Turn Off of the QGP

A Contrarians Point of View

RANP
2013

Paul Sorensen
Brookhaven National Laboratory

BROOKHAVEN
NATIONAL LABORATORY

QCD and the Energy Frontier

Two salient features of QCD: Asymptotic Freedom and Confinement

Asymptotic Freedom:

- at high energies Q^2, coupling between charges is weak
- allows us to *test* QCD using perturbative calculations: small $\alpha_s(Q^2)$

For these reasons, we've tended to dwell on the energy frontier

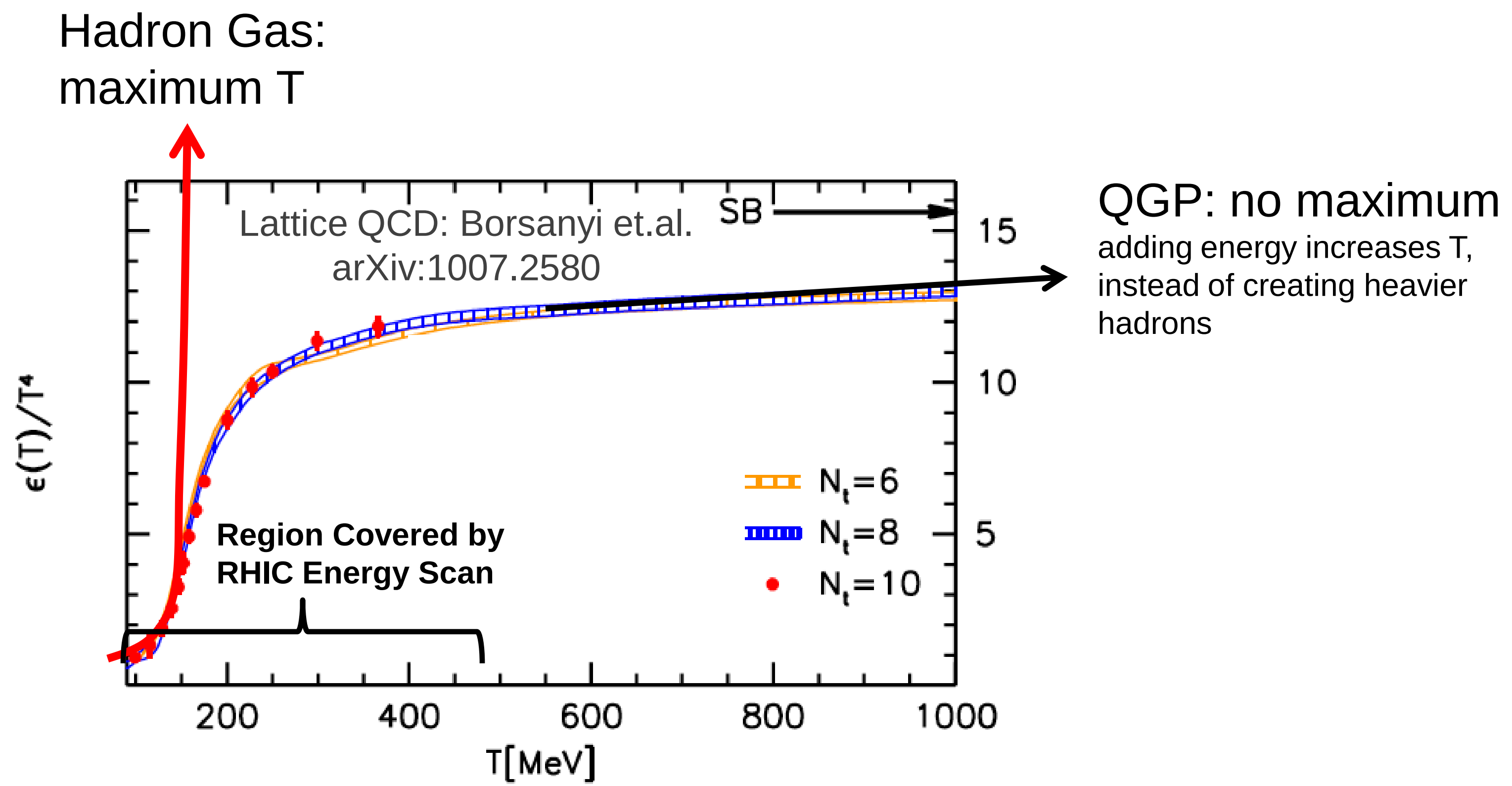
But in Heavy Ions, we are studying

- the **Confinement/Deconfinement transition** (Tc~200 MeV)
- and the properties of the matter that emerges from QCD above Tc

The most interesting region is the transition region

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

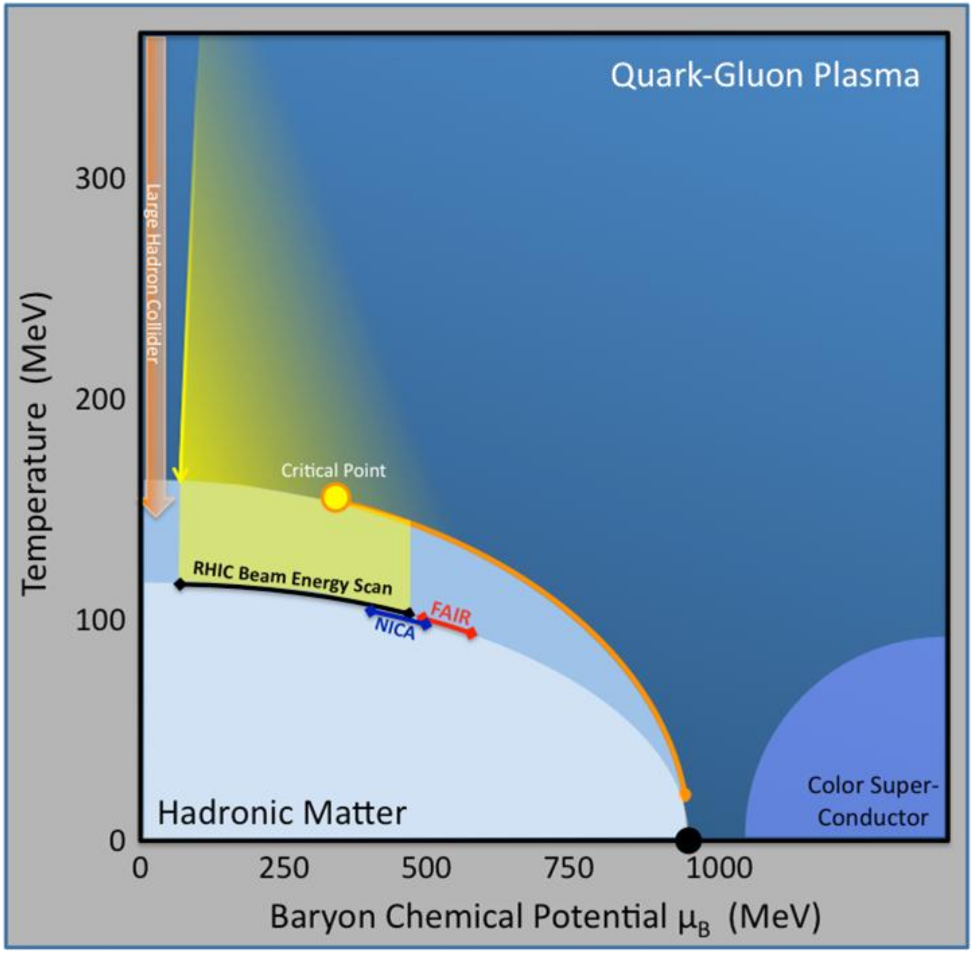
Beam Energy Scan Motivations

Varying the energy changes

- the initial energy density and T
- baryon chemical potential
- the equation of state

Search for

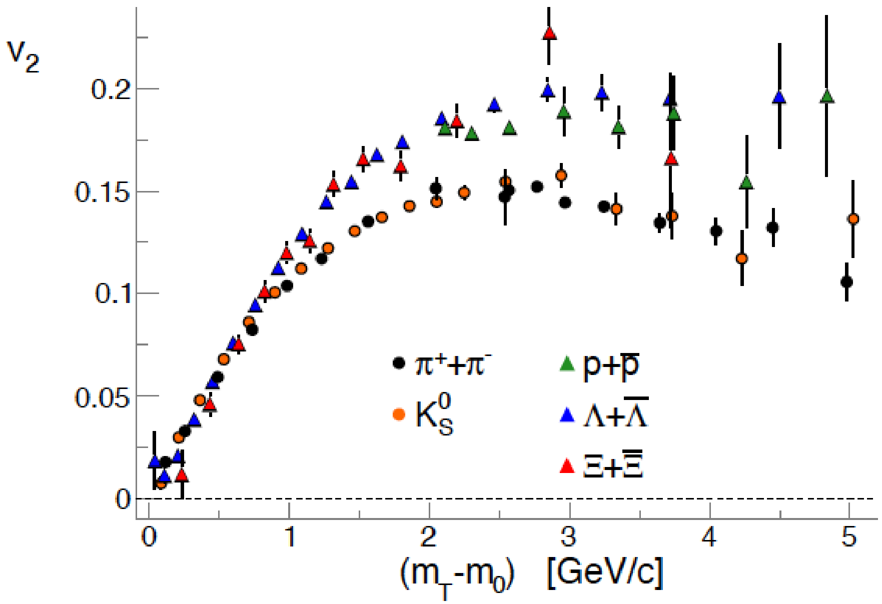
- turn off of QGP signatures and change in the degrees of freedom
- evidence of a first order phase transition ending at a critical point

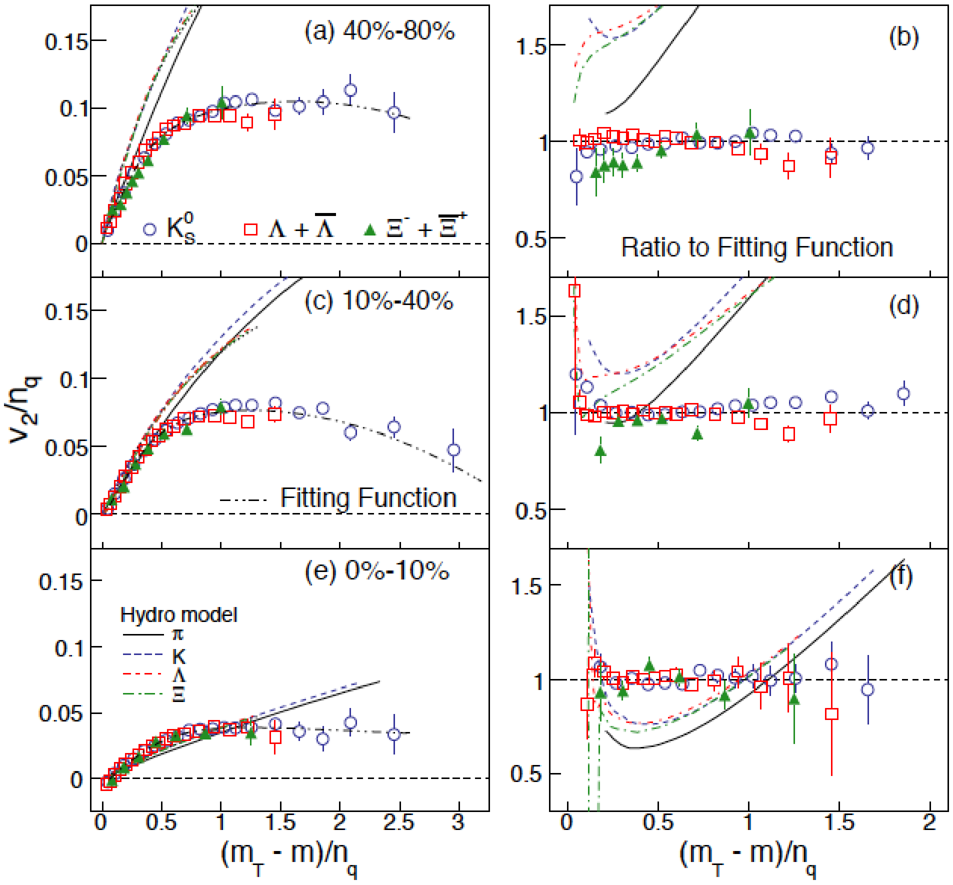


Can we map out the transition? Can we turn the QGP off?

