Transport model study of HBT at RHIC

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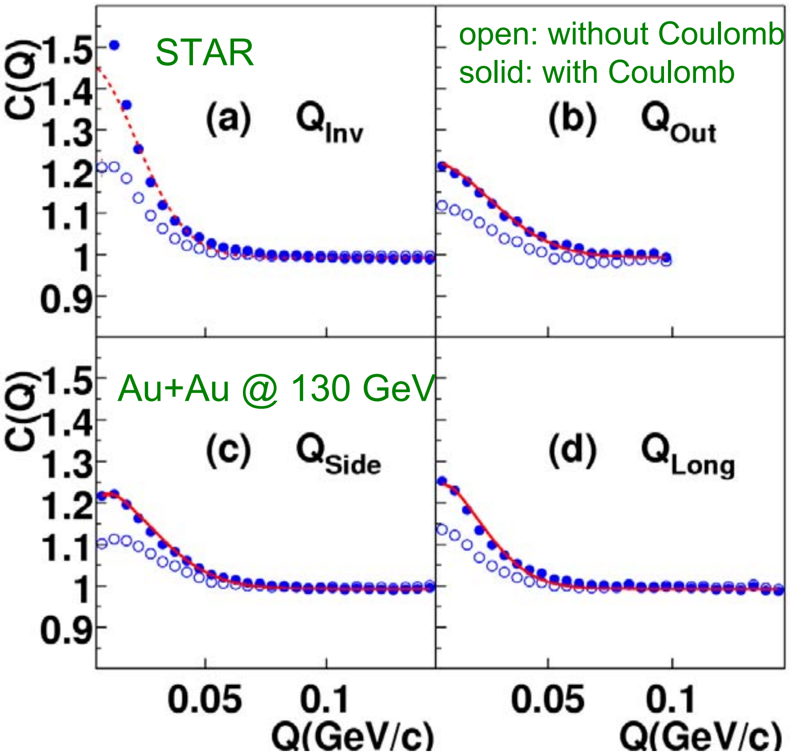
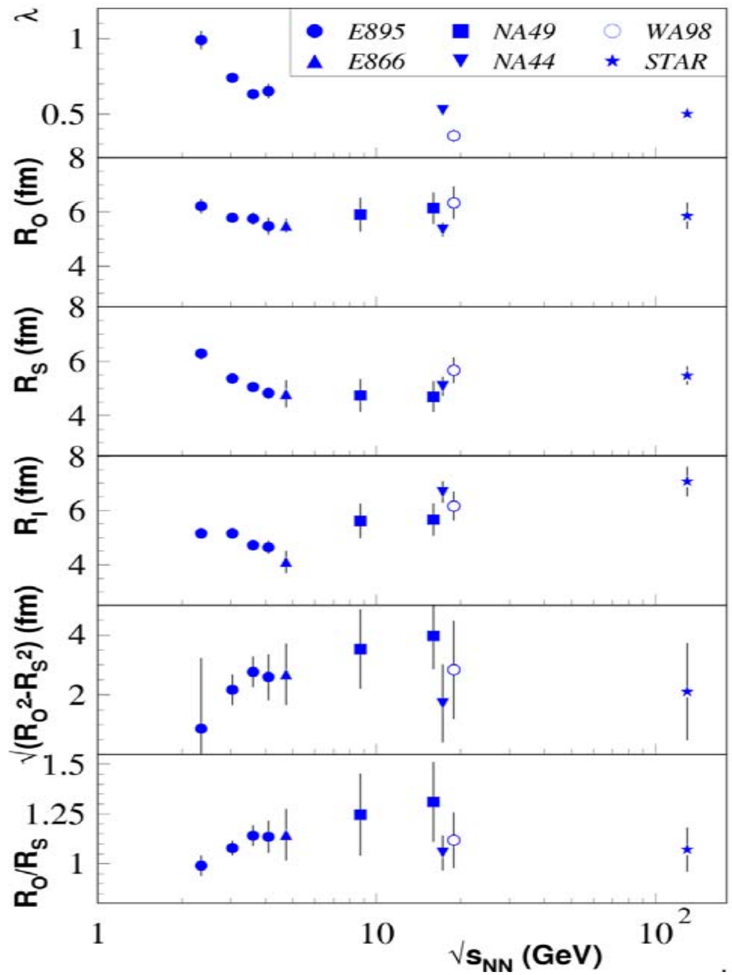
- Introduction
- A multi-phase transport (AMPT) model
- HBT at RHIC
- Summary

Pion interferometry in heavy ion collisions



$$C(q)=1+\exp(-q_{inv}^2 R_{inv}^2)$$
$$=1+\exp(-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2)$$



- R_o/R_s~1 smaller than expected > 1 as first suggested by Pratt & Bertsch

$$R_o^2 \simeq \langle x^2 \rangle + \langle v^2 \rangle \Delta t^2$$
$$R_s^2 \simeq \langle y^2 \rangle$$

A multiphase transport (AMPT) model

- Default: Lin, Pal, Zhang, Li & Ko, PRC 61, 067901 (00);
  64, 041901 (01); nucl-th/0411110

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

- String melting: PRC 65, 034904 (02); PRL 89, 152301 (02)

  - Convert hadrons from string fragmentation to quarks and antiquarks
  - Evolve quarks and antiquarks in ZPC
  - When stop interacting, combine nearest quark and antiquark to meson, and nearest three quarks to baryon using the coalescence model but with hadron flavors determined by quarks' invariant mass

Zhang's parton cascade (ZPC)

Bin Zhang, Comp. Phys. Comm. 109, 193 (1998)

$$\boxed{p^{\mu}\partial_{\mu}f_1(x,p,t) \propto \int dp_2 d\Omega\, |\vec{v}_1 - \vec{v}_2|(d\sigma/d\Omega)(f_1' f_2' - f_1 f_2)}$$

$$\boxed{\frac{d\sigma}{dt} \approx \frac{9\pi\alpha_s^2}{2(t-\mu^2)^2}, \quad \sigma = \frac{9\pi\alpha_s^2}{2\mu^2}\frac{1}{1+\mu^2/s}}$$

- Using α_s=0.5 and screening mass μ=gT≈0.6 GeV at T≈0.25 GeV, then $<s>^{1/2}$≈4.2T≈1 GeV, and pQCD gives σ≈2.5 mb and a transport cross section

$$\sigma_t \equiv \int d\Omega \frac{d\sigma}{d\Omega}(1-\cos\theta) \approx 1.5\text{mb}$$

- σ=6 mb → μ≈0.44 GeV, σ_t≈2.7 mb
- σ=10 mb → μ≈0.35 GeV, σ_t≈3.6 mb

Lund string fragmentation model

T. Sjostrand, CPC 82, 74 (1994)

- Fragmentation function (Schwinger mechanism)

$$f(z)=z^{-1}(1-z)^{a}\exp\left[-\frac{b\left(m^{2}+p_{t}^{2}\right)}{z}\right]$$

z : Light-cone momentum fraction

- HIJING: a=0.5, b= 0.9 GeV^{-2}

  Suppression factor: 0.3 for strangeness, 0.5 for vector meson

- AMPT: a=2.2, b=0.5 GeV^{-2} to reproduce measured charged hadron multiplicity in HI collisions at SPS

  Popcorn mechanism: $B\bar{B}, BM\bar{B}$ to reproduce measured proton and antiproton rapidity distributions

