Recent results on $K_S$ and $\pi^+$ production at large $p_t$

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Objective

Suppression of particle production in central Au+Au collisions has been observed for charged particles and p^0s to $p_t \sim 10$ GeV/c.

Measurements of charged particle $v_2$ extend to $p_t \sim 10$ GeV/c and show a gradual decrease or flat behavior beyond $p_t \sim 2.0$ GeV/c.

*Using decay topology in the STAR detector for PID we will study $R_{AA}$ and $v_2$ for $K_S$ and $\pi$.*

Outline

I. Centrality classes and reconstructing the reaction plane.
II. The azimuthal anisotropy of $K_S$ and $\pi$ to above $p_t \sim 5.5$ GeV/c.
III. $R_{AA}$ for $K_S$ and $\pi$ up to $p_t \sim 5.5$ GeV/c.

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The products of the decays $K_S \rightarrow p^+ p^-$ ($\Gamma_i/\Gamma \approx 69\%$) and $\phi \rightarrow pp$ ($\Gamma_i/\Gamma \approx 64\%$) are detected in the TPC. Topology cuts are made on the vertices and the yield is extracted from the invariant mass distributions.
Centrality classes and the event plane

The *centrality* is estimated from the number of charged tracks.

The *reaction plane* is estimated from the observed anisotropy in the azimuthal distribution of tracks.

To understand Au+Au collisions we study distributions of particles with respect to the event centrality and the reaction plane.
Azimuthal Anisotropy

\[
E \frac{d^3 N}{d^3 p} = \frac{1}{2\pi} \frac{d^2 N}{p_T dp_T dy} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)] \right)
\]

The spatial anisotropy \( \varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \) leads to a momentum anisotropy characterized best by \( v_2 = \langle \cos[2(\phi - \Psi_r)] \rangle \).
Event plane resolution correction factor

Maximum resolution correction factor from random sub-events

<table>
<thead>
<tr>
<th></th>
<th>Lambda $v_2$ (130 GeV)</th>
<th>K$_S$ $v_2$ (130 GeV)</th>
<th>Lambda $v_2$ (200 GeV)</th>
<th>K$_S$ $v_2$ (200 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 GeV</td>
<td>0.58</td>
<td>0.68</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>200 GeV</td>
<td>0.80</td>
<td>0.80</td>
<td></td>
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</tr>
</tbody>
</table>

Track–wise and event–wise cuts

- $N_{\text{hits}} > 15$
- $N_{\text{hits}} / N_{\text{max}} > 0.52$
- $|\text{eta}| < 1.5$
- $0.1 < p_t < 2.0$ GeV/c
- DCA < 2.0 cm
- $z$–vertex < 25 cm
$K_S$ and $\Lambda$ $v_2$ results at 130 GeV:

"Azimuthal Anisotropy of $K_S$ and Lambda + Anti-lambda Production at Midrapidity from Au+Au Collisions at $\sqrt{s_{NN}} = 130$ GeV"


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A clear species dependence for $v_2$

$v_2$ appears to saturate at approximately 0.16 for $K_S$ and 0.22 for $\Lambda$. Why is there a saturation and why is it different for $K_S$ and $\Lambda$?

The onset of the saturation in $v_2$ at high $p_t$ is different for $K_S$ and $\Lambda$ and the phenomenology seems to be better described in $m_t - m_0$ than $p_t$; Why?

What’s causing the $p_t$ dependence of $v_2$ for $K_S$ and $\Lambda$?

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Centrality dependence of $v_2$ for $K_S$ and $?$

Let’s look at $v_2$ as a function of particle species and event centrality.

The simpler $m_t - m_0$ dependence makes it easier to study the deviations between particle species.

The difference between $K_S$ and $?$ $v_2$ seems to be dependent on centrality.

Less species dependence is seen for central collisions.
For $p_t$ from 1.8-3.2 GeV/c in central collisions, production approximately follows $N_{bin}$ scaling.

At higher $p_t$, however, a suppression with respect to $N_{bin}$ scaling is seen for both $K_S$ and $\pi$.

