# Beam energy dependence of $d$ and $\bar{d}$ production in Au + Au collisions at RHIC

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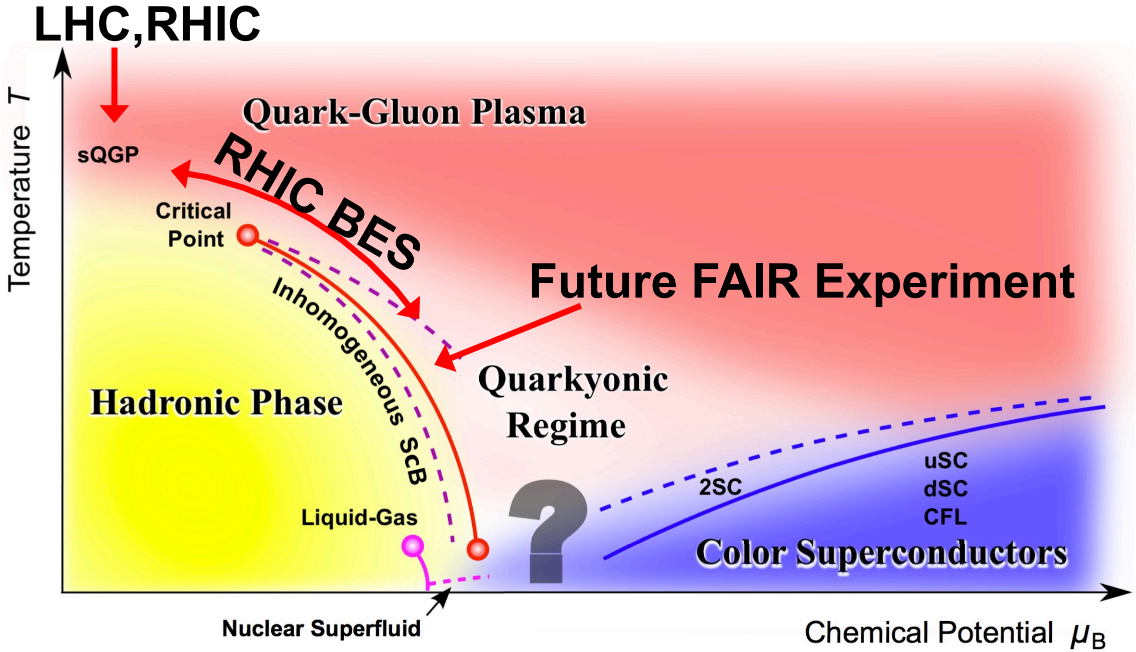
for the STAR Collaboration

# Outline

- ✫ Introduction
- ✫ STAR Experiment
- ✫ Results and Discussions
- ✫ Summary

# QCD Phase Diagram




K. Fukushima and C. Sasaki
Prog. Part. Nucl. Phys, 72, (2013) 99

Phase transition
↓
Correlations of nucleons
↓
Light nuclei

- ✩ High temperature: QGP properties
- ✩ High baryon density:
  - ✓ Critical point and phase boundary
  - ✓ Possible new phase structure : quarkyonic matter

# Light Nuclei Formation in HI Collisions

- Light (anti)nuclei with small binding energy $(\varepsilon)$, such as $d$ and $\bar{d}$ with binding energy $\varepsilon = 2.2$ MeV, are formed via **final-state coalescence**

$$E_A \frac{d^3N_A}{d^3p_A} = B_A \left( E_p \frac{d^3N_p}{d^3p_p} \right)^Z \left( E_n \frac{d^3N_n}{d^3p_n} \right)^{A-Z} \approx B_A \left( E_p \frac{d^3N_p}{d^3p_p} \right)^A, \; p_A = Ap_p$$

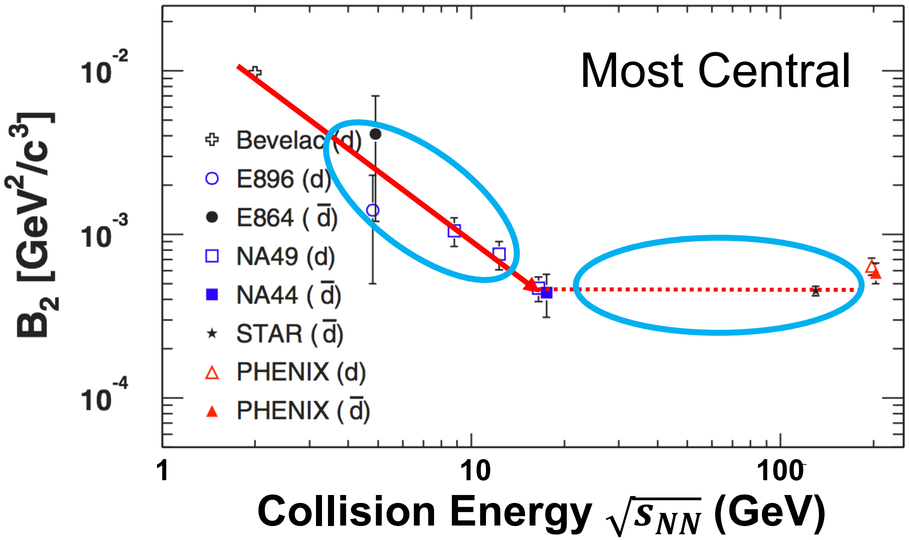
- In thermodynamics, $B_A$ is related to the nucleon freeze-out correlation volume $V_f$ or baryon density

$$B_A \propto V_f^{1-A}, \qquad B_2 = \frac{6\pi^3 R_{np} m_d}{m_p^2 V_f}, \qquad R_{np} = \frac{N_n}{N_p}$$

- Light nuclei may serve as probes of space-momentum density and correlation of nucleons at freeze-out. We will focus on $d$ $(\bar{d})$ in this talk.

László P. Csernai, Joseph I. Kapusta Phys. Reps, 131,223(1986)
B. Monreal, *et. al.* PRC60,031901(1999), PRC60,051902(1999)

# Energy Dependence of $B_A$

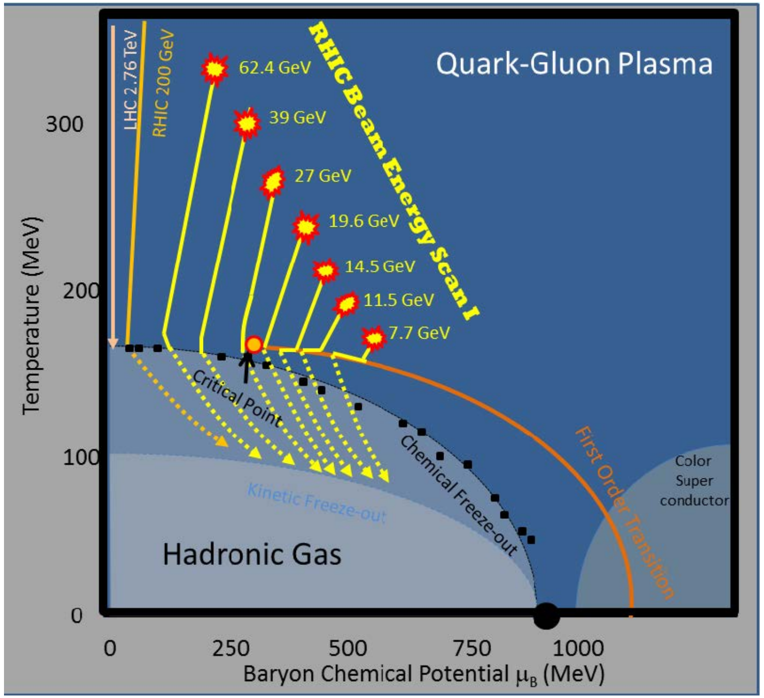



PHENIX, PRL. 94, 122302 (2005).

