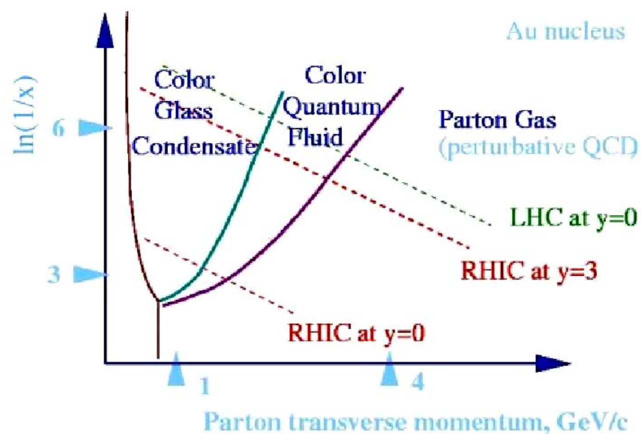
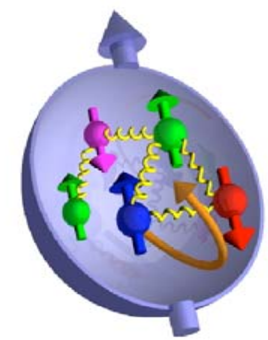
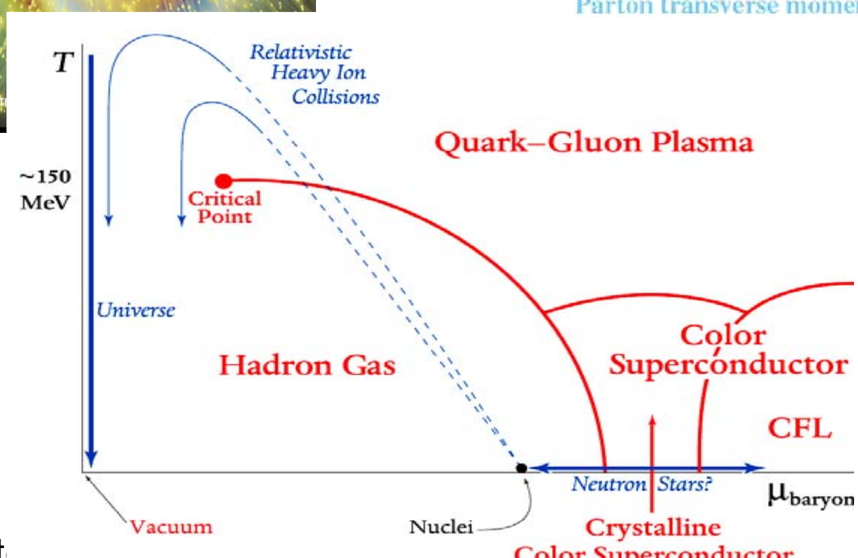
Phases of QCD Matter

2007 JLab Users' Meeting





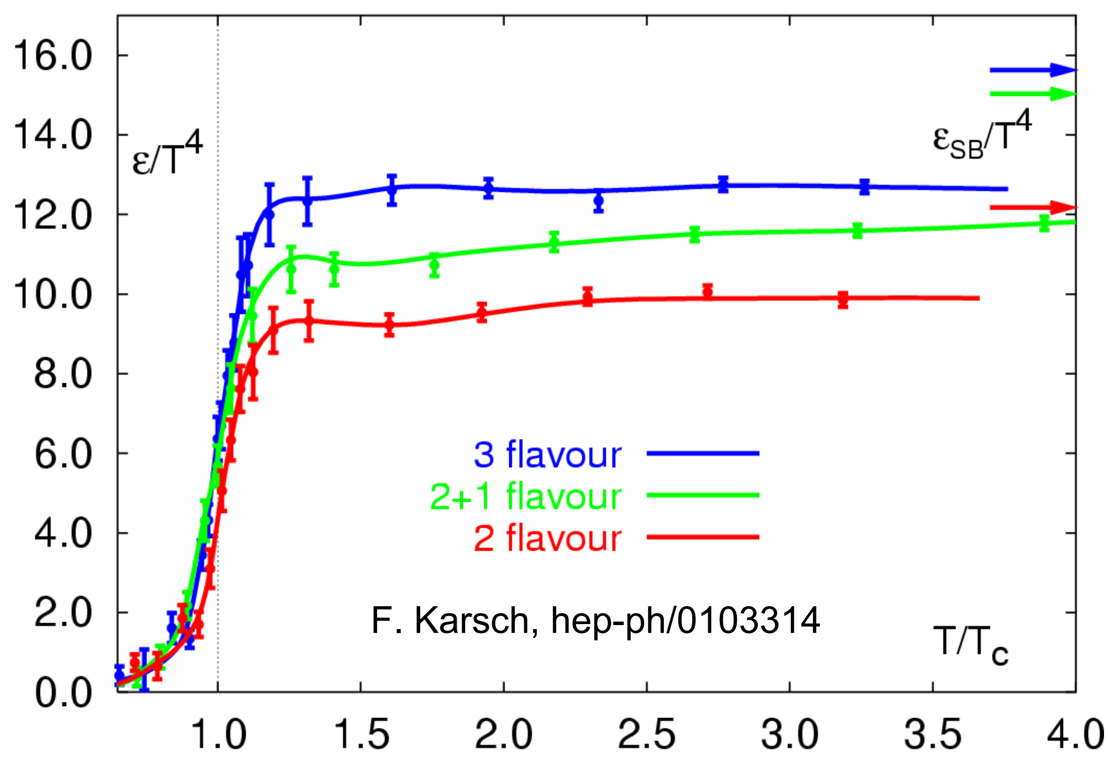


Carl A. Gagliardi
Texas A&M University

RHIC: the Relativistic Heavy Ion Collider

- Search for and study the Quark-Gluon Plasma
- Explore the partonic structure of the proton
- Determine the partonic structure of nuclei

What we expected: lattice QCD at finite temperature



Ideal gas (Stefan-Boltzmann limit)

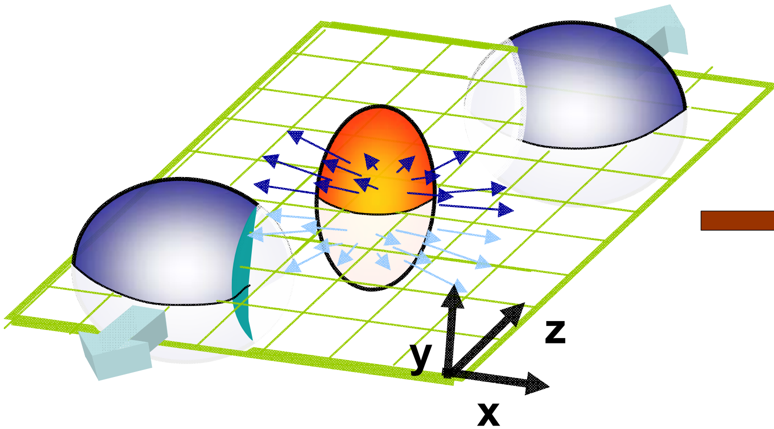
Critical energy density: $\varepsilon_C = (6 \pm 2) T_C^4$

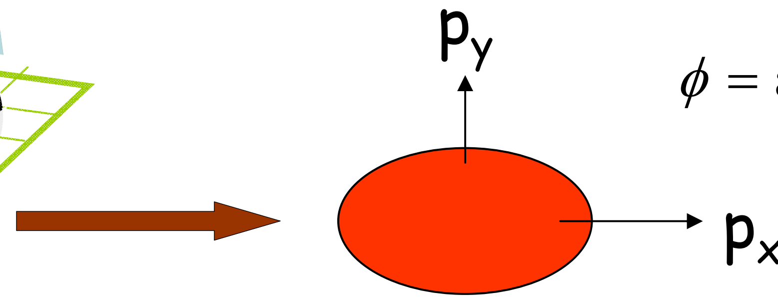
$T_C \sim 175$ MeV $\Rightarrow \varepsilon_C \sim 1$ GeV/fm^3

What we found: four fundamental new discoveries

- Enormous collective motion of the medium, consistent with near-zero viscosity hydrodynamic behavior
  - Very fast thermalization
  - A "perfect liquid"
- Jet quenching in the dense matter
  - Densities up to 100 times cold nuclear matter and 15 times the critical density from lattice calculations
- Anomalous production of baryons relative to mesons
  - Strongly enhanced yields of baryons relative to mesons
  - Scaling of yields and collective motion with the number of valence quarks
  - Hadrons form by constituent quark coalescence
- Indications of gluon saturation in heavy nuclei
  - Relatively low multiplicities in Au+Au collisions
  - Suppressed particle production in d+Au collisions

Collective motion: "elliptic flow"





$$\phi = \operatorname{atan} \frac{p_y}{p_x}$$

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

$$v_2 = \left\langle \frac{p_x^{\ 2} - p_y^{\ 2}}{p_x^{\ 2} + p_y^{\ 2}} \right\rangle$$

Initial coordinate-space anisotropy

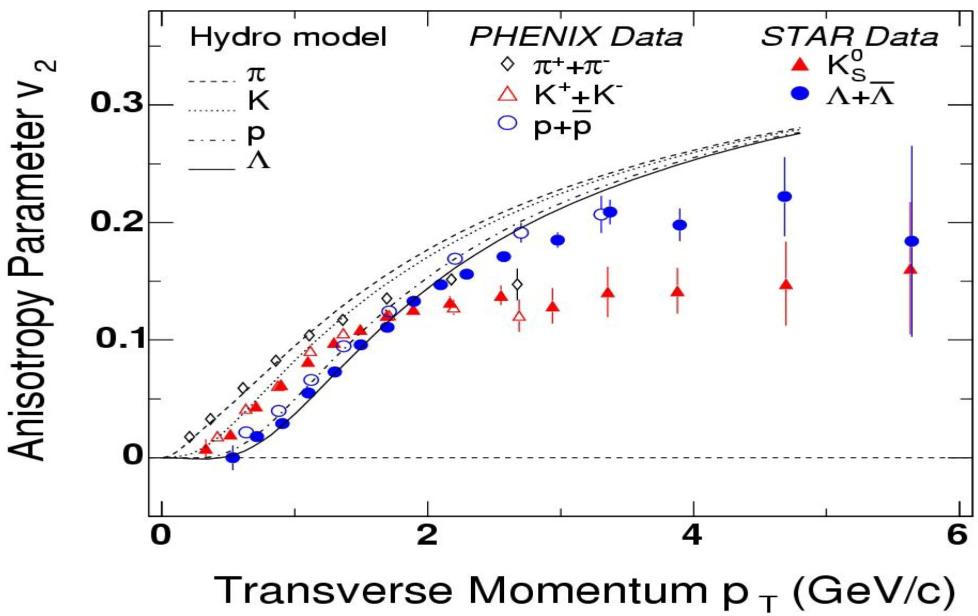
Final momentum-space anisotropy

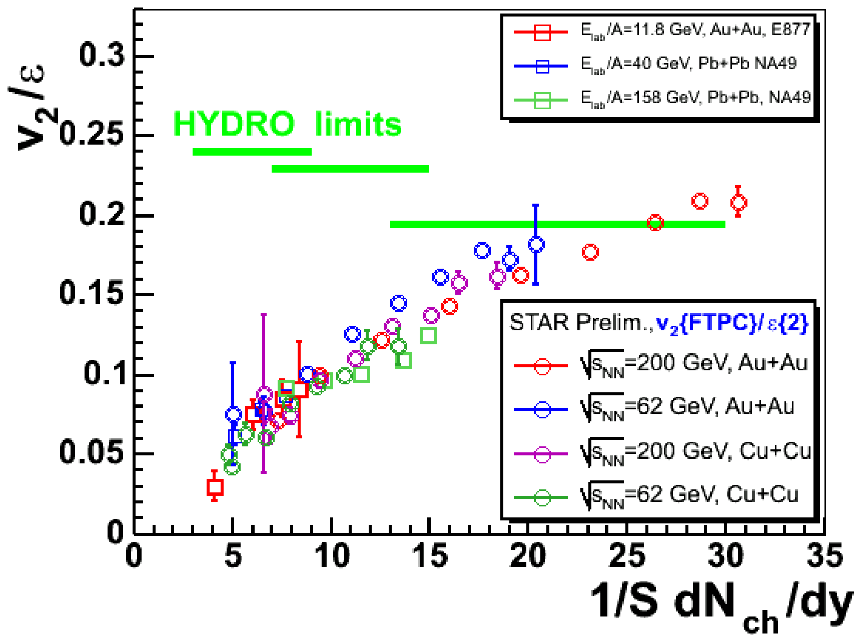
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_R)] + 2v_4 \cos[4(\phi - \Psi_R)] + \ldots$$

Elliptic term

Anisotropy self-quenches, so
v_2 is sensitive to early times

Elliptic flow in the hydrodynamic regime



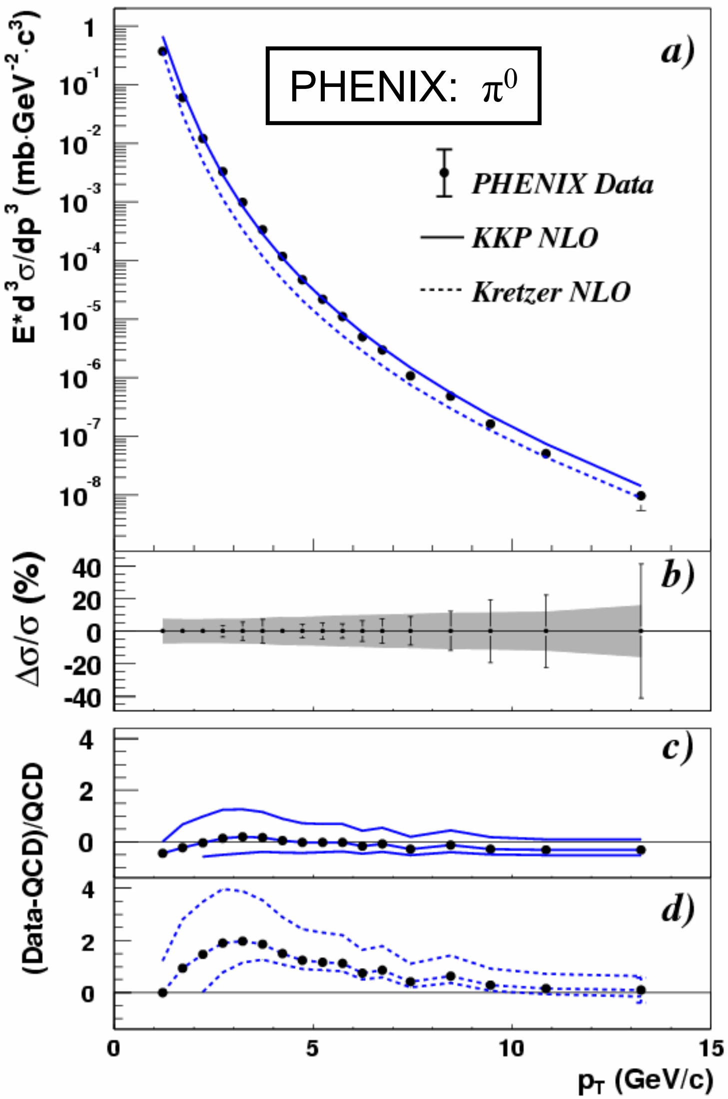


- Hydrodynami ... ed EOS and near-zero viscosity ... $_T$ ~ 1.5 GeV/c
- Elliptic flow sa ...