A significant difference is seen between the $p_t$ dependence of $K_S$ and $\pi R_{AA}$.

**Nuclear modification factor:**

$$R_{AA} = \frac{d^2N^{AA}/dp_Tdy}{T_{AA}d^2\sigma^{NN}/dp_Tdy}$$

**Geometric modification factor:**

$$R_{AA}^{geo} = \frac{d^2N^{Central}/dp_Tdy}{d^2N^{Peripheral}/dp_Tdy} \left\langle N_{Peripheral}^{bin} \right\rangle$$

$$\left\langle N_{Central}^{bin} \right\rangle$$
Comparison to \( \frac{(h^+ + h^-)}{2} \)
$R_{AA}$ vs. transverse mass.
Species dependence of $v_2$ and $R_{AA}$ vs. $p_t$.

What physics is behind the $p_t$ scales of the saturation in $v_2$ and the suppression in $R_{AA}$.

How does the particle species influence the $p_t$ dependences?

The $v_2$ saturation and the decrease in $R_{AA}$ appear to be loosely correlated for both $K_S$ and $\Lambda$. 

STAR Preliminary (Au+Au; 200 GeV; $|y|<1.0$)
Summary

• $v_2$ and $R_{AA}$ for $K_S$ and $?\text{ show a strong species dependence:}$
  – Compared to $K_S$, $?$ production shows a **larger azimuthal anisotropy** but a **smaller suppression** (central relative to peripheral) for $2.5 < p_t < 5.0 \text{ GeV/c.}$

• The species dependence of $v_2$ appears to be centrality dependent:
  – Little difference is seen between the maximum $v_2$ for $K_S$ and the maximum $v_2$ for $?$ in the most central bin.

• $R_{AA}$ for $?$ coincides with our estimate of $N_{bin}$ scaling expectations for $1.8 < p_t < 3.2 \text{ GeV/c.}$

• $R_{AA}$ for $K_S$ and $?$ and $(h^++h^-)/2$ seem to merge at $p_t \sim 5-6 \text{ GeV/c.}$
Outlook

• Comparing $v_2$ to $R_{AA}$ for $K_S$ and ? :
  – In a simple scenario where $v_2$ is established from the opacity of the source $v_2$ for $K_S$ vs. ? would imply a greater opacity for ? than for $K_S$.
  – Within a simple scenario where $R_{AA}$ is explained through energy loss, $R_{AA}$ would imply that partons that fragment into $K_S$ experience greater energy loss.

• Are we seeing non-pQCD effects on baryons, is this a mass dependence, or a 2-quark/3-quark dependence?

• As we continue the systematic study of identified particles ($f$, ?, O, etc.) we will resolve many open issues.

• The opportunity to make predictions for $v_2$ and $R_{AA}$ for identified particles is slipping away quickly.
Supplementary Slides

-Lambda vs. Anti-lambda $v_2$-

-Reaction plane distribution-

-$N_{\text{bin}}$ and $N_{\text{part}}$ scaling-

-$v_2$ for 130 GeV identified particles-

-Modified blast wave fits-

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Monte Carlo Glauber Calculation $\sqrt{s_{NN}} = 200$ GeV

<table>
<thead>
<tr>
<th>$%\sigma_{geo}$</th>
<th>$&lt;N_{part}&gt;$</th>
<th>$&lt;N_{bin}&gt;$</th>
<th>$&lt;N_{bin}/N_{part}&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>352 ($^{6}_{7}$)</td>
<td>990.0 ($^{69}_{77}$)</td>
<td>2.85 (0.17)</td>
</tr>
<tr>
<td>5-10</td>
<td>298 ($^{10}_{10}$)</td>
<td>783.7 ($^{71}_{74}$)</td>
<td>2.65 (0.17)</td>
</tr>
<tr>
<td>10-20</td>
<td>232 ($^{11}_{10}$)</td>
<td>563.2 ($^{64}_{59}$)</td>
<td>2.43 (0.17)</td>
</tr>
<tr>
<td>20-30</td>
<td>165 ($^{13}_{12}$)</td>
<td>355.0 ($^{53}_{49}$)</td>
<td>2.14 (0.17)</td>
</tr>
<tr>
<td>30-40</td>
<td>114 ($^{13}_{12}$)</td>
<td>213.9 ($^{41}_{36}$)</td>
<td>1.86 (0.16)</td>
</tr>
<tr>
<td>40-60</td>
<td>61 ($^{10}_{10}$)</td>
<td>91.8 ($^{22}_{23}$)</td>
<td>1.44 (0.14)</td>
</tr>
<tr>
<td>60-80</td>
<td>19.8 ($^{5}_{6}$)</td>
<td>20.0 ($^{7}_{9}$)</td>
<td>0.96 (0.10)</td>
</tr>
</tbody>
</table>

