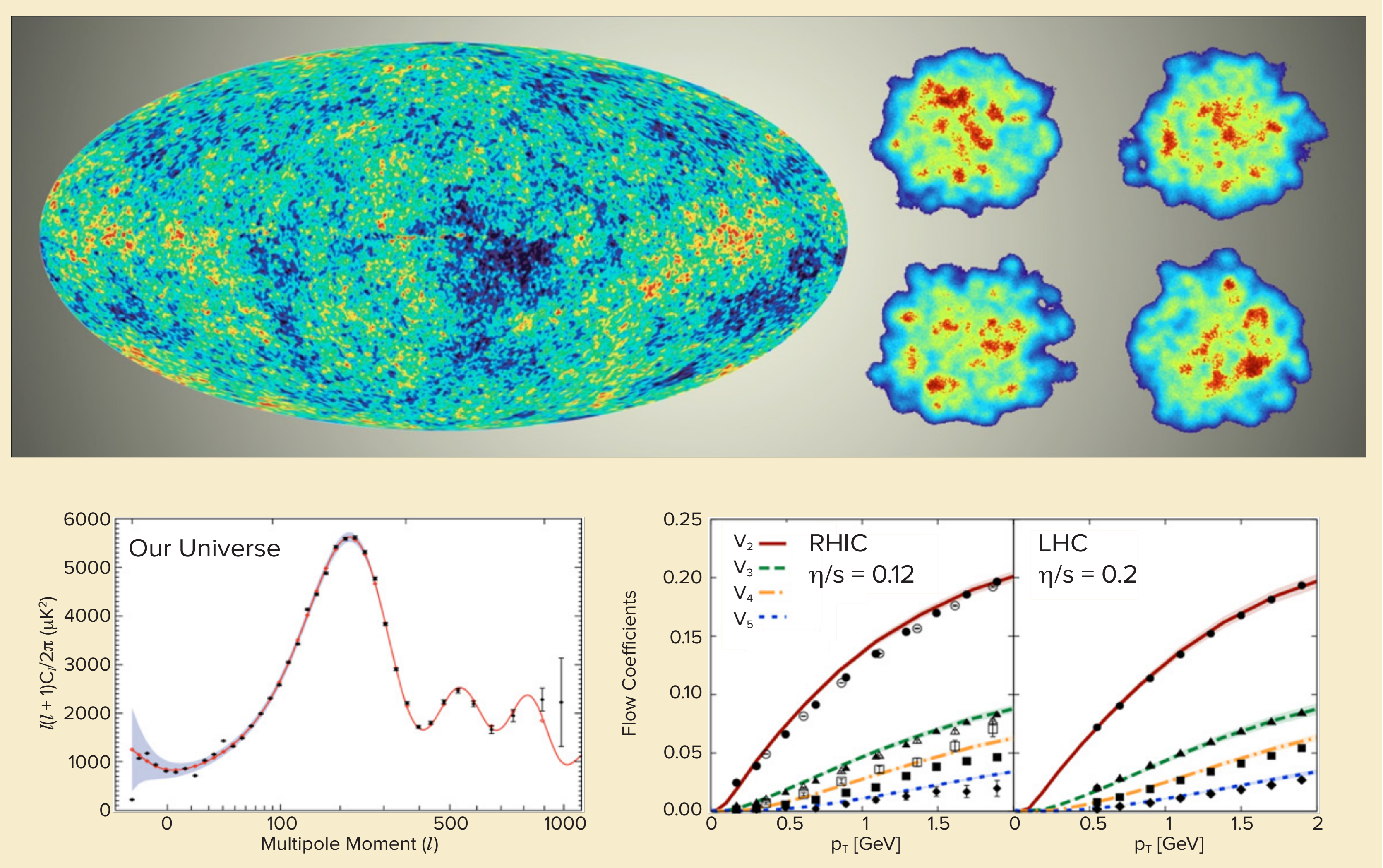
Evolution of the Jet Opening Angle Distribution in Strongly Coupled Plasma

Krishna Rajagopal
MIT

based on 1602.04187 by KR, Sadofyev, van der Schee

ULtraRelatIvistiCH HEavy IoNZ 2016
CERN, July 18, 2016



Using modes of analysis that owe so much to our honoree, we are learning about the stuff of the Big Bang from our *billions* **of Little Bangs. . .**

But There is One and Only One...

... and he has been making Big Bangs of his own for a long time.

Big Bangs from the LIL BANG

- Kinetic Theory for Nonabelian Plasmas. (1983; what you read when you were a student when I was a student.)
- Thermal phenomenology of hadrons from 200 A-GeV S+S Collisions. (1993, with Schnedermann and Sollfrank; my first intro to Ulrich at the first QM that I attended.)
- Particle interferometry for relativistic heavy ion collisions. (1999, with Wiedemann. Ulrich the Zen Master of HBT.)
- Early Thermalization at RHIC. Hydrodynamic description of ultrarelativistic heavy ion collisions. (2001 and 2003, with Kolb; a pillar of our modern understanding.)
- Causal viscous hydrodynamics in 2+1 dimensions for relativistic heavy-ion collisions. (2007, with Song; pushing toward the precision era.)
- Hydrodynamic elliptic and triangular flow in Pb-Pb collisions at $\sqrt{s} = 2.76$ ATeV. (2011, with Qiu and Shen; precision in the v_n era.)

HAPPY BIRTHDAY

TO THE LIL BANG

And, best wishes for many more Big Bangs in decades to come. . .

My little birthday present for you will be told as a story with two beginnings (the first of them lengthy) that will appear to contradict each other, followed by a calculation that shows that this is not so.

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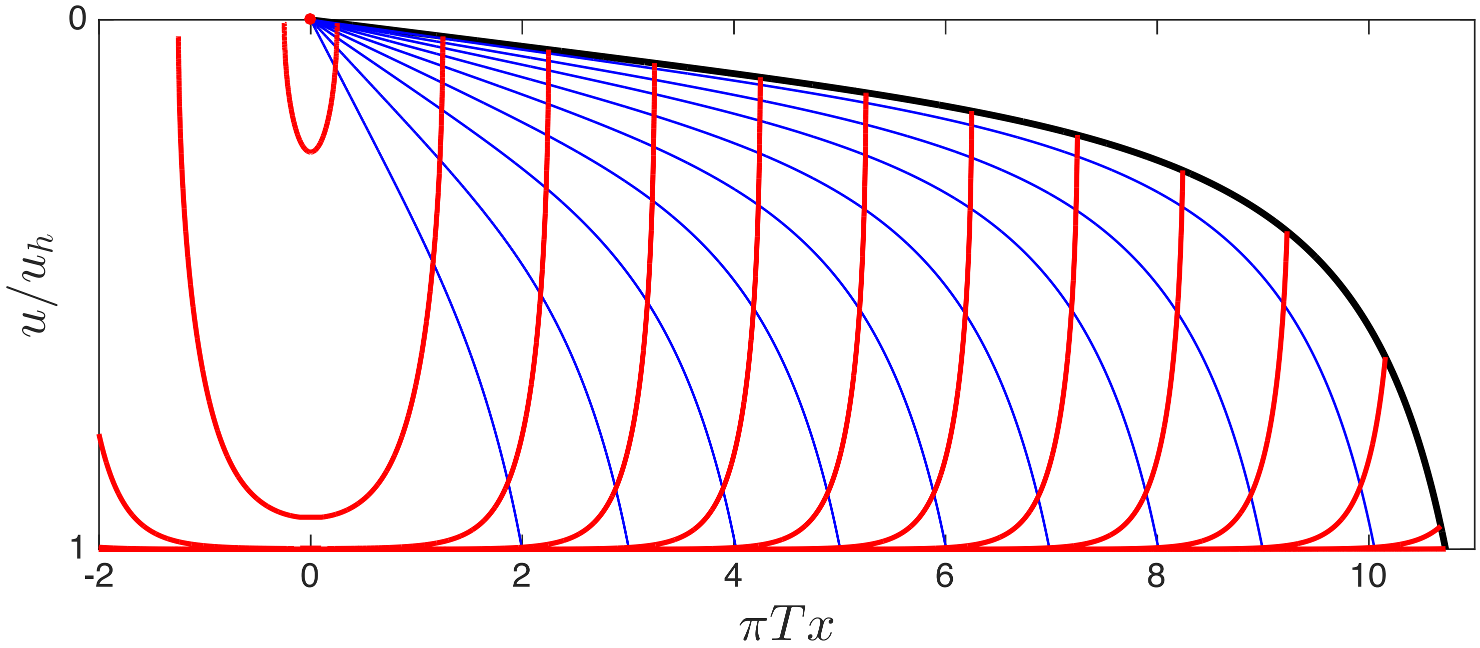
Holographic "Parton" Energy Loss

Chesler, Rajagopal, arXiv:1402.6756, 1511.07567



- Take a highly boosted light quark and shoot it through strongly coupled plasma...
- A fully geometric characterization of energy loss. Which is to say a new form of intuition. Energy propagates along the blue curves, which are null geodesics in the bulk. When one of them falls into the horizon, that's energy loss! Precisely equivalent to the light quark losing energy to a hydrodynamic wake in the plasma.

