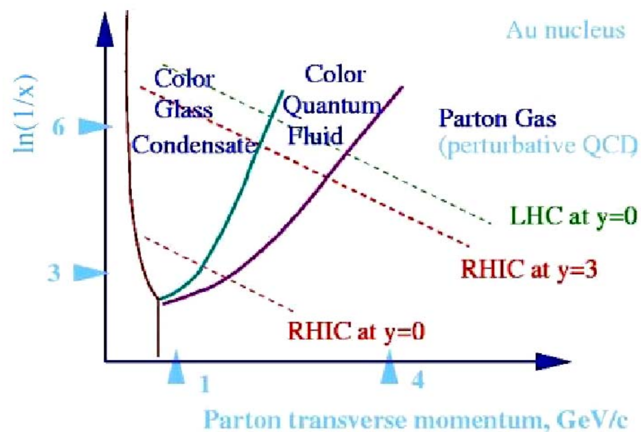
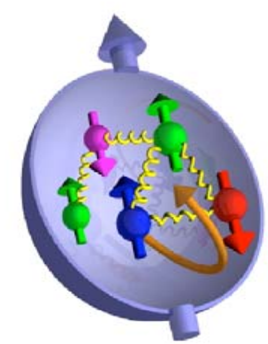
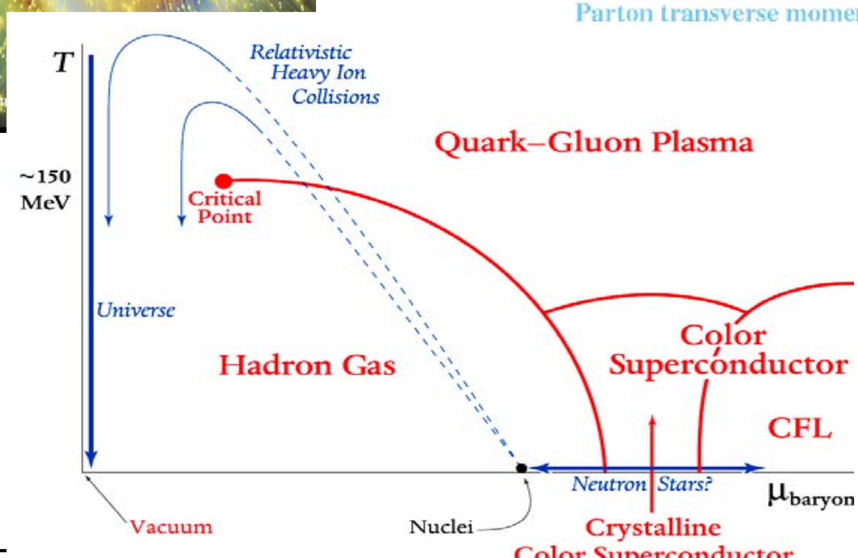
Future Science at RHIC

A summary of the RHIC II Science Working Groups







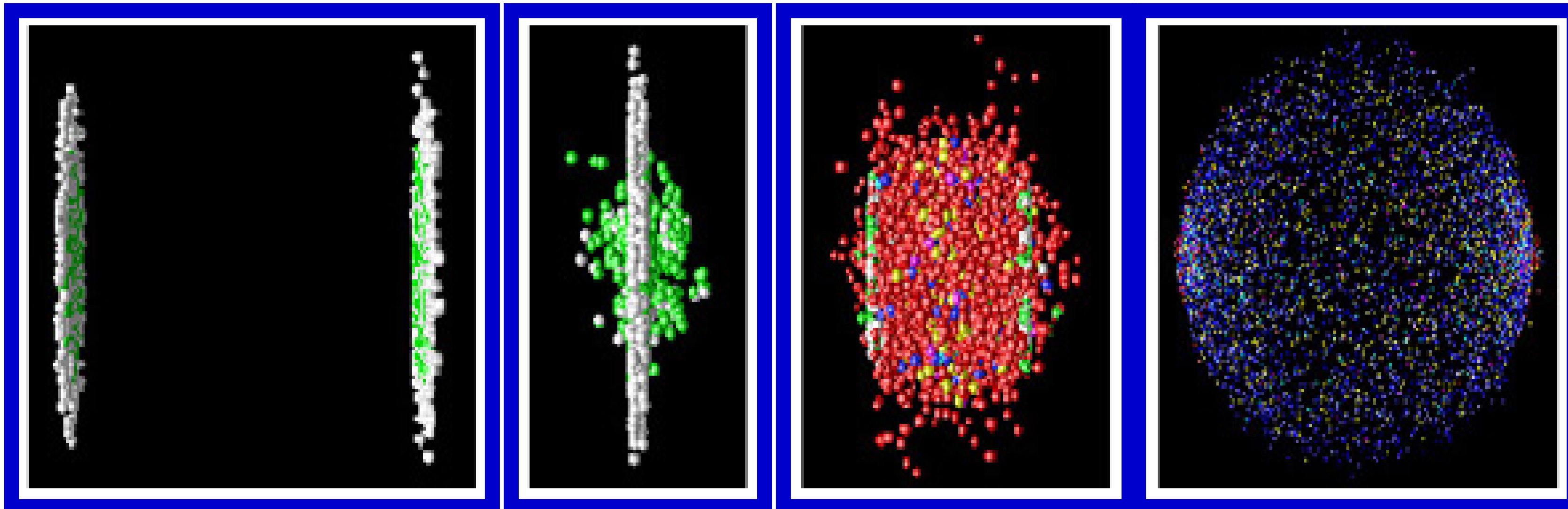
Carl A. Gagliardi
Texas A&M University

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 finite nuclei

Time line of a relativistic heavy ion collision

1 2 3 4



Two thin disk
quark
a

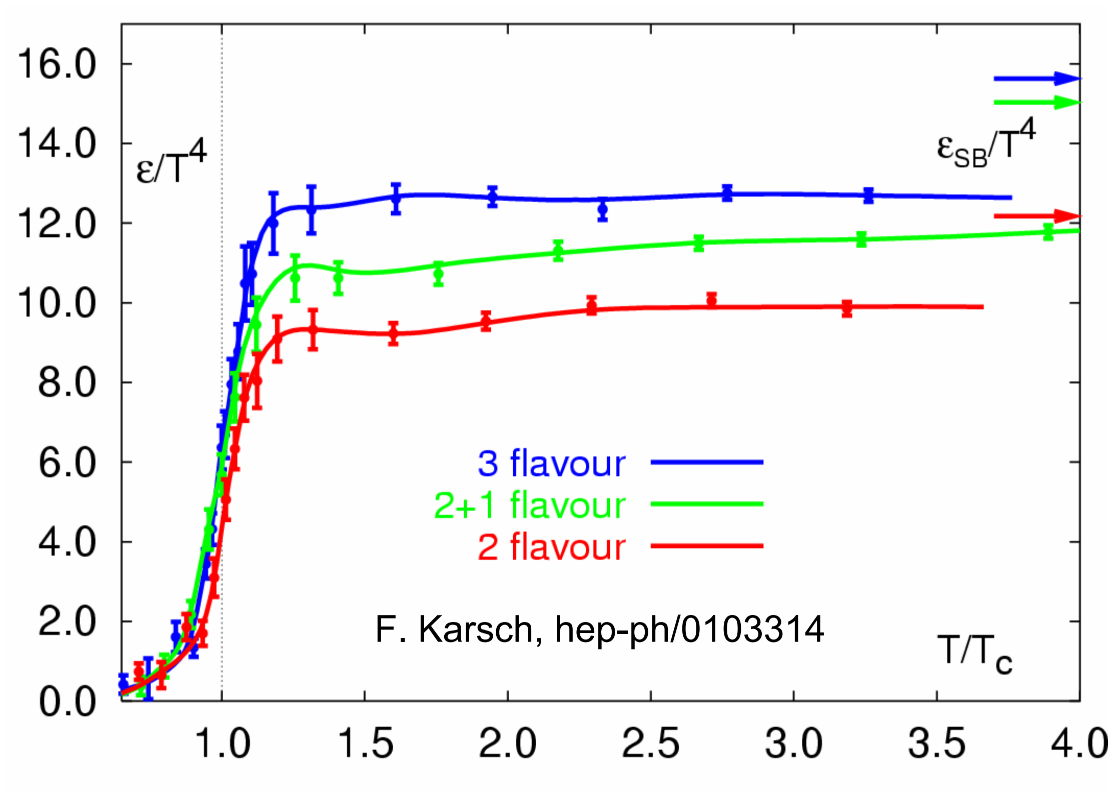
Initial collisi

Dense partonic

Hadron gas phase

Outline: What have we learned at RHIC?
What fundamental questions will we explore in the next 10 years?

What we expected: lattice QCD at finite temperature



Ideal gas (Stefan-Boltzmann limit)

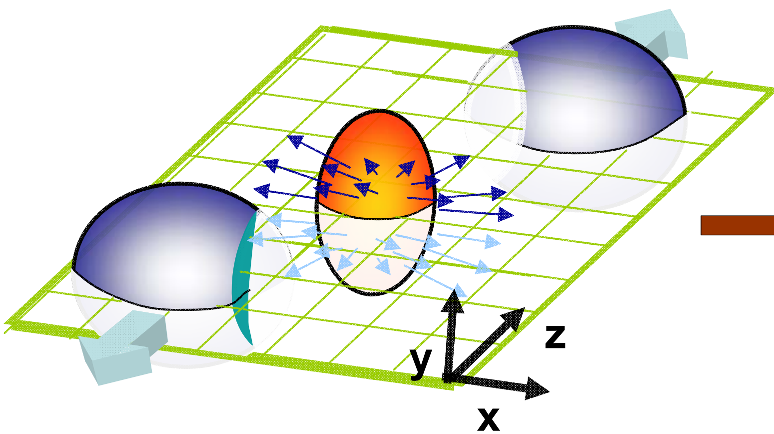
Critical energy density: $\varepsilon_C = (6 \pm 2) T_C^4$

