# Transport Model Description of Flow

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- Transport model (AMPT)
- Parton coalescence
- Elliptic flow

Collaborators:

Z.W. Lin, S. Pal, B. Zhang, B.A. Li:
PRC 61, 067901 (00); 64, 041901 (01);
NPA 698, 375c (02)

V. Greco, P. Levai: PRL 90, 202102 (2003);
PRC 68, 034904 (2003)

L.W. Chen

# A multiphase transport model

- Initial conditions: HIJING
  Hard minjet partons and soft strings

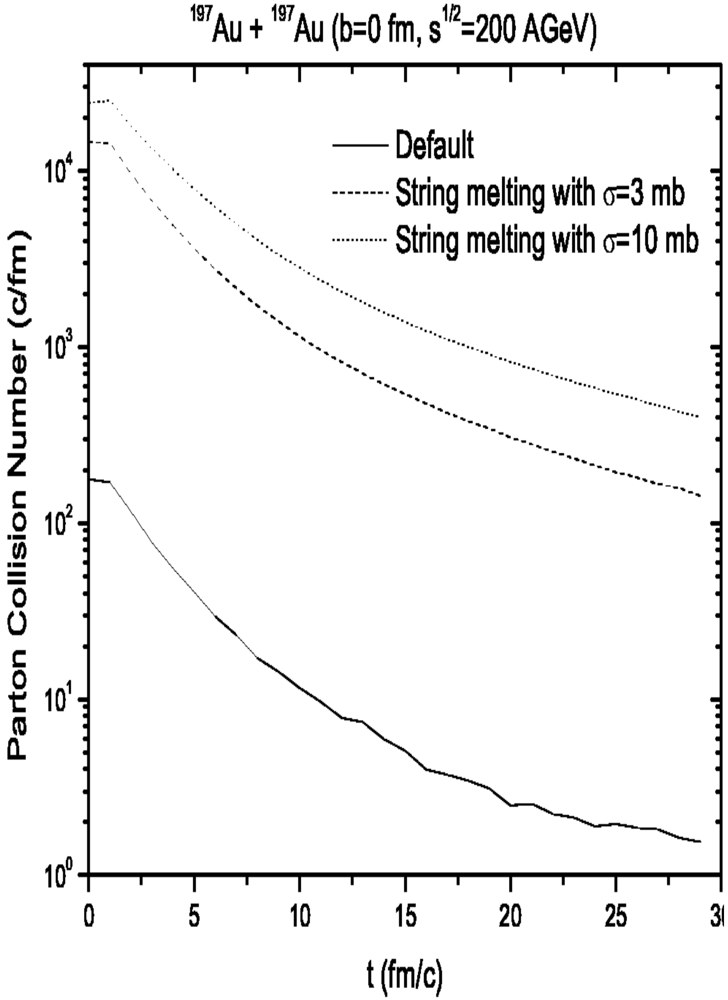
- Parton evolution: ZPC
  Default: Minijet partons
  String melting: Minijet partons and soft partons

- Hadronization:
  Default: Lund string model
  String melting: quark coalescence or recombination

- Hadronic transport: ART

PRC 61, 067901 (00); 64, 041901 (01); NPA 698, 375c (02)

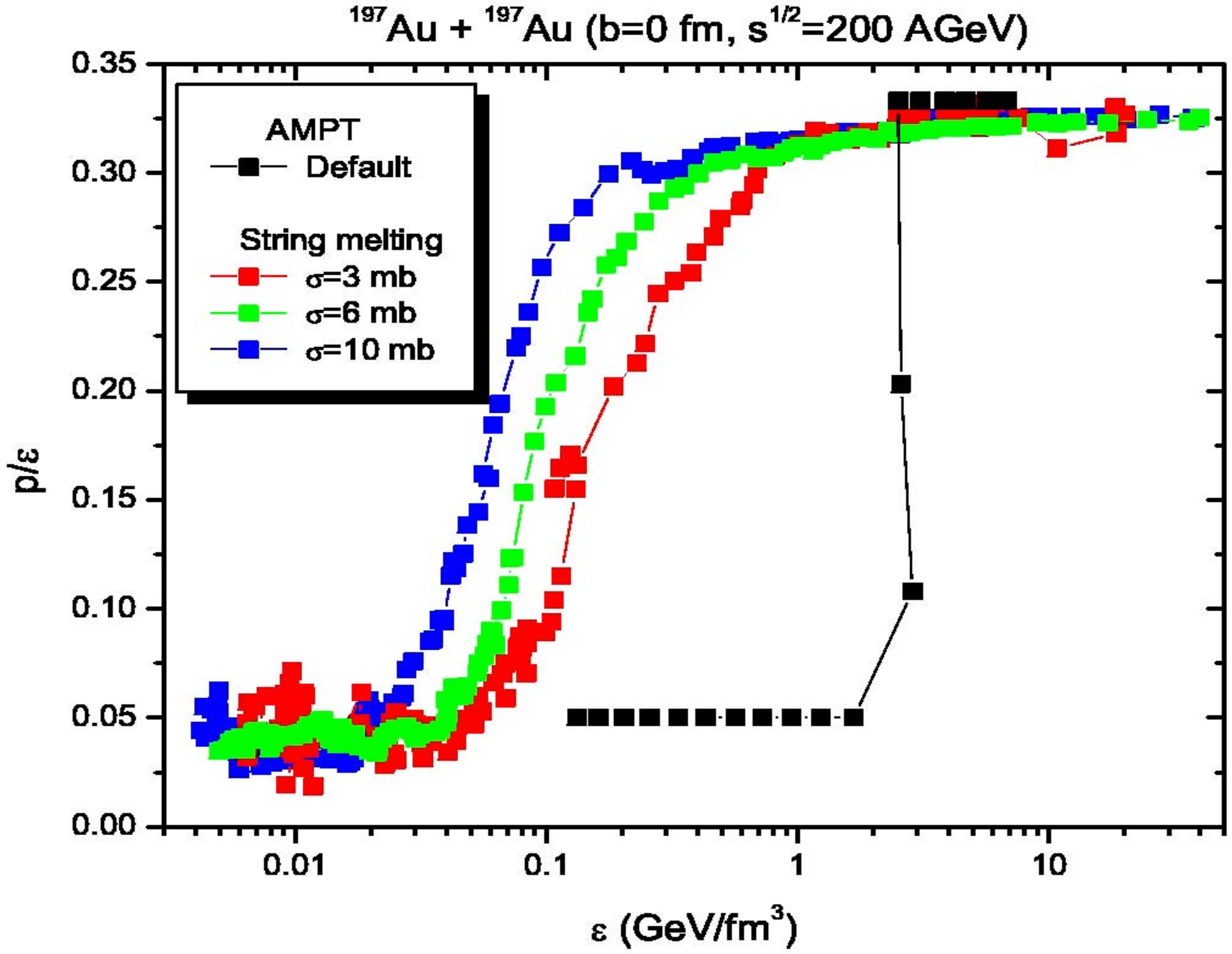
# Parton collision rate



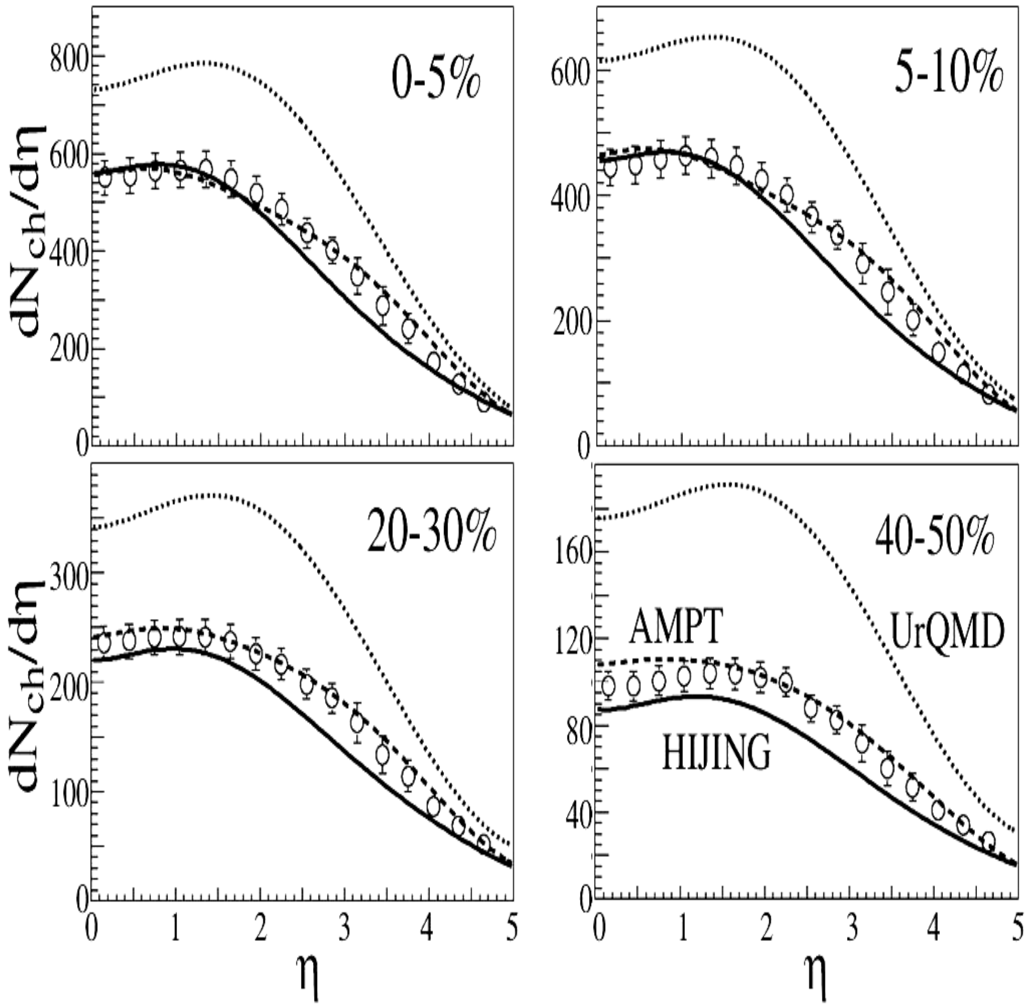
- **Default**: 800 collisions for 1600 partons, i.e., about one collision per parton

