Hadronic rescattering in elliptic flow & Heavy quarks at RHIC

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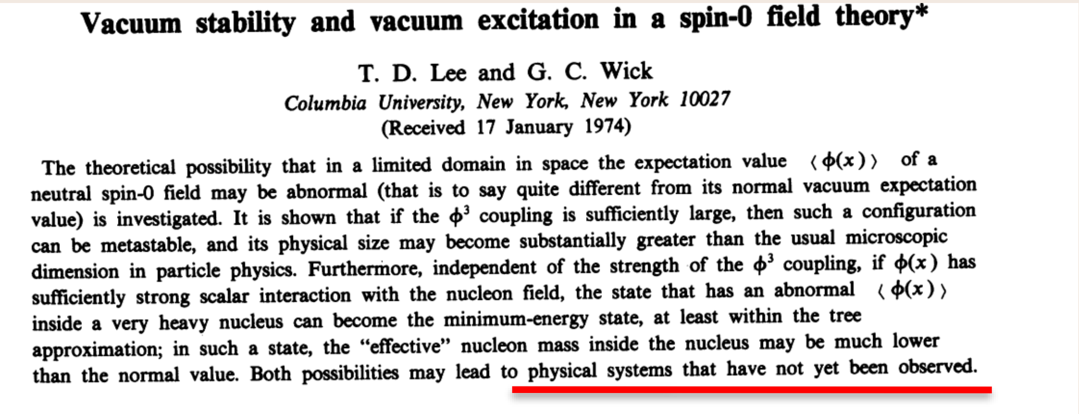
1. Introduction

- Relativistic heavy ion collision
  - QGP: a new state of matter



Vacuum stability and vacuum excitation in a spin-0 field theory*

T. D. Lee and G. C. Wick

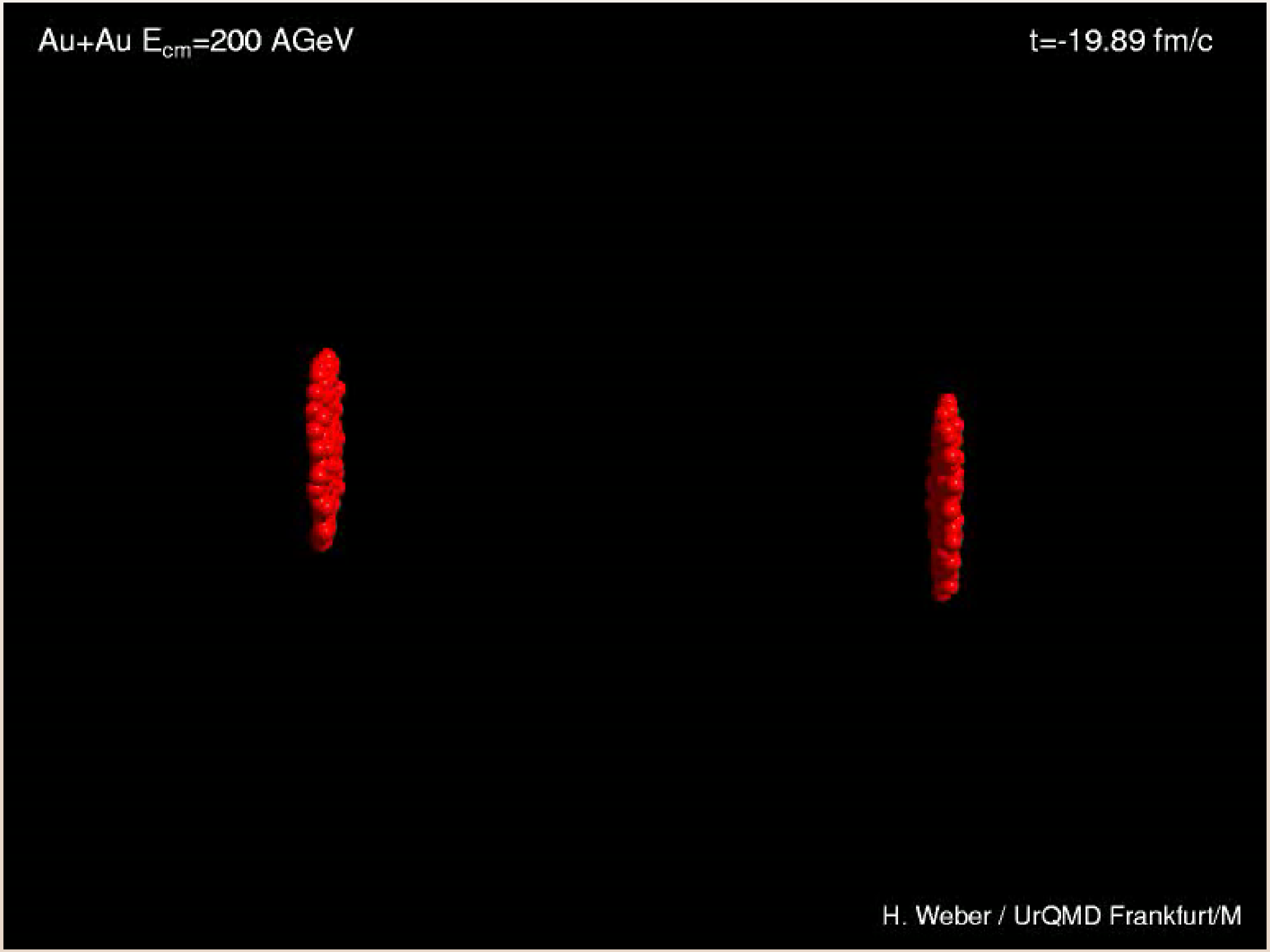
Columbia University, New York, New York 10027

(Received 17 January 1974)

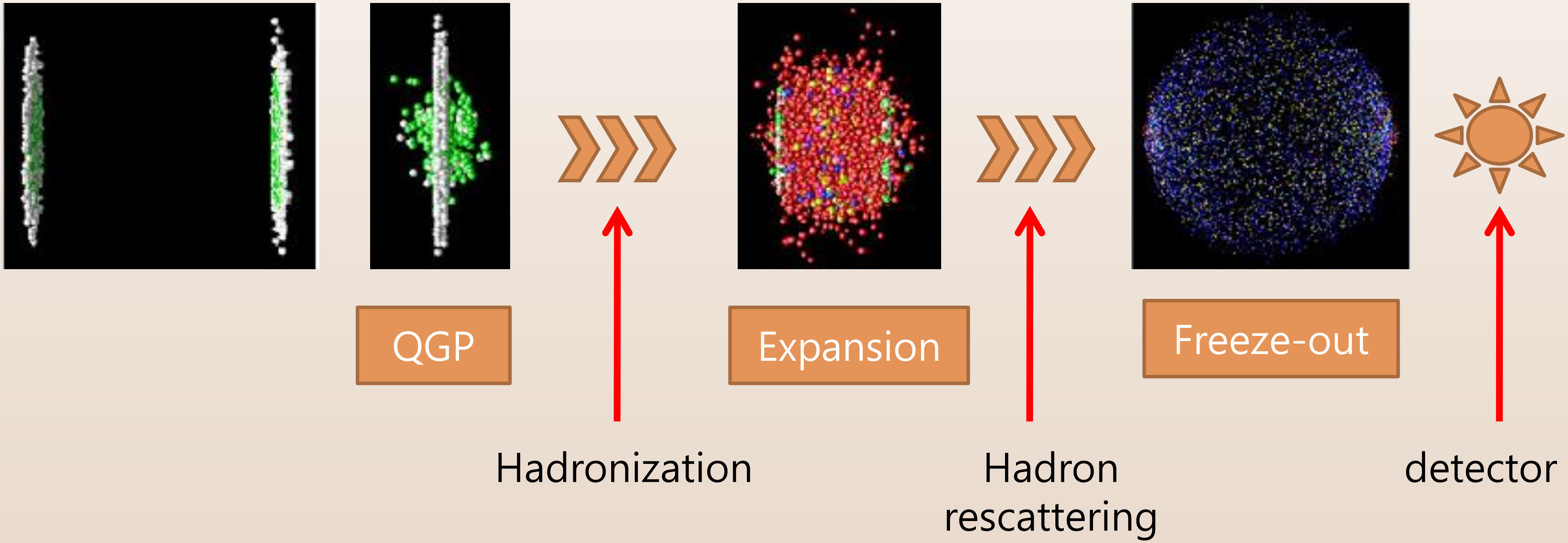
The theoretical possibility that in a limited domain in space the expectation value $\langle \phi(x) \rangle$ of a neutral spin-0 field may be abnormal (that is to say quite different from its normal vacuum expectation value) is investigated. It is shown that if the ϕ^3 coupling is sufficiently large, then such a configuration can be metastable, and its physical size may become substantially greater than the usual microscopic dimension in particle physics. Furthermore, independent of the strength of the ϕ^3 coupling, if $\phi(x)$ has sufficiently strong scalar interaction with the nucleon field, the state that has an abnormal $\langle \phi(x) \rangle$ inside a very heavy nucleus can become the minimum-energy state, at least within the tree approximation; in such a state, the "effective" nucleon mass inside the nucleus may be much lower than the normal value. Both possibilities may lead to physical systems that have not yet been observed.

