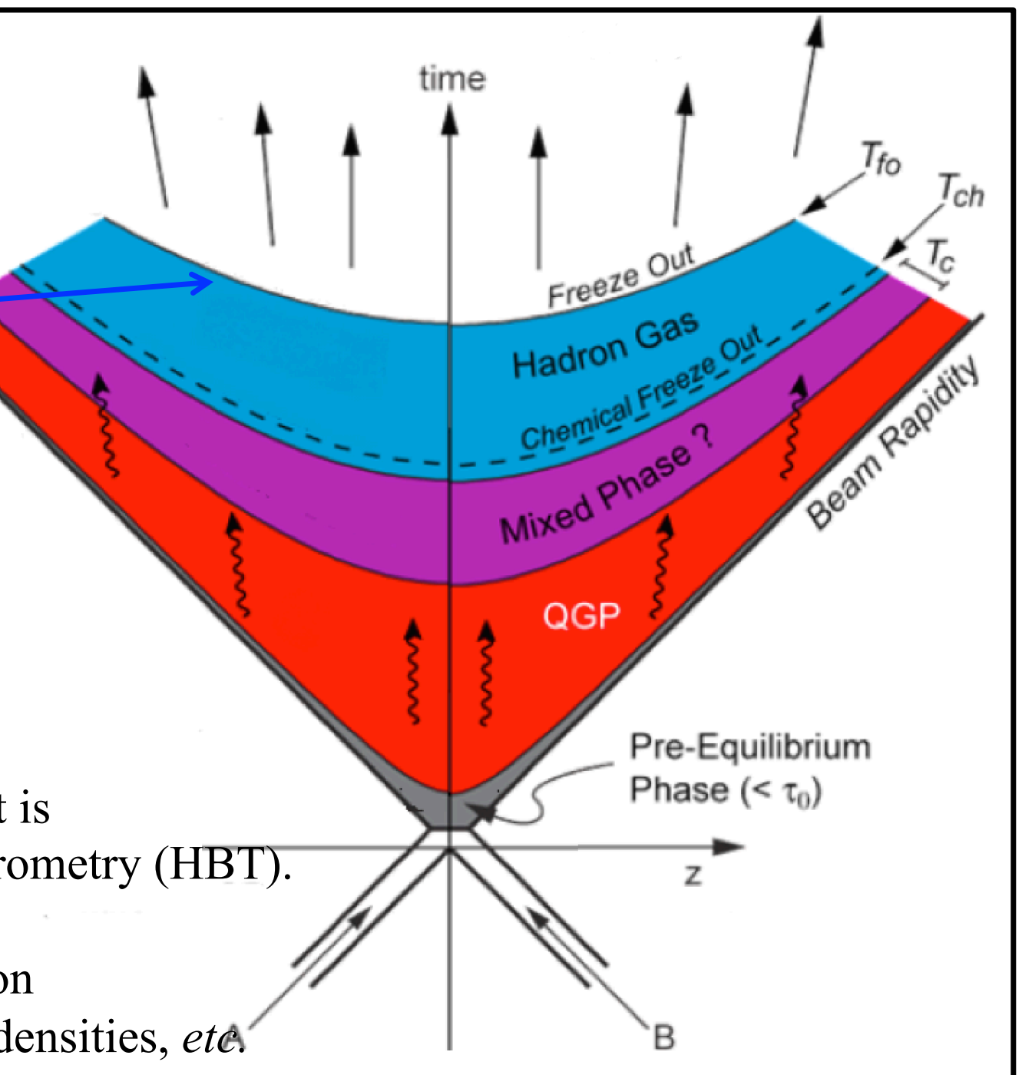
Light (anti)nucleus production in $\sqrt{s_{NN}}$ = 7.7 - 200 GeV Au+Au collisions in the STAR Experiment

W.J. Llope, *for the STAR Collaboration*

Abstract

In the dense and high-temperature systems formed in relativistic heavy-ion collisions, final-state composites - light nuclei and antinuclei - are formed close to the freeze-out hypersurface. Their spectra, compared to those of the constituent (anti)nucleons, can be described by picturing the formation process as the coalescence of a number of nucleons that are close to each other in phase space. This makes the composite spectra sensitive to the distribution of the constituent nucleons in phase space. It also implies a sensitivity of the spectra to the local densities and flow velocities of the source. In the coalescence picture, specific ratios of these spectra provide information on the baryon densities and homogeneity volumes. The STAR experiment has collected data from Au+Au collisions at seven beam energies, $\sqrt{s_{NN}}$, ranging from 7.7 to 200 GeV. The particle identification is performed for transverse momenta from ~0.3 to >3 GeV/c using a combination of the ionization energy loss in the Time Projection Chamber and the time of flight. The spectra for (anti)protons, (anti)deuterons, and (anti)tritons at mid-rapidity, and the source information inferred from these spectra, will be presented and compared to several dynamic coalescence models.

