Looking at Protons Through a QGP Lens

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2026 Simons Collaboration on Confinement
and QCD Strings Workshop
MIT; Cambridge, MA; May 18, 2026

Quark-Gluon Matter
Under Pressure

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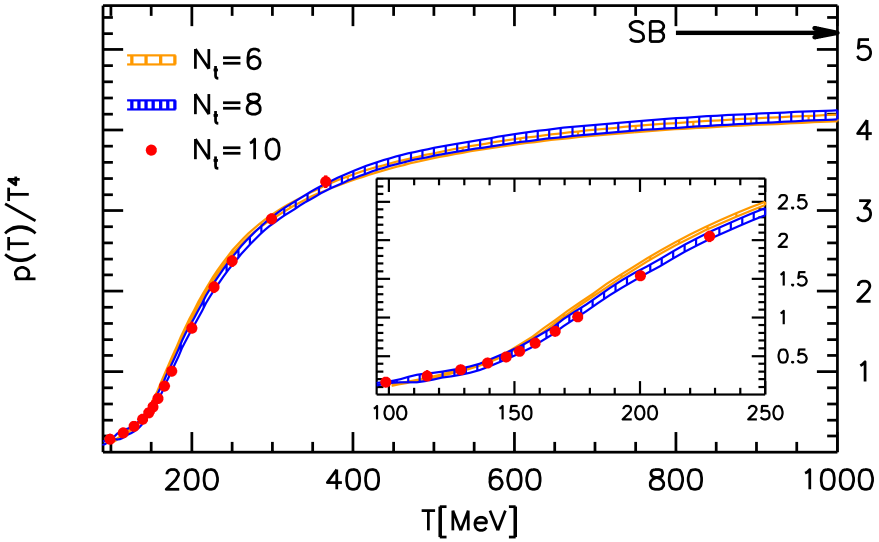
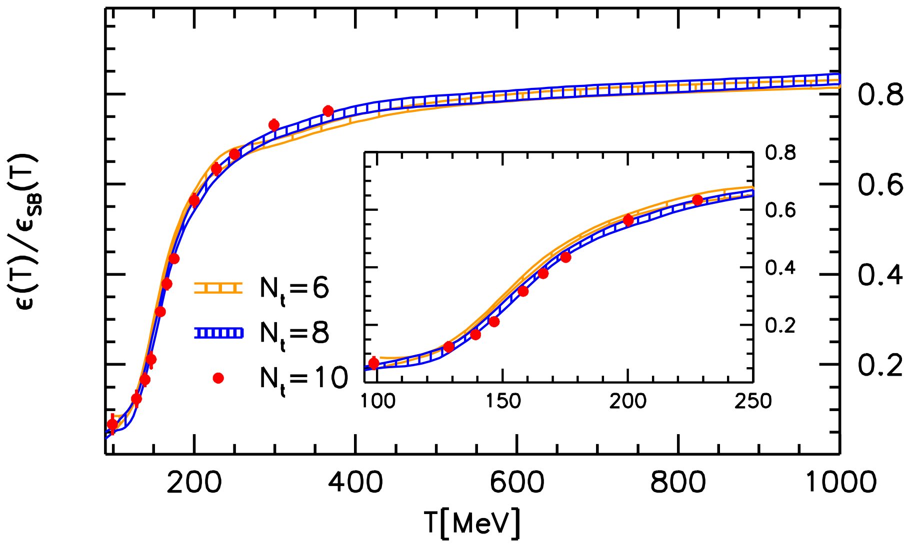
QGP Thermodynamics

Endrodi et al, 2010





Above $T_{\text{crossover}} \sim$ 150 MeV (1.7 trillion degrees), QCD = QGP. QGP pressure and energy and entropy can be calculated reliably.

P(5 trillion degree quark matter)=P(430 MeV quark matter) $=2.5\times10^{31}$ atmospheres!! Hot quark matter, under pressure! $=7\times10^{24}\times$ pressure at the center of the earth...

BUT: Although its pressure is almost that of ideal, noninteracting gas, QGP, this stuff is *very* different in its dynamical properties...

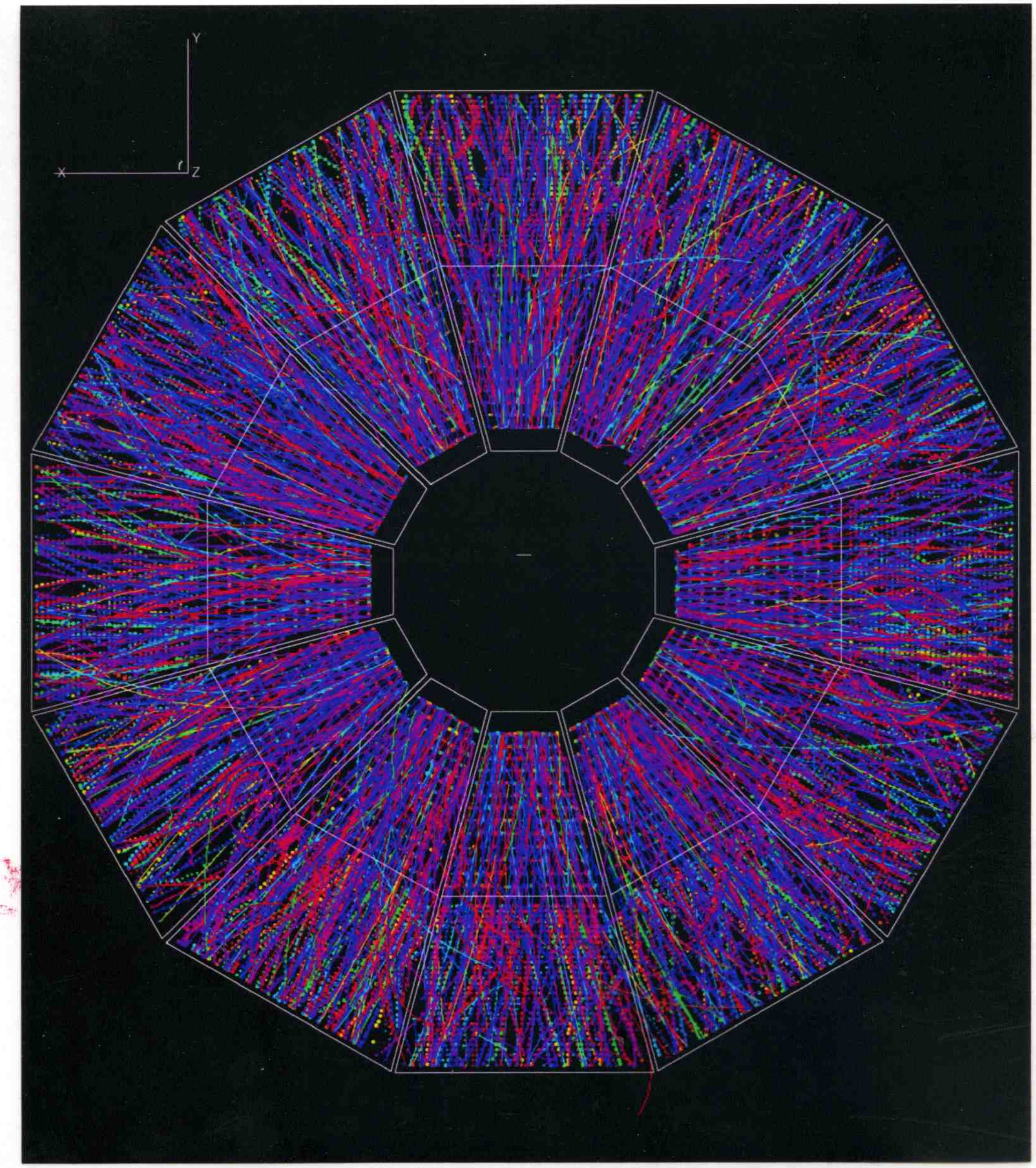
Hot Quark Matter Dynamics

- Understanding what hot quark matter is *actually* like, how it behaves, had to wait until scientists reproduced droplets of it!! By accelerating, and colliding, heavy nuclei to make droplets of hot quark matter.

- In 1983, Busza and Goldhaber calculated that collisions with energies > 100 GeV were needed. Almost a factor of 100 greater than accelerators could produce in 1983.

- Since 2000, the Relativistic Heavy Ion Collider, RHIC at Brookhaven National Lab near New York, achieves 200 GeV collisions of Au nuclei. Since 2010, the Large Hadron Collider, LHC at CERN near Geneva, achieves 2700-5000 GeV collisions of Pb nuclei.

- Recreating "Little Bangs". Only 10^{-14} m in size. Hot quark matter explodes, expands, cools, forms ordinary protons and it's cousins within 10^{-22} seconds.



