Qualitative Lessons about Jet Quenching and Heavy Ion Collisions from Holographic Calculations

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MIT & CERN

Heavy Ion Forum

CERN, July 15, 2013

Gauge/String Duality, Hot QCD and Heavy Ion Collisions

Casalderrey-Solana, Liu, Mateos, Rajagopal, Wiedemann

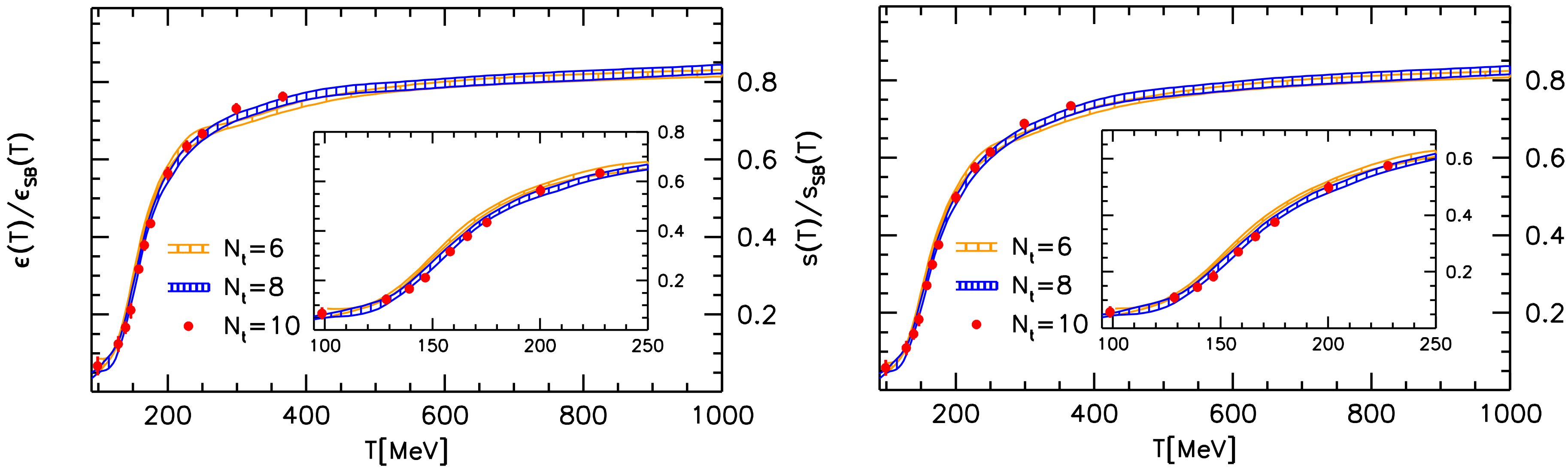
A 500 page book. We finished the manuscript a few weeks ago. To appear in early 2014, Cambridge University Press.

95 page intro to heavy ion collisions and to hot QCD, including on the lattice. 70 page intro to string theory and gauge/string duality. Including a 'duality toolkit'.

280 pages on holographic calculations that have yielded insights into strongly coupled plasma and heavy ion collisions. Hydrodynamics and transport coefficients. Thermodynamics and susceptibilities. Far-from-equilibrium dynamics and hydrodynamization. Jet quenching. Heavy quarks. Quarkonia. Some calculations done textbook style. In other cases just results. In all cases the focus is on qualitative lessons for heavy ion physics.

QGP Thermodynamics

Endrodi et al. 2010



Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

Lesson of the past decade: don't try to infer dynamic properties from static ones. Although its thermodynamics is almost that of ideal-noninteracting-gas-QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories with holographic duals whose plasmas have ε and s at infinite coupling 75% that at zero coupling, a result that goes back to 1996 that was not appreciated initially.]

Rapid Equilibration?

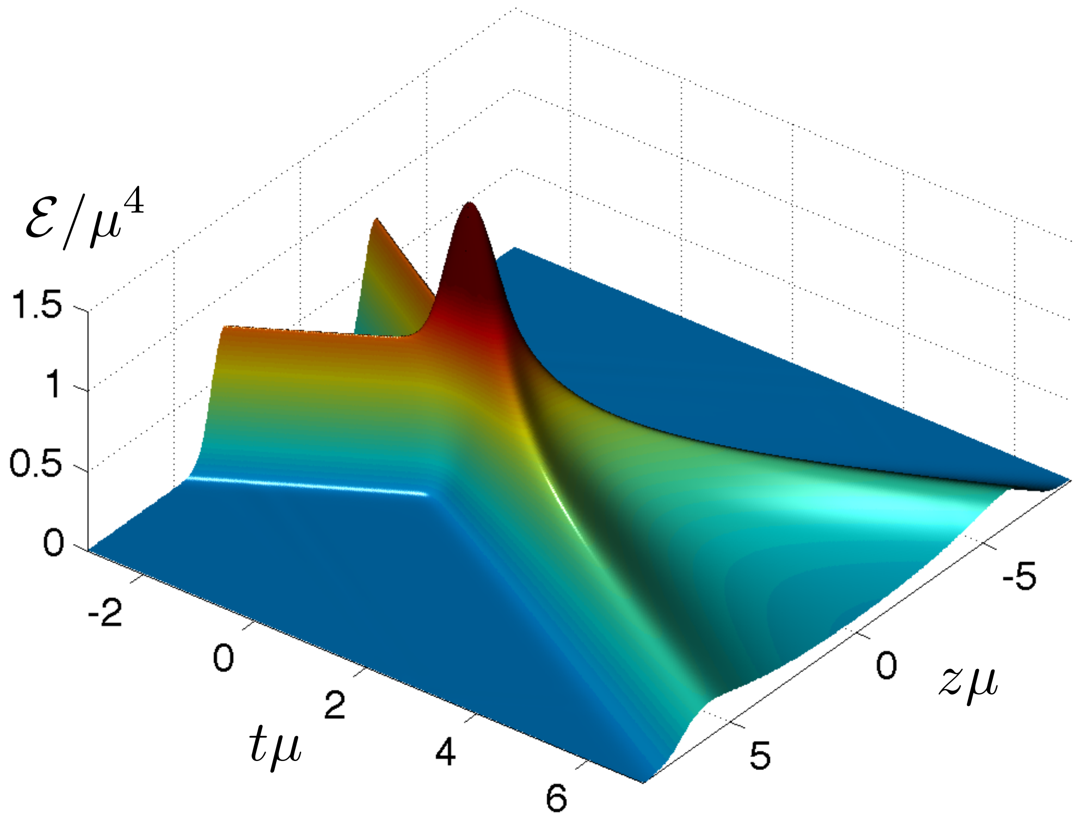
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

- Long-standing estimate is that a hydrodynamic description must already be valid only 1 fm after the collision.

- This has always been seen as *rapid equilibration*. Weak coupling estimates suggest equilbration times of 3-5 fm. And, 1 fm just sounds rapid.

- But, is it really? How rapidly does equilibration occur in a strongly coupled theory?

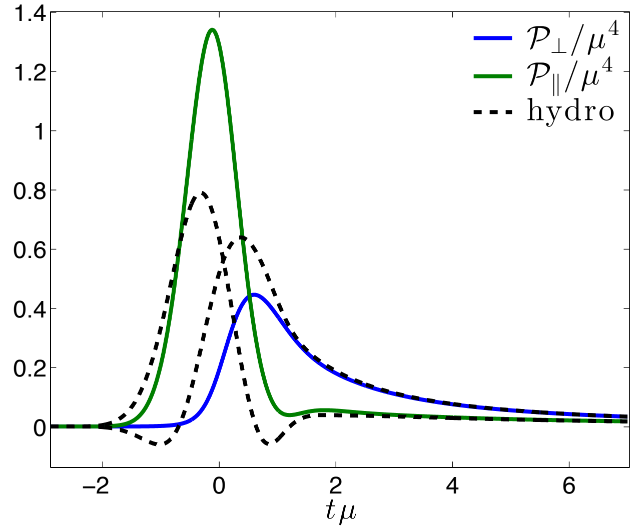
Colliding Strongly Coupled Sheets of Energy



Hydrodynamics valid ~ 3 **sheet thicknesses after the collision, i.e.** ~ 0.35 **fm after a RHIC collision. Equilibration after** ~ 1 **fm need not be thought of as rapid.** Chesler, Yaffe arXiv:1011.3562

Similarly 'rapid' hydrodynamization times ($\tau T \lesssim 0.7 - 1$**) found for** *many* **non-expanding or boost invariant initial conditions.** Heller et al, arXiv:1103.3452, 1202.0981, 1203.0755, 1304.5172

Anisotropic Viscous Hydrodynamics



Hydrodynamics valid so early that the hydrodynamic fluid is not yet isotropic. 'Hydrodynamization before isotropization.' An epoch when first order effects (spatial gradients, anisotropy, viscosity, dissipation) important. Hydrodynamics with entropy production.

