Observation of $\frac{4}{A} \bar{H}$

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Introduction

• Matter-antimatter asymmetry is a precondition necessary to explain the existence of our world made predominately of matter over antimatter

• $\frac{4}{3}H$
  - The heaviest anti-hypernucleus ever observed experimentally
  - New opportunity for the study of matter-antimatter asymmetry

• Reconstruction channels
  \[ \frac{3}{2}H \rightarrow \frac{3}{2}He + \pi^- \], \[ \frac{3}{2}H \rightarrow \frac{3}{2}He + \pi^+ \] (Assumed branching ratio 25%)
  \[ \frac{4}{2}H \rightarrow \frac{4}{2}He + \pi^- \], \[ \frac{4}{2}H \rightarrow \frac{4}{2}He + \pi^+ \] (Assumed branching ratio 50%)

• Datasets from STAR at RHIC facility

<table>
<thead>
<tr>
<th>Year</th>
<th>$\sqrt{s_{NN}}$ GeV</th>
<th>System</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>200</td>
<td>Au+Au</td>
<td>0.67B</td>
</tr>
<tr>
<td>2011</td>
<td>200</td>
<td>Au+Au</td>
<td>0.68B</td>
</tr>
<tr>
<td>2012</td>
<td>193</td>
<td>U+U</td>
<td>0.67B</td>
</tr>
<tr>
<td>2018</td>
<td>200</td>
<td>Ru+Ru, Zr+Zr</td>
<td>4.61B</td>
</tr>
</tbody>
</table>

➢ Due to low production yield, data from various collision systems and triggers are used in the search, to maximize the statistics.
Particle identification

- Event selection:
  \(-40<V_z<40\text{ cm},\sqrt{V_x^2 + V_y^2}<2\text{ cm}\)

- Track selection:
  \(n_{\text{Hits}}>20,\quad \frac{n_{\text{Hits}}}{n_{\text{HitsMax}}}>0.52\)

- Particle identification:
  \(\pi: |n\sigma_\pi|<3\)
  \(^3\text{He}: |n\sigma_{^3\text{He}}|<3,\quad \text{if TOF matched,}\)
  \(1.0 < m^2/Q^2 < 3.0 \text{ GeV}^2/c^4\)
  \(^4\text{He}: |n\sigma_{^4\text{He}}|<3 \& \& (|n\sigma_{^3\text{He}}|>3.5 \quad || (2.8 < m^2/Q^2<4.1\text{ GeV}^2/c^4 \& \& |\text{TOF local } y|<2))\)

\(^4\text{He}\) need much tighter cuts because of \(^3\text{He}\) contamination
\[\frac{3}{\Lambda}H, \frac{3}{\Lambda}H, \frac{4}{\Lambda}H \text{ and } \frac{4}{\Lambda}H \text{ signals}\]

- Kalman-Filter package is used

<table>
<thead>
<tr>
<th>Cuts</th>
<th>[\frac{3}{\Lambda}H, \frac{4}{\Lambda}H]</th>
<th>[\frac{3}{\Lambda}H, \frac{4}{\Lambda}H]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\chi^2_{\text{prim}}) (\pi)</td>
<td>&gt;10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>(\chi^2_{\text{prim}}) (\text{He})</td>
<td>&lt;2000</td>
<td>&lt;2000</td>
</tr>
<tr>
<td>(\chi^2_{\text{ndf}})</td>
<td>&lt;5</td>
<td>&lt;5</td>
</tr>
<tr>
<td>(\chi^2_{\text{topo}})</td>
<td>&lt;2</td>
<td>&lt;3</td>
</tr>
<tr>
<td>L/dL</td>
<td>&gt;3.4</td>
<td>&gt;3.4</td>
</tr>
<tr>
<td>L</td>
<td>&gt;3.5</td>
<td>&gt;3.5</td>
</tr>
<tr>
<td>He DCA</td>
<td>&lt;1</td>
<td>-</td>
</tr>
</tbody>
</table>

- Cuts obtained by optimizing \(\frac{3}{\Lambda}H\) signals to avoid biasing towards larger \(\frac{4}{\Lambda}H\) signals due to fluctuations

- First observation of heaviest anti-hypernucleus in experiment!
Production yield ratios

- Particle yields are efficiency corrected, with only minimum-bias trigger and
\[ \frac{p_T}{M} \in [0.7, 1.5], y \in [-0.7, 0.7] \]
- Various antimatter / matter ratios consistent with expectations
- The newly measured yield ratios are consistent with previous results and model

Conclusion and outlook
- \( \frac{4}{\Lambda}H \) signal observed for the first time with over 5\( \sigma \) significance
- Various antimatter / matter ratios consistent with expectations
- Lifetime measurement on-going
## Back up

### Equivalent Gaussian significance

- **Gaussian distribution precondition** is that the number of events is large enough to show the independence. For $\frac{3}{4}H$ and $\frac{3}{4}\bar{H}$, there are several hundreds counts per bin, so Gaussian distribution can be used to describe the significance. But for $\frac{4}{4}H$ and $\frac{4}{4}\bar{H}$, the candidates in one bin is rare (~10/bin), Gaussian distribution cannot be used in this situation.

- **Poisson distribution** is suitable for this situation. Significance is equal to the signal peak confidence level, according the side band region, we can get an expectation background counts ($\lambda$) if there is no signal in the peak range. But the fact is that counts in this region is $k$, so the possibility of the peak fluctuated by the background can be calculated by:

$$p(X = k) = e^{-\lambda} \frac{\lambda^k}{k!}$$

For example in $\frac{4}{4}\bar{H}$, the signal window is 3 bins, the expected background counts are 5.0, and the total bin counts are 22.0. If we believe this is caused by fluctuation, we can get the possibility:

$$p(X = 22) = e^{-5.0} \frac{5.0^{22}}{22!} = 1.4292267e^{-08}$$

This possibility shows that background fluctuated peak can be accepted within $1.4292267e^{-08}$, which we can believe the peak structure is from a bound state $\frac{4}{4}H$.

- But usually, we used Gaussian distribution significance to estimate the possibility, thus Equivalent Gaussian $N_\sigma$ significance is obtained by having equal integrals of the tail for Poisson above $N$ candidates and for Gaussian above $N_\sigma$. 

$$p(X = k) = e^{-\lambda} \frac{\lambda^k}{k!}$$

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KF particle package topology cuts

- $\chi^2_{ndf}$: DCA (distance of closest approach) between helium and pion tracks, in terms of uncertainty
- $\chi^2_{prim}$: helium deviation from PV, in terms of uncertainty
- $\chi^2_{prim}$: pion deviation from PV, in terms of uncertainty
- $\chi^2_{topo}$: V0 deviation from PV, in terms of uncertainty
- $L/dL$: decay length / decay length error
- $L$: decay length
- He DCA: helium DCA from PV