# STAR Results from Beam Energy Scan Program at RHIC

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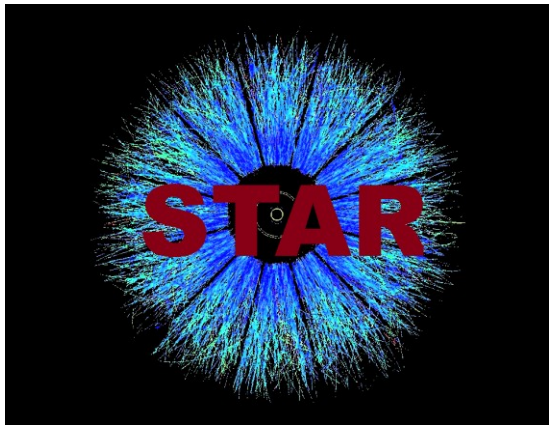
VECC, Kolkata




Outline:

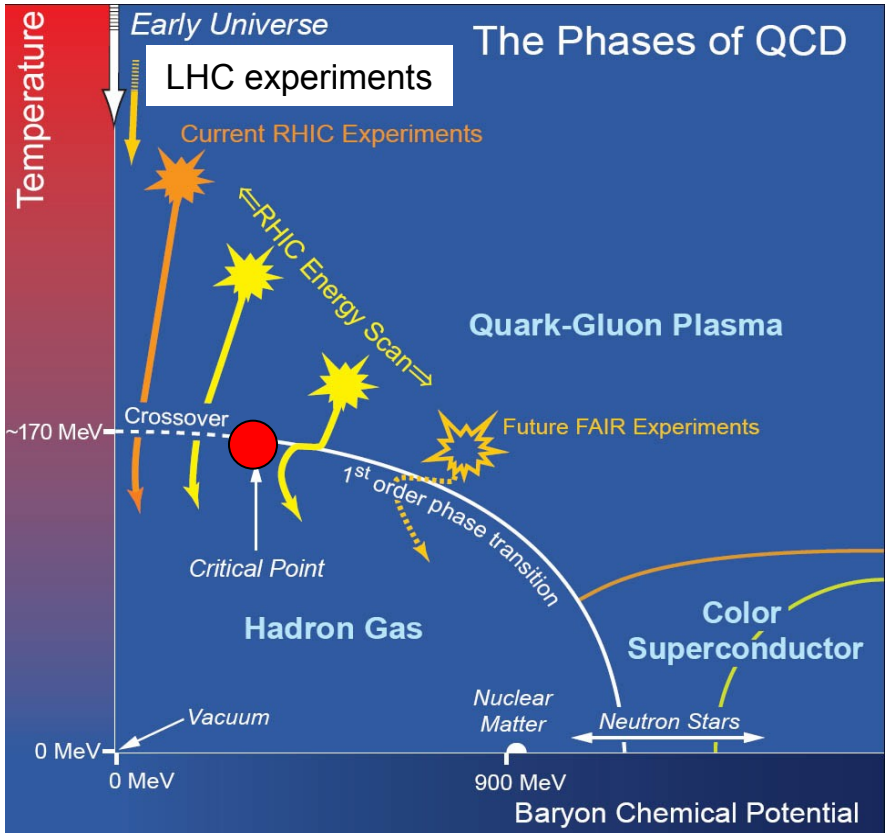
- BES program at RHIC (2010 - 2011)
- Freeze-out conditions
- Partonic vs. hadronic degrees of freedom
- Search for the signatures of the phase boundary
- Search for the signatures of the critical point
- Summary

QM2009: Summary Talk - *"Exploring the QCD phase diagram needs to be vigorously pursued to know properties of basic constituents of matter under extreme conditions. To make the QCD phase diagram a reality equal attention needs to be given to high baryon density region."*

# Beam Energy Scan at RHIC

## QCD Phase Diagram (Hadrons -- Partons)

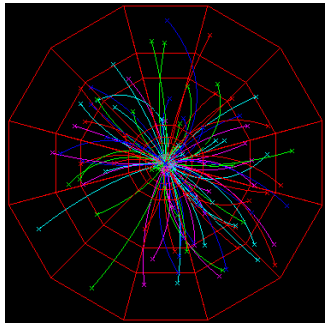
Theory and Experimental approaches




## History: Proposal in 2008

(A) Demonstrate RHIC/Experiment can operate below injection energy

Test run 2008/2009 -
STAR:PRC 81 (2010) 024911



(B) Establish observables

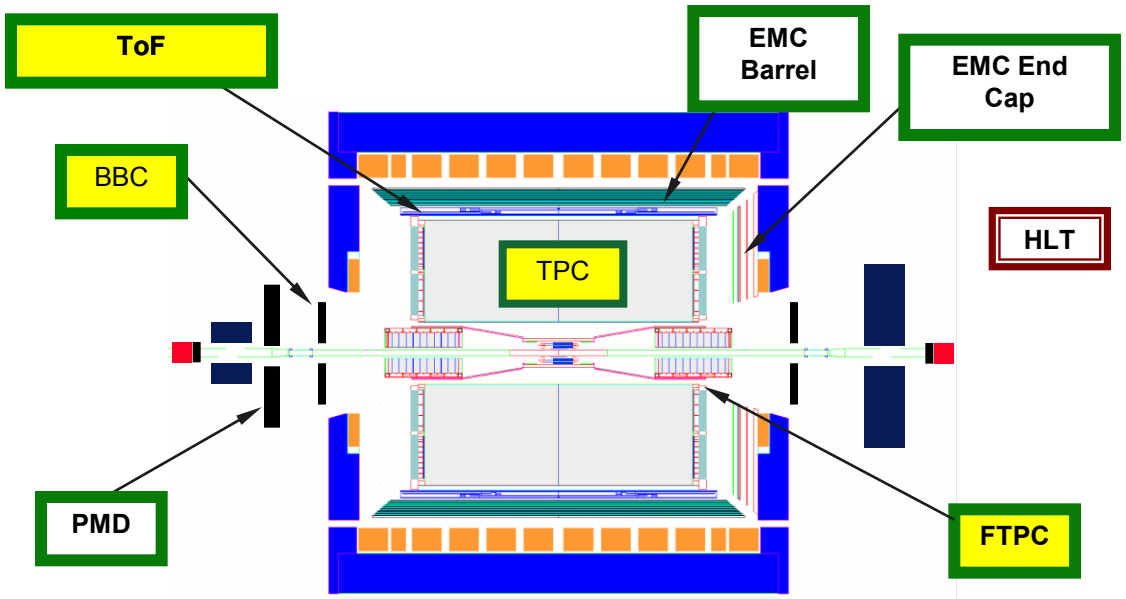
| | |
|---|---|
| NCQ scaling of $v_2$ | Partonic vs. hadronic degrees of freedom |
| Dynamical charge correlations | Partonic vs. hadronic degrees of freedom |
| Azimuthally sensitive HBT | 1st order phase transition |
| $v_1$ vs. rapidity | 1st order phase transition |
| Fluctuations | Critical point |

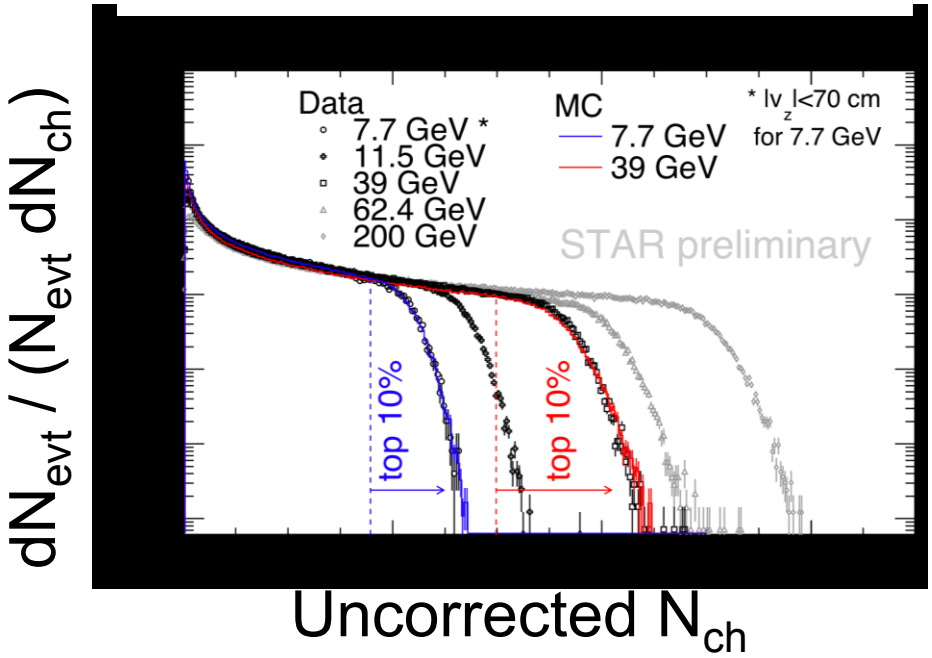
http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
arXiv:1007.2613

## Motivation:

Search for signals of phase boundary
Search for signals for critical point

# RHIC BES 2010-2011



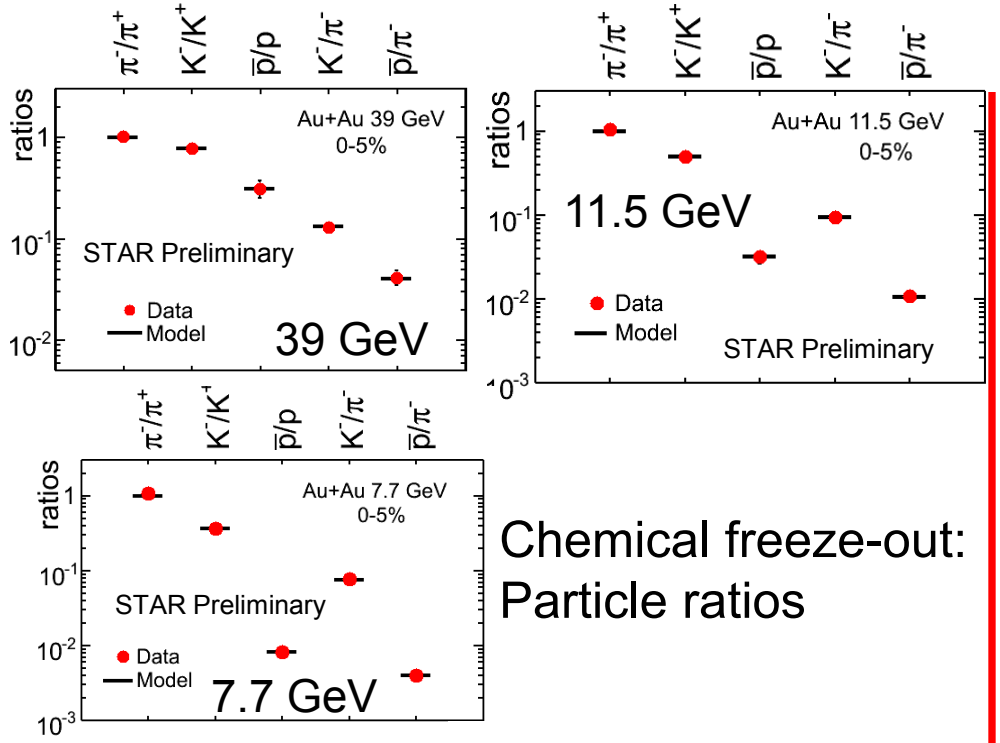




Particle identification over $2\pi$ in azimuthal angle and more than two units in rapidity

| $\sqrt{s_{NN}}$ (GeV) | Good events in Million MB |
|---|---|
| 5.0 | |
| 7.7 | ~ 5 |
| 11.5 | ~ 11 |
| 19.6 | ~ 17 |
| 27 | Expected ~ 150 |
| 39 | ~ 170 |

