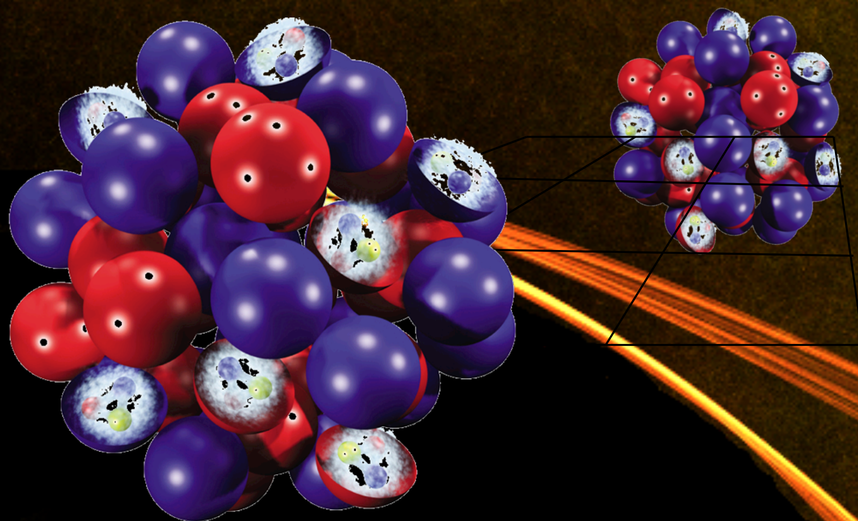
Emergent Properties of QCD and its Phase Diagram

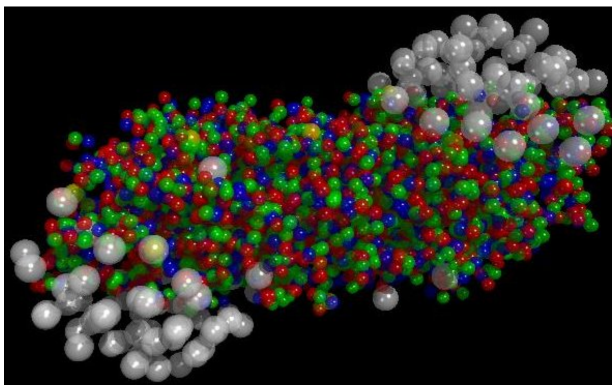


Paul Sorensen
BROOKHAVEN NATIONAL LABORATORY

QCD at Cosmic Energies
K. Greece, May 2016

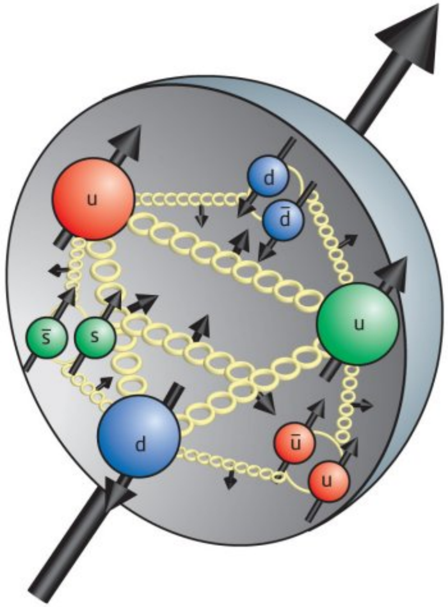
The Big Picture at RHIC

How do collective, many-body phenomena arise from first-principles QCD?



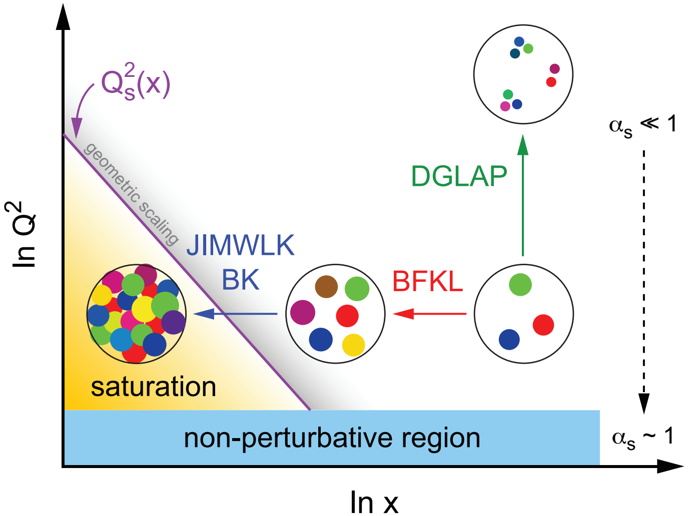
Quark-Gluon Plasma

How can this be described by a few numbers: T, μ, η/s?



Polarized Protons

How does this become ½?

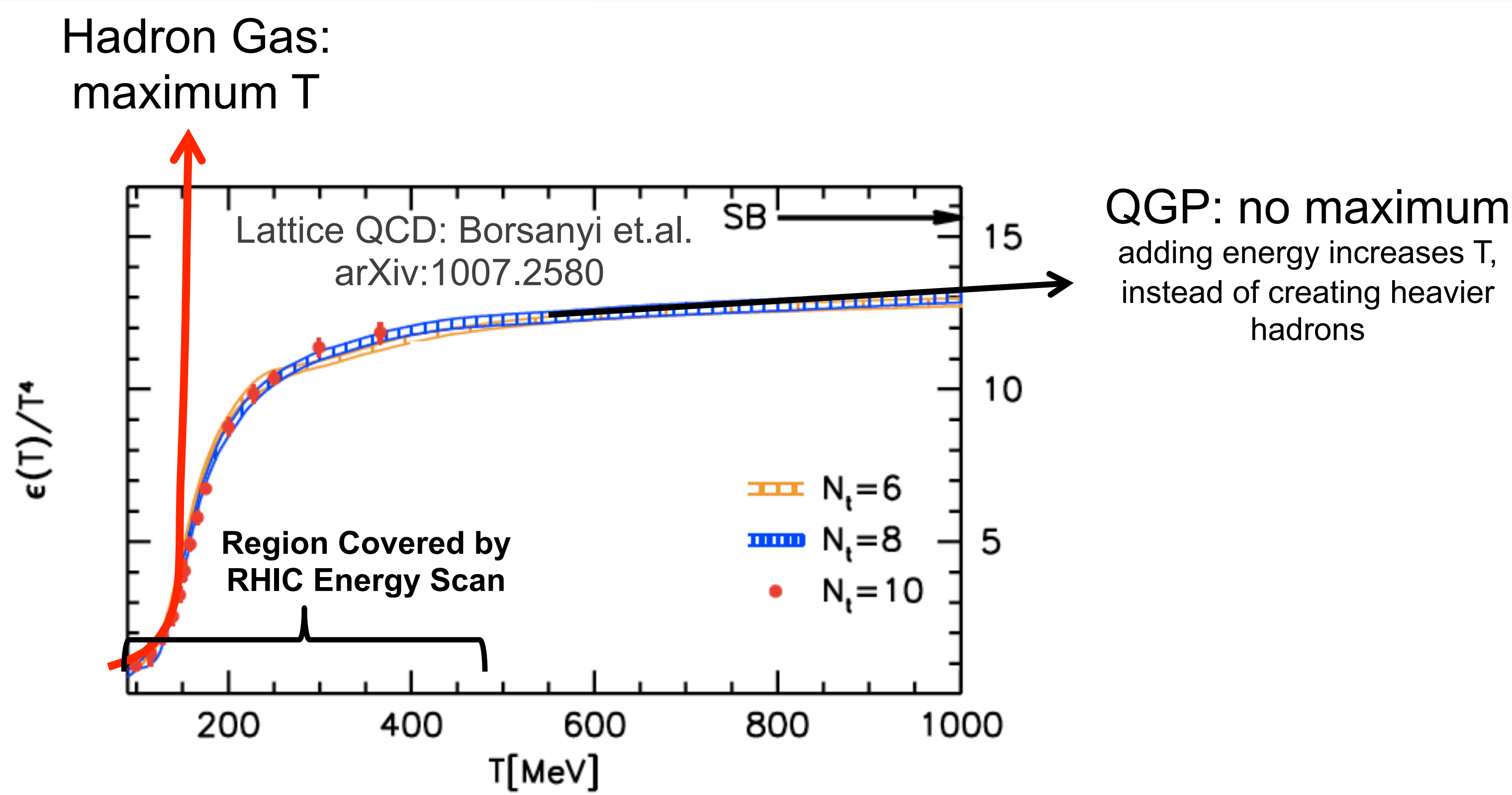


Gluons in Nuclei

How does Q_s emerge from a non-linear evolution

Thermodynamics of QCD

Quantum Chromodynamics shows a rapid crossover to QGP: ε/T^4 ($\propto$ # degrees-of-freedom) plateaus when quarks and gluons start to become the relevant degrees of freedom



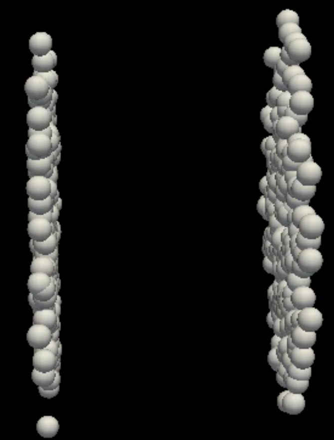
The QCD phase transition that occurred at one μ-sec after the Big Bang is accessible in lab experiments today

The density required is like packing the entire earth inside a stadium

These densities can be achieved in particle colliders


NORTHROP GRUMMAN
3

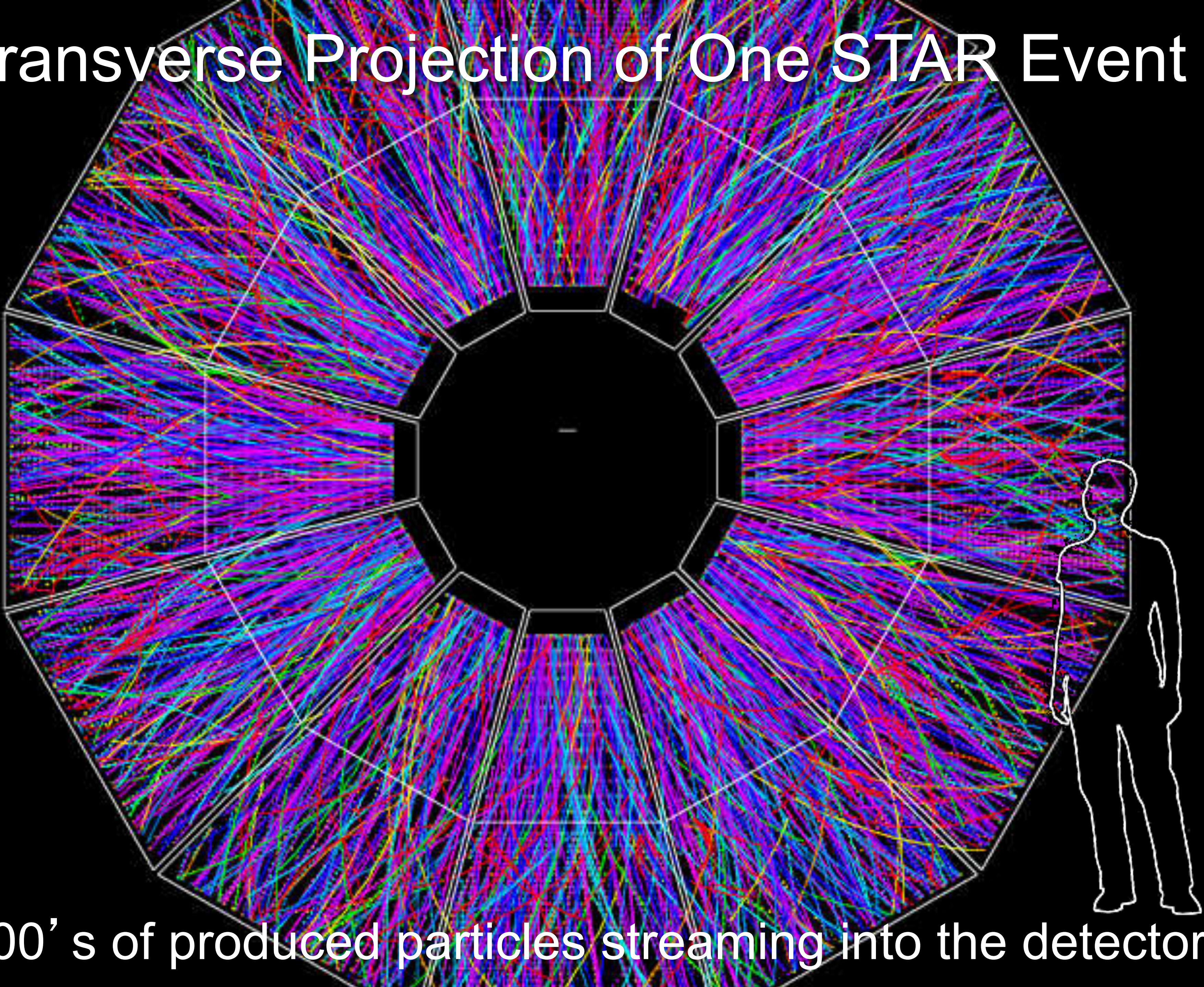
t = 0.1 fm



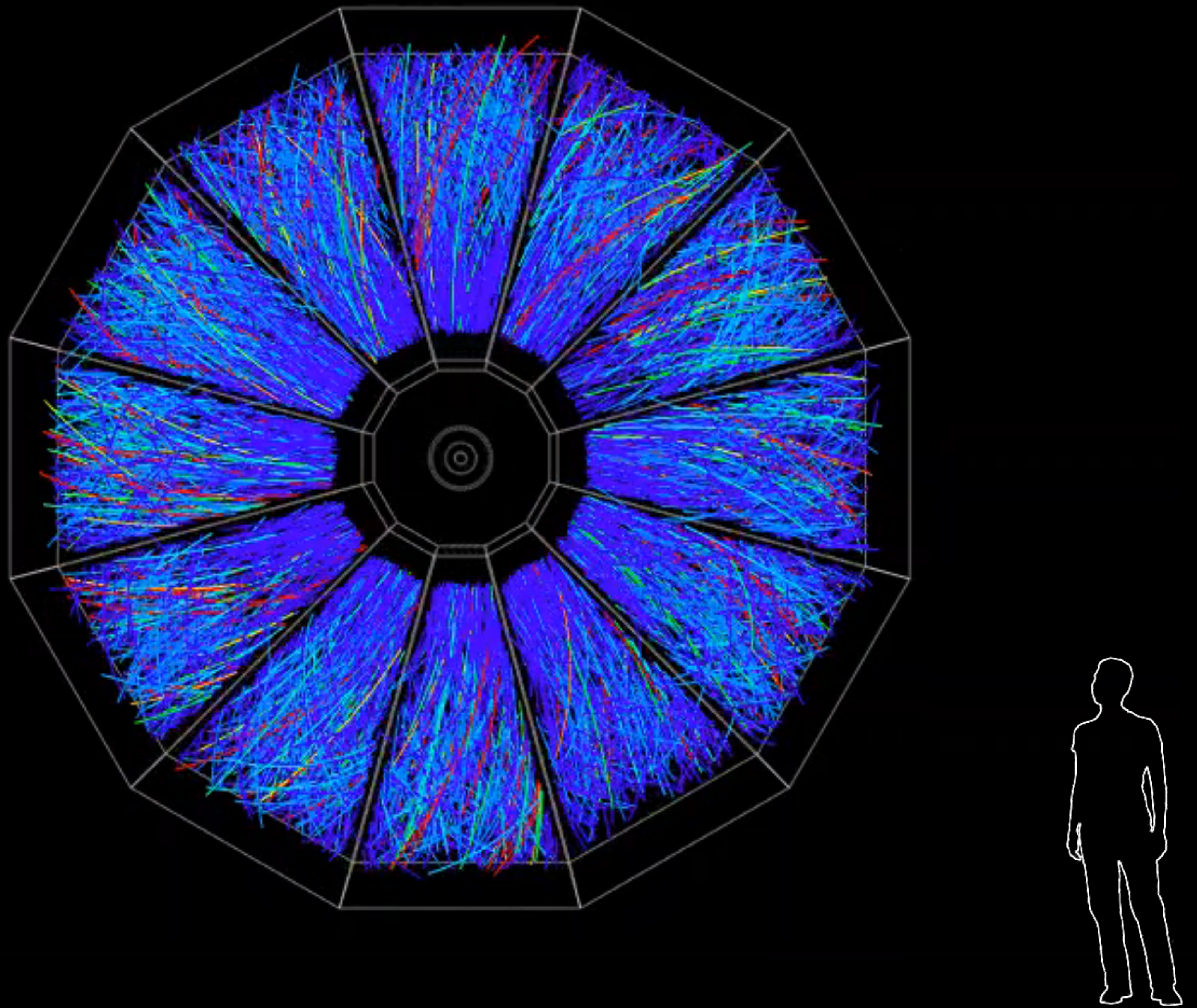
MADAI.us

The collision region is ~10^{-15} meters across
Fireball lasts for ~10^{-22} seconds