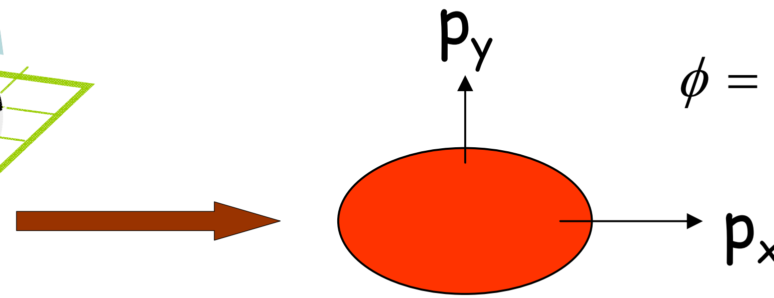
T_C ~ 175 MeV ⇒ ε_C ~ 1 GeV/fm^3

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

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

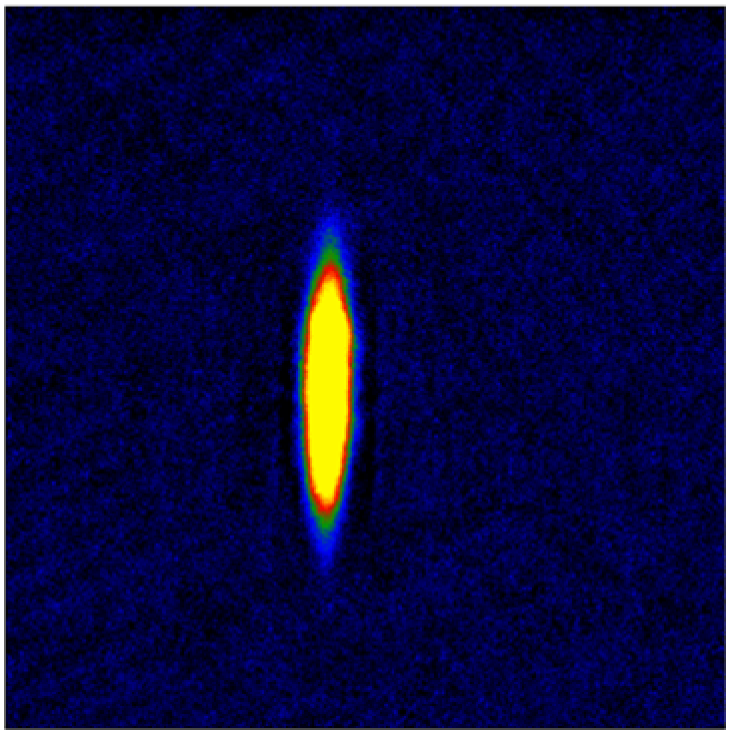
Elliptic term

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

Gas of weakly/strongly interacting Li atoms

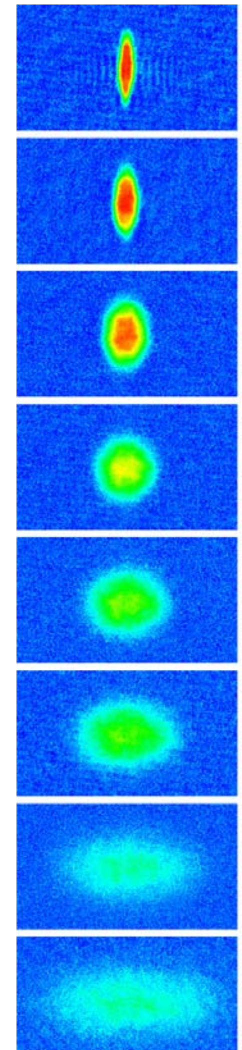
M. Gehm et al, Science 298, 2179

- excite Feshbach resonance

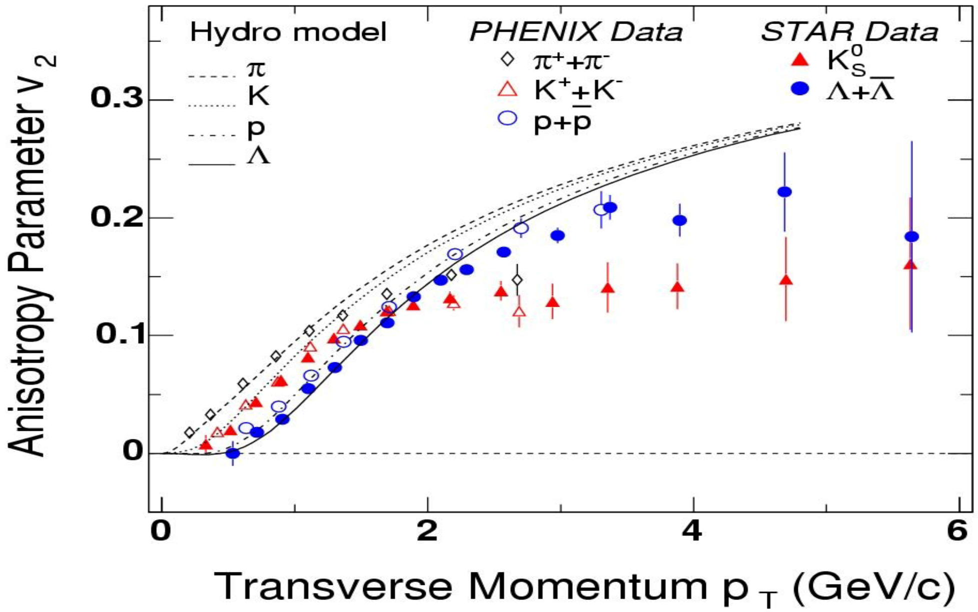


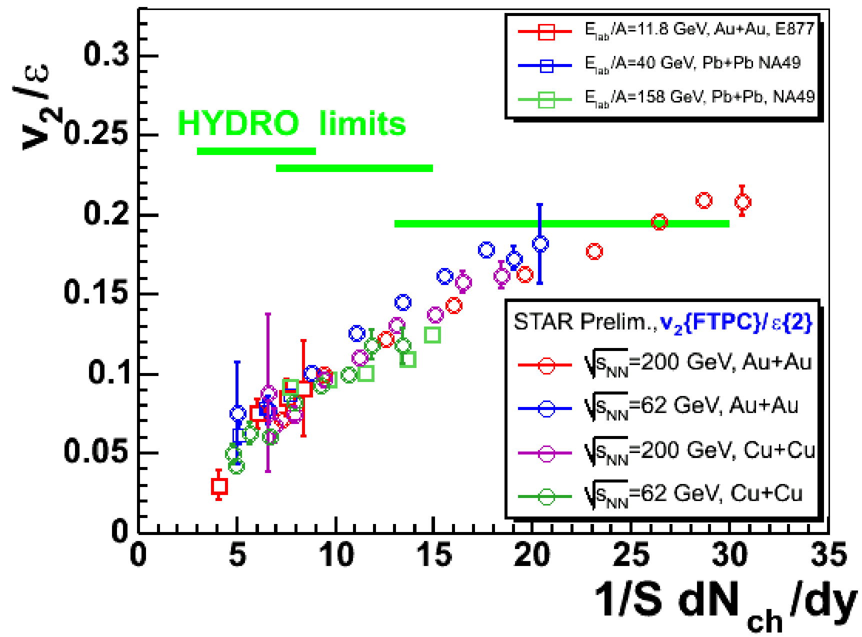
weakly coupled

strongly coupled



Elliptic flow in the hydrodynamic regime

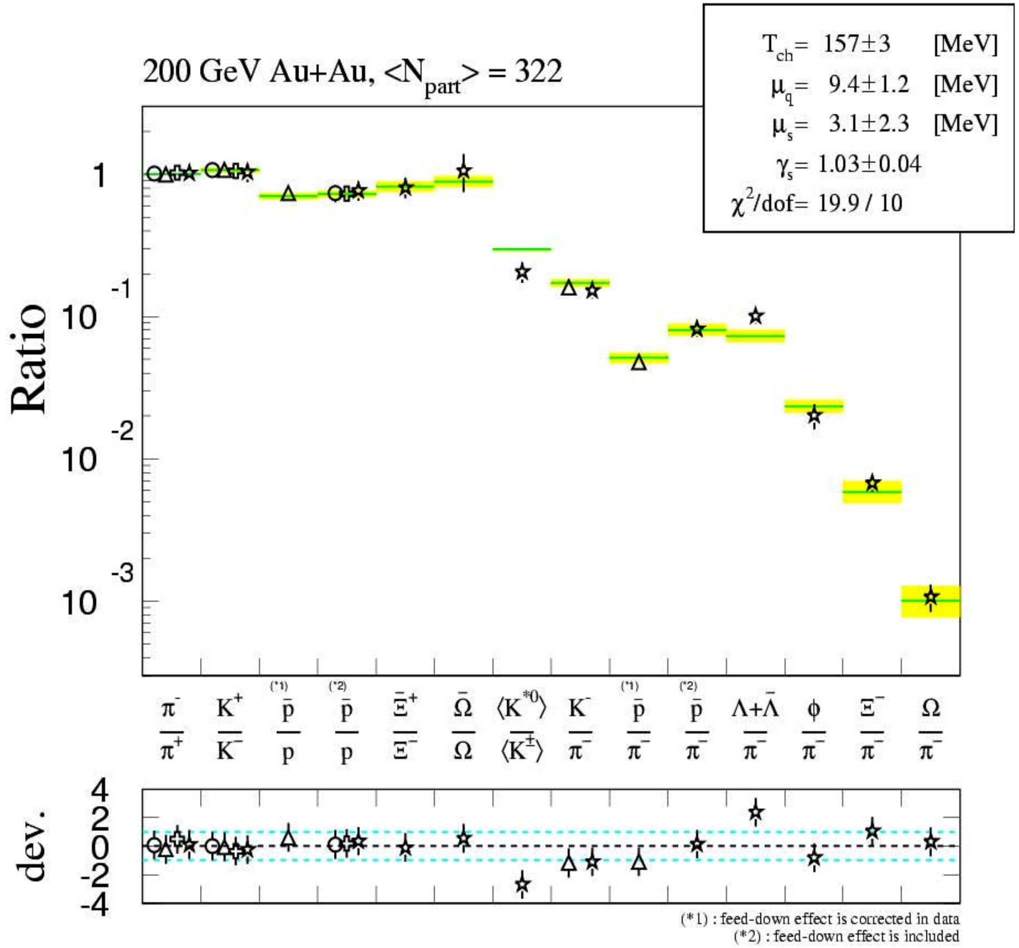




- Hydrodynamic calculations assuming a lattice-motivated EOS and near-zero viscosity ... $_T$ ~ 1.5 GeV/c
- Same calcula ... y
- Elliptic flow sa ...

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

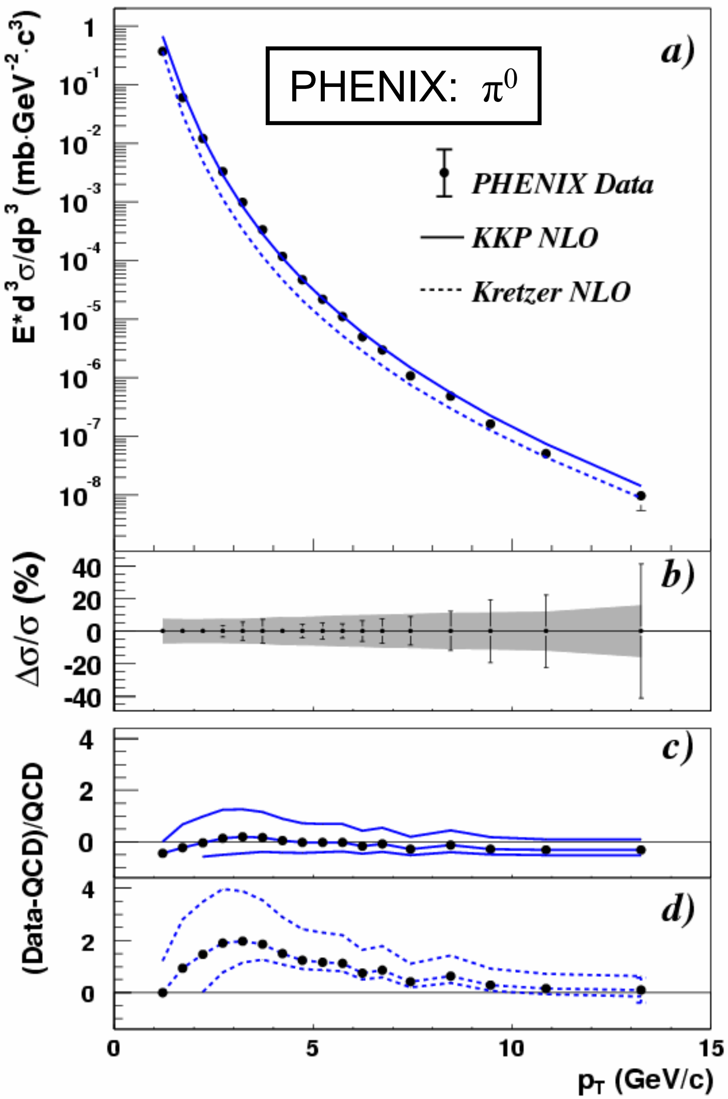
Additional evidence for thermalization



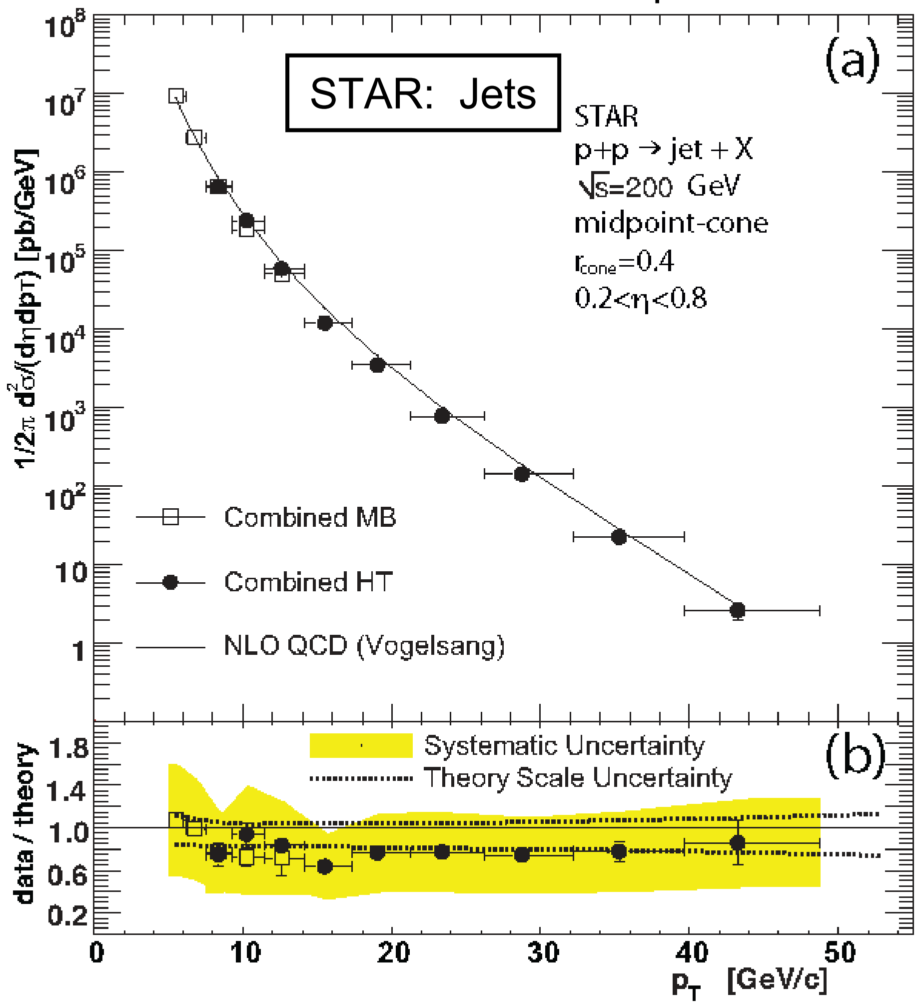
- Particle composition consistent with chemical equilibrium among the hadrons
- Largest deviation (K^*) arises from its short lifetime within the hadron gas phase

