Results and Perspectives of RHIC experiments

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Abstract. We discuss Results and Perspectives of RHIC experiments beginning from an overview of the physics and experimental tools at RHIC and then introducing the highlights of the experimental results to date: (i) collective flow, (ii) hard probes and (iii) other supporting evidence for the creation of a strongly coupled quark-guon plasma. We give an outlook to further, new physics results to be expected from RHIC experiments.

References

1. M. Harrison, T. Ludlam and S. Ozaki (Eds.), "The Relativistic Heavy Ion Collider Project: RHIC and its Detectors", Nuclear Instruments and Methods in Physics Research A **499**, 235 (2003).
2. M. Gyulassy, L. McLerran, "New Forms of QCD Matter Discovered at RHIC", Nucl. Phys. A **750**, 30 (2005).
3. J. Adams et al. (STAR collaboration), "Experimental and theoretical challenges in the search for the quark–gluon plasma: The STAR Collaboration's critical assessment of the evidence from RHIC collisions", Nucl. Phys. A **757**, 102 (2005).
4. K. Adcox et al. (PHENIX collaboration), "Formation of dense partonic matter in relativistic nucleus–nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration", Nucl. Phys. A **757**, 184 (2005).
5. I. Arsene et al. (BRAHMS collaboration), "Quark–gluon plasma and color glass condensate at RHIC? The perspective from the BRAHMS experiment", Nucl. Phys. A **757**, 1 (2005).
6. B.B. Back et al. (PHOBOS collaboration), "The PHOBOS perspective on discoveries at RHIC", Nucl. Phys. A **757**, 28 (2005).

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Results and Perspectives of RHIC Experiments

T. Hallman

Dense Matter in Heavy Ion Collisions and Astrophysics

Heavy Ion Summer School
July 14-26, JINR
Dubna, Russia

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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
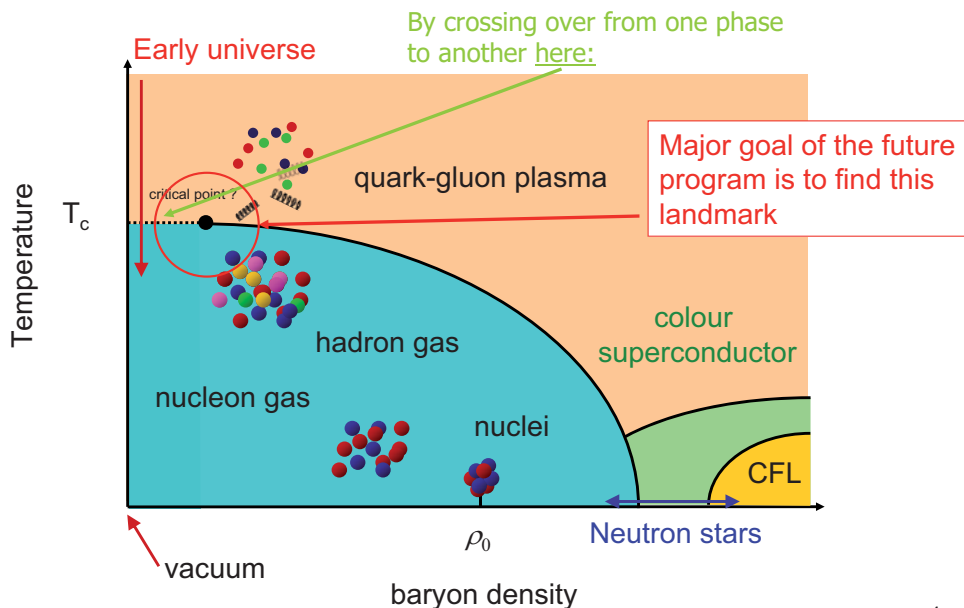
- Conclusions

2

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

3

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

By crossing over from one phase to another here:

Major goal of the future program is to find this landmark

Early universe

T_c

critical point ?

quark-gluon plasma

hadron gas

nucleon gas

nuclei

colour superconductor

CFL

Temperature

ρ_0

baryon density

Neutron stars

vacuum

4

What are the phases of QCD Matter?
What we expected: lattice QCD at finite temperature

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

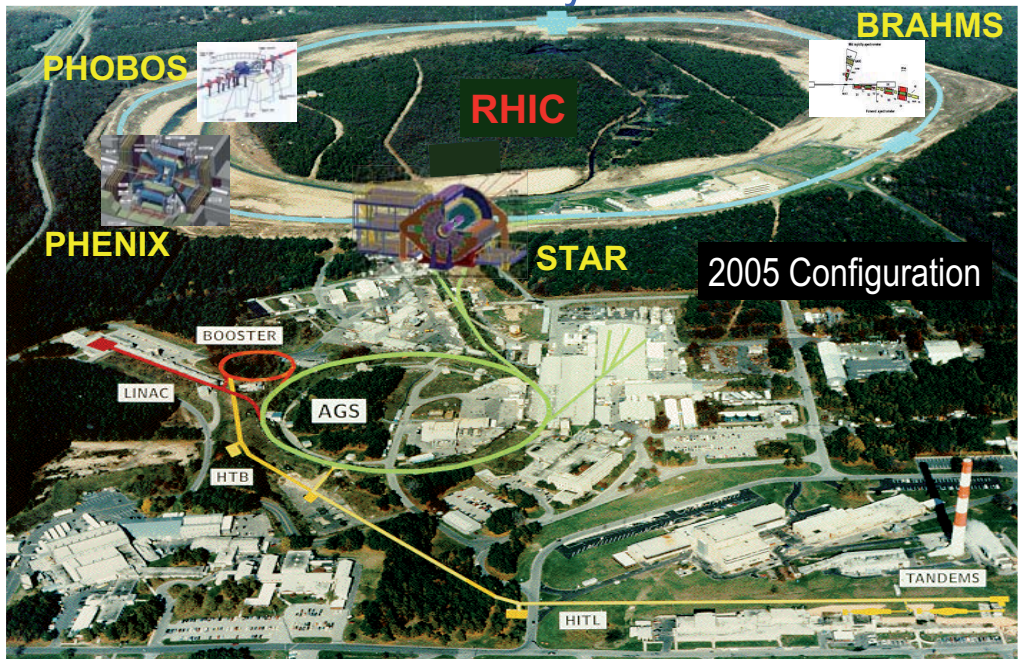(Stefan-
n limit)

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

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

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Relativistic Heavy Ion Collider

BRAHMS

PHOBOS

RHIC

PHENIX

STAR

2005 Configuration

BOOSTER

LINAC

AGS

HTB

HITL

TANDEMS

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Relativistic Heavy Ion Collider

RHIC

PHENIX   STAR   2007 Onward

BOOSTER
LINAC
AGS
HTB
HITL
TANDEMS

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Relativistic Heavy Ion Collider

PHOBOS   BRAHMS
RHIC
PHENIX
STAR
BOOSTER
LINAC
AGS
HTB
TANDEMS
HITL

Two Concentric Superconducting Rings

Ions: A = 1 ~ 200, p$\vec{\text{p}}$, 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 x 10^{26}	(3.6 x 10^{27})	1.4 x 10^{31}	(3.5 x 10^{31})
Interaction rates	1.4 khz	(~ 36 khz)	300 khz	(~ 750 khz)

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The (evolving) STAR detector

Solenoidal Magnet

DAQ and TPC
FEE Upgrade

Time Projection Chamber

Forward Meson
Spectrometer

Barrel EMC

Barrel Time Of Flight

Photon
Multiplicity
Detector

VPD

Beam-Beam Counters

TOF Start Counter

HFT:
2 layers of MAPS, 1 layer of strips
(+ existing double-sided SSD)

Forward GEM Tracker

Endcap Electromagnetic
Calorimeter built at IUCF
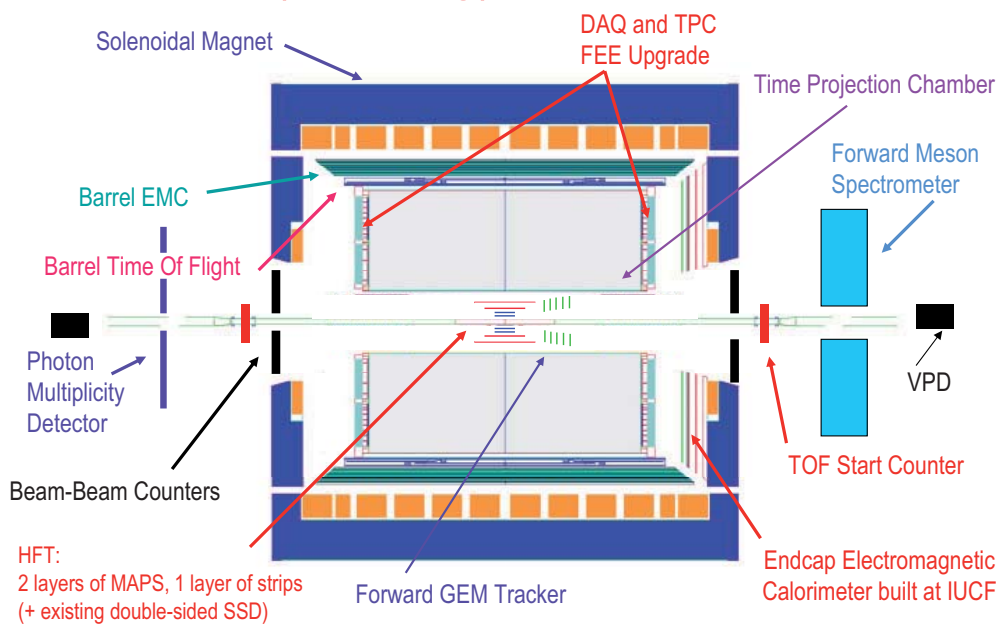
9

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

p+p →jet+jet
(STAR@RHIC)
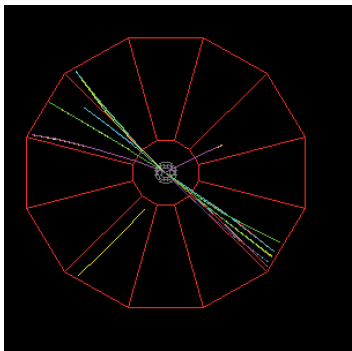
Au+Au → X
(STAR@RHIC)

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

Central Event

color code ⇒ energy loss

Strong focus on leptons and photons

PHENIX
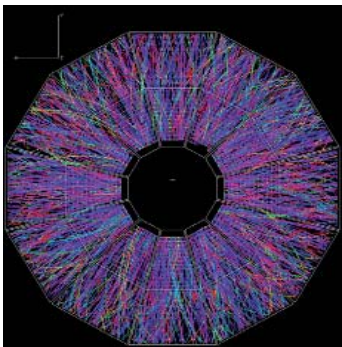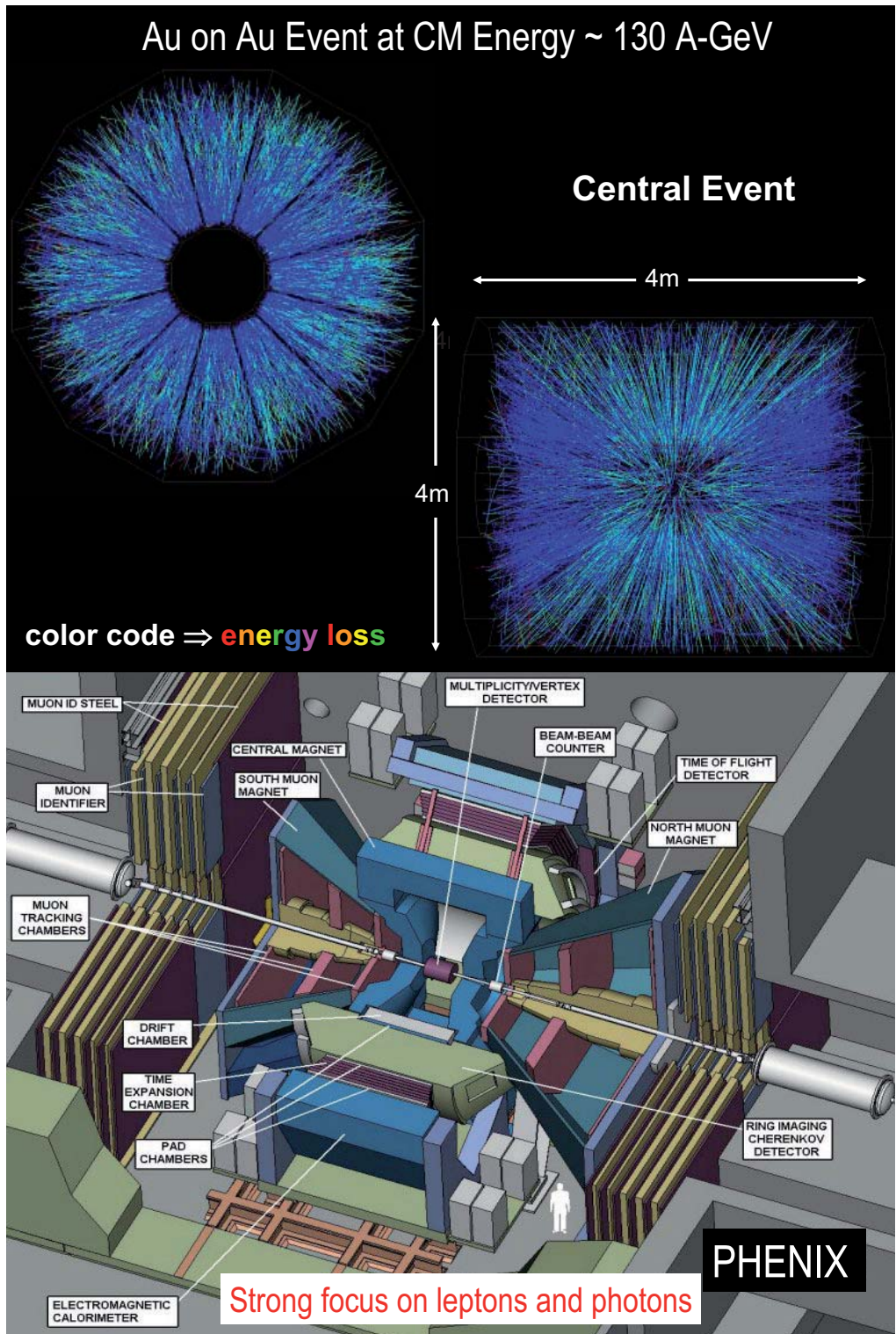
Time line of a relativistic heavy ion collision