  - sQGP (strongly interacting QGP)

Relativistic Heavy Ion Collisions



RHIC



QGP

Expansion

Freeze-out

Hadronization

Hadron rescattering

detector

- Test of hadron models
  - Large multiplicity
  - Find the physical quantities that are sensitive to hadron models

- QGP signals
  - Hadron rescattering effects

sQGP

- Observed state in relativistic heavy ion collisions @ RHIC
  - Perfect fluid behavior (hydrodynamics)
  - Strong collective behavior (large elliptic flow)
    - → Strong coupling nature of Quark-Gluon Plasma
- New lattice results
  - $c\bar{c}$ bound state could survive at T > Tc
  - Even at T > Tc, the interaction is still strong
    - → Possible existence of quasi bound states of quarks and gluons such as qq, gq, gg

Shuryak and Zahed, PRC 70

  - Diquarks in hadron physics
    - Existence of a diquark in baryons?

$$\Lambda_c / \Sigma_c \sim 7 \text{ in } e^+e^- \text{ collisions}$$

Lichtenberg, Anselmino, Wilczek & others

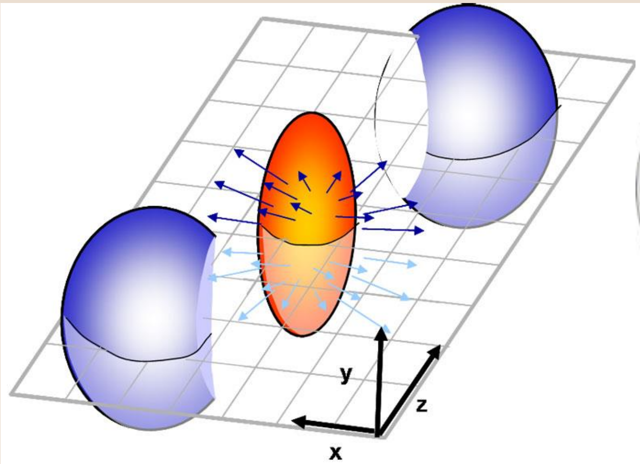
HADRON RESCATTERING IN ELLIPTIC FLOW

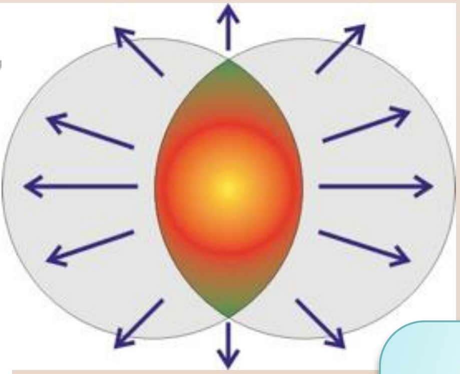
Elliptic Flow

- Elliptic flow v_2 : a measure of the strength of the second Fourier coefficient in the azimuthal angle distribution of particle transverse momentum relative to the reaction plane
  - ⇨ azimuthal anisotropy of the momentum distribution of particles

$$f(\varphi, p_T) \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_T)\cos n\varphi$$

Elliptic flow $v_2 = \left\langle \dfrac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$





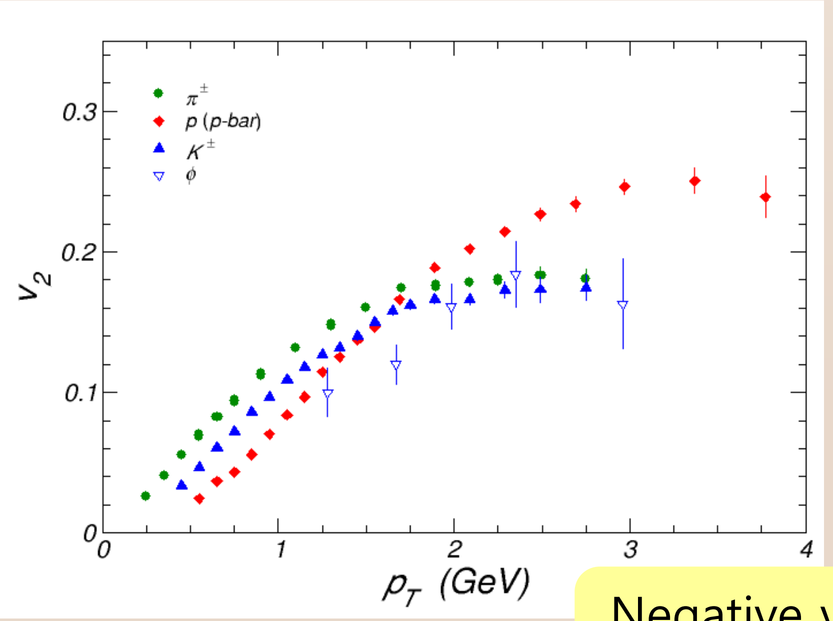
Elliptic Flow v_2: momentum anisotropy
⇒ RHIC data show large momentum anisotropy

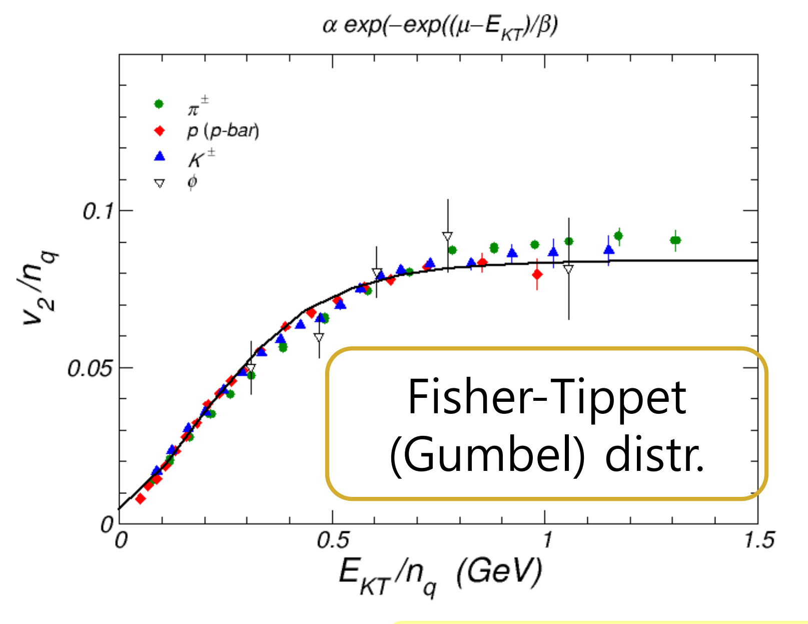
Elliptic flow

- information on the properties of the hot dense matter formed during the initial stage of RHIC
  - Mass ordering: v_2 decreases with increasing hadron mass
  - Constituent quark number scaling

Quark number scaling (quark recombination)

Mass ordering (hydrodynamics)





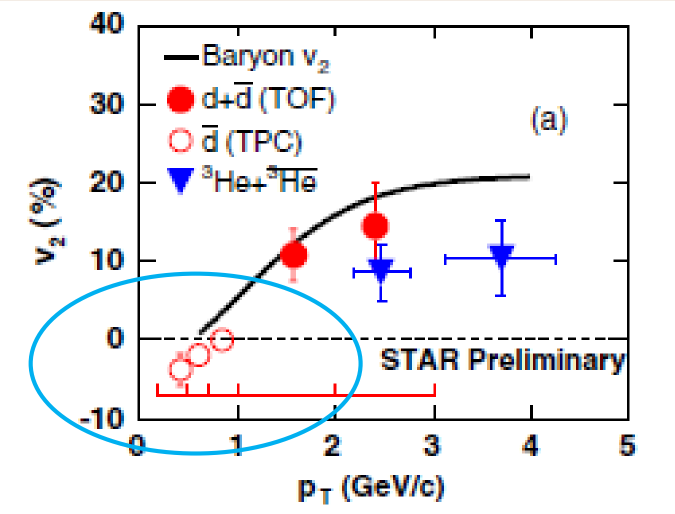
Fisher-Tippet (Gumbel) distr.

Negative v_2 for heavy mass?

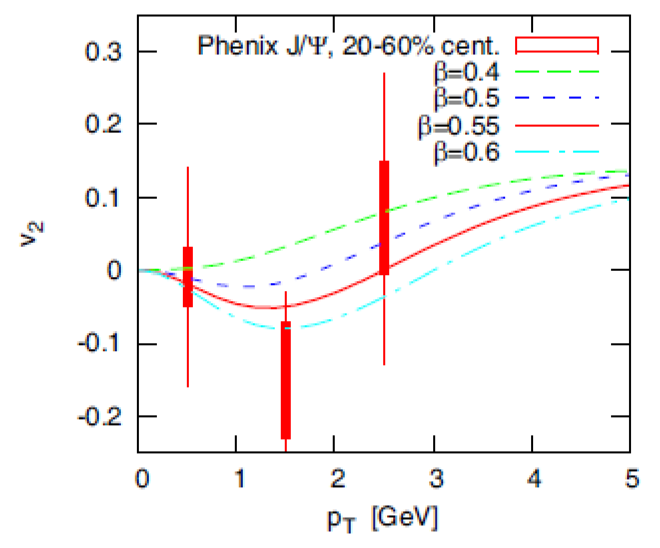
E_{KT} or p_T scaling

Elliptic flow

- Negative elliptic flow at small pT for heavy particles?
  - deuteron (~1.9 GeV)



  - J/ψ (~3 GeV)



Elliptic flow (scaling)

- Coalescence model

  $F(\varphi)$: distribution of the composite particle

  $f(\varphi)$: distributions of the constituents

  $$F(\varphi) \propto f(\varphi)^2 \propto 1 + 2V_2 \cos 2\varphi$$

  $$V_2 = 2v_2 \text{ for 2-body particles}$$

  $$f(\varphi, p_T) \propto 1 + 2\sum_{n=1}^{\infty} v_n(p_T) \cos n\varphi$$

- For J/ψ
  - charm quark + charm anti-quark
  - v_2 of the charm quark: negative at small p_T?
- For deuteron
  - proton + neutron
  - v_2 of the nucleon: positive (by experiments)
- Intriguing questions on the mechanism of particle production and their interactions

