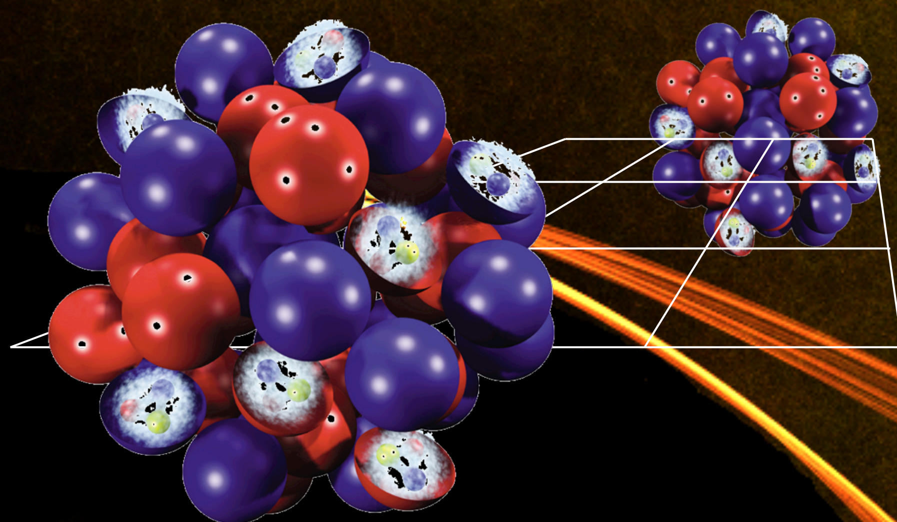
Probing the QGP Phase Diagram and Topological Charge Transitions at RHIC



Paul Sorensen

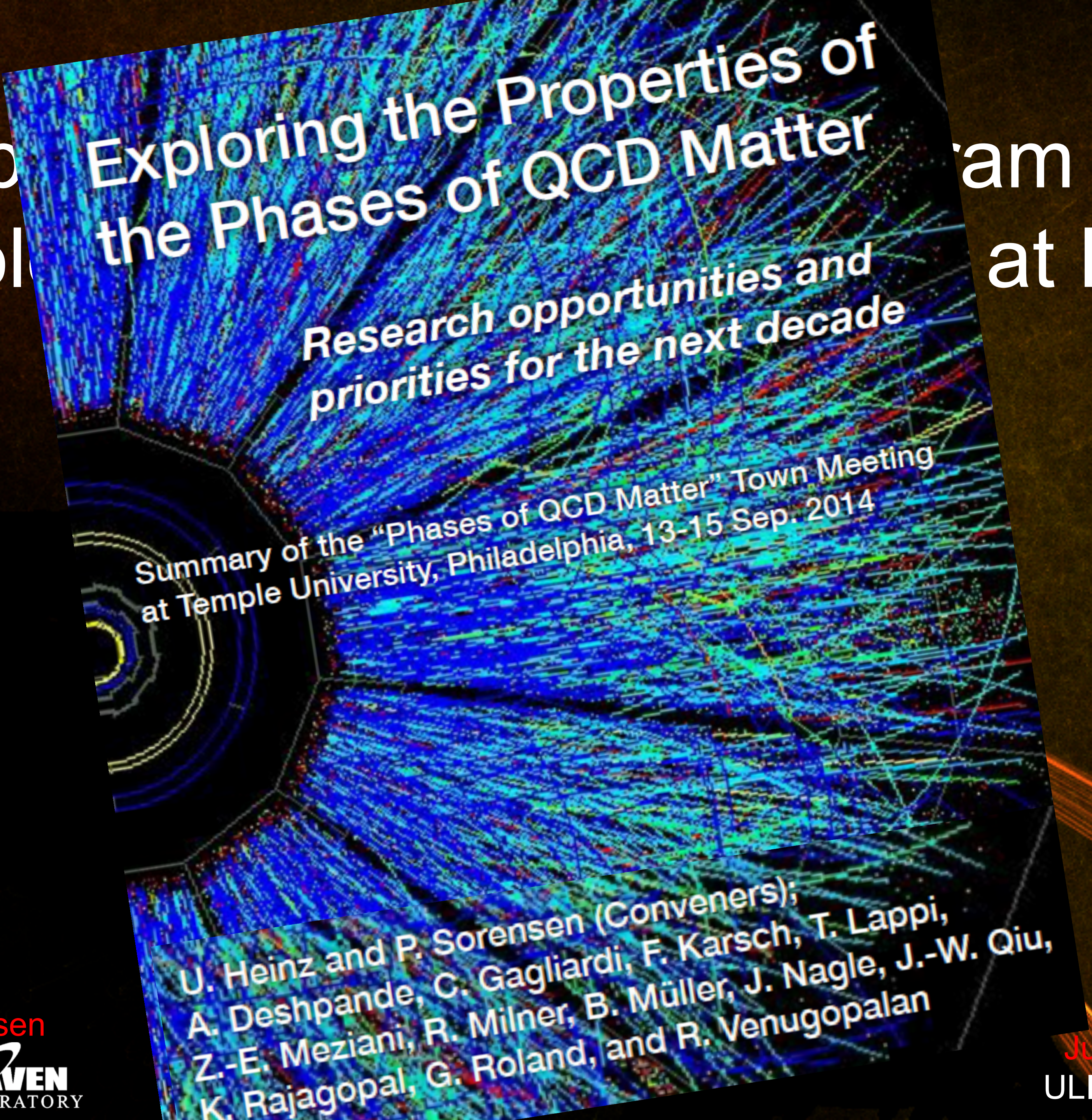
BROOKHAVEN NATIONAL LABORATORY

July 20th, 2016

ULI Fest; CERN

Prob ... ram and

Topol ... at RHIC



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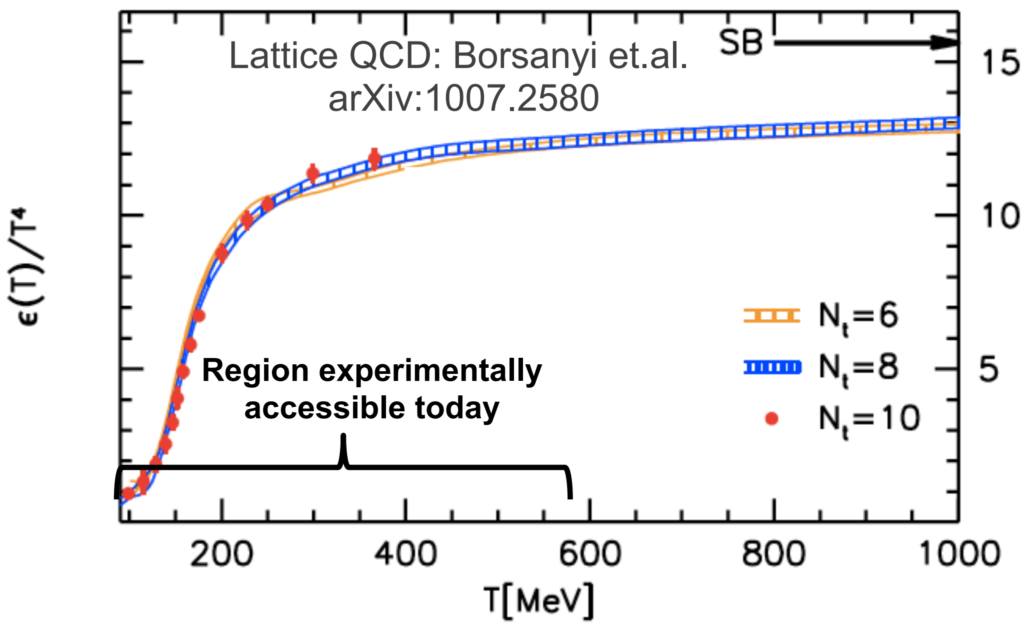
The Phase Transitions in the Early Universe

One microsecond after the Big Bang, the universe was filled with Quark Gluon Plasma: Quantum Chromodynamics describes how that QGP froze into the nuclear matter we are made of today



In todays experiments, we are ideally situated to study the phase transition that occurred a few microseconds after the Big Bang

What We Learn with ULtra-relatIvistic -HEavy IoNZ

Breaking of chiral symmetry in QCD generates 99% of the visible mass of the universe. Is chiral symmetry restored in heavy ion collisions?

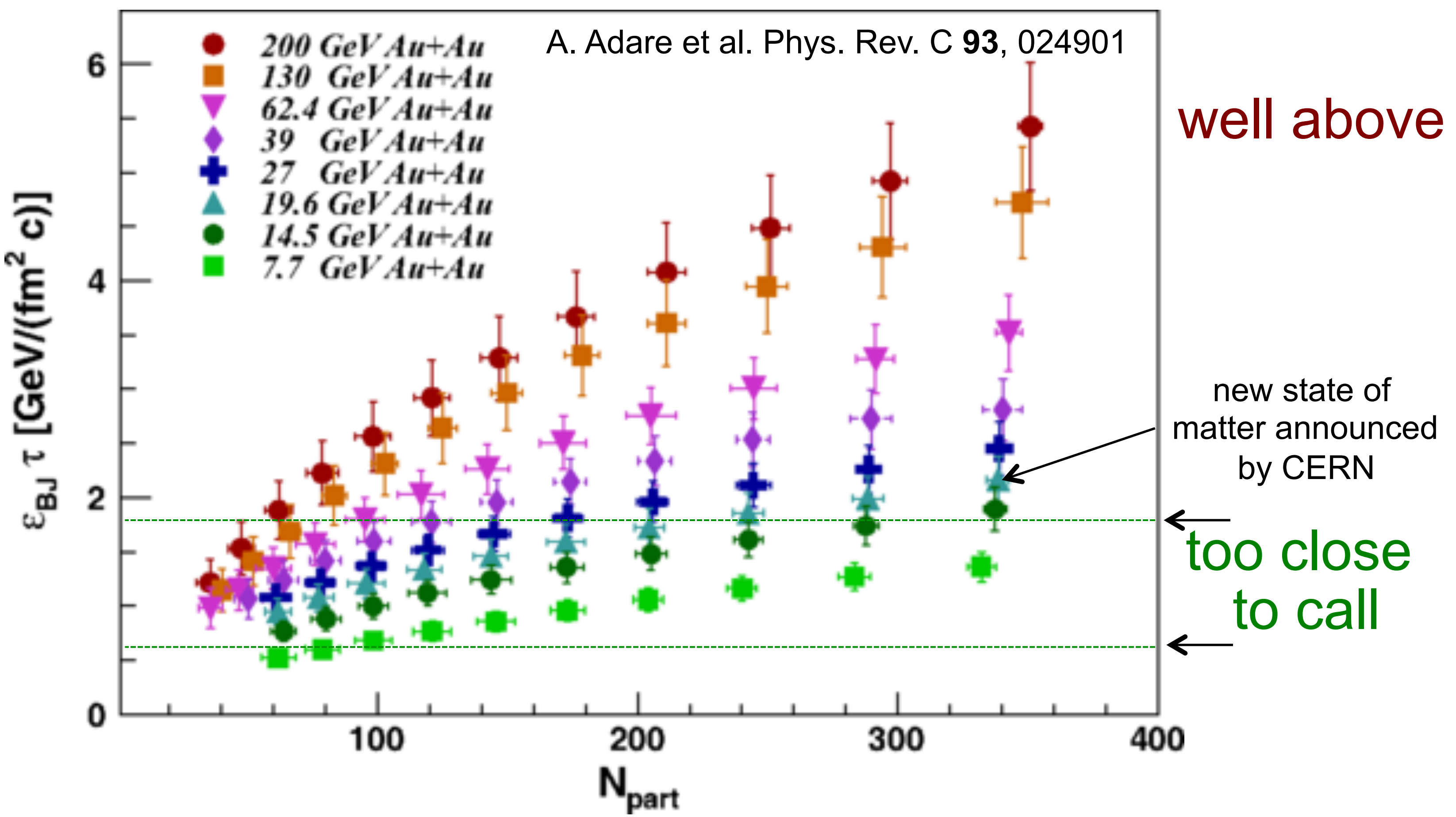
Can massless fermions in the chirally restored QGP be used to image the chiral anomaly of QCD?

At low density, the phase transition between QGP and hadrons is smooth. Is there a 1^{st} order transition and a critical point at higher density?

But first, where does the QGP exist and can we turn it off?

Do We Create QGP at Lower Energies?

Energy density measurements from BES-I



The minimum $\varepsilon_c\tau$ for QGP formation is between 0.6-1.8 GeV/fm^2

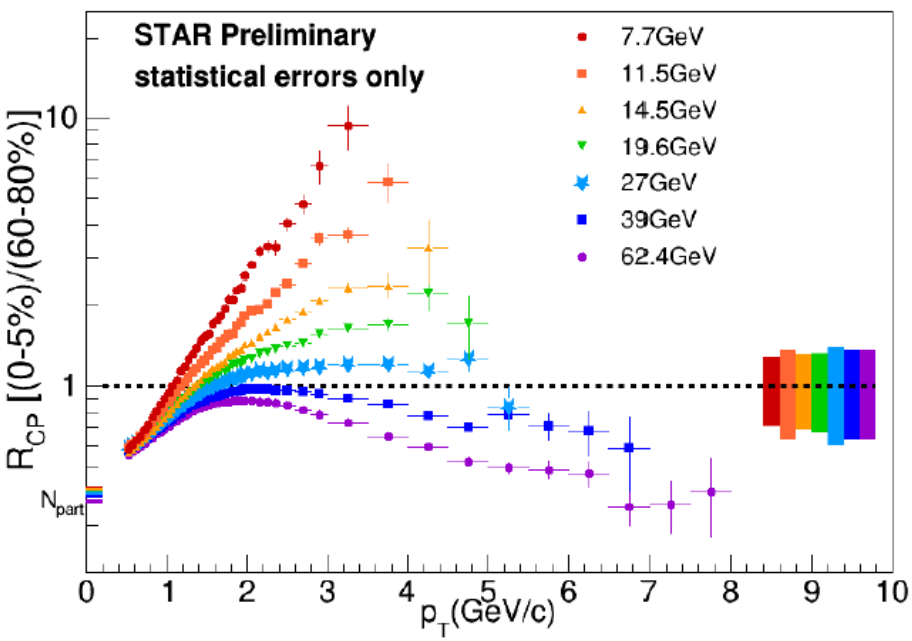
BES-I exploratory scan was carried out to shed light on this question

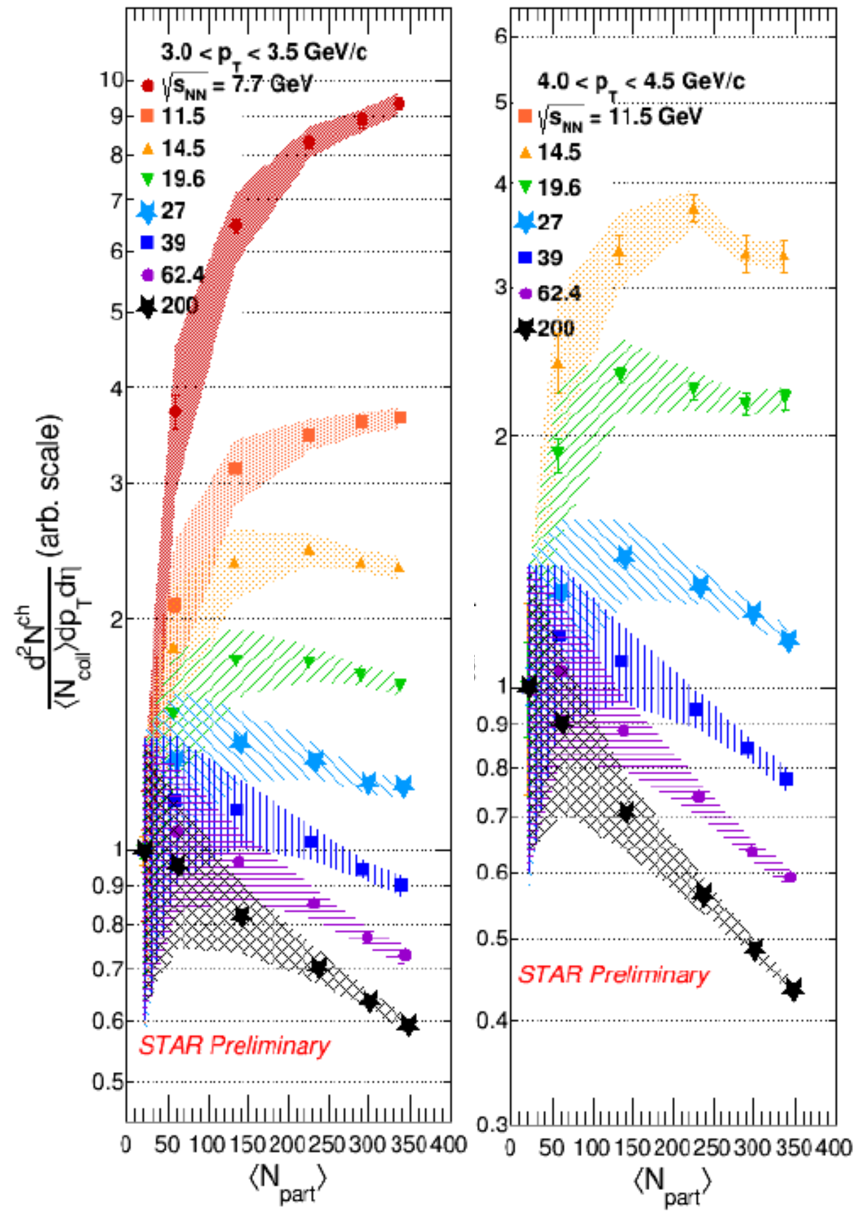
Do we see suppression/quenching?

Variation of hadron spectra with centrality suggestive of suppression at least down to 14.5 GeV

Difficult to draw conclusions since the spectra becomes so steep: affects of small perturbations from flow or “Cronin” become huge

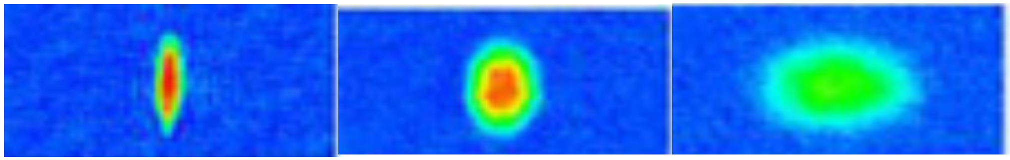
S. Horvat, QM2015





Elliptic Flow: 7.7 GeV to 2.76 TeV

coordinate-space anisotropy into momentum-space

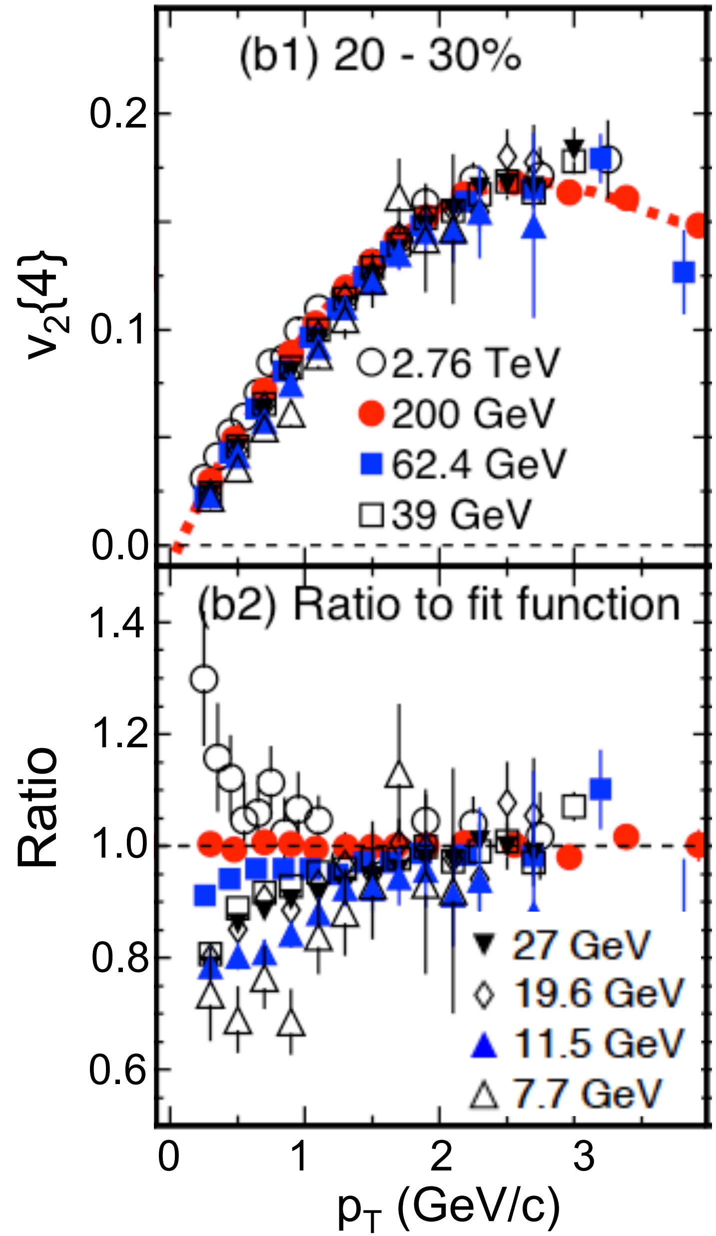


Surprisingly consistent as the energy changes by a factor ~400

Initial energy density changes by nearly a factor of 10

No evidence from v_2 for a turn off of the QGP

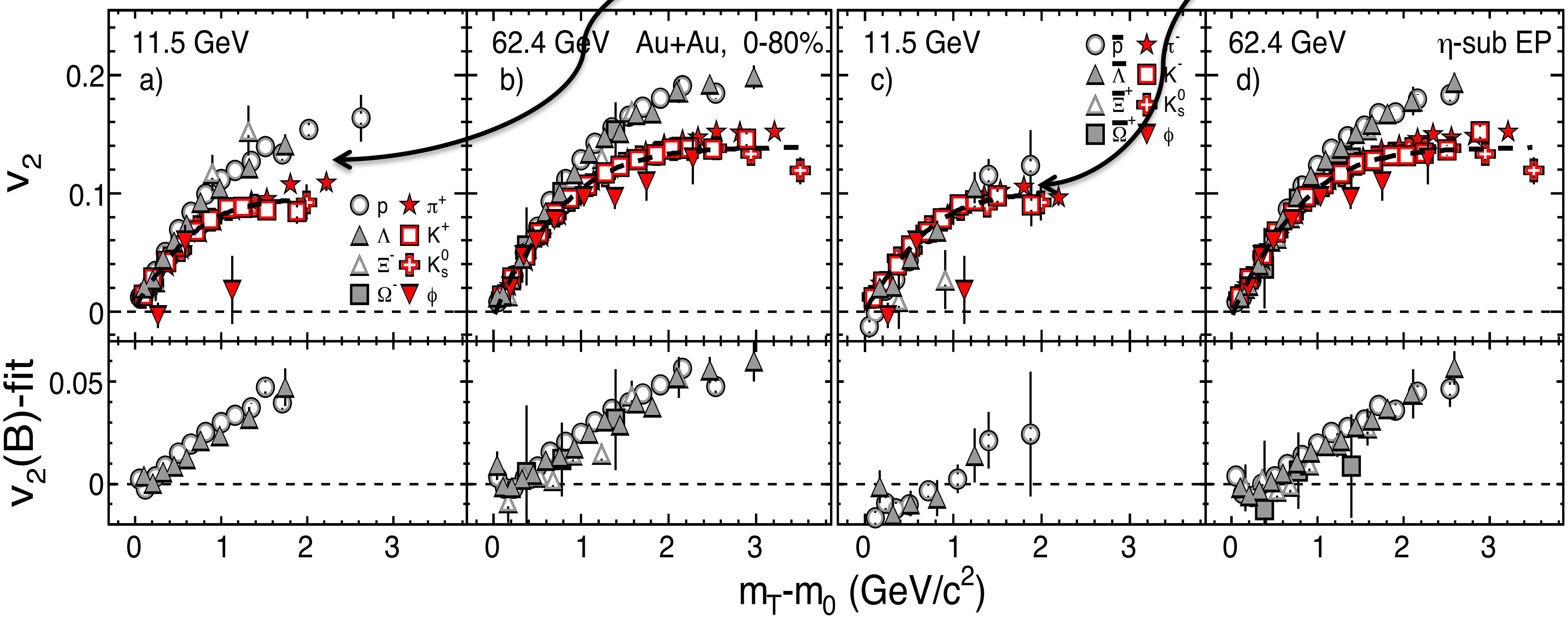
How sensitive is v_2 to QGP?



STAR Collaboration, Phys. Rev. C **86** (2012) 54908

v_2 from 2.76 TeV down to 11.5 GeV

At low energy,
NCQ dependence holds for particles but not anti-particles

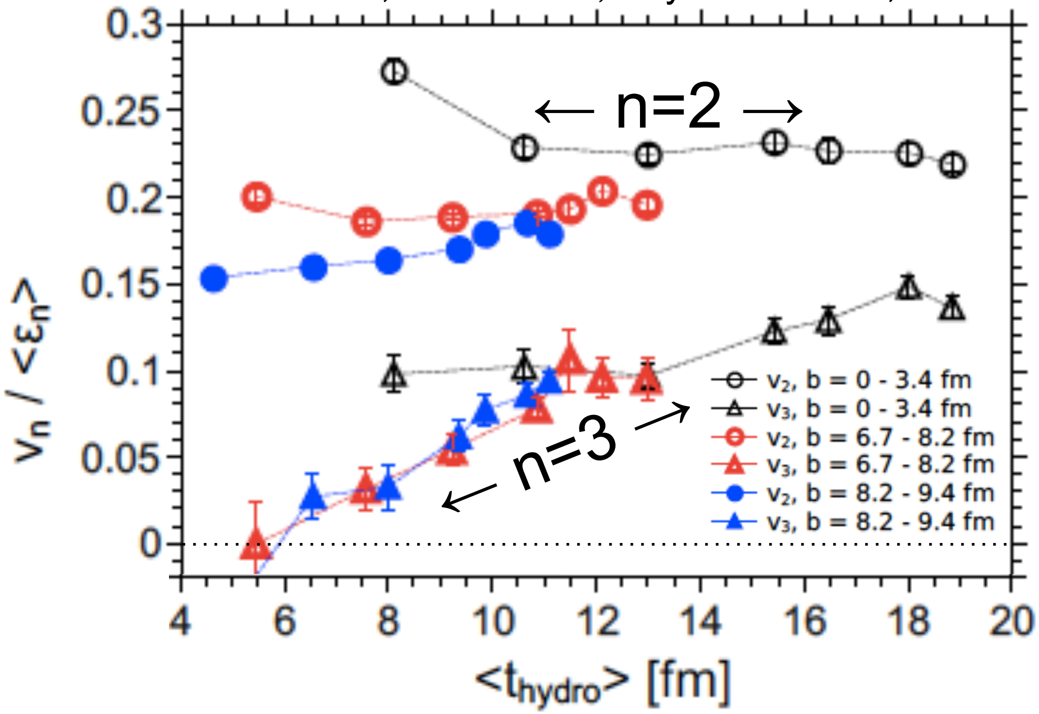


particles

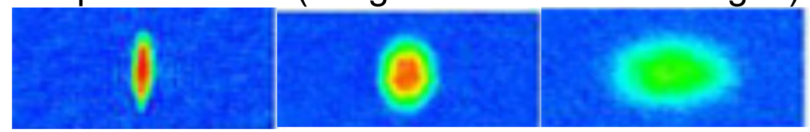
anti-particles

v_3 is more sensitive than v_2

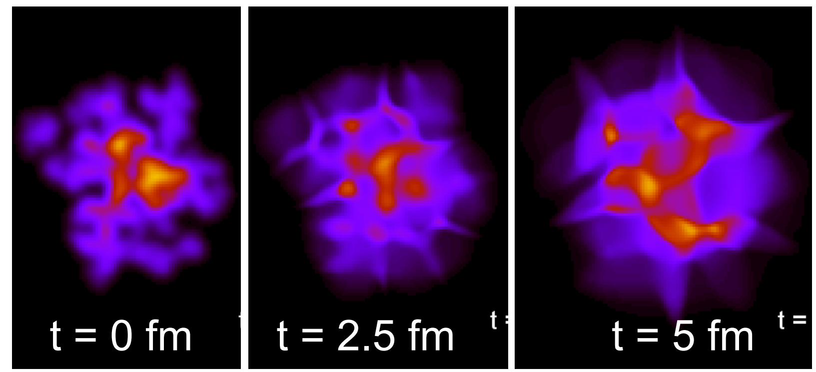
J. Auvinen, H. Petersen, Phys. Rev. C 88, 64908



Elliptic n=2 flow (image of an atomic fermi gas)



All harmonic flow (QGP simulation)

