Selected Results from STAR Beam Energy Scan

CERN EP Seminar

Yue-Hang Leung
University of Heidelberg
9th May, 2023

Outline

• Introduction
• STAR BES-II
  • Particle Production
  • Collective Flow
  • Higher Order Cumulants
  • Thermal Dileptons
  • Light Nuclei and Hypernuclei
  • Global Polarization and Spin Alignment
• Summary
Relativistic Heavy Ion Collider (RHIC)

- Located at Brookhaven National Laboratory
- STAR+sPHENIX (currently running)
- Collision species (p+p, p+Au, Au+Au, ...)
- Collision energies ($\sqrt{s_{NN}} = 3-200$ GeV for Au+Au)
The STAR (Solenoidal Tracker At RHIC) Detector

- Solenoidal magnet with 0.5T uniform field
- Time projection chamber (TPC)
- Time-of-flight (TOF) detector
- Electromagnetic calorimeters

- iTPC, EPD & eTOF upgrades completed
  - All are in data-taking for BES-II program
  - Larger acceptance
  - Excellent PID with uniform acceptance
Beam Energy Scan (BES)

- **BES-I (2009-2011)**
  - Au+Au collisions $\sqrt{s_{\text{NN}}} = 7.7-62$ GeV
  - Main objectives:
    - Search for onset of deconfinement
    - Search for critical end point

- **BES-II (2018-2021)**
  - High statistics Au+Au collisions $\sqrt{s_{\text{NN}}} = 3-54.4$ GeV
  - Fixed target (FXT) collisions extend energy reach down to $\sqrt{s_{\text{NN}}} = 3$ GeV
    - Search for possible formation and investigate properties of dense baryonic matter
• **QGP formation at top RHIC energies**
  \[ \sqrt{s_{NN}} = 200 \text{ GeV}, \mu_B = 20 \text{ MeV} \]

  • Probe characteristics with heavy flavor, strangeness, jets etc.


\[ \mu_B = 20 \text{ MeV} \]

\[ \mu_B / T = 2 \]

**Chemical freeze-out**

**Gas-Liquid**

**Baryonic Chemical Potential** \( \mu_B (\text{MeV}) \)

**Quark-Gluon Plasma**

**Hadron Gas**

**LHC SPS AGS SIS**

\[ \begin{align*}
0 & \quad 500 & \quad 1000 & \quad 1500 \\
0 & \quad 78 & \quad 156 & \quad \text{RHIC RHIC FXT FAIR NICA}
\end{align*} \]

**STAR, PRL126,9,092301(2021)**
Probing the QCD Phase Diagram

- QGP formation at top RHIC energies
  $\sqrt{s_{NN}} = 200$ GeV, $\mu_B = 20$ MeV
  - Probe characteristics with heavy flavor, strangeness, jets etc.

- Intermediate $\mu_B$ region: STAR collider mode
  $\sqrt{s_{NN}} = 7.7-27$ GeV, $\mu_B = 420 - 200$ MeV
  - Probe onset of deconfinement
  - Search for critical phenomena

\[ \mu_B / T = 2 \]

Chemical freeze-out

Gas-Liquid

Baryonic Chemical Potential $\mu_B$ (MeV)

Quark-Gluon Plasma

Hadron Gas

Temperature $T$ (MeV)

LHC SPS AGS SIS

0 500 1000 1500

RHIC RHIC FXT

FAIR

NICA

\[ \sqrt{s_{NN}} = 200 \text{ GeV}, \mu_B = 20 \text{ MeV} \]

\[ \sqrt{s_{NN}} = 7.7-27 \text{ GeV}, \mu_B = 420 - 200 \text{ MeV} \]

STAR, PRL126,9,092301(2021)
Probing the QCD Phase Diagram

- QGP formation at top RHIC energies
  $\sqrt{s_{NN}} = 200 \text{ GeV}, \mu_B = 20 \text{ MeV}$
  - Probe characteristics with heavy flavor, strangeness, jets etc.

