# Production of light nuclei in Au+Au collisions from STAR BES-II

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10th Asian Triangle Heavy-Ion Conference - ATHIC 2025

Supported in part by
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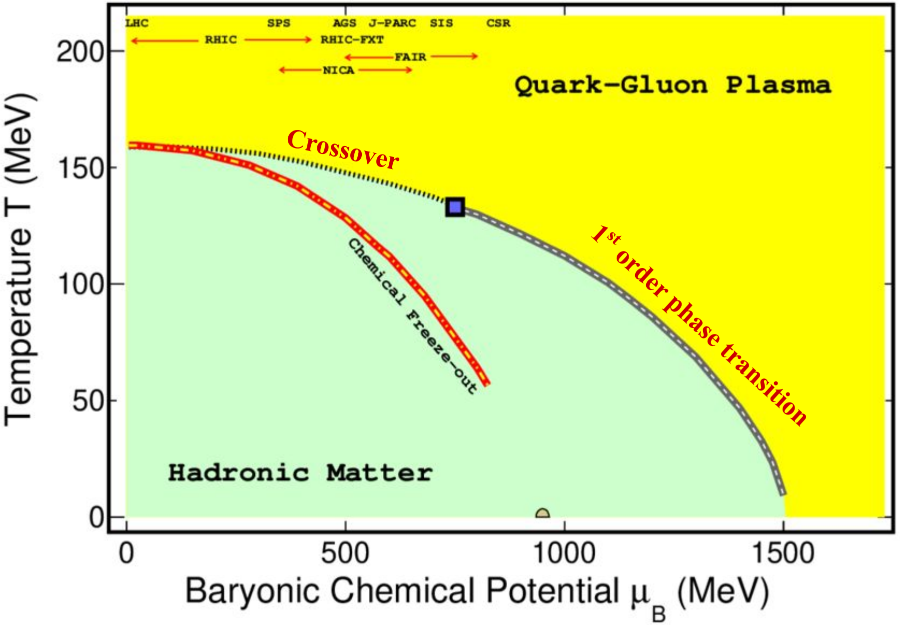
ENERGY

# Outline

- Introduction
- The STAR experiment
- Analysis details
- Results:
  - Transverse momentum ($p_T$) spectra
  - Yield and mean $p_T$ of light nuclei
  - Coalescence parameters ($B_A$)
- Summary

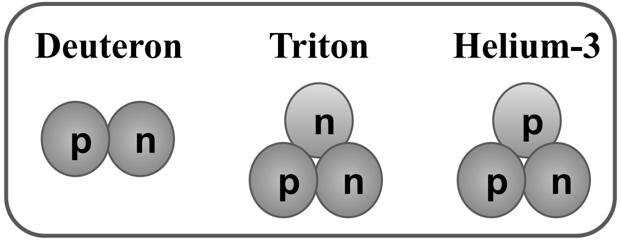



Progress in Particle and Nuclear Physics **125**, 103960 (2022)

- Goal of Beam Energy Scan (BES) program is to explore **QCD phase diagram**
  1. **QGP** to **hadronic matter** phase transition ➡ crossover at low $\mu_B$ & $1^{st}$ order at higher $\mu_B$
  2. Search for **critical point**
  3. **Turn off** of QGP signatures

