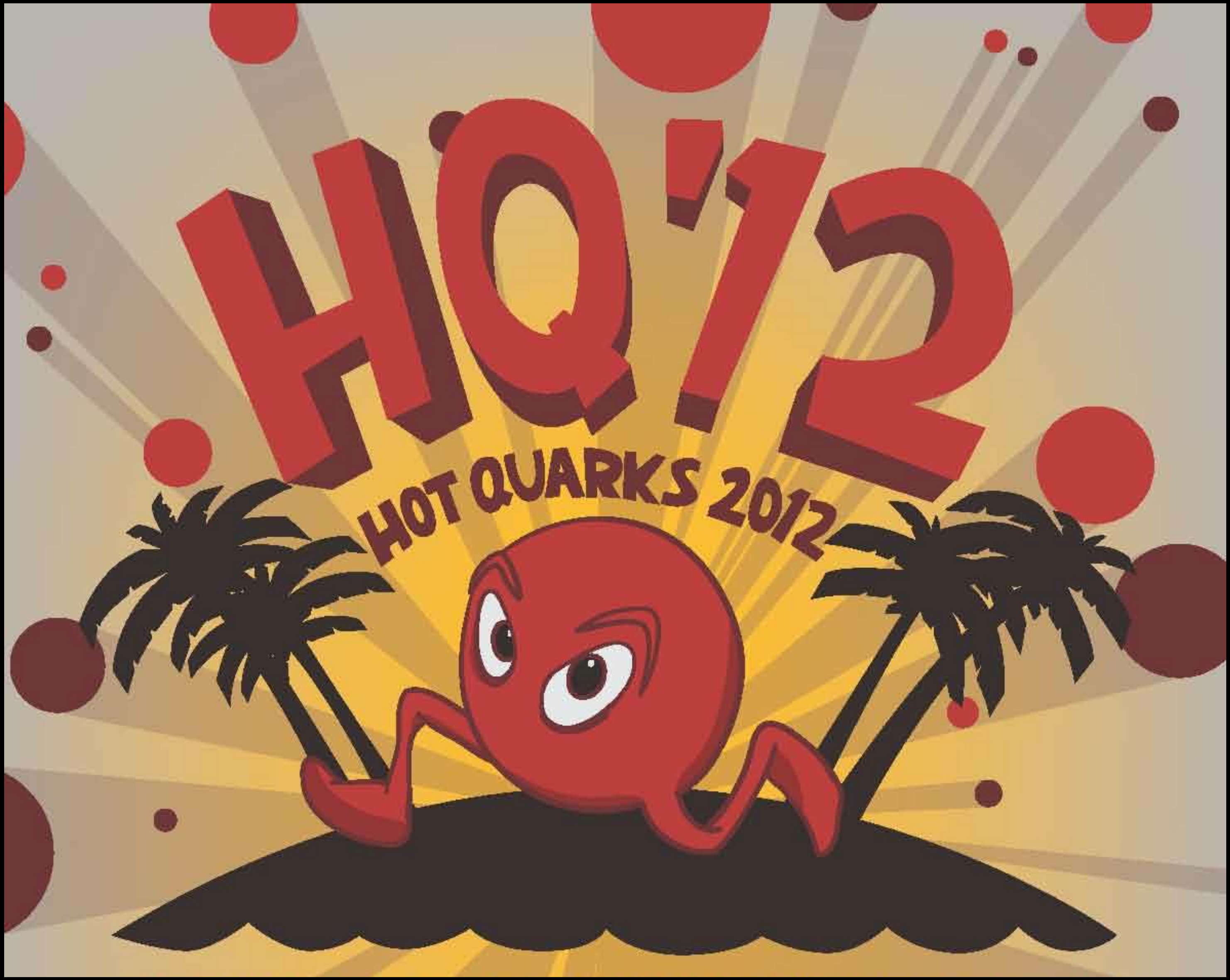
# Beam Energy Scan Results from RHIC



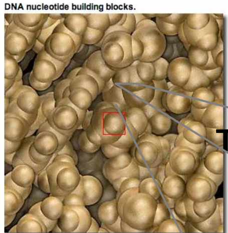

*Paul Sorensen*

BROOKHAVEN NATIONAL LABORATORY

# Particle Physics and the Energy Frontier

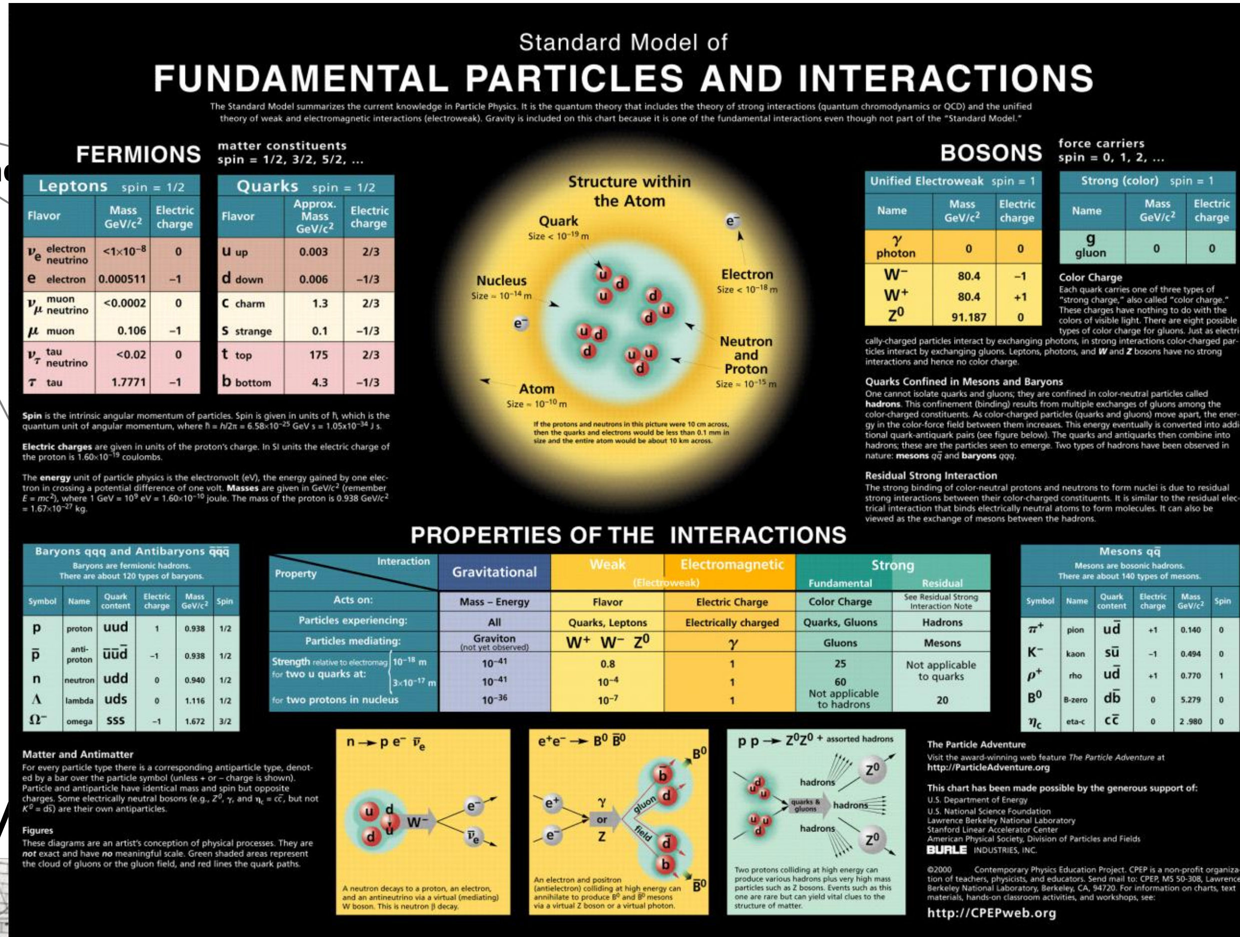
**Atoms (1800)**

DNA nucleotide building blocks.



$10^{-9}$ meters

Th




| Leptons Flavor | Mass GeV/c² | Electric charge |
|---|---|---|
| $\nu_e$ electron neutrino | $<1\times10^{-8}$ | 0 |
| e electron | 0.000511 | −1 |
| $\nu_\mu$ muon neutrino | <0.0002 | 0 |
| $\mu$ muon | 0.106 | −1 |
| $\nu_\tau$ tau neutrino | <0.02 | 0 |
| $\tau$ tau | 1.7771 | −1 |

| Quarks Flavor | Approx. Mass GeV/c² | Electric charge |
|---|---|---|
| u up | 0.003 | 2/3 |
| d down | 0.006 | −1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | −1/3 |
| t top | 175 | 2/3 |
| b bottom | 4.3 | −1/3 |

| Unified Electroweak Name | Mass GeV/c² | Electric charge |
|---|---|---|
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.4 | −1 |
| $W^+$ | 80.4 | +1 |
| $Z^0$ | 91.187 | 0 |

| Strong (color) Name | Mass GeV/c² | Electric charge |
|---|---|---|
| g gluon | 0 | 0 |

| Property | Gravitational | Weak (Electroweak) | Electromagnetic | Strong Fundamental | Strong Residual |
|---|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | Gluons | Mesons |
| Strength relative to electromag for two u quarks at $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 | Not applicable to quarks |
| for two u quarks at $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 | |
| for two protons in nucleus | $10^{-36}$ | $10^{-7}$ | 1 | Not applicable to hadrons | 20 |

| Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin |
|---|---|---|---|---|---|
| p | proton | uud | 1 | 0.938 | 1/2 |
| $\bar{p}$ | anti-proton | $\bar{u}\bar{u}\bar{d}$ | −1 | 0.938 | 1/2 |
| n | neutron | udd | 0 | 0.940 | 1/2 |
| $\Lambda$ | lambda | uds | 0 | 1.116 | 1/2 |
| $\Omega^-$ | omega | sss | −1 | 1.672 | 3/2 |

| Symbol | Name | Quark content | Electric charge | Mass GeV/c² | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | −1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.770 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2.980 | 0 |

*has always*

*tic probes:*

istently been

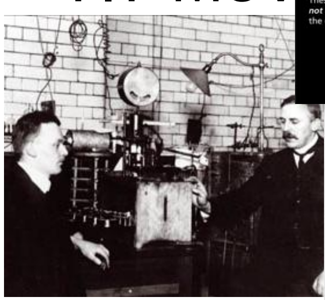
ergy frontiers

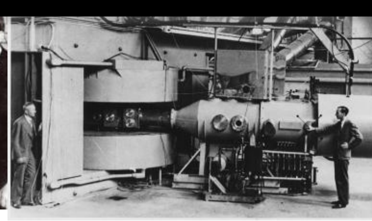
by ever more

accelerators

7.7 MeV

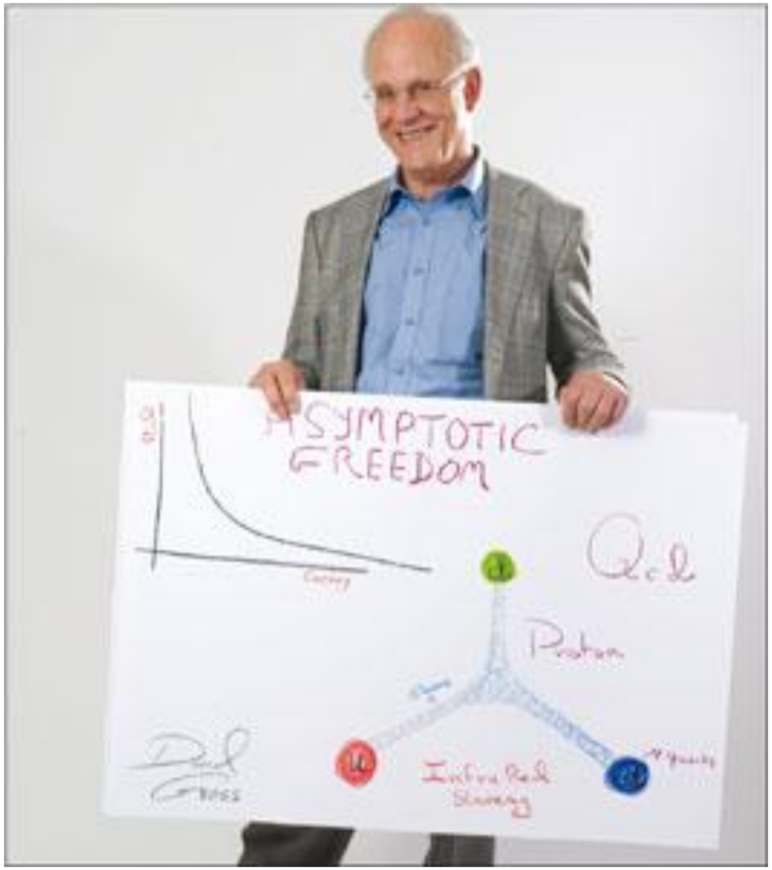
TeV





# QCD and the Energy Frontier

Two salient features of QCD: Asymptotic Freedom and Confinement




Asymptotic Freedom:

- at short length scales (high energies) coupling between charges is weak
- allows us to *test* QCD using perturbative calculations (asymptotically large energies) requiring high energy

