Ultimate Test of Quark Combination: Hadron Production in Pb+Pb Collisions at LHC
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Motivation

A collectively expanding hot and dense partonic fireball is formed at LHC, similarly as at RHIC.


Suppressed at large pt

Large collective flow

20-30%
Motivation

There are a few novel features that are unexpected by direct extrapolation from RHIC according to more than ten times larger collision energy.

- Hard pushed hadron distribution
- Low $p/\pi$
- Breaking of quark number scaling for $v_2$
- Non-zero elliptic flow for J/Psi …

Motivation

breaking of QNS

arXiv: 1202.0365 [nucl-ex]

Hadron Production at LHC

R.Q. Wang
These new features put additional constraints on different models and reveal some new properties of heavy ion collisions.

Hard-pushed proton distribution need bulk viscosity in hydrodynamics.

Low p/πi Baryon-antibaryon annihilation in thermal model

Large splitting needs shear viscosity in hydrodynamics.

*arXiv: 1108.5323 [nucl-ex]*
Motivation

Quark combination at RHIC


Quark combination at LHC

Che Ming Ko et al, Phys. Rev. C 84, 044907 (2011) charged v2 at low and intermediate pt


**SDQCM** more hadrons including charm sector large pt range
Method: quark combination model

Quarks with $y_q \in [-2,2]$ are set to distribute uniformly and are employed.

Hadrons with $y_h \in [-0.5,0.5]$ are collected to correctly include rapidity shift in hadron formation and resonance decay.
Particle ratios and multiplicities

SDQCM inputs:

\[ \frac{dN_{q_i}}{dy} \quad \text{and} \quad \frac{dN_{\bar{q}_i}}{dy} \quad \text{for} \quad u, d, s, c \]

Ignore net quarks in midrapidity

\[ \frac{dN_u}{dy} = \frac{dN_{\bar{u}}}{dy} = \frac{dN_{uu}}{dy} \]
\[ \frac{dN_d}{dy} = \frac{dN_{\bar{d}}}{dy} = \frac{dN_{dd}}{dy} \]

Isospin symmetry between up and down

\[ \frac{dN_{uu}}{dy} = \frac{dN_{\bar{u}\bar{u}}}{dy} \]

Strange and charm number conservations

\[ \frac{dN_s}{dy} = \frac{dN_{\bar{s}}}{dy} = \frac{dN_{ss}}{dy} \]
\[ \frac{dN_c}{dy} = \frac{dN_{\bar{c}}}{dy} = \frac{dN_{cc}}{dy} \]
Particle ratios and multiplicities

SDQCM inputs:

\[ \lambda = 2 \frac{dN_{ss}}{dy} / \left( \frac{dN_{uu}}{dy} + \frac{dN_{d\bar{d}}}{dy} \right) \]

Fix by charged particle multiplicity density

\[ \frac{dN_{qq}}{dy} = \frac{dN_{uu}}{dy} + \frac{dN_{d\bar{d}}}{dy} + \frac{dN_{ss}}{dy} \]

Average nuclear overlap function

\[ \frac{dN_{cc}}{dy} = \frac{dN_{D^0}}{dy} / R = \left\langle T_{AA} \right\rangle \frac{d\sigma_{D^0}}{dy} / R \]

Cross section

\[ R = 0.54 \pm 0.05 \]

0.42 same as RHIC

Hadron Production at LHC
One surprise of the first PbPb run at LHC

SU(3) Particle ratios Exp

SU(3) Particle ratios Theory

TABLE III. Particle multiplicities and particle number ratios, calculated within the hHKM model for most central (0%–5%) Pb + Pb collisions with $\sqrt{s} = 2.76$ TeV in different scenarios of particle production: full scenario (hydro + UrQMD), full-$B \bar{B}$ (baryon-antibaryon annihilator switched off in UrQMD), and thermal model (kinetic phase with resonance decays only).