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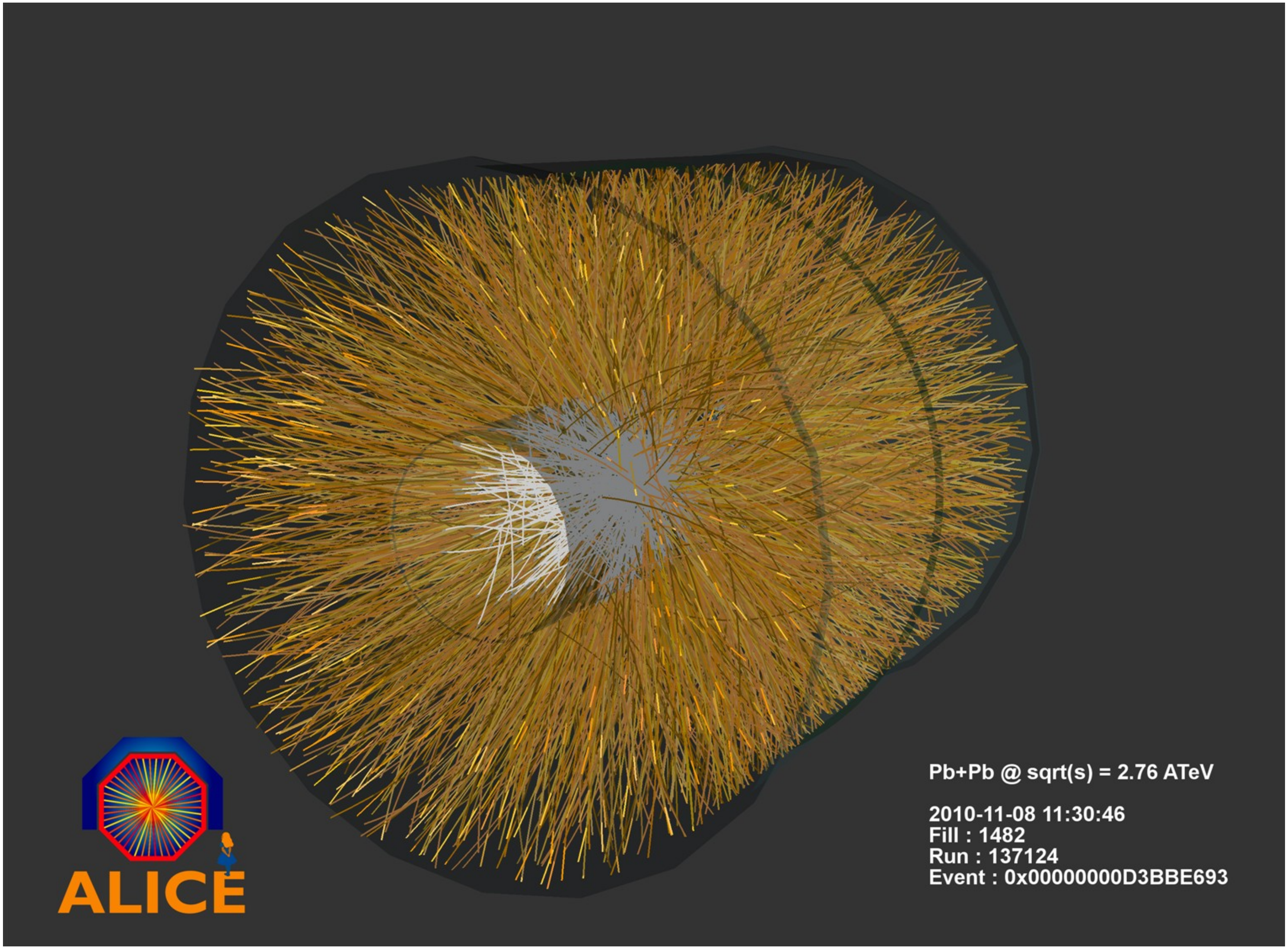

Pb+Pb @ sqrt(s) = 2.76 ATeV

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Hot Quark Matter Dynamics

- Understanding what hot quark matter is *actually* like, how it behaves, had to wait until scientists reproduced droplets of it!! By accelerating, and colliding, heavy nuclei to make droplets of hot quark matter.
- These collisions really are making little droplets of hot big bang matter!
- But what we see is the debris, after the hot matter has exploded.
- How can we learn about the behavior of the hot matter produced in the collision? What have we learned?

Hot Quark Soup!

- Surprise! By 2005, analyses of RHIC data on how *asymmetric* blobs of hot Big Bang matter expand (explode) revealed that trillions-of-degrees-hot quark matter is a LIQUID!!

- Rutherford looked for "pudding", and unexpectedly found point-like nuclei in atoms. Friedman, Kendall and Taylor unexpectedly found point-like quarks in protons.
  This surprise has the opposite character! Looking for a hot gas, found a hot liquid.

- Hot quark soup turns out to be *very* liquid-like. Less internal dissipation as it flows (quantified via a parameter called η/s) than in all other known liquids except one.

- The discovery that it is a strongly coupled liquid makes hot quark soup interesting to a broader scientific community. (Much more interesting than a gas.)

- How was this discovery made? Not à la Rutherford...

Ultracold Fermionic Atom Fluid

- The one terrestrial fluid with η/s comparably small to that of QGP.

- NanoKelvin temperatures, instead of TeraKelvin.

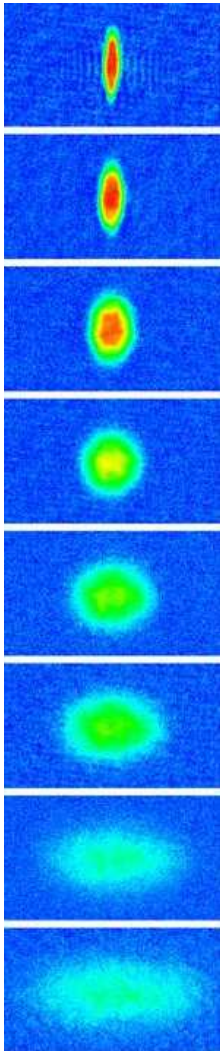
- Ultracold cloud of trapped atoms, with their interactions tuned to be infinite. A strongly coupled liquid indeed.

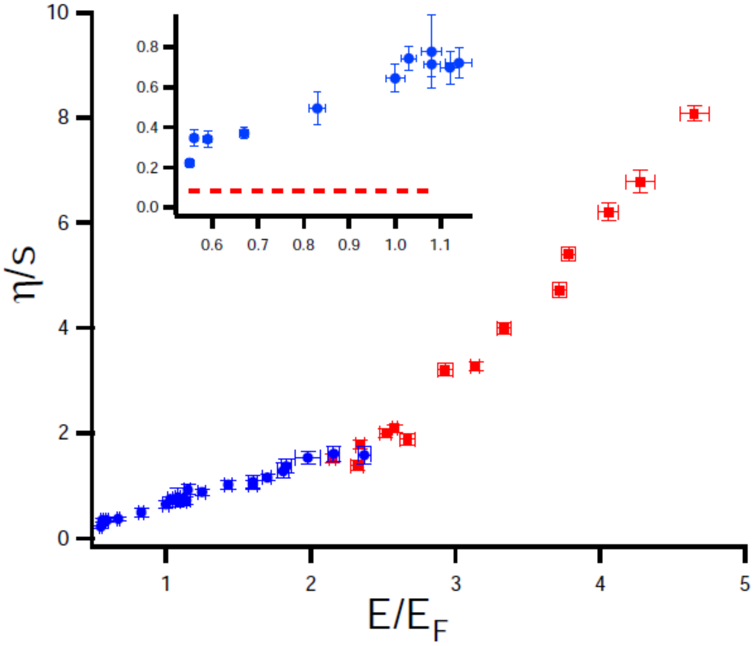
- Data on hydrodynamic flow patterns can be used to extract η/s as a function of temperature$\ldots$

Viscosity to entropy density ratio

consider both collective modes (low T)