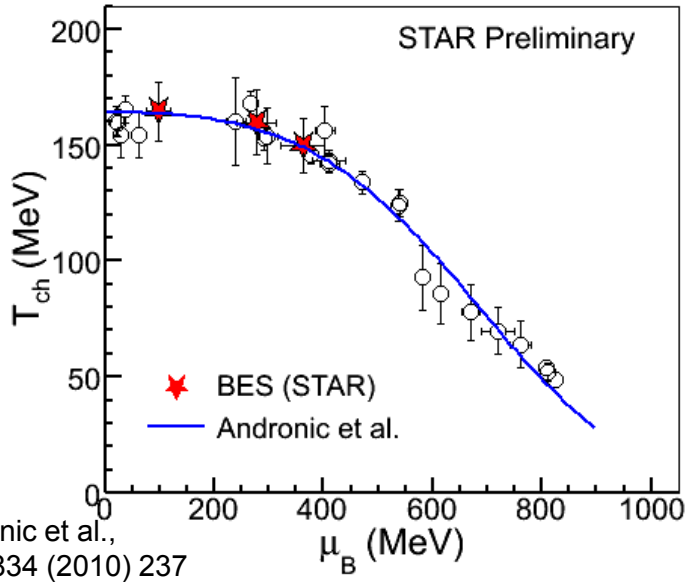
HLT: A. Tang, Poster Board No. 127

# Freeze-out Conditions



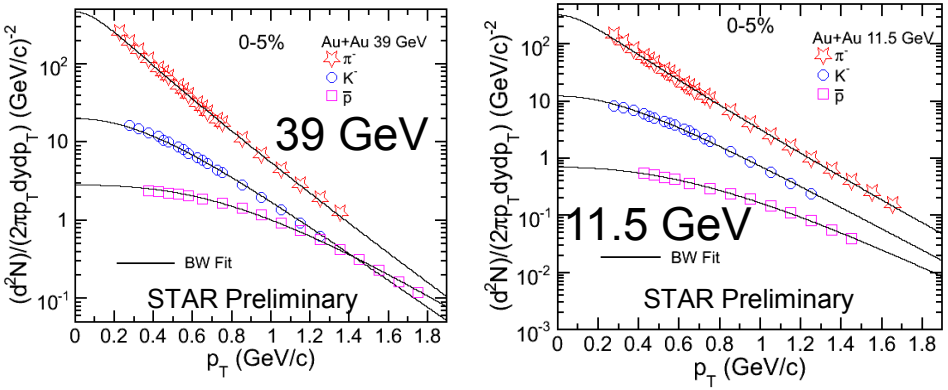

Chemical freeze-out: Particle ratios

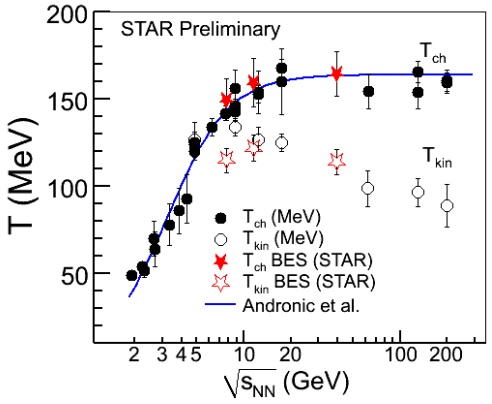
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.

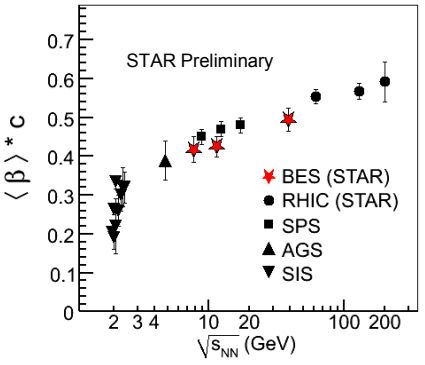



Andronic et al., NPA 834 (2010) 237

QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.



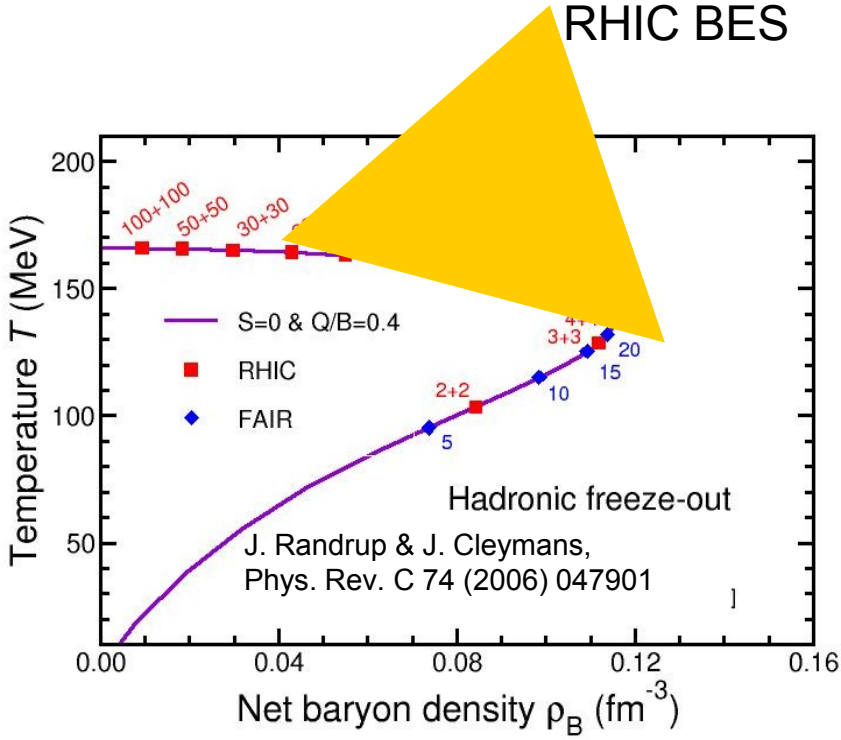




Kinetic freeze-out : Momentum distributions

L. Kumar, Energy scan, 27th May

# Partonic vs. Hadronic Degrees of Freedom

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.




## Identified Hadron Elliptic Flow

## Dynamical Charge Correlations

Related STAR presentations at QM2011:

(1) A. Schmah - Global & Collective dynamics, 23rd May
(2) D. Gangadharan - Global & Collective dynamics, 27th May
(3) S. Shi - Poster Board No. 16
(4) M. Mitrovski - Poster Board No. 19
(5) Q. Wang, Poster Board No. 34
(6) H. Wang, Poster Board No. 95

And ShinIchi Esumi for the PHENIX Collaboration

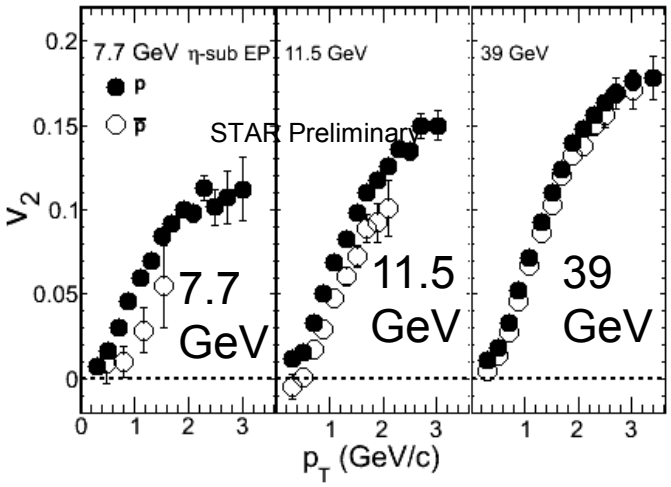
Published STAR papers
at top RHIC energies:
PRL 99 (2004) 112301
PRL 87 (2001) 182301
PRL 106 (2009) 251601

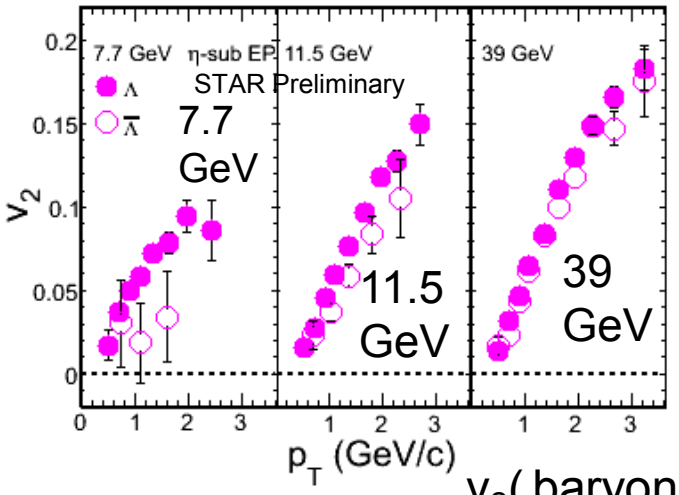
# Particle and Anti-Particle $v_2$

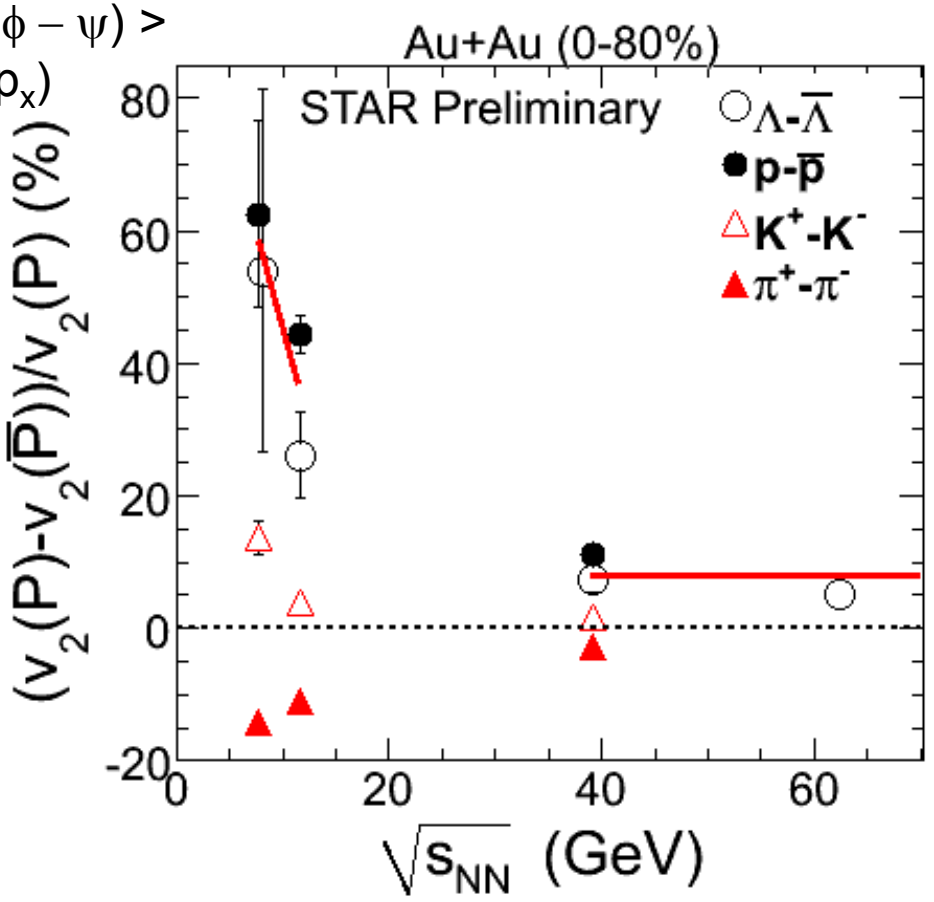
**Observations:** Different $v_2$ for particle and anti-particle.