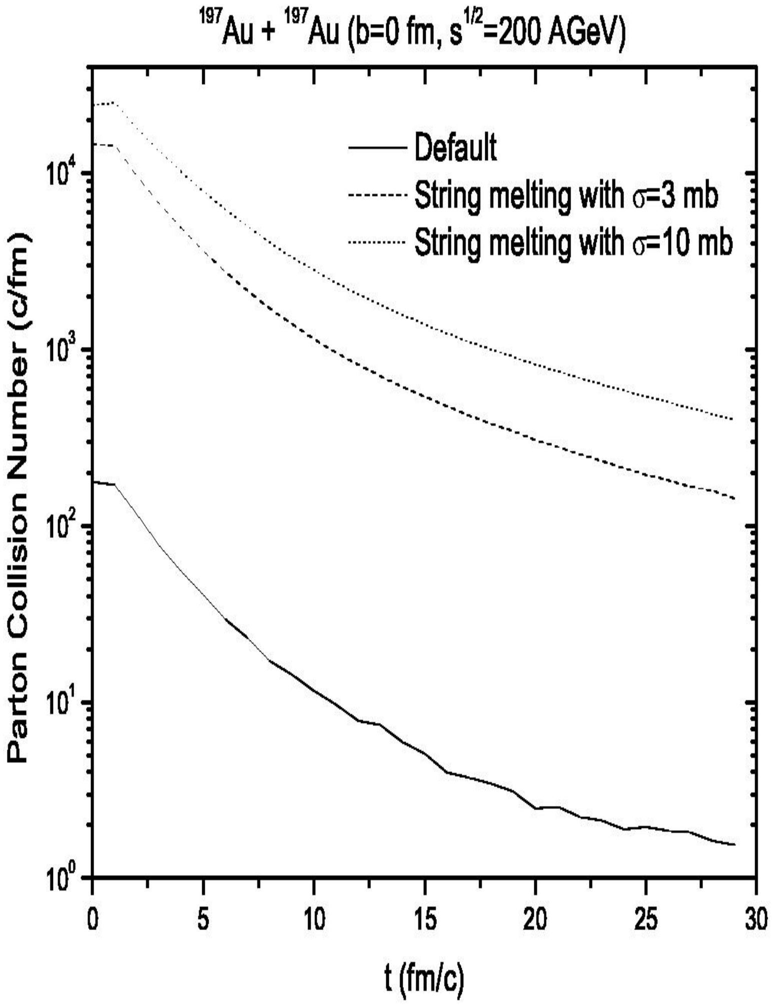
  Formation time: $\tau_f=\tau_0\cosh y$ with τ_0=0.7 fm/c

ART: A Relativistic Transport Model

B.A. Li and C.M. Ko, PRC 52, 2037 (1995)
Li, Sustich, Zhang & Ko, IJP E 10, 267 (2001)

- Baryons and antibaryons: N, Λ, Σ, Δ, N(1440), and N(1535) explicitly, higher resonances implicitly through meson-baryon scattering, Ξ and Ω perturbatively
- Mesons: π, ρ, ω, η, K, K^* and φ explicitly, charmonium perturbatively
- Baryon-baryon, meson-baryon, and meson-meson scattering
- Antibaryon annihilation: $N\bar{B} \rightarrow \pi\pi$, πρ, πω, ρρ, ρω, ωω
- Mean-field potentials for baryons and kaons

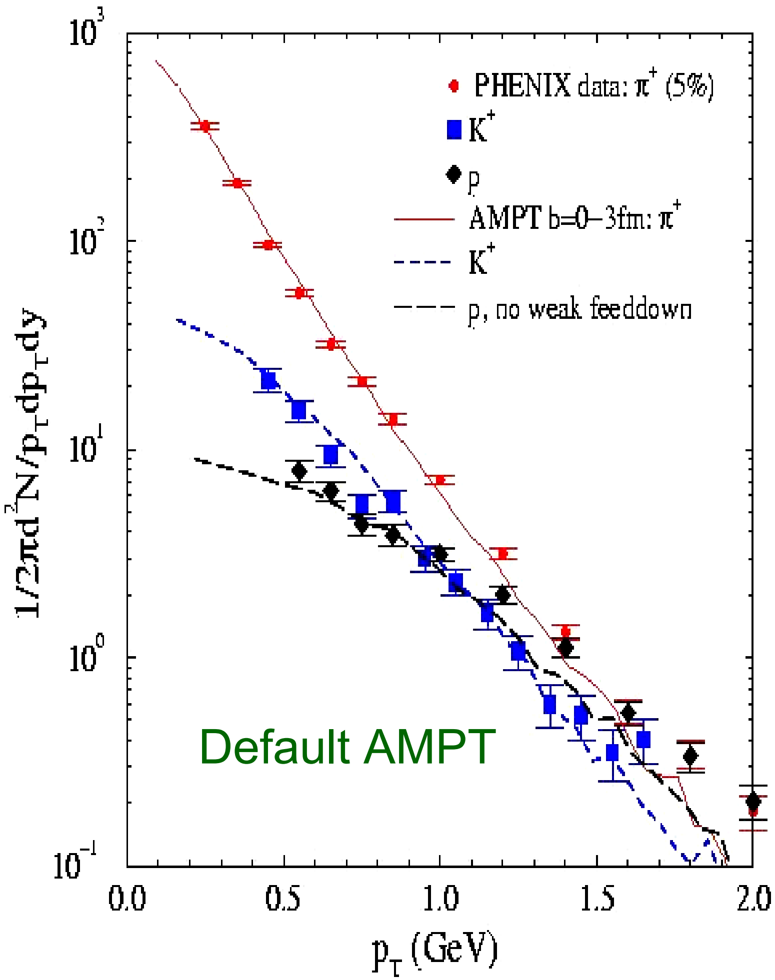
Parton collision rate

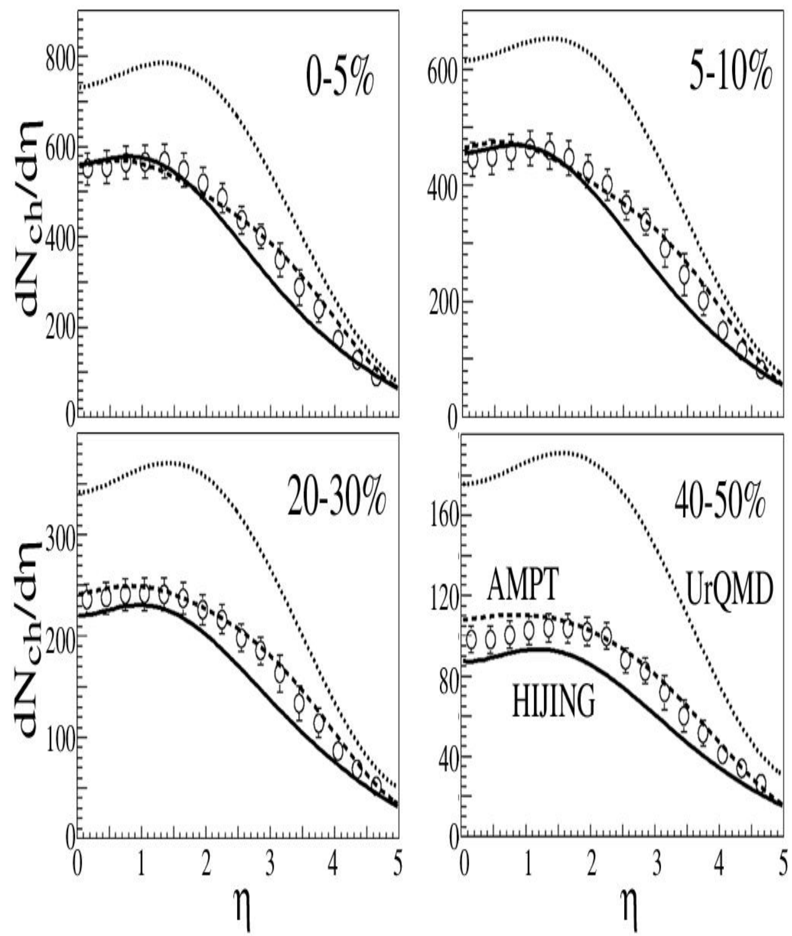


- Default: ~800 collisions for ~1600 partons, i.e., about one collision per parton
- String melting: both parton and collision numbers increase by about ten, i.e., about ten collisions per parton