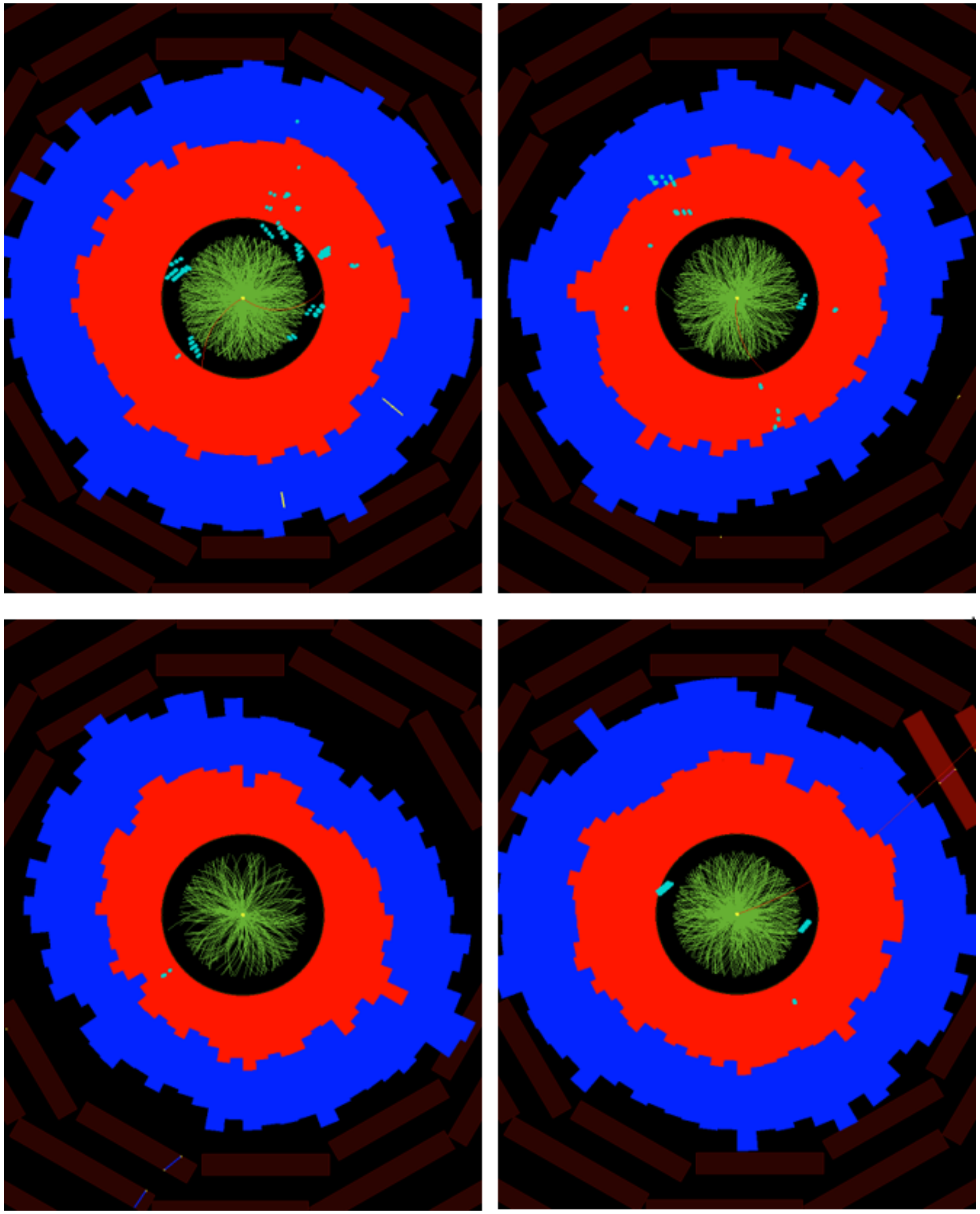
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



Hot Quark Soup!

- **Hydrodynamic analyses of how asymmetric blobs of hot Big Bang matter (produced in off-center collisions) explode reveal a very liquid-like liquid, with $0.1 < \eta/s < 0.2$.**

- **η/s is between 1 and 10 for ordinary liquids, and is > 100 for gases. Hot quark soup is "more hydrodynamic than the original hydro".**

- **Quarks and gluons in hot quark soup diffuse, without being confined in protons. Hot quark soup flows. Quarks and gluons are always bumping into each other. Very much *not* a gas; mean free paths so short as to be hard to define.**

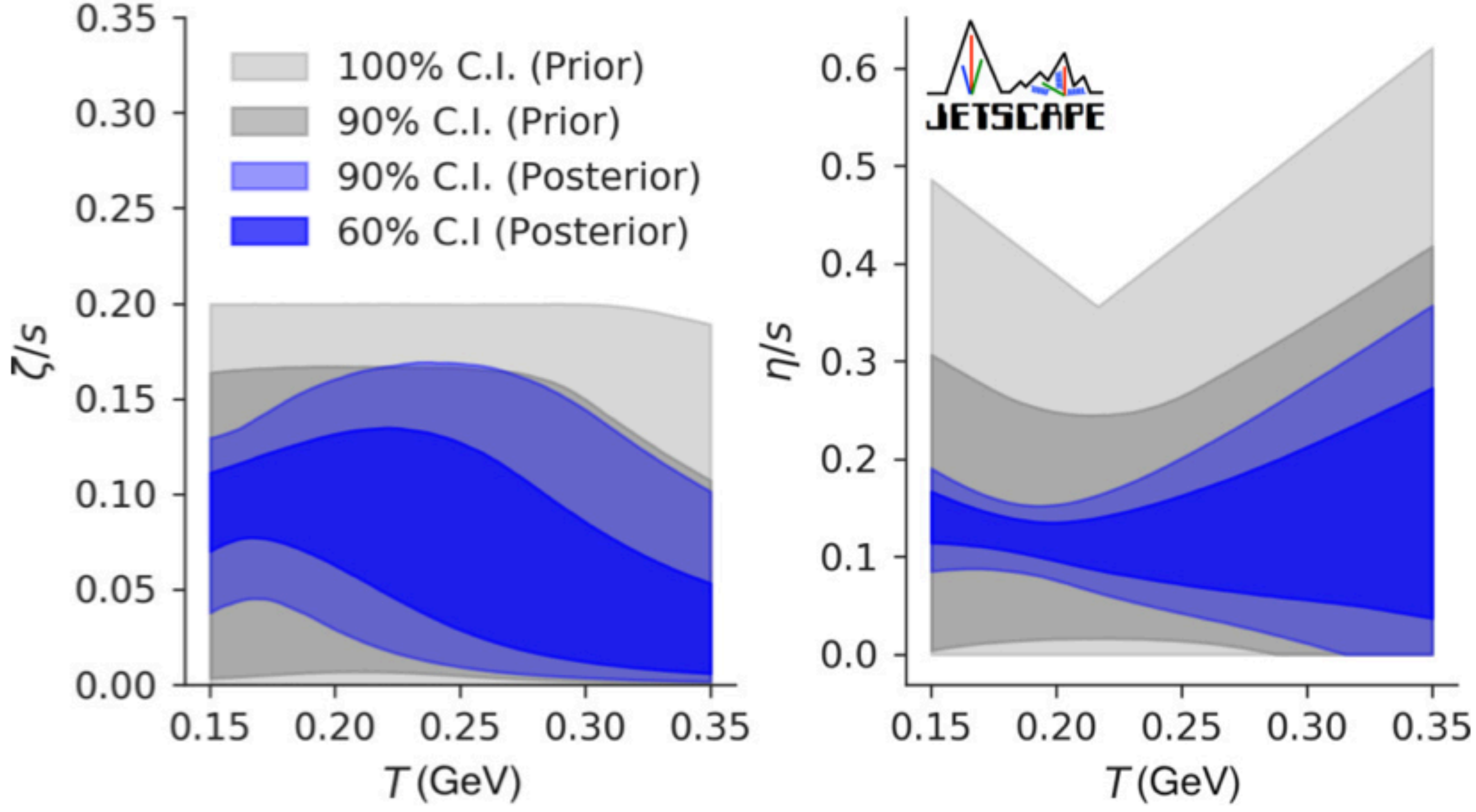
- **Quarks and gluons are *not* confined — but also *not* free.**

- **Aside: $\eta/s = 1/(4\pi) \approx 0.08$ for the "hot soup phases" in all known QCD-like theories with strongly coupled phases that are "holograms" of a 4+1-dimensional gravity theory "heated by" a 3+1-dimensional black hole.**

