BNL-98978-2012-CP
RBRC 988

RHIC – Relativistic Heavy Ion Collider: Its Evolution, Versatility, Discoveries and Continuing Productivity

N.P. Samios[1]

[1]RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973 USA

Part of the Conference Titled: "QCD Structure I" Held in Central China Normal University, Wuhan, China

October 2012

Physics Department/RBRC/Office of Science

Brookhaven National Laboratory
P.O. Box 5000
Upton, NY 11973-5000
www.bnl.gov

U.S. Department of Energy

DISCLAIMER

RHIC – Relativistic Heavy Ion Collider: Its Evolution, Versatility, Discoveries and Continuing Productivity

N.P. Samios

College of Physical Science and Technology,
Central China Normal University
Wuhan, China

October 8, 2012

Hadrons: P (Proton) N (Neutron)

Nuclei: ^{2}H (Hydrogen……) ^{238}U (Uranium……)

Strange Particles – Why?

$\pi^- p \rightarrow \Lambda^\circ + (K)$…. Production time 10^{-23} sec

$\Lambda^\circ \rightarrow p\pi^-$ Decay time 10^{-10} sec

Spectroscopy of particles

Mesons:	O^{-+}	$\pi(3)$	$K(4)$	$\eta(1)$	$\eta^1(1)$	9
	1^{-+}	$\rho(3)$	$K^*(4)$	$\omega(1)$	$\phi(1)$	9
Baryons:	$\frac{1}{2}^+$	$\Lambda(1)$	$\Sigma(3)$	$\Xi(2)$		8
	$\frac{3}{2}^+$	$\Delta(4)$	$\Sigma^*(3)$	$\Xi^*(2)$	$\Omega(1)$	10

SU(3) Particle families with same spin-parity and proper isospin, charge strangeness

Systematics led to Quarks: no $\overline{10}$.27 representation

Mesons: Quark anti-quark pair

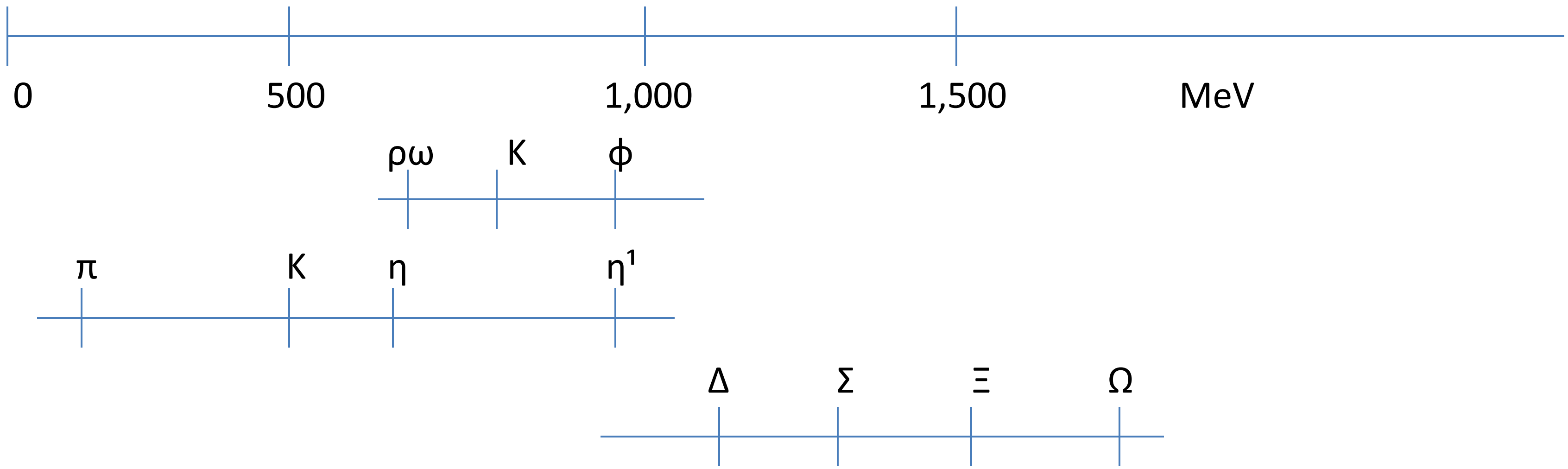
$3 \times \bar{3} \rightarrow 1+8$

Baryons: Three quarks

$3 \times 3 \times 3 \rightarrow 1+8+8+10$

Particle Mass Systematics: Asymptotic freedom

Constituent Quarks Mass



1^{-+}, $\frac{3}{2}^{+}$ Fine

O^{-+} Peculiar pattern – gluons

Deeply Inelastic Electron Scattering

$e\, p \rightarrow e + \ldots.$

Led to Partons (constituents inside proton)

Partons $\equiv$ Quarks

Subsequently: Charm, Bottom, Top

$+\frac{2}{3}$	u	c	t	mass scales	
$-\frac{1}{3}$	d	s	b	u,d	5 MeV
				top	175 GeV

Gluons, Color Field (8), Binds Quarks, Spin 1

Electron Position Collider

$e^- e^+ \rightarrow 3$ jets — and η^1 mass, instantons

2 quark, 1 gluon

Unique Feature:

3 gluon coupling; saturation; 3 photon coupling not allowed

Led to QCD

Asymptotic Freedom

At short distances – coupling weak

Confinement

At long distances – coupling strong

Quarks never leave nucleon!

How do you study these quarks and gluons since they never get out of the nucleon and does this offer any unique opportunities?

Supply a large amount of energy to a large nucleus increasing the energy density and temperature.

Au (198 nucleons) → Au (594 quarks & gluons)

T.D. Lee 1974

"Hitherto, in high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of "vacuum," we must turn to a different direction; we should investigate some "bulk" phenomena by distributing high energy over a relatively large volume. *The fact that this direction has never been explored should*, by itself, *serve as an incentive for doing such experiments."*

In this way one could temporarily restore broken symmetries of the physical vacuum and possibly create abnormal state of nuclear matter.

High Energy – Heavy Ion Collider

How big?

Energy:	Bevalac	~1 GeV/amu
	AGS	~10 GeV/amu
	Goal	~100 GeV/amu

Nucleons: As many species from hydrogen $A = 1$ to $A \geq 200$

RHIC – Relativistic Heavy Ion Collider

Process at BNL

1984-1985	Tandem to AGS Transfer Line Light Ions $A \approx 32$
1986-1990	Booster to AGS Heavy Ions $A \approx 200$
1991-1999	RHIC - collider

Statement from 1989 RHIC Conceptual Design Report:

The essential motivation for colliding nuclei at ultrarelativistic energies is the production of matter at extreme conditions of temperature and density: extended volumes of hadronic matter with energy densities greater than 10 times that of the nuclear ground state should be realizable. There is little direct knowledge about what to expect under such conditions. They have not been detected anywhere in the natural universe, and are just beginning to be approached through experiments with ion beams in experiments at Brookhaven and CERN. Thus the proposed facility represents a venture into an almost completely unknown regime for the study of basic properties of matter.

While this leap into the unknown is by itself compelling attraction for both experimenters and theorists, it is also true that very specific goals for discovery and exploration can be defined within the present understanding of Quantum Chromodynamics (QCD) – as developed from high energy collisions of elementary particles – and the low energy behavior of bulk nuclear matter. The parameters of the proposed machine complex will allow the experimenter to make contact with both regimes in the systematic study of new phenomenon.

The specific motivation from QCD is the belief that we can assemble macroscopic volumes of nuclear matter at such extreme thermodynamic conditions as to overcome the forces that confine constituents in normal hadrons, creating a new form of matter in an extended confined plasma of quarks and gluons.

Spin of the proton: s = ½

Early Conjectures – contributed by 3 quarks

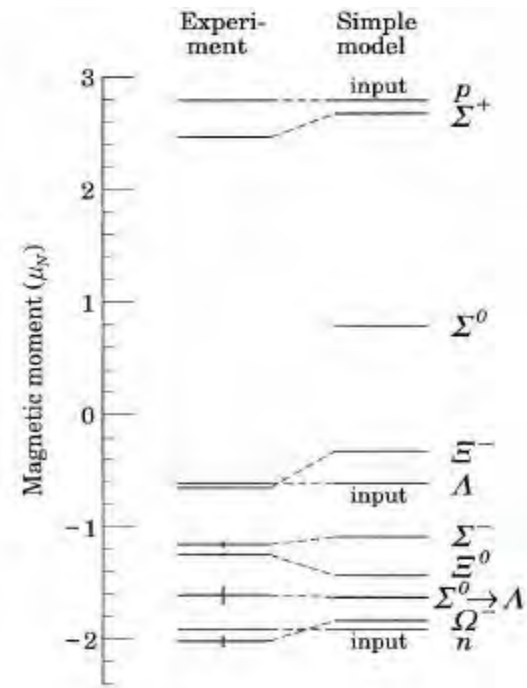
Reinforced by success of quark model fit to magnetic moments of hadrons

$$\mu_p = (4\mu_u - \mu_d)/3 \qquad \mu_n = (4\mu_d - \mu_u)/3$$
$$\mu_{\Sigma^+} = (4\mu_u - \mu_s)/3 \qquad \mu_{\Sigma^-} = (4\mu_d - \mu_s)/3$$
$$\mu_{\Xi^0} = (4\mu_s - \mu_u)/3 \qquad \mu_{\Xi^-} = (4\mu_s - \mu_d)/3$$
$$\mu_\Lambda = \mu_s \qquad \mu_{\Sigma^0} = (2\mu_u + 2\mu_d - \mu_s)/3$$
$$\mu_{\Omega^-} = 3\mu_s$$

and the $\Sigma^0 \to \Lambda$ transition moment is

$$\mu_{\Sigma^0\Lambda} = (\mu_d - \mu_u)/\sqrt{3}\,.$$

The quark moments that result from this model are $\mu_u = +1.852\,\mu_N$, $\mu_d = -0.972\,\mu_N$, and $\mu_s = -0.613\,\mu_N$. The corresponding effective quark masses, taking the quarks to be Dirac point particles, where $\mu = q\hbar/2m$, are 338, 322, and 510 MeV. As the figure shows, the model gives a good first approximation to the experimental moments. For efforts to make a better model, we refer to the literature [2].



