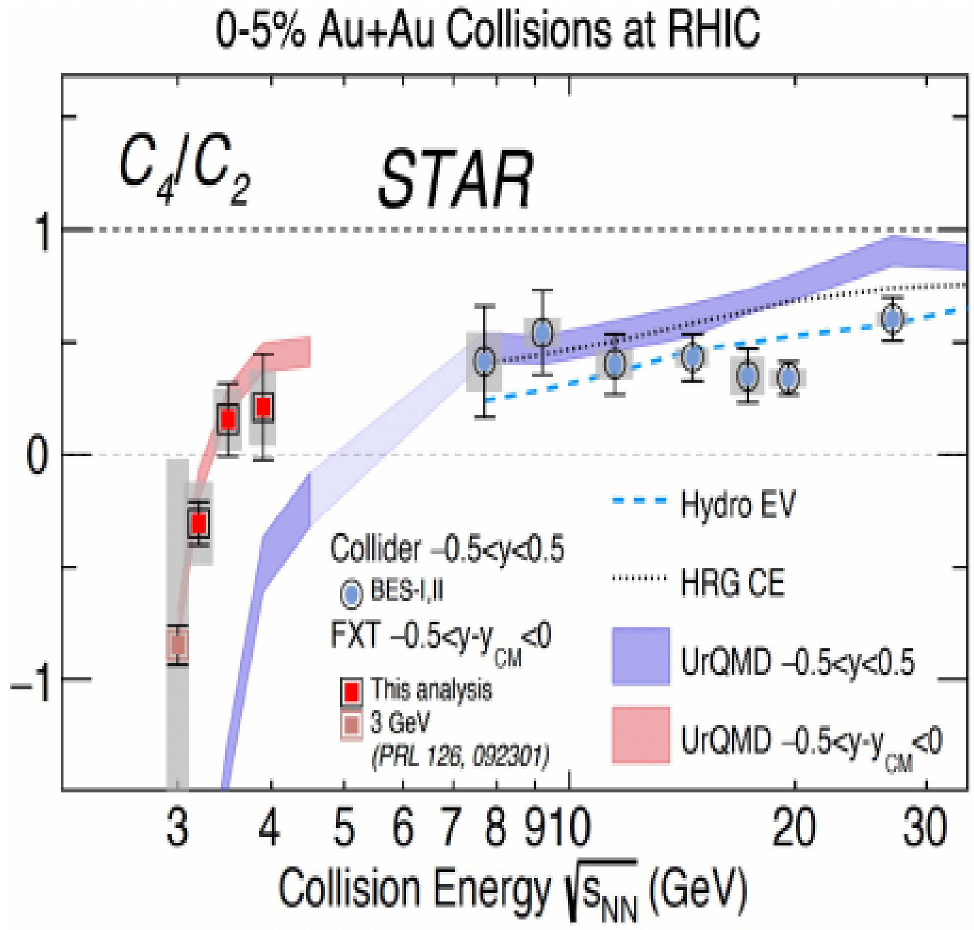
STAR
Cumulants (C)
Factorial cumulants (κ)

Others
Cumulants (κ)
Factorial cumulants (C)

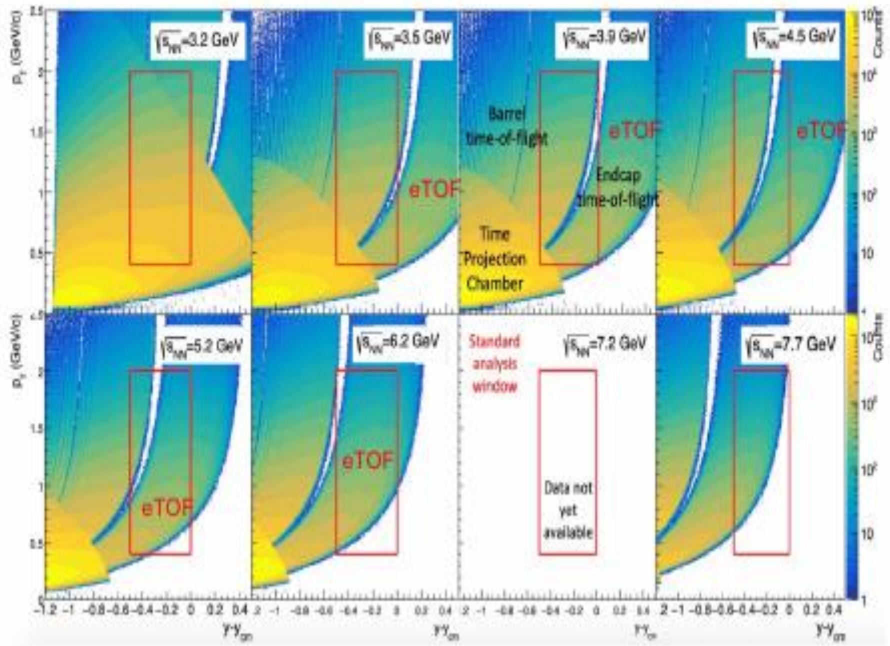


Net-proton higher order cumulants

- Precision measurements from STAR BES-II
- Final results for collider energies $\sqrt{s_{NN}}$ = 7.7 to 19.6 GeV and FXT energies $\sqrt{s_{NN}}$ = 3.2, 3.5 and 3.9 GeV



- In 3.2 - 3.9 GeV, C_4/C_2 is consistent with values from UrQMD
- Deviations seen at higher energies
- Analysis of 4.5 GeV and 2 billion events from Run21 3 GeV are ongoing



Talk by Zachary Sweger, Wed, P35

LQCD ↔ Experiment

Google Translate

Detect language English German Spanish **LQCD** ⇄ **EXPERIMENT** Spanish

$$\chi^{BQSC}_{klmn} = \frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B,\hat{\mu}_Q,\hat{\mu}_S,\hat{\mu}_C)/T^4]}{\partial\hat{\mu}_B^k\partial\hat{\mu}_Q^l\hat{\mu}_S^m\partial\hat{\mu}_C^n}\Big|_{\vec{\mu}=0}$$

Baryon number **(B)**, Strangeness **(S)**, Electric charge **(Q)**, Cham **(C)** 0 / 5,000

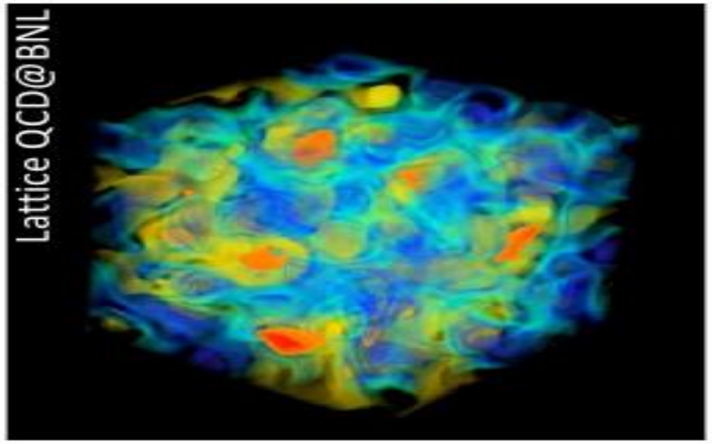
Translation

$$\chi_2^B = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\chi_4^B}{\chi_2^B}$$

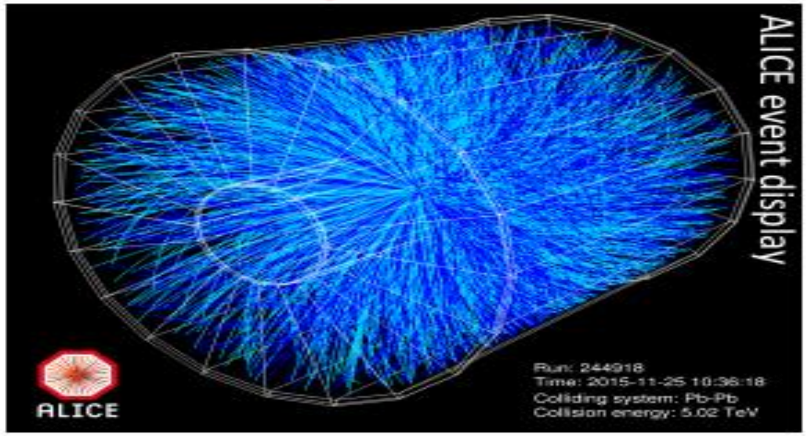
$\kappa_n \to$ cumulants of $\Delta N_B = N_B - N_{\bar{B}}$

Bridge experimental data to LQCD calculations

Theory

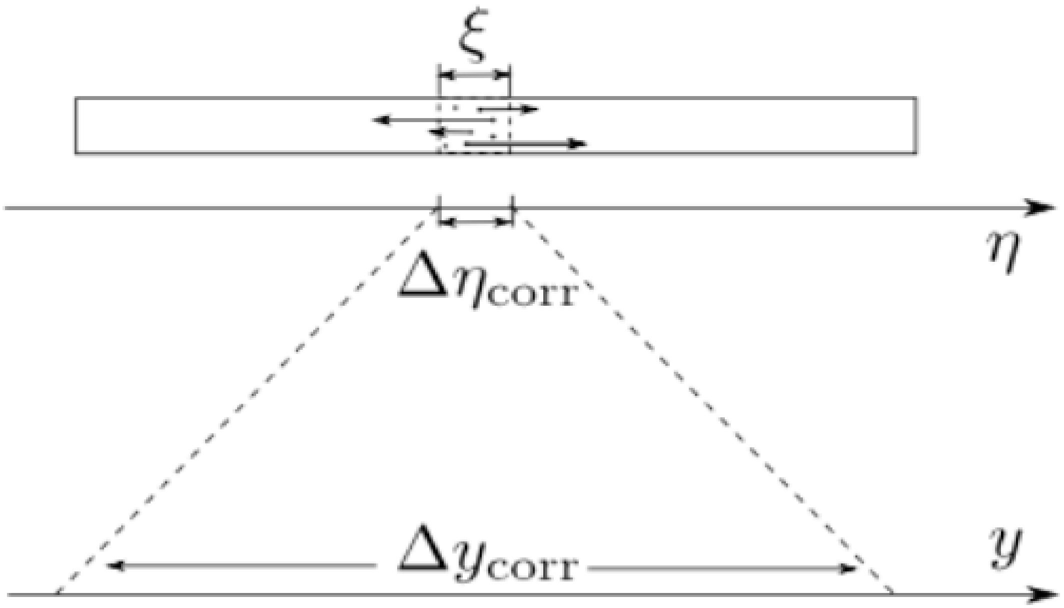


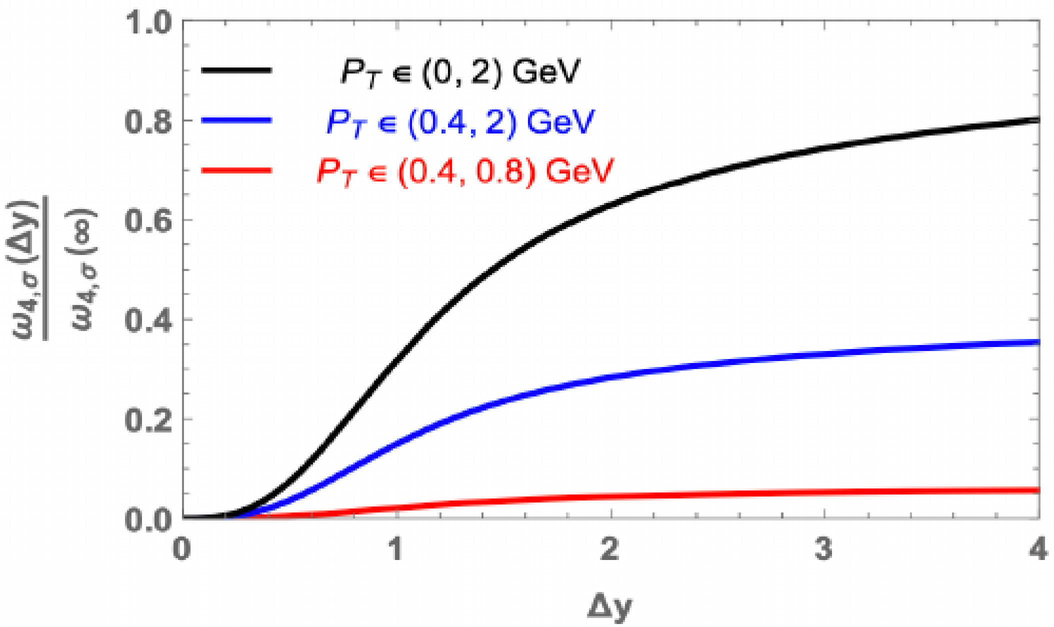
Experiment



Static	Dynamic
Coordinate space	Momentum space
Net-baryon	Net-proton
Fixed V	Fluctuating V
...	...