- **String melting**: both parton and collision numbers increase by ten, i.e., about ten collisions per parton

# Softening of equation of state



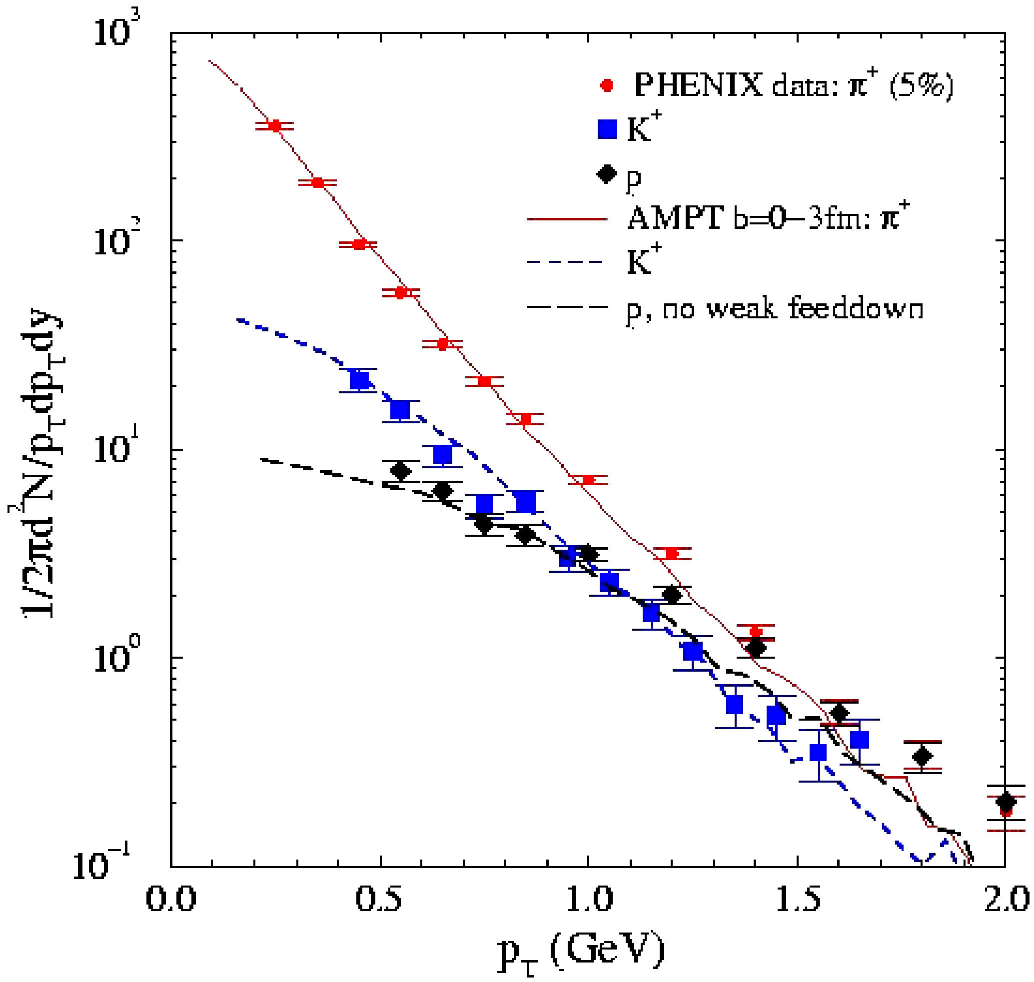
# Rapidity distributions



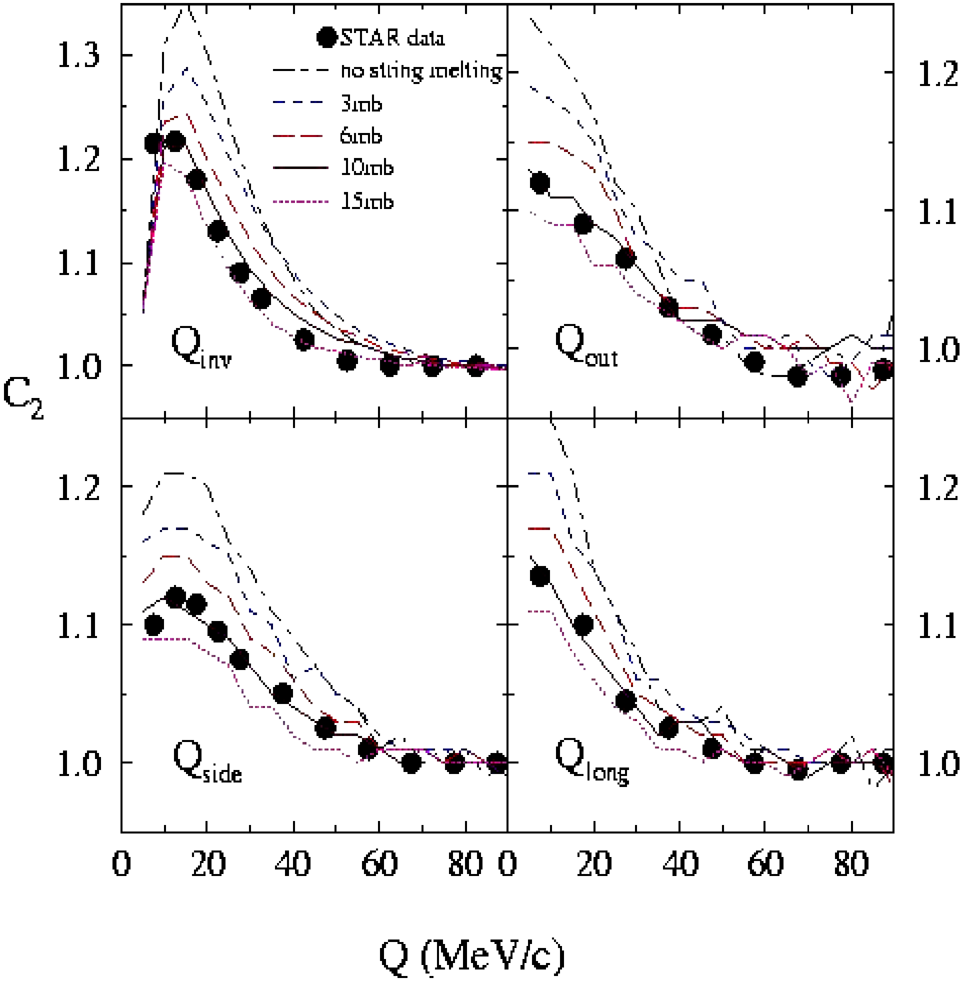
Au+Au @ 130 AGeV

- Data from BRAHMS
- Solid lines: default HIJING
- Dashed lines: AMPT prediction

# Transverse mass distributions

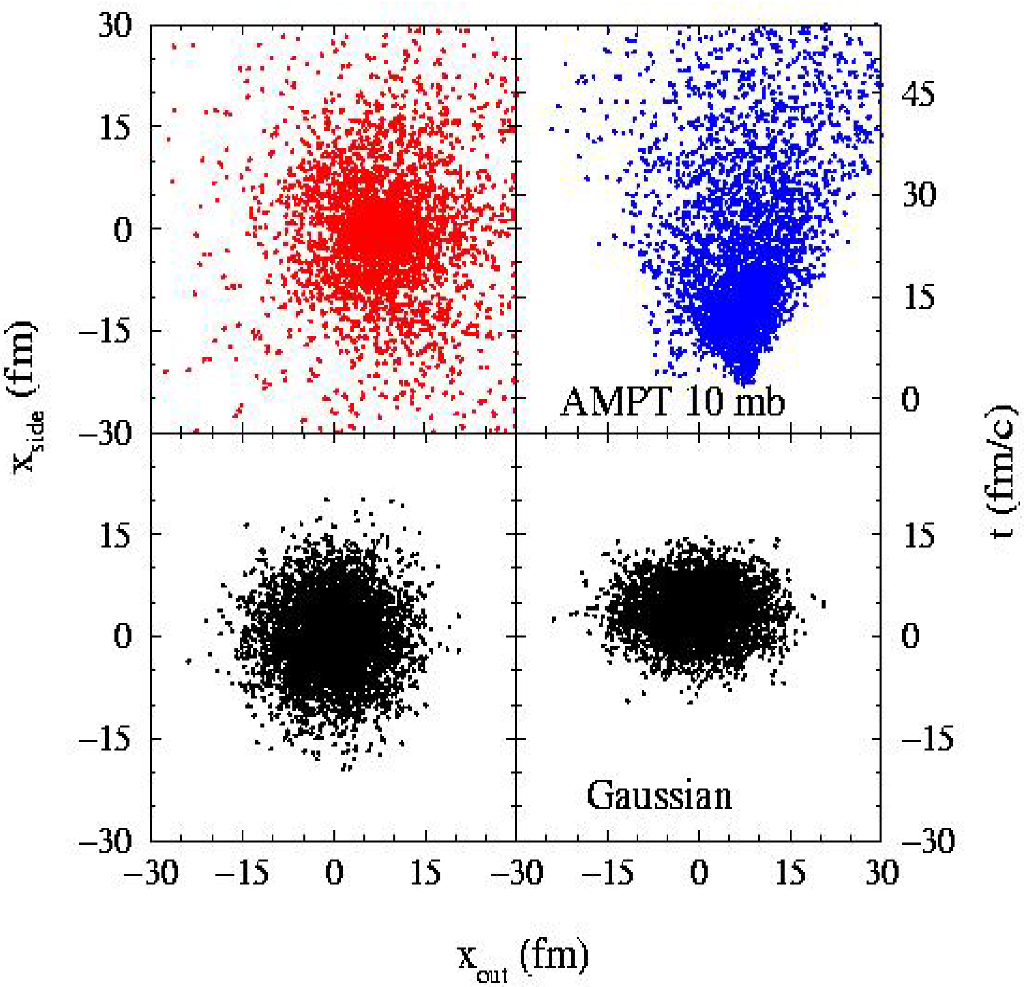


# Two-Pion Correlation Function



- Lin, Ko & Pal, PRL
- 89, 152301 (2002)
- Au+Au @ 130 AGeV
- Need string melting and large parton scattering cross section

