Identified Light and Strange Hadron Spectra at $\sqrt{s_{NN}} = 14.5$ GeV with STAR at RHIC BES I

DANIEL BRANDENBURG
RICE UNIVERSITY FOR THE STAR COLLABORATION

32ND WINTER WORKSHOP ON NUCLEAR DYNAMICS
MONDAY FEBRUARY 29TH
GAUDELOUPE, FRANCE
RHIC Beam Energy Scan (BES) Phase I

BES Phase I - Au+Au collisions at 7.7, 11.5, 14.5, 19.6, 27.0, and 39.0 GeV
- Search for Conjectured QCD critical point
- Search for 1st order phase transition
- Search for the onset of key QGP signatures
- $\sqrt{s_{NN}} = 14.5$ GeV
- Important measurement in the relatively large $\mu_B$ gap between 11.5 and 19.6 GeV

\[
\begin{array}{cccccccc}
\sqrt{s_{NN}} [\text{GeV}] & = & 7.7 & 11.5 & 14.5 & 19.6 & 27.0 & 39.0 \\
\sim\mu_B (\text{in central collisions}) [\text{MeV}] & = & 420 & 315 & 260 & 205 & 155 & 115 \\
\end{array}
\]

Onset of QGP Signatures

Nuclear Modification Factor $R_{CP}$

- High $p_T$ suppression $\equiv R_{CP} < 1.0$
  - Strong suppression observed in inclusive charged hadrons at top RHIC energies.
  - Attributed to energy loss in QGP
- Enhancement $\equiv R_{CP} > 1.0$
  - Cold nuclear matter effects, radial flow and coalescence.

$R_{CP}$ vs. $R_{AA}$

- $R_{CP}$ analysis can be done with a single dataset
- The pp baseline in $R_{AA}$ has no hot nuclear matter effects
- $R_{CP}$ is less sensitive than $R_{AA}$ to cold nuclear matter effects
- $R_{CP}$ has large correlated systematic uncertainty on the calculation of $N_{coll}$ in peripheral events
Inclusive Charged hadrons @ RHIC BES I

- Smooth transition in the intermediate to high $p_T$ range from suppression at $\sqrt{s_{NN}} = 39$ GeV to strong enhancement at $\sqrt{s_{NN}} = 7.7$ GeV
Onset of QGP Signatures

Baryon/Meson Ratio eg. \((\Lambda/K^0_S)\) and \((p/\pi)\)

- Baryon enhancement observed in Au+Au collisions at top RHIC energies
- Baryon/Meson ratio is sensitive to QGP formation through:
  - Parton recombination
  - Coalescence
- Baryon/Meson ratio is also sensitive to:
  - Radial flow
  - cold nuclear matter effects
**Time Projection Chamber (TPC)**
- Charged Particle Tracking
- Momentum reconstruction
- Particle identification from ionization energy loss ($dE/dx$)
- Pseudorapidity coverage $|\eta| < 1.0$

**Time Of Flight (TOF) Detector**
- Particle identification $1/\beta$
- Pseudorapidity coverage $|\eta| < 0.9$

The BBC detectors are used to trigger minimum bias collisions.
STAR Particle Identification @ STAR

Au+Au $\sqrt{s_{NN}} = 14.5$ GeV

TPC

TOF

Daniel Brandenburg | STAR
\[ \ln(\mathrm{d}E/\mathrm{d}x)_\pi = \] ideal \(\mathrm{d}E/\mathrm{d}x\) for pion from Bichsel

\[ \text{Au+Au} \sqrt{s_{NN}} = 14.5 \text{ GeV} \]

\[ \beta^{-1} \] - \[ \beta^{-1}_\pi \] = 

\[ \sqrt{1 + \left( \frac{m_\pi}{p} \right)^2} \]

\[ \text{Au+Au} \sqrt{s_{NN}} = 14.5 \text{ GeV} \]

Positive Tracks : \[ 0.8 < p_T \text{ [GeV/c]} < 0.9 \]
Particle Identification @ STAR

Positive Tracks: $0.8 < p_T [\text{GeV/c}] < 0.9$

Au+Au $\sqrt{s_{NN}} = 14.5$ GeV
Light Hadron Spectra @ Au+Au $\sqrt{s_{NN}}=14.5$ GeV

Centrality :
- $|y| < 0.25$
- $\pi^+/\pi^-$ and $p/\bar{p}$ are weak decay feed-down corrected

STAR Preliminary

$dN^2/(2\pi p_T d\Omega dy) (\text{GeV/c})^2$

$p_T$ [GeV/c]

$\pi^+$

$p$

$\pi^-$

$\bar{p}$
Topological Particle Identification

- Reconstruct secondary vertex from charged decay products
- Use topological cuts
- Extract yield by fitting to invariant mass peak

$$\Xi^{+(-)} \rightarrow \Lambda + \pi^{+(-)} \rightarrow (p + \pi^-) + \pi^{+(-)}$$

$$K_S^0 \rightarrow \pi^+ + \pi^-$$

$$\Lambda \rightarrow p + \pi^-$$

Au+Au
$$\sqrt{s_{NN}} = 14.5 \text{ GeV}$$
0 – 80% centrality
Full $p_T$ range
Strange Hadron Spectra @Au+Au $\sqrt{s_{NN}} = 14.5$ GeV

- Statistical Uncertainties only
- $|y| < 0.5$
- Fit with Levy function
Strange Hadron Spectra @Au+Au $\sqrt{s_{NN}} = 14.5$ GeV