2. Deuteron elliptic flow

- Coalescence model (the simplest version)
  - The deuteron yield in momentum space is proportional to the product of the proton and neutron densities at half the momentum of produced deuteron

$$\frac{dN_d}{d\vec{p}_d} \propto f_p(p_d/2)\, f_n(p_d/2)$$

  - The deuteron elliptic flow would satisfy exactly the nucleon number scaling and thus the quark number scaling as well.

$$\begin{aligned}
& f_d(p_d)\left(1+2v_{2,d}(p_d)\cos 2\phi\right) \\
& \approx f_p(p_d/2)\left(1+2v_{2,p}(p_d/2)\cos 2\phi\right) \times f_n(p_d/2)\left(1+2v_{2,n}(p_d/2)\cos 2\phi\right) \\
& \approx f_p(p_d/2) f_n(p_d/2) \times \left\{1+2\left[v_{2,p}(p_d/2)+v_{2,n}(p_d/2)\right]\cos 2\phi\right\}
\end{aligned}$$

$$\therefore \quad v_{2,d}(p_d) = v_{2,p}(p_d/2) + v_{2,n}(p_d/2) = 2v_{2,N}(p_d/2)$$

Elliptic flow: blast-wave model

- Blast-wave model

U. Heinz, K. S. Lee, and E. Schnedermann, Hadronization of a quark-gluon plasma, in *Advanced Series on Directions in High Energy Physics, Vol. 6, Quark-Gluon Plasma*, edited by R. C. Hwa, pp. 471–517, World Scientific, Singapore, 1990.

$$E\frac{d^3N}{dp^3} = \frac{g}{(2\pi)^3}\int_{\Sigma_f} f(x,p)\,p_\mu\, d\Sigma^\mu$$

g : spin-isospin degeneracy

Σ_f : freeze-out surface with normal vector $d\Sigma_\mu$

$f(x,p)$: local thermal distribution function

$$f(x,p) = \frac{1}{\exp\{(E-\mu)/T\}\pm 1} \Rightarrow$$ Lorentz boost with the flow velocity $\beta(x)$

- In cylindrical coordinates
  - Transverse flow velocity

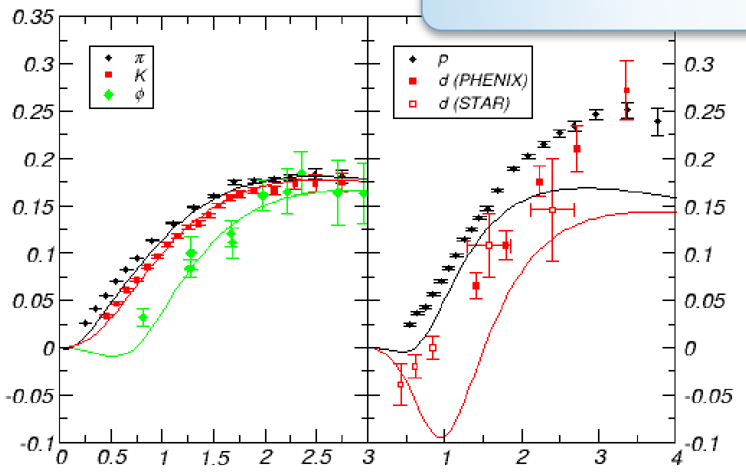
$$\gamma_T = 1/\sqrt{1-\beta_T^2}$$

- Test of a simple blast-wave model
  - Transverse flow velocity

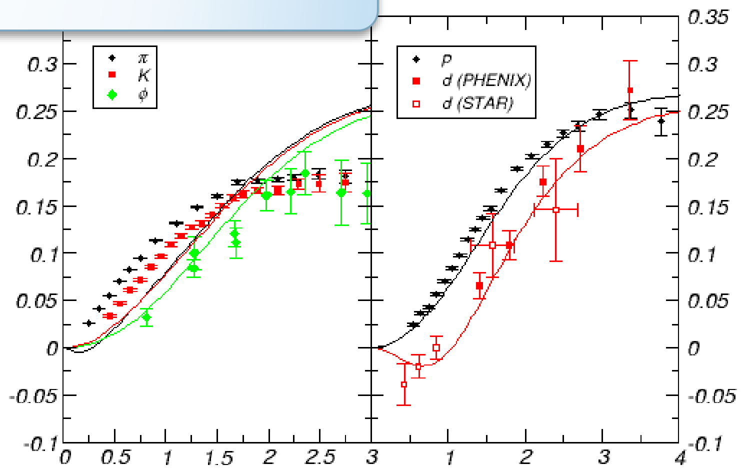
$$b_T = b_0\left(1 + e\cos 2f\right), \qquad e = a\exp(-\, p_T / b) \text{ with free parameters } a, b$$

Fitted results

Requires different parameter sets!



Fitted for mesons



Fitted for baryons

Modified coalescence model

- Take into account the momentum spread of the deuteron wave function

$$\frac{d^3N_d}{dp_d^3} = \frac{3}{4}\frac{V}{(2\pi)^3}\int d^3p_1 d^3p_2 f_p(p_1) f_n(p_2) \left|\Psi_d((p_1' - p_2')/2)\right|^2 \delta^{(3)}(p_1 + p_2 - p_d)$$

$$\Psi_d(k) = \frac{\sqrt{(a_d + b_d)^3 a_d b_d}}{\pi(a_d^2 + k^2)(b_d^2 + k^2)}, \qquad a_d = 0.23\ \mathrm{fm}^{-1}, \quad b_d = 1.61\ \mathrm{fm}^{-1}$$

Hulthen WF

- Gives small deviation from the exact quark number scaling
- Does not satisfy energy conservation.
    - Effects of energy conservation?

Dynamical model

- Use dynamical processes for deuteron production
  - Dominant deuteron production reaction: two-body scattering $NN \rightarrow d\mathrm{p}$
  - Only the rate can be calculated.

$$\frac{d^3R_d}{dp_d^3} = \frac{1}{(2\mathrm{p})^3 2E_d} \int \prod_{i=1}^{2} \frac{d^3p_i}{(2\mathrm{p})^3 2E_i} f_N(p_i) \frac{d^3p_\mathrm{p}}{(2\mathrm{p})^3 2E_\mathrm{p}} [1+f_\mathrm{p}(p_\mathrm{p})] \left|M(NN \rightarrow d\mathrm{p})\right|^2$$

$$\times (2\mathrm{p})^4 \mathrm{d}^{(4)}(p_1 + p_2 - p_\mathrm{p} - p_d)$$

No a priori restriction such a s $p_{T,d} = 2p_{T,N}$

Energy is conserved as well as momentum

  - 3-body reactions can be added such as $NNN \rightarrow dN$ and $NN\mathrm{p} \rightarrow d\mathrm{p}$

Dynamical model

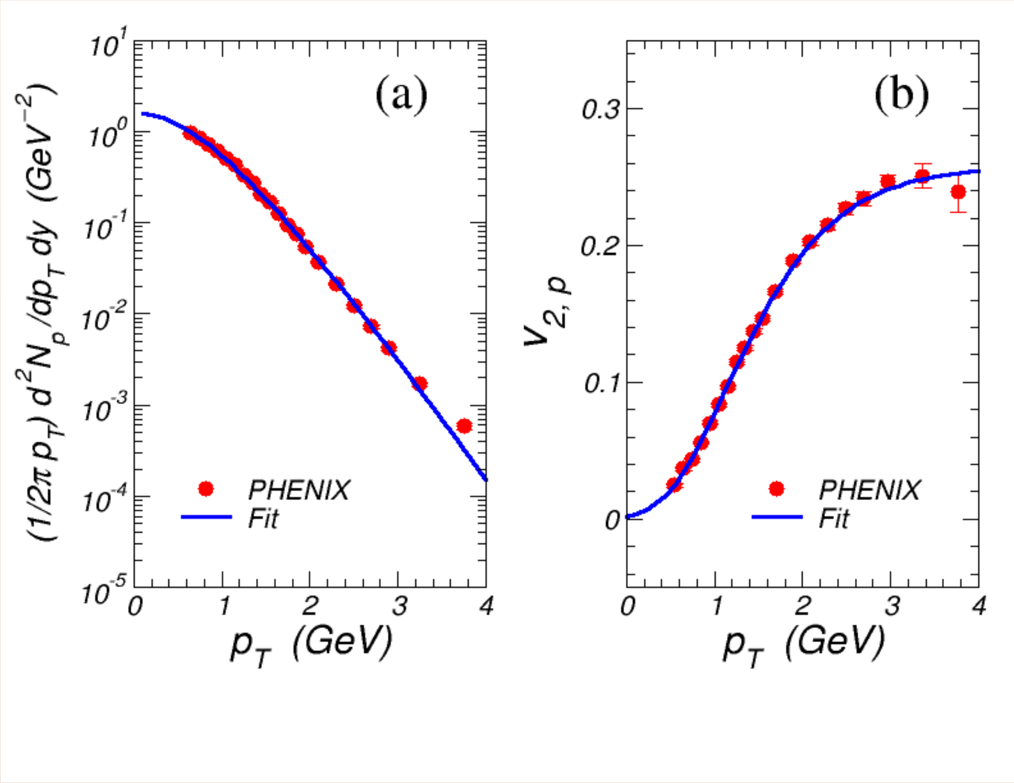
- Inputs (Nucleon spectrum)

$$f_N(p_T) = g_N \exp(-m_T/T_{\mathrm{eff}})\left[1 + 2v_{2,N}\cos 2f\right]$$

with $T_{\mathrm{eff}} = 295$ MeV, $g_N = 0.021$

$$v_{2,N}(p_T) = a_N \exp\left\{-\exp\left[\left(l_N - p_T\right)/b_N\right]\right\}$$

