50 years of scientific career and history of AMPT

Che-Ming Ko
Texas A&M University

Many thanks to the organizers (Zie-Wei Lin, Guo-Liang Ma, Jun Xu, Wei-Ning Zhang and Wei-Jie Fu) for giving me the opportunity to share with all of you my humble research journey during the past 50 years and the history of the AMPT model for relativistic heavy ion collisions

- 1966 – 68: Nuclear matter theory; M.S. from McMaster University under Donald Sprung.

Evaluation of perturbation theory terms in nuclear matter[1]

CHE-MING KO[2] AND DONALD W. L. SPRUNG
Department of Physics, McMaster University, Hamilton, Ontario
Received September 9, 1968

The second-order perturbation term in nuclear matter is reduced, for the most general nonlocal potential, to a triple quadrature. A kinematic function of three variables which includes all kinematic effects of the Pauli principle is defined and evaluated analytically. An improved angle average approximation for nuclear matter calculations is derived and found to be very accurate for evaluating the Pauli correction in the reference spectrum method.

Canadian Journal of Physics, 47, 123 (1969)

$$K(k, k', q) = \int_{\substack{|P\pm k|\leq 1 \\ |P\pm k'|>1}} \mathrm{d}^3 P$$

TABLE I

Pauli correction per nucleon for $^3S_1$–$^3D_1$ states in r.s.m. by using Reid's soft-core potential. The values are in MeV

$\int\{1\}_{\text{exact}}$	$\int\{1\}_{\text{c.a.a.}}$	$\int\{1\}_{\text{r.a.a.}}$	$\int\{2\}_{\text{exact}}$	$\int\{2\}_{\text{a.a}}$*
3.49954	3.73	3.50025	−0.00797	0

*Angle average.

- 1968 – 73: Nuclear deformation energies and weak-coupling model for ^{212}Pb and ^{204}Pb; Ph.D. from Stony Brook University under Gerry Brown and Tom Kuo.

A MICROSCOPIC, BUT NOT SELF-CONSISTENT APPROACH TO NUCLEAR BINDING AND DEFORMATION ENERGIES †

C. M. KO ††, H. C. PAULI †††, M. BRACK ‡ and G. E. BROWN

Department of Physics, State University of New York at Stony Brook, New York 11790, USA

Received 27 August 1974   NPA 236, 269 (1974)

Abstract: Using various versions of the Skyrme force and Negele's interaction, we calculate deformation energies of nuclei by evaluating the expectation value of the many-body Hamiltonian in wave functions taken to be antisymmetrized products of single-particle functions. These single-particle functions are eigenfunctions of a phenomenological potential, here taken to be a deformed Woods-Saxon well. The method can be thought of as an extension of the Strutinsky shell-correction method, to make the connection with the two-body interaction. The method employed here is checked by comparison with Hartree-Fock (HF) results; our method is, however, much faster than the HF method, and, therefore, suitable for a wide range of problems where one tests the sensitivity of results to changes in the two-body interaction. A fairly good agreement with the HF method is obtained for ground-state energies, radii and deformations, as well as for deformations of shape isomers. The main discrepancy is that our energies tend to increase slightly too rapidly with deformation, indicating that we may not have chosen the best phenomenological well. Two-dimensional energy surfaces, which agree quite well with those from the Strutinsky method, are found for ^{240}Pu.

PHYSICAL REVIEW C VOLUME 8, NUMBER 6 DECEMBER 1973

Weak-Coupling Model for ^{212}Pb and ^{204}Pb†

C. M. Ko and T. T. S. Kuo
Department of Physics, State University of New York, Stony Brook, New York 11790

and

J. B. McGrory*
Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
(Received 16 August 1973)

The weak-coupling model is applied to the study of the low-lying states of ^{212}Pb and ^{204}Pb. We first obtain the phonon states of ^{210}Pb and ^{206}Pb by shell-model calculations. The states of ^{212}Pb (^{204}Pb) are then obtained by solving the eigenvalue problem in a truncated Hilbert space consisting of a small number of basis vectors, each of which is a product of two phonon states of ^{210}Pb (^{206}Pb). A canonical transformation is used to orthonormalize these two-phonon basis vectors. The energies as well as the wave functions of many low-lying states of ^{212}Pb (^{204}Pb) given by the exact shell-model calculations are reproduced surprisingly well by the weak-coupling model where only three or four low-lying ^{210}Pb (^{206}Pb) phonons are included.

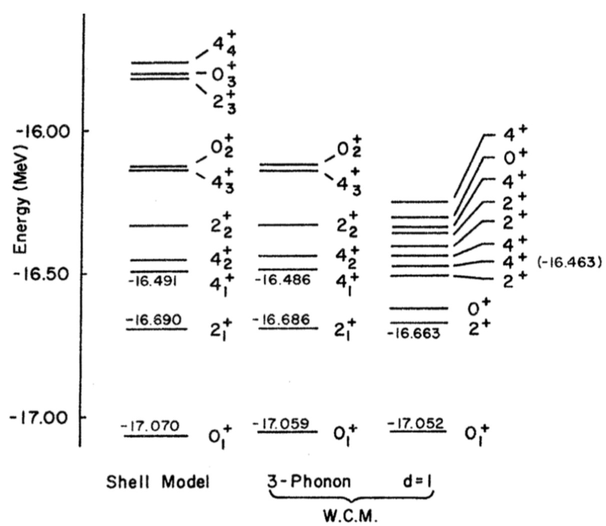


FIG. 2. Energy levels of ^{212}Pb (model space I).

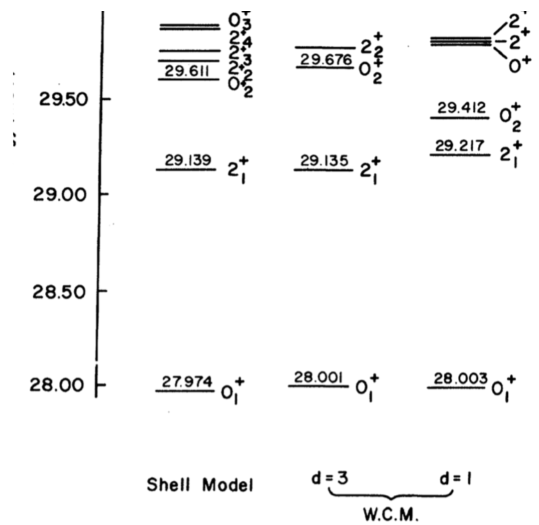


FIG. 7. Energy levels of ^{204}Pb.

- 1973 – 74: Density matrix expansion; postdoc at McMaster University with Donald Sprung

A NOTE ON THE VALIDITY OF THE DENSITY MATRIX EXPANSION

D. W. L. SPRUNG and M. VALLIERES

Physics Department, McMaster University, Hamilton, Ontario, Canada L8S 4M1

X. CAMPI

Institut de Physique Nucléaire, Division de Physique Théorique, 91406 Orsay, France†

and

CHE-MING KO

Max Planck Institut für Kernphysik, PO Box 1248 D-69 Heidelberg 1, Germany

Received 2 June 1975

Abstract: The density matrix expansion of Negele and Vautherin is formulated in one dimension, and compared against an analytically soluble model. In three dimensions, numerical tests are carried out using both the Brink and Boeker force and the density-dependent force G-0. These range from perturbative to Hartree-Fock calculations. We find that the DME method overbinds spherical nuclei by 1 MeV per particle compared to exact Hartree-Fock calculations. If the direct terms are calculated exactly and DME applied only to the exchange terms, the results are much better, with slight underbinding (about 200 keV per particle) occurring for most nuclei and the radii agree to within 1%.

- 1974 – 77: Transport theory for deeply inelastic heavy ion collisions; postdoc at Max-Planck Institute for Nuclear Physics under Hans Weidenmeuller

Transport Theory of Deeply Inelastic Heavy-Ion Collisions Based on a Random-Matrix Model. I. Derivation of the Transport Equation

D. AGASSI,* C. M. KO, AND H. A. WEIDENMÜLLER

Max-Planck-Institut für Kernphysik, Heidelberg, West Germany

Received November 18, 1976

A random-matrix model is used to describe the transformation of kinetic energy of relative motion into intrinsic excitation energy typical of a deeply inelastic heavy-ion collision. The random-matrix model is based upon statistical assumptions regarding the form factors coupling relative motion with intrinsic excitation of either fragment. Average cross sections are calculated by means of an ensemble average over the random matrix model. Summations over intermediate and final intrinsic spin values are performed. As a result, average cross sections are given by the asymptotic behavior of a probability density which in turn obeys a transport equation. In the transport equation there is no further reference to intrinsic spins. The physical and mathematical properties of this equation are exhibited.

- 1977 – 78: Mass diffusion in DIC and Pion optical potential: postdoc under George Bertsch and Dan Riska

NUCLEON TUNNELLING MODEL OF MASS DIFFUSION IN DEEP INELASTIC HEAVY ION COLLISIONS ☆

PLB 77, 174 (1978)

C.M. KO, G.F. BERTSCH and D. CHA
Department of Physics and Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

We derive a simple expression for the mass diffusion coefficient in deep inelastic collisions, based on a proximity formulation of nucleon tunnelling. The predicted value of the coefficient is consistent with empirical data. The mass diffusion coefficient has a negligible dependence on excitation energy in the physically interesting domain.

THE ABSORPTIVE P-WAVE PION-NUCLEUS OPTICAL POTENTIAL

C. M. KO † and D. O. RISKA

NPA 312, 217 (1978)

nt of Physics and Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

Received 12 June 1978

Abstract: We derive the absorptive part of the P-wave pion-nucleus optical potential from a two-body model for the absorption mechanism which involves rescattering of a pion and a ρ-meson through a Δ_{33} resonant state. The model gives an adequate explanation for the fundamental $\pi^+ d \to pp$ reaction cross section and leads to values for the optical potential parameter which are in fair agreement with those obtained from pionic atom level widths.

- 1978 – 80: Kaon production in HIC; postdoc at Lawrence Berkeley Laboratory

2.B: 2.N

Nuclear Physics **A343** (1980) 519 – 544; © *North-Holland Publishing Co., Amsterdam*

KAON PRODUCTION IN RELATIVISTIC NUCLEAR COLLISIONS †

J. RANDRUP and C. M. KO

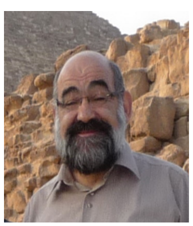
Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley, CA 94720, USA

Received 19 February 1980

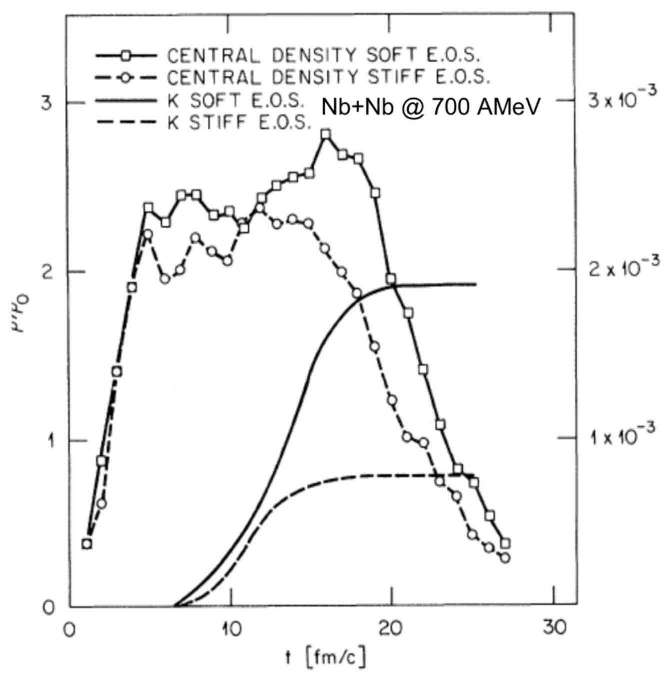
Abstract: Kaon production in relativistic nuclear collisions is studied on the basis of a conventional multiple-collision model. The input is the differential cross sections for kaon production in elementary baryon-baryon collisions, estimated in a simple model. Inclusive kaon spectra are calculated at 2.1 GeV/nucleon for a number of experimental cases. The calculated kaon yield is approximately isotropic in the mid-rapidity frame and extends considerably beyond the nucleon-nucleon kinematical limit.

- 1980 – 90: Joined TAMU as assistant professor in 1980 and promoted to associate professor in 1984 and Professor in 1988.

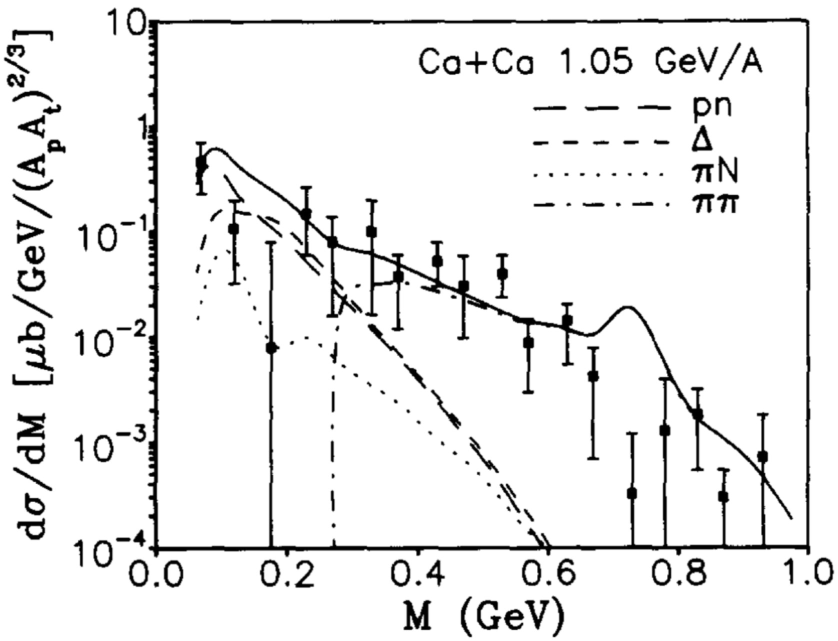
- K^- from $\pi Y \to K^- N$ and $NY \to NNK^-$, $\bar{p}$ from $\rho\rho \to p\bar{p}$, and photon from p+n bremsstrahlung (Bertsch, J. Aichelin, C. Y. Wong), eta from $\pi N \to N^* \to \eta N$ (Mosel & Cassing) in HIC
- Relativistic Vlasov-Uehling-Uhlenbeck (RVUU) Model for HIC (Q. Li, R. C. Wang)
- Suthreshold kaon production in HIC (Aichelin)
- Dilepton production in HIC (L. Xiong, Z. G. Wu, J. Q. Wu, L. H. Xia & P. J. Siemens)
- K/π in HIC at AGS (L. H. Xia, G. E. Brown)



Aichelin & Ko, PRL 55, 2661 (85)



Xiong, Wu, Ko & Wu, NPA 512, 772 (1990)



- 1991 – 2000:

- Medium effects on particle production in HIC: Phi from $K\overline{K} \rightarrow \varphi\rho$ and $K\Lambda \rightarrow \varphi N$ (B. H. Sa), phi (G. Q. Li, W. S. Chung), kaon, antikaon and antiproton (X. S. Fang, G. Q. Li, Y. M. Zheng, V. Koch), and dilepton (G. Q. Li, Brown) in HIC
- Rho and phi meson in-medium properties (M. Asakawa, P. Levai, X. J. Qiu, C. S. Song, S. H. Lee, C. Gale, P. W. Xia)
- A relativistic transport (ART) model for AGS (B. A. Li, C. Song)
- Isospin physics and nuclear symmetry energy (B. A. Li)

Volume 258, number 1,2 PHYSICS LETTERS B 4 April 1991

Phi meson production in hadronic matter

C.M. Ko and B.H. Sa [1]

Cyclotron Institute and Physics Department, Texas A&M University, College Station, TX 77843, USA

Received 6 September 1990; revised manuscript received 26 December 1990

The decrease of hadron masses in hot and dense hadronic matter as a result of the restoration of chiral symmetry increases substantially the phi meson production cross section from the reactions $K\bar{K} \rightarrow \phi\rho$ and $K\Lambda \rightarrow \phi N$. In the hydrochemical model, we show that this leads to an enhanced production of phi mesons in ultrarelativistic heavy-ion collisions and may be responsible for the large ϕ/ω ratio that has been recently observed in CERN experiments.

