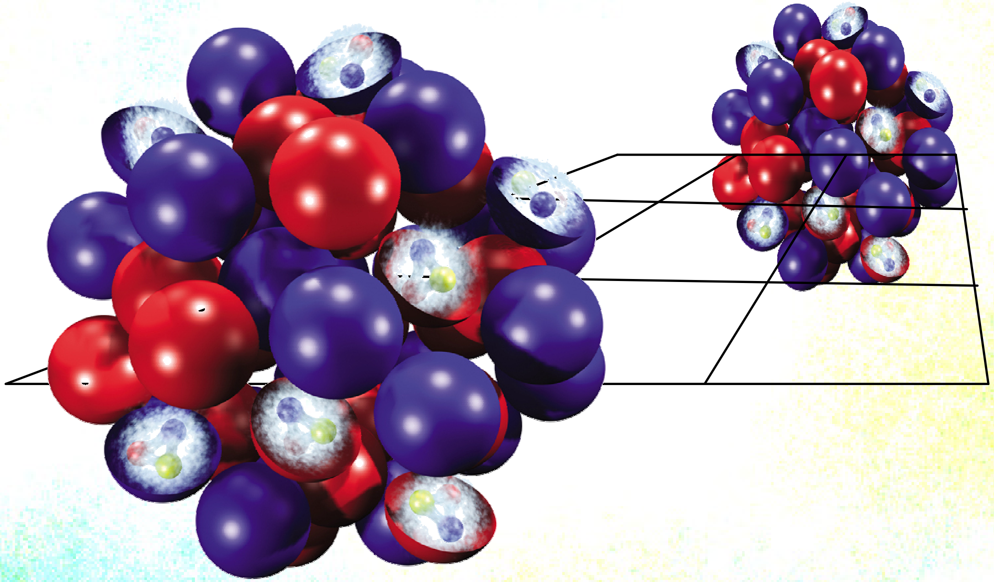
Search for the Critical Point in the QCD Phase Diagram



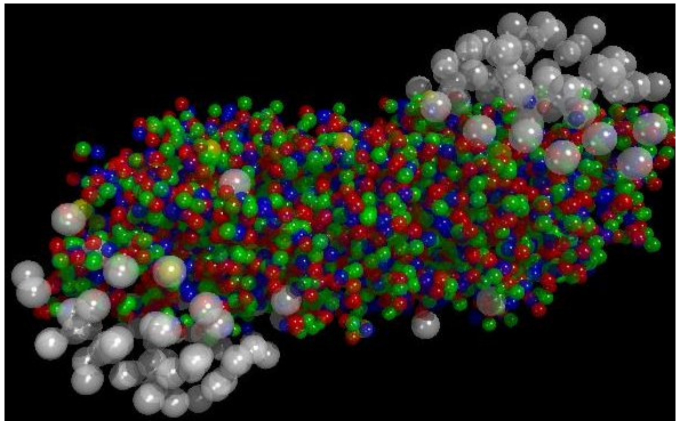
An Experimental Overview

Paul Sorensen
BROOKHAVEN NATIONAL LABORATORY

NED, Sicily
September 2015

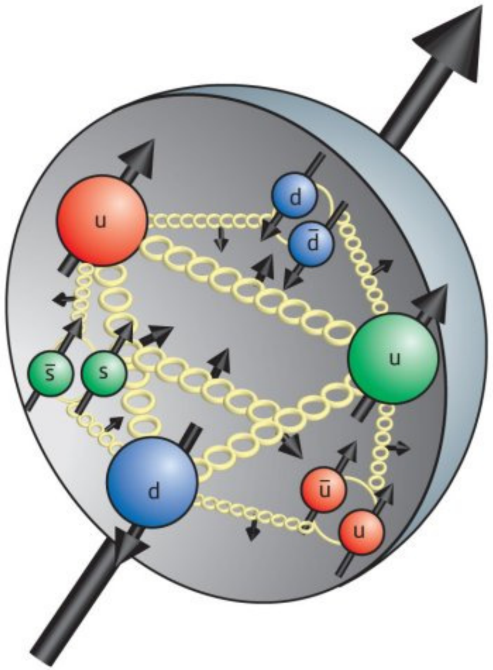
The Big Picture

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



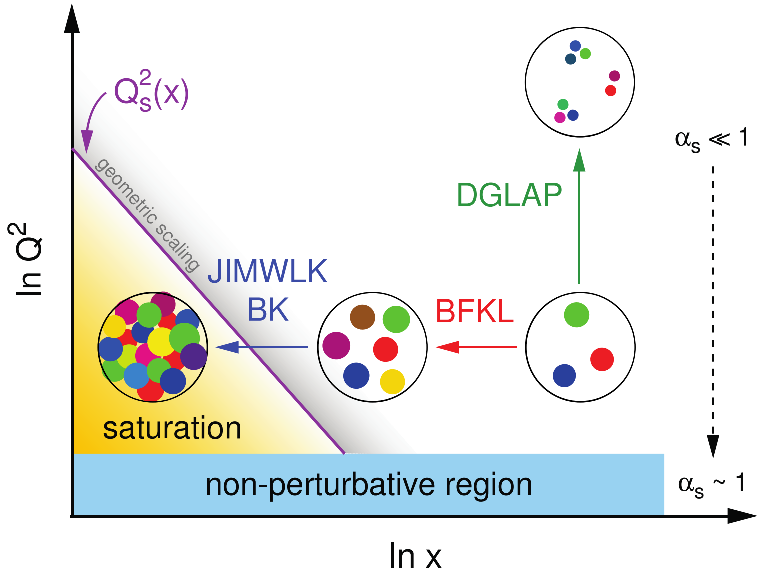
Quark-Gluon Plasma

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



Polarized Protons

How does this become ½?



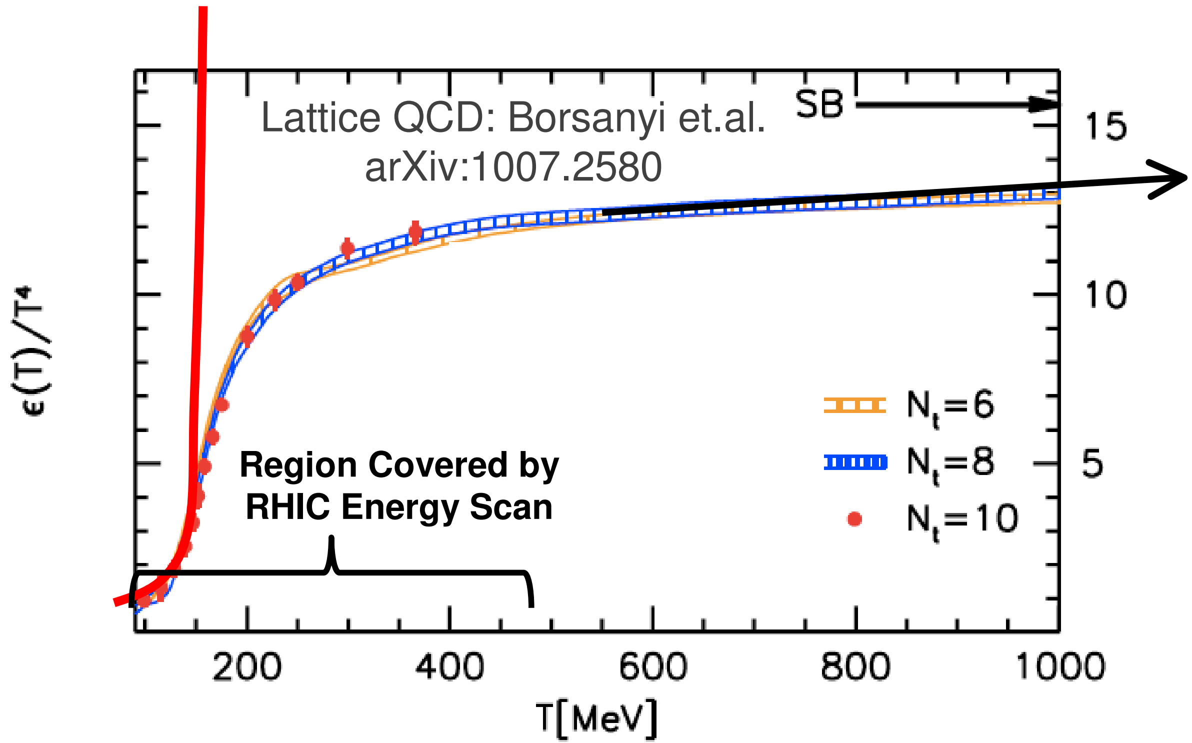
Gluons in Nuclei

How does Q_s emerge from a non-linear evolution

Thermodynamics of QCD

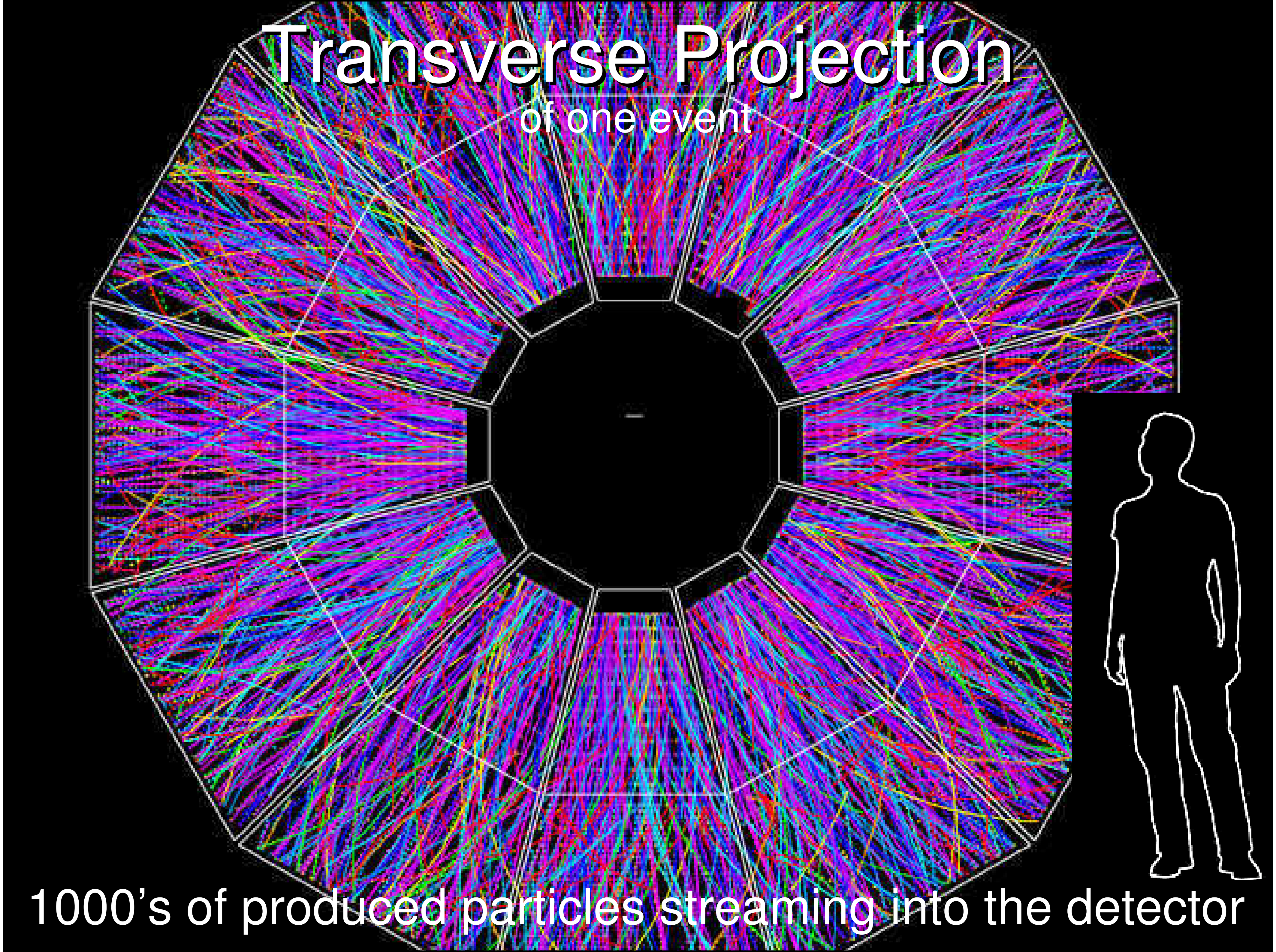
Quantum Chromodynamics shows a rapid crossover to QGP:
ε/T^4 ($\propto$ # degrees-of-freedom) plateaus when quarks and gluons start to become the relevant degrees of freedom

Hadron Gas: maximum T

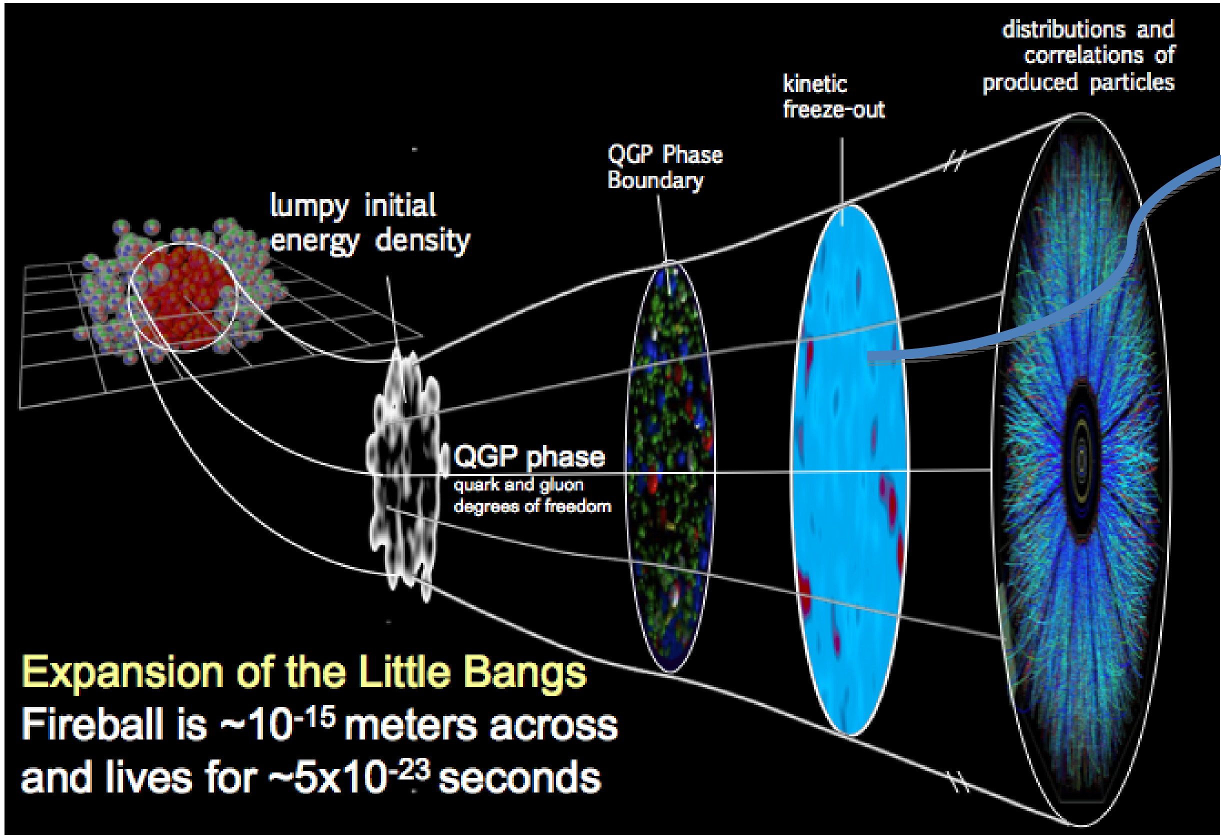


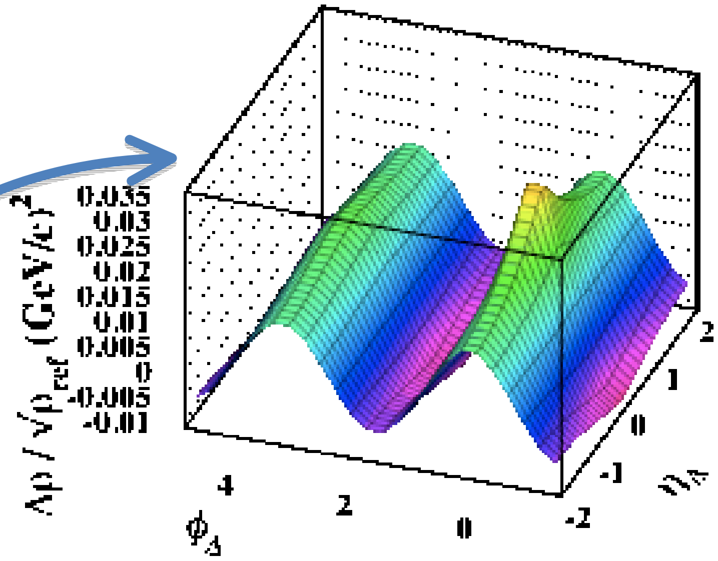
QGP: no maximum
adding energy increases T, instead of creating heavier hadrons

