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Elliptic flow splitting between protons and antiprotons from hadronic potentials

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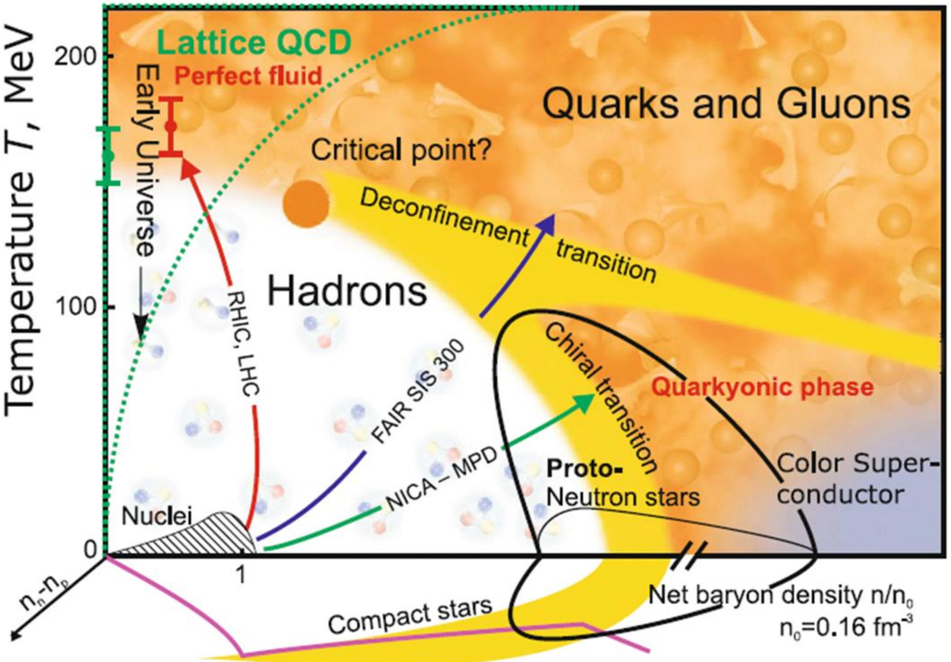
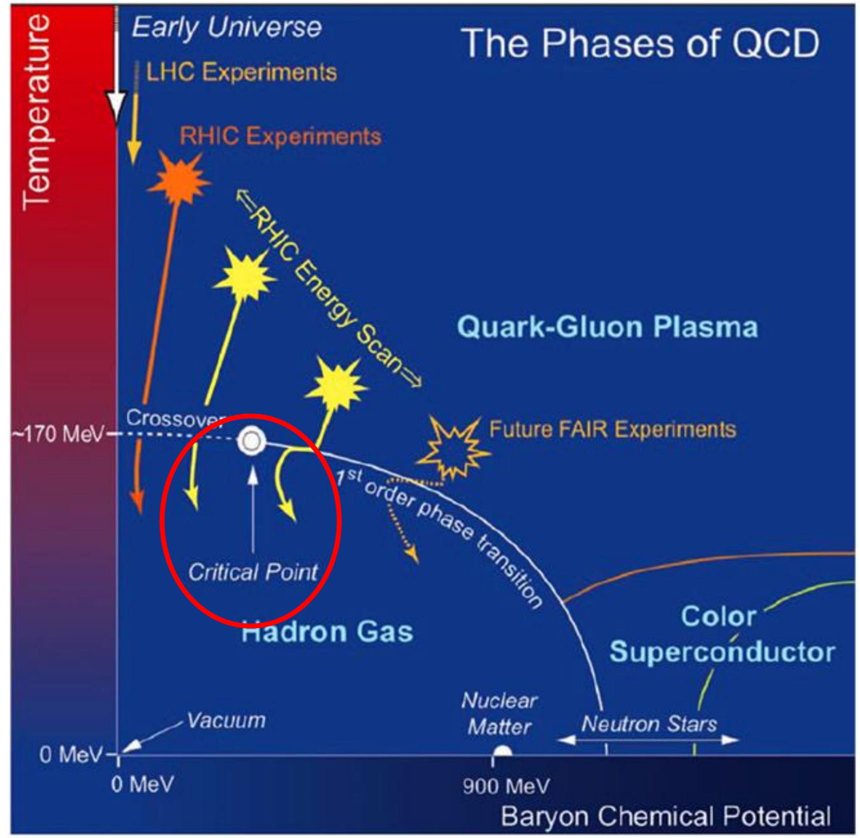
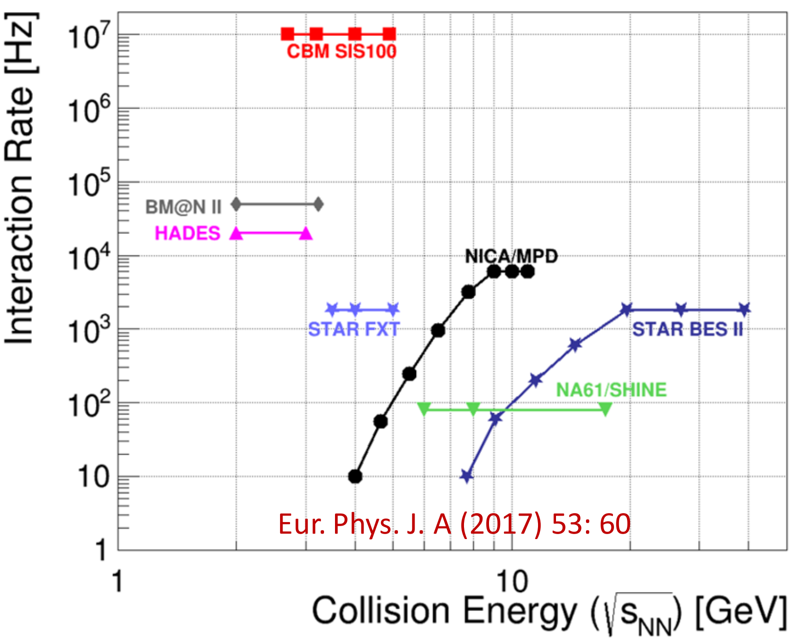
Background







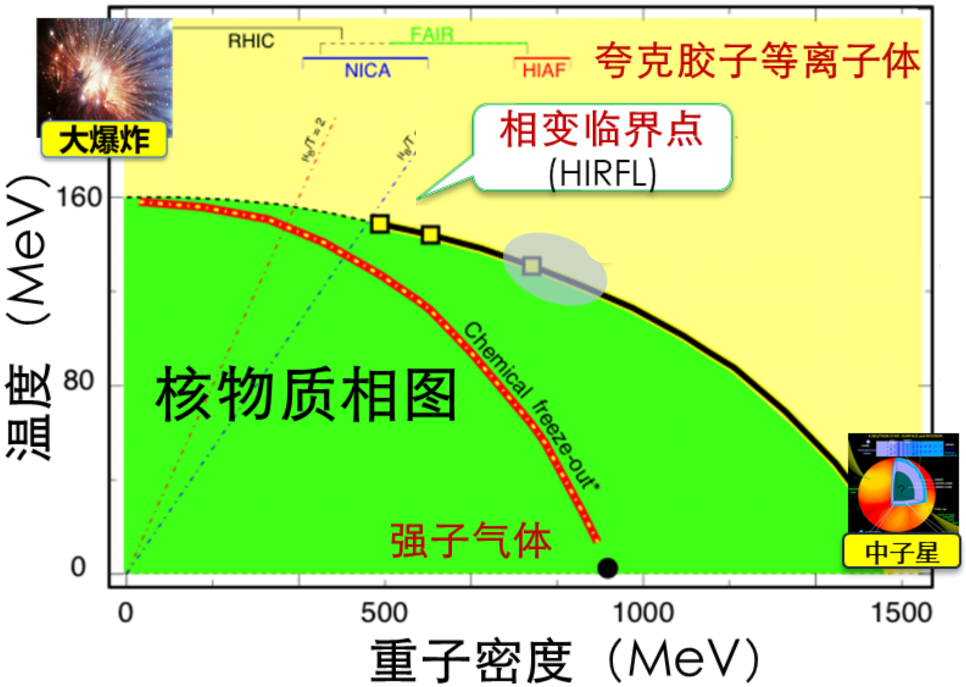
- Search for the critical point and the first order phase boundary.
- Study the properties of the QGP.

CBM at FAIR: $\sqrt{s_{NN}} = 2.7 - 4.9$ GeV

NICA: $\sqrt{s_{NN}} = 4 - 11$ GeV

STAR-BESⅡ: $\sqrt{s_{NN}} = 7.7 - 19.6$ GeV

Future in HIAF



1）基于HIRFL研究高重子密度区核物质相结构

- 研究目标：

  高重子密度区核物质相结构和临界点

2）核物质拓扑性质的研究

- 研究目标：

  强相互作用核物质的拓扑性质和在极限外场(极限角动量、极限强磁场)下的行为、QCD临界点

---From RIBLL 2019, Xiaohong Zhou

Table 1 Typical beam parameters from the BRing. The beam intensities are given in the unit of particles per pulse (ppp).

Ion species	Energy/(GeV/u)	Intensity/ppp
P	9.30	2.0×10^{12}
$^{18}O^{6+}$	2.60	6.0×10^{11}
$^{78}Kr^{19+}$	1.70	3.0×10^{11}
$^{209}Bi^{31+}$	0.85	1.2×10^{11}
$^{238}U^{34+}$	0.80	1.0×10^{11}

SRing

最大磁刚度15 Tm

1.5 GeV/u ($A/Z=2$)

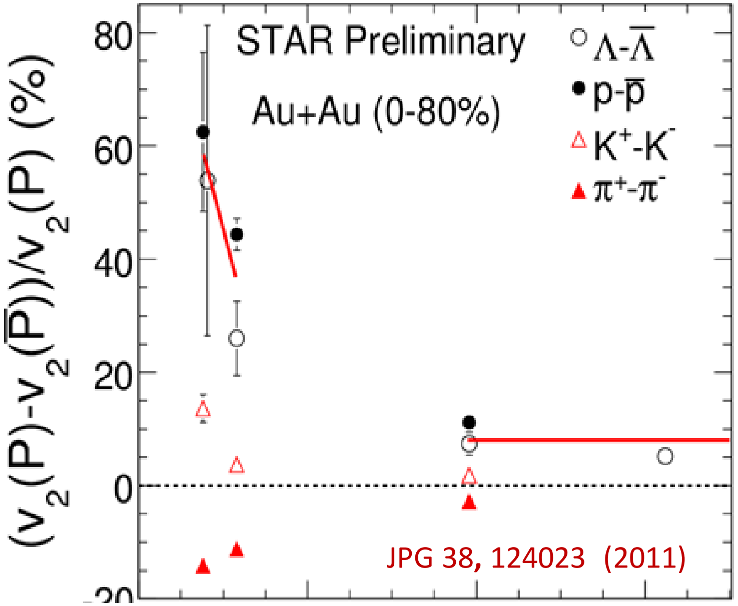
1.0 GeV/u ($^{238}U^{92+}$)

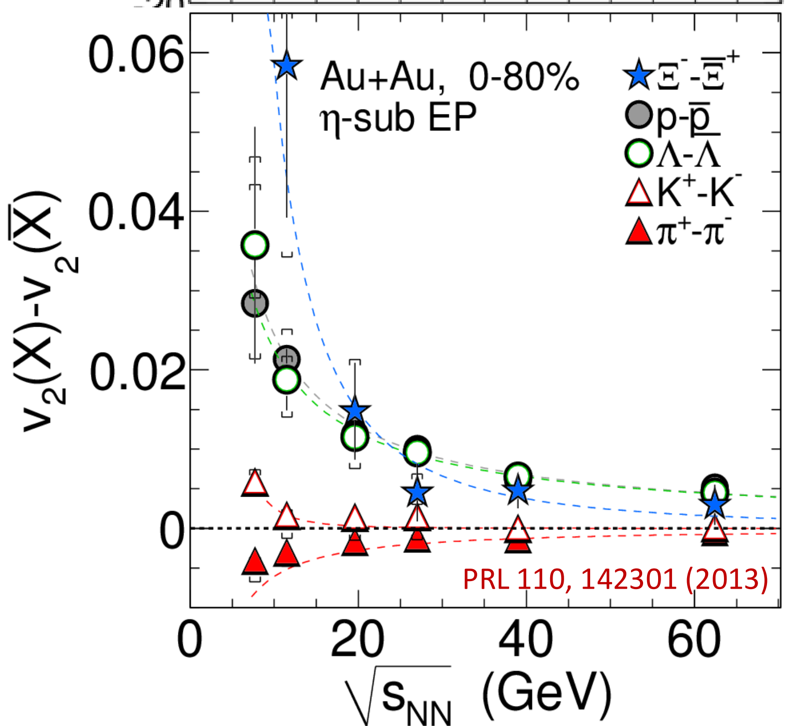
1.0×10^{7} ppp(放射性次级束流)

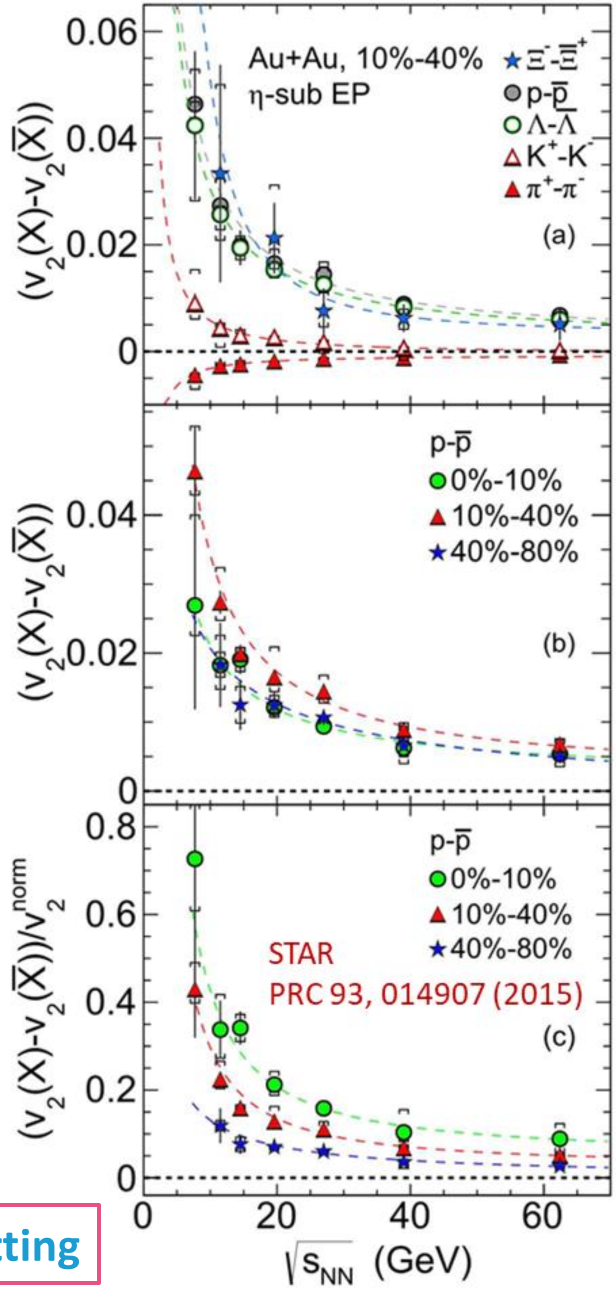
$10^{9\sim10}$ ppp(高电荷态稳定重离子束)

Guoqing Xiao, *et al.*, Nuclear Physics Review, 2017, 34(3): 275-283.
Xiaohong Zhou, Nuclear Physics Review, 2018, 35(4): 339-349.