Introduction



Light (anti)nuclei – *e.g.* (anti)deuterons & (anti)tritons – are weakly bound.
B_d ~ 2.2 MeV, B_t ~ 8 MeV

Implies that observed (anti)nuclei are formed:
- near thermal freeze-out hypersurface.
- from nucleons close to each other in phase space with rates that are thus sensitive to the local phase space densities and flow.

A complete understanding of the hot and dense partonic and/or nuclear systems formed at RHIC requires an understanding of the latest stages of the collisions.

Light nucleus rates and spectra are a "direct" nucleon correlation observable that is complementary to two-particle correlations obtained, *e.g.*, from intensity interferometry (HBT).

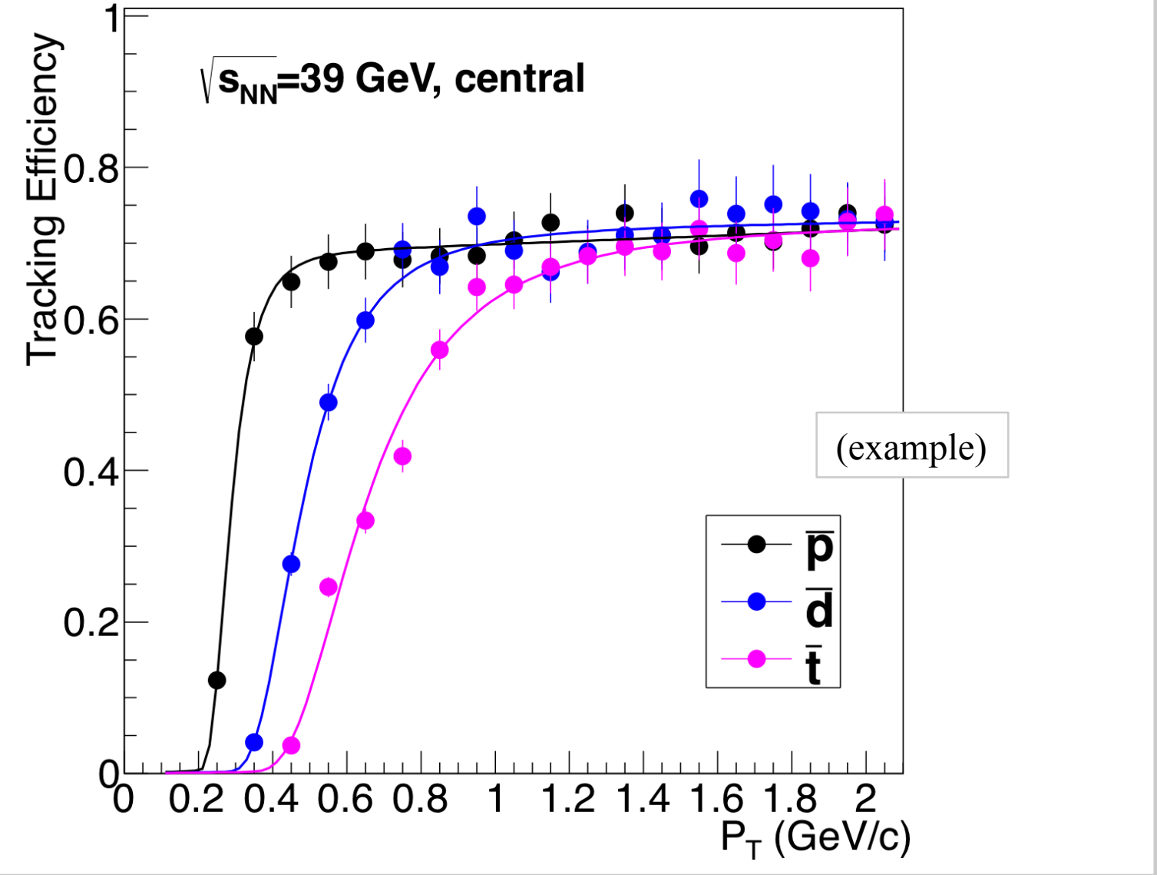
Thermodynamic approaches and the sudden approximation can provide insight on source "homogeneity volumes" and emission profiles, (anti)proton phase space densities, *etc.*