- ✭ The size of the fireball increase from low to high collision energy, $B_2$ decrease with energy
- ✭ The behavior of $B_2$ is different at high energy

- ✭ **Is there any structure in the energy dependence of $B_2$, from high energy to low energy ?**
- ✭ **Is there any centrality dependence of $B_2$?**
- ✭ **Is there any difference of $B_2$ between deuteron and anti-deuteron?**

# RHIC Beam Energy Scan




☆ BES-I Au+Au collisions at $\sqrt{s_{NN}} = 7.7$, 11.5, 14.5, 19.6, 27, 39 and 62.4 GeV

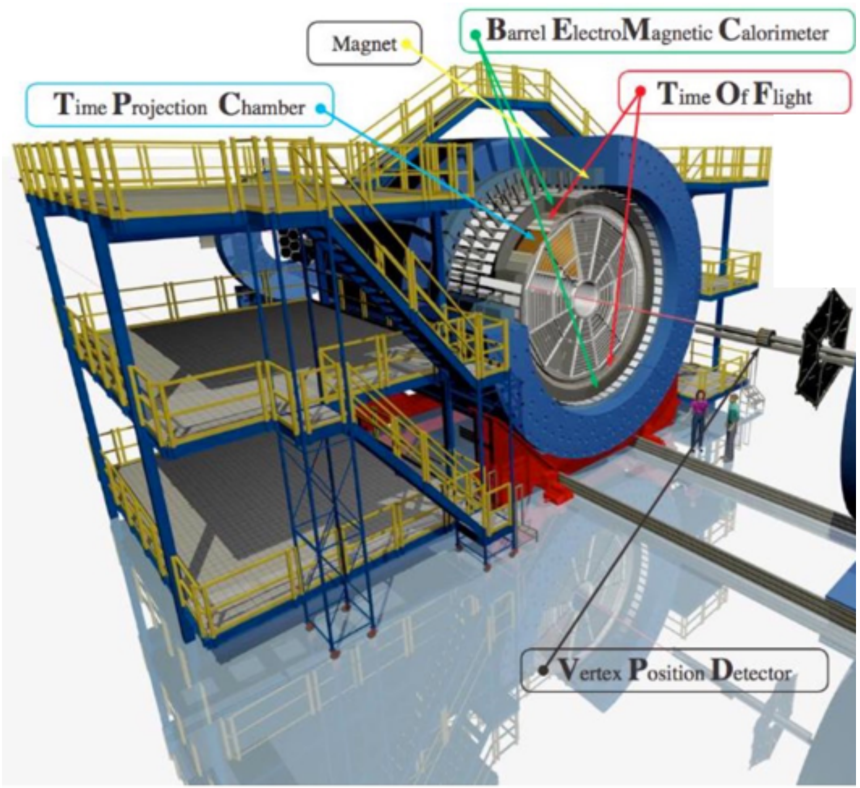
- ✓ Search for conjectured QCD critical point
- ✓ Search for the first order phase transition
- ✓ Search for the onset of key QGP signatures

STAR Collaboration, arXiv:1007.2613

| $\sqrt{s_{NN}}$(GeV) | 7.7 | 11.5 | 14.5 | 19.6 | 27 | 39 | 62.4 | 200 |
|---|---|---|---|---|---|---|---|---|
| $N_{eve}$(M) | 4 | 11 | 27 | 40 | 71 | 133 | 67 | 480 |
| $\mu_B$(MeV) | 420 | 315 | 260 | 205 | 155 | 115 | 72 | 20 |

J. Cleymans, H. Oeschler, K. Redlich, and S. Wheaton PRC 73,034905 (2006)

# Solenoidal Tracker At RHIC



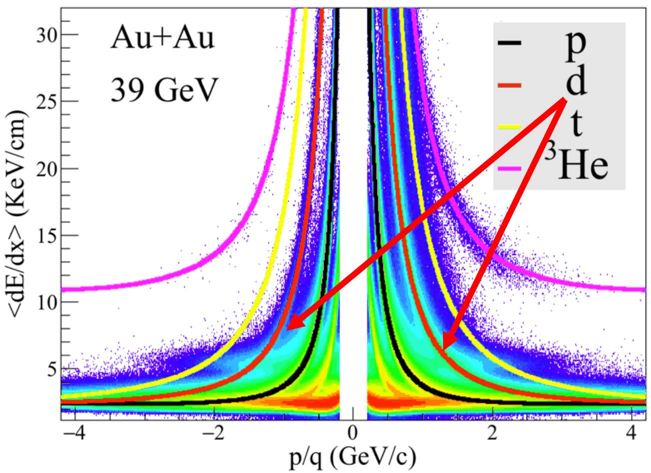

Time Projection Chamber（**TPC**）

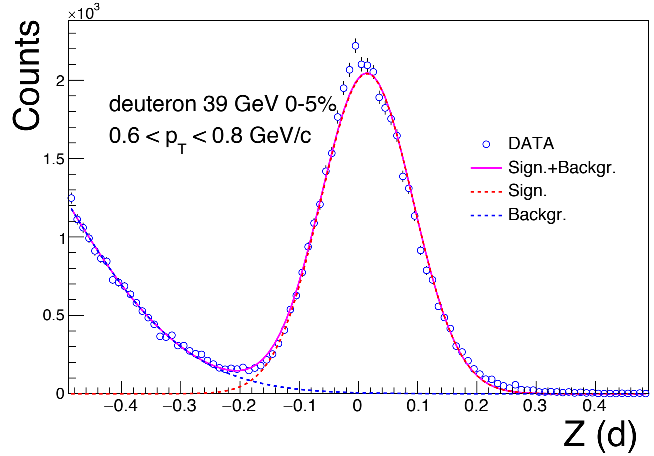
- ✓ Charged Particle Tracking
- ✓ Momentum reconstruction
- ✓ Particle identification from ionization energy loss (dE/dx)
- ✓ Pseudorapidity coverage $|\eta| < 1.0$

Time Of Flight (**TOF**)

