Systematics of Kinetic Freeze-out Properties in High Energy Collisions from STAR

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Outline:

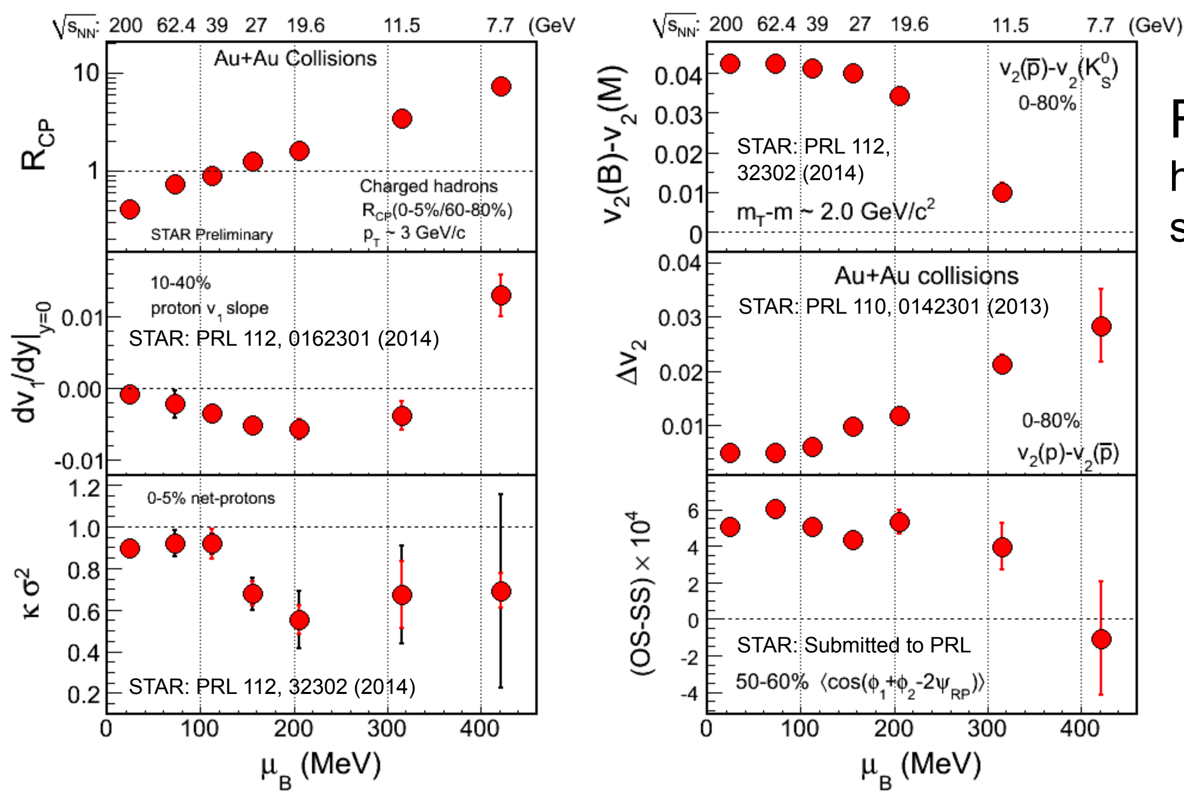
- Introduction & Motivation
- STAR Experiment and Particle Identification
- Invariant Yields and Average Transverse Mass
- Blast Wave Fits
- Summary

RHIC BES Program: Motivation

Explore QCD Phase Diagram: - Search signals of possible phase boundary
- Search for softening of EOS
- Search for the possible QCD Critical Point

BES-I findings:

Many interesting features as a function of beam energy/chemical potential



Ref: STAR BES white paper
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

This Talk:

Detailed study of kinetic freeze-out parameters

Freeze-out in Heavy-ion

Chemical Freeze-out:

Inelastic collisions among particles cease

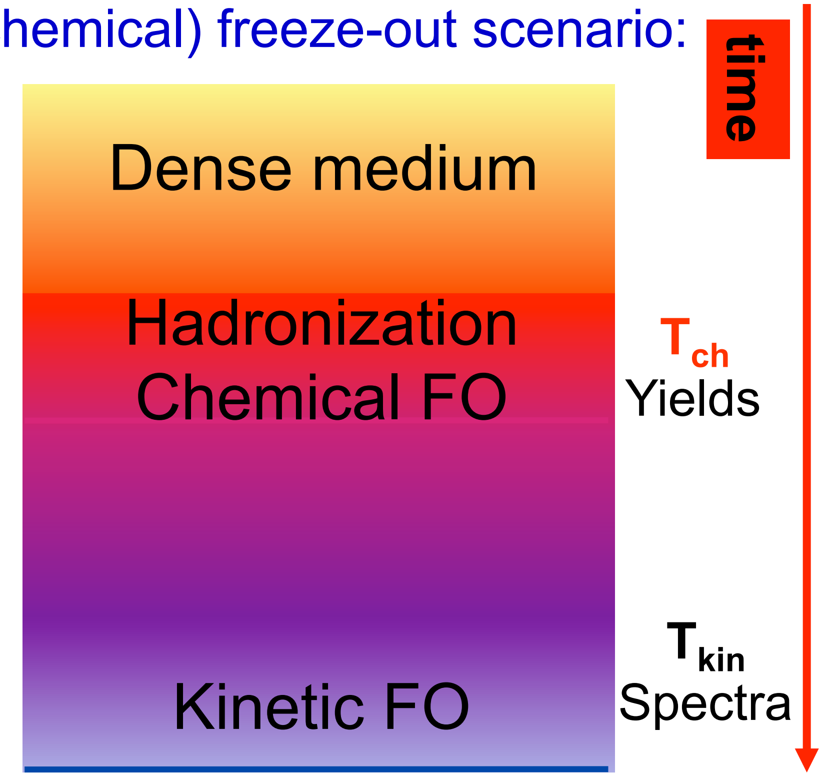
- Particle yields and ratios get fixed
- Chemical freeze-out temperature and baryonic chemical potential

Kinetic Freeze-out:

Elastic collisions among particles cease

- Particle spectral shapes get fixed
- Kinetic freeze-out temperature and average transverse flow velocity

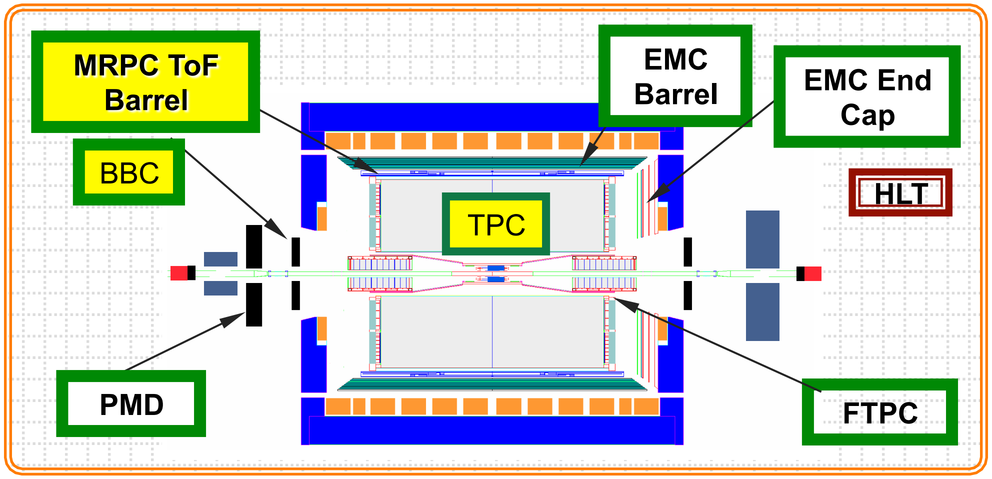
Single (chemical) freeze-out scenario:

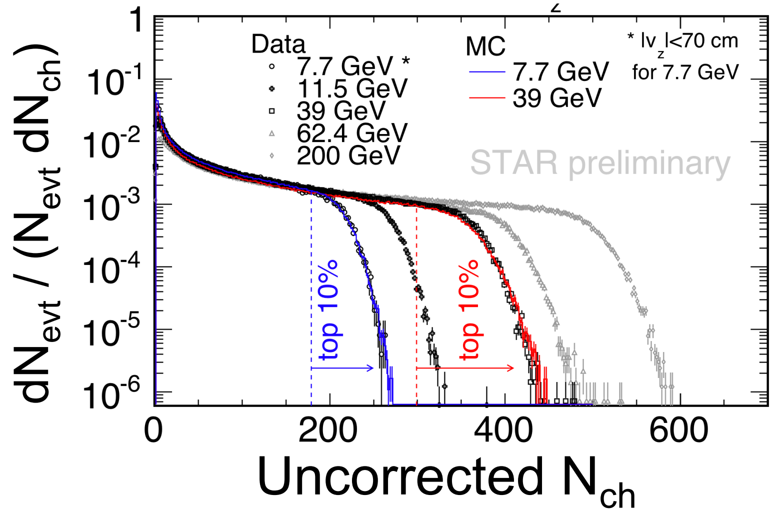


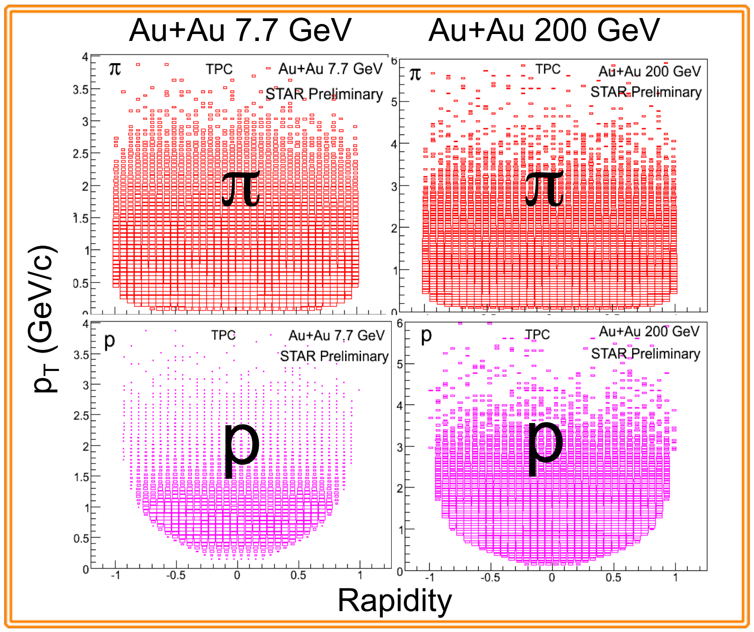
Beyond single (chemical) freeze-out:

1. J. Steinheimer et al. PRL 110, 042501 (2013)
2. S. Chatterjee et al. PLB 727, 554 (2013)
3. K. Bugaev et al., EPL 104, 22002 (2013)

STAR Experiment







Coverage:

$0 < \phi < 2\pi$

$|\eta| < 1.0$

Uniform acceptance:

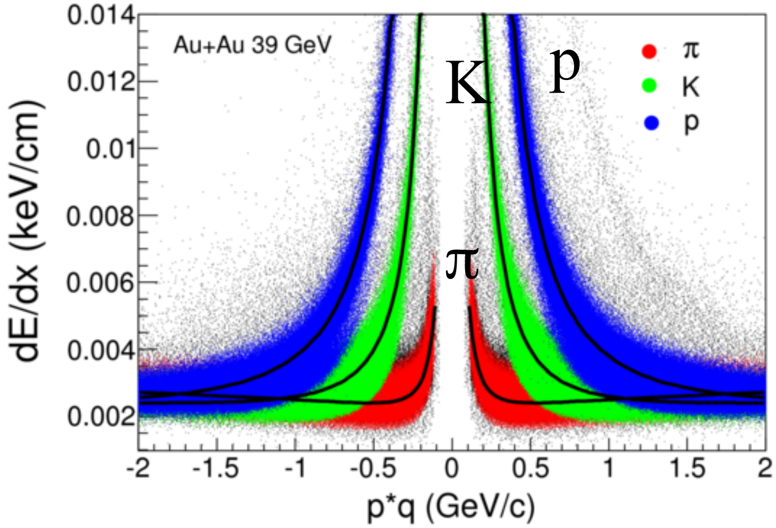
All energies and particles

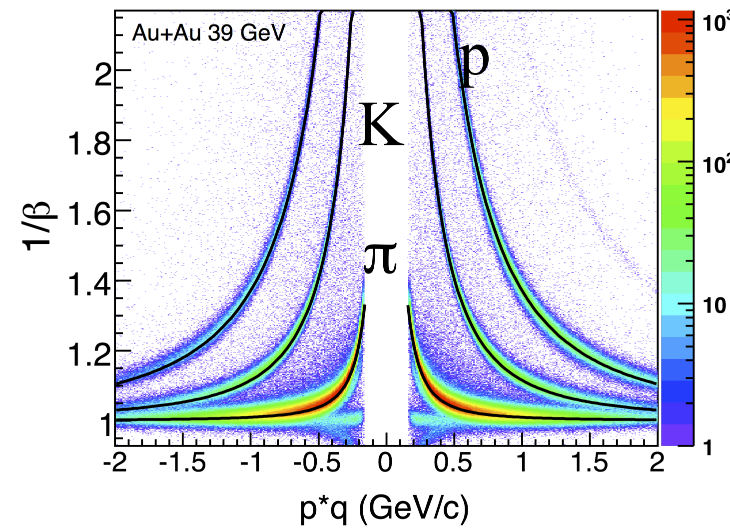
BES-I Data:

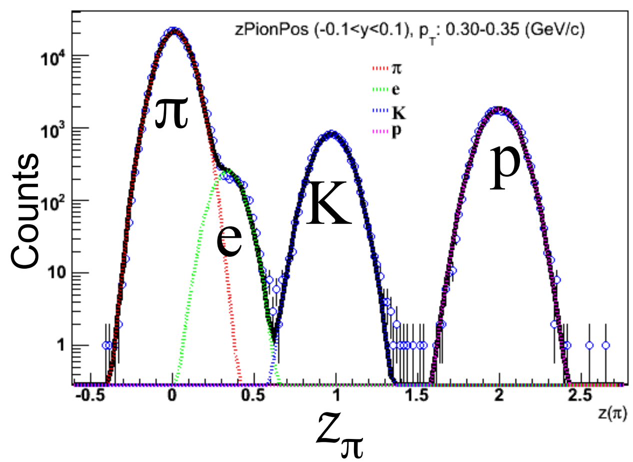
Year	$\sqrt{s_{NN}}$ (GeV)	Events (10^6)
2010	62.4	67
2010	39	130
2011	27	70
2011	19.6	36
2014	14.5	20*
2010	11.5	12
2010	7.7	5

Particle Identification

TPC $\sqrt{s_{NN}}$ **= 39 GeV Au + Au Collisions** ***TPC+ToF***





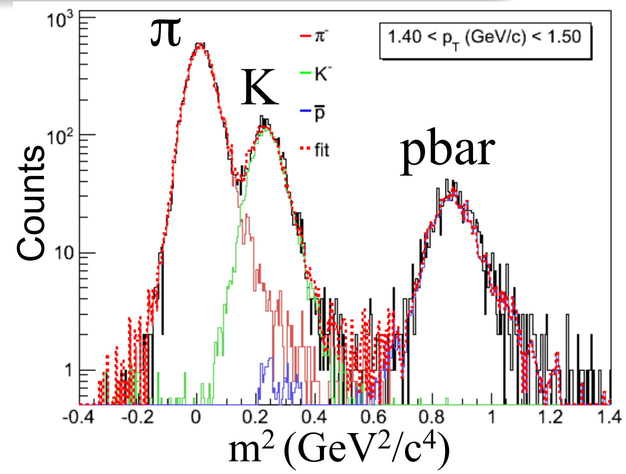


$$z = \log\left(\frac{(dE/dx)_{meas.}}{(dE/dx)_{theory}}\right)$$

H. Bichsel, NIM A. 562 (2006) 154

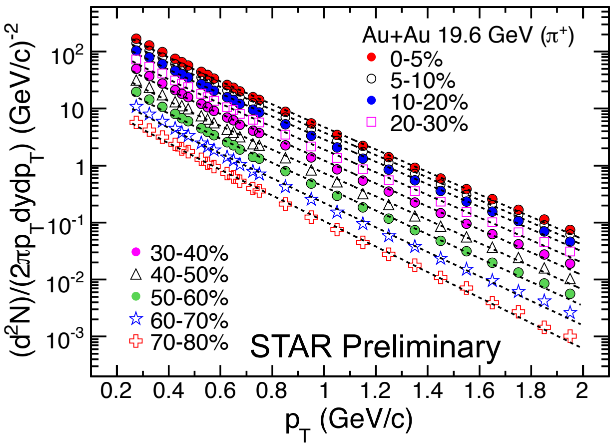
$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