[1]



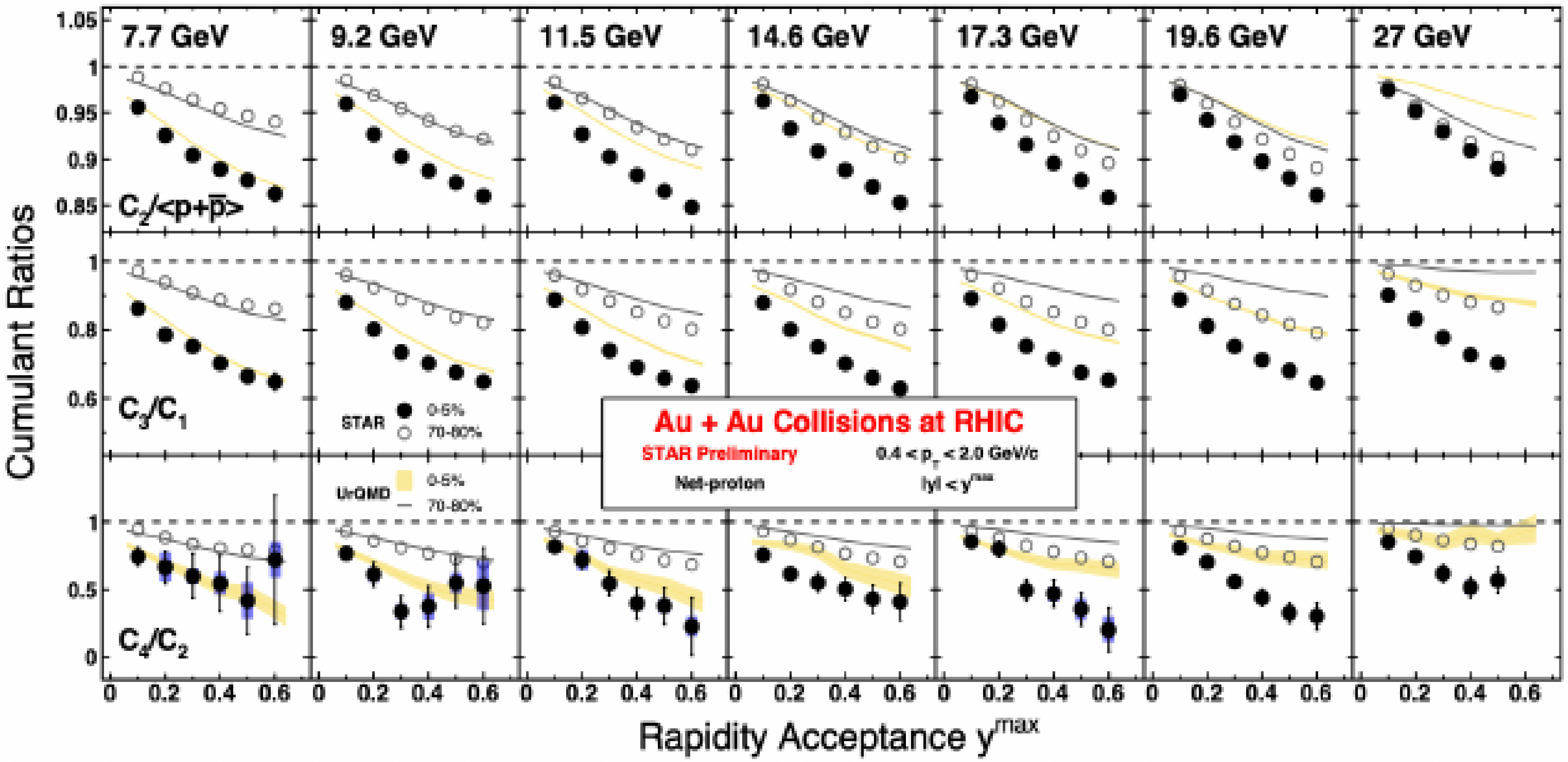


1. Long-range phenomena near critical point: increasing the measurement window in y and p_T magnifies the contribution to normalized cumulants;
2. For small rapidity window $\Delta y \ll \Delta y_{corr}$, and near the critical point, we expect $\kappa_n \sim (\Delta y)^n$[2];
3. The wide and uniform acceptance of the detector provides us with the opportunity to conduct kinematic scan.

[1]M.A.Stephanov: Phys.Rev.Lett. 107(2011),052301
[2]R.V.Ravai and S. Gupta: Phys.Lett.B 696(2011),459-463
[3]S.Ejiri, F.Karsch, K.Redlich: Phys.Lett.B 633(2006),275-282
[4]A.Bazavov, et al.: Phys.Rev.Lett. 109(2012),192302
[5]A.Borsanyi, et al.: Phys.Rev.Lett. 111(2013),062005

Rapidity scan of higher order cumulants

- Widening y, p_T windows of measurement enhances potential critical contributions

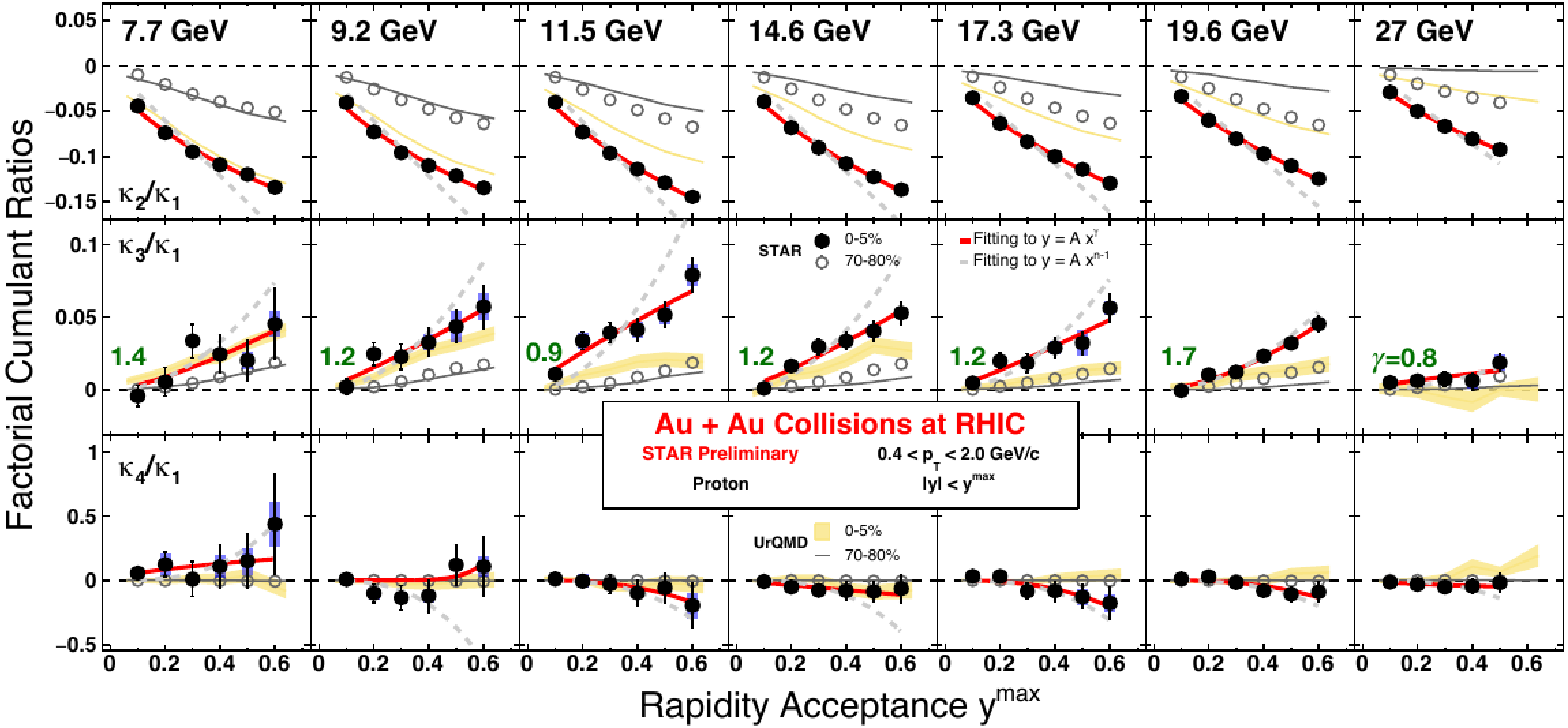


- Deviation from UrQMD increases with y acceptance and near 20 GeV

Poster by Yongcong Xu, #821 | Poster by Xin Zhang #902

Talk by Yige Huang, Wed, P30

Proton Factorial Cumulant Ratios: Rapidity Scan



Near the critical region, factorial cumulants' dependence on $\Delta y \; (= 2 \times y^{\max})$ is simpler and are suggested to study[1]

Deep red solid curve (—): Fitting to $y = Ax^{\gamma}$

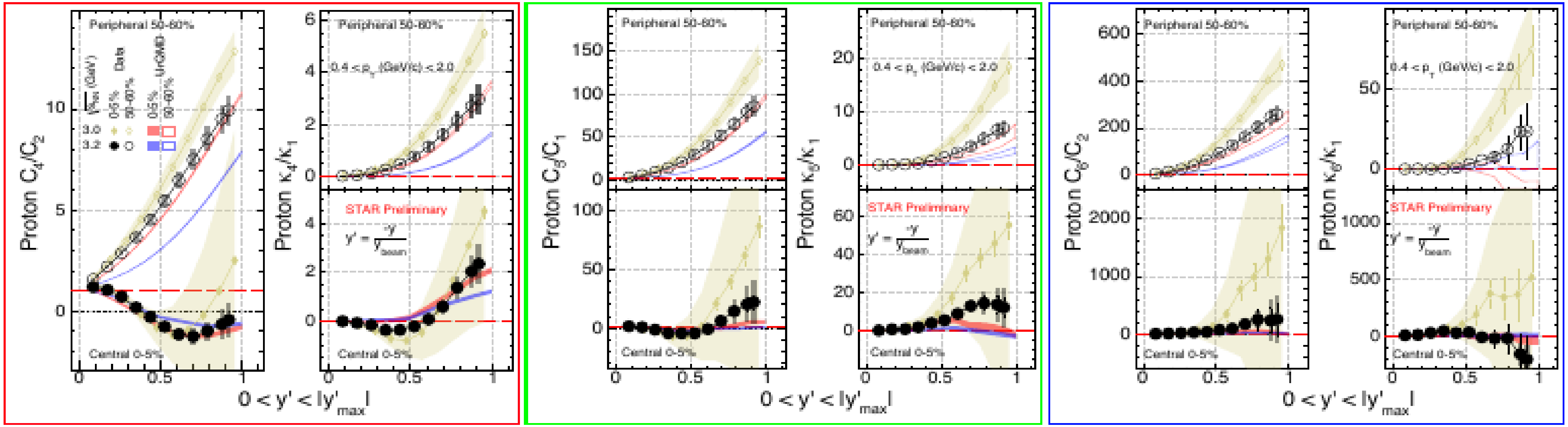
Light gray dashed curve (- -): Fitting to $y = Ax^{n-1}$