- Intermediate $\mu_B$ region: STAR collider mode
  $\sqrt{s_{NN}} = 7.7-27 \text{ GeV}, \mu_B = 420 - 200 \text{ MeV}$
  - Probe onset of deconfinement
  - Search for critical phenomena

- High $\mu_B$ region: STAR fixed-target (FXT)
  $\sqrt{s_{NN}} = 3.0-13.7 \text{ GeV}, \mu_B = 750 - 280 \text{ MeV}$
  - Nature of produced medium ( hadronic vs partonic? )
  - Investigate properties of dense baryonic matter
Probing the QCD Phase Diagram

Particle production

Collective flow

Global polarization

QCD Phase Diagram

- Light and strange flavor
- Nuclei
- Lepton pairs
- NN, YN interactions, density fluctuations (?)
- Number Fluctuations
- Temperature
- Early time dynamics
- Global spin alignment
- Vorticity, B-field
- Freezeout properties
- (?)
• 260M events collected in 2018
• Good mid-rapidity coverage for most particles
• Nuclei up to A=6, hypernuclei up to A=4
Baryon Stopping at 3 GeV

The stopping, $\delta y$, is defined as the shift of the participant proton peak from beam rapidity.

Baryon stopping $\rightarrow$ High baryon density
Kinematic Freezeout Properties at 3 GeV

- Extract common kinetic freeze-out temperature $T_{\text{kin}}$ and average transverse radial flow velocity $\beta$ through combined Blast Wave fit

\[
\frac{1}{2\pi p_T} \frac{d^3N}{dp_T dy} \propto \int_0^R \frac{\rho(r)}{T_{\text{kin}}} K_1(m_T \rho(r)) \frac{m_T \rho(r)}{T_{\text{kin}}}
\]

- At 3 GeV, $T_{\text{ch}} \sim 80\text{MeV}$, similar with $T_{\text{kin}}$


Few hadronic interactions b/w chemical and kinetic freeze-out at 3 GeV
Strangeness Production at 3 GeV

- Strange hadrons (Λ, Ks, φ, Ξ⁻) reconstructed via hadronic decay channels
- CE is mandatory to describe φ/K⁻ and φ/Ξ⁻ at 3 GeV


Strong effect from canonical suppression
**Strangeness Production at 3 GeV**

- Strange hadrons ($\Lambda$, $K$, $\phi$, $\Xi^-$) reconstructed via hadronic decay channels
- CE is mandatory to describe $\phi/K$ and $\phi/\Xi^-$ at 3 GeV

**In QGP:**

\[ gg \rightarrow s \bar{s} \]

**In hadronic matter:**

\[ NN \rightarrow N\Lambda K \]

\[ NN \rightarrow NN\phi \]

---

**Counts (per 1 MeV/c^2)\times10^3**

- $0.4 < p_T < 1.6$ GeV/c
- $0.5 < p_T < 2.0$ GeV/c

**Counts (per 1 MeV/c^2)**

- $M_{K^-}$ (GeV/c^2)
- $M_{\Lambda}$ (GeV/c^2)

**Particle Rapidity $y_{cm}$**

- $P_{1}$ (GeV/c)

**Collision Energy $\sqrt{s_{NN}}$ (GeV)**

- Strong effect from canonical suppression

---

**Phys. Lett. B 831 (2022) 137152**
Directed and Elliptic Flow

- $v_1$ "directed flow" characterizes sideward flow of particles

**Compression stage** $\rightarrow$ +ve $v_1$

**Expansion stage** $\rightarrow$ -ve $v_1$

$\frac{dN}{d\phi} \sim 1 + \sum_{n=1}^{\infty} 2v_n \cos(n(\phi - \Psi))$

- $v_2$ "elliptic flow" caused by pressure gradients from almond shaped interaction region

A. Ohnishi, HYP2022

$v_1$ and $v_2$ are very sensitive to the stiffness of nuclear EoS in the high baryon density region
Energy Dependence of Collective Flow

• Significant +ve $d v_1 / dy$ observed at 3 GeV

• -ve $v_2$ observed at 3 GeV

• Similar to expectations from hadronic transport models with baryon-mean-field

Suggests that the dominant degrees of freedom at 3 GeV are the interacting baryons


Yue Hang Leung - CERN EP Seminar

15
Disappearance of NCQ scaling at 3 GeV

- The number of constituent quark (NCQ) scaling for $v_2$ holds at high energies, consistent with partonic collectivity
  - Scaling deteriorates as energy decreases
- Disappearance of NCQ scaling at 3 GeV

