Heavy Ion Collisions: What Next?

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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. My talk will be about What Next?, namely the challenges for the decade to come. But first, Intro to the talk will be vintage 2015...

Quark-Gluon Plasma

- The $T \to \infty$ phase of QCD. Entropy wins over order; symmetries of this phase are those of the QCD Lagrangian.

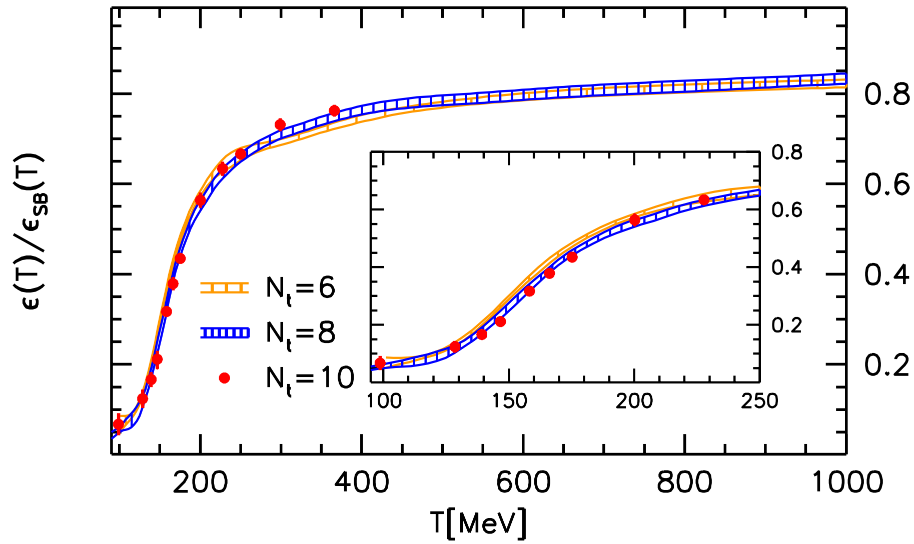
- Asymptotic freedom tells us that, for $T \to \infty$, QGP must be weakly coupled quark and gluon quasiparticles.

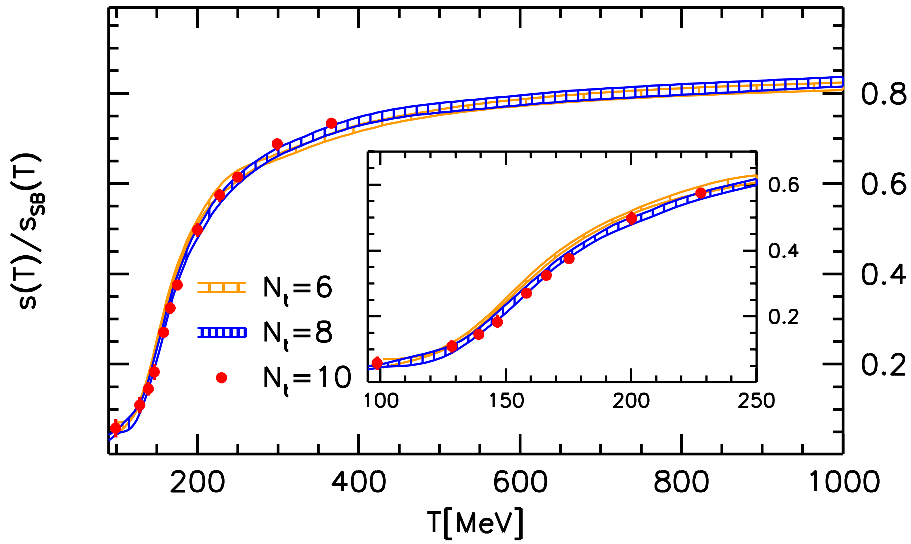
- Lattice calculations of QCD thermodynamics reveal a smooth crossover, like the ionization of a gas, occurring in a narrow range of temperatures centered at a $T_c \simeq 150$ MeV $\simeq 2$ trillion °C ~ 20 μs after big bang. At this temperature, the QGP that filled the universe broke apart into hadrons and the symmetry-breaking order that characterizes the QCD vacuum and gives mass to hadrons developed.

- Heavy ion collisions produce droplets of QGP at temperatures several times T_c, reproducing the stuff that filled the few-microseconds-old universe.

QGP Thermodynamics on the Lattice

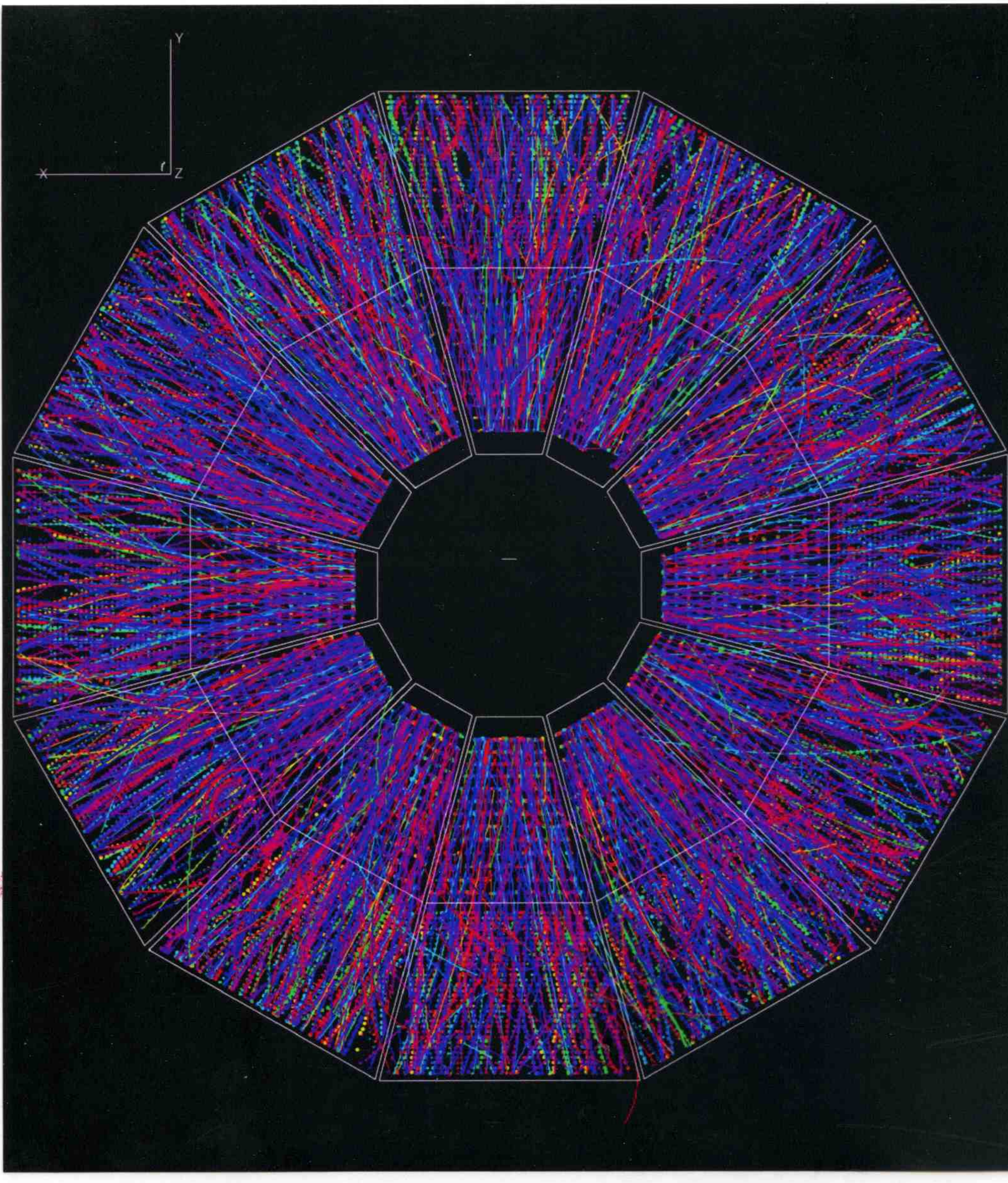
Endrodi et al, 2010





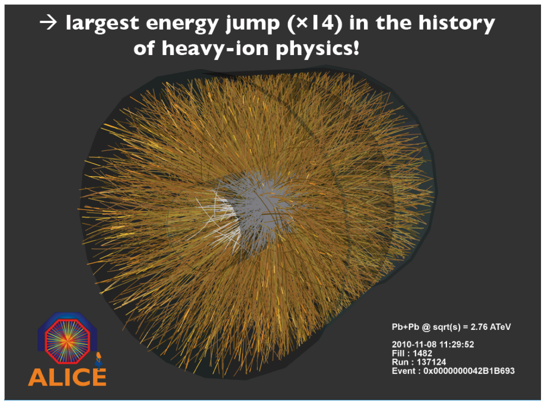
Above $T_{\text{crossover}} \sim$ 150-200 MeV, QCD = QGP. QGP static properties can be studied on the lattice.

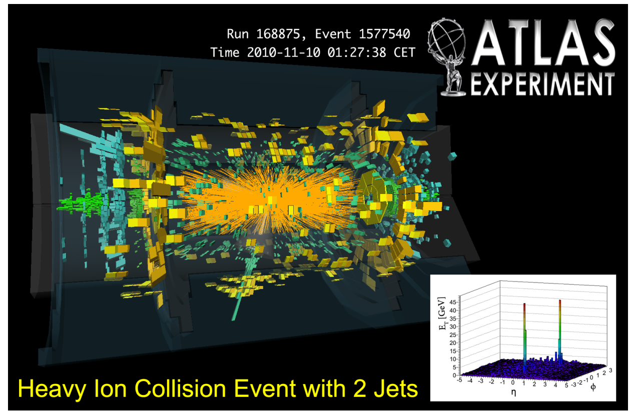
BUT: don't try to infer dynamic properties from static ones! Although its thermodynamics is almost that of ideal, noninteracting gas, QGP, this stuff is very different in its dynamical properties. [Lesson from experiment+hydrodynamics. But, also from the large class of gauge theories with holographic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



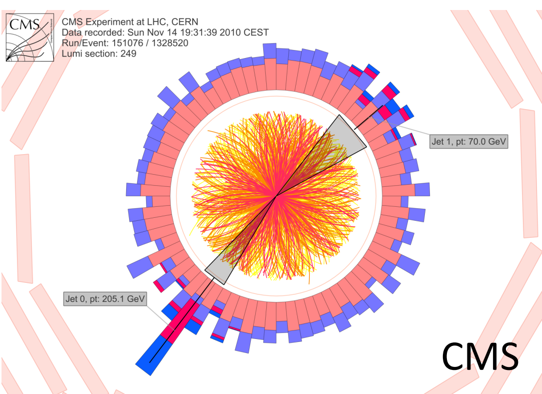
STAR

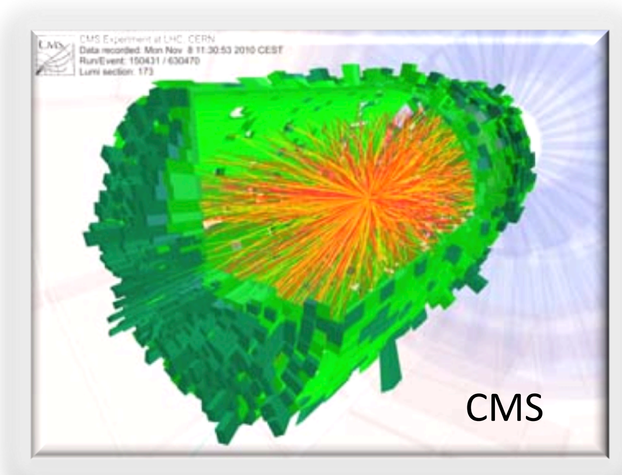
Nov 2010 first LHC Pb+Pb collisions





$\sqrt{s_{NN}}$ = 2760 GeV





Integrated Luminosity = 10 μb^{-1}

Liquid Quark-Gluon Plasma

- Hydrodynamic analyses of RHIC data on how asymmetric blobs of Quark-Gluon Plasma expand (explode) taught us that QGP is a strongly coupled liquid, with (η/s) — the dimensionless characterization of how much dissipation occurs as a liquid flows — much smaller than that of all other known liquids except one.