Highlights of recent RHIC physics







v_2 splitting

Explanations for v_2 splitting

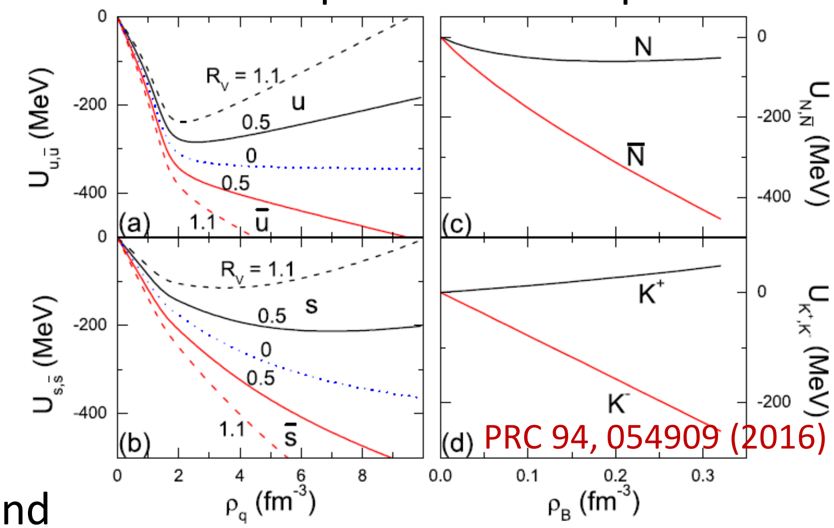
- Different hadronic and partonic potentials for particles and antiparticles

J. Xu, L.W. Chen, C.M. Ko, Z.W. Lin, PRC 85, 041901(R) (2012); J. Xu, T. Song, C. M. Ko, F. Li, PRL 112, 012301 (2014)

the different mean-field potentials for hadrons and antihadrons or quarks and antiquarks：

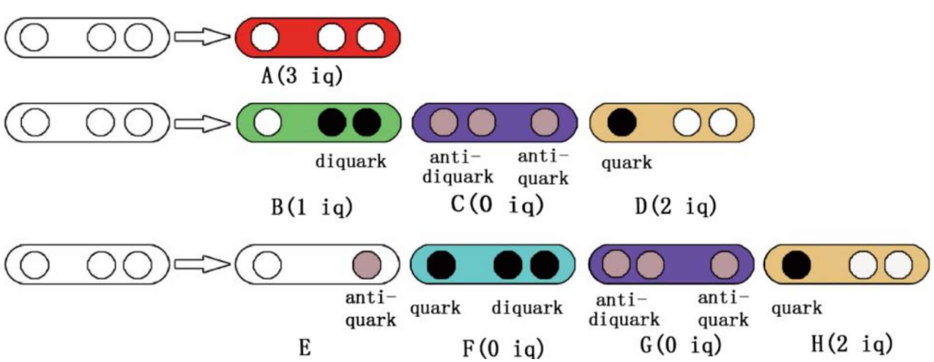
- Stronger attractive potential for $\bar{p}$ compared to p
  → smaller $v_2(p)$,
- Attractive potential for K^-, repulsive for K^+
  → $v_2(K^-)$ < $v_2(K^+)$,
- Slightly attractive potential for π^+, repulsive for π^-
  → $v_2(\pi^+) < v_2(\pi^-)$.

A repulsive vector mean-field potential for quarks but an attractive one for antiquarks in a baryon-rich quark matter.

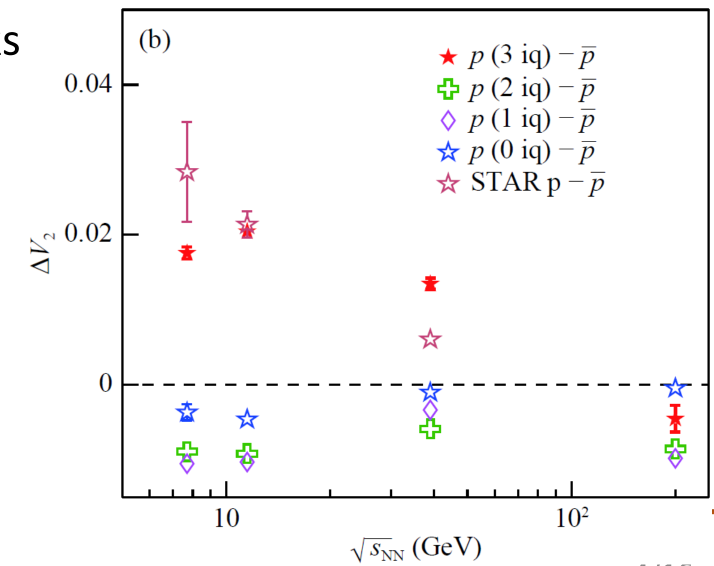


PRC 94, 054909 (2016)

- The difference of v_2 between transported quarks and produced quarks. (By tracing the number of initial quarks in protons) B. Tu, *et al.*, CPC 43, 054106 (2019).



Y. Gao, *et al.*, PRC 86, 044901 (2012).



- PRC 86, 044903 (2012); 86,044905(2012); 91,024903(2015); PRD 92,114010(2015); PRL 107,052303(2011)…

Outline

Brief introduction to the UrQMD

- Baryons are represented by Gaussian wave packets in the phase

$$\phi_i(\mathbf{r},t)=\frac{1}{(2\pi L)^{3/4}}\exp\left(-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{4L}\right)\exp\left(\frac{i\mathbf{p}_i\cdot\mathbf{r}}{\hbar}\right)$$

- The Wigner distribution function f_i of the baryon i

$$f_i(\mathbf{r},\mathbf{p})=\frac{1}{(\pi\hbar)^3}\exp\left(-\frac{(\mathbf{r}-\mathbf{r}_i)^2}{2L}\right)\exp\left(-\frac{(\mathbf{p}-\mathbf{p}_i)^2\cdot 2L}{\hbar^2}\right)$$

- Propagated according to Hamilton's equation of motion

$$\dot{\mathbf{r}}_i=\frac{\partial H}{\partial \mathbf{p}_i}\quad\text{and}\quad\dot{\mathbf{p}}_i=-\frac{\partial H}{\partial \mathbf{r}_i}$$

$$\begin{aligned}H&=T+U\\ T&=\sum_i(E_i-m_i)=\sum_i(\sqrt{m_i^2+\mathbf{p}_i^2}-m_i)\\ U&=U_{\text{Sky}}^2+U_{\text{Sky}}^3+U_{\text{Yuk}}+U_{\text{Cou}}+U_{\text{Pau}}\end{aligned}$$

Charged particles SIS energies

- The Skyrme potential

$$U=\alpha\left(\frac{\rho_b}{\rho_0}\right)+\beta\left(\frac{\rho_b}{\rho_0}\right)^\gamma\qquad \alpha,\beta,\gamma\rightarrow\text{stiffness of the EoS}$$

- The density of the baryon

$$\rho_b=\int\rho(\mathbf{r}_i)\rho\,d\mathbf{r}=\int\rho(\mathbf{r}_i)\sum_j\rho(\mathbf{r}_j)d\mathbf{r}=\frac{1}{(4\pi L^2)^{3/2}}\sum_j e^{-\frac{(\mathbf{r}_i-\mathbf{r}_j)^2}{4L^2}}$$

J. Aichelin, Phys. Rep. 202, 233 (1991);
M. Bleicher *et al.*, JPG 25 1859 (1999) ;
S. A. Bass *et al.*, Prog. Part. Nucl. Phys.41:255-369 (1998);
Q. F. Li *et al.*, PRC 83.044617 (2011).

Potential updates

- The momentum-dependent term： $U_{md}=\sum_{k=1,2}\frac{t_{md}^k}{\rho_0}\int d\mathbf{p}_j\frac{f(\mathbf{r}_i,\mathbf{p}_j)}{1+[(\mathbf{p}_i-\mathbf{p}_j)/a_{md}^k]^2}$
- Hamiltonian: the sum of the single-particle energy E_i

$$H=\sum_{i=1}^{N}\sqrt{\mathbf{p}_i^2+m_i^2+2m_iV_i},$$

The equations of motion are then:

$$\frac{d\mathbf{r}_i}{dt}\approx\frac{\partial H}{\partial\mathbf{p}_i}=\frac{\mathbf{p}_i}{E_i}+\sum_{j=1}^{N}\frac{m_j}{E_i}\frac{\partial V_i}{\partial\mathbf{p}_i},$$

$$\frac{d\mathbf{p}_i}{dt}\approx-\frac{\partial H}{\partial\mathbf{r}_i}=-\sum_{j=1}^{N}\frac{m_j}{E_i}\frac{\partial V_i}{\partial\mathbf{r}_i}.$$

The relativistic effects on the relative distance and the relative momentum:

$$\tilde{\mathbf{r}}_{ij}^2=\mathbf{r}_{ij}^2+\gamma_{ij}^2(\mathbf{r}_{ij}\cdot\beta_{ij})^2,$$

$$\tilde{\mathbf{p}}_{ij}^2=\mathbf{p}_{ij}^2-(E_i-E_j)^2+\gamma_{ij}^2\left(\frac{m_i^2+m_j^2}{E_i+E_j}\right),$$

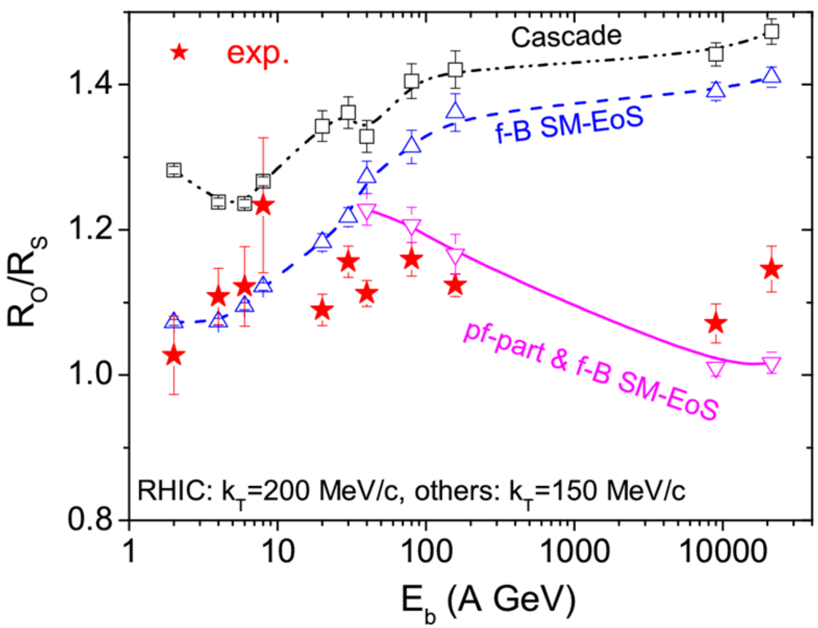
$$\beta_{ij}=\frac{\mathbf{p}_i+\mathbf{p}_j}{E_i+E_j},\qquad\gamma_{ij}=\frac{1}{1-\beta_{ij}^2}.$$

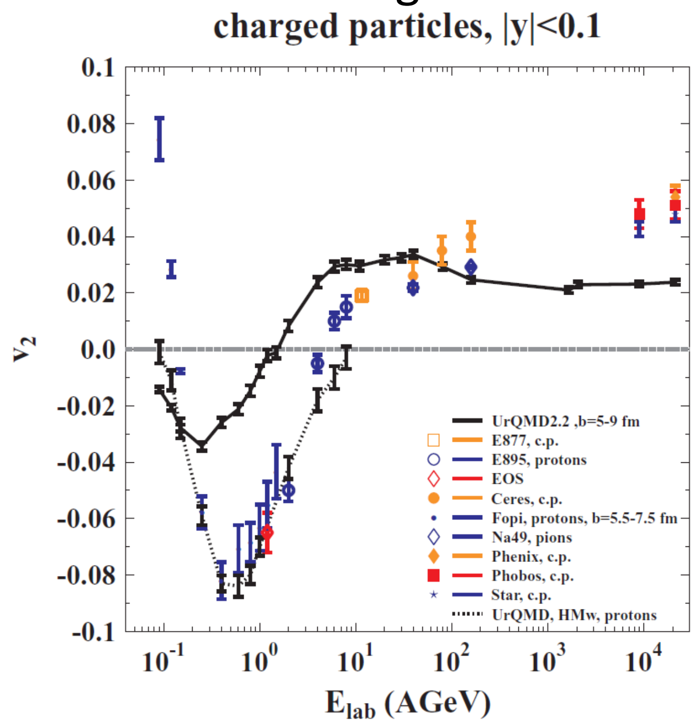
M. Isse *et al.*, PRC 72 064918 (2005)

Potential updates

- At higher beam energies, the Yukawa-, Pauli-, and symmetry-potentials of baryons becomes negligible, while the Skyrme- and the momentum-dependent part of potentials still influence the whole dynamical process of HICs

- Potentials for pre-formed hadrons
  - At high energies, particle production is dominated by the string mechanism
  - The formation time of the hadron is determined by the "yo-yo" mode. During this time, the **pre-formed particles (string fragments that will be projected onto hadron states later)** are usually treated to be free-streaming.





Potential updates

How to consider the potential for "pre-formed" hadrons?

A. For "pre-formed" particles from string fragmentation, the similar density dependent terms as the formed baryons are used, but without the Yukawa, the Coulomb, and the momentum dependent terms.

B. The "pre-formed" mesons act like "pre-formed" baryons but with a reduction factor (2/3) due to the quark-number difference.

C. The potential interaction between formed and "pre-formed" particles is neglected.

D. The "pre-formed" particles also contribute to the hadronic density (for "pre-formed" mesons, the 2/3 factor is considered).

$$U = \mu\left(\frac{\rho_h}{\rho_0}\right) + \nu\left(\frac{\rho_h}{\rho_0}\right)^g, \qquad \rho_h = \sum_{i \neq j} c_i c_j \rho_{ij}$$

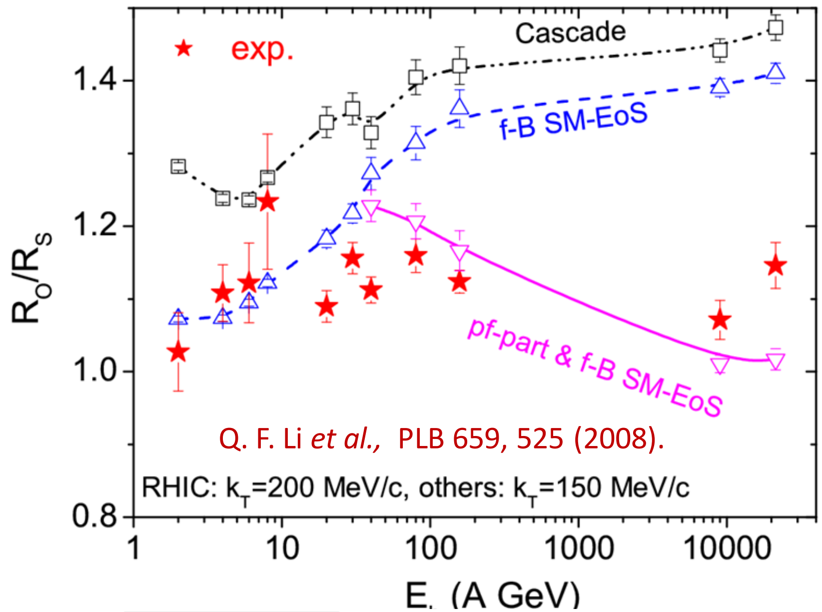
$c_{i,j} = 1$: formed and pre-formed baryons,

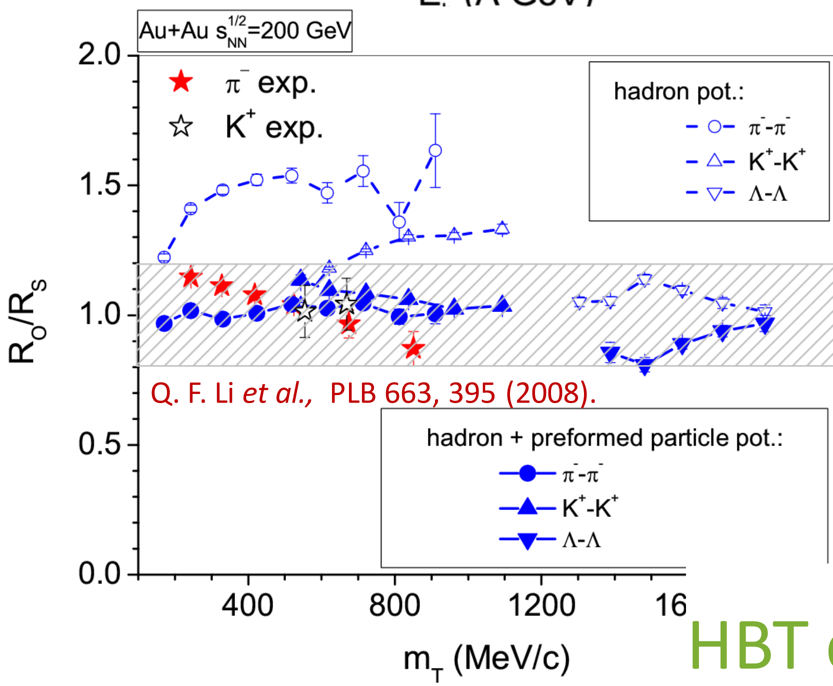
$c_{i,j} = 2/3$: pre-formed mesons;

