# Characterizing the new state of strongly interacting quark-gluon matter discovered at RHIC

T. Hallman

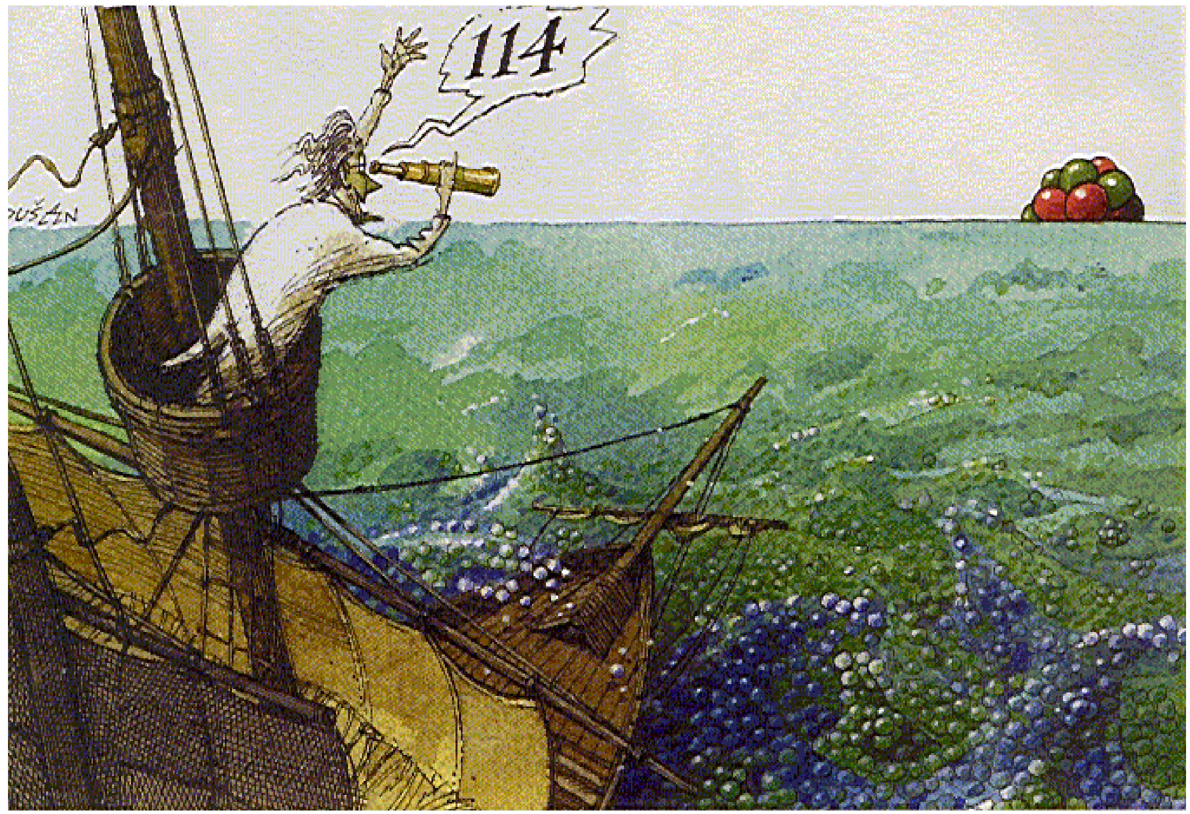
Trends in Heavy Ion Physics Research

in celebration of Prof. Yuri Oganessian's 75th anniversary

21-25 May, 2008
JINR, Dubna, Russia

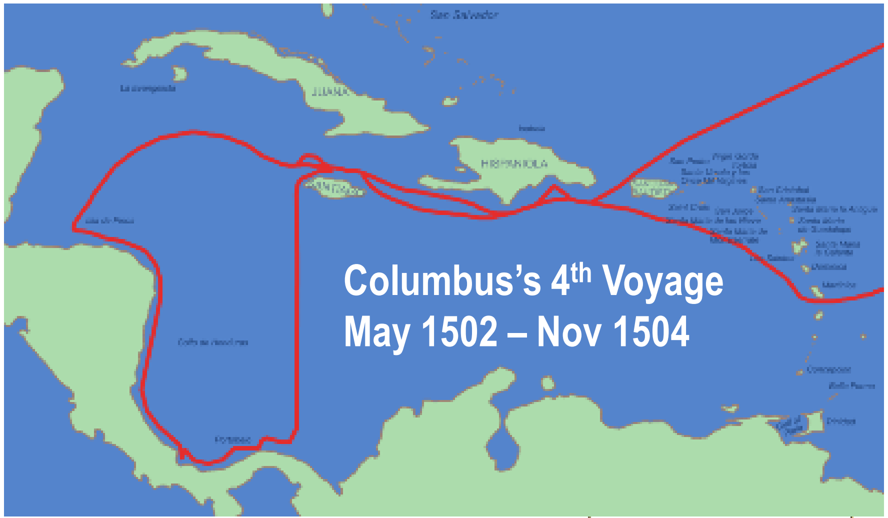
# But first, a word on the person we celebrate today and his work on super heavy elements and the search for the island of stability

Yu.Ts. Oganessian

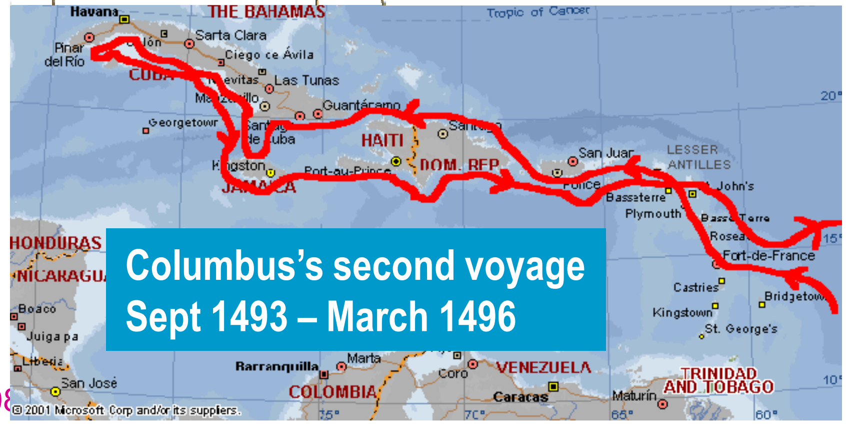



1999: element 114
2000: element 116
2002: element 118

# Columbus’ discovery of the new world





# A few observations on the comparison to Columbus' voyages

In contrast to Columbus, who never really understood where the land was he had discovered (he died thinking he had reached China), in his voyage of discovery Prof. Oganessian always knew very well where he was and where he intended to go

In similarity to Columbus, Prof. Oganessian has made many voyages to the same uncharted waters in the search for new answers

Columbus was not the first to discover the new continent. His exploration was significant and celebrated not because he kept going back to explore the territory further. He was the one that put this new land "on the European map"

One more parallel:

While Prof. Oganessian has been searching for the "island of stability", other scientists have been exploring other unknown regions of the phase diagram for strongly interacting matter

The story of one of those explorations is the next topic

There is a strong parallel to the explorations of Prof. Oganessian:

"A great experimenter is one who keeps asking the same question over and over in a deeper and more meaningful way" —

*Gene Sprouse, Neutrino Helicity at 50 in honor of Maurice Goldhaber's 96th anniversary*

By any measure, Prof. Oganessian is a great experimenter

# Plan of this lecture

- Overview of physics and experimental tools at RHIC
- Experimental results to date
  - Collective Flow
  - Hard Probes
  - Additional supporting evidence
- New physics coming in the future
- Conclusions

# The Science of RHIC

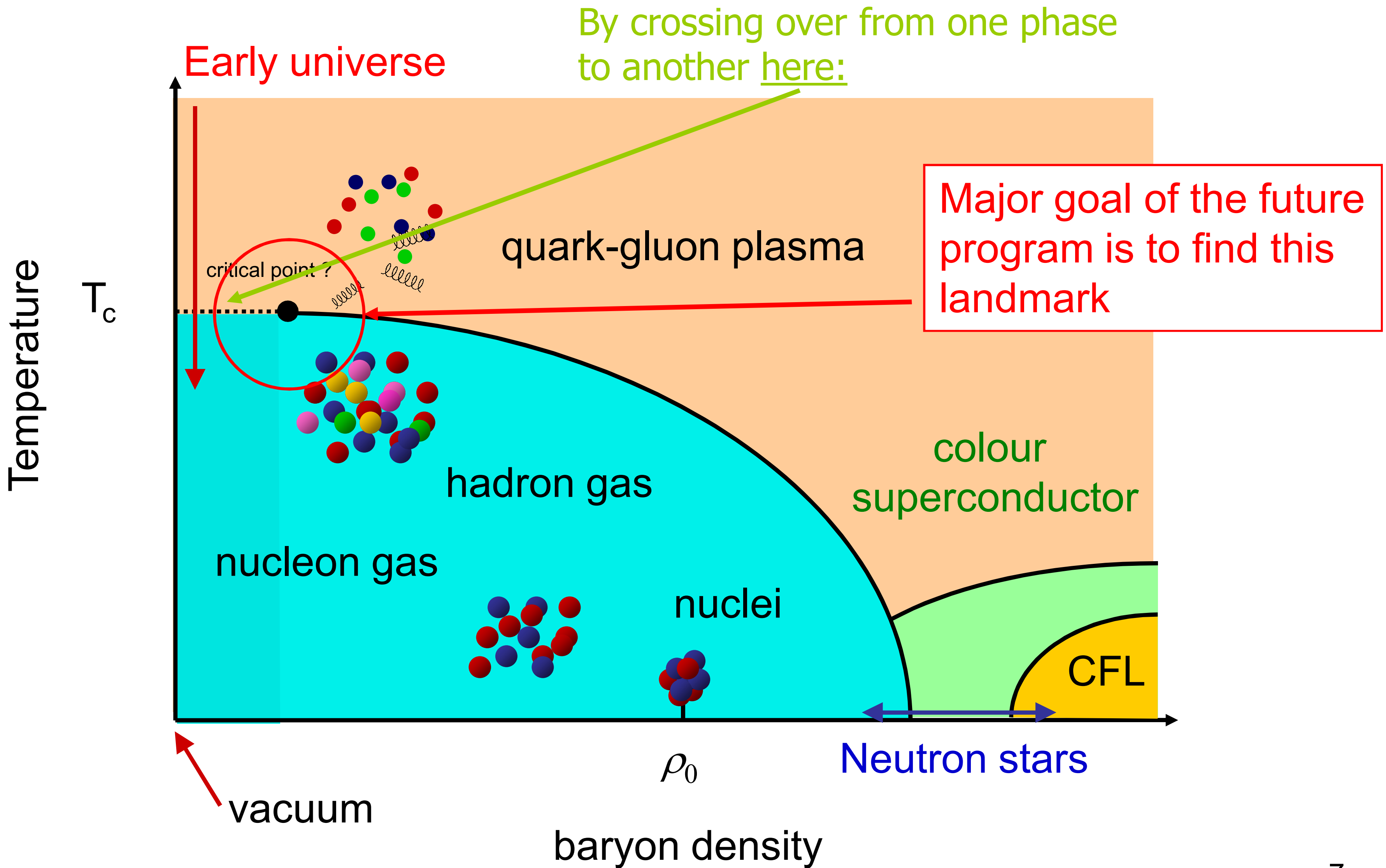
- RHIC's original science mission:
  - Discovery of a new state of matter (quark-gluon plasma) in central heavy ion collisions ( ✓)
  - Detailed unfolding of the spin structure of the nucleon
- "Value added" physics:
  - Low x structure of hadrons
  - Fundamental tests of QCD
  - Search for new exotics

Forward inclusive spectra and correlations

Tagged forward proton studies

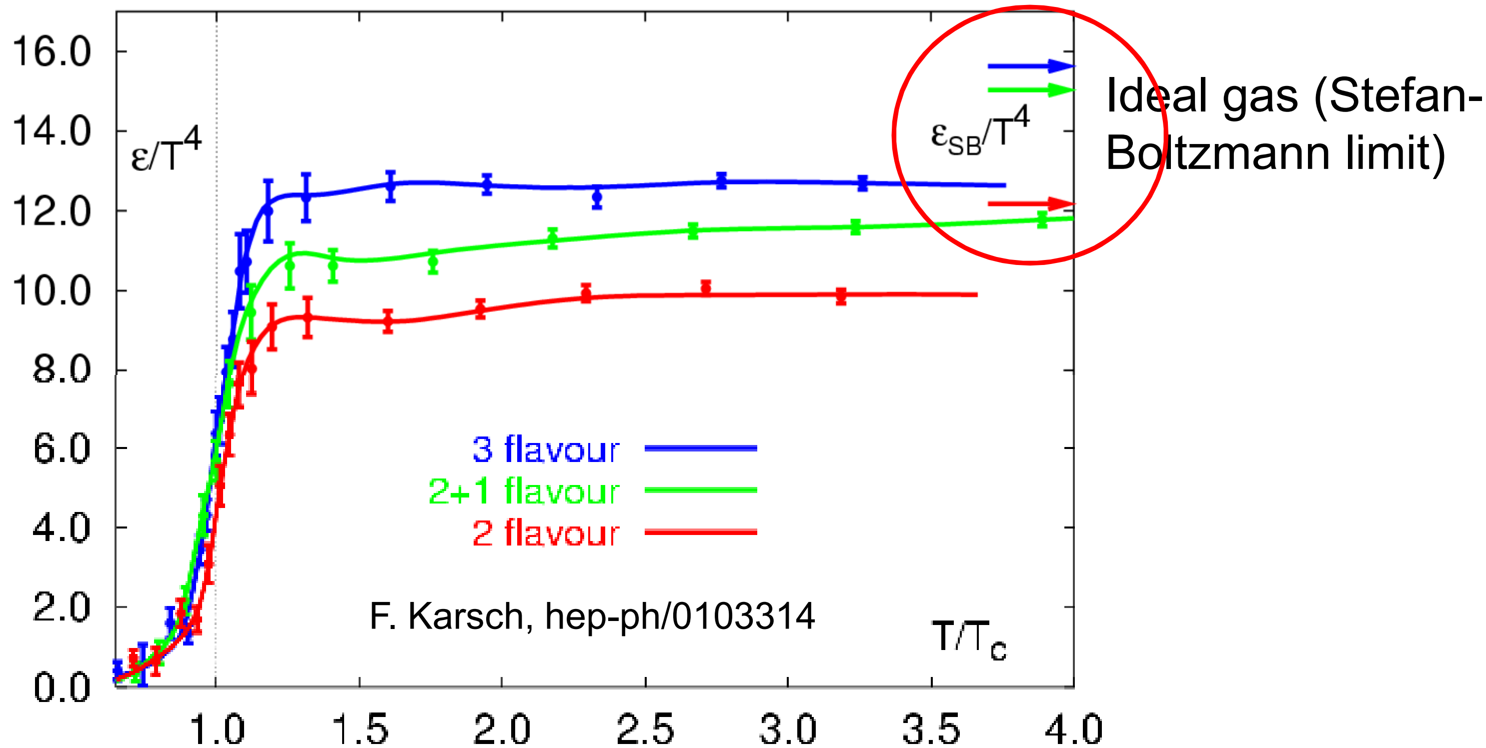
Ultra-peripheral collisions

The inspiration for the RHIC voyage of discovery: belief that under the right conditions, it is possible to "melt" protons and neutrons into their constituents



# What are the phases of QCD Matter?

## What we expected: lattice QCD at finite temperature




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 are the phases of QCD Matter?

# What we expected: lattice QCD at finite temperature

(Stefan-

n limit)

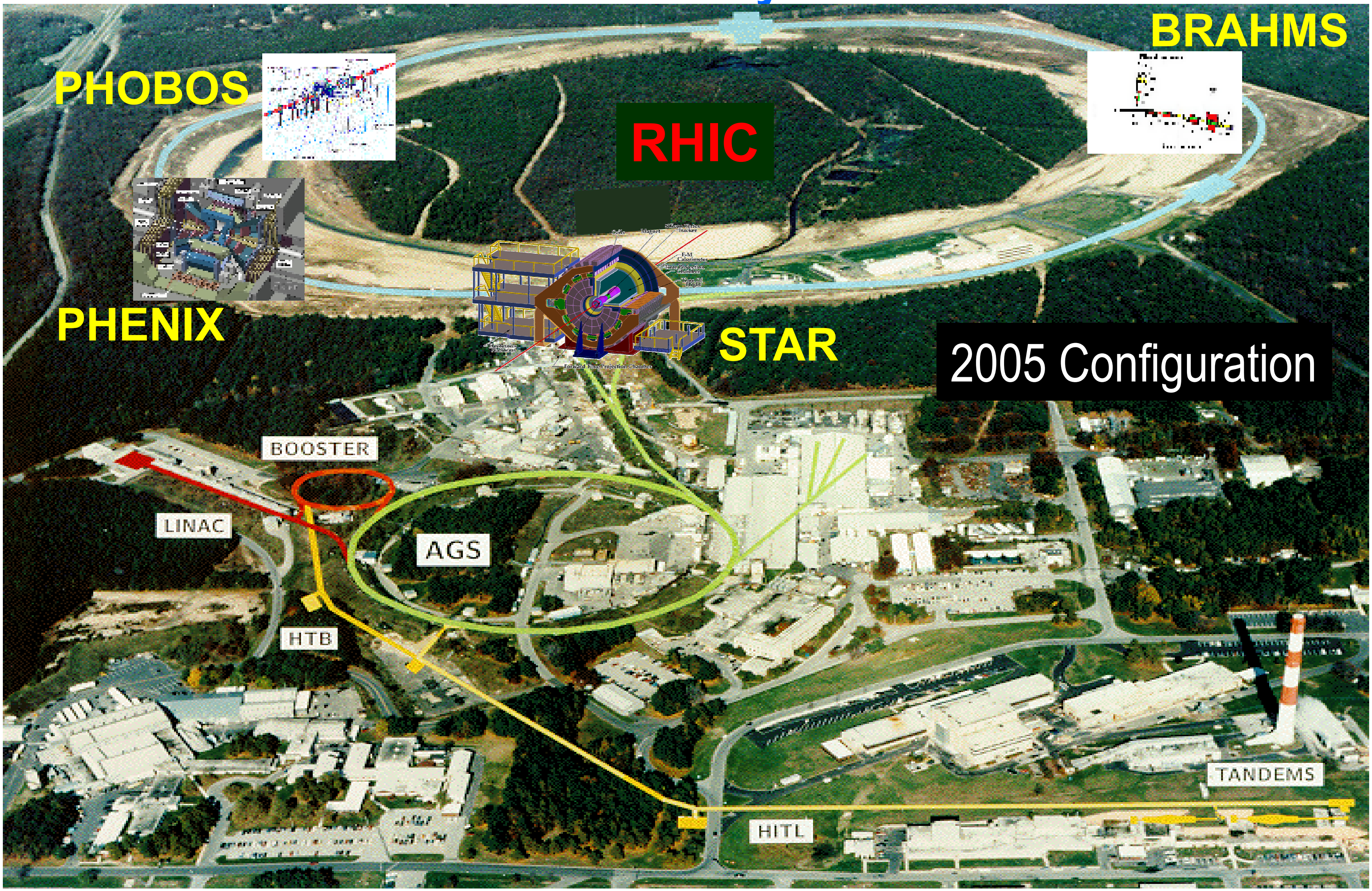
The nature of the transition?

The most realistic lattice calculations suggest there are no discontinuities in thermodynamic properties for the conditions at RHIC (i.e., no 1st- or 2nd-order phase transition), but that there is a smooth crossover transition with a rapid evolution vs. temperature near $T_c \approx$ 160 – 170 MeV

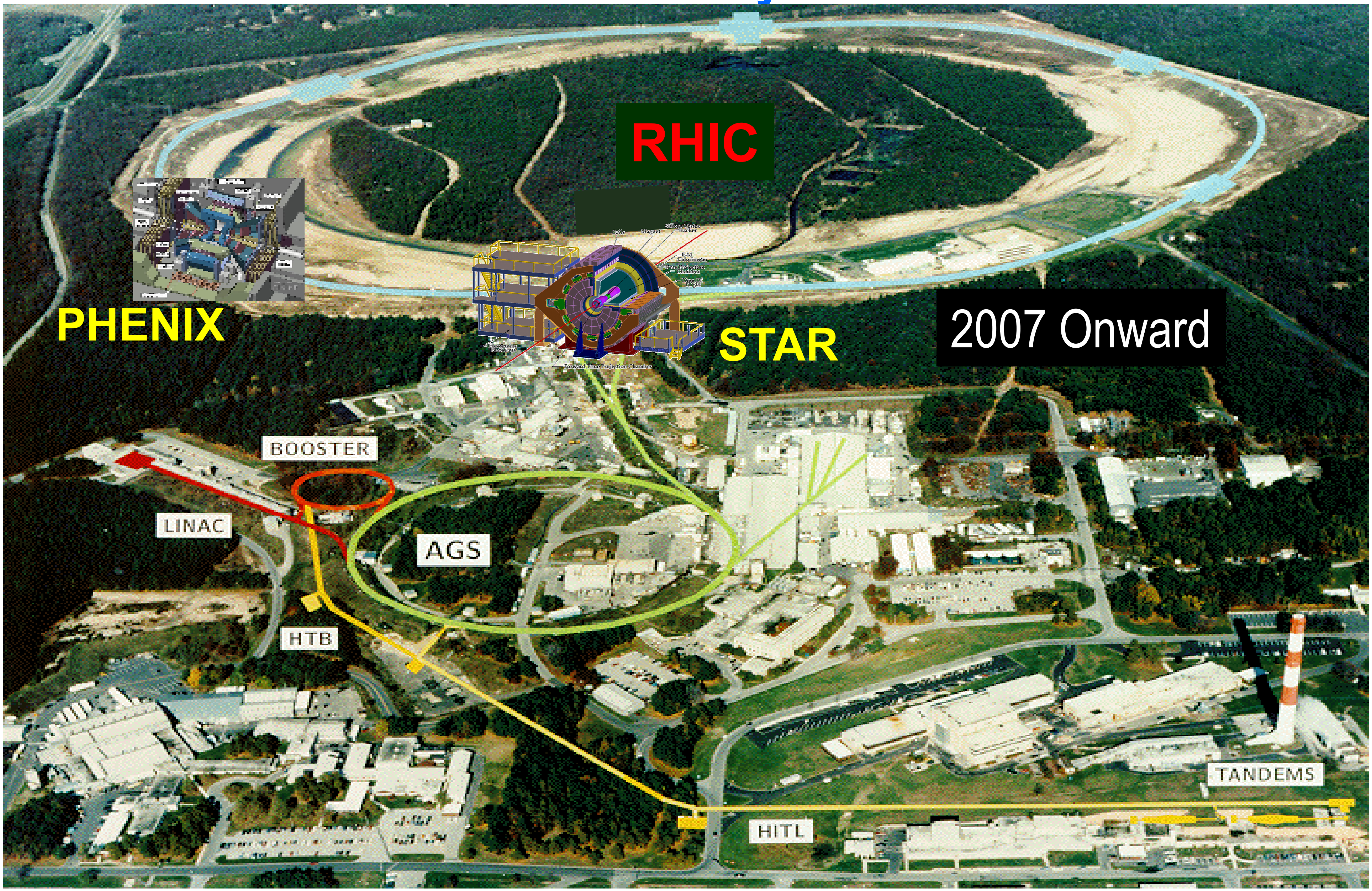
Critical energy density: $\varepsilon_C = (6 \pm 2) T_C^4$

