Bulk properties of the system formed in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV using the STAR detector at RHIC

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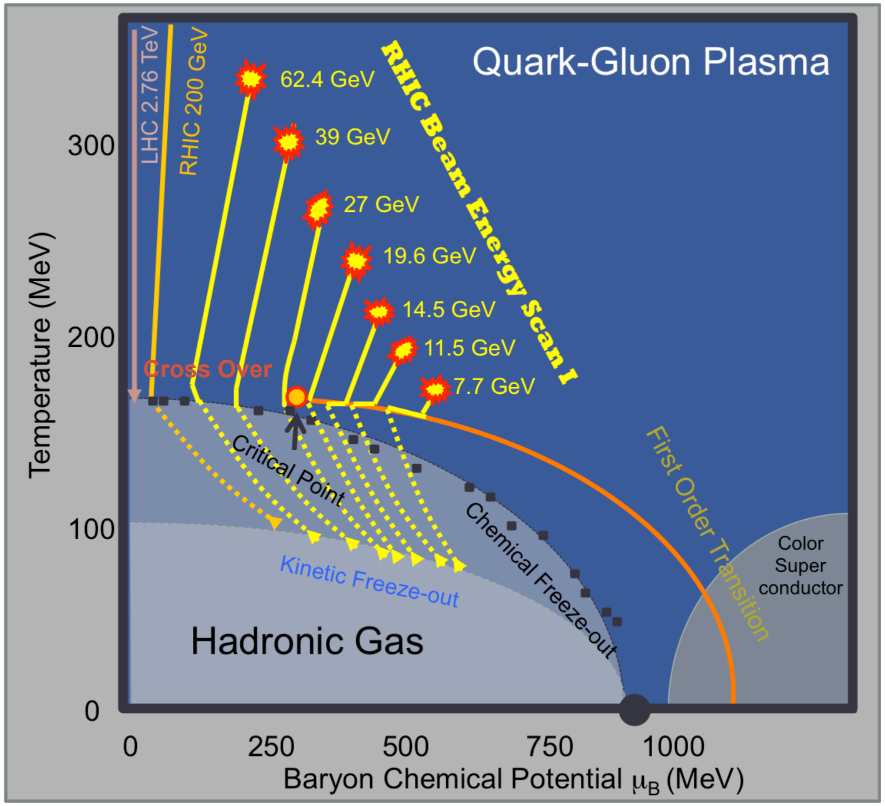
Outline

- Introduction & Motivation
- STAR Experiment at RHIC
- Results
  - Identified particle production and freeze out parameters
  - Azimuthal anisotropy of identified hadrons
- Summary

Quark Matter
Kobe, Japan
Sept. 27 – Oct. 3, 2015

Motivation: RHIC BES Program



QCD Phase Diagram

•https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Goals of RHIC beam energy scan program

✧ Search for turn-off of QGP signatures

✧ Search for the first-order phase transition

✧ Search for critical point

Freeze out in heavy-ion collisions

Chemical freeze out (T_{ch}, μ_B)

✧ Inelastic collisions among particles cease

Kinetic freeze out (T_{kin}, $\langle\beta\rangle$)

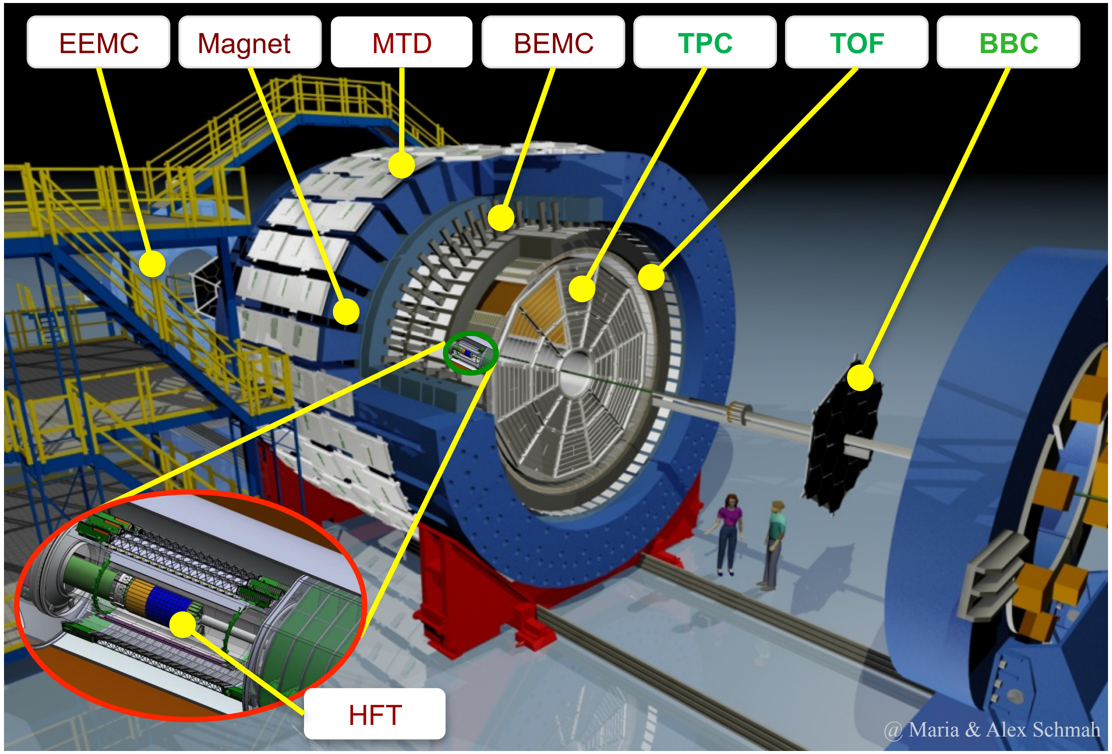
✧ Elastic collisions among particles cease

Elliptic flow (v_2) of identified hadrons

New data: Au+Au $\sqrt{s_{NN}}$ = 14.5 GeV

✧ Corresponding μ_B= 260 MeV fills a gap in μ_B of about 100 MeV between $\sqrt{s_{NN}}$= 11.5 GeV (μ_B= 315 MeV) and 19.6 GeV (μ_B= 205 MeV).

