The STAR Beam Energy Scan Program at RHIC

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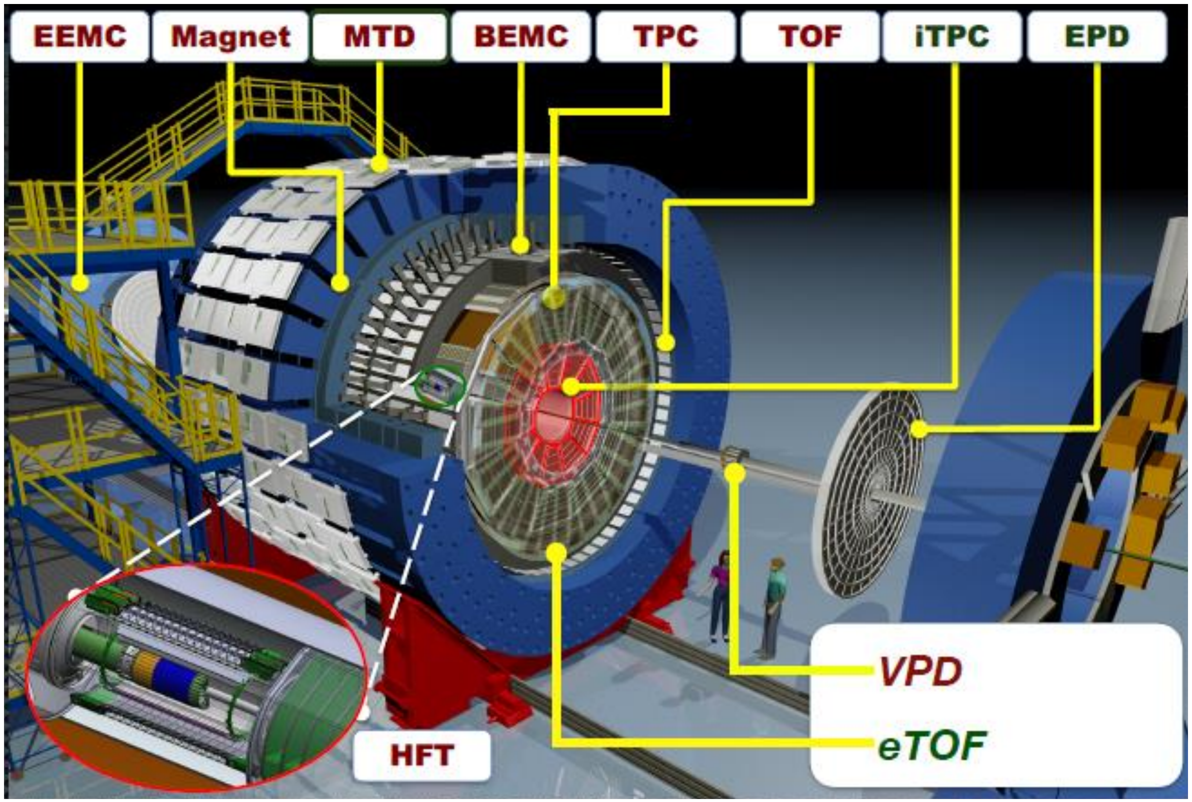
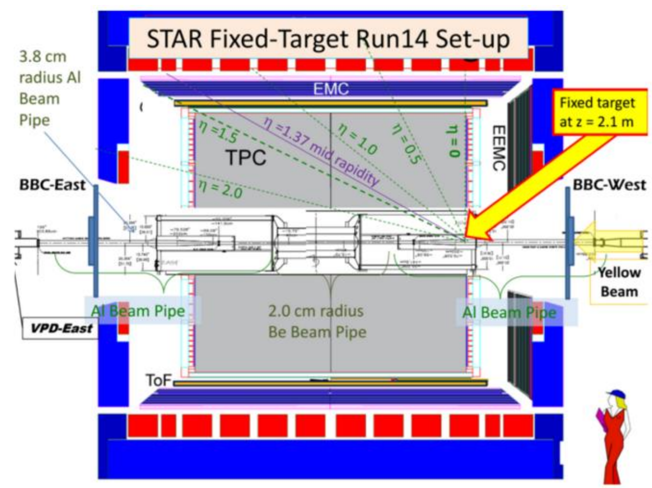
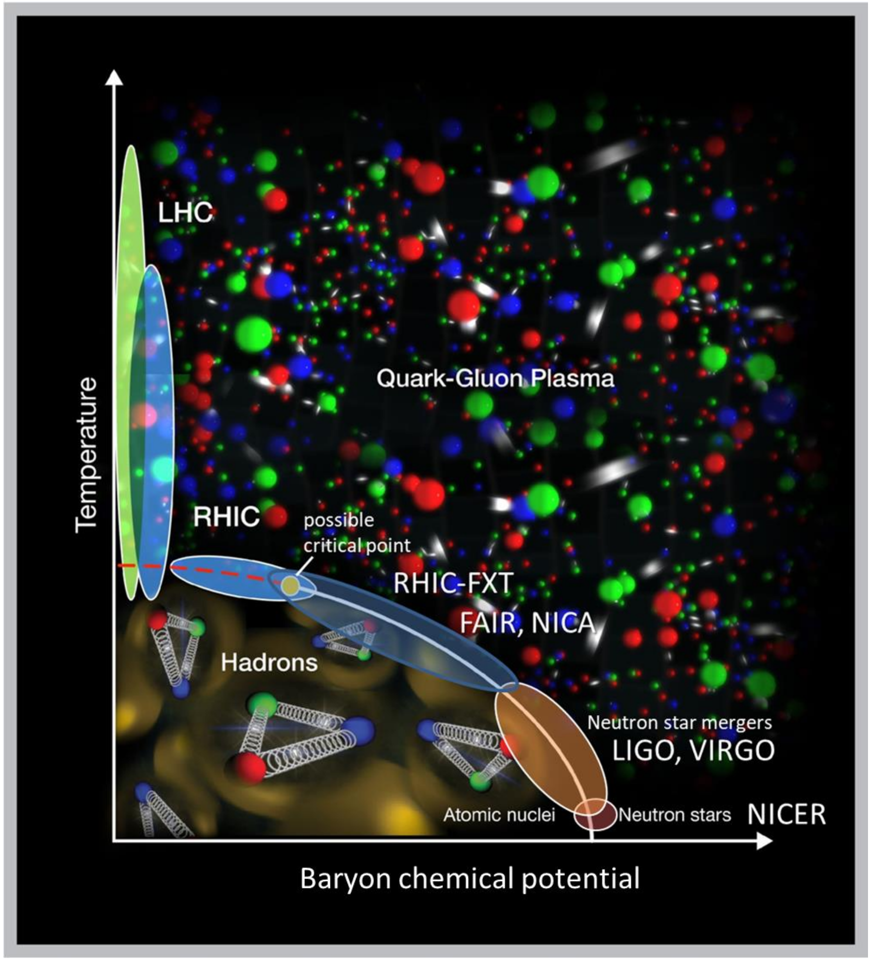


Part 1:
- the BES program to date
- bulk properties of matter
- collective flow
- fluctuations
- correlations
- femtoscopy



The BES Program to date



BES-I and prior:

- 2014-2016: > 5 Billion 200 GeV AuAu events
- BES-I: > 100 M 62.4, 54.4, 39 GeV AuAu events

BES-II: all AuAu events

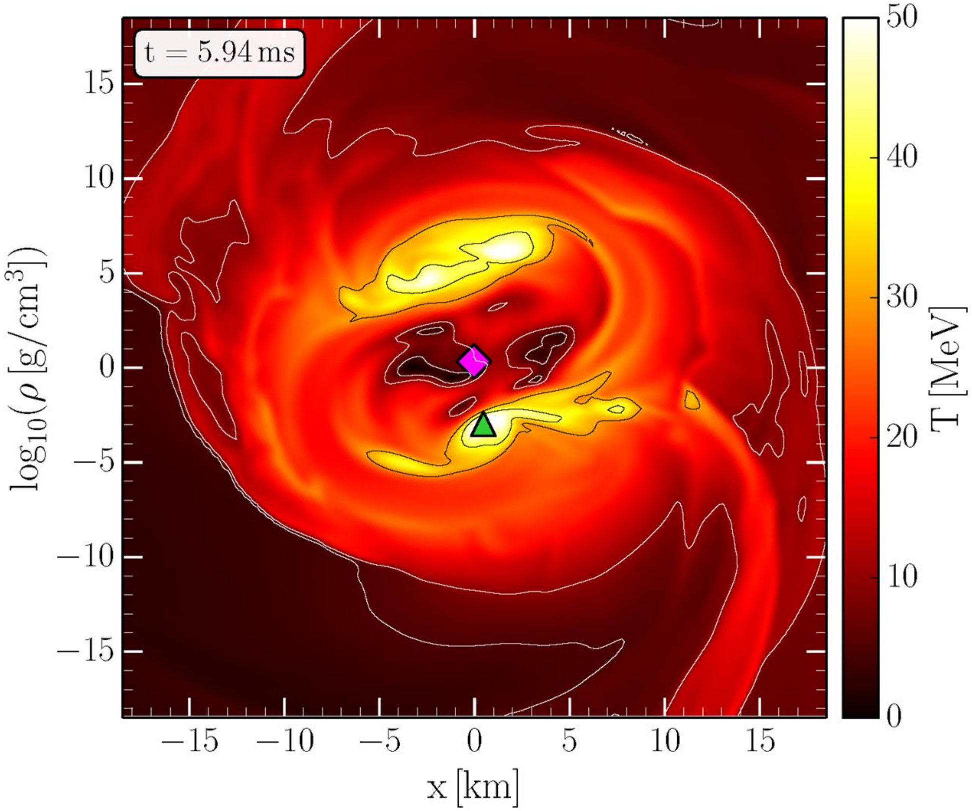
Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Run Time	Number Events Requested (Recorded)	Date Collected
13.5	27	156	24 days	(560 M)	Run-18
9.8	19.6	206	36 days	400 M (582 M)	Run-19
7.3	14.6	262	60 days	300 M (324 M)	Run-19
5.75	11.5	316	54 days	230 M (235 M)	Run-20
4.59	9.2	373	102 days	160 M (162 M)[1]	Run-20+20b
31.2	7.7 (FXT)	420	0.5+1.1 days	100 M (50 M+112 M)	Run-19+20
19.5	6.2 (FXT)	487	1.4 days	100 M (118 M)	Run-20
13.5	5.2 (FXT)	541	1.0 day	100 M (103 M)	Run-20
9.8	4.5 (FXT)	589	0.9 days	100 M (108 M)	Run-20
7.3	3.9 (FXT)	633	1.1 days	100 M (117 M)	Run-20
5.75	3.5 (FXT)	666	0.9 days	100 M (116 M)	Run-20
4.59	3.2 (FXT)	699	2.0 days	100 M (200 M)	Run-19
3.85	3.0 (FXT)	721	4.6 days	100 M (259 M)	Run-18
3.85	7.7	420	11-20 weeks	100 M	Run-21[2]

System size versatility: pp, pAl, pAu, dAu, HeAu, OO (in the future), CuCu, CuAu, AuAu, UU

Multidisciplinarity through link to astrophysics ?

