Light Nuclei Production and Yield Ratio（$N_t \times N_p / N_d^2$） in Au+Au Collisions at RHIC

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South China Normal University

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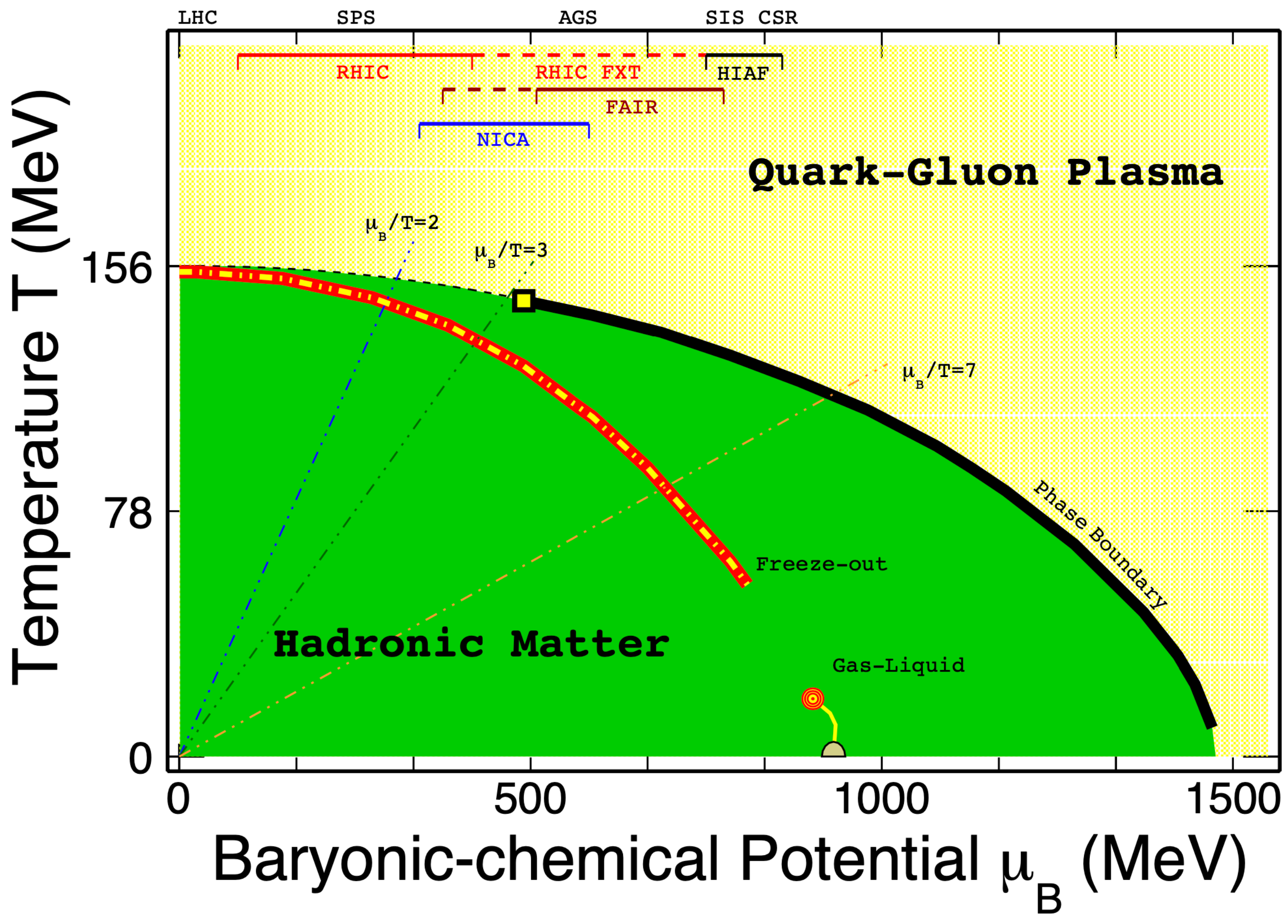
Outline

- **Introduction**
- **Analysis Details**
  - Triton Production
  - Proton Feed-down Corrections
- **Results**
  - Particle Yields
  - Coalescence Parameters
  - Light Nuclei Yield Ratios
- **Summary and Outlook**

QCD Phase Diagram



1) High temperature:

QGP properties

2) High baryon density:

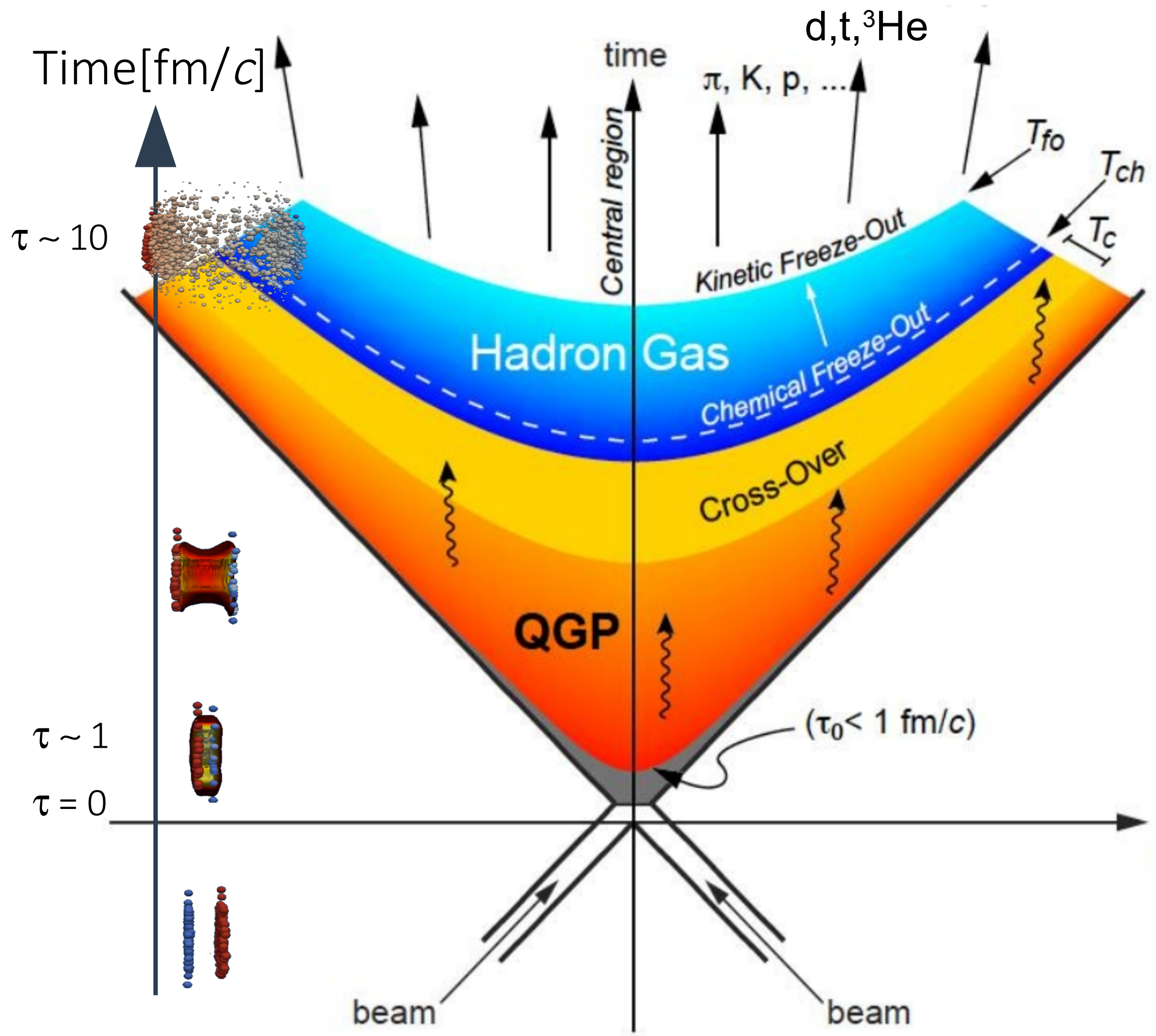
First-order phase boundary and critical point

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

Mechanisms of Light Nuclei in HIC

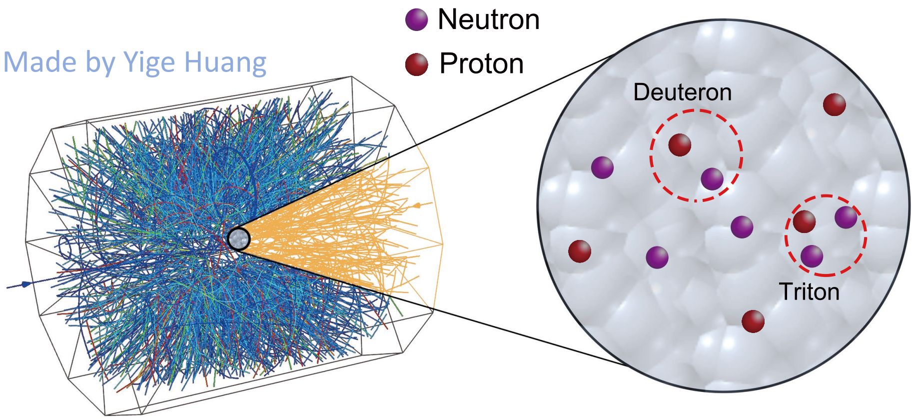


- Our understanding of the production mechanisms of light nuclei in relativistic heavy-ion collisions are currently incomplete

- Thermal emission
  $N_i = \frac{g_i V}{\pi^2} m_i^2 T K_2(m/T) e^{(\mu_i/T)}$
- 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
  $\pi NN \leftrightarrow \pi d, NNN \leftrightarrow Nd, NN \leftrightarrow \pi d \dots\dots$

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), Nature Commun. 15 no.1, 1074 (2024)

LN - Neutron Density Fluctuations



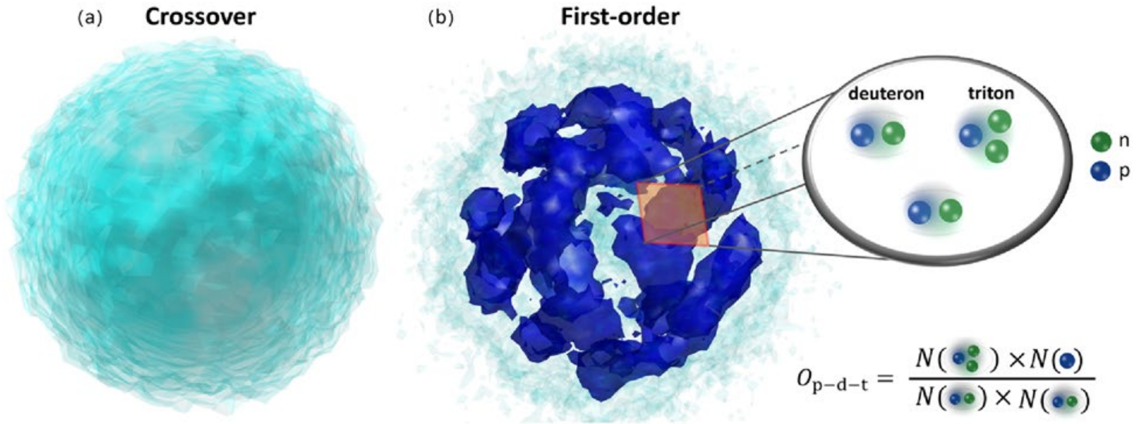
Coalescence picture：

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

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

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

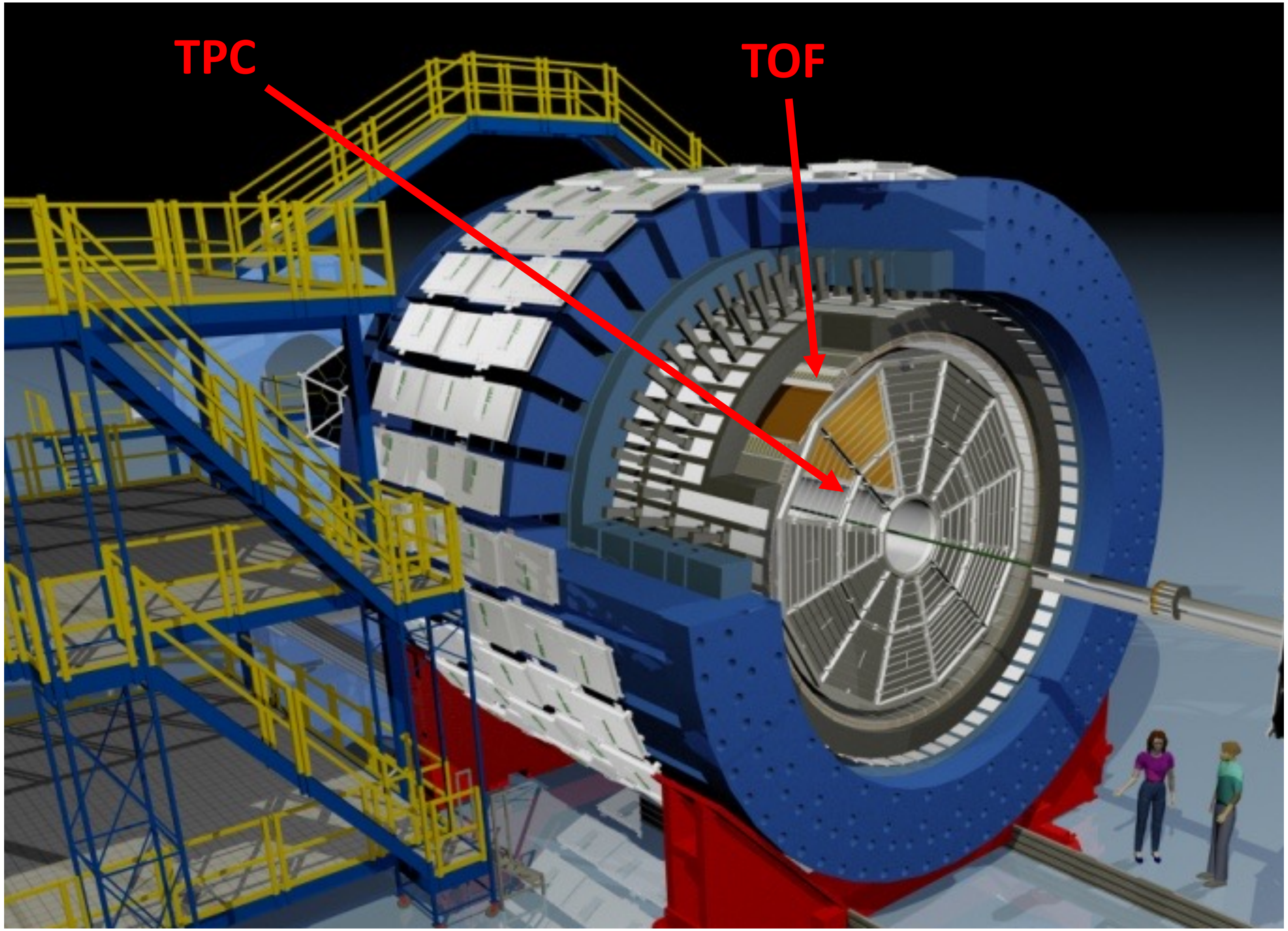
- In the vicinity of the critical point or the first order phase transition, density fluctuations become larger
- In the nucleon coalescence picture, nuclear compound yield ratio is sensitive to the baryon density fluctuations and can be used to probe 1st order phase transition and/or critical point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