Will we see a C.P. or 1st order P.T. before the QGP disappears

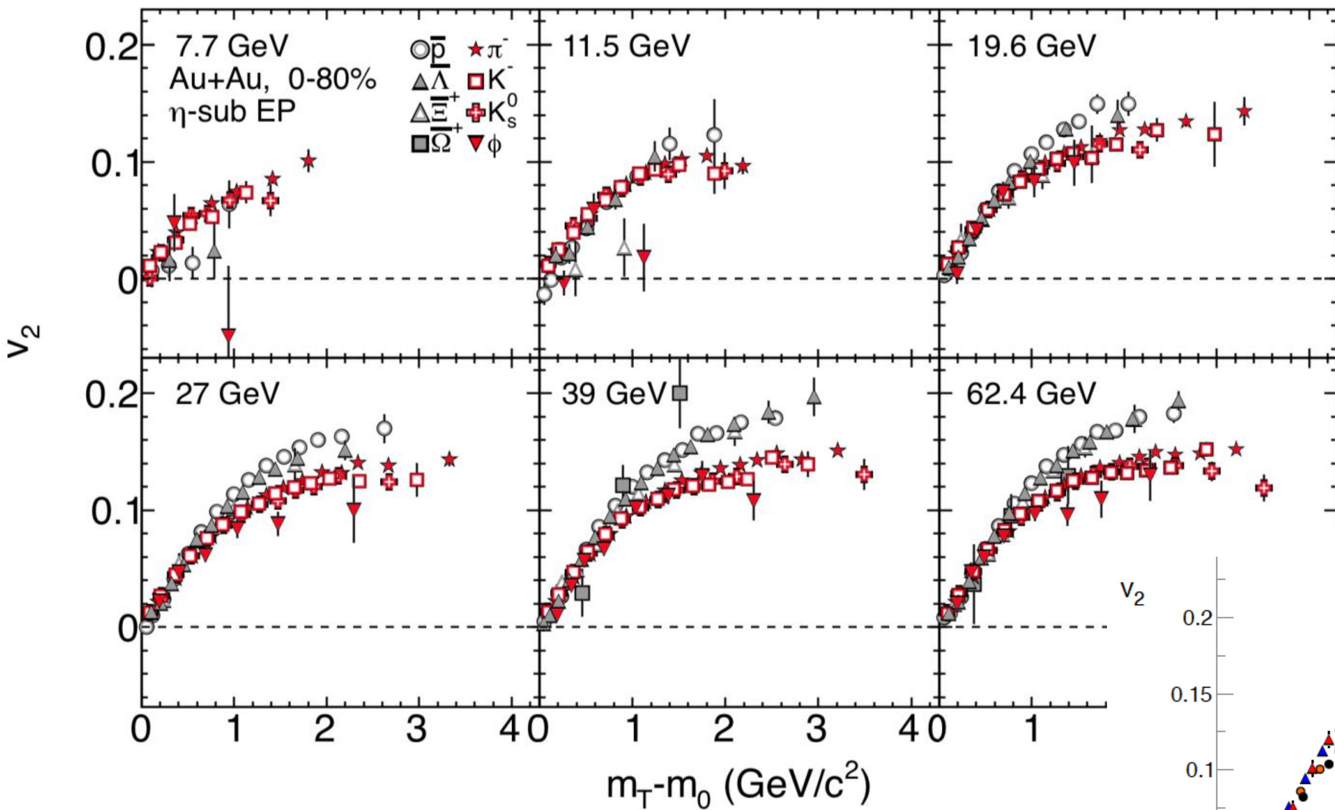
Disappearance of QGP? NCQ

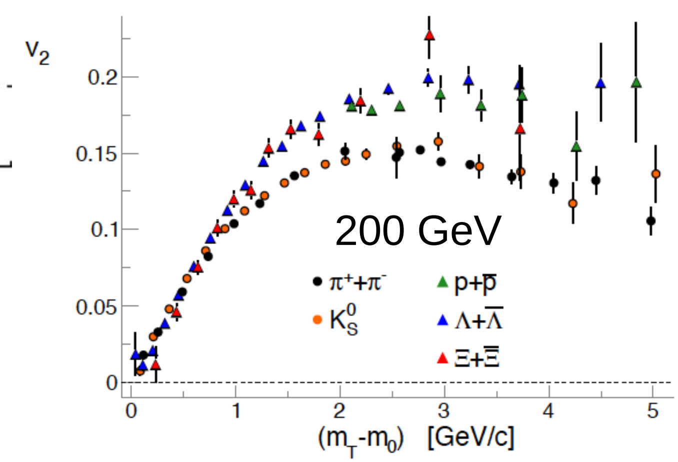




Large baryon v_2 taken as evidence of quark coalescence: relevance of quark degrees of freedom at full RHIC energy

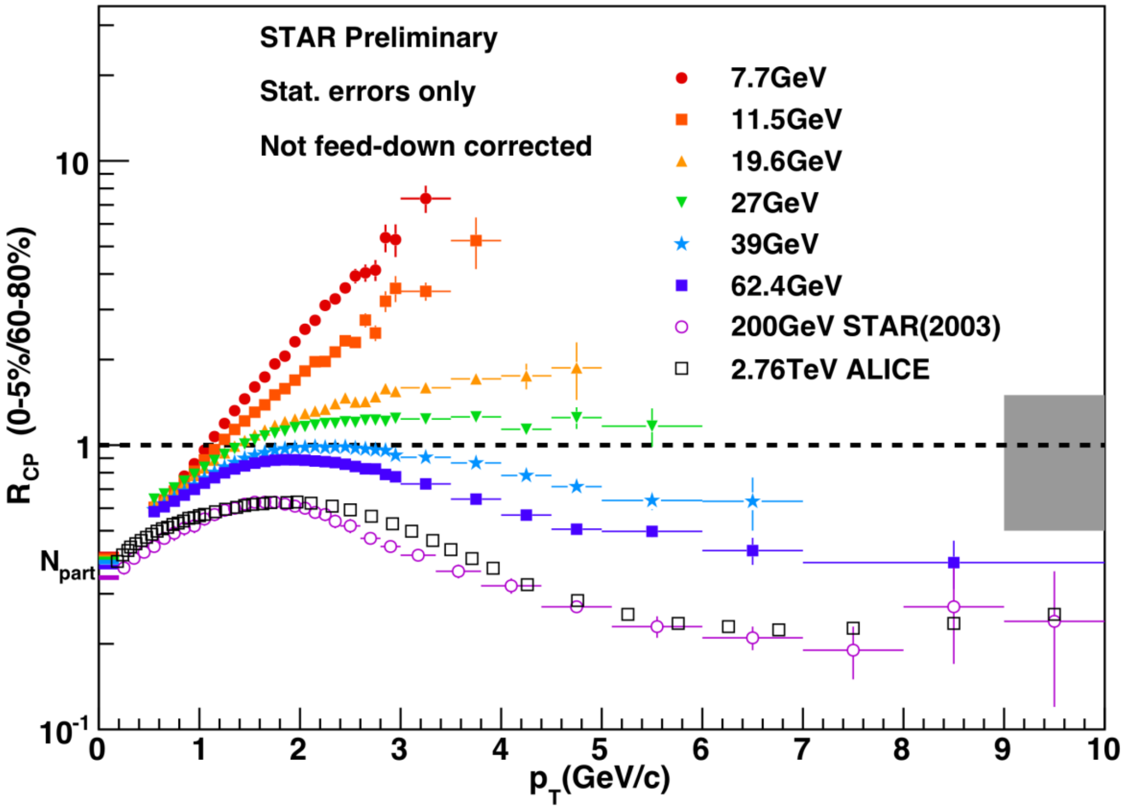
Disappearance of QGP? NCQ





Baryon enhancement and meson baryon seperation disappears below 19.6 GeV

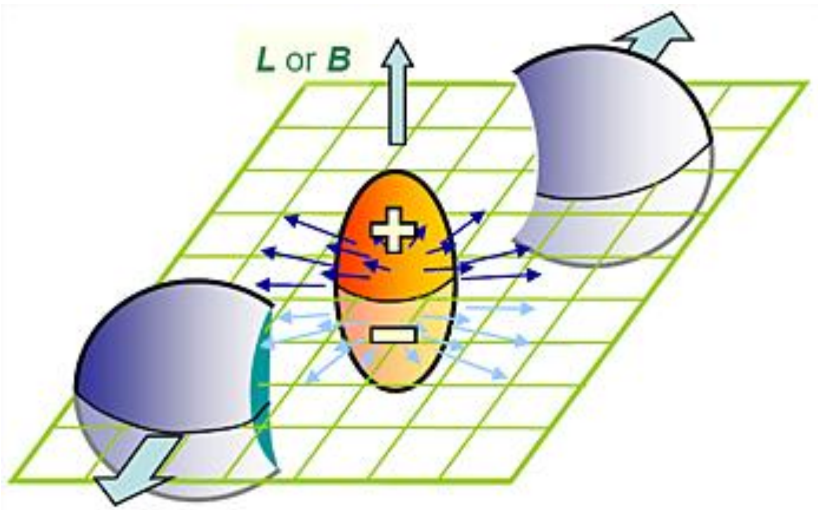
Disappearence of QGP? R_{CP}



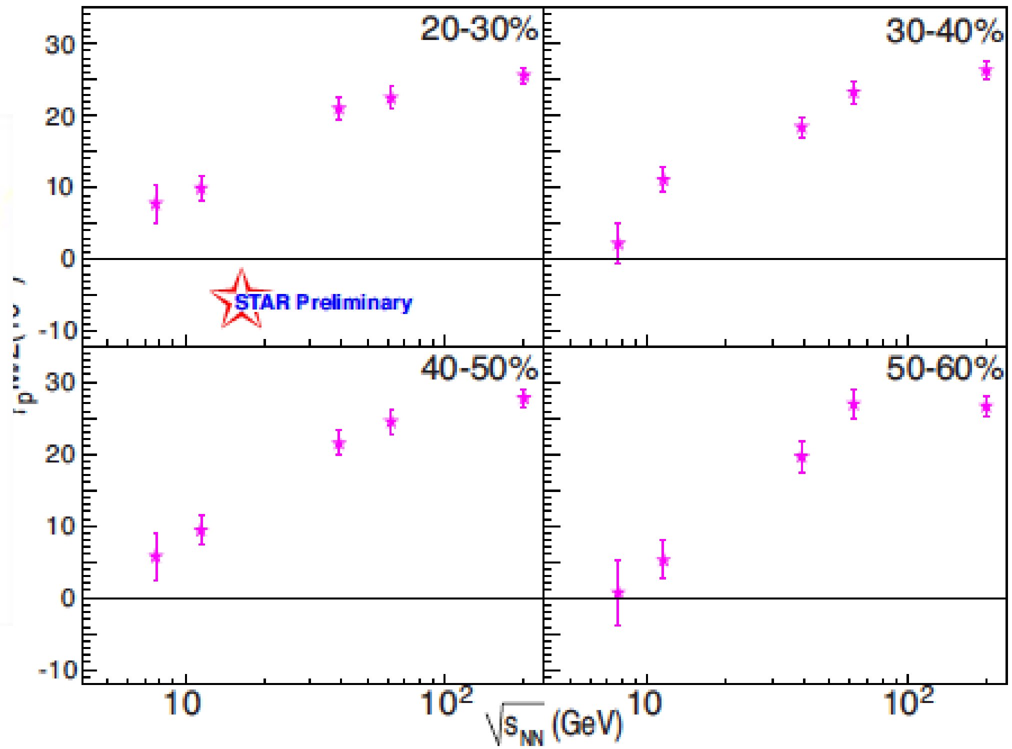
R_{CP} for 4-5 GeV particles gradually transitions from a suppresion at 200 GeV to an enhancement at 19.6 GeV

Opacity disappears below 39 GeV?