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

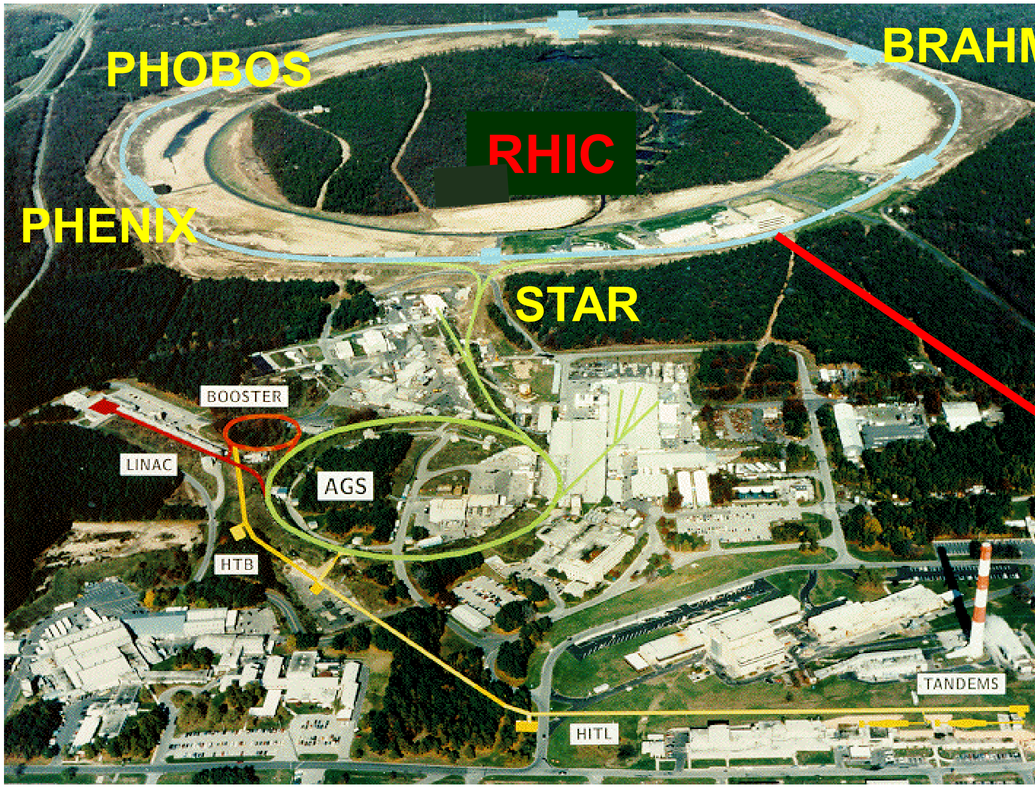
# Relativistic Heavy Ion Collider



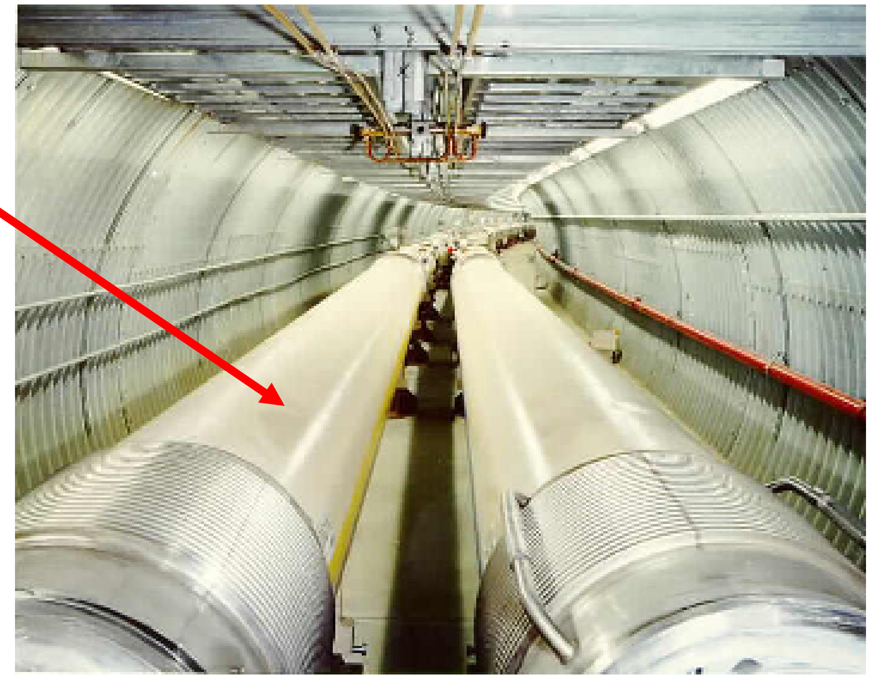
# Relativistic Heavy Ion Collider



# Relativistic Heavy Ion Collider



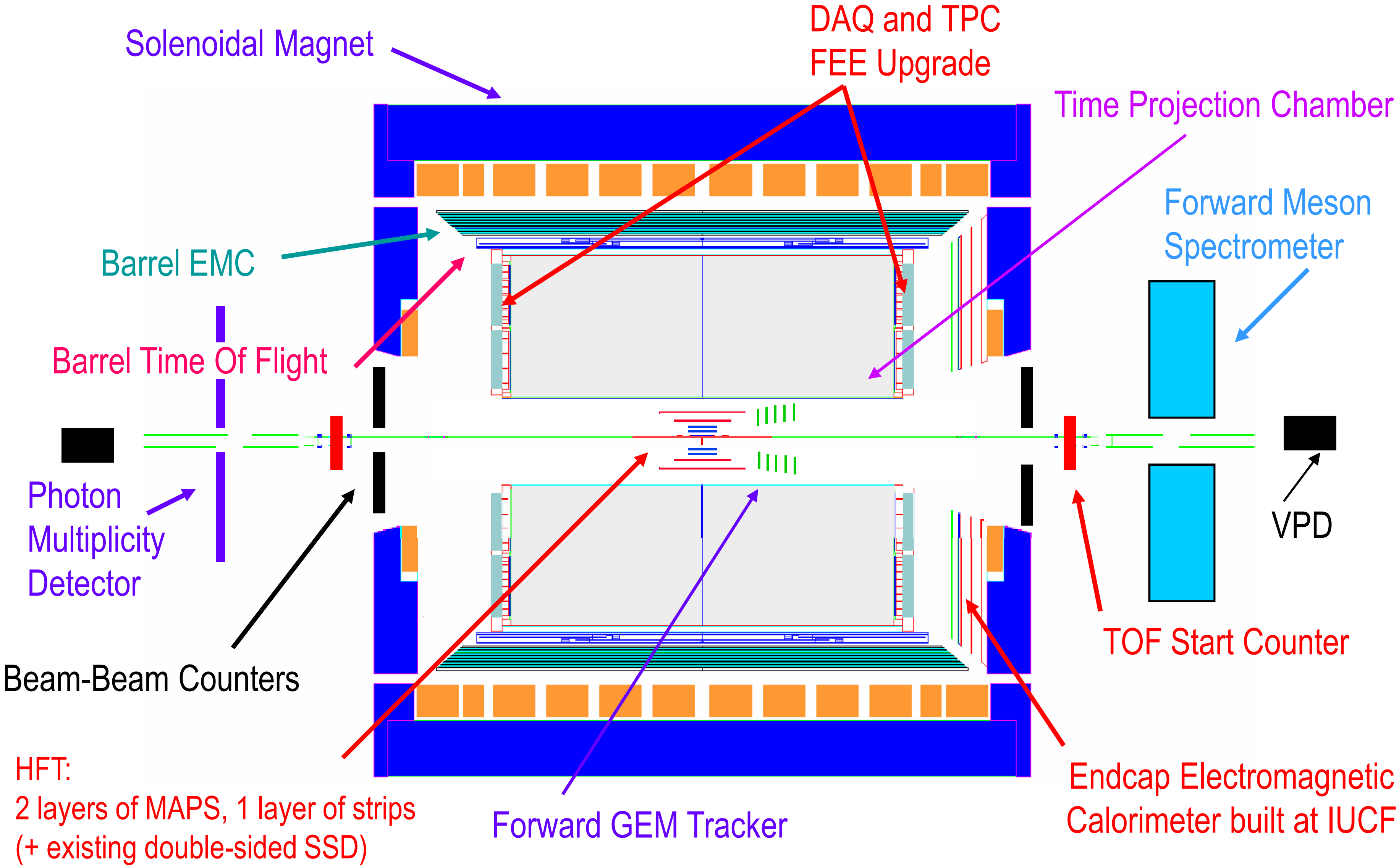

**Two Concentric Superconducting Rings**



Ions: A = 1 ~ 200, $\vec{p}\vec{p}$, pA, AA, AB

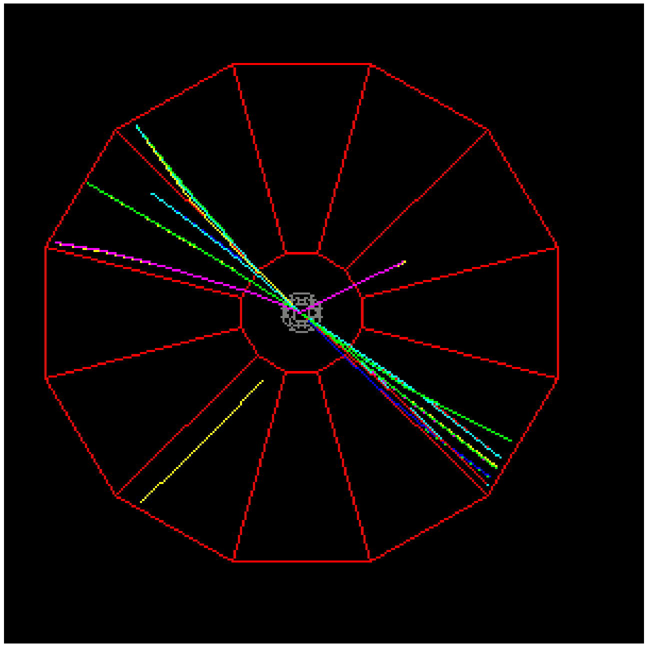
| Design Performance | Au + Au | (Now) | p + p | (Now @ 200) |
|---|---|---|---|---|
| Max $\sqrt{s_{nn}}$ | 200 GeV | | 500 GeV | |
| L [$cm^{-2}$ $s^{-1}$ ] | $2 \times 10^{26}$ | ($3.6 \times 10^{27}$ ) | $1.4 \times 10^{31}$ | ($3.5 \times 10^{31}$ ) |
| Interaction rates | 1.4 khz | (~ 36 khz) | 300 khz | (~ 750 khz) |

# The (evolving) STAR detector

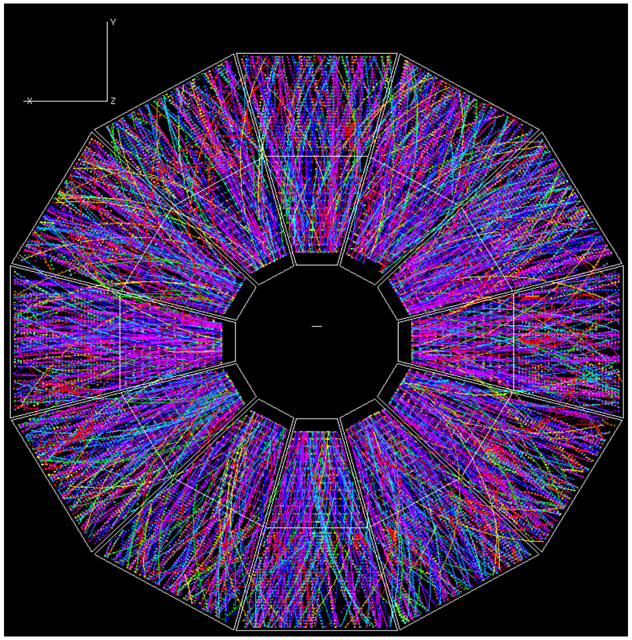


# From p+p to Au+Au in the STAR TPC

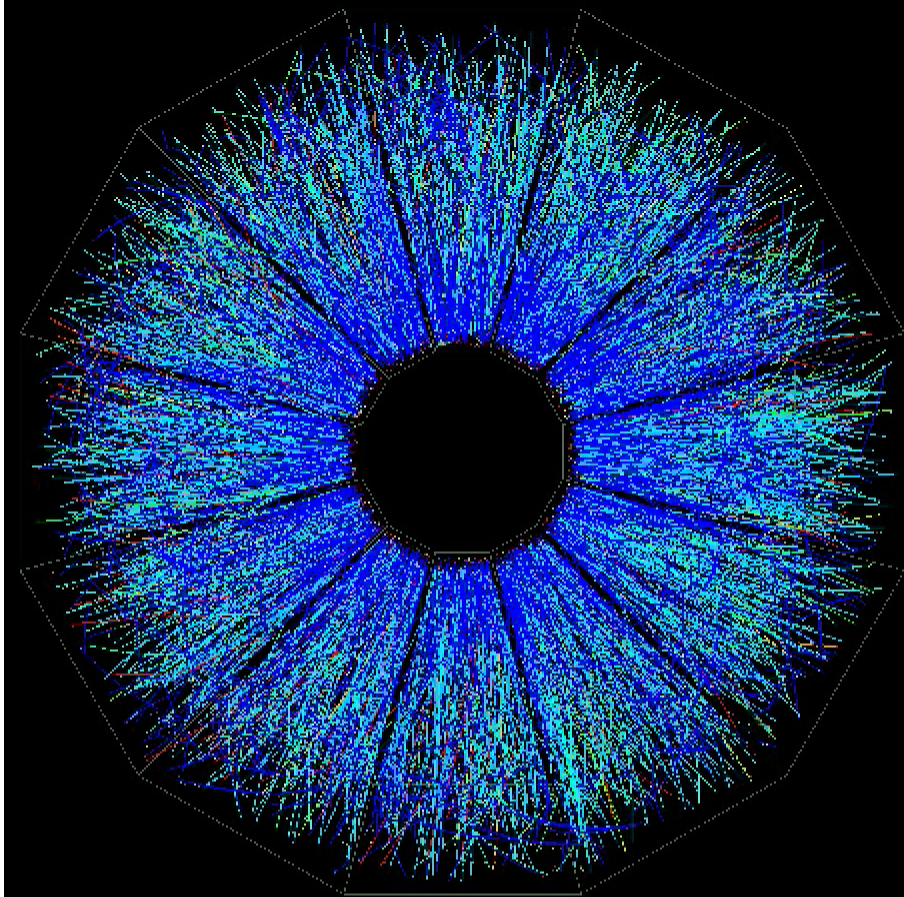
p+p $\rightarrow$jet+jet
(STAR@RHIC)



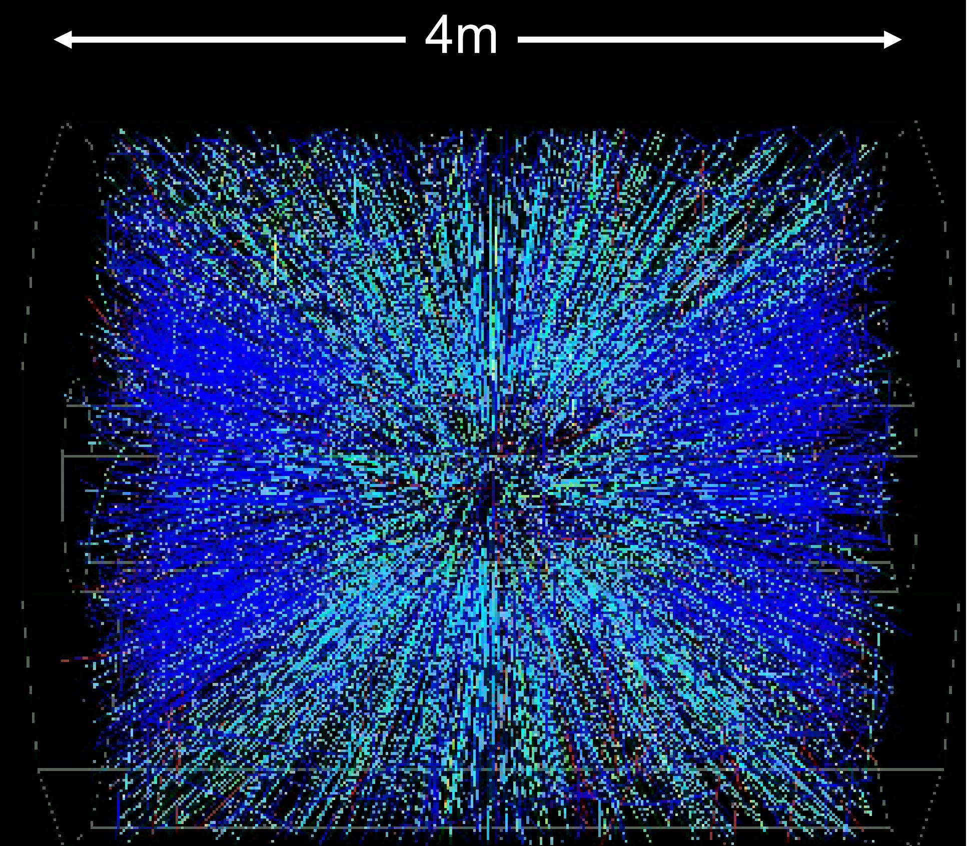
Au+Au $\rightarrow$ X
(STAR@RHIC)



# Au on Au Event at CM Energy ~ 130 A-GeV

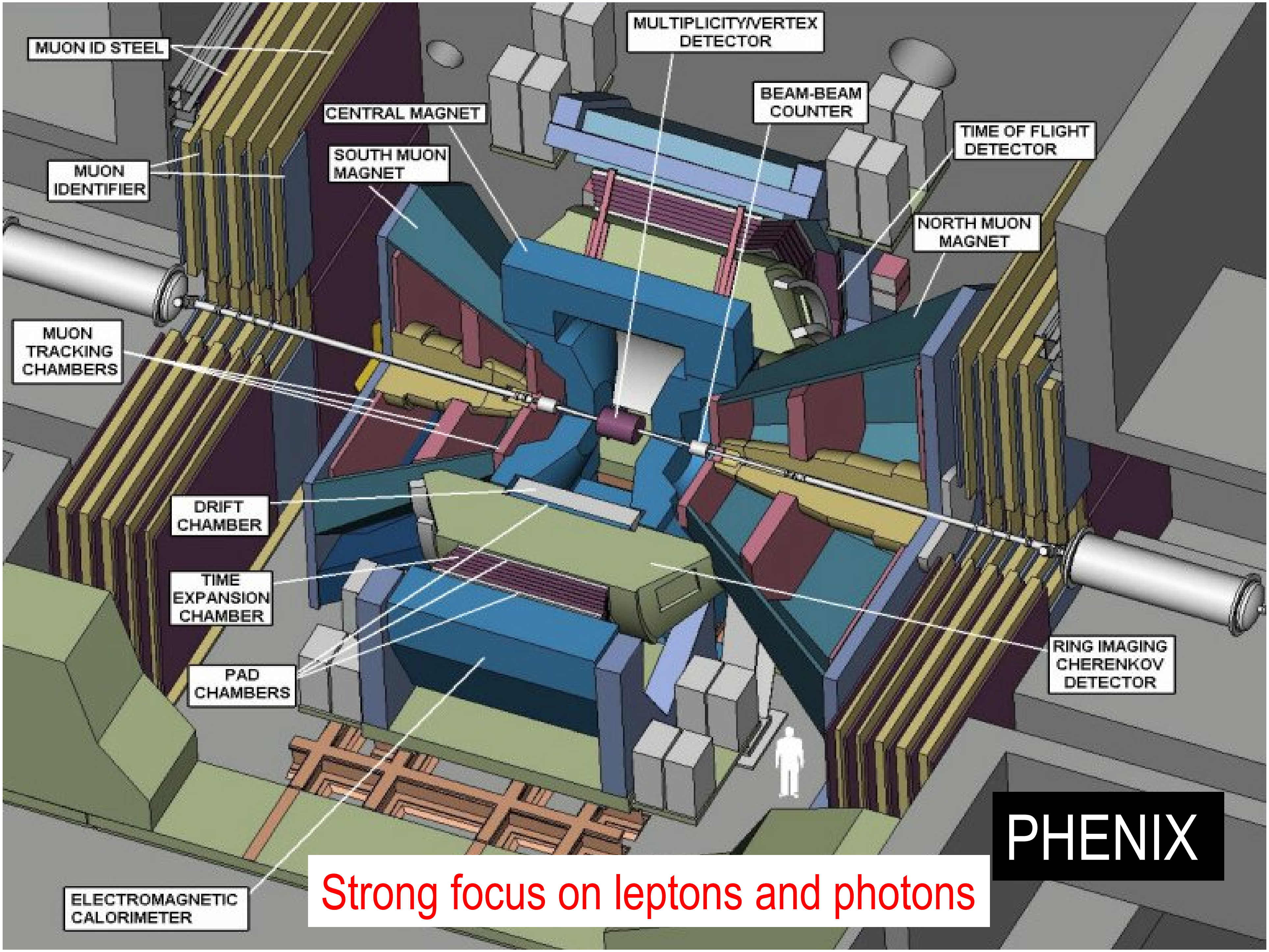


**Central Event**



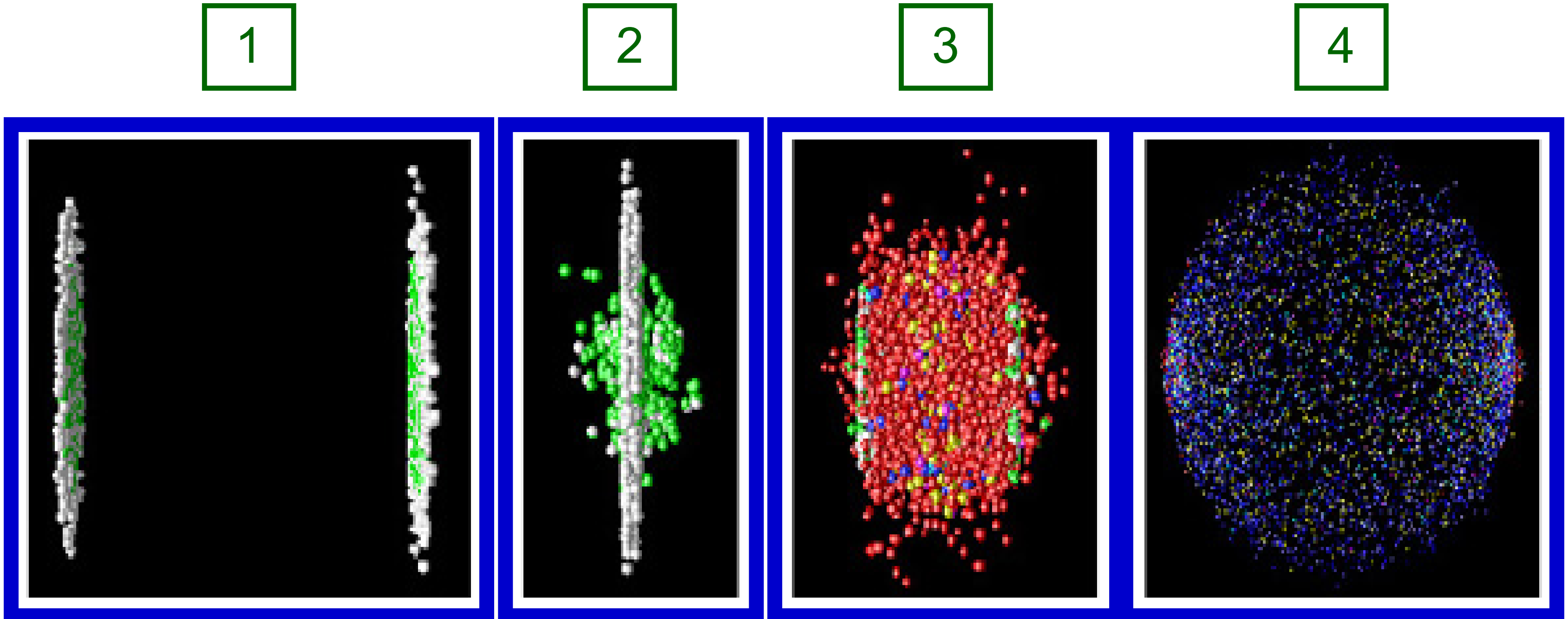

**color code ⇒ energy loss**

# PHENIX




Strong focus on leptons and photons

# Time line of a relativistic heavy ion collision




Two thin disks of quarks and gluons approach

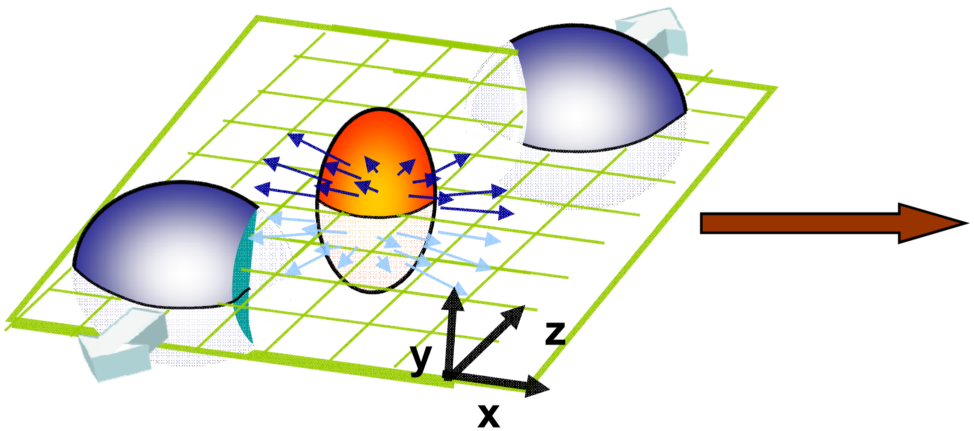
Initial collision – products of hard scattering created

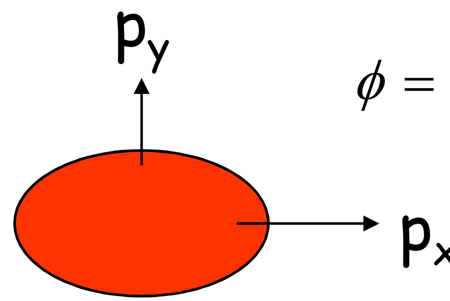
Dense partonic medium
The QGP?
The sQGP?
A “perfect liquid”?