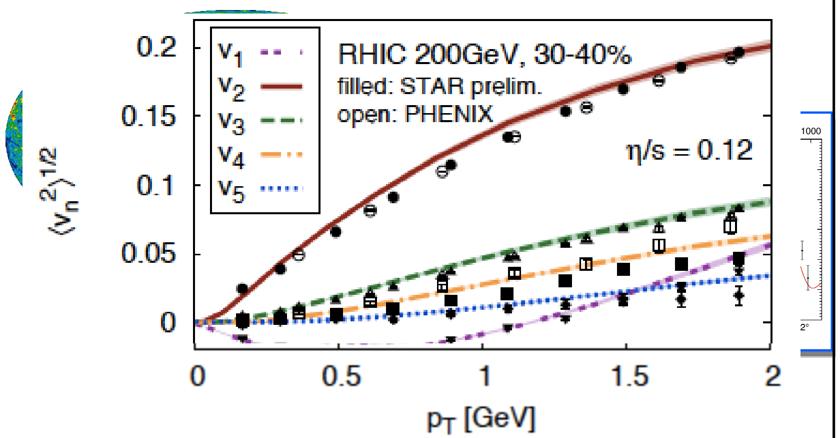
The QCD phase transition that occurred at one μ-sec after the Big Bang is accessible in lab experiments today


Transverse Projection
of one event
1000's of produced particles streaming into the detector

Phases of QCD: Standard Model of Little Bangs



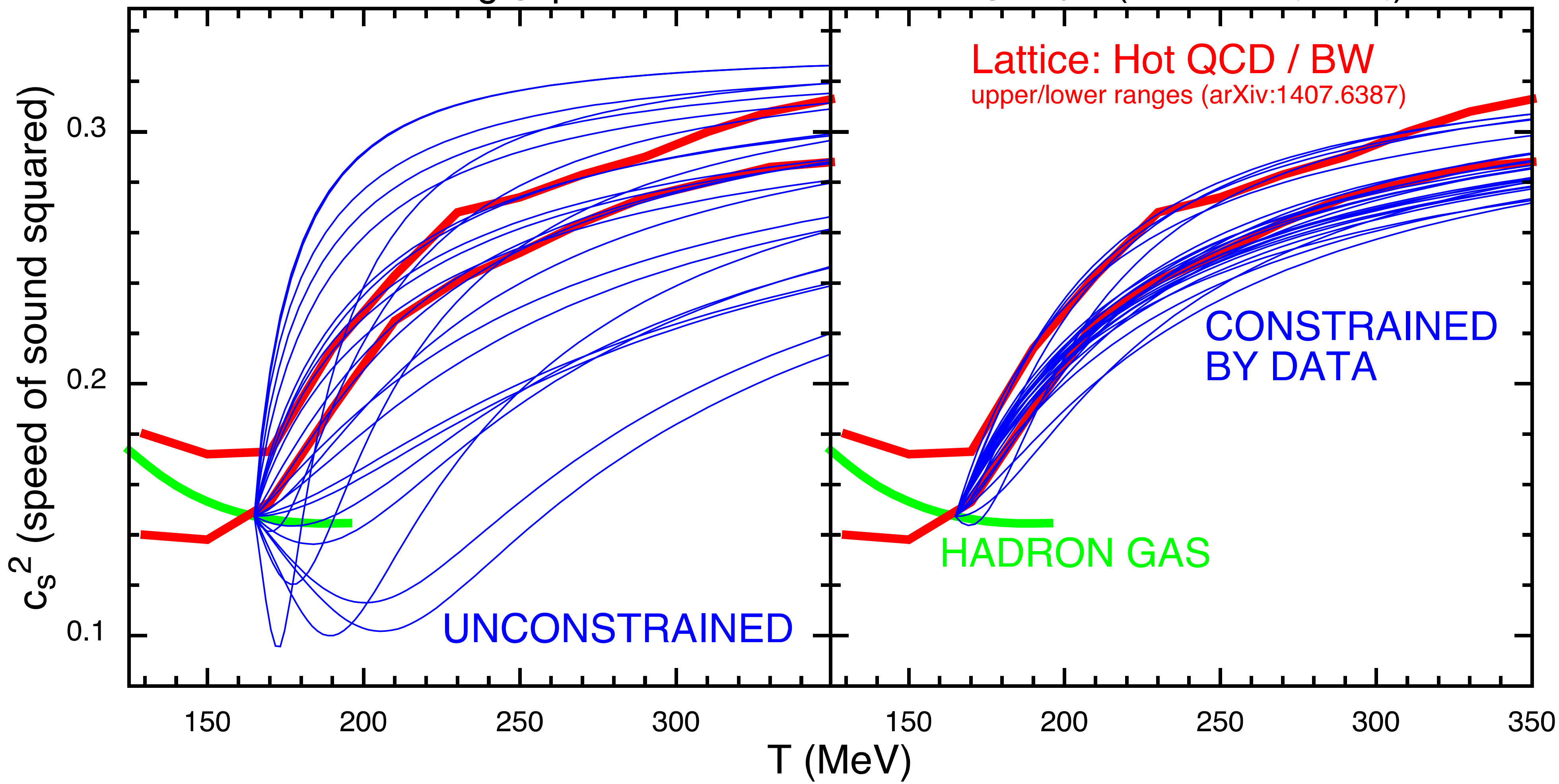




QCD theory+modeling ***and constant experimental guidance from RHIC and LHC*** now give us a detailed picture of the evolution of heavy ion collisions

Accessing Emergent Properties

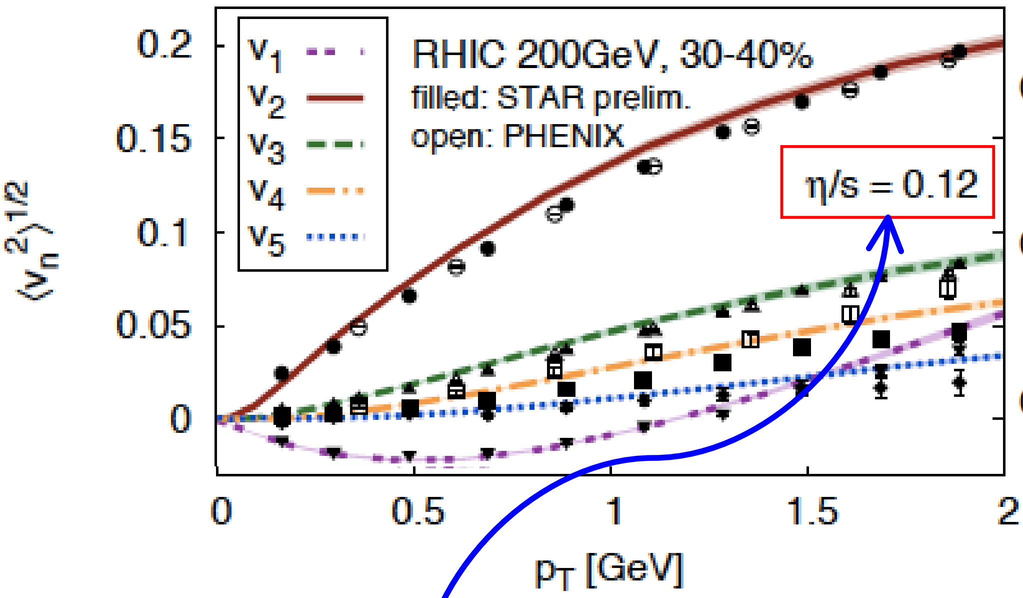
S. Pratt. E. Sangaline, P. Sorensen, H. Wang Phys. Rev. Lett. (2015)

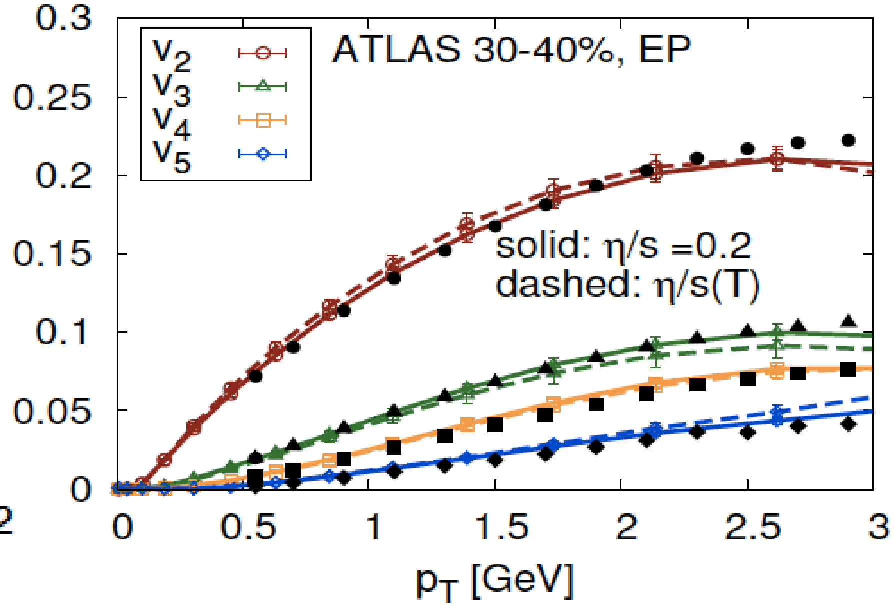


QCD theory+modeling ***and constant experimental guidance*** now give us a detailed picture of the evolution of nucleus-nucleus collisions

Emergent properties of QCD matter now experimentally accessible
Textbook Physics

Temperature Dependence of η/s



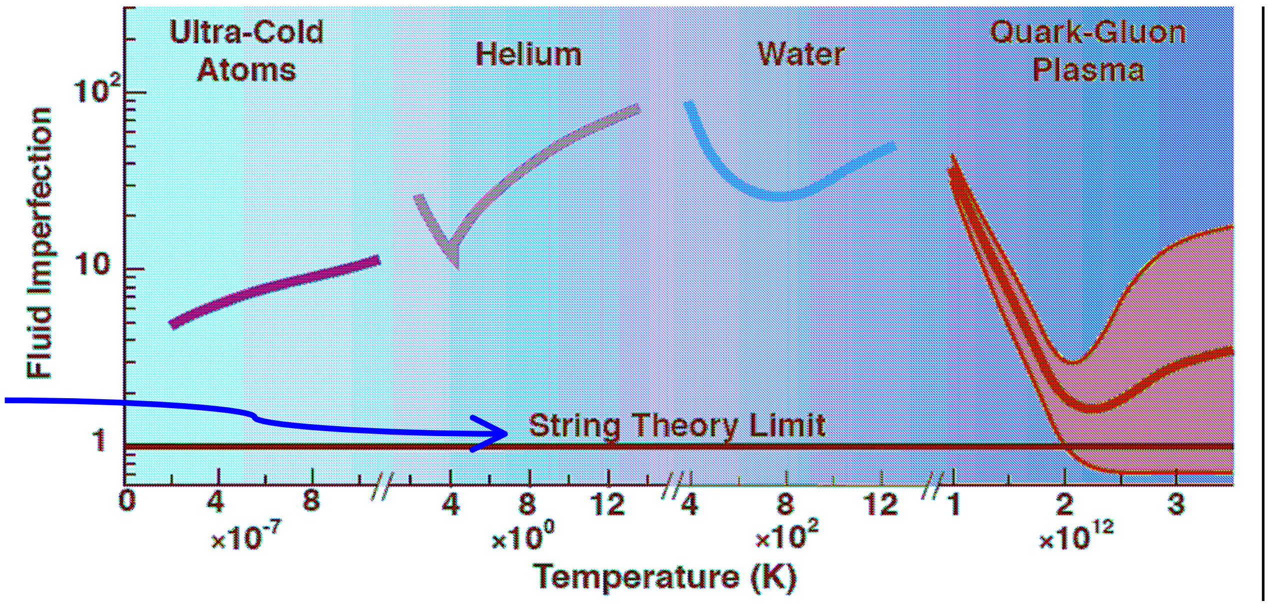


Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

η/s is 40% lower at RHIC:

Temperature dependence is accessible with an Energy Scan

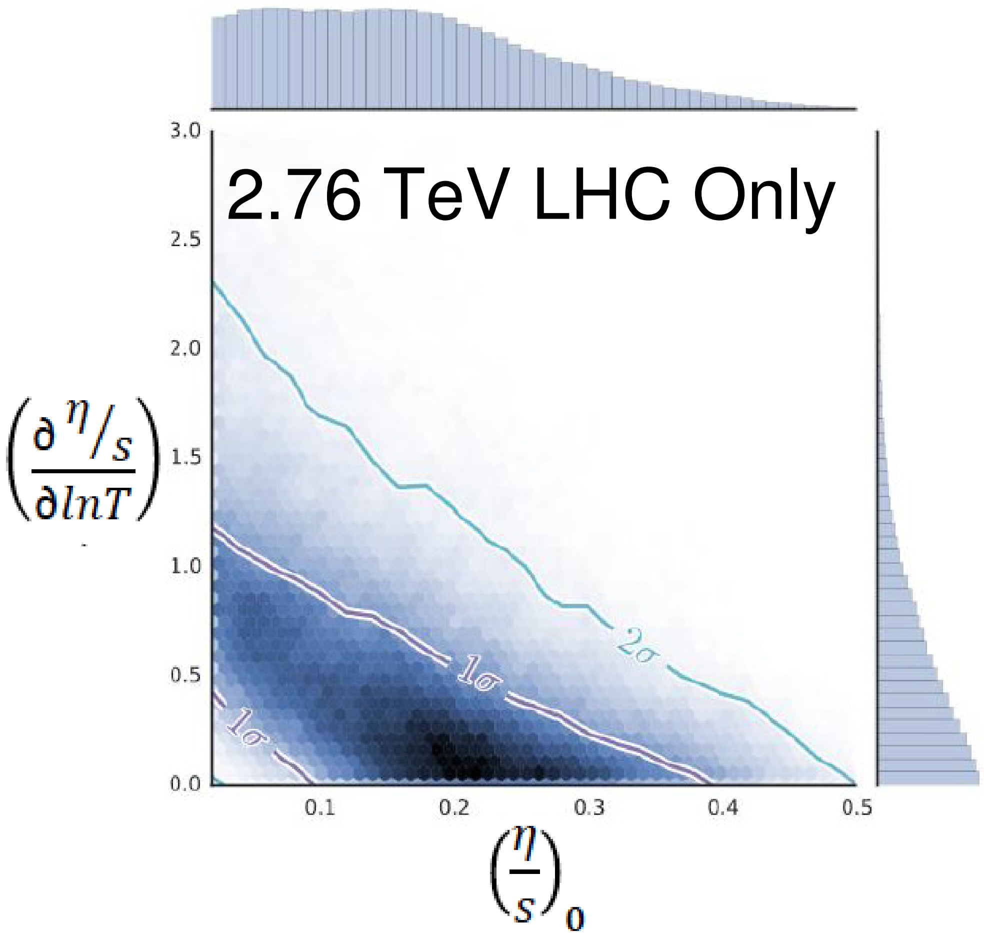
How close does η/s(T) get to the string theory limit for QCD?