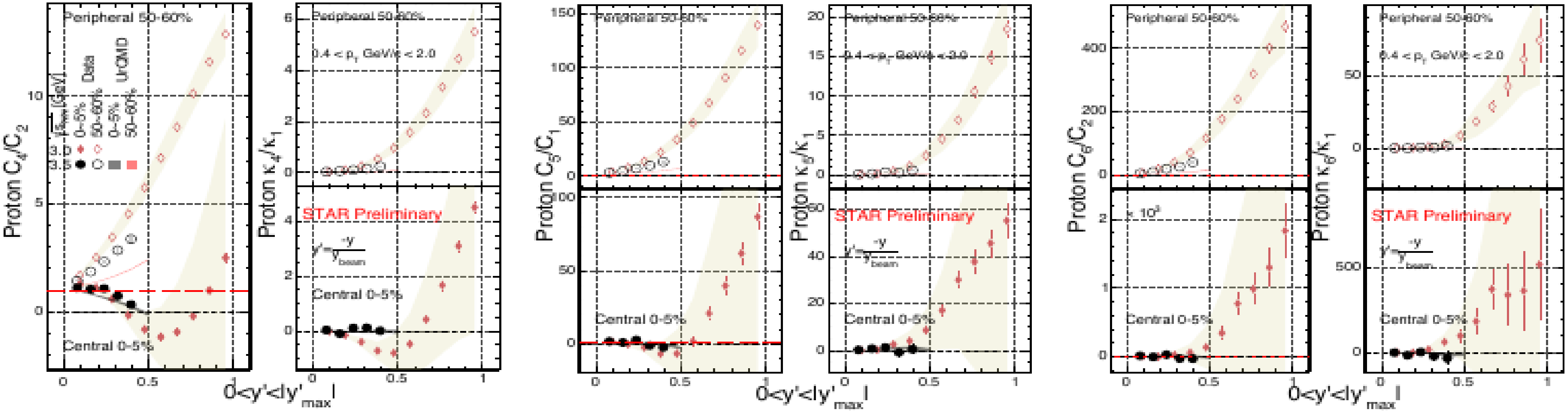
- Smaller exponents than expected power-law $\kappa_n/\kappa_1 \sim (\Delta y)^{n-1}$ are observed.

[1]B.Ling and M.A.Stephanov: Phys.Rev.C 93(2016)3,034915

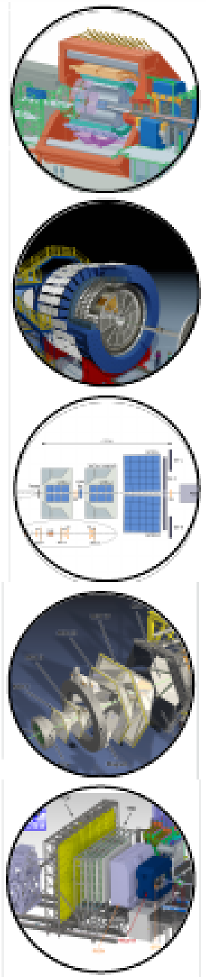
➤ Rapidity Acceptance Dependence

Y. Xu, X. Zhang, QM 2025 posters





Event-by-event fluctuations: Big picture



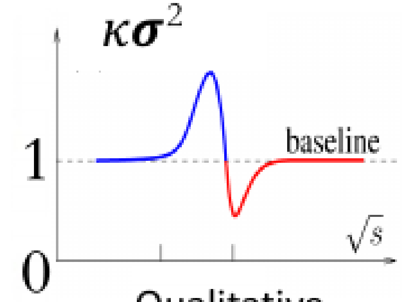
Experimental challenges:

- Detection efficiency correction: Unfolding, binomial
- Event pileup: Statistical approach
- Particle identification: Fuzzy logic vs cut based particle identification
- Volume fluctuation correction (VFC): Mixed event, centrality bin width correction (CBWC)

How to interpret: "Establishing a non-critical Baseline"

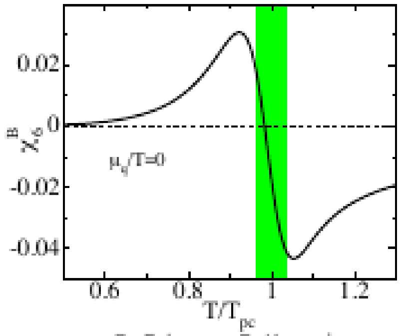
- **Critical fluctuations & Critical End Point (CEP) at < 5 GeV**
- Global/local charge conservation
- Contribution from different hadronisation mechanisms
- Annihilation, excluded volume, resonances, hydrodynamic evolution …

M. Stephanov, PRL107, 052301(2011)



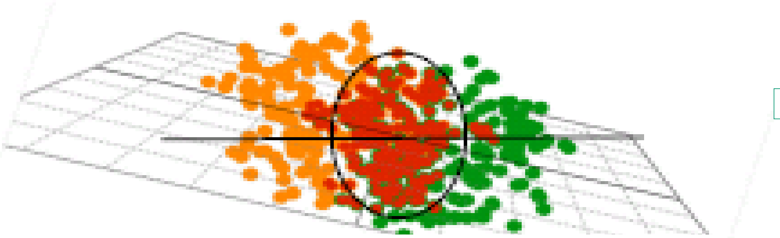
Qualitative

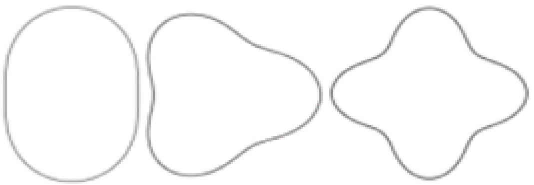
Quantitative



B. Friman, F. Karsch, K. Redlich, V. Skokov EPJC (2011) 71 1694

Anisotropic Flow at RHIC-LHC



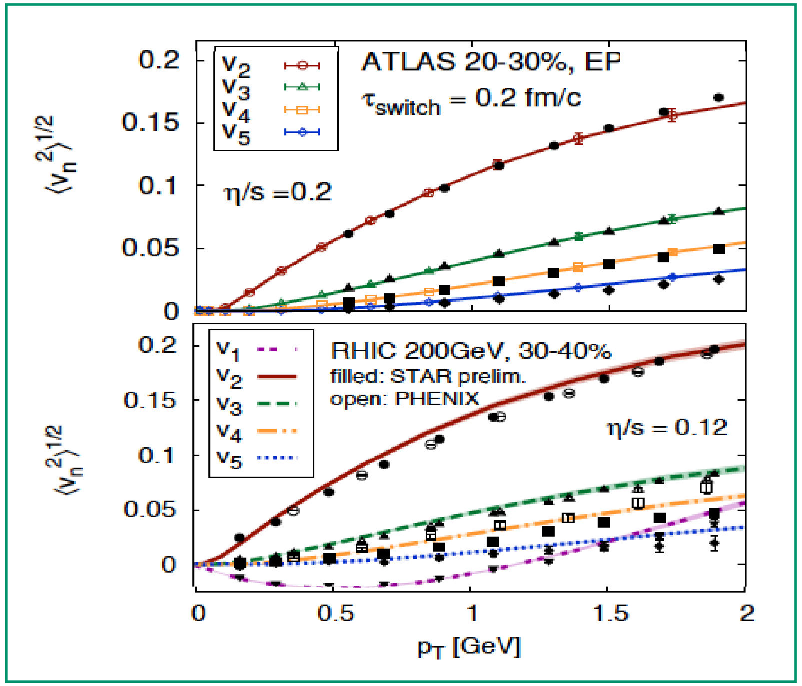


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

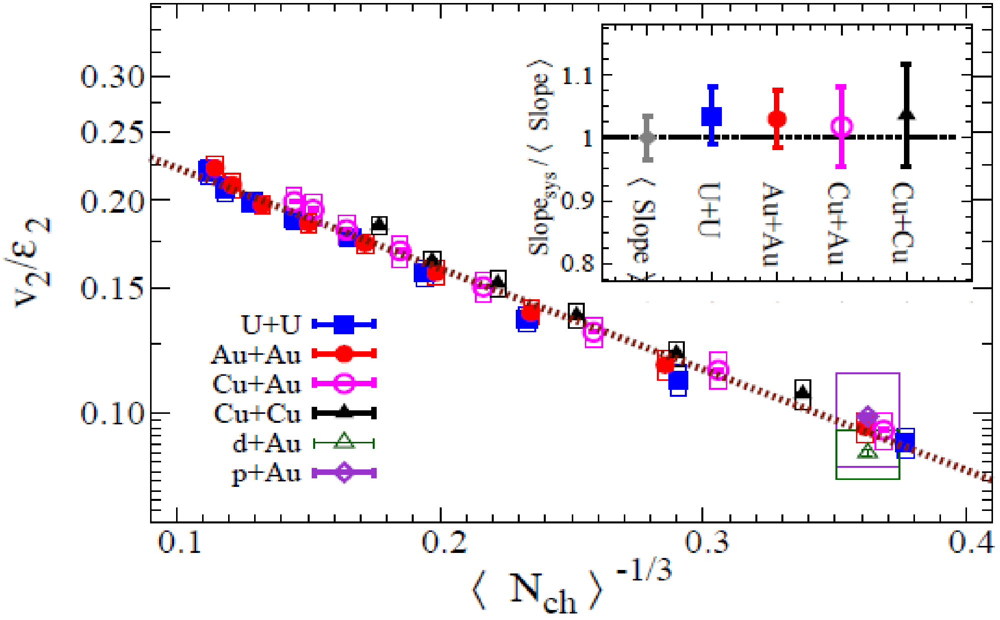
$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302



