Hadron productions using improved recombination model at $\sqrt{s_{NN}}$ =2.76 TeV, LHC energies

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Recombination model

- In relativistic nuclear collisions, two nuclei are collided and a set of hadrons, leptons, photons, light nuclei, antimatter etc. are produced.

- There are evidences that a locally equilibrated hot fireball of quarks and gluons is also formed as an intermediate step at very high colliding energies.

$$N_1 + N_2 \rightarrow \{q, g, l, \gamma,\} \rightarrow \{h\}, \{l\}, \{\gamma\}, \{N_{light}\}, etc.$$

- Hadrons detected in the experiments can provide important signatures of the possible deconfined quark-gluon plasma state formed at an early stage of heavy-ion collision.

- Effective backtracing from the hadronic state to the quark-gluon plasma state requires sufficient knowledge about the process of formation of hadrons from quarks and gluons.

It is necessary to proerly model how hadrons are formed.

Recombination Model

- Recombination model describes the hadron formation from quarks.

K. P. Das and R. C. Hwa, Phys. Lett. B 68, 459 (1977); Erratum ibid. 73, 504 (1978); R. G. Roberts, R. C. Hwa and S. Matsuda, J. Phys. G 5, 1043 (1979).

- In Recombination model, we consider the valence quarks of hadrons only. The sea quarks and gluons are not directly considered.

- The momenta of the recombining quarks should be almost equal. The probability of quarks recombining with relative momentum larger than the size of the produced hadron is negligible.

- The recombining quarks should move almost parallel to each other to successfully recombine.

- After recombination, the recombining quarks are assumed to move parallel to each other so that the hadron formed out of the recombination process may be thought of as a system of loosely bound co-moving quarks.

Successes of Recombination Model

- In Au+Au collisions at RHIC, baryons and mesons are created in nearly equal proportion (1:1). A proton/pion ratio $p/\pi \sim 1$ was observed in central Au+Au collisions for $1.5 < p_T < 4$ GeV/c.
- This is in contradiction to pQCD calculations, which predicts p/π 0.1 . . . 0.2 . Similar results for Λ / K^0_s suggest that there is a general pattern of baryon enhancement at RHIC energies. This enhancement is so strong that it neutralizes the strong jet quenching observed for mesons at RHIC.
- In the same p_T -region, the elliptic anisotropy (v_2) of baryons is also 50% larger than that for mesons. Therefore, baryon production is particularly enhanced in the direction of the impact vector between the colliding nuclei (in-plane).

Adams J, et al (STAR Collaboration). Phys. Rev. Lett. 92:052302 (2004), Adams J, et al (STAR Collaboration). Phys. Rev. C 72:014904 (2005)

- In the very forward (and low p_T) region of hadron-hadron collisions, the composition of particle species deviates from expectations in a fragmentation picture. With a π^- beam impinging on a fixed nuclear target, they measure a D^-/D^+ asymmetry that goes to 1 in the very forward direction. While fragmentation calculation predicts this asymmetry to be very close to 0. This is called leading particle effect. This result can be explained by recombination of the $\bar{c}$ from a $c\bar{c}$ pair produced in the collision with a d valence quark from the beam π^- beam remnants. The recombination $\bar{c}d \rightarrow D^-$ is enhanced with respect to $c\bar{d} \rightarrow D^+$, because the d is a valence quark in the beam of while the dbar is only a sea quark.

Recombination model

In Recombination model, hadrons are assumed formed from combination of valence quarks.

$$E\frac{dN}{dp^3} = \int \left(\Pi_i \frac{d^3 p_i}{E_i} \right) \mathrm{F}_{\{q_i\}}(\{p_i\}) \mathrm{R}^H_{\{q_i\}}(\{p_i\}; p)$$

Hwa et al. PRC 97, 054908 (2018)

