Suppression of the LHC $p/\pi$ ratio due to the QCD mass spectrum

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Outline

1. $p/\pi$ puzzle at ALICE
2. Extended Mass Spectrum
3. Model
4. Results and Outlook
5. Conclusions
Thermal fits at RHIC vs. LHC

RhIC vs. LHC

Thermal Fits worked at RHIC but overpredict $p/\pi$ at LHC

Extending the mass spectrum worked at RHIC, what about LHC?:


Improves thermal fits at RHIC
JNH, et al.,PRC82(2010)024913 Other suggestions:
- Final State interactions- PRL110,042501(2013)
- Different hadronization temperatures for light and strange quarks- PRD85,014004(2012)

Braun-Munzinger,Andronic, Redlich, and Stachel- various works
PRL109(2012)252301

Can extend the mass spectrum using Hagedorn States

Hagedorn States
"fireballs consist of fireballs, which consist of fireballs..."

- Proposed an exponentially increasing mass to explain spectra in $p - p$ and $\pi - p$ scattering
- Original model included hadronic states up to $\Delta(1232)$

Exponential mass spectrum
- Constant $T_H$: ↑ energy of system, ↑ new particles, NOT $T_H$
**Form of Hagedorn Spectrum**

Degeneracy of Hagedorn states

\[ \rho(M) = \int_{M_0}^{M} \frac{A}{[m^2 + (m_0)^2]^{a}} e^{\frac{m}{T_H}} dm \]  

(1)

- \(a = 3/2\), HS decay into 2 particles*
- \(a = 5/4\), HS decay into multiparticles
- \(a = 0\), ???

*Most likely, according to Frautschi
**Taken from Majumder & Muller 2010 (fitted to BMW)
*** Fitted to BMW (\(T_c = 160\) MeV) JNH, et. all, PRC86(2012)024913 , PRL103(2009)172302
- Original fits JNH,C. Greiner, I. Shovkovy PRL 2008

<table>
<thead>
<tr>
<th>(T_H) (MeV)</th>
<th>(A)</th>
<th>(m_0) (MeV)</th>
<th>(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_1^{**})</td>
<td>252</td>
<td>2.84 (1/GeV)</td>
<td>0</td>
</tr>
<tr>
<td>(\rho_2^{***})</td>
<td>180</td>
<td>0.63 (GeV^{3/2})</td>
<td>0.5</td>
</tr>
<tr>
<td>(\rho_3^{***})</td>
<td>175</td>
<td>0.37 (GeV^2)</td>
<td>0.5</td>
</tr>
</tbody>
</table>

currently using only non-strange, mesonic HS
Equation of State- HS fit lattice data to higher temperatures

Hadron resonance fits up until $T = 130 - 140$ MeV whereas Hagedorn states fit up until $T \approx 155$ MeV.

JNH, Jorge Noronha, Carsten Greiner PRC86 (2012) 024913
see also Majumder & Muller 2010
HS allow for $\eta/s$ to drop to the KSS limit- smooth transition for hydro
Sufficiently near $T_c$, $\eta/s$ can be close to the viscosity bound already in the
hadronic phase!!!!
**Extended Mass spectrum and Elliptical Flow**

\[ T_{SW} = 130 \text{ MeV} \]

\[ T_{SW} = 155 \text{ MeV} \]

JNH, et al., PRC89(2014)054904

Calculations within v-USPhydro (PRC88(2013)044916, see poster H-23)

Higher switching temperatures, mean larger effect from HS. **Need extended mass spectrum in decays!**
Rate Equations for the Chem. Eq. Time of Hadrons

\[ n_\pi \leftrightarrow HS \leftrightarrow n'_\pi + X\bar{X} \]

\[
\frac{d\lambda_i}{dt} = \Gamma_{i,\pi} \left( \sum_n B_{i,n} \lambda^\pi_n - \lambda_i \right) + \Gamma_{i,X\bar{X}} \left( \lambda^\pi_{\langle n_i,x \rangle} \lambda^2_{X\bar{X}} - \lambda_i \right),
\]

\[
\frac{d\lambda^\pi}{dt} = \sum_i \Gamma_{i,\pi} \frac{N^\text{eq}_i}{N^\text{eq}^\pi} \left( \lambda_{\langle n_i \rangle} - \sum_n B_{i,n} \lambda^\pi_n \right) + \sum_i \Gamma_{i,X\bar{X}} \frac{N^\text{eq}_i}{N^\text{eq}_{X\bar{X}}} \left( \lambda_i - \lambda^\pi_{\langle n_i,x \rangle} \lambda^2_{X\bar{X}} \right),
\]

\[
\frac{d\lambda_{X\bar{X}}}{dt} = \sum_i \Gamma_{i,X\bar{X}} \frac{N^\text{eq}_i}{N^\text{eq}_{X\bar{X}}} \left( \lambda_i - \lambda^\pi_{\langle n_i,x \rangle} \lambda^2_{X\bar{X}} \right)
\]

\[ \lambda = \frac{N}{N^\text{eq}}, \text{ } N \text{ is the total number of each particle, its equilibrium value is } N^\text{eq}. \pi \text{'s and } HS \text{ begin in chemical equilibrium} \]
Hydrodynamical Expansion

Use an isentropic expansion...