Depiction of neutron star merger **GW170817** detected by LIGO in August 2017

Simulation of neutron star merger by Frankfurt group published in *Particles 2, 44 (2019)*



Things to keep in mind for neutron star environment: strangeness, isospin, light nuclei, EOS

Evolution of a heavy ion collision (at 200 GeV)

(as a function of temperature and time)

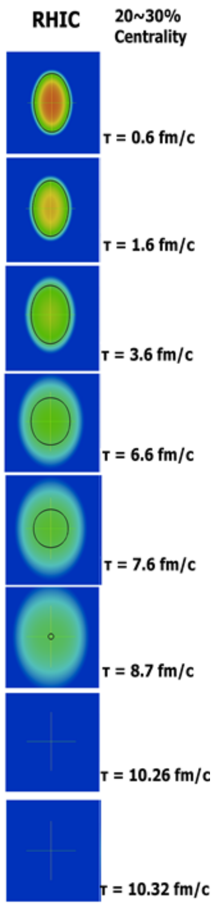
Model:	lQCD	SHM	Blastwave	
Effect:	hadronization	chemical f.o.	kinetic f.o.	
Freeze-out surface:	T_{crit}	T_{ch}	$T_{kin}(\Xi,\Omega)$	$T_{kin}(\pi,k,p,\Lambda)$
Temperature (MeV):	151	148	148	80
Expansion velocity (c):			β=0.45	β=0.6

Hydro condition ?

T_{init}
370 MeV

τ_0 τ_{QGP}

Experiment: time: ~5 fm/c ~4 fm/c
(STAR, PRL 97:132301,(2006))



References:

Lattice QCD:
arXiv:1005.3508
arXiv:1107.5027

Statistical Hadronization:
hep-ph/0511094
nucl-th/0511071

Blastwave:
nucl-ex/0307024
arXiv:0808.2041

Model descriptions

From Initial State to Initial Conditions

Weakly coupled, strongly interacting system = high gluon density = CGC ?

multi-parton interactions = color reconnection = pomeron ladders

The parton evolution

Transport: multi-parton interactions = partonic cascade ?

(BAMPS, EPOS, AMPT, UrQMD…..)

Or

Hydrodynamics

(hybrid codes (MUSIC…), IP-Glasma, Echo-QGP, VISHNU)

Hadronization

Cooper-Frye, lattice QCD, SHM-HRG

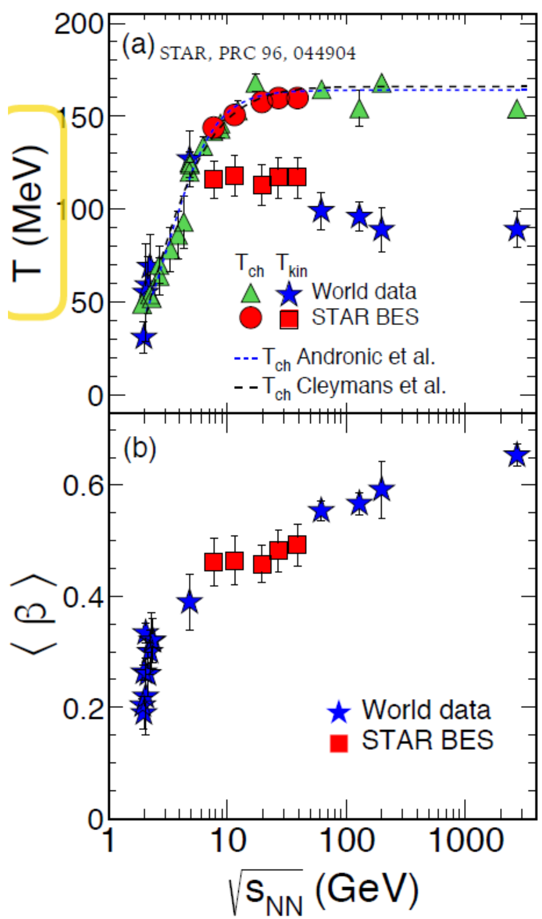
The hadron evolution

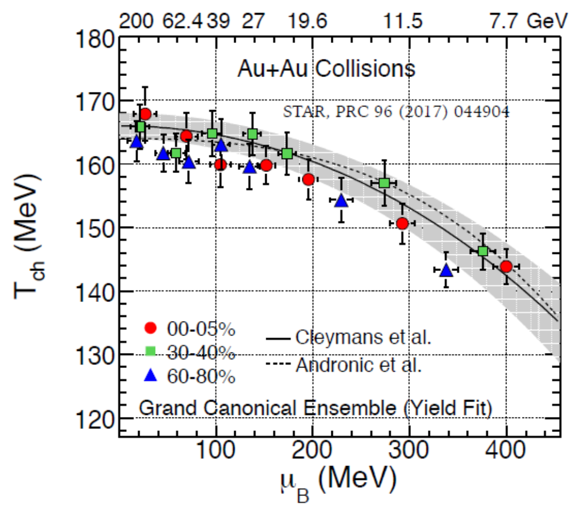
Similar transport than in quark phase (EPOS, UrQMD, SMASH….)

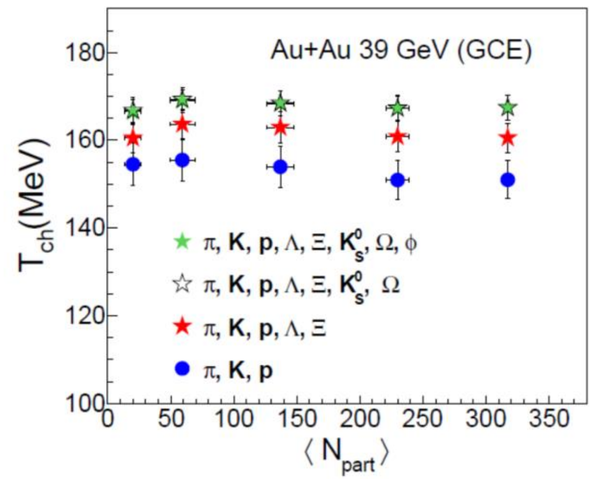
The basic bulk properties

(underlying questions: order of PT, do we reach a QGP ?)

T_{ch} from SHM model (THERMUS) based on yields, T_{kin} from blastwave based on π,k,p spectra







Relevant features:

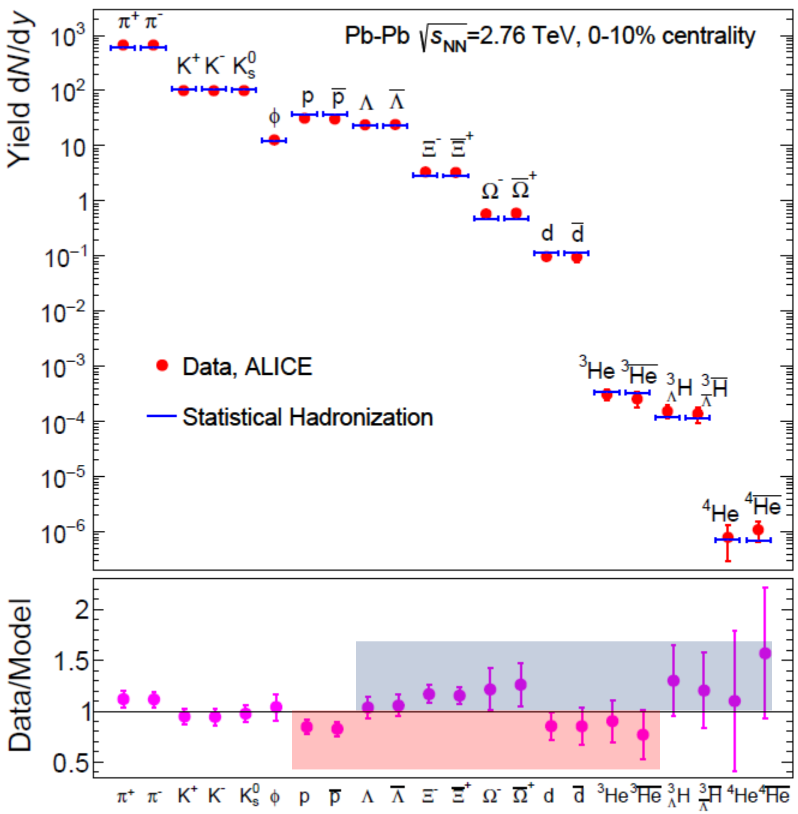
- T_{ch} and T_{kin} coincide at low beam energies
- Expansion velocity plateaus for intermediate energies
- SHM works for all centralities in the STAR energy range
- Species (flavor ?) dependent chemical freeze-out ?

