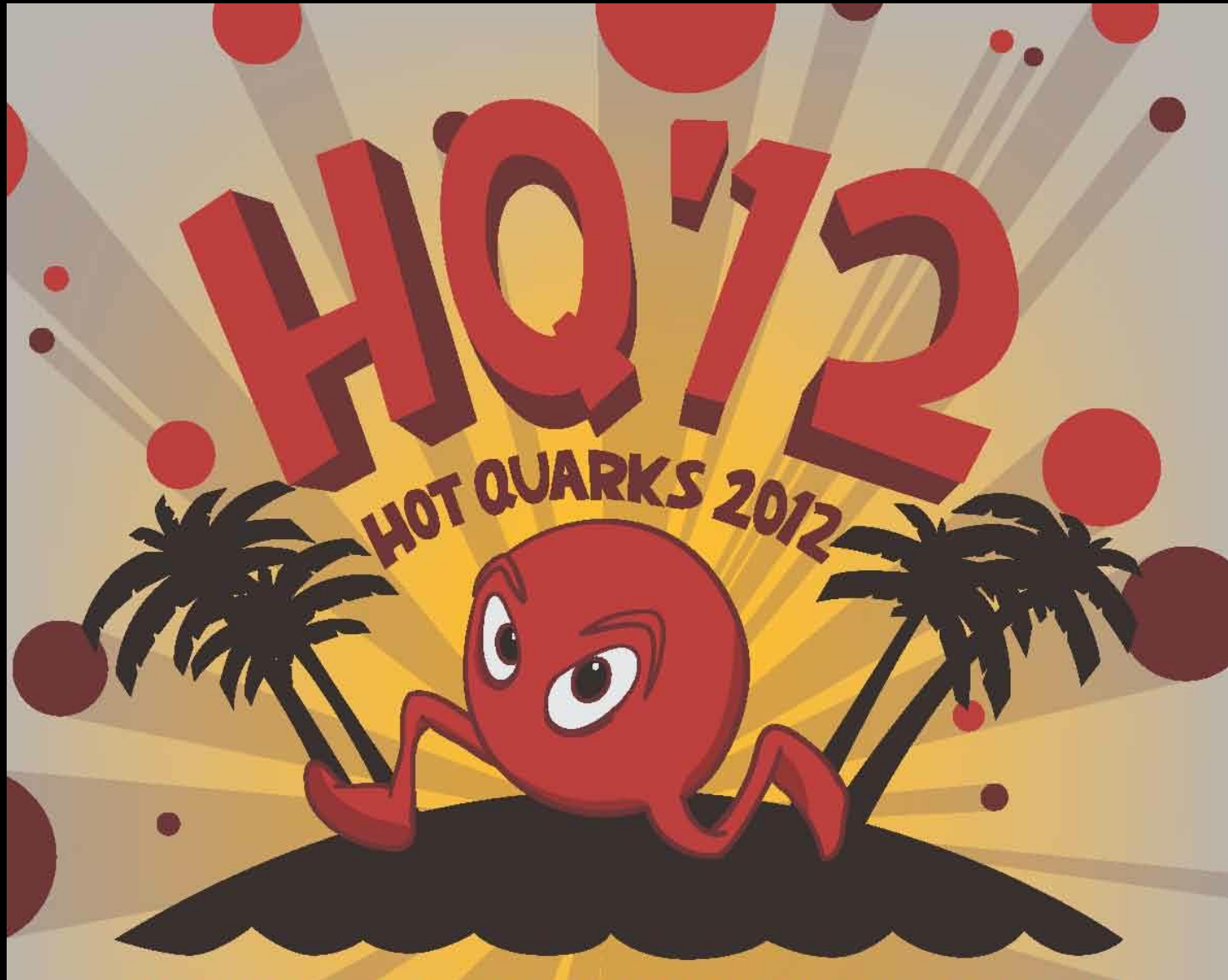


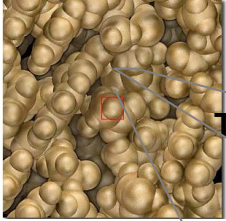
Beam Energy Scan Results from RHIC



Particle Physics and the Energy Frontier

Atoms (1800)

DNA nucleotide building blocks.



The

10⁻⁹ meters

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

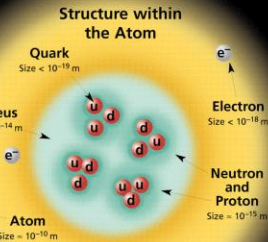
The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS			matter constituents		
spin = 1/2, 3/2, 5/2, ...			spin = 1/2, 3/2, 5/2, ...		
Leptons			Quarks		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_e electron	<1·10 ⁻⁸	0	u up	0.003	2/3
e electron	0.000511	-1	d down	0.006	-1/3
ν_μ muon	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	-1	s strange	0.1	-1/3
ν_τ tau	<0.02	0	t top	175	2/3
τ tau	1.7771	-1	b bottom	4.3	-1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \cdot 10^{-25} \text{ GeV s} = 1.05 \cdot 10^{-34} \text{ J s}$.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60 \cdot 10^{-19}$ coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember $E = mc^2$), where $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \cdot 10^{-10} \text{ joule}$. The mass of the proton is $0.938 \text{ GeV}/c^2 = 1.67 \cdot 10^{-27} \text{ kg}$.



If the protons and neutrons in this picture were 10 m across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS			force carriers		
spin = 0, 1, 2, ...			spin = 0, 1, 2, ...		
Unified Electroweak			Strong (color)		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1			
W^+	80.4	+1			
Z^0	91.187	0			

Color Charge Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons $q\bar{q}$ and baryons qqq .

Residual Strong Interaction The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

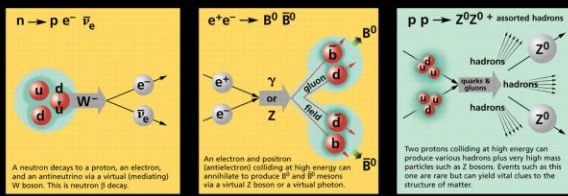
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
\bar{n}	anti-neutron	$\bar{u}\bar{d}\bar{d}$	0	1.116	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	-1	1.672	3/2

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

Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	-1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Matter and Antimatter For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (γ , Z^0 , η , and η_c) are their own antiparticles.

Figures These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

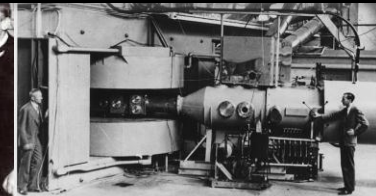
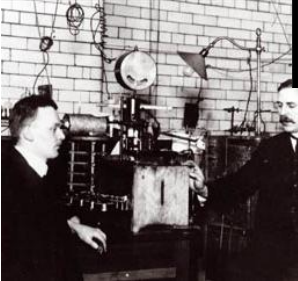


The Particle Adventure Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>. This chart has been made possible by the generous support of: U.S. Department of Energy, U.S. National Science Foundation, Lawrence Berkeley National Laboratory, Stanford Linear Accelerator Center, American Physical Society, Division of Particles and Fields, **DUPLER INDUSTRIES, INC.** ©2006 Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. Send mail to: CPEP, MS 55-268, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720. For information on charts, text materials, hands-on classroom activities, and workshops, see: <http://CPEPweb.org>

7.7 MeV

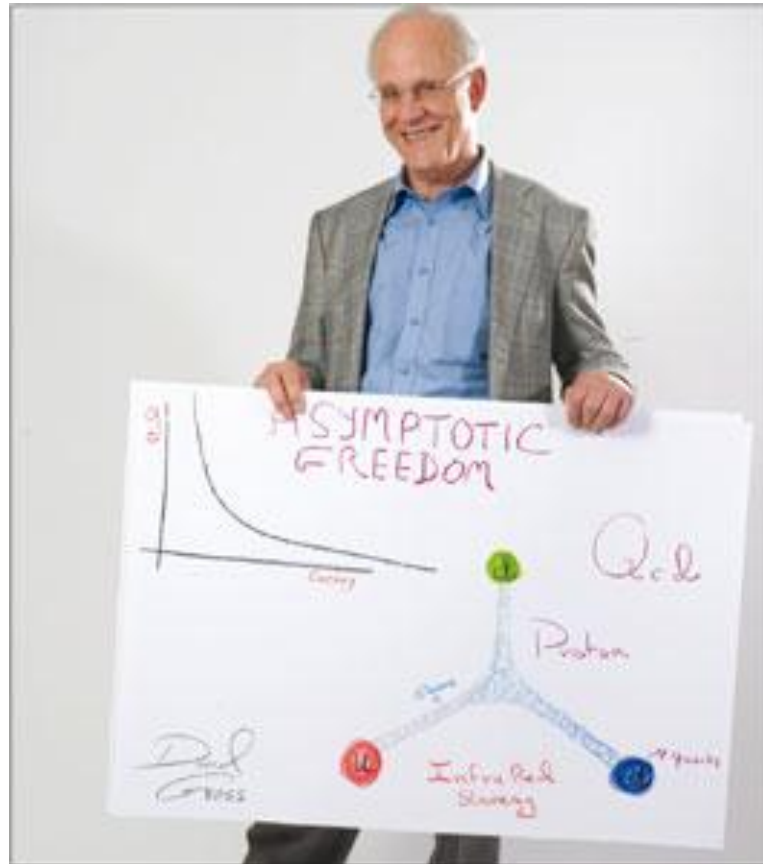
has always been energy frontiers by ever more accelerators

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

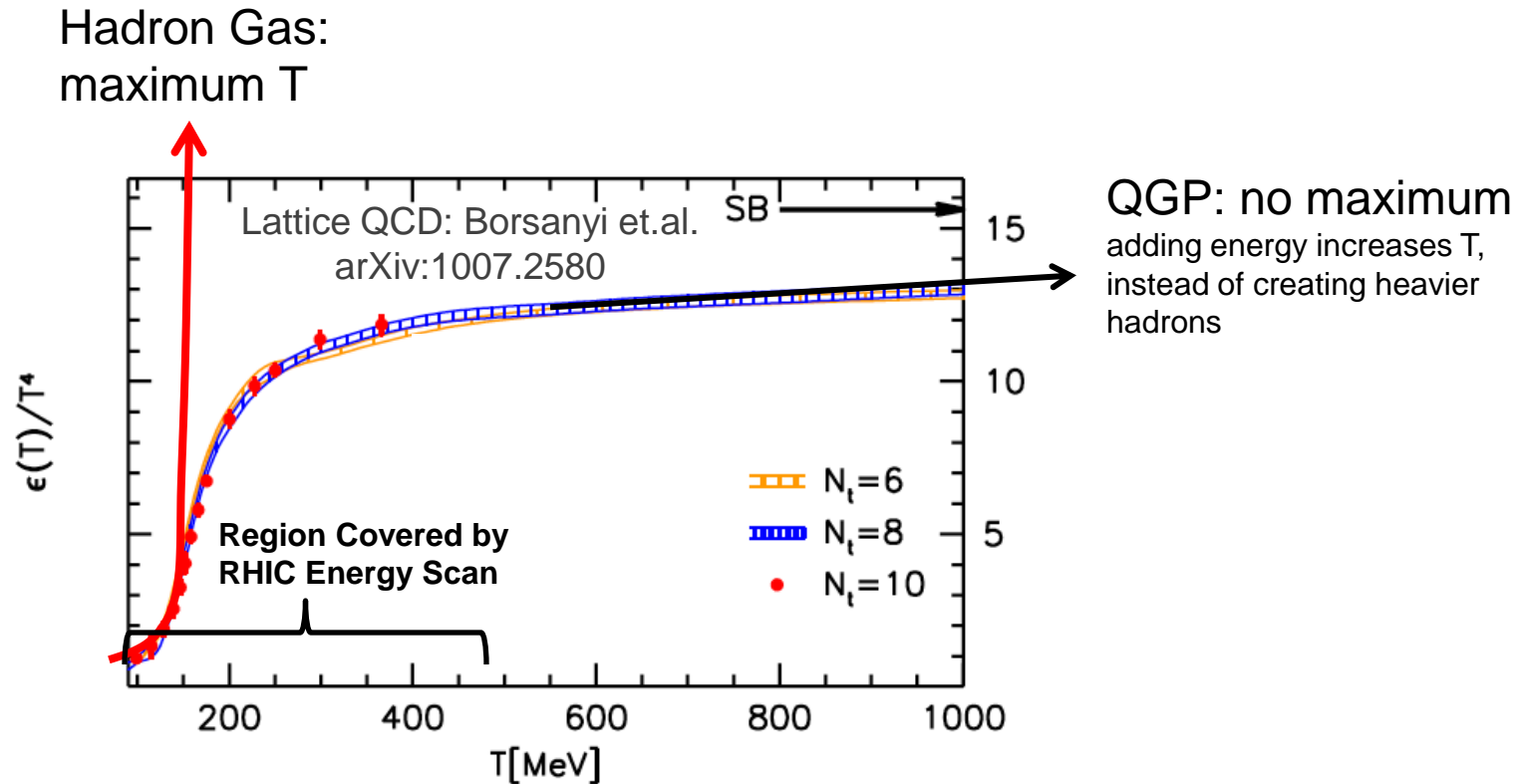
But we study the

Confinement/Deconfinement transition (~ 200 MeV)

