2015 KOBE JAPAN

Measurement of hadron suppression and study of its connection with vanishing v_3 at low $\sqrt{s_{NN}}$

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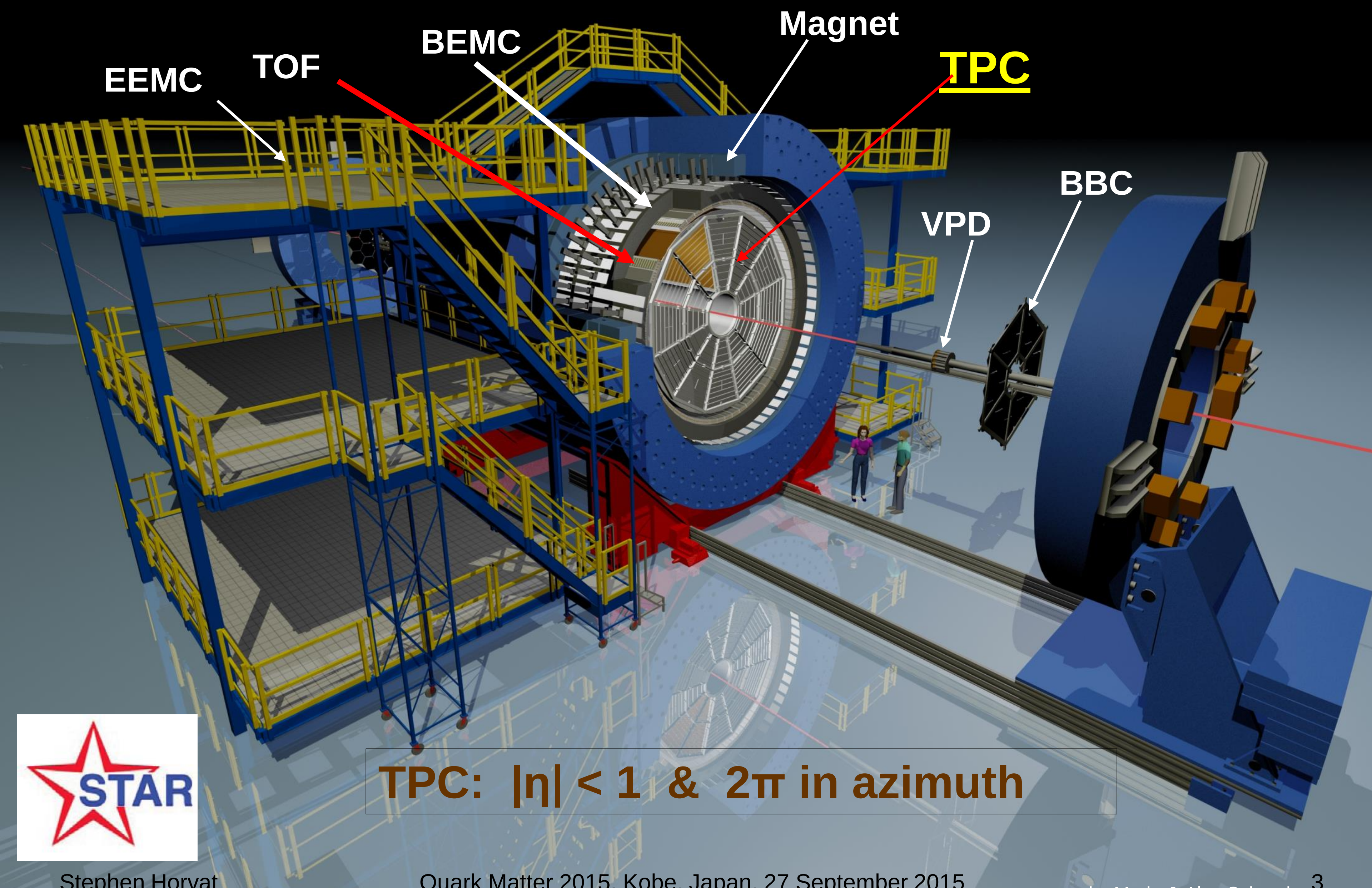
Outline

- Introduction
  - Beam Energy Scan (BES)
  - Motivation
  - Data
- $v_3^2\{2\}$ and its connection to a partonic phase
- Hadron suppression in BES with $Y(N_{part})$
- Conclusion

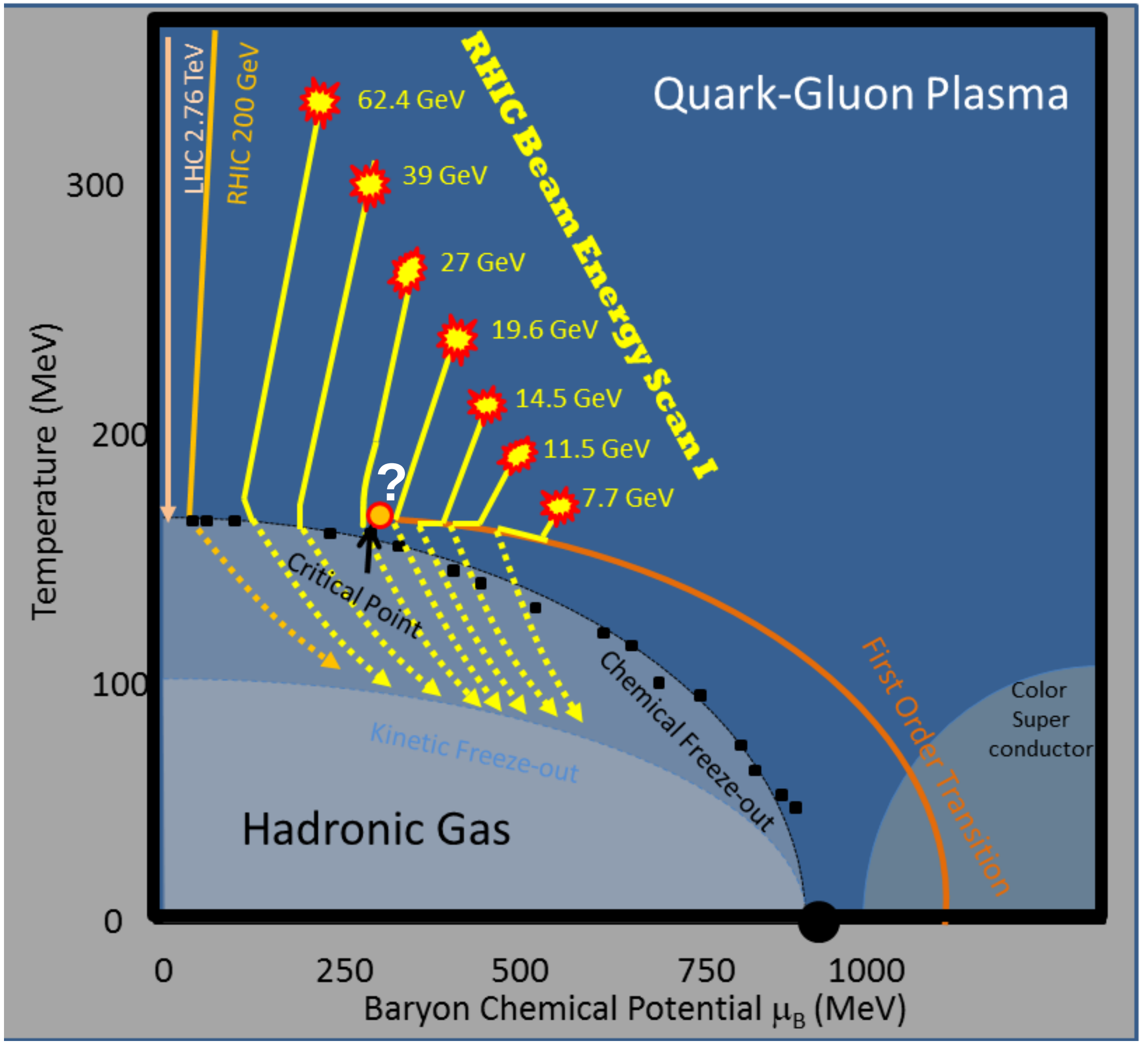
The Solenoidal Tracker At RHIC (STAR)



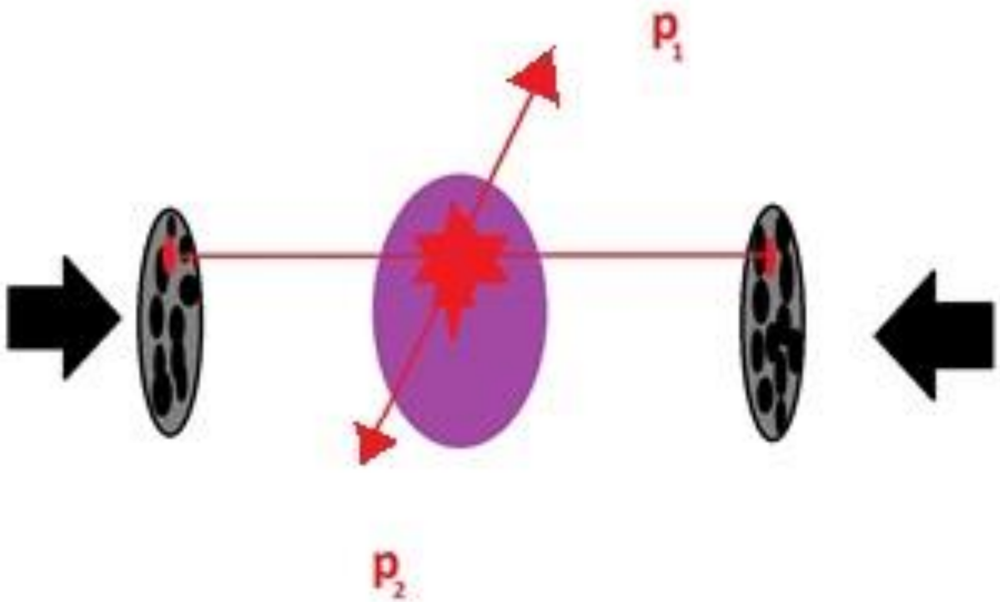
TPC: $|\eta| < 1$ & 2π in azimuth

Beam Energy Scan

- At what energy do key QGP formation signatures turn off?
- Is there a critical point and if so where?
- Is there evidence for a first order phase transition?