## Why light nuclei?

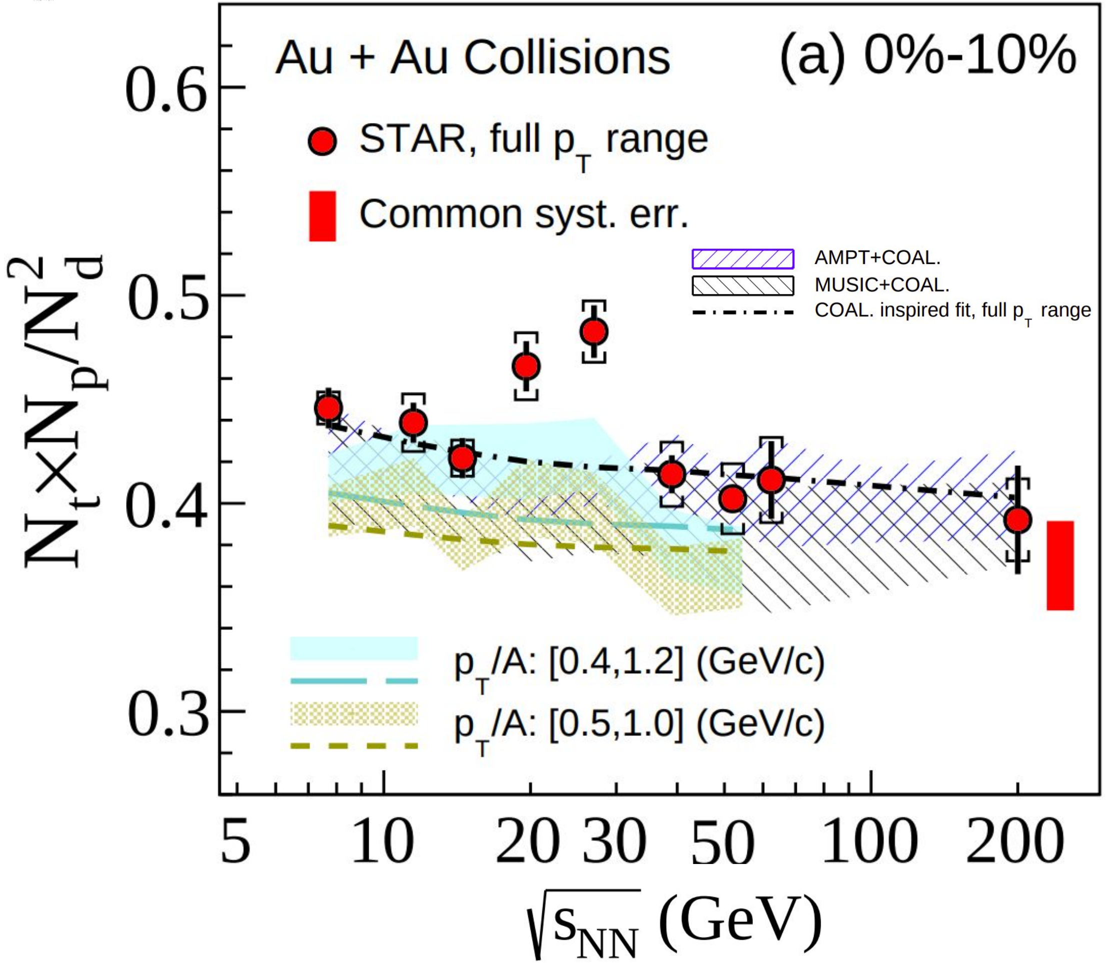
- Understand the production mechanism of light nuclei
- Light nuclei may carry information about the local baryon density fluctuations ➡ can be used as a tool to probe the QCD phase diagram




Choice of observable: compound light nuclei ratio ➡ $\frac{N_t \times N_p}{N_d^2} \propto (1 + \Delta n)$

$\Delta n$ : Neutron fluctuation density

PLB **774** 103-107 (2017)
PLB **781** 499-504 (2018)
EPJA **57** 11313 (2021)

