Pentaquark Search at $\sqrt{s_{NN}}=200$ GeV with STAR at RHIC

• Introduction to STAR
• Techniques and Analysis
• Simulation Studies
• Conclusions and Future Plans

Sevil Salur  Yale University  STAR Collaboration
2 concentric rings
3.8 km circumference
p+p ( s ≥ 500 GeV)
d+Au ( s ≥ 200 GeV)
Au+Au ( s ≥ 200 GeV)

• 2000 run: Au+Au @ s_{NN}=130 GeV
• 2001 run: Au+Au @ s_{NN}=200 GeV and p+p @ s=200 GeV
• 2003 run: d+Au @ s_{NN}=200 GeV and p+p @ s=200 GeV
• 2004 run: Au+Au @ s_{NN}=200 GeV [Starts Dec 2003]
Introduction to STAR

• Investigation of strongly interacting matter at high energy density
• Search for signatures of Quark-Gluon Plasma (QGP)

QGP Phase transition
Space time evolution

Time Projection Chamber (TPC)
1. Magnetic Field: 0.5 Tesla
2. Acceptance:
   charged particles |\(|< 1.5
dE/dx identification p<0.8 \text{ GeV/c}
V0 identifications |y| < 1.0
\( \pm 0.5 < < \)
3. Resolutions:
   dE/dx ~ 8%
   Momentum: 1.5%-5%
   at \( p_t \sim 0.2-10 \text{ GeV/c} \)

Solenoidal Tracker at RHIC is one of the two large detector systems constructed at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory.
The STAR Detector
Available Data

<table>
<thead>
<tr>
<th>System</th>
<th># of Events</th>
<th>dNch/dΔφ</th>
</tr>
</thead>
<tbody>
<tr>
<td>p+p</td>
<td>8 Million</td>
<td>3</td>
</tr>
<tr>
<td>d+Au</td>
<td>14 Million</td>
<td>15</td>
</tr>
<tr>
<td>Au+Au</td>
<td>1.5 Million</td>
<td>800</td>
</tr>
</tbody>
</table>
**What pentaquarks are we looking for?**

<table>
<thead>
<tr>
<th>Reaction</th>
<th>No/Yes</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{p}^+ \rightarrow n + K^+$</td>
<td>No</td>
<td>No id for n</td>
</tr>
<tr>
<td>$\bar{p}^+ \rightarrow p + K^0$</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$\bar{\Xi}^0 \rightarrow \bar{\Xi}^0 + K^0$</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$\bar{\Xi}^0 \rightarrow \bar{\Xi}^+ + K^-$</td>
<td>No</td>
<td>No id for $\Xi^0 \rightarrow n + \bar{\Xi}^0$</td>
</tr>
<tr>
<td>$\bar{p}^+ \rightarrow \bar{p}^0 + \bar{\Xi}^+$</td>
<td>No</td>
<td>No id for $\Xi^0 \rightarrow \bar{\Xi}^0 + \bar{\Xi}^0$</td>
</tr>
<tr>
<td>$\bar{p}^+ \rightarrow \bar{p}^+ + \bar{\Xi}^0$</td>
<td>No</td>
<td>No id for $\Xi^+ \rightarrow p + \bar{\Xi}^0$</td>
</tr>
<tr>
<td>$\bar{\Xi}^{++} \rightarrow p + \bar{\Xi}^0 + \bar{\Xi}^+$</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$\bar{\Xi}^0 \rightarrow \Xi^0 + n^0$</td>
<td>No</td>
<td>No id for n or $\Xi^0$</td>
</tr>
<tr>
<td>$\Xi^0 \rightarrow p + \bar{n}$</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$\Xi_5 \rightarrow \Xi^+ + n$</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$\Xi_5 \rightarrow \Xi^0 + \bar{n}$</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$\Xi_5 \rightarrow \Xi^0 + p$</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>$\Xi_5 \rightarrow \Xi^0 + \bar{n}$</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

**Good opportunity to observe anti pentaquarks** ($\bar{p}/p \sim 0.7$ at RHIC)

First we need to identify the decay daughters $\Xi^0$, $\Xi$, $\bar{\Xi}$, $\bar{\Xi}$ and $p$. 
Topological Analysis Technique

Decay Topology

Geometrical identification of secondary decay vertex

This technique is used to find long lived (~few cm) particles.
Particle Identification and Mixing Technique

Charged daughter particles are identified by dE/dx in the TPC.

□’s are reconstructed by:

Standard decay topology technique since □’s have a long lifetime (c□=7.89 cm).
Background subtracted Invariant Mass Spectra

**STAR Preliminary**

**p-p at** $s = 200\text{GeV}$

*Significance* $= 15\pm 2$

**STAR Preliminary**

$\Lambda^+ \pi^-$ [$\text{GeV}/c^2$]

<table>
<thead>
<tr>
<th>$M_{\Lambda^+ \pi^-}$</th>
<th>PDG values for $\Xi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$= 1387\pm 1$ MeV</td>
<td>$= 39\pm 2$ MeV</td>
</tr>
</tbody>
</table>

The width and the mass is consistent within the PDG and momentum resolution.