Suggests that hadronic matter is predominantly produced in 3 GeV Au+Au collisions
Scaling of $v_2$ within (10%)20% for (anti-)particles
Scaling of $v_3$ within (15%)30% for (anti-)particles
(except at low $p_T$ for $\bar{\Lambda}$ and $\bar{p}$)

Disappearance of partonic collectivity: a gradual process?
Higher Order Cumulants

- Cumulants of conserved quantities (Q, B, S) characterize event-by-event fluctuations
  - Sensitive to the correlation length, which diverges at CP
- Non-monotonic behavior of $\kappa \sigma^2$ of net protons proposed as signature of CP

Cumulants of conserved quantities:

- $C_1 = <N>$
- $C_2 = <(\delta N)^2>$
- $C_3 = <(\delta N)^3>$
- $C_4 = <(\delta N)^4> - 3 <(\delta N)^2>^2$
- $C_5 = <(\delta N)^5> - 5 <(\delta N)^3> <(\delta N)^2>$
- $C_6 = <(\delta N)^6> - 15 <(\delta N)^4> <(\delta N)^2> - 10 <(\delta N)^3>^2 + 30 <(\delta N)^2>^3$

Cumulants relation:

\[ \kappa \sigma^2 = \frac{C_4}{C_2} \]

M. A. Stephanov, PRL 107,052301(2011)

http://www.msm.cam.ac.uk
Non-monotonicity observed with 3.1\(\sigma\) significance from BES-I data

Phys.Rev.Lett. 126 (2021) 9, 092301
Net Proton Kurtosis from BES-II

- New 3 GeV measurement consistent with hadronic transport model UrQMD

- Suppression of $C_4/C_2$ is consistent with fluctuations driven by baryon number conservation

Hadronic interaction dominated region in central Au+Au collisions at 3 GeV
5th and 6th Order Cumulants

(a) $C_4/C_2$

(b) $C_5/C_1$

(c) $C_6/C_2$

- $C_6/C_2$ at 0-40% seems to be increasingly -ve from 200 to 7.7 GeV

- -ve $C_6/C_2$ predicted by LQCD which includes crossover quark-hadron transition

+ve $C_6/C_2$ at 50-60% 3 GeV, similar with UrQMD

LQCD predicts the ordering $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$

A reverse ordering seen at 3 GeV

Same trend from UrQMD

Suggests matter is predominantly hadronic at 3 GeV
Measuring the Temperature with Thermal Dileptons

Thermal dileptons can access the hot QCD medium at both QGP phase and hadronic phase
Cocktail Method

STAR Au+Au $\sqrt{s_{NN}} = 54.4$ GeV (0-80%)

$\pi^0 \rightarrow \gamma e^+ e^- \pi^0 \rightarrow ee$  
$\eta \rightarrow \gamma e^+ e^-$  
$\eta' \rightarrow \gamma e^+ e^-$  
$\phi \rightarrow e^+ e^- \phi \rightarrow \gamma e^+ e^-$  
$J/\psi \rightarrow ee$  
$c\bar{c} \rightarrow ee$  
$DY \rightarrow ee$  
Cocktail Sum

- Data

$M_{ee}(\text{GeV}/c^2)$

$\frac{dN}{dM} (c^2) (\text{GeV})$

"Excess" = "Inclusive" - "Cocktail Sum"

Inclusive lepton pairs

Signals of interest ("Excess")
- In-medium $\rho$ decays
- QGP radiation

Physical backgrounds ("Cocktail")
- Low mass mesons ($\pi^0$, $\eta$, $\eta'$, $\omega$, $\phi$)
  $\rho$ excluded
- Open heavy flavor
- Quarkonia
- Drell-Yan

• STAR Preliminary

\[ 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \]

$5 \times 10^{-5}$  $1 \times 10^{-3}$  $1 \times 10^{-1}$  $10^{-3}$  $10^{-5}$  $10^{-7}$  $10^{-9}$  $10^{-11}$  $10^{-13}$
The Low Mass Region

- In-medium ρ dominated

In-medium ρ dominated produced from a “similar hot bath” in 27/54.4 GeV Au+Au and 17.3 GeV In+In