PHYSICAL REVIEW C VOLUME 46, NUMBER 4 OCTOBER 1992

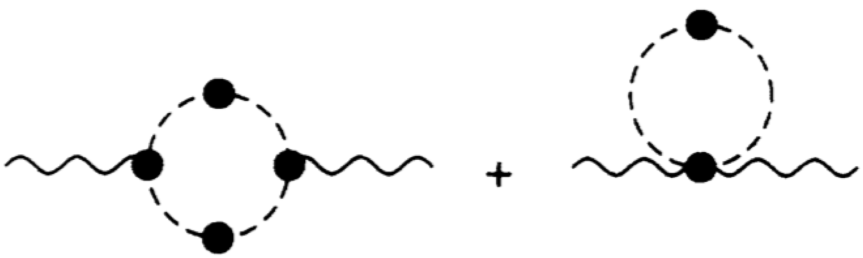
Rho meson in dense hadronic matter

M. Asakawa, C. M. Ko, P. Lévai,* and X. J. Qiu†

tron Institute and Physics Department, Texas A&M University, College Station, Texas 77

(Received 24 April 1992)

The spectral function of a rho meson that is at rest in dense hadronic matter and couples strongly to the pion is studied in the vector dominance model by including the effect of the delta-hole polarization on the pion. With the free rho-meson mass in the Lagrangian, we find that both the rho-meson peak and width increase with increasing nuclear density, and that a low-mass peak appears at invariant mass around three times the pion mass. Including the decreasing density-dependent hadron masses in the Lagrangian as suggested by the scaling law of Brown and Rho, we find instead that the rho peak moves to smaller invariant masses with diminishing strength when the nuclear density increases. The low-mass peak also shifts down with increasing density and becomes more pronounced. The relevance of the rho-meson property in dense matter to dilepton production in heavy-ion collisions is discussed.



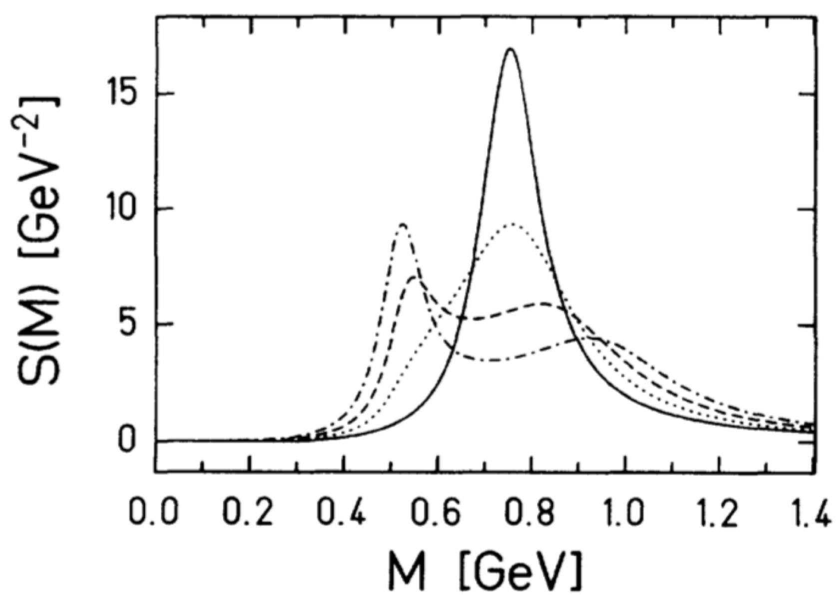
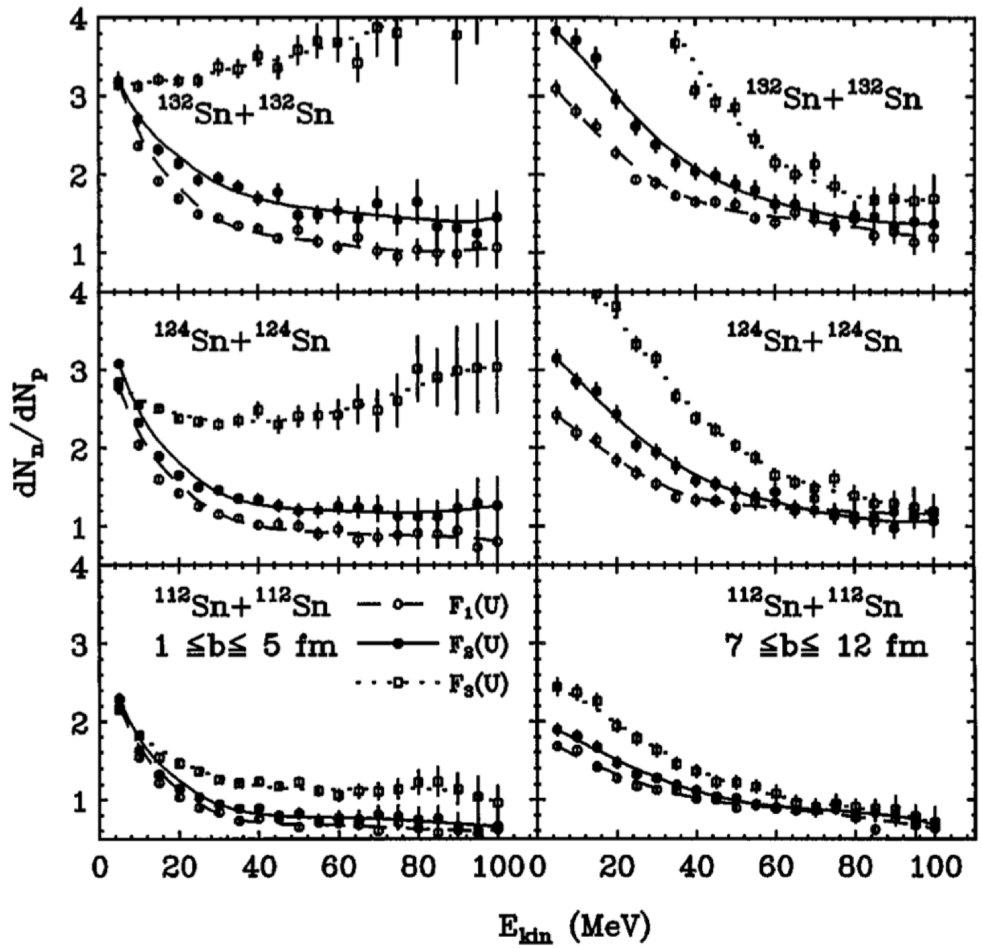


FIG. 4. The spectral function of a rho meson. The solid curve is for a rho meson in free space. For a rho meson in the medium, the dotted, dashed, and dash-dotted curves correspond, respectively, to nuclear densities of po, 2po, and 3po, where po is the normal nuclear matter density.

VOLUME 78, NUMBER 9 PHYSICAL REVIEW LETTERS 3 MARCH 1997

Equation of State of Asymmetric Nuclear Matter and Collisions of Neutron-Rich Nuclei

Bao-An Li,[1,*] C. M. Ko,[1,†] and Zhongzhou Ren[2,‡]
[1]Cyclotron Institute and Department of Physics, Texas A&M University, College Station, Texas 778
[2]Department of Physics, Nanjing University, Nanjing 210008, Peoples Republic of China
(Received 5 September 1996)



The ratio of pre-equilibrium neutrons to protons from collisions of neutron-rich nuclei is studied as a function of their kinetic energies. This ratio is found to be sensitive to the density dependence of the nuclear symmetry energy, but is independent of the compressibility of symmetric nuclear matter and the in-medium nucleon-nucleon cross sections. The experimental measurement of this ratio thus provides a novel means for determining the nuclear equation of state of asymmetric nuclear matter.

- 2001 - 2010:

- Model for charmonium absorption and charm meson scattering in hadronic matter (Z. W. Lin, W. Liu, T. G. Di)
- Charm hadron and pentaquark production in photo-proton and proton-proton scattering
- Ξ production from $\overline{K}Y \rightarrow \pi\Xi$ (C. H. Li)
- Symmetry energy and nuclear reactions of neutron-rich nuclei (L. W. Chen, B. A. Li)
- Light nuclei production in HIC (L. W. Chen, B. A. Li)
- Quark coalescence model for hadron production from QGP (V. Greco, P. Levai)
- A multiphase transport (AMPT) model (B. Zhang, Z. W. Lin, S. Pal, B. A. Li)
- Thermal charm production (B. W. Zhang, W. Liu)
- Charmonium mass in nuclear matter [S. H. Lee and C. M. Ko, PRC 67, 038202 (2003)]

The mass shift of charmonium states in nuclear matter is studied in the perturbative QCD approach. The leading-order effect due to the change of gluon condensate in nuclear matter is evaluated using the leading-order QCD formula, while the higher-twist effect due to the partial restoration of chiral symmetry is estimated using a hadronic model. We find that while the mass of J/ψ in nuclear matter decreases only slightly, those of $\psi(3686)$ and $\psi(3770)$ states are reduced appreciably. Experimental study of the mass shift of charmonium states in nuclear matter can thus provide valuable information on the changes of the QCD vacuum in nuclear medium.

PRL **94,** 032701 (2005) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2005

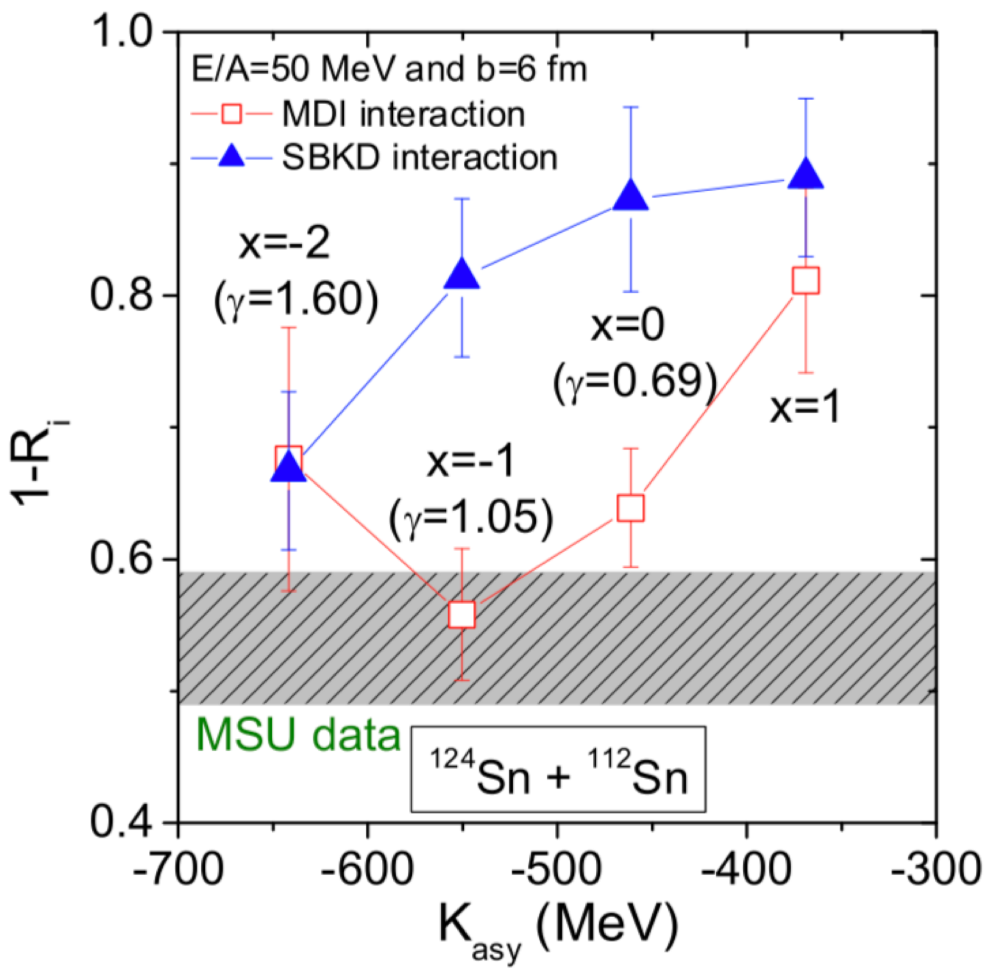
Determination of the Stiffness of the Nuclear Symmetry Energy from Isospin Diffusion

Lie-Wen Chen,[1,*] Che Ming Ko,[1] and Bao-An Li[2]

[1]*Cyclotron Institute and Physics Department, Texas A&M University, College Station, Texas 77843-336*

[2]*Department of Chemistry and Physics, P.O. Box 419, Arkansas State University, State University, Arkansas 72*

(Received 12 July 2004; published 26 January 2005)



With an isospin- and momentum-dependent transport model, we find that the degree of isospin diffusion in heavy-ion collisions at intermediate energies is affected by both the stiffness of the nuclear symmetry energy and the momentum dependence of the nucleon potential. Using a momentum dependence derived from the Gogny effective interaction, recent experimental data from NSCL-MSU on isospin diffusion are shown to be consistent with a nuclear symmetry energy given by $E_{sym} \approx 31.6\,(\rho/\rho_0)^{1.05}$ at subnormal densities. This leads to a significantly constrained value of about -550 MeV for the isospin-dependent part of the isobaric incompressibility of isospin asymmetric nuclear matter.

VOLUME 90, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 23 MAY 2003

Parton Coalescence and the Antiproton/Pion Anomaly at RHIC

V. Greco,[1] C. M. Ko,[1] and P. Lévai[1,2]
Institute and Physics Department, Texas A&M University, College Station, Texas 77843-3366, USA
KI Research Institute for Particle and Nuclear Physics, P.O. Box 49, Budapest 1525, Hungary
(Received 28 January 2003; published 22 May 2003)

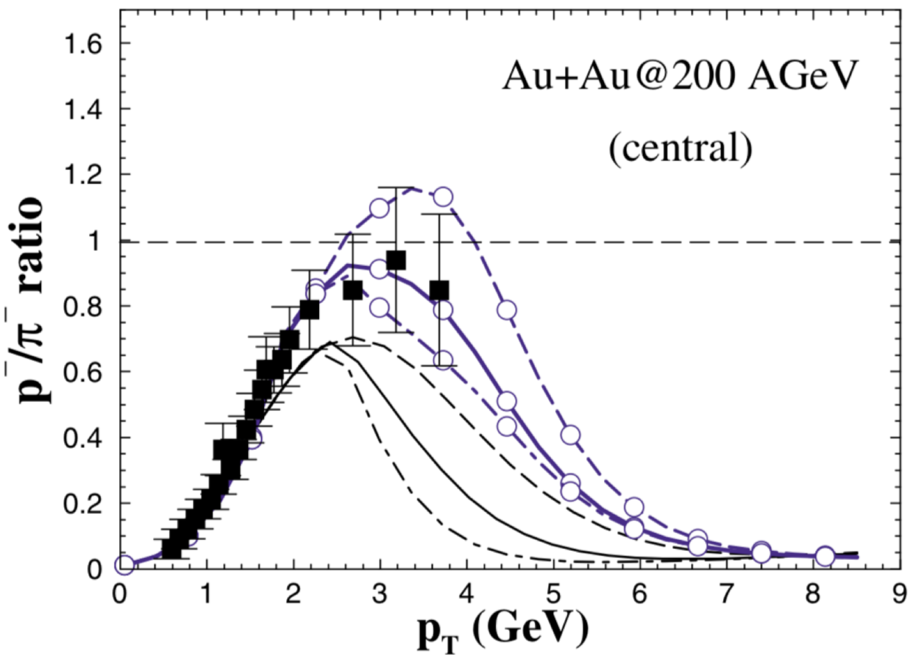


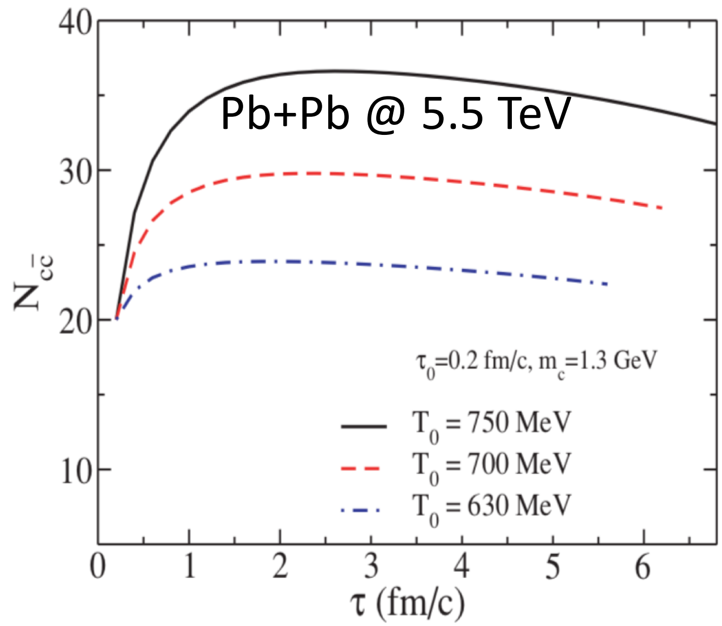
FIG. 3 (color online). Antiproton to pion ratios from Au + Au collisions at $\sqrt{s} = 200A$ GeV. The dash-dotted, solid, and dashed curves are results using, respectively, 240, 300, and 340 MeV for the inverse slope parameter of intermediate p_T antiprotons. Corresponding results including also contributions from coalescence of minijet and QGP partons are shown with open circles. The filled squares are the experimental data [11].

