The Hottest, and Most Liquid, Liquid in the Universe

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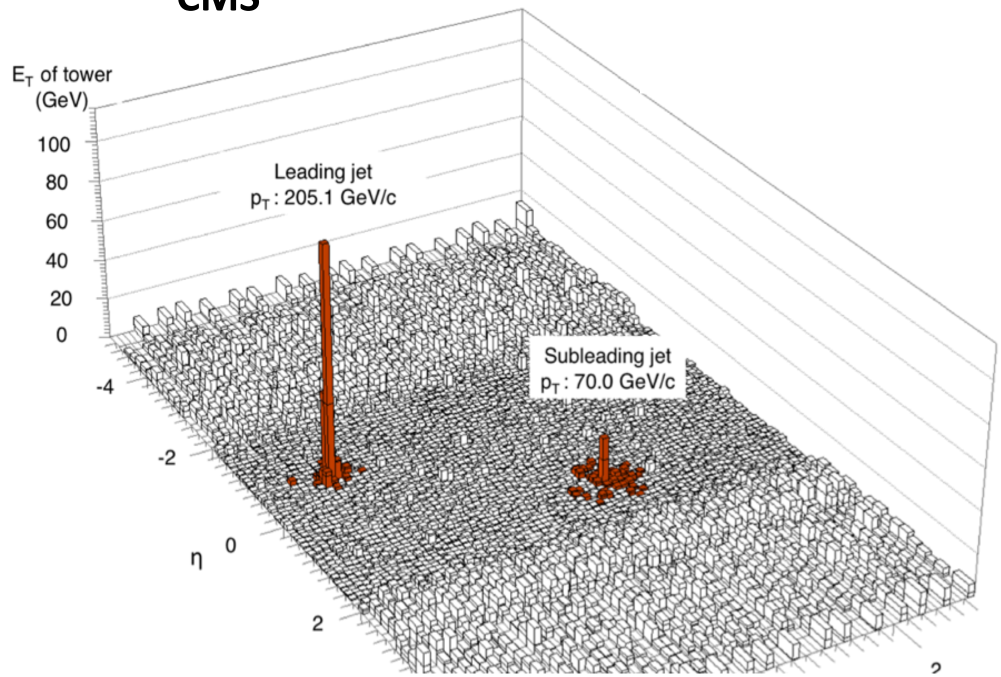
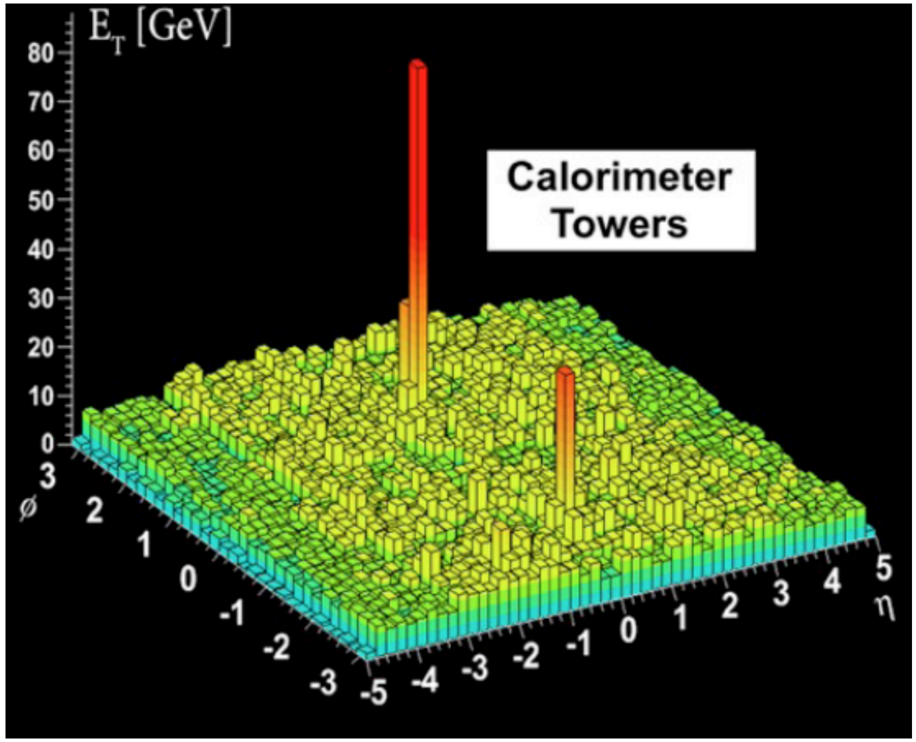
Jet Quenching at the LHC

CMS



ATLAS



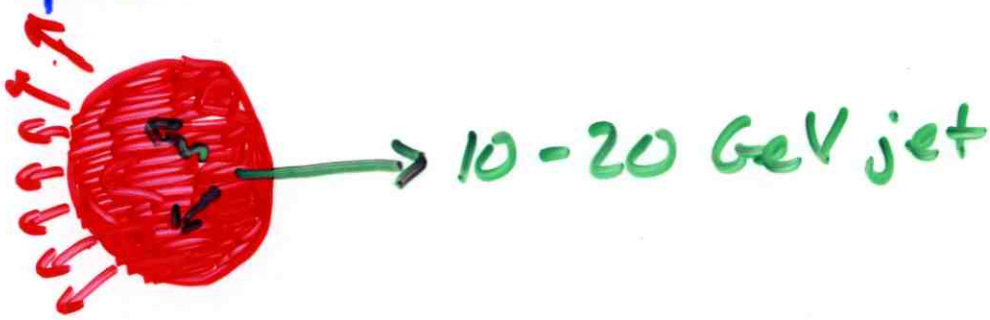
A very large effect at the LHC. 200 GeV jet back-to-back with a 70 GeV jet. A strongly coupled plasma indeed.... Jet quenching was discovered at RHIC (via the associated diminution in the number of high-p_T hadrons) but here it is immediately apparent in a single event.

Jet Quenching @ LHC

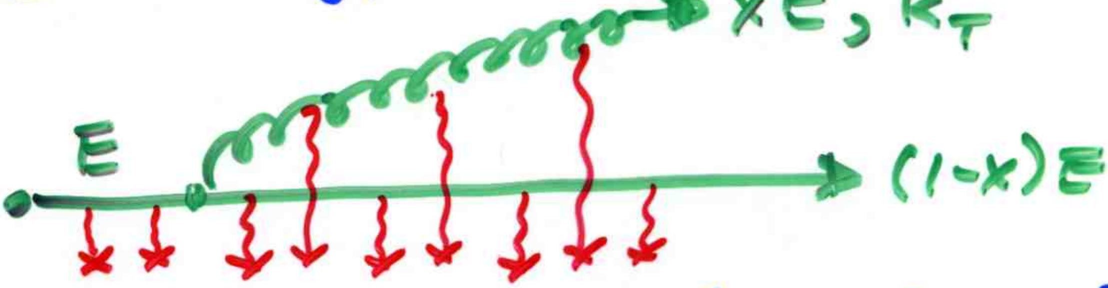
- Jet quenching apparent at the LHC, eg in events with, say, 205 GeV jet back-to-back with 70 GeV jet.
- But, the 70 GeV jet looks almost like a 70 GeV jet in pp collisions. It has lost a lot of energy passing through the QGP but emerges looking otherwise ordinary. Almost same fragmentation function; almost same angular distribution. The "missing" energy is *not* in the form of a spray of softer particles in and around the jet.
- Also, 70 GeV jet seems to be back-to-back with the 205 GeV jet; no sign of transverse kick.
- The "missing" energy is in the form of many ~ 1 GeV particles at large angle to the jet direction.
- Interestingly, STAR, PHENIX and ALICE may see evidence that lower energy jets emerge surrounded by their debris.

JET QUENCHING

Further evidence that QGP@RHIC is strongly coupled.



Radiative energy loss



dominates in high E limit. $(\underline{E \gg k_T \gg T})$

<u>If</u> so (RHIC? LHC?), energy loss sensitive to medium through <u>one</u> parameter $\hat{q}$, k_T^2 picked up by radiated gluon per distance L travelled.

Spectrum of radiated gluons: $\omega \frac{dI}{d\omega} \sim \alpha \sqrt{\frac{\hat{q}}{\omega}}\, L$

Energy loss $\Delta E \sim \alpha \hat{q} L^2$ for $\omega < \hat{q} L^2$

Jet Quenching @ LHC

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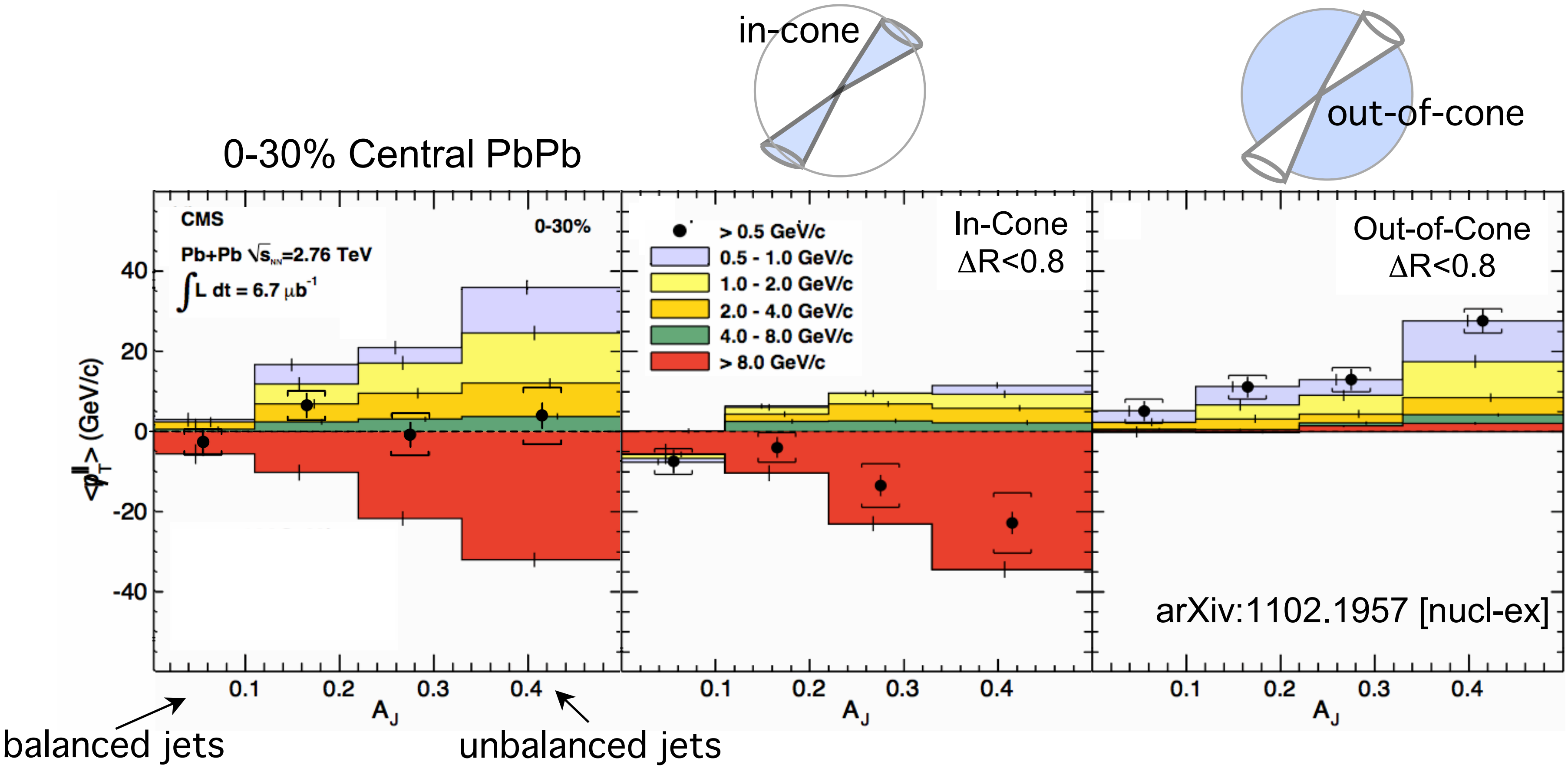
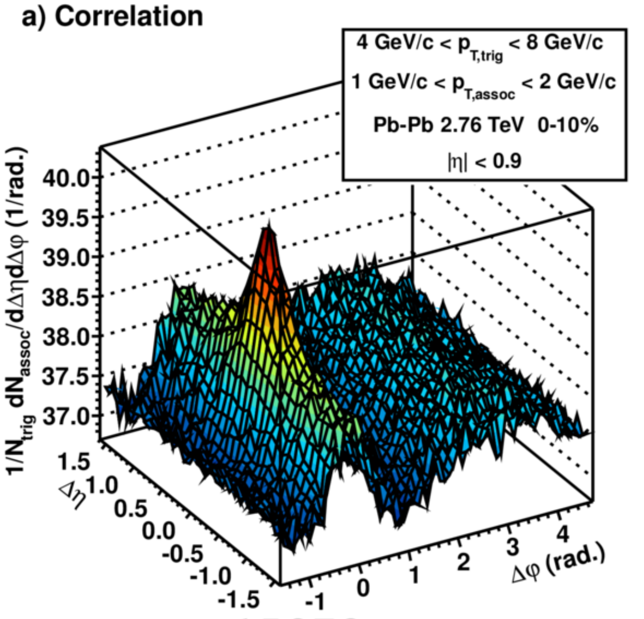
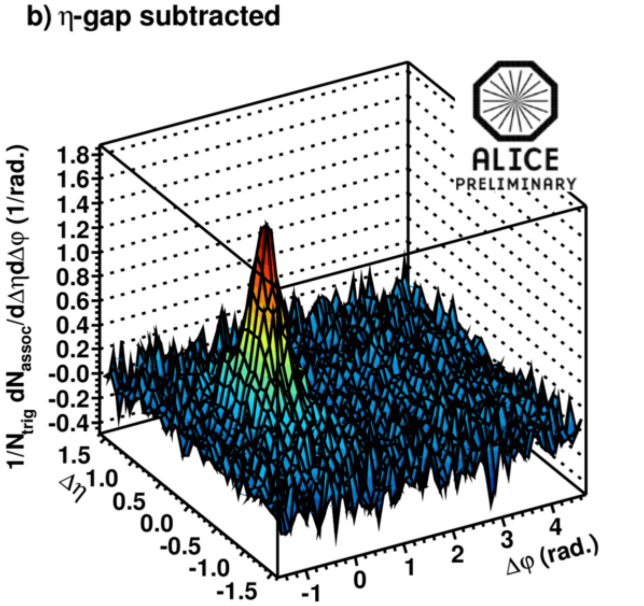
Missing-$p_T^{||}$

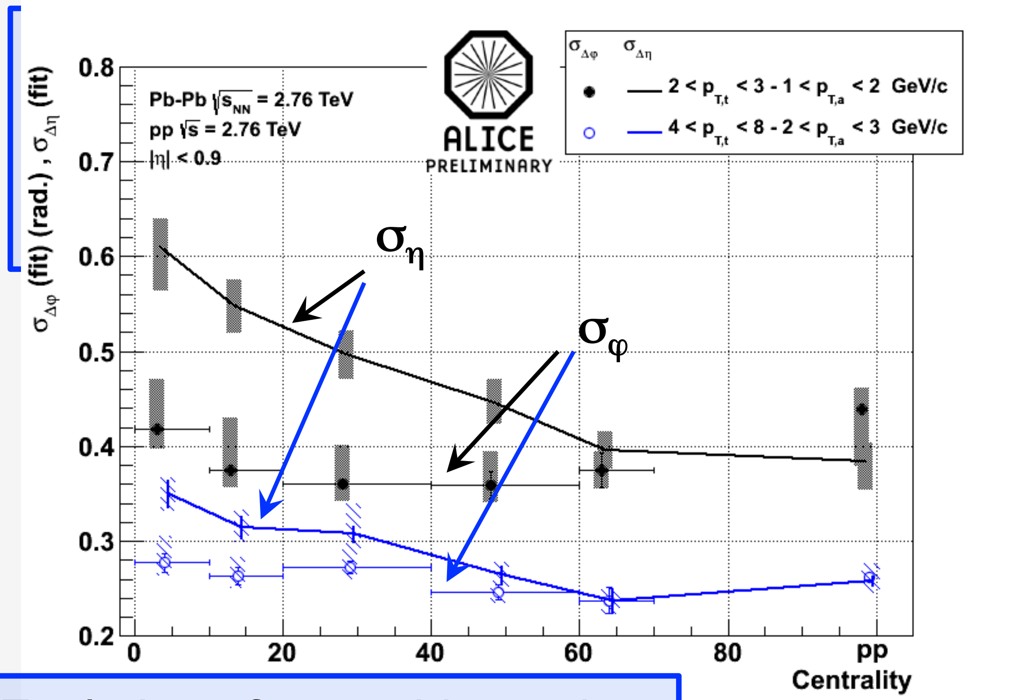


in-cone
out-of-cone
0-30% Central PbPb
CMS
0-30%
Pb+Pb √s_NN=2.76 TeV
∫L dt = 6.7 μb^-1
> 0.5 GeV/c
0.5 - 1.0 GeV/c
1.0 - 2.0 GeV/c
2.0 - 4.0 GeV/c
4.0 - 8.0 GeV/c
> 8.0 GeV/c
In-Cone
ΔR<0.8
Out-of-Cone
ΔR<0.8
arXiv:1102.1957 [nucl-ex]
<p_T^||> (GeV/c)
A_J
balanced jets
unbalanced jets