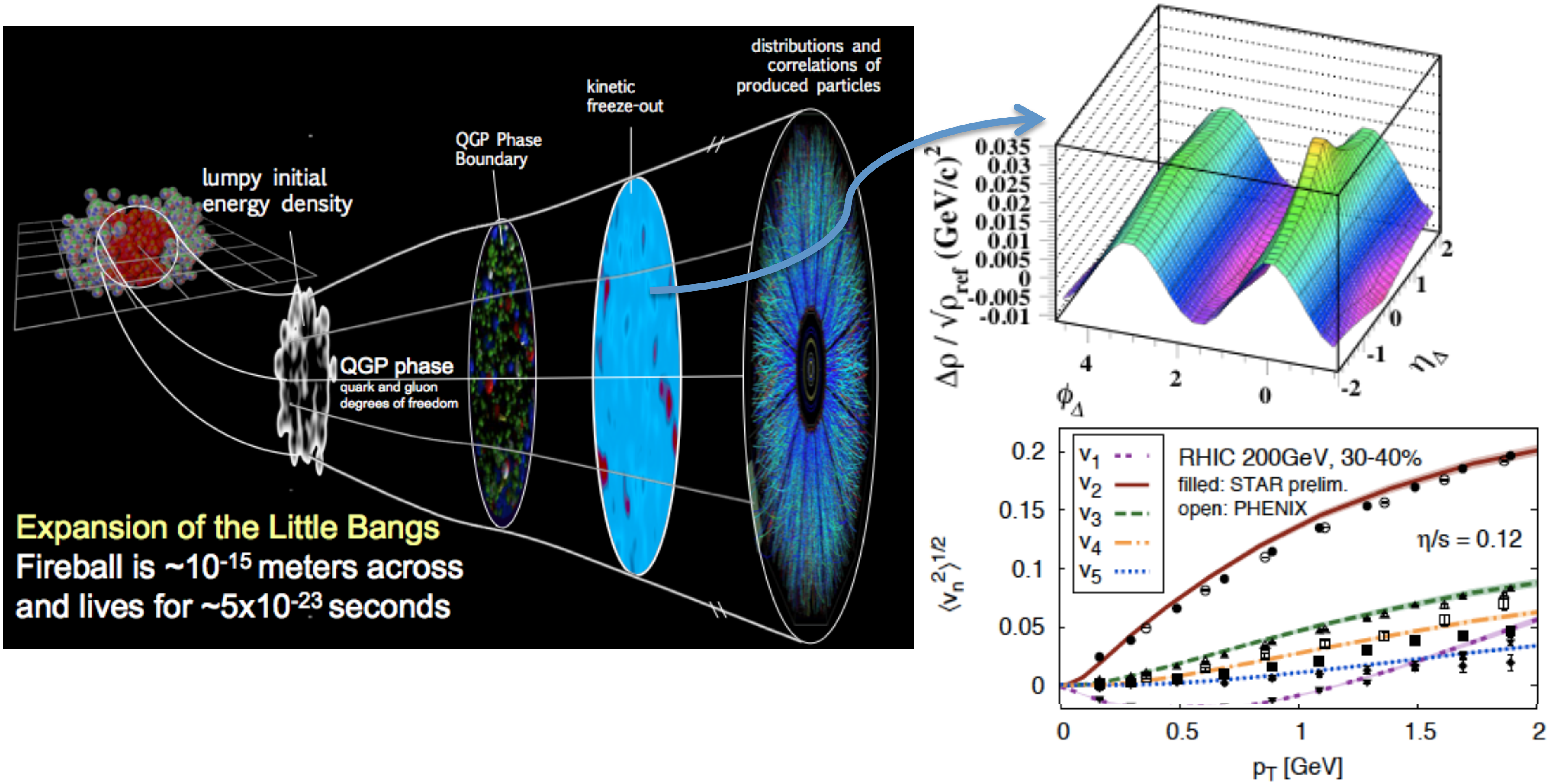
Transverse Projection of One STAR Event



1000’s of produced particles streaming into the detector



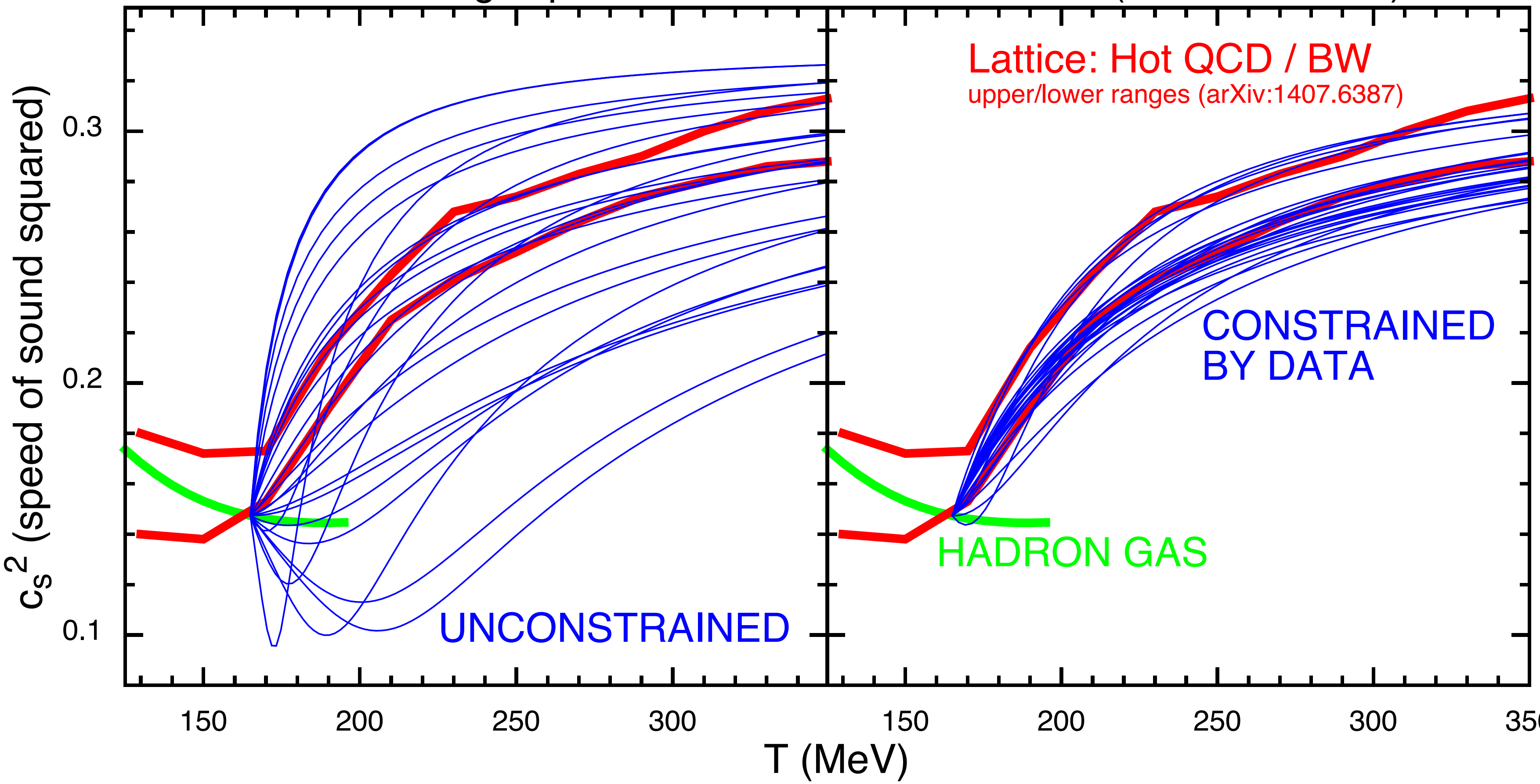
Phases of QCD: Standard Model of Little Bangs



QCD theory+modeling and constant experimental guidance from RHIC and LHC now give us a detailed picture of the evolution of heavy ion collisions

Accessing Emergent Properties

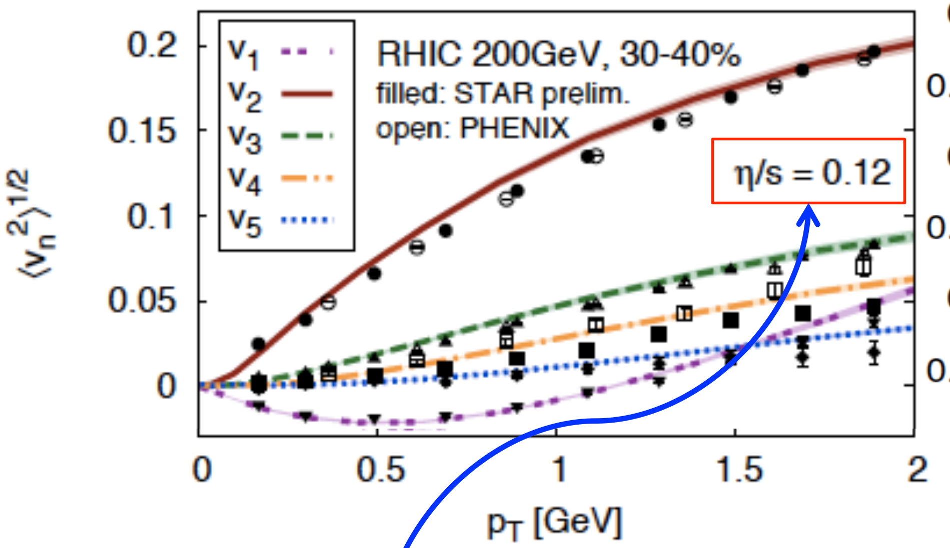
S. Pratt. E. Sangaline, P. Sorensen, H. Wang Phys. Rev. Lett. (2015)

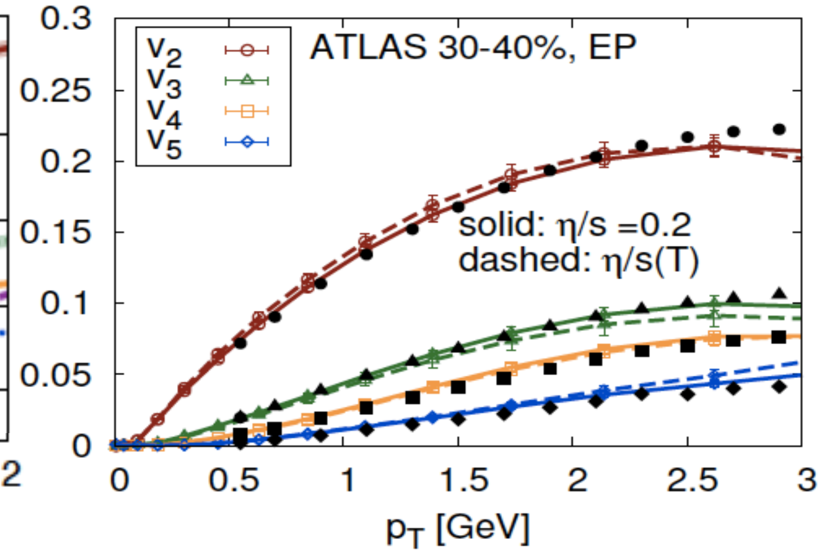


QCD theory+modeling ***and constant experimental guidance*** now give us a detailed picture of the evolution of nucleus-nucleus collisions

Emergent properties of QCD matter now experimentally accessible
Textbook Physics

Temperature Dependence of η/s



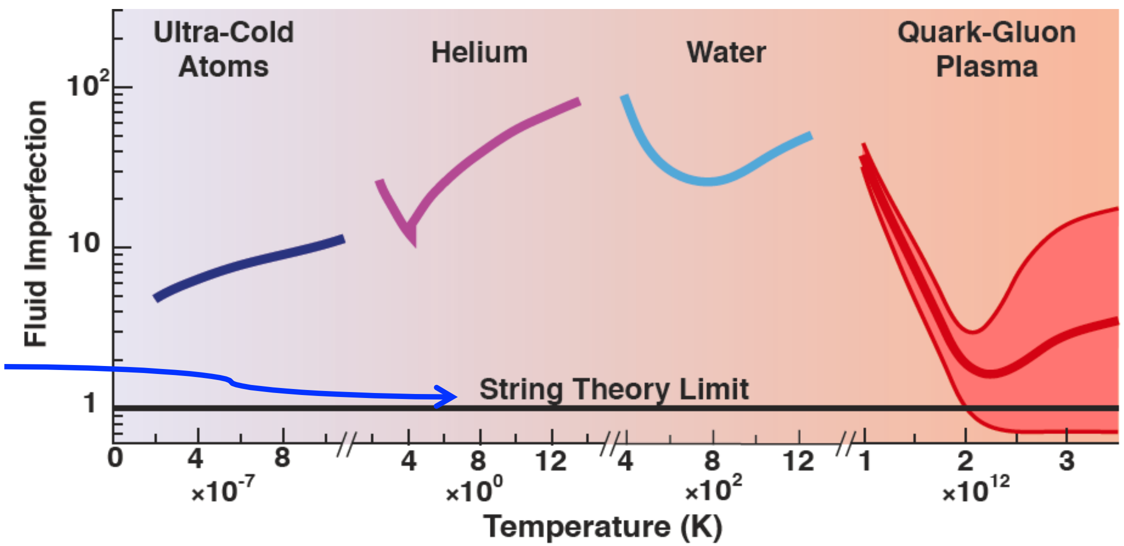


Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

η/s is 40% lower at RHIC:

Temperature dependence is accessible with an Energy Scan

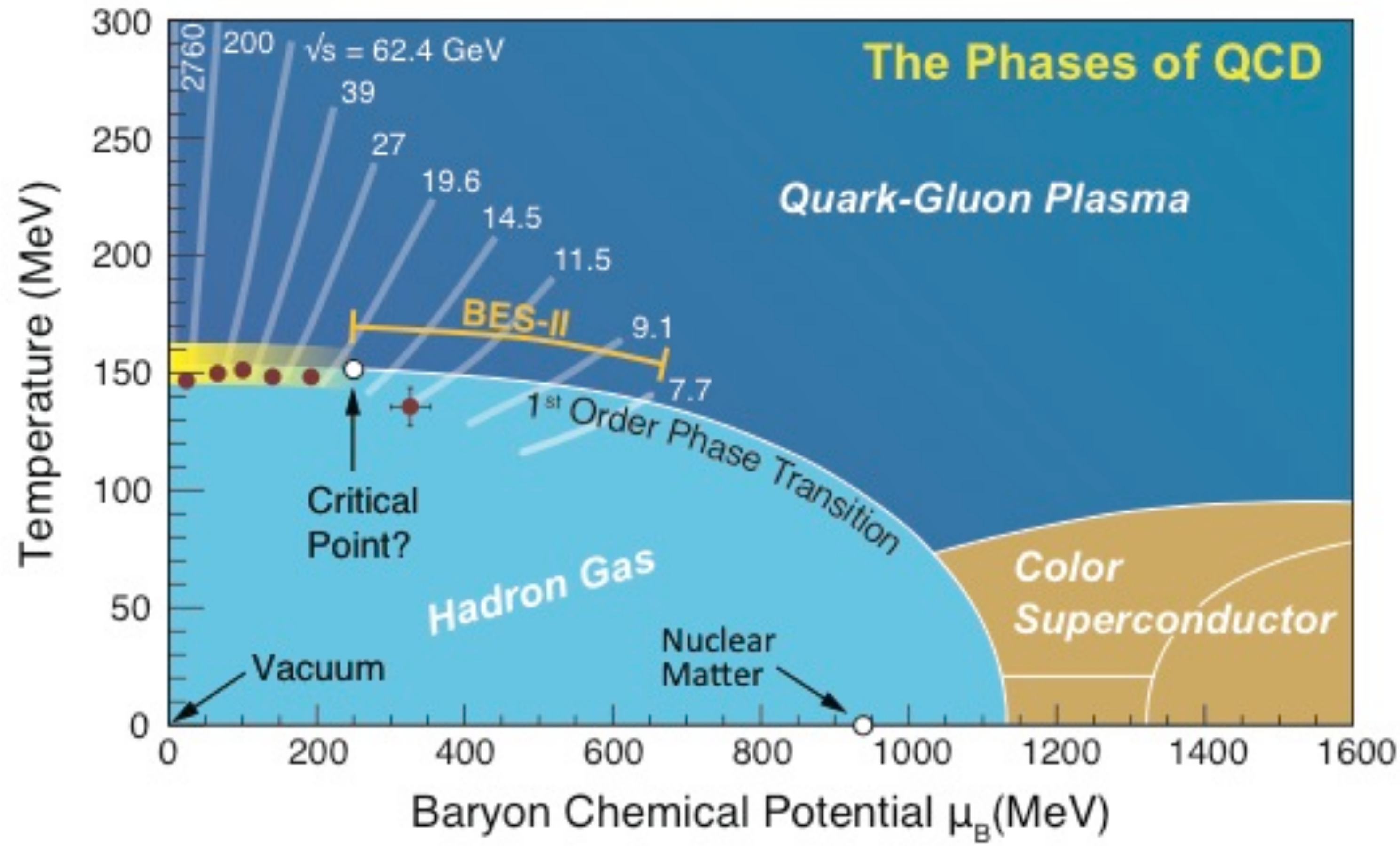
How close does η/s(T) get to the string theory limit for QCD?