- Quarks and gluons in QGP diffuse, without being confined in hadrons. QGP flows. Its energy density and coupling are so large that quarks and gluons are always bumping into each other. Far from noninteracting; mean free path hard to define; relaxation times $\sim 1/T$.

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

- The discovery that it is a strongly coupled liquid is what has made QGP interesting to a broad scientific community.

Ultracold Fermionic Atom Fluid

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

- NanoKelvin temperatures, instead of TeraKelvin.

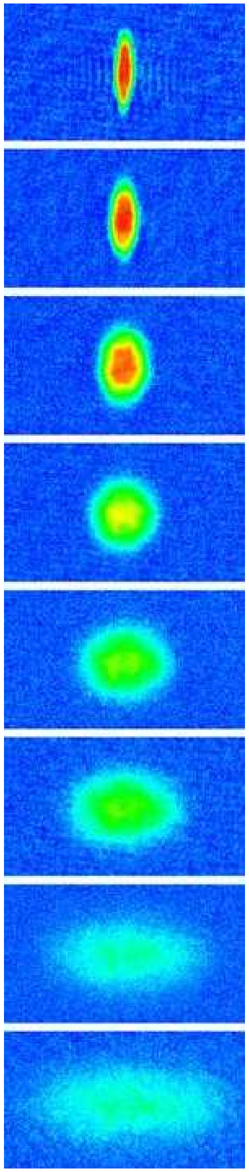
- Ultracold cloud of trapped fermionic atoms, with their two-body scattering cross-section tuned to be infinite. A strongly coupled liquid indeed. (Even though it's conventionally called the "unitary Fermi gas".)

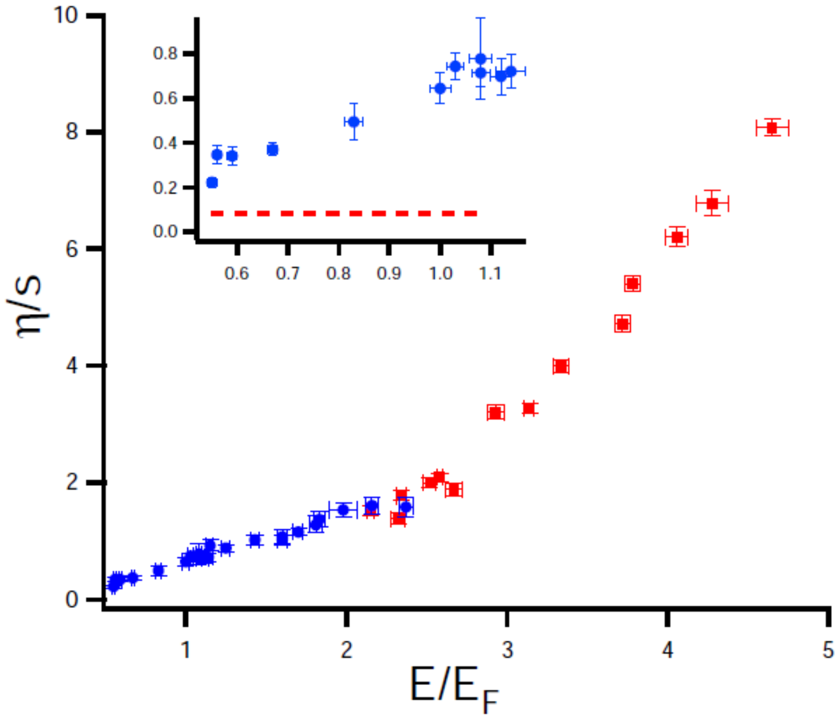
- Data on elliptic flow (and other hydrodynamic flow patterns that can be excited) used to extract η/s as a function of temperature...

Viscosity to entropy density ratio

consider both collective modes (low T)

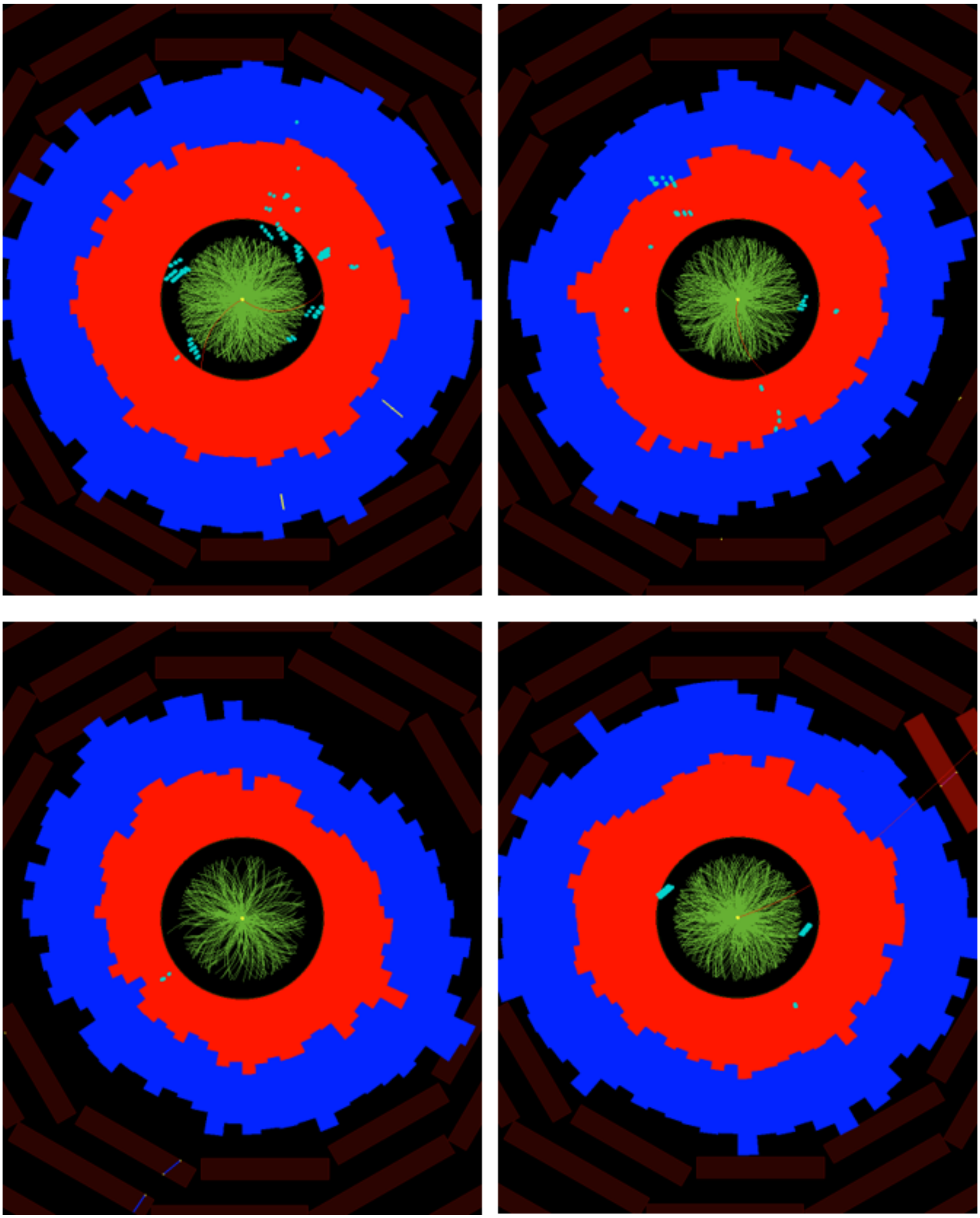
and elliptic flow (high T)





Cao et al., Science (2010)

$$\eta/s \leq 0.4$$



Rapid Equilibration?

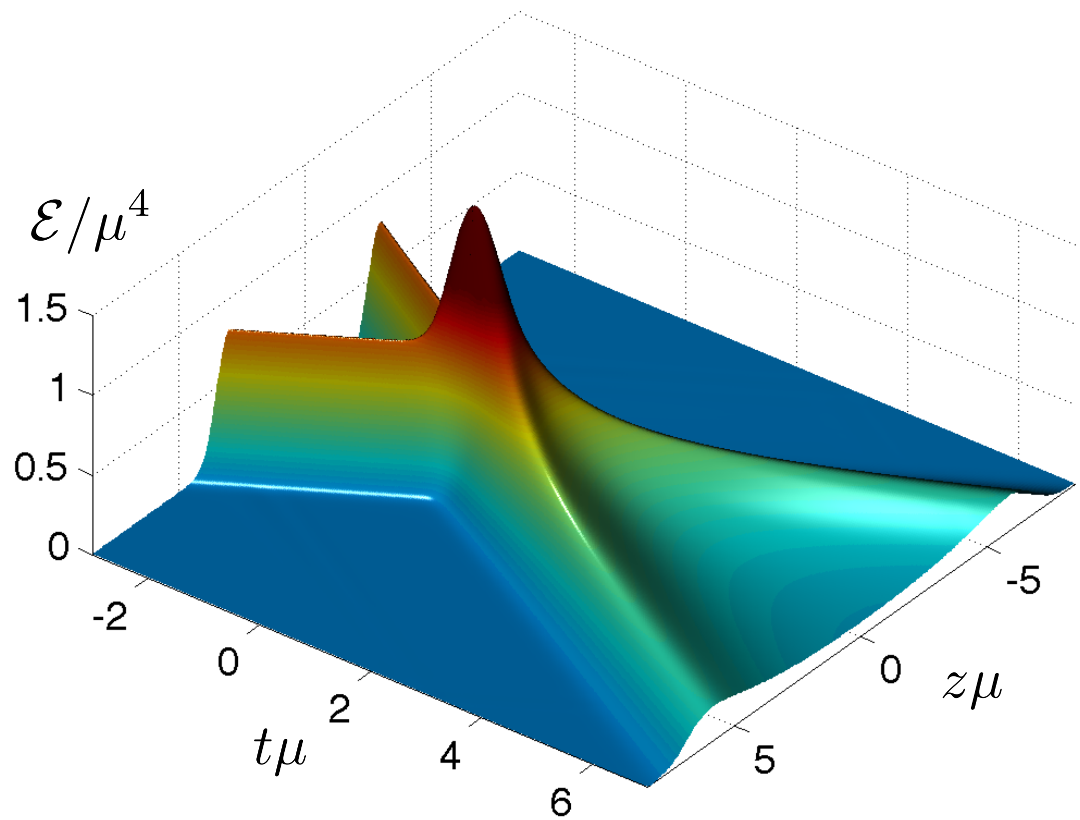
- Agreement between data and hydrodynamics can be spoiled either if there is too much dissipation (too large η/s) or if it takes too long for the droplet to equilibrate.