| 1 | 2 | 3 | 4 |

| Two thin disk quarks and glu approach | Initial collisi products of scattering cr | Dense partonic medium The QGP? The sQGP? A "perfect liquid"? | Hadron gas phase |

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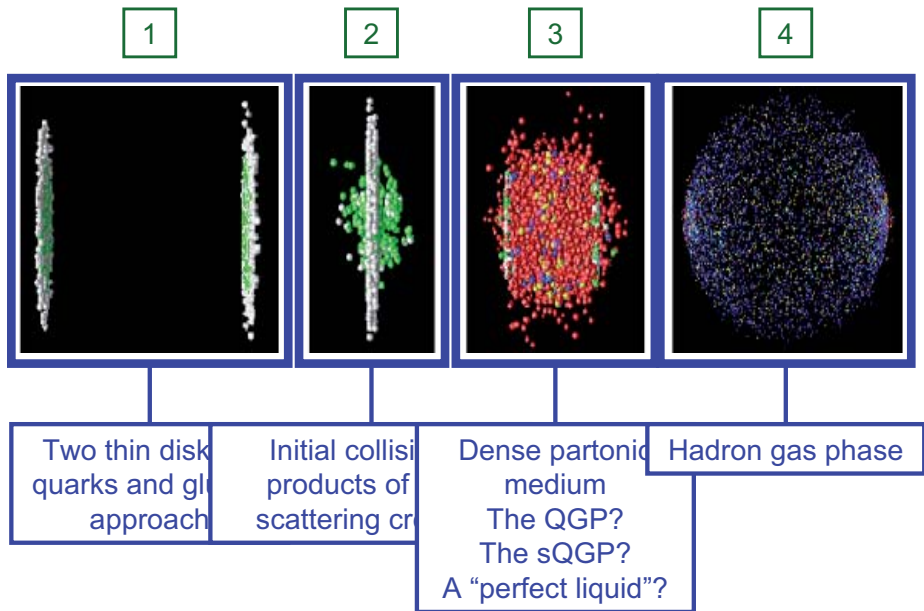
Kinematics for colliders

p_T

θ

$p_\parallel$
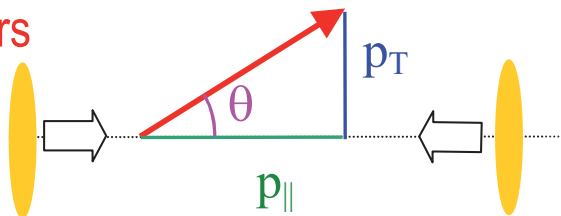
Pseudo-rapidity: $\eta = -\ln[\tan(\theta/2)] \approx y$

Transverse momentum (p_T) and pseudorapidity (η) provide a convenient description

$$p_z = p_T \sinh(\eta)$$

$$p_{tot} = p_T \cosh(\eta)$$

Mid-rapidity: $\eta = 0$, perpendicular to the incident beams
$\eta = 4$:   Scattering at $\theta = 2.1°$ in the CM (or lab) frame

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A few more terms in heavy-ion physics

Centrality:

participants   *spectators*

central (head-on) collision   peripheral (grazing shot)
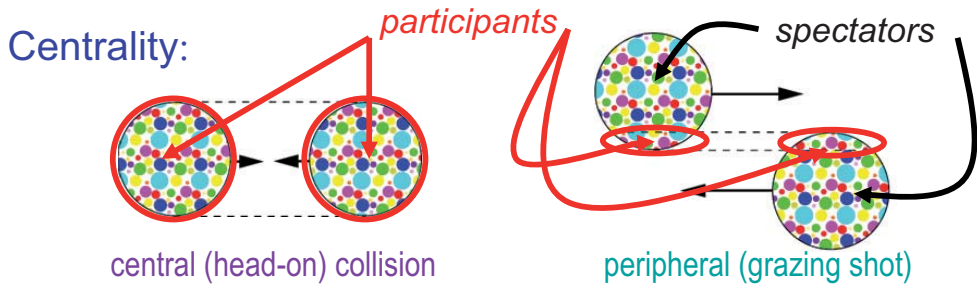
Number of Participants (N_{part}):

• Number of nucleons participating in the collision

• p+p   collisions = 2

• central Au+Au ~ 350   (Au = 79 p + 118 n = 197)

• Used to describe geometry of a collision

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What scale of excitation is required to liberate quarks and gluons ?

• In a normal nucleus the nucleon density is ~ .16 fm^{-3} → ~ .15 GeV fm^{-3}

• We might expect things to "get interesting" when two nucleons are more than 50% overlapping

– In this case the energy density is ε ~ 2 GeV / $\frac{4}{3} \pi$ r^3 ~ 1 GeV/ fm^3 where $r_{nucleon}$ ~ 0.8 fm

– More refined estimates indicated when ε ~ 2-3 GeV/ fm^3 we should see a transition

How does that compare with the heating in a nucleus-nucleus collision?
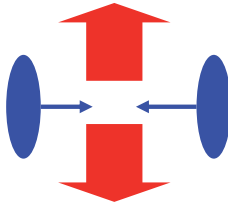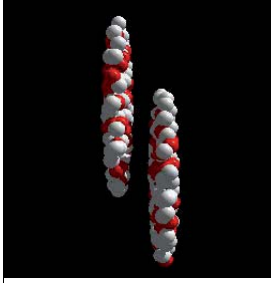
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## One way to tell is to estimate of the energy density at RHIC

EMCAL

by seeing how much energy ~~ed?~~
is "redirected" sideways (how much
transverse energy (E_T) there is)

PHENIX

Minimum bias E_T distribution at mid-rapidity

For the most central
events:

E_t (GeV)

$dE_T/d\eta |_{\eta=0}$
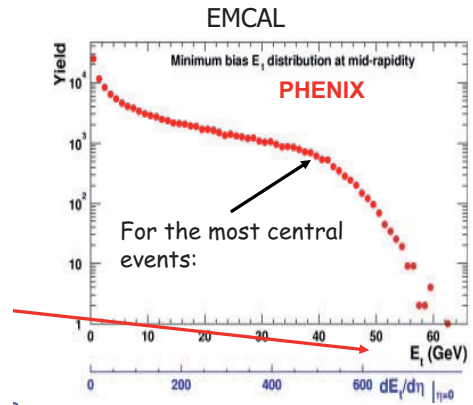
We are definitely in the "ball park" where we expect a transition

What discoveries has the first phase at RHIC yielded?
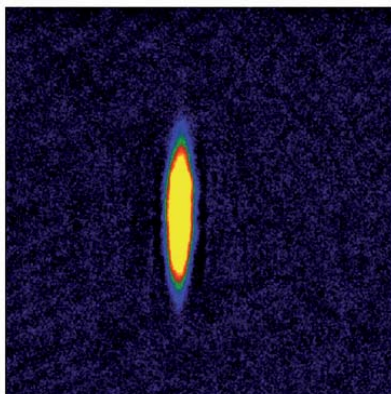
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How can we quantify the elliptic flow

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

$$f(x) = \frac{\pi}{2} - \frac{4}{\pi} \Sigma \, \frac{\cos(nx)}{n^2}$$
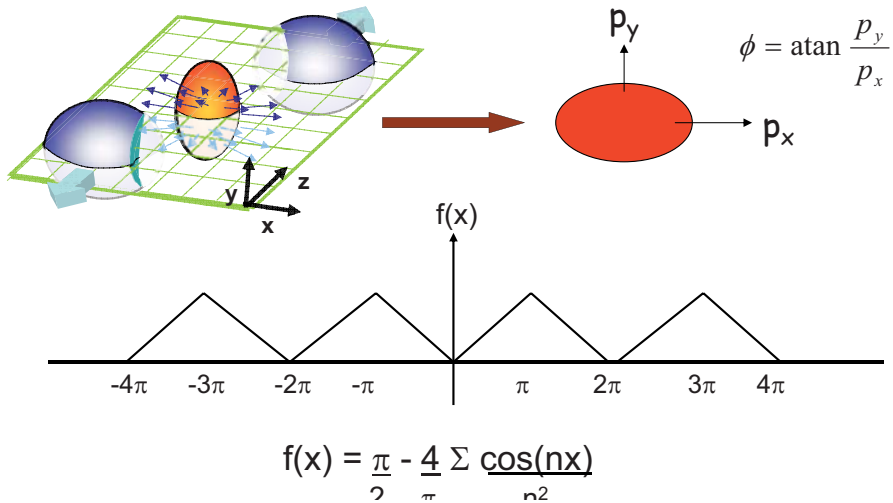
Elliptic flow establishes there is strongly interacting <u>matter</u> at t ~ 0

Gas of weakly/strongly interacting Li atoms

M. Gehm et al, Science 298, 2179

– excite Feshbach resonance

strongly coupled

weakly coupled

100 μs

200 μs

400 μs

600 μs

800 μs

1000 μs

1500 μs

2000 μs
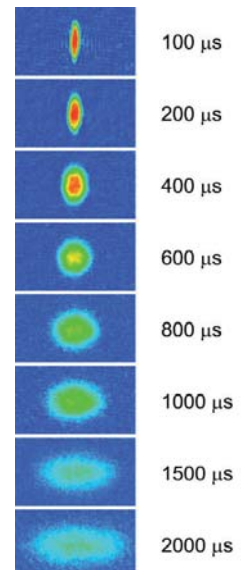
<u>Is there elliptic flow at RHIC?</u>

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

- • Hydrodynamic calculations ass
  and near-zero viscosity reprod
  p_T ~ 1.5 GeV/c
- • Same calculations fit the radia
- • Elliptic flow saturates the hydro
- • Very rapid thermalization, very
- • A perfect fluid?
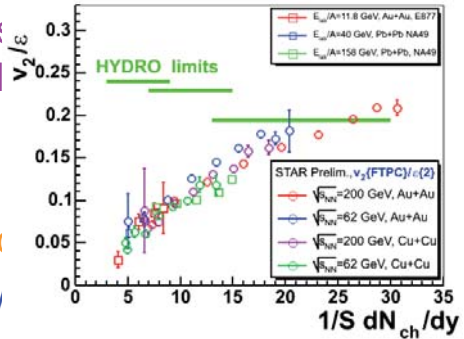
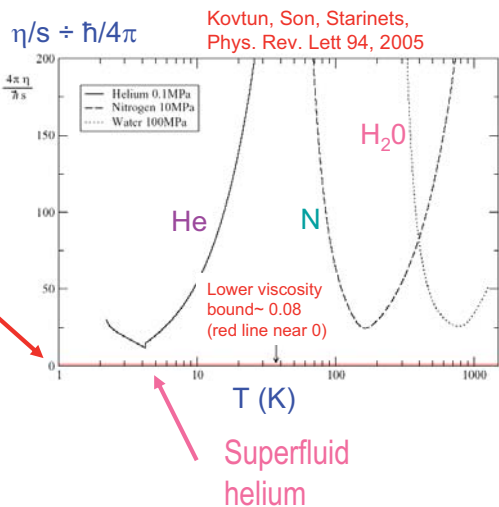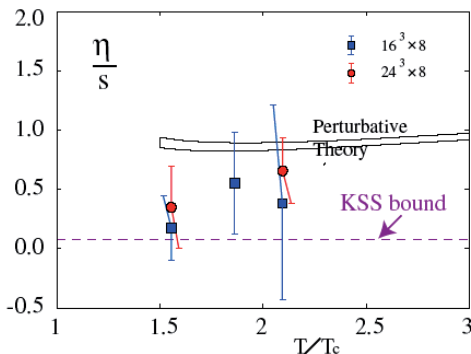Thermalization time τ < 1 fm/c and ε = 20 GeV/fm³

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What is the viscosity?
How perfect is our liquid?
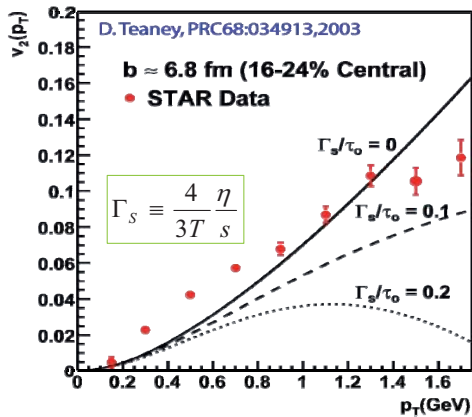
A. Nakamura and S. Sakai,
hep-lat/0406009

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

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

$\frac{\eta}{s}$

$16^3 \times 8$
$24^3 \times 8$

Perturbative
Theory

KSS bound

T/Tc

$\frac{4\pi\eta}{\hbar s}$

Helium 0.1MPa
Nitrogen 10MPa
Water 100MPa

H_2O

He   N

Lower viscosity
bound~ 0.08
(red line near 0)

T (K)

Superfluid
helium

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How to Quantify η/s at RHIC?