- ✓ Particle identification $m^2$
- ✓ Pseudorapidity coverage $|\eta| < 0.9$

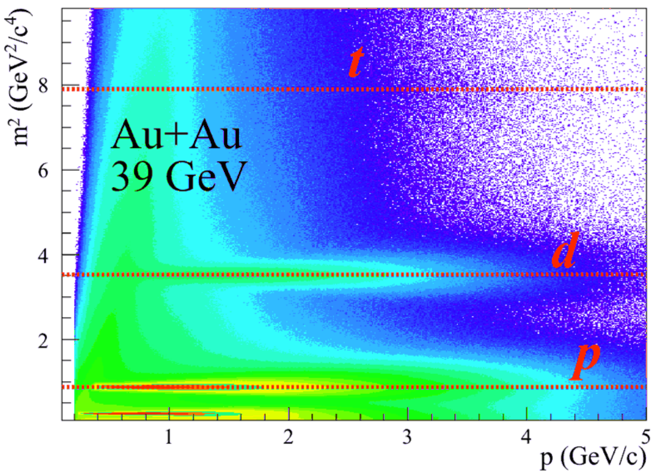
# Particle Identification

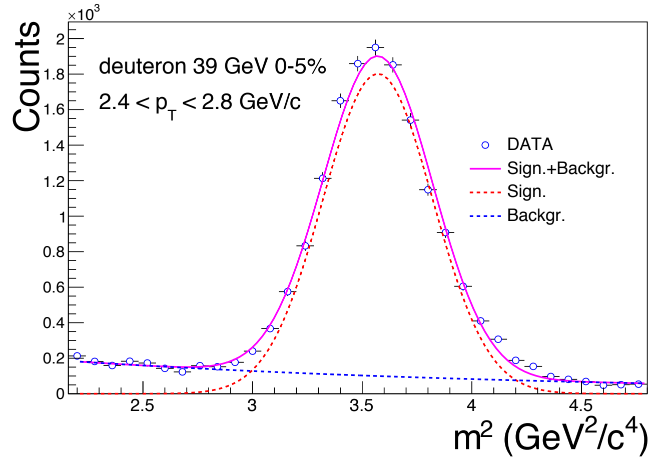



$$z_d = \log\left(\frac{\langle dE/dx\rangle}{\langle dE/dx\rangle_d^{BB}}\right)$$

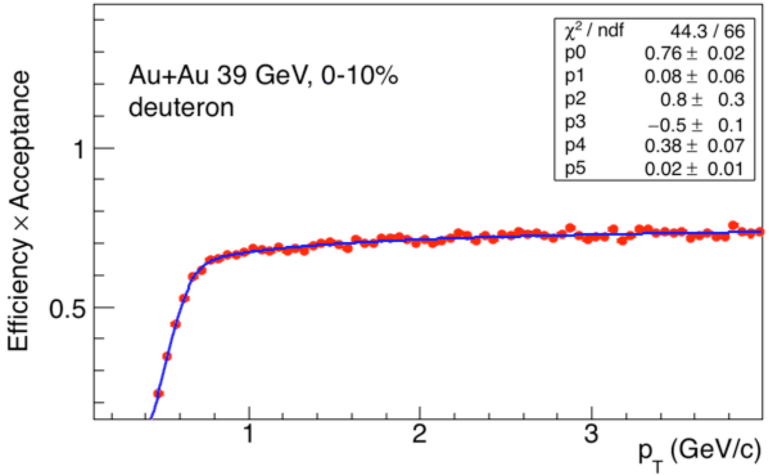
BB : Bethe-Bloch
H. Bichsel, Nucl. Instrum. Meth. A 562, 154 (2006).



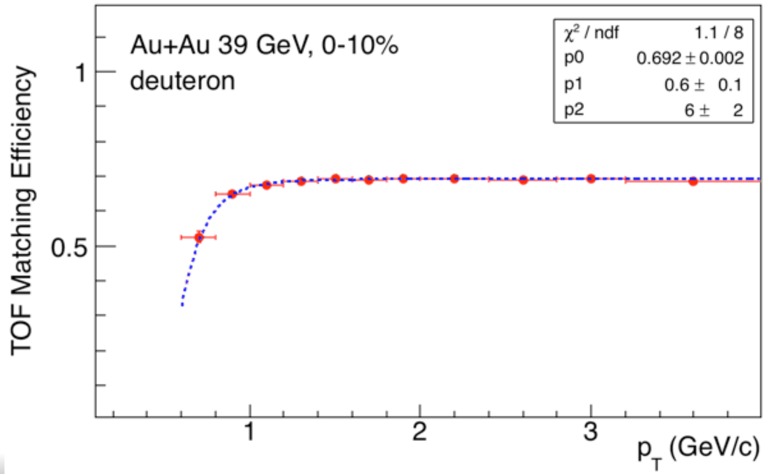




$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

# Efficiency and Acceptance




$$\varepsilon_{\mathrm{TPC}}(p_T) = a_0 \exp\left(-\frac{a_1}{p_T}\right)^{a_2} + pol(2)$$

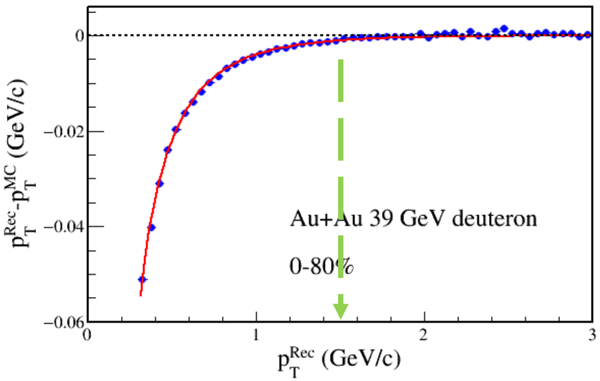


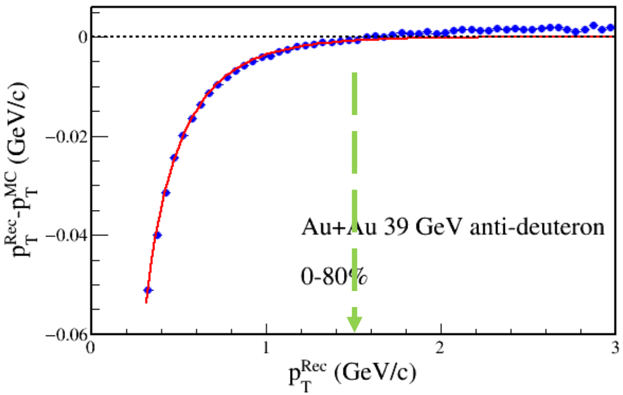

$$\varepsilon_{\mathrm{TOF}}(p_T) = \frac{\text{The number of TOF Matched Tracks}}{\text{The number of TPC Tracks}}$$

$$\varepsilon_{\mathrm{TOF}}(p_T) = a_0 \exp\left(-\frac{a_1}{p_T}\right)^{a_2}$$