K.-J. Sun, L.W. Chen, C. M. Ko, J. Pu, and Z. Xu, Phys. Lett. B 781, 499 (2018)
Che Ming Ko, Nuclear Science and Techniques (2023) 34:80

Analysis Details

The Solenoidal Tracker At RHIC (STAR)



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

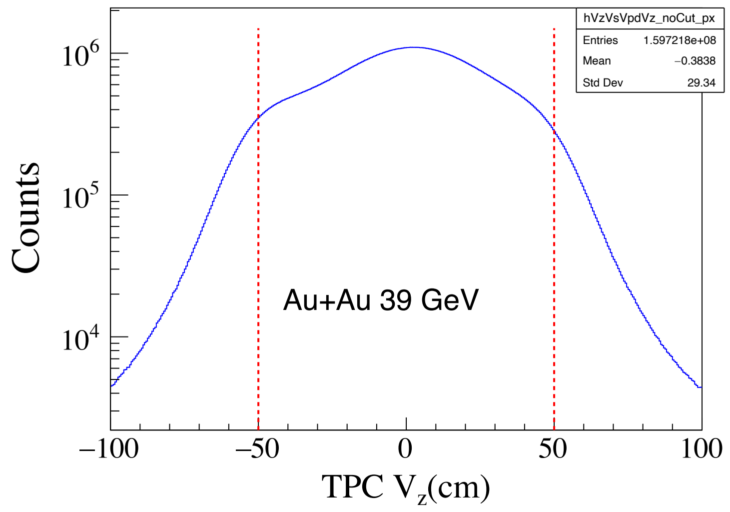
Analysis Details

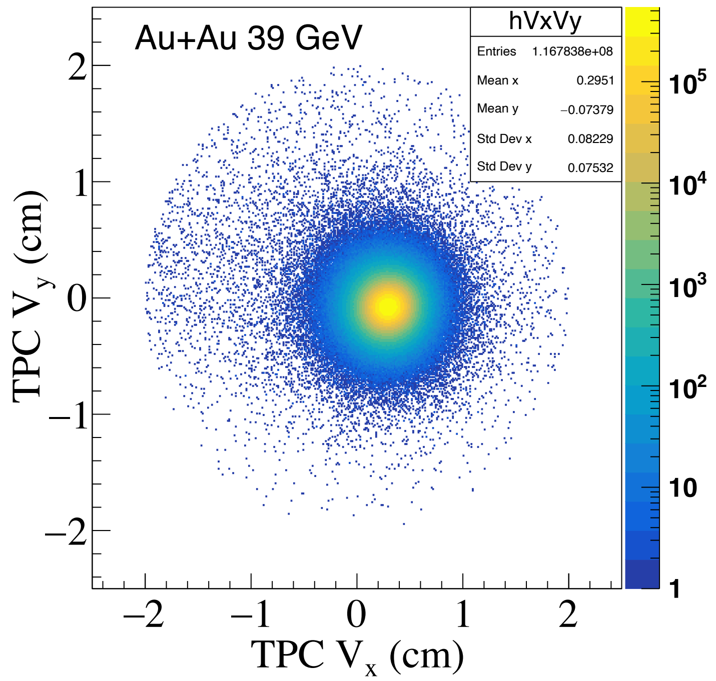
Datasets

- 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

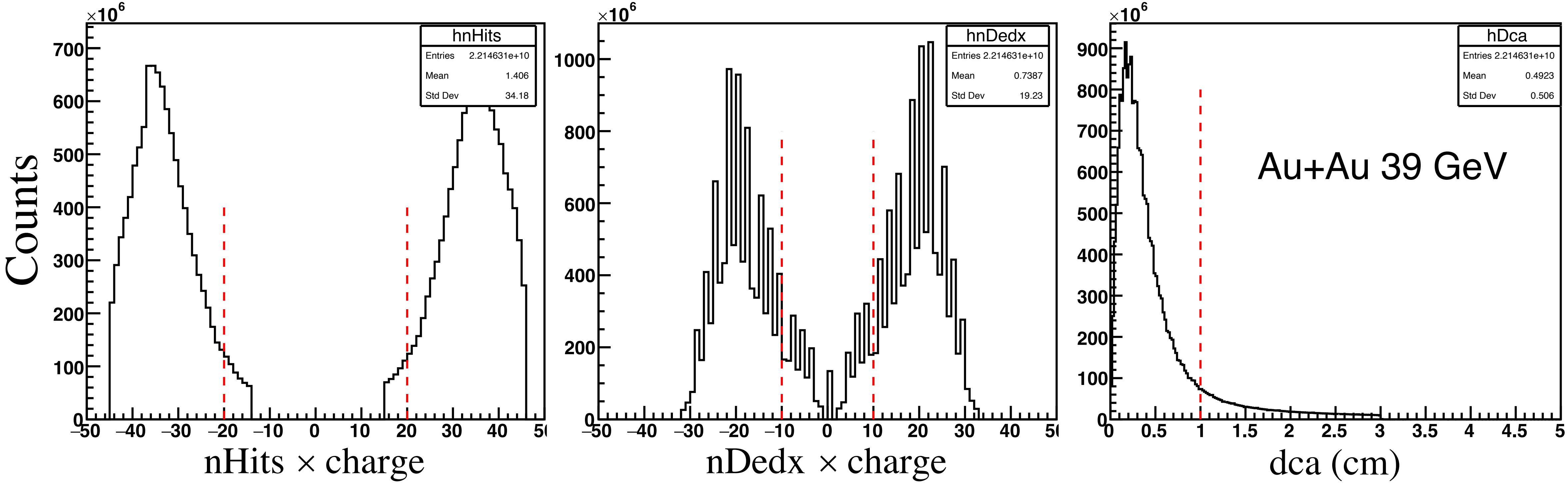
[1] Hui Liu (For the STAR Collaboration), QM2019, Poster ID: 389



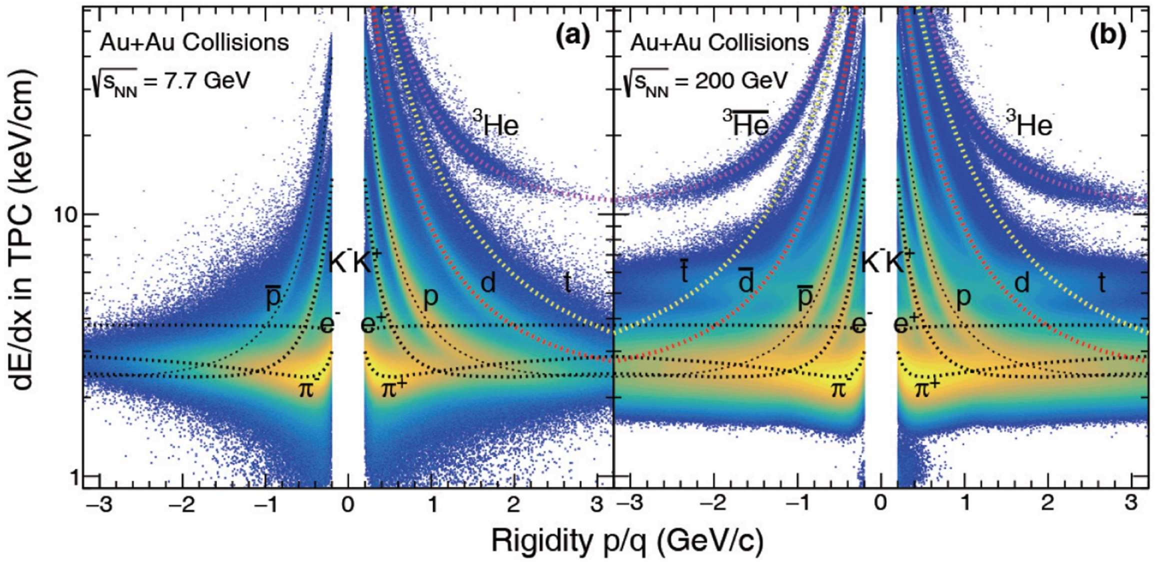


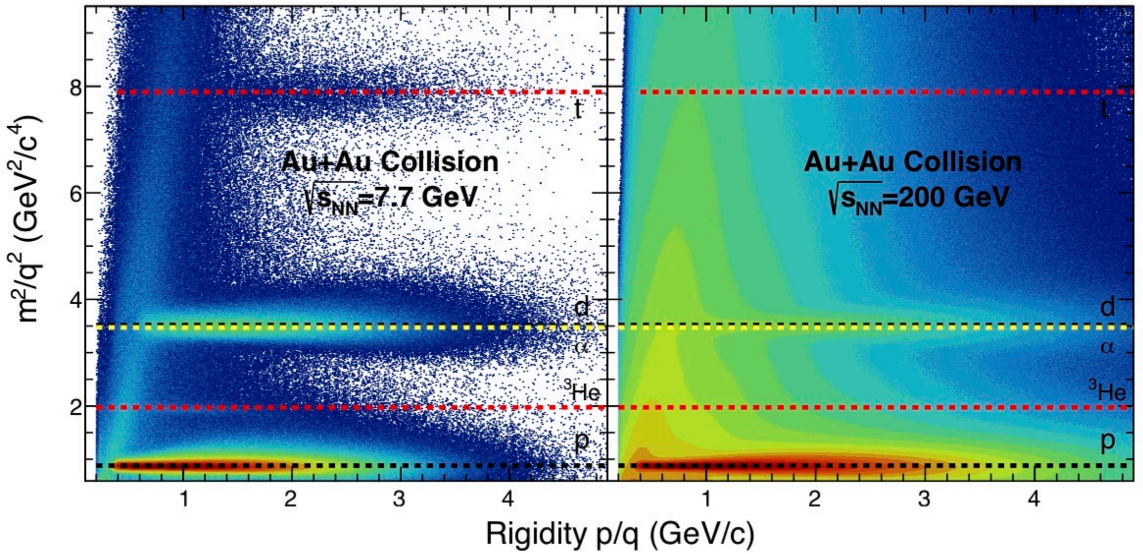
- Track Selection:

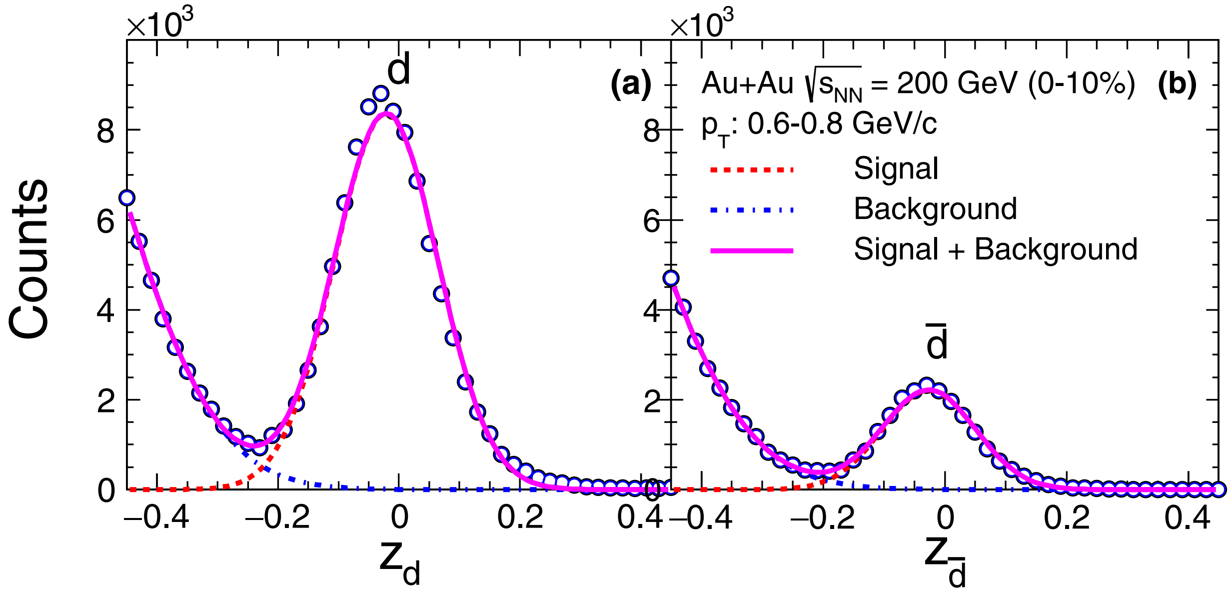
nHits	nHits/nHitsposs	ndEdxHits	DCA	$\|\eta\|$	$\|y\|$	p_T
> 20	> 0.52	> 10	< 1 cm	< 1	< 0.5	> 0.2 GeV