<table>
<thead>
<tr>
<th></th>
<th>$N_\pi$</th>
<th>$N_K$</th>
<th>$N_\rho$</th>
<th>$N_\Lambda$</th>
<th>$p/\pi$</th>
<th>$K/\pi$</th>
<th>$\Lambda/\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>775</td>
<td>123</td>
<td>40.5</td>
<td>20</td>
<td>0.052</td>
<td>0.158</td>
<td>0.026</td>
</tr>
<tr>
<td>Full-$B \bar{B}$</td>
<td>716</td>
<td>114</td>
<td>50.5</td>
<td>24</td>
<td>0.072</td>
<td>0.159</td>
<td>0.034</td>
</tr>
<tr>
<td>Thermal</td>
<td>679</td>
<td>127</td>
<td>54</td>
<td>20.3</td>
<td>0.08</td>
<td>0.188</td>
<td>0.03</td>
</tr>
</tbody>
</table>


**DATA**

$p/\pi = 0.046 \pm 0.003$

$\Lambda/\pi = 0.034 \pm 0.004$

B-Bbar annihilation can explain lower $p/\pi$, but effects on other baryons has not been observed till now.
SU(3) Particle ratios

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Data</th>
<th>$\lambda = 0.42$</th>
<th>$\lambda = 0.40$</th>
<th>$\lambda = 0.38$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{K^+}{\pi^+}$</td>
<td>0.149 ± 0.010</td>
<td>0.152</td>
<td>0.145</td>
<td>0.139</td>
</tr>
<tr>
<td>$\frac{\Lambda}{p}$</td>
<td>0.739 ± 0.099</td>
<td>0.816</td>
<td>0.779</td>
<td>0.741</td>
</tr>
<tr>
<td>$\frac{\Xi^-}{p}$</td>
<td>0.109 ± 0.023</td>
<td>0.137</td>
<td>0.125</td>
<td>0.113</td>
</tr>
<tr>
<td>$\frac{\Omega^-}{p}$</td>
<td>0.022 ± 0.005</td>
<td>0.020</td>
<td>0.018</td>
<td>0.015</td>
</tr>
<tr>
<td>$\frac{p}{\pi^+}$</td>
<td>0.046 ± 0.003</td>
<td>0.046</td>
<td>0.047</td>
<td>0.047</td>
</tr>
<tr>
<td>$\frac{\Lambda}{\pi^+}$</td>
<td>0.034 ± 0.004</td>
<td>0.038</td>
<td>0.036</td>
<td>0.035</td>
</tr>
<tr>
<td>$\frac{\Xi^-}{\pi^+}$</td>
<td>0.005 ± 0.001</td>
<td>0.006</td>
<td>0.006</td>
<td>0.005</td>
</tr>
<tr>
<td>$\frac{\Omega^-}{\pi^+}$</td>
<td>0.001 ± 0.0002</td>
<td>0.0009</td>
<td>0.0008</td>
<td>0.0007</td>
</tr>
<tr>
<td>$\frac{\Lambda}{K^+}$</td>
<td>0.228 ± 0.031</td>
<td>0.247</td>
<td>0.250</td>
<td>0.254</td>
</tr>
</tbody>
</table>

Strangeness production keeps invariant from RHIC to LHC. BM ratio can be reproduced by SDQCM.
Decay contribution from charm hadrons can make $p/\pi$ decrease.
# Charm hadron ratios

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Data</th>
<th>$\lambda = 0.42$</th>
<th>$\lambda = 0.40$</th>
<th>$\lambda = 0.38$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{D_s^+}{D^0}$</td>
<td>0.274</td>
<td>0.260</td>
<td>0.247</td>
<td></td>
</tr>
<tr>
<td>$\frac{D_s^+}{D^+}$</td>
<td>0.861</td>
<td>0.816</td>
<td>0.776</td>
<td></td>
</tr>
<tr>
<td>$\frac{2D_s^+}{D^0+D^+}$</td>
<td>0.415</td>
<td>0.394</td>
<td>0.374</td>
<td></td>
</tr>
<tr>
<td>$\frac{\Lambda_c}{D^0}$</td>
<td>0.301</td>
<td>0.304</td>
<td>0.307</td>
<td></td>
</tr>
</tbody>
</table>

- Production rate of baryons to mesons
- Production ratio of vector to pseudoscalar meson
- strangeness
Charm hadron ratios