STAR Experiment at RHIC



BES-I Dataset

Year	$\sqrt{s_{NN}}$ (GeV)	Minimum Bias 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	4

Large Coverage: $0 < \phi < 2\pi$, $|\eta| < 1.0$

Uniform acceptance: transverse momentum (p_T) and rapidity (y)

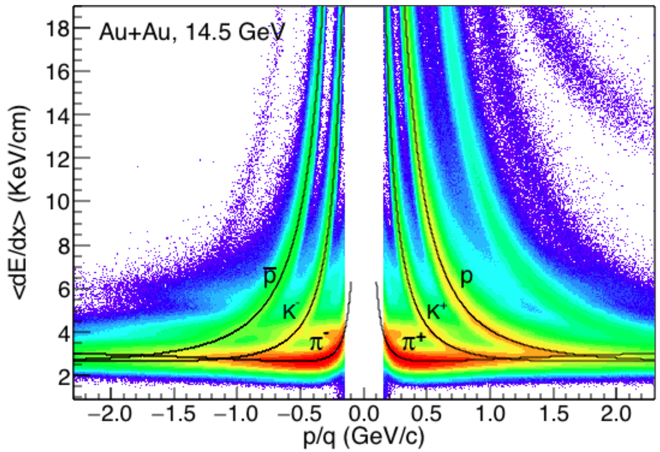
Excellent particle identification capabilities (TPC and TOF)

- *M. Anderson et al., Nucl. Instrum. Meth. A 499 (2003) 659*
- *W. J. Llope., Nucl. Instrum. Meth. A 661 (2012) S110–S113*

Particle Identification

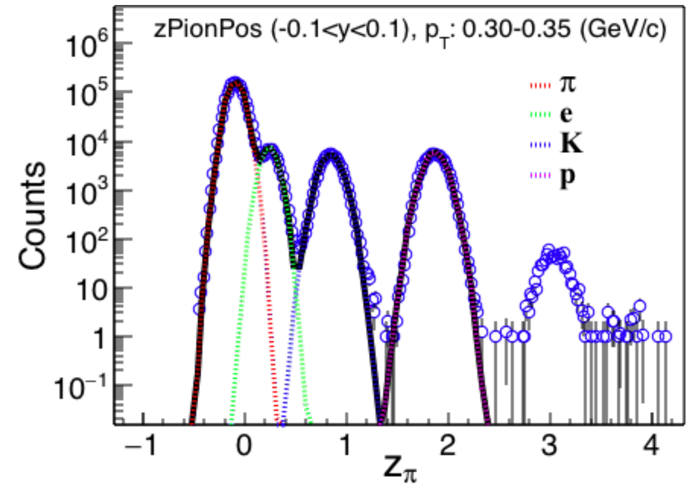
Time Projection Chamber (TPC)

Au + Au $\sqrt{s_{NN}}$ = 14.5 GeV

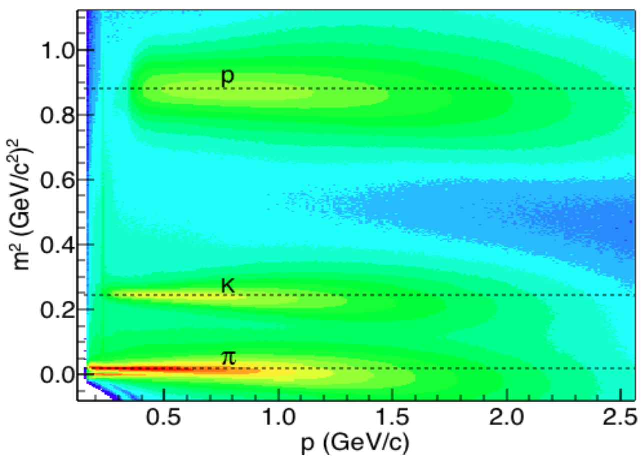


- *H. Bichsel, NIM A. 562 (2006) 154*

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



Time Of Flight (TOF)