Energy Scan and the QCD Phase Diagram

Provides access to the Temperature and μ_B dependence of the EOS, η/s, c_v...

A unique capability, a unique opportunity



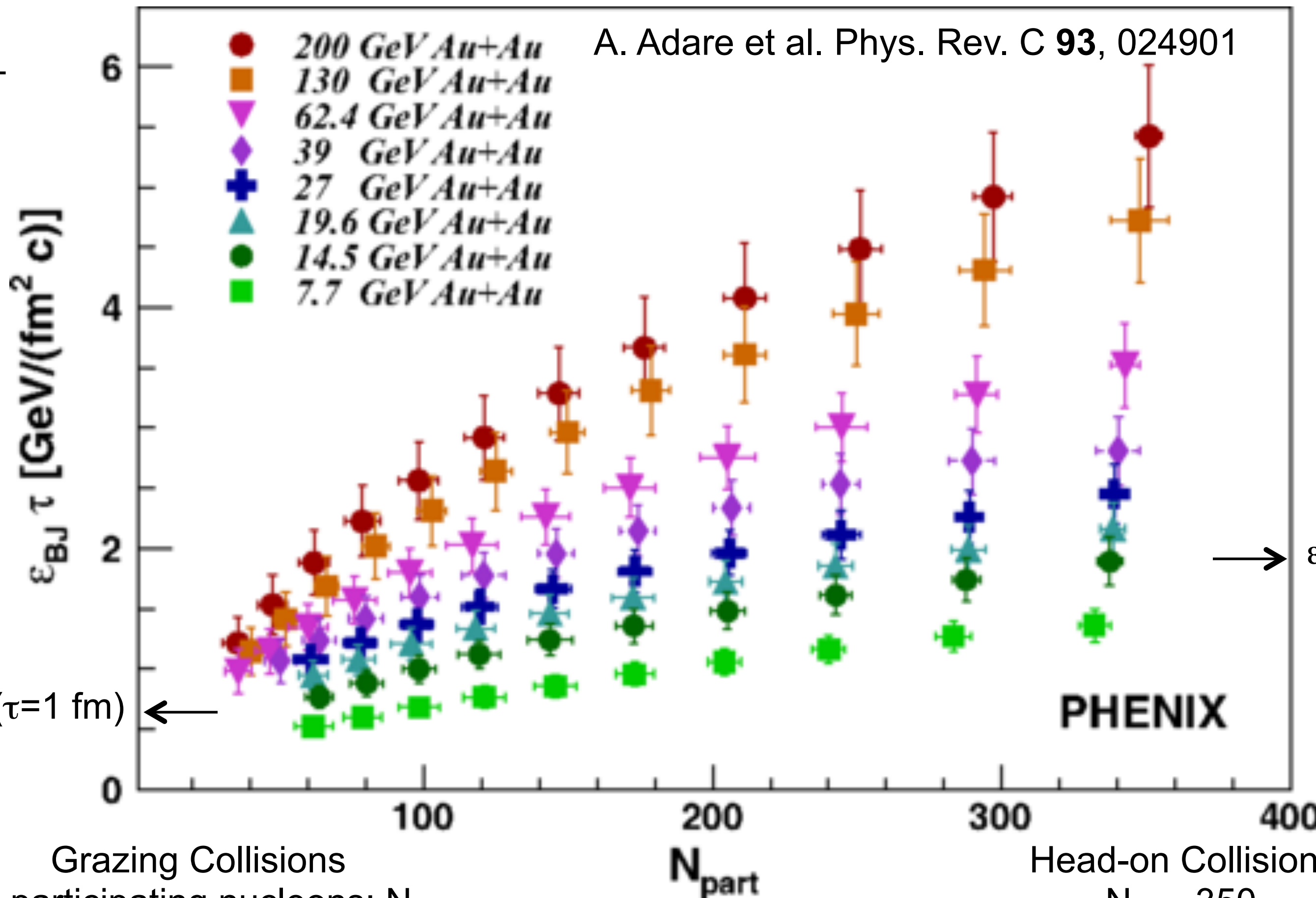
E-F-Theories suggest there should be a critical point at higher μ_B: is there?

Identification of this landmark → a significant discovery potential

Do We Still Create QGP at Lower Energies?

Phase 1: Exploratory Scan

$$\varepsilon_{BJ} = \frac{1}{\tau}\frac{dE_T}{dy}$$



Grazing Collisions
few participating nucleons: N_{part}

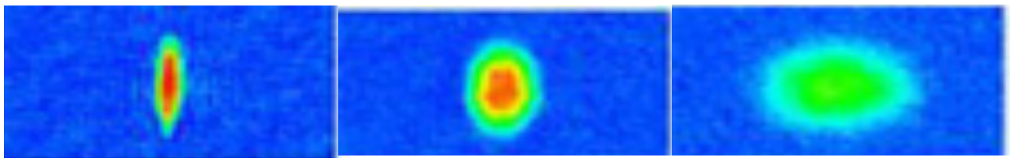
Head-on Collisions
N_{part}~350

The critical energy density for QGP is expected to be ε_c~0.6 GeV/fm^3

It's not clear that QGP will be formed at the lowest energies

Global Correlations: 7.7 GeV to 2.76 TeV

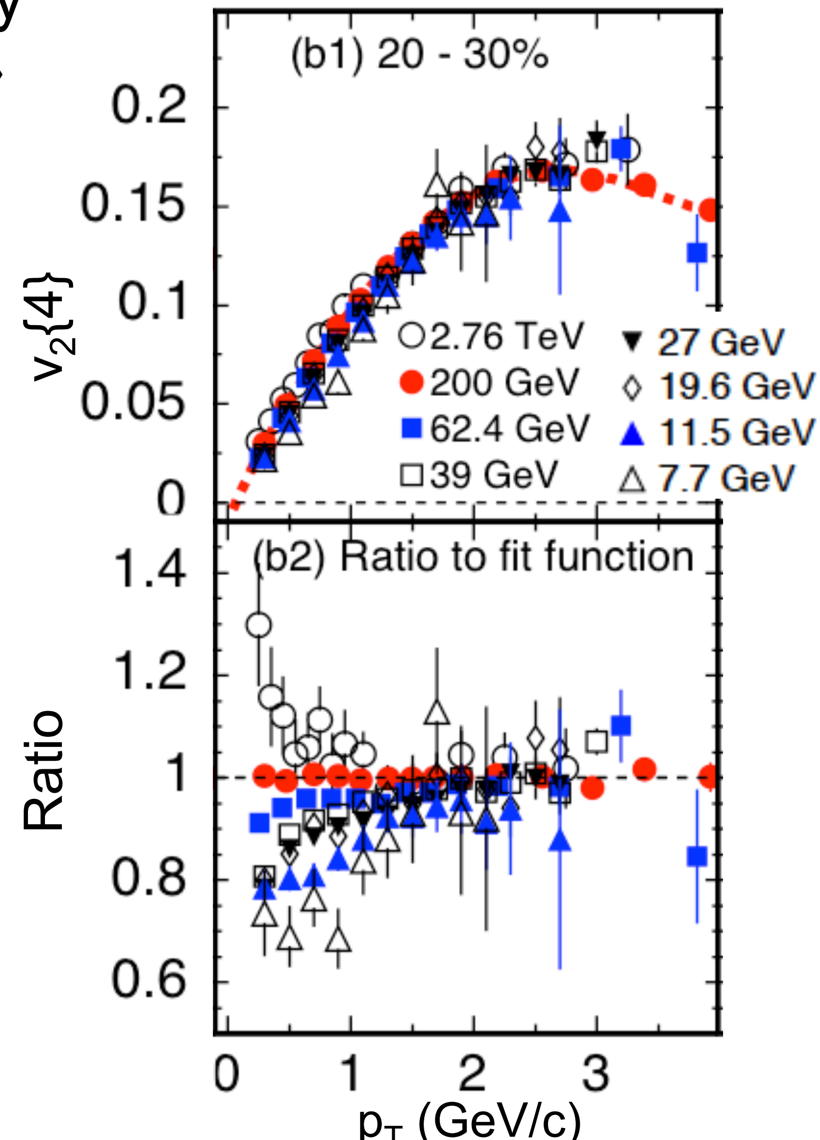
conversion of density inhomogeneity into momentum space: $\langle v_2 = \cos 2\varphi \rangle$



Surprising consistency as the collision energy changes by a factor ~400

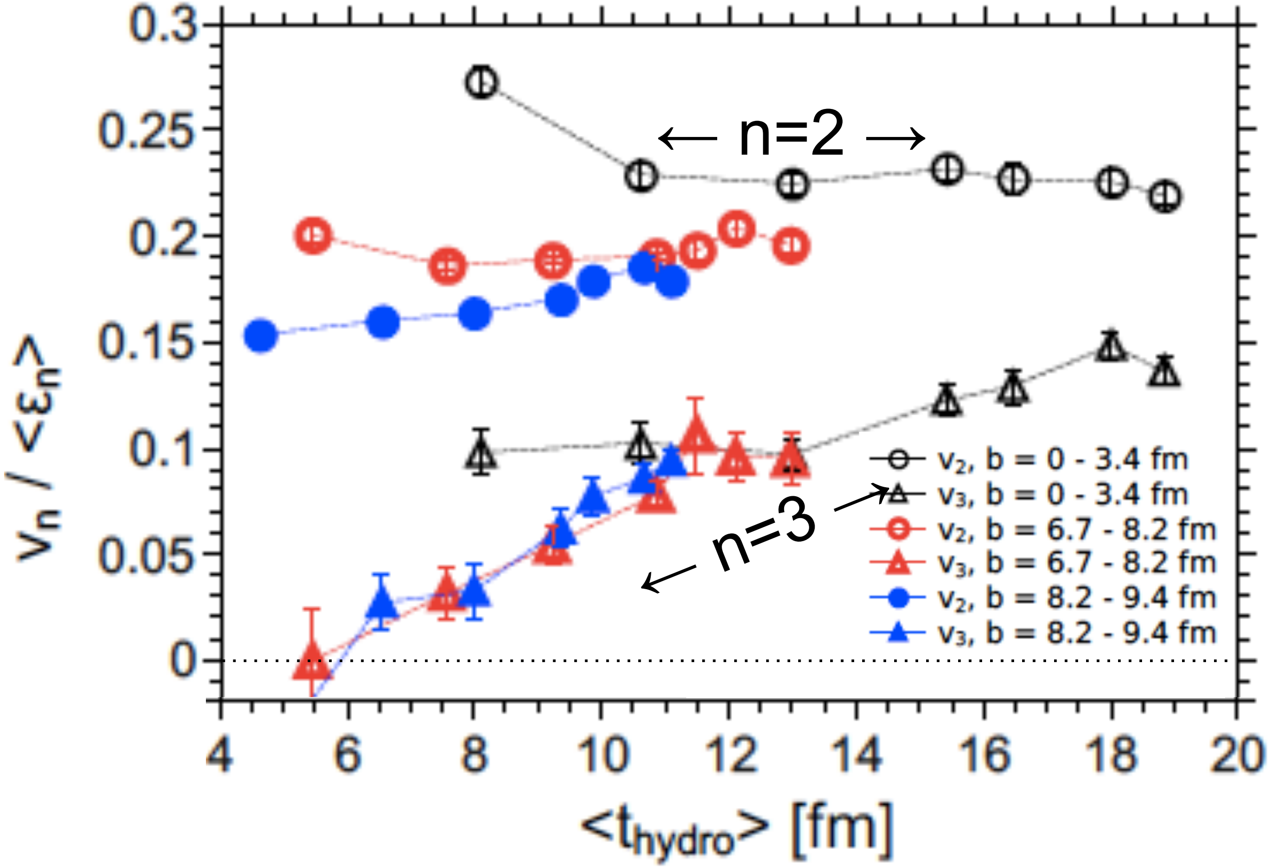
Initial energy density changes by nearly a factor of 10

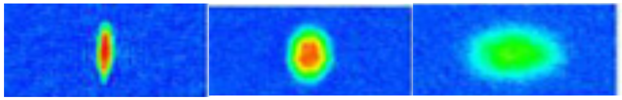
No indication of a turn off of the QGP

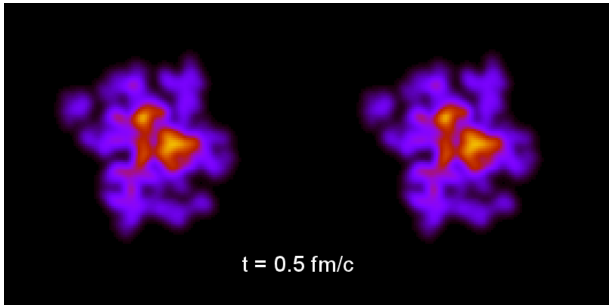


Sensitivity to Low Viscosity QGP Phase

J. Auvinen, H. Petersen, Phys. Rev. C 88, 64908 (2013)



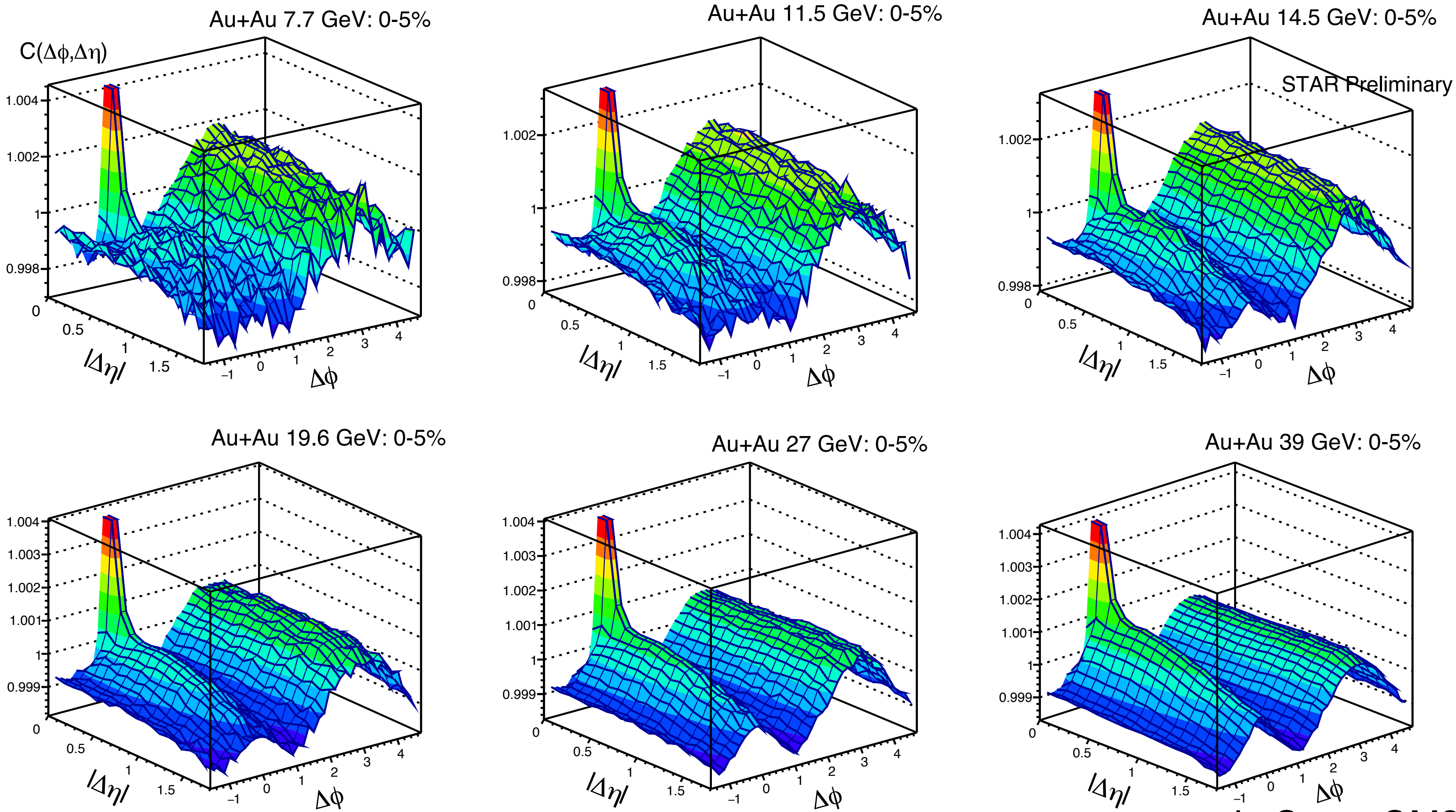




Models show that higher frequency ripples are more sensitive to the existence of a QGP phase

Higher harmonic v_3 goes away when the QGP phase disappears. v_2 doesn't.