I. A yield hierarchy is observed, i.e. $D^0 > D^{*+} > D^+$

$$D^{*0} (c\bar{u}) : D^0 (c\bar{u}) : D^{*+} (c\bar{d}) : D^+ (c\bar{d}) = \frac{R_{V/P}}{1 + R_{V/P}} : \frac{1}{1 + R_{V/P}} : \frac{R_{V/P}}{1 + R_{V/P}} : \frac{1}{1 + R_{V/P}}$$

$$D^0 : D^{*+} : D^+ = \frac{1 + R_{V/P} [Br(D^{*0} \rightarrow D^0) + Br(D^{*+} \rightarrow D^0)]}{1 + R_{V/P}} : \frac{R_{V/P}}{1 + R_{V/P}} : \frac{1 + R_{V/P} Br(D^{*+} \rightarrow D^+)}{1 + R_{V/P}}$$

$$= \frac{1 + 1.677 R_{V/P}}{1 + R_{V/P}} : \frac{R_{V/P}}{1 + R_{V/P}} : \frac{1 + 0.323 R_{V/P}}{1 + R_{V/P}} ,$$

$$\frac{R_{V/P}}{1 + R_{V/P}} > 0.60 \quad D^0 > D^{*+} > D^+ \text{ holds}$$

the default value 0.75
II. strangeness

\[ \frac{2D_s^+}{D^0 + D^+} = \lambda \]

Reflect the strangeness of the medium surrounding charm quarks

\[ \frac{2D_s^+}{D_0 + D^+} \rightarrow 0.42 \quad D \text{ meson is mainly formed inside QGP} \]

\[ \frac{2D_s^+}{D_0 + D^+} \rightarrow 0.3 \quad D \text{ meson is mainly formed outside QGP} \]

III. Relative production rate of baryons to mesons

\[ \frac{\Lambda_c}{D^0} \]

Justify whether the combination rule in light and strangeness sectors is suitable for charm hadrons.
## Multiplicities

<table>
<thead>
<tr>
<th>Hadron</th>
<th>$\pi^+$</th>
<th>$K^+$</th>
<th>$K_S^0$</th>
<th>$\phi$</th>
<th>$p$</th>
<th>$\Lambda$</th>
<th>$\Xi^-$</th>
<th>$\Omega^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>data</td>
<td>733 ± 54</td>
<td>109 ± 9</td>
<td>—</td>
<td>—</td>
<td>34 ± 3</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>QCM</td>
<td>733</td>
<td>111</td>
<td>106</td>
<td>15.0</td>
<td>33.7</td>
<td>27.5</td>
<td>4.63</td>
<td>0.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$D^+$</th>
<th>$D^0$</th>
<th>$D^{*+}$</th>
<th>$D_s^+$</th>
<th>$J/\Psi$</th>
<th>$\Lambda_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3.23</td>
<td>10.2</td>
<td>5.09</td>
<td>2.78</td>
<td>0.16</td>
<td>3.06</td>
</tr>
</tbody>
</table>

Rapidity densities of identified hadrons in 0-5% Pb+Pb collisions at 2.76 TeV
Transverse momentum spectra

SDQCM inputs:

\[
\frac{d^2 N_{q_i}}{p_T dp_T dy} \sim \text{Exp}( - \sqrt{p_T^2 + m_{q_i}^2} / T_{q_i} ) + R_{q_i} (1 + p_T)^{-S_{q_i}}
\]

\[ u, d, s \leftarrow \pi^\pm, \Lambda^0 \]

\[ c \leftarrow D^0 \]

Thermal quarks

Shower quarks
Transverse momentum spectra

Thermal components extend over about 2 GeV, compared with RHIC.
With the increased PT, strangeness decreases. The prediction for J/Psi only refers to those regenerated by ccbar combination. Justify whether the initially charmonia are eaten up by medium?
Quark combination mechanism not only dominates in low and intermediate $p_T$ range; in $p_T > 5$ GeV area, it could also deal with the hadron production basically.