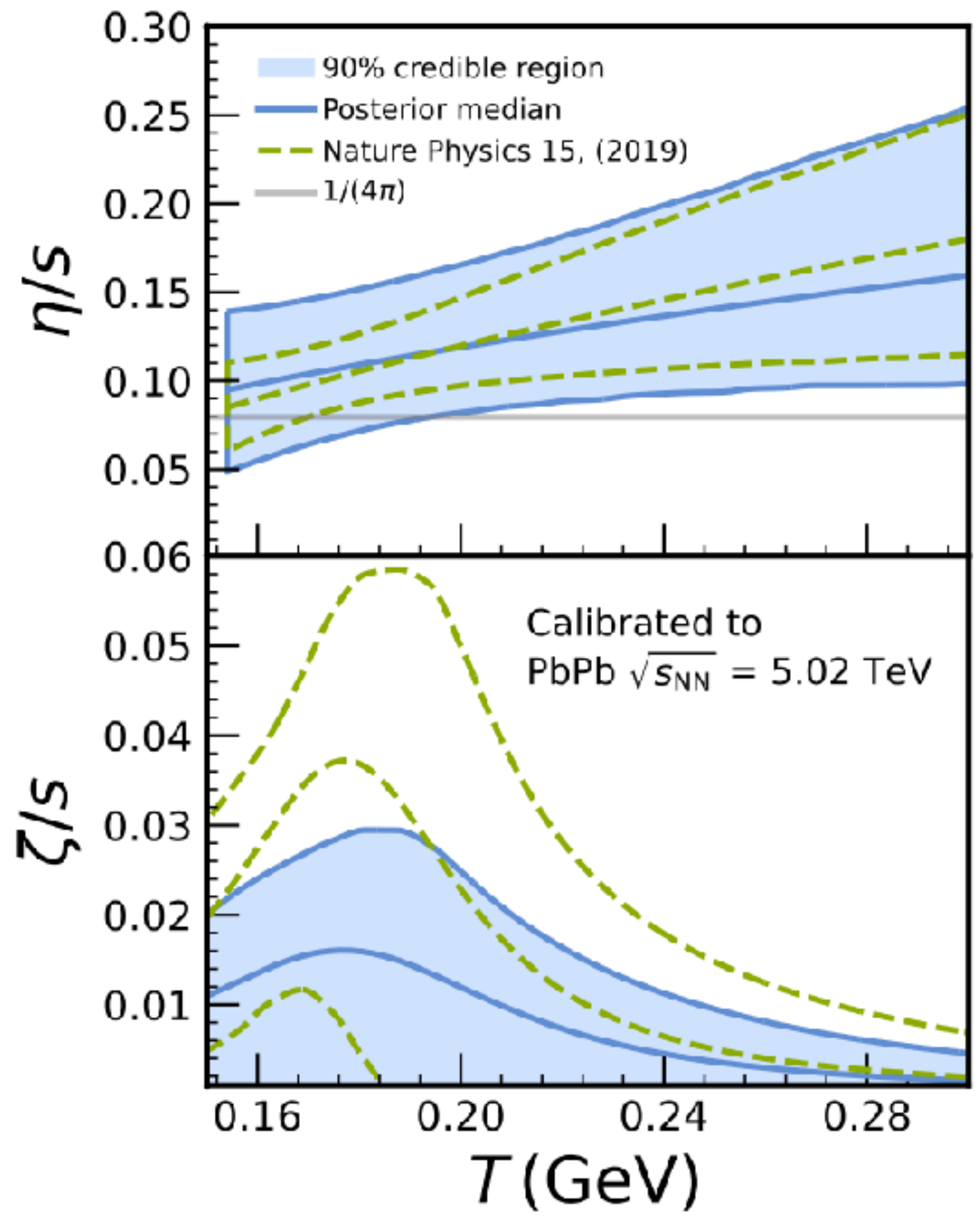
Bulk EoS: Non-equilibrium

Combined Bayesian analysis of Au+Au (RHIC) and Pb+Pb (LHC)

JETSCAPE, Phys. Rev. C **103** (2021) 054904

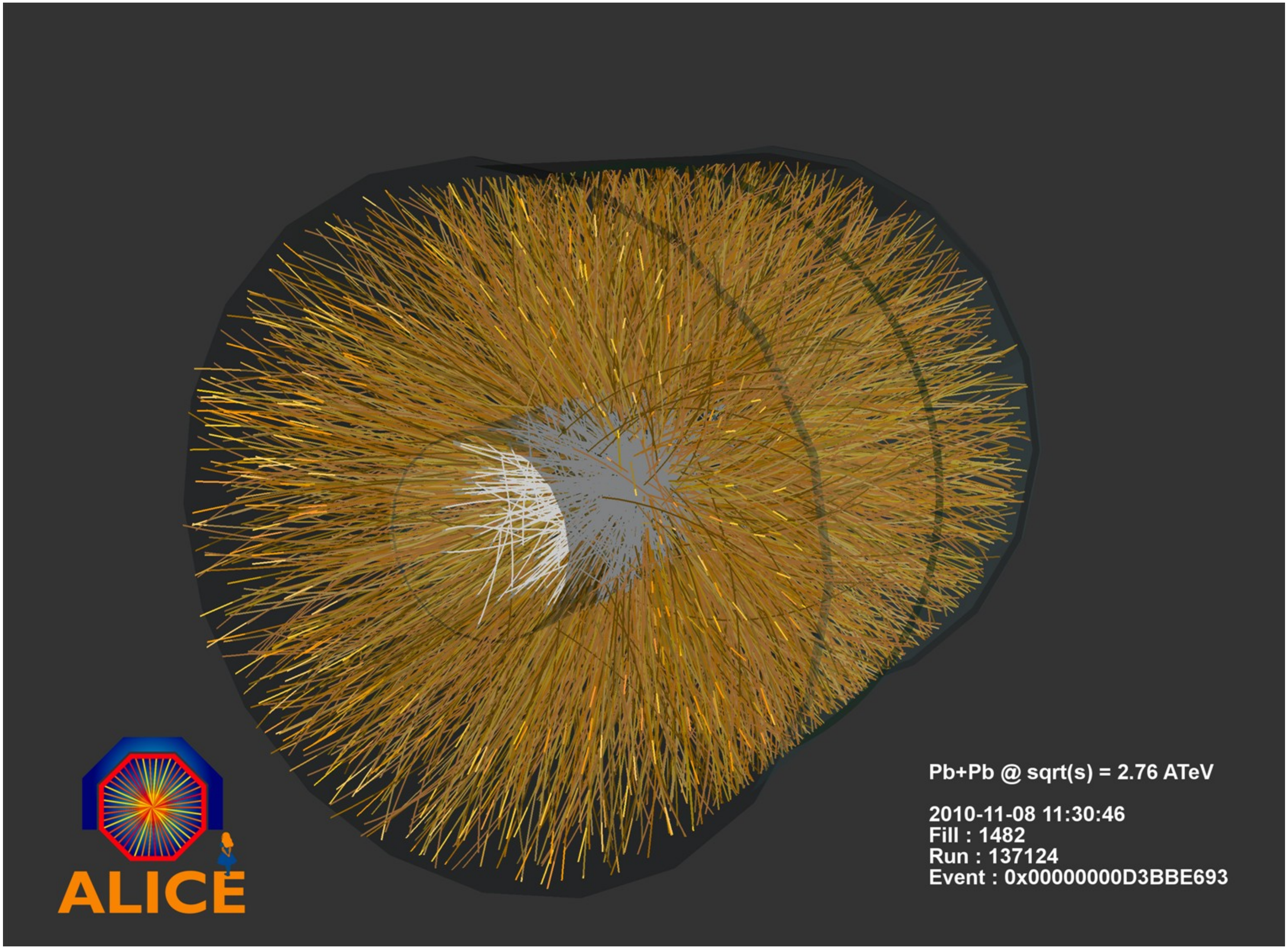


Parkkila, Onnerstad & Kim,
Phys. Rev. C **104** (2021) 054904



Hot Quark Soup, Under Pressure

- What does hot quark soup, with a pressure greater than 2×10^{31} atmospheres, do??
- If it fills the entire universe, it expands "slowly". It takes $\sim 10-20$ microseconds to cool, and fall apart into a mist of protons. (That continues to expand, and form structure, over the next 13 billion years.)
- If you make a little droplet of the stuff, with nothing around it, it explodes!
- And, the shape of the explosion tells you about the shape of the droplet, and about its liquidness.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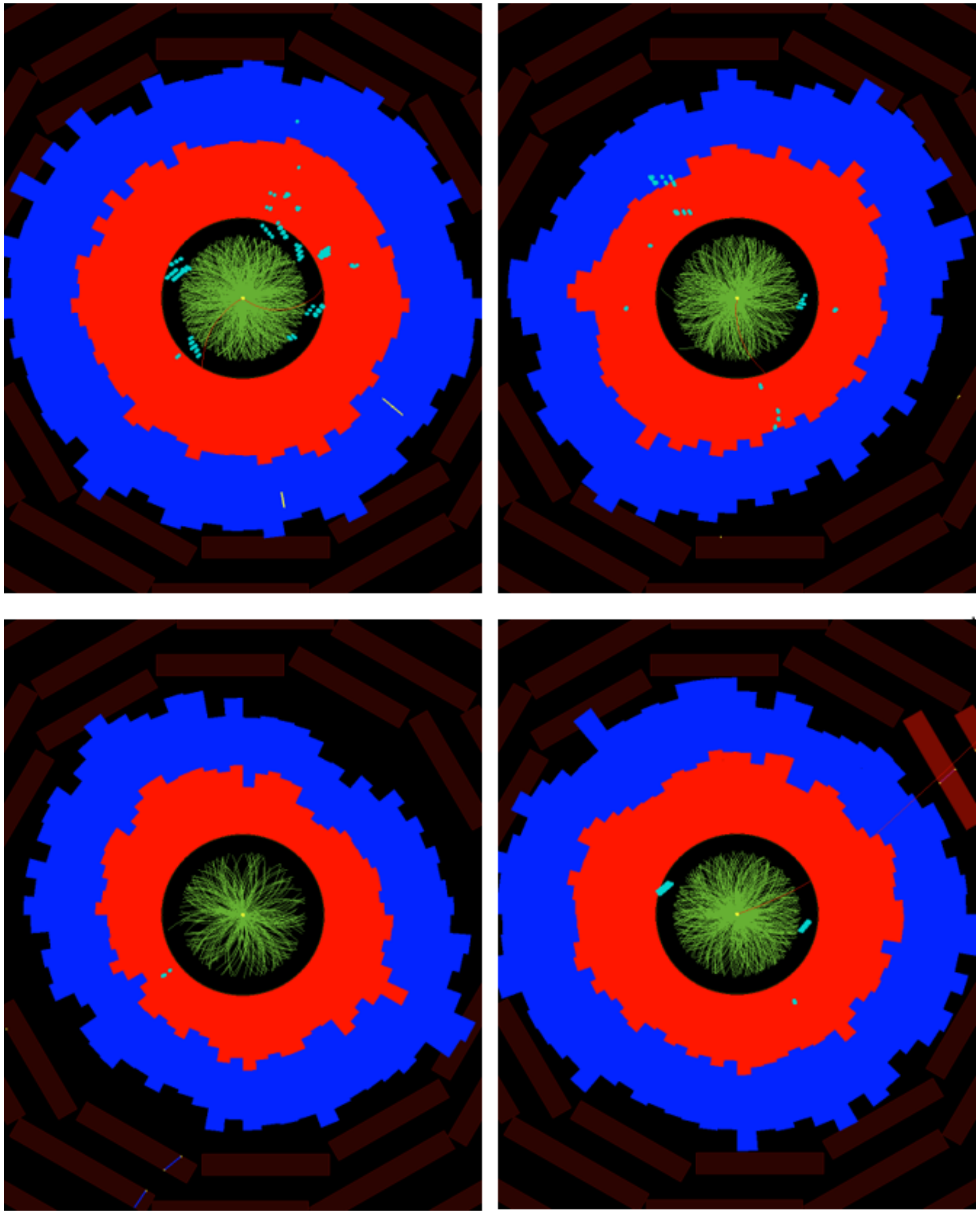