Motivation



- 2 suggested signatures of QGP formation are investigated
  - One measures $v_3^2\{2\}$
  - The other looks for "high-p_T" suppression ($Y(N_{part})$)
- These two techniques are distinct and complementary

Data

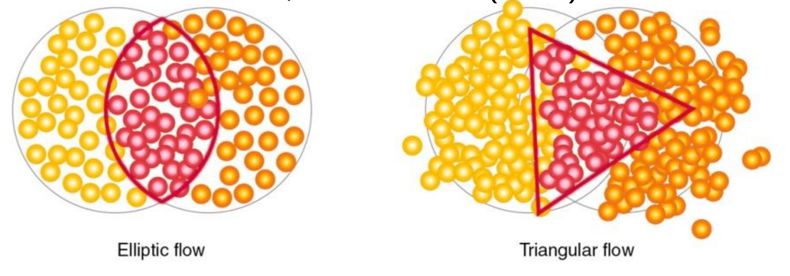
- These data are from phase 1 of the BES at RHIC
- Phase 2 of the BES will provide additional statistics and energies for $\sqrt{s_{\mathrm{NN}}} < 20\mathrm{GeV}$

$\sqrt{s_{NN}}$(GeV)	μ_B(MeV)	Year	N_{event}(10^6)
7.7	420	2010	4
11.5	315	2010	12
14.5	260	2014	20
19.6	205	2011	36
27	155	2011	70
39	115	2010	130
62.4	70	2010	67
200	20	2010	350

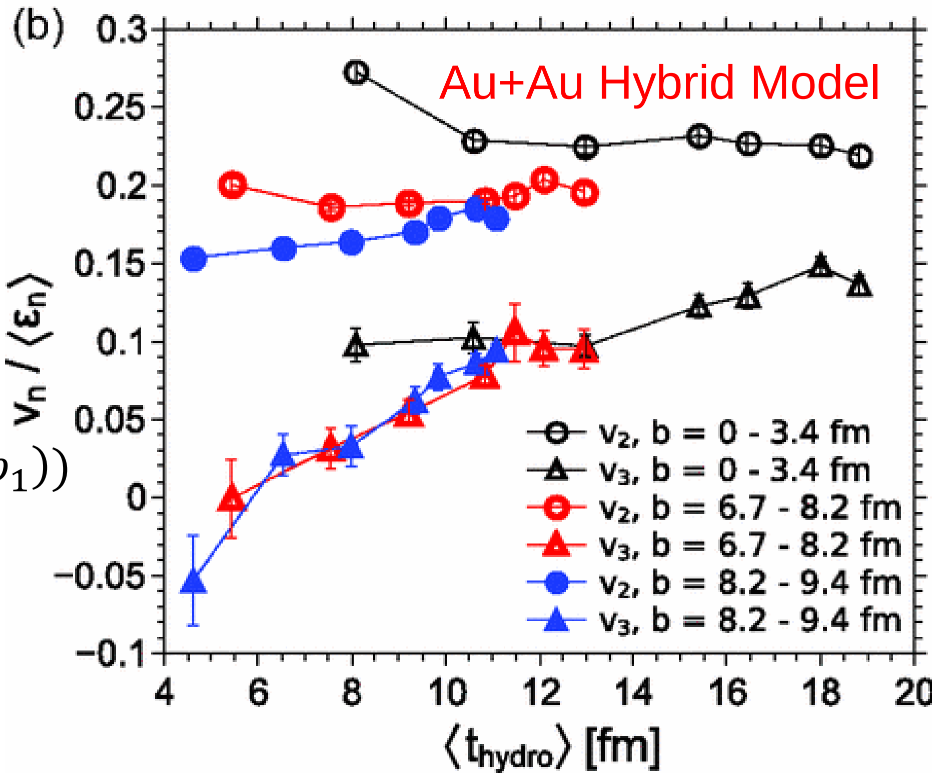
STAR Internal Note SN0598 (2014)

Signatures from the bulk ($v_3^2\{2\}$)

B. Jacak and B. Müller, Science 337 (2012) 310-314



$$\frac{dN}{d(\varphi_2 - \varphi_1)} \propto 1 + \sum_{n=1}^{\infty} 2{v_n}^2 \cos(n(\varphi_2 - \varphi_1))$$

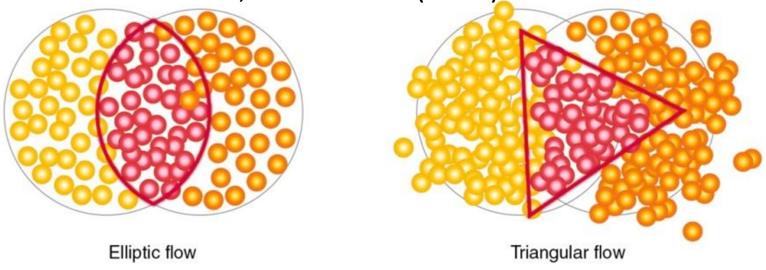


J. Auvinen and H. Petersen, Phys. Rev. C 88, no. 6, 397 064908 (2013)

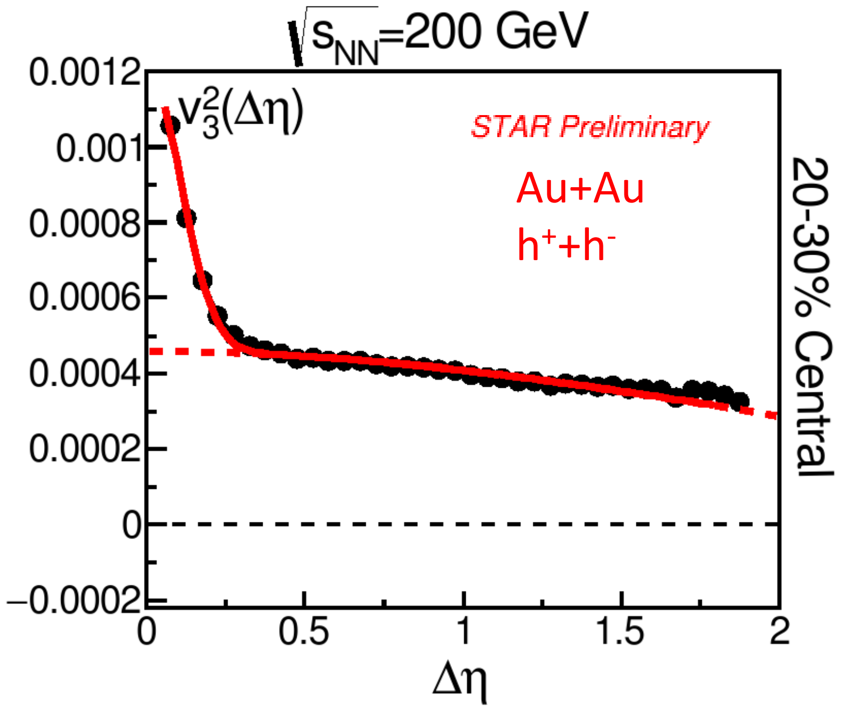
- Hybrid model shows v_3 as a signature for the formation of a low η/s partonic medium
- "shear viscosity suppresses the higher p_T-integrated v_n coefficients more strongly than v_2" – C. Chen *et al.*, Phys.Rev. **C** 91 (2015) 2, 024908

Extracting $v_3^2\{2\}$

B. Jacak and B. Müller, Science 337 (2012) 310-314



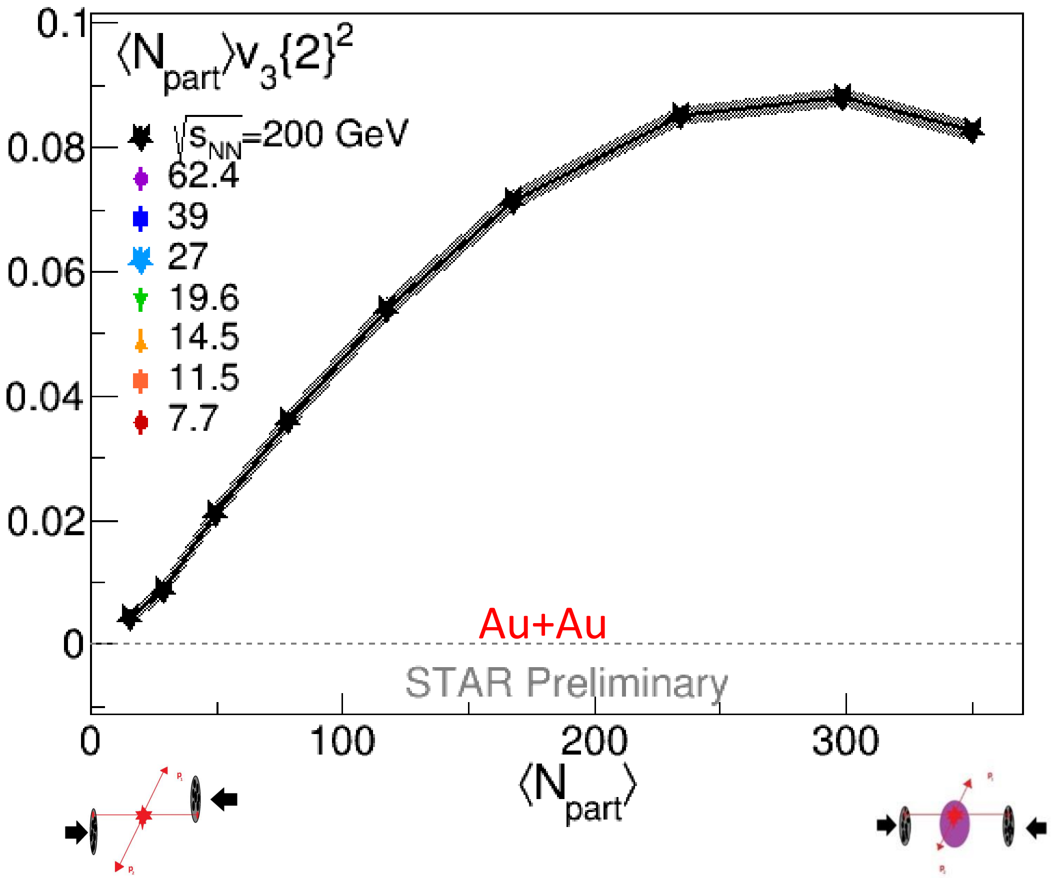
$$\frac{dN}{d(\varphi_2 - \varphi_1)} \propto 1 + \sum_{n=1}^{\infty} 2{v_n}^2 \cos(n(\varphi_2 - \varphi_1))$$



- Corrected for detector acceptance and efficiency
- The Δη distribution is fit with 2 Gaussians and the broader Gaussian is used to extract $\langle {v_3}^2\{2\} \rangle$
- The narrow Gaussian is dominated by HBT

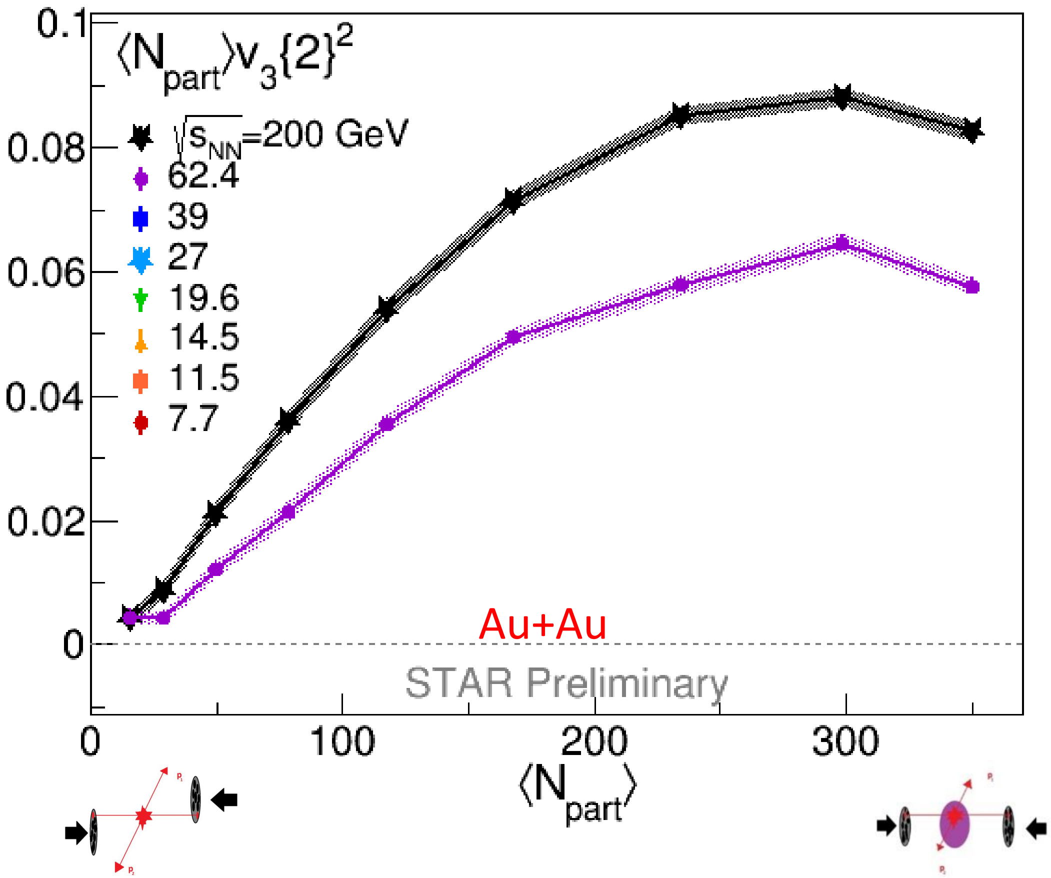
See Liao SONG's Talk
Tuesday 2:40
Correlations and Fluctuations IV