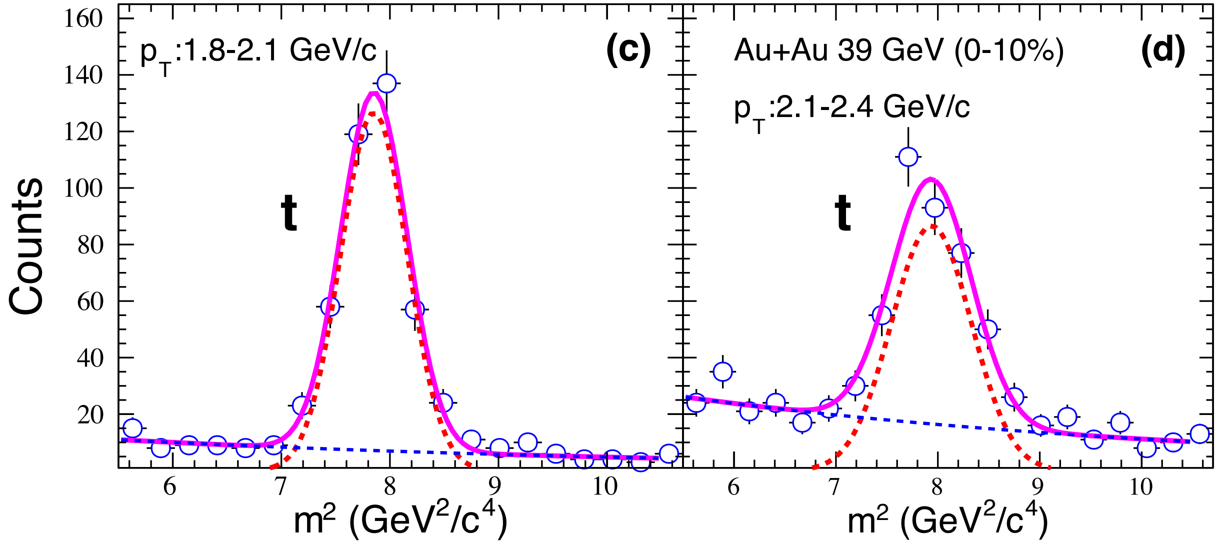


Analysis Details — Particle Identification & Signal Extraction



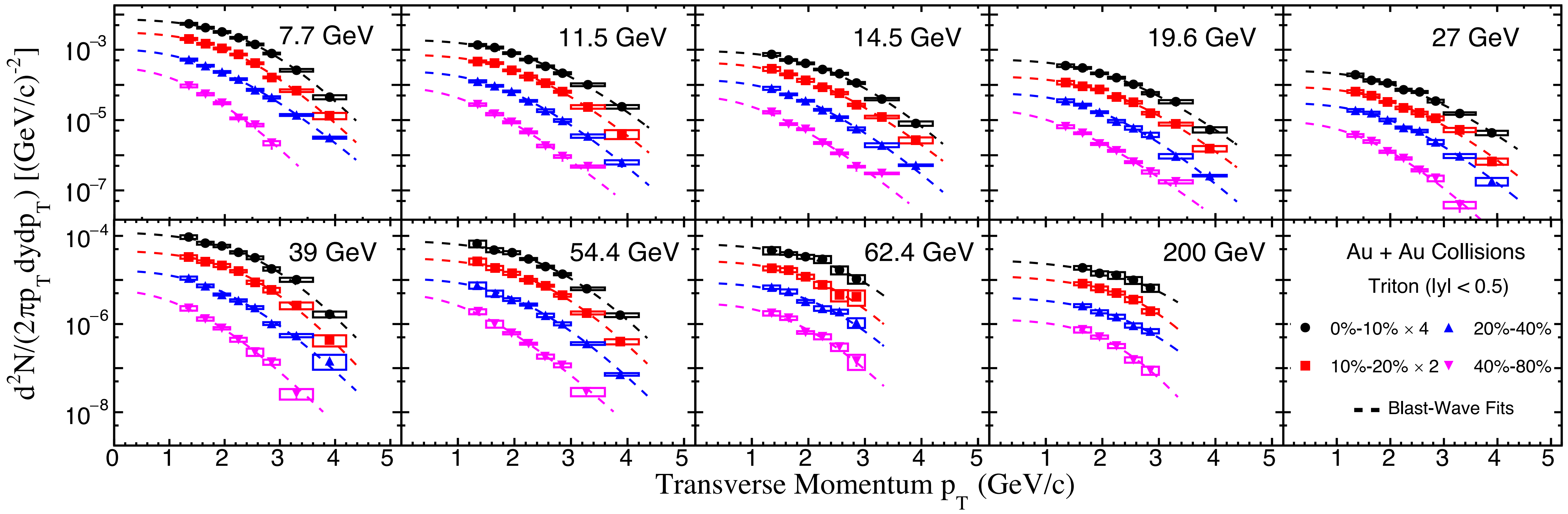






Results

Triton p_T Spectra



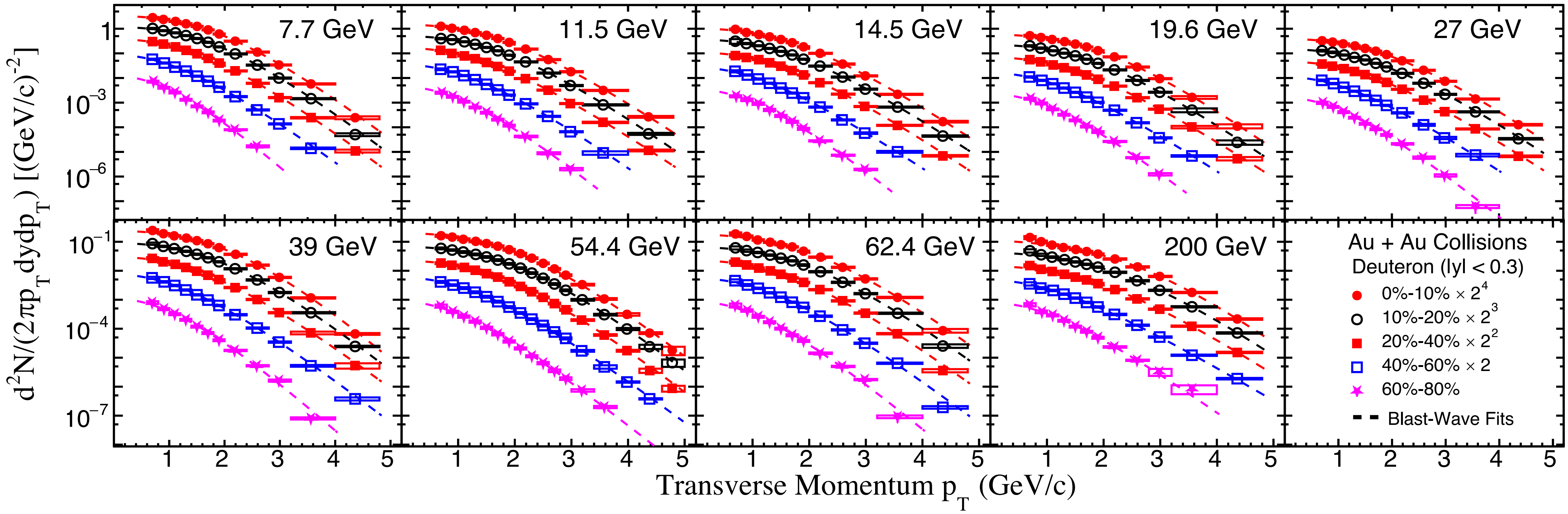
✮Mid-rapidity ($|y| < 0.5$) transverse momentum distributions for tritons

✮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)

Deuteron p_T Spectra

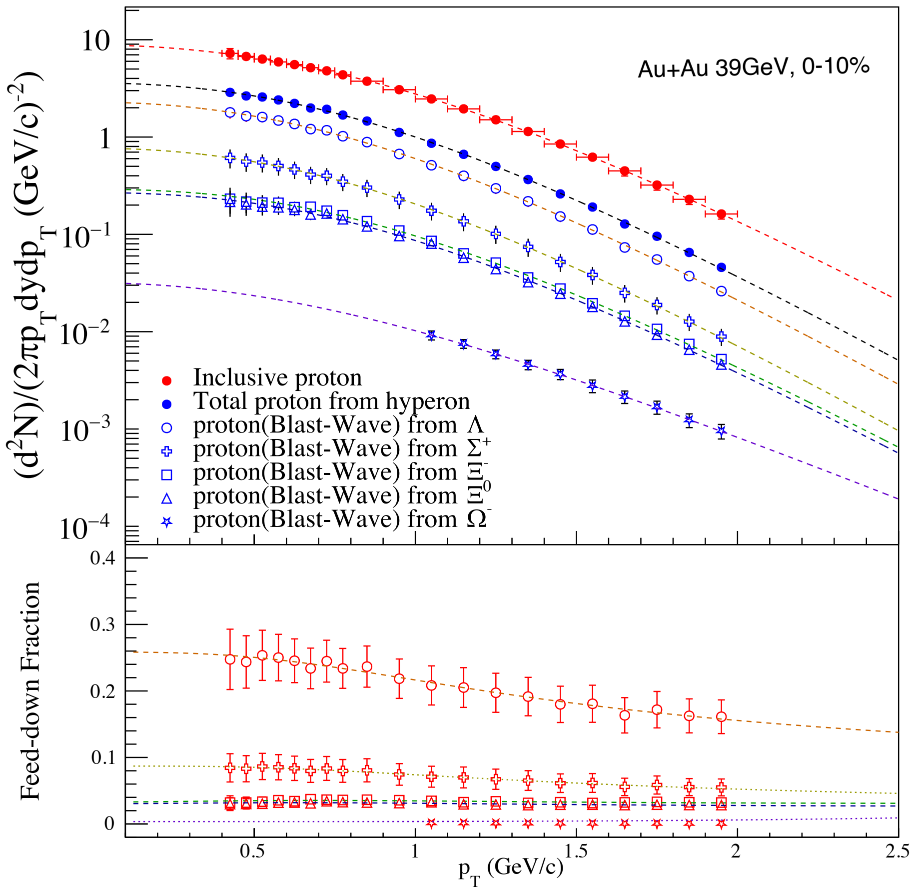


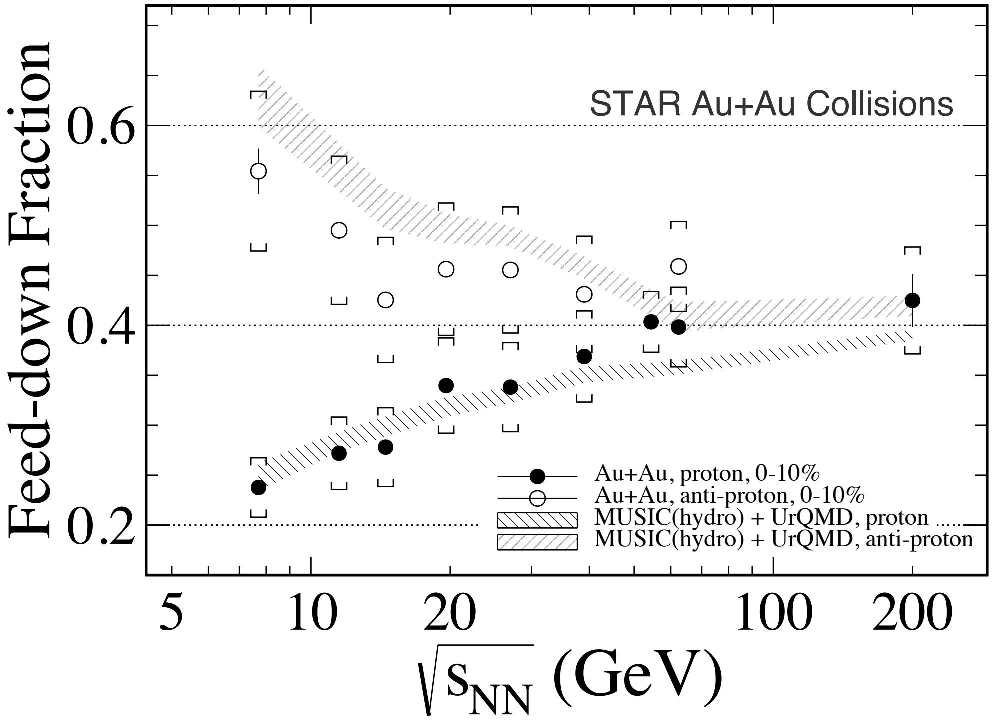
✯Mid-rapidity ($|y| < 0.3$) transverse momentum distributions for deuterons

✯Dashed lines: Blast-wave function fits

STAR: Phys. Rev. C 99, 064905 (2019)

Results   Proton Feed-down Corrections





$\Lambda \longrightarrow p + \pi^-$, branching ratio = 63.9%

$\Sigma^+ \longrightarrow p + \pi^0$, branching ratio = 51.57%

$\Xi^- \longrightarrow \Lambda + \pi^-$, branching ratio = 99.887%

$\Xi^0 \longrightarrow \Lambda + \pi^0$, branching ratio = 99.524%

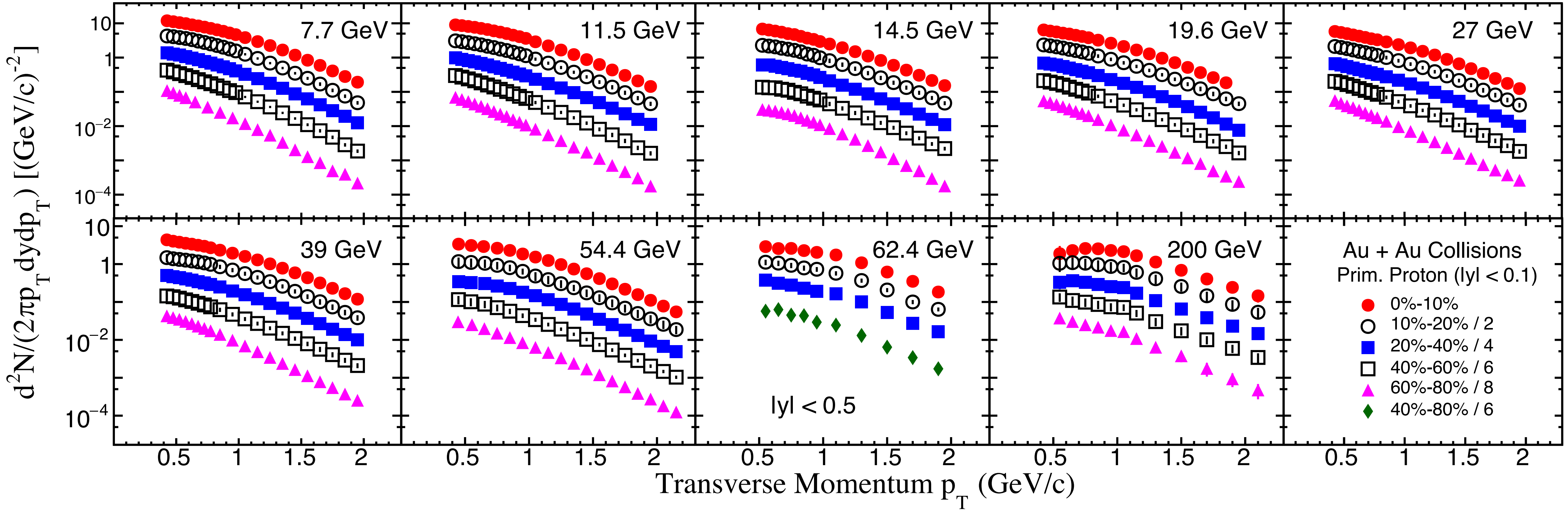
$\Omega^- \longrightarrow \Lambda + K^-$, branching ratio = 67.8%

