2023 RHIC/AGS ANNUAL USERS' MEETING

CELEBRATING NEW BEGINNINGS AT RHIC and EIC

August 1–4, 2023

Measurement of Triton Production and Yield Ratio ($N_t \times N_p / N_d^2$) in Au+Au Collisions at RHIC Beam Energy Scan

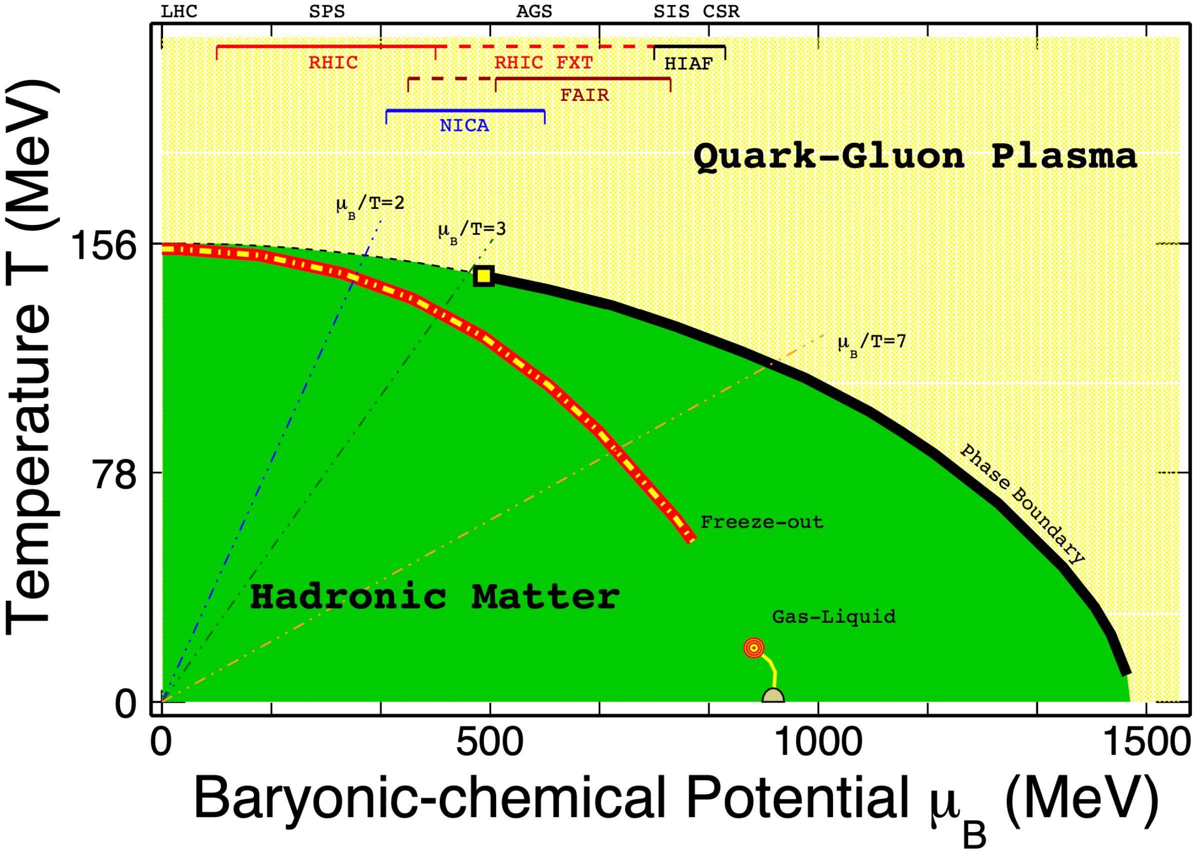
Dingwei Zhang

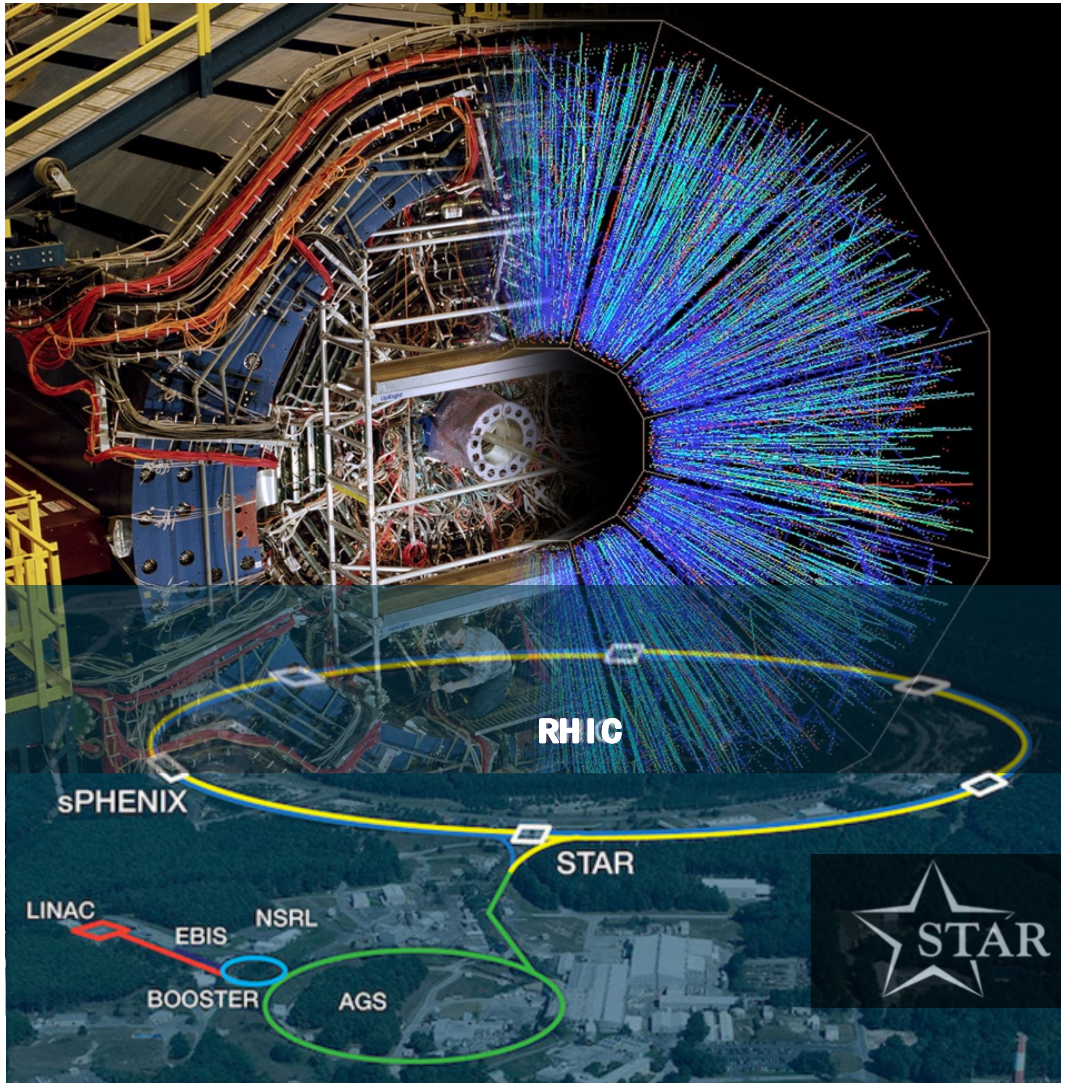
Central China Normal University

August 1-4, 2023

Introduction

QCD Phase Diagram and Critical Point





Au+Au Collisions at RHIC STAR [1]

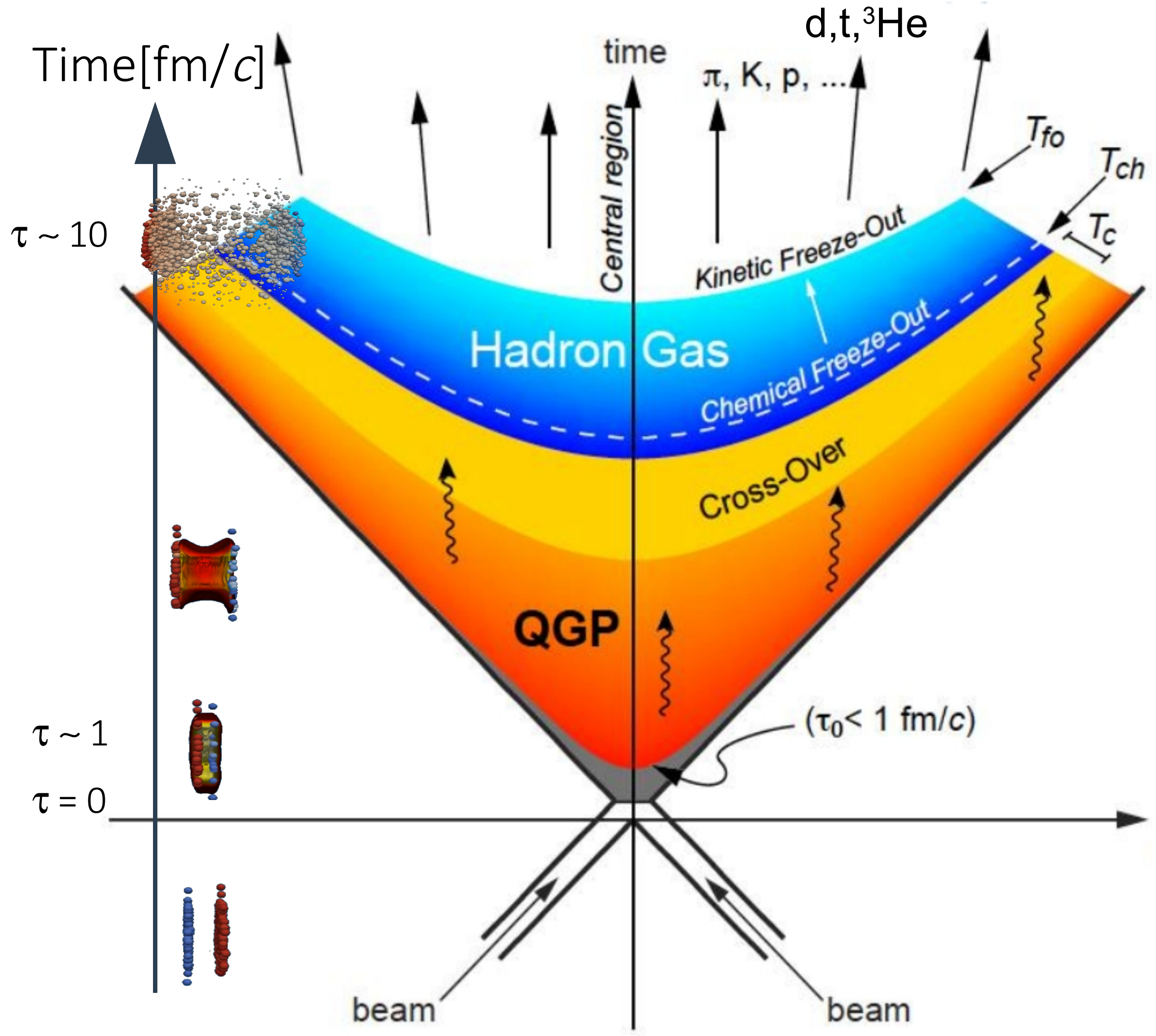
$\sqrt{s_{NN}}$: 3 - 200 GeV

μ_B : 750 - 25 MeV

[1] http://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Introduction

Production of Light Nuclei in HIC



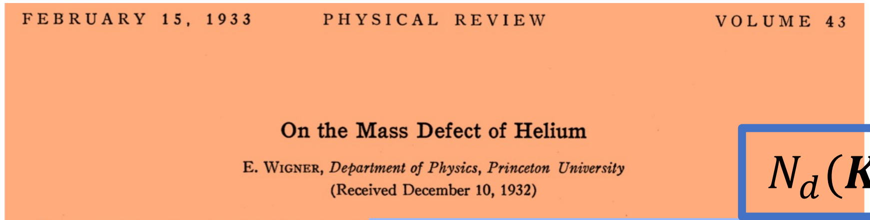
- ➢ Our understanding of the production mechanisms of light nuclei in relativistic heavy-ion collisions are currently incomplete