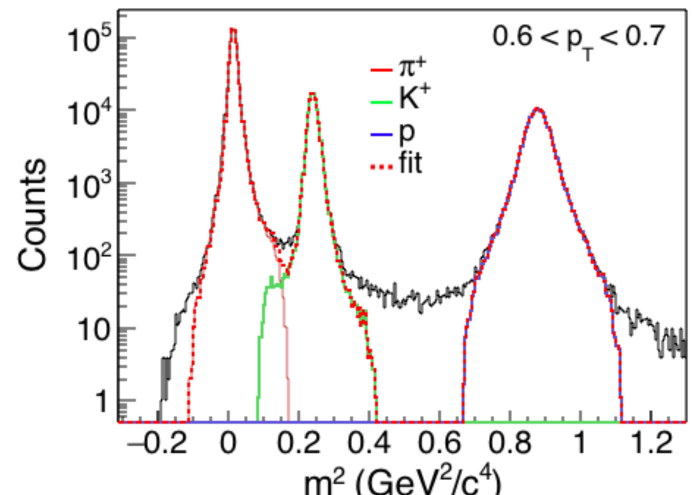


$$m^2 = p^2\left(\frac{c^2t^2}{L^2} - 1\right)$$

p = momentum

t = time of flight

L = path length



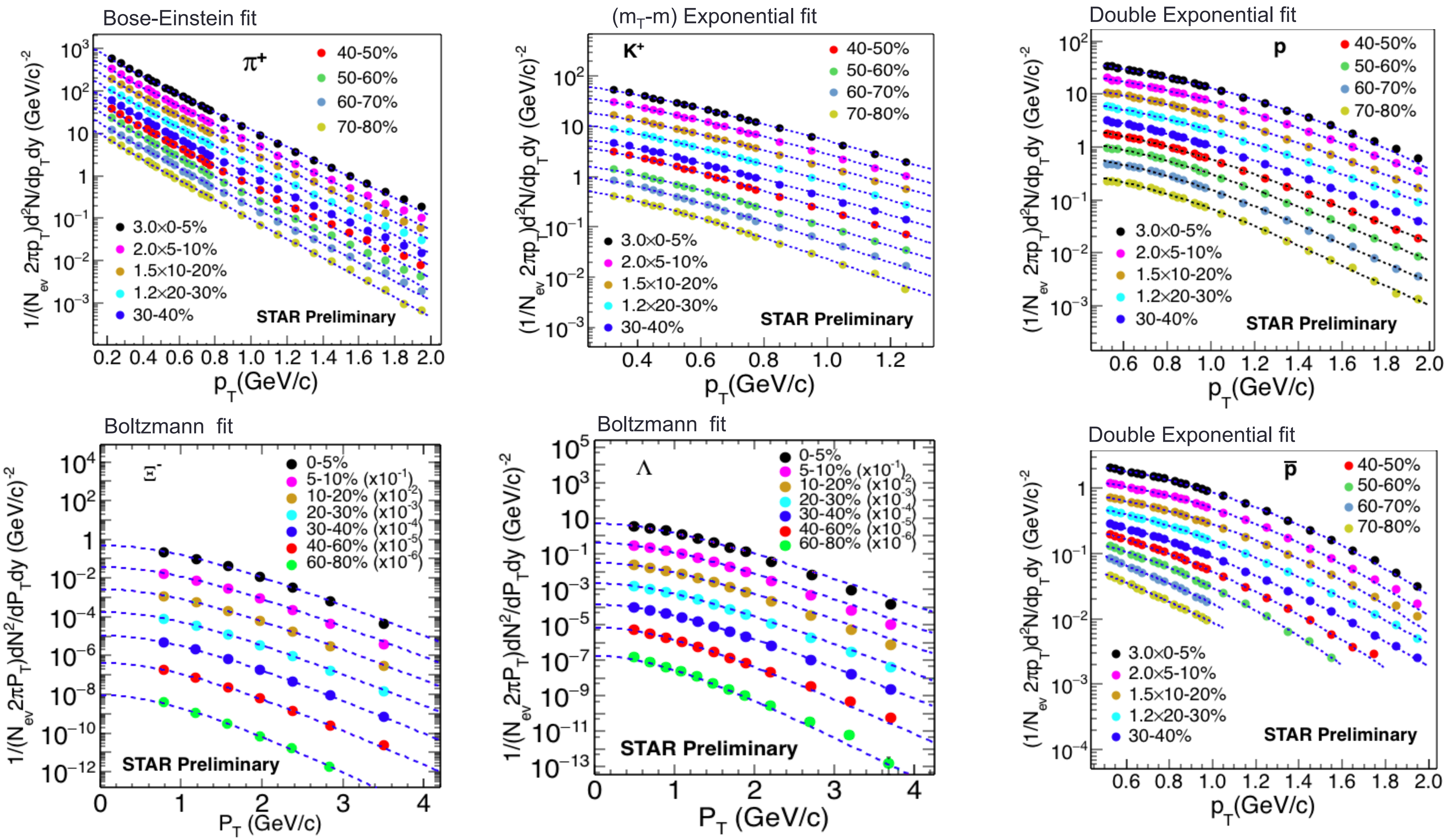
Identified particle production and freeze out properties

See also

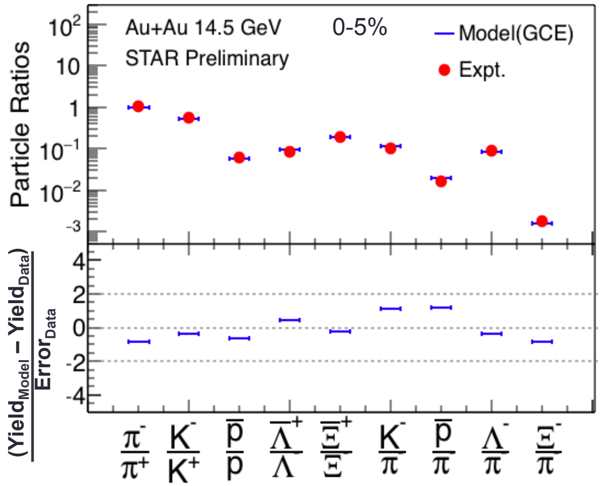
- Talk of James Brandenburg
  Heavy flavors and Strangeness
  Monday, 11.15-11.35