✯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)

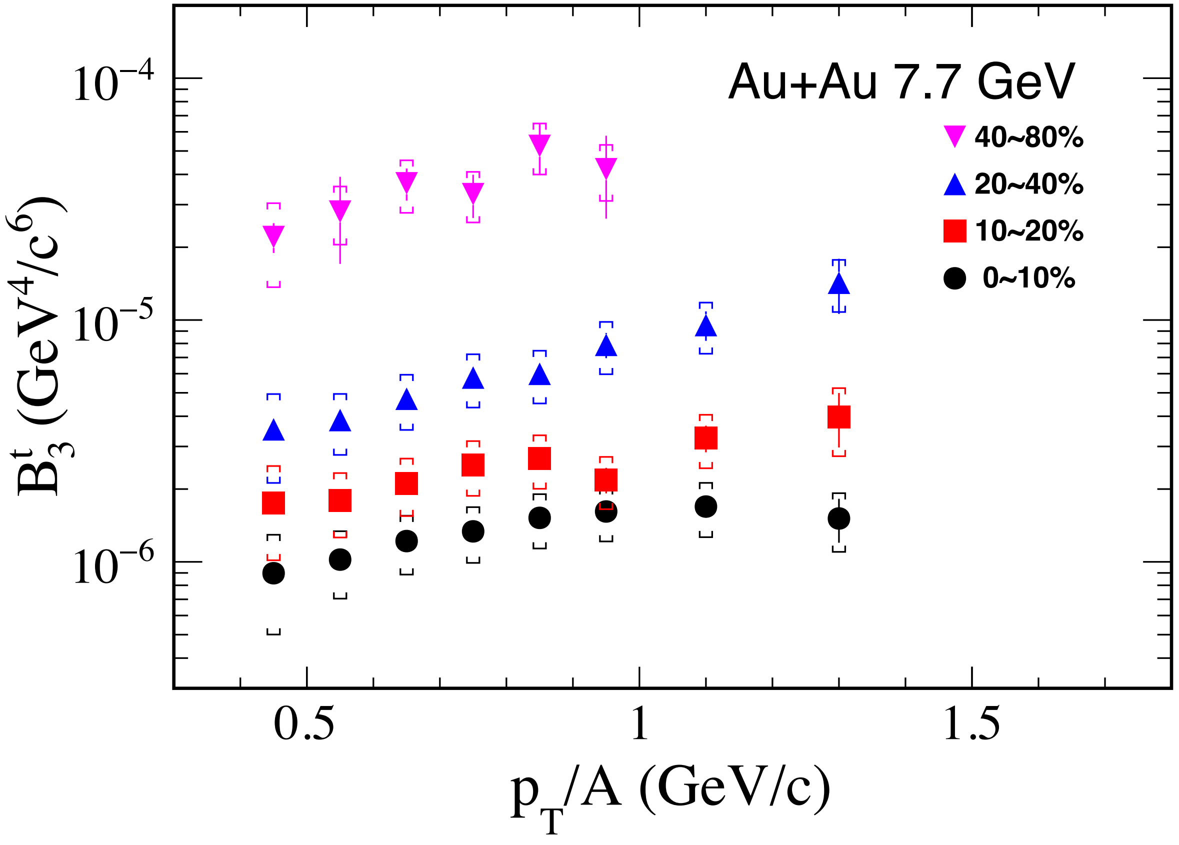
Primordial proton p_T Spectra

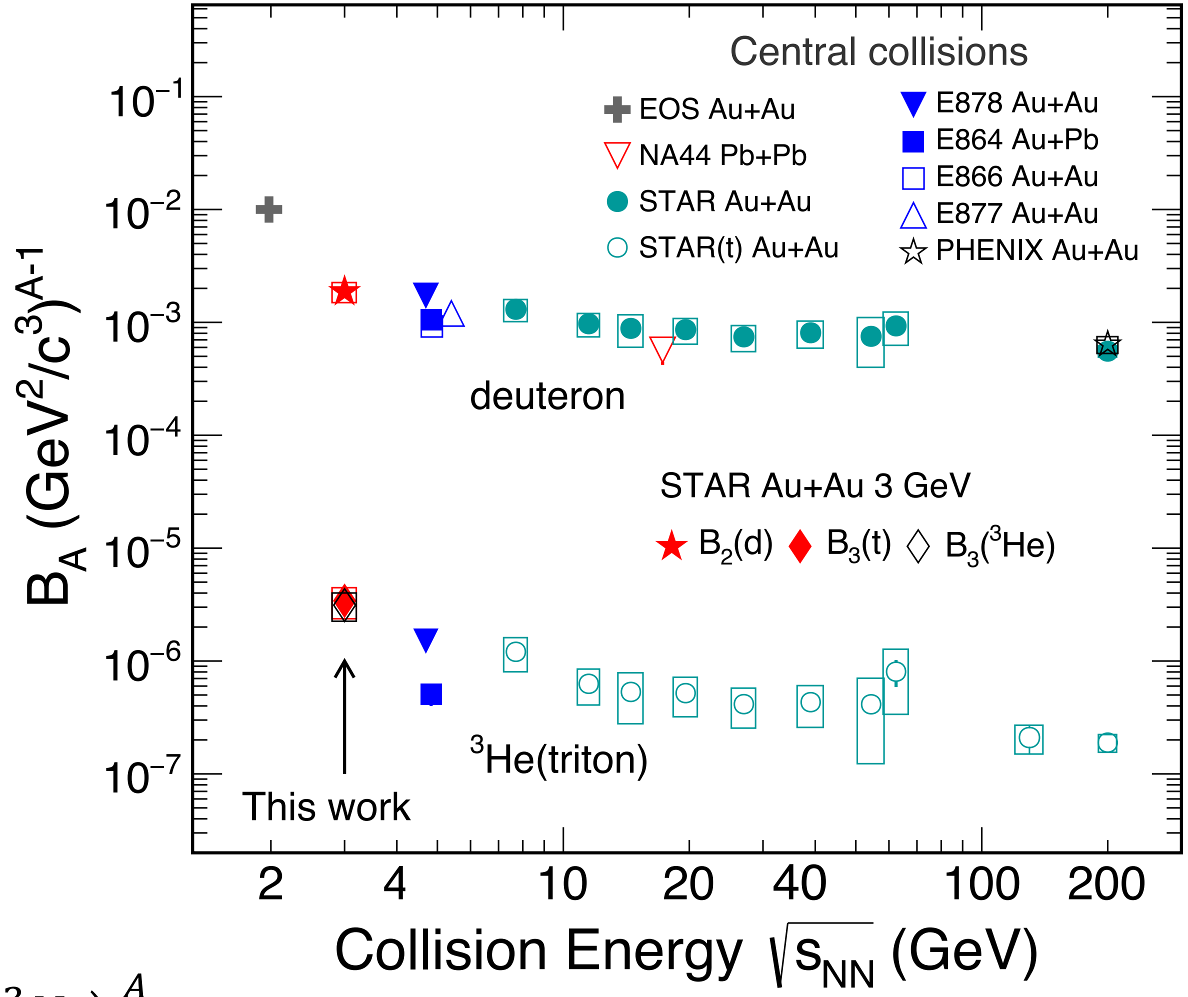


☆Mid-rapidity transverse momentum spectra for primordial protons

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

Results Coalescence Parameter





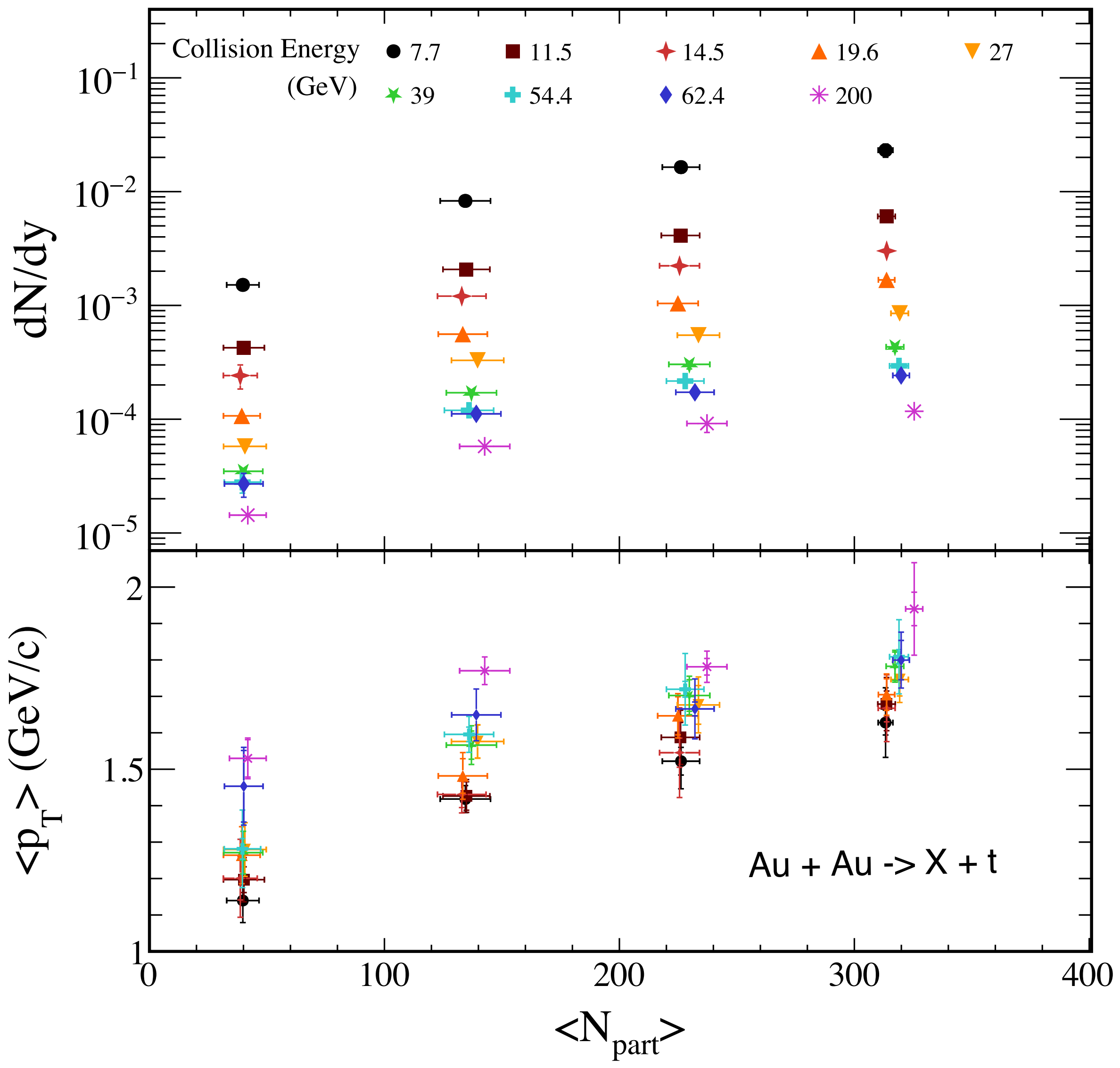
$$E_A \frac{d^3N_A}{d^3p_A} = B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^Z \left(E_n \frac{d^3N_n}{d^3p_n}\right)^{A-Z} \approx B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A$$

László P. Csernai, Joseph I. Kapusta Phys. Reps, 131,223(1986)
A.Z. Mekjian, Phys. Rev. C 17, 1051 (1978)

STAR: Nucl. Phys. A 1005 (2021) 121825
arXiv:2311.11020

Results

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

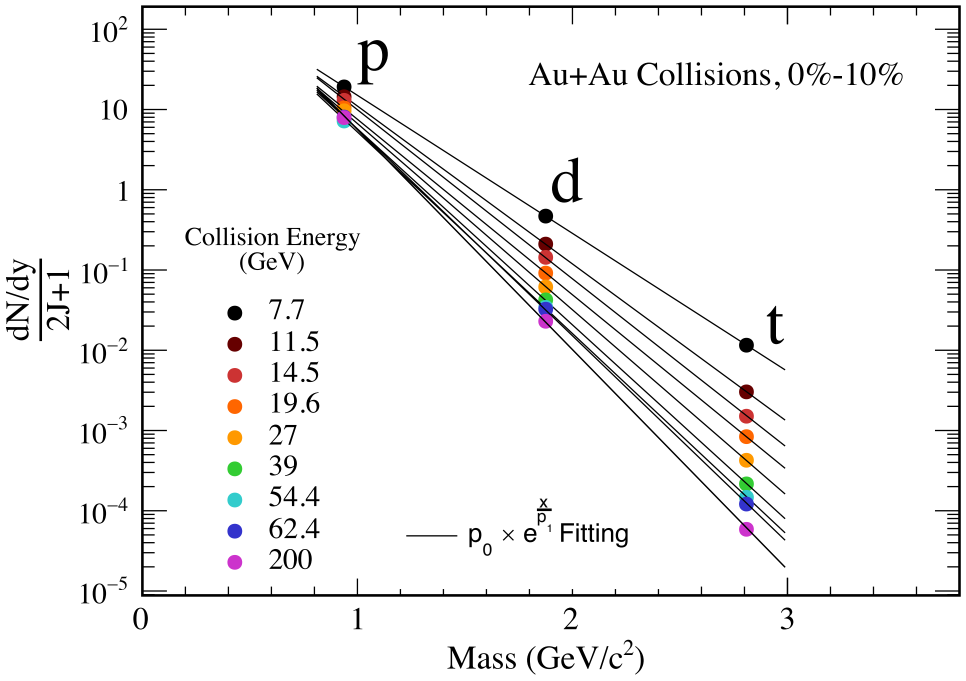


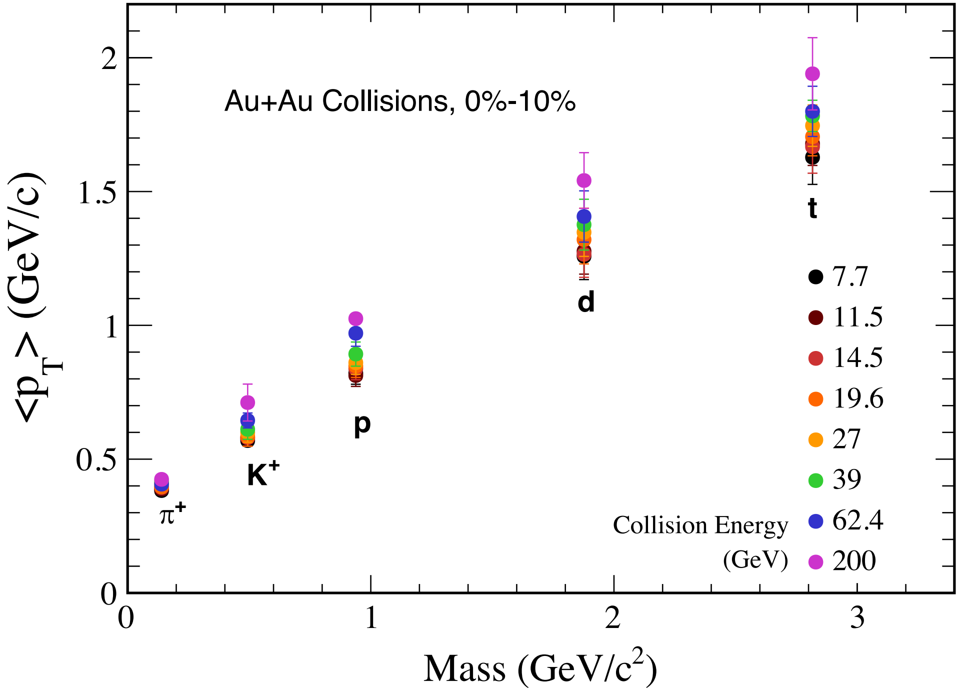
✭dN/dy for tritons increases with decreasing collision energy: yields driven by baryon density