Hard scattering at RHIC and NLO pQCD

PRL 91, 241803

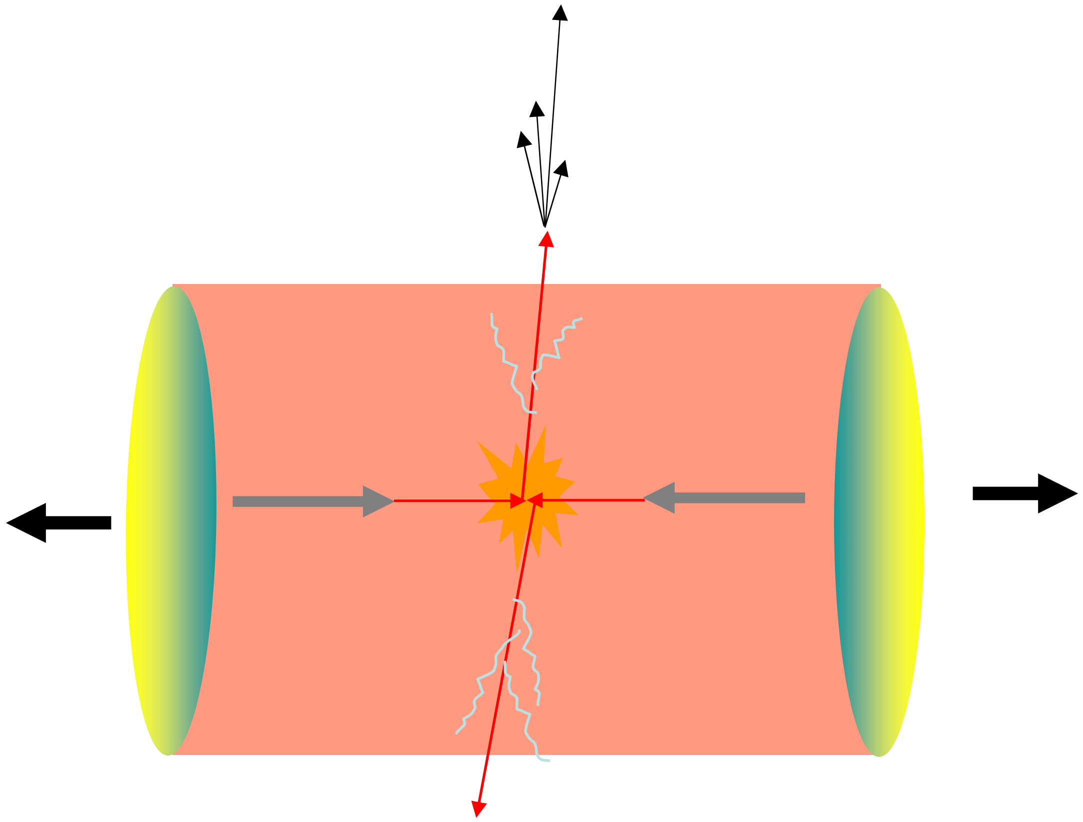


hep-ex/0608030



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

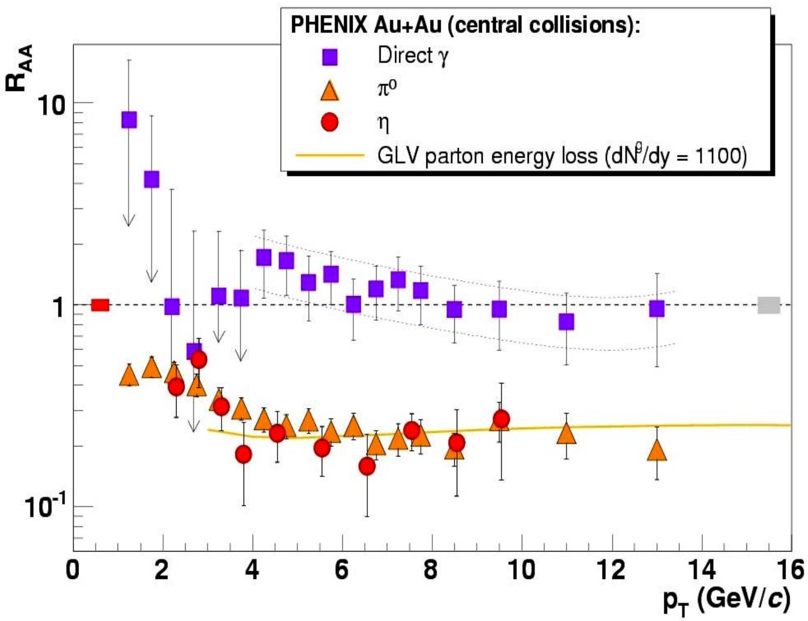
Hard partonic collisions and energy loss in dense matter

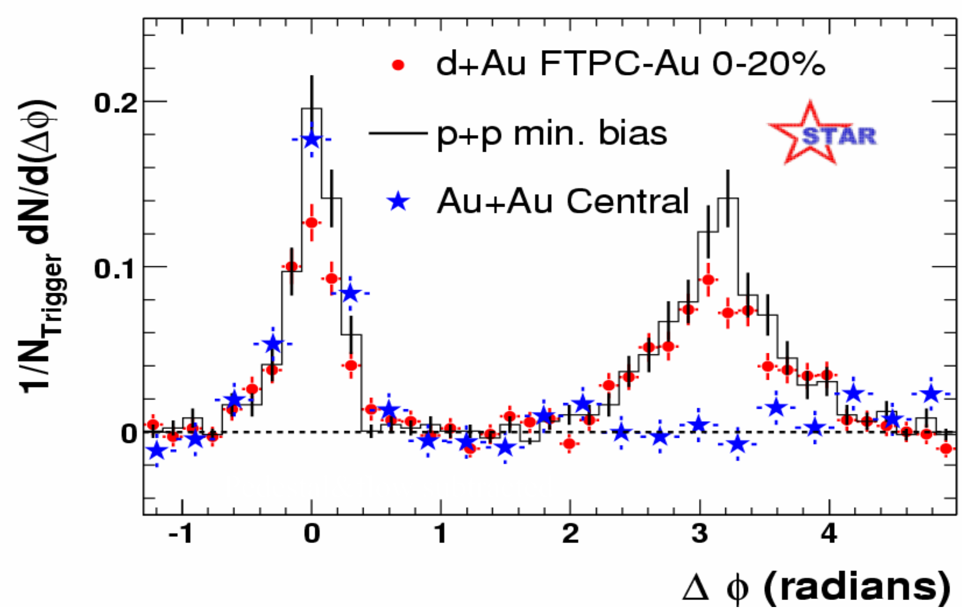


- Embed the hard scattering from a nucleon-nucleon collision into a Au+Au collision
- The final products will interact with the medium

Jet quenching at RHIC

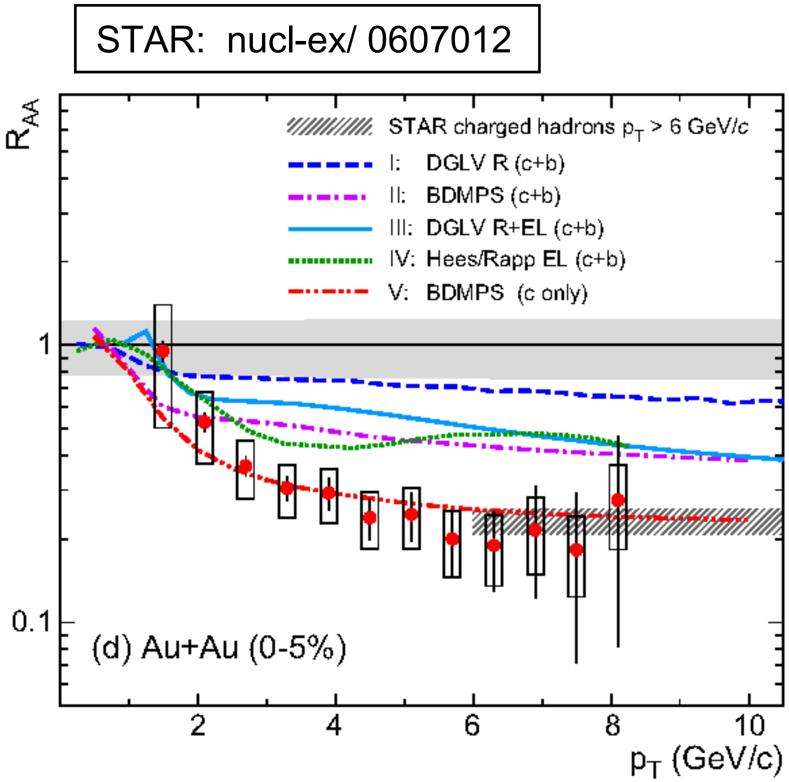
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

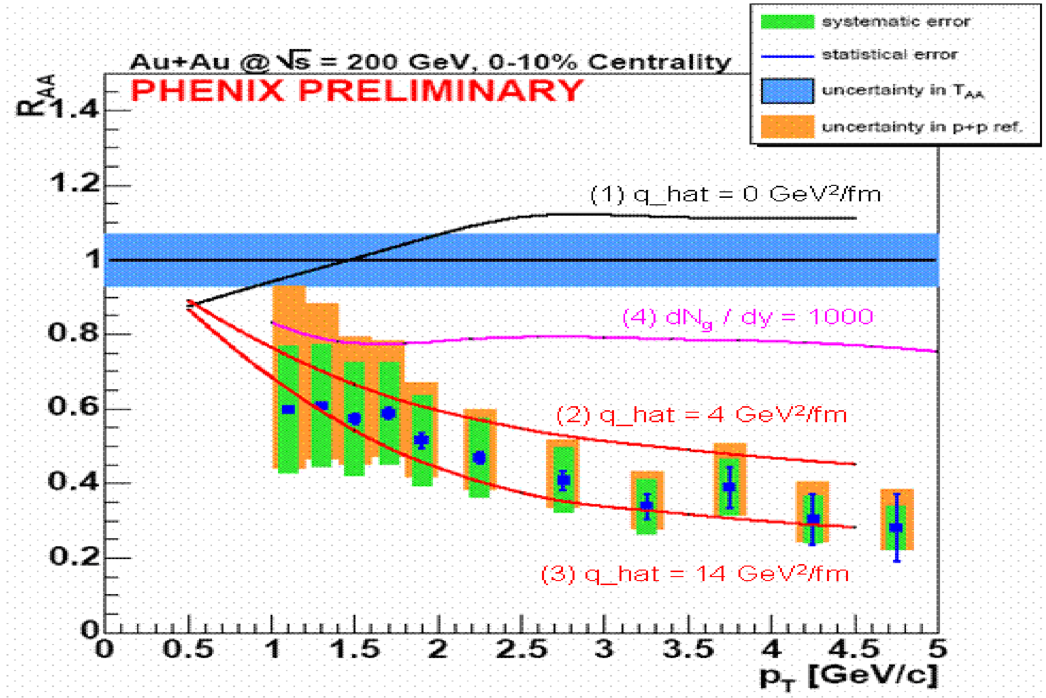




- In central Au+Au collisions:
  - Strong suppression of inclusive hadron production
  - Photons are not suppressed
  - Disappearance of the away-side jet
- d+Au looks like p+p
- Medium density up to 100 times normal nuclear matter

A big surprise: non-photonic electron yields

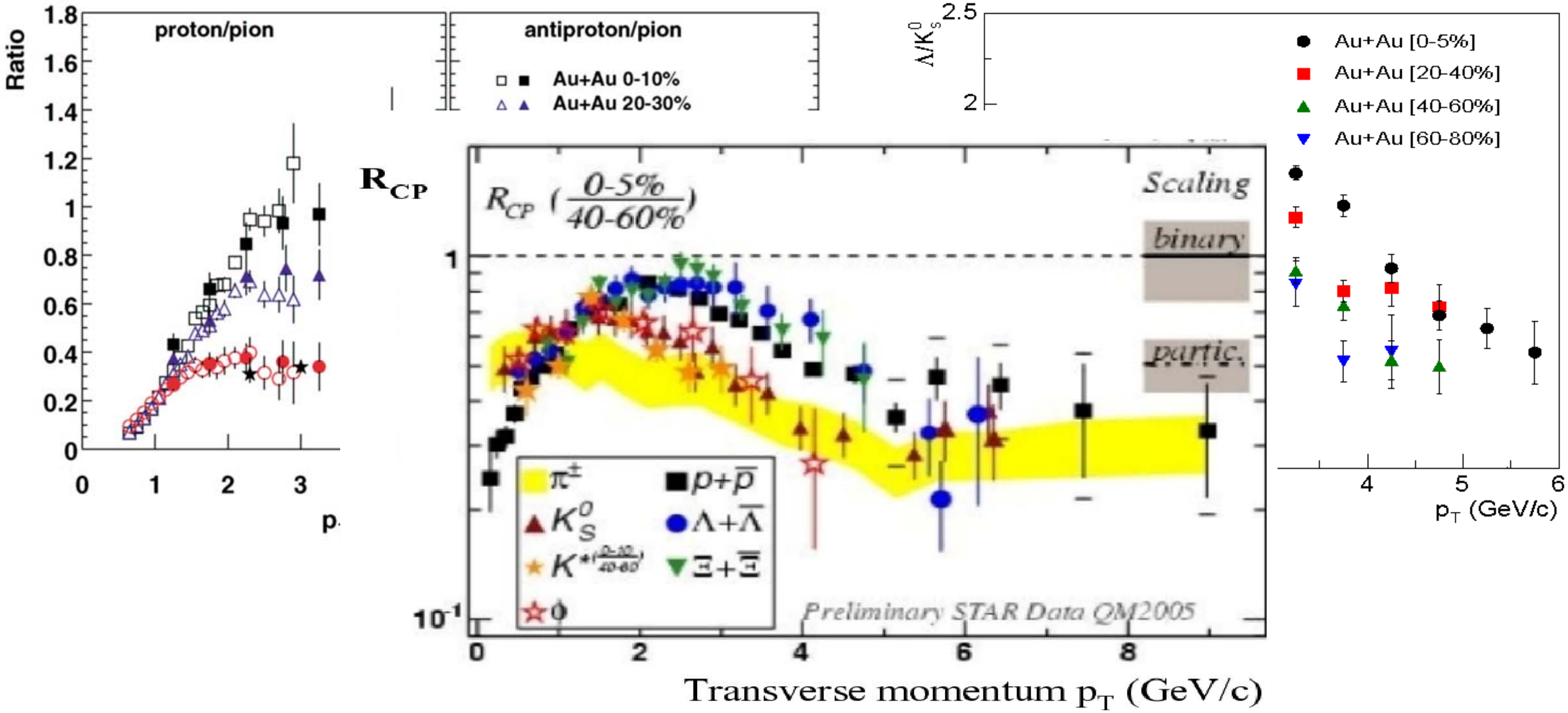




- Heavy quarks (c,b) appear as suppressed as light quarks
- Another indication of very short thermalization times and very strong interactions in the medium

