Reflections on AMPT

Che-Ming Ko
Texas A&M University

- AMPT
- Bao-An Li and ART
- Bin Zhang and ZPC as well as default AMPT
- Zie-Wei Lin and string-melting AMPT
- Subrata Pal and strangeness in AMPT
- Some applications of AMPT

Supported by US Department of Energy and the Welch Foundation

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

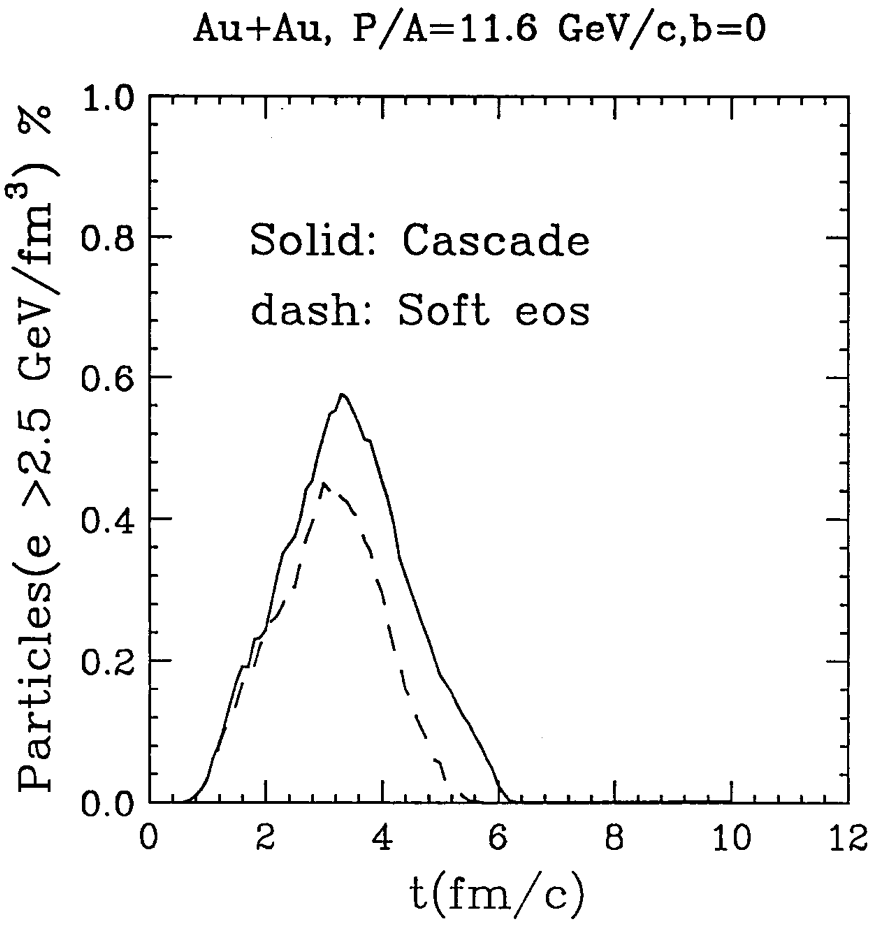
- Bao-An Li (Ph.D. 1991, Michigan State University): 1994 − 1998; Regent Professor, Texas A&M University at Commerce; ART
- Bin Zhang (Ph.D. 1998, Columbia University): 1998 − 2001; Associate Professor, Arkansas State University; ZPC and charm
- Zie-Wei Lin (Ph.D. 1996, Columbia University): 1998 − 2002; Associate Professor, East Carolina University; string melting
- Subrata Pal (Ph.D. 1997, Saha Institute for Nuclear Physics): 2000 − 2002; Associate 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; Associate Professor, Shanghai Institute of Applied Physics; mean fields and LHC
- Yongseok Oh (Ph.D. 1993, Seoul National University): 2010 - 2013; Associate Professor, Kyungpook National University; deuteron

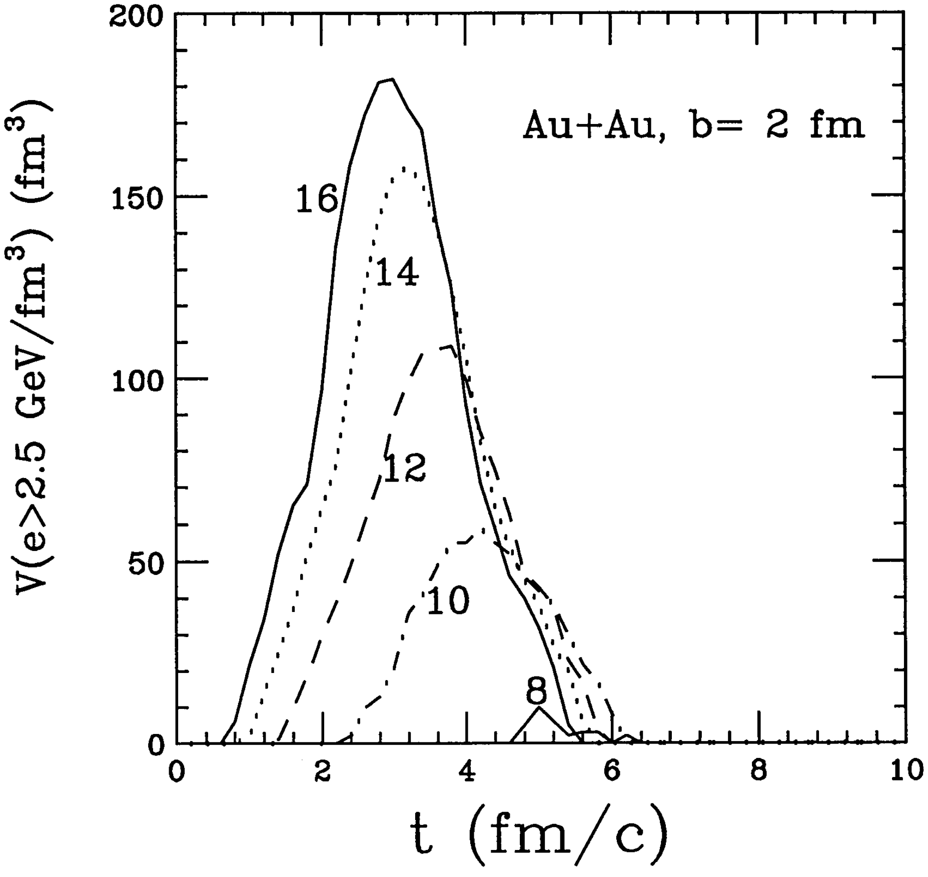
A relativistic transport (ART) model for HIC

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

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

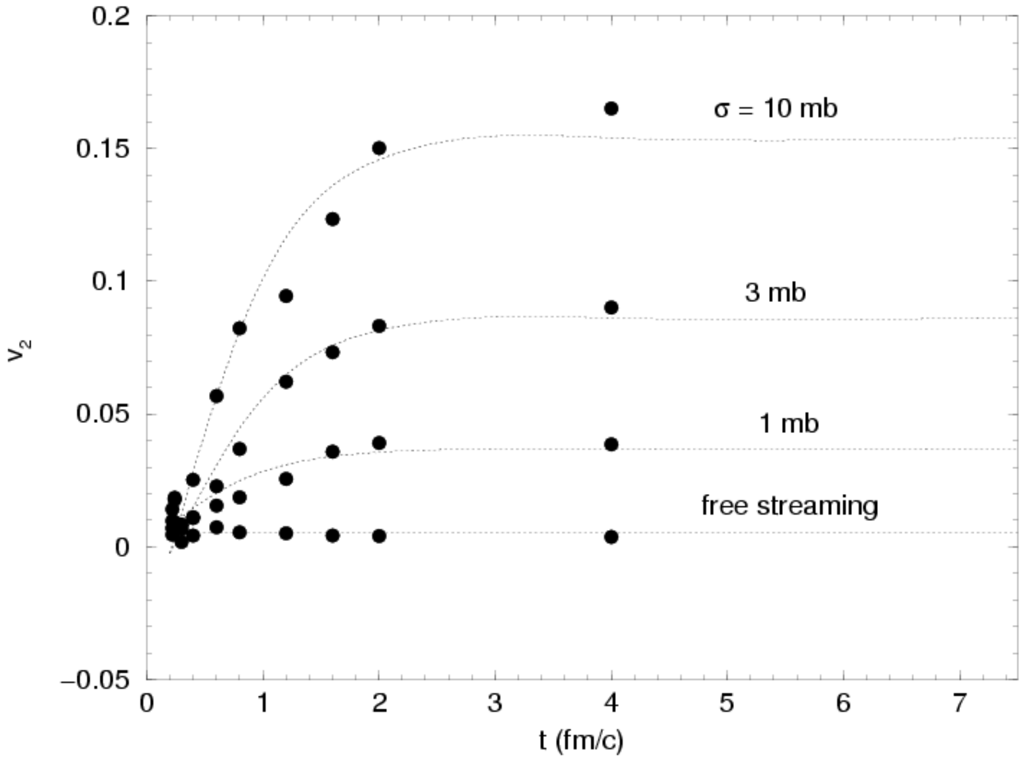
Instead of determining the screening mass from the parton phase-space distribution, it is taken as a constant to fix the total cross section:

$\mu = 3.2$ fm^{-1}, $\alpha_s = 0.47$ → $\sigma = 3$ mb
$\mu = 1.8$ fm^{-1}, $\alpha_s = 0.47$ → $\sigma = 10$ mb (A)
$\mu = 3.2$ fm^{-1}, $\alpha_s = 0.33$ → $\sigma = 1.5$ mb but more isotropic (B)