However: Contradicted by high energy electron/muon-hadron scattering experiments

Spin of Proton = ½ = ½ ΔΣ = 0.13 25%

Where is the rest? Gluons

$$½ = ½\,\Delta\Sigma + \Delta G = 0.13 + \Delta G$$

Add spin capability to RHIC RIKEN

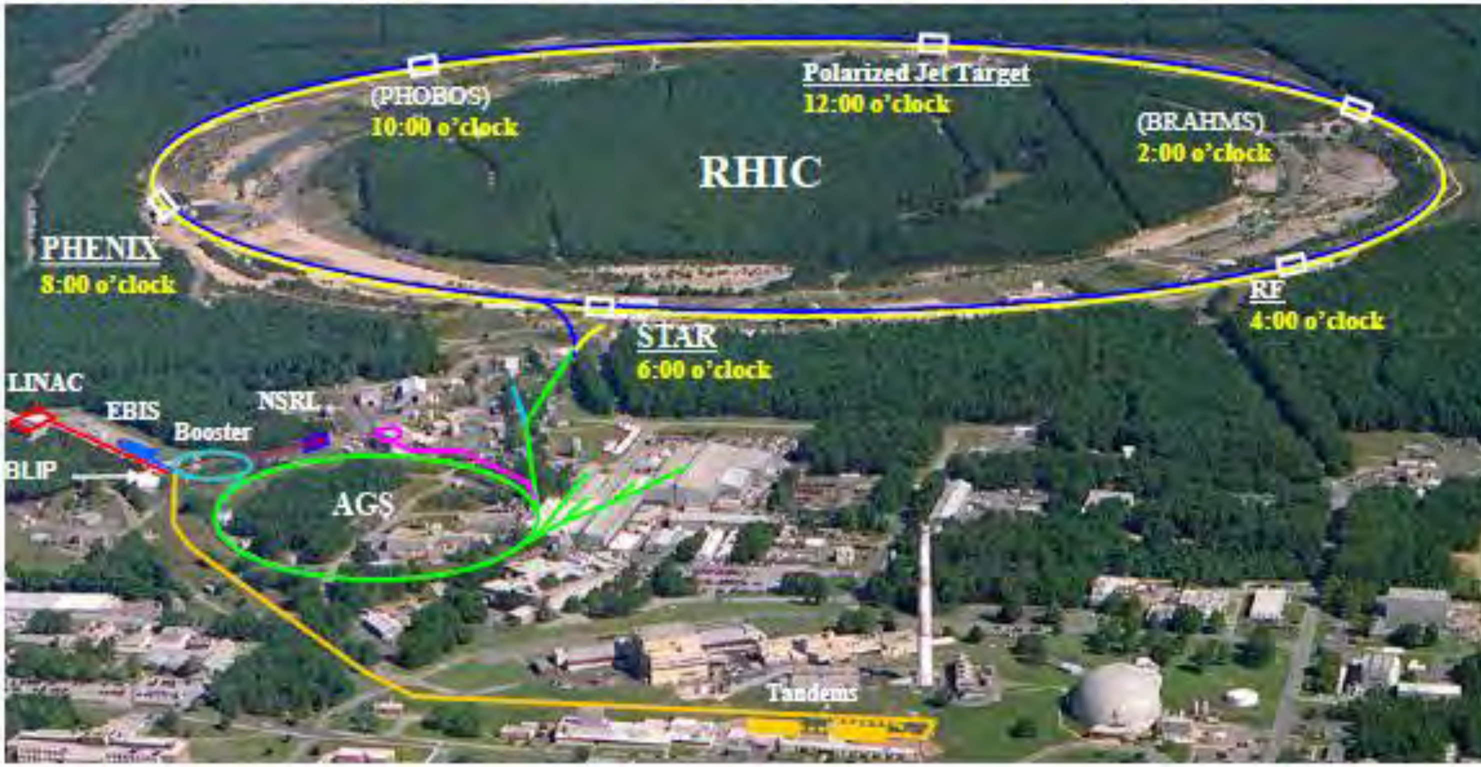
Accelerator Complex

- Accommodate Heavy Ions and polarized protons
  - Au x Au — 100 GeV/$_A$ x 100 GeV/$_A$
  - (Ux U) — (96 GeV/$_A$ x 96 GeV/$_A$)
  - and unequal species
    - d-Au, Cu-Au, etc.
  - polarized protons — 100 GeV x 100 GeV
    - 250 GeV x 250 GeV
- Utilize existence of
  - Tandem, Booster, AGS, CBA Ring, Refrigeration Plant, Tunnel
  - (EBIS)
- Emphasize
  - Flexibility – future upgrades and additions
  - Versatility
  - Reliability

Result:

- 2 Superconducting Concentric Rings of Magnets
  - (2 in 1 considered and not adopted)
- 6 Intersecting Regions
- 2 Large Detectors: Phenix and Star
- 2 Smaller Detectors: Brahms and Phobos
- 1 Area for Future Detector

RHIC's First Decade: A Discovery Machine



RHIC hallmarks:

Pioneering *- 1st facility to clearly see transition to quark-gluon matter;* ***world's only polarized collider***

Productive *-> 300 refereed papers, > 30K citations, > 300 Ph. D.'s in 1st 12 years, many more in pipeline, no rate falloff in sight*

Versatile *-* ***wide range of beam energies and ion species ⇒ string of definitive discoveries in both hot and cold QCD matter***

Accelerator Complex Record to Date

Achieved or surpassed all specifications (energy, luminosity, etc.)

i.e. luminosity: designed for Au x Au $2 \times 10^{26}/cm^2/sec$

Achieved $30 \times 10^{26}/cm^2/sec$

Upgrades: EBIS 2012

Electron Beam Ion Source – more species
higher current

Stochastic Cooling – heavy ions
≈ 10x luminosity increase
Accomplished in 3 years and 1/7 cost.

RHIC ions – 6 species and 15 energies to date

$^{238}U^{92+}$–$^{238}U^{92+}$ first time in 2012, 3 weeks physics

96.4 GeV/nucleon

$^{197}Au^{79+}$– $^{197}Au^{79+}$

3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 27.9, 31.2, 65.2, 100.0 GeV/nucleon