Baryons vs. mesons

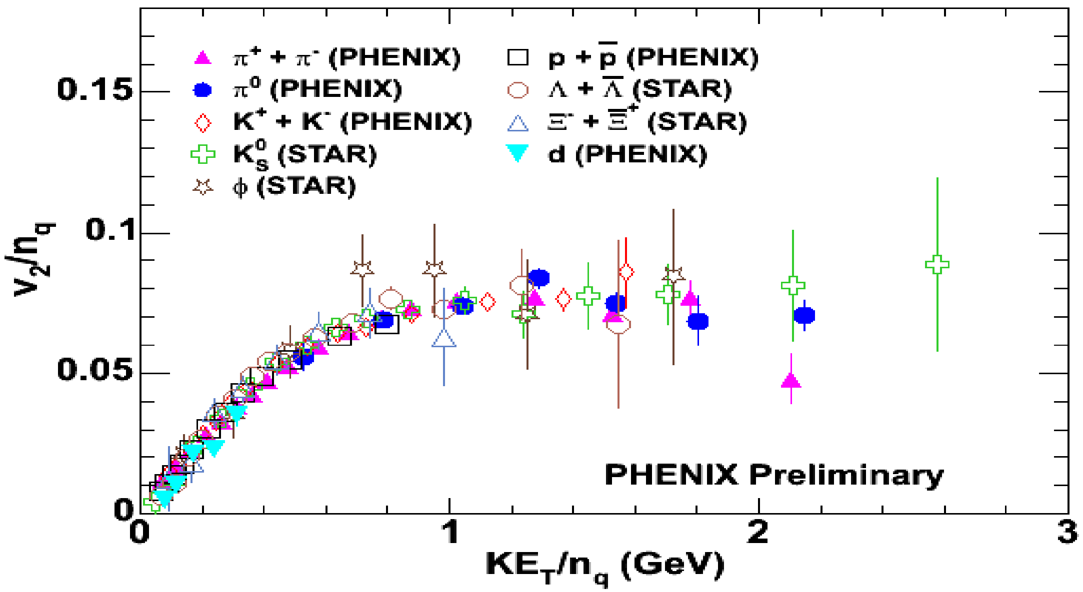
PHENIX: PRL 91, 172301 STAR: nucl-ex/0601042

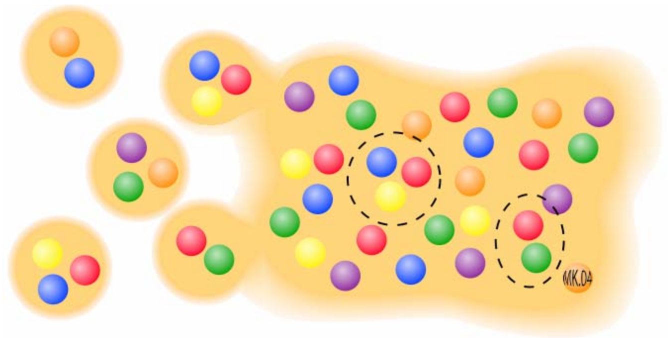


In central Au+Au collisions, baryons are substantially overproduced relative to mesons at intermediate p_T

Understood as evidence for hadron formation through quark coalescence

What if quarks coalesce to make hadrons?





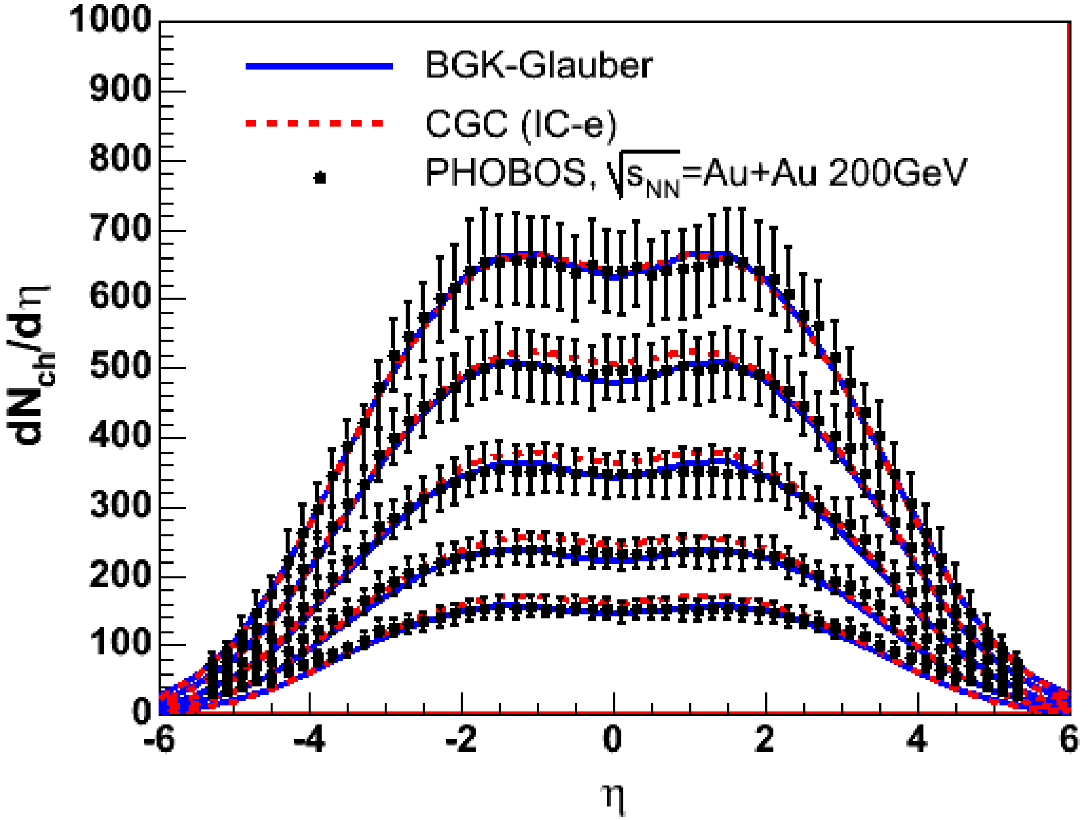
$$\frac{dN}{d\phi} \propto \left[1 + 2v_2(p_T)\cos(2\phi) + \cdots\right]$$

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

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

- v_2 obeys constituent quark scaling
  - Hadronization through **coalescence**
  - Evidence for **flowing quarks** (?)

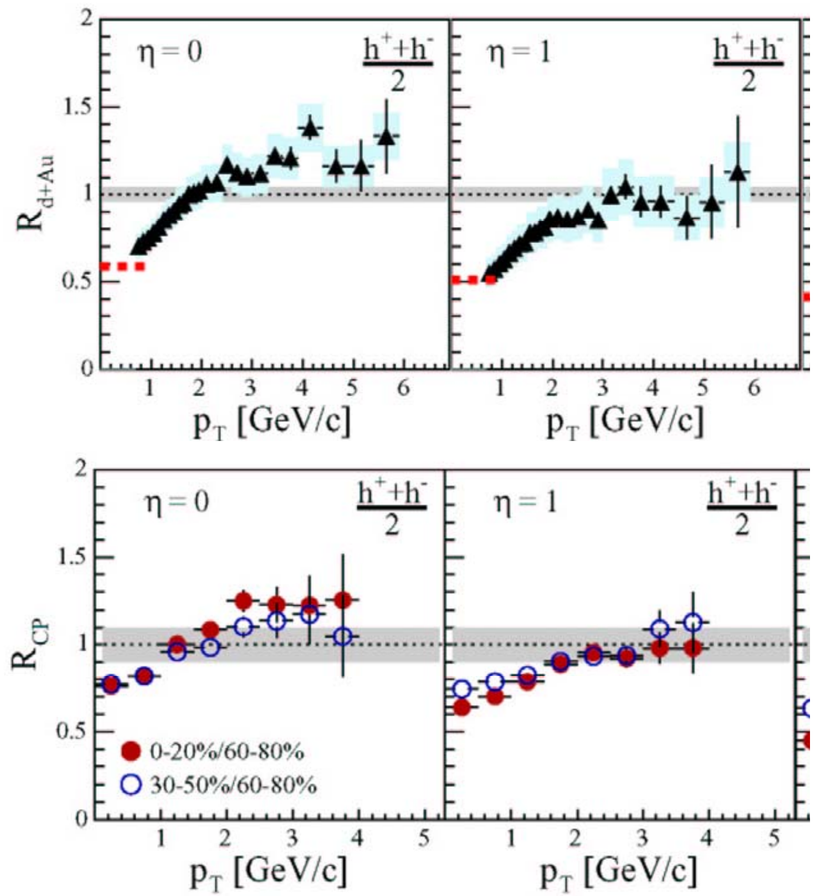
Particle multiplicity vs. pseudorapidity

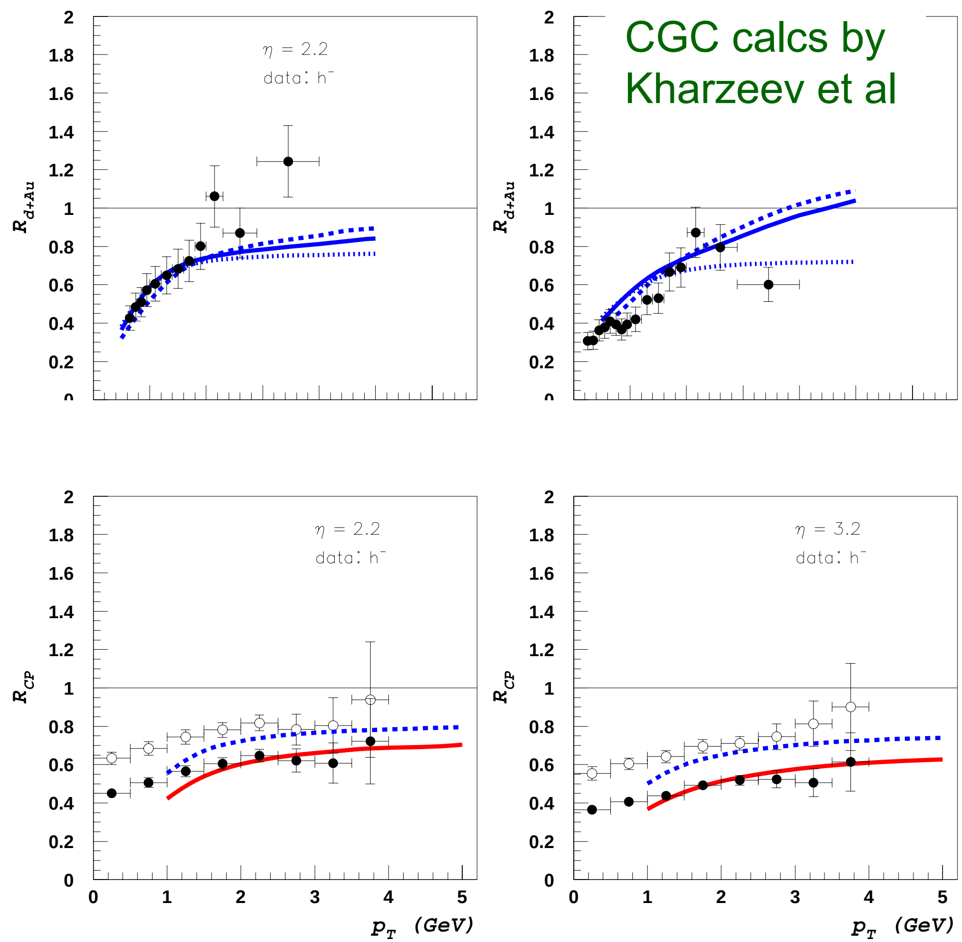


- Multiplicities well described by Color Glass Condensate model
- Evidence for saturated gluon fields in the Au nucleus?