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

- This is the time it takes light to cross a proton, and was long seen as *rapid equilibration*.

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

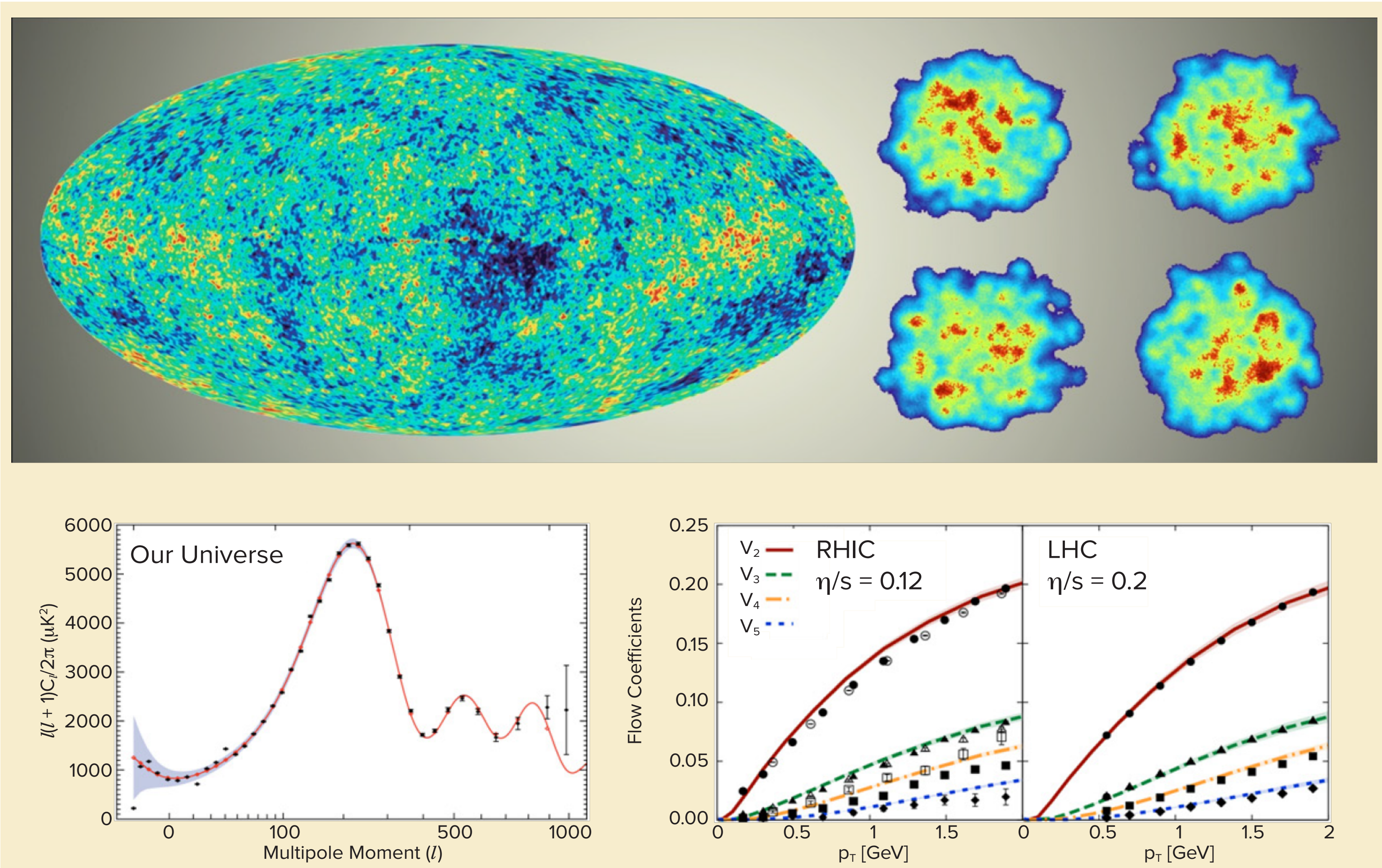
Colliding Strongly Coupled Sheets of Energy



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 1011.3562; generalized in C-S,H,M,vdS 1305.4919; CY 1309.1439 **Similarly 'rapid' hydrodynamization times ($\tau T \lesssim 0.7 - 1$) found for *many* non-expanding or boost invariant initial conditions.** Heller and various: 1103.3452, 1202.0981, 1203.0755, 1304.5172

η/s from RHIC and LHC data

- **I have given you the beginnings of a story that has played out over the past decade. I will now cut to the chase, leaving out many interesting chapters and oversimplifying.**
- **Using relativistic viscous hydrodynamics to describe expanding QGP,** *produced in an initially lumpy heavy ion collision*, **using microscopic transport to describe late-time hadronic rescattering, and using RHIC data on pion and proton spectra and** v_2 *and* v_3 *and* v_4 *and* v_5 *and* v_6 ... **as functions of** p_T **and impact parameter**...
- **QGP@RHIC, with** $T_c < T \lesssim 2T_c$**, has** $1 < 4\pi\eta/s < 2$ **and QGP@LHC, with** $T_c < T \lesssim 3T_c$ **has** $1 < 4\pi\eta/s < 3$**.**
  Nota bene: this was circa 2015.
- $4\pi\eta/s \sim 10^4$ **for typical terrestrial gases, and** 10 **to** 100 **for all known terrestrial liquids except one. Hydrodynamics works much better for QGP@RHIC than for water.**
- $4\pi\eta/s = 1$ **for any (of the by now very many) known strongly coupled gauge theory plasmas that are the "hologram" of a (4+1)-dimensional gravitational theory "heated by" a (3+1)-dimensional black-hole horizon.**



Our Universe
6000
5000
4000
3000
2000
1000
0
0
100
500
1000
Multipole Moment (l)
l(l + 1)C_l/2π (μK²)
RHIC
η/s = 0.12
LHC
η/s = 0.2
V₂
V₃
V₄
V₅
Flow Coefficients
0.25
0.20
0.15
0.10
0.05
0.00
0
0.5
1
1.5
2
p_T [GeV]

QGP cf CMB

- In cosmology, initial-state quantum fluctuations, processed by hydrodynamics, appear in data as c_ℓ's. From the c_ℓ's, learn about initial fluctuations, and about the "fluid" — eg its baryon content.

- In heavy ion collisions, initial state quantum fluctuations, processed by hydrodynamics, appear in data as v_n's. From v_n's, learn about initial fluctuations, and about the QGP — eg its η/s, ultimately its $\eta/s(T)$ and ζ/s.

- Cosmologists have a huge advantage in resolution: c_ℓ's up to $\ell \sim$ thousands. But, they have only one "event"!

- Heavy ion collisions only up to v_6 at present. But they have billions of events. And, they can do controlled variations of the initial conditions, to understand systematics...

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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;... Among the grand challenges at the frontiers of condensed matter physics today.

- In all these cases, after discovery two of the central strategies toward gaining understanding are *probing* and *doping*. To which we now turn...
  But first, what from 2015 Intro must be updated in 2022? Many improvements, but big picture was solid in 2015! Two updates I will highlight.

2022 Updates to 2015 Intro

- **Much more complete understanding now of how hydrodynamization happens in kinetic theory. A weakly coupled picture, applied at intermediate coupling. Hydrodynamization in 1 fm/c is no longer surprising in kinetic theory.** Berges, Heller, Kurkela, Mazeliauskas, Paquet, Schlichting, Spalinski, Strickland, Teaney, Zhu...

- **We had a qualitative, intuitive, understanding of how it can happen on this timescale at strong coupling in 2015. Now we have a qualitative, intuitive, understanding in kinetic theory also:** *adiabatic hydrodynamization.* Brewer, Scheihing-Hitschfeld, Yan, Yin...

- **Quantification! Via work of *many* experimentalists and theorists, we now have more, and more precise, experimental data that, together with improved theoretical modeling, are driving Bayesian determinations, by multiple groups, of the "shape" of the fluid at the time of hydrodynamization, and key properties of QGP and their temperature dependence. Quantification, including error bars.**

η/s from RHIC and LHC data

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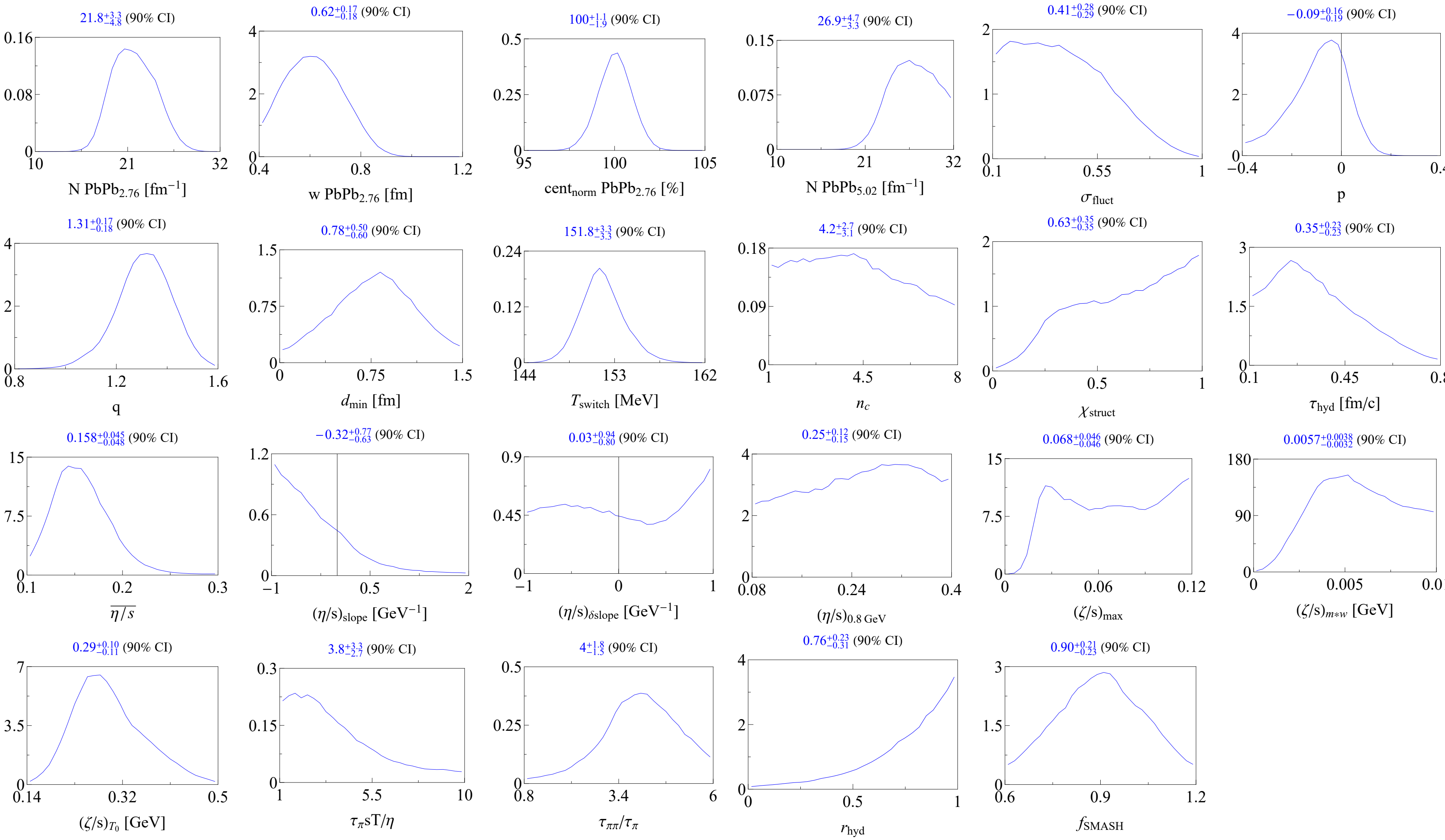
Eg. of Today's State of the Art