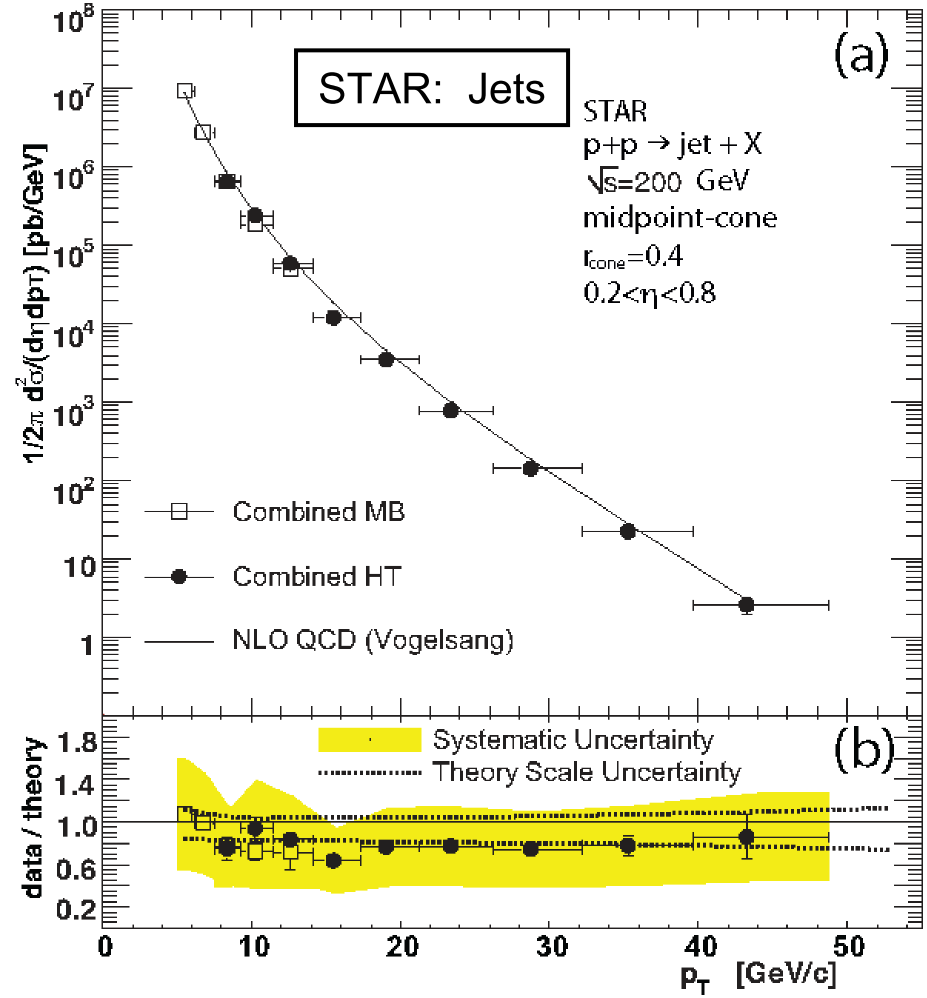
> - **Very rapid thermalization (<1 fm/c)**
> - **Very strong interactions**
> - **A "perfect liquid" ?**

Hard scattering at RHIC and NLO pQCD

PRL 91, 241803

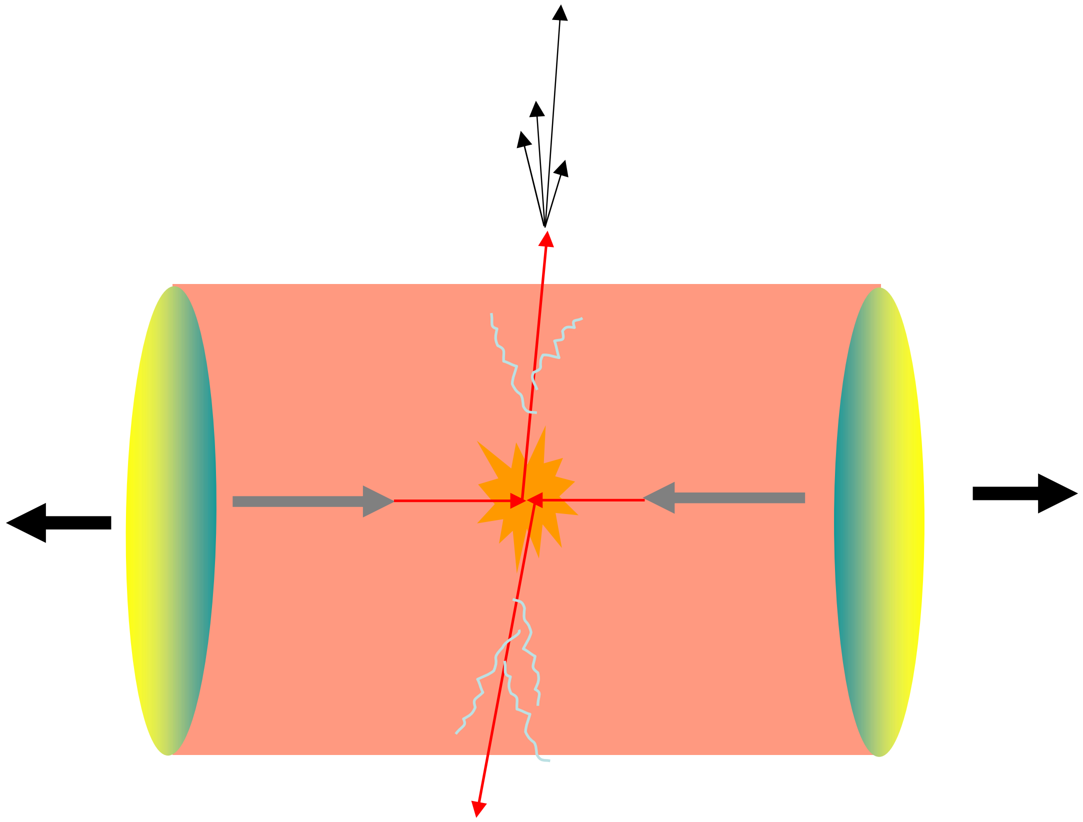


PRL 97, 252001



At 200 GeV, pQCD does a very good job describing high-p_T yields in p+p

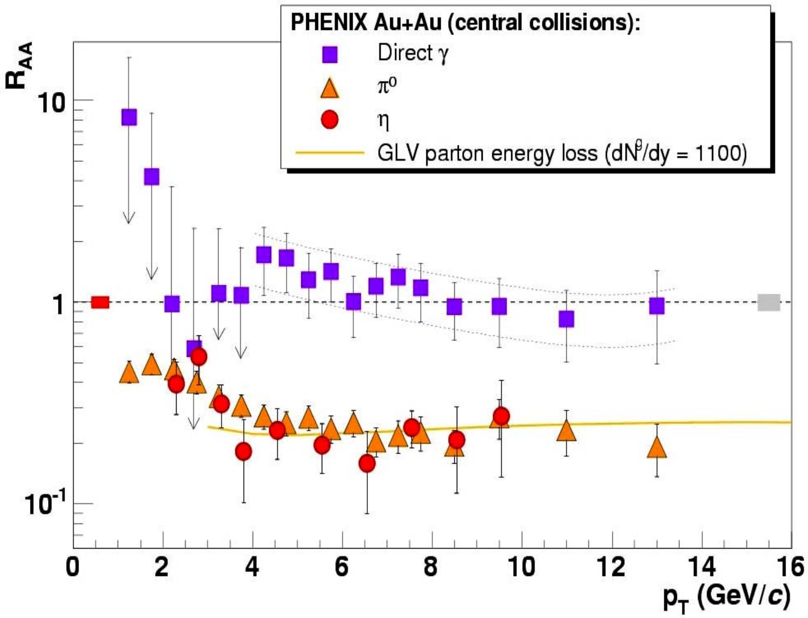
Hard partonic collisions and energy loss in dense matter

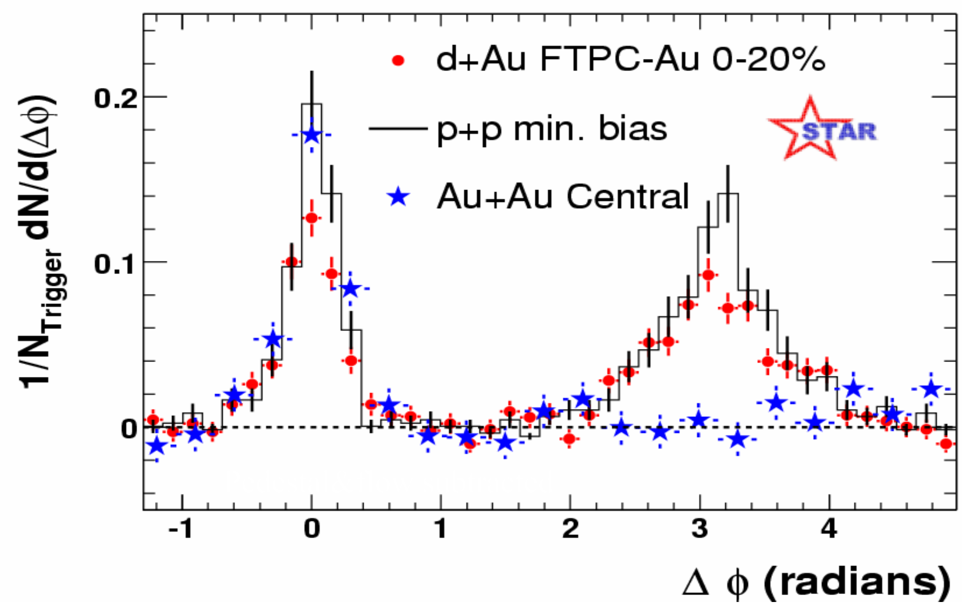


- Embed the hard scattering from a nucleon-nucleon collision into a Au+Au collision
- The final products will interact with the medium

Jet quenching at RHIC

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

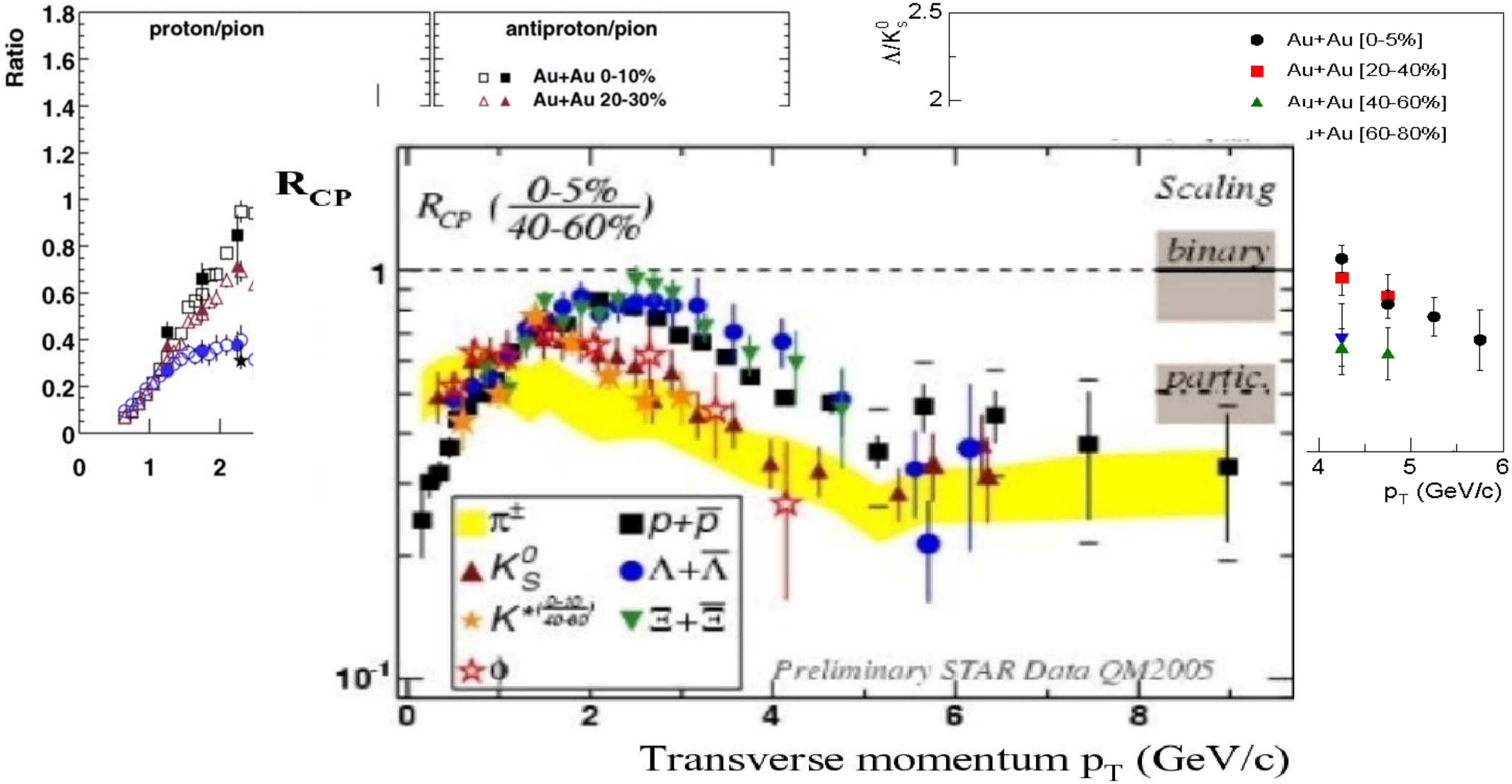




- In central Au+Au collisions:
  - Strong suppression of inclusive hadron production
  - Photons are not suppressed
  - Disappearance of the away-side jet
- d+Au looks like p+p
- Medium density up to 100 times normal nuclear matter

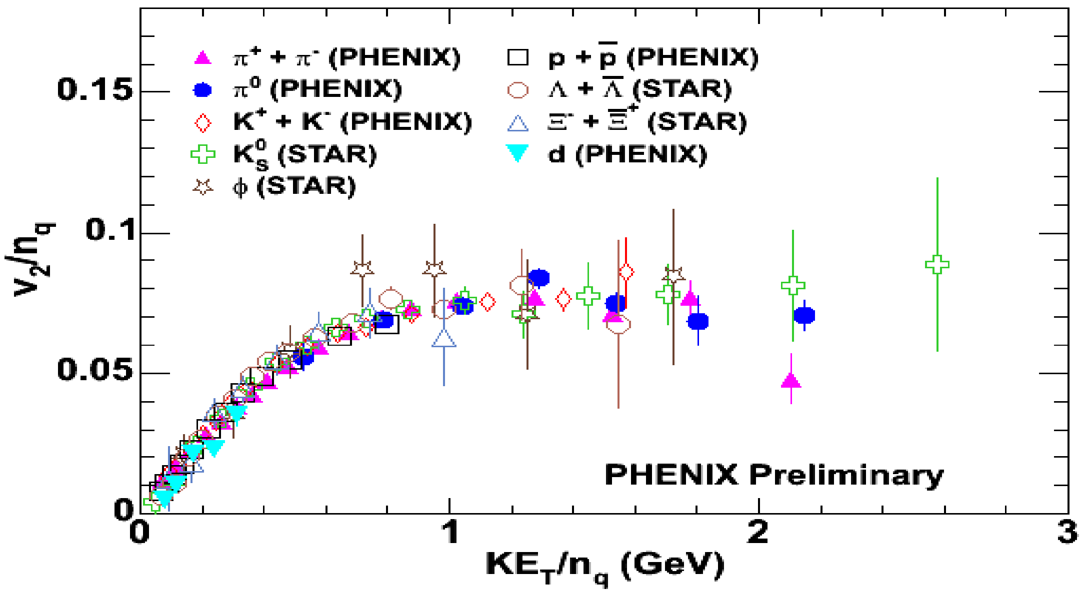
Baryon yields vs. meson yields

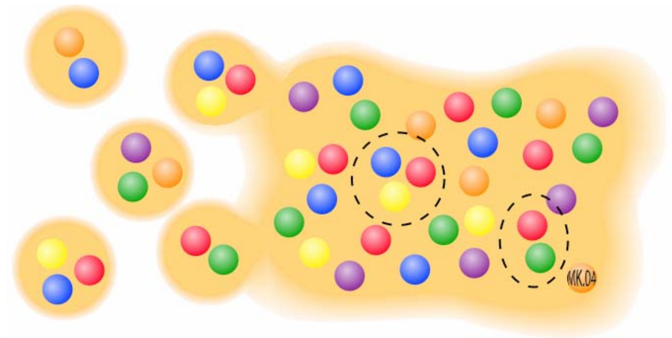
PHENIX: PRL 91, 172301 STAR: nucl-ex/0601042



In central Au+Au collisions, baryons are substantially overproduced relative to mesons at intermediate p_T