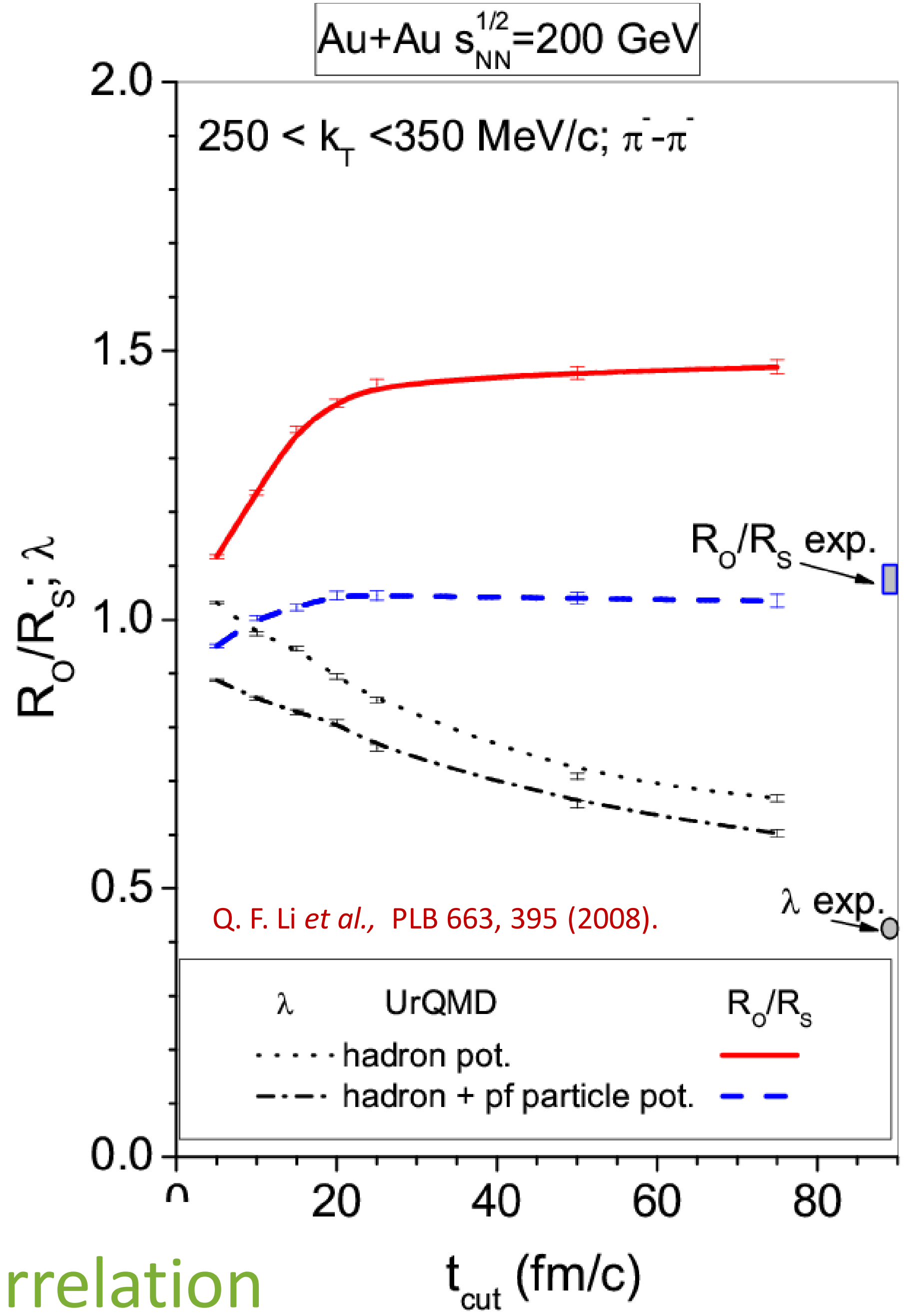
$c_{i,j} = 0$: formed mesons

Outline

Results and discussions







HBT correlation

Results and discussions

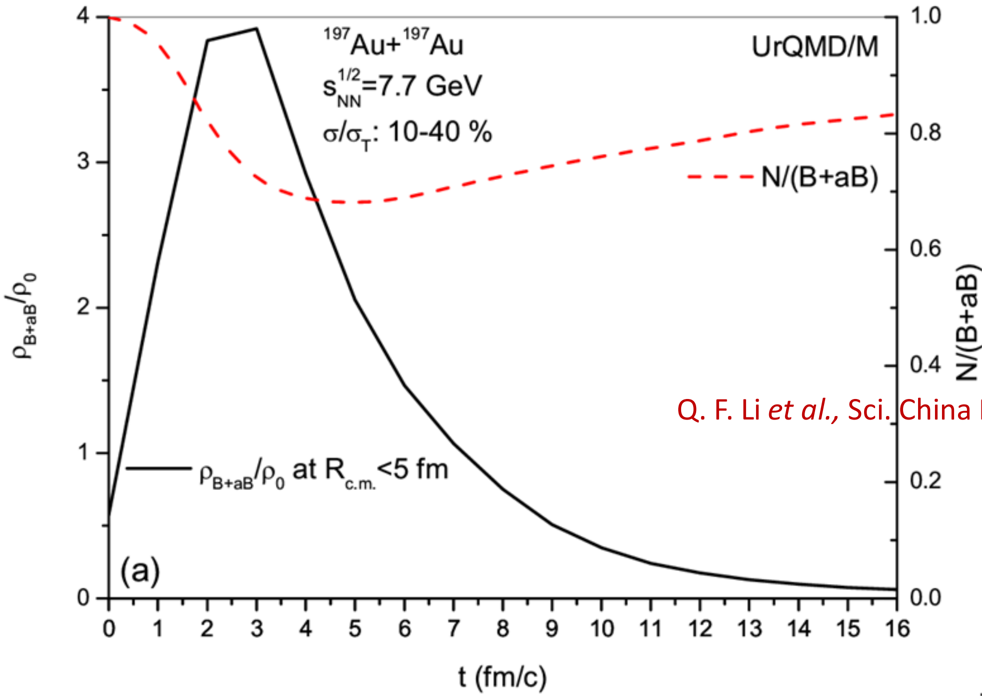


Fig.(a), the maximum value of $\rho_{B+\overline{B}}/\rho_0$ happens as early as ~3 fm/c, and returns to normal density at about 7~8 fm/c.

Q. F. Li *et al.*, Sci. China Phys. Mech. Astron. 59, 632001 (2016).

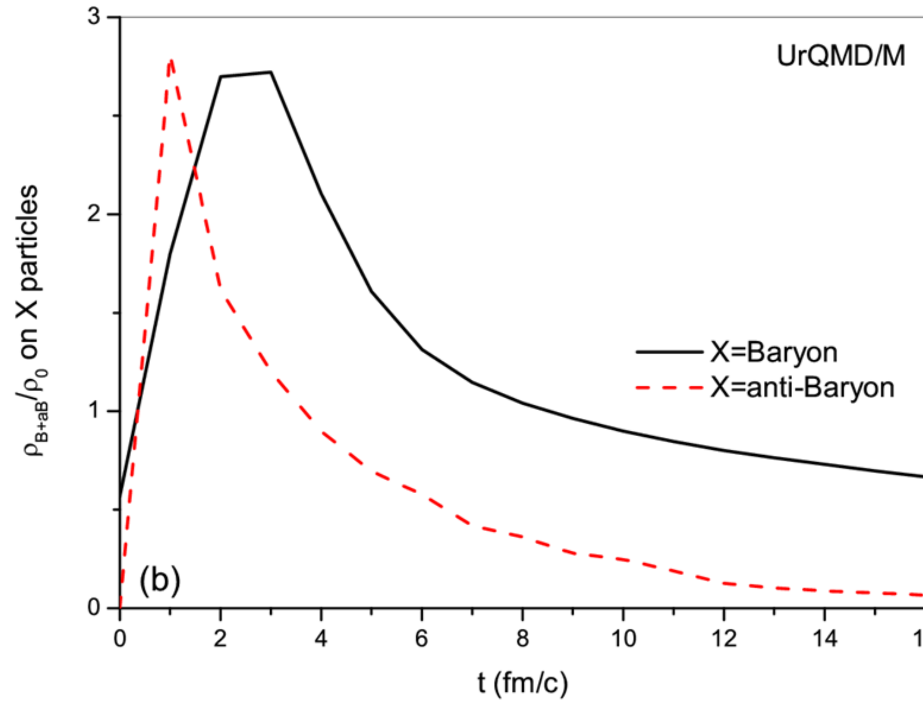
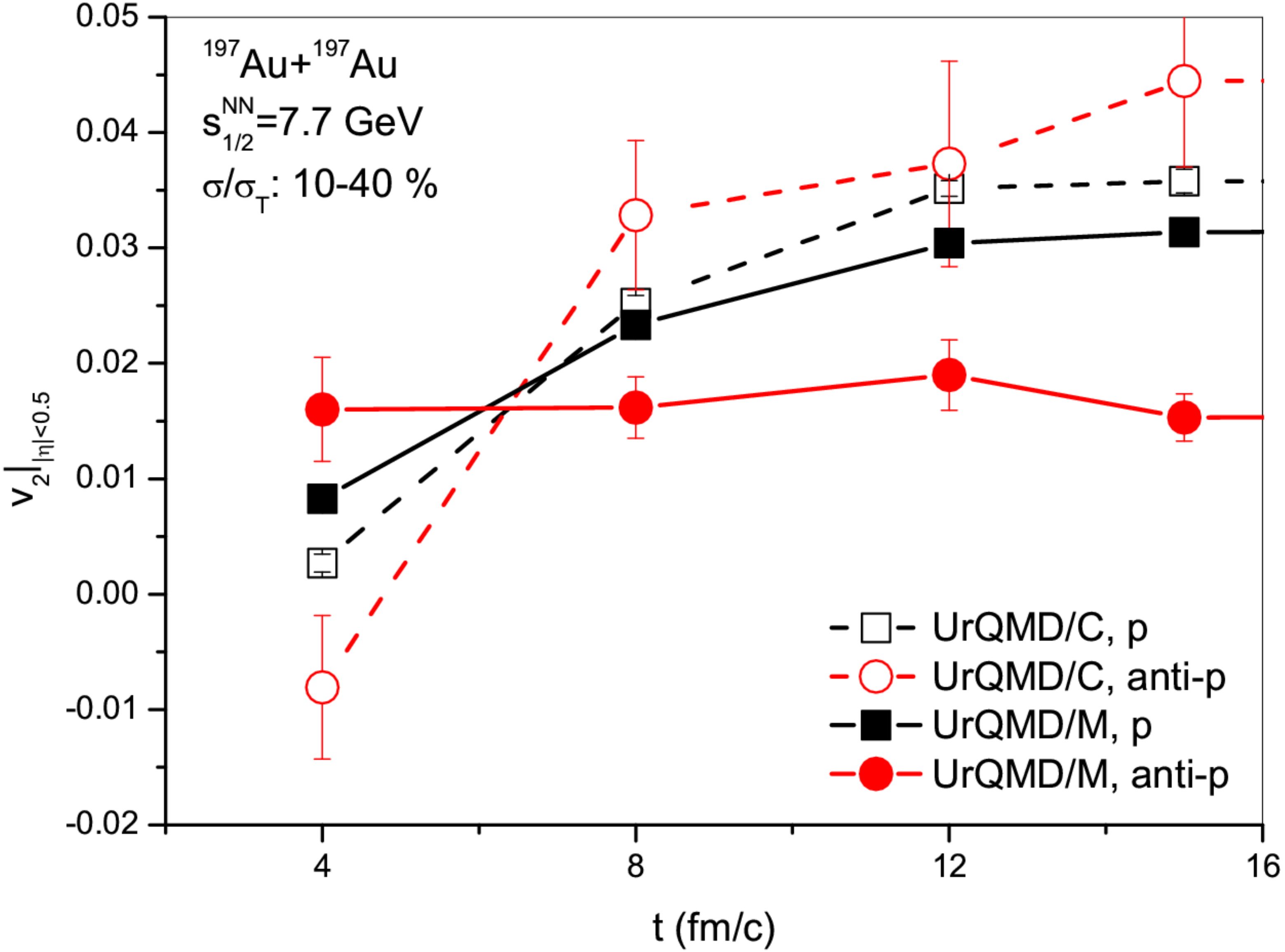


Fig.(b), the (pre-formed) anti-baryons are produced at even earlier times ~1fm/c, and frozen out faster than baryons, since at about 4 fm/c the reduced density has already turned back to the normal one.

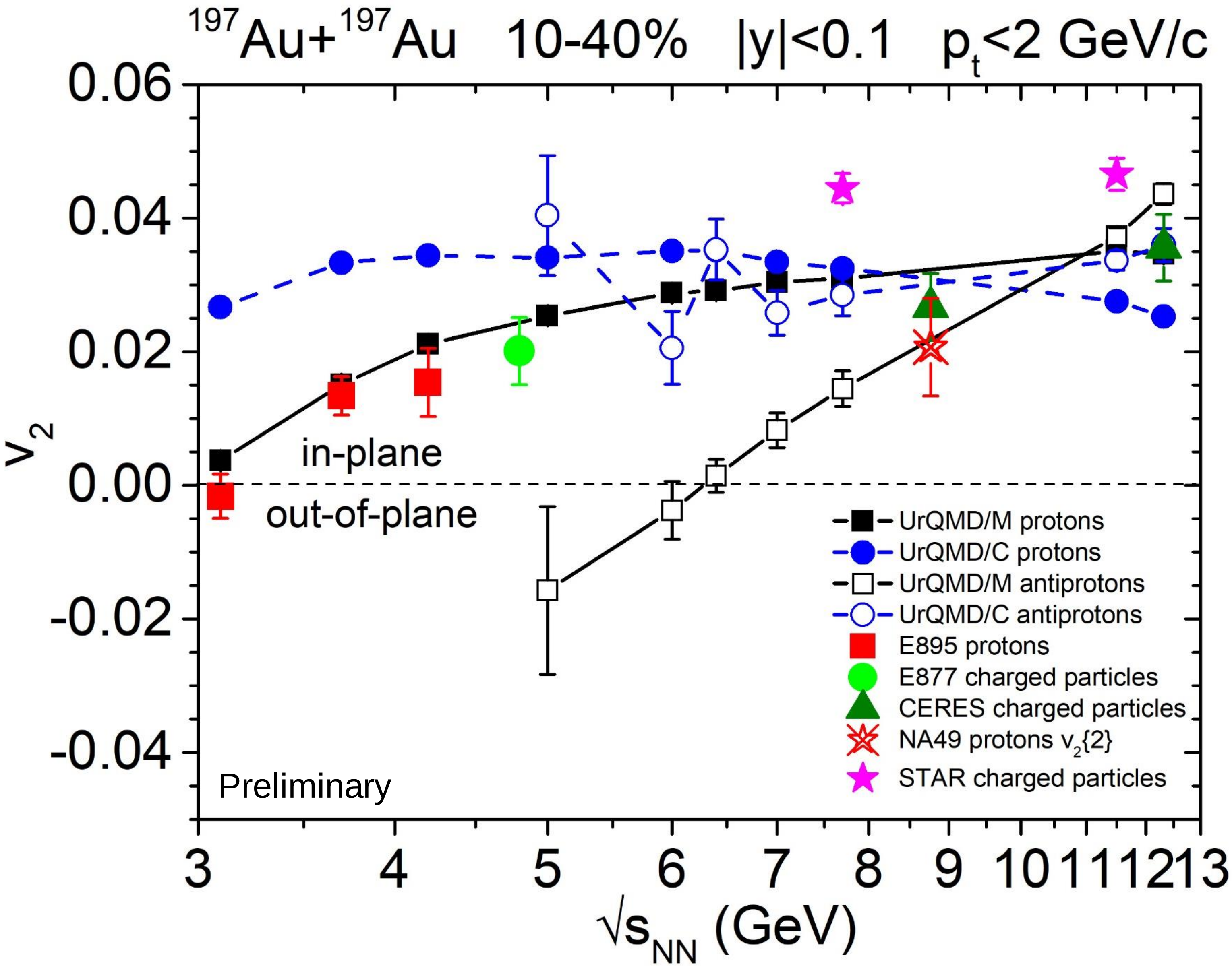
Time evolution of density

Results from UrQMD: v_2 difference



Effects of hadronic mean–field potentials on v_2 splitting

Results from UrQMD: v_2 difference



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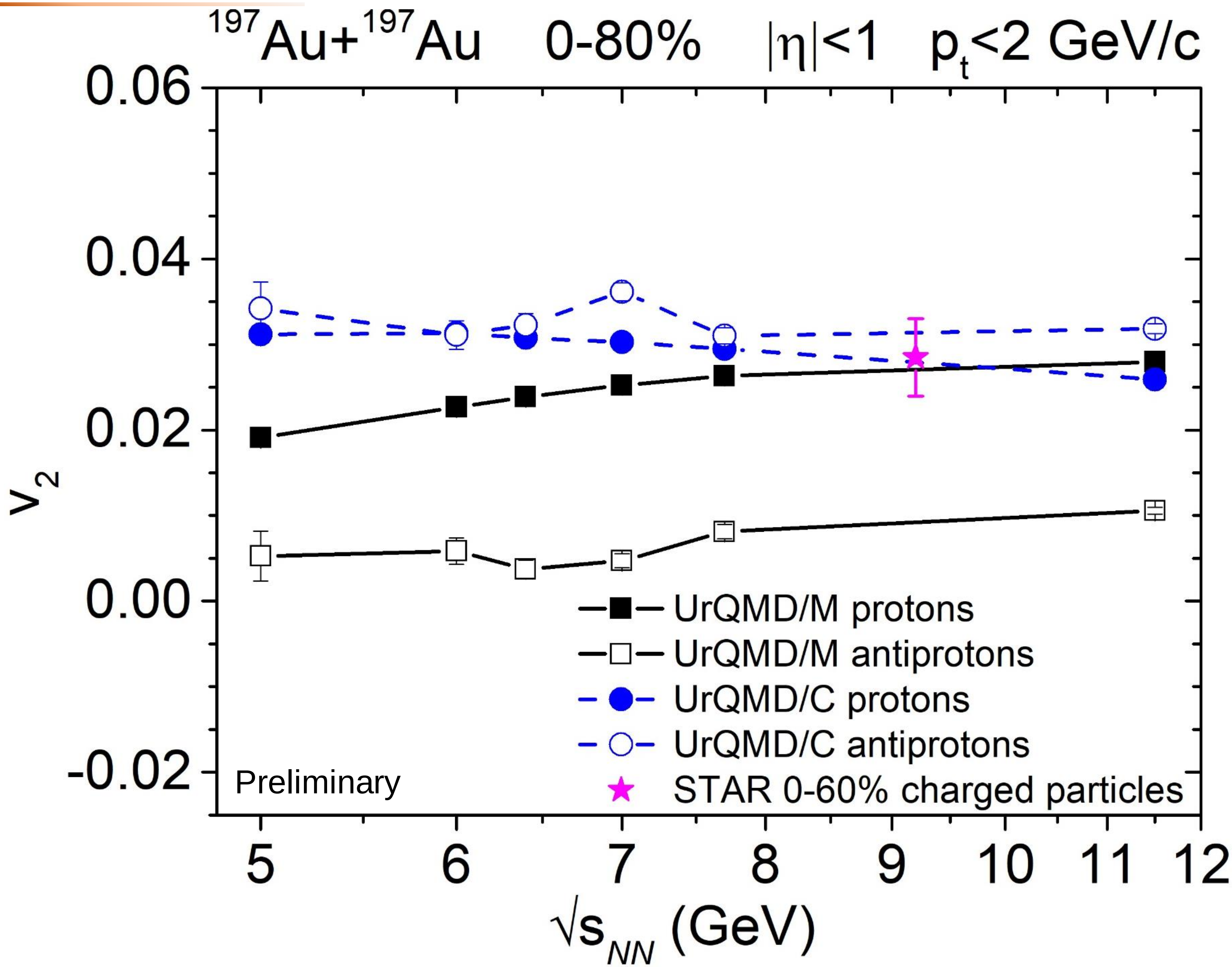