$^{63}Cu^{29+}$– $^{197}Au^{79+}$ first time in 2012, 5 weeks

99.9/100.0 GeV/nucleon

$^{63}Cu^{29+}$–$^{63}Cu^{29+}$

11.2, 31.2, 100.0 GeV/nucleon

d–$^{197}Au^{79+}$

100.7/100.0 GeV/nucleon

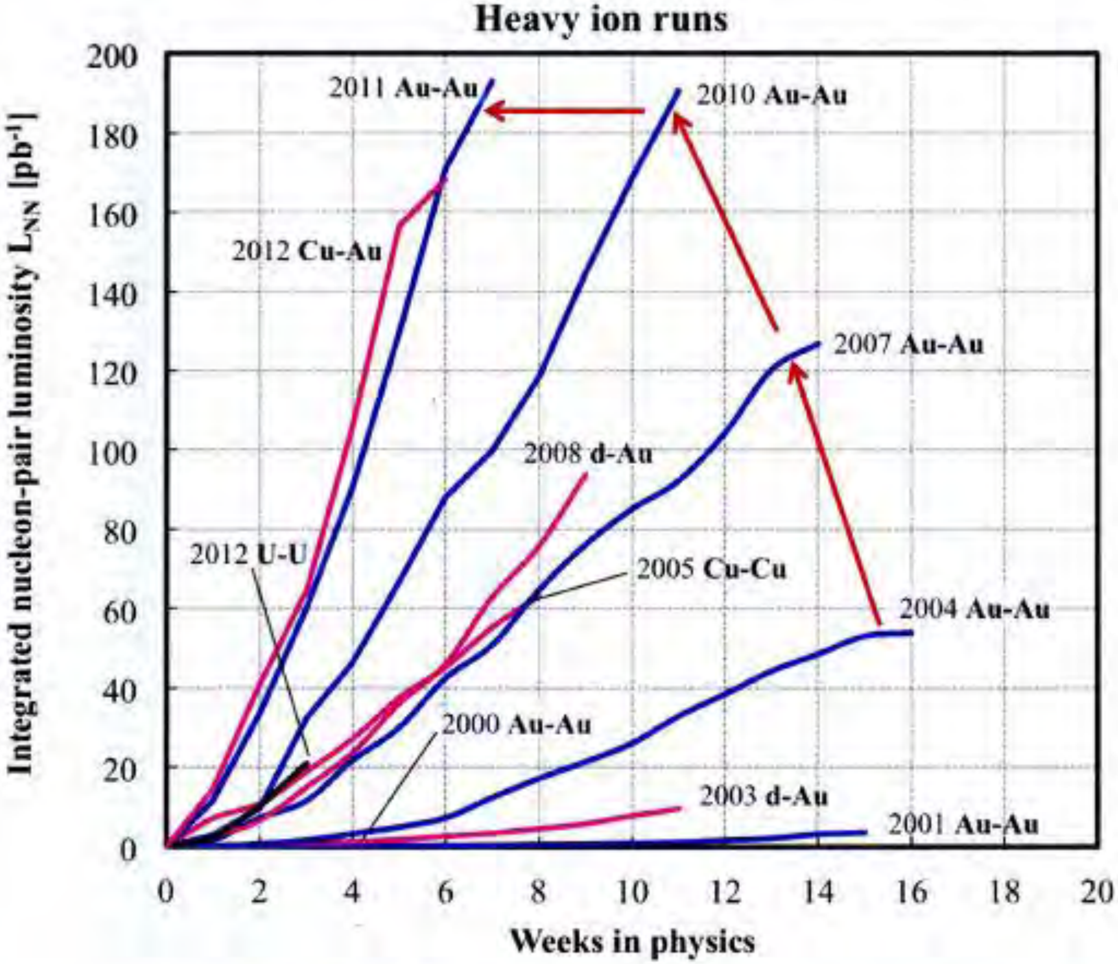
pol. p – pol. p

31.2, 100.2, 204.9, 249.9, 254.9 GeV

Can collide any species from protons (polarized) to uranium

- with each other or with another species

RHIC heavy ions – luminosity evolution to date



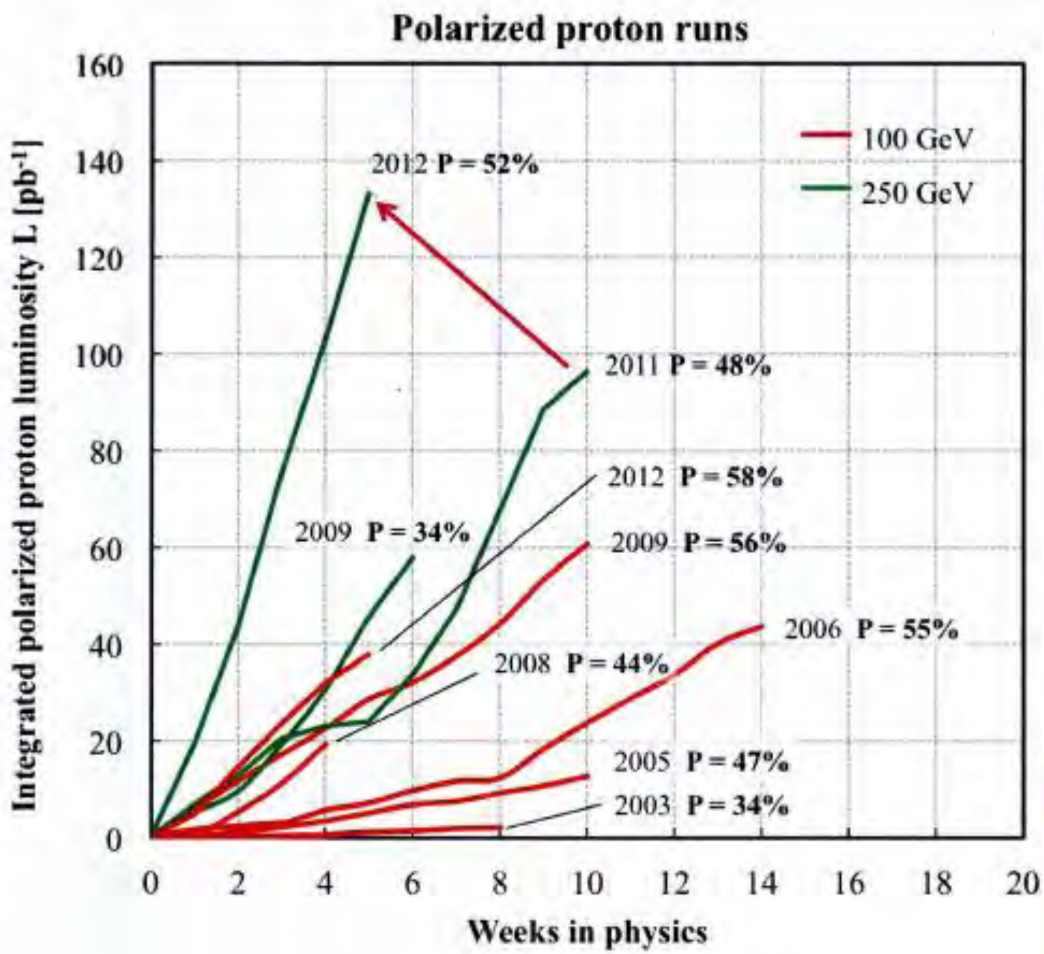
<L> = 15x design in 2011

About 2x increase in L_{int}/week each

- Run-4 to Run-7
- Run-7 to Run10
- Run-10 to Run-11

$\mathbf{L_{NN} = L\, N_1 N_2}$ (= luminosity for beam of nucleons, not ions)

RHIC polarized protons – luminosity and polarization



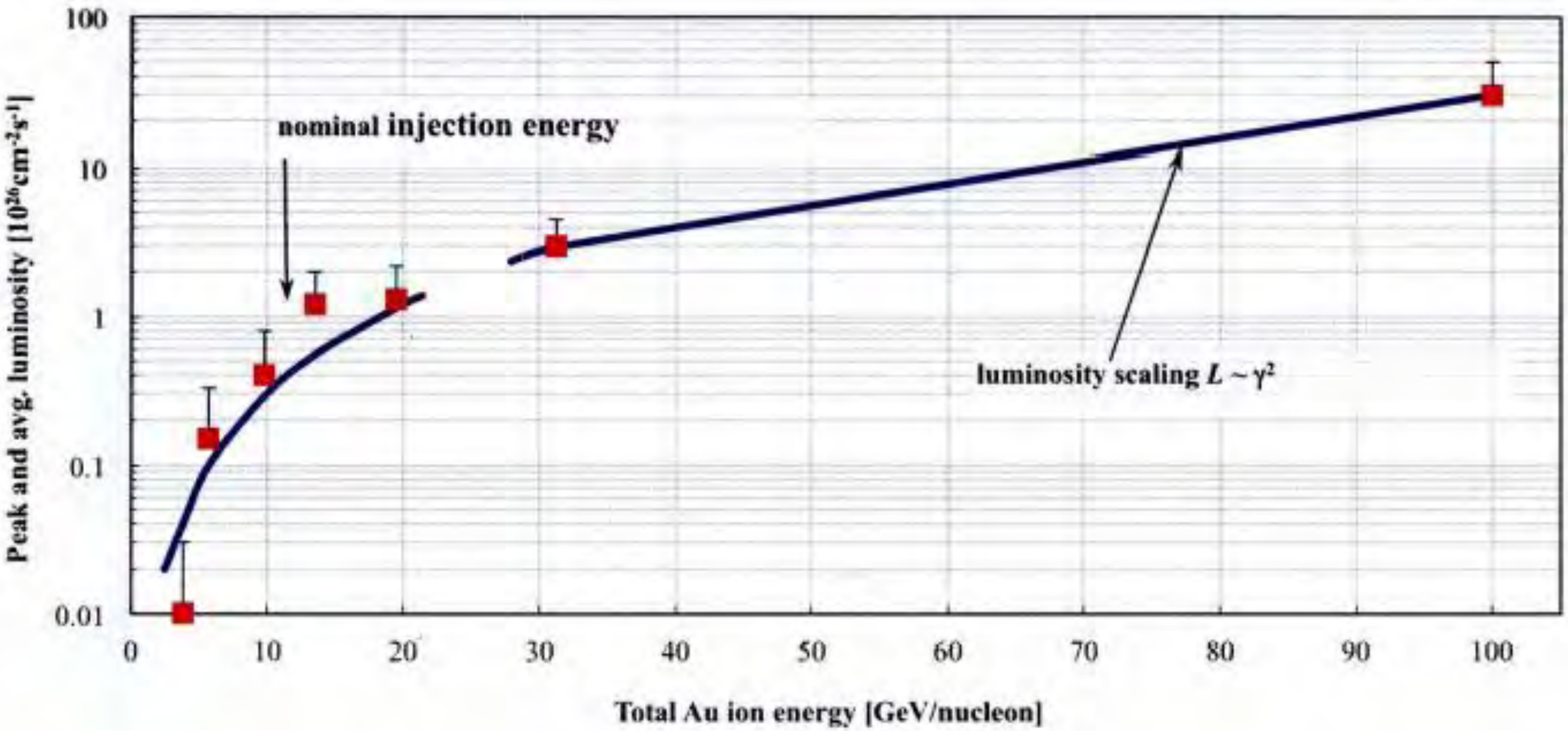
At 255 GeV in 2012
$L_{avg} = 105 \times 10^{30} cm^{-2}s^{-1}$
$P_{avg} = 52\%$

L_{avg} +15% relative to 2011
P_{avg} +8% relative to 2011

$FOM = LP^2$
(single spin experiments)

$FOM = LP^4$
(double spin experiments)

Au-Au energy scan to date



Peak and average luminosities fall faster than $1/\gamma^2$ at lowest energies
Need cooling at low energies to significantly increase luminosities