Near-side (jet-like) structure





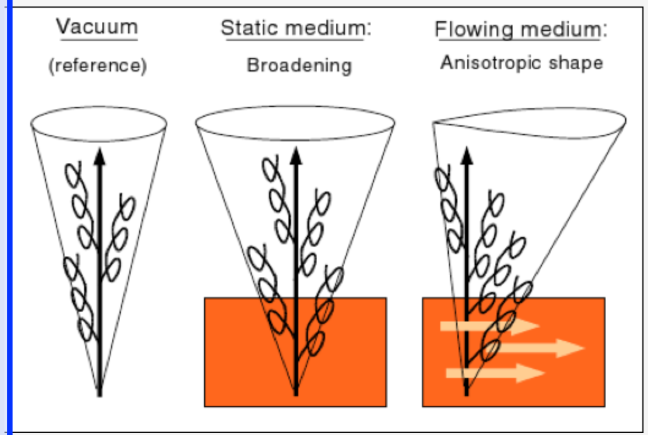


Talks by
A.M.Adare
F.Krizek

Evolution of near-side-peak σ_η and σ_φ with centrality: Strong σ_η increase for central collisions

Interestingly: AMPT describes the data very well

Influence of flowing medium?

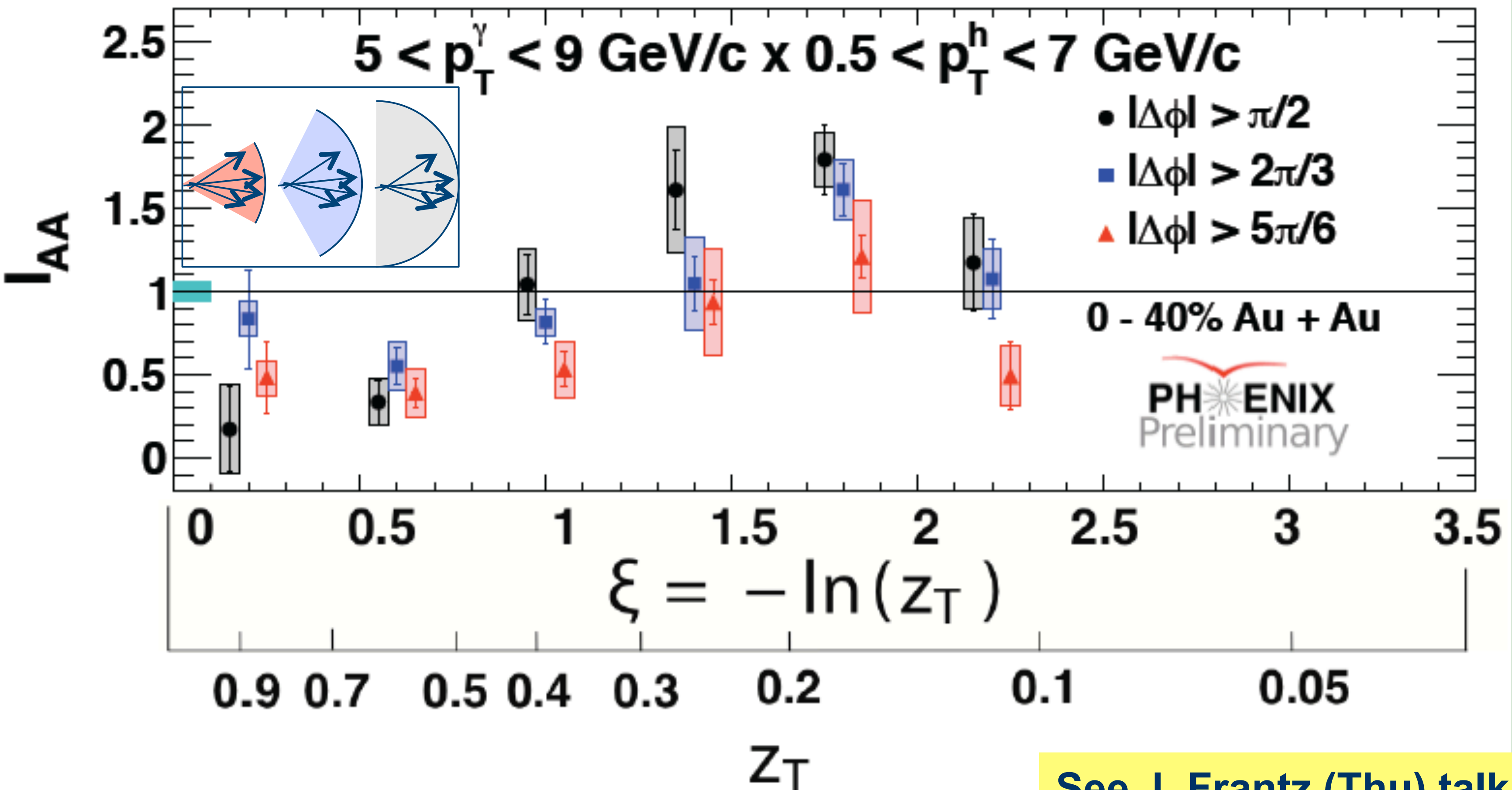


N.Armesto et al., PRL 93, 242301

γ-h correlation in Au+Au

$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

Low z_T away side particles distributed over wider angle



See J. Frantz (Thu) talk

- As if an initially-200-GeV parton/jet in an LHC collision just heats the plasma it passes through, losing significant energy without significant spreading in angle or degradation of its fragmentation function. Are even 200 GeV partons not "seeing" the q+g at short distances?

- One line of theoretical response: more sophisticated analyses of conventional weak-coupling picture of jet quenching. Advancing from parton energy loss and leading hadrons to modification of parton showers and jets.

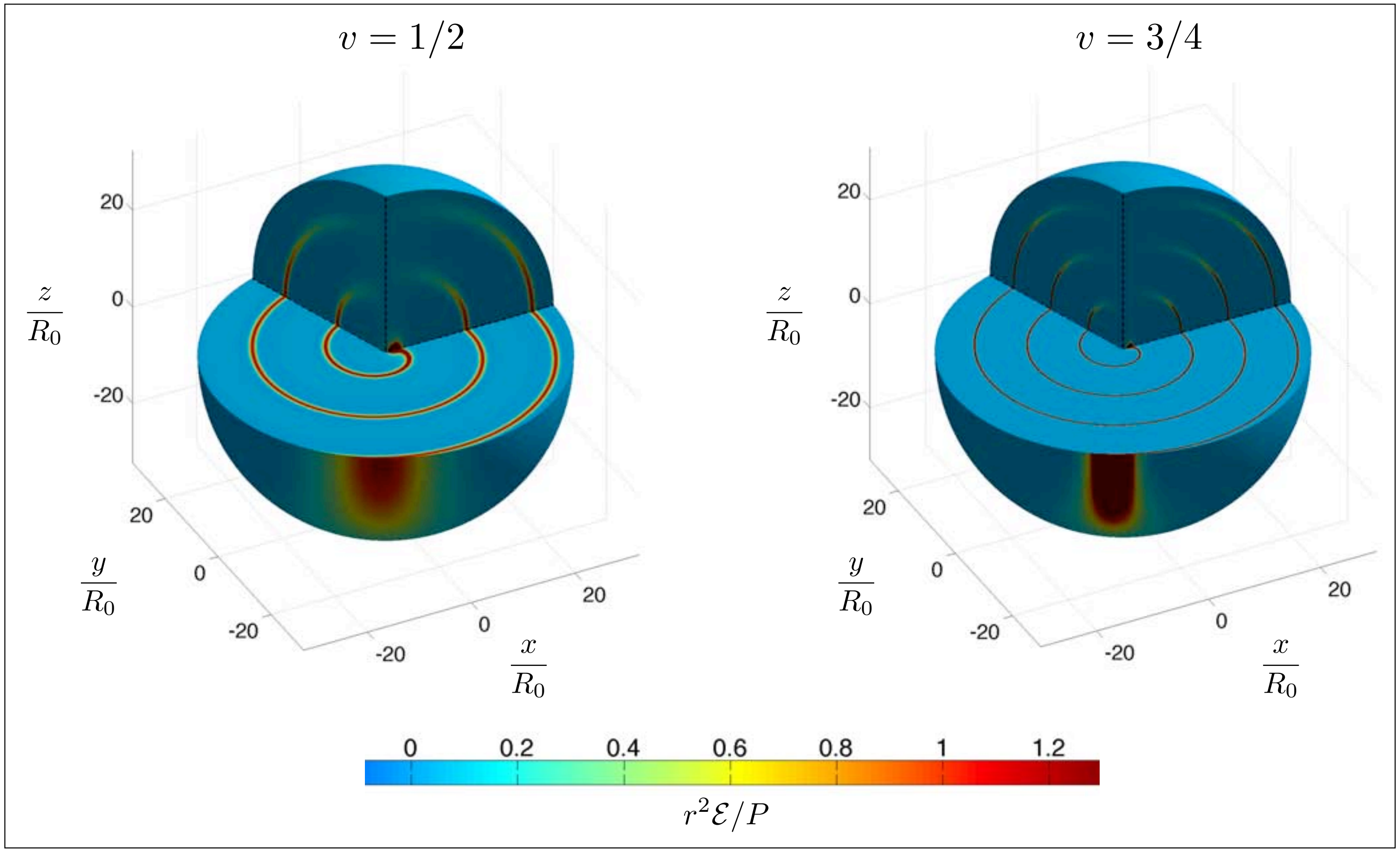
- We also need a strongly coupled approach to jet quenching, even if just as a foil with which to develop new intuition.

- Problem: jet production is a weakly-coupled phenomenon. There is no way to make jets in the strongly coupled theories with gravity duals.

- But we can make a beam of gluons...

Synchrotron Radiation in Strongly Coupled Gauge Theories

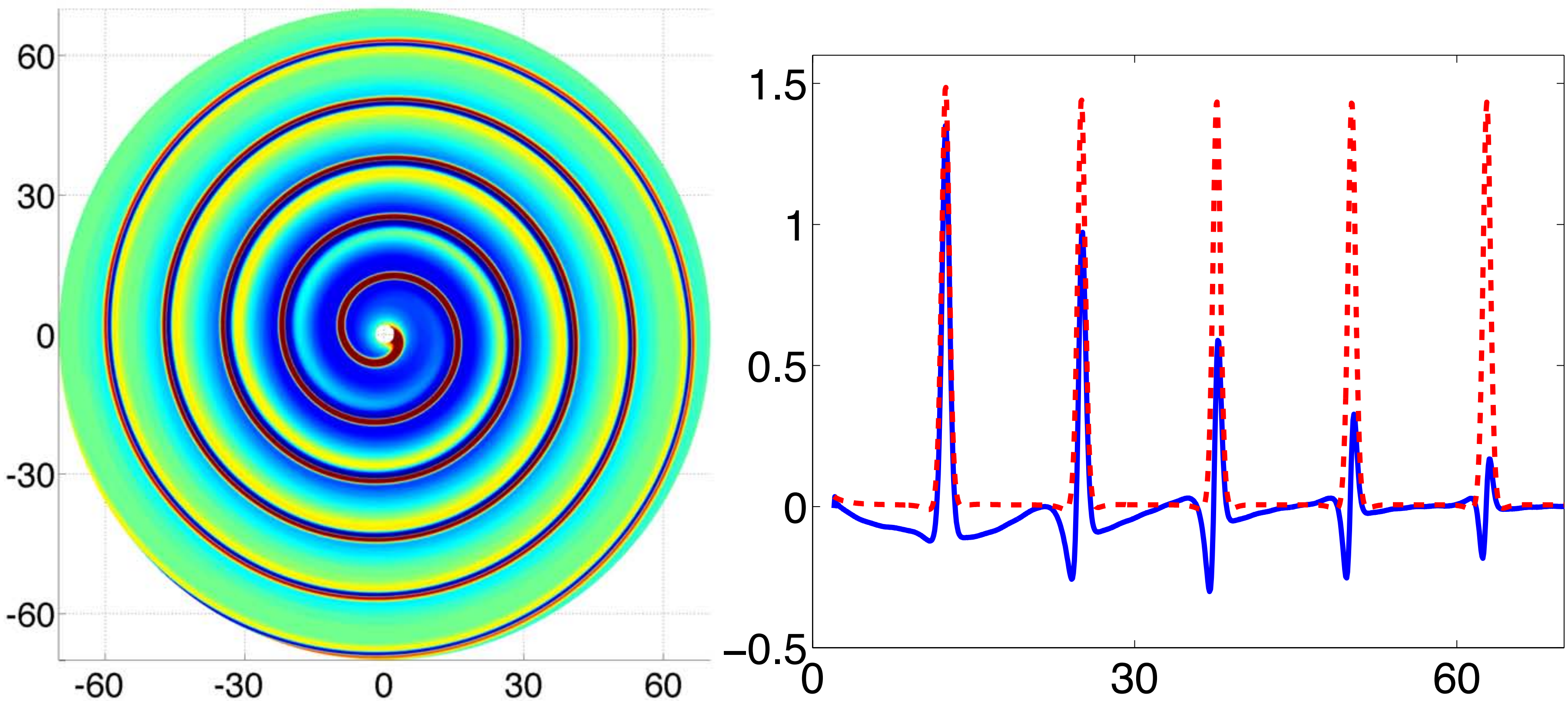
Athanasiou, Chesler, Liu, Nickel, Rajagopal; arXiv:1001.3880



Fully *quantum mechanical* **calculation of gluon radiation from a rotating quark in a** *strongly coupled* **large** N_c *non abelian* **gauge theory, done via gauge/gravity duality. "Lighthouse beam" of synchrotron radiation. Surprisingly similar to classical electrodynamics. Now, shine this beam through strongly coupled plasma...**

Quenching a Beam of Gluons

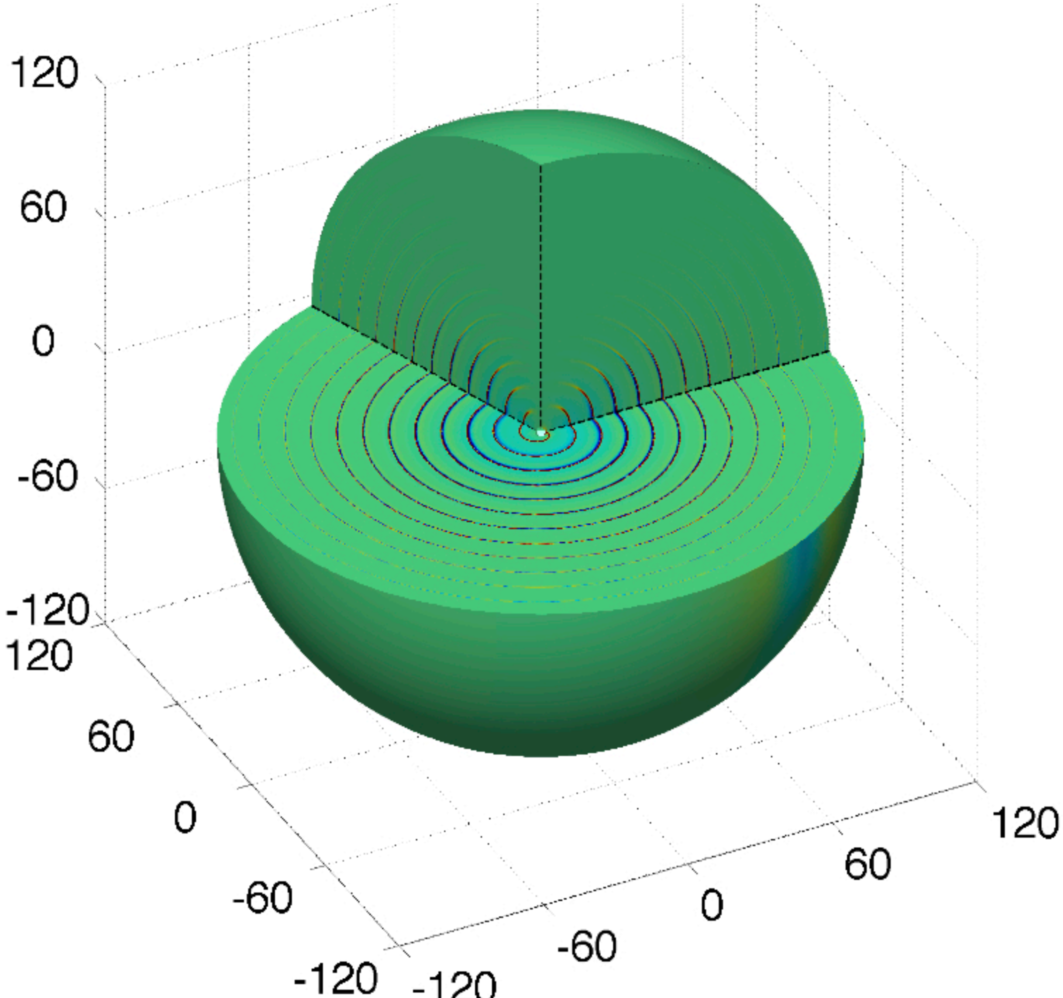
Chesler, Ho, Rajagopal, arXiv:1111.1691



Quark in circular motion ($v = 0.5$; $R\pi T = 0.15$) makes a beam of gluons that is attenuated dramatically by the plasma, without being significantly broadened — in angle or in momentum distribution.