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

Results

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



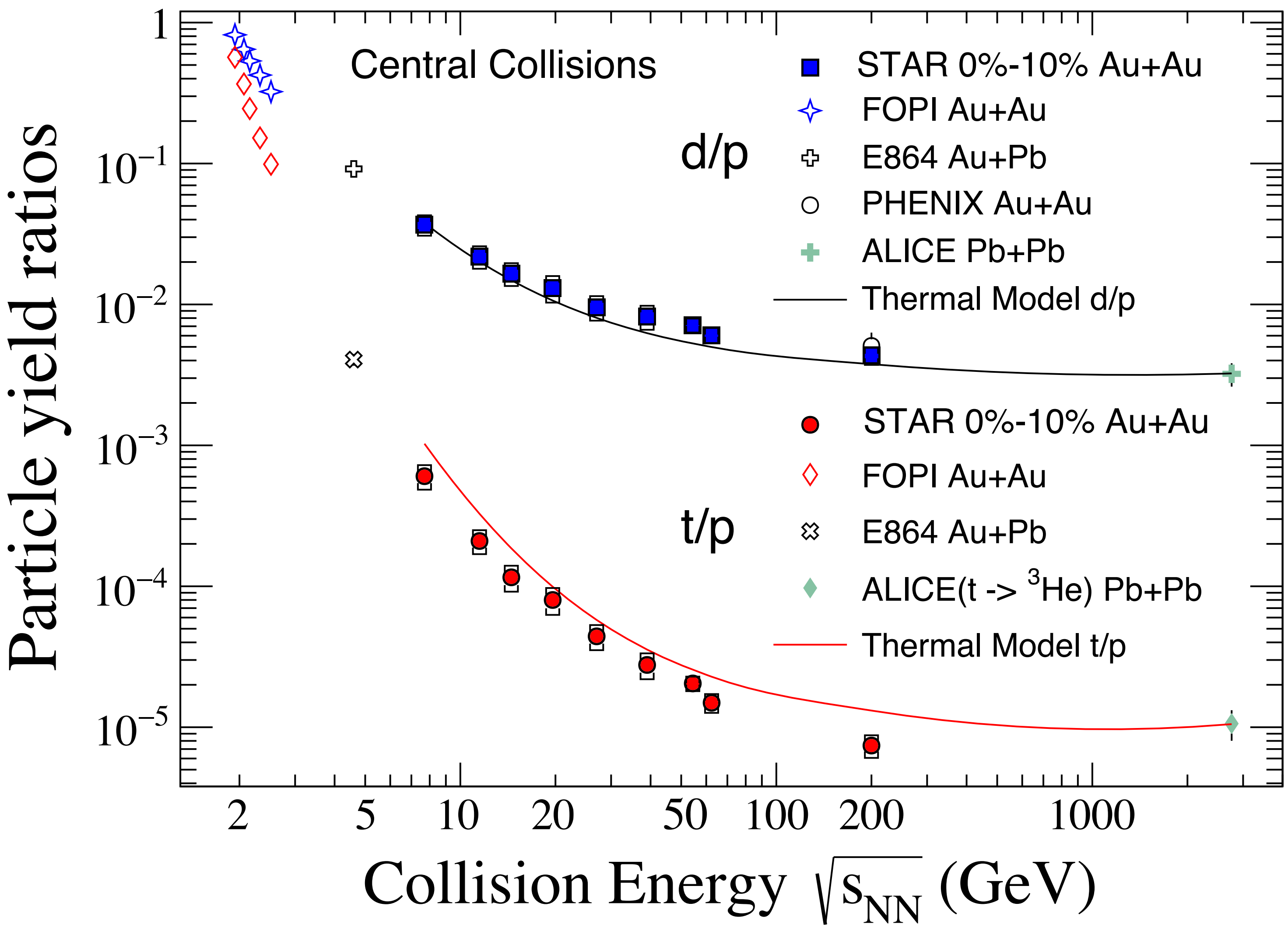


✮Mass dependence of light nuclei yields (divided by the spin degeneracy factor) well described by exponential functions

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

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);

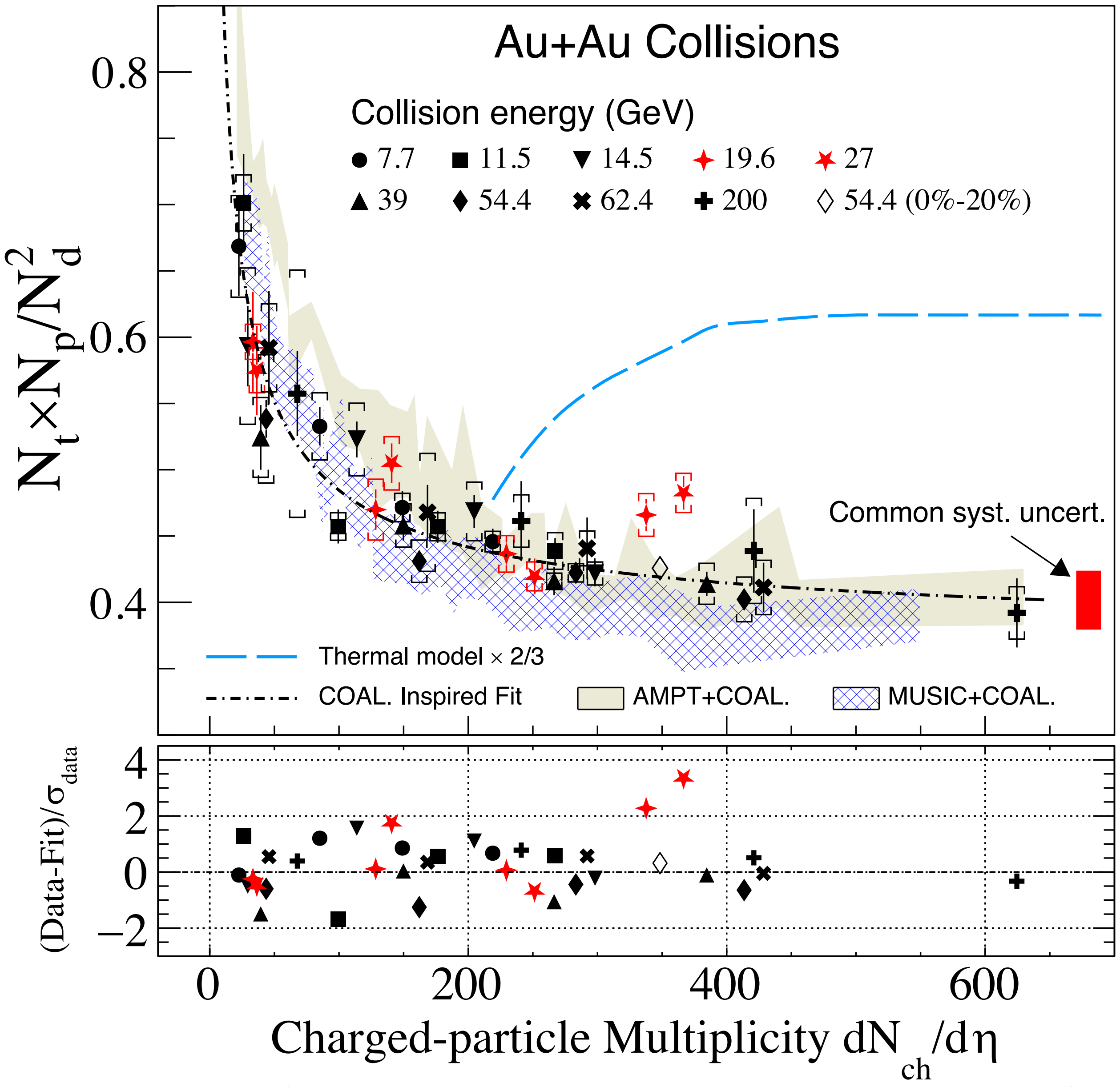
✮The effects of hadronic re-scatterings during hadronic expansion may play an important role in light nuclei production

K.-J. Sun, R. Wang, C. M. Ko, Y.-G. Ma, and C. Shen, (2022), Nature Commun. 15 no.1, 1074 (2024)

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

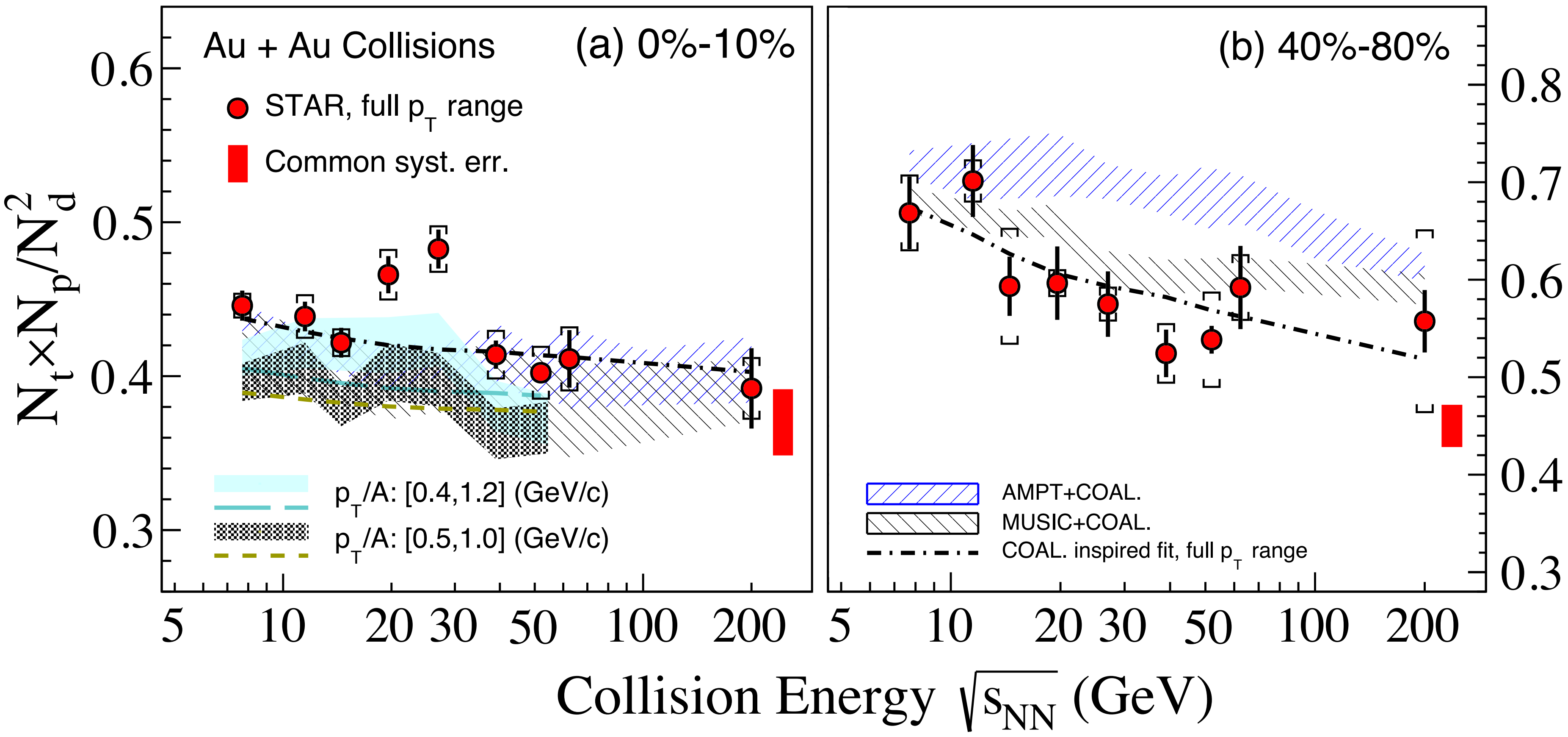


✯The ratio monotonically decreases with increasing $dN_{ch}/d\eta$ and exhibits a scaling behavior: trend driven by interplay between the size of light nuclei and the size of fireball created in HIC