- Thermal emission
  $N_A \approx g_A V (2\pi m_A T)^{3/2} e^{(A\mu_B - m_A)/T}$
- Nucleon coalescence
  $N_A = g_c \int d\Gamma \, \rho_s(\{x_i, p_i\}) \times W_A(\{x_i, p_i\})$
- Hadronic re-scattering
  $\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd, NN \leftrightarrow \pi d \ldots\ldots$

L. P. Csernai and J. I. Kapusta, Phys. Rept. 131, 223 (1986); R. Scheibl and U. W. Heinz, Phys. Rev. C 59, 1585 (1999); Y. Oh, Z.-W. Lin, and C. M. Ko, Phys. Rev. C 80, 064902 (2009); A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, Nature 561, 321 (2018); J. Chen, D. Keane, Y.-G. Ma, A. Tang, and Z. Xu, Phys Rept. 760, 1 (2018); D. Oliinychenko, L.-G. Pang, H. Elfner, and V. Koch, Phys. Rev. C 99, 044907 (2019); K.-J. Sun, R. Wang, C. M. Ko, Y.-G. Ma, and C. Shen, (2022),arXiv:2207.12532

Introduction

Formation Mechanisms of Light Nuclei



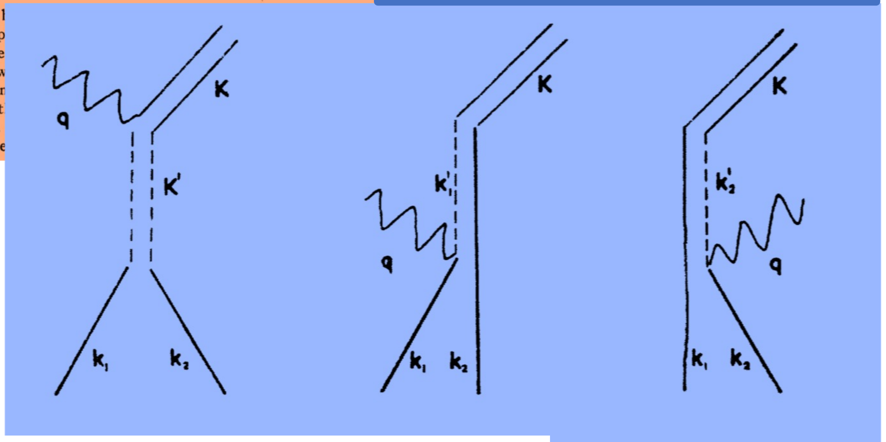
FEBRUARY 15, 1933 PHYSICAL REVIEW VOLUME 43

On the Mass Defect of Helium

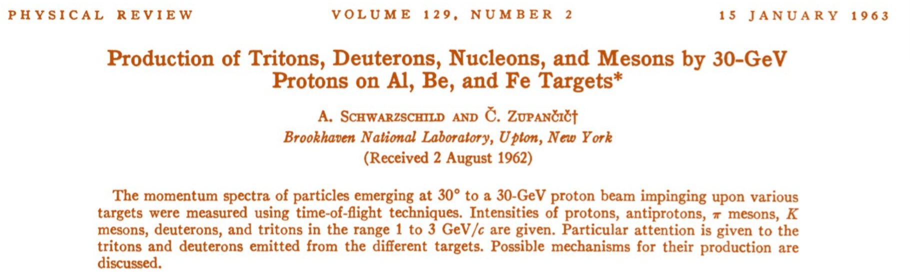
E. WIGNER, *Department of Physics, Princeton University*
(Received December 10, 1932)

If one assumes that the potential energy
protons and neutrons has the shape of a simple p
hole, it is possible from the experimental value
mass defect of the H², to derive a connection betw
mean width and the depth of this curve. This con
proves to be, to a large extent, independent of t
details of the potential curve. By assuming a
probable value, obtained from scattering experime

$$N_d(\boldsymbol{K}) \propto [N_p\ (\boldsymbol{K}/2)]^2$$



(c)



PHYSICAL REVIEW VOLUME 129, NUMBER 2 15 JANUARY 1963

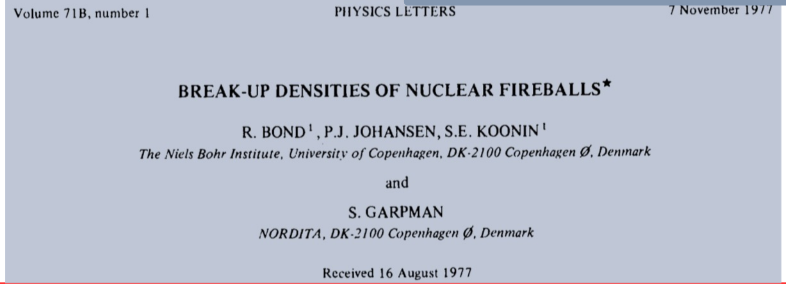
Production of Tritons, Deuterons, Nucleons, and Mesons by 30-GeV Protons on Al, Be, and Fe Targets*

A. SCHWARZSCHILD AND Č. ZUPANČIČ†
Brookhaven National Laboratory, Upton, New York
(Received 2 August 1962)

The momentum spectra of particles emerging at 30° to a 30-GeV proton beam impinging upon various targets were measured using time-of-flight techniques. Intensities of protons, antiprotons, π mesons, K mesons, deuterons, and tritons in the range 1 to 3 GeV/c are given. Particular attention is given to the tritons and deuterons emitted from the different targets. Possible mechanisms for their production are discussed.

$$dN_d(K)/dN_p(K) \propto \frac{4\pi\rho^3}{3}$$

$$\mathcal{P} = |<f|i>|^2$$



Volume 71B, number 1 PHYSICS LETTERS 7 November 1977

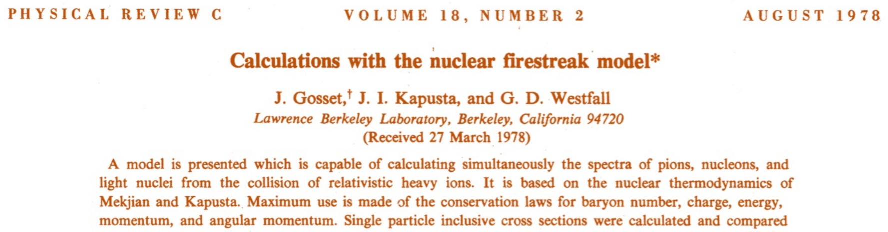
BREAK-UP DENSITIES OF NUCLEAR FIREBALLS*

R. BOND[1], P.J. JOHANSEN, S.E. KOONIN[1]
The Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen Ø, Denmark

and

S. GARPMAN
NORDITA, DK-2100 Copenhagen Ø, Denmark

Received 16 August 1977



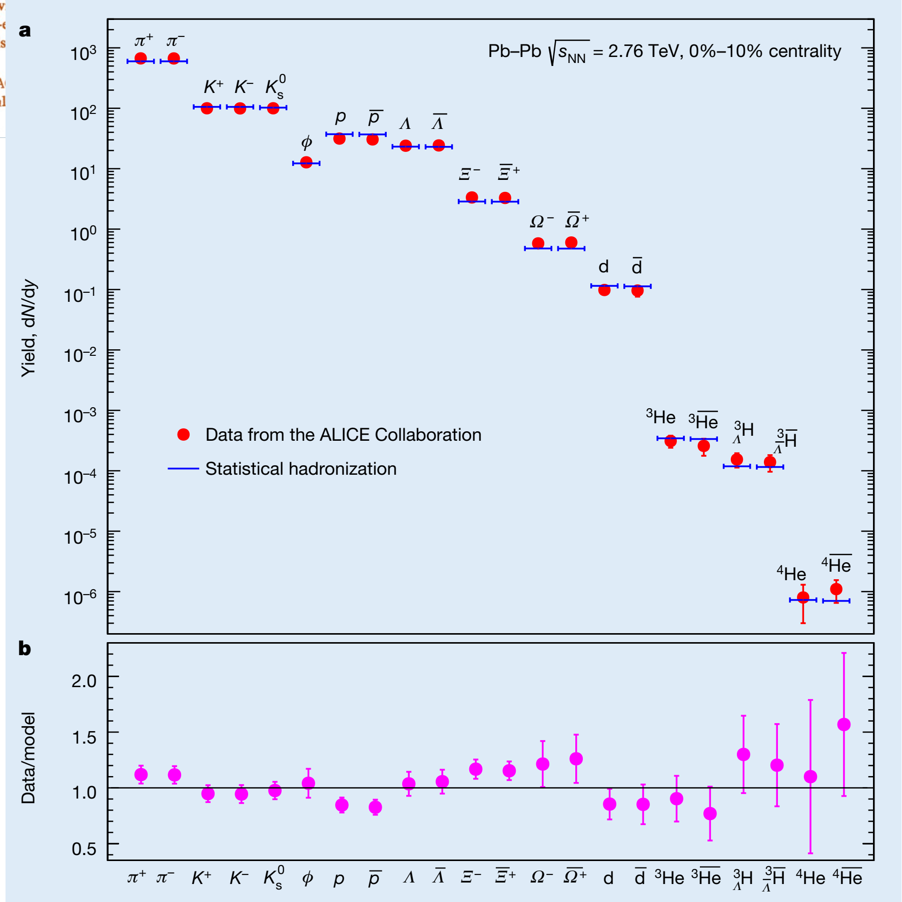
PHYSICAL REVIEW C VOLUME 18, NUMBER 2 AUGUST 1978

Calculations with the nuclear firestreak model*

J. Gosset,† J. I. Kapusta, and G. D. Westfall
Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 27 March 1978)

A model is presented which is capable of calculating simultaneously the spectra of pions, nucleons, and light nuclei from the collision of relativistic heavy ions. It is based on the nuclear thermodynamics of Mekjian and Kapusta. Maximum use is made of the conservation laws for baryon number, charge, energy, momentum, and angular momentum. Single particle inclusive cross sections were calculated and compared
with experiment for a w
normalizations and high-
cease to interact, which is