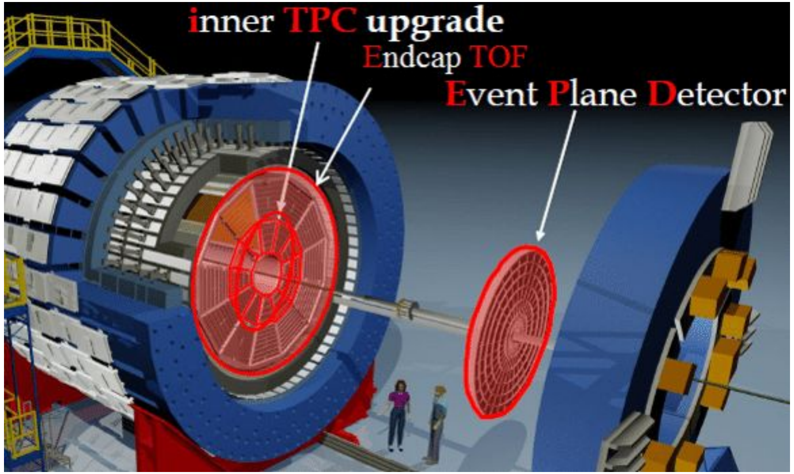


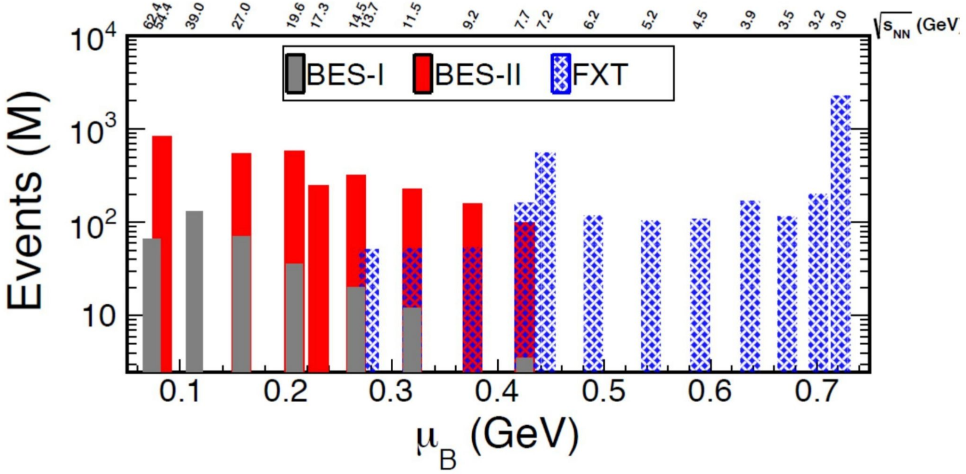

**Beam Energy Scan program (BES-I) collider mode:**

**7.7, 11.5, 14.5, 19.6, 27, 39, 62.4, and 200 GeV**

- ➢ Total deviation from coalescence baseline is 4.2 sigma (19.6 and 27 GeV)
- ➢ Light nuclei yields and ratios could provide a probe to search for signature of critical phenomena

STAR, PRL **130** 202301 (2023)




- ➢ Particle identification is done using:
  - *<dE/dx>* information from **Time Projection Chamber (TPC)**
  - $m^2$ information from **Time of Flight (TOF)**
- ➢ BES-II upgrades:
  - iTPC & eTOF: Large pseudorapidity coverage (-1.5 < η < 1.5)
  - Better momentum and *dE/dx* resolution

JPCS **742** 012022 (2016)

**BES-I energies:**

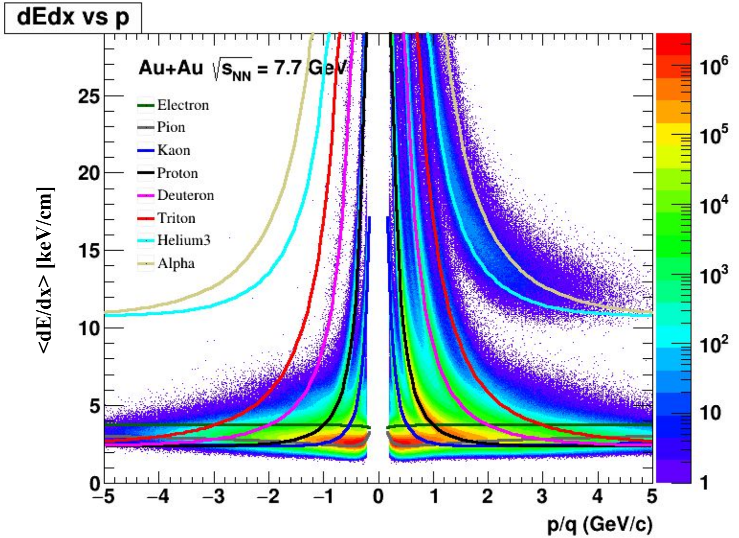
$\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, and 62.4 GeV

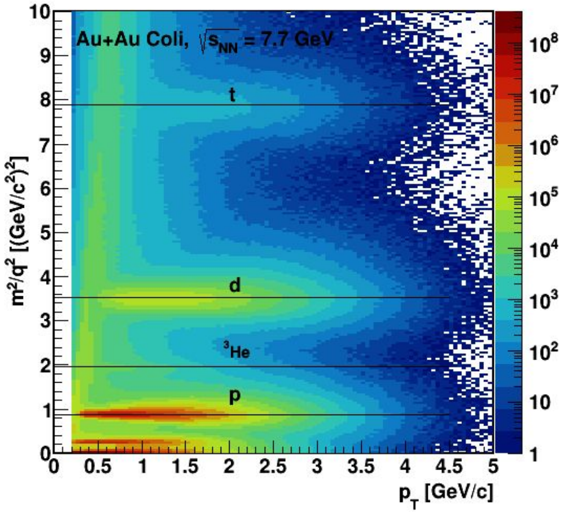
**BES-II energies:**

$\sqrt{s_{NN}}$ = **7.7**, 9.2, 11.5, **14.6** ,17.3, **19.6, 27**, and **54.4** GeV

$\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7, 9.2, 11.5, and 13.7 GeV (**FXT**)

# Light nuclei identification using TPC and TOF




- **PID** using **dE/dx** information from **TPC** at low $p_T$ (0.5 - 1.0 GeV/c)