"Excess" = "Inclusive" - "Cocktail Sum"
The Intermediate Mass Region

STAR Au+Au \( \sqrt{s_{NN}} = 54.4\) GeV (0-80%)

- \( \pi^0 \rightarrow \gamma\pi^0 \rightarrow \gamma\gamma \)
- \( \eta \rightarrow \gamma\eta \)
- \( \phi \rightarrow \gamma\pi^0 \rightarrow \eta\pi^0 \)
- \( \eta' \rightarrow \gamma\pi^0 \rightarrow \eta\pi^0 \)
- \( c\bar{c} \rightarrow \gamma\pi^0 \rightarrow \eta\pi^0 \)

**Data**

- \( dN/dM (c^2) = 54.4 \) GeV (0-80%)

**STAR Preliminary**

**Cocktail Sum**

- \( dN/dM (c^2) = 20 \) MeV/c

**IMR**

- \( \eta/dch/dM/dy)/(dN_{ch}) \)

*Excess* = "Inclusive" - "Cocktail Sum"

- T_{IMR} from STAR data: \( \sim 320\) MeV

- T_{IMR} > T_{PC} (156 MeV): consistent with the emission source dominantly from QGP
No clear centrality dependence of the temperatures at IMR and LMR
Temperature Measurement of the QGP

\[ T_{LMR} \approx T_{PC} \approx T_{ch} \]

LMR dileptons emitted from hadronic phase around phase transition

\[ T_{IMR} > T_{PC} \]

IMR dileptons emitted from QGP phase
Nuclei and Hypernuclei

- Nuclei and hypernuclei yields have been suggested to be sensitive to critical fluctuations and the onset of deconfinement.

- Assume coalescence formation of nuclei

\[ \frac{t \times p}{d^2} \]

\[
\frac{^3\Lambda H}{^3\text{He} \times \frac{\Lambda}{p}}
\]

Sensitive to neutron density fluctuations

Sensitive to baryon-strangeness correlations

Need to first understand light nuclei production mechanisms

Light Nuclei Production Models

Thermal models

- Nuclei are formed earlier at the hadronic chemical freeze-out
- Thermal and chemical equilibrium ($T, \mu_B$)

Coalescence models

- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

Dynamical models

$\pi d \leftrightarrow \pi np$
$\pi t \leftrightarrow \pi npn$
$\pi^3\text{He} \leftrightarrow \pi npn$

- Disintegration cross-sections are large

**Light Nuclei Production Models**

**Thermal models**
- Nuclei are formed earlier at the hadronic chemical freeze-out
- Thermal and chemical equilibrium \((T, \mu_B)\)

**Coalescence models**
- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

**Dynamical models**
- \(\pi d \leftrightarrow \pi np\)
- \(\pi t \leftrightarrow \pi npn p\)
- \(\pi^3 He \leftrightarrow \pi np pp\)
- Disintegration cross-sections are large

---


Nuclei are formed **FIRST** then resonances decay into nucleons

Resonances decay into nucleons **FIRST** then nucleons coalescence into nuclei
• d/p fairly well described by thermal model, but t/p is overestimated

• Effects from hadronic re-scattering?

arXiv:2207.12532

arXiv:2209.08058 (accepted by PRL)
Nuclear Compound Yield Ratio

• Light nuclei yield ratio deviates strongly from thermal model from $\sqrt{s_{NN}} = 7.7-200$ GeV

Yield ratio exhibits approx. scaling behavior with $dN_{ch}/d\eta$;

Described by coalescence

arXiv:2209.08058 (accepted by PRL)
In a coalescence picture, compound yield ratio is sensitive to baryon density fluctuations.

In the vicinity of the critical point, density fluctuations become larger.

In central collisions, non-monotonic behavior around 19.6 and 27 GeV observed with a combined significance of 4.1σ.