Elliptic flow from Zhang's parton cascade

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

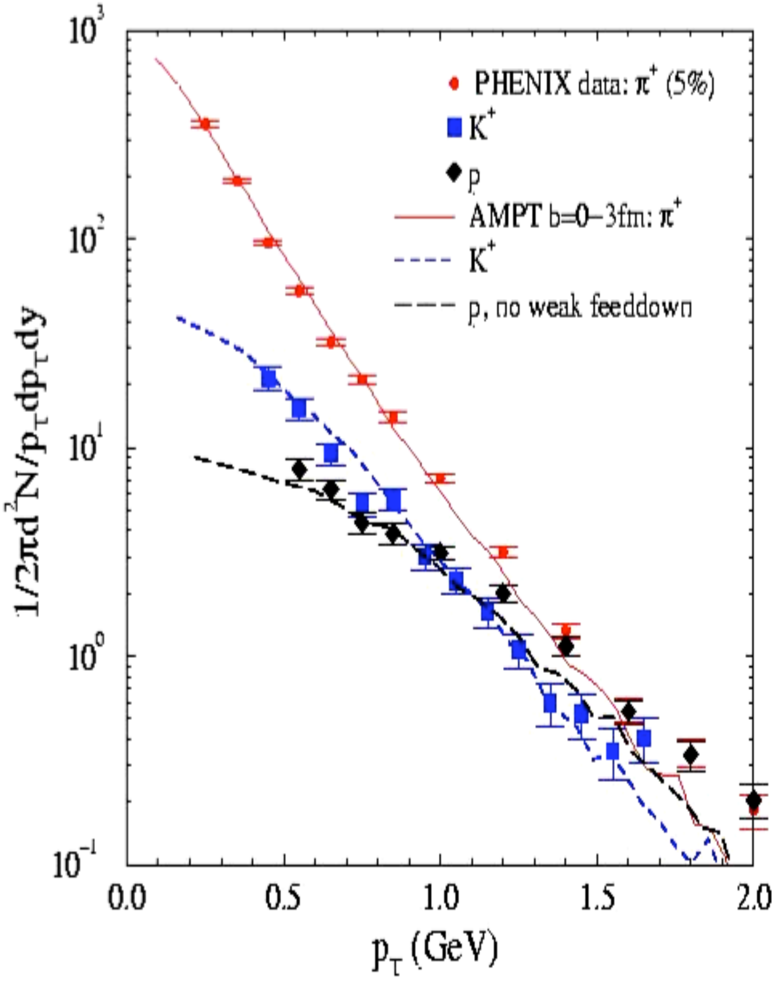
Based on Zhang's parton cascade (ZPC) (CPC 109, 193 (1998)), using minijet partons from HIJING for Au+Au @ 200 AGeV and b=7.5fm

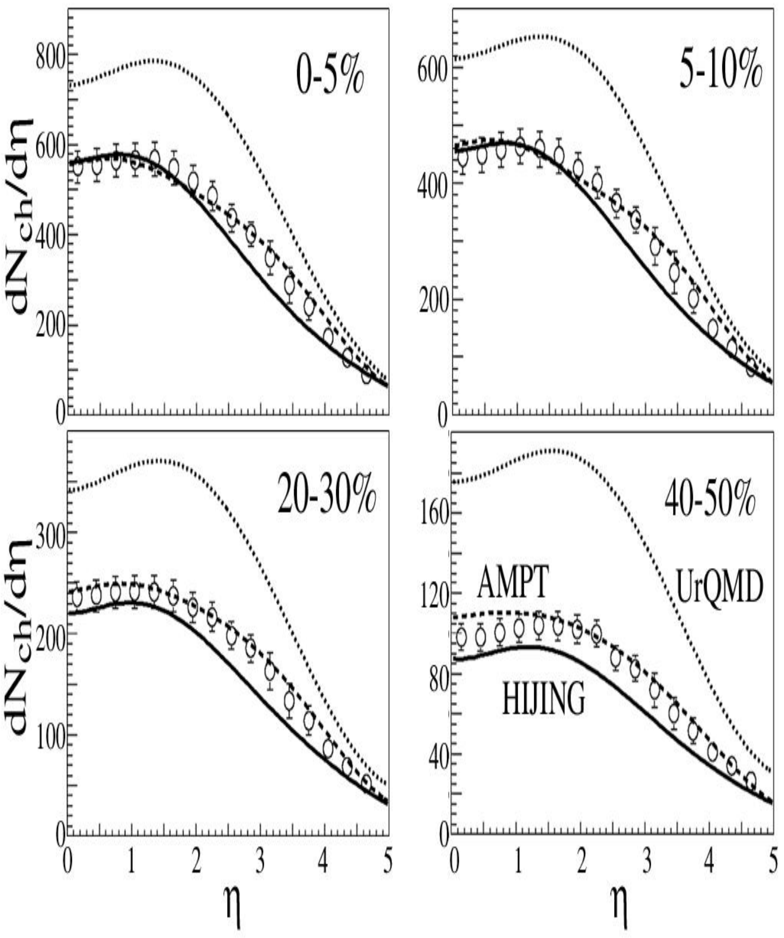


v_2 of partons is sensitive to their scattering cross section.

Transverse momentum and rapidity distributions from default AMPT

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

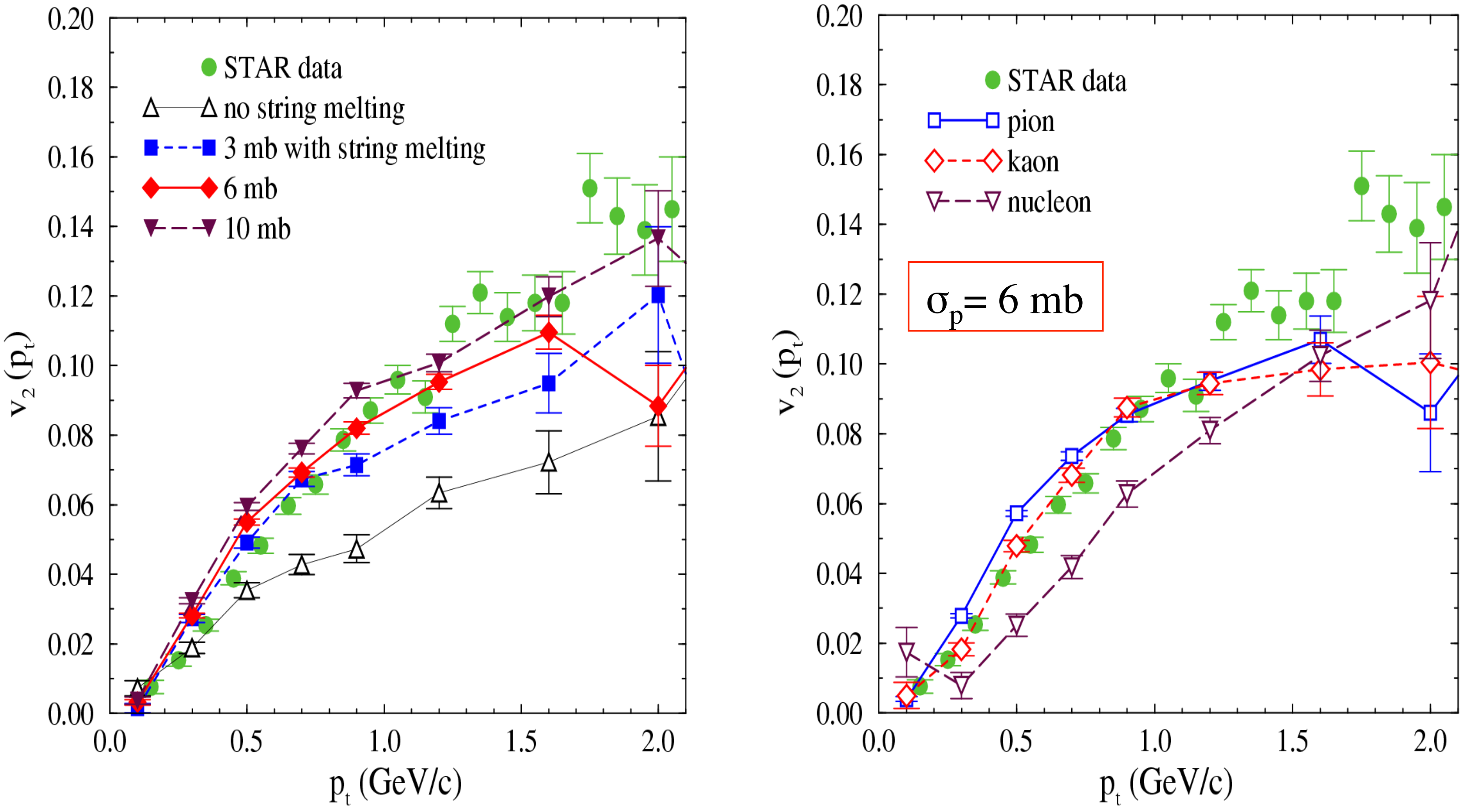



BRAHMS Au+Au @ 200 GeV

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

Elliptic flow from AMPT

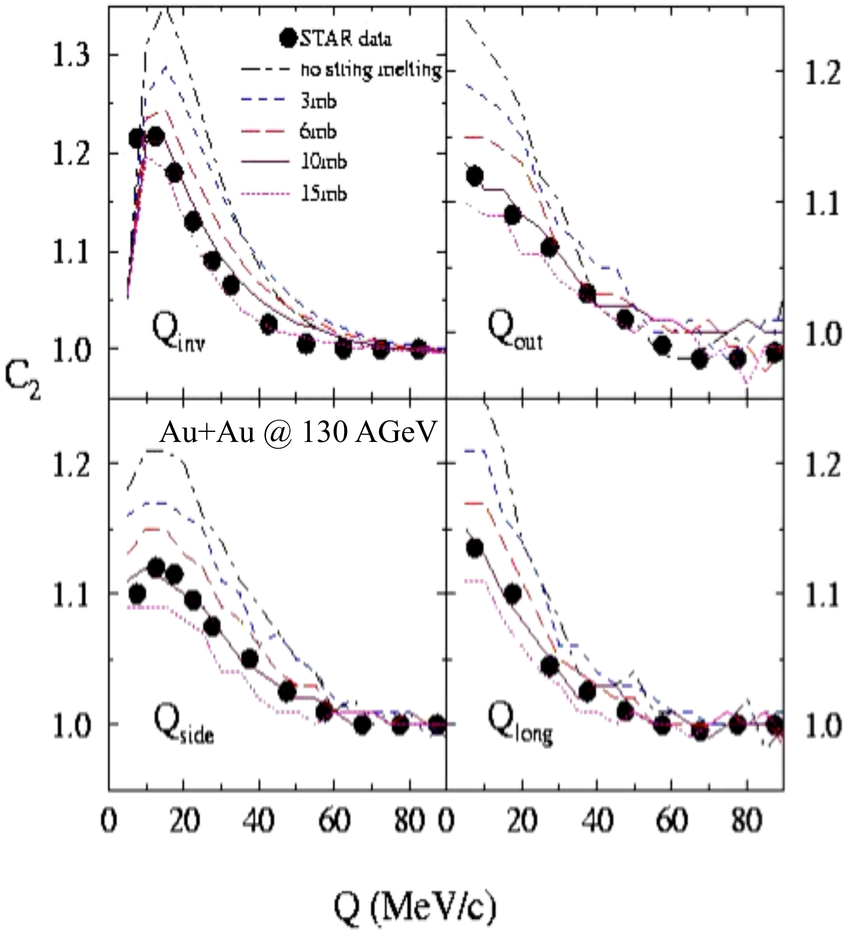
Lin & Ko, PRC 65, 034904 (2002)