Hadron gas phase

## What discoveries has the first phase at RHIC yielded?

# Collective motion: "elliptic flow"




$$\phi = \mathrm{atan}\,\frac{p_y}{p_x}$$

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

**Initial coordinate-space anisotropy**

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

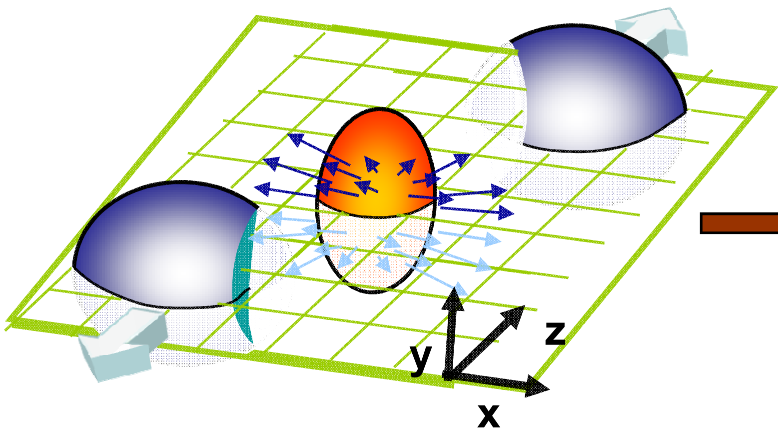
**Final momentum-space anisotropy**

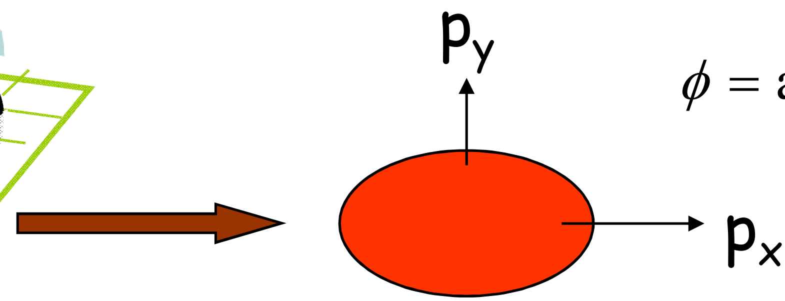
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos[2(\phi - \Psi_R)] + 2v_4 \cos[4(\phi - \Psi_R)] + \ldots$$

Elliptic term

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

# Collective motion: “elliptic flow”

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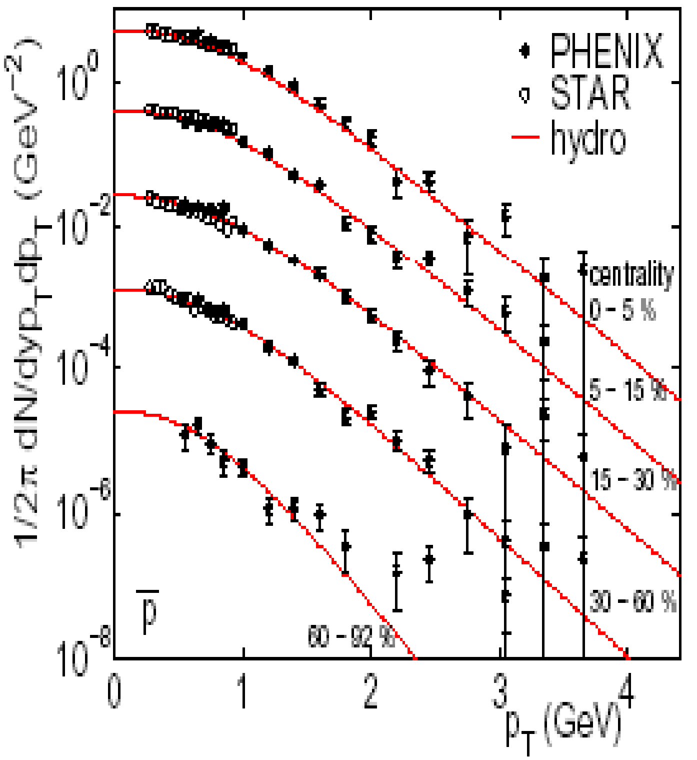
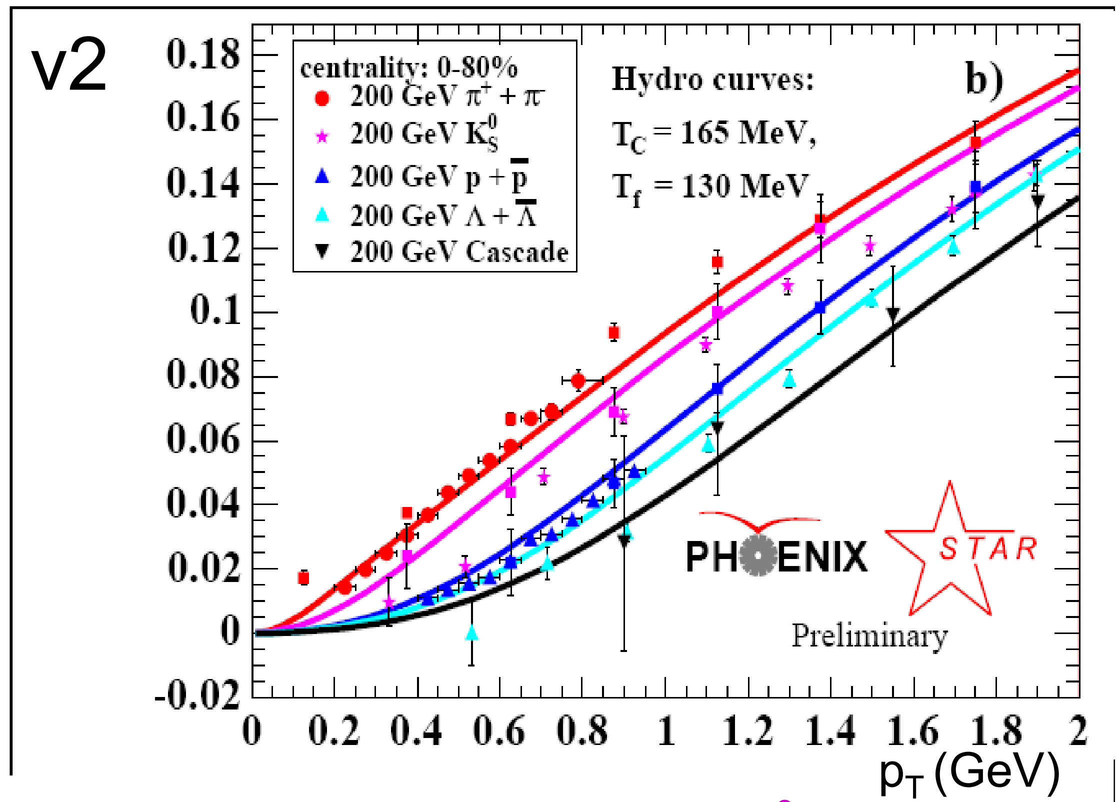
Elliptic flow establishes there is strongly interacting <u>matter </u>at t ~ 0

# Is there elliptic flow at RHIC?

Yes! First time hydrodynamics without any viscosity describes heavy ion reactions.




Thermalization time $\tau < 1$ fm/c and $\varepsilon = 20$ GeV/fm$^3$

# Is there elliptic flow at RHIC?

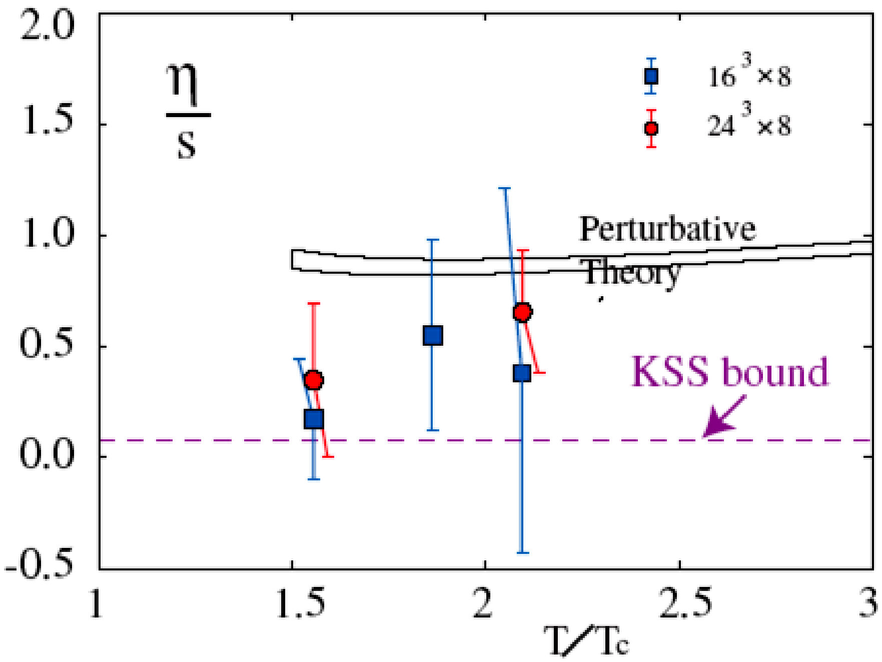
## Yes! First time hydrodynamics without any viscosity describes heavy ion reactions.

- Hydrodynamic calculations assuming a lattice-motivated EOS and near-zero viscosity reproduce the mass splitting well up to $p_T \sim 1.5$ GeV/c
- Same calculations fit the radial flow data simultaneously
- Elliptic flow saturates the hydrodynamic limit
- Very rapid thermalization, very strong interactions
- A perfect fluid?

Thermalization time $\tau < 1$ fm/c and $\varepsilon = 20$ GeV/fm$^3$

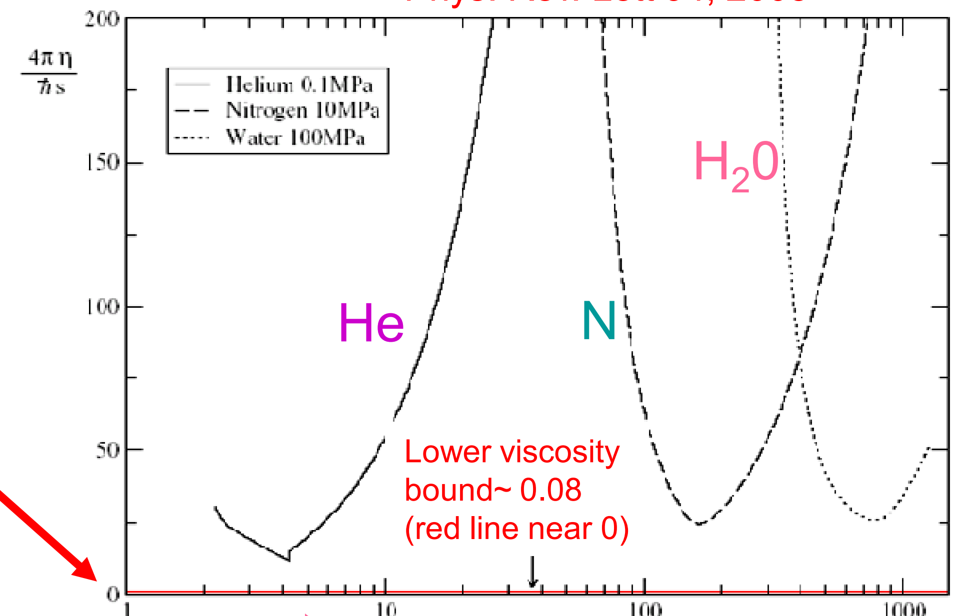
# What is the viscosity?
# How perfect is our liquid?

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




$\eta/s \div \hbar/4\pi$

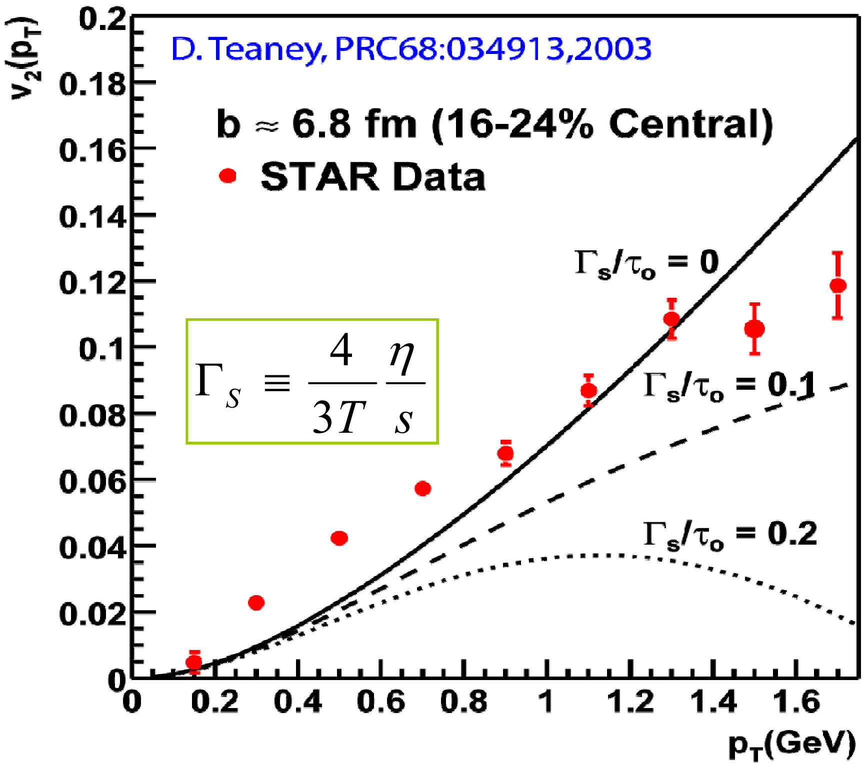
Kovtun, Son, Starinets,
Phys. Rev. Lett 94, 2005




T (K)

Superfluid helium

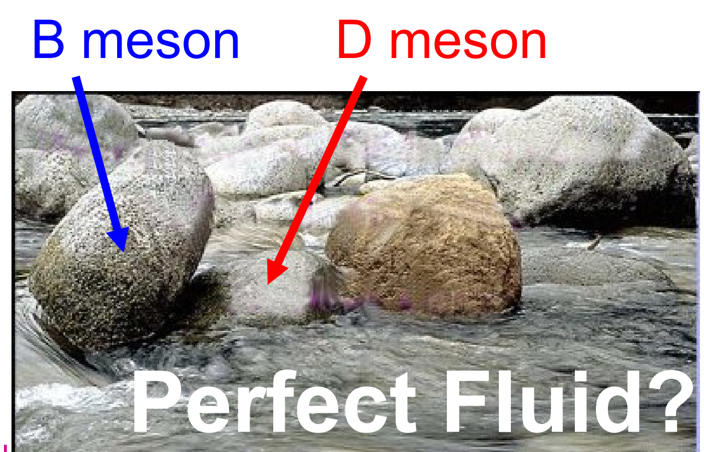
# How to Quantify η/s at RHIC?




$\Gamma_S$ = sound attenuation length
(~ mean free path)

For reasonable T (~ $2T_C$ ) and τ (~ 1 fm/c) data suggest η/s << 0.3

- Ultimately Needed:
  - Continued progress on viscous relativistic hydrodynamic theory
  - Radial, directed, elliptic flow measurements for several identified hadron species. Particularly valuable:
    - Multi-strange hadrons φ, Ξ, Ω (reduced coupling to hadron gas phase) to determine viscous effects in the hadronic phase
    - D mesons (establish thermalization time scale)

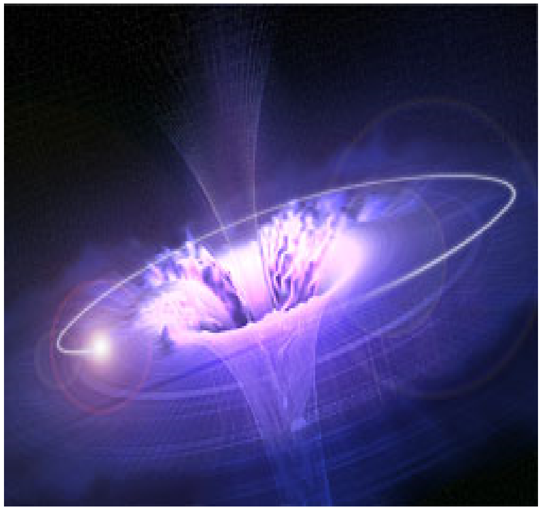


# String Theory ?

What could this have to do with our physics?

The Maldacena duality, know also as AdS/CFT correspondence, has opened a way to study the strong coupling limit using classical gravity where it is difficult even with lattice Quantum Chromodynamics.

It has been postulated that there is a universal lower viscosity bound for all strongly coupled systems, as determined in this dual gravitational system.



# A second discovery: jet quenching

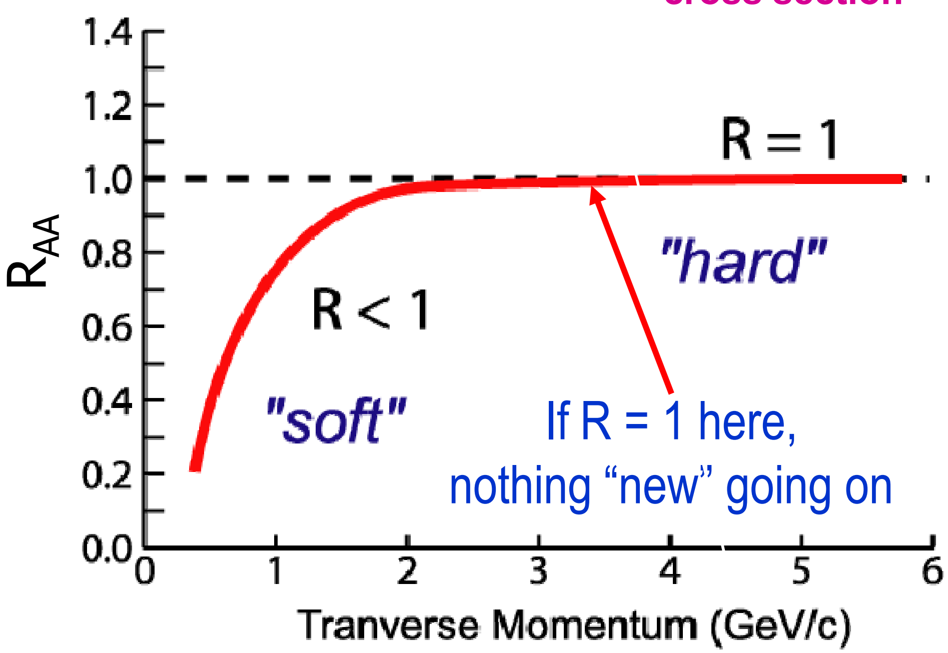
An "inclusive" measure:

the "Nuclear Modification Factor:"

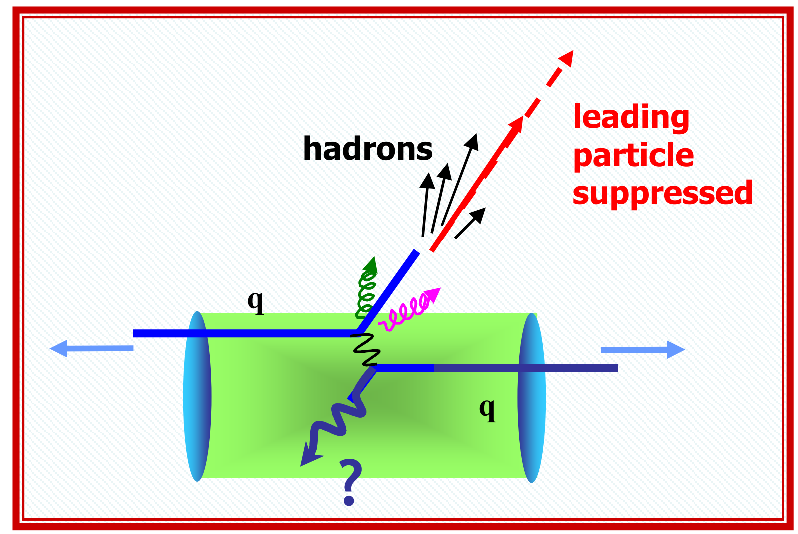
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta}$$

$\langle N_{binary} \rangle / \sigma_{inel}^{p+p}$

nucleon-nucleon cross section




A second test: back-to-back correlations from di-jets jets

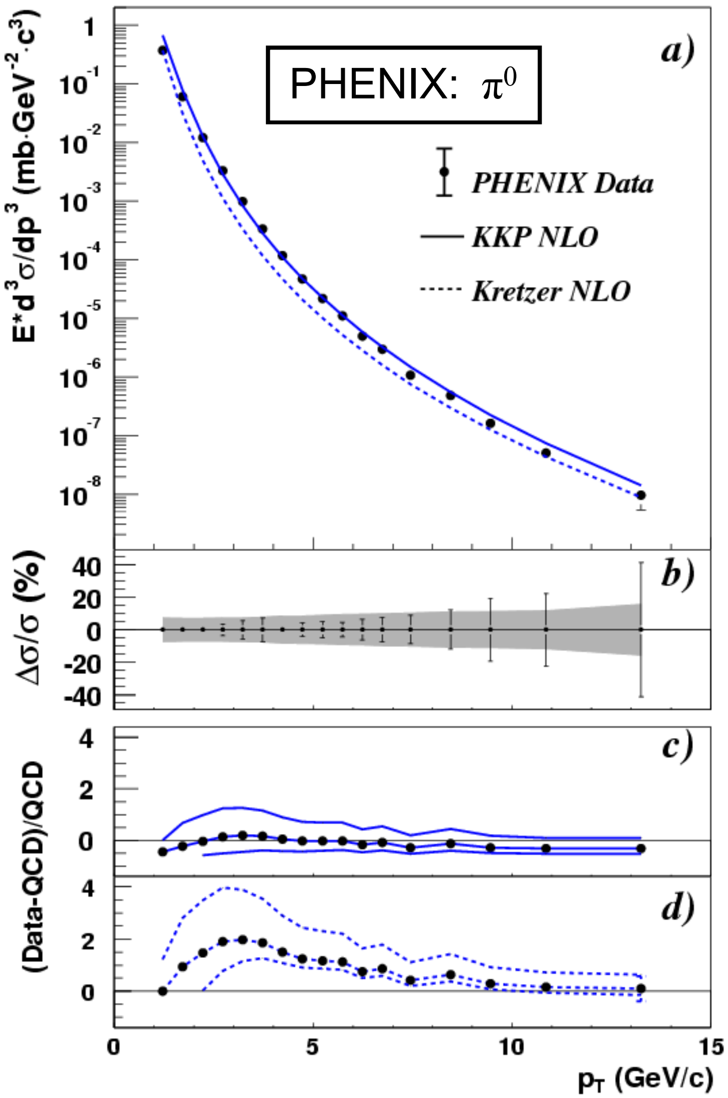



Will our calibrated penetrating probe go through the same way?

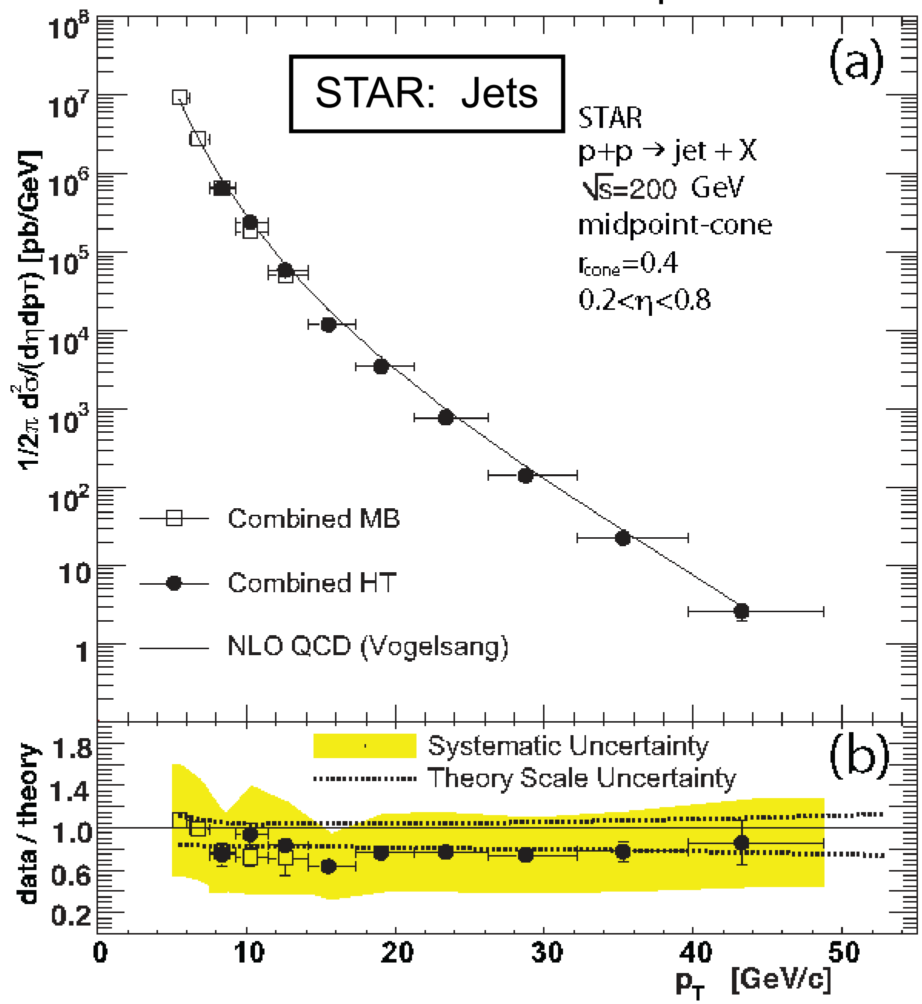
-- or will it be quenched ? --

# Hard scattering at RHIC and NLO pQCD

PRL 91, 241803

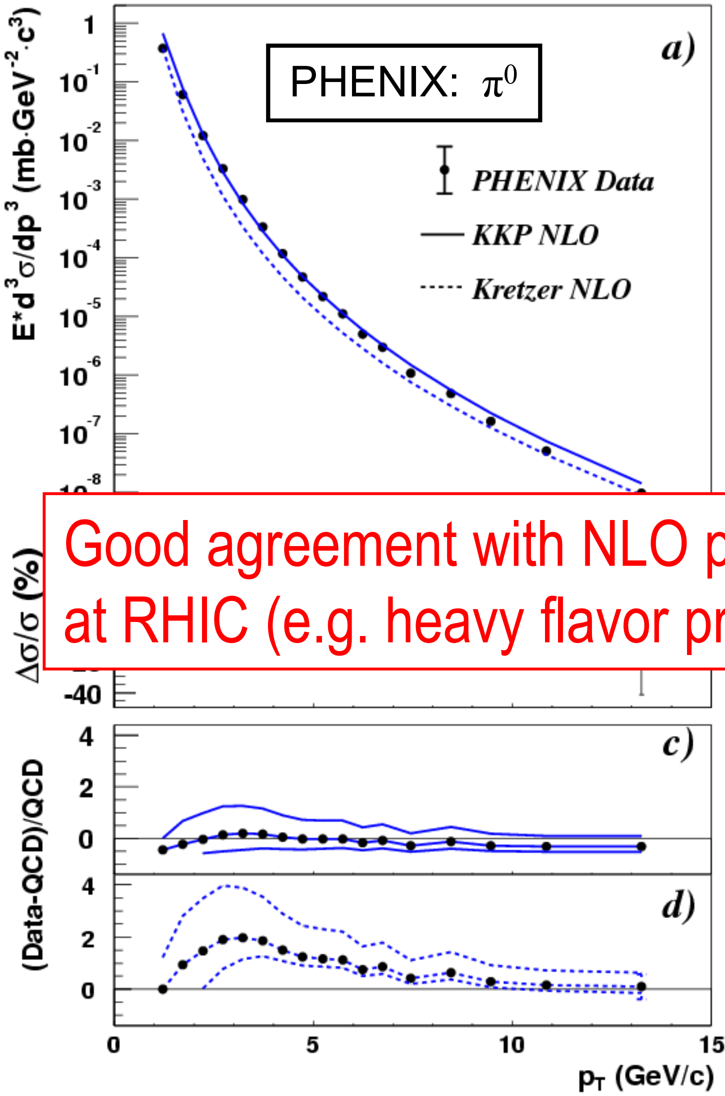



hep-ex/0608030

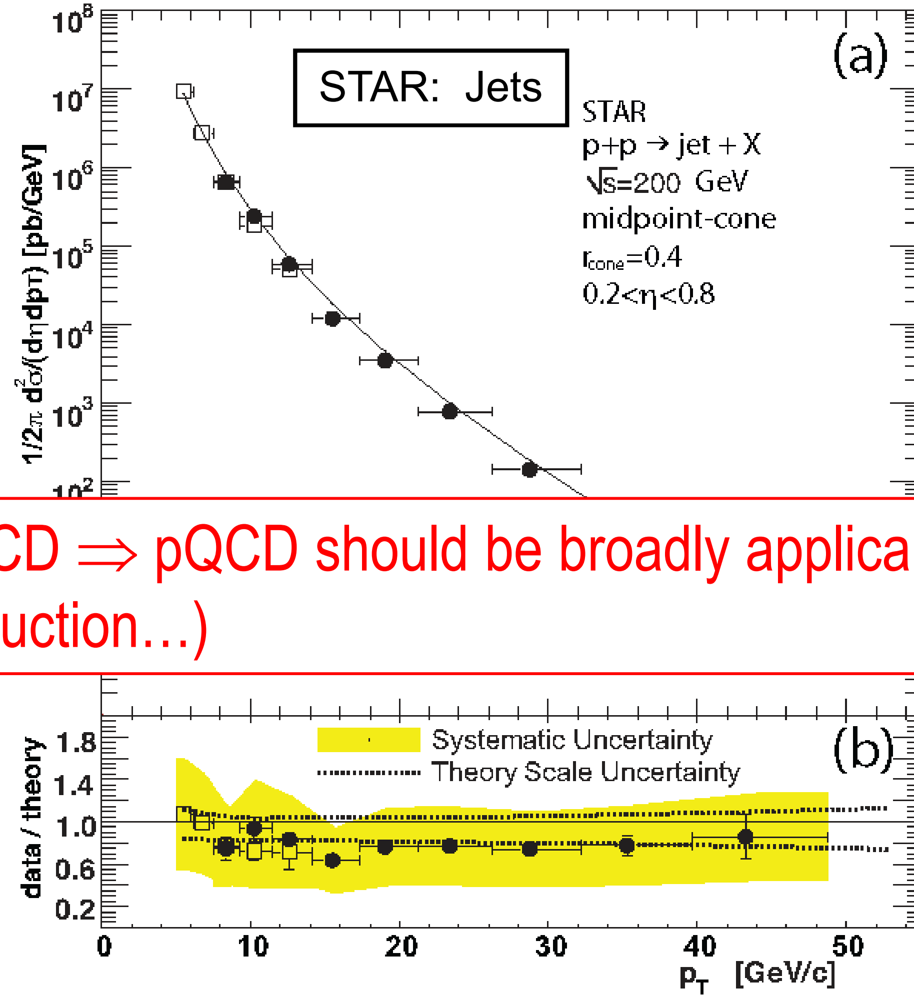


# Hard scattering at RHIC and NLO pQCD

PRL 91, 241803




hep-ex/0608030




Good agreement with NLO pQCD ⇒ pQCD should be broadly applicable at RHIC (e.g. heavy flavor production…)