Disappearence of QGP? LPV



Event-by-event charge separation



Charge seperation (thought to be related to parity violating regions in a QGP) “disappears” below ~19.6 GeV

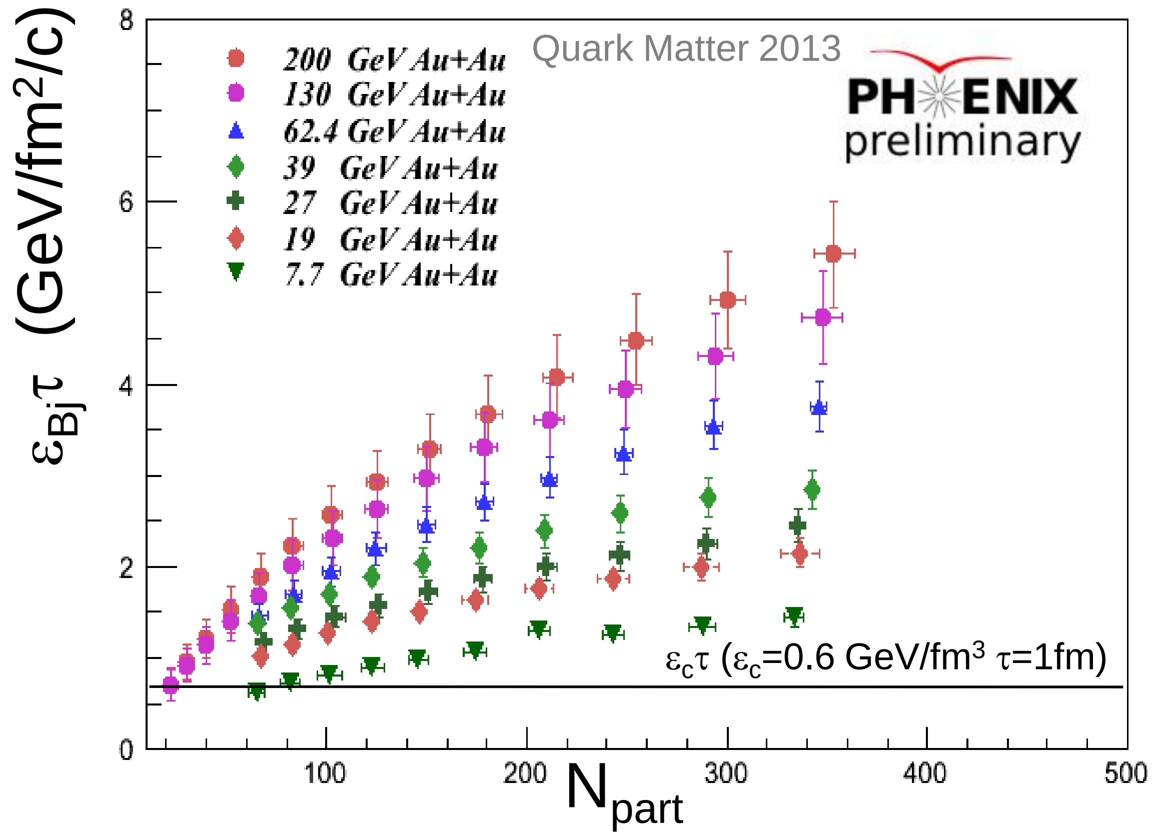
To be, or not to be; An Optimist

Our "QGP signatures" are certainly disappearing…

- High p_T hadron suppression
- NCQ scaling
- Charge seperation

but… is it related to the QGP disappearing?

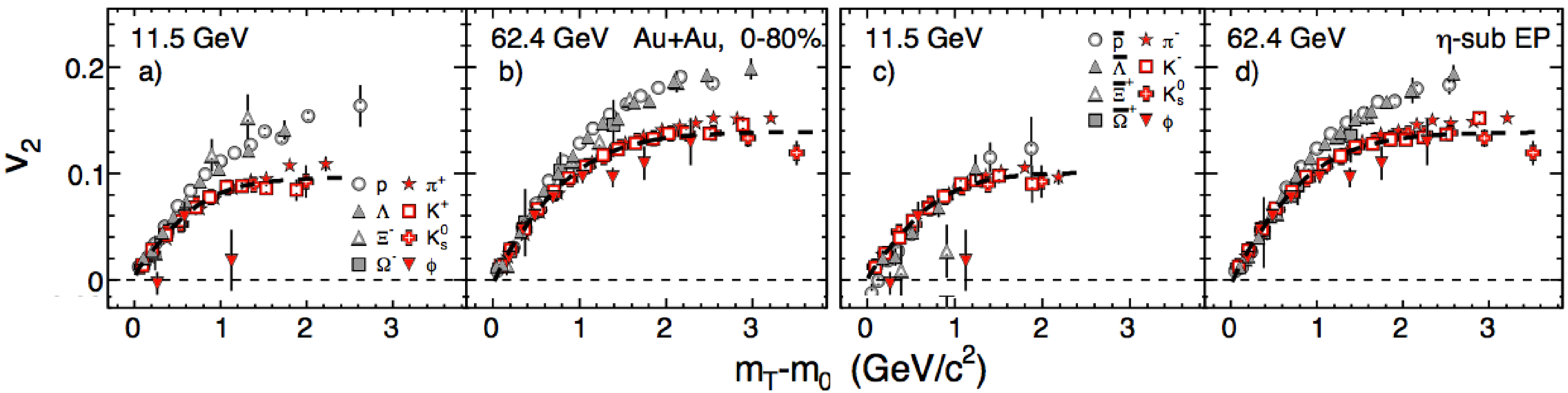
Where Do we Expect the QGP to Turn Off?



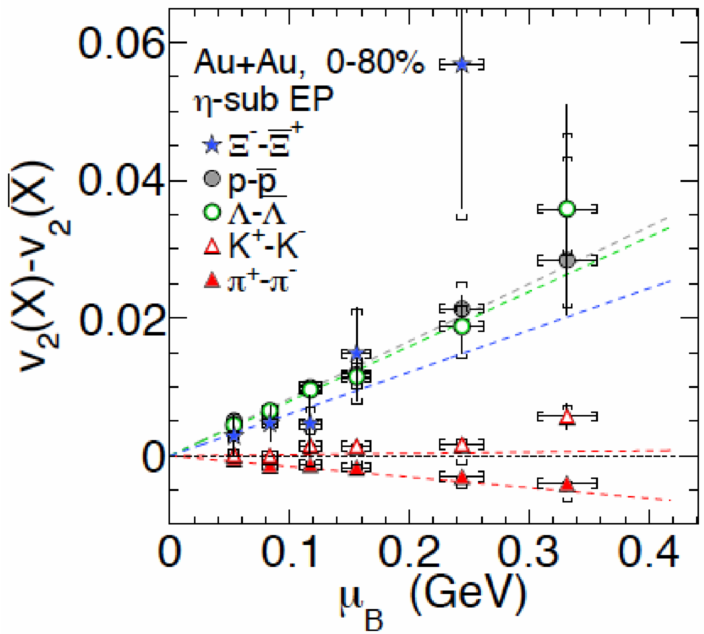
Critical ε_c from lattice ~0.6 GeV/fm^3: lowest energy range explored still expected to be above transition region

No guarantee to see turn-off of QGP: Lets reinvestigate the “turn-off of the QGP” signatures

Disappearance of QGP? NCQ



Baryon meson splitting only broken for negative particles; NCQ scaling persists for positive particles



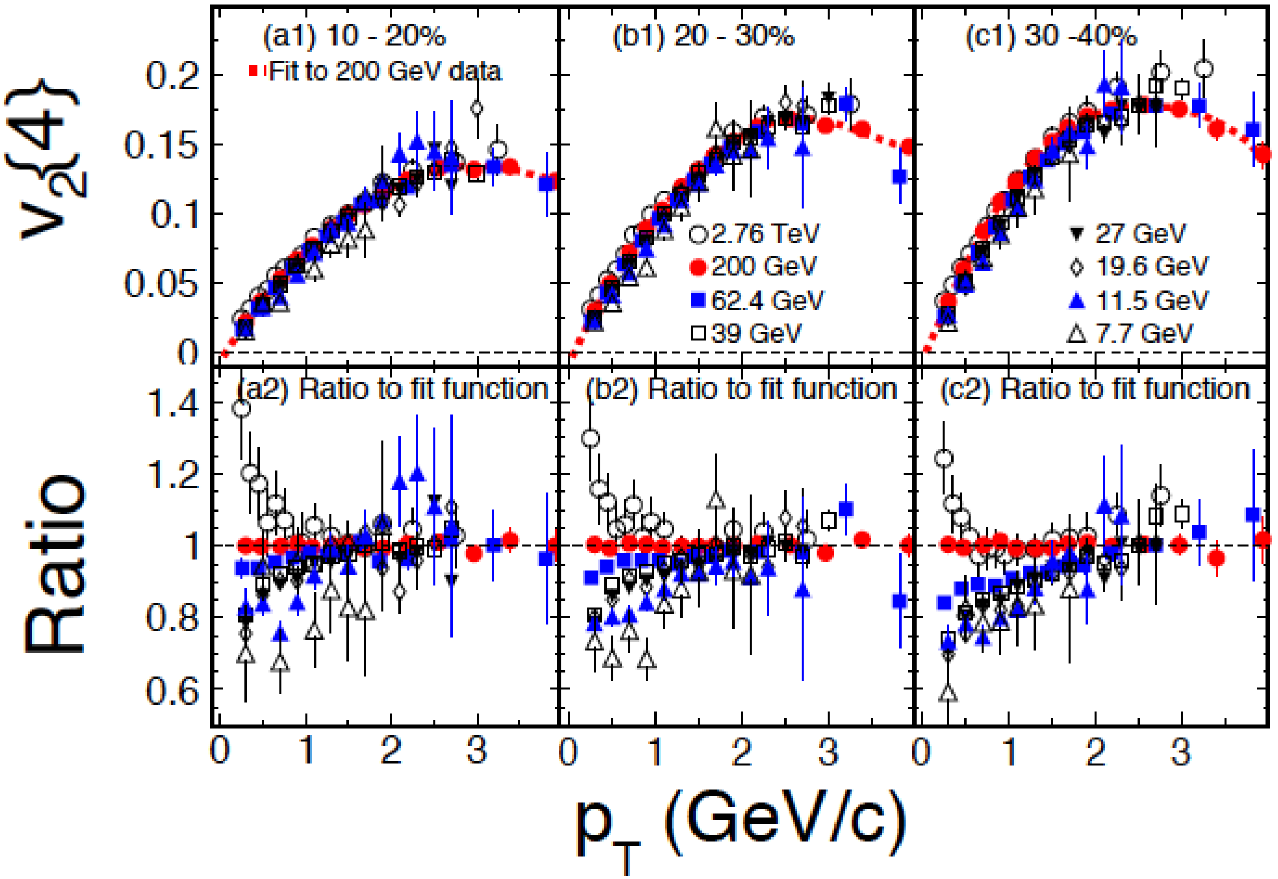
The difference between + & - is linearly with μ_B: that doesn't require or even suggest QGP turn off