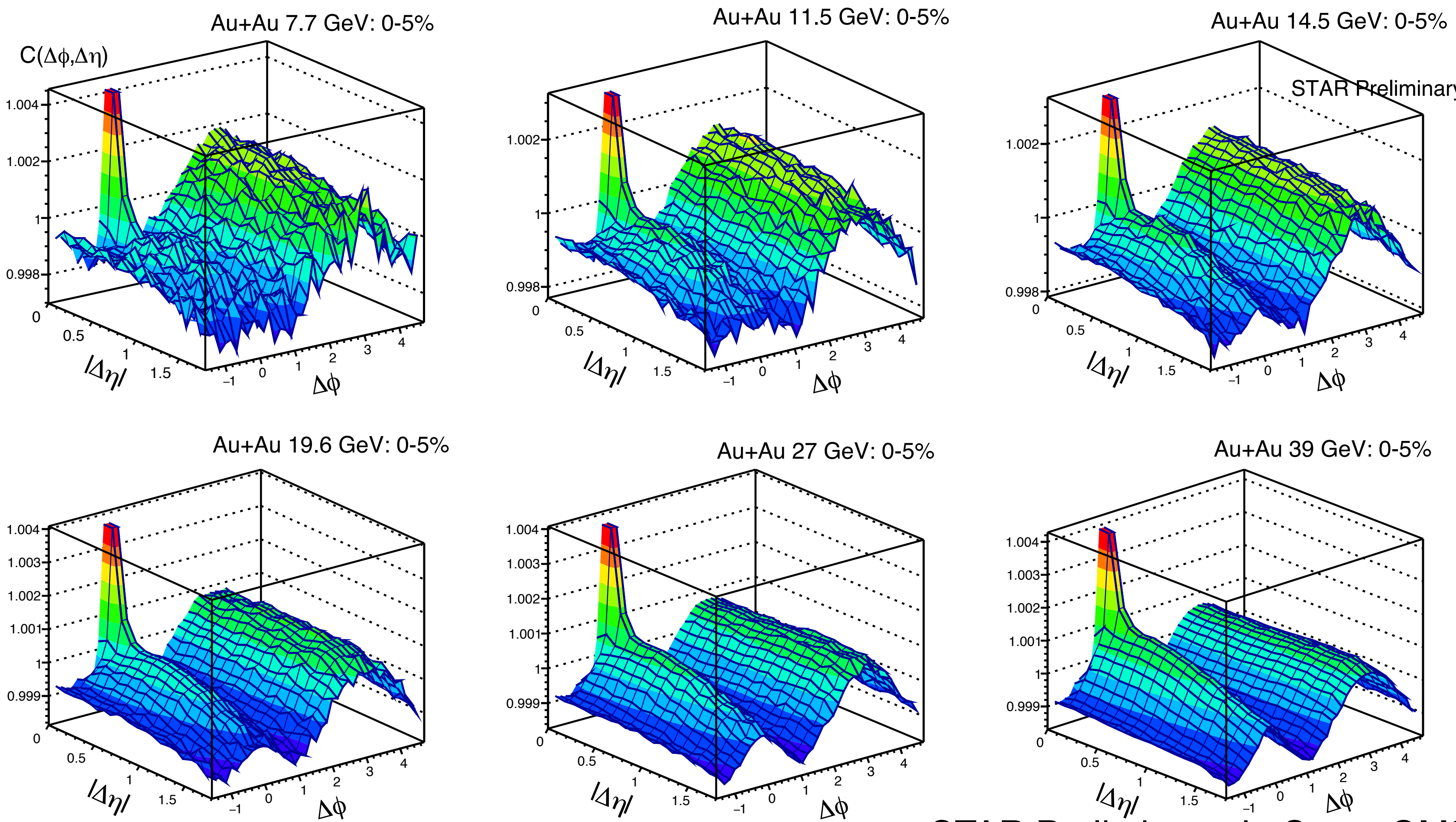


B. Schenke et.al., Phys. Rev. C 85, 024901

Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

In models, v_3 goes away when the QGP phase disappears

Correlation Functions



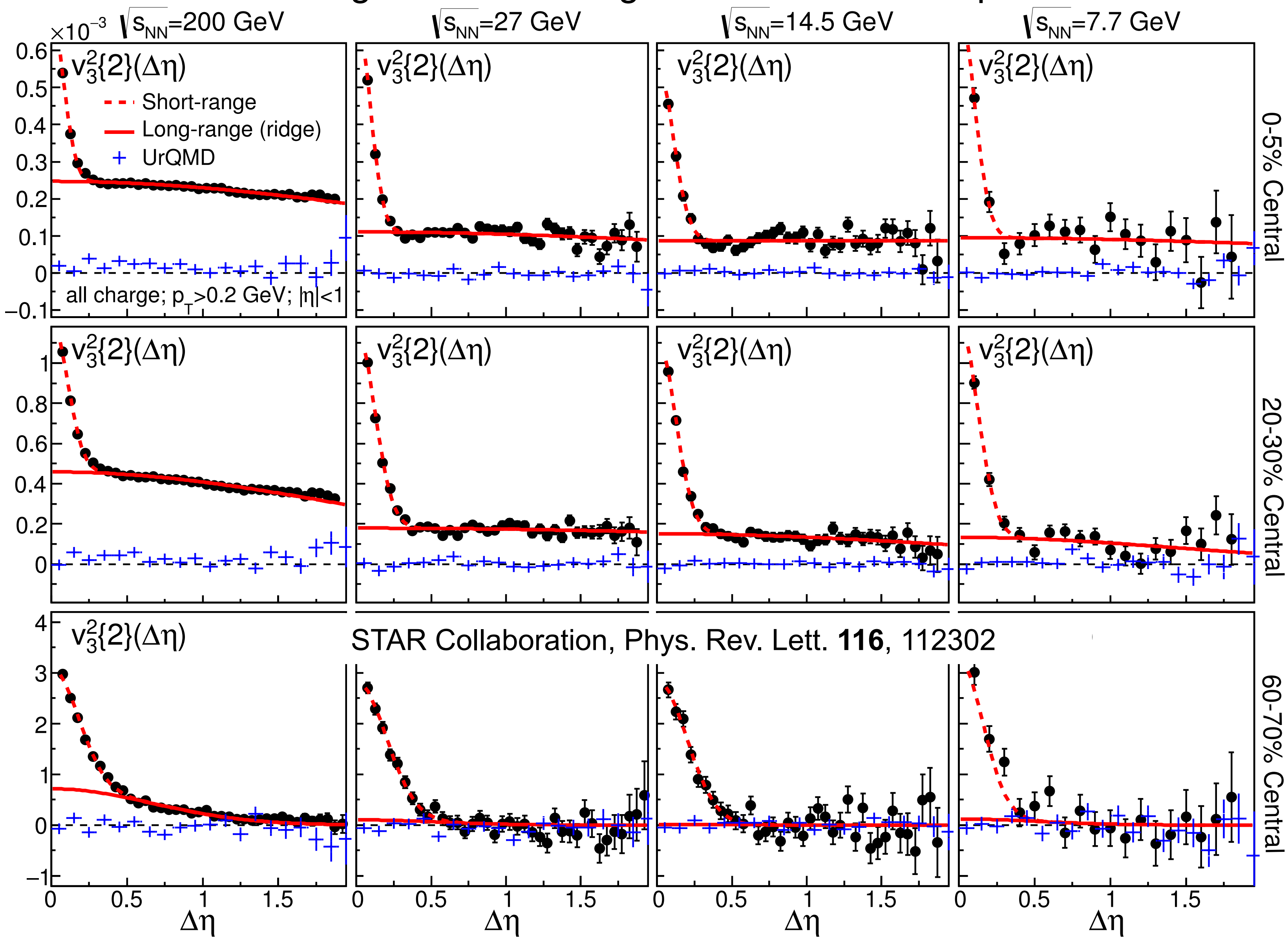
STAR Preliminary; L. Song, QM2015

Correlations can be decomposed into Δη dependent harmonics

$$v_n^2\{2\}(\Delta\eta) = \langle \cos n(\varphi_1 - \varphi_2) \rangle = \sum \frac{dN}{d\Delta\varphi} \cos(n\Delta\varphi) d\Delta\varphi \Big/ \sum \frac{dN}{d\Delta\varphi} d\Delta\varphi$$

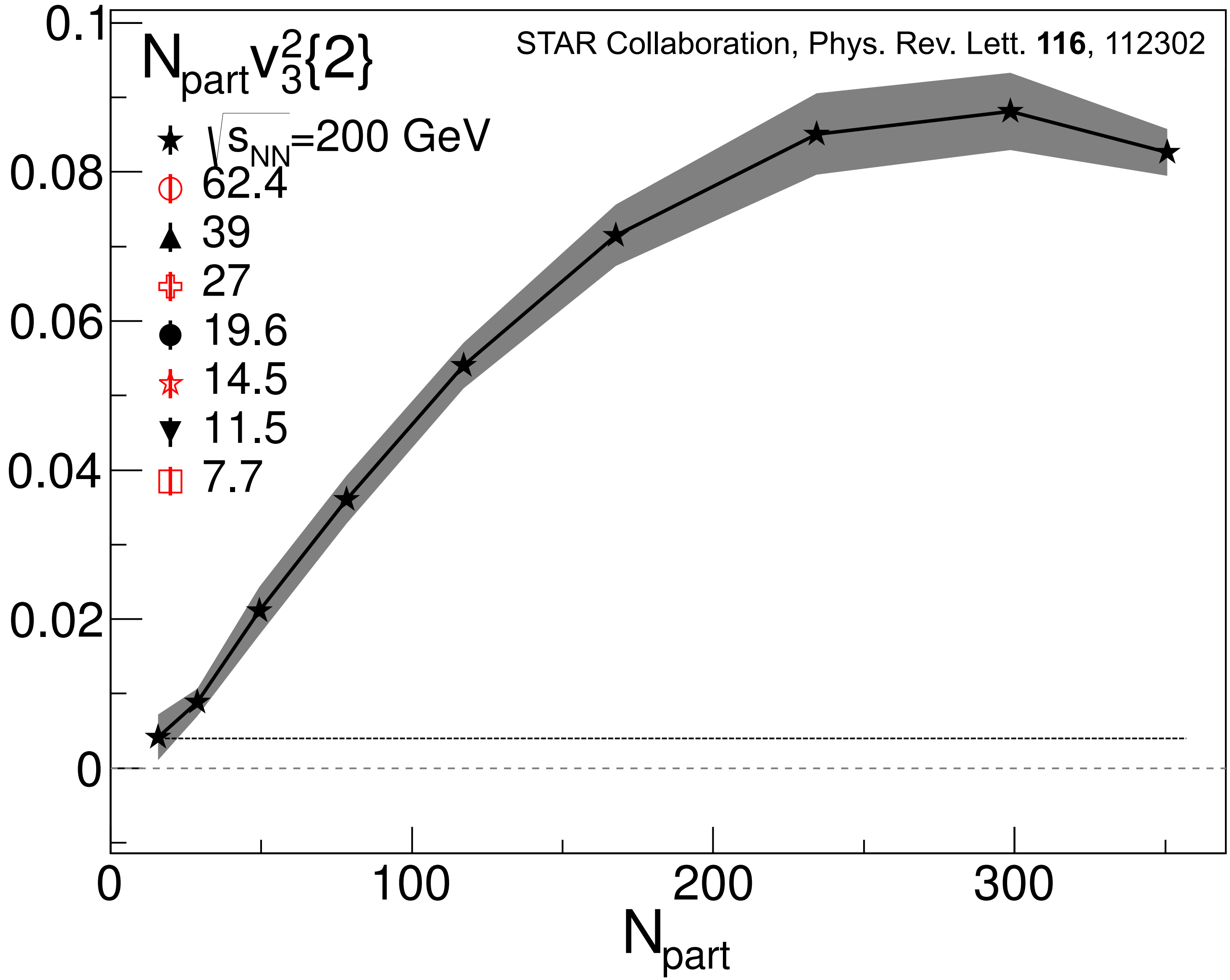
3rd Harmonic Decomposition

this probes how much long- and short-range fluctuations are expressed in the final state



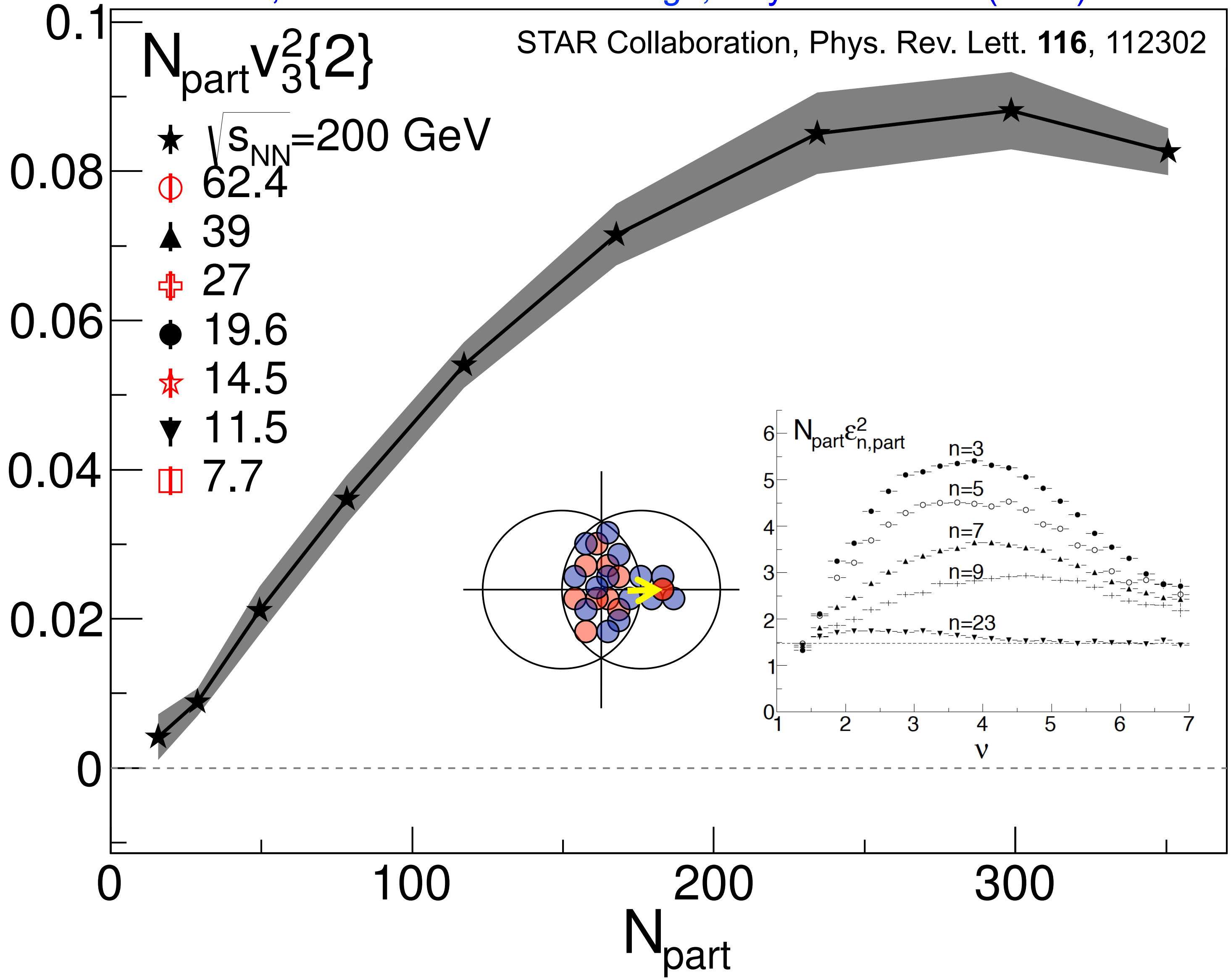
Centrality Dependence

N_{part} scales out trivial 1/N system size dependence: *linear superposition of N+N*



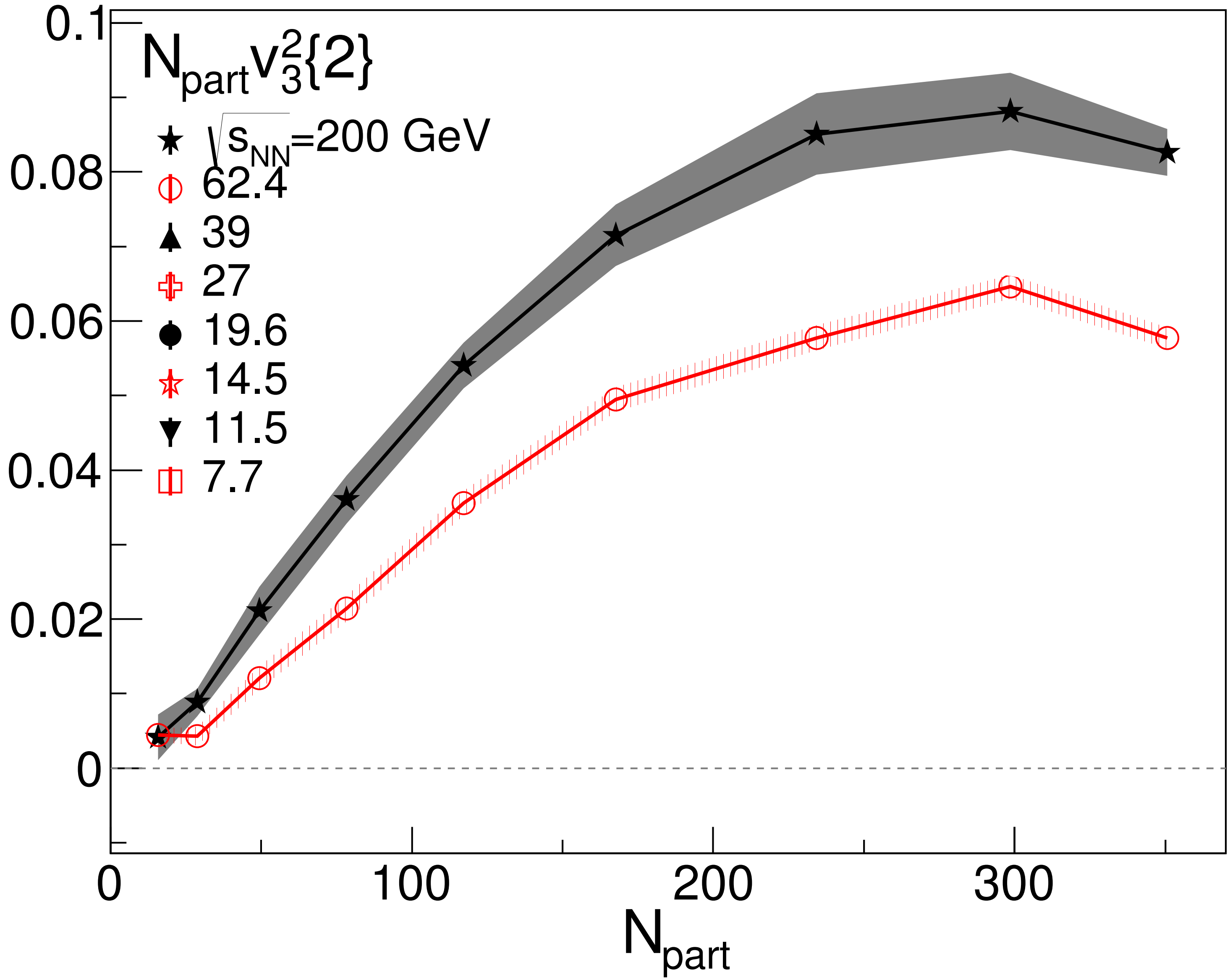
Centrality Dependence

Centrality dependence well understood in terms of initial geometry:
P.S. et.al., *Rise and Fall of the Ridge,* Phys.Lett. B705 (2011) 71-75



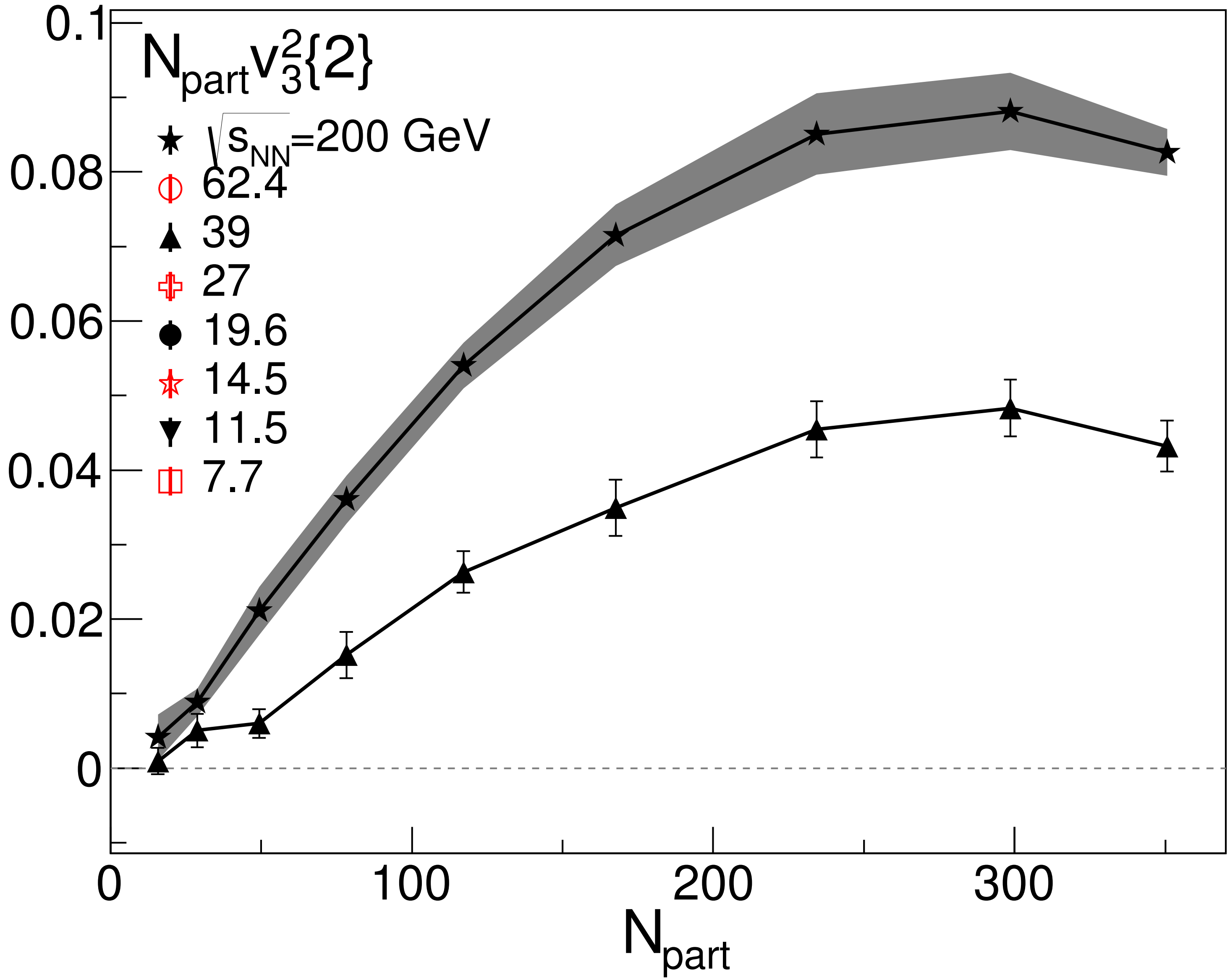
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



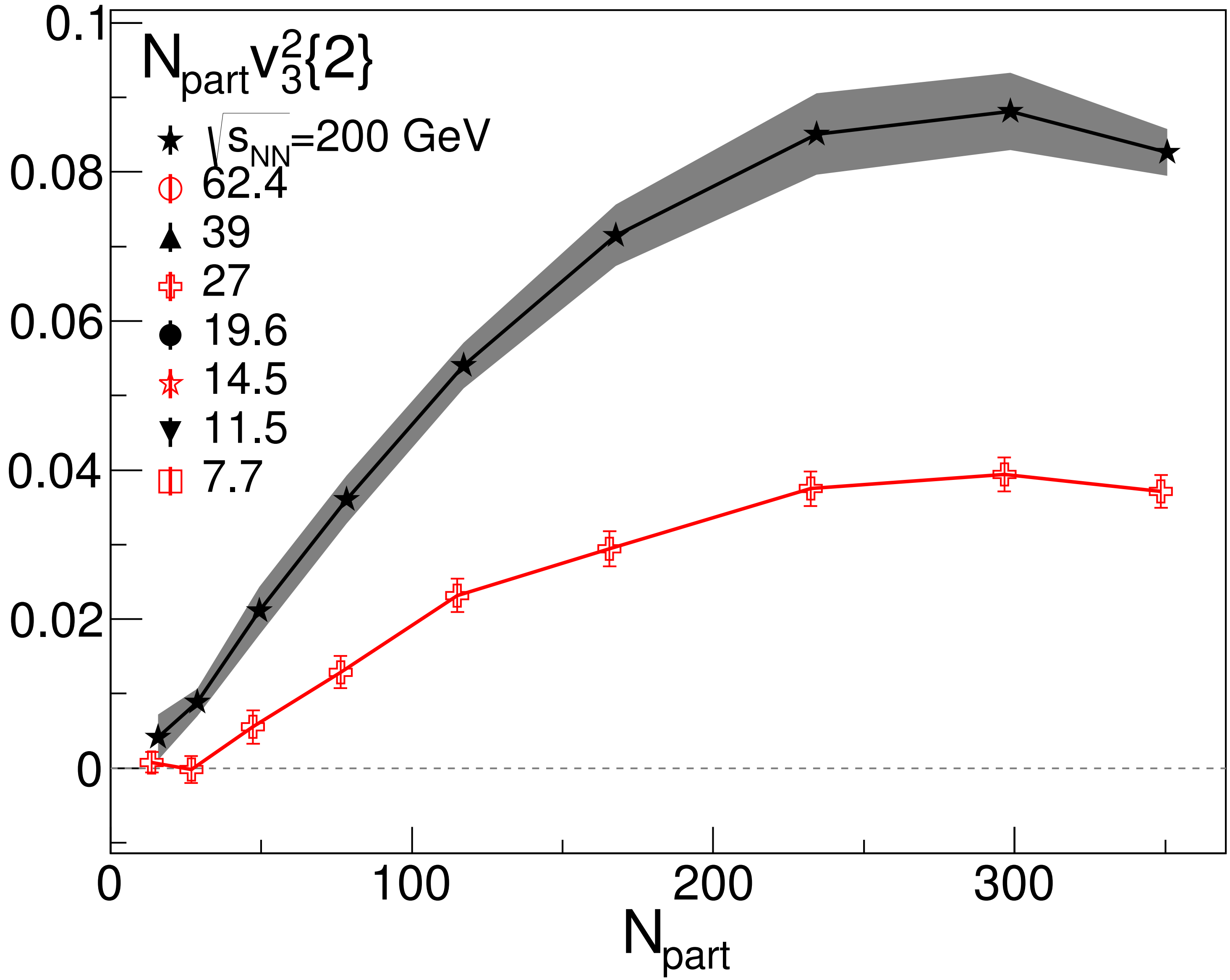
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



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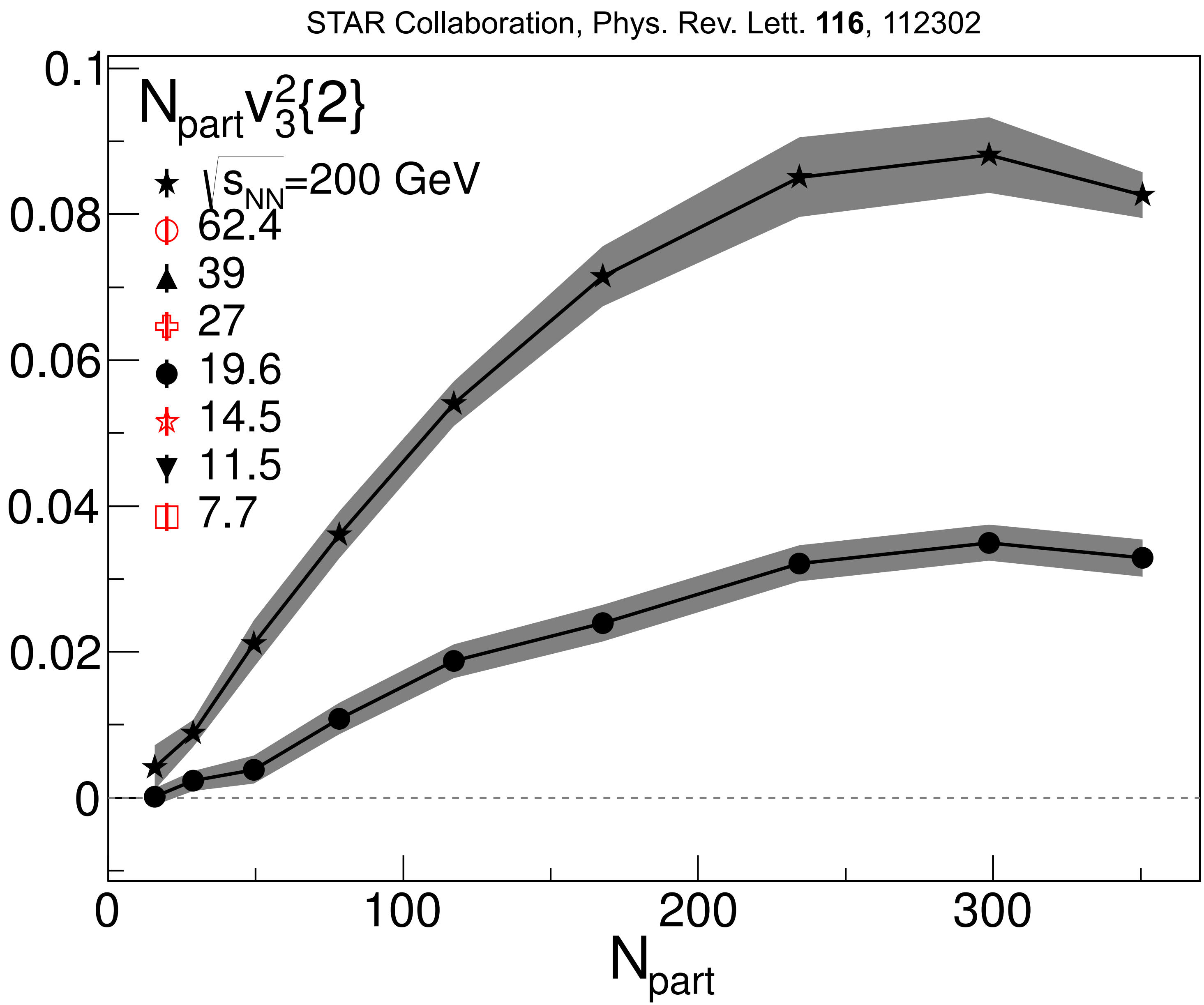
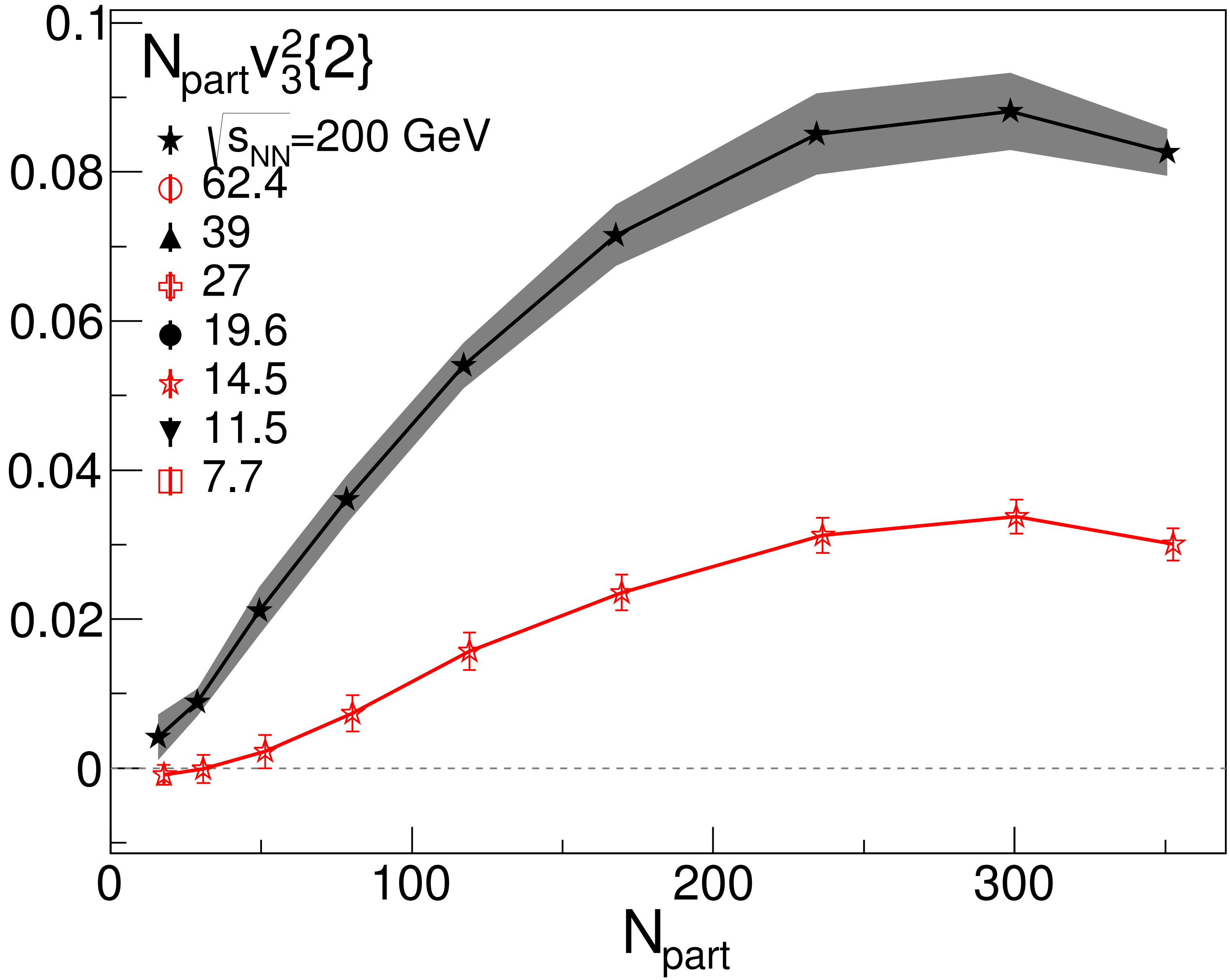