Enhancements decreases with decreasing p_T acceptance.
Hypernuclei

- Strangeness carrying nuclei which decays weakly
- Production yields/flow:
  
  Provides another deg. of freedom to study production mechanisms
- Intrinsic properties (e.g.: $\tau$, $B_\Lambda$)
  
  Constrains the $\Lambda N$ interaction $\rightarrow$ EoS neutron stars
- Search for exotic states

Hypernuclei Lifetime, Branching Ratio and Binding Energy

BES-II data improves our understanding of hypernuclei structure

Phys. Rev. Lett. 128 (2022) 20, 202301

ΔB₃(0⁺) = 0

Theoretical calculations

Previous experimental results

This work

ΔB₃(0⁺) = 0


ΔB₃(0⁺) (keV)

0 50 100 150 200 250 300 350 400

0.1 0.2 0.3 0.4 0.5 0.6

3H Hypernuclei Lifetime, Branching Ratio and Binding Energy

3H

Λ

Δ

A. Gal (2022)

4H

Λ

Δ

HADES preliminary

JPARC (2023)

STAR (2022)

HyphI (2013)

ALICE (2019)

STAR (2018)

ALICE (2016)

HyphI (2013)

STAR (2010)

G. Keyes et al (1973)

G. Keyes et al (1970)

G. Bohm et al (1970)

Phillips, Schneps (1969)

G. Keyes et al (1968)

Prem, Steinberg (1964)

S. Avramenko et al (1992)

Y. W. Kang et al (1965)

Prem, Steinberg (1964)

N. Crayton et al (1962)


ΔB₃(0⁺) (keV)

0 50 100 150 200 250 300 350 400

0.1 0.2 0.3 0.4 0.5 0.6

3H

Λ

Δ

A. Gal (2022)

4H

Λ

Δ

HADES preliminary

JPARC (2023)

STAR (2022)

HyphI (2013)

ALICE (2019)

STAR (2018)

ALICE (2016)

HyphI (2013)

STAR (2010)

G. Keyes et al (1973)

G. Keyes et al (1970)

G. Bohm et al (1970)

Phillips, Schneps (1969)

G. Keyes et al (1968)

Prem, Steinberg (1964)

S. Avramenko et al (1992)

Y. W. Kang et al (1965)

Prem, Steinberg (1964)

N. Crayton et al (1962)


ΔB₃(0⁺) (keV)

0 50 100 150 200 250 300 350 400

0.1 0.2 0.3 0.4 0.5 0.6

3H

Λ

Δ

A. Gal (2022)

4H

Λ

Δ

HADES preliminary

JPARC (2023)

STAR (2022)

HyphI (2013)

ALICE (2019)

STAR (2018)

ALICE (2016)

HyphI (2013)

STAR (2010)

G. Keyes et al (1973)

G. Keyes et al (1970)

G. Bohm et al (1970)

Phillips, Schneps (1969)

G. Keyes et al (1968)

Prem, Steinberg (1964)

S. Avramenko et al (1992)

Y. W. Kang et al (1965)

Prem, Steinberg (1964)

N. Crayton et al (1962)
Thermal model comparisons

- Similar to tritons, hypertritons are overestimated by the thermal model

- Effects from hadronic re-scattering? [arXiv:2207.12532]

- Suppression due to large size? [Phys.Rev.C 107 (2023)]
Strangeness population factor $S_3$ as a Probe for Medium Properties?

- Increasing trend of $S_3$ originally proposed as a signature of onset of deconfinement
  - Model is not quantitatively compatible with data
    $$S_3 = \frac{\Lambda}{p} \left( \frac{\Lambda}{3\text{He}} \right)$$

- Thermal-FIST also suggest increasing trend

- Unstable nuclei breakup enhance $^3\text{He}$ yields?

- Coalescence+transport also suggest increasing trend
  - Suppression of $\Lambda/^3\text{He}$ due to large size

**Assuming B.R.($^3\Lambda\rightarrow^3\text{He} + \pi$) = 25%**

**Data**
- Au+Au 0-40% ($p_t/A>0.4$ GeV/$c$)
- E864 Au+Pt 0-10%
- STAR Au+Au 0-80%
- ALICE Pb+Pb 0-10%

**Models**
- Coal. (Default AMPT)
- Coal. (String Melting AMPT)
- Coal. (UrQMD, $\Delta r=9.5$fm)
- Coal. (UrQMD, $\Delta r=4.3$fm)
- Thermal-FIST
- Thermal Model (GSI)
Nuclei and Hypernuclei Directed Flow

- $v_1$ slope of light nuclei follow mass number scaling at 3 GeV

- First observation of hypernuclei collectivity $v_1$ in HI collisions

- Hypernuclei $v_1$ slope also follows mass number scaling, consistent with coalescence models