STAR, Phys. Rev. Lett. 122 (2019) 172301



Anisotropic flow in heavy-ion collisions at high baryon density

M. Abdallah et al. STAR, Phys. Lett. B 827, 137003 (2022)

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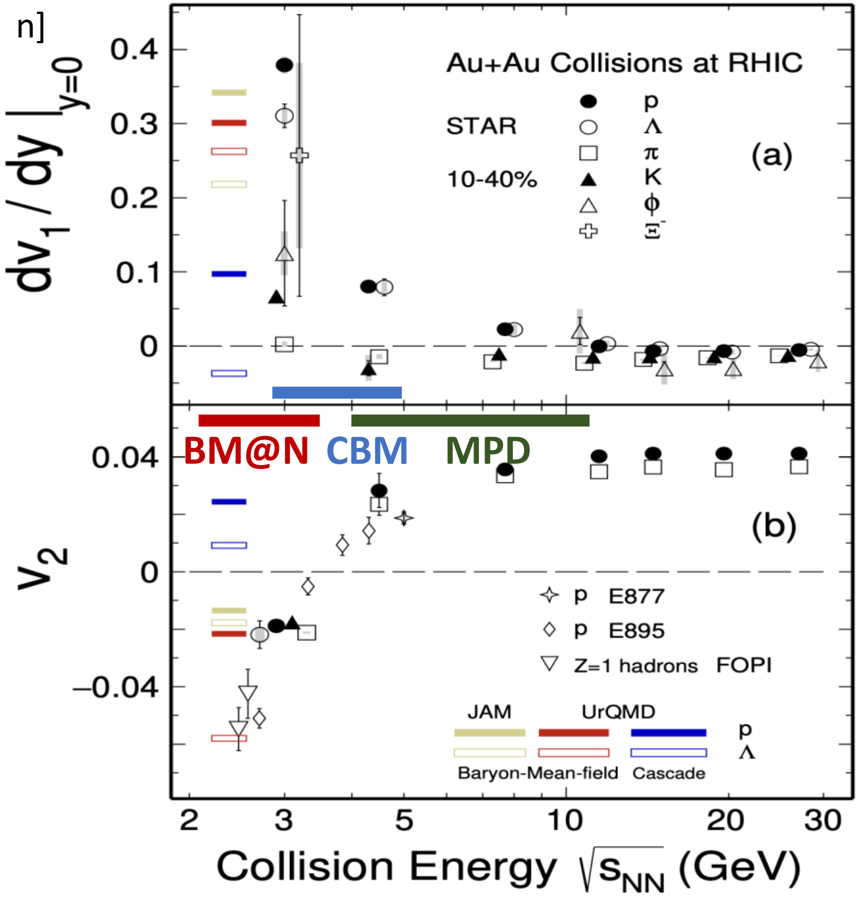
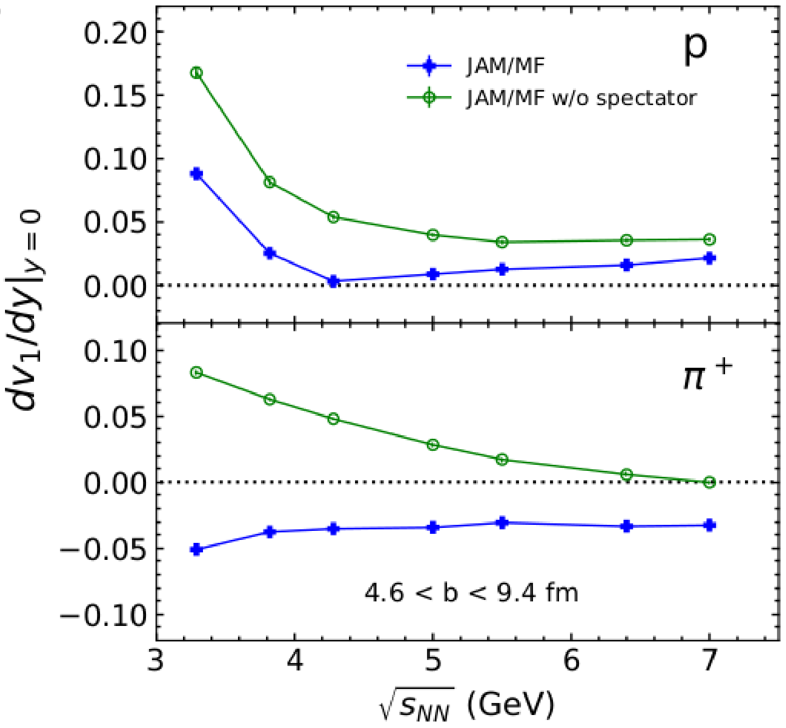
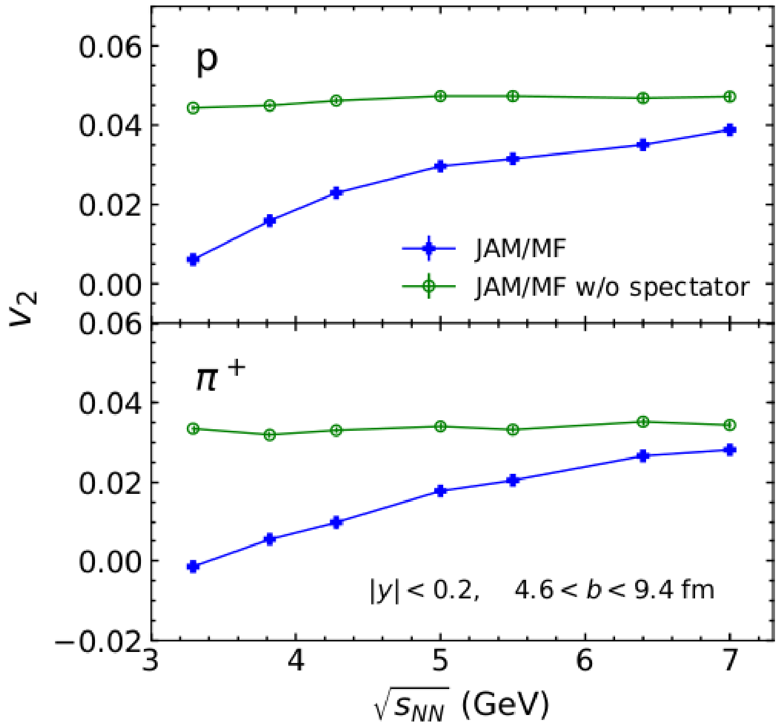






Phys. Rev. C 97, 064913 (2018)

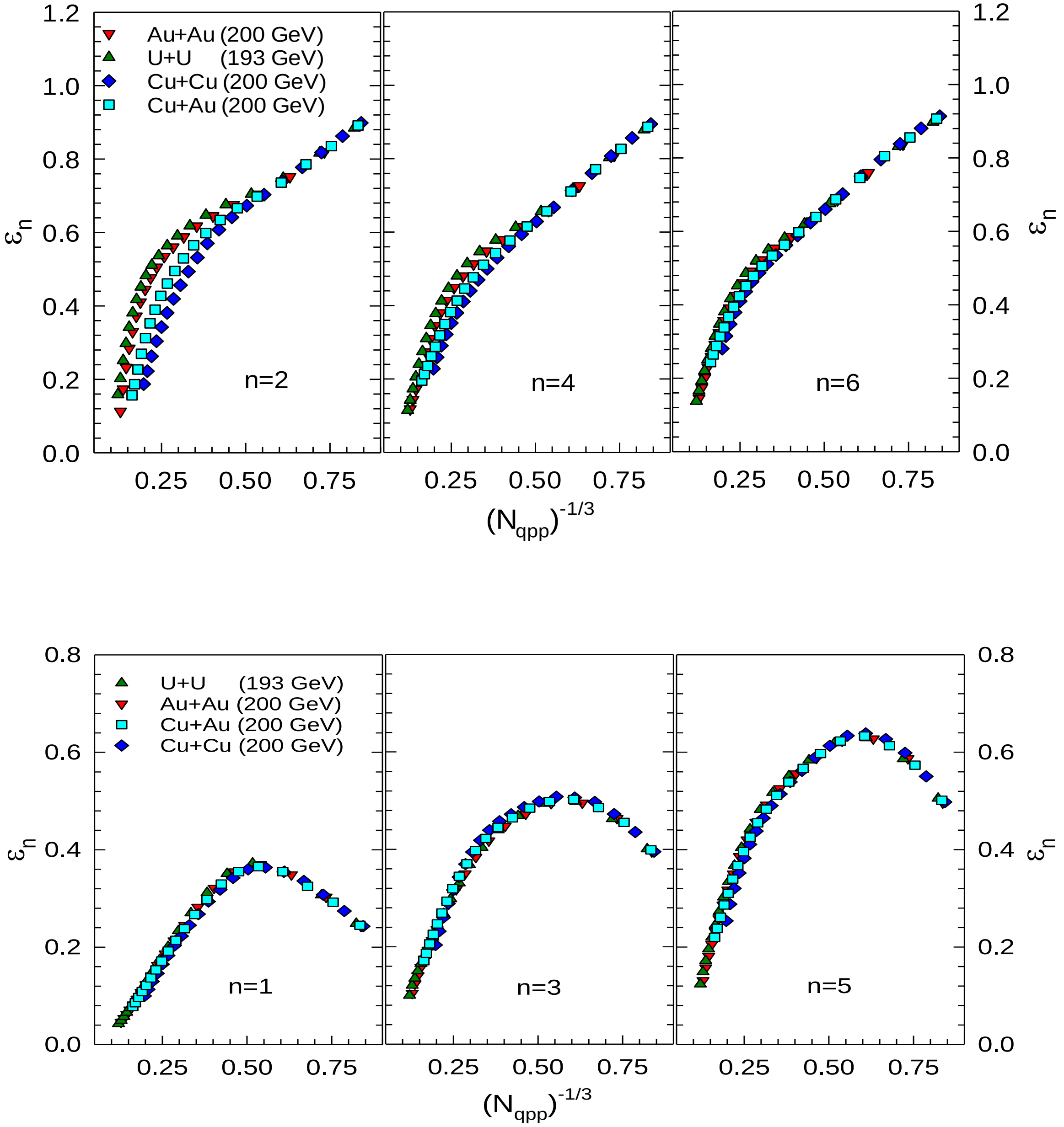
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

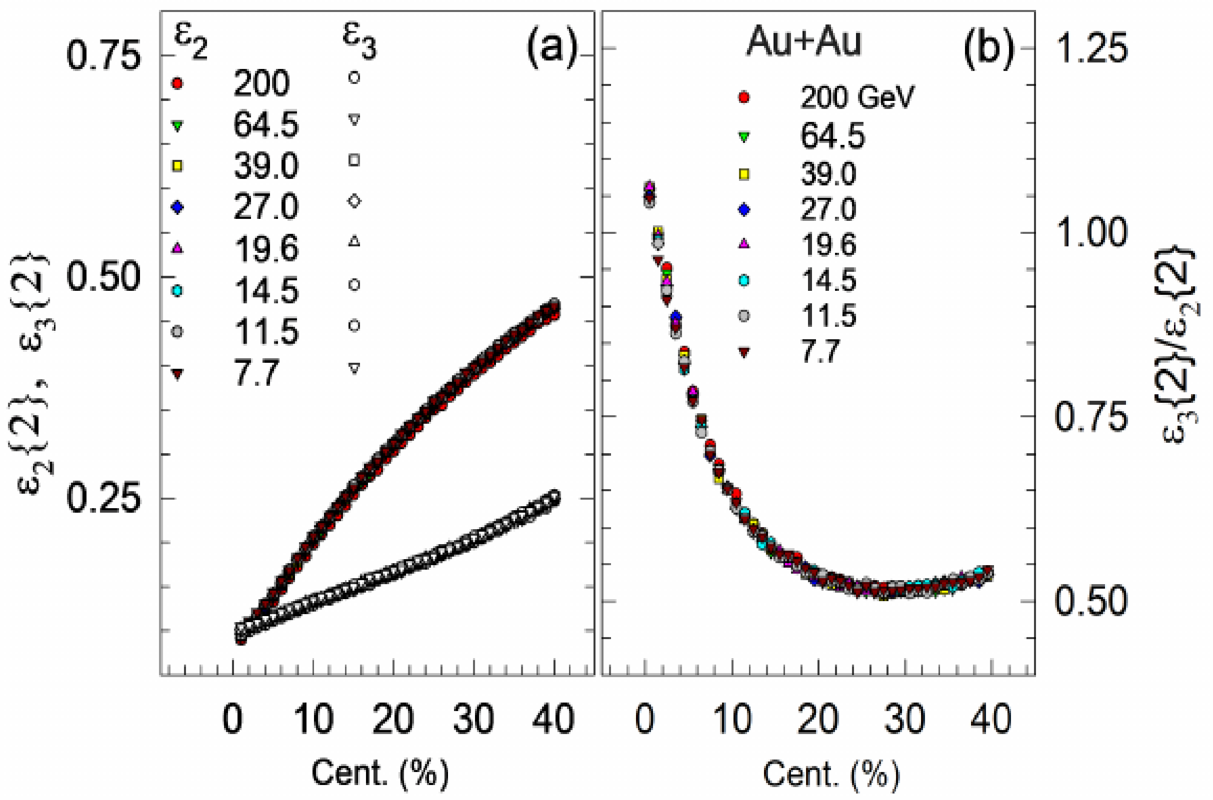
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s\,, c_s = c\sqrt{dp/d\varepsilon}$) and