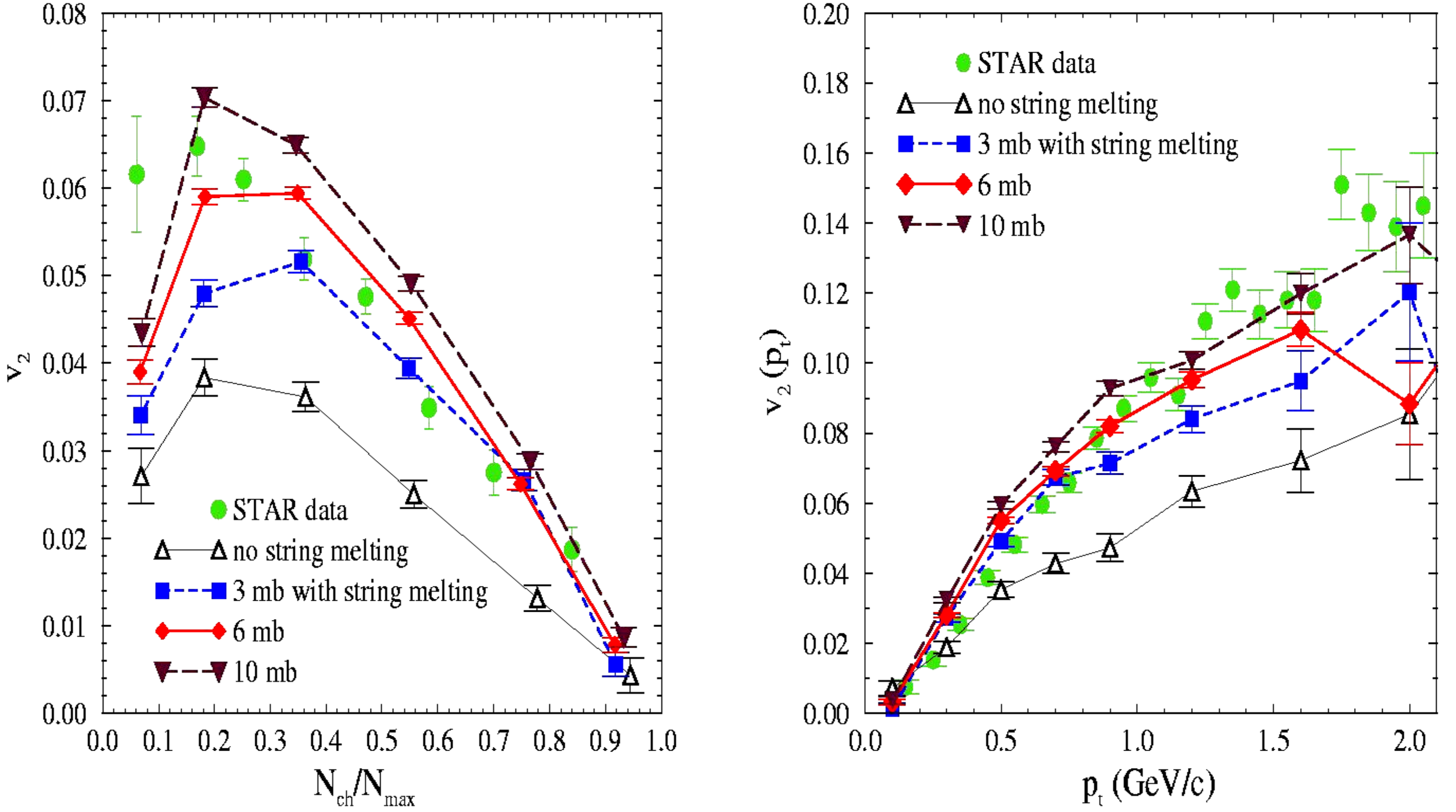
# Emission Function



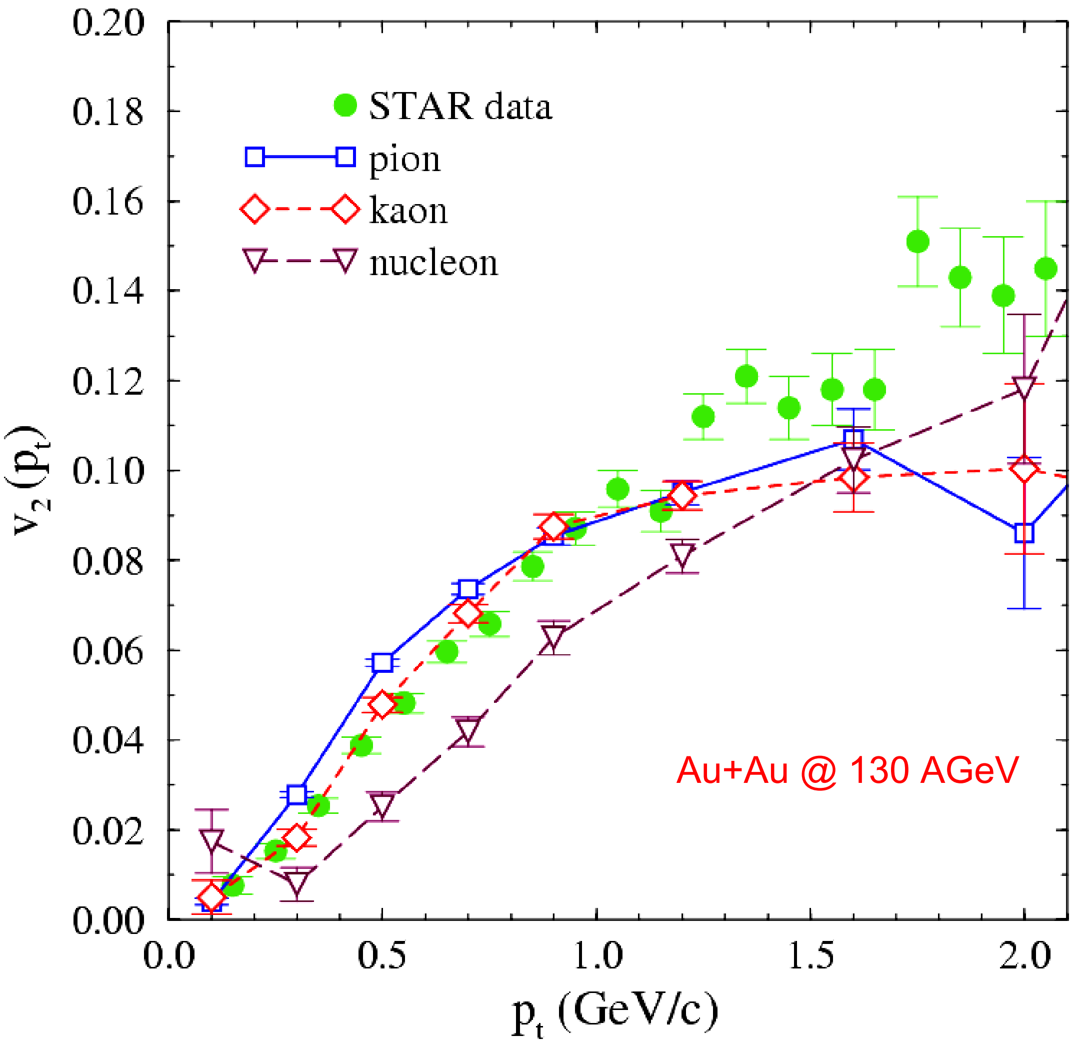
- Shift in out direction
- Strong correlation between out position and emission time
- Large halo due to resonance ($\omega$) decay and explosion

→ non-Gaussian source

# Elliptic flow in Au+Au @ 200 AGeV



Lin & Ko, PRC 65, 034904 (2002)

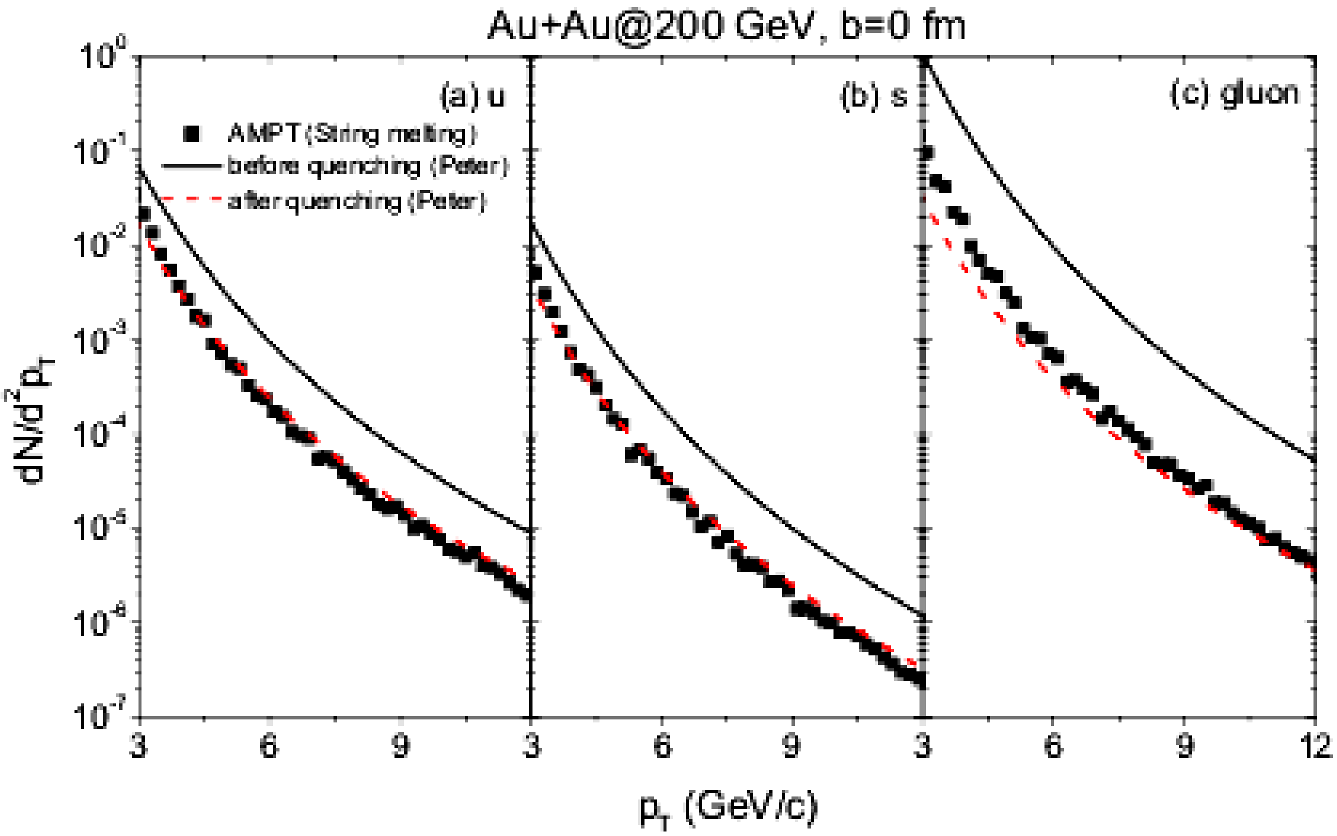

0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
$v_2(p_t)$
0.0
0.5
1.0
1.5
2.0
$p_t$ (GeV/c)
● STAR data
pion
kaon
nucleon
Au+Au @ 130 AGeV