c=velocity of light,
L=path length

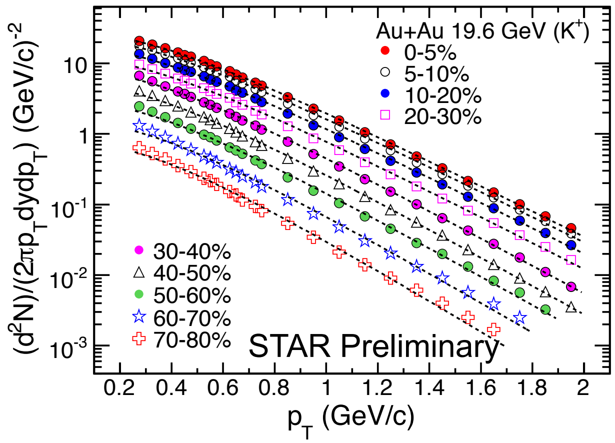


Invariant Yield

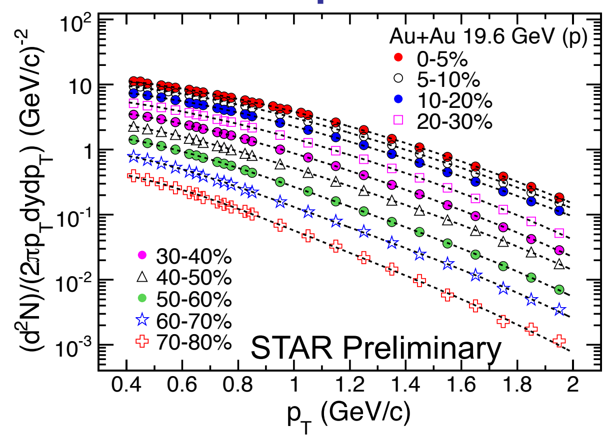
π^+



K^+



p



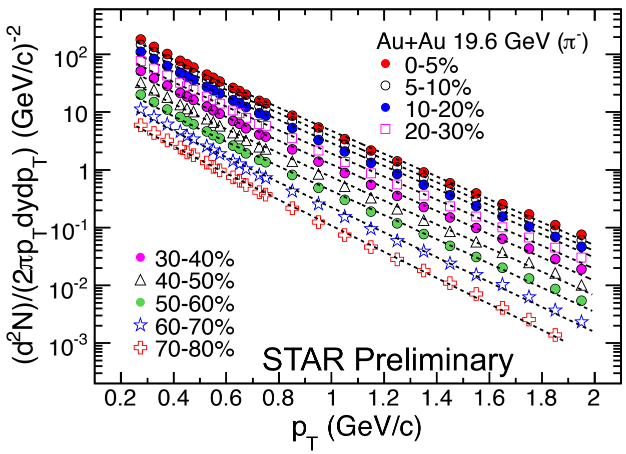
Pion curves:
Bose-Einstein fits

Au+Au 19.6 GeV

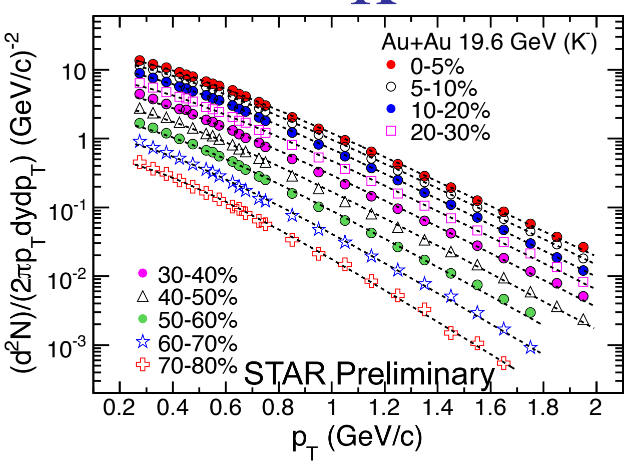
Kaon curves:
(m_T-m) exponential fits

proton curves:
Double exponential fits

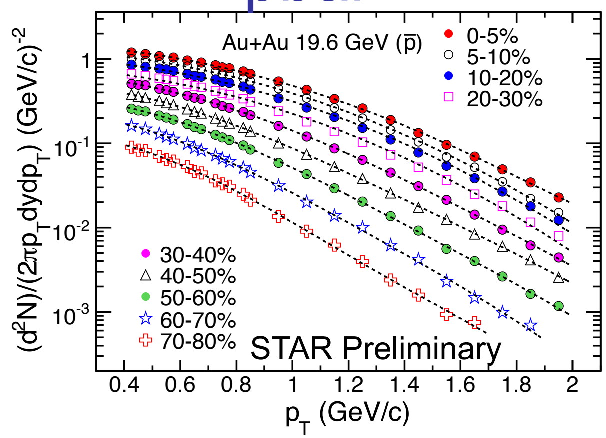
π^-



K^-

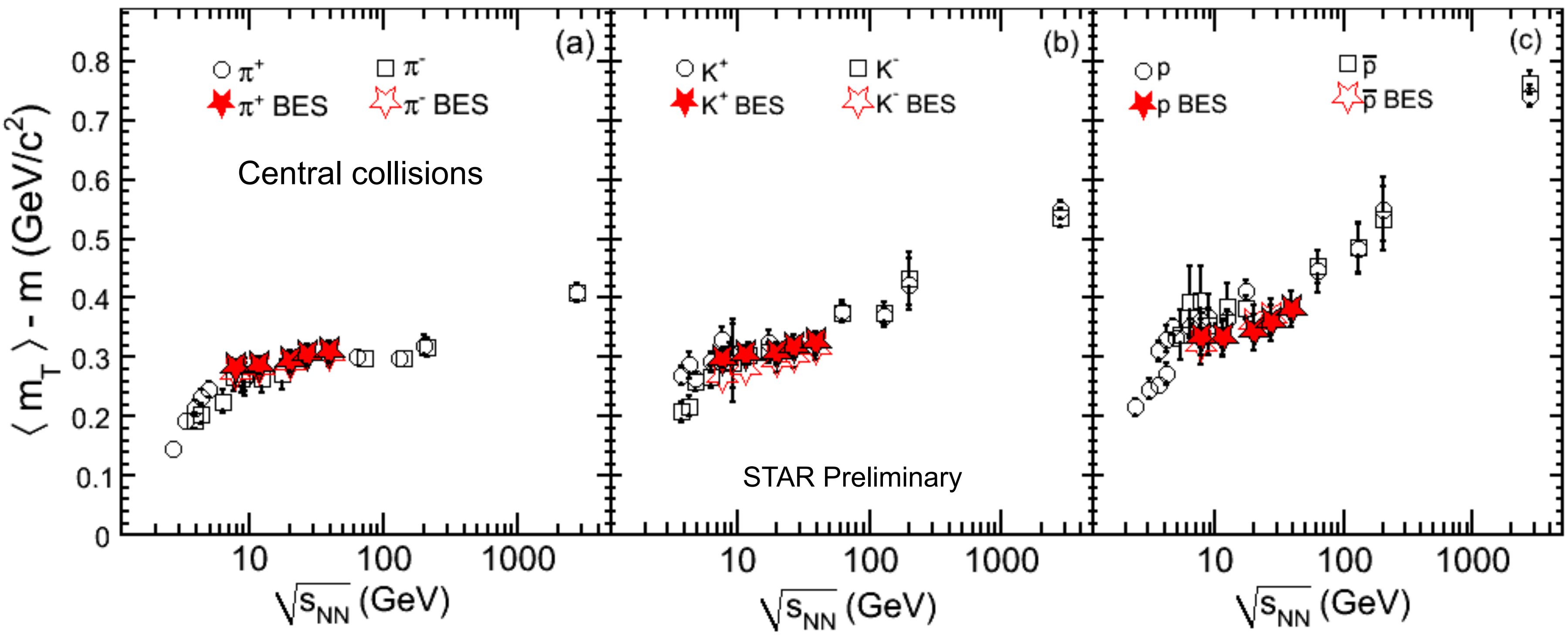


pbar



Spectra are characterized by dN/dy and $\langle p_T \rangle$ or $\langle m_T \rangle$

Average Transverse Mass



NA49 : PRC 66 (2002) 054902, PRC 77 (2008) 024903, PRC 73 (2006) 044910 ; STAR : PRC 79 (2009) 034909, PRC 81, 024911 (2010); E802(AGS) : PRC 58 (1998) 3523, PRC 60 (1999) 044904; E877(AGS) : PRC 62 (2000) 024901 E895(AGS) : PRC 68 (2003) 054903; ALICE: PRL109, 252301 (2012), PRC 88, 044910 (2013)

$m_T = \sqrt{(p_T^2 + m^2)}$

$\langle m_T \rangle$ - m is almost constant around BES energies for π, K, p

Thermodynamic system: T ~ $\langle m_T \rangle$ - m, Entropy ~ dN/dy ∝ log($\sqrt{s_{NN}}$)

L. Van Hove, Phys. Lett. B 118, 138 (1982)

Kinetic Freeze-out: Blast Wave Model

Elastic collisions among the particles stop and the momentum distribution gets fixed

Blast-Wave (BW) Model:

$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

E. Schnedermann, J. Sollfrank, and U. W. Heinz, Phys. Rev. C 48, 2462 (1993).

I_0, K_1: Modified Bessel functions

$\rho(r) = \tanh^{-1}\beta$, r/R: relative radial position; R: radius of fireball