Trajectum (Gürsoy, Nijs, Snellings, van der Schee)
this fig: Nijs, van der Schee, to appear

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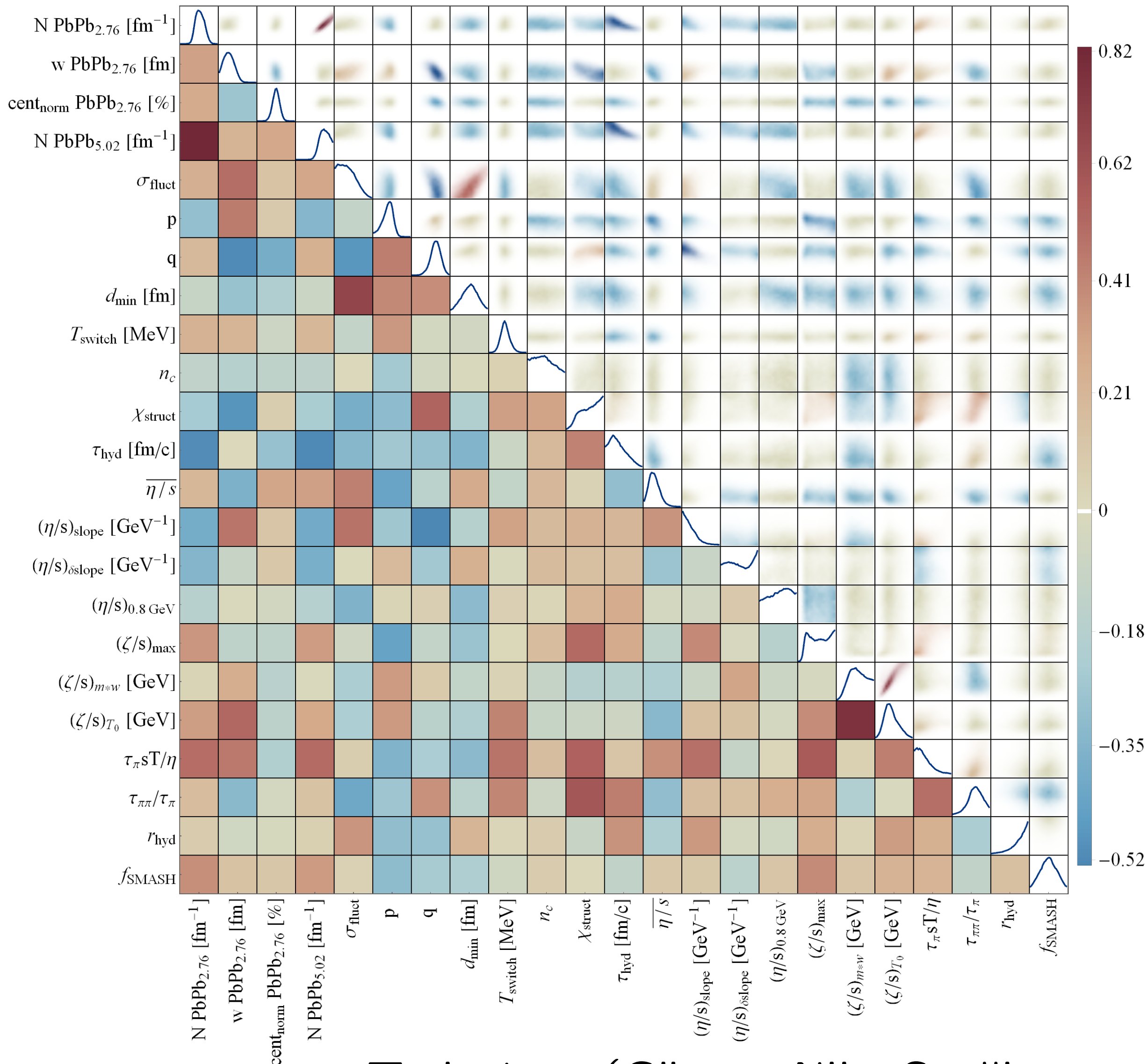

Trajectum (Gürsoy, Nijs, Snellings, van der Schee)
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What the State of the Art Makes Possible...

INT PROGRAM INT-23-1A

Intersection of nuclear structure and high-energy nuclear collisions

January 23, 2023 - February 24, 2023

HIGH-RESOLUTION IMAGES

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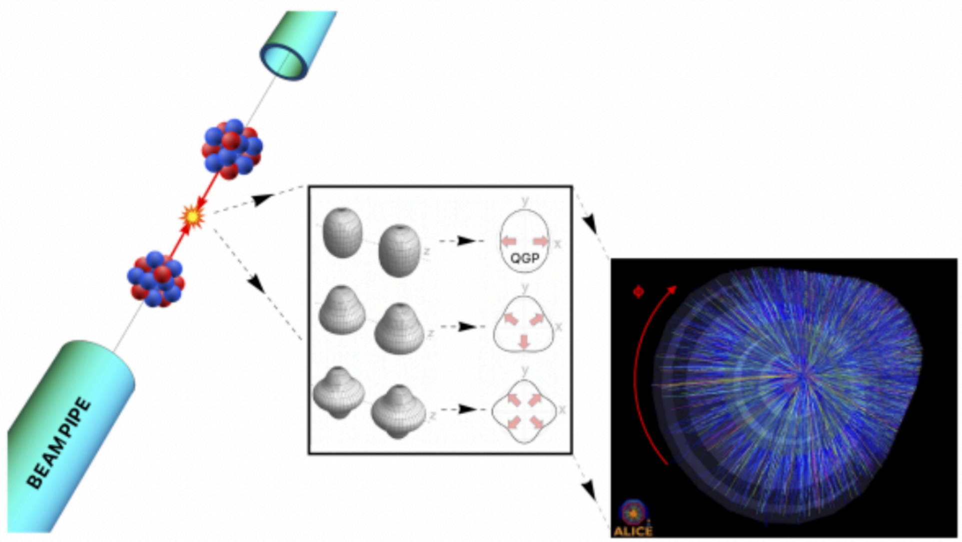


High-energy heavy-ion collisions producing a quark gluon plasma whose energy density profile reflects the collective structure of the colliding ions