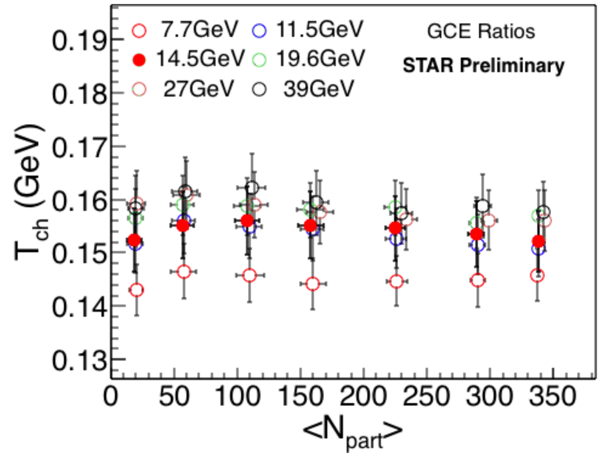
Transverse Momentum Spectra

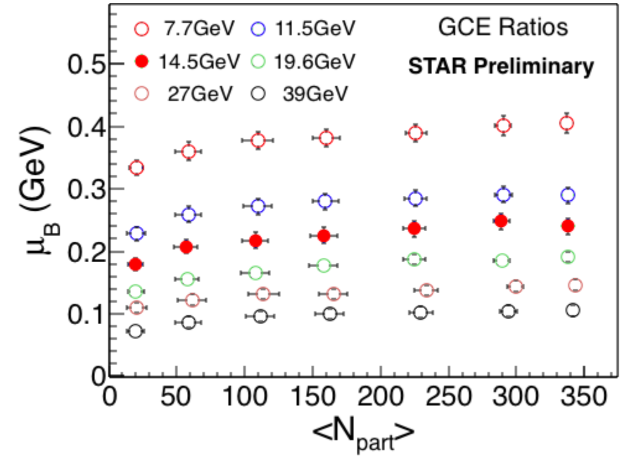
Au + Au $\sqrt{s_{NN}}$ = 14.5 GeV



Chemical Freeze out





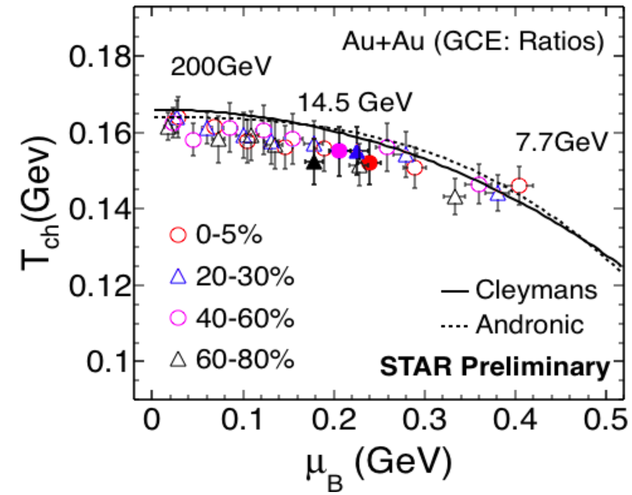


STAR, SQM 2013, Brimingham, UK

- *S. Wheaton & Cleymans, Comput. Phys. Commun., **180**, 84-109 (2009)*

New results for Au+Au, 14.5 GeV

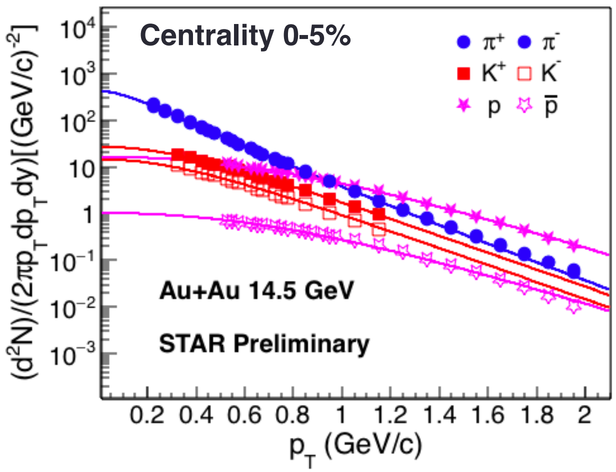
- ✓ Particles used in fit : π, K, p, Λ, Ξ and their anti-particles.
- ✓ T_{ch} increases as collision energy increases.
- ✓ μ_B decreases with increase in collision energy.
- ✓ Centrality dependence is observed for μ_B.

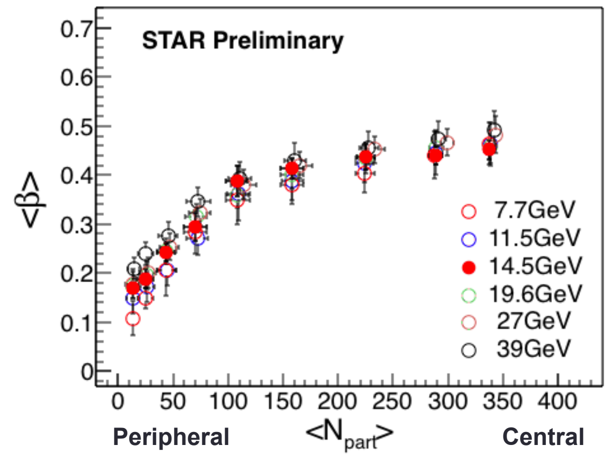


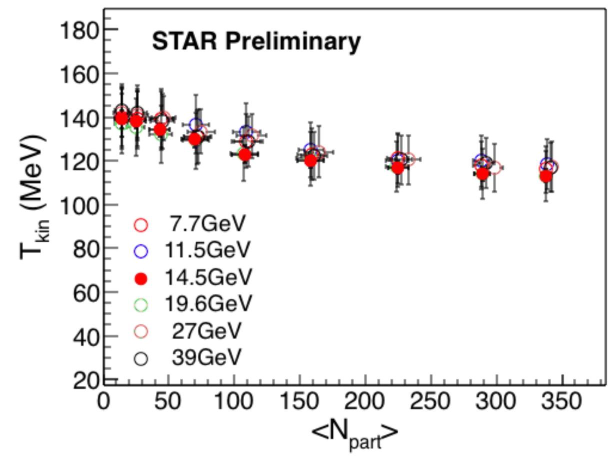
- *J. Cleymans et al. Phys. Rev. C 73, 034905 (2006)*
- *A. Andronic et al. Nucl. Phys. A 834, 237C (2010)*

Kinetic Freeze out

Blast-Wave Fit



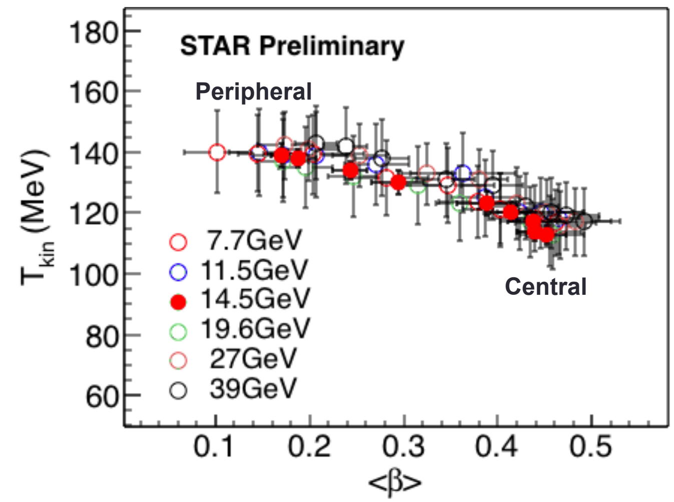




- *E. Schnedermann, J. Sollfrank, and U. W. Heinz, Phys. Rev. C 48, 2462 (1993).*

New results for Au+Au 14.5 GeV data

- ✓ <β> decreases from central to peripheral collisions.
- ✓ T_{kin} increases from central to peripheral collisions.
- ✓ An anti-correlation observed between T_{kin} and <β>.