Baryon flow vs. meson flow





$$\frac{dN}{d\phi} \propto \left[1 + 2v_2(p_T)\cos(2\phi) + \cdots\right]$$

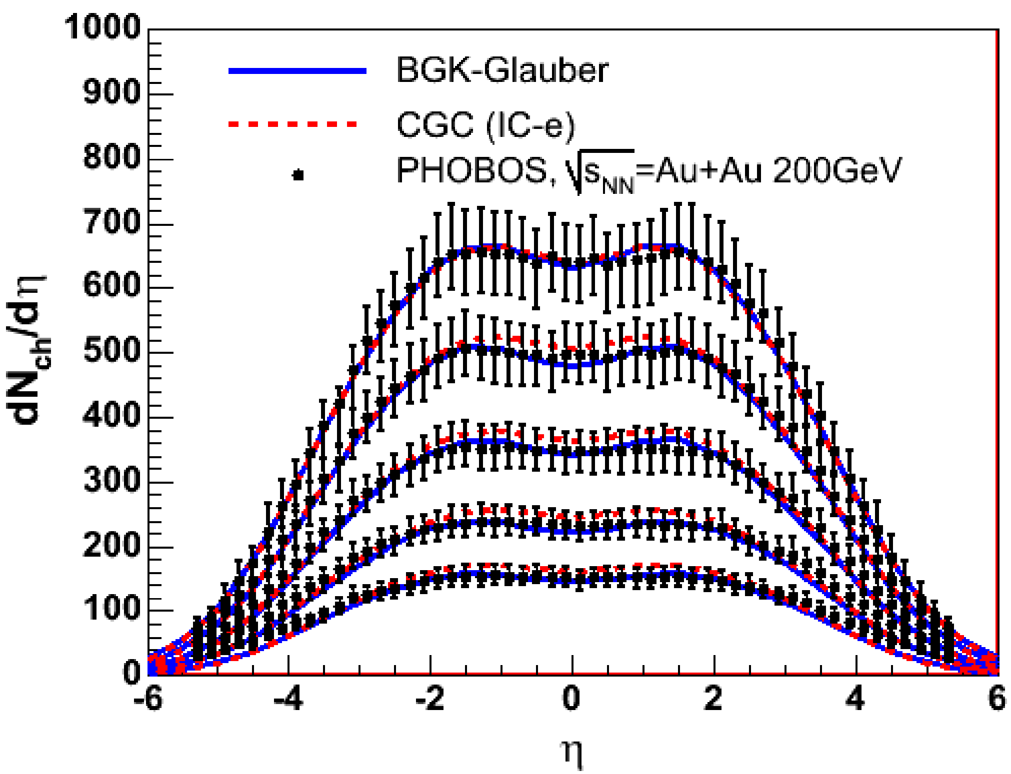
$$= \left[1 + 2v_2^q(p_T^q)\cos(2\phi) + \cdots\right]^{n_q}$$

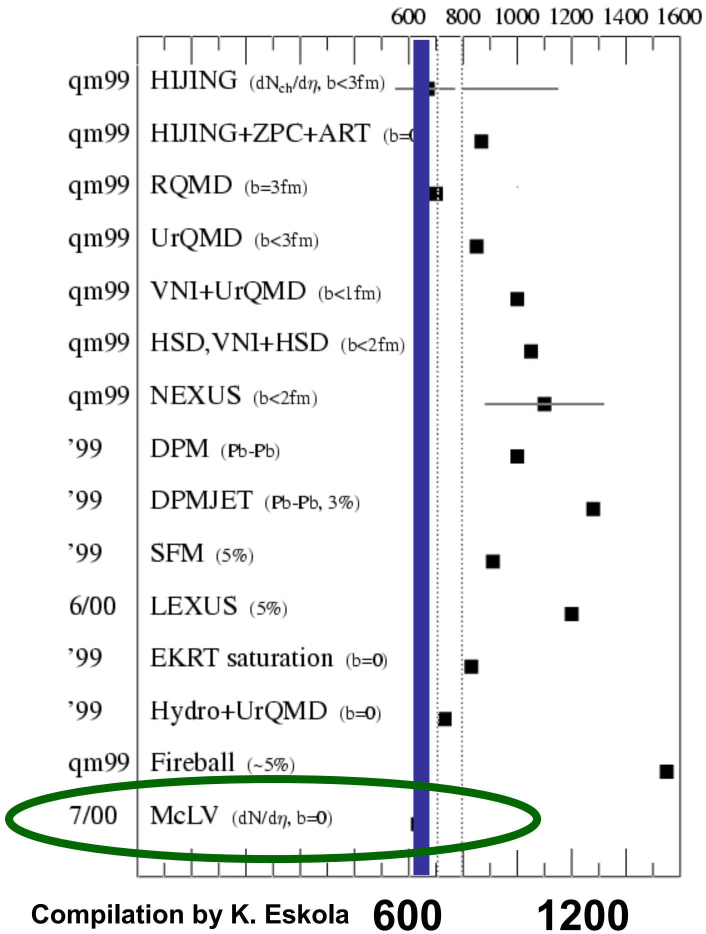
$$\approx 1 + 2n_q v_2^q\left(\frac{p_T}{n_q}\right)\cos(2\phi) + \cdots$$

- v_2

- **Hadronization through quark coalescence**
- **Constituent quarks flow**

Low multiplicity in central Au+Au

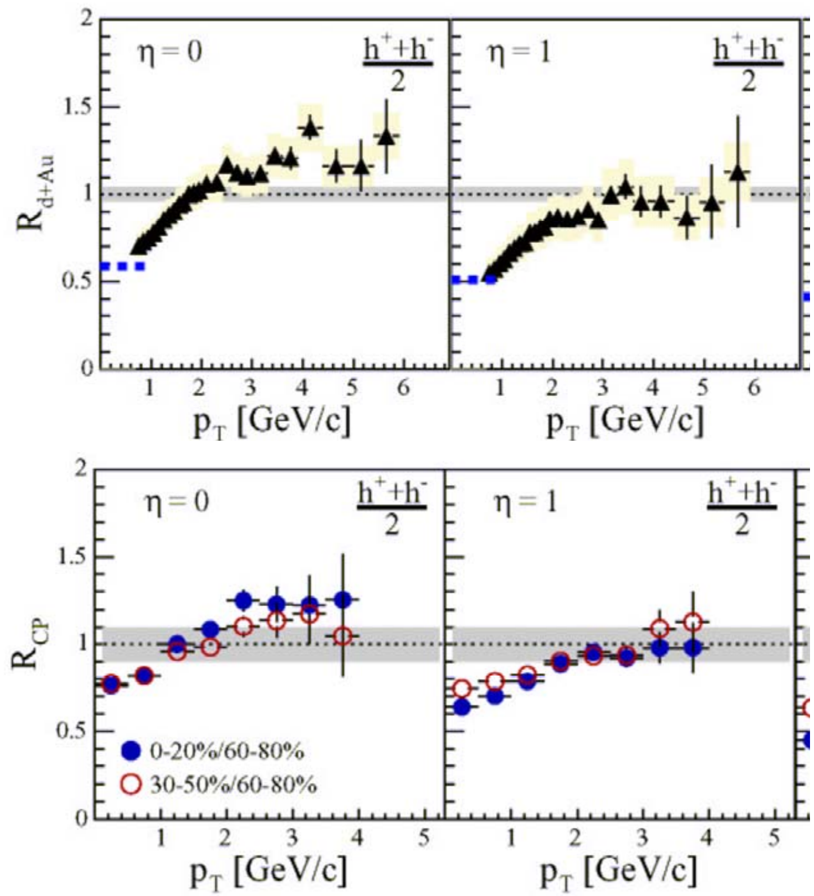


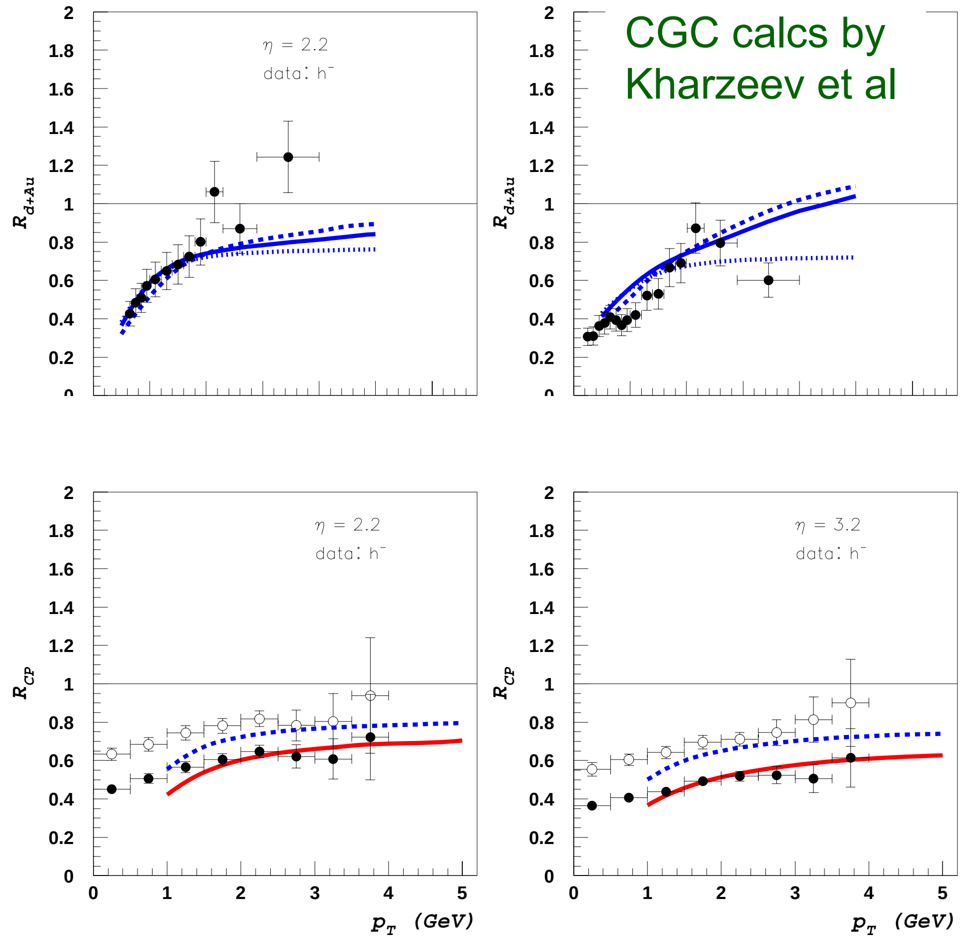


- Multiplicities well described by **Color Glass Condensate** model
- Evidence for saturated gluon fields in the Au nucleus?

Forward particle production in d+Au collisions

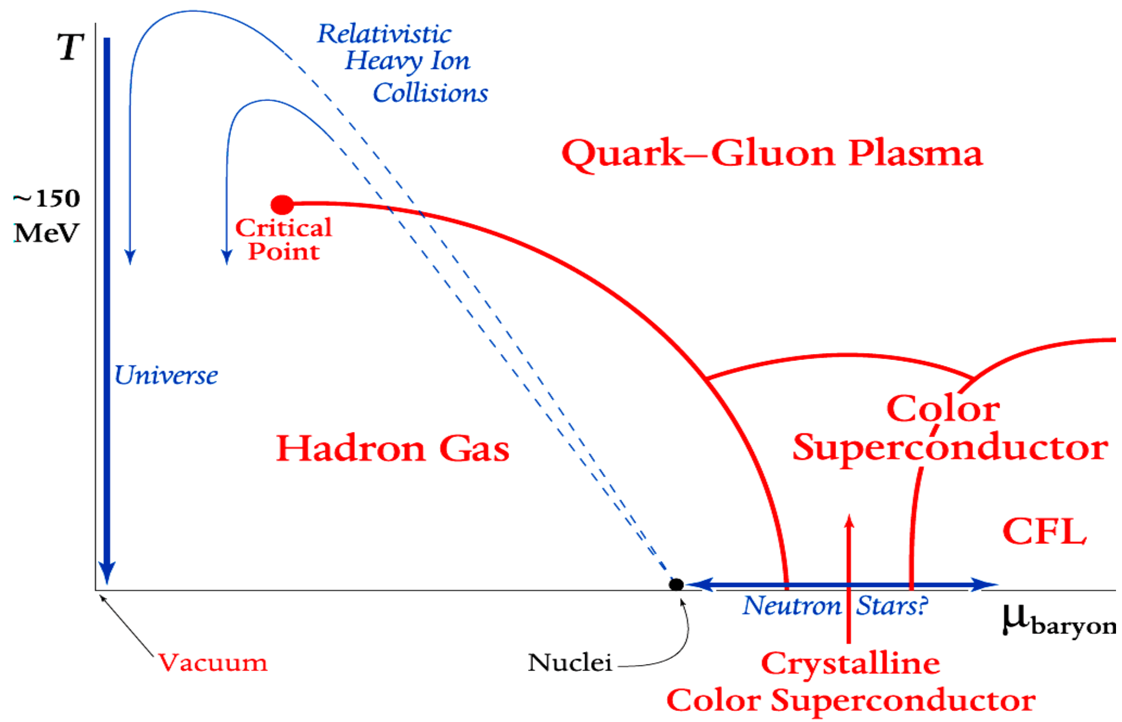
BRAHMS, PRL 93, 242303





- Sizable suppression of charged hadron yield in forward d+Au
- Evidence for a saturated gluon field in the Au nucleus?
- Several other mechanisms have also been proposed

Where do we go from here?

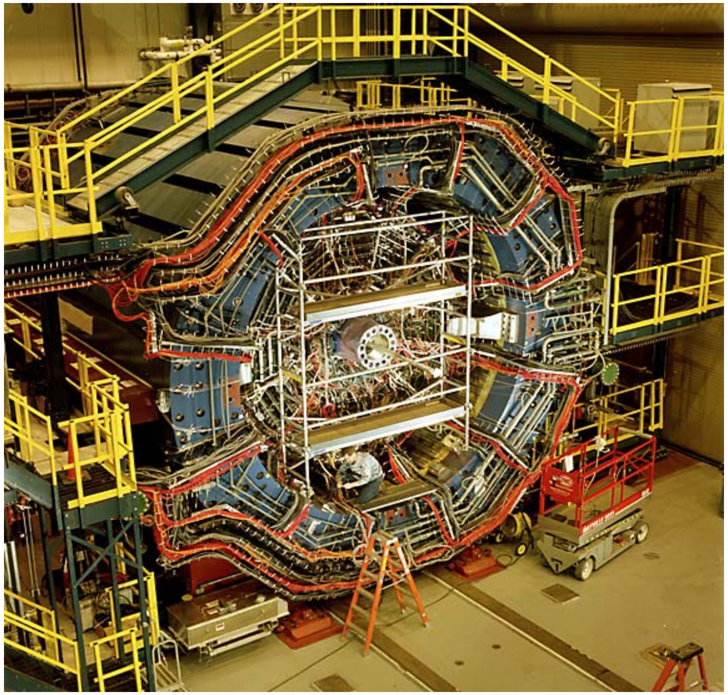


- We've learned stunning things over the past six years!
- Now we need to develop a **detailed, quantitative understanding** of the dense, strongly interacting matter that's been created
  - Thermalization mechanism?
  - Equation of state?
  - Viscosity?
  - QCD critical point?
  - ……

- **RHIC detector and luminosity upgrades**
- **Significant advances in theory**
- **Complementary measurements at higher (LHC) and lower (FAIR) energies**

RHIC detector upgrades

STAR

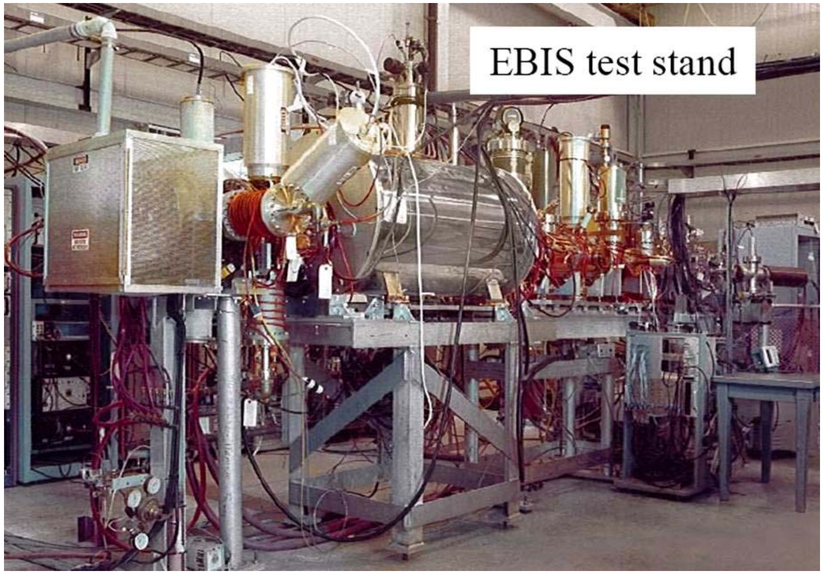


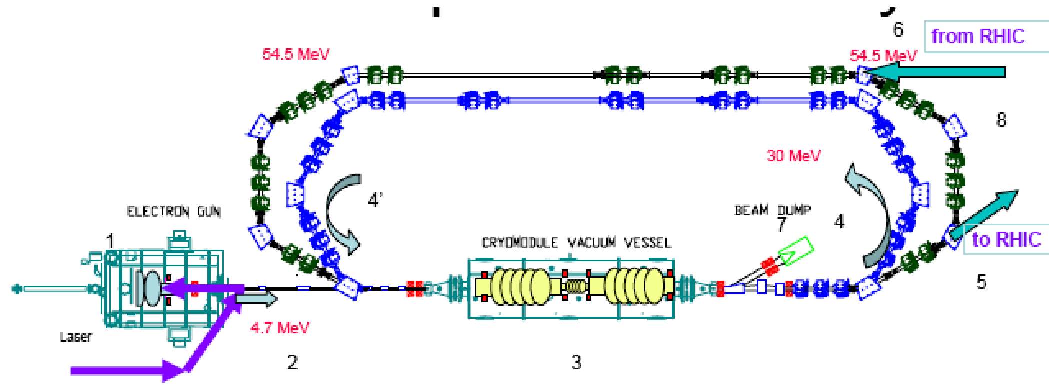
PHENIX

Forward Meson Spectrometer – completed – Hadron Blind Detector

DAQ & TPC electronics Time of Flight barrel	ongoing	Muon Trigger Silicon Vertex Barrel (VTX)
Heavy Flavor Tracker Barrel Silicon Tracker Forward Tracker	in preparation	Forward Silicon Forward EM Calorimeter