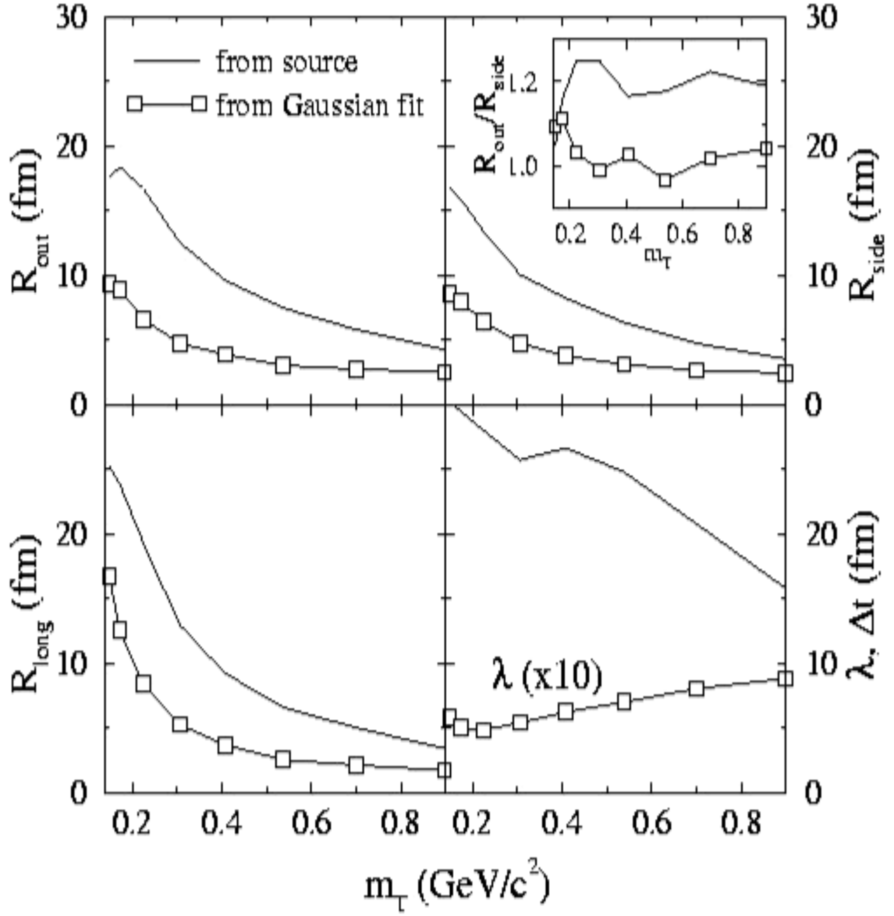


- Need string melting and large parton scattering cross section
- Mass ordering of v_2 at low p_T as in hydrodynamic model

Two-Pion Correlation Functions and source radii from AMPT

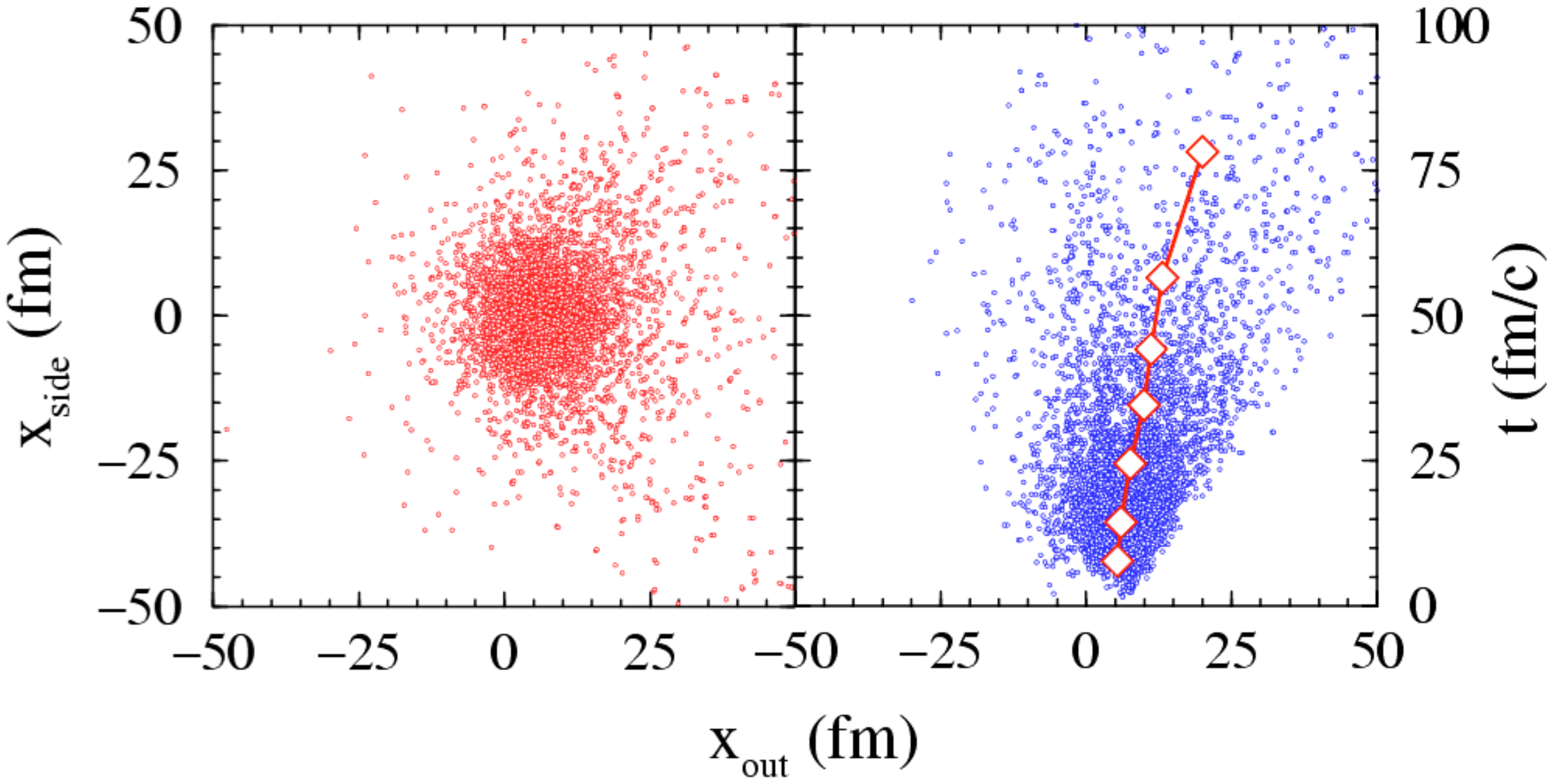
Lin, Ko & Pal, PRL 89, 152301 (2002)





- Need string melting and large parton scattering cross sections

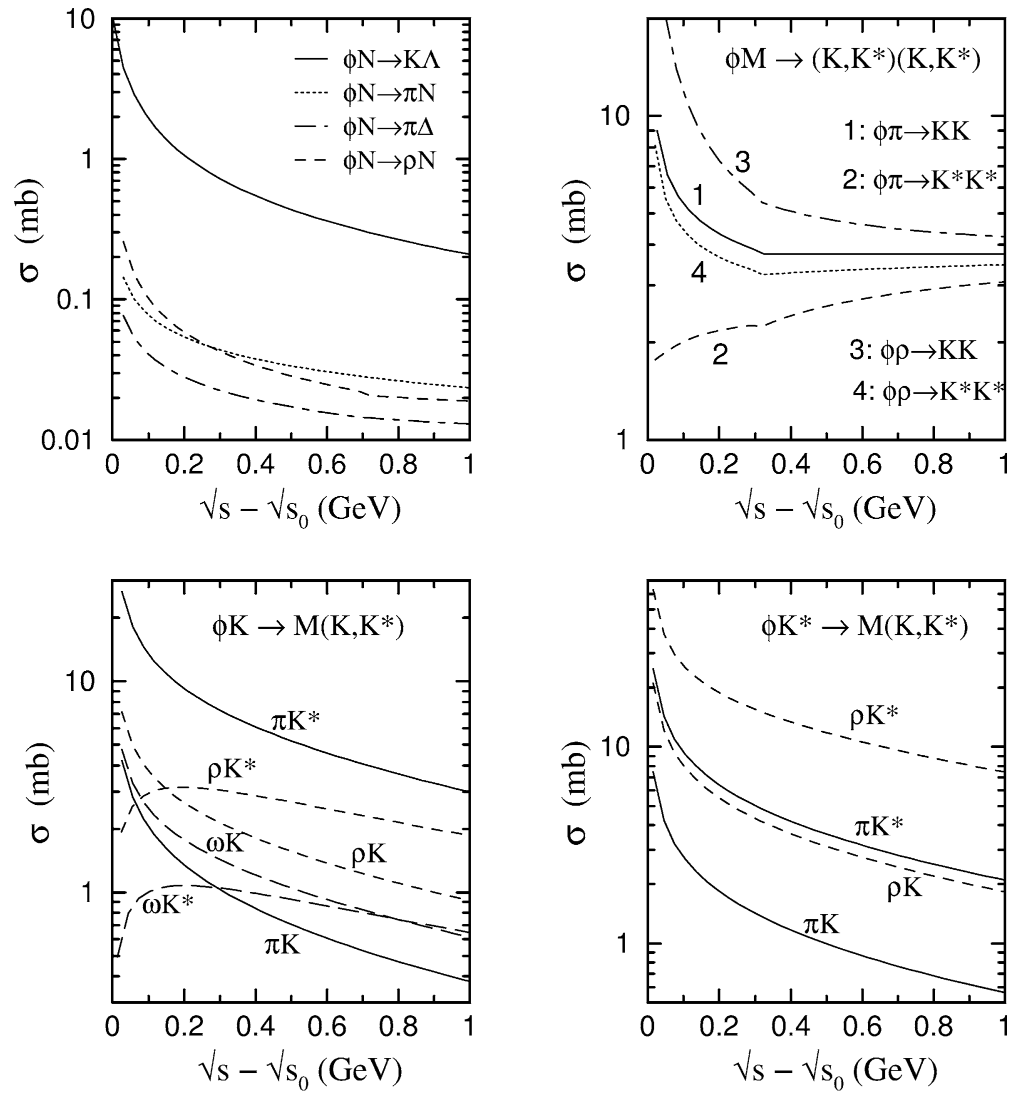
Emission Function from AMPT



- Shift in out direction ($\langle x_{out} \rangle > 0$)
- Strong positive correlation between out position and emission time
- Large halo due to resonance (ω) decay and explosion

  → non-Gaussian source

Phi meson absorption and production cross sections



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

Besides $\phi \leftrightarrow K\overline{K}$, phi meson can be produced and absorbed via various hadronic reactions, calculable by

- Meson-exchange model

  Chung, Li, and Ko, NPA 625, 347 (97)

- Chiral Lagrangian with hidden local symmetry

  Averez-Ruso and Koch, PRC 65, 054901 (02)