This has now been seen in very many strongly coupled analyses of hydrodynamization. Janik et al., Chesler et al., Heller et al., ...

Could have been anticipated as a possibility without holography. But, it wasn't — because in a weakly coupled context isotropization happens first.

η/s and Holography

- $4\pi\eta/s = 1$ for any (of the very many) known strongly coupled large-N_c gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.
- Geometric intuition for dynamical phenomena at strong coupling. Hydrodynamization = horizon formation. Nontrivial hydrodynamic flow pattern = nontrivial undulation of black-hole metric. Dissipation due to shear viscosity = gravitational waves falling into the horizon.
- Conformal examples show that hydrodynamics need not emerge from an underlying kinetic theory of particles. A liquid can just be a liquid.
- $1 < 4\pi\eta/s < 3$ for QGP at RHIC and LHC.
- Suggests a new kind of universality, not yet well understood, applying to dynamical aspects of strongly coupled liquids. To which liquids? Unitary Fermi 'gas'?

Why care about the value of η/s?

- **Here is a theorist's answer...**

- **Any gauge theory with a holographic dual has $\eta/s = 1/4\pi$ in the large-N_c, strong coupling, limit. In that limit, the dual is a classical gravitational theory and η/s is related to the absorption cross section for stuff falling into a black hole. If QCD has a dual, since $N_c = 3$ it must be a string theory. Determining $(\eta/s) - (1/4\pi)$ would then be telling us about string corrections to black hole physics, in whatever the dual theory is.**

- **For fun, quantum corrections in dual of $\mathcal{N} = 4$ SYM give:**

$$\frac{\eta}{s} = \frac{1}{4\pi}\left(1 + \frac{15\,\zeta(3)}{(g^2N_c)^{3/2}} + \frac{5}{16}\frac{(g^2N_c)^{1/2}}{N_c^2} + \ldots\right)$$

Myers, Paulos, Sinha

with $1/N_c^2$ and N_f/N_c corrections yet unknown. Plug in $N_c = 3$ and $\alpha = 1/3$, i.e. $g^2N_c = 12.6$, and get $\eta/s \sim 1.73/4\pi$. And, $s/s_{SB} \sim 0.81$, near QCD result at $T \sim 2 - 3T_c$.

- **A more serious answer...**

Beyond Quasiparticles

- QGP at RHIC & LHC, unitary Fermi "gas", gauge theory plasmas with holographic descriptions are all strongly coupled fluids with no apparent quasiparticles.
- In QGP, with η/s as small as it is, there can be no 'transport peak', meaning no self-consistent description in terms of quark- and gluon-quasiparticles. [Q.p. description self consistent if $\tau_{\rm qp} \sim (5\eta/s)(1/T) \gg 1/T$.]
- Other "fluids" with no quasiparticle description include: the "strange metals" (including high-T_c superconductors above T_c); quantum spin liquids; matter at quantum critical points;...
- Emerging hints of how to look at matter in which quasiparticles have disappeared and quantum entanglement is enhanced: "many-body physics through a gravitational lens." Black hole descriptions of liquid QGP and strange metals are continuously related! But, this lens is at present still somewhat cloudy...

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 have two big advantages: (i) direct experimental access to the fluid of interest without extraneous degrees of freedom; (ii) weakly-coupled quark and gluon quasiparticles at short distances.

- We can quantify the properties and dynamics of Liquid QGP at its natural length scales, where it has no quasiparticles.

- Can we probe, quantify and understand Liquid QGP at *short distance scales*, where it is made of quark and gluon quasiparticles? See *how* the strongly coupled fluid emerges from well-understood quasiparticles at short distances.

- The LHC and newly upgraded RHIC offer new probes and open new frontiers.

Two Early Lessons from Holographic Calculations

- **Jet quenching parameter $\hat{q}$ is not proportional to "number of scattering centers", which is $\propto N_c^2$.** Liu, Rajagopal, Wiedemann, 2006

$$\hat{q} \propto \sqrt{g^2 N_c}\, T^3$$

After all, there are no scattering centers if the liquid is strongly coupled on all length scales.

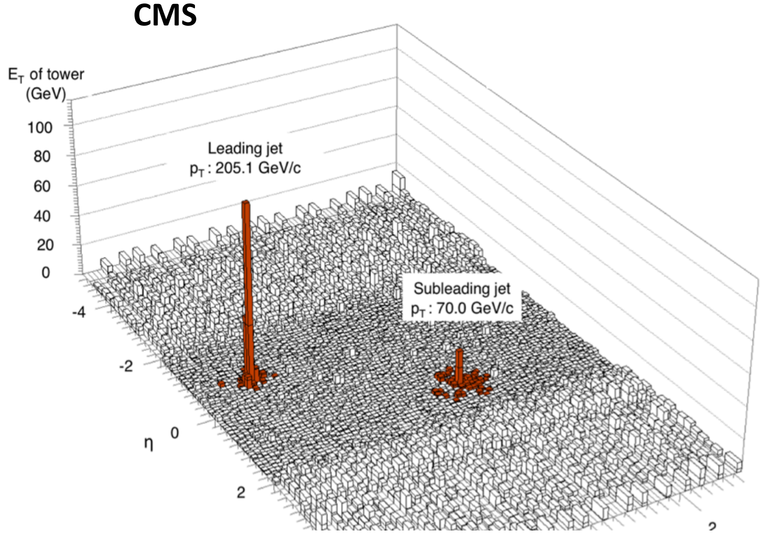
- **Heavy quarks with mass M lose energy via drag, or friction,** Gubser, 2006; Herzog, Karch, Kovtun, Kozcaz, Yaffe, 2006; Casalderrey-Solana, Teaney, 2006

$$\frac{dE}{dt} \propto -E\,\frac{T^2}{M}\ ,$$

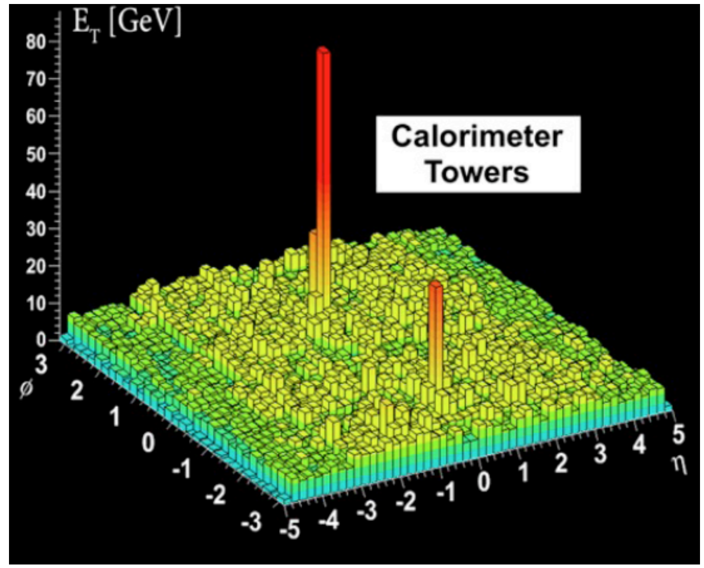
and then diffuse with $D \sim 1/(2\pi T)$. So, the heavy quarks quickly end up "going with the flow". Lost energy becomes sound waves. This latter is generic (to energy loss of anything) in strongly coupled liquid; more below.

Jet Quenching, in brief

CMS



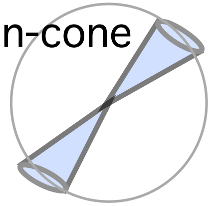
ATLAS

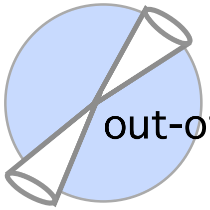


Caricature of jet quenching @ RHIC & LHC:

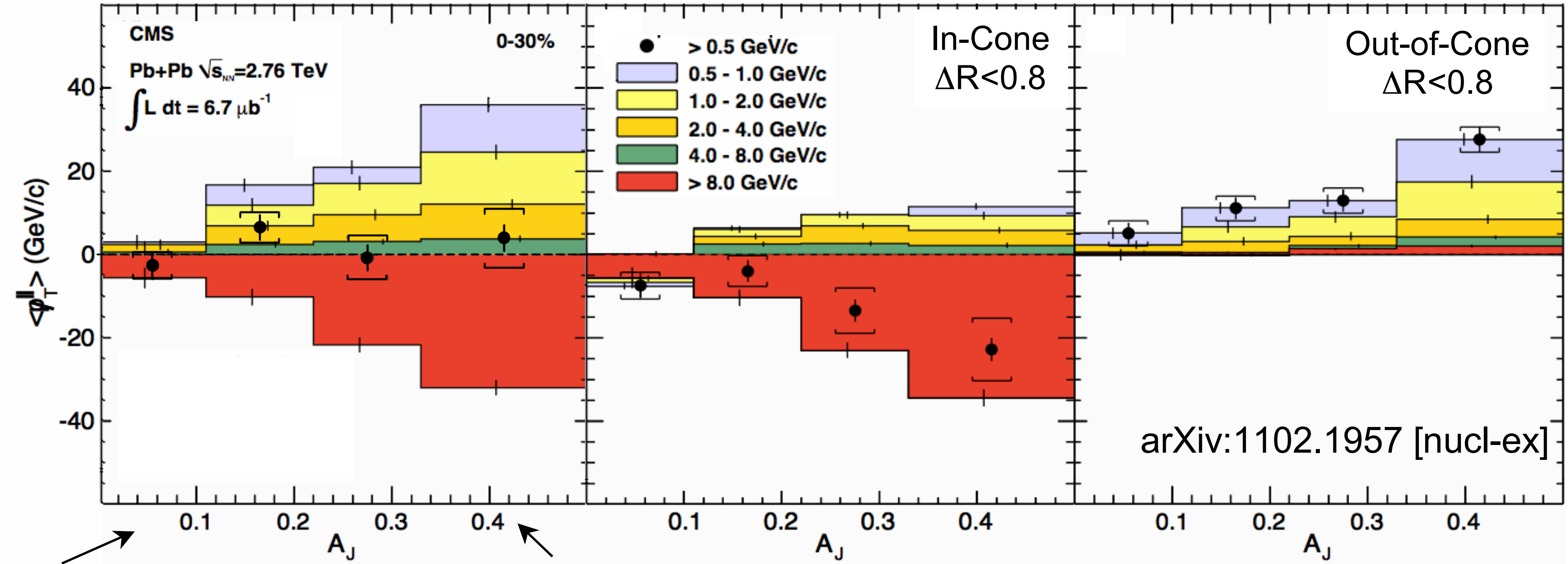
- 200+ GeV jets lose many tens of GeV passing through the liquid QGP, but jets emerge looking in other respects rather ordinary.
- Lost energy turns into many soft particles at all angles.
- Lower energy jets, seen by ALICE and at RHIC, may emerge surrounded by their debris?

Missing-$p_T^{||}$





0-30% Central PbPb

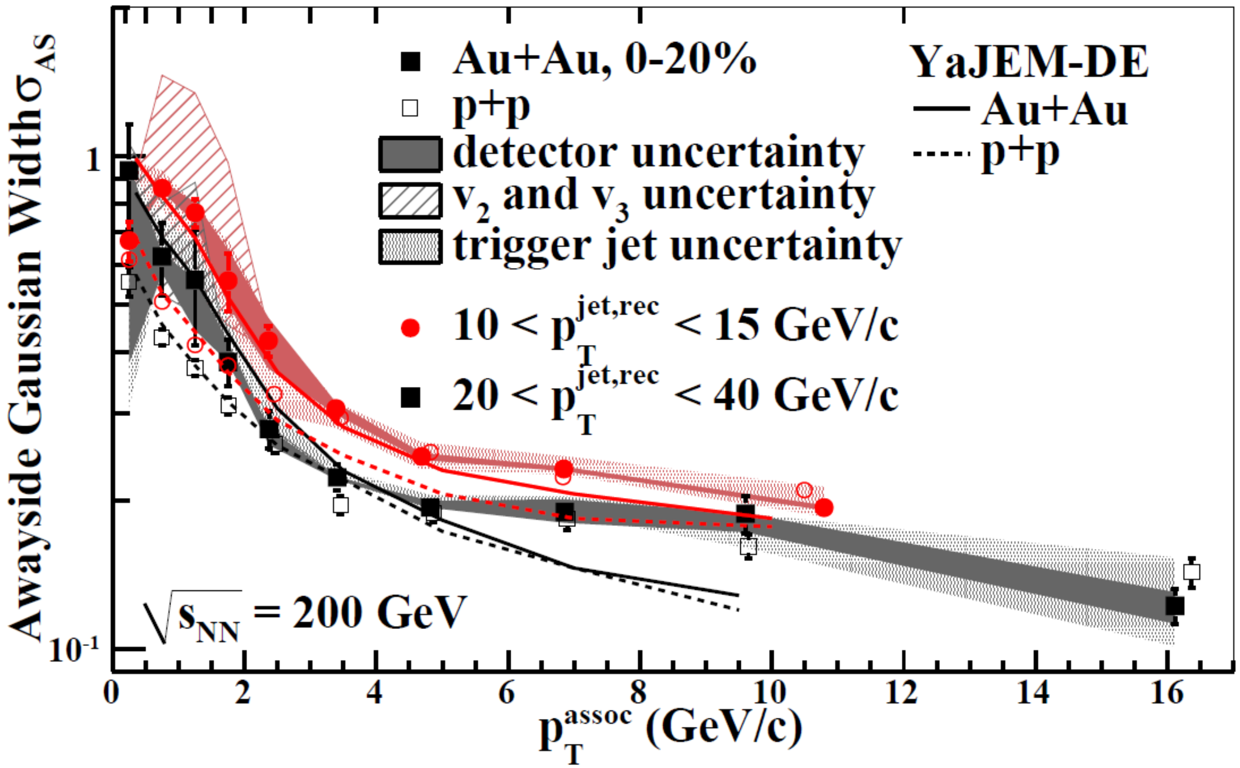


balanced jets

unbalanced jets

STAR, arXiv:1302.6184 [nucl-ex]
Submitted to PRL

Awayside Gaussian Widths

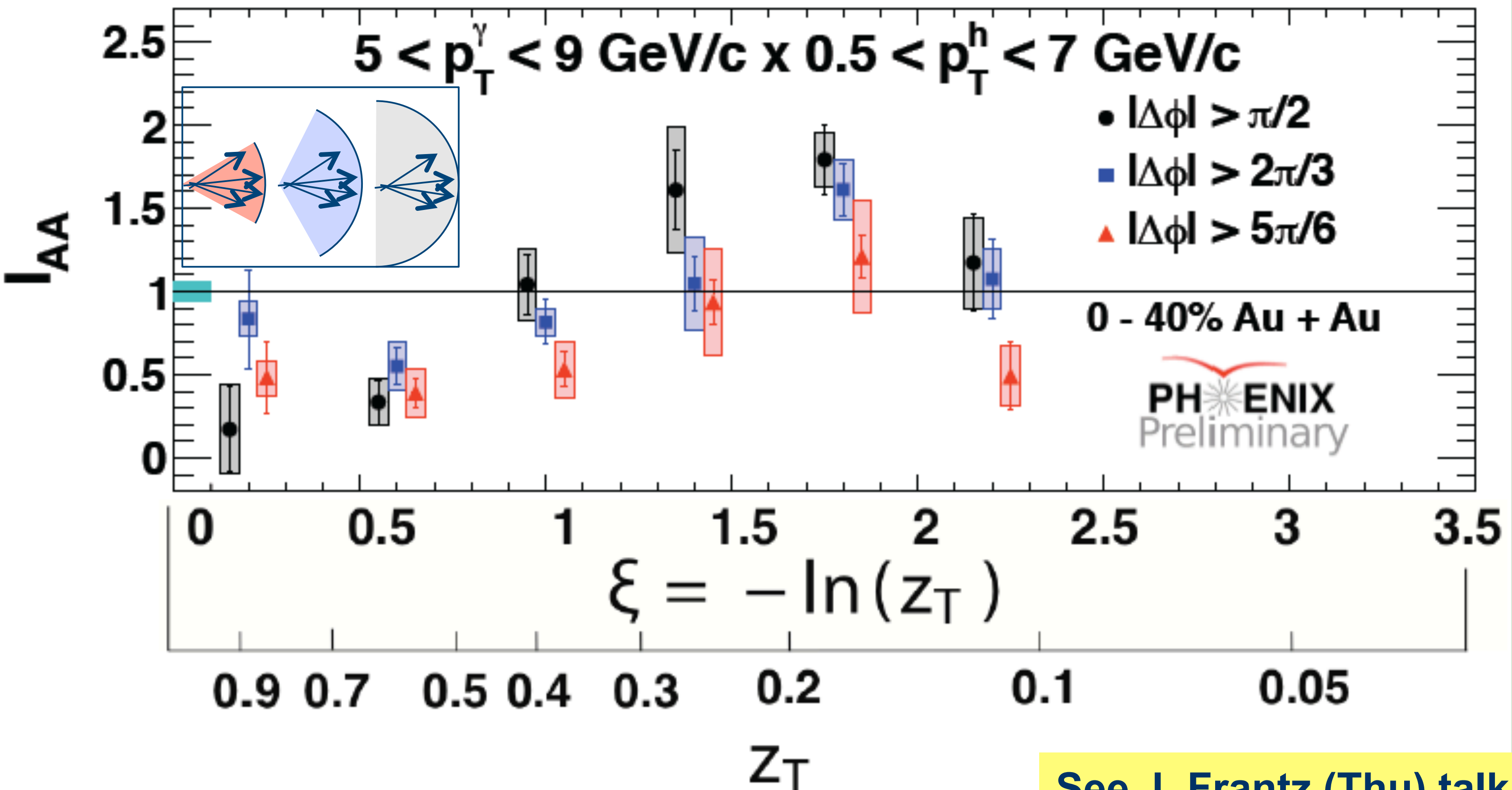


Awayside widths suggest jet broadening, but they are highly-dependent on v_3 modulation.
Further information is needed about v_2^{jet}, v_3^{jet} (possible correlation of jets with reaction plane / participant planes)…