Heavy Ion Collisions: What Next?

By recreating droplets of the matter that filled the microseconds-old universe in ultrarelativistic heavy ion collisions, we have discovered a liquid that, as far as we now know, is:

- The first liquid that ever existed; the “original liquid”...
- The liquid from which the protons and neutrons in today’s universe formed, as the liquid fell apart into mist.
- At a few trillion degrees, the hottest liquid that has ever existed.
- The earliest complex form of matter.
- The most liquid liquid that has ever existed, with a specific viscosity $\eta/s \sim 0.1$.
- In a sense the simplest form of complex matter, namely in the sense that it is “close” to the fundamental degrees of freedom of the standard model.

All great discoveries pose new challenges...

What Next?

Two kinds of What Next? questions for the coming decade. . .

- A question that one asks after the discovery of any new form of complex matter: What is its phase diagram? For high temperature superconductors, for example, phase diagram as a function of temperature and doping. Same here! For us, doping means excess of quarks over anti-quarks, rather than an excess of holes over electrons.
- A question that we are privileged to have a chance to address, after the discovery of “our” new form of complex matter, which is so close to the fundamentals: How does the strongly coupled liquid emerge from laws governing quarks and gluons? Maybe answering this question could help to understand how strongly coupled matter emerges in other contexts.

Probing the Original Liquid

- The question How does the strongly coupled liquid emerge from the fundamental laws governing quarks and gluons? is one of today's most active research frontiers.
- Seeing the inner workings of hot quark soup.
- First step to seeing what they are doing is we need to "see" the individual quarks and gluons that make up the liquid. Need a high-resolution, fast shutter-speed, look at one quark or gluon at one moment.
- Need to do for hot quark soup what Rutherford did for atoms and Friedman, Kendall and Taylor did for protons.
- Need to probe the liquid, see how the liquid responds, *and watch how the probe scatters*.
- Can't bring a drop of Big Bang matter from Geneva to Stanford to image it with an electron beam; it only lives for 10^{-22} seconds! Have to use a probe made in the same collision that makes the drop of hot quark soup. Jets!

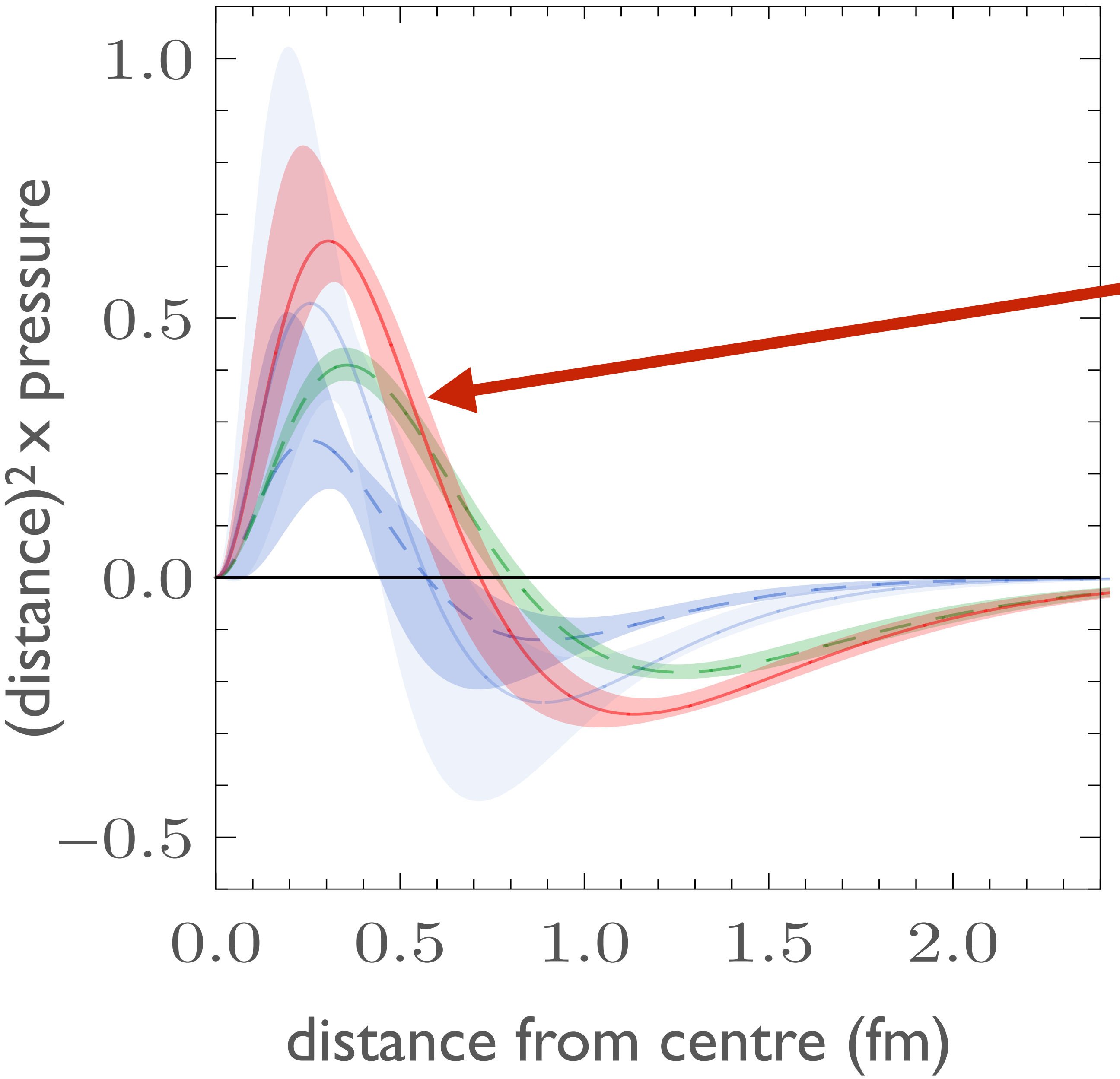
Why Jets?

- The remarkable utility of hydrodynamics, eg. in describing the dynamics of small lumps in the initial state in heavy ion collisions, tells us that to see the inner workings of hot quark soup, namely to see how the liquid is put together from quarks and gluons, we will need probes with fine resolution.
- Jets in heavy ion collisions provide best chance for scattering off a droplet of hot Big Bang matter to see its inner workings à la Rutherford.
- Jets in heavy ion collisions *also* offer best chance of watching how the droplet responds. Jets leave a wake in the droplet of liquid. Can we see how this wake ripples and dissipates? Jets are our best shot at seeing this, too.
- → not easy to decode the wealth of info that jets contain! Need high statistics LHC and sPHENIX data; and need to use today's data to build baseline of understanding.