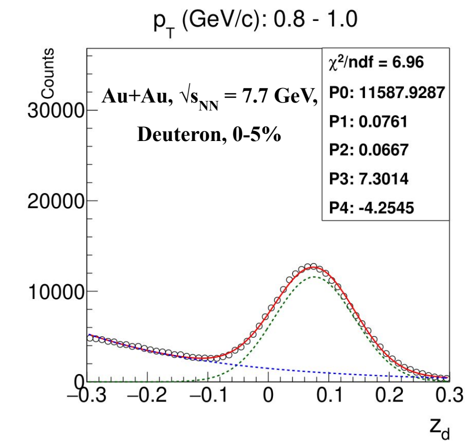
$$Z = ln\left(\frac{<dE/dx>}{<dE/dx>_{theory}}\right)$$

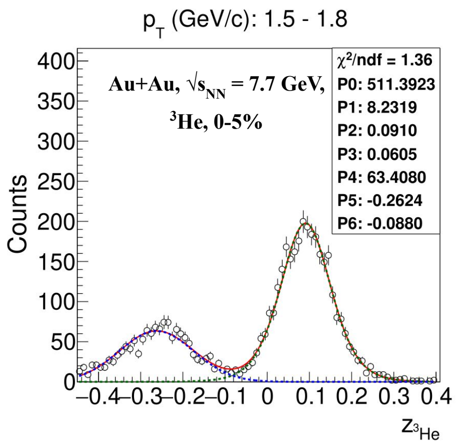
- **PID** using $\mathbf{m^2/q^2}$ information from **TOF** at intermediate $p_T$ (1.0 - 5.0 GeV/c)

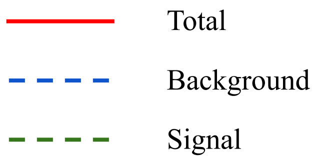
$$\frac{m^2}{q^2} = \frac{p^2}{q^2}(1/\beta^2 - 1)$$

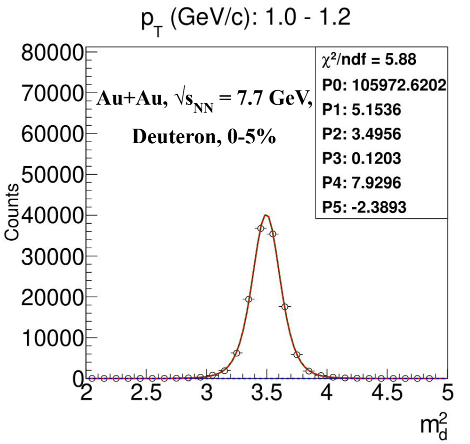
NIMA **562** 154-197 (2006)

# Signal extraction using TPC and TOF



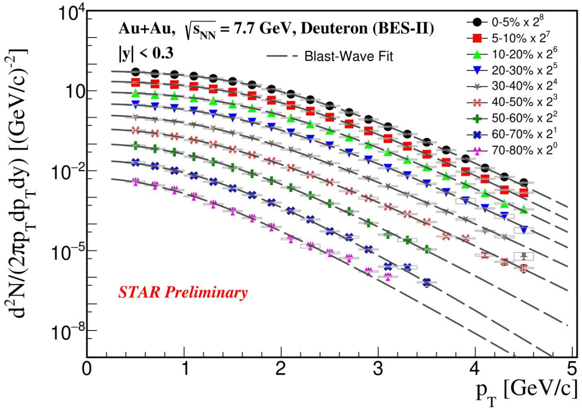

- At low $p_T$ (Gaussian+Exponential) :

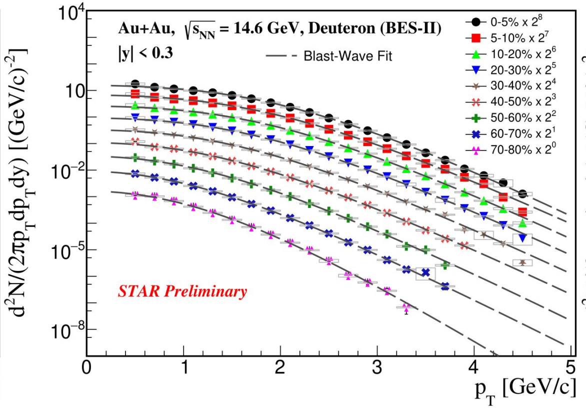
$$\frac{1}{\sqrt{2\pi\sigma^2}} e^{(x-\mu)^2/2\sigma^2} + ae^{bx}$$

