Stranger than Fiction:
Adventures in the QCD Wonderland

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Joint Meeting of the DNP/JPS
Hawai’i - October 14, 2009
An invitation

...we invite you to give a plenary talk on

“QCD at Work”
An Advice

A concise summary of the insights from nearly a decade of physics with RHIC

by the DNP

AS REQUESTED, I FIT MY PRESENTATION ON ONE POWERPOINT SLIDE.

I HAD TO USE ALL OF THE WHITE SPACE, BUT I THINK IT WAS WORTH IT TO FIT EVERYTHING ON ONE PAGE.
Part 1

Theoretical and Experimental Tools for the Study of QCD Matter
Quantum chromodynamics

\[ L_{\text{QCD}} = -\frac{1}{4} G_{\mu\nu}^{a} G^{a\mu\nu} + \sum_{f} \bar{\Psi} \gamma^{\mu} \left( \partial_{\mu} + g A_{\mu}^{a} t^{a} \right) \Psi + \sum_{f} m_{f} \bar{\Psi} \Psi \]

**perturbative QCD**

works for processes involving a hard momentum scale
Quantum chromodynamics

\[ L_{QCD} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} + \sum_f \bar{\Psi} \gamma^\mu \left( \partial_\mu + g A_\mu^a t^a \right) \Psi + \sum_f m_f \bar{\Psi} \Psi \]

Lattice QCD

\[ U_{x,\mu} = \exp \left( ig A_\mu^a t^a \right) \]

\[ \Psi \]
LQCD equation of state

Degrees of freedom:

\[ \nu = \left[ (2 \times 8) + \frac{7}{4} \times (2 \times 3 \times N_f) \right] \times \left( 1 - O(g^2) \right) \]

\[ \frac{\varepsilon}{T^4} = \frac{\pi^2}{30} \nu_{\text{eff}} \]

SPS, RHIC, LHC

HotQCD

Monday, October 19, 2009
QGP properties

**Speed of sound**

\[ c_s^2 = \frac{1}{3} \]

**Susceptibilities \( \chi \)**

- \( B = \) baryon number
- \( Q = \) electric charge
- \( S = \) strangeness

**HotQCD Collaboration**

**Free light quarks**

**Conserved quantum number susceptibilities**

- open: \( N_\tau = 4 \)
- full: \( N_\tau = 6 \)
The 21\textsuperscript{st} century path to the QGP…

…is hexagonal and 3.8 km long

Relativistic Heavy Ion Collider
The 21st century path to the QGP…

…is hexagonal and 3.8 km long

Relativistic Heavy Ion Collider
Observables

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data?
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\[ T_{\mu\nu} \Leftrightarrow \varepsilon, p, s \]

**Equation of state:** spectra, collective flow
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\[ c_s^2 = \frac{\partial p}{\partial \varepsilon} \]

**Speed of sound:** multiparticle correlations
Observables

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data?

\[ T_{\mu\nu} \leftrightarrow \varepsilon, p, s \quad \text{Equation of state: spectra, collective flow} \]

\[ c_s^2 = \frac{\partial p}{\partial \varepsilon} \quad \text{Speed of sound: multiparticle correlations} \]

\[ \eta = \frac{1}{T} \int d^4x \langle T_{xy}(x)T_{xy}(0) \rangle \quad \text{Shear viscosity: anisotropic collective flow} \]
Observables

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data?

\[ T_{\mu \nu} \leftrightarrow \epsilon, p, s \quad \textbf{Equation of state: } \text{spectra, collective flow} \]

\[ c_s^2 = \frac{\partial p}{\partial \epsilon} \quad \textbf{Speed of sound: } \text{multiparticle correlations} \]

\[ \eta = \frac{1}{T} \int d^4x \langle T_{xy}(x)T_{xy}(0) \rangle \quad \textbf{Shear viscosity: } \text{anisotropic collective flow} \]

\[ \hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F_{a+i}^-(y^-) F_{a+i}^+(0) \rangle \]

\[ \hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle i \partial^- A_{a+i}^+(y^-) A_{a+i}^+(0) \rangle \]

\[ \hat{e}_2 = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F_{a+i}^{++}(y^-) F_{a+i}^{++}(0) \rangle \quad \textbf{Momentum/energy diffusion: } \text{parton energy loss} \]

\text{modified jet fragmentation}
Observables

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data?