- Statistical Uncertainties only
- $|y| < 0.5$
- $\Lambda$ spectra are weak decay feed-down corrected

- Fit with Boltzmann function
Strange Hadron Spectra @Au+Au $\sqrt{s_{NN}} = 14.5$ GeV

\[ \Xi^- \text{ spectra, } \text{Au}+\text{Au} \ 14.5 \text{ GeV} \]

\[ \Xi^+ \text{ spectra, } \text{Au}+\text{Au} \ 14.5 \text{ GeV} \]

- Statistical Uncertainties only
- $|y| < 0.5$

- Fit with Boltzmann function

STAR Preliminary
- Enhancement observed for protons
- Pions around unity for $p_T > 2.0$ GeV/c

$R_{CP}$ \((0\%-5\%)/(60\%-80\%)\)@ Au+Au $\sqrt{s_{NN}} = 14.5$

- Stat. uncertainties – vertical bars
- Syst. uncertainties - vertical boxes
- Bin width – horizontal box size
Enhancement observed for all species @ $p_T \sim 2.0$ in $\sqrt{S_{NN}} = 14.5$ GeV and below – key signature of QGP no longer visible at these energies

- $R_{CP}$ of different energies splits between $p_T \sim 1.5 - 3.0$ GeV/c (except in $\bar{p}$)
- $R_{CP}$ of $\sqrt{S_{NN}} = 7.7, 11.5, 19.6, 27, 39$ GeV shown previously at CPOD 2013
For $\sqrt{s_{NN}} = 14.5$ GeV and below:

- $R_{CP}$ is greater than or equal to 1 for $p_T > \sim 1.5$ GeV/c
- $R_{CP}$ particle type dependence becomes less significant
- Specifically baryon vs. meson difference at intermediate $p_T$ becomes less pronounced

$\Omega$ $R_{CP}$ in 19.6 and 27 GeV: ($0$-$10\%$) / ($40$-$60\%)$
Baryon/Meson Ratio: $p/\pi^+$ @ BES I

- Separation between centralities decreases with decreasing $\sqrt{S_{NN}}$
- “Double ratio” peak $p_T$ value changes with $\sqrt{S_{NN}}$
- “Double ratio” for $\sqrt{S_{NN}} = 7.7$ GeV turns over (0-5%) Central (Red) (60-80%) Peripheral (Yellow)

Centrality:
- 0-5%
- 5-10%
- 10-20%
- 20-40%
- 40-60%
- 60-80%

Baryon/Meson Ratio:
- $p/\pi^+$

STAR Preliminary

Daniel Brandenburg | STAR
Baryon/Meson Ratio: $\Lambda/K_S^0$ @ BES I

- Separation between centralities decreases with decreasing $\sqrt{S_{NN}}$
- "Double ratio" peak $p_T$ value changes with $\sqrt{S_{NN}}$
- "Double ratio" for $\sqrt{S_{NN}} = 7.7$ consistent with unity

Statistical Uncertainty Only

(0-5%) Central (Red)
(40-60%) Peripheral (Dark Blue)

Separation between centralities decreases with decreasing $\sqrt{S_{NN}}$

"Double ratio" peak $p_T$ value changes with $\sqrt{S_{NN}}$

"Double ratio" for $\sqrt{S_{NN}} = 7.7$ consistent with unity
Conclusions

Au+Au Collisions at $\sqrt{s_{NN}} = 14.5$ GeV

- **New** (at QM15) STAR results in the large $\mu_B$ gap between 11.5 and 19.6 GeV
- Completes the RHIC Beam Energy Scan Phase I

**Onset of QGP signatures**

- $R_{CP}$ from $\sqrt{s_{NN}} = 14.5$ GeV in both light and strange hadrons agrees with the trends from other BES I energies
- No evidence of suppression at intermediate $p_T$ in the $R_{CP}$ of all species for energies at and below $\sqrt{s_{NN}} = 14.5$ GeV
- Baryon/Meson ratios show evidence for change in collision dynamics for $\sqrt{s_{NN}}$ below 19.6 GeV

**Beam Energy Scan Phase II is needed for conclusive results**

- More statistics – push kinematic reach to higher $p_T$
- More energies below $\sqrt{s_{NN}} = 20$ GeV
THANK YOU
Baryon/Meson Ratio: $\bar{\Lambda}/K^0_S$ @ BES I

Statistical Uncertainty Only

Au+Au 39

Au+Au 27

Au+Au 19.6

Au+Au 14.5

Au+Au 11.5

Au+Au 7.7

(0-5%) Central (Red)
(40-60%) Peripheral (Dark Blue)
Baryon/Meson Ratio $p$-$\bar{p}$/$\pi^-$ @ BES I

Baryon/Meson Ratio $p$-$\bar{p}$/$\pi^-$ @ BES I

Most Central (Red)  
Most Peripheral (Yellow)  

Centrality:
- 0-5%  
- 5-10%  
- 10-20%  
- 20-40%  
- 40-60%  
- 60-80%  

STAR Preliminary

Ratio $p$/$\pi^-$

0-5% central / 60-80% central

Daniel Brandenburg | STAR

23
Extract yields by simultaneously fitting the dE/dx and 1/β distributions.

\[ 0.9 < p_T \text{ [GeV/c]} < 1.0 \]

Combined TPC + TOF for a single \( p_T \) bin

Positive Tracks: \( 0.9 < p_T \text{ [GeV/c]} < 1.0 \)

- Grey bands show +/- 2σ around each particle peak
- The pion and kaon peaks are merged in dE/dx but are still well separated in 1/β
- The black band is the total fit result