# In central Au+Au collisions something dramatically new occurs: jet quenching

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

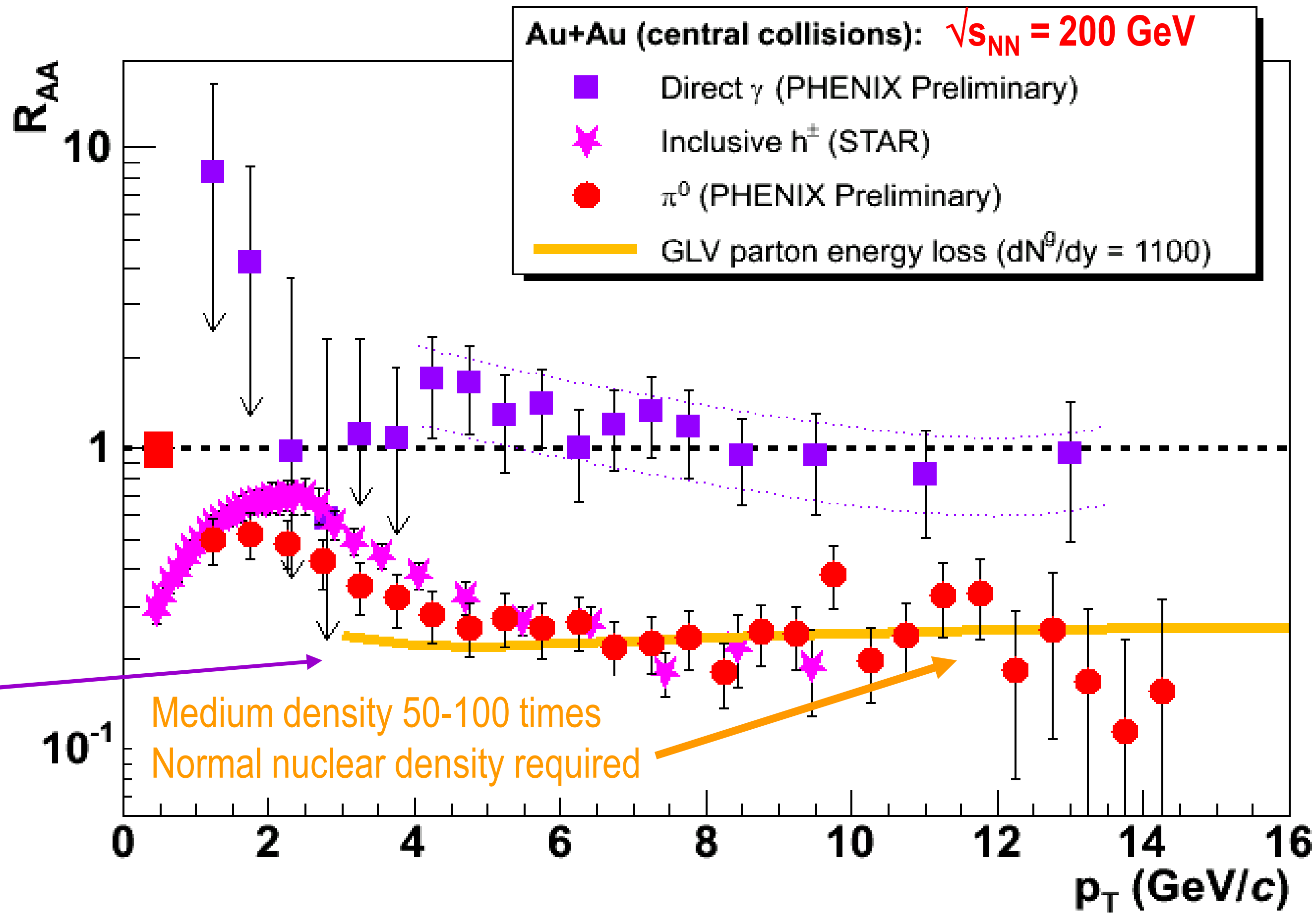
← Nuclear Modification Factor

Binary collision scaling

Particles which are made up from colored quarks and gluons are strongly suppressed

Direct photons are not

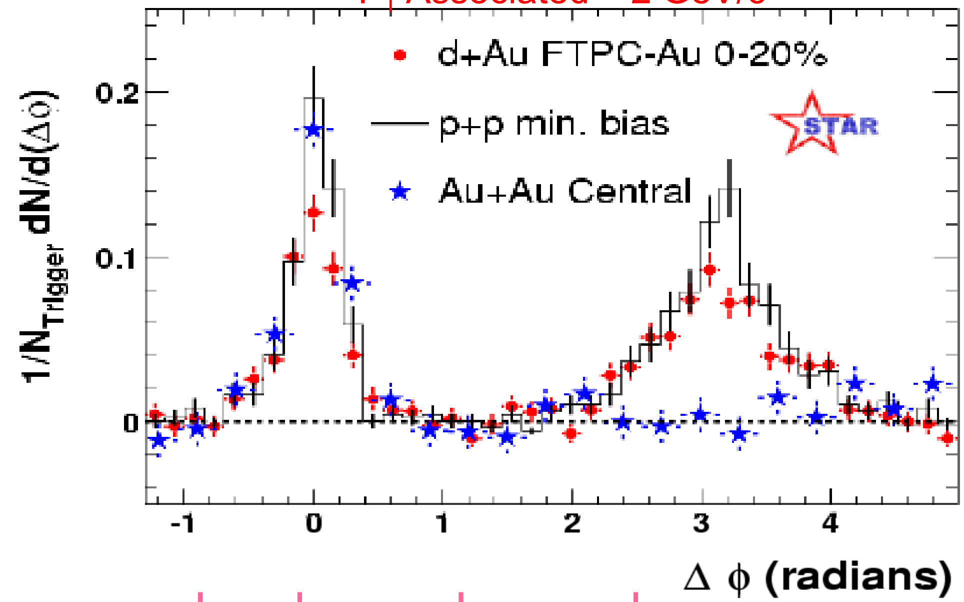
The contsant level of suppression indicates the effect occurs before the final particles are made (hadronization)



# Jet quenching at RHIC

The effect is seen even more dramatically in di-hadron correlations: recoiling jets are strongly modified due to quenching

$P_T$ Associated > 2 GeV/c




Unequivocally, a new phenomena has been observed

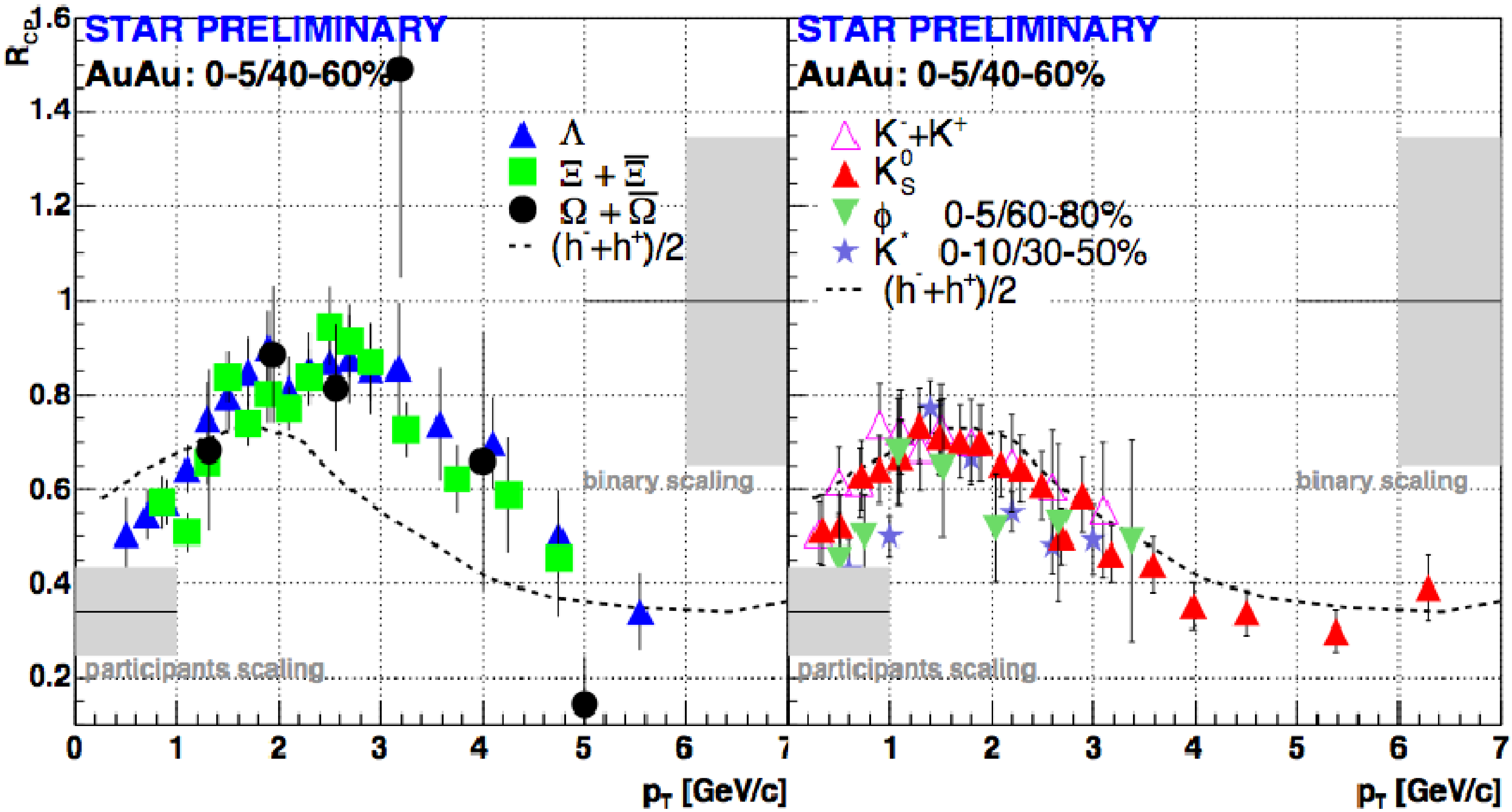
- In central Au+Au collisions:

Not everything is understood:

Electrons from the semi-leptonic decay of charm + bottom appear as suppressed as particles containing light quarks. That raises new questions (one subject of tomorrows seminar)

But evidence for jet quenching in some new form of opaque matter is unequivocal

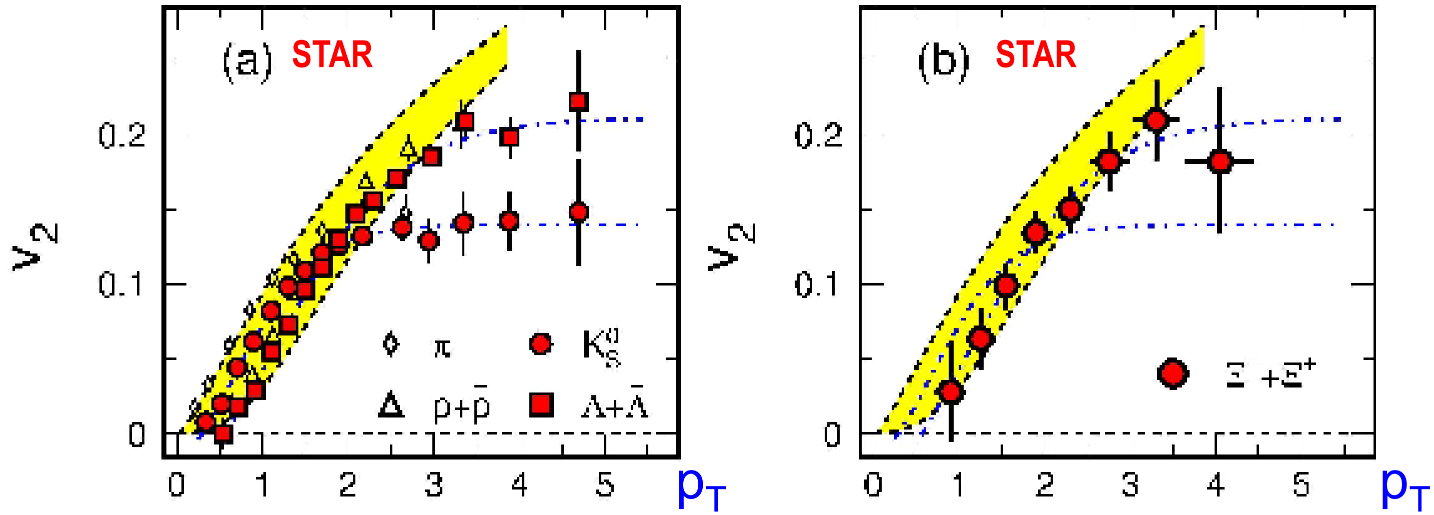
# Additional evidence from something that was not predicted

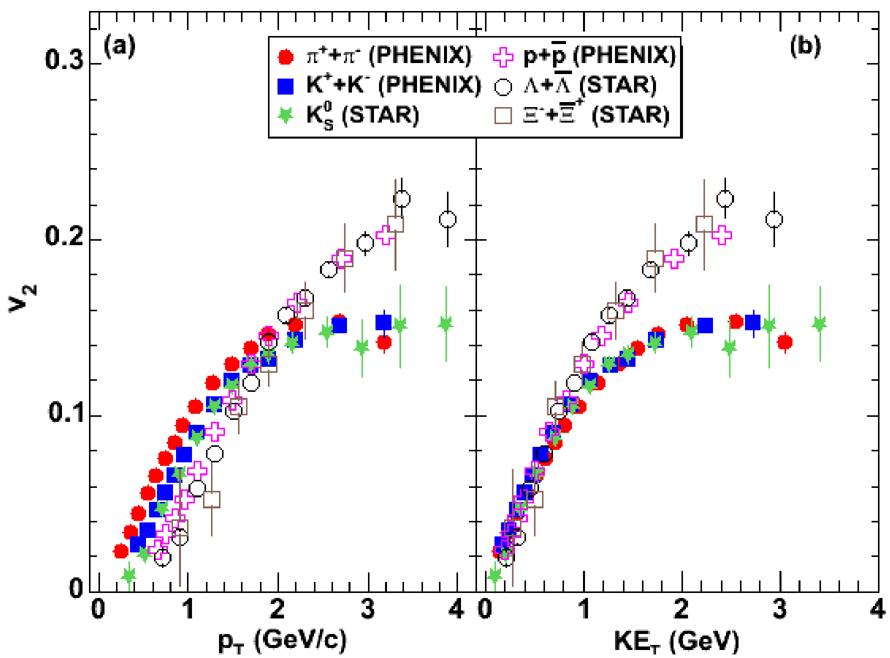


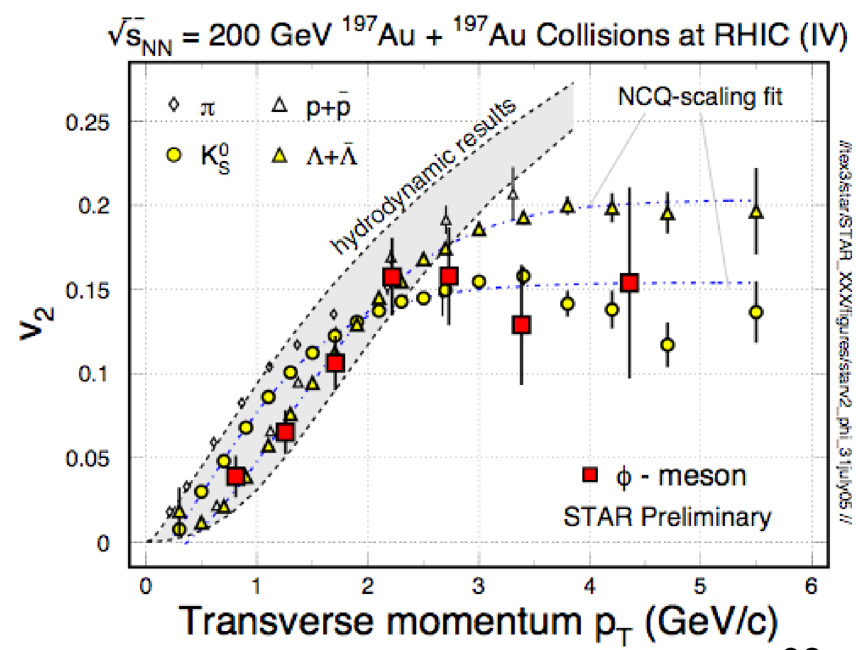

The mesons (quark-antiquark) and the baryons (3 quarks) exhibit two distinct behaviors below transverse momenta of ~ 6 GeV/c

(K*, ϕ which are as heavy as the proton follow the mesons !)

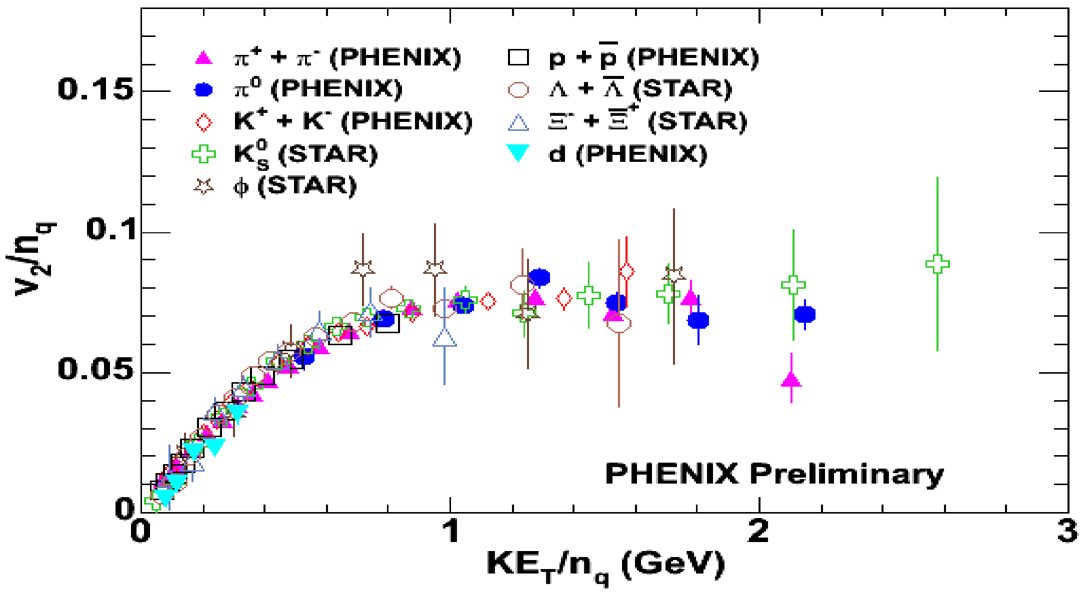
# Same "splitting" of mesons/baryons if you look at elliptic flow

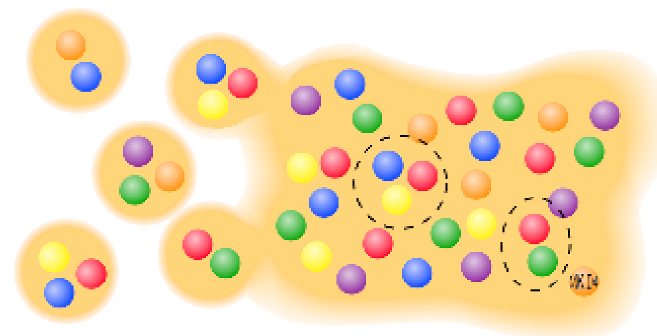


# What if quarks coalesce to make hadrons?



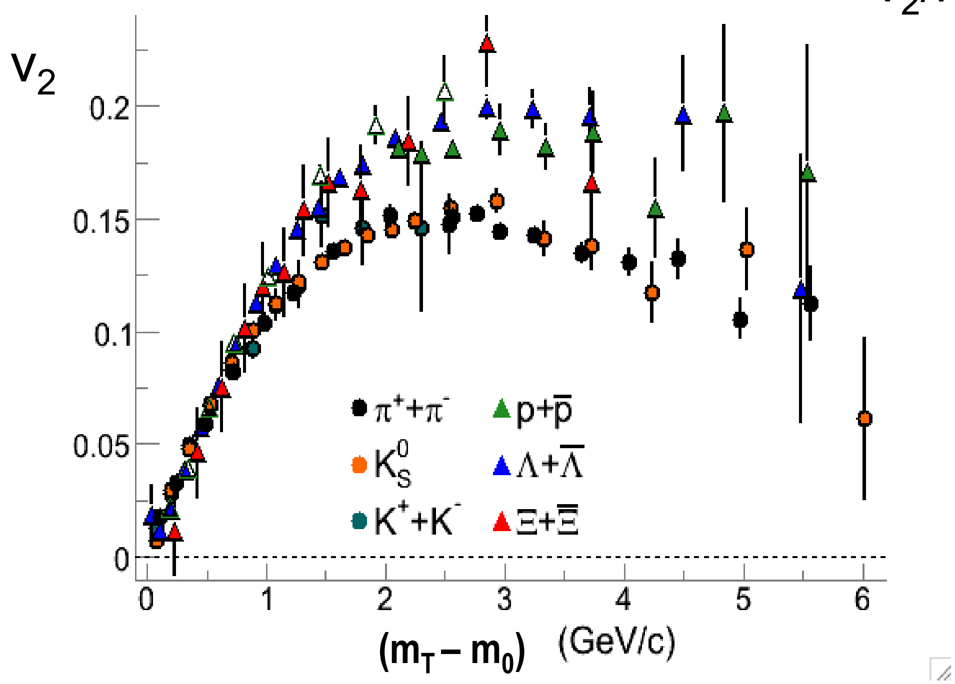
$$\frac{dN}{d\phi} \propto \left[1 + 2v_2(p_T)\cos(2\phi) + \cdots\right]$$

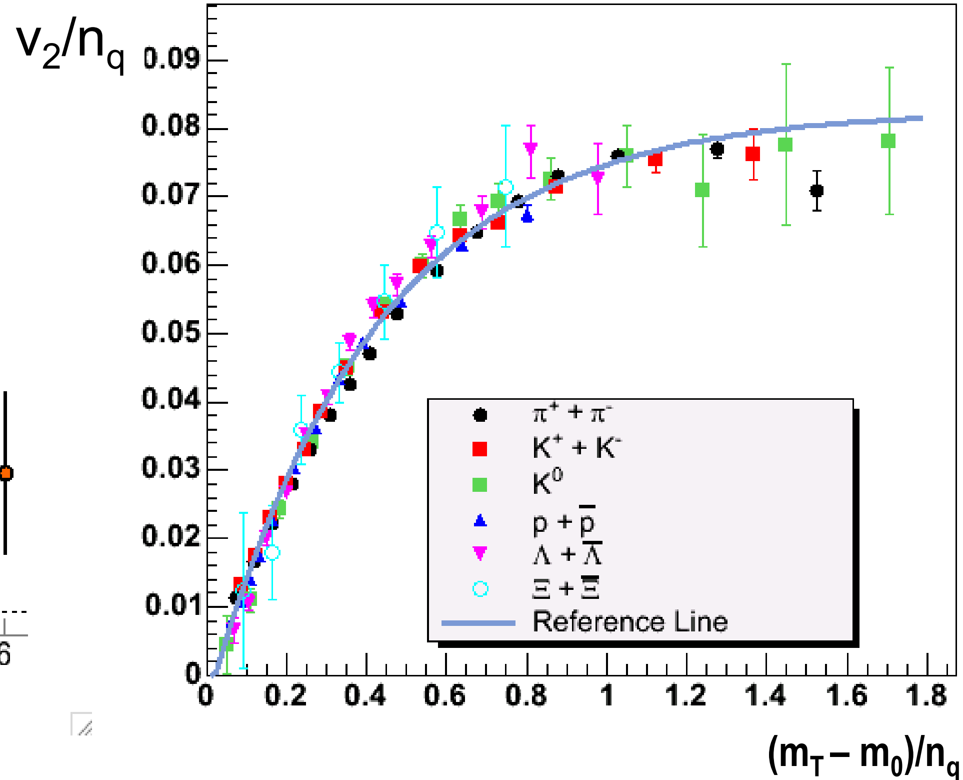
$$= \left[1 + 2v_2^q(p_T^q)\cos(2\phi) + \cdots\right]^{n_q}$$