Equation of state: spectra, collective flow

Speed of sound: multiparticle correlations

*Momentum/energy diffusion:*
- parton energy loss
- modified jet fragmentation

\[ T_{\mu\nu} \leftrightarrow \varepsilon, p, s \]
\[ c_s^2 = \frac{\partial p}{\partial \varepsilon} \]

\[ \eta = \frac{1}{T} \int d^4x \langle T_{xy}(x)T_{xy}(0) \rangle \]

Shear viscosity: anisotropic collective flow

\[ \hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{a+i}(y^-)F^{a+i}_i(0) \rangle \]
\[ \hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle i\partial^- A^{a+}(y^-)A^{a+}(0) \rangle \]
\[ \hat{e}_2 = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{a+-}(y^-)F^{a+-}(0) \rangle \]
Observables

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data?

\[ T_{\mu\nu} \Leftrightarrow \varepsilon, p, s \]

Equation of state: spectra, collective flow

\[ c_c^2 = \frac{\partial p}{\partial \varepsilon} \]

Speed of sound: multiparticle correlations

\[ \eta = \frac{1}{T} \int d^4 x \langle T_{xy}(x)T_{xy}(0) \rangle \]

Shear viscosity: anisotropic collective flow

\[
\dot{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{a+i}_{-}(y^-)F^{a+}_{i}(0) \rangle \\
\dot{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle i\partial^- A^{a+}(y^-)A^{a+}(0) \rangle \\
\dot{e}_2 = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \langle F^{a+-}(y^-)F^{a+-}(0) \rangle
\]

Momentum/energy diffusion: parton energy loss

modified jet fragmentation

Progress using parton cascades - see talk by S. Bass & poster by J. Fuini

Easy for LQCD

Hard for LQCD

Monday, October 19, 2009
Part 2

The (almost)

“Perfect Liquid”
Elliptic Flow ($v_2$)

$v_2 = \cos(2\phi)$

Coefficient of the azimuthal distribution

Hydrodynamics:
Flow is generated by $\nabla P$

$\nabla P(\leftrightarrow) > \nabla P(\uparrow\downarrow)$
$v_2(p_T)$ vs. hydrodynamics

![Graph showing $v_2(p_T)$ vs. hydrodynamics](image-url)
$v_2(p_T)$ vs. hydrodynamics

Hydro model

$\pi$

$K$

$p$

$\Lambda$

PHENIX Data

$\pi^+ + \pi^-$

$K^+ + K^-$

$p + p$

STAR Data

$K^0_S$

$\Lambda + \bar{\Lambda}$

Anisotropy Parameter $v_2$

Transverse Momentum $p_T$ (GeV/c)

Mass splitting characteristic property of hydrodynamics
\( v_2(p_T) \) vs. hydrodynamics

Failure of ideal hydrodynamics tells us how hadrons form

Mass splitting characteristic property of hydrodynamics
Elliptic flow “measures” \( \eta_{\text{QGP}} \)

We finally have a \textit{complete}, \textit{causal} formulation of relativistic viscous hydrodynamics:

\[
\ell_{\mu \tau} \frac{d \Pi_{\mu \nu}}{d \tau} + (u^\mu \Pi^{\nu \lambda} + u^\nu \Pi_{\mu \lambda}) \frac{du^\lambda}{d \tau} = \eta \left( \ell_{\mu \tau} u^\tau + \ell^\nu u_{\mu} - \text{trace} \right) - \Pi_{\mu \nu}
\]

\[
\partial_{\mu} T^{\mu \nu} = 0 \quad \text{with} \quad T^{\mu \nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu \nu} + \Pi^{\mu \nu}
\]
We finally have a complete, causal formulation of relativistic viscous hydrodynamics:

\[ \partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \Pi^{\mu\nu} \]