Four Detectors

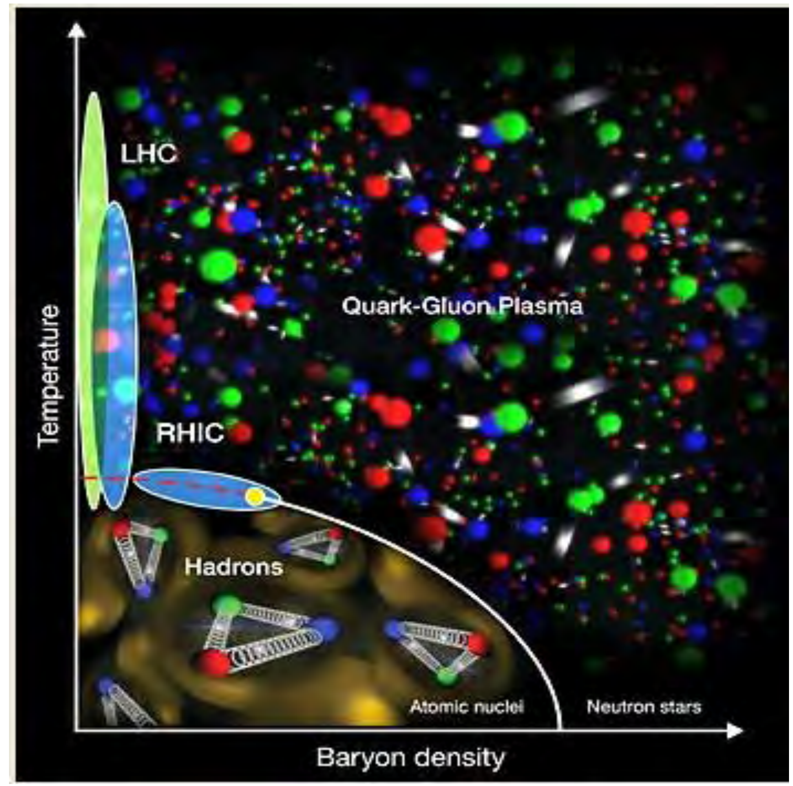
1200 Physicists

50 Countries

2000 Publications

Physics Program

The vision for RHIC has been realized, even surpassed



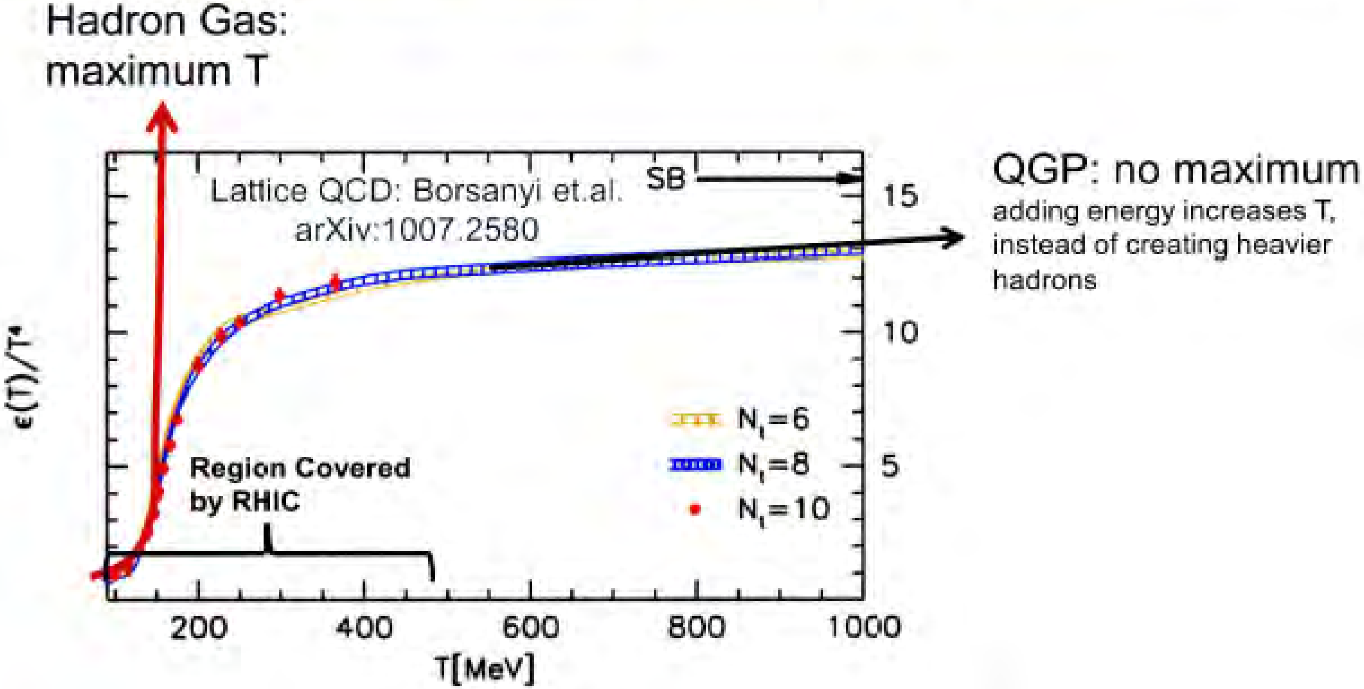
RHIC has pioneered
a vibrant new sub field –
a laboratory study
of condensed QCD
matter physics

Major Discovery

A new form of matter created at the extreme temperature characteristic of the universe a few micro seconds after the Big Bang behaves like nearly viscosity free liquid (perfect liquid) composed of quarks and gluons. This is in contrast to expectations of an ideal, asymptotically free gas of a quark gluon plasma.

Thermodynamics of QCD

Quantum Chromodynamics shows a rapid crossover to QGP:
ε/T^4 ($\propto$ # degrees-of-freedom) plateaus when quarks and gluons start to become the relevant degrees of freedom



The transition region (not the asymptotic limit) is of most interest

Observables

Nuclear Modification Factor

$R_{AA} = \frac{d^2N^{AA}/dp_t d\eta}{T_{AA} d^2N^{pp}/dp_t d\eta}$

Collective Effect – more than individual nucleons

Suppression by factor of ≈ 5

Collective Flow

Converts spatial asymmetries into momentum space

$\frac{dN}{d\phi_\eta} \approx 1 + 2 \sum_\eta V_\eta \cos \eta(\phi_\eta - \psi)$

$V_2 = \langle \cos 2 \phi_2 \rangle$

Strongly interacting quark gluon plasma → perfect liquid

Jet Correlations

Medium Effects

$\frac{dN}{d\phi_\eta}$ vs $\Delta\phi$

Highly dense matter - 3x normal

Direct Photons

Plasma Temperature

$T \approx$ 300-400 MeV $> T_c$ (150 MeV)

Longitudinal Jet Asymmetries in polarized proton collision, A_{LL}

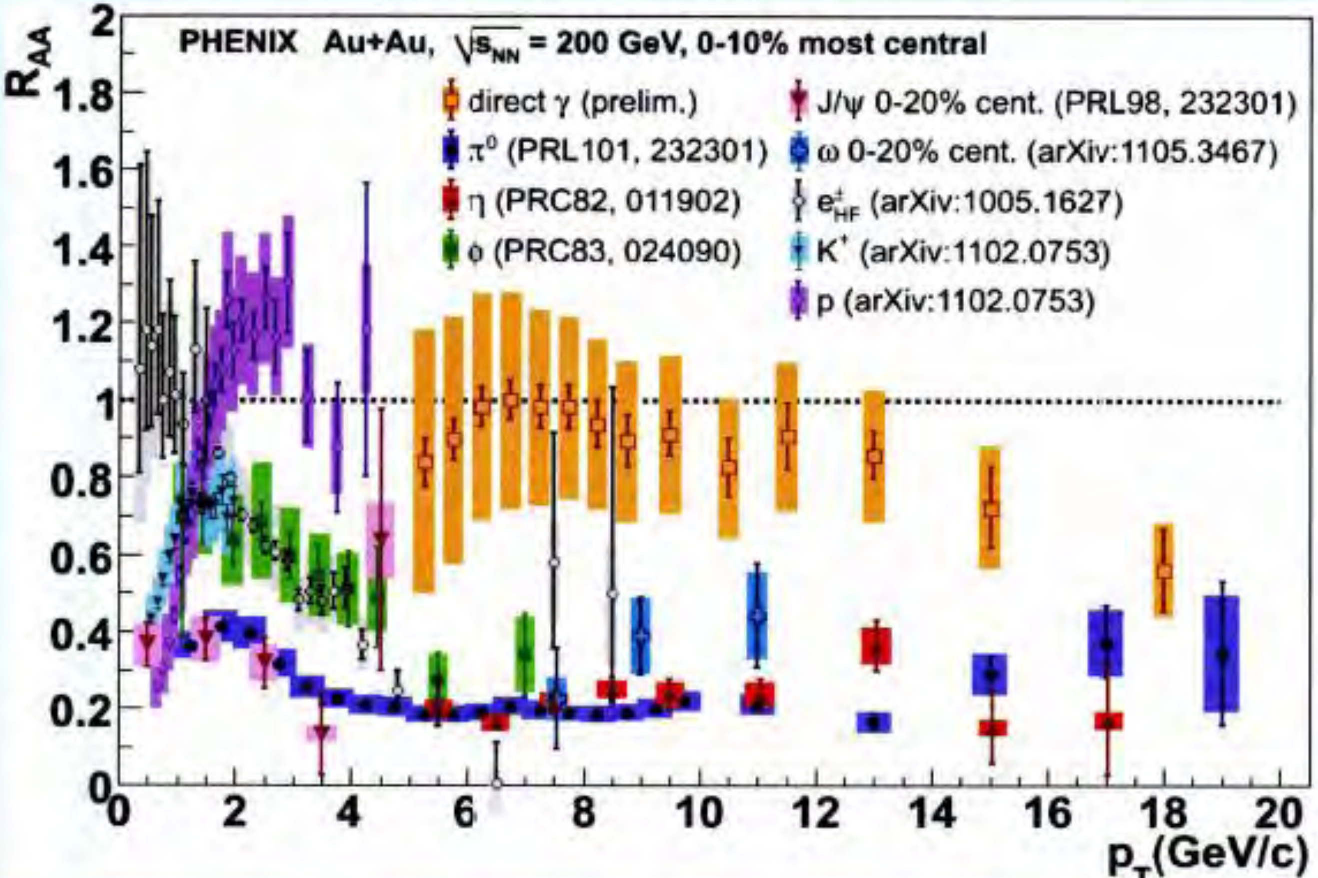
Gluon Contribution to Proton Spin – observed

$\Delta G \approx .12$ (limited x range)

Gluon and Quark Contributions are Comparable ≈ 20-25% each

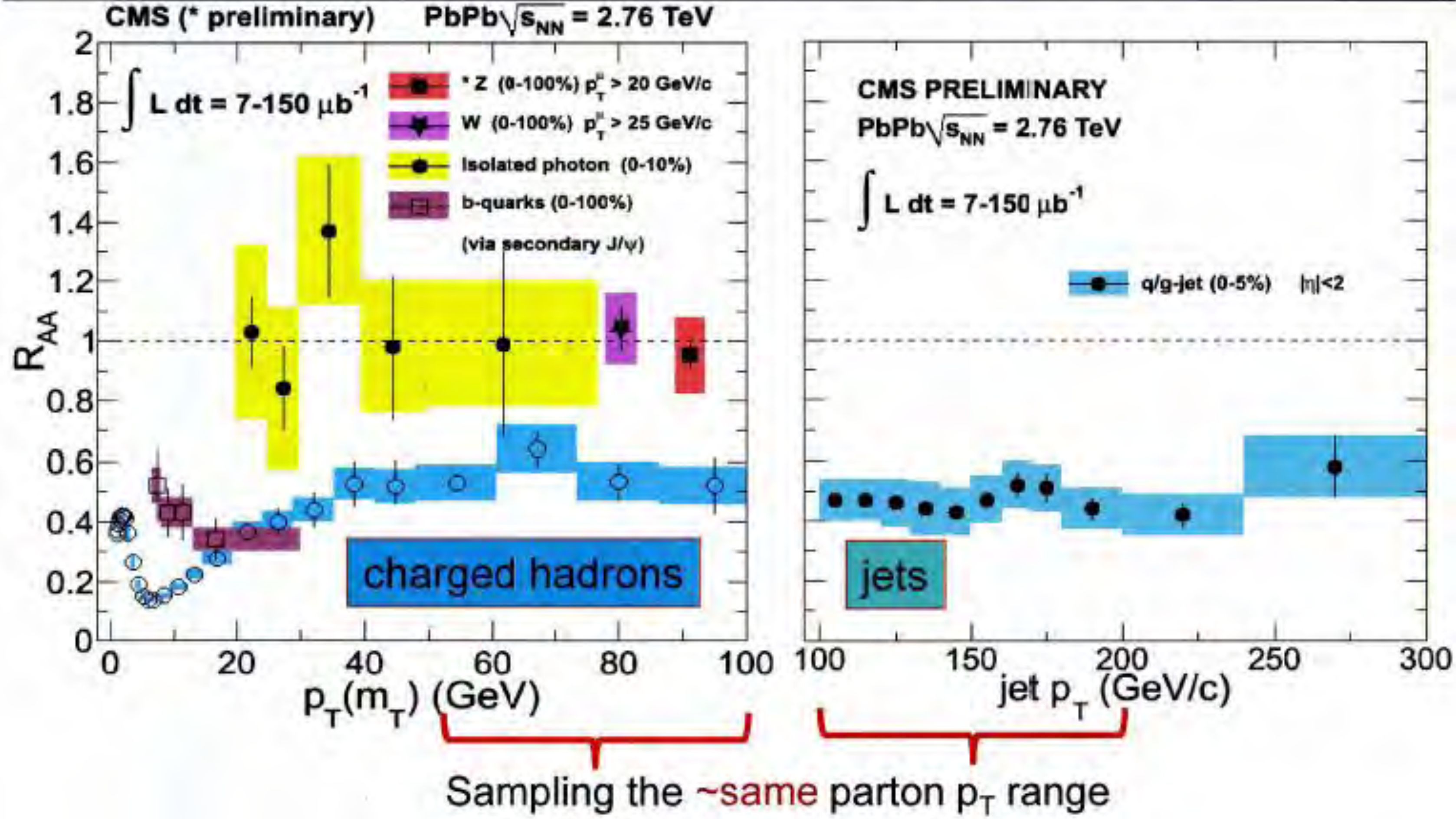
Leads to $\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta G + L_Q + L_G$