γ-h correlation in Au+Au

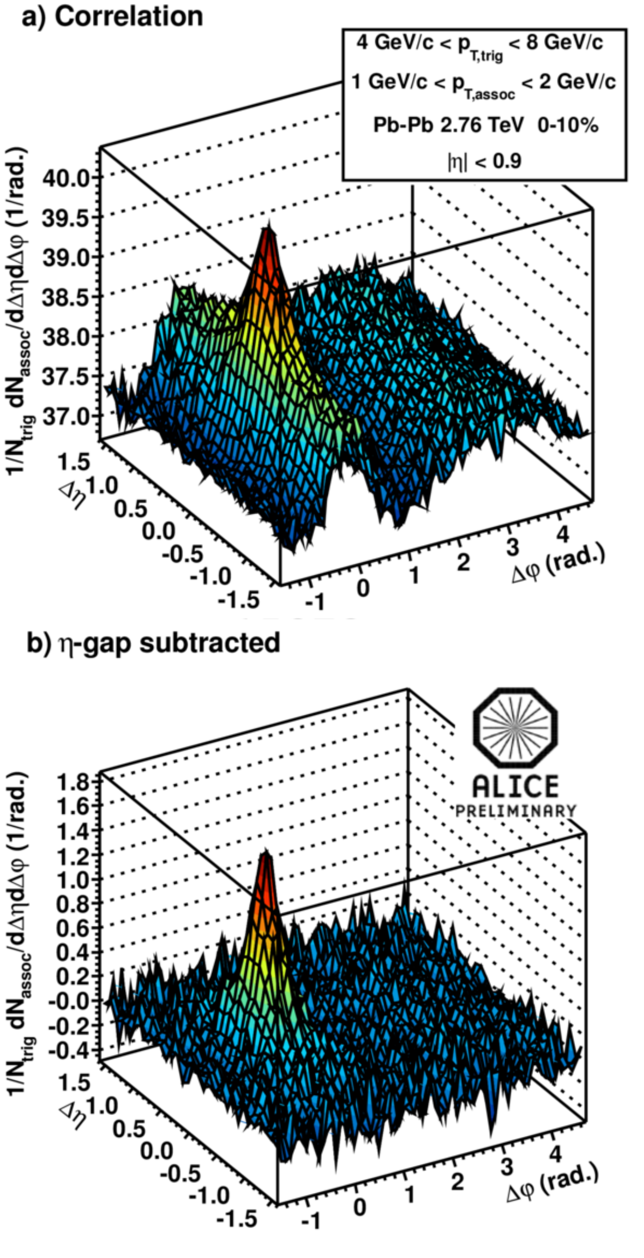
$$I_{AA} \equiv \frac{(1/N_{trig} dN/d\xi)_{AA}}{(1/N_{trig} dN/d\xi)_{pp}}$$

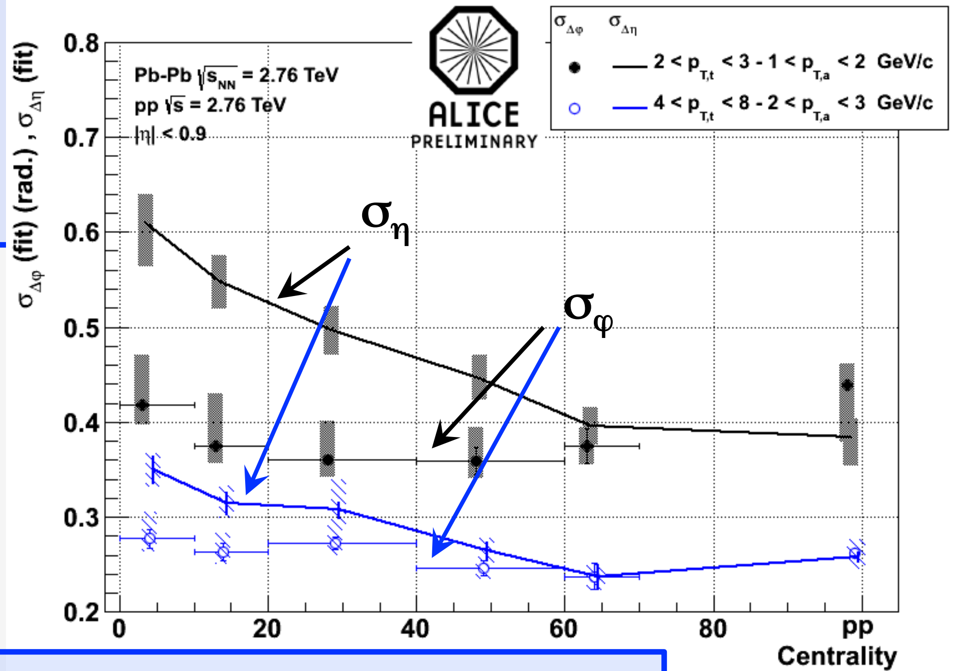
Low z_T away side particles distributed over wider angle



See J. Frantz (Thu) talk

Near-side (jet-like) structure



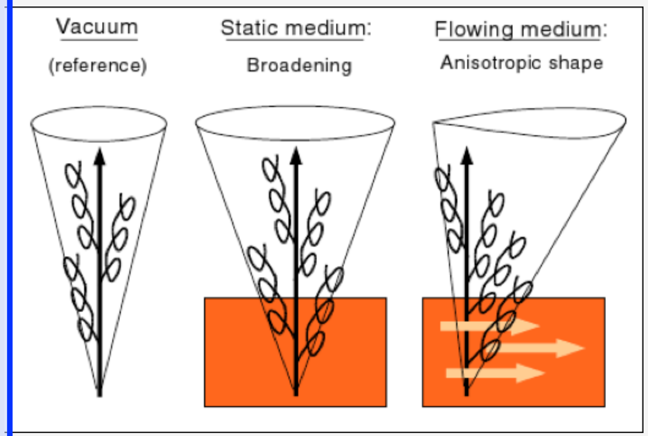


Talks by
A.M.Adare
F.Krizek

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?