# Jet quenching in quark-gluon plasma

$$\Delta E = C\int_{\tau_0}^{\infty} d\tau\,\rho(\tau,\vec{x}(\tau))(\tau - \tau_0)\ln\left(\frac{2E_0}{\mu^2 L}\right)$$

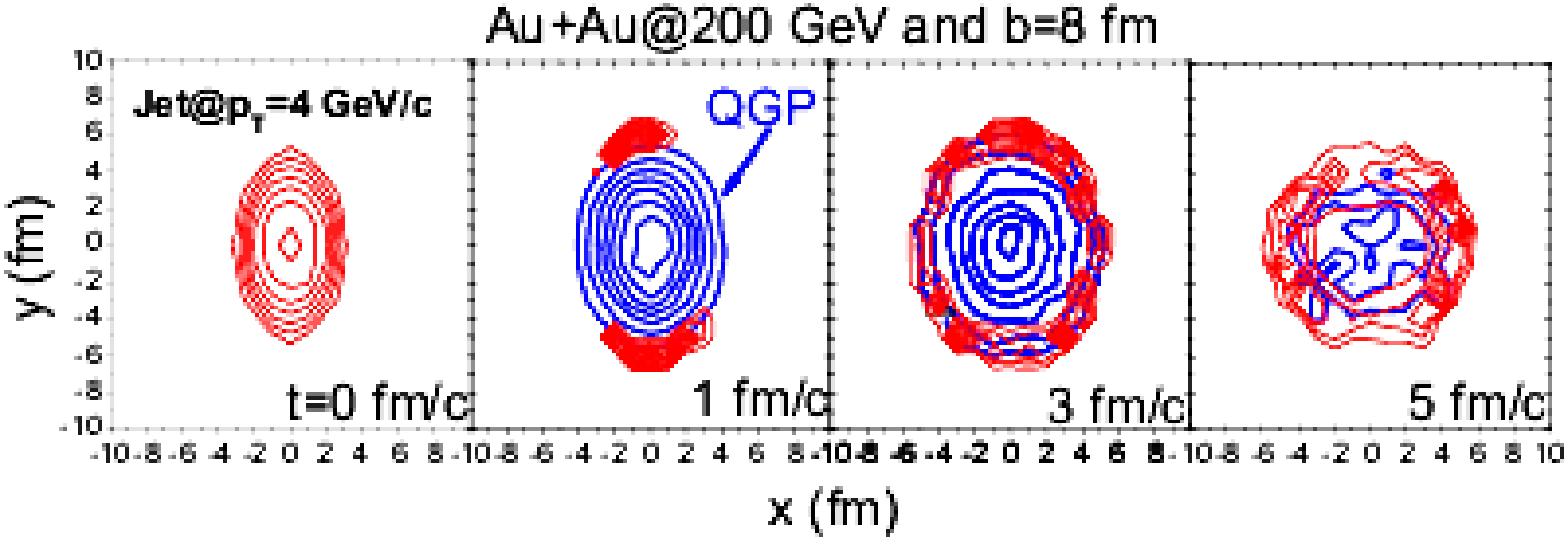
Gyulassy, Levai, Vitev,
PRL, 85, 5535 (2000)

Screening mass $\mu \sim 0.5\,\mathrm{GeV}$ Path length $L \sim 4\ \mathrm{fm}$ $C \sim 0.5$

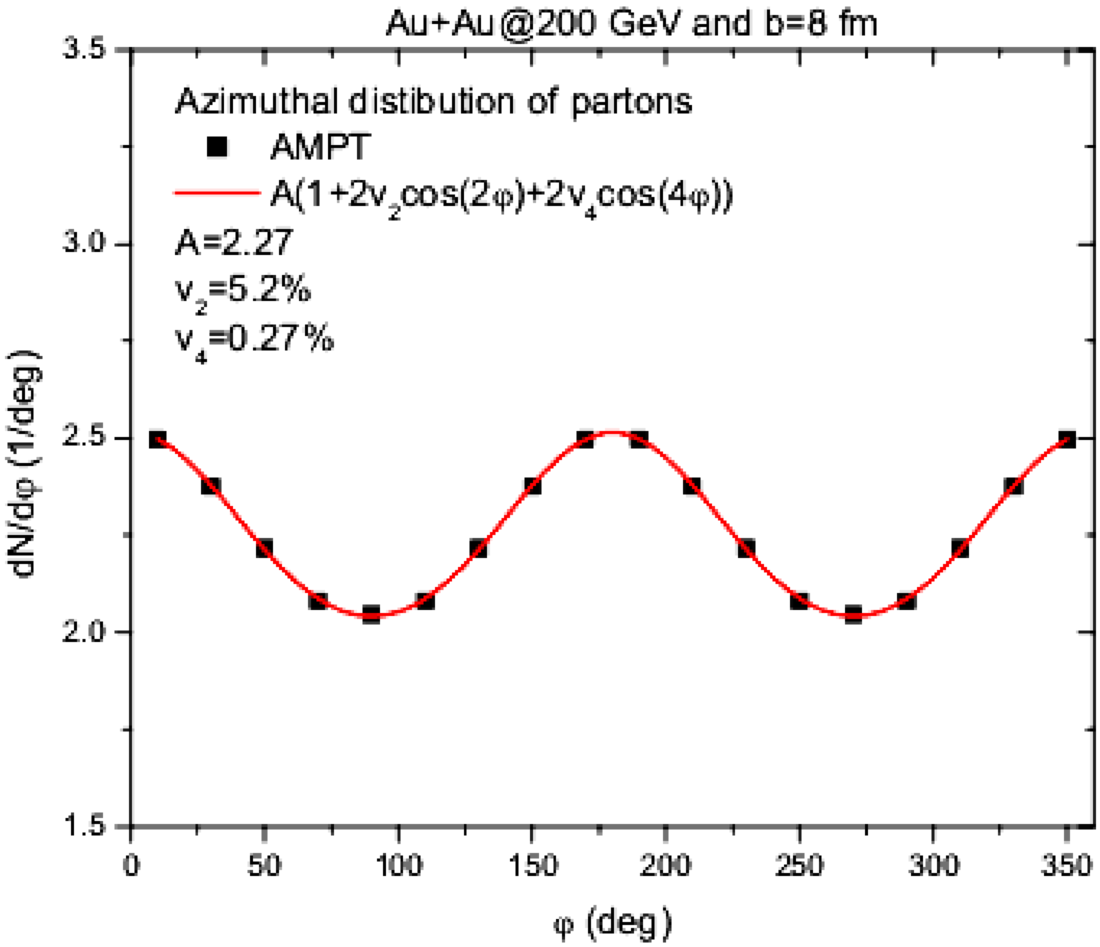


# Transverse positions of minijet partons at freezeout

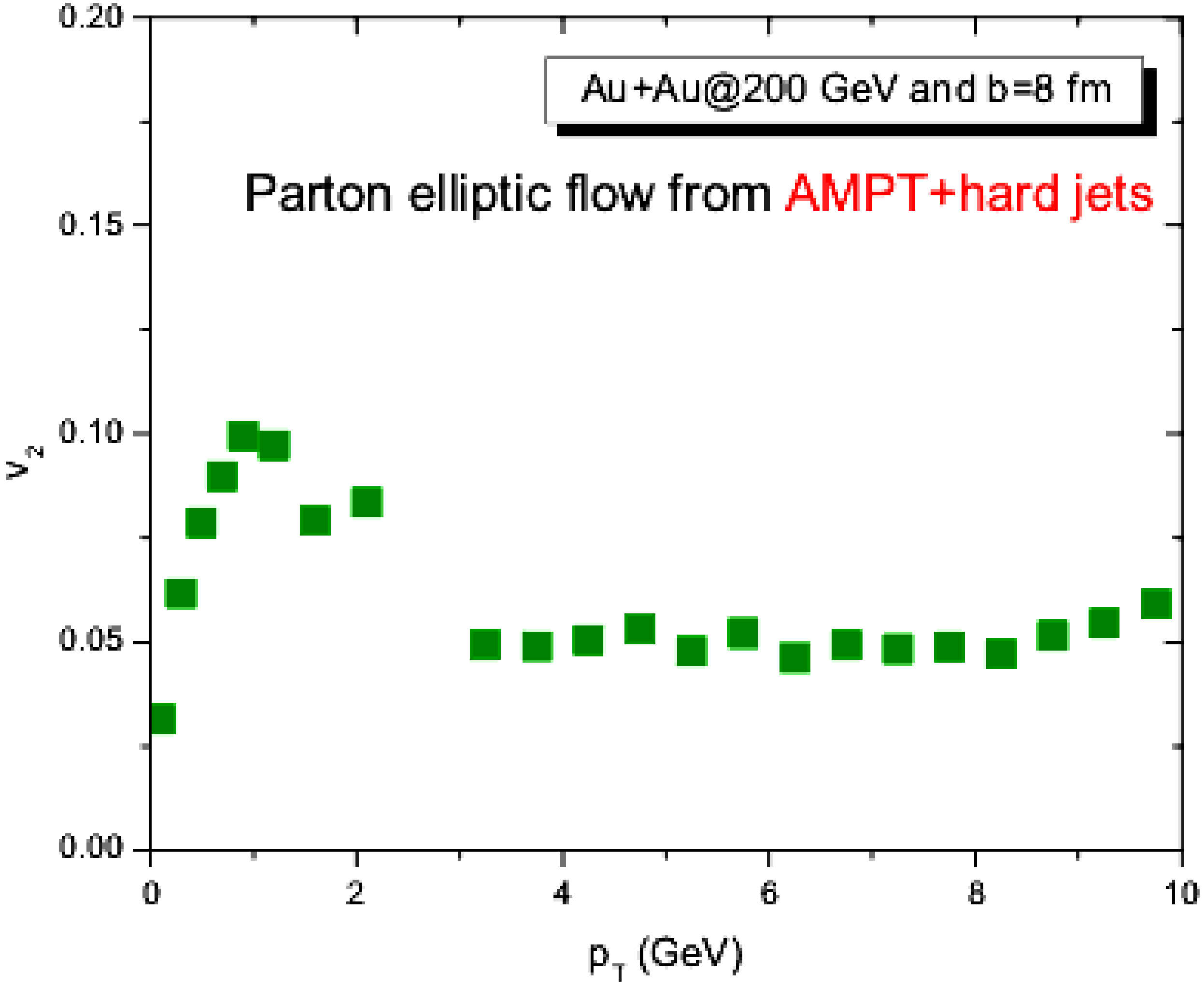
$$n_{\text{parton}}(\tau_f) = 1\ \text{fm}^{-3}$$