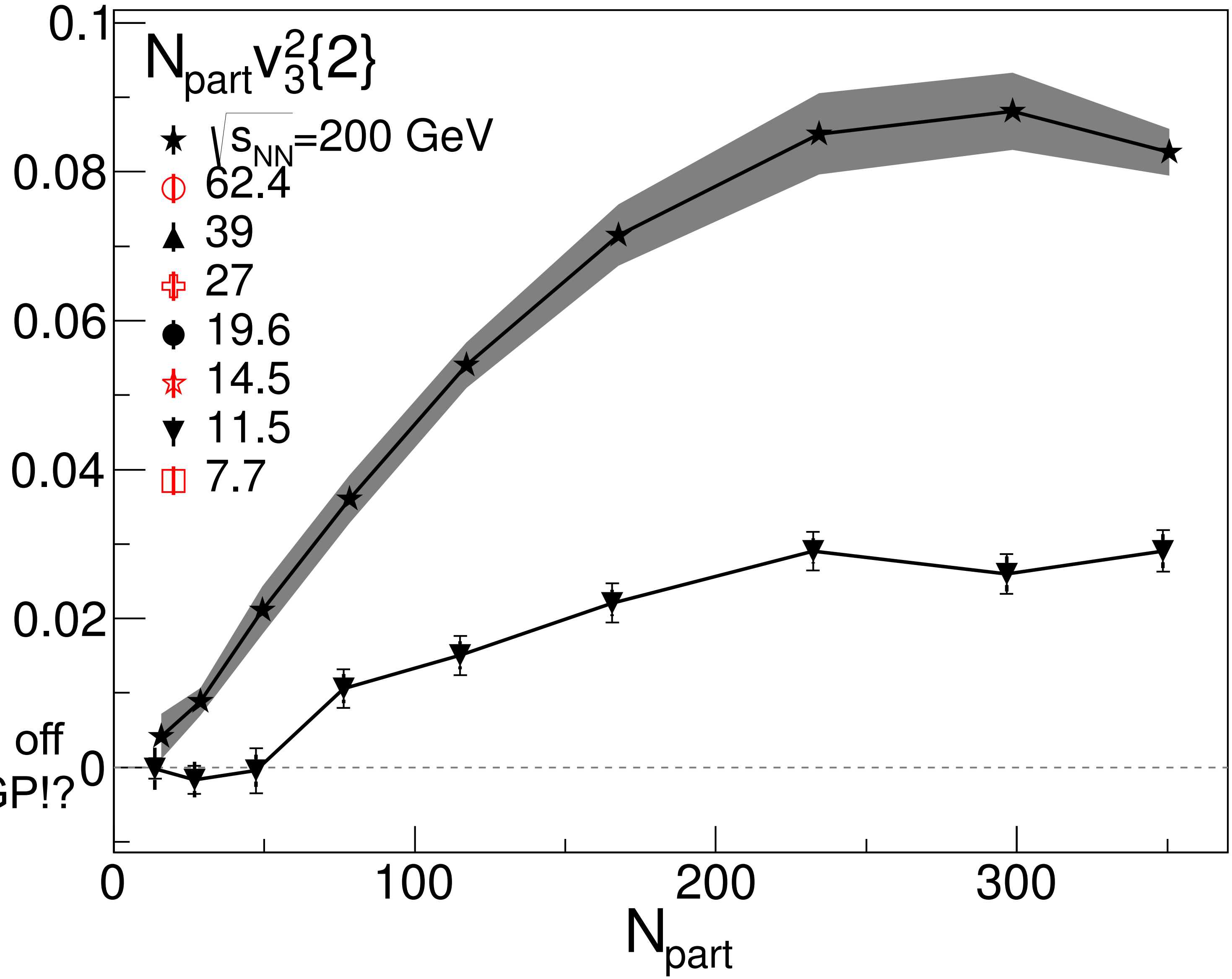
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



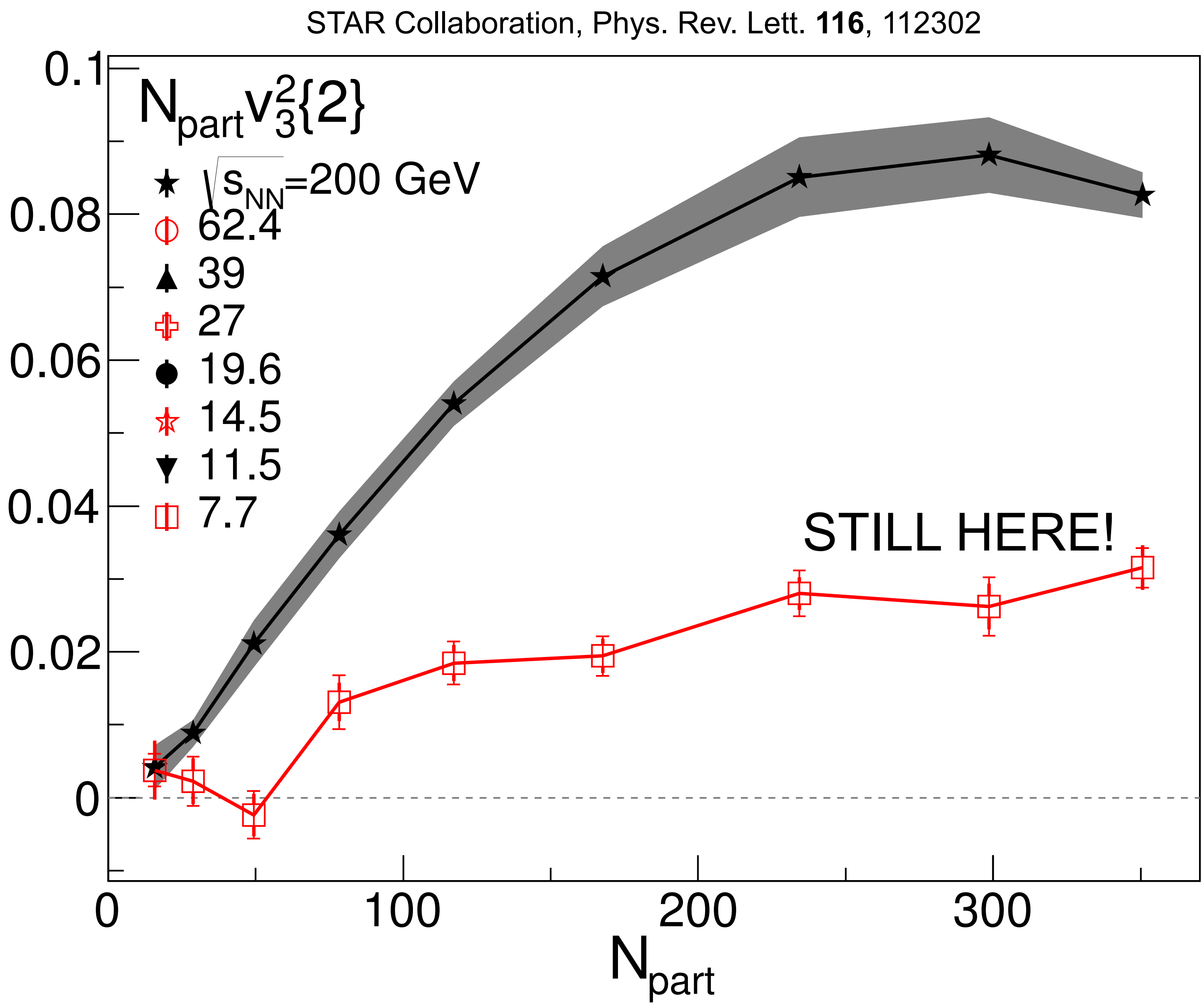
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



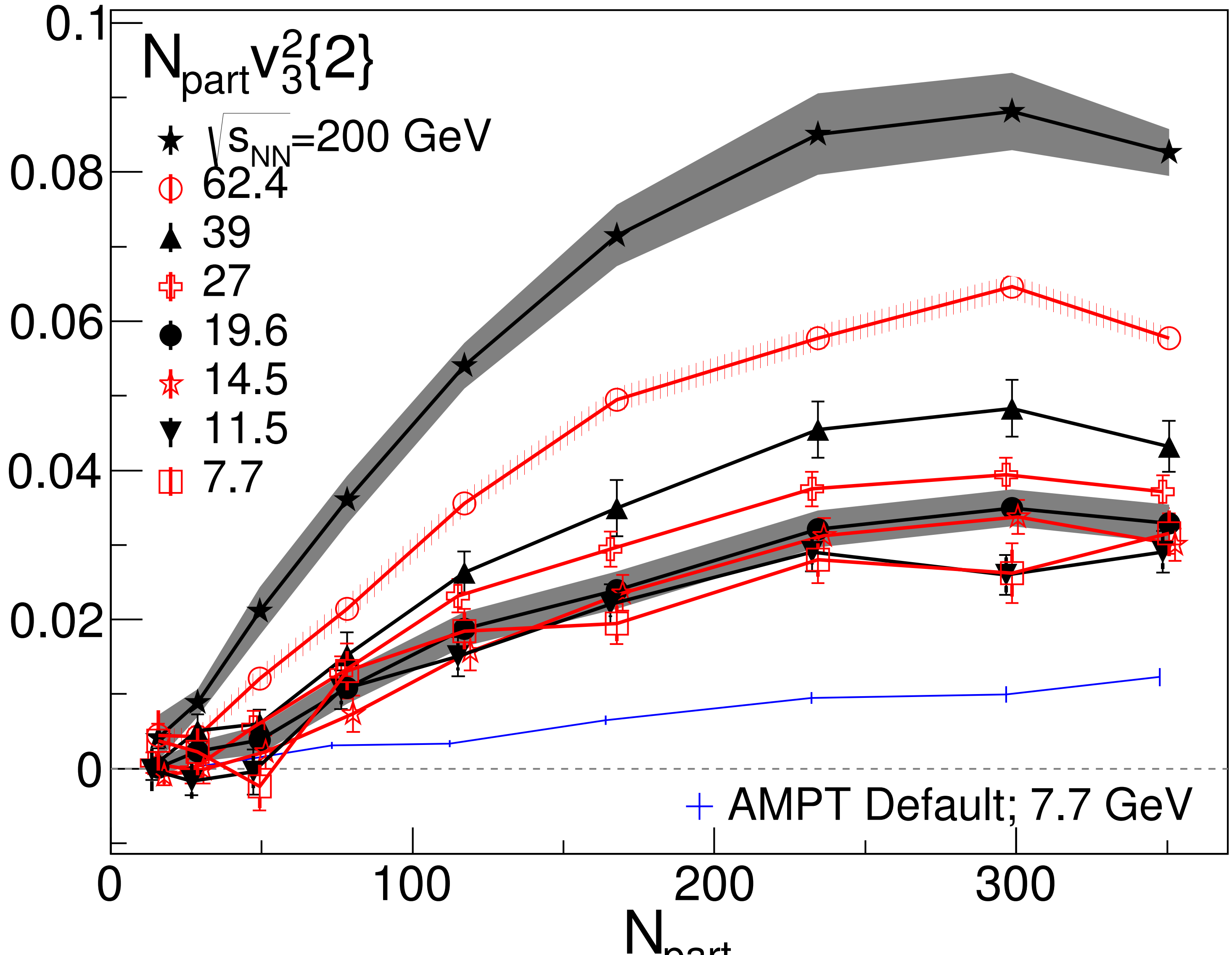
turning off the QGP!?

Centrality Dependence



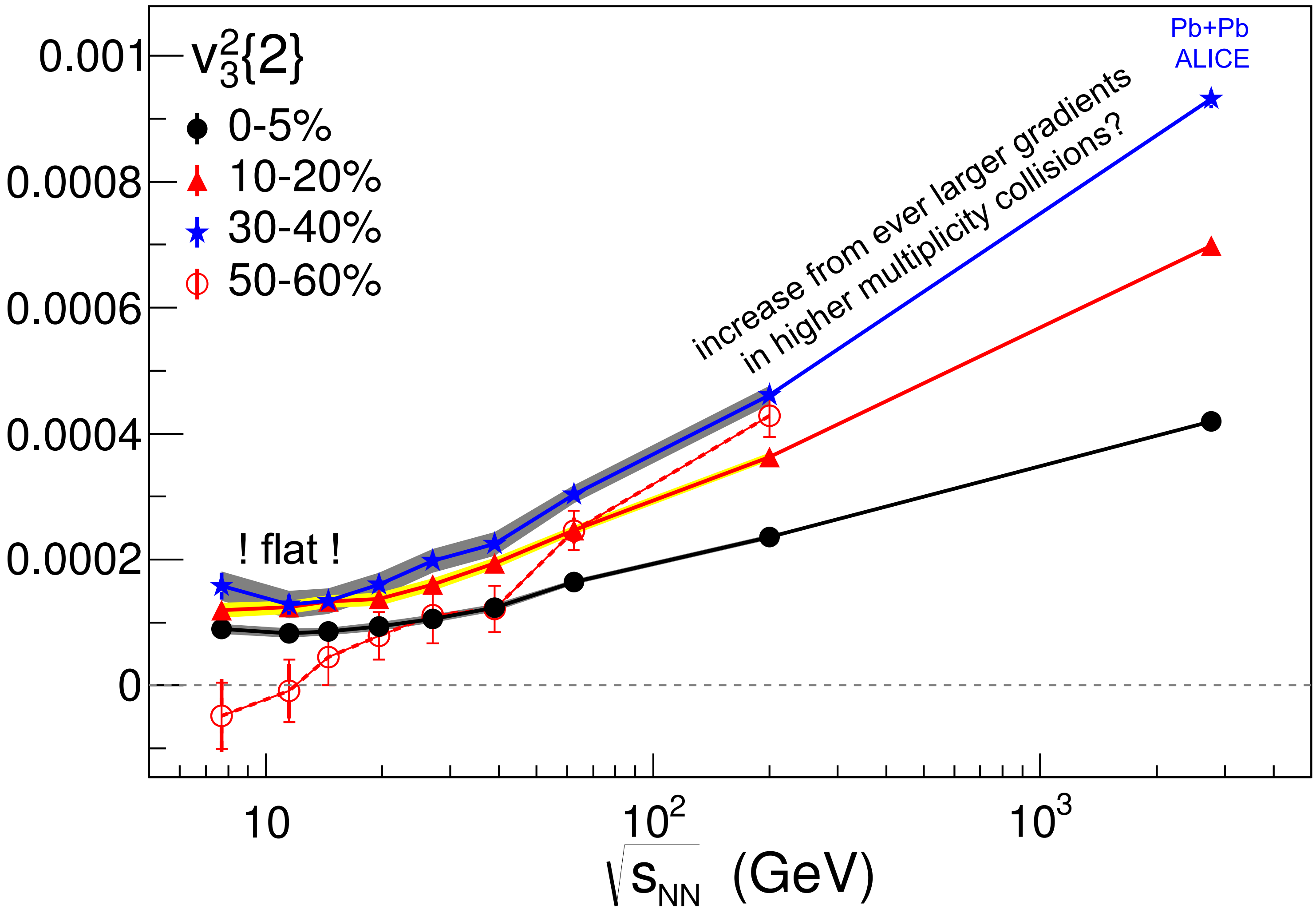
Centrality Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302



Energy Dependence

STAR Collaboration, Phys. Rev. Lett. **116**, 112302

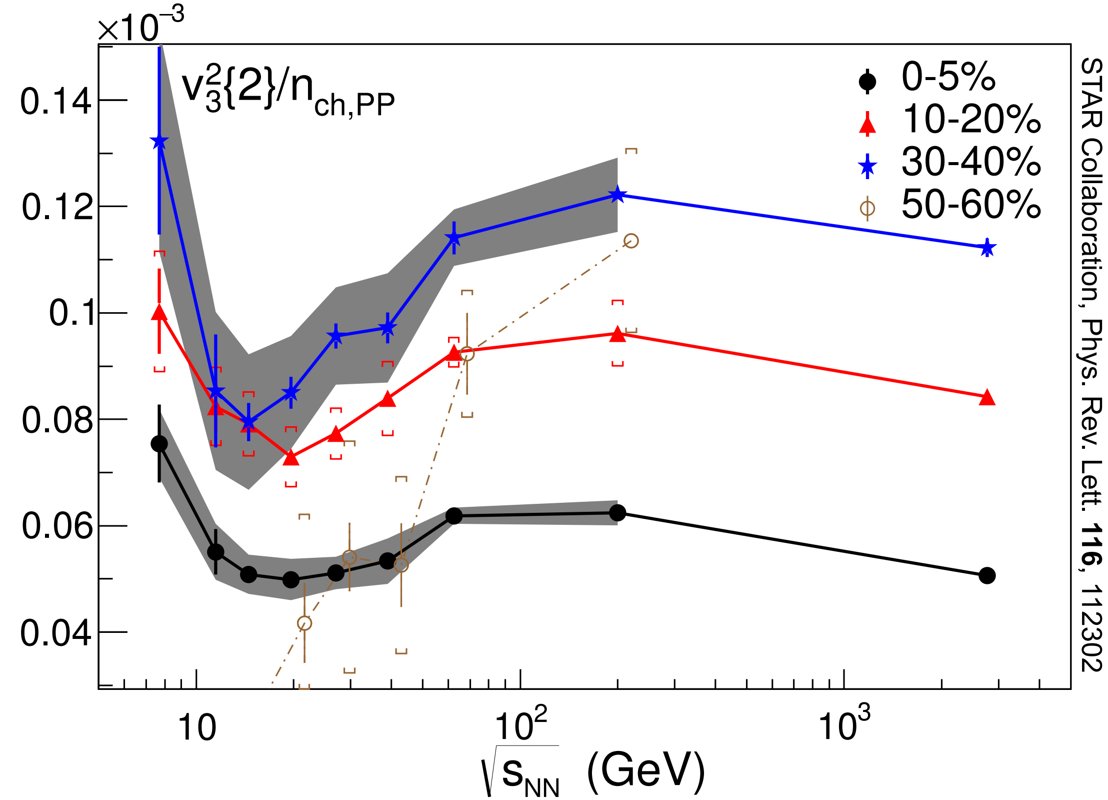


While the 3rd harmonic grows as ~log(√s) at higher energy, it is nearly independent of energy below 20 GeV.

Anomalies in the Pressure?

Higher energy collisions producing more particles and higher pressure should more effectively convert fluctuations into v_3.

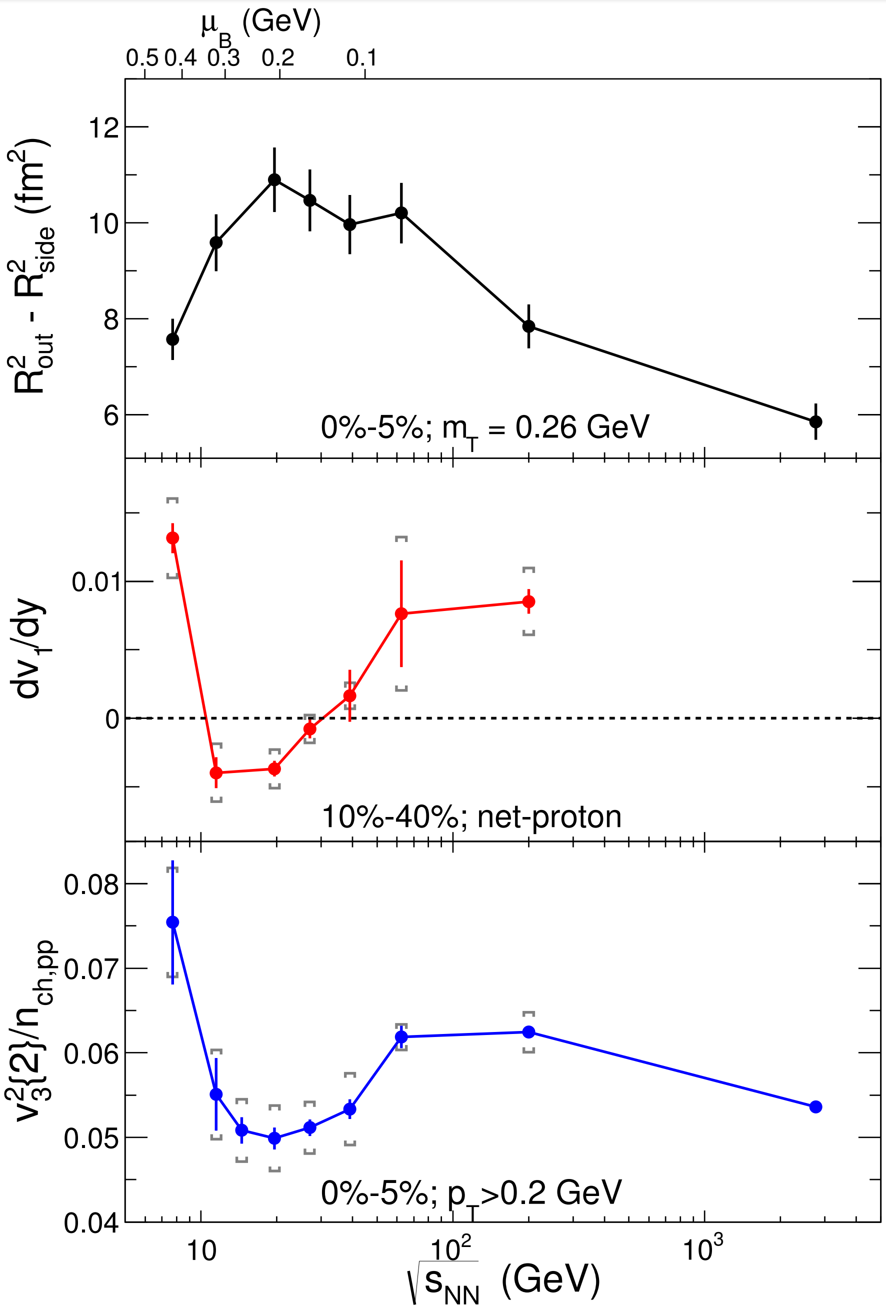
Deviations from that expectation could be indicative of interesting physics.



If QGP exists at 7.7 GeV, what causes the dip at 15 GeV?

Increased bulk viscosity? Monnai, Mukherjee, and Yin (arXiv:1606.00771)
Increased thermal fluctuations? Kapusta and Torres-Rincon Phys. Rev. C **86**, 054911

Are Data Indicative of Anomalies in the Pressure?



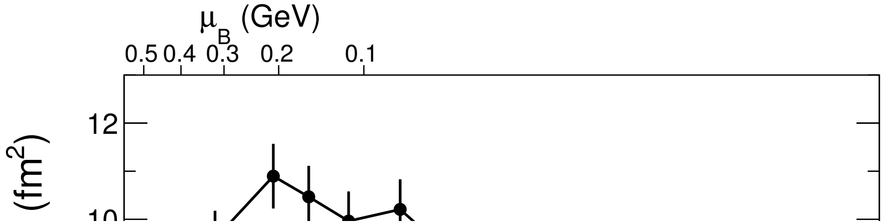
Maximum in lifetime?

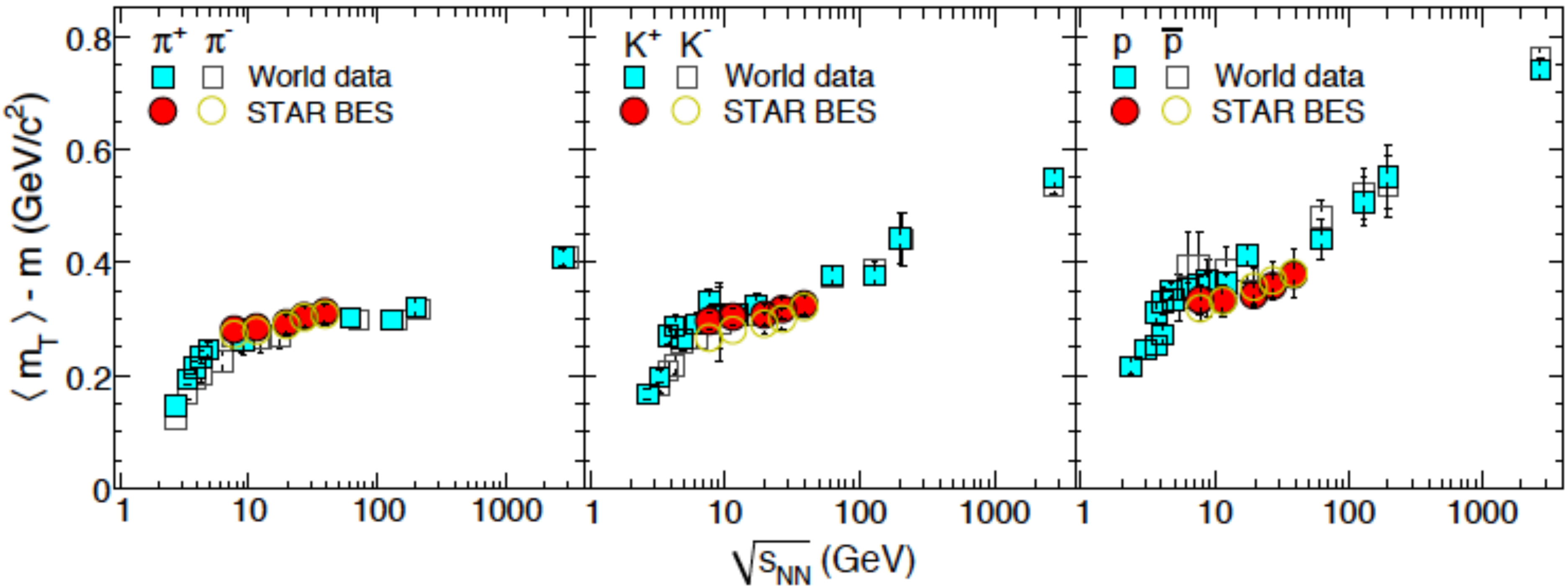
Minimum in pressure?

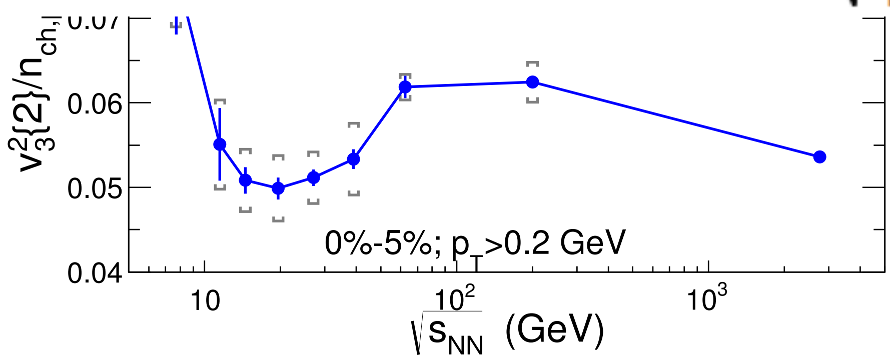
Region of interest $\sqrt{s_{NN}}$~20 GeV, however, is complicated by a changing B/M ratio, baryon transport dynamics, longer nuclear crossing times, etc.

Requires concerted modeling effort: the work of the BEST collaboration is essential

Are Data Indicative of Anomalies in the Pressure?





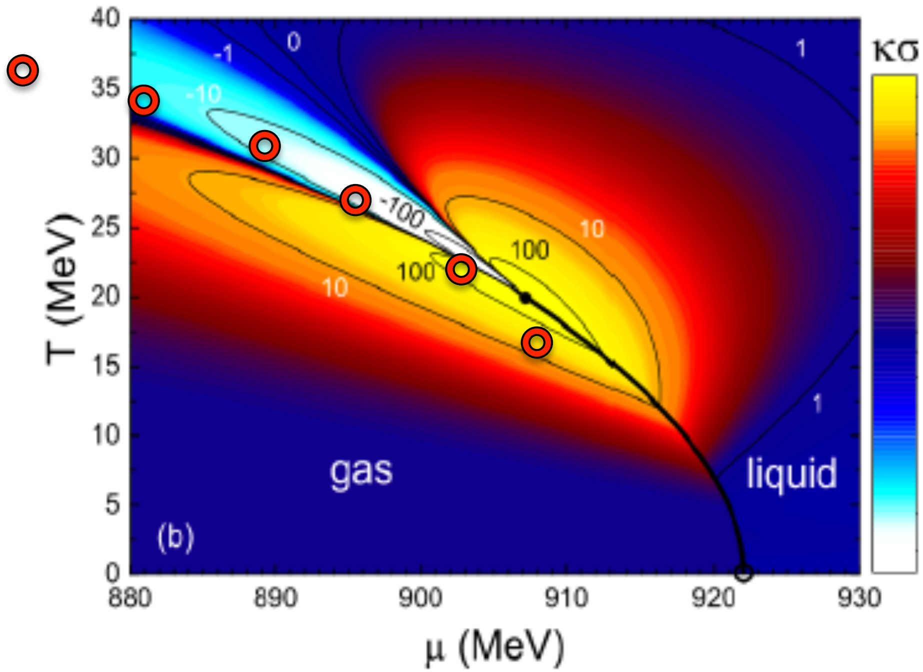


transport dynamics, longer nuclear crossing times, etc.

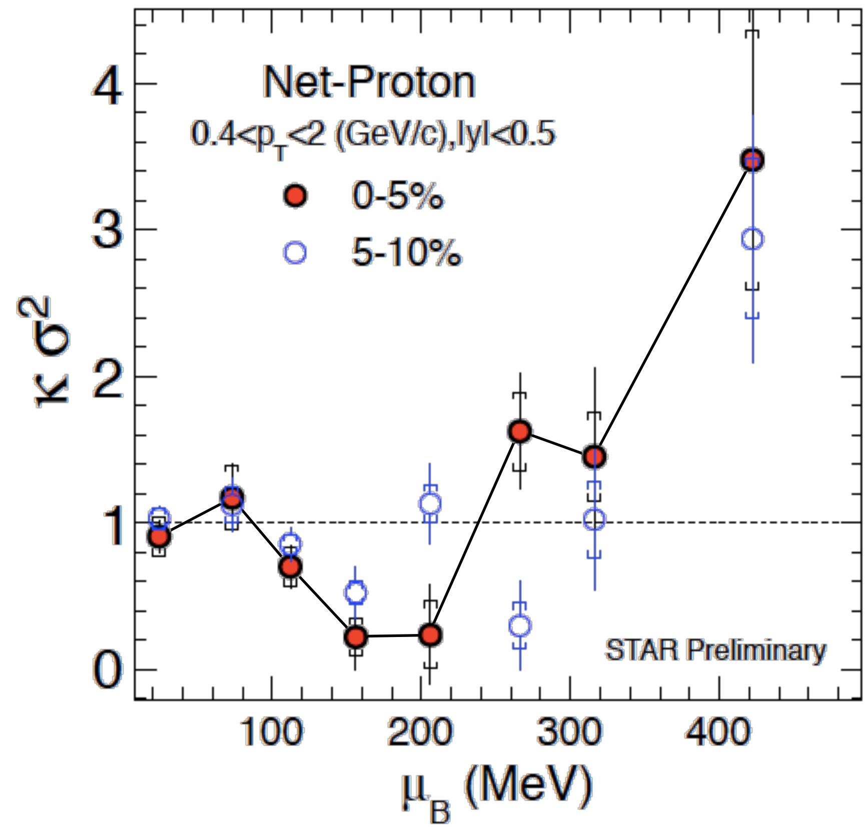
Requires concerted modeling effort: the work of the BEST collaboration is essential

BES-I: Critical Behavior?