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

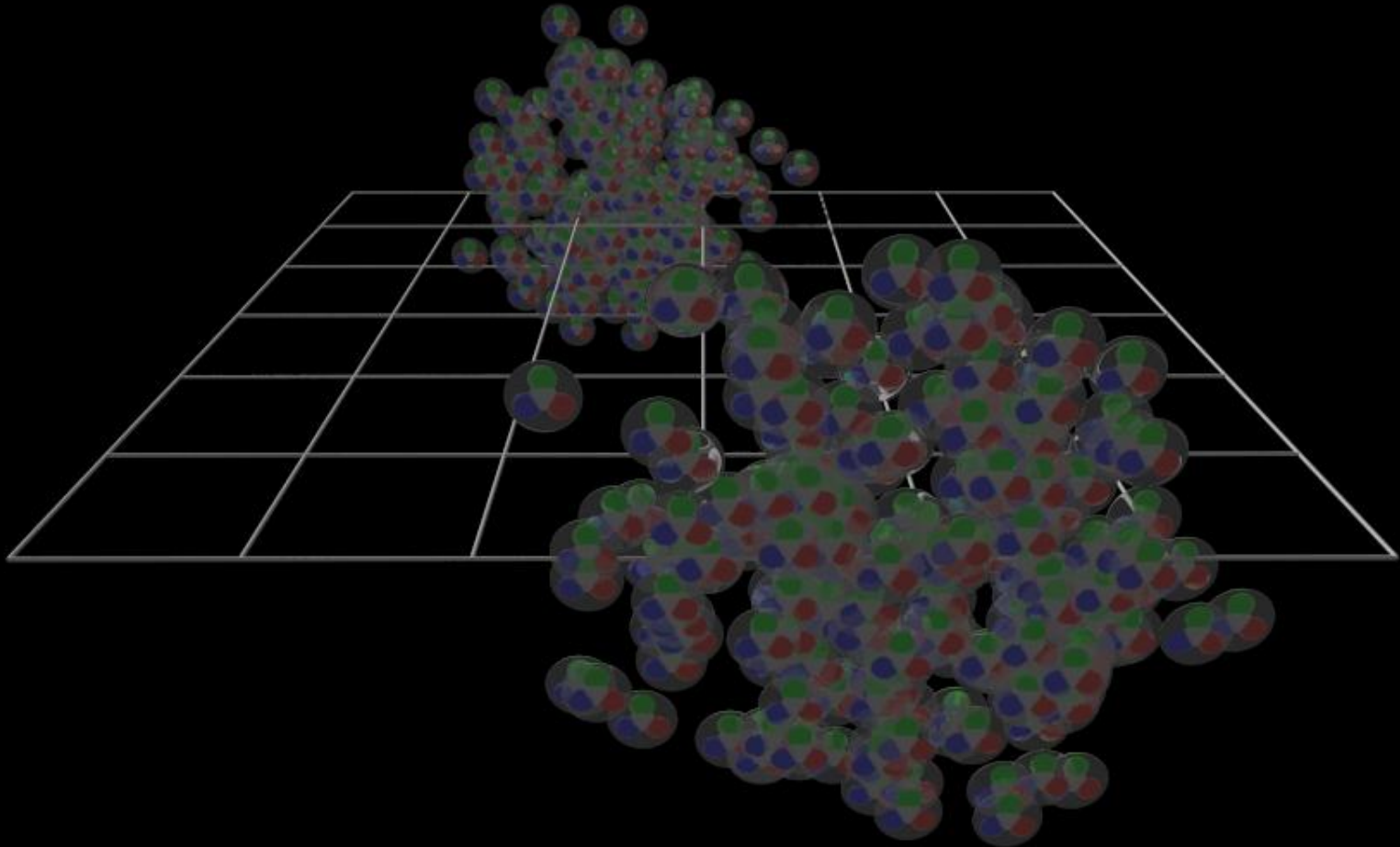
Thermodynamics of QCD

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

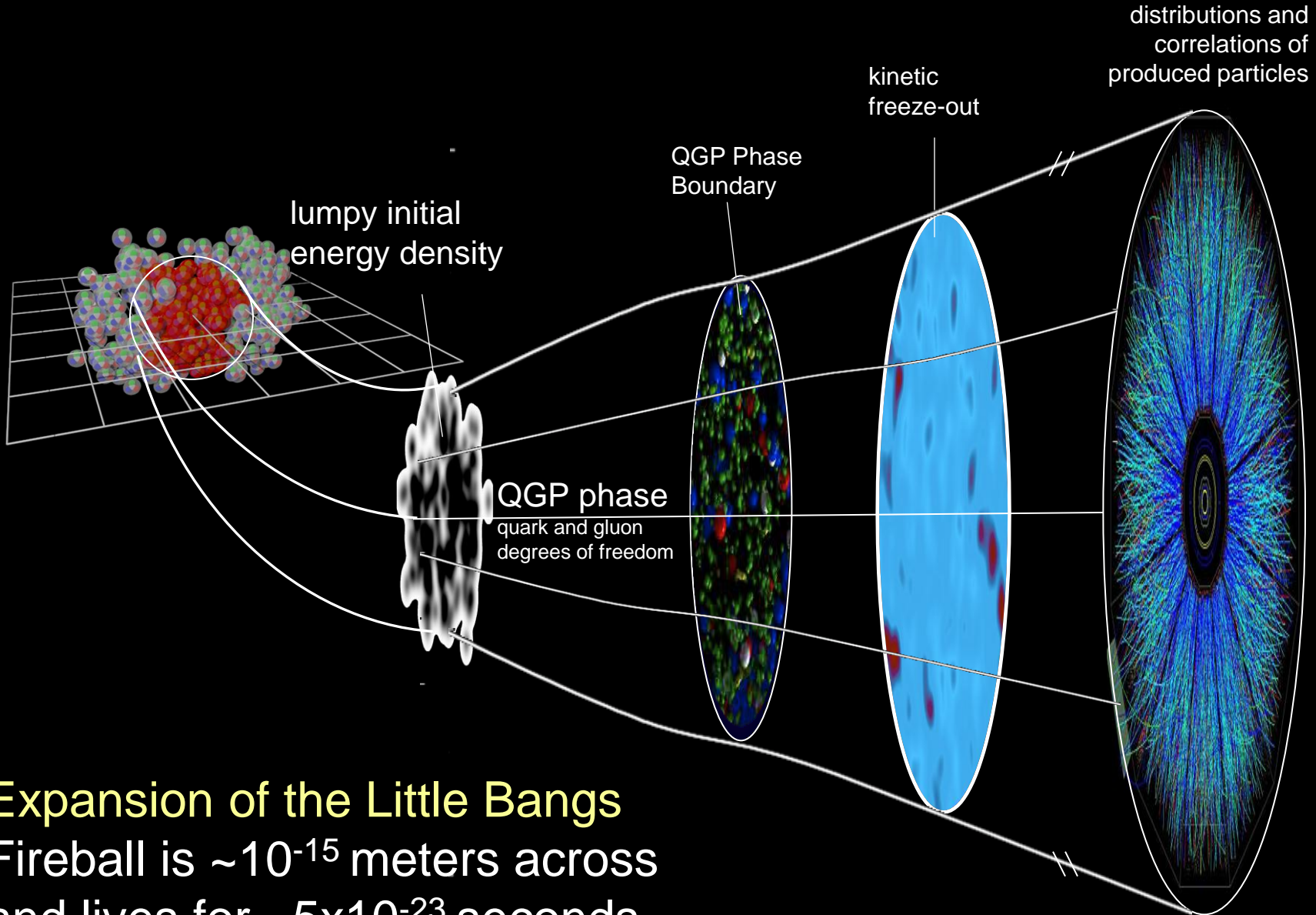


The transition region (not the asymptotic limit) is of most interest

Finite Temperature QCD in the Lab

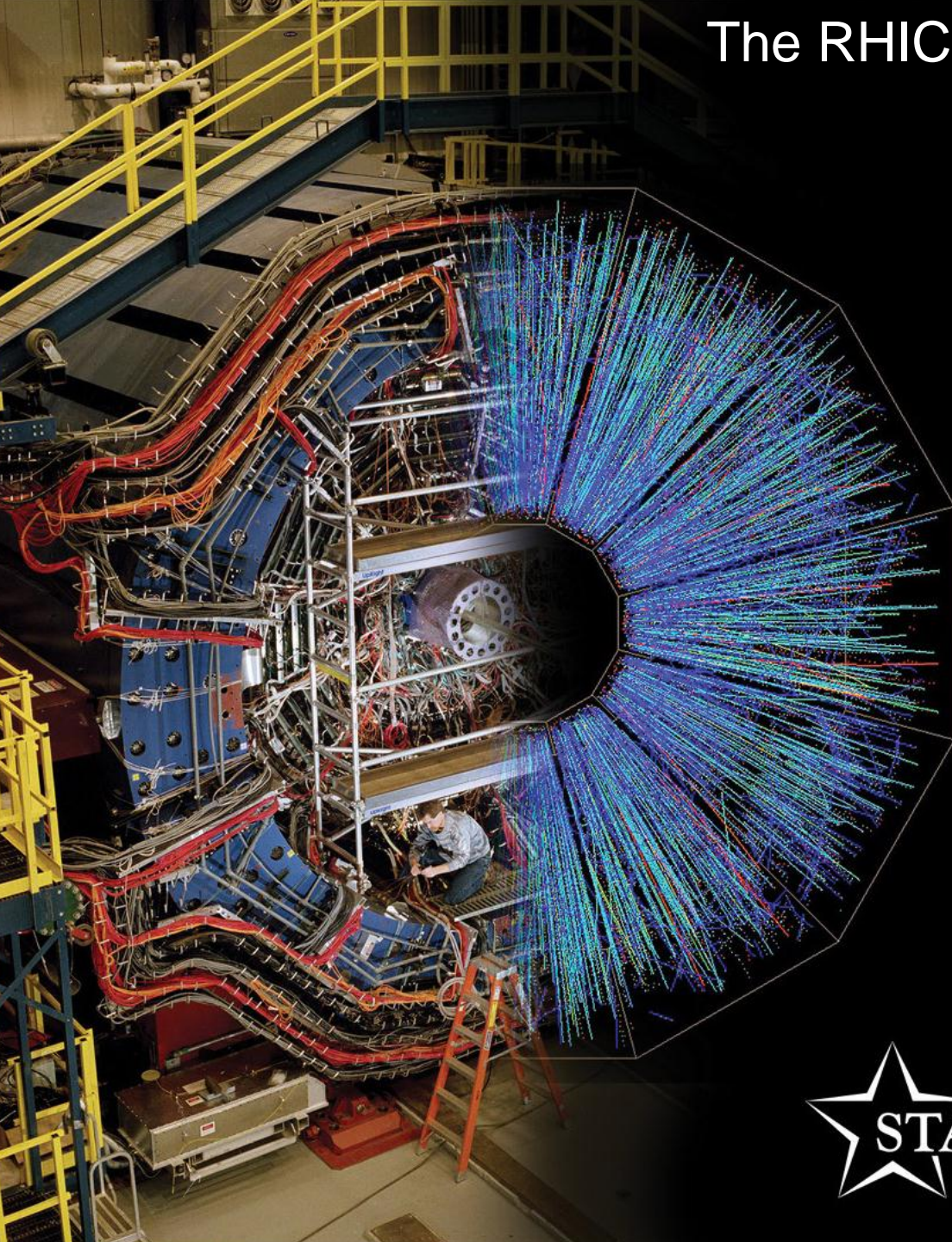


Finite Temperature QCD in the Lab



Expansion of the Little Bangs
Fireball is $\sim 10^{-15}$ meters across
and lives for $\sim 5 \times 10^{-23}$ seconds

The RHIC Detectors



STAR



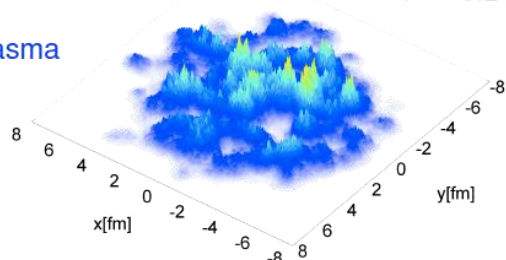
A Standard Model for Little Bangs

Initial state including geometric and quantum fluctuations from

1st principles

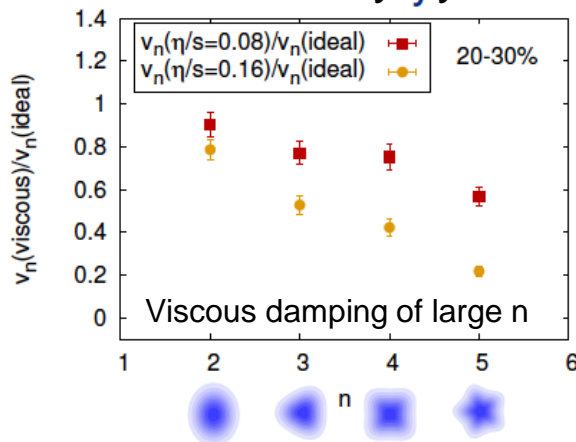
$\tau = 0.2 \text{ fm}$

Glasma



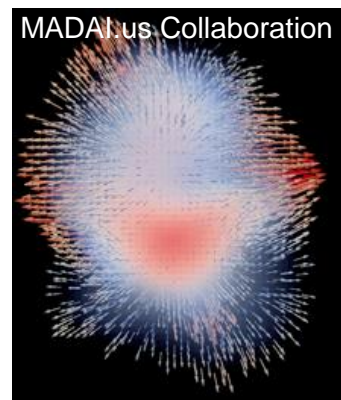
Schenke, Tribedy, Venugopalan, Phys.Rev.Lett. 108:25231 (2012)