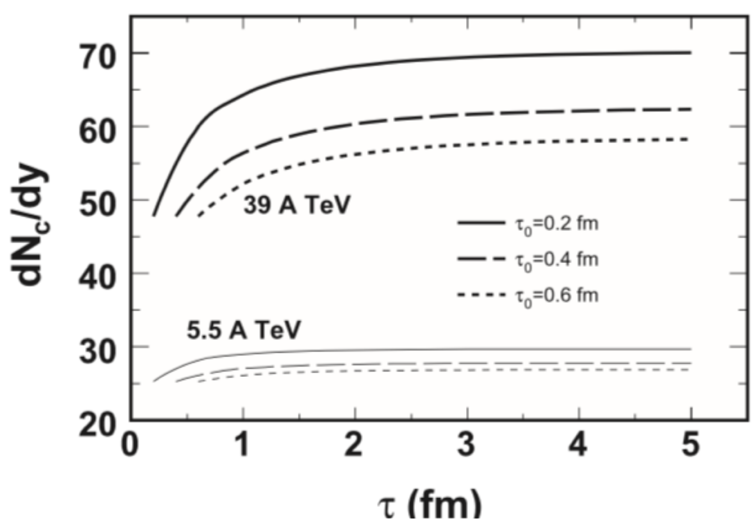
Coalescence of minijet partons with partons from the quark-gluon plasma formed in relativistic heavy ion collisions is suggested as the mechanism for production of hadrons with intermediate transverse momentum. The resulting enhanced antiproton and pion yields at intermediate transverse momenta give a plausible explanation for the observed large antiproton to pion ratio. With further increasing momentum, the ratio is predicted to decrease and approach the small value given by independent fragmentations of minijet partons after their energy loss in the quark-gluon plasma.

PHYSICAL REVIEW C **77**, 024901 (2008)

Thermal charm production in a quark-gluon plasma in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV

Ben-Wei Zhang,* Che Ming Ko, and Wei Liu





Charm production from the quark-gluon plasma created in the midrapidity of central heavy ion collisions at the Large Hadron Collider (LHC) is studied in the next-to-leading order in QCD. Using a schematic longitudinally boost-invariant and transversally expanding fire-cylinder model, we find that charm production could be appreciably enhanced at LHC as a result of the high temperature that is expected to be reached in the produced quark-gluon plasma. Sensitivities of our results to the number of charm quark pairs produced from initial hard scattering, the initial thermalization time and temperature of the quark-gluon plasma, and the charm quark mass are also studied.

Yupeng Liu & Ko, JPG 43, 125108 (2016)

Future Circular Collider (FCC)

PHYSICAL REVIEW C **79**, 044905 (2009)

Ratios of heavy baryons to heavy mesons in relativistic nucleus-nucleus collisions

Yongseok Oh,[1,*] Che Ming Ko,[1,†] Su Houng Lee,[2,‡] and Shigehiro Yasui[3,§]

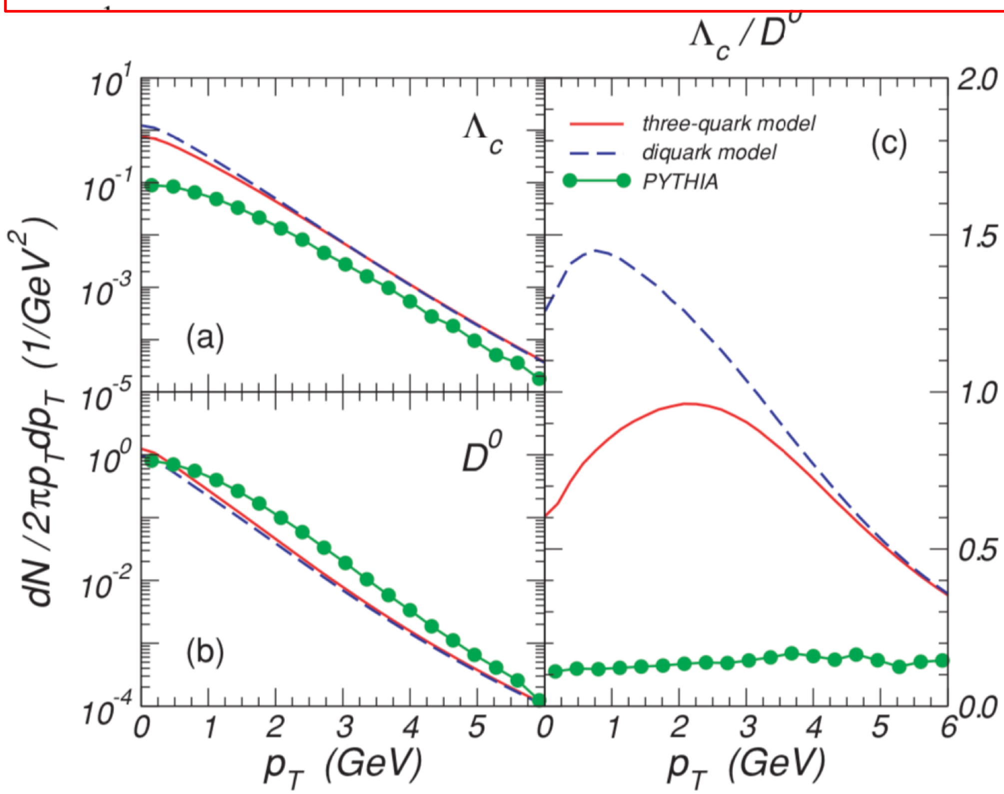
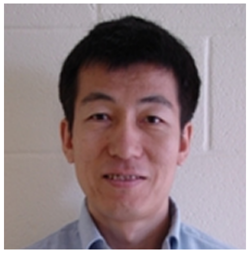
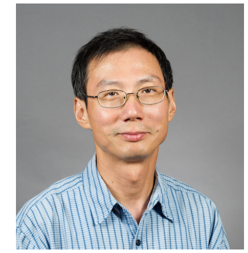


FIG. 1. (Color online) Spectra of (a) Λ_c and (b) D^0, and (c) the ratio Λ_c/D^0 in midrapidity ($|y| \leqslant 0.5$) for central Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Solid lines are for the three-quark model and dashed lines are for the diquark model. Results from the PYTHIA model are shown by filled circles.

Heavy baryon/meson ratios in relativistic heavy ion collisions are studied in the quark coalescence model. For heavy baryons, we include production from coalescence of heavy quarks with free light quarks as well as with bounded light diquarks that might exist in the strongly coupled quark-gluon plasma produced in these collisions. Including the contribution from decays of heavy hadron resonances and also that due to fragmentation of heavy quarks that are left in the system after coalescence, the resulting ratios in midrapidity from central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV are about a factor of five and ten, respectively, larger than those given by the thermal model, and about a factor of ten and twelve, respectively, larger than corresponding ratios in the PYTHIA model for pp collisions.



A multiphase transport (AMPT) model



Lin, Ko, Li, Zhang & Pal, PRC 72, 064901 (05);
http://www-cunuke.phys.columbia.edu/OSCAR

Default: Zhang, Ko, Li & Lin, PRC 61, 067901 (00); Lin, Pal, Ko, Li & Zhang, PRC 64, 041901 (01);

- Initial conditions: HIJING (soft strings and hard minijets)
- Parton evolution: ZPC
- Hadronization: Lund string model for default AMPT
- Hadronic scattering: ART

String melting: Lin & Ko, PRC 65, 034904 (02); Li, Ko & Pal, PRL 89, 152301 (02)

- Convert hadrons from string fragmentation into quarks and antiquarks
- Evolve quarks and antiquarks with ZPC
- When partons stop interacting, combine nearest quark and antiquark to meson, and nearest three quarks to baryon (coordinate-space coalescence)
- Hadron flavors are determined by the invariant mass of quarks

The casts

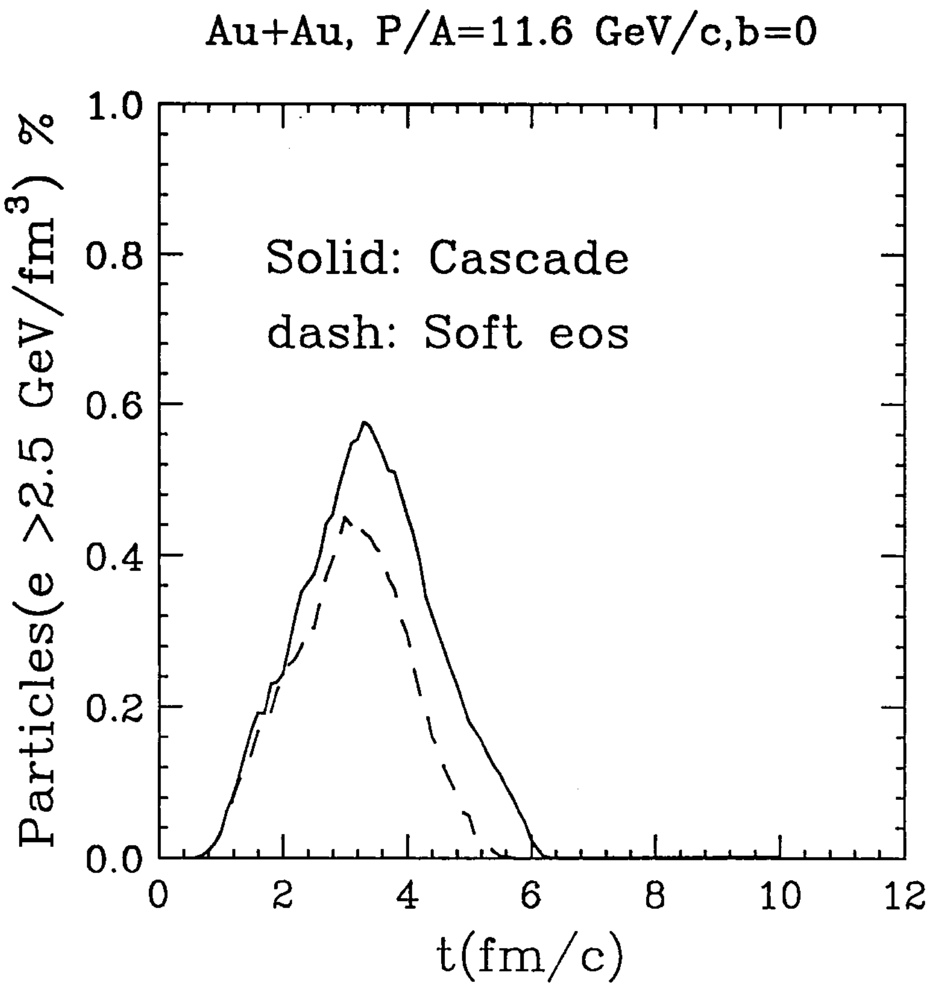
- Bao-An Li (Ph.D. 1991, Michigan State University): 1994 – 1998; Regent Professor, Texas A&M University at Commerce; ART
- Bin Zhang (Ph.D. 1998, Columbia University): 1998 – 2001; Professor, Arkansas State University; ZPC and charm
- Zie-Wei Lin (Ph.D. 1996, Columbia University): 1998 – 2002; Professor, East Carolina University; string melting
- Subrata Pal (Ph.D. 1997, Saha Institute for Nuclear Physics): 2000 – 2002; Professor, Tata Institute of Fundamental Research; strangeness
- Lie-Wen Chen (Ph.D. 2000, Institute of Modern Physics): 2002 – 2004; Professor, Shanghai Jiao Tong University; higher-order flow harmonics
- Jun Xu (Ph.D. 2008, Shanghai Jiao Tong University): 2008 – 2011; Professor, Shanghai Institute of Applied Physics; mean fields and LHC
- Yongseok Oh (Ph.D. 1993, Seoul National University): 2010 - 2013; Professor, Kyungpook National University; deuteron

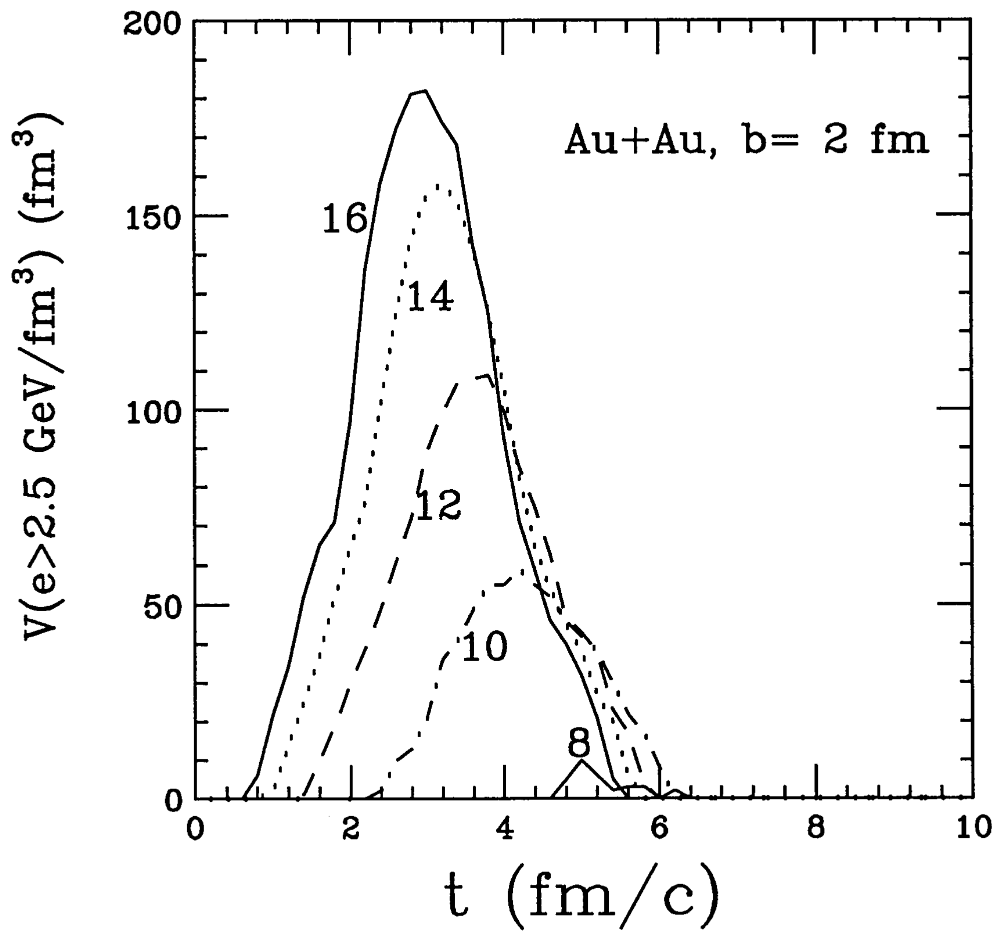
A relativistic transport (ART) model for HIC

Li & Ko, PRC 52, 2037 (1995)

- Based on BUU model with explicit isospin dependence
- Including baryons N, Δ(1232), N*(1440), N*(1535), Λ, Σ and mesons π, ρ, ω, η, K, K^*, ϕ
- Including baryon-baryon, meson-baryon and meson-meson elastic and inelastic scattering with empirical cross sections if available, otherwise from theoretical models
- Effects of higher nucleon and delta resonances up to 2 GeV are included as intermediate states in meson-baryon scattering
- Very successful in describing many experimental results at AGS
- Used as a hadronic afterburner in the AMPT model
- Extended to include deuteron production and annihilation as well as elastic scattering

Energy density in HIC at AGS





- Almost 50% particles are in region of energy density > 2.5 GeV/fm^3.
- Substantial volumes of matter have energy density > 2.5 GeV/fm^3.