Results – N_{part} $v_3^2\{2\}$



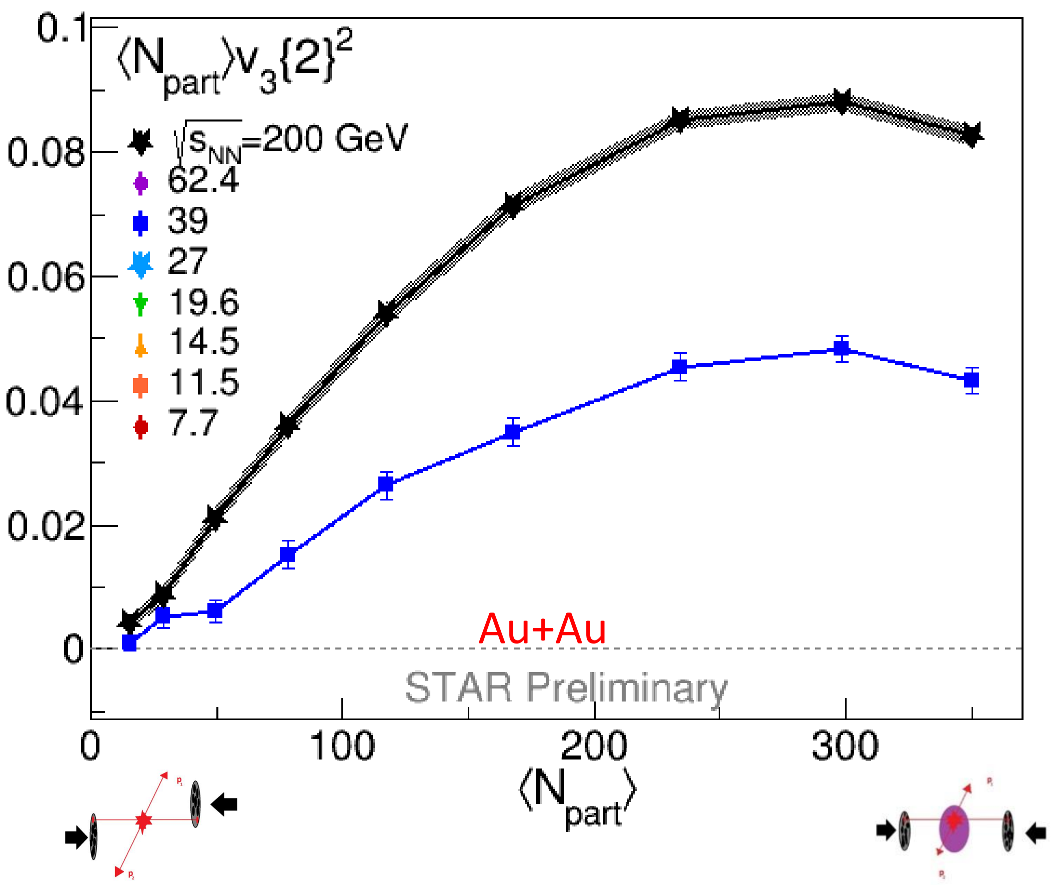
Scaled by N_{part} to counter the approximate 1/ N_{part} dependence one would expect from fluctuation driven $v_3^2\{2\}$

Results – N_{part} $v_3^2\{2\}$



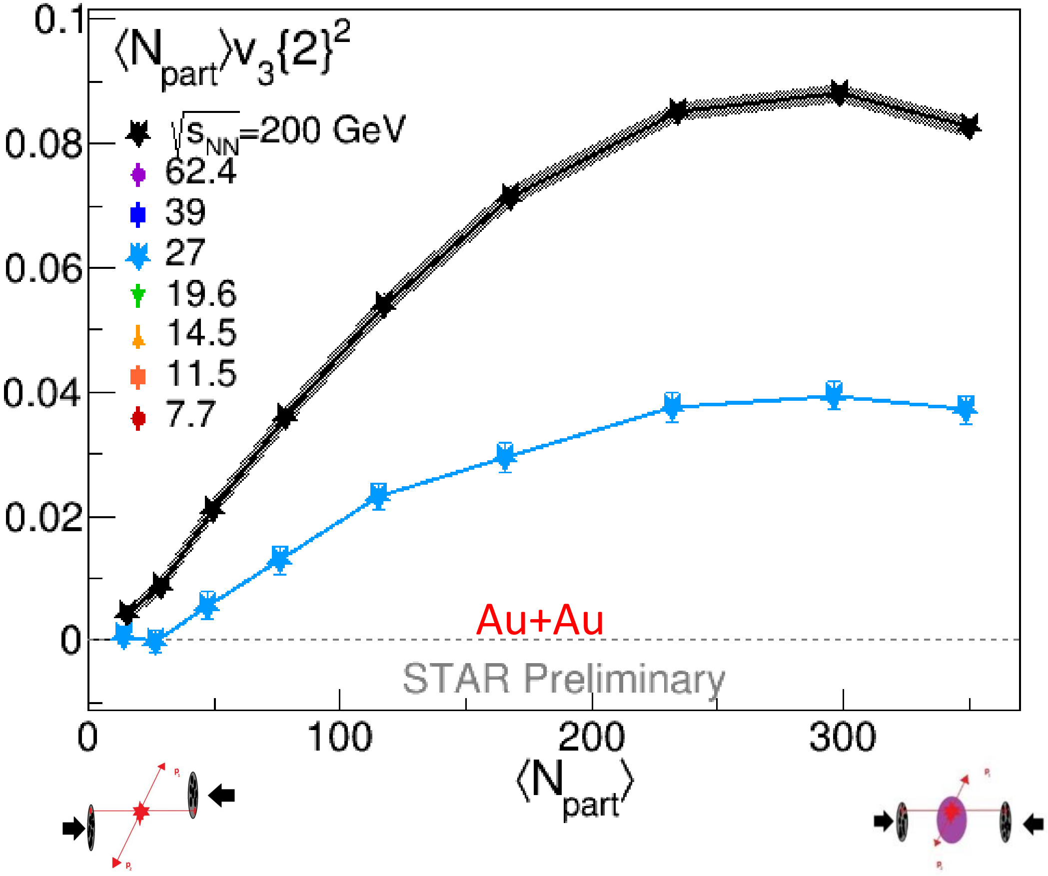
Scaled by N_{part} to counter the approximate 1/ N_{part} dependence one would expect from fluctuation driven $v_3^2\{2\}$

Results – N_{part} $v_3^2\{2\}$



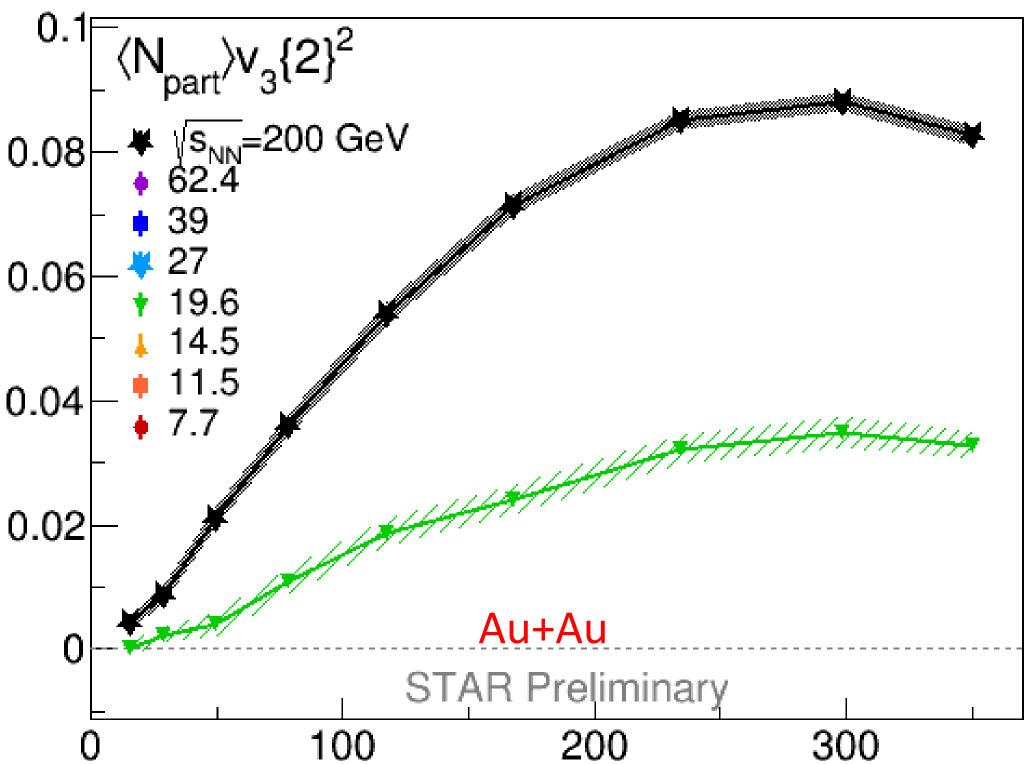
Scaled by N_{part} to counter the approximate 1/ N_{part} dependence one would expect from fluctuation driven $v_3^2\{2\}$

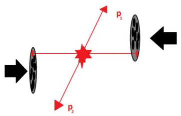
Results – $N_{part}\ v_3^2\{2\}$

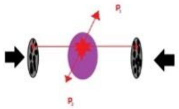


Scaled by N_{part} to counter the approximate 1/ N_{part} dependence one would expect from fluctuation driven $v_3^2\{2\}$