PHENIX: unprecedented reach and precision



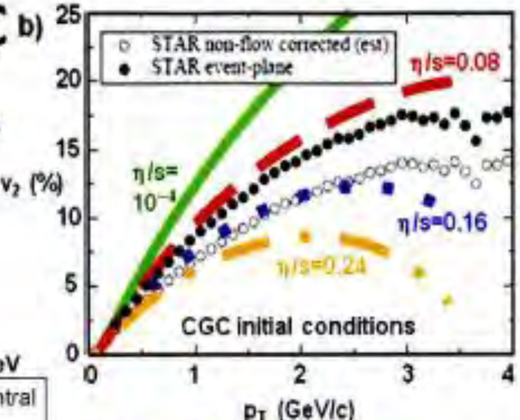
Superb particle ID, high rate capability and excellent trigger: broad physics capabilities over a large kinematic range

Nuclear modification factors

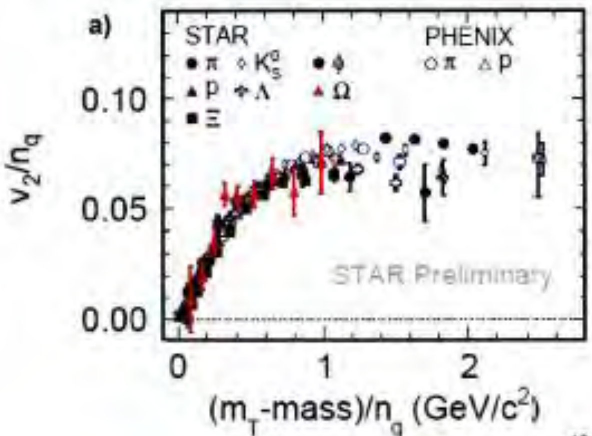


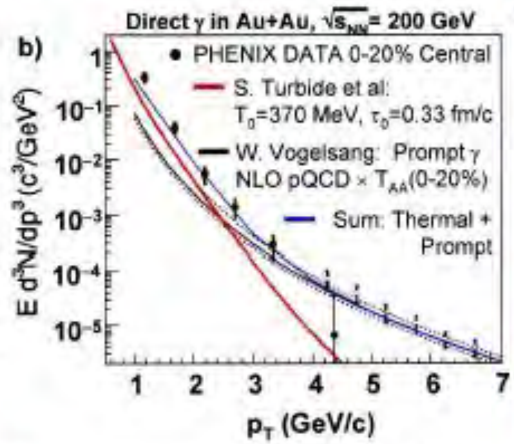
Note: jets fragment into high-p_T particles in pp and PbPb the same way – *see later*..

Compelling Hot QCD Discoveries at RHIC



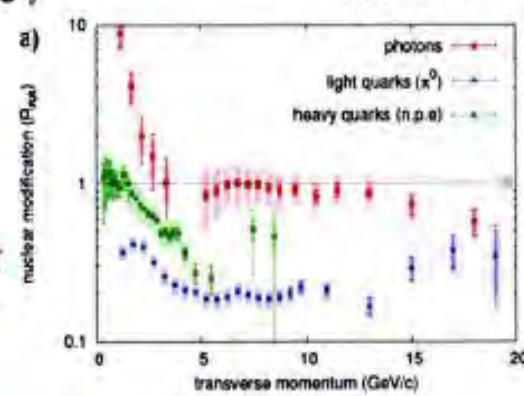
- ❑ *Near-perfect liquid nature of early universe matter, markedly different from anticipated ideal gas*
- ❑ *Shear viscosity near lower quantum limit predicted via String Theory work on black holes*

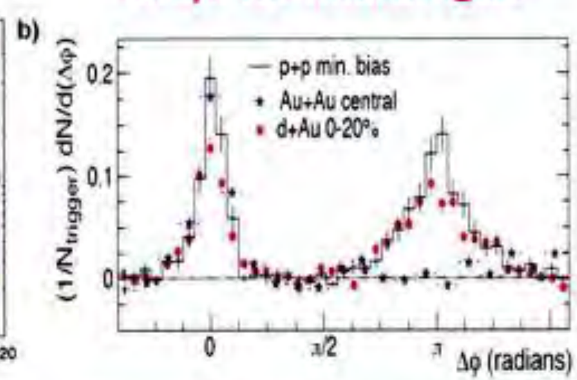


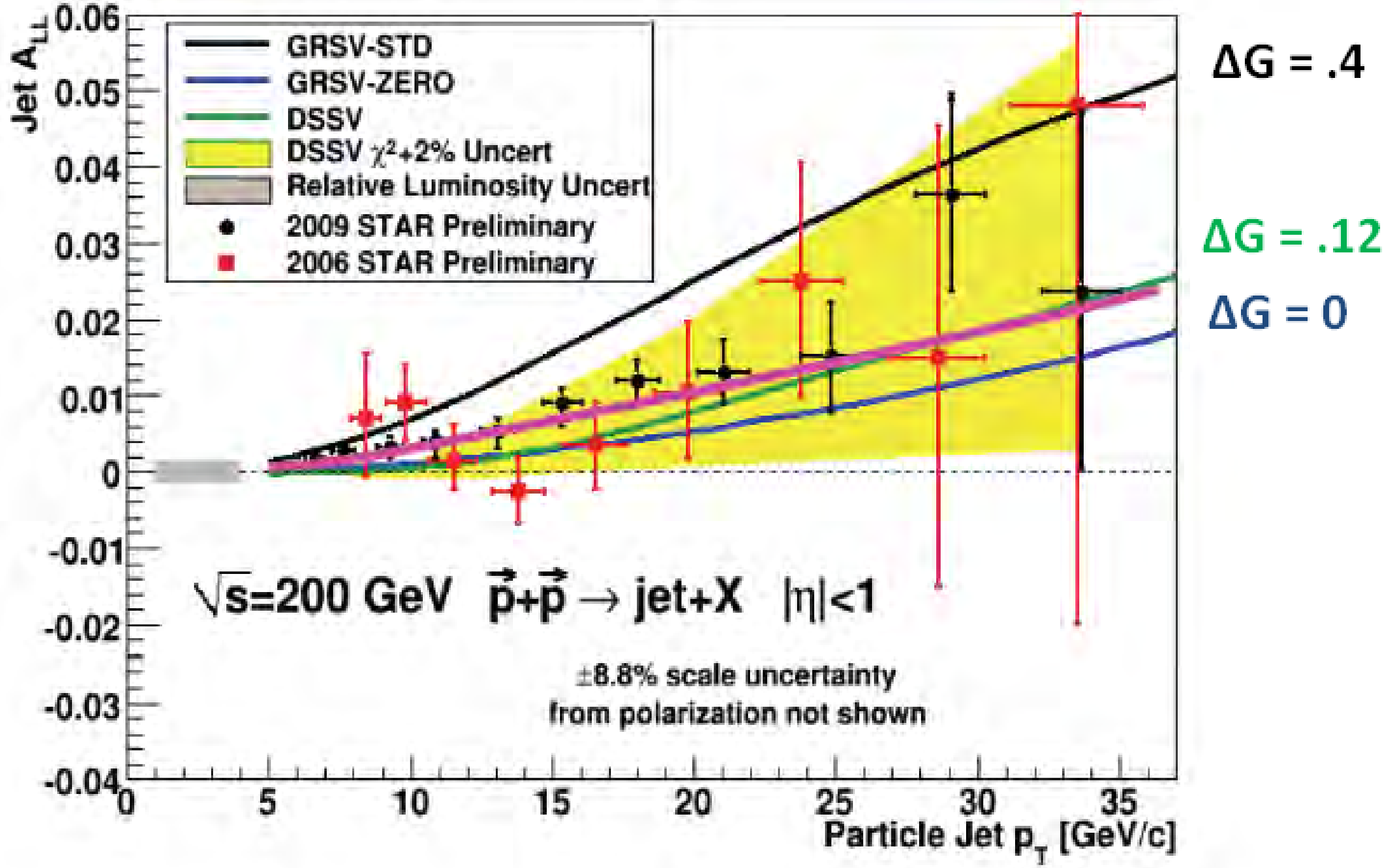


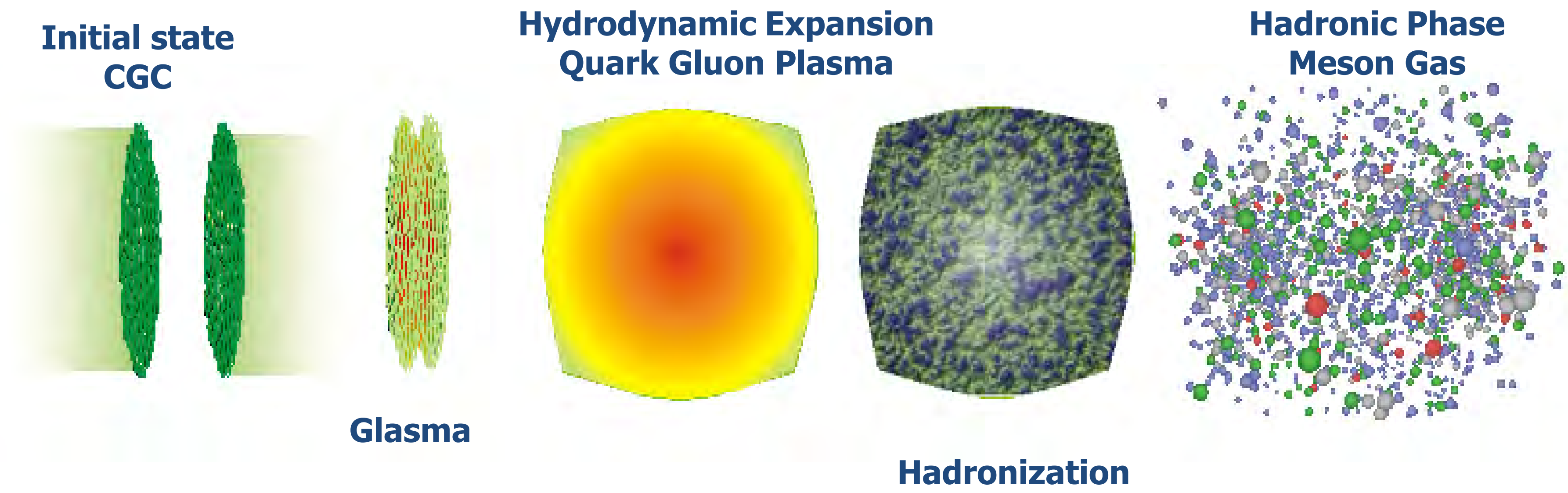
- ❑ *Collective flow established at quark level*
- ❑ *Matter first equilibrates ~4×10[12] K, well above max. allowed temp. for hadron gas*