Quark-Gluon Matter Under Pressure

- **Where else do we find quark-gluon matter under pressure?**
- **In a proton!! Protons form from tiny drops of QGP, 10-20 microseconds after the big bang, or 10**$^{-22} - 10^{-21}$ **seconds after a HIC. What is the pressure inside a proton?**
- **Answer:** $\sim$ **(0.07-0.7) GeV/fm**^{3} $\sim (1.1 - 11) \times 10^{29}$ **atmospheres!** [Extracted from SIDIS data (Burkert, Elouadrhiri, Girod, '18) and from lattice calculations (Shanahan, Detmold '18; Pefkou, Hackett, Shanahan '21, '23)]
- **This is pressure of QGP at** $T = T_p \sim 155 - 200$ **MeV, at or just above** T **at which it falls apart into a mist of protons!**
- **Remarkably, protons have kept this high interior pressure since they formed.**
- **Even more remarkably, protons don't explode! That is the essence of confinement — which squeezes/compresses a tiny bit of 155 MeV QGP into each proton at its birth.**

Pressure inside the proton



Total pressure
including **gluon**
(lattice QCD) and
quark (experiment)
contributions

- Total pressure by combining theory + experiment
- Peak pressure near centre $\sim 10^{35}$ Pascal, greater than estimated for neutron stars
- Gluons extend radial pressure distribution

[*Phys.Rev.Lett.* 122, 072003 (2019), *Phys.Rev.D* 99, 014511 (2019), *Phys.Rev.D* 108, 114504 (2023), *Phys.Rev.Lett.* 132, 251904 (2024)]

[V. D. Burkert et al, Nature 557 (2018)]

Quark-Gluon Matter Under Pressure

- Where else do we find quark-gluon matter under pressure?

- In a proton!! Protons form from tiny drops of QGP, 10-20 microseconds after the big bang, or $10^{-22} - 10^{-21}$ seconds after a HIC. What is the pressure inside a proton?

- Answer: $\sim$ (0.07-0.7) GeV/fm^3. This is the pressure of QGP at $T = T_p \sim 155 - 200$ MeV, at or just above T at which it falls apart into a mist of protons!

- Note: spherical droplet of QGP with $V_p \equiv 938$ MeV$/\varepsilon(T_p)$, $\varepsilon(T)$ from lattice QCD, and radius 0.86 fm / 0.49 fm has $T_p =$ 155/200 MeV, ie. ε and pressure of a proton.

- Remarkably, protons have kept this high interior pressure since they formed.

- Even more remarkably, protons don't explode! That is the essence of confinement — which squeezes/compresses a tiny bit of 155 MeV QGP into each proton at its birth.

Entropy of Protons through a QGP Lens

- **If pressure in a proton is pressure of hot quark-gluon plasma with** $T = T_p \sim 155 - 200$ **MeV**...
- **What about entropy? The hot QGP from which one proton forms after the Big Bang has** $S_{\text{thermal}} \sim (5.2 - 7.3)k_B$**. Isn't the entropy of a proton zero? What about the second law of thermodynamics?**
- **Quantum state of a proton has** *entanglement entropy*. **Three estimates, each qualitative, with different uncertainties:** $(7{-}8)k_B$; $(7{-}8)k_B$; $(5{-}9)k_B$ [Kharzeev, KR, arXiv:2605.19058]
- **Thermal entropy from Big Bang QGP → entanglement entropy inside protons → released as thermal entropy (and more entropy produced) when nuclei collide.**
- **Confinement (the essence of confinement?) as the rearrangement of thermal entropy into entanglement entropy!**

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

- One estimate (that I won't describe today) extrapolates from past work quantifying longitudinal entanglement entropy of struck parton in DIS with the other partons.
- Second estimate (that I also won't describe today) is an attempt to use basic facts that we know about protons to estimate the entanglement entropy of the three valence quarks, by tracing over all the rest.
- Both give similar rough estimate: $S_{\text{entanglement}}/k_B \sim 7-8$, with uncertainties hard to quantify, but different.
- Third estimate starts by taking seriously the notion that a proton has an internal effective temperature $T_p \ldots$. Although $\rho = |p\rangle\langle p|$ has $\mathrm{Tr}\rho \ln \rho = 0$, if we decompose the Hilbert space into resolved (infrared) and unresolved (ultraviolet) sectors, the reduced density matrix $\rho_{\text{IR}} = \mathrm{Tr}_{\text{UV}}|p\rangle\langle p|$ can take an approximately thermal form.

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058; with thanks to Mark Srednicki

- **A somewhat formal argument, that does not yield a quantitative estimate. . .**
- **If $E_p = \mathrm{Tr}\rho_p H$, where the reduced density matrix of the proton takes the thermal form**

$$\rho_p = \frac{1}{Z(T_p)} e^{-H/T_p} \;, \qquad Z(T_p) = \mathrm{Tr} e^{-H/T_p}$$

where T_p is some effective internal temperature characterizing the entanglement spectrum of the quantum state of the proton, not the temperature of an external bath, then

- **formally, equating $E_p = \mathrm{Tr}\rho_p H = -\partial/\partial\beta \ln Z$ serves to fix T_p in terms of E_p.**
- **Then, $S/k_B = -\mathrm{Tr}\rho_p \ln \rho_p$. Voilà!**

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

- **A somewhat informal argument, that yields an estimate** . . .
- **A proton has a Hagedorn density of excited states with invariant mass M: $\rho_p^H(M) = A_p \exp(M/T_H)/(M^2+M_r^2)^{5/4}$ where a fit to masses of $>$ 3000 hadrons gives $M_r = 0.5$ GeV, $T_H = 0.1672$ GeV, and $A_p < A = 0.4735$ GeV$^{3/2}$.**
- **Take the idea of T_p seriously: probability that proton is found in an excited state with mass M is**

$$p(M) = \frac{1}{Z}\rho_p(M)\exp\left(-\frac{M}{T_p}\right) \qquad Z = \int_{M_p}^{\infty} dM\,\rho_p^H(M)\exp\left(-\frac{M}{T_p}\right)$$

and

$$S/k_B = -\int_{M_p}^{\infty} dM\,\rho_p^H(M)\frac{p(M)}{\rho_p^H(M)}\ln\left(\frac{p(M)}{\rho_p^H(M)}\right) = \int_{M_p}^{\infty} dM\,p(M)\left(\frac{M}{T_p}+\ln Z\right)$$

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

- $\rho_p^H(M) = A_p \exp(M/T_H)/(M^2 + M_r^2)^{5/4}$ **with** $M_r = 0.5$ GeV**,** $T_H = 0.1672$ **GeV, and** $A_p < A = 0.4735$ **GeV**$^{3/2}$**.**

- **Take the idea of** T_p **seriously: probability that proton is found in an excited state with mass** M **is**

$$p(M) = \frac{1}{Z}\rho_p(M)\exp\left(-\frac{M}{T_p}\right) \qquad Z = \int_{M_p}^{\infty} dM\,\rho_p^H(M)\exp\left(-\frac{M}{T_p}\right)$$

and

$$S/k_B = -\int_{M_p}^{\infty} dM\,\rho_p^H(M)\frac{p(M)}{\rho_p^H(M)}\ln\left(\frac{p(M)}{\rho_p^H(M)}\right) = \int_{M_p}^{\infty} dM\,p(M)\left(\frac{M}{T_p} + \ln Z\right)$$

- **Note:** Z **is finite as long as** $T_p < T_H$**. Note:** S **depends on** A_p **only logarithmically; take** $A_p = A/10$**; lack of knowledge of** $\ln A_p/A$ **is a source of uncertainty.**

