Hadronization by coalescence plus fragmentation from RHIC to LHC

Vincenzo Minissale
University of Catania - INFN LNS

Nucleus Nucleus 2015, 22 June 2015

Vincenzo Greco
Francesco Scardina
arXiv:1502.06213
Outline

• Hadronization:
  – Coalescence
  – Fragmentation

• Coalescence model and Parameters

• Comparison with data
  – RHIC  Au+Au  $\sqrt{s} = 200 \text{ GeV}$
  – LHC  Pb+Pb  $\sqrt{s} = 2.76 \text{ TeV}$

• Elliptic Flow
Ultrarelativistic heavy-ion collisions

HIC sequence

Initial Stage

Pre-equilibrium stage

Expansion

QGP

Hadronization

Chemical and kinetic freeze-out

freeze out
hadrons
 gluons & quarks in eq.
gluons & quarks out of eq.
strong fields
 incoming nuclei
Ultrarelativistic heavy-ion collisions

HIC sequence

Initial Stage

Pre-equilibrium stage

Expansion

QGP

Hadronization

Chemical and kinetic freeze-out

freeze out

hadrons

 gluons & quarks in eq.

 gluons & quarks out of eq.

strong fields

incoming nuclei
• Fragmentation

\[
\frac{dN_h}{d^2 p_h} = \sum_f \int dz \frac{dN_f}{d^2 p_f} D_{f \to h}(z)
\]

\[0 < z < 1\]

• **Fragmentation**

\[
\frac{dN_h}{d^2 p_h} = \sum_f \int dz \frac{dN_f}{d^2 p_f} D_{f \rightarrow h}(z) \\
0 < z < 1
\]

• **Coalescence**

**Hadronization**

- **Fragmentation**

\[
\frac{dN_h}{d^2 p_h} = \sum_f \int dz \frac{dN_f}{d^2 p_f} D_{f \rightarrow h}(z)
\]

- **Coalescence**

\[
\frac{dN_H}{d^2 p_T} = g_H \int \prod_{i=1}^n \left( p_i d\sigma_i \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i) f_H(x_1...x_n, p_1...p_n) \delta(p_T - \Sigma p_{iT}) \right)
\]
Hadronization

- **Fragmentation**
  \[
  \frac{dN_h}{d^2 p_h} = \sum_f \int d\vec{z} \frac{dN_f}{d^2 p_f} D_{f \rightarrow h}(z)
  \]
  \[0 < z < 1\]

- **Coalescence**

\[
\frac{dN_H}{d^2 p_T} = g_H \int \prod_{i=1}^{n} \left( \frac{dN}{d^3 p_i} \frac{d^3 p_i}{(2\pi)^3} f_q(x_i, p_i) \right) f_H(x_1 \ldots x_n, p_1 \ldots p_n) \delta(p_T - \Sigma p_{iT})
\]

- **Parton Distribution Function**

- **Statistical factor colour-spin-isospin**

- **Hadron Wigner Function**

- **Fragmentation Function**

\[
f_M = \frac{9\pi}{2} \Theta(\Delta_x^2 - (x_1 - x_2)^2) \Theta(\Delta_y^2 - (p_1 - p_2)^2 + (m_1 - m_2)^2)
\]

\[\Delta_x = 1/\Delta_p \quad \text{free parameter}\]
RHIC Observables

Proton to pion ratio
Enhancement

In the vacuum, from fragmentation functions the ratio is

\[
\frac{D_{c \to p}(z)}{D_{c \to \pi}(z)} < 0.25
\]

Elliptic Flow Splitting
RHIC Observables

Proton to pion ratio Enhancement

In the vacuum, from fragmentation functions the ratio is

\[ \frac{D_{c \rightarrow p}(z)}{D_{c \rightarrow \pi}(z)} < 0.25 \]

Elliptic Flow Splitting
Coalescence code

• Consider $i$ particles
• Give a probability $P(i)$ from the partonic distribution
• Compute the coalescence integral

$$\frac{dN_M}{d^2p_T} = g_M \sum_{i,j} P_q(i)P_{\bar{q}}(j)\delta^{(2)}(p_T - p_{iT} - p_{jT})f_M(x_i, x_j; p_i, p_j)$$
Fireball parameters