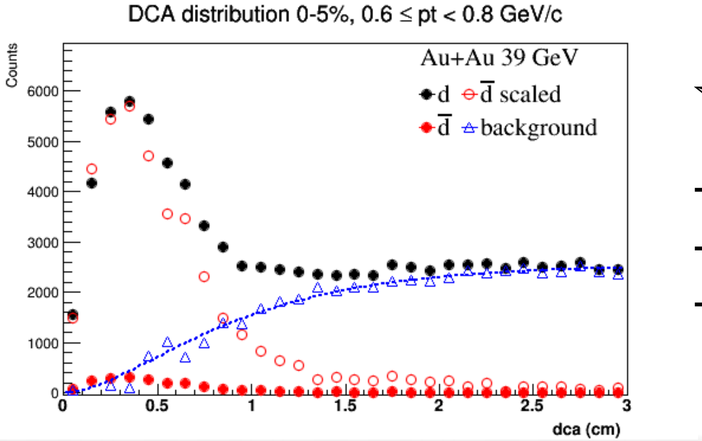
# Corrections

## ✮ Energy Loss



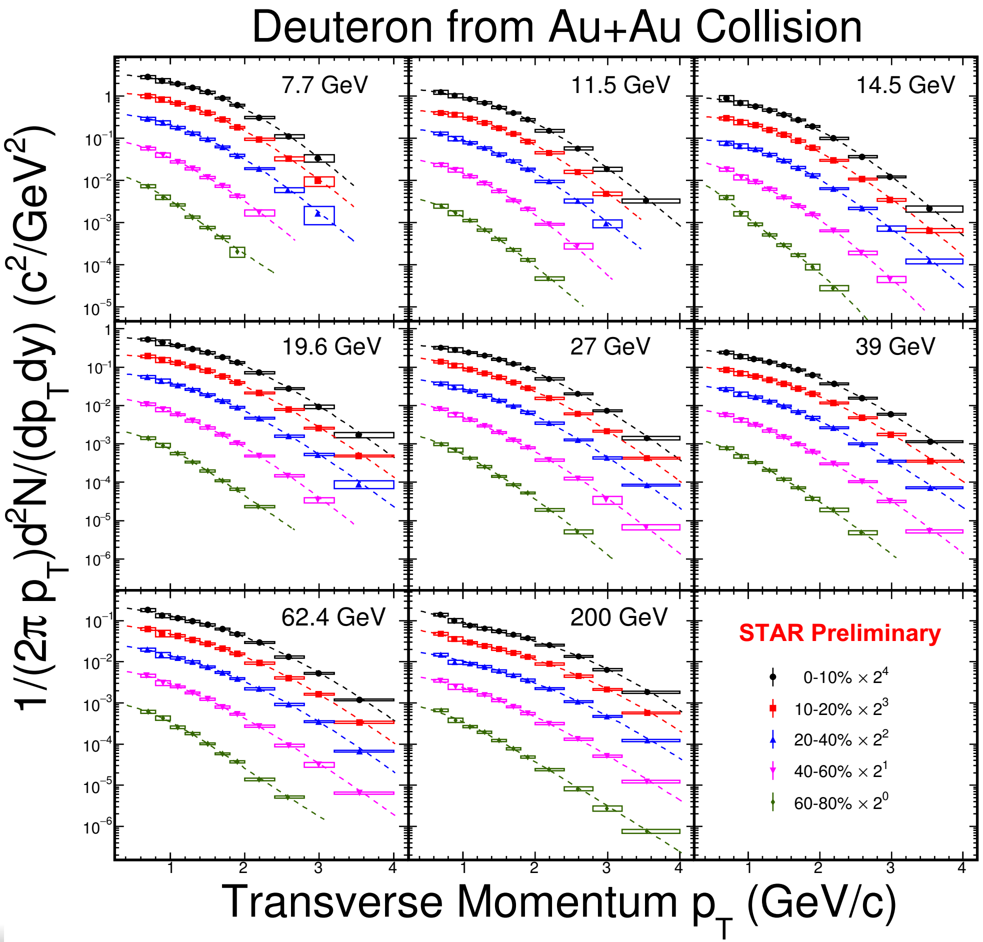

$$f(p_T) = A + B\left(1 + \frac{C}{p_T^2}\right)^D$$




## ✮ Background in $d$ analysis

- No centrality dependence of energy loss
- Energy loss of $d$ and $\bar{d}$ are the same
- The energy loss for all the collision energy are the same except 14.5 GeV (different material budget)

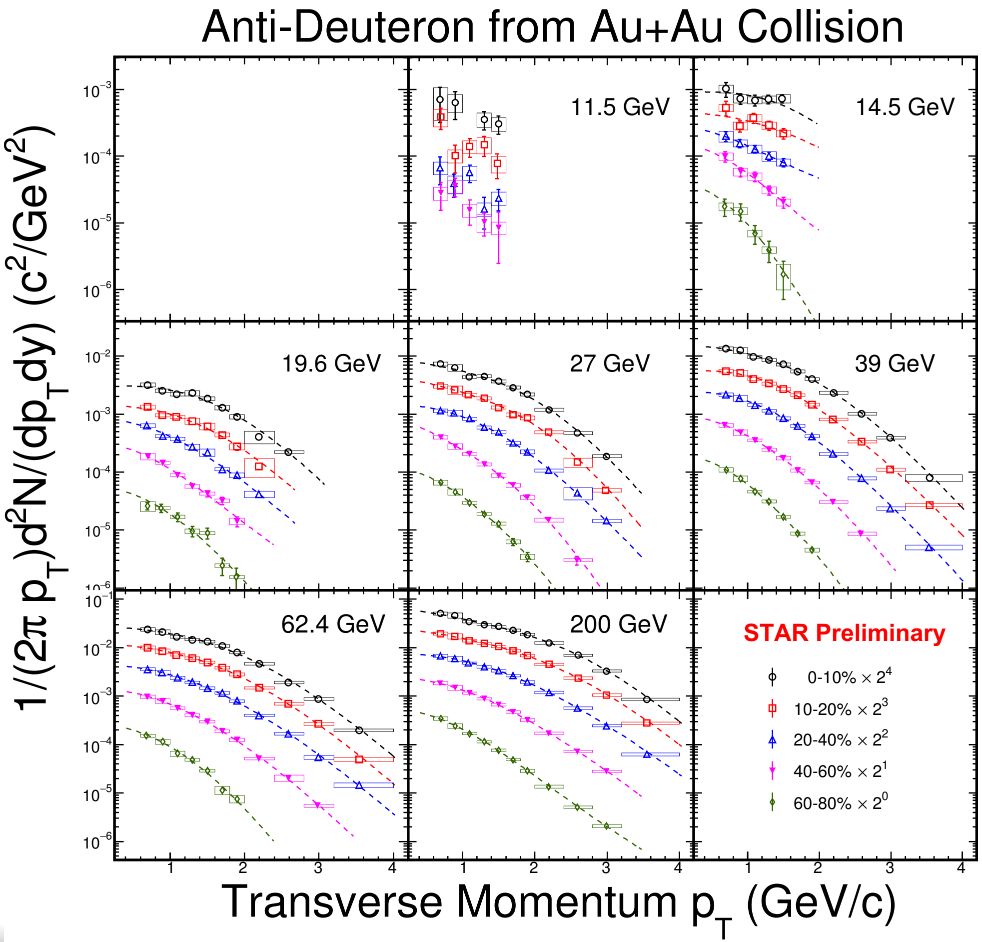
# Deuteron Spectra




- ☆ Mid-rapidity ($|y| \leq 0.3$) transverse momentum distribution of $d$ from Au+Au Collision
- ☆ Dash line: blast-wave function fits

$$\frac{\mathrm{d}^2N}{m_T dm_T} \propto \int_0^R r\mathrm{d}r m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

