Charmed and exotic hadron measurements with ALICE at the LHC

Yosuke Watanabe (CNS, University of Tokyo) for the ALICE collaboration
Outline

- Motivation
- ALICE detector
- Results
- Future plans
- Summary
Particle production in heavy-ion collisions

- **Statistical model**
  - Thermodynamic approach assuming thermally and chemically equilibrated system

- **Coalescence model**
  - Hadrons (or nuclei) are formed by quarks (or nucleons) which are close in phase space
  - Yields of hadrons provide insights into their internal structure and also into the degrees of freedom in the QGP
    - $\Lambda_c$ production is related to the abundance of di-quark structures in the QGP (S.H.Lee et al PRL100(2008)222301)
    - Different hadrons probe different degrees of freedom
  - Abundant strange quarks coalesce into exotica, such as H-dibaryon?

- **Heavy-quark vacuum fragmentation**
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ALICE detector

Central Barrel ($|\eta|<0.9$)
- $2\pi$ tracking & PID
- ITS
- TPC
- TOF

Forward detectors
- Trigger, centrality, timing

pp 7 TeV
p-Pb 5.02 TeV
Pb-Pb 2.76 TeV
ALICE detector

- Excellent PID (hadrons, leptons, photons) and jets
- Excellent vertex capability (HF, V^0s, cascades, conversions)
- Efficient low-momentum tracking down to 150 MeV/c
Anti-nuclei

- Anti-nuclei are abundantly produced in heavy-ion collisions
- Mass difference between nuclei and anti-nuclei provides a test of the CPT invariance
- Mass and binding energies of nuclei and anti-nuclei are compatible within experimental uncertainties
Hypertriton (pnΛ) is measured in $^3\Lambda$H decay mode

Topological cuts are applied to reduce combinatorial background

Measured hypertriton lifetime is compatible with other measurements

$\tau = 181^{+54}_{-39}(stat) \pm 33(syst)$ ps
Different statistical models describe light particle yields with $T_{\text{chem}} \sim 156$ MeV. Hypernuclei production is also compatible with the models.
$S_3 \approx 1$ in a simple coalescence model
• Sensitive also to local baryon-strangeness correlation of the medium (PLB 684 (2010) 224)

- The $S_3$ measurements at AGS, RHIC and LHC are compatible
- Thermal model and hybrid UrQMD describe the ALICE data
Searches for dibaryons

- $\Lambda\Lambda$: Predicted by Jaffe in bag model calculation (PRL 38 (1977) 195)
  - $\Lambda\Lambda \rightarrow \Lambda + p + \pi^-$
  - $\Lambda n$-bar $\rightarrow d$-bar + $\pi^+$
- Both $\Lambda\Lambda$ and $\Lambda n$-bar are expected to be seen with the analyzed statistics (if they exist)
No peak observed → Set upper limits on $dN/dy$

Upper limits are compared to various model calculations as a function of BR

- Upper limits are one order of magnitude smaller than model calculations
Heavy-flavor hadrons

- Fragment into hadrons
  - Same as vacuum fragmentation?
  - Recombination with surrounding light quarks?

- Lose energy while traversing the medium
  - Collisional energy loss?
  - Radiative energy loss?

- Heavy quarks are produced in initial hard scattering processes
  - They will experience the whole system evolution
D-meson reconstruction

- Only full reconstruction studies are presented
- Signal extraction is performed through invariant mass analysis
- S/B improvement
  - TPC and TOF particle identification
  - Secondary vertex finding with ITS

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<th>$c\tau$ (μm)</th>
<th>BR (%)</th>
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<tr>
<td>$D^0 \rightarrow K^-\pi$</td>
<td>123</td>
<td>3.88</td>
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<tr>
<td>$D^+ \rightarrow K^-\pi^+\pi^+$</td>
<td>312</td>
<td>9.13</td>
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<tr>
<td>$D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$</td>
<td>67.7</td>
<td></td>
</tr>
<tr>
<td>$D_s^+ \rightarrow \phi^+ \rightarrow K^+K^-\pi^+$</td>
<td>150</td>
<td>2.28</td>
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Nuclear modification factor $R_{AA}$

Charm production in heavy-ion collisions is expected to scale with $N_{\text{coll}}$

- $R_{AA} = 1$: no medium effects
- $R_{AA} \neq 1$:
  - Cold-nuclear-matter effects
  - Energy loss of charm quark in the QGP
  - Change in hadronization
  - etc
D-meson $R_{AA}$ and $R_{pA}$

- Strong suppression of D mesons at high $p_T$ in Pb-Pb collisions
  - Not seen in p-Pb collisions
    - Strong suppression is due to final-state effects
  - Stronger suppression in central than in semi-central collisions
    - In-medium energy loss of charm quarks
Comparison with other hadrons