Results – N_{part} $v_3^2\{2\}$

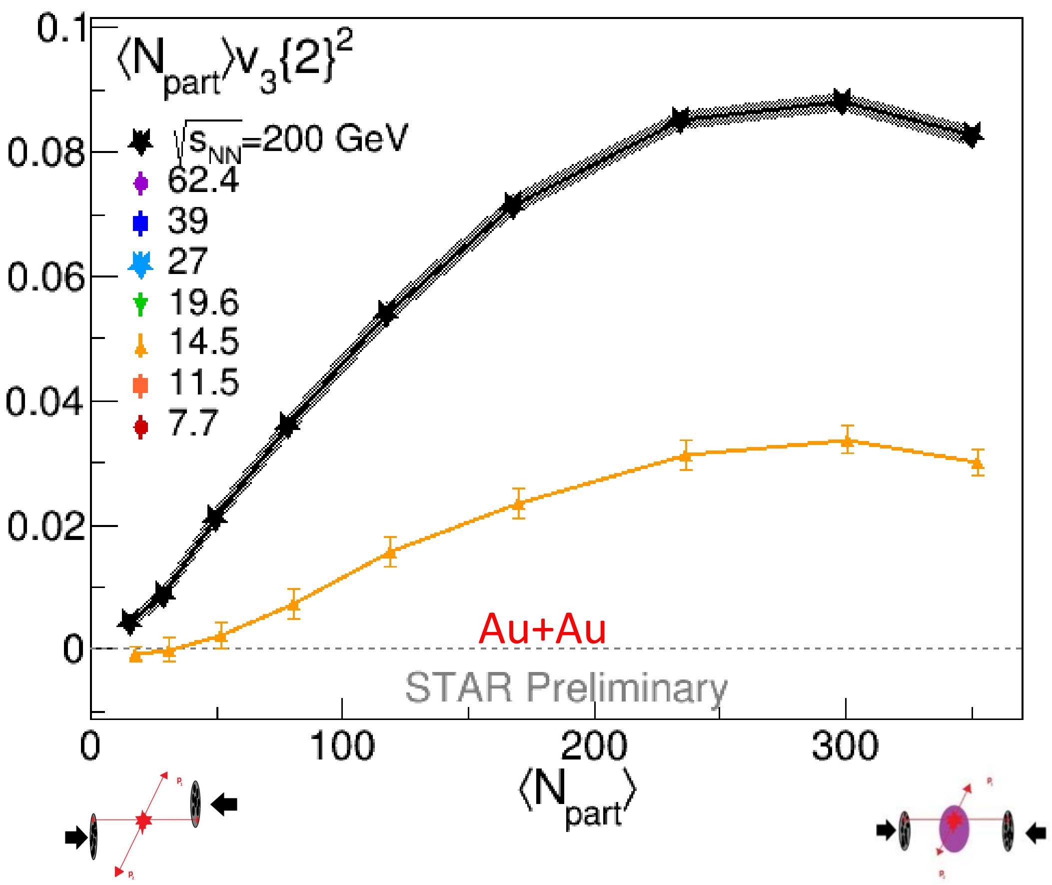






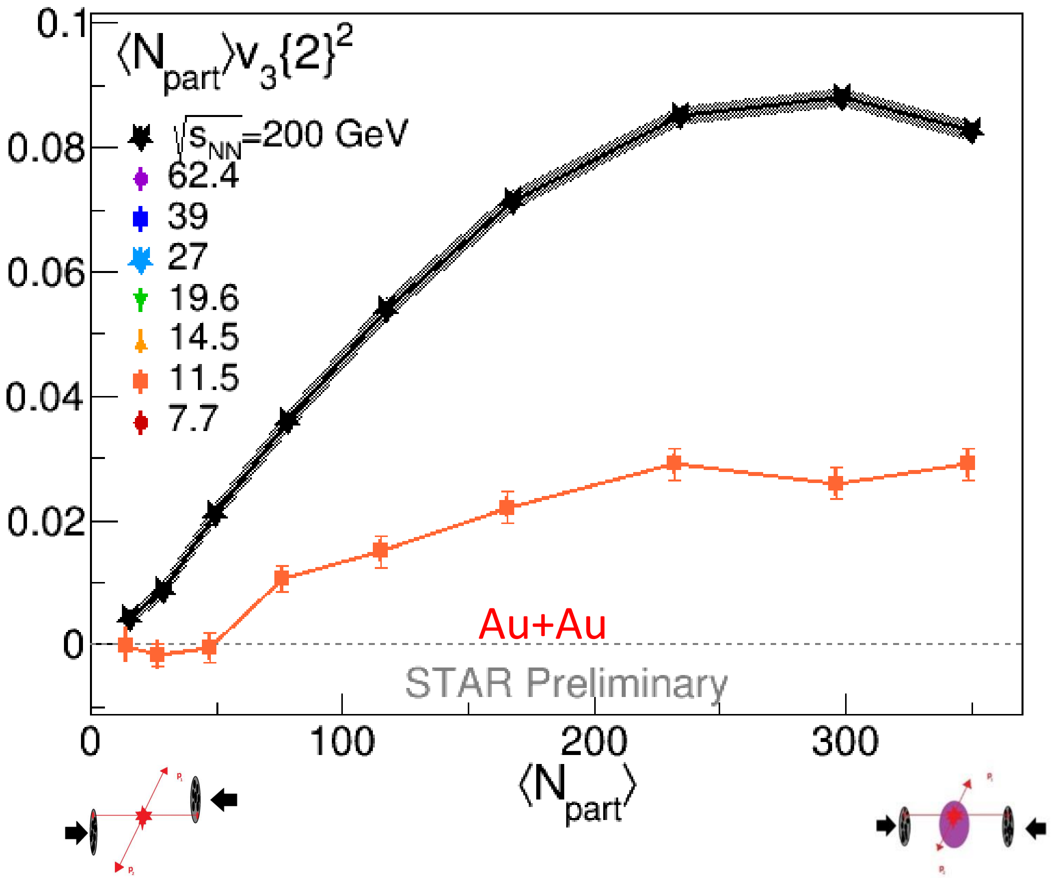
Scaled by N_{part} to counter the approximate 1/ N_{part} dependence one would expect from fluctuation driven $v_3^2\{2\}$

Results – $N_{part}\ v_3^2\{2\}$



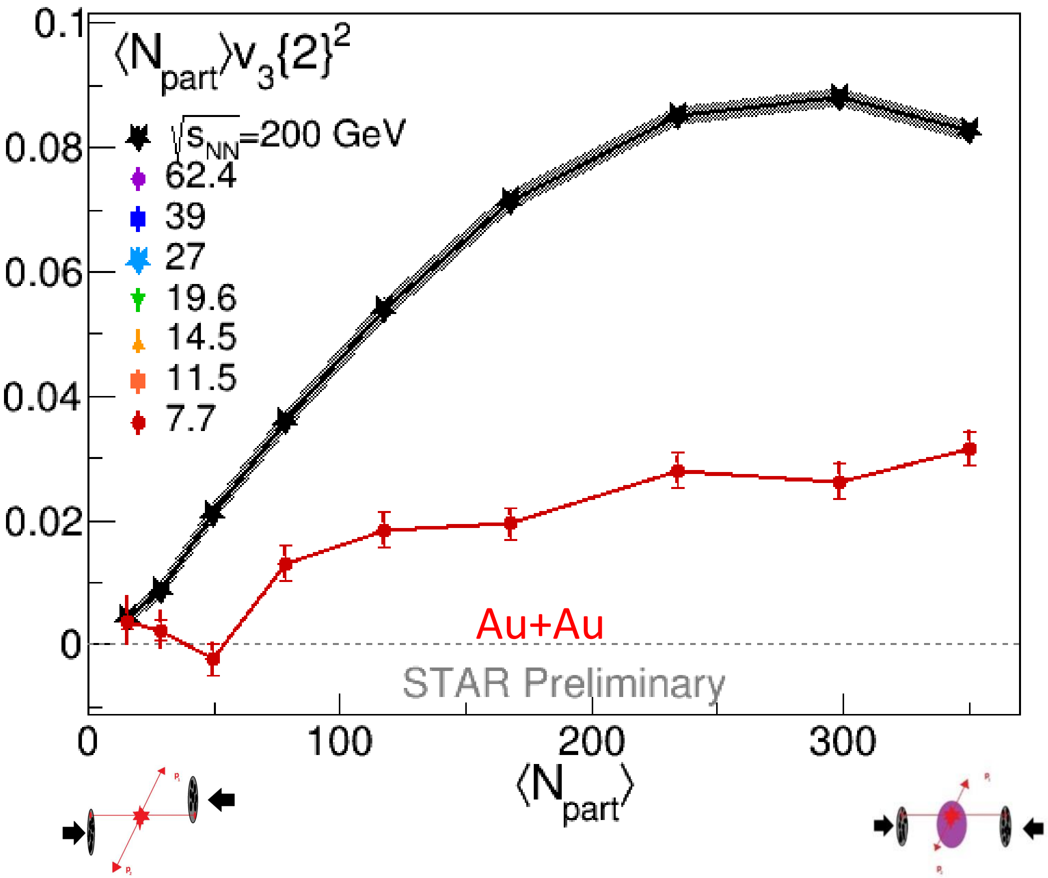
Scaled by N_{part} to counter the approximate $1/\ N_{part}$ dependence one would expect from fluctuation driven $v_3^2\{2\}$

Results – N_{part} $v_3^2\{2\}$



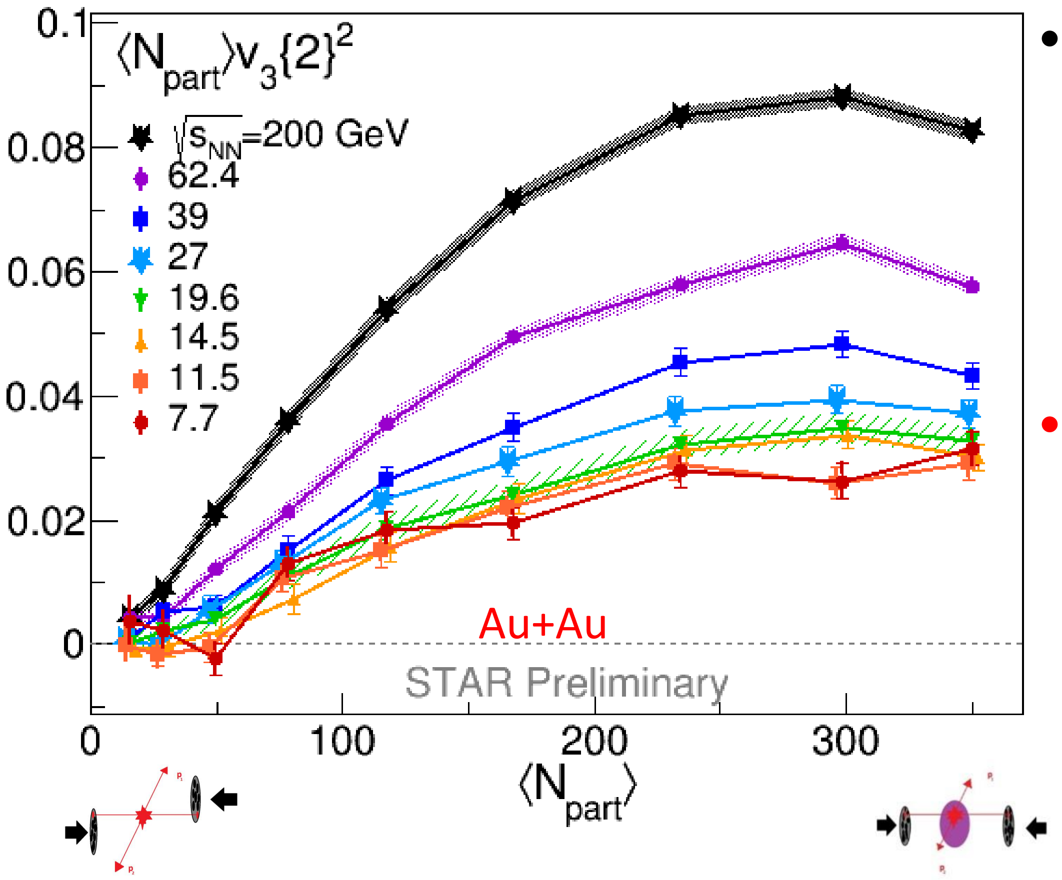
Scaled by N_{part} to counter the approximate 1/ N_{part} dependence one would expect from fluctuation driven $v_3^2\{2\}$

Results – $N_{part}\ v_3^2\{2\}$



Scaled by N_{part} to counter the approximate $1/\ N_{part}$ dependence one would expect from fluctuation driven $v_3^2\{2\}$