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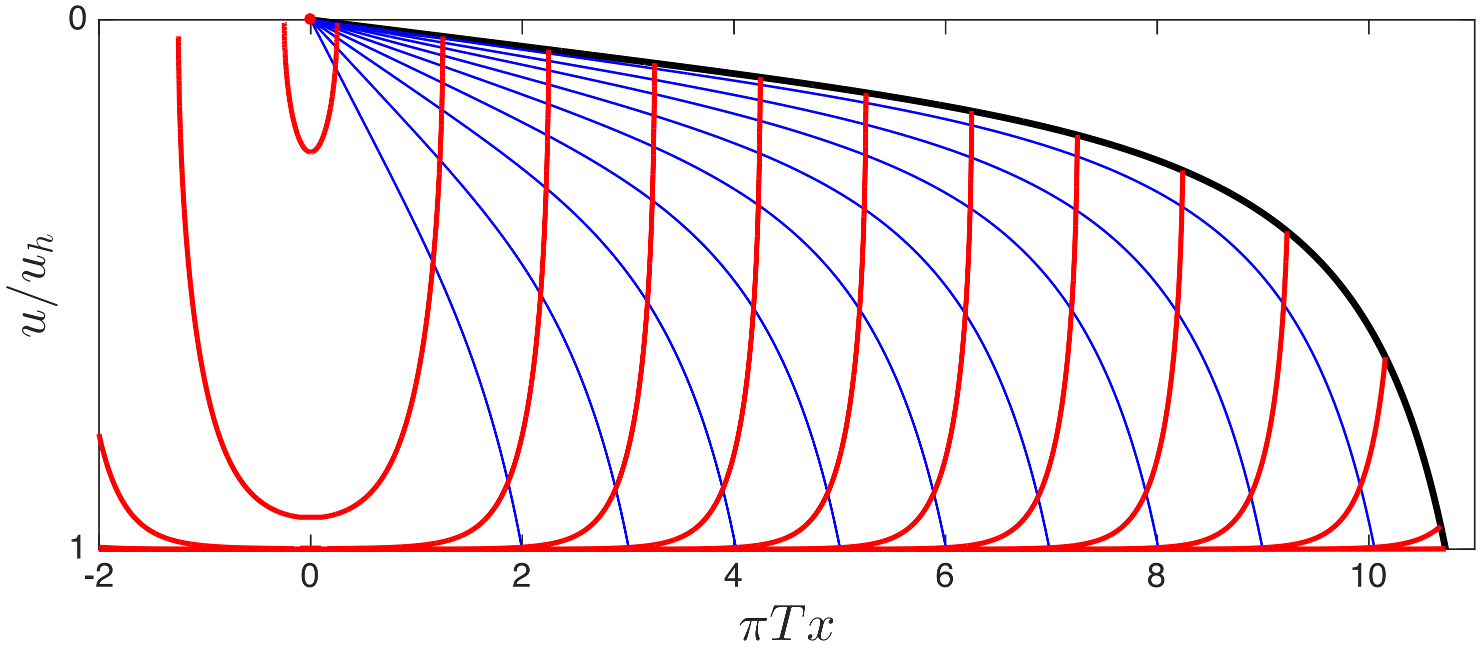
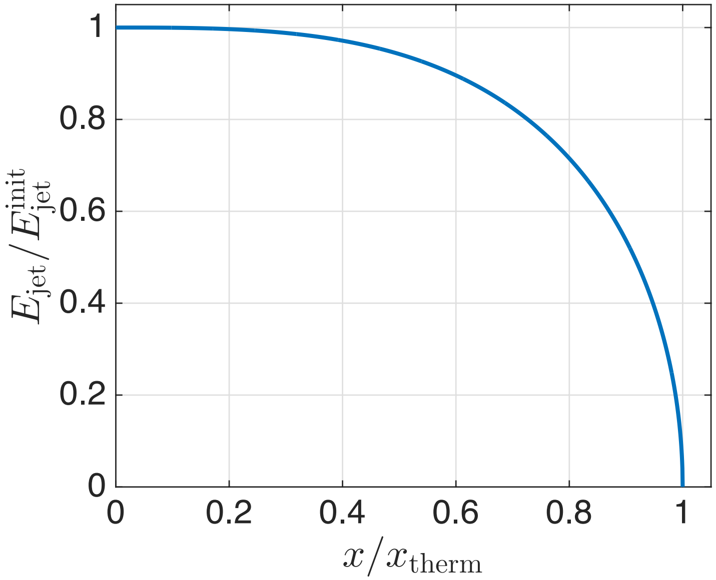


- **A fully geometric characterization of energy loss. Which is to say a new form of intuition. Energy propagates along the blue curves, which are null geodesics in the bulk. When one of them falls into the horizon, that’s energy loss!**
- **Calculation shows that energy density on a particular blue geodesic $\propto 1/\sqrt{\sigma - \sigma_{\text{endpoint}}}$, with σ the initial downward angle of that geodesic. Immediately implies maximal energy loss rate as the last energy is lost.**

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756, 1511.07567



We compute E_{jet} analytically, by integrating the energy flowing into hydrodynamic modes, and showing its equivalence to that falling into the horizon. Geometric derivation of analytic expression for dE_{jet}/dx

$$\frac{1}{E_{\text{jet}}^{\text{init}}}\frac{dE_{\text{jet}}}{dx} = -\frac{4x^2}{\pi x_{\text{therm}}^2}\frac{1}{\sqrt{x_{\text{therm}}^2 - x^2}}$$

where $T x_{\text{therm}} = \mathcal{C}(E_{\text{jet}}^{\text{init}}/(\sqrt{\lambda}T))^{1/3}$ where $\mathcal{C}$ is $\mathcal{O}(1)$, depends on how the quark "jet" is prepared (more later), and has a maximum possible value $\simeq 1$.

A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815,
1607.nnnnn; Hulcher, Pablos, KR, 160n.nnnnn

- **Hard scattering and the fragmentation of a hard parton produced in a hard scattering are weakly coupled phenomena, well described by pQCD.**
- **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.**
- **Try a hybrid approach. Think of each parton in a parton shower à la PYTHIA losing energy à la dE/dx for light quarks in strongly coupled liquid from previous slide.**
- **We have looked at R_{AA}, dijet asymmetry, jet fragmentation function, photon-jet and Z-jet observables. Upon fitting one parameter, *lots* of data described well. Value of the fitted parameter is reasonable: x_{therm} in QGP is 2-3 times longer than in $\mathcal{N} = 4$ SYM plasma with same T.**
- **In progress: adding momentum broadening, adding wake in the plasma, adding resolution effects, looking at jet shapes and related observables.**

What if We Try a Bolder Approach?