It is generally recognized that at such high energy in the TeV regime hard partons are copiously produced. The density of shower quarks from such hard partons is therefore expected to be much higher. There is no reason to conclude that these shower quarks have no chance to capture thermal quarks or shower quarks to combine into intermediate or high $p_T$ hadrons.
Elliptic flows v2

\[ \frac{dN}{p_T dp_T dy d\varphi} \equiv f(\varphi) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} a_n \cos(n\varphi) + \sum_{n=1}^{\infty} b_n \sin(n\varphi) \]

\[ a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\varphi) \cos(n\varphi) d\varphi; \quad b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\varphi) \sin(n\varphi) d\varphi \]

\[ f(\varphi) = f(-\varphi) \Rightarrow b_n = 0; \quad f(\varphi) = f(\pi + \varphi) \Rightarrow a_1 = 0 \]

\[ a_2 = \frac{1}{\pi} \int_{-\pi}^{\pi} f(\varphi) \cos(2\varphi) d\varphi = \frac{1}{\pi} \left\langle \cos(2\varphi) \right\rangle \]

\[ \frac{dN}{p_T dp_T dy d\varphi} = \frac{1}{2\pi} \frac{dN}{p_T dp_T dy} [1 + 2v_2 \cos(2\varphi) + \cdots] \]
Elliptic flows

\[ v_2 = \langle \cos(2\varphi) \rangle \]

\[ = \langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \rangle \]

SDQCM inputs

\[ v_{2q_i} = \text{Exp}(-m_{q_i}^2)[a + bp_T + c \tanh(0.8p_T)] \]

\[ ud,s \leftrightarrow \Xi,\Omega \quad \text{Multistrange hadrons are less affected by hadronic interactions.} \]

\[ c \leftrightarrow D^0 \]
Elliptic flows

Hadronic interactions make the proton $v2$ decrease at low $pt$. 
Baryons and mesons separate into two clusters at intermediate pt. After scaled by the constituent quark number, perfect QNS is not observed, but mesons and baryons join together.
Resonance decay can enhance $v_2$ for $\pi$, $k$, $p$, lambda at low $p_T$, but influence $\xi$, omega little. The mass order for mesons and baryons, respectively, can be reproduced by quark combination.
Elliptic flows

\[ |X(3872)\rangle = \frac{1}{\sqrt{2}} (|D^0 \overline{D}^*\rangle + |\overline{D}^0 D^*\rangle) \]

v2 is an effective probe to explore exotic hadrons.
QCM has reproduced the available particle ratios, especially for the low p/π. The predictions for multiplicities of identified hadrons are presented.

- Quark combination dominates in the pt range of 0~10 GeV.
- \( v_2 \) are basically explained by QCM except for protons at low pt.
Thanks a lot!

This is not the END!
Diffusion of charm quarks in QGP

Less data on charm hadrons

We try our best to adopt a more reasonable method to deal with charm quarks.
Diffusion of charm quarks in QGP

Boltzmann equation for the density of charm quarks

\[
\frac{\partial}{\partial t} f(\vec{x}, \vec{p}, t) = \left. \frac{\partial f}{\partial t} \right|_{\text{collisions}} - \frac{\vec{p}}{E} \cdot \frac{\partial f}{\partial \vec{x}} - \vec{F} \cdot \frac{\partial f}{\partial \vec{p}}
\]

\[
\approx \left. \frac{\partial f}{\partial t} \right|_{\text{collisions}}
\]

Langevin equation

\[
d \vec{x} = \frac{\vec{p}}{E} dt
\]

\[
d \vec{p} = -\Gamma \vec{p} dt + \sqrt{2D(\vec{p} + d\vec{p})} dt \rho
\]

\[
D = \Gamma ET
\]

\[
\Gamma = \Gamma(e, P, T)
\]

hydrodynamics

Drag/friction coefficient       Gaussian noise variable
Pt Data Reference

P. Christiansen (for the ALICE Collaboration), arXiv:1208.5368v1 [nucl-ex].
Roberto Preghenella (for the ALICE Collaboration), arXiv:1203.5904v1 [nucl-ex].
B. Abelev et al. (ALICE Collaboration), JHEP 09, 112 (2012).
Gian Michele Innocenti (for the ALICE Collaboration), arXiv:1210.6388v1 [nucl-ex].