Phi meson rapidity distribution at SPS

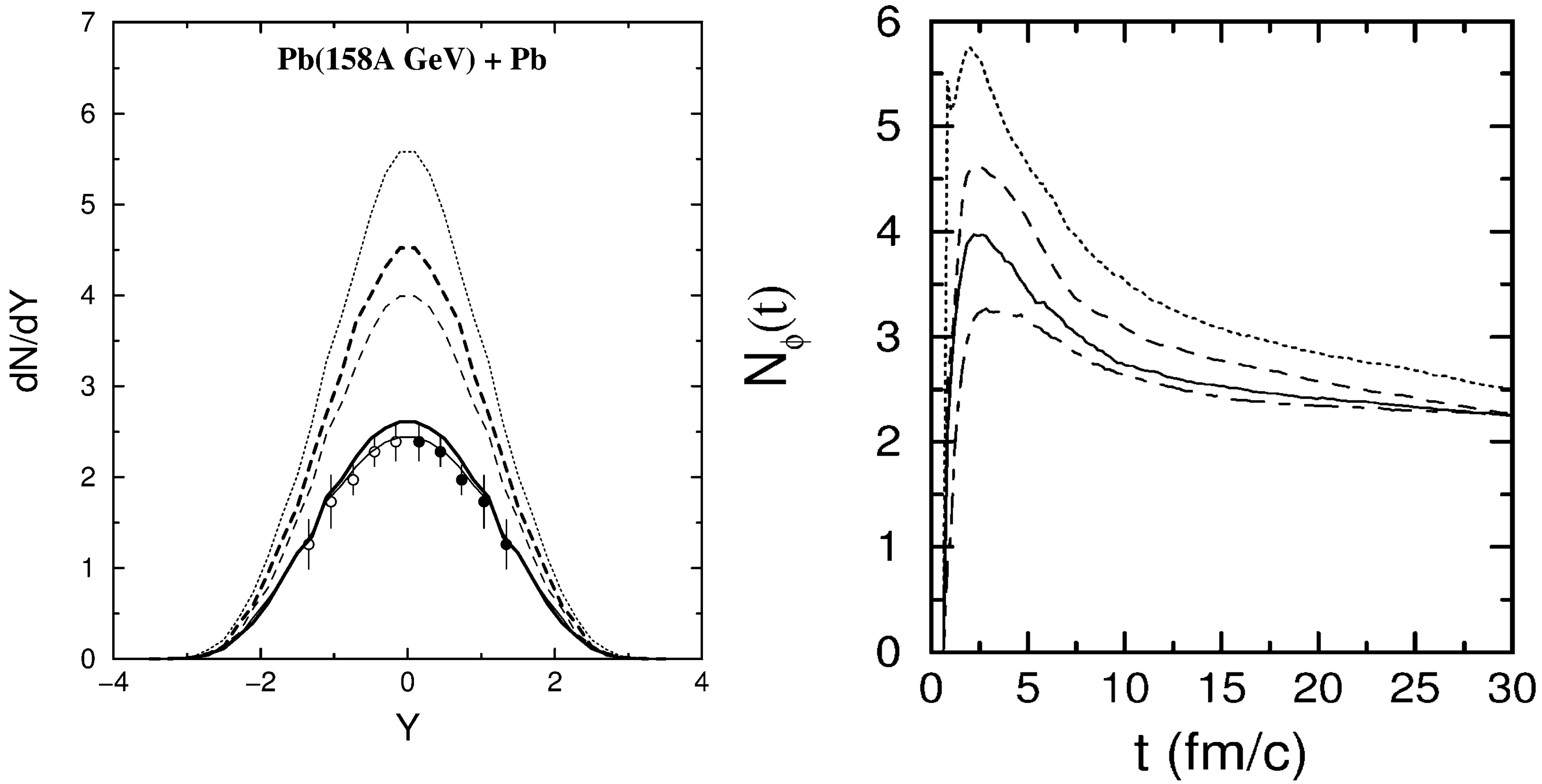


Fig. 3. Rapidity distribution of phi meson reconstructed from K^+K^- pairs (solid curves) and from $\mu^+\mu^-$ channel (dashed curves) for Pb+Pb collisions at 158 A GeV at an impact parameter of $b \leqslant 3.5$ fm in the AMPT model. The results are for without (thin curves) and with (thick curves) in-medium mass modifications. The dotted curve corresponds to phi mesons from the dimuon channel with in-medium masses and with the phi meson number from HIJING increased by a factor of two. The solid circles are the NA49 experimental data [7] from the K^+K^- channel.

Phi meson production at RHIC

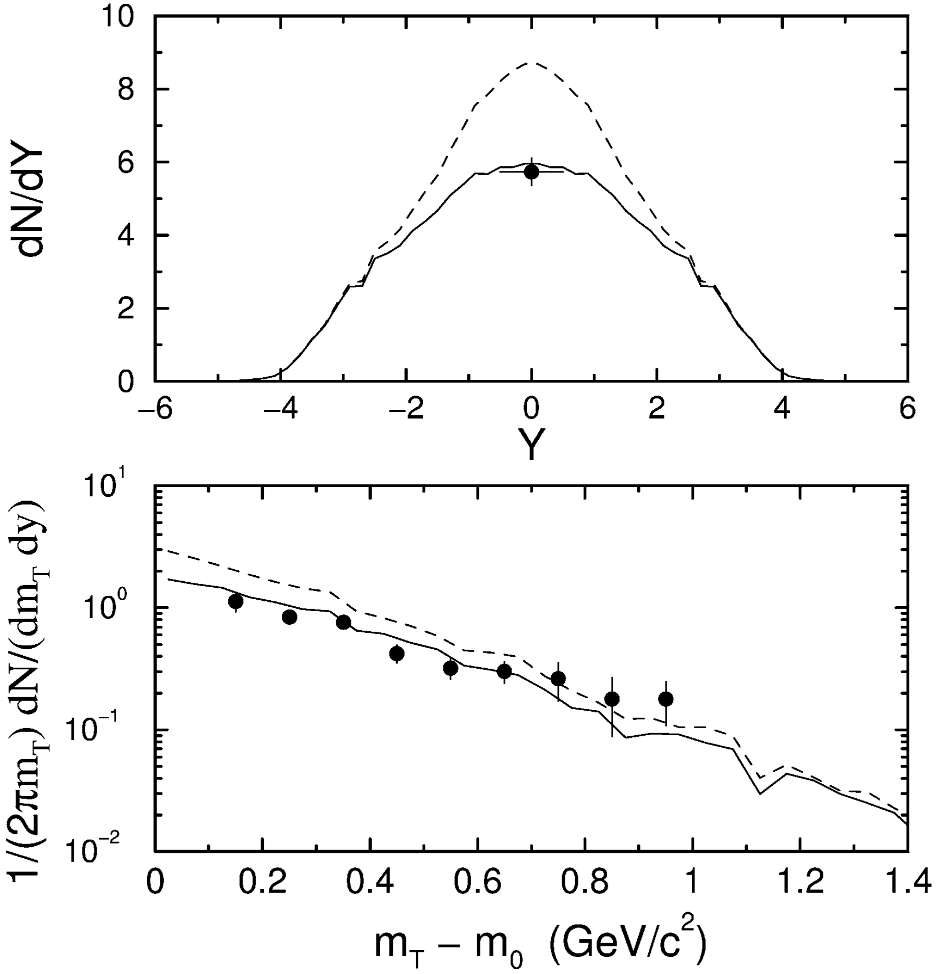
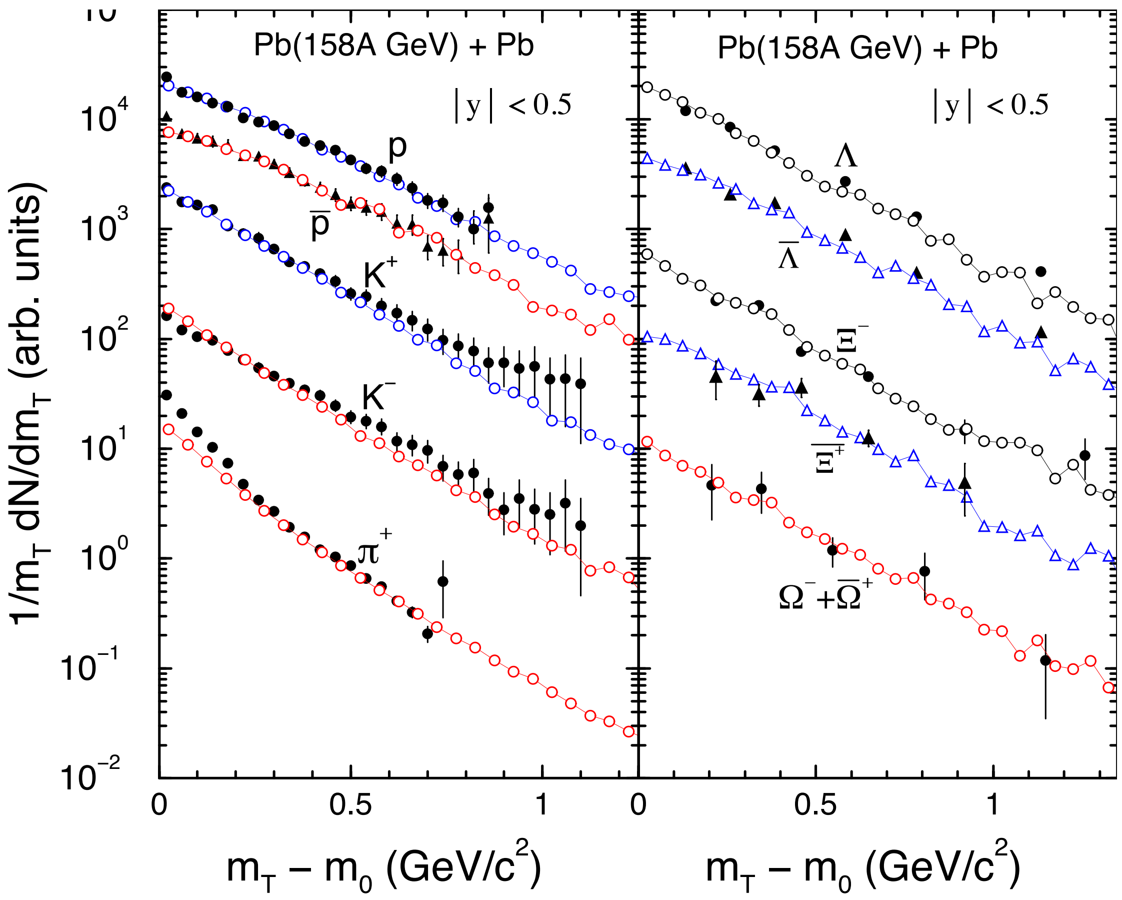


Fig. 5. The rapidity distribution (top panel) and the transverse mass spectra (bottom panel) for midrapidity ($|y| < 0.5$) phi mesons reconstructed from K^+K^- pairs (solid curves) and from $\mu^+\mu^-$ channel (dashed curves) for Au+Au collisions at RHIC energy of $\sqrt{s} = 130\ A\,\mathrm{GeV}$ at an impact parameter of $b \leqslant 5.3$ 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)