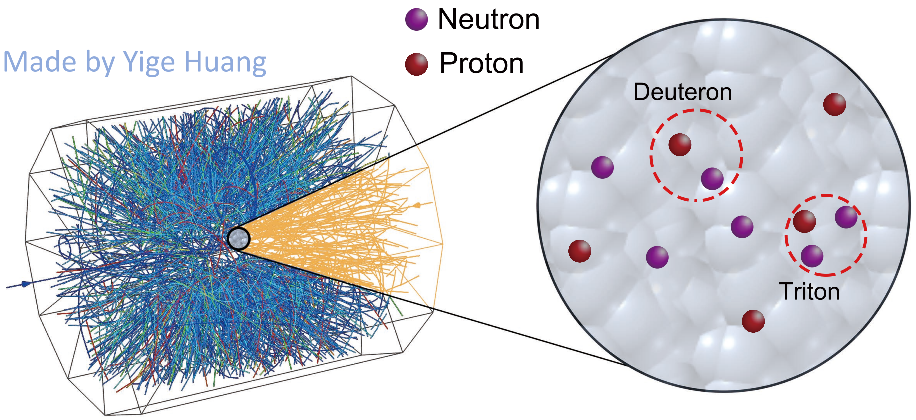
NUCLEAR REA
equilibrium; cal

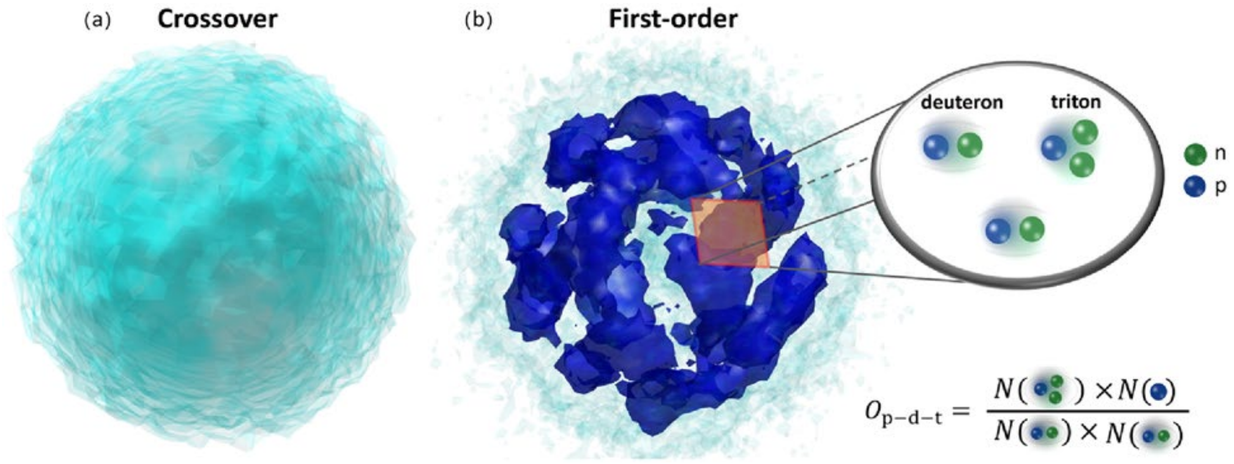


Nature (London) 561, 321 (2018)

Introduction

Searching for QCD Critical Point with LN





Nucleon Coalescence picture:

$$N_d = \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3/2} N_p\langle n\rangle(1 + C_{np})$$

$$N_t = \frac{3^{\frac{3}{2}}}{4}\left(\frac{2\pi}{m_0 T_{eff}}\right)^{3} N_p\langle n\rangle^2(1 + \Delta n + 2C_{np})$$

$$\boxed{N_t \times N_p / N_d^2 = g(1 + \Delta n)}$$

- In the vicinity of the critical point or the first order phase transition, density fluctuations become larger
- In the coalescence picture, nuclear compound yield ratio is sensitive to the baryon density fluctuations and can be used to probe 1st order phase transition and/or critical point in heavy-ion collisions

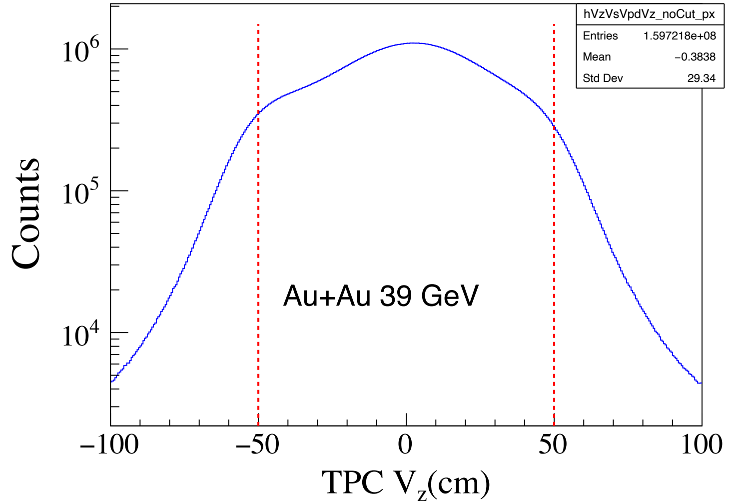
K.-J. Sun, L.-W. Chen, C. M. Ko, J. Pu, and Z. Xu, Phys. Lett. B 781, 499 (2018); E. Shuryak and J. M. Torres-Rincon, Phys. Rev. C 101, 034914 (2020); W. Zhao, K.-j. Sun, C. M. Ko, and X. Luo, Phys. Lett. B 820, 136571 (2021); K.-J. Sun, R. Wang, C. M. Ko, Y.-G. Ma, and C. Shen, (2022), arXiv:2207.12532; Che Ming Ko, Nuclear Science and Techniques (2023) 34:80

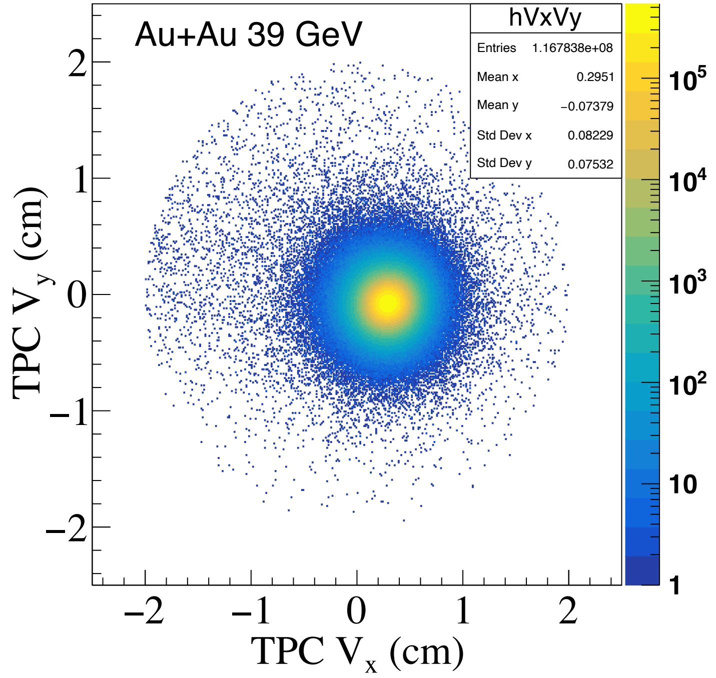
Analysis Details

Datasets

- Event Selection:

Energy(GeV)	Year	Vr(cm)	Vz(cm)	Event(M)
7.7	2010	2	40	2.37
11.5	2010	2	40	8.52
14.5	2014	1	40	16.69
19.6	2011	2	40	19.64
27	2011	2	40	38.42
39	2010	2	40	116.78
54.4[1]	2018	2	40	566.15
62.4	2010	2	40	61.69
200	2011	2	30	465.07