with $a_N = 0.258$, $b_N = 0.683$ GeV, $l_N = 1.128$ GeV



Dynamical model

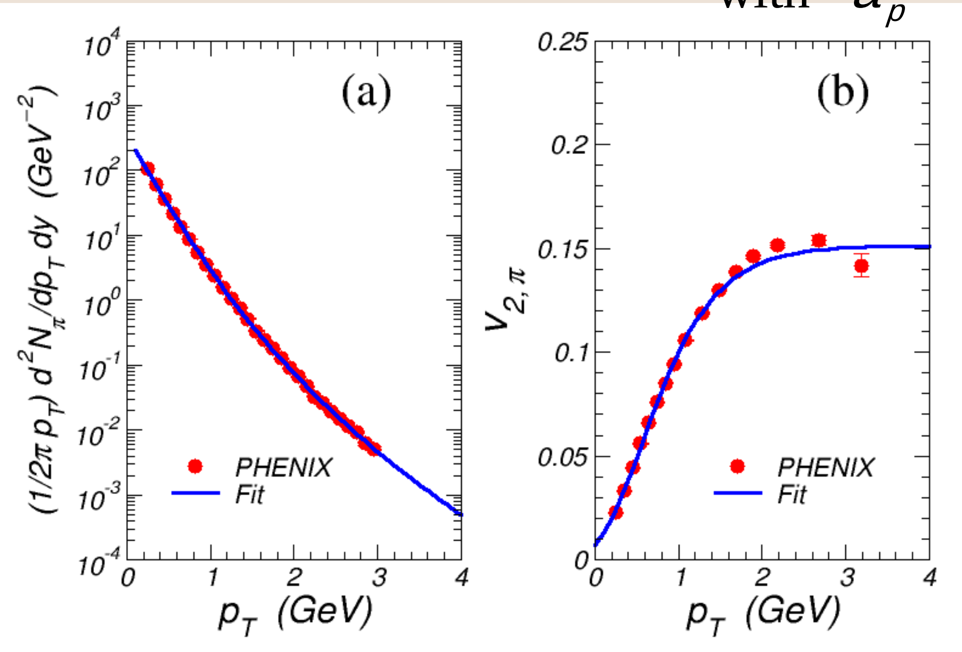
- Inputs (pion)

$$f_\pi(p_T) = \gamma_\pi \left(1 + \frac{p_T}{a}\right)^b \left[1 + 2v_{2,\pi}\cos 2\phi\right]$$

with $a = 1.29$ GeV, $b = -12.0$, $\gamma_\pi = 2.0$

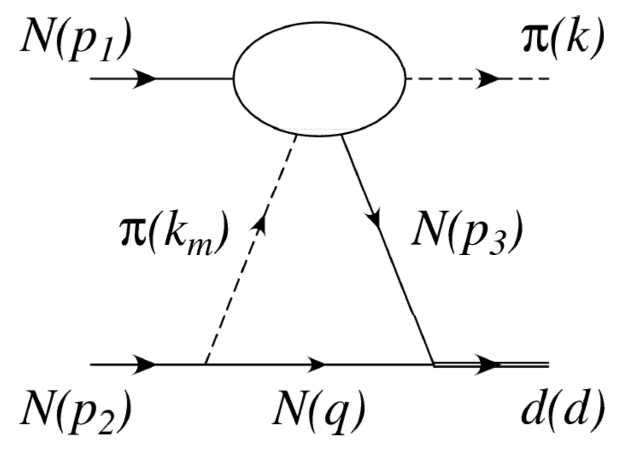
$$v_{2,\pi}(p_T) = \alpha_\pi \exp\left\{-\exp\left[\left(\lambda_\pi - p_T\right)/\beta_\pi\right]\right\}$$

with $\alpha_\pi = 0.184$, $\beta_\pi = 0.461$ GeV, $\lambda_\pi = 0.547$ GeV



Dynamical model

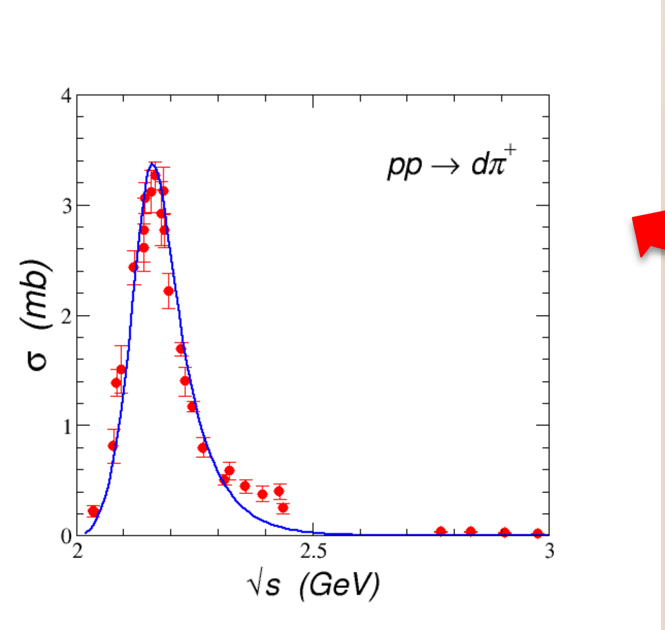
- Input for the production amplitude of $NN \rightarrow d\pi$



$$T = -\frac{i}{(2\pi)^4}\int d^4q\,\bar{v}(p_2)\Gamma_{\pi NN}\frac{1}{(p_2-q)^2-m_\pi^2}\frac{-\not{q}+M_N}{q^2-M_N^2}\Gamma_{dNN}$$

$$\times\frac{\not{d}-\not{q}+M_N}{(d-q)^2-M_N^2}\left(A+B\not{k}\right)u(p_1),$$

