Experimental overview on hadronic resonance production in high-energy nuclear collisions

Yosuke Watanabe (CNS, the University of Tokyo)
Outline

- Hadronic resonances
  - Low mass vector mesons
- Dilepton decays
- Hadronic decays
- Summary
In-medium properties of hadrons
- Partial restoration of chiral symmetry
- Suitable for dilepton decays

Evolution dynamics of hot hadron gas
- Rescattering and regeneration of resonances
- Suitable for hadronic decays

Information from the partonic stage
- $\phi$ has a long lifetime
- Small hadronic interaction cross sections of $\phi$

<table>
<thead>
<tr>
<th></th>
<th>$\rho$</th>
<th>$\omega$</th>
<th>$\phi$</th>
<th>$K^*(892)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (MeV/c²)</td>
<td>775</td>
<td>783</td>
<td>1019</td>
<td>896</td>
</tr>
<tr>
<td>Lifetime (fm/c)</td>
<td>1.3</td>
<td>23</td>
<td>46</td>
<td>4.2</td>
</tr>
<tr>
<td>Decay modes</td>
<td>$l^+l^-, \pi^+\pi^-$</td>
<td>$l^+l^-$</td>
<td>$l^+l^-, K^+K^-$</td>
<td>$K^+\pi^-$</td>
</tr>
</tbody>
</table>
Physics motivations

In-medium properties of hadrons
- Dielectron spectra in Au-Au (HADES)
- Dielectron spectra in Pb-Pb (ALICE)

Evolution dynamics of hot hadron gas
- $K^*$ vs multiplicity in $pp$, $p$-$Pb$, $Pb$-$Pb$ (ALICE)
- $\rho \rightarrow \pi \pi$ in $Pb$-$Pb$ (ALICE)

Information from the partonic stage
- $\phi$ meson’s $v_2$ in Au-Au (STAR)
Dilepton decays
Expected hadronic decay contributions: “cocktail”

- Excess at $m_{ee} \sim 500$ MeV/c$^2$: $\pi\pi \rightarrow \rho \rightarrow ee$
- Excess spectra are consistent with $\rho$ broadening model
  - Confirmed by NA60 with very high statics data (EPJC 61 (2009) 711)
In-medium $\rho$ spectra at RHIC

- There were discrepancies between PHENIX and STAR for $\sqrt{s_{NN}} = 200$ GeV.
- New PHENIX results were presented in QM2015:
  - Hadron Blind Detector upgrade
  - Analysis improvements in eID and background subtraction
  - Phys. Rev. C 93 (2016) 014904
- PHENIX and STAR are now consistent.
- Spectra from both experiments are consistent with $\rho$ broadening.

<table>
<thead>
<tr>
<th></th>
<th>value±stat ±syst ±model</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHENIX (New)</td>
<td>2.3 ± 0.4 ± 0.4 ± 0.2</td>
</tr>
<tr>
<td>STAR</td>
<td>1.76 ± 0.06 ± 0.26 ± 0.29</td>
</tr>
</tbody>
</table>

Data/cocktail ($0.3 < m_{ee} < 0.76$ GeV/$c^2$)
Energy, $p_T$, centrality dependence

Broadening of $\rho$ meson explains the LMR excess in the energy region $\sqrt{s_{NN}} = 20$-200 GeV including $p_T$ and centrality dependence.
ρ broadening describes the excess also in U-U collisions
LHC-ALICE

- Dielectron spectra in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are presented
  - ALICE $p_T^e > 0.4$ GeV/c, PHENIX/STAR: $p_T^e > 0.2$ GeV/c
- Consistent with no enhancement
  - Extracted limits compatible with ALICE real photon measurements and previous results from PHENIX and STAR
  - Large charm cross sections at LHC energies
Understanding of the charm contributions in cocktail is crucial to study in-medium $\rho$ spectra.

New PHENIX result: PYTHIA and MC@NLO
- 40% difference in data/cocktail ($0.3 < m_{ee} < 0.76$ GeV/c$^2$)
  - PYTHIA: $2.3 \pm 0.4 \pm 0.4 \pm 0.2$, MC@NLO: $1.7 \pm 0.3 \pm 0.3 \pm 0.2$
- Cross sections are derived using IMR of $d$-Au collisions
- Uncertainty in extrapolation to $m \sim 0$
  - Lack of understanding in $c\bar{c}$ cross section and correlation

Vertex detectors (PHENIX, STAR, ALICE) and MTD (STAR)

<table>
<thead>
<tr>
<th>d$\sigma_{cc}/dy$ ((\mu b))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PYTHIA</strong></td>
</tr>
<tr>
<td><strong>MC@NLO</strong></td>
</tr>
<tr>
<td><strong>STAR (D meson)</strong></td>
</tr>
</tbody>
</table>