Quenching a Beam of Gluons

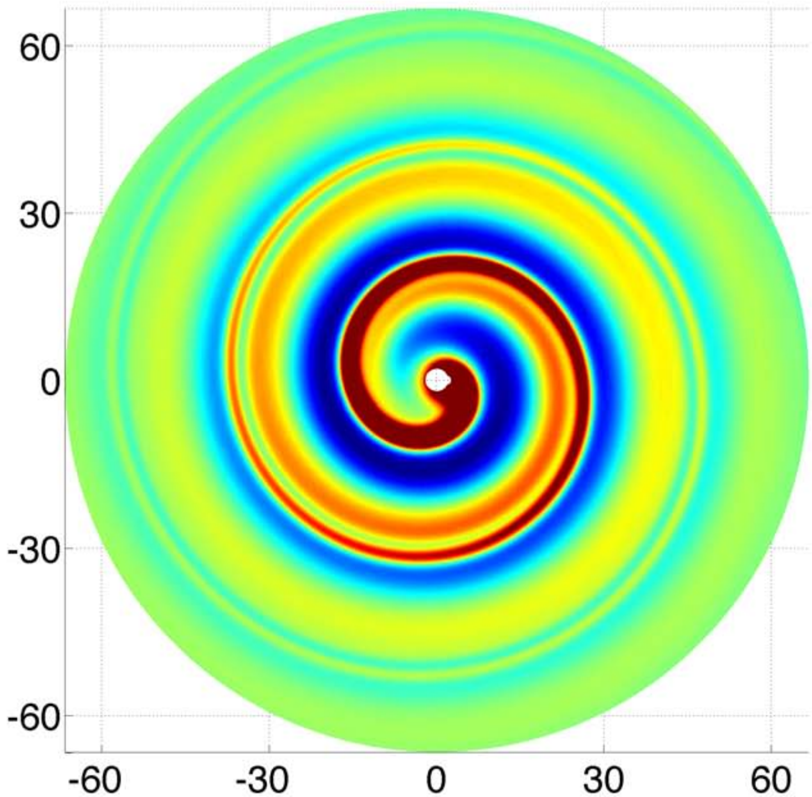
Chesler, Ho, Rajagopal, arXiv:1111.1691

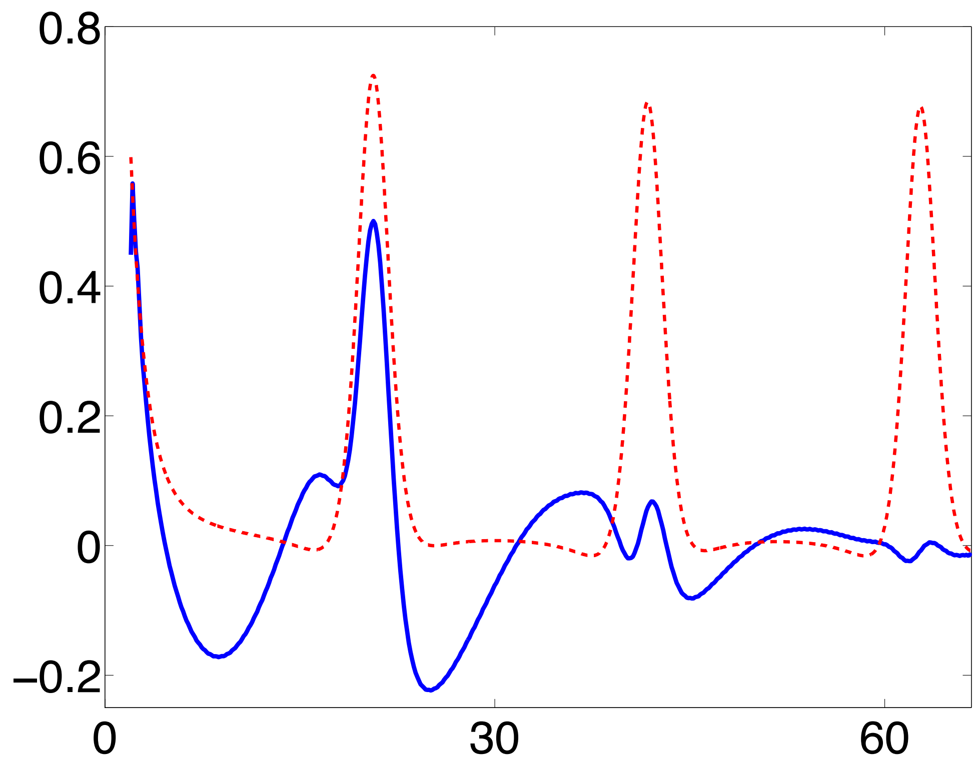


A narrower beam made of higher momentum gluons travels farther, still gets attenuated without spreading in angle or degradation of its momentum distribution.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691





Quark in circular motion ($v = 0.3$; $R\pi T = 0.15$) makes a beam of lower momentum gluons that is quenched rapidly, and is followed closely by its 'debris' — a sound wave.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

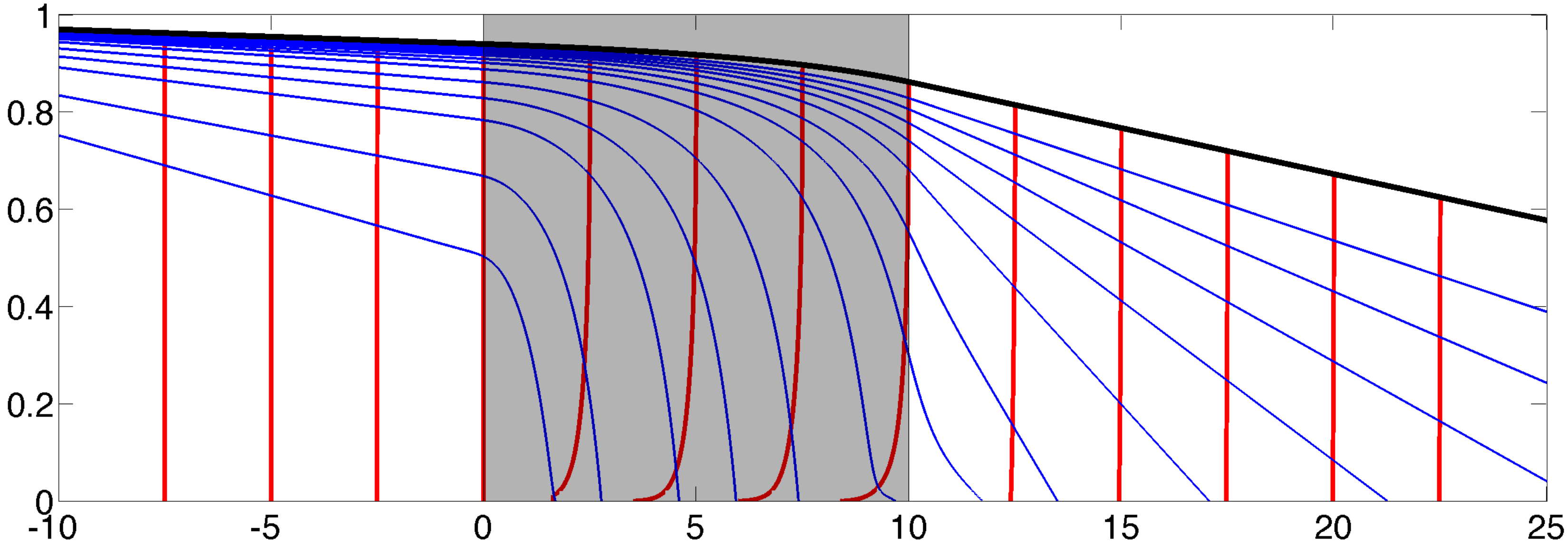
- **A beam of gluons with wave vector $q \gg \pi T$ shines through the strongly coupled plasma at close to the speed of light, and is attenuated over a distance $\sim q^{1/3}(\pi T)^{-4/3}$.**

- **Beam shows no tendency to spread in angle, or shift toward longer wavelengths, even as it is completely attenuated. Like quenching of highest energy jets at LHC?**

- **Beam sheds a trailing sound wave with wave vector $\sim \pi T$. A beam of higher q gluons travels far enough that it leaves the sound far behind; sound thermalizes. (Highest energy LHC jets?) A beam of not-so-high-q gluons does not go as far, so does get far ahead of its trailing sound wave, which does not have time to thermalize. If it were to emerge from the plasma, it would be followed by its 'lost' energy. (Lower energy jets at RHIC and LHC? Moreso at RHIC since sound thermalizes faster in the higher temperature LHC plasma.)**

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, in progress



A light quark 'jet', incident with $E \sim 205\pi T$, shoots through a slab of strongly coupled $\mathcal{N} = 4$ SYM plasma, temperature T, thickness $L\pi T = 10$. What comes out the other side? A 'jet' with $E \sim 85\pi T$, that looks *just* like a vacuum 'jet' with that energy. And, entire calculation of energy loss is geometric!

Two very different holographic approaches, quenching a beam of gluons, quenching a light quark 'jet', give similar conclusions, in qualitative agreement with aspects of what is seen.

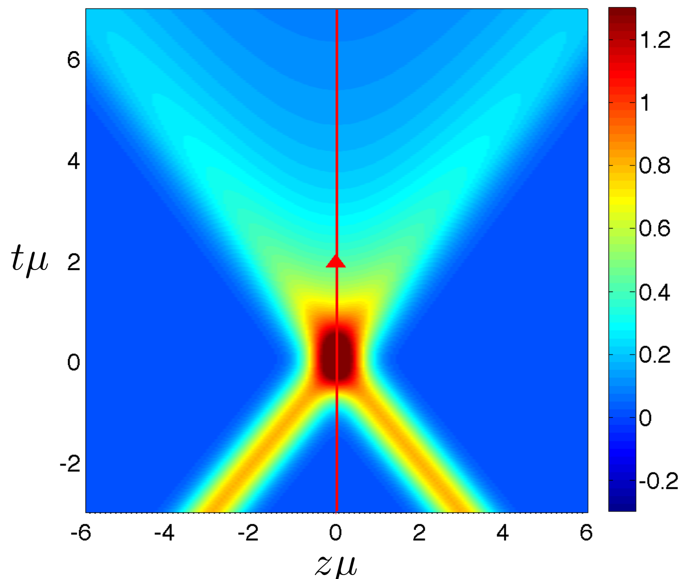
A Hybrid Weak+Strong Coupling Approach to Jet Quenching?

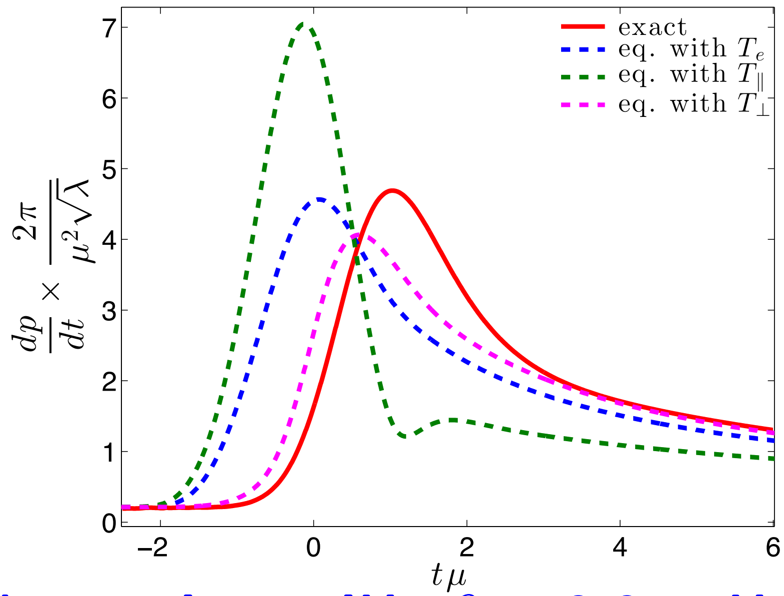
Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, in progress

- **Although various holographic approaches at strong coupling capture many qualitative features of jet quenching (e.g. the previous two), it seems quite unlikely that the high-momentum "core" of a quenched LHC jet can be described quantitatively in any strong coupling approach. (Precisely because so similar to jets in vacuum.)**
- **We know that the medium itself is a strongly coupled liquid, with no apparent weakly coupled description. And, the energy the jet loses seems to quickly become one with the medium.**
- **A hybrid approach may be worthwhile. Eg think of each parton in a parton shower losing energy to "friction", à la light quarks in strongly coupled liquid.**
- **We are exploring various different ways of adding "friction" to PYTHIA, looking at R_{AA}, energy loss distribution, dijet asymmetry, jet fragmentation function.**

Heavy Quark Energy Loss, Far-from-Equilibrium

Chesler, Lekaveckas, Rajagopal 1306.0564



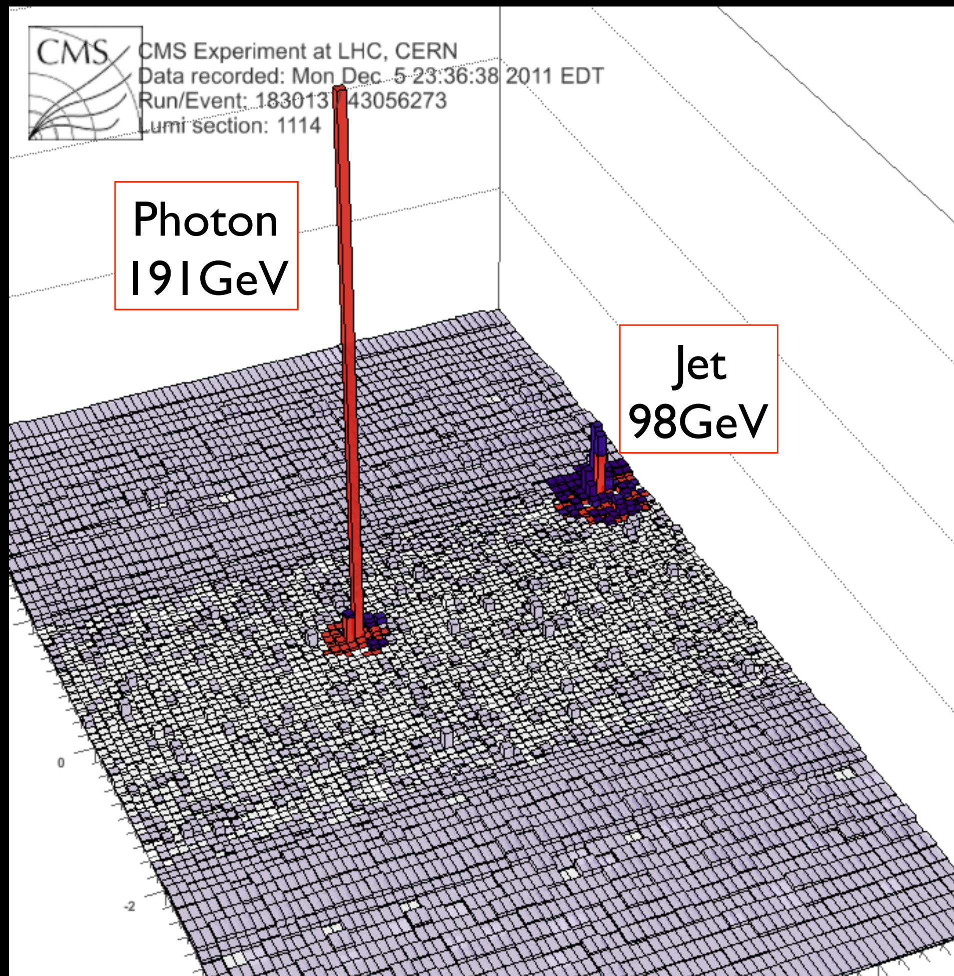


Drag force on a heavy quark moving with $\beta = 0.95c$ through strongly coupled far-from-equilibrium matter, and then anisotropic fluid, made in the collision of two sheets of energy.
Eqbm plasma with same instantaneous $\mathcal{E}$ provides a reasonable guide to magnitude, but there is a time delay.
Surprises at nonzero rapidity (not shown).
Guidance for modelling heavy quark energy loss early in h.i.c.

