Probing the QCD Phase diagram with the Measurement of $\phi$-meson Production and Elliptic Flow in Heavy-Ion Collisions at STAR

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Outline

• Motivation
  – Beam Energy Scan at RHIC
  – $\phi$-meson as a clean probe for onset of deconfinement

• The STAR experiment

• Results
  – $p_T$-spectra, $R_{cp}, N(\Omega)/N(\phi)$
  – Elliptic flow: $v_2(\phi)/v_2(p)$, NCQ scaling

• Summary
Motivation

The RHIC Beam Energy Scan (BES)

- BES Motivations
  - Search for phase boundary
  - Search for Critical point

- Observables of de-confinement
  a) Strange hadron dynamics
     \( N(\Omega)/N(\phi) \) and \( R_{CP}(\phi) \)
  b) Strange hadron collectivity
     Elliptic flow \( (v_2) \) of \( \phi \)
**φ-meson : A clean probe**

Partonic $\phi$-meson $v_2$ large

Hadronic $\phi$-meson $v_2$ small

- mass: proton $\sim \phi(s\bar{s}) \sim \Lambda$
- $\phi$: meson, proton & $\Lambda$: baryon
- $s+\bar{s} \rightarrow \phi$ not $K^+ + K^- \rightarrow \phi$
- small hadronic cross section $
\sigma_{\phi-hadron} < \sigma_{p-\pi, \pi-\pi}$

In the hadronic case, no number-of-quark scaling and the value of $\phi$ meson $v_2$ is expected to be small

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**AMPT model**

- $\pi$, $K$, $p$ Freeze out
- Crossover
- Phase Boundary
- expected $\phi$-meson $f_0$
- chemical freeze-out

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The STAR Experiment at RHIC

- Collisions: Au+Au
- Collisions centrality from uncorrected $\frac{dN_{ch}}{d\eta}$ in $|\eta| < 0.5$

<table>
<thead>
<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>Good MB events in Million</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>~ 4 M</td>
</tr>
<tr>
<td>11.5</td>
<td>~ 12 M</td>
</tr>
<tr>
<td>19.6</td>
<td>~ 36 M</td>
</tr>
<tr>
<td>27</td>
<td>~ 70 M</td>
</tr>
<tr>
<td>39</td>
<td>~ 130 M</td>
</tr>
<tr>
<td>62.4</td>
<td>~ 67 M</td>
</tr>
<tr>
<td>200</td>
<td>~ 240 M</td>
</tr>
</tbody>
</table>
Particle identification and $v_2$ measurement method

- **Time projection chamber (TPC)**
  - full azimuth, $|\eta| < 1$
  - $dE/dx$ v.s. momentum

- **Barrel Time-Of-Flight (TOF)**
  - full azimuth, $|\eta| < 0.9$
  - Particle flight time
  - Clean separation of $K$, $\pi$ up to $p_T = 1.6$ GeV/c

- $v_2 = \langle \cos 2(\varphi - \psi_2)/Res \rangle$

- **TPC $\eta$-sub event plane for $v_2$ analysis**
  - Non-flow effect reduced

- **TPC particle identification (PID)** is used for spectra analysis, TPC+TOF PID is used for $v_2$ analysis

• $\phi$ meson transverse momentum distribution can be well described by a Levy function

\[
\frac{1}{2\pi p_T} \frac{d^2N}{dp_T dy} = \frac{dN/dy}{2\pi nT(nT + m(n - 2))} \frac{(n - 1)(n - 2)}{(nT + m(n - 2))} \left(1 + \frac{\sqrt{p_T^2 + m^2} - m}{nT}\right)^{-n}
\]
Nuclear Modification Factor ($R_{cp}$)

$K_S^0 \ R_{CP} : 0-05%/40-60%$

$\phi \ R_{CP} : 0-10%/40-60% \ and \ 0-05%/40-60% \ for \ 200 \ GeV$

- \phi\text{-meson} \ R_{CP} \geq 1 \ at \ intermediate \ p_T \ for \ \sqrt{s_{NN}} \leq 39 \ GeV.
Strange Quark Dynamics

- Intermediate $p_T$ $\Omega/\phi$ ratios: Indication of separation between $\geq 19.6$ and $11.5$ GeV. The $\chi^2/ndf$ for deviation between $11.5$ and $19.6$ GeV is $\sim 8.3/2$ for $p_T > 2.4$ GeV/c.

- Derived strange quark $p_T$ distributions show a trend of separation between $\geq 19.6$ and $11.5$ GeV.

\textit{Change of particle production mechanism?}

\[ v_2(\phi) \text{ vs. } v_2(p) \]

- Mass: proton \( \sim \phi \)
- At low \( p_T \), \( v_2(\phi)/v_2(p) \) decreases with decreasing beam energies
  - Indicating less partonic collectivity with decreasing beam energy.

$v_2(\phi)$ vs. $v_2(p)$

- Mass: proton $\sim \phi$
- At low $p_T$, $v_2(\phi)/v_2(p)$ decreases with decreasing beam energies
  → Indicating less partonic collectivity with decreasing beam energy.

- Au+Au, $\sqrt{s_{NN}} = 200$ GeV
- At low $p_T$, $v_2(\phi)/v_2(p) > 1.0$
  → proton $v_2$ possibly affected by hadronic re-scattering.

NCQ scaling: $\phi$-meson $v_2$

- $\phi$ meson $v_2$ deviates from other particles $\sim 2\sigma$ at the highest $p_T$ data in 7.7 and 11.5 GeV collisions.
  
  → Small or zero $v_2$ for $\phi$ meson implies hadronic interactions are more important at lower energies.

More data for 7.7 and 11.5 GeV are needed for clear conclusion.

Summary

- STAR preliminary $\phi$ meson spectra and elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 7.7 - 200$ GeV have been presented.

- $\phi$-meson $R_{CP} \geq 1$ at intermediate $p_T$ for $\sqrt{s_{NN}} \leq 39$ GeV.

- Intermediate $p_T$ $\Omega/\phi$ ratios and derived strange quark $p_T$ distribution show a indication of separation between $\geq 19.6$ GeV and $11.5$ GeV.
  → May suggests change of production mechanism.

- At low $p_T$, $v_2(\phi)/v_2(p)$ decreases with decreasing beam energies.
  → Indicating less partonic collectivity with decreasing beam energy.
  Top RHIC Energy ($\sqrt{s_{NN}} = 200$ GeV): At low $p_T$, $v_2(\phi)/v_2(p) > 1.0$.
  → Could be the effect of hadronic re-scattering.

- $\phi$-meson $v_2$ deviates from other particles $\sim 2\sigma$ at the highest $p_T$ data in 7.7 and 11.5 GeV collisions.
  → It may indicate hadronic interactions are more important at lower energies.
Back-up