Corrections

Reconstruction, TOF Matching, & Absorption
Efficiencies depend on year, $\sqrt{s_{NN}}$, centrality, species, rapidity, P_T

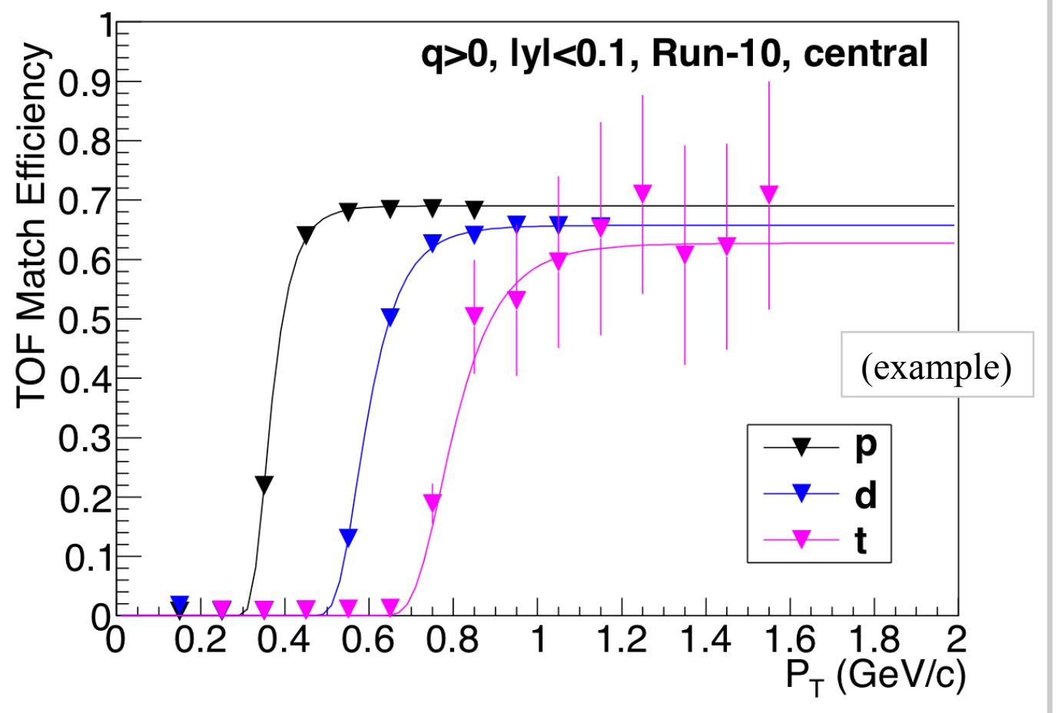
Track Reconstruction Efficiency

embed simulated tracks into real events, careful sampling by day done for 7 different particles (p,d,t & antiparticles) & $\sqrt{s_{NN}}$ values
interpolation by track multiplicity for other data sets



TOF Matching Efficiency

determined from data using TPC-identified tracks



Antinucleus Absorption

Geant**3** does not know nucleus+X cross-sections…
Use phenomenological model
T. F. Hoang, *et al.*, Z. Phys. C29, 611 (1985)
Check material budget via p & pbar embedding