The moments of the distributions of conserved charges are related to susceptibilities and are sensitive to critical fluctuations



Higher moments like kurtosis*variance $\kappa\sigma^2$ change sign near the critical point

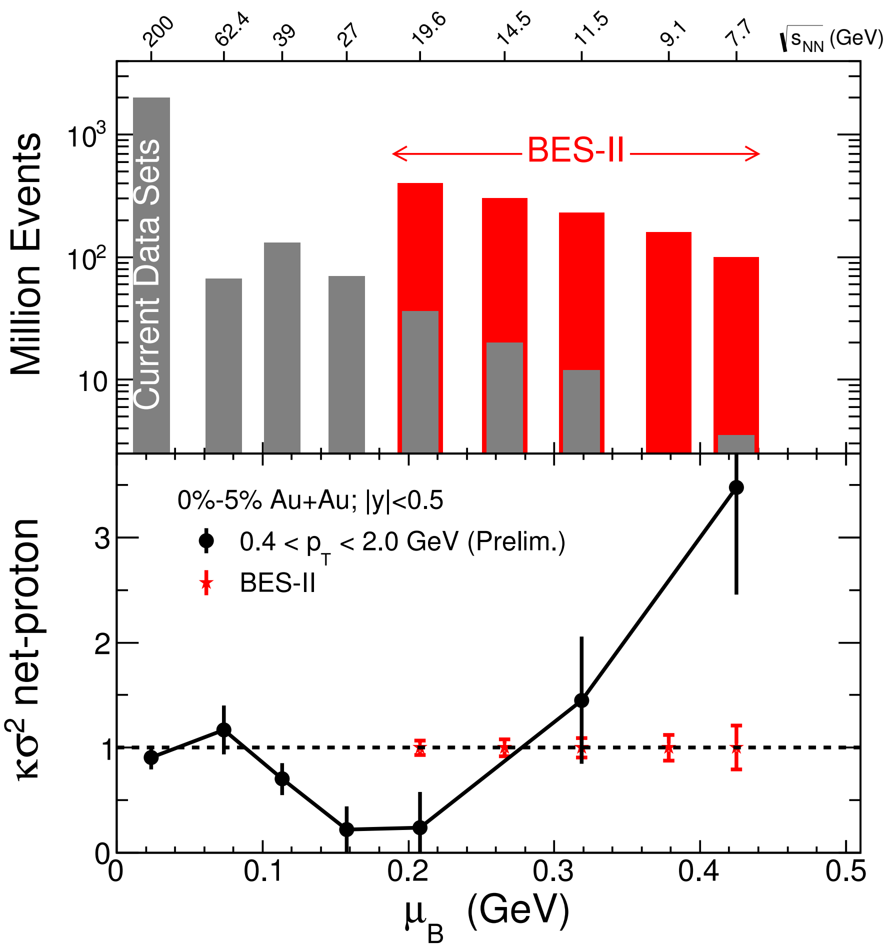


Non-monotonic trend observed in derivatives of the pressure, but statistical precision is limited

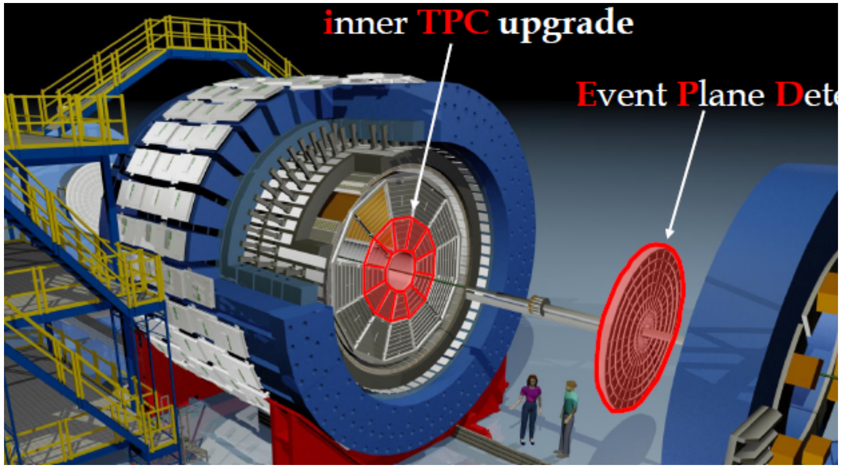
Mapping the region of interest: BES-II

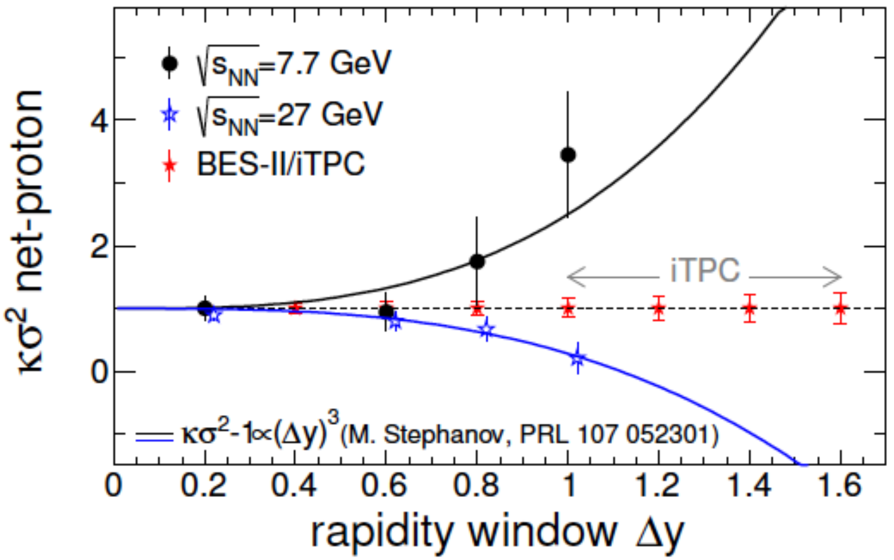
More Data

RHIC Luminosity Upgrade for Low Energies



Better Coverage





BES-II: detector and accelerator upgrades for 2019 and 2020

What about the chiral anomaly?

For more central collisions, v_3 persists down to 7.7 GeV suggesting QGP may be present.

For peripheral collisions however, v_3 disappears in lower energy collisions: Turn off of the QGP

many measurements suggest an anomalously low pressure in heavy ion collisions with $\sqrt{s_{NN}}$ near 15-20 GeV

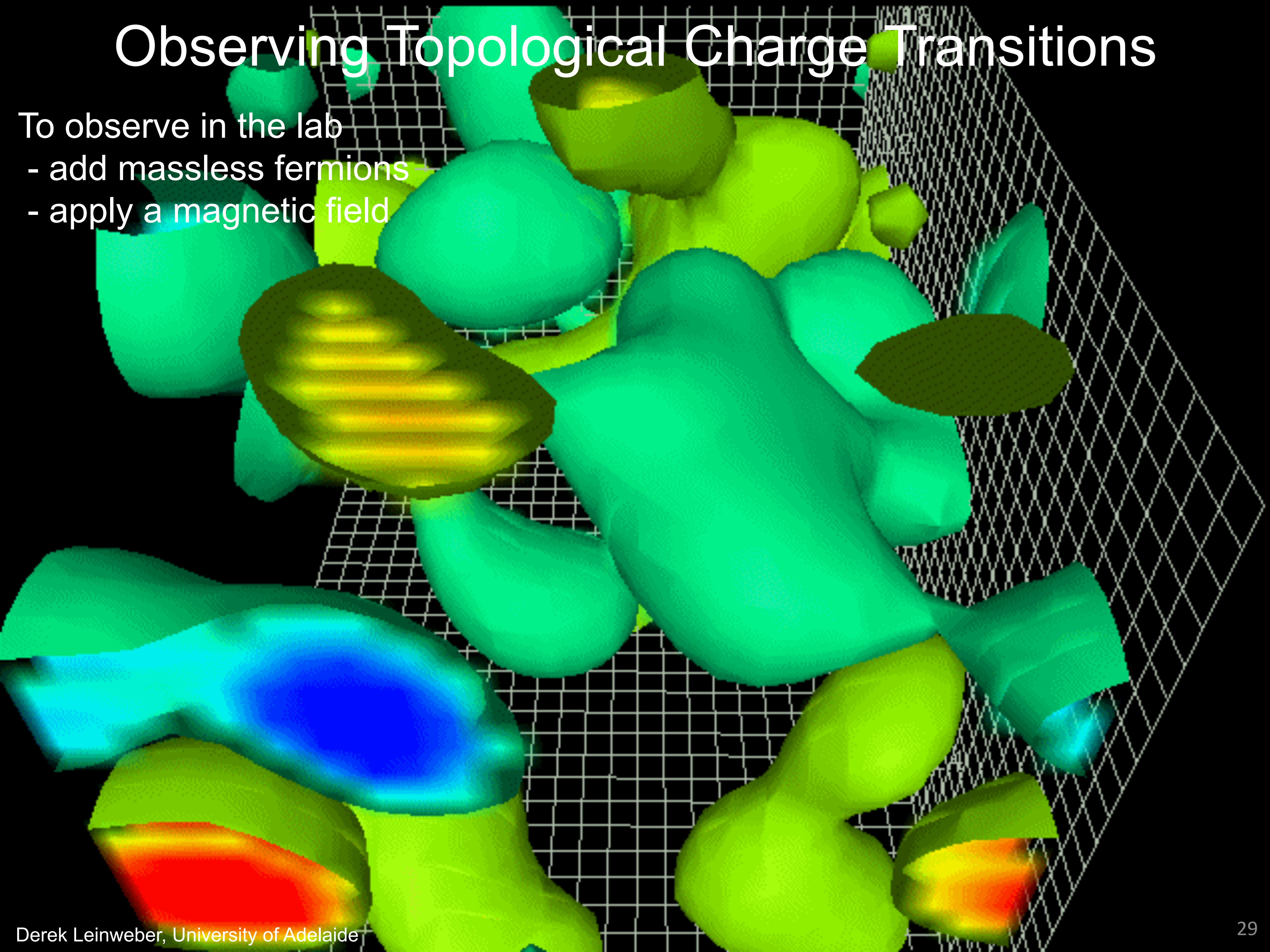
Is chiral symmetry restored in these collisions?

Have we observed evidence of the chiral anomaly of QCD?

What can we do to make progress on this problem?

Observing Topological Charge Transitions

To observe in the lab
- add massless fermions
- apply a magnetic field



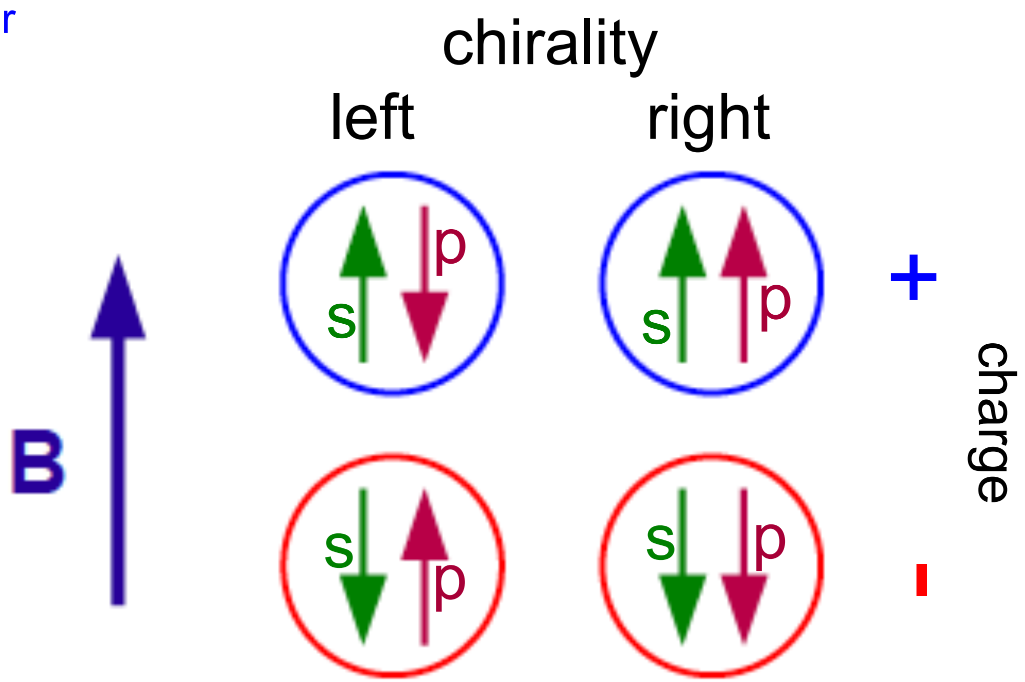
The Chiral Magnetic Effect

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

spin alignment in B-field:
opposite direction for opposite charges

handedness:
momentum and spin, aligned or anti-aligned



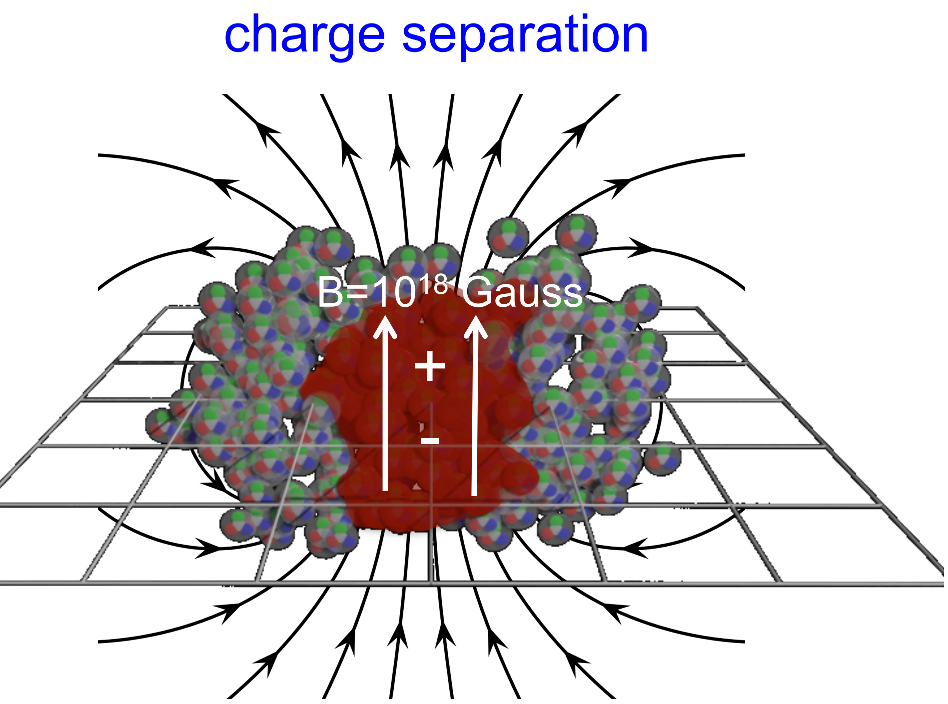
negative goes up
positive goes down

positive goes up
minus goes down

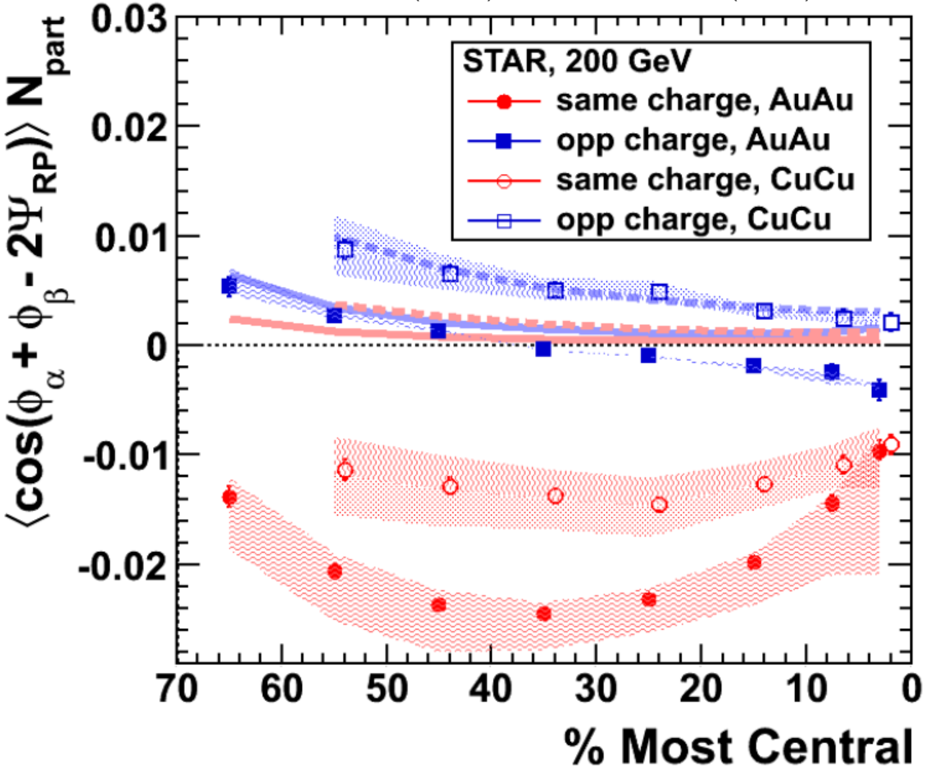
An excess of right or left handed quarks should lead to a current flow along the magnetic field

Measuring Topological Charge Transitions

Charge separation observed. But behavior is more complicated than initial cartoon: γ_{OS} is small and even sometimes the wrong sign



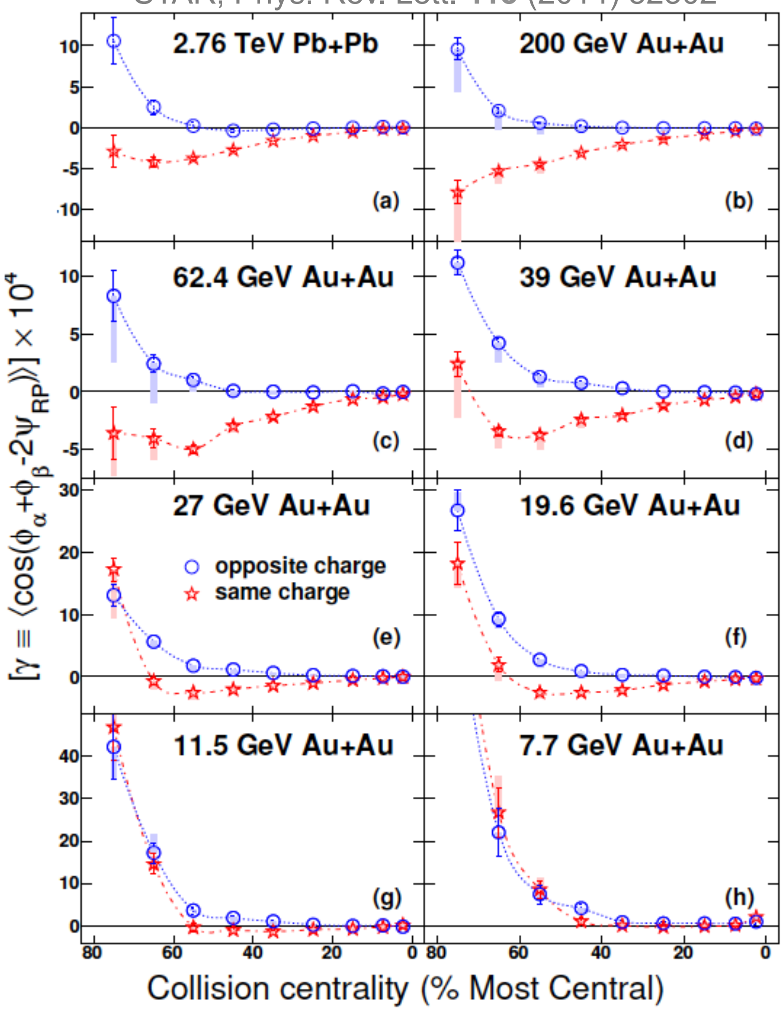
STAR; PRL **103** (2009) 251601; PRC **81** (2010) 54908



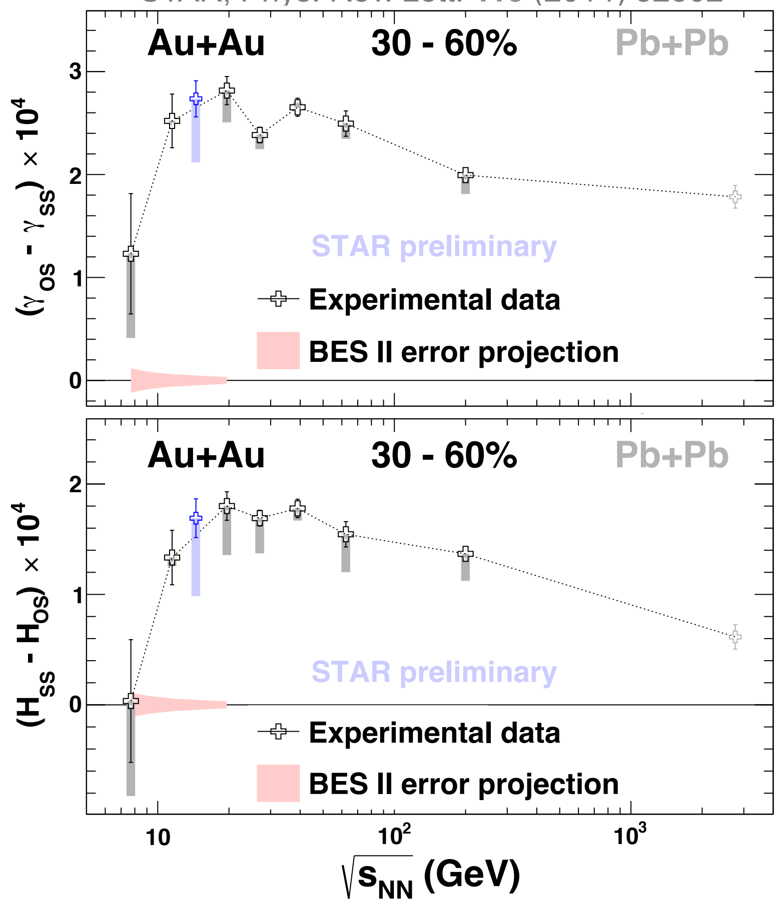
It was speculated that quenching and expansion dynamics suppress charge flow across the plane: requires more sophisticated modeling

Beam Energy Dependence

STAR, Phys. Rev. Lett. **113** (2014) 52302



STAR, Phys. Rev. Lett. **113** (2014) 52302



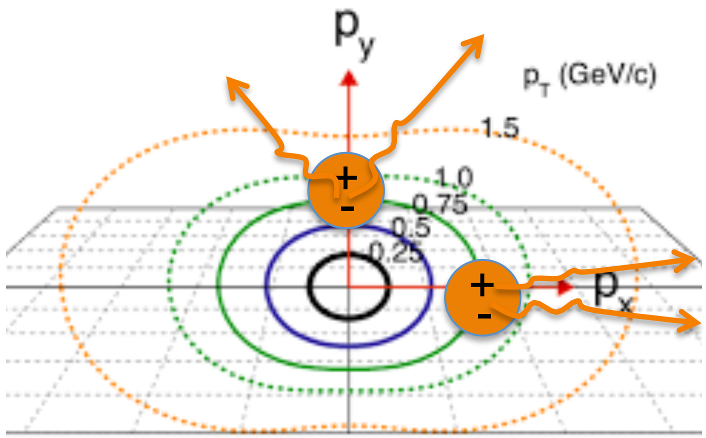
assuming factorization, background subtracted $H = \frac{\kappa v_2 \delta - \gamma}{1 + \kappa v_2}$

Bzdak, Koch and Liao, Lect. Notes Phys. 871, 503

Significant charge separation observed at all but the lowest energy: Consistent with evidence for QGP

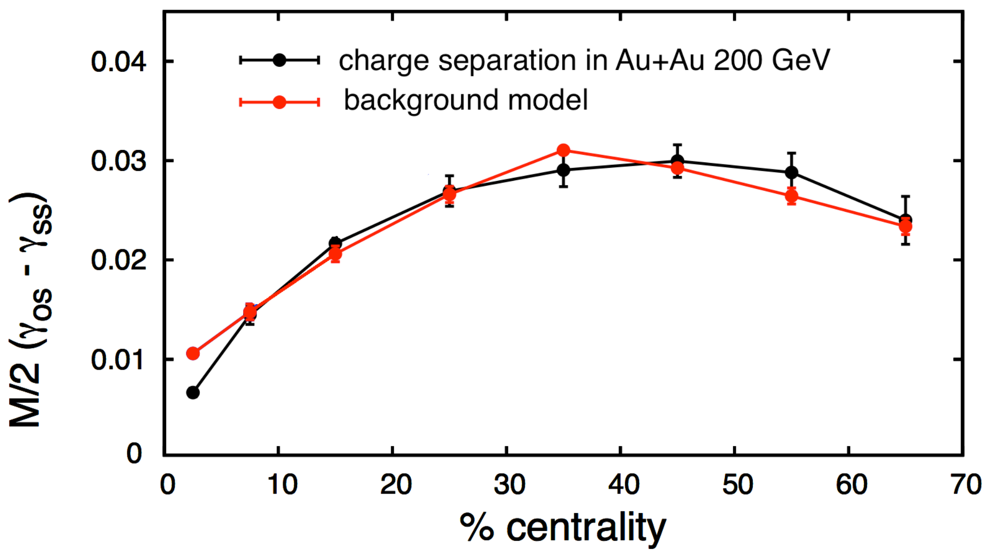
Questions of Interpretation Remain

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation



Flow boost collimates pairs more strongly in-plane than out of plane

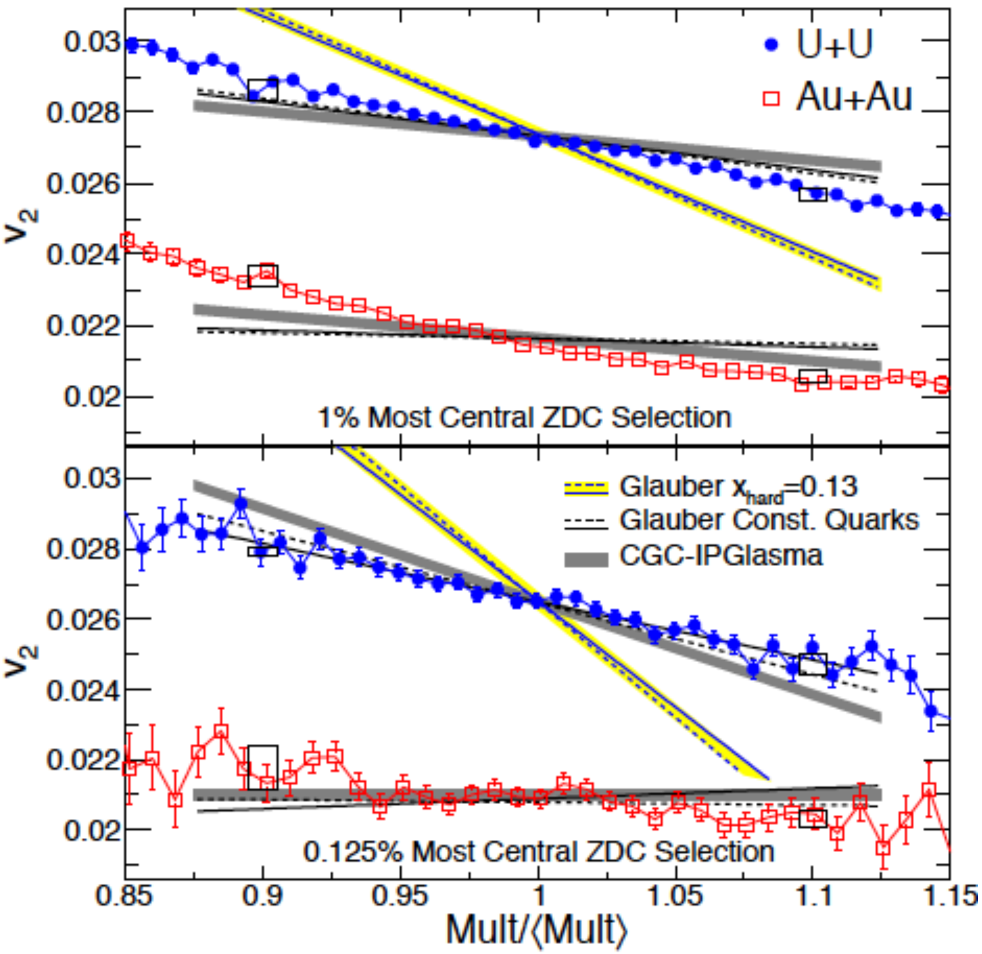
S. Schlichting and S. Pratt, Phys. Rev. C **83**, 014913 (2011)



Difficult to draw definitive conclusions without better models, and an independent lever arm for magnetic field and v_2: can U+U help?