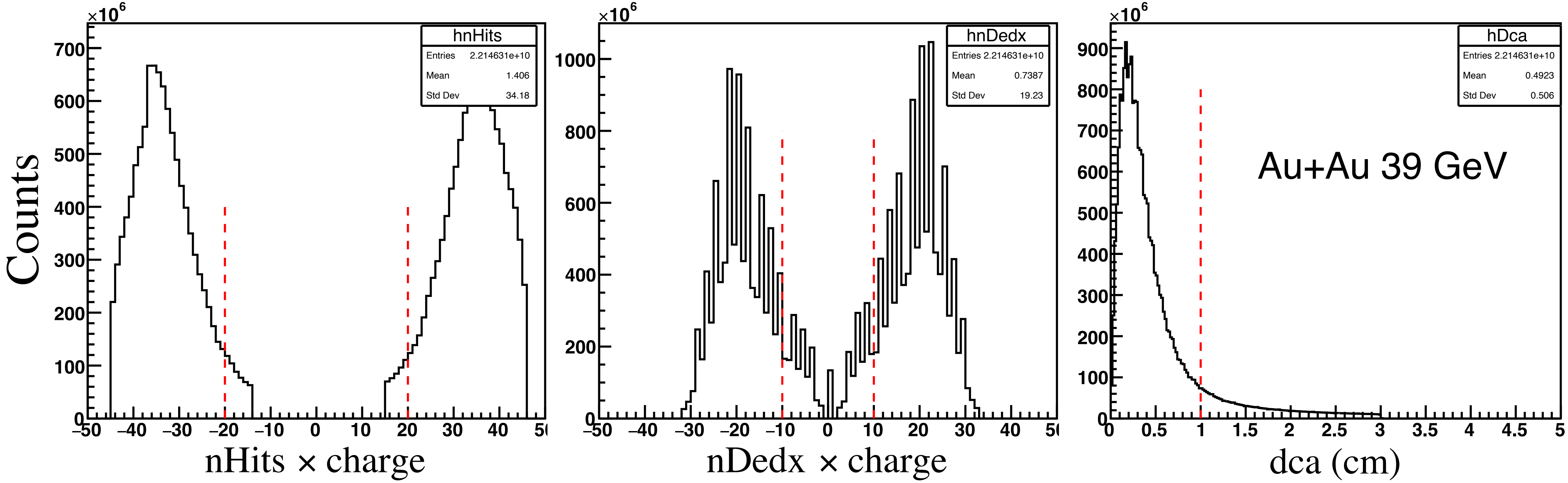


[1] Hui Liu (For the STAR Collaboration), QM2019, Poster ID: 389

Analysis Details Datasets

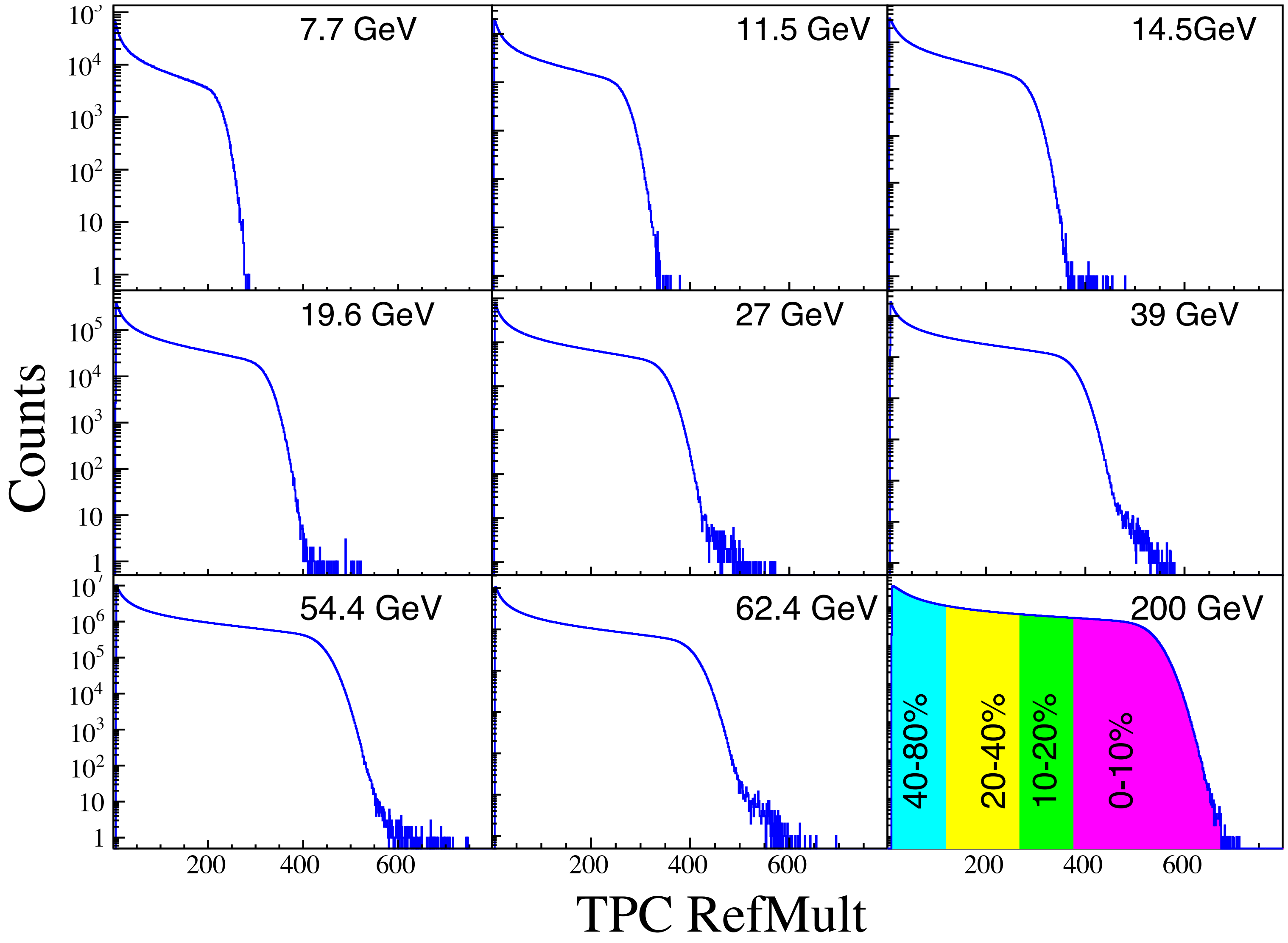
- Track Selection:

$\mathbf{nHits}$	$\mathbf{nHits/nHitsposs}$	$\mathbf{ndEdxHits}$	$\mathbf{DCA}$	$\lvert\eta\rvert$	$\lvert\mathbf{y}\rvert$	p_T
> 20	> 0.52	> 10	< 1 cm	< 1	< 0.5	> 0.2 GeV



Analysis Details

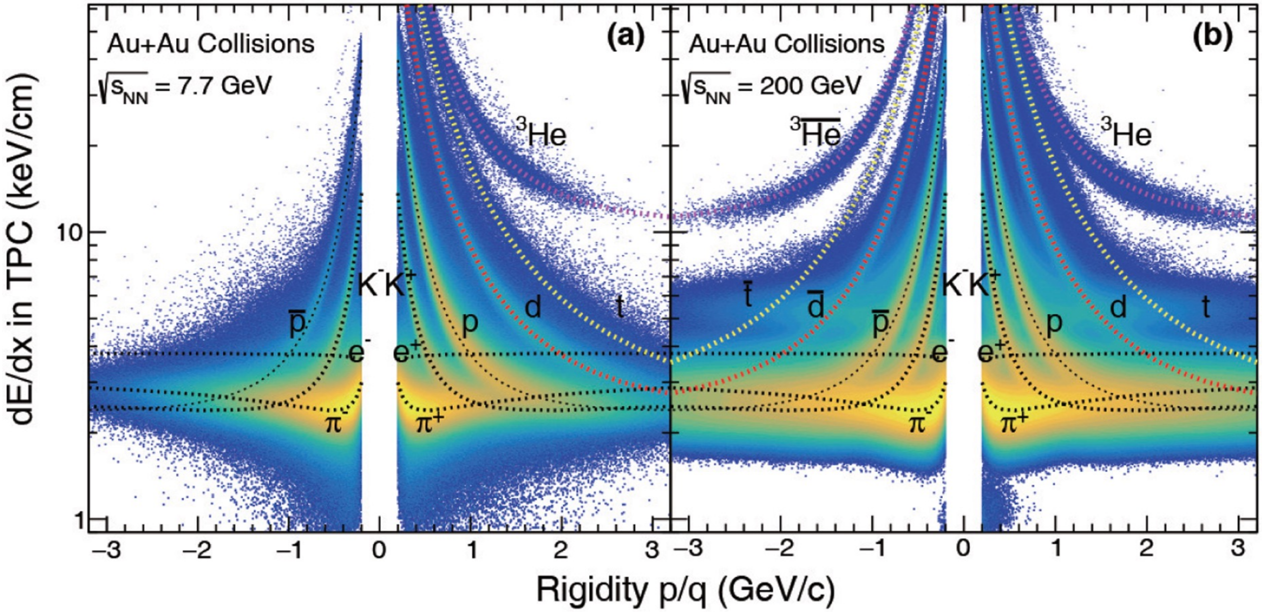
Centrality Determination

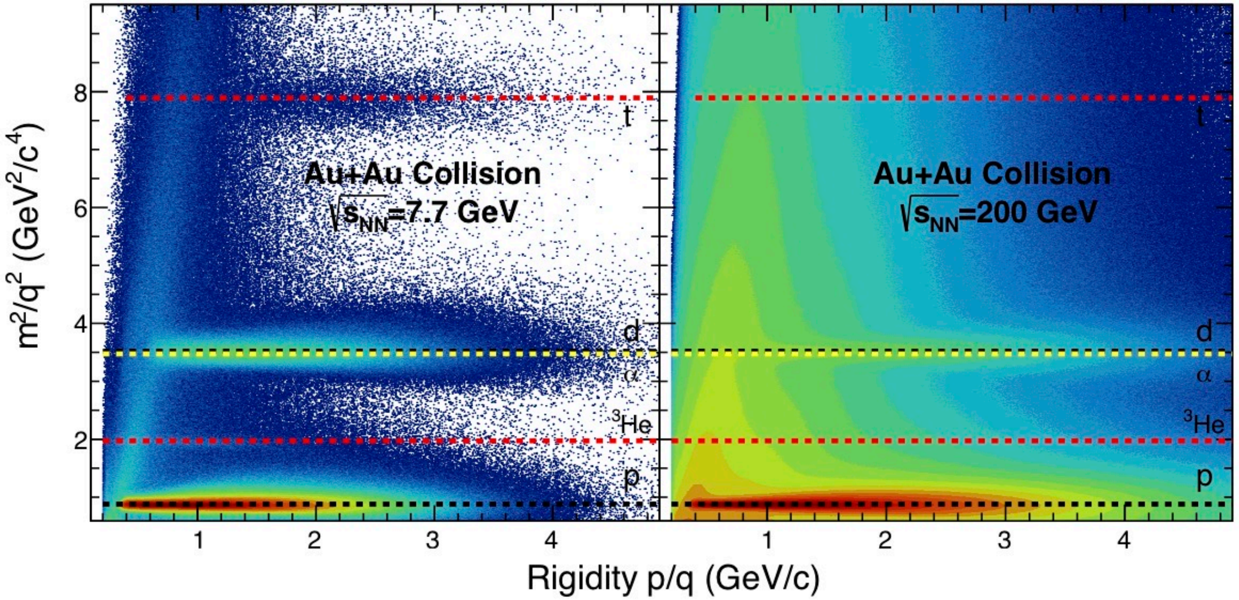


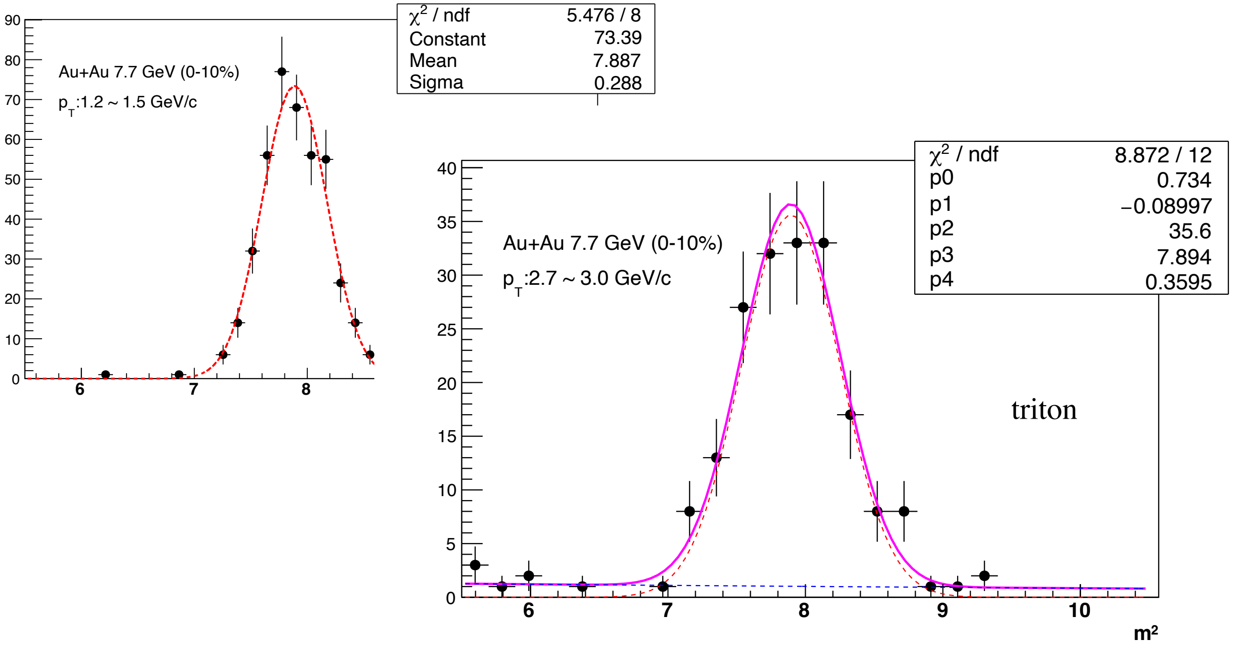
http://www.star.bnl.gov/protected/common/common2010/centrality/index.html.