✯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

Energy Dependence of Light Nuclei Yield Ratio

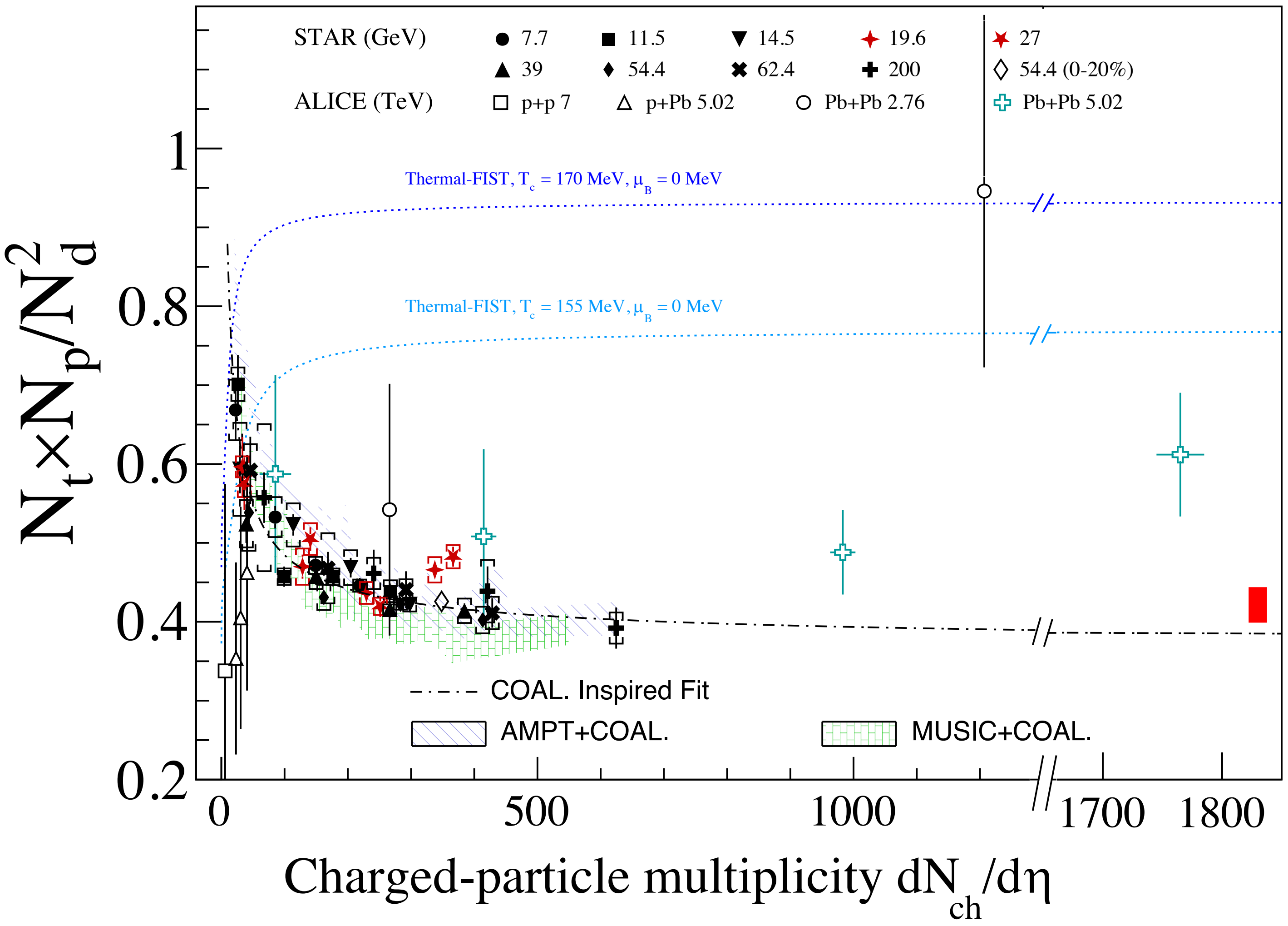


✯Non-monotonic behavior observed in the energy dependence of the yield ratio from 0%-10% central Au+Au collisions around 19.6 and 27 GeV

✯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

Comparison of Light Nuclei Yield Ratio



✮Production mechanism of light nuclei in the heavy-ion collision

✮Understanding of the QCD phase diagram

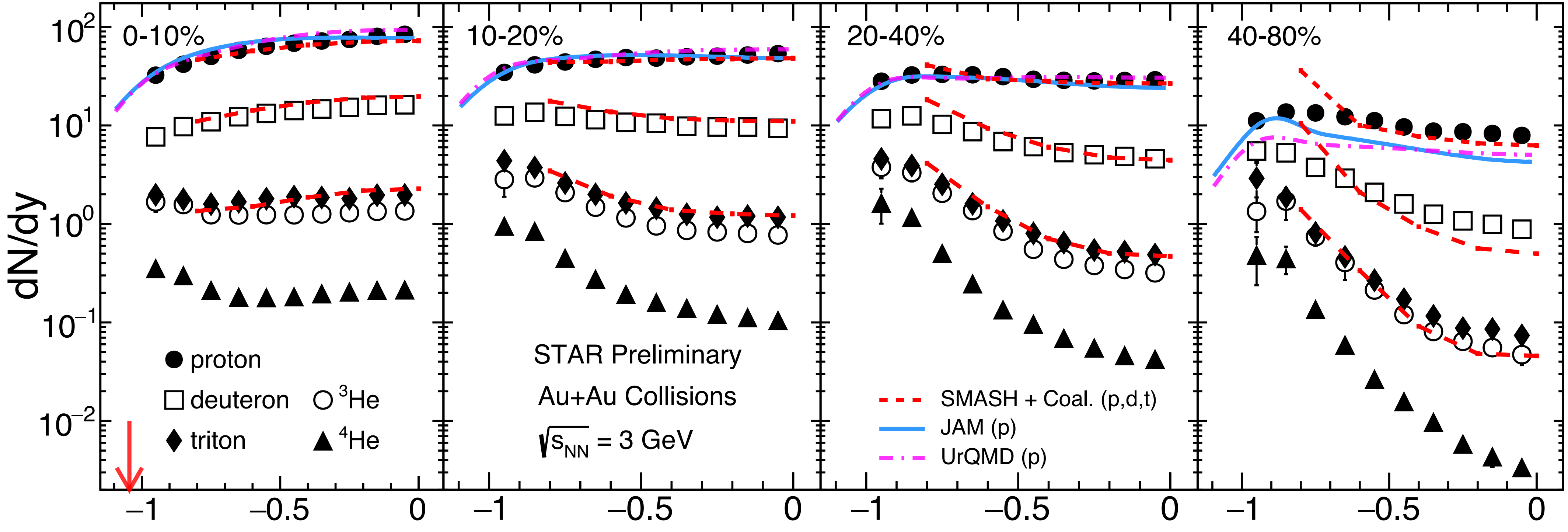
ALICE:
Pb+Pb 2.76 TeV: Phy. Rev. C 88, 044910 (2013)
Phy. Rev. C 93, 024917 (2016)
p+p 7 TeV: Eur. Phys. J. C 75, 226 (2015)
Phys. Lett. B 794, 50 (2019)
p+Pb 5.02 TeV: Phys. Rev. C 101, 044906 (2020)
Phys. Lett. B 800, 135043 (2020)
Phys. Lett. B 728, 25 (2014)
Pb+Pb 5.02 TeV: JHEP 01, 106 (2022)

THERMAL: Phys. Lett.424 B 785, 171 (2018)

Results

LN Production in FXT Au+Au Collisions

3 GeV : Hui Liu (for STAR), QM2022



$y_{target} = -1.045$

Light nuclei coalescence via Wigner function

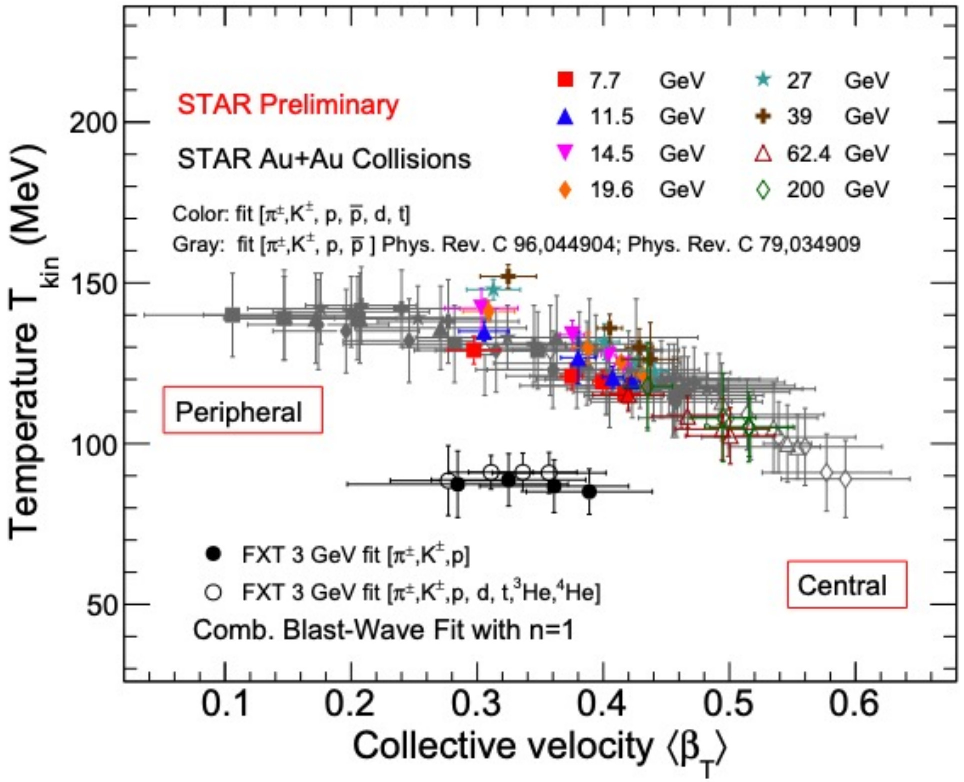
- Integral dN/dy of protons and light nuclei show significant centrality and rapidity dependence
- The 3 GeV with good rapidity coverage provide the opportunity to calculate 4π yields accurately

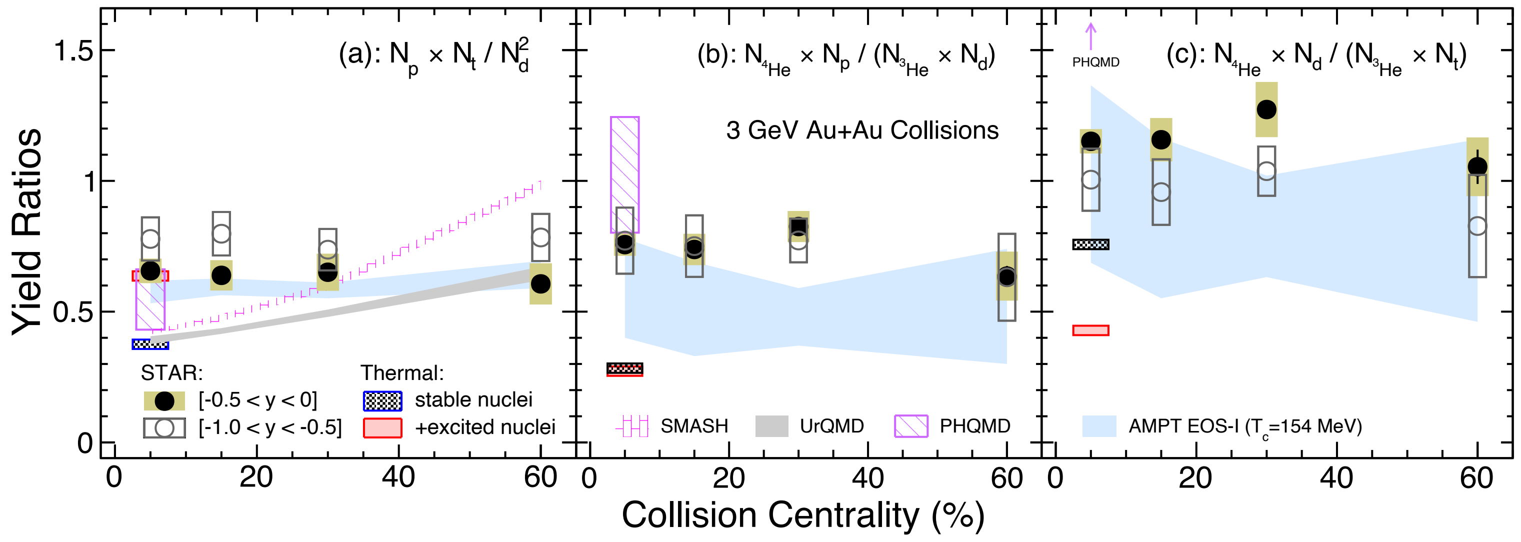
STAR: arXiv:2311.11020

Results

LN Production in FXT Au+Au Collisions

3 GeV : Hui Liu (for STAR), QM2022





- FXT 3 GeV shows different trend compared to BES-I Au+Au collisions, indicating a different medium equation of state (EoS) at 3 GeV
- The AMPT model with 1st order P.T. EoS with a critical temperature (~154MeV) shows the same centrality dependence as that observed by STAR experiment