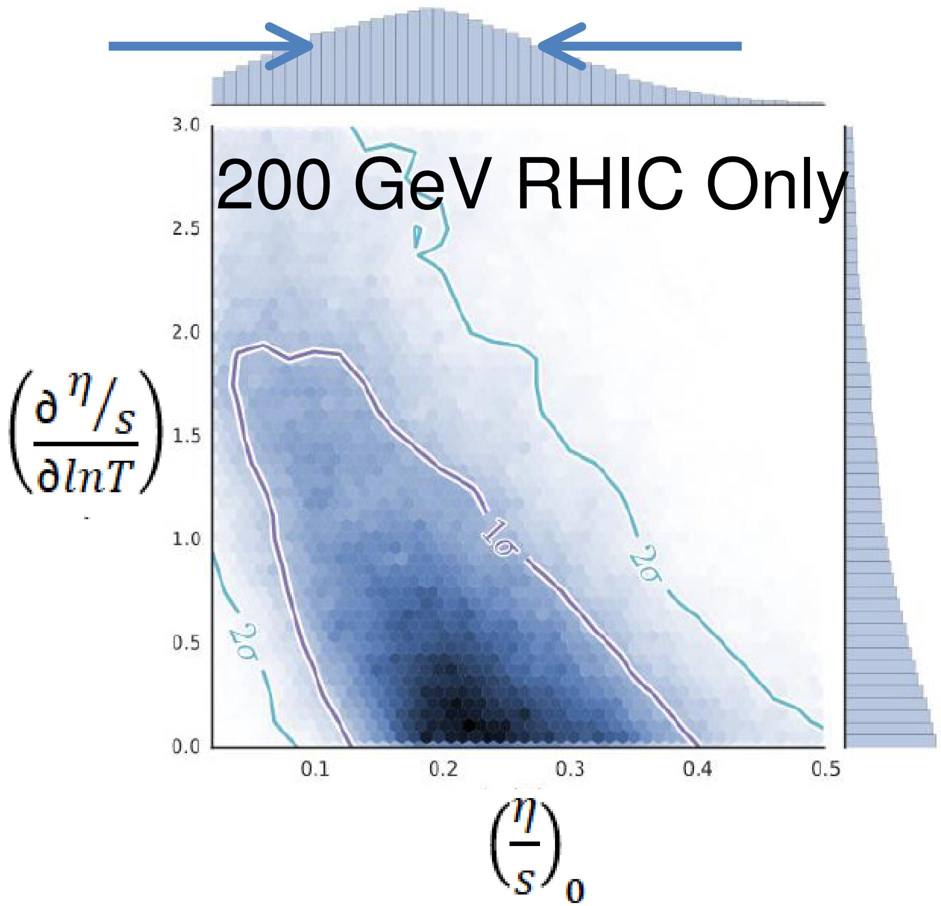


Temperature Dependence of η/s

$$\frac{\eta}{s} = \left(\frac{\eta}{s}\right)_0 + \left(\frac{\partial \eta/s}{\partial \ln T}\right) \ln\frac{T}{T_c}$$

Evan Sangaline
CPOD2014



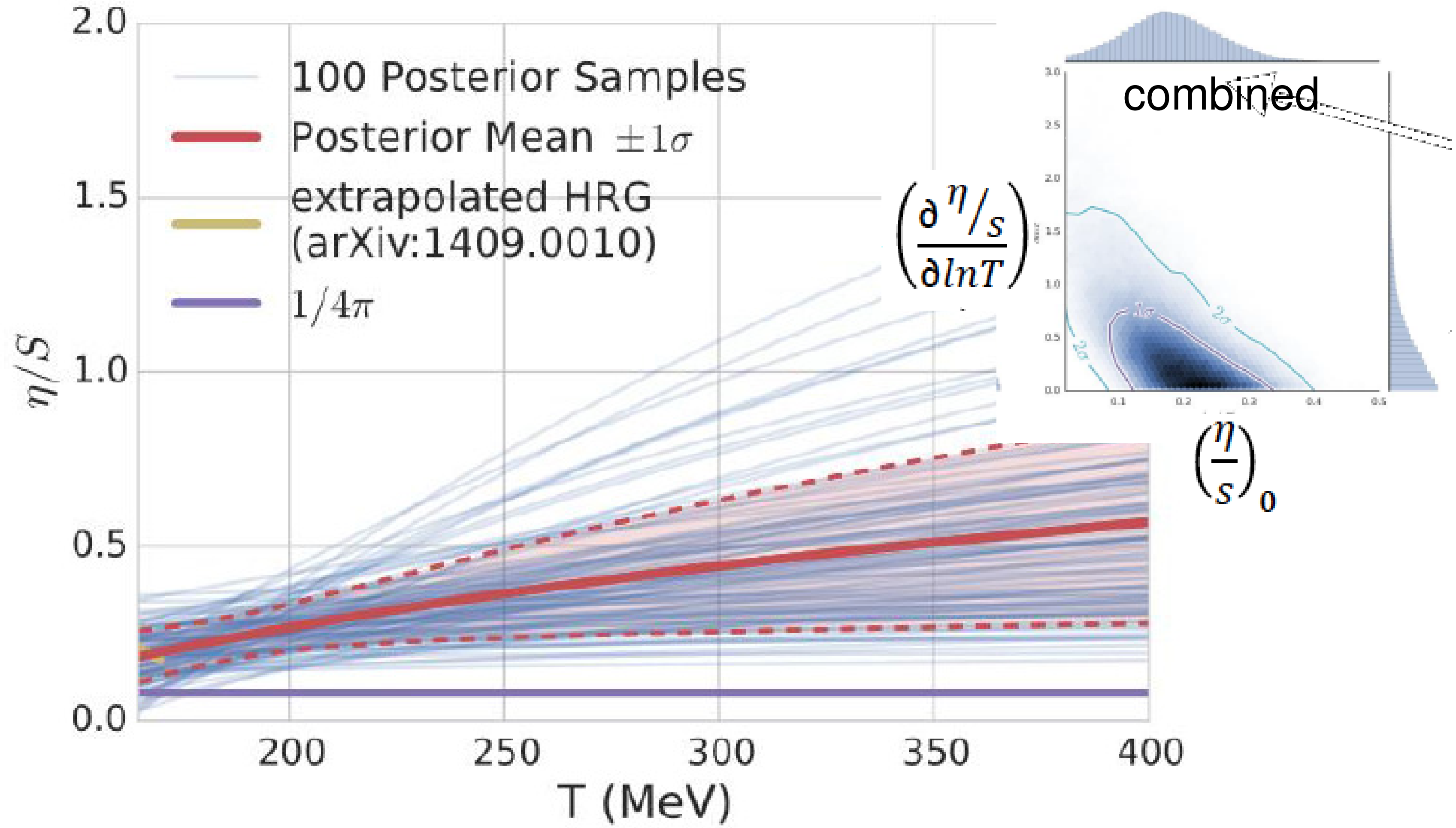


RHIC data provides the best constraint on η/s at T_c

Temperature Dependence of η/s

$$\frac{\eta}{s} = \left(\frac{\eta}{s}\right)_0 + \left(\frac{\partial\, \eta/s}{\partial \ln T}\right) \ln \frac{T}{T_c}$$

Evan Sangaline
CPOD2014

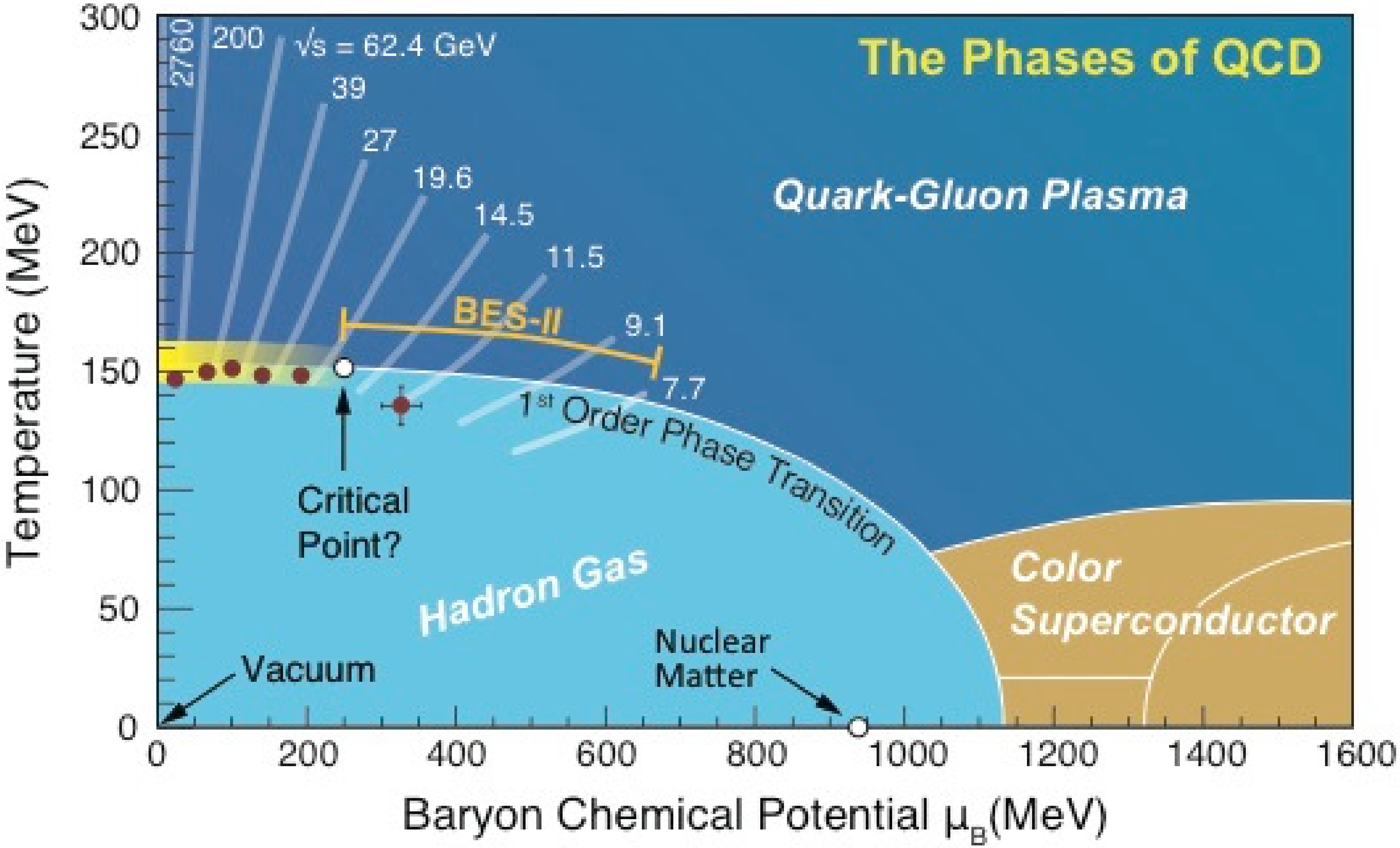


Study of η/s vs T_c still needs improved constraint that can be provided in an energy scan at RHIC

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

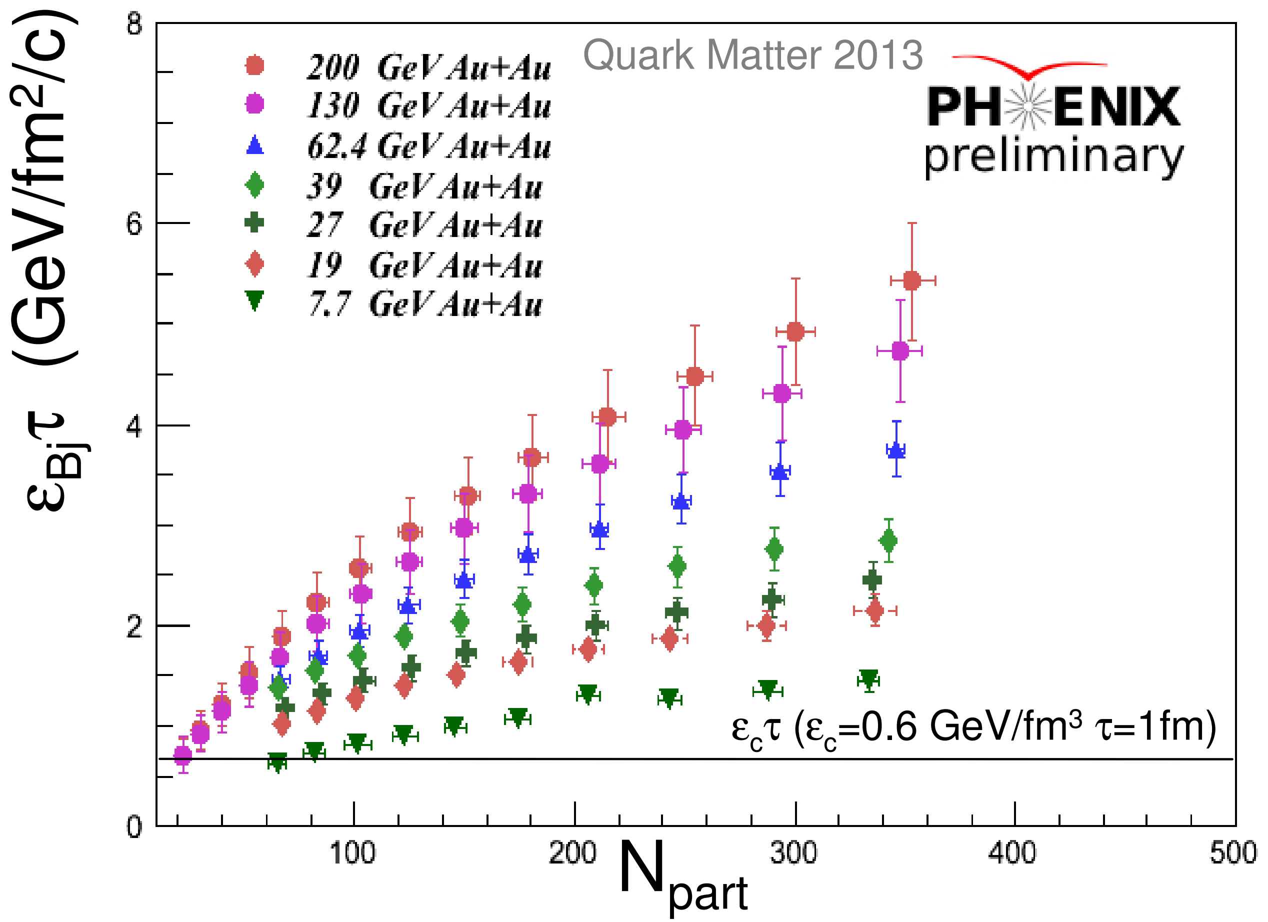


E-F-Theories suggest there should be a critical point at higher μ_B: is there?

Identification of this landmark → a significant discovery potential

Do We Still Create QGP at Lower Energies?