$v_2 = < \cos 2(\phi - \psi) >$

$\phi = \tan^{-1}(p_y / p_x)$




**Possible interpretation:**

$v_2$( baryon) > $v_2$ (anti-baryon) -- High net-baryon density ?

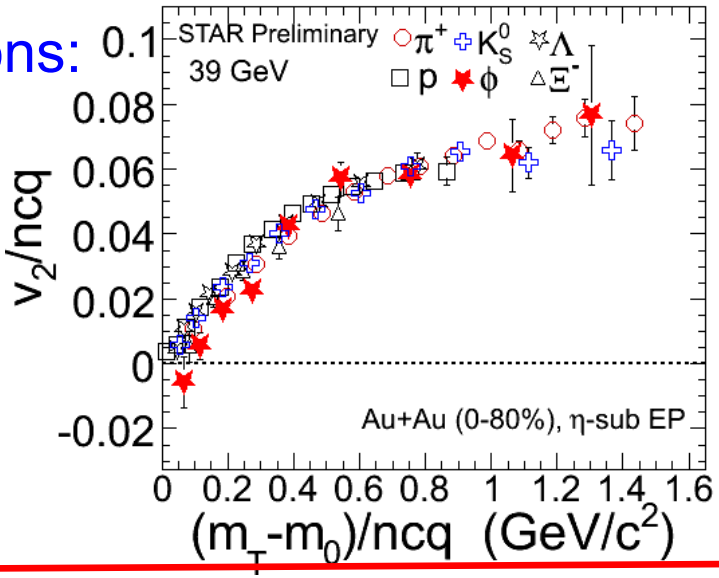
$v_2$( $K^+$) > $v_2$ ($K^-$) at 7.7 GeV -- $K^-$ absorption, associated prod. ?

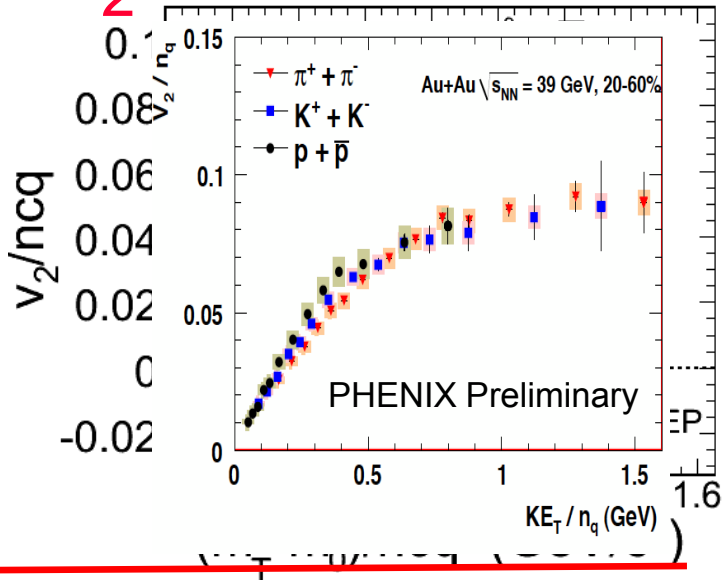
$v_2$( $\pi^+$) < $v_2$ ($\pi^-$) -- Coulomb repulsion of $\pi^+$, resonances or Chiral Magnetic Effect ?

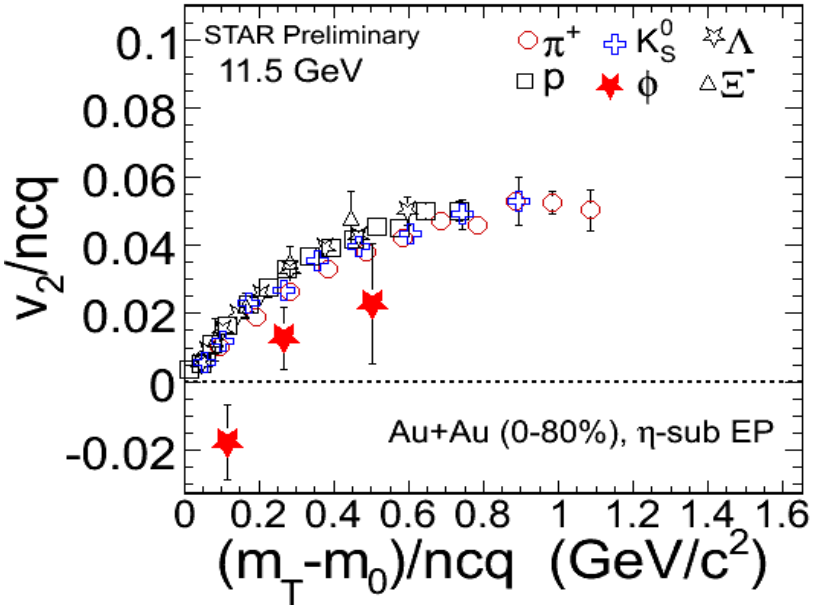
Y. Burnier et al., arXiv:1103.1307

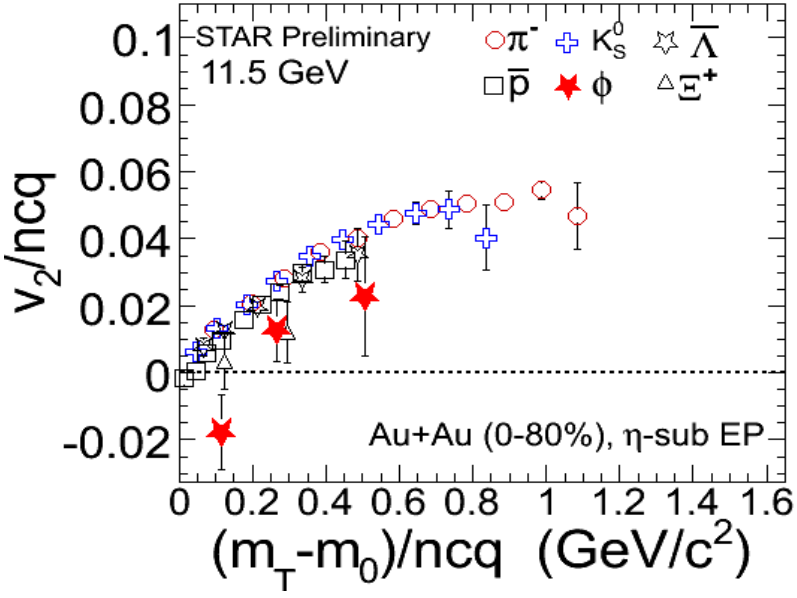
# NCQ scaling of $v_2$

Observations:



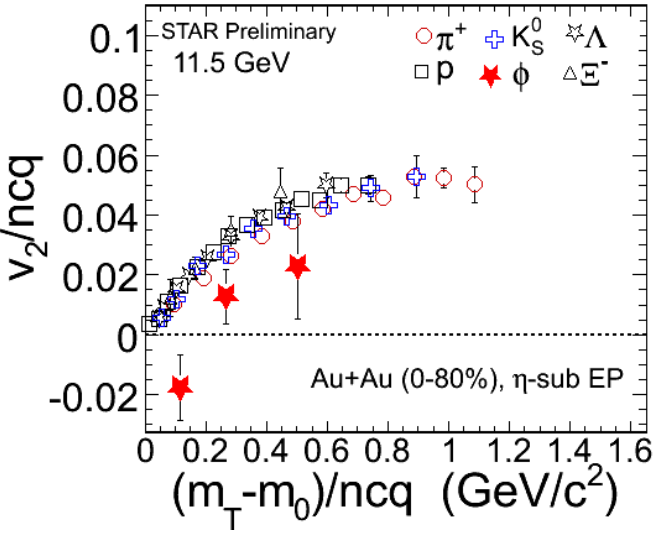



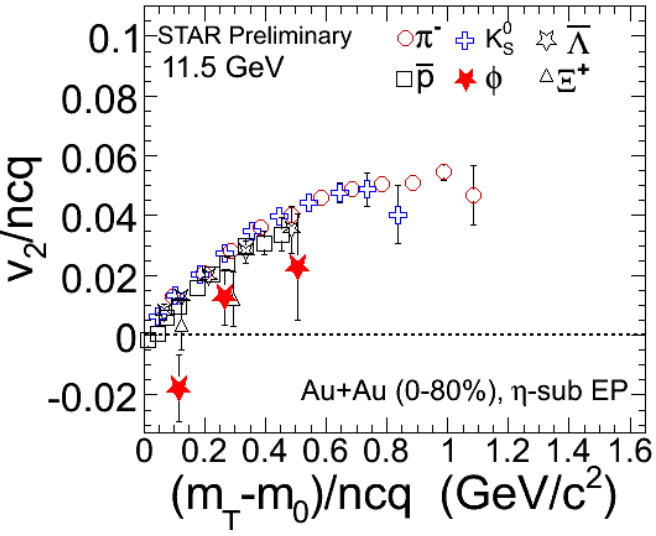




$\phi$ meson $v_2$ falls off the trend from other hadrons at 11.5 GeV

# Small $\phi$ $v_2$

## Possible interpretations:

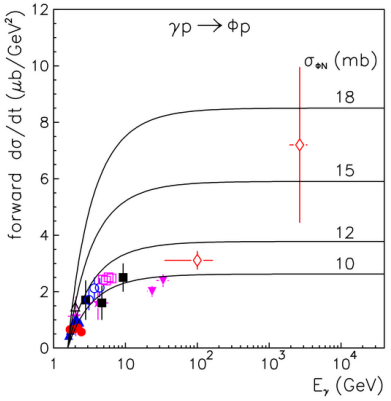



(A) Collectivity from partonic phase at 200 GeV

(B) $\phi$ decouples from the system early

arXiv:nucl-th/0606044




$\sigma_{\rho N} \sim 3\ \sigma_{\phi N}$

$\sigma_{\pi N} \sim 2.6\ \sigma_{\phi N}$

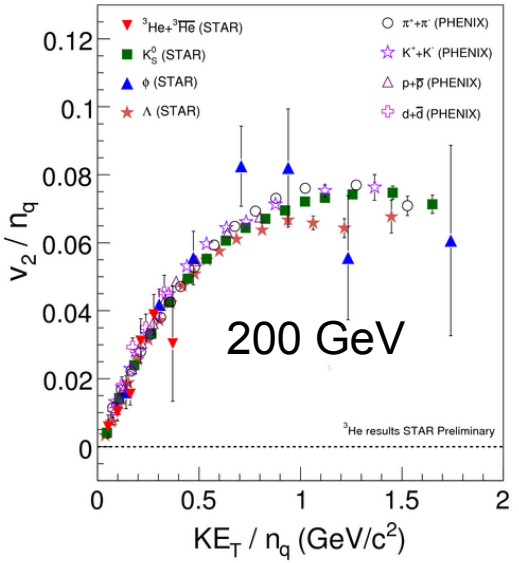
$\sigma_{KN} \sim 2.1\ \sigma_{\phi N}$

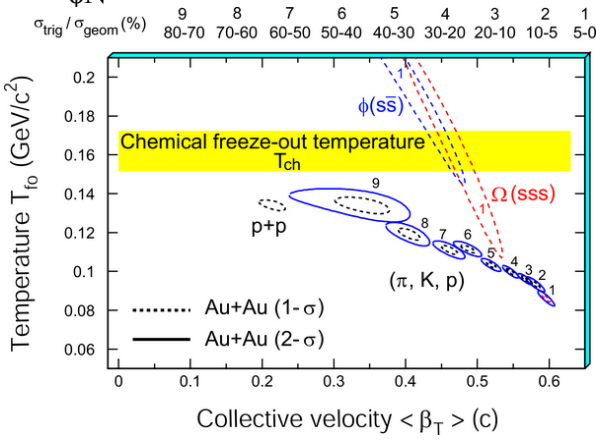
$\sigma_{\Lambda N} \sim 3.5\ \sigma_{\phi N}$