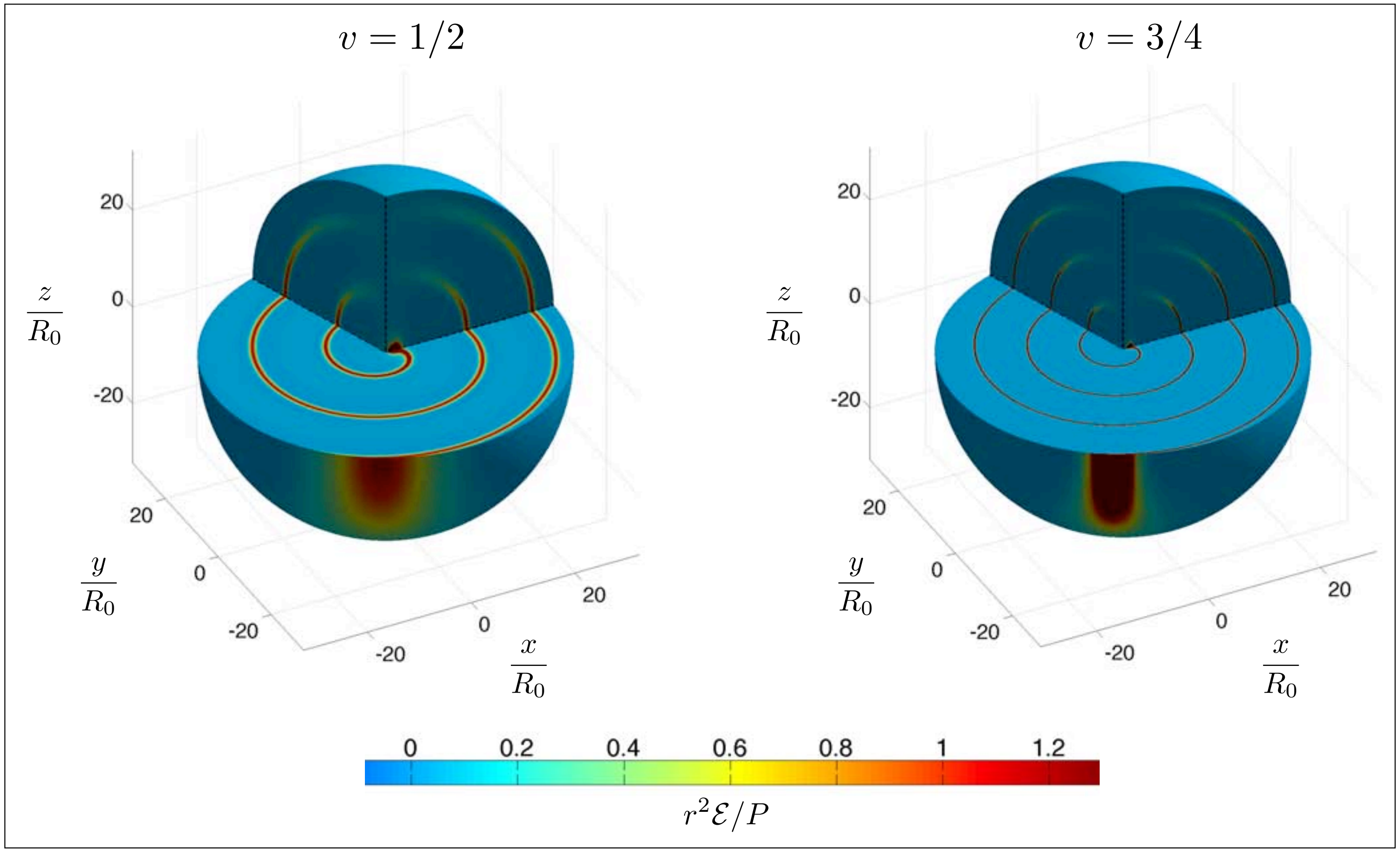


N.Armesto et al., PRL 93, 242301

- 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 strongly coupled approaches 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 beams of gluons... and ‘jets’ ...

Synchrotron Radiation in Strongly Coupled Gauge Theories

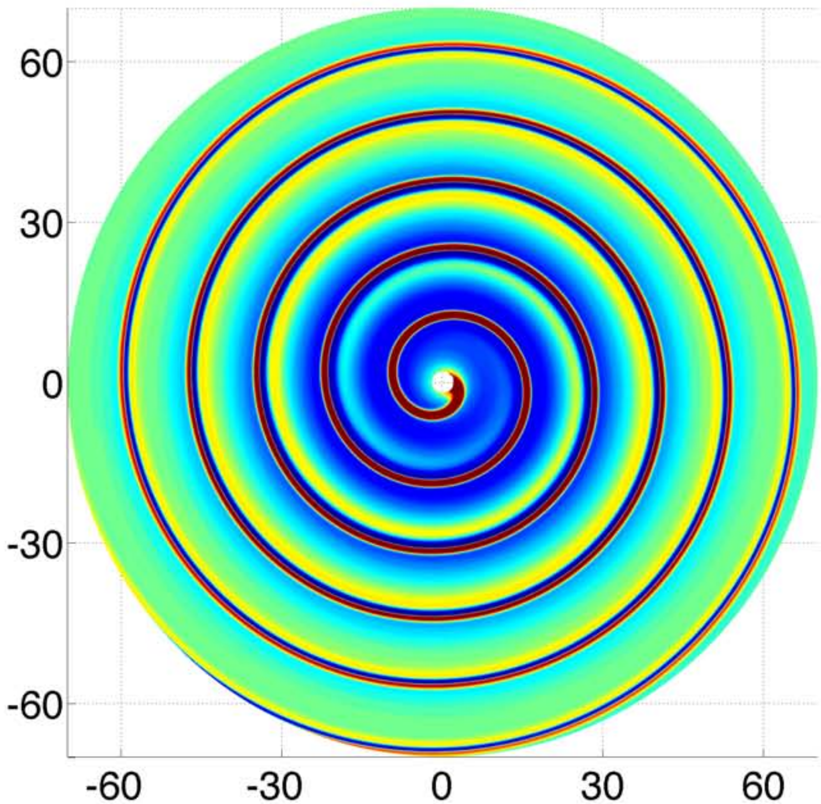
Athanasiou, Chesler, Liu, Nickel, Rajagopal; arXiv:1001.3880

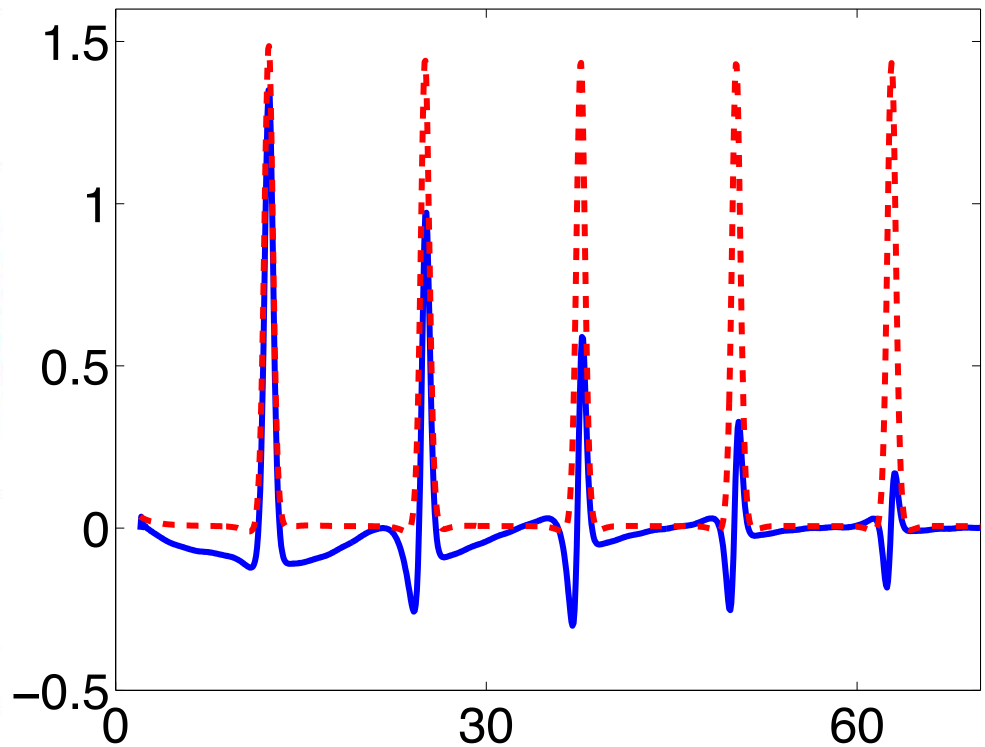


Fully *quantum mechanical* **calculation of gluon radiation from a rotating quark in a** *strongly coupled* **large** N_c *non abelian* **gauge theory, done via gauge/gravity duality. "Lighthouse beam" of synchrotron radiation. Surprisingly similar to classical electrodynamics. Now, shine this beam through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

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691

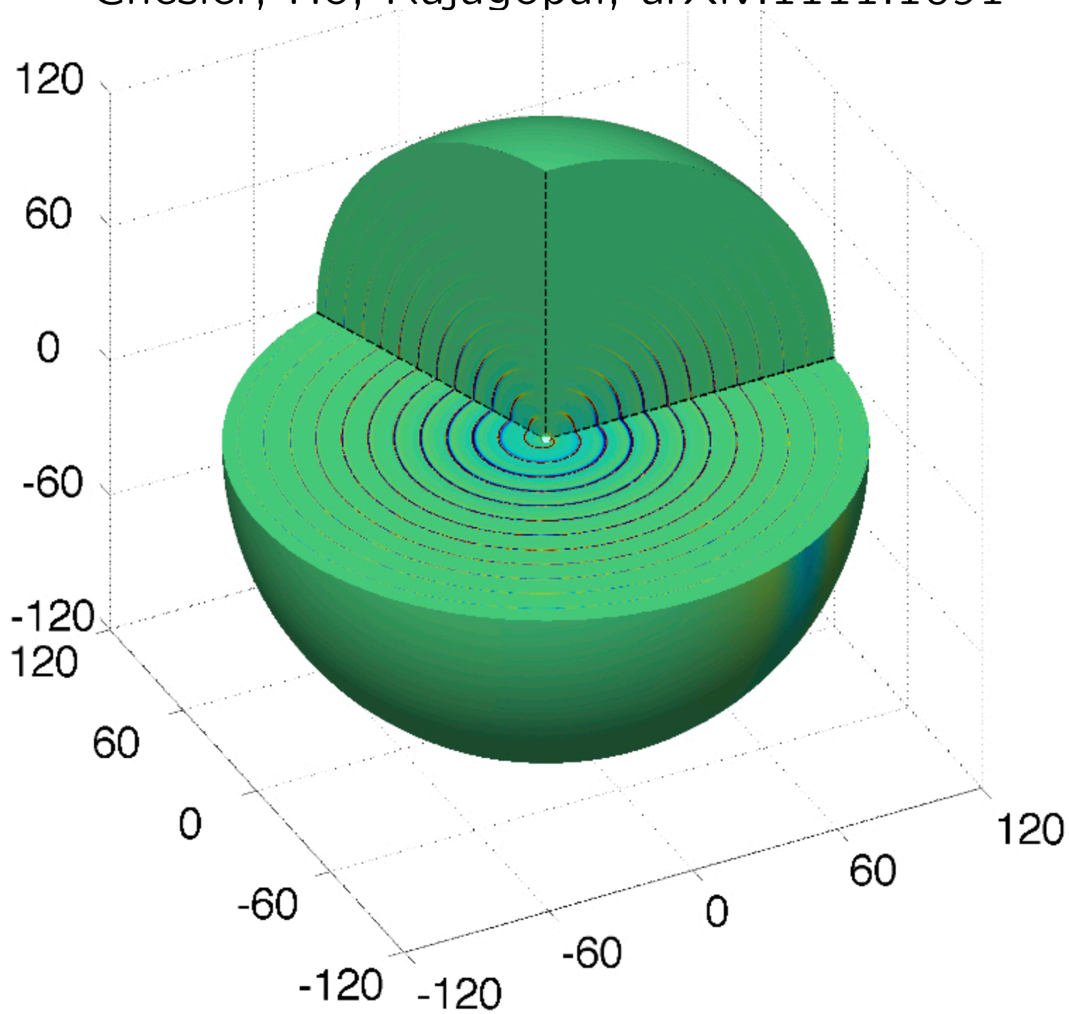




Quark in circular motion makes a beam of gluons that is attenuated dramatically by the plasma, without being significantly broadened — in angle or in momentum distribution.