Analysis Details

Particle Identification & Signal Extraction



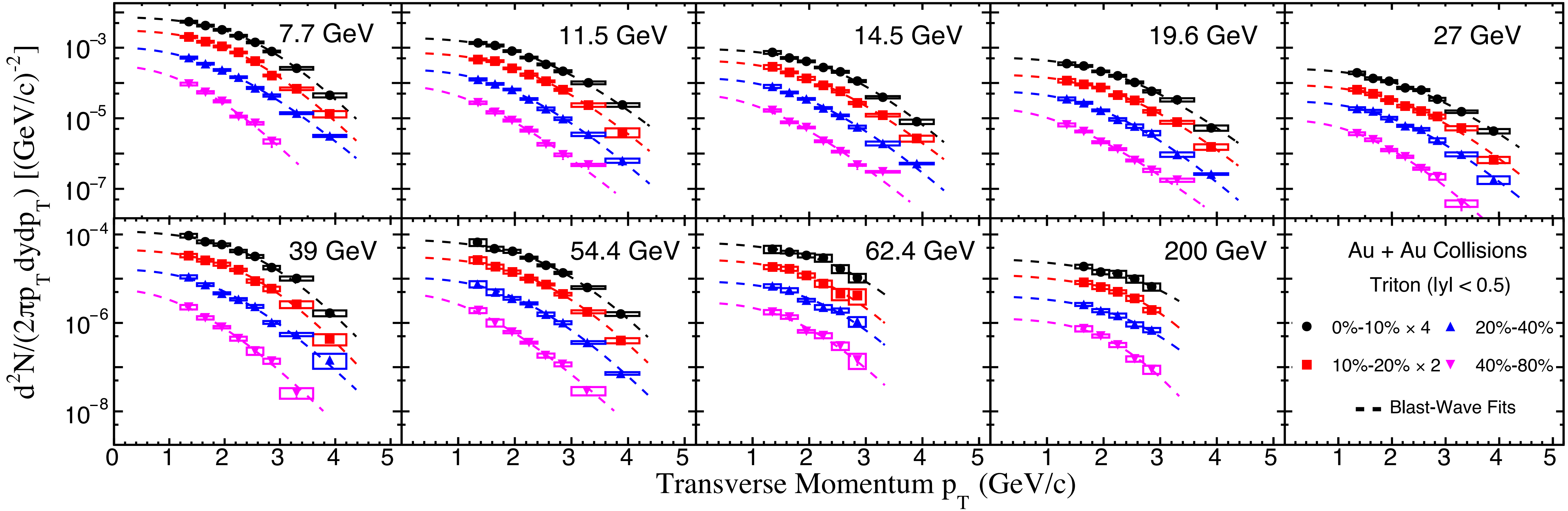




- ✓ **Energy loss corrections**
- ✓ **Absorption corrections**

- ✓ **TPC tracking efficiency**
- ✓ **TOF matching efficiency**

Results Triton p_T Spectra



✯Mid-rapidity ($|y| < 0.5$) transverse momentum distributions for tritons

✯Dashed lines: Blast-wave function fits

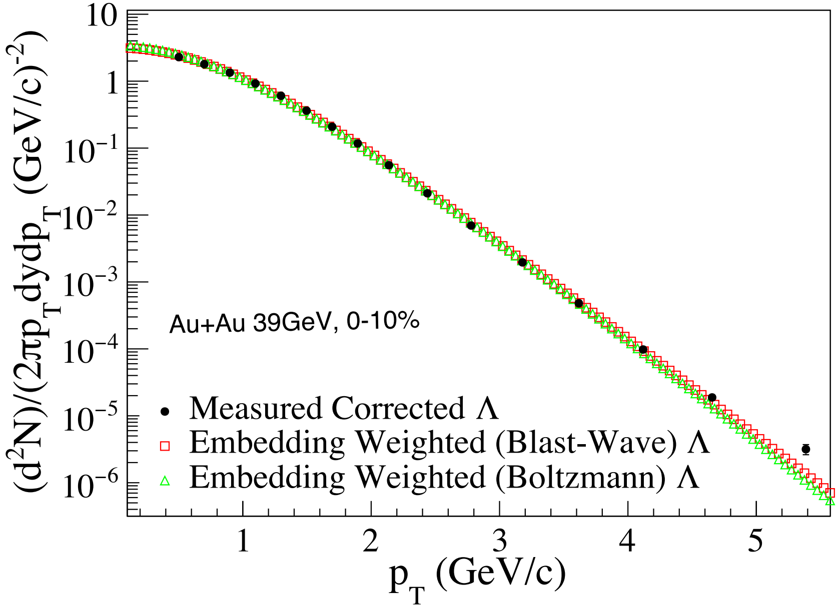
$$\frac{d^2N}{p_T dp_T d_y} \propto \int_0^R r dr m_T I_0\left(\frac{p_T sinh\rho}{T}\right) K_1\left(\frac{m_T cosh\rho}{T}\right)$$

STAR: Phys. Rev. Lett. 130, 202301 (2023)
Blast-Wave Fit: E. Schnedermann, J. Sollfrank, and U. Heinz, PRC 48,2462 (1993)

Analysis Details

Proton Feed-down Corrections

$$\Lambda \longrightarrow p + \pi^-\text{, branching ratio} = 63.9\%$$
$$\Sigma^+ \longrightarrow p + \pi^0\text{, branching ratio} = 51.57\%$$
$$\Xi^- \longrightarrow \Lambda + \pi^-\text{, branching ratio} = 99.887\%$$
$$\Xi^0 \longrightarrow \Lambda + \pi^0\text{, branching ratio} = 99.524\%$$
$$\Omega^- \longrightarrow \Lambda + K^-\text{, branching ratio} = 67.8\%$$

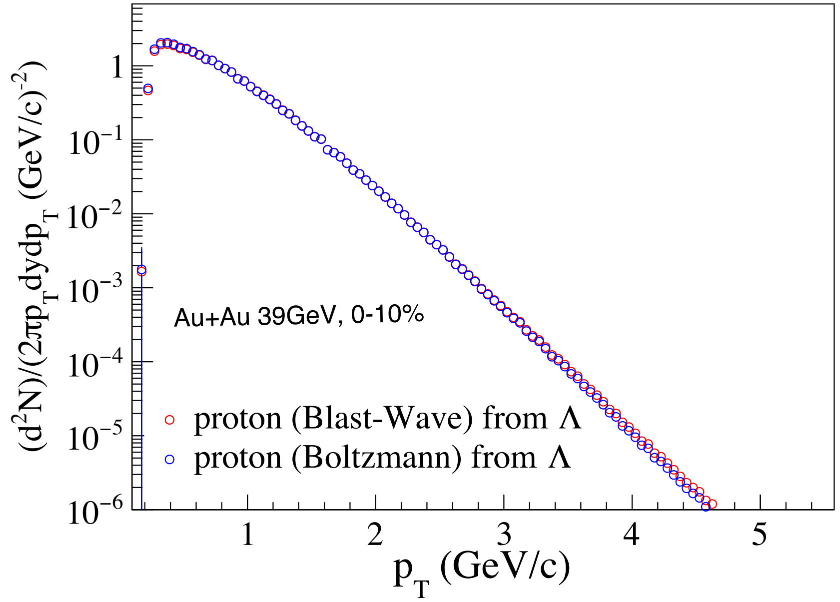


- ➢ Correction Procedure:

① Parameterized the strange hadron and proton spectra by Blast-Wave function

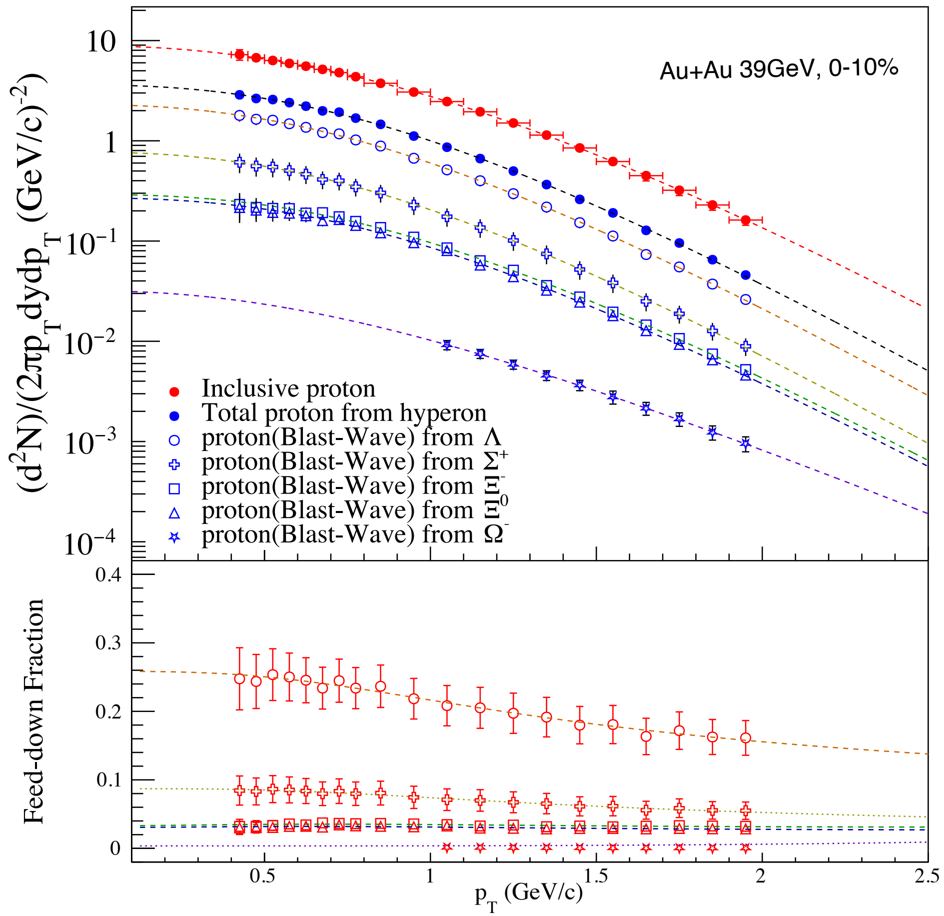
② Weight the embedding input Monte Carlo strange particle to the corrected spectra

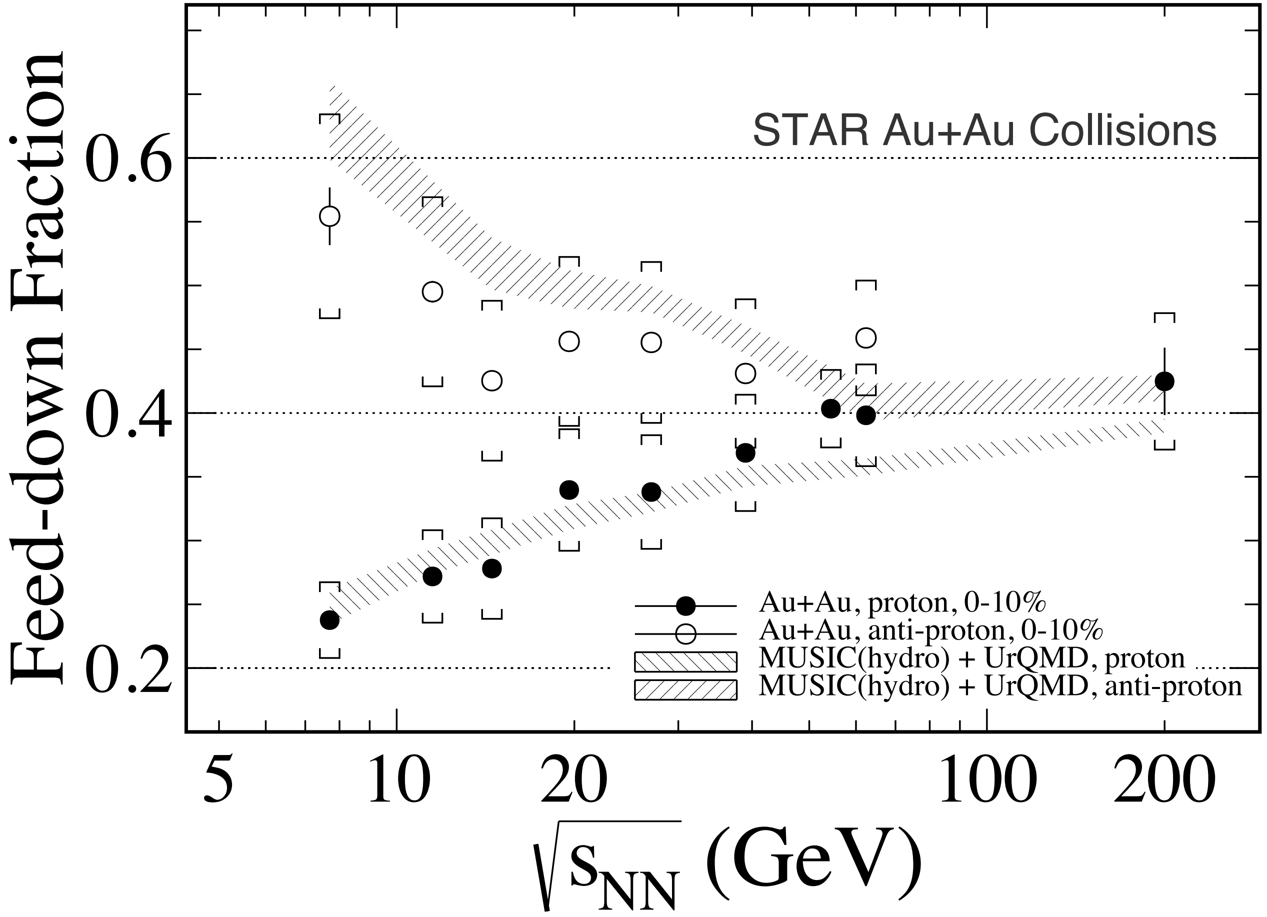
③ Obtain the daughter proton coming from the embedding and scale by the weight factor from step 2.