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

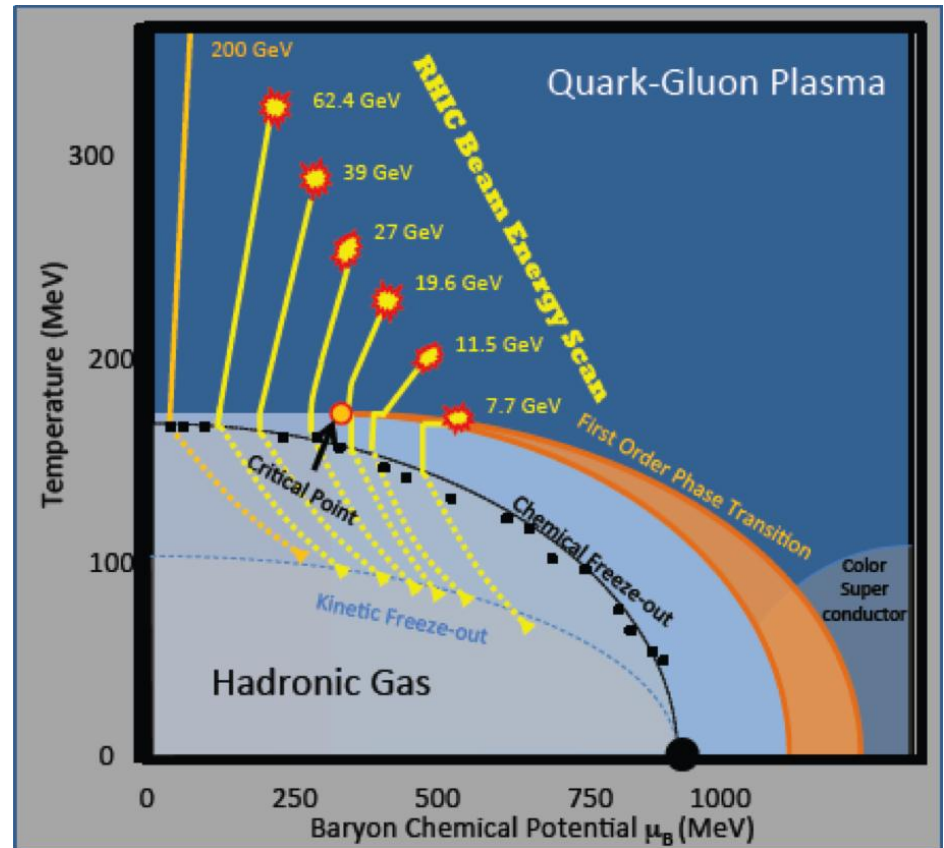
Varying the beam energy changes

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

Search for

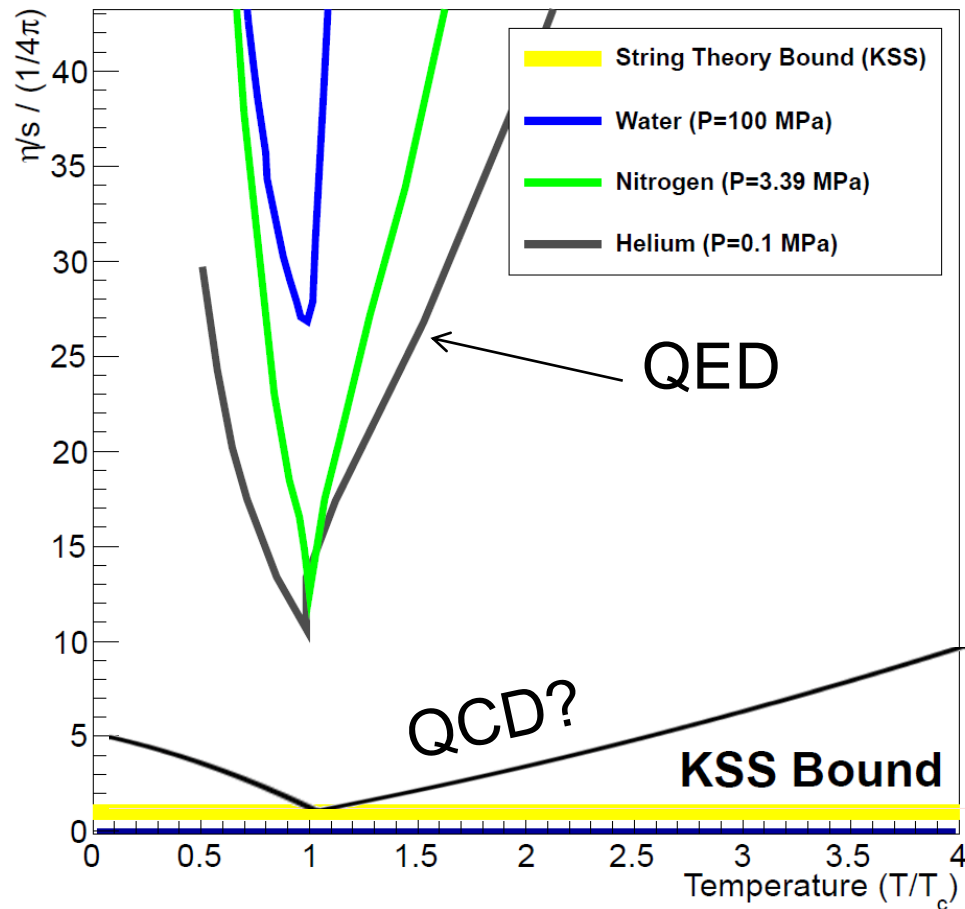
- turn off of QGP signatures
- change in the degrees of freedom
- evidence of a first order phase transition ending at a critical point

Study the temperature dependence of various transport parameters



Temperature Dependence of η/s

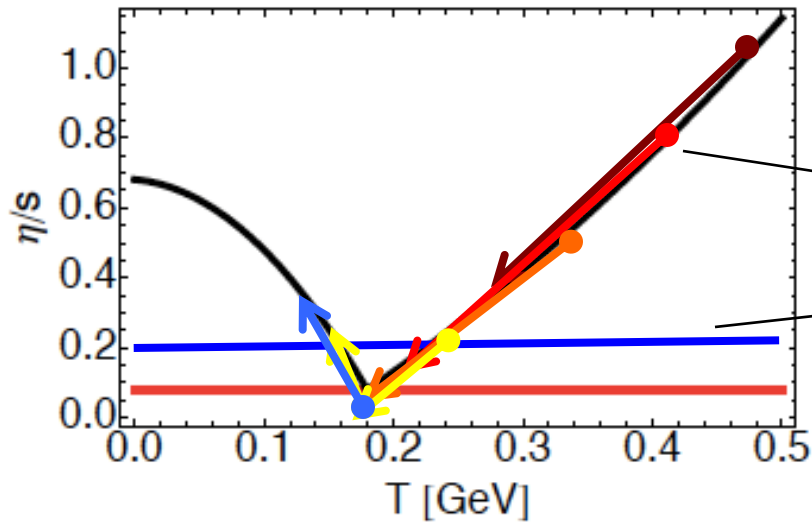
A. Majumder, B. Muller, X.N. Wang, PRL (2007)



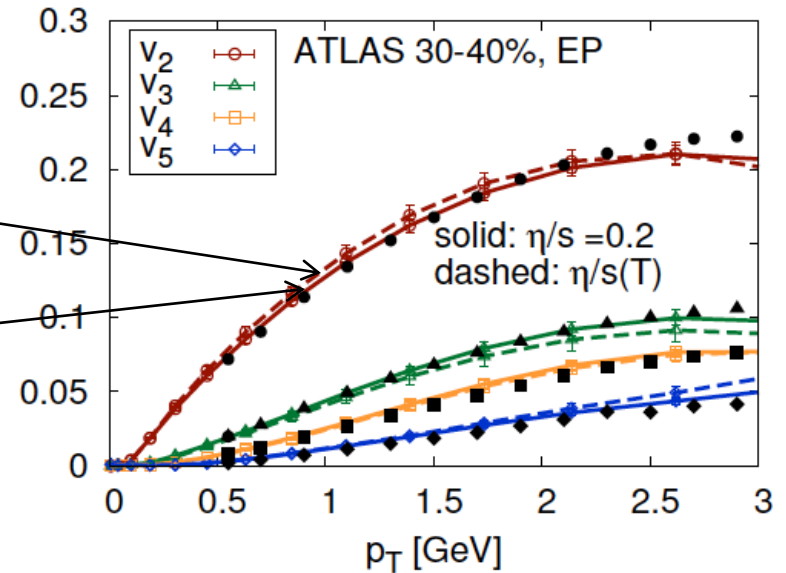
An understanding of the emergent properties of QCD requires coverage of a broad energy range

Temperature Dependence of η/s

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



$\langle v_n^2 \rangle^{1/2}$



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

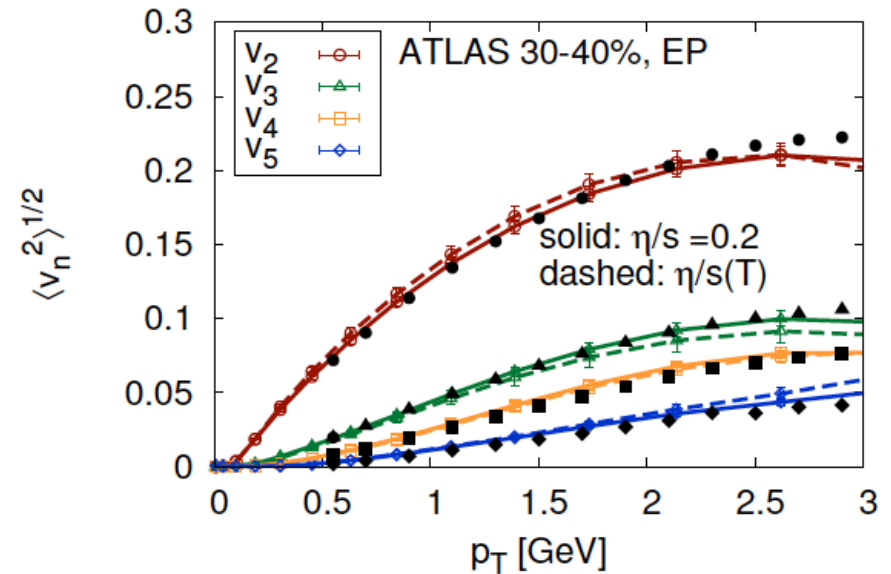
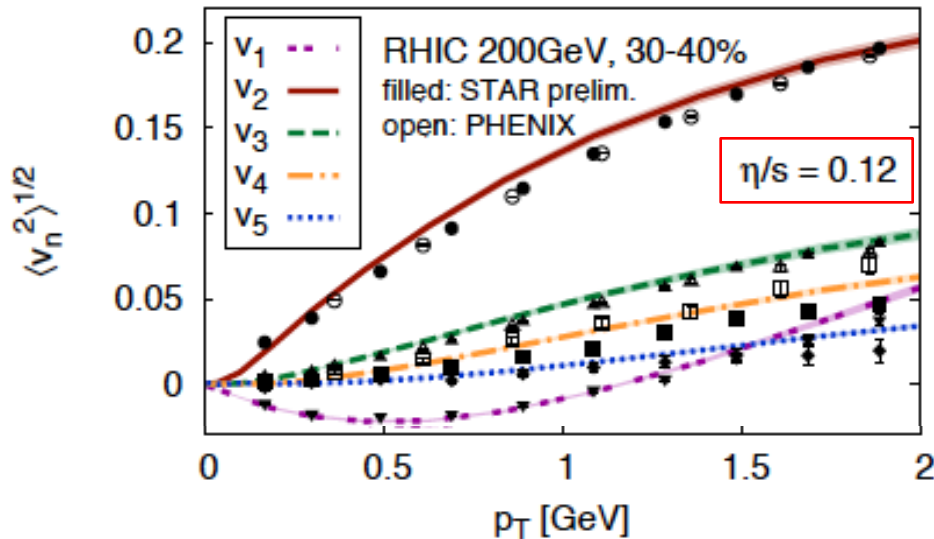
Model doesn't distinguish between a constant η/s or a temperature dependent η/s with a minimum of $1/4\pi$ at T_C