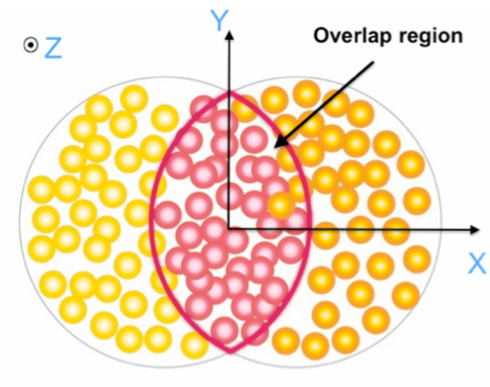
STAR, QM 2014, Darmstadt, Germany

Elliptic flow (v_2) of Identified hadrons

See also

- Talk of Liao Song, Session: Correlations and fluctuations
  Tuesday, 14.40-15.00
- Poster by Shusu Shi, Board: 0833 / 351,
  Tuesday, 16.30-18.30

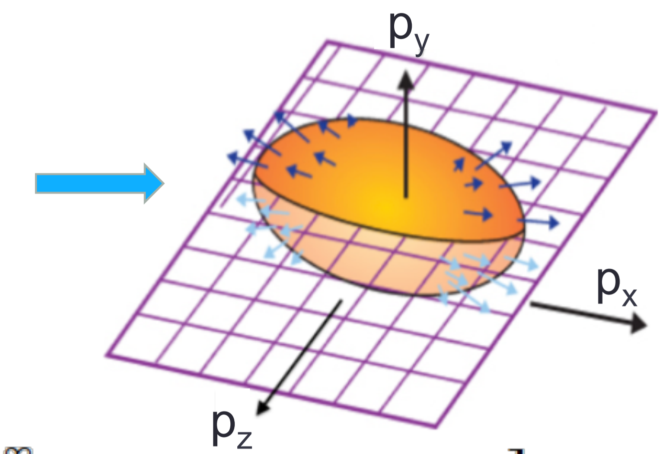
Elliptic Flow (v_2)



Interactions

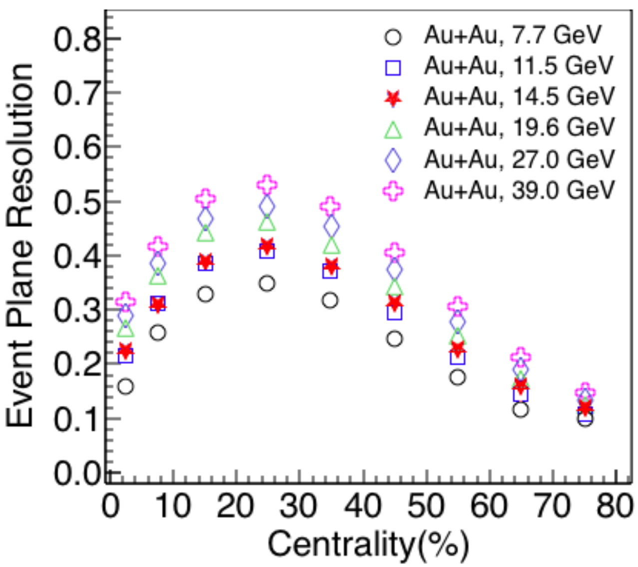
Pressure(P)

$$y > x \rightarrow \frac{\partial P}{\partial x} > \frac{\partial P}{\partial y}$$



$$\frac{dN}{d\phi} \propto \frac{1}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \psi_{rp})\right)\right]$$

$$v_n = \langle \cos\left[n(\phi - \psi_{rp})\right] \rangle$$



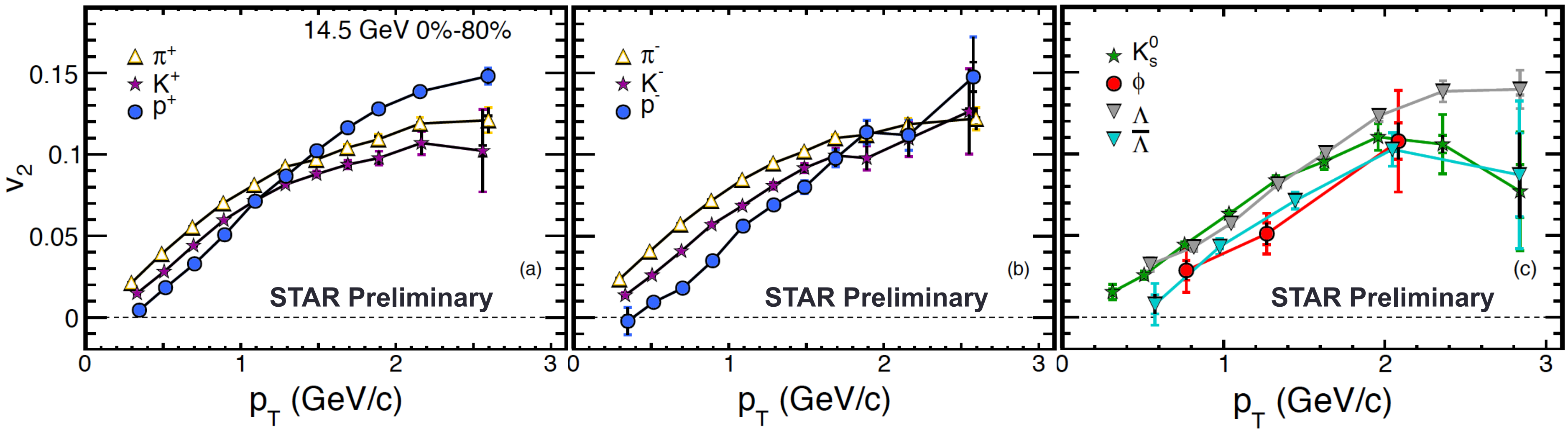
- ✓ η-sub event plane method is used for calculation of v_2.
- ✓ The observed v_2 is corrected for event plane resolution.