At midrapidity, when the longitudinal momentum is negligible, $\frac{d_i^3 p}{p_i^0} \simeq \frac{dp_{T_i}}{p_{T_i}}$

for meson $$E\frac{dN^M}{dp_T} = \int \frac{dp_{T1}}{p_{T1}} \frac{dp_{T2}}{p_{T2}} \mathrm{F}_{q_1\bar{q}_2}(p_{T1}, p_{T2}) \mathrm{R}^M_{q_1\bar{q}_2}(p_{T1}, p_{T2}; p_T)$$

probability of forming a meson from quarks with momenta p_{T1} and p_{T2}

probabilities of finding quarks with momenta p_{T1} and p_{T2}

for baryons $$E\frac{dN^B}{dp_T} = \int \frac{dp_{T1}}{p_{T1}} \frac{dp_{T2}}{p_{T2}} \frac{dp_{T3}}{p_{T3}} \mathrm{F}_{q_1 q_2 q_3}(p_{T1}, p_{T2}, p_{T3}) \mathrm{R}^B_{q_1 q_2 q_3}(p_{T1}, p_{T2}, p_{T3}; p_T)$$

$$\mathrm{F}_{q_1\bar{q}_2}(p_{T1}, p_{T2}) = \mathrm{TT} + \mathrm{TS} + \mathrm{SS}$$

Thermal Thermal Thermal Shower

$$\mathrm{F}_{q_1 q_2 q_3}(p_{T1}, p_{T2}, p_{T3}) = \mathrm{TTT} + \mathrm{TTS} + \mathrm{TSS} + \mathrm{SSS}$$

Recombination model contd..

$$T_i = C_i \frac{p_T^{x+1}}{\left(\sqrt{p_T^2 + m_i^2}\right)^x} e^{-\sqrt{p_T^2+m_i^2}/T_i}$$

$$R^M_{q_1\bar{q}_2}(p_{T1}, p_{T2}; p_T) = g_M \delta\left(\frac{\sqrt{m_1^2 + p_{T1}^2} + \sqrt{m_2^2 + p_{T2}^2}}{\sqrt{m_M^2 + p_T^2} + B} - 1\right) \delta\left(\frac{p_{T1}}{p_{T2}} - 1\right)$$

Here *i* denotes the quark flavour and C_i depends on the quark flavour.

$$E\frac{dN^M}{dp_T} = C_1 C_2 g_M \int dp_{T1}\, e^{-\frac{\sqrt{m_1^2+p_{T1}^2}+\sqrt{m_2^2+p_{T1}^2}}{T}} \frac{p_{T1}^{2x}}{\left(\sqrt{m_1^2 + p_{T1}^2}\sqrt{m_2^2+p_{T1}^2}\right)^x} \delta\left(\frac{\sqrt{m_1^2 + p_{T1}^2} + \sqrt{m_2^2 + p_{T1}^2}}{\sqrt{m_M^2 + p_T^2} + B} - 1\right) p_{T1}$$

For charged pions, m_1 = 0.00216 GeV, m_2 = 0.00467 GeV, m_π = 0.13957 GeV,
B = $m_\pi - m_1 - m_2$.

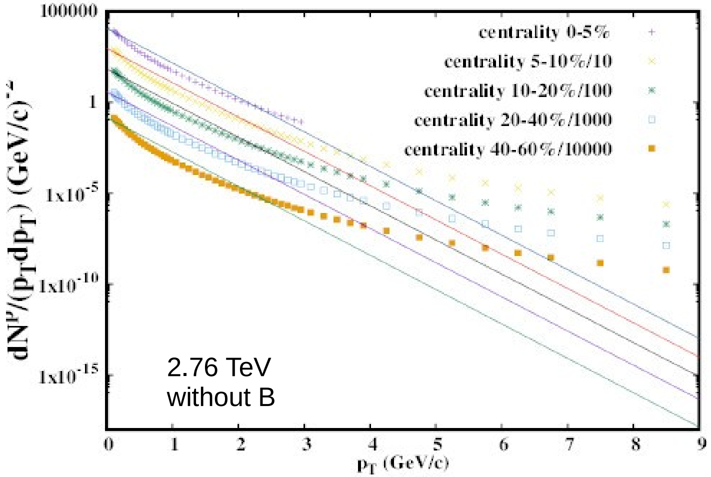
$$\sqrt{m_1^2 + p_{T1}^2} + \sqrt{m_2^2 + p_{T1}^2} = z$$