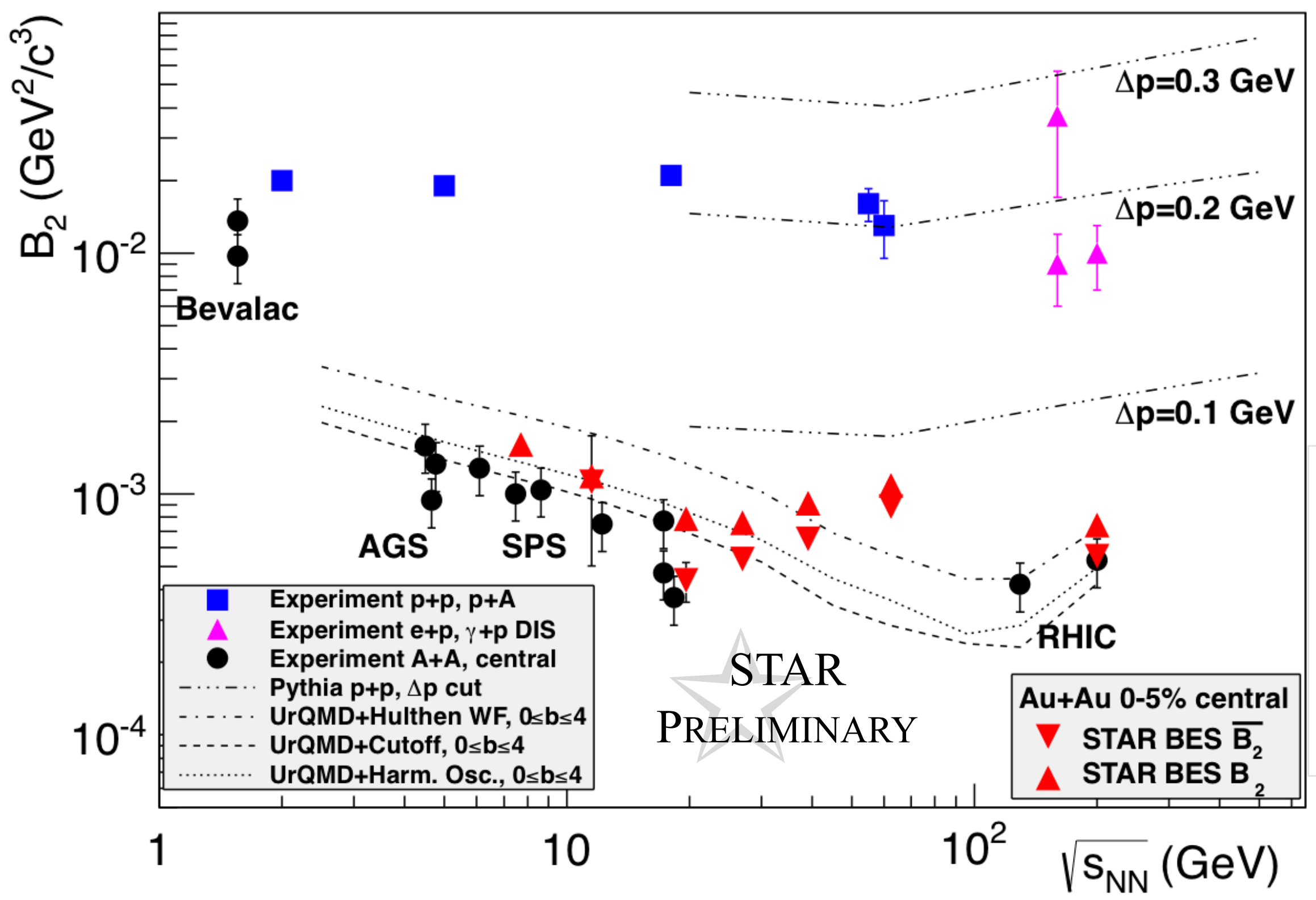
(anti)proton Feed-down (Λ,Σ → p)
UrQMD 3.3p1 simulations with full reconstruction

Coalescence Ratio

$B_2 = \sigma_d/\sigma_p^2$, where the cross-sections are evaluated at the same velocity (P_T/A)

B_2 is a dimensioned ratio that can be related in one of many model-dependent ways to a "homogeneity volume": $\mathbf{B_A \sim 1/V}$

WJL, S. Pratt *et al.*, Phys. Rev. C **52**, 2004 (1995), R. Scheibl & U. Heinz, Phys. Rev. C **59**, 1585 (1997)



for data points see *e.g.*
N. George, Ph.D, Thesis
Yale University (1999)

