System Size and Energy Dependence of Resonance production

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Outline

• Motivation

• Resonances

• Particle ratios
  - system size dependence
  - energy dependence
  - resonances to long-lived particle ratios

• Nuclear modification factor
  - centrality, energy, particle species

• Spin alignment: $\rho_{00}$ vs. $\rho_T$, $\langle N_{\text{part}} \rangle$, energy
Motivation

1. Probing the properties of hadronic phase

- Resonances have different short lifetimes similar to Hadronic phase
  - allows the study of properties of hadronic phase in terms of regeneration and re-scattering effects

2. In-medium energy loss

- Hard partons propagating through hot and dense medium are predicted to lose energy via multiple scattering
  - suppression of high-$p_T$ production

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{(1/N_{\text{evt}}^{AA})d^2N^{AA}/dydP_T}{(1/N_{\text{evt}}^{pp})d^2N^{pp}/dydP_T}$$

$$R_{AA} = 1 \rightarrow \text{no modification}$$

$$R_{AA} \neq 1 \rightarrow \text{medium effects}$$

Resonance decay | Regeneration | Re-scattering
---|---|---
$\rho(1.3) < K^*(4.2) < \Sigma^*(5.5) < \Lambda^*(12.6) < \Xi^*(21.7) < \phi(46.4)$

Lifetime (fm/c)
Motivation

3. Resonance production contributes spin alignment in HI collisions

![Image of resonance production and spin alignment]

$\rho_{00}$: Element of spin density matrix

$\frac{dN}{d(cos\theta^*)} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)cos^2\theta^*$

- Large angular momentum [1] and intense magnetic field [2] is expected in initial stage of heavy-ion collisions
- Spin alignment of vector meson could occur

4. Strangeness production
5. Chiral symmetry restoration

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### Resonances (particles & decay modes)

#### Meson

<table>
<thead>
<tr>
<th>Meson</th>
<th>quark content</th>
<th>Decay modes</th>
<th>B.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho(770)^0)</td>
<td>(u\bar{u}+d\bar{d}) \sqrt{2}</td>
<td>(\pi^+\pi^-)</td>
<td>100</td>
</tr>
<tr>
<td>(K^*(892)^0)</td>
<td>d\bar{s}</td>
<td>K^+\pi^-</td>
<td>66.6</td>
</tr>
<tr>
<td>(K^*(892)^\pm)</td>
<td>u\bar{d}</td>
<td>K^0_s\pi^+</td>
<td>33.3</td>
</tr>
<tr>
<td>(f_0(980), f_2(1270))</td>
<td>unknown</td>
<td>(\pi^+\pi^-)</td>
<td>46(84)</td>
</tr>
<tr>
<td>(K^{*0,2}(1430)^0)</td>
<td>d\bar{s}</td>
<td>K^+\pi^-</td>
<td>93(49.4)</td>
</tr>
<tr>
<td>(\phi(1020))</td>
<td>s\bar{s}</td>
<td>K^+K^-</td>
<td>48.9</td>
</tr>
</tbody>
</table>

#### Baryon

<table>
<thead>
<tr>
<th>Baryon</th>
<th>quark content</th>
<th>Decay modes</th>
<th>B.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Sigma(1385)^+)</td>
<td>uus</td>
<td>(\Lambda\pi^+)</td>
<td>87</td>
</tr>
<tr>
<td>(\Sigma(1385)^-)</td>
<td>dds</td>
<td>(\Lambda\pi^-)</td>
<td>87</td>
</tr>
<tr>
<td>(\Lambda(1520))</td>
<td>uds</td>
<td>pK^-</td>
<td>22.5</td>
</tr>
<tr>
<td>(\Xi(1530)^0)</td>
<td>uss</td>
<td>(\Xi^-\pi^+)</td>
<td>66.7</td>
</tr>
<tr>
<td>(\Xi(1820)^\pm,0)</td>
<td>dss (uss)</td>
<td>(\Lambda K^\mp) (\Lambda K^0_s)</td>
<td>unknown</td>
</tr>
<tr>
<td>(\Omega(2012)^\mp)</td>
<td>sss</td>
<td>(\Xi^\mp K^0_s)</td>
<td>unknown</td>
</tr>
</tbody>
</table>