$$M(\pi N \rightarrow \pi N) = \bar{u}(p')\left(A+B\not{k}\right)u(p)$$

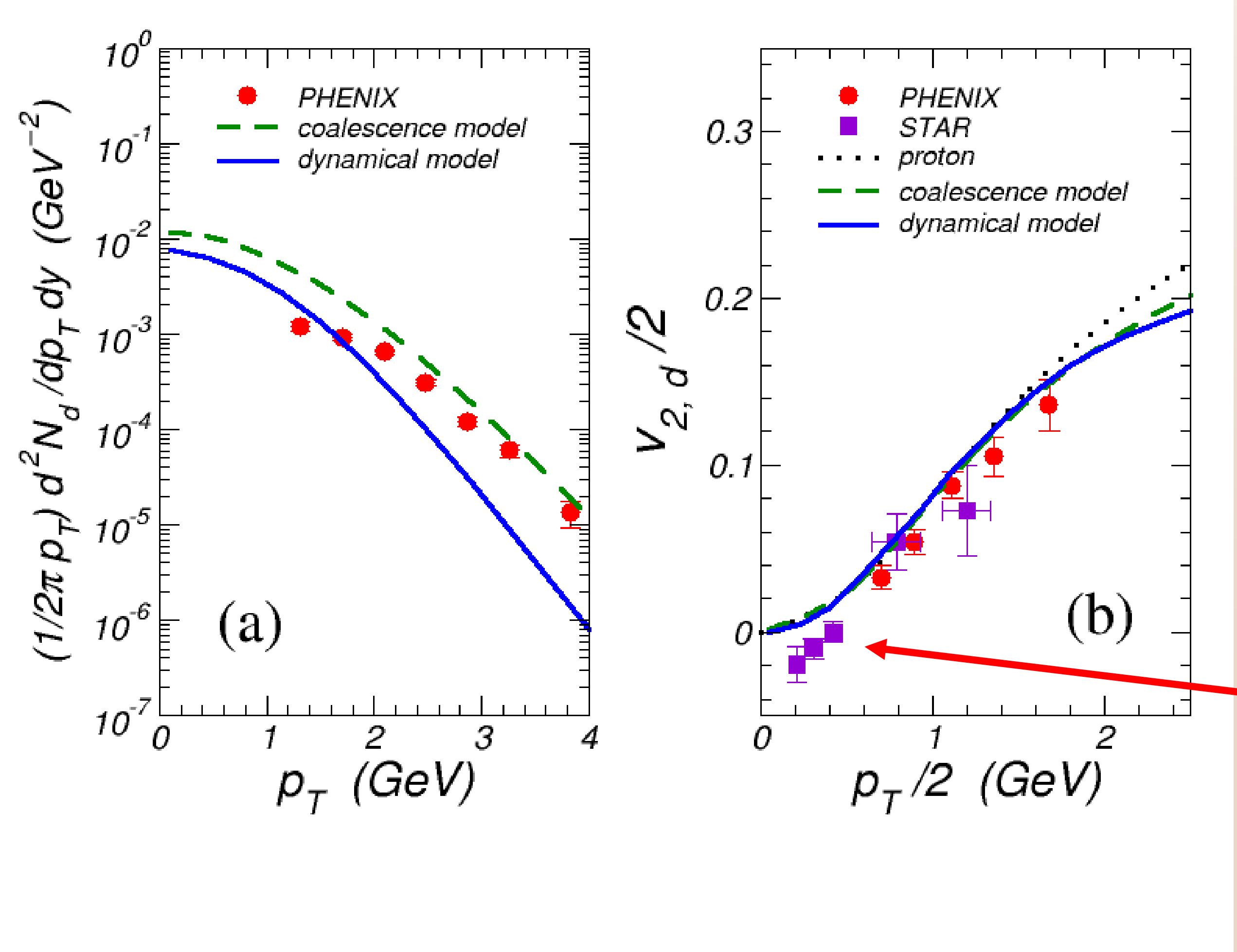


Adjusted to fit the data

Dynamical model

- Results

Oh and Ko, **PRC76**



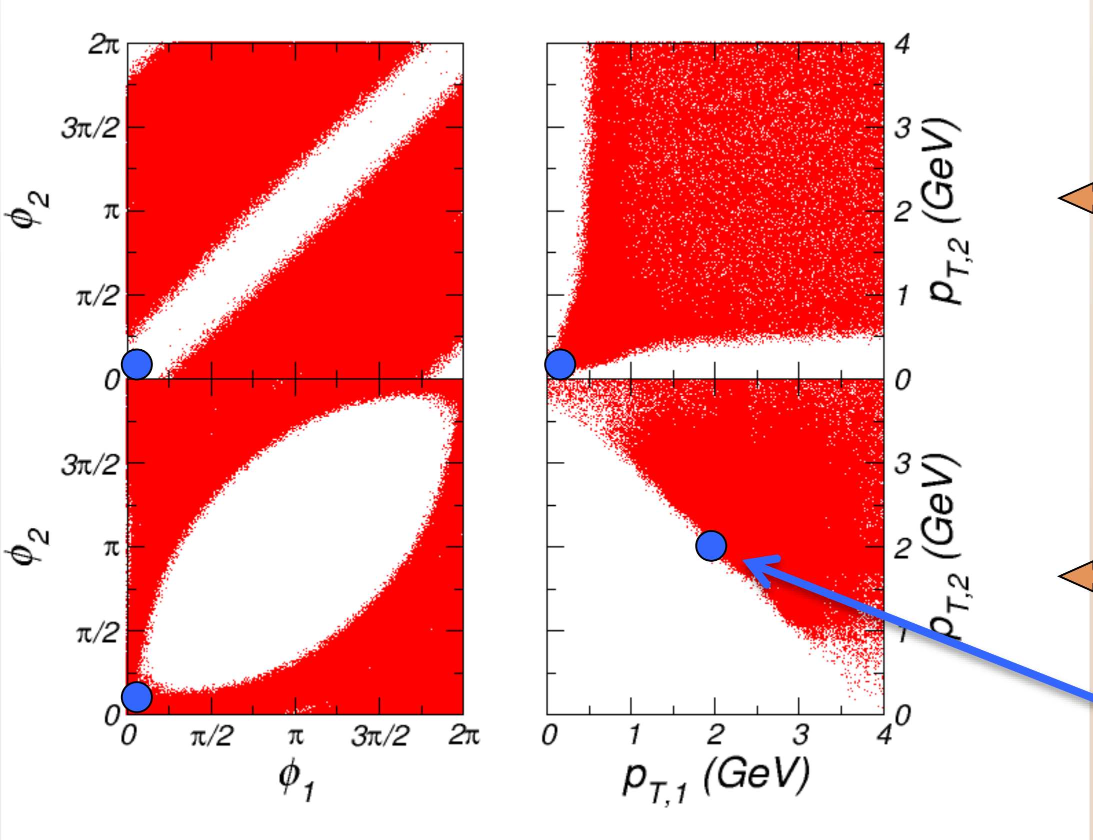
Negative v_2

Dynamical model

- Results
  - Deuteron spectrum
    - Radial flow effect is not fully taken into account
  - Deuteron elliptic flow
    - Consistent with the PHENIX data
    - Cannot explain the negative v_2 of preliminary STAR data
    - Support coalescence model at medium p_T
    - Momentum conservation has more important role in this region.
    - Holds also for low momentum region?

Dynamical model vs Coalescence model

- In coalescence model, $p_d/2=p_1=p_2$
- In dynamical model, energy-momentum conservation determines the physical region



$$p_{T,d} = 0.1\ \mathrm{GeV}$$

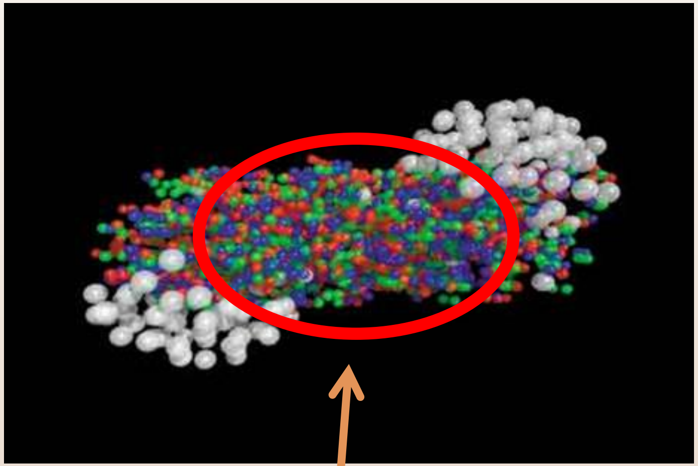
$$p_{T,d} = 4.0\ \mathrm{GeV}$$

Allowed by the coalescence model

Dynamical model vs Coalescence model

- At low p_T region
  - The momenta chosen by the coalescence model is not physically allowed region.
  - So, the similarities between the dynamical model and coalescence model are accidental,
    - If v_2 of the nucleon at low p_T is negative
      - Coalescence model gives negative deuteron v_2
      - Dynamical model gives positive deuteron v_2

Transport model



$$f(x,p) \propto \exp\left(-p^{\mu}u_{\mu}/T_C\right)$$

p^{μ} : four - momentum of the particle

u_{μ} : flow four - velocity

$$u_{\mu} = \gamma_T\left(\cosh\eta, \vec{\beta}, \sinh\eta\right); \quad \vec{\beta} = \beta(r)\left[1+\varepsilon(p_T)\cos(2\varphi)\right]\hat{n}$$

$$\beta(r) = \beta_0\left(\frac{r}{R}\right), \quad \varepsilon(p_T) = c_1\exp(-p_T/c_2)$$

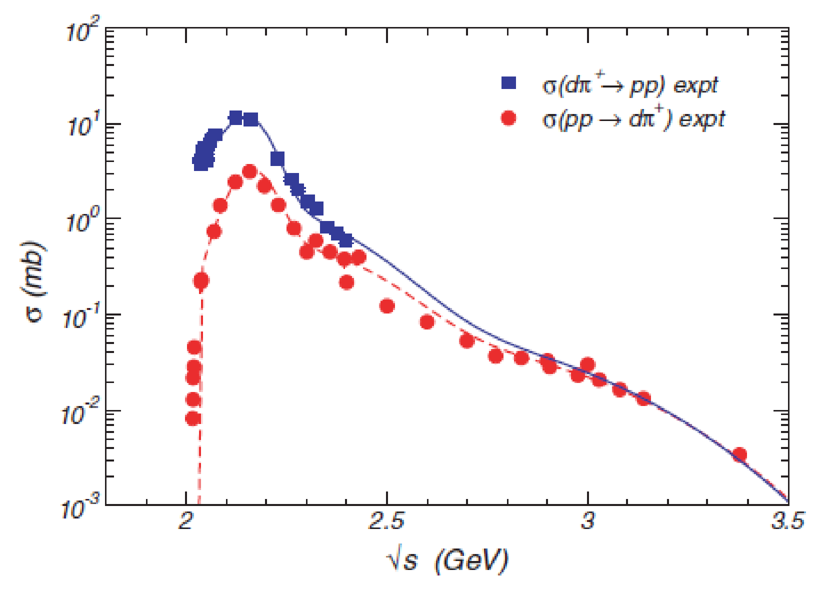
Assume that initial hadrons formed by
the QGP are thermalized.
(blast-wave model)
⇒
and, then, hadronic rescattering

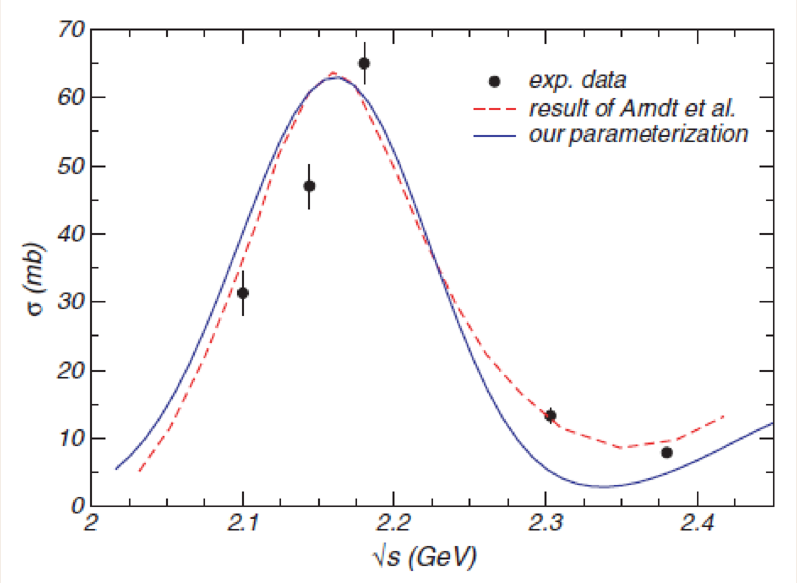
Initial state

Hadron rescatterings/collective expansion via ART

Transport model

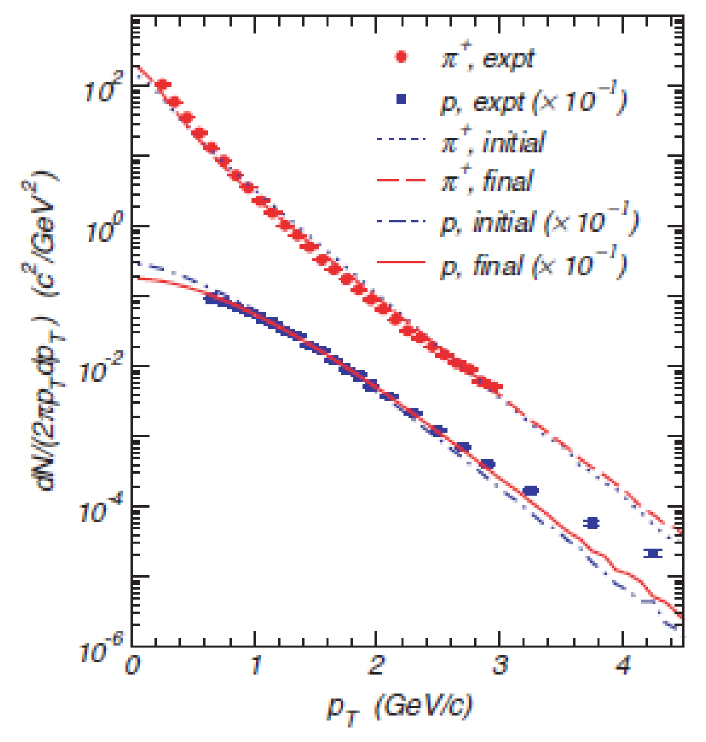
- Transport model ART (A Relativistic Transport model)
  - includes
    mesons (π, ρ, ω, η, K, K*, ϕ)
    and baryons (N, Δ, Λ, Σ and their anti-particles)
  - In this work, we include the interactions with the deuteron