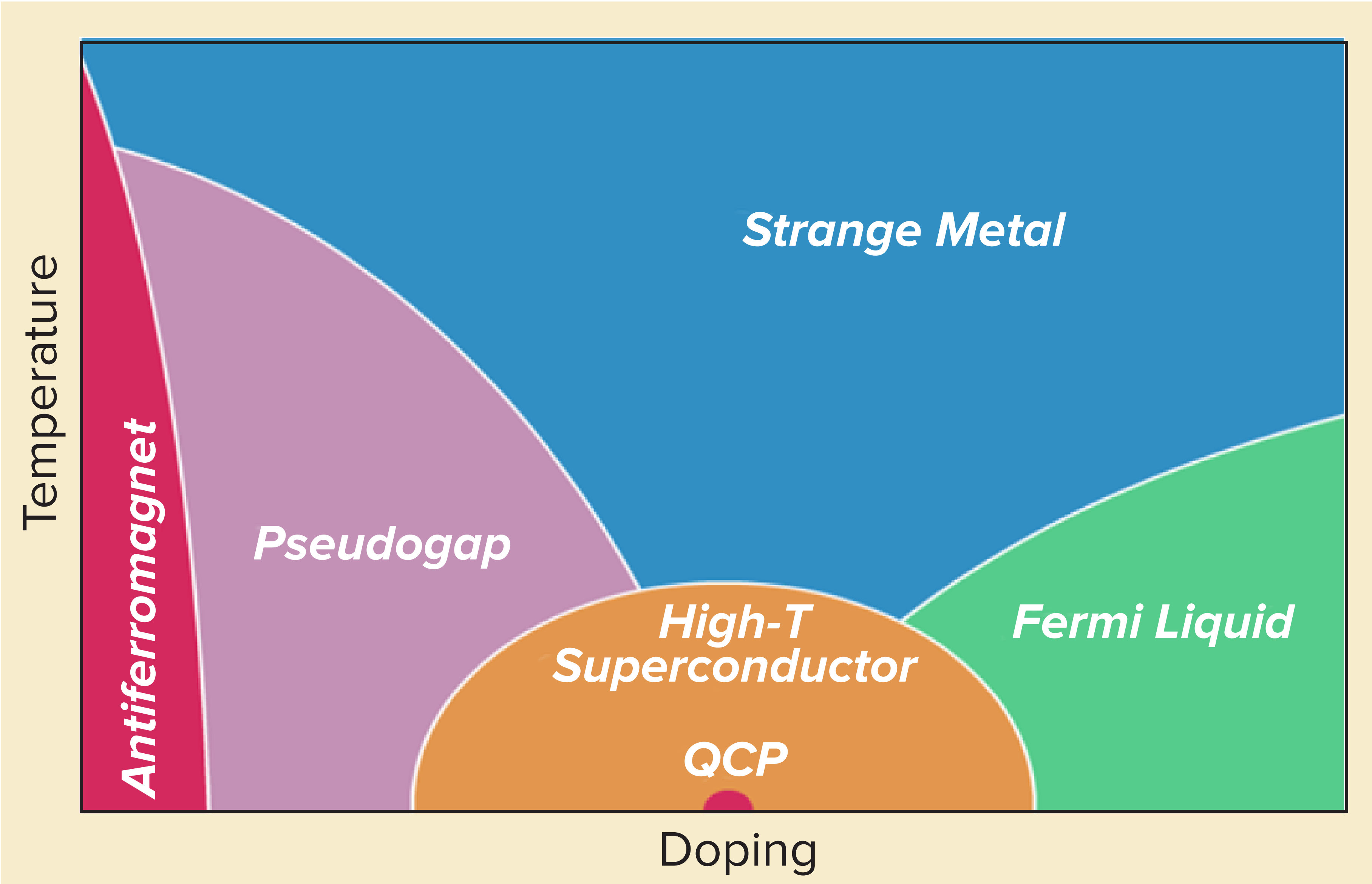
APPLICATION FORM - FOR FULL CONSIDERATION, APPLY BY SEPT. 12, 2022

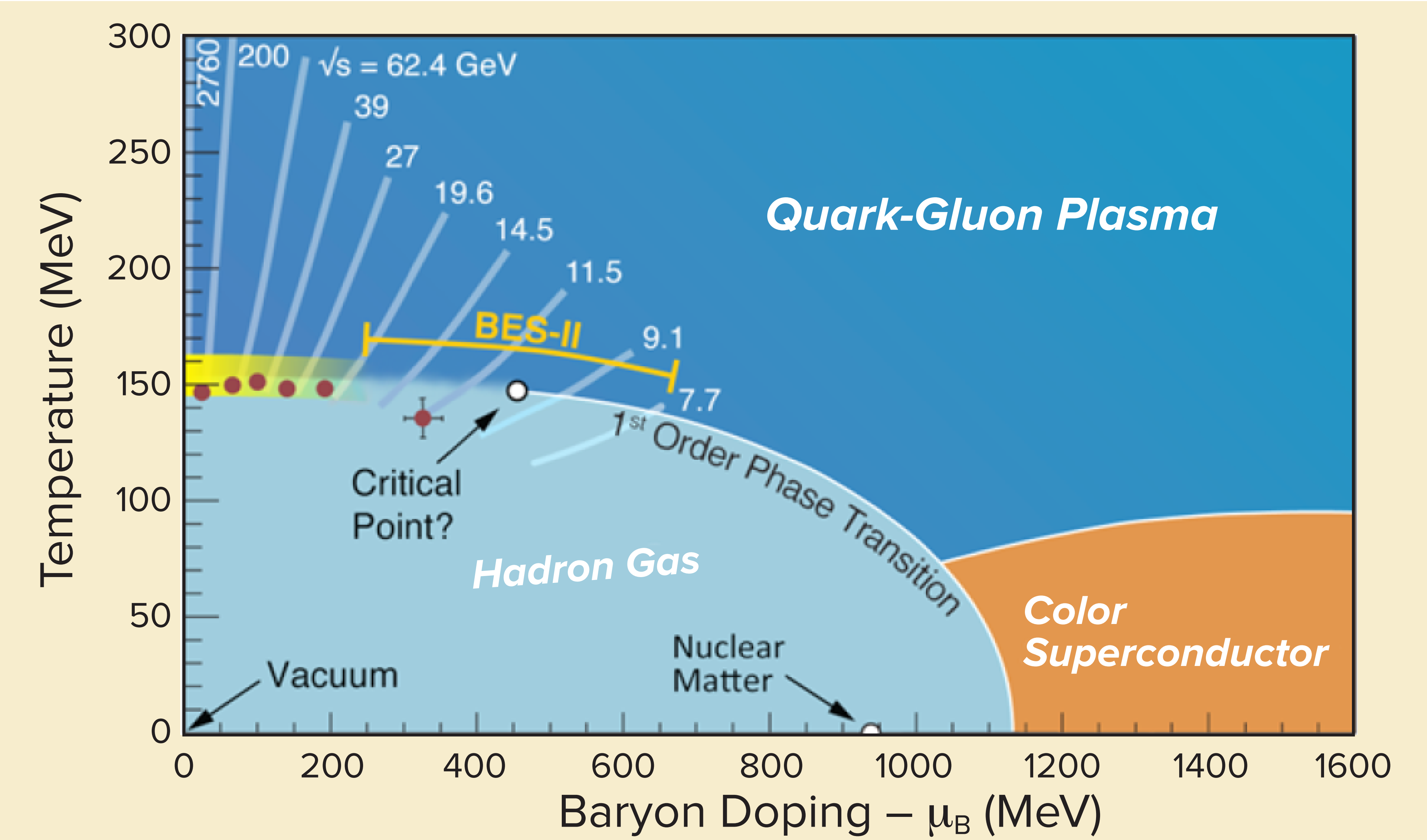
What Next?

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 antiquarks, 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: How does the strongly coupled liquid emerge from an asymptotically free gauge theory? Maybe answering this question could help to understand how strongly coupled matter emerges in other contexts.

  Three different variants of this question...


Strange Metal
Pseudogap
Antiferromagnet
High-T
Superconductor
QCP
Fermi Liquid
Temperature
Doping



300
250
200
150
100
50
0
Temperature (MeV)
2760
200
√s = 62.4 GeV
39
27
19.6
14.5
11.5
9.1
7.7
BES-II
Quark-Gluon Plasma
Critical Point?
1st Order Phase Transition
Hadron Gas
Color Superconductor
Vacuum
Nuclear Matter
0
200
400
600
800
1000
1200
1400
1600
Baryon Doping – μB (MeV)

Mapping the QCD Phase Diagram

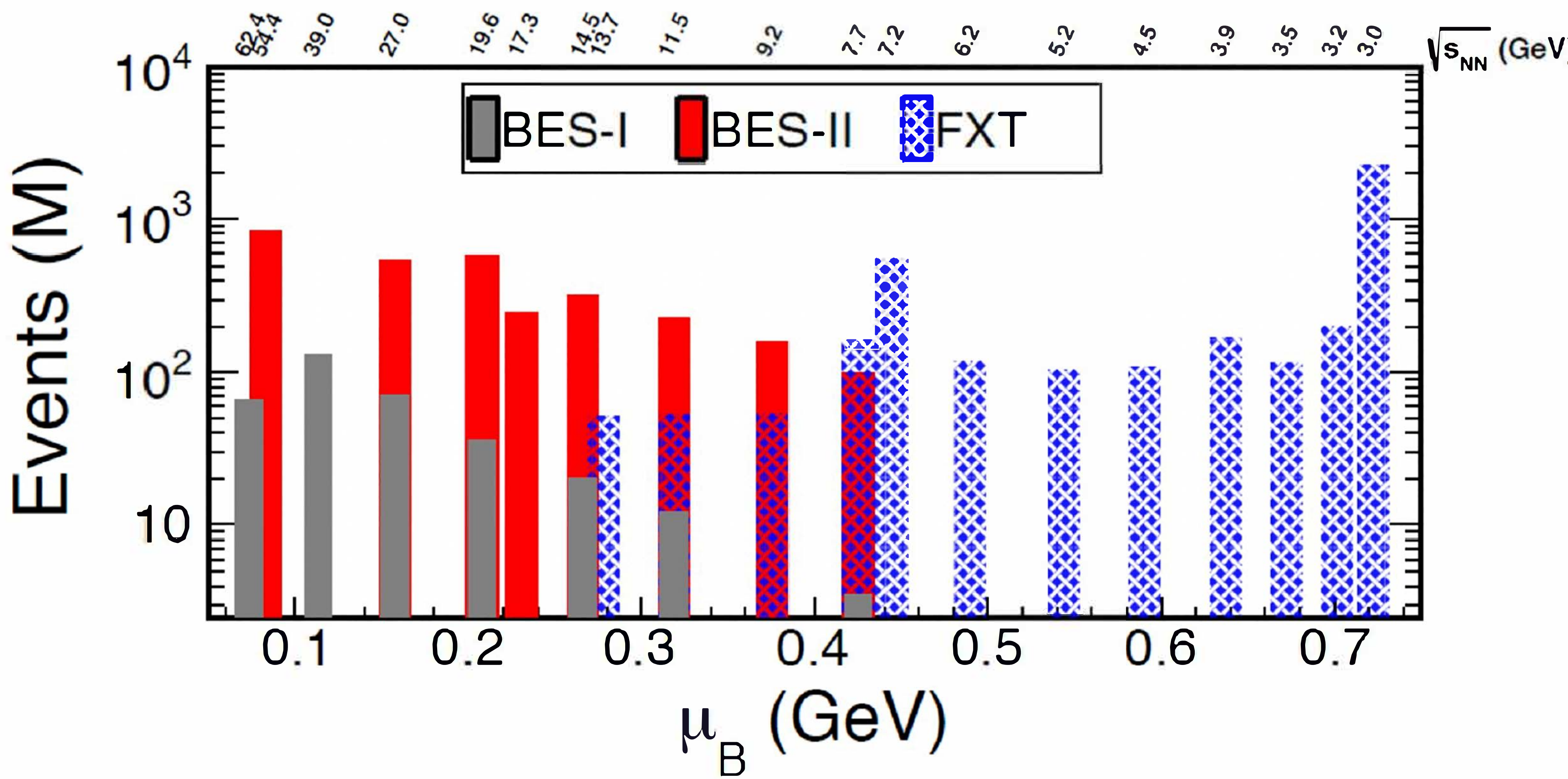
- How does QGP change as you "dope" it with a larger and larger excess of quarks over antiquarks, i.e. larger and larger μ_B?

- Substantial recent progress... Slides from 2015 almost completely superseded.