# Parton azimuthal distribution



# Parton elliptic flow



# The coalescence model

Dover et al., PRC 44, 1636 (1991)

$$N_M = g_M \int p_1 \cdot d\sigma_1 p_2 \cdot d\sigma_2 \frac{d^3p_1}{E_1} \frac{d^3p_2}{E_2}$$

$$\times f_q(x_1, p_1) f_q(x_2, p_2) f_M(x_1, x_2; p_1, p_2)$$

Quark distribution function $f_q(x,p)$ $\int p \cdot d\sigma \frac{d^3p}{(2\pi)^3 E} f_q(x,p) = N_q$

Spin-color statistical factor $g_M$ e.g. $g_\pi = g_K = 1/36 \quad g_\rho = g_{K^*} = 1/12$

Coalescence probability function $f_M(x_1, x_2; p_1, p_2) \equiv f_2(x_1 - x_2; p_1 - p_2)$

# Coalescence probability function

$$f_2(x_1 - x_2; p_1 - p_2) = \exp[(x_1 - x_2)^2 / 2\Delta_x^2]$$
$$\times \exp\{[(p_1 - p_2)^2 - (m_1 - m_2)^2] / 2\Delta_p^2\}$$

Quark mass

Coalescence radii $\Delta_x \cdot \Delta_p \geq \hbar$

$$(x_1 - x_2)^2 = 2\tau^2[1 - \cosh(\eta_1 - \eta_2)] - (\vec{r}_1 - \vec{r}_2)^2$$

$$(p_1 - p_2)^2 = m_{1T}^2 + m_{2T}^2 - 2m_{1T}m_{2T}\cosh(y_1 - y_2) - (\vec{p}_{1T} - \vec{p}_{2T})^2$$

# Monte-Carlo method

Introduce quark probabilities $P_q(i)$ according to their transverse momentum and spatial distributions

$$\frac{dN_M}{d^2\vec{p}_T} = g_M \prod_{i,j} P_q(i) P_{\bar{q}}(j)\, \delta^{(2)}(\vec{p}_T - \vec{p}_{iT} - \vec{p}_{jT}) \times f_M(x_i, x_j; p_i, p_j)$$

$$\frac{dN_B}{d^2\vec{p}_T} = g_B \sum_{i\neq j\neq k} P_q(i) P_q(j) P_q(k)\, \delta^{(2)}(\vec{p}_T - \vec{p}_{iT} - \vec{p}_{jT} - \vec{p}_{kT}) \times f_B(x_i, x_j, x_k; p_i, p_j, p_k)$$

# Minijet partons

Gyulassy, Levai, Vitev, PRL, 85, 5535 (2000)

$$\frac{dN_{jet}}{d^2\vec{p}_T} = \frac{1}{\sigma_{tot}} \int d^2\vec{b}\, d^2\vec{r}\, t_{Au}(\vec{r}) t_{Au}(\vec{b}-\vec{r}) \sum_{a,b} \int dx_a dx_b d^2\vec{k}_{aT} d^2\vec{k}_{bT}$$

$$\times g(\vec{k}_{aT}) g(\vec{k}_{bT}) f_{a/Au}(x_a, Q^2) f_{b/Au}(x_b, Q^2)$$

$$\times \frac{\hat{s}}{\pi} \delta(\hat{s}+\hat{t}+\hat{u}) \frac{d\sigma^{ab}}{d\hat{t}}$$

After jet quenching using opacity parameter $L/\lambda = 3.5$

$$\frac{dN_{jet}}{d\vec{p}_T} = A\left(\frac{B}{B+p_T}\right)^n$$

| | $g$ | $u,d$ | $\bar{u},\bar{d}$ | $s,\bar{s}$ |
|---|---|---|---|---|
| $A(10^4/GeV^2)$ | 3.2 | 9.8 | 1.9 | 6.5 |
| B(GeV) | 0.5 | 0.5 | 0.5 | 0.5 |
| n | 7.1 | 6.8 | 7.5 | 7.4 |

# Quark-gluon plasma

$$\frac{dN_q}{dy d^2\vec{p}_T} = \frac{g_q \tau \pi R^2 m_T}{(2\pi)^3} \exp\left( - \frac{m_T - \mu_q}{T} \right)$$

Light quarks $g_{u,d} = 6, \quad m_{u,d} = 300 \ \mathrm{MeV}, \quad \mu_{u,d} = 10 \ \mathrm{MeV}$

Strange quarks $g_s = 6, \quad m_s = 475 \ \mathrm{MeV}, \quad \mu_s = 10 \ \mathrm{MeV}$

Gluons $g_g = 16, \quad m_g = 300 \ \mathrm{MeV}, \quad \mu_g = 0$

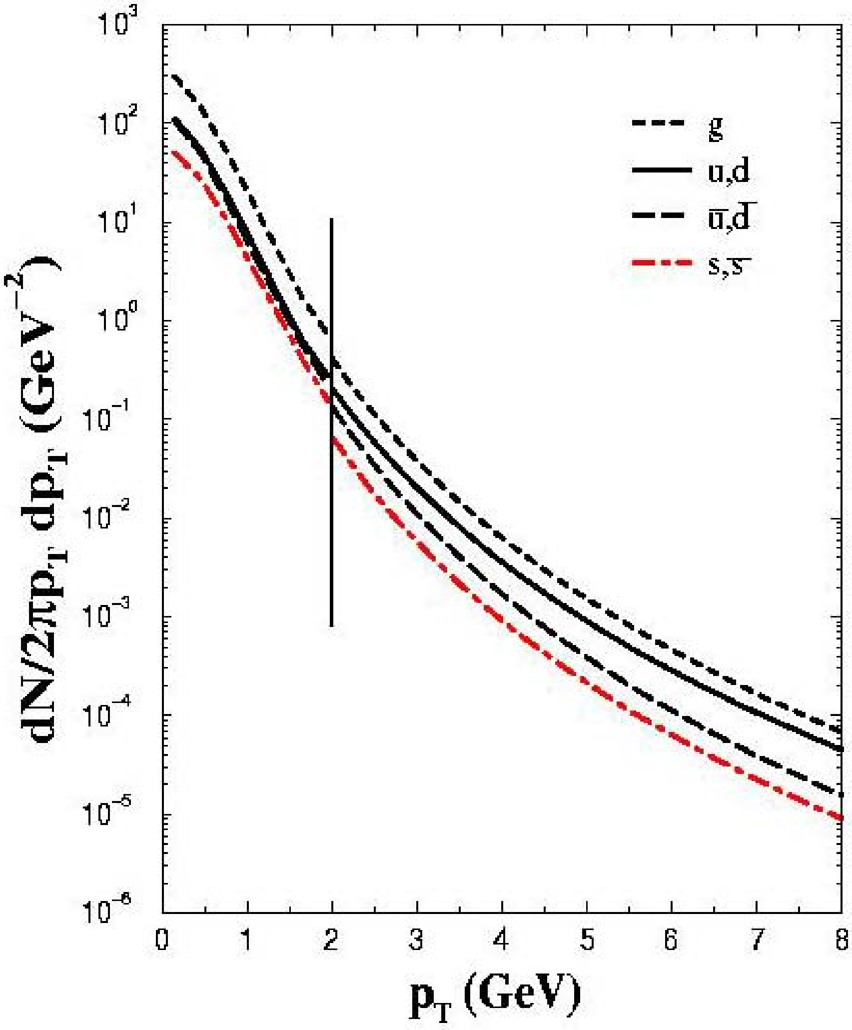
Take T=170 MeV

$$\Rightarrow \quad \bar{u}/u = \bar{d}/d = 0.89, \quad \bar{s}/s = 1 \quad s/u = 0.27$$

$$\Rightarrow \quad \bar{p}/p = 0.7, \quad K \ /K^+ = 89, \quad K \ /\pi \ = 0.24$$

as in experimental data

# Parton transverse momentum distributions



- Thermal QGP $p_T \leq 2\,\text{GeV}$
- Power-law minijets $p_T \geq 2\,\text{GeV}$

Choose

$$R = 8.3\ \text{fm}$$

$$\tau = 4\ \text{fm}, \quad |y| \leq 0.5$$

$$\Rightarrow \quad V = 900\ \text{fm}^3$$

$$\left.\frac{dE_T}{dy}\right|_{|y|\leq 0.5} = 590\ \text{GeV}$$

Consistent with data (PHENIX)

# Other inputs or assumptions

- Minijet fragmentation via KKP fragmentation functions

$$\frac{dN}{d^2\vec{p}_{had}} = \sum_{jet} \int dz \frac{dN}{d^2\vec{p}_{jet}} \frac{D_{had/jet}(z,Q^2)}{z^2}, \quad z = \frac{p_{had}}{p_{jet}}$$