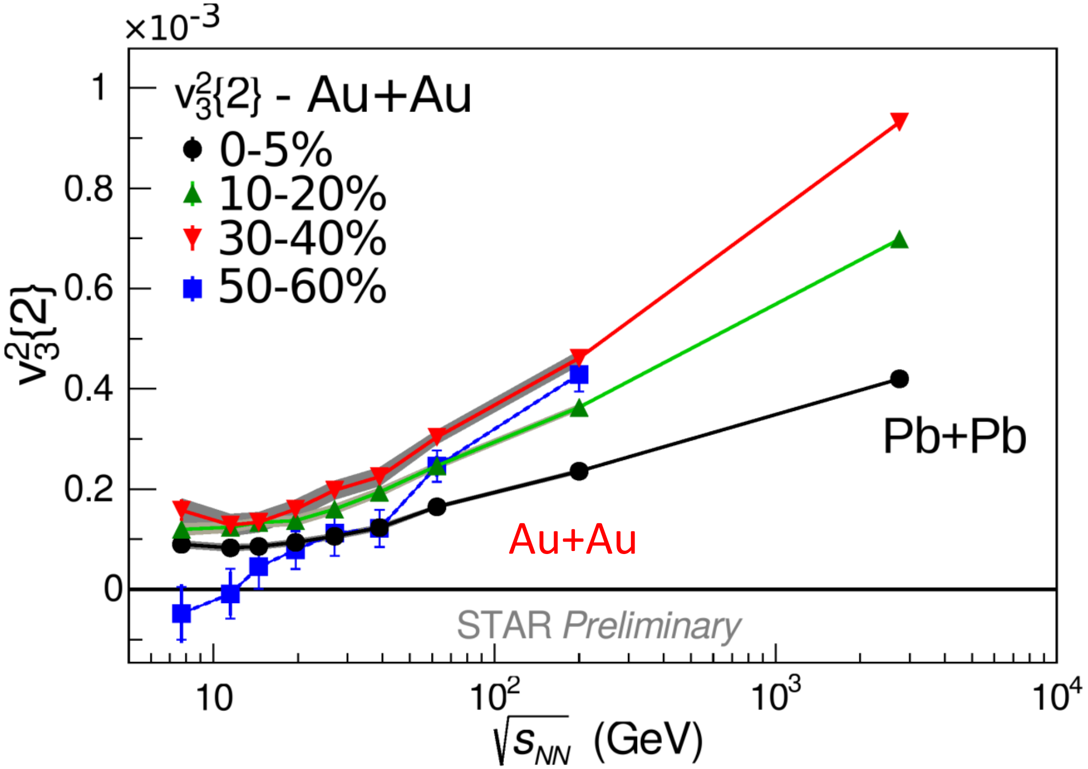
Results – N_{part} $v_3^2\{2\}$



- $v_3^2\{2\}$ is positive for data more central than 50-60% centralities, for all energies measured here
- Hybrid UrQMD expectations suggest that these results are consistent with QGP formation, even in the lowest energy collisions at RHIC

Scaled by N_{part} to counter the approximate 1/ N_{part} dependence one would expect from fluctuation driven $v_3^2\{2\}$

Results – $v_3^2\{2\}$



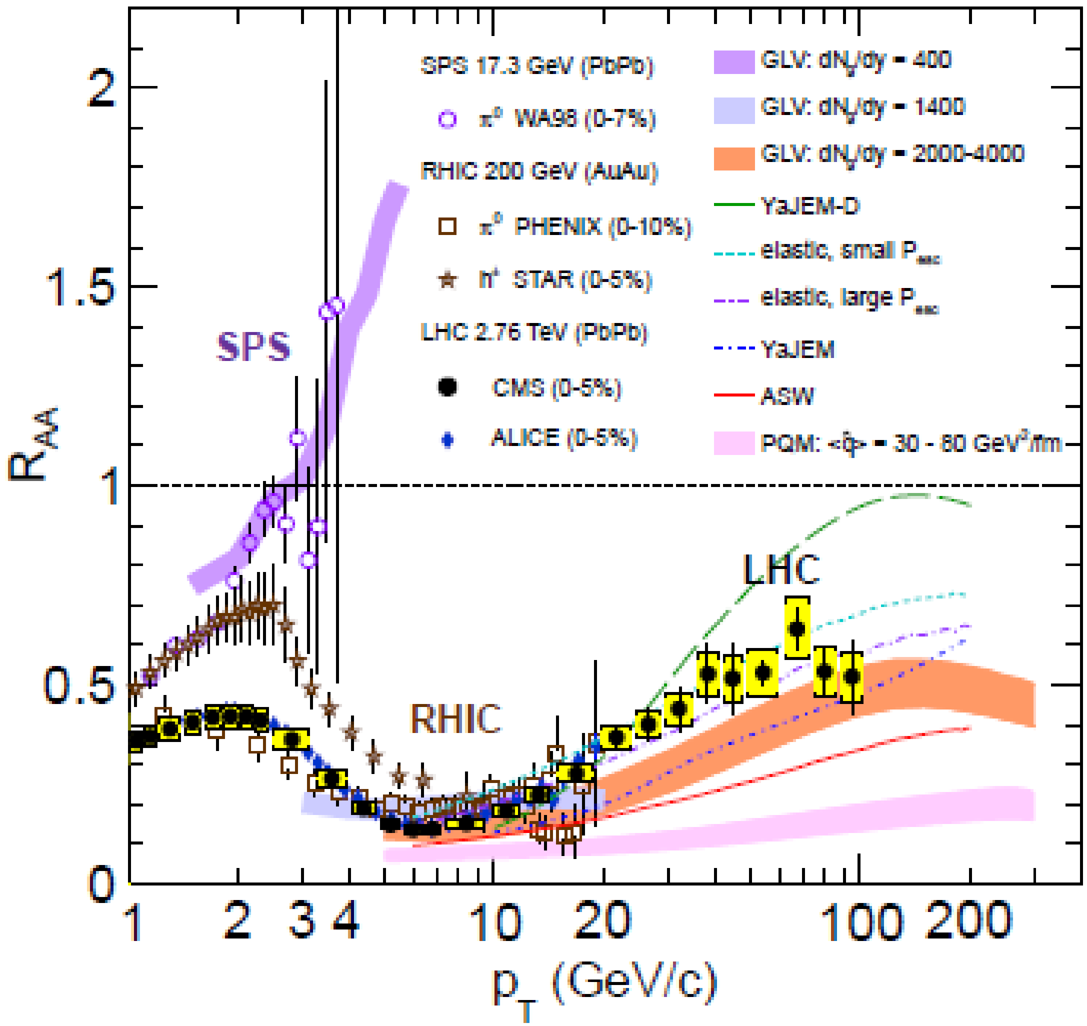
2.76 TeV data from ALICE,
Phys. Rev. Lett. **107**, 032301 (2011)

- $v_3^2\{2\}$ vanishes for the lowest energy peripheral data
- This is consistent with the hybrid UrQMD model's expectations for the turn-off of QGP formation

State of world's R_{AA}

- We use R_{CP} in the BES since we do not have a p+p reference

CMS: Eur. Phys. J. C **72** (2012) 1945

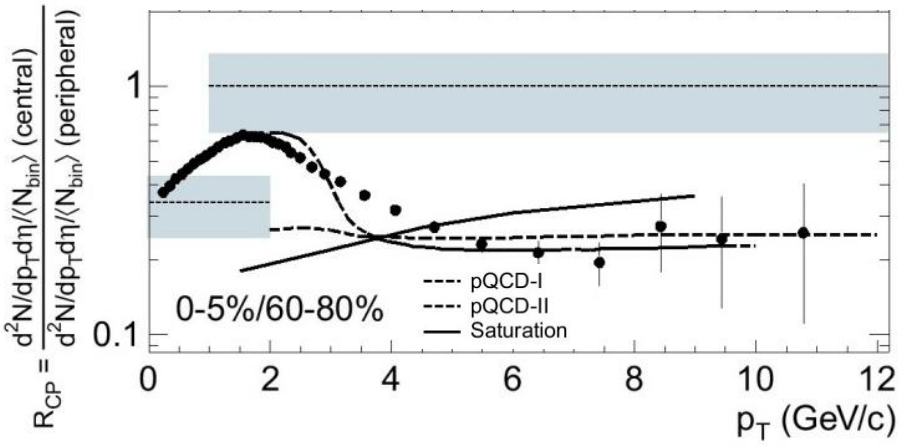


Suppression of high p_T

'Suppression' ≡ $R_{CP} < 1$

'Quenching' ≡ loss of energy for high momentum particles

Au+Au 200

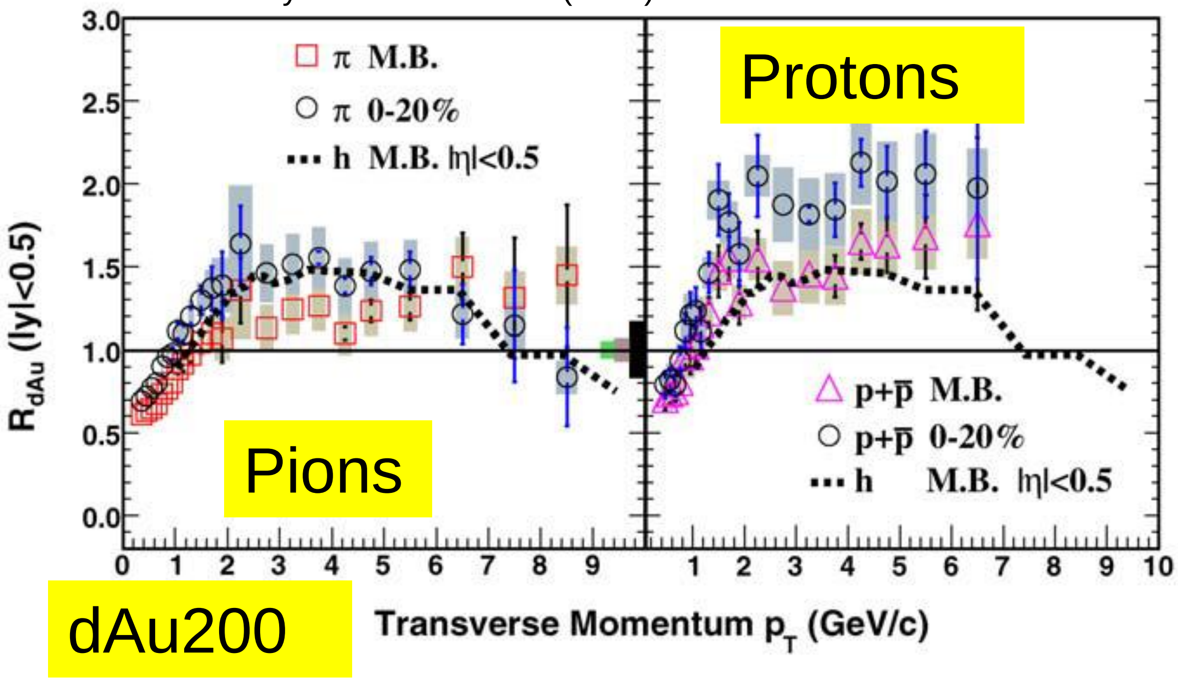


STAR: Phys. Rev. Lett. 91, 172302 (2003)

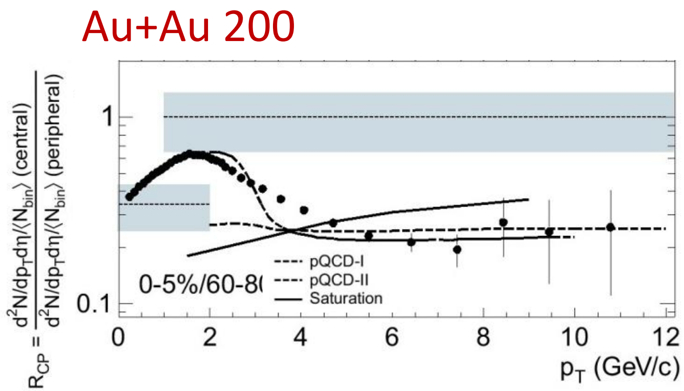
high p_T charged hadrons are suppressed at $\sqrt{s_{NN}}$ = 200GeV

d+Au for Cold Nuclear Matter (CNM)