- Central collision (0–10%)  
- Temperature \( T = 160 \text{ MeV} \)
- Collective flow \( \beta_T = \beta_{\text{max}} \frac{r}{R} \)
  
\[ \beta_{\text{max}} \text{ from radial expansion } R = R_0 + \beta_{\text{max}} a x \tau \]
- Uniform in \((x, y)\); \( z = \tau \sinh y \)
- \( V = \pi r_T^2 \tau \)
- Fireball radius+radial flow constraints \( \frac{dN_{\text{ch}}}{dy} ; \frac{dE_T}{dy} \)
Fireball parameters

- Central collision (0–10%)
- Temperature $T = 160 \text{ MeV}$
- Collective flow $\beta_T = \beta_{\text{max}} \frac{r}{R}$
  - $\beta_{\text{max}}$ from radial expansion $R = R_0 + \beta_{\text{max}} ax \tau$
- Uniform in $(x, y); \ z = \tau \sinh y$
- $V = \pi r_T^2 \tau$
- Fireball radius+radial flow constraints $\frac{dN_{ch}}{dy}; \frac{dE_T}{dy}$

Typical QGP lifetime
- RHIC = 4.5 $fm/c$
- LHC = 7.8 $fm/c$
Fireball parameters

- Central collision (0–10%)
- Temperature $T = 160$ MeV
- Collective flow $\beta_T = \beta_{\text{max}} \frac{r}{R}$
  
  $\beta_{\text{max}}$ from radial expansion $R = R_0 + \beta_{\text{max}} ax \tau$

- Uniform in $(x, y)$; $z = \tau \sinh y$

- $V = \pi r_T^2 \tau \sim 1000 \text{ fm}^3 \text{ RHIC} \sim 2500 \text{ fm}^3 \text{ LHC}$

- Fireball radius+radial flow constraints $\frac{dN_{\text{ch}}}{dy}$; $\frac{dE_T}{dy}$

  $R_T = 8.7 \text{ fm at RHIC}$ \quad $\beta_{\text{max}} = 0.37 \text{ at RHIC}$
  
  $R_T = 10.2 \text{ fm at LHC}$ \quad $\beta_{\text{max}} = 0.63 \text{ at LHC}$

Typical QGP lifetime

RHIC = 4.5 fm/c
LHC = 7.8 fm/c
Parton Distribution

- Thermal Distribution ($< 2 \text{ GeV}$)

\[
\frac{dN_{q,\bar{q}}}{d^2 r_T d^2 p_T} = \frac{g_{q,\bar{q}} \pi m_T}{(2\pi)^3} \exp \left( -\frac{\gamma_T (m_T - p_T \cdot \beta_T \mp \mu_q)}{T} \right)
\]

- Minijet Distribution ($> 2 \text{ GeV}$)

\[
\frac{dN_{\text{jet}}}{d^2 p_T} = A \left( \frac{B}{B + p_T} \right)^n \quad \text{RHIC}
\]

\[
\frac{dN_{\text{jet}}}{d^2 p_T} = \left[ 1 + \left( \frac{p_T}{A_2} \right)^2 \right]^{A_3} + \left[ 1 + \left( \frac{p_T}{A_5} \right)^2 \right]^{A_6} \quad \text{LHC}
\]
Resonance Decay

- \( \pi (I = 1, J = 0) \)
  \[ k^* (I = 1, J = 1/2) \rightarrow k\pi \]
  \[ \rho (I = 1, J = 1) \rightarrow \pi\pi \]
  \[ \Delta (I = 3/2, J = 3/2) \rightarrow N\pi \]

- \( p (I = 1/2, J = 1/2) \)
  \[ \Delta (I = 3/2, J = 3/2) \rightarrow N\pi \]

- \( k^\pm (I = 0, J = 1/2) \)
  \[ k^* (I = 1, J = 1/2) \rightarrow k\pi \]

- \( \Lambda (1116) (I = 0, J = 1/2) \)
  \[ \Sigma^0 (1193) (I = 1, J = 1/2) \rightarrow \Lambda\gamma \]
  \[ \Lambda (1405) (I = 0, J = 1/2) \rightarrow \Sigma\pi \]
  \[ \Sigma^0 (1385) (I = 1, J = 3/2) \rightarrow \Lambda\pi \quad \text{with B.R.} = 88\% \]
  \[ \rightarrow \Sigma\pi \quad \text{with B.R.} = 11,7\% \]

\[ \text{Suppression factor} \quad \left( \frac{m_{H^*}}{m_H} \right)^{3/2} e^{-\frac{E_{H^*} - E_H}{T}} \]
Results RHIC
RHIC – Pion
RHIC – Antiproton
RHIC – Kaon & Lambda
RHIC – Ratios
Results LHC
LHC – Pion
LHC – Proton
LHC - Kaon & Lambda

- $d^3N/dp_T^2d\eta$ for $K$ data, $K$coal.+frag., $K$coal. total, and fragmentation AKK.