- The hybrid approach takes insights from AdS/CFT calculations of parton energy loss and uses them to model the quenching of pQCD jets in a way that can be confronted with jet observables.
- What if we try to be non-hybrid? By which I mean what if we try to compare the AdS/CFT calculations directly with the phenomenology of jets in heavy ion collisions?
- This bolder approach starts off well, but then seems to be contradicted in a qualitative way by data. . .

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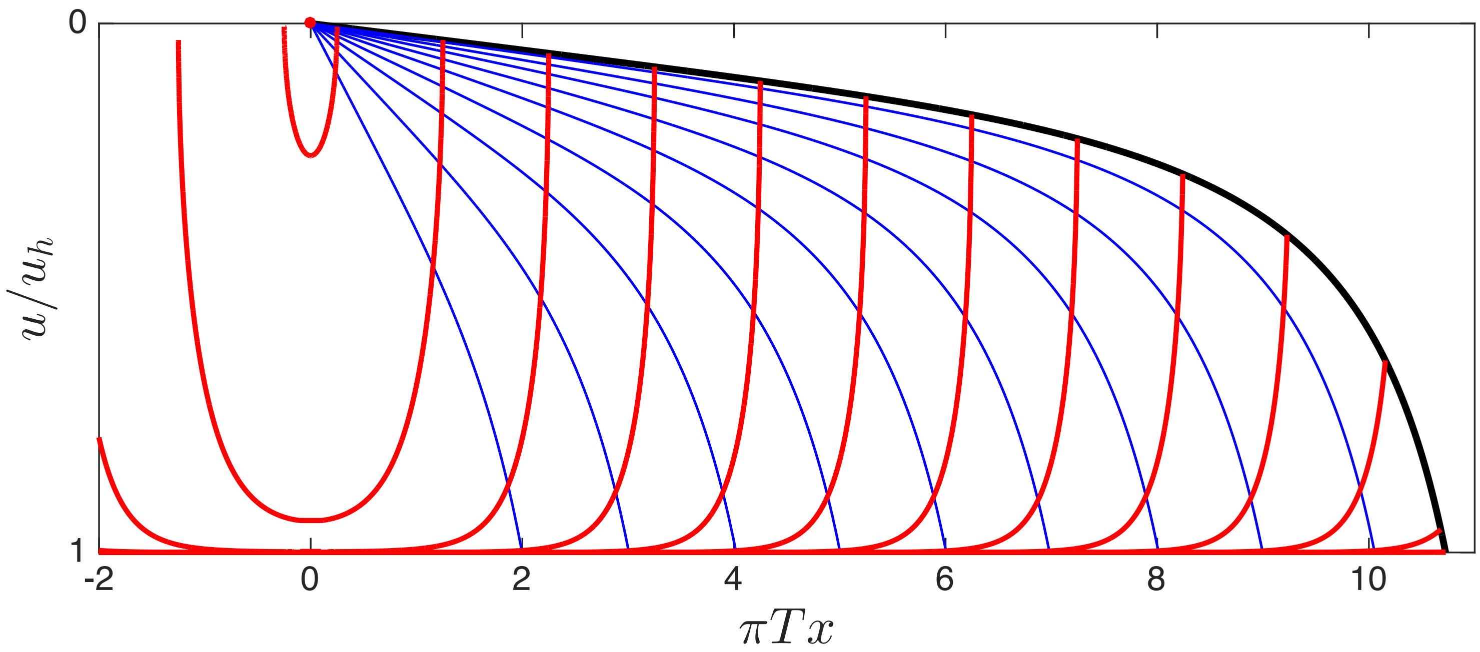

- Interpret this object as a toy model for a jet.
- Depth into the bulk $\leftrightarrow$ transverse size of the gauge theory object being described.
- Thus, downward angle into the bulk $\leftrightarrow$ opening angle.
- Since energy density is largest close to the string endpoint, for intuition focus on the endpoint trajectory.
- This calculation describes a “jet” with some initial $\theta_{\text{jet}}^{\text{init}} \propto$ initial downward angle of the endpoint.

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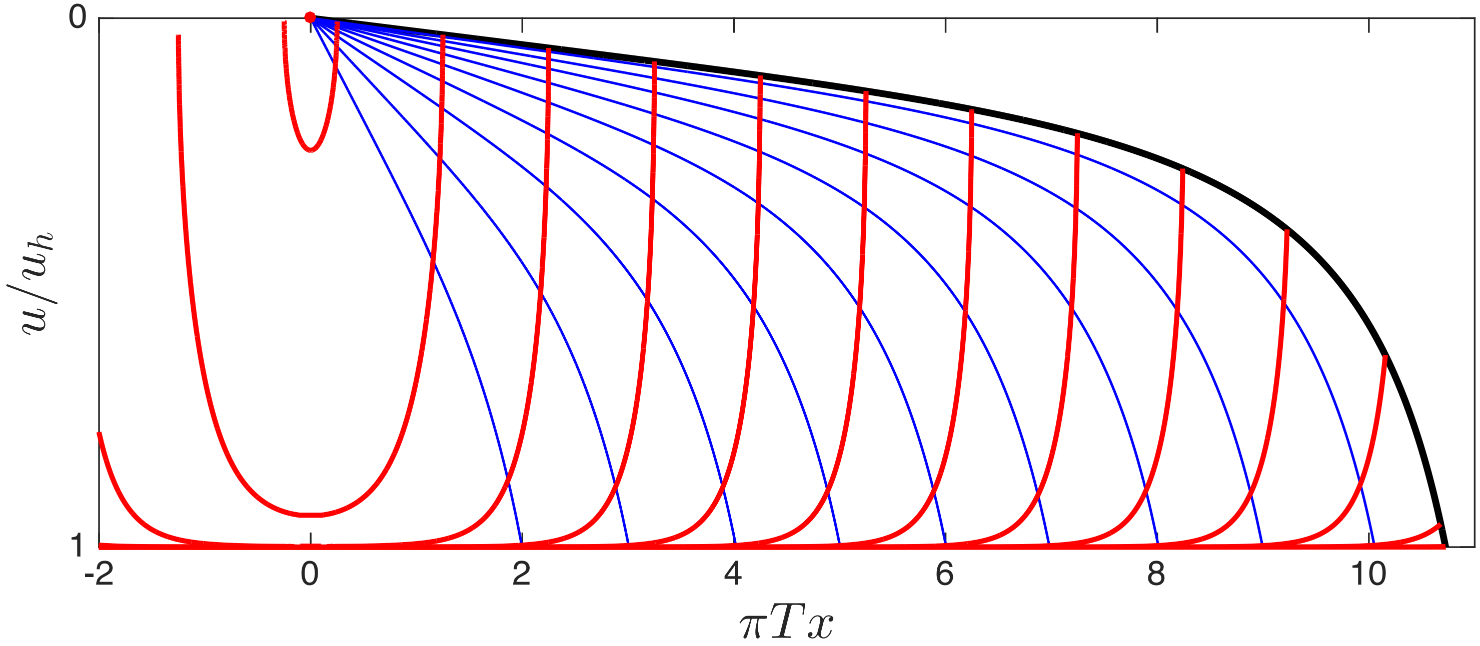

Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

- **First, every jet broadens in angle as it propagates through the strongly coupled plasma.** θ_{jet} **increases as** E_{jet} **decreases.**

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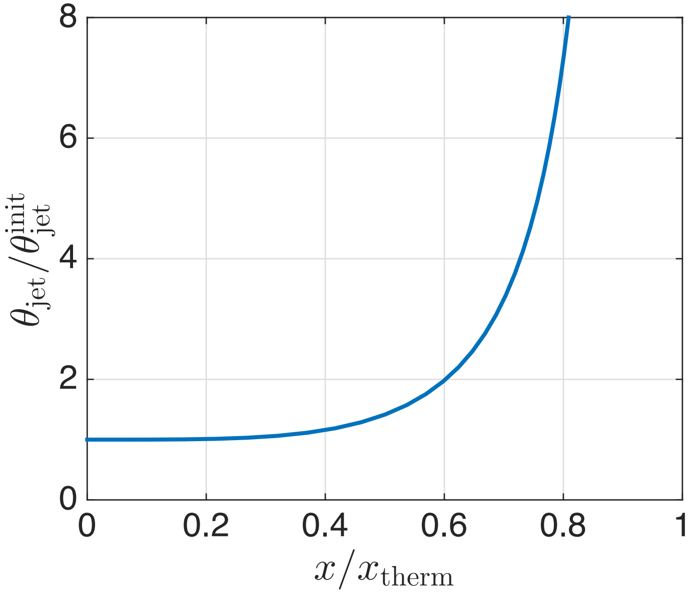