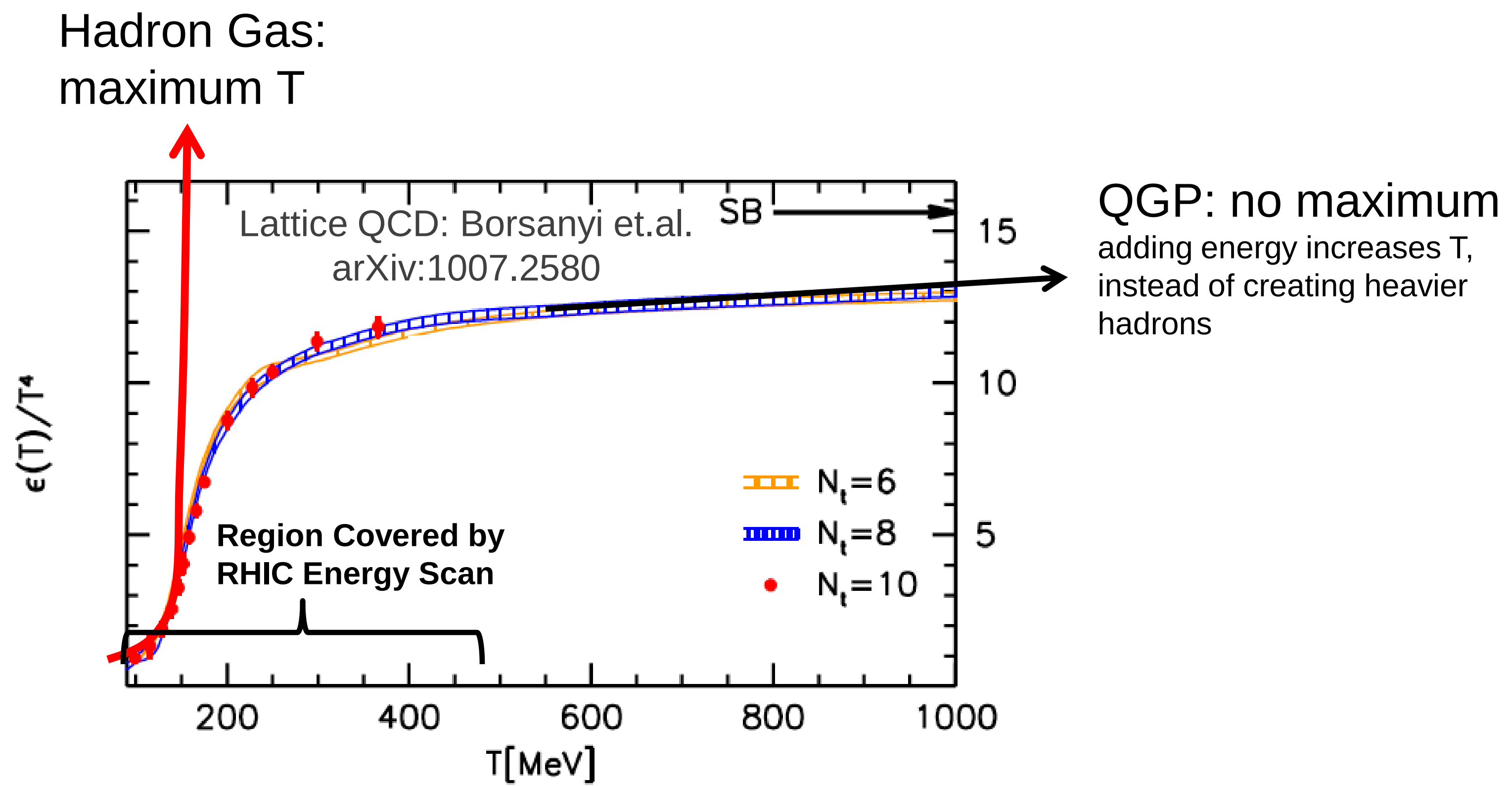
For all these reasons, particle physicists tend to dwell on the energy frontier

But we study the **Confinement/Deconfinement transition** (~200 MeV)

There's more to understanding QCD than testing it at high $Q^2$

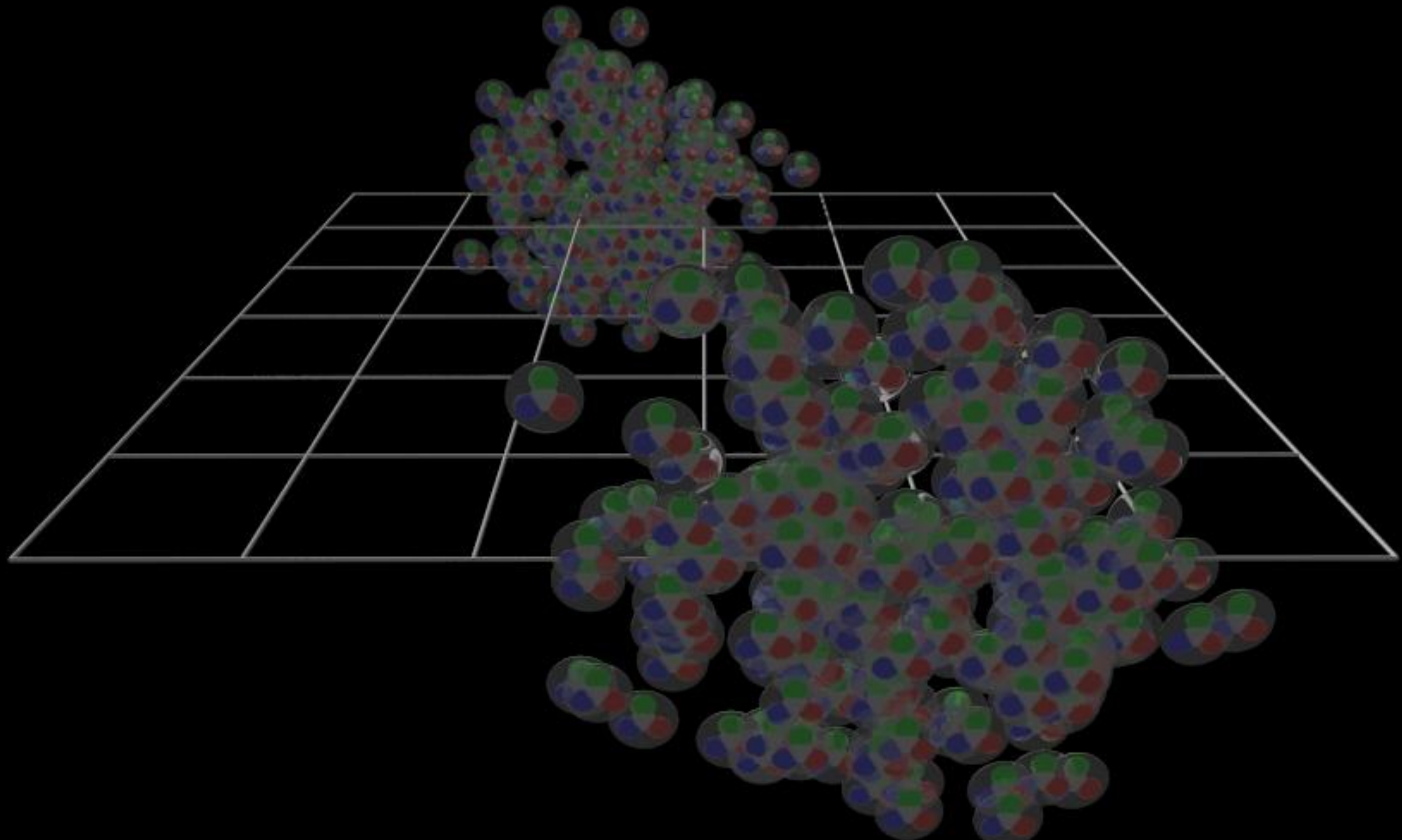
# Thermodynamics of QCD

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

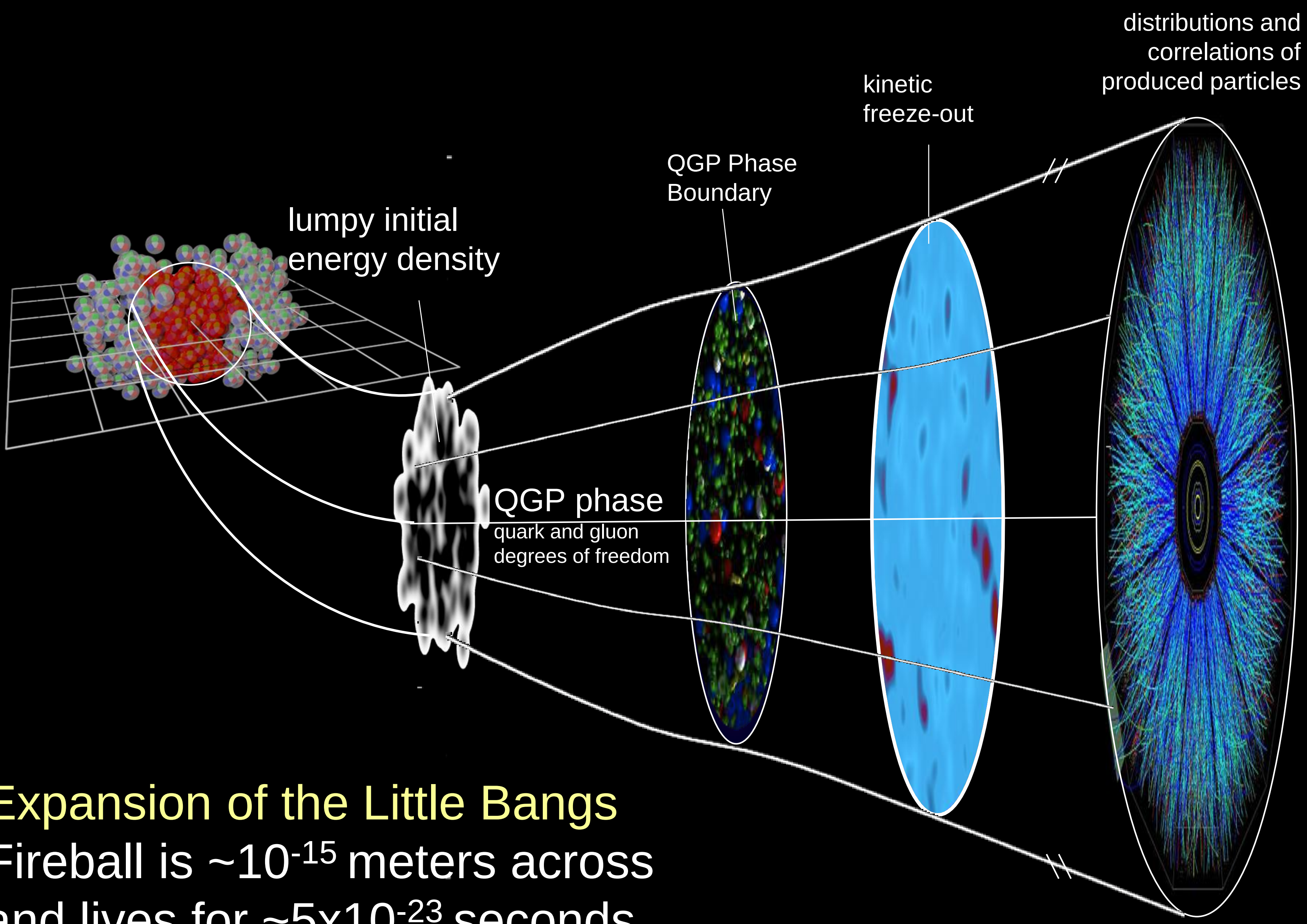



The transition region (not the asymptotic limit) is of most interest

# Finite Temperature QCD in the Lab



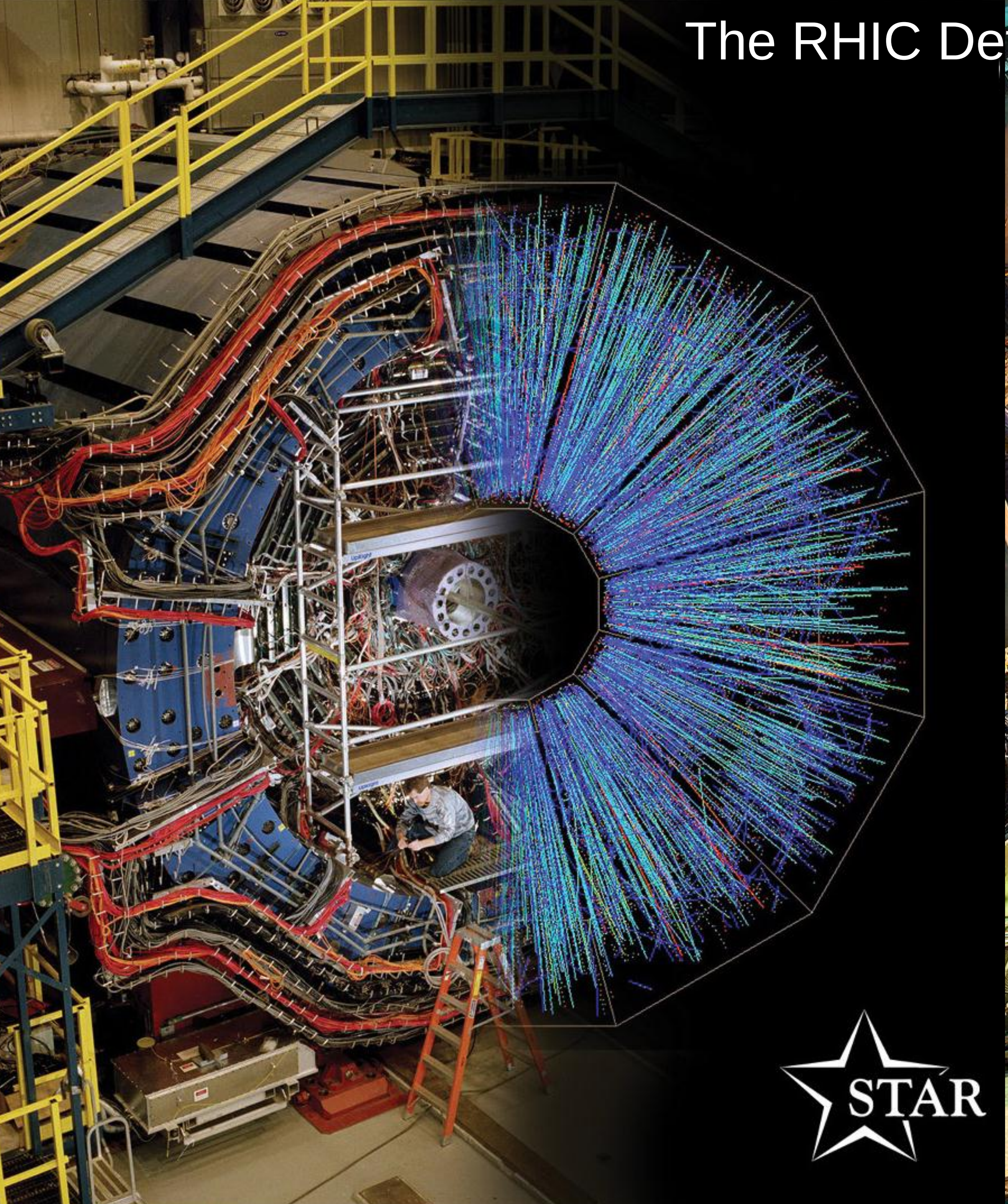
# Finite Temperature QCD in the Lab




Expansion of the Little Bangs

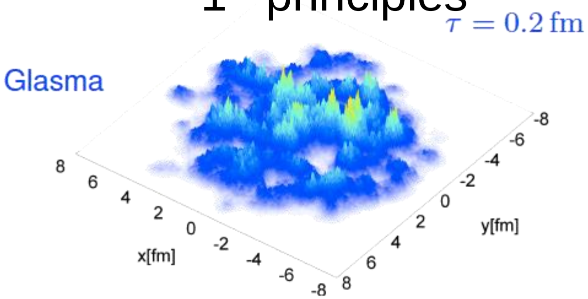
Fireball is ~$10^{-15}$ meters across and lives for ~$5 \times 10^{-23}$ seconds