→ Larger pressure generated in the partonic stage

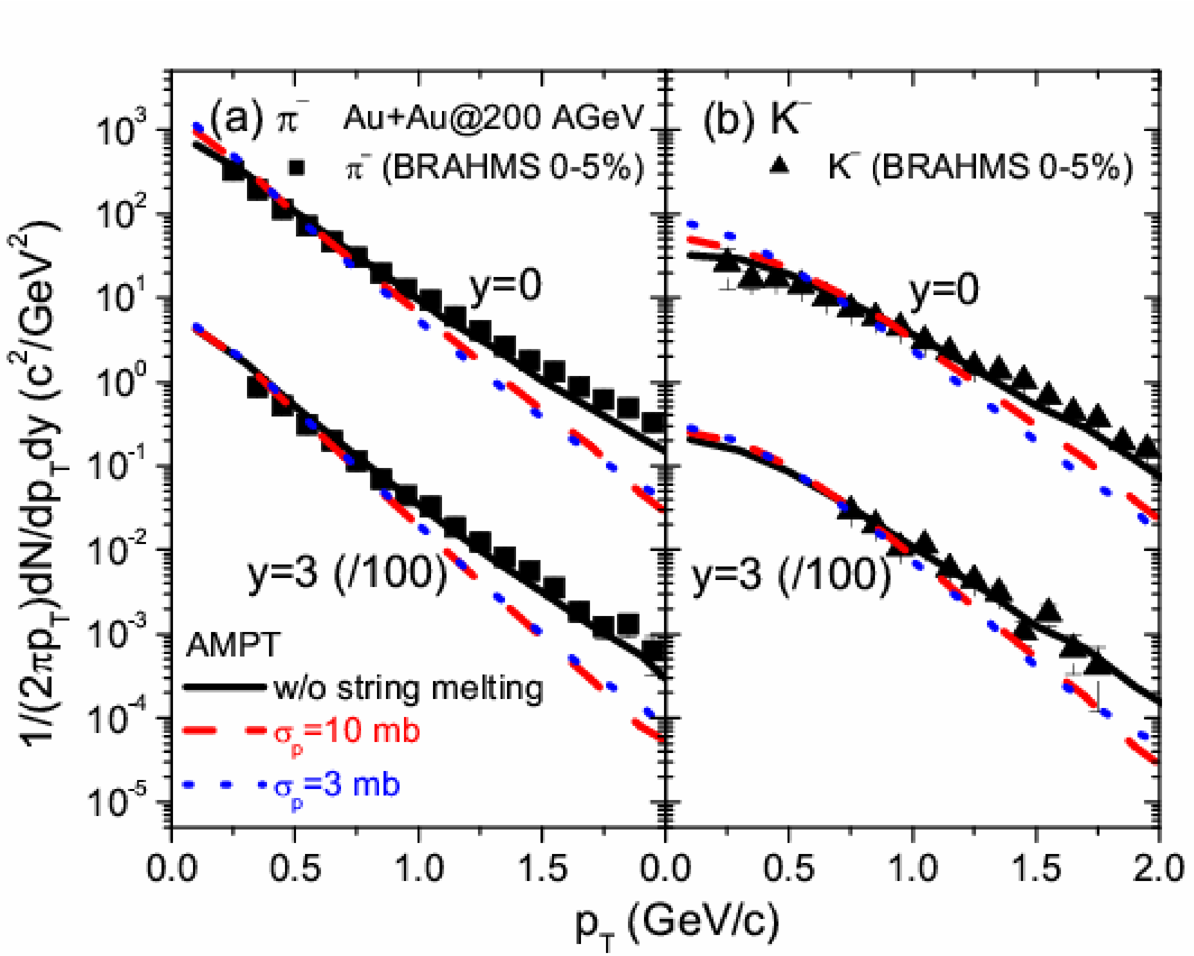
Transverse momentum and rapidity distribution from default AMPT





BRAHMS Au+Au @ 200 GeV

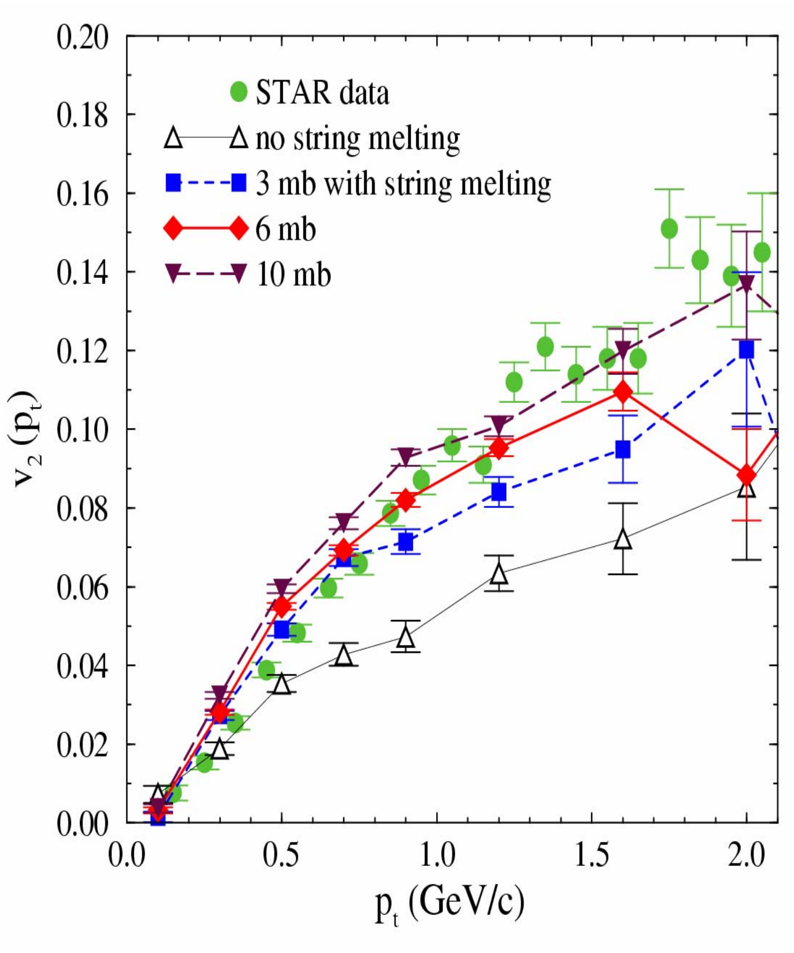
Transverse momentum spectra from AMPT with string melting