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

- $v_2$ obeys constituent quark scaling
  - Hadronization through **coalescence**
  - Evidence for **flowing quarks**

# A remarkable scaling of the “fine structure” of elliptic flow is observed



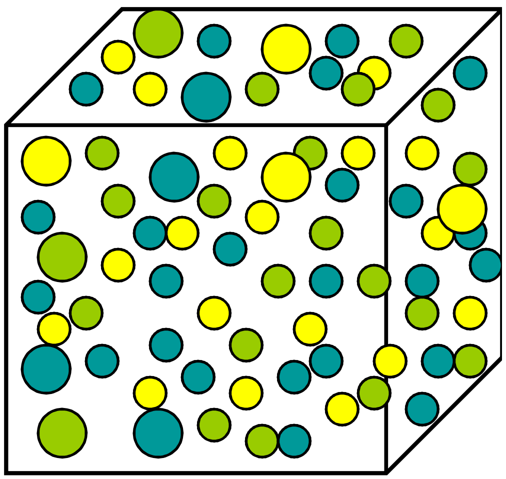



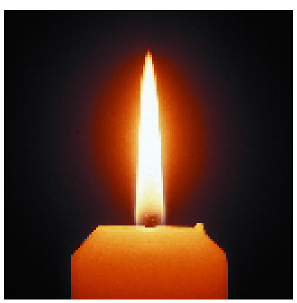

Fluid→QuasiParticles→Hadrons

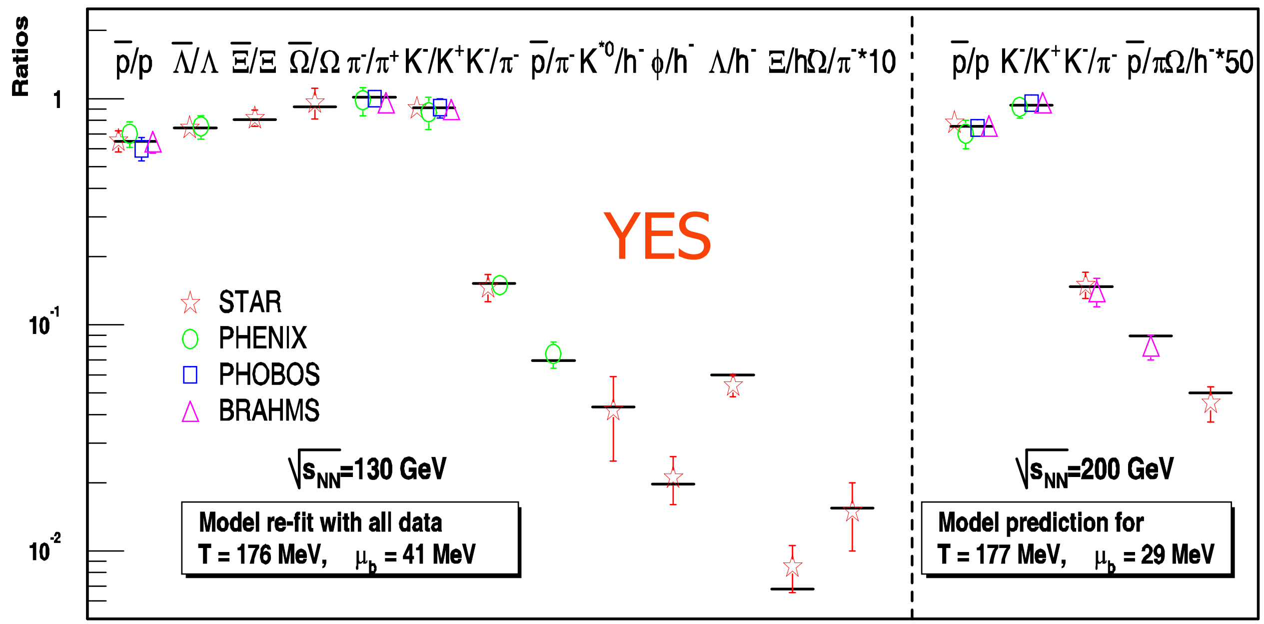
Evidence for fluid breaking up into quasi-particles with quantum numbers of quarks before hadrons

# Supporting Evidence :

For a thermalized system of quarks (describable by thermodynamic properties such as temperature and chemical potential) then the ratios of the yields of particles distilled (hadronized) out of this quark soup should be predictable by statistical thermodynamics. Is it?








Horizontal bars are the prediction, points are data

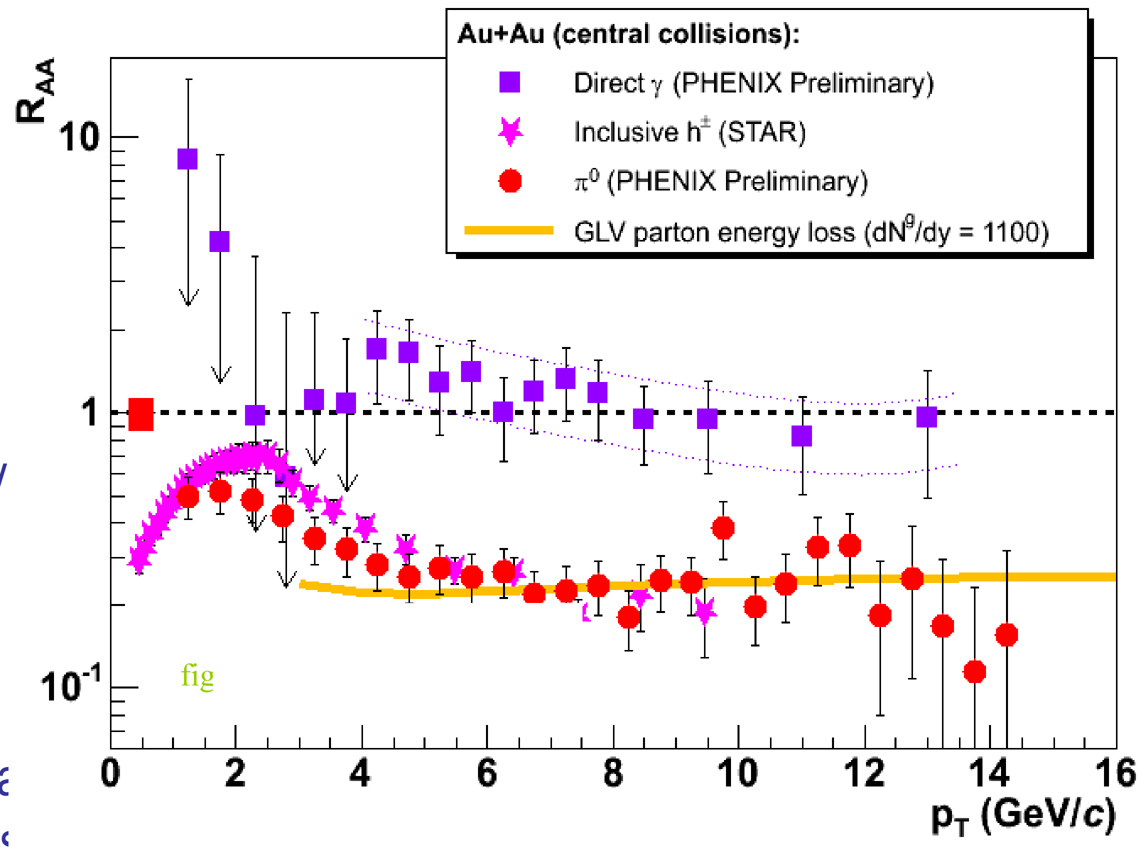
pT-integrated particle yield ratios in central Au+Au collisions consistent with Grand Canonical Stat. distribution @ Tch = (160 ± 10) MeV, $\mu B \approx 25$ MeV, across u, d and s quark sectors. Inferred Temp. consistent with Tcrit (LQCD) $\Rightarrow$ phase transition

# Three major discoveries at RHIC which point unequivocally to a new state of strongly interacting quark-gluon matter

The hottest, densest matter yet examined in the laboratory

T ~ 200-400 MeV, $\varepsilon_i \sim 30\text{-}60\ \varepsilon_0$

It is highly opaque to colored probes– quarks and gluons – but not to photons




It flows as a relativistic quantum liquid with minimal shear viscosity

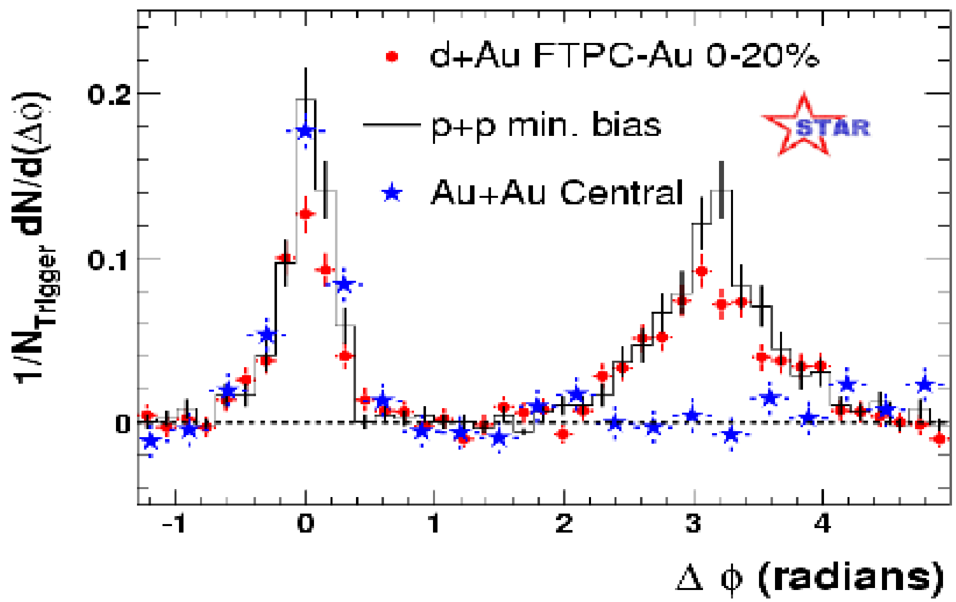
It produces copious mesons and baryons with yield ratios and flow properties that suggest their forma via coalescence of valence quarks from a hot thermal bath.

# Three major discoveries at RHIC which point unequivocally to a new state of strongly interacting quark-gluon matter

The hottest, densest matter yet examined in the laboratory

T ~ 200-400 MeV, $\varepsilon_i \sim$ 30-60 $\varepsilon_0$

It is highly opaque to colored probes– quarks and gluons – but not to photons




It flows as a relativistic quantum liquid with minimal shear viscosity

It produces copious mesons and baryons with yield ratios and flow properties that suggest their formation via coalescence of valence quarks from a hot thermal bath.

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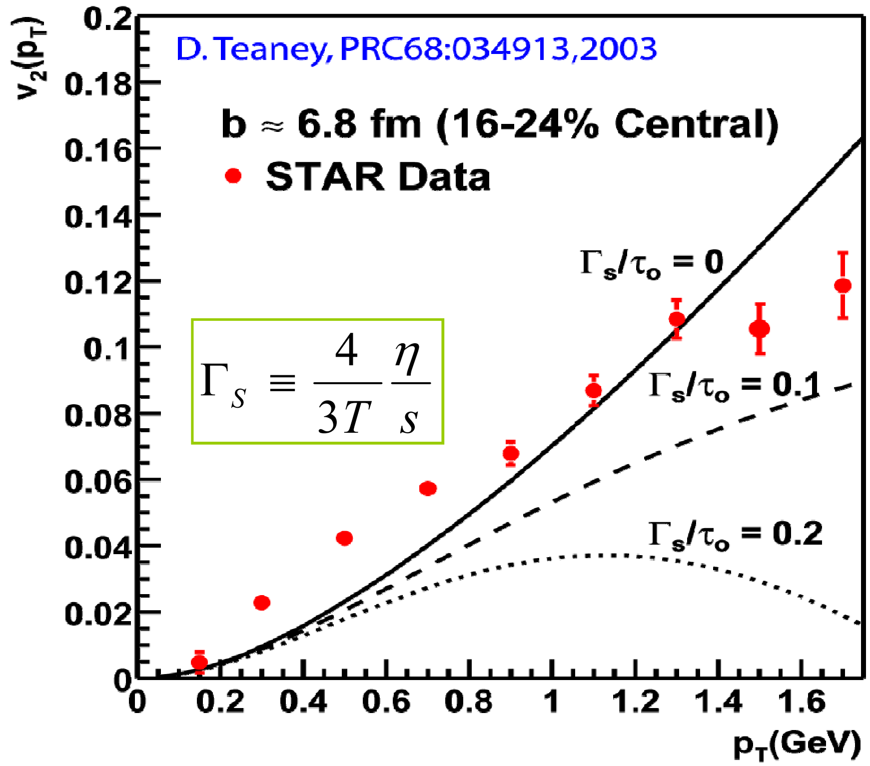


$\Gamma_S$ = sound attenuation length (~ mean free path)

For reasonable T (~ $2T_C$) and $\tau$ (~ 1 fm/c) data suggest $\eta/s \ll 0.3$

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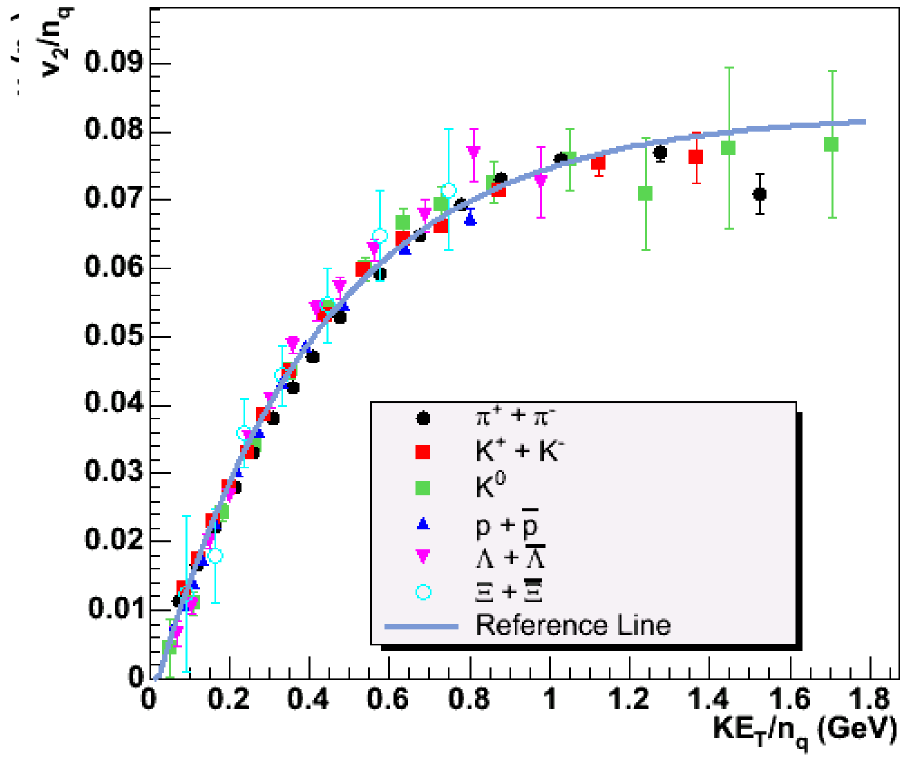



Fluid→QuasiParticles→Hadrons

Evidence for fluid breaking up into quasi-particles with quantum numbers of quarks before hadrons

These phenomena were not observed at the SPS (some were not even predicted) and they constitute important new discoveries

Are we done?

No, only just begun

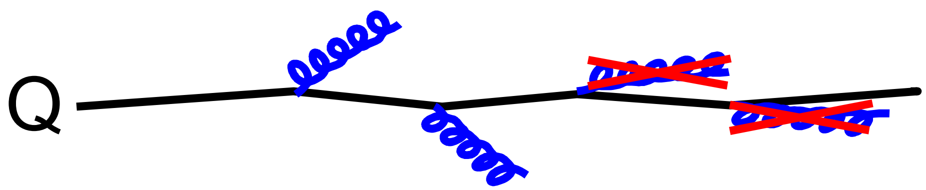
New questions have emerged from exploring this terra incognita

A new puzzle which emerges:

Initially there was a reasonably strong consensus that the suppression was basically understood: radiative energy loss in a medium 50-100 times normal nuclear matter density

Then these measurements were extended to the heavy quark sector (c, b) by studying suppression of electrons from their semi-leptonic decays

# Heavy quark energy loss




Dokshitzer, Khoze, Troyan, JPG 17 (1991) 1602.
Dokshitzer and Kharzeev, PLB 519 (2001) 199.

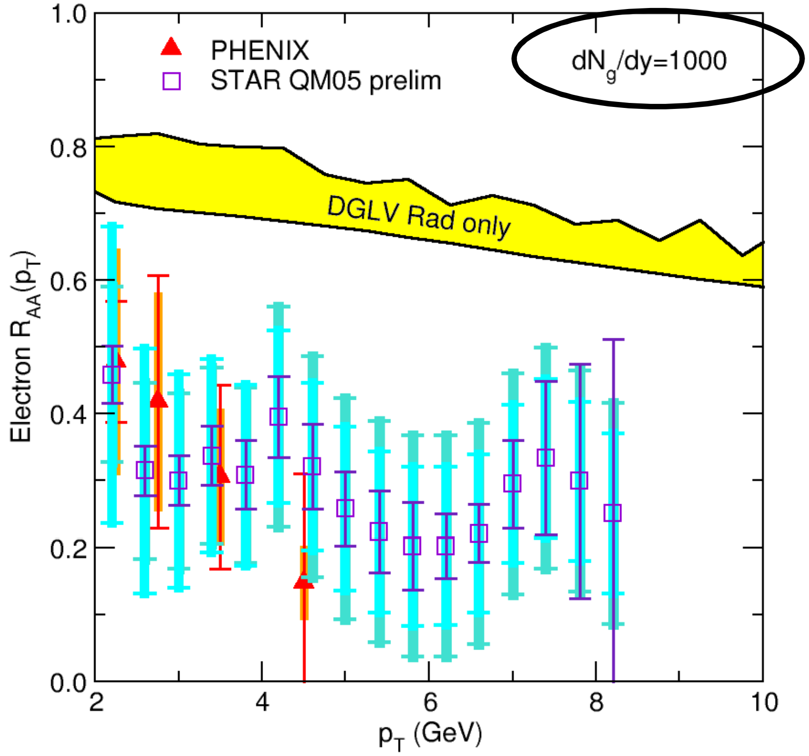
- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$
- "dead cone" effect: heavy quarks fragment hard into heavy mesons

Dead cone also implies lower heavy quark energy loss in matter: (Dokshitzer-Kharzeev, 2001)

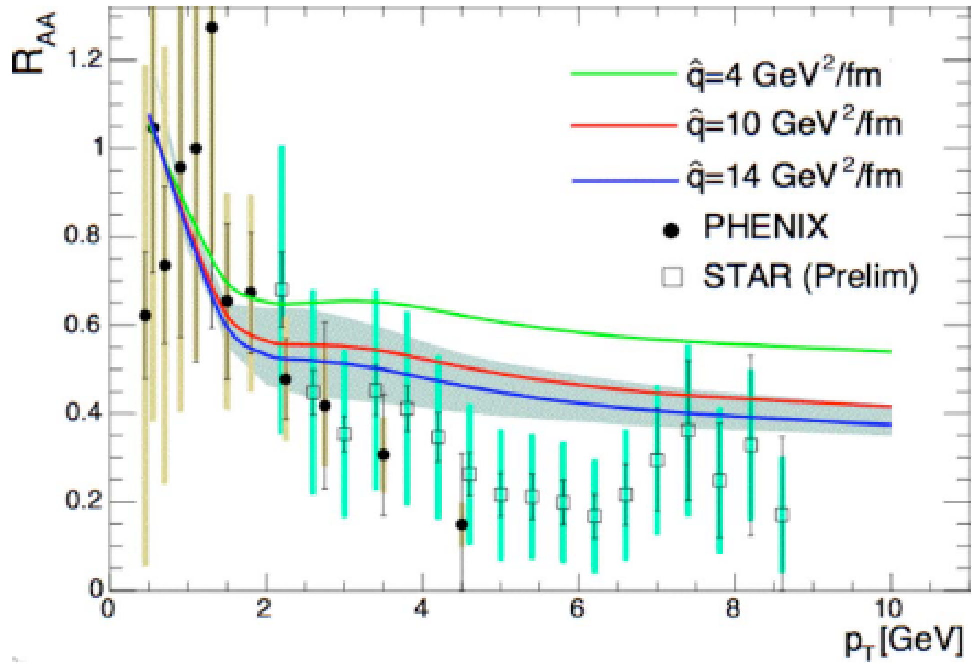
$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_{HEAVY} = \frac{\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{LIGHT}}{\left(1+\left(\frac{m_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^2}$$

# Heavy flavor suppression via b,c → e+X

S.Wicks et al., nucl-th/0512076




Armesto et al., Phys.Lett.B637:362-366,2006




**$R_{AA}$(non-photonic electrons) ~ 0.2 ~ $R_{AA}(\pi^0)$ !!**

Gluon density/qhat constrained by light quark supression+entropy density (multiplicity)

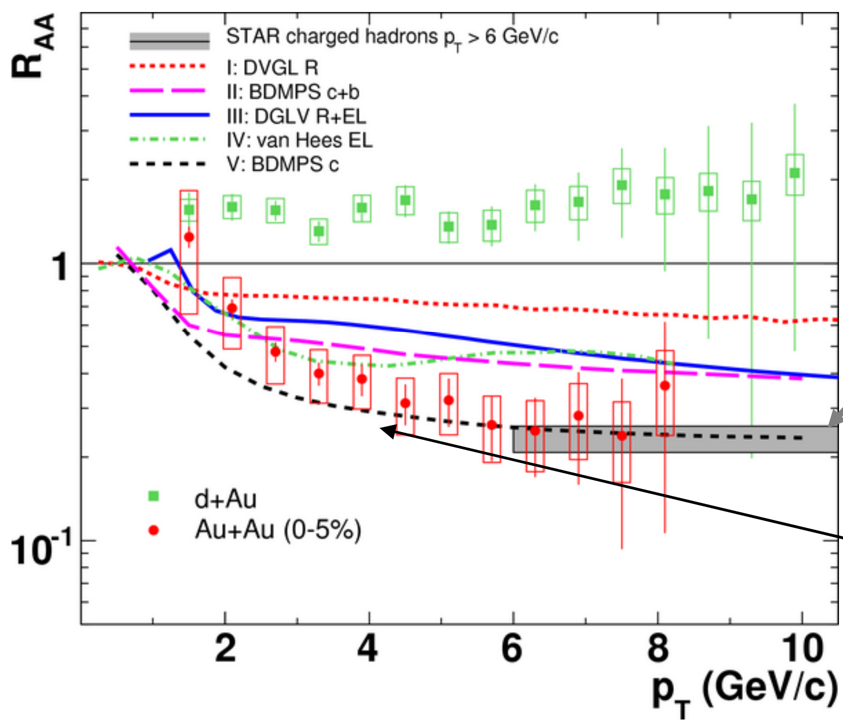
⇒ under-predicts electron suppression

⇒ charm vs beauty? elastic energy loss? …?

# Surprising results on suppression of High-$p_T$ Charm via Electrons

Using non-photonic electrons
as a surrogate for charm semi-leptonic
decays….