Weakly Coupled qg in Liquid QGP

- We *know* that at a short enough lengthscale, QGP *is* made of weakly coupled quarks and gluons, even though on its natural length scales QGP is a strongly coupled fluid with no quasiparticles.
- Long-term challenge: understand *how* liquid QGP emerges from an asymptotically free theory.
- First things first: how can we see the point-like quarks and gluons at short distance scales? Need a 'microscope'. Need to look for large-angle scattering not as rare as it would be if QGP were liquid-like on all length scales. (Think of Rutherford.)
- Gamma-jet events: Gamma tells you initial direction of quark. Measure deflection angle of jet. Closest analogy to Rutherford. (Today, only thousands of events. Many more ~ 2015.)

2011: Detected 3000 photon-jet pairs in 10^9 PbPb collisions



Unbalanced photon-jet event in PbPb

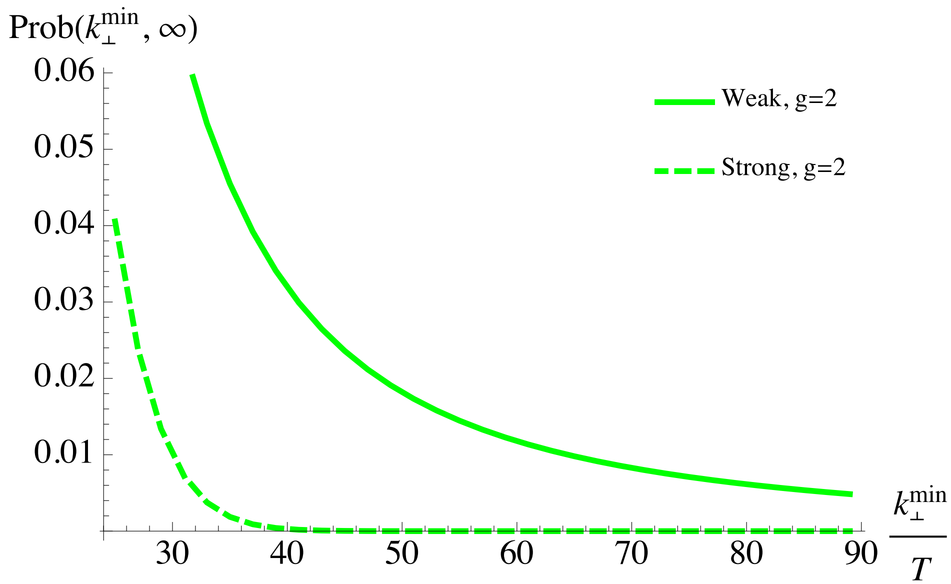
Momentum Broadening in Weakly Coupled QGP

D'Eramo, Lekaveckas, Liu, Rajagopal, 1211.1922

Calculate $P(k_\perp)$, the probability distribution for the $k_\perp$ that a parton with energy $E \to \infty$ picks up upon travelling a distance L through the medium:

- $P(k_\perp) \propto \exp(-\#k_\perp^2/(T^3 L))$ **in strongly coupled plasma. Qualitative calculation done via holography.** D'Eramo, Liu, Rajagopal, arXiv:1006.1367
- **For a weakly coupled plasma containing point scatterers** $P(k_\perp) \propto 1/k_\perp^4$ **at large** $k_\perp$. **In the strongly coupled plasma of an asymptotically free gauge theory, this must win at large enough** $k_\perp$. **Quantitative calculation done via SCET+HTL.**

Expect Gaussian at low $k_\perp$, with power-law tail at high $k_\perp$. Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.

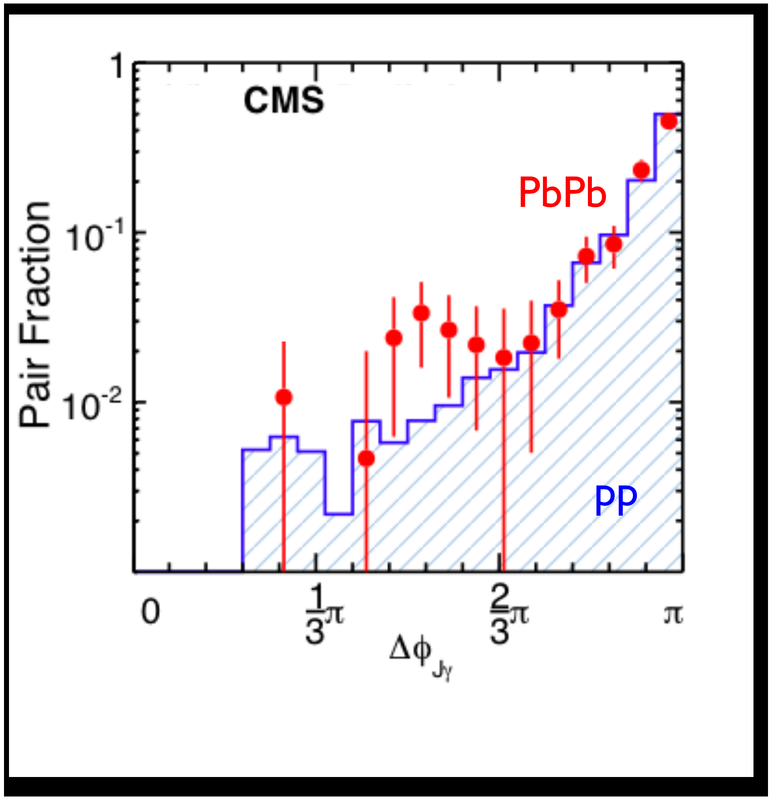


D'Eramo, Lekaveckas, Liu, Rajagopal, arXiv:1211.1922

- **Probability that a parton that travels $L = 7.5/T$ through the medium picks up $k_\perp > k_{\perp\text{min}}$, for:**
  - **Weakly coupled QCD plasma, in equilibrium, analyzed via SCET+HTL. With $g = 2$, i.e. $\alpha_{\text{QCD}} = 0.32$.**
  - **Strongly coupled $\mathcal{N} = 4$ SYM plasma, in equilibrium, analyzed via holography. With $g = 2$, i.e. $\lambda_{\text{'t Hooft}} = 12$.**

- **Eg, for $T = 300$ MeV, $L = 5$ fm, a 60 GeV parton that picks up $70\,T$ of $k_\perp$ scatters by 20°.**

Measure the angle between jet and photon



CMS, arXiv:1205.0206

Tantalizing, but need many more events before this can be a "QGP Rutherford Experiment". Something to look forward to circa 2015?

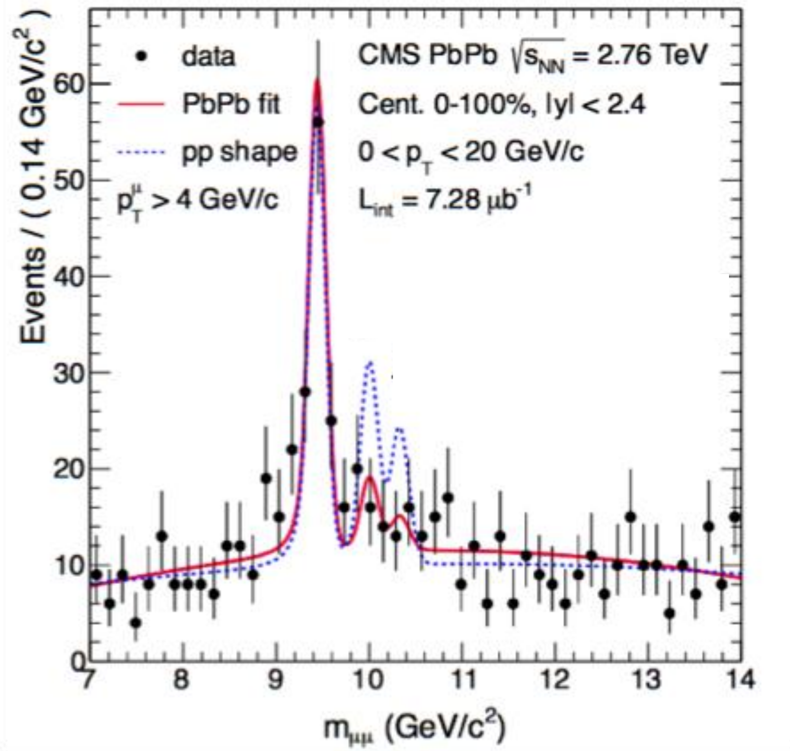
Heavy quarks? Upsilons?

- **Heavy quarks are 'tracers', dragged along by and diffusing in the liquid. Diffusion constant tells you about the medium, complementary to η/s. Holographic calculations indicate the heavy quarks should 'go with the flow'.**
- **If very energetic heavy quarks interact with strongly coupled plasma as holographic calculations indicate, which is to say like a bullet moving through water, b and c quark energy loss is same for quarks with same *velocity*. Quite different than weakly coupled expectations, where both γ and M matter. Want to study b and c quark energy loss vs. momentum. Data on identified b and c quarks coming soon, at RHIC via upgrades being completed.**
- **Upsilons probe plasma on different length scales. 1S state is very small. 3S state is the size of an ordinary hadron. They "melt" (due to screening of $b - \bar{b}$ attraction) at different, momentum-dependent (cf holographic calculations), temperatures. This story is just beginning. Stay tuned.**

Sequential Upsilon suppression

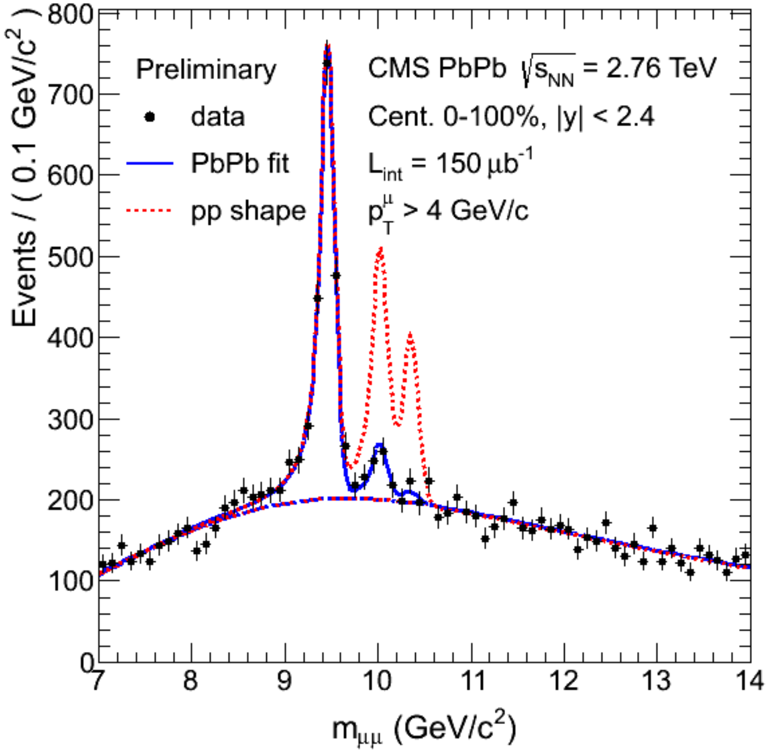
2010 data

PRL 107 (2011) 052302



Indication of suppression
of (Y(2S)+Y(3S)) relative to Y(1S)
→2.4σ significance

2011 data



Observation of sequential
suppression of Y family
→Detailed studies

A Grand Challenge

- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?
- We are developing more, and better, ways of studying the properties and dynamics of Liquid QGP — "our" example of a fluid without quasiparticles.
- At some short length scale, a weakly coupled picture of the QGP as made of quarks and gluons must be valid, even though on its natural length scales it is a strongly coupled fluid. It will be a challenge to see and understand *how* the liquid QGP emerges from short-distance quark and gluon quasiparticles .
- Holographic calculations have yielded, and are yielding, many qualitative insights that are helping advance the ongoing campaigns on both these fronts.

HOW TO CALCULATE PROPERTIES OF STRONGLY COUPLED QGP LIQUID?

① LATTICE QCD
- perfect for THERMODYNAMICS (ie static properties)
- calculation of η, and other transport coefficients, beginning
- jet quenching and other dynamic properties not in sight

② PERTURBATIVE QCD
- right theory but wrong approximation

③ Calculate QGP properties in other theories that are analyzable at strong coupling.
- Are some dynamical properties universal? I.e. same for strongly coupled plasmas in a large class of theories. What properties? What class of theories?

UNIVERSALITY?

Is there a new notion of universality for strongly coupled, (nearly) scale invariant LIQUIDS ?

To what systems does it apply?

- quark-gluon plasma dual to string theory + black hole
- QCD quark-gluon plasma?
- gas of fermionic atoms in the unitary (strongly coupled and scale invariant) regime

To what quantities does it apply?

- η/s ?
- other suggestions on the QCD side relate to "JET QUENCHING"......

$\mathcal{N}=4$ Supersymmetric Yang Mills

- A gauge theory specified by two parameters: N_c and $g^2 N_c \equiv \lambda$.
- Conformal. (λ does not run.)
- If we choose λ large, at $T \neq 0$ we have a strongly coupled plasma.
- This 3+1 dimensional gauge theory is equivalent to a particular string theory in a particular spacetime: $\underbrace{AdS_5}_{4+1 \text{ "big" dimensions}} \times \underbrace{S_5}_{} \rightarrow$ 5 "curled up" dim.
- In the $N_c \to \infty$, $\lambda \to \infty$ limit, the string theory reduces to classical gravity. ∴ calculations easy at strong coupling.

AdS/CFT

We now know of infinite classes of different gauge theories whose quark-gluon plasmas:

- are all equivalent to string theories in higher dimensional spacetimes that contain a black hole
- all have

$$\frac{\varepsilon}{T^4} = \frac{3}{4}\left(\frac{\varepsilon}{T^4}\right)_0$$

Gubser Klebanov Tseytlin Peet....

$$\eta/s = \frac{1}{4\pi}$$

Son Policastro Starinets Kovtun Buchel Liu....

in the limit of strong coupling and large number of colors.

⌜Not known whether QCD in this class.⌟

AdS / CFT

Maldacena; Witten; Gubser
Klebanov Polyakov;
....