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



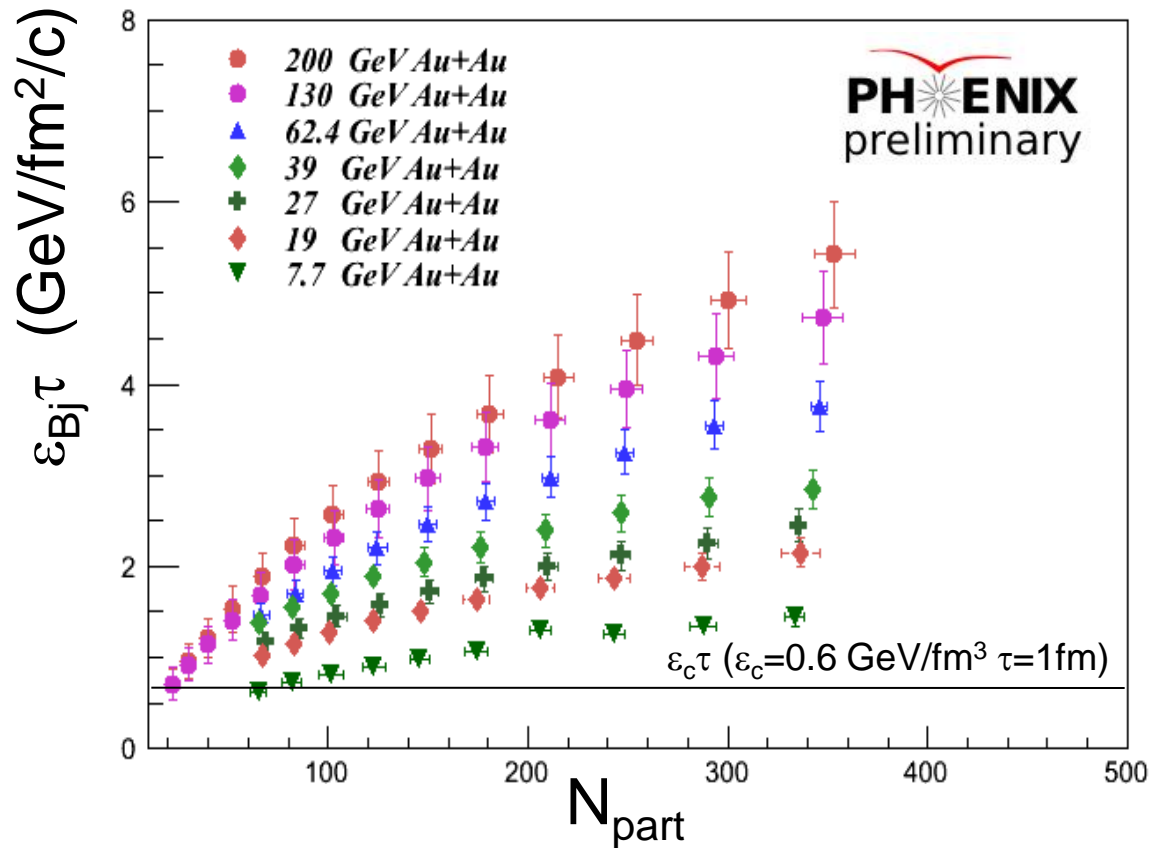
$\langle \eta/s \rangle$ at RHIC is 40% smaller than the LHC

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 $1/4\pi$ at T_C

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

Where Does the QGP Turn Off?



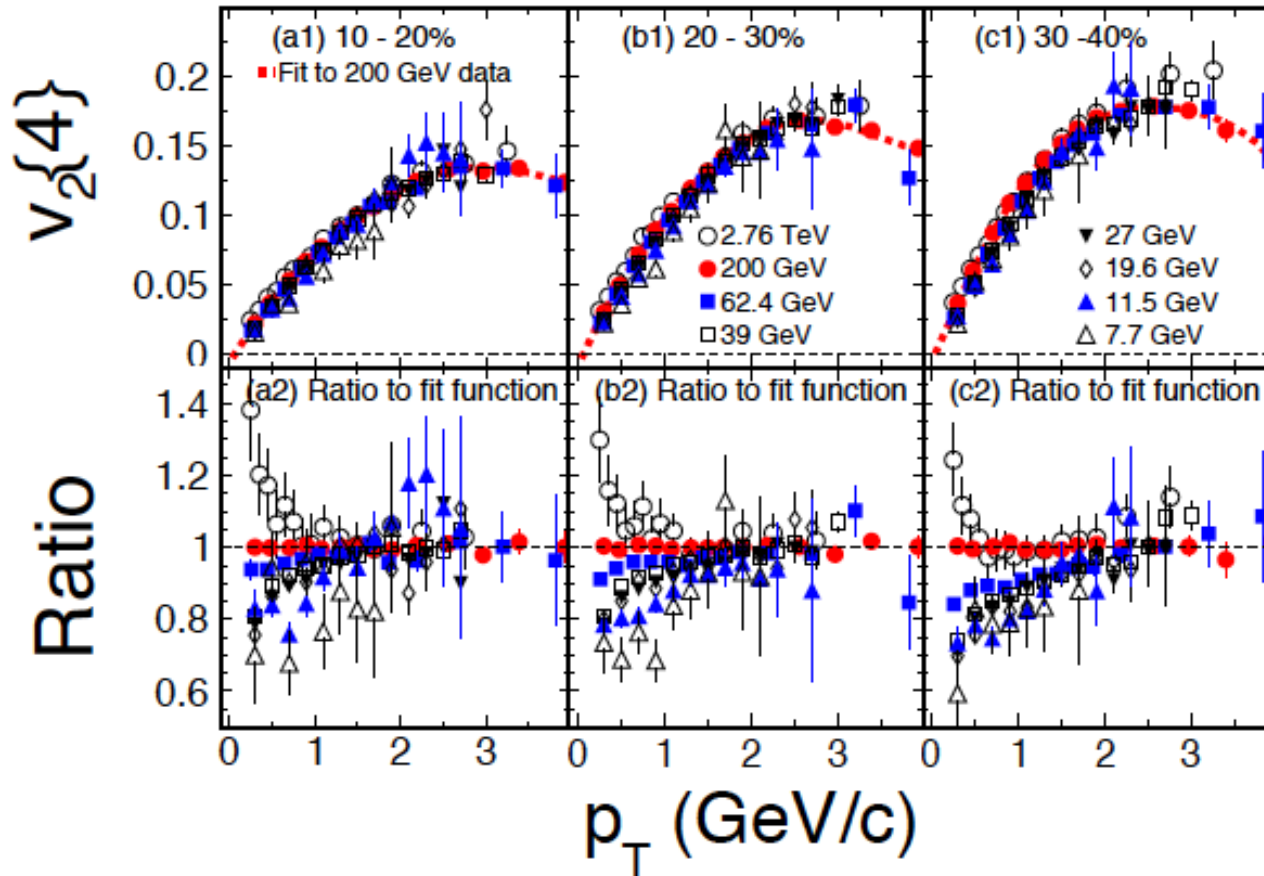
Critical ϵ_c from lattice ~ 0.6 GeV/fm³: lowest energy range explored still expected to be above transition region

No guarantee to see turn-off of QGP

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

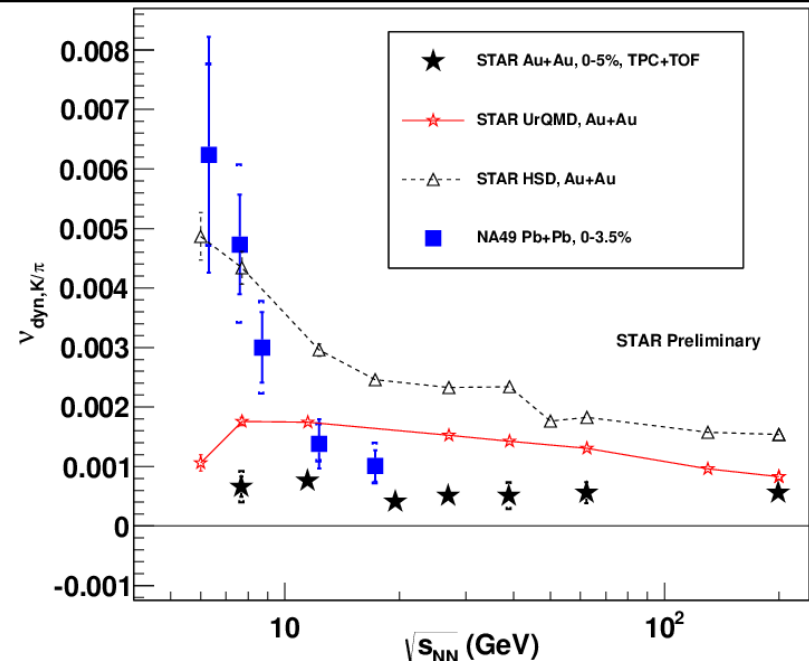
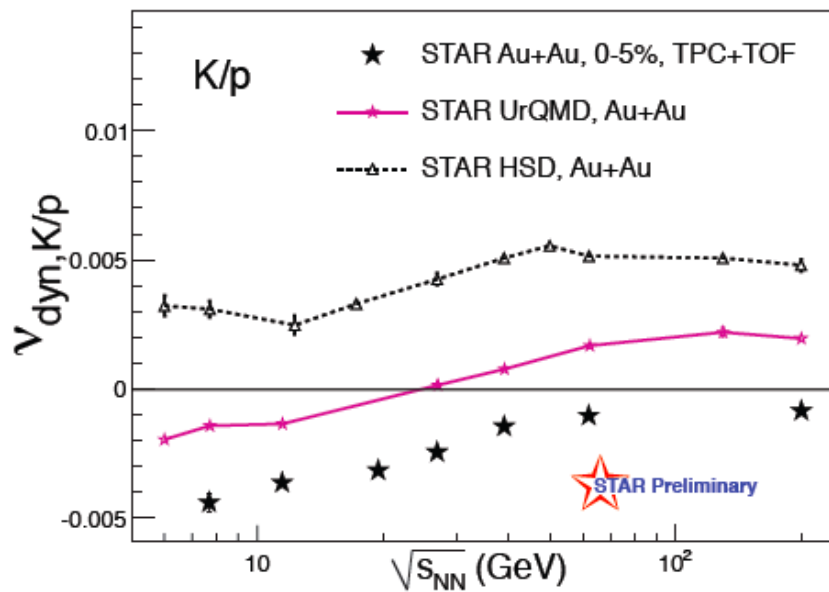
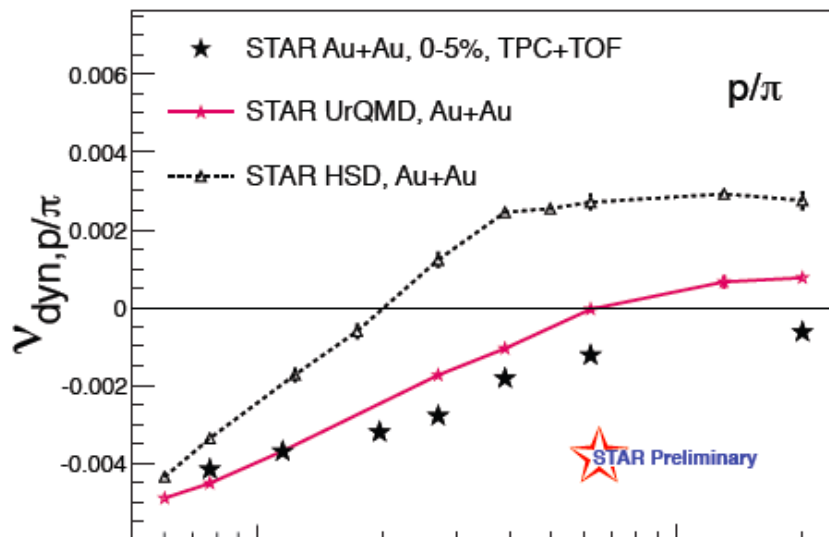
$v_2\{4\}$

STAR: Submitted to Phys.Rev.C



at $p_T=0.5$ GeV, $v_2\{4\}$ shows $\sim 40\%$ 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



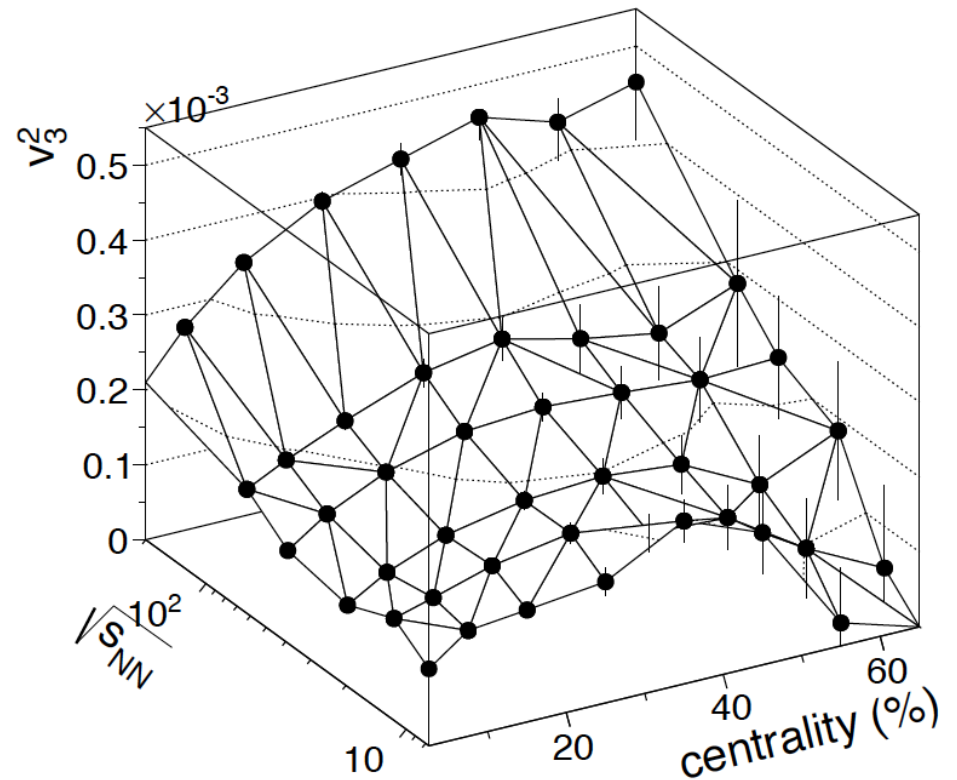
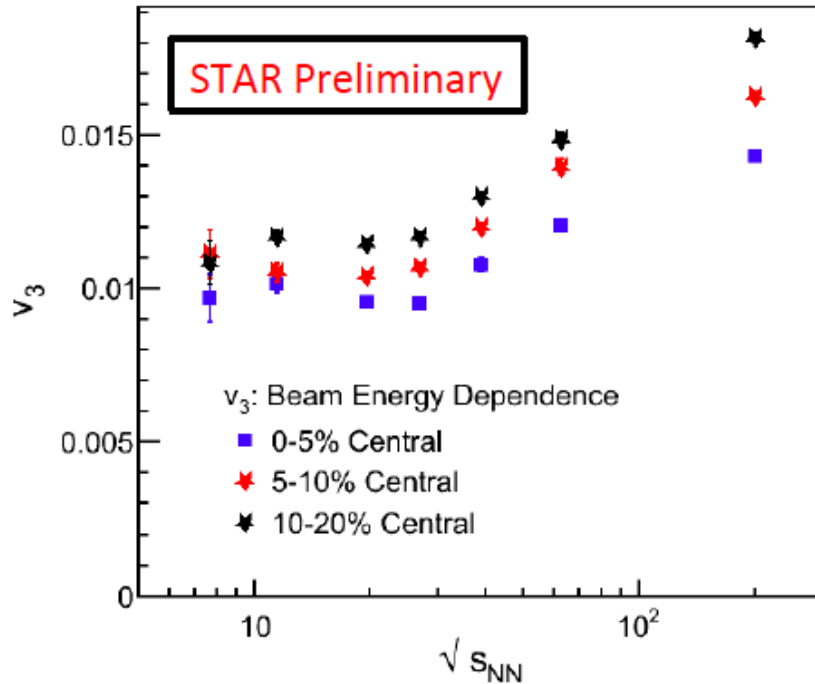
Measurement of event-to-event variation of particle ratios:

For 1st order phase transition: enhanced fluctuations

Observed energy dependence: fairly monotonic

Third Harmonic

Y. Pandit: QM2012



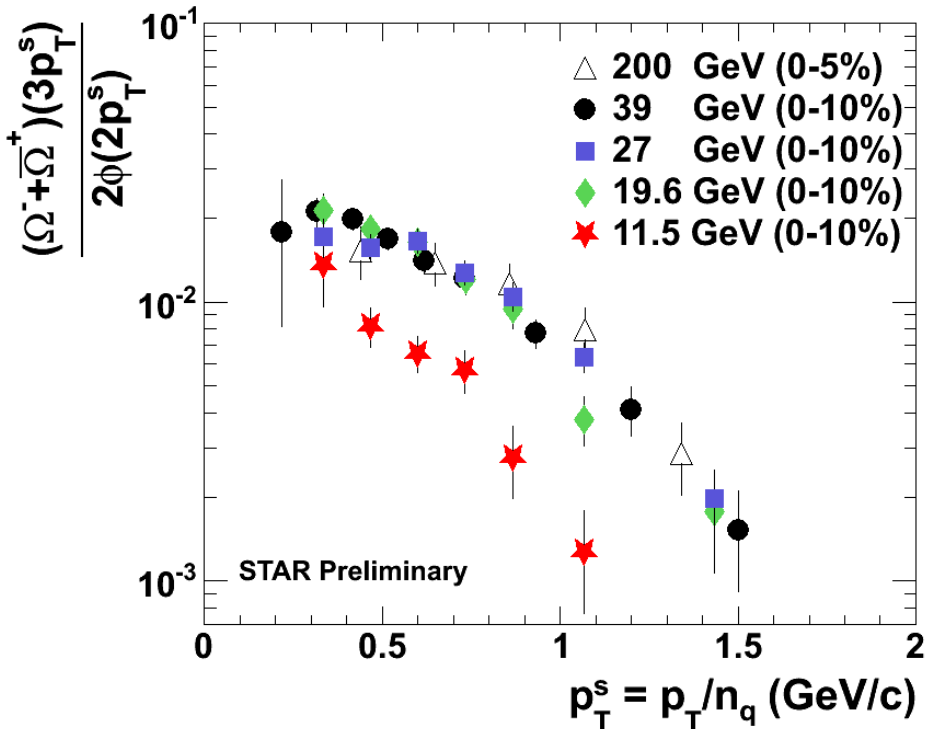
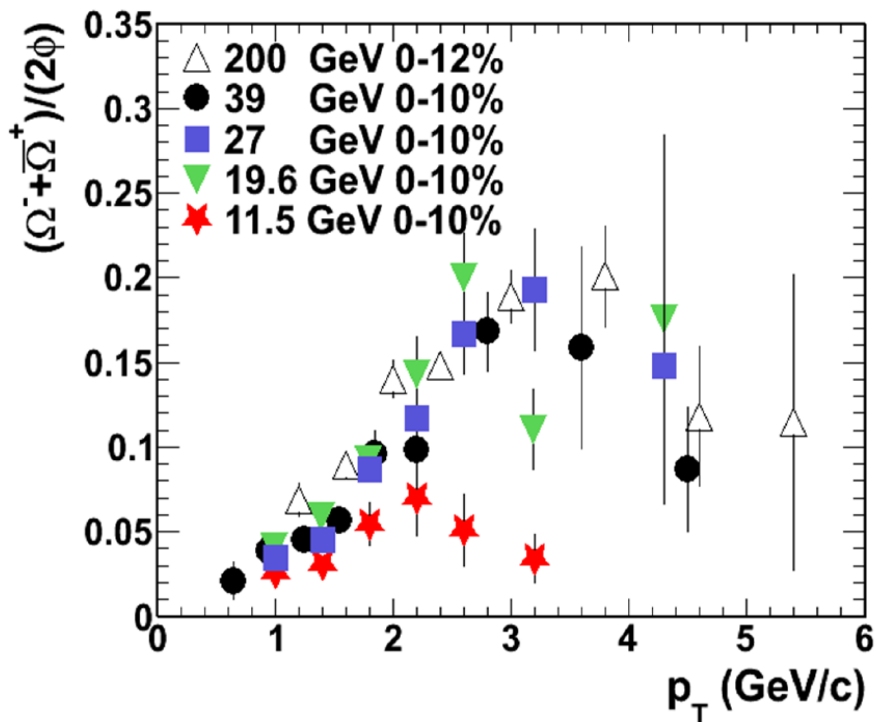
Observable sensitive to interactions at earliest moments

$\langle \cos 3\Delta\phi \rangle$ persist to lowest energy, even where jets are non-existent

AMPT requires a QGP phase at all energies to match magnitude

What Does Change? Ω/ϕ

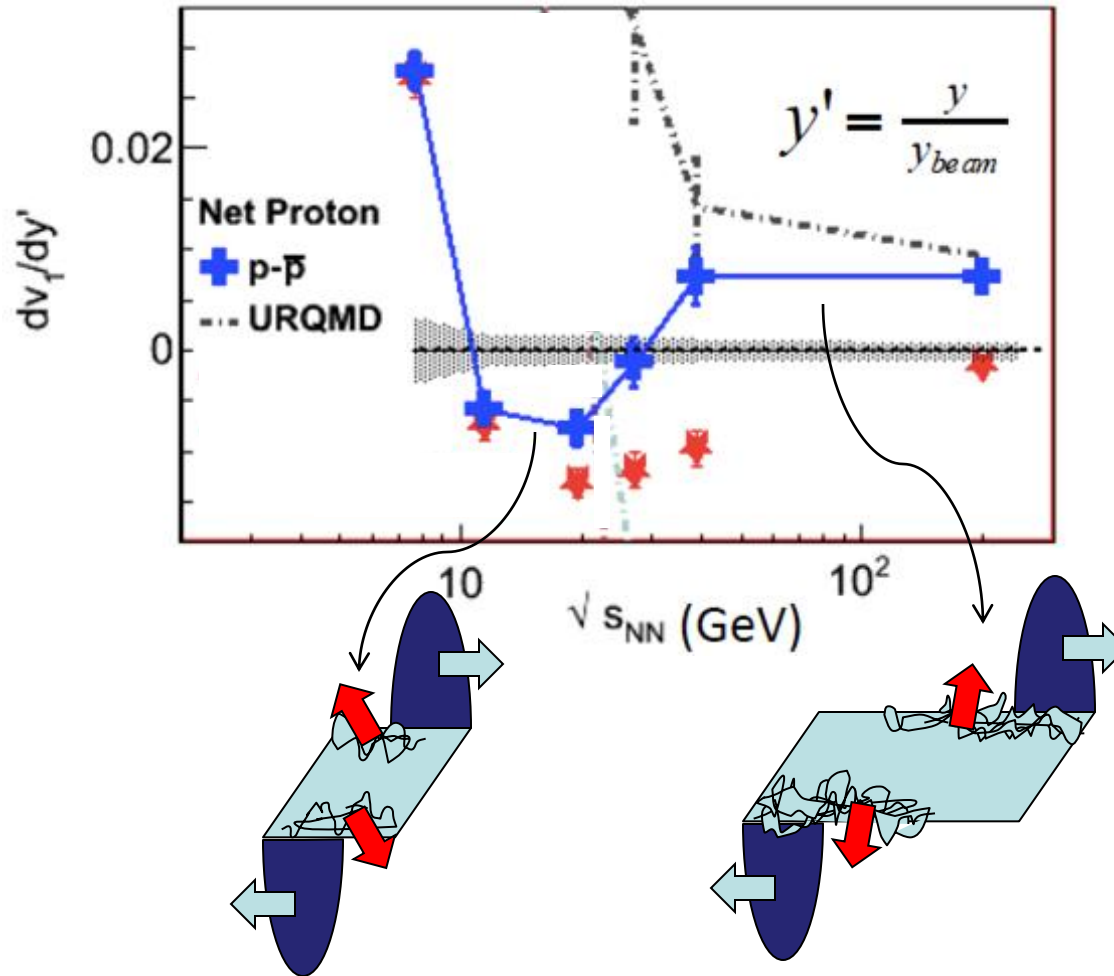
Reduction of s-quark population?



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

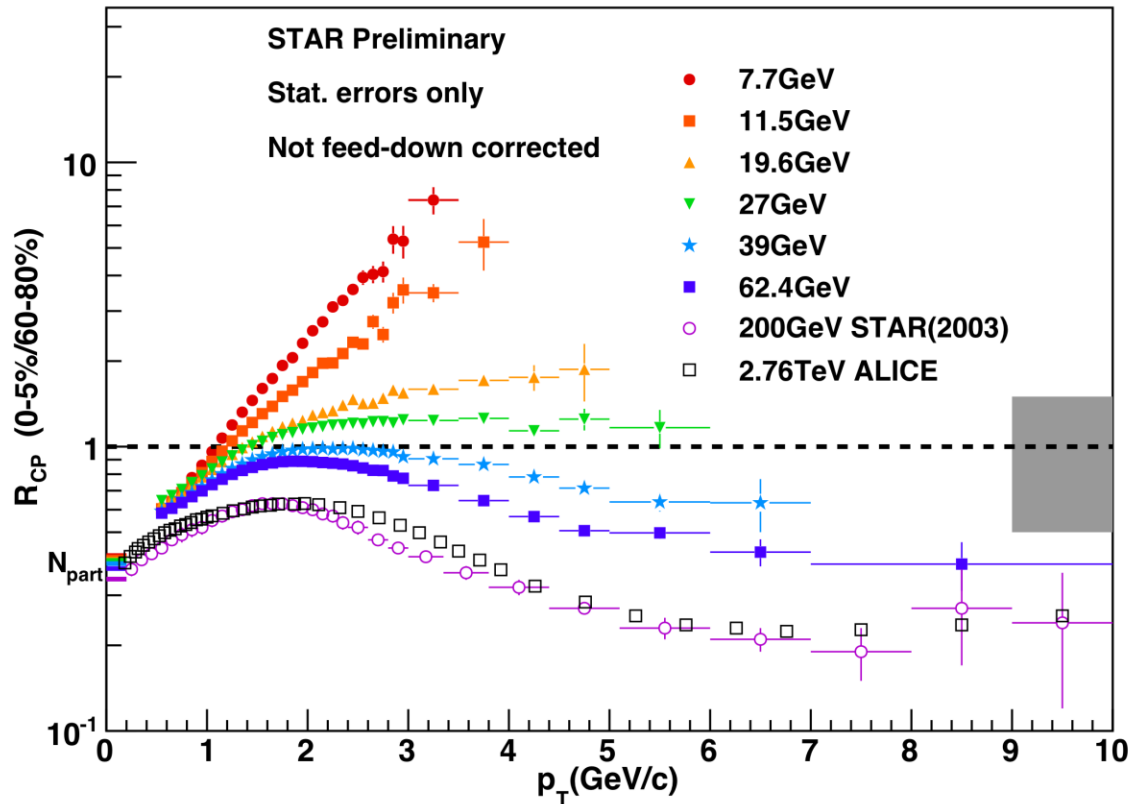


What causes this non-monotonic behavior? Related to the Equation of State? Or simple geometry?