Uranium collisions

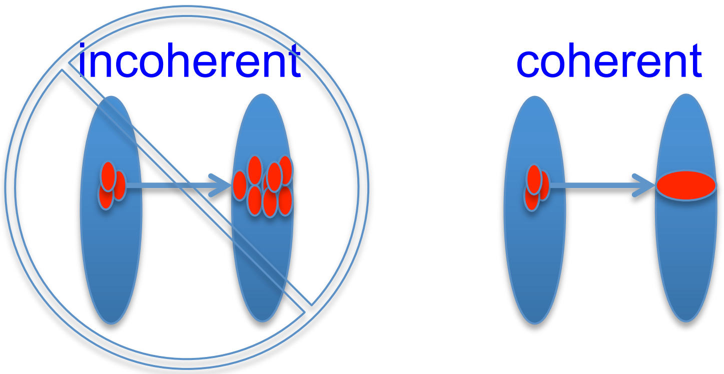
STAR Collaboration, Phys. Rev. Lett. **115** (2015) 222301



U. Heinz, A. Kuhlman, Phys.Rev.Lett. 94 (2005) 132301

Redefining our understanding of particle production: data requires more coherence (e.g. saturation or quark-participant models)

Coherence: the colliding constituents don't see all the other individual constituents



Separation of tip-tip from body-body requires more statistics than thought

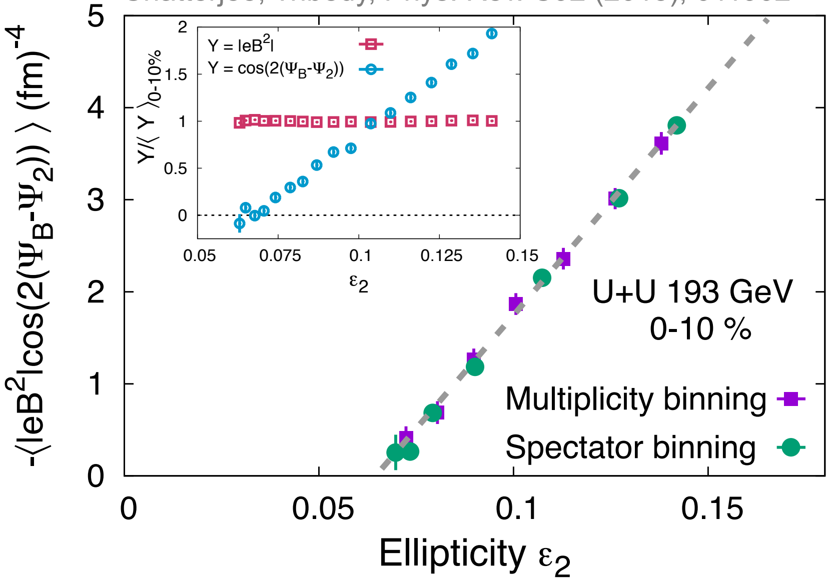
U+U still provides a valuable input on CME (large v_2 at b=0, unique geometry)

Charge separation in ultra-central U+U

Charge separation in central collisions follows projected B-Field, not v_2

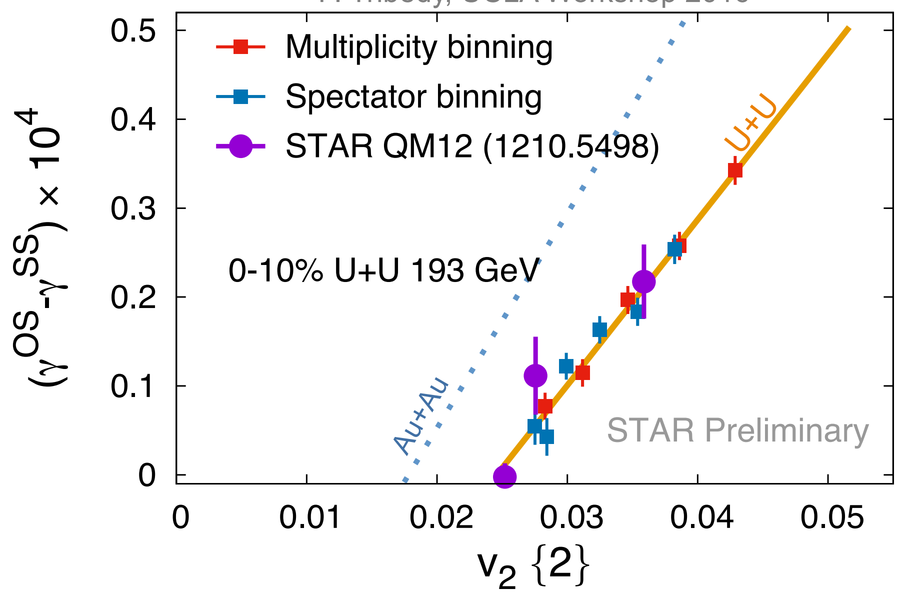
Calculated projected B-field

Chatterjee, Tribedy, Phys. Rev. C92 (2015), 011902



Measured charge separation

P. Tribedy, UCLA Workshop 2016

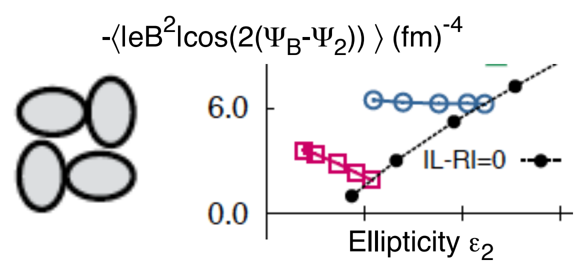


In central collisions, fluctuations keep $\langle B^2 \rangle$ large but drive $\langle \cos(2\psi_B - 2\psi_2) \rangle$ to zero

U+U data suggests charge separation is driven by the B-Field, not background

Studies of ZDC asymmetry, event-shape engineering in U+U are forthcoming

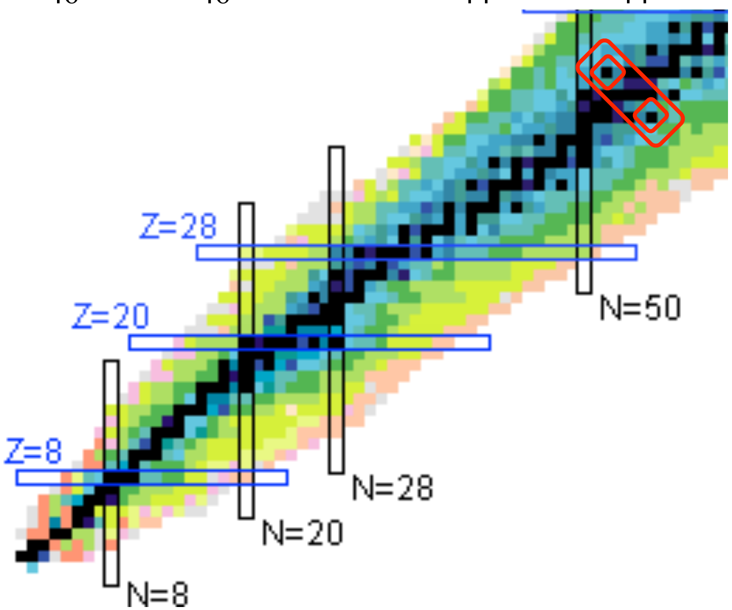
Chatterjee, Tribedy, Phys. Rev. C92 (2015), 011902

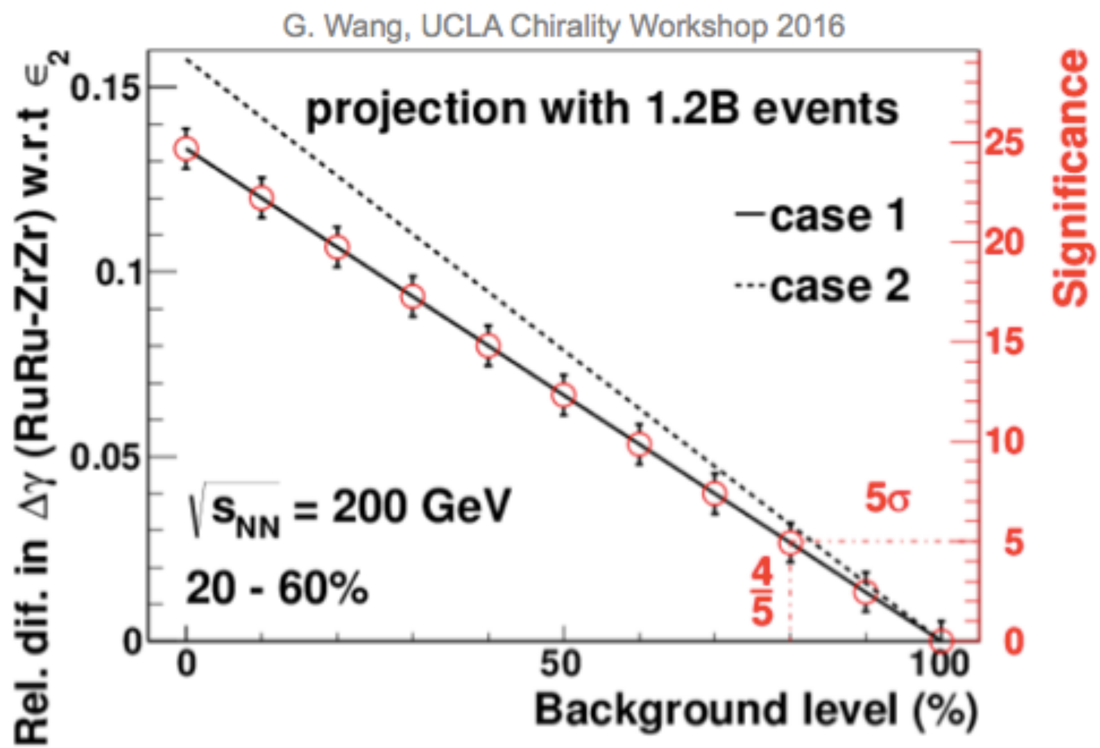


Definitive Measurements of B-Field Dependence

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation

$^{96}_{40}Zr + ^{96}_{40}Zr$ vs. $^{96}_{44}Ru + ^{96}_{44}Ru$

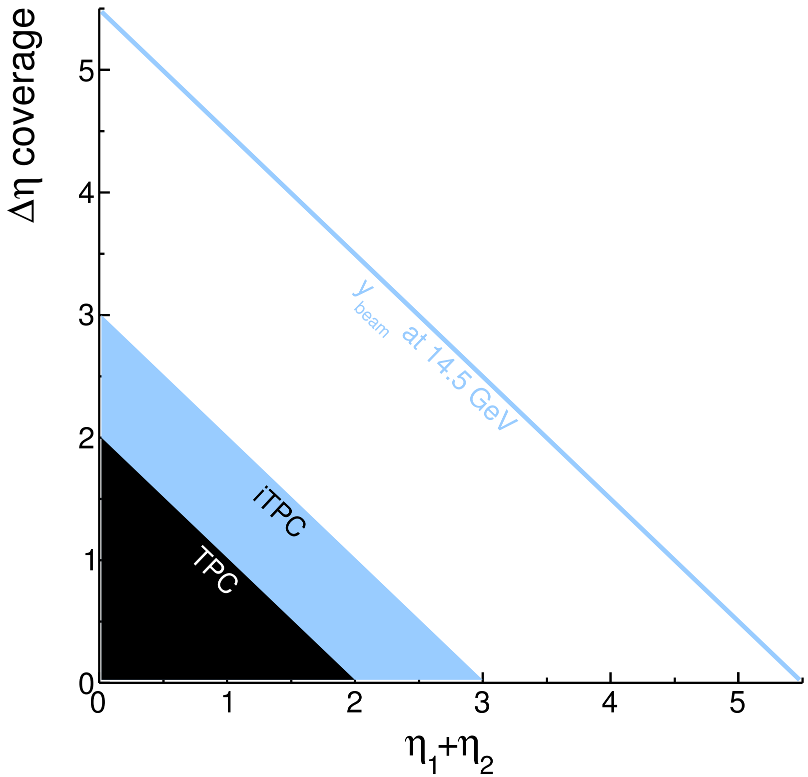


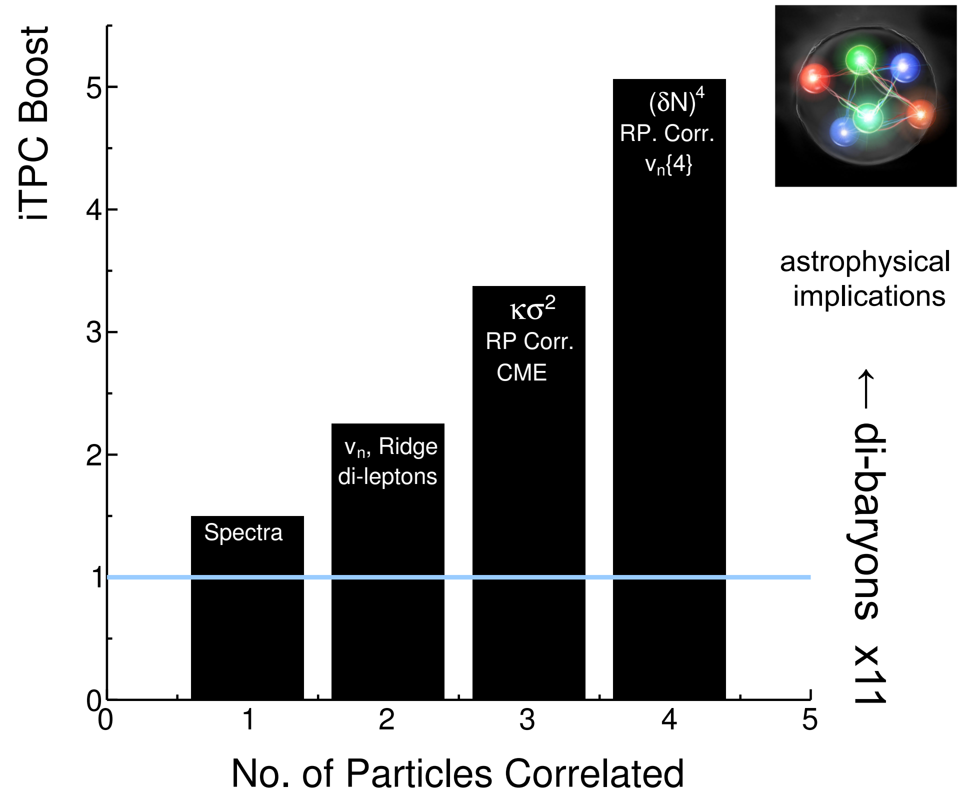


Isobar collisions in 2018 can tell us what percent of the charge separation is due to CME to within +/- 6% of the current signal

RHIC Run Plan

2016	2017	2018	2019	2020	2021	2022+
-200 GeV Au+Au -d+Au Energy Scan	-500 GeV p+p -62.4 or 27 GeV?	Isobar Zr+Zr and Ru+Ru	BES-II	BES-II		Full Energy Au+Au



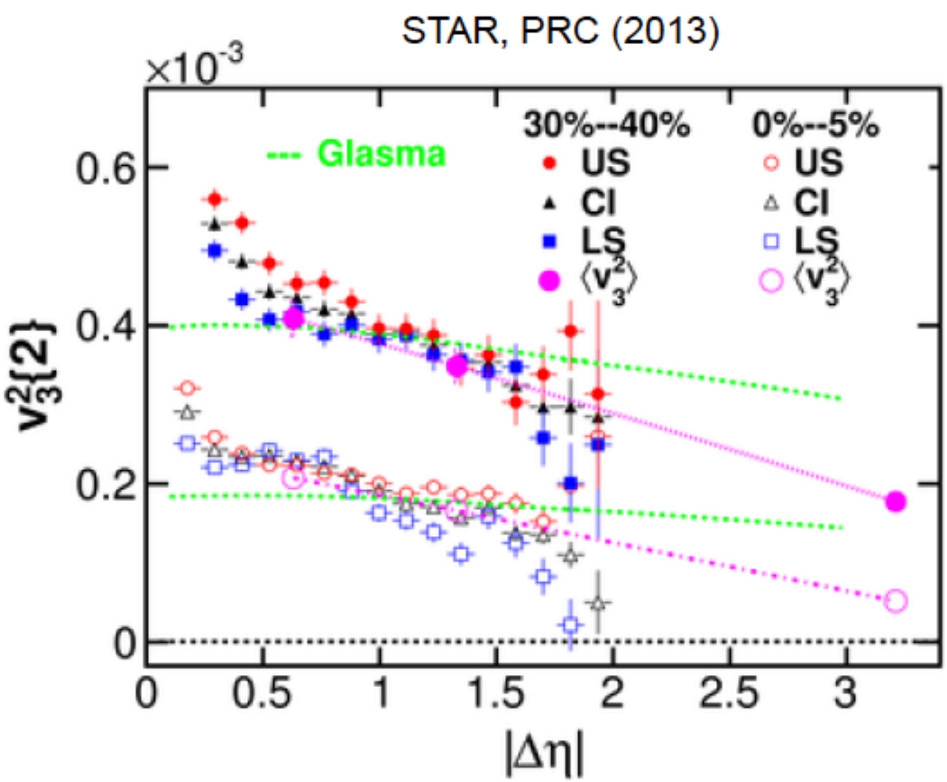


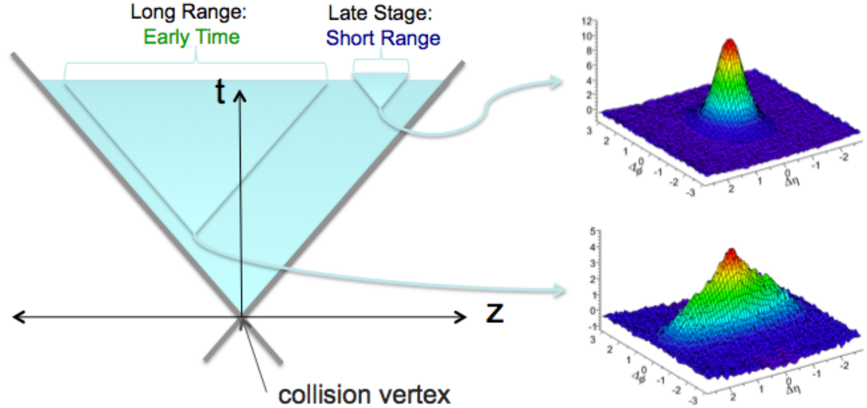
By 2022, large acceptance BESII detector will never have seen 200 GeV Au+Au

Untapped potential for a broad physics program including longitudinal dynamics complimentary to the jet and Quarkonium program of sPHENIX

Early Time Dynamics

2016	2017	2018	2019	2020	2021	2022+
-200 GeV Au+Au -d+Au Energy Scan	-500 GeV p+p -62.4 or 27 GeV?	Isobar Zr+Zr and Ru+Ru	BES-II	BES-II		Full Energy Au+Au



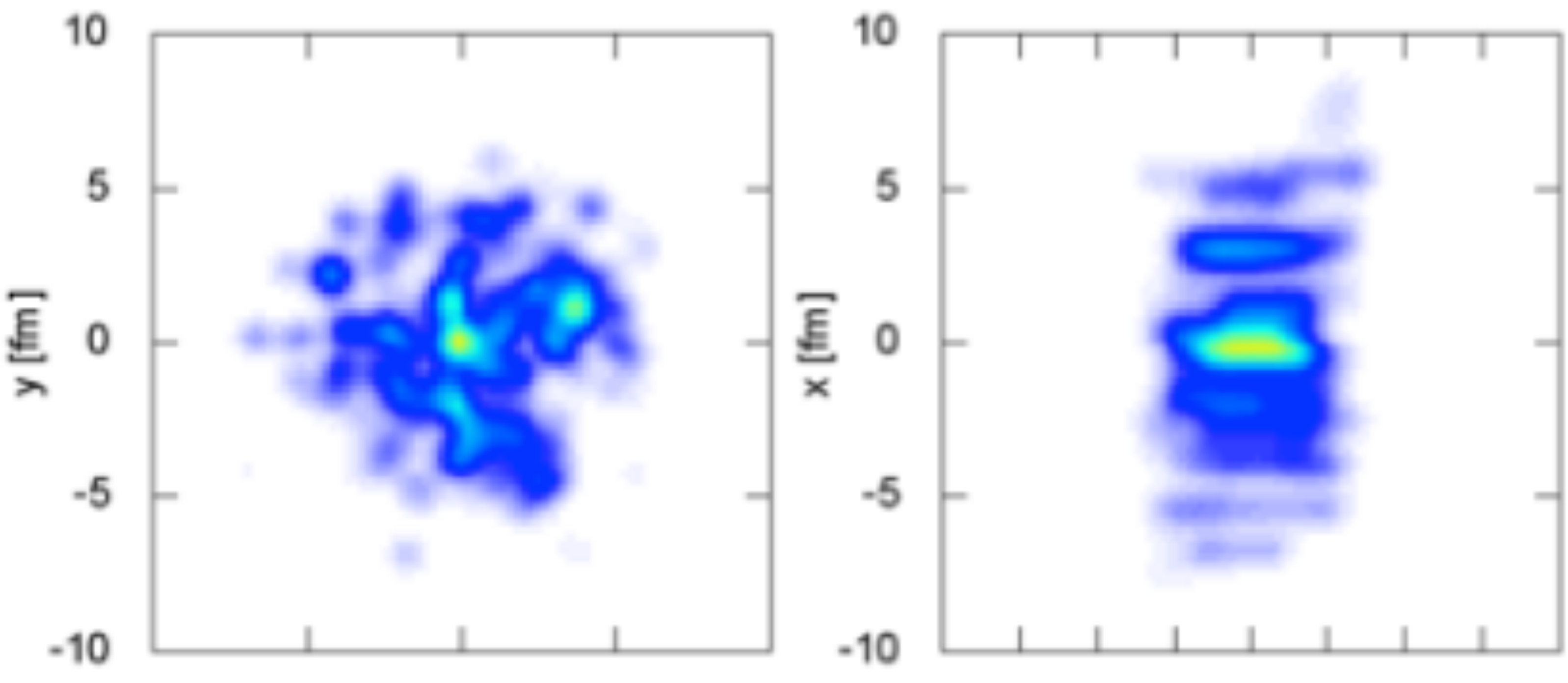


By 2022, large acceptance BESII detector will never have seen 200 GeV Au+Au

Untapped potential for a broad physics program including longitudinal dynamics complimentary to the jet and Quarkonium program of sPHENIX

Early Time Dynamics

2016	2017	2018	2019	2020	2021	2022+
-200 GeV Au+Au -d+Au Energy Scan	-500 GeV p+p -62.4 or 27 GeV?	Isobar Zr+Zr and Ru+Ru	BES-II	BES-II		Full Energy Au+Au

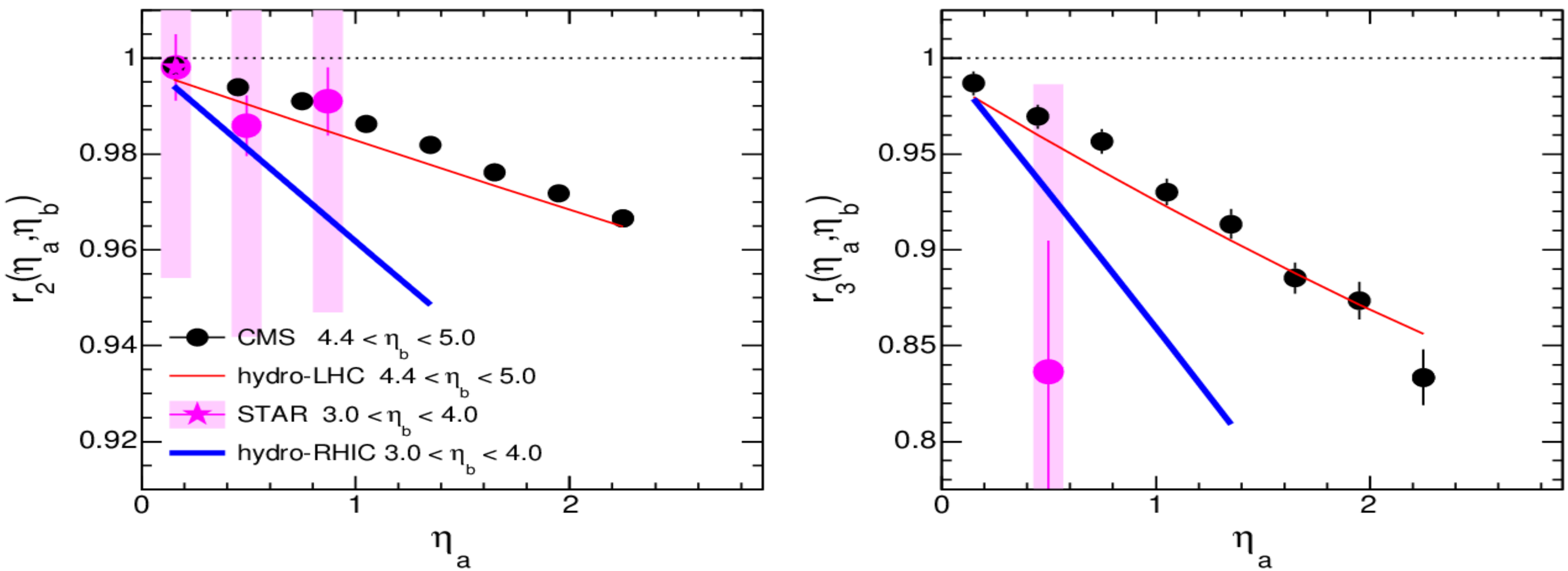


By 2022, large acceptance BESII detector will never have seen 200 GeV Au+Au

Untapped potential for a broad physics program including longitudinal dynamics complimentary to the jet and Quarkonium program of sPHENIX

Current Measurements

2016	2017	2018	2019	2020	2021	2022+
-200 GeV Au+Au -d+Au Energy Scan	-500 GeV p+p -62.4 or 27 GeV?	Isobar Zr+Zr and Ru+Ru	BES-II	BES-II		Full Energy Au+Au



By 2022, large acceptance BESII detector will never have seen 200 GeV Au+Au

Untapped potential for a broad physics program including longitudinal dynamics complimentary to the jet and Quarkonium program of sPHENIX

Exploring the Properties of the Phases of QCD

Great progress on emergent phenomena of QCD:

- Hottest man-made temperature: 300k times hotter than the center of the sun
- Data shown to prefer an Equation-of-State consistent with lattice QCD
- The QGP created at RHIC is the most perfect liquid ever known
- Exploratory scan finds QGP and intriguing behavior below 20 GeV

Following this progress we want to make measurements needed

- to define the phase structure in the QCD phase-diagram (critical point?)
- study the chiral properties of the QGP
- map the T dependence of η/s and other transport properties

In 2018: Isobar collisions will provide definitive evidence on the chiral magnetic effect

in 2019-2020: Detector and accelerator upgrades will provide key abilities in the search for a critical point

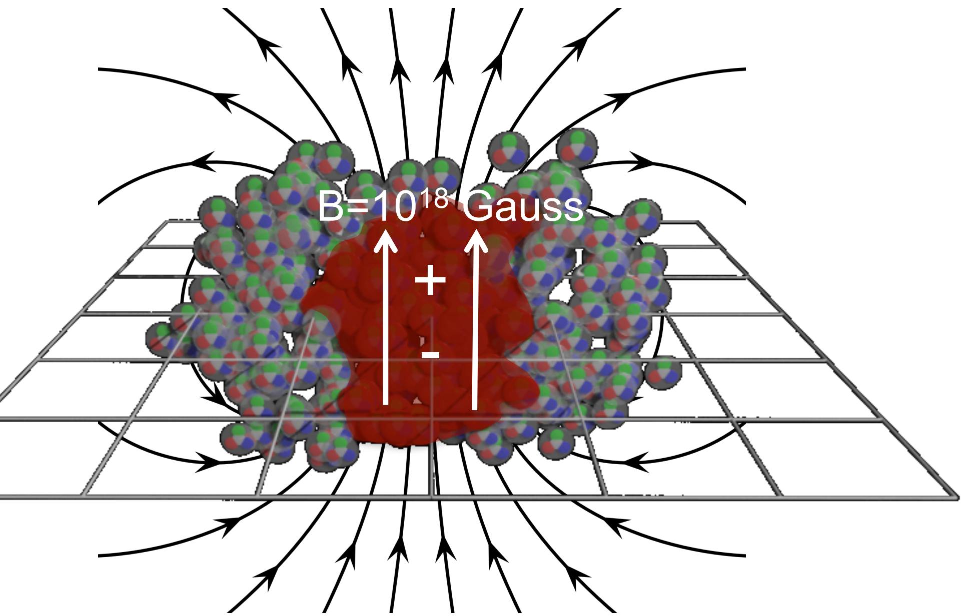
Extended coverage intended for BESII opens up many opportunities for a diverse program in 2022+

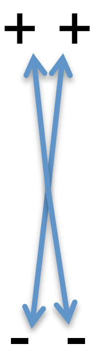
Measuring Topological Charge Transitions

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

charge separation





observable

$$\langle \cos(\varphi_{\pm} + \varphi_{\pm}) \rangle = -1$$

$$\langle \cos(\varphi_{\pm} + \varphi_{\mp}) \rangle = +1$$

in the lab frame we can measure

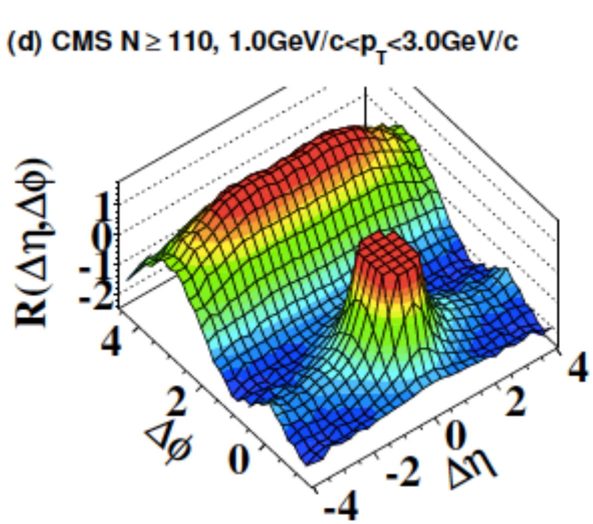
$$\gamma_{SS} = \langle \cos(\varphi_{\pm} + \varphi_{\pm} - 2\psi_{RP}) \rangle$$

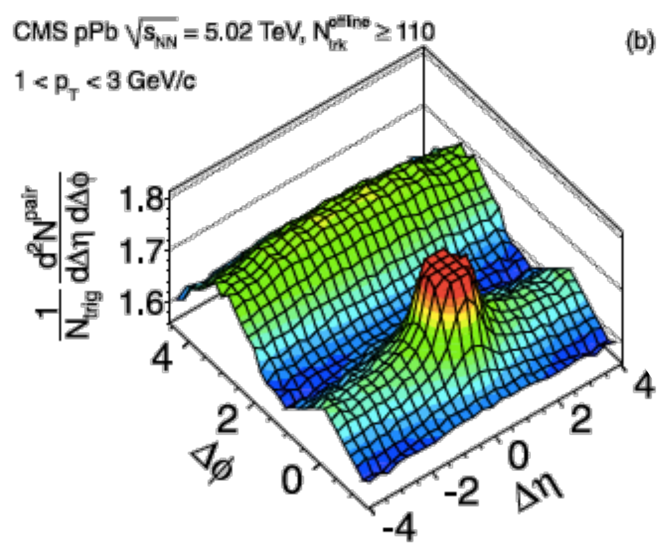
$$\gamma_{OS} = \langle \cos(\varphi_{\pm} + \varphi_{\mp} - 2\psi_{RP}) \rangle$$

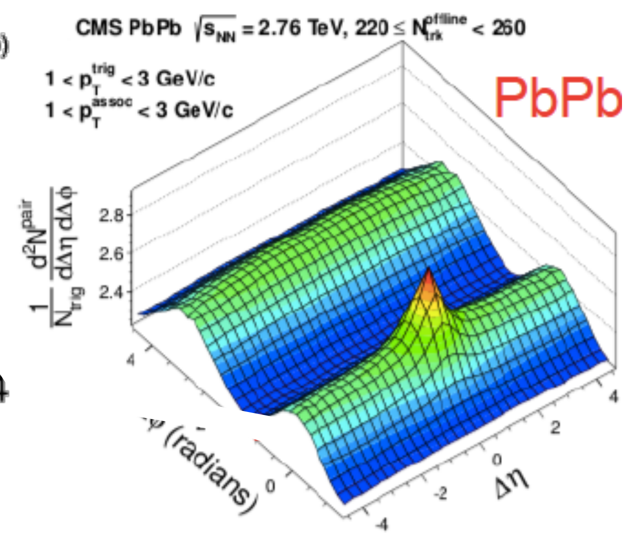
$$\Delta\gamma = \gamma_{OS} - \gamma_{SS}$$

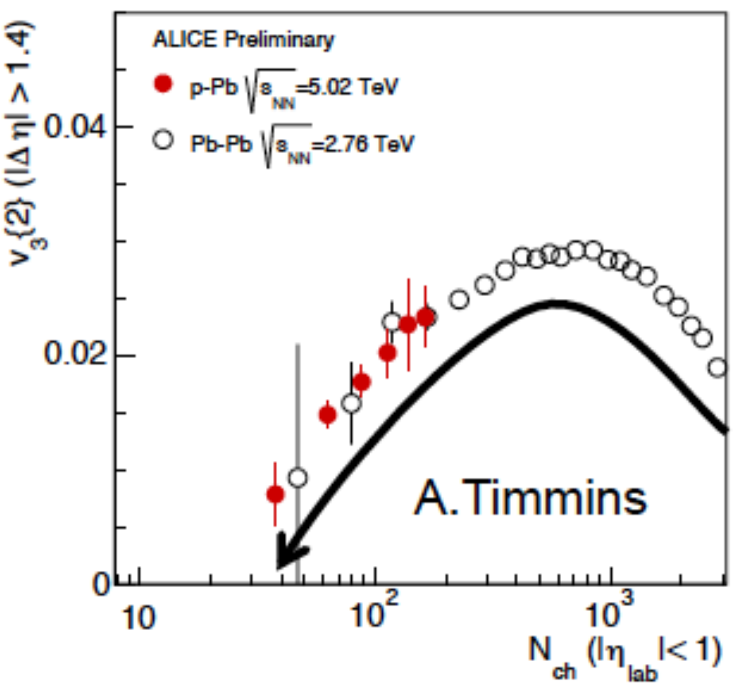
Topological charge fluctuates positive or negative, event-to-event or region-to-region: observe through angular correlations

The Ridge and v_3 in Smaller Systems



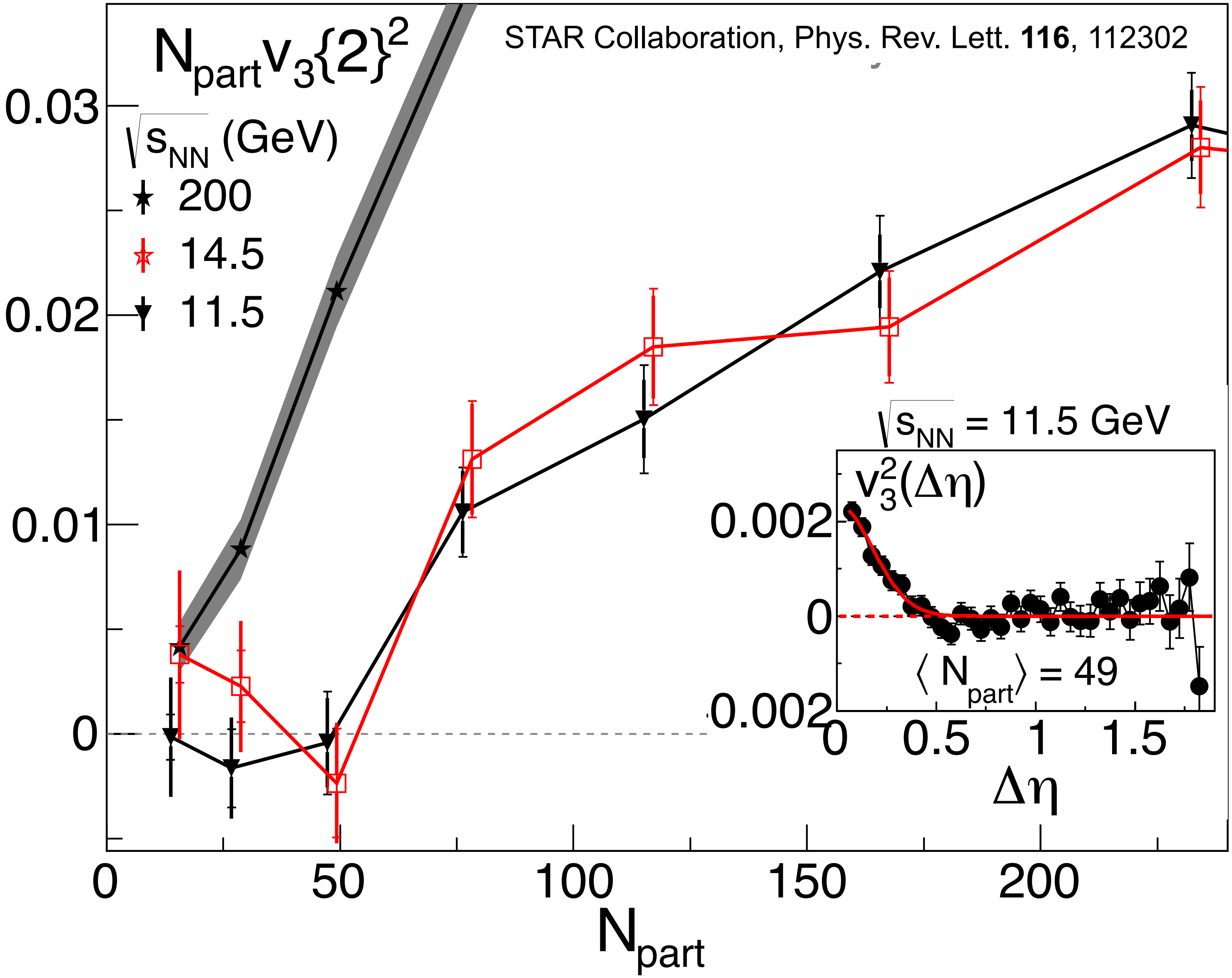






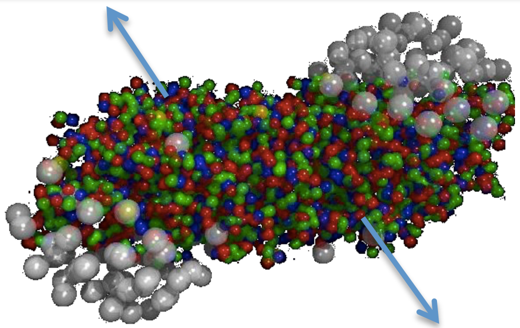
Demonstrating that we can turn off the QGP is a major goal of our field.