$\sigma_{NN} \sim 4\ \sigma_{\phi N}$

(C ) $\phi$ frezee-out at RHIC ~ $T_c$ from Lattice QCD

STAR : Nucl. Phys. A 757 (2005) 102



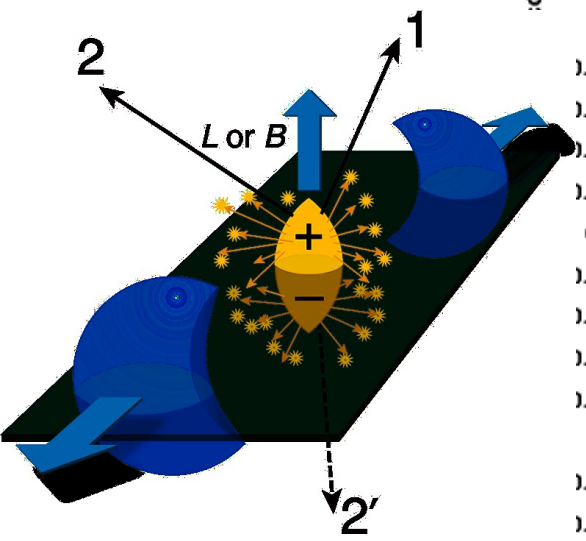



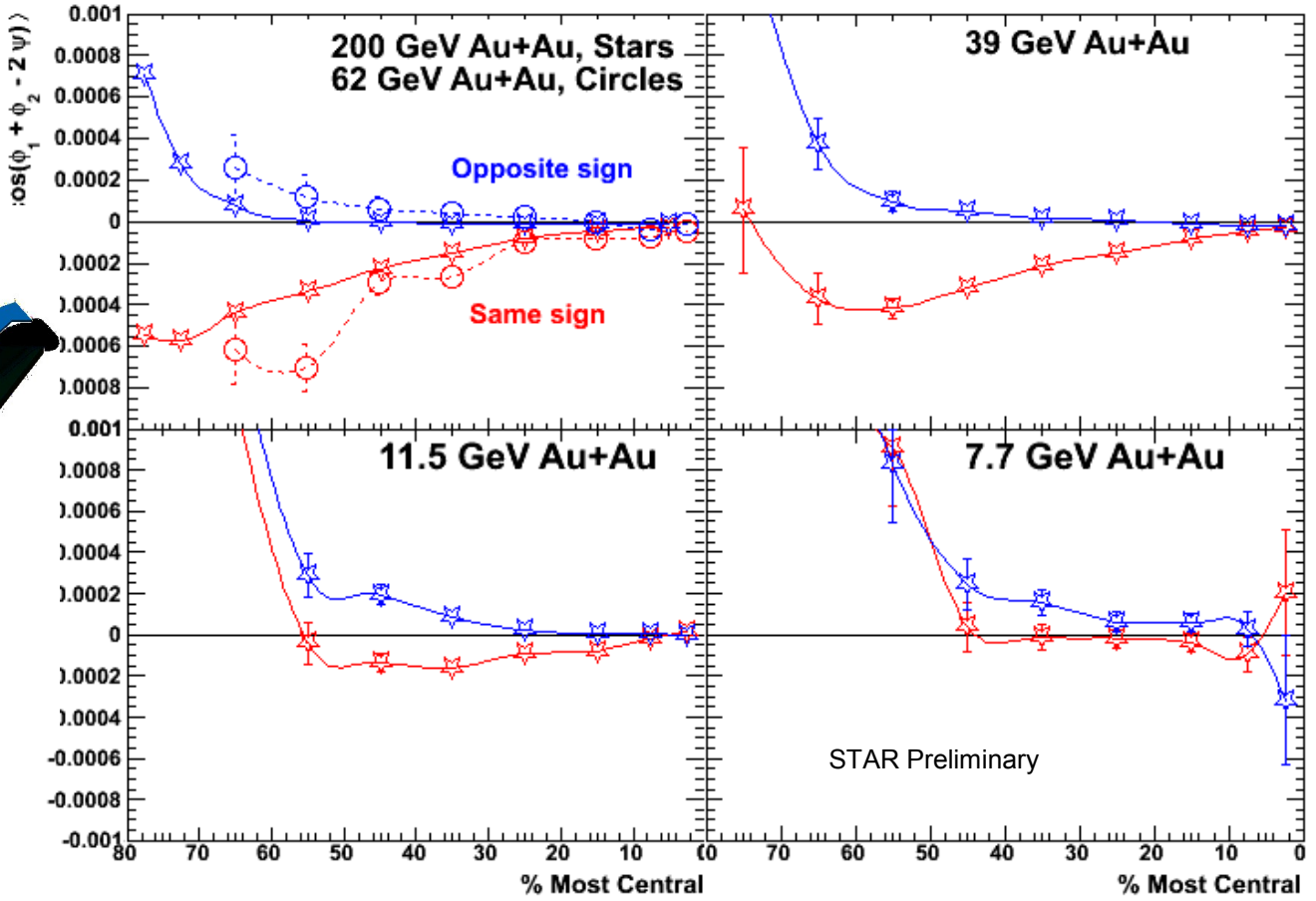

Small $\phi$ meson $v_2$ indicates collectivity contribution from partonic interactions decreases with decrease in beam energy

# Dynamical Charge Correlations

## Observations:

Measurement of charge correlations with respect to event plane

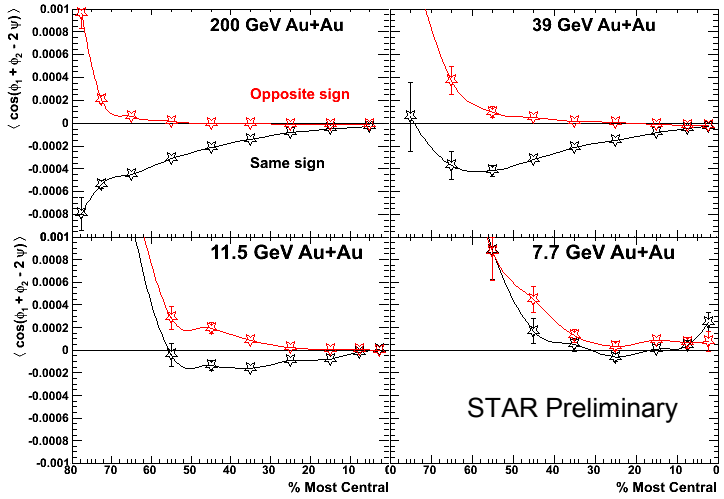


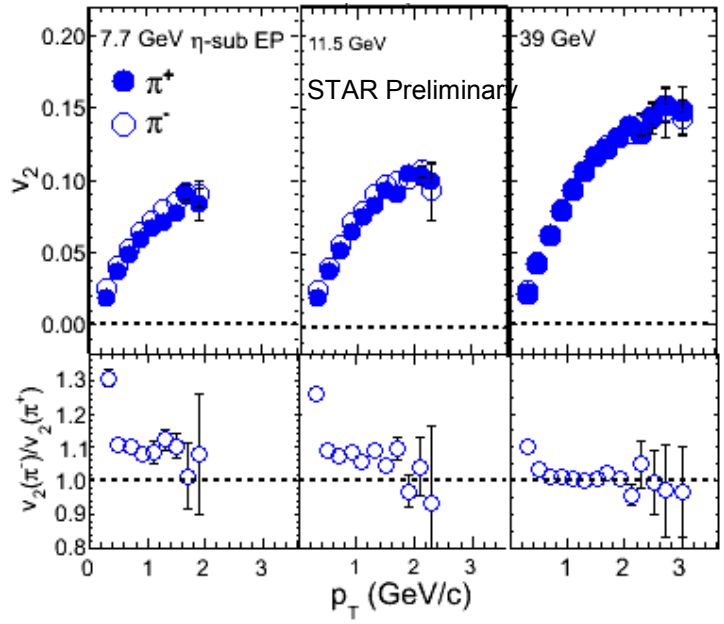




Difference between same sign and opposite sign charge correlations decreases as beam energy decreases.
Same sign charge correlations become positive at 7.7 GeV.

# Dynamical Charge Correlations

## Possible interpretations:



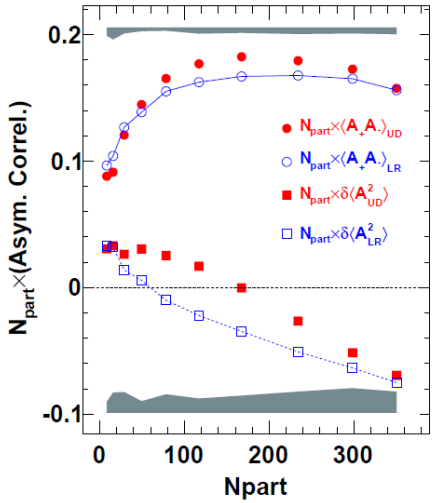

(A) If linked to LPV effect - de-confinement and chiral symmetry restoration. Absence of difference in correlations means absence of phase transition.

K. Fukushima et al, PRD 78, 074033 (2008)

## Alternate Observables

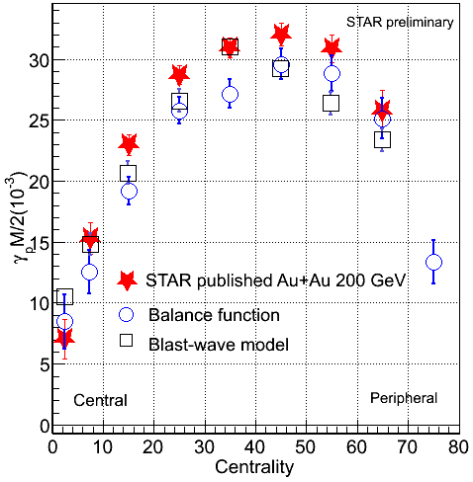
(B) Charge asymmetry

LPV: $\langle A_+A_-\rangle_{UD} < \langle A_+A_-\rangle_{LR}$




(C ) Conservation effects: momentum & Local charge and flow.

Reaction plane dependence balance function ~ difference between opposite and same charge correlations.