Analysis Details

Proton Feed-down Corrections





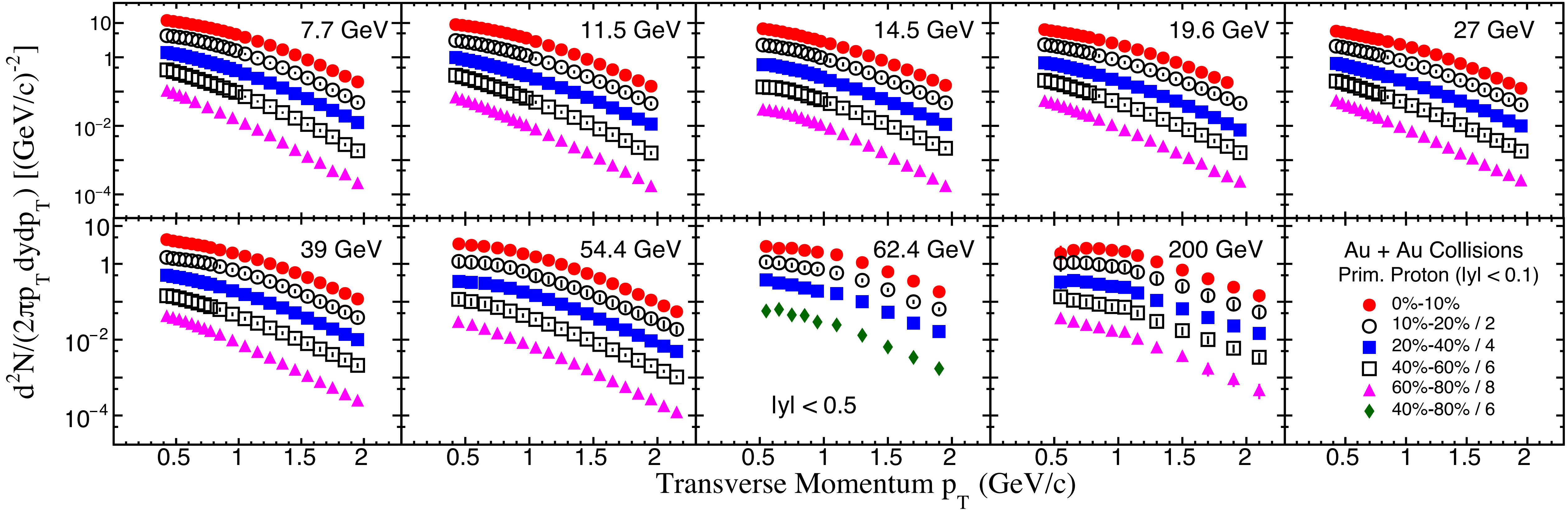
✫Data driven method: Use STAR published strange particle yields

✫From 7.7 – 200 GeV, proton feed-down fraction increases from 25% to 45%

STAR: Phys. Rev. Lett. 130, 202301 (2023); Phys. Rev. Lett. 97, 152301 (2006); Phys Rev. C 102, 034909 (2020)

Results

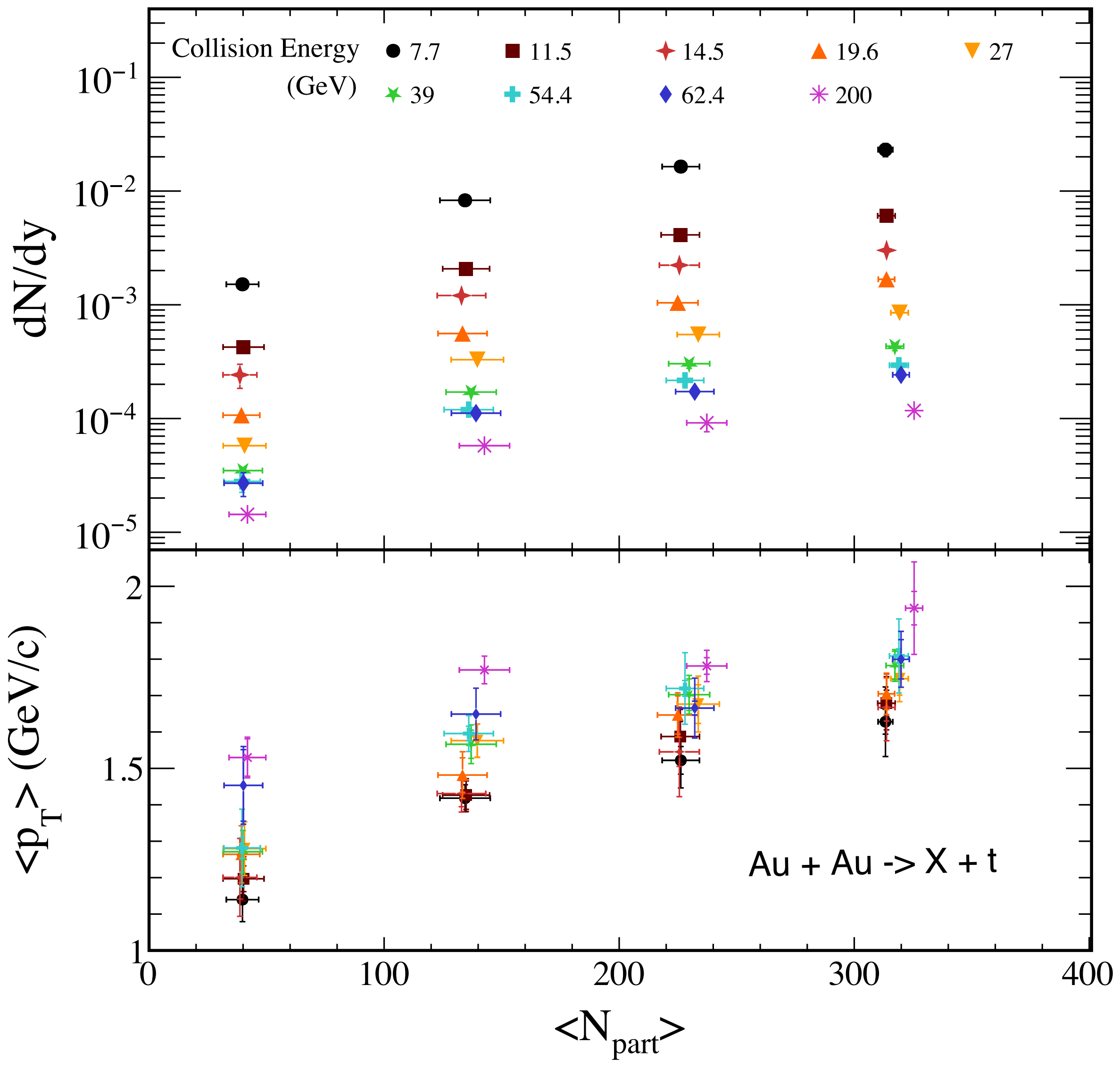
Primordial proton p_T Spectra



✯Mid-rapidity transverse momentum spectra for primordial protons

STAR: Phys. Rev. Lett. 97, 152301 (2006); Phys. Rev. Lett. 130, 202301 (2023)