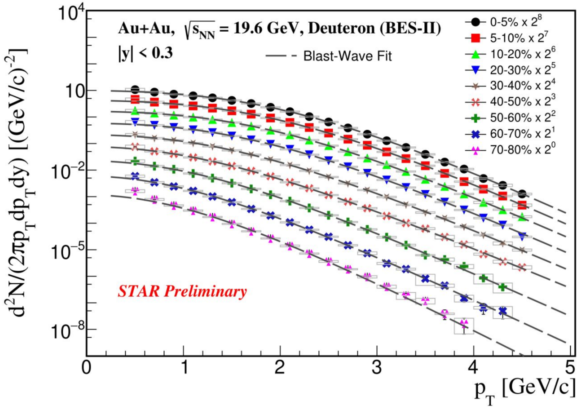
- At intermediate $p_T$ (Student-t+Exponential/Gaussian) :

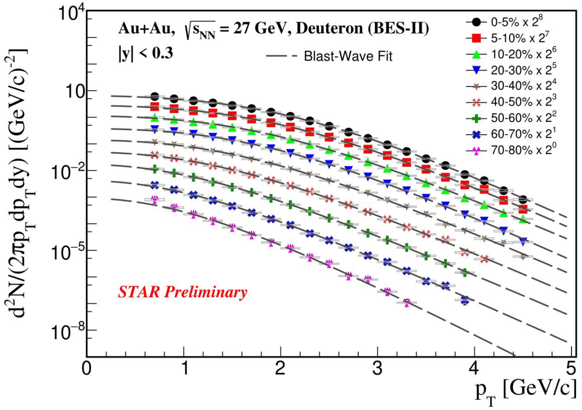
$$\frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2}\sqrt{\pi\nu\sigma^2})}\left[1+\frac{1}{\nu}\left(\frac{x-\mu}{\sigma}\right)^2\right]^{-\frac{\nu+1}{2}} + ae^{bx}$$

# Corrected $p_T$ spectra: Deuteron




$$\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

$$\rho = \tanh^{-1}\beta_r \,,\ \beta_r(r) = \beta_s\left(\frac{r}{R}\right)^n$$

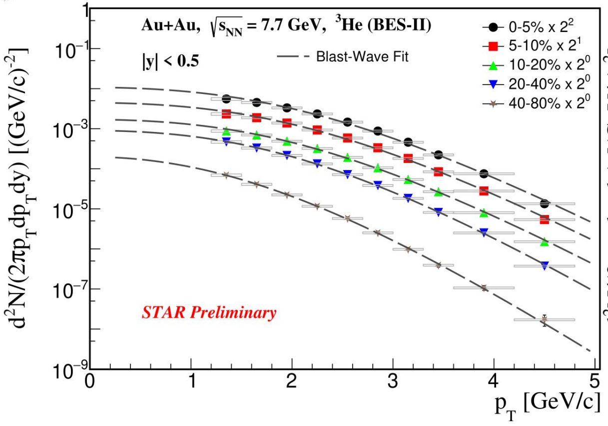
PRC **99**, 064905 (2019)

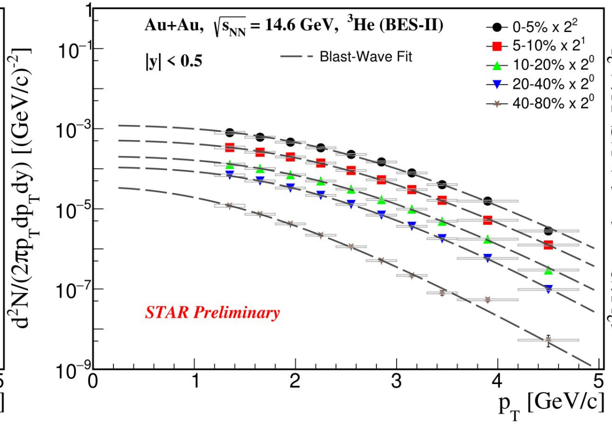
- ❏ Energy loss correction (✅)
- ❏ TPC efficiency and acceptance (✅)
- ❏ TOF efficiency (✅)
- ❏ Absorption correction (✅)
- ❏ Background subtraction (✅)

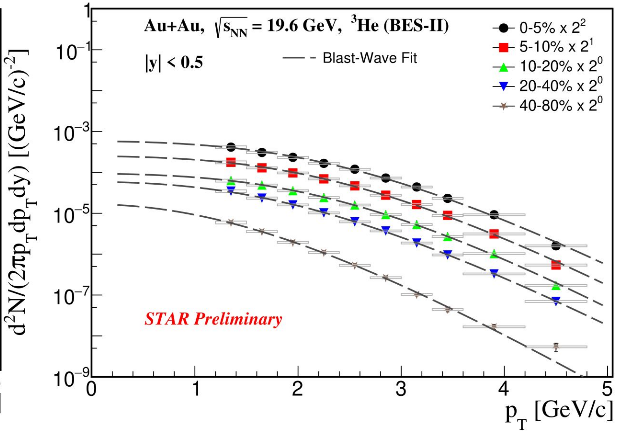
- ➢ More precise measurement is done compared to BES-I due to larger statistics (~10x)
- ➢ $p_T$ spectra is used to calculate the yield and mean $p_T$ of light nuclei