Two major STAR papers: Phys.Rev.C 96 (2017) 4, 044904
Phys.Rev.C 102 (2020) 3, 034909

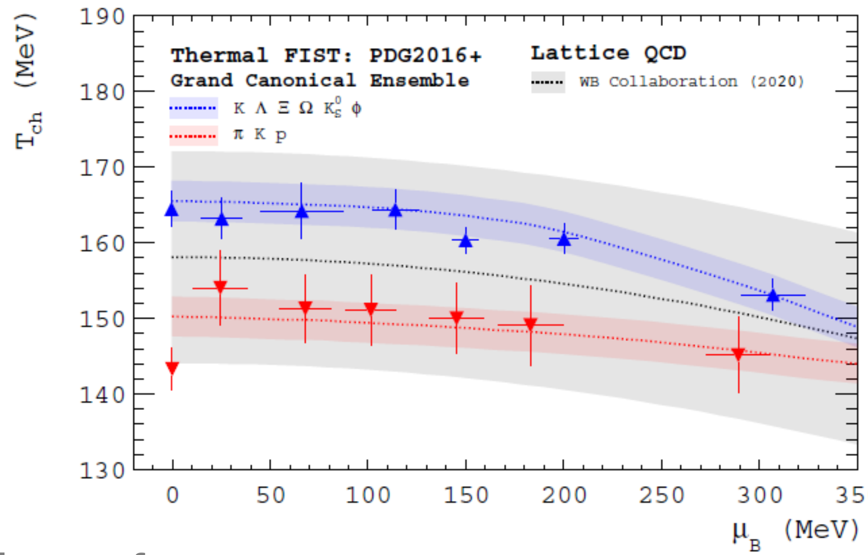
Flavor dependence of hadronization temperature

(underlying question: quantum number dependent transition)

The standard SHM picture
e.g. GSI-Heidelberg (Nature 561,321(2018))



The two flavor SHM picture
e.g. FIST-UH (arXiv:2009.14781)



Relevant features:

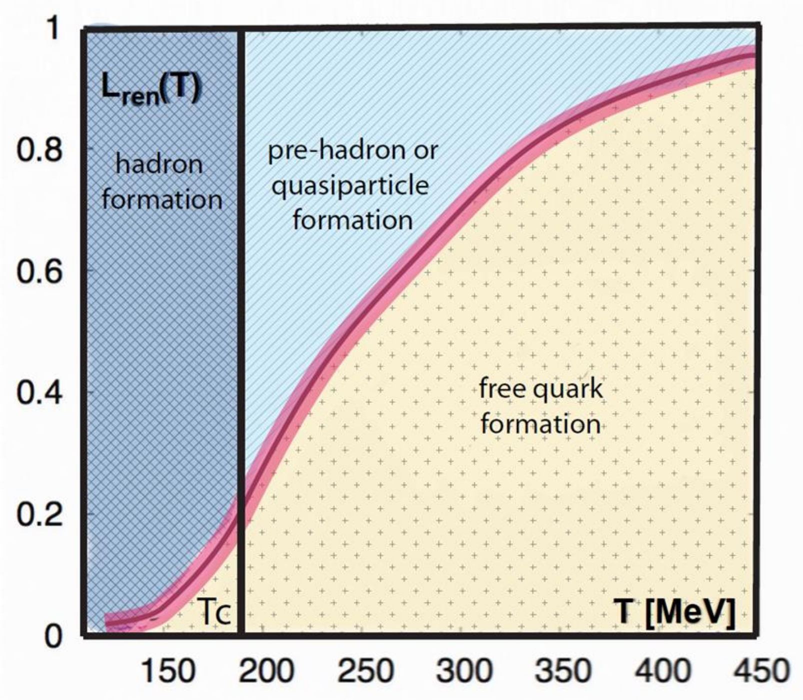
- Flavor dependent two temperatures significantly improves fit quality in particular for baryons
- Consistent picture from 5.02 TeV to 11.5 GeV
- Temperatures might converge at low energy – approaching the critical region ?

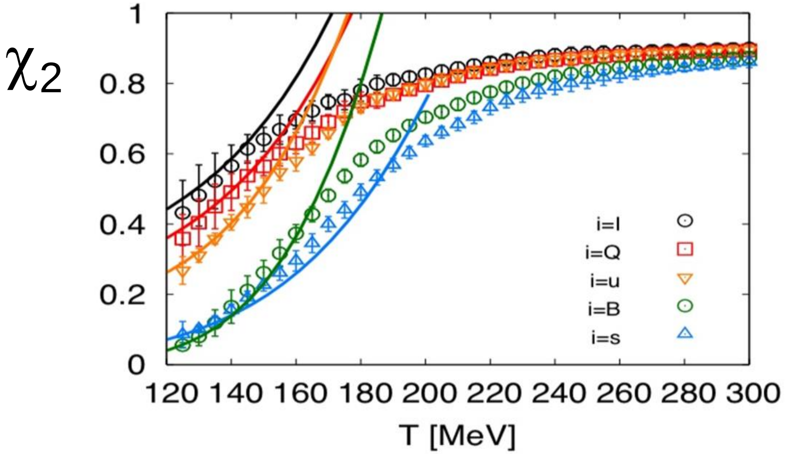
Further evidence through lattice QCD predictions

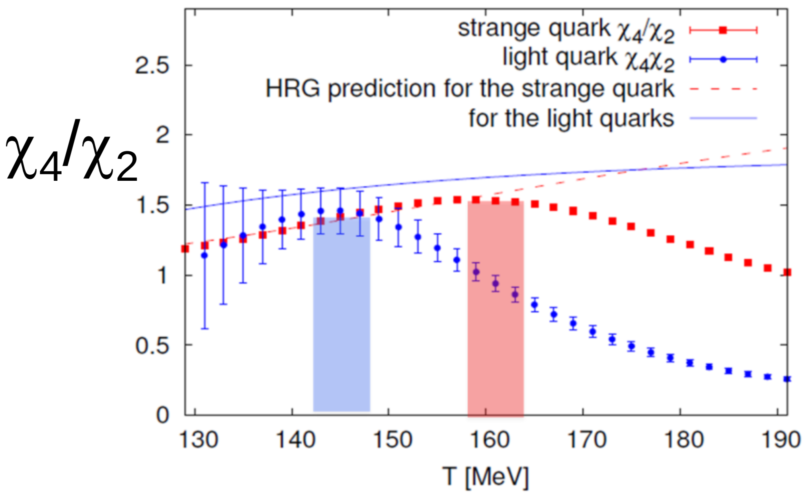
(underlying question: quantum number dependent transition)

Moments of event-by-event net-particle multiplicity distributions can be directly related to quantum number susceptibilities in lattice QCD.

Lattice QCD predictions of flavor hierarchy in chemical freeze-out temperature during QCD crossover. (S. Borsanyi et al., JHEP 1201,138 (2012) and R.Bellwied et al., PRL 111, 202302 (2013))







Further evidence through fluctuation measurements

(underlying question: quantum number dependent transition)

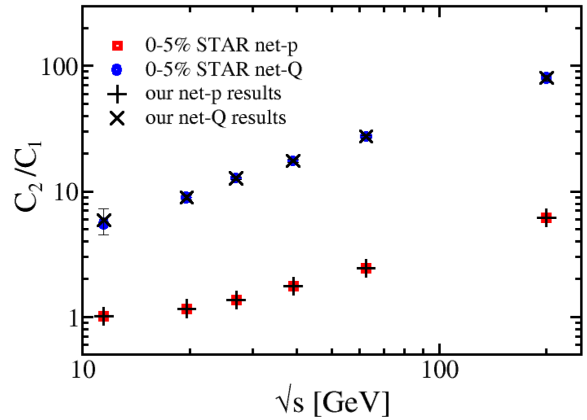
Using fluctuation measurement not to search for criticality but for hadronization parameters.
Need lower moments that are not impacted by critical behavior

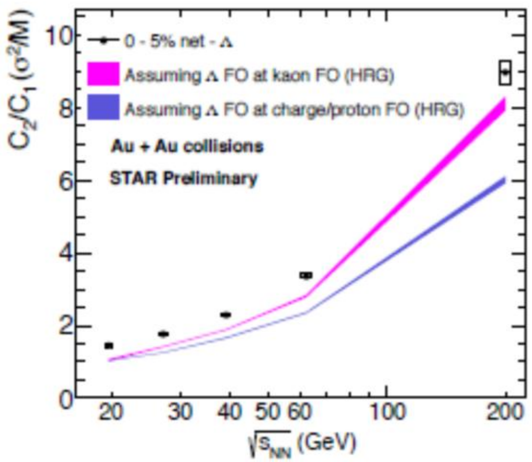
$$\frac{\sigma_B^2}{M_B} = \frac{\chi_{2,\mu}^B}{\chi_{1,\mu}^B}, \quad S_B\sigma_B = \frac{\chi_{3,\mu}^B}{\chi_{2,\mu}^B}, \quad \kappa_B\sigma_B^2 = \frac{\chi_{4,\mu}^B}{\chi_{2,\mu}^B}$$

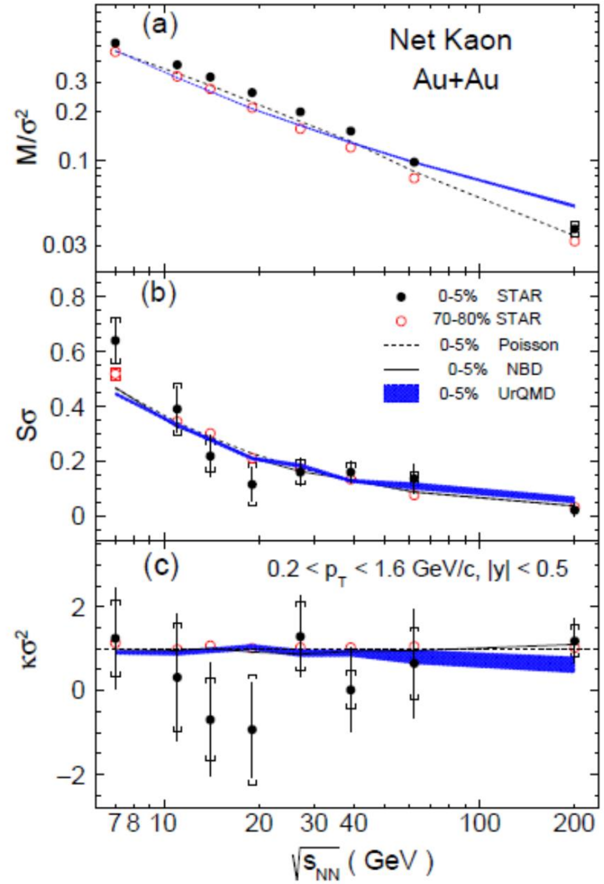
STAR data on:

- net-protons
PRL 112, 032302 (2014)
Update: 2001.02852
- net-charge
PRL 113, 092301 (2014)
- net-kaon
PLB 785, 551 (2018)
- net-lambda
PRC 102, 024903 (2020)

More on critical point in Bedanga's talk

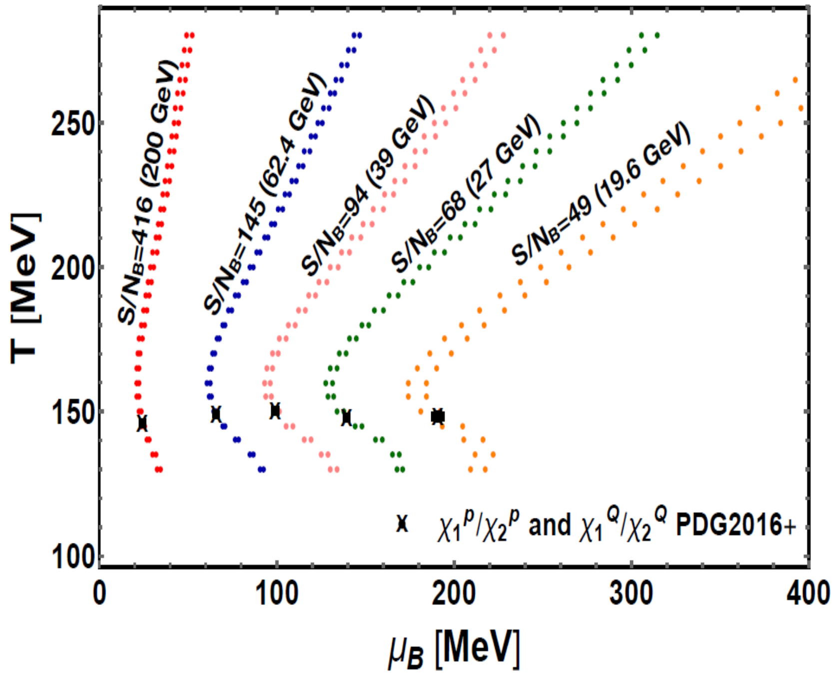


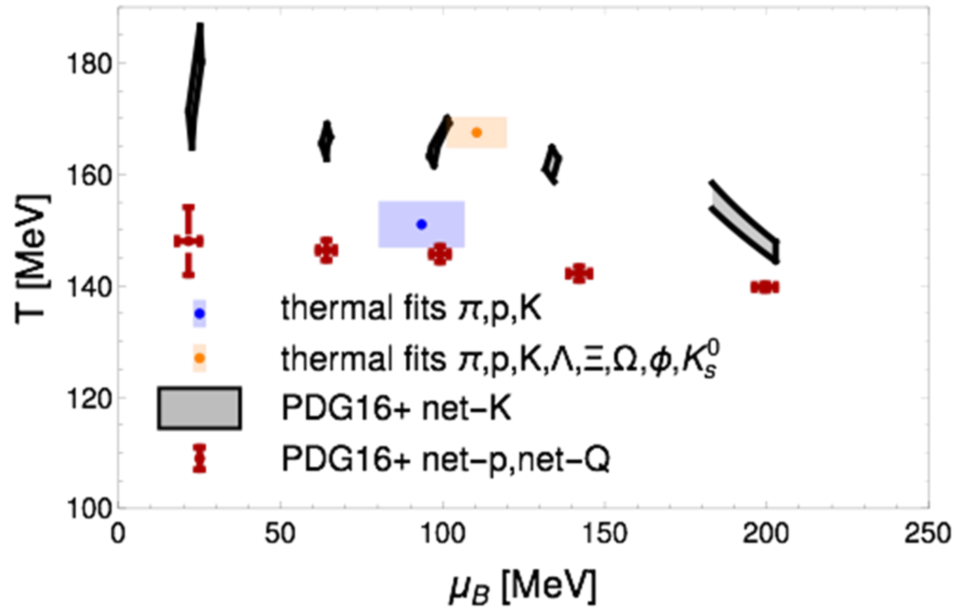




SHM results based on fluctuation measurements

(underlying question: quantum number dependent transition)





R. Bellwied et al., Phys.Rev.C 99 (2019) 3, 034912

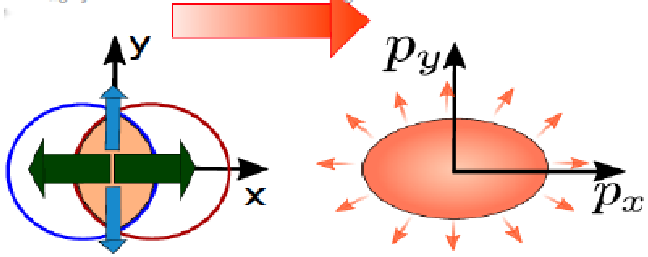
Main features:

- Trajectories (lines of constant entropy (S/N)) converge at chemical freeze-out point
- Strange (kaon) freeze-out about 15-20 MeV higher than light (proton, charge) freeze-out
- Temperatures converge at higher chemical potential (towards critical region ?)

Anisotropic flow

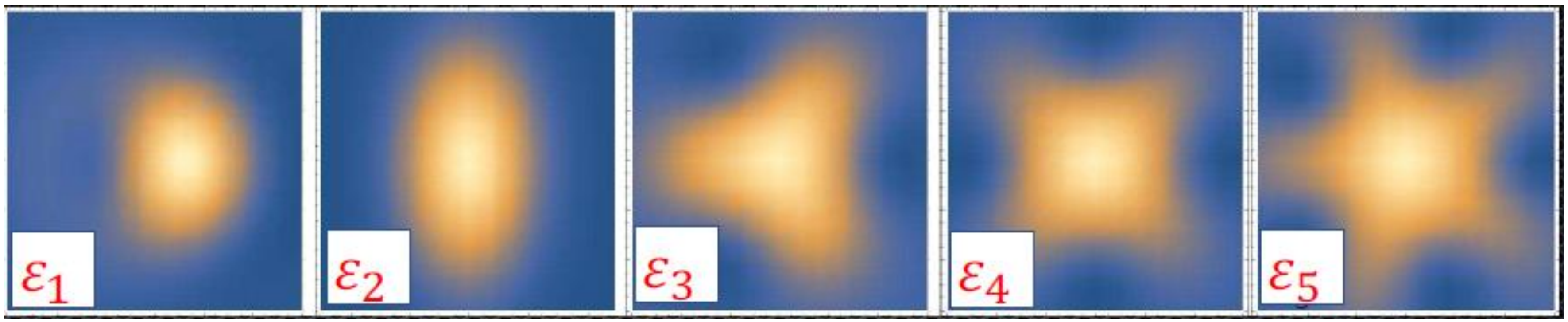
(underlying question: collectivity, degrees of freedom, criticality)

N. Magdy - RHIC & AGS Users Meeting 2019



$$\frac{d^3N}{dp_t\,dy\,d\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}\left(1 + 2v_1\cos(\varphi) + 2v_2\cos(2\varphi) + \ldots\right)$$

Directed flow   Elliptic flow

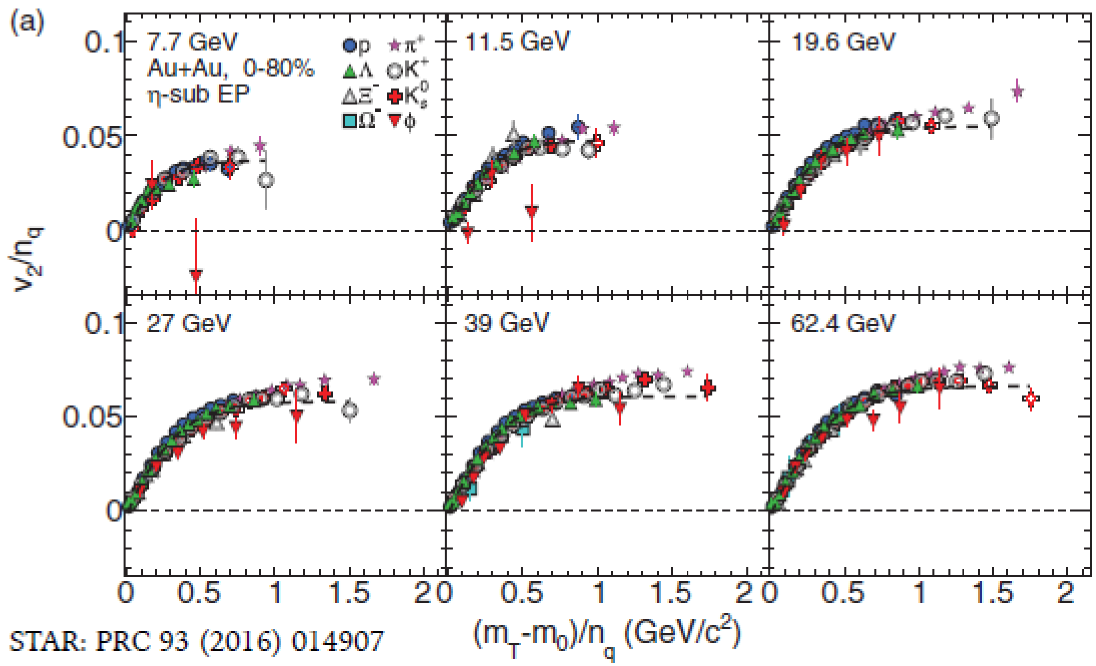


Main measurements during BES:

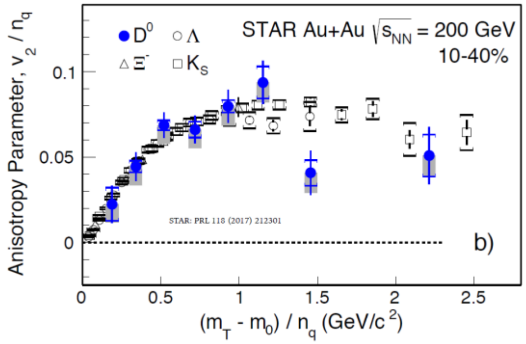
- Particle identified v_2 as a function of beam energy to determine quark scaling
- Particle identified v_1 to determine compressibility
- Charged particle v_2 as a function of system size to determine collectivity in small systems

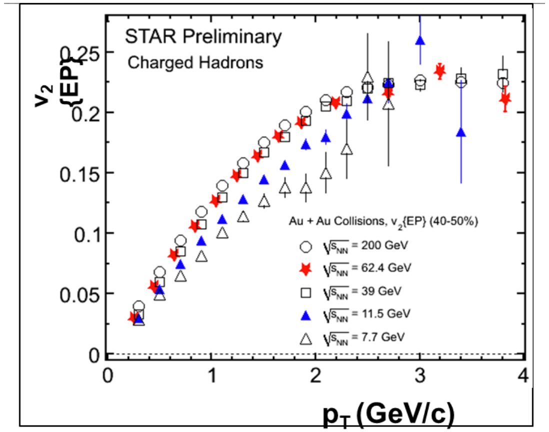
Identified particle v_2

(underlying question: collectivity, degrees of freedom)



STAR: PRC 93 (2016) 014907



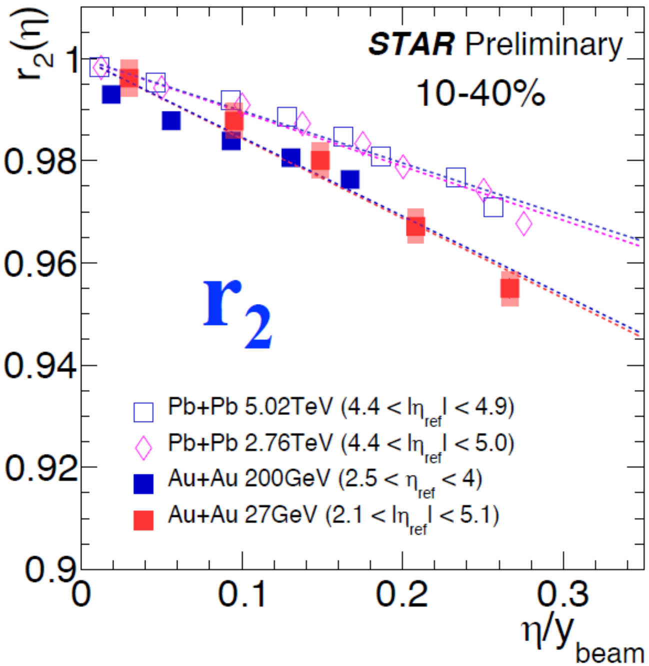


Main features:

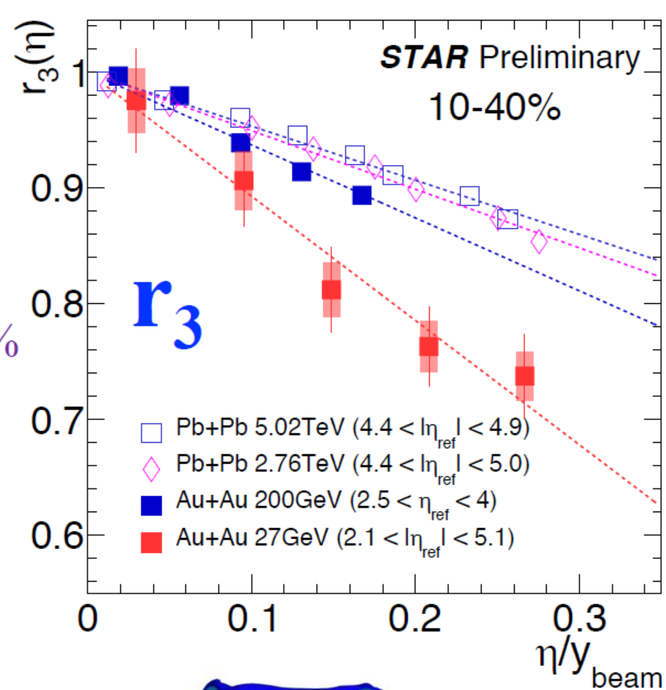
- Constituent quark scaling is dominant from p to D-meson (at the highest energy)
- Constituent quark scaling seems to break down below 10-20 GeV collision energy
- Viscous hydrodynamics shows rise in η/s by a factor 2 below 39 GeV (e.g. arXiv:1509.07351)

Longitudinal flow de-correlation

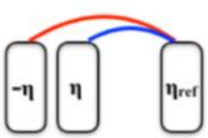
(underlying question: collectivity, viscosity)

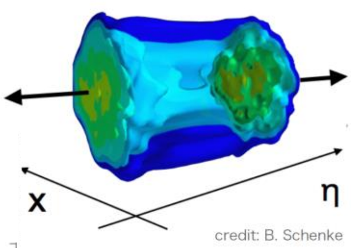


r_3 shows up to 30% decorrelation



$$r_n(\eta) = \frac{\langle V_n(-\eta) V_n^*(\eta_{\rm ref})\rangle}{\langle V_n(\eta) V_n^*(\eta_{\rm ref})\rangle}$$



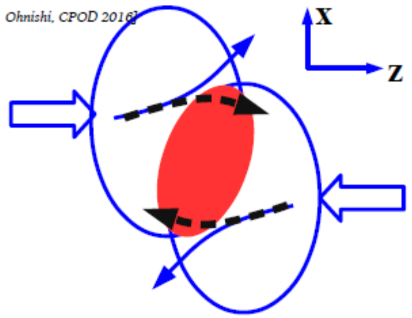


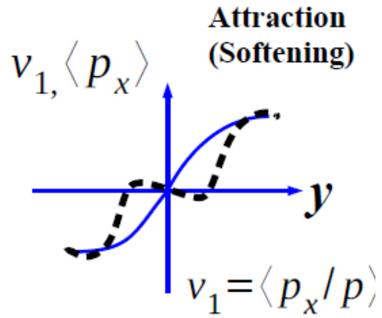
Main feature:

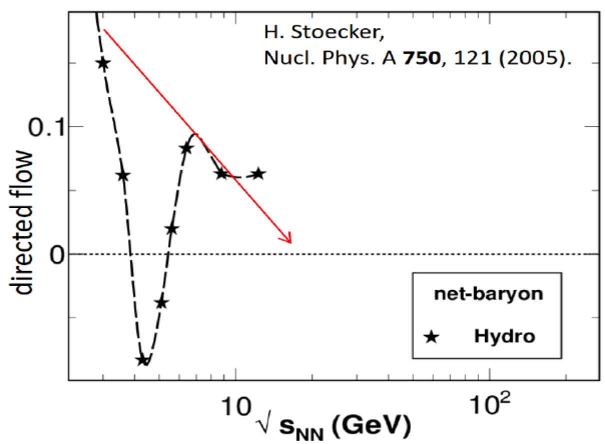
- r_2 is energy independent, r_3 de-correlates at lower energies, ideal hydro breaks down

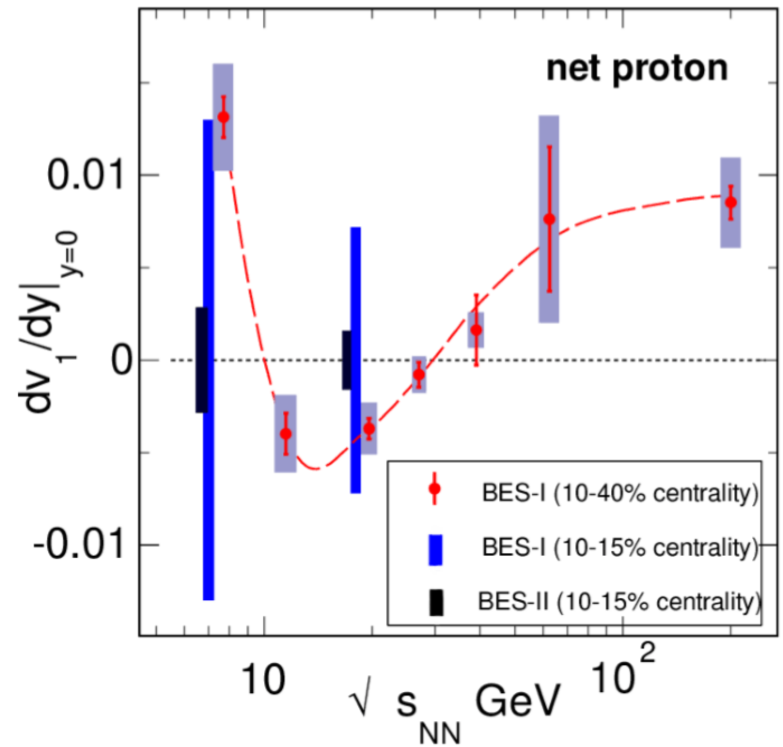
Identified particle directed flow v_1

(underlying question: collectivity, criticality)