# The RHIC Detectors



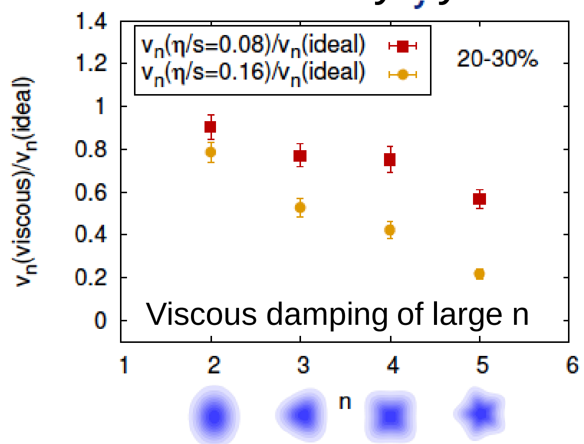

# A Standard Model for Little Bangs

Initial state including geometric and quantum fluctuations from 1st principles



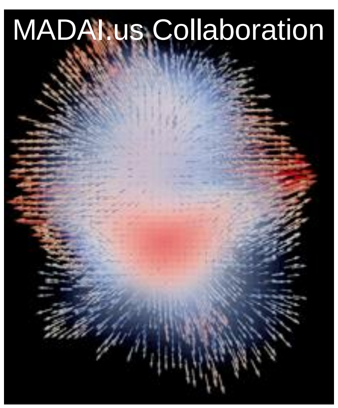

Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

Low η/s plasma phase modeled by hydro




Relativistic Viscous Hydro: effective theory studied at 1st and 2nd order, shown to converge

Hadronic phase and freezeout




Compare to experiment

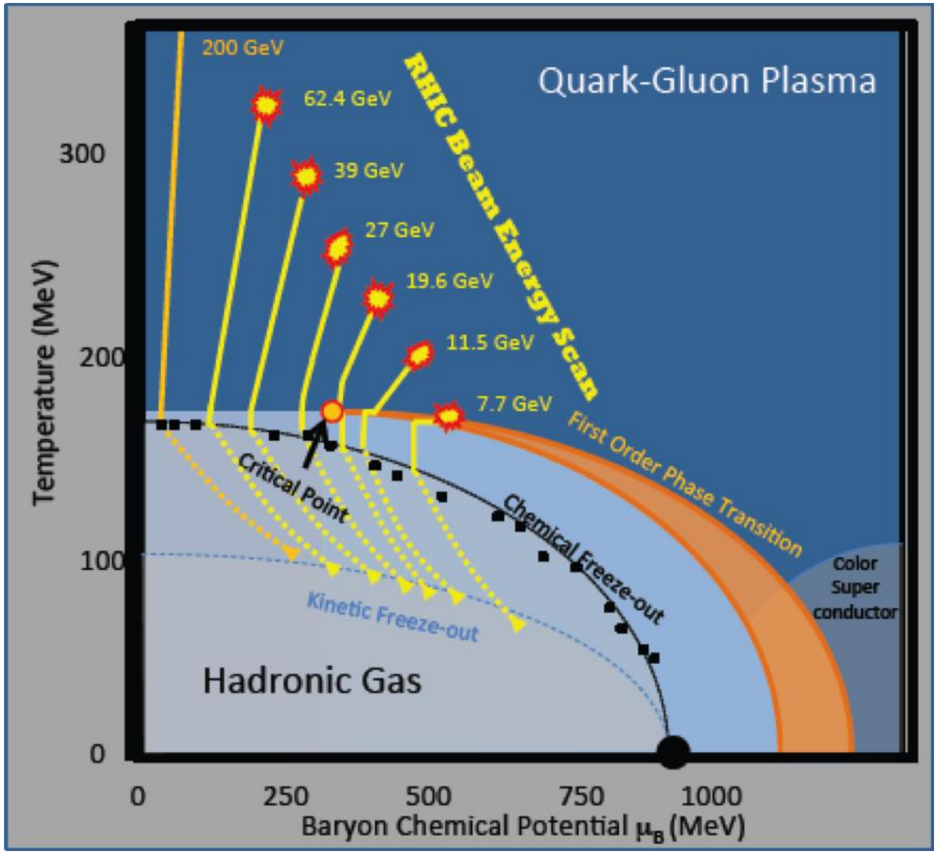
# Beam Energy Scan Motivation

To characterize QCD matter in different regions of the theory

Varying the beam energy changes
• the initial energy density and Temp.
• baryon chemical potential
• the equation of state
• the wave-function of the incoming nuclei

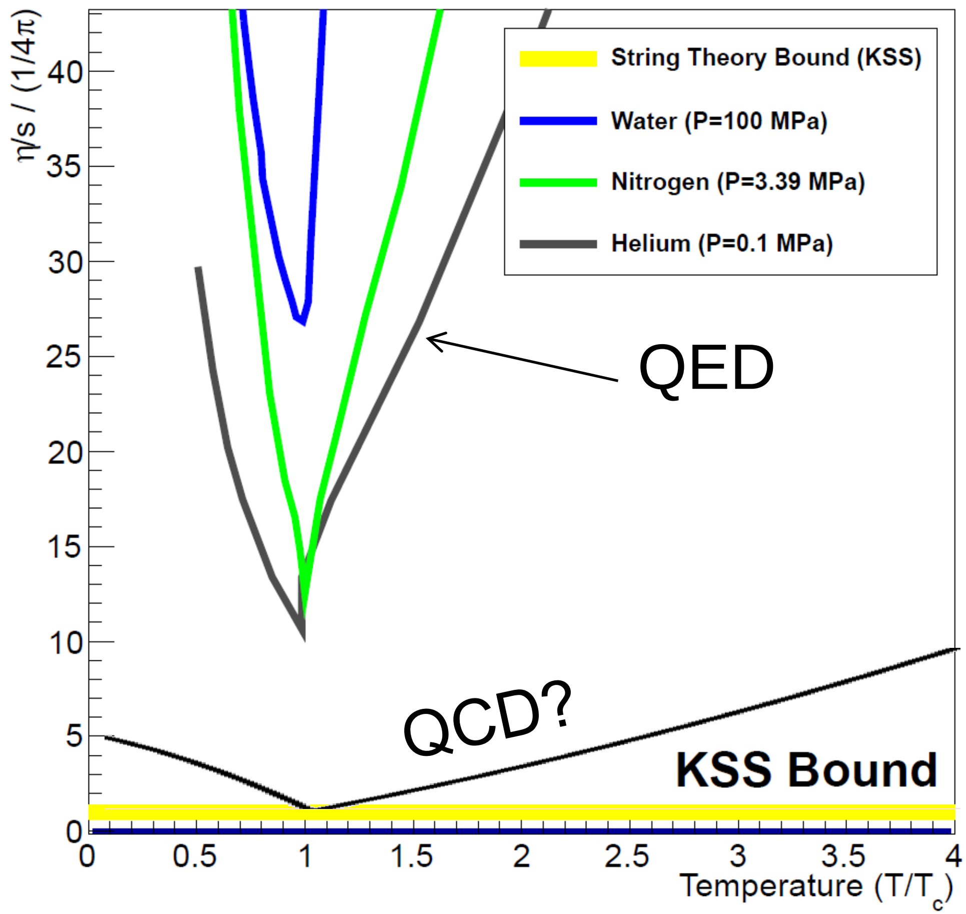
Search for
• turn off of QGP signatures
• change in the degrees of freedom
• evidence of a first order phase transition ending at a critical point

Study the temperature dependence of various transport parameters



# Temperature Dependence of η/s

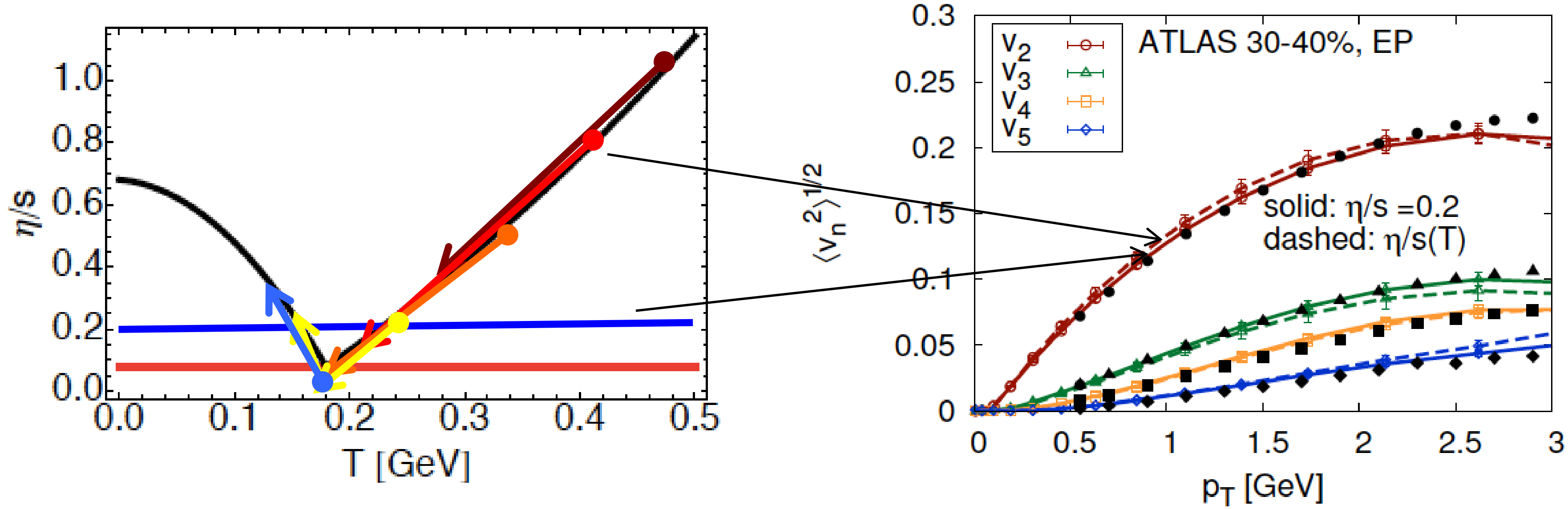
A. Majumder, B. Muller, X.N. Wang, PRL (2007)




An understanding of the emergent properties of QCD requires coverage of a broad energy range

# Temperature Dependence of η/s

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan



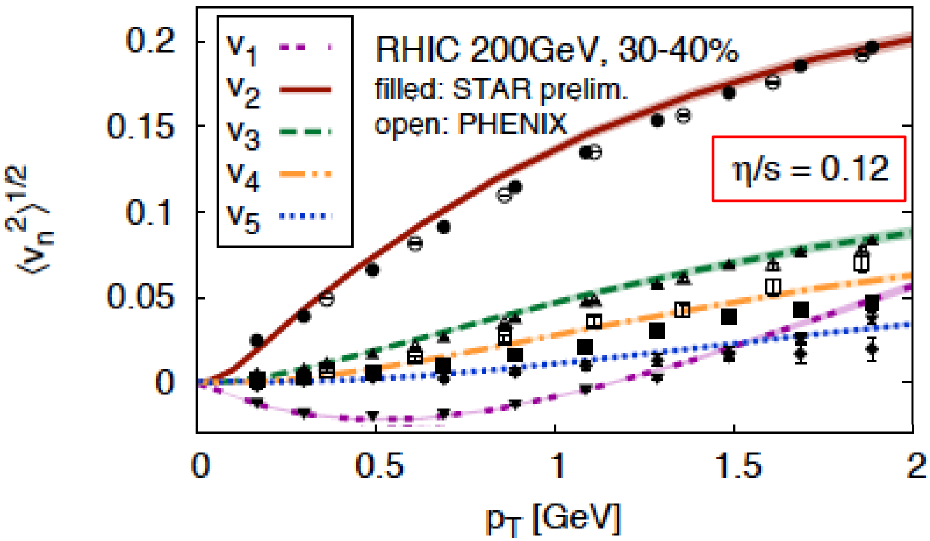

Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

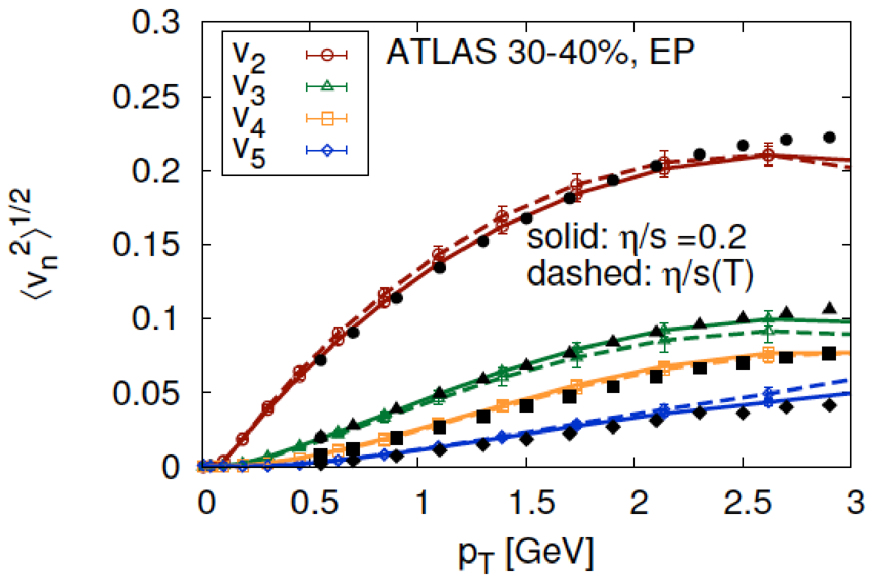
Model doesn't distinguish between a constant η/s or a temperature dependent η/s with a minimum of 1/4π at $T_C$