Ratio of charm spectra in Au+Au to p+p normalized by
No. of binary collisions & comparison with models of
pQCD energy loss primarily based on radiation of gluons




## A total shock:

Heavy quark hadrons appear to be just as suppressed as light quark Hadrons (gray box)

Only reasonable agreement
is if no B mesons are produced
(black dashed curve--not realistic)

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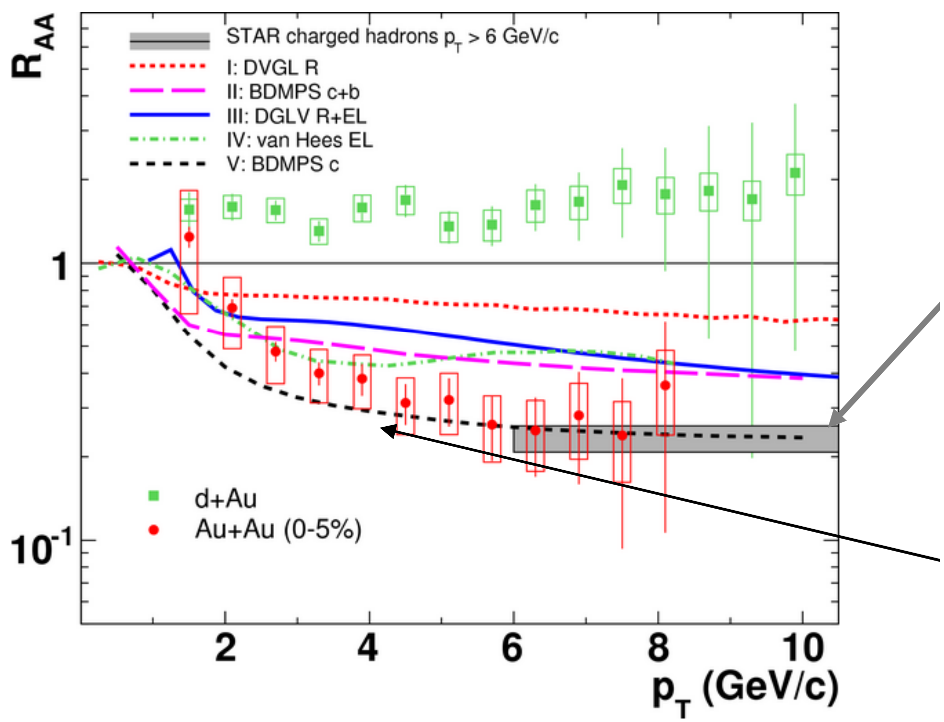
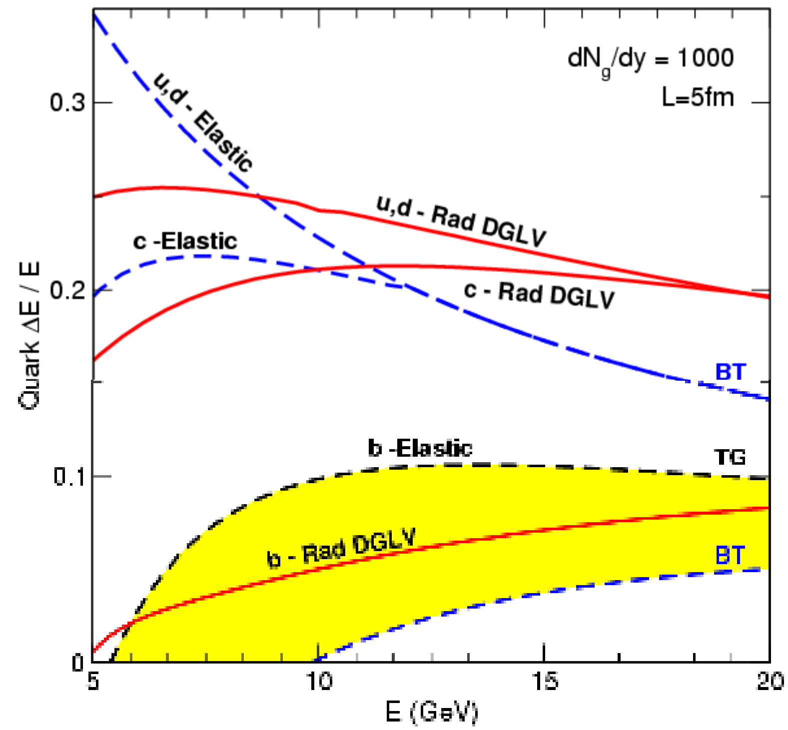



Results caused a shift of paradigm on importance of collisional energy loss

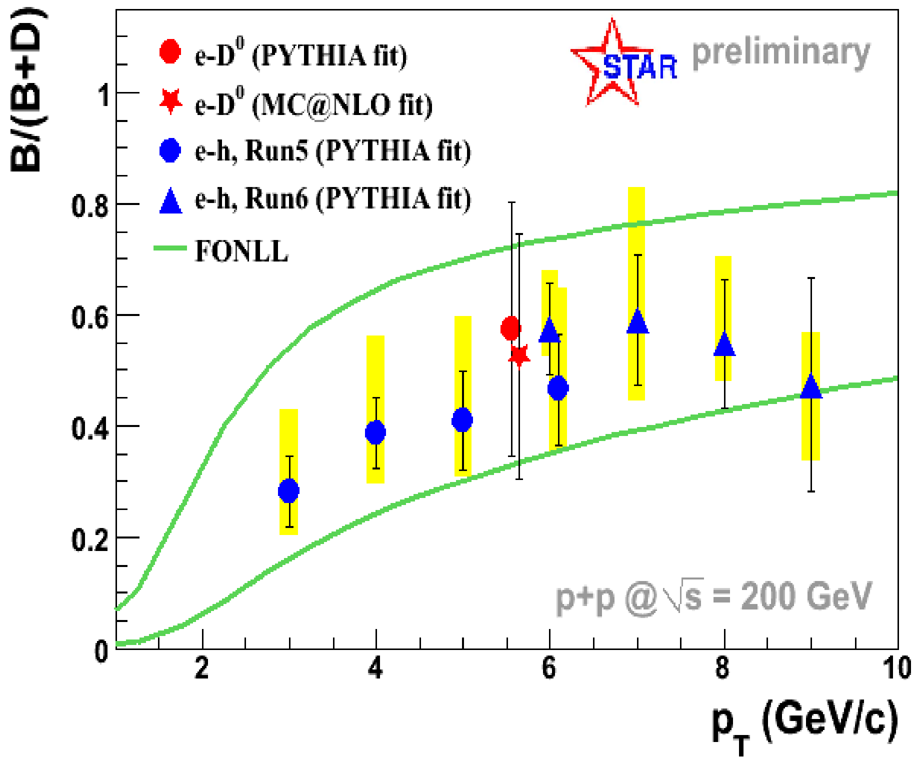
S.Wicks et al., nucl-th/0512076




- Measurement of non-photonic electrons from semileptonic D decays show substantial suppression in central Au+Au collisions comparable to that from light mesons
- Describing the suppression is difficult for models→ theory paradigm shift on radiative energy loss, collisional E-loss, fragmentation and dissociation in medium?
- Energy loss models need to be revisited!

# Insight from heavy flavor correlations in p+p

All measurements in p+p at sqrt(s) = 200 GeV




In p+p collisions:

- The B contribution to non-photonic electrons is sizeable based on e-hadron and e-D meson correlations

Taken together with suppression of non-photonic electrons in Au+Au, this suggests significant suppression of non-photonic electrons from bottom in the medium

This may be hinting our paradigm needs to change

# Possible example of paradigm shift at RHIC

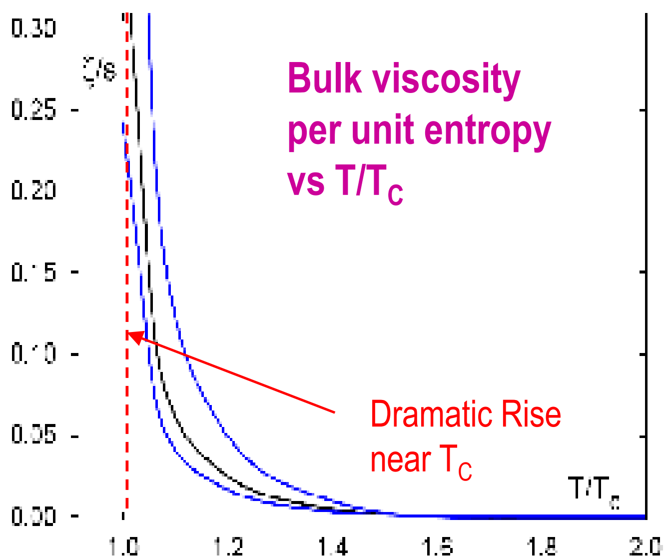
- From Dmitri Kharzeev on pQCD energy loss: "if it is really true that bottom is suppressed, there's just no way.."

## First glimpses of a new paradigm?

BNL-NT-07/47
RBRC-703

**Universal properties of bulk viscosity near the QCD phase transition**

Frithjof Karsch, Dmitri Kharzeev and Kirill Tuchin




arXiv:0711.0914v1 [hep-ph] 6 Nov 2007

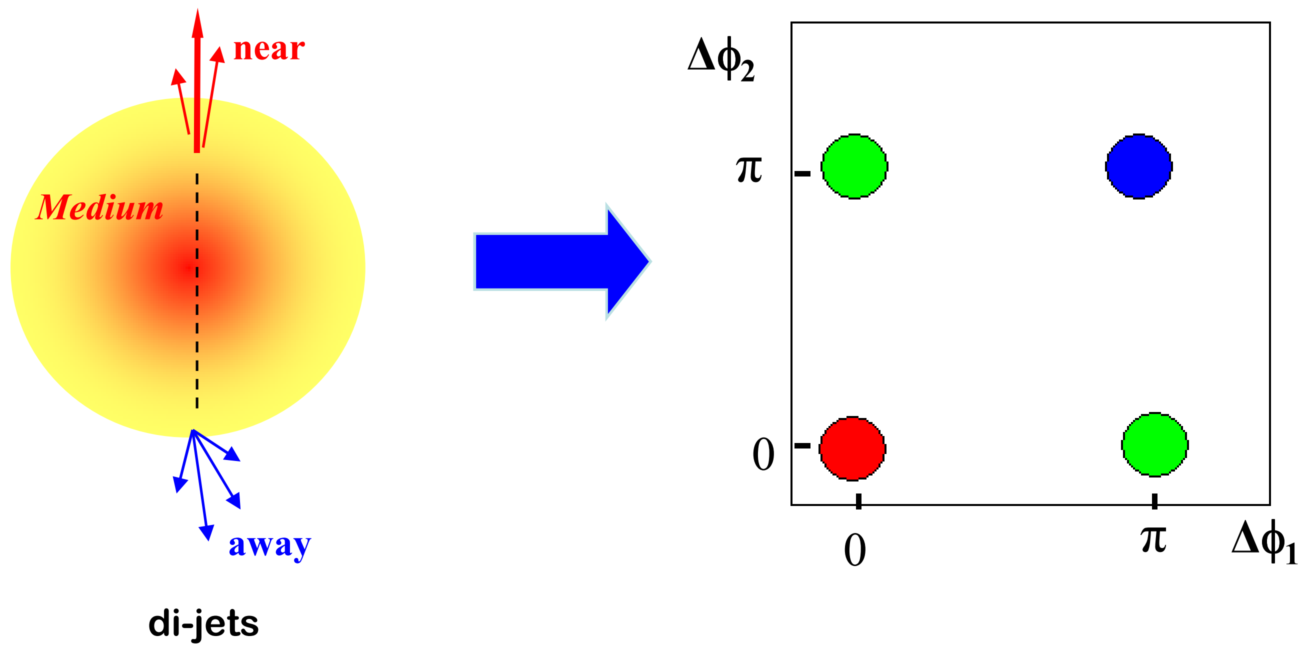
Bulk viscosity of hot qgp in the presence of light quarks from lattice data on QCD equation of state

- Large Bulk Viscosity →
  - strong coupling between dilatational modes and internal degrees of freedom
  - Production of large number of soft partons
  - Screening of color charge of pre-existing quarks and gluons
  - Soft statistical hadronization
  - Decrease in $\langle p_T \rangle$ and increase of M due to rapid increase in entropy and associated quenching of transverse hydro expansion

(Observed effect for $^3$He)

# A possible collective mode of excitation

Using 3-particle correlation to discriminate different physical mechanisms.



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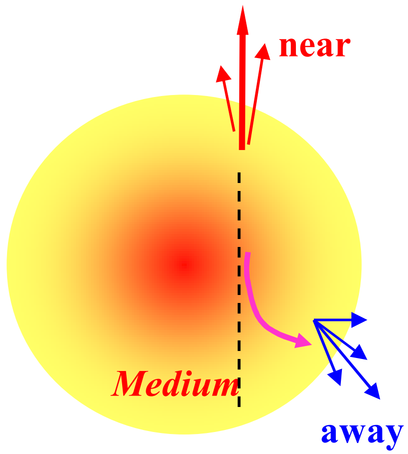
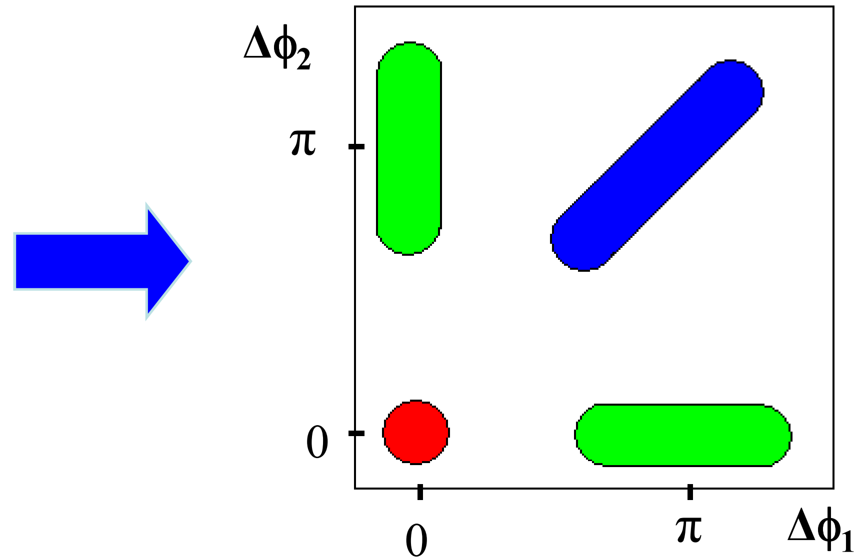



deflected jets



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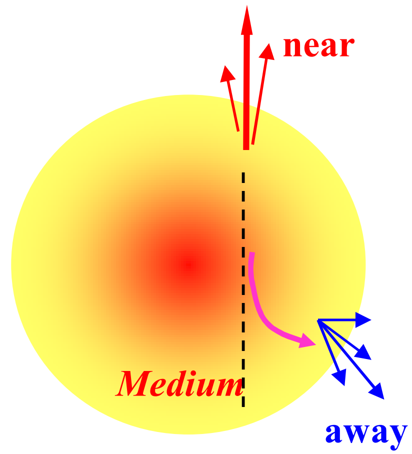


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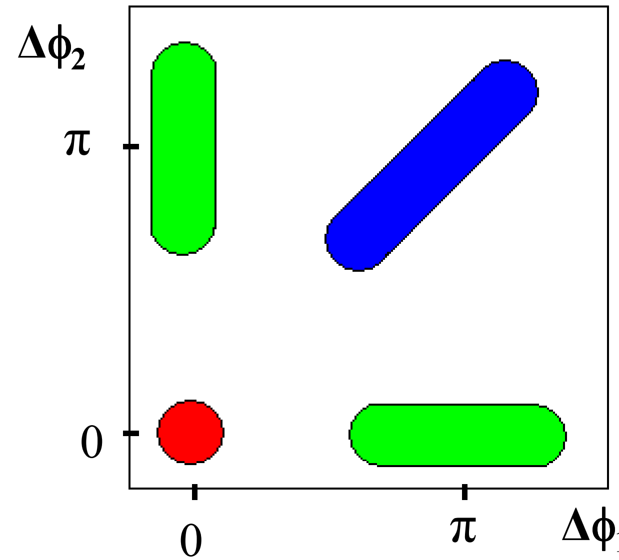
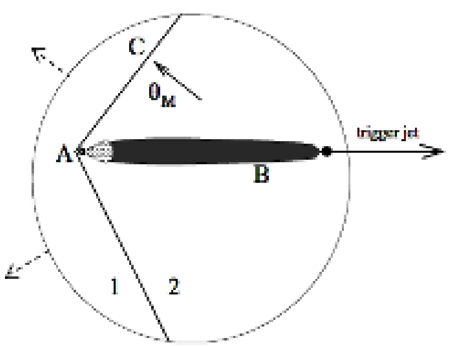
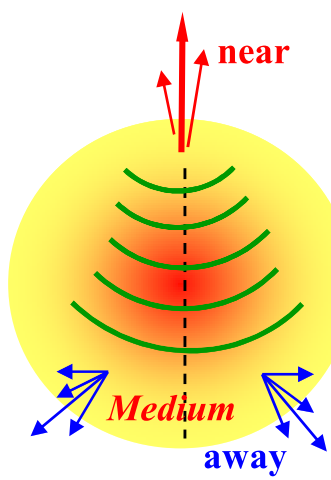
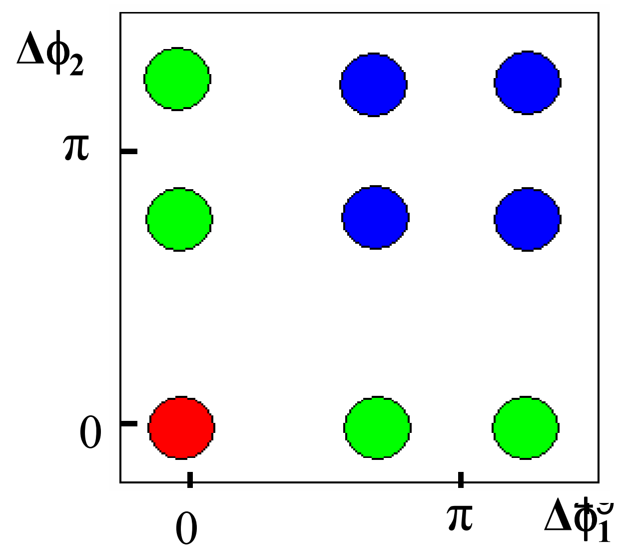



mach cone

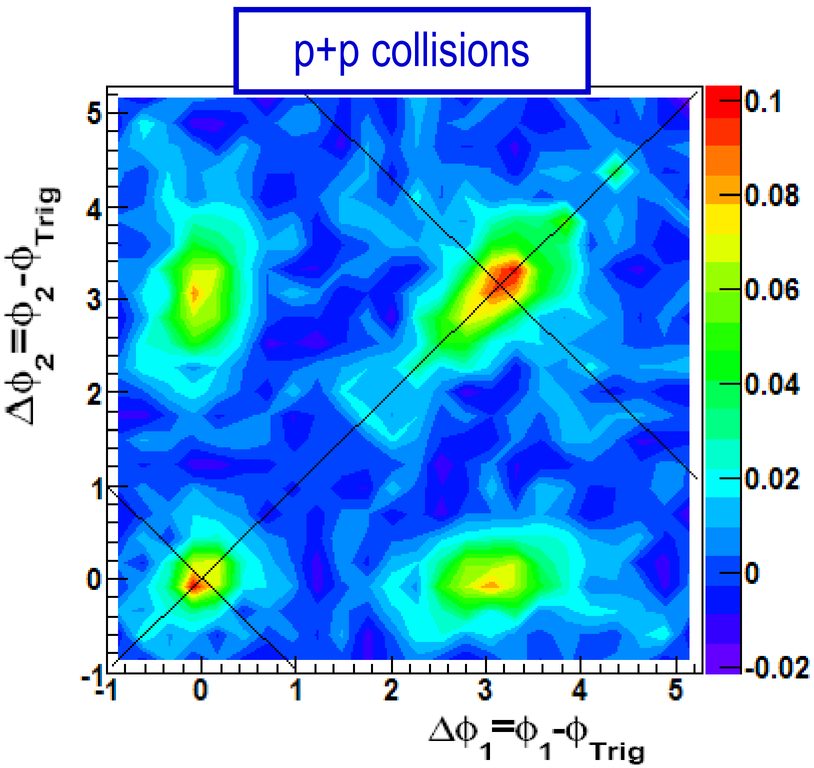


# The experimental evidence

## Indications of Conical Emission of Charged Hadrons at RHIC

arXiv:0805.0622v1 [nucl-ex] 6 May 2008

Three-particle azimuthal correlation measurements with a high transverse momentum trigger particle are reported for *pp*, d+Au, and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR experiment. The acoplanarities in *pp* and d+Au indicate initial state $k_\perp$ broadening. Larger acoplanarity is observed in Au+Au collisions. The central Au+Au data show an additional effect signaling conical emission of correlated charged hadrons.




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

# The experimental evidence

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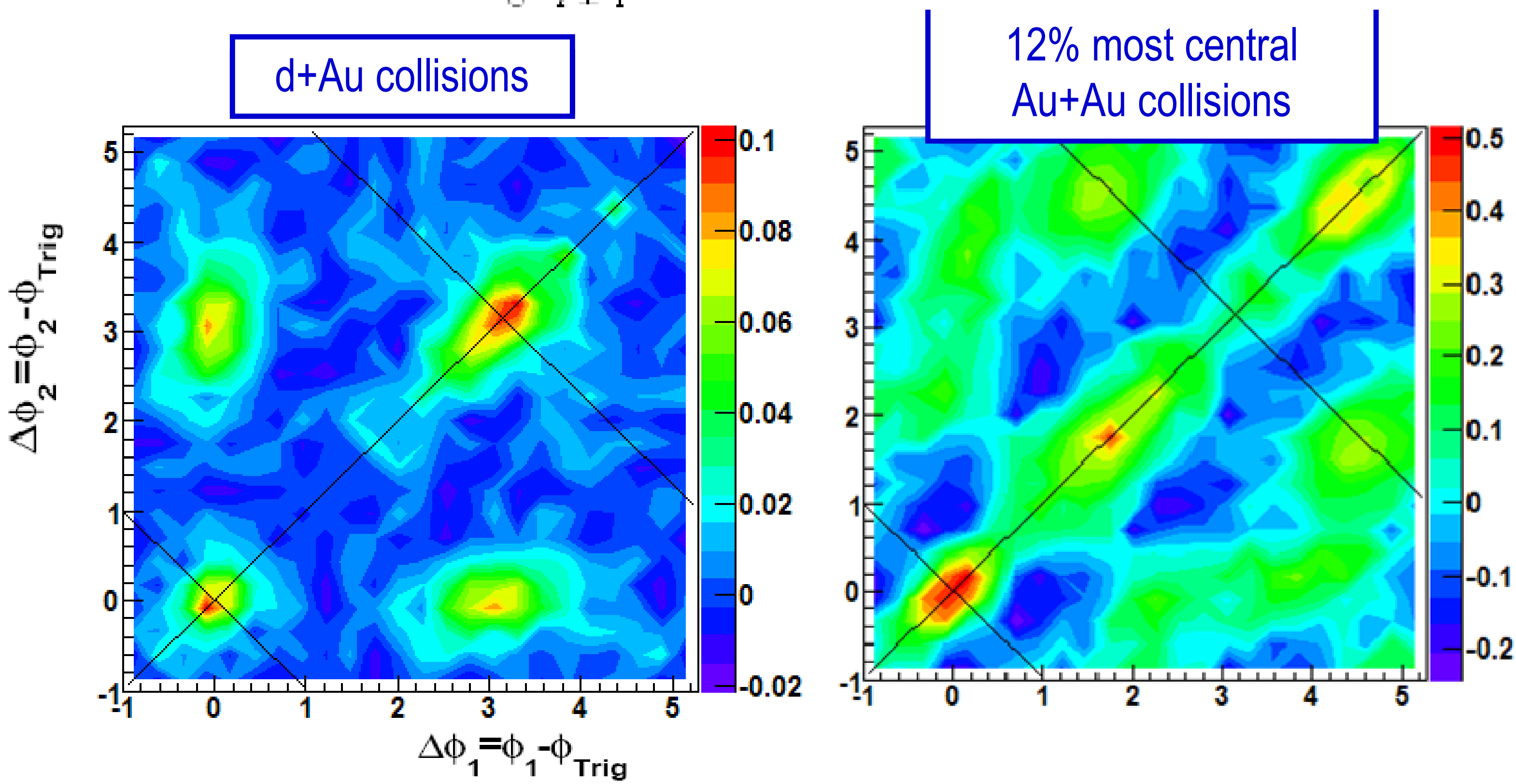
….. Distinct peaks at $\theta = 1.38 \pm 0.02(\text{stat}) \pm 0.06(\text{syst.})$ from $\pi$ are observed on the away side in central Au+Au collisions, with correlated hadron pairs far apart, symmetric about $\pi$, as well as close together. These structures are evidence of conical emission of hadrons correlated with high $p_\perp$ particles.

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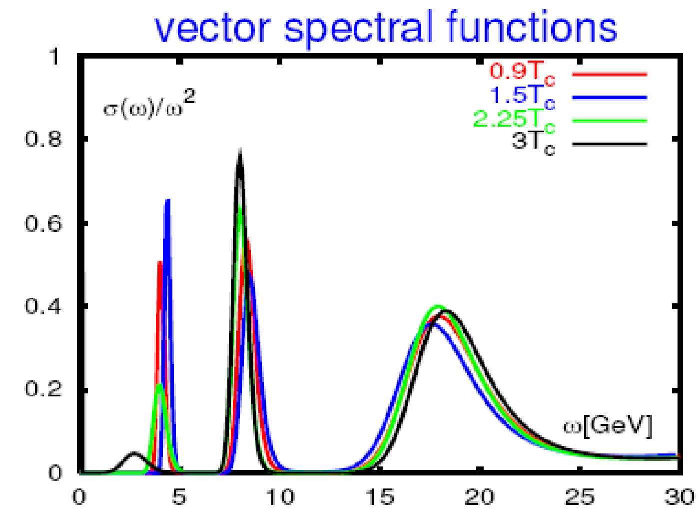
# Future tools

# 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 $T_c$.

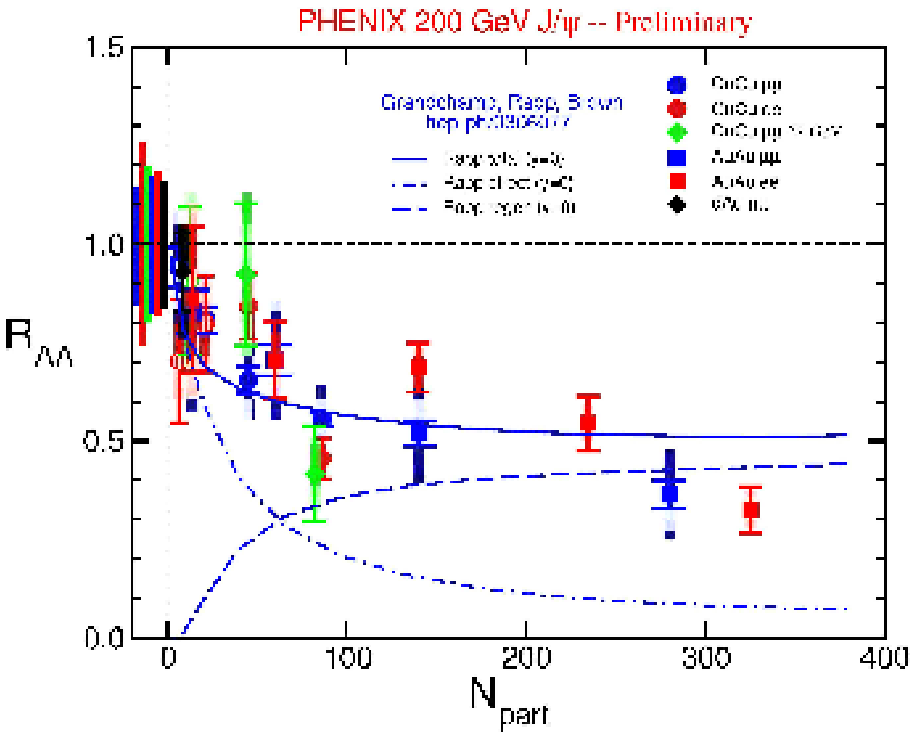


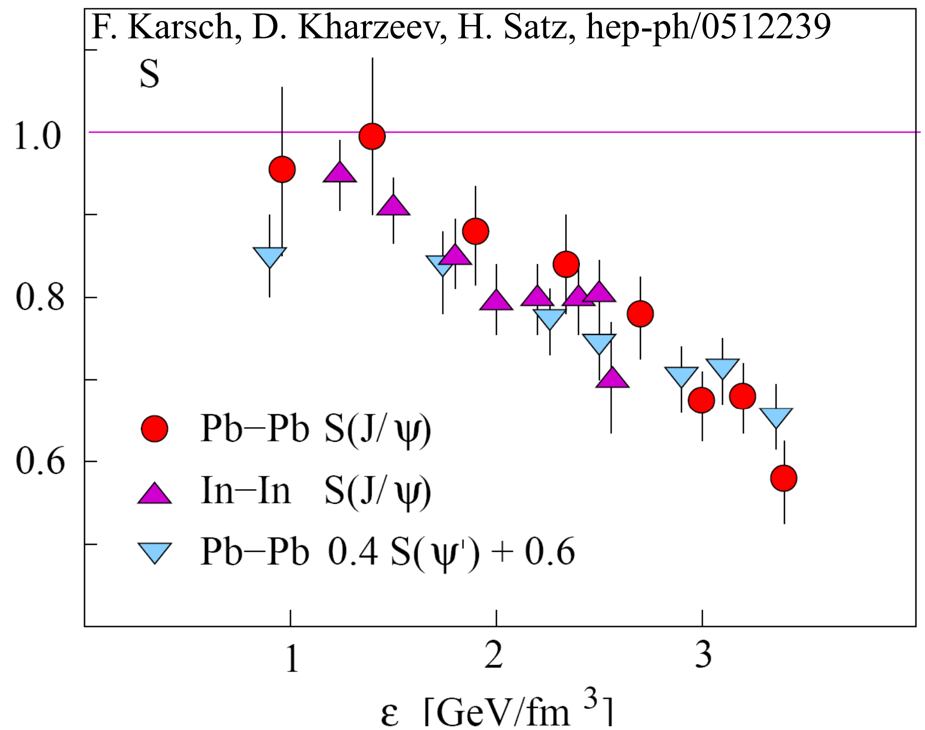

- Hierarchy of melting:

| 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: $c + \bar{c} \longrightarrow J/\psi$