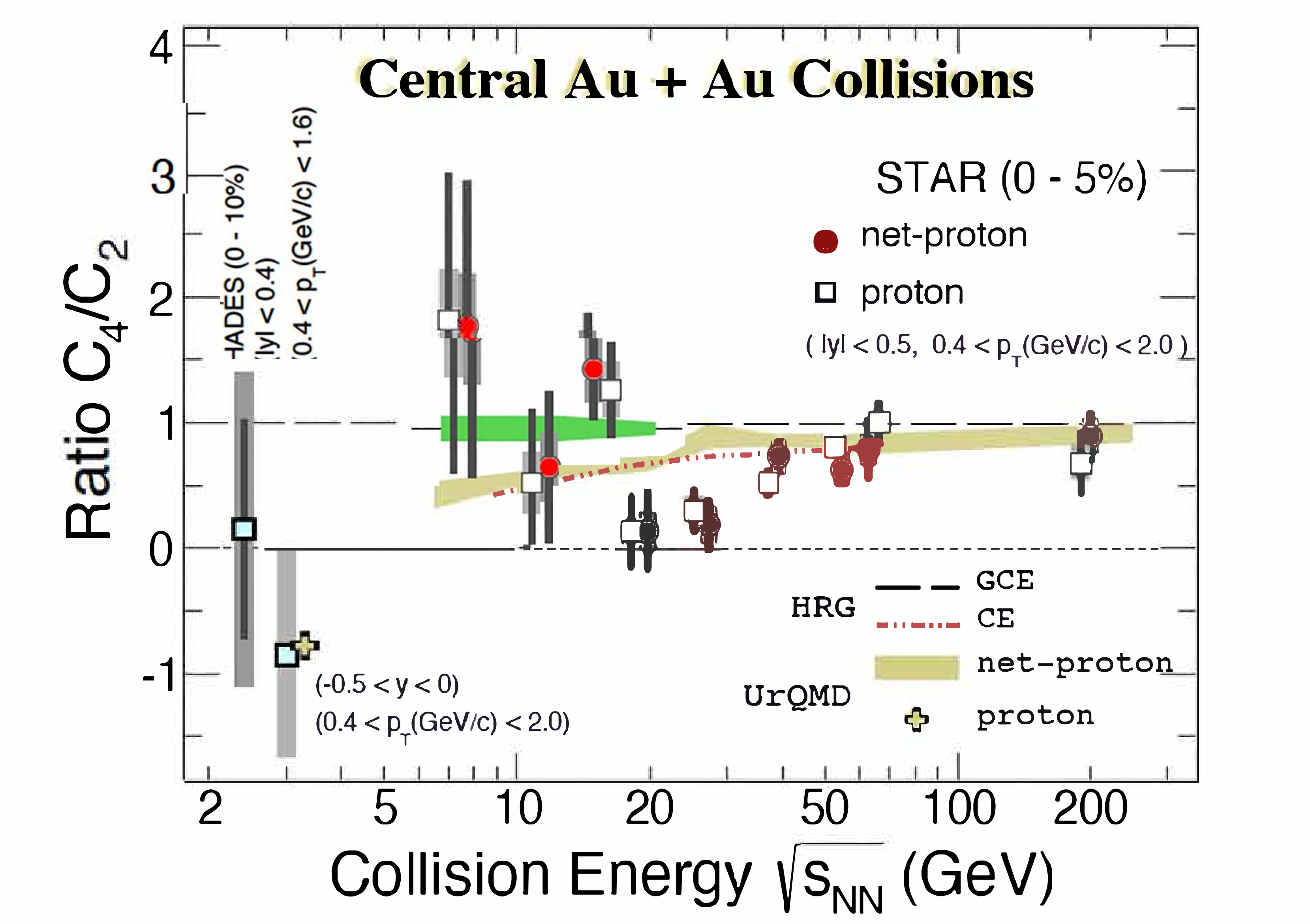
- Enormous progress on theory and modeling, by many people. Including by the BEST collaboration – see 2108.13867 for a summary. Many previous and future RHIC-BES talks on this work. Following my instructions, I will not review.

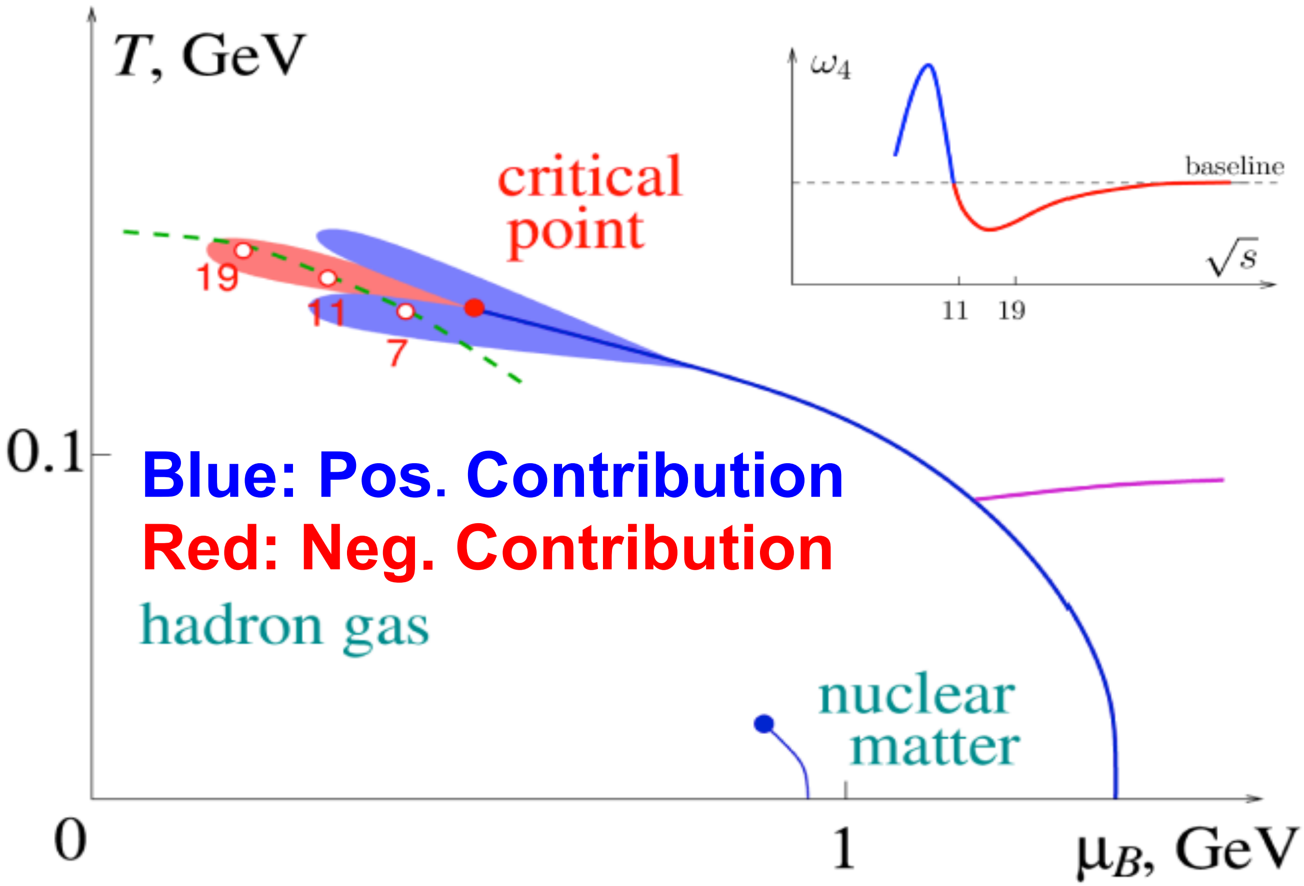
- Phase II of the RHIC Beam Energy Scan data taking was completed in 2021. We await results with great interest and anticipation.

RHIC BES II Data Taken...



Proton Kurtosis, before BES II




T, GeV
0.1
0
1
μB, GeV
critical point
19
11
7
ω4
baseline
√s
11
19
Blue: Pos. Contribution
Red: Neg. Contribution
hadron gas
nuclear matter

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  Three different variants of this question...

Probing the Original Liquid

The question How does the strongly coupled liquid emerge from an asymptotically free gauge theory? can be thought of in three different ways, corresponding to three meanings of the word "emerge": as a function of resolution, time, or size.

- How does the liquid emerge as a function of resolution scale? What is the microscopic structure of the liquid? Since QCD is asymptotically free, we know that when looked at with sufficient resolution QGP must be weakly coupled quarks and gluons. How does a liquid emerge when you coarsen your resolution length scale to $\sim 1/T$?
- Physics at $t = 0$ in an ultrarelativistic heavy ion collision is weakly coupled. How does strongly coupled liquid form? How does it hydrodynamize?
- How does the liquid emerge as a function of increasing system size? What is the smallest possible droplet of the liquid?

Each, in a different way, requires stressing or probing the QGP. Each can tell us about its inner workings.

Smallest possible droplet of liquid?

- What is the smallest possible droplet of QGP that behaves hydrodynamically? Anyone doing holographic calculations at strong coupling, or anyone seeing effects of small lumps in the initial state visible in the final state, could have asked this question, but didn't. Question was asked by data: pPb collisions @LHC; pAu, dAu and ^{3}HeAu data @RHIC.
- Subsequently, holographic calculations of a "proton" of radius R colliding with a sheet show hydrodynamic flow in the final state as long as the collision has enough energy such that $RT_{\text{hydrodynamization}} \gtrsim 0.5$ to 1.
- Many recent theoretical advances. Hydrodynamic behavior in small-big collisions at top RHIC energy and LHC energy less surprising, *a posteriori*. But still remarkable.
- Not our focus today. For today, tells us that to see "inside" the liquid we will need probes which resolve short length scales...

Why Jets?

- The remarkable utility of hydrodynamics, for example in describing the dynamics of small lumps in the initial state in AA collisions, tells us that to see the inner workings of QGP, namely to see how the liquid is put together from quarks and gluons, we will need probes with much finer resolution.
- Need resolution scale that is $\ll$ size of a proton, $\ll$ size of lumps coming from the initial state that behave hydrodynamically, $\ll 1/T_{\text{hydrodynamization}}$.
- Jets are multiscale probes. (Scales associated with: hard production, splittings in the shower, momentum transfers as jet partons interact with the medium, response of medium. So, from very hard to very soft.)
- They provide our best, and I would in fact argue only, chance of seeing the inner workings of the QGP.
- Jets in heavy ion collisions are the closest we will ever come to doing a scattering experiment off a droplet of Big Bang matter.

Why Jets?

- Closest we will ever come to doing a scattering experiment off a droplet of Big Bang matter.
- Jets in heavy ion collisions *also* offer the best chance of watching how QGP hydrodynamizes. Jets leave a wake in the medium. Can we see how it hydrodynamizes, and then flows? Best shot at experimental access to this physics.
- But, precisely because they are multiscale probes, jets sure don't make it easy to decode the information about the nature of QGP at various length scales that are encoded in the modification of their energies, shapes, and structure.
- For example, how do we separate effects on experimental observables due to wake from those due to scattering off quasiparticles?

Jets as Probes of QGP

- When looked at with sufficient resolution, QGP must be made of weakly coupled quarks and gluons. Seeing them is a necessary precondition for addressing the question: How does the strongly coupled liquid emerge, at length scales $\sim 1/T$, from an asymptotically free gauge theory?
- Need experimental evidence for point-like scatterers in QGP when QGP is probed with large momentum transfer.
- But jets sure don't make it easy. That is why we need high statistics data from sPHENIX and the high luminosity LHC on rare events in which jet partons scatter off QGP partons by a sufficient angle to yield observable consequences.
- And, that is why theorists are using the data of today to build the baseline of understanding with and against which to look for and interpret such effects.

Sensitivity of Some Jet Observables to the Presence of Quasiparticles in the QGP

Zachary Hulcher, *Stanford*

Dani Pablos, *INFN Torino*

Krishna Rajagopal, *MIT*

arXiv:2208.13593; 22nn.nnnnn

What you can do with, and learn from, a model…

There are things you can do with a model (in this talk, the Hybrid Model) that you can't do with experimental data (eg turn physical effects off) …

But that nevertheless teach us important lessons for how to look at, and learn from, experimental data…

This talk provides examples: on which jet observables are more sensitive to the presence of quasiparticles in the strongly coupled QGP-soup, and which are more sensitive to the wakes that jets make in the soup.