D. Teaney, PRC68:034913, 2003

b ≈ 6.8 fm (16-24% Central)
STAR Data

$\Gamma_s/\tau_0 = 0$

$$\Gamma_S \equiv \frac{4}{3T}\frac{\eta}{s}$$

$\Gamma_s/\tau_0 = 0.1$

$\Gamma_s/\tau_0 = 0.2$

Γ_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)

B meson   D meson

Perfect Fluid?
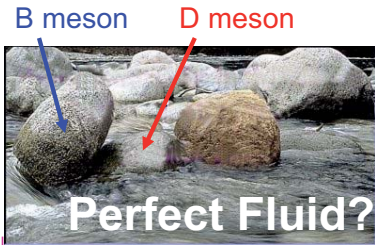
String Theory ?

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.
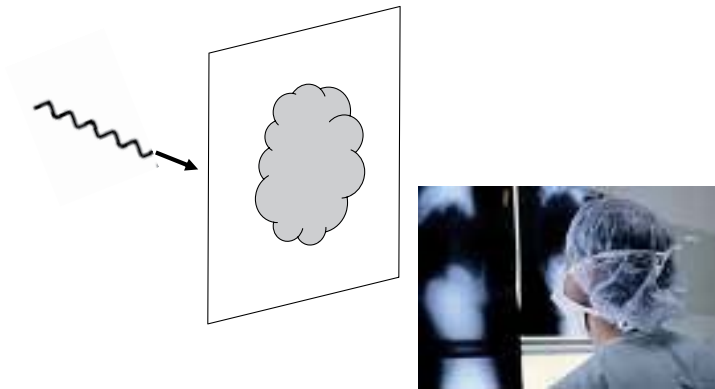
What other dynamical effects allow access the properties of this fleeting matter ?

How do we look inside something we can't physically take apart ?

We use a penetrating probe (one that can go through) which is well calibrated

In the case of RHIC, the probe is the quarks and gluons in the
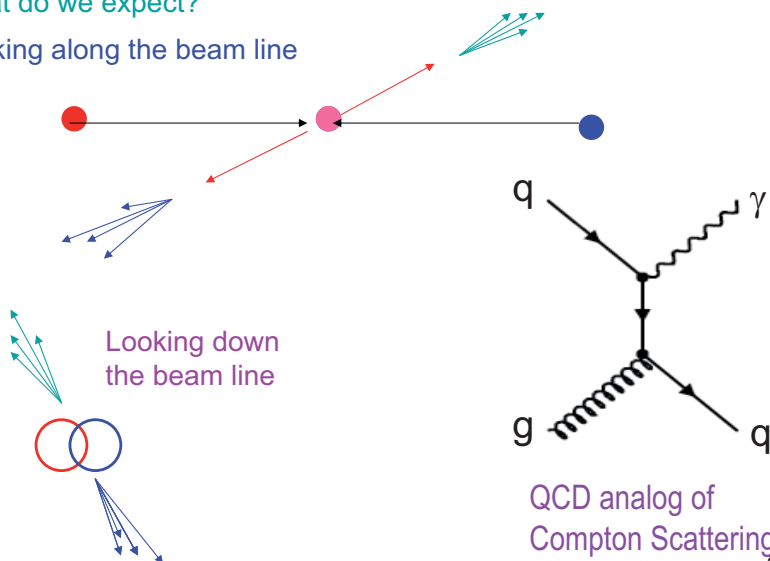beam to start with– inside the protons and neutrons of the Au nucleus !

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They allow us to search for new physics. The calibrated probe is the back to back
correlation which results when the quarks & gluons in the two beams scatter
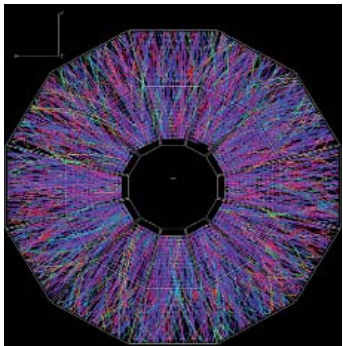
What do we expect?

Looking along the beam line

Looking down
the beam line

q

γ

g

q

QCD analog of
Compton Scattering

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

p+p →jet+jet
(STAR@RHIC)

Au+Au → X
(STAR@RHIC)

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In principle, there is a <u>lot</u> of information needed to understand High p_T Particle Production in A+A Collisions
(According to pQCD...)

$$\frac{dN^h_{AB}}{dy\,d^2p_T} = K \sum_{abcd} \int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$

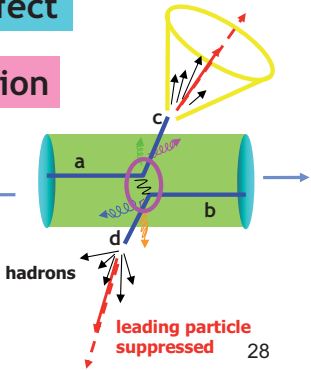$\times f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2)$ — **Parton Distribution Functions**

$\times g(\mathbf{k}_a) g(\mathbf{k}_b)$ — **Intrinsic k_T , Cronin Effect**

$\times S_A(x_a, Q_a^2) S_B(x_b, Q_b^2)$ — **Shadowing, EMC Effect**

$\times \frac{d\sigma}{d\hat{t}}(ab \to cd)$ — **Hard-scattering cross-section**

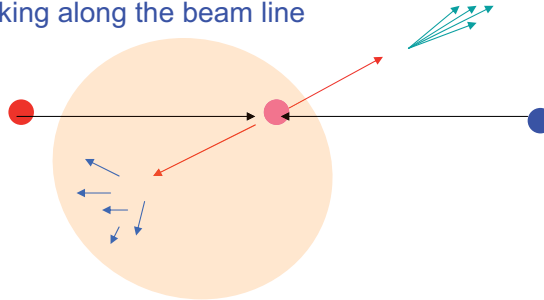$\times \int_0^1 d\varepsilon P(\varepsilon) \frac{z_c^*}{z_c}$ — **Partonic Energy Loss**

$\frac{D^0_{h/c}(z_c^*, Q_c^2)}{\pi z_c}$ — **Fragmentation Function**

c
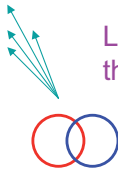
a

b

d

hadrons

leading particle suppressed

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But using our calibrated probe we can try something simpler to start

Looking along the beam line

Looking down
the beam line

If some new form of dense,
opaque matter is formed, we
might see the effects on our
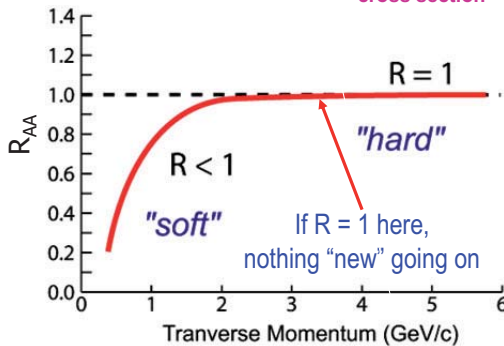"calibrated" probe
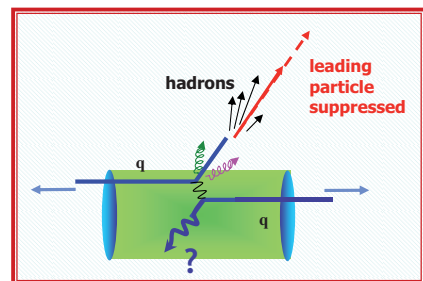(back-to-back correlation)

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A second discovery: jet quenching

An "inclusive" measure:
the "Nuclear Modification Factor:"

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

$<N_{binary}>/\sigma_{inel}^{p+p}$

nucleon-nucleon
cross section

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

leading
particle
suppressed

hadrons

q

q

?

$R = 1$

$R < 1$

"hard"

"soft"

If R = 1 here,
nothing "new" going on

R_{AA}

Tranverse Momentum (GeV/c)

Will our calibrated penetrating
probe go through the same way?
-- or will it be quenched ? --

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Hard scattering at RHIC and NLO pQCD

PRL 91, 241803

hep-ex/0608030

PHENIX: π^0

STAR: Jets

Good agreement with NLO pQCD $\Rightarrow$ pQCD should be broadly applicable at RHIC (e.g. heavy flavor production…)
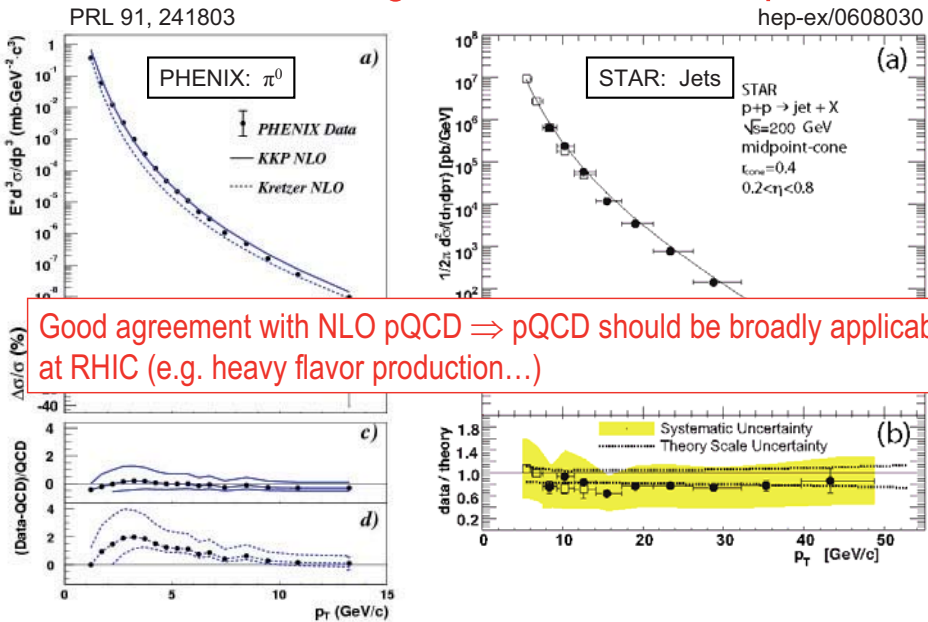
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In central Au+Au collisions something dramatically new occurs: jet quenching

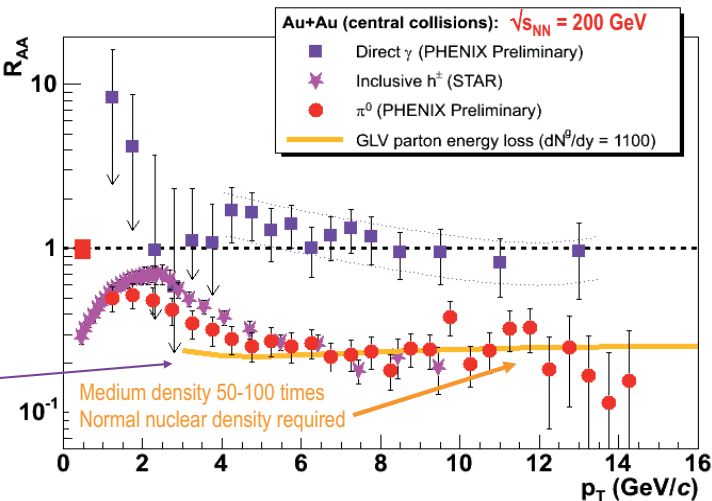$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{NN} / dp_T d\eta}$$