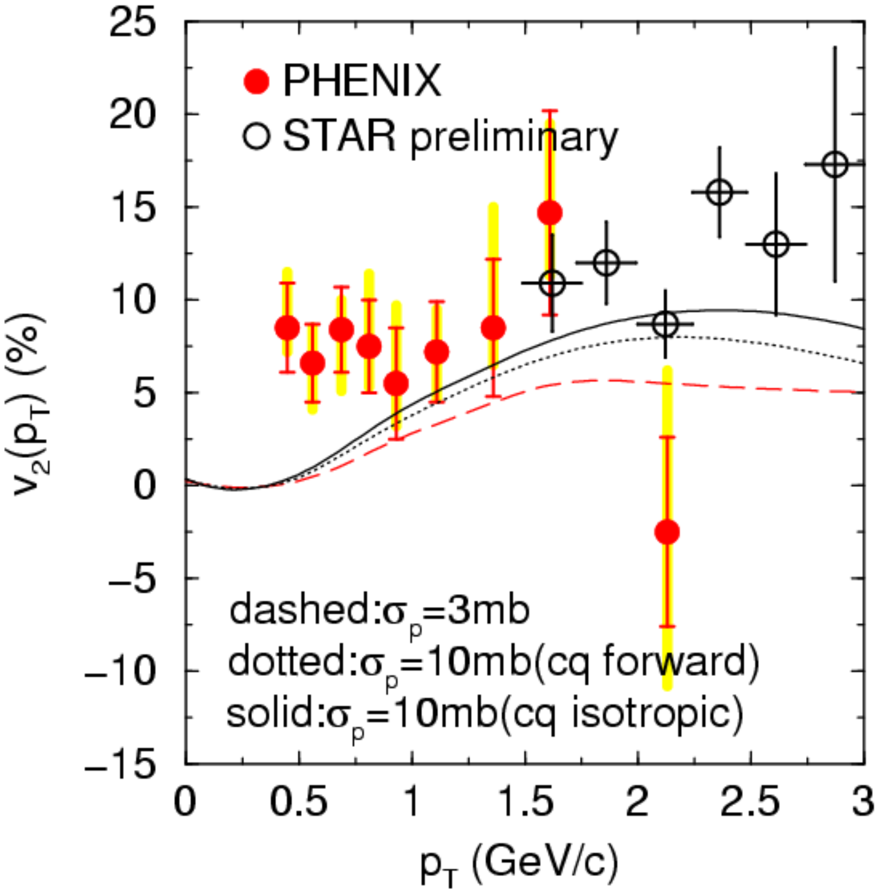
Strange-exchange reactions

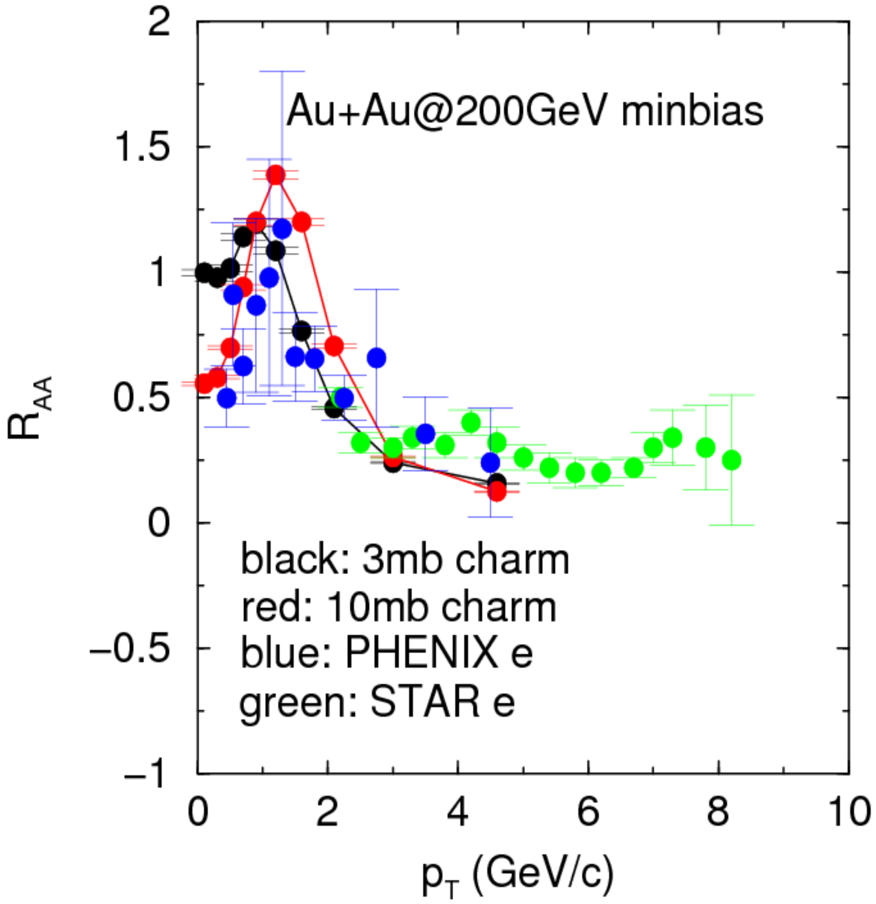
$$\bar{K}\Lambda \leftrightarrow \Xi\pi(\eta)$$
$$\bar{K}\Sigma \leftrightarrow \Xi\pi(\eta)$$
$$\bar{K}\Xi \leftrightarrow \Omega\pi(\eta)$$
$$K\bar{\Lambda} \leftrightarrow \bar{\Xi}\pi(\eta)$$
$$K\bar{\Sigma} \leftrightarrow \bar{\Xi}\pi(\eta)$$
$$K\bar{\Xi} \leftrightarrow \bar{\Omega}\pi(\eta)$$

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

Charm R_{AA} and elliptic flow from AMPT

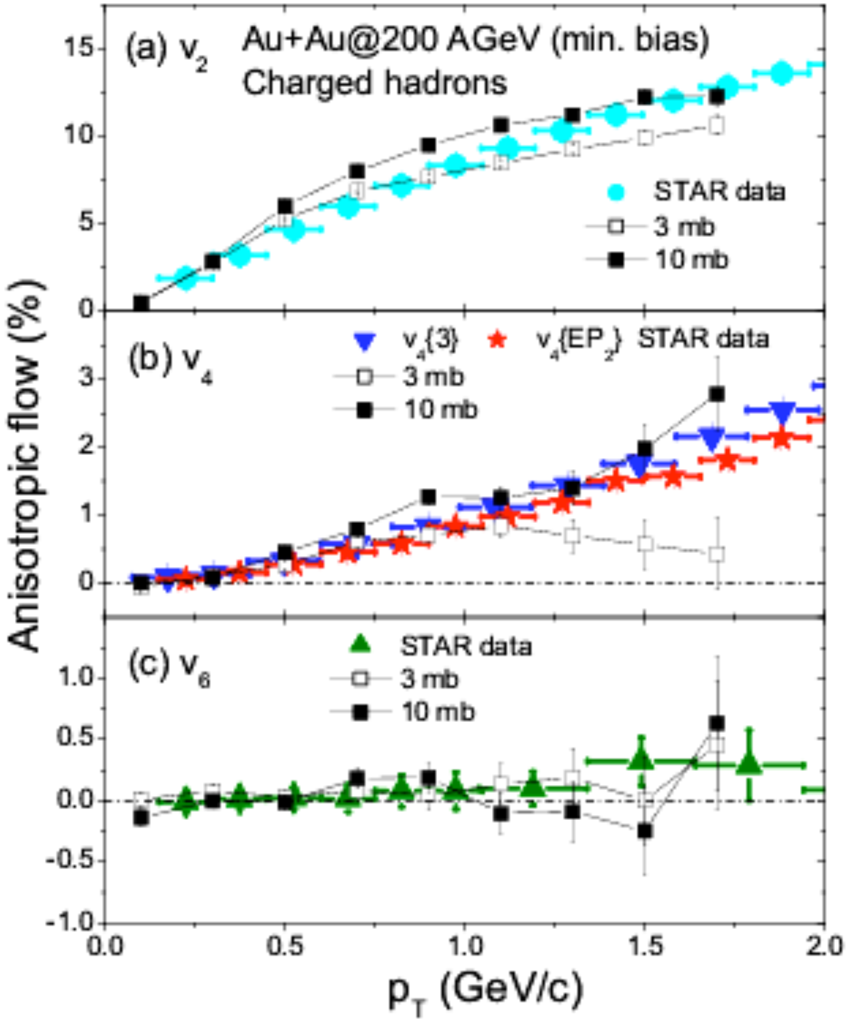
Zhang, Chen & Ko, PRC 72, 024906 (05)



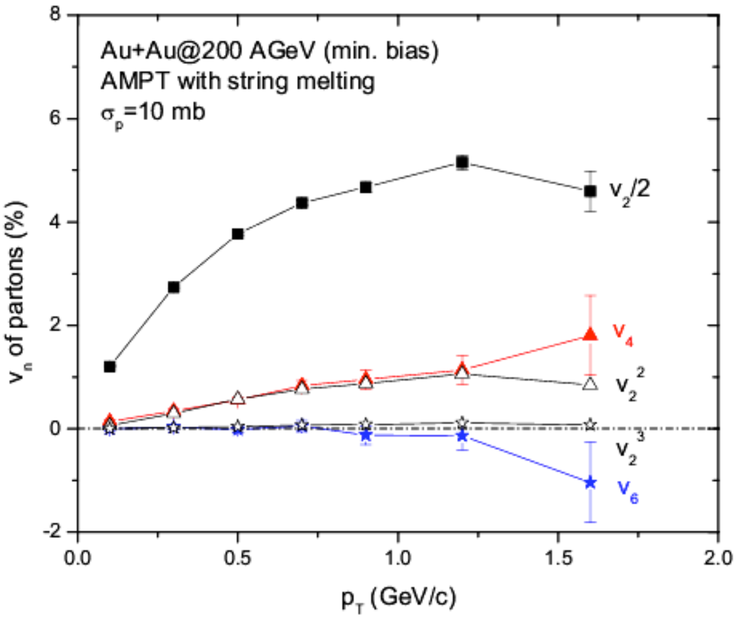


- Need large charm scattering cross section to explain data.
- Smaller charmed meson elliptic flow is due to use of current light quark masses in ZPC.