STAR: Physics Letters B 637 (2006) 161–169



- The suppression observed at 200GeV is due to quenching

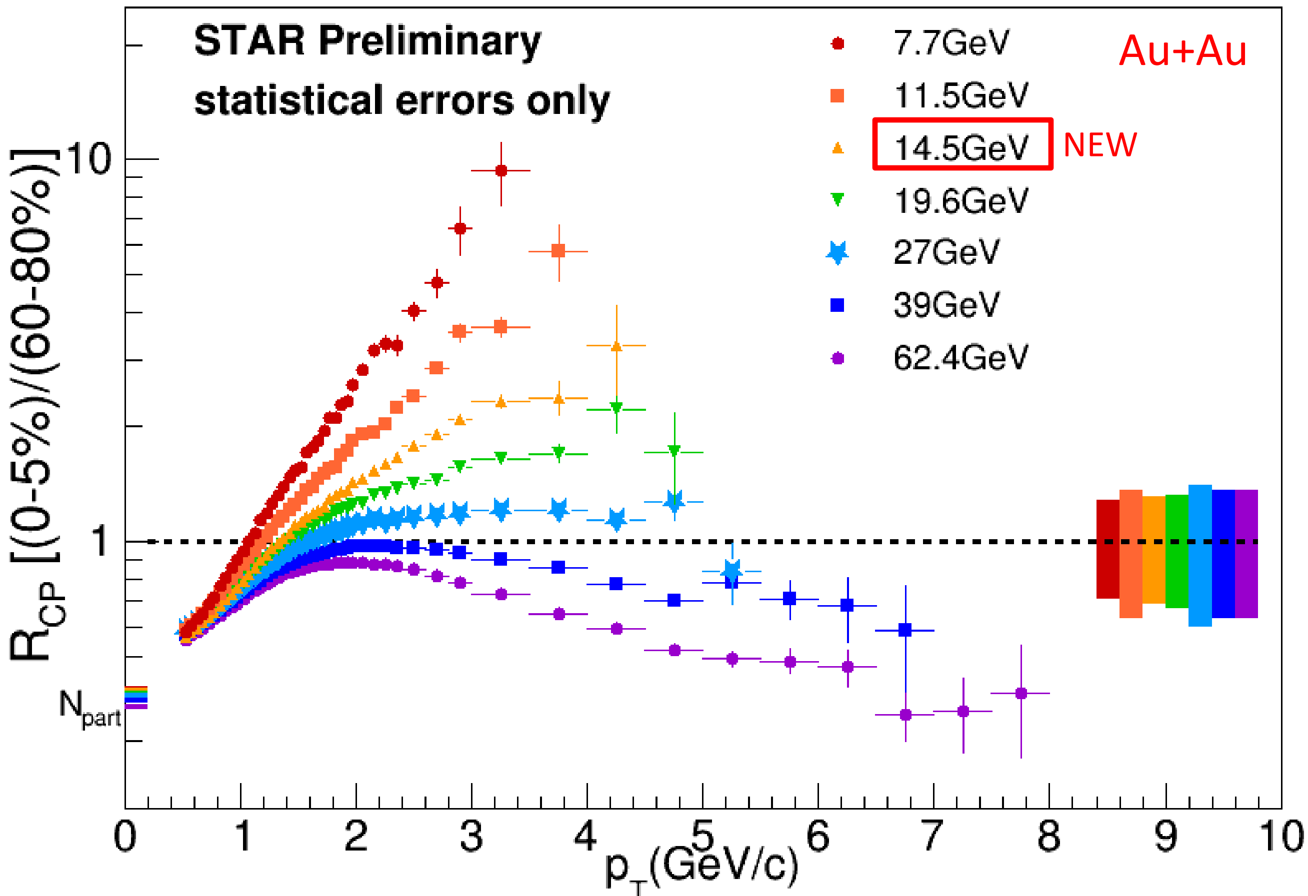


STAR: Phys. Rev. Lett. 91, 172302 (2003)

The 'Cronin Effect' is the experimentally observed enhancement of spectra in p+A collisions relative to a p+p reference

PRL 68, 452 (1992) Straub

BES I Charged Hadron R_{CP}



- Enhancement effects compete against suppression effects concealing the turn off of QGP formation at low $\sqrt{s_{NN}}$

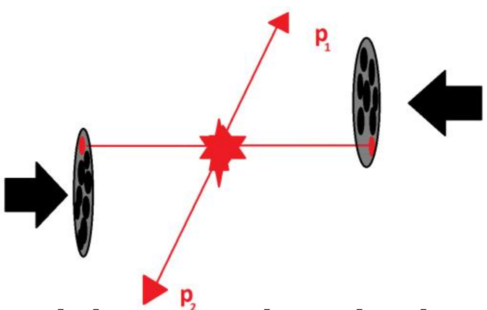
$Y(N_{part})$

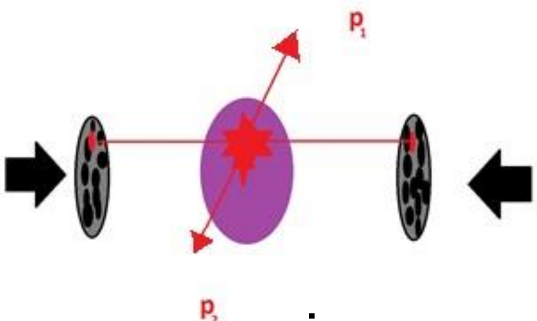
- $Y(N_{part})$ takes a projection at high-p_T of the numerator from R_{CP} and investigates its centrality dependence

Au + Au
Peripheral

$$Y(N_{part}) = \left(\frac{d^2N}{\langle N_{coll}\rangle dp_T d\eta}\right)_{high-p_T\ bin}$$

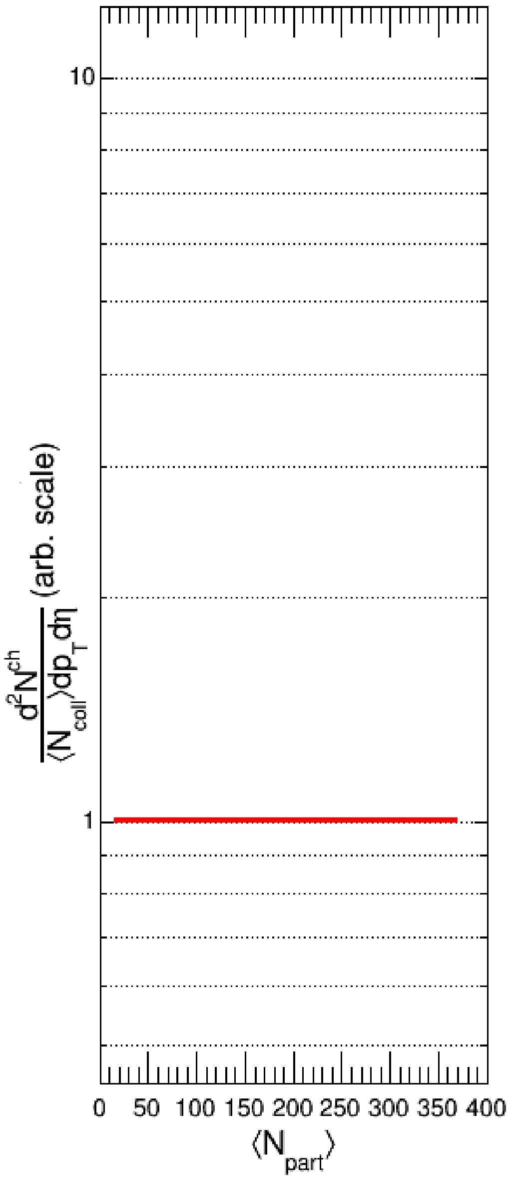
Au + Au
Central





- This method should increase sensitivity to suppression
- Provides possible evidence for where a QGP **is** formed

N_{coll} ≡ number of binary collisions (from Glauber MC)

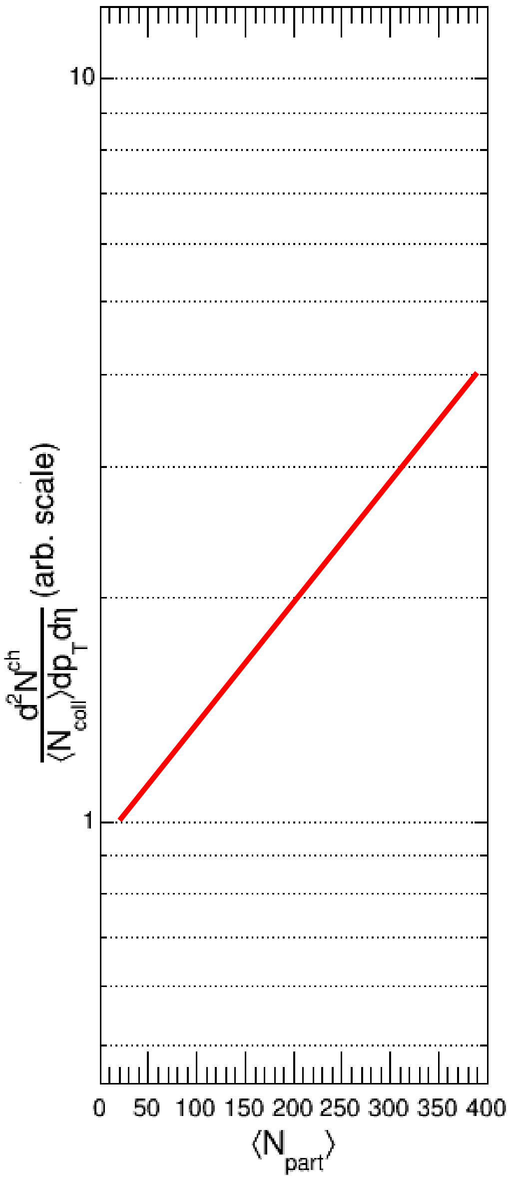


$Y(N_{part})$

- If the "high-p_T" region scales with N_{coll} such that we can consider the Au+Au collision to be a linear superposition of p+p-like collisions then we would expect $Y(N_{part})$ to be flat at unity

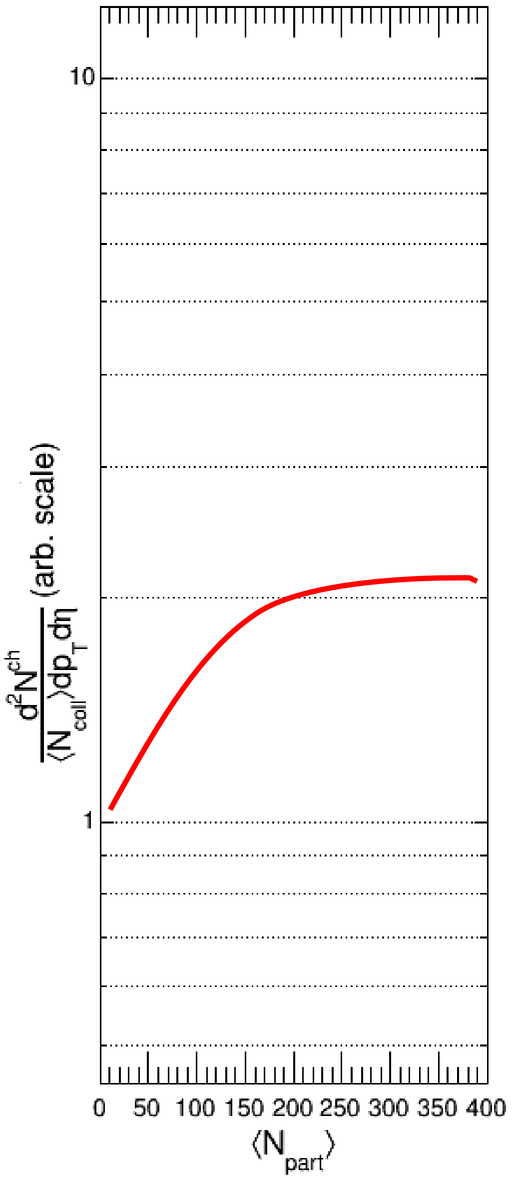
$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll}dp_T d\eta}\right)_{high-p_T\ bin}$$