- Gluons are converted to quarks and antiquarks with flavor probabilities similar to quarks in QGP
- Quark-gluon plasma is given a transverse collective flow velocity of $\beta = 0.5c$, so partons have an additional velocity

$$v(r) = \beta(r/R)$$

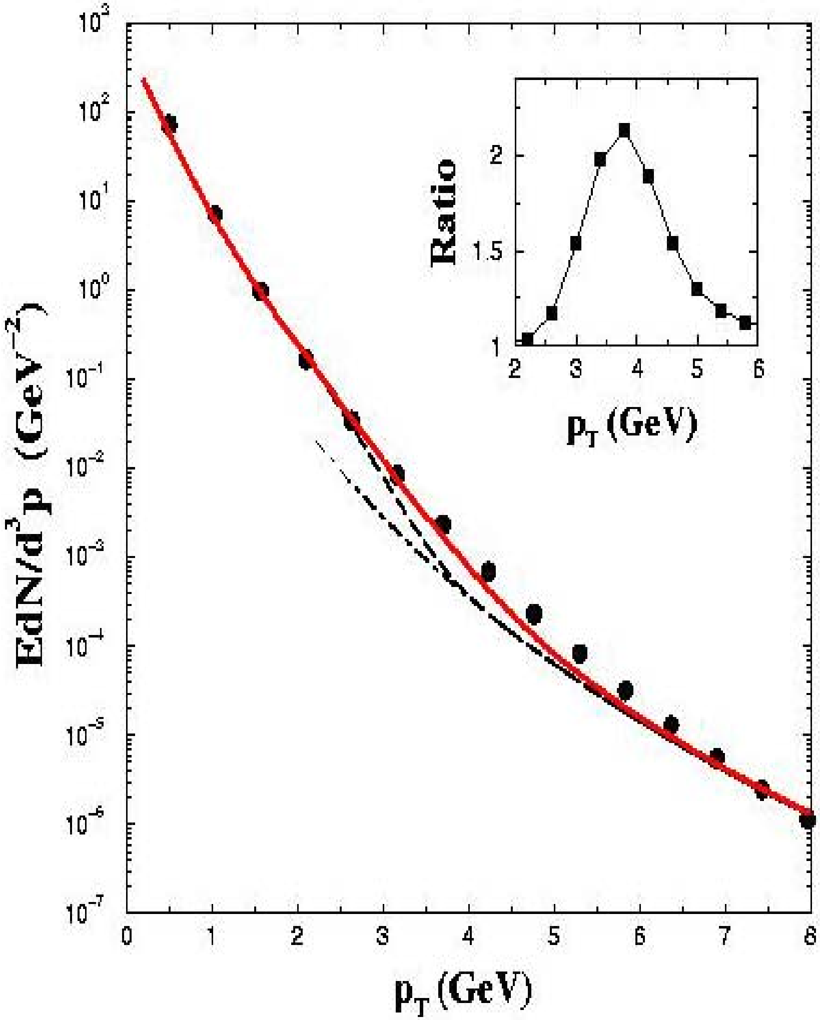
- Minijet partons have current quark masses

$$m_{u,d} = 10\ \text{MeV}, \quad m_s = 175\ \text{MeV}$$

- Use coalescence radii $\Delta p = \Delta x^{-1} = 0.24\ \text{GeV}$ for mesons

$\Delta p = \Delta x^{-1} = 0.45\ \text{GeV}$ for baryons

# Pion spectrum including rho decays

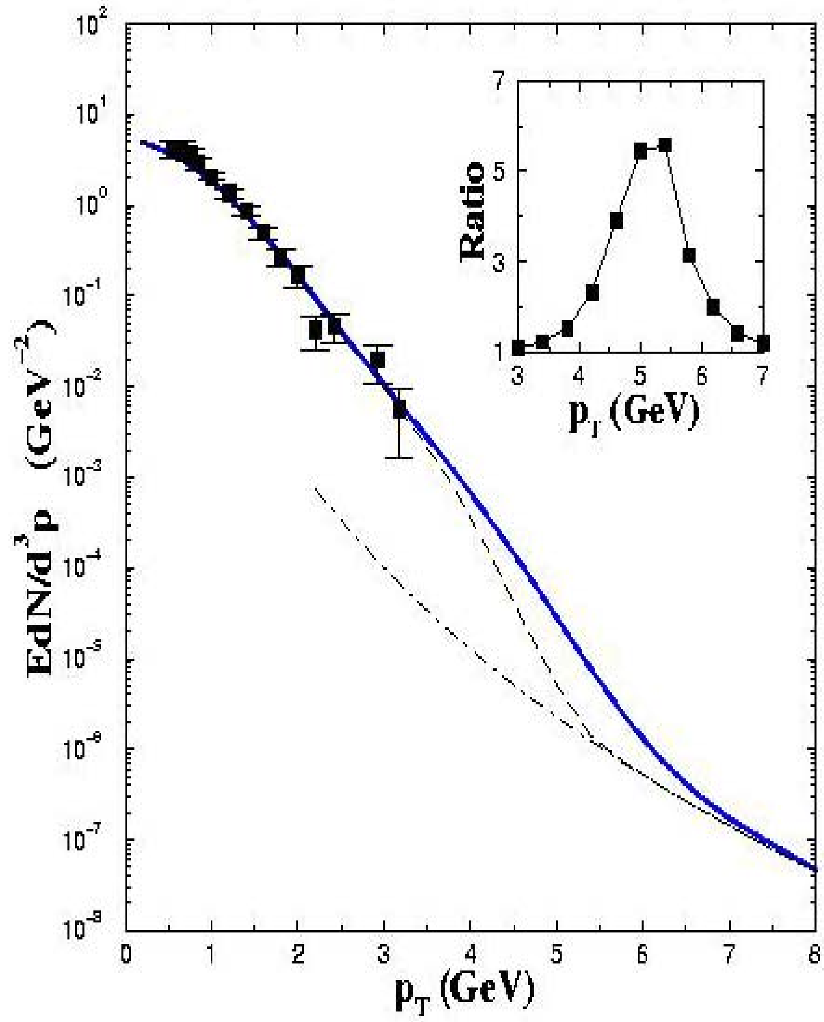


- Au+Au @ 200 AGeV

- Dash-dotted: minijets
- Dashed: QGP+minijets
- Solid: QGP+minjets+soft-hard coalescence
- Filled circles: data
- Inset: ratio of with and without soft-hard coalescence

- Reproduce data at all momenta
- Hard+hard coalescence negligible

# Antiproton spectrum including antidelta decays

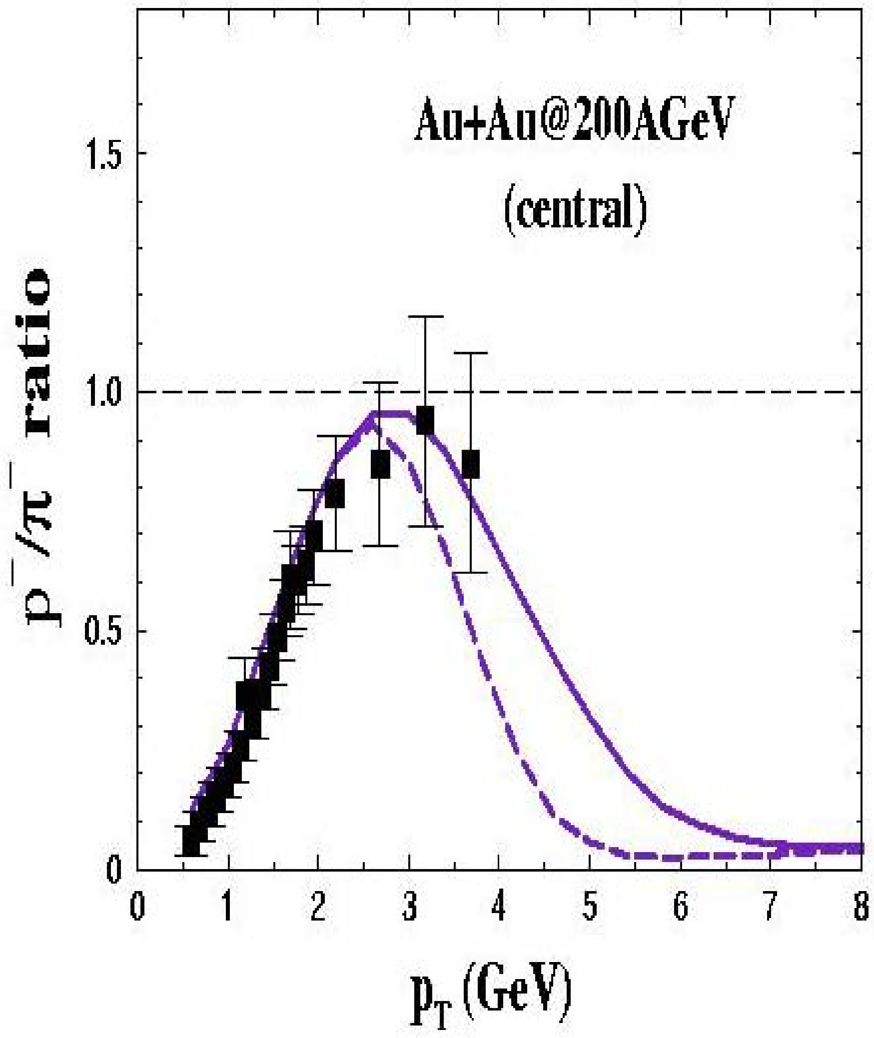


- Au+Au @ 200 AGeV

- Dash-dotted: minijets
- Dashed: QGP+minijets
- Solid: QGP+minijets+soft-hard coalescence
- Filled squares: data (PHENIX)
- Inset: ratio of with and without soft-hard coalescence

- Reproduce data at low momenta
- Soft+hard coalescence more important than in pions
- Soft +2hard and 3hard coalescence negligible