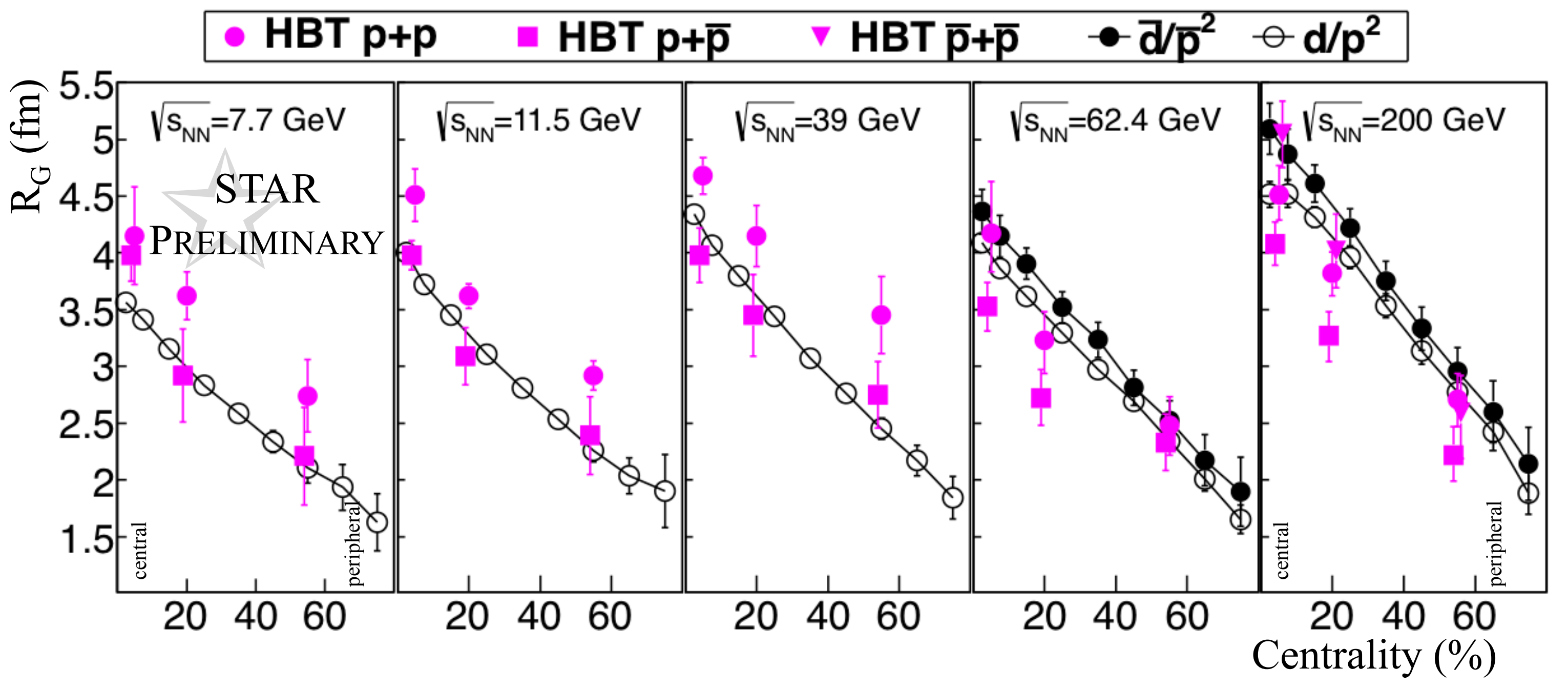
p+X: ZEUS, HERA, H1, E886, NA44
Bevalac: EOS
AGS: E814, E896, E864, E878, E877
SPS: NA44, NA49, NA52
RHIC: STAR, PHENIX, BRAHMS

Lines are UrQMD 3.3p1 or Pythia model calculations plus a "dynamic coalescence afterburner"
…uses 6D coalescence with one of three d wave functions for A+A (UrQMD), 3D coalescence for p+p from Pythia.
J. L Nagle et al., Phys. Rev. C **53**, 367 (1996), B. Monreal, WJL, *et al.*, Phys. Rev. C **60**, 31901 (1999)

Source "Homogeneity" Radius

$$B_2 = \frac{\sigma_d}{\sigma_p^2}, \quad (R_G^2 + \frac{\delta^2}{2})^{3/2} = \frac{3}{2}\frac{\pi^{3/2}\hbar^3}{B_2 m_p c^2}$$

(anti)deuteron Gaussian width: δ ~ 2 fm
m_p = proton mass



HBT results from H. Zbroszczyk, 7th WPCF, 2011, http://http://tkynt2.phys.s.u-tokyo.ac.jp/wpcf2011/talks/sept20/Zbroszczyk.pdf

Data Sets, Cuts, and Particle Identification

$\sqrt{s_{NN}}$	Run	N_{events}
7.7	2010	5M
11.5	2010	15M
19.6	2011	37M
27	2011	46M*
39	2010	58M*
62.4	2010	59M*
200	2010	51M*
200	2011	47M*

*Not entirety of available data.

Cuts
Outlier run rejection based on multiple global observables.