Forward particle production in d+Au collisions

BRAHMS, PRL 93, 242303





CGC calcs by Kharzeev et al

- 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

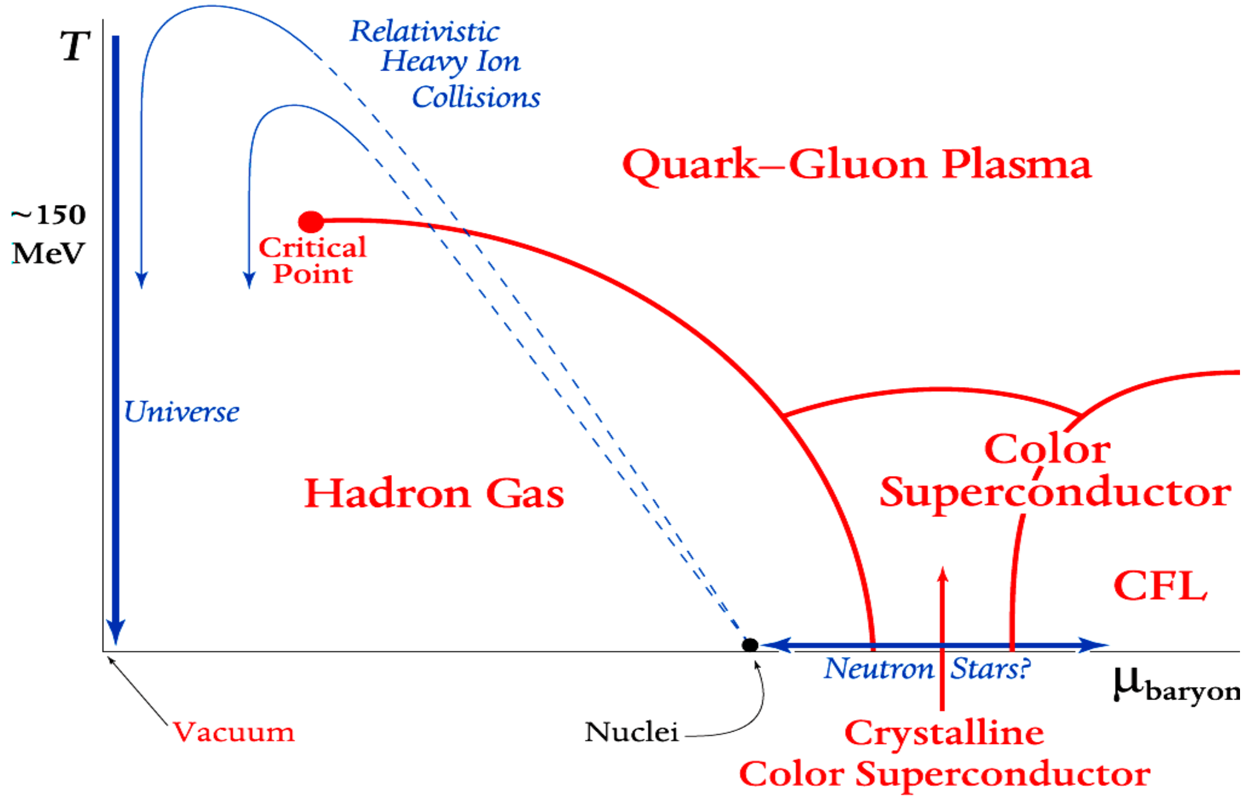
Looking backward – looking forward

- Some critical aspects of RHIC's success to date
  - First-ever colliding beams of heavy nuclei
  - World's first and only polarized proton collider
  - Dedicated, flexible facility
    - Multiple collision systems and/or energies in a single years
    - Ability to respond rapidly to emerging physics results
  - Rapidly improving machine performance
  - Powerful detectors to unravel the physics
- Some critical aspects of RHIC's future success
  - Enhance the ability to observe crucial rare signals
    - PHENIX and STAR detector upgrades
    - RHIC II luminosity upgrade: a factor of 10 for heavy ions and 3 for polarized protons
  - Enhance the flexibility of the facility
    - Many critical questions can only be answered by comparative studies of several different collision systems and/or energies
  - Unique beams (e.g., polarized protons) and energy regime
  - Complementary programs coming on-line at LHC (2009) and FAIR (~2014)

Fundamental questions for the future of RHIC

- To be explored with heavy ion collisions:
  - **What are the phases of QCD matter?**
  - **What is the nature of non-equilibrium processes in a fundamental theory?**
- To be explored with p(d)+A collisions:
  - **What is the wave function of a heavy nucleus?**
- To be explored with polarized p+p collisions:
  - **What is the wave function of the proton?**

What are the phases of QCD matter? What is the nature of non-equilibrium processes in a fundamental theory?



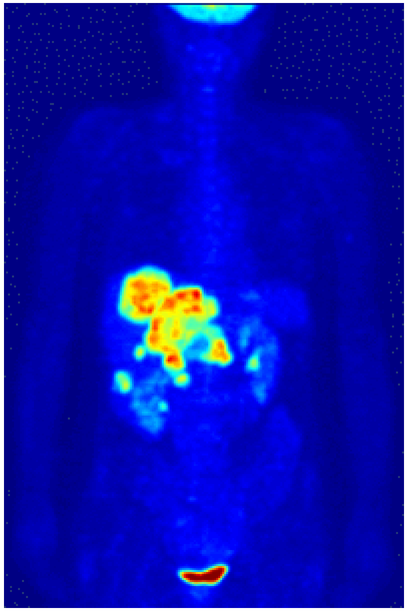
- We've learned stunning things over the past six years!
- Now we need to develop a **detailed, quantitative understanding** of the dense, strongly interacting matter that's been created

Some key scientific questions

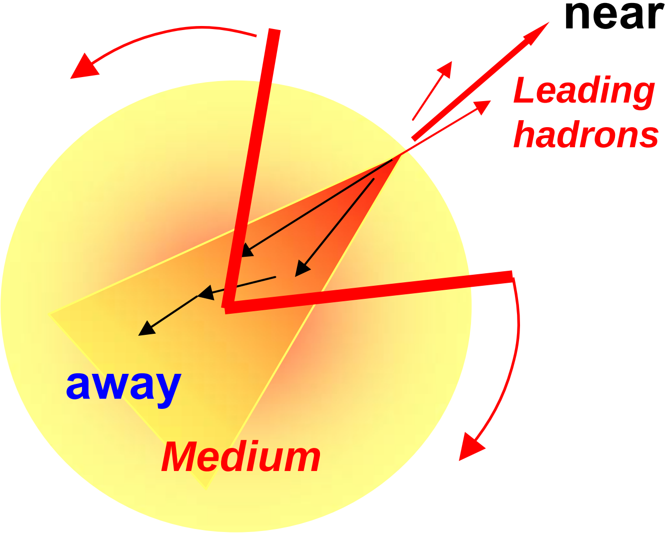
- What is the mechanism of the unexpectedly fast thermal equilibration?
- What is the initial temperature and thermal evolution of the produced matter?
- What is the energy density and equation of state of the medium?
- What is the viscosity of the produced matter?
- Is there direct evidence for deconfinement, color screening, and a partonic nature of the hot, dense medium? What is the screening length?
- Can we directly observe a QCD phase transition? Where is the QCD critical point?
- Is chiral symmetry restored, as predicted by QCD?
- How does the new form of matter hadronize at the phase transition?

Energy density and equation of state?

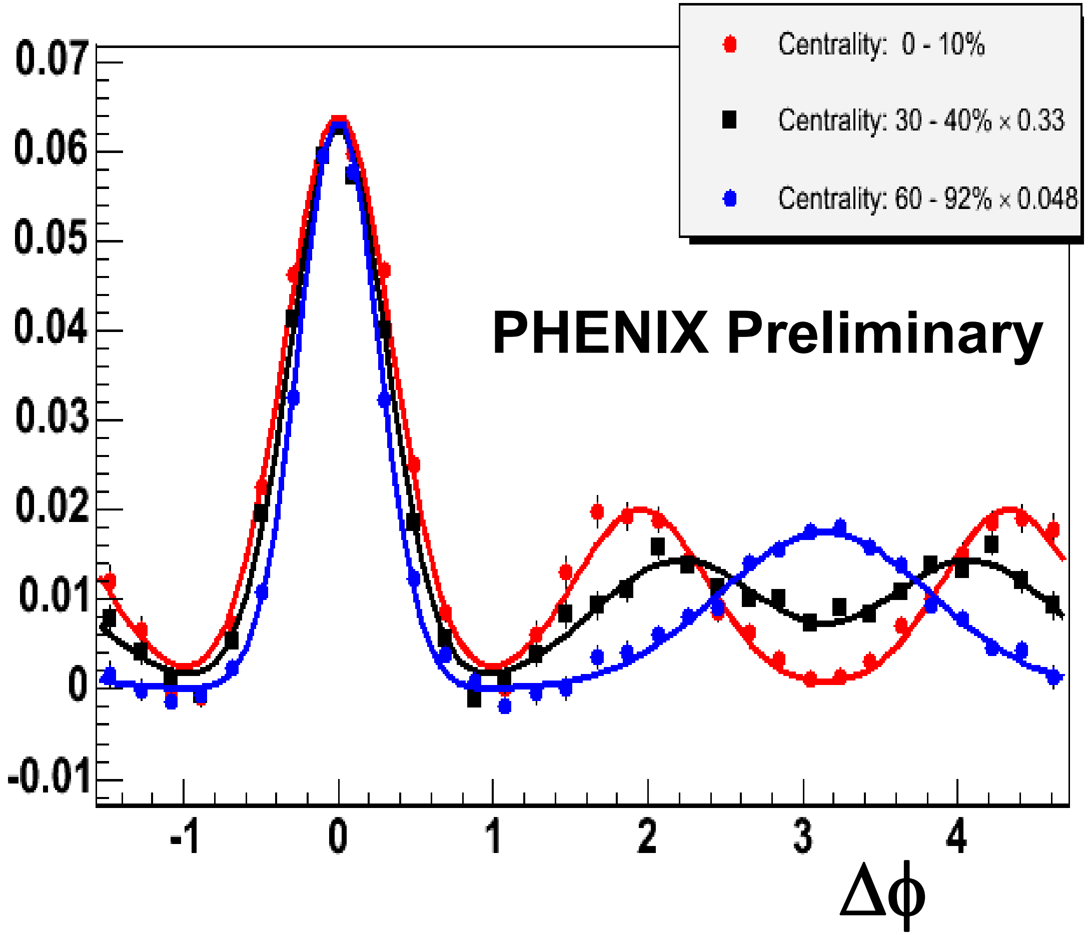
- One goal: use jets as a tomographic probe to map the medium
  - Compare light-quark, heavy-quark, and gluon jet interactions
  - Calibrate with γ+jet coincidences
  - Need both upgrades to PHENIX and STAR and RHIC II luminosities
  - Will be done at both RHIC and LHC
    - **How will the plasmas be different?**



- Another goal: use jets to induce excitations of the medium



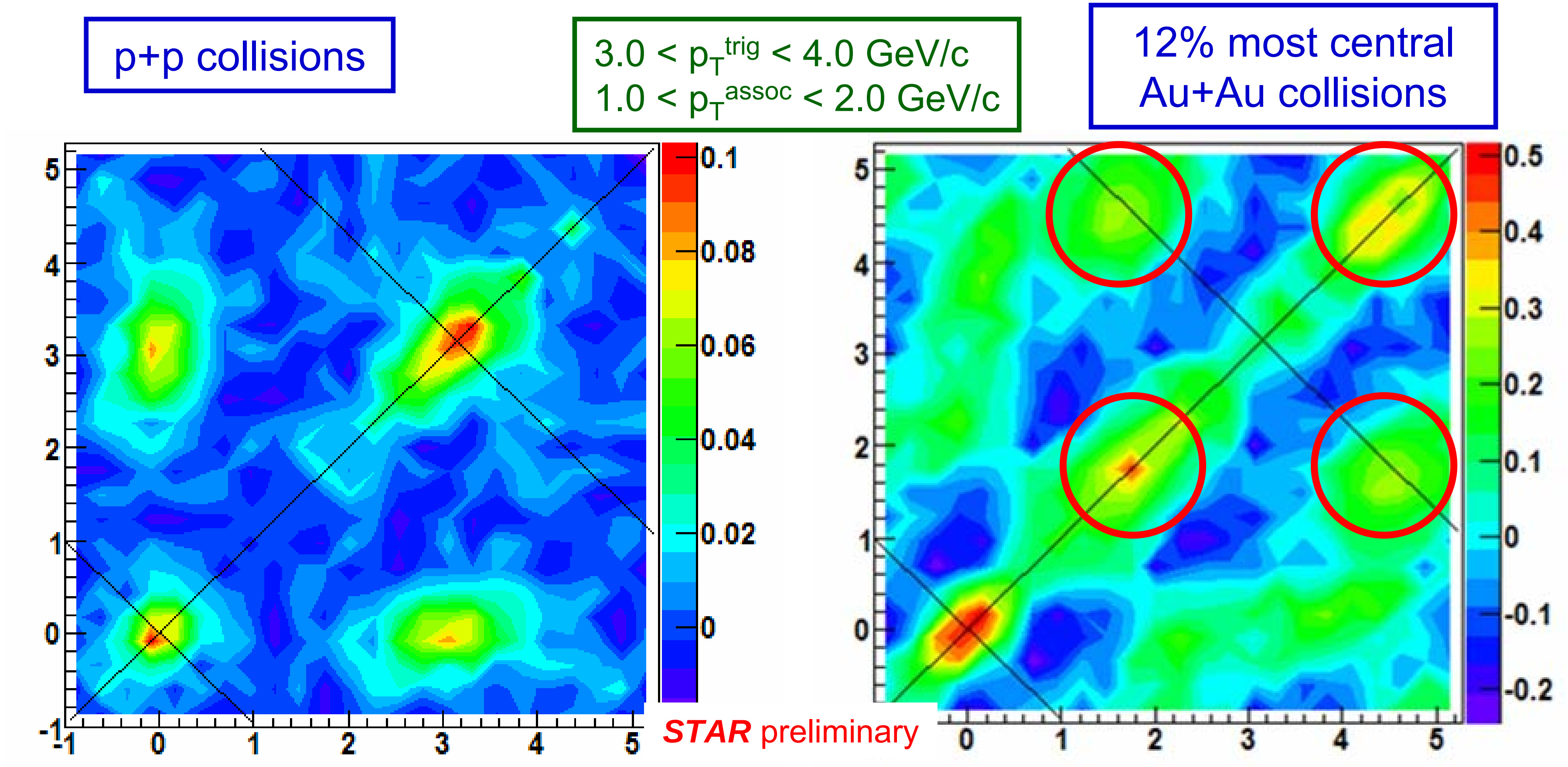
How does the medium respond to a jet?