$Y(N_{part})$



- If there are enhancement effects that grow stronger as you go more central then you would expect $Y(N_{part})$ to increase with N_{part}

$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll}dp_T d\eta}\right)_{high-p_T\ bin}$$

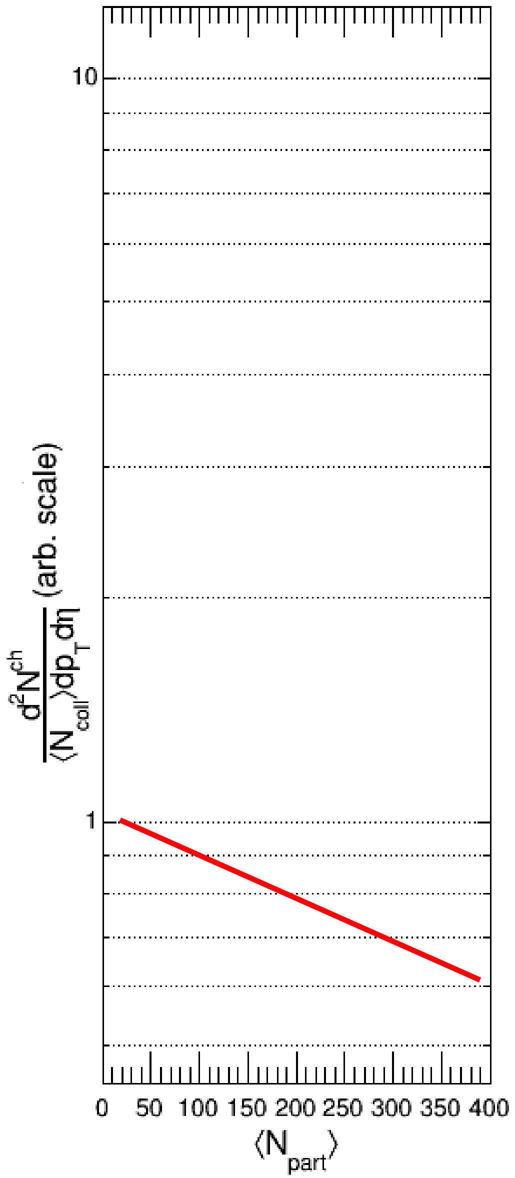


$Y(N_{part})$

- If the enhancement effects grow stronger as you go more central and then saturate then you would expect:

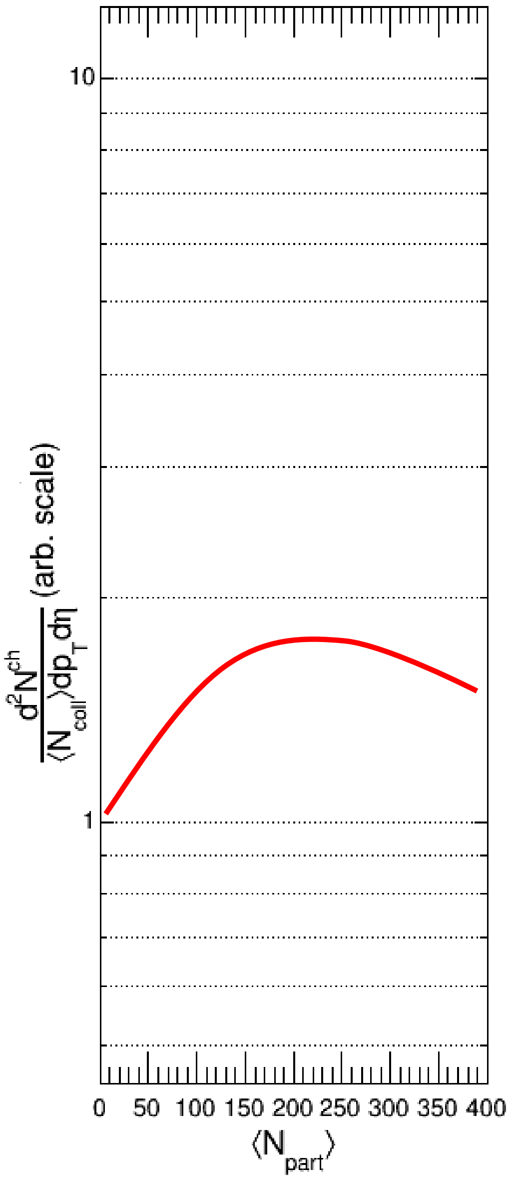
$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll}\,dp_T\,d\eta}\right)_{high-p_T\ bin}$$

Y(N_{part})



- Suppression that grows stronger as you go more central would give:

$$Y\left(N_{part}\right) = \left(\frac{\mathrm{d}^2\mathrm{N}}{N_{coll}\mathrm{dp_T d\eta}}\right)_{high-p_T\ bin}$$

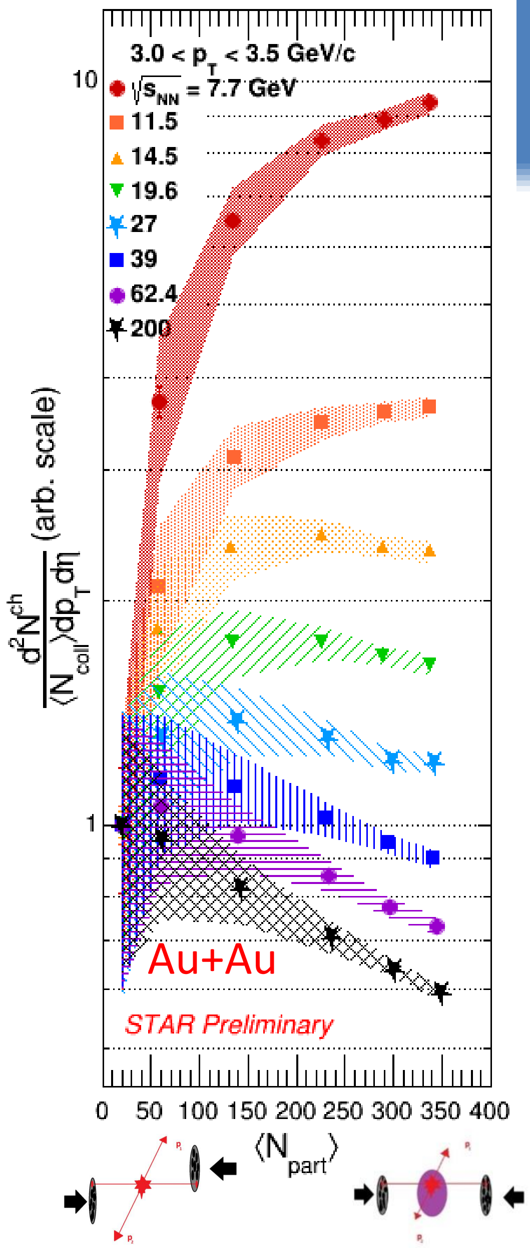


Y(N_{part})

- Enhancement and suppression effects compete against each other
- Y(N_{part}) measures the net change in these as a function of centrality
- If enhancement grows faster initially but suppression effects become more dominant as you go more central (or enhancement effects become weaker) then there will be a turnover in Y(N_{part})
- The suppression is measured relative to a centrality that contains enhancement effects (Cronin, Radial Flow, etc.) rather than a p+p-like system

$$Y(N_{part}) = \left(\frac{d^2N}{N_{coll} dp_T d\eta}\right)_{high-p_T\ bin}$$

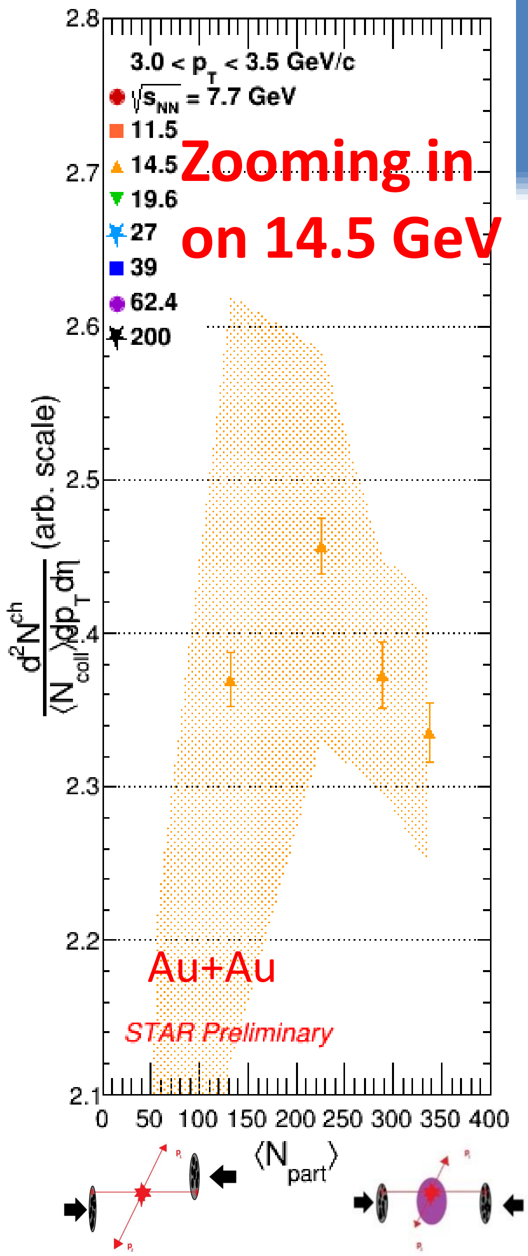
$Y(N_{part})$ $3.0 < p_T < 3.5$ GeV/c



- Most central data are suppressed (turnover) for $\sqrt{s_{NN}} \geq 14.5$ GeV
  - This does not rule out the formation of a QGP at lower energies than 14.5 GeV
- 7.7 and 11.5 GeV results increase monotonically
- 200 GeV results decrease monotonically

Error bands are correlated uncertainties

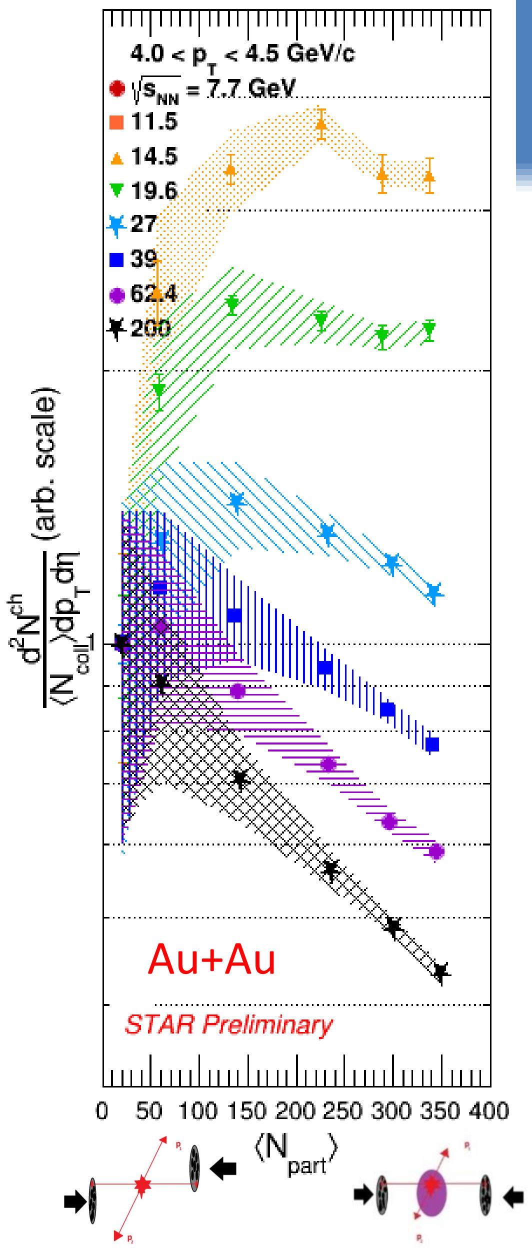
Y(N_{part}) 3.0 < p_T < 3.5 GeV/c



- Most central data are suppressed (turnover) for $\sqrt{s_{NN}}$ ≥ 14.5 GeV
  - This does not rule out the formation of a QGP at lower energies than 14.5 GeV
- 7.7 and 11.5 GeV results increase monotonically
- 200 GeV results decrease monotonically