Ripples from the QGP

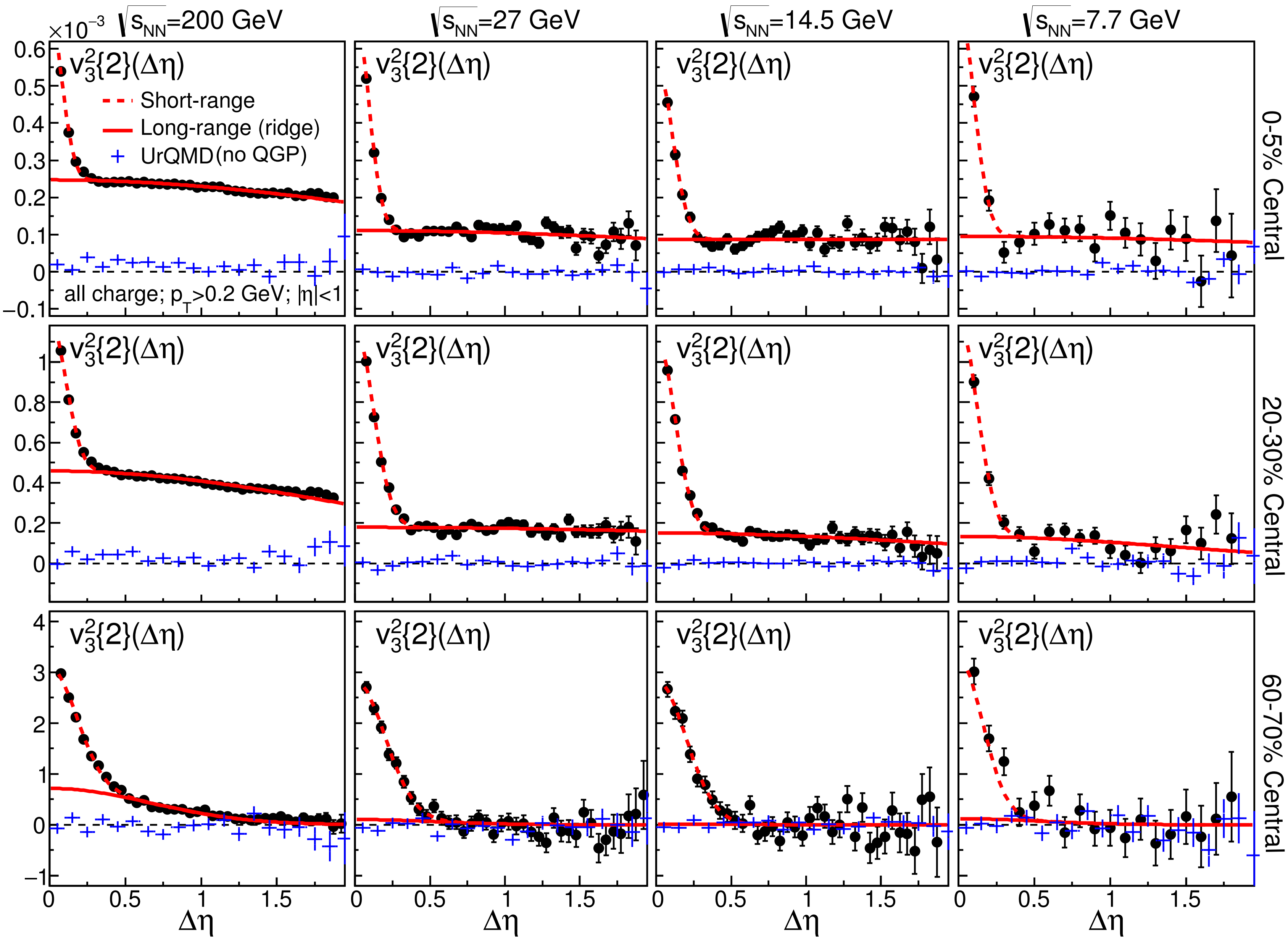


L. Song; QM2015

Correlations can be decomposed into Δη dependent harmonics

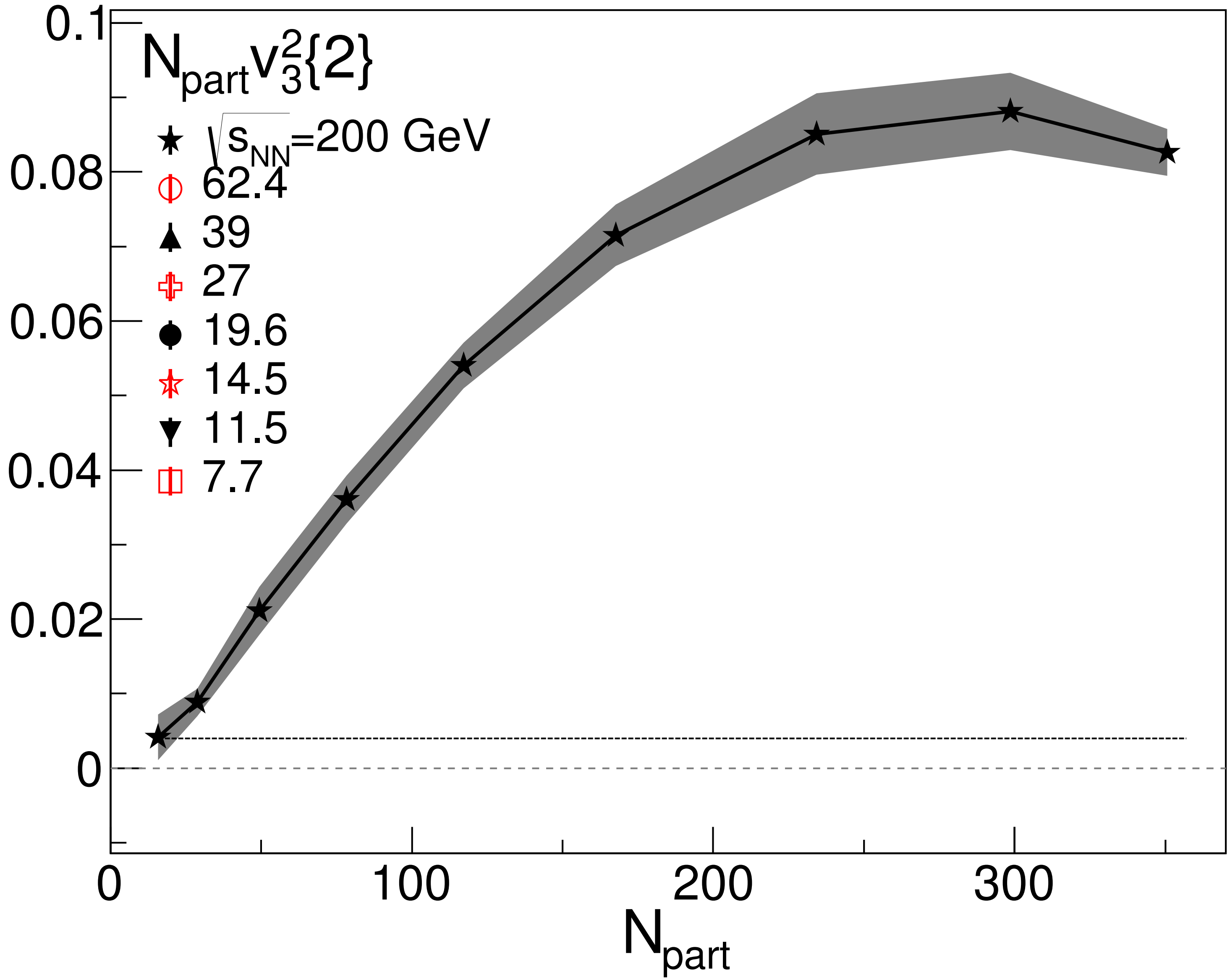
$$v_n^2\{2\}(\Delta\eta) = \langle \cos n(\varphi_1 - \varphi_2) \rangle = \sum \frac{dN}{d\Delta\varphi} \cos(n\Delta\varphi)\, d\Delta\varphi \Big/ \sum \frac{dN}{d\Delta\varphi} d\Delta\varphi$$

3rd Harmonic Decomposition

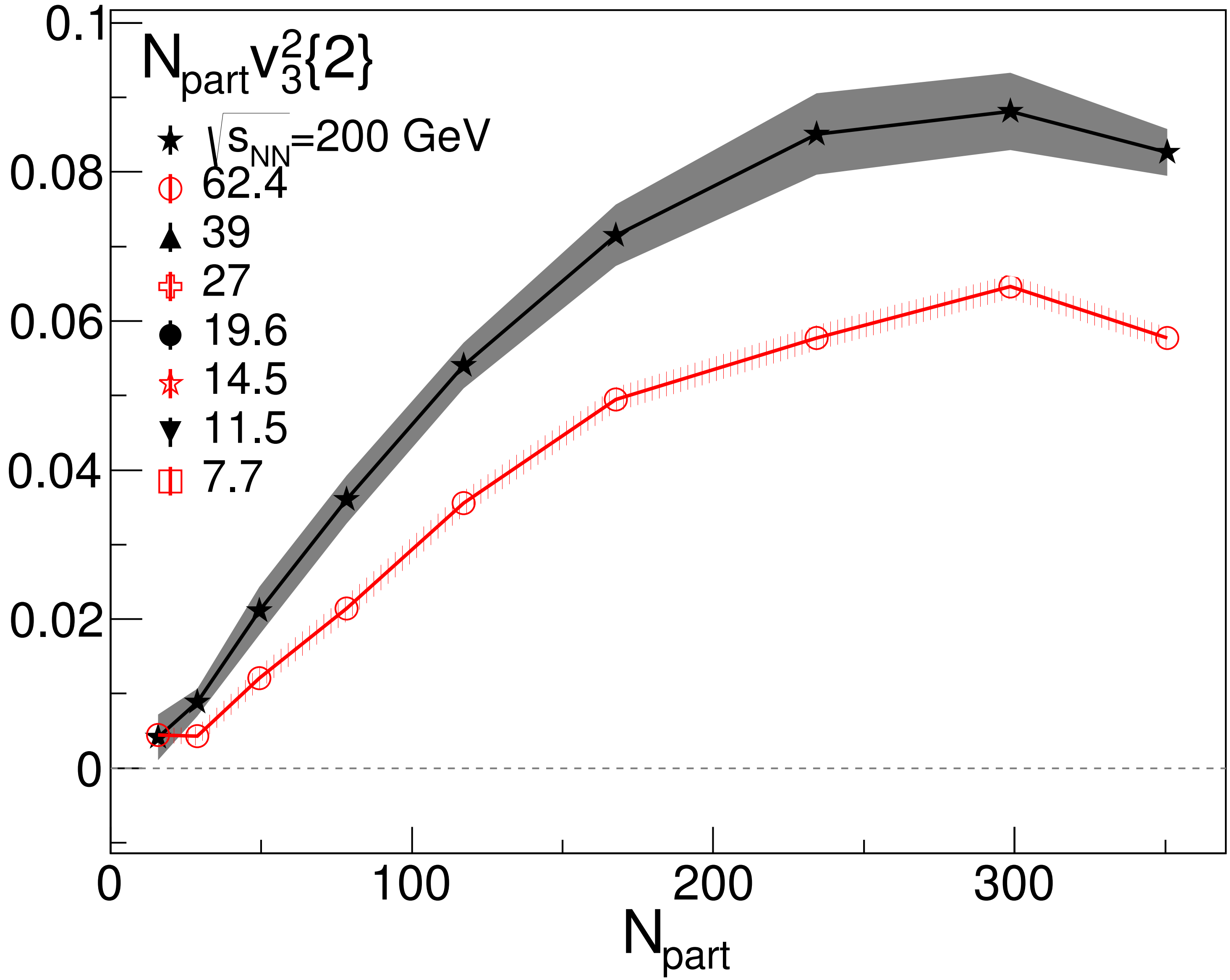


Centrality Dependence

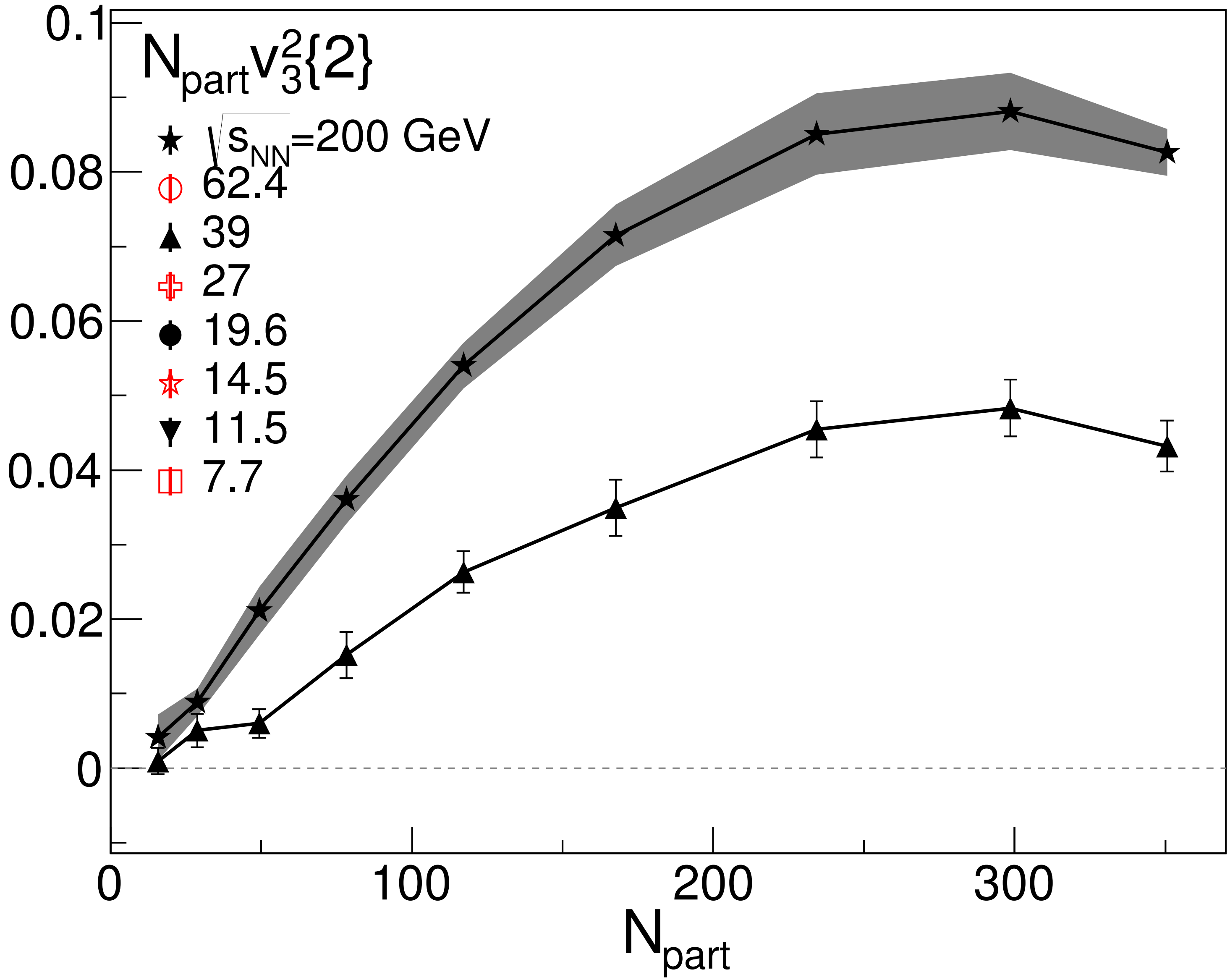
N_{part} scales out trivial 1/N system size dependence: *linear superposition of p+p*