Temperature dependence can't be assessed with the one energy.
**Requires full analysis across a range of initial energy densities**

# Temperature Dependence of η/s

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan



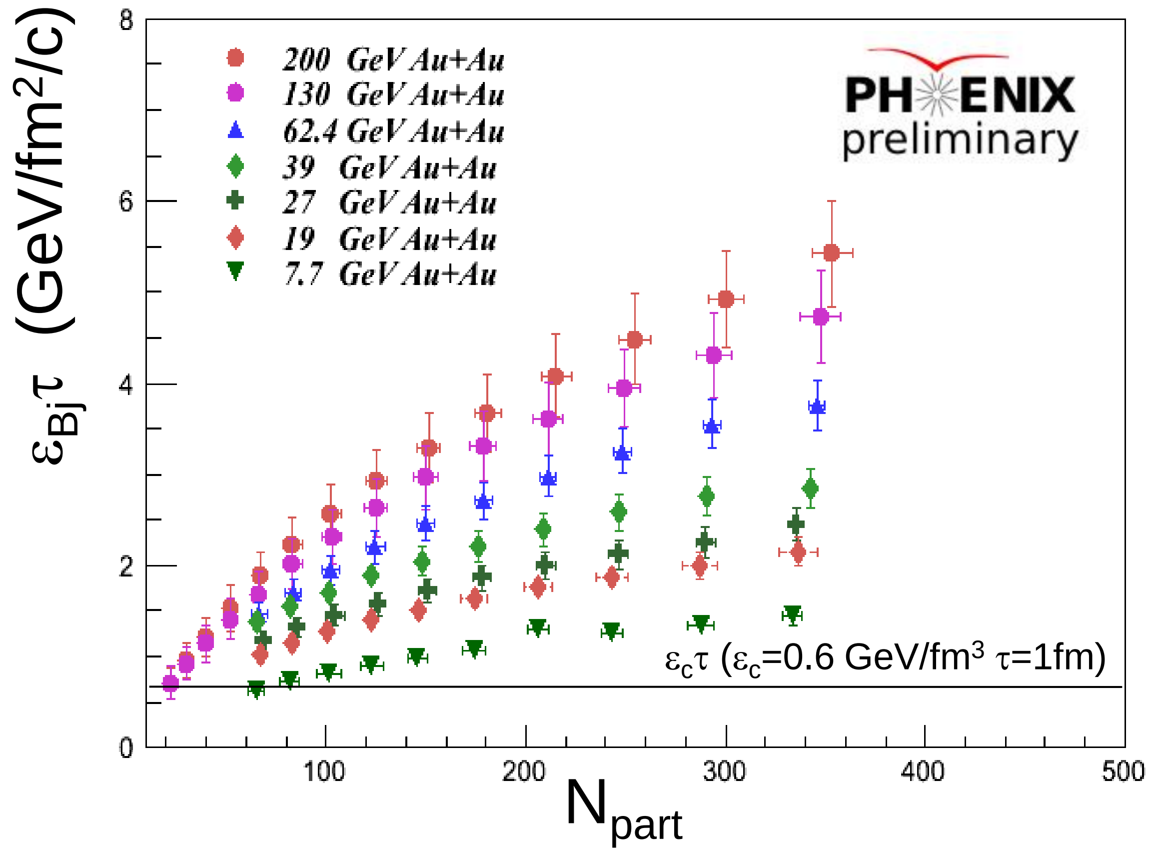

<η/s> at RHIC is 40% smaller than the LHC

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

Model doesn't distinguish between a constant η/s or a temperature dependent η/s with a minimum of 1/4π at $T_C$

Temperature dependence can't be assessed with one energy. **Requires full analysis across a range of initial energy densities ➔BES data**

# Where Does the QGP Turn Off?



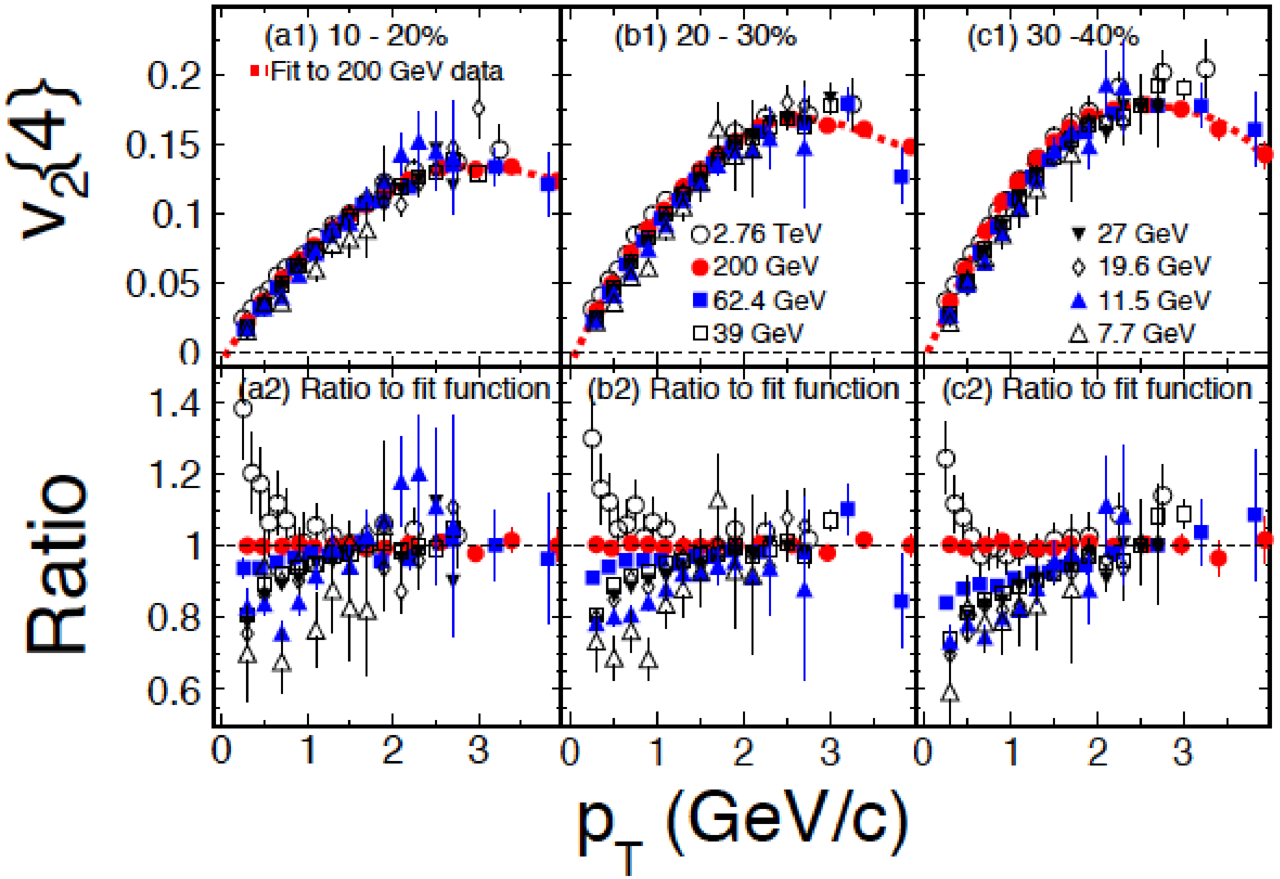

Critical $\varepsilon_c$ from lattice ~0.6 GeV/fm$^3$: lowest energy range explored still expected to be above transition region

No guarantee to see turn-off of QGP

¿What is the $\sqrt{s}$ and $N_{part}$ dependence of τ?

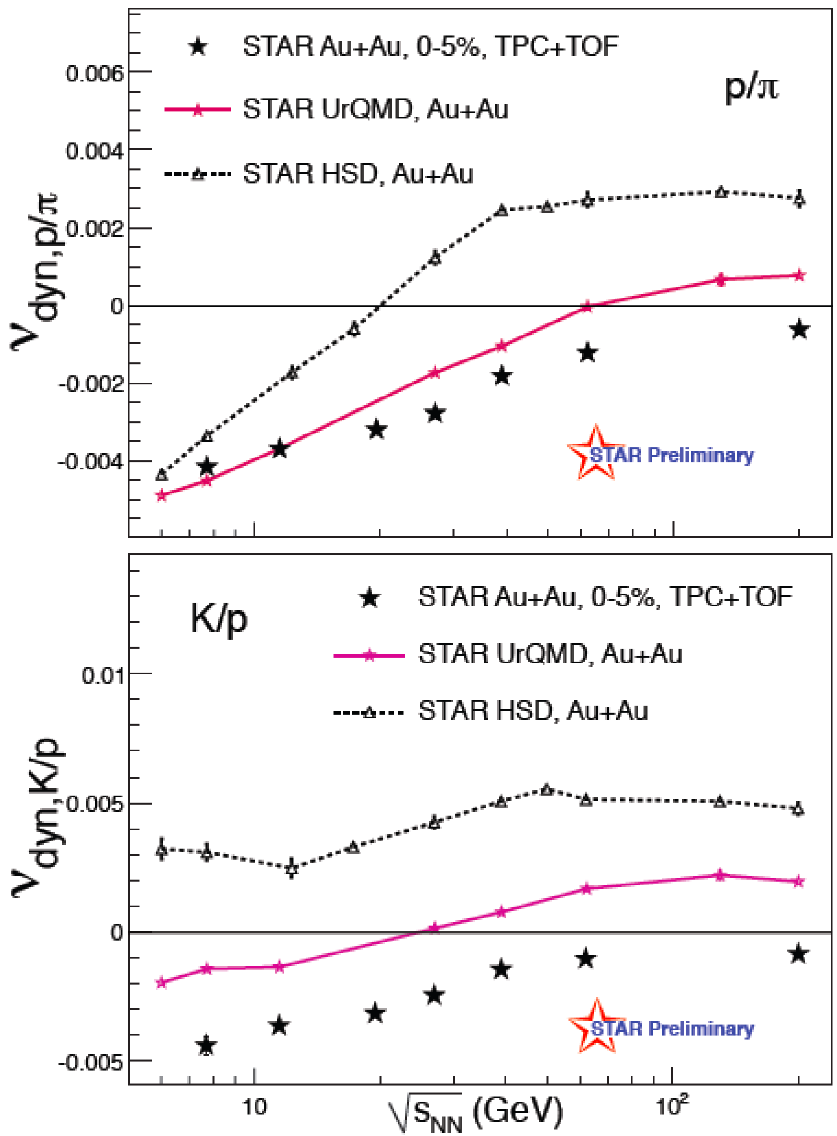
# $v_2\{4\}$

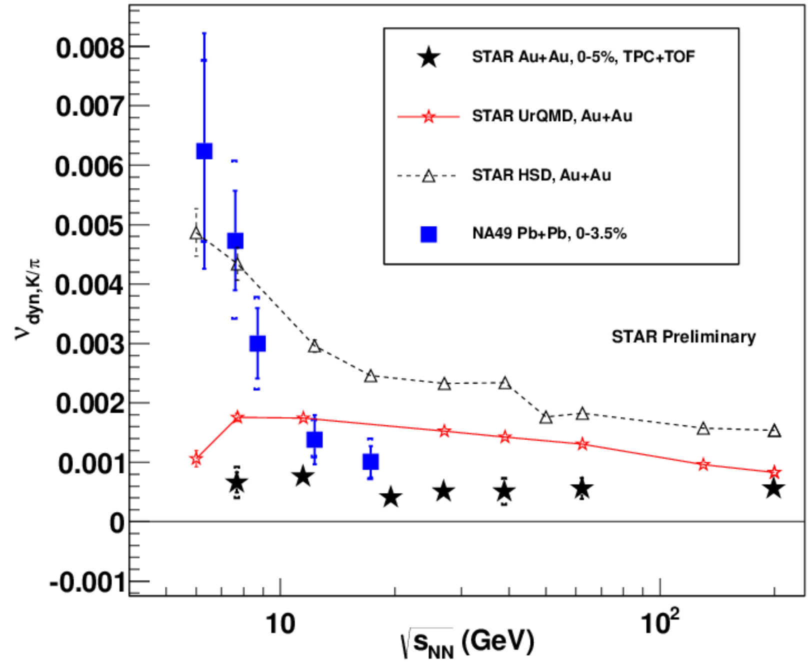
STAR: Submitted to Phys.Rev.C




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



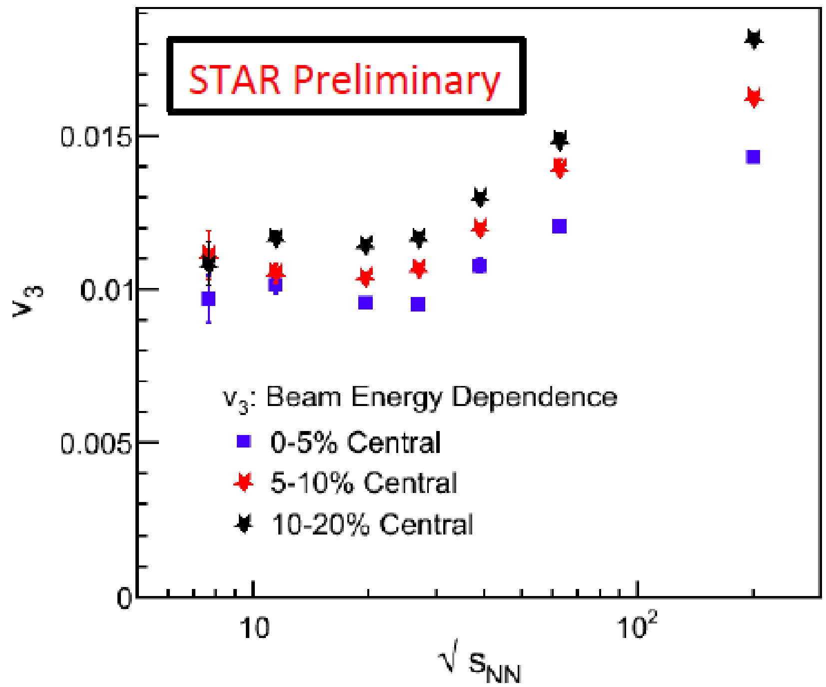

Measurement of event-to-event variation of particle ratios:

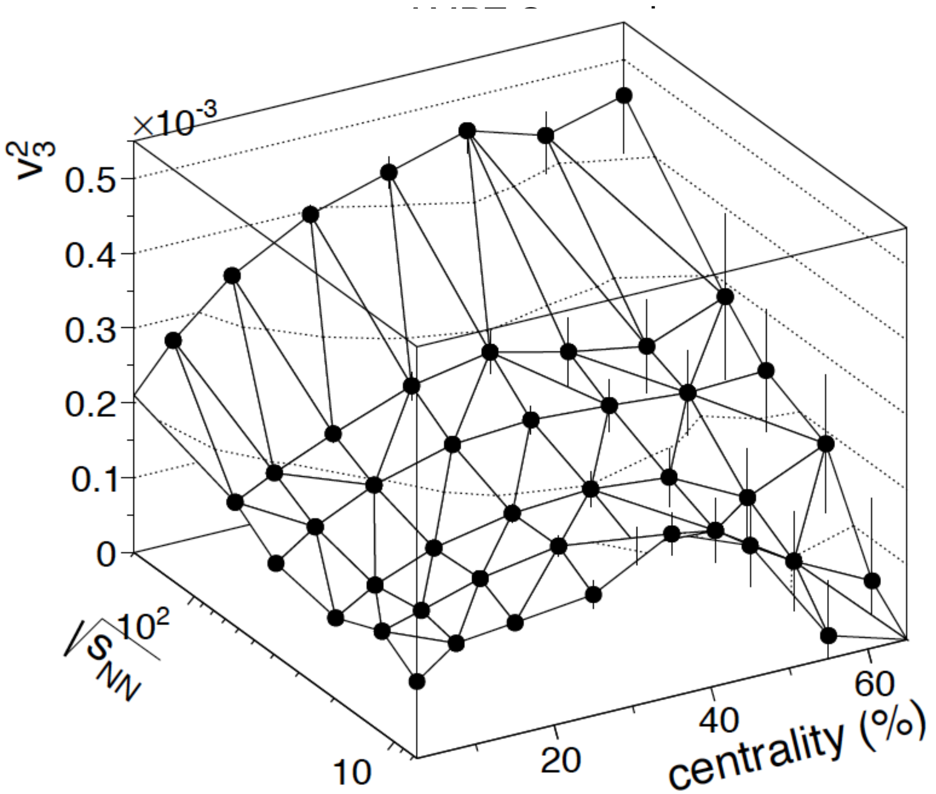
For 1st order phase transition: enhanced fluctuations

Observed energy dependence: fairly monotonic

# Third Harmonic

Y. Pandit: QM2012



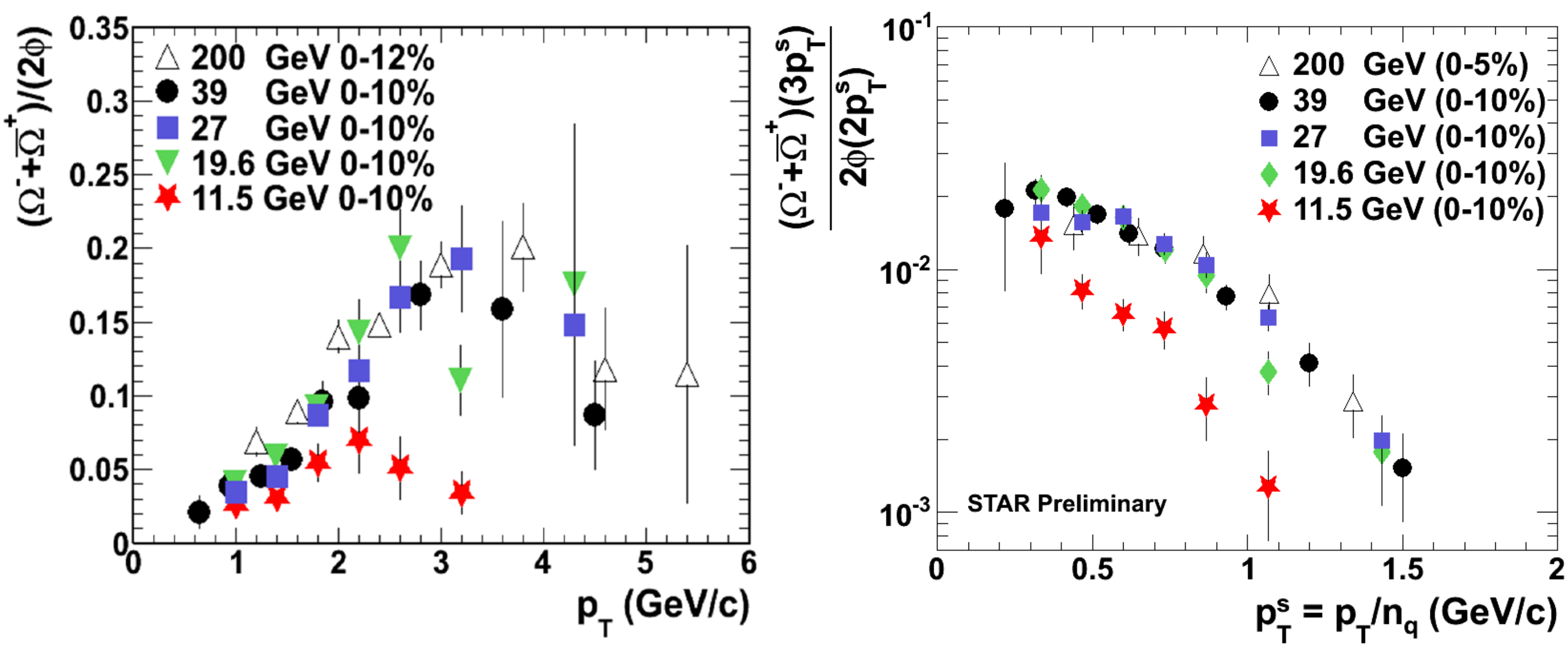

Observable sensitive to interactions at earliest moments

<cos3Δφ> persist to lowest energy, even where jets are non-existant

AMPT requires a QGP phase at all energies to match magnitude

# What Does Change? Ω/φ

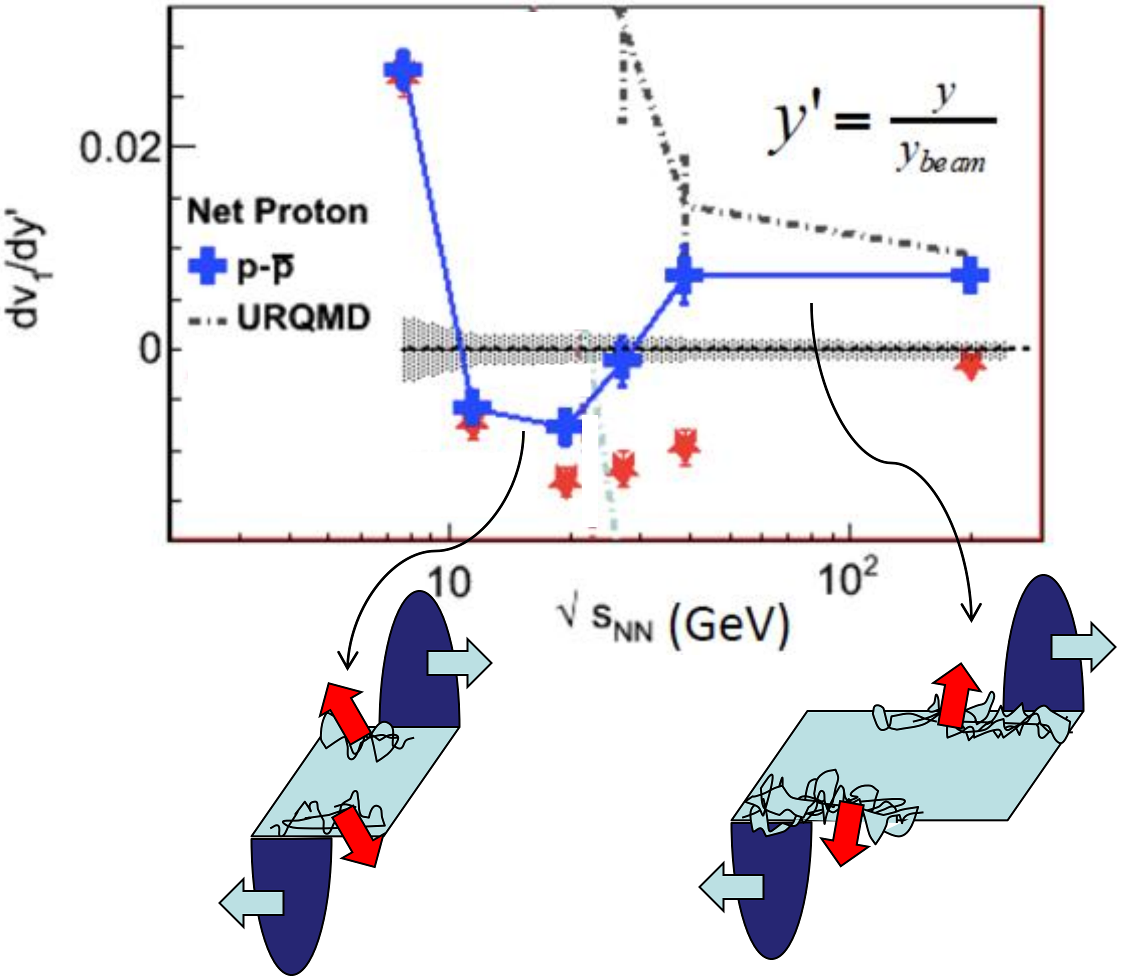
Reduction of s-quark population?




Drop in Ω/φ ratio between 19.6 GeV and 11.5 GeV: Reduction in s-quark population? T<200 MeV?

Or approach to kinematic limit for Ω baryons?

# What Does Change? Net-proton $v_1$ Slope

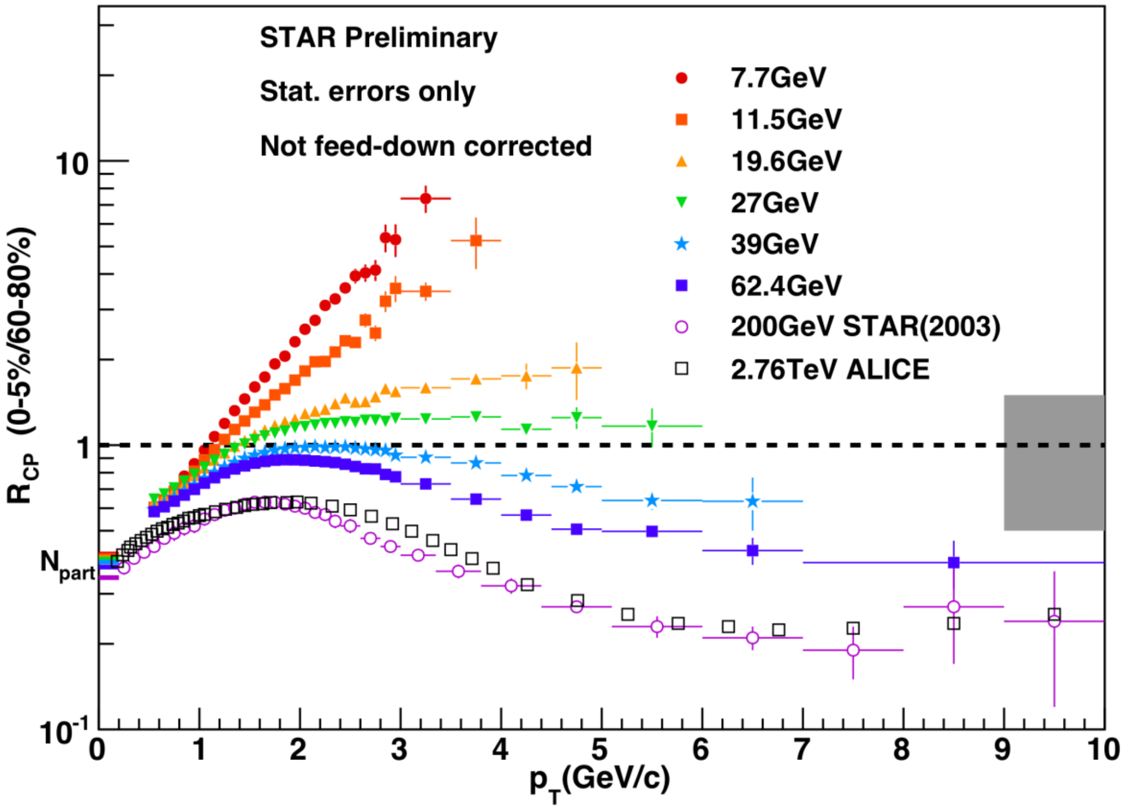



What causes this non-monotonic behavior? Related to the Equation of State? Or simple geometry?

It seems to require strong flow (outward pressure): QGP?