PRC 93 (2016) 014904
- Baryon dominated matter
- Excess from the elementary collisions in Au-Au collisions
  - Excess is well described by models with ρ broadening + system evolution described by UrQMD
- System size dependence is also studied, such as p-Nb, C-C, Ar-KCl
  - Gradual increase of the enhancement factor as going to the heavier system
  - The same model also works in Ar-KCl collisions
In-medium $\rho$ spectra are well described by the models with "$\rho$ broadening"

Measurement of the $a_1$ meson is experimentally difficult

According to PLB 731 (2014) 103, the medium-modified $\rho$ and $a_1$ meson degenerate with each other at high $T$

---

R. Rapp, PLB 731 (2014) 103
Acceptance correction

- Acceptance correction is needed to learn more things from experimental data
  - Dielectron excess $\propto \tau_{\text{fireball}}$ (R. Rapp PLB 753 (2016) 586)

- Acceptance-corrected excess in STAR is consistent with that in NA60 within experimental uncertainties
Excess yield and fireball lifetime

- Fireball lifetime is longer in central collisions than in peripheral collisions
- Fireball lifetime is longer in central 200 GeV than in low energies

QM2015 talk by S. Yang
Excess yield and fireball lifetime

- Fireball lifetime is longer in central collisions than in peripheral collisions
- Fireball lifetime is longer in central 200 GeV than in low energies
Fireball lifetime is longer in central collisions than in peripheral collisions

Fireball lifetime is longer in central 200 GeV than in low energies

QM2015 talk by S. Yang
**$\omega$ and $\phi$ at RHIC**

- Detailed analysis of $\phi$ spectral shape is performed by STAR
  - No significant difference ($<2\sigma$) from vacuum mass and width
- Yields are well described by Tsallis blast-wave function within experimental uncertainties
- $\phi \rightarrow ee$ and $\phi \rightarrow KK$ give consistent results
Hadronic decays
Mass and width reconstructed with hadronic decays are affected by:

- Chiral symmetry restoration
- Final state interactions (rescattering/regeneration)

Mass and width are consistent with vacuum values

- No centrality nor $p_T$ dependence
$\phi/K$ and $K^*/K$

- $K^*/K$ decreases with increasing multiplicity
  - Rescattering $>$ Regeneration
  - Lower limit for the hadronic phase lifetime: $\sim 2$ fm

- Comparison with other strange baryons ($ct$ $K^*$: 4 fm, $\Lambda^*$: 13 fm, $\Sigma^*$: 5 fm)
  - $\Lambda^*(1520)/\Lambda \sim K^*/K$, No suppression for $\Sigma^*/\Lambda$
  - Need to consider other effects, e.g. regeneration, etc
**K*/K in small systems**

- **K*/K decreases as going to the higher multiplicity bin**
  - Qualitatively similar trend as Pb-Pb
  - Rescattering also in small systems?

**Graph**
- ALICE pp, p-Pb, Pb-Pb
- Talk by A. Knospe and F. Bellini
$\rho \rightarrow \pi^+\pi^-$

- Clear peak also in the most central bin
  - Peripheral bins are previously studied by STAR (PRL 92 (2004) 092301)
- $\rho/\pi$ ratio is suppressed from pp to central Pb-Pb
  - Well described with EPOS3 with UrQMD
Hadronic decays
Violation of mass ordering for $\phi$

- Hydrodynamic models predict mass ordering of elliptic flow ($v_2$)
- The mass ordering is broken between $\phi$ and $p$
  - Late stage hadronic scattering effects on proton
  - Small hadronic cross section for $\phi$
- $\phi$ (and other multi-strange hadrons) is a penetrating probes carrying the information from the partonic stage

T. Hirano et al, PRC 77 (2008) 044909

STAR Au-Au

PRL 116 (2016) 062301
Recent results related to low mass vector mesons are presented

Dilepton decays

- Dielectron excess up to RHIC energies are described by “$\rho$ broadening”
  - Preliminary dielectron spectra from ALICE and HADES are presented
- Understanding of $c\bar{c}$ contribution is crucial for high energies
- Acceptance corrected excess is studied as a function of system size and collision energy

Hadronic decays

- $K^*$ production is suppressed in the most central collisions
  - Similar trend for $\rho \rightarrow \pi\pi$
- $K^*$ production is also suppressed in high multiplicity pp and p-A collisions
- The elliptic flow of the $\phi$ meson violates “mass ordering”
Backup
\[ \omega \text{ and } \phi \text{ at SPS} \]

- Clear peaks are visible
- Suppression of \( \omega \) at low \( p_T \) was observed
  - Suppression is larger in the most central collisions