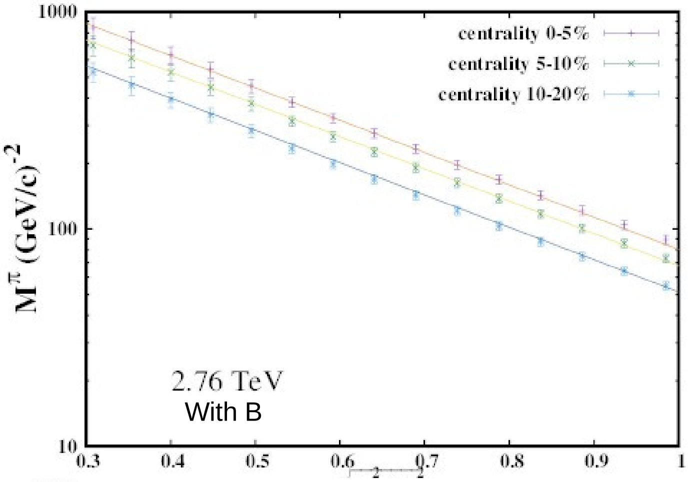
$$E\frac{dN^M}{dp_T} = \frac{C_1 C_2}{4^x} g_M \int dz\, e^{-z/T}\left(\sqrt{m_M^2+p_T^2}+B\right)\delta\left(z - \sqrt{m_M^2+p_T^2} - B\right)\frac{\left(z^4 + (m_1^2 - m_2^2)^2 - 2z^2(m_1^2+m_2^2)\right)^x}{z^3\left(z^4 - (m_1^2 - m_2^2)^2\right)^{x-1}}$$

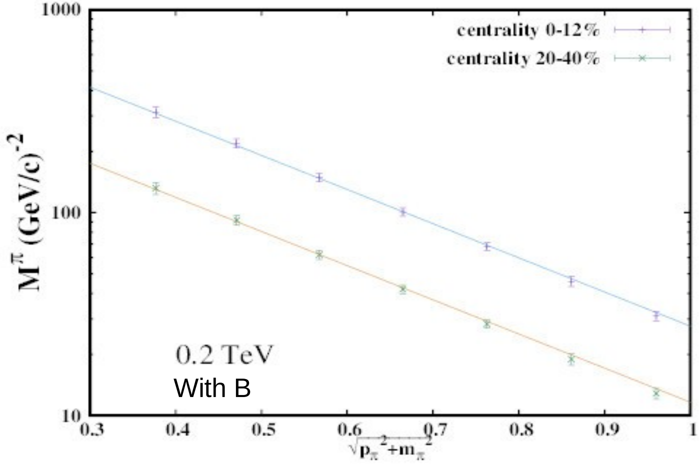
$$M^M = \frac{E\frac{dN^M}{dp_T}}{\frac{\left(z^4 + (m_1^2 - m_2^2)^2 - 2z^2(m_1^2+m_2^2)\right)^x}{z^3\left(z^4 - (m_1^2 - m_2^2)^2\right)^{x-1}}\left(\sqrt{m_M^2+p_T^2}+B\right)}$$