- ❑ *QGP is ~opaque to quarks and gluons, but transparent to photons*
- ❑ *"Bubbles" where quark matter appears to violate normal QCD symmetries*






Jet A_{LL}
GRSV-STD
GRSV-ZERO
DSSV
DSSV χ^2+2% Uncert
Relative Luminosity Uncert
2009 STAR Preliminary
2006 STAR Preliminary
$\sqrt{s}$=200 GeV $\vec{p}+\vec{p} \rightarrow$ jet+X $|\eta|<1$
±8.8% scale uncertainty
from polarization not shown
Particle Jet p_T [GeV/c]
ΔG = .4
ΔG = .12
ΔG = 0

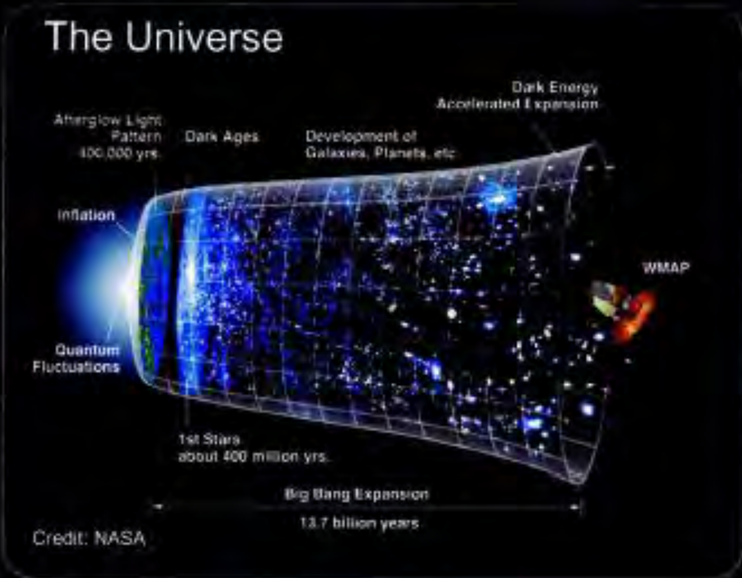


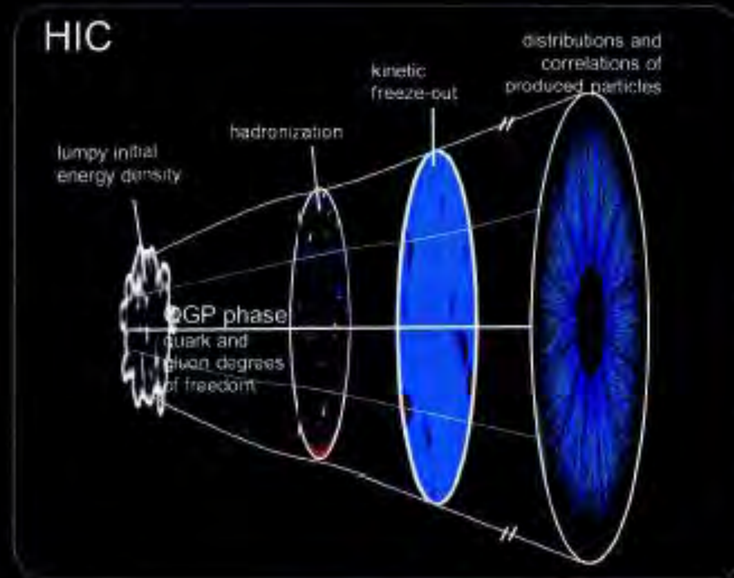
Initial State:	Color Glass Condensate	(Color – charge)
	High Density of Gluons	(Glass – disordered)
Collision:		(Condensate – high density)

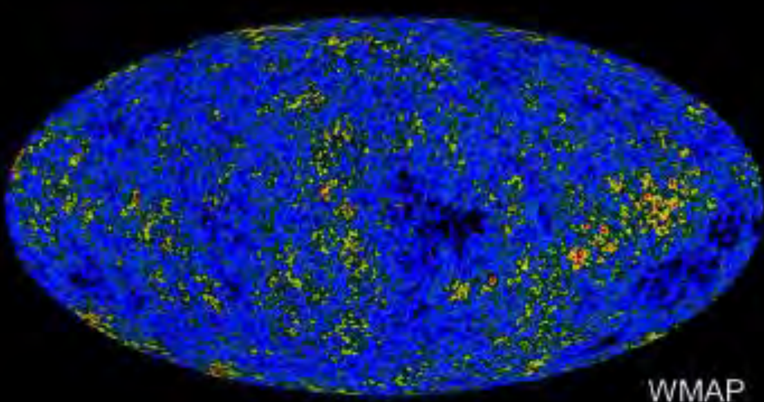
Glasma: Non-equilibrium matter – described by longitudal chromo – E & B fields – flux tubes along collision axis

Quark Gluon Plasma:	Strongly interacting quarks and gluons (sQGP)	
	Perfect Liquid	
	η/s ≈ ¼π	viscosity/entropy
	Possibly connected to string theory	
Hadronization:	Recombination of quarks, gluons into hadrons	
Meson Gas:	Dilution of hadrons	

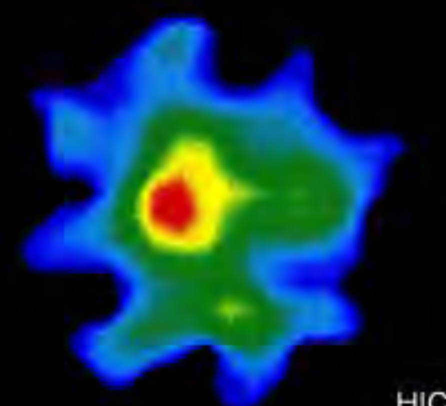
The Big Bang vs the Little Bangs







WMAP



HIC

More Recent Developments

Higher harmonic flow

Perfect Liquid – allows for accessing initial state fluctuations

Higher harmonics also allow determination of η/s

$\eta/s \approx .16; (.08 - .4); ¼ \pi = .08$

Higher harmonic flow

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n (2v_n \cos[n(\phi - \psi_n)]\right)$$

When including fluctuations, all moments appear:

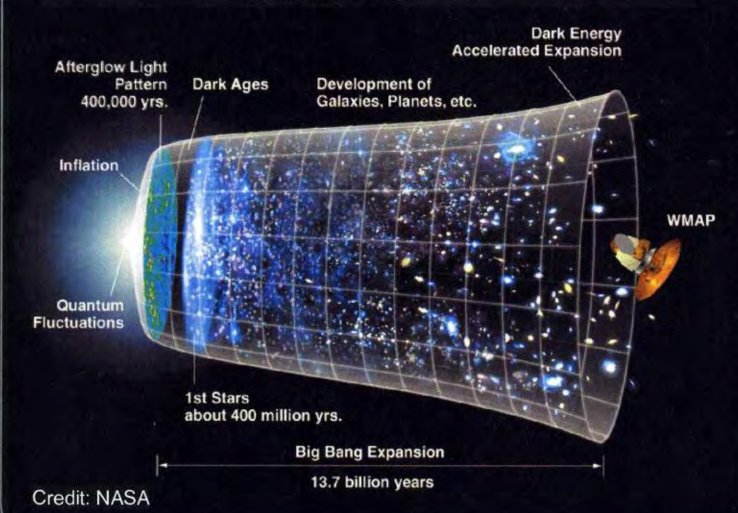
$n = 2$ $n = 3$ $n = 4$ $n = 5$ $n = 6$

also v_1 and $n > 6$

Compute $v_n = \langle \cos[n(\phi - \psi_n)] \rangle$
with the event-plane angle $\psi_n = \frac{1}{n} \arctan \frac{\langle \sin(n\phi) \rangle}{\langle \cos(n\phi) \rangle}$