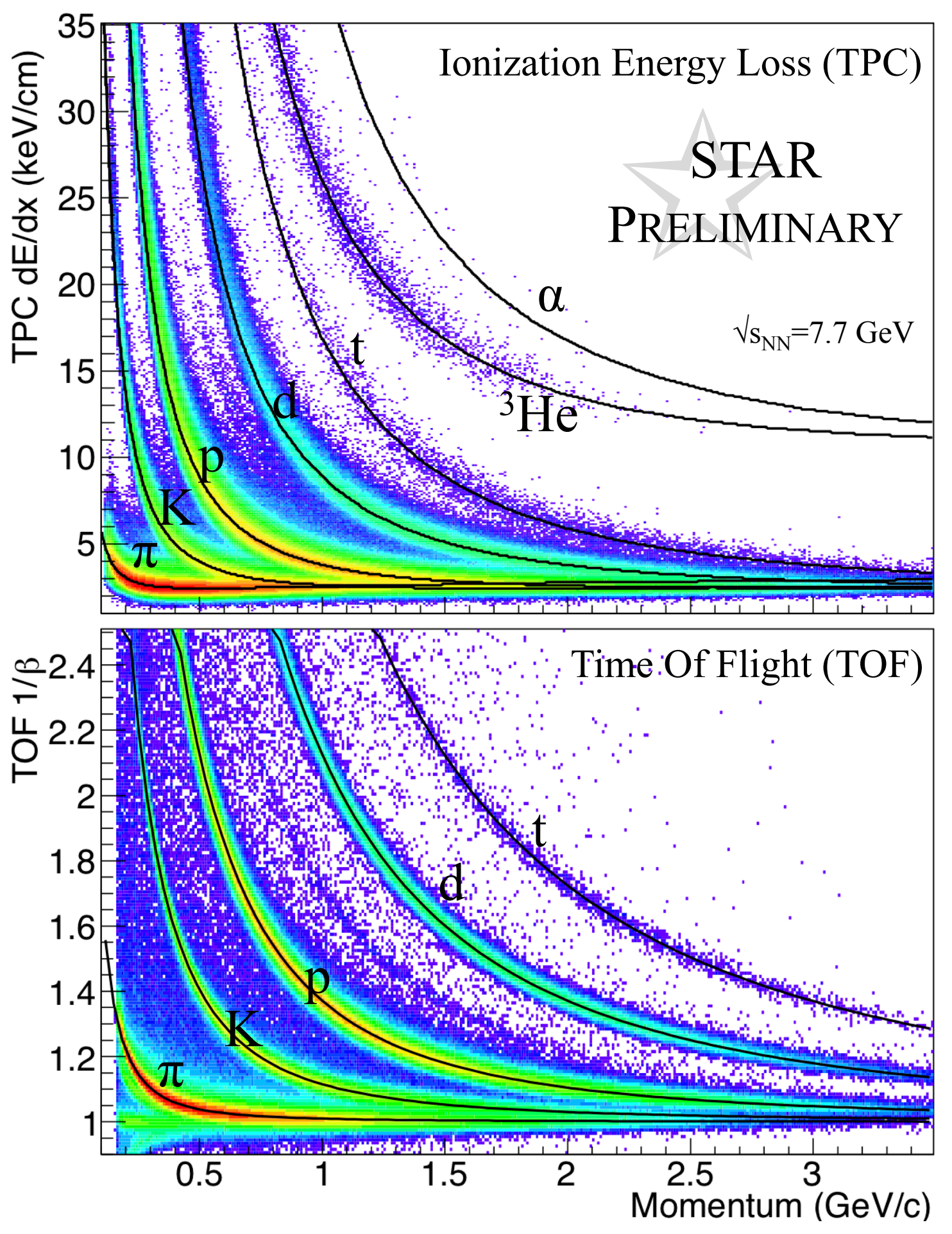
Event Cuts
$|Z_{vtx}|$ < 50cm for $\sqrt{s_{NN}}$≤39 GeV, $|Z_{vtx}|$<30cm otherwise
R_{vtx} < 2cm
Pileup event rejection based on multiple global observables.

Primary Track Cuts
$N_{hitsfit}$ > 15 (of 45 possible)
$N_{hitsdedx}$ > 10 (of ~35 possible)
Global partner D.C.A. to primary vertex < 3 cm
TOF: "good match" criterion ≥ 1
TOF: Y_{local} < 1.8 cm

Centrality
Uses primary track multiplicity within |η|<0.5
Corrected for Z_{vtx} and beam luminosity dependence

Particle Identification
Uses TPC dE/dx and Time Of Flight (TOF) independently
…Careful avoidance of dE/dx "merged tracks"
Statistical, in small (P_T,y,centrality) bins

Uncertainties are statistical only.