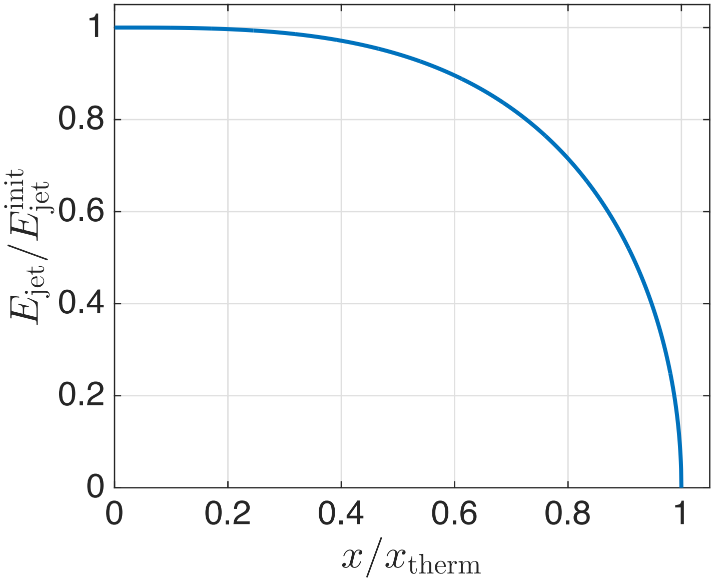

Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

- **First, every jet broadens in angle as it propagates through the strongly coupled plasma. $\theta_{\rm jet}$ increases as $E_{\rm jet}$ decreases. (The result plotted for $\theta_{\rm jet}/\theta_{\rm jet}^{\rm init}$ is in the limit of small $\theta_{\rm jet}^{\rm init}$, meaning large $x_{\rm therm}T$. See the paper for results away from this limit.)**

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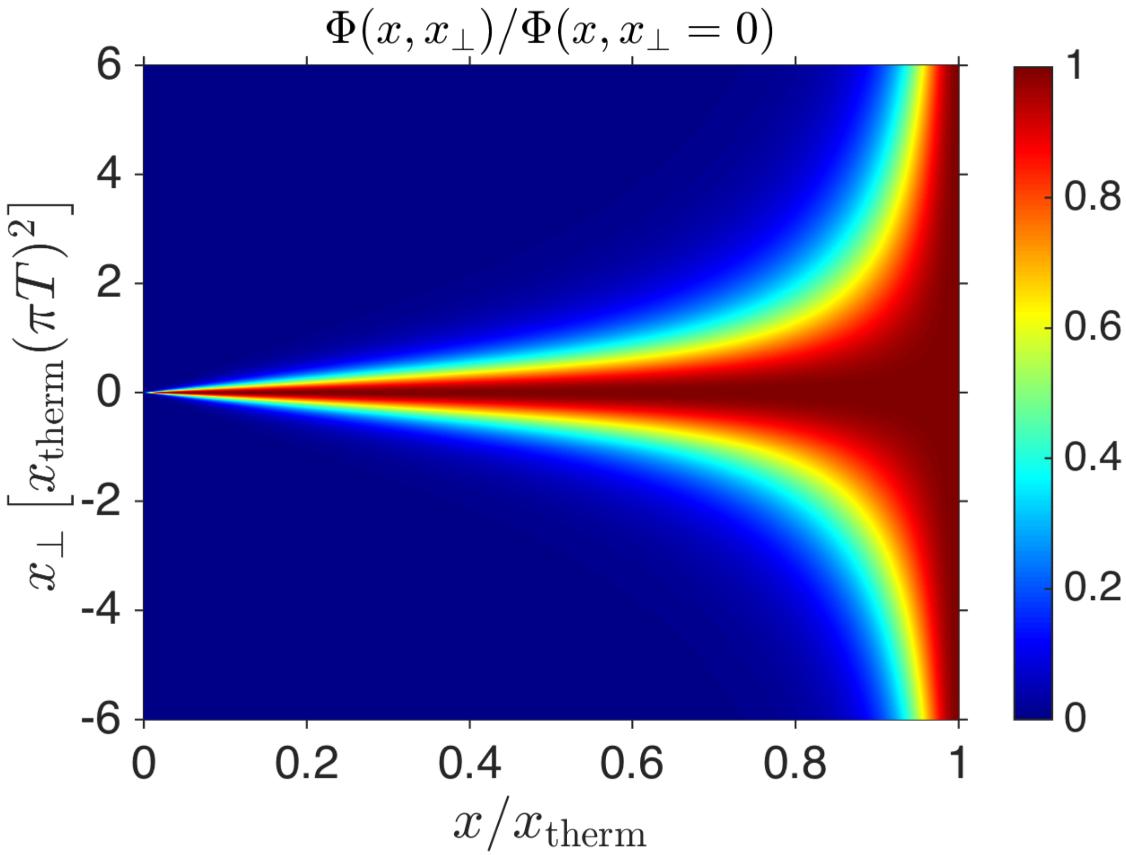

- **First, every jet broadens in angle as it propagates through the strongly coupled plasma. $\theta_{\rm jet}$ increases as $E_{\rm jet}$ decreases. (What is plotted here is energy flux, renormalized at every x so loss of energy is not visible. Plot is for the small $\theta_{\rm jet}^{\rm init}$ limit.)**