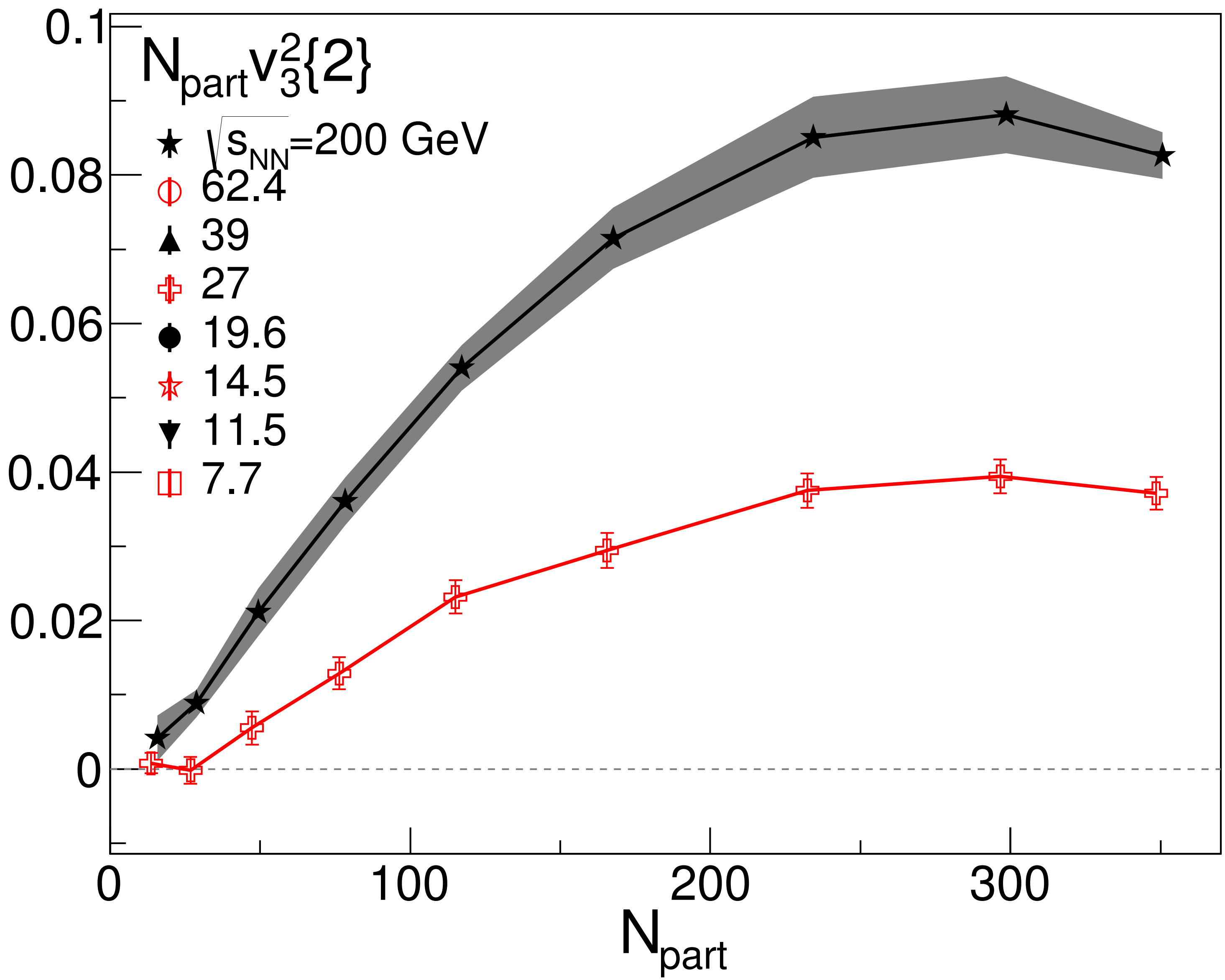
Centrality Dependence



Centrality Dependence



Centrality Dependence



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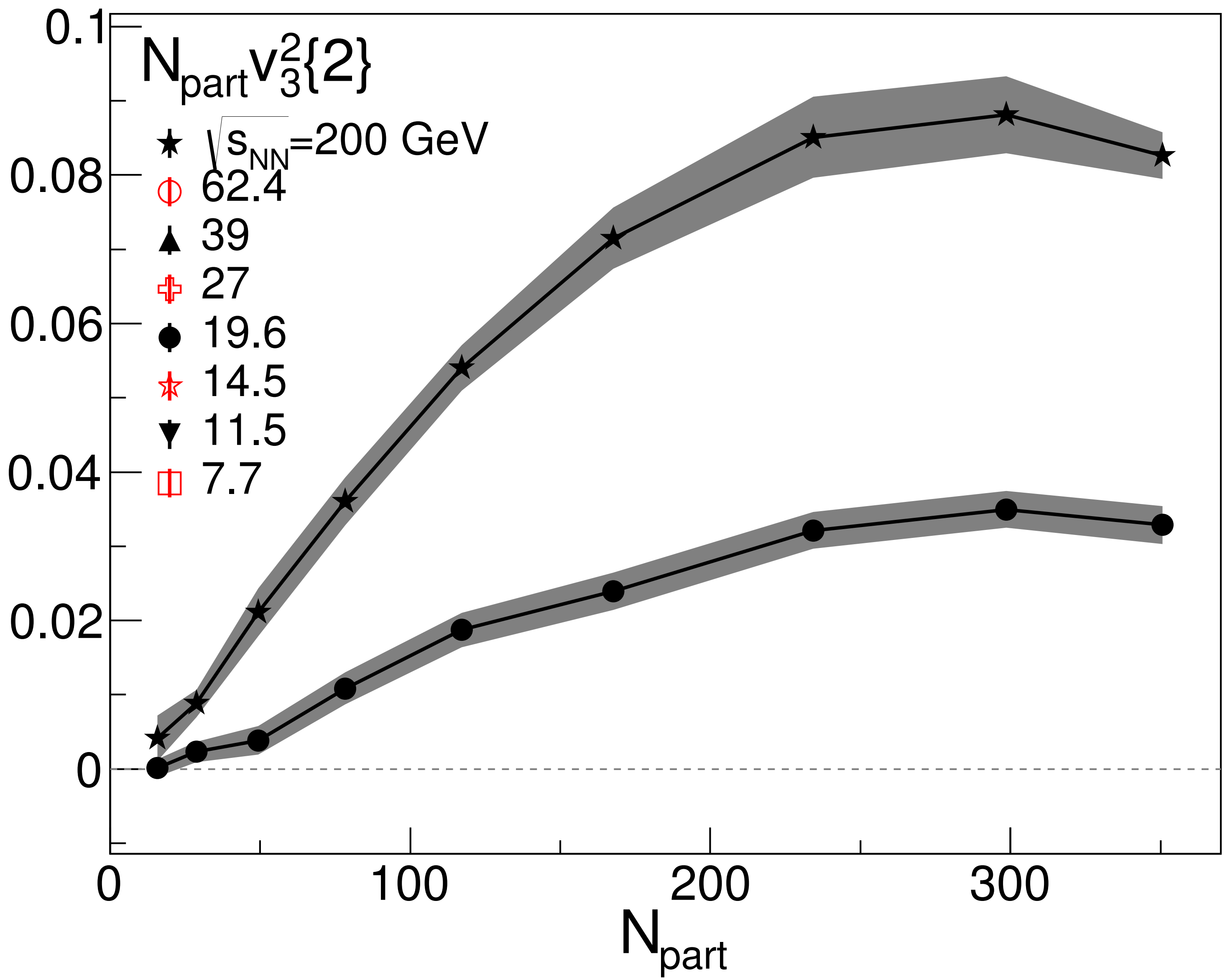

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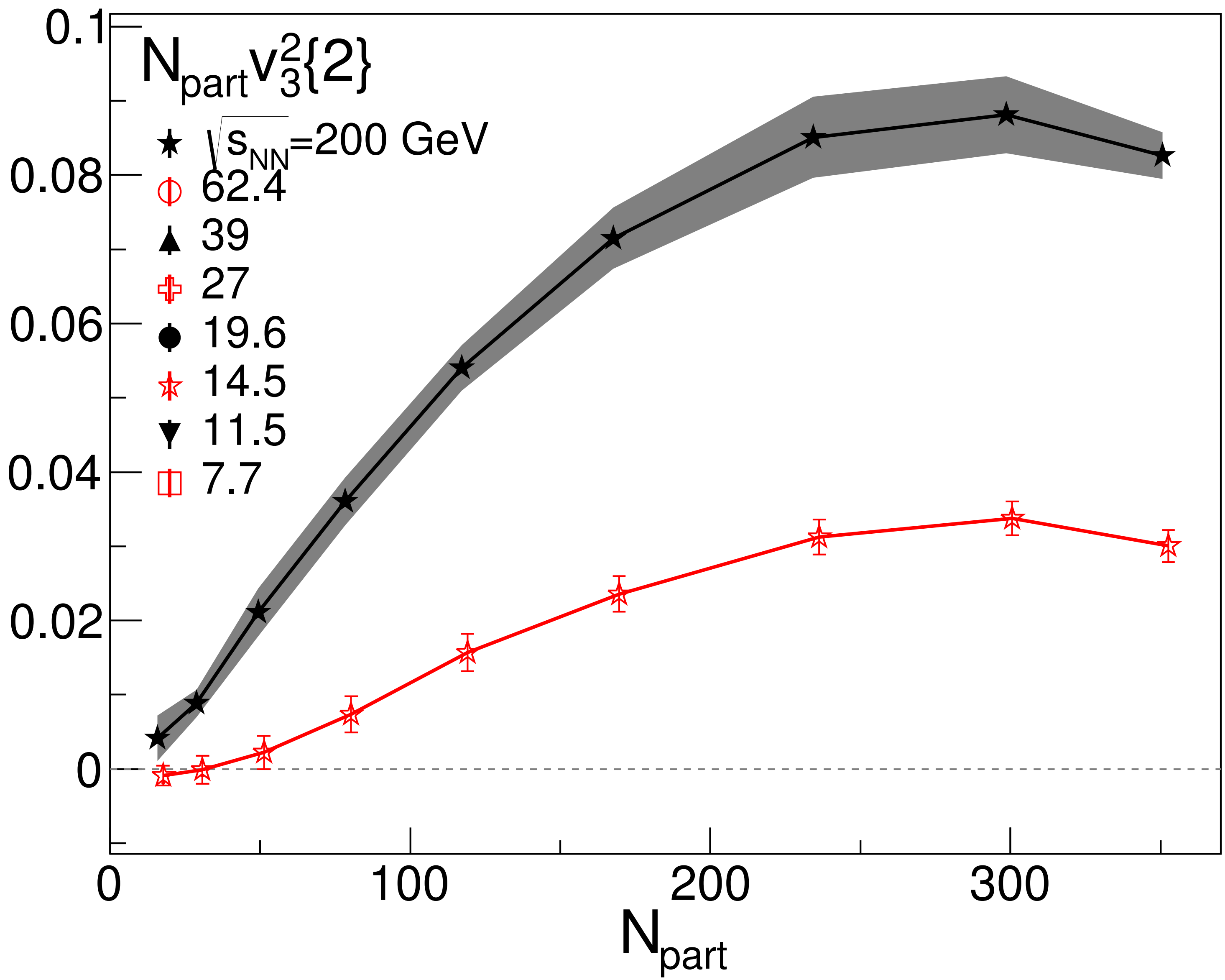

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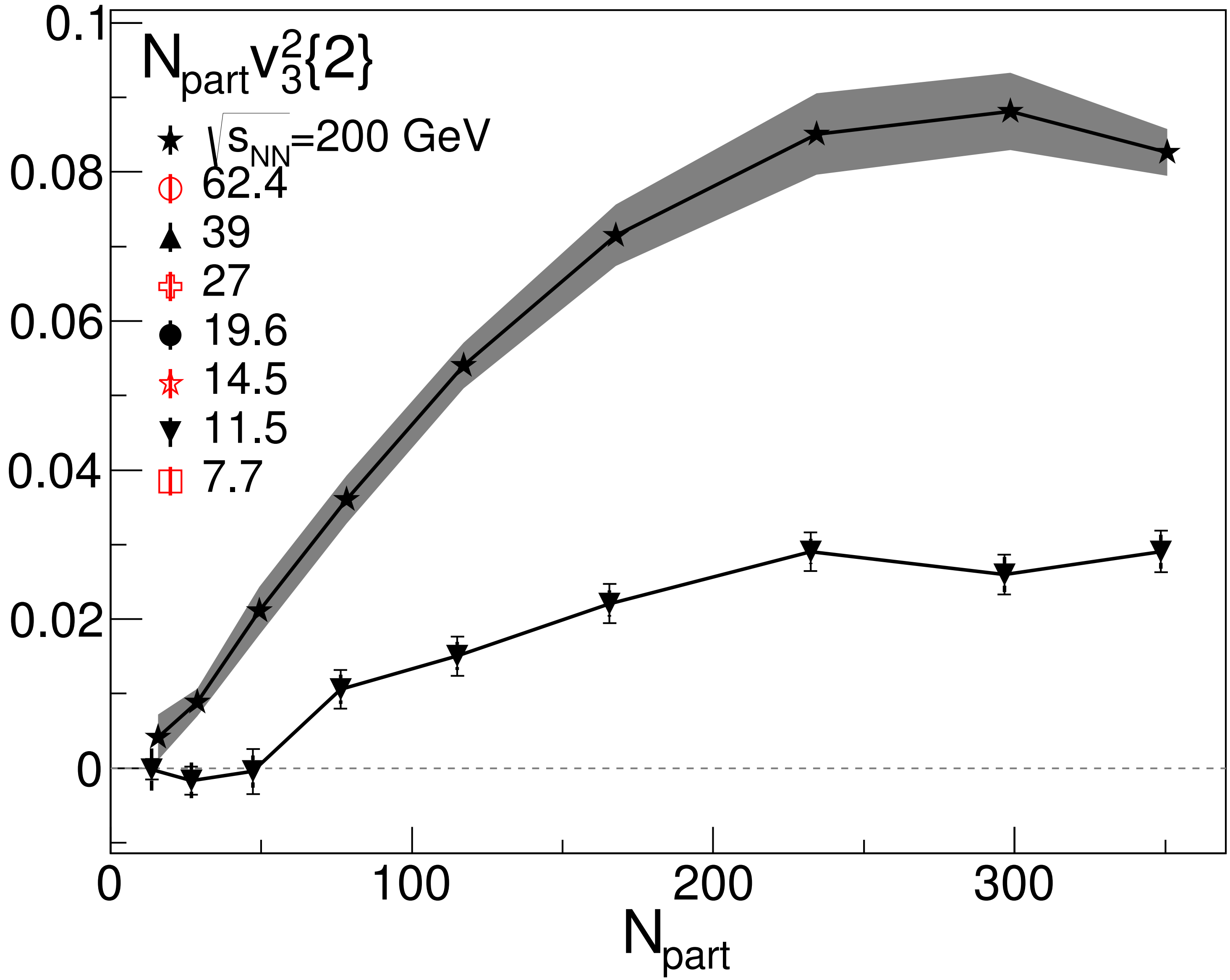

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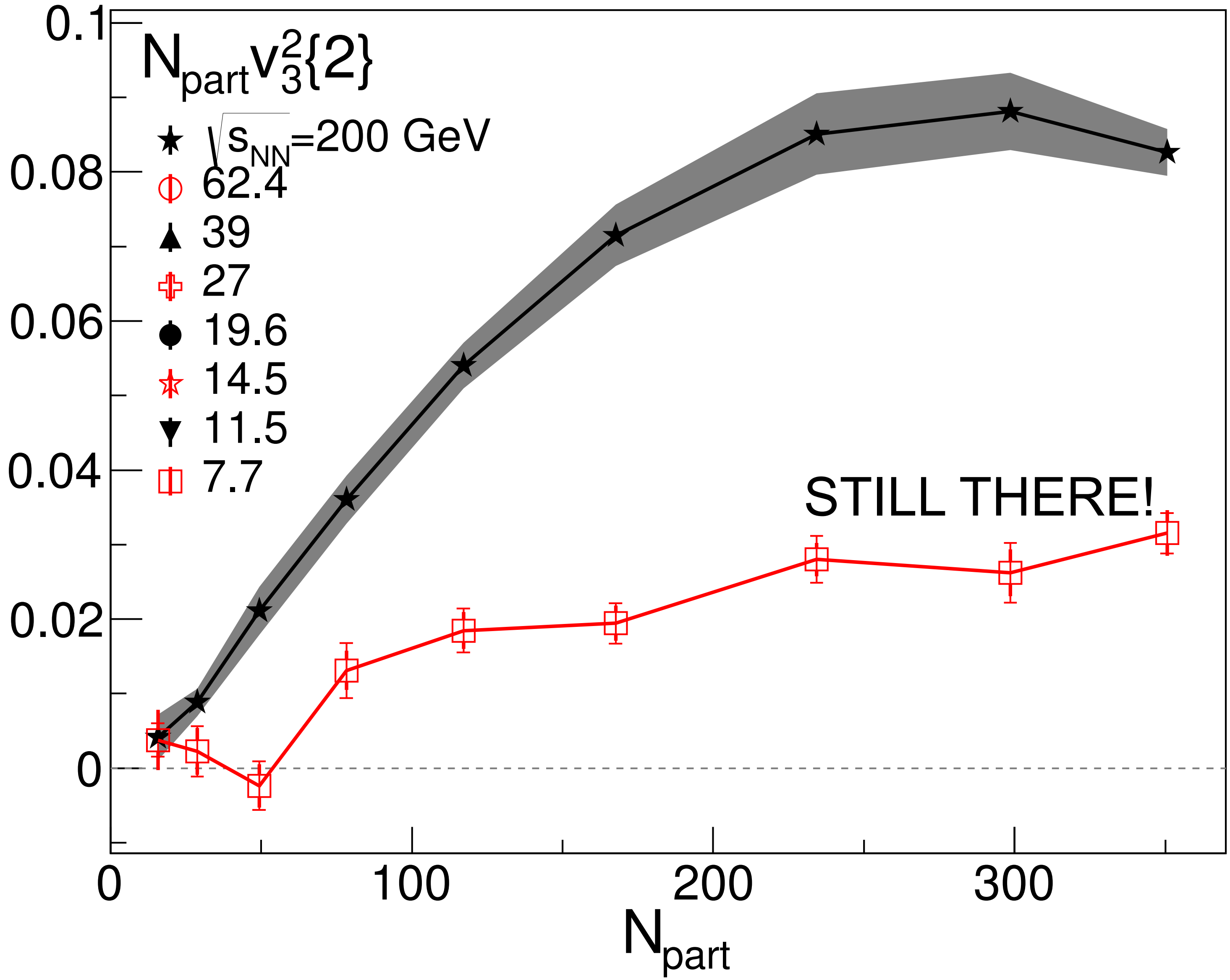