Higher-order anisotropic flows



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



Parton cascade

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

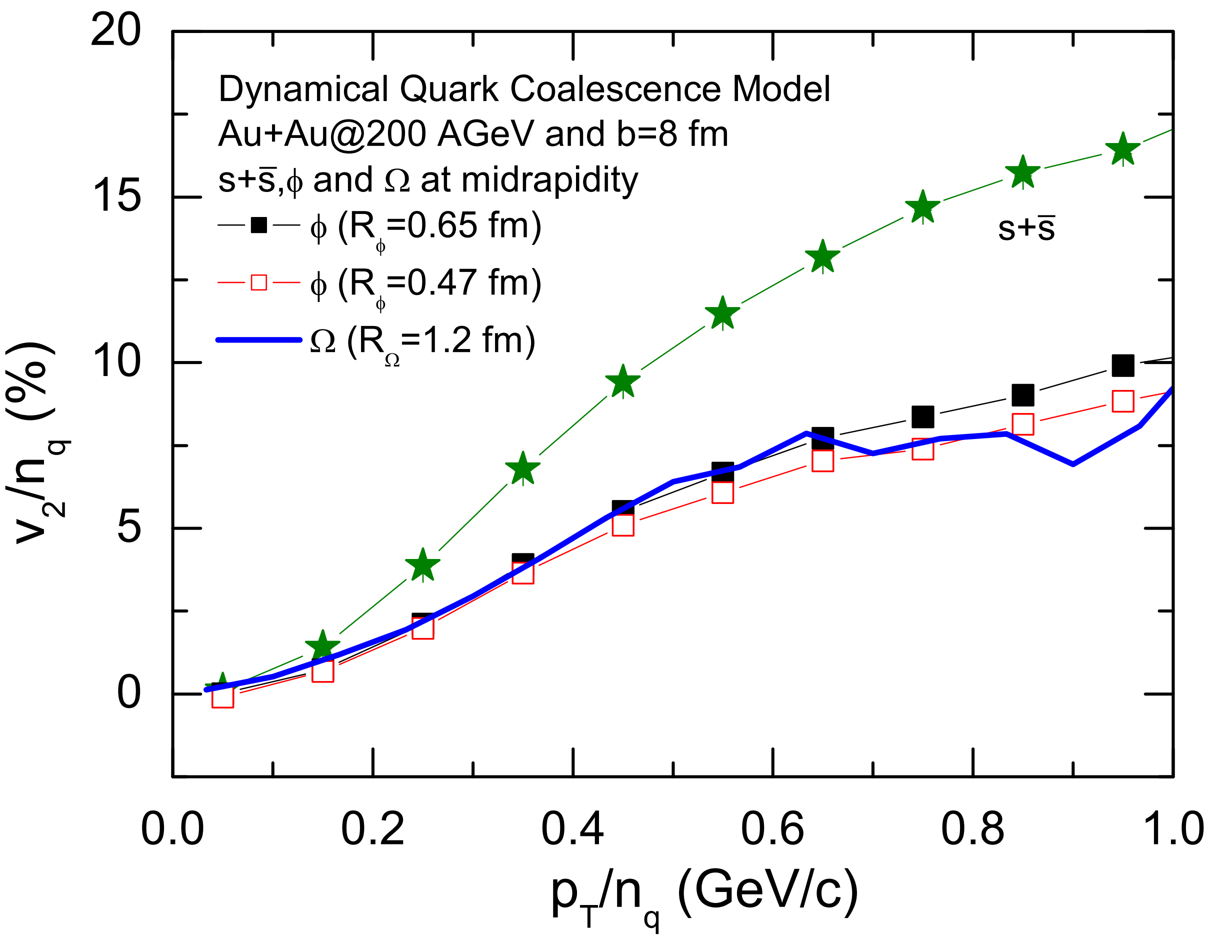
Data

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

Dynamical quark coalescence model

Chen & Ko, PRC 73, 044903 (06)

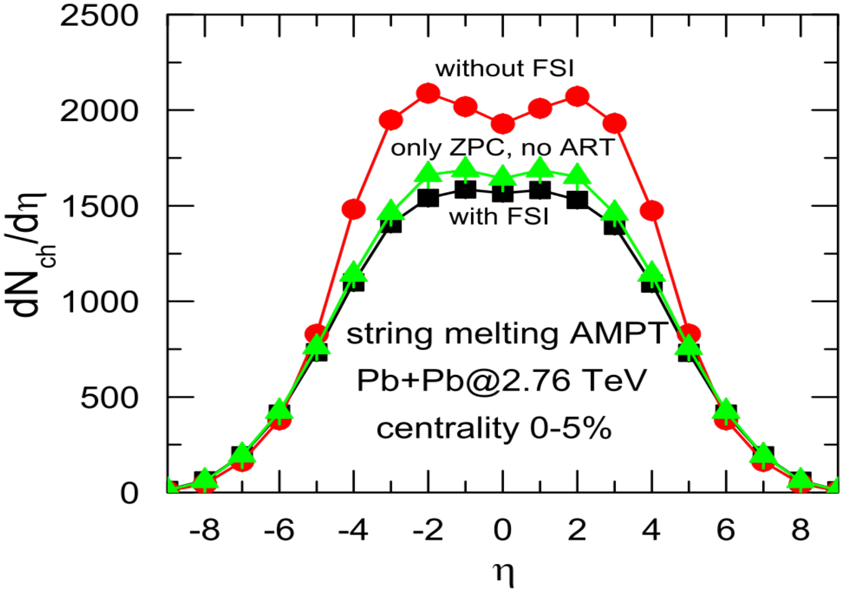
Based on the phase-space distribution of strange quarks from AMPT and including quark spatial and momentum distribution in hadrons

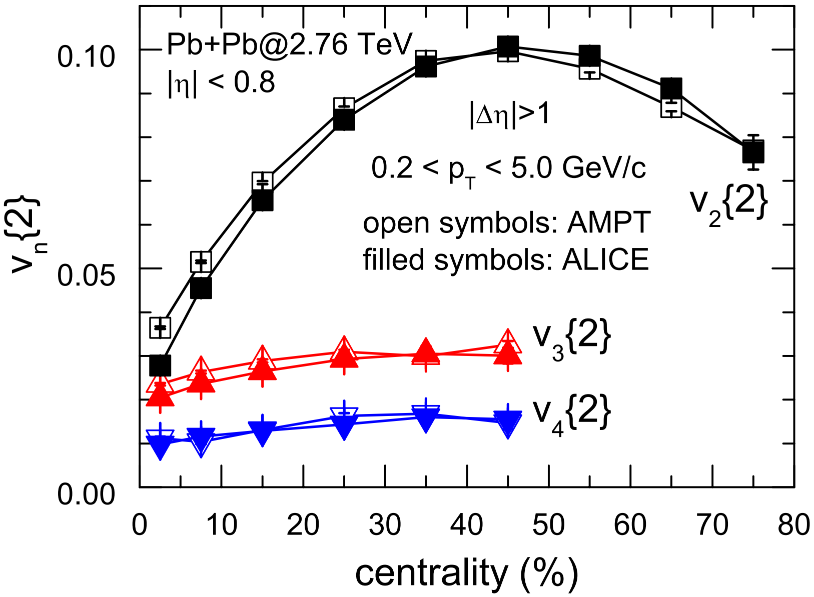


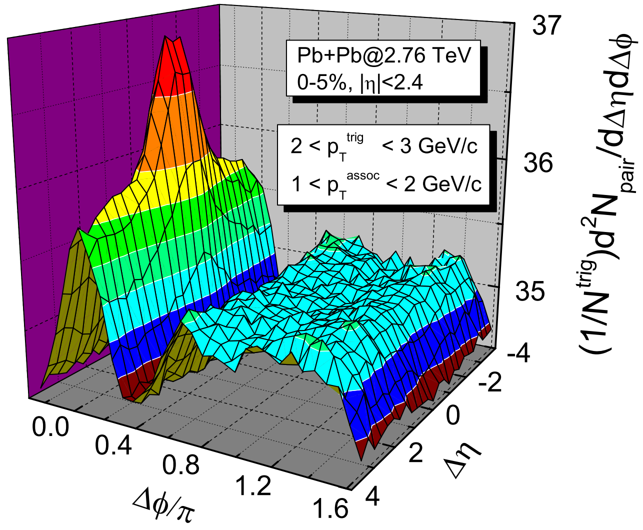
Although scaled phi and Omega satisfy constituent quark number scaling, they are smaller than the strange quark elliptic flow

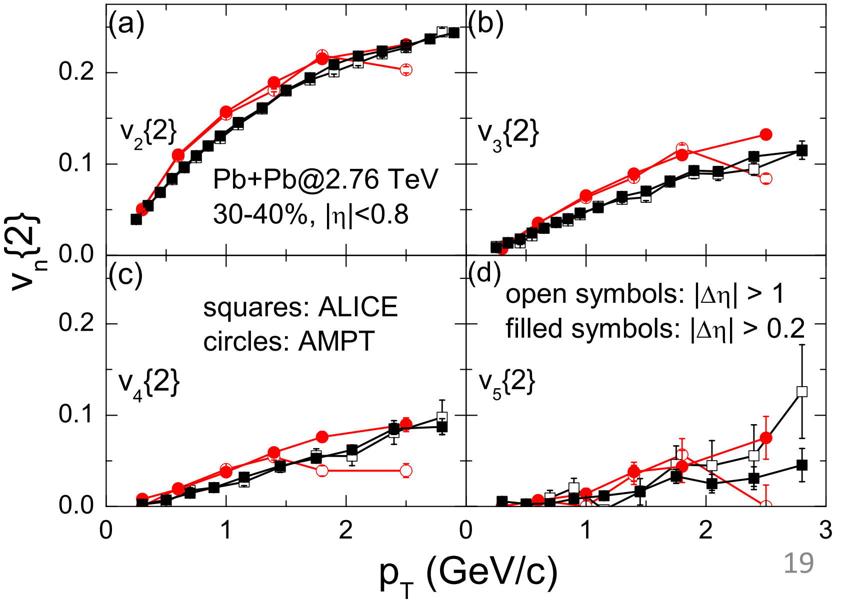
AMPT results for LHC

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









Mean-field potentials in AMPT

- Nucleon and antinucleon: Relativistic mean-field model

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

→ - 60 MeV for nucleon and -260 MeV for antinucleon at normal nuclear density

- Kaon and antikaon: chiral effective Lagrangian

$$U_{K,\overline{K}} = \sqrt{m_K^2 - a_{K,\overline{K}}\rho_s + (b_K\rho_b^{net})^2} \pm b_K\rho_b^{net} - m_K$$

→ 20 MeV for kaon and -120 MeV for antikaon at normal nuclear density

- Pions: self energy [Kaier & Weise, PLB 512, 283 (2001)]