Disappearance of v_3



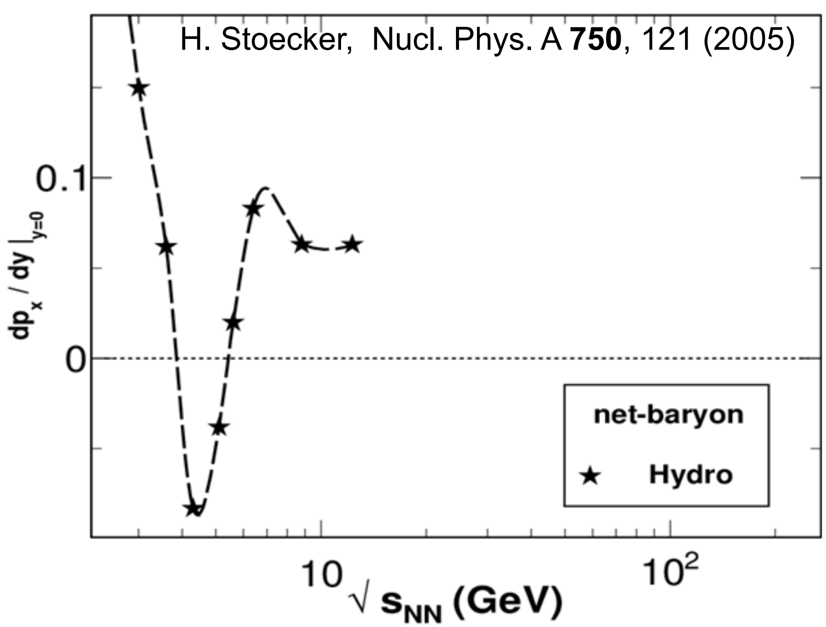
Looking forward to results from the 2016 d+Au energy scan

Anomalies in the Pressure?

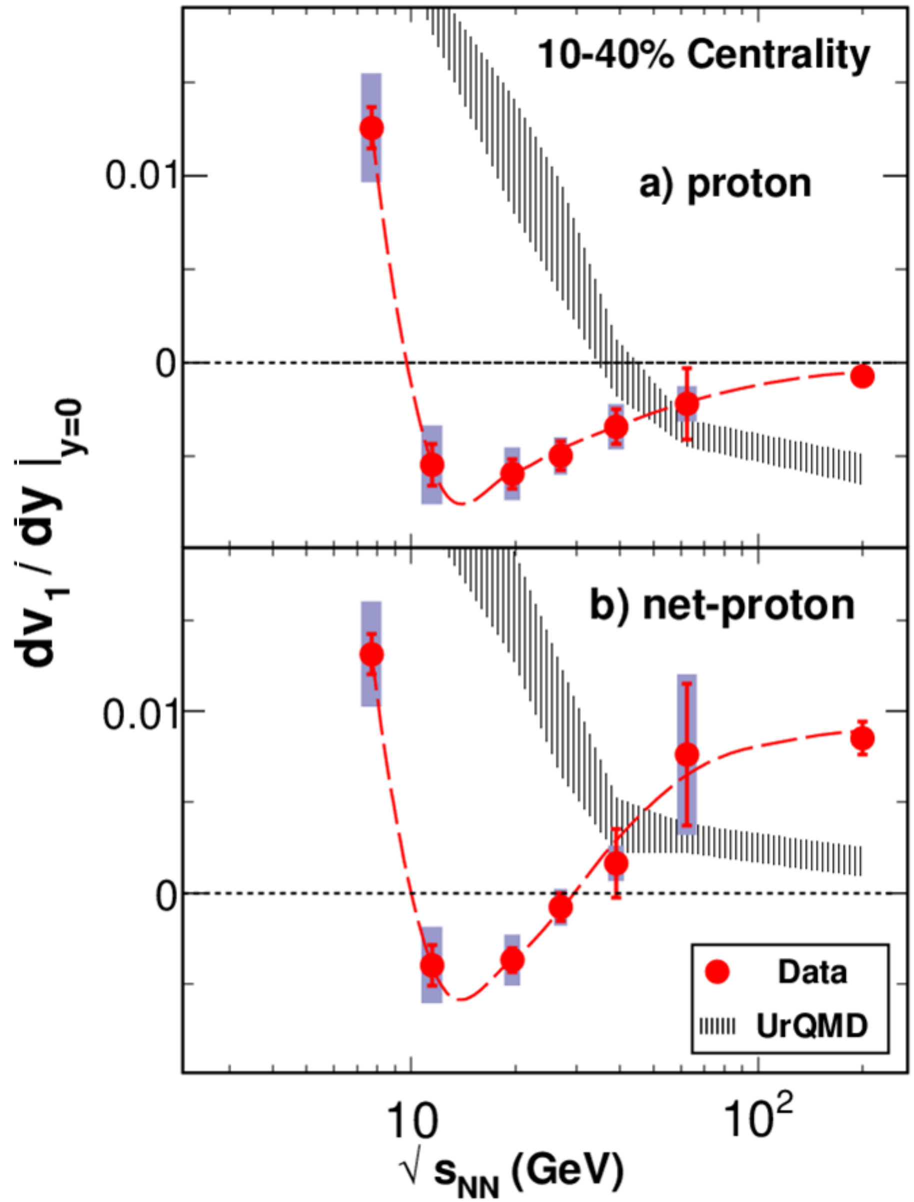


v_1 for both *p* & net-*p* qualitatively resemble collapse signature

Calculations with more sophisticated treatments of early times are needed

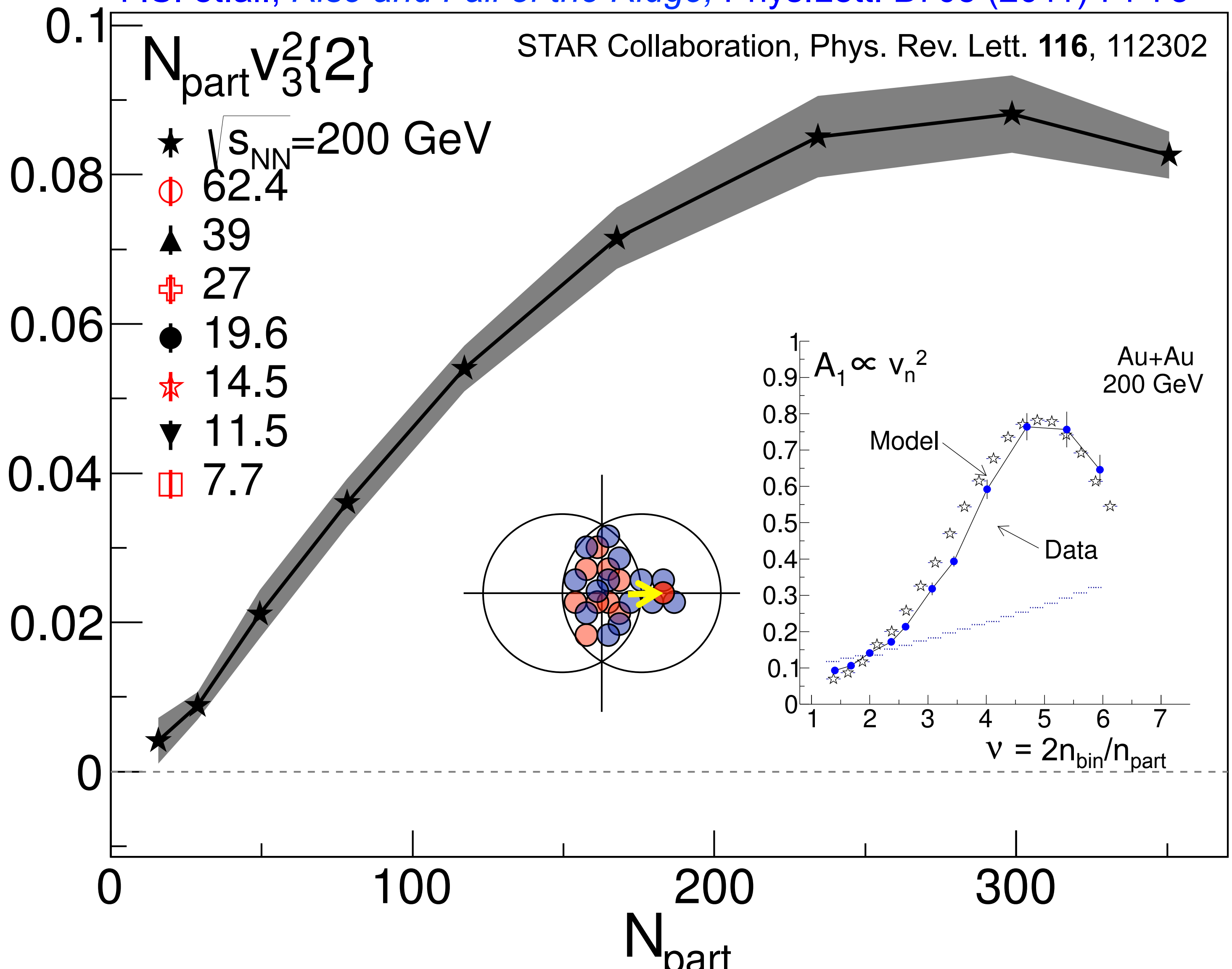


STAR, PRL **112**, 162301 (2014); arXiv:1401.3043



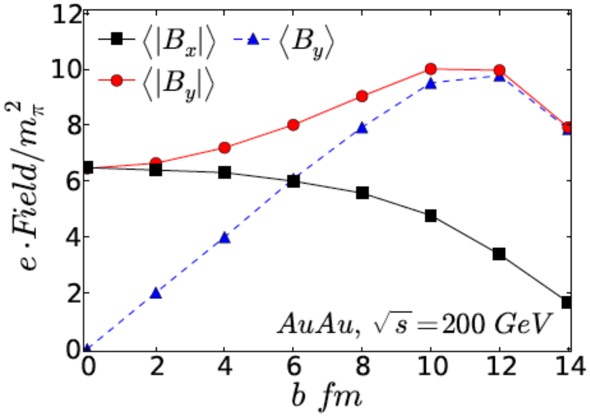
Centrality Dependence

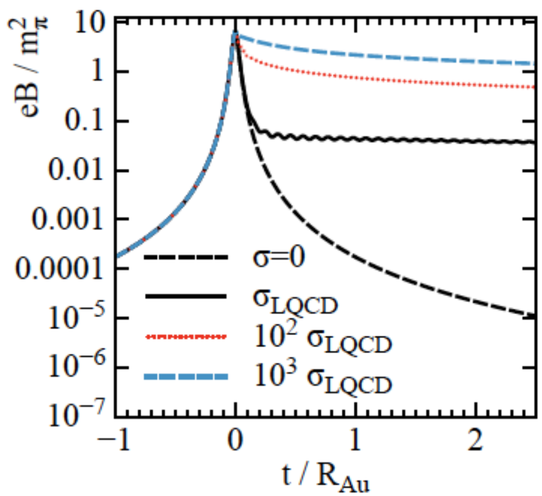
Centrality dependence well understood in terms of initial geometry:
P.S. et.al., *Rise and Fall of the Ridge,* Phys.Lett. B705 (2011) 71-75



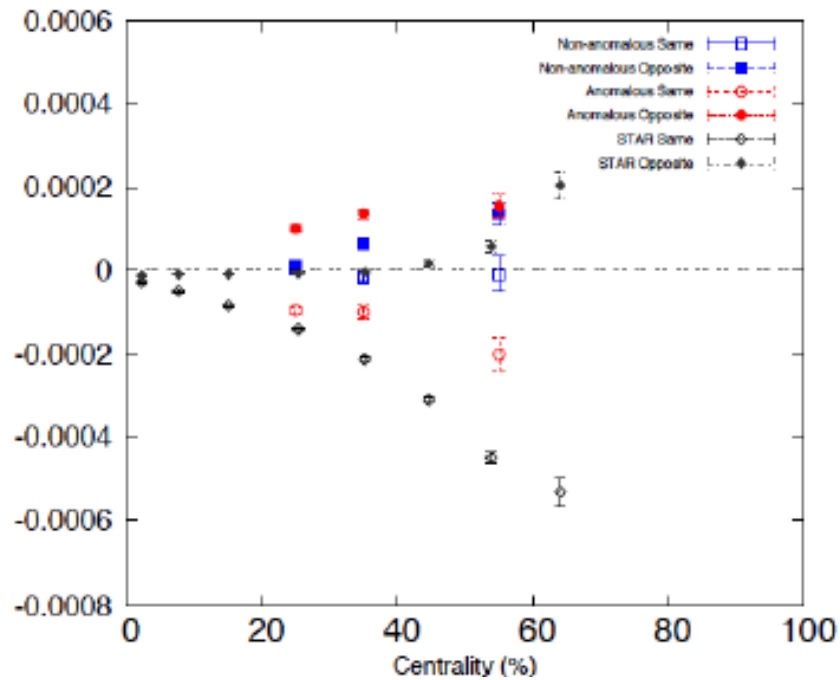
Assessment of Present Understanding

Solid predictions for CME are still difficult





Y. Hirono, T. Hirano and D. E. Kharzeev, arXiv:1412.0311 [hep-ph]



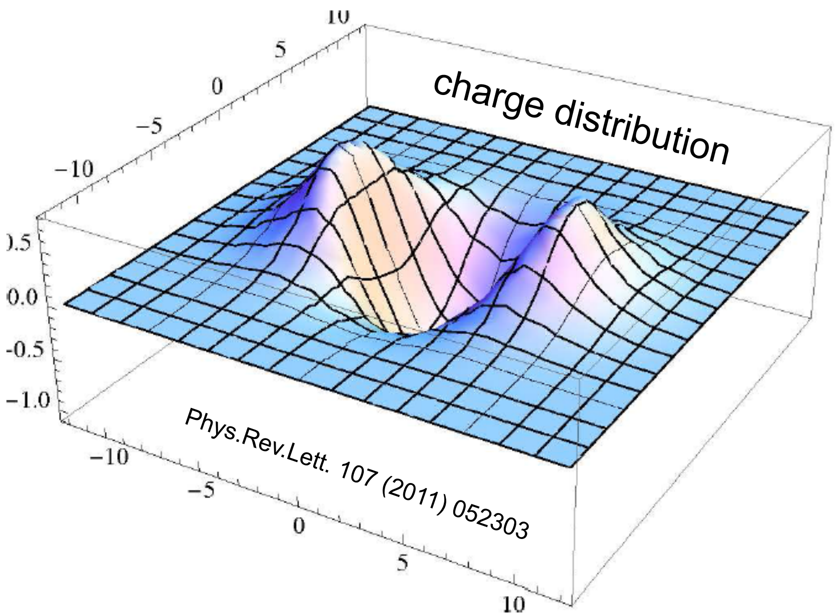
Magnetic field:
- effects of fluctuations are large
- lifetime still poorly understood

Anomalous hydro calculations are needed: BEST Collaboration

Chiral Magnetic Wave

Predicted Effect

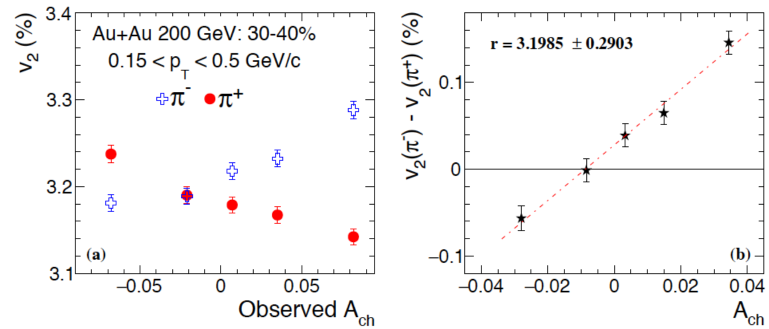
$$\vec{J}_V = \frac{N_c e}{2\pi^2}\mu_A \vec{B} \qquad \vec{J}_A = \frac{N_c e}{2\pi^2}\mu_V \vec{B}$$

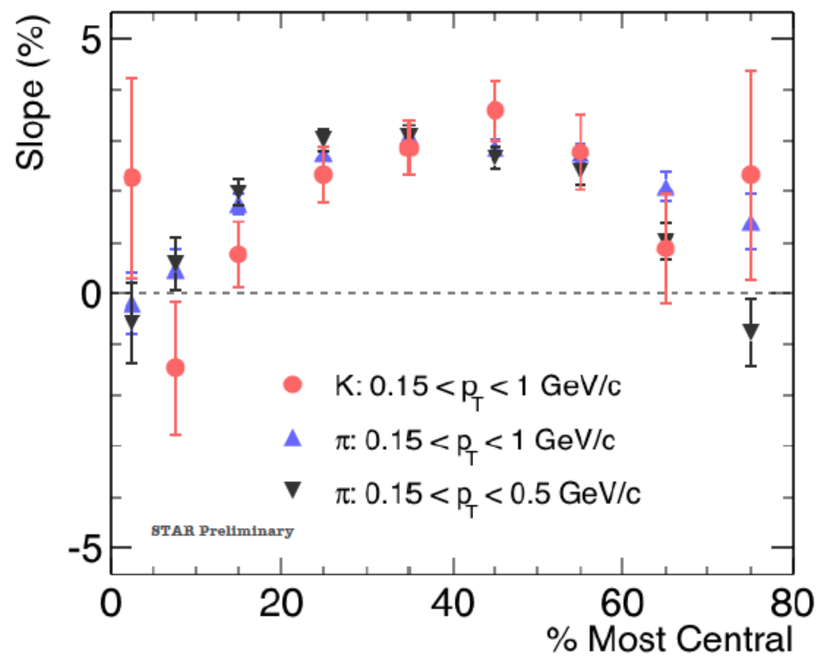


$$\Delta v_2 \equiv v_2(\pi^-) - v_2(\pi^+) = r\ A_\pm$$

$$A_\pm \equiv \frac{N_+ - N_-}{N_+ + N_-}$$

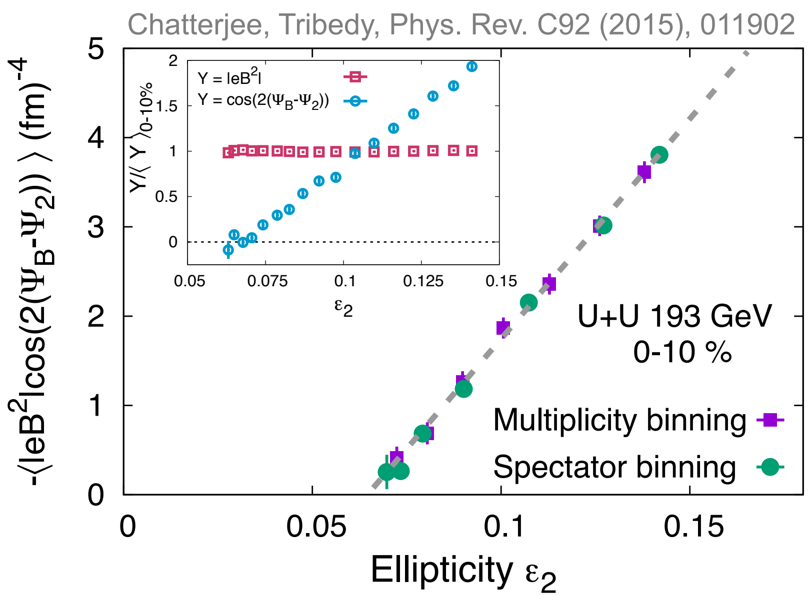
Confirmed in Data

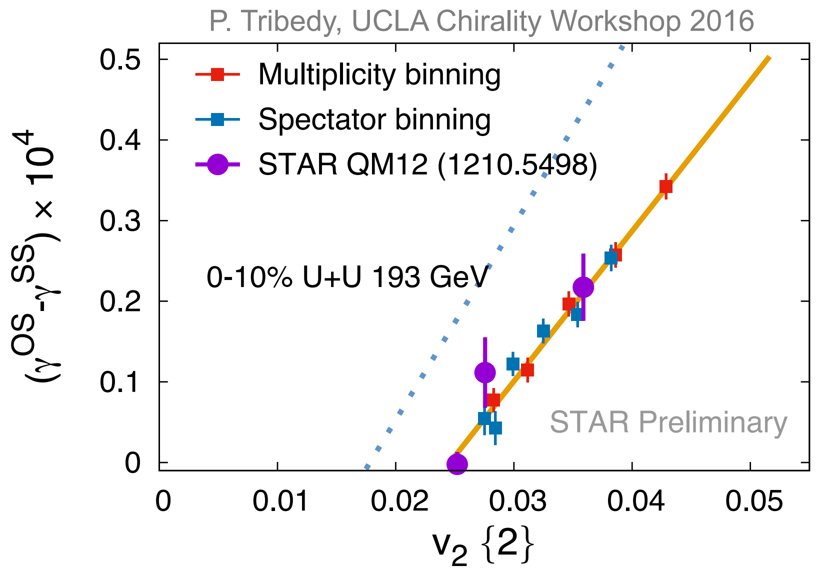


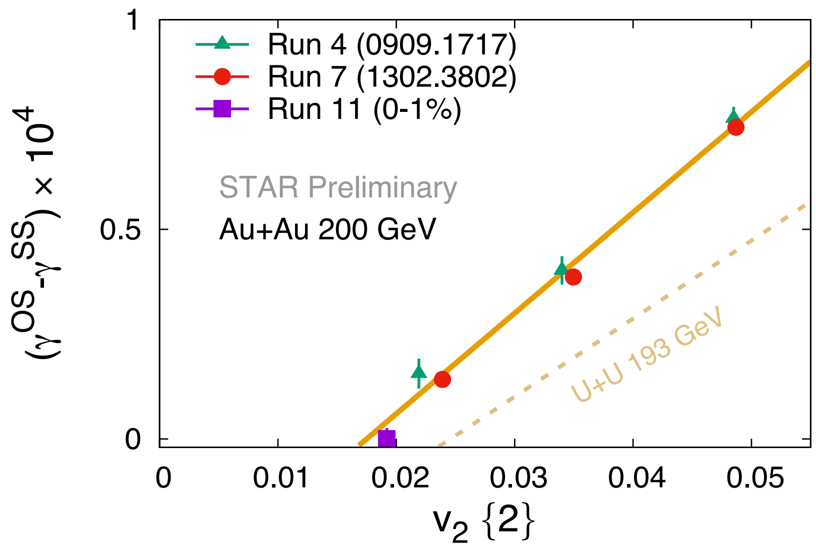


Ultra-central Au+Au and U+U

Charge separation in central collisions follows projected B-Field, not v_2

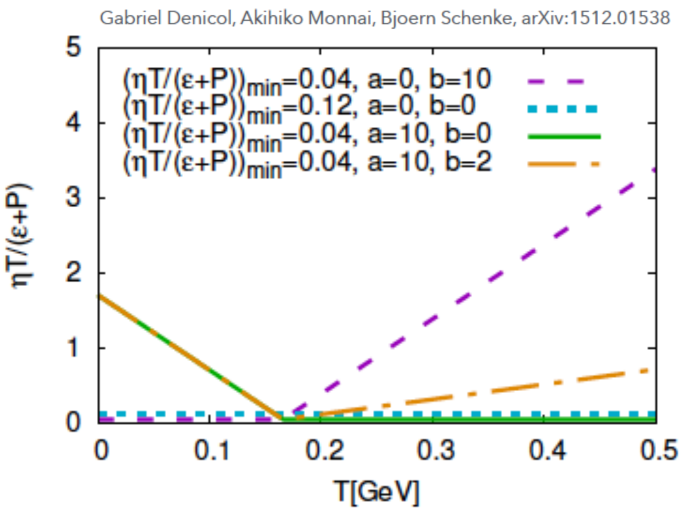


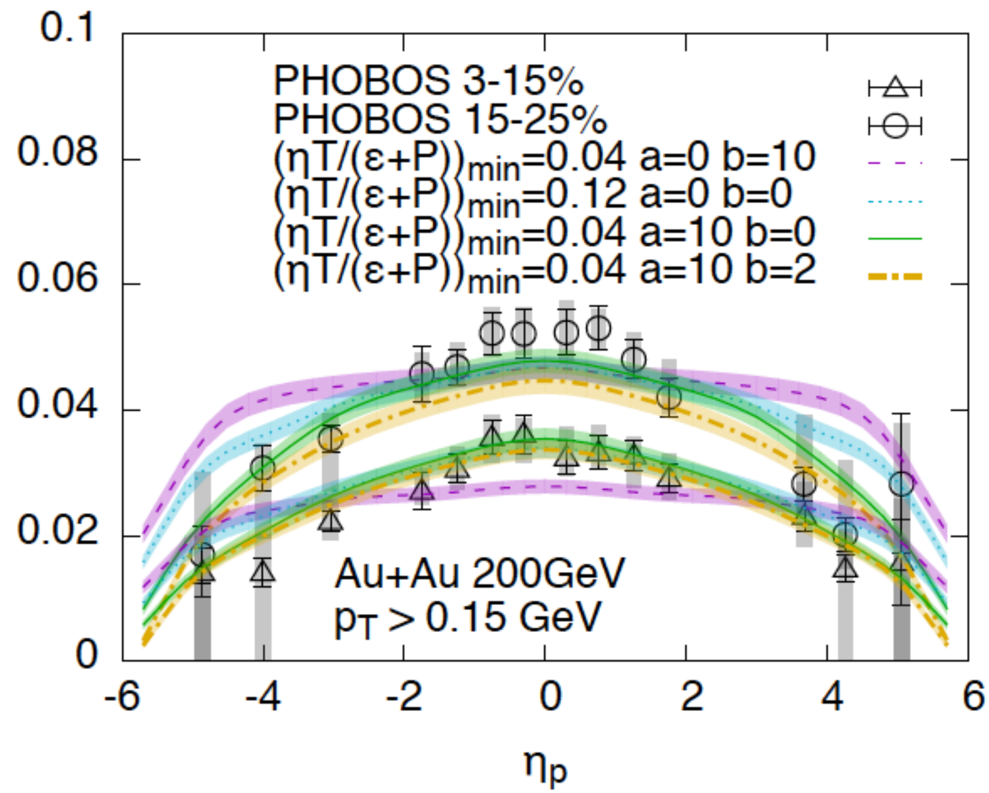




Temperature Dependence of η/s

2016	2017	2018	2019	2020	2021	2022+
-200 GeV Au+Au -d+Au Energy Scan	-500 GeV p+p -62.4 or 27 GeV?	Isobar Zr+Zr and Ru+Ru	BES-II	BES-II		Full Energy Au+Au