Woods-Saxon nuclear geometry parameters:

$\rho_0 = 0.16935 \text{ nucl.}/\text{fm}^3$ \hspace{1cm} $r_0 = 6.38 \pm 0.06 \text{ fm}$ \hspace{1cm} $c_0 = 0.535 \pm 0.027 \text{ fm}$

Cross-sections:

$\sigma_{NN} = 42 \pm 1 \text{ mb}$ \hspace{1cm} $\sigma_{geo} = 7.2 \pm 0.4 \text{ b}$
$v_2$ vs $m_t - m_0$ for 130 GeV identified particles

A simultaneous fit to both particles at all $p_t$ fails.

A simultaneous fit to both particles for $p_t$ less than 1.0 GeV/c gives results similar to those reported by STAR for 130 GeV identified particle $v_2^*$.  

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From 2-5 GeV/c the production of lighter mesons is dominated by pQCD processes giving rise to a gradual reduction in $v_2$ for mesons, while baryon production is still dominated by non-perturbative mechanisms – such as baryon junctions or hydro – and exhibits a larger $v_2$. The inclusive charged particle $v_2$ is a superposition of the two and “saturates.”
How do we maintain an azimuthal anisotropy in the number of particles produced at a given $p_t$ while the azimuthal anisotropy of $<p_t>$ disappears?
Surface N-binary Scaling for High $p_T$ (Model Calculations by An Tai)

**Au+Au at $\sqrt{s_{NN}}=200$ GeV**

- **Centrality $<5\%$**
  - $N_{bin\_v}=1016, N_{part}=347$

- **5$\%<Centrality<10\%$**
  - $N_{bin\_v}=816, N_{part}=293$

- **10$\%<Centrality<20\%$**
  - $N_{bin\_v}=592, N_{part}=226$

- **30$\%<Centrality<40\%$**
  - $N_{bin\_v}=237, N_{part}=107$

- **Woods-Saxon distribution.**
- **A binary collision occurs if** $d_{min} \leq \sqrt{(\sigma/\pi)}$.
- **Pythia is used to handle particle production for each binary collision with** $\sqrt{s} > 4$ GeV, otherwise, particles are produced through resonance, eg $NN \leftrightarrow \Delta N$. 
The relative probability to produce mesons or baryons depends on the density of the quarks.

\[
\frac{d^3n_{\text{baryon}}}{dp^3} \propto \left( \frac{d^3n_{\text{quark}}}{dp^3} \right)^3; \quad \frac{d^3n_{\text{meson}}}{dp^3} \propto \left( \frac{d^3n_{\text{quark}}}{dp^3} \right)^2
\]

Hadronization Schemes:
- Parton-hadron duality
- Independent fragmentation
- Whatever works?

The hadronization scheme may be important for understanding the species dependence of \( R_{AA} \) and \( v_2 \).

Coalescence is qualitatively consistent with the species dependence of \( v_2 \) and \( R_{AA} \).
Species/mass dependence scenarios:

• Species are created at different times.
  • Perhaps in combination with a surface emission;

• The onset of pQCD is earlier for meson;

• Quark coalescence effects;

• From partonic to hadronic:
  • $<p_{t}^{\text{meson}}>$ $\sim$ $v^2$ $<p_{t}^{\text{quark}}>$
  • $<p_{t}^{\text{meson}}>$ $\sim$ $v^3$ $<p_{t}^{\text{quark}}>$;