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

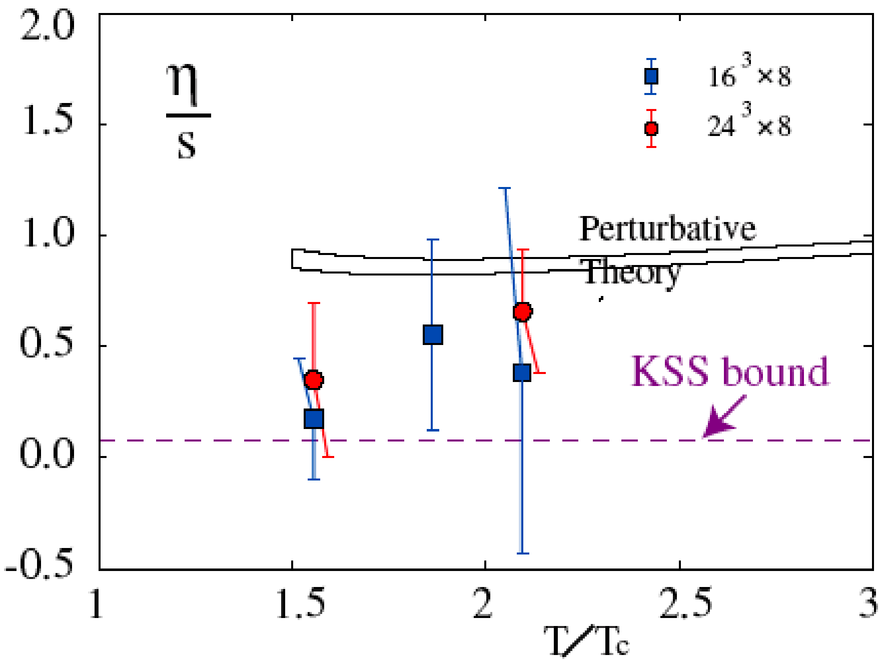


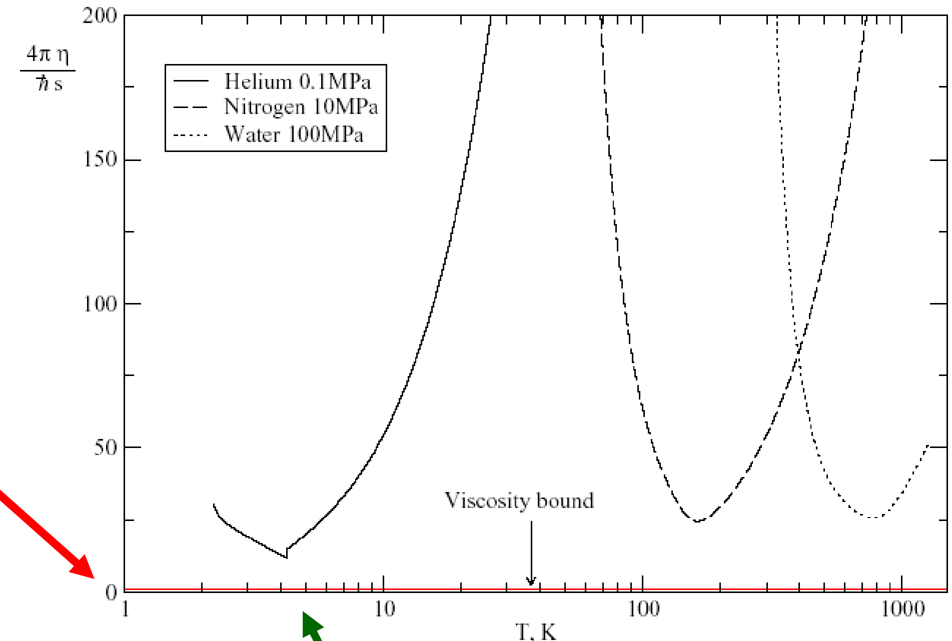
- Enhancements on the diagonals at ~ $\pi \pm 1.4$ radians?
- Would profit greatly from an order of magnitude more data than were taken in Run 4 and large-acceptance particle identification
- May be difficult to measure at the LHC due to the large number of “soft” jets present in each head-on Pb+Pb event

What is the viscosity?

How perfect is our liquid?

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





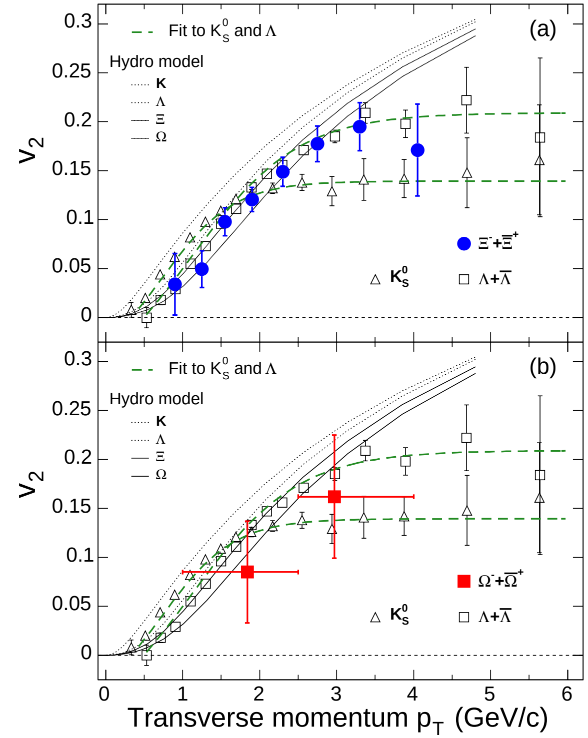
Superfluid helium

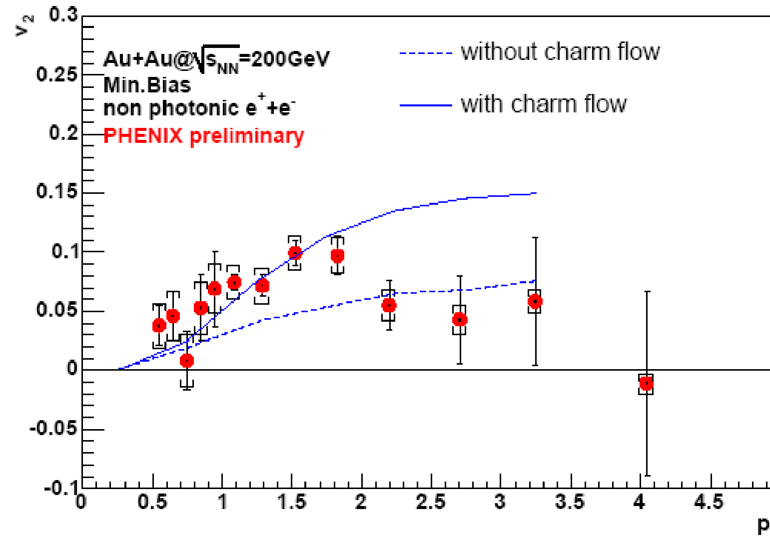
KSS bound:
strongly coupled SUSY QCD = classical supergravity

How do we measure viscosity?

STAR:
PRL 95, 122301

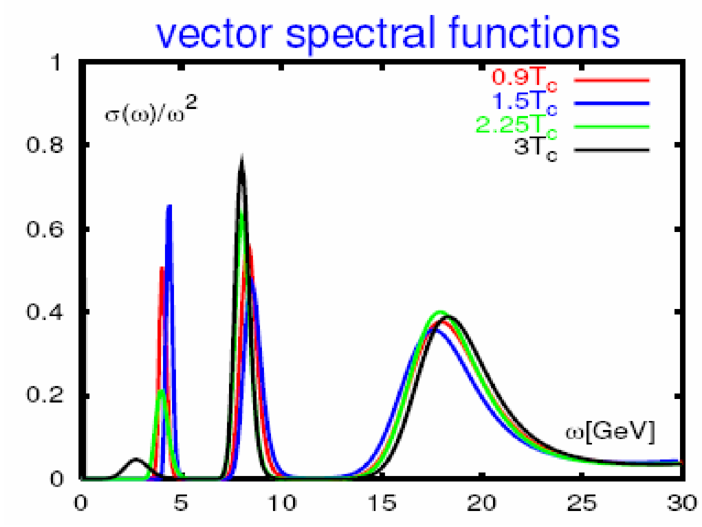
- Need:
  - Radial, directed, elliptic flow measurements for several identified hadron species. Particularly valuable:
    - Multi-strange hadrons φ, Ξ, Ω (reduced coupling to hadron gas phase)
    - D mesons (establish thermalization time scale)
  - A large number of symmetric and asymmetric collision systems and beam energies
  - Continued progress on viscous relativistic hydrodynamic theory
- **Only practical** in a finite time **at RHIC II**





Deconfinement and color screening?

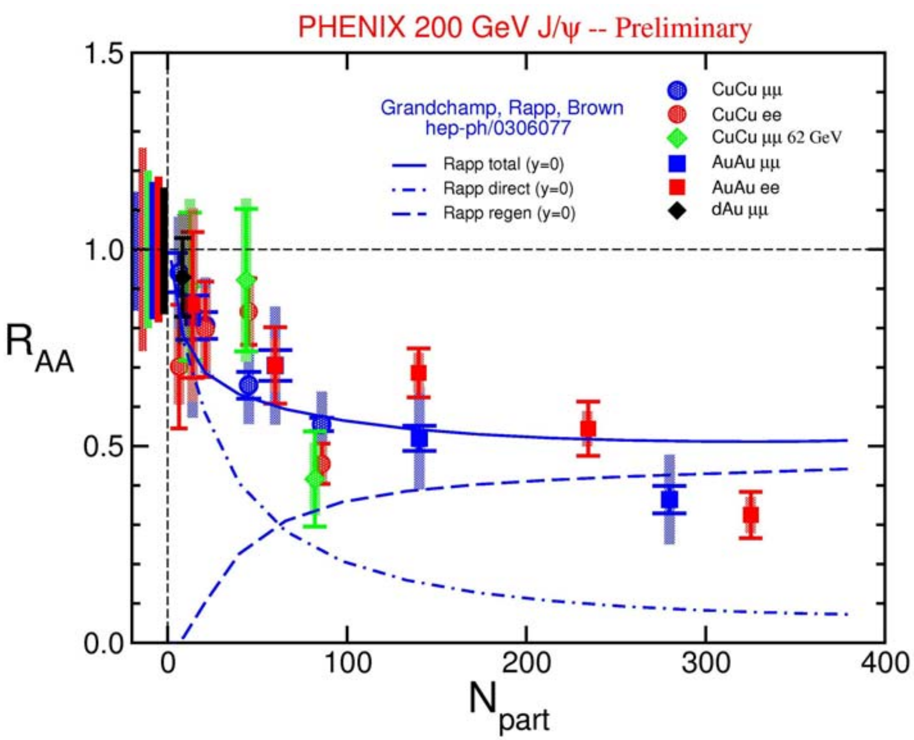
- Classic proposal: quarkonium suppression by color screening.
- Lattice QCD calculations tell us the world is more complicated than we thought! Quarkonium resonances should persist above T_c.
- Hierarchy of melting:

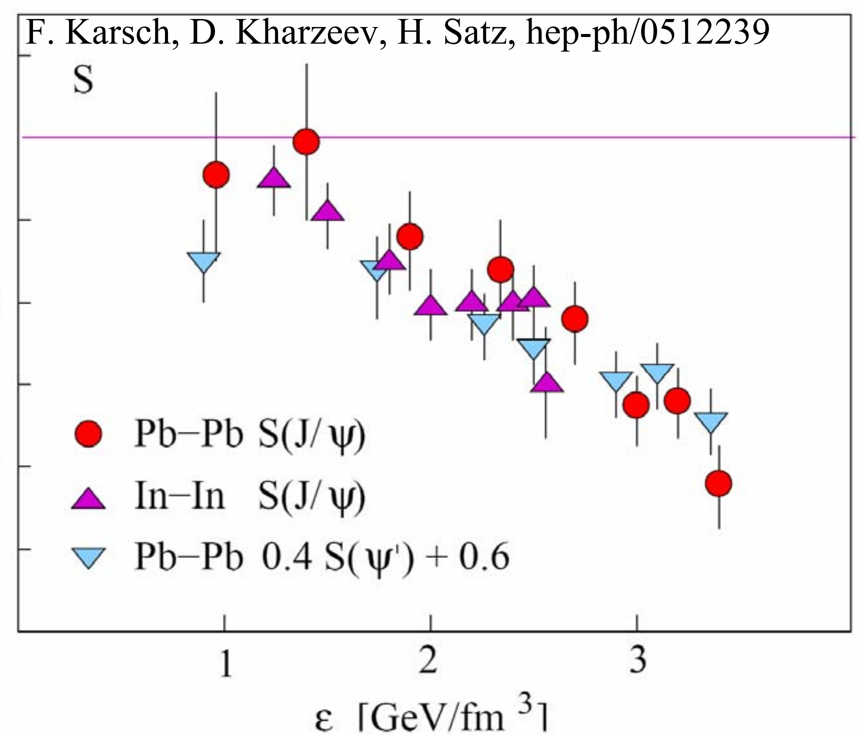


State	$J/\psi(1S)$	$\chi_c(1P)$	$\psi'(2S)$	$\Upsilon(1S)$	$\chi_b(1P)$	$\Upsilon(2S)$	$\chi_b(2P)$	$\Upsilon(3S)$
T_d/T_c	2.10	1.16	1.12	>4.10	<1.76	1.60	1.19	1.17

- Also recombination: c+c → J/ψ

Current status





- Suppression + regeneration describes PHENIX results well
- Sequential melting also works if you assume the *J/ ψ* doesn't melt

How to discriminate?