II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

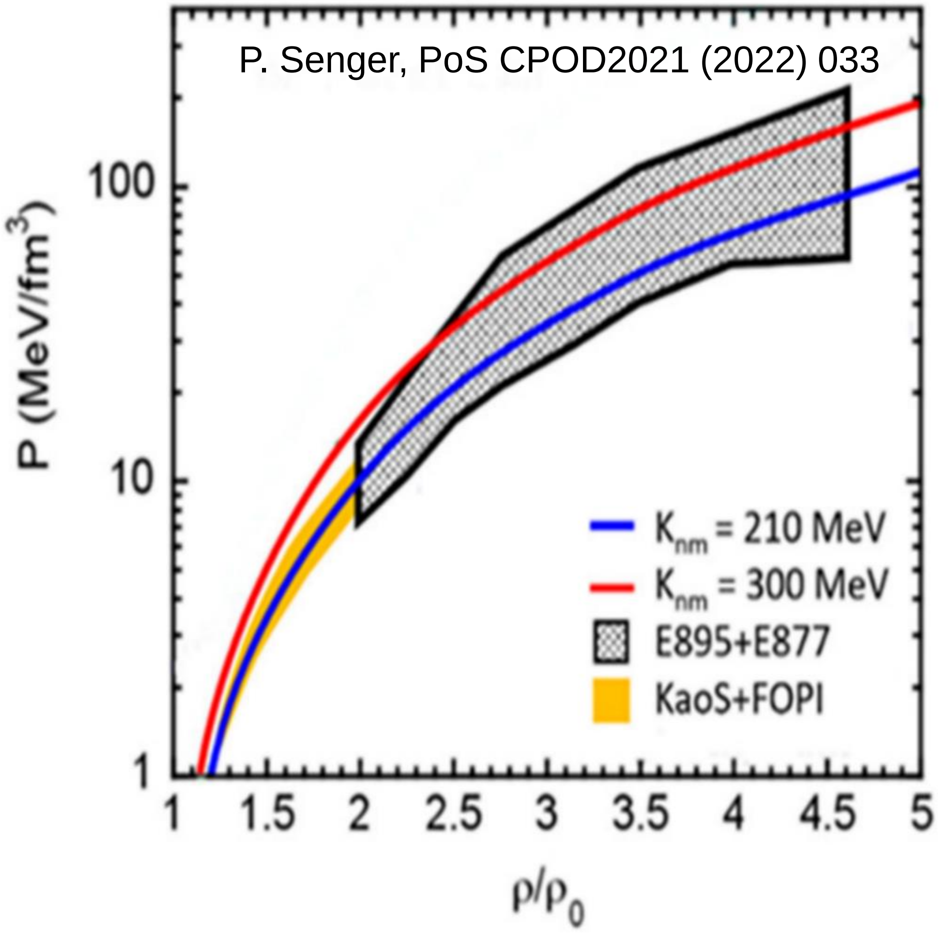
Anisotropic Flow – Expected Shapes

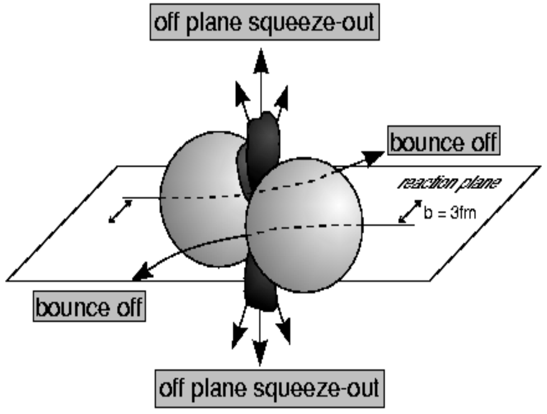
courtesy of R.A. Lacey

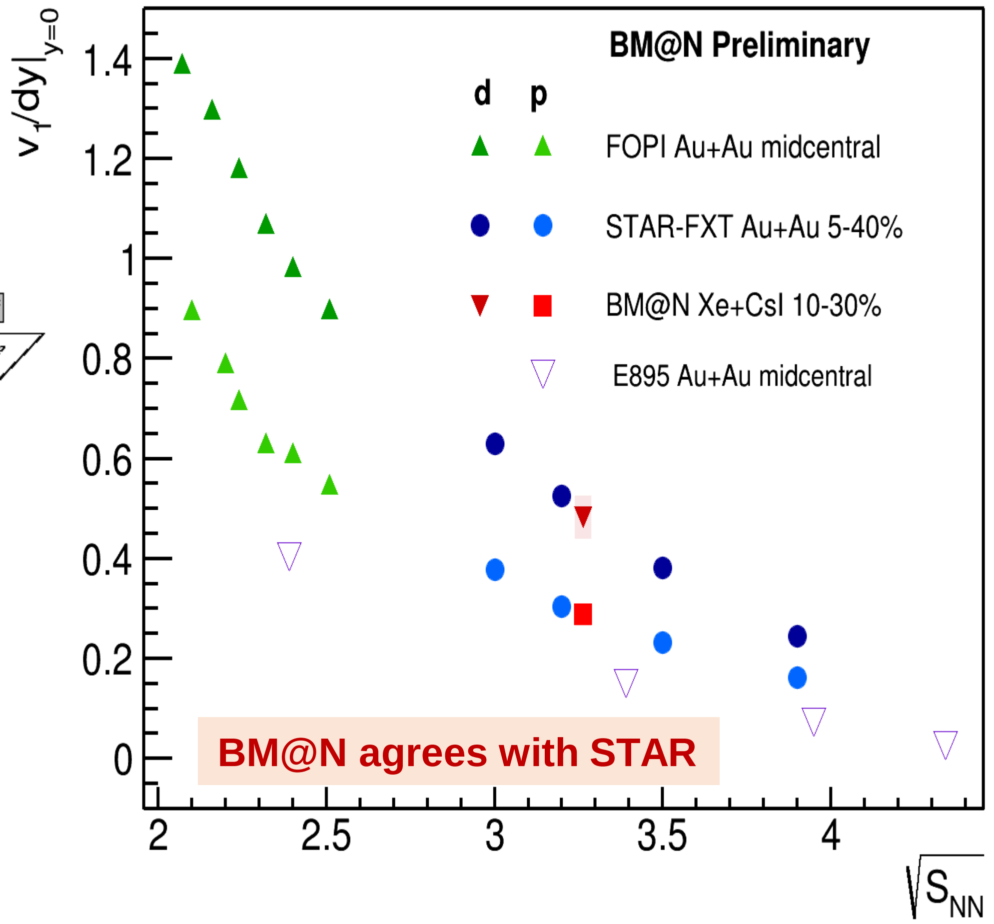




Directed flow of protons and EOS of symmetric matter





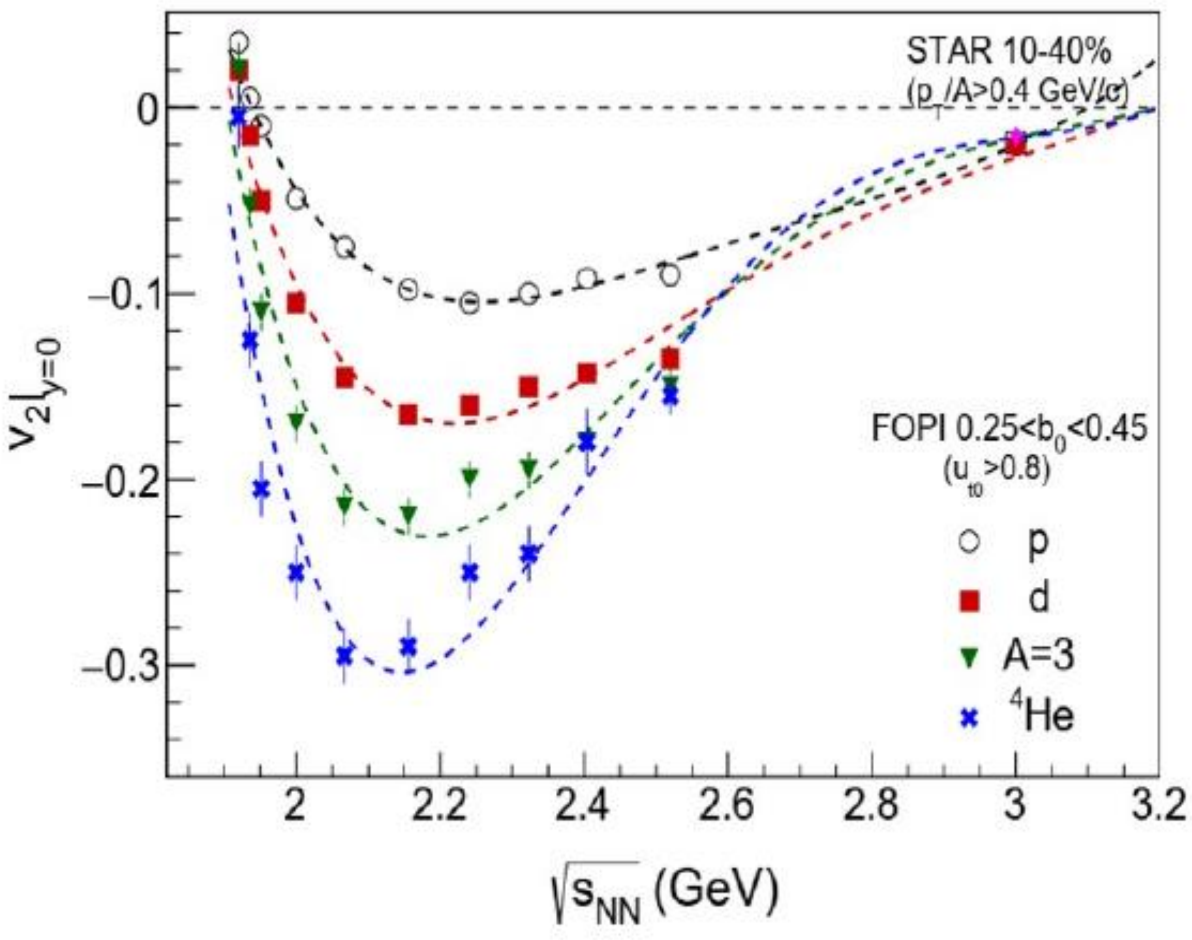


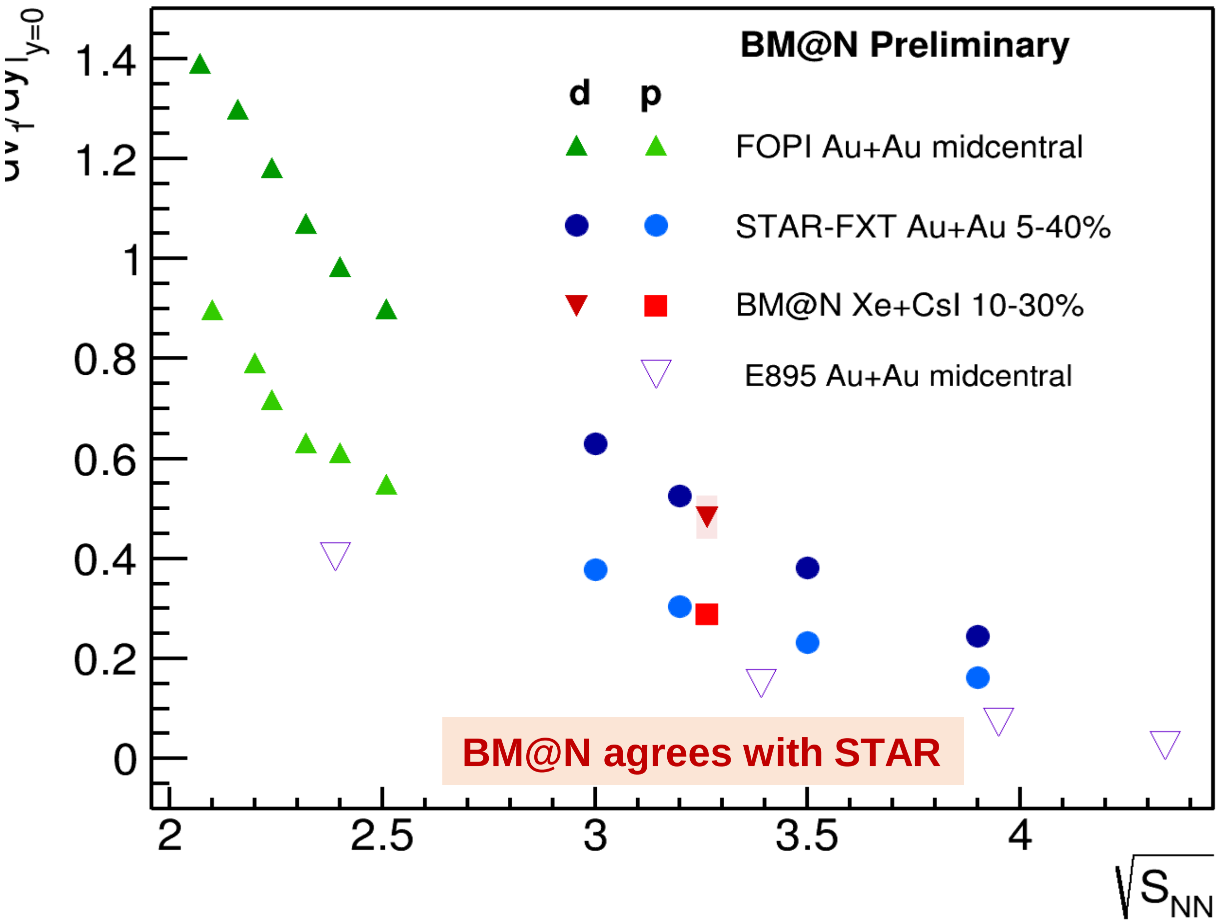
Nuclear incompressibility from collective proton flow