# What Does Change? $R_{CP}$

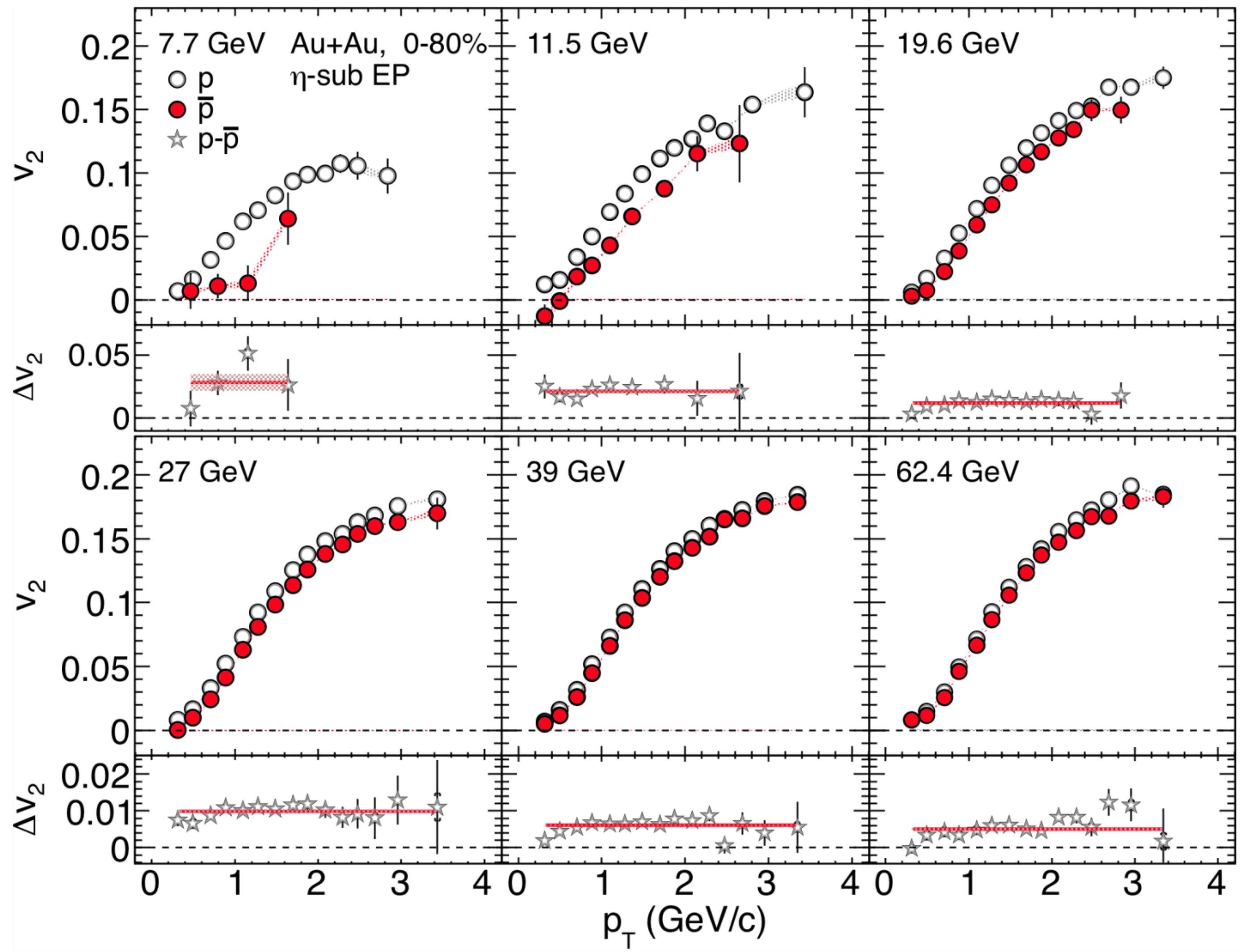
See Stephan Horvat's talk




$R_{CP}$ for 4-5 GeV particles gradually transitions from a suppresion at 200 GeV to an enhancement at 19.6 GeV: Disappearence of opacity?

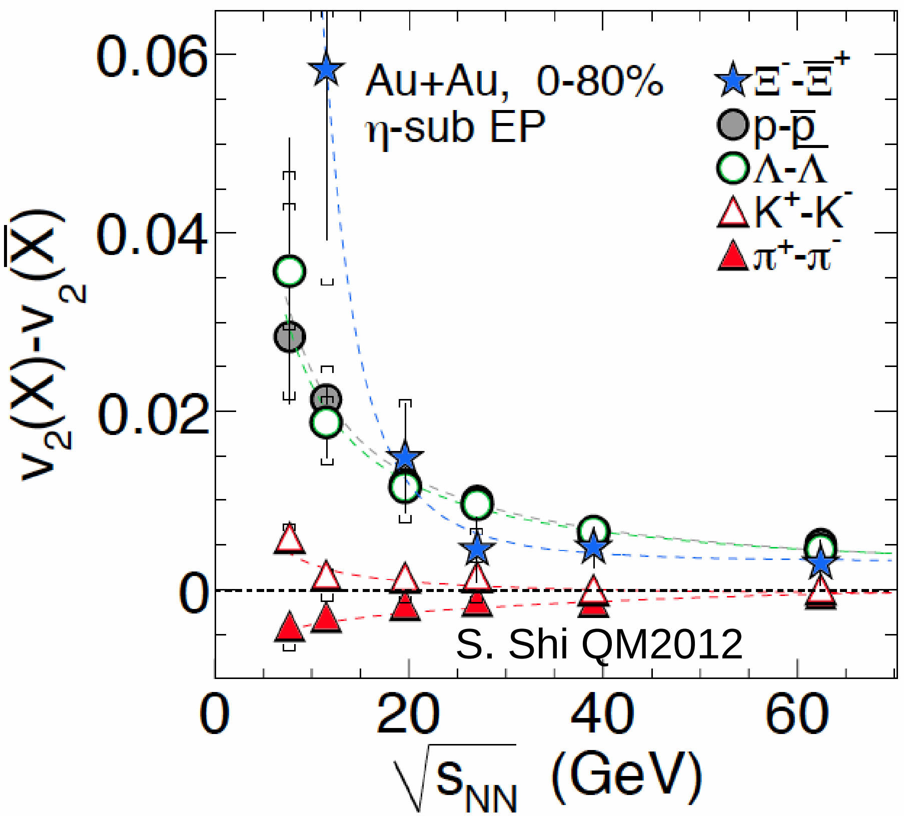
Or dominance of flow at low energies where the hard component of the spectrum is small?

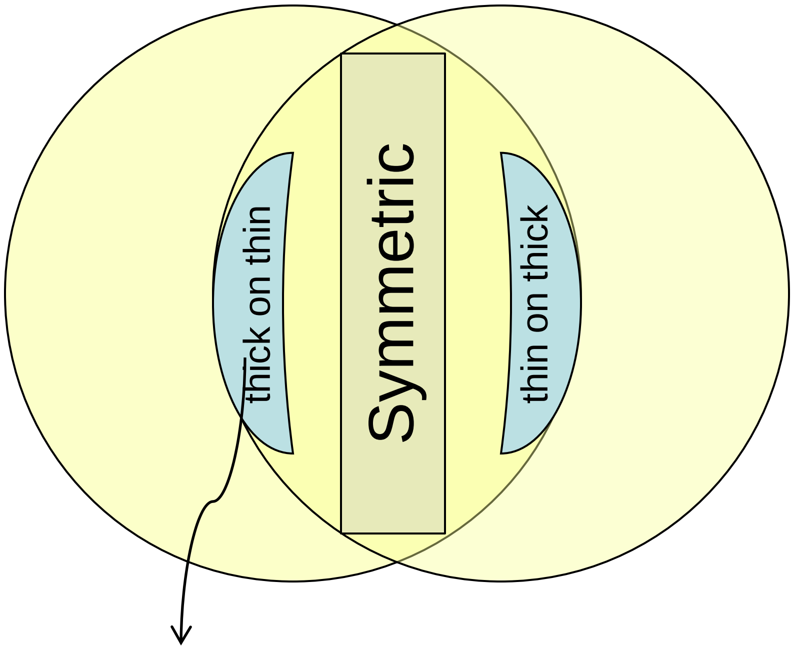
# Particle/Antiparticle Dependence




Low energy data also show a particle/anti-particle dependence

# Strong $\mu_B$ Dependence of Flow



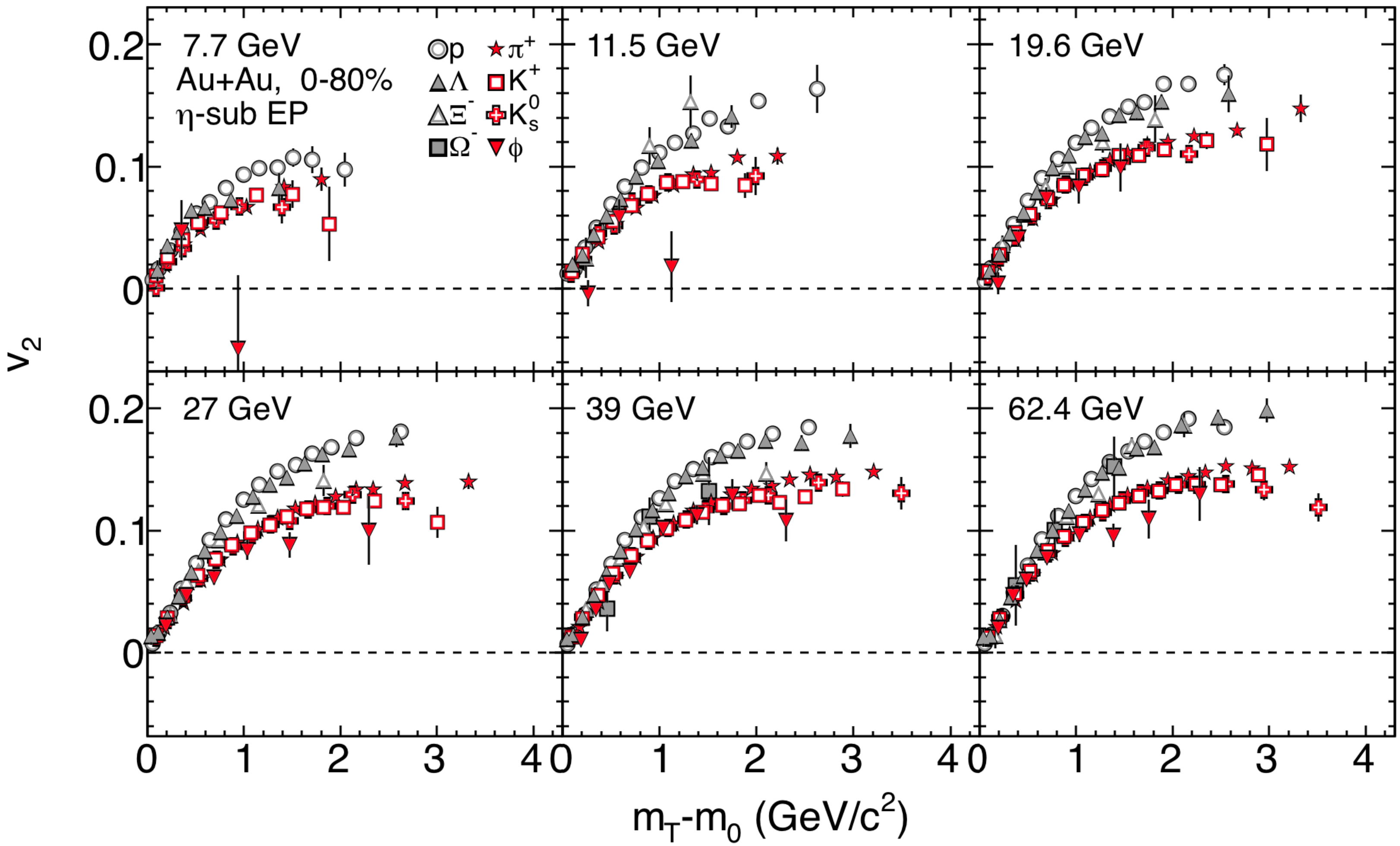

Increasing difference in flow of particles and anti-particles: linear with $\mu_B$

Relevance of strong mean fields? (Greco et al, arXiv:1201.4800)

Coalescence with transported quarks? (See John Campbell's Talk)

Mean field potentials in the hadronic stage? (Xu et al, arXiv:1201.3391)