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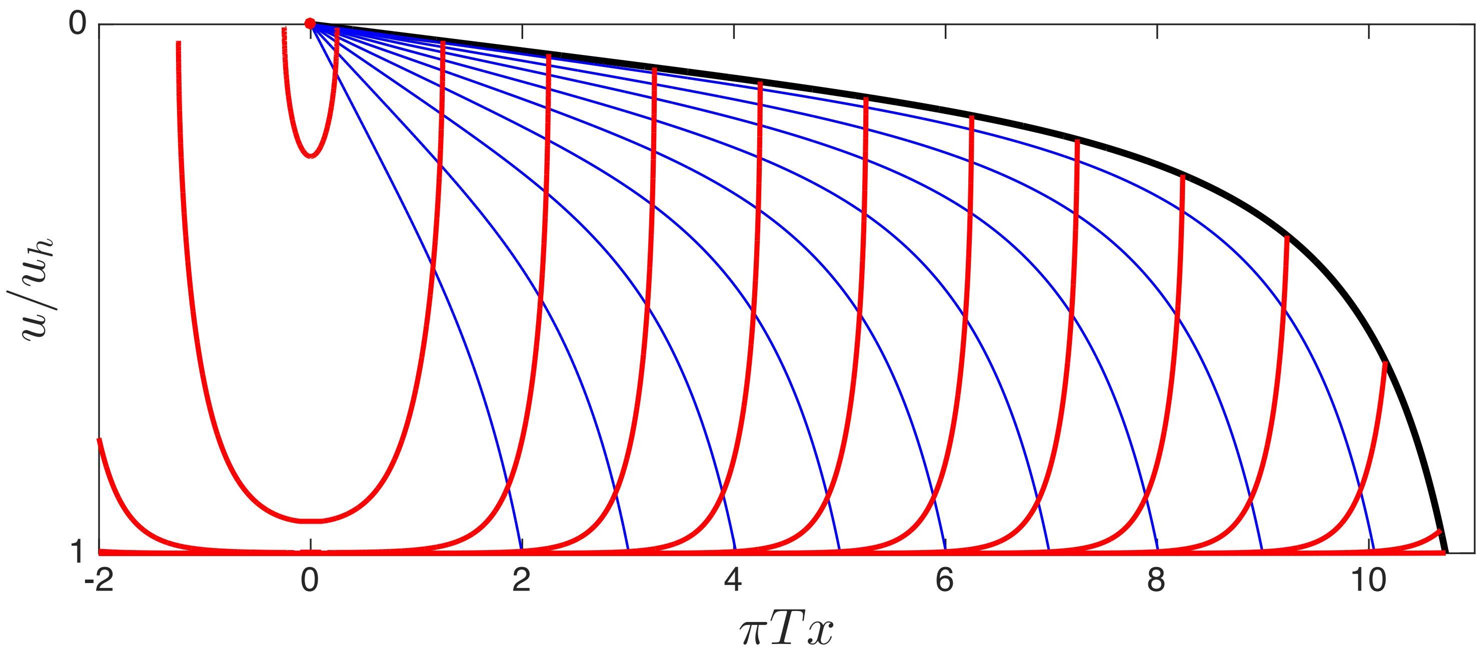
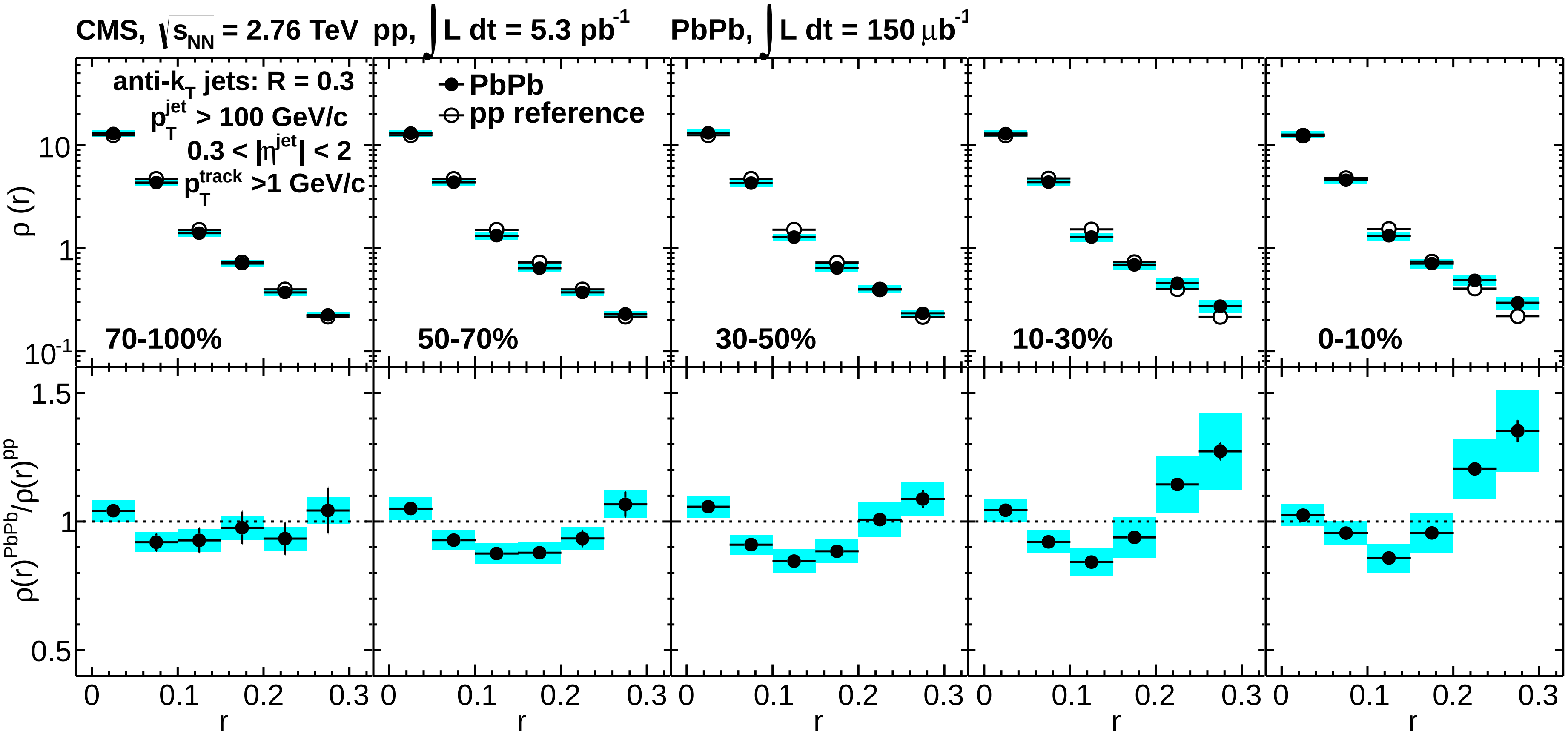


Two immediate, inescapable, qualitative consequences, of geometric origin when described holographically:

- **Second, jets with smaller initial $\theta_{\rm jet}^{\rm init}$ have a longer $x_{\rm therm}$. They lose their energy more slowly, over a longer distance. (In fact, $T x_{\rm therm} \propto 1/\sqrt{\theta_{\rm jet}^{\rm init}}$.)**
- **That is, for jets with the same $E_{\rm jet}^{\rm init}$ that travel through the same plasma, those with larger $\theta_{\rm jet}^{\rm init}$ will lose more energy.**