⟵ 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)

Au+Au (central collisions): $\sqrt{s_{NN}}$ = 200 GeV

- Direct γ (PHENIX Preliminary)
- Inclusive $h^{\pm}$ (STAR)
- π^0 (PHENIX Preliminary)
- GLV parton energy loss (dN^g/dy = 1100)

Medium density 50-100 times Normal nuclear density required

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Jet quenching at RHIC

The effect is seen even more dramatically in di-hadron correlations: recoiling jets are strongly modified due to quenching
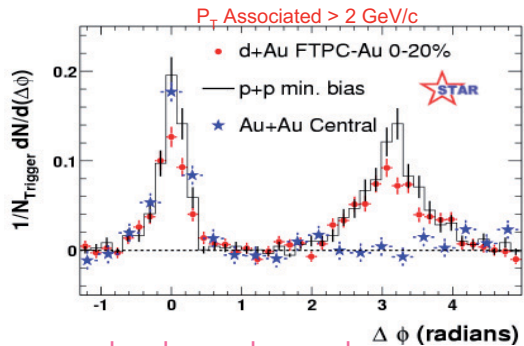
Unequivocally, a new phenomena has been observed

- 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

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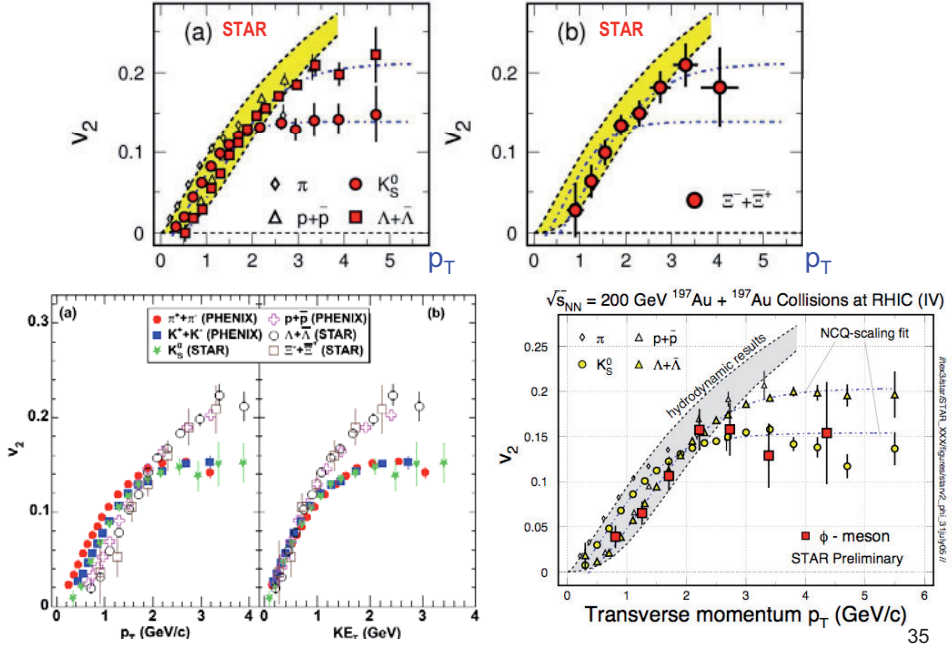
Additional evidence from something that was not predicted
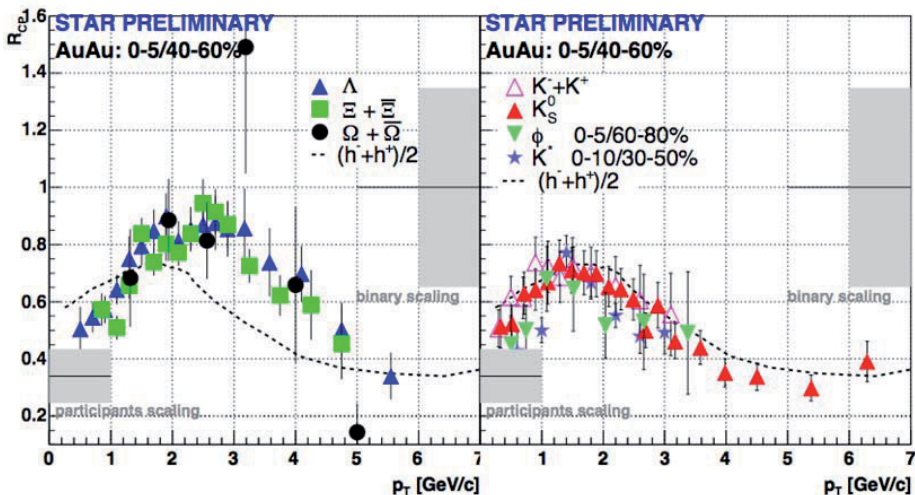
The mesons (quark-antiquark) and the baryons (3 quarks) exhibit two distinct behaviors below transverse momenta of ~ 6 GeV/c
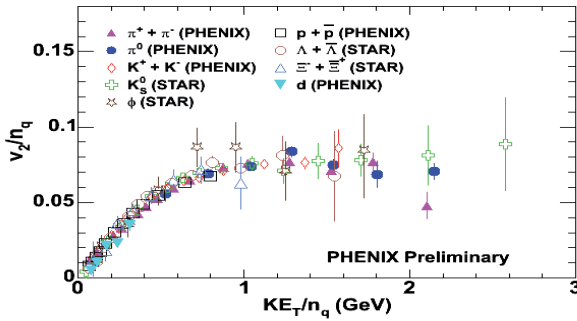(K*, φ which are as heavy as the proton follow the mesons !)

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

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What if quarks coalesce to make hadrons?

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

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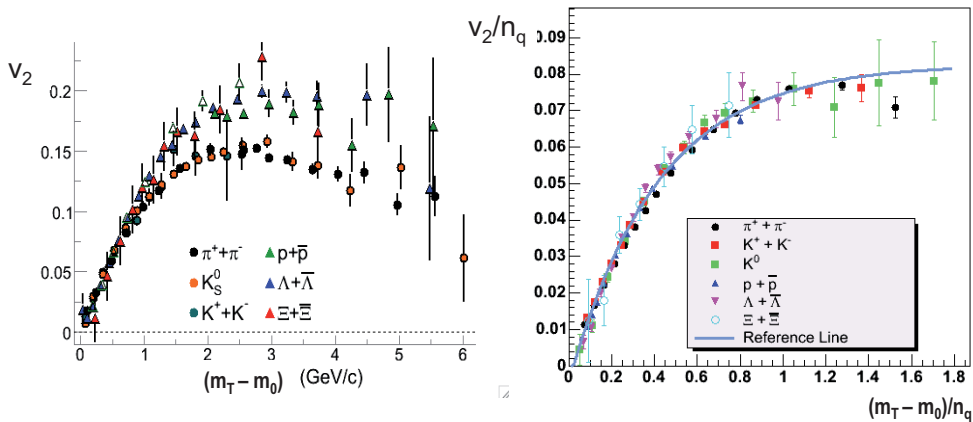
$$\approx 1 + 2n_q v_2^q \left(\frac{p_T}{n_q}\right)\cos(2\phi) + \cdots$$

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

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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

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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?
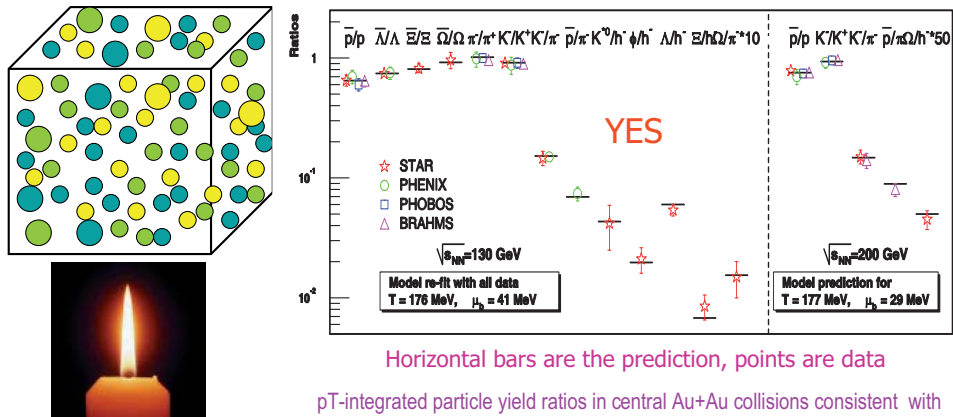
Horizontal bars are the prediction, points are data

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

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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

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.
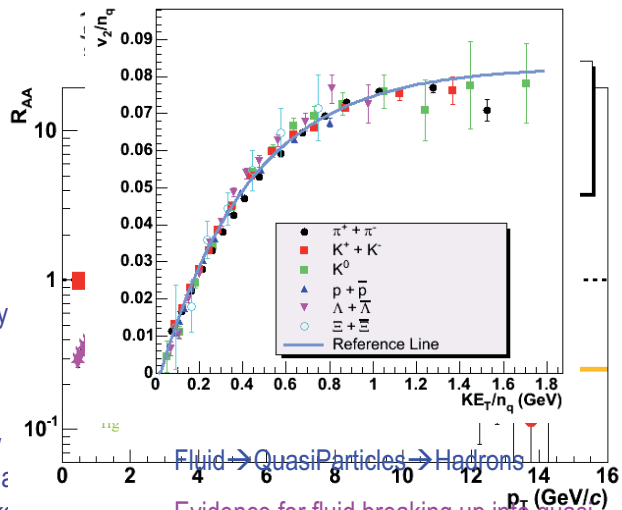
Fluid → QuasiParticles → Hadrons

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

For reasonable T (~ 2T$_c$) and τ (~ 1 fm/c) data suggest $\eta/s \ll 0.3$
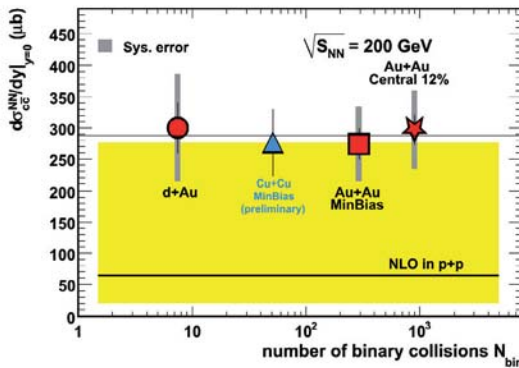
These phenomena were not observed at the SPS (some were not even predicted) and they constitute important new discoveries
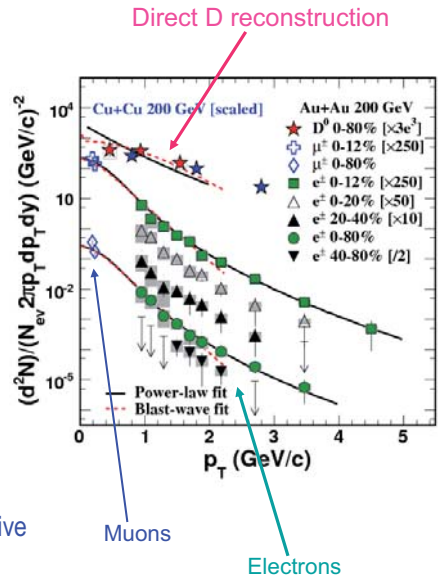
Are we done?