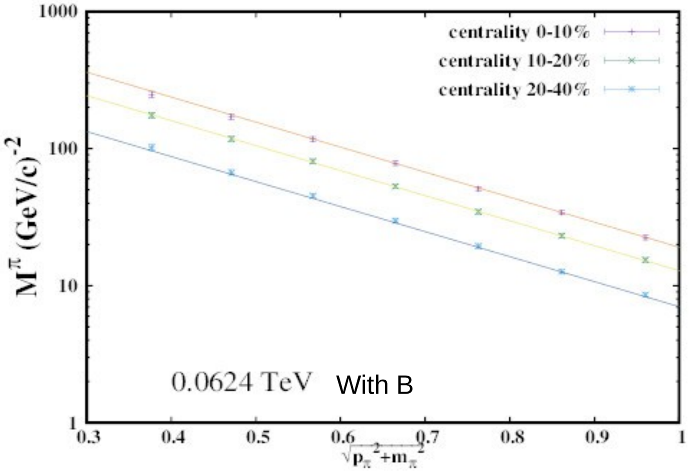
vs *z* plot should be exponential

Pion transverse momentum spectra

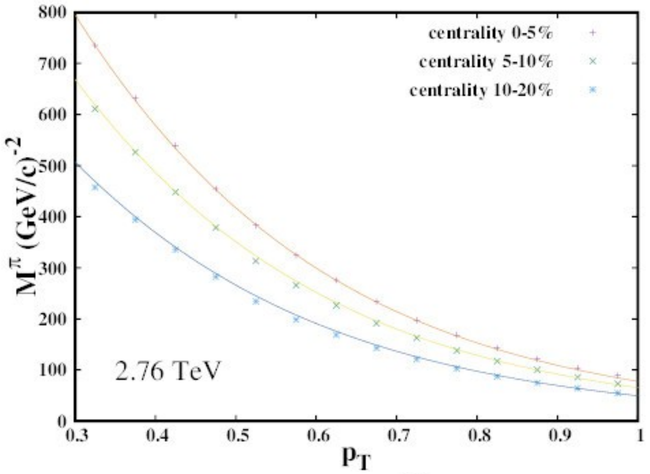


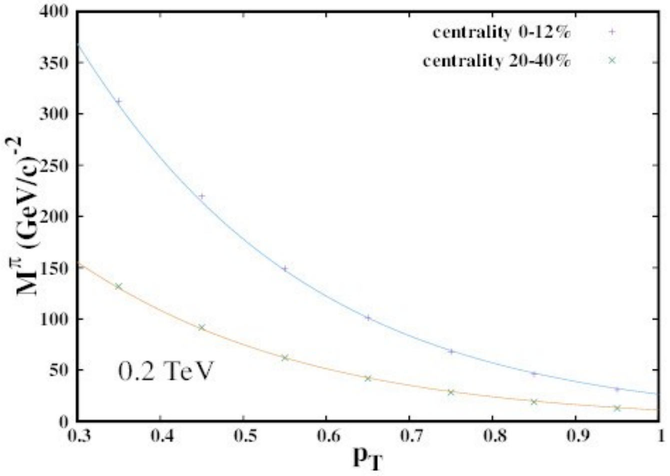


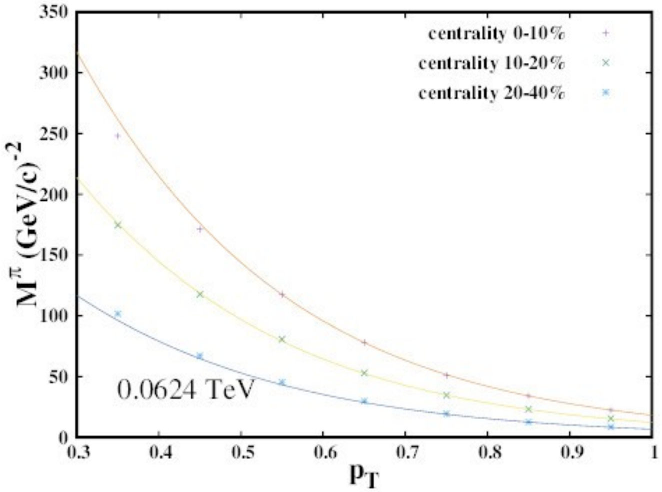




Pion transverse momentum spectra







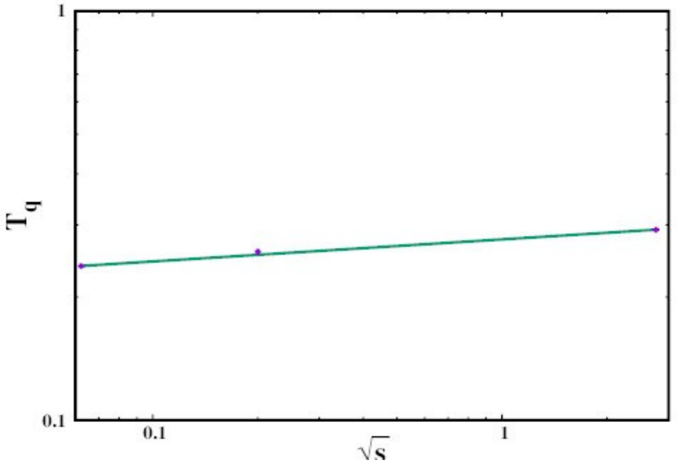
An emperical formula for hadron yields

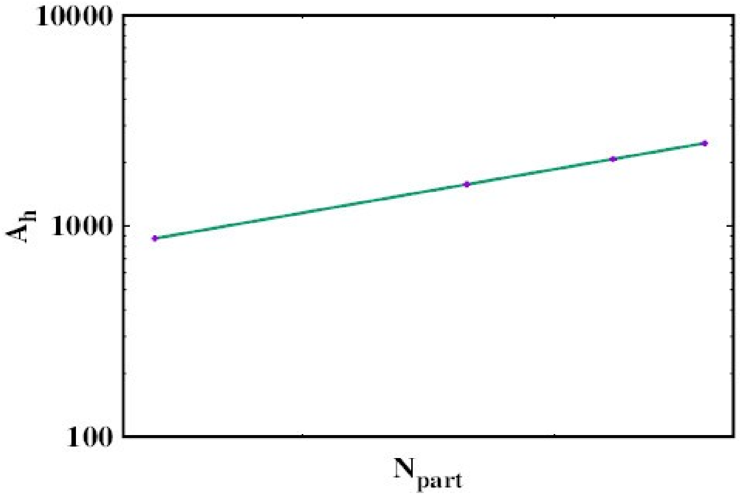
$$E\frac{dN^M}{dp_T}=A_h^0\sqrt{s}^{\,-b_h}N_{part}^{a_h}e^{-(\sqrt{p_T^2+m^2}+B)/T}$$

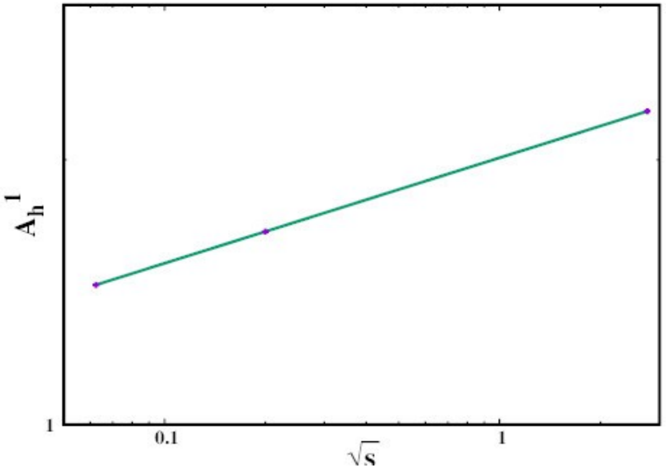
$$A_h(\sqrt{s},N_{part})=A_h^1(\sqrt{s})N_{part}^{a_h} \qquad A_h^1(\sqrt{s})=A_h^0\sqrt{s}^{\,-b_h}$$

$\sqrt{s}(TeV)$	*0.0624*	*0.2*	*2.76*
T	0.238	0.258	0.292

A_π = 1.176
B_π =0.12
A^0_π =2.01







Summary and Conclusions

Recombination model with some modifications has been used to describe the process of formation of pions by recombination of quarks.

- We have considered the quark mass explicitly in the p_T -distribution of the quarks produced after collision, which was ignored in previous studies.
- The energy distribution of the initial quarks considered here has the familiar statistical distribution type form with some additional factors. Such a p_T distribution of quarks, through the recombination process, is shown to lead to a similar exponential distribution of the produced pions.
- It has been shown that, the $\sqrt{p_T^2+m^2}$ spectra shows almost exponentially decaying behaviour when a confinement energy equal to the difference of the pion mass and the valence quark masses is taken into account.
- We present a phenomenological expression for the low-p_T hadron spectra showing some universal behaviour that was missing in the earlier works. The origin of this universality can be attributed to the physical constraints included in the model.
- We have proposed a phenomenological expression for the low-p_T spectra of mesons at mid-rapidity in relativistic heavy ion collisions.

References

[1] R. C. Hwa and C. B. Yang, Phys. Rev. C 70, 024905 (2004).

[2] R. C. Hwa and L. Zhu, Phys. Rev. C 84, 064914 (2011).