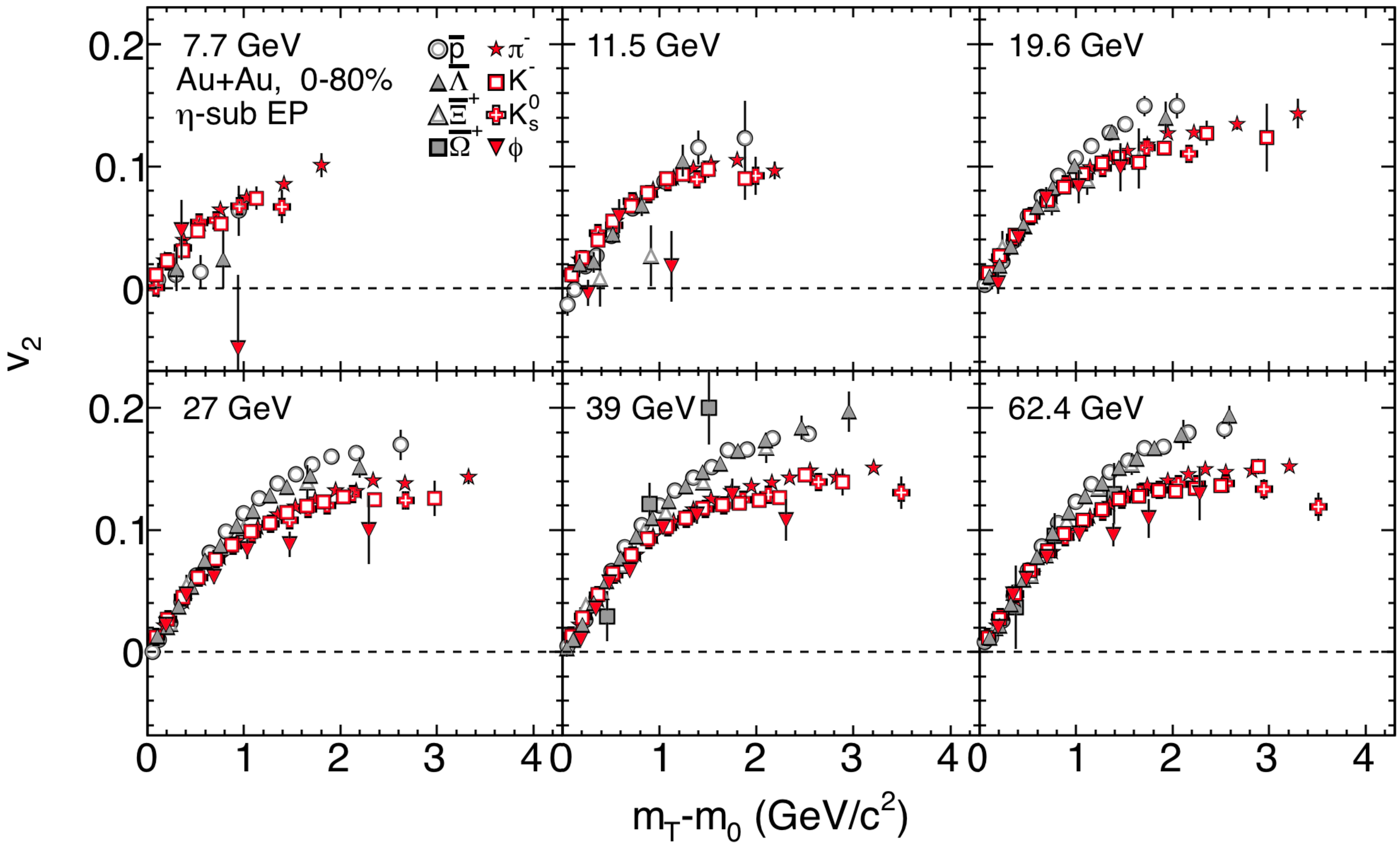
# Lower Energy NCQ




Baryon meson splitting persists down to 11.5 GeV

*(But not for anti-baryons)*

# Lower Energy NCQ




Baryon meson splitting persists down to 11.5 GeV

*(But not for anti-baryons)*

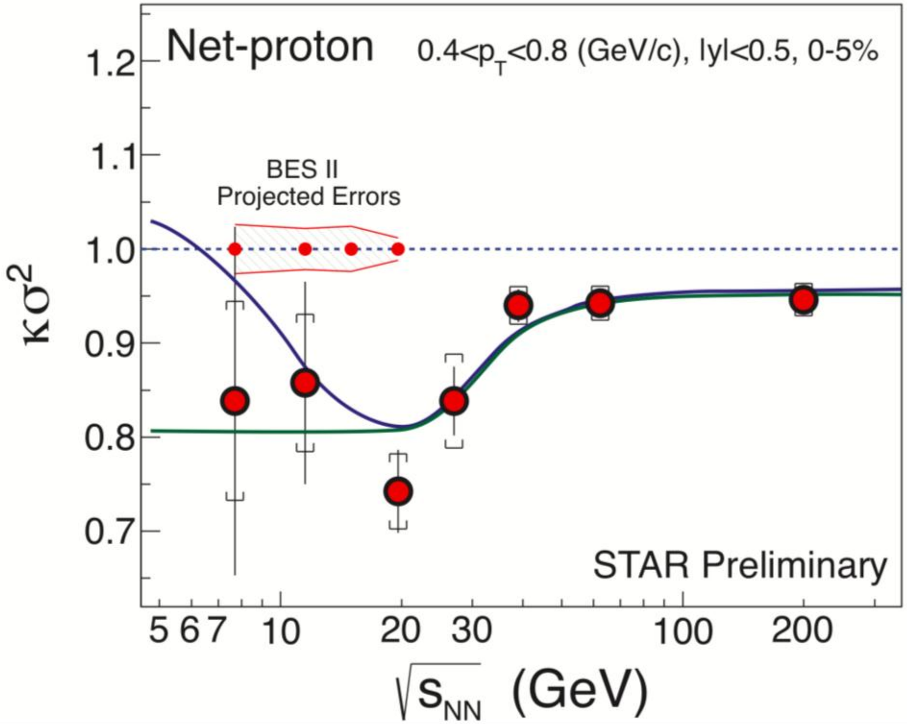
# Beam Energy Scan Phase II

| $\sqrt{s_{NN}}$ (GeV) | $\mu_B$ (MeV) | BES-I | BES-II | Physics Motivation | Weeks** |
|---|---|---|---|---|---|
| 200 | 24 | | **0.5-2** (B) | Heavy flavor hadron $v_2$ & $R_{AA}$ | |
| 39 | 112 | 130 (M) | | | |
| 27 | 156 | 70 (M) | | | |
| 19.6 | 206 | 36 (M) | **400** (M) | LMR di-electron*, net-p κ>5σ | **2** |
| 15 | 250 | | **100** (M) | Ω yield, ϕ-meson $v_2$ (≤ 3GeV/c) | **2** |
| 11.5 | 316 | 12 (M) | **120** (M) | net-p κ | **3.5** |
| 7.7 | 420 | 5 (M) | **80** (M) | net-p κ | **10** |

* Di-electron measurements below 19.6 GeV are not planned
** Estimates are based on electron cooling upgrade currently under development and are approximate without electron cooling, the program would require ~150 weeks

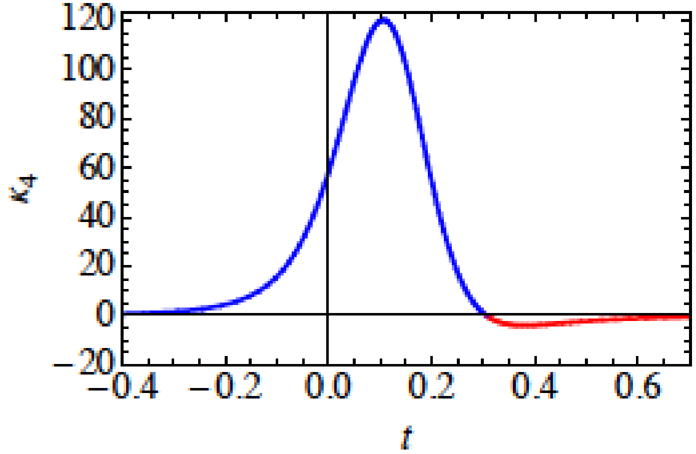
Program requires e-cooling upgrade (x10 improvement in luminosity): Timescale 2017

# BESII and Higher Moments




$$\langle(\delta N)^4\rangle_c = \langle N\rangle + \langle\sigma_V^4\rangle_c \left(\frac{g\,d}{T}\int_{\mathbf{p}} \frac{n_{\mathbf{p}}}{\gamma_{\mathbf{p}}}\right)^4 + \ldots,$$

M. Stephanov, Phys.Rev.Lett. 107 (2011) 052301



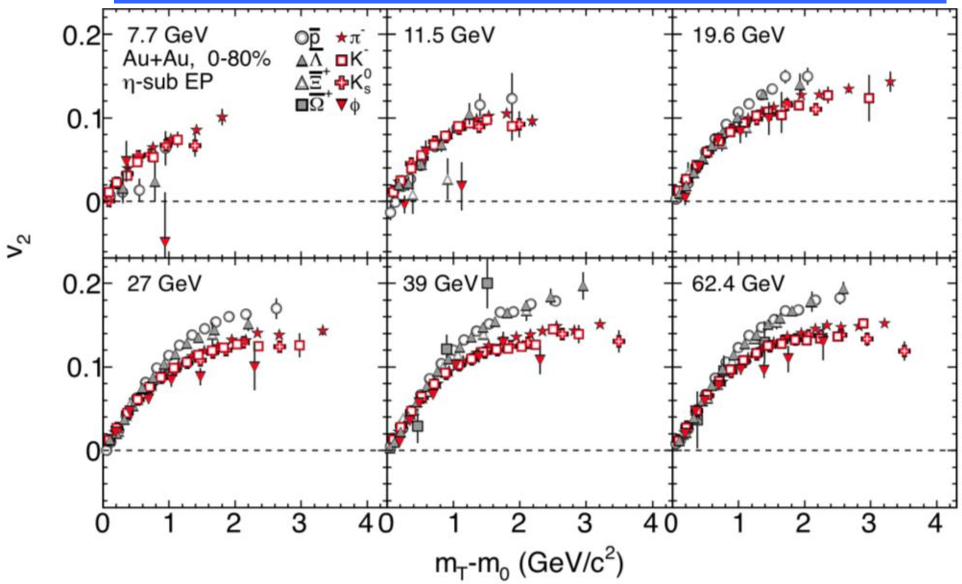

Prediction for a non-monotonic trend in 4th moment: is the structure in the data the start of the predicted non-monotonic behavior?

BESII will provide statistics necessary to determine if the data exhibit the predicted trend

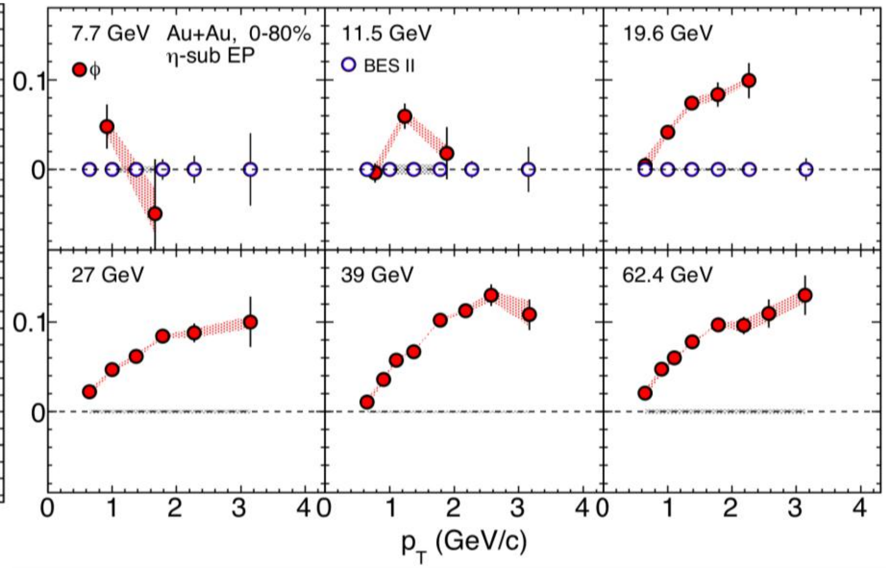
# Also In Need of More Data

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 BESII



# Conclusions

Heavy ion collisions create conditions similar to those present one microsecond after the Big Bang

-RHIC sits in a very interesting region for QCD thermodynamics

-Heavy-ion physics is not energy frontier physics: Bulk phenomena remain key to our field

-RHIC data require a smaller $\eta/s$ than LHC data: provides access to the temperature dependence of transport properties

RHICs beam energy scan has led to several surprising discoveries:

-Non-monotonic net proton v1

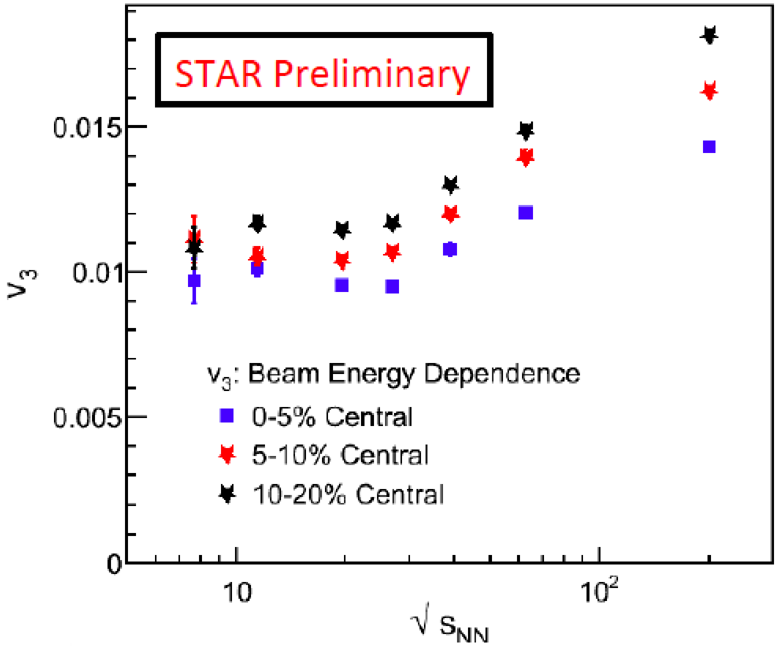
-$\mu B$ dependence of flow

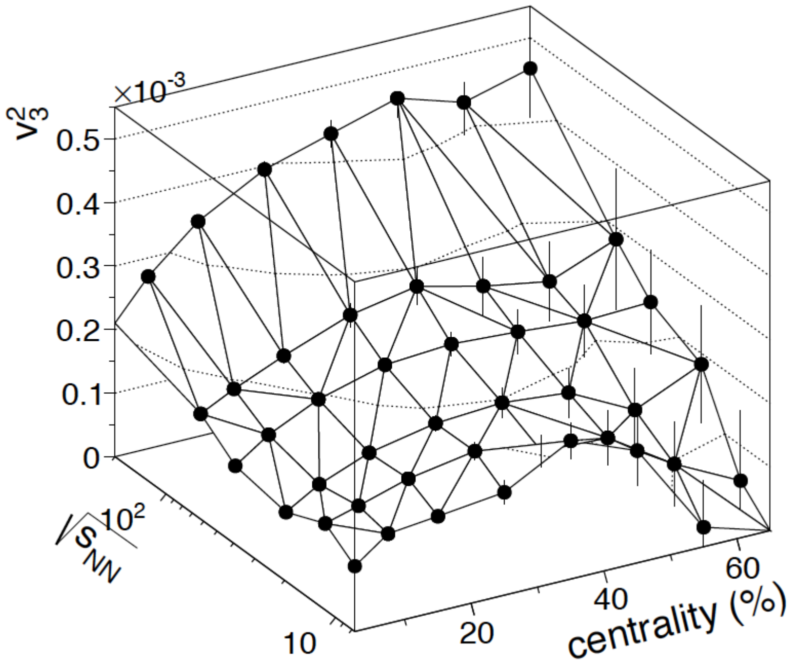
-sudden drop in s-quark density

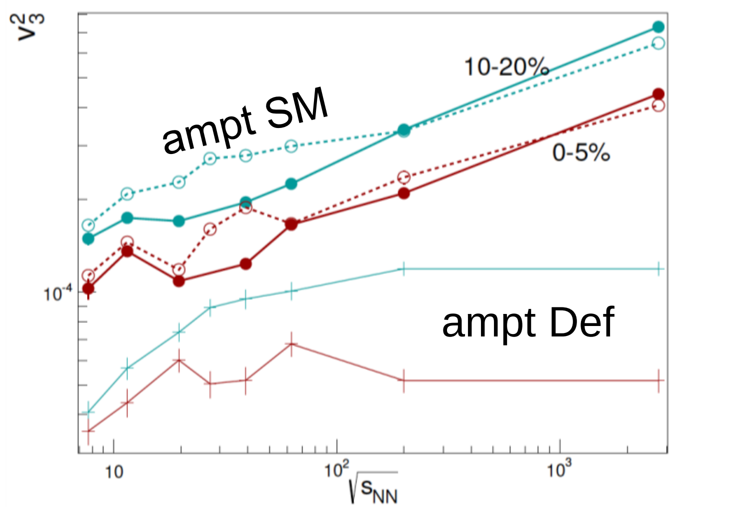
-many observables show interesting/revealing changes, but we may still have a QGP even at 7.7 GeV