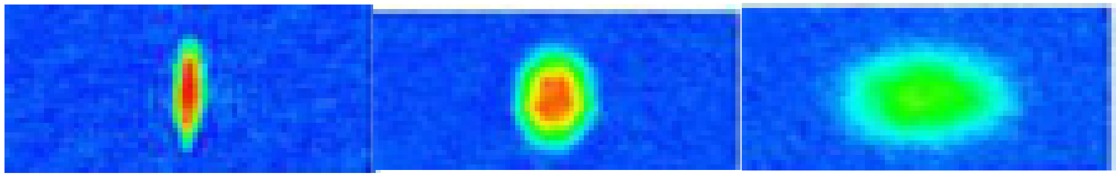
BES phase 1: An Exploratory Energy Scan

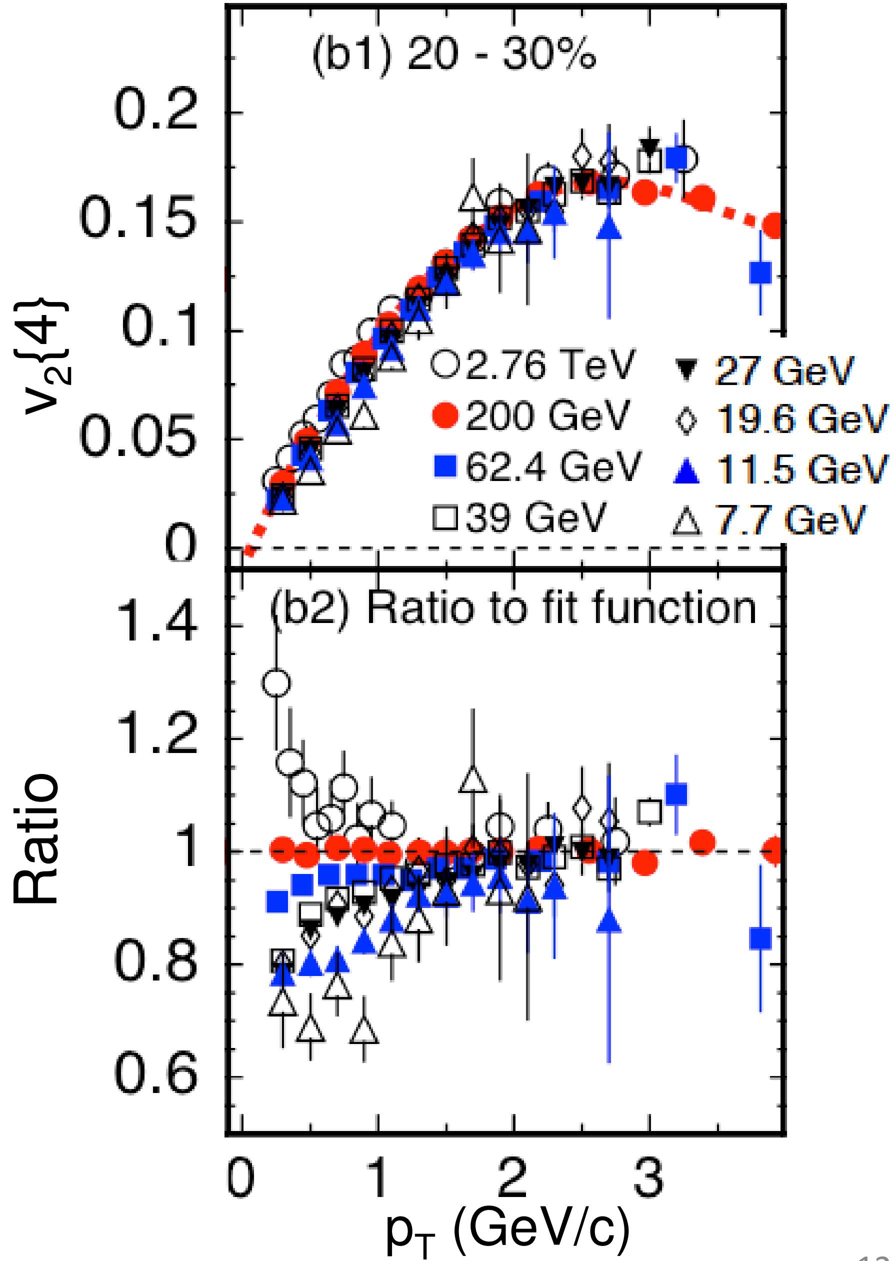


Critical ε_c from lattice ~0.6 GeV/fm^3: lowest energy range explored still likely to be above transition region

Global Correlations: 7.7 GeV to 2.76 TeV

conversion of density inhomogeneity
into momentum space





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

Initial energy density changes by nearly a factor of 10

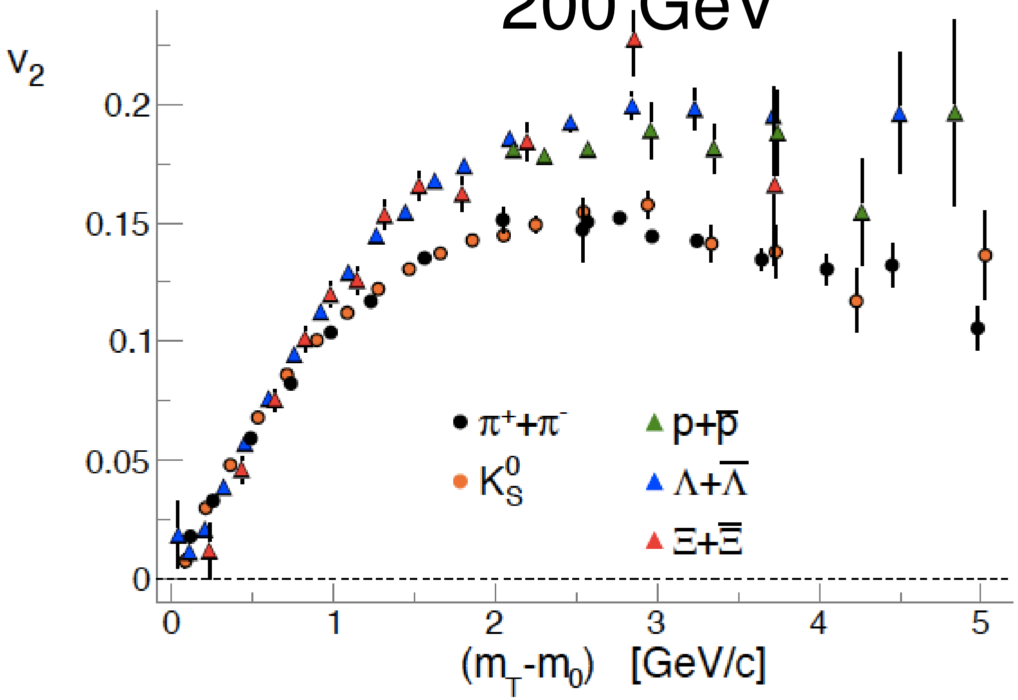
No indication of a turn off of the QGP

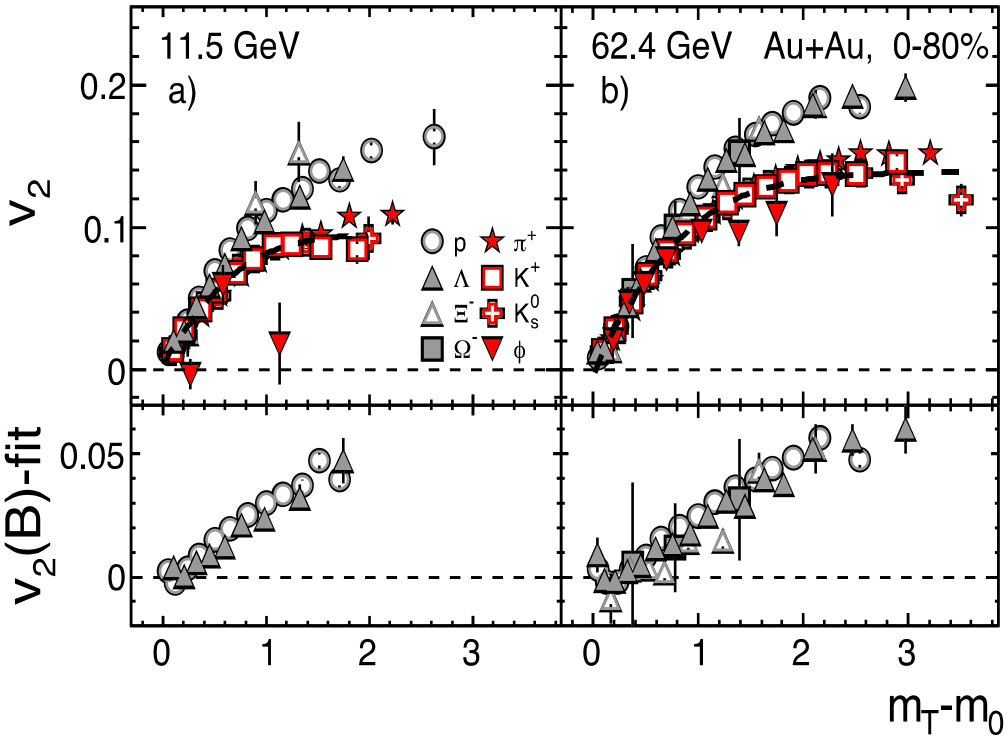
v_2 from 2.76 TeV down to 7.7 GeV

elliptic asymmetry depends on quark number: thought to be a signal of a hadron formation from a quark-gluon plasma

$$\rho_B \sim \rho_q^3; \qquad \rho_M \sim \rho_q^2;$$

200 GeV



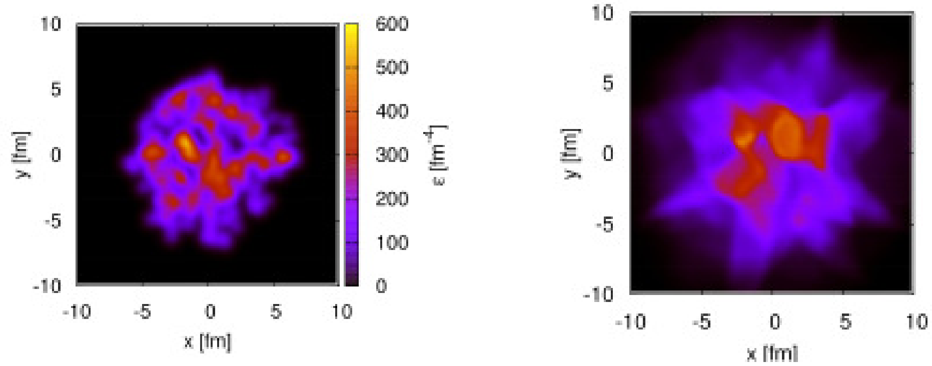


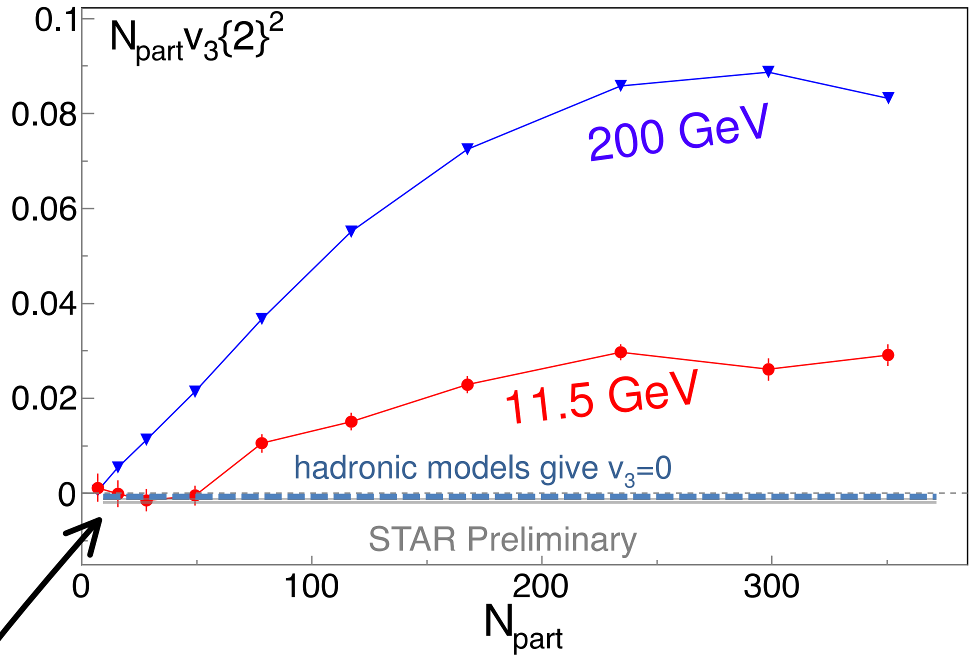
The baryon-meson quark number grouping persists to the lowest energies

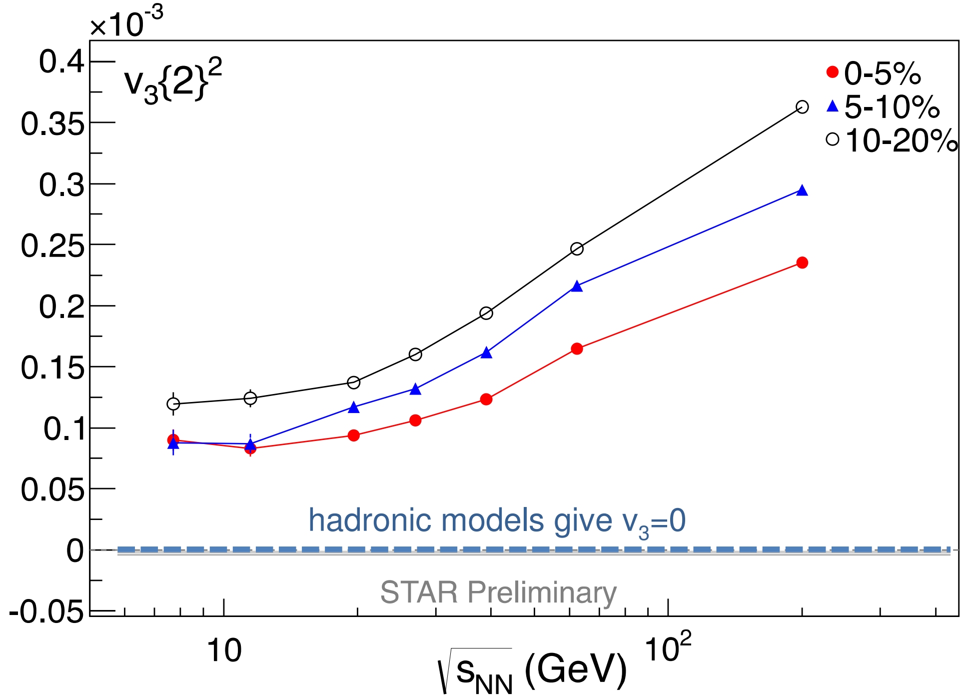
Turning off the QGP

v_3: low η/s plasma transfers fluctuations from the initial overlap density into final-state

requires early QGP phase



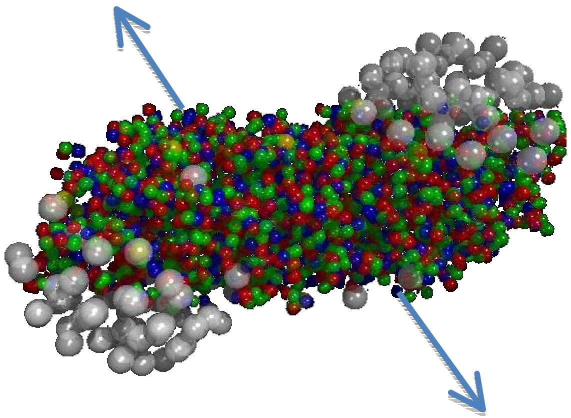




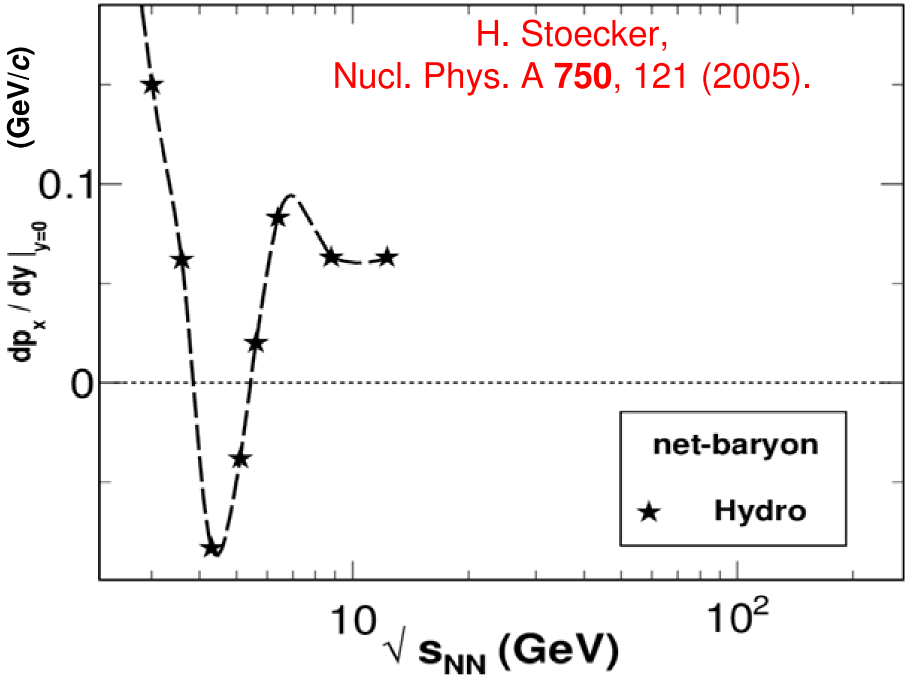
QGP signatures go away in smaller/less dense collisions