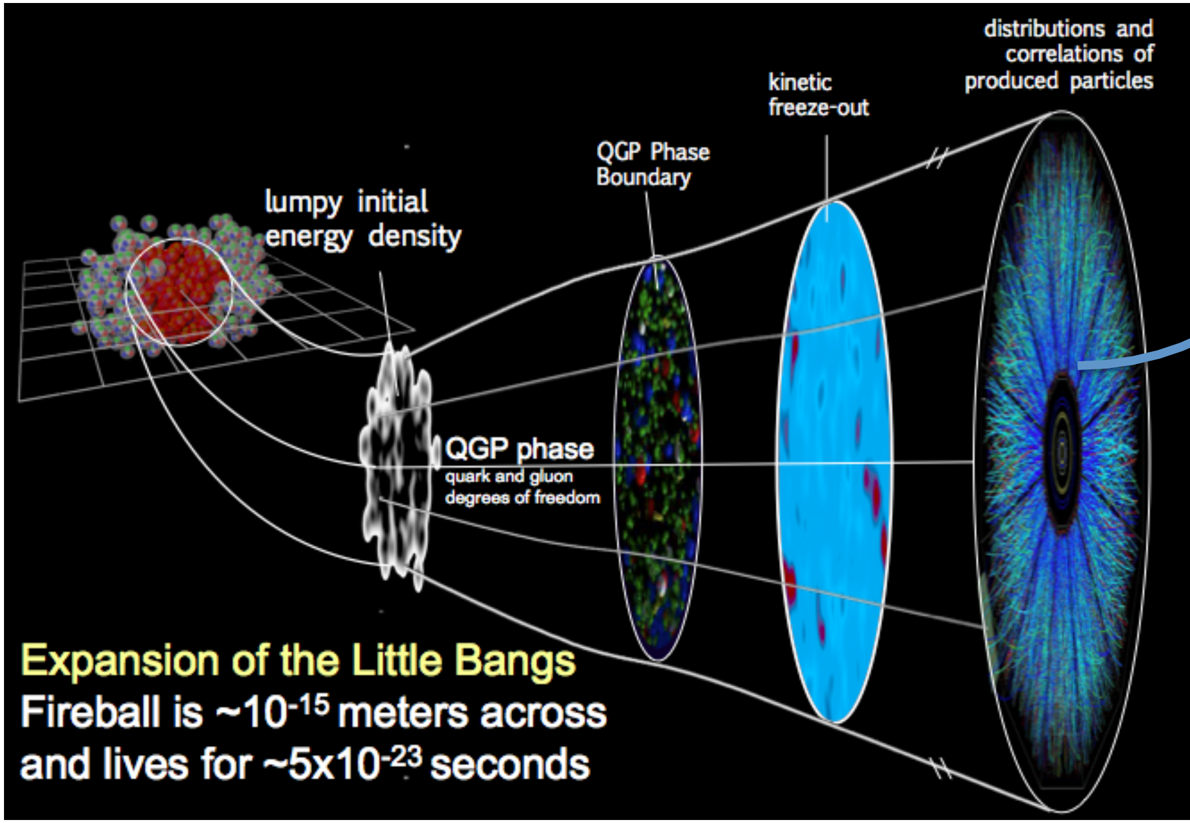


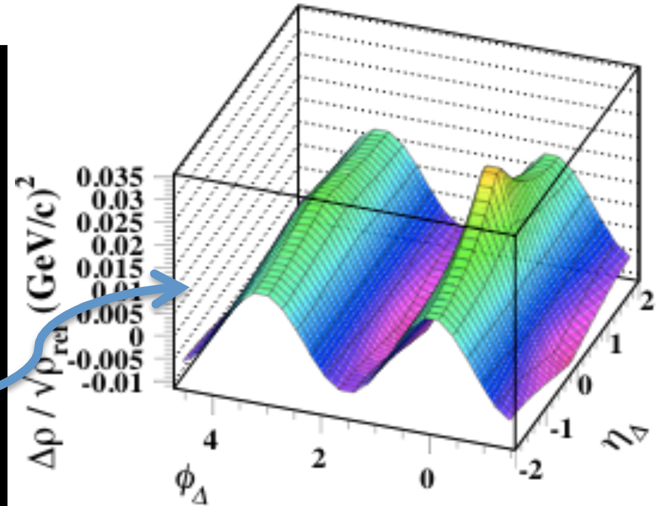


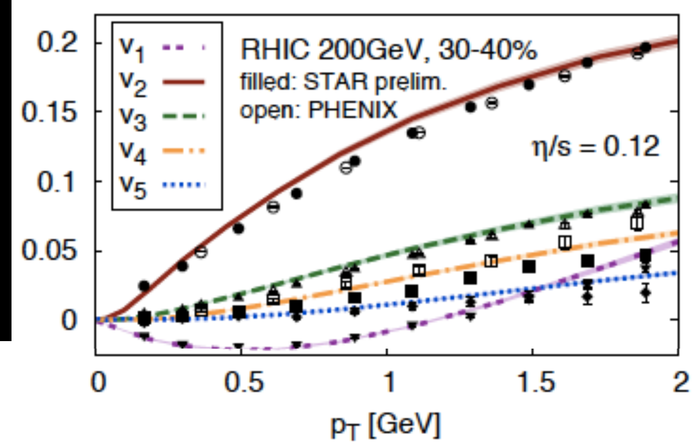
By 2022, large acceptance BESII detector will never have seen 200 GeV Au+Au

Untapped potential for a broad physics program including longitudinal dynamics complimentary to the jet and Quarkonium program of sPHENIX

Standard Model of the Little Bangs







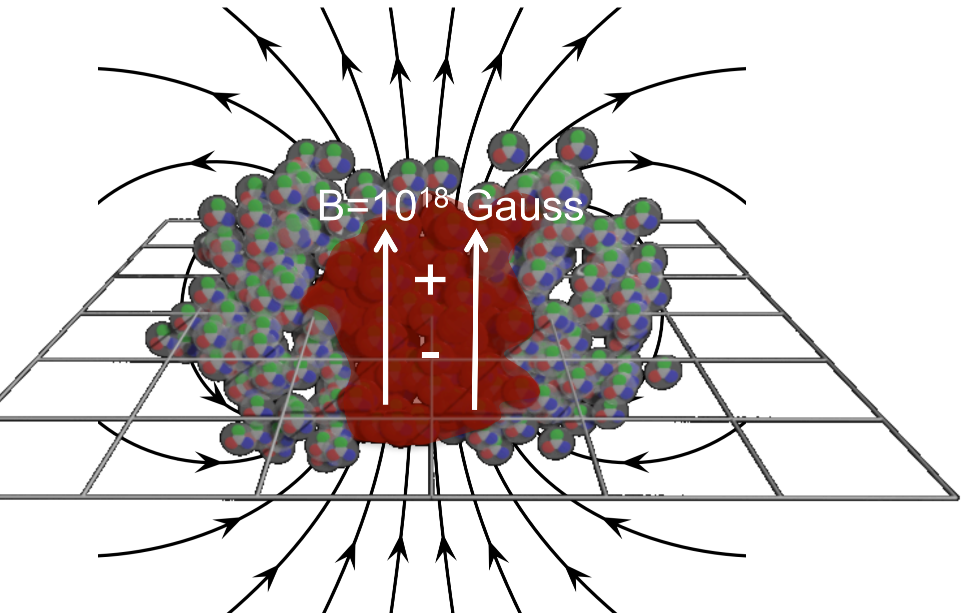
Long range correlations understood as arising from initial state density fluctuations. Conversion into momentum space requires a low η/s plasma

Sensible to express as v_n. Jettiness/non-flow subdominant until higher p_T

Detecting the Chiral Anomaly in U+U

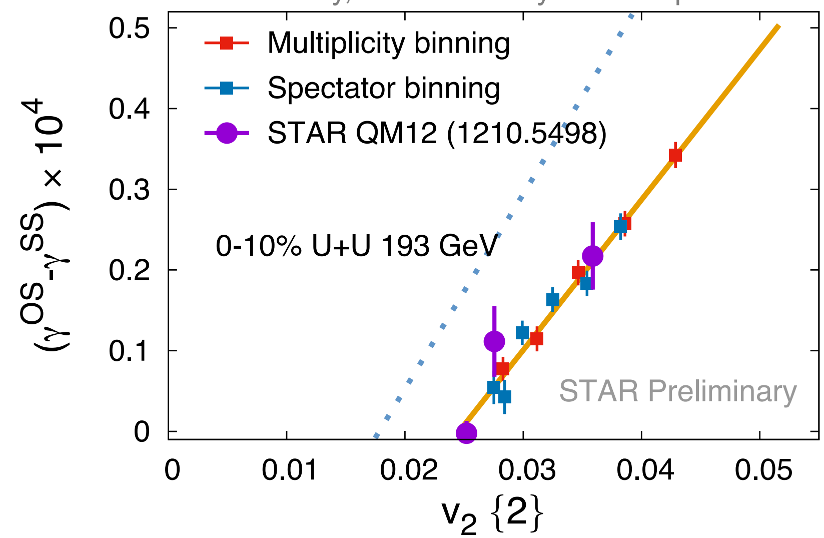
Charge separation in central collisions follows projected B-Field, not v_2

charge separation caused by anomaly induced chiral imbalance

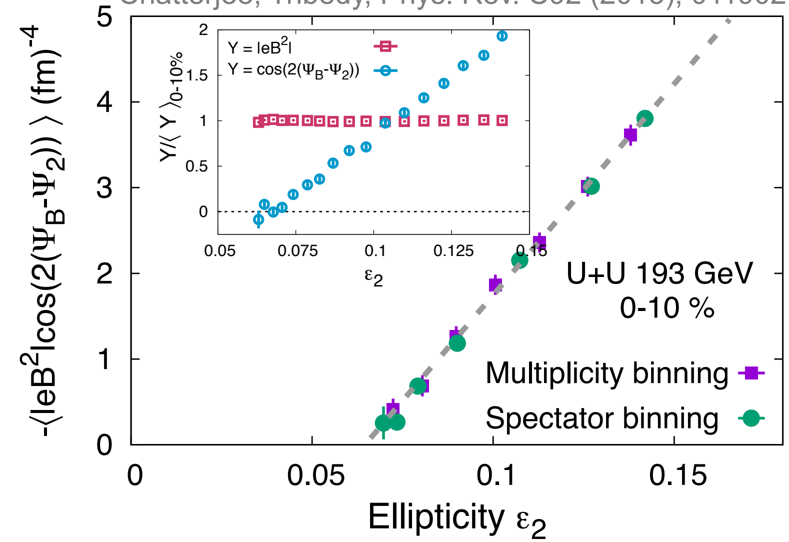


Evidence pointing to charge separation caused by the chiral anomaly of QCD

P. Tribedy, UCLA Chirality Workshop 2016

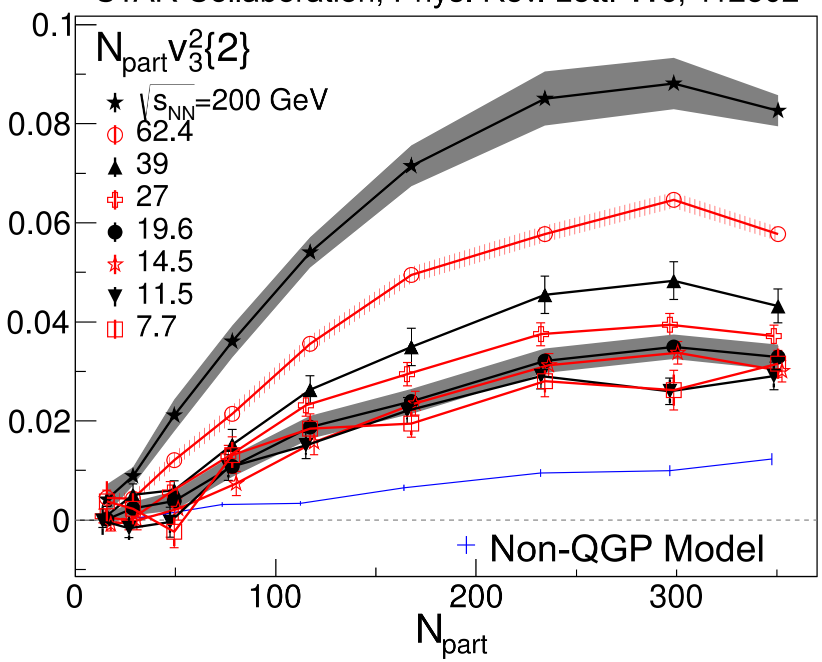


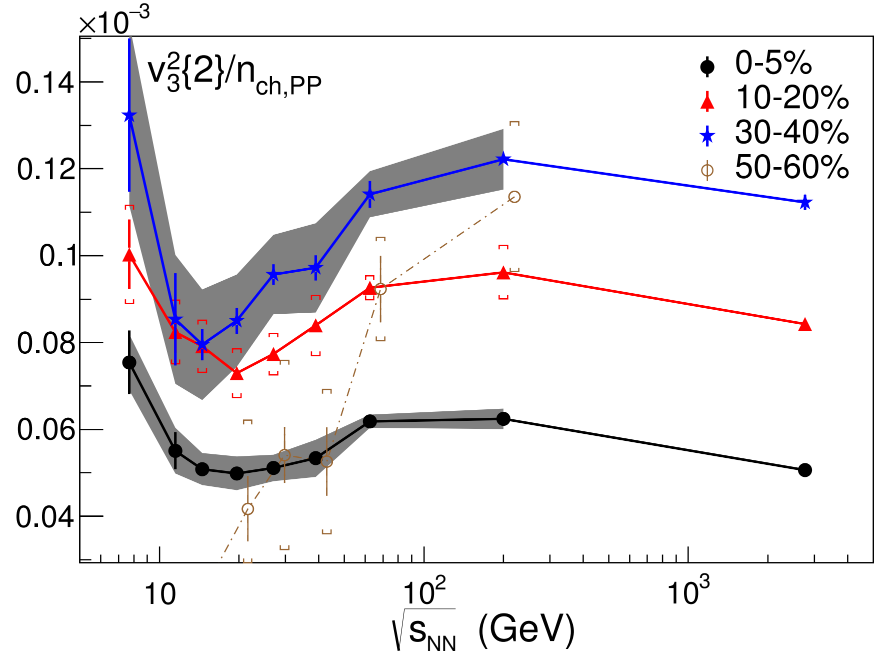
Chatterjee, Tribedy, Phys. Rev. C92 (2015), 011902

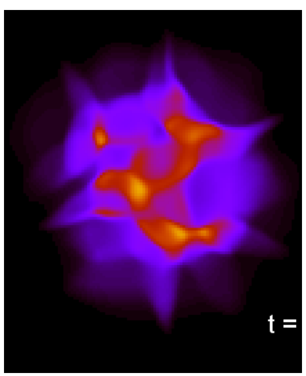


Mapping the Phase Diagram: Higher Harmonics

STAR Collaboration, Phys. Rev. Lett. **116**, 112302







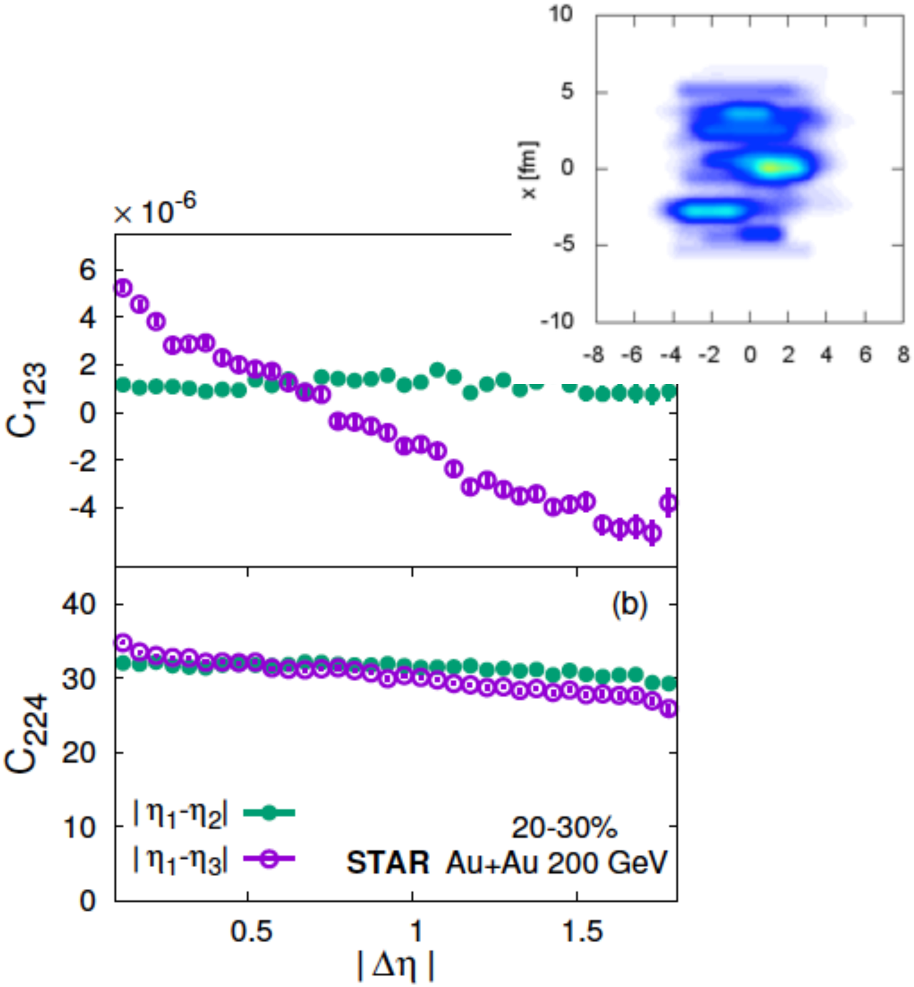
Models show that higher harmonic ripples are sensitive to the presence of a QGP: v_3 goes away when the QGP goes away

In more central collisions, v_3 is present at the lowest energies, but disappears at lower energies for N_{part}<50 (turn-off of QGP)

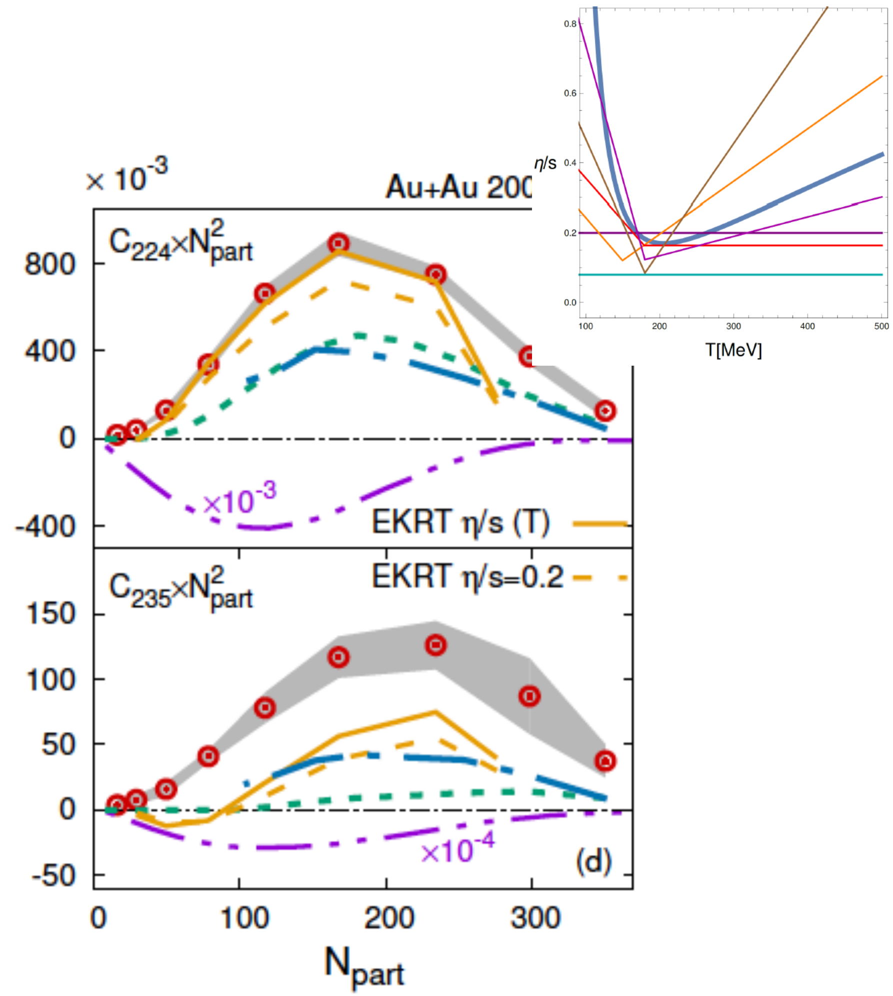
When scaled by entropy density, v_3 shows a minimum near 15 GeV consistent with an increased bulk viscosity and decreased effective pressure

Road Map to Constraining η/s(T)

Δη dependence maps 3-D initial state



3-D models will constrain η/s(T)

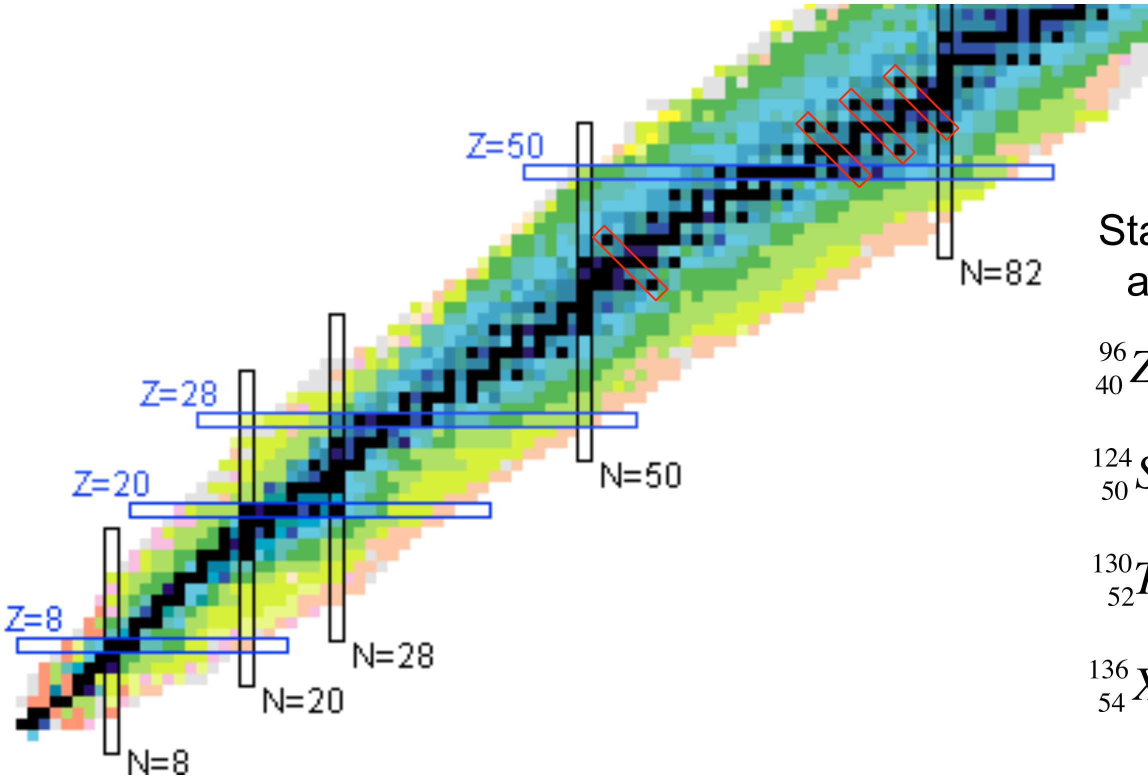


Understanding the initial state in 3-D required to constrain η/s(T)

Data on 3-particle correlations shows the way to do both

Evaluation of Running with Nuclear Isobars

Isobars: nuclei with the same mass number but different charges



Stable isobar pairs with ΔZ=4
and natural abundance > 0

${}^{96}_{40}Zr + {}^{96}_{40}Zr$	vs.	${}^{96}_{44}Ru + {}^{96}_{44}Ru$	preferred by CAD
${}^{124}_{50}Sn + {}^{124}_{50}Sn$	vs.	${}^{124}_{54}Xe + {}^{124}_{54}Xe$	not promising
${}^{130}_{52}Te + {}^{130}_{52}Te$	vs.	${}^{130}_{56}Ba + {}^{130}_{56}Ba$	still possible
${}^{136}_{54}Xe + {}^{136}_{54}Xe$	vs.	${}^{136}_{58}Ce + {}^{136}_{58}Ce$	not promising

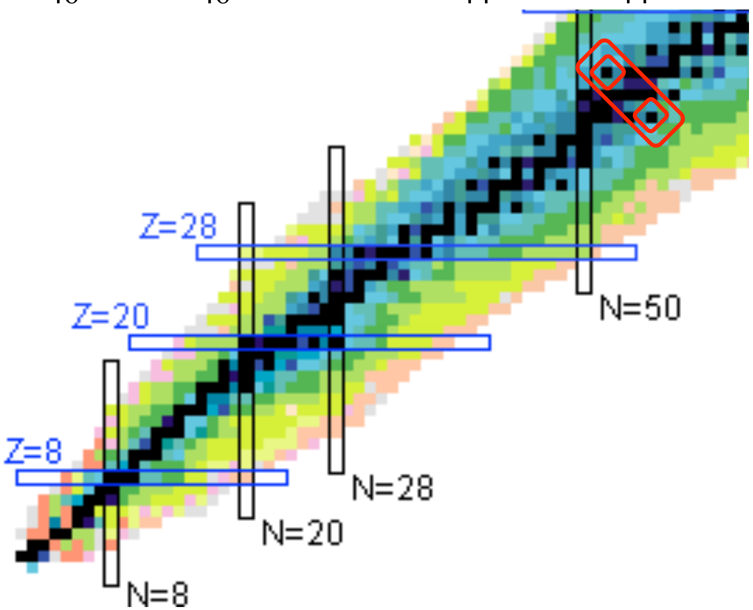
Would make it possible to change the B-field about 10% while most other variables are fixed. But,

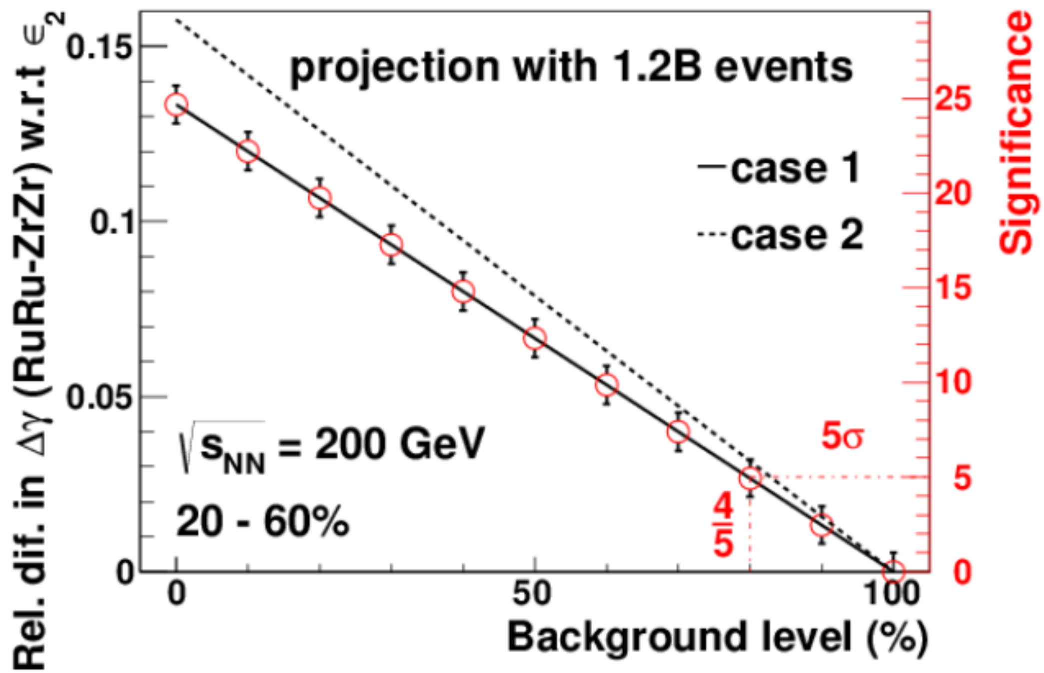
- how well do we understand the magnetic field?
- how well do we understand the effect of the nuclear geometry?
- will the measurements be discerning enough?

Probing Chiral Symmetry with Quantum Currents

Current understanding: backgrounds unrelated to the chiral magnetic effect may be able to explain the observed charge separation

$^{96}_{40}Zr + ^{96}_{40}Zr$ vs. $^{96}_{44}Ru + ^{96}_{44}Ru$





Isobar collisions in 2018 can tell us what percent of the charge separation is due to CME to within +/- 6% of the current signal

Conclusions

Large uncertainties in interpretation exist: *Current CME measurements could be entirely from background*

There remain analyses to be done that are likely to provide some help in clarifying the relevance of CME but, *none so far have proven to be decisive*

Reliable handles on the effect of the B-field may prove crucial

Along with the sphaleron transition rate, uncertainty in the duration of the B-field will probably remain one of the key challenges to reliable predictions for the CME effect

So far, the isobar program looks promising: as long as the isotopes can be acquired there seem to be no show-stoppers: *note proposed statistics are sufficient for CME but not CMW studies*

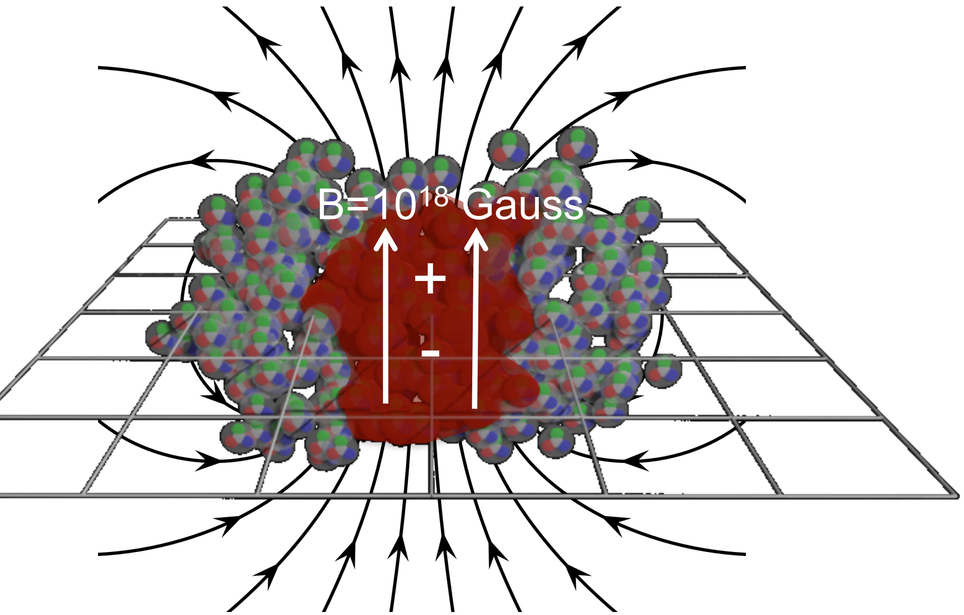
Probing Chiral Symmetry with Quantum Currents

The chiral anomaly of QCD creates differences in the number of left and right handed quarks.