Find $T(t)$ for the 5% most central collisions

$$\frac{S_\pi}{N_\pi} \int dN_\pi dy = s(T) V(\tau) = \text{const}.$$ 

Volume

$$V_{\text{eff}}(\tau \geq \tau_0) = \pi \tau \left( r_0 + v_0(\tau - \tau_0) + 0.5 a_0(\tau - \tau_0)^2 \right)^2$$

- $\tau_0 = 0.6$ and 1.0 fm for LHC and RHIC, respectively.
- Begin resonance decays at $T_{sw} = 155$ MeV
- $T_{\text{end}}$ varies on Hagedorn State description
Results: Extended mass spectrum fits the low $p/\pi$ at ALICE

Initially unpopulated p, K, and $\Lambda$'s fit experimental data.

- When all hadrons begin in chem. eq. there is an overpopulation of p’s!
- $T_{\text{end}} = 133, 136, \text{and } 128 \text{ MeV for } \rho_1\text{-}\rho_3$, respectively
- The hydro expansion is significantly shorter at RHIC ($\Delta\tau \approx 5\text{ fm vs. } \Delta\tau \approx 10\text{ fm at LHC}$) whereas the time in the hadron resonance gas phase is roughly the same $\Delta\tau \approx 4 - 6\text{ fm.}$
Results: Hagedorn States fits are robust

- Changing the expansion has almost no effects.
- Increasing the decay width still fits, decreasing is below data (slightly)
- Too high switching temperature=overpopulation
- Increased maximum mass of HS still fits data
- Similar results obtained for other HS descriptions (see upcoming paper)
Beitel, Gallmeister, and Greiner arXiv:1402.1458

- Allows for resonance input, depends on mass, baryon number, strangeness, and charge.
- Includes all resonance decays.
- Maintains $p_T$ dependence - can be coupled to hydro!
- Finds that the Hagedorn temperature is the same for mesons and baryons, matches well with known hadrons.
Conclusions

- Both Lattice QCD and experimental results appear to indicate that heavier resonances are needed.
- Using the extended mass spectrum we are able to match experimental particle yields at both RHIC and ALICE.
- When all hadrons begin at their chemical equilibrium values, an overpopulation of protons is produced.
- Hagedorn states are now available in transport methods and will be investigated with v-USPhydro in the future.
- Effects of the Hagedorn spectrum do not depend on the details of the mass distribution: the only true requirement seems to be exponentially rising number of states. Hence, predictions from these hadron gas models are robust.
Slightly different setup as previous work but still matches data well

May indicate a non-zero number of $\Lambda$’s or that strange and/or baryonic Hagedorn states are needed
Other work on resonances

- Strangeness enhancement: P. Koch, B. Muller, and J. Rafelski
- $\bar{p} + N \leftrightarrow n\pi$ at SPS: R. Rapp and E. Shuryak
- Anti-hyperons at SPS: C. Greiner and S. Leupold.
Contribution of HS to Chemical Equilibrium Values

Effective $X = p, K, \text{or } \Lambda$

$$\tilde{N}_X = N_X + \sum_i N_i \langle X_i \rangle$$

Effective $\pi$'s

$$\tilde{N}_\pi = N_\pi + \sum_i N_i \langle n_i \rangle$$

$\langle X_i \rangle$ and $\langle n_i \rangle$ are calculated within a microcanonical model

Liu, et.al. PRC68(2003)024905,
Decay Width

- **Linear fit (PDG)**

\[ \Gamma_i = 0.15m_i - 58 \]
\[ = 250 - 1000 \text{ MeV} \]

- **X\bar{X} (microcanonical)**

\[ \Gamma_{i,X\bar{X}} = \langle X \rangle \Gamma_i \]
\[ \Gamma_{i,\pi} = \Gamma_i - \Gamma_{i,X\bar{X}} \]


\[ \langle B \rangle \approx 0.06 \text{ to } 0.4 \]
\[ \langle K \rangle \approx 0.4 \text{ to } 0.5 \]
\[ \langle \Lambda \rangle \approx 0.01 \text{ to } 0.2 \]
Branching Ratios

- Branching ratios for $n\pi \leftrightarrow HS$ are described by a Gaussian distribution

$$B_{i,n} \approx \frac{1}{\sigma_i \sqrt{2\pi}} e^{-\frac{(n-\langle n_i \rangle)^2}{2\sigma_i^2}}$$

- Average pion number (Liu, Werner, Aichelin, Phys. Rev. C 68, 024905 (2003).)

$$\langle n_i \rangle = 0.9 + 1.2 \frac{m_i}{m_p}$$

- Standard deviation

$$\sigma_i^2 = (0.5 \frac{m_i}{m_p})^2$$

- After cutoff $n \geq 2$, $\langle n_i \rangle \approx 3$ to 9 and $\sigma_i^2 \approx 0.8$ to 11

- For $HS \leftrightarrow n'\pi + X\bar{X}$, $\langle n_{i,x} \rangle = 2 - 4$

- Assume $\langle n_{i,p} \rangle = 2\langle n_{i,K} \rangle$