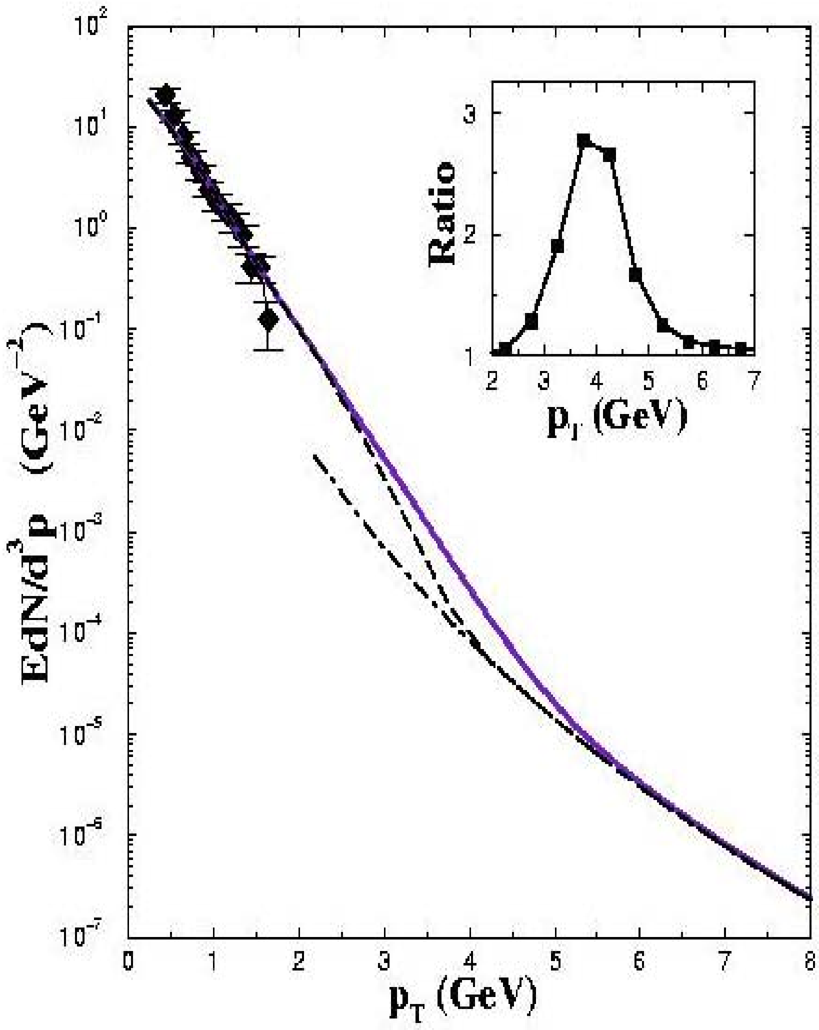
# Antiproton to pion ratio



- Dashed: without soft-hard coalescence
- Solid: with soft-hard coalescence
- Filled squares: data (PHENIX)

- Reproduce data at low and intermediate momenta
- Small ratio at high momenta due to minjets

# Kaon spectrum including K* decays

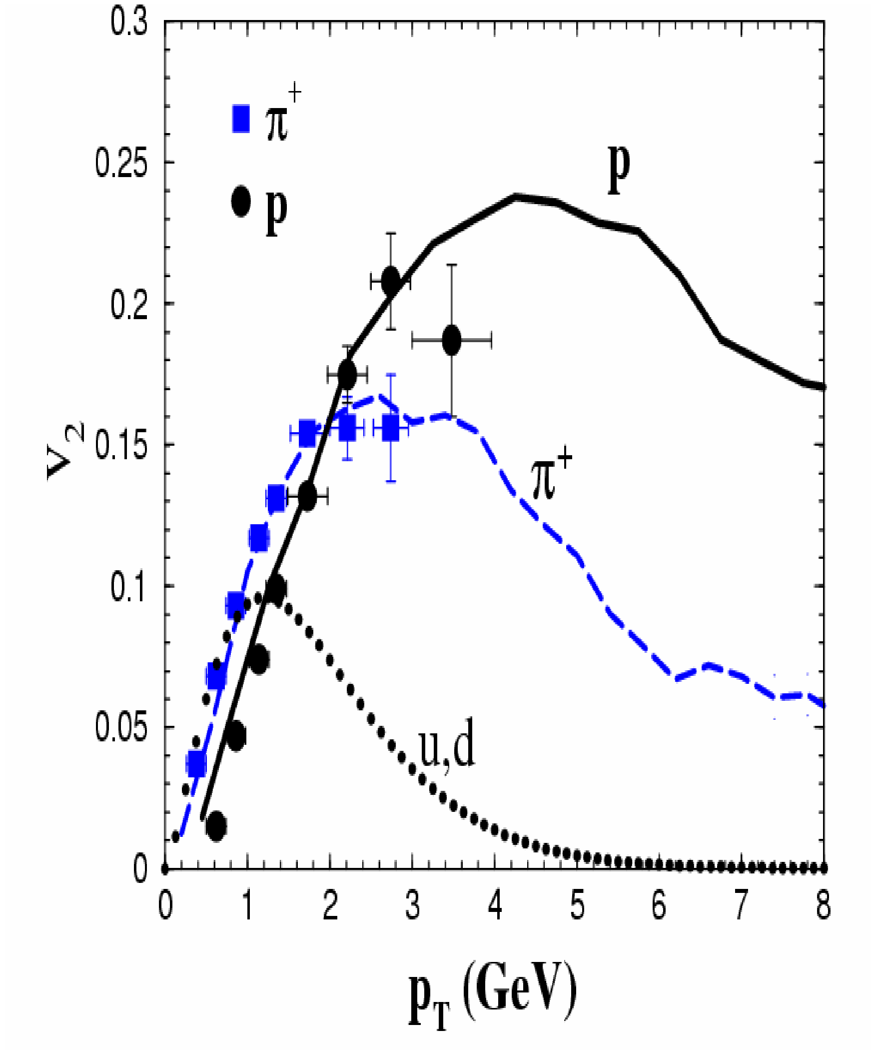


- Au+Au @ 200 AGeV

- Dash-dotted: minijets
- Dashed: QGP+minijets
- Solid: QGP+minijets+sof-hard coalescence
- Filled diamonds: data (PHENX)
- Inset: ratio of with and without soft-hard coalescence

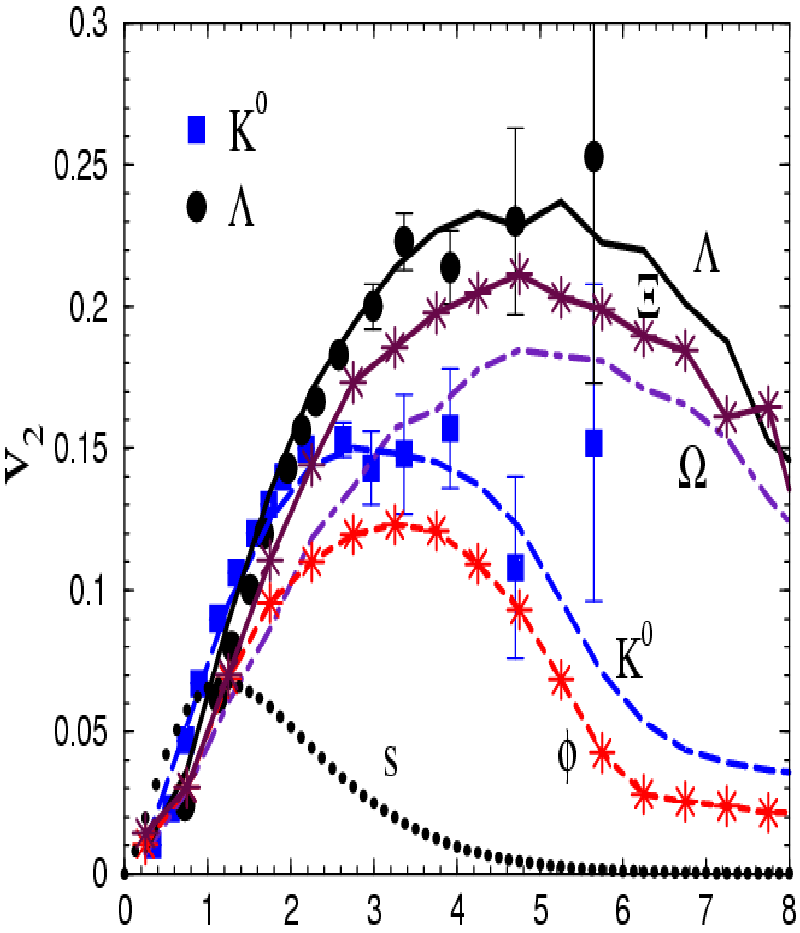
- Reproduce data at low momenta

# Elliptic flows of pions and protons



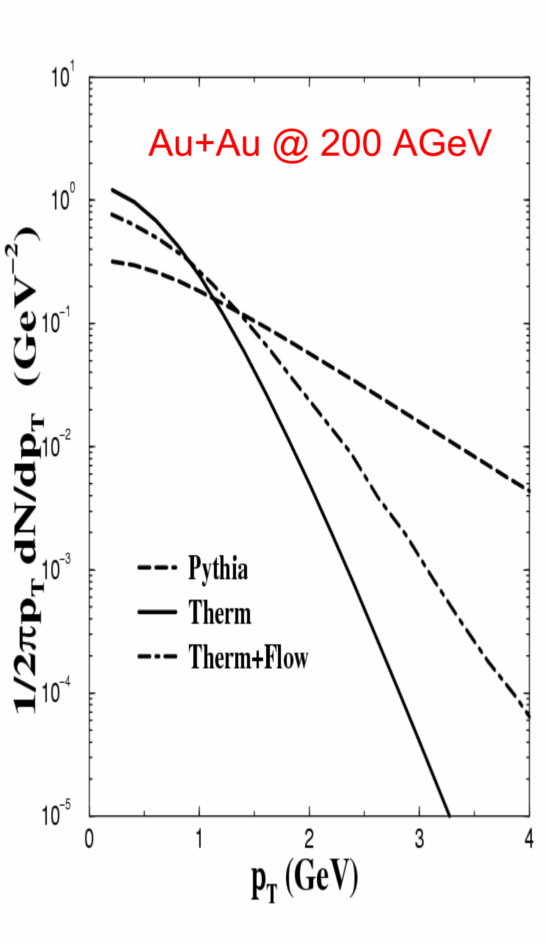
- Au+Au @ 200 AGeV
- Elliptic flow of light quarks is extracted from fitting measured pion elliptic flow
- Proton elliptic flow is then predicted and agrees with data (STAR)