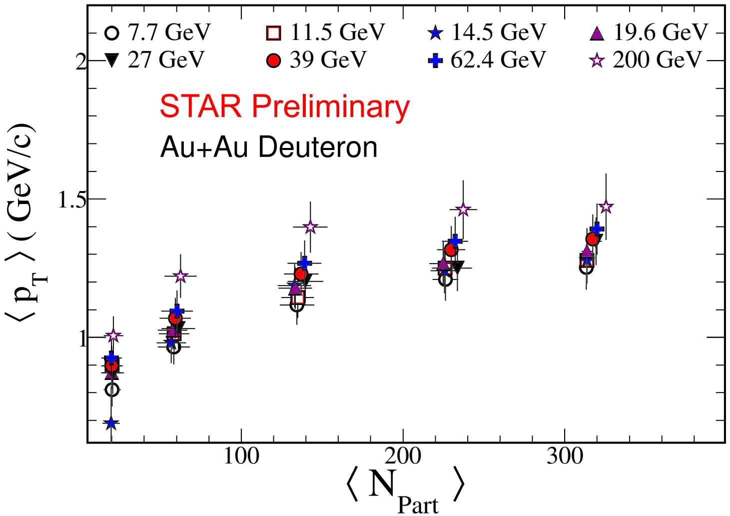
# Anti-Deuteron Spectra

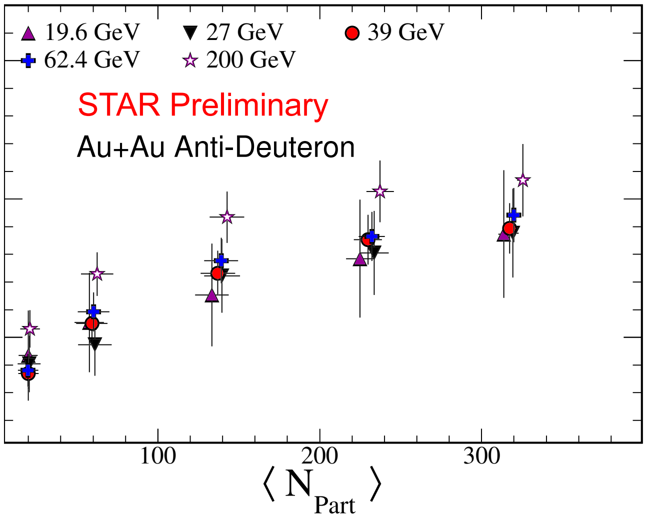



- ☆ Mid-rapidity ($|y| \leq 0.3$) transverse momentum distribution of $\bar{d}$ from Au+Au Collision
- ☆ Dash line: blast-wave function fits

$$\frac{\mathrm{d}^2 N}{m_T dm_T} \propto \int_0^R r\mathrm{d}r m_T I_0\left(\frac{p_T \mathrm{sinh}\rho}{T}\right) K_1\left(\frac{m_T \mathrm{cosh}\rho}{T}\right)$$

# $\langle p_T \rangle$ and $T_{kin}$, $\beta$



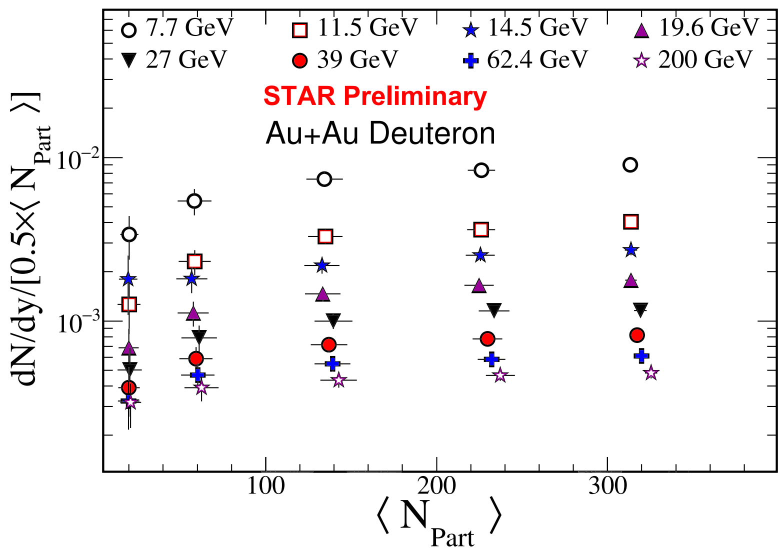



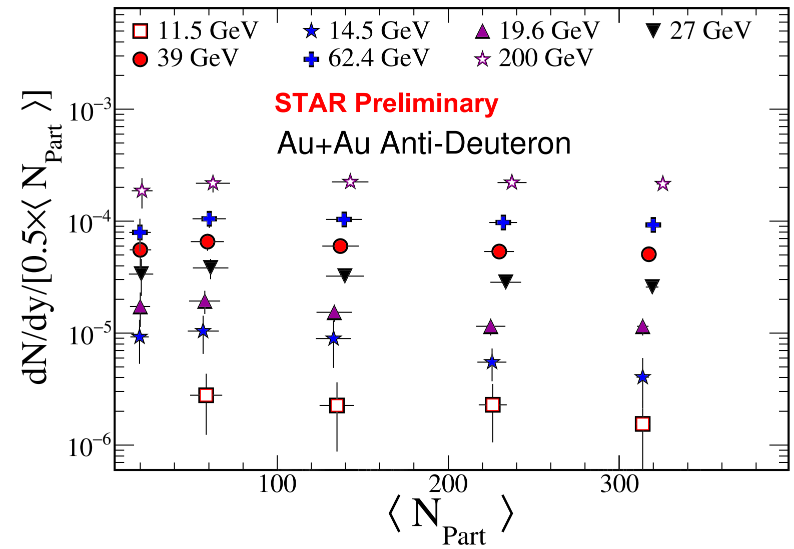

- ☆ $\langle p_T \rangle$ decrease from central to peripheral collision
- ☆ $\langle p_T \rangle$ of $d$ and $\bar{d}$ are consistent within error
- ☆ B.W. can describe both $d$ and $\pi, K, p$ with similar parameters

| 39 GeV | $d$ | | | $\bar{d}$ | $\pi, K, p$ * | | |
|---|---|---|---|---|---|---|---|
| Cent. | $T_{kin}$(MeV) | $\beta$(c) | $\langle p_T \rangle$(GeV/c) | $\langle p_T \rangle$(GeV/c) | $T_{kin}$(MeV) | $\beta$(c) | $\langle p_T \rangle$(GeV/c) |
| 0-10% | 99±12 | 0.45±0.02 | 1.35±0.09 | 1.39±0.09 | 118±11 | 0.48±0.04 | 0.85±0.05 |
| 10-20% | 110±14 | 0.43±0.02 | 1.32±0.09 | 1.35±0.05 | 120±11 | 0.46±0.03 | 0.83±0.05 |
| 20-40% | 135±23 | 0.39±0.02 | 1.23±0.08 | 1.23±0.08 | 126±11 | 0.41±0.03 | 0.79±0.05 |