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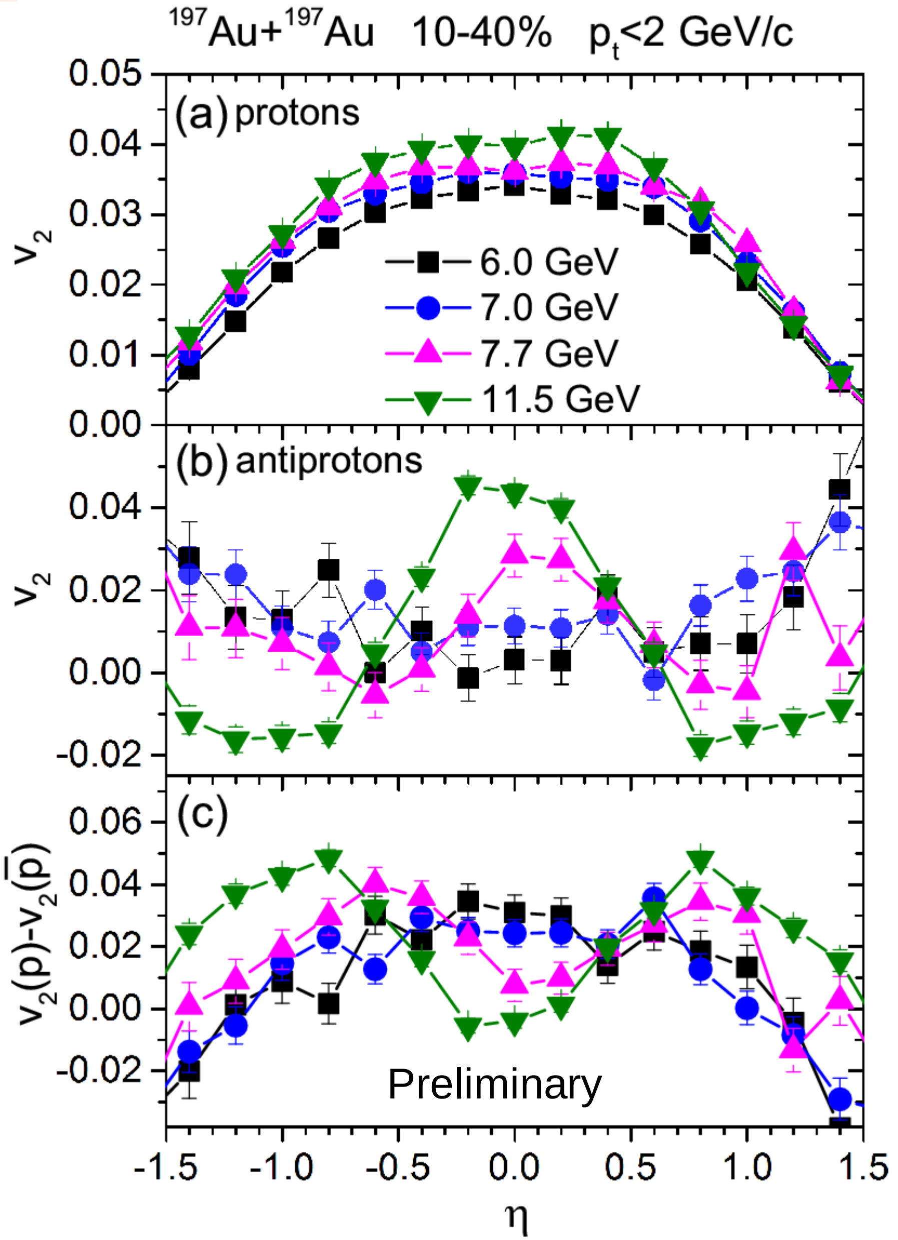
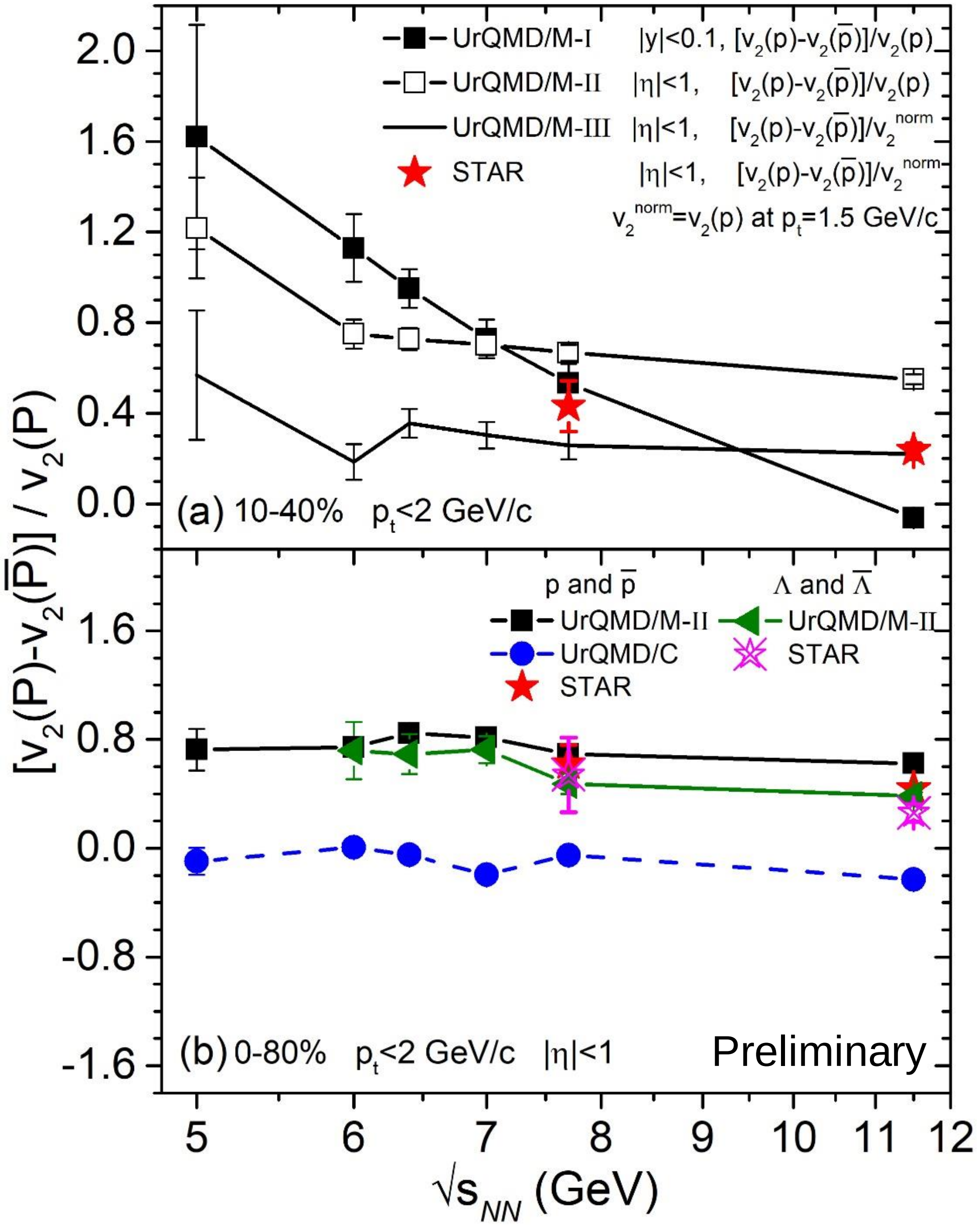
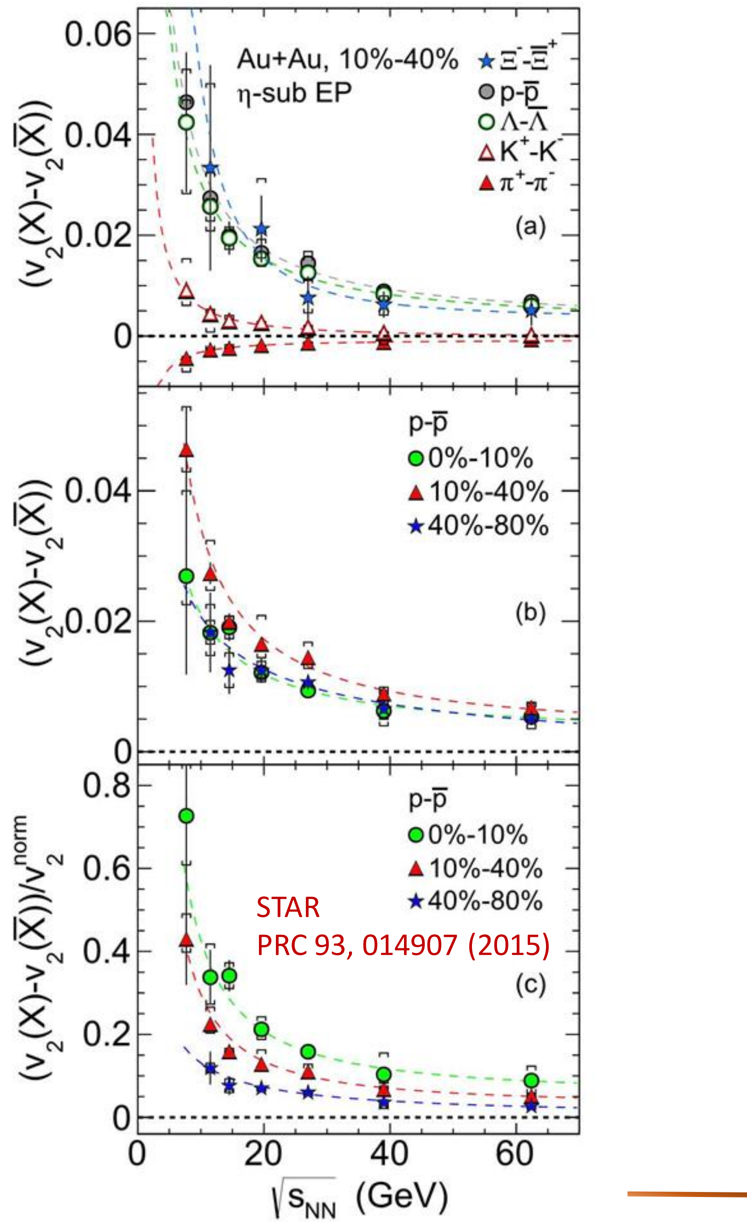


Effects of hadronic mean–field potentials on v_2 splitting

Results from UrQMD: v_2 difference





Effects of hadronic mean–field potentials on v_2 splitting

Outline

Summary and outlook

- The v_2 splitting, observed for particles and antiparticles, can be explained by the inclusion of proper hadronic interactions.
- The difference in v_2 between protons and antiprotons depends on the centrality and the rapidity windows. With smaller centrality and/or rapidity acceptance, the observed v_2 splitting is more sensitive to the beam energy, indicating a stronger net baryon density dependence of the effect.
- The v_2 splitting for 0-80% central Au+Au collisions with $|\eta|<1$ still exists below 7.7 GeV, and the splitting does not strongly depend on the collision energy.
- We therefore suggest to measure the difference of v_2 between protons and antiprotons at various centralities and rapidity bins at lower beam energies as an indicator to explore the nuclear potential in this beam energy range.

THANKS

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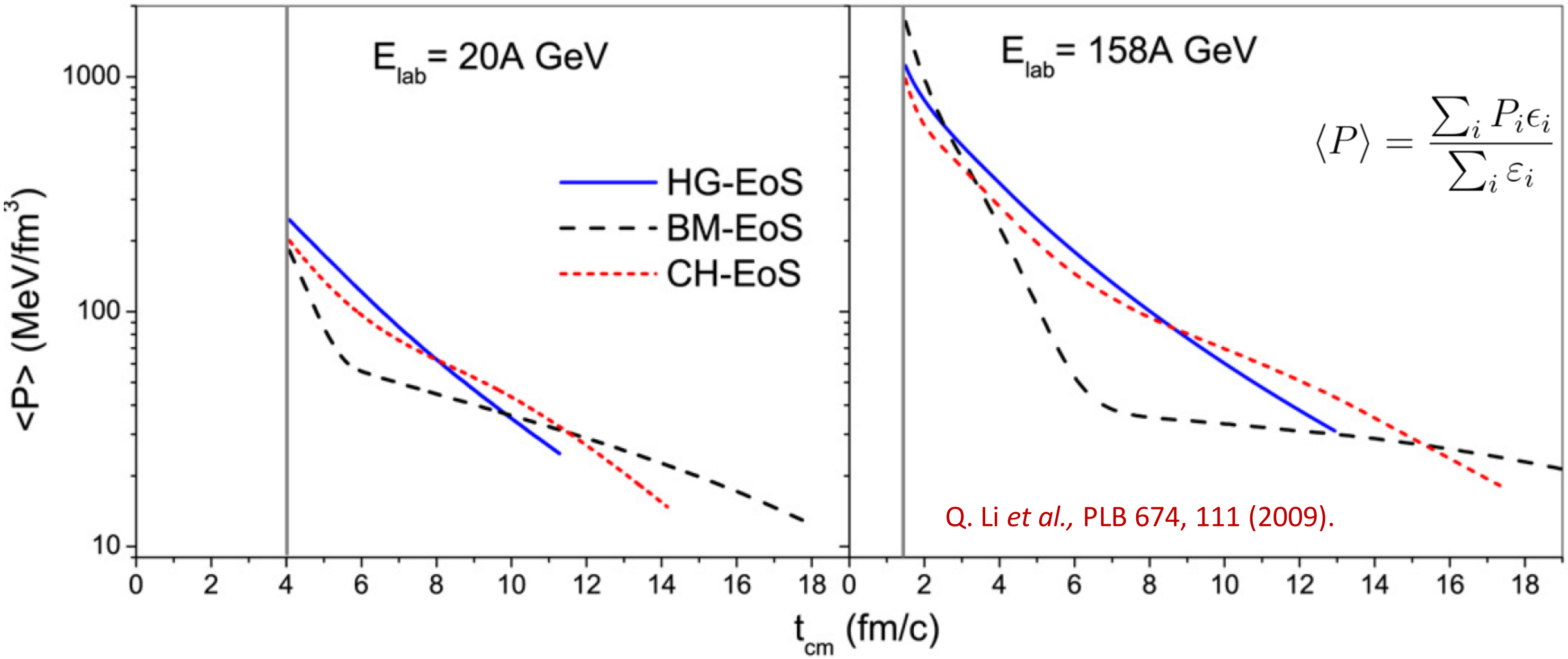
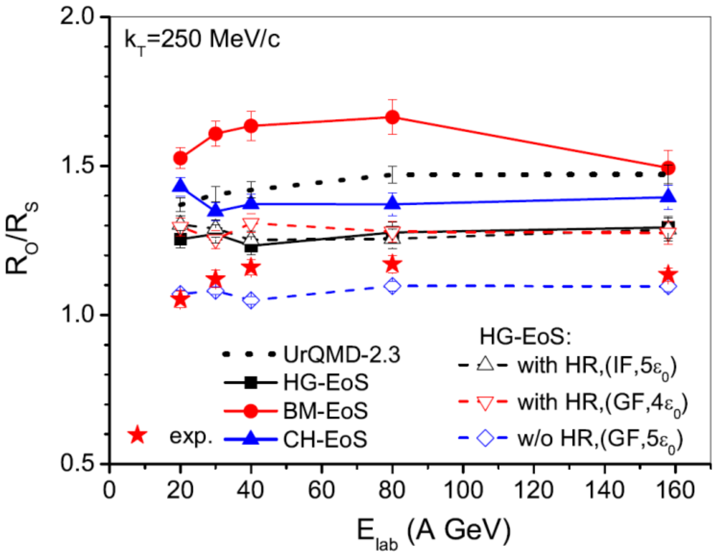
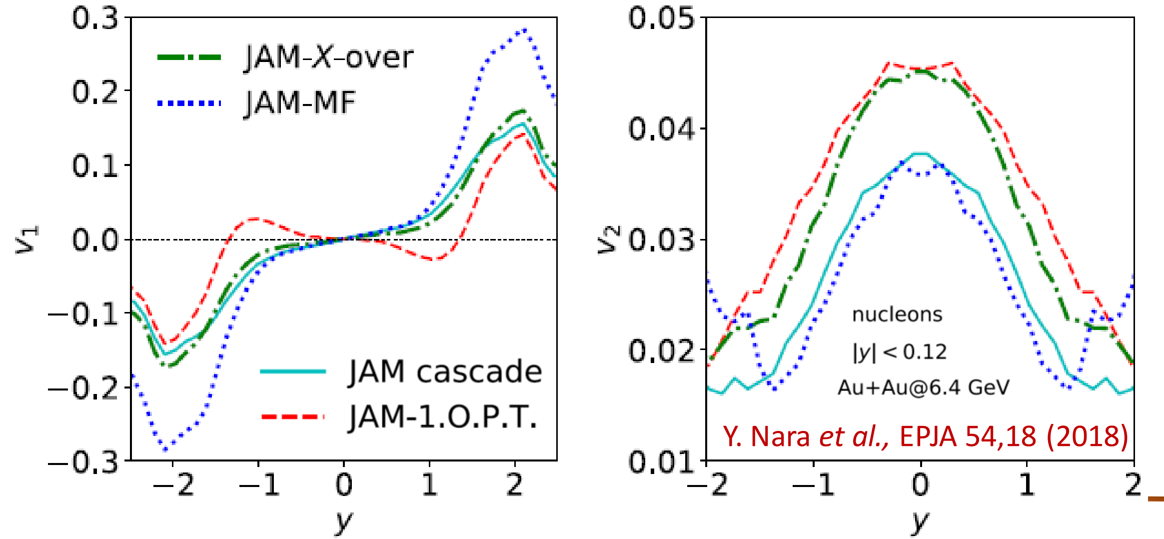
Effects of EoS