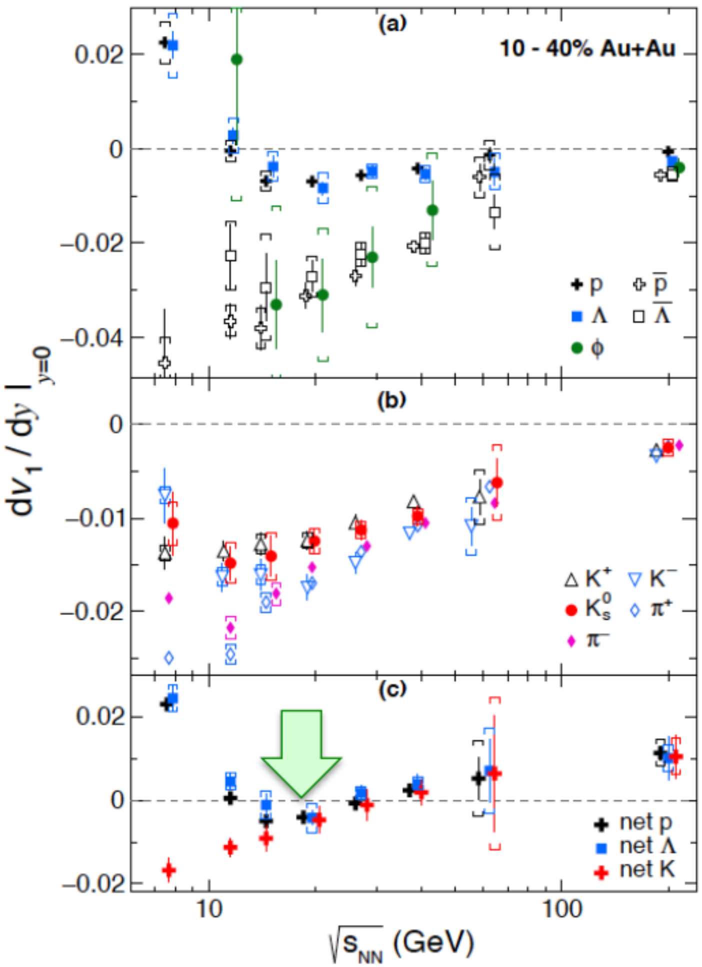
Main features:

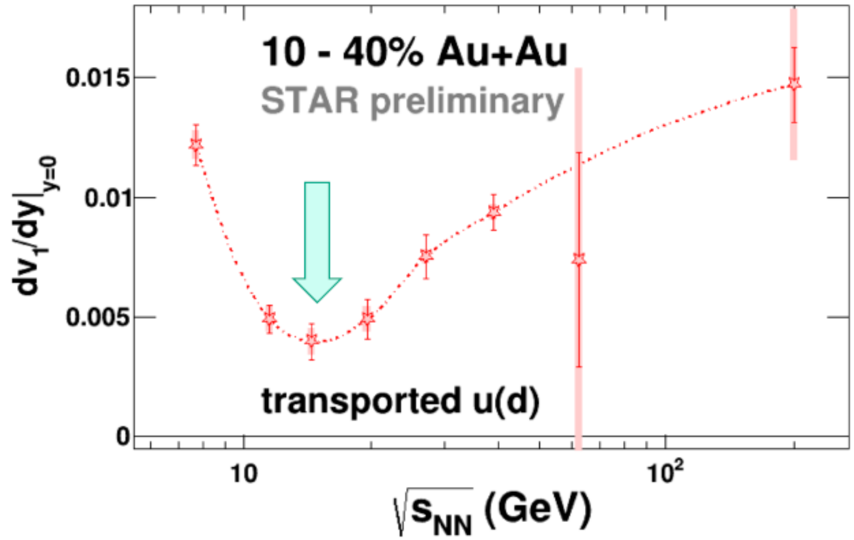
- ‘Softest point’ (double sign change in v_1) signals change in Equation of State
- Hydro prediction for baryons, confirmed with protons & Lambdas (see next slide)
- Particle identified v_1 to determine compressibility

Identified particle directed flow v_1

(underlying question: collectivity, criticality)

STAR, Phys. Rev. Lett. **120** (2018) 62301





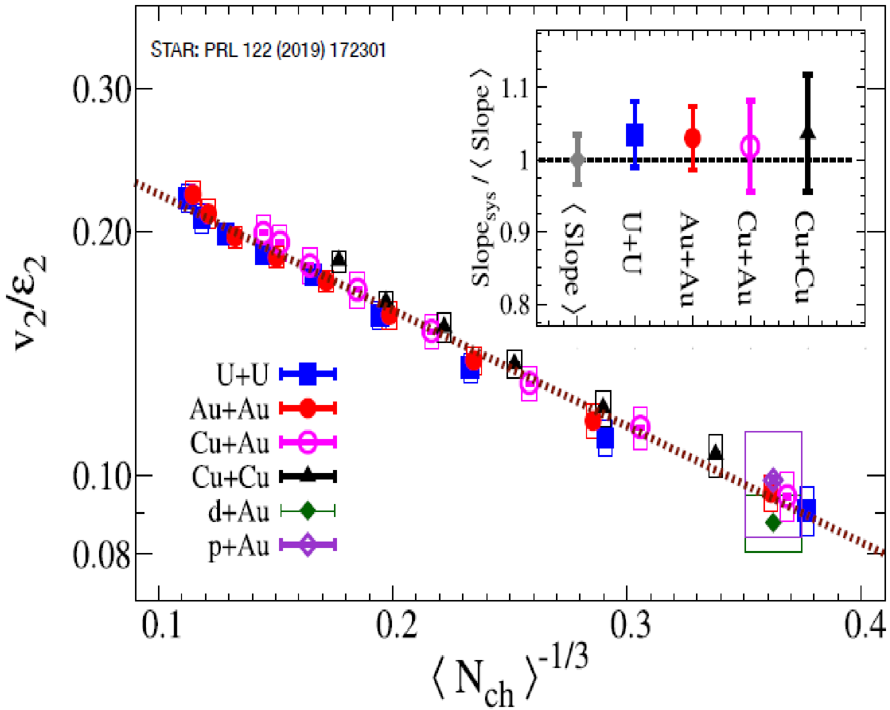
$$(v_1)_{trans.u(d)} = \left[(v_1)_{net\ p} - \left(3 - N_{trans.u(d)}\right)(v_1)_{\bar{u}(\bar{d})}\right]/N_{trans.u(d)}$$

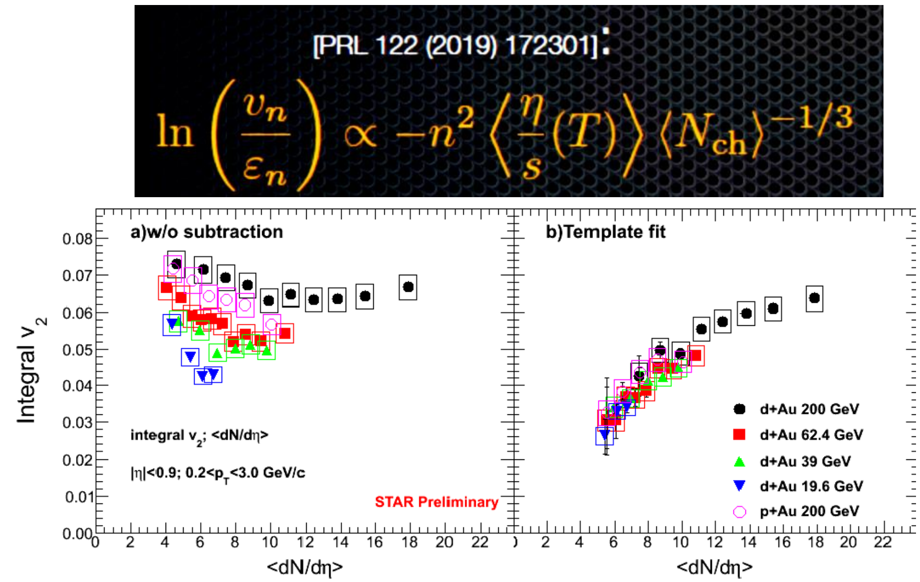
$$N_{trans.u(d)} = 3\left[1 - exp\left(-2\mu_{u(d)}/T_{ch}\right)\right]/\left(1 - r_{\bar{p}/p}\right)$$

- 10 species & 8 energies allow a detailed study of constituent-quark v_1. In most cases, the coalescence picture works for both “produced” particles and “net” particles
- “Transported quark” v_1 has a local minimum at ~14.5 GeV

Identified particle v_2 in small systems

(underlying question: collectivity)





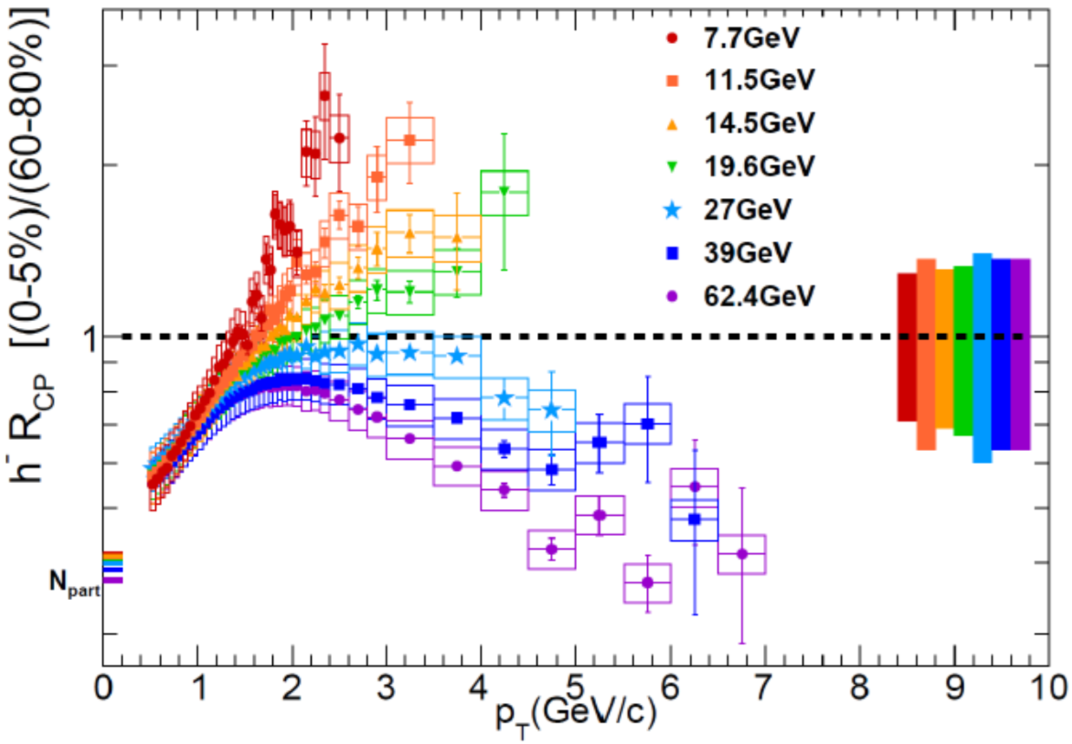
Main features:

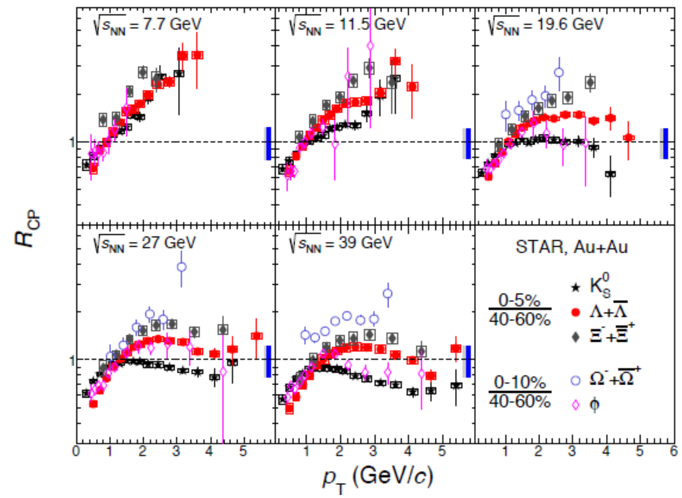
- Acoustic scaling works down to smallest systems (sign for collectivity)
- Non-flow contributions increase in small systems, but after subtraction v_2 is consistent with expected system size dependence (sign for collectivity)

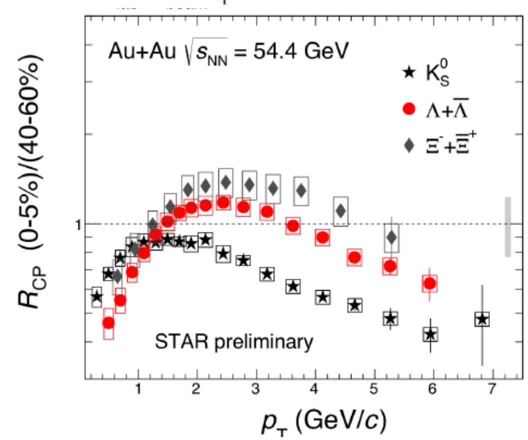
Nuclear suppression factor

(underlying question: transition)

PRC 102, 034909 (2020)





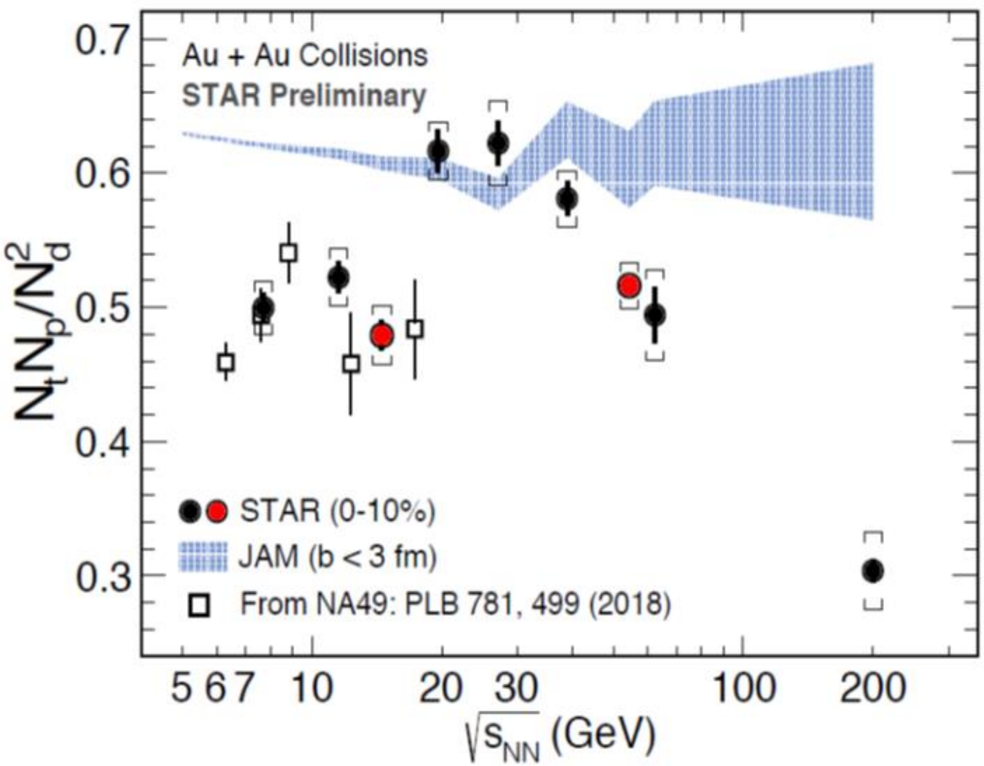


Main features:

- Suppression 'turns off' below 27 GeV
- Particle identified features important for interpretation of suppression

Neutron density fluctuations

(underlying question: equation of state, transition)



K. J. Sun, L. W. Chen, C. M. Ko, Z. Xu, Phys. Lett. B774, 103 (2017).
K. J. Sun, L. W. Chen, C. M. Ko, J. Pu, Z. Xu, Phys. Lett. B781, 499 (2018).

$$N_t \cdot N_p / N_d^2 = g(1 + \Delta n),$$

$$with\ g = 0.29$$

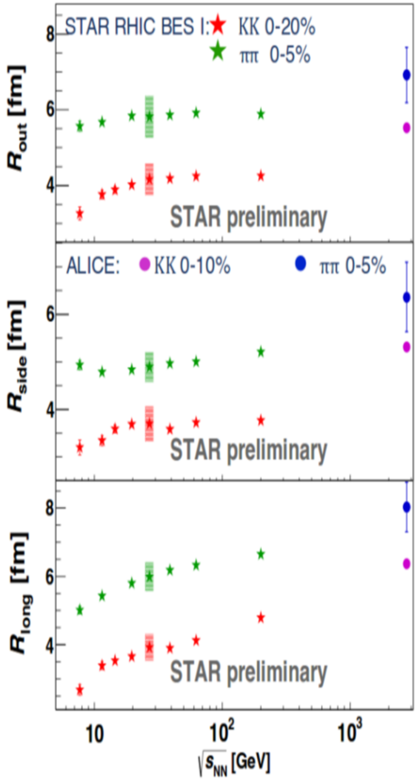
Yield ratio is related to neutron density fluctuations.

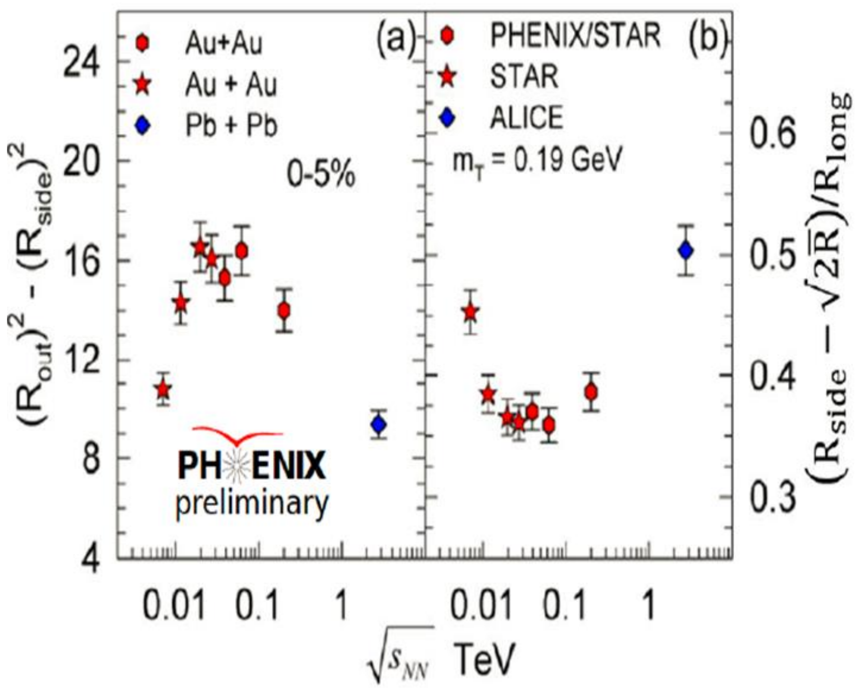
Main features:

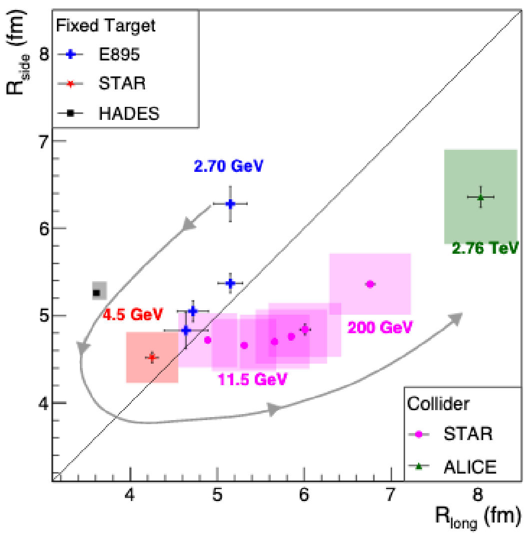
- Fluctuations peak around 20-30 GeV
- Change in EOS ? Softest point ?