ZPC: Zhang's Parton Cascade

B. Zhang, CPC 109, 193 (1998)

Includes only elastic parton-parton scattering with cross section regulated by screening mass and taken to be energy independent

$$\frac{d\sigma}{dt} \approx \frac{9\pi\alpha^2}{2s^2}\left(1+\frac{\mu^2}{s}\right)\left(\frac{1}{t-\mu^2}\right)^2, \quad \sigma \approx \frac{9\pi\alpha^2}{2\mu^2}$$

Instead of determining the screening mass from the parton phase-space distribution, it is taken as a constant to fix the total cross section:

μ = 3.2 fm^{-1}, α_s = 0.47 → σ = 3 mb

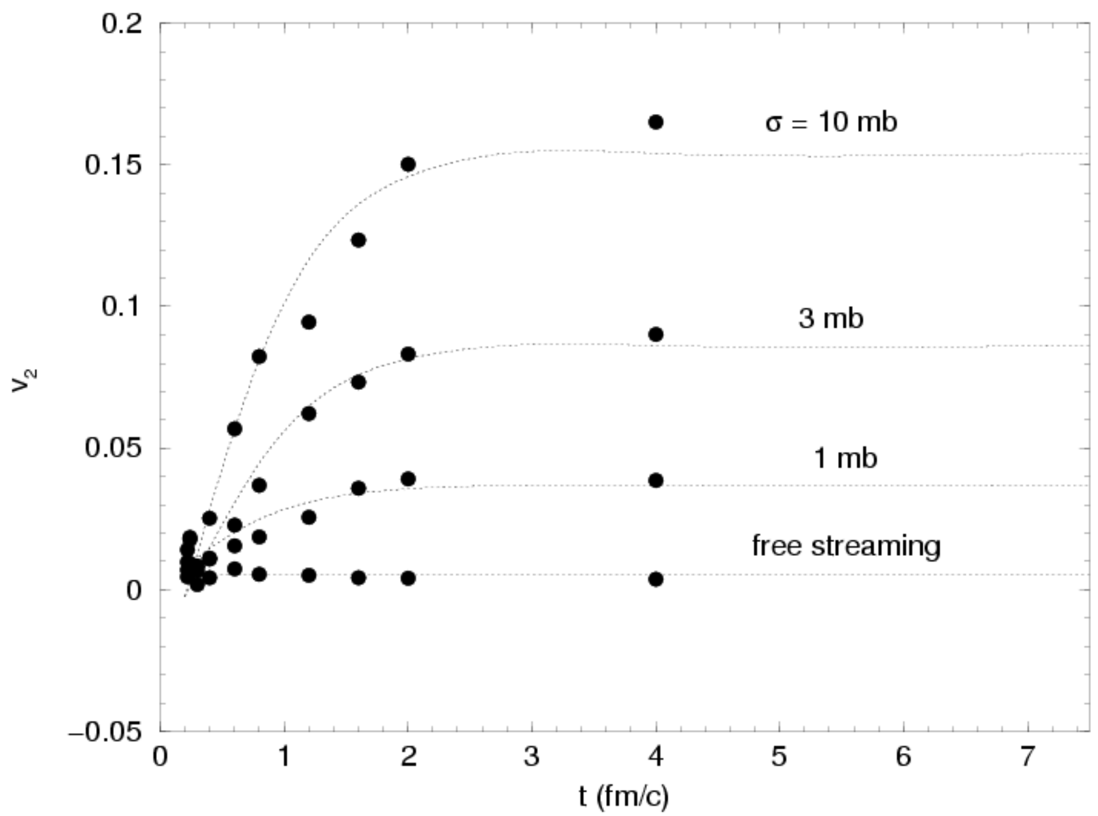
μ = 1.8 fm^{-1}, α_s = 0.47 → σ = 10 mb (A)

μ = 3.2 fm^{-1}, α_s = 0.33 → σ = 1.5 mb but more isotropic (B)

Elliptic flow from Zhang's parton cascade

Zhang, Gyulassy & Ko, PLB 455, 45 (1999)

Based on Zhang's parton cascade (ZPC) (CPC 109, 193 (1998)), using minijet partons from HIJING for Au+Au @ 200 AGeV and b=7.5fm

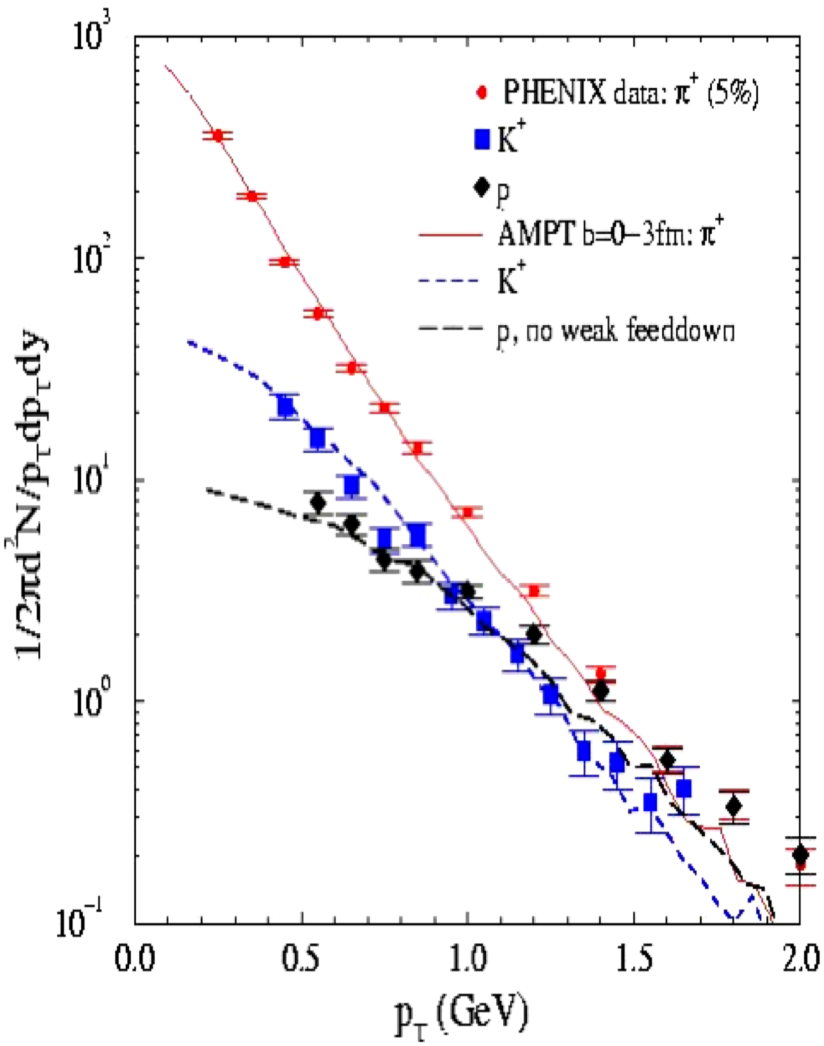


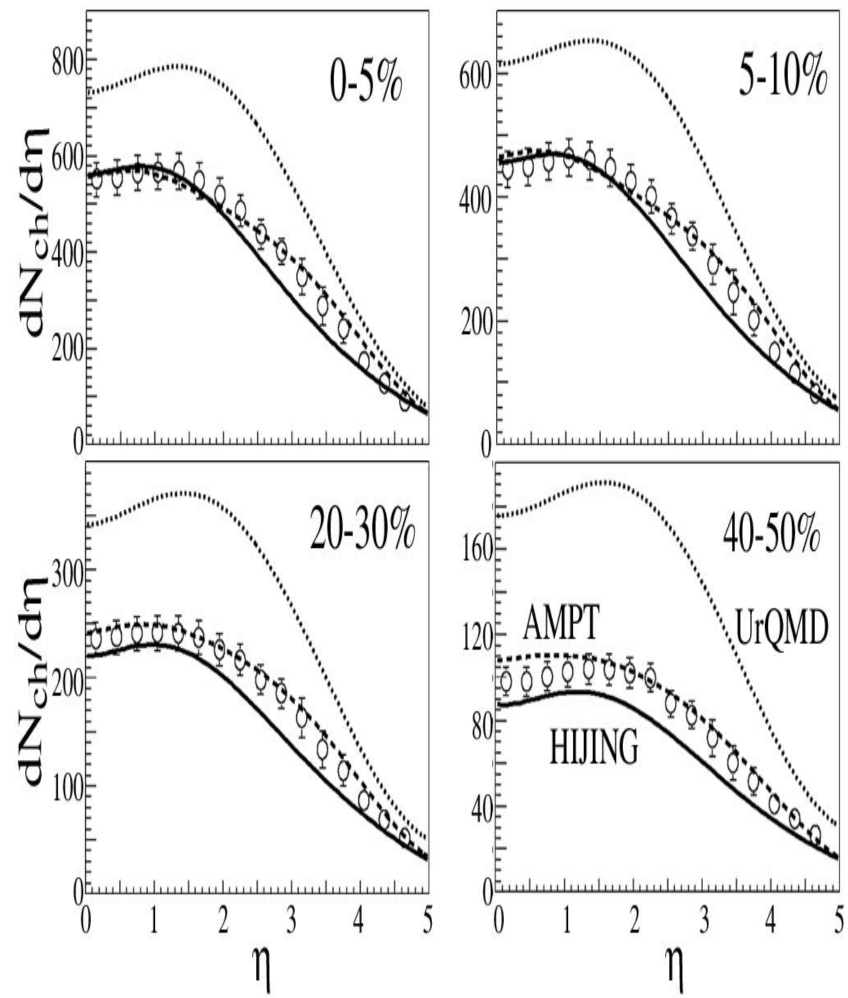
v_2 of partons is sensitive to their scattering cross section.

Transverse momentum and rapidity distributions from default AMPT

Zhang, Ko, Li & Lin, PRC 61, 067901 (2000)

BRAHMS Au+Au @ 200 GeV

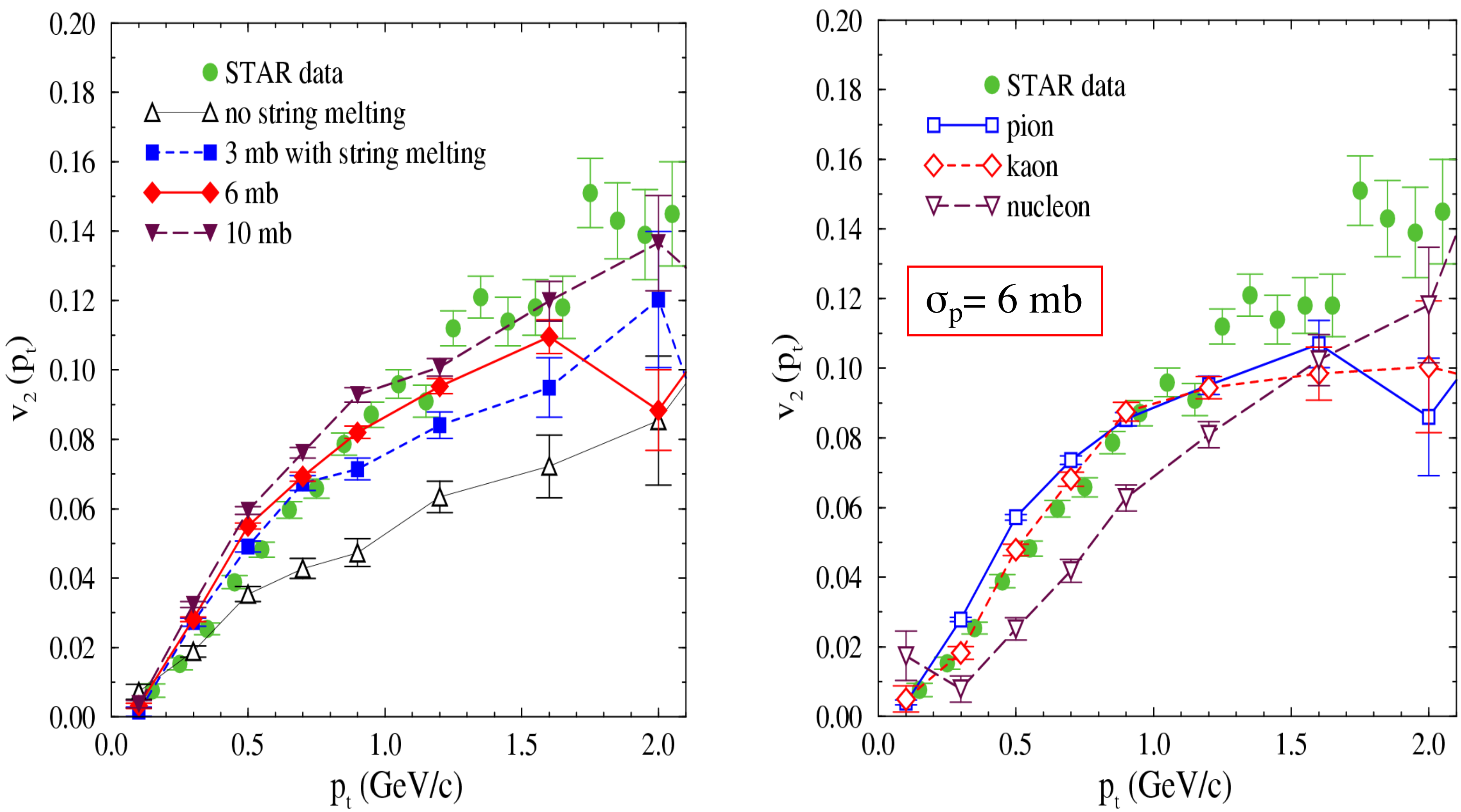




- Default AMPT describes well measured transverse momentum spectra and rapidity distribution.