Cross-sections vs M_T-M_0

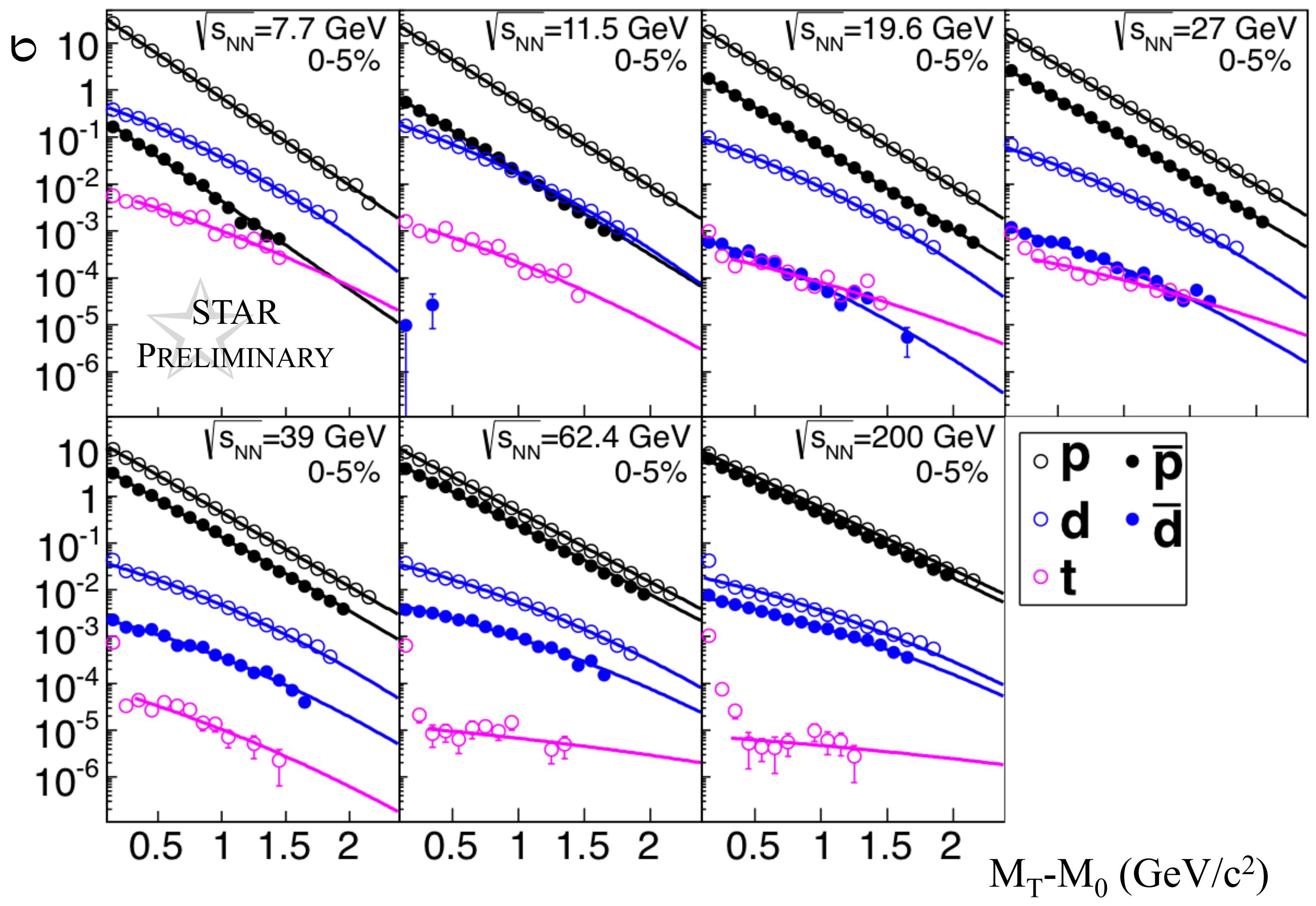
$M_T^2 = P_T^2 + M_0^2$
p: M_0 = 0.9383 GeV/c²
d: M_0 = 1.8756 GeV/c²
t: M_0 = 2.8093 GeV/c²

(Anti)protons: ~exp[M_T/T]
(Anti)nuclei: ~exp[$(M_T/T)^2$]

Spectra become harder with mass number, A.
Reflects strong transverse expansion

Sharp increase in nucleus cross-sections at low M_T is due to spallation:
X + Beam Pipe = p,d,t + Y