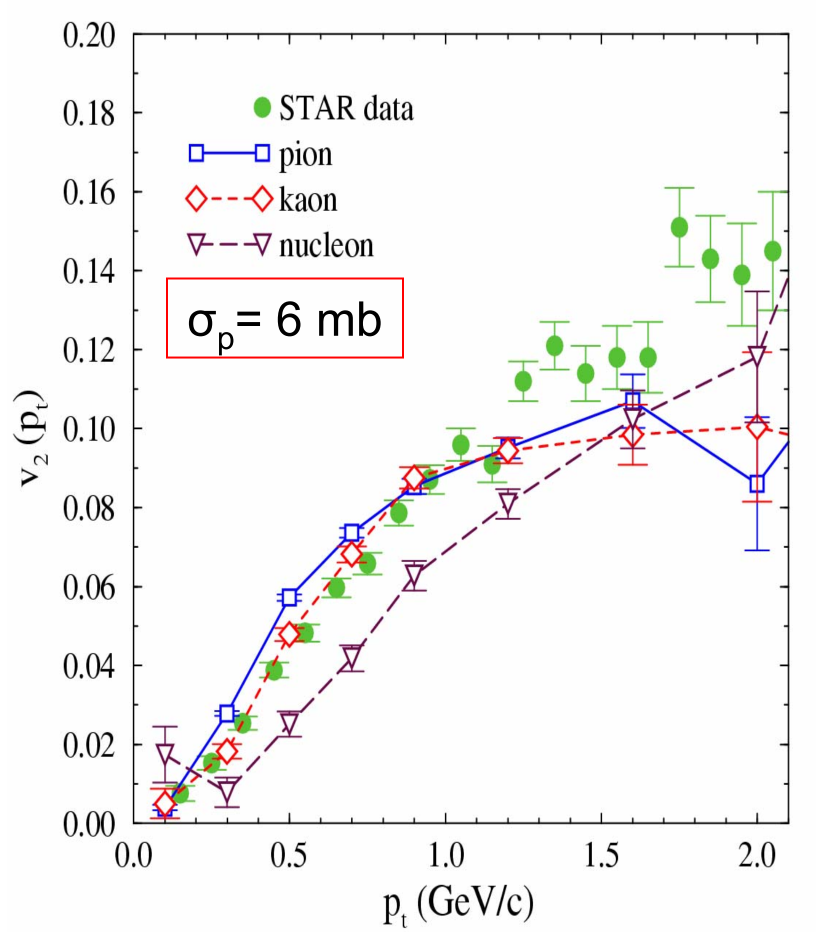


- Spectra are softer than in default AMPT as current quark masses are used, whose spectra are less affected by collective radial flow

Elliptic flow from AMPT

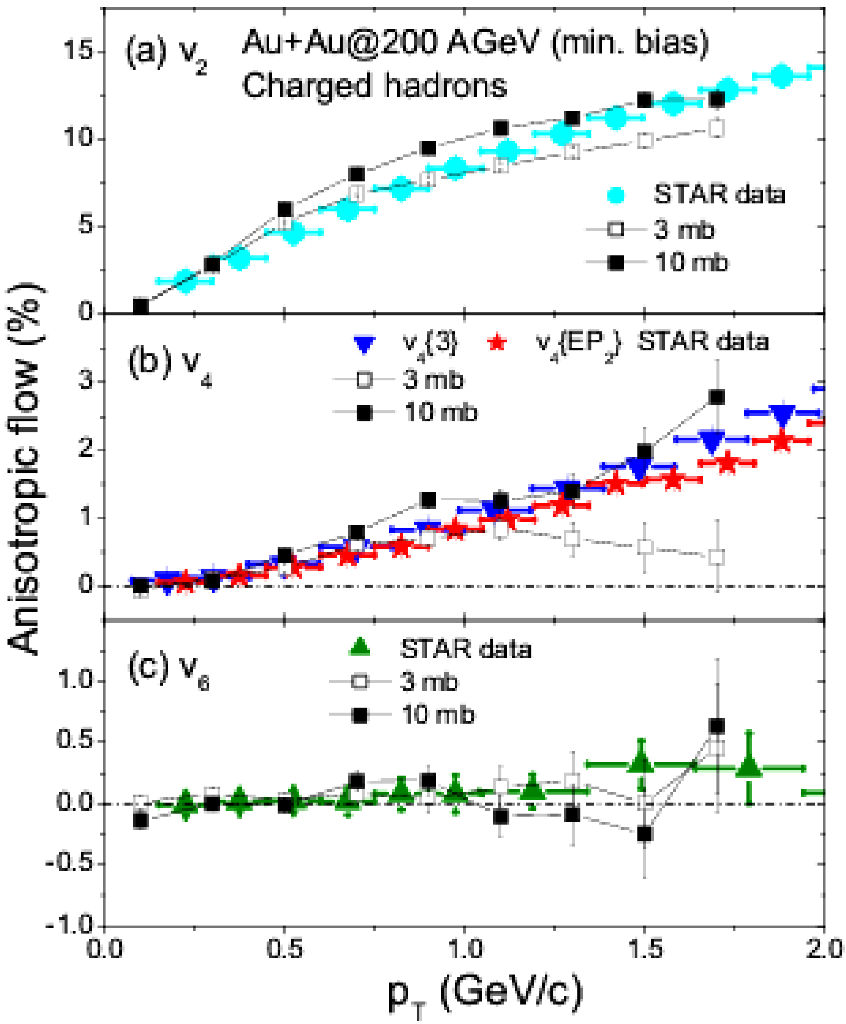
Lin & Ko, PRC 65, 034904 (2002)



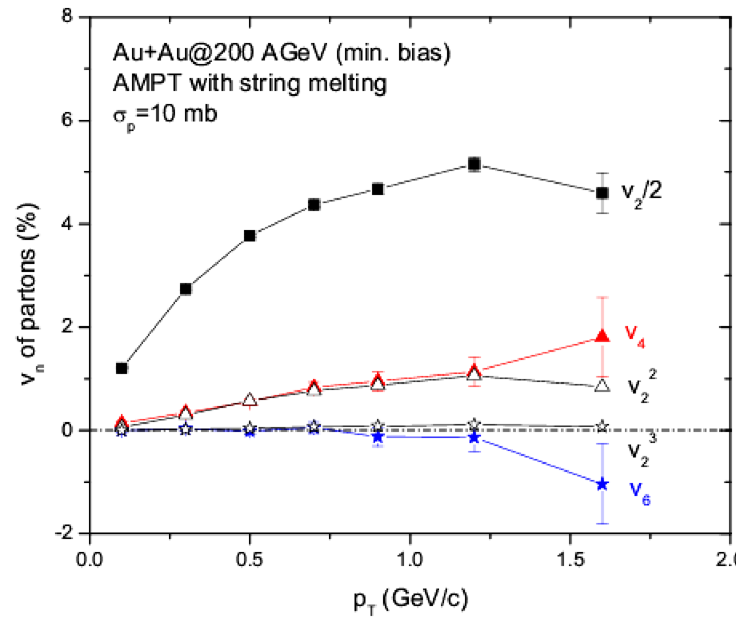


- Need string melting and large parton scattering cross section to reproduce data
- Mass ordering of v_2 at low p_T as in ideal hydrodynamic model

Higher-order anisotropic flow



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



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

naïve coalescence model

Data $\boxed{\frac{v_4}{v_2^2} \approx 1.2 \Rightarrow v_{4,q} \approx 2v_{2,q}^2}$ $\longleftarrow$ $\boxed{\frac{v_4}{v_2^2} \approx \frac{1}{4} + \frac{1}{2}\frac{v_{4,q}}{v_{2,q}^2}}$