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)

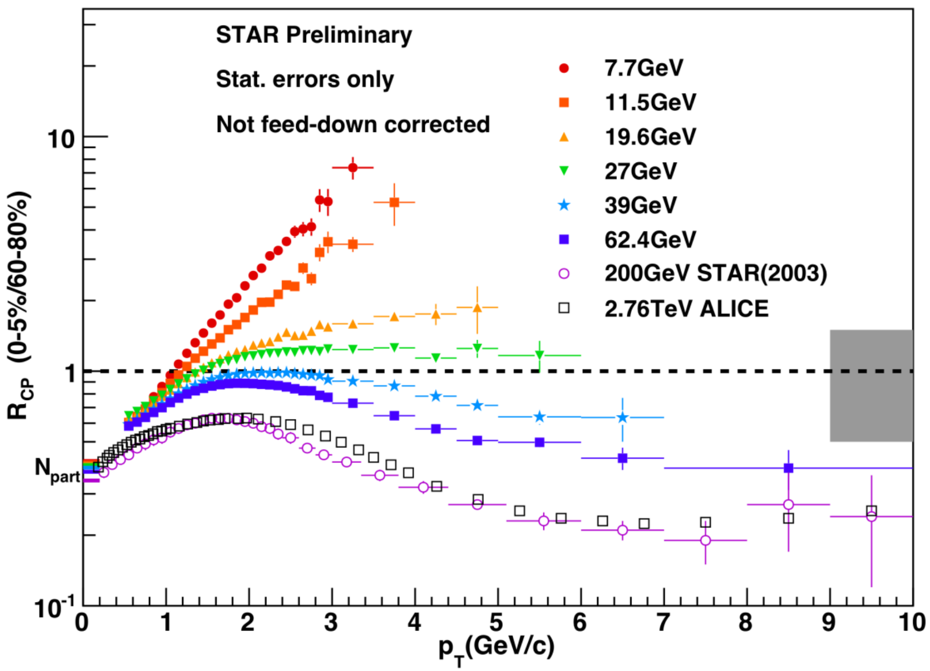
$v_2\{4\}$

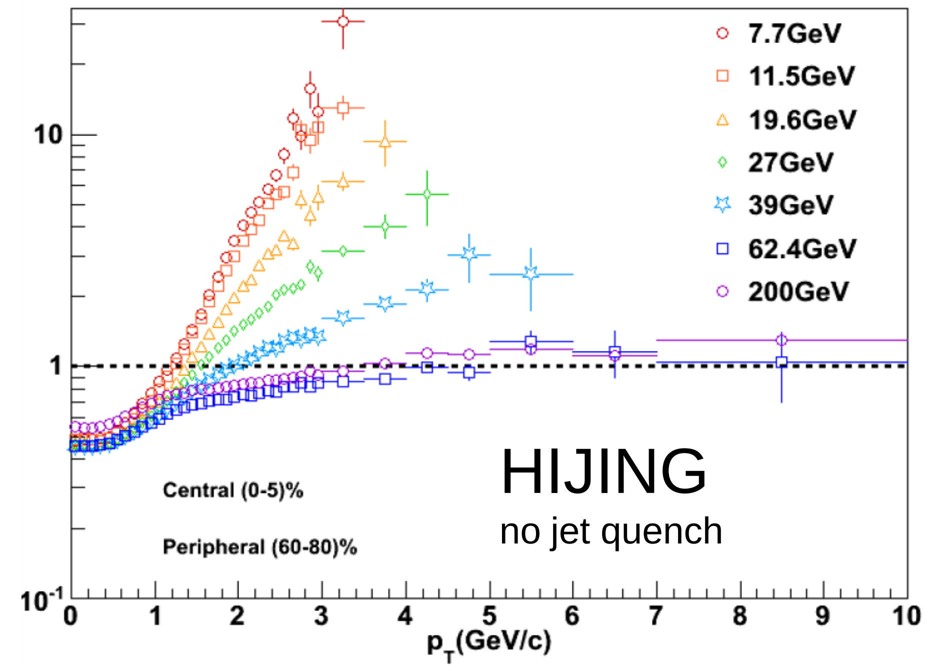
Phys.Rev. C86 (2012) 054908



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

QGP Opacity: Rcp



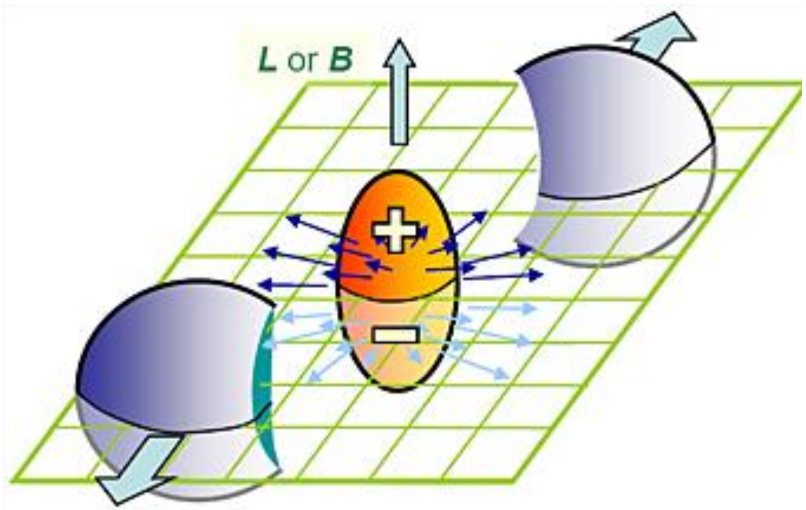


At low s_{nn} the spectrum is very steep; small initial state effects or flow cause huge distortions that dominate R_{CP}

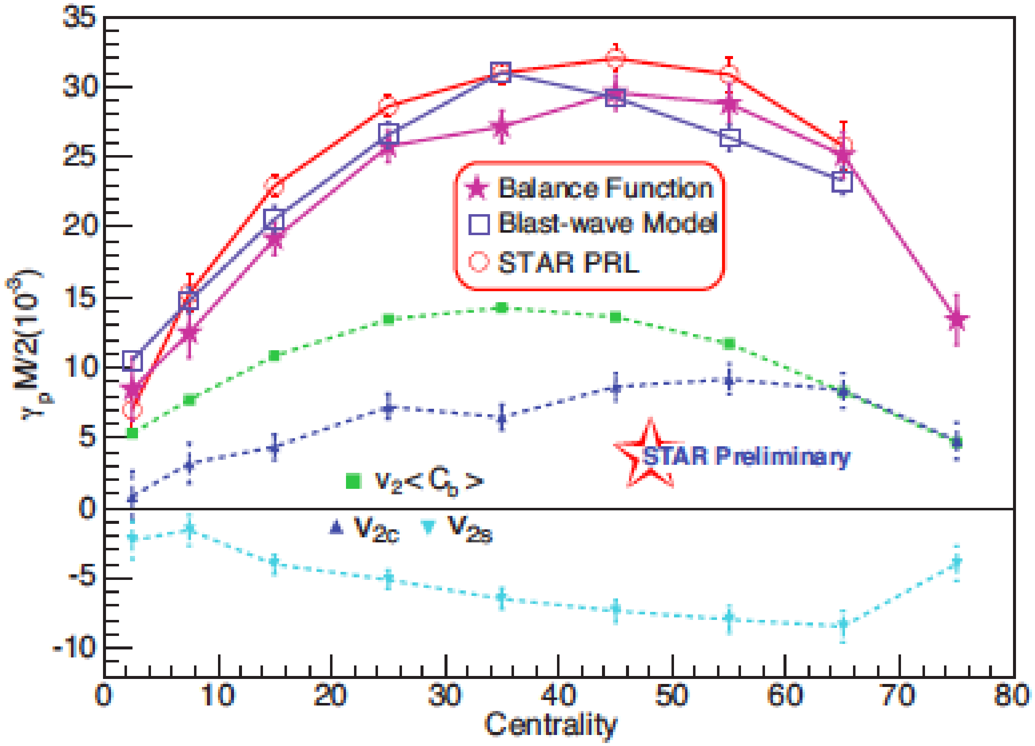
For a steep spectrum, tickling the particles causes R_{CP} to go to infinity: opacity may still be there but can’t be easily probed.

“Disappearence” of opacity is NOT established.

Disappearence of QGP? LPV



Event-by-event charge separation

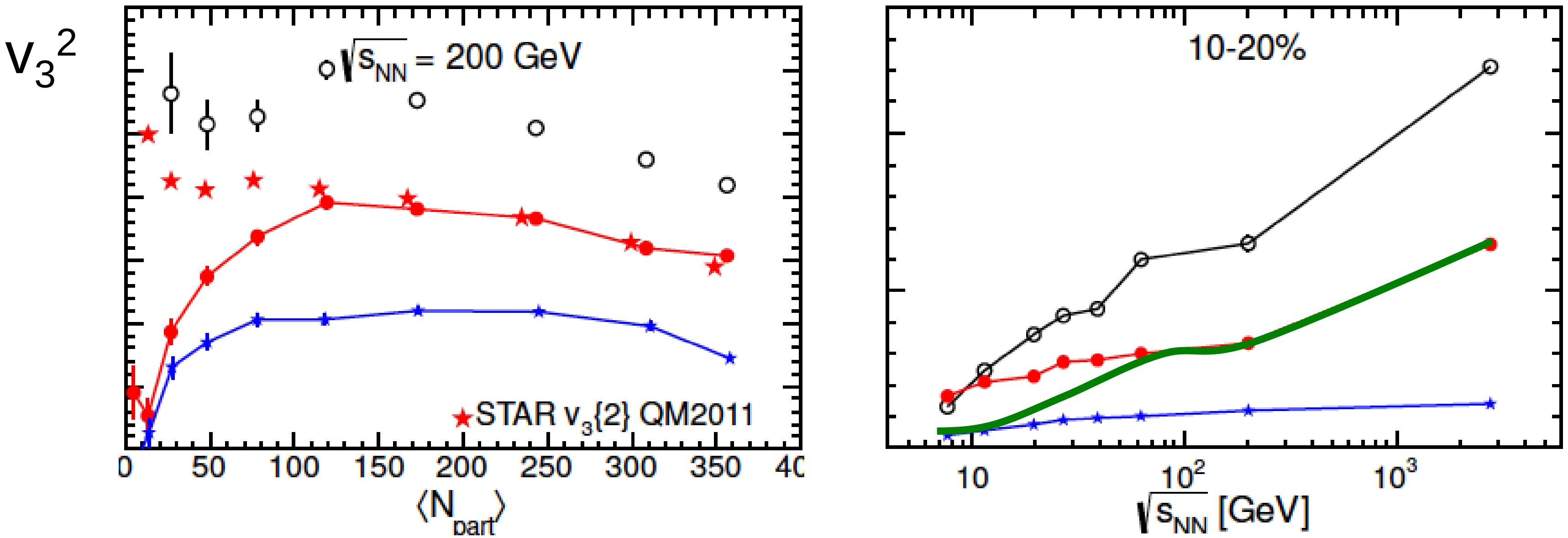


Charge seperation (thought to be related to parity violating regions in a QGP) “disappears” below ~19.6 GeV