$$R = \sqrt{\cos\left(2\left(\psi_2^a - \psi_2^b\right)\right)}$$

- *A.M. Poskanzer & S. Voloshin, Phys. Rev. C58 (1998)*

v_2 measurement

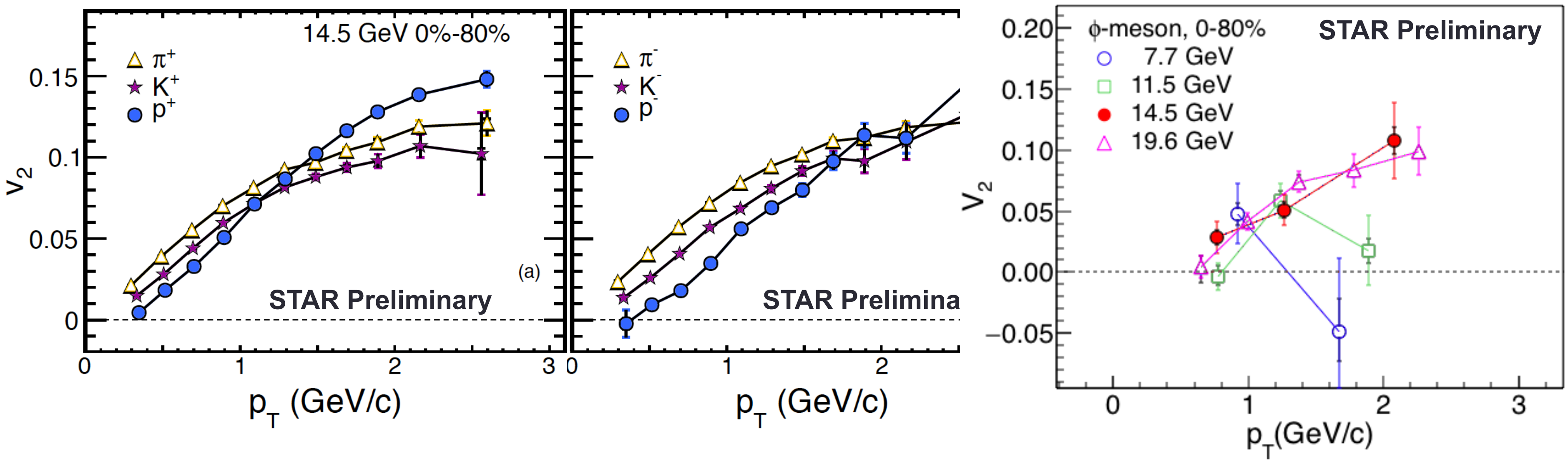
New measurement for Au+Au, 14.5 GeV data



- ✓ Mass ordering of v_2 is observed at low p_T for π^+, K^+, p and their antiparticles.
- ✓ No mass ordering observed for K_s^0, ϕ, Λ and Λ-bar.
- ✓ Difference between v_2 of Λ and Λ-bar observed.

v_2 measurement

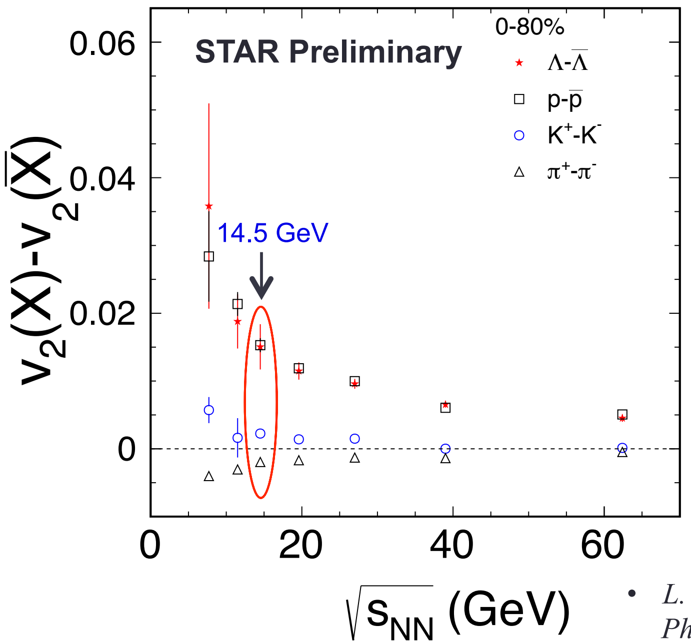
New measurement for Au+Au, 14.5 GeV data