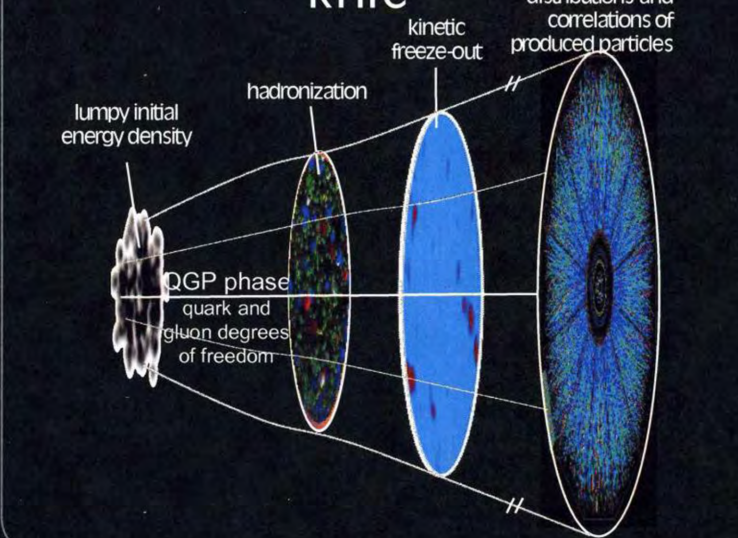
The Evidence Validates this Analogy

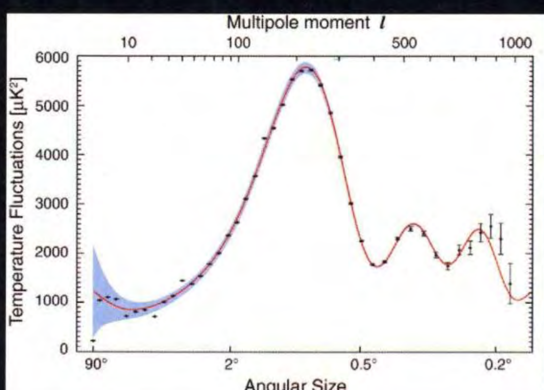
The Universe



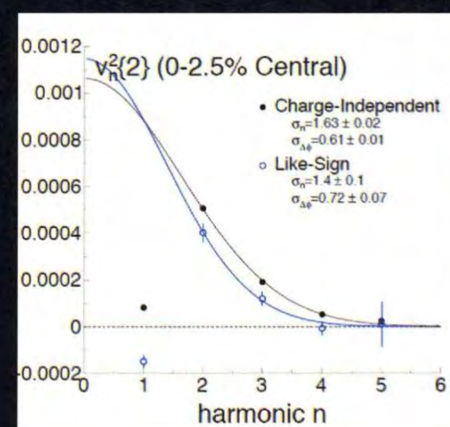
Credit: NASA

RHIC





WMAP

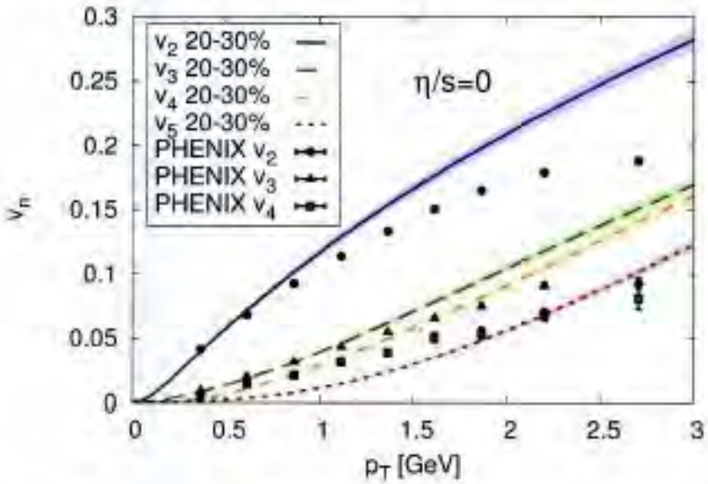


RHIC

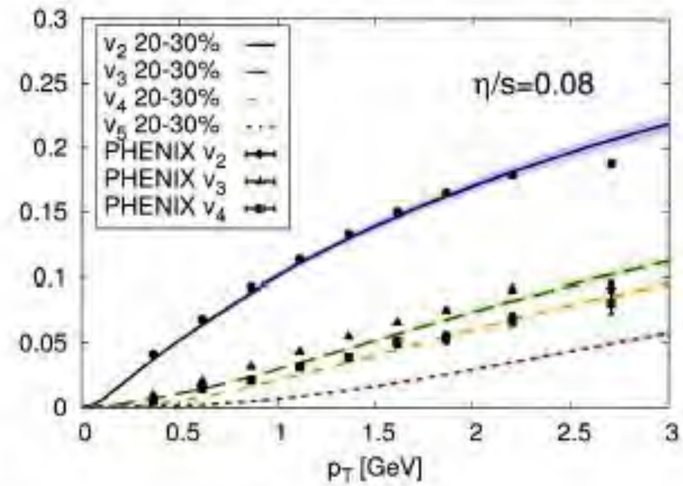
Using higher harmonics to determine η/s

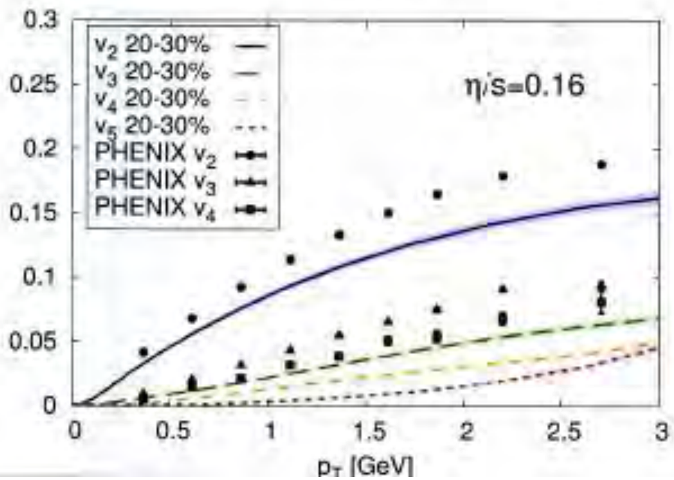
B. Schenke, S. Jeon, C. Gale, arXiv:1109.6289

Data is from event-plane method. Calculations are $\sqrt{\langle v_n^2 \rangle}$.



MC-Glauber initial conditions

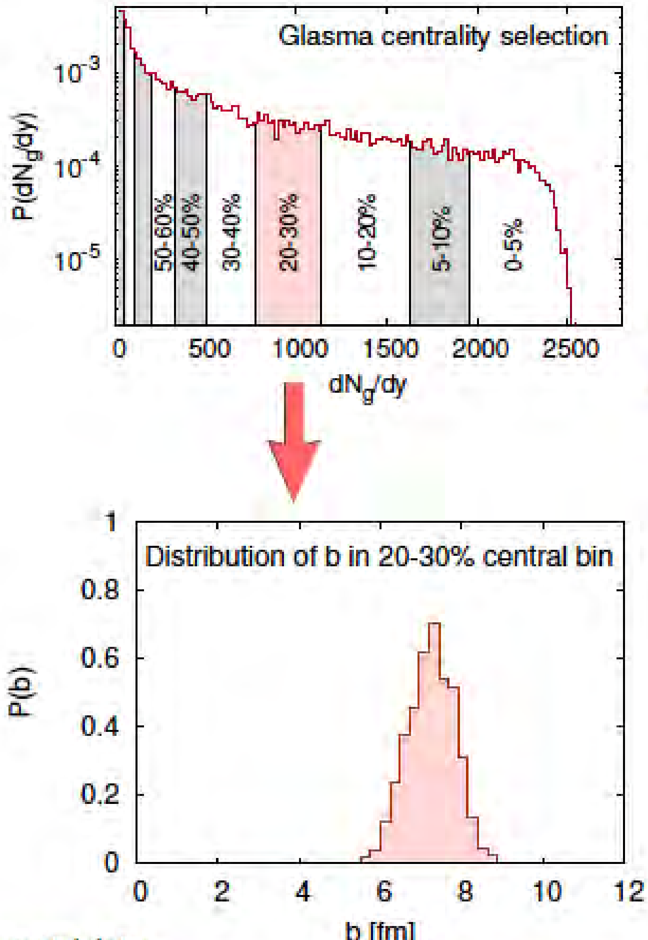


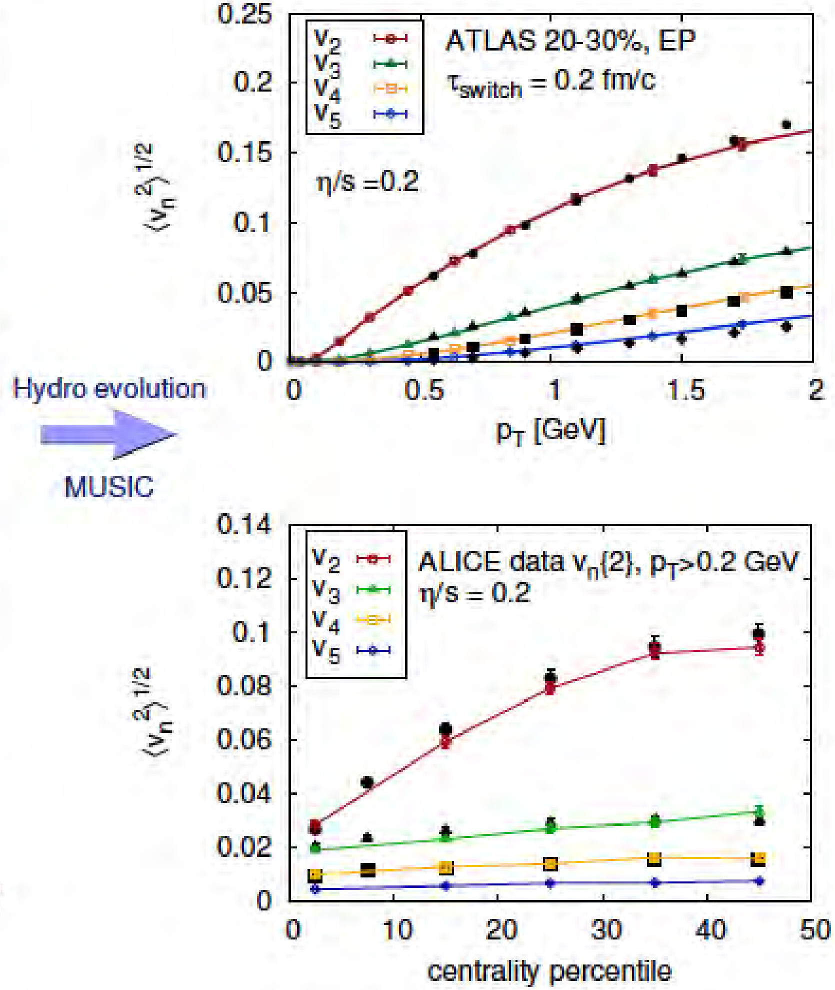


This is promising.
Need systematic study of all v_n as function of initial conditions, granularity, η/s, ...