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

What Does Change? R_{CP}

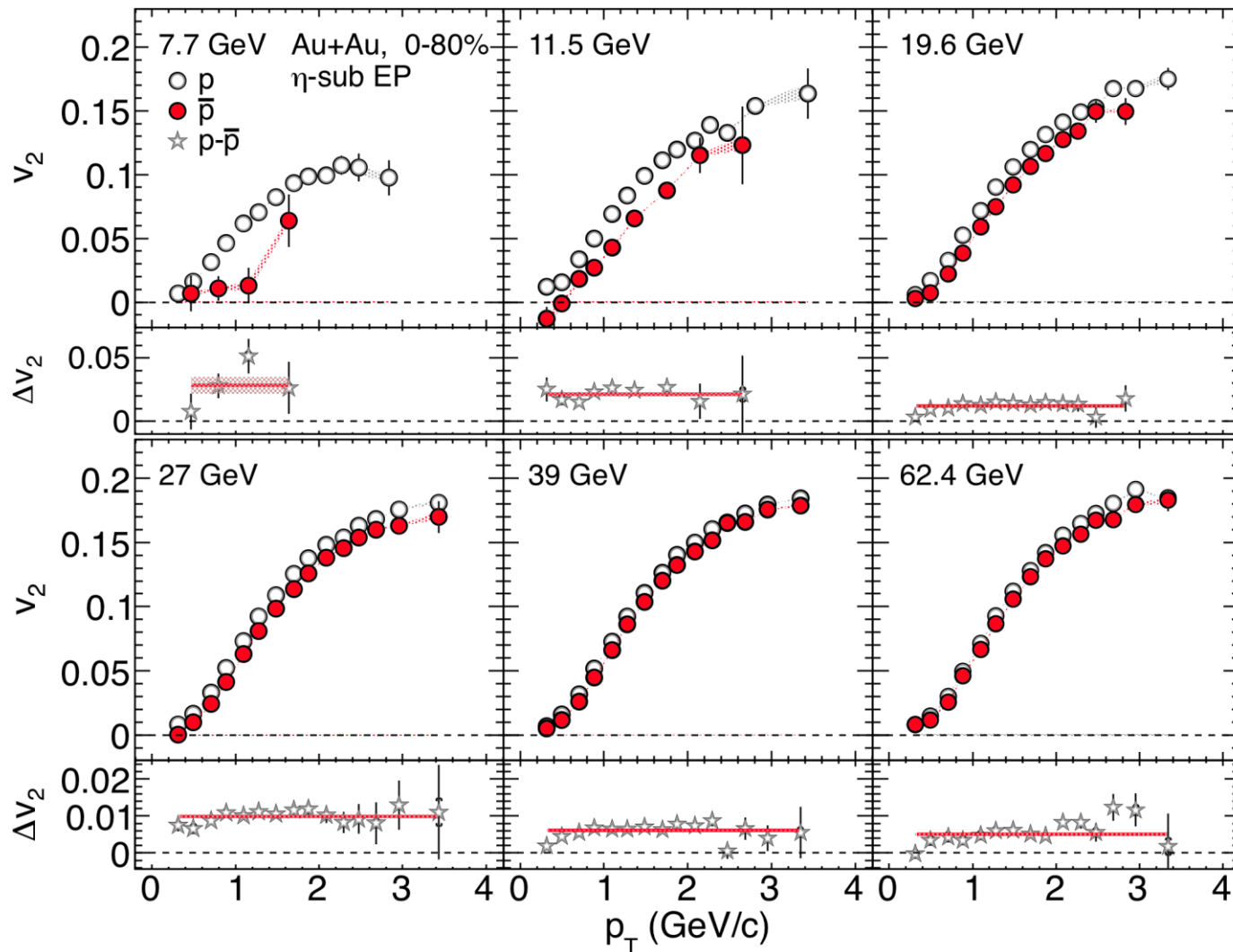
See Stephan Horvat's talk



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

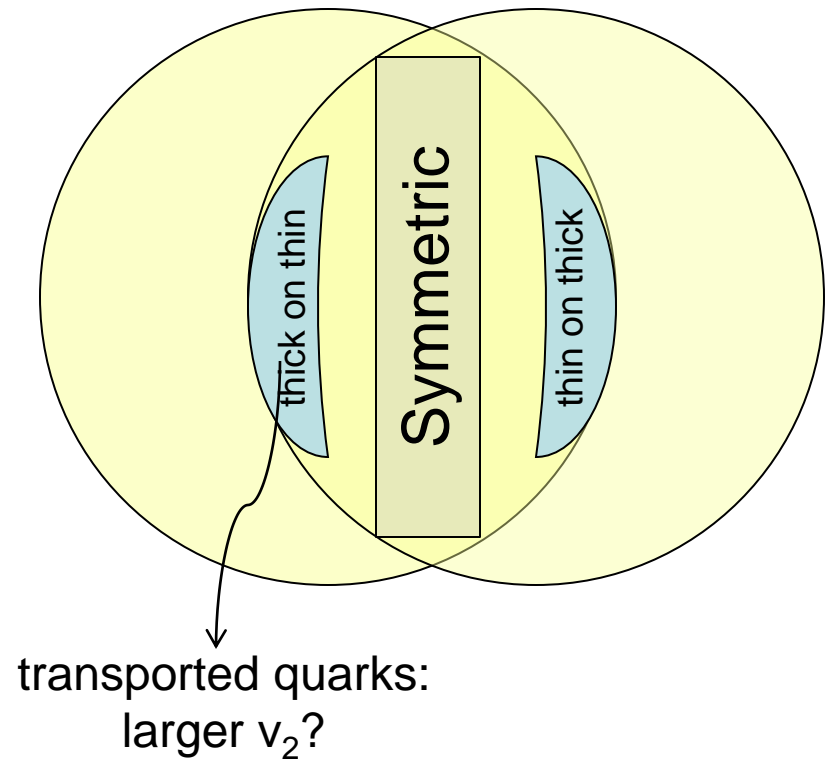
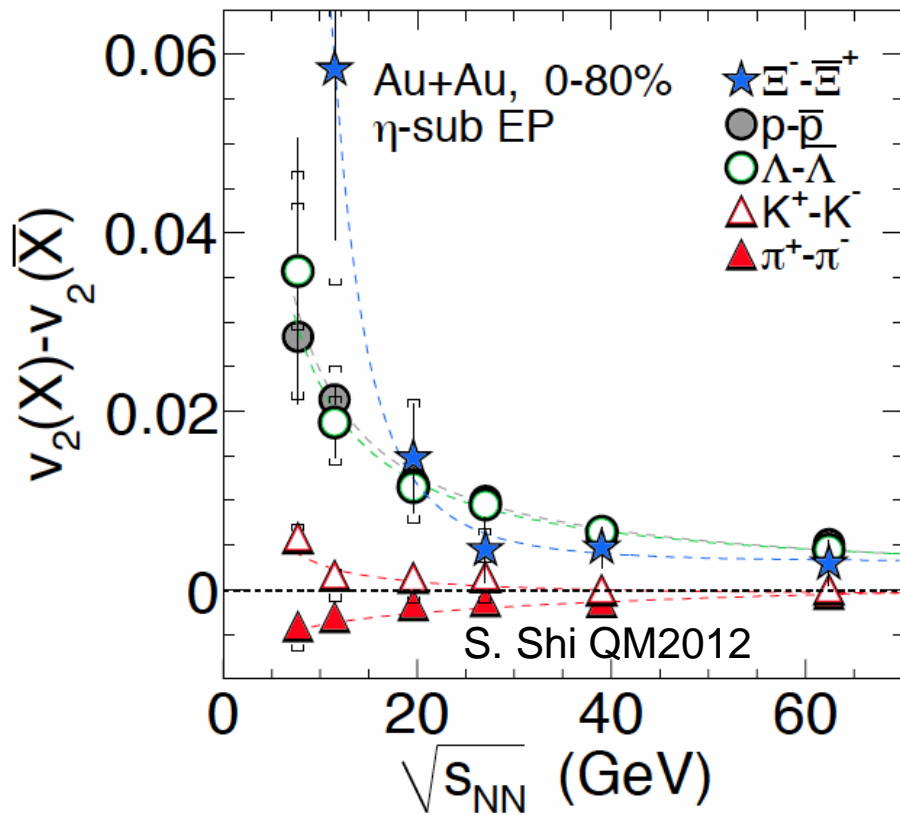
Or dominance of flow at low energies where the hard component of the spectrum is small?

Particle/Antiparticle Dependence



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

Strong μ_B Dependence of Flow



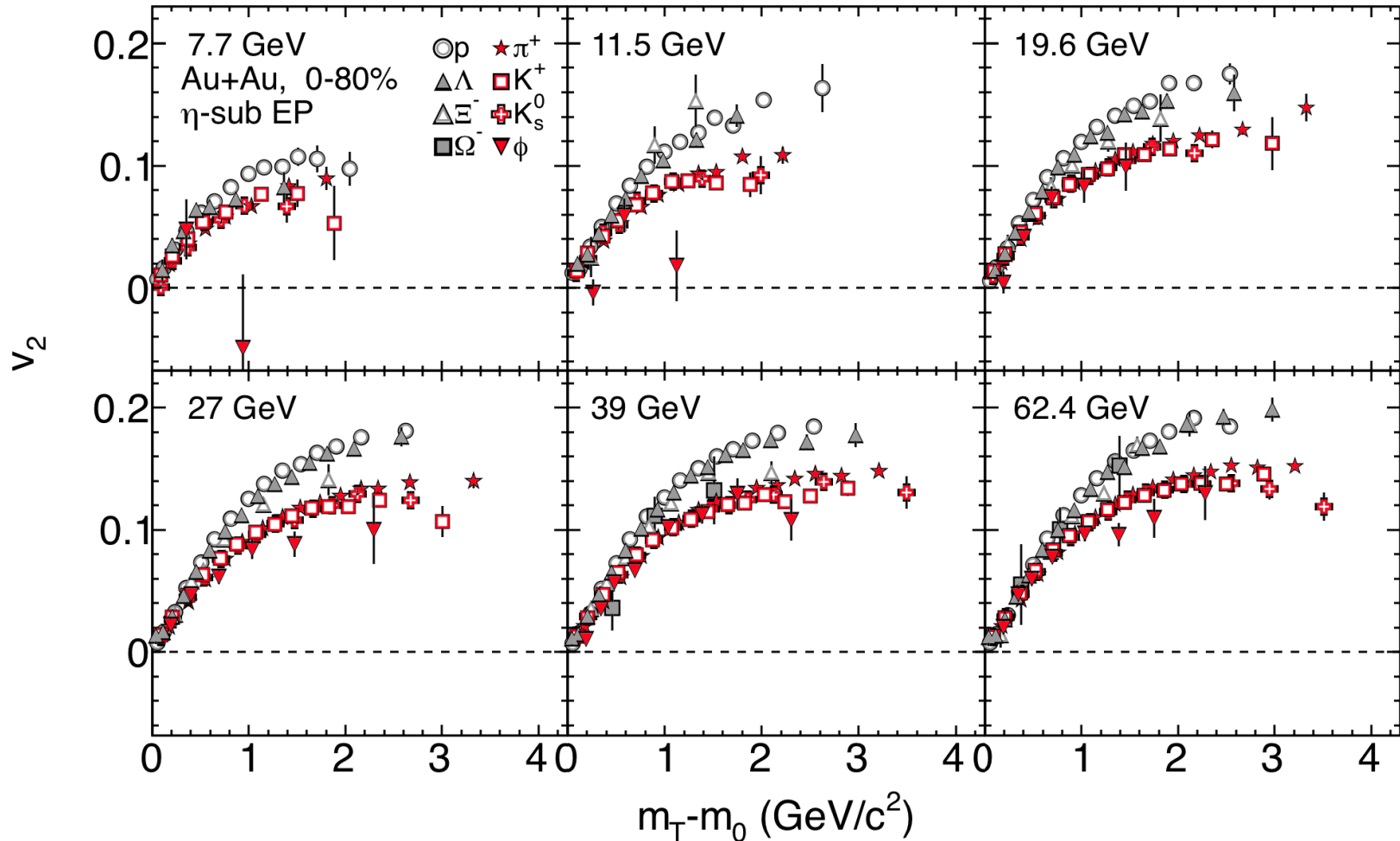
Increasing difference in flow of particles and anti-particles: linear with μ_B