Hanbury-Brown-Twiss interferometry

Two-particle correlation function

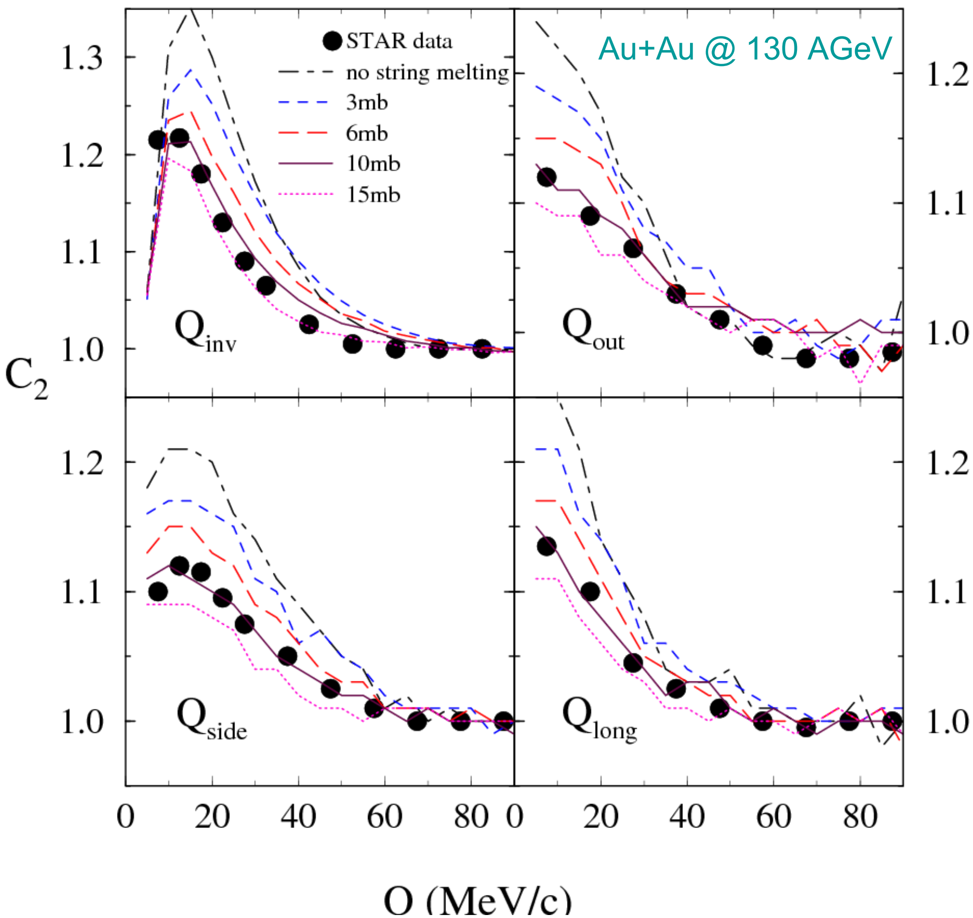
$$C(\vec{K},\vec{q}) = 1 + \frac{\int d^4x_1 d^4x_2 S(x_1,p_1) S(x_2,p_2) \cos[q\cdot(x_1-x_2)]}{\int d^4x_1 S(x_1,p_1) \int d^4x_2 S(x_2,p_2)}$$

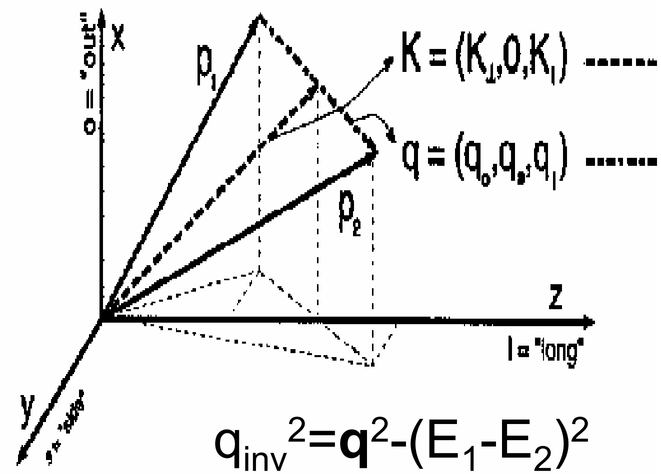
with $\vec{K} = \left(\vec{p}_1 + \vec{p}_2\right)/2,\ \ q = (\vec{p}_1 - \vec{p}_2,\ E_1 - E_2)$

- S(x,p) is the emission source function and is given by the phase space distribution at freeze out in the AMPT model
- C(K,q) can be evaluated using Correlation After Burner (Pratt, NPA 566, 103c (94))

Two-pion correlation functions from AMPT

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



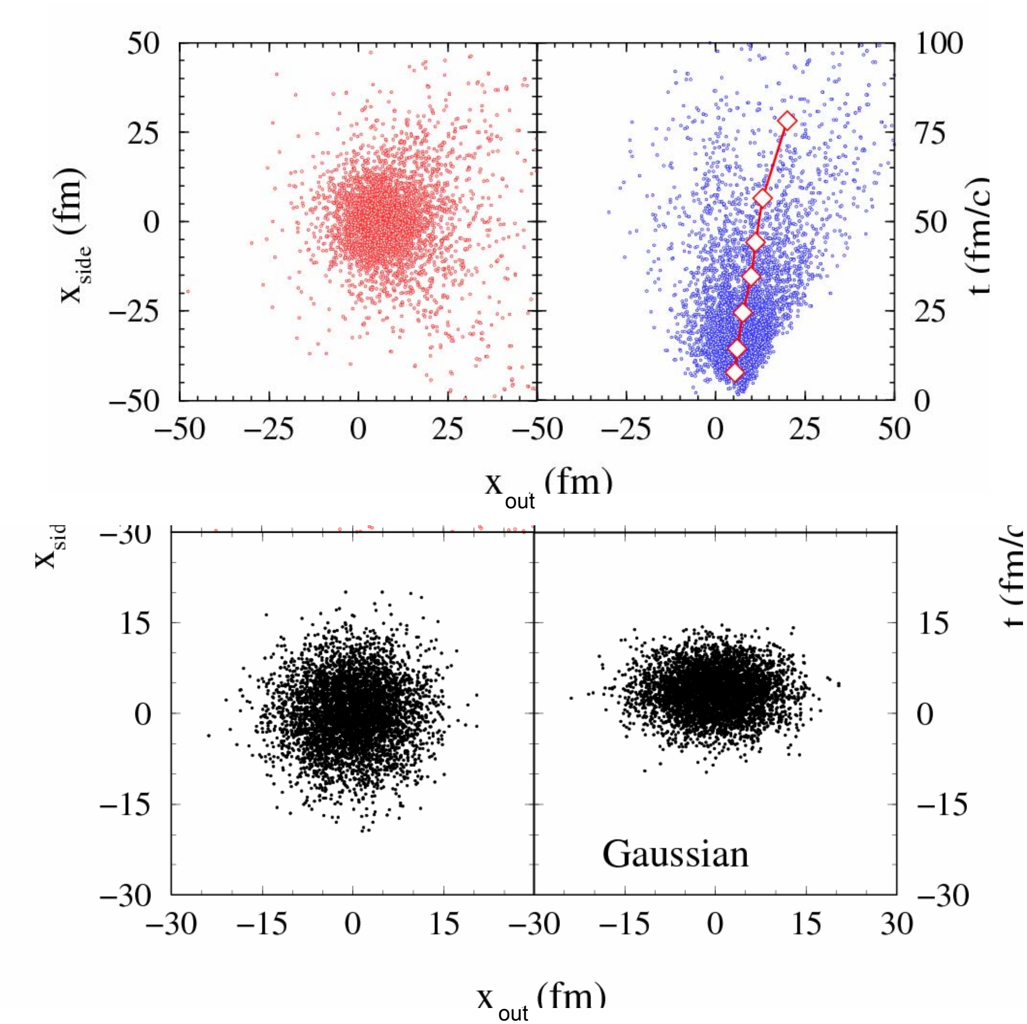


$q_{inv}^2 = \mathbf{q}^2 - (E_1 - E_2)^2$

- For pions with $-0.5 < y < 0.5$ and $125 < p_T < 225$ MeV/c in central collisions
- Projected correlation functions evaluated with other two Q components integrated from 0 to 35 MeV/c