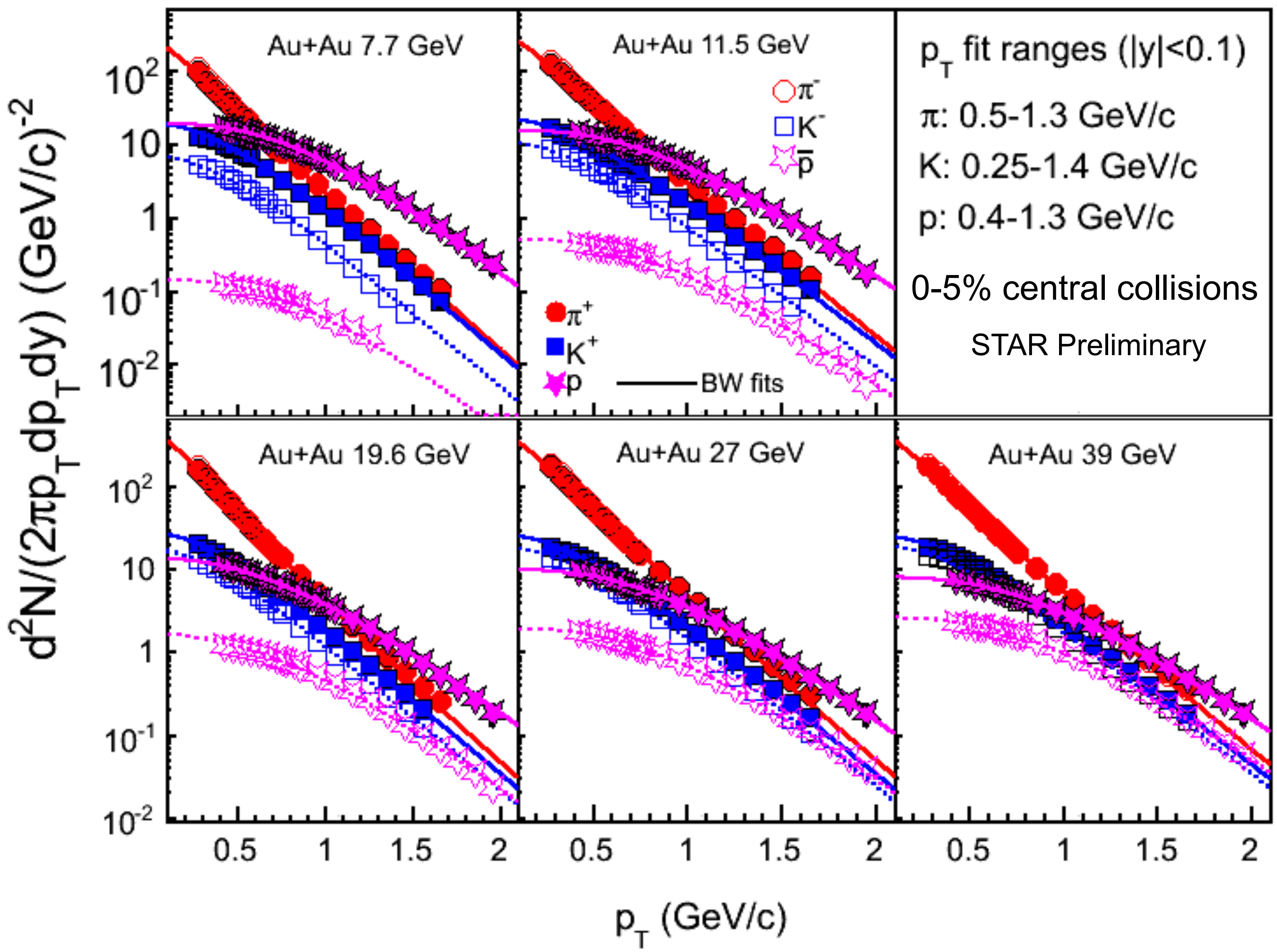
β: transverse radial flow velocity, T_{kin}: Kinetic freeze-out temperature

- Hydrodynamic based model
- Assumes particles are locally thermal at a kinetic freeze-out temperature and moving with a common radial flow velocity

✧ Momentum distributions are fitted simultaneously with BW

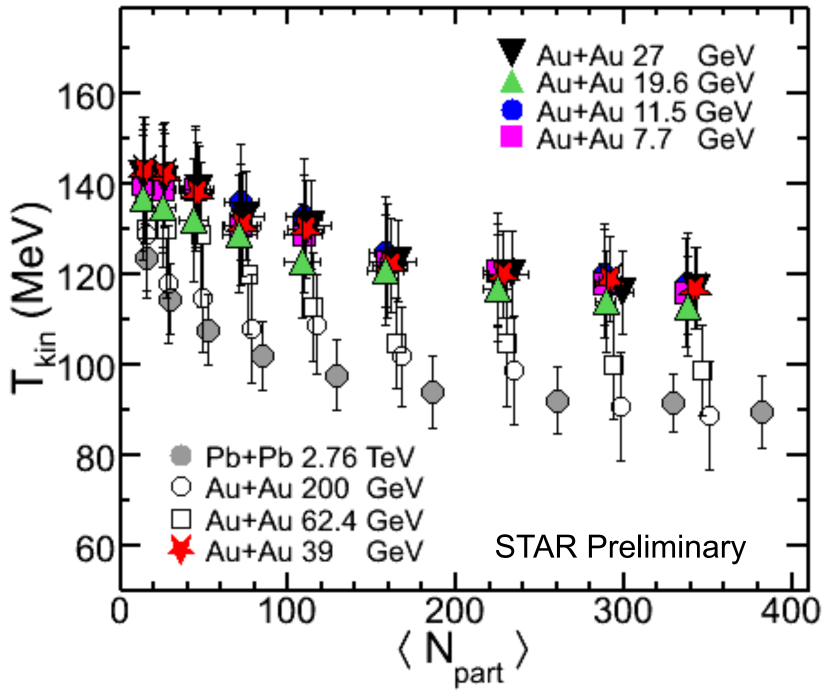
✧ Two main parameters: T_{kin} and $\langle\beta\rangle$

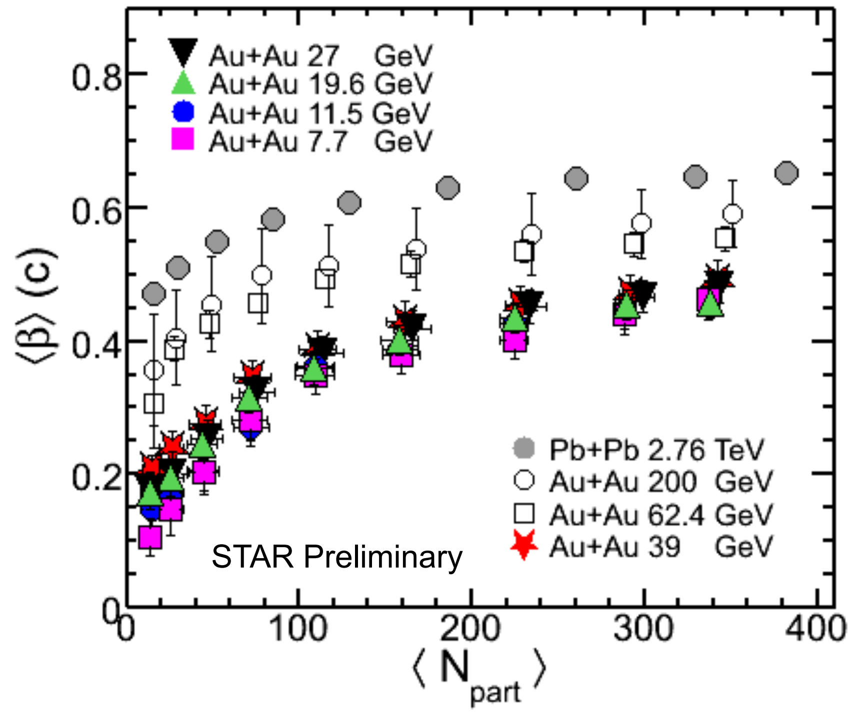
Blast Wave Fits: π, K, p



BW well explains the π, K, p spectra simultaneously

Centrality Dependence: T_{kin} and <β>





STAR : PRC 79 (2009) 034909; ALICE: PRC 88, 044910 (2013)