- **For** $T_p = 155/160/165$ **MeV, we find** $S/k_B = 5.3/6.3/8.5$ **!!!**

- **Third estimate:** $S \sim (5 - 9)k_B$**.**

Entropy of Protons through a QGP Lens

Kharzeev, KR 2605.19058

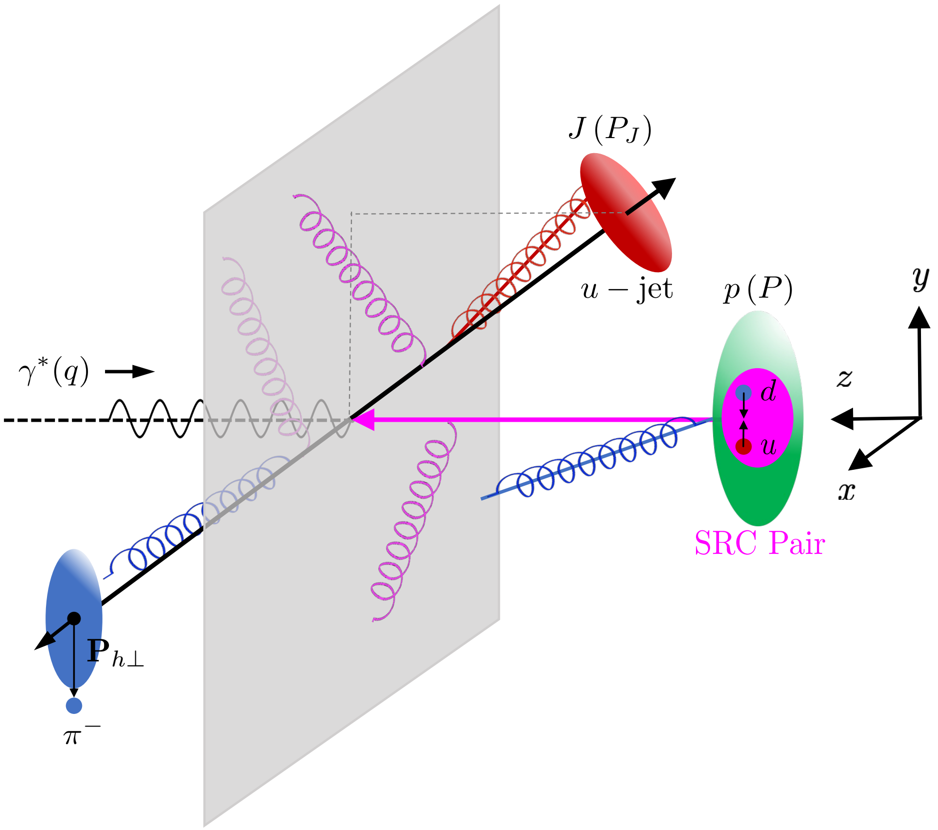
- The agreement between the Gibbs entropy of the drop of QGP from which a proton forms at freezeout and three very different estimates of the internal (entanglement) entropy of a proton could be a quadruple coincidence.
- Or, will poking at this coincidence — and the questions it raises — advance our understanding of confinement, hadron structure, QGP, and the QCD crossover transition?
- How does idea that at the QCD transition Gibbs entropy of QGP rearranges into quantum entanglement entropy within hadrons help us to understand freezeout? Entropy production in collisions? Confinement?

Quark-Gluon Matter, Under Pressure

- **Where else do we find quark-gluon matter under pressure? In a proton!!**
- **Protons form from tiny drops of QGP. The internal pressure, energy density,** *and entropy* **of a proton are comparable to that of the drop of QGP from which it formed.**
- **What further lessons can we learn about the interior of a proton from hot QGP? The same strong correlations that make QGP a liquid, and that give the proton its entanglement entropy, can be directly measured at the Electron-Ion Collider!!** [Peng, KR, Terry, in progress]
- **QGP at temperatures** $\sim T_p$ **is a strongly coupled fluid: strong correlations between the momenta of fluid cells that are near each other in position space. Strong** *Short-Range Correlations*. **How can partonic SRCs be measured at the EIC?** [Peng, KR, Terry, in progress]

An EIC Measurement. . .

[Peng, KR, Terry, in progress]



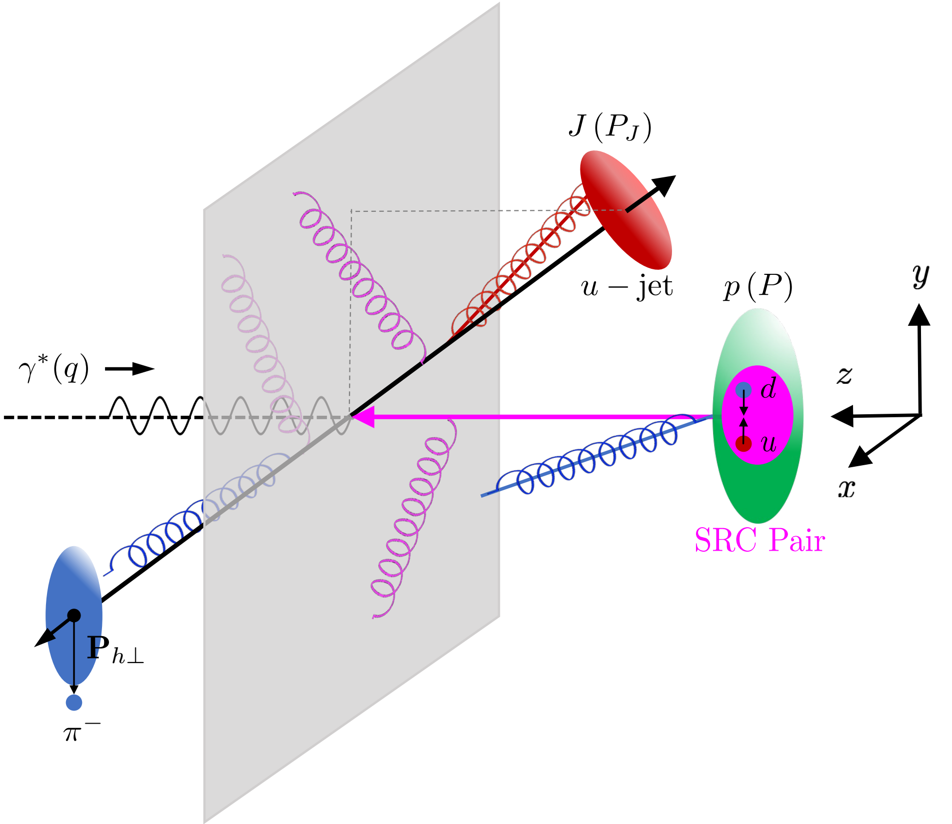
Incident electron (via virtual photon) kicks a u quark from the proton.

If all you measure is the scattered electron and the jet, all you can learn about is (generalized) parton distribution functions.

So, measure the blue hadron too!

An EIC Measurement. . .

[Peng, KR, Terry, in progress]



Measure the correlations in ϕ (azimuthal angle around the virtual-photon direction) between. . .

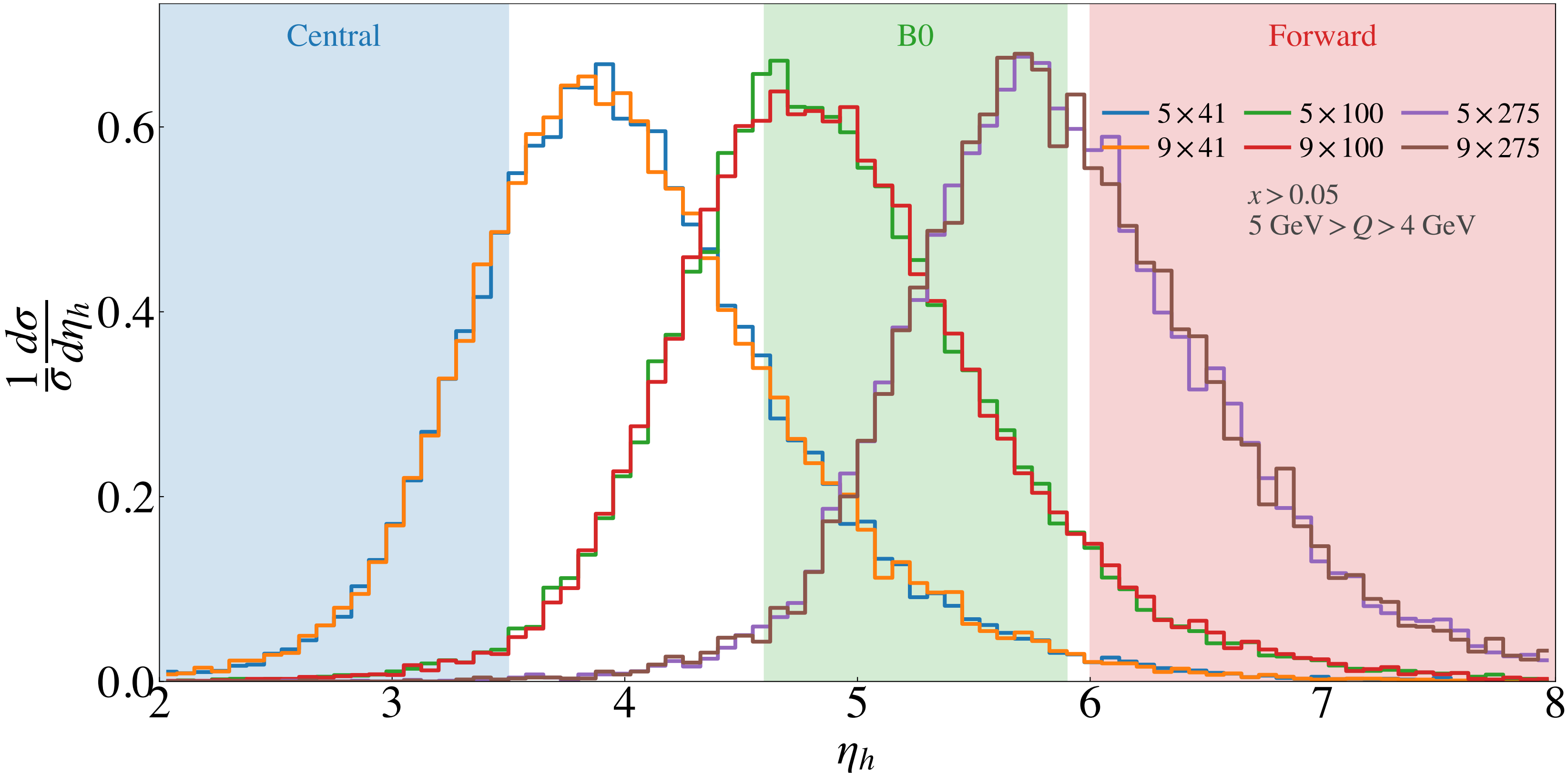
. . . the u-jet (jet with leading π^+) that the virtual photon kicked . . .