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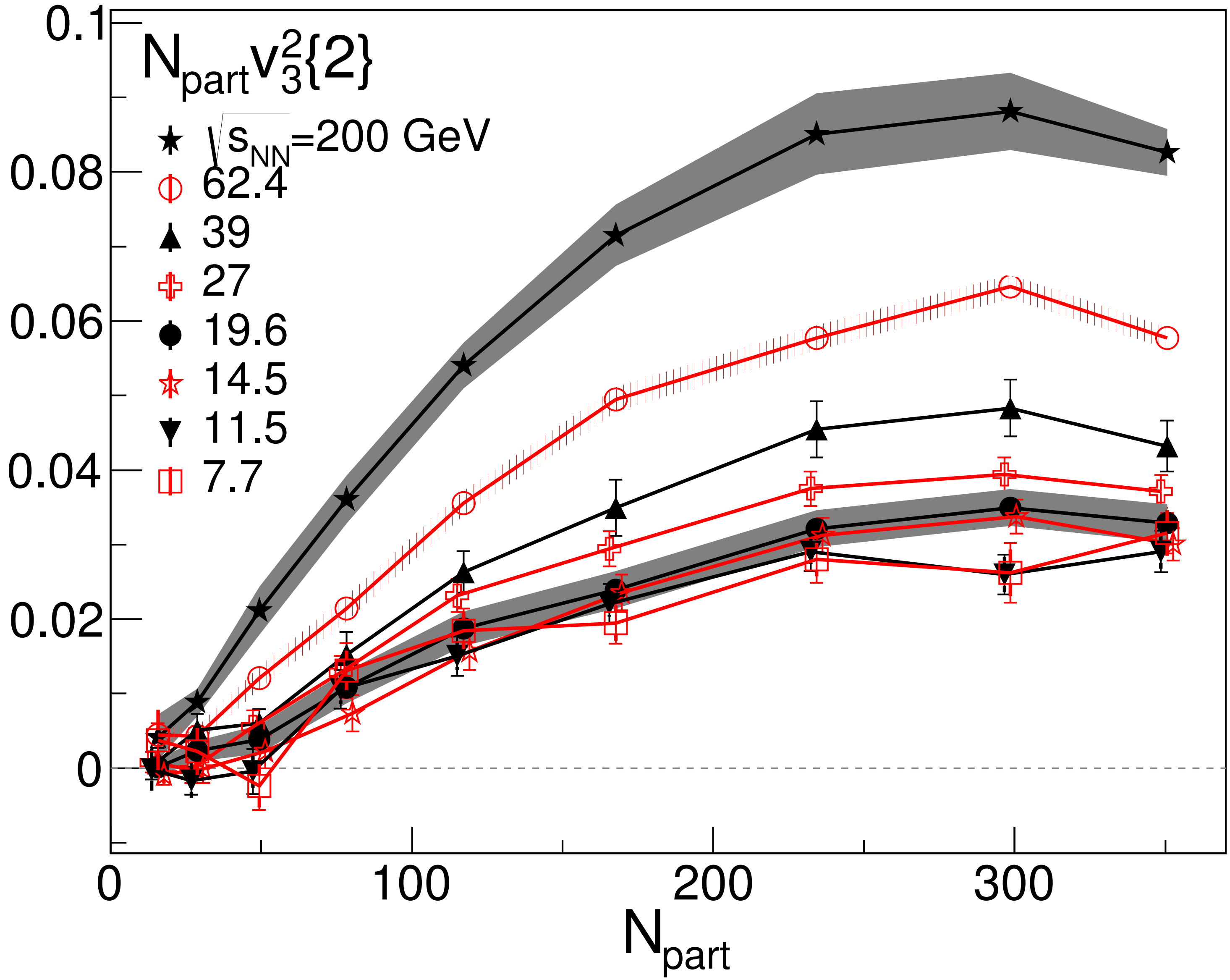
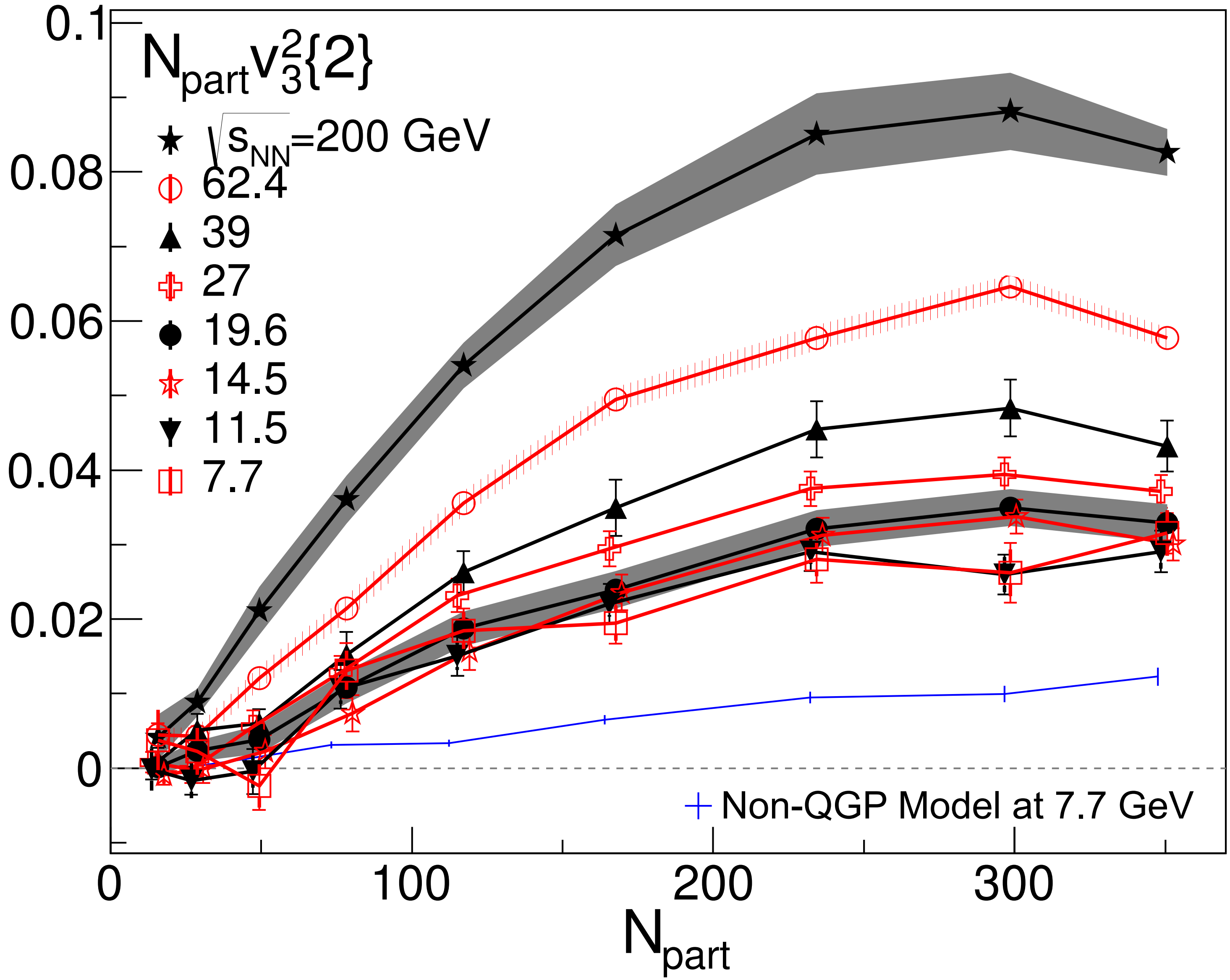
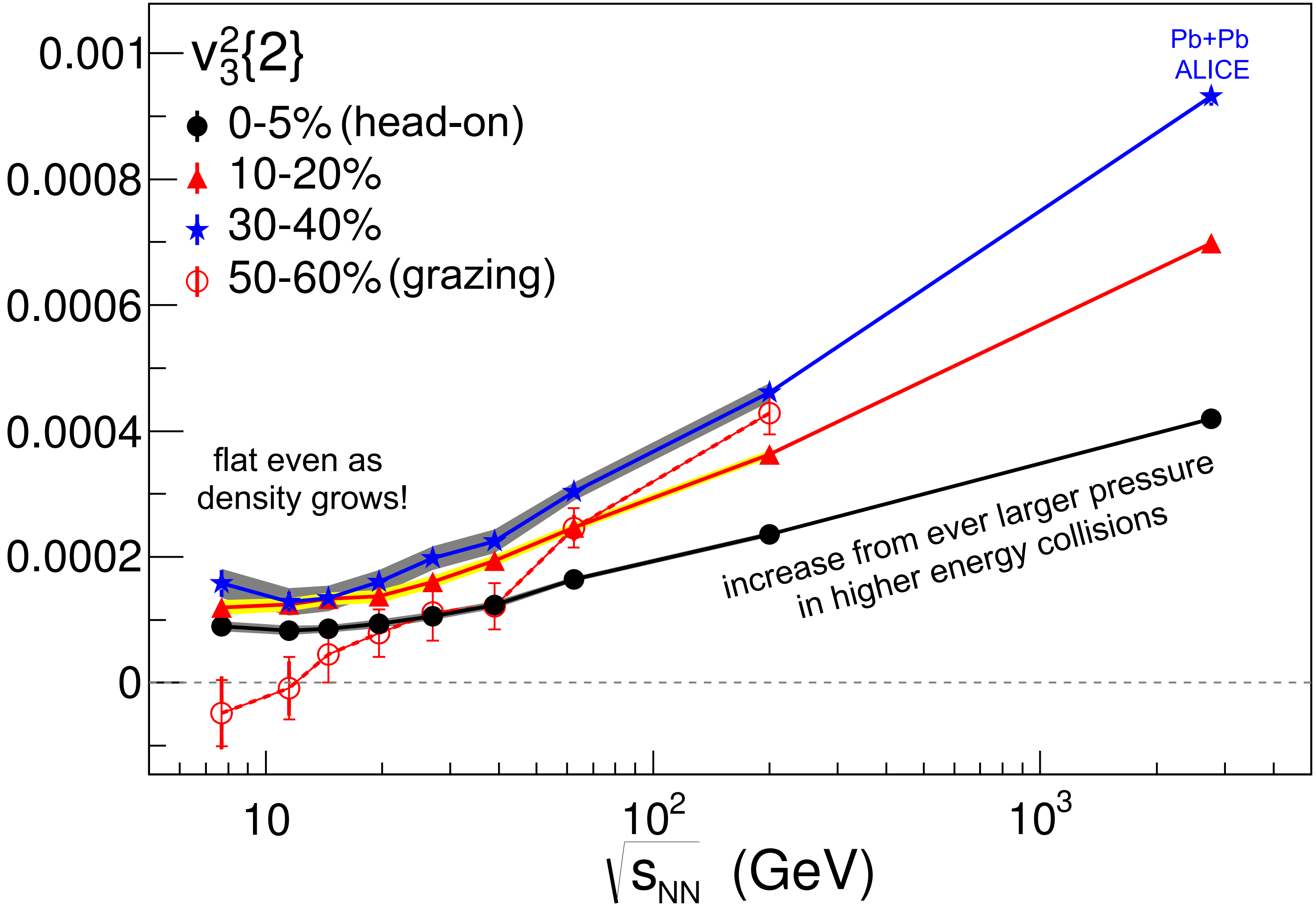


Centrality Dependence



Energy Dependence

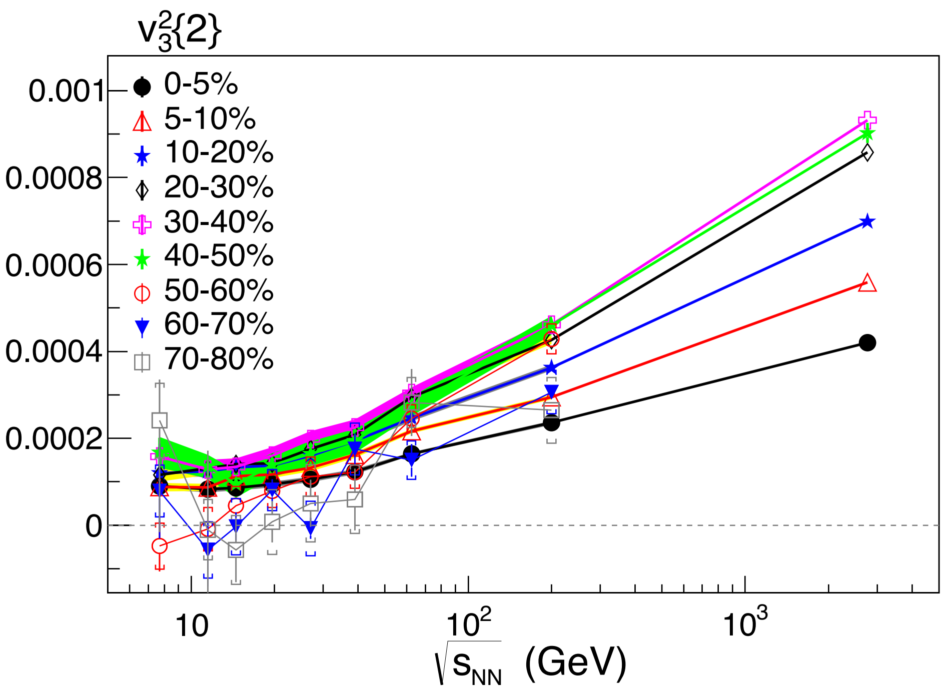


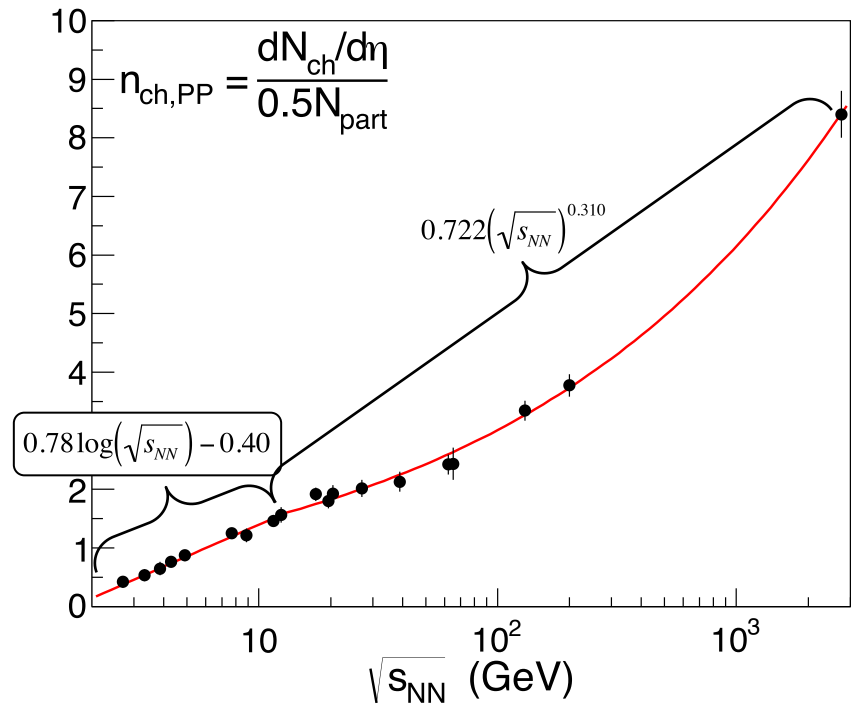
Above 20 GeV the ripples grow with energy, but below that they barely change!