Large system exhibits QGP behavior even at the lowest energies

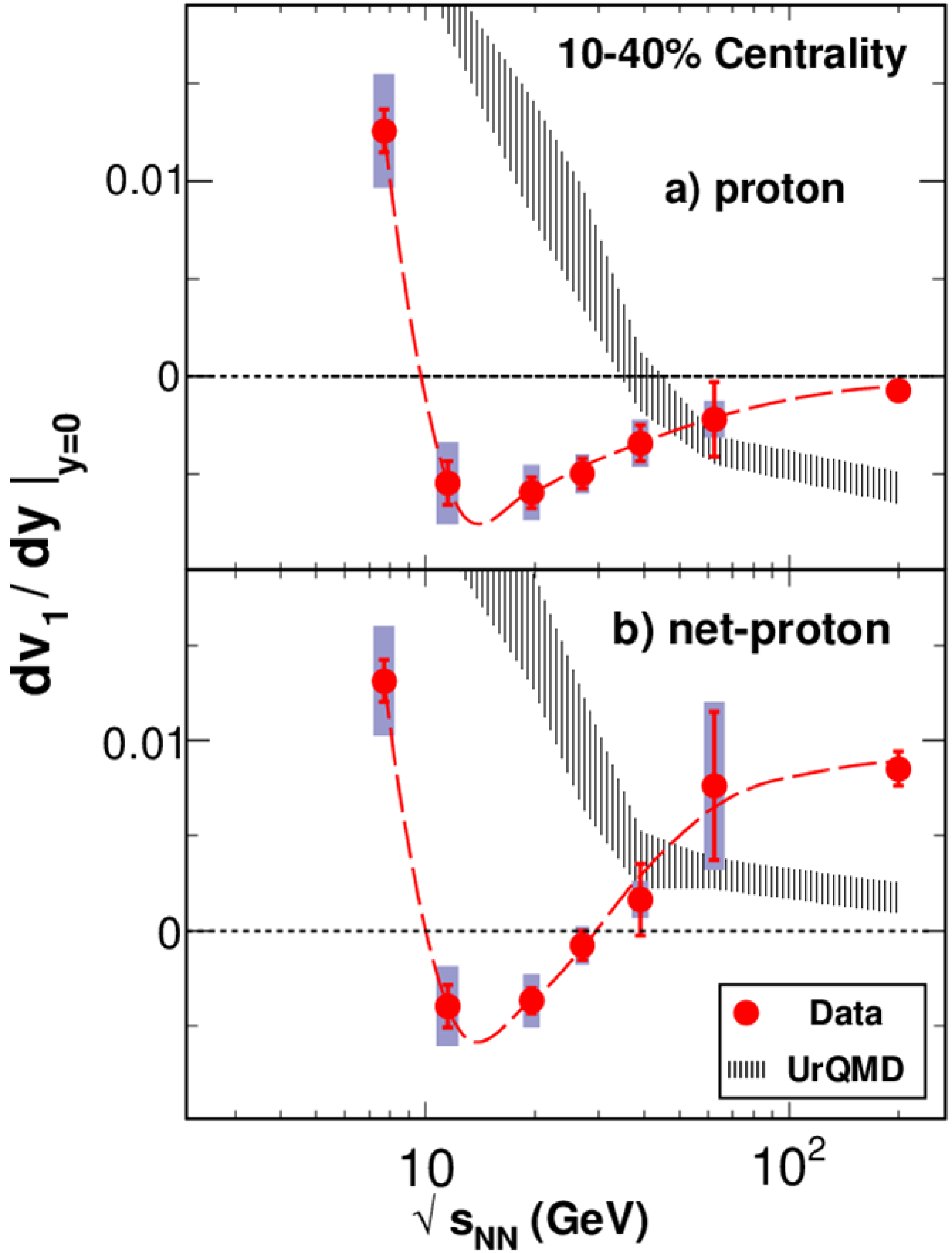
Anomalies in the Pressure?



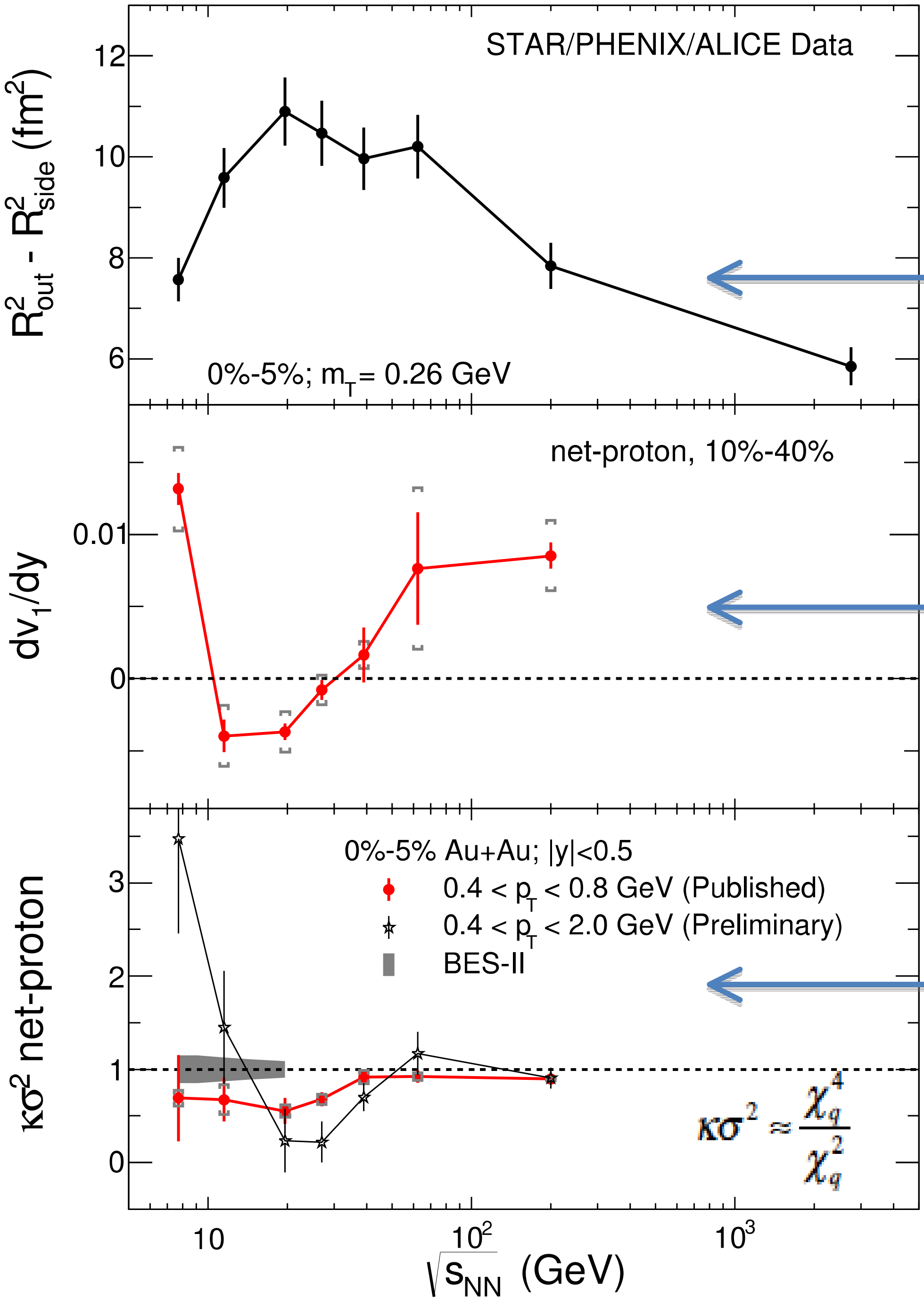
v_1 for both p & net-p qualitatively resemble collapse signature and are very different from the hadronic model



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



First Beam Energy Scan: Exploratory Study



Many measurements suggest anomalies in the pressure

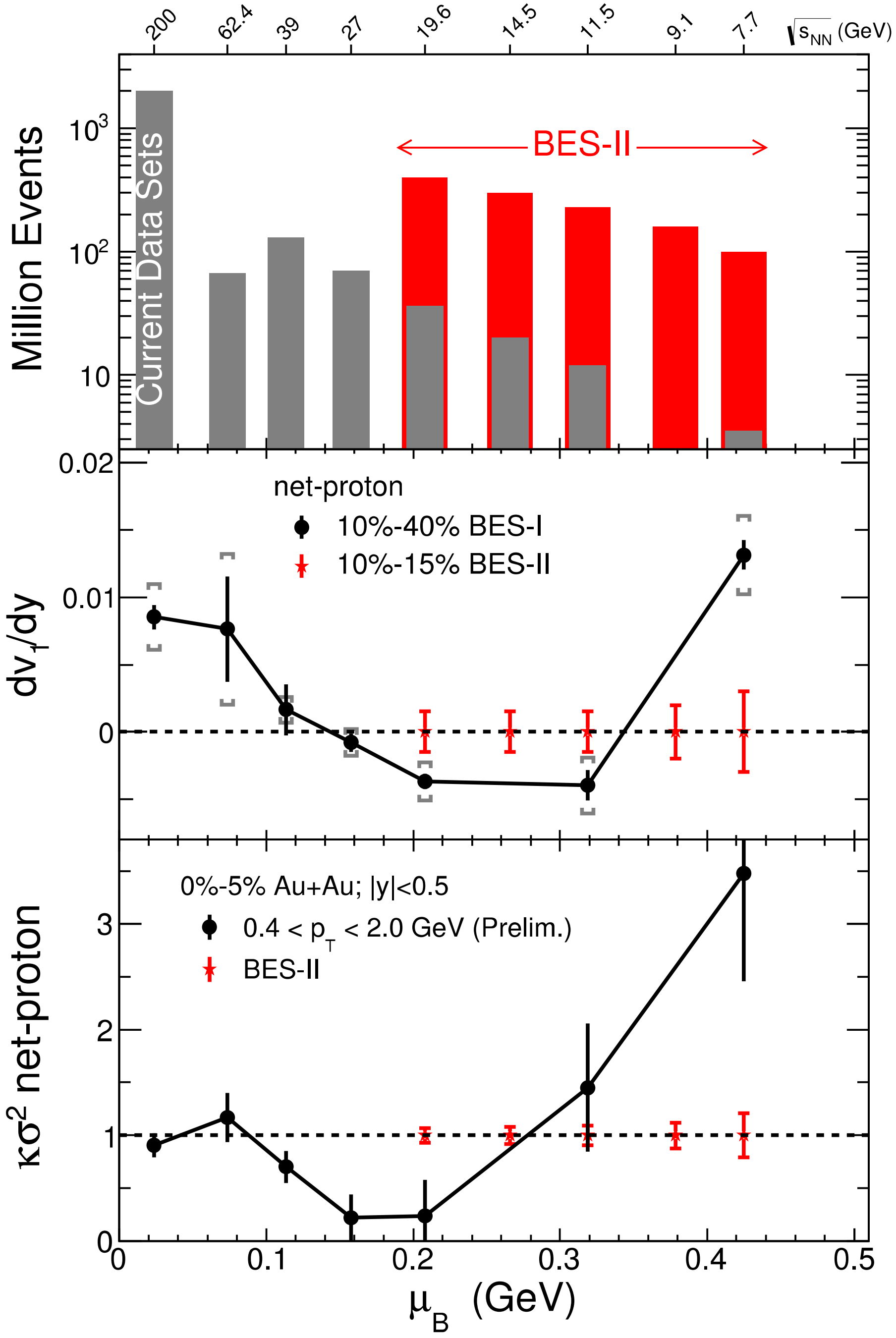
Related to the lifetime

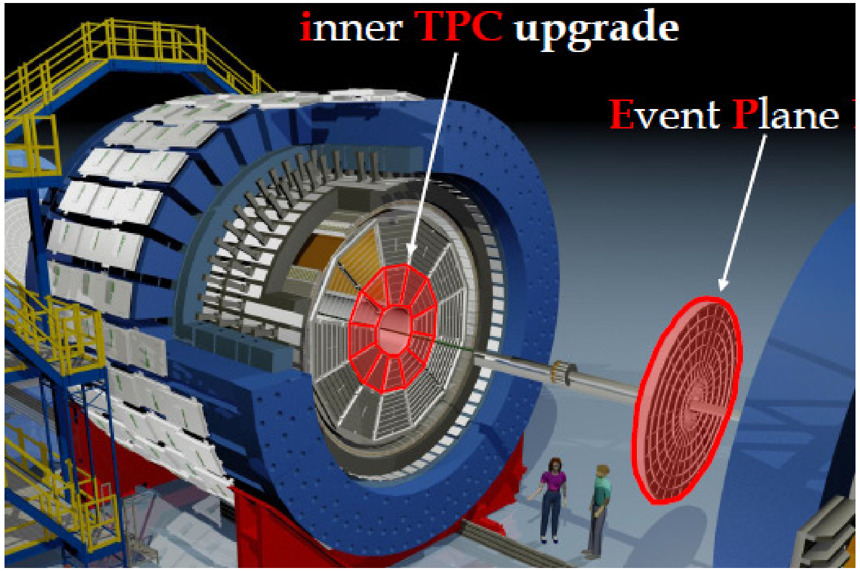
Related to the early pressure

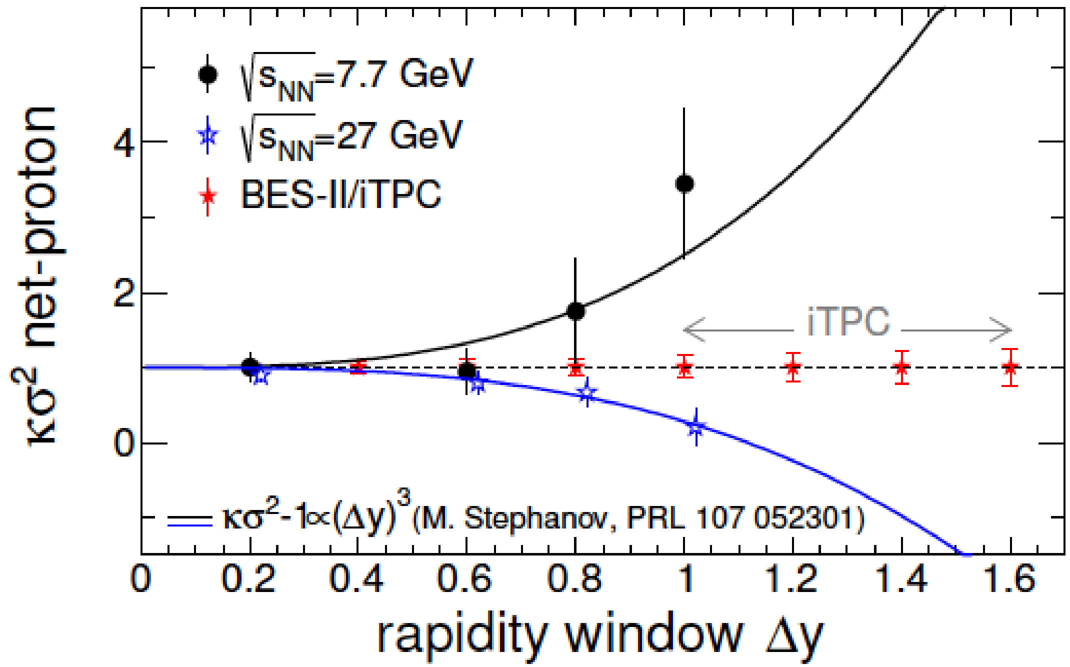
Related to the susceptibilities: derivatives of the pressure