RHIC accelerator upgrades





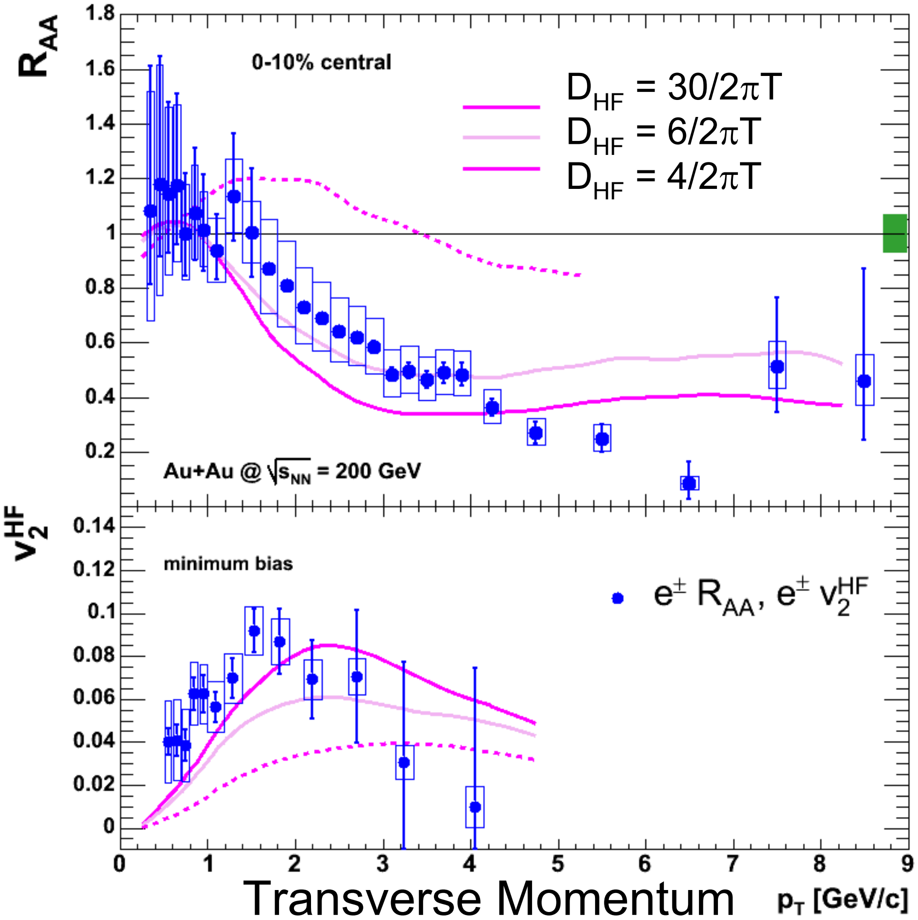
EBIS ion source

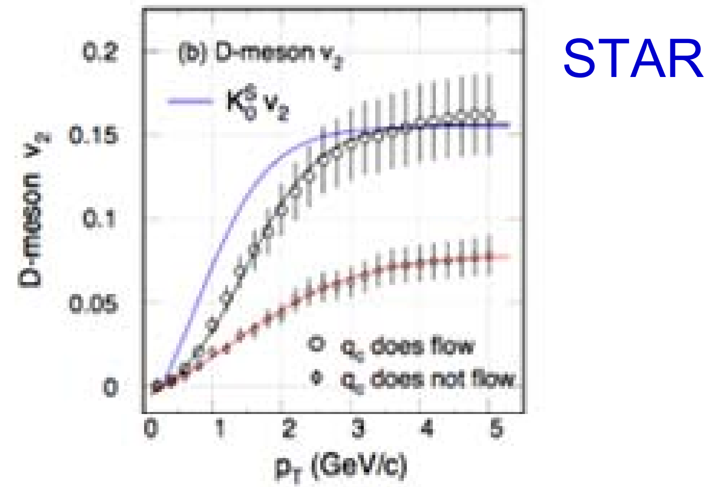
- Replaces 35 year old Tandems
- Improved reliability, lower ops costs
- Enables new beams: U+U, pol. ^{3}He
- In progress, commissioned and operational in 2010

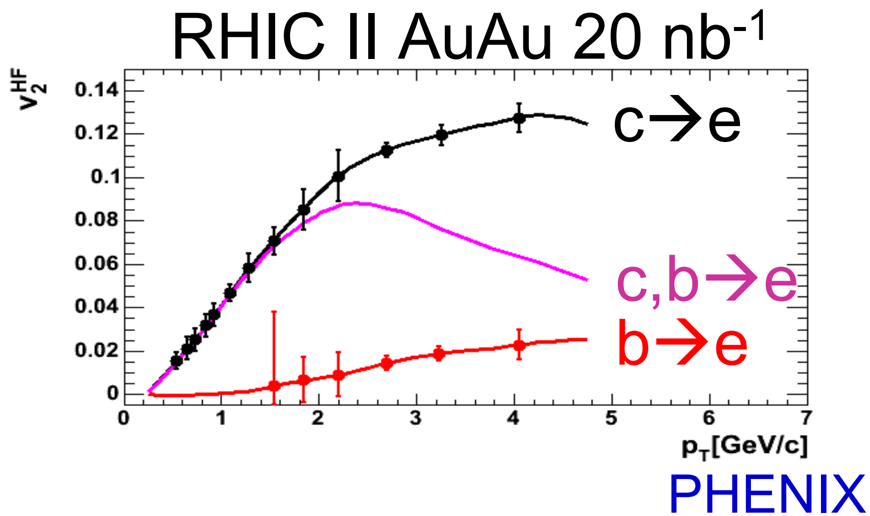
Electron cooling

- Increase Au+Au luminosity by factor of 10 ⇒ **RHIC II**
- TPC: $95M (FY07$)
- Technically driven schedule: construction start ~2010

Thermalization: heavy quark pebble in QGP stream

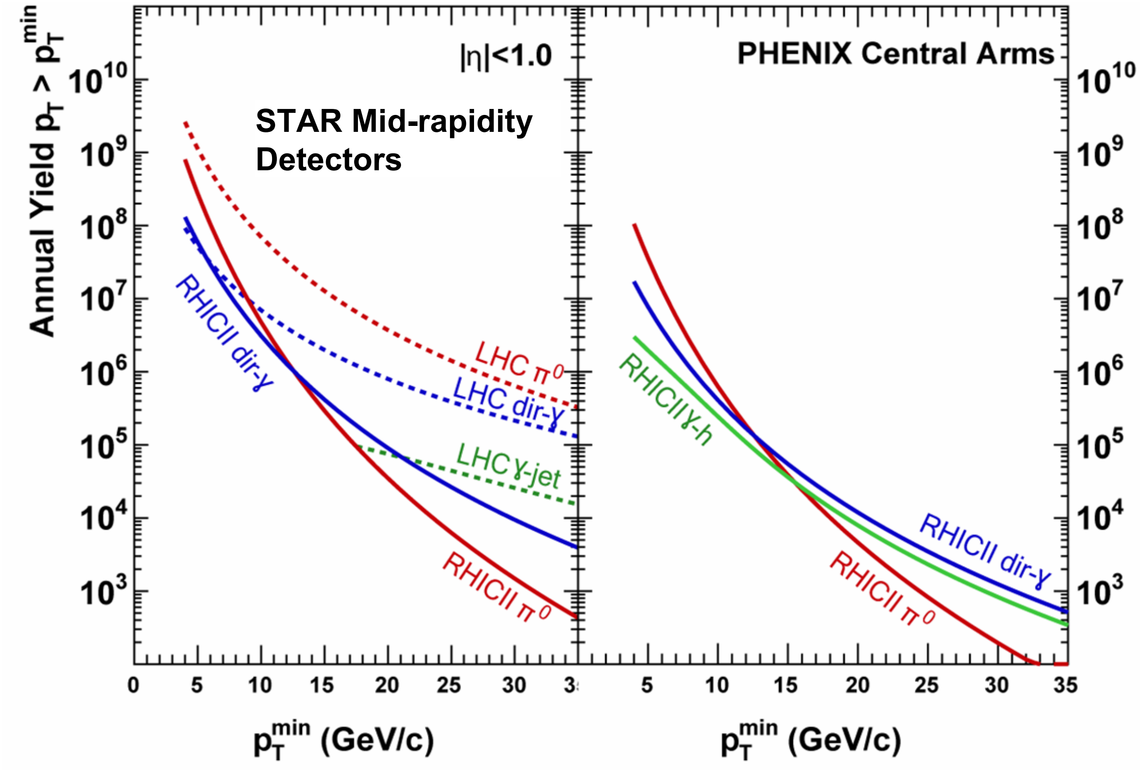






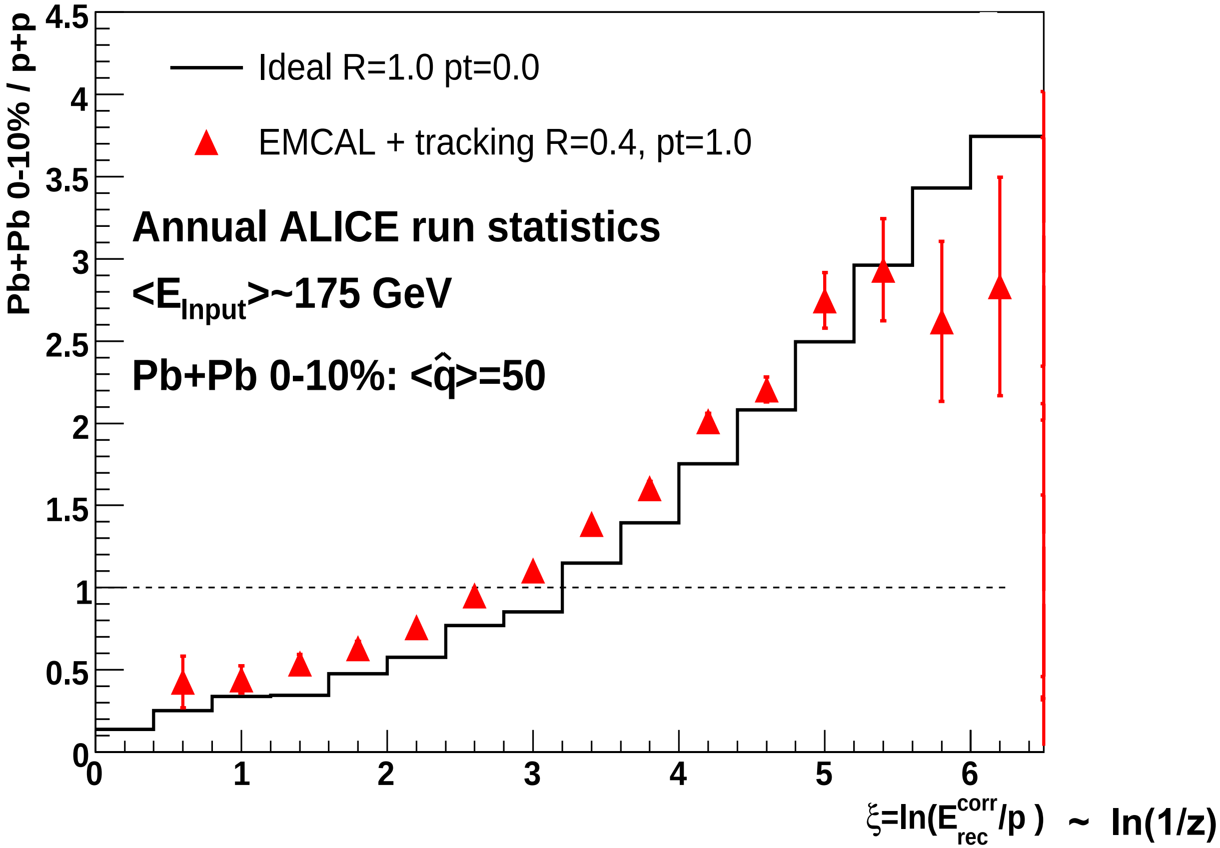
- Heavy quarks are pushed around by the dense medium
- **Vertex detectors are essential** for precise D and B measurements

Energy density and equation of state



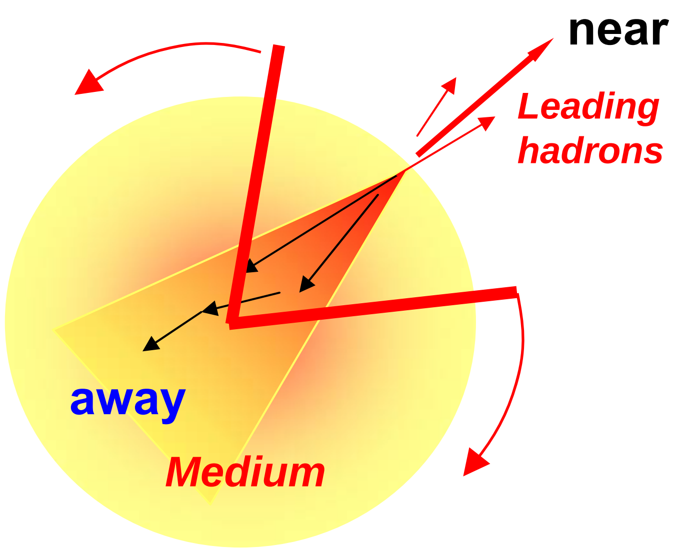
- Jets as a tomographic probe to map the medium
  - Compare light-quark, heavy-quark, and gluon jet interactions
  - Calibrate with γ+jet coincidences
  - γ/π^0 ratio favors direct photons at RHIC
  - Will be done at both RHIC and LHC
    - **How will the plasmas differ?**

Very high energy jets -- the LHC playground



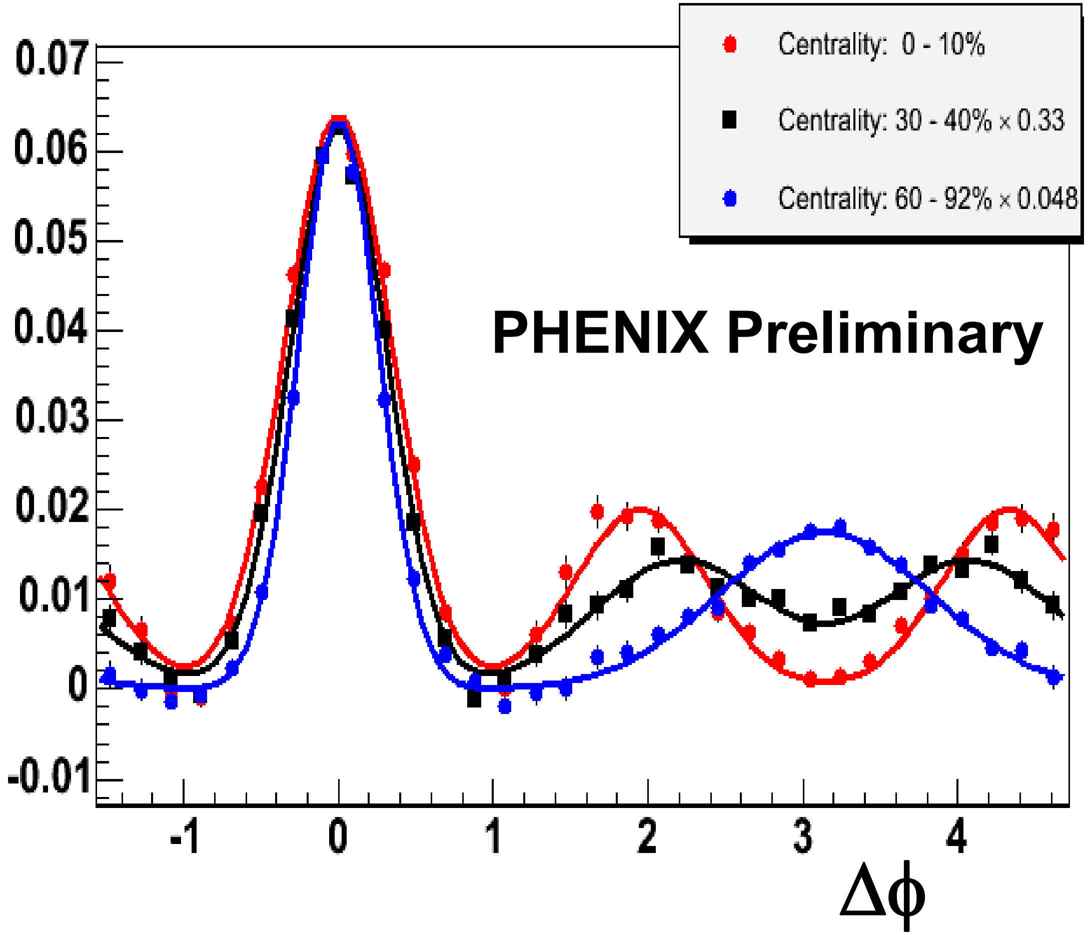
- LHC annual jet yields significant to >200 GeV
- Full jet reconstruction possible over the combinatoric background
- Detailed studies of jet modifications practical

How does the medium respond to a jet?