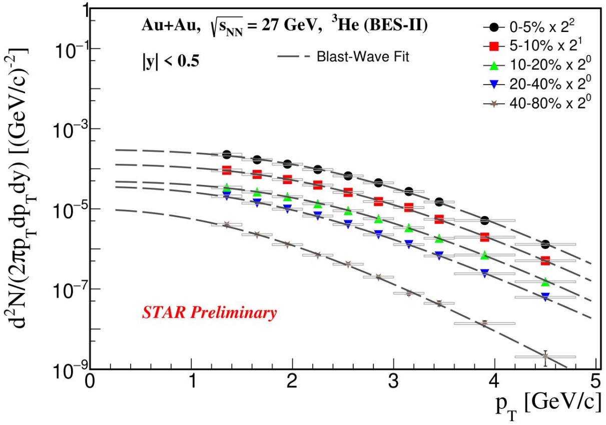
# Corrected $p_T$ spectra: $^3$He






$$\frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

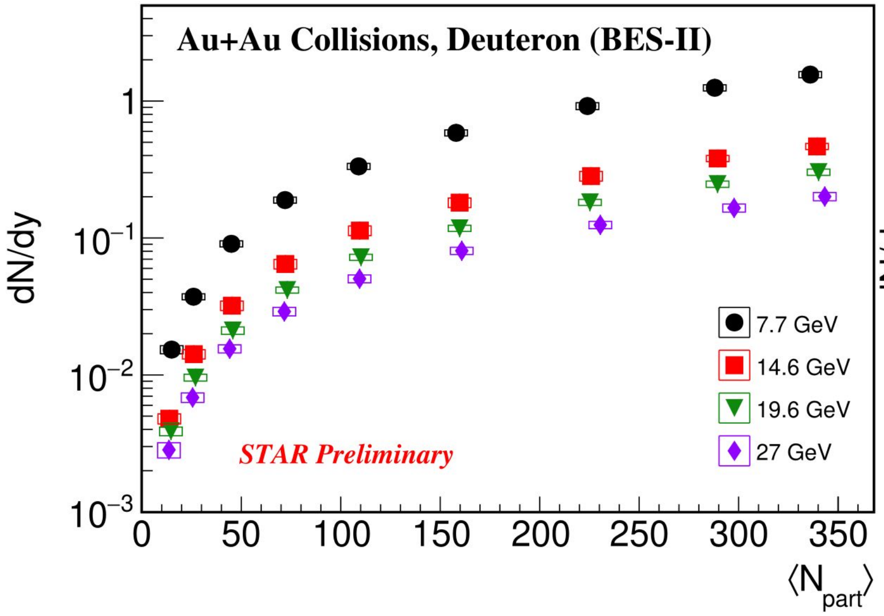
$$\rho = \tanh^{-1}\beta_r \ , \ \beta_r(r) = \beta_s\left(\frac{r}{R}\right)^n$$

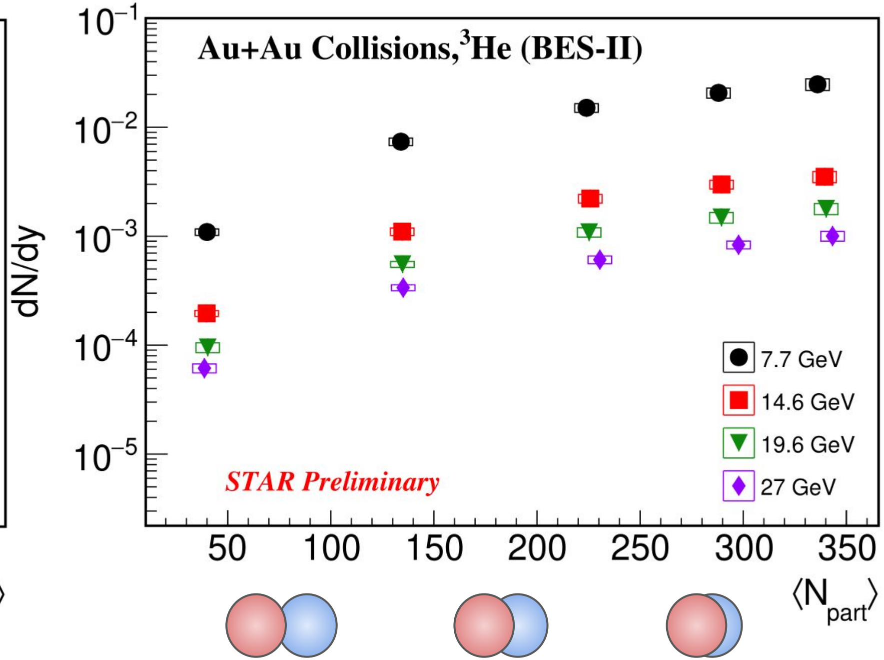
PRC **99**, 064905 (2019)