Quenching a Beam of Gluons

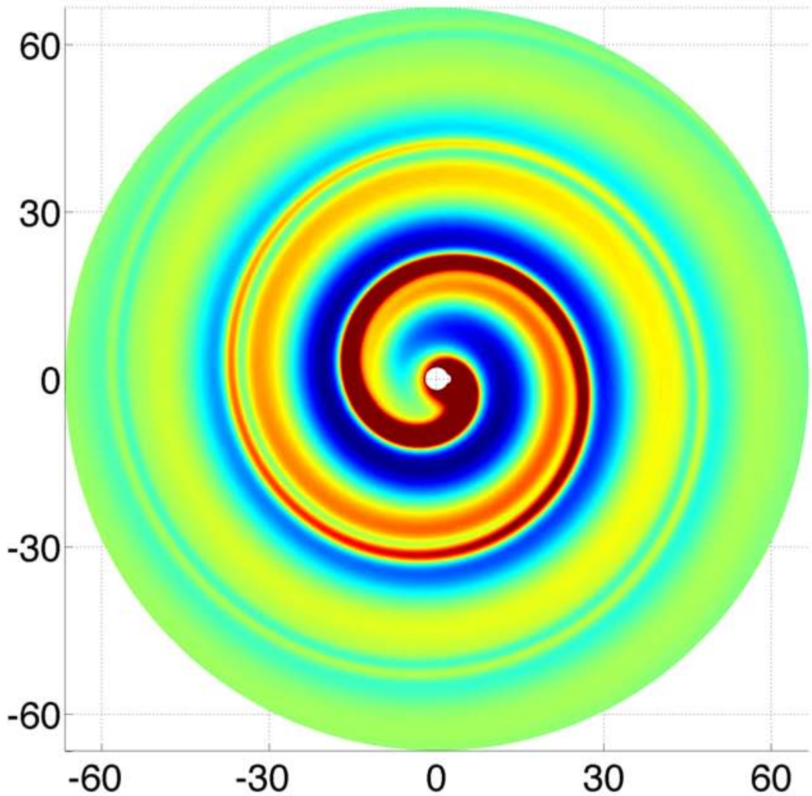
Chesler, Ho, Rajagopal, arXiv:1111.1691

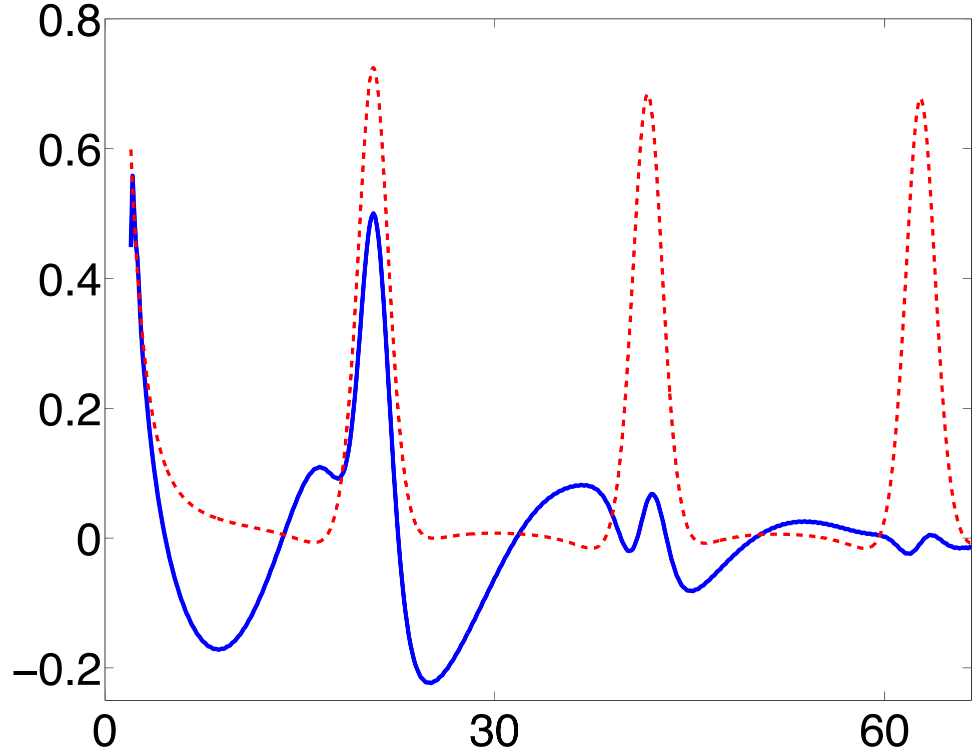


A narrower beam made of higher momentum gluons travels farther, still gets attenuated without spreading in angle or degradation of its momentum distribution.

Quenching a Beam of Gluons

Chesler, Ho, Rajagopal, arXiv:1111.1691





Beam of lower momentum gluons 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.)**

What happens to the lost energy?

- **Initially, sound waves with wave vector $\sim \pi T$.**
- **The attenuation distance for sound with wave vector q is**

$$x^{\rm sound}_{\rm damping} = v^{\rm sound} \frac{1}{q^2} \frac{3Ts}{2\eta}$$

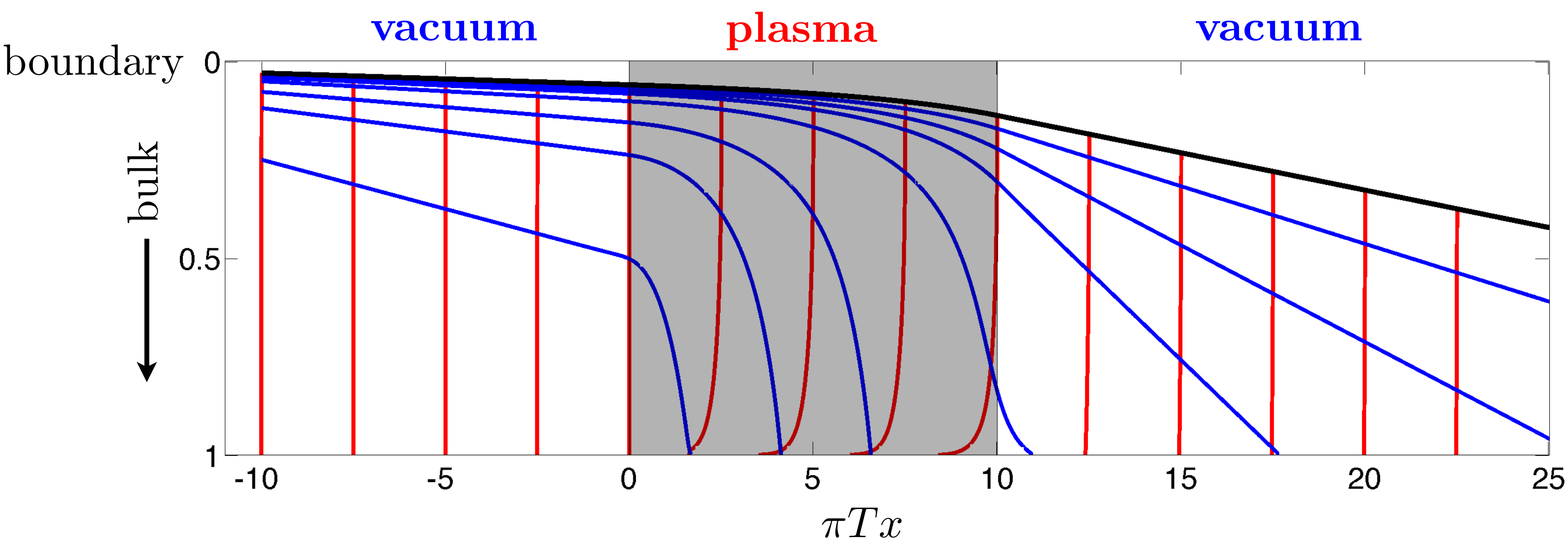
which means that for $q \sim \pi T$ and $v^{\rm sound} \sim 1/\sqrt{3}$ and $\eta/s \sim 2/4\pi$ we have

$$x^{\rm sound}_{\rm damping} \sim 0.6/T \ .$$

- **Energy lost more than a few times $x^{\rm sound}_{\rm damping}$ before the jet emerges will have thermalized, becoming soft particles in random directions. Only the energy lost a few $x^{\rm sound}_{\rm damping}$ before the jet emerges will persist as sound waves moving in roughly the same direction as the jet, resulting in a pile of soft particles around the jet. This should be easier to see for lower energy jets, and in lower temperature plasma.**

Quenching a Light Quark 'Jet'

Chesler, Rajagopal, in progress



A light quark 'jet' with its string attached, incident energy $E \sim 205\pi T$, 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 $E \sim 85\pi T$; looks *just* like a vacuum 'jet' with that energy. Entire calculation of energy loss is geometric! (Blue lines: null geodesics in the bulk.)**

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.