# Elliptic flows of kaons,  lambdas and omegas

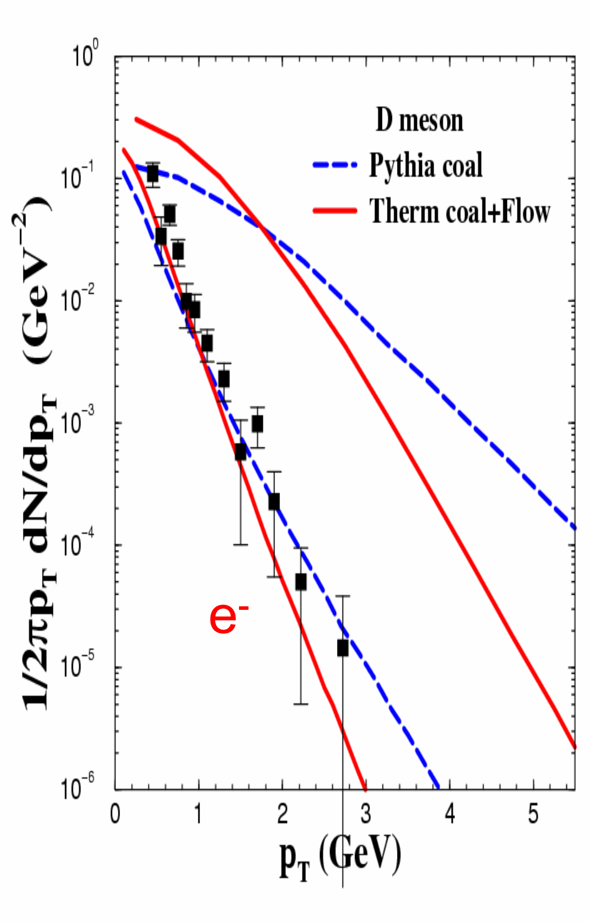


- Au+Au @ 200 AGeV
- Elliptic flow of strange quarks is extracted from fitting measured kaon elliptic flow.
- Predicted lambda elliptic flow agrees with data (STAR)
- Omega elliptic flow is predicted to be smaller than that of lambda

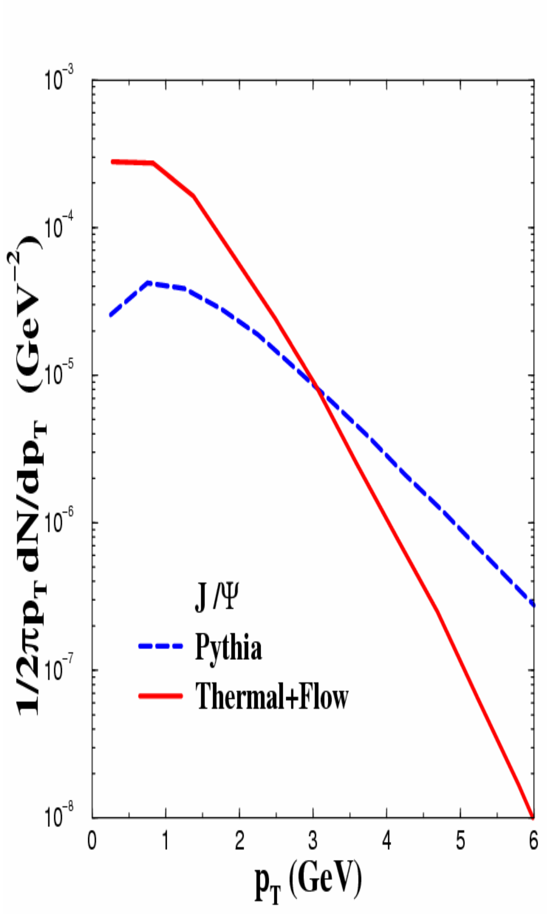
# Charm production



charm quark

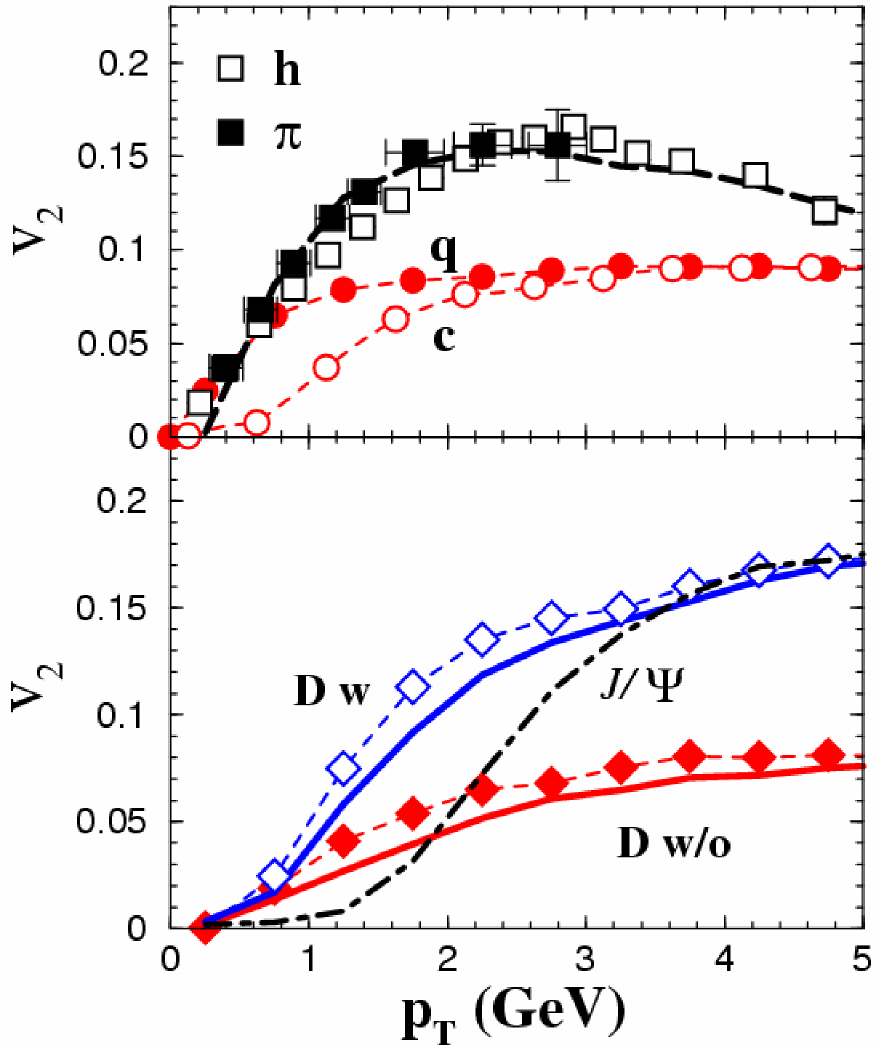


D meson

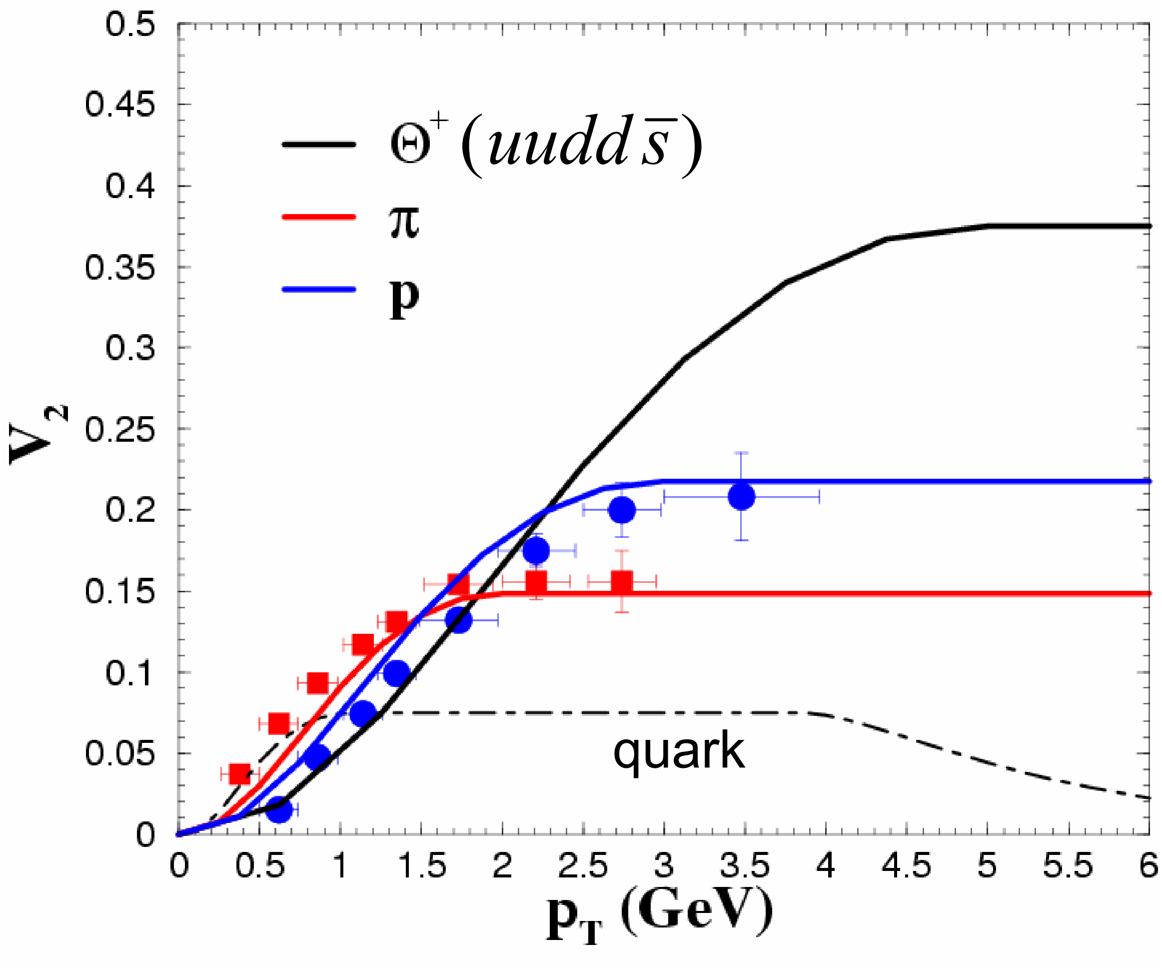


charmonium

# Charm flow



# Pentaquark Theta+ flow



# Summary

- Transport model can describe rapidity and transverse momentum distributions as well as two-particle correlations.

- Large elliptic flow is obtained in transport model that includes scattering of soft partons from melted strings.

- Radiative energy loss of minijet partons in QGP leads to appreciable elliptic flow at high momenta.

- Quark coalescence can explain elliptic flow of identified hadrons and large baryon/pion ratio at intermediate transverse momenta.

- Elliptic flow of D meson and J/psi based on quark coalescence are sensitive to charm quark collective dynamics.