N=4 SYM is equivalent to Type IIB
String theory on $\underbrace{AdS_5}_{\text{4+1 "big" dimensions}} \times \underbrace{S_5}_{\text{5 curled up dimension}}$

Translation Dictionary:

N=4 SYM gauge theory in 3+1 dim — String theory in 4+1(+5) dim

$$\frac{g^2 N_c}{4\pi N_c} = g_{string}$$

[$N_c \to \infty$ at fixed $g^2 N_c$ means $g_{string} \to 0$]

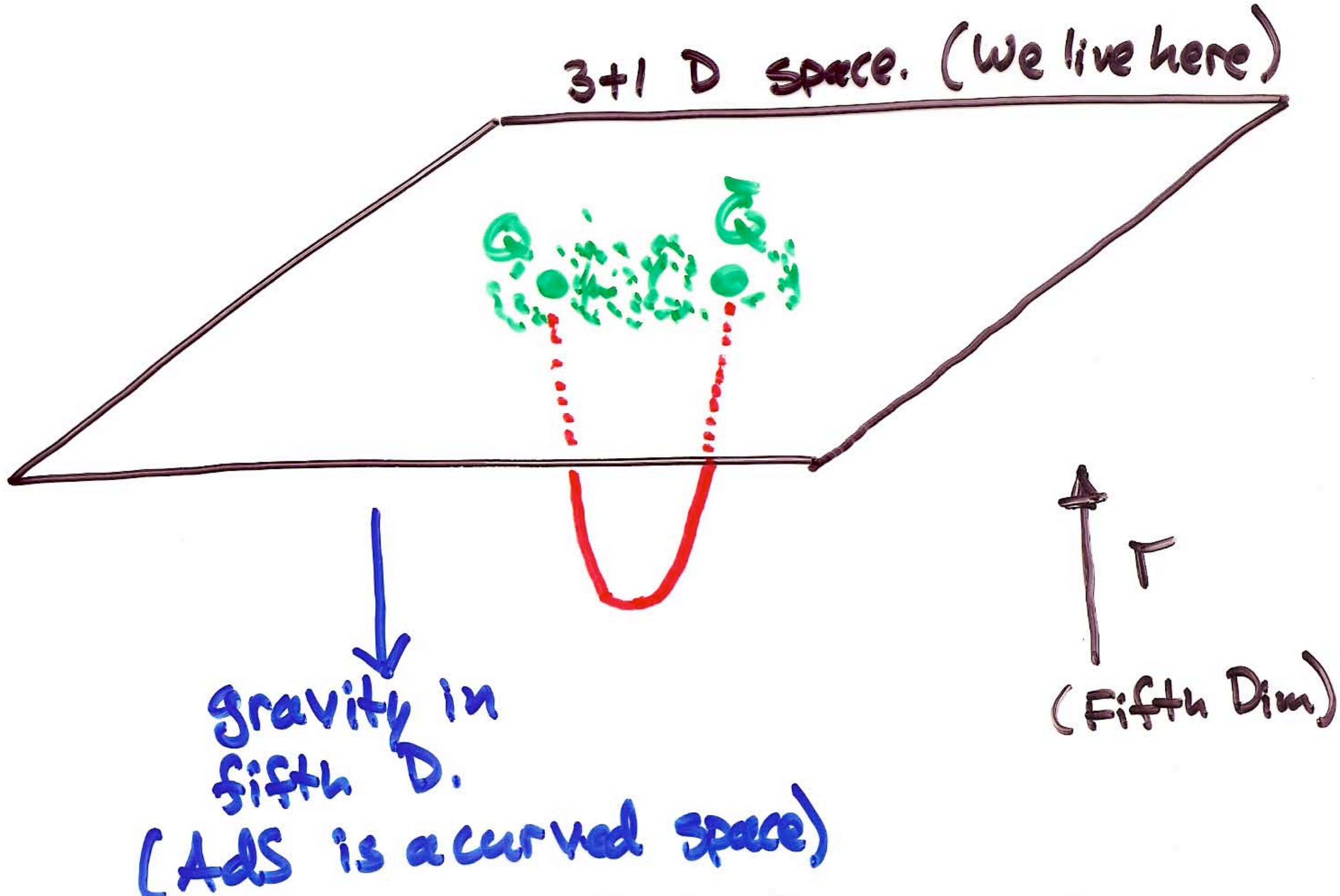
$$\sqrt{g^2 N_c} = R^2/\alpha'$$

[R: AdS curvature
$\frac{1}{2\pi\alpha'}$: string tension]

Heat the gauge theory to a temperature T. $= T_H = r_0/\pi R^2$ — Add a Black hole in the 5th dimension, with

[r_0: location of BH horizon in fifth dim.]

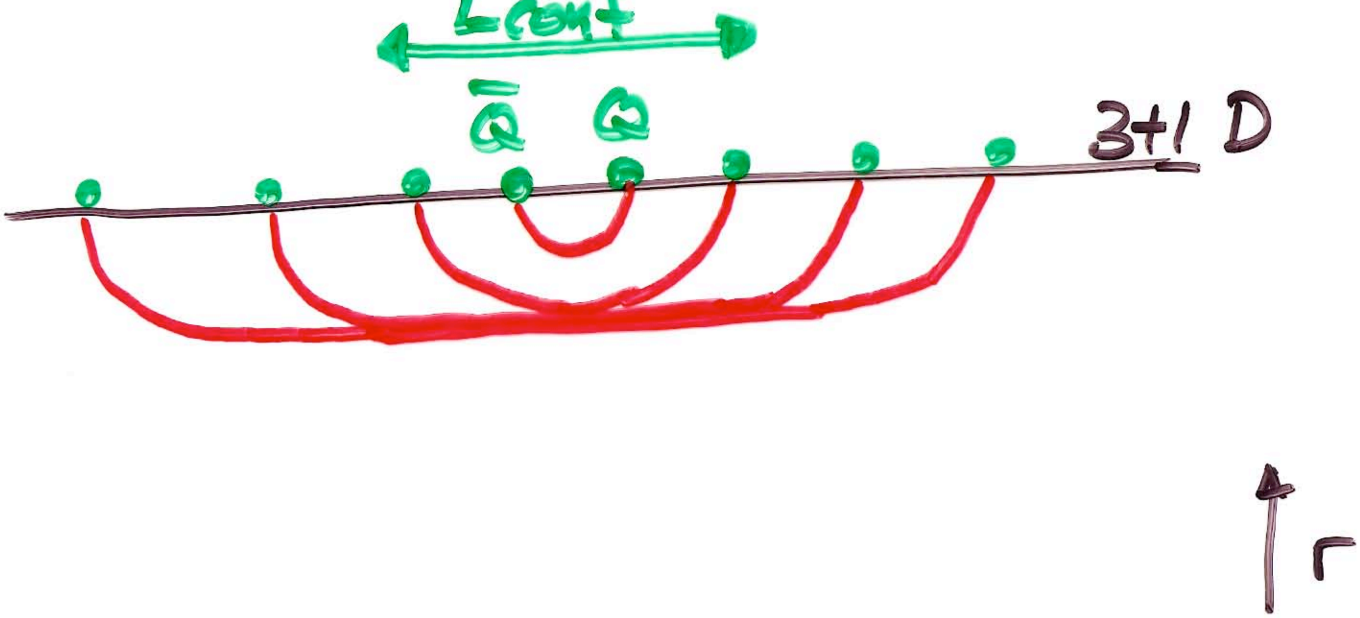
How can strings in $\underline{5D}$ describe, say, force between Q and $\bar{Q}$ in a 4D gauge theory?



- Extremize energy of U string. (Like catenary problem, in unusual gravitational field.)
  - Large $g^2 N_c$ → Large tension → no fluctuation
  - Large N_c → Small g_{string} → no loops break off.
- Force between Q and $\bar{Q}$ $= \dfrac{d}{d\,\text{separation}}\left(\text{Energy of string}\right)$

CONFINEMENT ?

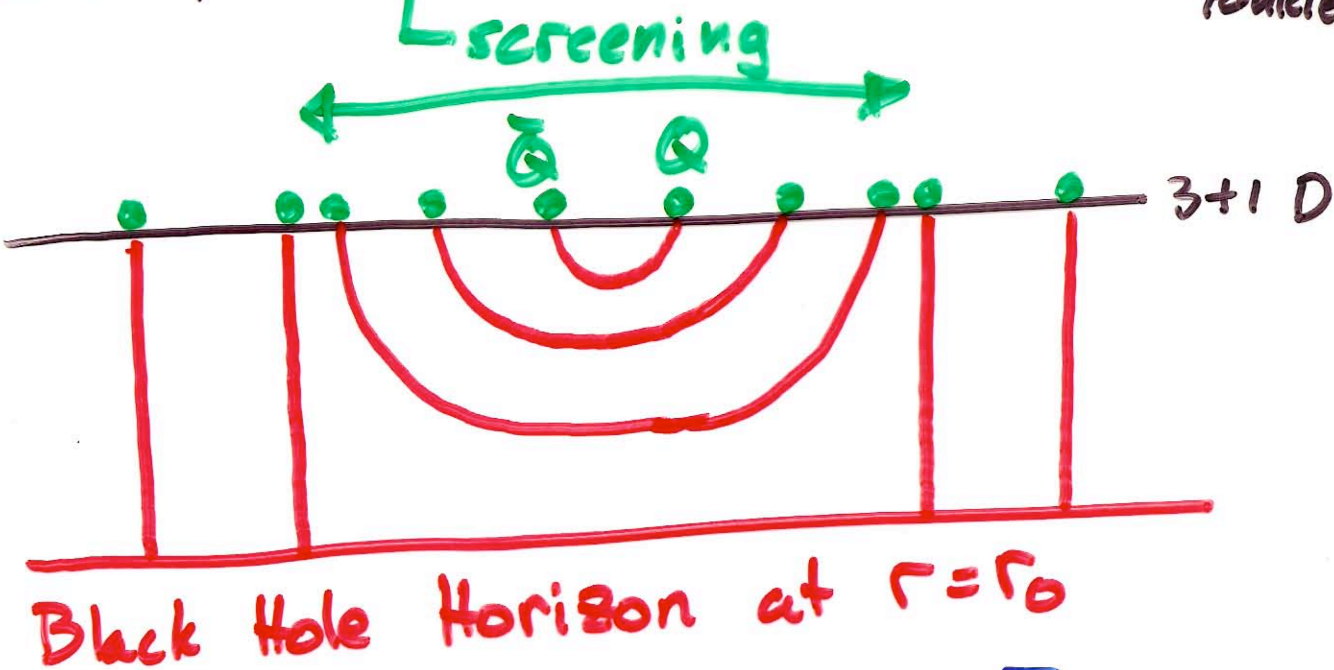
Here's how confinement can arise ....



- This does <u>not</u> happen in $N=4$
  - shape of string stays same as L increases. ($N=4$ is conformal)
- Confining gauge theories with dual descriptions like this <u>are</u> known.
- QCD not known to have a description like this.
- Don't use $N=4$ as a guide to QCD at $T=0$.

DECONFINEMENT AT $T \neq 0$

Maldacena; Rey Yee; Rey Theisen Yee; Brandhuber Itzhaki Sonnenschein Yankielowicz



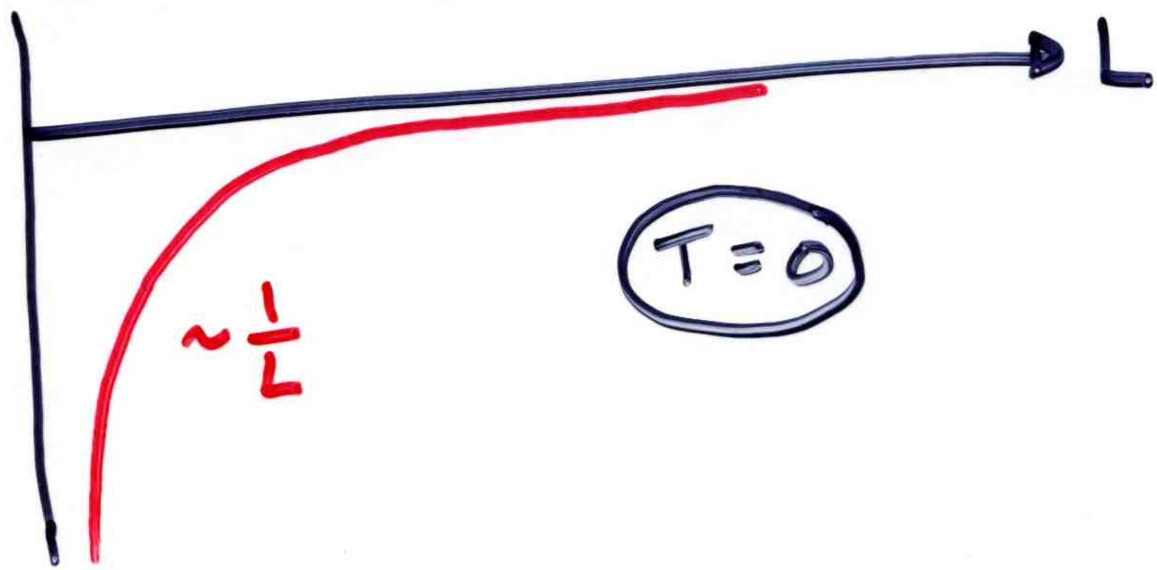
- For $L < L_s$, force between Q & $\bar{Q}$.
- For $L > L_s$, force is screened. Q & $\bar{Q}$ deconfined.
- In $N=4$ SUSY QCD,

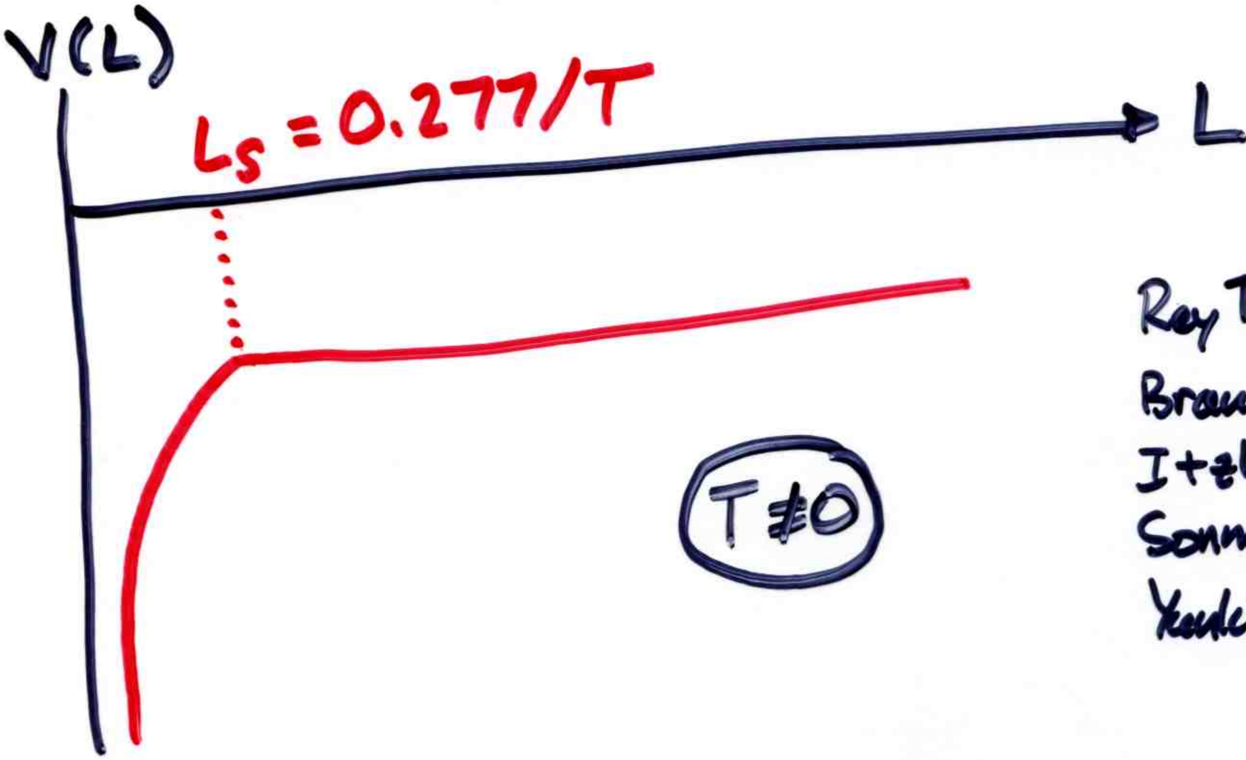
$$L_s = \frac{0.277}{T}$$

- In QCD, force between static Q & $\bar{Q}$ in QGP can be calculated. (Lattice QCD) Can define L_s, though it is not a sharp boundary. Find: $L_s \sim \frac{0.5}{T} \to \frac{0.7}{T}$ Kaczmarek Karsch Zantow Petreczky
- $N=4$ gets this feature of the QCD strongly interacting QGP to within factor of 2!