But models not relying on parity violation do a better job of describing the measurements at full RHIC energy

Beam Energy Dependence of v_3

D. Solanki et. al.: Physics Letters B 720 (2013), pp. 352-357

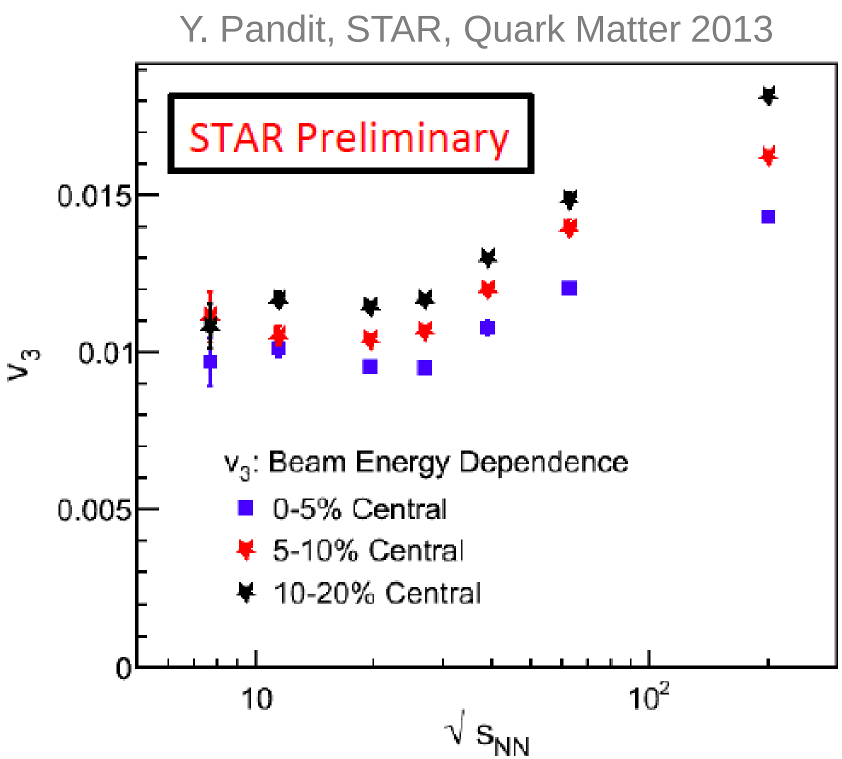


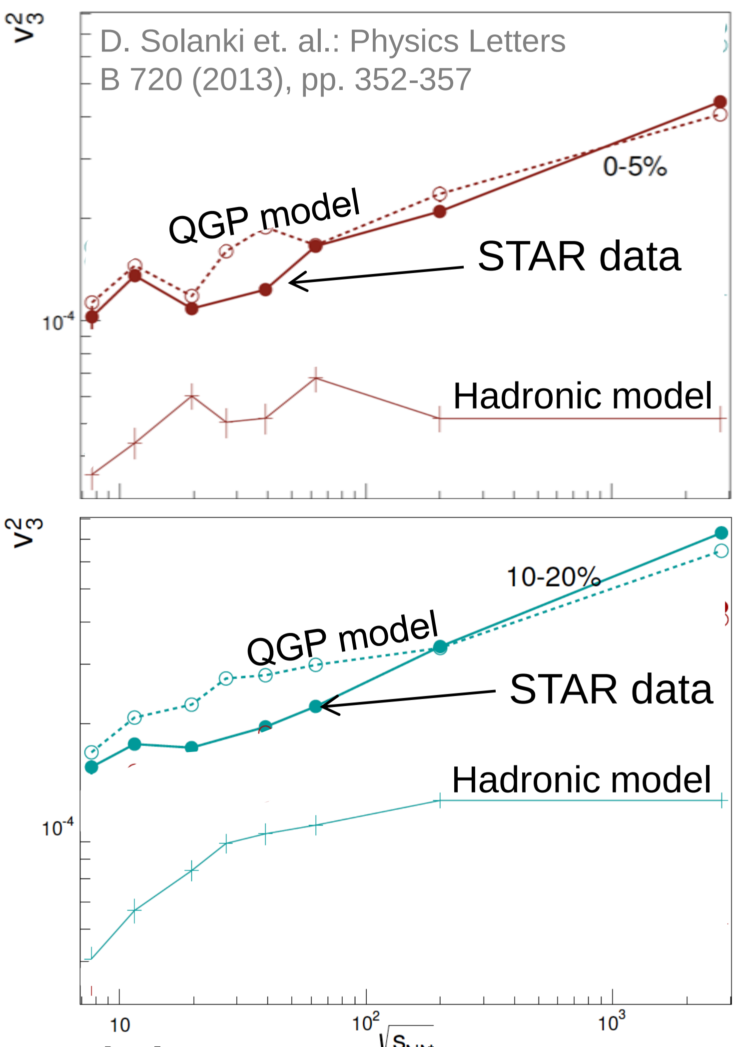
AMPT with string melting can be tuned to match v_n at 200 GeV

When QGP is gone, one might expect data to match Default (hadronic) model

Do we see anything like that from data?

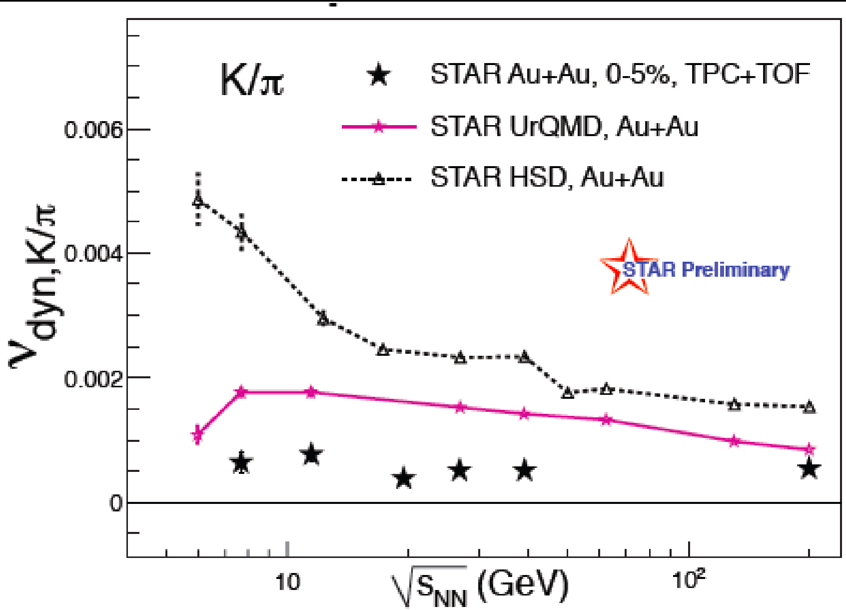
Beam Energy Dependence of v_3

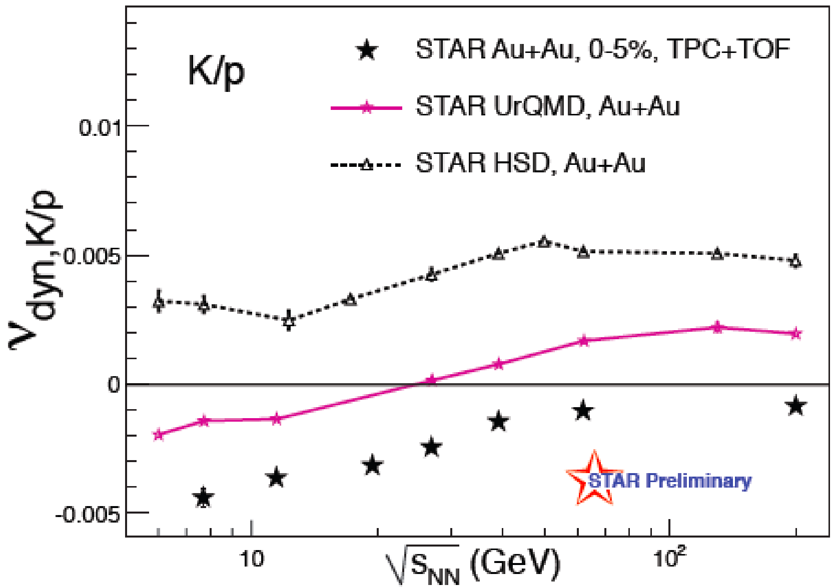




STAR data follows the AMPT QGP model expectations throughout the measured energy range

Particle Ratio Fluctuations

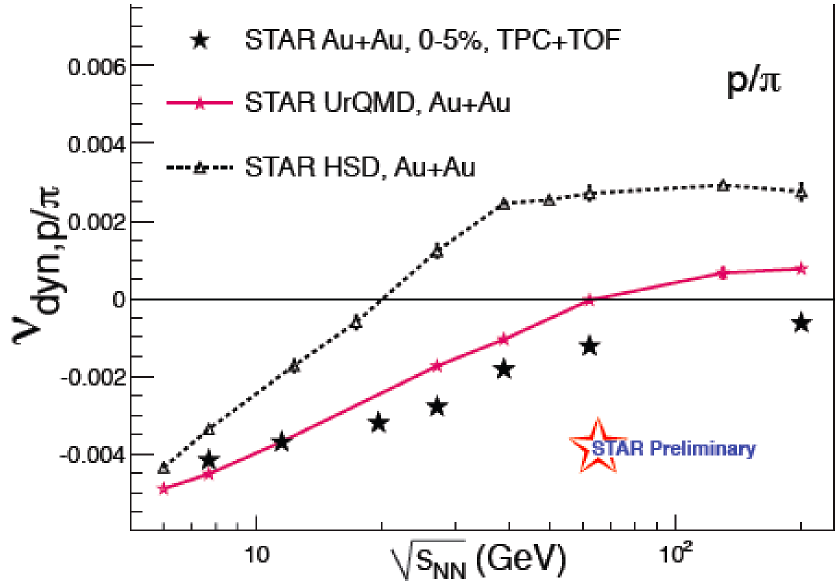




Measurement of event-to-event variation of particle ratios:

For 1st order phase transition: enhanced fluctuations

Observed energy dependence: monotonic along with other fluctuation observables



Have we seen the disappearence?