No, only just begun

New questions have emerged from exploring this terra incognita

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Progress on the basics: the charm cross-section

Direct D reconstruction

- Charm cross section scales with the number of binary collisions
- Multiple measurements in different channels all give the same result

Muons

Electrons

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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

Q

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

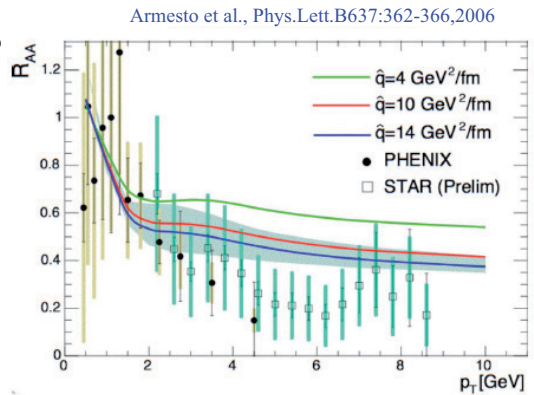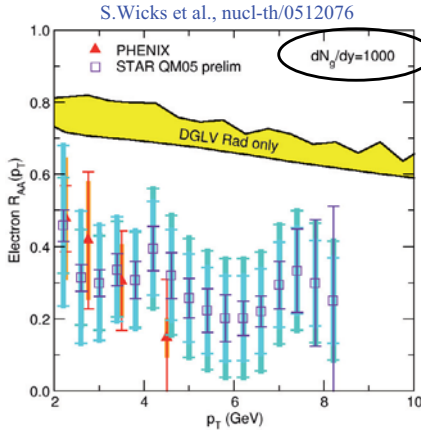Dead cone also implies lower heavy quark energy loss in matter: (Dokshitzer-Kharzeev, 2001)

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

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Heavy flavor suppression via b,c → e+X

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

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

$$R_{AA}(\text{non-photonic electrons}) \sim 0.2 \sim R_{AA}(\pi^0) \;!!$$

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

⇒ under-predicts electron suppression

⇒ charm vs beauty? elastic energy loss? …?
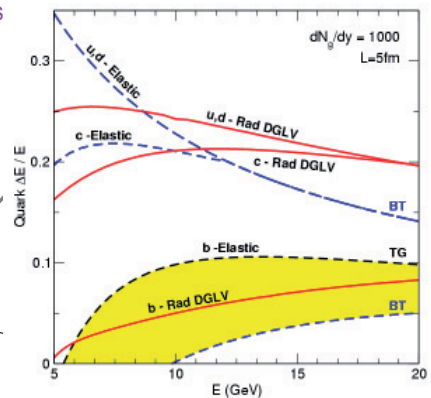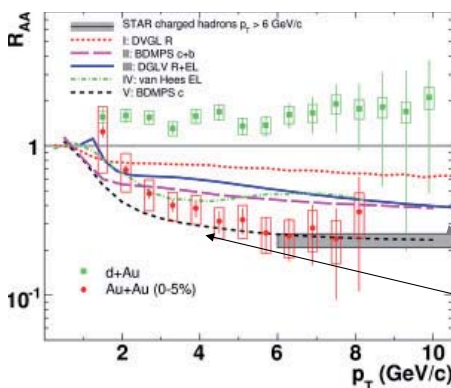
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Surprising results on suppression of High-p_T Charm via Electrons

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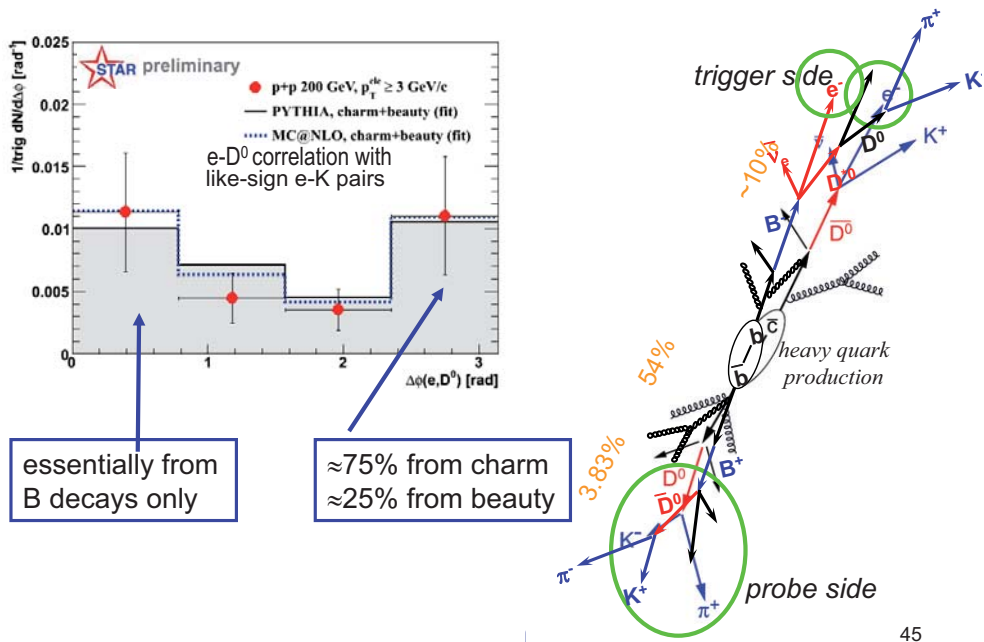
Results caused a shift of paradigm on importance of collisional energy loss

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?
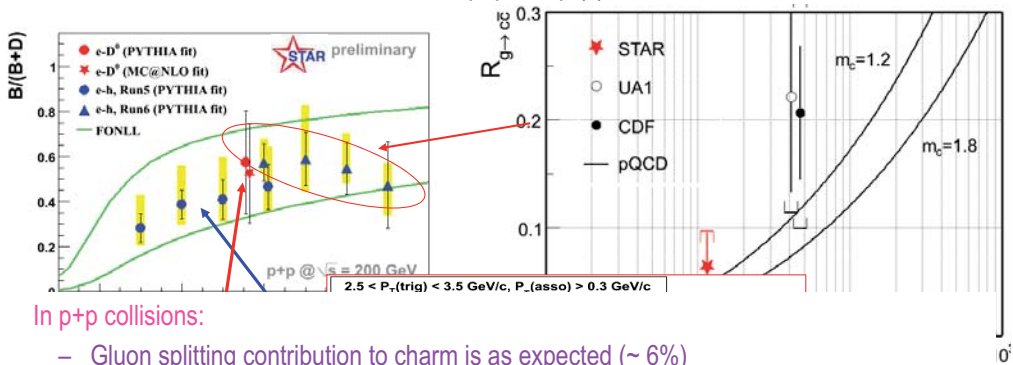- Energy loss models need to be revisited!

Additional insight is possible using electron tagged correlations

STAR preliminary

p+p 200 GeV, $p_T^{e/e} \geq 3$ GeV/c
— PYTHIA, charm+beauty (fit)
····· MC@NLO, charm+beauty (fit)

e-D^0 correlation with
like-sign e-K pairs

$1/trig\ dN/d\Delta\phi$ [rad^{-1}]

$\Delta\phi(e,D^0)$ [rad]

essentially from
B decays only

≈75% from charm
≈25% from beauty

trigger side

heavy quark
production

probe side

~10%

54%

3.83%

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Additional insight from heavy flavor correlations

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

B/(B+D)

● e-D^0 (PYTHIA fit)
★ e-D^0 (MC@NLO fit)
● e-h, Run5 (PYTHIA fit)
▲ e-h, Run6 (PYTHIA fit)
— FONLL

STAR preliminary

p+p @ √s = 200 GeV

$R_{g \to c\bar{c}}$

★ STAR
○ UA1
● CDF
— pQCD

m_c=1.2

m_c=1.8

2.5 < P_T(trig) < 3.5 GeV/c, $P_{(asso)}$ > 0.3 GeV/c

In p+p collisions:

– Gluon splitting contribution to charm is as expected (~ 6%)

– The B contribution to non-photonic electrons is sizeable based on e-h and e-D 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

Insight from heavy flavor correlations in p+p

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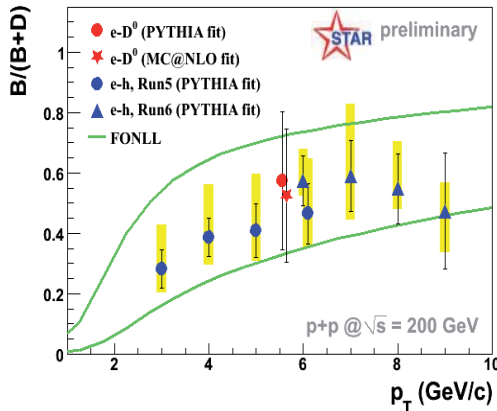
In p+p collisions:

– 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

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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[a], Dmitri Kharzeev[a] and Kirill Tuchin[b,c]

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
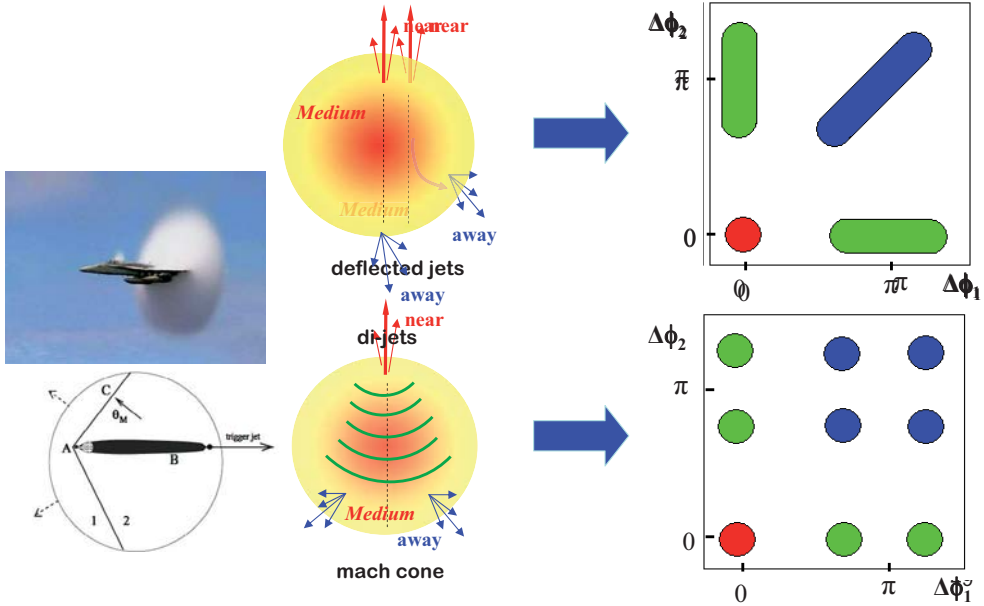
(Observed effect for ^{3}He)

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

A possible collective mode of excitation

Using 3-particle correlation to discriminate different physical mechanisms.

The experimental evidence

Indications of Conical Emission of Charged Hadrons at RHIC

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

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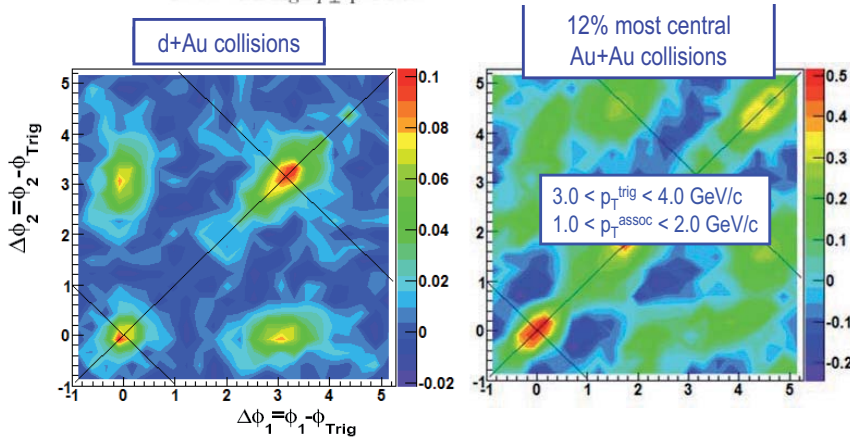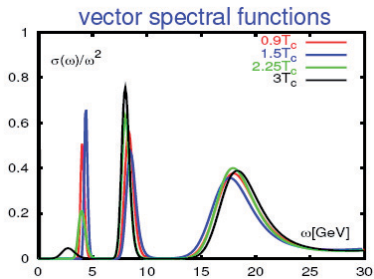
Future tools

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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.
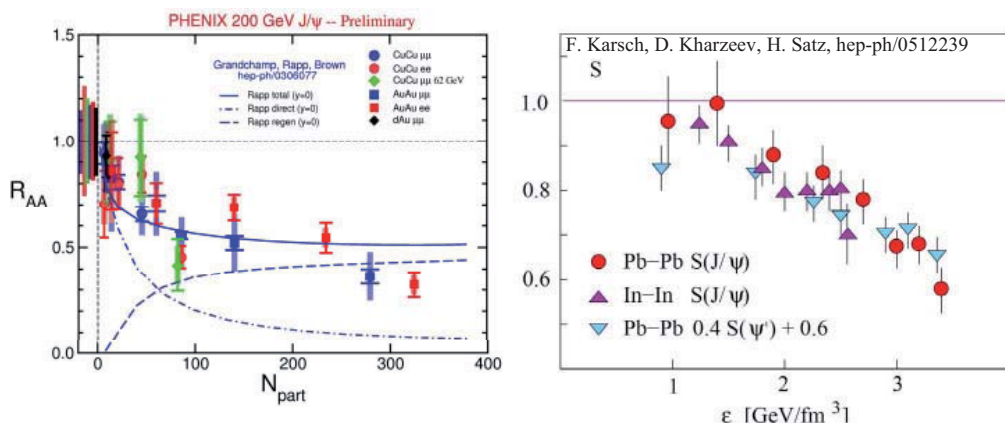
- Hierarchy of melting:

vector spectral functions

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+c̄ → J/ψ

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Current status

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

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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 higher "RHIC II" luminosity