**Lifetime (fm/c):** \(\rho(1.3) < K^*(4.2) < \Sigma^*(5.0-5.5) < \Lambda^*(12.6) < \Xi^*(21.7) < \phi(46.2)\)

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Suppression of $K^*$ is observed in different collision systems from various experiments (NA49, NA61/SHINE, STAR) - more suppression for larger collision systems.
Suppression of $K^*$ w.r.t. the statistical Hadron Resonance Gas Models (HGM) is observed for heavier system.

Suppression of $\Lambda(1520)$ while no suppression for $\phi$ w.r.t. the HGM from NA49 measurement.
Particle ratios: energy dep.

$K^*/K$ and $\phi/K$ ratios have been measured at different energies in STAR and ALICE - no clear energy dependence from RHIC to LHC.
• Flat behavior in wide range of energy for small collision systems

• Yield ratios for central Au+Au and Pb-Pb collisions are significantly lower than the pp collisions

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Flat behavior in wide range of energy (~10-10^4 GeV)

Increase for low energies due to canonical suppression
- reproduced by statistical model calculation with strangeness correlation radius parameter $R_c = 2.2$ fm
Particle ratios

- $K^0/K$
  - decrease with increasing multiplicity (system size)
  - larger in central Cu-Cu than central Au-Au
  - higher in pp collisions than in central Au-Au and Pb-Pb

- $\phi/K$
  - constant as a function of multiplicity
  - slightly larger in Au-Au and Cu-Cu than Pb-Pb
  - independent of collision energy and system from RHIC to LHC energies

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Resonance to long-lived particle ratios

- No multiplicity dependence of $\rho^0/\pi$ at RHIC in p+p, d+Au and Au+Au collisions
- $\rho^0/\pi$ is suppressed at LHC with increasing multiplicity
  - qualitatively described by EPOS with UrQMD

Lifetime (fm/c): $\rho(1.3)$

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Resonance to long-lived particle ratios

• Multiplicity dependence of $K^{*0}/K$ at RHIC and LHC
  - smooth trend:
    $p+p \rightarrow d+Au(p+Pb) \rightarrow Au+Au(Pb+Pb)$

Lifetime(fm/c): $p(1.3) < K^{*0}(4.2)$
Resonance to long-lived particle ratios

- No modification of $\Sigma^*/\Lambda$ at d+Au, p+Pb and Au+Au
- while suppression of $\Sigma^*/\Lambda$ is observed in Pb+Pb
  - not described by EPOS3

Lifetime (fm/c): $\rho(1.3) < K^0(4.2) < \Sigma^*(5.5)$
Resonance to long-lived particle ratios

- Suppression of $\Lambda^*/\Lambda$ at Au+Au and Pb+Pb
- A+A: qualitatively described by EPOS with UrQMD

Lifetime (fm/c): $p(1.3) < K^*(4.2) < \Sigma^*(5.5) < \Lambda^*(12.6)$
Resonance to long-lived particle ratios

- $\Xi^*/\Xi$ and $\phi/K$: no significant centrality dependence across the different collision systems

Lifetime (fm/c): $\rho(1.3) < K^0*(4.2) < \Sigma^*(5.5) < \Lambda^*(12.6) < \Xi^*(21.7) < \phi(46.2)$

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Resonance to long-lived particle ratios

ALICE Preliminary

\( p^0/\pi, K^*/K, \Sigma^*/\Lambda \) and \( \Lambda^*/\Lambda \) in Pb-Pb collisions indicates dominance of re-scattering over regeneration for short lived resonances

\( \Sigma^*/\Lambda \) and \( \Lambda^*/\Lambda \): flat in small systems and no energy dependence from RHIC to LHC