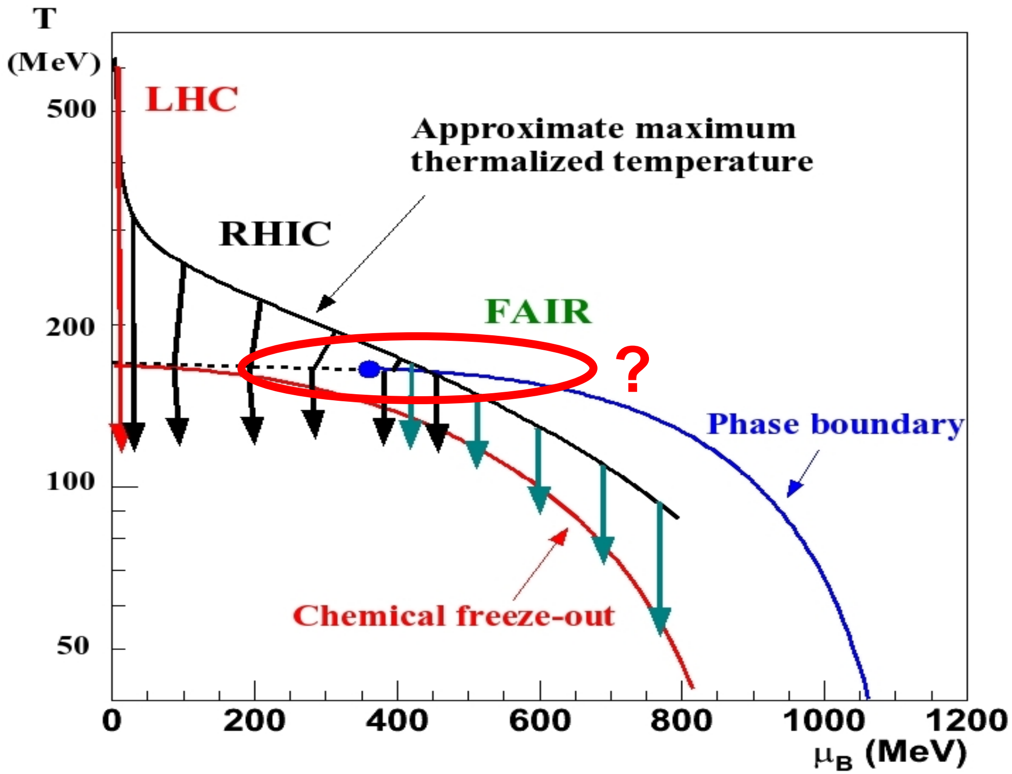
- Compare model predictions to measurements of:
  - *J*/ψ spectrum modifications vs. rapidity and beam energy
  - *J*/ψ elliptic flow
- Need ψ' and χ_c measurements, both as inputs to the model calculations and to provide direct evidence for melting
- Need bottomonium (separated 1s,2s,3s), where the expected effects are quite different from charmonium

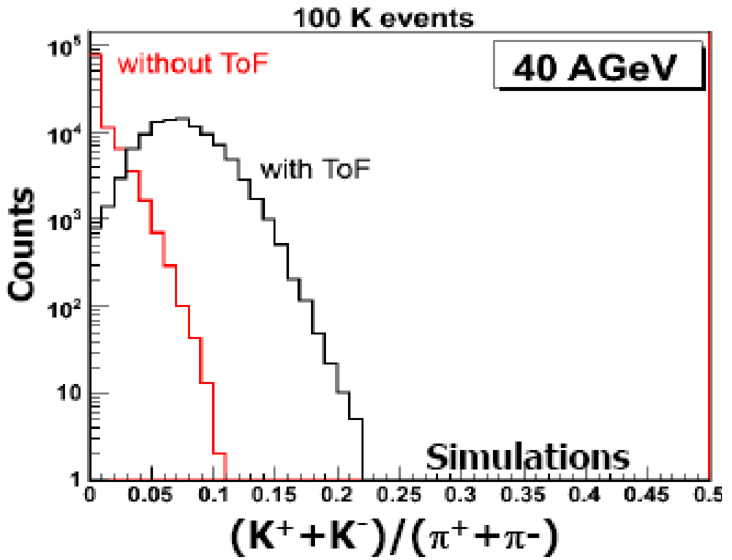
- These measurements require upgraded detector capabilities and RHIC II luminosity

Complementarity of RHIC II and LHC

- Far more heavy quarks per collision at LHC:
  - Head-on Au+Au collision at RHIC: $N_{cc} \sim 10$ $N_{bb} \sim 0.05$
  - Head-on Pb+Pb collision at LHC: $N_{cc} \sim 115$ $N_{bb} \sim 5$
- Far more collisions per year at RHIC II
- Detected quarkonium per year will be comparable at RHIC II (full energy) and LHC
- But:
  - For **charmonium**: mixture of effects at full energy RHIC II, can turn off recombination with longer runs at lower energy; recombination at LHC
  - For **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

Where is the QCD critical point?

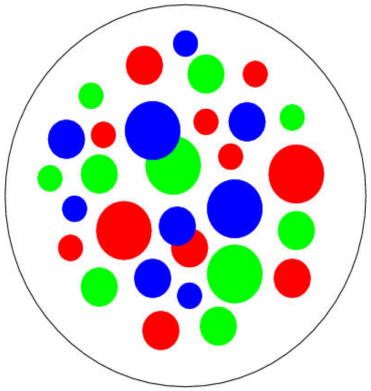




A possible signature: event-by-event K/π fluctuations. Needs large-acceptance PID.

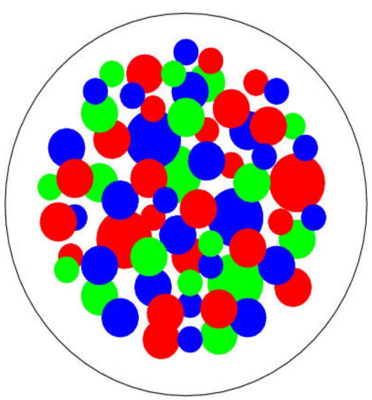
- **The "landmark" on the QCD phase diagram!**
- Lattice calculations: between μ_B of <~200 and >~700 MeV.
- **RHIC can find it if μ_B < 500 MeV**
- Need detailed study of many different collision energies
- Significant advantage of RHIC: with collider detectors, most systematic effects are constant with beam energy
- Low energy electron cooling would greatly increase the luminosity

What is the wave function of a heavy nucleus?

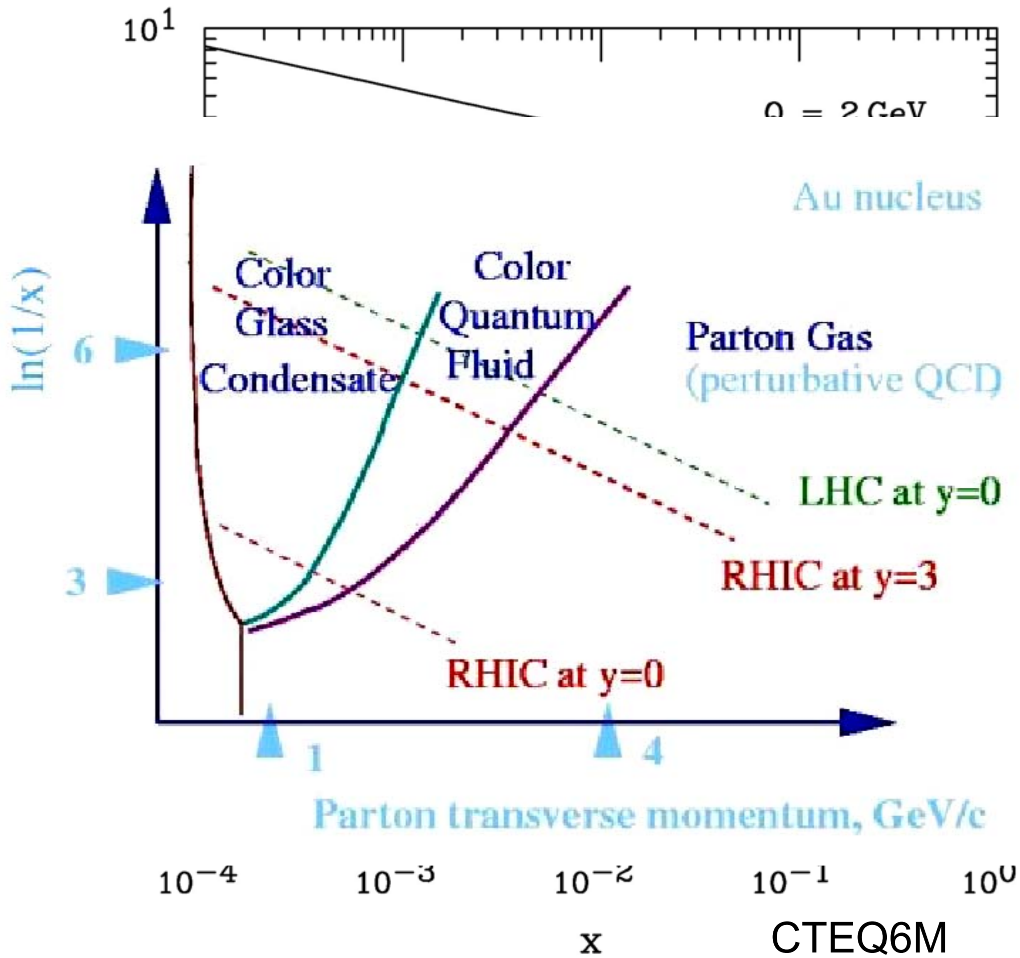


Mid Rapidity

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



Forward Rapidity

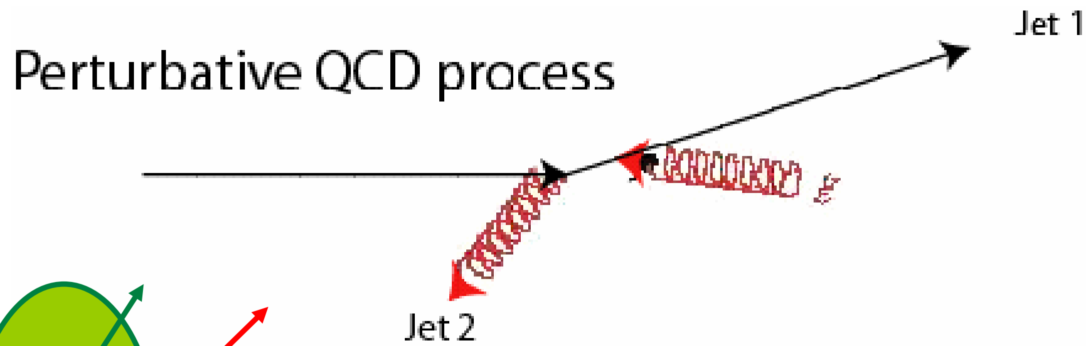


Gluon density can't grow forever.

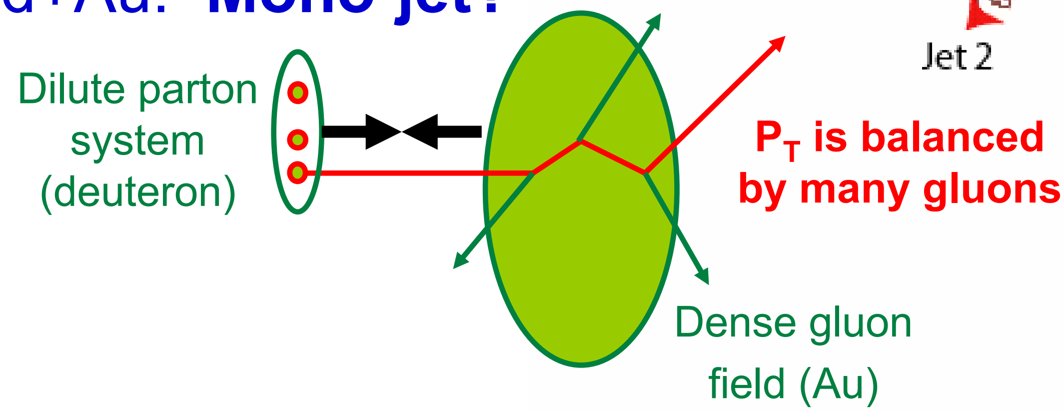
Saturation must set in at forward rapidity when the gluons overlap.