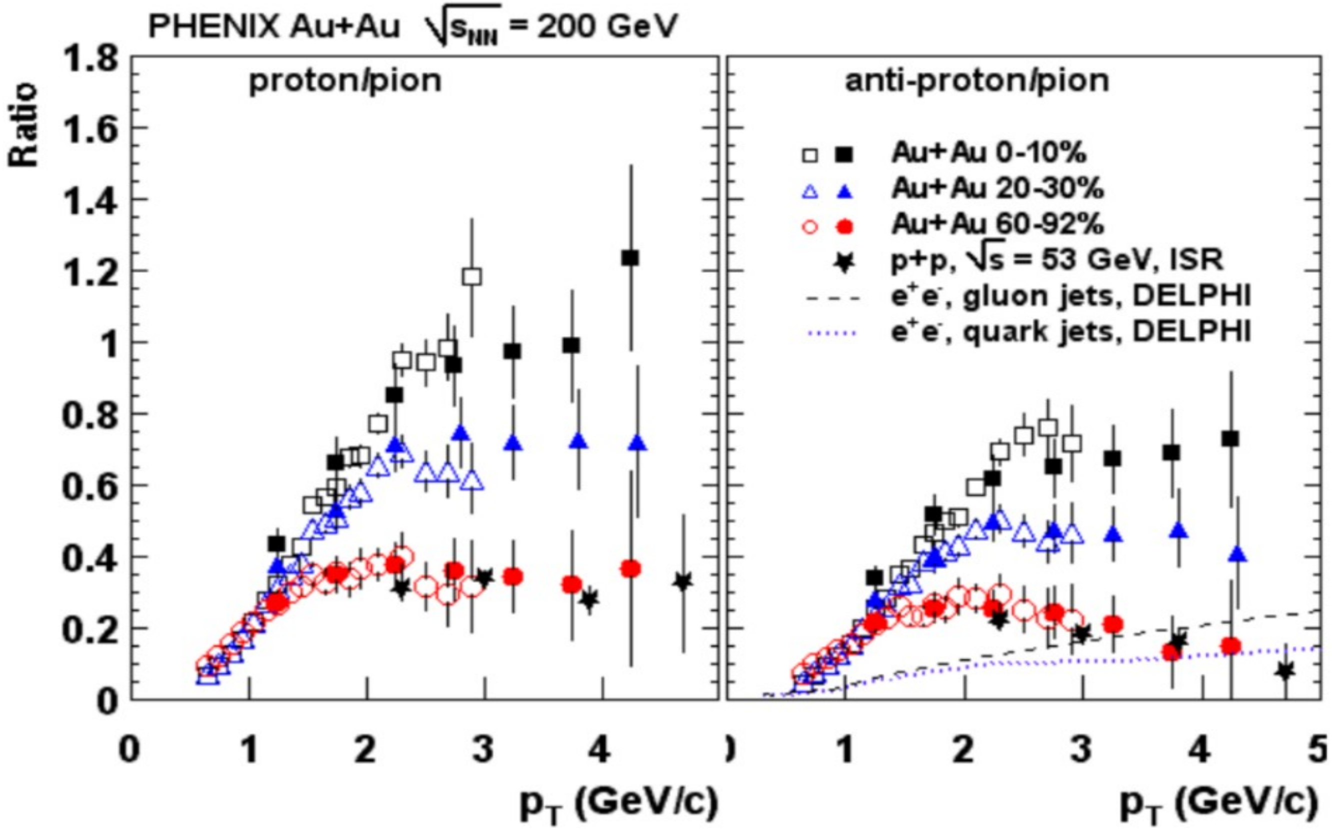
[3] L. Zhu and R. C. Hwa, Phys. Rev. C 88, 044919 (2013).

[4] R. C. Hwa and C. B. Yang, Phys. Rev. C 67, 034902 (2003).

[5] R. C. Hwa and L. Zhu, Phys. Rev. C 97, 054908 (2018).