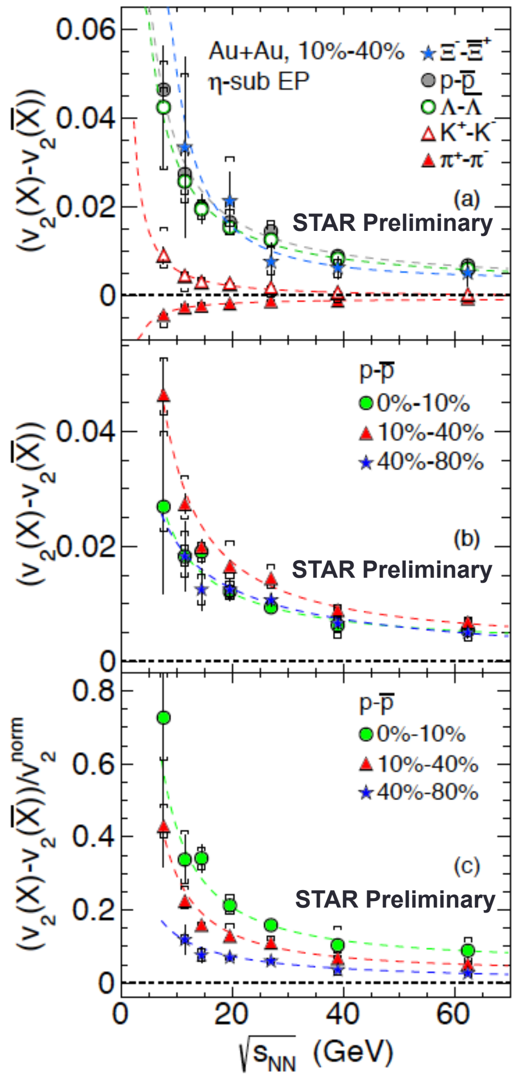
- ✓ Mass ordering of v_2 is observed at low p_T for π^+, K^+, p and their antiparticles.
- ✓ No mass ordering observed for K_s^0, ϕ, Λ and Λ-bar.
- ✓ Difference between v_2 of Λ and Λ-bar observed.
- ✓ Finite ϕ-meson v_2 in Au+Au at 14.5 GeV.

v_2 of Particles and Antiparticles

New result for Au+Au, 14.5 GeV data



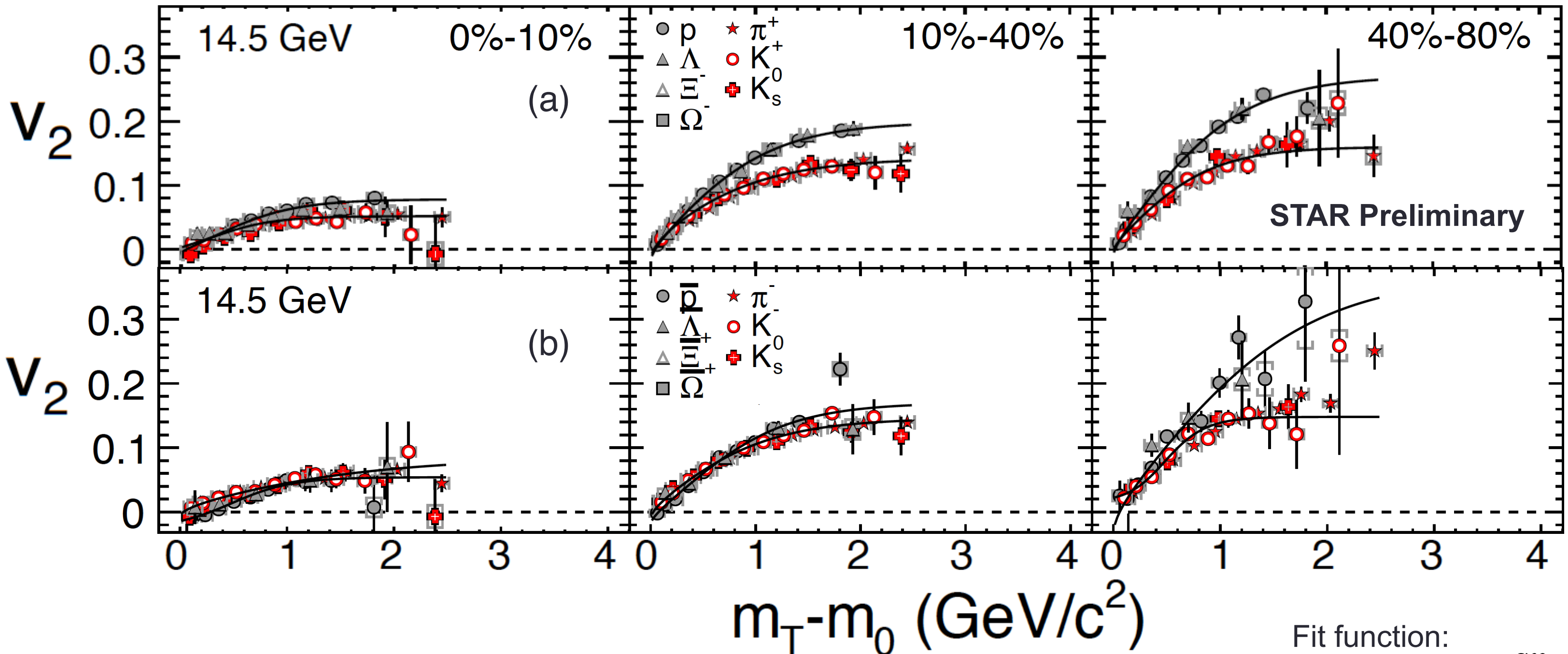
- *L. Adamczyk et. al, (STAR Collaboration) Phys. Rev. C 88 (2013) 14902*



✓ $\Delta v_2 = v_2(X) - v_2(\bar{X})$ increases with decrease in energy.

✓ $\Delta v_2 = v_2(X) - v_2(\bar{X})$ relative to proton v_2 (at p_T = 1.5 GeV/c) shows a centrality dependence.

Centrality dependence



Fit function:

$$fv_2(n) = \frac{an}{1 + e^{-((m_T - m_0)/n - b)/c}} - dn$$

n = 3 for baryons, 2 for mesons

- ✓ Centrality dependence of v_2 is observed.
- ✓ Baryon-meson separation of v_2 is more prominent for particles compared to anti-particles at transverse kinetic energy $(m_T - m_0) > 1$ GeV/c^2

Summary

(A) New Measurements:

- Transverse momentum spectra and elliptic flow v_2 of identified hadrons in Au+Au collisions at 14.5 GeV were presented.
- The results for Au+Au collisions at 14.5 GeV are consistent with the trends established by the other BES energies.

(B) Observations:

Chemical Freeze-out:

- T_{ch} increases as collision energy increases.
- μ_B decreases collision energy increases.
- Centrality dependence of μ_B is observed.

Kinetic Freeze-out:

- Centrality dependence is observed for T_{kin} and <β>.
- T_{kin} and <β> are anti-correlated.