**d-Au at** $s_{\text{NN}} = 200\text{GeV}$

*Significance* $= 60\pm 4$

**STAR Preliminary**

$m_{\text{Inv}}(\Lambda^+ \pi^-)$ [$\text{GeV}/c^2$]

**Au-Au at** $s_{\text{NN}} = 200\text{GeV}$

*Significance* $= 20\pm 3$

**STAR Preliminary**

$m_{\text{Inv}}(\Lambda^+ \pi^-)$ [$\text{GeV}/c^2$]
Some Other Resonance Invariant Mass Spectra

STAR Preliminary

\( K^0 + \bar{K}^0 \)

Au+Au minimum bias
\( p_T \geq 0.2 \text{ GeV/c} \)
\( |y| \leq 0.5 \)
Statistical error only

\( \begin{align*} \text{Au+Au} & \quad \text{40\% to 80\%} \\ 0.2 \leq p_T < 0.9 \text{ GeV/c} \\ |y| \leq 0.5 \end{align*} \)

\( \begin{align*} \text{K}^0 & \\ \text{f}_0 & \\ \text{K}^0_S & \\ \text{K}^*0 & \end{align*} \)

Statistical error only

\( \Lambda(1520) \)

\( \begin{align*} M & = 1.516 \pm 0.002 \\ \Gamma & = 0.012 \pm 0.006 \end{align*} \)

central Au+Au
\( p_T = 0.9 - 1.5 \text{ GeV} \)

\( m_{\text{inv}}(p \text{K}) \) [GeV/c^2]
Acceptance Study for $\Xi^+$ in $p+p$

One $\Xi$ per event

Simulation

$\Theta^+ \rightarrow p + K^0$

$T_{\text{inv slope}} = 250$ MeV

Efficiency $\times$ Acceptance $\sim 3\%$. This factor depends highly on cuts applied. Investigating!
Acceptance Study for $\Xi^- \rightarrow \Xi^- + \pi^-$ in $p+p$

Simulation

$\Xi^- \rightarrow \Xi^- + \pi^-$

$N_{\text{entries}}$

$1000$

$0$

$2000$

$1.8$

$1.9$

$2$

$m_{\text{inv}} (\Xi^- + \pi^-) [\text{GeV/c}^2]$

Output

$N_{\text{Entries}}$

$M_{\text{inv}} (\Xi^- + \Xi^-)[\text{GeV/c}^2]$

$1 \Xi^- \Xi^-’s$ per event

Acceptance $\sim 2.3\%$

$\Xi^- (1530) \rightarrow \Xi^- + \Xi^-$
Feasibility Studies with current p+p data

Ballpark Number

~0.1-1 \(\pi\) per \(\phi\) (1520) for p+p

- Preliminary \(dN/dy\)
of \(\phi\) (1520) in pp \(\Rightarrow 0.004\) per event
- 8 Million \(\times 0.004\) \(\Rightarrow 32\) K \(\phi\) (1520)
- 0.1-1 \(\times 32\) K \(\pi\) in pp \(\Rightarrow 3-32\) K
- Efficiency 3% \(\Rightarrow 90-960\)
- Branching Ratio 50% \(\Rightarrow 45-480\)

Background pairs per event in the mass range of \(\phi\) is 0.0004.
- 0.0004 \(\times 8\) Million \(\Rightarrow 3200\)

Significance \(\pi\) = Signal/\(\sqrt{(2 \times \text{Background} + \text{Signal})}\)

\(\pi\) \(\Rightarrow 0.5-6\)
Feasibility Studies with current Au+Au data

From AuAu to pp we have a slightly smaller efficiency with a much higher background!

J.Letessier, G.Torrieri, S.Steinke and J.Rafelski *hep-ph/0310188*
Jorgen Randrup *nucl-th/0307042*

\[ \sim 0.5-1.5 \text{ K} \text{ per event for } \text{AuAu} \]

- 0.5-1.5 X 1.5 Million \(\rightarrow\) 0.8-2.3 Million
- Efficiency 3% \(\rightarrow\) 25-70 K
- Branching Ratio 50% \(\rightarrow\) 10-35 K

Background pairs per event in the mass range of \(\text{K}\) is 2.

- 2 X 1.5 Million \(\rightarrow\) 3 Million

Significance \(\text{K} = \frac{\text{Signal}}{\sqrt{2 \times \text{Background} + \text{Signal}}}

\[ \text{K} \sim 4-14 \]

But bin by bin fluctuations …
We might be losing some of it via re-scattering of daughters.
Resonance Ratios

\[ r_{p+p}(1.3 \text{ fm/c}) \]

\[ K^{*+} \rightarrow K^+ p \ (4 \text{ fm/c}) \]

\[ *(1520) \rightarrow p + K \ (13 \text{ fm/c}) \]

Lost \[ * \] due to re-scattering

Found \[ * \]

STAR Preliminary
Au-Au and p-p
\[ \sqrt{s}=200 \text{GeV} \]
Conclusion & Near Future Plans

• Preliminary acceptance and efficiency studies shows that we should be able to find the pentaquarks at the few % level.