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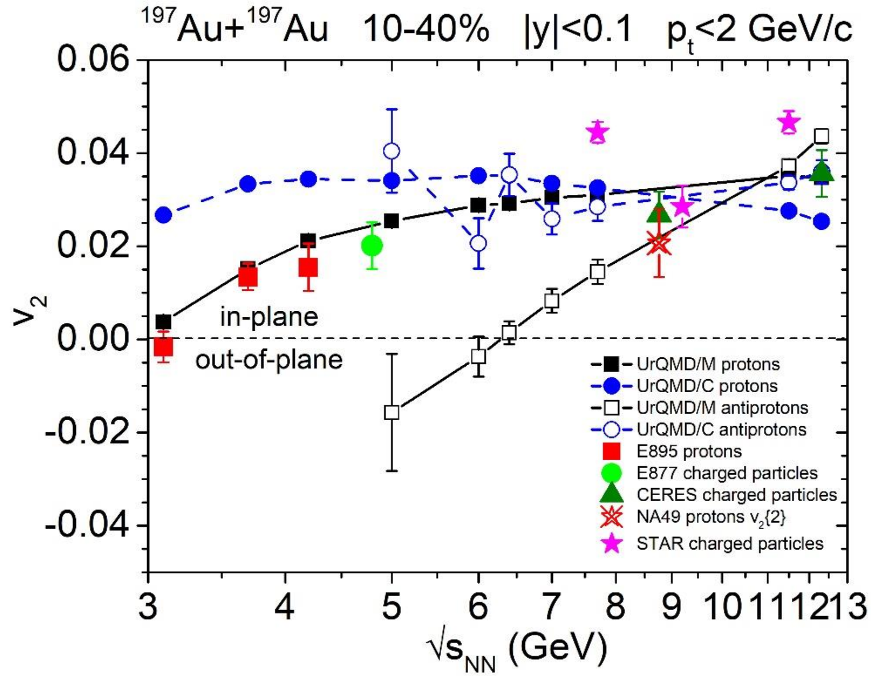
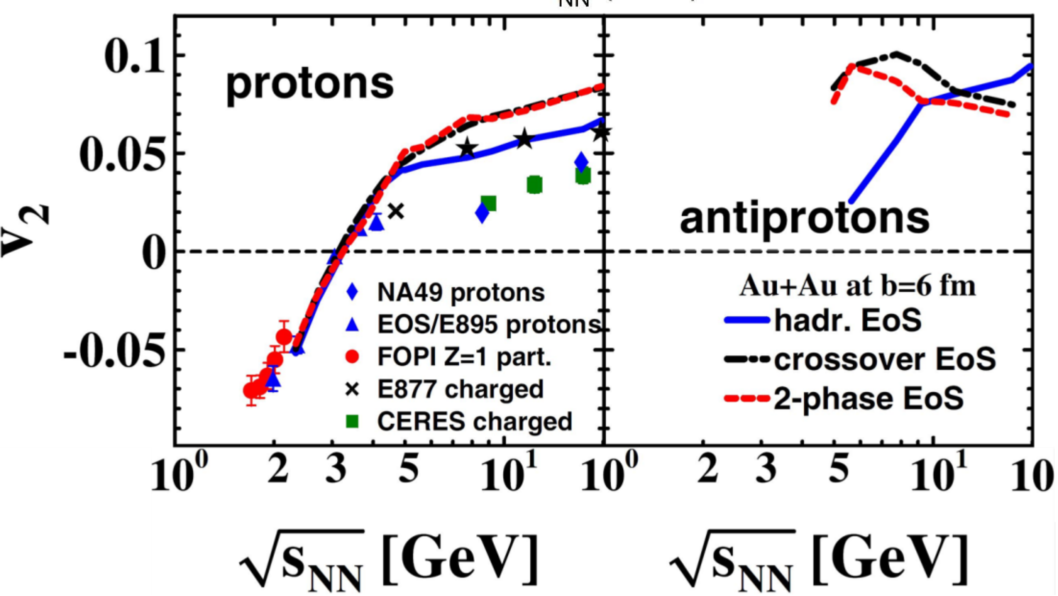
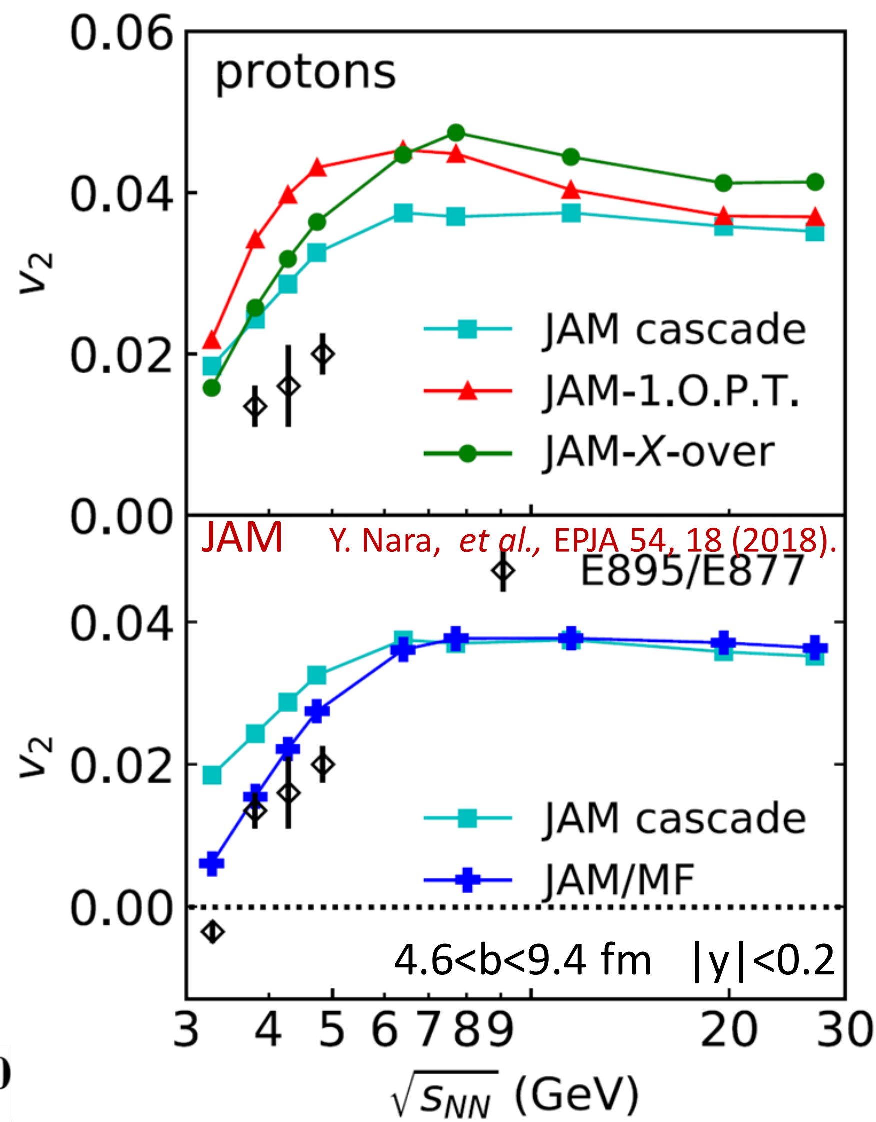
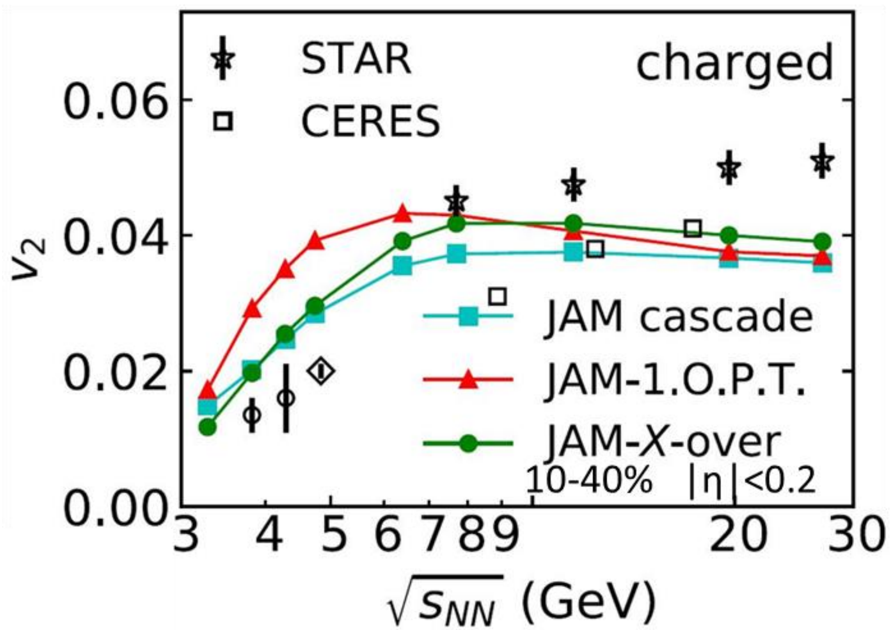




Three-fluid model Yu. B. Ivanov, *et al.,* EPJA 52, 247 (2016).



JAM Y. Nara, *et al.,* EPJA 54, 18 (2018).



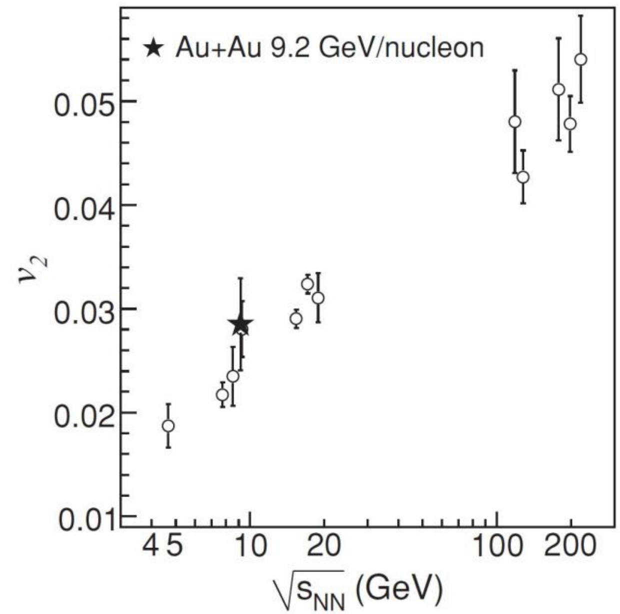
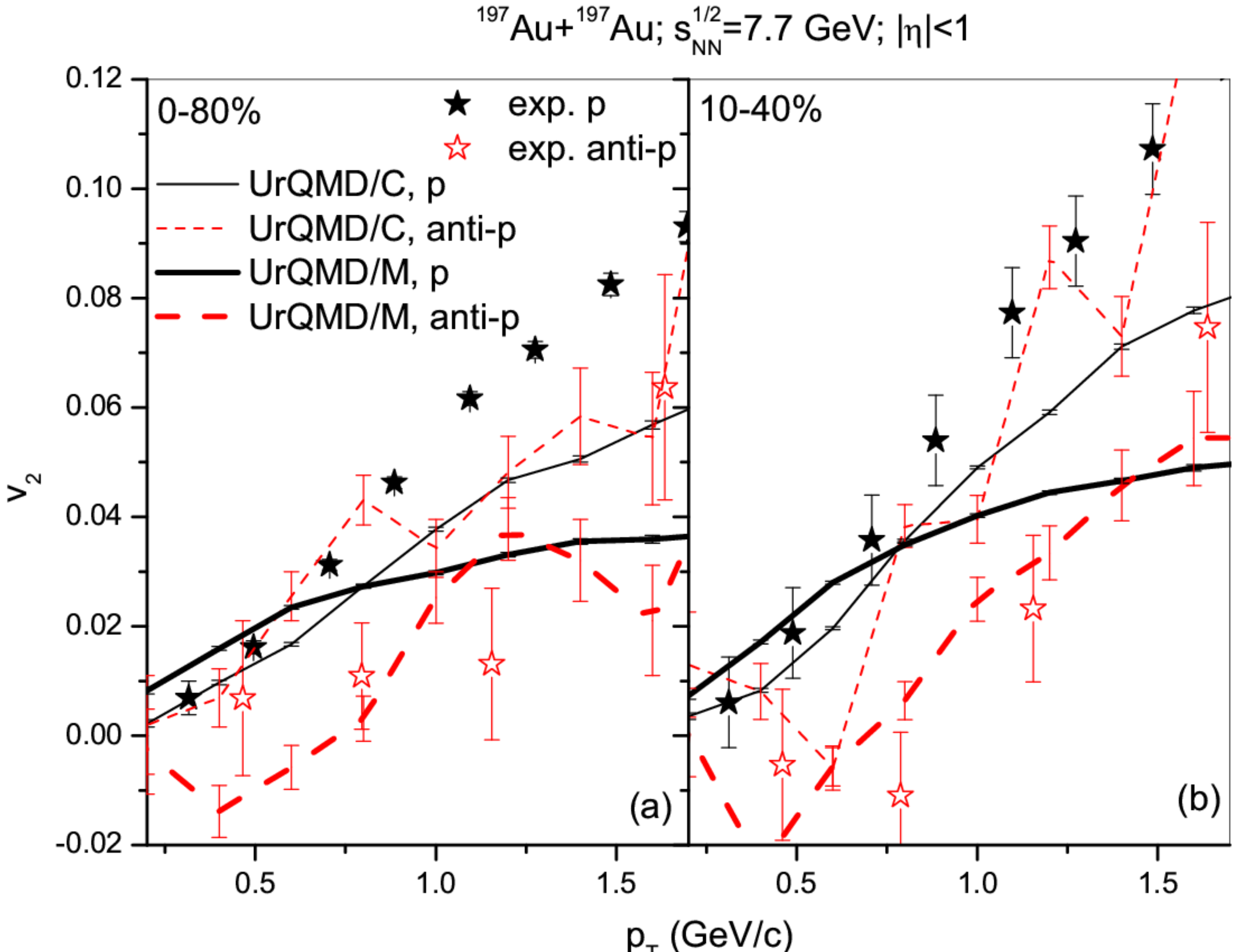
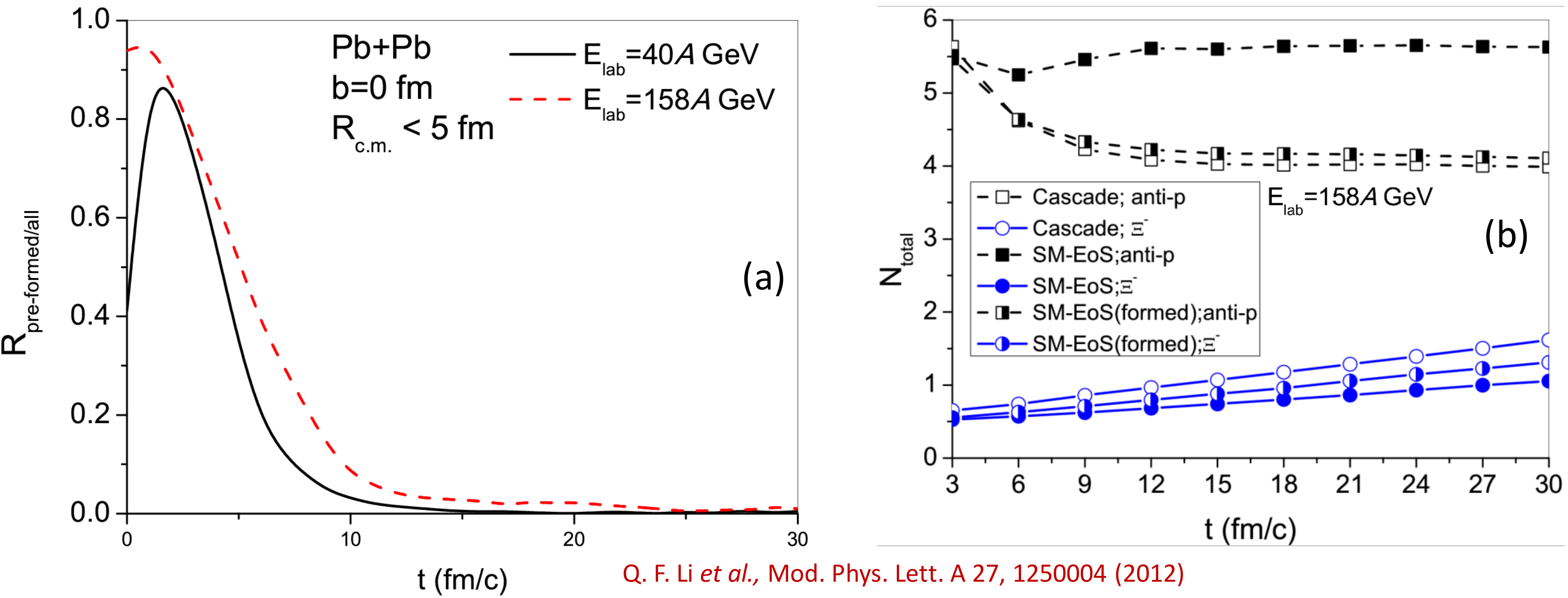