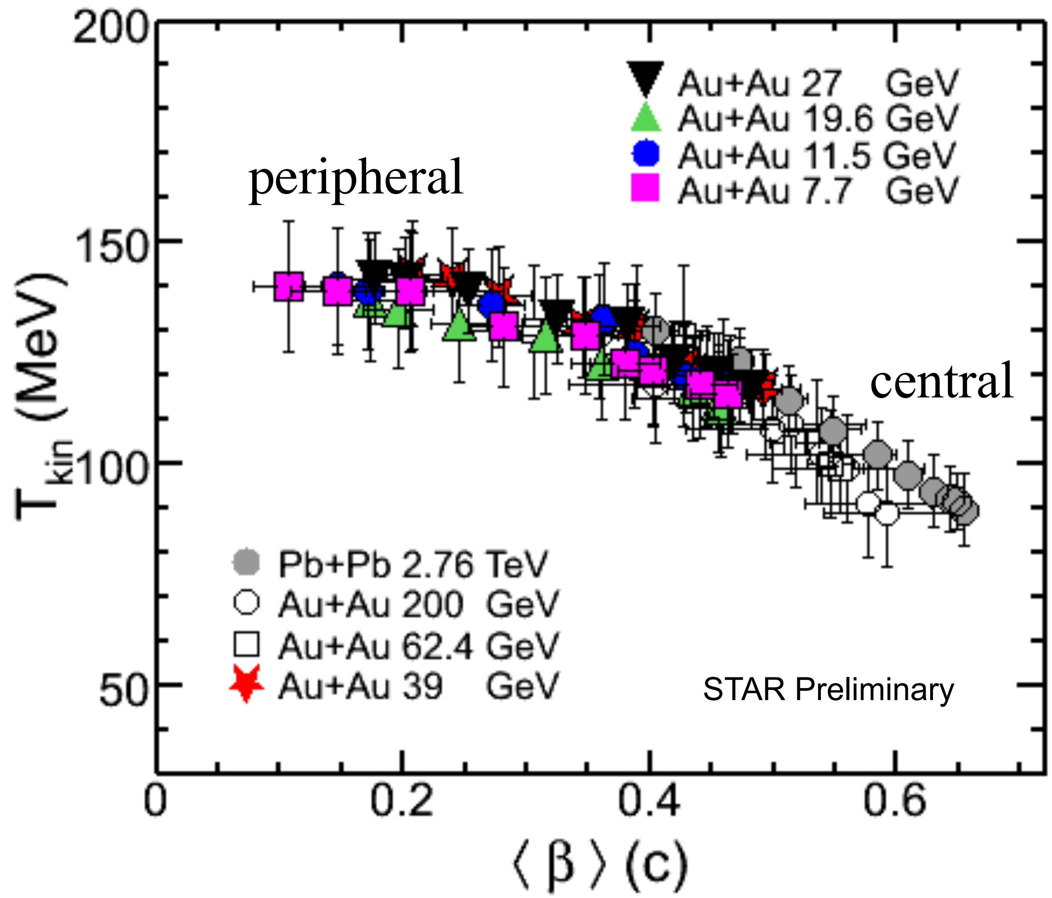
T_{kin} decreases from peripheral to central collisions

-- Longer lived fireball in central collisions

<β> increases from peripheral to central collisions

-- More rapid expansion in central collisions

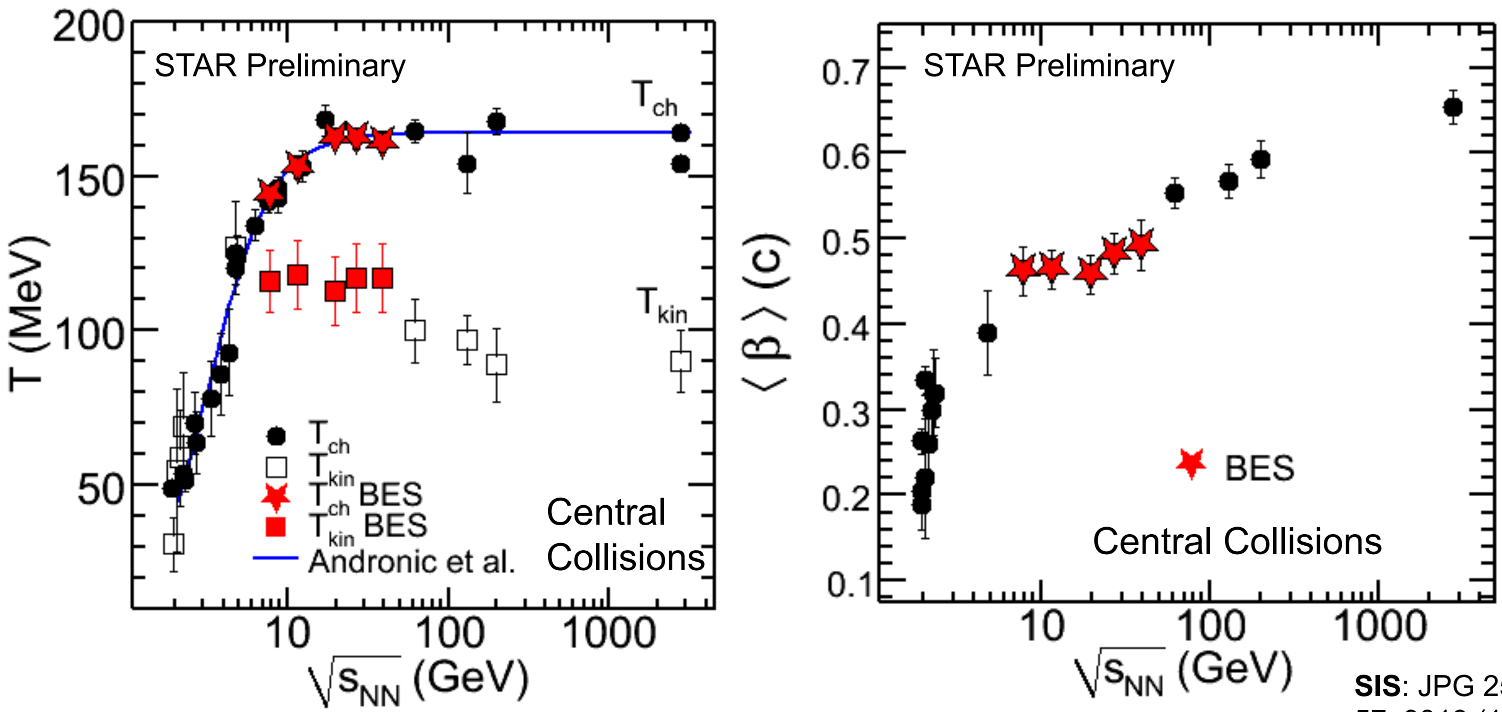
T_{kin} versus <β>



STAR : PRC 79 (2009) 034909; ALICE: PRC 88, 044910 (2013)

Anti-correlation: T_{kin} increases,<β> decreases and vice-versa

Energy Dependence: T_{kin} and <β>

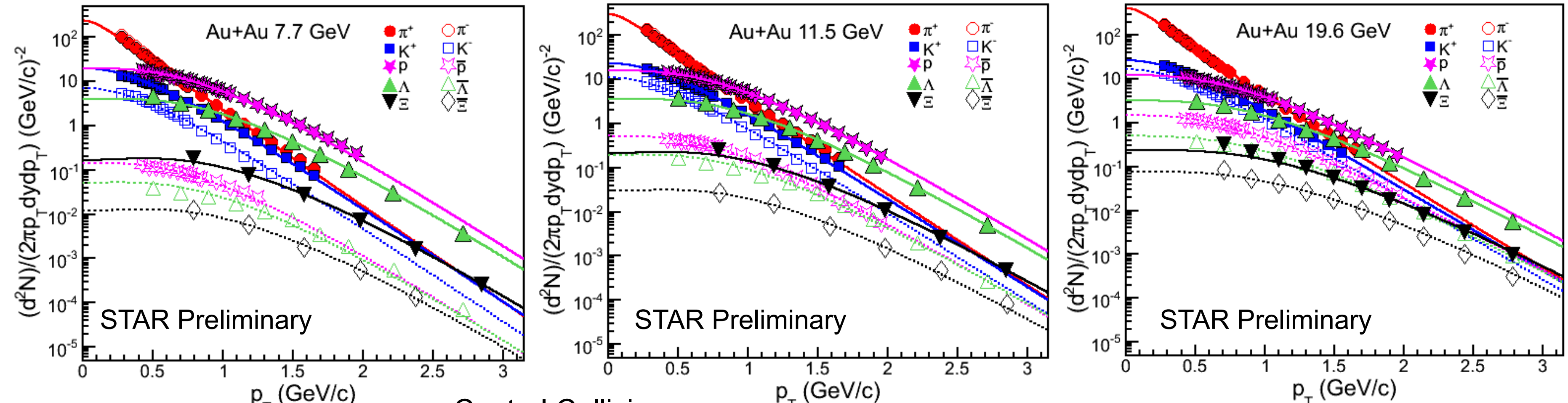


FOPI: NPA 612, 493 (1997); **EOS**: PRL 75, 2662 (1995); **E866**: arXiv:nucl-ex/9806002; **STAR** : PRC 79 (2009) 034909; **ALICE**: PRC 88, 044910 (2013; PRL109, 252301 (2012).