But first a *very* brief intro to the Hybrid Model…

Perturbative Shower … Living in Strongly Coupled QGP

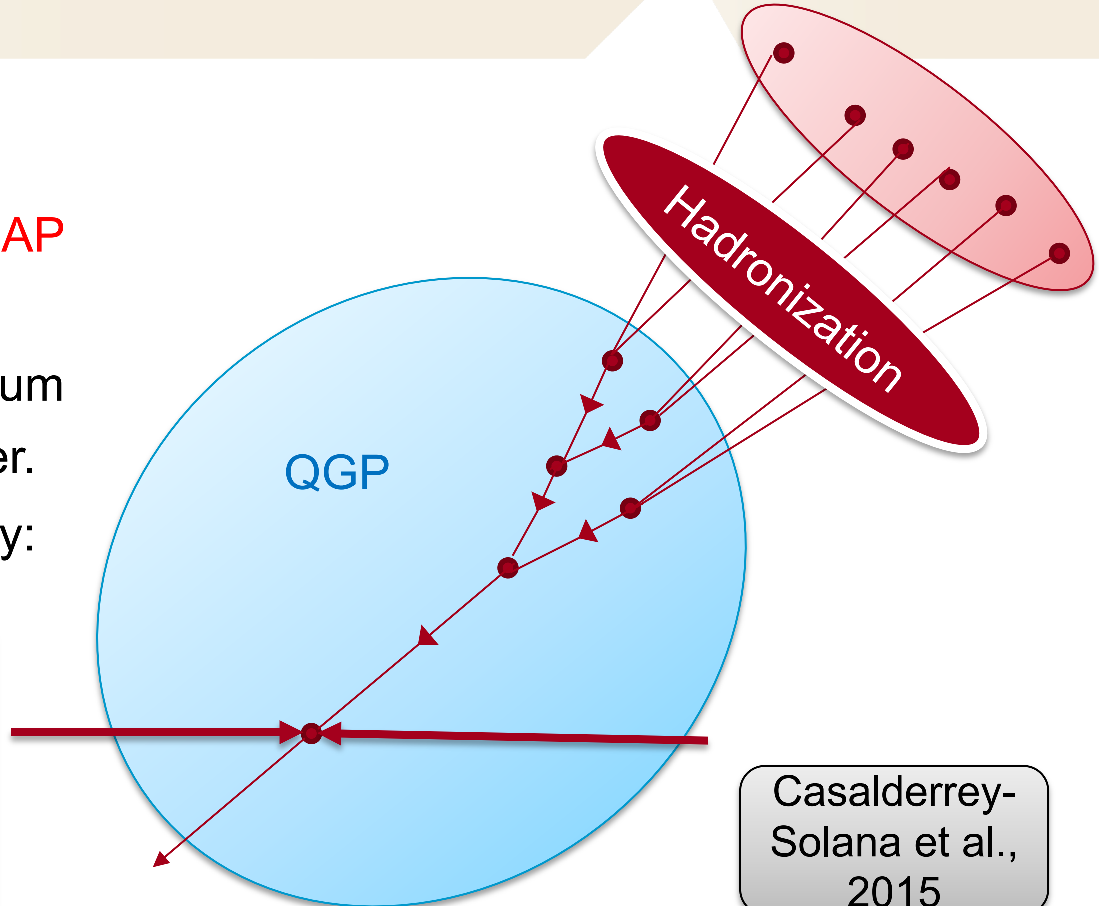
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}}$$

$$\tau = \frac{2E}{Q^2}$$

O(1) fit const.



Casalderrey-Solana et al., 2015

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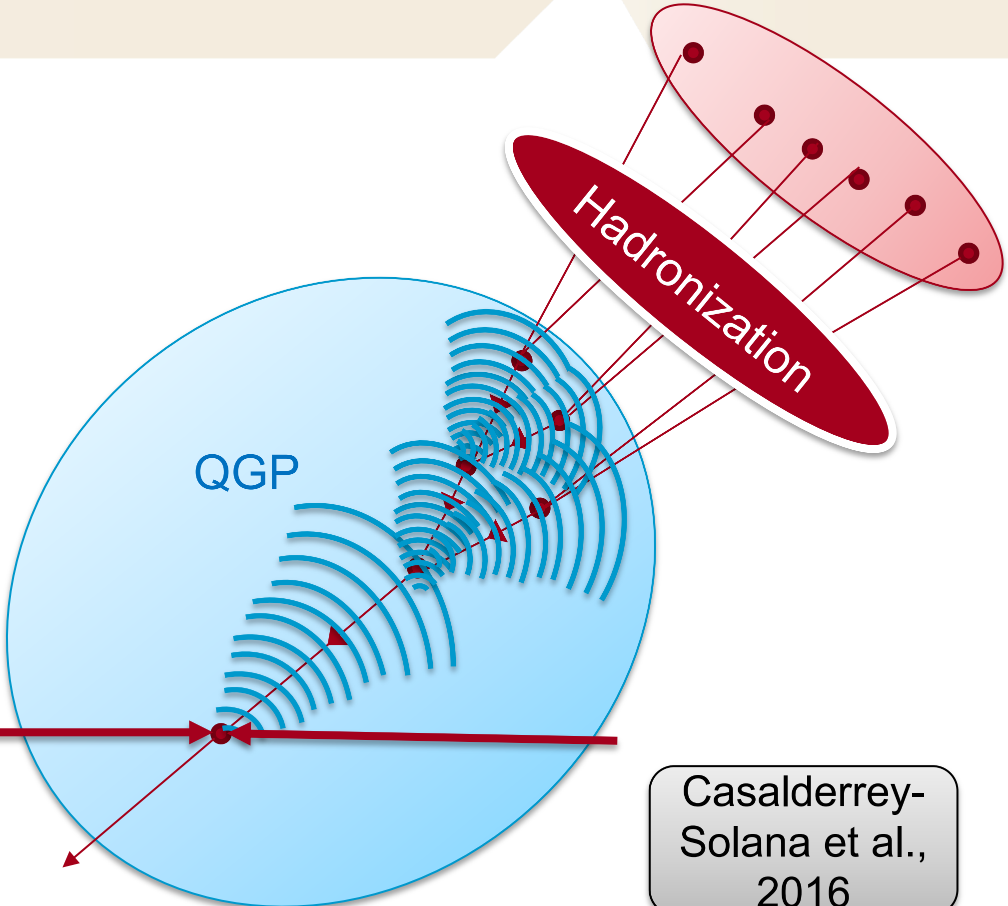


Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$

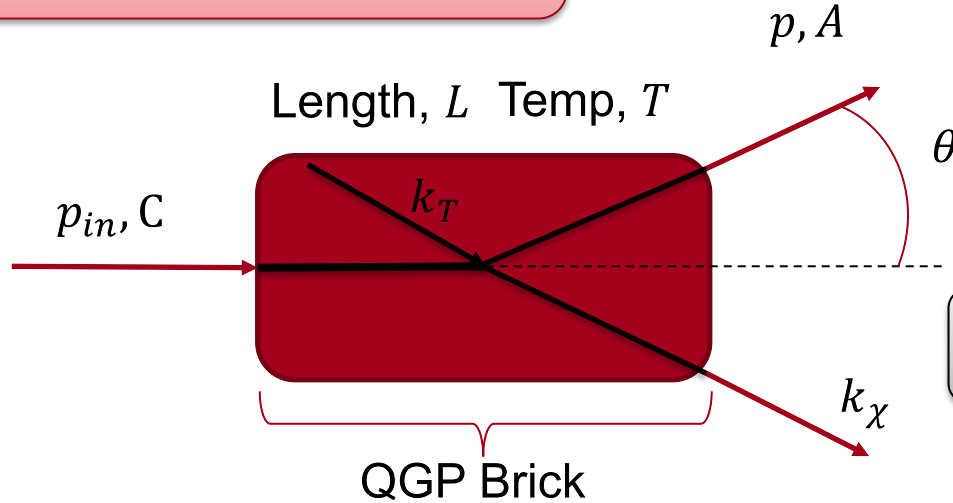
Why Moliere scattering? Why add to Hybrid Model?

- QGP, at length scales of $O(T^{-1})$, including flow and parton energy loss, is well-described as a strongly coupled liquid. In hybrid model (to date) there are no quasiparticles in the QGP.
- At shorter length scales, probed at high exchanged-momentum, asymptotic freedom → quasiparticle behavior.
- High energy partons in jet showers have the potential to probe the particulate nature of QGP via power-law-rare, high-momentum-transfer, large-angle, Moliere scattering.
- "Seeing" such scattering is first step to probing microscopic structure of QGP
- What jet observables are sensitive to effects of Moliere scattering? To answer, need to turn it off/on.
- Start from Hybrid Model – where Moliere and any particulate effects are definitely off! Add Moliere, and look at its effects…

Moliere Scattering in a brick of QGP (D'Eramo, KR, Yin, 2019)

Power-law-rare medium kicks which can probe particle constituents of QGP

In JEWEL, LBT, MARTINI, harder to turn off



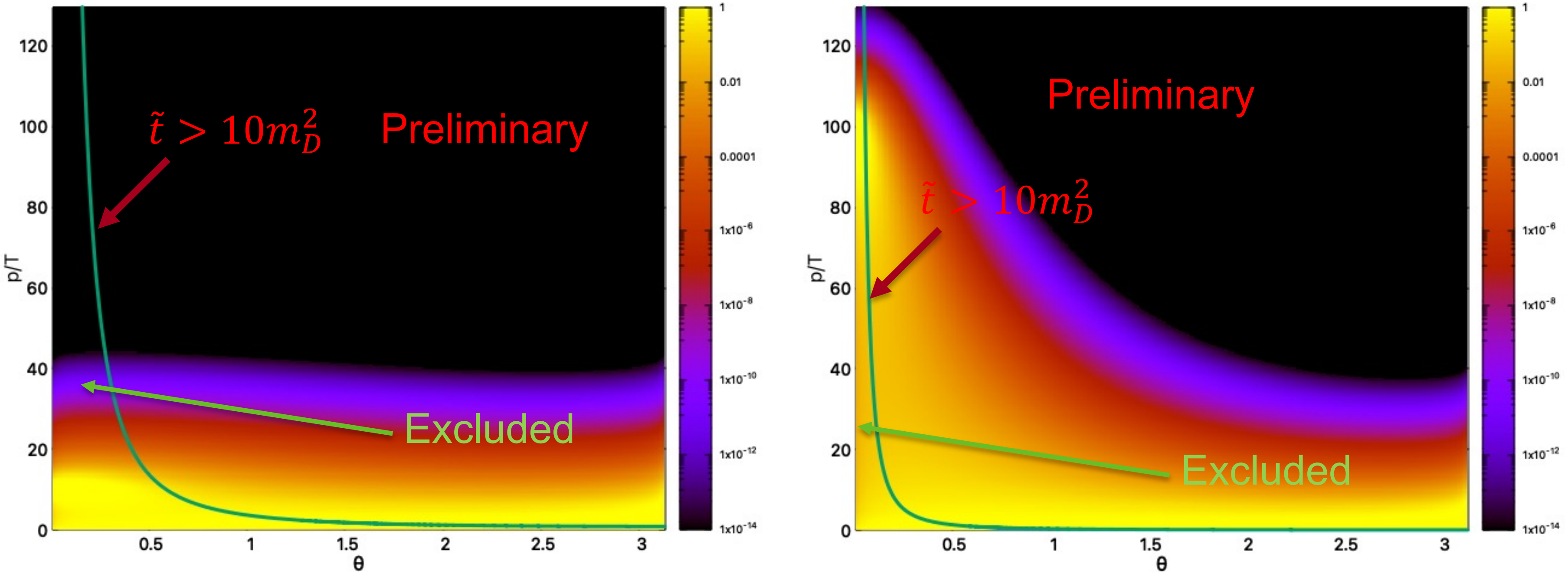
D'Eramo et al., 2019

- Sufficiently hard scattering should be perturbative.
- High p_T particle can be deflected, changing its energy and direction.
- Recoiling particle, k_χ, a new particle to be quenched
- Thermal particle, k_T, from BE/FD distribution, removed from medium.