Light Quark Energy Loss

Chesler, Jensen, Karch, 2008; Arnold, Vaman, 2010-12

A light quark 'jet' with initial energy $E_{\rm init}$ stops after travelling for a time that is at most

$$t_{\rm stopping} \propto E_{\rm init}^{1/3} T^{-4/3} \ .$$

Aside: this does *NOT* mean $dE/dx \propto x^2 T^4$, as some have misinterpreted.

The light quark loses energy according to

$$\frac{dE}{dt} \propto -\frac{E_{\rm init}^{2/3}\, T^{4/3}}{\sqrt{1 - t/t_{\rm stopping}}}$$

whose solution is

$$E(t) = E_{\rm init}\sqrt{1 - t/t_{\rm stopping}}$$

and which can therefore be written as

$$\frac{dE}{dt} \propto -\frac{E_{\rm init}^{5/3} T^{4/3}}{E(t)}.$$

For $t \ll t_{\rm stopping}$, i.e. for light quarks (or gluons) that have not lost a large fraction of their energy and so have $E(t)$ not $\ll E_{\rm init}$, this becomes

$$\frac{dE}{dt} \propto -E^{2/3} T^{4/3}.$$

So, not quite friction. Lets call it "friction".

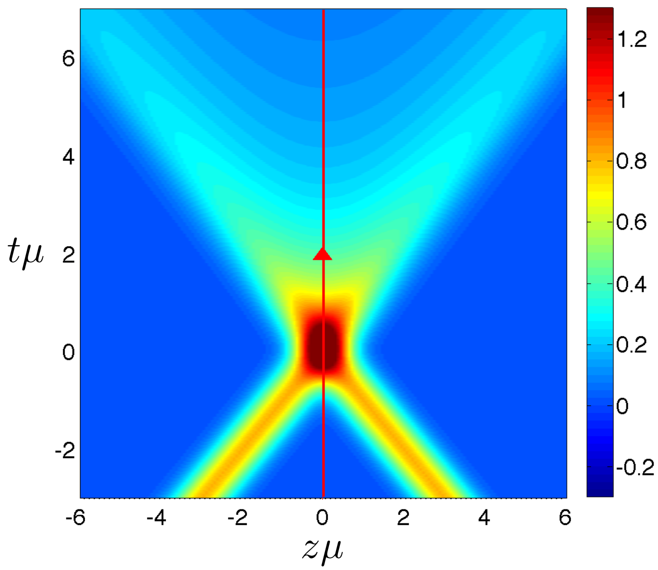
A Hybrid Weak+Strong Coupling Approach to Jet Quenching?

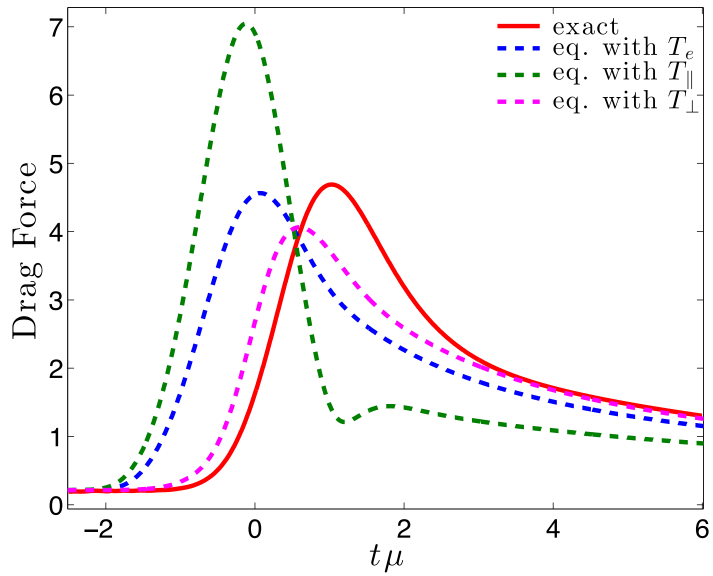
Casalderrey-Solana, Gulhan, Milhano, Pablos, Rajagopal, in progress

- **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.**
- **Motivates hybrid approaches. Eg each parton in a pQCD parton shower losing energy to "friction" à la light quarks in strongly coupled liquid, with $dE/dx \propto -E^{2/3}T^{4/3}$.**
- **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





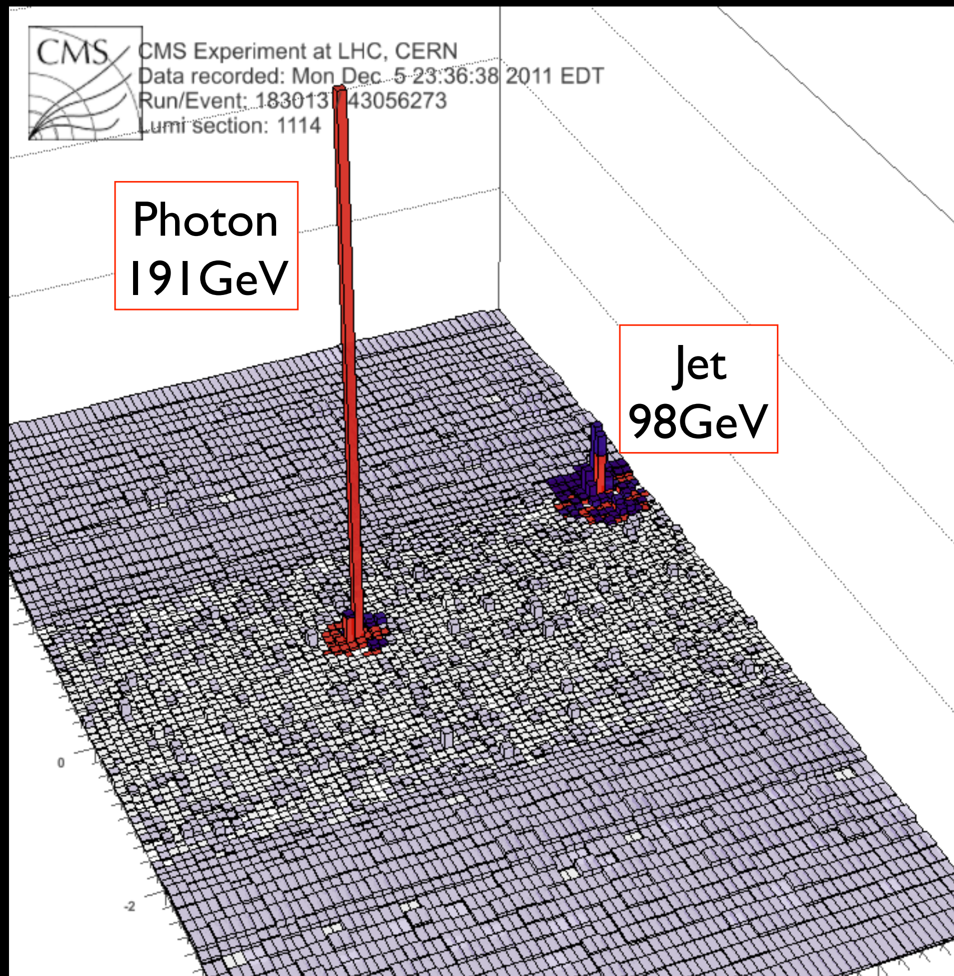
- Drag force on a heavy quark moving with $\beta = 0.95c$ through far-from-equilibrium matter, and then anisotropic fluid, made in the collision of two sheets of energy in strongly coupled $\mathcal{N} = 4$ SYM theory.
- Guidance for modeling heavy quark energy loss early in a heavy ion collision: at mid-rapidity, eqbm expectations provide a reasonable guide to magnitude, but there is a time delay. Surprises at nonzero rapidity (not shown).
- Analytic calculation of effect of $\vec{\nabla} v^{\text{fluid}}$ on energy loss seems possible. Lekaveckas, Rajagopal, in progress.