FIG. 24. Energy dependence of v_2 near midrapidity ($-1 < \eta < 1$) for $\sqrt{s_{NN}} = 9.2$ GeV 0–60% central Au + Au collisions. Only statistical errors are shown. The results of STAR charged-hadron v_2 [55] are compared with those measured by E877 [56], NA49 [54], PHENIX [57], and PHOBOS [46,50,58] collaborations.



Q. F. Li *et al.*, SCPMA 59, 632001 (2016)

Effects of hadronic mean-field potentials on v_2 splitting

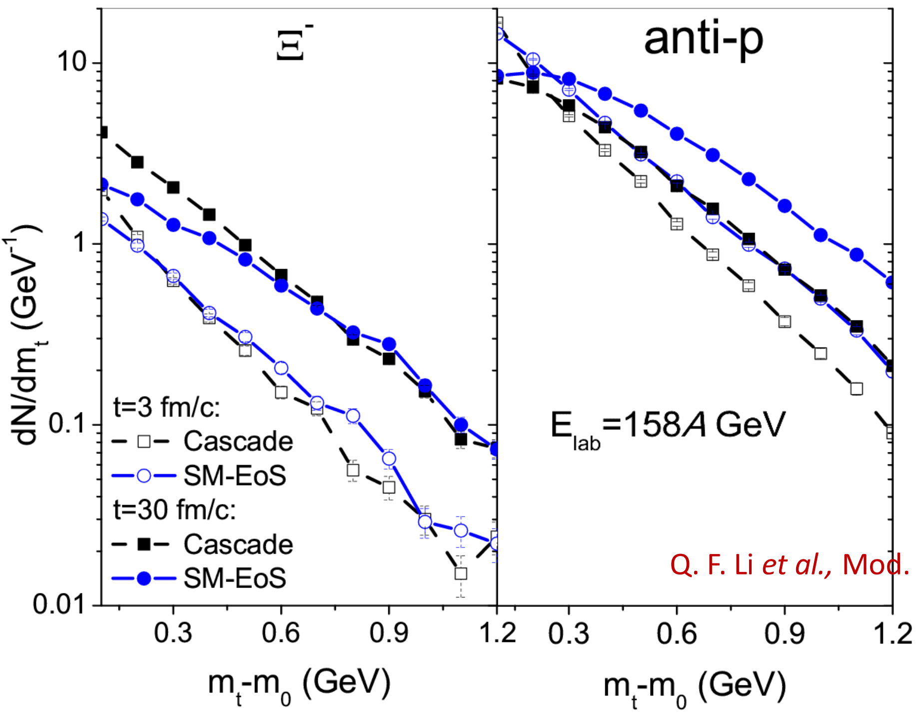


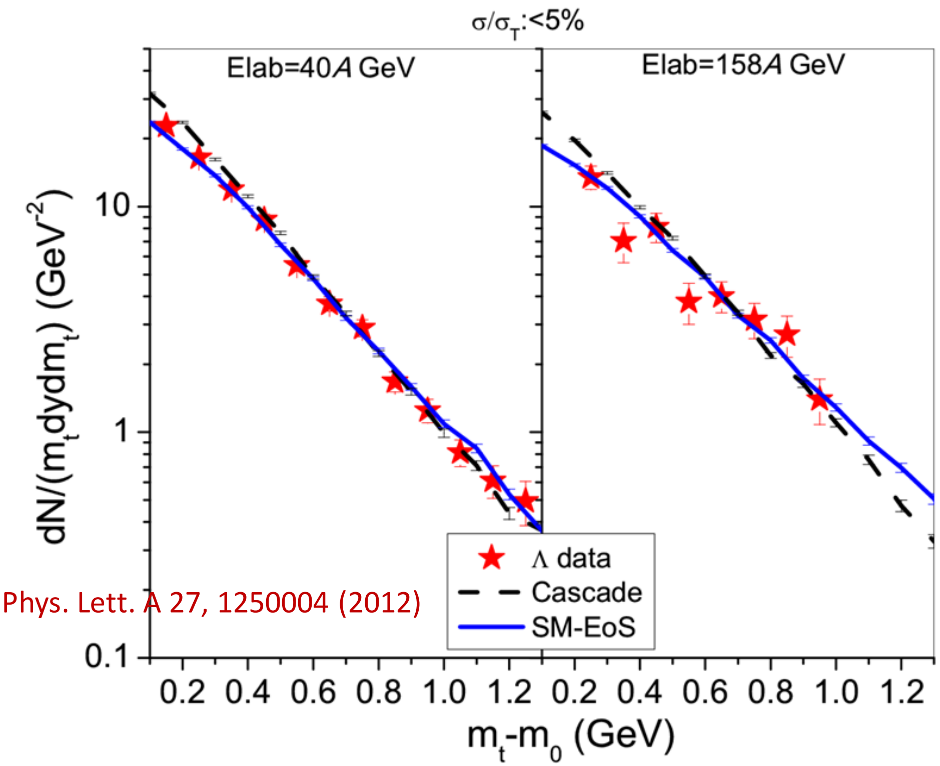
Q. F. Li *et al.,* Mod. Phys. Lett. A 27, 1250004 (2012)

Fig.(a), the main production mechanism at t< 5 fm/c is string excitation and fragmentation, and that this production mechanism still plays visible role up to t ~10 fm/c. Hence, the pre-formed hadron potentials will definitely provide a visible contribution to the early pressure.

Fig.(b), if switch off the pre-formed hadron potentials but keep the formed ones, the time evolution of $\bar{p}$ is almost the same as that with the cascade mode. Means that the mechanism of string excitation and fragmentation is essential to the production of $\bar{p}$.

Time evolution of yields





Q. F. Li *et al.*, Mod. Phys. Lett. A 27, 1250004 (2012)

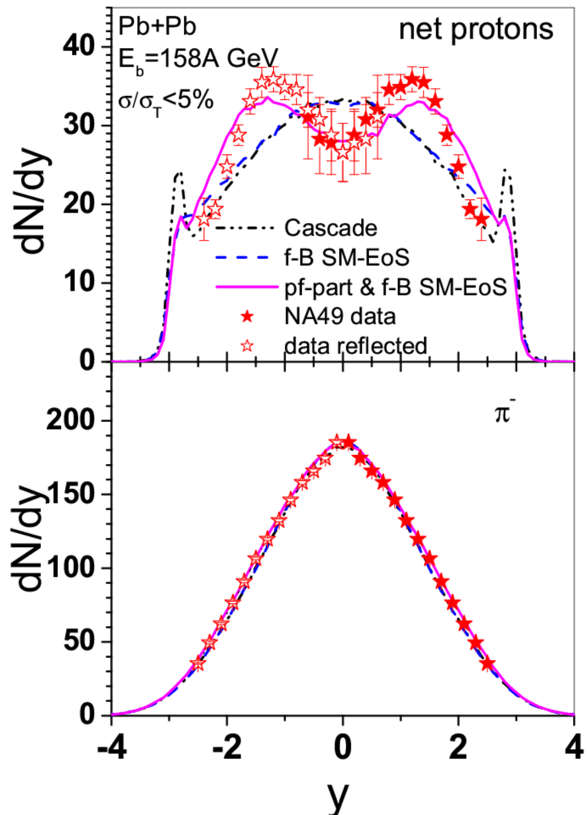
For strange particle production, in addition to the string mechanism, the rescattering process of hadrons are also important:

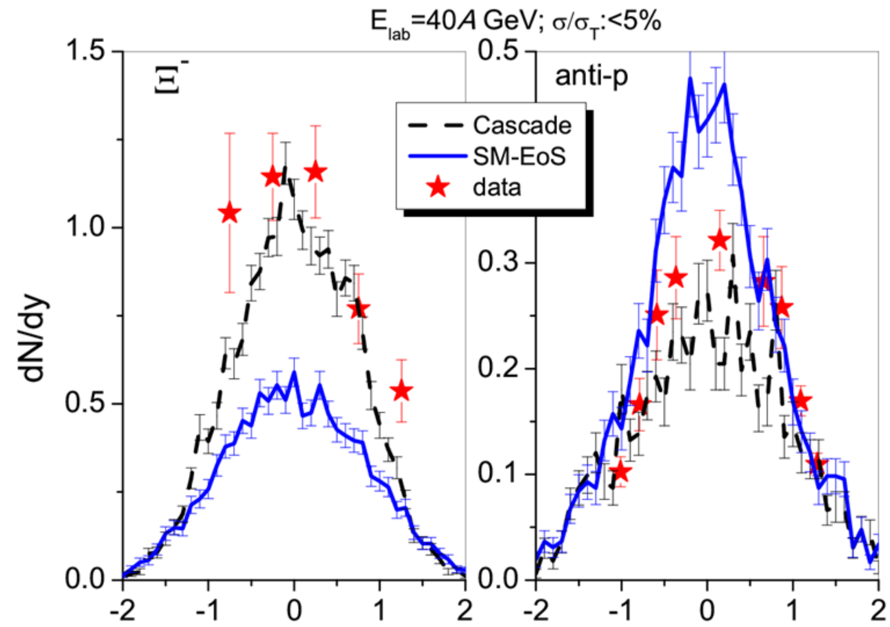
(i) the rapid increase of the Ξ^- yield during the time 3~30 fm/c,

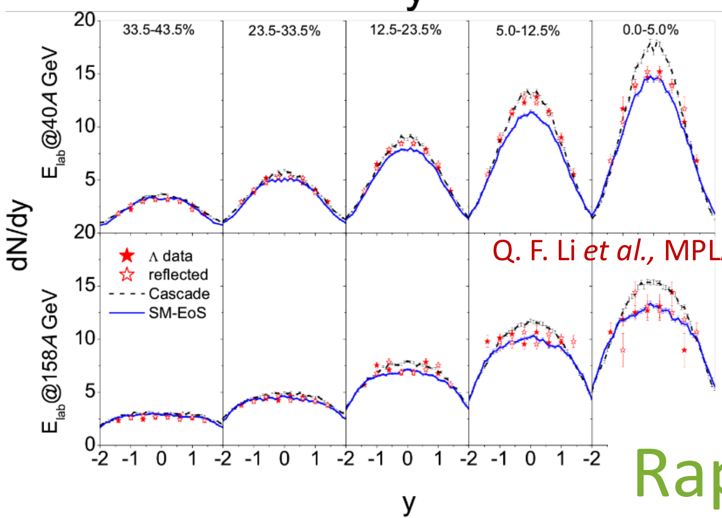
(ii) the suppression effect of potentials on both the yield mainly at the low transverse masses and the total yield at t = 30 fm/c,

(iii) the contribution of formed hadron potentials to Ξ^- yield.