* STAR Collaboration, arXiv:1701.07065 (submitted to PRC)

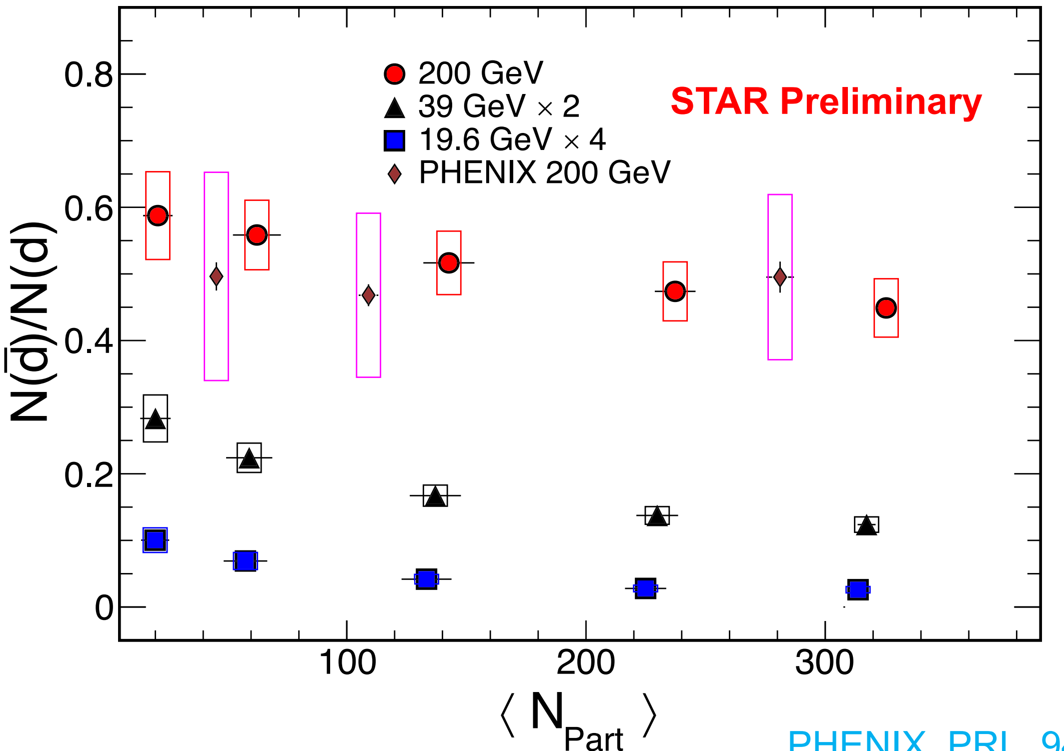
# Integral Yield $dN/dy$




- ☆ $dN(d)/dy$ is smaller at higher energy: baryon stopping
- ☆ $dN(\overline{d})/dy$ increases with increasing energy: baryon pair production
- ☆ $N_{\text{part}}$ scaled $dN/dy$ for $\overline{d}$ show weak centrality dependence, for $d$ increase slightly from peripheral to central collision

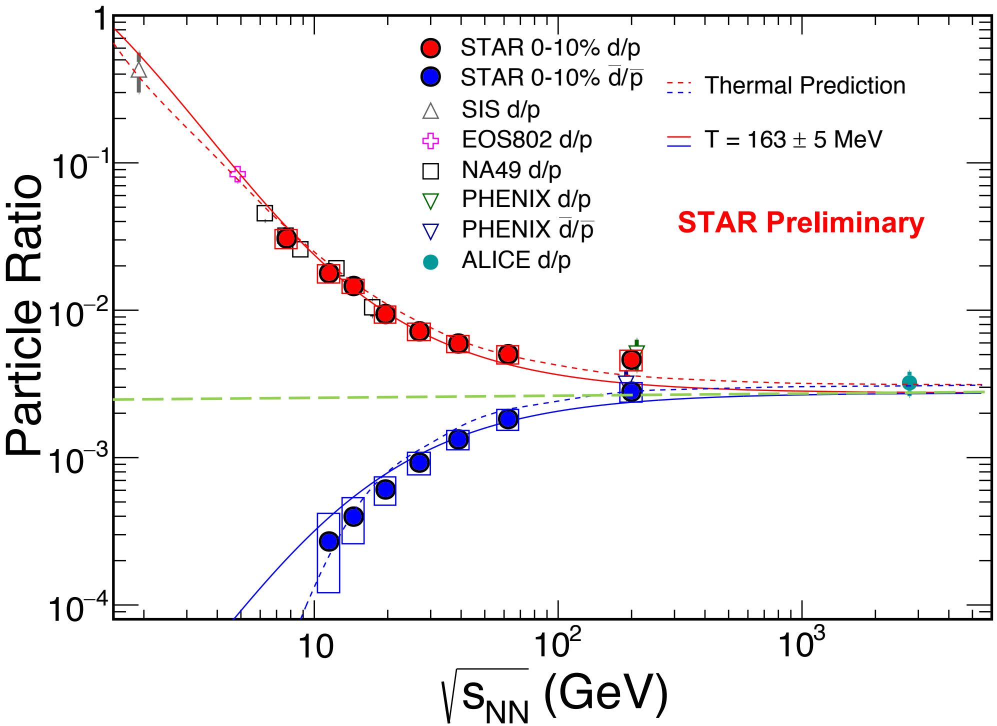
# Antiparticle to Particle Ratios




PHENIX, PRL. 94, 122302 (2005).