- Need string melting and large parton scattering cross section to reproduce data

Emission function for pions



- Upper: emission source from AMPT
  - Shift in out direction
  - Strong correlation between out position and emission time
  - Large halo due to resonance (ω) decay and explosion

  → non-Gaussian source
- Lower: Gaussian source fitted to correlation functions

Source radii from emission function

Pratt showed in '84 $$C(\vec{K},\vec{q}) \cong 1+\left|\left\langle \exp\left[i\vec{q}\cdot(\vec{x}-\vec{\beta}t)\right]\right\rangle\right|^2$$

with $\beta = K/(E_1+E_2)$ and averaging over emission function S(x,p)

Source radii $$R_{ij}^2 = -\frac{1}{2}\frac{\partial^2 C(\vec{K},\vec{q})}{\partial q_i \partial q_j}\Big|_{q=0} \simeq \left\langle\left(\tilde{x}_i - \beta_i \tilde{t}\right)\left(\tilde{x}_j - \beta_j \tilde{t}\right)\right\rangle$$

$$= D_{x_i,x_j} - D_{x_i,\beta_j t} - D_{\beta_i t, x_j} + D_{\beta_i t,\beta_j t}$$

with $\tilde{x} = x - \langle x \rangle, \quad D_{x,y} = \langle xy \rangle - \langle x \rangle \langle y \rangle$

Source radii from Gaussian fit to correlation function

$$C(\vec{K},\vec{q}) = 1 + \lambda \exp\left[-\sum_{i,j} R_{ij}^2\left(\vec{K}\right) q_{ij}^2 \right]$$

Similar radii only for a Gaussian emission function without strong space-momentum correlation

Source radii in the out-side-long coordinates

$$R^2_{out} = D_{x_{out},x_{out}} - 2D_{x_{out},\beta_\perp t} + D_{\beta_\perp t,\beta_\perp t}$$

$$R^2_{side} = D_{x_{side},x_{side}}$$

$$R^2_{long} = D_{x_{long},x_{long}} + D_{\beta_{||}t,\beta_{||}t}$$

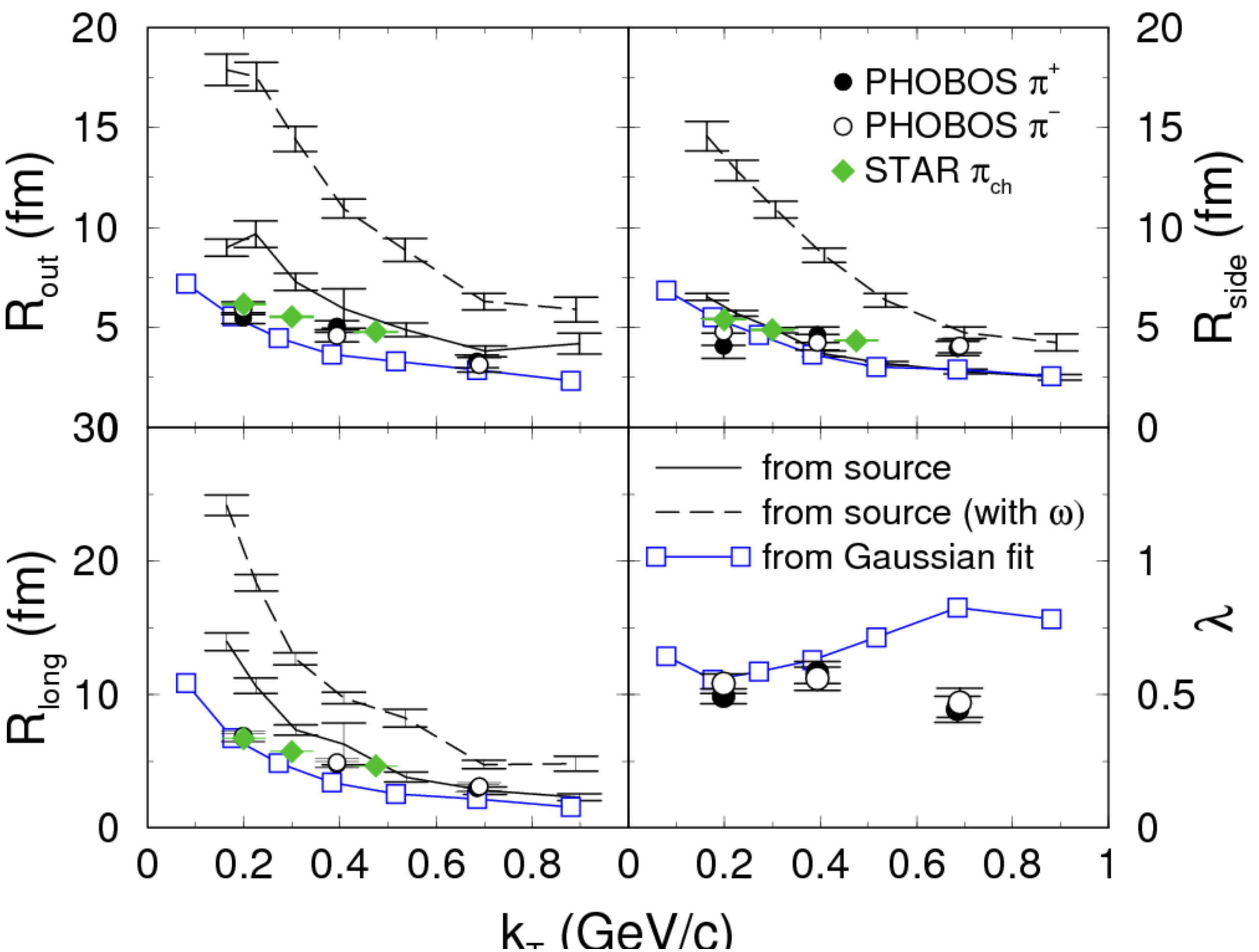
For pion pairs with K_T~200 MeV/c, AMPT gives

$$R_{out} \approx 17\ \mathrm{fm}, \quad D_{x_{out},x_{out}} \approx 185\ \mathrm{fm}^2,$$

$$D_{x_{out},\beta_\perp t} \approx 168\ \mathrm{fm}^2, \quad D_{\beta_\perp t,\beta_\perp t} \approx 431\ \mathrm{fm}^2$$