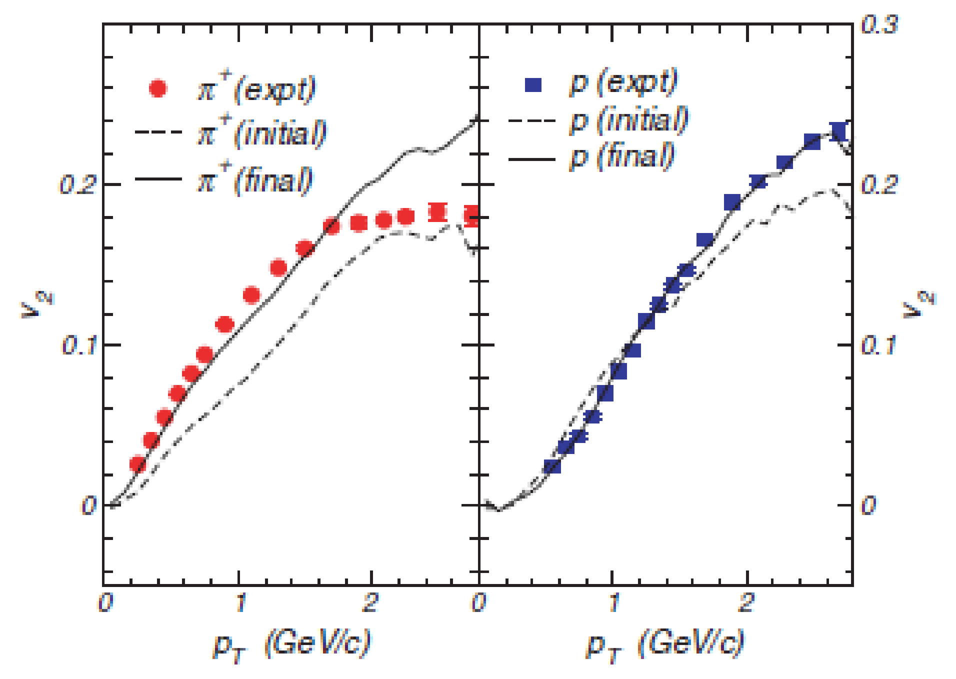




Transport model

- Inputs
  - The parameters for the initial state are determined to reproduce the measured pion/nucleon data



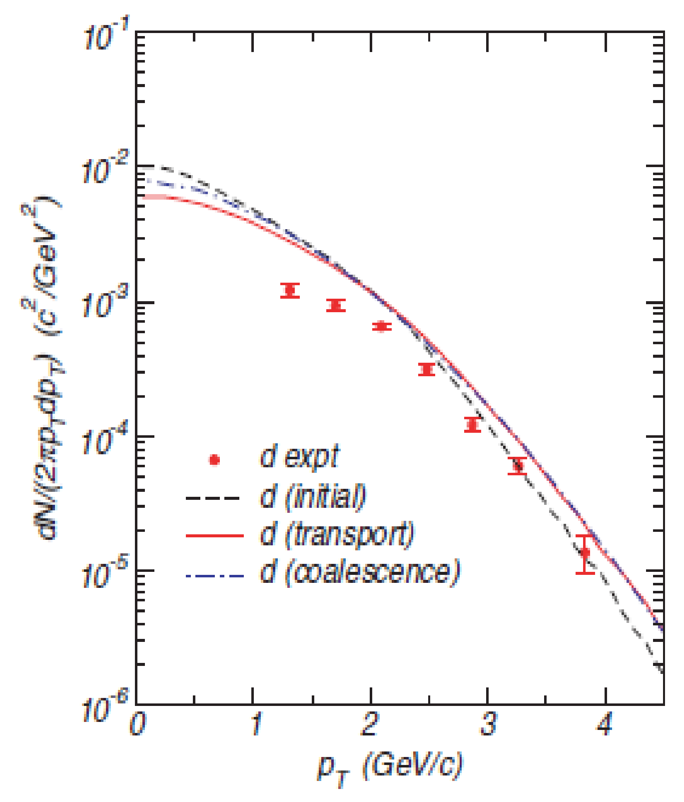


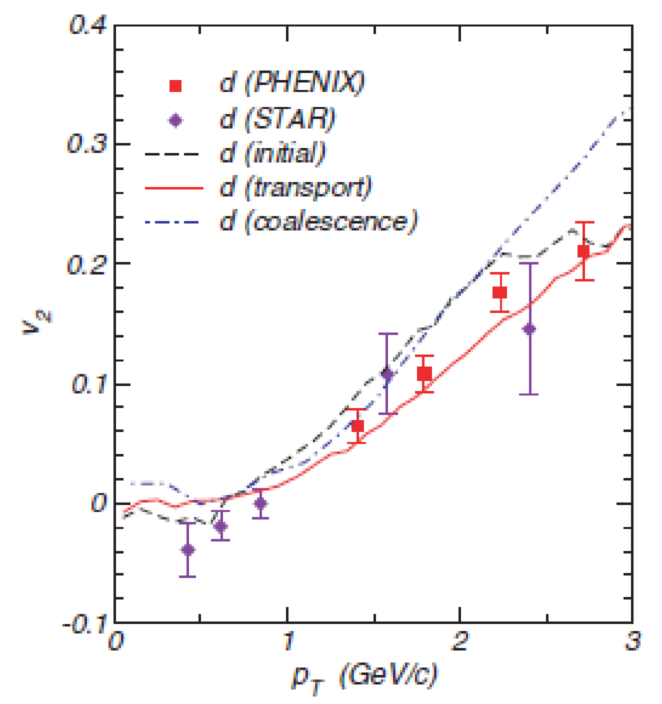
Large rescattering effects in the elliptic flow

Transport model

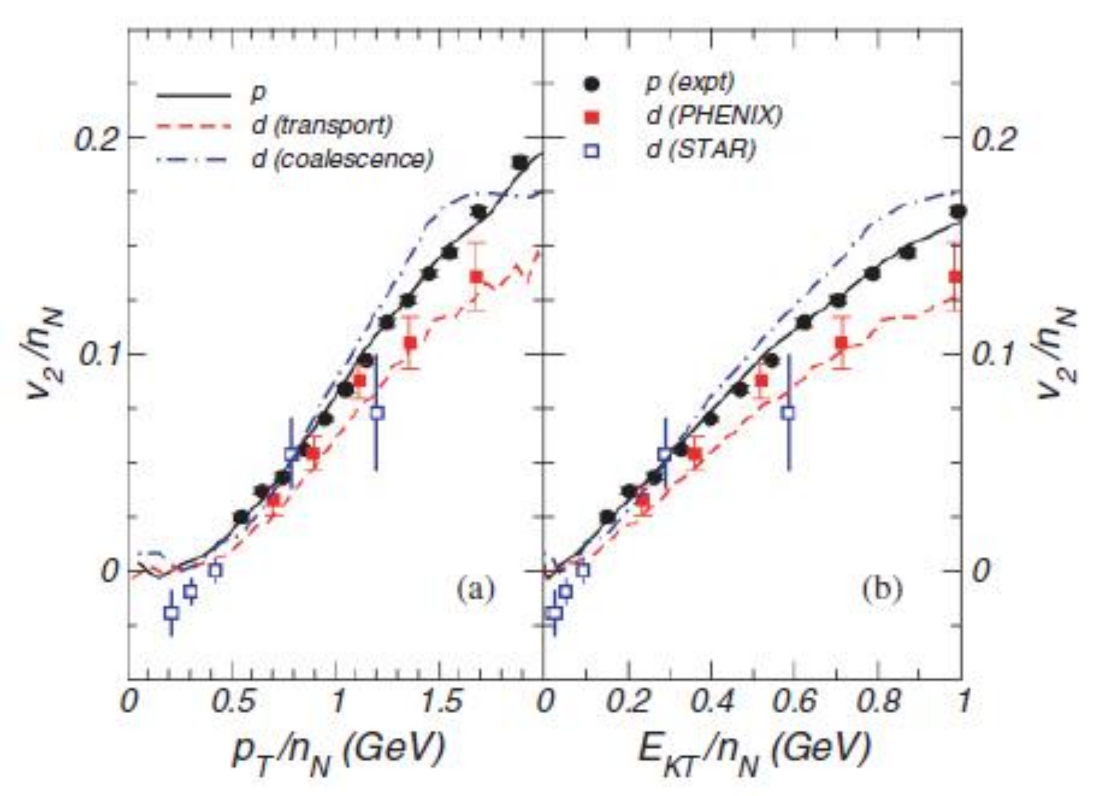
- Output
  - Deuteron spectrum p_T spectrum and elliptic flow