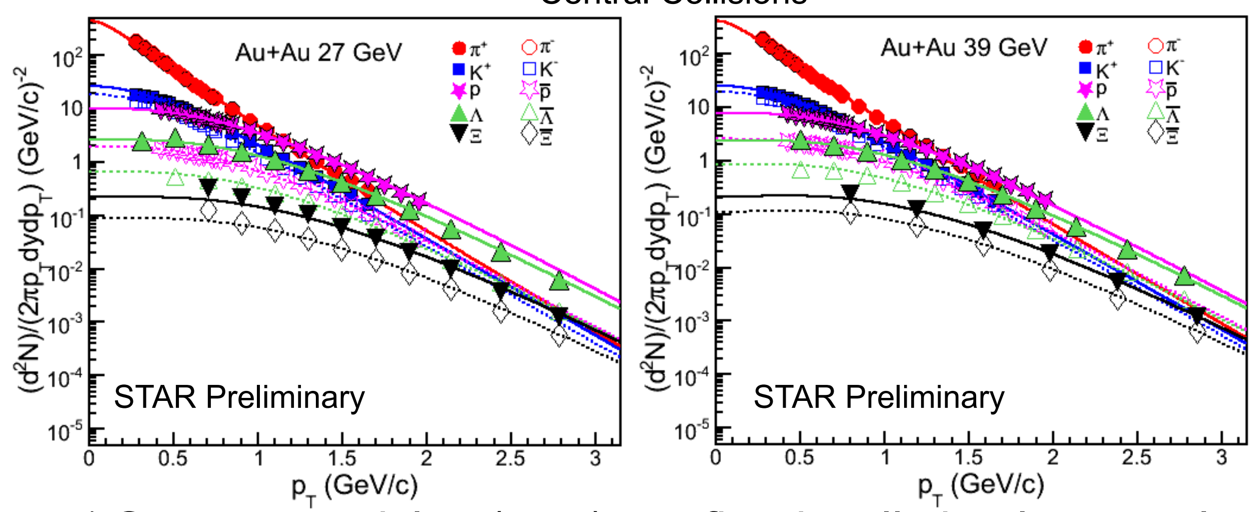
SIS: JPG 25, 281 (1999); PRC 57, 3319 (1998); **AGS**: PLB 344, 43 (1995); PLB 365, 1 (1996); PRC 67, 015205 (2003); **SPS**: PLB 365, 1 (1996); PLB 465, 15 (1999); PRC 67, 015205 (2003); JPG 28, 1861 (2002); PRC 64, 024901 (2001); PRC 73, 034905 (2006); NPA 772, 167 (2006) ;

- Systematic study of chemical and kinetic freeze-out in heavy-ion collisions
- <β> similar at low BES energies and then increases for higher energies up to LHC

BW Fits: Including Λ and Ξ



Central Collisions

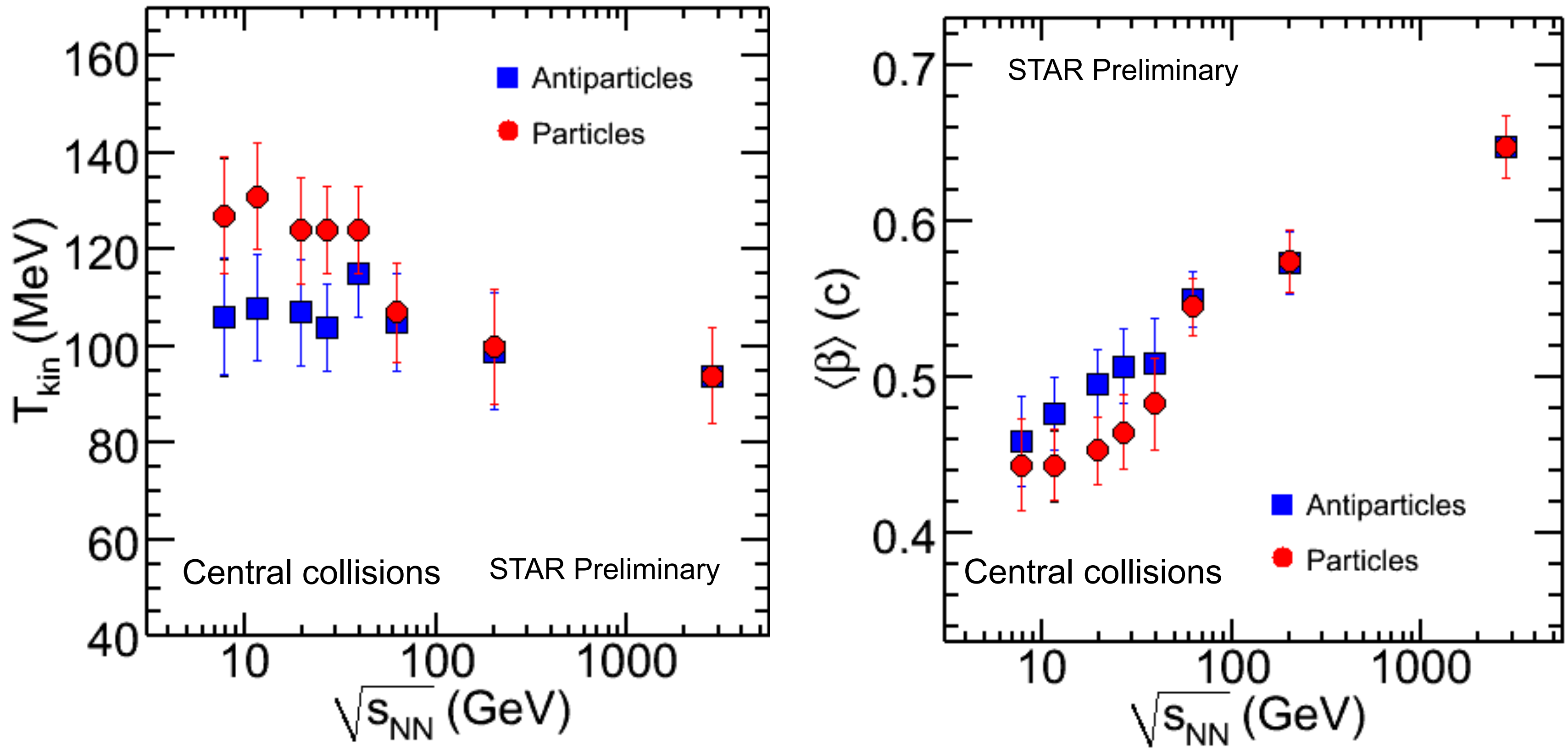


Particle	Rapidity	p_T fit range (GeV/c)
$\pi^{\pm}$	$\|y\| < 0.1$	0.5-1.3
$K^{\pm}$	$\|y\| < 0.1$	0.25-1.4
p/pbar	$\|y\| < 0.1$	0.4-1.3
Λ/Λbar	$\|y\| < 0.5$	0.5-2.0
Ξ/Ξbar	$\|y\| < 0.5$	0.7-2.0

- ✧Strange particles (Λ, Ξ) are fitted well simultaneously with π,K,p in Blast wave
- ✧T_{kin} and <β> extracted are similar as from fits to π,K,p spectra only