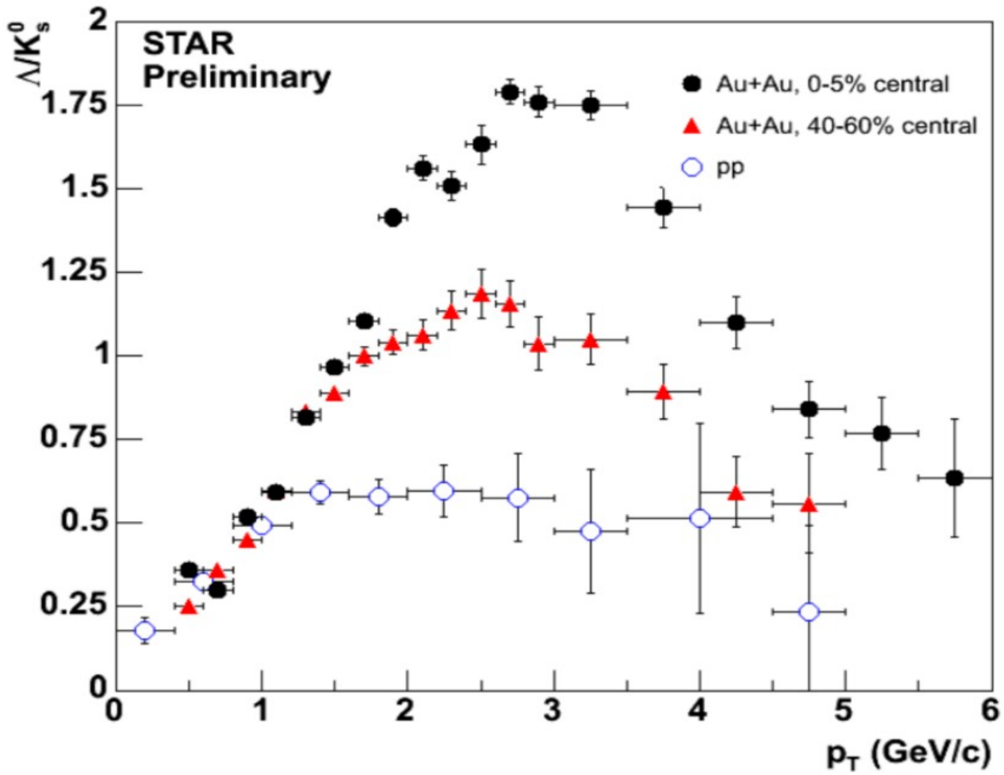
[6] L. Zhu, H. Zheng, and R. C. Hwa, Phys. Rev. C 104, 014902 (2021).

Baryon Puzzle: More baryons at intermediate pT , 1.5 < pT < 5



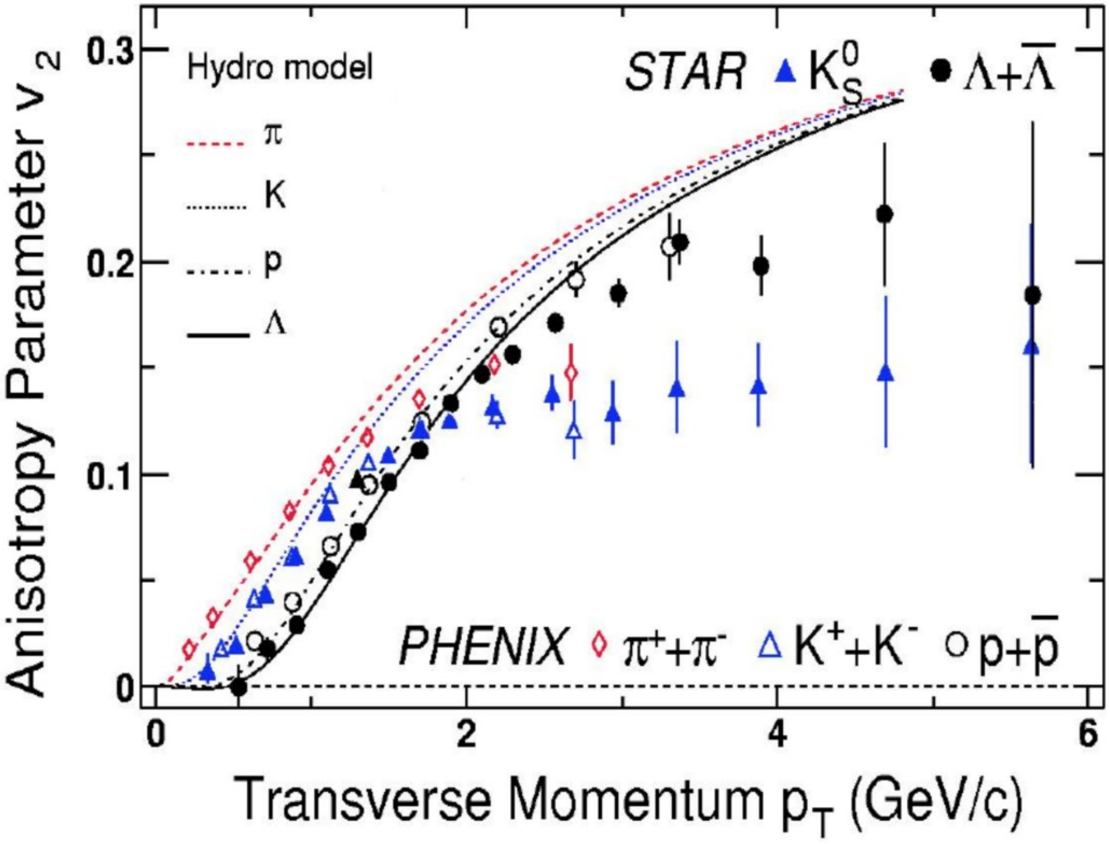
p/π ratio and p̄/π ratio from RHIC. proton and pions are equally produced (1:1) at hight pT in central collision.