\( \Xi^*/\Xi \) and \( \phi/K \): no significant centrality dependence

**Summary**

Lifetime(fm/c): \( \rho(1.3) < K^*(4.2) < \Sigma^*(5.5) < \Lambda^*(12.6) < \Xi^*(21.7) < \phi(46.2) \)

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Nuclear modification factor ($R_{AA}$)

$R_{AA}$ helps in understanding the evolution of parton energy loss in the medium

**Centrality dependence**

\[
R_{AA}(p_T) = \frac{\text{Yield}_{AA}(p_T)}{\text{Yield}_{pp}(p_T) \times \langle N_{\text{coll}} \rangle}
\]

- $p_T < 5 \text{ GeV/c}$
  - $R_{AA}$ of $K^*$ is lower than $\phi$
  - dominance of re-scattering effect

- $p_T > 6 \text{ GeV/c}$
  - $R_{AA}$ of $K^*$ and $\phi$ are comparable within uncertainties
  - suppression due to parton energy loss
  - pronounced suppression in the most central collisions
Nuclear modification factor ($R_{AA}$)

**Center-of-mass energy dependence**

- $R_{AA}$ values for $\sqrt{s_{NN}} = 5.02$ TeV are compared to the values at $\sqrt{s_{NN}} = 2.76$ TeV
- No significant differences for both the $K^0$ and $\phi$ are observed
- measurement of other mesonic and baryonic resonances ($\rho(770)^0$, $\Delta(1232)^{++}$, $\Sigma(1385)$, $\Lambda(1520)$) are required to further support
Nuclear modification factor ($R_{AA}$, $R_{pA}$)

**Hadron species dependence**

Intermediate-$p_T$ ($2 < p_T < 8$ GeV/c)
- baryon-meson splitting
- hint of **mass ordering** among mesons
- higher $R_{AA}$ values for proton (might be due to baryon-meson effect)

High-$p_T$ (>8 GeV/c)
- similar **suppression** for different light flavor hadrons
- No flavor (u,d,s) dependence

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Spin alignment: $\rho_{00}$ vs. $\rho_T$

- RHIC
  - $\rho_{00} < \frac{1}{3}$ for $K^*$ and consistent with $\frac{1}{3}$ for $\phi$

- LHC
  - Spin alignment ($\rho_{00} < \frac{1}{3}$) of vector meson in heavy-ion collisions at low $p_T$
  - No spin alignment for vector meson in pp collisions
  - No spin alignment for spin 0 hadron ($K^0_s$)

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Spin alignment: $\rho_{00}$ vs. $\langle N_{\text{part}} \rangle$

- Spin alignment ($\rho_{00} < 1/3$) of vector meson in heavy-ion collisions at low $p_T$
- $\rho_{00} \sim 1/3$ at high-$p_T$
- $\rho_{00} \sim 1/3$ in central and peripheral collisions
Spin alignment: $\rho_{00}$ vs. energy

- $K^*0\rho_{00}$
  - low-$p_T$ and in mid central collisions is smaller than 1/3
  - no beam-energy dependence is observed

- $\phi\rho_{00}$
  - larger than 1/3 at RHIC energies (~ 3σ significance at 200 GeV)
  - smaller than 1/3 at LHC energy (~ 2σ significance)

$\sqrt{s_{NN}} = 11.5 - 200$ GeV/c
Conclusion

• Hadronic resonances are valuable probes to study the properties of hadronic phase, spin alignment and in medium energy loss (+ strangeness production, chiral symmetry restoration, etc.)

• Suppression of short-lived resonances in large collision systems
  - dominance of re-scattering over regeneration
  - no suppression observed for the longer-lived resonances

• High-$p_T$ particle suppression is observed for Pb-Pb
  - No flavor(u/d/s) dependencies (ground state particles & resonances)

• Spin alignment ($\rho_{00} < 1/3$) of vector meson is found in heavy-ion collisions at low $p_T$ in mid-central Au-Au and Pb-Pb collisions

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electric part of vector $\phi$ field to spin alignment

$$C_s^{(y)} \equiv g_\phi^4 \left\langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \right\rangle.$$