- Jets deposit their energy in the medium
- How does it react?

Double-peaked away-side "jet"



Intermediate-p_T di-hadron distributions show novel structure in central Au+Au collisions

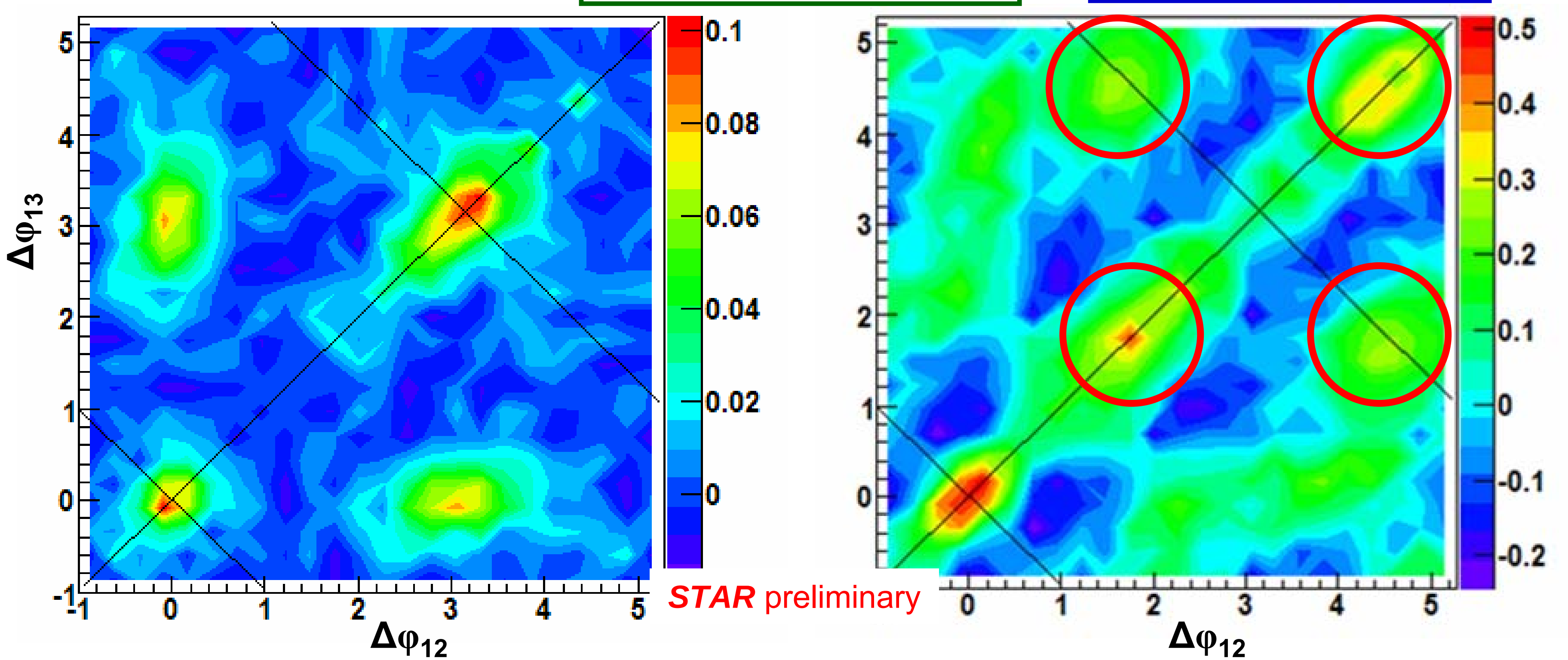
- Mach cone? **(Sound velocity of the medium)**
- Gluon Cherenkov radiation? **(Color dielectric constant)**

Explore the dynamics with 3-particle correlations

p+p collisions

$3.0 < p_T^{trig} < 4.0$ GeV/c
$1.0 < p_T^{assoc} < 2.0$ GeV/c

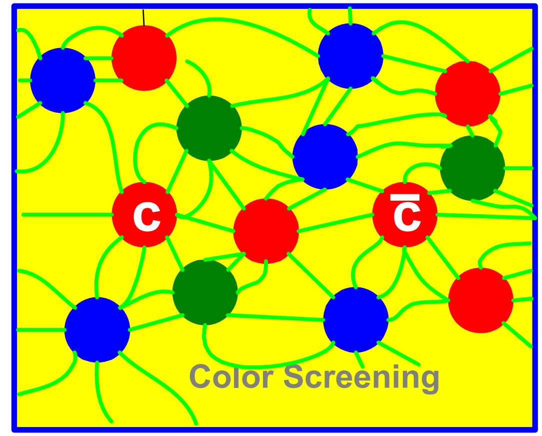
12% most central Au+Au collisions



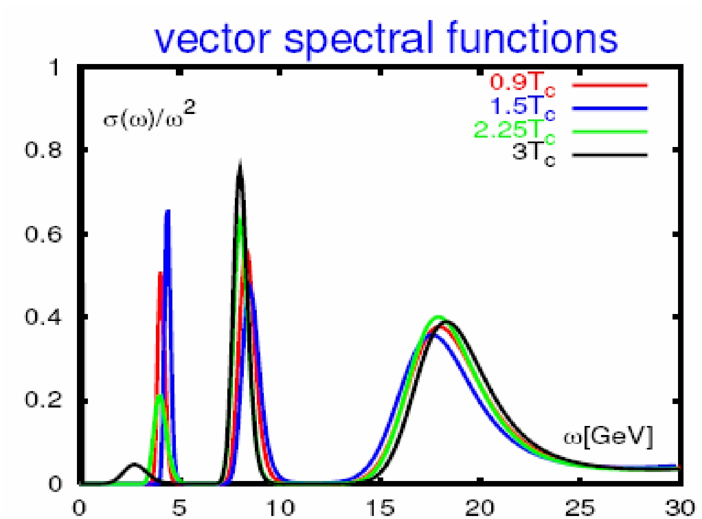
- **Enhancements on the diagonals** at ~ $\pi \pm 1.4$ radians?
- **Need large-acceptance particle ID** to unravel the dynamics
- May be difficult to measure at the LHC due to the large number of “soft” jets present in each head-on Pb+Pb event

Quarkonium – the thermometer

- Classic proposal: quarkonium suppression by color screening.



- Lattice QCD calculations tell us the world is more complicated than we thought! Quarkonium resonances should persist above T_c.

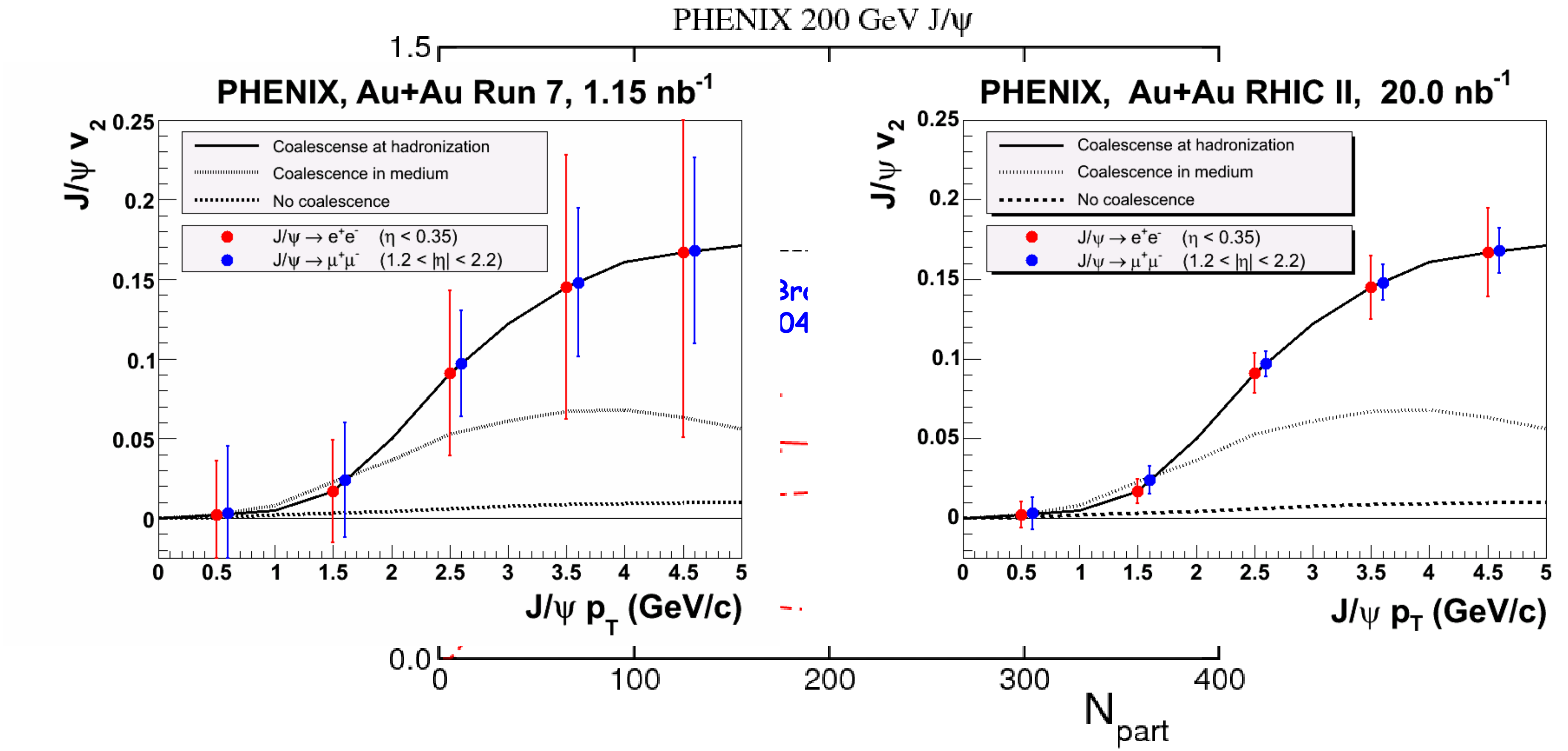


- Hierarchy of melting:

State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	> 4.10	< 1.76	1.60	1.19	1.17

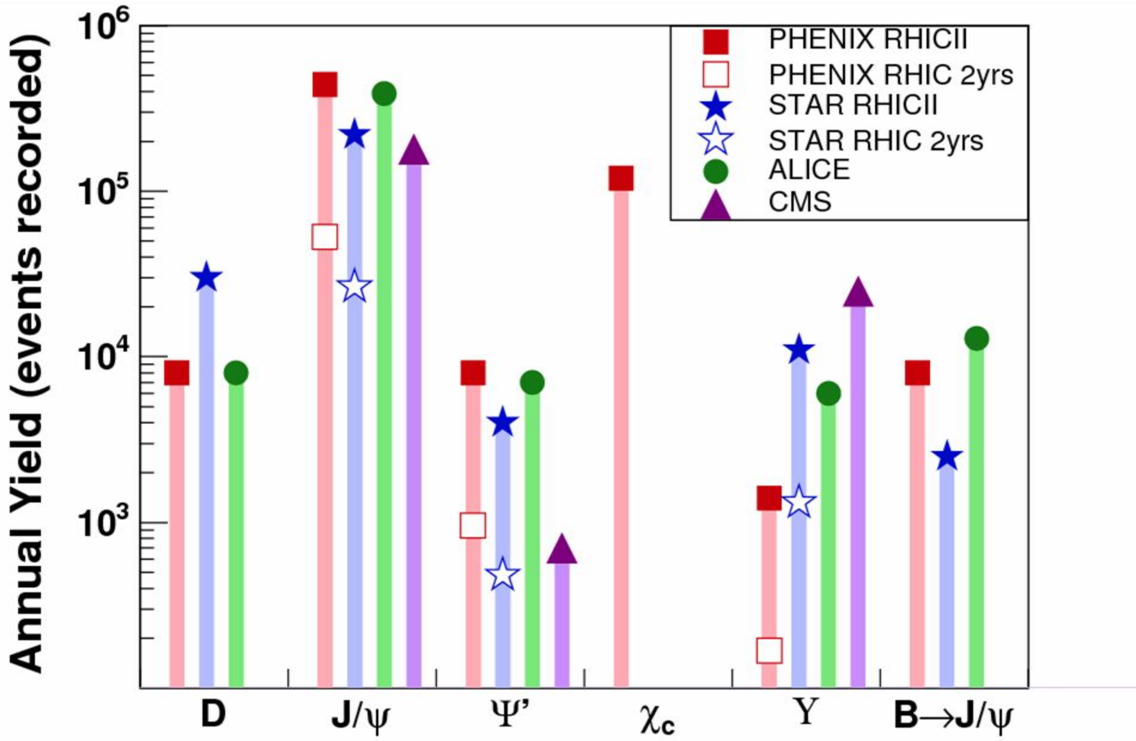
- Also recombination: $c+\bar{c} \rightarrow J/\psi$

Current status



- Suppression + regeneration describes PHENIX results well
- Sequential melting also works if you assume the J/ψ doesn't melt
- How to distinguish?
  - Energy dependence
  - J/ψ flow
  - Both **need RHIC II luminosity upgrade**

Complementarity of RHIC II and LHC

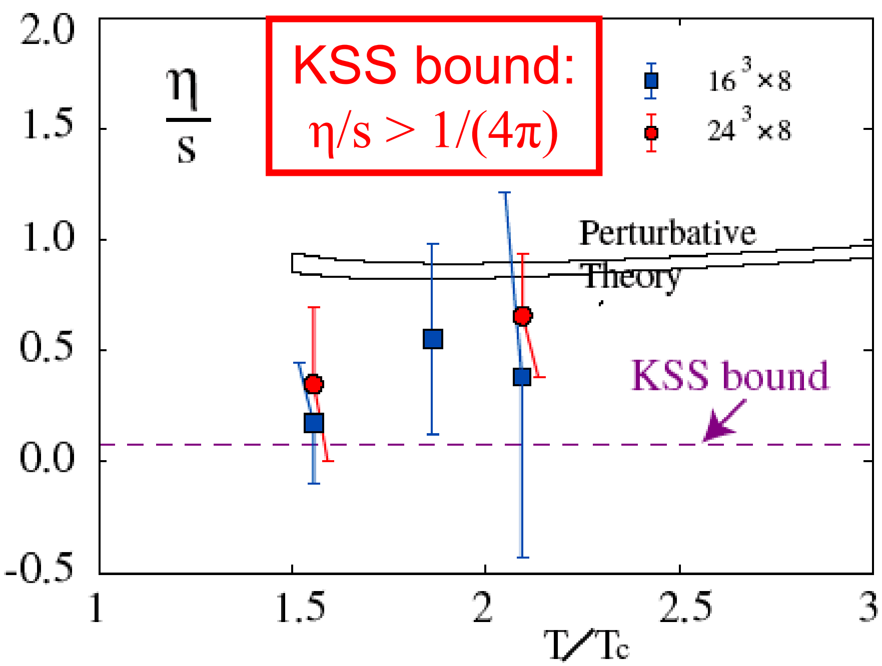


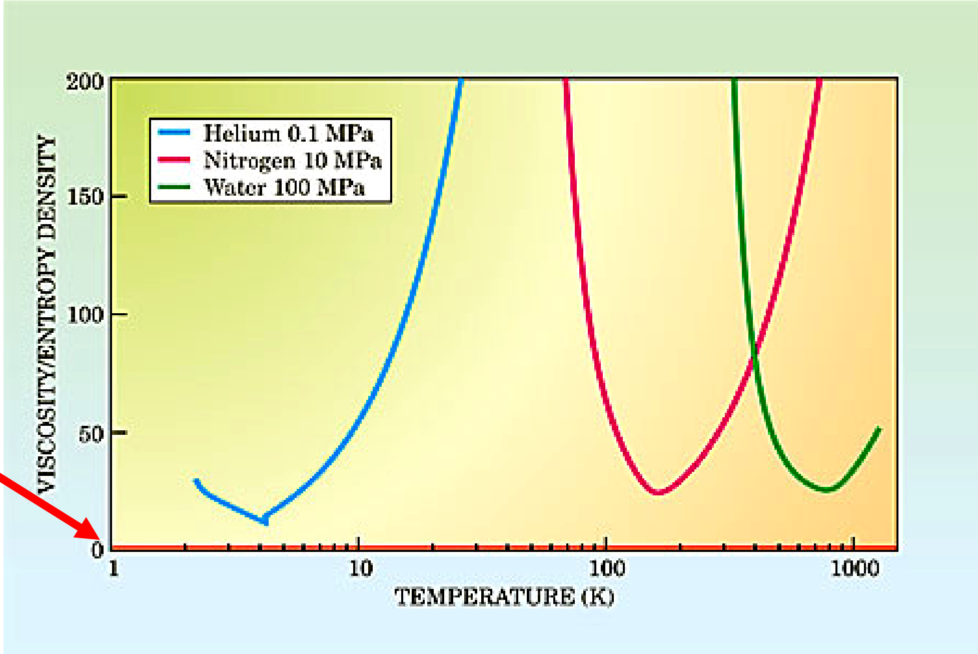
- Charmonium
  - Mixture of effects at full energy RHIC II, can turn off recombination with longer runs at lower energy
  - Recombination at LHC
- Bottomonium
  - Pure suppression at full energy RHIC II
  - Mixture of effects at LHC
- **Both RHIC II and LHC will be essential** to gain maximal information from either

What is the viscosity?