Experimental Results

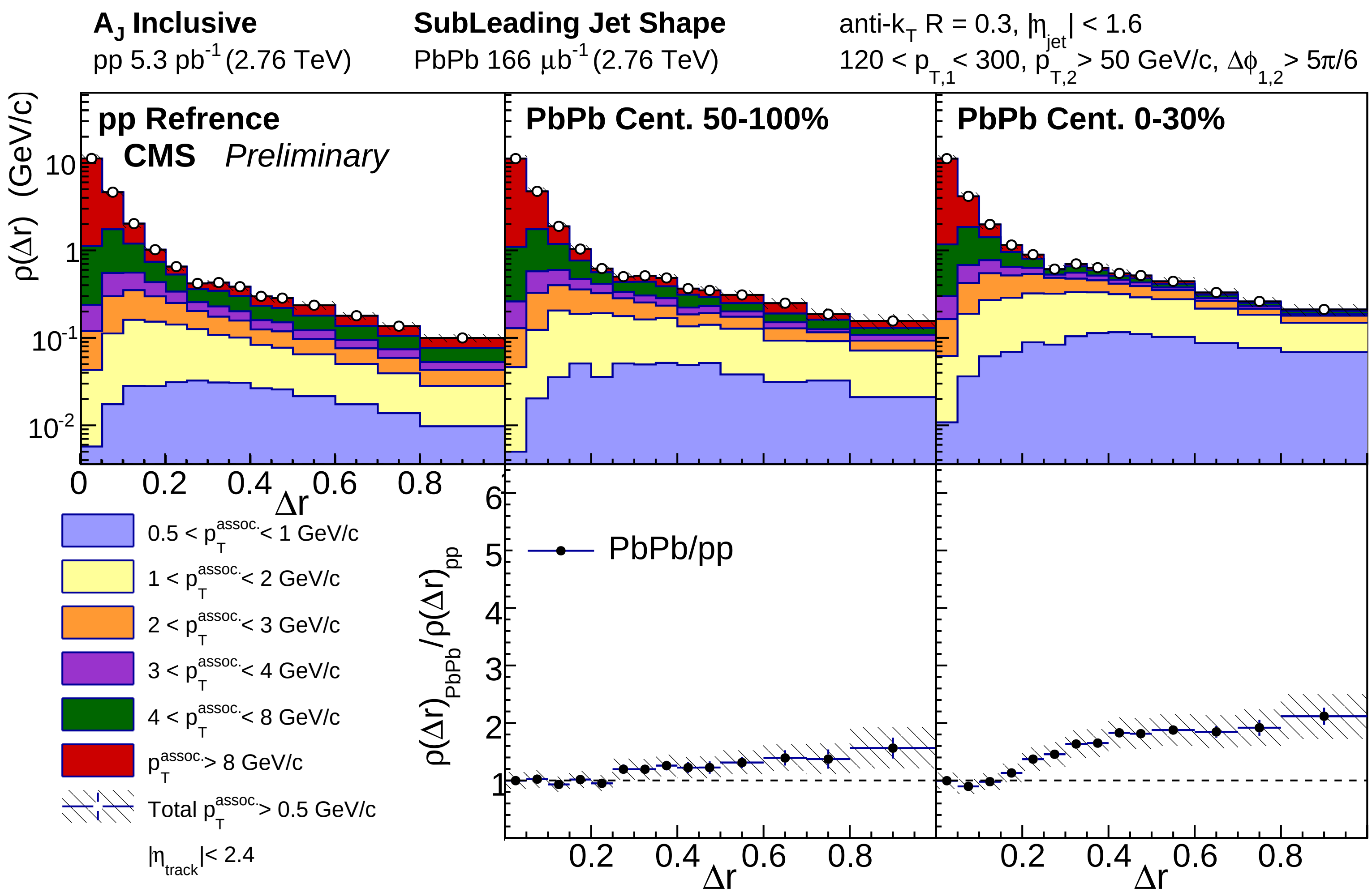
CMS, arxiv:1310.0878



The second beginning to my story. Jets in PbPb are a little narrower than jets with the same energy in pp at small r. Then get a little wider at larger r.

Experimental Results

CMS, HIN-15-011



The narrowing at small angles comes from the hard component of the jet. The broadening at large, and very large, angles is in the softest particles, likely those coming from the wake in the plasma that are reconstructed as part of the jet.

A Contradiction?

In the holographic calculation, every jet gets wider as it propagates through the plasma.

When you compare jets in PbPb and pp collisions *with the same final energy* the quenched jets in PbPb collisions may be a bit narrower, and certainly are not significantly wider.

Is this a contradiction? Not necessarily. . .

In order to compare quenched jets and unquenched jets with the same final energy, we need to follow what happens to an ensemble of jets.

Since energy loss depends on initial opening angle, we need an ensemble with a reasonable distribution of both initial opening angle and initial energy. (The angle and energy that the jet would have had if not plasma.)

Our goal is only to assess whether there is a blatant contradiction. So we will simplify many things. . .

Evolution of Jet Opening Angle Distribution

KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

Choose an ensemble of holographic jets, distributed as follows:

- **Initial energy distributed $\propto (E_{\text{jet}}^{\text{init}})^{-6}$.**
  - **(The energy density on the string is $A/(\sigma^2\sqrt{\sigma - \sigma_{\text{endpoint}}^{\text{init}}})$; this specifies the distribution of A.)**
- **We take advantage of a pQCD calculation of the distribution for**

$$C_1^{(1)} \equiv \sum_{i,j} z_i z_j \left(\frac{\left|\theta_{ij}\right|}{R}\right) \quad ,$$

a measure of the opening angle of a jet, for $R = 0.3$ jets with a given energy in pp collisions with $\sqrt{s} = 2.76$ TeV. **(Larkoski, Salam, Thaler 1305.0007; Larkoski, Marzani, Soyez, Thaler 1402.2657)**
  - **(For us, $C_1^{(1)} = a\,\sigma_{\text{endpoint}}^{\text{init}}$. Crude calculation gives $a \sim 1.7$ but we take a as the first of two free parameters in the model. So, this specifies distribution of $\sigma_{\text{endpoint}}^{\text{init}}$.)**

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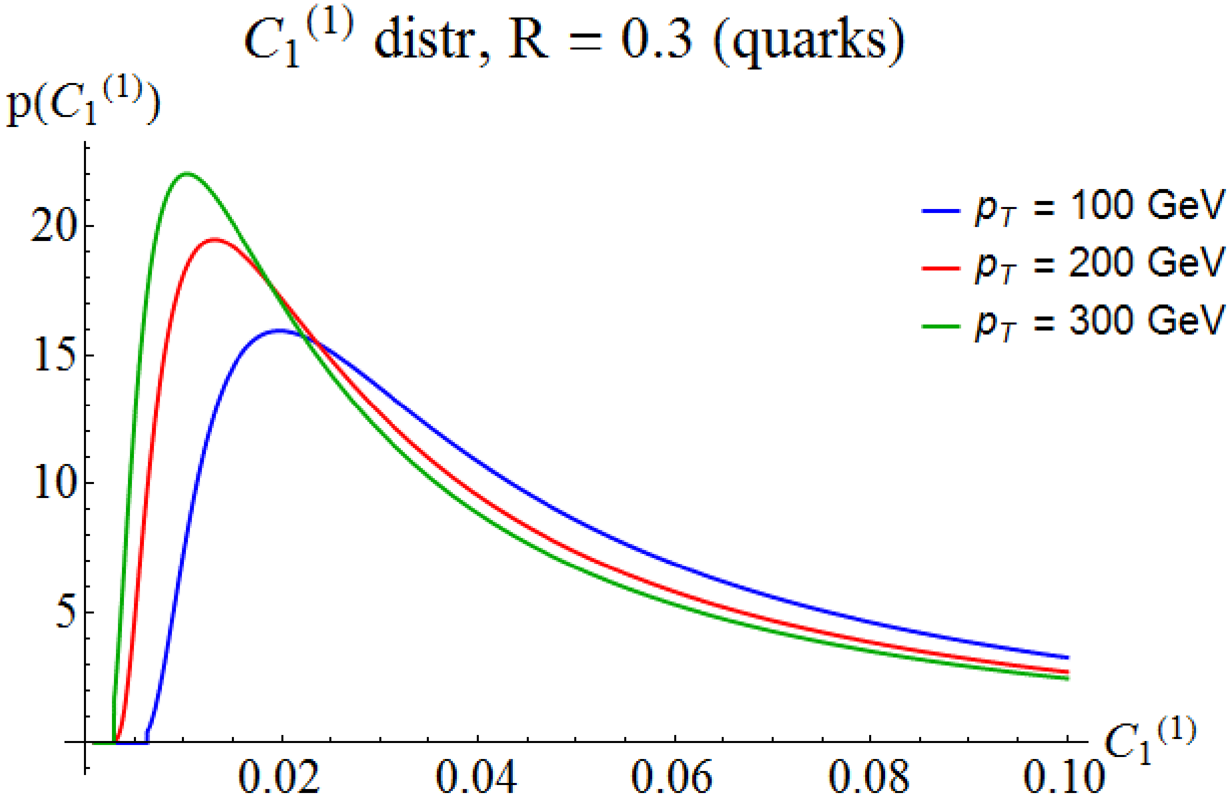

Larkoski, Marzani, Soyez, Thaler 1402.2657

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. . . and follow the propagation of this ensemble through an AdS/BH metric with a space-time varying horizon that describes strongly coupled plasma with a spacetime-varying temperature. We assume boost-invariant longitudinal expansion and a blast-wave approximation (taken from Ficnar, Gubser, Gyulassy 1311) for the transverse expansion:

$$T(\tau,\vec{x}_\perp) = b\left[\frac{dN_{\rm ch}}{dy}\frac{1}{N_{\rm part}}\frac{\rho_{\bf part}(\vec{x}_\perp/r_{\bf bl}(\tau))}{\tau\, r_{\bf bl}(\tau)^2}\right]^{1/3},$$

where $r_{\bf bl}(\tau) \equiv \sqrt{1+(v_T\tau/R_{\rm Pb})^2}$, and where we take $N_{\rm part} = 383$, $dN_{\rm ch}/dy = 1870$, $v_T = 0.6$, $R_{\rm Pb} = 6.7$ fm and $\rho_{\rm part}(\vec{x}_\perp)$ is given by an optical Glauber model.

A naive calculation gives $b \sim 0.8$, but recognizing that the strongly coupled plasma of $\mathcal{N} = 4$ SYM theory and QCD differ (in s/T^3, for example) we treat b as the second free parameter in the model.