Experimental data: PHENIX, arXiv:1105.3928

Centrality selection and flow



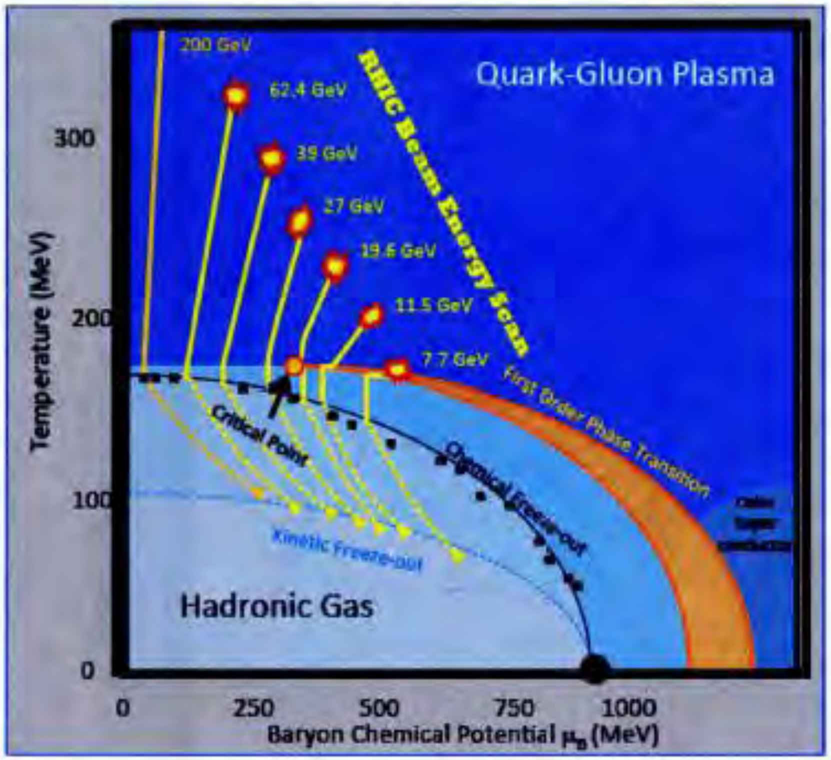


Experimental data:
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)
ALICE collaboration, Phys. Rev. Lett. 107, 032301 (2011)

Beam Energy Scan

- Search for Hadronic– QGP Phase Boundary
- Search for critical point
- $\sqrt{S}$ (c of m) 7.7 – 62.4 GeV   Au x Au
- Suppression ceases below 27 GeV
- Kurtosis (K), Variance (σ) and skewness (S)
- Indicates 5-20 GeV as an energy of interest for critical point

Beam Energy Scan



Vary the initial temperature, energy density and baryon density

Search for phase boundaries, QGP turning off

Search for Critical Point and 1st order phase transition line

Study variation of transport properties, and the equation of state

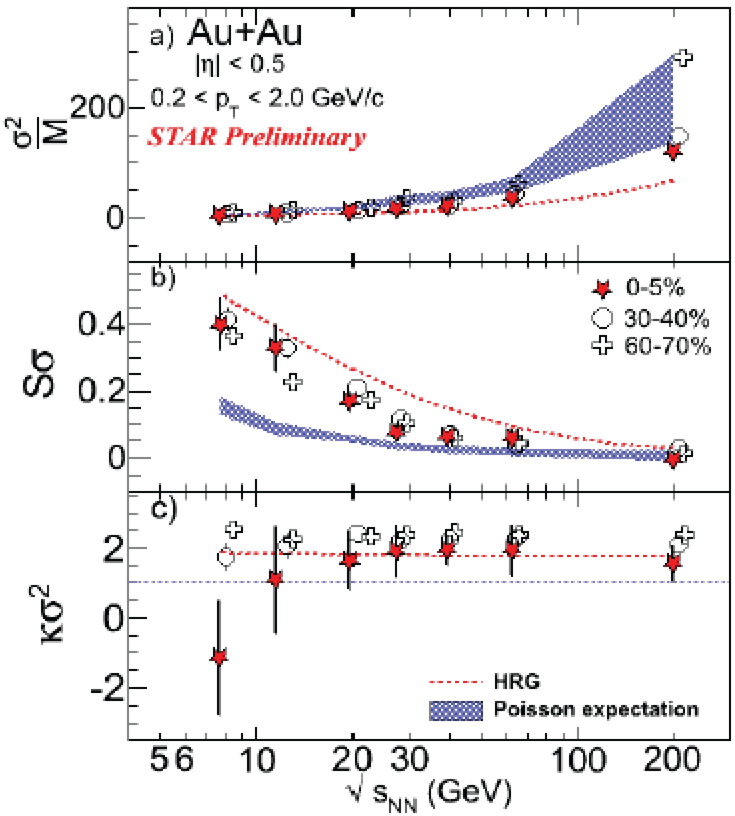
$$\sigma = \sqrt{<(N-<N>)^2>}$$

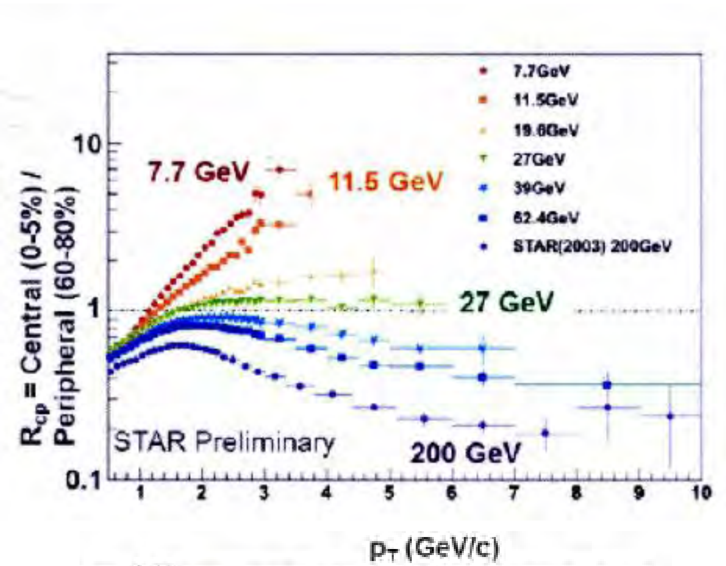
$$s = \frac{<(N-<N>)^3>}{\sigma^3}$$

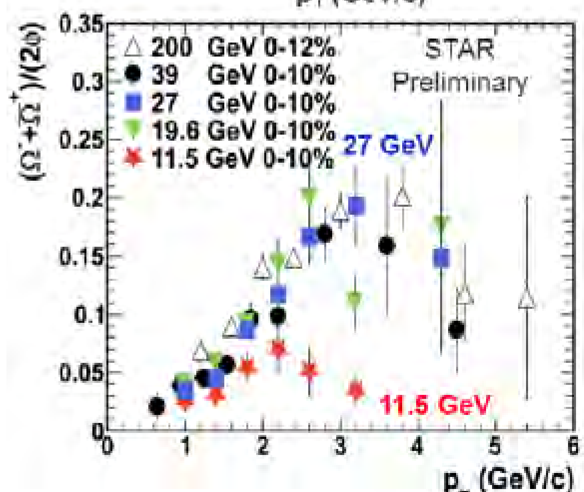
$$\kappa = \frac{<(N-<N>)^4>}{\sigma^4} - 3$$

$$S\sigma \sim \chi_B^{(3)}/\chi_B^{(2)}$$

$$\kappa\sigma^2 \sim \chi_B^{(4)}/\chi_B^{(2)}$$







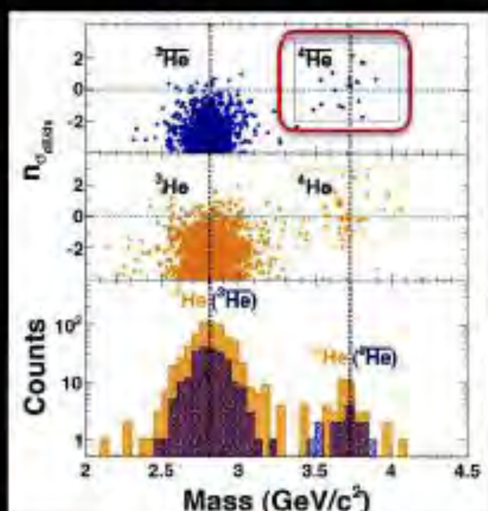
STAR Antimatter Discoveries by STAR at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

by ***STAR Collaboration***

Nature*, 473, 353(2011).*

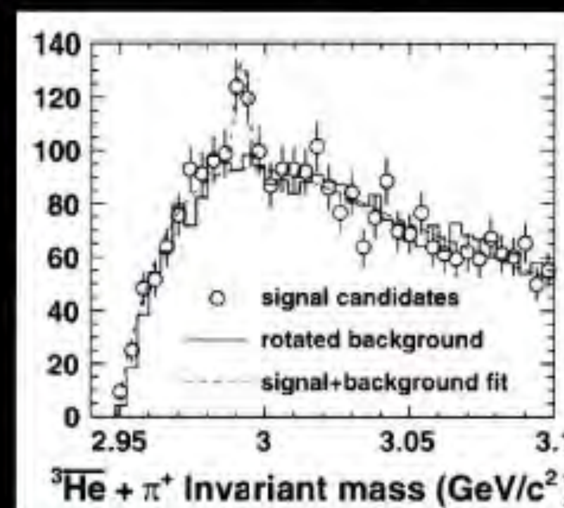


Science March, 2010

"Observation of an Antimatter Hypernucleus"

by ***STAR Collaboration***

Science*, 328, 58(2010).*



Bonus:

Observation of

Antimatter Helium 4 Nucleus

Antimatter Hypernucleus $^{\bar{3}}_{\Lambda}\overline{H} \rightarrow {}^{3}\overline{He}\ \pi^{+}$

Possible Observation of Local Parity Violating Bubbles

Consequence of strong magnetic field generated in RHIC heavy ion collisions

10^{17} gauss

Future:

RHIC's second decade is devoted to quantifying properties of the QGP and features of the QCD phase diagram, and continuing explorations of the role of soft gluons in cold nuclear matter. In parallel with quantification, the envisioned program will also pursue new discovery potential associated with the location of a possible QCD critical point, the nature of initial-state quantum fluctuations, and effects of QCD sphalerons.

Followed by

eRHIC

eρ; 5-30 GeV e^{-}, 250 protons; polarized

eA; 5-30 GeV e^{-}: Au = 100 GeV/$_{A}$

Truly an extraordinary and exciting Physics Program

Important Questions

How perfect is the near-perfect liquid QGP as a function of its temperature?

What is the nature of the initial density fluctuations in the matter prior to QGP formation?

How does a strongly coupled liquid emerge from an asymptotically free theory?

Do we observe evidence for the onset of deconfinement and/or a QCD critical point?

Do we observe melting of different quarkonium states?

Are the hints of sphaleron effects seen in the data real?

Do we reach saturated gluon densities in RHIC d/p+A collisions?

Where is the missing proton spin?