BESII will provide statistics necessary toresolve lower energies

# Energy Dependence



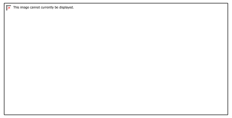



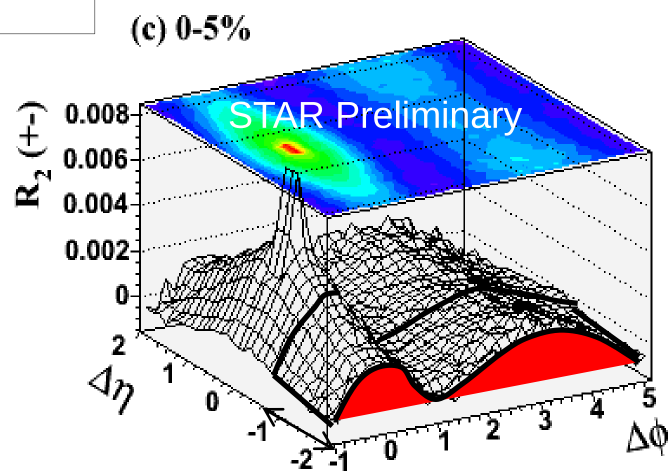

$v_3$ persists to 7.7 GeV with a similar centrality dependence

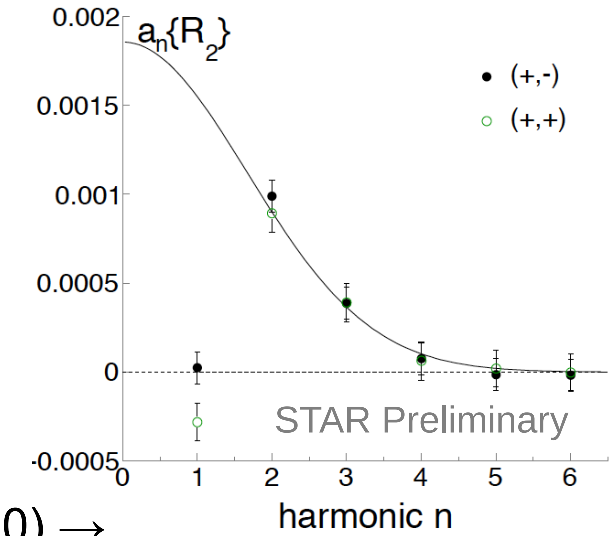
AMPT SM describes values to lowest energy

# Spectrum From 2-particle Correlations

if flow dominates the correlations $a_n \approx 2v_n^2$



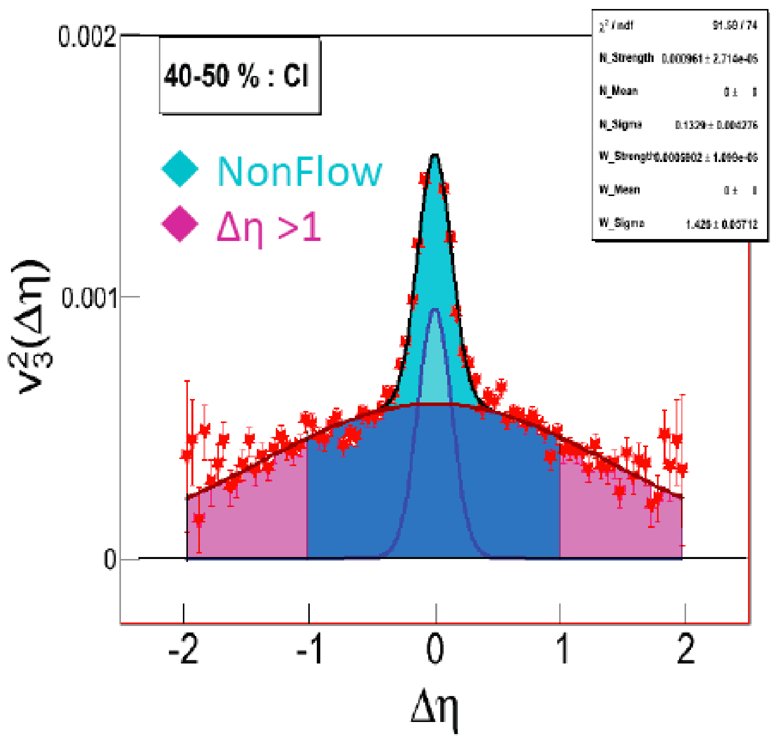


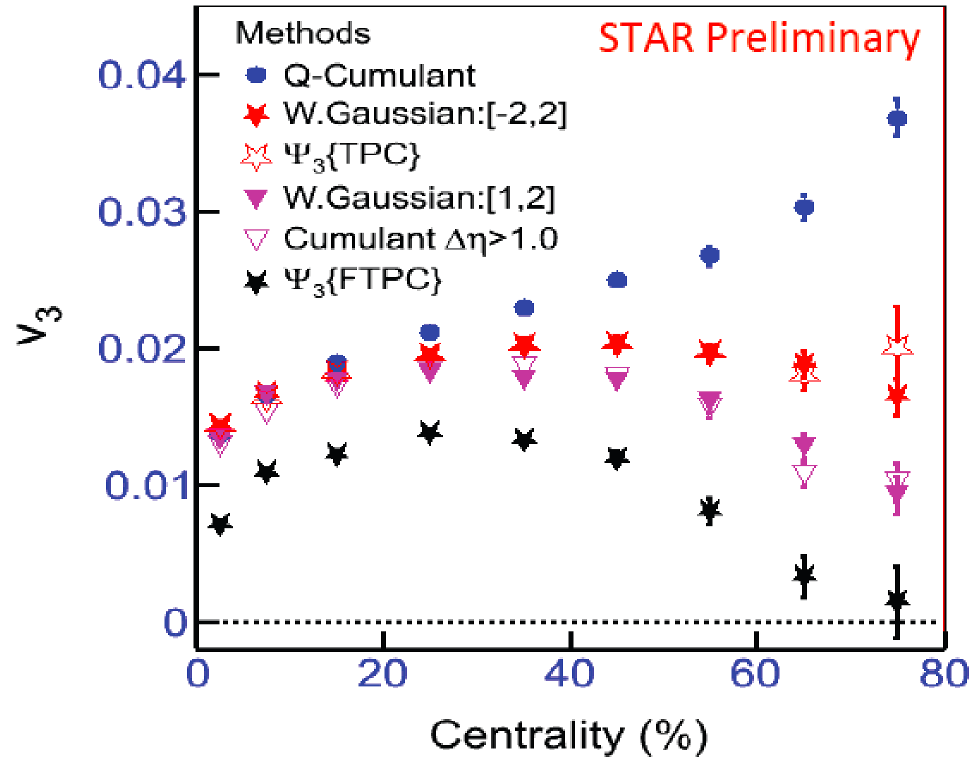




→ Fourier Tr. (0.7<Δη<2.0) →

but clear structure in the longitudinal direction (Δη dependence): IMO it's shape is NOT fully explained yet

# Low momentum $v_3$




for low $p_T$, $\langle \cos 3(\varphi_1 - \varphi_2) \rangle$ vs $\eta_1 - \eta_2$ drops off as a gaussian
Different from intermediate $p_T$ where the ridge is flat

# FAIR-SIS100 $\sqrt{s_{NN}}$ 2-4.7 GeV

Fixed target facility: SIS100 is scheduled for 2018 and reaches 4.7 GeV. SIS300 would reach 8.2 GeV. It's not clear when or if it will be realized: 202?

Fixed target energy scans are extremely difficult because of changing acceptance

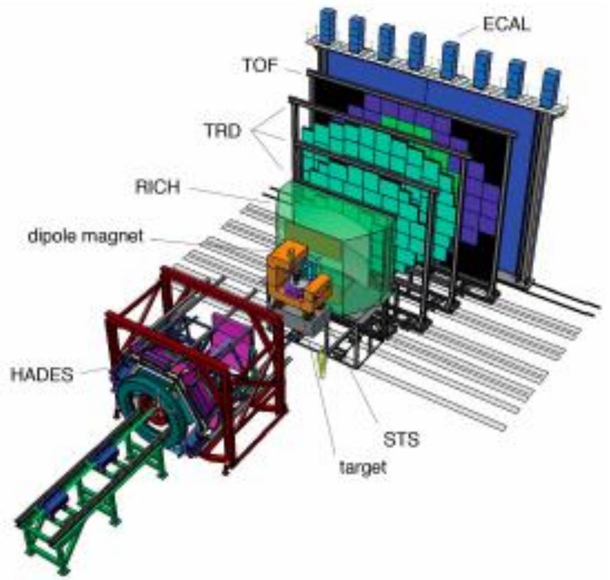
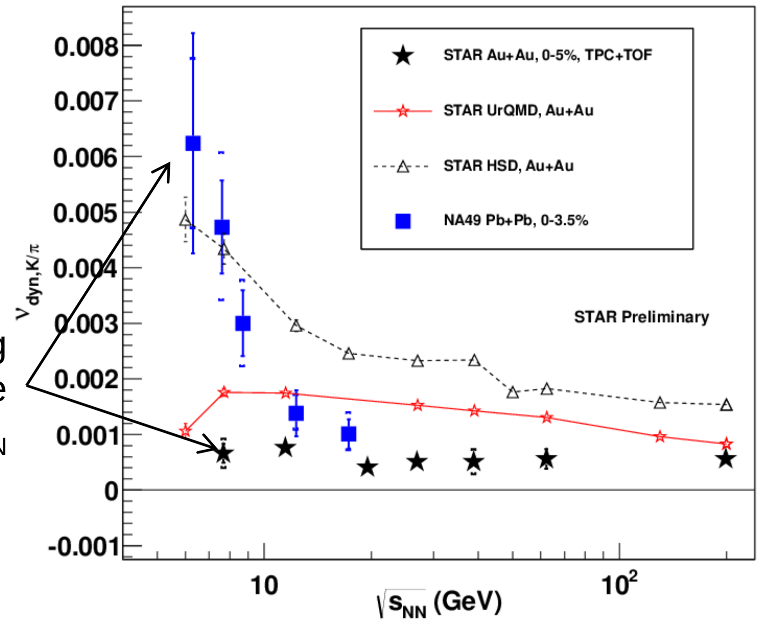



Fig. 1.5 Sketch of the planned Compressed Baryonic Matter (CBM) experiment together with the HADES detector.

effect of varying acceptance with $\sqrt{s_{NN}}$




physics signals masked or false signals created by changing acceptance with $\sqrt{s_{NN}}$

http://www-alt.gsi.de/documents/DOC-2009-Sep-120-1.pdf
http://www.fair-center.eu/fileadmin/fair/publications_FAIR/FAIR_GreenPaper_2009.pdf

# NICA: $\sqrt{s_{NN}}$ from 4-11 GeV

According to the CDR NICA should be commissioned in 2013. At QM2012, Commissioning was listed as 2017. Will updated timelines and performance goals be met?

Au+Au: $\sqrt{s_{NN}}$=4-11 GeV

A+A design luminosity: ~$10^{27}$ /cm/sec

Polarized proton: $\sqrt{s_{NN}}$=12-27 GeV

Ave. 27 GeV pp luminosity: $10^{30}$ /cm/s

polarized deuteron: $\sqrt{s_{NN}}$=4-13.8 GeV

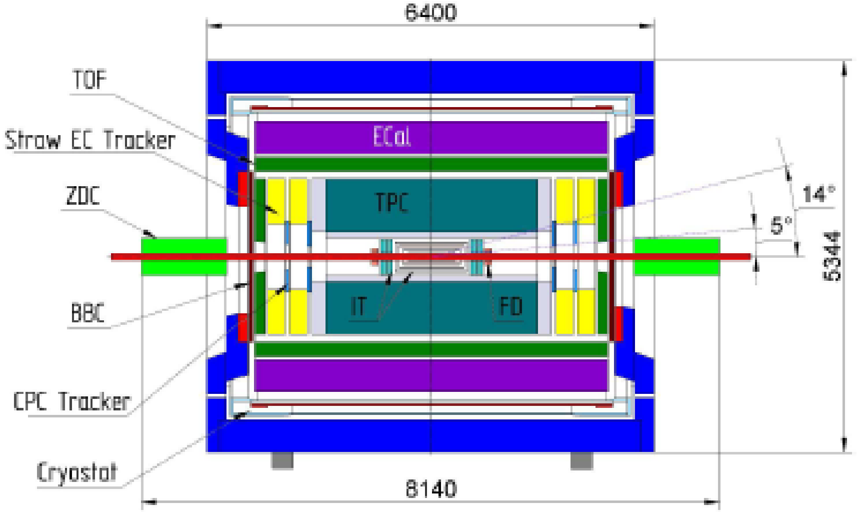



*Fig. 2.2: Cutaway side view of the Central Detector of MPD with based dimensions.*

The Multipurpose Detector is nearly identical to the STAR detector with a 0.5 T B-field, inner tracking, TPC, barrel TOF, and barrel E-M calorimeter

Focus is on high baryon density range: insufficent energy to explore potential transition region identified at RHIC (7-27 GeV)

http://nica.jinr.ru/files/CDR_MPD/MPD