Significant for P_T < ~0.5*A
Does not produce antinuclei

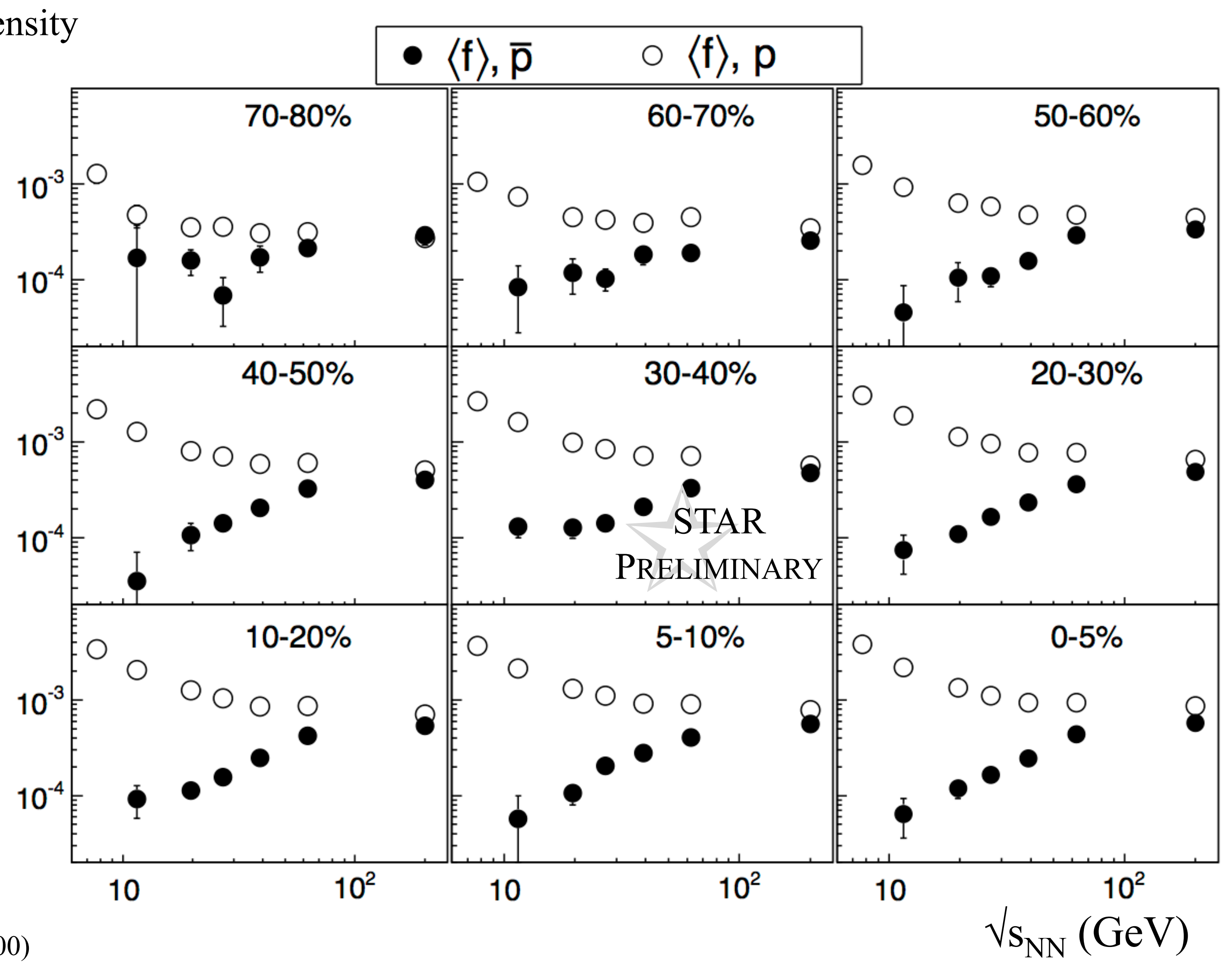


(Anti)Proton Average Phase Space Density

$$<f> = \frac{1}{3}\frac{\sigma_d}{\sigma_p}$$

Proton density falls with $\sqrt{s_{NN}}$
Antiproton density rises with $\sqrt{s_{NN}}$

Trends reflect decreasing baryochemical potential, μ_B, with increasing $\sqrt{s_{NN}}$



see also:
NA44, Nucl. Phys. A 661, 456 (1999)
BRAHMS, Phys. Rev. C 83, 044906 (2011)
F. Wang *et al.*, Phys. Rev. C 61, 021904R (2000)

Summary

- Light (anti)nuclei have been measured at seven beam energies by STAR at RHIC.
- Spectra versus P_T, P_T/A, M_T/A, and M_T-M_0 provide information on the nucleon source near freeze-out.
- Spectra by mass number reflect strong transverse flow.
- Qualitative reproduction of B_2 values by UrQMD+dynamic coalescence calculation.
- Gaussian radii from B_2 values similar to that from (anti)proton intensity interferometry (HBT).
- Antiproton and proton phase space densities approach each other as $\sqrt{s_{NN}}$ increases, reflecting decreasing μ_B.

The STAR Collaboration: http://drupal.star.bnl.gov/STAR/presentations