How perfect is our liquid?

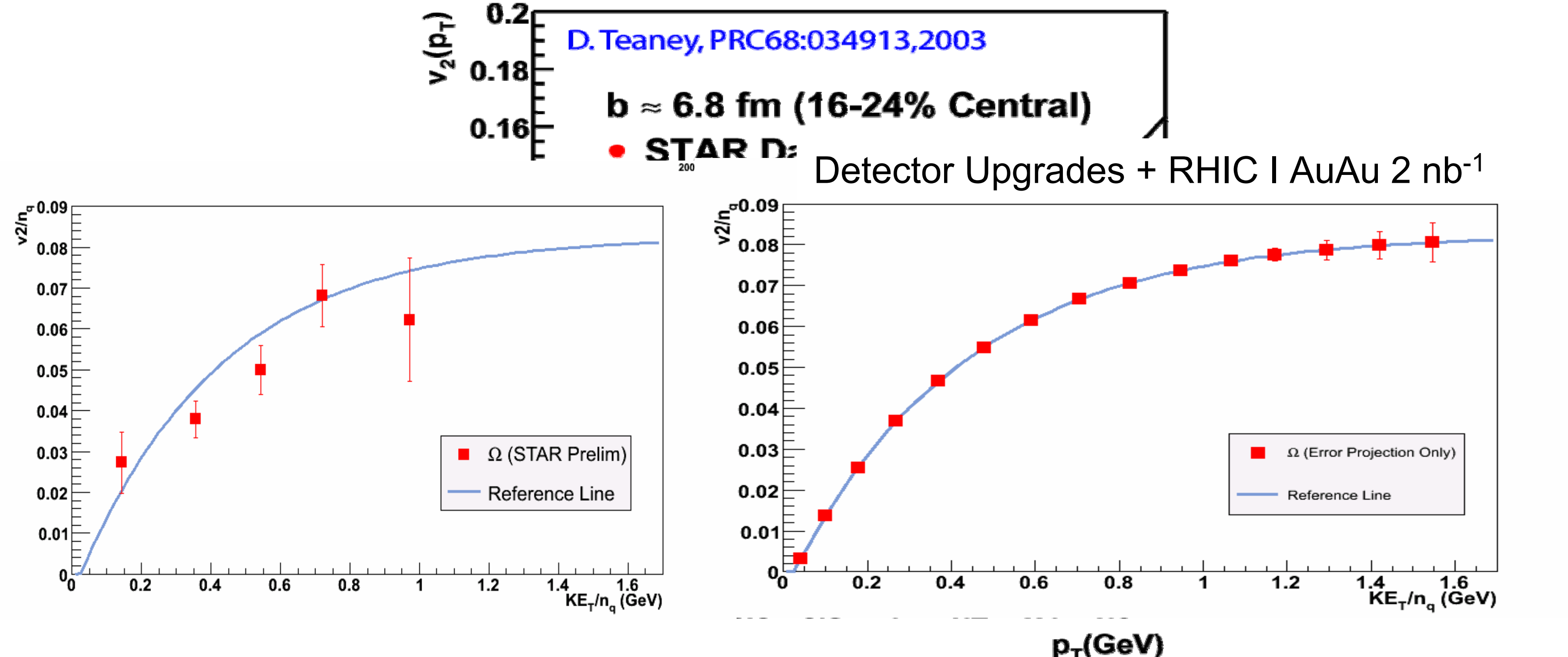
A. Nakamura and S. Sakai,
hep-lat/0406009





- Lower limit found from AdS/CFT correspondence
  - Strongly coupled supersymmetric gauge theory in 3+1 dimensions
  - Classical string theory near a black hole in 4+1 dimensions
- Other quantities of interest can also be calculated
- Which are “universal”?

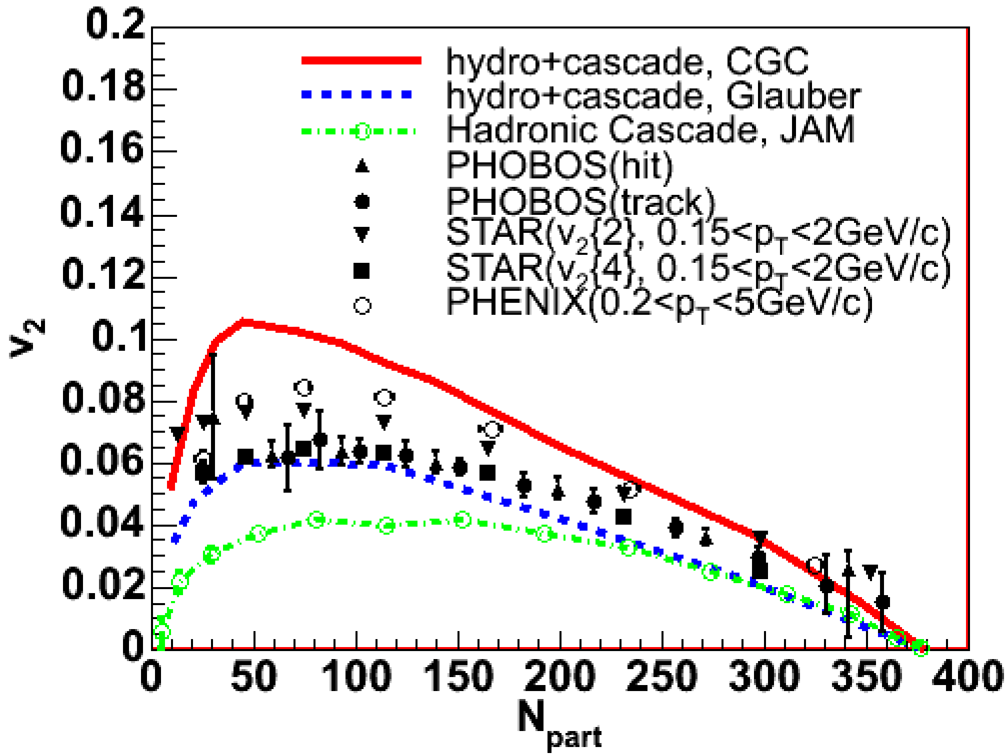
Quantifying η/s

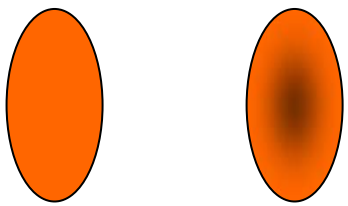


- Theory:
  - Need 3-d relativistic, viscous hydrodynamics
  - Need realistic Equation of State from lattice QCD
- Experiment:
  - Constrain the initial conditions
  - Quantify effects of viscous hadron gas final stage
    - Elliptic flow of Ω particularly valuable

Glauber vs Color Glass Condensate

Hirano et al, PLB 636, 299



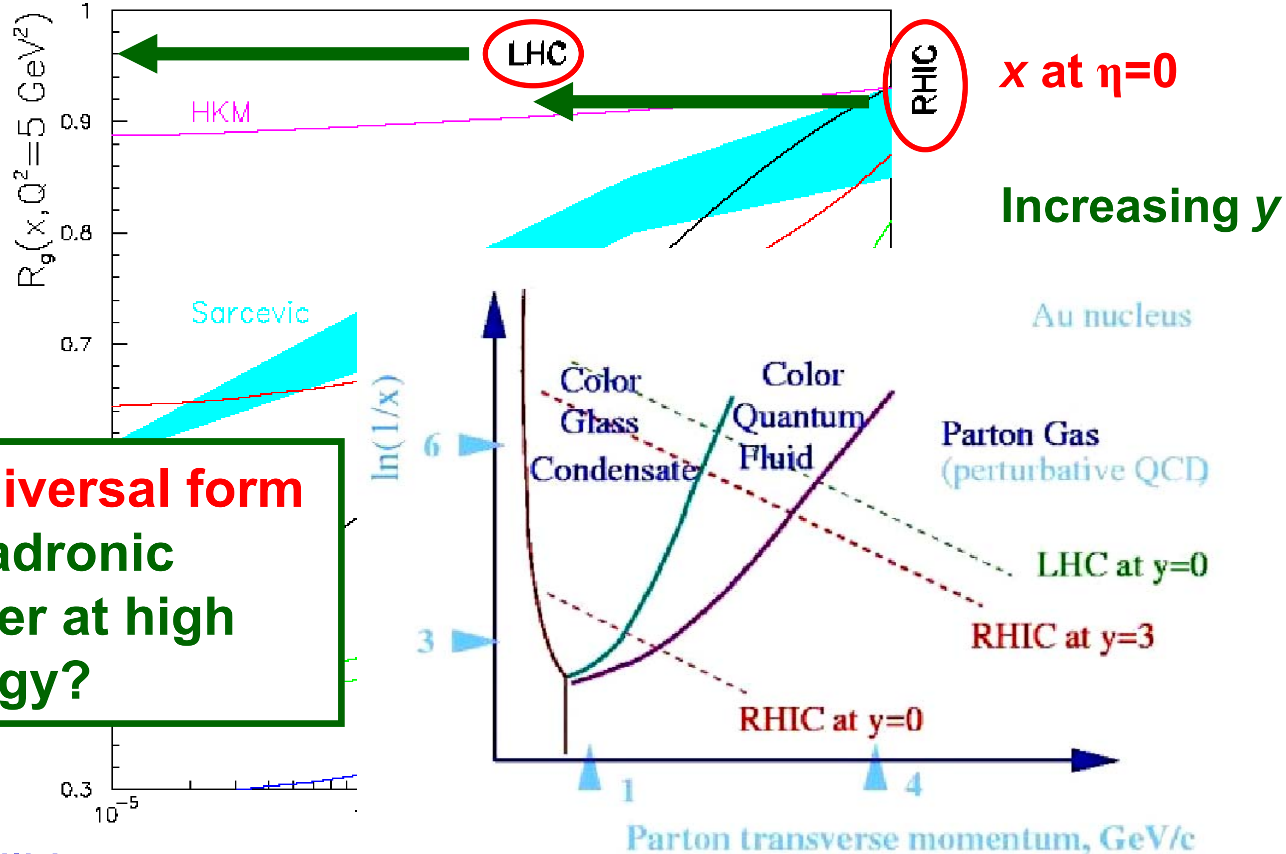


CGC: Treats the nucleus as a saturated gluon field

- Do we have **Glauber matter distribution + perfect liquid**, or **Color Glass Condensate distribution + viscous matter**?
- Is the gluon field in the Au nucleus saturated?
- **Forward d+Au collisions** provide information about the gluon density in Au at low gluon momentum fractions

Gluon saturation: RHIC-II and LHC

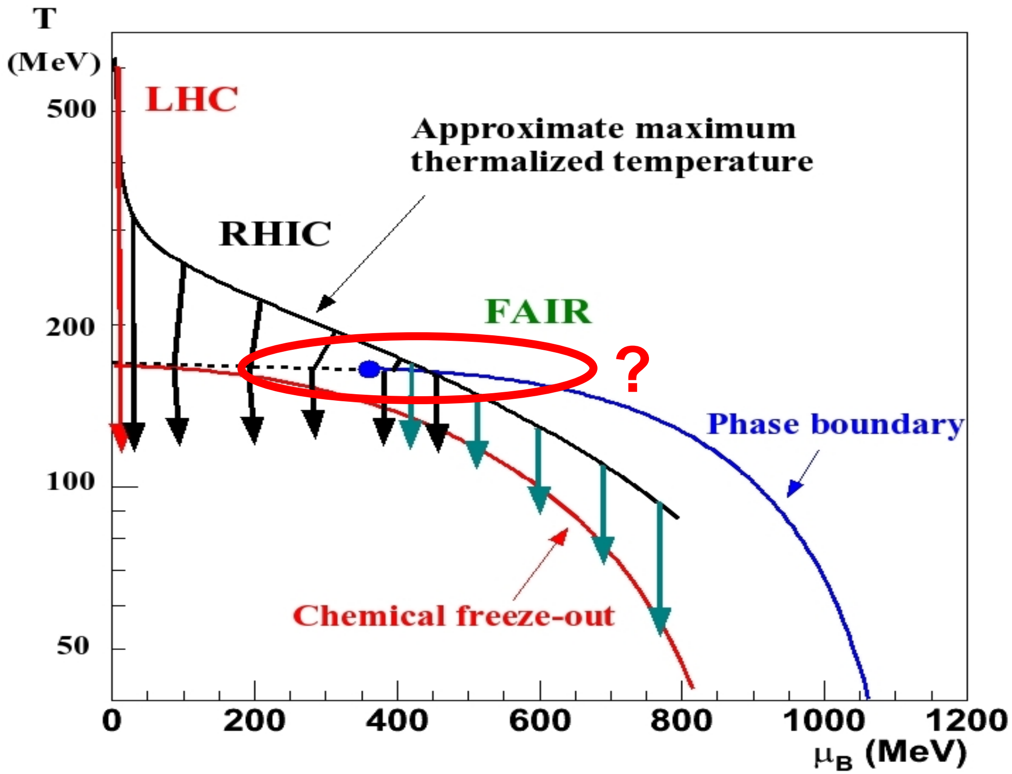
Armesto, J Phys G 32, R367

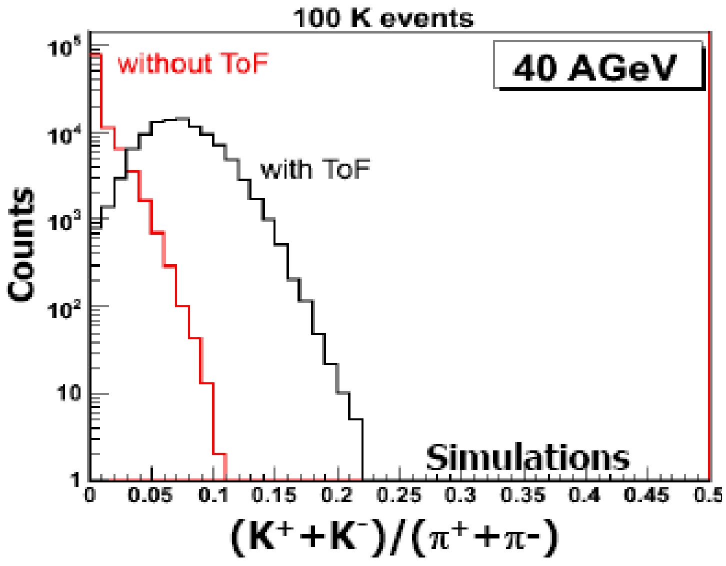


A universal form of hadronic matter at high energy?

- Two possibilities:
  - RHIC-II explores the onset of saturation; LHC looks deep in the saturation domain
  - RHIC-II is dominated by other effects; LHC observes those other effects in combination with saturation
- In either case, **RHIC-II and LHC will be complementary**
- Comparisons between p(d)+A and **e+A at EIC** will test universality

Where is the QCD critical point?





One proposed signature:
event-by-event K/π fluctuations.
Needs large-acceptance PID.