- Energy loss correction (✅)
- TPC efficiency and acceptance (✅)
- Absorption correction (✅)

- ➢ More precise measurement is done compared to BES-I due to larger statistics (~10x)
- ➢ $p_T$ spectra is used to calculate the yield and mean $p_T$ of light nuclei

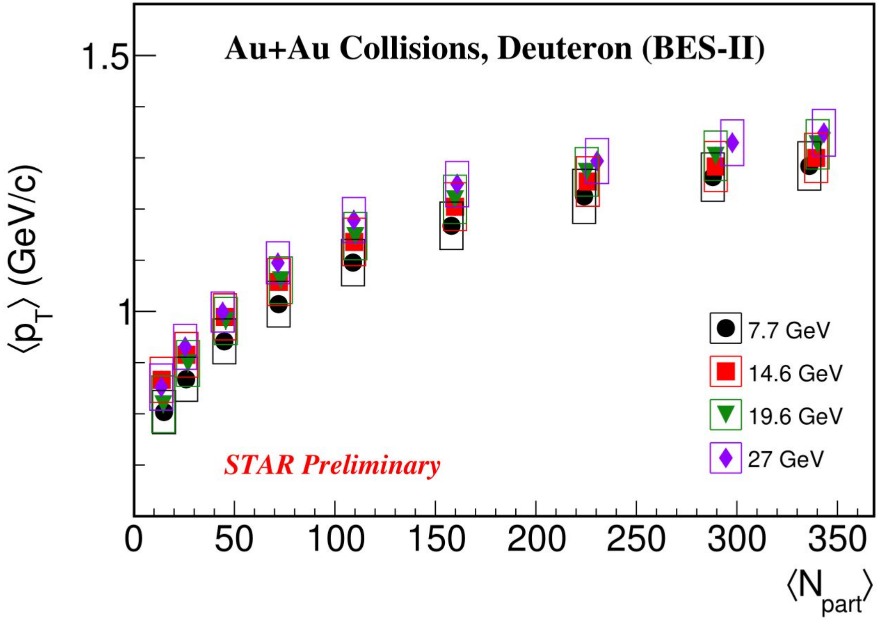
# Integrated yield (dN/dy)

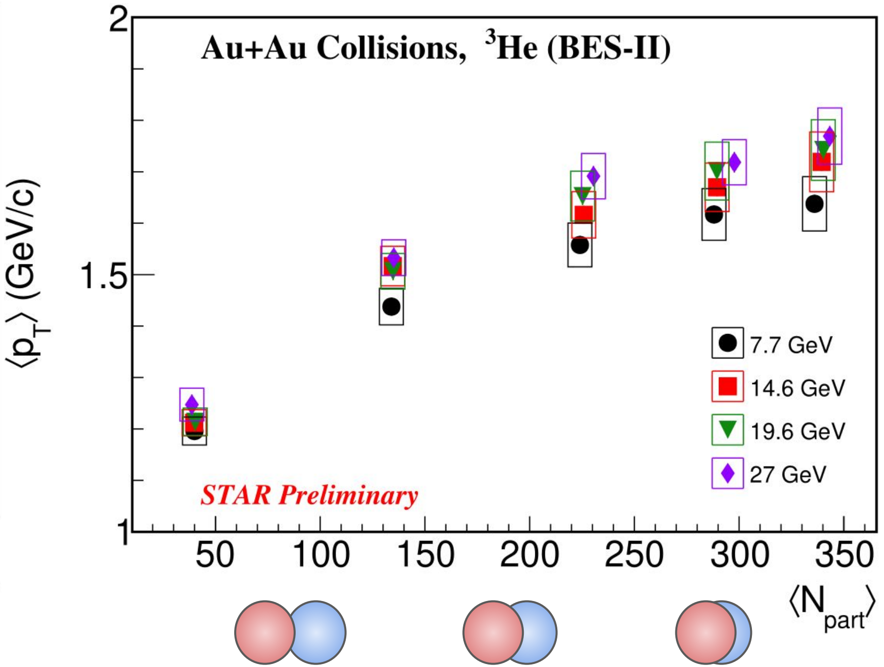



- dN/dy increases with increasing centrality ➡ energy density is larger in central collisions
- dN/dy increases with decreasing collision energy ➡ baryon stopping effect is dominant at lower collision energy