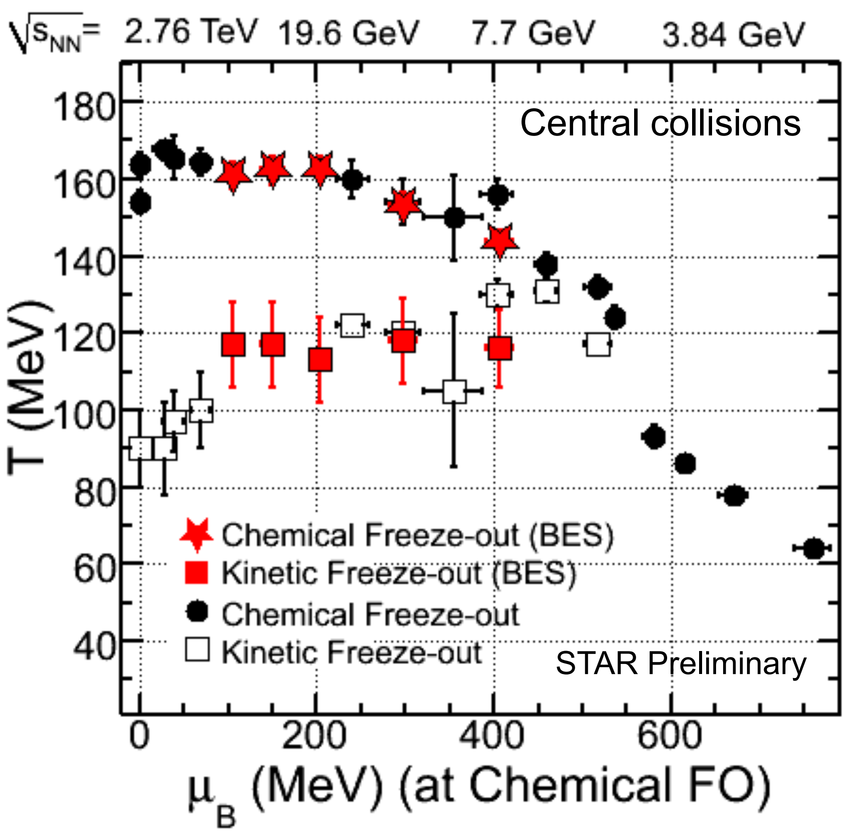
BW Fits: Particle-Antiparticle

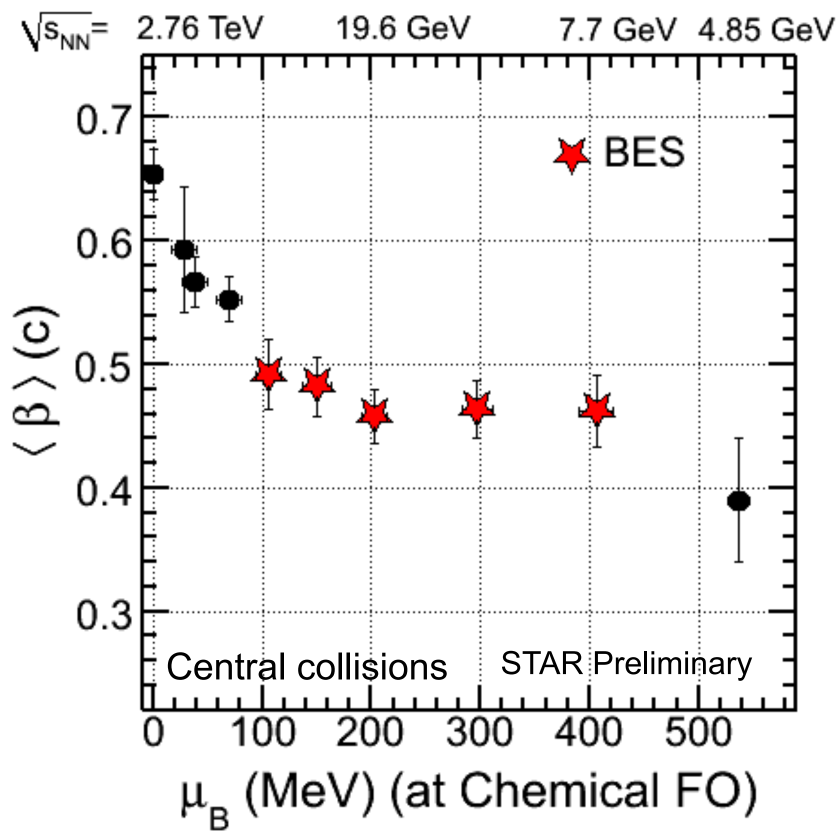
Particles: π^+, K^+, p, Λ, Ξ^- ; Antiparticles: π^-, K^-, pbar, Λbar, Ξ^+



- ✧ Interesting trends at lower energies but errors are large
- ✧ More detailed studies underway…

Current Status of Phase Diagram





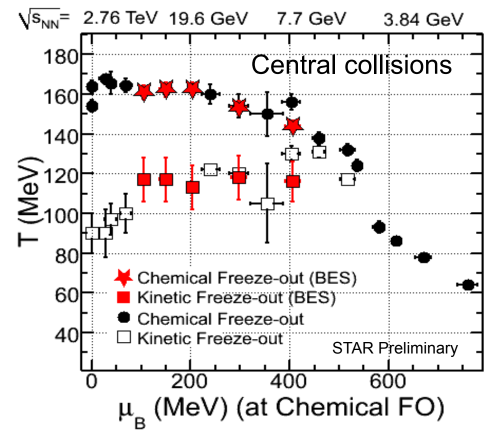
- Covering large portion of QCD phase diagram
- Difference between T_{kin} and T_{ch} increases for lower μ_B : Effect of hadronic interactions between chemical and kinetic freeze-out

- <β> is almost similar from μ_B 200-400 MeV

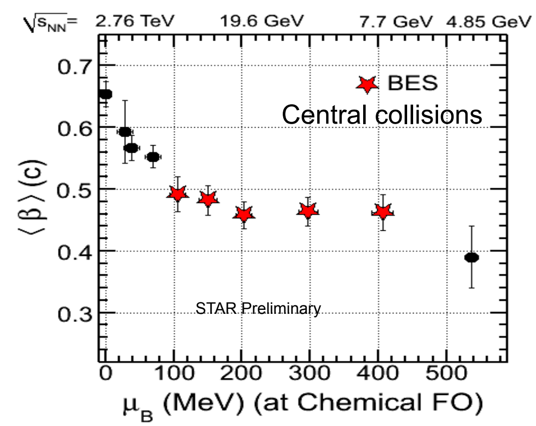
Summary

- Systematic study of kinetic freeze-out properties in heavy-ion collisions (μ_B : 20-400 MeV)

- T_{kin} and <β> show anti-correlation:
  - T_{kin} decreases towards central collisions
    - -- longer lived fireball
  - <β> increases towards central collisions
    - -- more rapid expansion



- T_{kin} is similar at low BES energies
  - Decreases for higher energies
  - Difference b/w T_{ch} and T_{kin} is large at lower μ_B
    - -- effect of hadronic interactions b/w chemical and kinetic FO



- <β> is almost constant for lower BES energies and increases for higher energies : $\langle m_T \rangle - m$ for π, K, p also shows similar behavior

Thanks to STAR Collaboration

Back up

Chemical Freeze-out

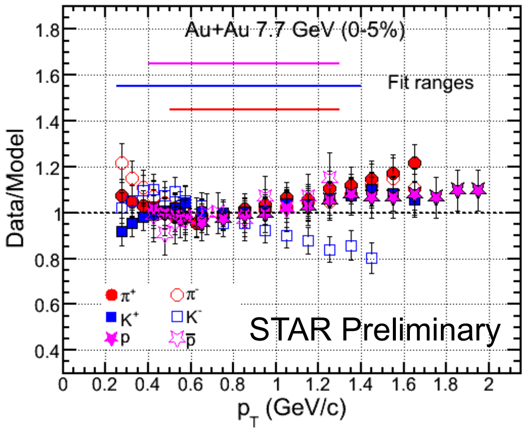
Statistical-Thermal Model (THERMUS):

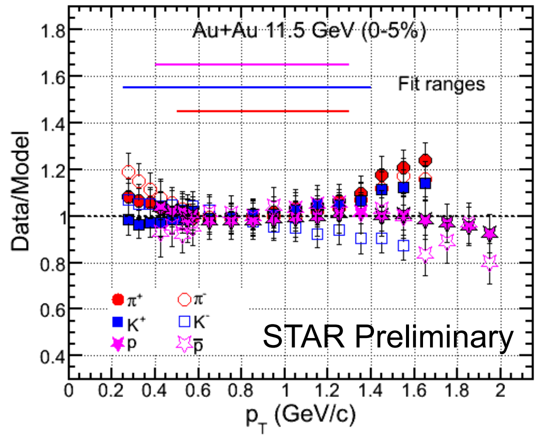
$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} = \frac{VTm_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm1)^{k+1}}{k}\left(e^{\beta k\mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

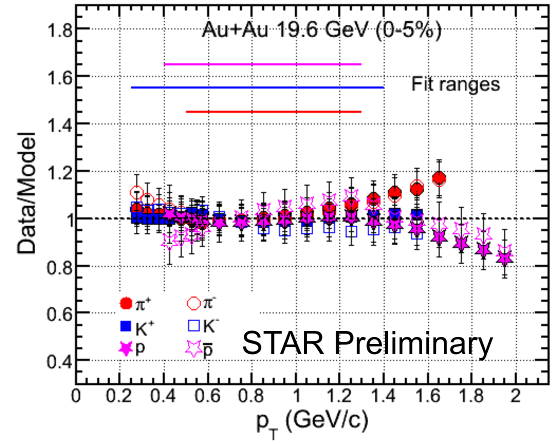
$\beta=1/T$; -1(+1) for fermions (bosons),
Z=partition function;
m_i = mass of hadron species i;
V = volume; T = Temperature;
K_2= 2nd order Bessel function;
g_i = degeneracy; μ_i = chemical potential

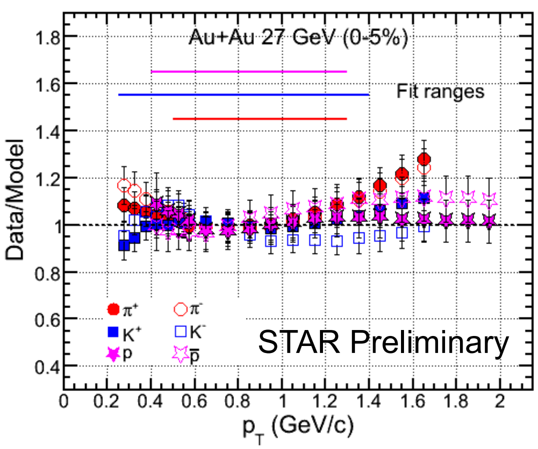
- Fitted particle ratios with THERMUS
- Used grand-canonical approach
- Two main parameters: T_{ch} and μ_B

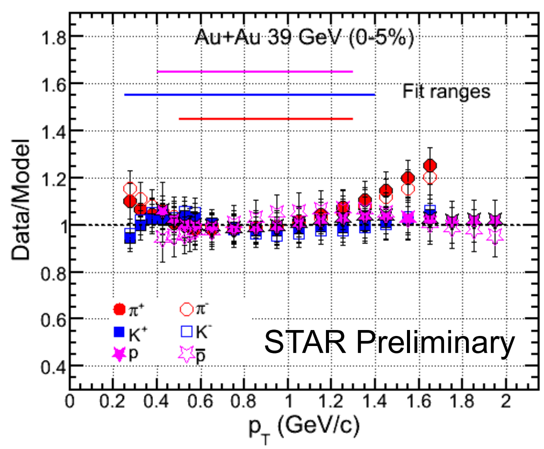
BW fits (data/model)