To elucidate the underlying dynamics: large acceptance correlation measurements

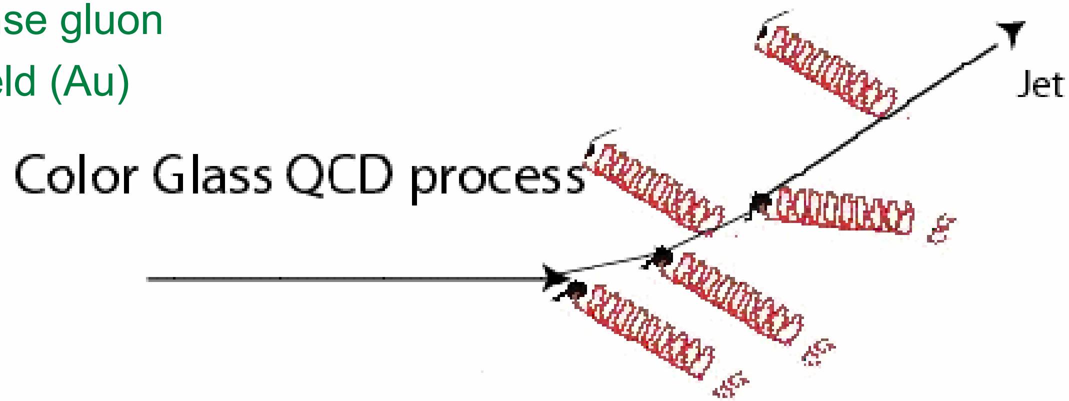
p+p: **Di-jet**



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



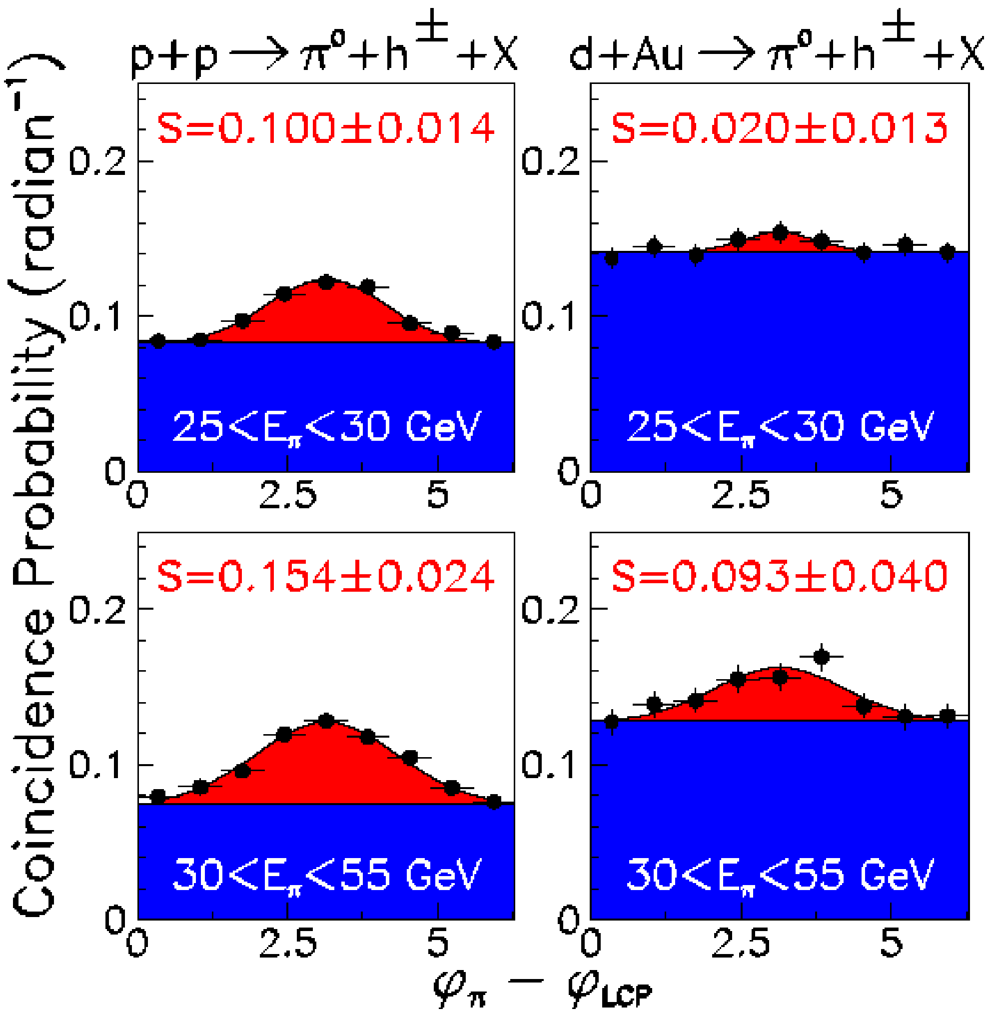
Kharzeev, Levin, McLerran gives physics picture (NPA748, 627)



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

Maybe we have a hint

STAR: nucl-ex/0602011



π^0: $|\langle\eta\rangle| = 4.0$

$h^{\pm}$: $|\eta| < 0.75$; $p_T > 0.5$ GeV/c

- An exploratory measurement shows the right trends, but is far from conclusive.
- Detector upgrades underway now will facilitate seminal measurements within the next few years.
- **If gluon saturation is the right answer, then RHIC II will be the ideal place to explore the underlying mechanism in follow-up measurements with more sensitive – but much rarer – probes.**

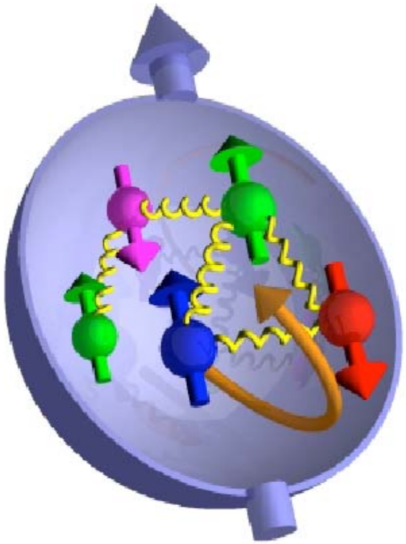
What is the wave function of the proton?

Proton spin:

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

Only ~25% of the total

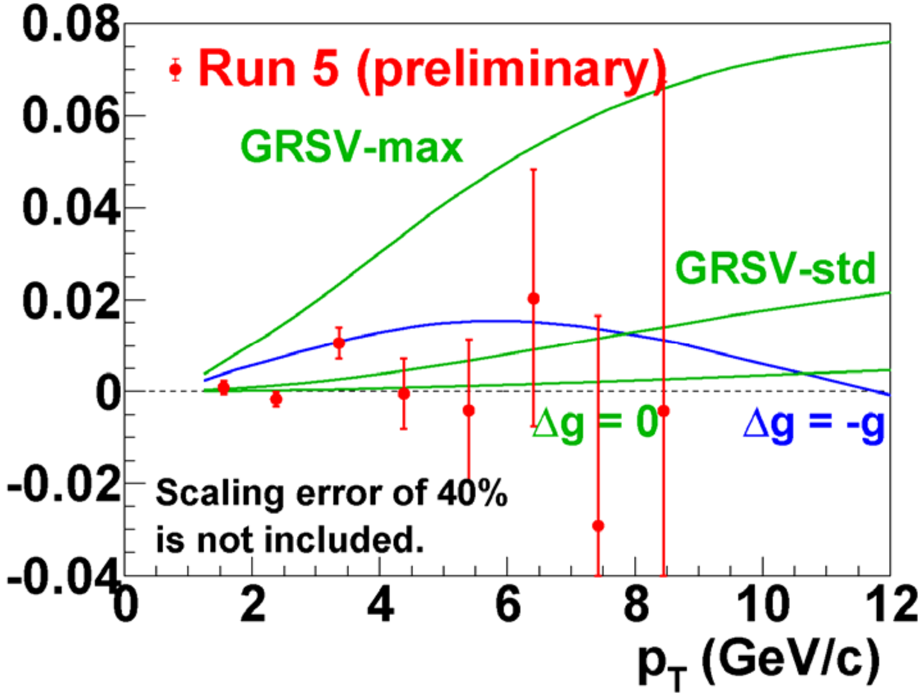
"Spin crisis"



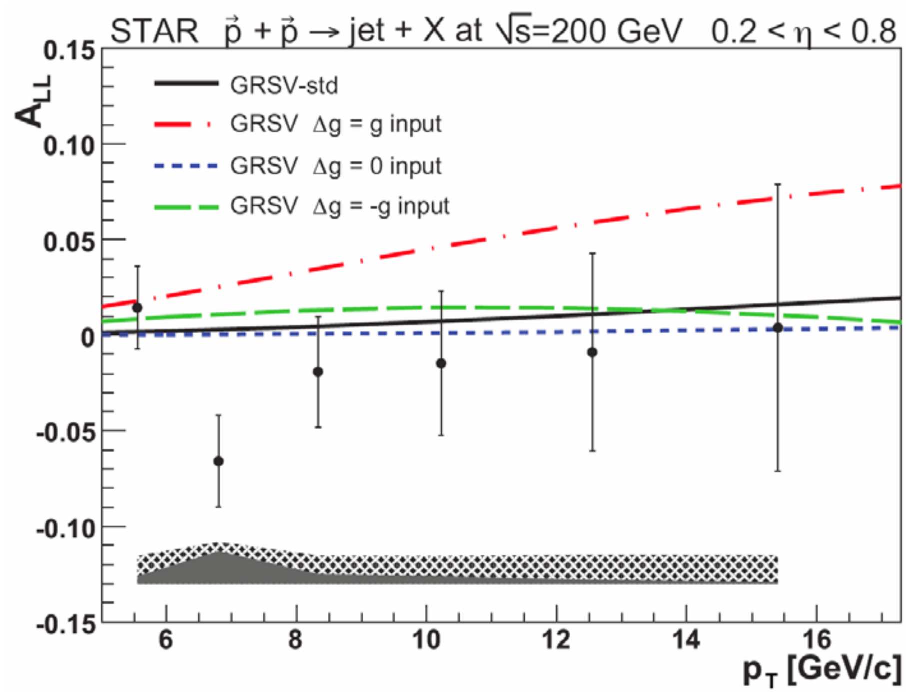
- RHIC spin program is on a multi-year quest to find the proton spin
  - Gluon polarization – underway
  - Orbital motion and transversity – in the early exploratory phase
  - Anti-quark polarization – needs detector and accelerator improvements (underway now) for first measurements
- All will **profit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

Initial results for gluon polarization

PHENIX prelim Run 5 $A_{LL}(\pi^0)$

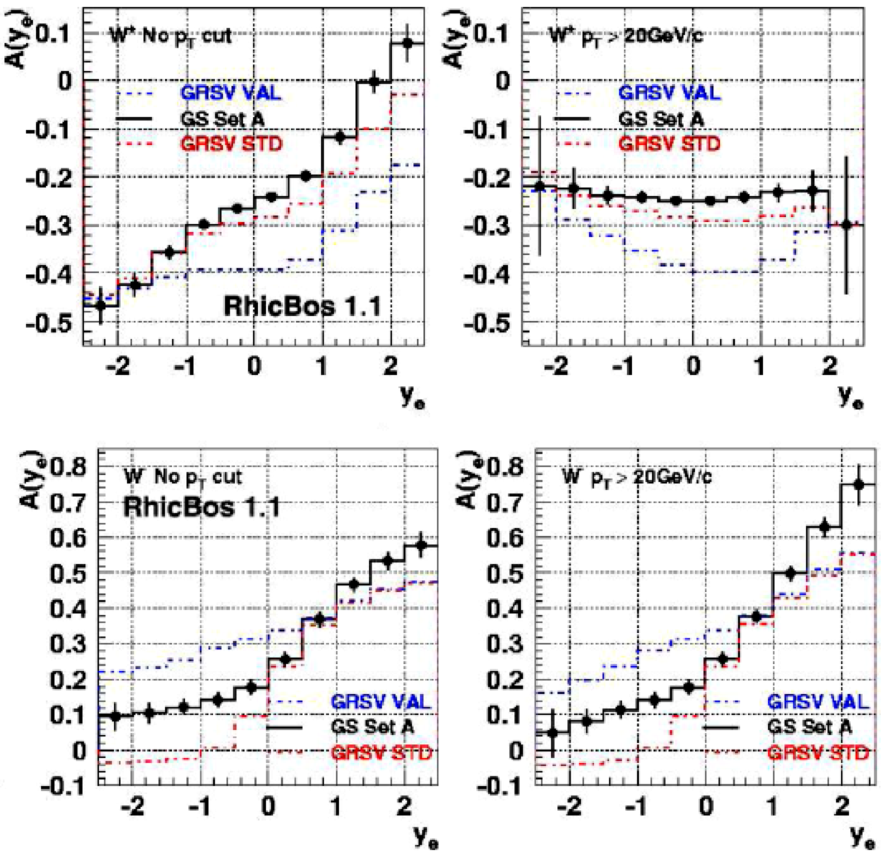


STAR Run 3+4 A_{LL}(jets): hep-ex/0608030

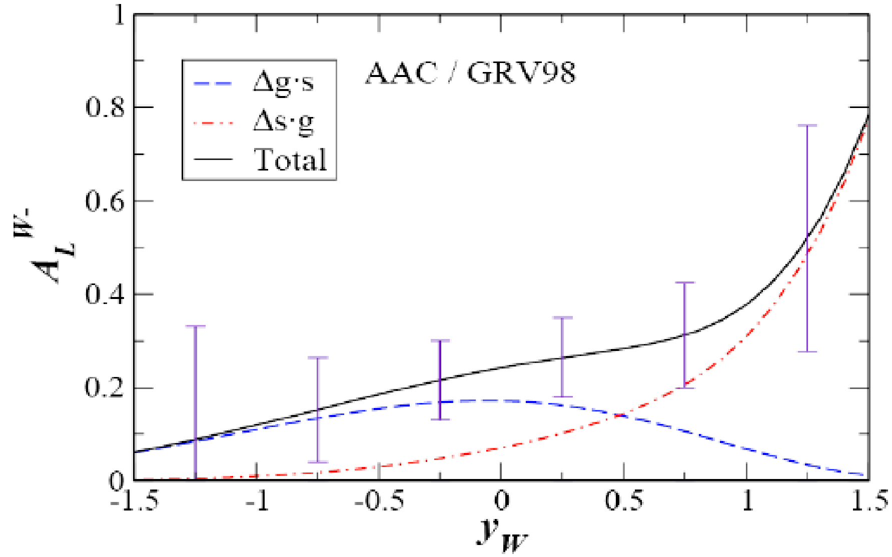


- Early results show the gluon polarization is not “too large”
- Within the next few years, we’ll learn if it’s “about right”
- RHIC II luminosities will permit a measurement of ΔG to ±0.1

Example spin measurements in the RHIC II era



High precision measurement of the contributions Δu, Δd, $\Delta \bar{u}$, $\Delta \bar{d}$ with **inclusive W boson production**



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

Conclusion

- The first six years of RHIC physics have 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 wave function of heavy nuclei at high energy
    - The origin of the proton spin
- During the coming decade, upgrades to the PHENIX and STAR detectors, coupled with the RHIC II luminosity upgrade will allow us to:
  - **Understand the properties of this new matter**
  - **Determine the partonic composition of the Au nucleus (and perhaps, all high energy hadronic matter)**
  - **Isolate the various partonic contributions to the proton spin**