A. Bzdak, et al., PRC 83 (2011) 014905
S. Schlichting et al., PRC 83 (2011) 014913
Y. Burnier et al., arXiv:1103.1307

How to reconcile (A) with the fact $v_2(\pi^+) < v_2(\pi^-)$ at 7.7 GeV

# Search for Signatures of Softening of Equation of State

Azimuthally Sensitive HBT

Directed Flow

Published STAR papers at top RHIC energies:
PRL 93 (2004) 012301
PRL 101 (2008) 252301
PRL 92 (2004) 062301

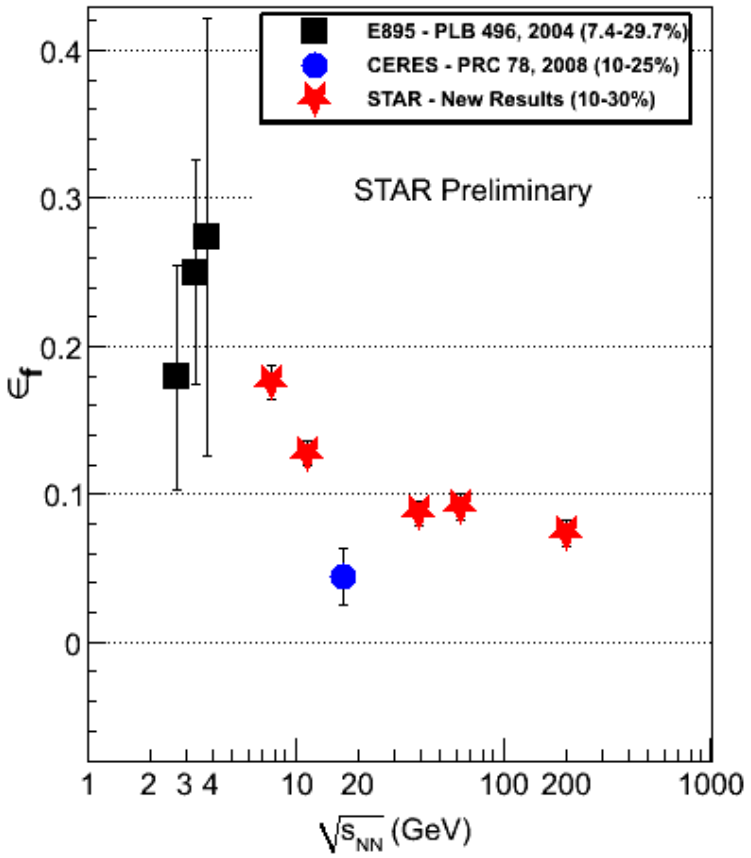
Related STAR Presentations at QM2011:
(1) Christopher Anson - Energy scan, 27th May
(2) Yadav Pandit - Poster Board No. 17

# Azimuthally Sensitive HBT

## Observations:

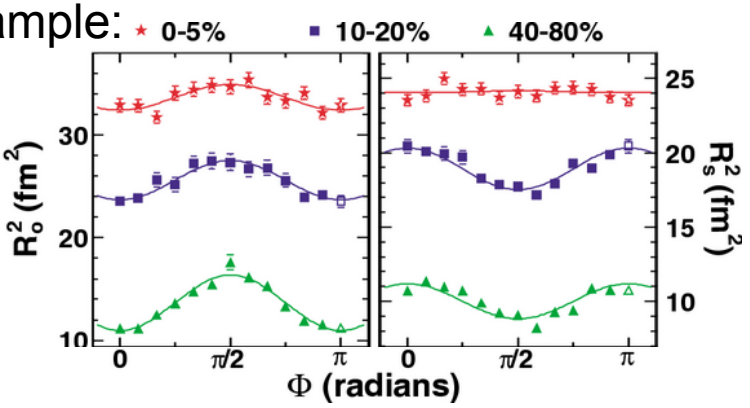
Freeze-out eccentricity:

$(R^2_y - R^2_x) / (R^2_y + R^2_x) = 2 R^2_{s,2} / R^2_{s,0}$




E895: PLB 496 (2000) 1
CERES: PRC 78 (2008) 064901
NA49: PRC 77 (2008) 064908
STAR: PRL 93 (2004) 012301

Example:




Squared HBT radii relative to reaction plane angle

| Expt | $\sqrt{s_{NN}}$ (GeV) | Centrality | η | Event Plane |
|---|---|---|---|---|
| AGS/ E895 | 2.35,3.32, 3.84 | 7.4 - 29.7 | +/- 0.6 | 1st order |
| SPS/ CERES | 17.3 | 10 - 25 | -1.0 - 0.5 | 2nd order |
| RHIC/ STAR | **7.7, 11.5, 39,** 62.4 200 | 10 - 30 | +/- 0.5 | 2nd order |

Non-monotonic variation in freeze-out eccentricity vs. beam energy

# Azimuthally Sensitive HBT

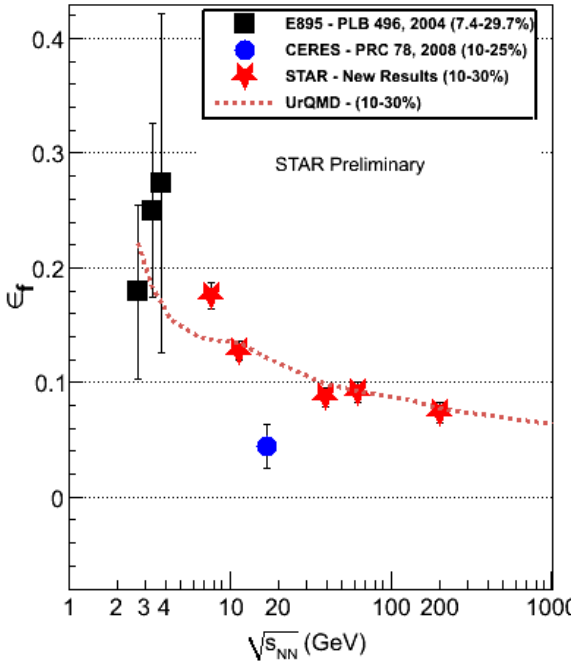
## Possible interpretations:

Eccentricity at freeze-out:

(i) life time of source

(ii) pressure gradient

(or energy density) and $c^2_s$




(B) Hadronic - Mixed Phase - QGP

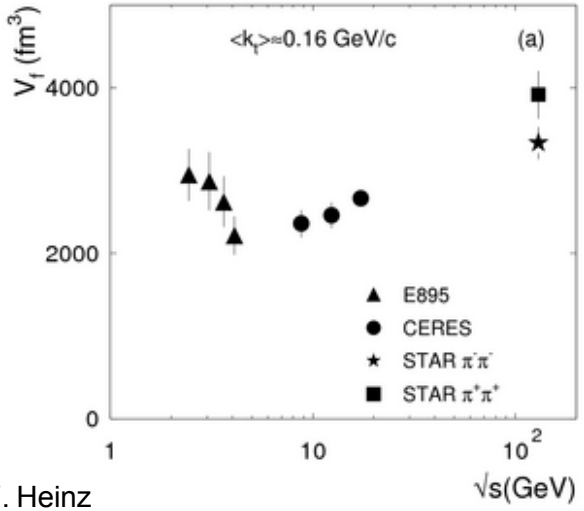
M. Lisa et al., 1104.5267

Transport models show monotonic trends.
Could presence of mixed phase signal such a non-monotonic trend ?

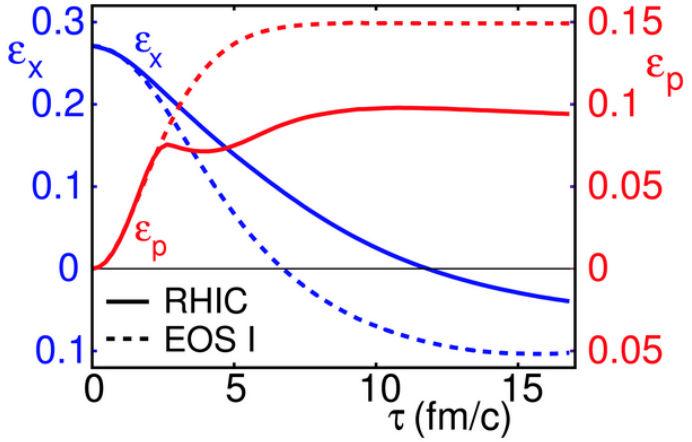
(A) Non-monotonic trends: Using HBT observables - Volume

Constant $\lambda_f$ (~ 1fm) and transition from nucleon to pion dominated freeze-out

- CERES: PRL 90 (2003) 022301; NA49: PRC 77 (2008) 064908



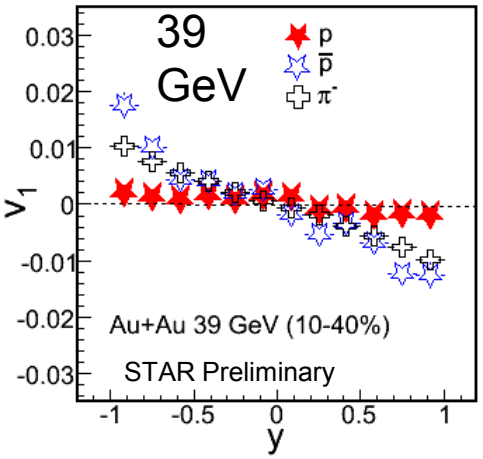

P. Kolb, U. W. Heinz
nucl-th/0305084

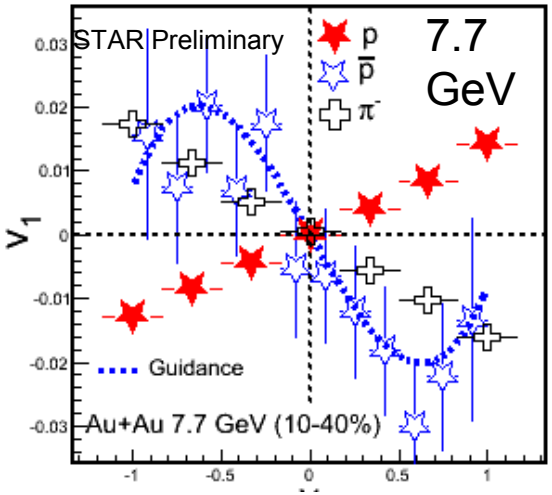


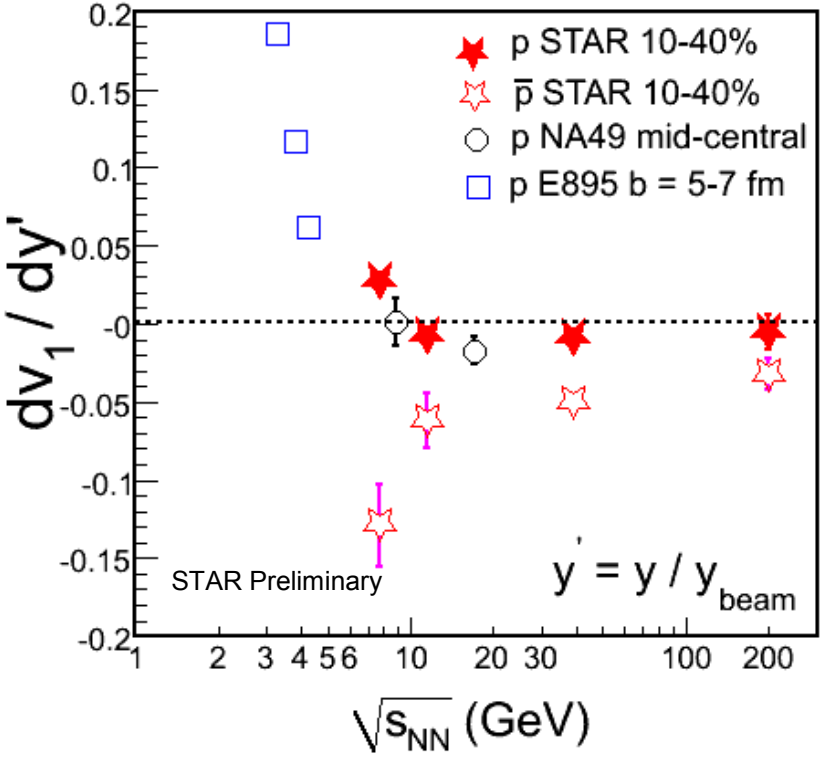
# Identified Hadron Directed Flow

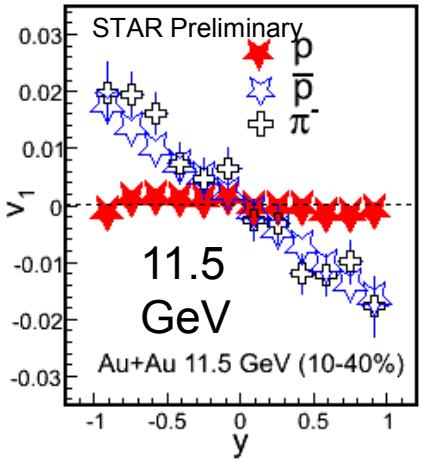
Observations: $v_1 = \langle \cos(\phi - \psi) \rangle$