- ☆ $N(\bar{d})/N(d)$ ratio decreases as a function of collision centrality
- ☆ $N(\bar{d})/N(d)$ ratio decreases with decreasing energy

# $N(d)/N(p)$ Ratio vs. Energy




- ☆ The $N(d)/N(p)$ ratios by thermal model prediction are consistent with the data from SIS energies up to LHC
- ☆ A temperature of $T = 163 \pm 5$ MeV can be extracted from $N(d)/N(p)$ and $N(\bar{d})/N(\bar{p})$

$$\frac{N(d)}{N(p)} \sim \frac{K_2(m_d/T)}{K_2(m_p/T)} e^{\frac{\mu_B}{T}}$$

$$\frac{N(\bar{d})}{N(\bar{p})} \sim \frac{K_2(m_d/T)}{K_2(m_p/T)} e^{-\frac{\mu_B}{T}}$$

The lines are from thermal model prediction

A. Andronic, P. Braun-Munzinger, J. Stachel, H. Stöcker, PLB697 (2011)203

# $d/p^2$ and $\bar{d}/\bar{p}^2$ Ratios

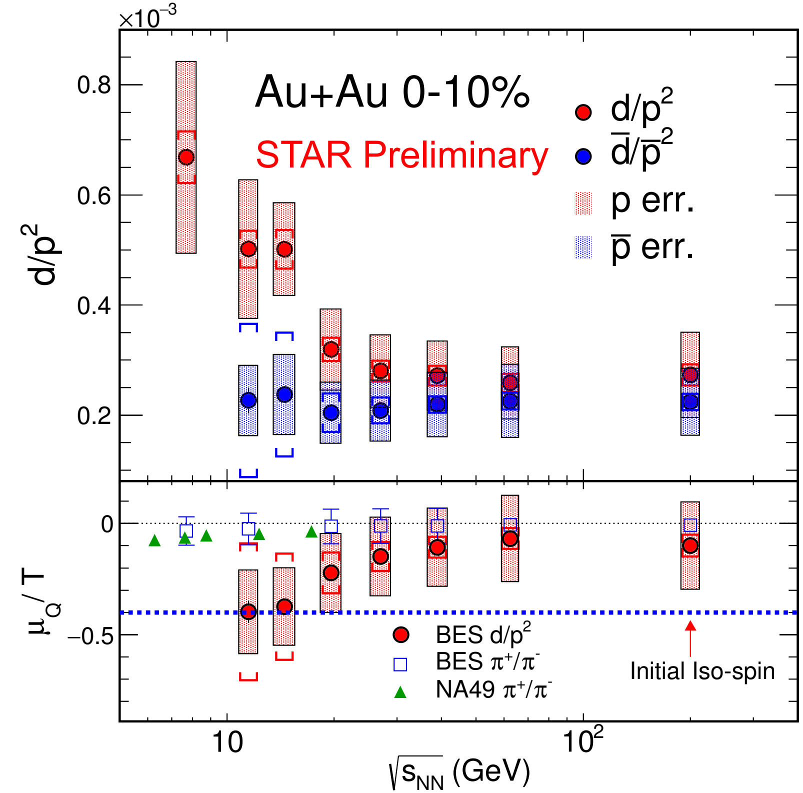
- ✭ In thermal model with GCE (grand canonical ensemble), $d/p^2$ and $\bar{d}/\bar{p}^2$ should be the same if iso-spin effect can be neglected

$$\frac{\mu_Q}{T} = \frac{1}{2}\ln\left(\frac{\bar{d}/\bar{p}^2}{d/p^2}\right)$$

- ✭ The $\mu_Q/T$ can also be obtained by

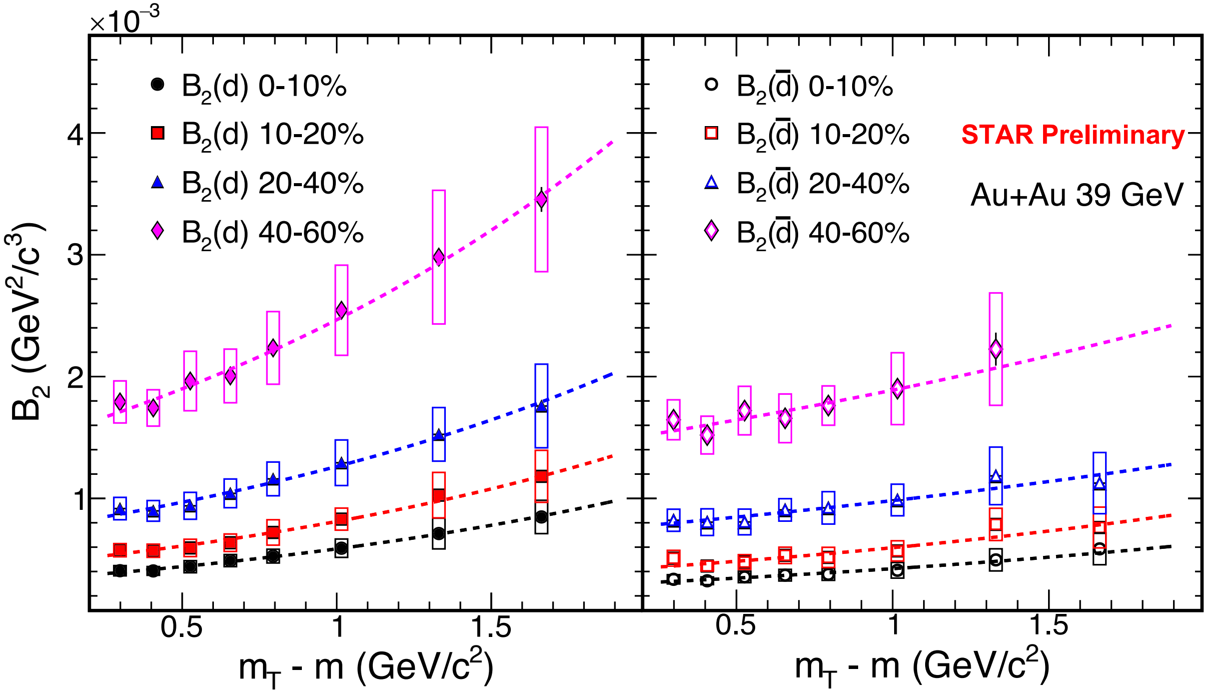
$$\frac{\mu_Q}{T} = \frac{1}{2}\ln\left(\frac{\pi^+}{\pi^-}\right)$$

The results are close to zero implying small iso-spin effect




NA49, PRC 94, 044906 (2016)