Increasing Multiplicity

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

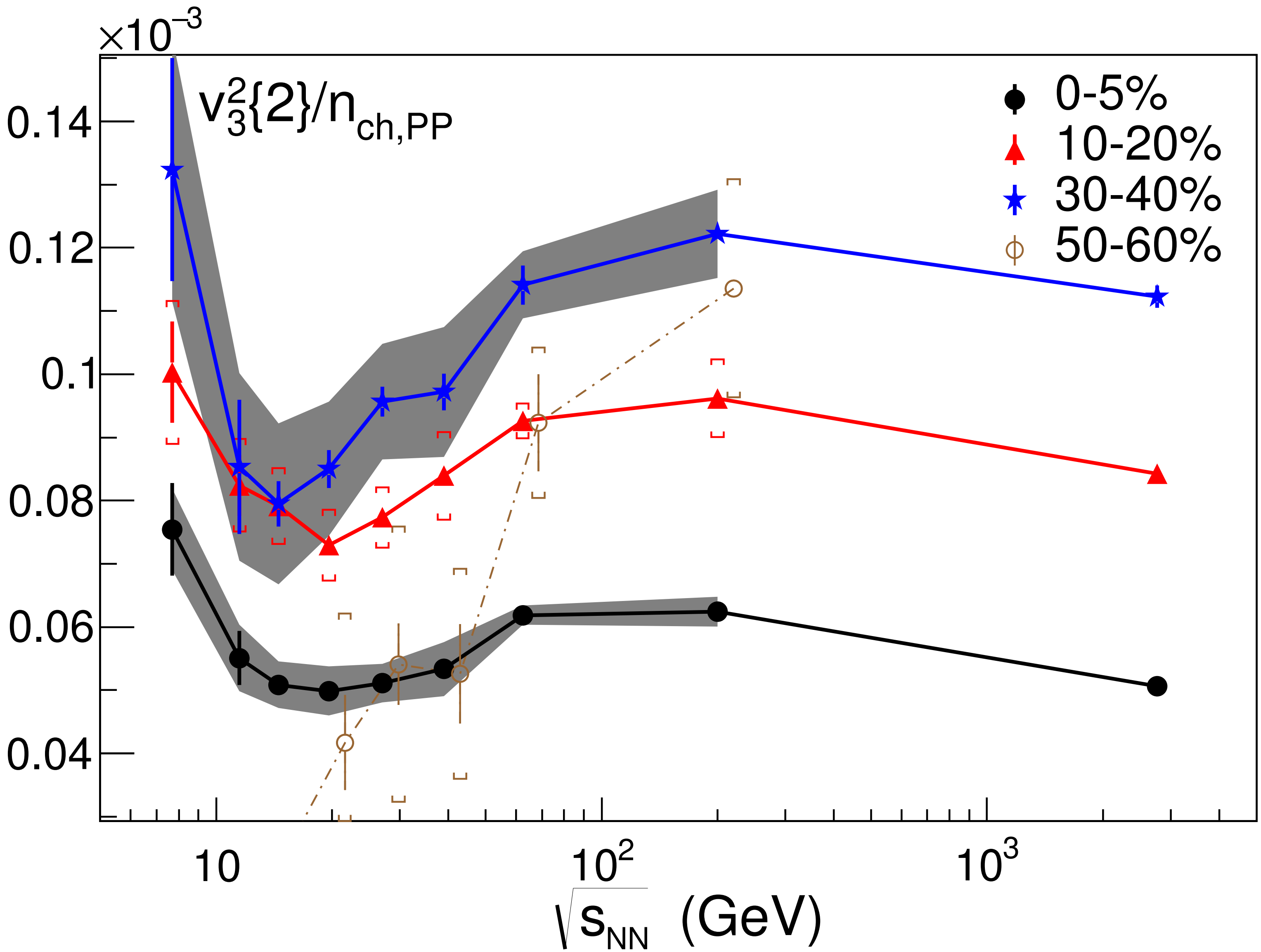
Deviations from that expectation could be indicative of interesting trends like a softening of the equation of state. What does v_3^2/N_{ch} look like?



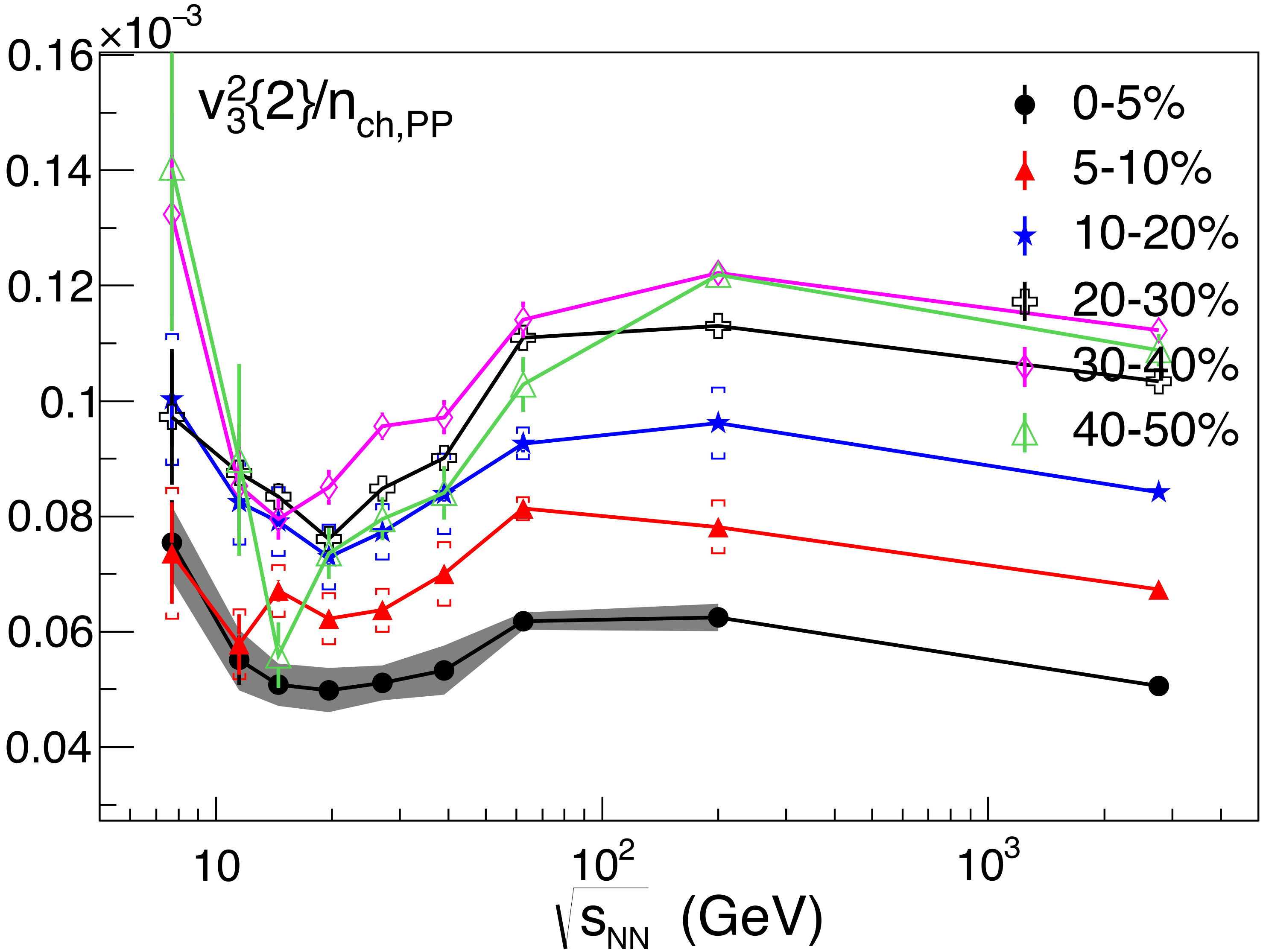


We parameterize the worlds data and take the ratio

Anomalously Low Pressure?

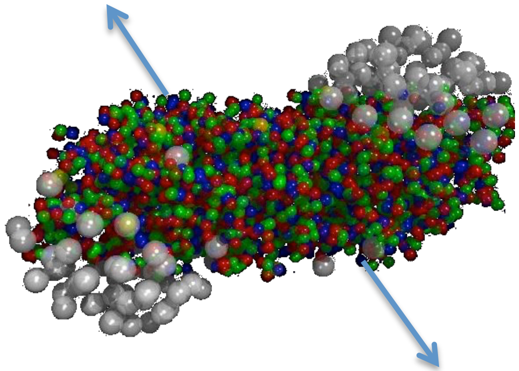


Anomalously Low Pressure?

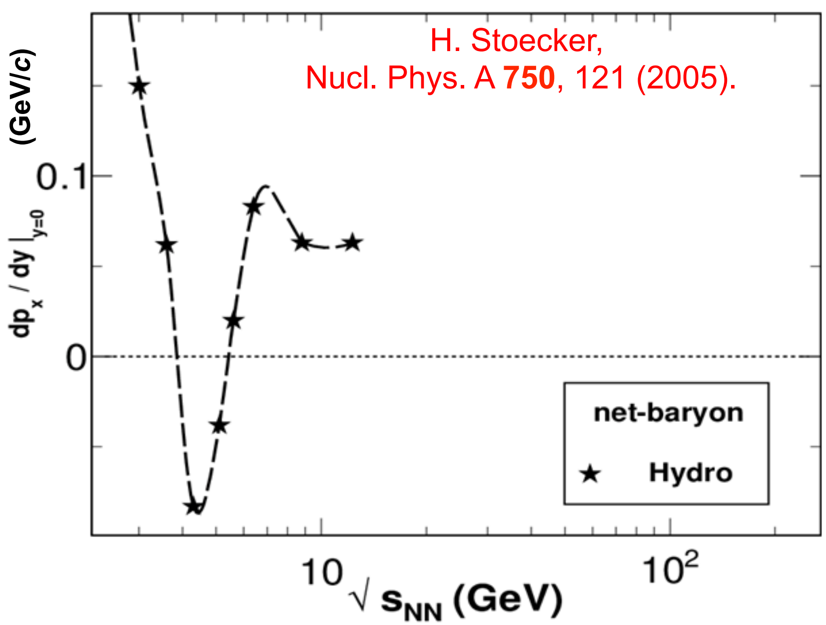


Local minima is present for all centralities between 0 and 50%

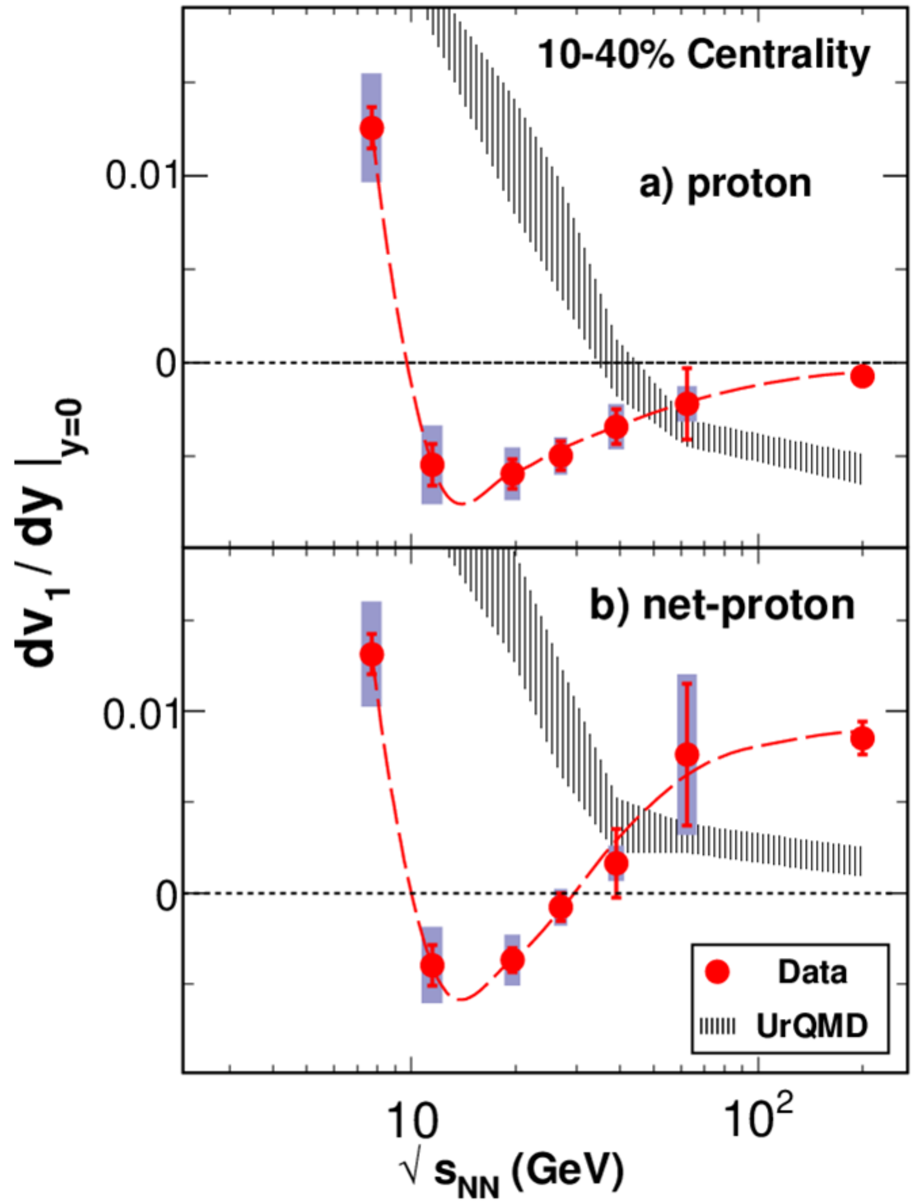
Anomalies in the Pressure?



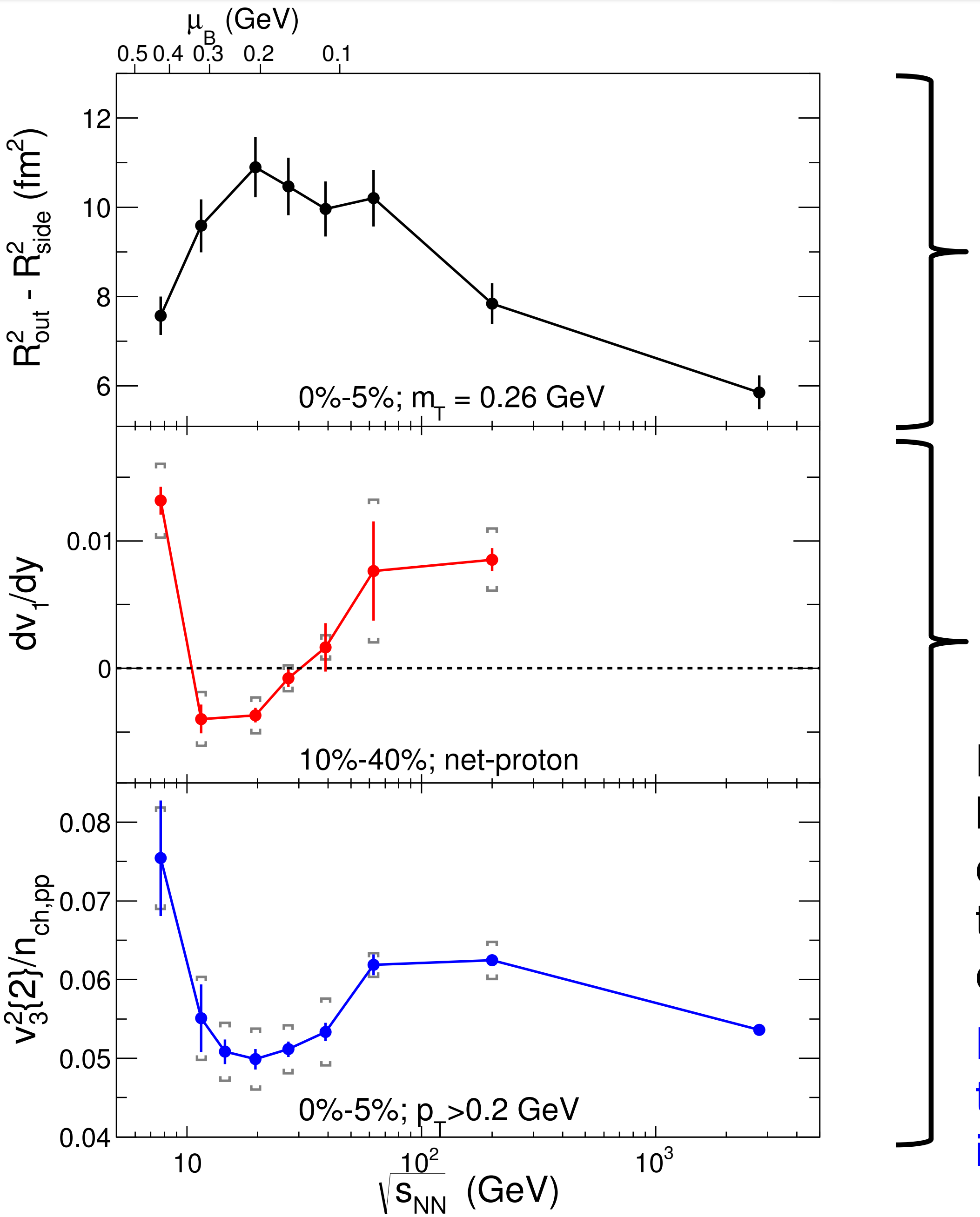
v_1 for both *p* & net-*p* qualitatively resemble collapse signature and are very different from the hadronic model



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



Are Data Indicative of Anomalies in the Pressure?