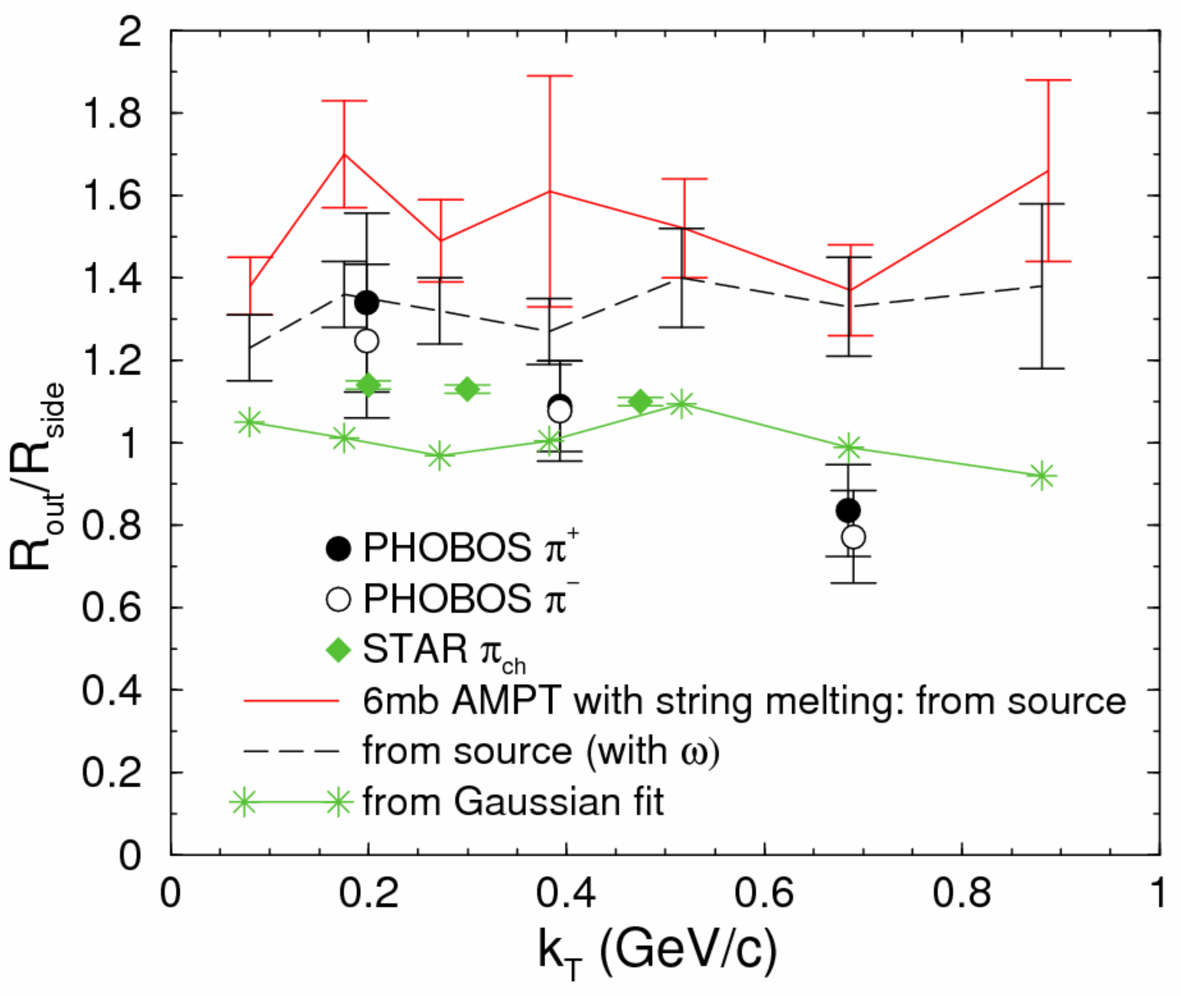
- Large positive out position and emission time correlation reduces out radius
- Without x_{out}-t correlation, R_{out}/R_{side}~1.5 instead 1

Radii of pion emission source



- Radii from emission function > radii from Gaussian fit
- Including ω decay leads to larger radii