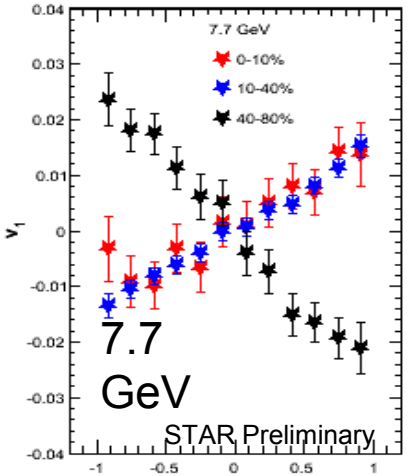
$\phi = \tan^{-1}(p_y / p_x)$




E895: PRL 84 (2000) 5488
NA49: PRC 68 (2003) 034903

| Expt | $\sqrt{s_{NN}}$ (GeV) | Centrality |
|---|---|---|
| AGS/ E895 | 2.35,3.0, 3.6,4.1 | b = 5 - 7 fm |
| SPS/ NA49 | 8.76, 17.3 | b = 5.3 - 9 fm |
| RHIC/ STAR | **7.7, 11.5, 39,** 200 | 10-40% |

Mid-rapidity proton $v_1$ slope changes sign

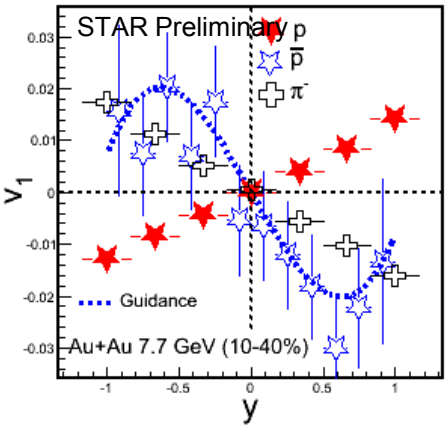
Difference seen between proton and anti-proton

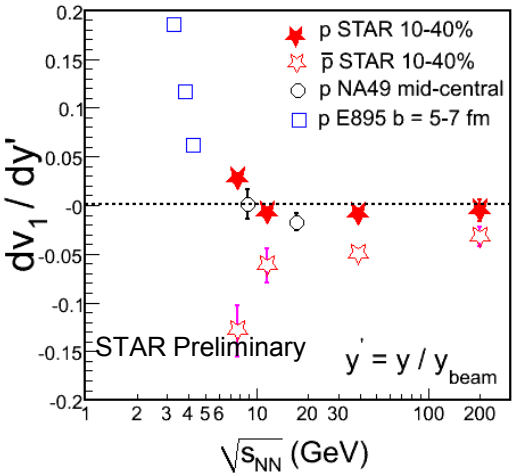
# Identified Hadron Directed flow

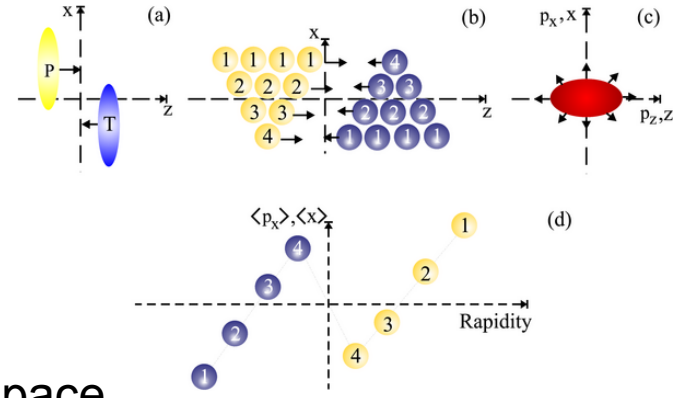
## Possible interpretations:

$v_1$ probes earliest stage of collisions

The slope ***$dv_1/dy'$:*** transverse side motion relative to the beam direction.



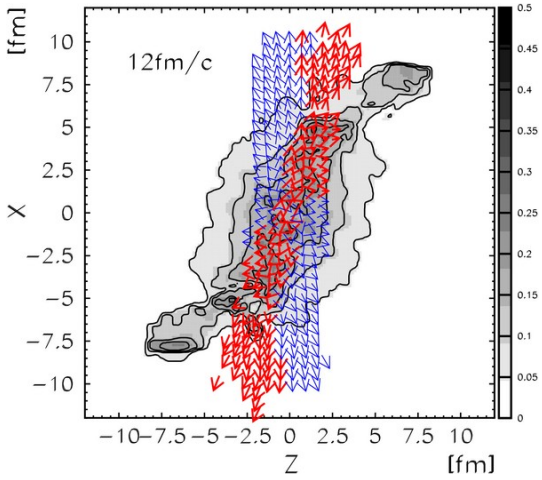




(A) For nucleons, postive space momentum correlations + baryon stopping leads to wiggle or negative slope

-- R. Snellings et al., PRC 84 (2000) 2803

(B) 1st order phase transition could lead to event shape tilled w.r.t beam axis. Different kind of flow orthogonal to normal flow (bounce-off).

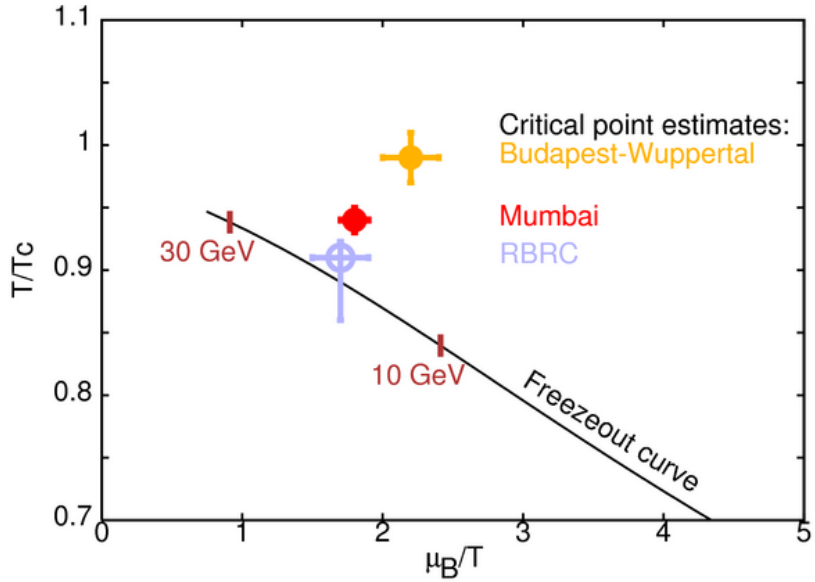
-- J. Brachmann et al., PRC 61 (2000) 24909; L. P. Cernai, D. Rohrich 458 (1999) 454.




Relation between collective radial flow and baryon stopping

Measurements could provide information EOS

# Search for Critical Point




S. Gupta, QM2011


T. Andrews.
Phil. Trans. Royal Soc., 159:575, 1869

## Conserved number fluctuations
## Particle Ratio fluctuations

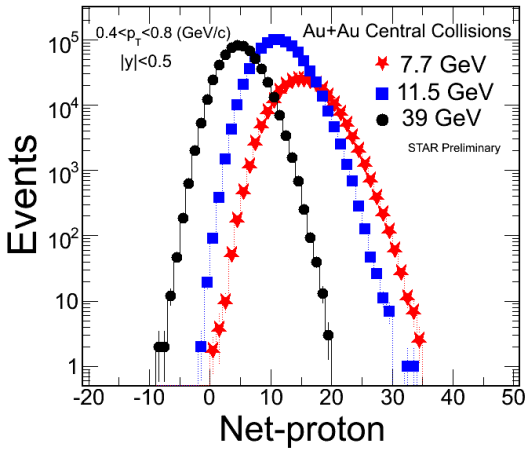
Related STAR Presentations at QM2011:
(1) T. Tarnowsky, Correlations and fluctuations, 23 May 2011
(2) A. Sarkar, Poster Board No. 93
(3) X. Luo, Poster Board No. 141
(4) L. Chen, Poster Board No. 146
(5) N. R. Shaoo, Poster Board No. 151

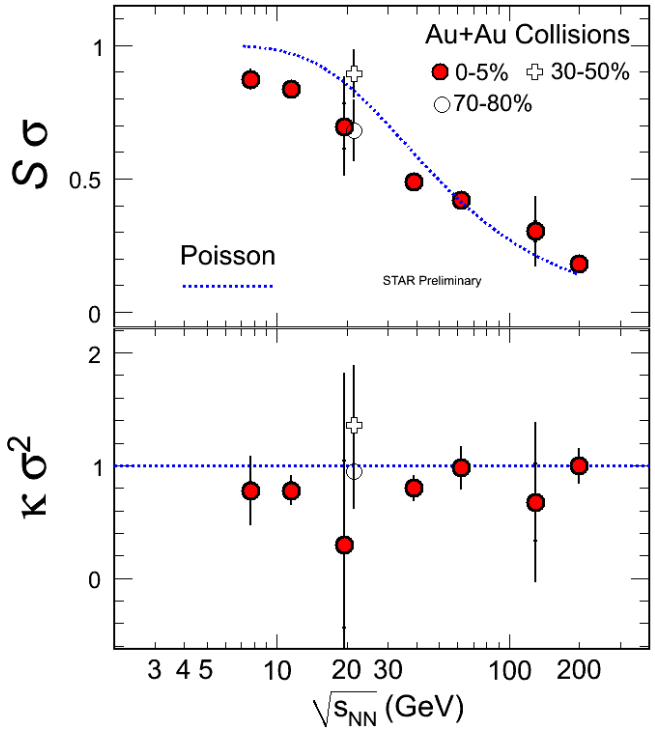
Published STAR papers
at top RHIC energies:
PRL 105 (2010) 022302
PRL 103 (2009) 092301

Fodor and Katz, JHEP 0404 (2004) 050.
Gavai and Gupta, PR D 78 (2008) 1143503
Cheng et al,PR D 79 (2009) 074505
Gupta, POS Lattice2010 (2010) 007

# Higher Moments of Net-Protons

## Observations:




## Critical point:

Correlation length and Susceptibilities diverge
Long wavelength or low momentum number fluctuations. Distributions are non-Gaussian

## Higher moments:

M. A. Stephanov, PRL 102 (2009) 032301

Measure of non-Gaussian nature
Proportional to higher powers of $\xi$
Kurtosis x Variance ~ $\chi^{(4)}/\chi^{(2)}$
Skewness x Sigma ~ $\chi^{(3)}/\chi^{(2)}$
Product of moment - Volume effect cancels