Region of interest: $\sqrt{s_{NN}} \lesssim 20$ GeV

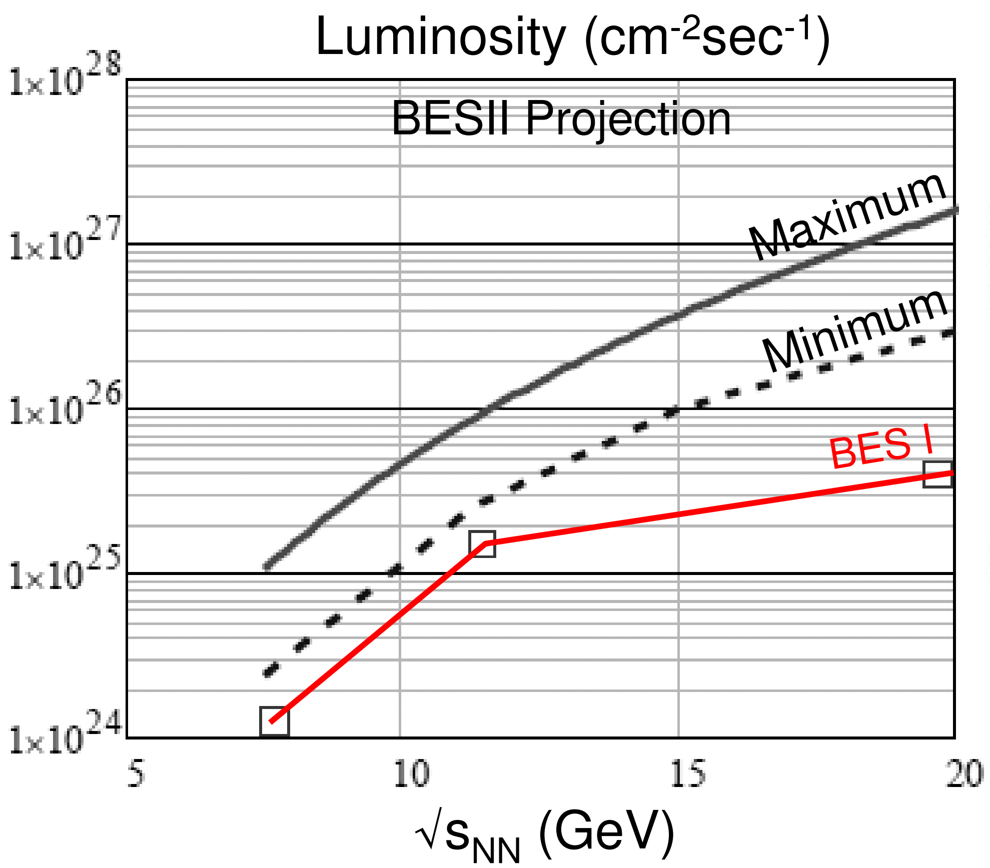
Mapping the region of interest: BES-II

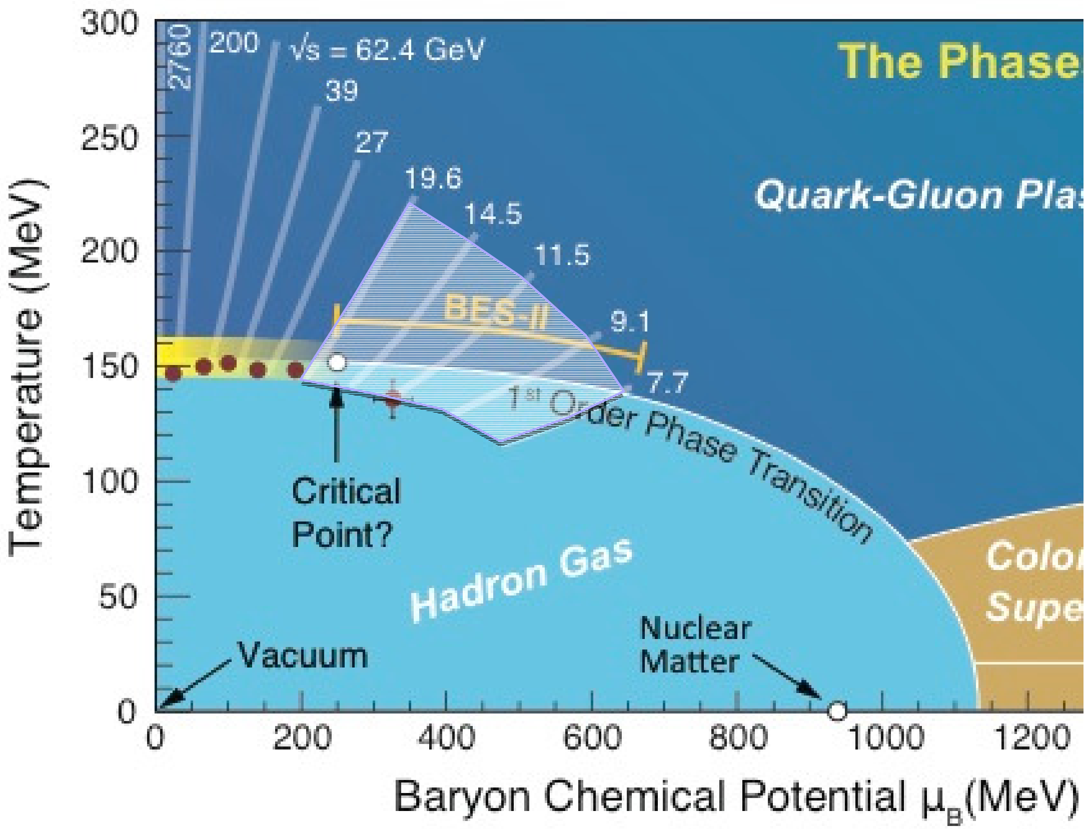






Scan Enabled by Luminosity Upgrade





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

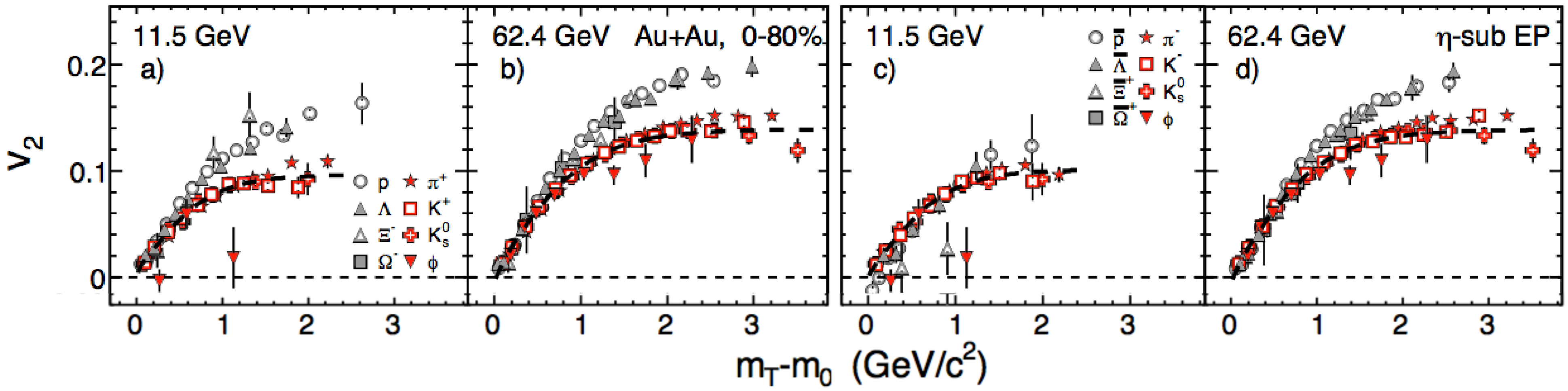
Provides access to emergent phenomena of QCD:
- Hottest man-made temperature: 300k times hotter than the center of the sun
- Data shown to prefer an Equation-of-State consistent with lattice QCD
- extracted η/s indicates this is the most perfect liquid ever known

Following on this progress at $\mu_B \sim 0$ 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

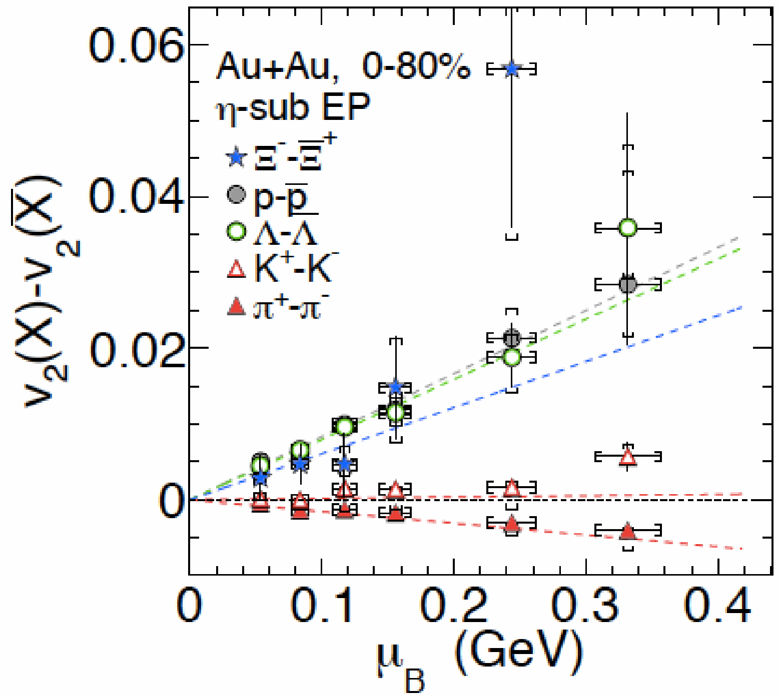
Unique opportunity for discovery. *Results from initial scan are highly suggestive.* BES-II will enable far stronger conclusions

Baryon and charge currents



Models need to include baryon and charge currents in order to model μ_B>0 data.

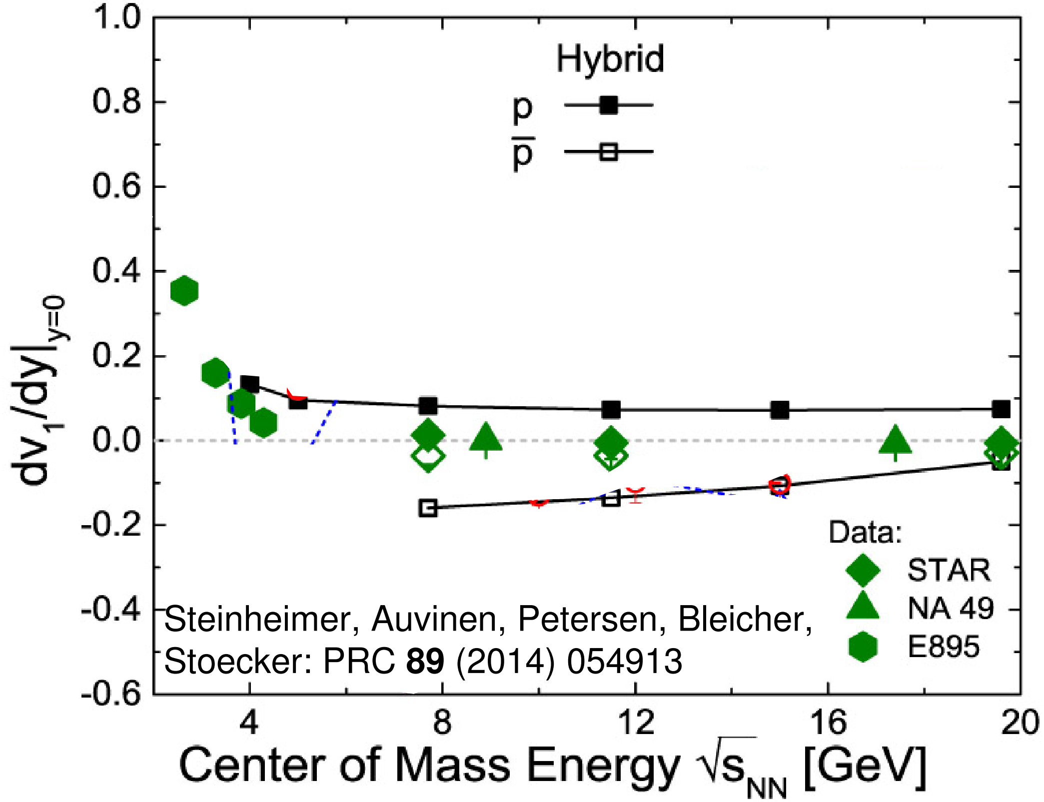
Effects of the hadronic phase are also more prevalent

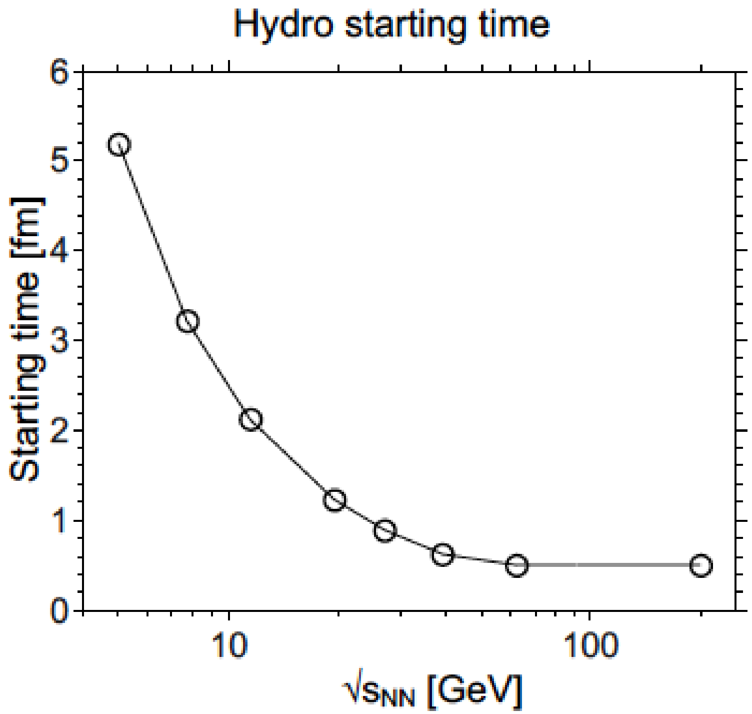


Strong mean fields partonic and hadronic? (Xu et al, arXiv:1201.3391 & Greco et al, arXiv:1201.4800)
Coalescence with transported quarks? (Phys.Rev. C84 (2011) 044914)

Theory/Model Work

hybrid hydro off by a lot





Nuclei haven't finished passing each other until after 5 fm/c at the lowest energies!