‘Standard’ femtoscopy

(underlying question: softest point, changing EOS)







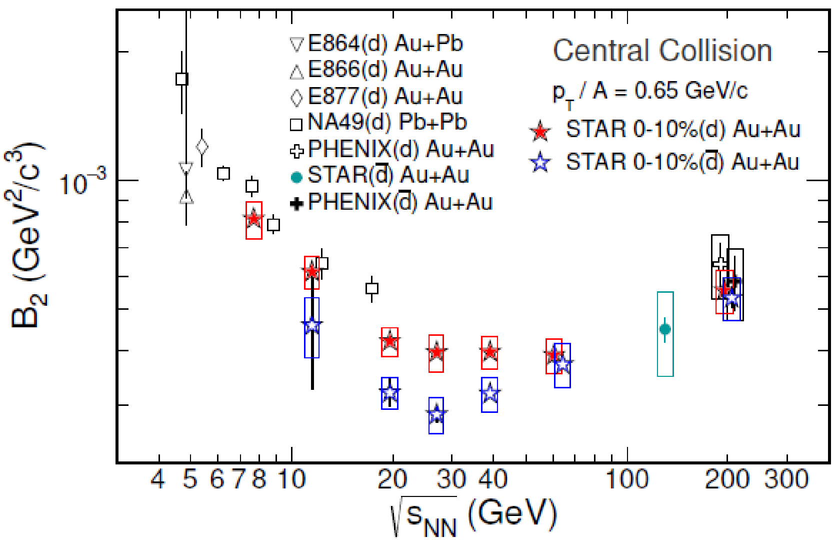
Main features:

- Source continues to grow as a function of collision energy, kaon source larger than pion source
- Compression in baryon dense regime, expansion at higher energies, softest point: ~10-30 GeV

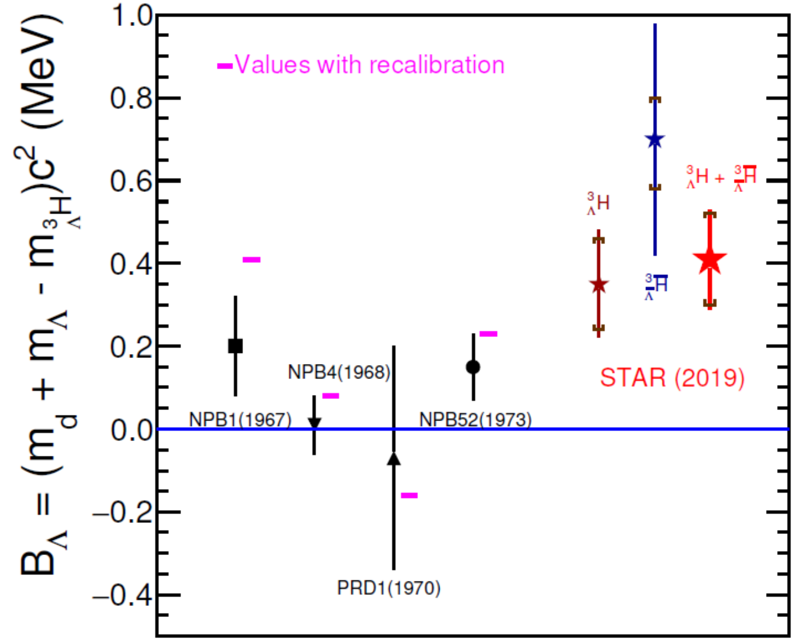
Light nuclei production

(underlying question: collectivity, statistical hadronization, neutron stars)

STAR, Phys.Rev.C 99 (2019) 6, 064905



STAR, Nature Physics 16 (2020) 4, 409



Main features:

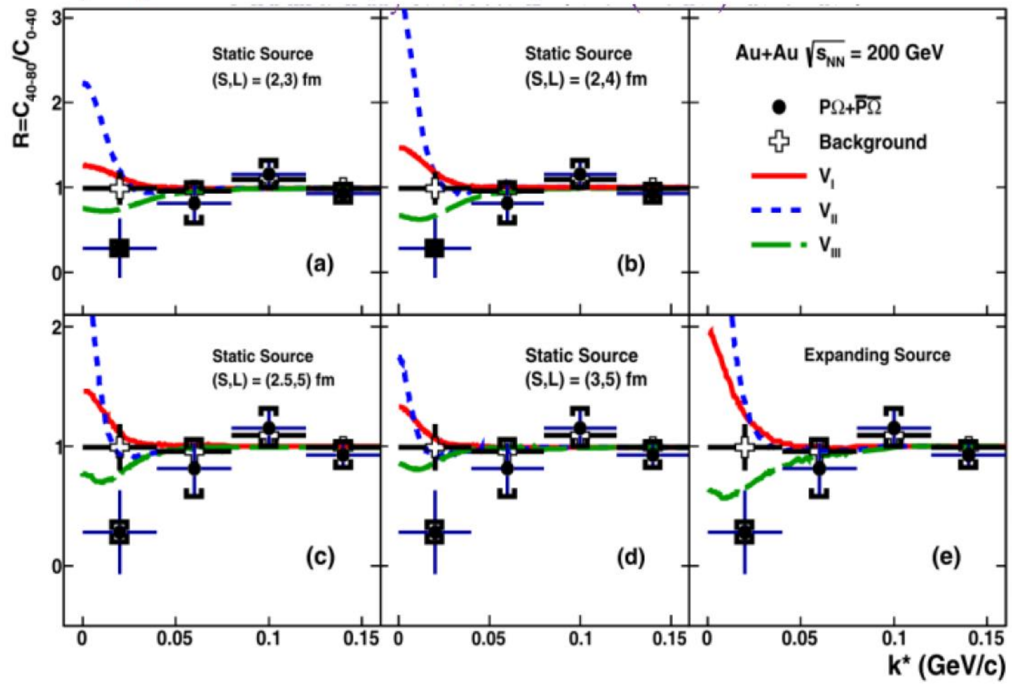
- Coalescence parameter (B_2) minimum around 20-30 GeV (change of EOS ?)
- Coalescence parameter for d larger than for anti-d. Different radius and temperature ?
- Hyper-triton binding energy larger than expected – hyperon-nucleon interaction stronger and attractive: impact on hyper-matter (see next slide)

Unlike particle femtoscopy

(underlying question: neutron stars)

pΩ correlation functions

STAR, Phys. Lett. B 790, 490 (2019)



K. Morita et al. Phys. Rev. C 94, 031901 (2016)

TABLE I. Binding energy (E_B), scattering length (a_0), and effective range (r_{eff}) with and without the Coulomb attraction in the $p\Omega$ system. Physical masses of the proton and Ω are used.

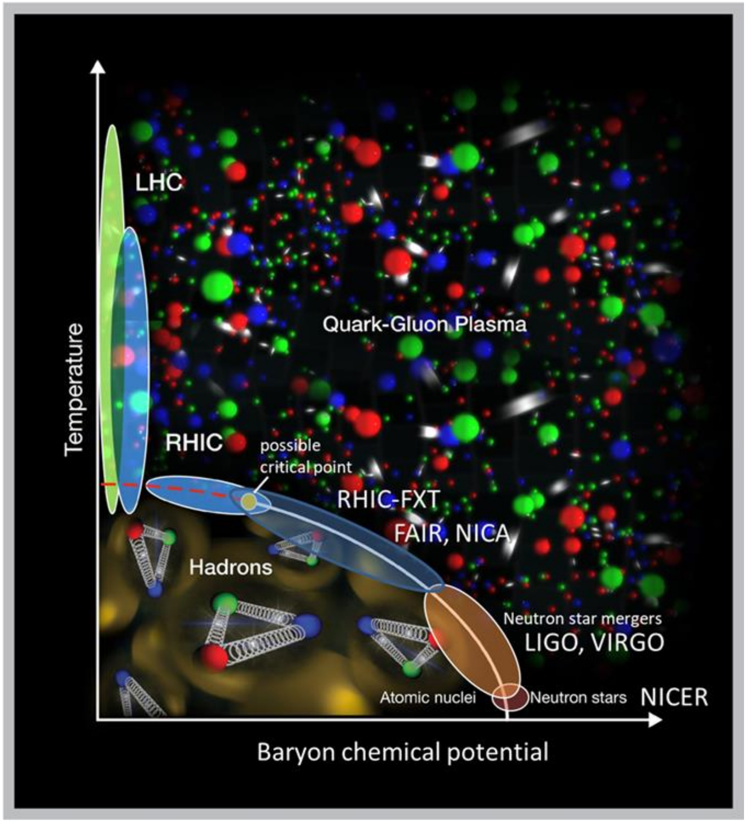
Spin-2 $p\Omega$ potentials		V_I	V_{II}	V_{III}
	E_B (MeV)		0.05	24.8
Without Coulomb	a_0 (fm)	−1.0	23.1	1.60
	r_{eff} (fm)	1.15	0.95	0.65
	E_B (MeV)		6.3	26.9
With Coulomb	a_0 (fm)	−1.12	5.79	1.29
	r_{eff} (fm)	1.16	0.96	0.65

Main features:

- Positive scattering length and binding energy for pΩ-dibaryon similar to pΞ and pΛ in ALICE.
- Potentially far reaching consequences for EOS in dense system (hyper-matter in stellar object such as neutron stars)

Summary

- The BES program at RHIC, in parallel with ALICE, has allowed us to explore the first stage of finite density systems at high temperature. NICA might bring us closer to astrophysical systems and new phases of matter



- <u>The main measurements explored by STAR:</u>
  - Criticality and change in the phase transition
  - Compressibility and change in the equation of state
  - Constituent quark scaling and the 'turn-off' of the QGP
  - Flavor dependence in the hadronization process
  - Probability of hyper-matter in dense regimes
  - Phase transition in small systems
- **The physics of dense systems is very rich, thus the physics opportunities at NICA are very rich**