evidence from identified particle spectra for

Active Quark and Gluon
degrees-of-freedom

thanks to the organizers and particularly to Huan Huang, Nu Xu, Hans Georg Ritter, Art Poskanzer and Sergei Voloshin
Heavy-ion collisions

Nucleus-nucleus collisions may probe the physics of this quark-hadron transition

\[^{197}\text{Au} \rightarrow ^{197}\text{Au}\]

\[\sqrt{s_{NN}} = 200 \text{ GeV}\]

Today
- Solar system
- Quasars
- Galaxy formation
  - Epoch of gravitational collapse
- Recombination
  - relic radiation decouples (CBR)
- Matter domination
  - onset of gravitational instability

Nucleosynthesis
- Light elements created - D, He, Li

Quark-hadron transition
- Hadrons form - protons & neutrons

Electroweak phase transition
- Electromagnetic & weak nuclear forces become effective:
  \[SU(3)SU(2)U(1) \rightarrow SU(3)U(1)\]

Grand unification transition
- \( G \rightarrow SU(3)SU(2)U(1) \)
- Inflation, baryogenesis, monopoles, cosmic strings, etc.

The Planck epoch
- \( t = 5 \times 10^{17} \text{ sec} \)
  - \( T = 1 \text{ meV} \)
- \( t = 1 \text{ second} \)
  - \( T = 1 \text{ MeV} \)
- \( t = 3 \text{ minutes} \)
  - \( T = 1 \text{ GeV} \)
- \( t = 1 \text{ day} \)
  - \( T = 10^{-11} \text{ GeV} \)
- \( t = 10^{11} \text{ years} \)
  - \( T = 10^{-13} \text{ GeV} \)

\[ \sqrt{s_{NN}} = 200 \text{ GeV} \]

UrQMD Group – Frankfurt
For intermediate $p_T$ probes, $R_{CP}$ depends on the number of quarks in the hadron.

Production increases more quickly for hadrons with three instead of two quarks.

$p_T$ indicates the length scale the hadron can probe

$0.6 < \frac{p_T}{n} (\text{GeV}/c) < 2.0$

$0.33 > \lambda \text{ (fm)} > 0.1$
identified particle $R_{AA}/R_{CP}$

With high precision:
- a common suppression pattern for $K_S$, $\eta$, $K^*(892)$ and $\phi$ mesons.
- proton, $\Lambda$ and $\Xi$ grouped together
- pions at intermediate $p_T$ deviate from other mesons
not very anomalous

the faster increase of baryon production is common to many systems: it can’t be q vs. g fragmentation → multi-parton dynamics (power corrections, higher twist)
existence of a smaller length scale is related to chiral symmetry breaking
the $\Omega/\phi$ ratio does not continue to increase: probably due to underlying power-law shape in collision the corona
Q: Is the baryon “enhancement” just due to pion suppression?
A: No, at $\sqrt{s_{NN}}=17.3$ GeV, baryons are enhanced w/o meson suppression.

If the baryon enhancement is from a larger $p_T$ kick (or flow) for baryons, why doesn’t B/M increase when the spectrum is steeper?
implications for “charm”

charm→electron branching ratios depend on the hadron type:

\( \Lambda_c \) decays yield electrons less frequently than \( D^0 \) decays

A baryon enhancement in the charm sector can result in a non-photonic electron suppression
comparison to light hadrons

Consider $\Lambda_c/D$ similar to $\Lambda/K_S$ and charm $R_{AA}$ similar to light hadron $R_{AA}$

A $\chi^2$ analysis shows that for this scenario, preliminary PHENIX data prefer charm hadron $R_{AA} = 1.35 \times$ light hadron $R_{AA}$
- At $p_T$-s probing constituent quark length scales, $v_2$ of hadrons display a quark number dependence.
- Baryon yields have more in-plane enhancement than meson yields.
Since hadronization is a soft process, it can be modified by the presence of a QGP.

Simple models of *hadronization by coalescence* relate quark and hadron $v_2$:

$$v_2^q = v_2^h \left( \frac{p_T}{n} \right)/n,$$

$n$ is the number of quarks in the hadron.

**Models imply**

- $v_2$ is developed before hadrons form.
- deconfinement: long range interactions amongst quarks not hadrons.
Strange Quark Matter 2006 — Los Angeles

Interesting but potentially misleading: the linear region (low \( m_T - m_0 \)) can be scaled by any arbitrary number \( (m_T - m_0) / n \) hides the boundary between mass ordering and constituent quark number ordering (BTW hydro does not follow \( m_T - m_0 \) scaling)
With higher precision, fine structure is observed: the scaling doesn’t follow NCQ (3 vs 2) exactly.

Is this related to a jet component, a breakdown of simple approximations, or something new?

**Q:** Are coalescence models invalidated?

**A:** Not necessarily. Imperfect $v_2/n$ was also anticipated within ReCo models.
comparisons to theory

Inclusion of gluons in recombination was predicted to lead to a larger meson $v_2/n$ than baryon $v_2/n$: B. Müller, et al. nucl-th/0503003

Tantalizing indication for the fate of gluons and the nature of the constituents
Systematic errors on the data and calculations need to be carefully addressed
Effect of the quark momentum distribution inside the hadron:
V. Greco, et al.
*Phys. Rev. C*70:024901, 2004

A momentum distribution within hadrons leads to $v_2/n$ breaking similar to data. Fragmentation component may be necessary at higher $p_T$. 
The original parton $v_2$ is not recovered from scaling so the **opacity puzzle remains**. Calculation fails for $p/\pi$ and $R_{CP}$ but it does predict the **gradual drop in $v_2$ at high $p_T$**.
comparisons to theory

here, scaling is related to the additive quark model for hadronic cross sections. The affect of cross-sections should depend on eccentricity at hadronization.