## Net-protons:

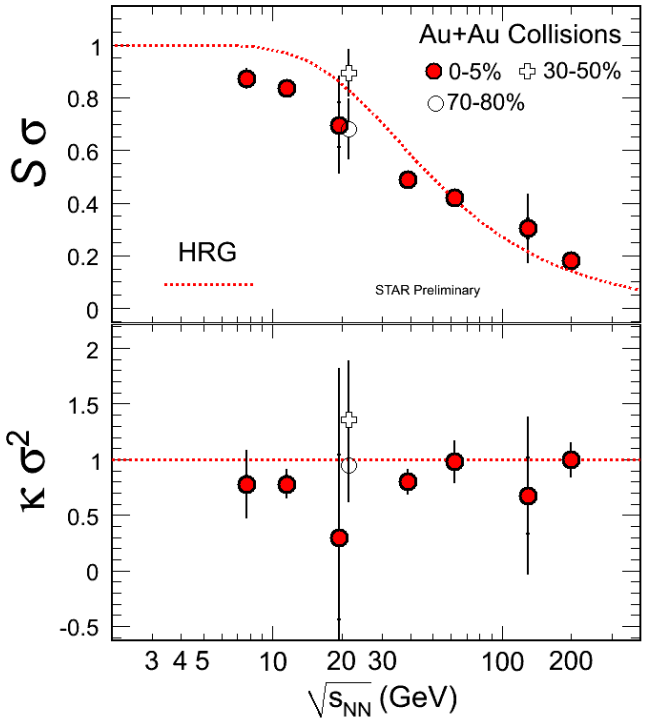
Y. Hatta et al., PRL 91 (2003) 102003

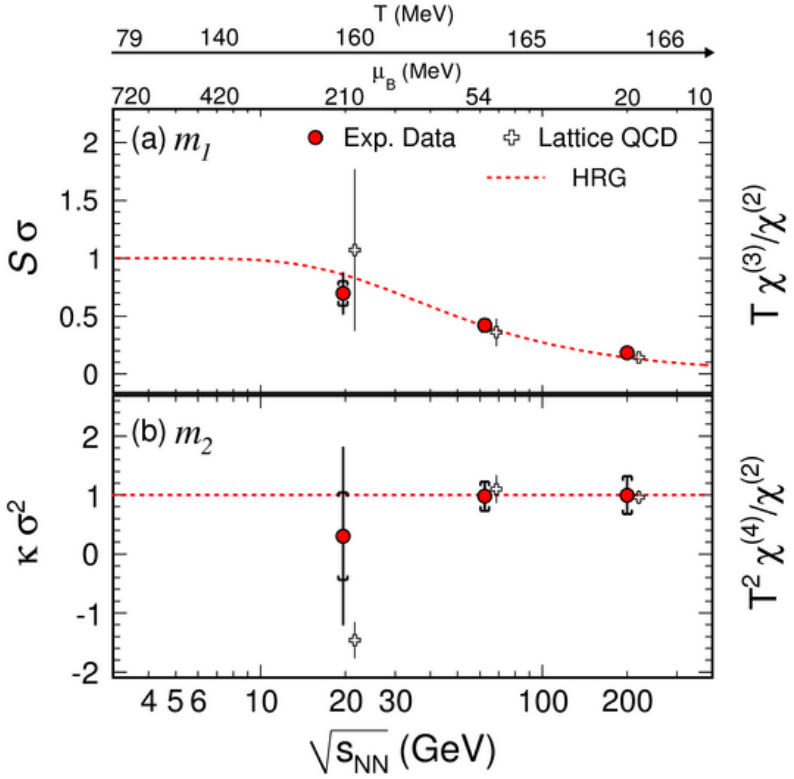
~ reflects net-baryons - conserved quantity
Neutrons immaterial due to isospin
blindness of $\sigma$ field

Deviation from Poissionian expectations from 39 GeV and below

# Higher Moments of Net-protons

## Possibilities with this measurement:




(A) Higher order correlations/ fluctuations deviate from HRG expectations at lower energies

(B) Significant deviations could potentially be linked to Chiral phase transition and Critical Point

(C) Study non-pertubative QCD

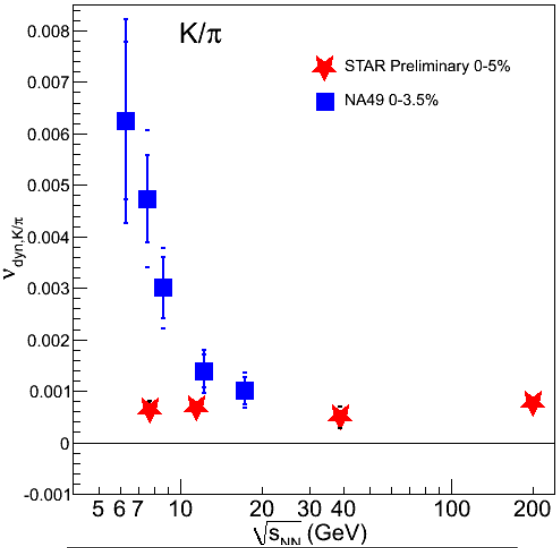
Accepted in Science: S. Gupta, X. Luo, B. Mohanty, H. Ritter and N. Xu; arXiv: 1105.3934

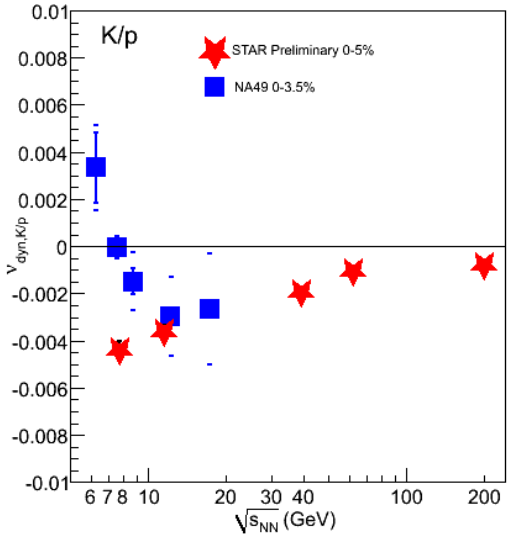
HRG: F. Karsch, K. Redlich, PLB 695 (2011) 136

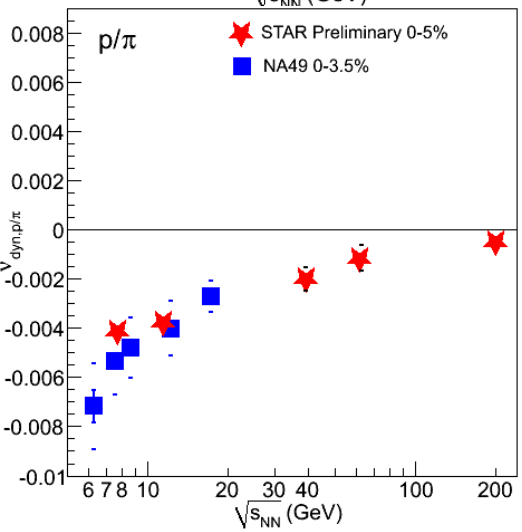
B. Friman, arXiv:1103.3511
M. A. Stephanov, arXiv:1104.1627

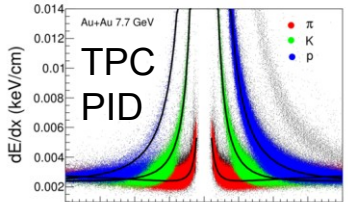
# Particle Ratio Fluctuations

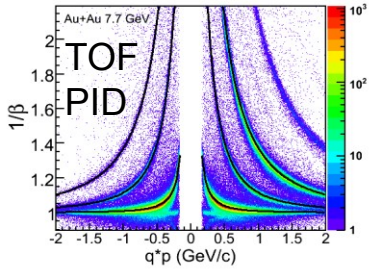
## Observations:



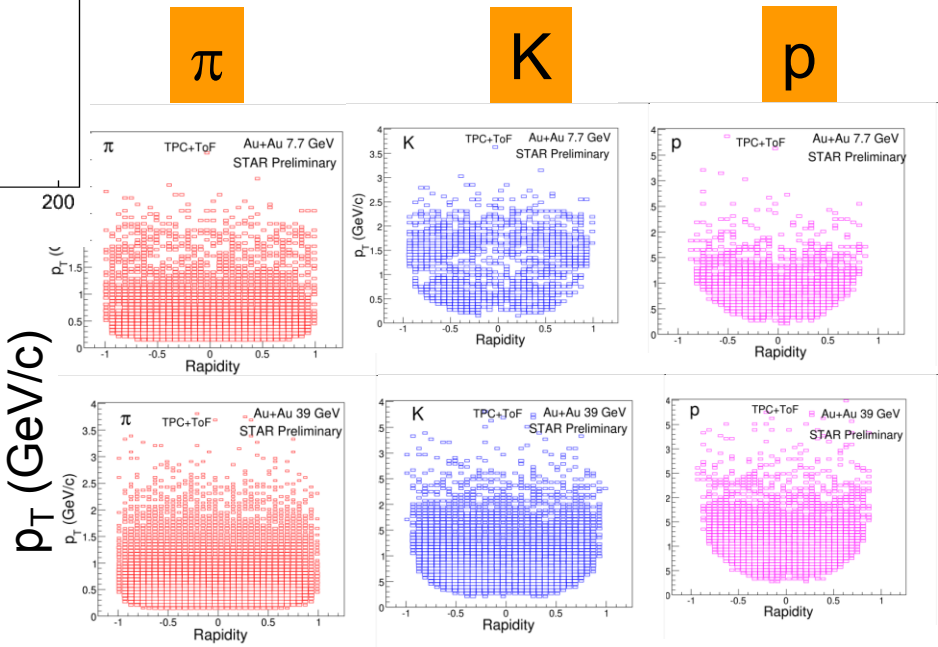




Fluctuations in particle ratios
-- Sensitive to particle numbers at chemical FO not kinetic FO
-- Volume effects may cancel

S. Jeon, V. Koch, PRL 83, 5435 (1999)




Constant or monotonic trends observed
Apparent differences (results with Kaons) with SPS

Differences could be due to difference in acceptance and/or PID selections --- under discussion

# Summary

Successful RHIC BES Program from Collider/Accelerator and experimental side

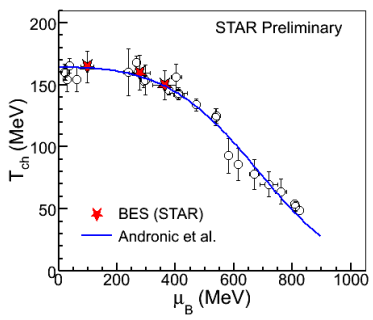
New observations:

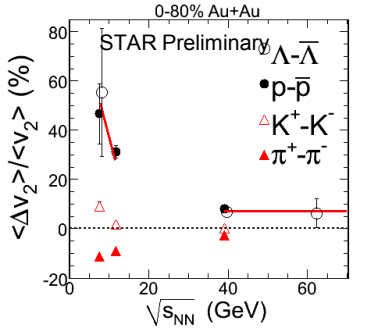
- Identified hadron production & freeze-out parameters reveals high net-baryon density at these energies.
  Effect on several observables seen.

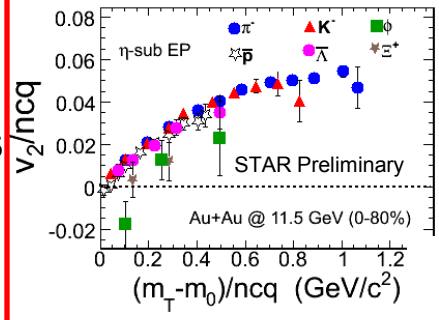
- Hadronic interactions at low energy.
  Small $\phi$ meson $v_2$ at 11.5 GeV.
  Disappearance of dynamical charge correlations

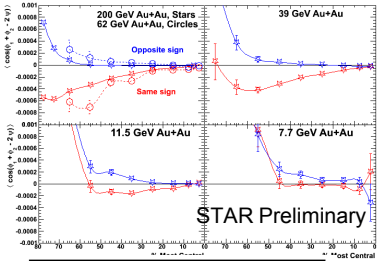
- Interesting trends for observables related to softening of EOS. Non-monotonic variation of freeze-out eccentricity. Change in sign of proton $v_1$ with energy and centrality.