# Current status



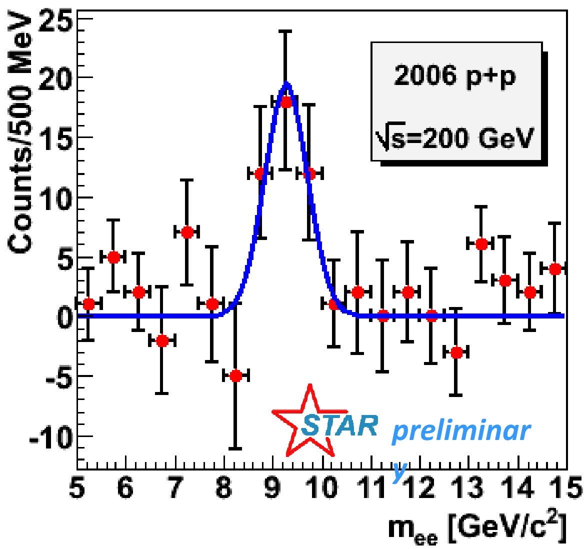

- Suppression + regeneration describes PHENIX results well
- Sequential melting also works if you assume the *J/ψ* doesn't melt

# How to discriminate?

- Compare model predictions to measurements of:
  - *J*/ψ spectrum modifications vs. rapidity and beam energy
  - *J*/ψ elliptic flow
- Need ψ' and $\chi_c$ 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 higher "RHIC II" luminosity

# A future test of color screening in the plasma: Bottomonium (ϒ)

First ϒ measurement

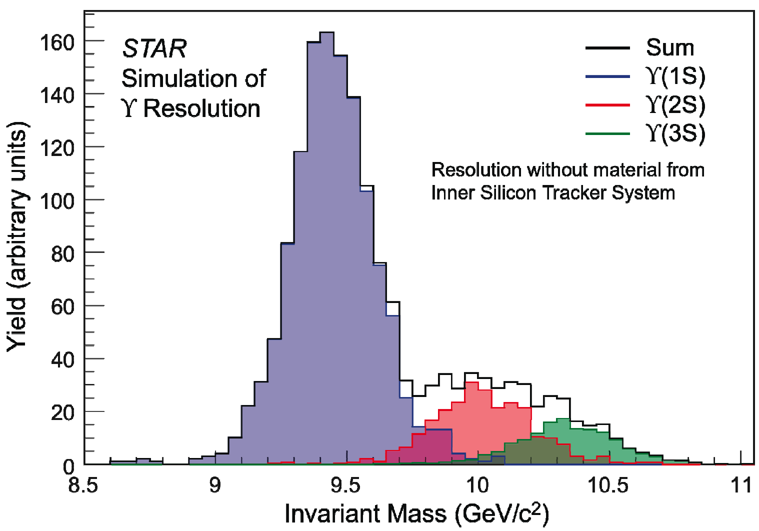


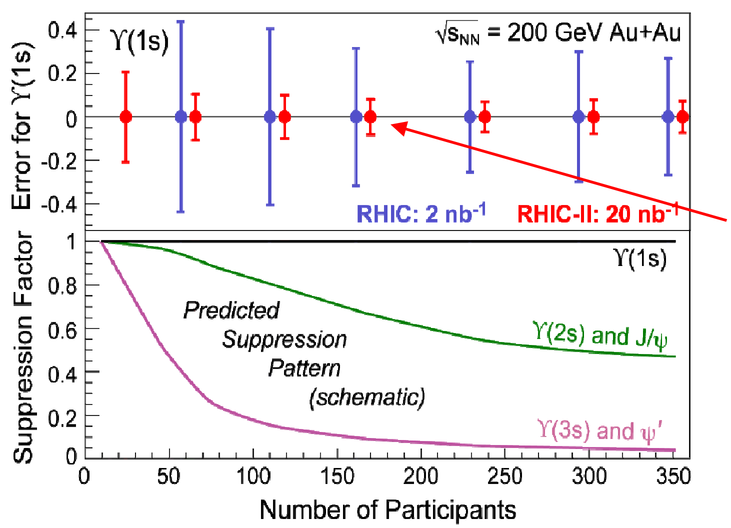

The ϒ, ϒ', ϒ'' should behave differently than the J/Ψ

- ϒ(1S) no melting at RHIC ⇒ standard candle
- ϒ(2S) likely to melt at RHIC (analog J/ψ)
- ϒ(3S) melts at RHIC (analog ψ')

Features

- co-mover absorption negligible
- recombination negligible at RHIC




ϒ→$e^+e^-$:
T. Ullrich et al

Statistical precision
Expected with RHIC II
luminosity



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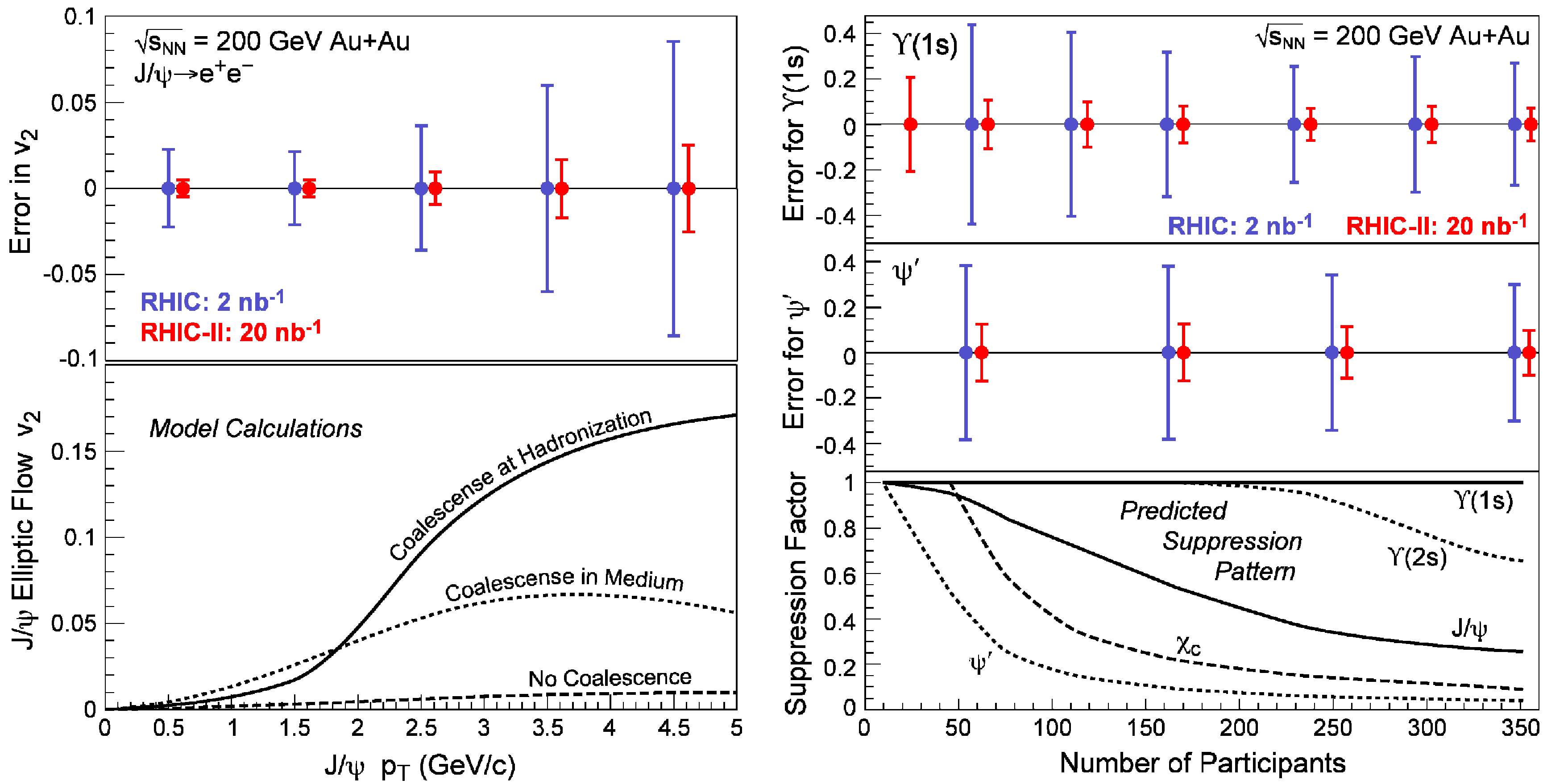
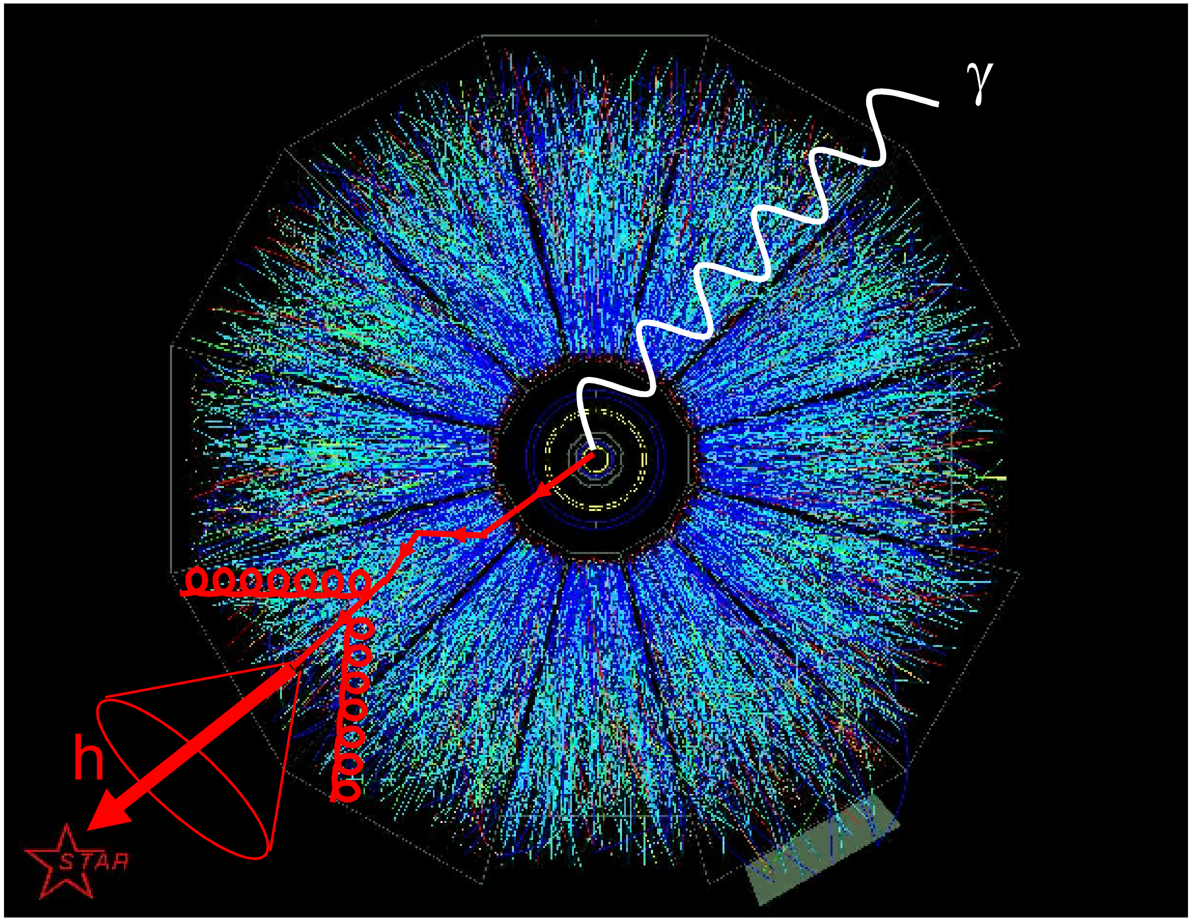
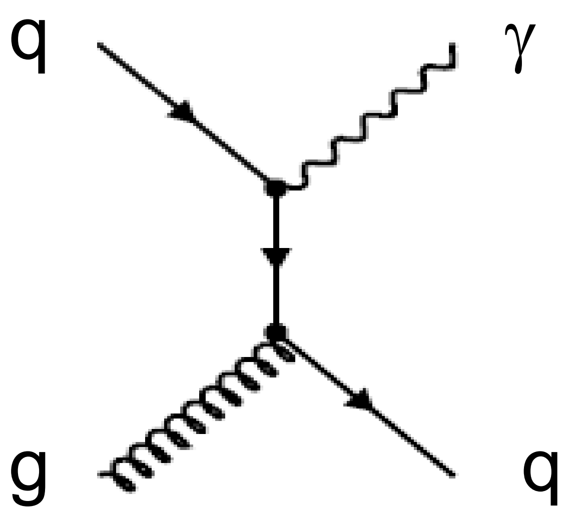
# RHIC-II Science Goals: Quantifying Properties of the Perfect Liquid

Enhanced luminosity (by 2012) + detector upgrades will enable rare probe studies of quarkonium (*qqbar* systems) yield & flow, sensitive to color screen-ing (deconfinement) and parton equilibration/coalescence in the QGP.



# γ-Jet: Golden Probe of QCD Energy Loss



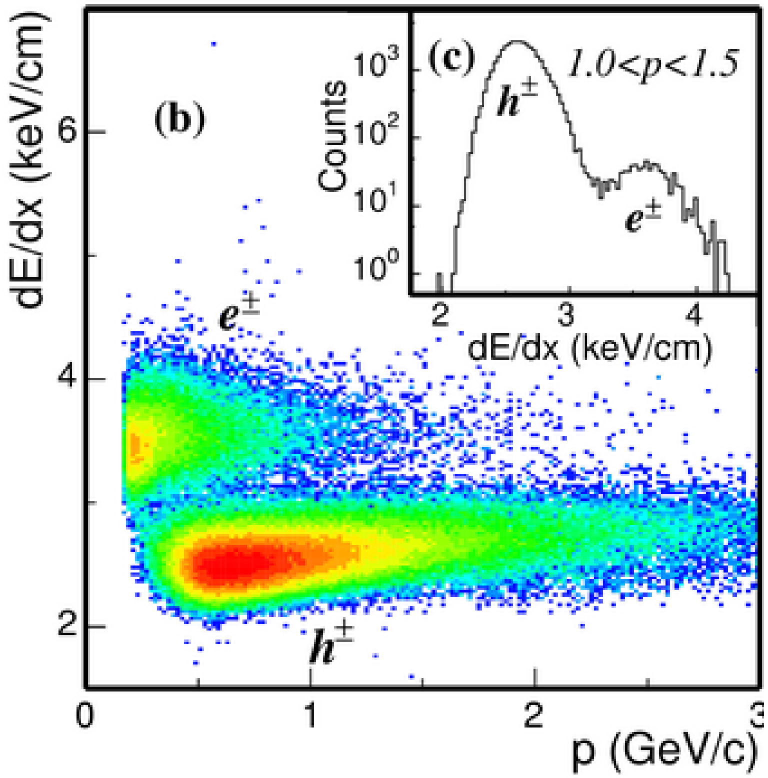



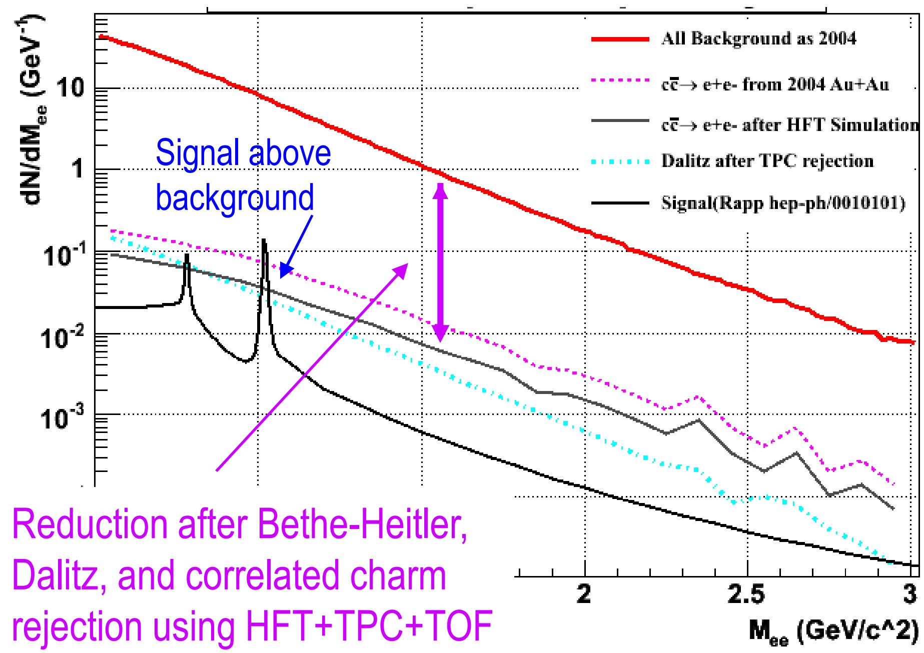

QCD analog of
Compton Scattering

- γ emerges unscathed from the medium
  - This probe is valuable for comparison with di-hadron correlations
  - It provides fully reconstructed kinematics: measure real fragmentation function D(z)

# Future di-lepton program to study in-medium effects

BNL-developed technique: dE/dx for β = 1 particles (TOF)



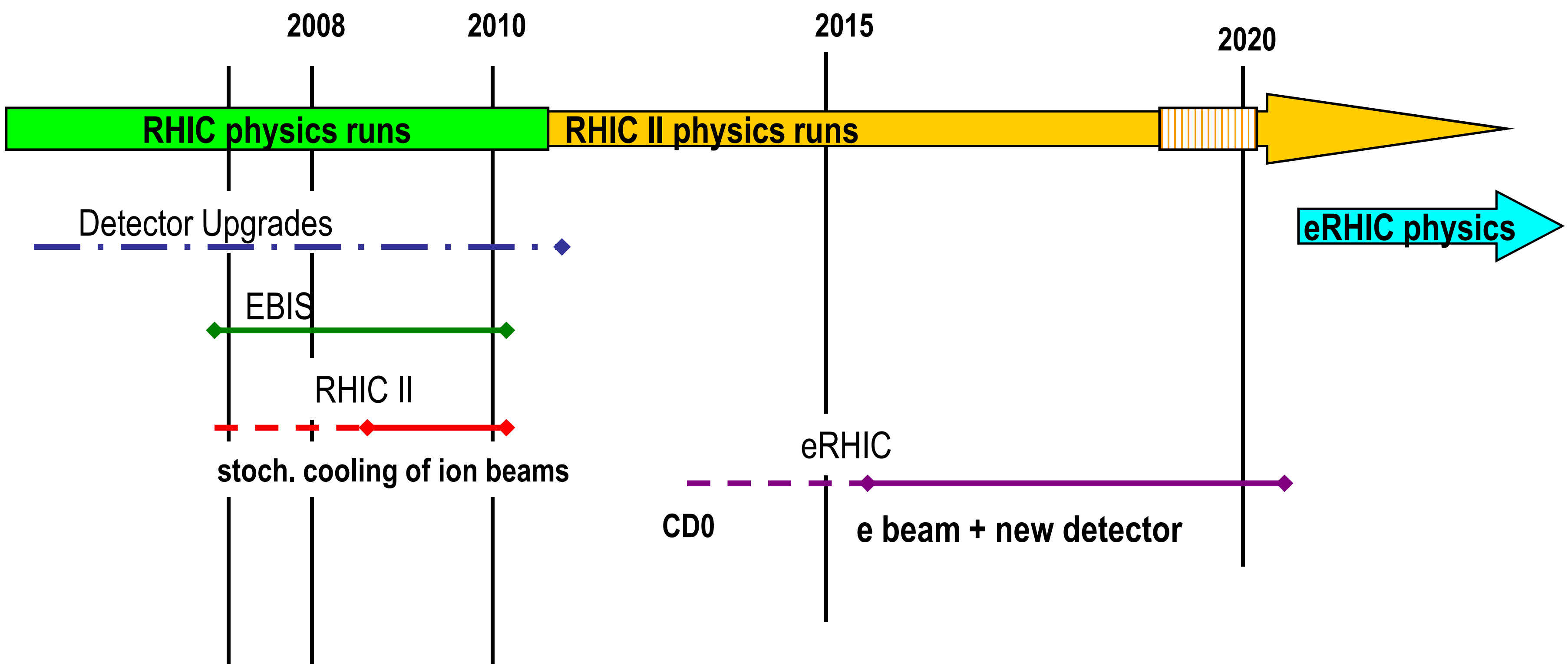




- Initiate and develop electron PID with TPC+TOF
- Utilize either low material (pre-HFT) or HFT
- Develop di-lepton program at STAR with resonance techniques + electron PID
- Statistics comparable to NA60

Projected $e^+e^-$: yields for 200M central Au+Au events

| Detectors | ω | ϕ |
|---|---|---|
| TPC+TOF+HFT | 20K | 6K |

# A Long Term (Evolving) Strategic View for RHIC



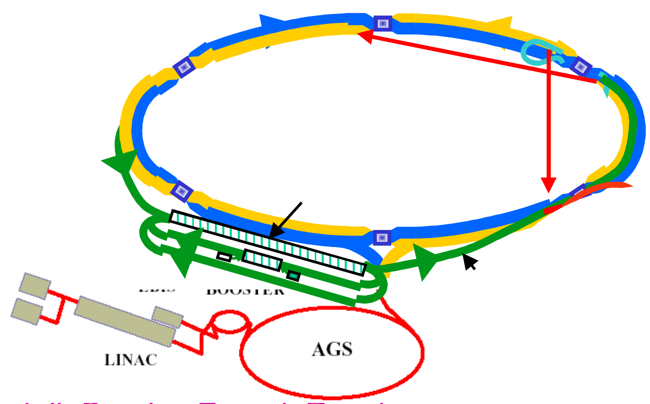

***Legend:***

- - - - - - - - - *R&D*

◆———◆ *Construction*

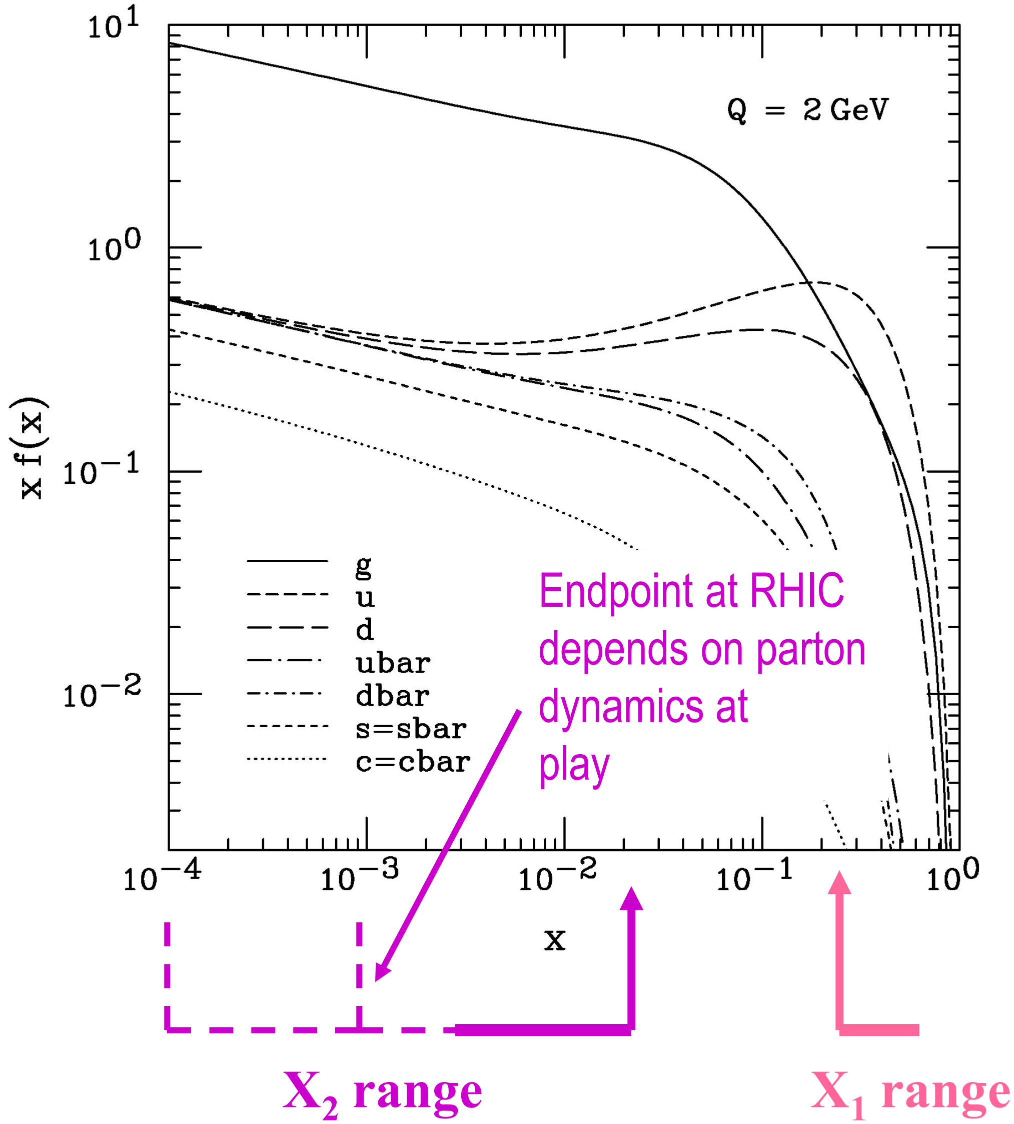
— · — · — ◆ *Multiple small projects*

*CD0: DOE Critical Decision, mission need*



And then, there is the question of the initial conditions

# What are the initial-state parton distribution functions and how they effect the time it takes to thermalize




Measurements needed at high rapidity to set the dominant parton type:

Projectile ($x_1$ ~1) mostly valence quarks.