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

Both STAR and BM@N results for directed flow prefer stiff EOS

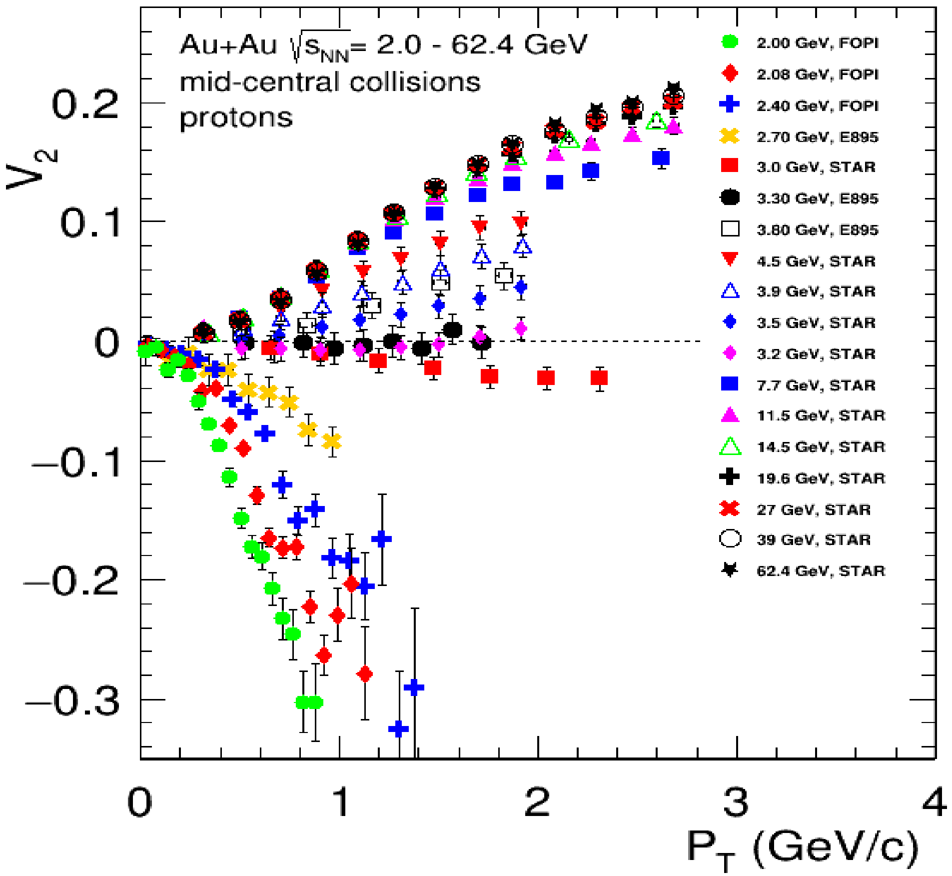
Directed and elliptic flows of and EOS of symmetric matter

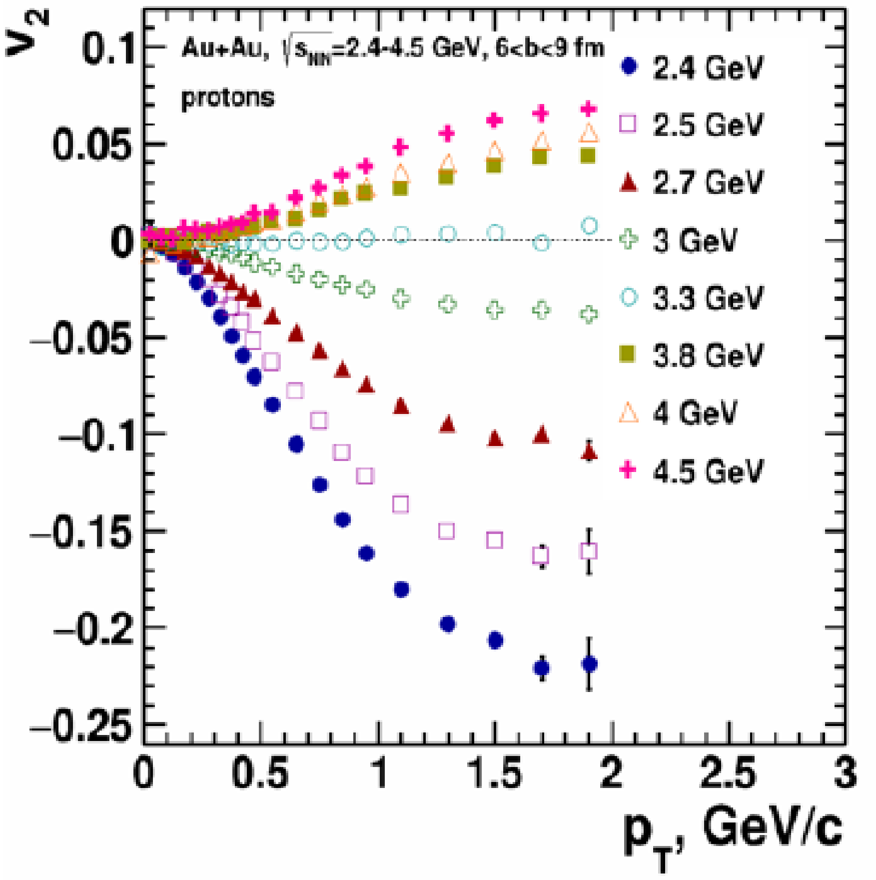




Anisotropic flow in Au+Au collisions at Nuclotron-NICA energies

Particles 6 (2023) 2, 622-637





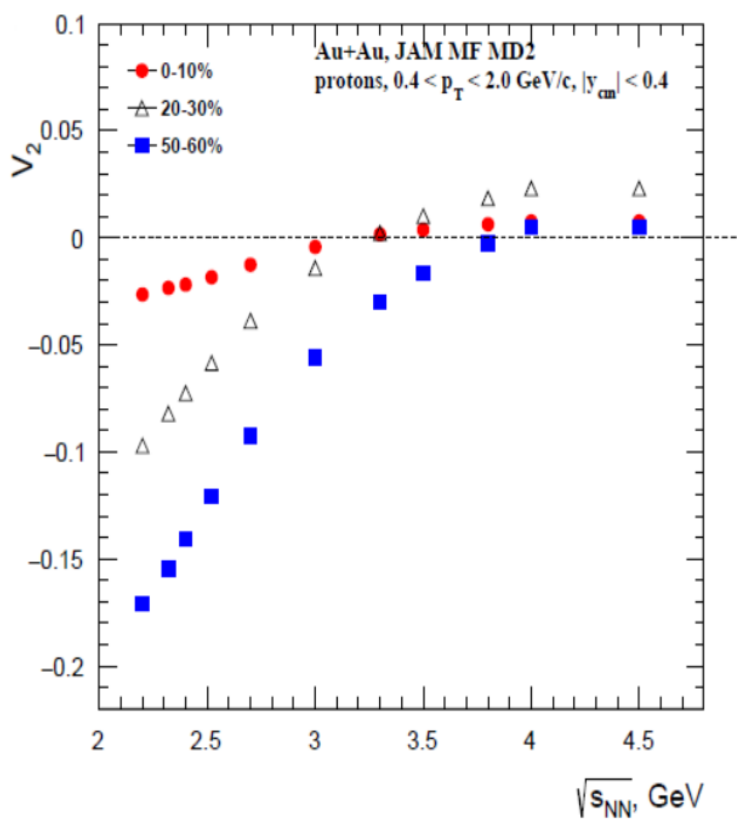
Anisotropic flow at FAIR/NICA energies is a delicate balance between:

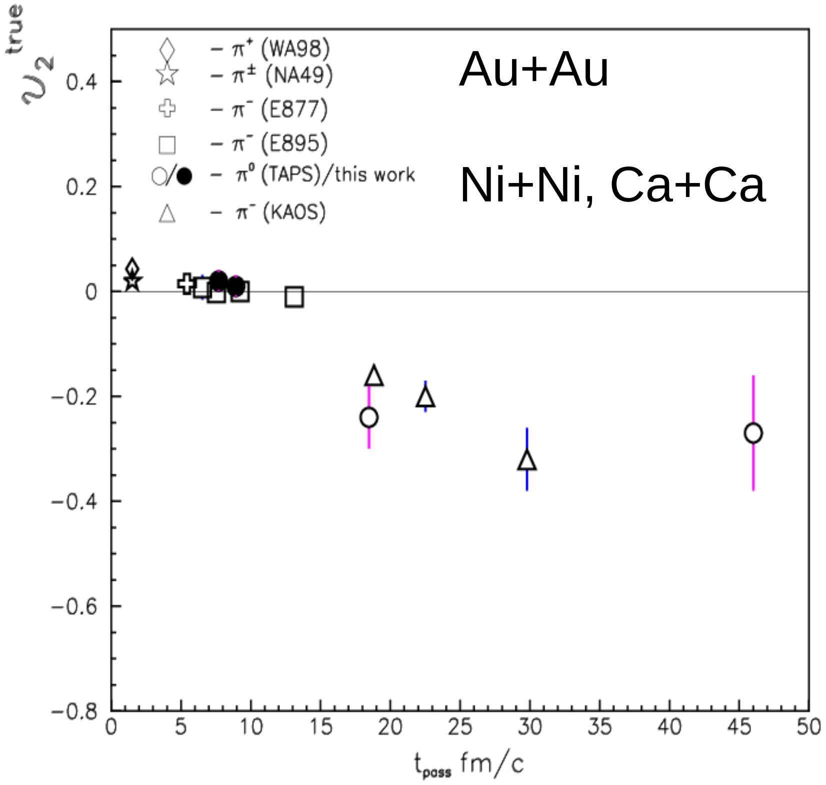
I. The ability of pressure developed early in the reaction zone ($t_{exp} = R/c_s\,, c_s = c\sqrt{dp/d\varepsilon}$) and