Results qualitatively consistent with (hyper)nuclei production from coalescence

Au+Au Collisions at RHIC
- Energy: $\sqrt{s_{NN}} = 3$ GeV
- Centrality: 5-40%

Particle Mass (GeV/c²) vs. $dN/dy|_{y=0}$

- $^3$He, $^4$He, $^3$ΛH, $^4$ΛH

Data vs. Model:
- UrQMD
- JAM

Hyper-nuclei vs. Light-nuclei

arXiv:2211.16981 (accepted by PRL)
Global Hadron Polarization

- $\Lambda$ global polarization: evidence for the most vortical fluid

$$\bar{P}_H \equiv \langle \vec{P}_H \cdot \hat{J}_{\text{sys}} \rangle = \frac{8}{\pi \alpha_H} \frac{\cos \left( \phi^*_p - \phi^*_f \right)}{R^{(1)}_{\text{EP}}}$$

Global polarization is the alignment between:

- Spin of emitted particles
- Orbital angular momentum (OAM) of a non-central collision

Decay proton tends to be emitted along the spin direction of the parent $\Lambda$

- Increasing trend of $\bar{P}_H$ persists at 3 GeV
- May imply that hadronic system evolves hydrodynamically

Preliminary

- STAR, 20-50%, Au+Au, $0.5<y<2$
- STAR, 20-50%, Au+Au, $|y|<1$
- HADES, 10-40%, Au+Au, $-0.5<y<0.3$
- HADES, 10-40%, Ag+Ag, $-0.5<y<0.3$
- STAR, 20-50%, Au+Au, $|y|<1$, 2021
- STAR, 20-50%, Au+Au, $|y|<1$, '17-'18
- ALICE, 15-50%, Pb+Pb, $|y|<0.5$
Global Spin Alignment

Nature 614 (2023) 7947, 244-248

\[
\frac{dN}{d(\cos \theta^*)} \propto (1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2 \theta^*
\]

- \( \rho_{00} = 1/3 \) -> 3 spin states have equal probability to be occupied
- \( \rho_{00} \neq 1/3 \) -> spin alignment

- OAM also influences production of vector mesons such as \( \phi(1020) \) and \( K^*(892) \)
Energy Dependence of Global Spin Alignment

Observed spin-alignment for φ cannot be explained by conventional mechanisms

- Model with a connection to strong force fields accommodates the data
  
  \[ G_s^{(y)} = 4.64 \pm 0.73 \text{ m}^4 \]

- Decreasing trend is explained by \( 1/T^2_{\text{eff}} \) dependence originating from the polarization of quarks in the φ-meson field

- Absence of spin-alignment for K*0 could be due to in-medium effects/different quark content

\[ \phi \quad (|y| < 1.0 \text{ & } 1.2 < p_T < 5.4 \text{ GeV}/c) \]

\[ K^{*0} \quad (|y| < 1.0 \text{ & } 1.0 < p_T < 5.0 \text{ GeV}/c) \]

filled: STAR (Au+Au & 20% - 60% Centrality)
open: ALICE (Pb+Pb & 10% - 50% Centrality)
Results on strangeness production, collective flow, global polarization, net-proton cumulants are compatible with a predominantly hadronic medium formed in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions.
Summary

- Results on strangeness production, collective flow, global polarization, net-proton cumulants are compatible with a predominantly hadronic medium formed in $\sqrt{s_{\text{NN}}} = 3$ GeV Au+Au collisions

- No concrete conclusions on search for critical point
  - If exist, it should lie b/w 3 and 27 GeV
  - FXT (3-7.7 GeV) and high statistics COL(7.7-27 GeV) data are crucial for further investigations
Summary

- Results on strangeness production, collective flow, global polarization, net-proton cumulants are compatible with a predominantly hadronic medium formed in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions.

- No concrete conclusions on search for critical point
  - If exist, it should lie b/w 3 and 27 GeV
  FXT (3-7.7 GeV) and high statistics COL(7.7-27 GeV) data are crucial for further investigations

- New probes to diagnose the QCD medium: (hyper)nuclei, spin alignment, etc.