\[ \tau_{\Pi} \left[ \frac{d\Pi^{\mu\nu}}{d\tau} + (u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda}) \frac{d\lambda^\lambda}{d\tau} \right] = \eta \left( \partial^\mu u^\nu + \partial^\nu u^\mu - \text{trace} \right) - \Pi^{\mu\nu} \]

\[ \Pi = \Pi_{NS} - \tau_\Pi \Pi \]
\[ + \tau_{q\Pi} q \cdot \dot{u} - \ell_{q\Pi} \partial \cdot q - \zeta \delta_0 \Pi \theta \]
\[ + \lambda_{q\Pi} q \cdot \nabla \alpha + \lambda_{q\Pi} \pi^{\mu\nu} \sigma_{\mu\nu} \]
\[ = \Pi_{NS} - \tau_q \Delta^{\mu\nu} \dot{q}_{\nu} \]
\[ - \tau_{q\Pi} \Pi \dot{u}^\mu - \tau_{q\Pi} \Pi^{\mu\nu} \dot{u}_{\nu} + \ell_{q\Pi} \nabla^\mu \Pi - \ell_{q\Pi} \Delta^{\mu\nu} \partial^\lambda \pi_{\nu\lambda} + \tau_{q} \omega^{\mu\nu} q_{\nu} - \frac{\kappa}{\beta} \delta_1 q^\mu \theta \]
\[ - \lambda_{qq} \sigma^{\mu\nu} q_{\nu} \]
\[ + \lambda_{q\Pi} \Pi \nabla^{\mu} \alpha + \lambda_{q\Pi} \pi^{\mu\nu} \nabla_{\nu} \alpha \]
\[ = \pi^{\mu\nu}_{NS} - \tau_{\Pi} \nabla^{\mu} \dot{\pi}^{\nu} \]
\[ + 2 \tau_{\pi q} q_{<\mu \dot{u}^\nu>} + 2 \ell_{\pi q} \nabla<\mu q^\nu> + 2 \tau_{\pi} \pi_{<\mu \omega^\nu>} \lambda - 2 \eta \delta_2 \pi^{\mu\nu} \theta \]
\[ - 2 \tau_{\pi} \pi_{<\mu \sigma^\nu> \lambda} - 2 \lambda_{pq} q_{<\mu \nabla^\nu>} \alpha + 2 \lambda_{\pi \Pi} \Pi \sigma^{\mu\nu} \]
Elliptic flow “measures” $\eta_{\text{QGP}}$

We finally have a complete, causal formulation of relativistic viscous hydrodynamics:

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - Pg^{\mu\nu} + \Pi^{\mu\nu}$$

$$\tau_\Pi \left[ \frac{d\Pi^{\mu\nu}}{d\tau} + \left( u^\mu \Pi^{\nu\lambda} + u^\nu \Pi^{\mu\lambda} \right) \frac{d\gamma}{d\tau} \right] = \eta \left( \partial_\mu u^\nu + \partial_\nu u^\mu - \text{trace} \right) - \Pi^{\mu\nu}$$

Glauber model

Saturation model

Shear viscosity

$\eta/s = 0.08$

$\eta/s = 0.16$
AdS/CFT duality

J. Maldacena (1997):

(3+1)-dim SYM theory in the $N_c, \sqrt{g^2 N_c} \to \infty$ limit is dual to classical supergravity theory on AdS$_5$. 

Monday, October 19, 2009
AdS/CFT duality

J. Maldacena (1997):

(3+1)-dim SYM theory in the $N_c$, $\sqrt{g^2N_c} \to \infty$ limit is dual to classical supergravity theory on AdS$_5$.

Application to RHIC invokes a 5th dim. BH.

*Thermal CFT* ↔ *AdS BH Dictionary*

Stress tensor ↔ Asymptotic metric

Entropy ↔ Horizon area

Viscosity ↔ Graviton absorption
Perfect fluid

Dissipation is dominated by absorption of gravitons on the black brane:

\[ \frac{\eta}{s} = \frac{\hbar}{4\pi} \]

Universal bound?  Kovtun, Son & Starinets (2005)

Similar bound in kinetic theory from unitarity limit of cross sections and/or uncertainty relation [Danielewicz & Gyulassy ’85].
Perfect fluid

Dissipation is dominated by absorption of gravitons on the black brane:

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

Universal bound?  