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

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

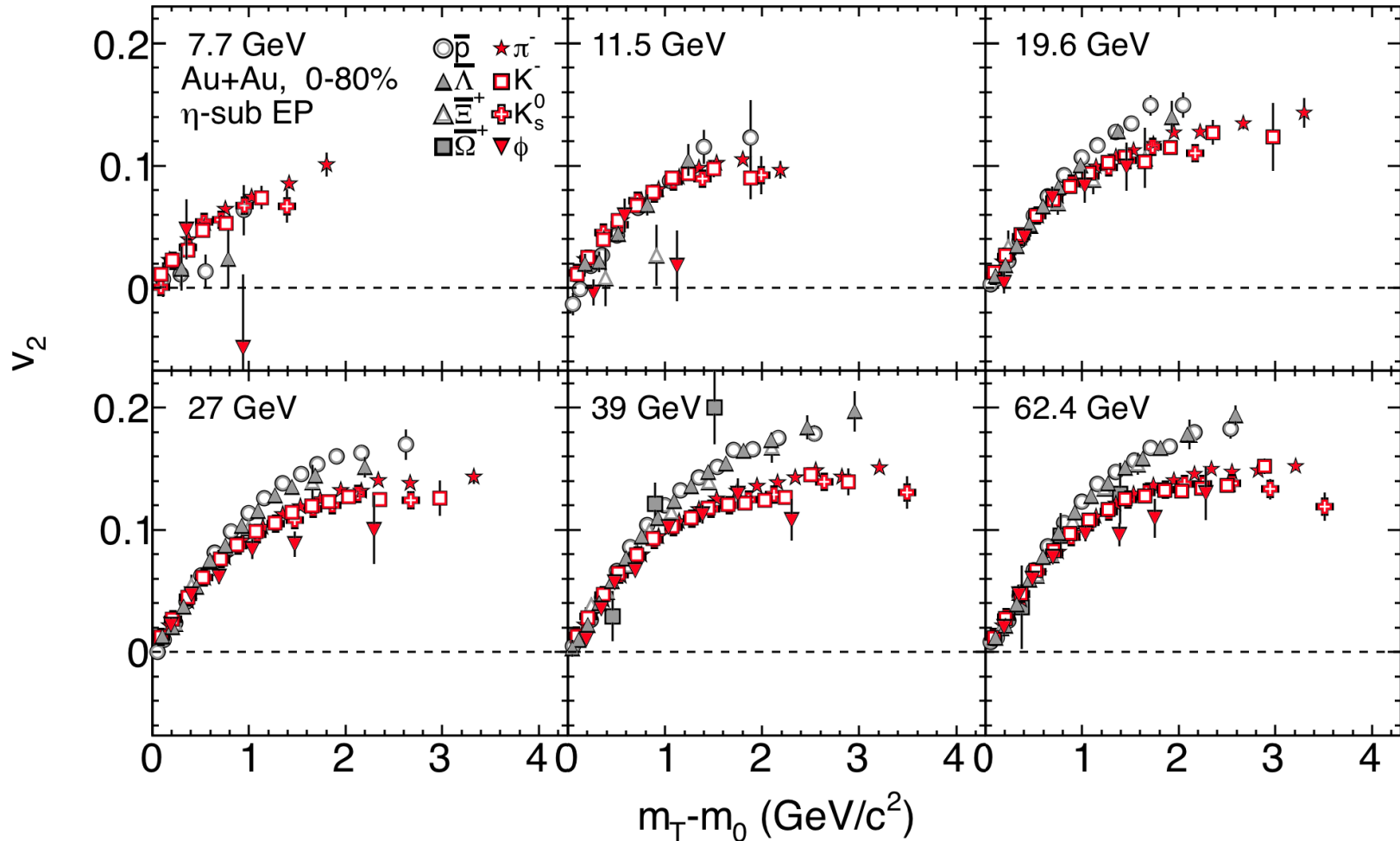
Mean field potentials in the hadronic stage? (Xu et al, arXiv:1201.3391)

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

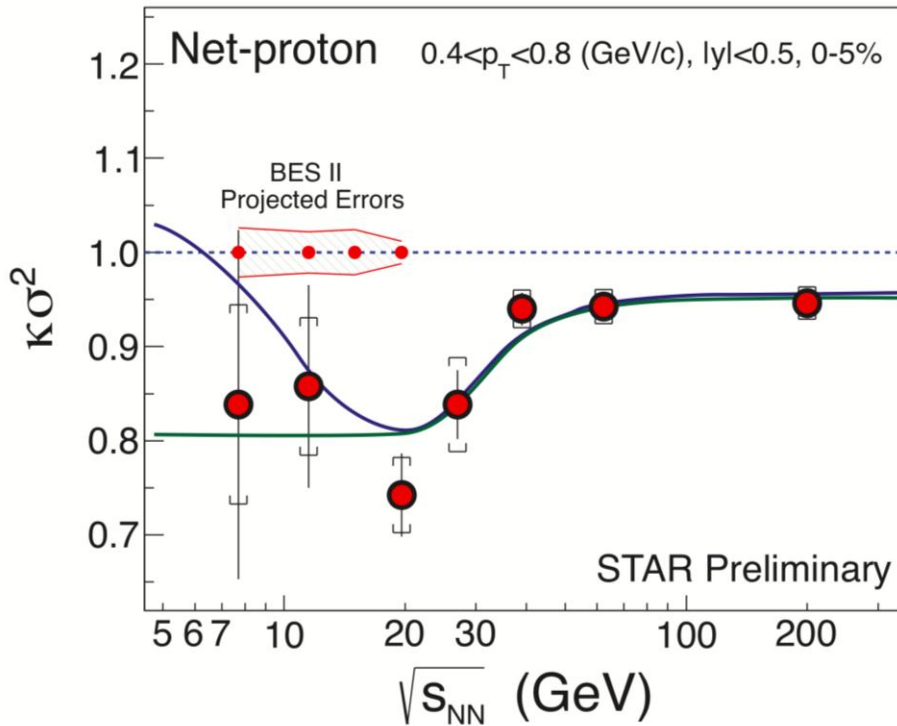
$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	BES-I	BES-II	Physics Motivation	Weeks**
200	24		0.5-2 (B)	Heavy flavor hadron v_2 & R_{AA}	
39	112	130 (M)			
27	156	70 (M)			
19.6	206	36 (M)	400 (M)	LMR di-electron*, net-p $\kappa > 5\sigma$	2
15	250		100 (M)	Ω yield, ϕ -meson v_2 ($\leq 3\text{GeV}/c$)	2
11.5	316	12 (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

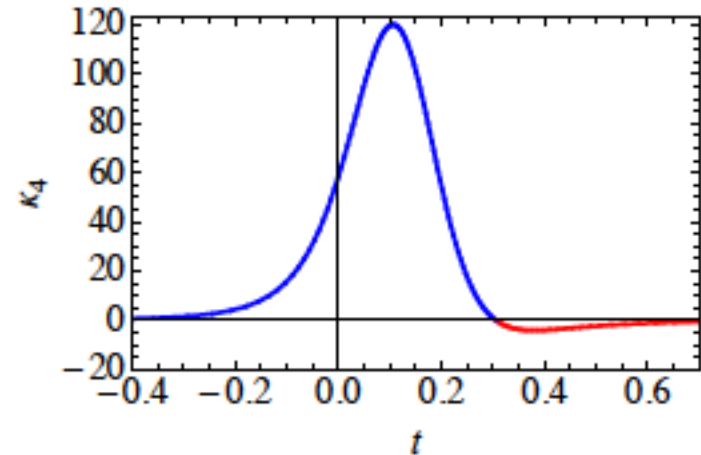
Program requires e-cooling upgrade (x10 improvement in luminosity): Timescale 2017

BESII and Higher Moments



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

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



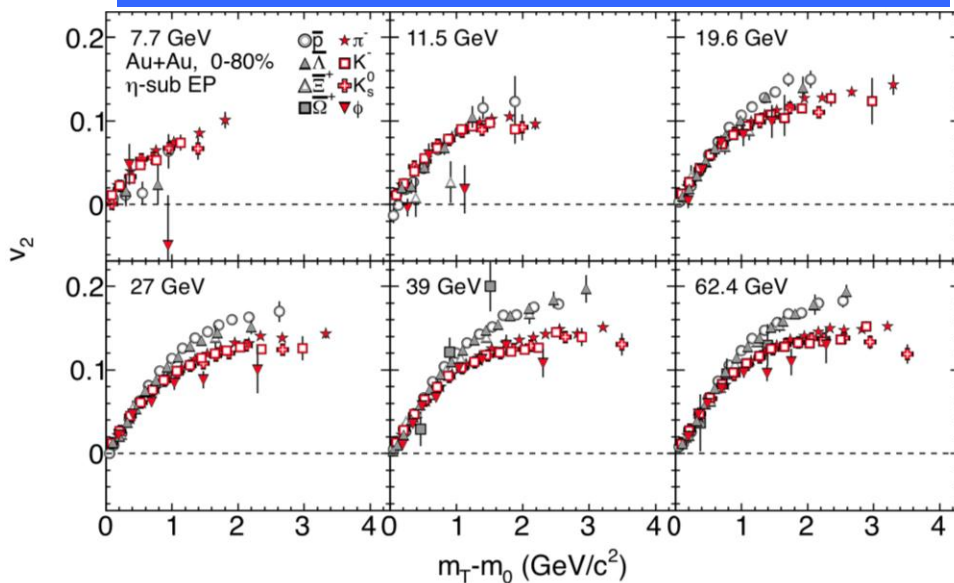
Prediction for a non-monotonic trend in 4th moment: is the structure in the data the start of the predicted non-monotonic behavior?

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

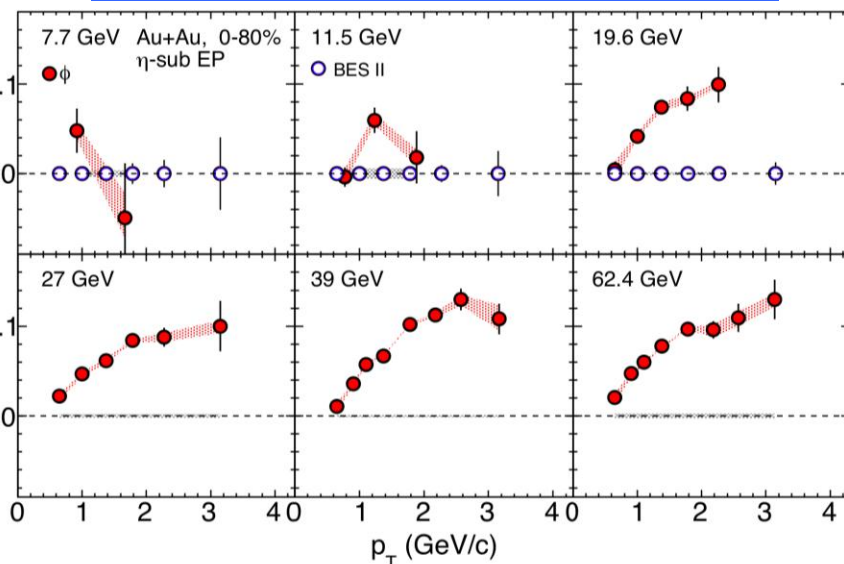
Also In Need of More Data

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 \sqrt{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

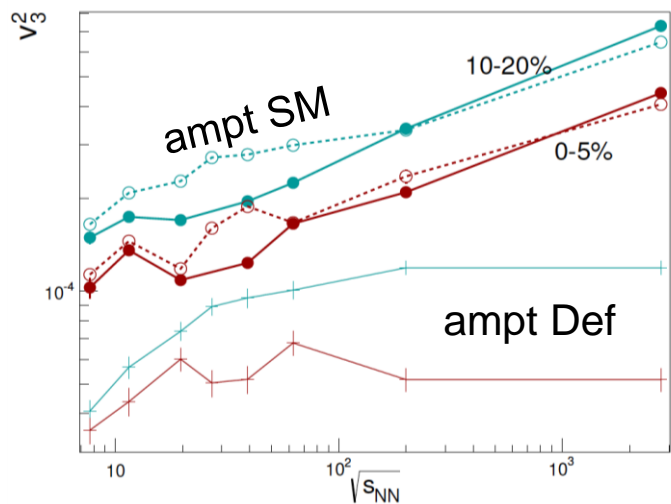
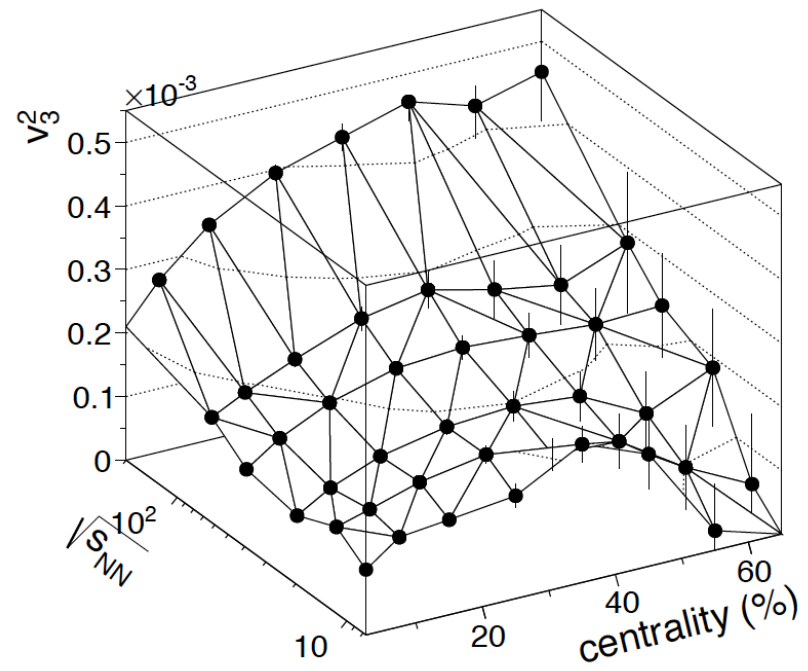
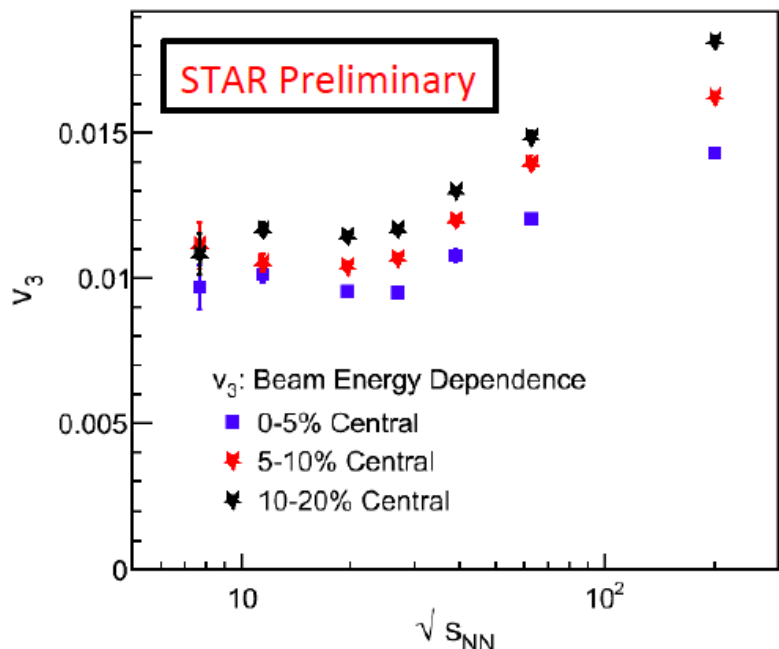
- RHIC sits in a very interesting region for QCD thermodynamics
- Heavy-ion physics is not energy frontier physics: Bulk phenomena remain key to our field
- RHIC data require a smaller η/s than LHC data: provides access to the temperature dependence of transport properties