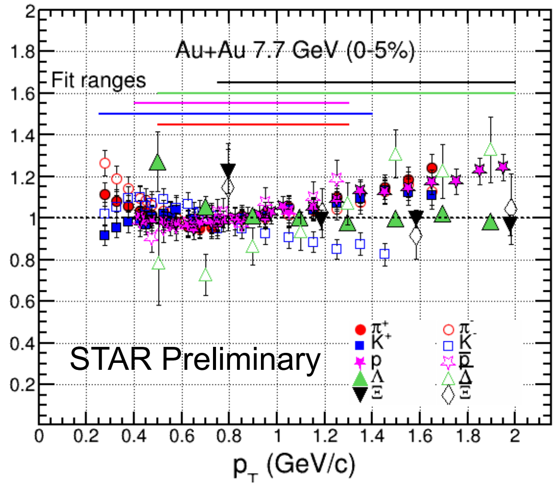


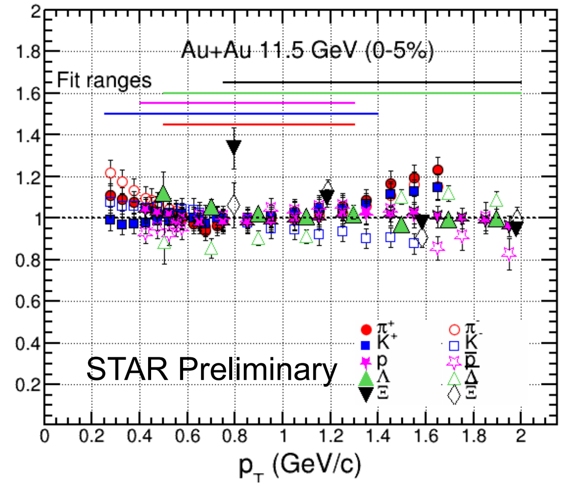


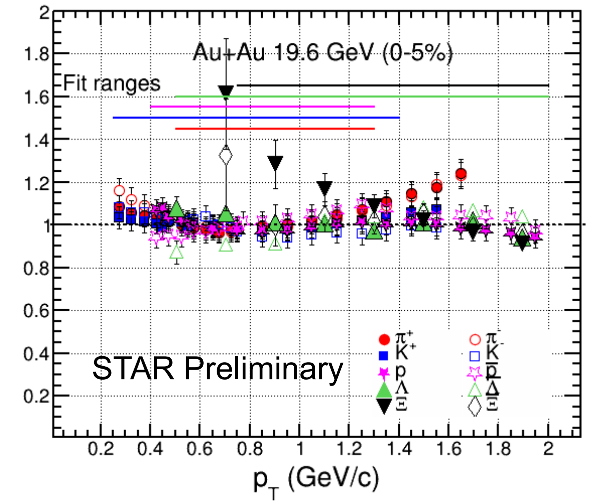


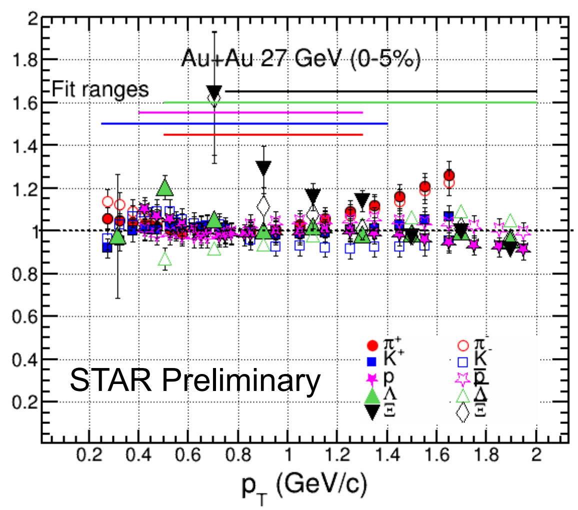
π , K, p
and antiparticles

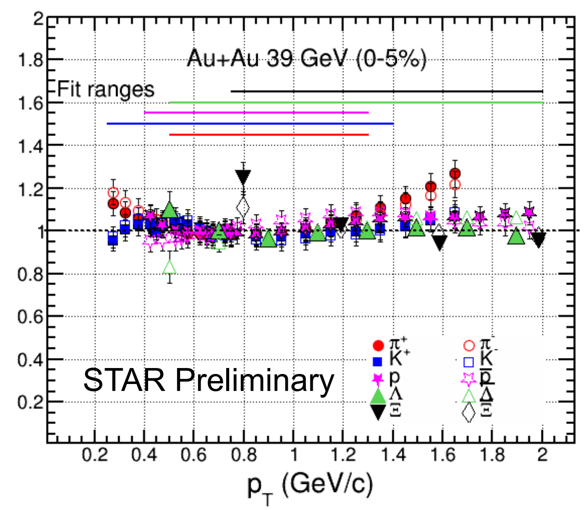
BW fits (data/model)







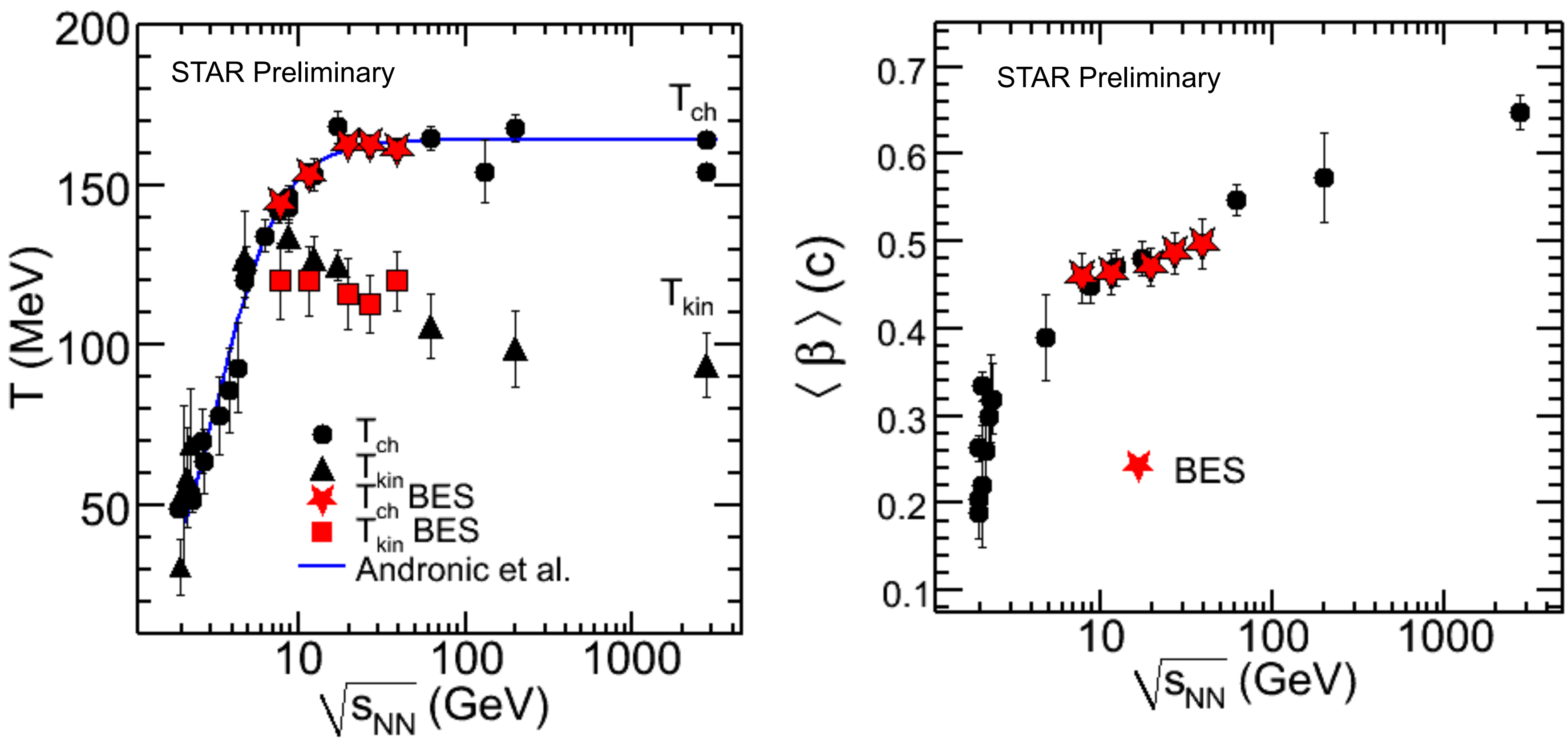




π, K, p, Λ, Ξ and antiparticles

Energy dependence: fits with Λ and Ξ

BW fits include: π, K, p, Λ, Ξ and corresponding antiparticles



BW Fits: Particle-Antiparticle

BW fits include: π, K, p only and corresponding antiparticles