# Mean $p_T$ (<$p_T$>)



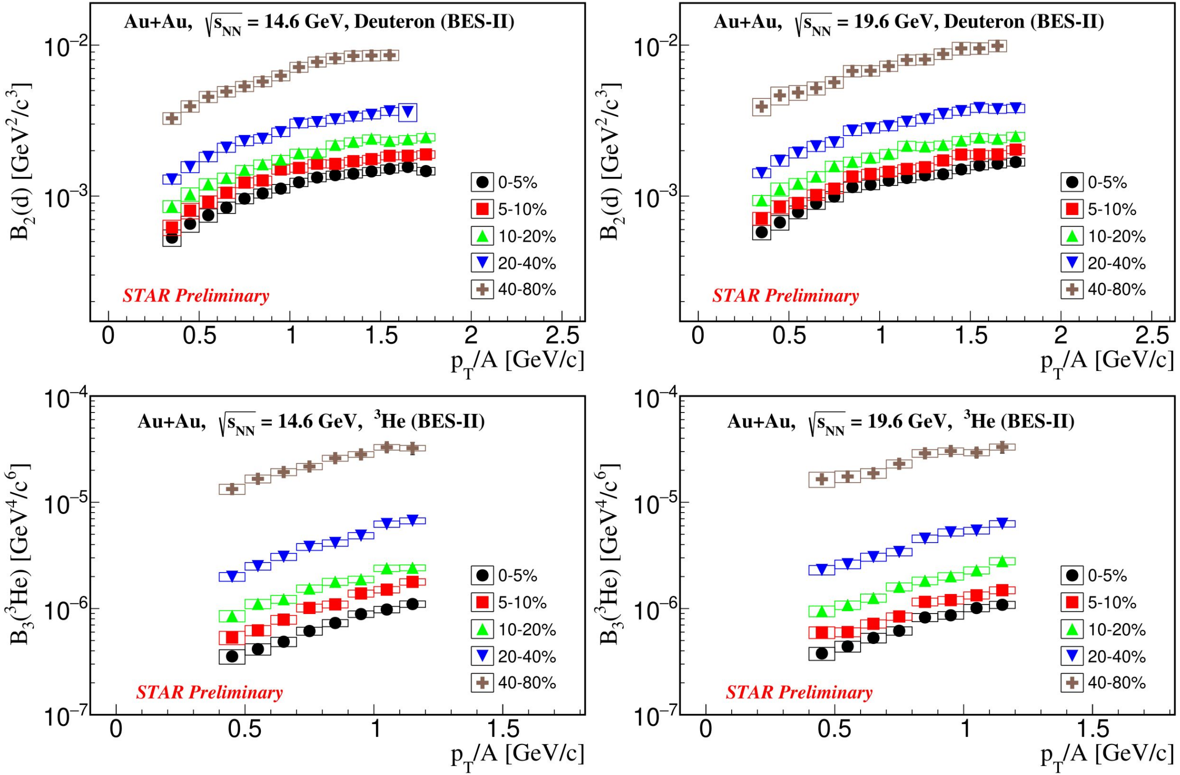




- <$p_T$> increases with increasing centrality ➡ large radial flow in central collisions
- Comparable <$p_T$> is observed at a given centrality in various collision energies

# Coalescence parameters ($B_A$)

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3}\right)^Z \left(E_n \frac{d^3 N_n}{dp_n^3}\right)^{A-Z} \simeq B_A \left(E_p \frac{d^3 N_p}{dp_p^3}\right)^A$$

- ➢ $B_A$ reflects the probability of nucleon coalescence




- ➢ $B_A$ increases with $p_T$ ➡ collective flow of hadrons
- ➢ $B_A$ increases from central to peripheral ➡ decrease in source volume

- Transverse momentum spectra of d and $^{3}$He in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 - 27 GeV
- Yield of light nuclei is observed to increases with increasing centrality
- Light nuclei yield increases with decreasing beam energy due to baryon stopping effect
- Mean $p_T$ increases with centrality due to large radial flow
- $B_A$ increases with increasing $p_T$ and also from central to peripheral collisions

Thank you all!

# Backup slides