Predictions for hadronic observables from Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV from a simple kinematic model

Tom Humanic
Ohio State University

WPCF-Kiev September 14, 2010
Outline

• Motivation & goals of the model
• Brief description of the model
• Comparison of model calculations with RHIC experiments STAR, PHENIX, and PHOBOS
• Predictions for LHC
  \[ \text{Pb+Pb, } \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \]
Motivation and goals of this work

The LHC will be giving us Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in November, 2010 !!

Make predictions for common hadronic observables which will be initially measured by experiments for LHC Pb + Pb collisions.

Use a model which has been shown to describe the overall trends of the main hadronic observables of the RHIC data and which can be easily scaled up to give predictions for these hadronic observables for LHC Pb + Pb collisions.

A simple hadronic rescattering model satisfies these requirements. The picture behind it is to use only hadrons as degrees of freedom in a Monte Carlo calculation to obtain a “limiting case scenario.”

Study the successes and failures of this picture @LHC when the predictions are eventually compared with data ➔ may already see this in December 2010 !!
Simple superposition-rescattering model for A+A collision

Initial p+p “thin disk” of radius \( r = 1 \text{ fm} \)

* Superimpose \( f \) A PYTHIA pp events, where \( f \) = overlap fraction for impact param.
* Assume all particles have the same proper time for hadronization, \( \tau \), so that the hadronization space-time for each particle is given by “geometry+causality”, i.e.
  \[
  t_i = \tau \frac{E_i}{m_i} \quad ; \quad x_i = x_{oi} + \tau \frac{p_{xi}}{m_i} \quad ; \quad y_i = y_{oi} + \tau \frac{p_{yi}}{m_i} \quad ; \quad z_i = \tau \frac{p_{zi}}{m_i}
  \]
* Perform hadronic rescattering using a “full” Monte Carlo rescattering calculation
Rescattering hadron

Frozen-out hadron

Time evolution of hadronic rescattering

$t \sim 1 \text{ fm/c}$
All hadrons are rescattering

$t \sim 10 \text{ fm/c}$
Some hadrons have stopped rescattering, i.e. “frozen out”

$t \sim 30 \text{ fm/c}$
Most hadrons have stopped rescattering --> “freezeout”
Other details of the model…..

• Use PYTHIA v.6409 to generate hadrons for 200 GeV and 2.76 TeV p+p “minimum bias” (non-elastic and non-diffractive) events
  “final” hadrons from PYTHIA to use: \( \pi, K, N, \Delta, \Lambda, \omega, \rho, K^*, \phi, \eta, \eta' \)

• Use mult > 20 or 34 (RHIC or LHC) cut on p+p events --> cuts out ~ 20-25% of events and helps \( dn/d\eta \) agree better with PHOBOS 200 GeV/n Au+Au

• Monte Carlo hadronic rescattering calculation:
  Let hadrons undergo strong binary collisions (elastic and inelastic) until the system gets so dilute that all collisions cease. Use 0.5 fm/c timesteps to 200 or 400 fm/c (RHIC or LHC)
  --> isospin-averaged \( \sigma(i,j) \) from Prakash, etc..
  Record the time, mass, position, and momentum of each hadron when it no longer scatters. \( \rightarrow \) freezout condition

• Take \( \tau = 0.1 \) fm/c for all calculations --> found to agree with Tevatron HBT data (T.J.H., Phys.Rev.C76, 025205 (2007))

$d\sigma/dp_T$ from PYTHIA compared with a PHENIX parameterization for 200 GeV p+p collisions (absolute normalizations)
Time evolution up to 50 fm/c of the particle density calculated at mid-rapidity ($-1 < y < 1$) and the number of rescatterings per time step from the model for minimum bias $\sqrt{s_{NN}}=200$ GeV Au+Au collisions.