Elliptic flow from AMPT

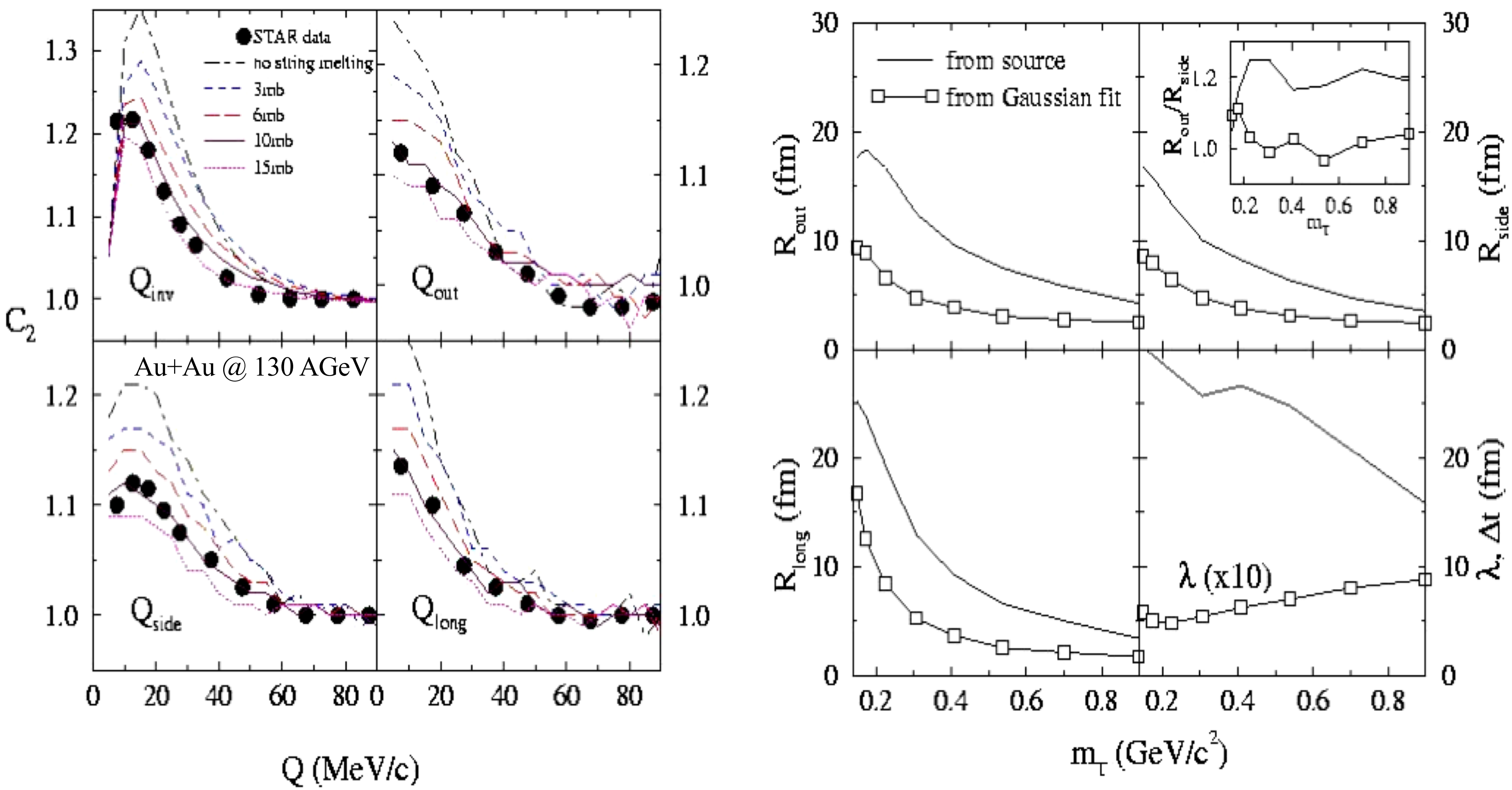
Lin & Ko, PRC 65, 034904 (2002)



- Need string melting and large parton scattering cross section
- Mass ordering of v_2 at low p_T as in hydrodynamic model

Two-Pion Correlation Functions and source radii from AMPT

Lin, Ko & Pal, PRL 89, 152301 (2002)



- Need string melting and large parton scattering cross sections

Phi meson production at RHIC

Pal, Ko & Lin, NPA 707, 525 (2002)

Besides $\varphi \leftrightarrow K\bar{K}$, phi meson can be produced and absorbed via various hadronic reactions, calculable in meson-exchange model [Chung, Li, and Ko, NPA 625, 347 (1997)]

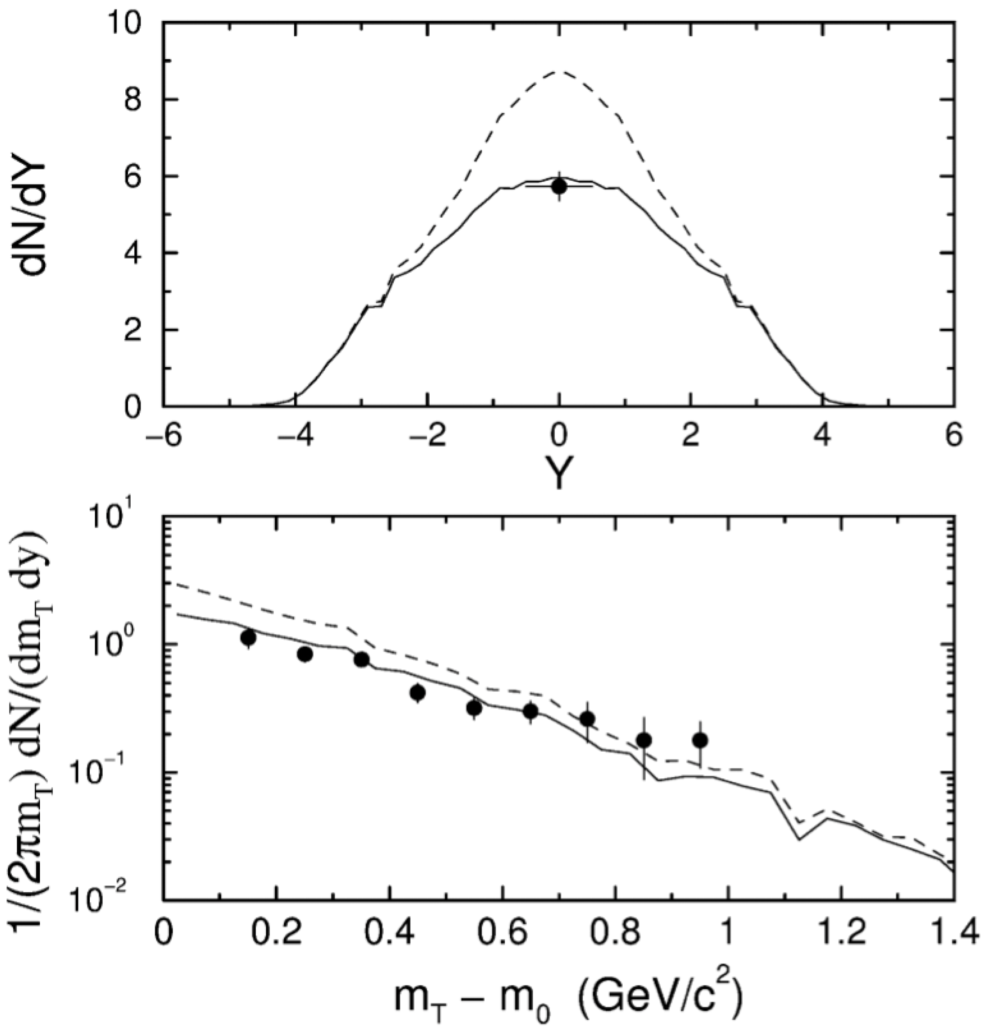
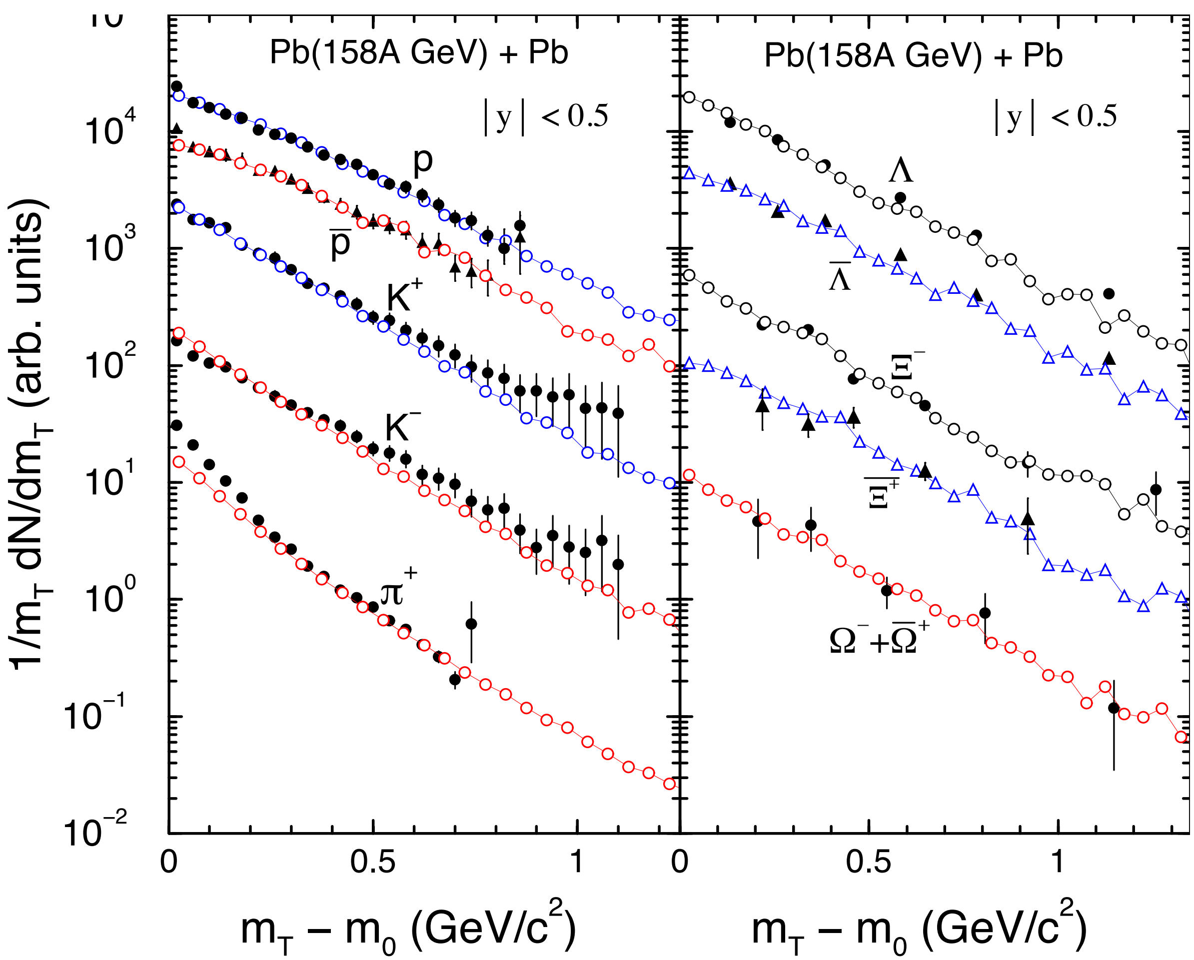


Fig. 5. The rapidity distribution (top panel) and the transverse mass spectra (bottom panel) for midrapidity ($|y| < 0.5$) phi mesons reconstructed from K^+K^- pairs (solid curves) and from $\mu^+\mu^-$ channel (dashed curves) for Au+Au collisions at RHIC energy of $\sqrt{s}$= 130 A GeV at an impact parameter of b = 5.3 fm in the AMPT model. The solid circles are the STAR experimental data [41] for 0–11% central collisions for ϕ reconstructed from K^+K^- decay.

Multistrange baryon production

Pal, Ko & Lin, NPA 730, 143 (2004)



Strange-exchange reactions

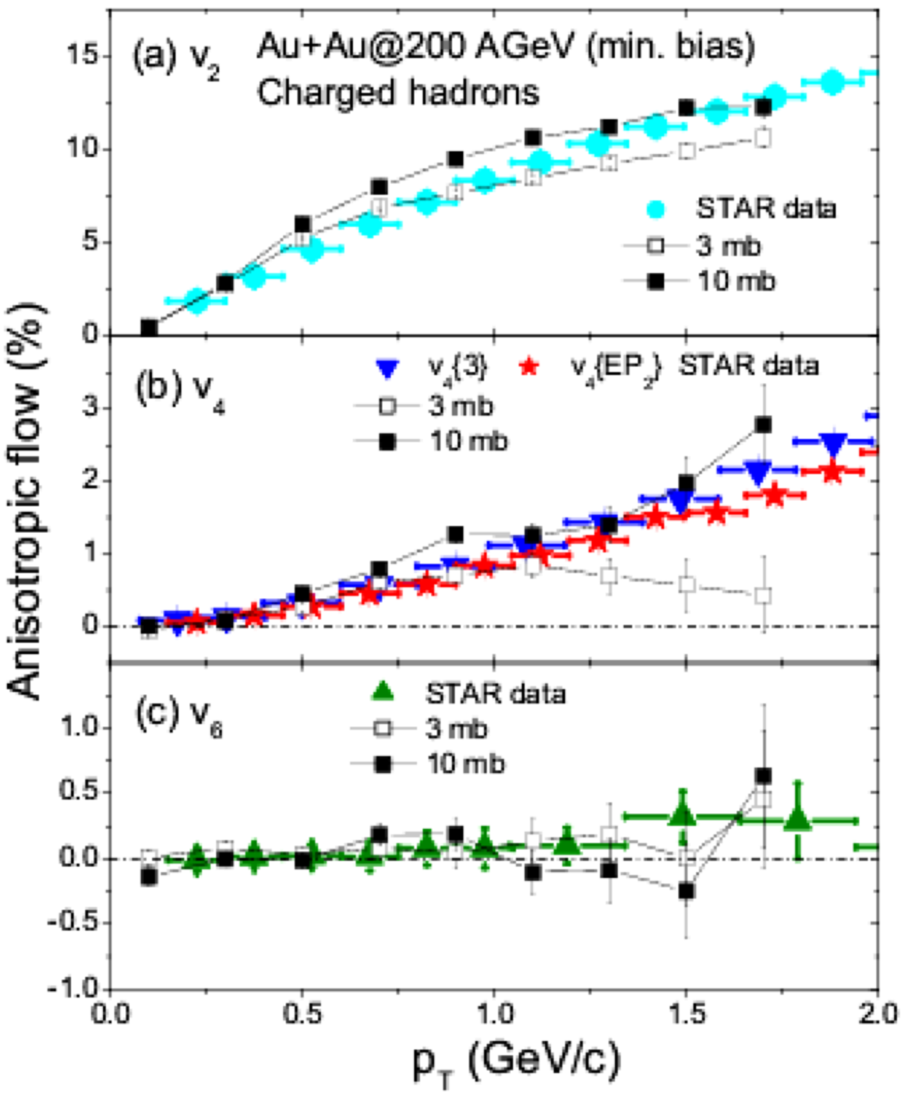
$$\bar{K}\Lambda \leftrightarrow \Xi\pi(\eta)$$
$$\bar{K}\Sigma \leftrightarrow \Xi\pi(\eta)$$
$$\bar{K}\Xi \leftrightarrow \Omega\pi(\eta)$$
$$K\bar{\Lambda} \leftrightarrow \bar{\Xi}\pi(\eta)$$
$$K\bar{\Sigma} \leftrightarrow \bar{\Xi}\pi(\eta)$$
$$K\bar{\Xi} \leftrightarrow \bar{\Omega}\pi(\eta)$$

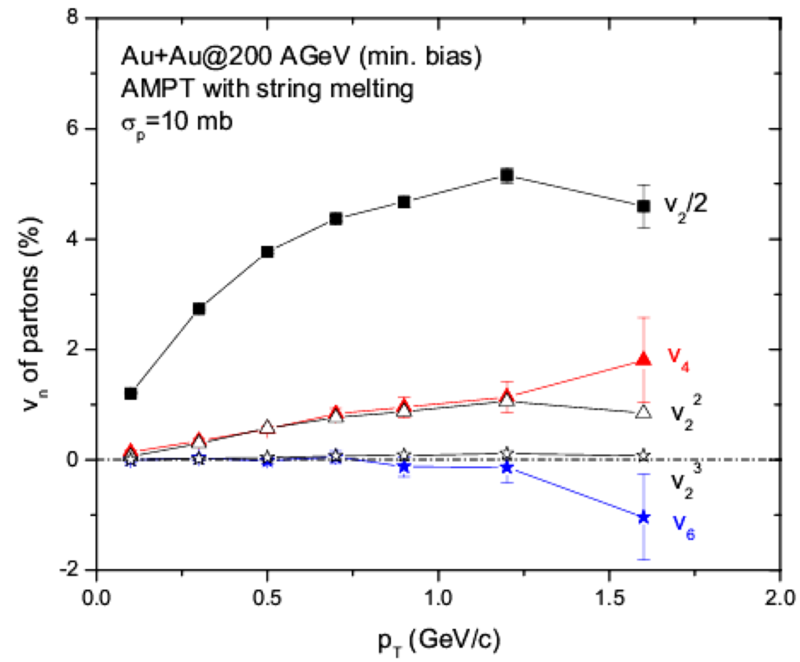
- AMPT gives a good description of multistrange hadrons measured in experiments.