Maximum in lifetime?

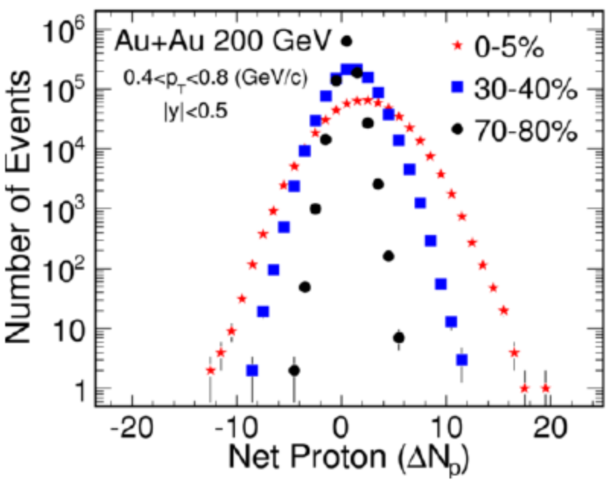
Minimum in pressure?

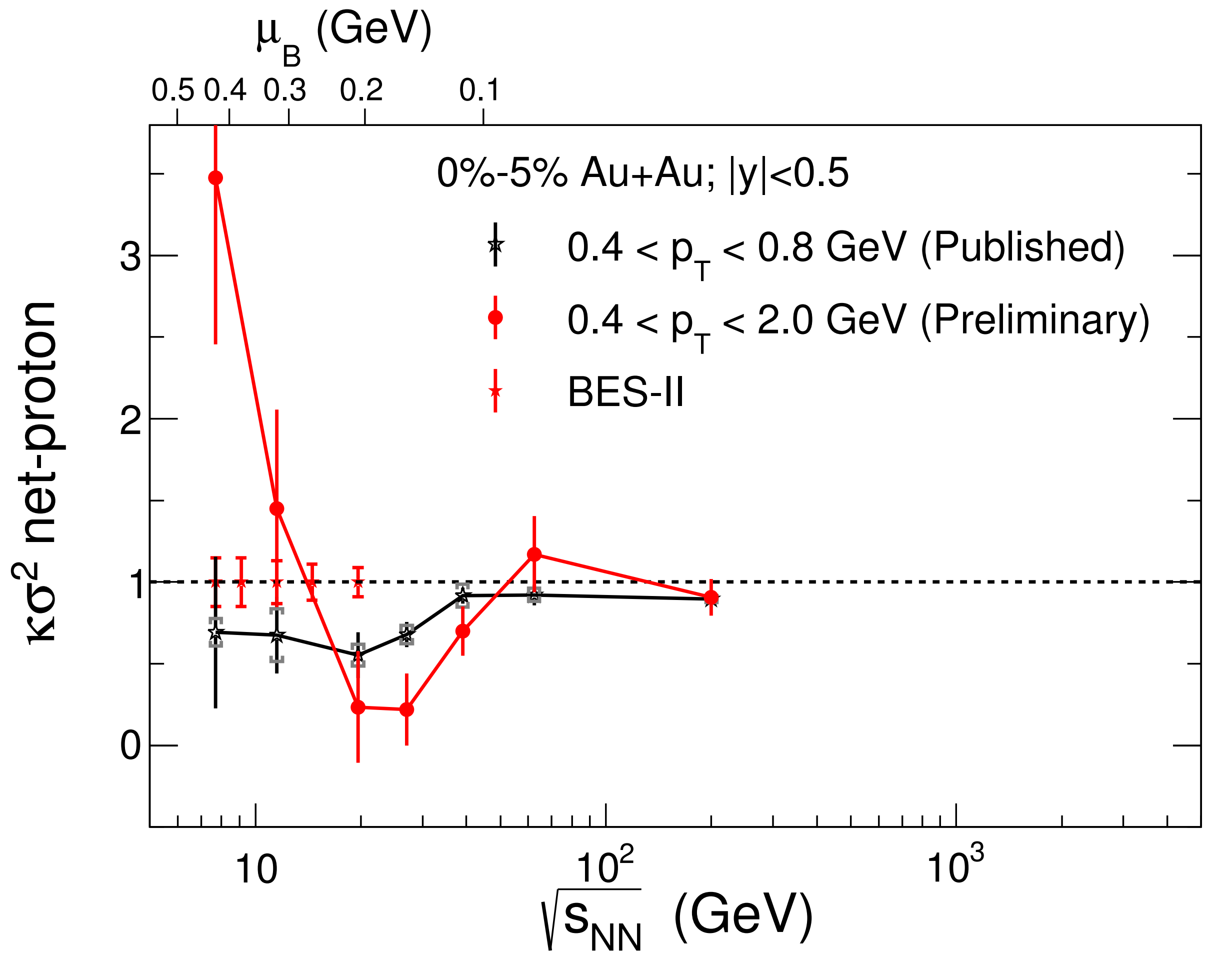
Region of interest $\sqrt{s_{NN}}$~20 GeV, however, is complicated by a changing B/M ratio, baryon transport dynamics, longer nuclear crossing times, etc.

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

Are Data Indicative of Anomalies in the Pressure?

Similar trends in the fourth moment of the net-proton distribution



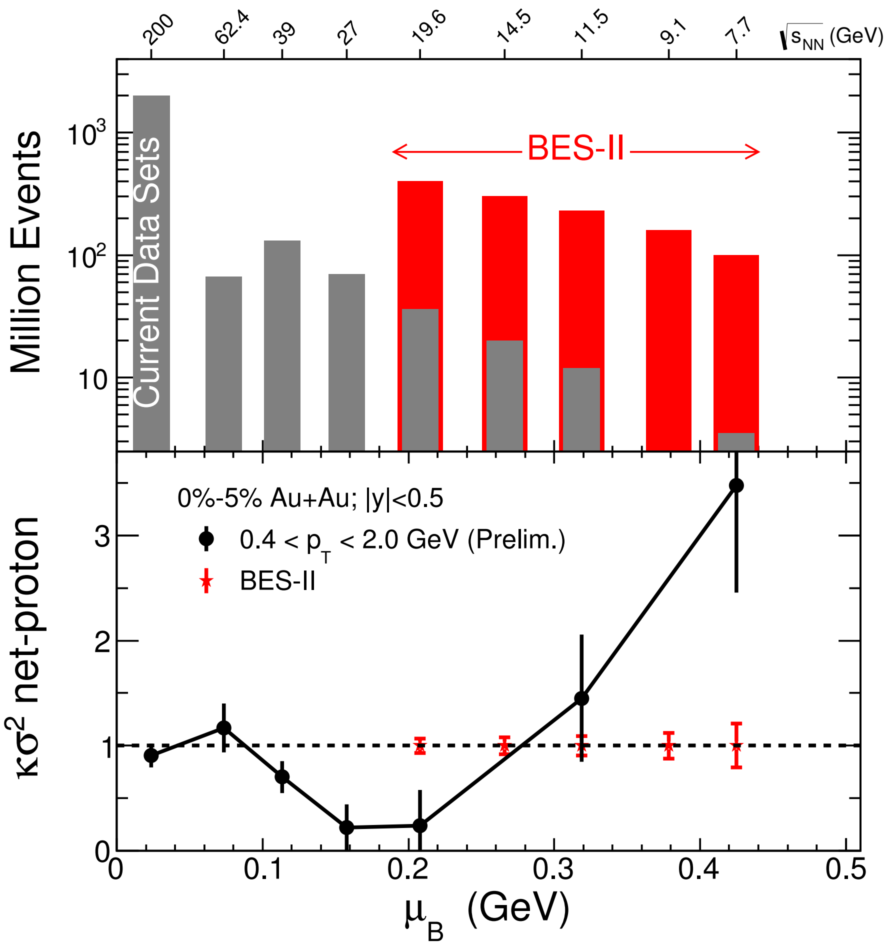


Related to susceptibilities: derivatives of the pressure

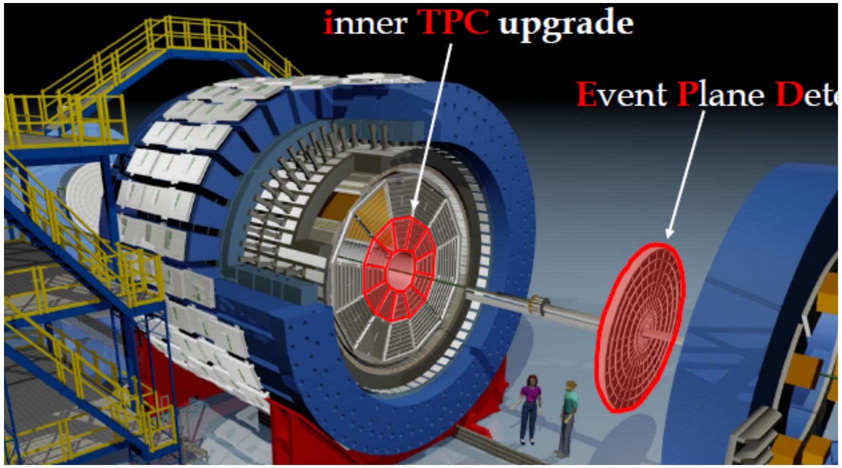
$$\kappa\sigma^2 \approx \frac{\chi_q^4}{\chi_q^2}$$

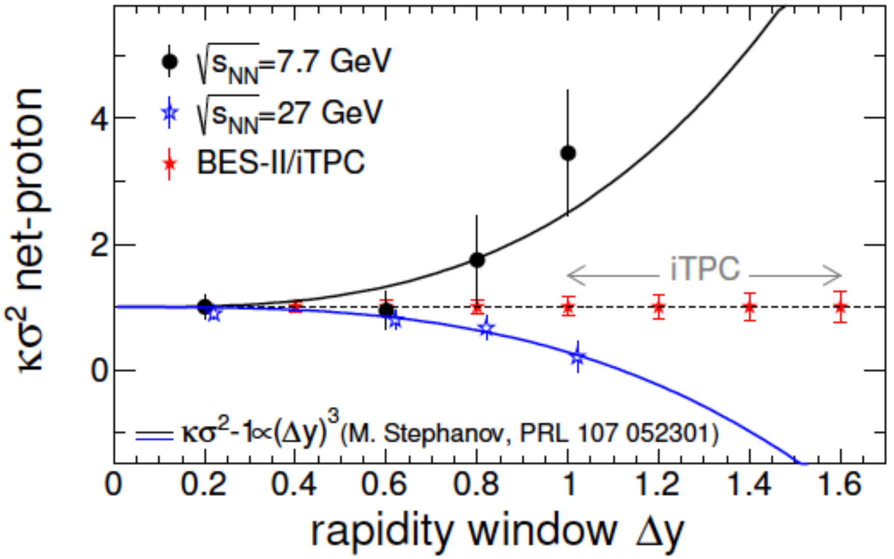
Mapping the region of interest: BES-II

More Data

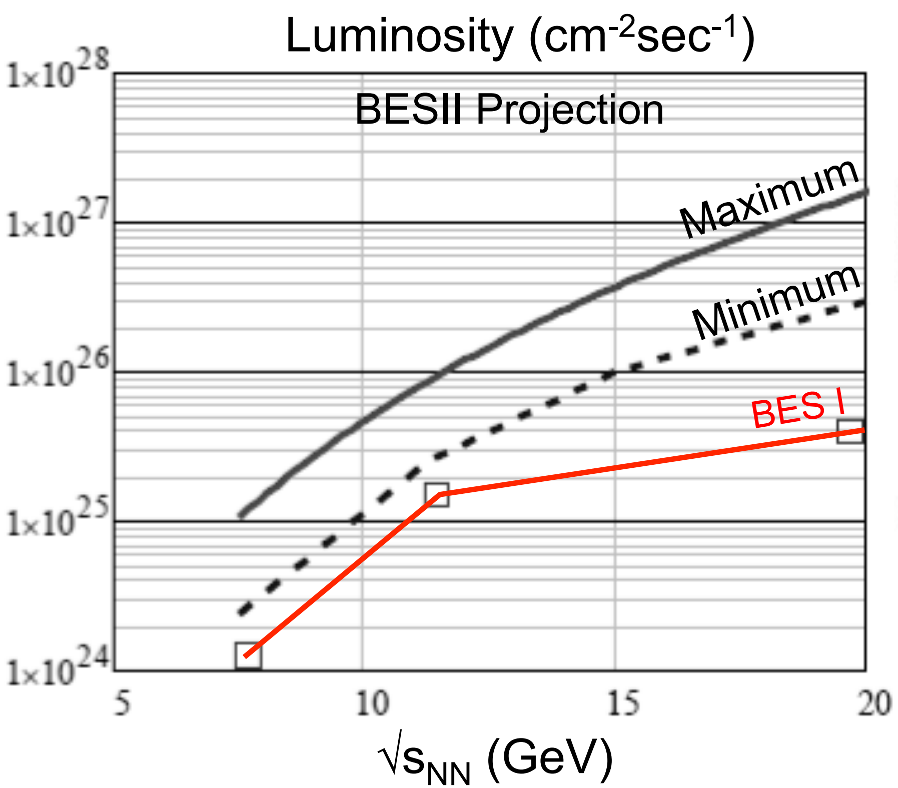


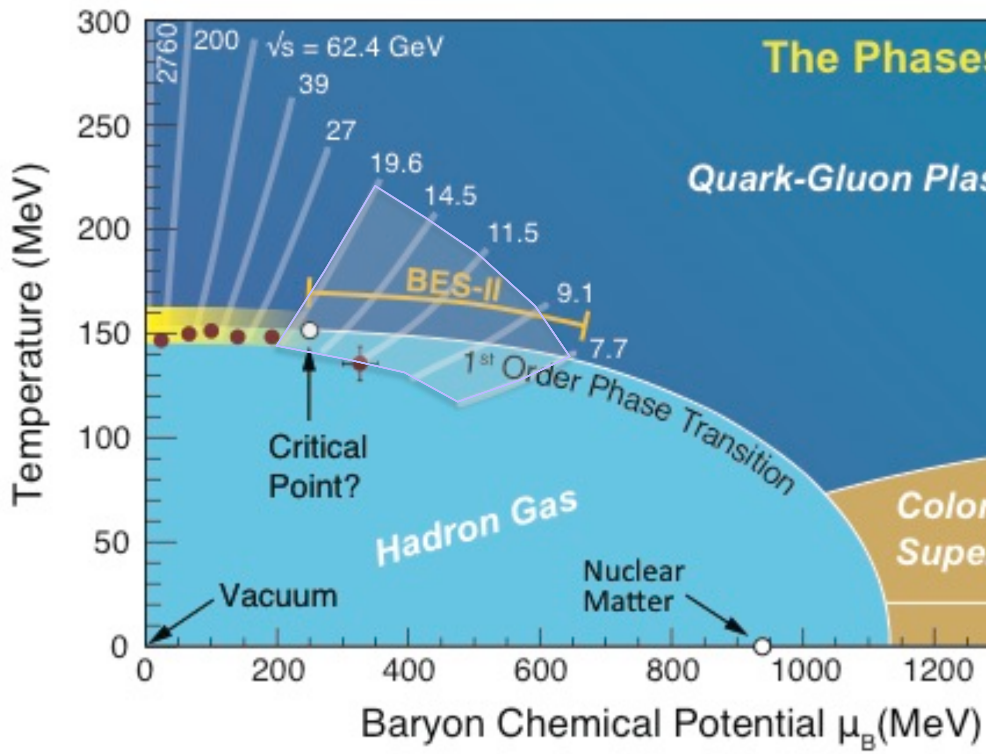
Larger Coverage





Scan Enabled by Luminosity Upgrade





Upgrade requires staging BESII over at least two years perhaps 3.

Stage I: $\sqrt{s_{NN}}$ = 5-9 GeV

Stage II: $\sqrt{s_{NN}}$ = 9-20 GeV *(requires addition of 3 MeV booster cavity)*

Successes and Next Steps

Theory and experiment have provided us with an accurate model for the little bangs created at RHIC and the LHC

Provides access to 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
- extracted η/s indicates this is the most perfect liquid ever known

Following on this progress at μ_B~0 we want to:

- measure T dependence of η/s esp. near the cross-over
- explore the phase structure in the T-μ_B phase-diagram (critical point?)

Experimental and theoretical upgrades are underway

Results from initial scan are highly suggestive. BES-II focuses on region with high discovery potential

End