Baryon Puzzle: Strange baryon to strange meson ratio at intermediate pT like p/π



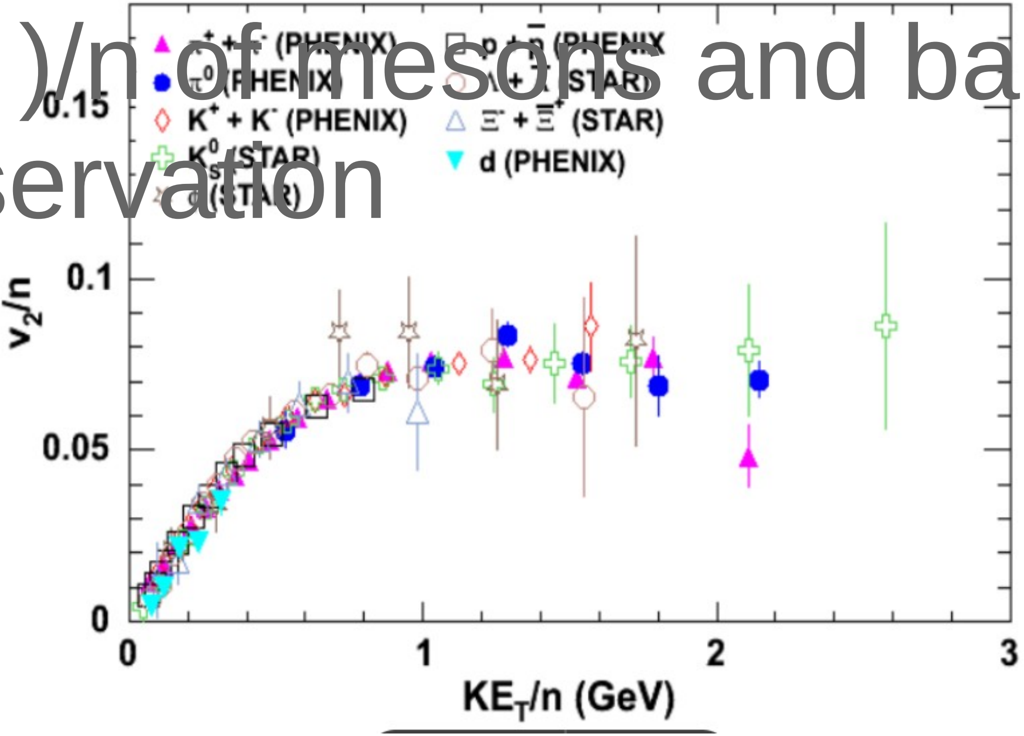
Λ/Ks0 ratio from RHIC. 1.5 < pT < 5

Baryon Puzzle: v2(pT) of mesons and baryons from RHIC observation



At low pT (PT <2GeV) hydro works well

Success of recombination: Scaled v2 :v2(pT)/n of mesons and baryons from RHIC observation



Elliptic flow parameter, v2 scaled with number of constituent quarks of mesons and baryons. This says about the flow of partons also. Data are taken by STAR and PHENIX from Au+Au collisions.

J. Adams et al. (STAR Collaboration), Phys. Rev. Lett. 92, 052302 (2004); S. S. Adler et al. (PHENIX Collaboration), Phys. Rev. Lett. 91, 182301 (2003).

Other experiments hinting towards recombination model

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