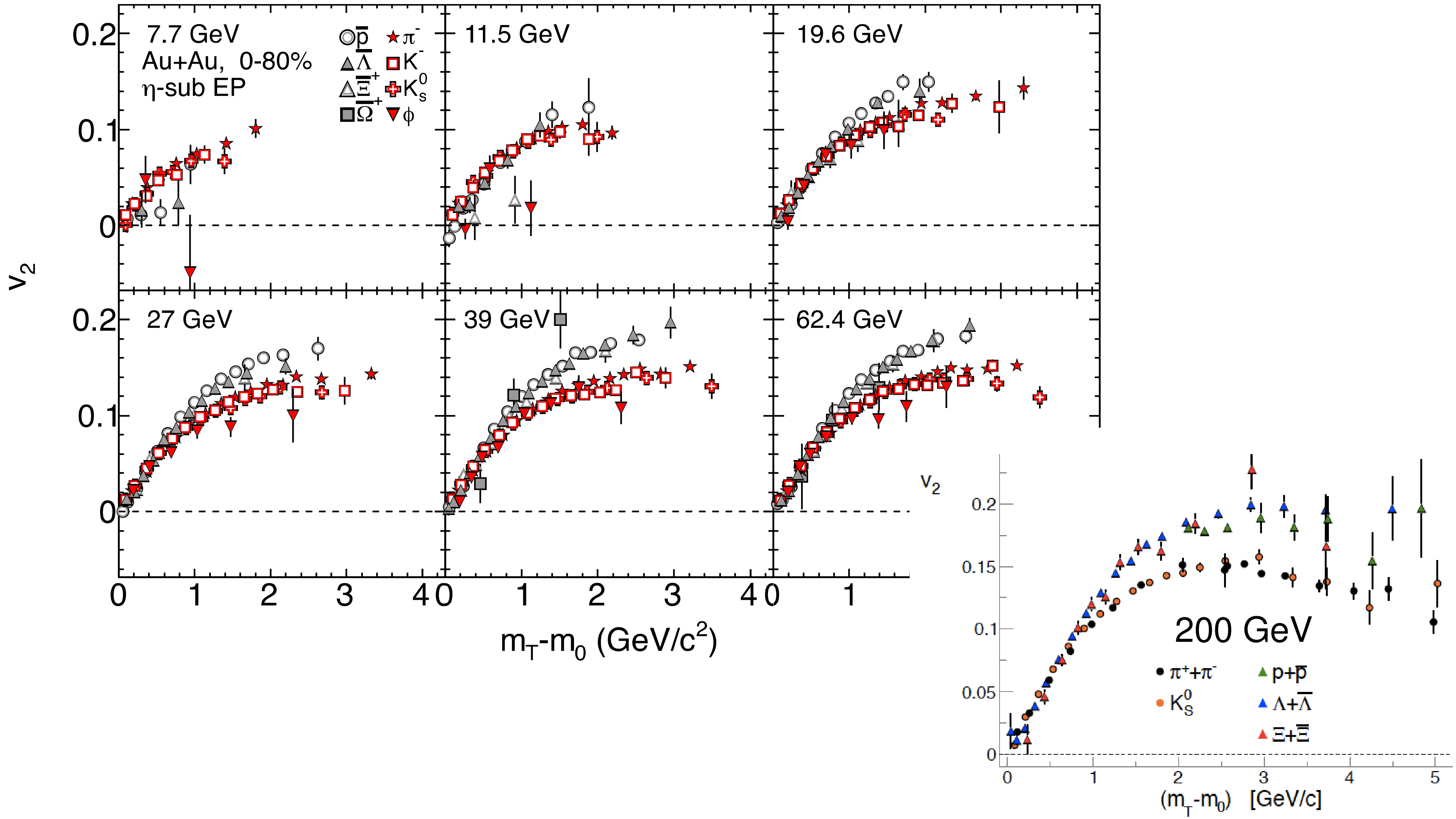
The initial state becomes more complicated to model and more important at the lower energies

End

Statistics Needed in BES phase II

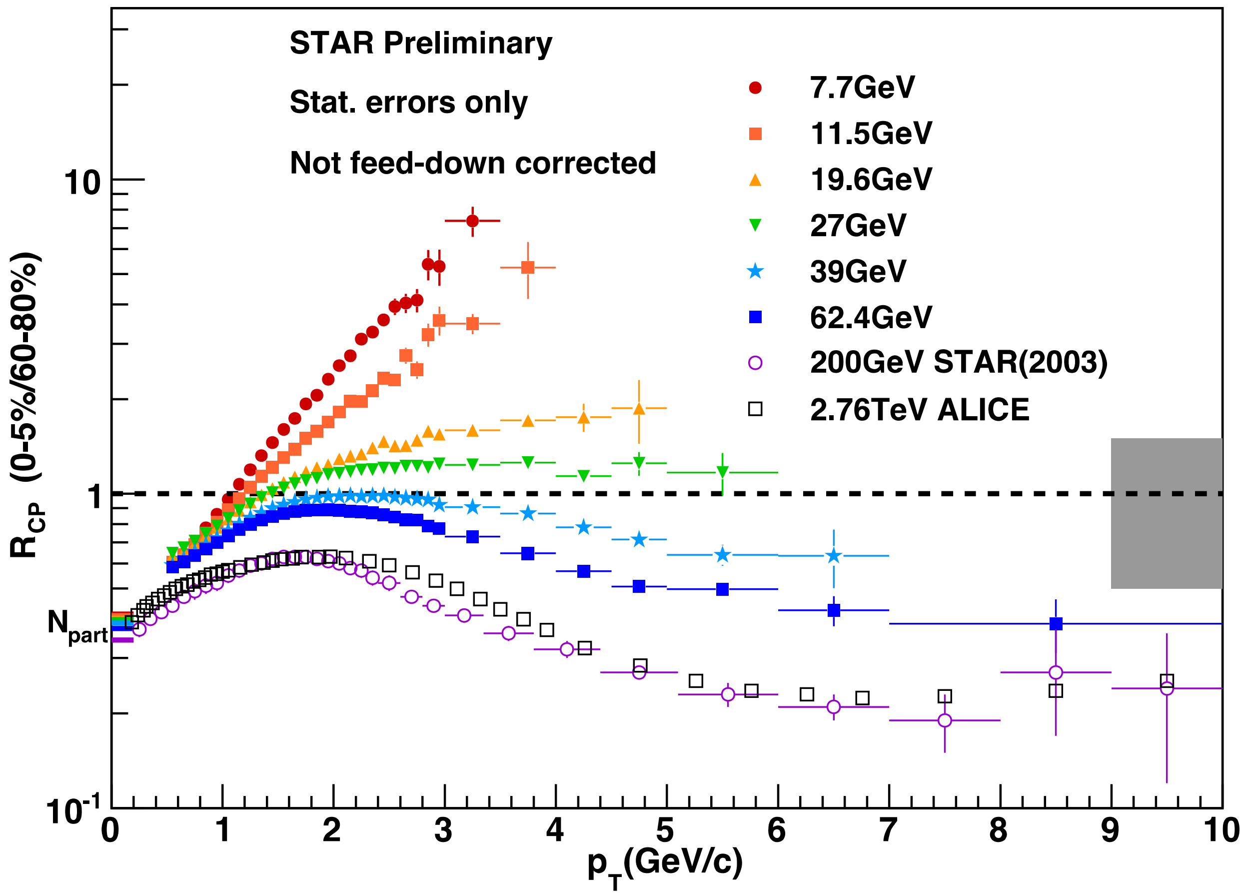
Collision Energies (GeV):	**7.7**	**9.1**	**11.5**	**14.5**	**19.6**
Chemical Potential (MeV):	**420**	**370**	**315**	**260**	**205**
Observables	Millions of Events Needed				
R_{CP} up to p_T 4.5 GeV	NA	NA	160	92	22
Elliptic Flow of ϕ meson (v_2)	100	150	200	300	400
Local Parity Violation (CME)	50	50	50	50	50
Directed Flow studies (v_1)	50	75	100	100	200
asHBT (proton-proton)	35	40	50	65	80
net-proton kurtosis ($\kappa\sigma^2$)	80	100	120	200	400
Dileptons	100	160	230	300	400
Proposed Number of Events:	**100**	**160**	**230**	**300**	**400**

Disappearance of QGP? NCQ



Baryon enhancement and meson baryon seperation
disappears below 19.6 GeV

Disappearence of QGP? R_{CP}

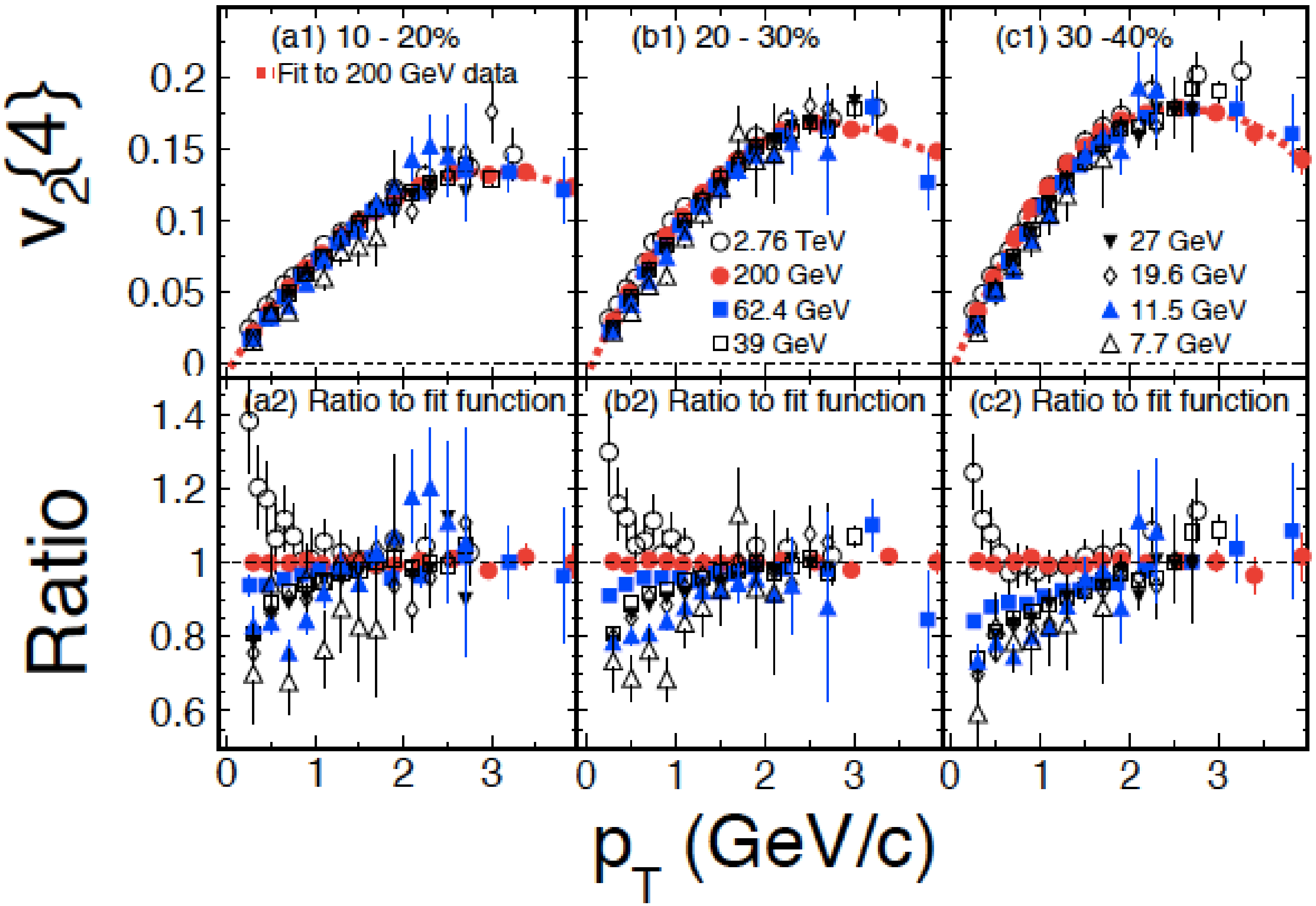


R_{CP} for 4-5 GeV particles gradually transitions from a suppresion at 200 GeV to an enhancement at 19.6 GeV

Opacity disappears below 39 GeV?

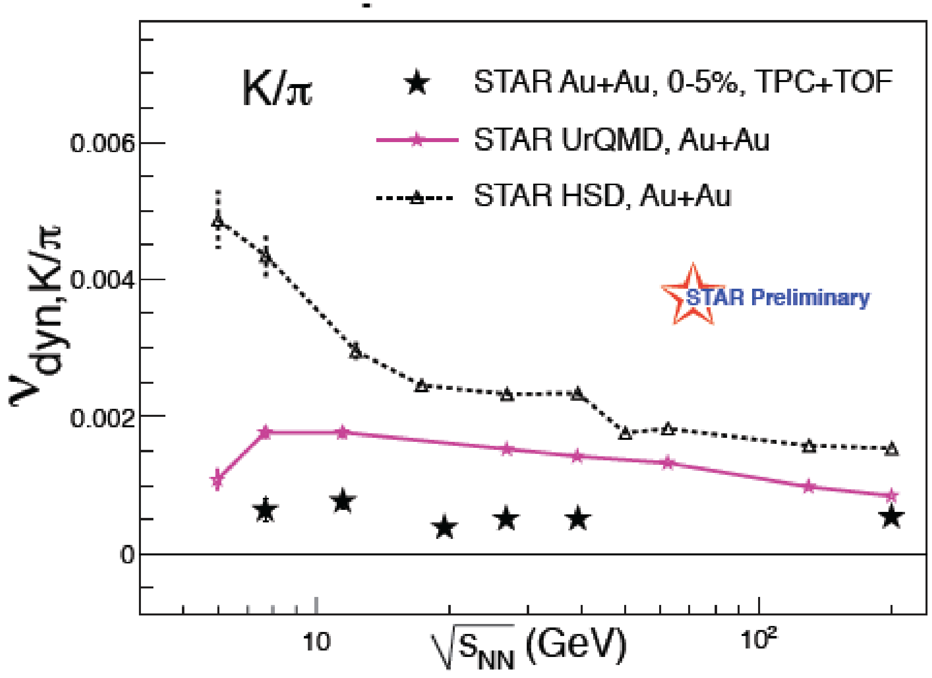
$v_2\{4\}$

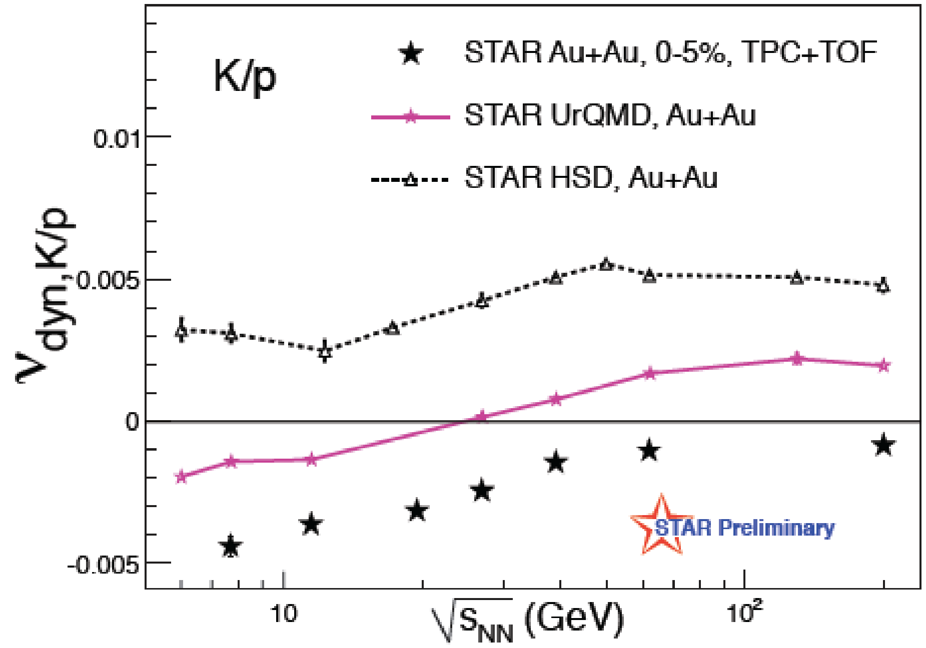
Phys.Rev. C86 (2012) 054908



at p_T=0.5 GeV, $v_2\{4\}$ shows ~40% variation from 7.7 GeV to 2.76 TeV
at p_T=2.0 GeV, $v_2\{4\}$ shows almost no change over that range