SCREENING IN N=4

V(L) = potential between static Q & $\bar{Q}$

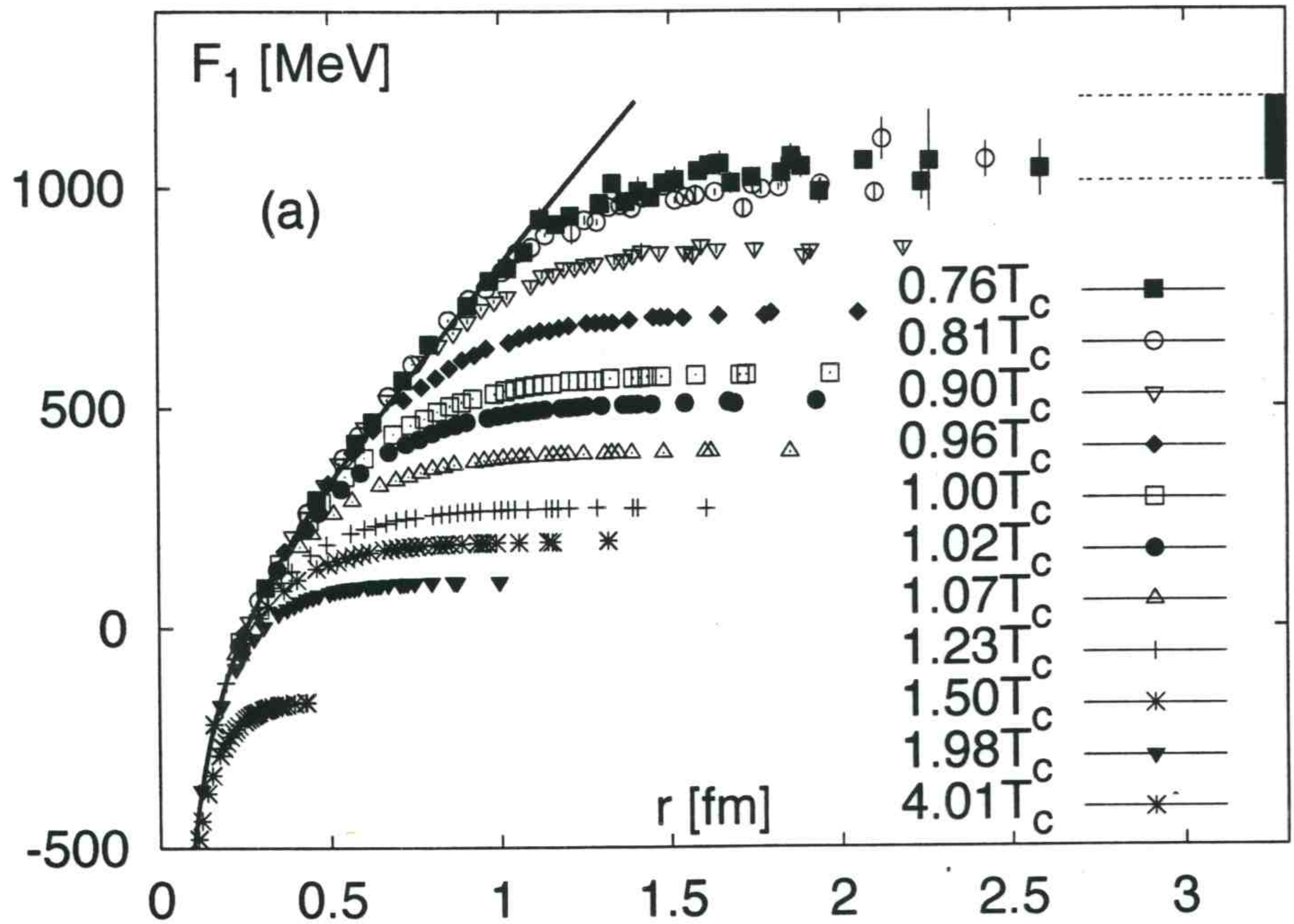




Ray Theisen Yee;
Brandhuber
Itzhaki
Sonnenschein
Yankielowicz

Similar to screening in QCD above QCD's T_c....

SCREENING IN QCD



Kaczmarek, Zantow

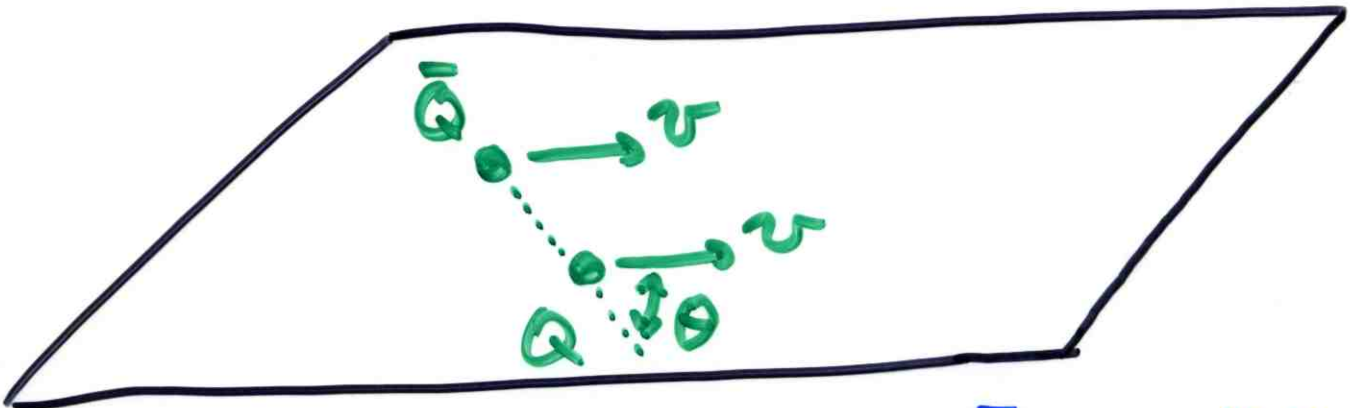
lattice QCD calculation

[Unquenched. $N_f = 2$]

Upon defining an L_s, the authors find $L_s \sim 0.5/T$

A PREDICTION FOR EXPERIMENT

H. Liu, KR, Wiedemann



- Calculate force between $Q + \bar{Q}$ <u>moving</u> through the N=4 QGP. (Not known how to do this calculation in QCD.) Find:

$$L_s = \frac{f(v,\theta)}{\pi T}(1-v^2)^{1/4}$$

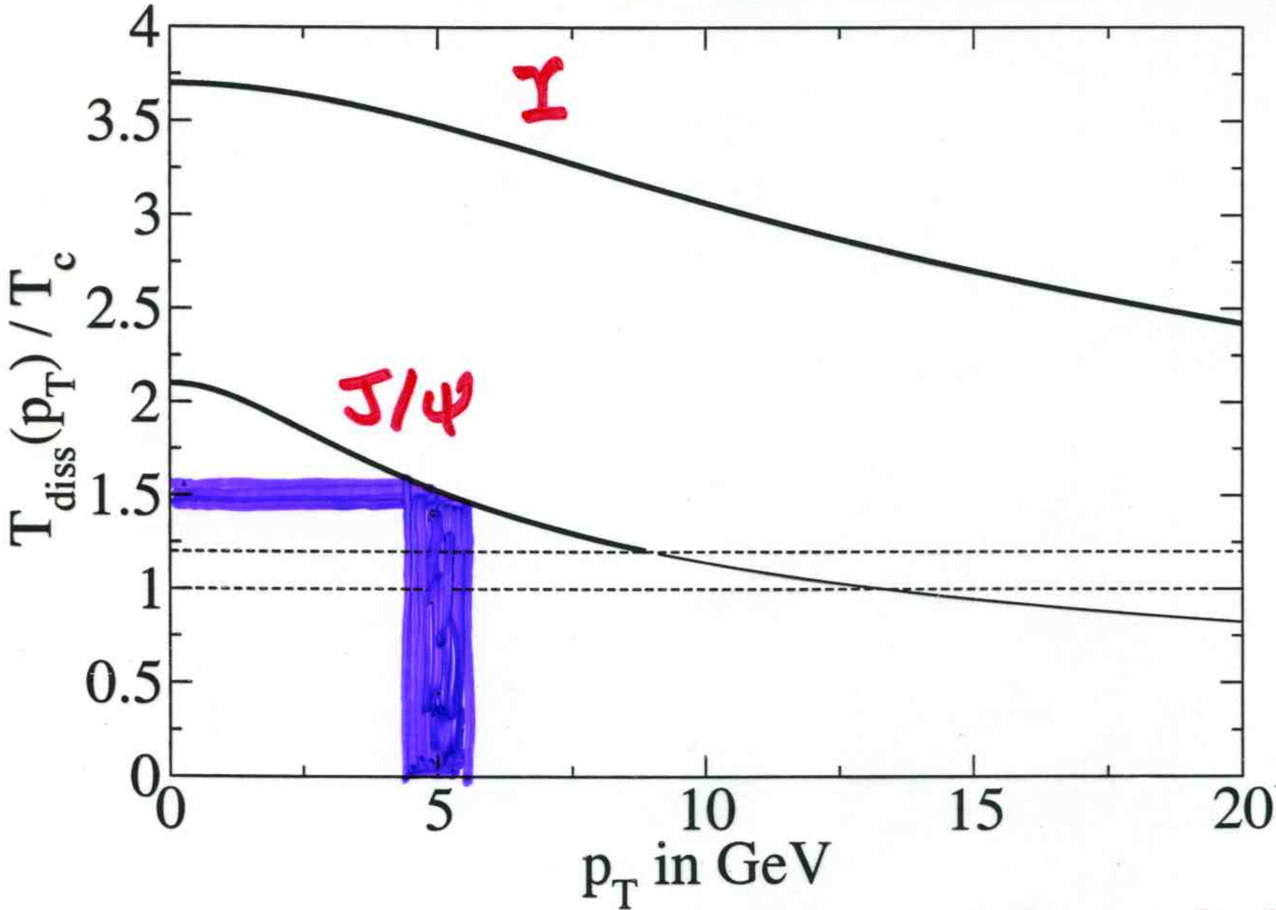
LRW; Peeters et al; Chernicoff et al; Caceres et al

where f is almost a constant. ($f(0,0) = 0.869$; $f(0,\frac{\pi}{2}) = .743$)

- So, $L_s(v,T) \simeq L_s(0,T)/\sqrt{\gamma}$
- Makes sense if L_s controlled by ε, since $\varepsilon \sim T^4$ and $\varepsilon(v) = \varepsilon(0)\gamma^2$.
- J/ψ ($\bar{c}c$) and Υ ($\bar{b}b$) mesons dissociate when T reaches T_{diss}, at which $L_s \sim$ meson size.
- Suggests: $T_{diss}(v) \sim T_{diss}(0)/\sqrt{\gamma}$!

$T_{dissociation}$ vs. P_T

- At $P_T = 0$, $T_{diss}^{J/\psi} \simeq 2.1\, T_c$, from lattice QCD
- Υ curve schematic. (Scaled rel. to J/ψ by meson size in vacuum.)

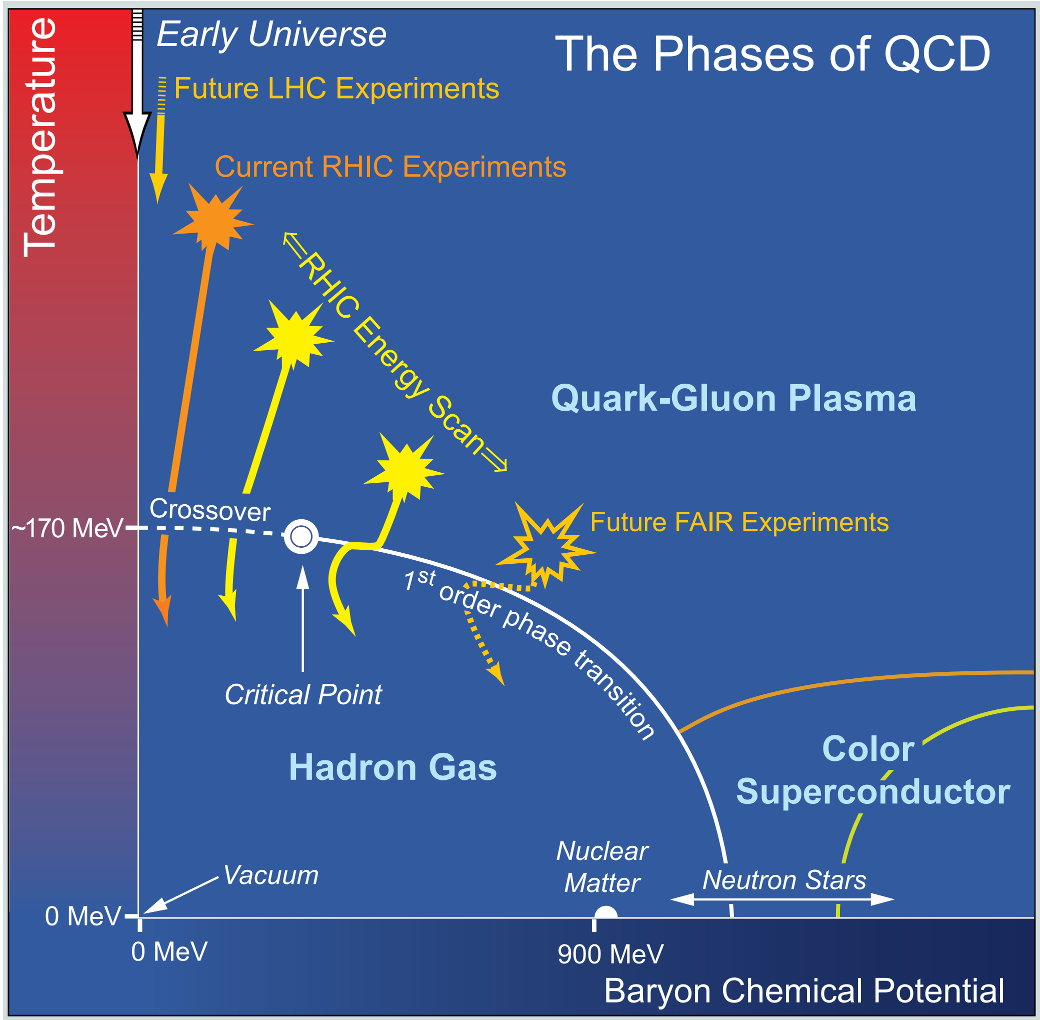


- Our velocity scaling: $T_{diss}(v) \simeq T_{diss}(0)/\sqrt{\gamma}$

+ Karsch Kharzeev Satz model
  (ie $2.1\,T_c < T_{RHIC} < 1.2\,T_c$)

$\Rightarrow$ J/ψ <u>themselves</u> dissociate for
$P_T > 5$ GeV if $T_{RHIC} \sim 1.5\,T_c$
$P_T > 9$ GeV if $T_{RHIC} \sim 1.2\,T_c$

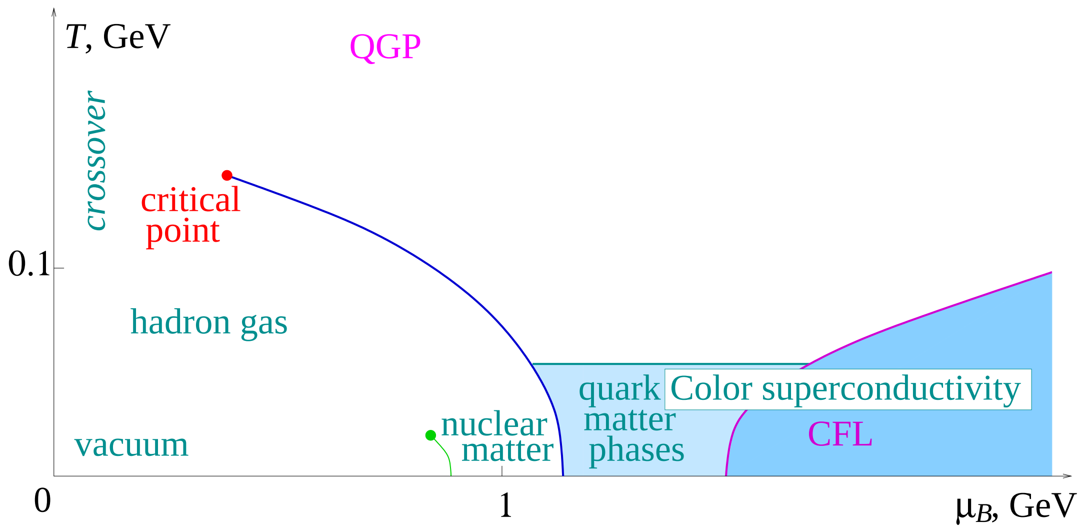
Seeking the QCD Critical Point

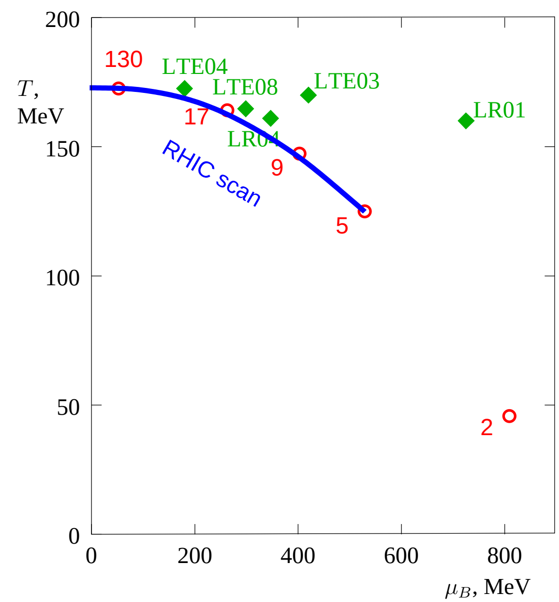


2007 NSAC Long Range Plan

Another grand challenge... Data from first phase of RHIC Energy Scan... And, theory developments...