- **The “landmark” on the QCD phase diagram!**
- Lattice calculations: between μ_B of <~200 and >~700 MeV.
- **RHIC can find it if μ_B < 500 MeV**

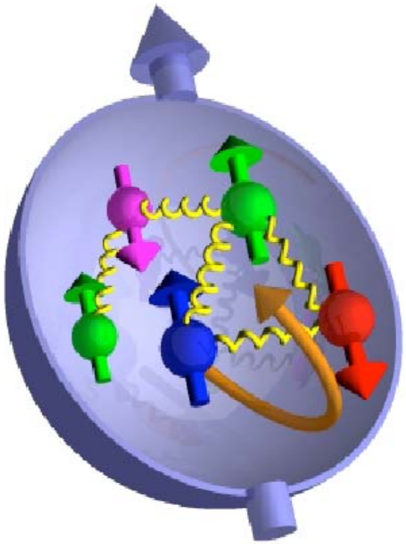
What is the wave function of the proton?

Proton spin:

$\frac{1}{2} = \frac{1}{2}\,\Delta\Sigma + \Delta G + L_q + L_g$

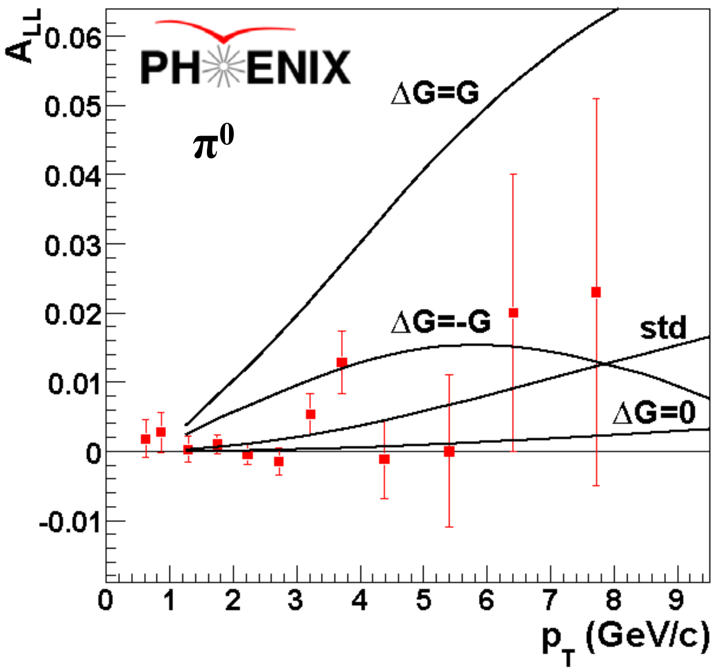
Only ~25% of the total

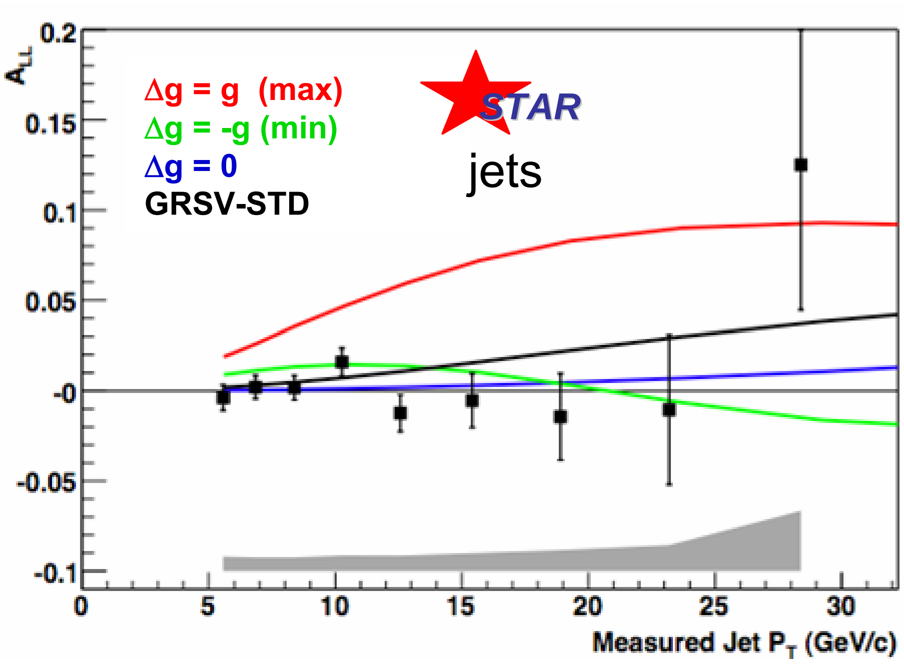
"Spin crisis"



- RHIC spin program
  - Gluon polarization – underway
  - Orbital motion and transversity – in the early exploratory phase
  - Anti-quark polarization – needs detector and accelerator improvements (underway now) for first measurements
- All will **profit dramatically from the enhanced RHIC II luminosity**

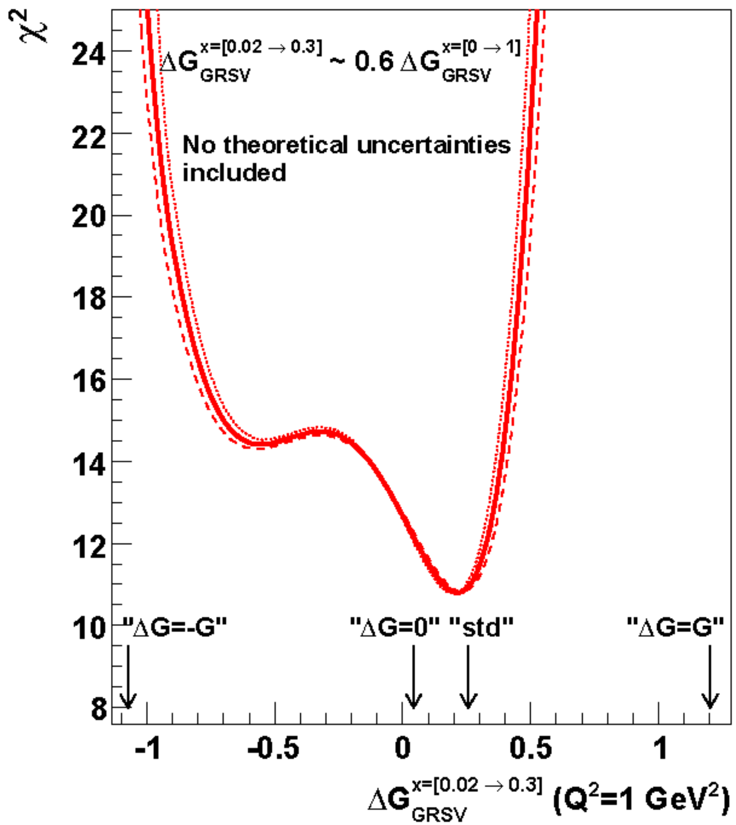
Current (2005) results for gluon polarization

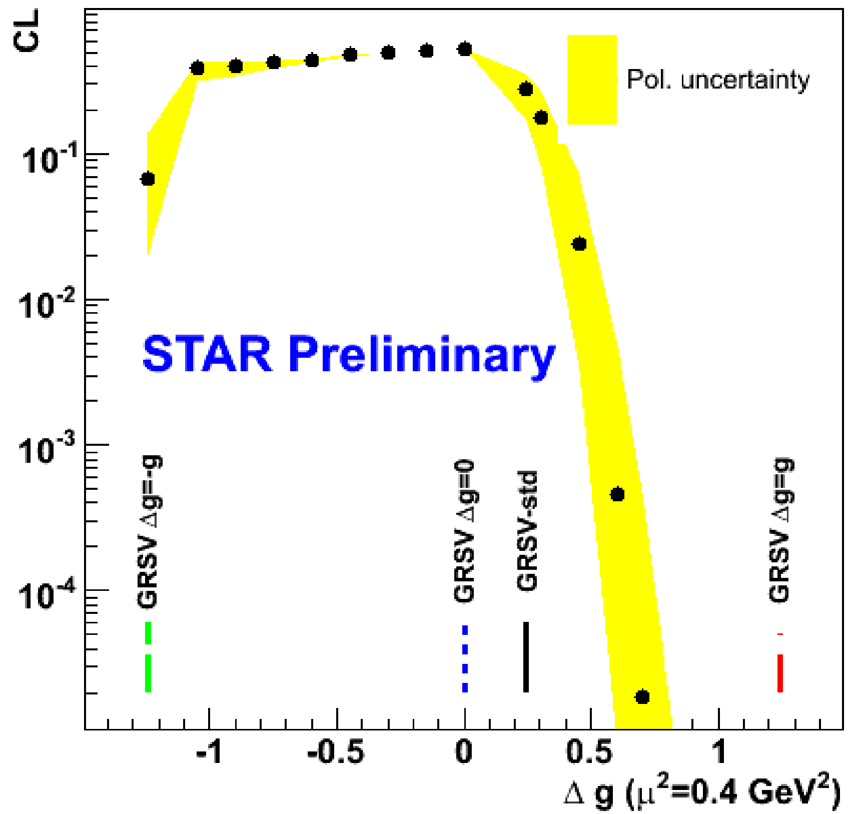




- To date, have focused on inclusive measurements with large cross sections (π^0 and jets)
- First significant sample of di-jets (2006) is now being analyzed

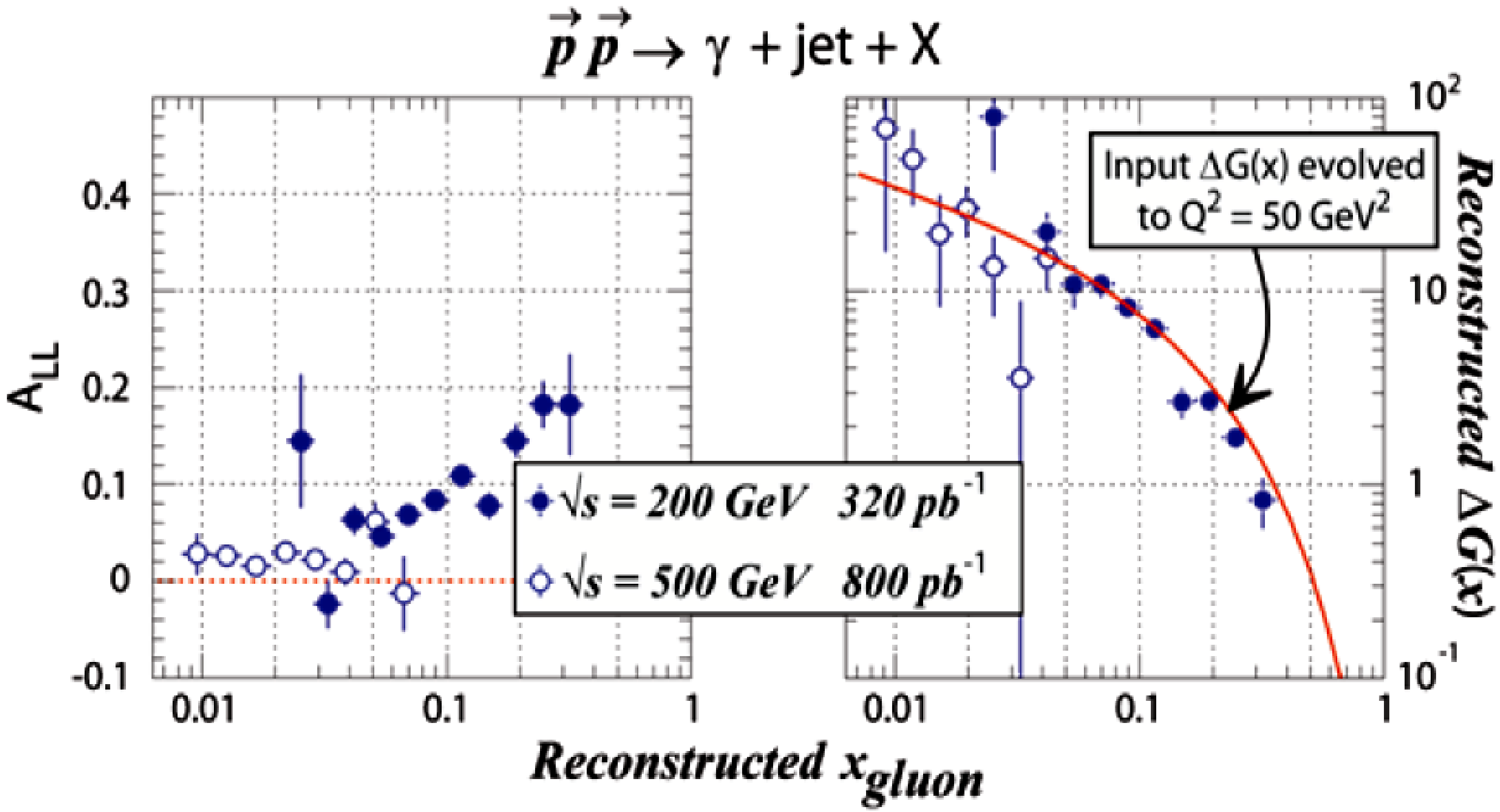
Comparisons to one global analysis





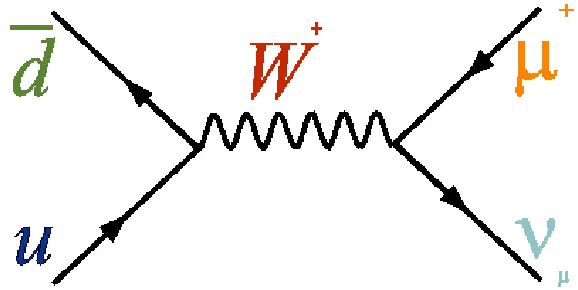
- GRSV best fit gluon polarization: Δg = -0.45 to +0.7 for (χ^2 + 1)
- Uncertainties associated with GRSV functional form not included

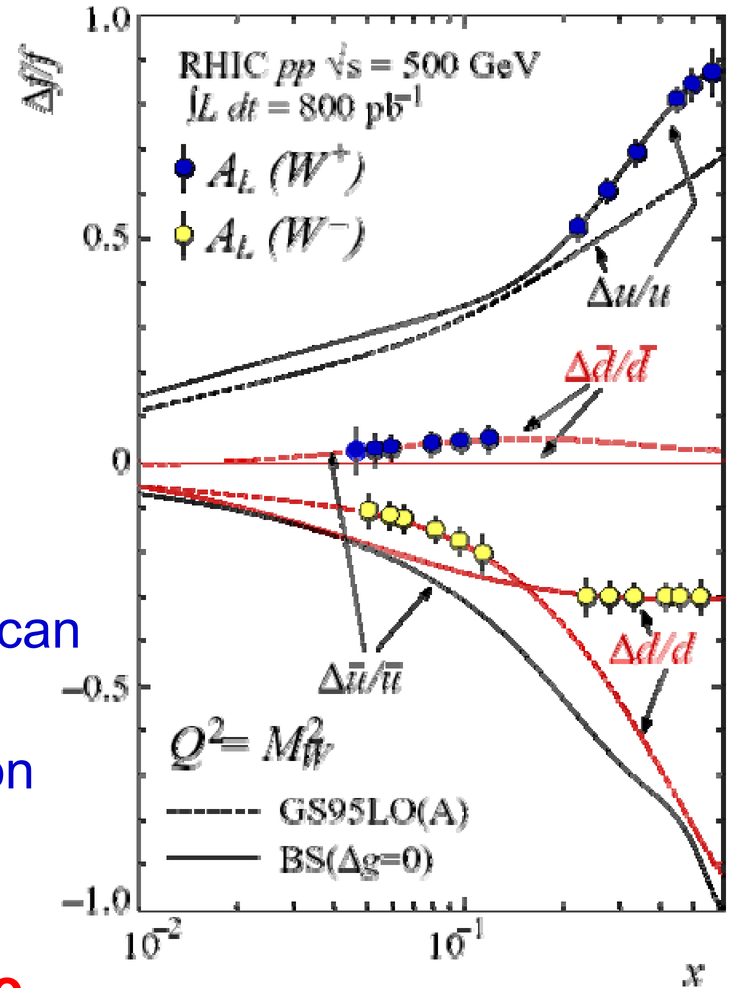
Constraining $\Delta G(x)$



- γ+jet permits LO determination of x_1 and x_2
- Can select those events with maximal sensitivity
- Measure the same x for different values of Q^2