Higher-order anisotropic flows

Chen, Ko & Lin, PRC 69, 031901(R) (2004)

Data can be described by a multiphase transport (AMPT) model





Parton cascade

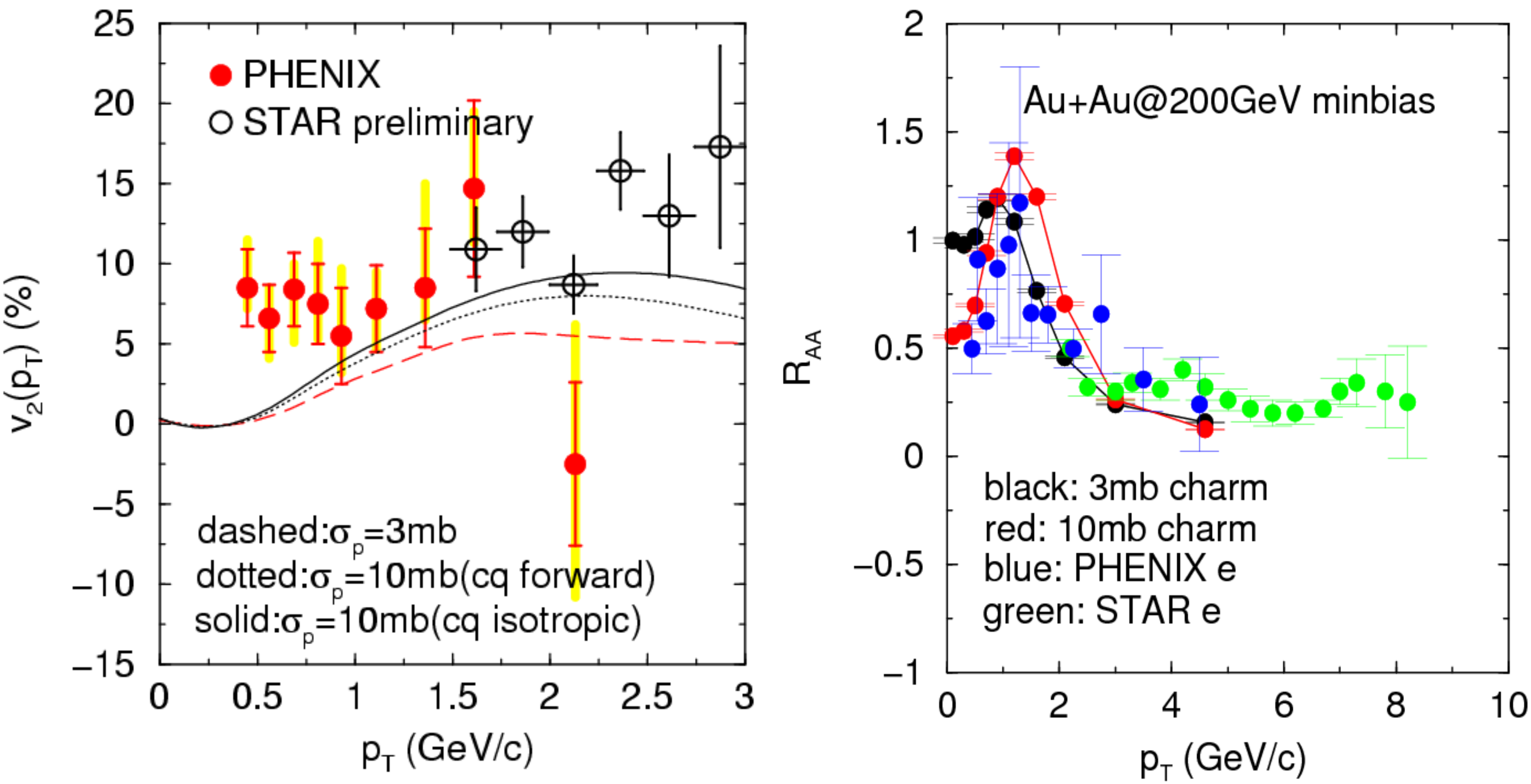
$$v_{4,q} \approx v_{2,q}^2$$

Data

$$\frac{v_4}{v_2^2} \approx 1.2 \Rightarrow v_{4,q} \approx 2v_{2,q}^2 \text{ in naive quark coalescence model}$$

Charm R_{AA} and elliptic flow from AMPT

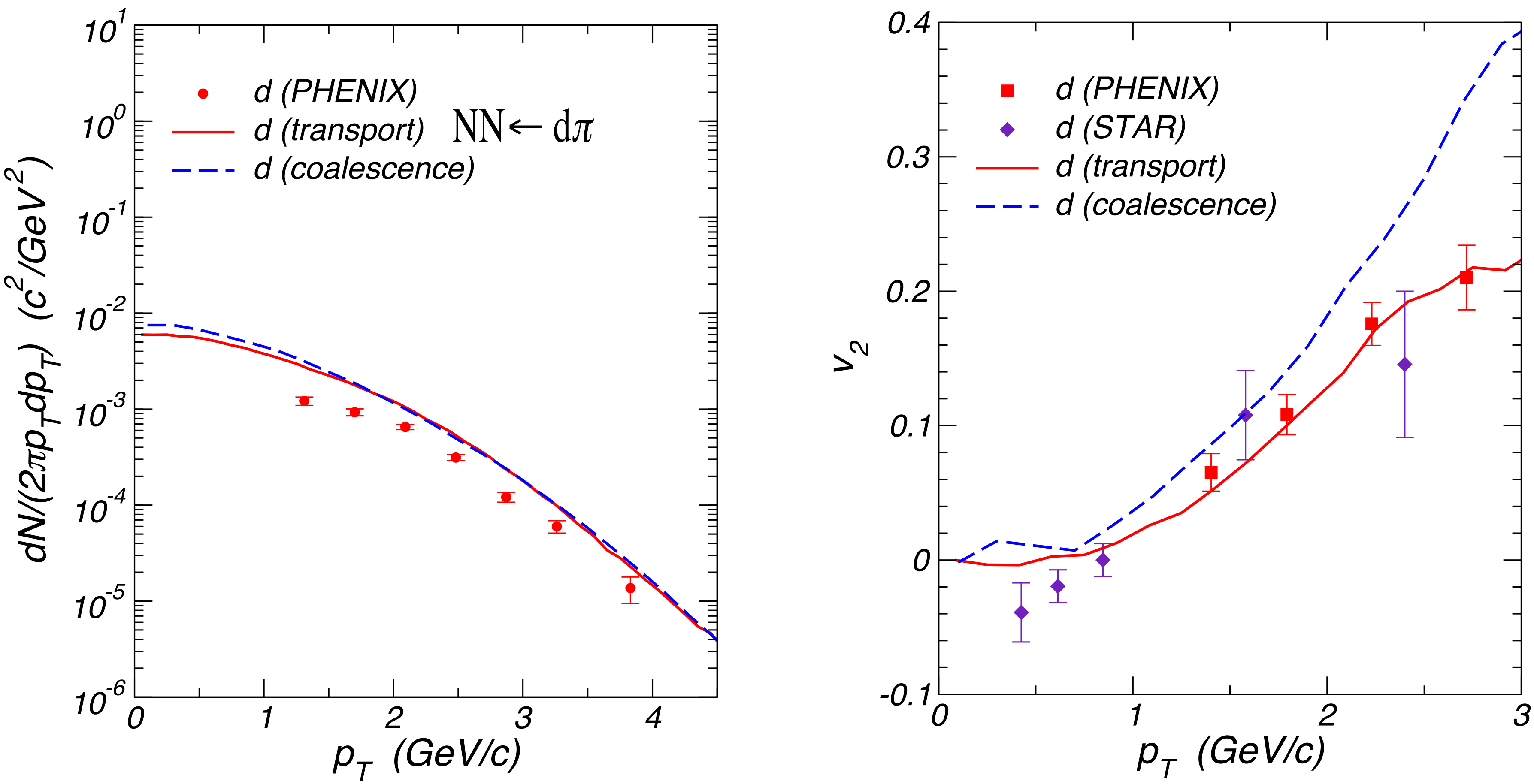
Zhang, Chen & Ko, PRC 72, 024906 (05)



- Need large charm scattering cross section to explain data.
- Smaller charmed meson elliptic flow is due to use of current light quark masses in ZPC.

Deuteron p_T spectrum and elliptic flow

Oh, Lin & Ko, PRC 80, 064902 (2009)

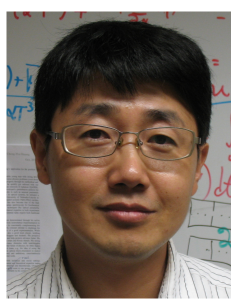


- Similar p_T spectrum from transport and coalescence models
- Smaller elliptic flow at large p_T from transport model than from coalescence model

- 2011 – 2019:

- Subthreshold cascade production (F. Li)
- Quarkonia production in HIC (T. Song, K. C. Han, Y. P. Liu)
- Charmonium at finite temperature (T. Song, S. H. Lee, K. Morita)
- Exotic hadron production in HIC (S. H. Lee, A. Ohnish, S. Choi, et al.)
- Triangular flow and dihadron correlations (J. Xu)
- Effects initial fluctuations on jet energy loss (H. Z. Zhang, T. S. Song)
- Partonic and hadronic potential effects in HIC (J. Xu, T. Song, L. W. Chen, S. H. Lee)
- Density fluctuations in HIC (F. Li)
- Hadronization via quark recombination (K. C. Han, R. J. Fries)
- Chiral magnetic and vortical effects (Y. F. Sun)
- Light nuclei production (L. L. Zhu, X. J. Yin, H. Zheng, W. B. Zhao, H. Z. Song, K. J. Sun, L. W. Chen, Z. B. Xu)
- Isospsin-dependent RVUU and charged pion ratio (T. Song, Z. Zhang)
- Nuclear effective interactions and chiral nuclear forces (Z. Zhang, J. Holt, Y. Lin, J. Xu, A. Carbone)

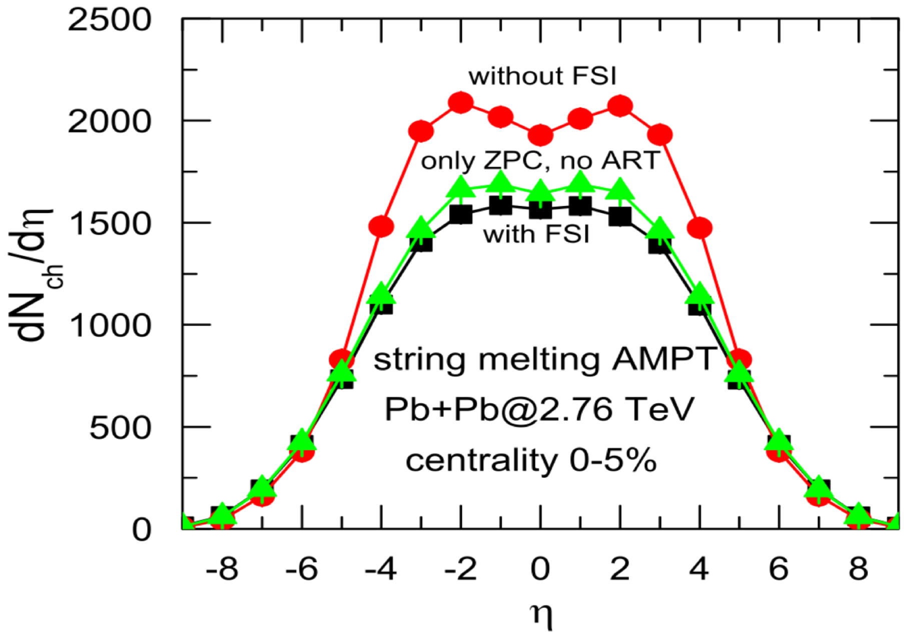


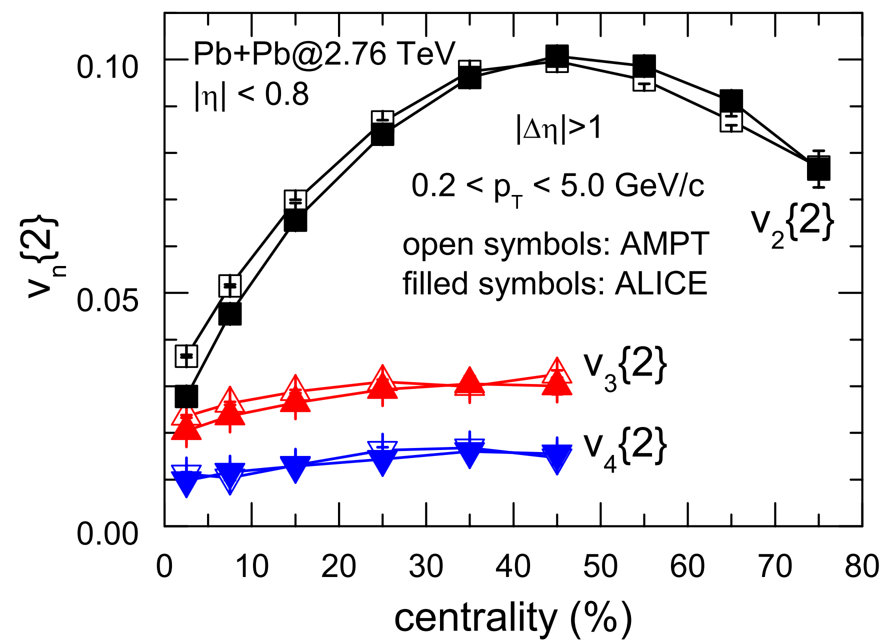


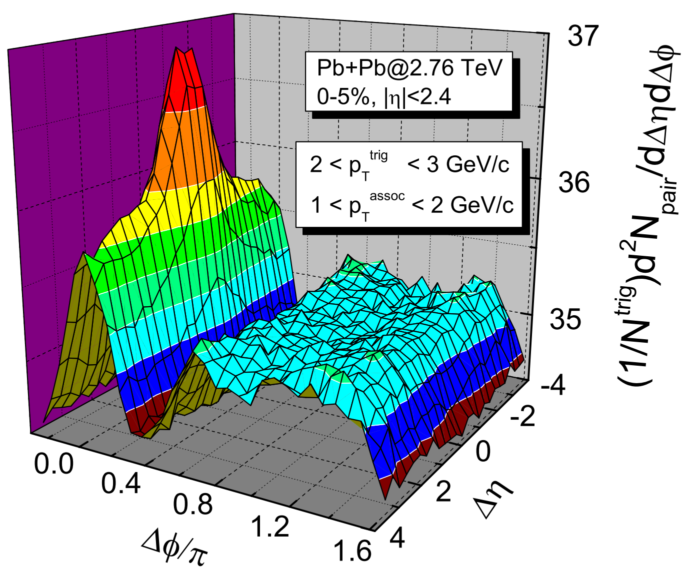


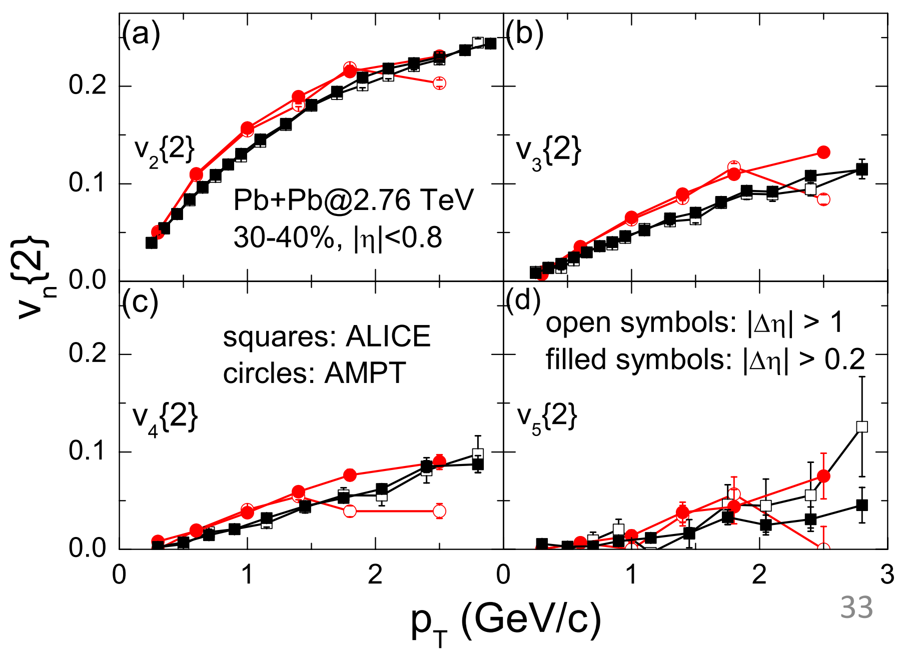
AMPT results for LHC

Jun & Ko, PRC 83, 034904 (11); 84, 044907 (11)