QCD phase diagram, critical point and RHIC





- Models (and lattice) suggest the transition becomes 1st order at some μ_B.
- Can we observe the critical point in heavy ion collisions, and how?
- Near critical point fluctuations grow and become more non-Gaussian.
- Challenge: develop measures most sensitive to the critical point and use them to locate the critical point by scanning in $\sqrt{s}$ and therefore in $\mu_{\text{freezeout}}$.
- Example: kurtosis (of the event-by-event distribution of the number of protons, pions or protons-antiprotons) depend strongly on the correlation length (ξ^7), which is non-trivial, non-monotonic function of μ and therefore $\sqrt{s}$. And, the prefactor in front of ξ^7 changes sign! Stephanov, 1104.1627

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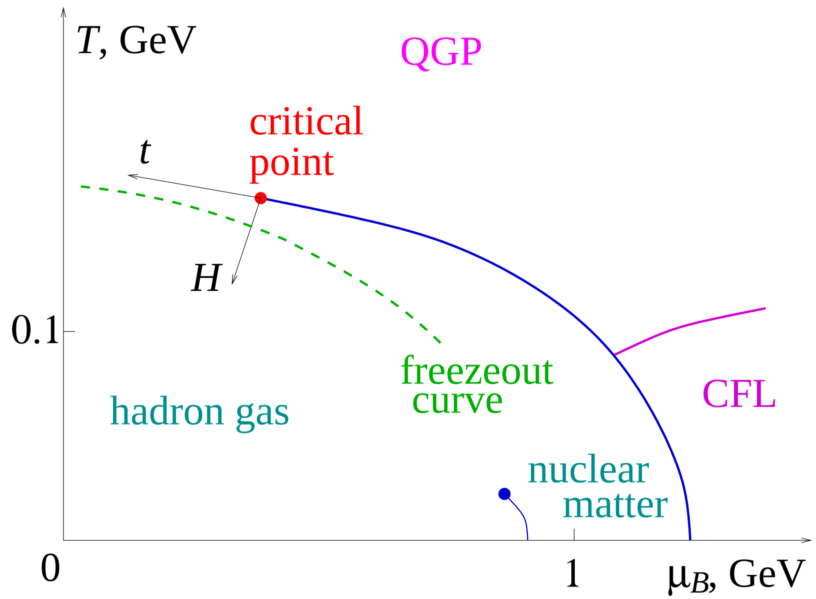

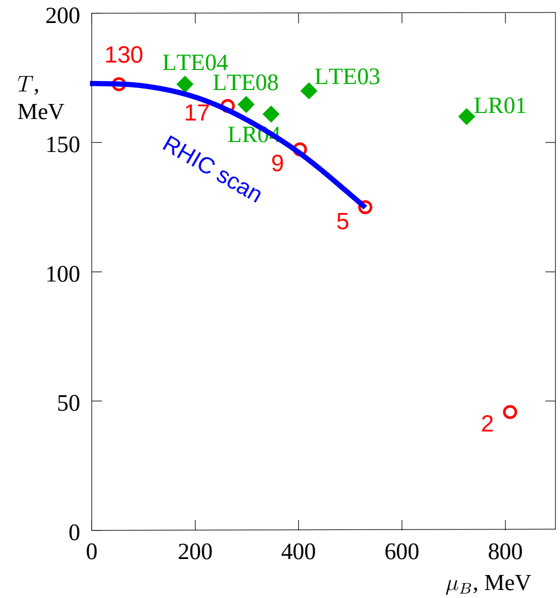

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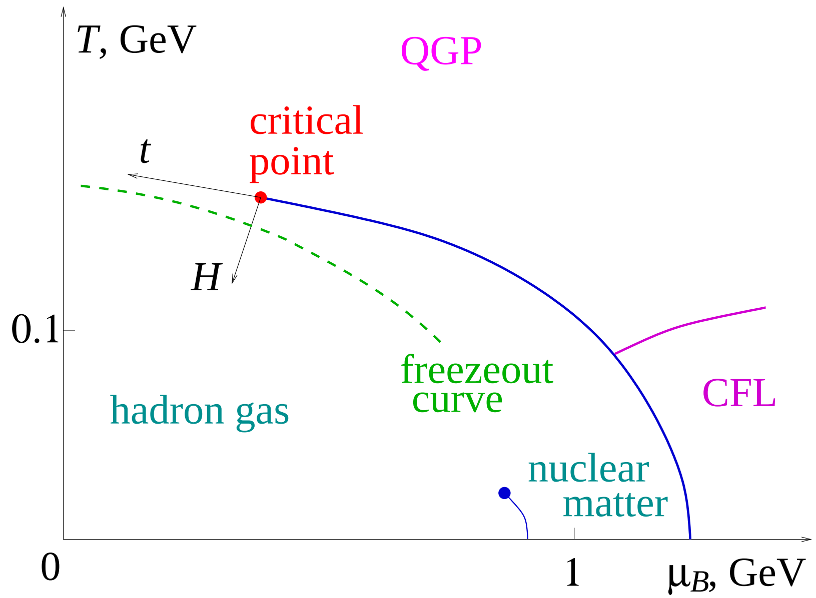

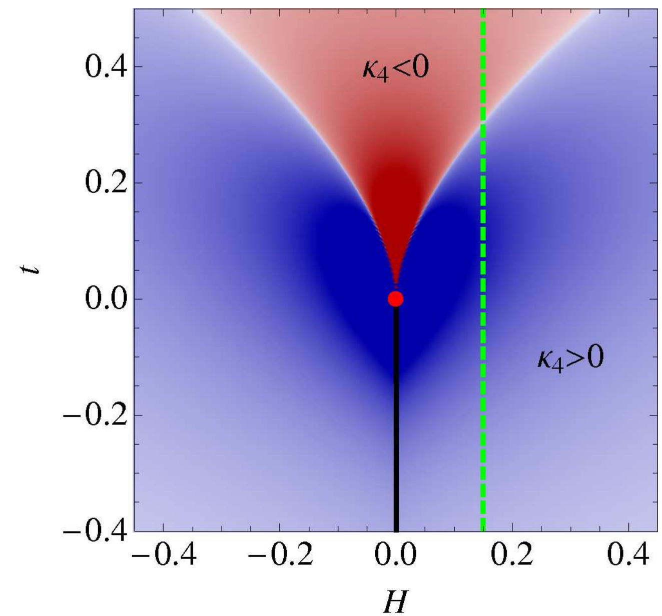

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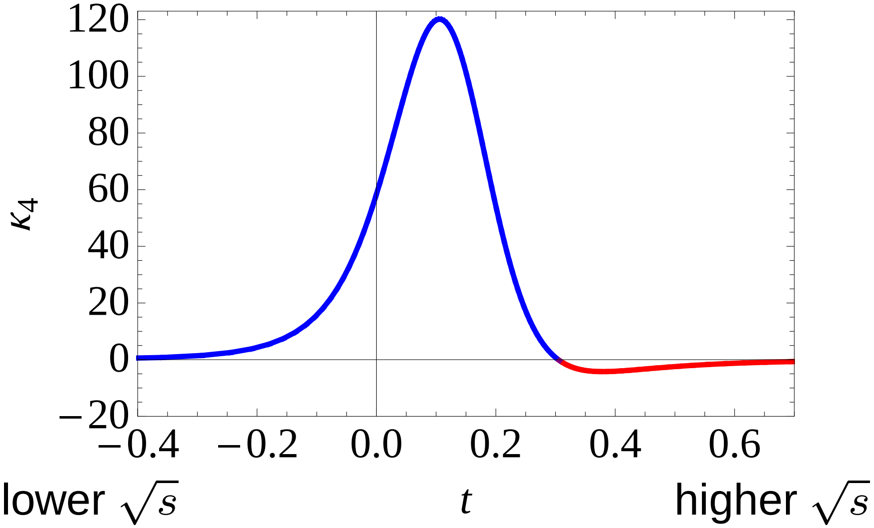
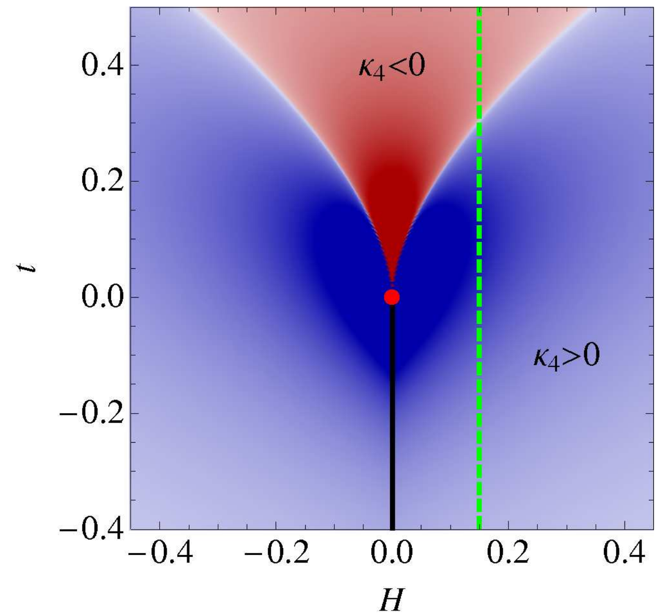
crit. contribution to Kurtosis (arb. units)





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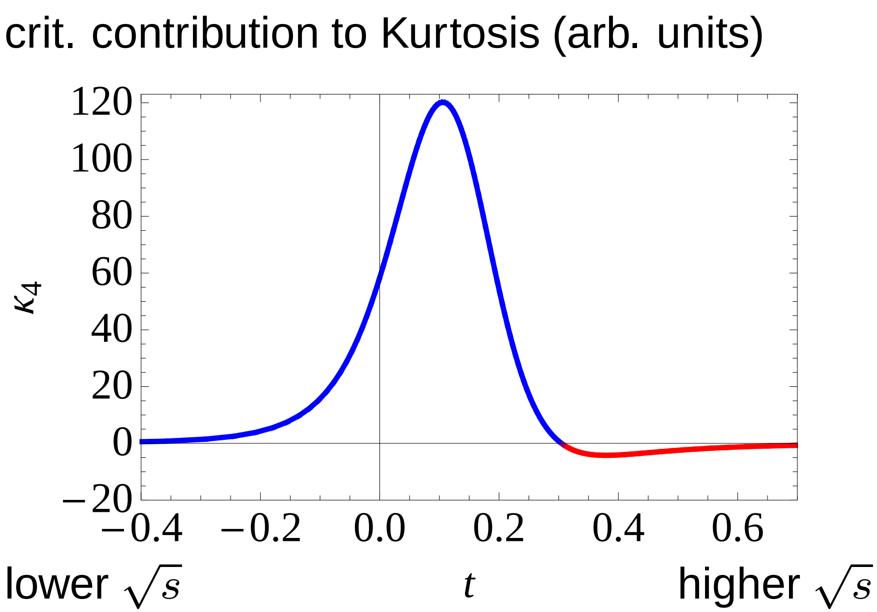