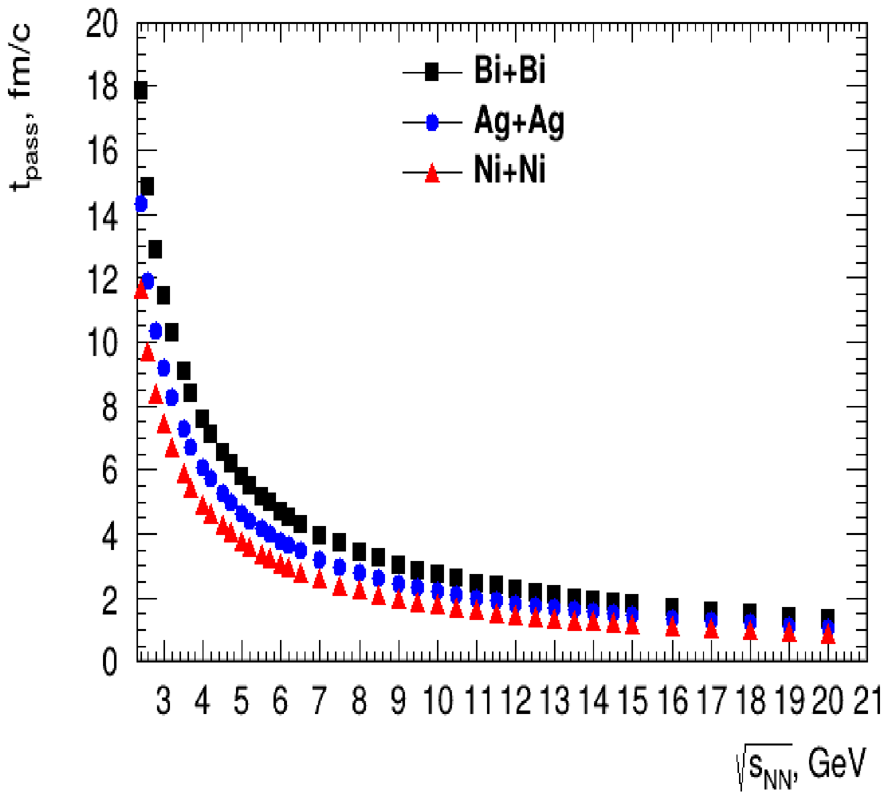
II. The passage time for removal of the shadowing by spectators ($t_{pass} = 2R/\gamma_{CM}\beta_{CM}$)

Elliptic flow: transition from out-of-plane to in-plane: geometry

P. Parfenov, Particles 5 (2022) 4, 561-579   A.T Czech.J.Phys. 50S4 (2000) 139-16(



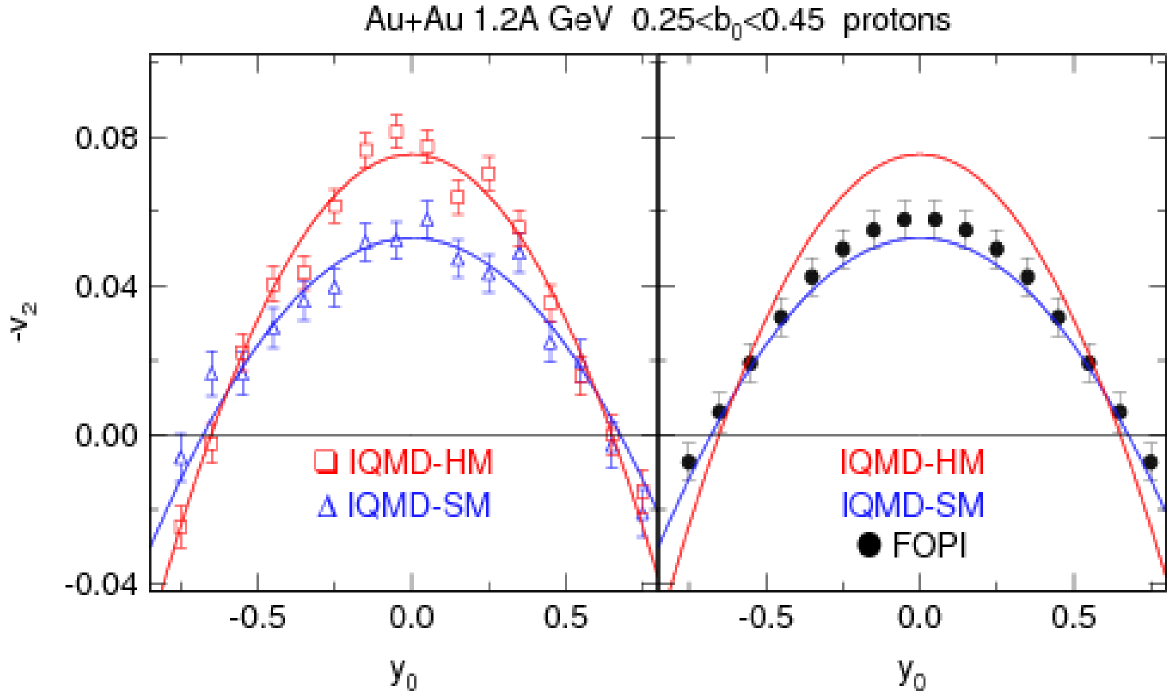


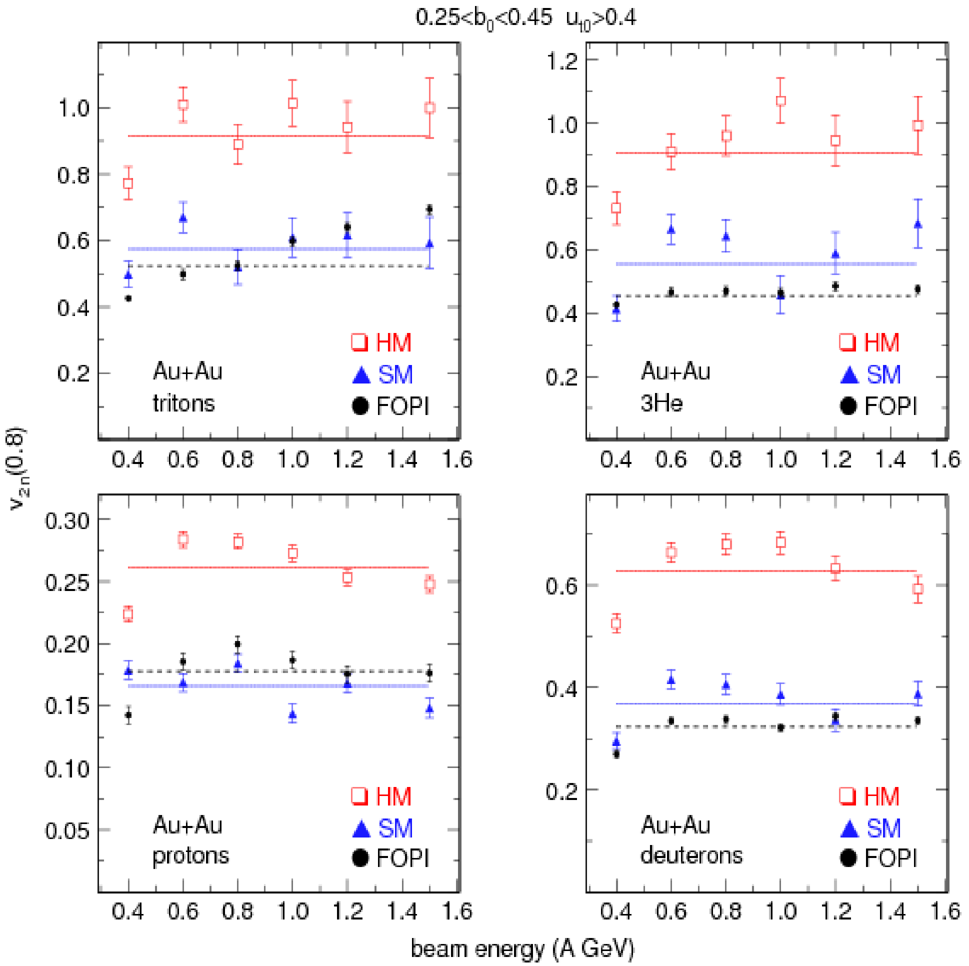


Rapidity dependence of v2 and EOS

HM – stiff momentum dependent with K=376 MeV
SM – soft momentum dependent with K=200 MeV

FOPI data : Nucl. Phys. A 876 (2012) 1
IQMD : Nucl Phys. A 945 (2016)



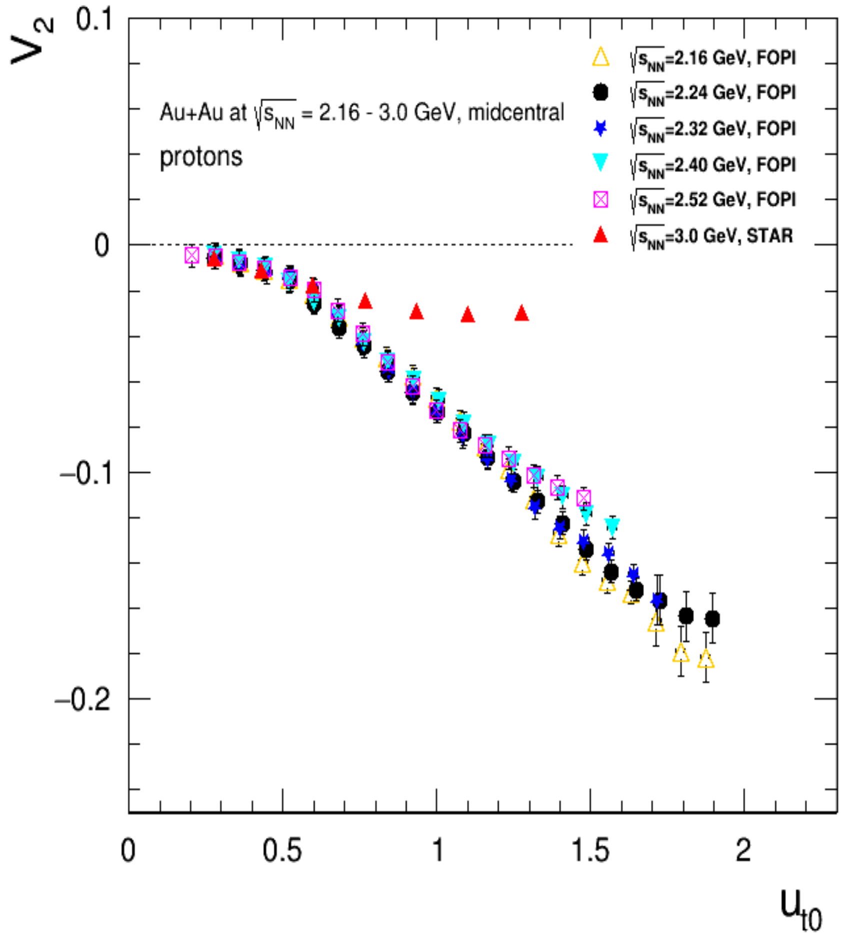


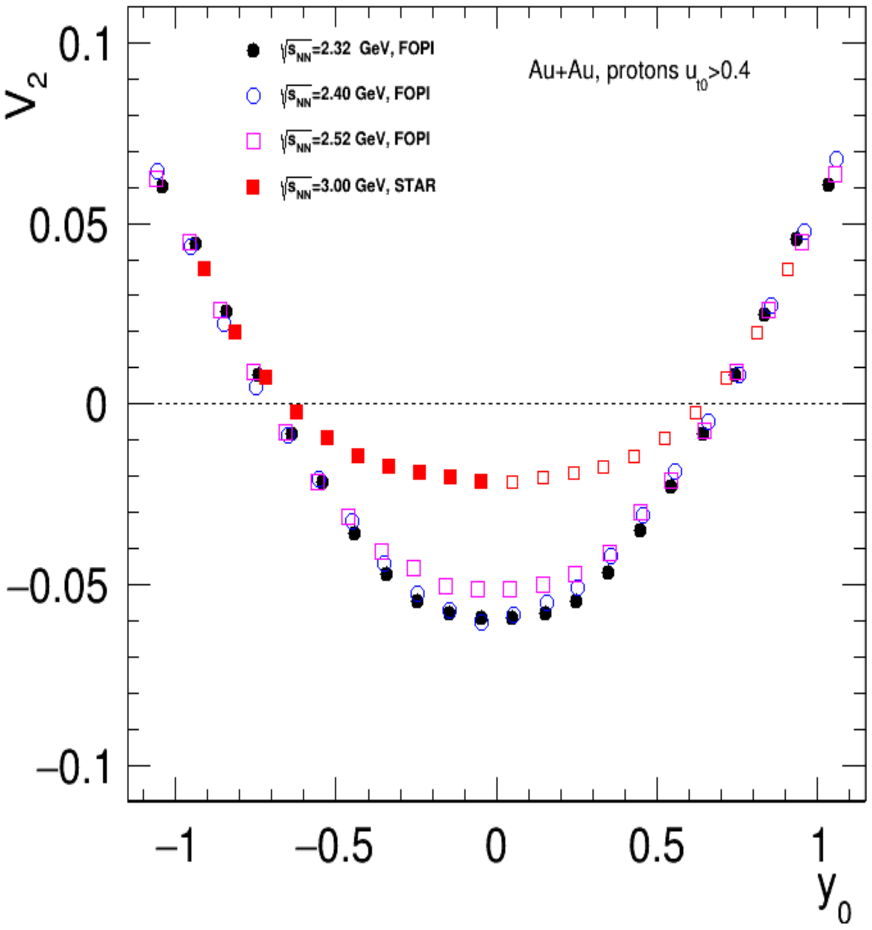
V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

Large rapidity coverage is important for flow measurements: MPD forward upgrade

u_{t0} scaling: FOPI/STAR data

STAR published results for protons : Scaling breaks at $\sqrt{s_{NN}}$=3GeV – but holds at forward rapidity?