H. Liu. [STAR Collaboration] Acta Phys. Polon. Supp. 16, 1-A148 (2023)
STAR: arXiv:2311.11020

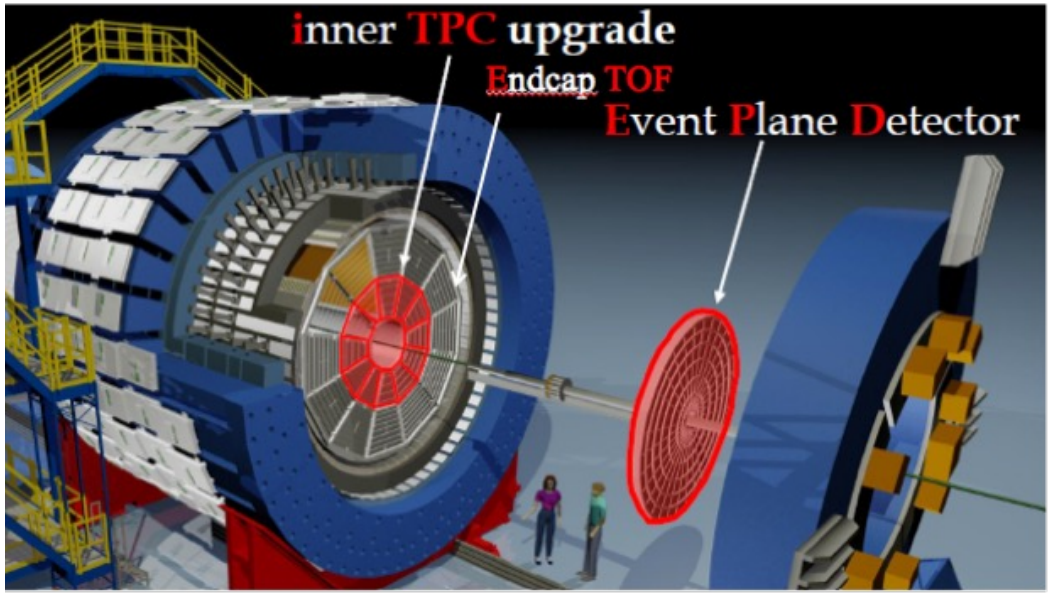
Summary & Outlook

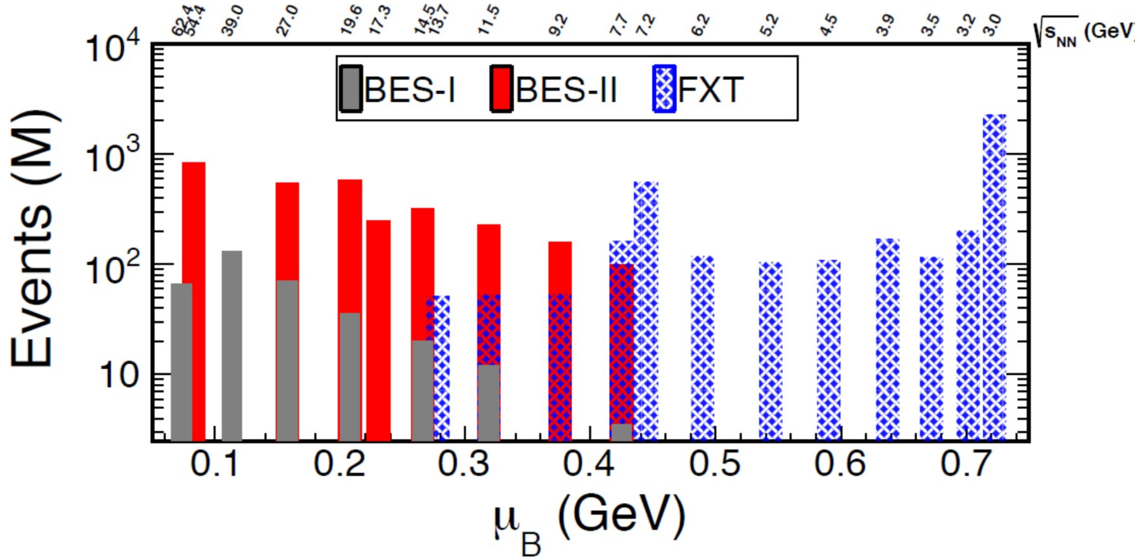
✯We performed systematic measurements of light nuclei production in heavy-ion collisions at the STAR experiment, including deuteron, triton, etc…

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

✯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.

Outlook:



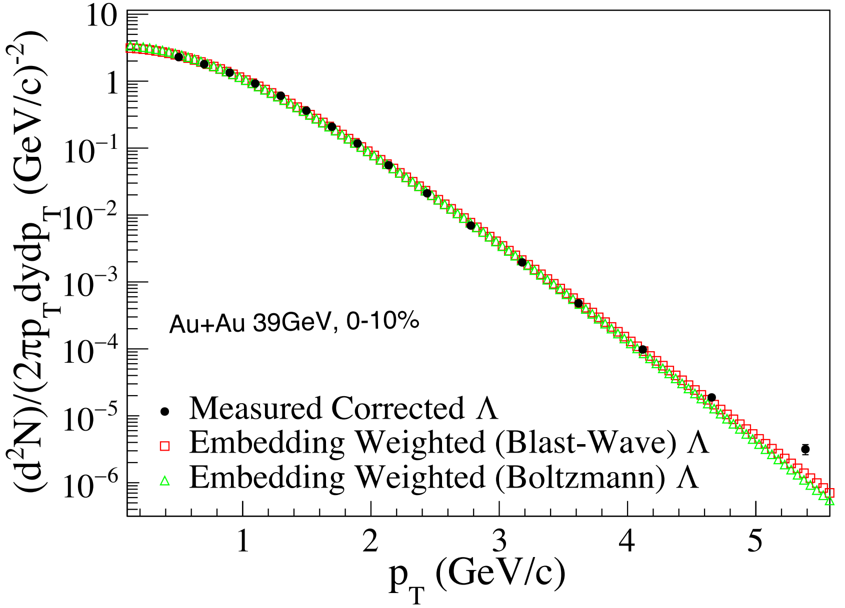


- BES-II: 10-20 times higher statistics that BES-I
- FIX-target mode: $\sqrt{s_{NN}} = 3 - 13.7$ GeV
- iTPC, ETOF, and EPD upgrade completed

Thank you for your attention!

Proton Feed-down Corrections

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

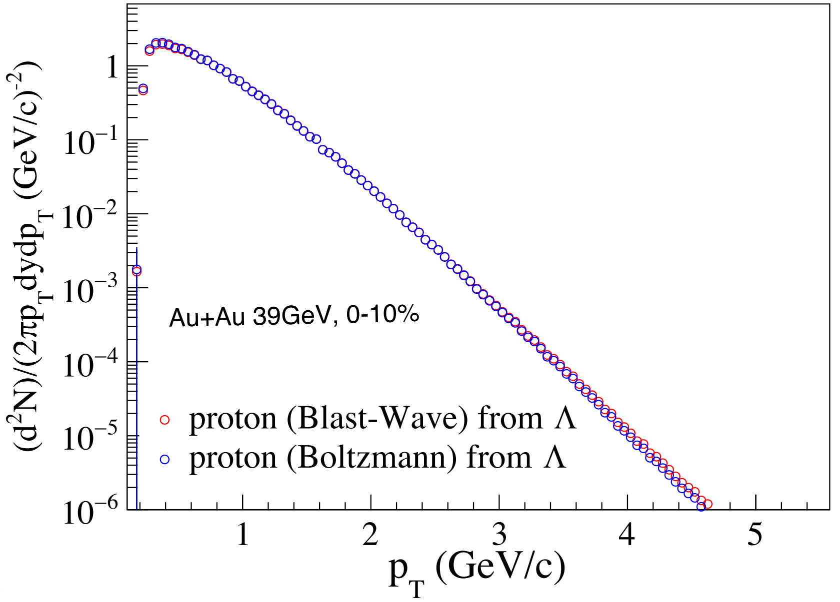


- Correction Procedure:

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

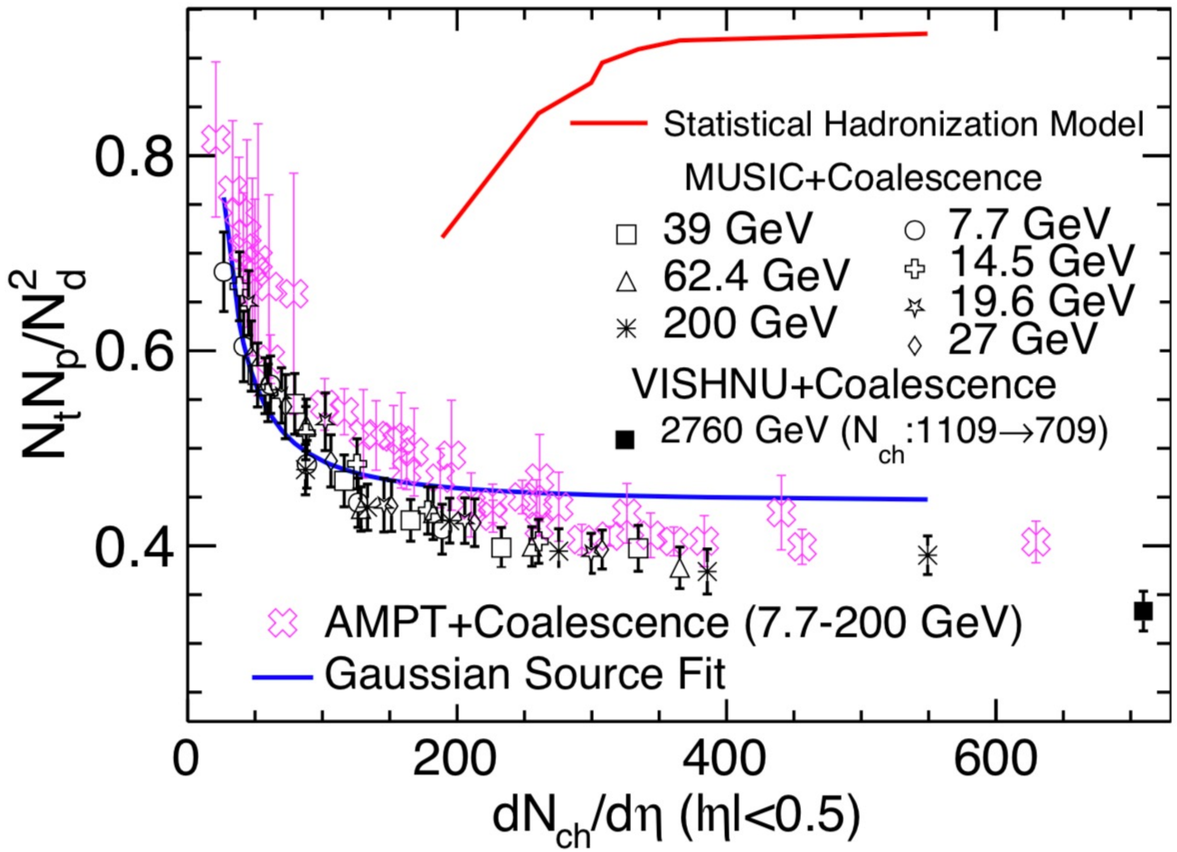
  ② Weight the embedding input Monte Carlo strange particle to the corrected spectra

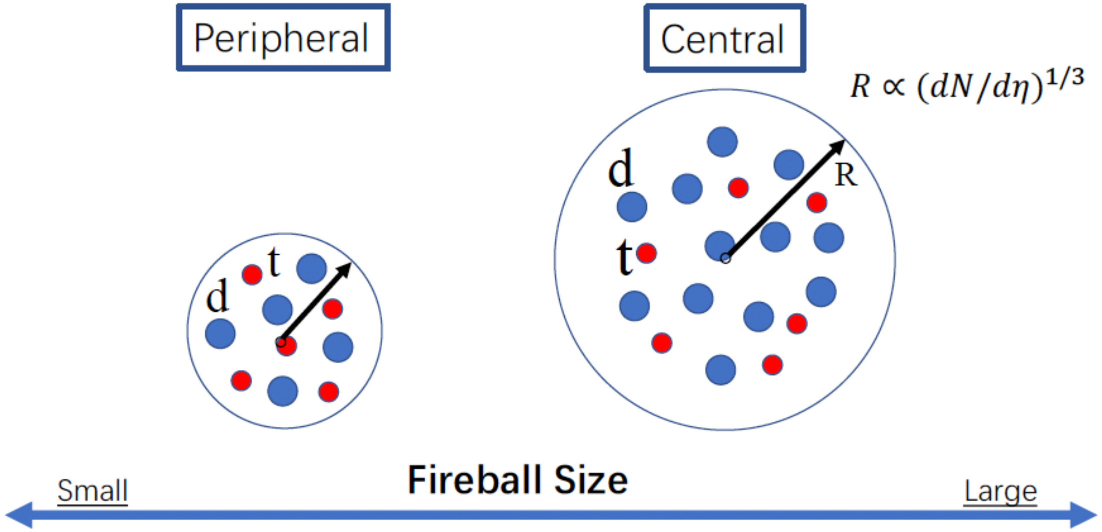
  ③ Obtain the daughter proton coming from the embedding and scale by the weight factor from step 2.



Backup

Source Size Effect in Coal. Production of LN





$$\frac{N_t \times N_p}{N_d^2} = \frac{4}{9}\left(\frac{1+\frac{2r_d^2}{3R^2}}{1+\frac{r_t^2}{2R^2}}\right)^3$$

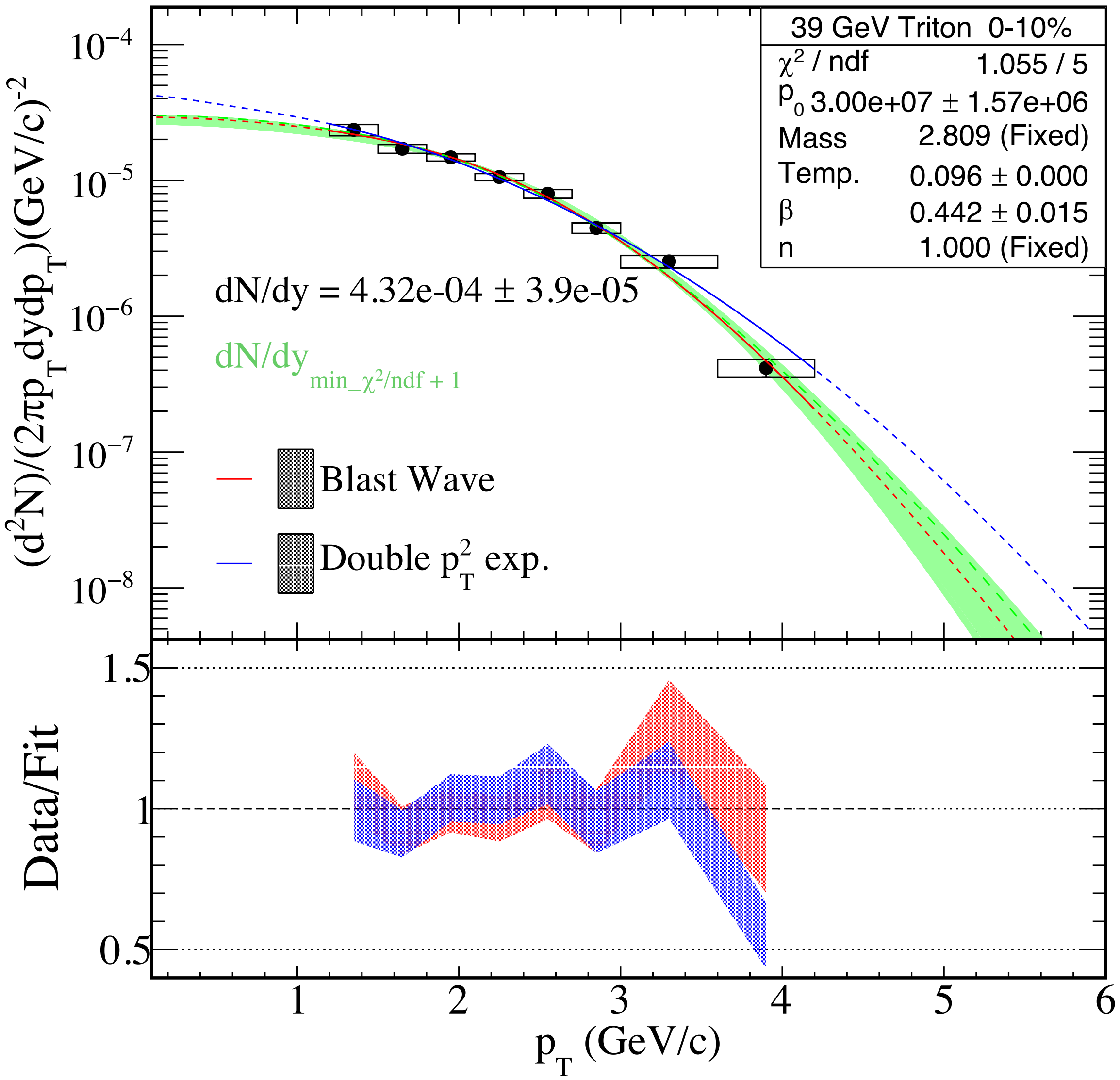
r_t and r_d: matter radius of triton and deuteron.