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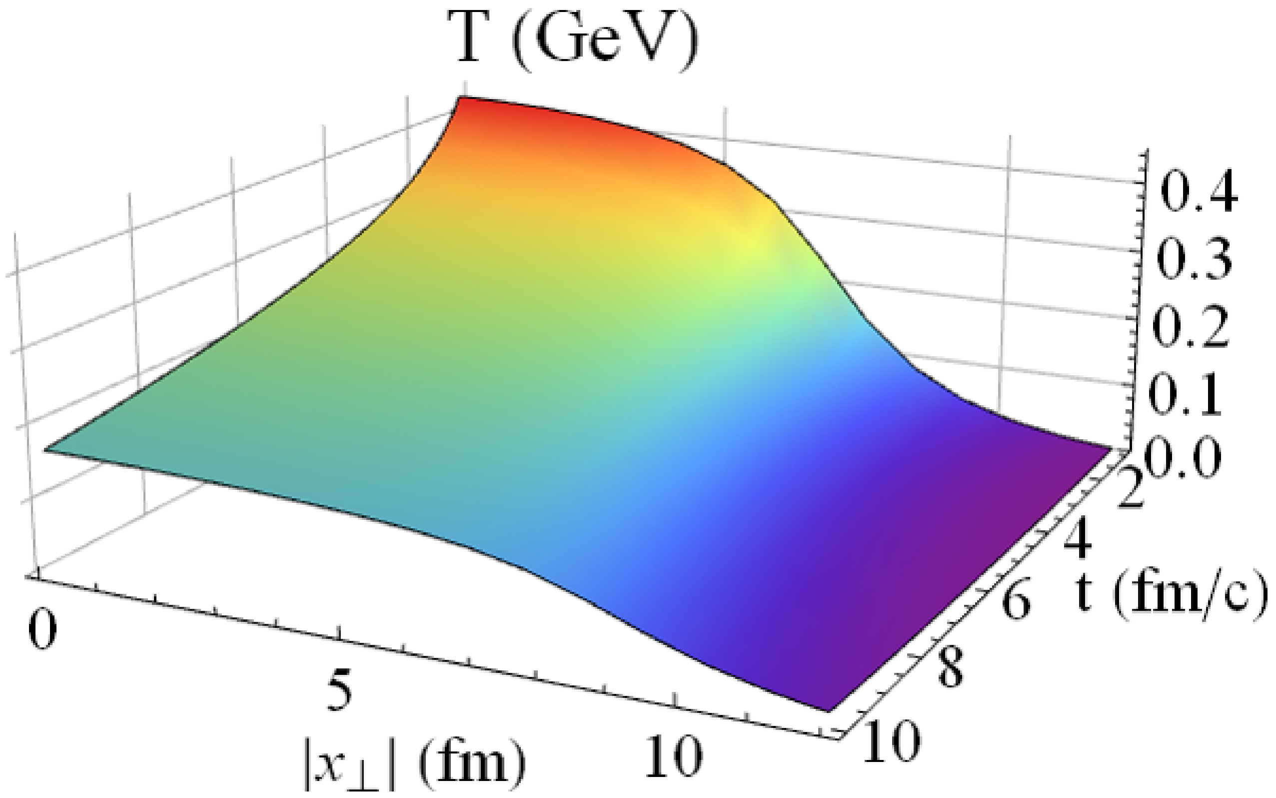

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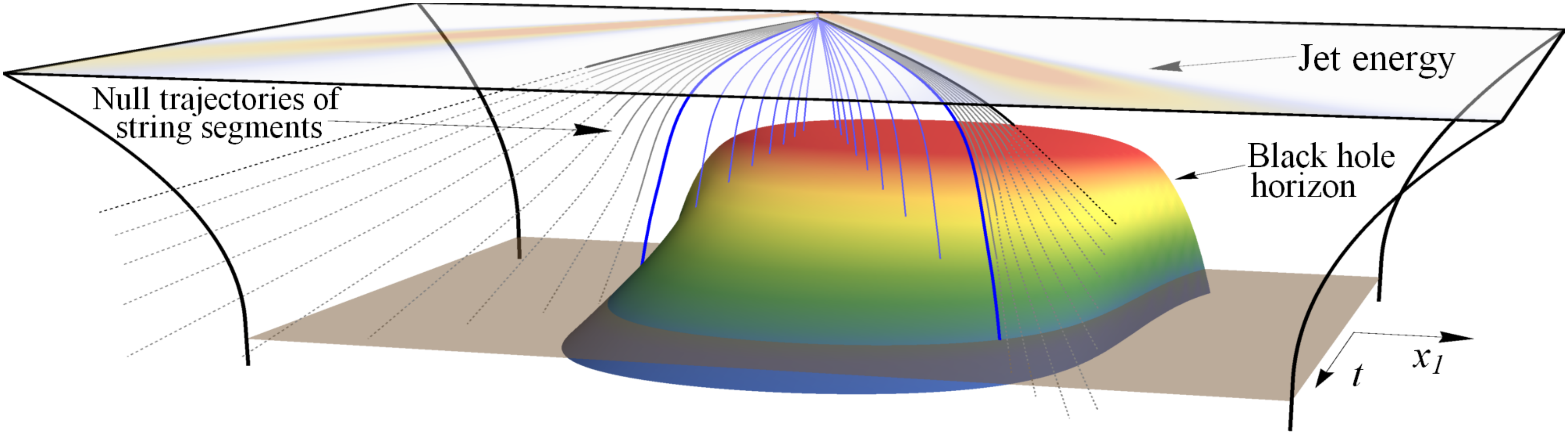

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We initialize our simplified model for the expanding cooling droplet of plasma at $\tau = 1$ fm$/c$, and initialize our ensemble of jets at the same τ, choosing their initial transverse position $\propto \rho_{\rm part}(\vec{x}_\perp)^2$ and choosing their transverse direction randomly. (Clearly, early time physics could be improved.)

For each value of the two model parameters a and b, we generate an ensemble of many tens of thousands of jets as described, send them through the droplet of plasma, and turn quenching off when T drops below 175 MeV. (Clearly, late time physics could be improved.)

We track $E_{\rm jet}$ and $\sigma_{\rm endpoint}$, and extract the modified distribution of jet energies and opening angles.

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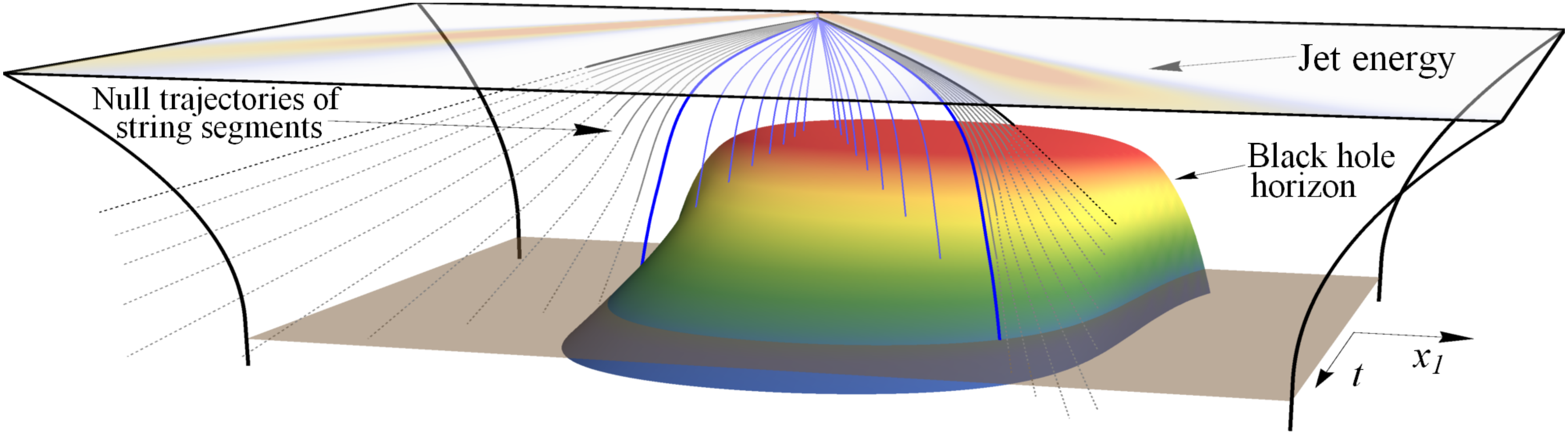