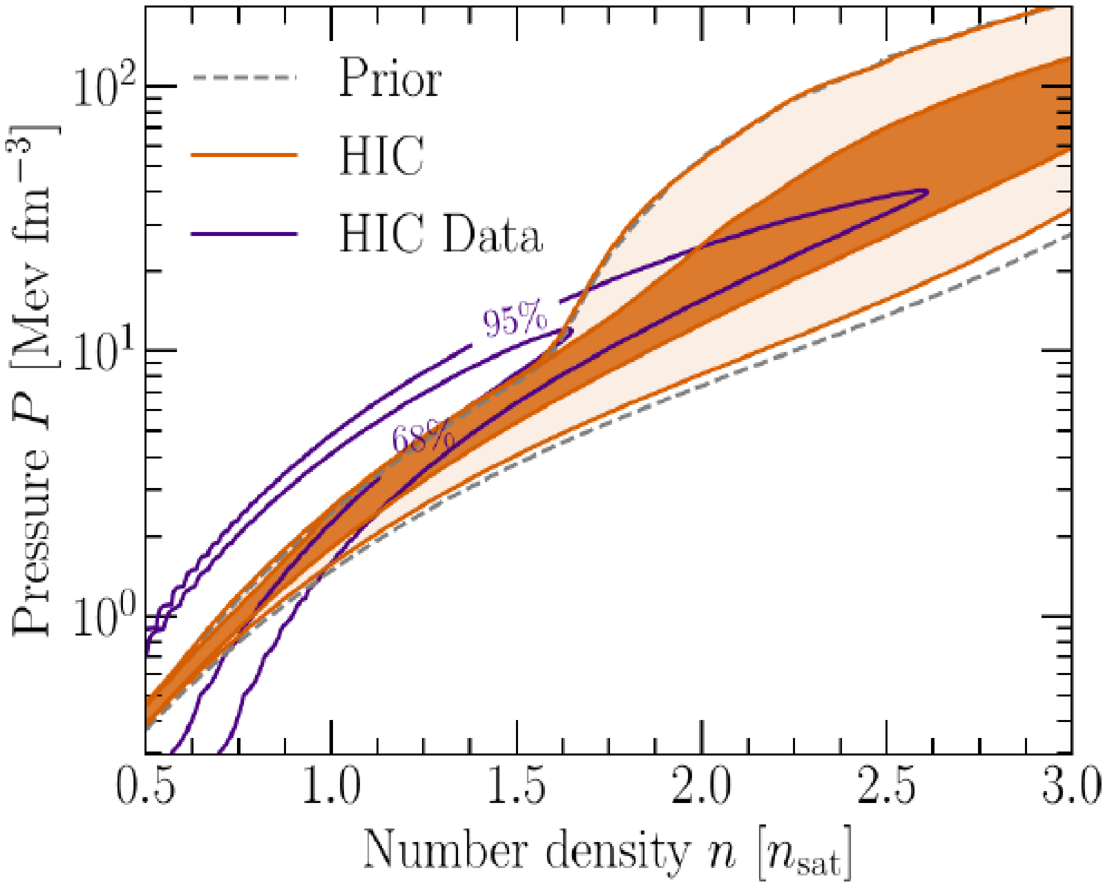


Constraining neutron-star matter with microscopic and macroscopic collisions

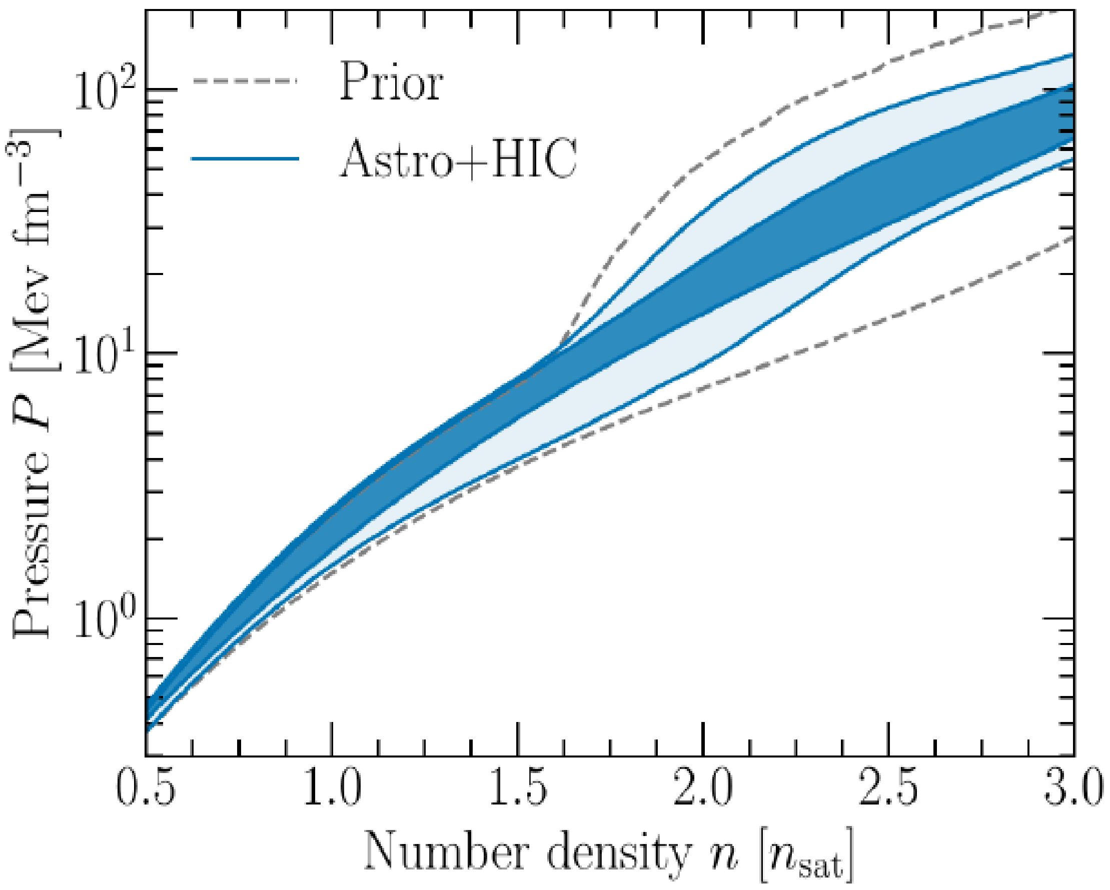
Huth, Pang et al. Nature 606(22)276

HIC experiments:

Bayesian combinations



HIC and Astro combined:

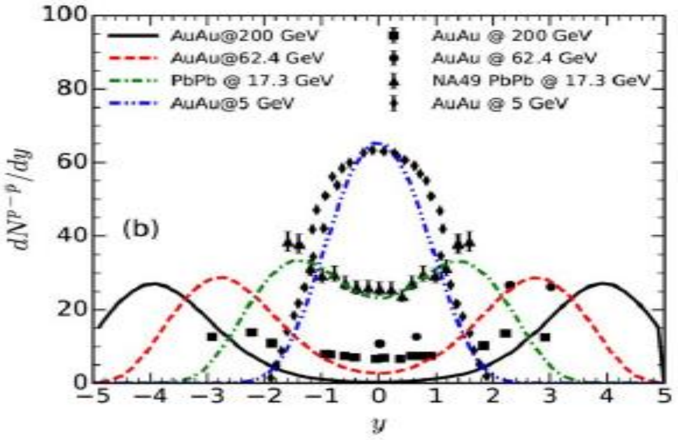


Astrophysical observations narrow constraints above 2 n_{sat}

Rapidity Scan with MPD at NICA

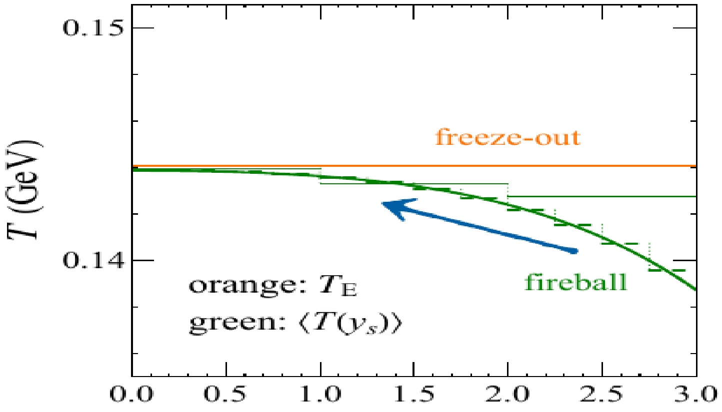
Rapidity dependence of cumulant observables can enhance the prospect of discovering a CEP

J.Li, L.Du and S.Shi,
Rapidity scan approach for net-baryon cumulants"
Phys. Rev. C 109, no.3, 034906 (2024)
J. Brewer et al., Phys. Rev. C 98, 061901 (2018)



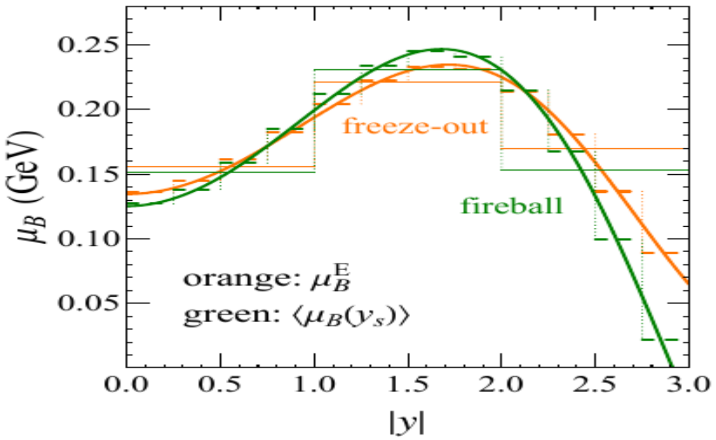
Rapidity-dependent yields offers an extra method to explore the EoS at finite chemical potentials.

L.Du,`Bulk medium properties of heavy-ion collisions from the beam ene
scan with a multistage hydrodynamic model,"
Phys. Rev. C 110 (2024) no.1, 014904



Thermodynamic properties, especially the baryon chemical potential (μ_B) , undergo significant variations across rapidity,

L.Du, H.Gao, S.Jeon and C.Gale,
Rapidity scan with multistage hydrodynamic model,
Phys. Rev. C 109, no.1, 014907 (2024)



Rapidity dependence of anisotropic flow provides provides sensitivity to (T,μ_B) dependence of specific shear (η/s) and bulk (ζ/s) viscosities

S.A.Jahan, H.Roch and C.Shen,
Bayesian analysis of (3+1)D relativistic nuclear dynamics with the RHIC data, Phys.Rev.C 110 (2024) 5, 054905

Backup slides