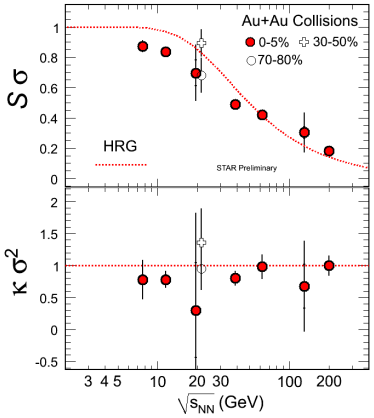
- Large acceptance & excellent PID allows for fluctuations measurements. Deviations from HRG and Poisson statistics. Is being used to study structure of the QCD phase diagram.

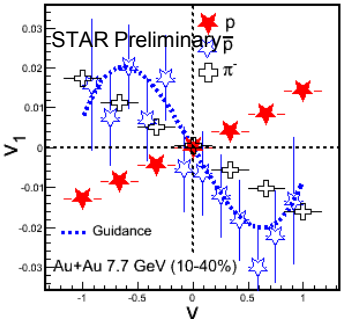


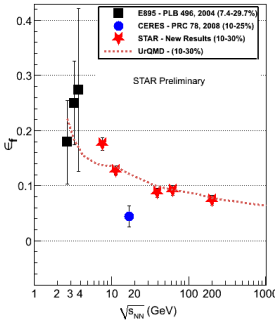



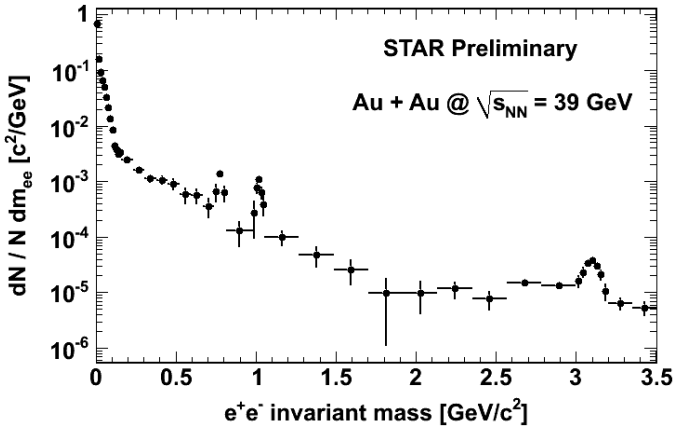



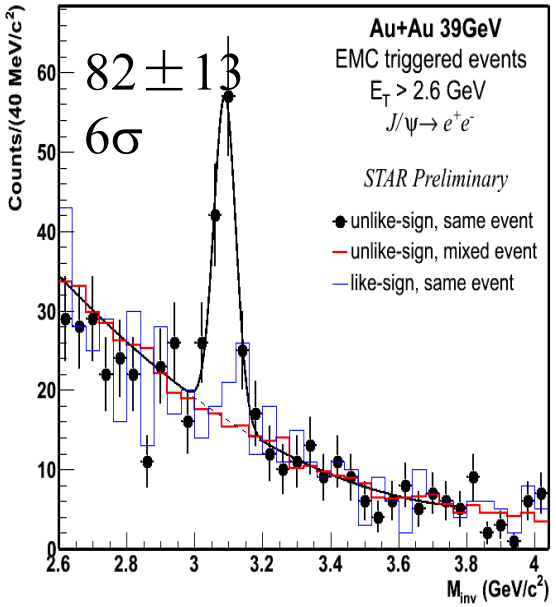

Need to complete the first phase of BES program

# Outlook

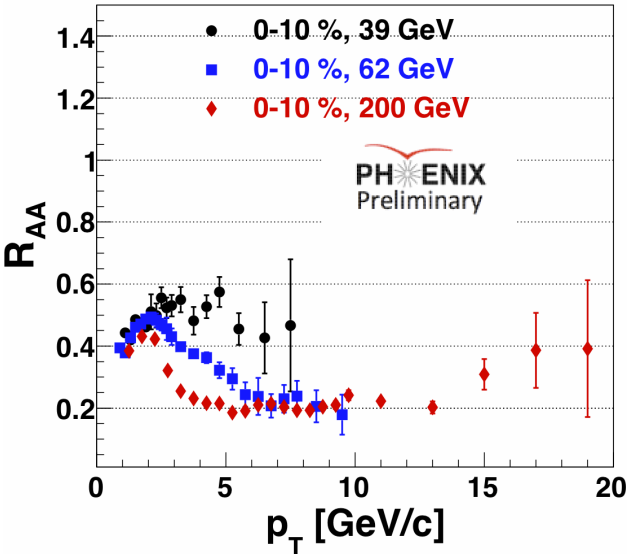
Patrick Huck, Poster Board No. 97




Z. Tang,Heavy Flavor,24th May




Stefan Bathe for PHENIX

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University of California, Los Angeles, California 90095
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University of Illinois at Chicago, Chicago, Illinois 60607
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Czech Technical University in Prague, FNSPE, Prague, 115 19, Czech Republic
Nuclear Physics Institute AS CR, 250 68 \v{R}e\v{z}/Prague, Czech Republic
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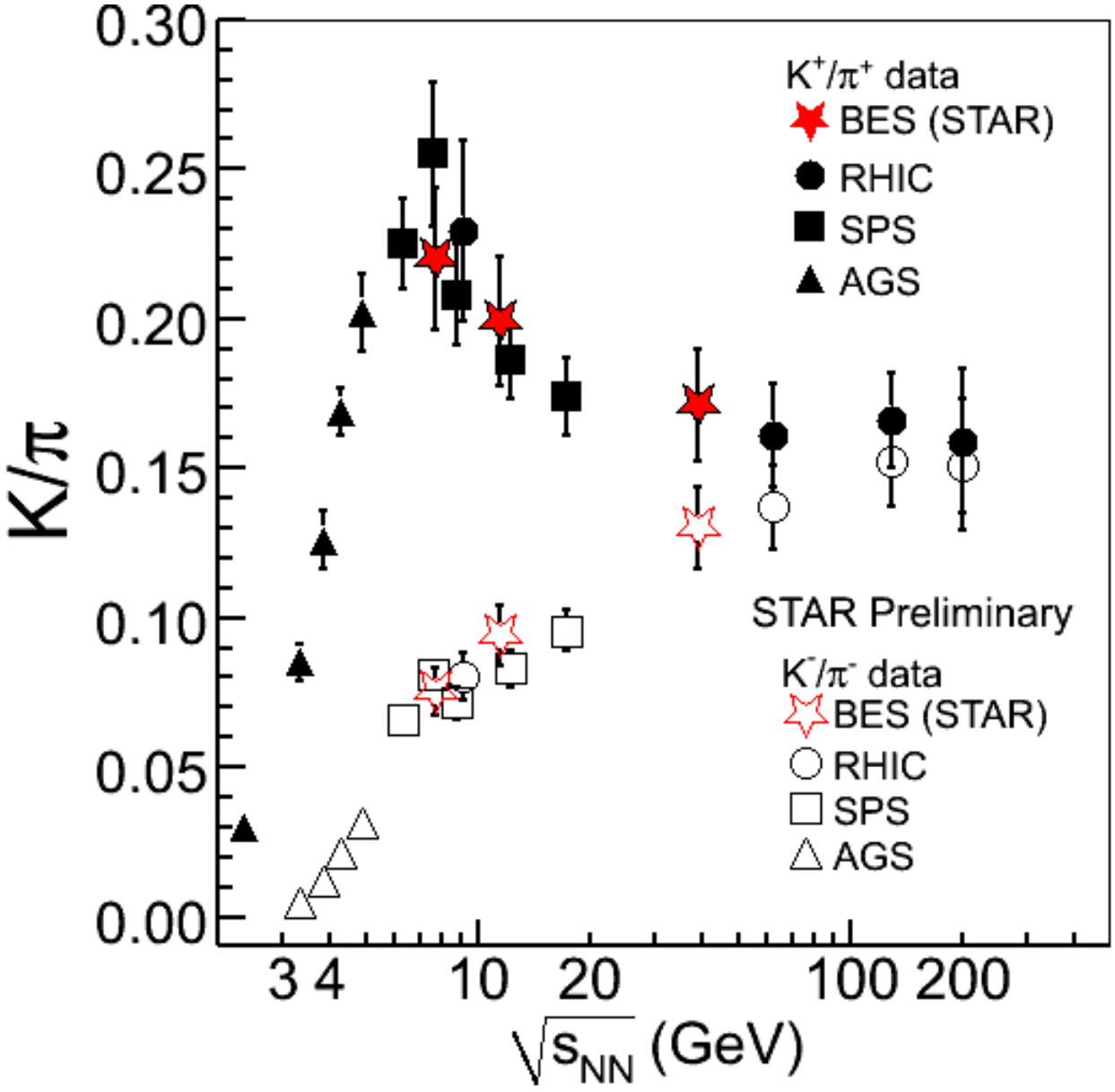
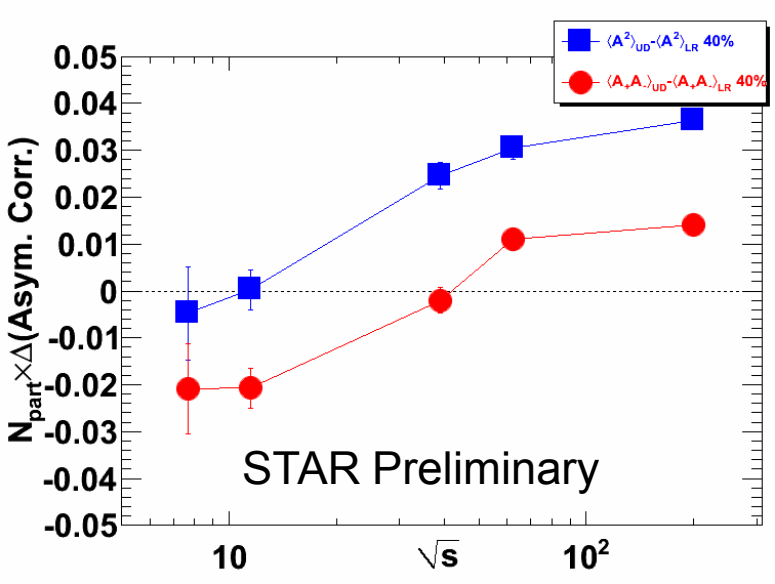
Thanks

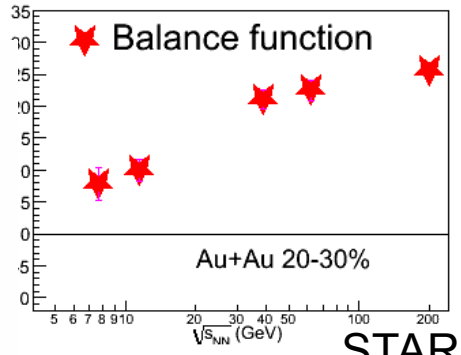
# Back up

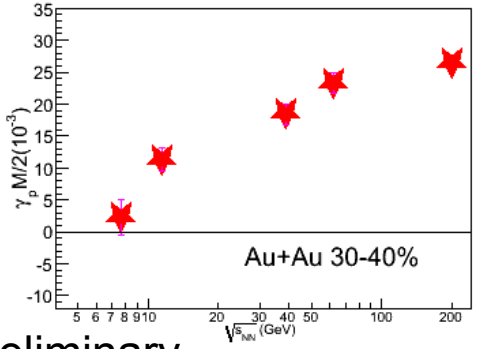
# K/π


0.30
0.25
0.20
0.15
0.10
0.05
0.00
K/π
3 4
10
20
100 200
√sNN (GeV)
K+/π+ data
BES (STAR)
RHIC
SPS
AGS
STAR Preliminary
K-/π- data
BES (STAR)
RHIC
SPS
AGS

# LPV energy dependence




STAR Preliminary