Estimates suggest sufficient energy densities may be created even at 7.7 GeV

Some of our key QGP signatures have changed

- Quark number scaling of v_2 (meson vs baryon)
- High p_T suppression R_{CP}
- Charge seperation across the reaction plane

but they changed in ways not obviously related to the turn of QGP

Many observables don’t show a transition to hadronic expectations or non-monotonic behavior

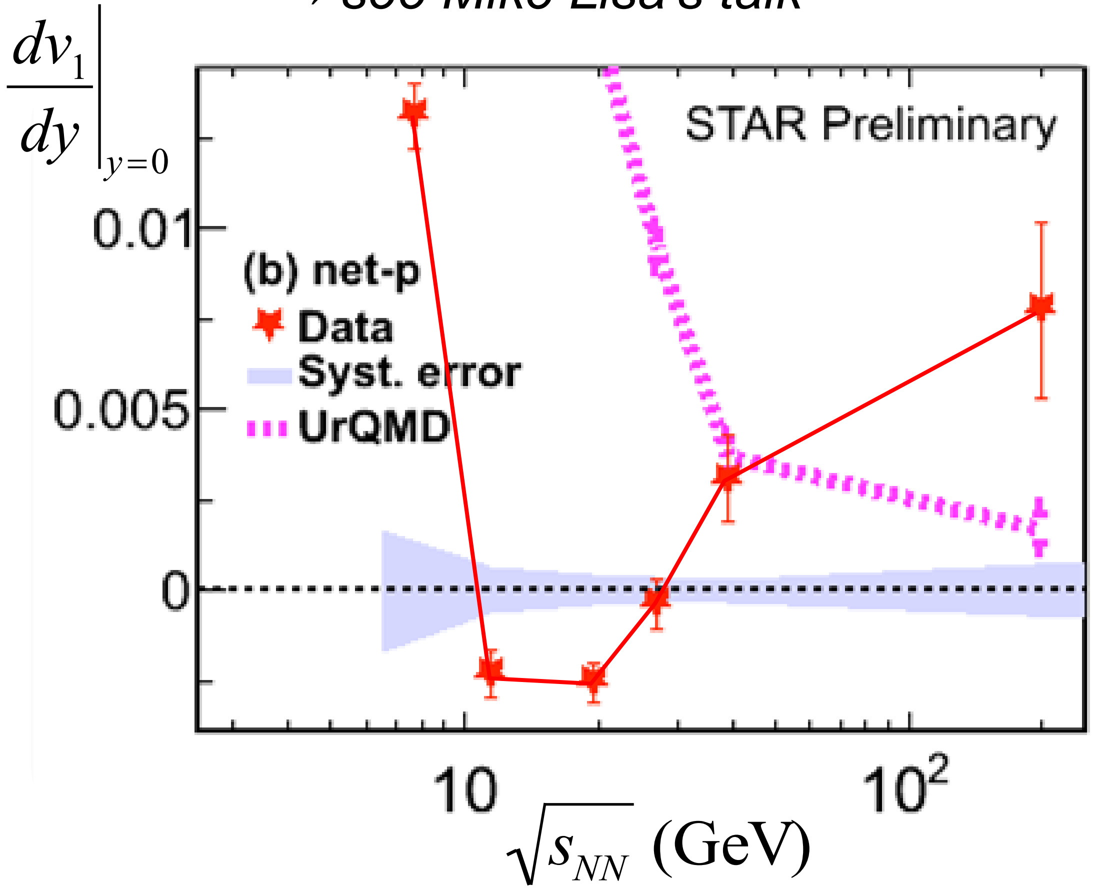
- $v_2\{4\}(p_T)$
- v_3
- various fluctuations

Is there evidence that DOES suggest we’ve turned of the QGP?

To Be an Optimist

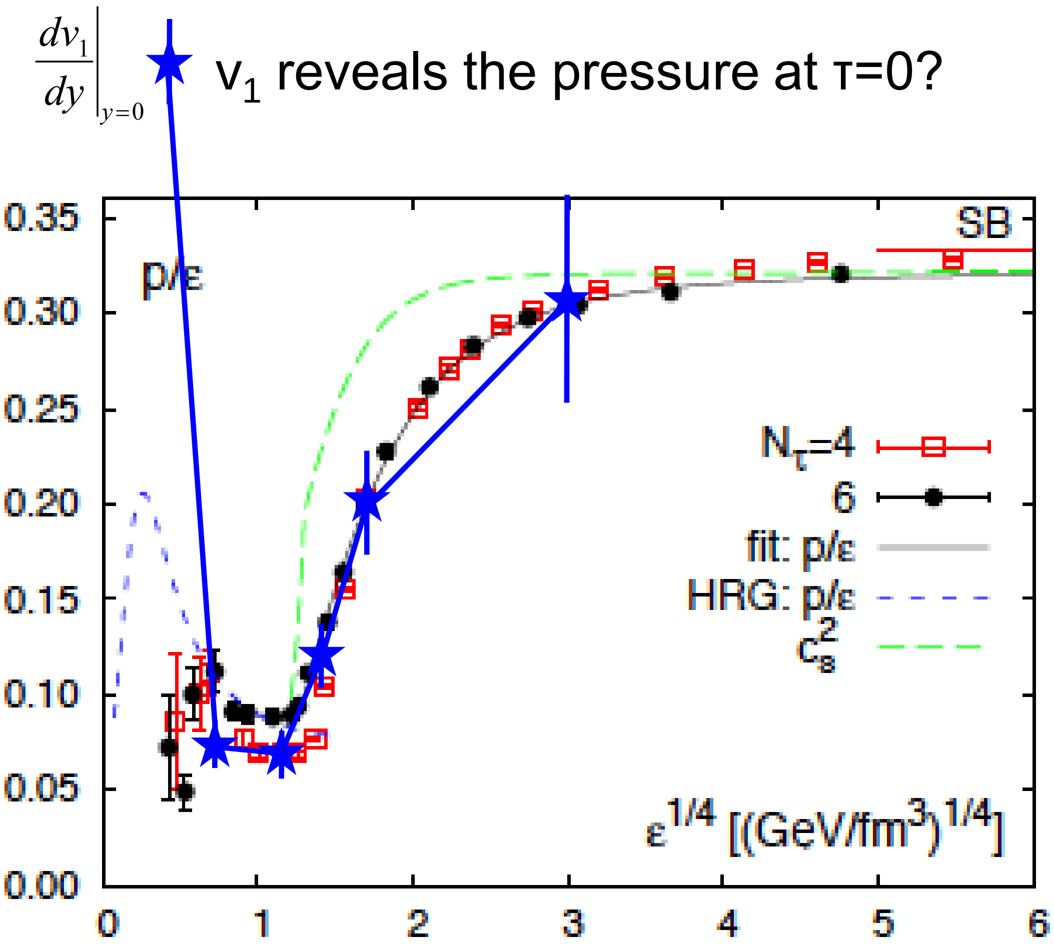
v_1 samples the pressure at the earliest moments

→ *see Mike Lisa's talk*



The one observable for which the only explanation *I know of* relies on the turn-off of the QGP

To Be an Optimist



dv_1/dy for net protons very well may be the smoking gun we've been looking for. It deserves more theoretical attention!

Conclusions

In planning the 1st phase of the Beam-Energy-Scan; we listed 3 signatures for the turn off of the QGP: NCQ, Rcp, LPV

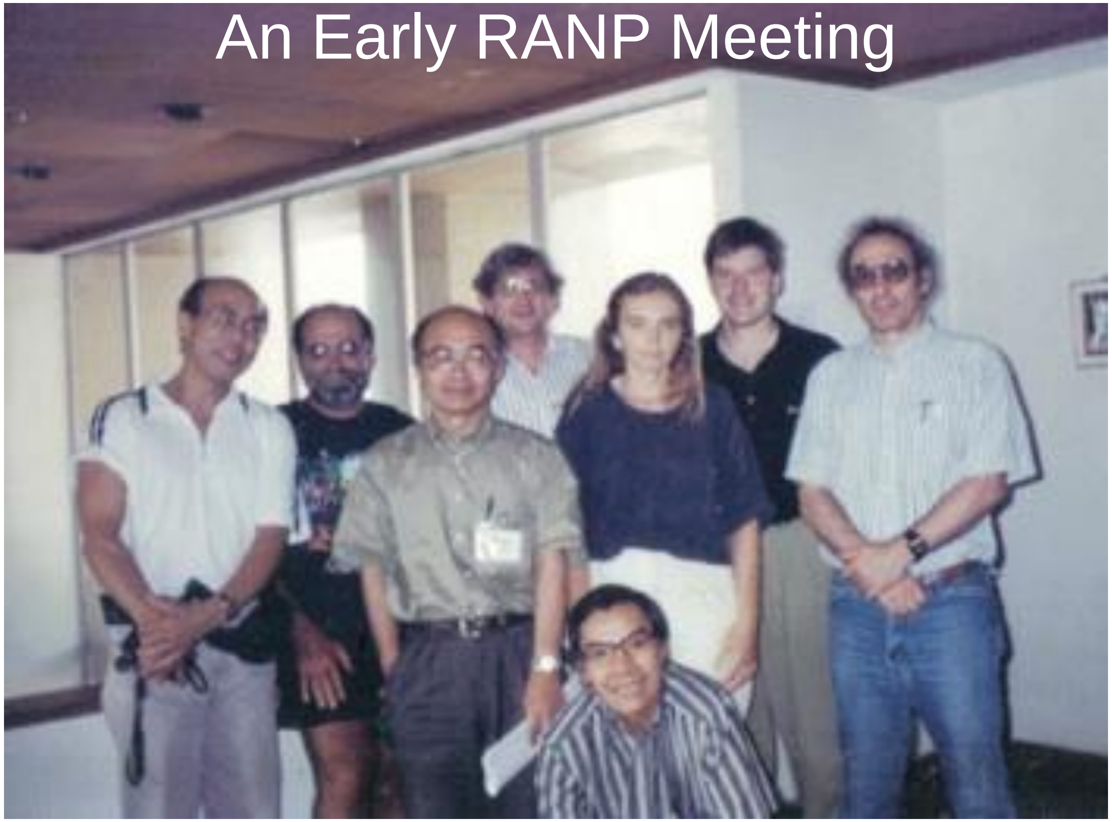
Each changed, but they changed in a way that is still consistent with a QGP all the way down to $\sqrt{s_{nn}}$=7.7 GeV

Not yet clear we've reached a QGP-free system at lowest $\sqrt{s_{nn}}$

BUT: dv_1/dy for net protons may be the smoking gun we've been looking for: Deserves more attention to better tie it to a softening in the EOS

Experimentally, we should study the energy region between $\sqrt{s_{nn}}$ of 10 and 30 (mixed phase?) GeV more closely in BESII