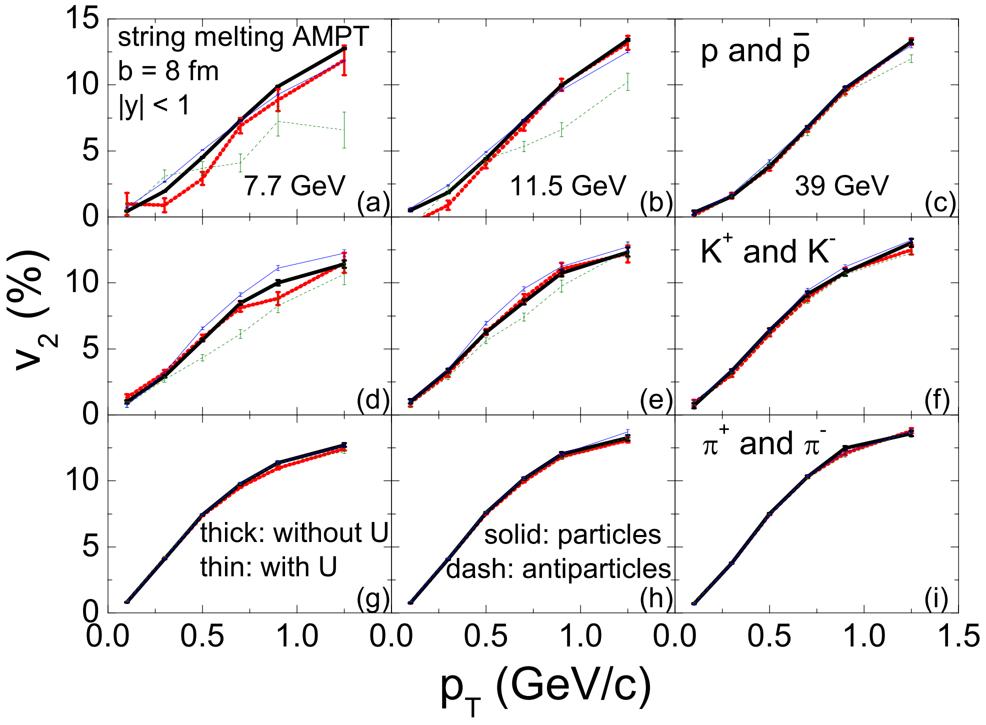
$$\Pi^-(\rho_n,\rho_p) = \rho_n[T_{\pi N}^- - T_{\pi N}^+] - \rho_p[T_{\pi N}^- + T_{\pi N}^+] + \Pi_{\mathrm{rel}}^-(\rho_n,\rho_p) + \Pi_{\mathrm{cor}}^-(\rho_n,\rho_p)$$

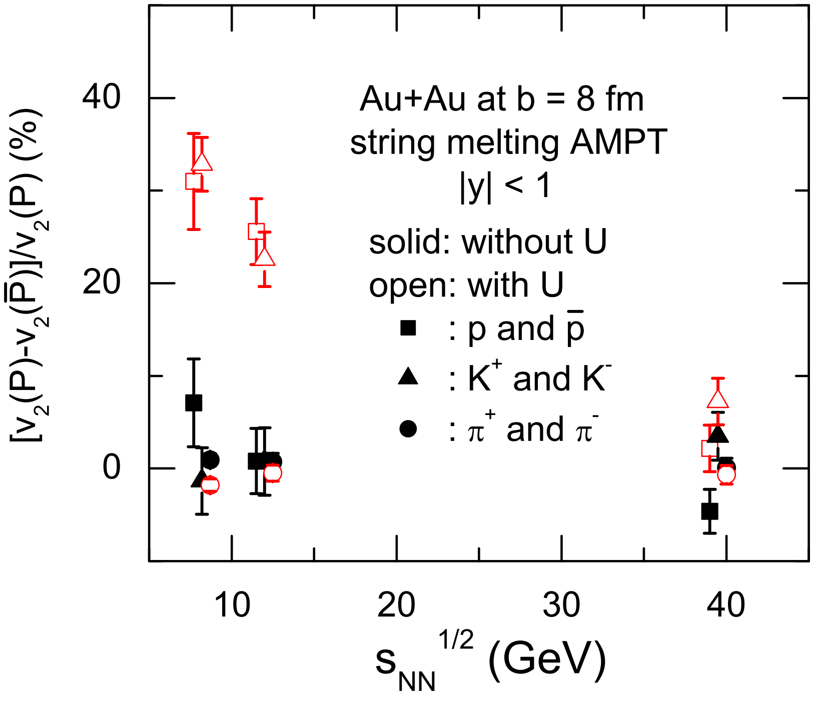
$$\Pi^+(\rho_p,\rho_n) = \Pi^-(\rho_n,\rho_p)$$

→ π^- increases by 13.8 MeV and π^+ decreases by 1.2 MeV in asymmetric nuclear matter of normal density and isospin asymmetry δ=0.2

Mean-field effects on particle and antiparticle elliptic flows

Jun, Chen, Ko & Lee, PRC 85, 041901(R) (2012)

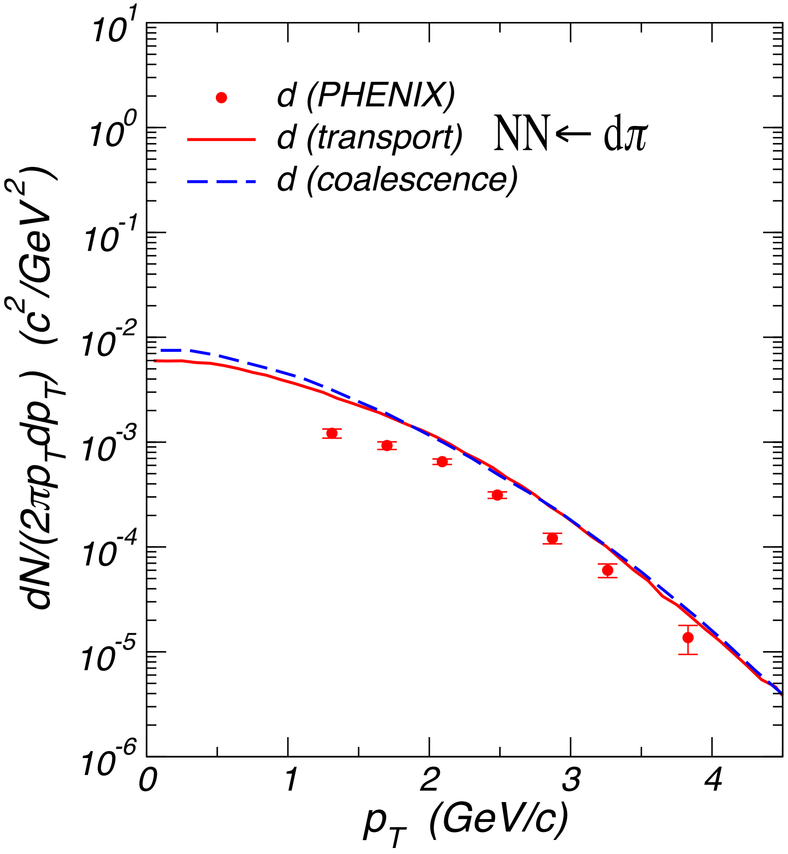


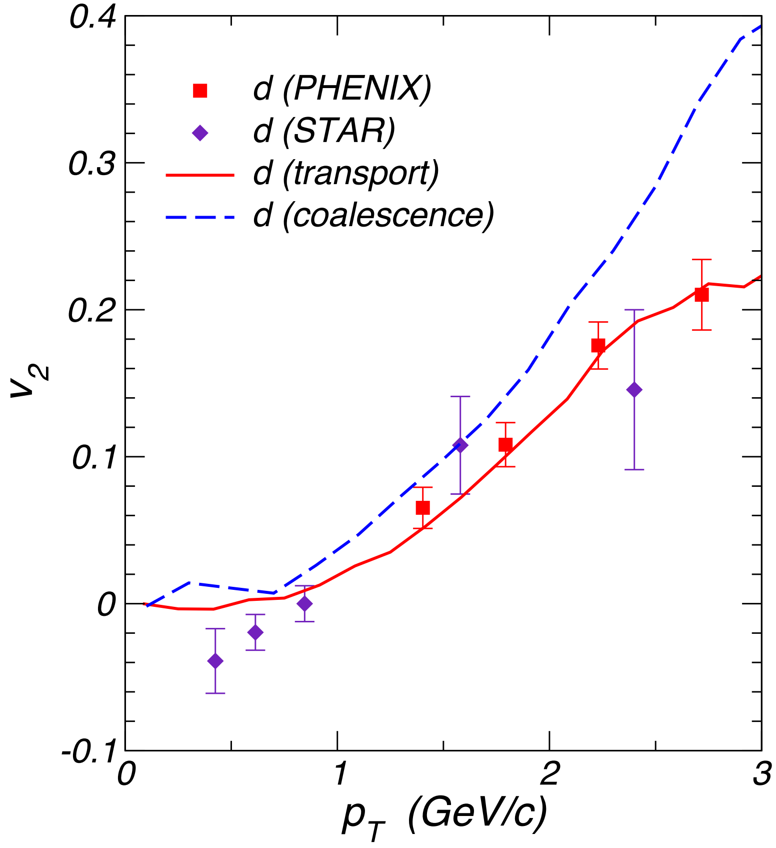


- Hadronic mean fields lead to splitting of particle and antiparticle elliptic flows in baryon-rich matter, diminish with increasing collision energies, similar to experimental observations by STAR
- Expect additional effects from partonic mean-fields