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

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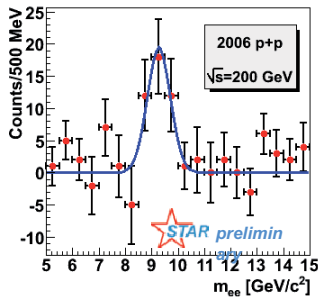
The ϒ, ϒ', ϒ'' should behave differently than the J/Ψ

- 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
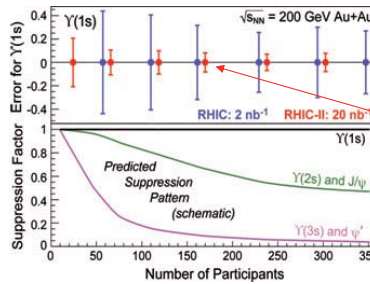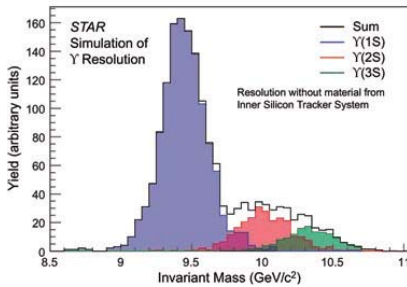
ϒ→e+e−:
T. Ullrich et al

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.
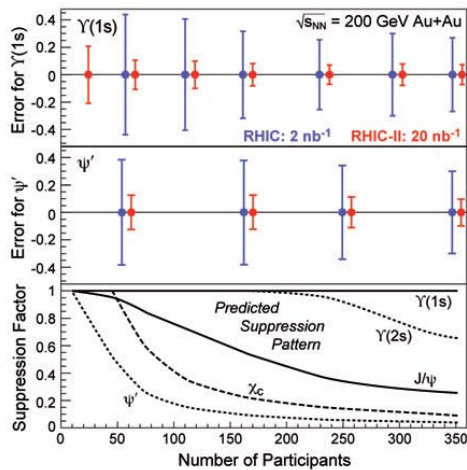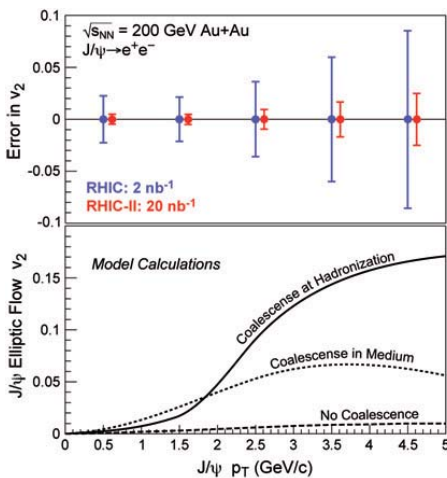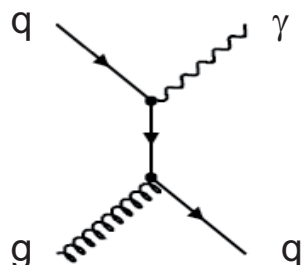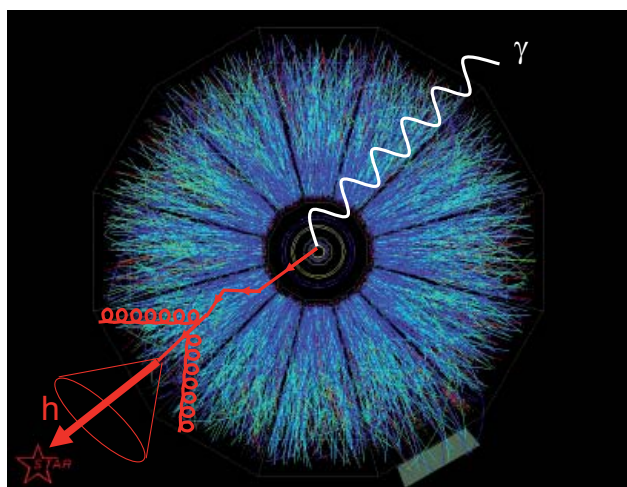

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γ-Jet: Golden Probe of QCD Energy Loss

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)

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The next step for one of the detectors

Full prototype TPC sector now in operation and working flawlessly

STAR DAQ1000 FEE   STAR DAQ1000 RDO

Collaboration Plan:

Increase of DAQ rate to1000 times design by Run 9 leveraging CERN/ALICE Altro chip development (thank you)

Construction of HFT in time for full operation in Run 12 (Fall 2011)

TJH: JINR Heavy Ion Summ...

Five "final item" mrpc trays in place and in the STAR data stream now
• PID information for > 95% of kaons and protons in the STAR acceptance
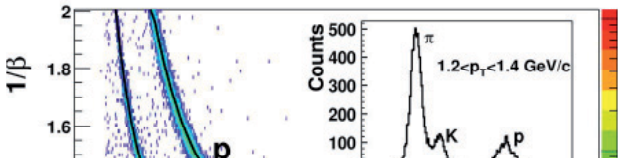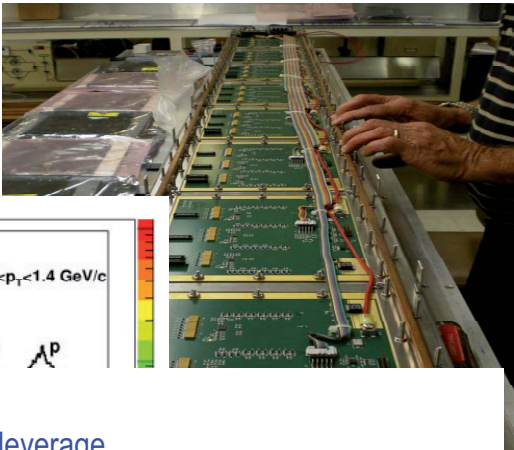
Collaboration plan

120 trays of MRPC modules which leverage

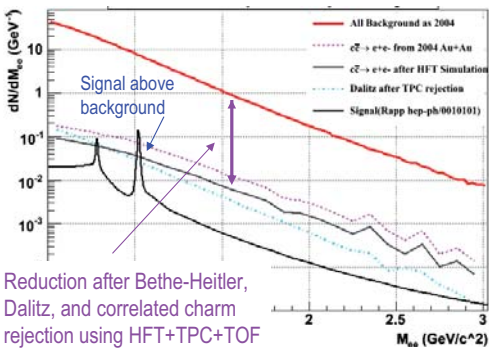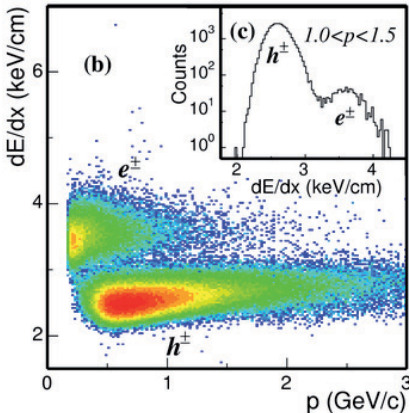MRPC development at CERN (Crispin Williams et al)

Development of HPTDC Chip

MRPC tech transfer and construction (contributed) in China

Thanks

Fully complete in time for run 10 (fall 2009)

Future di-lepton program to study in-medium effects

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

Signal above background

Reduction after Bethe-Heitler, Dalitz, and correlated charm rejection using HFT+TPC+TOF

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

| Detectors	ω	ϕ
TPC+TOF+HFT	20K	6K

❑ 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

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A Long Term (Evolving) Strategic View for RHIC

2008   2010   2015   2020

RHIC physics runs   RHIC II physics runs

Detector Upgrades

EBIS

RHIC II

stoch. cooling of ion beams

eRHIC

CD0   e beam + new detector

eRHIC physics

Legend:
- - - - - - - R&D
Construction
Multiple small projects

CD0: DOE Critical Decision, mission need

TJH: JINR Heavy Ion Summer School   July 14-26 Dubna, Russia
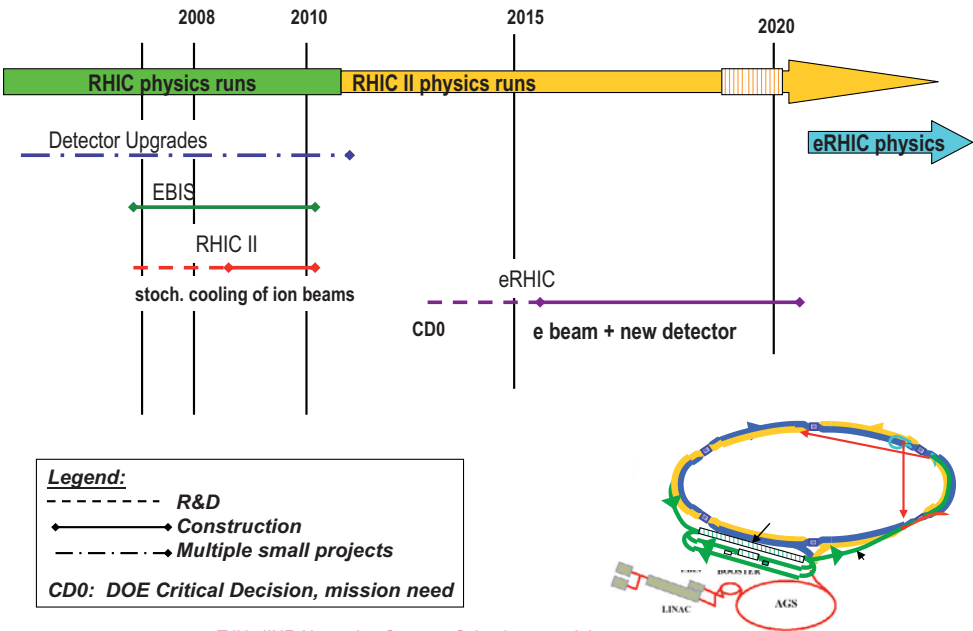
And then, there is the question of the initial conditions

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What are the initial-state parton distribution functions and how they effect the time it takes to thermalize
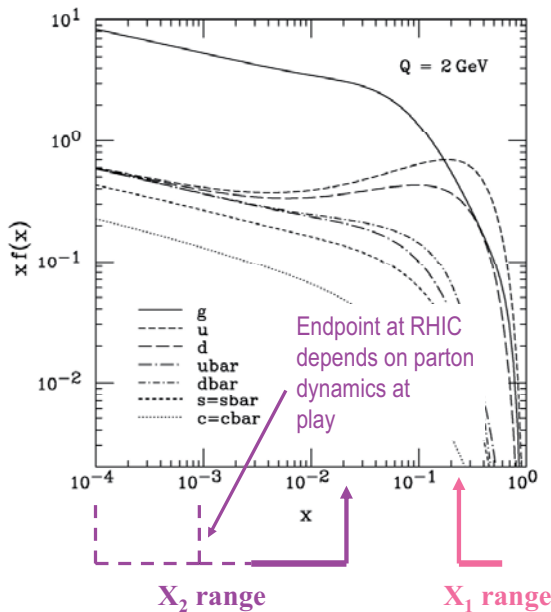
Measurements needed at high rapidity to set the dominant parton type:

Projectile (x_1 ~1) mostly valence quarks.

Target (x_2<0.01) mainly gluons.

Sensitive to x_g ~ 10^{-3} in pQCD picture

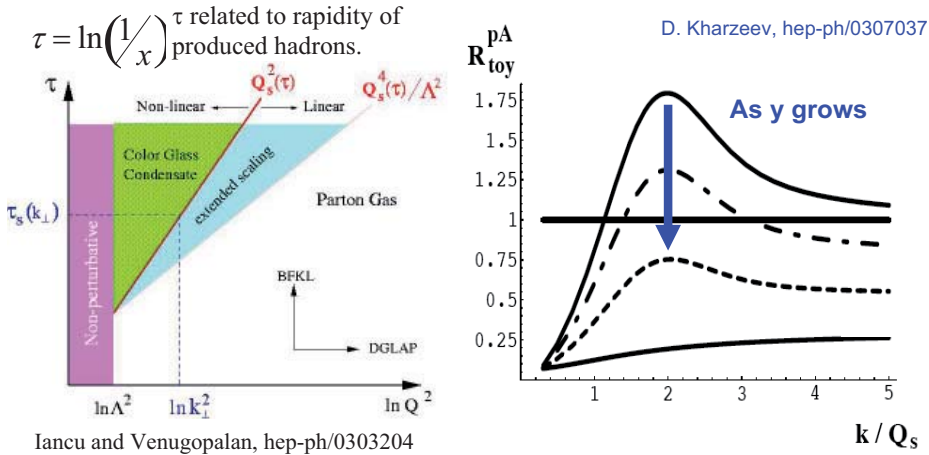Sensitive to x_g ~ 10^{-4} in CGC picture

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- ## 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 ?