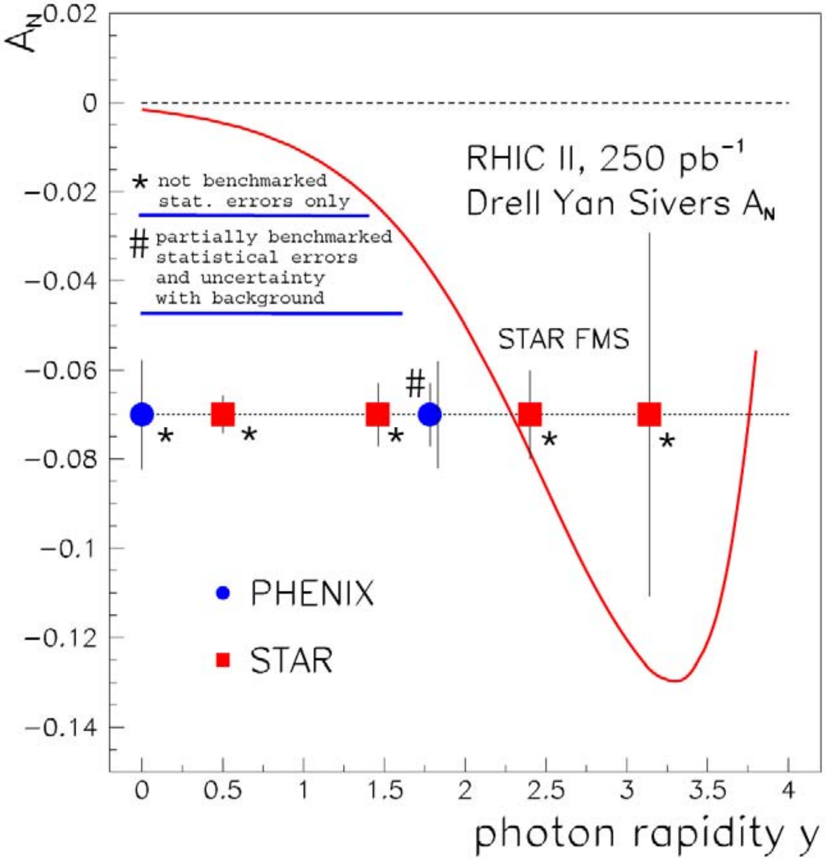
Next step: anti-quark polarization



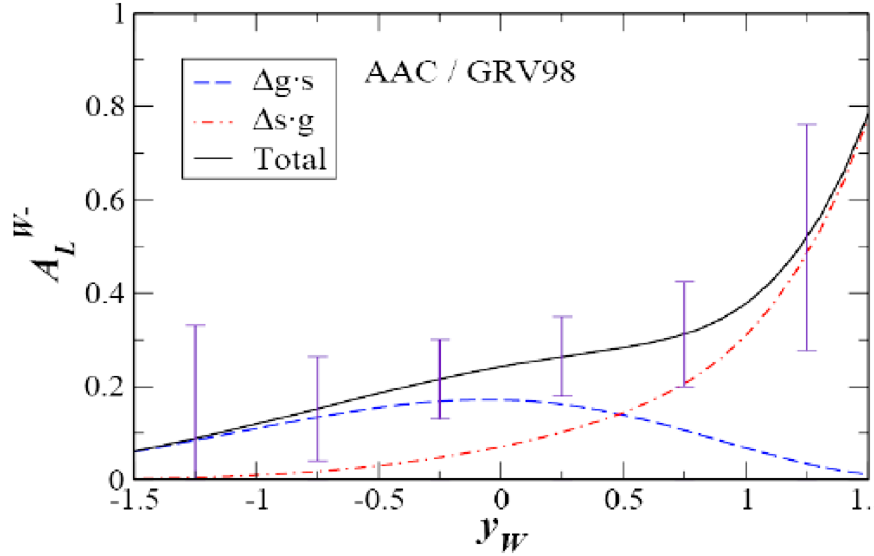


- With two polarized beams and W^+ and W^-, can separate *u*, *d*, $\bar{u}$, $\bar{d}$ polarizations
- These simulations are for the PHENIX muon arms
- STAR will do this with electrons
- Need **500 GeV collisions** and **upgrades to both PHENIX and STAR**

Additional spin measurements in the RHIC II era



Sivers asymmetry A_N
for Drell-Yan di-muon and di-electron production



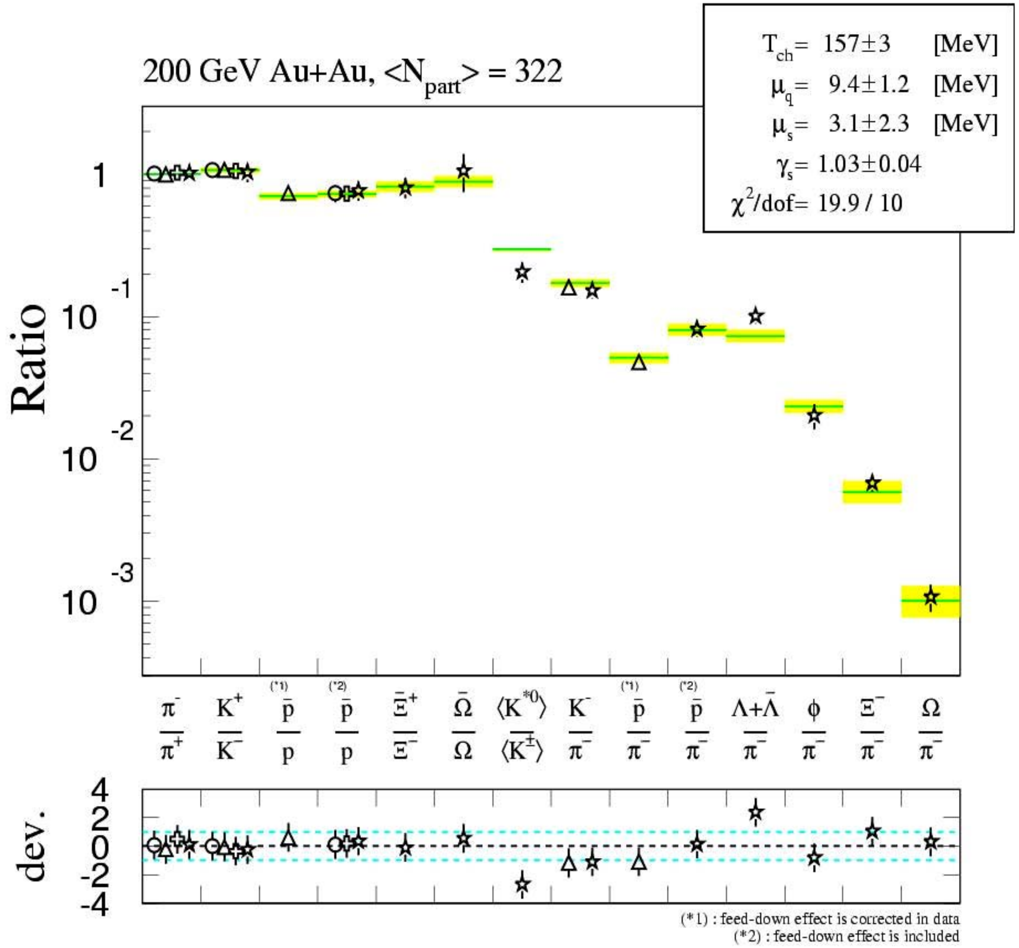
Direct measurement of the contributions Δs, $\Delta\bar{s}$ in **charm-tagged W boson production**

Conclusion

- RHIC has been a spectacular success!
  - Found a fundamentally new form of thermalized matter in Au+Au collisions
  - Took the first steps on the road to determining:
    - The origin of the proton spin
    - The wave function of heavy nuclei at high energy

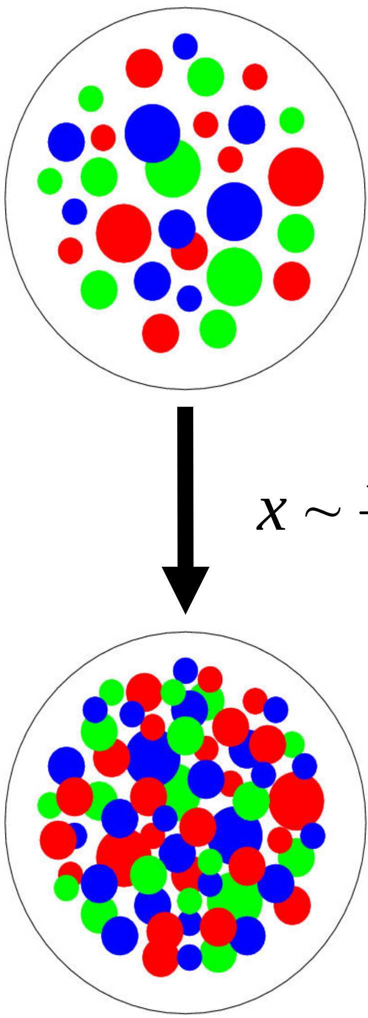
- Over the next decade, we need to turn our new **qualitative insights** into **quantitative understanding**

Additional evidence for thermalization



- Particle composition consistent with chemical equilibrium among the hadrons
- Largest deviation (K^*) arises from its short lifetime within the hadron gas phase

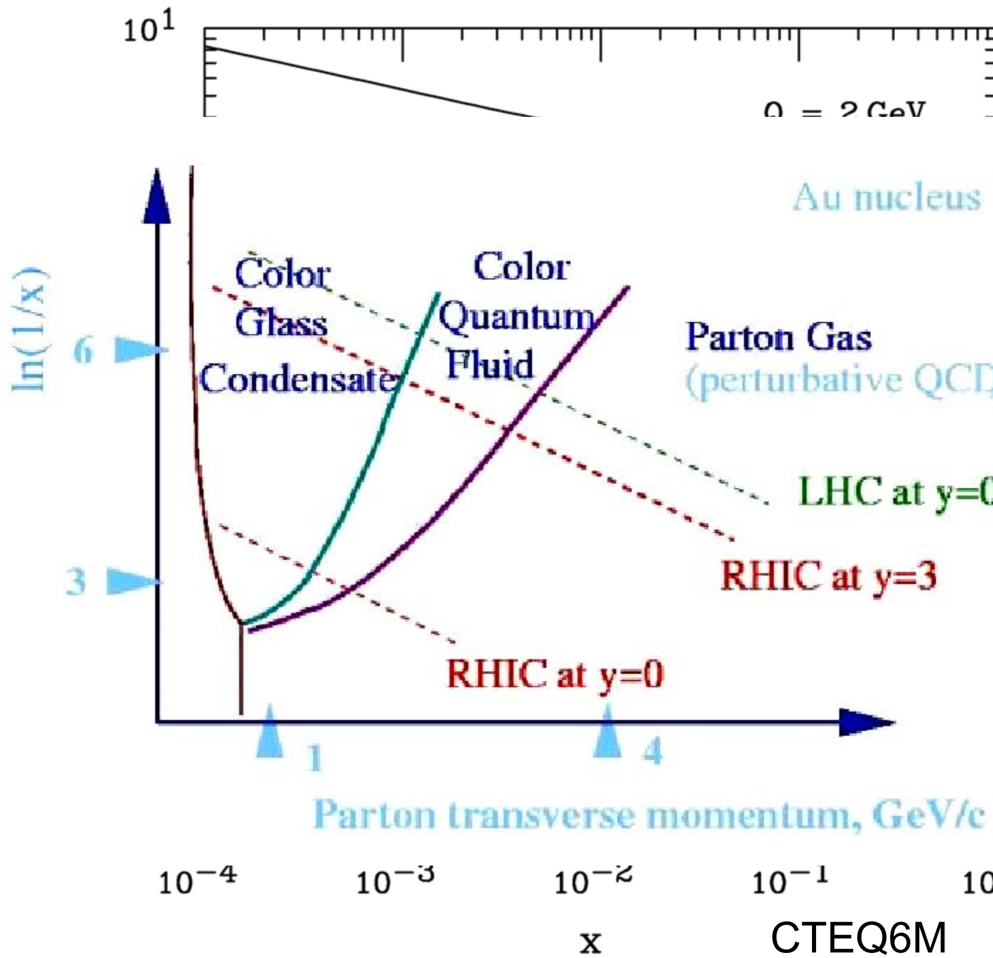
What is the wave function of a heavy nucleus?



Mid Rapidity

$$x \sim \frac{2 p_T}{\sqrt{s}} e^{-y}$$

Forward Rapidity

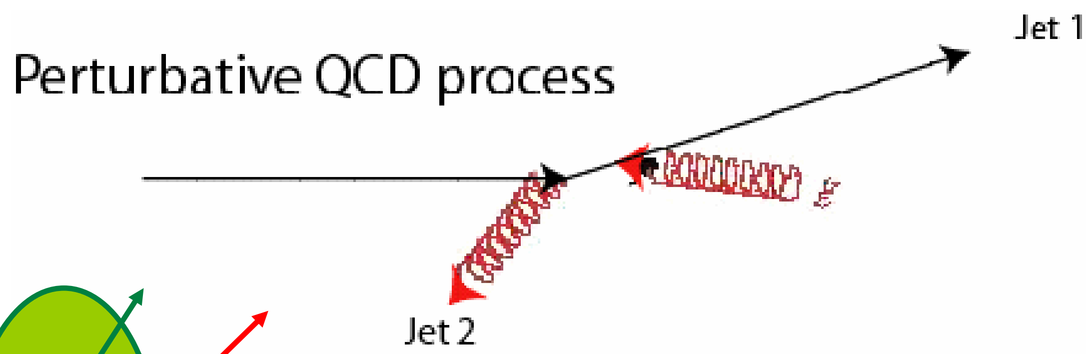


Gluon density can't grow forever.

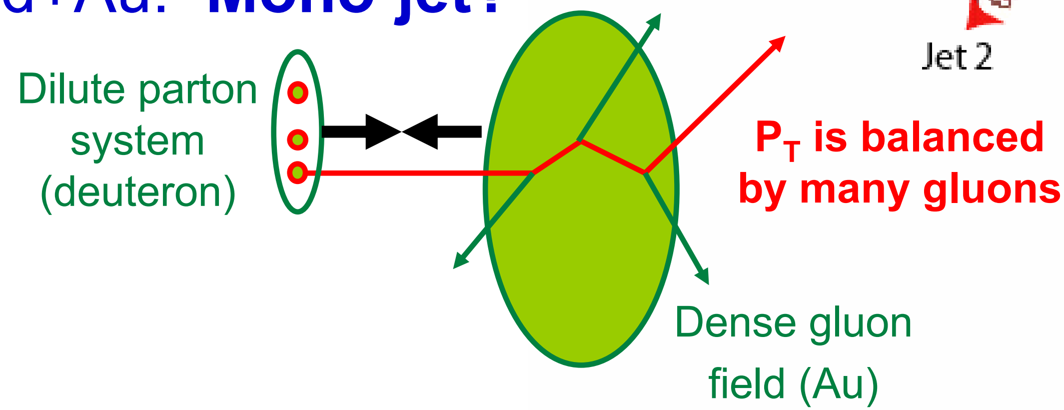
Saturation must set in at forward rapidity when the gluons overlap.

To elucidate the underlying dynamics: large acceptance correlation measurements

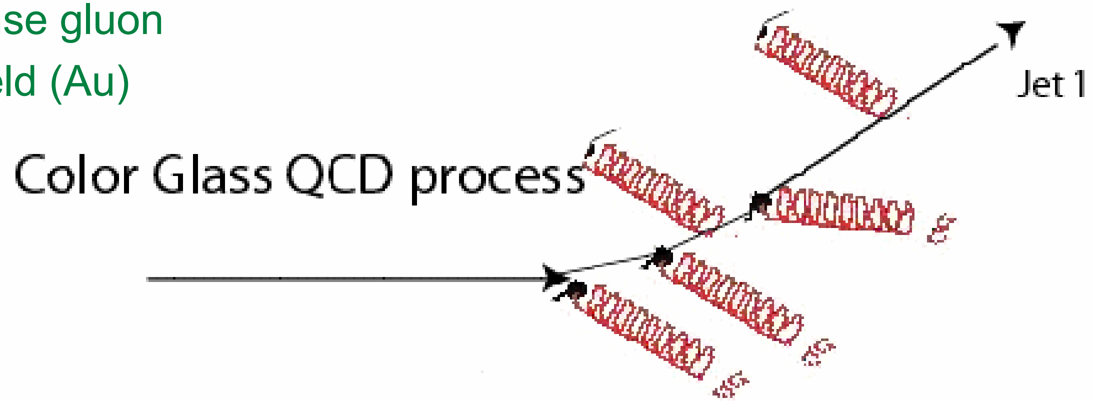
p+p: **Di-jet**



d+Au: **Mono-jet?**



Kharzeev, Levin, McLerran gives physics picture (NPA748, 627)



Color glass condensate predicts that the **back-to-back correlation** from p+p **should be suppressed**