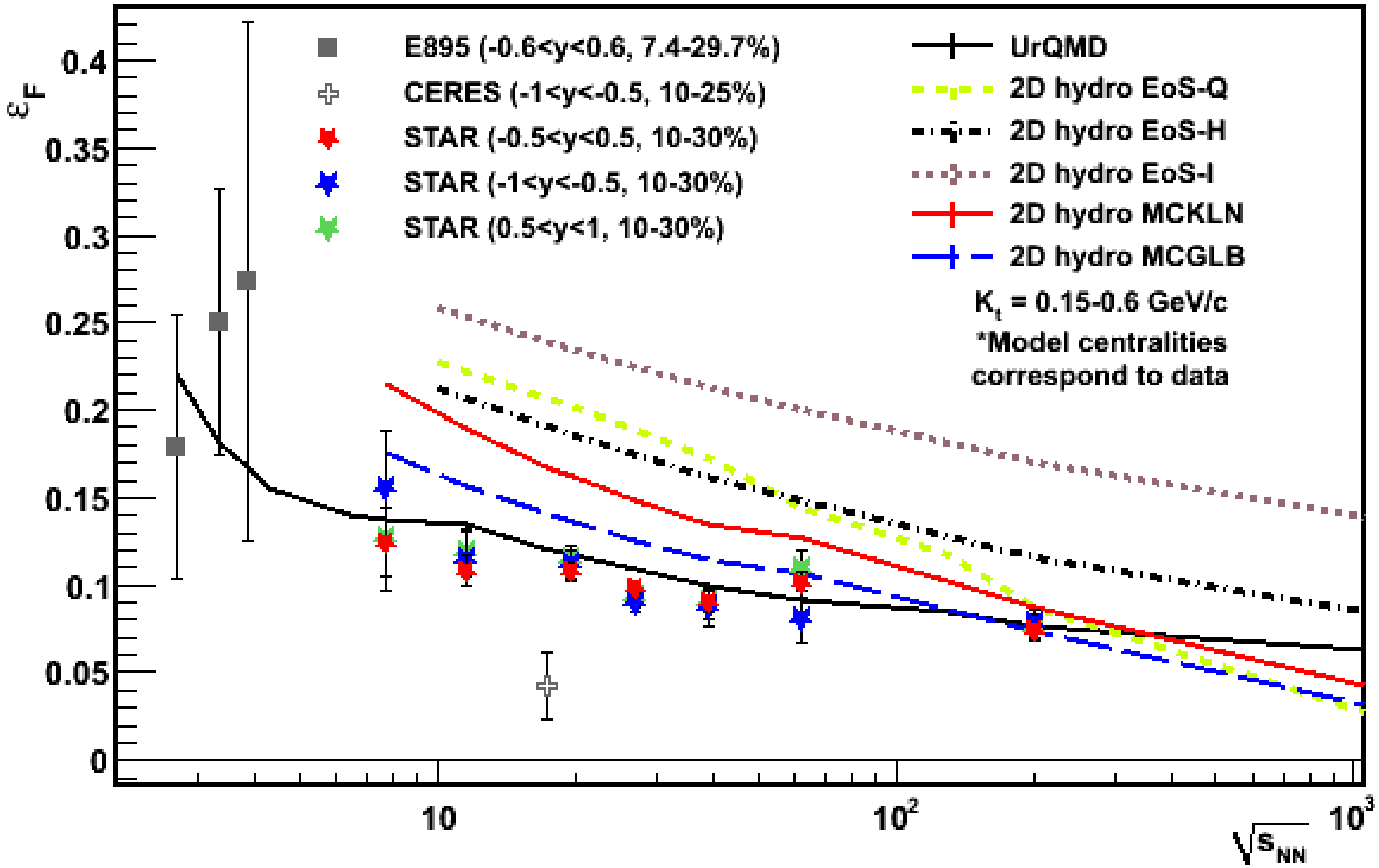
In Conclusion



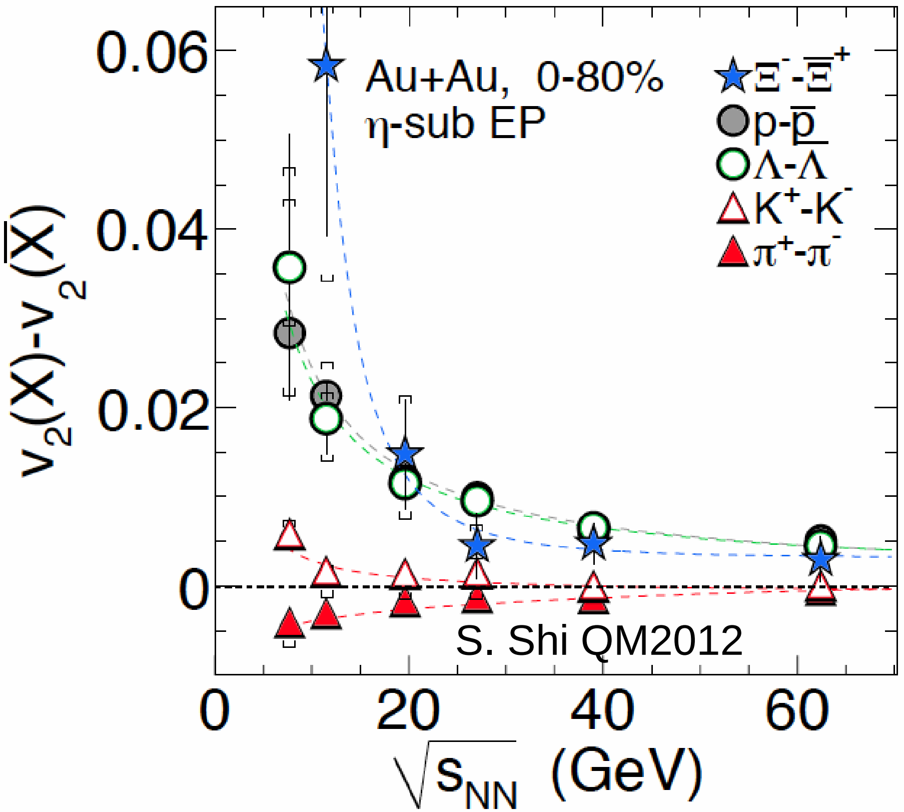
I just want to say…

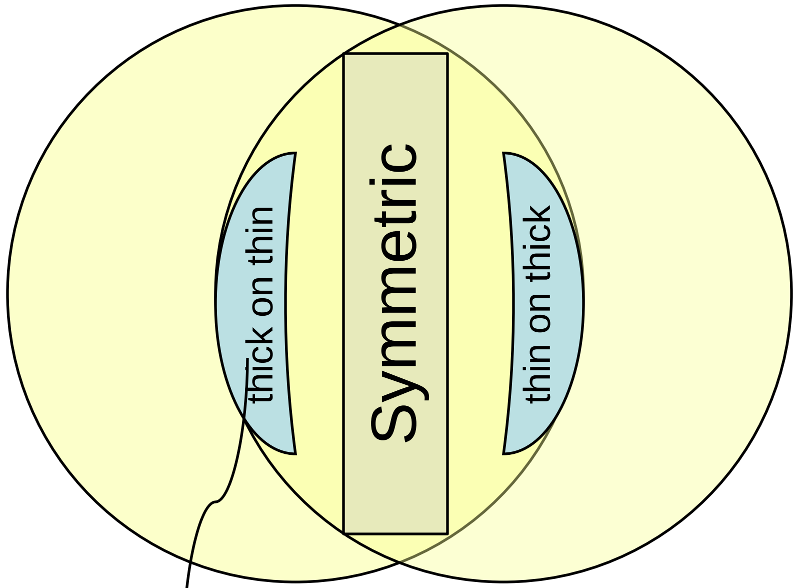
~~Nice legs Larry!~~ Happy Birthday Takeshi

Final eccentricity



Strong μ_B Dependence of Flow





transported quarks: larger v_2?

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

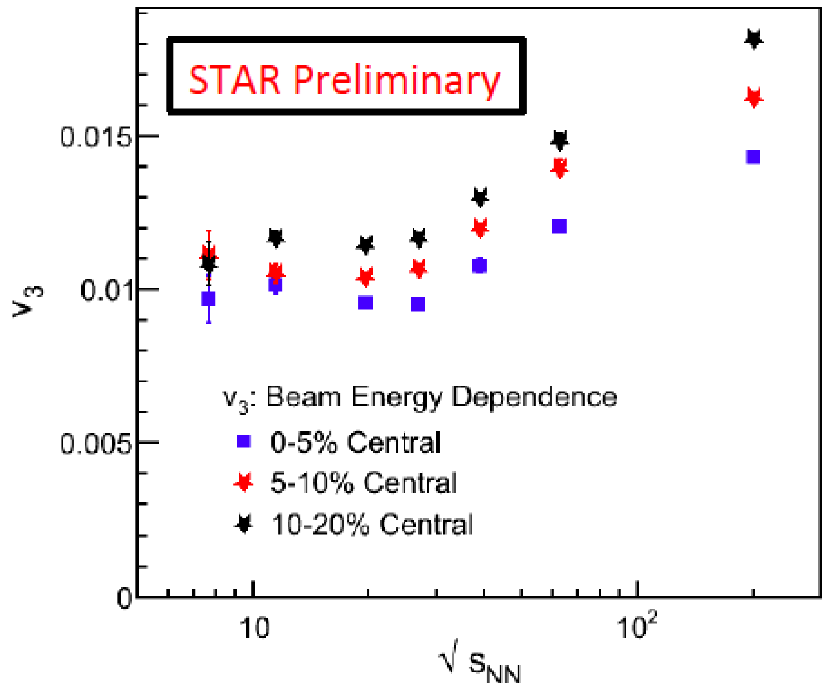
Relevance of strong mean fields? (Greco et al, arXiv:1201.4800)

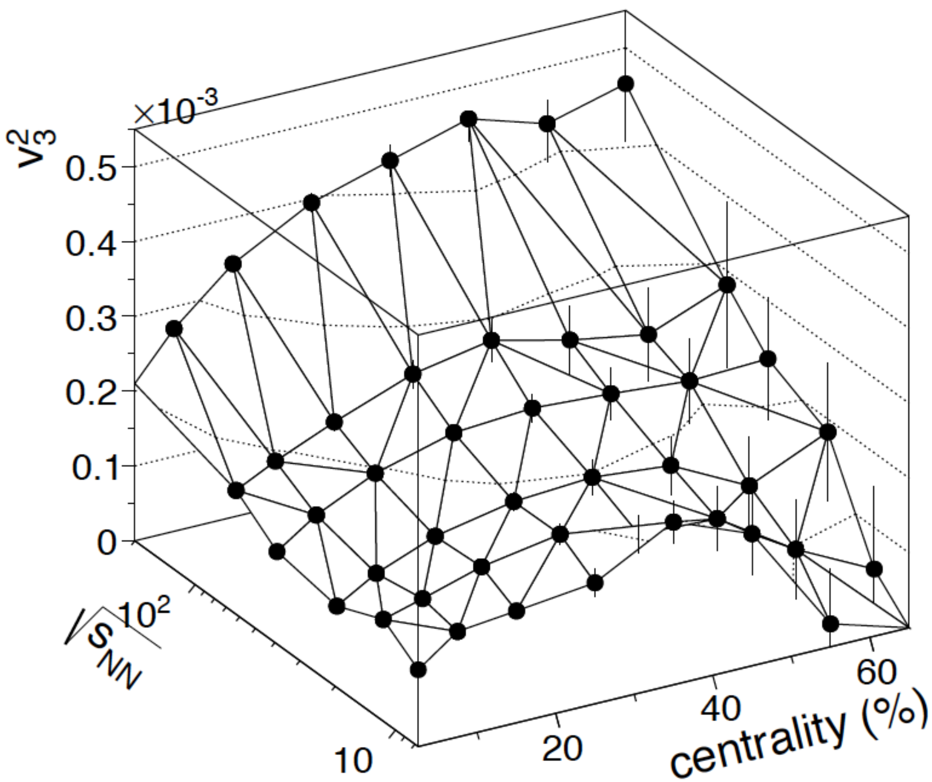
Coalescence with transported quarks? (See John Campbell's Talk)