Kovtun, Son & Starinets (2005)

Similar bound in kinetic theory from unitarity limit of cross sections and/or uncertainty relation [Danielewicz & Gyulassy ’85].

Bound is probably not completely universal, but far below $\eta/s$ of any known material (except ultra-cold gases of fermionic atoms with unitary interactions).
Hunting for perfection...
Hunting for perfection...

My best bet
Hunting for perfection...

Does it bother you to live in times like these, Lucy?

I mean, everything is so uncertain and so confused.

Does it worry you or bother you, or do you...

What are you trying to do, start an argument?
Hunting for perfection...

We know how to settle the argument!

Viscous hydro &
global data fit
Part 3

Collective Flow and Deconfined Quarks
Bulk hadronization

Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons.

\[ p_B \approx 3p_Q \]

\[ p_M \approx 2p_Q \]
Fast hadrons experience a rapid transition from medium to vacuum for fast hadrons.

Bulk hadronization

Sudden recombination

\[ p_B \approx 3p_Q \]

\[ p_M \approx 2p_Q \]

\[ v_2^M(p_t) = 2v_2^Q \left( \frac{p_t}{2} \right) \]

\[ v_2^B(p_t) = 3v_2^Q \left( \frac{p_t}{3} \right) \]
Quark number scaling of $v_2$

$$\frac{1}{2} v_2^M (p_t) = v_2^Q \left( \frac{p_t}{2} \right)$$

$$\frac{1}{3} v_2^B (p_t) = v_2^Q \left( \frac{p_t}{3} \right)$$
Quark number scaling of $v_2$

$$\frac{1}{2} v_2^M (p_t) = v_2^Q \left( \frac{p_t}{2} \right)$$
$$\frac{1}{3} v_2^B (p_t) = v_2^Q \left( \frac{p_t}{3} \right)$$

Emitting medium is composed of unconfined, flowing quarks.
Quark number scaling of $v_2$

\[
\frac{1}{2} v_2^M(p_t) = v_2^Q \left(\frac{p_t}{2}\right) \quad \frac{1}{3} v_2^B(p_t) = v_2^Q \left(\frac{p_t}{3}\right)
\]

Emitting medium is composed of unconfined, flowing quarks.
The QGP is *strange*!

Strange hadrons production is enhanced, as predicted, Yield is chemically equilibrated with error of less than 4%!
Strange hadrons production is enhanced, as predicted, Yield is chemically equilibrated with error of less than 4%!

Combined with valence quark scaling law we can utilize strange quarks for ...
Quark spectroscopy

An amazing idea only experimentalists can come up with...

Use ratios of hadron spectra to infer valence quark spectra:

\[ \Xi^- = (ssd), \quad \phi = (ss\bar{s}), \quad \Omega^- = (sss) \]

\[
d(p_T) = \frac{\Xi^- \left( \frac{1}{3} p_T \right)}{\phi \left( \frac{1}{2} p_T \right)}
\]

\[
s(p_T) = \frac{\Omega^- \left( \frac{1}{3} p_T \right)}{\phi \left( \frac{1}{2} p_T \right)} \propto \left[ \frac{\phi \left( \frac{1}{2} p_T \right)}{\Omega^- \left( \frac{1}{3} p_T \right)} \right]^2
\]

STAR/UCLA group

Fitting with Fries' model (T_{th} = 170 \text{ MeV})
- n_{\text{nf}} = 26.6/41
- \chi^2/n_{\text{df}} = 11/12
Use ratios of hadron spectra to infer valence quark spectra:

$$\Xi^- = (ssd), \quad \phi = (ss\bar{s}), \quad \Omega^- = (sss)$$

$$d(p_T) = \frac{\Xi^-(\frac{1}{3} p_T)}{\phi(\frac{1}{2} p_T)}$$

$$s(p_T) = \frac{\Omega^-\left(\frac{1}{3} p_T\right)}{\phi\left(\frac{1}{2} p_T\right)} \propto \left[\frac{\phi\left(\frac{1}{2} p_T\right)}{\Omega^-\left(\frac{1}{3} p_T\right)}\right]^2$$
Quark spectroscopy

An amazing idea only experimentalists can come up with...