Oh et al., **PRC80**



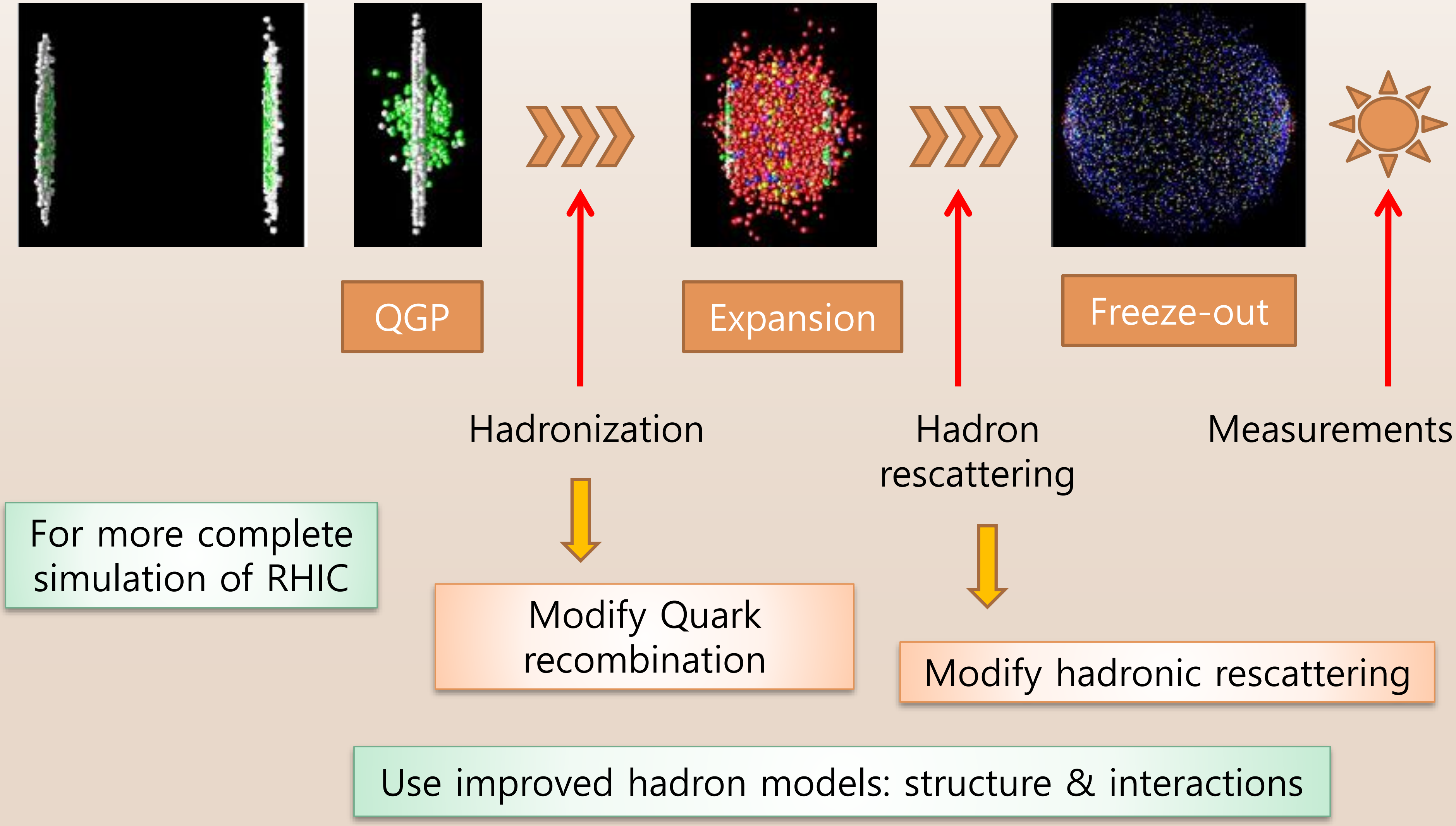


Transport model



Deviation from the scaling behavior

Outlook



QGP

Expansion

Freeze-out

Hadronization

Hadron rescattering

Measurements

For more complete simulation of RHIC

Modify Quark recombination

Modify hadronic rescattering

Use improved hadron models: structure & interactions

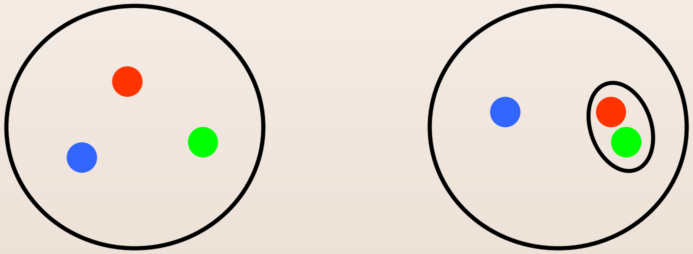
HEAVY QUARKS IN RHIC

Hadron models @ RHIC

Test of diquark model for baryons at RHIC

S.H. Lee et al., PRL100 (2008)
Sateesh, PRD45 (1992)

$\Lambda_Q = (udQ)$



Three-quark model

Diquark model

Wilczek

$\Lambda_c / \Sigma_c \sim 7$ in e^+e^- collisions

The most attractive diquark channel: scalar diqaurk $\bar{3}_c$
How to distinguish diquark model from the three-quark model

Λ_c : diquark + heavy-quark or three-quark
Σ_c : three-quark

⇨ use the production of Λ_c and Σ_c in relativistic heavy ion collisions

L_c / D^0 ratio will be enhanced by a factor of 4-8: S.H. Lee et al., PRL100 (2008)
L_c / S_c ratio will be enhanced by a factor of 80: Sateesh, PRD45 (1992)

pp & AA collisions

- PYTHIA model (pp)

Oh et al., **PRC79**, 044905
067902

$$\left(\frac{D^0}{D^+}\right)_{pp} \cong 3.1, \quad \left(\frac{\Lambda_c}{D^0}\right)_{pp} \cong 0.13, \quad \left(\frac{\Lambda_b}{B^0}\right)_{pp} \cong 0.7$$

Mostly due to D* decay: $D^{*0} \rightarrow D^+\pi^-$
is prohibited by energy conservation

- Thermal model (AA)

$$N \propto g m^2 K_2(m/T), \quad g: \text{degeneracy}, \quad K_2: \text{ modified Bessel function}$$

$$\left(\frac{\Lambda_c}{D^0}\right) \cong 0.27, \quad \left(\frac{\Lambda_b}{B^0}\right) \cong 0.86$$

Thermal model (AA)

- Role of resonance decays

$$\frac{D^0}{D^+} = 1 \quad \text{without resonances}$$

$$\text{At } T_c = 175\text{ MeV},\ \frac{D^{*0}}{D^0} \approx 1.47$$

$$\mathrm{BR}(D^{*0} \to D^0\pi^0) = 100\%, \qquad \mathrm{BR}(D^{*0} \to D^+\pi^-) = 0\%$$

$$\mathrm{BR}(D^{*+} \to D^+\pi^0) = 32\%, \qquad \mathrm{BR}(D^{*0} \to D^+\pi^-) = 68\%$$

Considering D^* decays,

$$\frac{D^0}{D^+} = \frac{1+(1+0.68)\times 1.47}{1+0.32\times 1.47} = 2.36$$

Likewise,

$$\frac{\Lambda_c}{D^0} = \frac{\Lambda_c\left\{1+\Sigma_c(2455)/\Lambda_c + \Sigma_c^*(2520)/\Lambda_c\right\}}{D^0\left(1+1.68D^*/D\right)} = 0.28$$

Including $D_1(2420)$ gives

$$\frac{\Lambda_c}{D^0} = 0.27$$

Cf. In bottom sector, the B* meson cannot decay into the B meson.

Coalescence model (AA)

- Coalescence model
  - Production of a particle is proportional to the overlap integral of the wave functions of the constituents
    (parameters: fitted by the rms radii of the particles)

$$\frac{dN_M}{dp_M} \propto \int dp_1 dp_2 \frac{dN_1}{dp_1} \frac{dN_2}{dp_2} \exp(-k^2\sigma^2)\delta\left(p_M - p_1 - p_2\right)$$

$$k = \frac{1}{m_1 + m_2}\left(m_2 p_1' - m_1 p_2'\right)$$

$$\frac{dN_B}{dp_B} \propto \int dp_1 dp_2 dp_3 \frac{dN_1}{dp_1} \frac{dN_2}{dp_2} \frac{dN_3}{dp_3} \exp(-k_1^2\sigma_1^2 - k_2^2\sigma_2^2)\delta\left(p_B - p_1 - p_2 - p_3\right)$$

  - Thermal distributions for light quarks and diquarks
  - Heavy quark distributions: from pQCD

Results: Coalescence model (AA)