Target ($x_2$<0.01) mainly gluons.

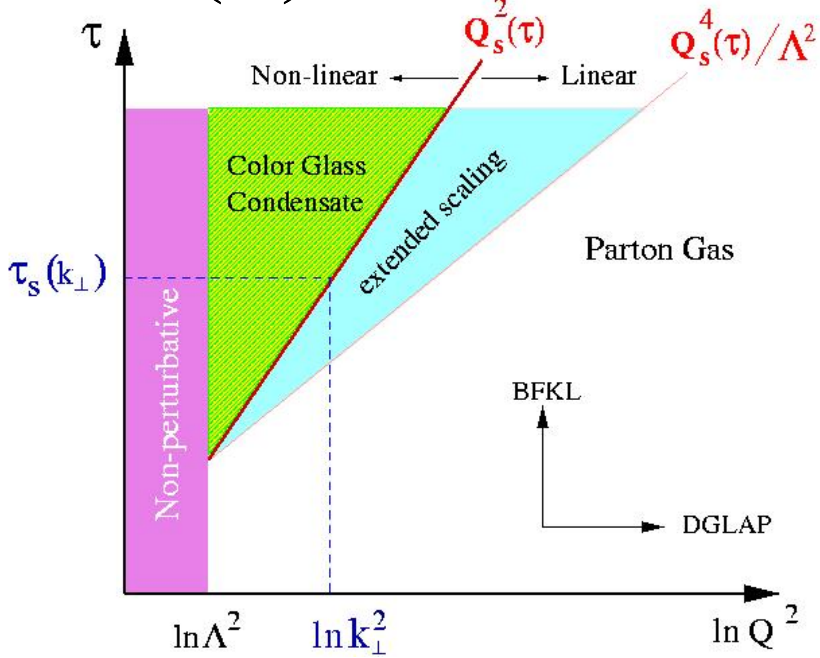
Sensitive to $x_g \sim 10^{-3}$ in pQCD picture

Sensitive to $x_g \sim 10^{-4}$ in CGC picture

- Question
  - At low-x in the previous plot, the gluon distribution continues to grow exponentially
  - But, it can not grow indefinitely without bound
  - What happens at when x becomes very small ?

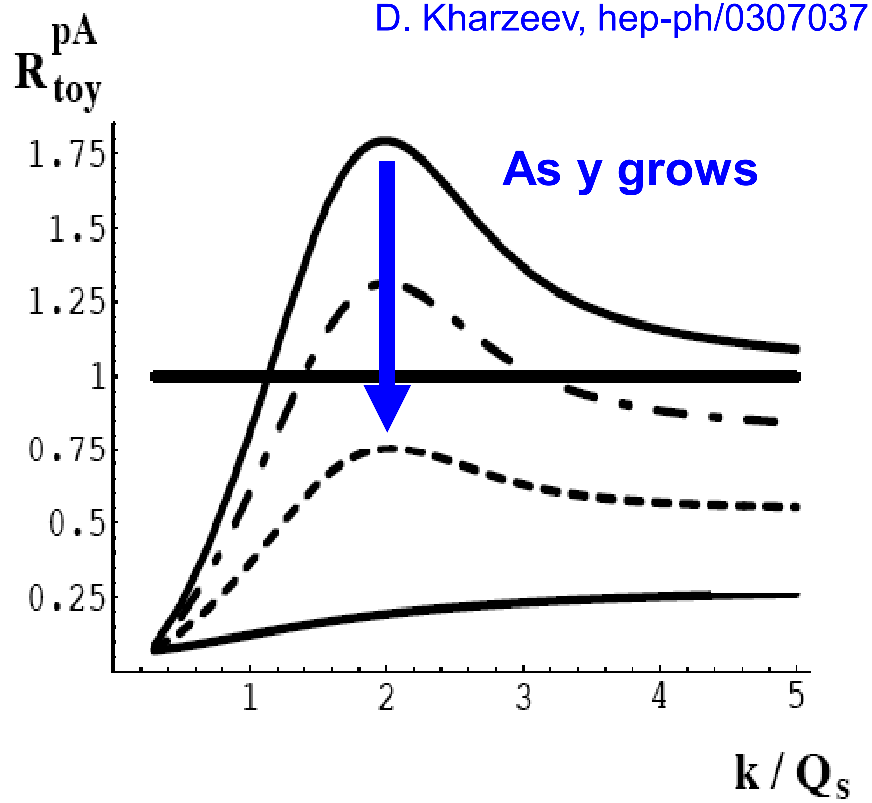
# Attempt at a semi-classical, effective field approach: conceptual expectation for a Color Glass Condensate

$\tau = \ln\left(\frac{1}{x}\right)$ $\tau$ related to rapidity of produced hadrons.




Iancu and Venugopalan, hep-ph/0303204

D. Kharzeev, hep-ph/0307037

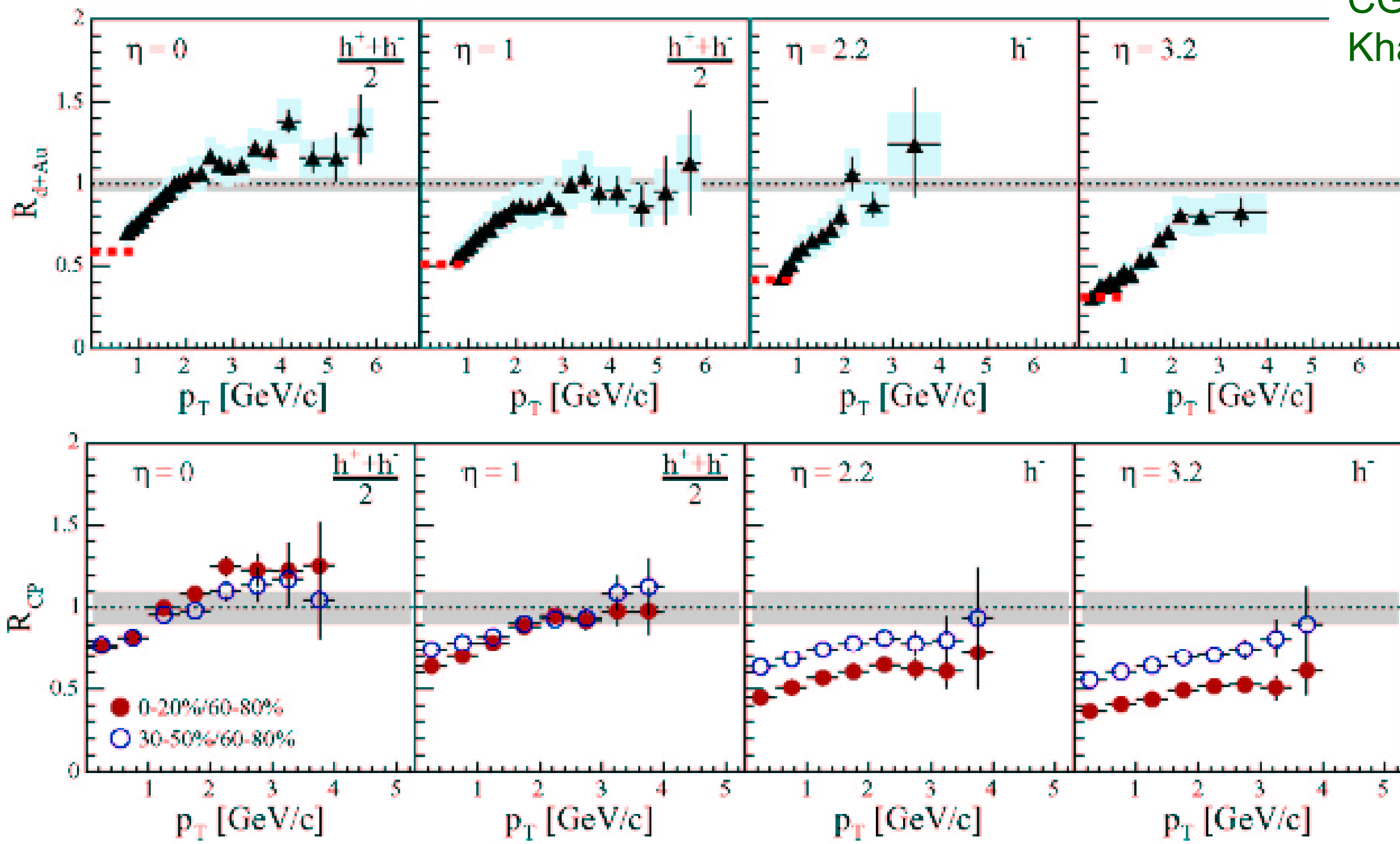



Is there evidence for **gluon saturation at RHIC energies**?

# Forward particle production in d+Au collisions

BRAHMS, PRL 93, 242303

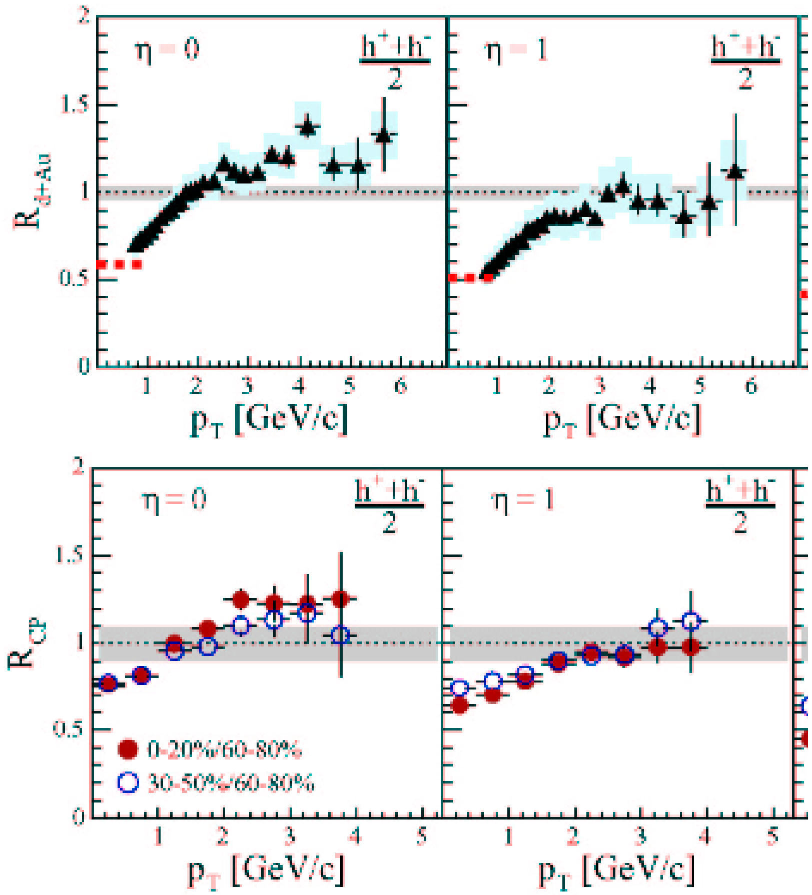
CGC calcs by Kharzeev et al

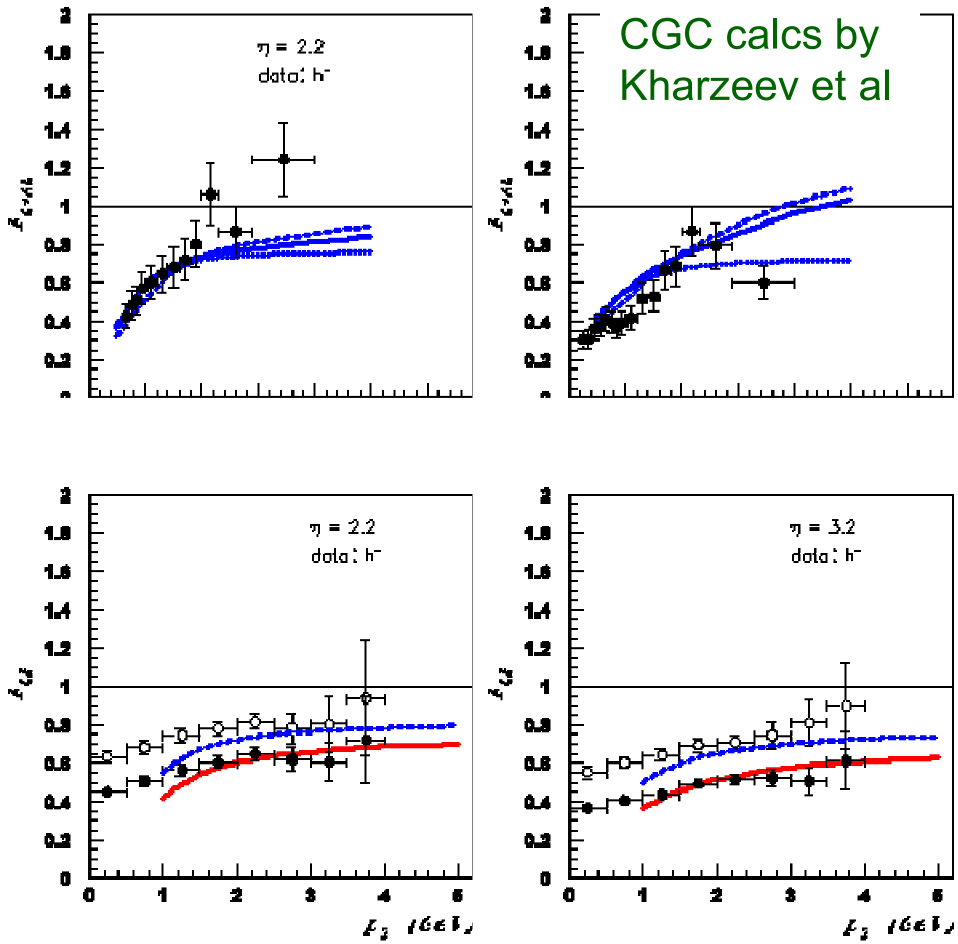



- Sizable suppression of charged hadron yield in forward d+Au
- Evidence for a saturated gluon field in the Au nucleus?
- Several other mechanisms have also been proposed

# Forward particle production in d+Au collisions

BRAHMS, PRL 93, 242303




CGC calcs by Kharzeev et al

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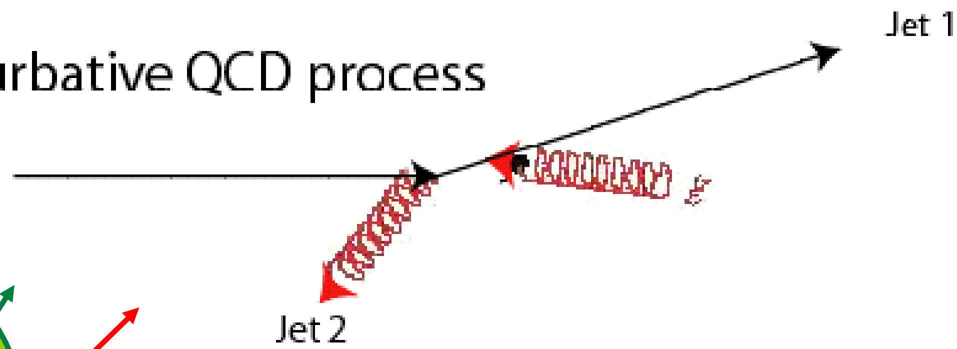
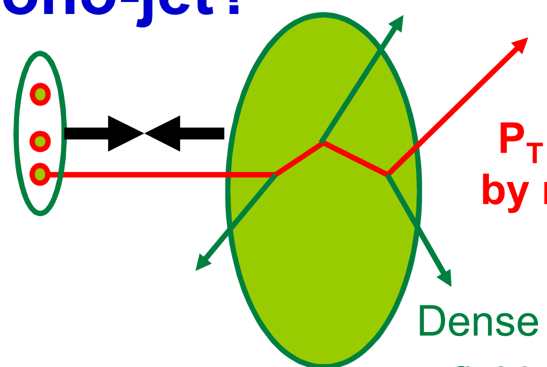
# Correlations will provide a more sensitive probe

p+p: **Di-jet**




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

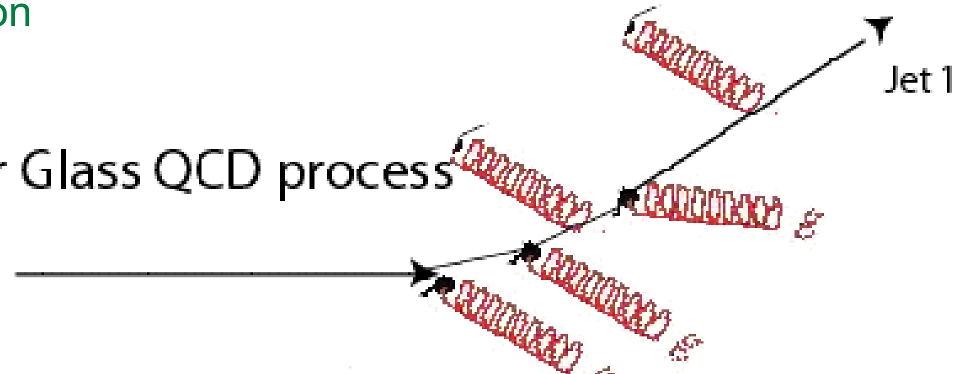
Dilute parton system (deuteron)



**$P_T$ is balanced by many gluons**

Dense gluon field (Au)

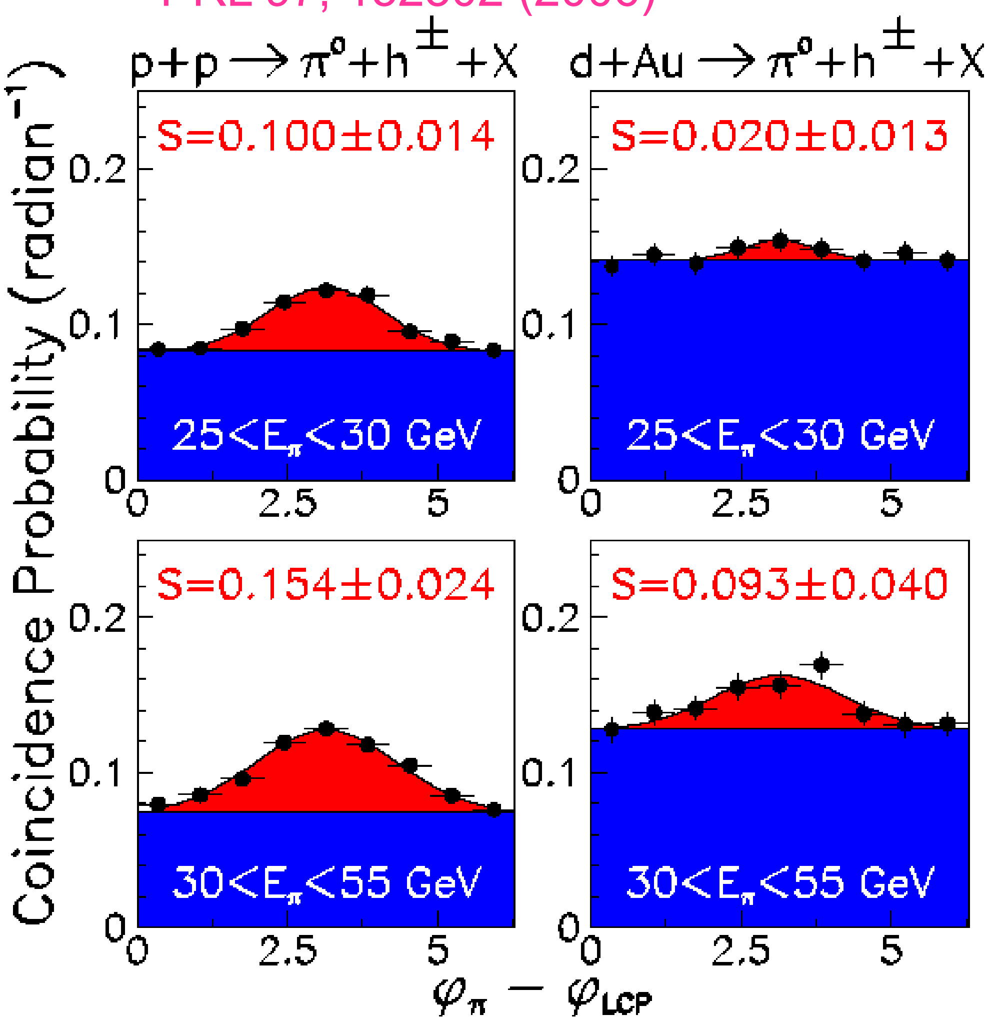
Kharzeev, Levin, McLerran gives physics picture (NPA748, 627)




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

# An initial glimpse: correlations in d+Au

PRL 97, 152302 (2006)




$\langle p_{T,\pi} \rangle \sim$ 1.0 GeV/c

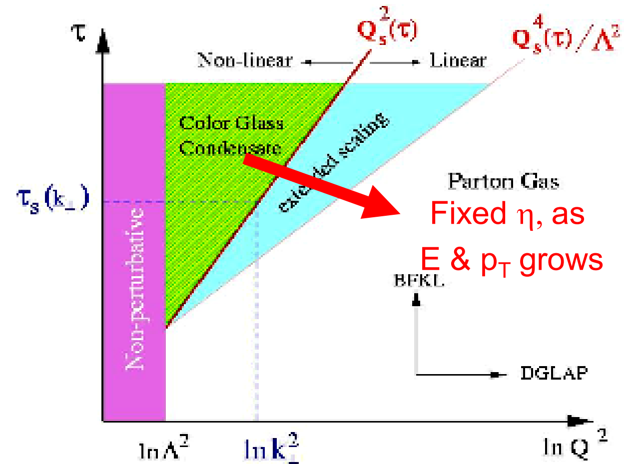
$\langle p_{T,\pi} \rangle \sim$ 1.3 GeV/c

$\pi^0$: $|\langle\eta\rangle| = 4.0$

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

- are suppressed at small $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$

consistent with CGC picture




- are similar in d+Au and p+p at larger $\langle x_F \rangle$ and $\langle p_{T,\pi} \rangle$

As expected by HIJING

Ultimately, to study the low-x gluon distribution in heavy nuclei properly, a new Electron-Ion Collider (EIC) is needed (BNL + TJNAF)

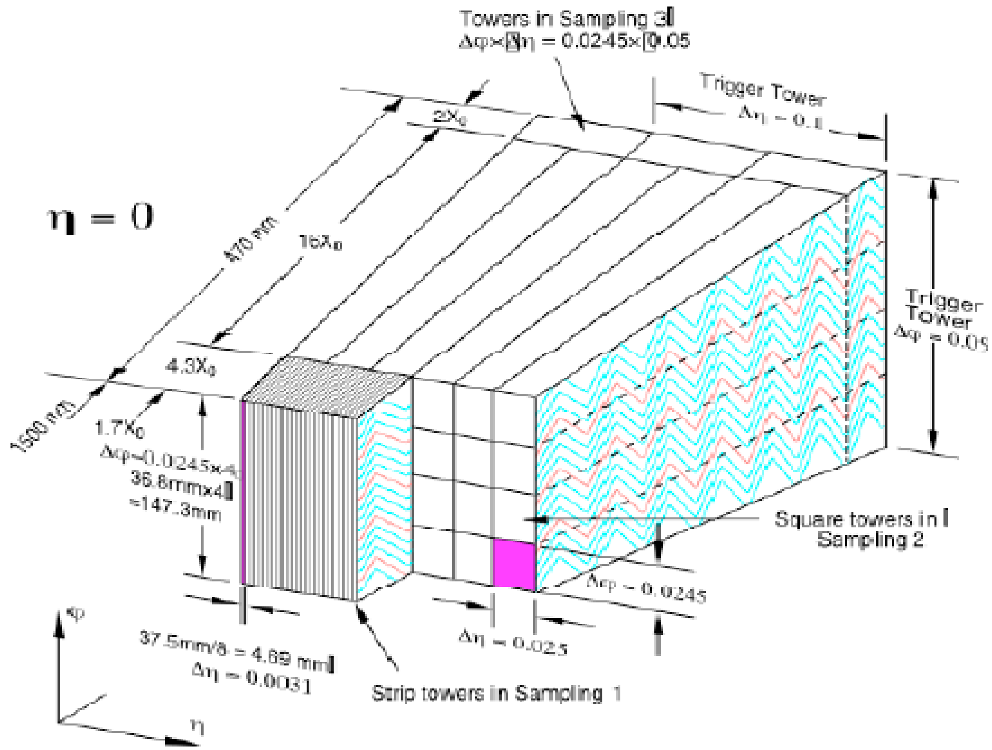
# BNL Involvement in LHC Heavy Ions

Limit to ~2.5 FTE, currently spread among: M. Baker, R. Debbe, J. Jia, P. Steinberg, F. Videbaek, S. White

Involvement motivated by pursuit of common science with RHIC, but modest due to primary BNL responsibility to RHIC operations

Why ATLAS?

- BNL hosts US-ATLAS & largest Tier 1 computing facility ⇒ amplify impact of modest HI involvement
- ATLAS has sharpest tools in LHC box for jet and $\gamma$ - jet reconstruction, with BNL expertise on calorimetry
- Synergy with BNL focus on $\gamma$ and $\gamma$ - jet at RHIC, to calibrate parton E loss




Longitudinally segmented large-acceptance EMCAL w/ precision strips (in $\eta$ direction) ⇒ factor ~5 improvement in S/B ratio for $E_T$ = 20-70 GeV $\gamma$

# What has been found: $3^+$ 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

# New 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?

These are the topics of RHIC II……

# The outlook

There is much more exploration and new discoveries which await in the RHIC region of the QCD phase diagram.

We look forward to new voyages of discovery taking place in parallel with those of our fellow explorer for many, many years to come

Congratulations on your 75th birthday!

Thank you for your work, your brilliance, and the knowledge and inspiration which have resulted