- $R_{AA}$ integrated over high $p_T$ region, $8 < p_T < 16$ GeV/c
- Expected hierarchy in the energy loss: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
- What we see: $R_{AA}(\pi) \sim R_{AA}(D) < R_{AA}(B)$
  - Different shapes of the parton $p_T$ spectra
  - Different parton fragmentation functions
  - Different energy loss for charm and beauty is confirmed
$D_s^+$ provides a unique insight into charm-quark hadronization mechanism
  - Strangeness enhancement in heavy-ion collisions affects charm-quark hadronization in the coalescence picture
  - $p_T > 8 \text{ GeV}/c$: compatible with other D mesons
  - $p_T < 8 \text{ GeV}/c$: hint of less suppression

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D-meson azimuthal anisotropy

- Low and intermediate $p_T$
  - Rescattering of charm quarks with the surrounding medium
    - Degree of charm-quark thermalization
  - Hadronization mechanisms
- High $p_T$
  - Path-length dependence of charm-quark energy loss

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

$v_2$: elliptic flow
D-meson $v_2$

- Positive $v_2$ is observed (5σ effect for 2 < $p_T$ < 6 GeV/c in 30-50% centrality bin).
- D-meson $v_2$ tends to be larger in semi-central than in central collisions.
- D-meson $v_2$ is similar to that of charged particles.
  - Significant interaction of charm quarks with the medium (PRL 111 (2013) 102301)
Various models with different energy-loss mechanisms, fireball evolution, hadronization, etc

Simultaneous description of $R_{AA}$ and $v_2$ seems challenging for models
D mesons in small systems

- D-meson production is studied as a function of multiplicity in pp and p-Pb collisions
  - Study the interplay between hard and soft processes of particle production
  - The increase of self-normalized yields with multiplicity is faster than linear
  - EPOS 3 including hydro describes the data slightly better than the one without hydro

### Figures

- **Figure 1**: ALICE Average $D^0$, $D^*$, $D^{**}$ meson production in pp, $p + \bar{p} = 7$ TeV and p-Pb, $\sqrt{s_{NN}} = 5.02$ TeV collisions.
  - $2 < p_T < 4$ GeV/c, $|y| < 0.5$
  - $p$ in red, $\bar{p}$ in green.
  - Normalization uncertainty not shown.

- **Figure 2**: B feed-down and normalization uncertainty.
  - $1 < p_T < 2$ GeV/c.
  - $2 < p_T < 4$ GeV/c.

### References

`arXiv: 1602.07240`
Λ_c production is sensitive to the abundance of di-quark structures in the QGP.

Λ_c production is not well known even in elementary collisions at LHC energies.

- We are currently working on its measurement in pp and p-Pb collisions.
Beauty hadron’s $R_{AA}$

- Beauty-hadron measurements are currently limited to semileptonic decay and $B \rightarrow J/\psi + X$ (JHEP 1507(2015)051)
- Semileptonic decay analysis
  - Electrons from beauty can be identified with their large impact parameter
  - Hint of $R_{AA} < 1$ for $p_T > 3$ GeV/c
Planned upgrades (2021-)

- These are possible only with significant upgrade of detectors
  - TPC: continuous readout using GEM technology
  - ITS: High resolution, low material budget

~100 times larger statistics
~3 times better impact parameter resolution


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<td>$D_0$ meson $R_{AA}$</td>
<td>0</td>
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<td>$D$ meson from $B$ decays $R_{AA}$</td>
<td>2</td>
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<tr>
<td>$D$ meson elliptic flow ($\nu_2 = 0.2$)</td>
<td>0</td>
</tr>
<tr>
<td>$D$ from $B$ elliptic flow ($\nu_2 = 0.1$)</td>
<td>2</td>
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<tr>
<td>Charm baryon-to-meson ratio</td>
<td>2</td>
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<td>$D_s$ meson $R_{AA}$</td>
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Hypernuclei + Exotica

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<tr>
<td>Anti-α</td>
<td>30,000</td>
</tr>
<tr>
<td>$^{3}_{\Lambda}H$</td>
<td>300,000</td>
</tr>
<tr>
<td>$^{4}_{\Lambda}H$</td>
<td>800</td>
</tr>
<tr>
<td>$^{4}_{\Lambda\Lambda}H$</td>
<td>34</td>
</tr>
<tr>
<td>$^{XX}$</td>
<td>150,000</td>
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10^{10} central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV
8% efficiency per detected baryon is assumed
Charm and beauty hadrons

- Increased statistics + better vertexing capability will enable further studies of $\Lambda_c$
- Beauty hadrons can also be fully reconstructed

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Summary

- ALICE is an ideal place to measure rare hadron production in heavy-ion collisions
- Hypertriton yield and lifetime are measured
- Our data do not support the existence of $\Lambda\Lambda$ and $\Lambda n$
  - Our upper limits are one order of magnitude smaller than model calculations
- D-meson production in Pb-Pb collisions is intensively studied
  - Strong suppression ($R_{AA} < 1$)
    - $R_{AA}(\pi) \sim R_{AA}(D) < R_{AA}(B)$
  - Positive $v_2$
  - Combination of $R_{AA}$ and $v_2$ starts constraining theoretical models
  - Hint of less suppression for $D_s^+$
- More to come from existing data, e.g. $\Lambda_c$
- ... much more to come after ALICE upgrade