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)

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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

\[ {}^{197}\text{Au} + {}^{197}\text{Au} \ (b=0 \ \text{fm, } s^{1/2}=200 \ \text{AGeV}) \]

\begin{align*}
\text{AMPT} \\
- \text{Default} \\
\end{align*}

\begin{align*}
\text{String melting} \\
\text{σ=3 mb} \\
\text{σ=6 mb} \\
\text{σ=10 mb} \\
\end{align*}

\begin{align*}
p/\varepsilon \\
0.35 & \quad 0.30 & \quad 0.25 & \quad 0.20 & \quad 0.15 & \quad 0.10 & \quad 0.05 & \quad 0.00 \\
0.01 & \quad 0.1 & \quad 1 & \quad 10 \\
\varepsilon \ (\text{GeV/fm}^3) \\
\end{align*}
Rapidity distributions

Au+Au @ 130 AGeV

- Data from BRAHMS
- **Solid lines**: default HIJING
- **Dashed lines**: AMPT prediction
Transverse mass distributions

![Graph showing transverse mass distributions for various particles and their comparisons with AMPT simulations. The x-axis represents $p_T$ (GeV) and the y-axis represents $1/2 \pi d^2 N / p_T dp_T dy$. The graph includes data points for PHENIX, $\pi^+$, $K^+$, and $p$, with different lines for AMPT simulations at $b=0-3$ fm.](image)
Two-Pion Correlation Function

- 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

$\rightarrow$ non-Gaussian source
Elliptic flow in Au+Au @ 200 AGeV

Lin & Ko, PRC 65, 034904 (2002)
Jet quenching in quark-gluon plasma

\[ \Delta E = C \int_0^\infty d\tau \rho(\tau, \bar{x}(\tau))(\tau - \tau_0) \ln\left( \frac{2E_0}{\mu^2 L} \right) \]

Screening mass \( \mu \sim 0.5 \text{ GeV} \) \quad Path length \( L \sim 4 \text{ fm} \) \quad \( C \sim 0.5 \)

Transverse positions of minijet partons at freezeout

\[ n_{\text{parton}}(\tau_f) = 1 \text{ fm}^{-3} \]
Parton azimuthal distribution

\[ \text{Au+Au@200 GeV and } b=8 \text{ fm} \]

Azimuthal distribution of partons

- AMPT
- \[ A(1+2v_2 \cos(2\phi) + 2v_4 \cos(4\phi)) \]

- \( A = 2.27 \)
- \( v_2 = 5.2\% \)
- \( v_4 = 0.27\% \)
Parton elliptic flow

Au+Au@200 GeV and b=8 fm

Parton elliptic flow from AMPT+hard jets
The coalescence model

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

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

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

Quark distribution function

\[ f_q(x, p) \quad \int p \cdot d\sigma \frac{d^3 p}{(2\pi)^3 E} f_q(x, p) = N_q \]

Spin-color statistical factor

\[ g_M \quad \text{e.g.} \quad g_\pi = g_K = 1/36 \quad g_\rho = g_{K^*} = 1/12 \]

Coalescence probability function

\[ f_M(x_1, x_2; p_1, p_2) = f_2(x_1 - x_2; p_1 - p_2) \]
Coalescence probability function

\[
f_2(x_1 - x_2; p_1 - p_2) = \exp\left[\frac{(x_1 - x_2)^2}{2\Delta^2_x}\right] \times \exp\left[\frac{[(p_1 - p_2)^2 - (m_1 - m_2)^2]}{2\Delta^2_p}\right]
\]

Coalescence radii  \( \Delta_x \cdot \Delta_p \geq \hbar \)

Quark mass

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

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


\[
\frac{dN_{\text{jet}}}{d^2 p_T} = \frac{1}{\sigma_{\text{tot}}} \int d^2 \vec{b} d^2 \vec{r} t_{\text{Au}}(\vec{r}) t_{\text{Au}}(\vec{b} - \vec{r}) \sum_{a,b} \int dx_a dx_b d^2 \vec{k}_a \sigma_{\text{jet}} d^2 \vec{k}_b \sigma_{\text{jet}}
\]

\[
\times g(\vec{k}_a) g(\vec{k}_b) f_{a/\text{Au}}(x_a, Q^2) f_{b/\text{Au}}(x_b, Q^2)
\]

\[
\times \frac{\hat{S}}{\pi} \delta(\hat{S} + \hat{t} + \hat{u}) \frac{d\sigma_{ab}}{dt}
\]

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

\[
\frac{dN_{\text{jet}}}{dp_T} = A \left( \frac{B}{B + p_T} \right)^n
\]

\[
A(10^4 / \text{GeV}^2) = \begin{array}{cccc}
g & u, d & \bar{u}, \bar{d} & s, \bar{s} \\
3.2 & 9.8 & 1.9 & 6.5 \\
\end{array}
\]

\[
B(\text{GeV}) = \begin{array}{cccc}
0.5 & 0.5 & 0.5 & 0.5 \\
\end{array}
\]

\[
n = \begin{array}{cccc}
7.1 & 6.8 & 7.5 & 7.4 \\
\end{array}
\]
Quark-gluon plasma

\[
\frac{dN_q}{dyd^2p_T} = \frac{g_q \tau \pi R^2 m_T}{(2\pi)^3} \exp\left(-\frac{m_T - \mu_q}{T}\right)
\]

Light quarks \( g_u, d = 6, \ m_{u,d} = 300 \text{ MeV}, \ \mu_{u,d} = 10 \text{ MeV} \)

Strange quarks \( g_s = 6, \ m_s = 475 \text{ MeV}, \ \mu_s = 10 \text{ MeV} \)

Gluons \( g_g = 16, \ m_g = 300 \text{ MeV}, \ \mu_g = 0 \)

Take \( T = 170 \text{ MeV} \)

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

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

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

\[ R = 8.3 \text{ fm} \]
\[ \tau = 4 \text{ fm}, \quad |y| \leq 0.5 \]
\[ \Rightarrow V = 900 \text{ fm}^3 \]
\[ \frac{dE_T}{dy}\bigg|_{|y| \leq 0.5} = 590 \text{ GeV} \]

Consistent with data (PHENIX)
Other inputs or assumptions

- **Minijet fragmentation** via KKP fragmentation functions

\[
\frac{dN}{d^2p_{\text{had}}} = \sum_{\text{jet}} \int dz \frac{dN}{d^2p_{\text{jet}}} \frac{D_{\text{had/\jet}}(z,Q^2)}{z^2}, \quad z = \frac{p_{\text{had}}}{p_{\text{jet}}}
\]

- **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

\[ \Delta p = \Delta x^{-1} = 0.45 \text{ GeV} \quad \text{for baryons} \]
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+soft-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, lamdas 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

Au+Au @ 200 AGeV

charm quark

D meson

charmonium
Charm flow
Pentaquark Theta+ flow

\[ \Theta^+ (uudd \bar{s}) \]

\[ \pi \]

\[ p \]

quark

\[ p_T \text{ (GeV)} \]
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.