Use ratios of hadron spectra to infer valence quark spectra:

$$\Xi^- = (ssd), \quad \phi = (ss\bar{s}), \quad \Omega^- = (sss)$$

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$$s(p_T) = \frac{\Omega^- \left(\frac{1}{3} p_T\right)}{\phi \left(\frac{1}{2} p_T\right)} \propto \left[\frac{\phi \left(\frac{1}{2} p_T\right)}{\Omega^- \left(\frac{1}{3} p_T\right)}\right]^2$$
Quark spectroscopy
Part 4

Color Opacity
Jet quenching in Au+Au

No suppression for photons

Suppression of hadrons

Yield in A+A

\[ R_{AA}(p_T) = \frac{d^2 N_{AA}/dp_Tdy}{T_{AA} \left( d^2 \sigma_{NN}/dp_Tdy \right)} \]

Area density of p+p coll's in A+A

Cross section in p+p coll's

Without nuclear effects:

\[ R_{AA} = 1. \]
Radiative energy loss

\[ \Delta E \sim \rho L^2 \left< k_T^2 \right> \]

\[ \hat{q} = \rho \int q^2 \, dq^2 \frac{d\sigma}{dq^2} = \int dx^- \left< F_i^+(x^-) F^{+i}(0) \right> \]
Towards measuring $\hat{q}$

Good fits for light hadrons are obtained for all rad. energy loss models in 3-D hydrodynamics

Bass, Gale, Majumder, Nonaka, Qin, Renk & Ruppert
Towards measuring $\hat{q}$

Good fits for light hadrons are obtained for all rad. energy loss models in 3-D hydrodynamics

Transport parameter $\hat{q}$ deviates by more than factor 2 between different implementations.

Caused by differences in the cut-offs in collinear approximation used in all implementations of gluon radiation.
Towards measuring $\hat{q}$

Good fits for light hadrons are obtained for all rad. energy loss models in 3-D hydrodynamics.

Transport parameter $\hat{q}$ deviates by more than factor 2 between different implementations.

Caused by differences in the cut-offs in collinear approximation used in all implementations of gluon radiation.

Generalized, robust new approach needed.
The heavy quark conundrum

Heavy quark \((c, b)\) energy loss deduced from suppression of weak decay electron spectrum

Suppression stronger than expected.

3 parameters: \(\hat{q}, \hat{e}, \hat{e}_2\)

Fit:
\[
\frac{\hat{q}_c}{\hat{q}_{u/d/g}} \approx 1.1 \quad \frac{\hat{q}_b}{\hat{q}_{u/d/g}} \approx 1.6
\]

contrary to expectations for a weakly coupled QGP.
Caveat explorator

---

A QUEEN SNAKE! A QUEEN SNAKE!

THAT'S NOT A QUEEN SNAKE... THAT'S JUST AN OLD TREE BRANCH

HELP!

WELL, I'LL BE! SO IT IS!

I SUPPOSE YOU THINK YOU'RE SMART PRETENDING YOU'RE A QUEEN SNAKE!

---

Monday, October 19, 2009
QCD makes it hard to distinguish between “queen snakes” and “old tree branches”
Part 5

“Sounding out” the Quark-Gluon Plasma
Where does the “lost” energy go?

Away-side jet  Trigger jet
Where does the “lost” energy go?