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

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

D. Kharzeev, hep-ph/0307037

Iancu and Venugopalan, hep-ph/0303204

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

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Forward particle production in d+Au collisions
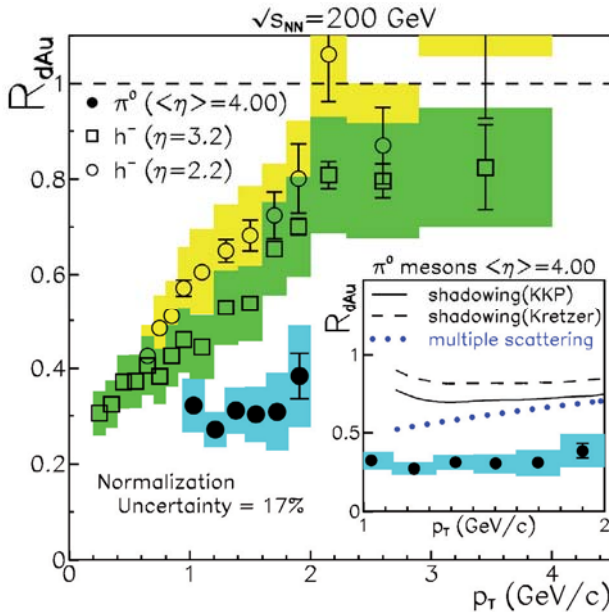
BRAHMS, PRL 93, 242303

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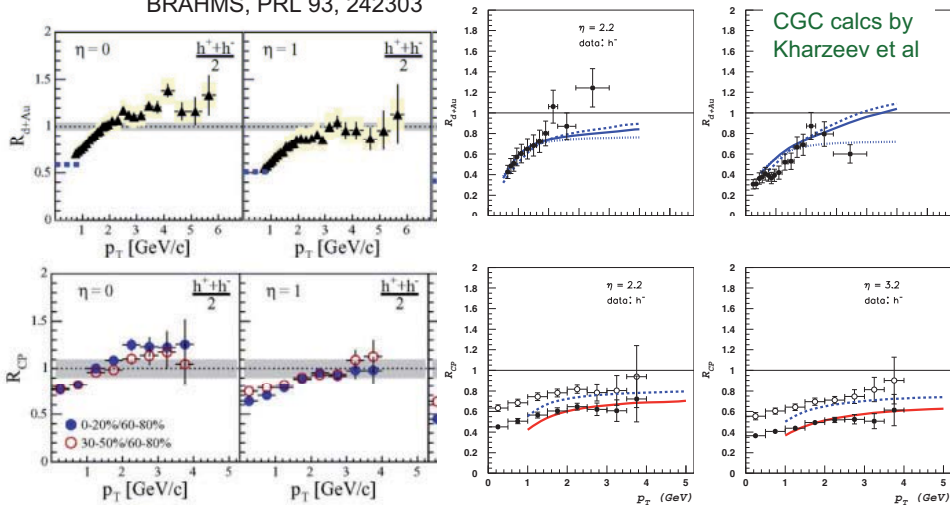
- Sizable suppression of charged hadron yield in forward d+Au
- Evidence for a saturated gluon field in the Au nucleus?
- Several other mechanisms have also been proposed

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STAR Nuclear Modification Factor at high rapidity

$$R_{\text{dAu}}^Y = \frac{\sigma_{\text{inel}}^{pp}}{\langle N_{\text{bin}}\rangle\sigma_{\text{hadr}}^{dAu}}\frac{E\,d^3\sigma/dp^3(d+Au\to Y+X)}{E\,d^3\sigma/dp^3(p+p\to Y+X)}$$

BRAHMS published result consistent with new STAR once an isospin suppression of h⁻ in p+p is taken into account (factor of 2/3).

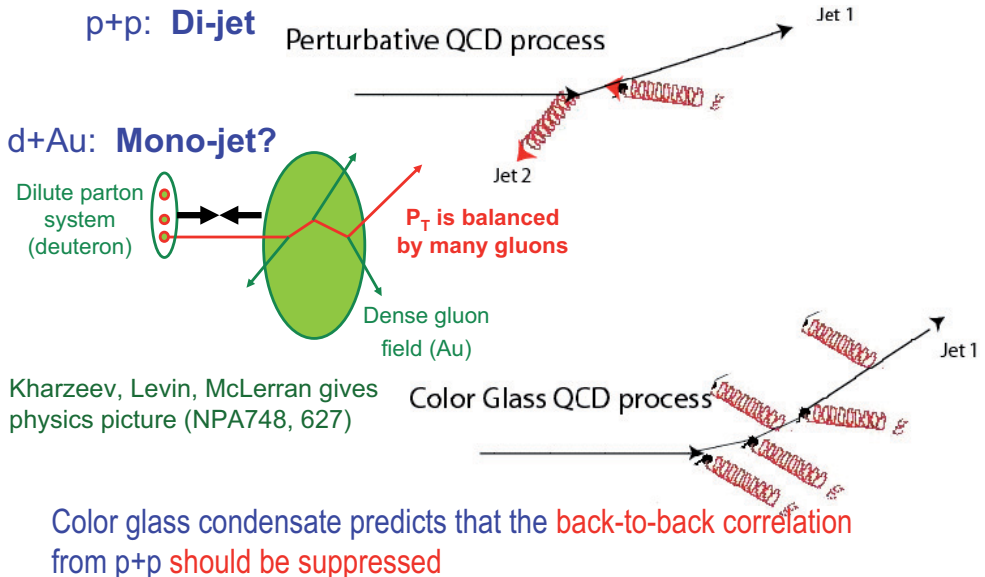Calculations that do not include mod. of Au wave function cannot reproduce data.

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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

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An initial glimpse: correlations in d+Au

PRL 97, 152302 (2006)

$p+p \rightarrow \pi^0 + h^{\pm} + X$ $d+Au \rightarrow \pi^0 + h^{\pm} + X$

$S=0.100\pm0.014$ $S=0.020\pm0.013$

$25 < E_\pi < 30$ GeV $25 < E_\pi < 30$ GeV $<p_{T,\pi}> \sim$ 1.0 GeV/c

$S=0.154\pm0.024$ $S=0.093\pm0.040$

$30 < E_\pi < 55$ GeV $30 < E_\pi < 55$ GeV $<p_{T,\pi}> \sim$ 1.3 GeV/c

Coincidence Probability (radian^{-1})

$\varphi_\pi - \varphi_{LCP}$

π^0: $|<\eta>| = 4.0$
$h^{\pm}$: $|\eta| < 0.75$; $p_T > 0.5$ GeV/c
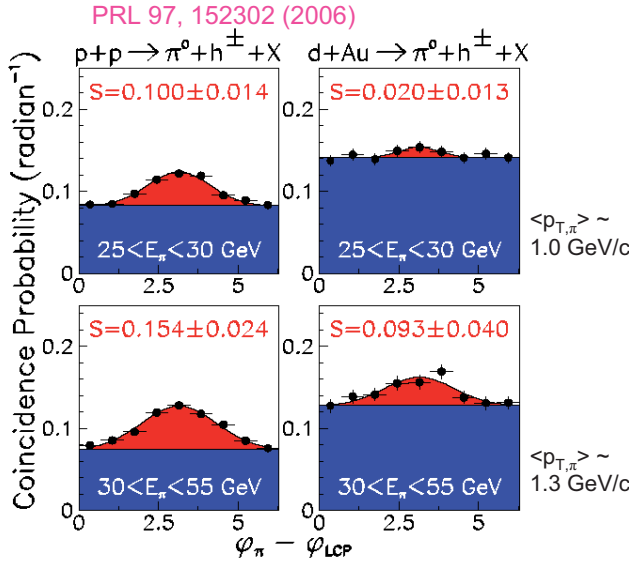
• are suppressed at small $<x_F>$ and $<p_{T,\pi}>$

consistent with CGC picture
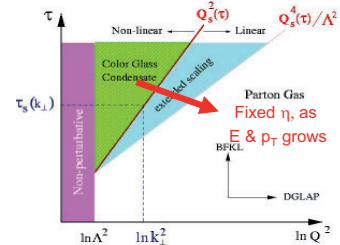
• are similar in d+Au and p+p at larger $<x_F>$ and $<p_{T,\pi}>$

As expected by HIJING

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★ STAR

p+p and d+Au $\rightarrow \pi^0 + \pi^0 + X$ correlations with forward π^0

p+p in PYTHIA $\eta_1 + \eta_2 = \ln(x_1/x_2)$ d+Au in HIJING   hep-ex/0502040

$p + p \rightarrow \pi^0 + \pi^0 + X$
$\sqrt{s} = 200$ GeV
$3 < \eta_\pi < 4$
$p_{T1} > 2.5$ GeV/c
$1.5 < p_{T2} < p_{T1}$

$3 < \eta_{\pi,2} < 4$

$\varphi_{\pi,1} - \varphi_{\pi,2}$

$\log_{10}(x_{min})$

--- No shadowing
— Shadowing

$3 < \eta_\pi < 4$
$1 < \eta_{\pi 2} < 4$
$p_{T1} > 2.5$ GeV/c
$1.5 < p_{T2} < p_{T1}$

$d+Au \rightarrow \pi^0 + \pi^0 + X$
$\sqrt{s} = 200$ GeV, HIJING 1.381

$\delta\varphi = \varphi_{\pi 1} - \varphi_{\pi 2}$
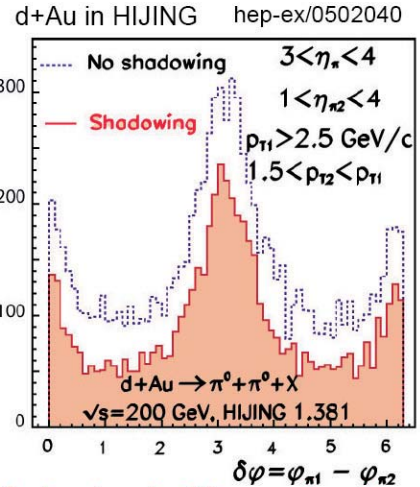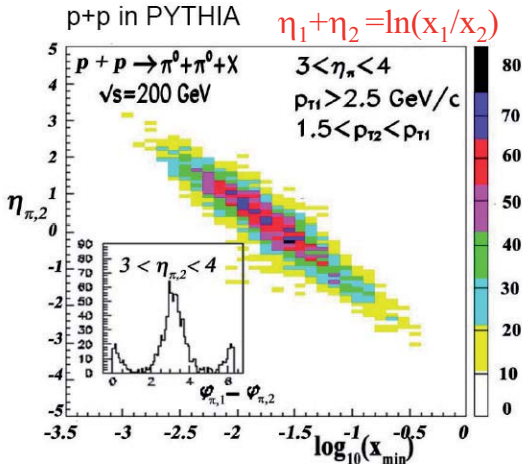
Conventional shadowing will **change yield, but not coincidence structure**.
Coherent effects such as CGC evolution will **change the structure**.
Sensitive to $x_g \sim 10^{-3}$ **in pQCD** scenario; **few x 10^{-4} in CGC** scenario.