Error bands are correlated uncertainties

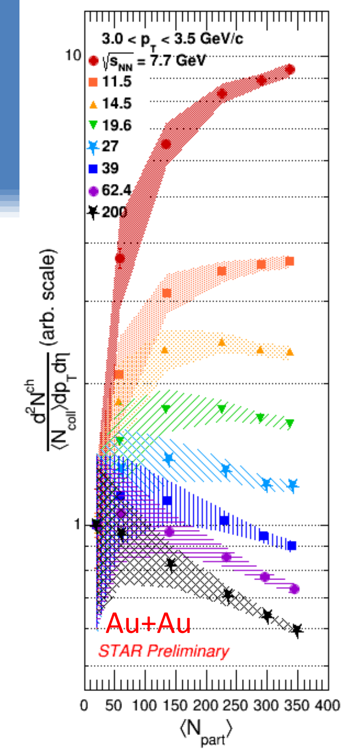
$Y(N_{part})$ $4.0 < p_T < 4.5$ GeV/c



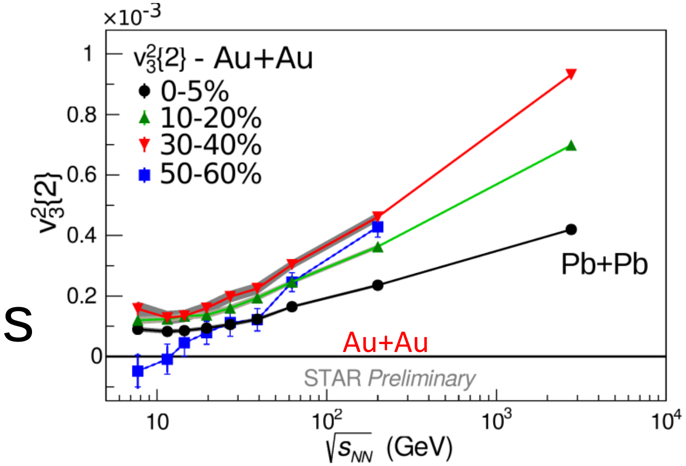
- Most central data are suppressed for $\sqrt{s_{NN}} \geq 14.5$ GeV
- This method is sensitive to charged hadron suppression to a lower energy than previous techniques
- To prove the suppression is due to quenching, possible contributions from hadronic energy loss and impact parameter dependent nPDFs need further investigation
- p+p and d+Au collisions for the BES will help

Conclusions

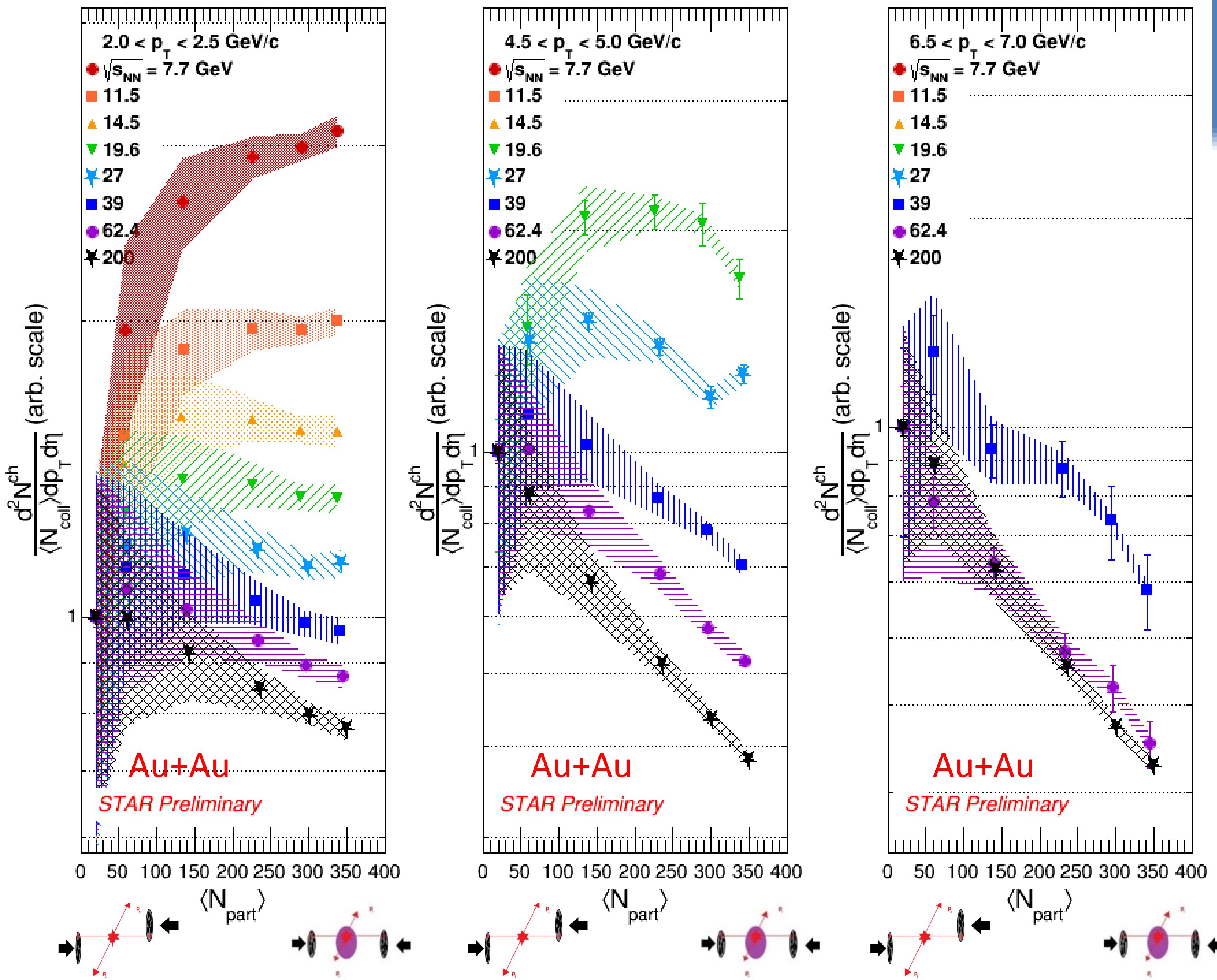
- Suggested QGP signatures
  - Some models suggest $v_3^2\{2\}$ as a signature for the formation of a low η/s partonic medium
  - Suppression measured by $Y(N_{part})$ may be due to in-medium energy loss



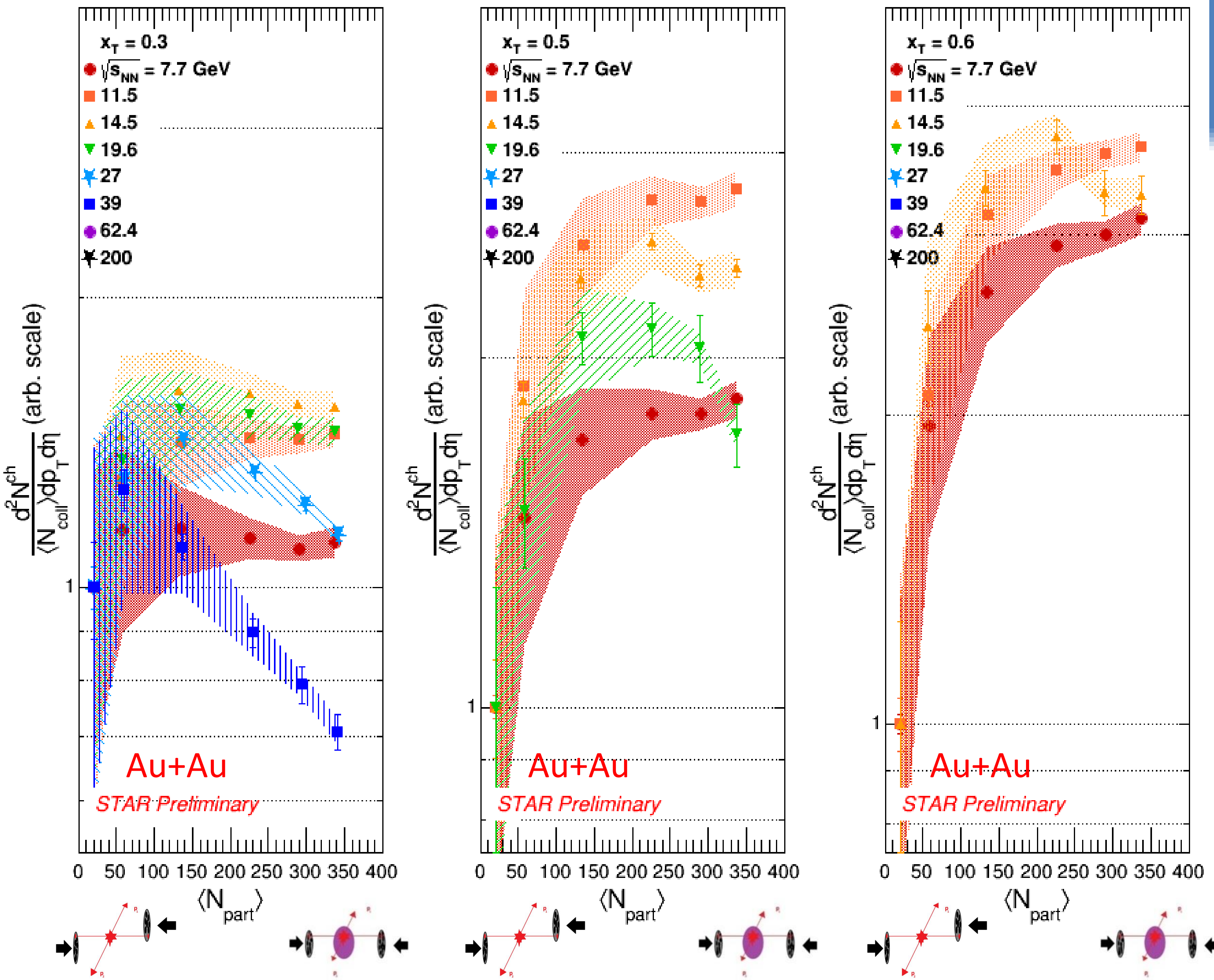
- Measurements
  - For sufficiently central collisions, $v_3^2\{2\}$ persists for $\sqrt{s_{NN}} \geq 7.7$ GeV and $Y(N_{part})$ exhibits relative suppression for $\sqrt{s_{NN}} \geq 14.5$ GeV
  - For lower energy peripheral collisions these signatures are turned off



Backups


2.0 < p_T < 2.5 GeV/c
4.5 < p_T < 5.0 GeV/c
6.5 < p_T < 7.0 GeV/c
$\sqrt{s_{NN}}$ = 7.7 GeV
11.5
14.5
19.6
27
39
62.4
200
$\frac{d^2N^{ch}}{\langle N_{coll}\rangle dp_T d\eta}$ (arb. scale)
$\langle N_{part}\rangle$
Au+Au
STAR Preliminary

x_T



x_T = 0.3
√s_NN = 7.7 GeV
11.5
14.5
19.6
27
39
62.4
200
d²N^ch / ⟨N_coll⟩dp_T dη (arb. scale)
Au+Au
STAR Preliminary
⟨N_part⟩
x_T = 0.5
x_T = 0.6