Lost energy is redistributed to angles away from 180° Mach cone?
Parton-medium coupling

\[
\left[ \frac{p^\mu}{E} \frac{\partial}{\partial x^\mu} - \nabla_p \cdot D(x, p) \cdot \nabla_p \right] f_0(x, p) = C[f_0]
\]

with

\[
D_{ij}(x, p) = \int_{-\infty}^{t} dt' F_i(\bar{x}, t) F_j(\bar{x} + \bar{v}(t' - t), t') .
\]

\[\frac{\partial}{\partial x^\mu} T^{\mu\nu} = J^\nu \]

Energy and momentum deposition

\[J^\nu = \int dp \ p^\nu \nabla_p \cdot D(x, p) \cdot \nabla_p f(x, p)\]

Color field of moving parton interacts with the quanta of the medium
Mach cone

\( u = 0.99955 \, c \)

(\( \gamma \approx 30 \))

\( \eta/s = 0.08 \)

\( \gamma \approx 30 \)

Monday, October 19, 2009
Mach cone

\[ \frac{|\vec{x}| e(\vec{x})}{m v^2 T} \]

\[ \frac{|\vec{x}| g(\vec{x})}{m v^2 T} \]

\[ \eta/s = 0.08 \]

\[ u = 0.99955 \ c \]

(\( \gamma \approx 30 \))

R. Bryon Neufeld

Monday, October 19, 2009
Mach cone

\[ \frac{|\ddot{x}|}{m_0^2 T} \eta = 0.08 \]

\[ \frac{|\ddot{x}|}{m_0^2 T} \eta = 0.13 \]

\[ \frac{|\ddot{x}|}{m_0^2 T} \eta = 0.48 \]

Mach cone requires low shear viscosity

\[ u = 0.99955 \ c \]

\( \gamma \approx 30 \)

R. Bryon Neufeld

Monday, October 19, 2009
QCD vs. \( N=4 \) SYM

approximate QCD

\[ u = 0.99955 \ c \]

Neufeld et al.

arXiv:0802.2254
QCD vs. $N=4$ SYM

approximate QCD

exact AdS/CFT

$u = 0.99955 \, c$

Neufeld et al. arXiv:0802.2254

$u = 0.75 \, c$

Chesler & Yaffe arXiv:0712.0050

Monday, October 19, 2009
The ultimate Crescendo

Radiated gluons contribute to sound source:

R.B. Neufeld & BM, PRL 103, 042301

Sound source strength $S$

gluon swarm

primary quark

$S$

$L$ (fm)
The ultimate Crescendo

Radiated gluons contribute to sound source:

R.B. Neufeld & BM, PRL 103, 042301

Sound source strength $S$

Mach cone intensity is peaked at late times

The *crescendo* could explain why experiments show sound velocity $c_s = 0.3$ corresponding to $T_c$. 
The ultimate Crescendo

Radiated gluons contribute to sound source:

R.B. Neufeld & BM, PRL 103, 042301

Sound source strength $S$

Mach cone intensity is peaked at late times


The *crescendo* could explain why experiments show sound velocity $c_s = 0.3$ corresponding to $T_c$. 

Monday, October 19, 2009
RHIC data

Cone-shaped emission shows up in 3-particle correlations as signal on both sides of backward direction.

Angle $D$ corresponds to $c_s^2 \approx 0.1$
RHIC data

Cone-shaped emission shows up in 3-particle correlations as signal on both sides of backward direction.

Central Au+Au 0-12% (STAR)

Angle $D$ corresponds to $c_s^2 \approx 0.1$

Not yet confirmed with full jet analysis
A temptation...

DEAR GREAT PUMPKIN,  
I AM LOOKING FORWARD  
TO YOUR ARRIVAL ON  
HALLOWEEN NIGHT.

I HOPE YOU WILL BRING  
ME LOTS OF PRESENTS.

10-10-09

EVENYEONE TELLS ME YOU ARE  
A FAKE, BUT I BELIEVE IN  
YOU.  
SINCERELY,  
LINUS VAN PELT

P.S. IF YOU REALLY ARE A  
FAKE, DON'T TELL ME. I  
DON'T WANT TO KNOW.
A temptation...

Dear Great Pumpkin,
I am looking forward to your arrival on Halloween Night.

I hope you will bring me lots of presents.

But we’re NOT tempted!