# $B_2$ v.s. $m_T$ and Collision Centrality

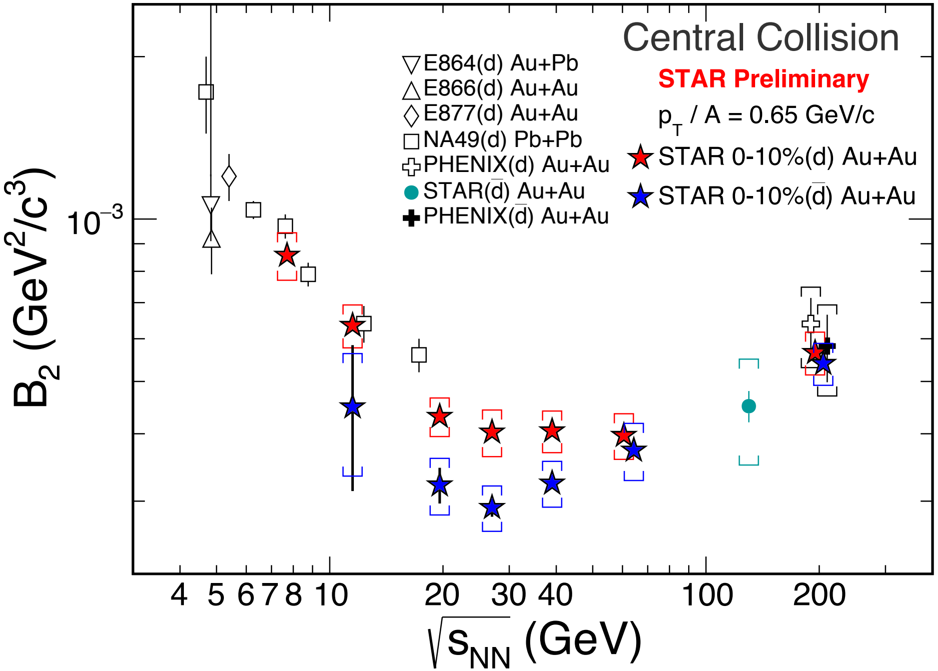


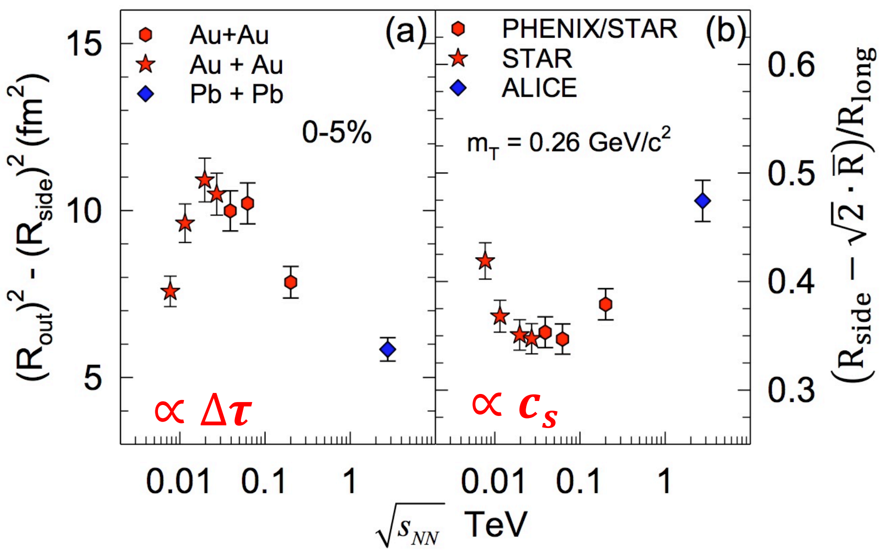

$$B_2 = a \cdot \exp[b(m_T - m)]$$

NA44, EPJ C. 23, 237 (2002)

- ☆ The values of $B_2$ increase as a function of $m_T$ and decrease with collision centrality : collective expansion
- ☆ $B_2(\overline{d})$ are smaller than that of $B_2(d)$, anti−baryon freeze out at a larger source

# Coalescence Parameters v.s. Collision Energy

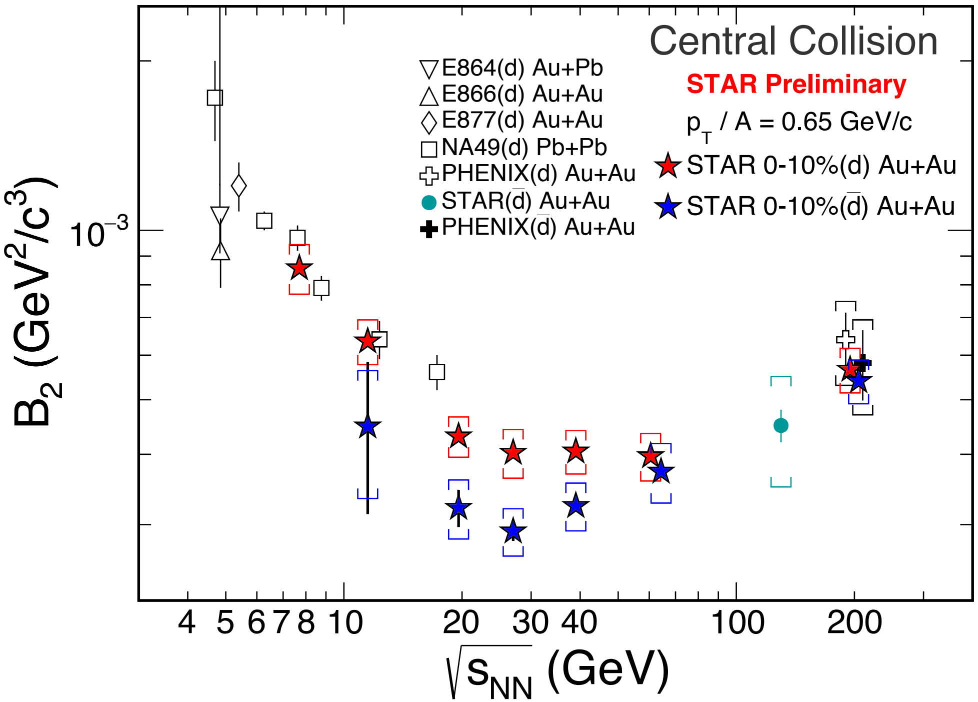



arXiv:1410.2559

- ✫ $B_2$ decrease with collision energy. A minimum around $\sqrt{s_{\mathrm{NN}}} = 20$ GeV : **change of EOS?!**
- ✫ $B_2(\bar{d})$ values are systematically lower than that of $B_2(d)$ implying emitted source of anti-baryons is larger than those of baryons

# Discussion




- ☆ Is there any structure in energy dependence of $B_2$, from high energy to low energy ? (BES: Yes)
- ☆ Is there any centrality dependence of $B_2$? (Yes)
- ☆ Is there any difference of $B_2$ between deuteron and anti-deuteron? (Yes)

# Summary

- ✯ STAR systematic results of $d(\bar{d})$ production ($dN/dy$, $\langle p_T \rangle$) from Au + Au collisions at $\sqrt{\boldsymbol{s}_{\mathbf{NN}}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 62.4 and 200 GeV
- ✯ Coalescence parameter $B_2$ for $d$ and $\bar{d}$ are extracted. $B_2(d)$ and $B_2(\bar{d})$ are found to be different in the most central collisions
- ✯ Similar to the $\pi$ HBT and net-proton high moment, around $\sqrt{s_{\mathrm{NN}}} = 20$ GeV, $B_2$ reaches a minimum implying EOS changes around the energy
- ✯ High statistics data are needed for future studies, especially at the high net-baryon density, i.e., low collision energy region

# *Thank you*