Au+Au, 14.5 GeV
0-5% Most Central

T_{ch}(MeV)	152 ± 6
μ_B (MeV)	240 ± 12
T_{kin}(MeV)	113 ± 3
<β>	0.45 ± 0.02

Elliptic flow v_2:

- Low p_T mass ordering of v_2 for π^+, K^+, p and their anti-particles is observed for Au+Au at 14.5 GeV.
- Centrality dependence is observed for $v_2(p)–v_2(\bar{p})$ when normalized to proton v_2 for all BES energies.

BackUp

Chemical Freeze-out: THERMUS Model

Chemical freeze out:

Inelastic collisions among the particles ceases and particle yields get fixed.

THERMUS: Statistical thermal model

Grand Canonical Ensemble: Quantum numbers (B, S, Q) conserved on average

$$n_i = \frac{T m_i^2 g_i}{2\pi^2} \sum_{k=1}^{\infty} \frac{(\pm 1)^{k+1}}{k} \left(e^{\frac{k\mu_i}{T}} \right) K_2\left(\frac{k m_i}{T} \right)$$

- *S. Wheaton & Cleymans, Comput. Phys. Commun., **180**, 84-109 (2009)*

Thermodynamics quantities extracted:

Chemical freeze out temperature T_{ch}

Baryon chemical potential μ_B

Kinetic Freeze-out: Blast Wave Model

Kinetic freeze out:
Elastic collisions among the particles stop and the momentum distribution gets fixed

Blast-Wave (BW) Model:

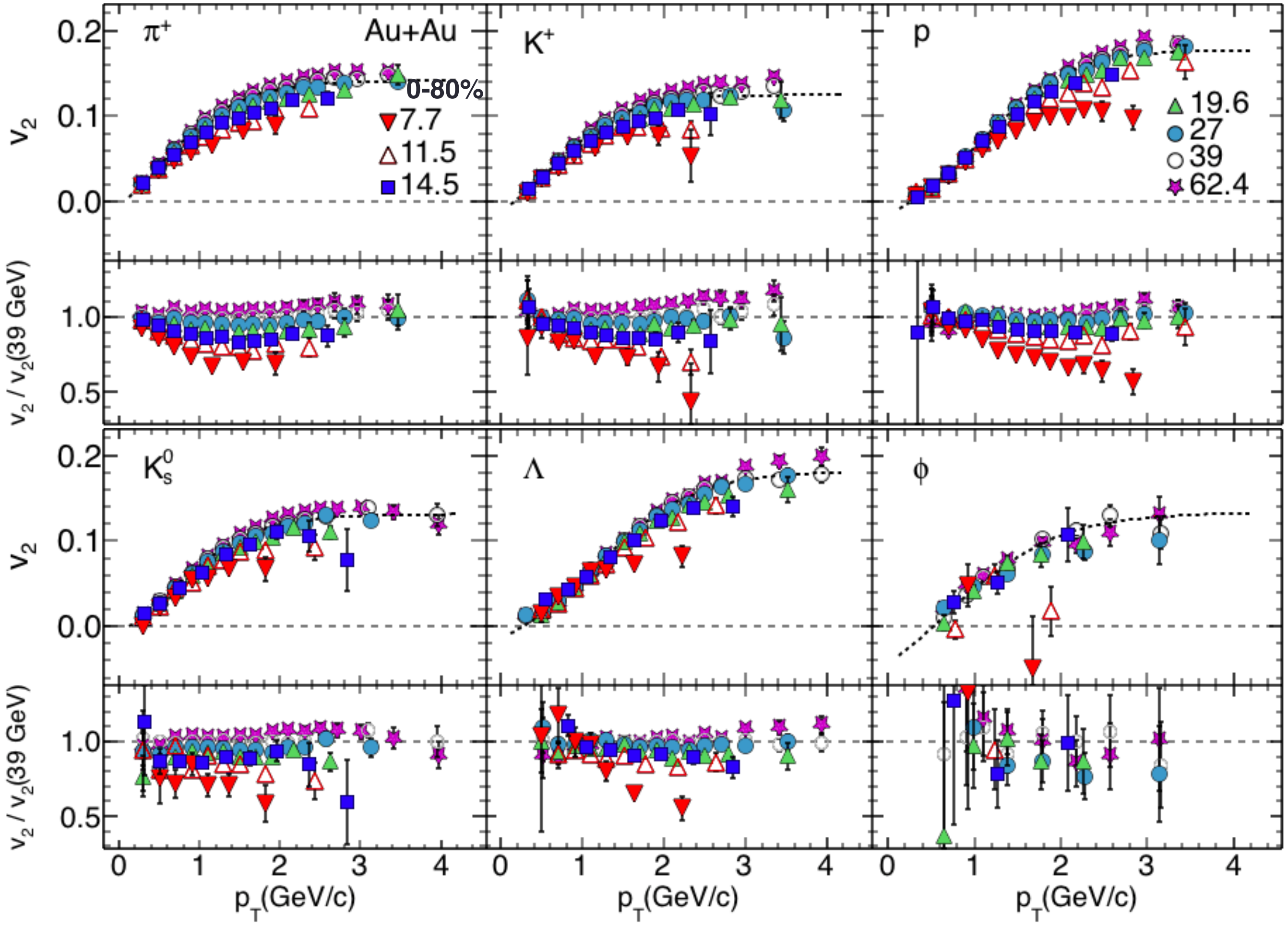
$$\frac{dN}{p_T dp_T} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

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

I_0, K_1: Modified Bessel functions
$\rho(r) = \tanh^{-1}b$, b: transverse radial flow velocity,
r/R: relative radial position; R: radius of fireball
T_{kin}: Kinetic freeze-out temperature

- Hydrodynamic based model
- Assumes local thermalization of particles at a kinetic freeze-out temperature and moving with a common radial flow velocity

Comparison with BES energies



- *L. Adamczyk et. al, (STAR Collaboration) Phys. Rev. C 88 (2013) 14902*