. . . and a π^- (containing a d-quark that the u was strongly correlated with).

Direct access to strong Diquark Short Range Correlations inside a proton. Which is to say inside quark-gluon matter under pressure.

An EIC Measurement. . .

[Peng, KR, Terry, in progress]

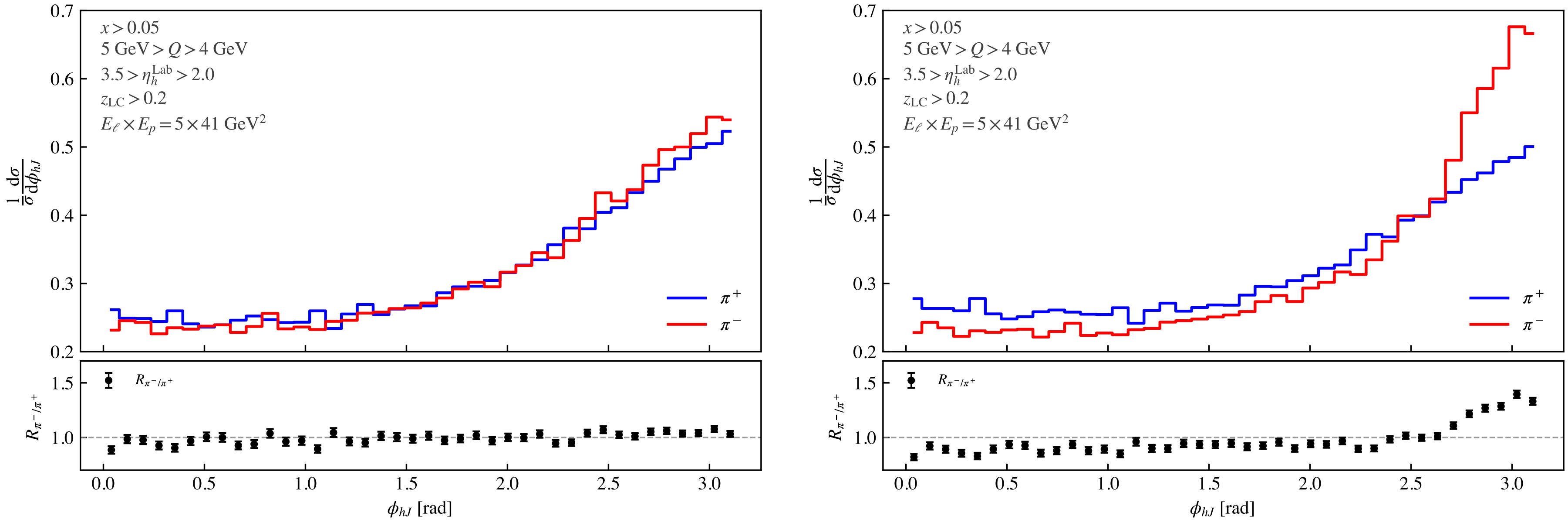


EIC is *designed* to measure the scattered electron and hence Q. EIC is *deisgned* to measure the jet that the virtual photon kicked.

PYTHIA simulation shows that $\pi^{+/-}$ from fragments of the proton can be measured in the central detector in EIC collisions with $E_e = 5$ or 9 GeV and $E_p = 41$ GeV. Also makes clear that B0 detector is important for larger E_p, if it can identify $\pi^{+/-}$. On next slides, $E_p = 41$ GeV and $\eta_h < 3.5$.

An EIC Measurement. . .

[Peng, KR, Terry, in progress]

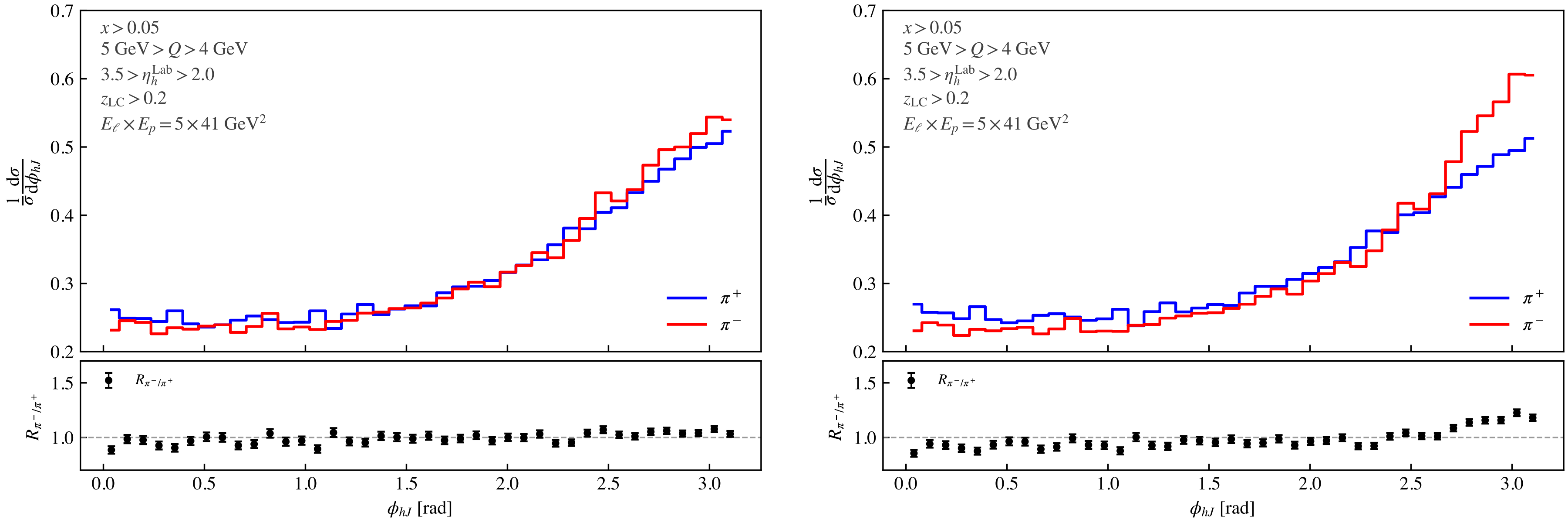


Left panel: PYTHIA, unaltered. $\phi_{hJ} \equiv \phi_h - \phi_J$. J **is** u**-jet.** ϕ_{hJ} **distribution** $\sim$ **same for** π^+ **and** π^-**: no diquark SRC in protons in PYTHIA. Shape of** ϕ_{hJ} **distribution comes from momentum conservation.**

Right panel: we have altered 10% of the events in the PYTHIA simulation. Crude model of effects of ud**-diquark SRCs in proton. Only** π^- **affected in simulation;** u**-jet;** d **from proton remnant** $\to \pi^-$**. Signal is** π^-/π^+ **ratio above one around** $\phi_{hJ} \sim 180°$**. Nb: this crude model is not a prediction; an illustration of how to look for partonic SRCs with the EIC.**

An EIC Measurement...

[Peng, KR, Terry, in progress]



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Right panel: we have altered 5% of the events in the PYTHIA simulation. Crude model of effects of ud**-diquark SRCs in proton. Only** π^- **affected in simulation;** u**-jet;** d **from proton remnant** $\rightarrow \pi^-$**. Signal is** π^-/π^+ **ratio above one around** $\phi_{hJ} \sim 180°$**. Nb: this crude model is not a prediction; an illustration of how to look for partonic SRCs with the EIC.**

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- **Protons form from tiny drops of QGP. The internal pressure, energy density,** *and entropy* **of a proton are comparable to that of the drop of QGP from which it formed.**
- **What lessons can we learn about the interior of a proton from hot QGP?**
- **QGP at temperatures $\sim T_p$ is a strongly coupled fluid: strong correlations between the momenta of fluid cells that are near each other in position space. Strong** *Short-Range Correlations*. **How can partonic SRCs be measured at the EIC?** [Peng, KR, Terry, in progress]
- **Seeing strong parton-parton correlations would show that protons cannot be described one parton at a time by (generalized) PDFs. As important as seeing that QGP is a strongly coupled liquid.**

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