RHICs beam energy scan has led to several surprising discoveries:

- Non-monotonic net proton v_1
- μ_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 to resolve lower energies

Energy Dependence

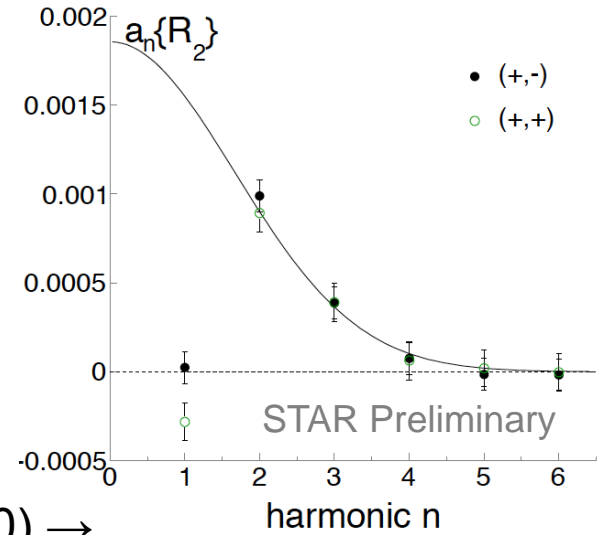
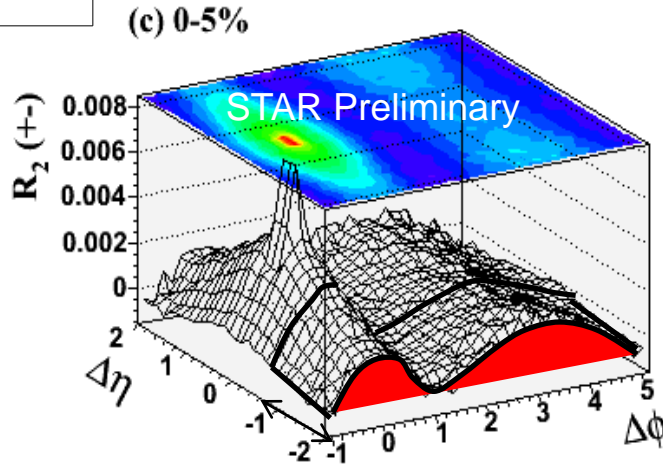


v_3 persists to 7.7 GeV with a similar centrality dependence

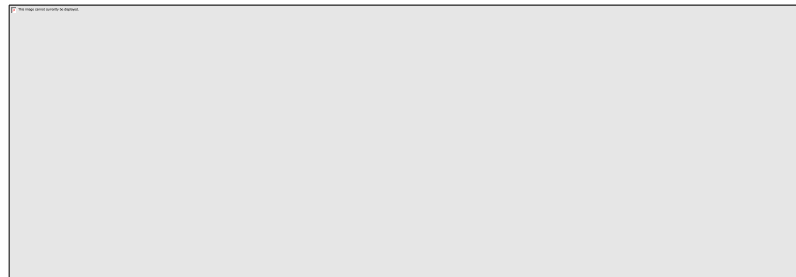
AMPT SM describes values to lowest energy

Spectrum From 2-particle Correlations

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

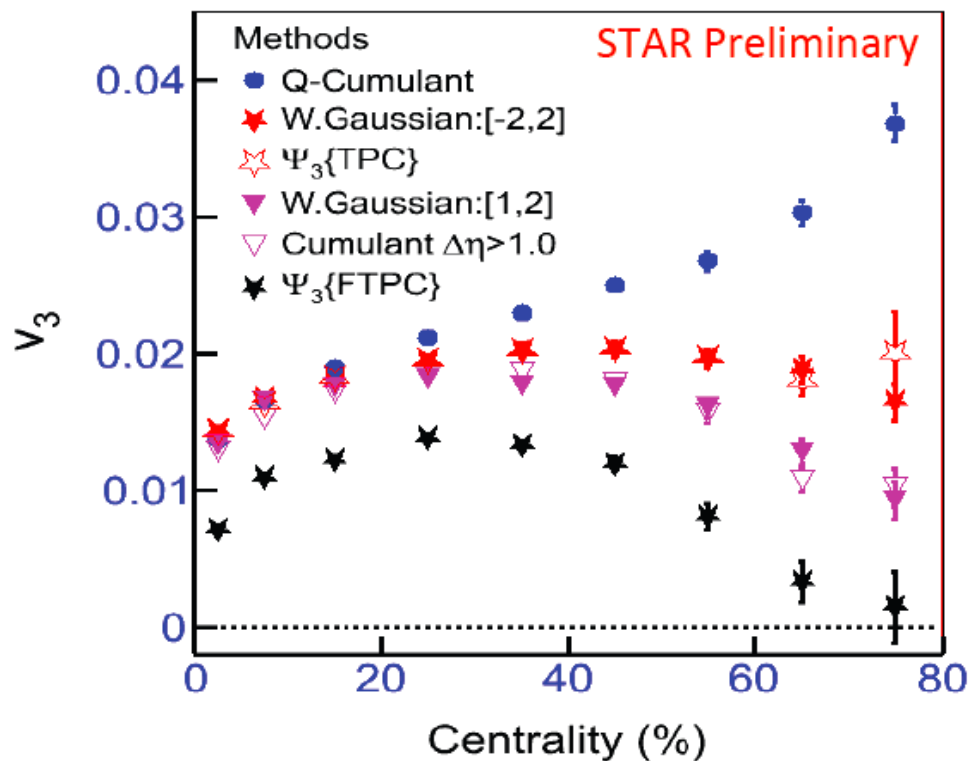
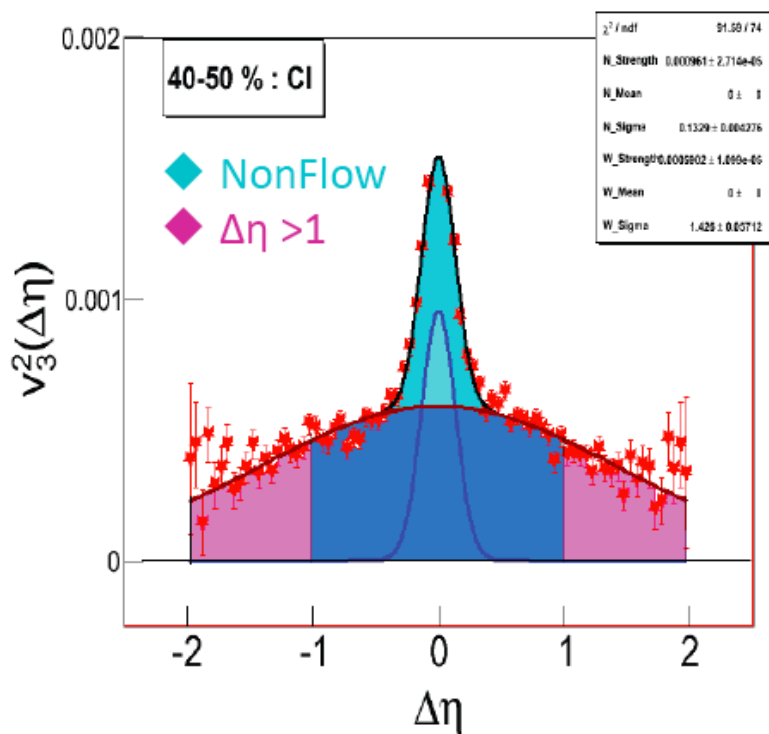


→ Fourier Tr. ($0.7 < \Delta\eta < 2.0$) →



but clear structure in the longitudinal direction ($\Delta\eta$ 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: 2022?

Fixed target energy scans are extremely difficult because of changing acceptance

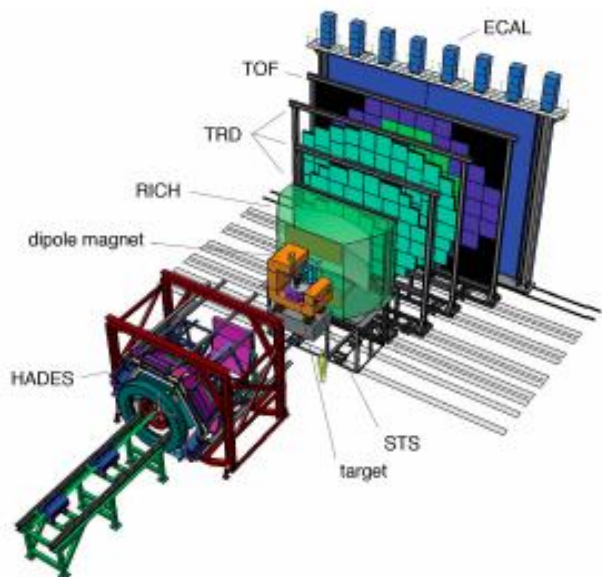
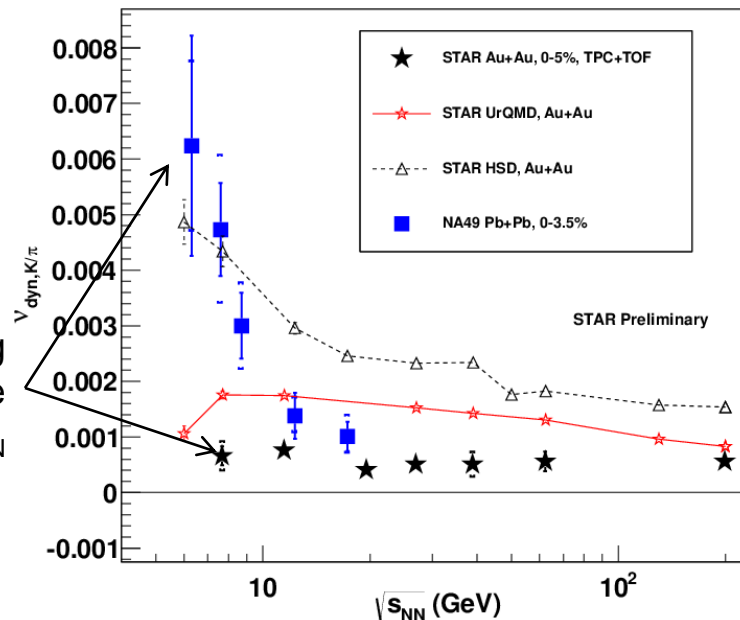


Fig. 1.5 Sketch of the planned Compressed Baryonic Matter (CBM) experiment together with the HADES detector.

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: $\sim 10^{27}$ /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

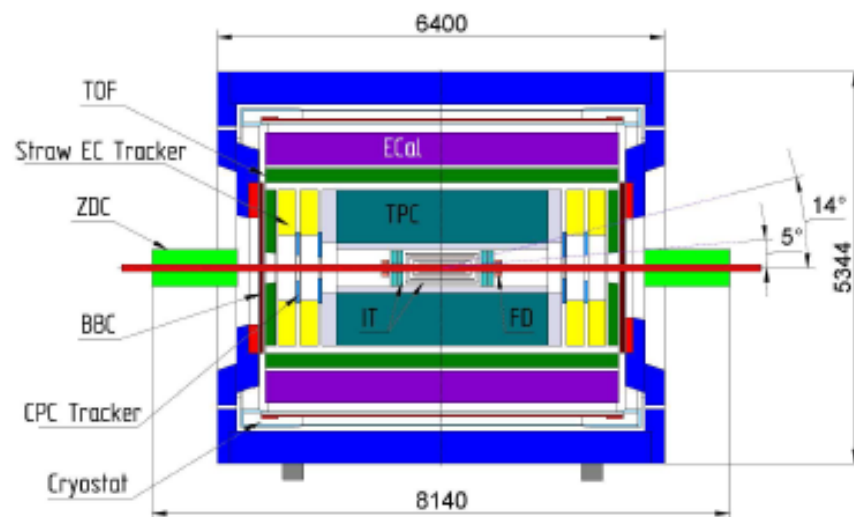


Fig. 2.2: Cutaway side view of the Central Detector of MPD with based dimensions.

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: insufficient energy to explore potential transition region identified at RHIC (7-27 GeV)

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