**Big assumption:**
binary collisions of hadrons or hadron-like particles here, too!! $\tau = 0.1$ fm/c
Advantages of this model

• Well-defined initial conditions: PYTHIA for kinematics and causality for geometry
• Jets are built into the model via PYTHIA so high-$p_T$ observables can be studied
• Initial conditions easily scalable to LHC energies for predictions there
• Simplicity -- hadrons+geometry+rescattering with a few well-defined parameters

Disadvantages of this model

• Simplicity -- Surely leaves out some early-phase physics, e.g. quark and gluon degrees of freedom
• Therefore, will be satisfied to get a qualitative description of trends of at least some experimental observables
Comparisons with RHIC experiments

• Made a 90K event 200 GeV/n Au+Au minimum bias run with model --> apply centrality cuts (via multiplicity cuts) and kinematic cuts to this run to make “absolute comparisons” with experiments

• Comparisons made with published 200 GeV/n Au+Au experimental results:
  - spectra with PHENIX, PHOBOS and STAR
  - $V_2$ with PHENIX, PHOBOS and STAR
  - HBT with STAR
  - $R_{AA}$ with PHENIX
Spectra: Model vs PHOBOS, PHENIX, and STAR
Elliptic flow vs. centrality, $p_T$, and $\eta$
Model vs. STAR and PHOBOS

$$V_2 = < \cos(2\phi) > , \quad \phi = \arctan(\frac{p_y}{p_x})$$
$V_2$ vs. $p_T \rightarrow$ large $p_T$: Model vs. STAR

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot}
\caption{\textit{V2 vs. pt} \newline Model vs. STAR charged particles \newline 200 GeV/n Au+Au \newline 10-40\% centrality, -1<\eta<1}
\end{figure}
$V_2/n_q$ vs. $p_T/n_q$ for Model vs. PHENIX
For pions, kaons, and protons.

Model $V_2$ shows scaling with quark number like exp.
HBT/Femto - how implemented in model

* Form two-boson correlation function from the model:

$$C(q) = \frac{A(q)}{B(q)}$$

$$A(q) = \sum \{\text{real pairs weighted by } 1 + \cos(q \Delta x)\}$$

$$B(q) = \sum \{\text{background pairs from event mixing}\}$$

$$q = p_1 - p_2 \quad \Delta x = x_1 - x_2 \ (4\text{-vectors})$$

* Fit Gaussian function to $C(q) = C(q_{\text{out}}, q_{\text{side}}, q_{\text{long}})$ to extract pion source parameter $R_{\text{out}}, R_{\text{side}}, R_{\text{long}}, \lambda$

$$C(q_0, q_s, q_l) = 1 + \lambda \exp[-(q_0 R_0)^2 - (q_s R_s)^2 - (q_l R_l)^2]$$
ππ HBT from Model: projections --> $q_{out}$, $q_{side}$, $q_{long}$
$\pi\pi$ HBT vs. $k_T$: Model vs. STAR

Model vs. STAR $\pi\pi$ HBT vs. $kt$
200 GeV/n Au+Au
-0.5 < $y$ < 0.5, 0.15 < $p_T$ < 0.8 GeV/c
0-5% centrality

$R_{out}$

$R_{long}$
\[ R_{AA} \text{ vs. } p_T: \text{Model vs. PHENIX} \]

\[ R_{AA} = \frac{1/N_{ev}}{T_{AuAu}} \frac{d^2 N_{AuAu}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta} \]

\[ T_{AuAu} \text{ -- Glauber overlap function} \]

(Use PHENIX values for each centrality cut)

High \( p_T \) suppressed
LHC Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV
predictions from this model

- Use PYTHIA 2.76 TeV p+p collisions as input
- Make multiplicity cut on p+p collisions > 34, cuts out ~20% of p+p events (comparable to multiplicity cut used for RHIC Au+Au)
- Substitute 197 --> 208
- Make a minimum bias run with model for 3200 Pb+Pb events
- Show predictions for spectra, $R_{AA}$, $V_2$, and HBT
Spectra for Pb + Pb, \( \sqrt{s_{\text{NN}}} = 2.76 \text{ TeV} \)

\[ \frac{1}{N} \frac{dN}{d\eta} (0-5\%, \eta=0) \rightarrow \sim 1200 \]
Unnormalized $R_{AA}$ for min. bias Pb + Pb, $\sqrt{s_{NN}} = 2.76$ TeV

$(1/N \frac{d^2 n_{PbPb}}{dp_T d\eta})/(1/N \frac{d^2 n_{pp}}{dp_T d\eta})$

- Rescattering ON
- Rescattering OFF

$p_T (GeV/c)$
Elliptic flow for Pb + Pb, $\sqrt{s_{NN}} = 2.76$ TeV
$\pi-\pi$ HBT/Femto for Pb + Pb, $\sqrt{s_{NN}} = 2.76$ TeV
K-K HBT/Femto for Pb + Pb, $\sqrt{s_{NN}} = 2.76$ TeV