PRL 112, 012301 (2014) PHYSICAL REVIEW LETTERS week ending 10 JANUARY 2014

Elliptic Flow Splitting as a Probe of the QCD Phase Structure at Finite Baryon Chemical Potential

Jun Xu,[1,*] Taesoo Song,[2] Che Ming Ko,[2] and Feng Li[2]

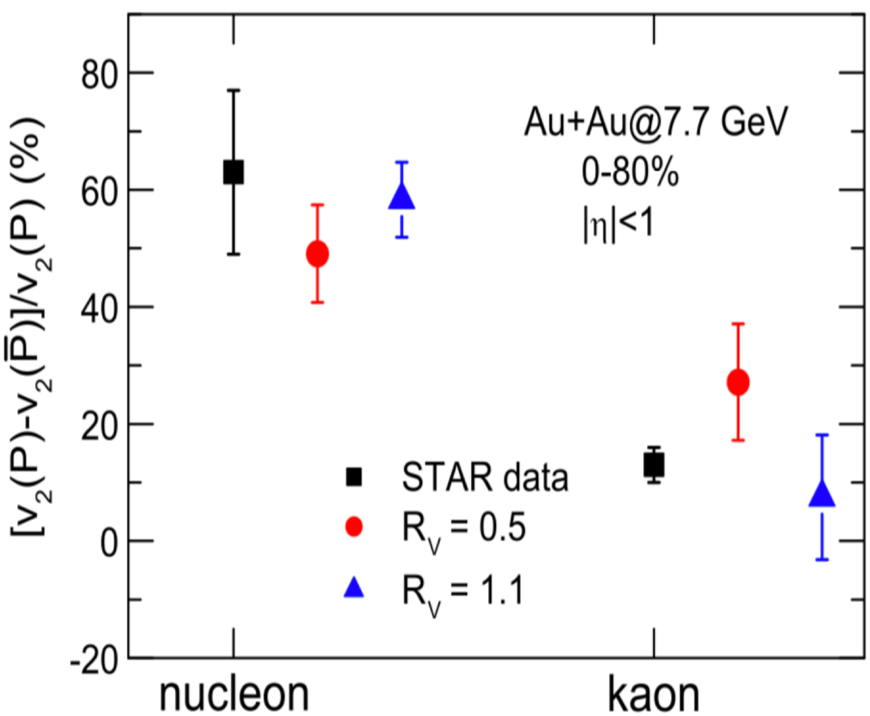


FIG. 4 (color online). Relative elliptic flow difference between nucleons and antinucleons as well as kaons and antikaons for different values of $R_V = G_V/G$ in the NJL model compared with the STAR data [8].

Using a partonic transport model based on the 3-flavor Nambu–Jona-Lasinio model and a relativistic hadronic transport model to describe, respectively, the evolution of the initial partonic and the final hadronic phase of heavy-ion collisions at energies carried out in the beam-energy scan program of the BNL Relativistic Heavy Ion collider, we study the effects of both the partonic and hadronic mean-field potentials on the elliptic flow of particles relative to that of their antiparticles. We find that to reproduce the measured relative elliptic flow differences between nucleons and antinucleons as well as between kaons and antikaons requires a vector coupling constant as large as 0.5–1.1 times the scalar coupling constant in the Nambu–Jona-Lasinio model. Implications of our results in understanding the QCD phase structure at finite baryon chemical potential are discussed.

PHYSICAL REVIEW C **87**, 054902 (2013)

Effects of initial-state fluctuations on jet-energy loss

Hanzhong Zhang, Taesoo Song, and Che Ming Ko

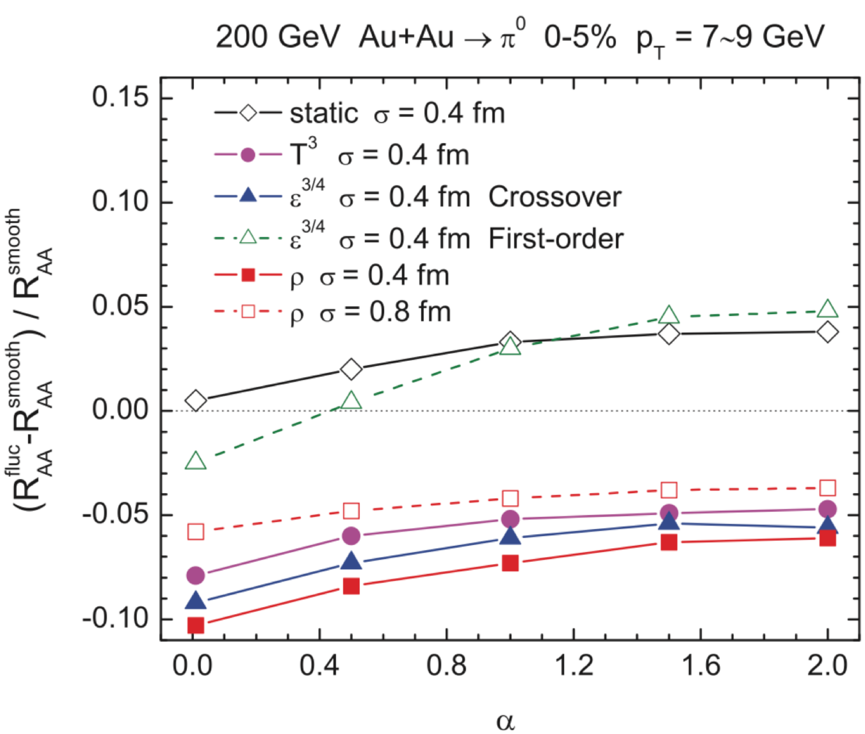


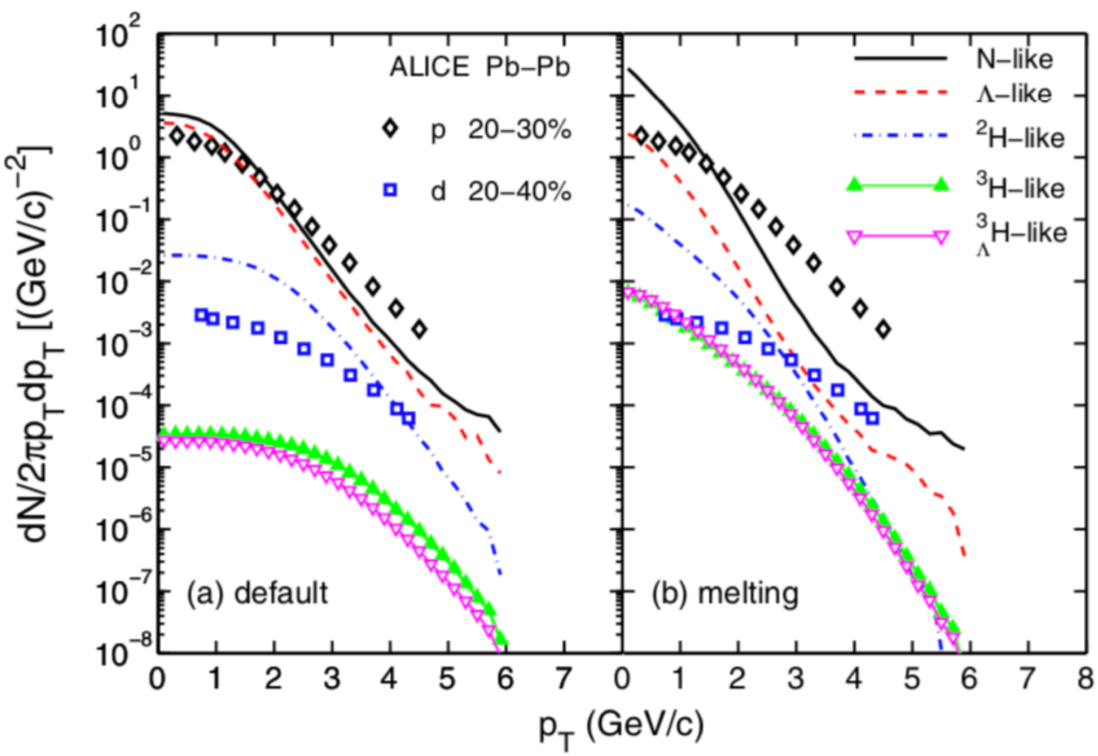
FIG. 4. (Color online) Relative difference between the nuclear modification factors of $p_T = 7$–9 GeV hadrons as a function of the path-length dependence parameter α for different medium dependence in central Au + Au collisions.

The effect of initial-state fluctuations on jet-energy loss in relativistic heavy-ion collisions is studied in a 2 + 1-dimensional ideal hydrodynamic model. Within the next-to-leading order perturbative QCD description of hard scatterings, we find that a jet loses slightly more energy in the expanding quark-gluon plasma if the latter is described by the hydrodynamic evolution with fluctuating initial conditions compared to the case with smooth initial conditions. A detailed analysis indicates that this is mainly due to the positive correlation between the fluctuation in the production probability of parton jets from initial nucleon-nucleon hard collisions and the fluctuation in the medium density along the path traversed by the jet. This effect is larger in noncentral than in central relativistic heavy ion collisions and also for jet-energy loss that has a linear than a quadratic dependence on its path length in the medium.

PHYSICAL REVIEW C **92**, 064911 (2015)

Light (anti-)nuclei production and flow in relativistic heavy-ion collisions

Lilin Zhu,[1,*] Che Ming Ko,[2,†] and Xuejiao Yin[1,‡]
[1] *Department of Physics, Sichuan University, Chengdu 610064, China*
[2] *Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*
(Received 13 October 2015; revised manuscript received 10 November 2015; published 28 December 2015)



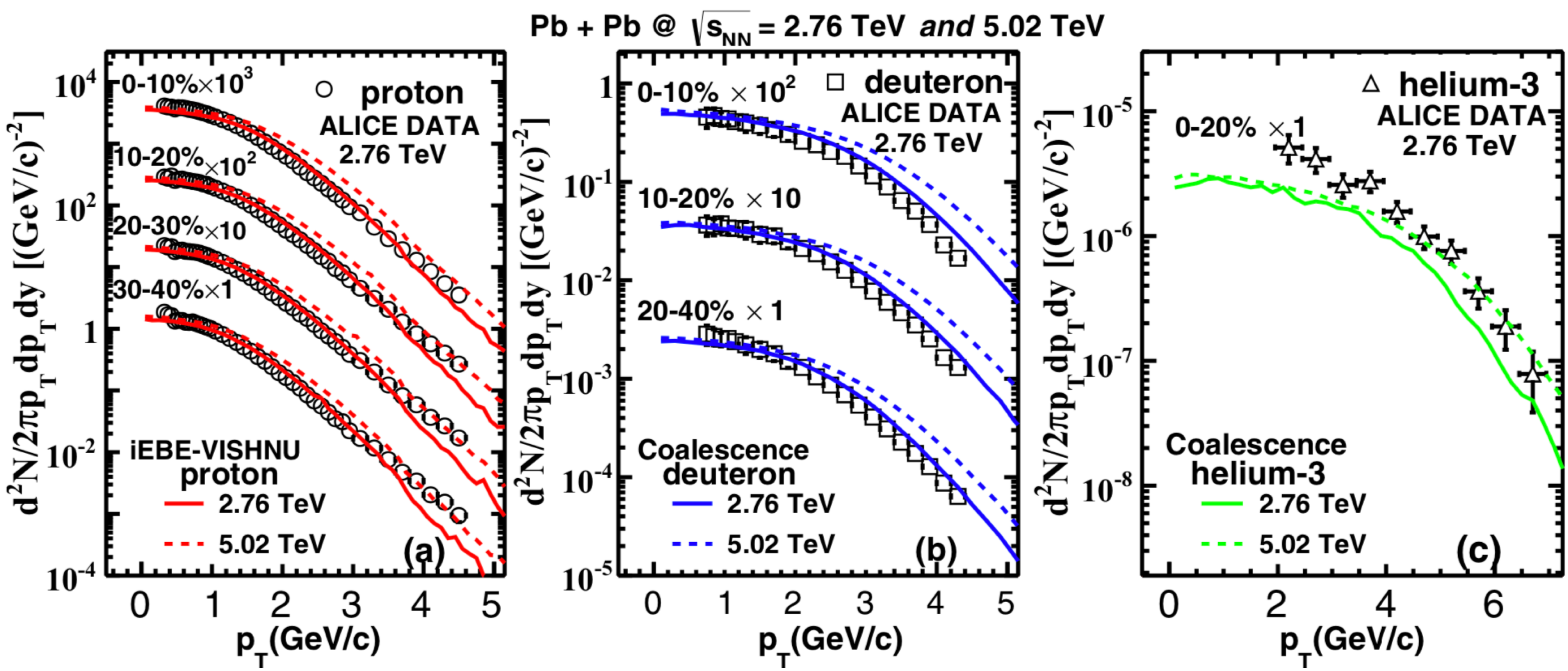
Using the coalescence model based on the phase-space distributions of protons, neutrons, Λs, and their antiparticles from a multiphase transport (AMPT) model, we study the production of light nuclei (^{2}H, ^{3}H, ^{3}He, $^3_\Lambda$H) and their antinuclei in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. The resulting transverse momentum spectra, elliptic flows, and coalescence parameters for these nuclei are presented and compared with available experimental data. We also show the constituent number scaled elliptic flows of these nuclei and discuss its implications.

PHYSICAL REVIEW C **98**, 054905 (2018)

Spectra and flow of light nuclei in relativistic heavy ion collisions at energies available at the BNL Relativistic Heavy Ion Collider and at the CERN Large Hadron Collider

Wenbin Zhao,[1,2] Lilin Zhu,[3] Hua Zheng,[4,5] Che Ming Ko,[6] and Huichao Song[1,2,7]

IEBE-VISHNU hybrid model with AMPT initial conditions



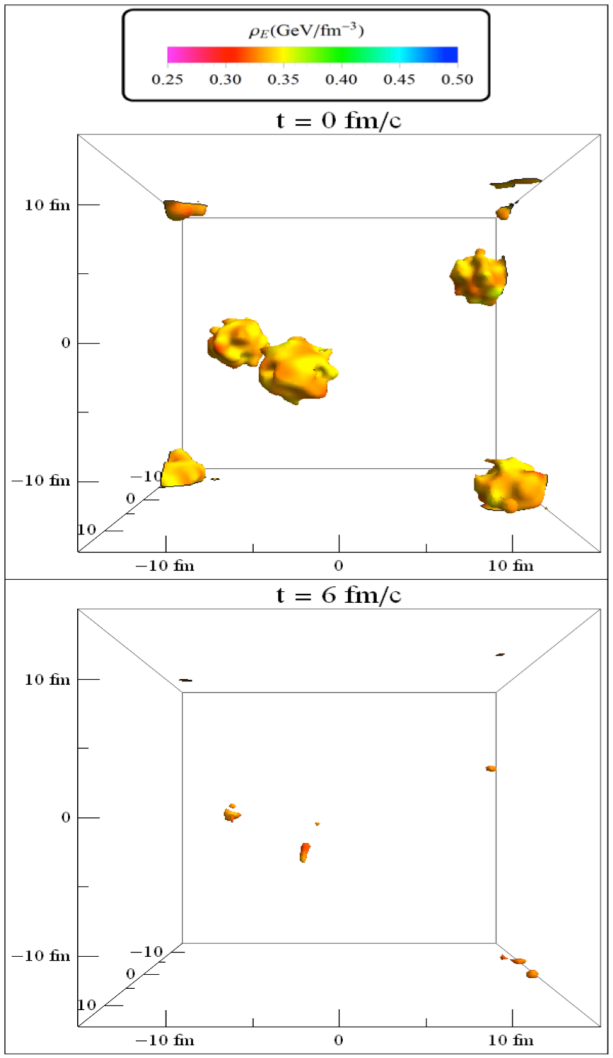
Elliptic flow of deuteron measured by ALICE is also satisfactorily described.