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

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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

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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……

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First results on high-p_T di-hadron,γ-hadron correlations
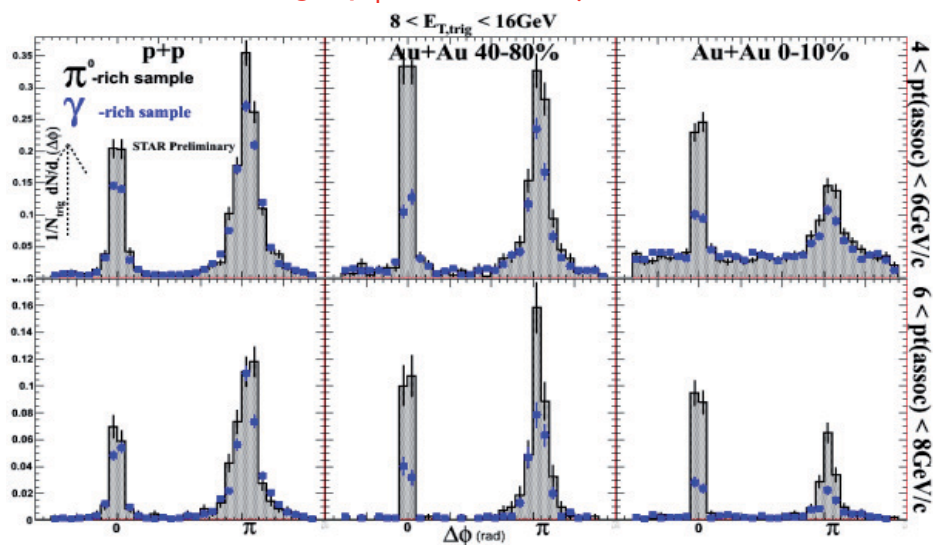
First steps to precision study with high luminosity at RHIC

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Stochastic Cooling at RHIC

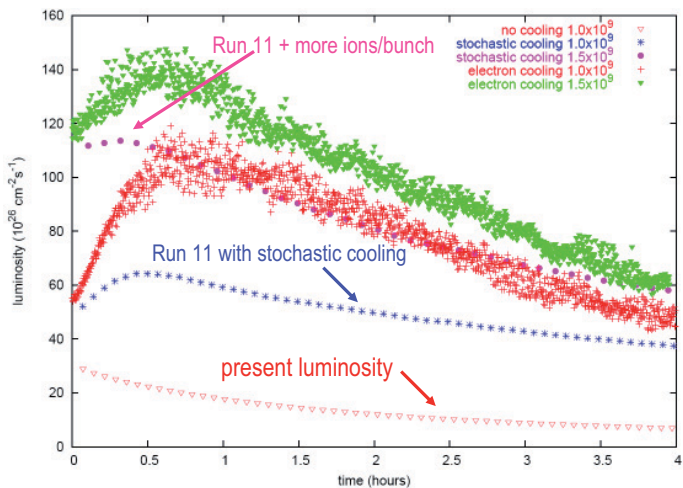

Figure 2. *Simulations of the luminosity vs. time during a 4-hour store for √sNN = 200 GeV Au+Au collisions, with and without beam cooling and for two different assumed initial bunch intensities. The performance of electron-cooled vs. stochastically cooled beams is compared.*

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Relevance of the answer to the QGP: v_2 and the hydro limit—Glauber vs Color Glass Condensate

Hirano et al, PLB 636, 299
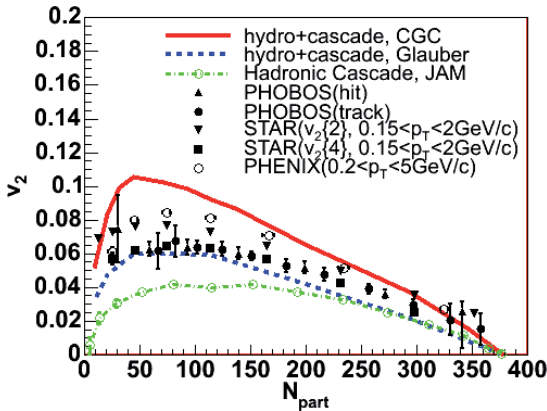
CGC   Glauber

CGC: Treats the nucleus as a saturated gluon field

Effects initial eccentricity of the overlap zone

- Do we have Glauber matter distribution + perfect liquid, or Color Glass Condensate distribution + viscous matter?

- Understanding the initial state is **crucial to understand what we are seeing in the final state**

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TJH: JINR Heavy Ion Summer School   July 14-26 Dubna, Russia

In fact there is a strong coupling to understanding the story at mid-rapidity:

Answers are (urgenetly) needed to:

Understand the initial state conditions for relativistic heavy nuclei at RHIC and confirm our understanding of multiplicities and rapidity dependence

Understand how thermalization appears to be established so quickly at RHIC

Understand whether we have really reached the hydro limit for v_2

Understand mid-rapidity particle production at the LHC in the future

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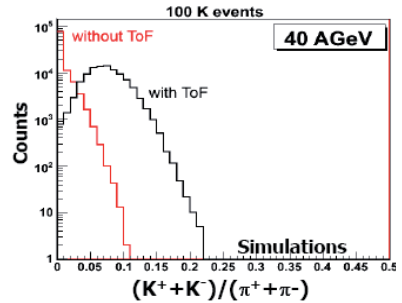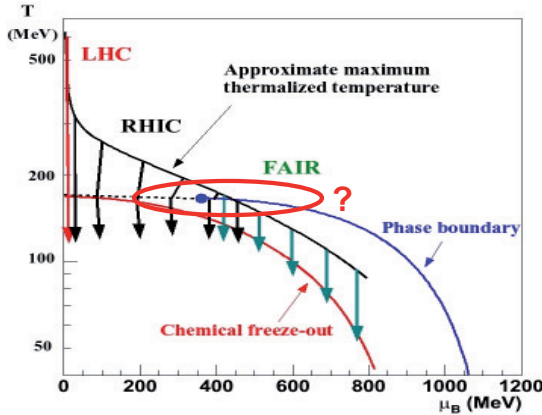
A possible signature:
event-by-event K/π fluctuations.
Needs large-acceptance PID.

- 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

Evidence for thermalization in sQGP
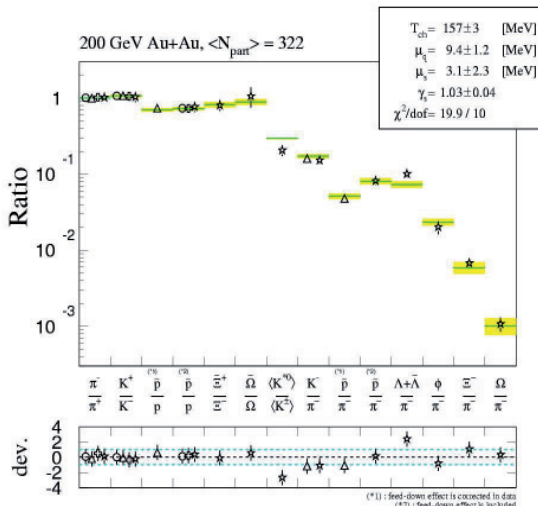
p_T-integrated particle yield ratios in central Au+Au collisions consistent with Grand Canonical Stat. distribution @ T_{ch} = (160 ± 10) MeV, $\mu_B \approx$ 25 MeV, across u, d and s quark sectors.

Inferred Temp. consistent with T_{crit} (LQCD) $\Rightarrow$ phase transition

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

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Particle multiplicity vs. pseudorapidity
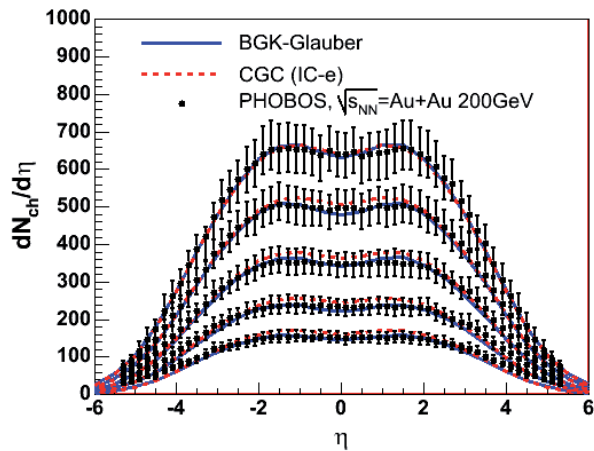
- Multiplicities well described by Color Glass Condensate model
- Evidence for saturated gluon fields in the Au nucleus?

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In principle, there is a <u>lot</u> of information needed to understand High p_T Particle Production in A+A Collisions

(According to pQCD...)

$$\frac{dN_{AB}^{h}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b \int d^2\mathbf{k}_a d^2\mathbf{k}_b$$
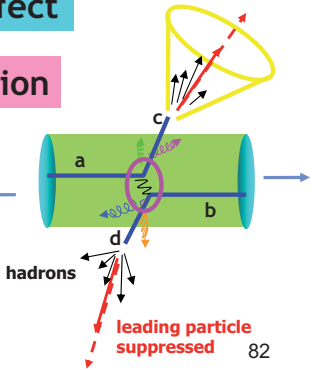
$\times f_{a/A}(x_a,Q^2)f_{b/B}(x_b,Q^2)$ **Parton Distribution Functions**

$\times g(\mathbf{k}_a)g(\mathbf{k}_b)$ **Intrinsic k_T , Cronin Effect**

$\times S_A(x_a,Q_a^2)S_B(x_b,Q_b^2)$ **Shadowing, EMC Effect**

$\times \dfrac{d\sigma}{d\hat{t}}(ab\to cd)$ **Hard-scattering cross-section**

$\times \displaystyle\int_0^1 d\varepsilon P(\varepsilon)\dfrac{z_c^*}{z_c}$ **Partonic Energy Loss**

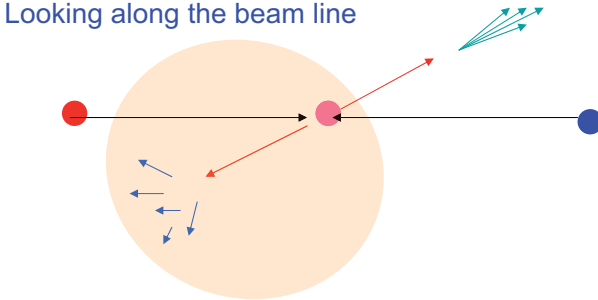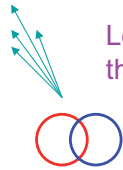$\dfrac{D_{h/c}^0(z_c^*,Q_c^2)}{\pi z_c}$ **Fragmentation Function**

a

b

c

d

hadrons

leading particle suppressed 82

But using our calibrated probe we can try something simpler to start

Looking along the beam line

**Looking down
the beam line**

If some new form of dense, opaque matter is formed, we might see the effects on our "calibrated" probe
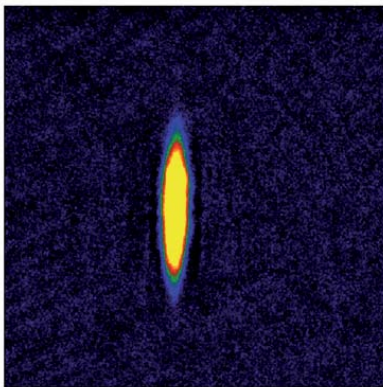(back-to-back correlation)

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Gas of weakly/strongly interacting Li atoms

M. Gehm et al, Science 298, 2179

– excite Feshbach resonance

strongly coupled

100 µs
200 µs
400 µs
600 µs
800 µs
1000 µs
1500 µs
2000 µs

weakly coupled
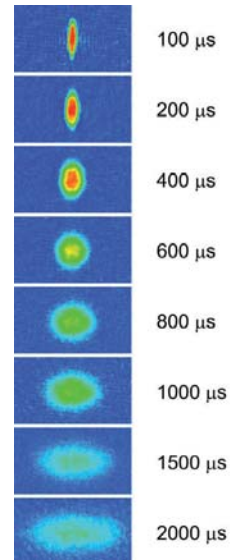
RHIC / RHIC-II / LHC-HI / EIC ⟹ Laboratory Exploration of Condensed Strongly Interacting Matter

Profound questions: What are the unique quantum many-body manifestations of a *non-Abelian* gauge theory? Are there lessons for other fundamental theories? How do we pump/probe partonic matter in 10^{-23} s?
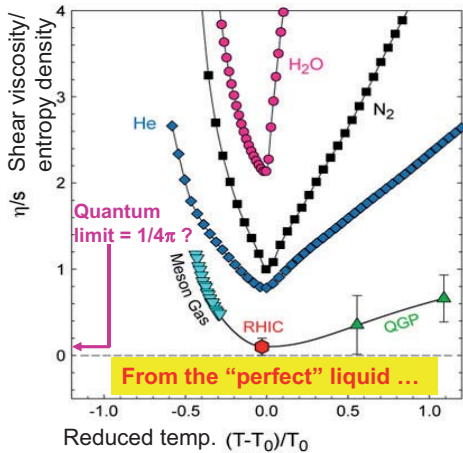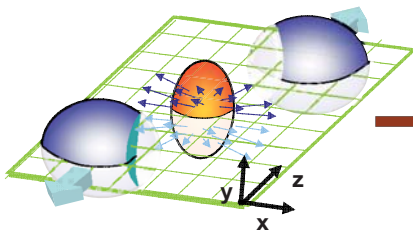

RHIC, RHIC-II, perhaps LHC probe very strong coupling limit: LQCD ⟹ quantitative theory for static properties; AdS/CFT ⟹ qualitative insight + gravity connection.
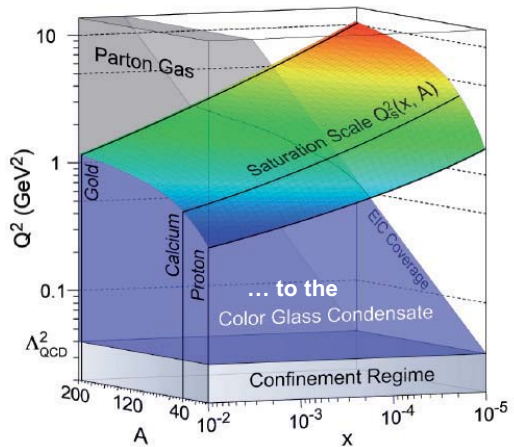
EIC probes weak coupling regime with gauge boson occupancy >> 1 ⟹ intense semi-classical (gluon) force field at the heart of matter.

Collective motion: "elliptic flow"

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

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

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

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

Elliptic term

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

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