Deuteron p_T spectrum and elliptic flow

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

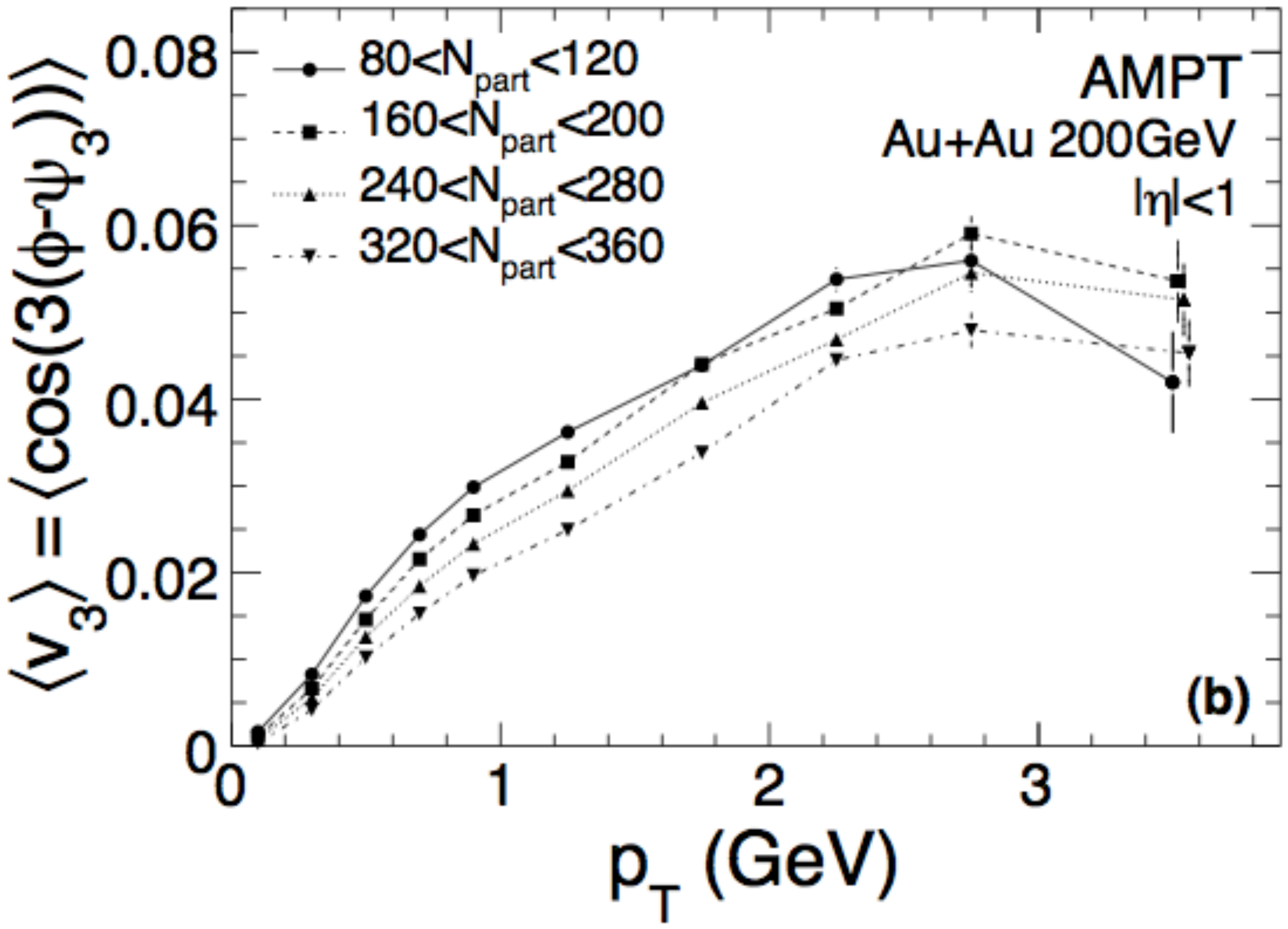




- Similar p_T spectrum from transport and coalescence models
- Smaller elliptic flow at large p_T from transport model than from coalescence model

Triangular flow

Alver & Roland, PRC 81, 054905 (2010)

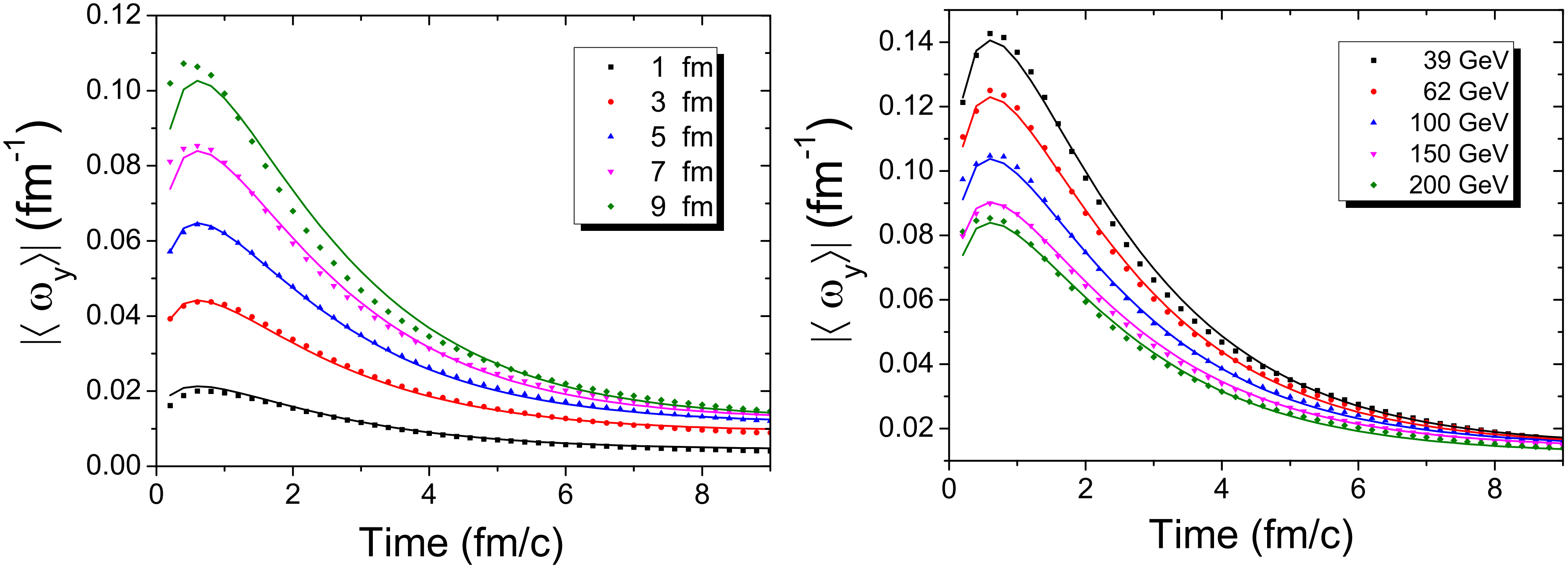


- Contrary to elliptic flow, triangular flow is not sensitive to centrality
- Similar results from hydrodynamic model (Petersen et al., PRC 82, 041901 (2010), Alver et al., PRC 82, 034913 (2010))

Vorticity in relativistic heavy ion collisions

Jiang, Lin & Liao, PRC 94, 044910 (2016)

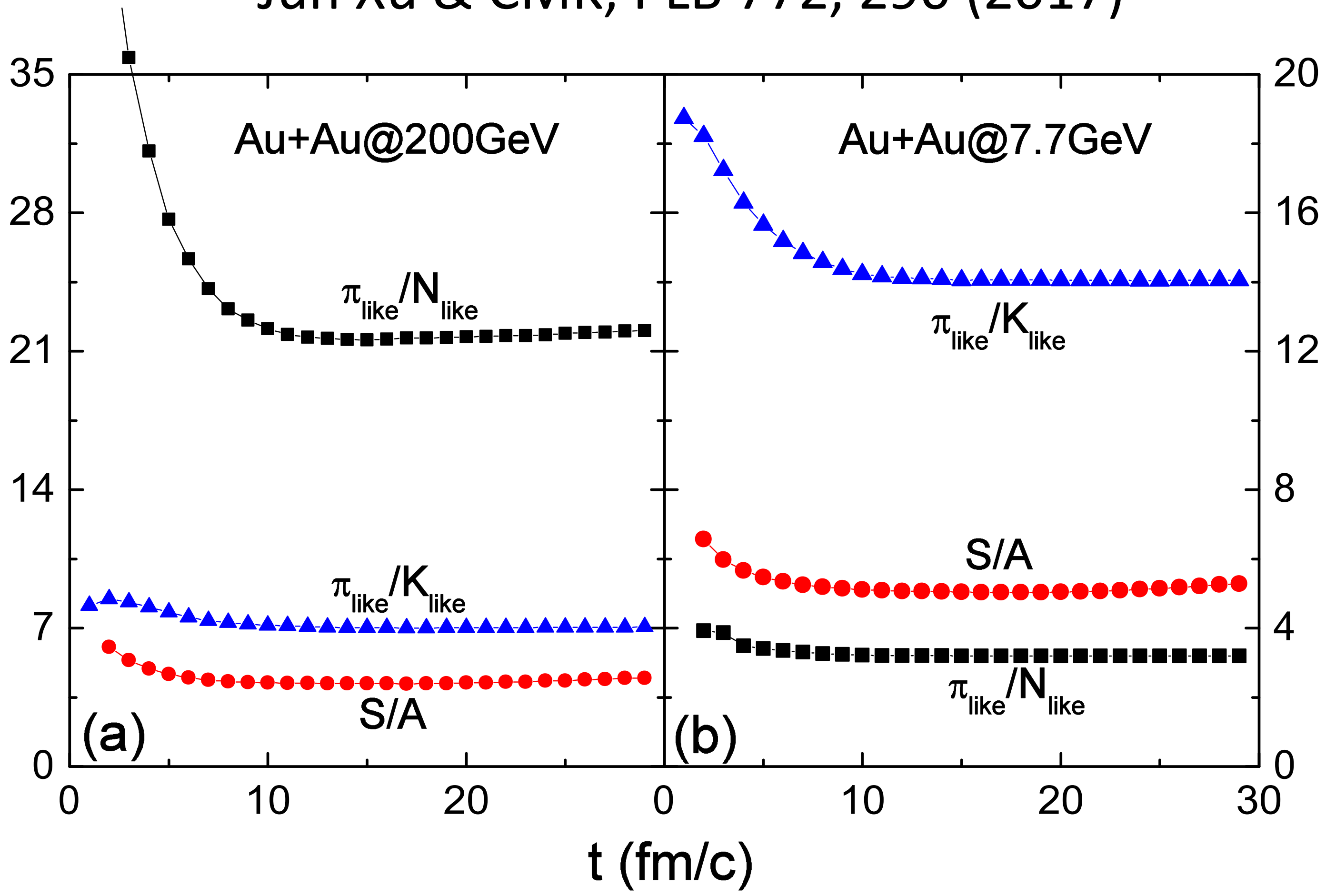
$$\vec{\omega} = \frac{1}{2}\nabla \times \vec{v}, \quad \langle \omega_y \rangle = \frac{\int d^3\vec{r}\,[\mathcal{W}(\vec{r})]\,\omega_y(\vec{r})}{\int d^3\vec{r}\,[\mathcal{W}(\vec{r})]}, \quad \mathcal{W}(\vec{r}) = \rho\epsilon(\vec{r})$$



- Average vorticity decreases with time, decreasing impact parameter, and increasing collision energy.

Chemical freeze-out in relativistic heavy ion collisions

Jun Xu & CMK, PLB 772, 290 (2017)



- Both ratio of effective particle numbers and entropy per particle remain essentially constant from chemical to kinetic freeze-out.

Summary

- AMPT was developed to describe heavy ion collisions at relativistic heavy ion collisions.
- It has been used to understand both the transverse momentum spectra of various hadron species and their anisotropic flows.
- It had led to a better understanding of the measured HBT correlations.
- It had led to the discovery of triangular flow.
- It had allowed the study of vorticity field generated in HIC.
- It provided insight to the validity of statistical hadronization model.
- The AMPT model with its fluctuating initial conditions and strong parton scatterings can capture the essential collision dynamics of relativistic heavy ion collisions as revealed in various observables measured in experiments.
- In 2002 AMPT won RHIC Predictions Competition Prize of Institute of Nuclear Theory at Seattle.
- As of July 25, 2017, 603 citations of Lin, Ko, Li, Zhang & Pal, PRC 72, 064901 (05) in INSPIRE.