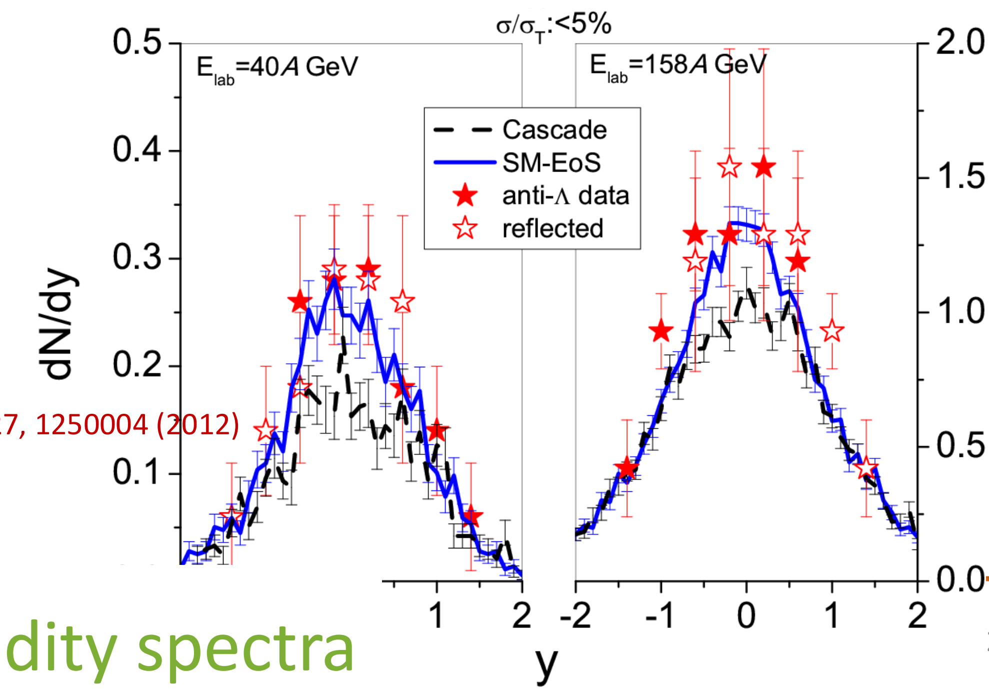
Transverse mass spectra



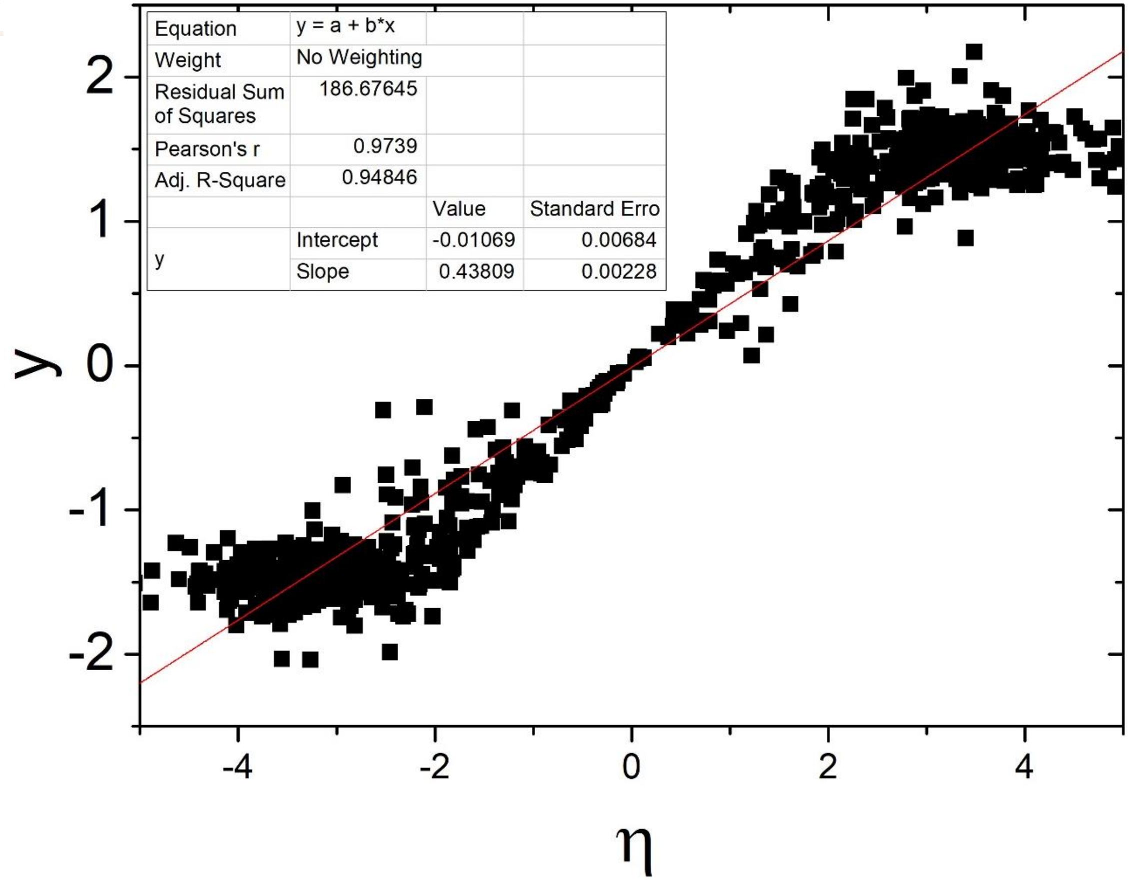




Q. F. Li *et al.*, MPLA 27, 1250004 (2012)



Rapidity spectra

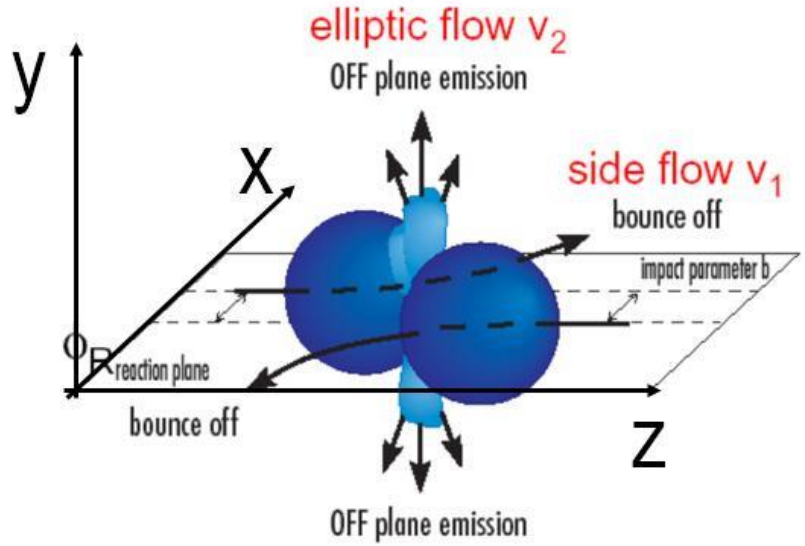


$y=\frac{1}{2}\ln\frac{E+p_{//}}{E-p_{//}}=\frac{1}{2}\ln\frac{1+v_{//}}{1-v_{//}}$ 来表示，$v_{//}=\frac{p_{//}}{E}$ 是粒子的纵向速度

另外，当粒子的质量与纵向动量相比可以忽略时，$E=p$，由此可得

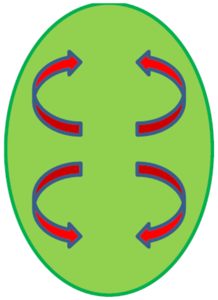
$$y\approx\frac{1}{2}\ln\frac{1+\cos\theta}{1-\cos\theta}=-\ln tg\frac{\theta}{2}=\eta,$$

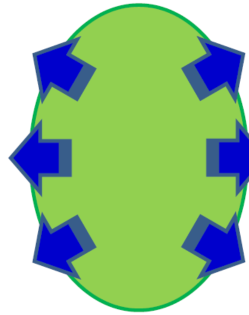
其中 θ 是粒子动量与纵方向的夹角，η 是实验中常用的量，称为赝快度。



Particles with attractive potentials are more likely to be trapped in the system

v_2 decrease





Particles with repulsive potentials are more likely to leave the system

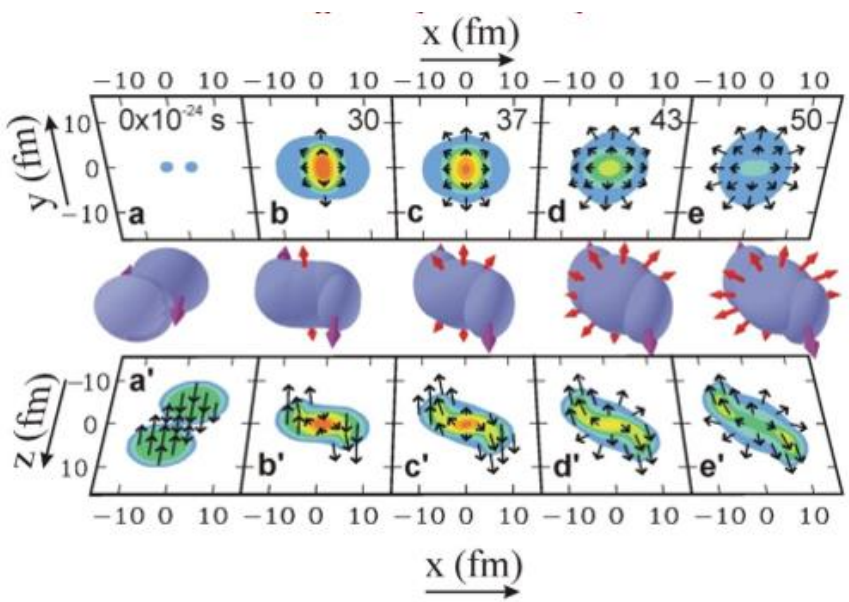
v_2 increase

$$p_t = \sqrt{p_x^2 + p_y^2}$$

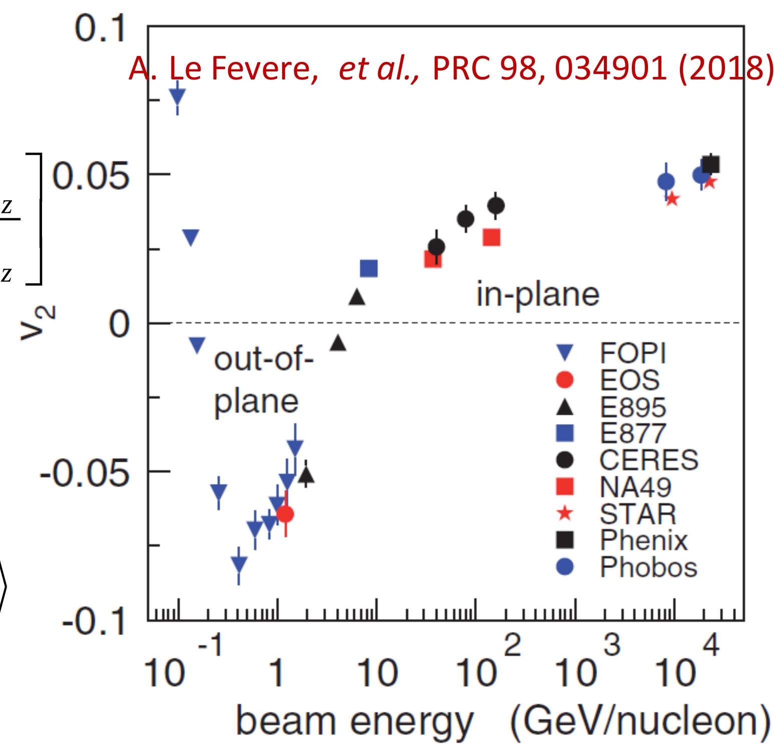
$$y = \frac{1}{2}\ln\left[\frac{E + p_z}{E - p_z}\right]$$

$$v_1 = \left\langle \frac{p_x}{p_t} \right\rangle$$

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$



P. Danielewicz *et al.,* Science (2002).



A. Le Fevere, *et al.,* PRC 98, 034901 (2018)

Explanations for v_2 splitting

- Different hadronic and partonic potentials for particles and antiparticles

J. Xu, L.W. Chen, C.M. Ko, Z.W. Lin, PRC 85, 041901(R) (2012); J. Xu, T. Song, C. M. Ko, F. Li, PRL 112, 012301 (2014)

the different mean-field potentials for hadrons and antihadrons or quarks and antiquarks：

A multiphase transport (AMPT) model with string melting

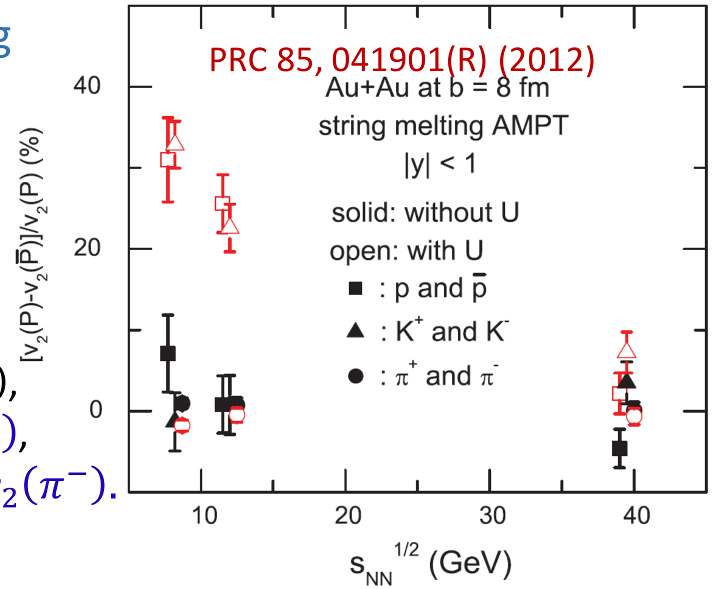
$$U_{N,\bar{N}}(\rho_B, \rho_{\bar{B}}) = \Sigma_s(\rho_B, \rho_{\bar{B}}) \pm \Sigma_v^0(\rho_B, \rho_{\bar{B}})$$

$\Sigma_s(\rho_B, \rho_{\bar{B}})$ nucleon scalar self-energies,

$\Sigma_v^0(\rho_B, \rho_{\bar{B}})$ nucleon vector self-energies

"+" for nucleons, "-" for antinucleons

Stronger attractive potential for $\bar{p}$ compared to p → smaller $v_2(p)$,
Attractive potential for K^-, repulsive for K^+ → $v_2(K^-)$ < $v_2(K^+)$,
Slightly attractive potential for π^+, repulsive for π^- → $v_2(\pi^+)$ < $v_2(\pi^-)$.

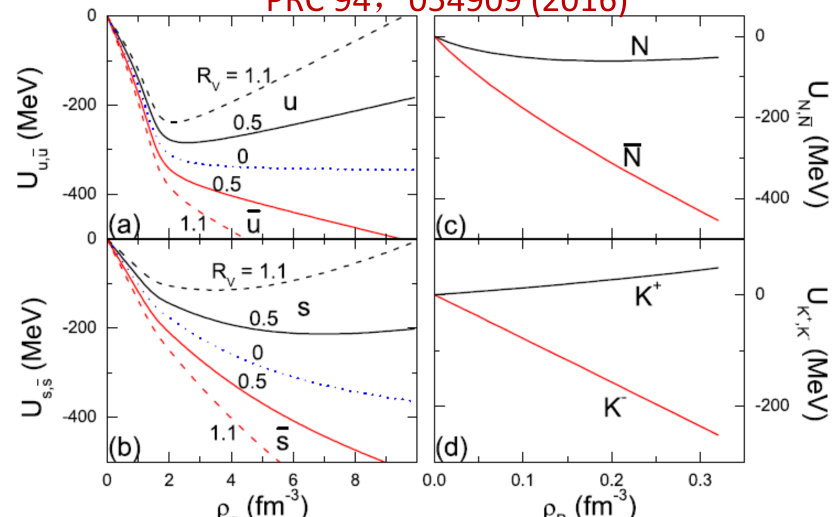


3-flavor Nambu-Jona-Lasinio transport model

$$\mathcal{L} = \bar{\psi}(i \not{\partial} - M)\psi + \frac{G}{2}\sum_{a=0}^{8}\left[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma_5\lambda^a\psi)^2\right]$$
$$+ \sum_{a=0}^{8}\left[\frac{G_V}{2}(\bar{\psi}\gamma_\mu\lambda^a\psi)^2 + \frac{G_A}{2}(\bar{\psi}\gamma_\mu\gamma_5\lambda^a\psi)^2\right]$$
$$- K\left[\det{}_f\left(\bar{\psi}(1+\gamma_5)\psi\right) + \det{}_f\left(\bar{\psi}(1-\gamma_5)\psi\right)\right],$$

With a nonvanishing G_V, it further gives rise to a repulsive vector mean-field potential for quarks but an attractive one for antiquarks in a baryon-rich quark matter.

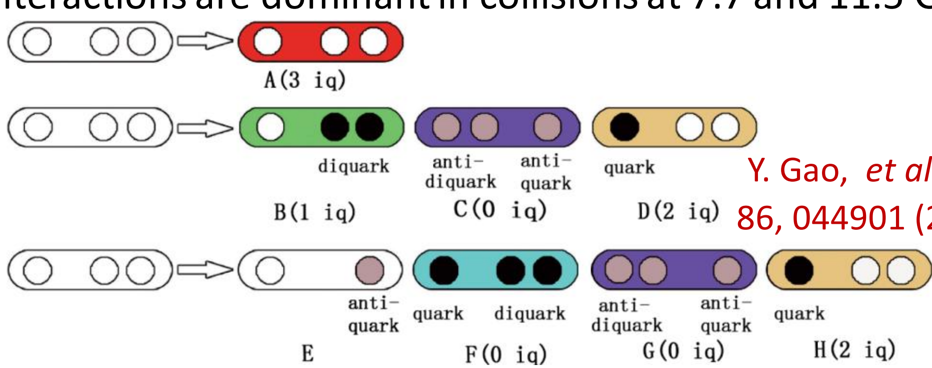
PRC 94，054909 (2016)



Explanations for v_2 splitting

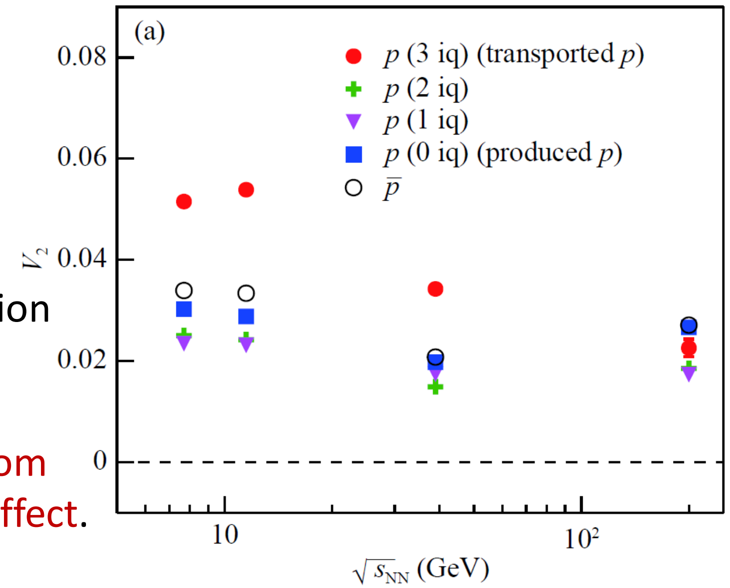
- The difference of v_2 between transported quarks and produced quarks during the initial stage of HICs. J. C. Dunlop, *et al.*, PRC 84, 044914 (2011).
- Baryon stopping effect and scattering. (By tracing the number of initial quarks in protons in the UrQMD) .
  B. Tu, *et al.*, CPC 43, 054106 (2019).

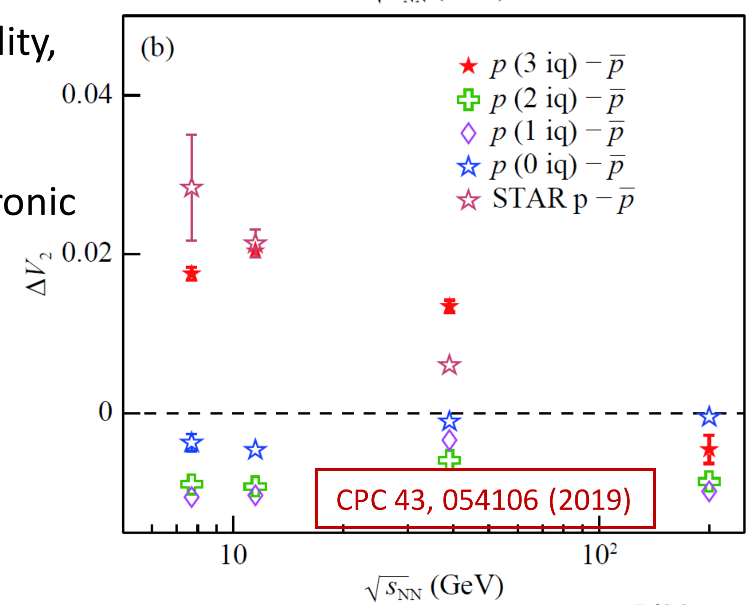
1. Produced protons (0 iq) and antiprotons: made of produced quarks, produced in the early stage, experience the full evolution of the system, experience similar magnitude of interactions.
   $\rightarrow v_2(p(0\,iq)) \approx v_2(\bar{p})$
2. v_2 of transported protons (3 iq) derives from the transport from forward rapidity to mid-rapidity due to the nuclear stopping effect.
   $\rightarrow v_2(p(3\,iq)) > v_2(p(0\,iq)) \approx v_2(\bar{p})$
3. Transported quarks, which are transported over a large rapidity, suffer more scatterings than produced quarks.
   $\rightarrow v_2(p(3\,iq)) > v_2(p(0\,iq))$
4. Large deviation at high energies ≥39 GeV suggests that hadronic interactions are dominant in collisions at 7.7 and 11.5 GeV.