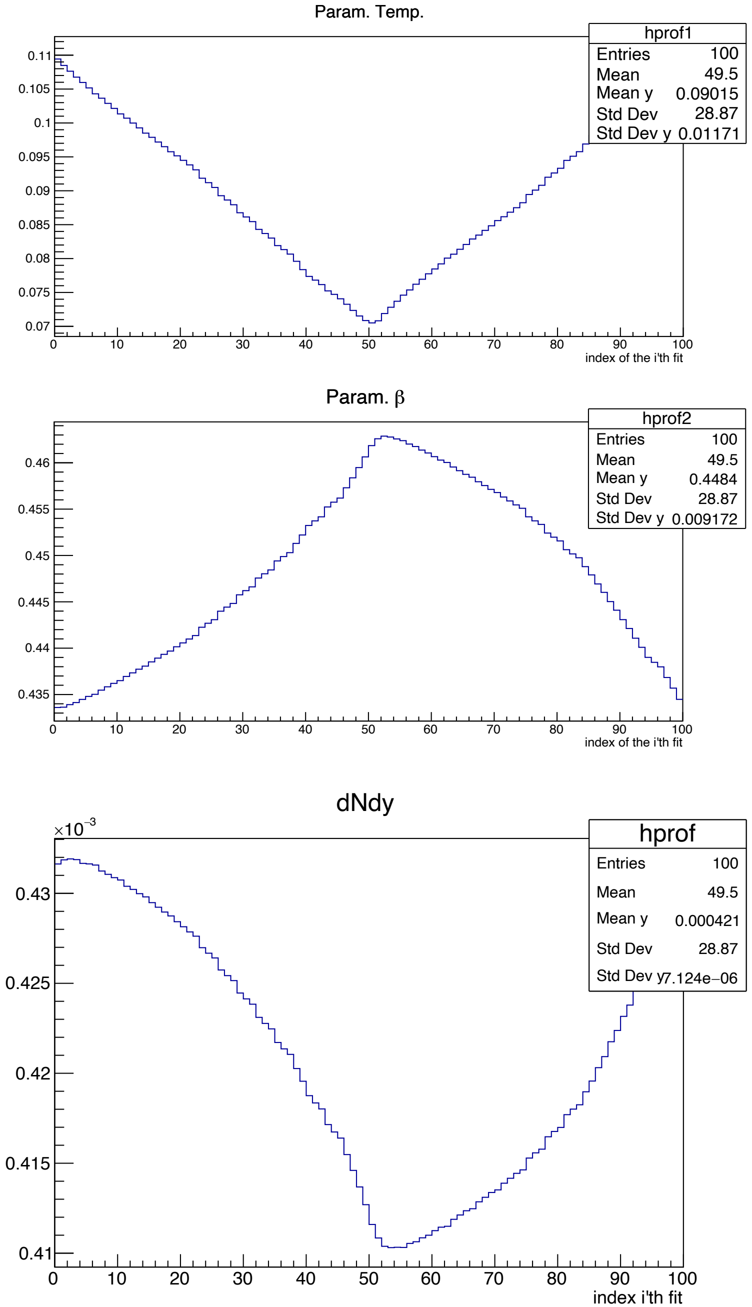
☆ Due to the source size effect in coalescence picture, yield ratio shows scaling behavior and decreasing with increasing the charged particle multiplicity

☆This multiplicity scaling can be used to validate the production mechanism of light nuclei and serve as a baseline to search for the critical point in heavy-ion collisions

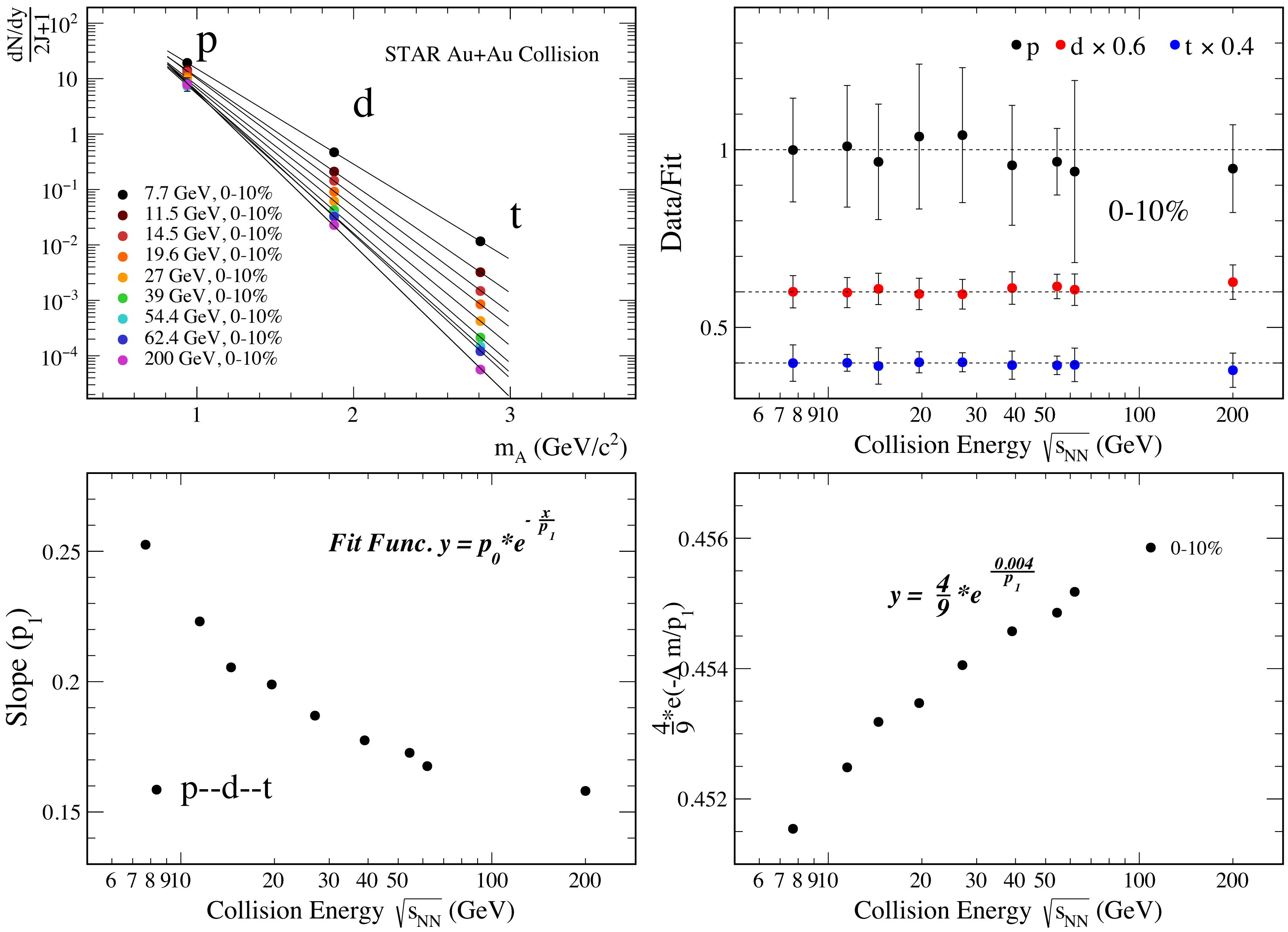
W. Zhao, K.-j. Sun, C. M. Ko, and X. Luo, Phys. Lett. B 820, 136571 (2021); K.-J. Sun, C. M. Ko, and B. Dönigus, Phys. Lett. B 792, 132 (2019)

Backup


39 GeV Triton 0-10%
χ^2 / ndf 1.055 / 5
p_0 3.00e+07 ± 1.57e+06
Mass 2.809 (Fixed)
Temp. 0.096 ± 0.000
β 0.442 ± 0.015
n 1.000 (Fixed)
dN/dy = 4.32e-04 ± 3.9e-05
$dN/dy_{min\_\chi^2/ndf + 1}$
Blast Wave
Double p_T^2 exp.
$(d^2N)/(2\pi p_T dydp_T)(GeV/c)^{-2}$
Data/Fit
p_T (GeV/c)

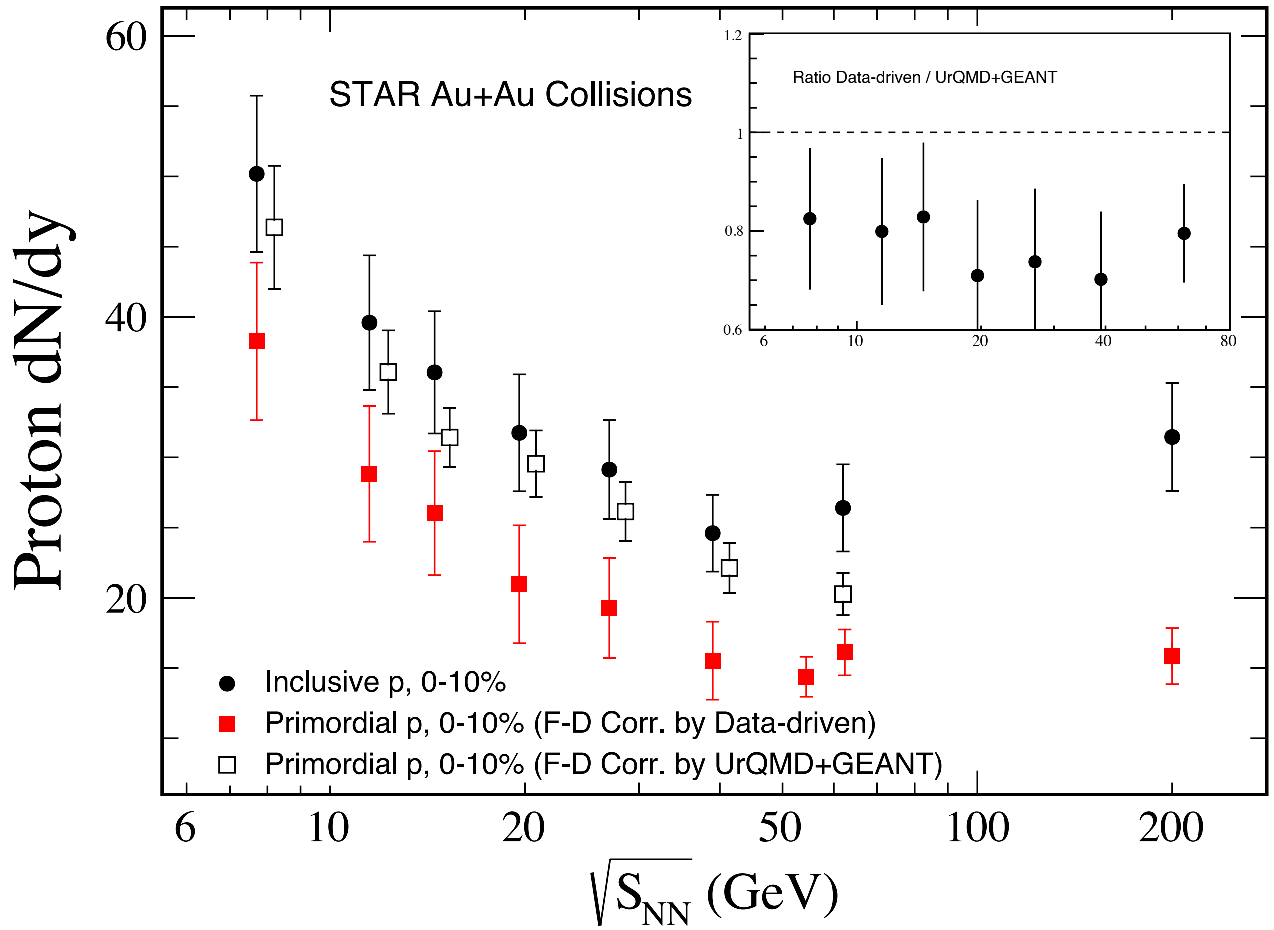

Param. Temp.
hprof1
Entries 100
Mean 49.5
Mean y 0.09015
Std Dev 28.87
Std Dev y 0.01171
index of the i'th fit
Param. β
hprof2
Entries 100
Mean 49.5
Mean y 0.4484
Std Dev 28.87
Std Dev y 0.009172
index of the i'th fit
dNdy
hprof
Entries 100
Mean 49.5
Mean y 0.000421
Std Dev 28.87
Std Dev y 7.124e−06
index i'th fit

Backup



STAR Au+Au Collision
p
d
t
7.7 GeV, 0-10%
11.5 GeV, 0-10%
14.5 GeV, 0-10%
19.6 GeV, 0-10%
27 GeV, 0-10%
39 GeV, 0-10%
54.4 GeV, 0-10%
62.4 GeV, 0-10%
200 GeV, 0-10%
m_A (GeV/c^2)
p
d × 0.6
t × 0.4
0-10%
Data/Fit
Collision Energy √s_NN (GeV)
Fit Func. y = p_0*e^(-x/p_1)
p--d--t
Slope (p_1)
Collision Energy √s_NN (GeV)
y = 4/9 *e^(0.004/p_1)
0-10%
Collision Energy √s_NN (GeV)

Comparison of Proton Yields



✯The primordial proton yield obtained from the UrQMD+GEANT method [Phys. Rev. Lett. 121, 03230 (2018)] is significantly larger than that from the data driven method

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