Larger than the thermal model predictions

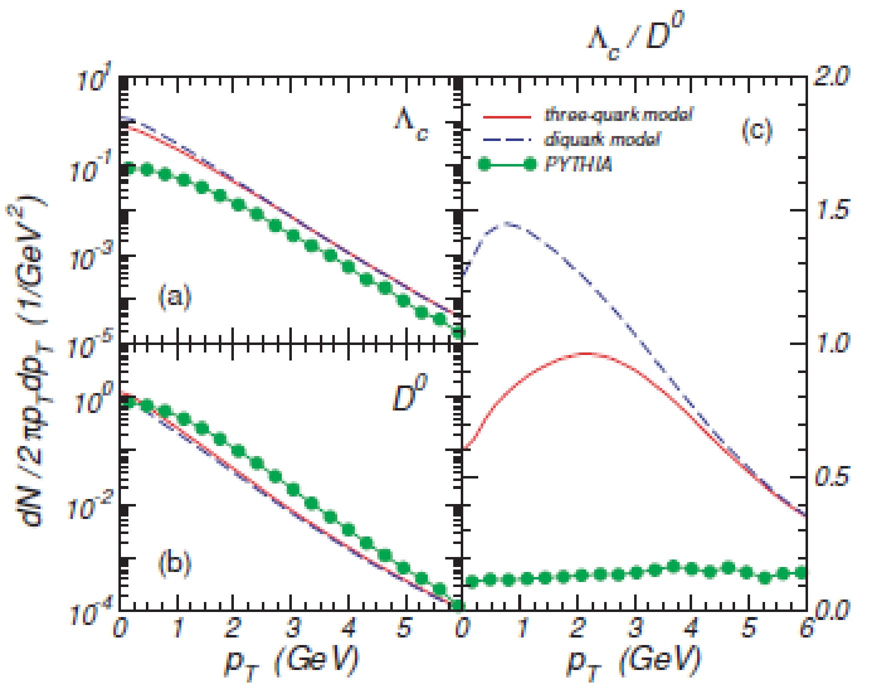
- Results

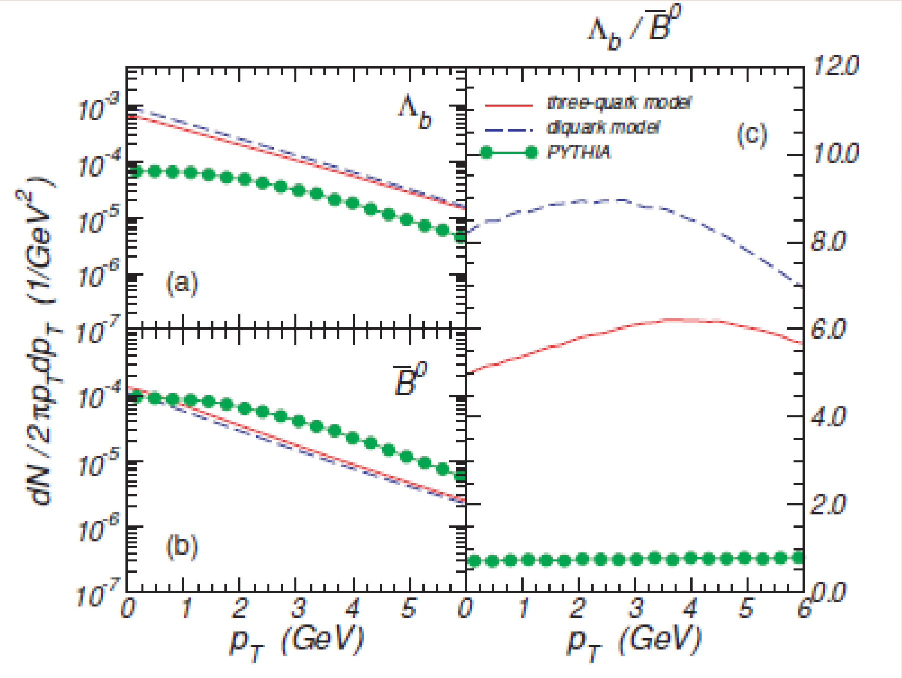
~1.6 times

$$\left(\frac{\Lambda_c}{D^0}\right)_{pp} \cong 0.83, \quad \left(\frac{\Lambda_b}{B^0}\right)_{pp} \cong 6.0$$ Three-quark model

$$\left(\frac{\Lambda_c}{D^0}\right)_{pp} \cong 1.34, \quad \left(\frac{\Lambda_b}{B^0}\right)_{pp} \cong 8.8$$ diquark model

Meson/baryon ratio

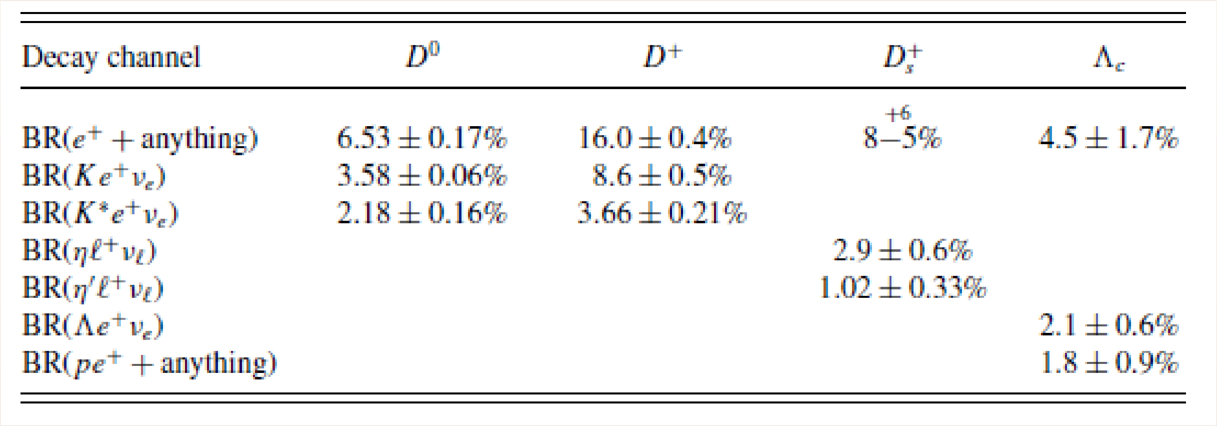




Nuclear modification factor

- Non-photonic electron R_{AA}

$$R_{AA} = \frac{dN^e_{AA}/dp_T}{\langle N^{AA}_{coll}\rangle dN^e_{pp}/dp_T}$$



Decay channel	D^0	D^+	D_s^+	Λ_c
$\mathrm{BR}(e^+ + \text{anything})$	$6.53 \pm 0.17\%$	$16.0 \pm 0.4\%$	$8^{+6}_{-5}\%$	$4.5 \pm 1.7\%$
$\mathrm{BR}(K e^+ \nu_e)$	$3.58 \pm 0.06\%$	$8.6 \pm 0.5\%$		
$\mathrm{BR}(K^* e^+ \nu_e)$	$2.18 \pm 0.16\%$	$3.66 \pm 0.21\%$		
$\mathrm{BR}(\eta \ell^+ \nu_\ell)$			$2.9 \pm 0.6\%$	
$\mathrm{BR}(\eta' \ell^+ \nu_\ell)$			$1.02 \pm 0.33\%$	
$\mathrm{BR}(\Lambda e^+ \nu_e)$				$2.1 \pm 0.6\%$
$\mathrm{BR}(p e^+ + \text{anything})$				$1.8 \pm 0.9\%$

The R_{AA} puzzle.

The electron R_{AA} shows that the production of heavy-flavor hadrons is suppressed as much as that of pions.

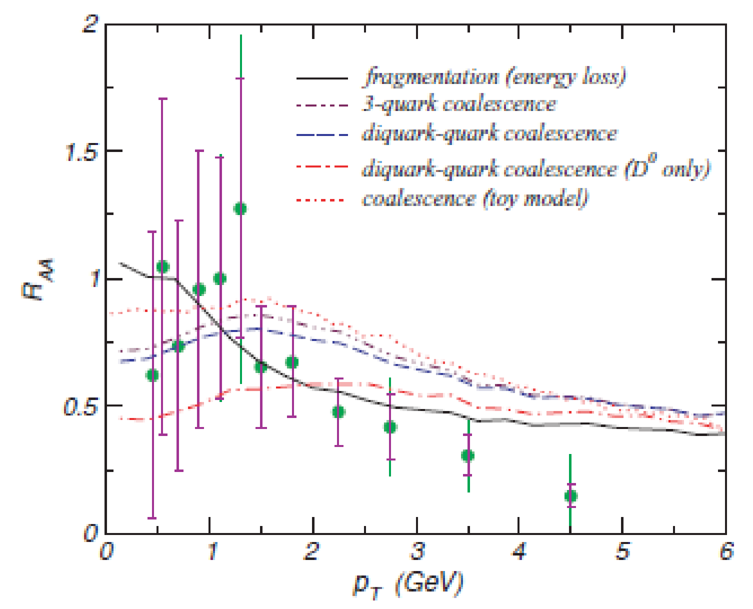
⟺ pQCD: the energy loss of heavy quark is smaller.

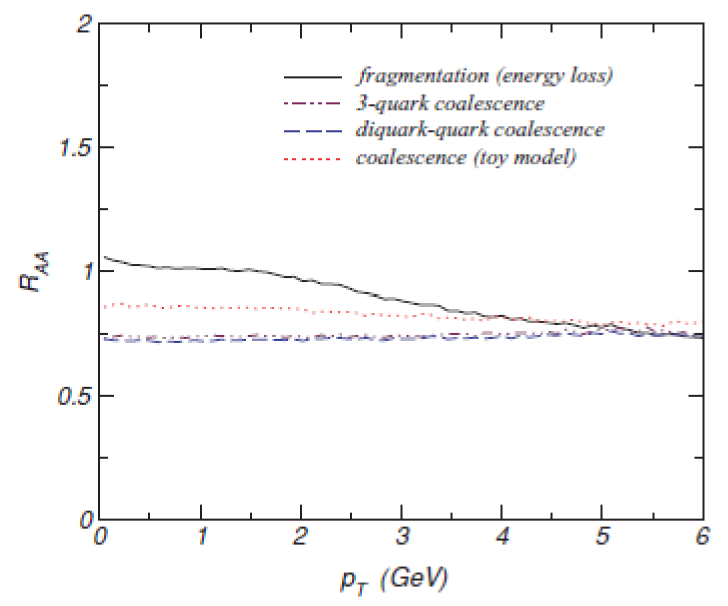
$\mathrm{BR}(D \to eX)$ is larger than $\mathrm{BR}(\Lambda_c \to eX)$.

Does enhanced $\frac{\Lambda_c}{D^0}$ can reduce R_{AA}?

Nuclear modification factor

- Non-photonic electron R_{AA}





The enhancement of $\frac{\Lambda_c}{D^0}$ occurs in the low p_T.

So it cannot solve the puzzle unless we assume the enhancement at large p_T.