- $d^3N/dp_T^2d\eta$ for ALICE data, $\Lambda$coal.+frag., $\Lambda$coal. total, and fragmentation AKK.
LHC – Ratios

- Height and $p_T$ position of the peak well described.
- Lack of fragmentation at $p_T \approx 6$ GeV (seen also in pp with AKK)
- Soft-minijet coalescence contribution around and above the peak (similar to EPOS)
- Only coalescence would give higher peak shifted in $p_T$
- Without radial flow … (→ pp collisions but not exactly)
RHIC Observables

Elliptic Flow splitting
Elliptic Flow

- Fourier expansion of the azimuthal distribution

\[ f(\varphi, p_T) = 1 + 2 \sum_{n=1}^{\infty} v_n(p_T) \cos n\varphi \]

momentum anisotropy in the transverse plane

coalesscence brings to

- Partonic elliptic flow
- Hadronic elliptic flow

\[ v_{2,M}(p_T) \approx 2v_{2,q}(p_T/2) \]
\[ v_{2,B}(p_T) \approx 3v_{2,q}(p_T/3) \]
Elliptic Flow

- Fourier expansion of the azimuthal distribution

\[ f(\varphi, p_T) = 1 + 2 \sum_{n=1}^{\infty} v_n(p_T) \cos n\varphi \]

momentum anisotropy in the transverse plane

- Elliptic flow coalescence brings the

\[ v_{2,M}(p_T) \approx 2v_{2,q}(p_T/2) \]

\[ v_{2,B}(p_T) \approx 3v_{2,q}(p_T/3) \]
Preliminary on radial flow impact

Same approach, but with an anisotropic radial flow in the quark distrib. function

$$\frac{dN}{d^2 r_T d^2 p_T} = \frac{g \tau m_T}{(2\pi)^3} \exp\left( - \frac{\gamma_T (m_T - p_T \cdot \beta_T)}{T} \right)$$

$$\beta_T(r, \phi) = \beta_0(r) + \beta_2(r) \cos(2\phi)$$

About 20% quark number scaling breaking:
- 3D
- finite width wave function
- anisotropic radial flow
Summary

- Good agreement with RHIC & LHC data
  - $\pi, p, k, \Lambda$ spectra
  - ratio peak shift at LHC with no parameters change
- $v_2$ QNS breaking

Outlooks

- other particles ($\phi, \Xi, \Omega$)
- other centrality
- Next order in $v_n$ and effect of radial flow on the Quark Number Scaling
Backup slides
Elliptic Flow and $v_3$

- Fourier expansion of the azimuthal distribution

$$f(\phi, p_T) = 1 + 2 \sum_{n=1}^{\infty} v_n(p_T) \cos n\phi$$

momentum anisotropy in the transverse plane

Fluctuations $\rightarrow$ $n=3$
Next order: $v_3 - \text{LHC}$
* What's the approach working in the range $p_T \approx 2-10$ GeV?
* Is the coalescence necessary?

EPOS = (half)-viscous-hydro + soft-jet recombination

- $p/\pi$ ?
- $\nu_2$ of $\Lambda$ and $K$ ?
- Also $p_T$ spectra check
We do not have the fragm. function for $\phi$.

It is clear that coalescence predict a similar slope for $\phi$ and $p$.

Soft part same slope $\phi$ and $p$

Missing fragmentation

Contribution usually half of the yield at $p_T \approx 4$ GeV
In case of a partonic thermal distribution

\[ f_{th} \approx Ae^{-p/T} \]

for a two-quark hadron,

\[ e^{-p_1/T} e^{-p_2/T} \Rightarrow e^{-xP/T} e^{-(1-x)P/T} = e^{-P/T} \]

in the \( n \) quark case

\[ \prod_{n} e^{-p_n/T} \rightarrow e^{-n \frac{P}{nT}} \propto e^{-\frac{P}{T}} \]

Baryon/Meson Ratio = 1