Centrality Dependence of dN/dy & $< p_T >$

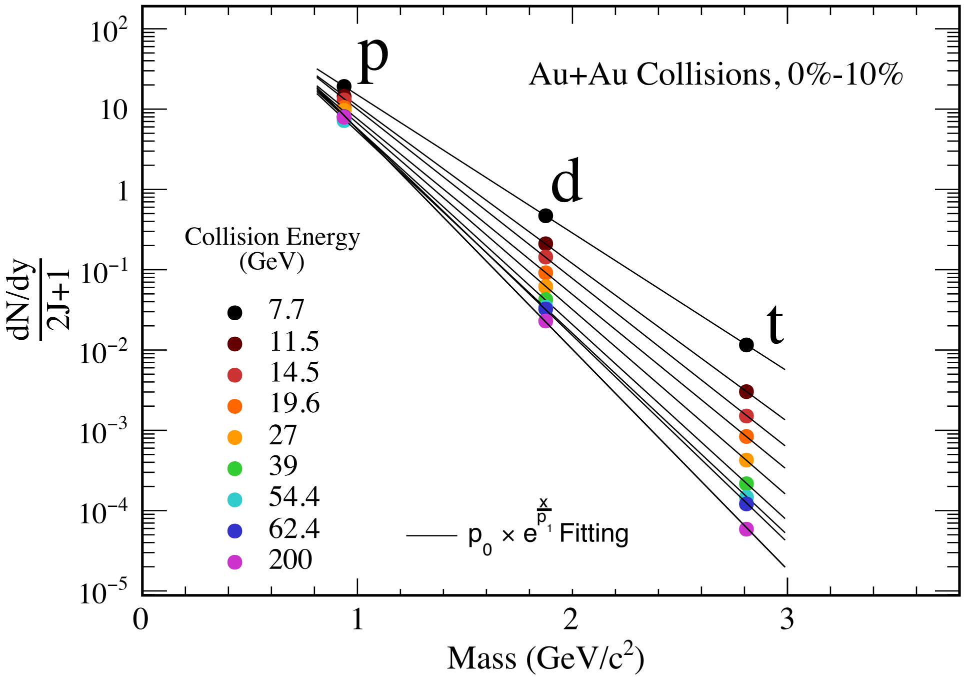


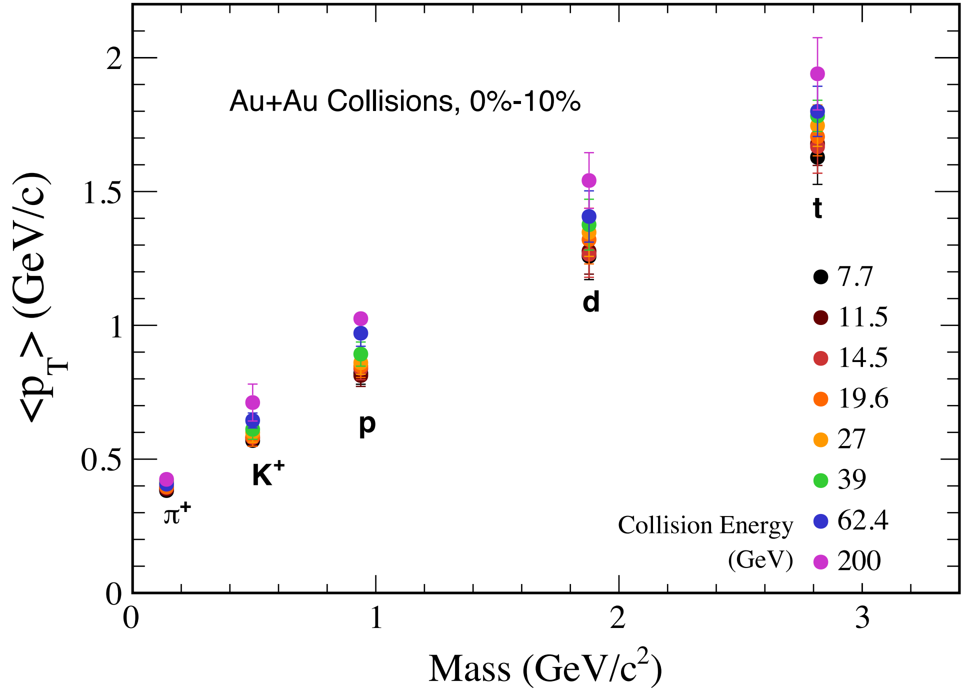
✯dN/dy for tritons increases with decreasing collision energy: yields driven by baryon density

✯$< p_T >$ decreases from central to peripheral collisions and with decreasing collision energy

Results

Centrality Dependence of dN/dy & $< p_T >$





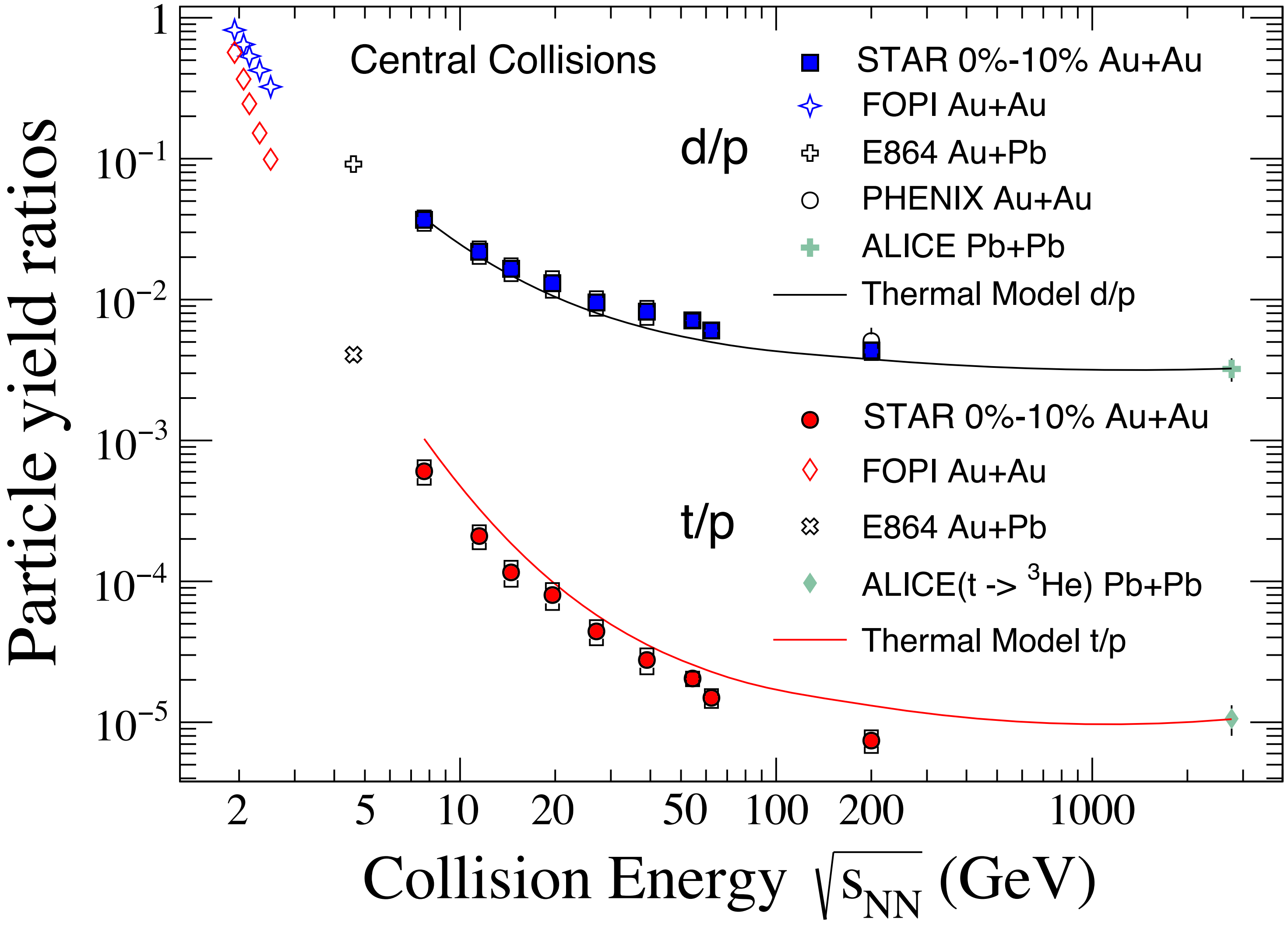
✮Mass dependence of light nuclei yields (divided by the spin degeneracy factor) well described by exponential functions

✮ Average transverse momentum increase with increasing collisions energy and increasing particle mass: influence of radial flow

STAR: Phys. Rev. C 96, 044904 (2017); Phys. Rev. Lett. 97, 152301 (2006); Phys. Lett. B, 655: 104–113, 2007; Phys. Rev. C 101, 024905 (2020); Phys. Rev. Lett. 130, 202301 (2023)

Results

Particle Yield Ratios



✯The triton results follow the trend of the world data, and thermal model overestimates the N_t/N_p ratios

V. Vovchenko, B. Dönigus, B. Kardan, M. Lorenz, and H. Stoecker, Phys. Lett. B , 135746 (2020);

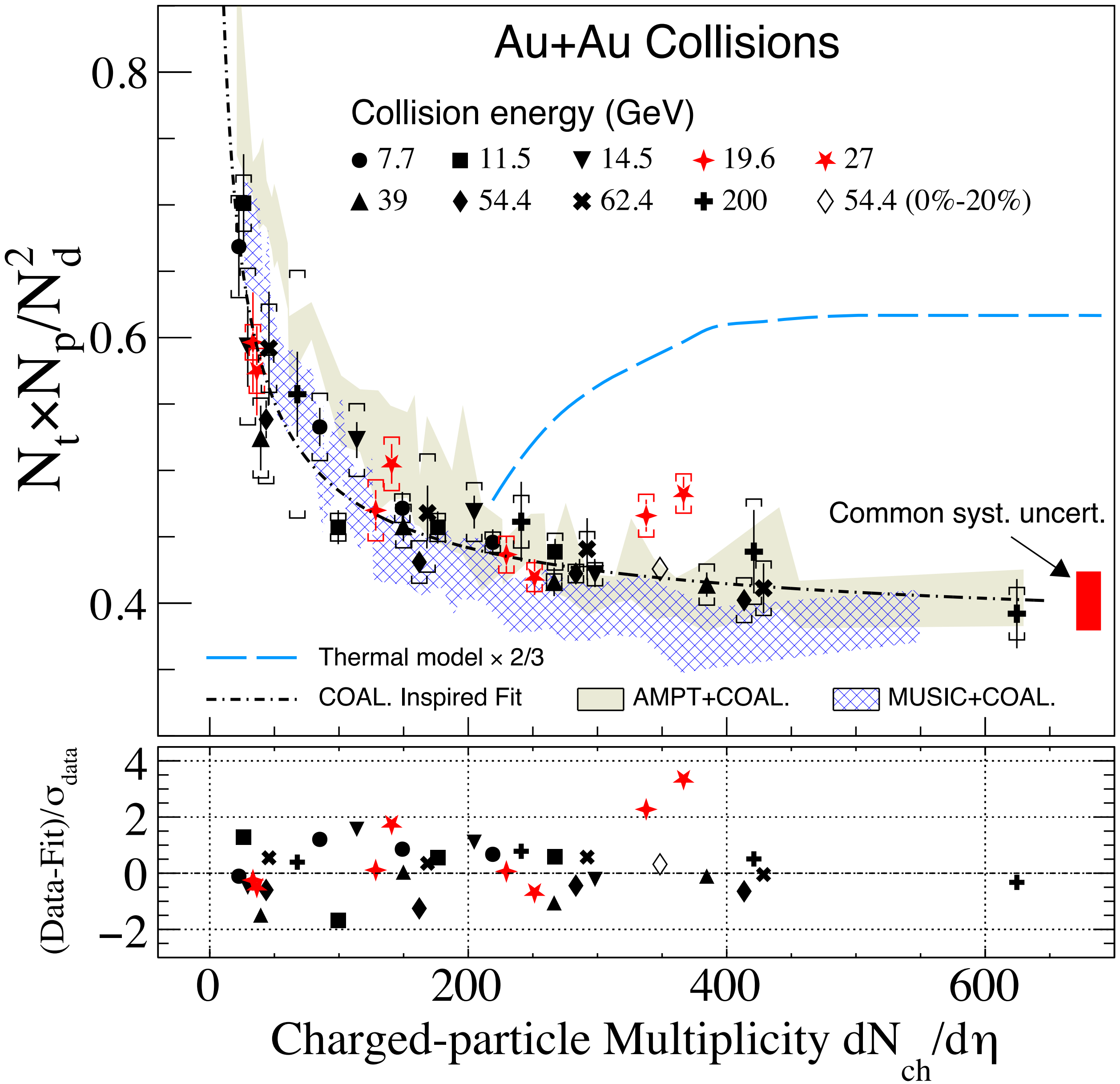
✯The effects of hadronic re-scatterings during hadronic expansion may play an important role in light nuclei production

K.-J. Sun, R. Wang, C. M. Ko, Y.-G. Ma, and C. Shen, (2022), arXiv:2207.12532

STAR: Rev. Lett. Phys. 130, 202301 (2023)
W. Reisdorf et al. (FOPI), Nucl. Phys. A 781, 459 (2007);
T. A. Armstrong et al. (E864), Phys. Rev. C 61, 064908 (2000);
S. S. Adler et al. (PHENIX), Phys. Rev. Lett. 94 , 122302 (2005);
S. S. Adler et al. (PHENIX), Phys. Rev. C 69, 034909 (2004);
J. Adam et al. (ALICE), Phys. Rev. C 93, 024917 (2016)