![Graph showing correlation between $Q_{side}$, $Q_{out}$, and $Q_{long}$ with $\langle C(Q_{side, out, long}) \rangle$](image)
$R_{\text{out}}$, $R_{\text{side}}$, $R_{\text{long}}$ and $\lambda$ for $\pi\pi$ and KK vs. $m_T$
Conclusions

• The present simple hadronic rescattering model qualitatively describes the trends for a range of experimental results for 200 GeV/n Au+Au collisions at RHIC

• This suggests that the hadronization proper time in these collisions is short, ~0.1 fm/c

• Predictions from this model for LHC Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV suggest:
  * $dn/d\eta \sim 1200$ for charged hadrons at mid-rapidity for central collisions
  * High-$p_T$ suppression of $R_{AA}$ should still be present
  * $V_2$ appears to be comparable to that at RHIC
  * $\pi\pi$ HBT should give ~20% higher radius parameters compared to RHIC
Backup slides
Elliptic Flow $\rightarrow V_2$

Origin: spatial anisotropy of the system when created and rescattering of evolving system → probe of the early stage of the collision

Almond shape overlap region in coordinate space

Spatial anisotropy

Momentum anisotropy

\[
\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}
\]

\[
v_2 = \langle \cos 2\phi \rangle
\]

\[
\phi = \text{atan} \frac{p_y}{p_x}
\]
**HBT*** -- probing source geometry with boson pairs

\[ \Psi = U(x_1,p_1)\exp\{i(r_1-x_1)p_1\}U(x_2,p_2)\exp\{i(r_2-x_2)p_2\} \]

\[ + U(x_1,p_2)\exp\{i(r_2-x_1)p_2\}U(x_2,p_1)\exp\{i(r_1-x_2)p_1\} \]

\[ \Psi^*\Psi = (U_1^*U_1)(U_2^*U_2)[1+\cos(q\Delta x)] \]

\[ q = p_1 - p_2 \]
\[ \Delta x = x_1 - x_2 \]

Integrate \( \Psi^*\Psi \) over \( \rho(x) \)

\[ C(p_1,p_2) = \frac{P(p_1,p_2)}{P(p_1)P(p_2)} = 1 + |\tilde{\rho}(q)|^2 \]

Measurable!

F.T. of pion source

\[ * \text{ Hanbury-Brown-Twiss interferometry} \]

**Width \( \sim \frac{1}{R} \)**

![Graph showing the dependence of \( C(q) \) on \( q \) (GeV/c)]
Jets in heavy-ion collisions

Goal: Use jets to probe properties of medium

Some Basic Observables:
- $R_{AA}$ (nuclear modification factor) leading jet particles suppressed?
- $\Delta \phi$ Azimuthal Correlations of di-jets backward jet suppressed?
Motivation & Goal of the present work

Motivation:
* RHIC experiments have produced many interesting studies of hadronic observables from A+A collisions over the past six or so years.

* general categories of hadronic observables:
  Spectra -- e.g. $dn/d\eta$, $dn/dp_T$, and $dn/dm_T$ distributions
  Elliptic flow ($V_2$) -- e.g. $V_2$ vs. $\eta$ and $V_2$ vs. $p_T$ distributions
  Femtoscopy (HBT) -- e.g. $\pi\pi$ correlation studies vs. $p_T$ and azimuthal angle
  High $p_T$ -- targeted as sensitive to jet effects, e.g. $R_{AA}$ vs. $p_T$ and $dn/d\Delta\phi$ distributions

* Models which describe the early stages of the collision in terms of partonic degrees of freedom, e.g. parton cascade or hydrodynamics, have been successful in describing the experimental systematics of some of these observables in some kinematic ranges, but no single model has thus far succeeded (to my knowledge) in making an adequate overall description of the systematics of all of these observables in a wide kinematical range.

Goal of the present work:
To see how far one can get in describing the experimental systematics of all of the observables mentioned above in a wide kinematical range for $\sqrt{s_{NN}}=200$ GeV Au+Au collisions using a simple kinematic model with hadronic degrees of freedom (which a simple experimentalist can put together), and make predictions for LHC Pb+Pb collisions.
$V_2$ vs $p_T$ --> $\pi$, $K$, $p$: Model vs. PHENIX