Y. Gao, *et al.*, PRC 86, 044901 (2012).

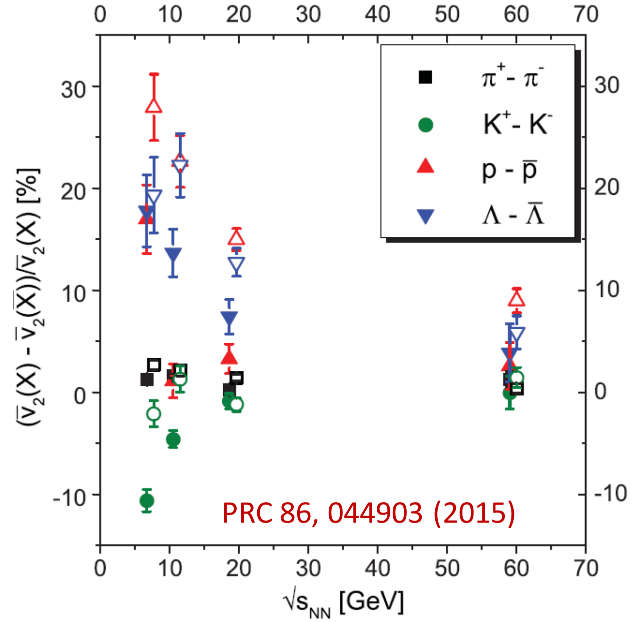
Particle production in a string-excitation scheme in UrQMD.



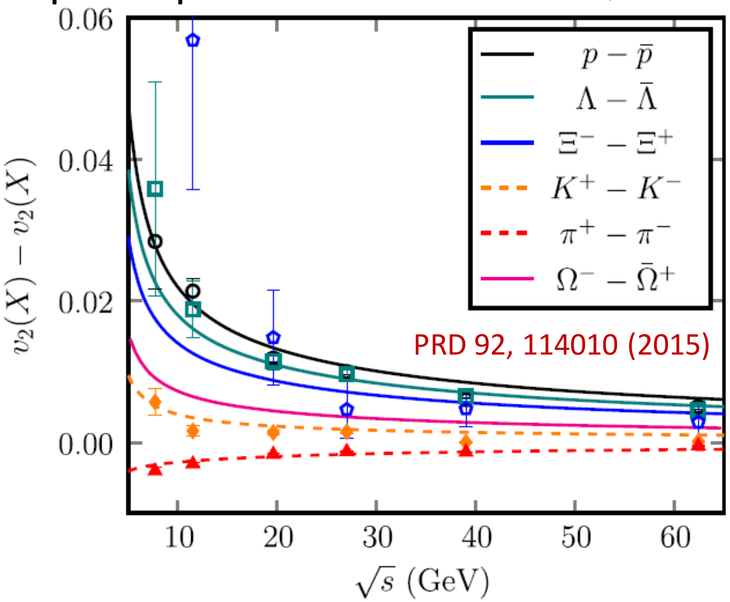


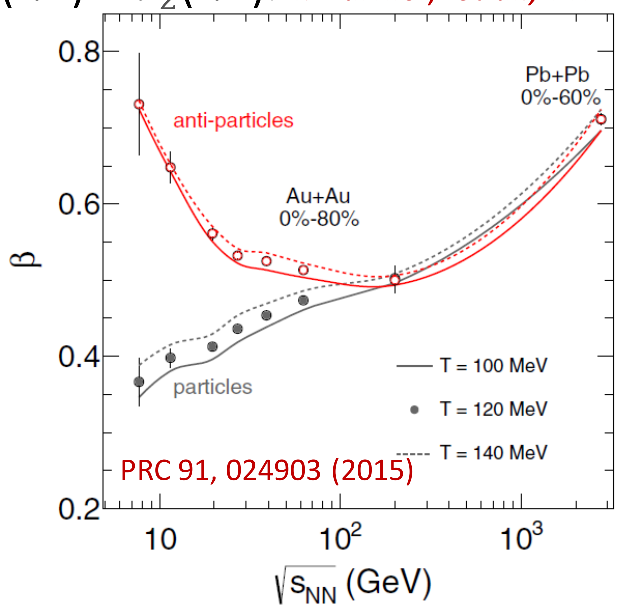
Explanations for v_2 splitting

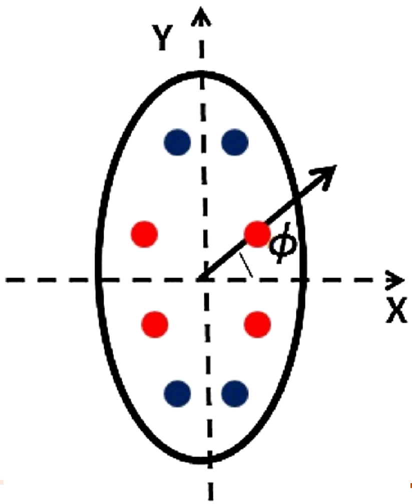
- By variations in the widths of quark and antiquark rapidity distribution. V. Greco, *et al.*, PRC 86, 044905 (2012).
- Conservation of baryon charge, strangeness, and isospin. J. Steinheimer, *et al.*, PRC 86, 044903 (2012)
- Hydrodynamics at finite baryon chemical potential. Y. Hatta, *et al.*, PRD 92, 114010 (2015).
- Energy dependent difference of the transverse expansion velocity β between particles and corresponding antiparticles. X. Sun, *et al.*, PRC 91, 024903 (2015).



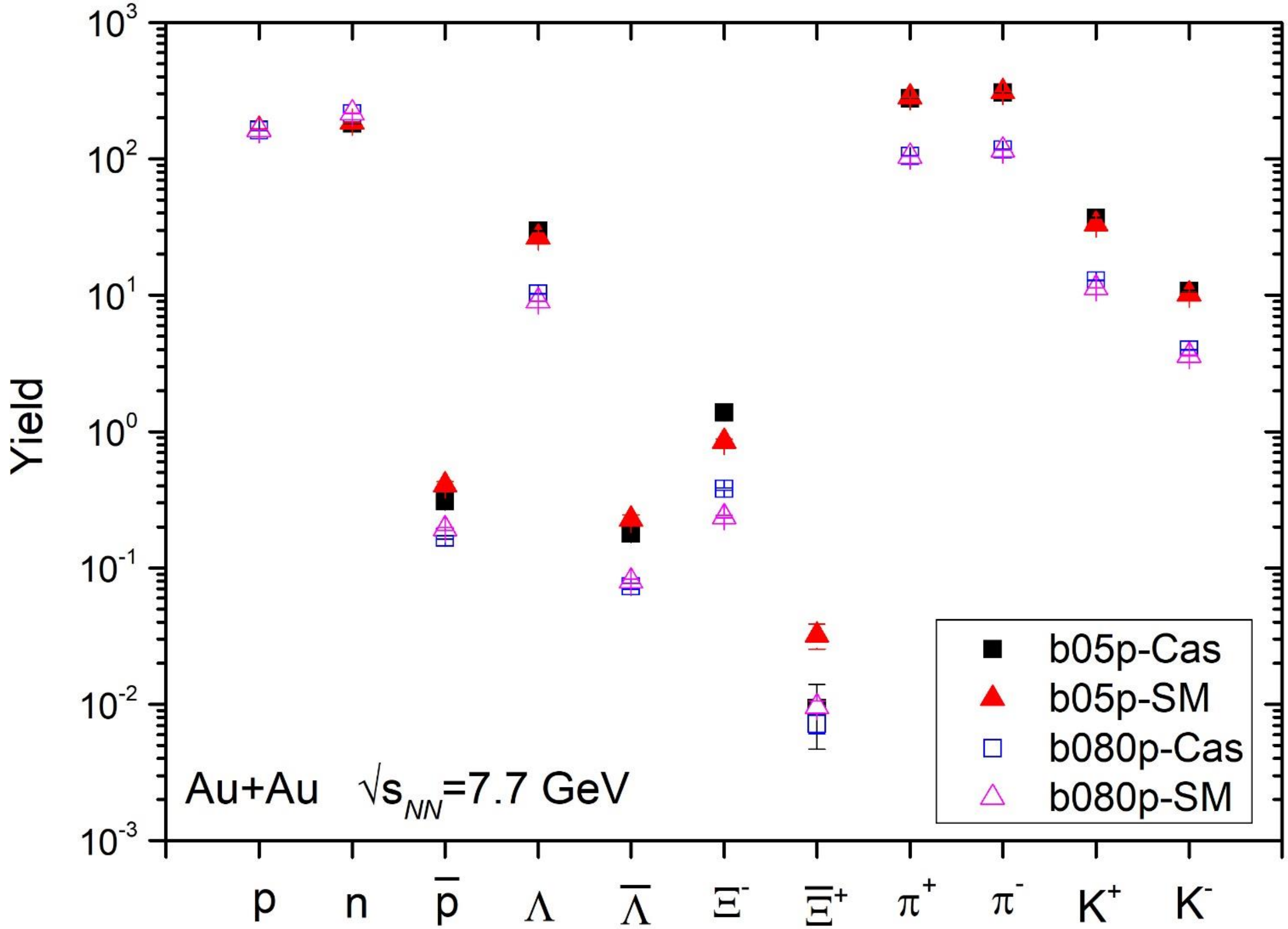
- The strong magnetic field in noncentral collisions→ Chiral magnetic wave → the electric quadrupole moment of the QGP→ $v_2(\pi^+) < v_2(\pi^-)$. Y. Burnier, *et al.*, PRL 107, 052303 (2011).



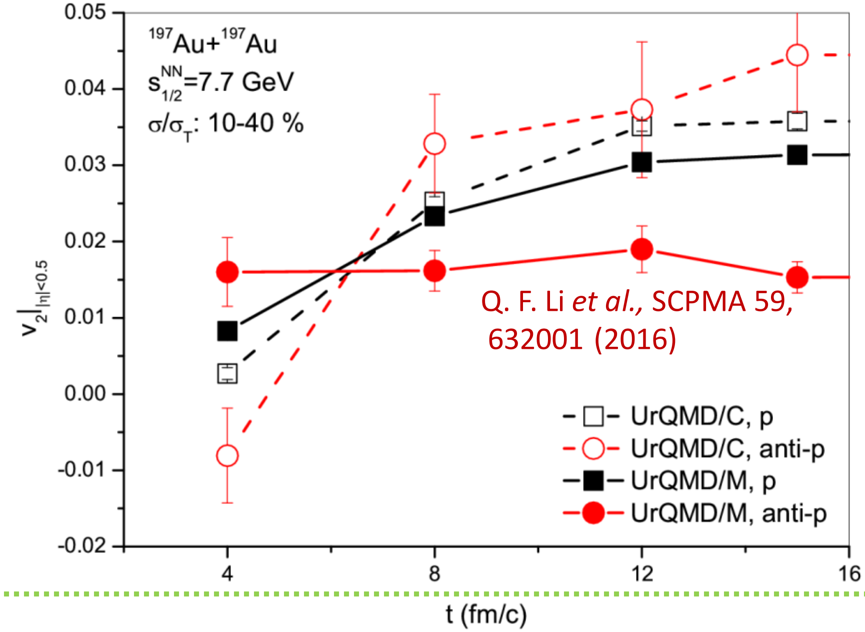




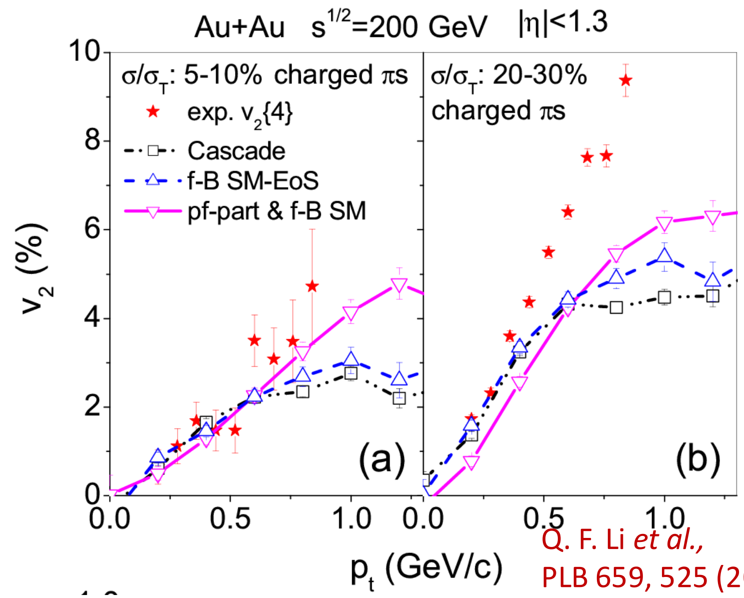
PRL 107, 052303 (2011)


Yield
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
p n p̄ Λ Λ̄ Ξ- Ξ̄+ π+ π- K+ K-
b05p-Cas
b05p-SM
b080p-Cas
b080p-SM
Au+Au √sNN=7.7 GeV

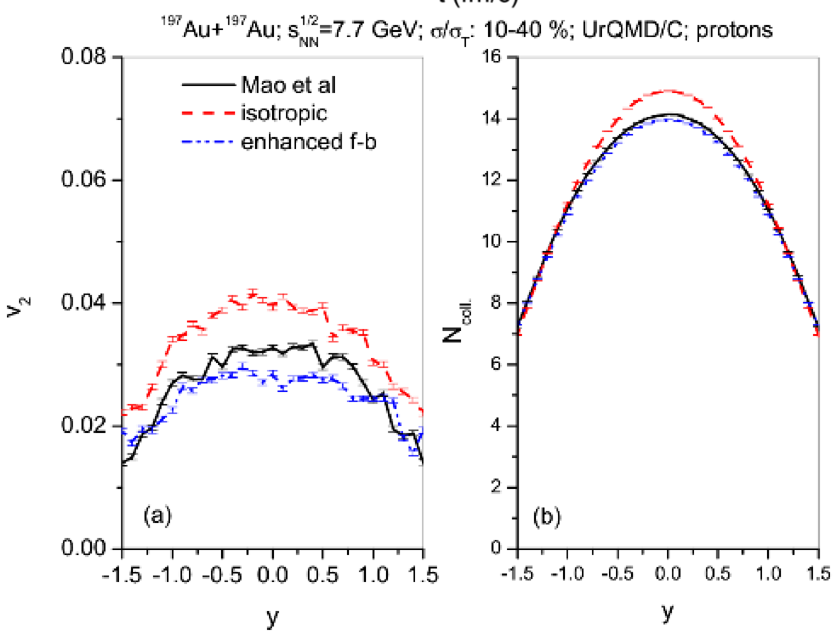
Results from UrQMD: v_2 difference

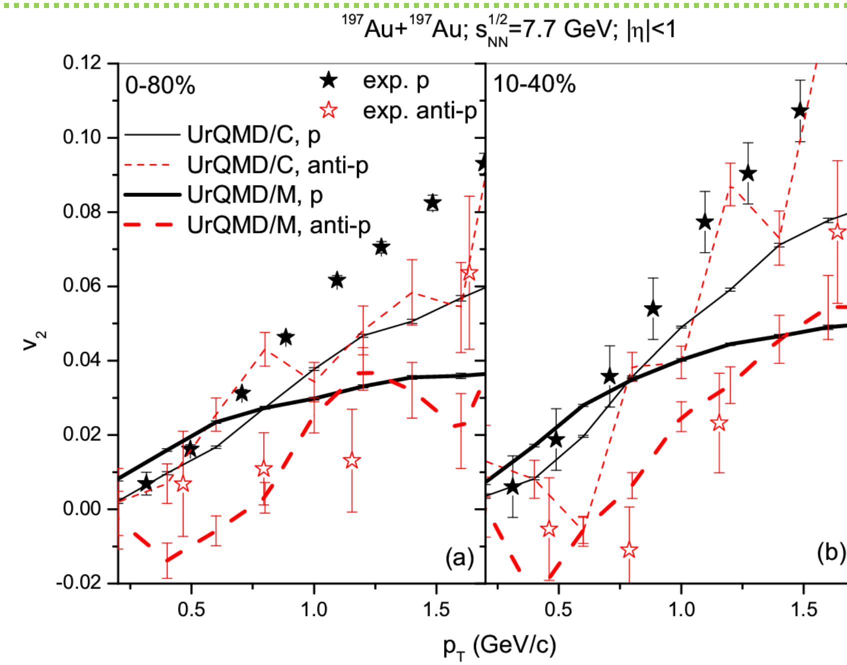


Q. F. Li *et al.*, SCPMA 59, 632001 (2016)



Q. F. Li *et al.*, PLB 659, 525 (2008)





Effects of hadronic mean–field potentials on v_2 splitting