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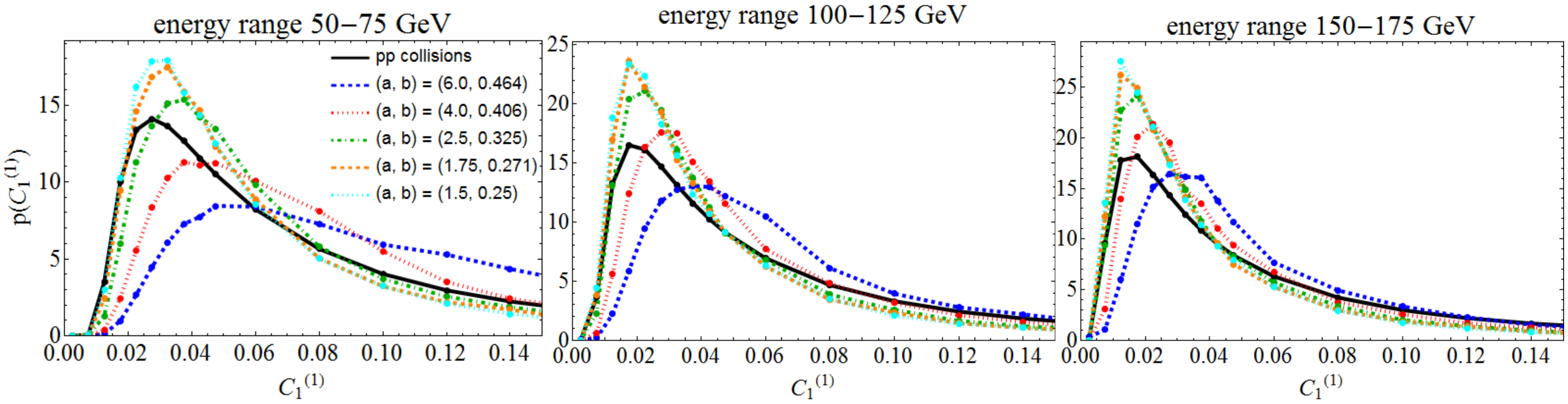
energy range 50–75 GeV

energy range 100–125 GeV

energy range 150–175 GeV

For small angles, opening angle distribution pushed toward larger angles. (Every jet gets wider as it propagates.)

At large angles, opening angle distribution pushed down, and therefore toward smaller angles. (Jets that are initially wider lose more energy. And, the jet energy distribution is steeply falling.)

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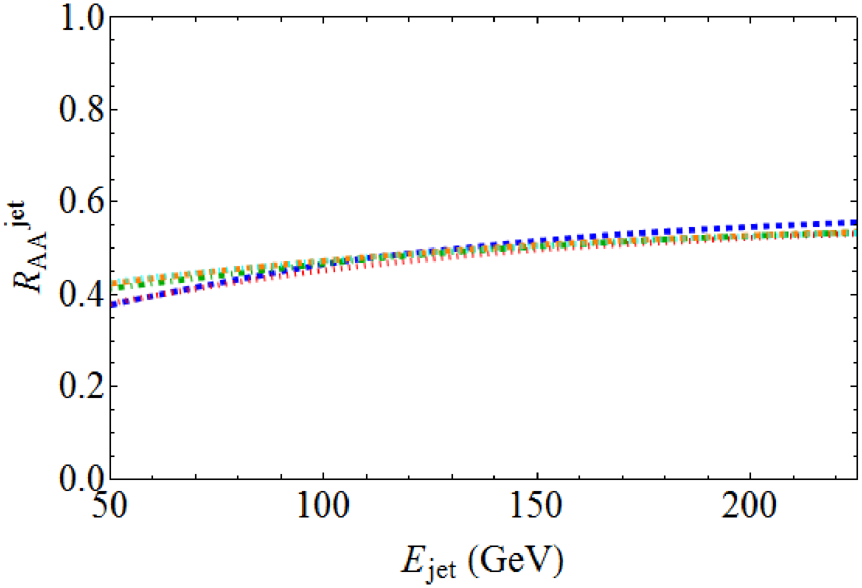

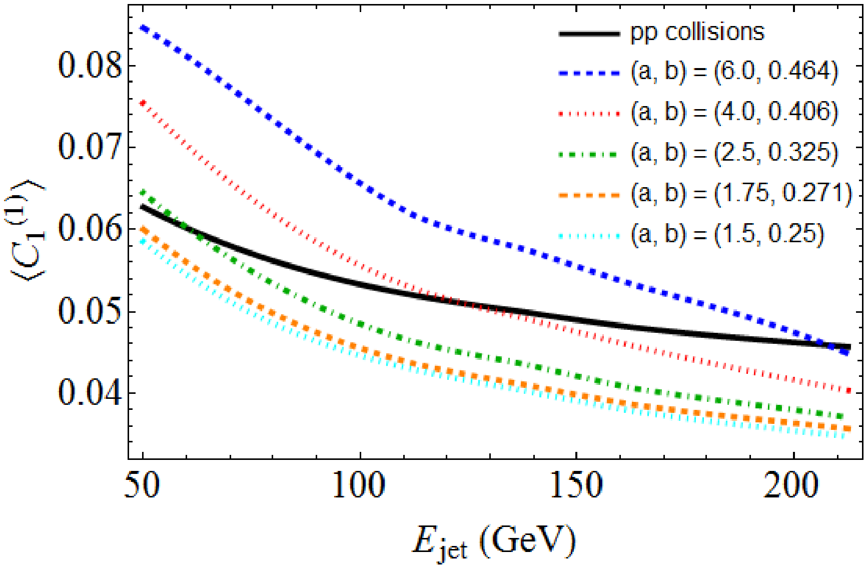

All our choices of a, b give same, not unreasonable, suppression in the number of jets in the final ensemble with a given E_{jet} relative to that number in the initial distribution.

The *mean* opening angle of the jets with a given E_{jet} in the final ensemble can easily be pushed downward, even though the opening angle of every jet in the ensemble increases.

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KR, A. Sadofyev, W. van der Schee, arxiv:1602.04187

There is no contradiction.

- **Because of inescapable qualitative fact # 2 (holographic jets that are initially wider lose more energy)**. . .
- . . . **and because of the steeply falling** E_{jet} **distribution**. . .
- . . . **there is no contradiction between inescapable qualitative fact #1 (every holographic jet broadens in angle as it propagates through strongly coupled plasma)** . . .
- . . . **and the indication from CMS data that jets in PbPb with** $E_{\text{jet}} > 100$ **GeV or** $E_{\text{jet}} > 50$ **GeV are a little narrower than jets in** pp **with the same energy, if you focus on the harder particles in the jet so as not to be distracted by particles coming from the wake in the plasma.**

Evolution of Jet Opening Angle Distribution

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Bottom line: because wider jets with a given initial energy lose more energy than narrower jets with that energy, quenching can make the mean width of jets with a given energy narrower – even as every individual jet gets wider as it loses energy.

Same effect seen in an ensemble of weakly coupled jets in JEWEL (Milhano, Zapp 1512). At weak coupling, initially wider jets lose more energy than initially narrower ones because they contain more energy-losers (Casalderrey-Solana, Mehtar-Tani, Salgado Tywoniuk 1210).

Same effect seen in hybrid model also (Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 160n).

The "bolder approach" (comparing holographic jets directly to data) is at present less well developed than the hybrid model, vis-a-vis comparison to jet observables. We (Brewer, KR, Sadofyev, van der Schee) are working on improving various aspects of the simplified analysis I have presented. . . .

Conclusion

I hope that our LIL BANG has enjoyed his little birthday present. And, once again, I wish him many more decades of Big Bangs of his own — and a happy birthday.