Everyone tells me you are a fake, but I believe in you. Sincerely, Linus Van Pelt

P.S. If you really are a fake, don’t tell me. I don’t want to know.
Toward better theory

https://wiki.bnl.gov/TECHQM/index.php/Main_Page

Next TECHQM-CATHIE workshop: BNL 14-18 December 2009
Toward better theory

Next TECHQM-CATHIE workshop: BNL 14-18 December 2009

Goal: Formation of a Global Observables Working Group
perform comprehensive theory-data comparison for $\eta/s$, $\varepsilon_0$, EOS
Toward rarer probes

RHIC detector upgrades

STAR

- forward meson spectrometer
- DAQ & TPC electronics
- Time of Flight barrel
- heavy flavor tracker
- barrel silicon tracker
- forward tracker

PHENIX

- completed – hadron blind detector
- ongoing
  - muon Trigger
  - silicon vertex barrel (VTX)
- in preparation
  - forward silicon
  - forward EM calorimeter

Monday, October 19, 2009
Toward higher energies…

LHC
Toward higher energies…
Observables revisited

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data?

\[ T_{\mu\nu} \leftrightarrow \varepsilon, p, s \quad \text{Equation of state: spectra, collective flow} \]

\[ c_c^2 = \frac{\partial p}{\partial \varepsilon} \quad \text{Speed of sound: multiparticle correlations} \]

\[
\begin{align*}
\eta &= \frac{1}{T} \int d^4 x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle \\
\hat{q} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F_{i+}^a (y^-) F_{i+}^a (0) \right\rangle \\
\hat{e} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle i\partial^- A^a_+(y^-) A^a_+ (0) \right\rangle \\
\hat{e}_2 &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F_{a-}^a (y^-) F_{a-}^a (0) \right\rangle
\end{align*}
\]

\text{Shear viscosity: anisotropic collective flow}

\text{Momentum/energy diffusion:}
\begin{itemize}
\item parton energy loss
\item modified jet fragmentation
\end{itemize}
Observables revisited

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\[ T_{\mu\nu} \leftrightarrow \varepsilon, p, s \]

**Equation of state**: spectra, collective flow

\[ c_s^2 = \frac{\partial p}{\partial \varepsilon} \]

**Speed of sound**: multiparticle correlations

\[ \eta = \frac{1}{T} \int d^4 x \left\langle T_{xy}(x)T_{xy}(0) \right\rangle \]

**Shear viscosity**: anisotropic collective flow

\[ \hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+i}(y^-)F_i^{a+}(0) \right\rangle \]

\[ \hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle i\partial^- A_i^{a+}(y^-)A^a(0) \right\rangle \]

\[ \hat{e}_2 = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+}(y^-)F^{a+}(0) \right\rangle \]

**Momentum/energy diffusion**: parton energy loss

modified jet fragmentation

Monday, October 19, 2009
Observables revisited

Which properties of hot QCD matter can we hope to determine from relativistic heavy ion data?

\( T_{\mu\nu} \iff \epsilon, p, s \)

**Equation of state**: spectra, collective flow

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**Speed of sound**: multiparticle correlations

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\hat{e} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle i\partial^- A^{a+}(y^-)A^{a+}(0) \right\rangle \\
\hat{e}_2 = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+-}(y^-)F^{a+-}(0) \right\rangle
\]

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Ready for a serious attempt

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Momentum/energy diffusion: parton energy loss
modified jet fragmentation

Ready for a serious attempt

Serious theoret. developments needed
Instead of a Summary

BY THE TIME I'M EIGHTEEN, I EXPECT THIS WORLD TO BE PERFECT!

WHY SHOULD I HAVE TO LIVE IN A WORLD SOMEBODY ELSE HAS MESSSED UP?! I'LL GIVE THEM TWELVE YEARS TO GET EVERYTHING IN ORDER!

WHAT IF THEY NEED MORE TIME?

TELL THEM NOT TO BOTHER WIRING FOR AN EXTENSION... THE ANSWER WILL BE, "NO!"
Instead of a Summary

We are ready to beat Lucy’s deadline and prove that

*the world was once*(13.7 billion years ago)

* a perfect fluid
THE END