Particle Ratio Fluctuations

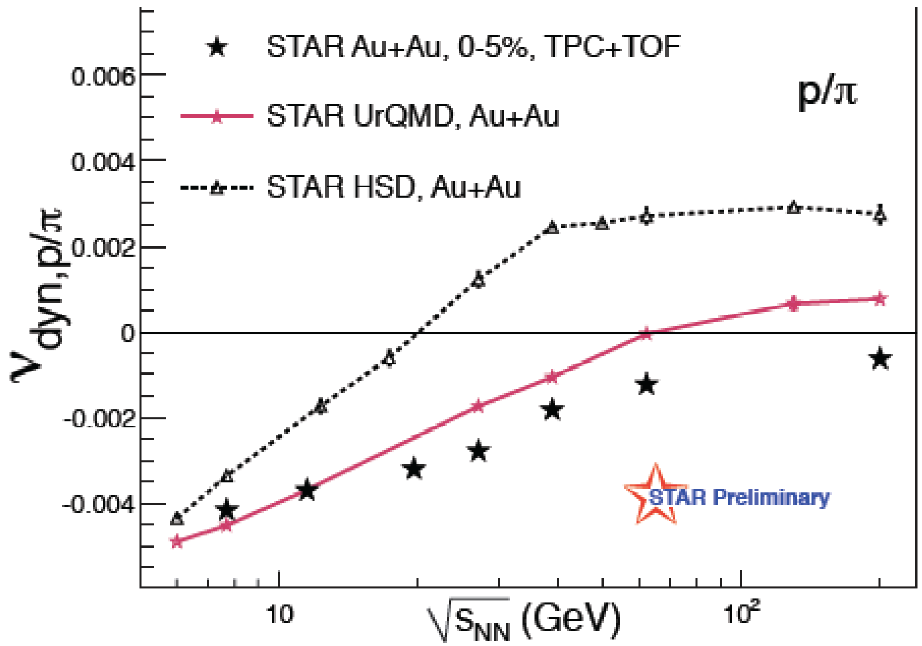




Measurement of event-to-event variation of particle ratios:

For 1st order phase transition: enhanced fluctuations

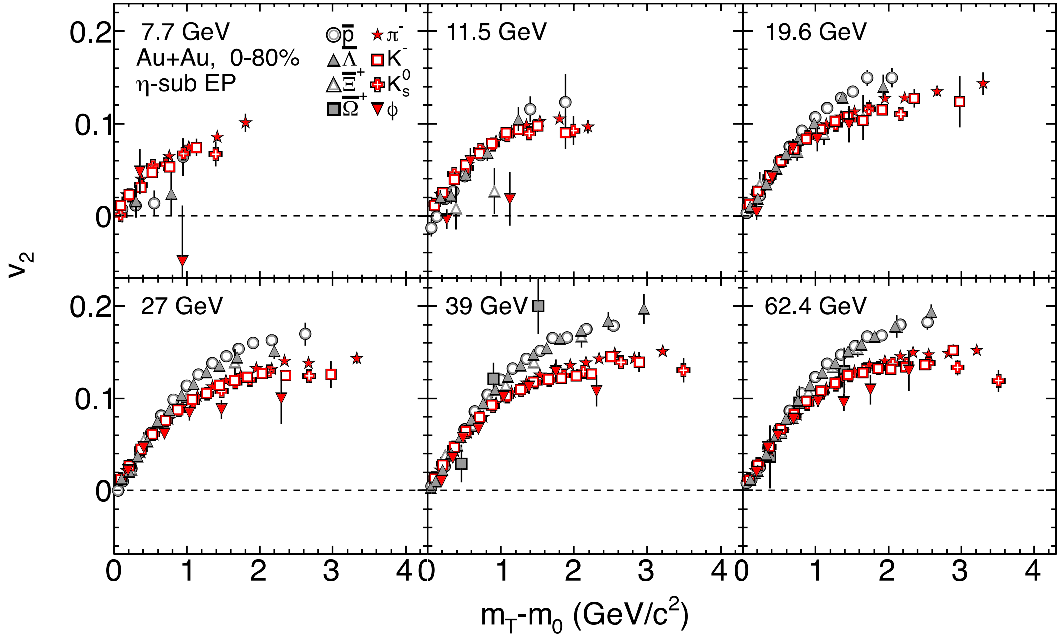
Observed energy dependence: monotonic along with other fluctuation observables



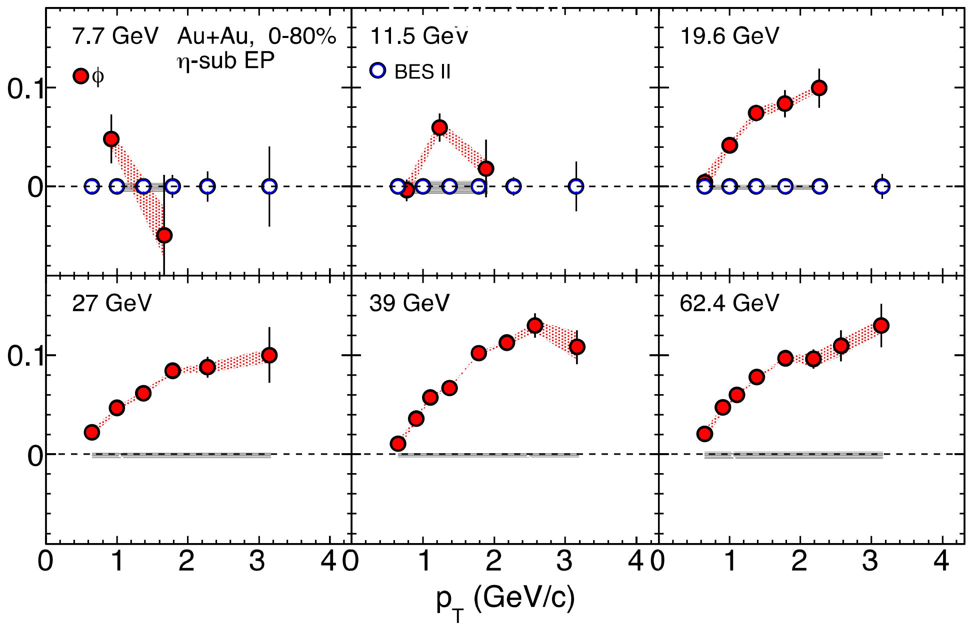
Also In Need of More Data

When the system is a hadron gas instead of a QGP, φ v_2 is expected to fall below the trends set by other particle types

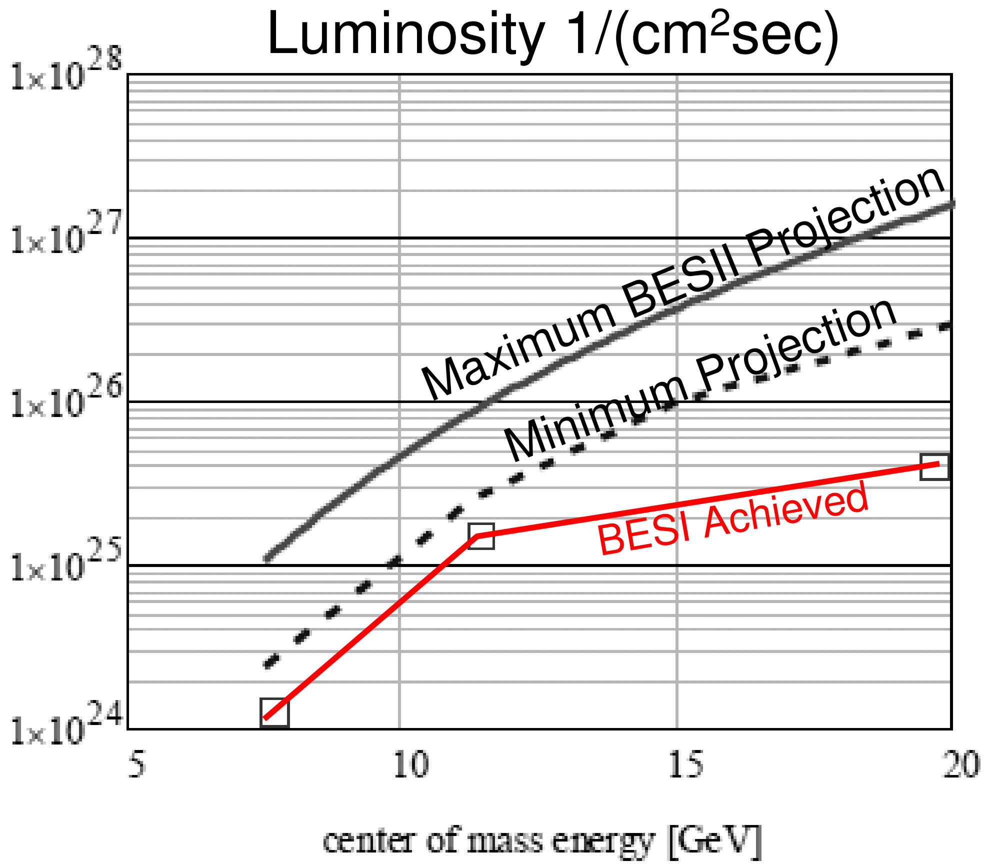
Does the φ fall below the trend at low √s?

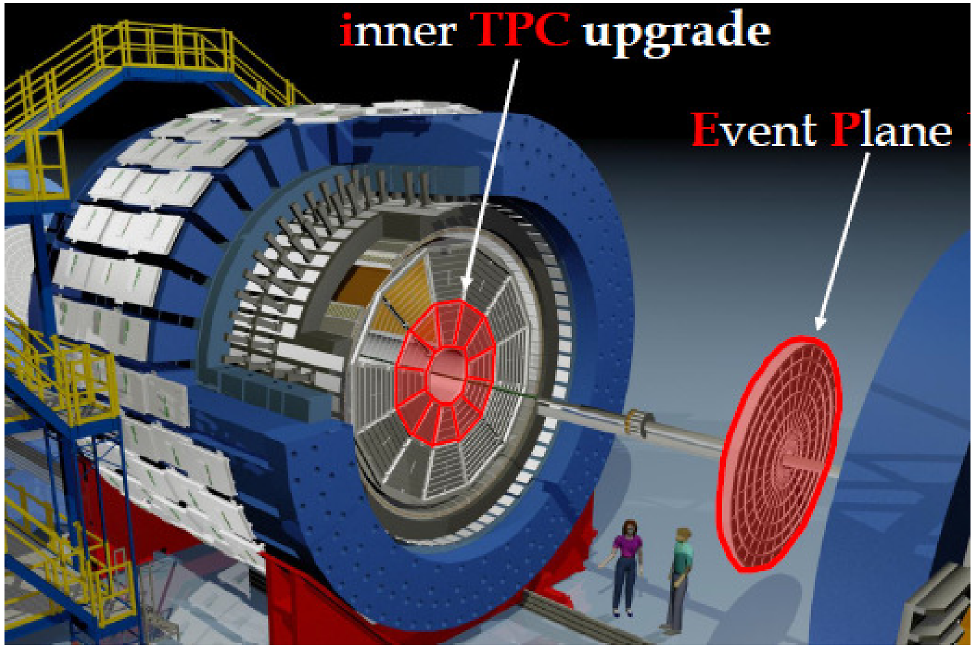


Error estimates for φ v_2 with



RHIC Upgrades for BESII



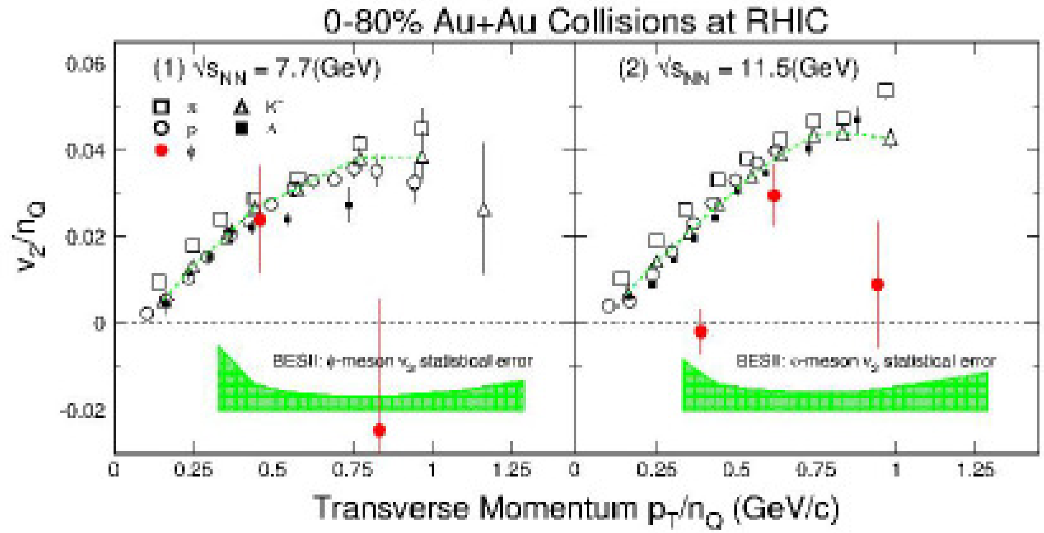


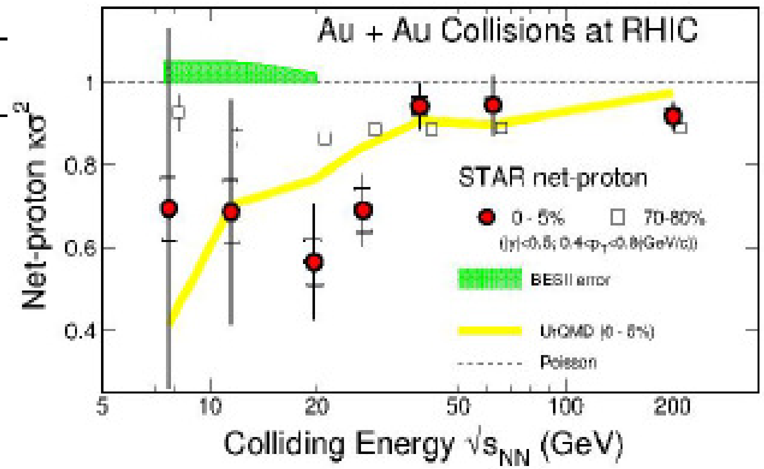
Accelerator and detector upgrades, motivated by observations from BESI, will bring a level of clarity to the region of interest

With evocative data already in hand, discovery potential is high!

RHIC Upgrades for BESII

Collision Energy (GeV)	7.7	9.1	11.5	14.5	19.6
μ_B (		)	315	260	205
Ob					
R_{CP}					
Elli		)			
Chi					
Dir					
Azi					
Net		)			
Dileptons	100	160	230	300	400
Required Number of Events	**100**	**160**	**230**	**300**	**400**





factor of 25 increase in statistics

Accelerator and detector upgrades, motivated by observations from BESI, will bring a level of clarity to the region of interest

With evocative data already in hand, discovery potential is high!