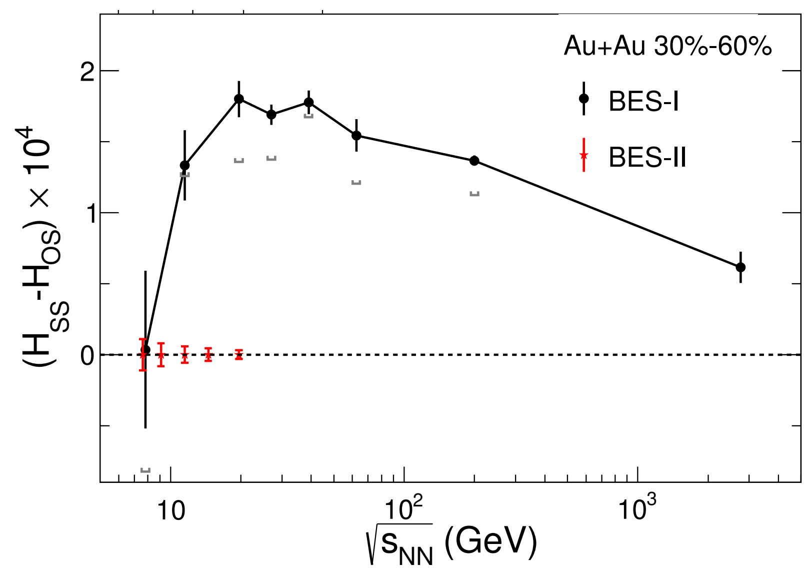
a similar mechanism in electroweak theory is likely responsible for the matter/antimatter asymmetry of our universe

In a chirally symmetric QGP, this imbalance can create charge separation along the magnetic field

charge separation

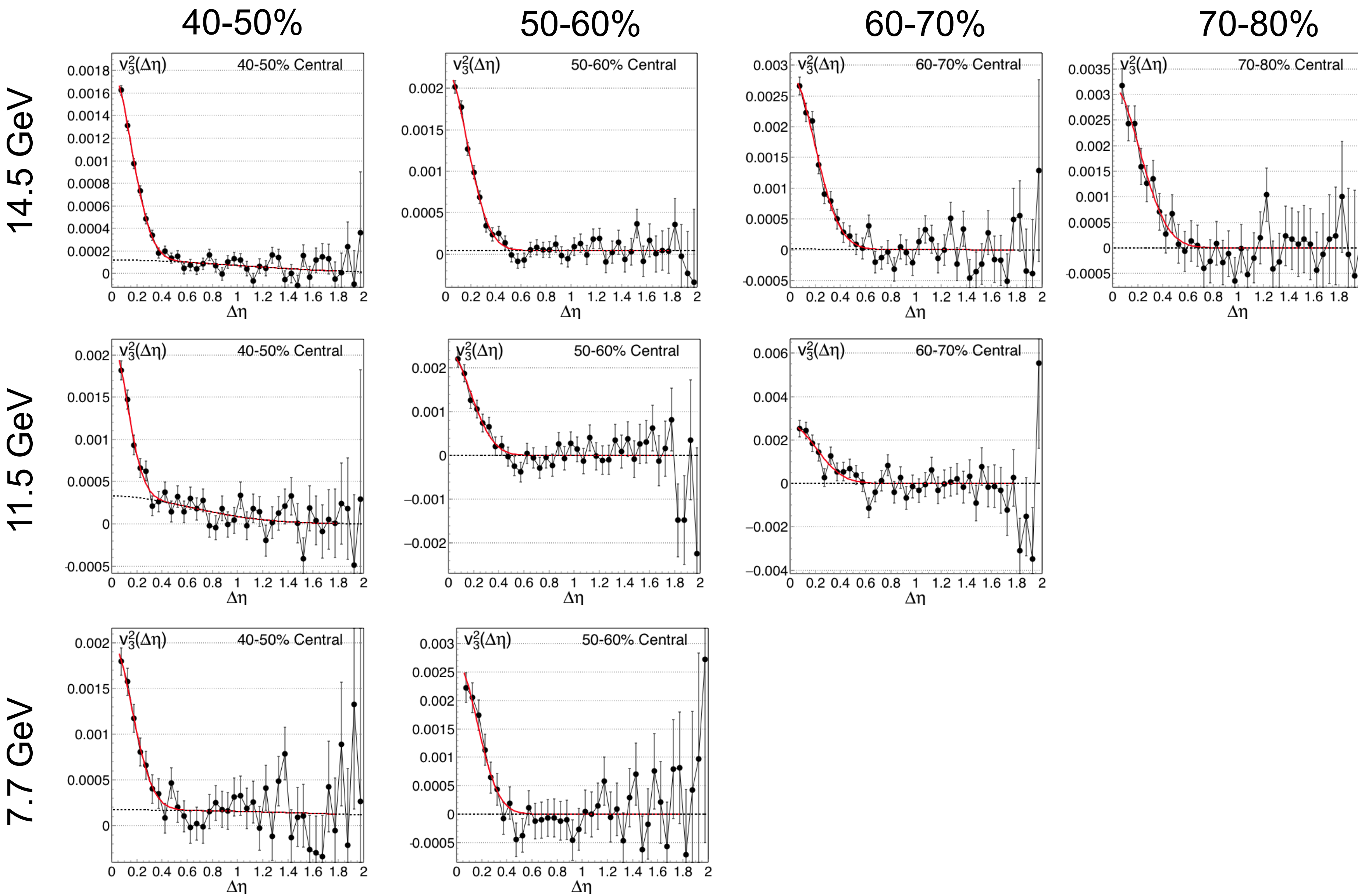


observed at all but the lowest energy



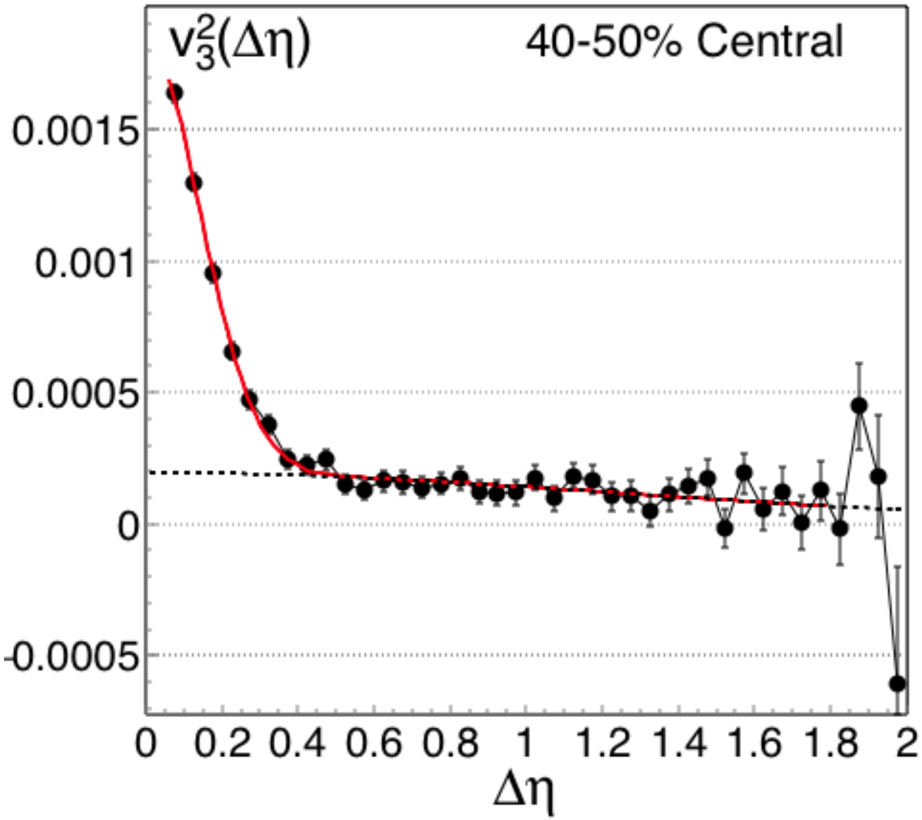
But models with magnetic field-independent backgrounds can also be tuned to reproduce the observed charge separation

Disappearance of v_3



Δη Integrated Results

27 GeV

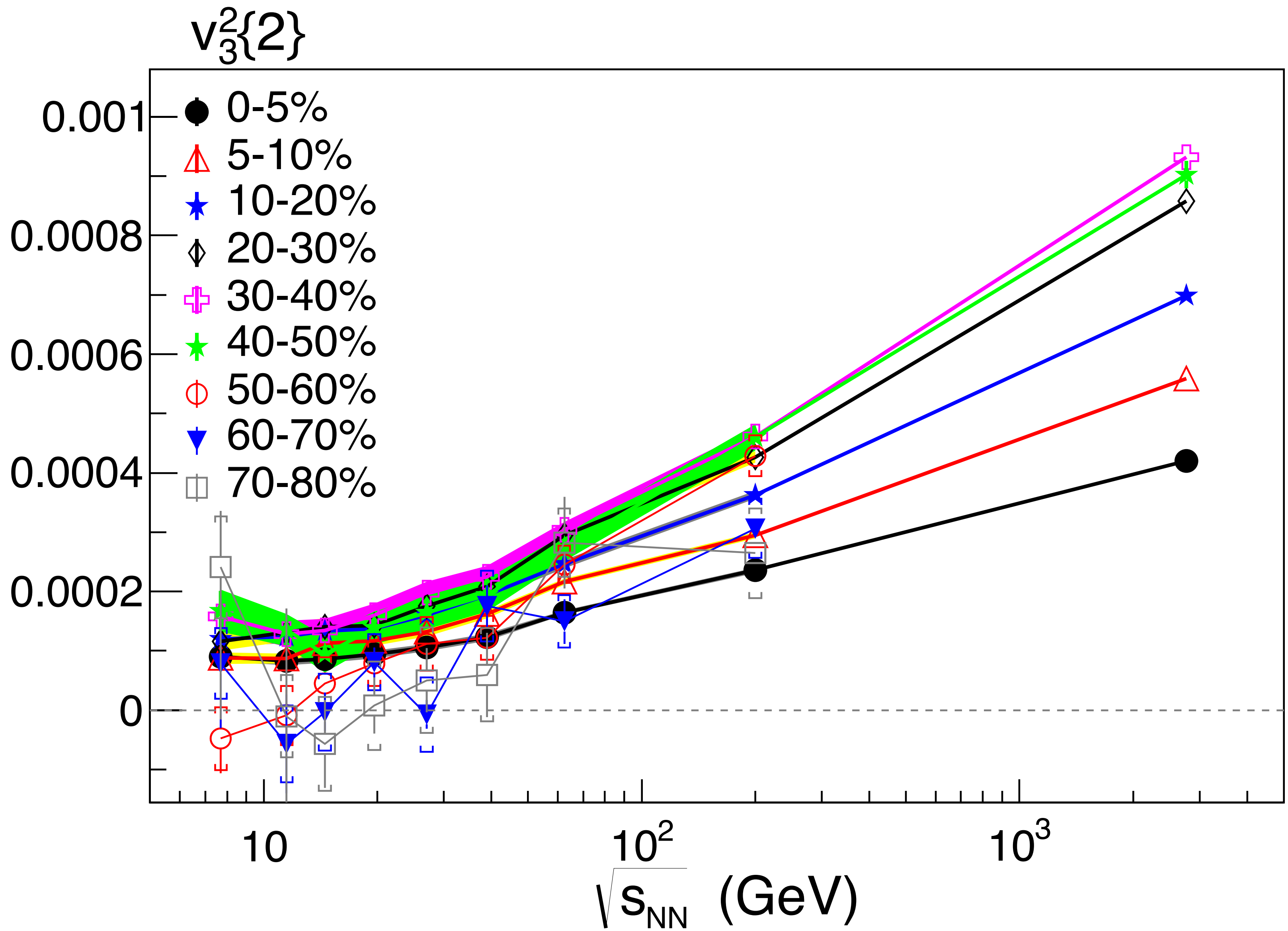


Integrate over the whole Δη range but subtract off short-range contribution

$$v_n^2\{2\} = \frac{\sum_i \left(v_n^2\{2\}(\Delta\eta_i) - \delta_i\right)\frac{dN_i}{d\Delta\varphi_i}}{\sum_i \frac{dN_i}{d\Delta\varphi_i}}$$

Acceptance and efficiency corrected results for p_T>0.2 GeV and η<1 with no arbitrary |Δη| cuts: easy for model comparisons and study of energy trends

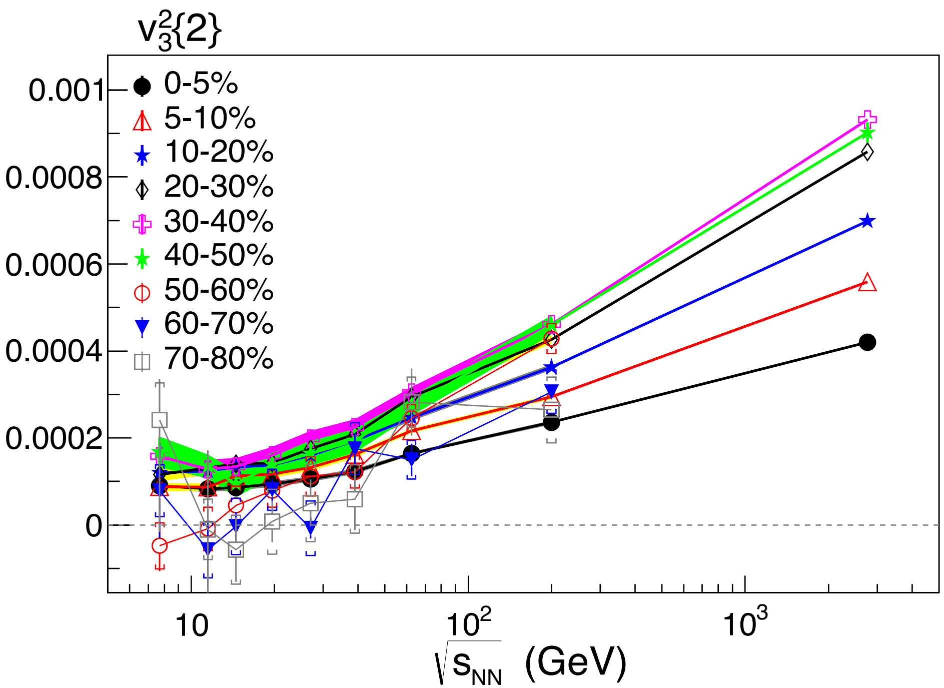
All Centralities

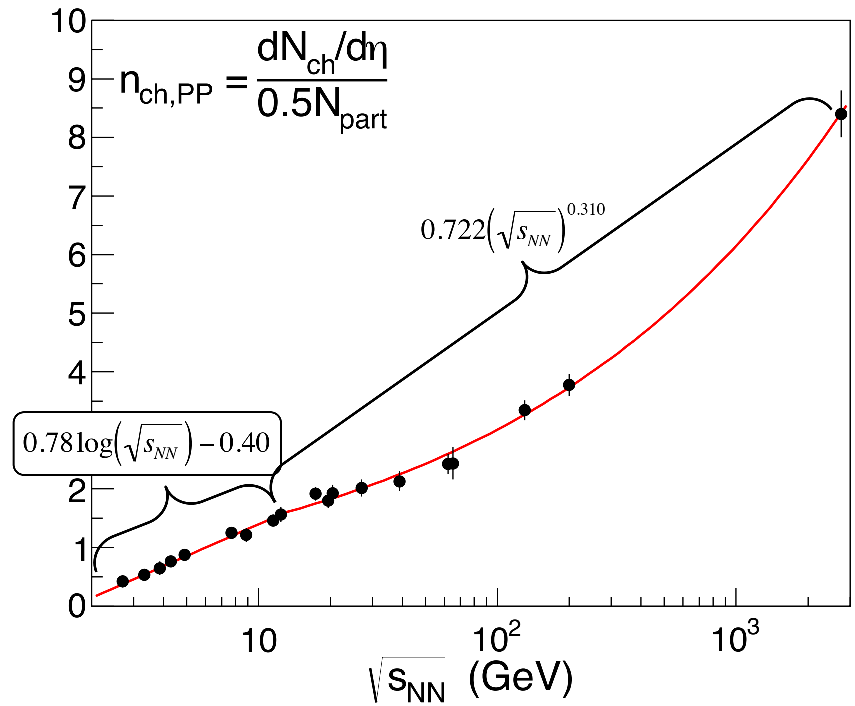


Increasing Multiplicity

Independent of energy range, one expects higher energy collisions producing more particles to more effectively convert geometry fluctuations into v_3.

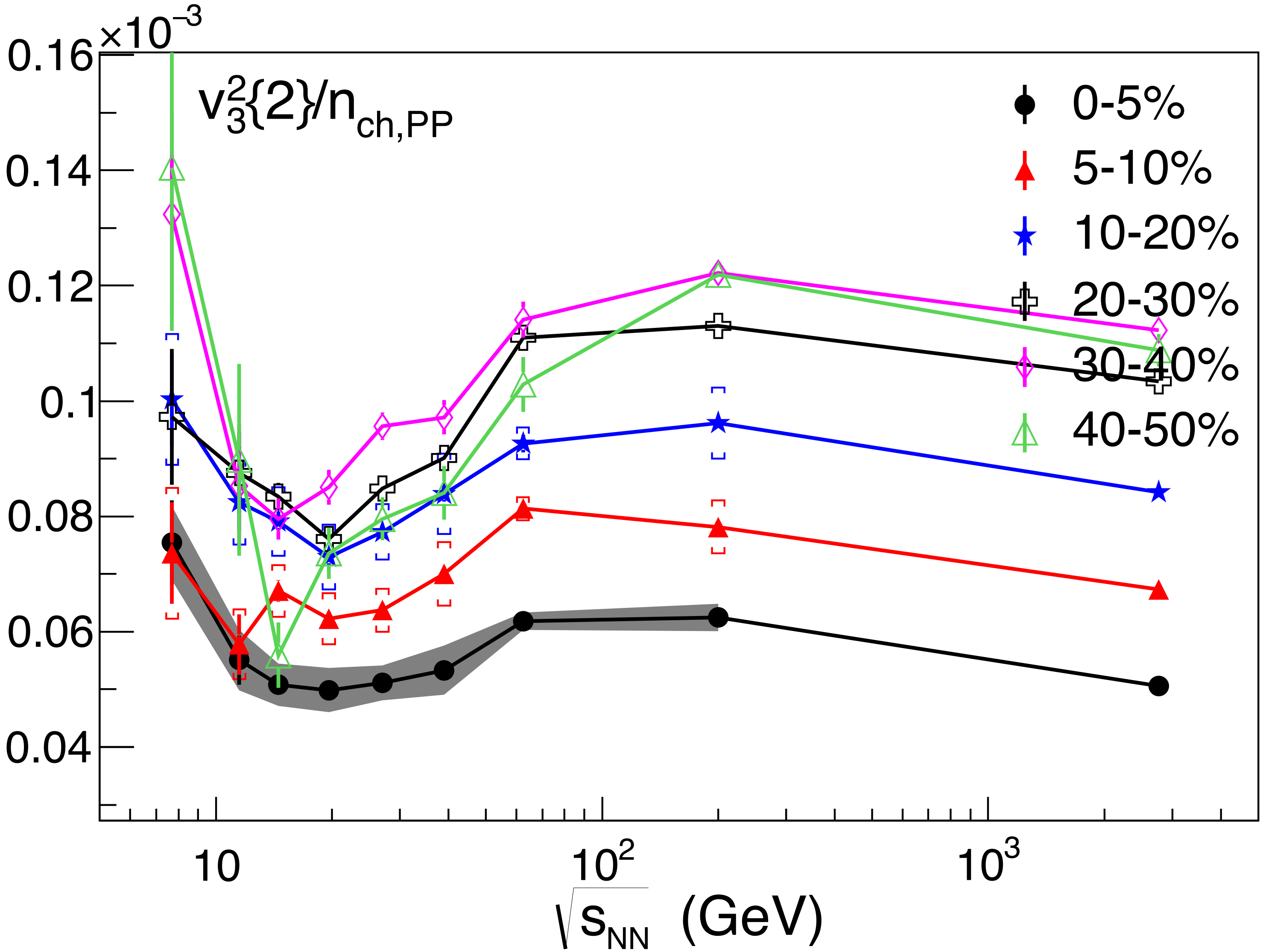
Deviations from that expectation could be indicative of interesting trends like a softening of the equation of state. What does v_3^2/N_{ch} look like?





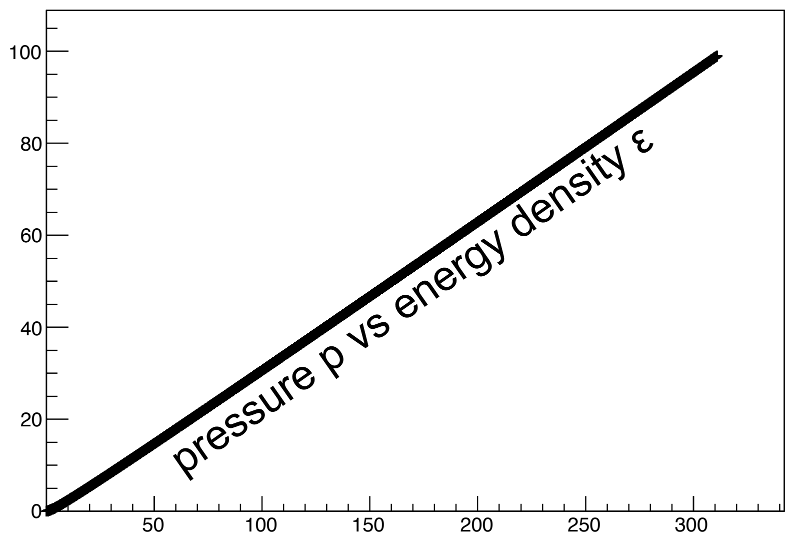
We parameterize the worlds data and take the ratio

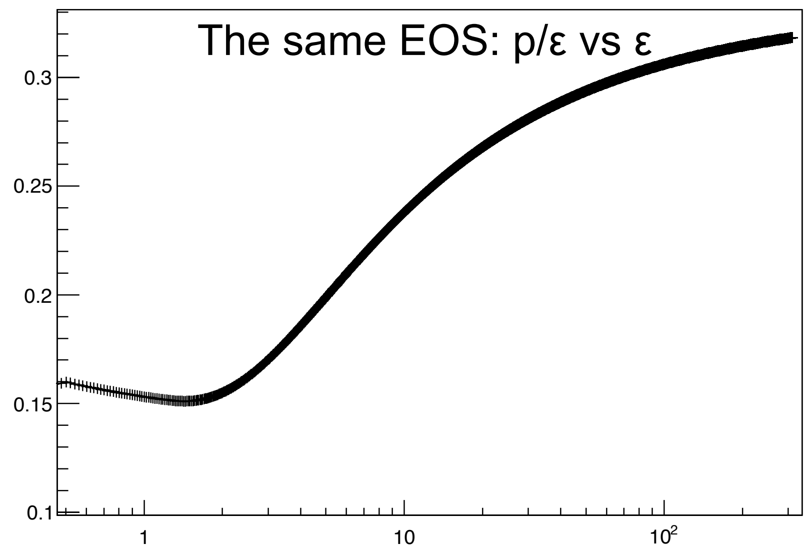
Softening?



Local minima is present for all centralities between 0 and 50%

Lattice EOS

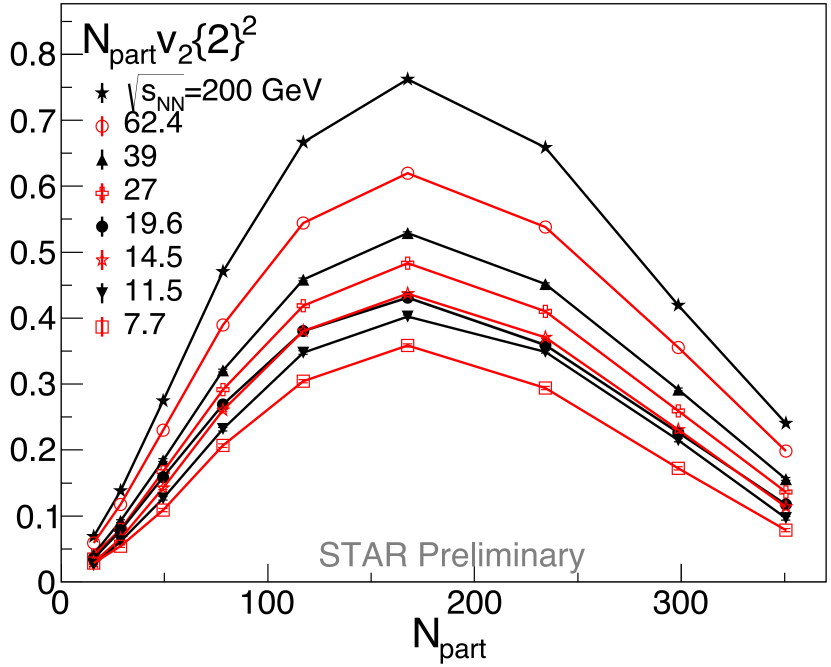


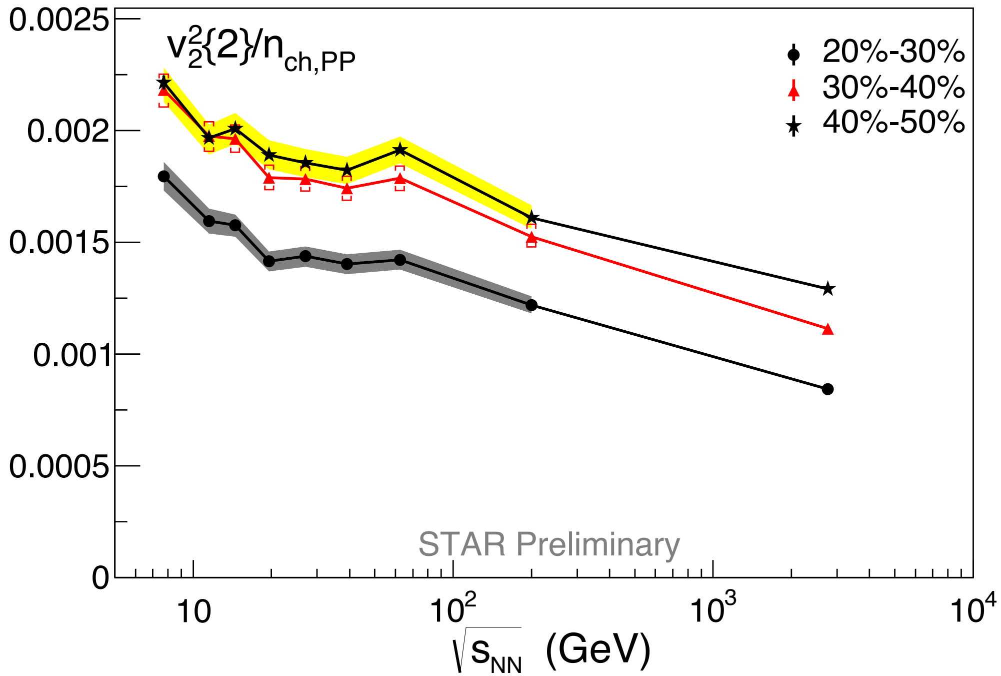


Plotting format matters!

especially when looking for trends in pressure vs energy density

What about v_2?



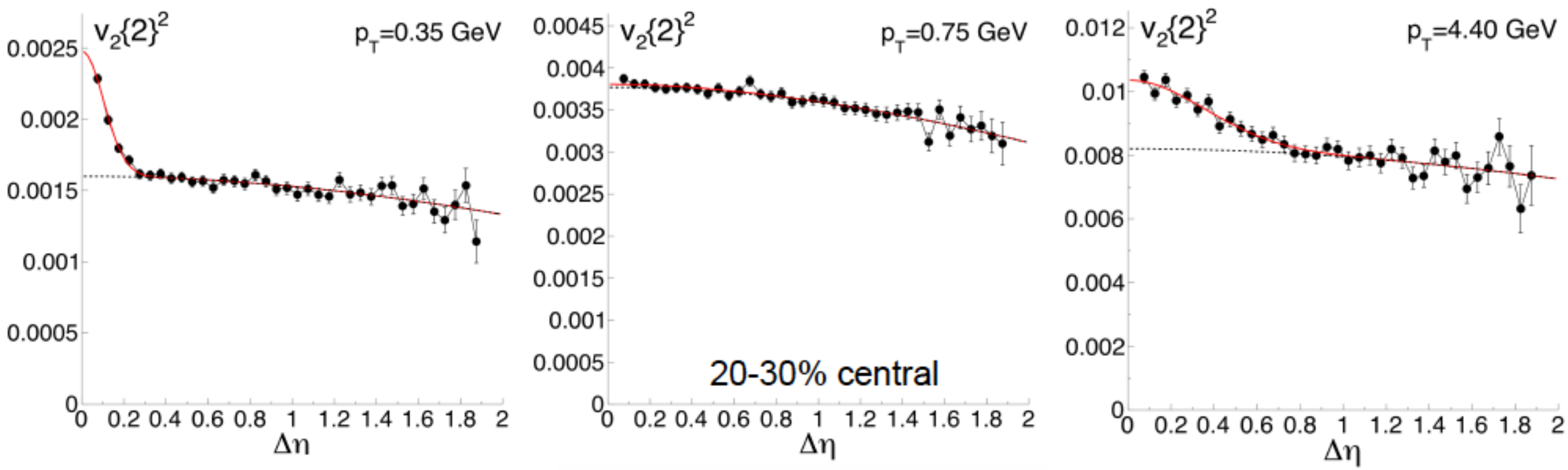


p_T Dependence of the Decomposition

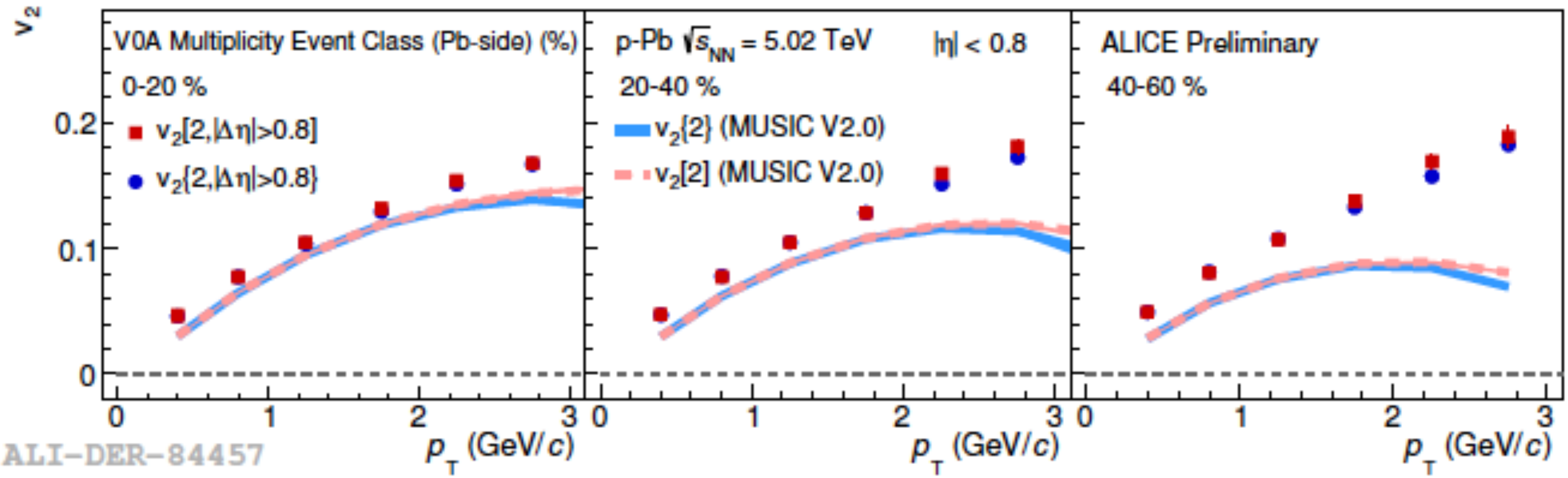
Short range correlations can be subtracted by looking at the $\Delta\eta$ dependence

HBT/Coulomb prominent at low p_T

Jets appear at higher p_T



Correlations in Small Systems



Hydro-based dynamic calculations also start to agree with the data for central p+Pb collisions

Surprisingly smooth continuity across multiplicities from 30 to 3000 (but what should we have expected?)