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

Third Harmonic

Y. Pandit: QM2012



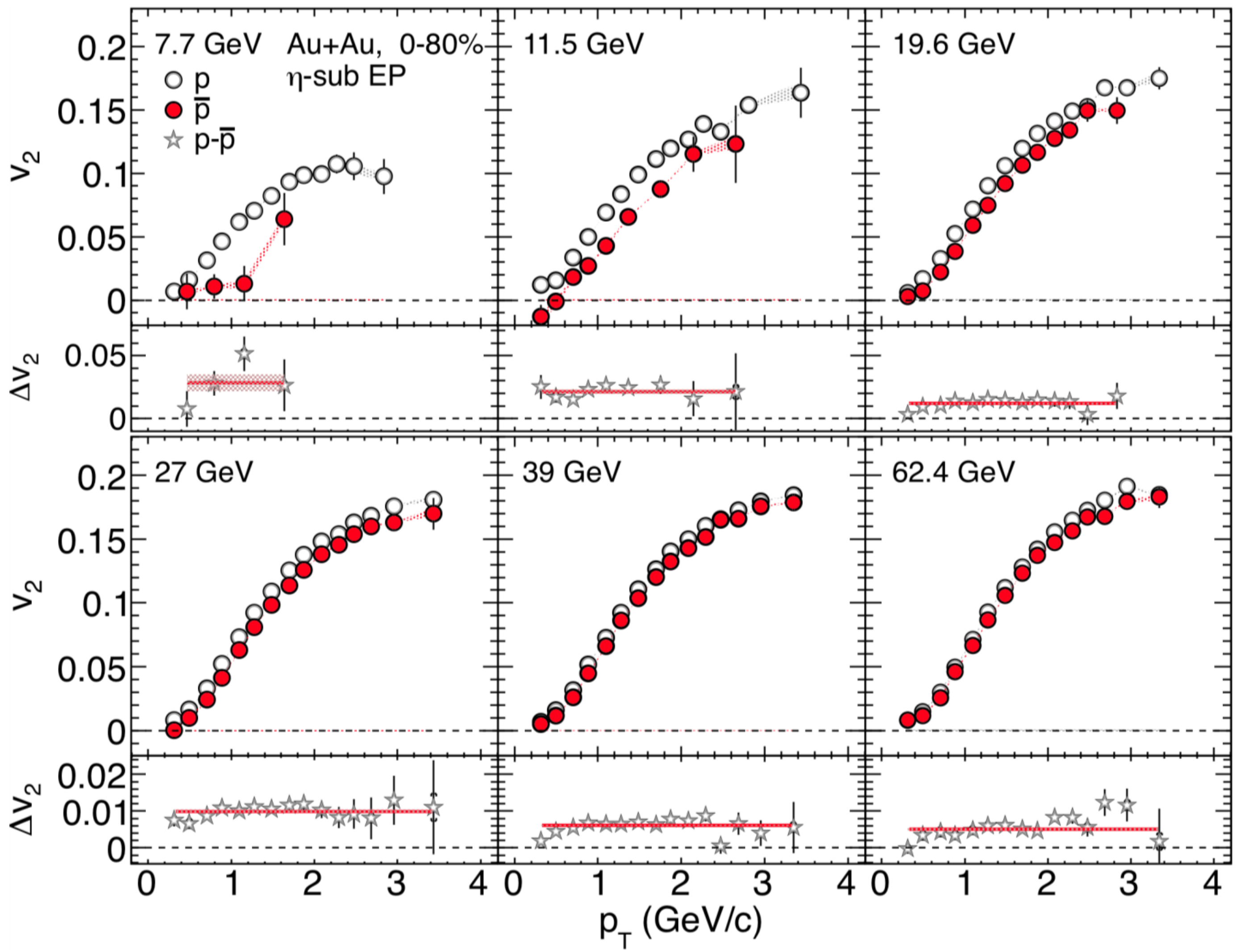


Observable sensitive to interactions at earliest moments

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

AMPT requires a QGP phase at all energies to match magnitude

Particle/Antiparticle Dependence



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

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 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**

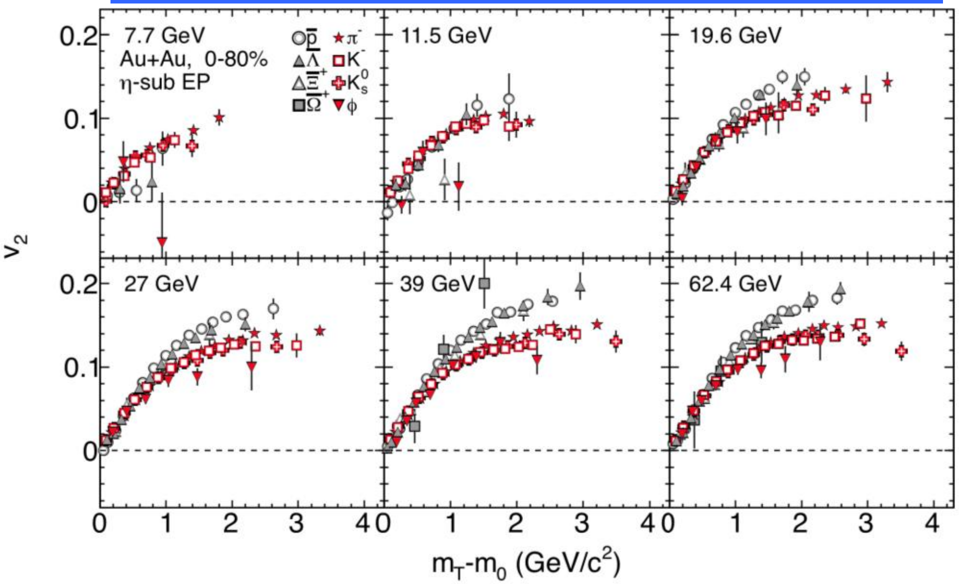
* Di-electron measurements below 19.6 GeV are not planned
** Estimates are based on electron cooling upgrade currently under development and are approximate without electron cooling, the program would require ~150 weeks

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

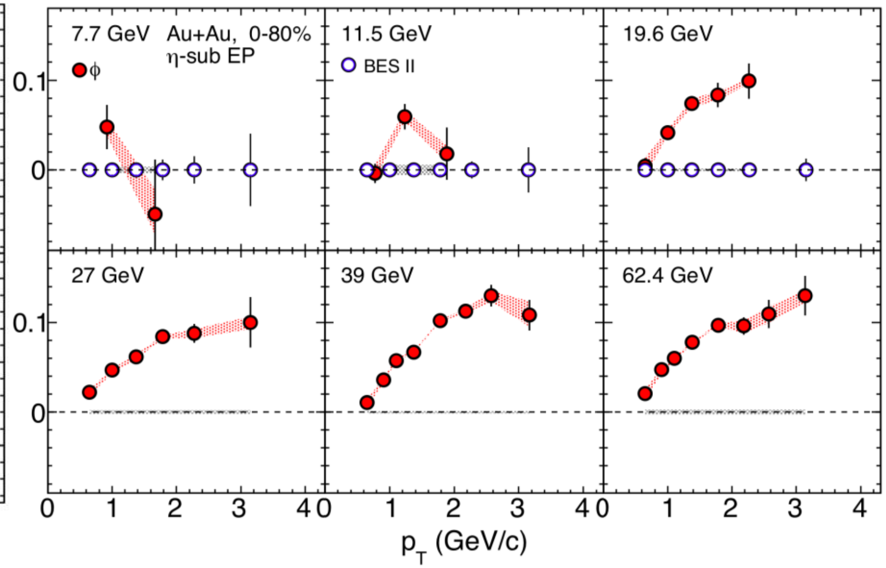
Also In Need of More Data

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



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

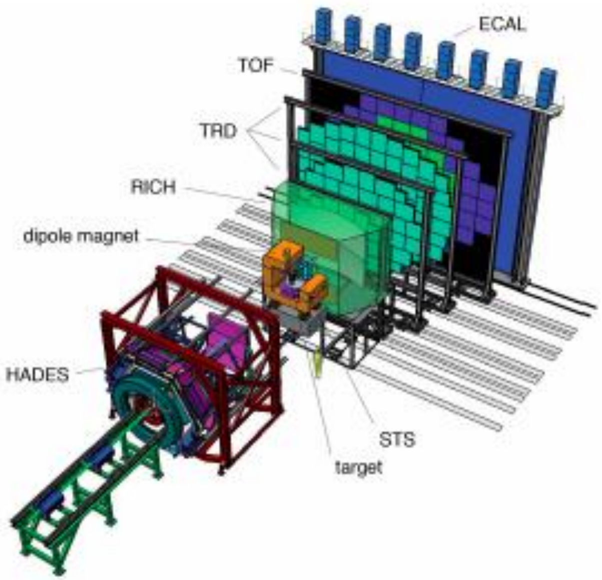
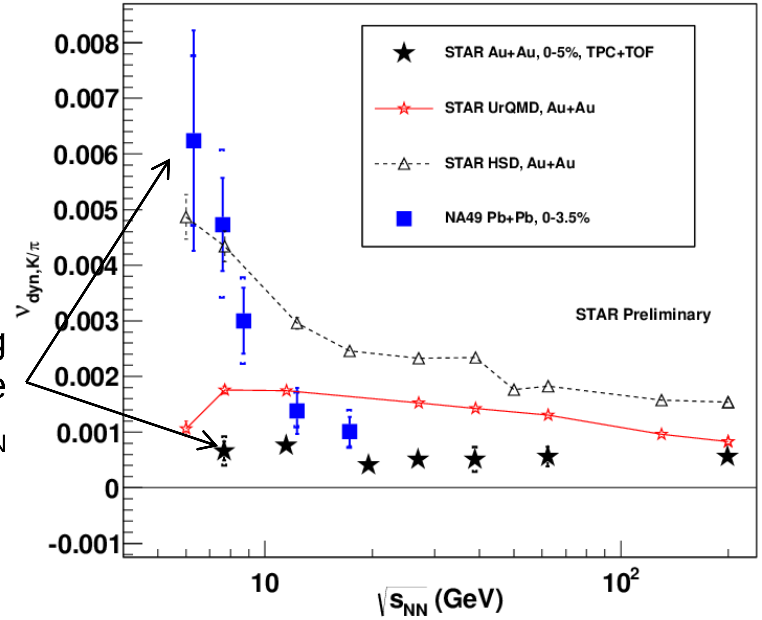


Fig. 1.5 Sketch of the planned Compressed Baryonic Matter (CBM) experiment together with the HADES detector.

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

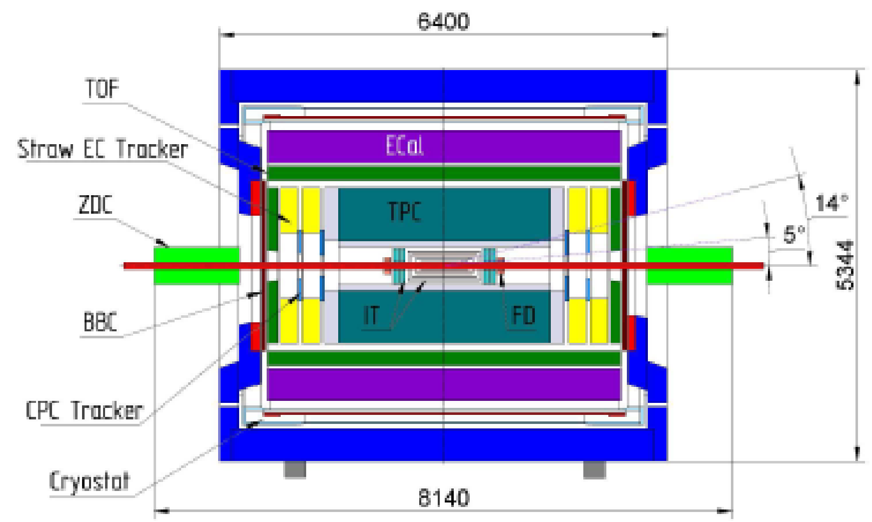


Fig. 2.2: Cutaway side view of the Central Detector of MPD with based dimensions.

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