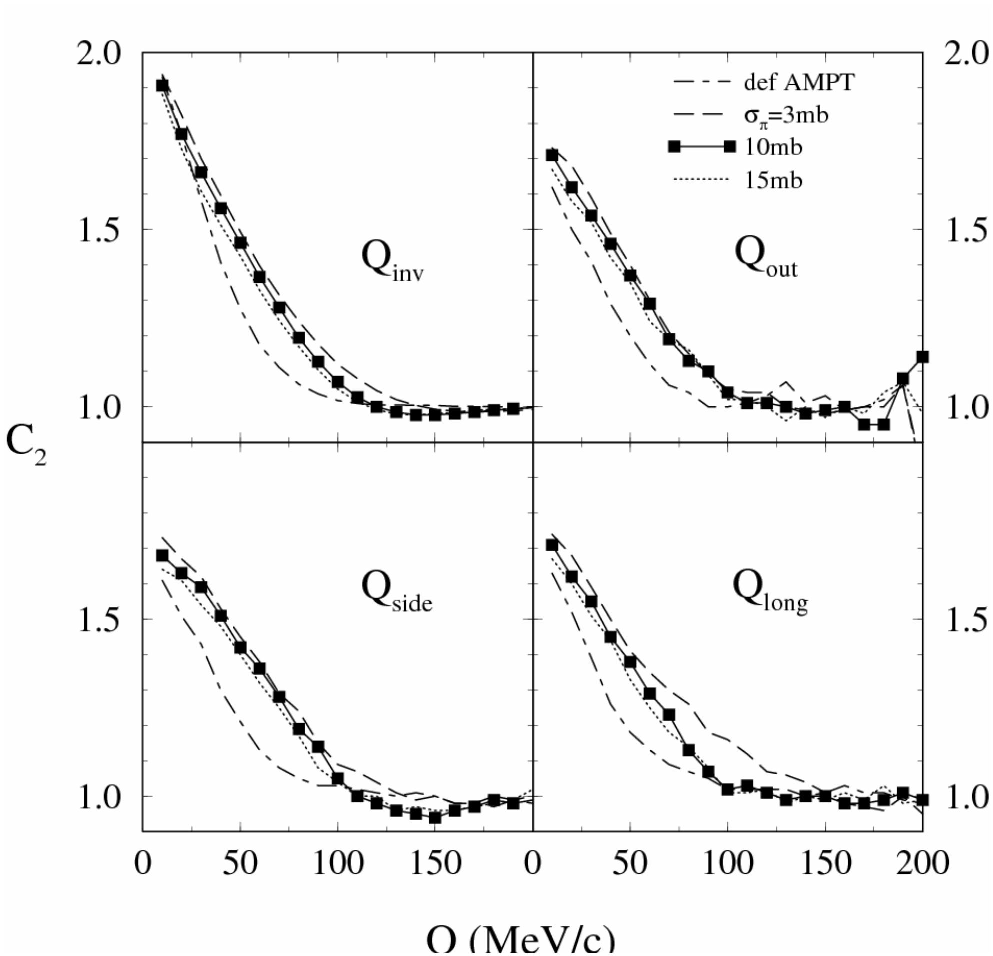
Ratio of source radii from AMPT



- R_{out}/R_{side} >1 is larger from emission function than from Gaussian fit

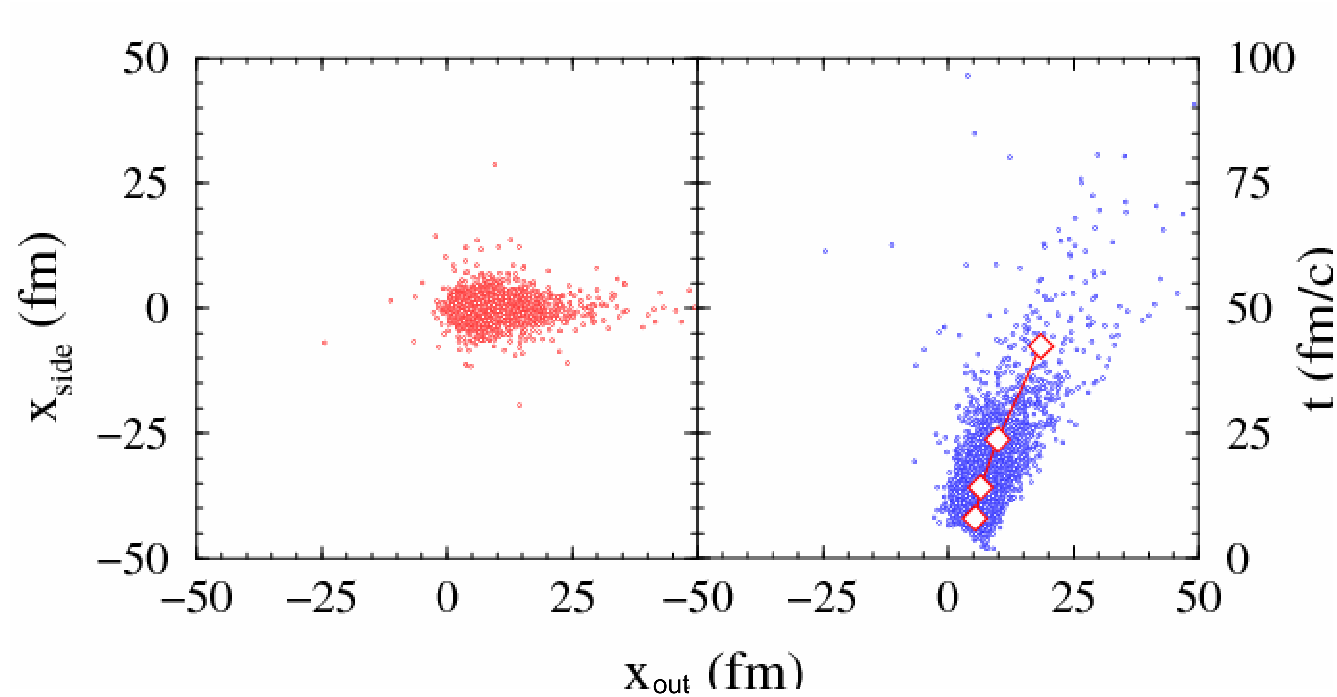
Two-kaon correlation functions from AMPT

Lin & Ko, JPG 30, S263 (2004)



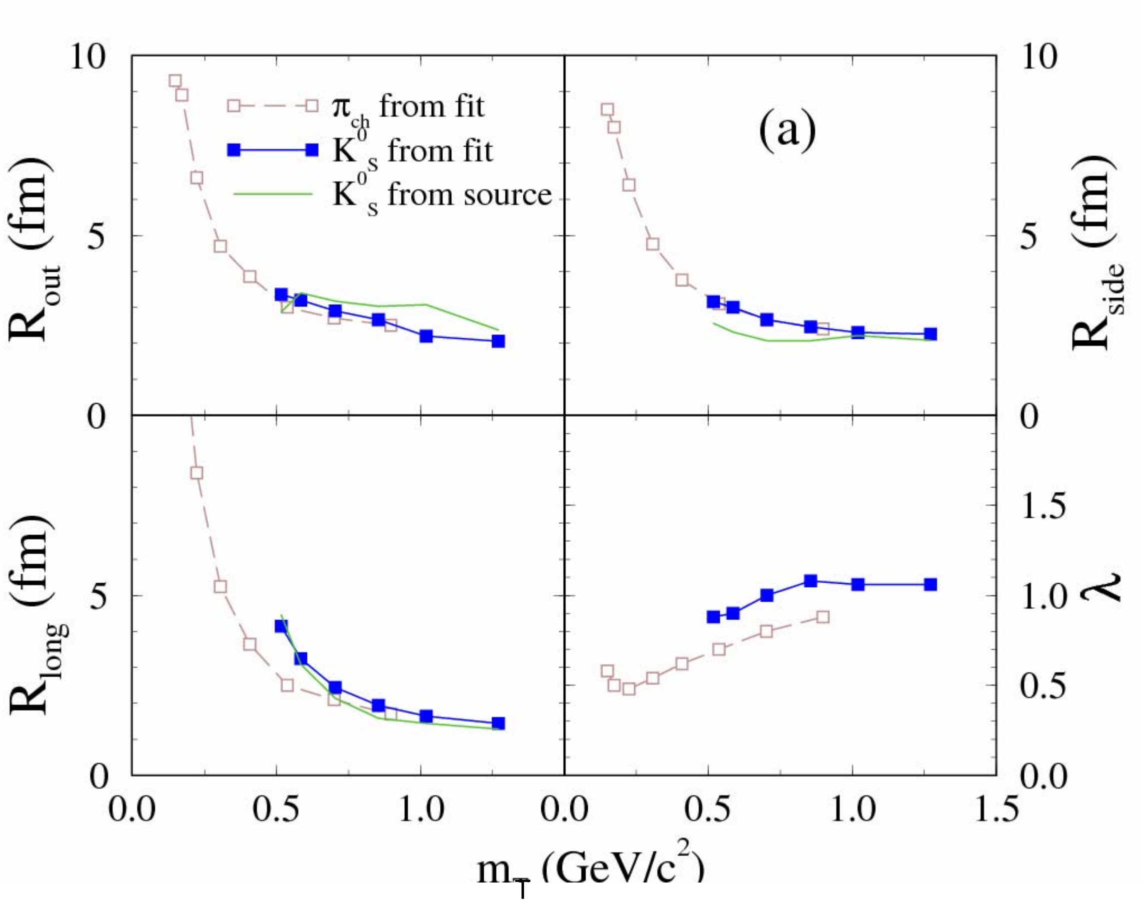
- For kaons with -1< y < 1 and 200 < p_T < 400 MeV/c
- Projected correlation functions evaluated with other two Q components integrated from 0 to 40 MeV/c
- Significant difference between default AMPT and with string melting
- Less sensitive to parton cross section than the case of pions

Emission function for kaons



- Similarity to pion emission function
  - shift in out direction
  - strong correlation between out position and emission time
- Difference from pion emission function
  - smaller source size
  - no large halo

Radii of kaon emission source



- Radii from emission function ~ radii from Gaussian fit
- Radii for kaons < radii fro pions at same p_T but the two show approximate m_T scaling

Summary

- The AMPT model with string melting and large parton cross section reproduces observed
  - large elliptic flow and mass ordering at low p_T
  - scaling of hadron anisotropic flows $v_4 \approx 1.2 v_2^2$
  - two pion correlation functions

- Emission function in AMPT
  Pions:
  - non-Gaussian with large halo due to resonance decay and explosion
  - shift in out direction
  - strong correlation between out position and time

  Kaons: similar to pions but without halo, thus closer to Gaussian and smaller

- Large parton cross section may be due to quasi bound states in QGP and/or multiparton dynamics $gg \leftrightarrow ggg$ and $ggg \rightarrow ggg$