Weakly Coupled q & g in Liquid QGP

D'Eramo, Lekaveckas, Liu, Rajagopal, 1211.1922

- **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.)**
- **γ-jet events: γ 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

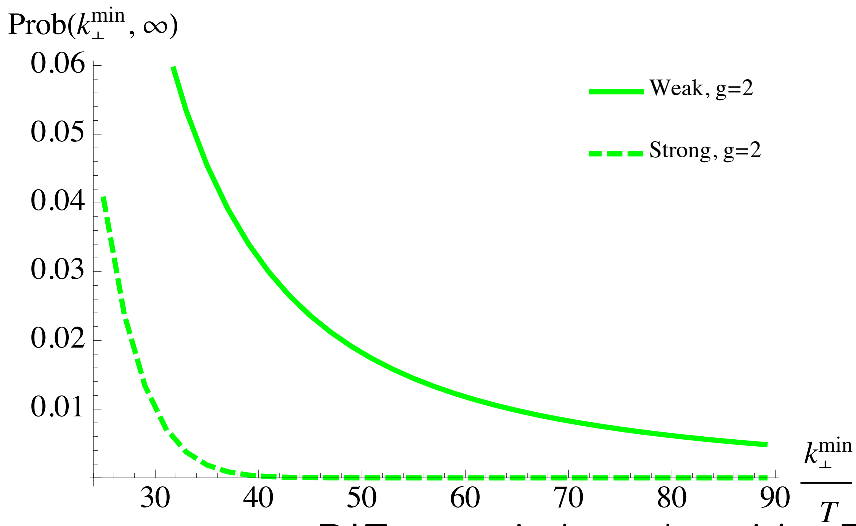
Momentum Broadening in Weakly Coupled QGP

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.**

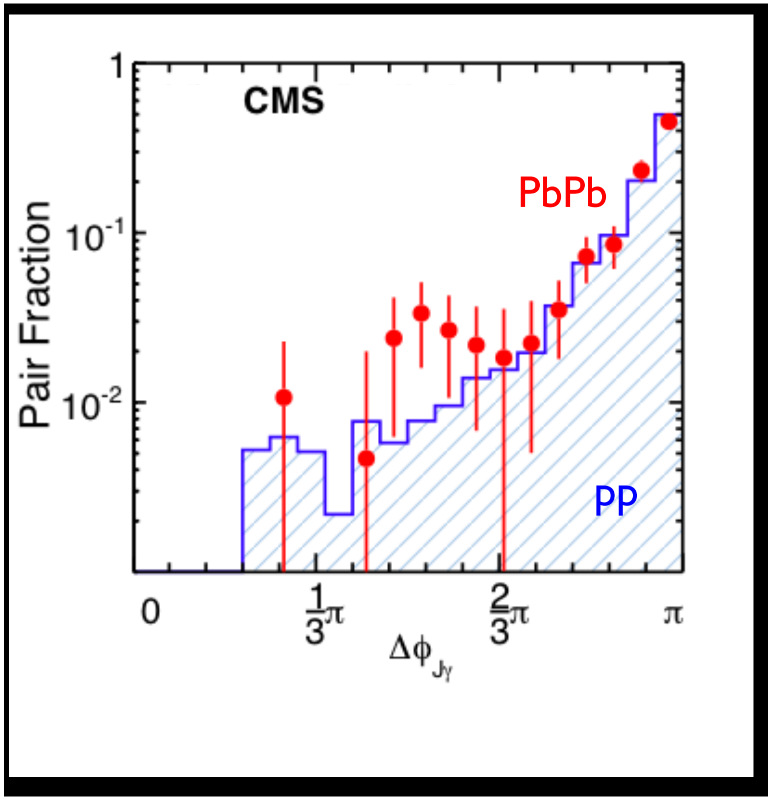
Expect Gaussian at low $k_\perp$, with power-law tail at high $k_\perp$. Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.



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

- **Probability that a parton that travels $L = 7.5/T$ through the medium picks up $k_\perp > k_{\perp\mathrm{min}}$, for:**
  - **Weakly coupled QCD plasma, in equilibrium, analyzed via SCET+HTL. With $g = 2$, i.e. $\alpha_{\mathrm{QCD}} = 0.32$.**
  - **Strongly coupled $\mathcal{N} = 4$ SYM plasma, in equilibrium, analyzed via holography. With $g = 2$, i.e. $\lambda_{\mathrm{'t\ Hooft}} = 12$.**
- **Eg for $T = 300$ MeV, $L = 5$ fm, a 60 GeV parton that scatters by 20° picks up $k_\perp = 70\,T$. Prob. $\sim 1\%$ vs. negligible.**
- **Large deflections rare, but not as rare as if the liquid were a liquid on all scales. They indicate point-like scatterers.**

Measure the angle between jet and photon



CMS, arXiv:1205.0206

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

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.

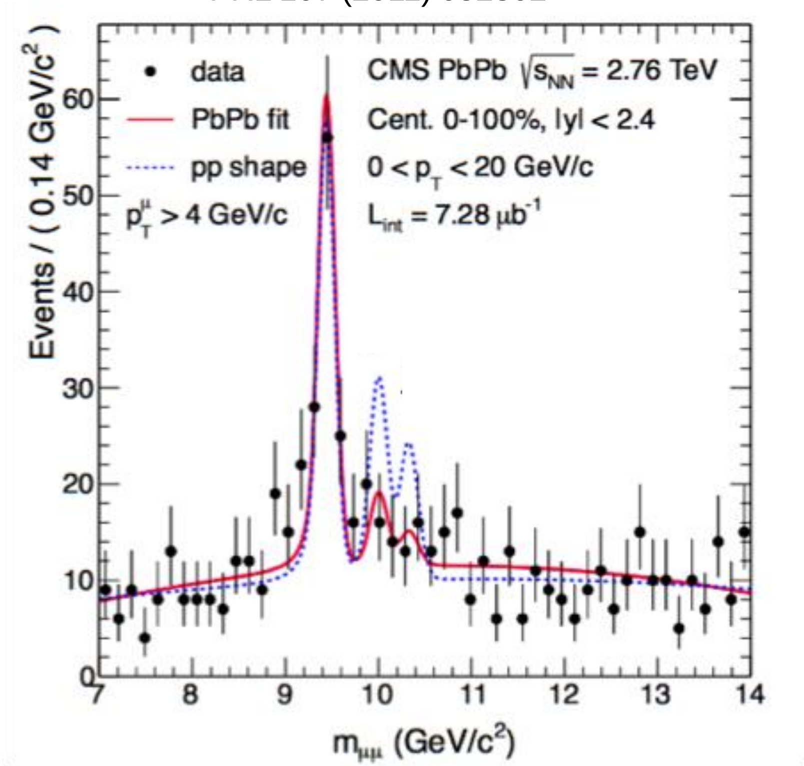
Heavy quarks? Upsilons?

- **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.**

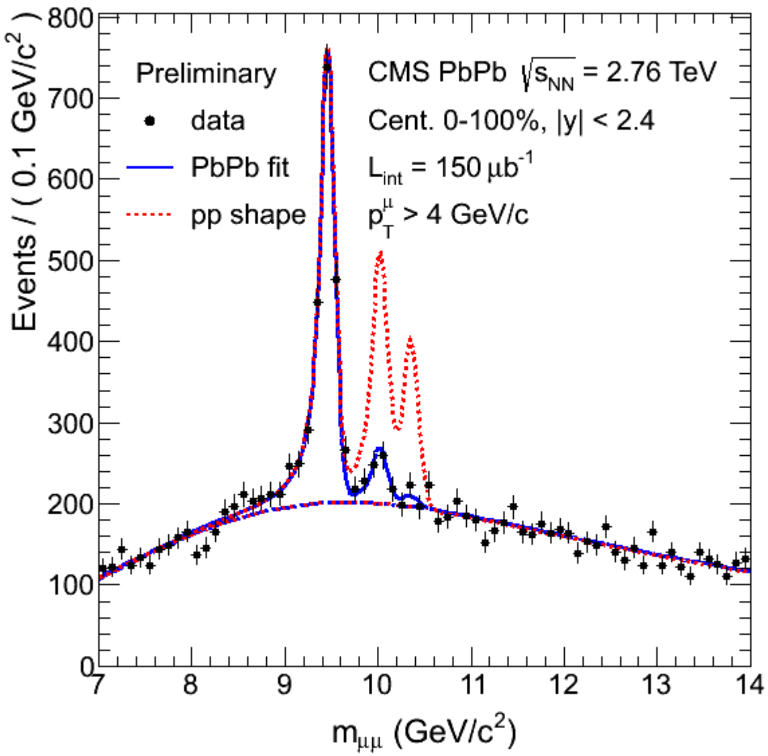
Sequential Upsilon suppression

2010 data

PRL 107 (2011) 052302



2011 data



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

Observation of sequential suppression of Y family
→Detailed studies