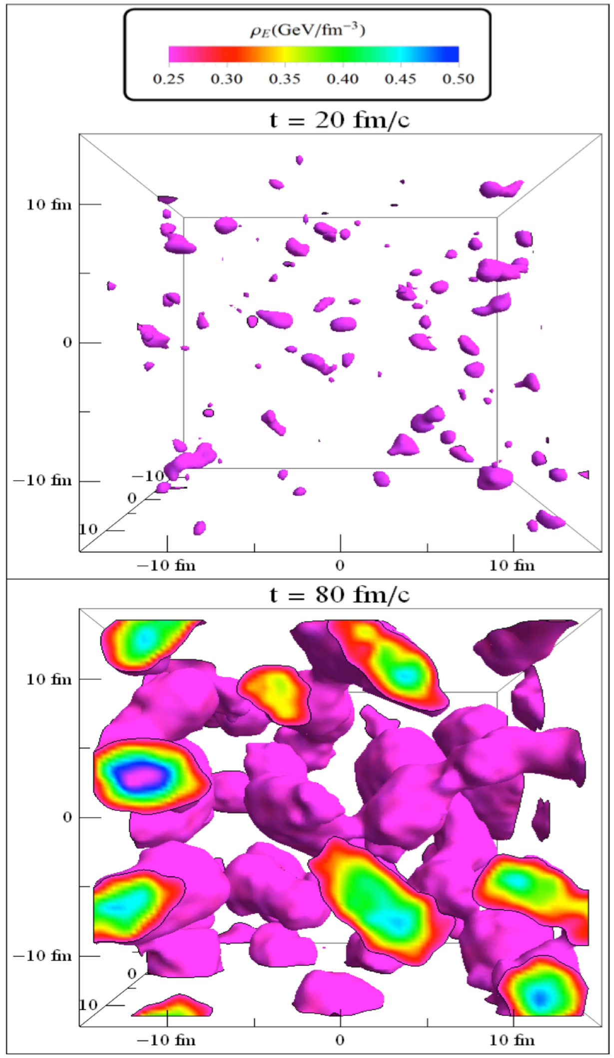
Transport description of quark matter in a box

$$\partial_t f + \mathbf{p}/E \cdot \nabla f - \nabla H \cdot \nabla_p f = \mathcal{C}[f]$$

F. Li and Ko, PRC 93, 035205 (2016)

C[f] includes quark elastic scattering with cross section of 3 mb

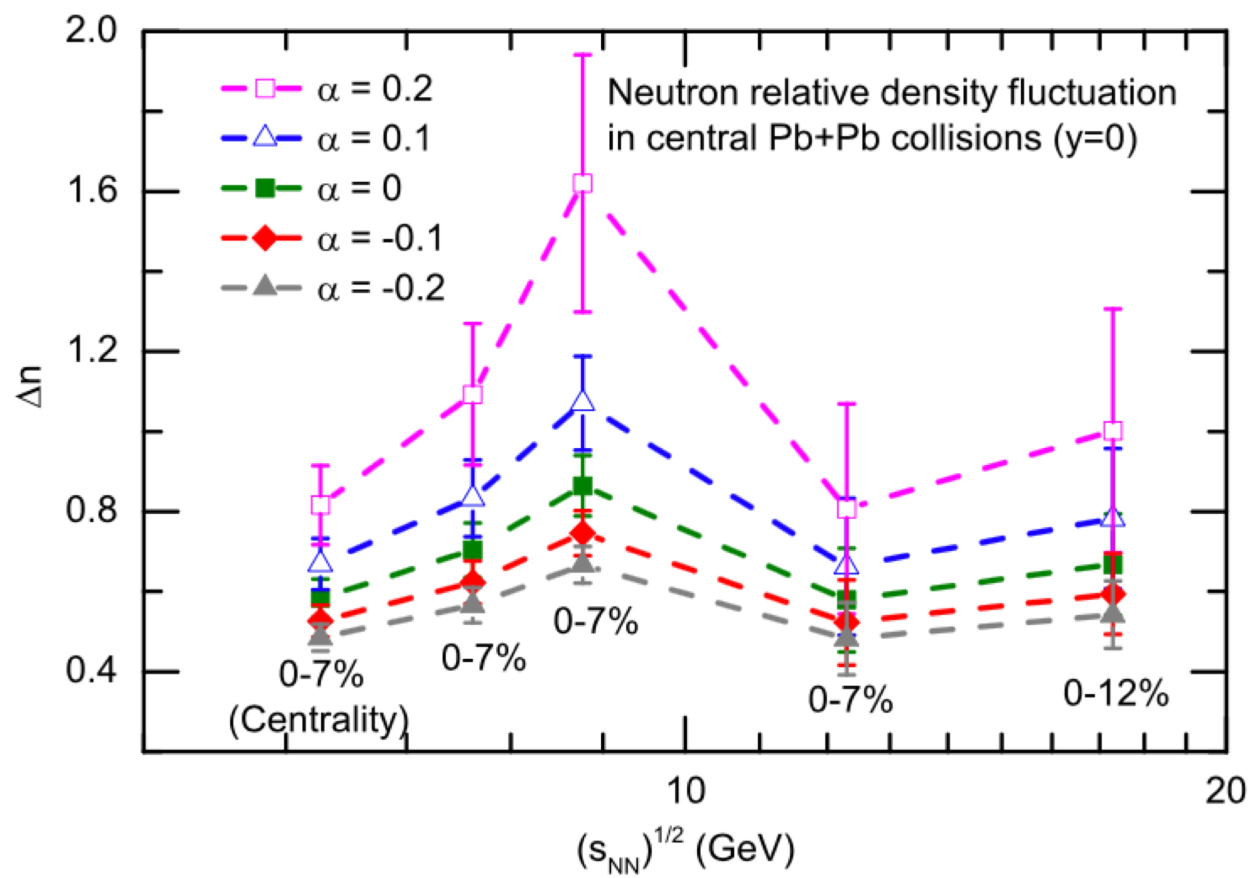




- Left: $n_q = 0.4/fm^3$, T = 100 MeV; outside spinodal region
- Right: $n_q = 0.4/fm^3$, T = 20 Mev, inside Spinodal region; large density fluctuations appear due to growth of unstable modes
- Colored regions correspond to $N_q > 0.6/fm^3$

Probing QCD critical fluctuations from light nuclei production in relativistic heavy-ion collisions PLB 774, 103 (2017)

Kai-Jia Sun [a], Lie-Wen Chen [a,*], Che Ming Ko [b], Zhangbu Xu [c,d]



$$\langle \delta n \delta n_p \rangle = \alpha \frac{\langle n_p \rangle}{\langle n \rangle} \langle (\delta n)^2 \rangle$$

α is a correlation coefficient describing how neutron and Proton density fluctuations are correlated.

Fig. 1. Collision energy dependence of the neutron relative density fluctuation Δn in central Pb + Pb collisions at SPS energies based on data from Ref. [47]. Results for $\alpha = -0.2, -0.1, 0, 0.1$ and 0.2 are shown by various dotted lines.

- Lambda global polarization

Yifeng Sun & Ko, PRC 96, 024906 (2017)

$$\dot{\mathbf{r}} = \frac{\hat{\mathbf{p}} + 2\lambda p(\hat{\mathbf{p}}\cdot\mathbf{b})\boldsymbol{\omega}}{1 + 2\lambda p(\boldsymbol{\omega}\cdot\mathbf{b})}, \quad \dot{\mathbf{p}} = 0.$$

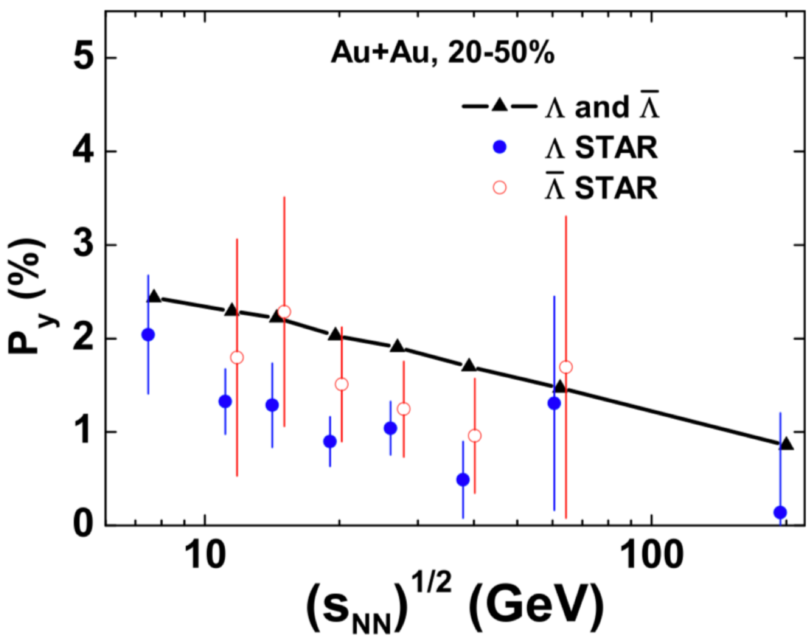


FIG. 4. Energy dependence of the spin polarization of midrapidity ($|y| \leqslant 1$) Λ and $\overline{\Lambda}$ hyperons in Au+Au collisions at energies from 7.7 to 200 GeV. Data with error bars are from the STAR Collaboration [21,46].

- Multiplicity up-down asymmetry as a probe of topological charge fluctuations in QCD

Yifeng Sun and Ko, PLB 789, 228 (2019)

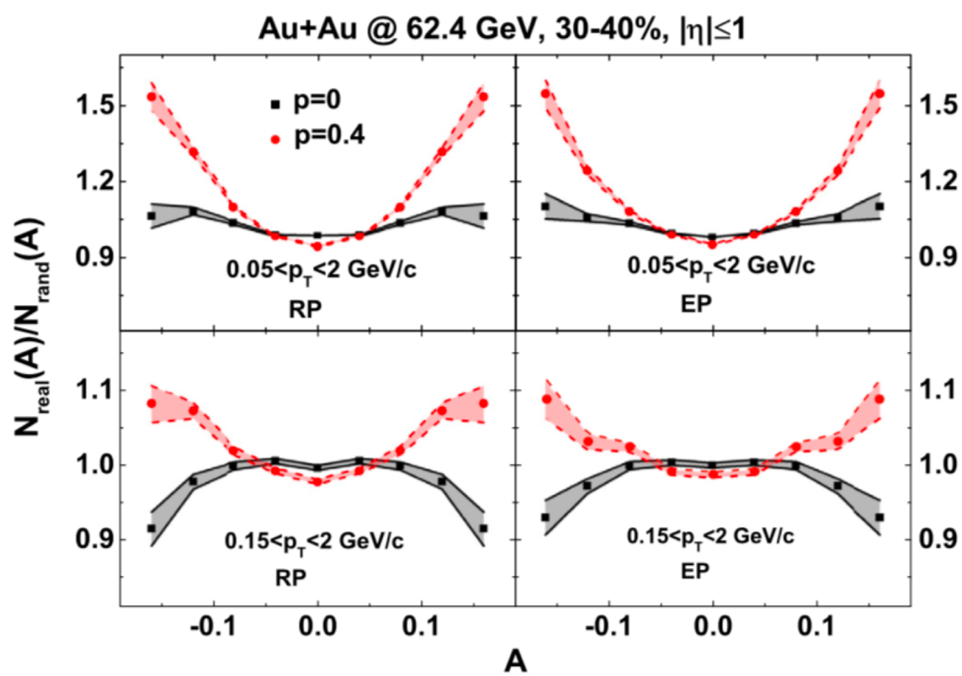


Fig. 4. Ratio of multiplicity up–down asymmetry event distribution to $N_{\rm real}(A)$ to that with random up–down momentum distributions $N_{\rm rand}(A)$ for mid-pseudorapidity light quarks in different transverse momentum ranges in Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV and centrality of 30–40%.

PHYSICAL REVIEW C **95**, 064604 (2017)

Medium effects on pion production in heavy ion collisions

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Cyclotron Institute and Department of Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA
(Received 30 January 2017; published 7 June 2017)

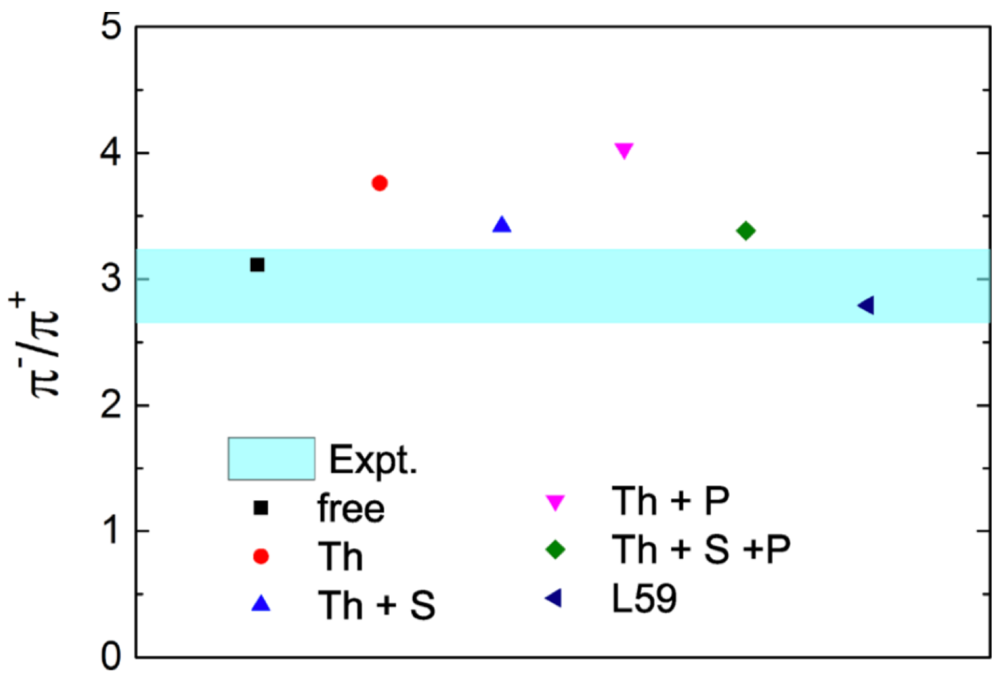

FIG. 7. The π^-/π^+ ratio in Au + Au collisions at impact parameter of 1.4 fm and energy of $E/A = 400$ MeV from the NLρ model in different cases (see text for details). Experimental data [26] from the FOPI collaboration are shown as the cyan band.

Within the framework of the relativistic Vlasov–Uehling–Uhlenbeck transport model based on the relativistic nonlinear NLρ interaction, we study pion in-medium effects on the π^-/π^+ ratio in Au + Au collisions at the energy of E/A = 400 MeV. These effects include the isospin-dependent pion s-wave and p-wave potentials, which are taken from calculations based on the chiral perturbation theory and the Δ-hole model, respectively. Including also the in-medium threshold effects on ? resonance production and decay, our result is in good agreement with measured π^-/π^+ ratio from the FOPI Collaboration.

Summary

- I am grateful to my mentors (Donald Sprung, Gerry Brown, Hans Weidenmuller, and George Bertsch) and collaborators (Su Houng Lee, Ben Hao Sa, Huichao Song, Weibin Zhao, etc.), including 23 postdoctoral research associates (Li-Wen Chen, Yongseok Oh, Jun Xu, Ben-Wei Zhang, etc.) and 11 students, for the exciting and rewarding research career during past fifty years.

- The AMPT model with its fluctuating initial conditions and strong parton scatterings as well as comprehensive hadronic evolution can capture the essential collision dynamics of relativistic heavy ion collisions as revealed in various observables measured in experiments.

- In 2002 AMPT won the RHIC Predictions Competition Prize of Institute of Nuclear Theory at Seattle.

- As of May 10, 2019, 801 citations of Lin, Ko, Li, Zhang & Pal, PRC 72, 064901 (2005) in INSPIRE.