UrQMD results also show an ordering by quark number:

Y. Lu nucl-th/0602009
hadronic cross-sections

\[ \frac{\Omega}{\phi} \] ratio should distinguish hadronic cross-sections from coalescence.

Is there a duality between the pictures?

- interacting co-moving quarks form a hadron
- interacting hadrons described by the sum of their constituent quarks

Both yield \(~\text{NCQ scaling}\).

here, larger proton \(v_2\) is from the additive quark model for hadronic cross-sections

\[ Y. \text{ Lu, et. al: nucl-th/0602009} \]
Where is the sensitivity to a pre-hadronic phase? The hadronic afterburner distorts $\pi$, $p$, $\Lambda$, and $\Xi$ spectra but the $\phi$ and $\Omega$ spectra are largely unaffected by the hadronic phase.
Strange Quark Matter 2006

$\phi$ and $\Omega$ $v_2$

NCQ scaling for $\phi$ and $\Omega$

$\sqrt{s_{NN}} = 200$ GeV $^{197}$Au+$^{197}$Au Collisions at RHIC (run IV)

Transverse Momentum $p_T$ (GeV/c)

S. Blyth, J. Chen, Y. Lu, M. Oldenburg
TABLE II: The ratio $v_4/v_2^2$ for $p_T/n_q > 0.6$ GeV/c from a combined fit and from data. Pion data points are used for fit I and excluded for fit II.

<table>
<thead>
<tr>
<th></th>
<th>data</th>
<th>fit I</th>
<th>fit II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^\pm$</td>
<td>1.10 ± 0.09</td>
<td>1.16 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>$K^0_S$</td>
<td>1.39 ± 0.19</td>
<td>1.16 ± 0.08</td>
<td>1.33 ± 0.15</td>
</tr>
<tr>
<td>$\Lambda + \bar{\Lambda}$</td>
<td>0.98 ± 0.15</td>
<td>0.94 ± 0.05</td>
<td>1.05 ± 0.10</td>
</tr>
<tr>
<td>quark</td>
<td>1.81 ± 0.15</td>
<td>2.15 ± 0.30</td>
<td></td>
</tr>
</tbody>
</table>

Cooper-Frye + hydro implies $v_4/v_2^2 = 0.5$ (*Borghini*): Data exclude 0.5. But careful comparisons need to be made.

ReCo relates meson and baryon $v_4/v_2^2$ quark $v_4/v_2^2$
Demonstrates that the corona effect can yield interesting $p_T$ and particle type dependences

but if the corona affects explain the baryon enhancement, why is there an enhancement in $e^+e^-$, $p+p$ and $d+Au$ collisions?

The saturation of $R_{AA}$ and $v_2$ are determined by the spectra from corona production. Can this model explain $\phi$ or $\Omega$ $v_2$: \textit{wouldn't} $\phi$ or $\Omega$ $v_2$ \textit{saturate even higher?}
The large away-side B/M ratio also points to **multi-gluon/quark dynamics**: wherever the **density of comoving constituents** is larger

- in-plane: $v_2$
- central vs. peripheral: $R_{CP}$

**and now in the wake of quenched jets**, it becomes easier to produce baryons.
Conclusions:

the baryon enhancement in $e^+e^- \rightarrow \Upsilon \rightarrow ggg$ rules out a quark vs gluon jet fragmentation explanation: $\bar{p}/p$ ratios also confirm this

a mass hypothesis is strongly disfavored by $\eta$, $\phi$, $\Xi$, and $\Omega$ $R_{CP}$ and $v_2$

The baryon enhancement is generic to many systems ($e^+e^-$, $d+Au$): but the presence of constituent quark scaling in $v_2$ may point to interactions between constituents of a deconfined phase!

Still open questions:

How much do hadronic cross sections contribute to the hadron-type dependence?

The collision system and $\sqrt{s_{NN}}$ dependence challenge current interpretations

Outlook:

the manifestation of a constituent quark length scale ($\sim 0.3$ fm) may be a valuable tool to study $\chi$-symmetry and confinement
What about $D_s/D^0$?

Depending on the poorly known branching ratio, a $D_s$ enhancement can also contribute to an electron suppression.

- Enhance the $D_s$ yield by 50% (for this plot the $D_s/D^0$ ratio is taken to be $p_T$ independent, not really a good assumption)
quark-number scaling

Poster by Y. Lu: SQM2006
Inclusion of gluons in recombination was predicted to lead to a larger meson $v_2/n$ than baryon $v_2/n$:

\[ B.\text{Müller, et al. nucl-th/0503003} \]

- To 1st order: the constituents look like massive valence quarks with no sub-structure
- Probing more deeply reveals substructure in the form of sea quarks or gluons
- Further daughter partons are revealed as the scale $Q^2$ is increased

Including contributions from sea quarks and gluons should cause deviations from $v_2/n$.
anti-baryon to baryon

gluon vs quark hadronization predictions don’t work in A+A or p+p collisions

“soft” physics extends quite high in $p_T$
Probing the fireball

We can’t perform scattering experiments with the fireball so we rely on internally created probes. This only tells us half the story.

How a scattering experiment would work

- the probe scattered off the fireball
- fireball created in the heavy-ion collision
- the information about the matter acquired by the probe
- probe emitted from fireball: exact source is unknown, less can be learned about the matter

What we have to work with

Hadrons produced with different momentum $p'$ probe different length scales and different physics