Theoretical developments and experimental efforts necessary to understand such probes
Outlook

- **iTPC and eTOF upgrades in 2019**
  
  *Crucial to maintain mid-rapidity coverage b/w 3.2-4.5 GeV*

- **High statistics data from 3-27 GeV**
  
  *Including 2B events at 3 GeV taken in 2021*

---

Double-Λ hypernuclei: $^4\Lambda\Lambda \text{H}$

Neutron-rich hypernuclei: $^6\Lambda \text{H}$

Unstable nuclei: $^4\text{Li} \rightarrow ^3\text{He} + \text{p}$

---

BES-II FXT data: fill the gap b/w 3-7.7 GeV

BES-II COL data: with 10-20X statistics to confirm the non-monotonicity

---

Measure the magnetic field from $P_\Lambda - P_\pi$ splitting?
Many more BES results to come!
Stay tuned, and

Thank you for listening!
Backup slides follow
S₃ and S₄ at 3 GeV

- **Strangeness population factor:**

\[
S_A = \frac{AΛH}{AHe} \times \frac{Λ}{p} 
\]

- **Differential analogue** = ratio of coalescence parameters for hypernuclei and nuclei

\[
\frac{AΛH(A \times p_T)}{AHe(A \times p_T) \times \frac{Λ}{p}(p_T)} = \frac{B_A(ΛH)(p_T)}{B_A(AHe)(p_T)}
\]

- **Bₐ** of light nuclei follows similar trends in pₜ, rapidity, centrality

**Mechanics behind formation for hypernuclei and nuclei are similar**
Net Proton Kurtosis from BES-II

- New 3 GeV measurement consistent with hadronic transport model UrQMD
- Suppression of $C_4/C_2$ is consistent with fluctuations driven by baryon number conservation

**Hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV**

BES-II FXT data: fill the gap b/w 3-7.7 GeV

BES-II COL data: with 10-20X statistics to confirm the non-monotonicity

Phys.Rev.Lett. 128 (2022) 20, 202303
Light Nuclei Ratios in Central Collisions

- Light nuclei yields, when scaled by spin degeneracy, follow exponential scaling very well.

Trend is not expected for thermal models (due to feed-down contributions to proton from baryonic resonances).
Energy Dependence of Kinetic and Chemical Freeze-out
Probing the Magnetic-Field

- Vorticity gives +ve contribution to $P_\Lambda$ and $P_{\bar{\Lambda}}$
  
  *Quarks and anti-quarks’ spins are aligned with the angular momentum.*

- Magnetic field enhances $P_{\bar{\Lambda}}$ but suppresses $P_\Lambda$
  
  *Quarks and anti-quarks get aligned in the opposite direction due to opposite signs of their magnetic moments.*

- Magnetic field in QGP can be probed by $P_{\bar{\Lambda}} - P_\Lambda$

**No splitting observed at 54.5 GeV**

Await results from high statistics data at 19.6 and 27 GeV from BES-II
Hypernuclei and light nuclei ratio at 3 GeV

- Thermal/coalescence models predict approx. exponential dependence of yields/(2J+1) vs A

- $^4_AH$ lies a factor of 6 above exponential fit to $(\Lambda, {}^3_AH, {}^4_AH)$
Excited Hypernuclei States?

• Non-monotonic behavior in light-to hyper-nuclei ratio vs A observed

• Thermal model calculations including excited $^4_Λ^*H$ feed-down show a similar trend

Data support creation of excited hypernuclei from heavy-ion collisions
Energy Dependence of Hypernuclei Yields

- $^3\Lambda H$ yield at mid-rapidity increases from 2.76 TeV to 3 GeV

- Driven by increase in baryon stopping at low energies

![Graph showing energy dependence of hypernuclei yields](image)
Light Nuclei Production Models

Thermal models
- Nuclei are formed earlier at the hadronic chemical freeze-out
- Thermal and chemical equilibrium ($T, \mu_B$)

Coalescence models
- Nuclei are formed at late stages of collision
- Nucleons bind into nuclei if they are close in phase space

Dynamical models
- Disintegration cross-sections are large

π$d$ ↔ πnp
π$t$ ↔ πnnp
π$^3$He ↔ πnpp

Prob. of formation may depend on wave-function

Probe structure of (hyper)nuclei with production yields?

Anti-nuclei yield detected in space

Implications for dark matter searches?