Results

$dN_{ch}/d\eta$ Dependence of LN Yield Ratio



✯The ratio monotonically decreases with increasing $dN_{ch}/d\eta$ and exhibits a scaling behavior: trend driven by interplay between the size of light nuclei and the size of fireball created in HIC

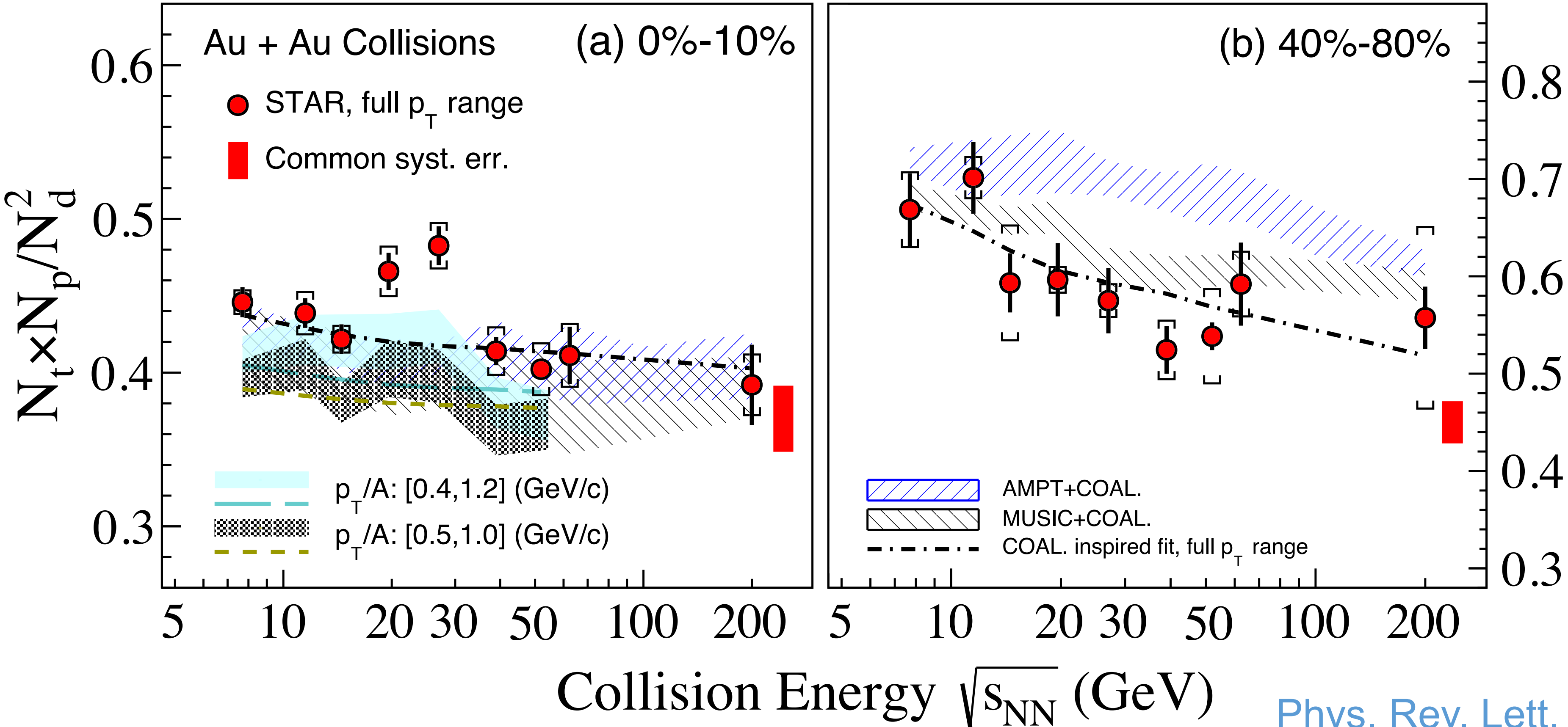
✯The ratio can be described by the coalescence model, but thermal model overestimates the data

✯The ratios at 19.6 and 27 GeV from 0%-10% centrality show enhancements to the coalescence baseline with a combined significance of 4.1 σ

Phys. Rev. Lett. 130, 202301 (2023)

Results

Energy Dependence of Light Nuclei Yield Ratio



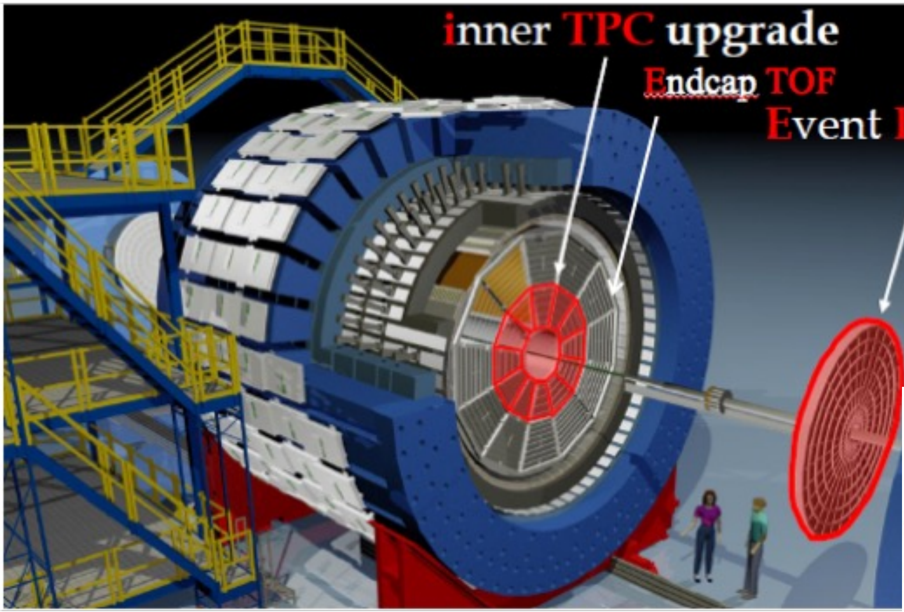
Phys. Rev. Lett. 130, 202301 (2023)

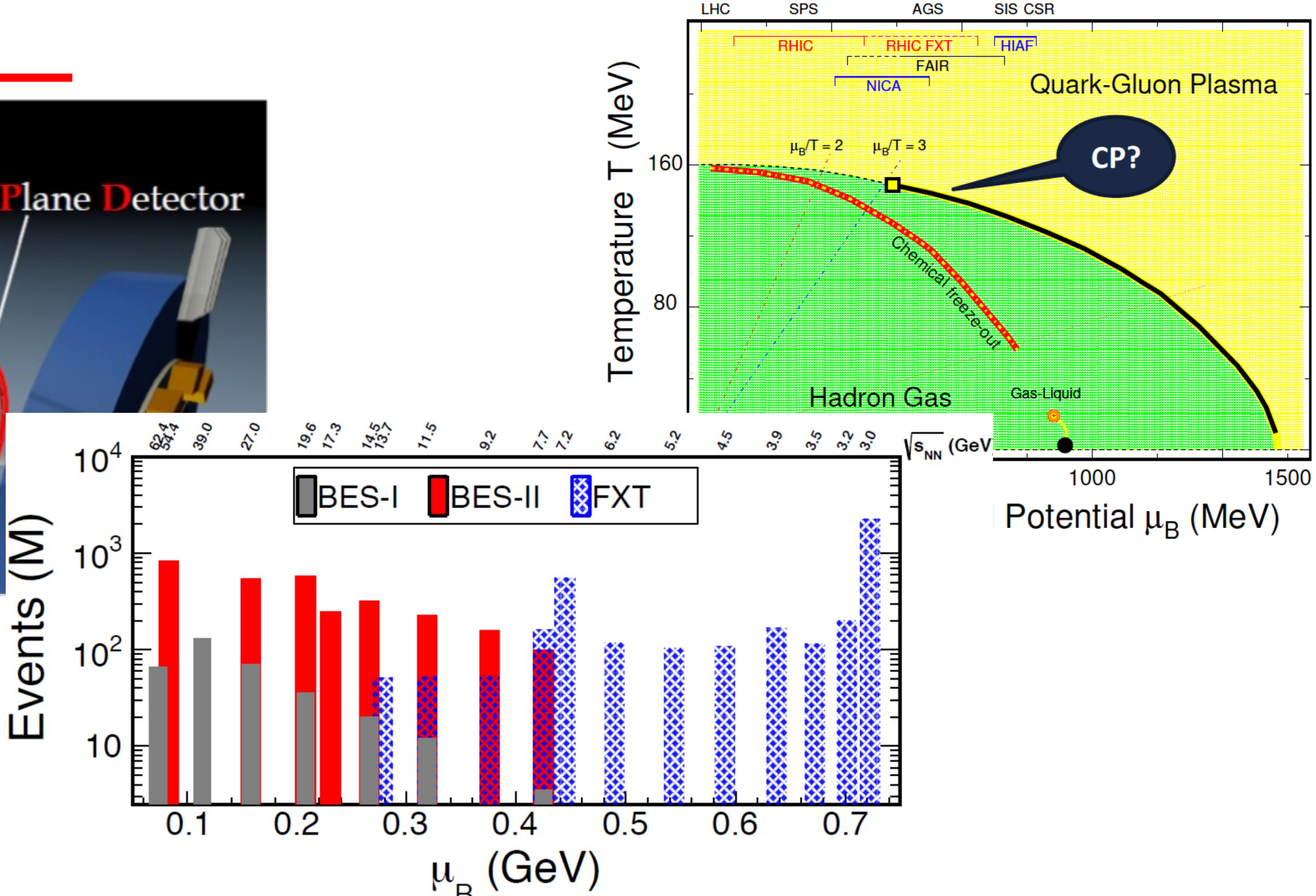
✭Non-monotonic behavior observed in the energy dependence of the yield ratio from 0%-10% central Au+Au collisions around 19.6 and 27 GeV

✭The yield ratio in peripheral (40%-80%) collisions exhibits a monotonic trend and the data can be well described by coalescence models within uncertainties

✭The significance of the enhancements decreases with decreasing p_T acceptance in the region of interest

Outlook





Mapping out the QCD phase structure at high baryon density with high precision:

(1) RHIC BES-II : Collider ($\sqrt{s_{NN}}$ =7.7 - 19.6 GeV) and FXT ($\sqrt{s_{NN}}$ = 3 - 7.7 GeV) mode

Stay tuned for the exciting physics from High Baryon Density !

Summary

✯We report triton and primordial proton production in Au+Au collisions from RHIC-STAR BES-I

✯The thermal model can describe the N_d/N_p ratio but not N_t/N_p ratio.

✯The light nuclei yield ratio ($N_t{\times}N_p/N_d^2$) decreases monotonically with increasing $dN_{ch}/d\eta$ and exhibits a scaling behavior, which can be well described by the coalescence model. However, the thermal model over estimates the N_t/N_p and $N_t{\times}N_p/N_d^2$ ratio at RHIC energies, possibly due to the effect of hadronic re-scatterings during the hadronic expansion stage.

✯Relative to the coalescence baseline, enhancements of the yield ratio $N_t{\times}N_p/N_d^2$ are observed in the 0%-10% most central collisions at 19.6 and 27 GeV with a combined significance of 4.1σ. The enhancements are not observed in peripheral collisions and in model calculations without critical fluctuations.

Thank you!