  (Resonances can be clearly reconstructed via event mixing techniques in p-p, d-Au and Au-Au central collisions.)

• Can measure the anti pentaquarks at RHIC. (antibaryon/baryon~1)

• STAR measures particles at mid rapidity \(|y|<1\) and \(|y_{\text{Beam}}|\sim 6\).

  Are the pentaquarks made away from the fragmentation region?

• Much more data from upcoming Run 4 !!!

  Au+Au at \(\sqrt{s_{NN}}=200\) GeV 100 Million Events planned. (70 times the Current Data)

  STAR continues to search pentaquarks with Bern University, UCLA, Yale University
The STAR Collaboration

Argonne National Laboratory • Institute of High Energy Physics, Beijing • Institute of Physics, Bhubaneswar • University of Birmingham • Brookhaven National Laboratory • University of California, Berkeley • University of California, Davis • University of California, Los Angeles • Carnegie Mellon University • Creighton University • Laboratory for High Energy (JINR), Dubna • Particle Physics Laboratory (JINR), Dubna • University of Frankfurt • Indiana University, Bloomington • Institut de Recherches Subatomiques, Strasbourg • Jammu University • Kent State University • Institute of Modern Physics, Lanzhou • Lawrence Berkeley Laboratory • Max-Planck-Instit fuer Physik, Munich • Michigan State University • Moscow Engineering Physics Institute • Indian Institute of Technology, Mumbai • City College of New York • Ohio State University • Panjab University • Pennsylvania State University • Institute of High Energy Physics, Protvino • Purdue University • University of Rajasthan • Rice University • Universidade de Sao Paulo • University of Science and Technology of China (USTC) • Shanghai Institute of Nuclear Research (SINR) • SUBATECH, Nantes • Texas A & M • University of Texas, Austin • Tsinghua University • Variable Energy Cyclotron Centre, Kolkata • Warsaw University • Warsaw University of Technology • University of Washington • Wayne State University • Institute of Particle Physics, Wuhan • Yale University
EXTRAS .....
Trigger

- Zero Degree Calorimeter (ZDC)
- BBC
- Central Multiplicity Detectors

Graphs showing distribution of signal and energy in different trigger levels.
Statistical Model

\[ \frac{p}{p} \quad \frac{\Lambda}{\Lambda} \quad \frac{\Xi}{\Xi} \quad \frac{\Omega}{\Omega} \quad \frac{\pi}{\pi} \quad \frac{K}{K} \quad \frac{K^{*}}{K^{*}} \quad \frac{p}{p} \quad \frac{K^{0}}{h} \quad \frac{\phi}{h} \quad \frac{\Lambda}{h} \quad \frac{\Xi}{h} \quad \frac{\Omega}{h} \times 10 \]

\[ \frac{p}{p} \quad \frac{K}{K^{+}} \quad \frac{K}{K^{-}} \quad \frac{p}{p} \quad \frac{\Omega}{h} \times 50 \]

\[ s_{NN} = 130 \text{ GeV} \]

Model re-fit with all data
\[ T = 176 \text{ MeV}, \quad \mu_{b} = 41 \text{ MeV} \]

\[ s_{NN} = 200 \text{ GeV} \]

Model prediction for
\[ T = 177 \text{ MeV}, \quad \mu_{b} = 29 \text{ MeV} \]

Braun-Munzinger et al., PLB 518 (2001) 41
D. Magestro (updated July 22, 2002)
Anti Baryon to Baryon Ratio

STAR preliminary

Strangeness Content per Particle

STAR Au+Au 130 GeV
STAR Au+Au 200 GeV
STAR p+p 200 GeV via mixing analysis
nances in figures 2 and 3. These yields vary strongly with collision energy for the case of $\Theta^+(1540)$ in figure 2, but are rather constant in figure 3. Certainly our result differs greatly from expectations arising from an earlier study of the statistical model production of the $\Theta^+(1540)$ resonance [23] where the decisive variation of the particle yield with chemical potentials was not explored. Moreover, the hadron yields, presented in [23], did not include the contributions from decay of short lived hadron resonances. We checked that the relative particle yields shown in [23] for zero chemical potentials and varying temperature are mathematically correct, also as a cross check of our program.

In figure 2, we show from top to bottom: the relative yields $\Sigma^-(1670)/\Lambda(1500)$, $\Sigma^-(1670)/\Lambda(1680)$, $\Sigma^- (1776)/\Lambda(1862)$, for chemical nonequilibrium (solid line), quasi-equilibrium ($\gamma = 1$, dashed line) and chemical equilibrium (dotted line). The yields of $\Lambda$ used here include 50% weak interaction cascade from $\Xi^-$. The reason that the chemical nonequilibrium is leading to greater than equilibrium yields is that the
Resonances cannot be directly identified with the decay topology information due to their very short lifetime.

Example: Reconstructing $\Xi^*$

A $\Xi$ candidate is mixed with a $\Lambda$ to get a $\Xi^*(1385)$. The background is formed by mixing $\Xi$’s from one event with the $\Xi$ candidates from another event.

STAR measures charged particles with the Time Projection Chamber

This technique can be extended to identify Pentaquarks.