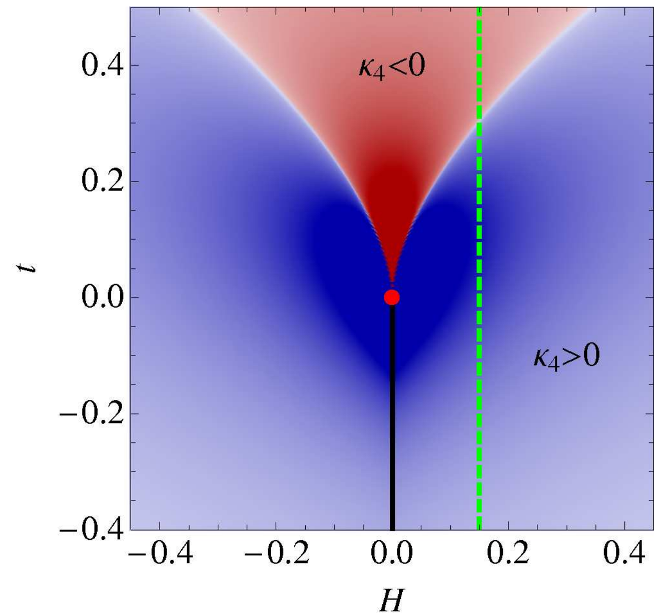

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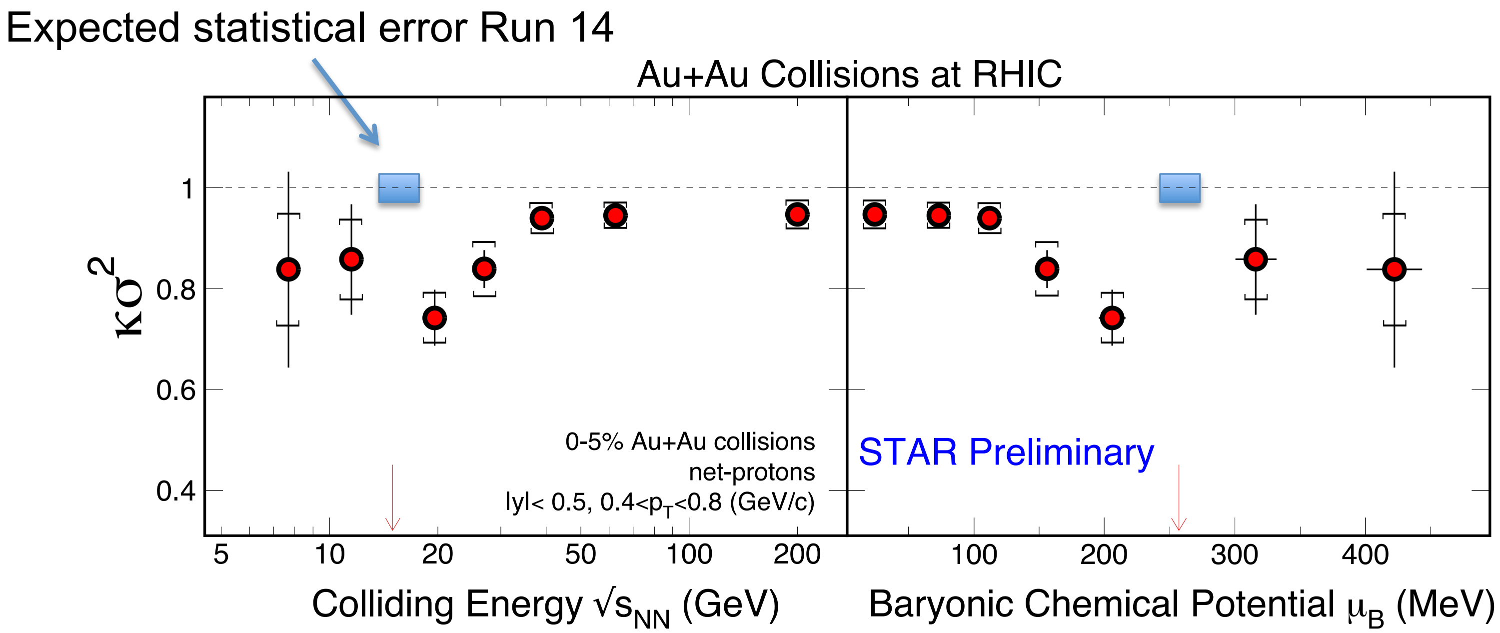
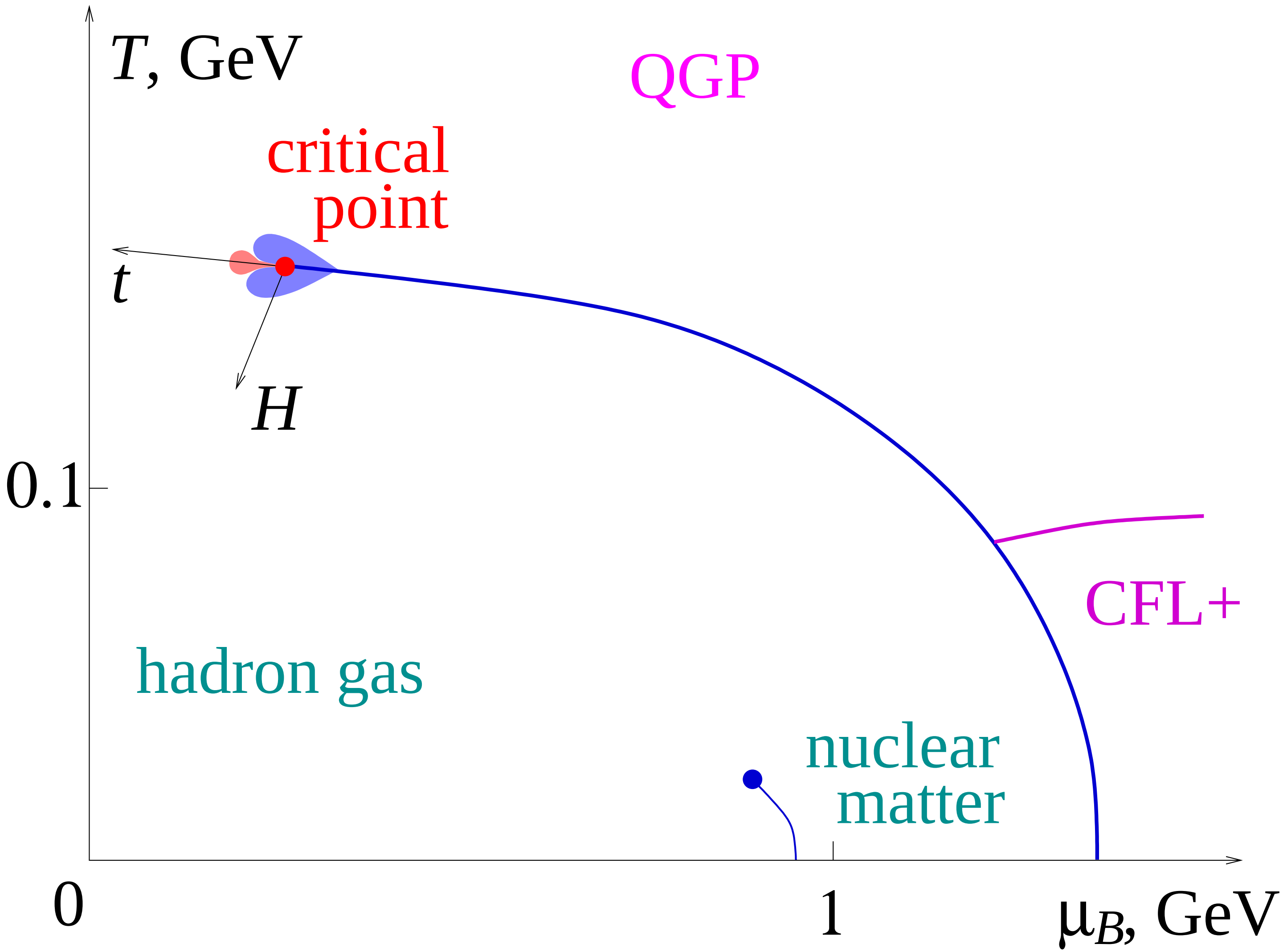
- Once we find the μ (i.e. the $\sqrt{s}$) where the critical contribution to κ_4 is large enough — e.g. the "blue peak" — then there are then robust, parameter-independent, predictions for various ratios of the kurtosis and skewness of protons and pions. Athanasiou, Stephanov, Rajagopal 1006.4636.

Seeking the QCD Critical Point



If **negative contribution to kurtosis at $\sqrt{s} = 19.6$ GeV is due to fluctuations near the critical point, results from** Athanasiou, Rajagopal, Stephanov 1006.4636 **imply correlation length $\xi \gtrsim 1.2$ fm. And, *if* critical region is ~ 100 MeV wide in μ_B, then expect larger ξ, and larger and positive contribution to kurtosis (whose magnitude is proportional to ξ^7), at $\sqrt{s} = 15$ GeV. If 2014 data at $\sqrt{s} = 15$ GeV points this way, much more to be done. (Today tantalizing, but it *is* only one data point.)**

Implications for the energy scan



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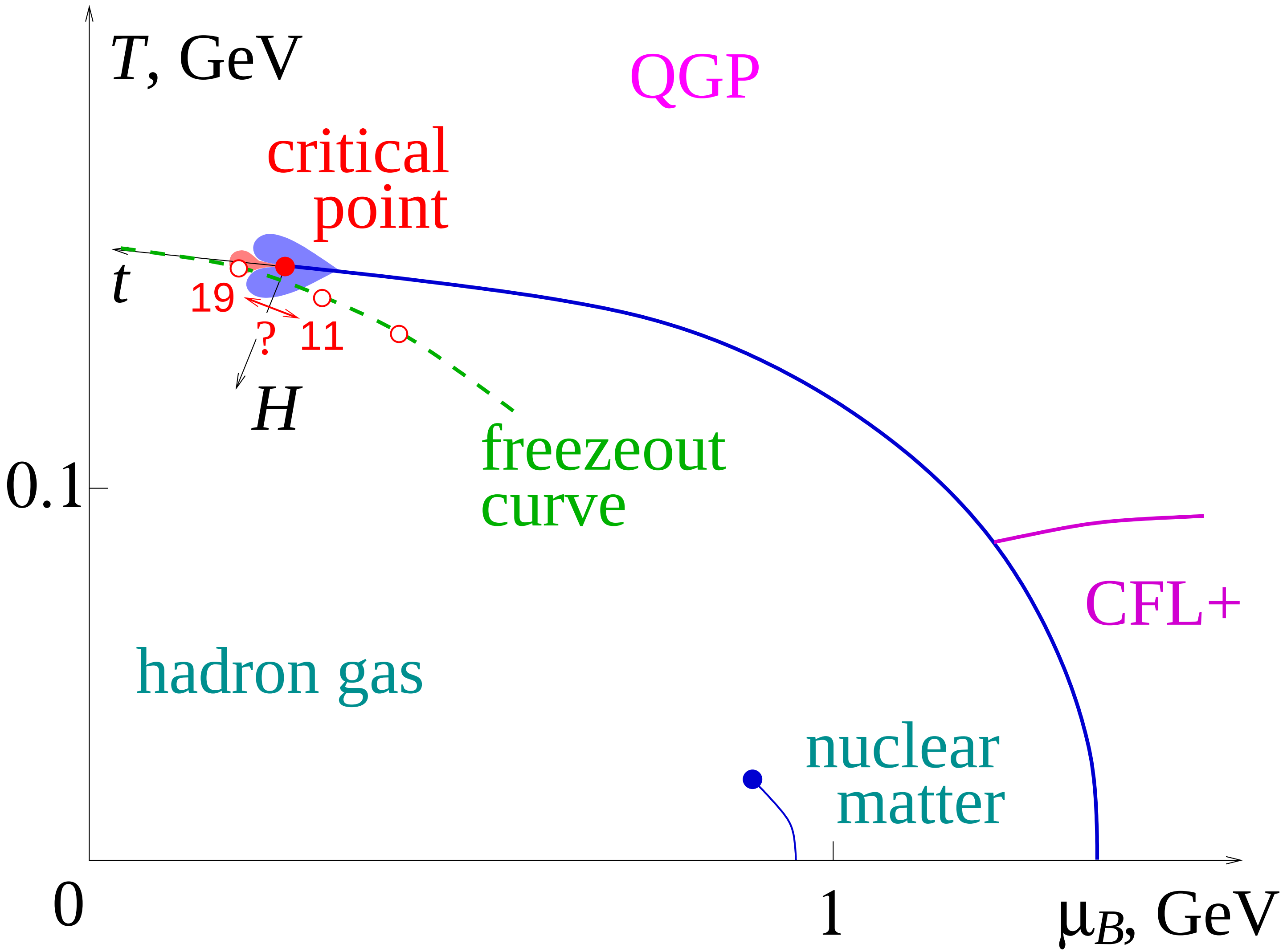

- If the kurtosis stays significantly below Poisson value in 19 GeV data, the logical place to take a closer look is between 19 and 11 GeV.

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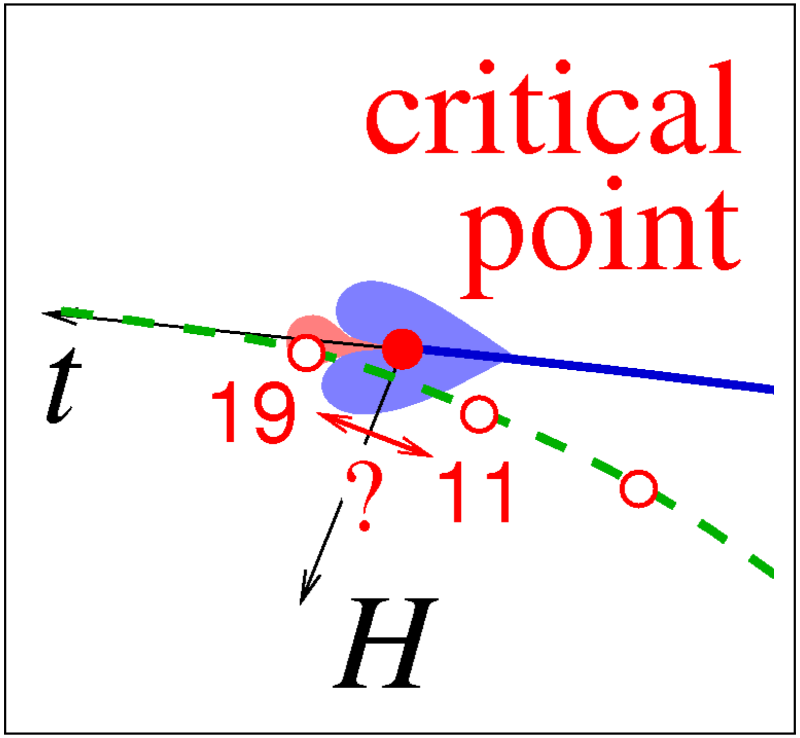

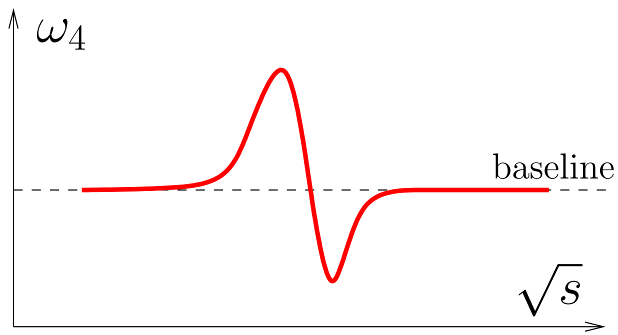

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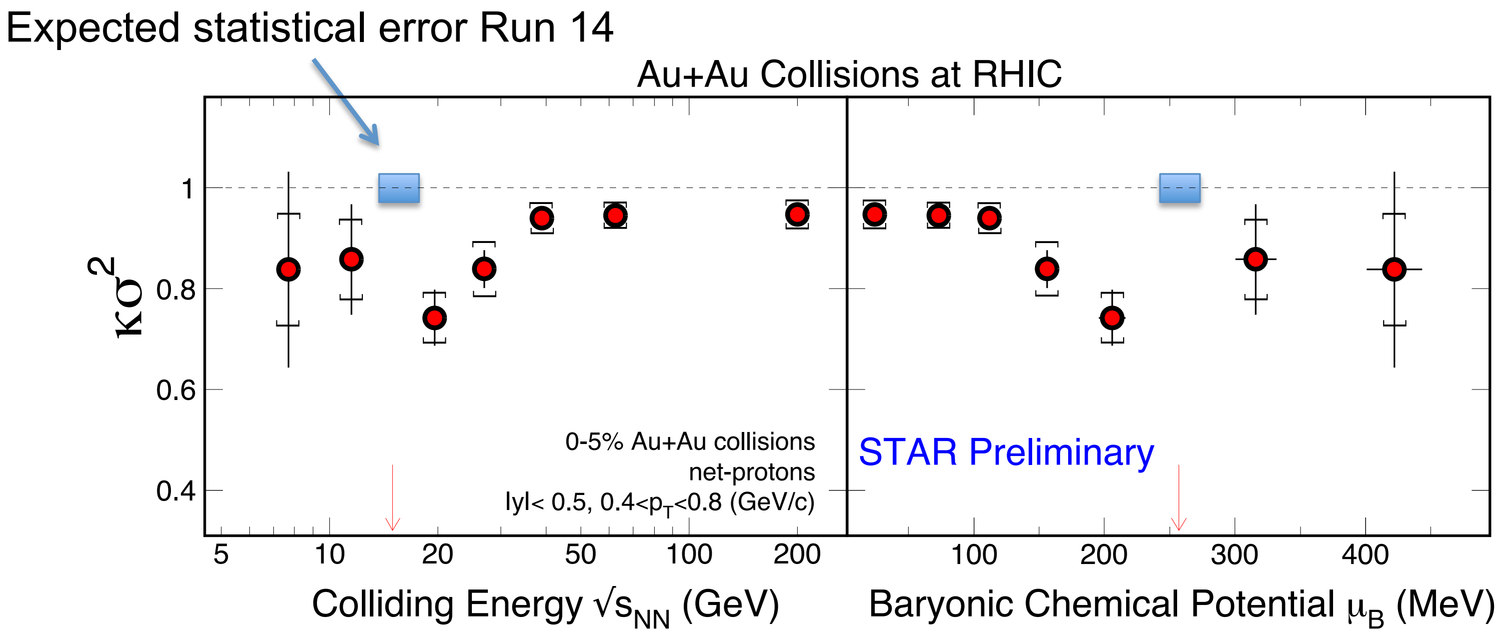

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Stay Tuned...

Liquid QGP at LHC and RHIC. New data (v_n at RHIC and LHC; CuAu and UU collisions at RHIC) and new calculations tightening the constraints on η/s and perhaps its T-dependence ...

Probing the Liquid QGP. Jet quenching. Heavy quark energy loss. Upsilons. Photons. Photon+jet. Each of these is a story now being written. Seeing, and then understanding, how the liquid QGP emerges from asymptotically free quarks and gluons remains a challenge, as well as an opportunity...

Mapping the QCD phase diagram via the RHIC energy scan has begun...