Tree-Level 2-2 massless scattering amplitudes

$$F^{C\to A}(p,\theta;p_{in}) = \sum_{nDB} \frac{c^{C\to A}_{DBn}}{2(4\pi)^3}\left(\frac{p\sin(\theta)}{p_{in}|\boldsymbol{p}-\boldsymbol{p_{in}}|T}\right)\int_{k_{min}}^{\infty} dk_T\, n_D(k_T)\left[1\pm n_B(k_\chi)\right]\int_0^{2\pi}\frac{d\phi}{2\pi}\frac{\left|M^{(n)}\right|^2}{g_s^4}$$

Results (for a QGP brick)



Incoming gluon, $p_{in} = 10T, \mathrm{L} = 15/T$

Incoming gluon, $p_{in} = 100T, \;\; \mathrm{L} = 15/T$

- Also exclude $\tilde{u} > 10m_D^2$; not a simple curve on this plot
- Restricting to $\tilde{u}, \tilde{t} > 10 \cdot m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

Perturbative Shower … Living in Strongly Coupled QGP

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}} \qquad \tau = \frac{2E}{Q^2}$$

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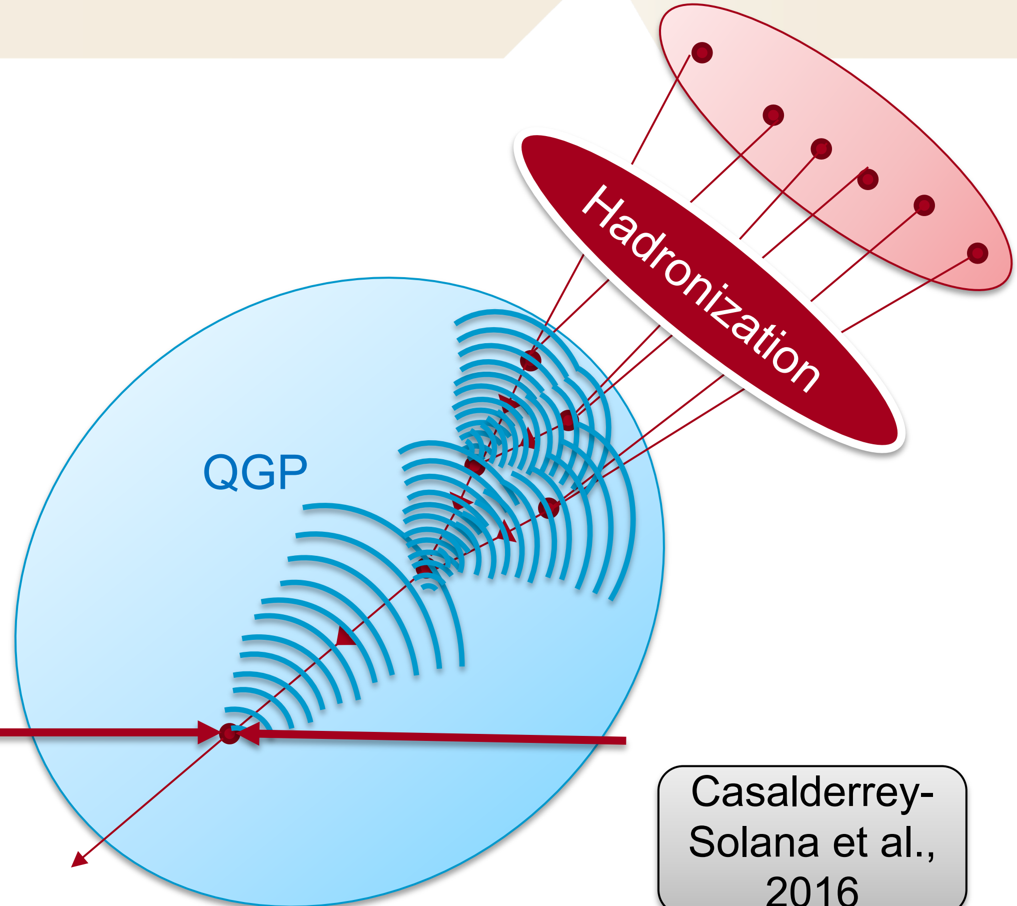

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$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Adding Moliere Scattering to Hybrid Model

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
    - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

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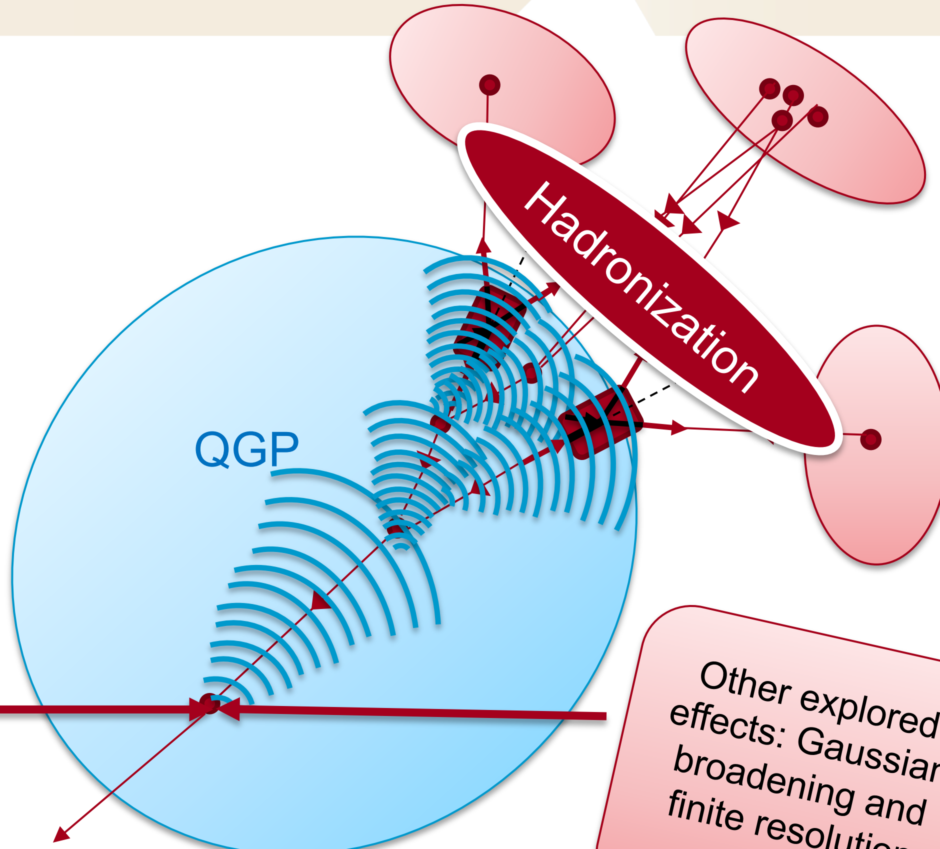


Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation → activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y - \eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Gaussian Broadening vs Large Angle Scattering

- Elastic scatterings of exchanged momentum $\sim m_D$

  → Gaussian broadening due to multiple soft scattering

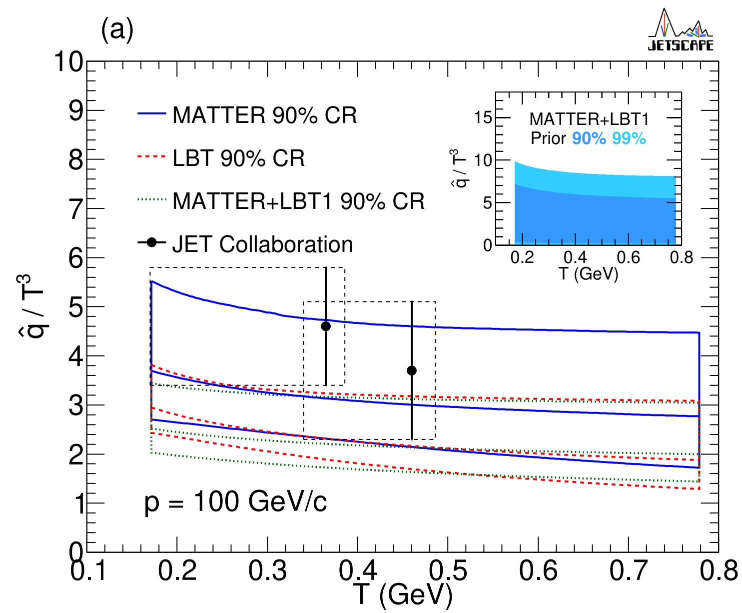
- At strong coupling, holography predicts Gaussian broadening without quasi-particles (ex: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yields very little effect on jet observables

- Restrict to momentum exchanges $\gg m_D$

  → perturbative regime with a power law distribution separated from Gaussian broadening



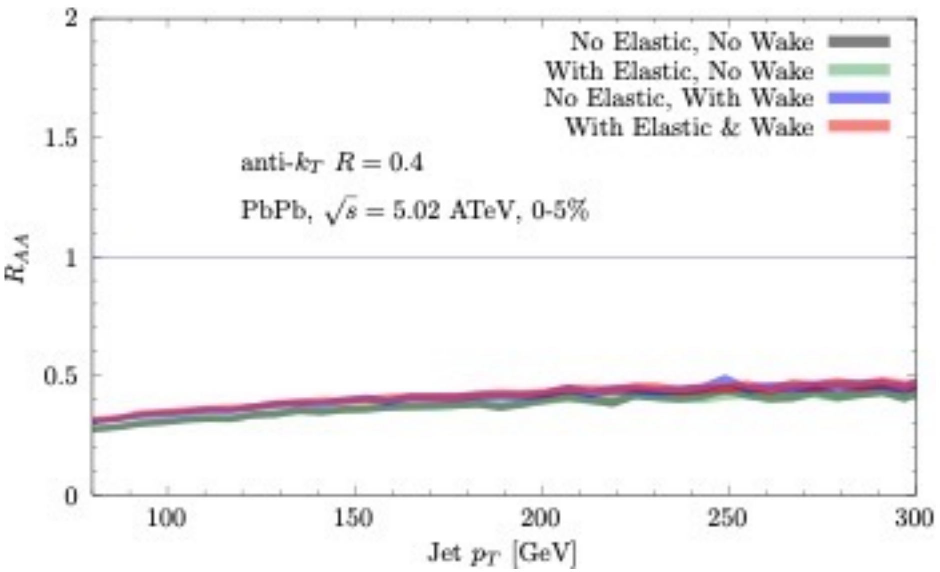
D'Eramo et al., 2011, 2018
+
Mehtar-Tani et al., PRD 2021

Jet R_{AA}

Casalderrey-Solana et al. 2019

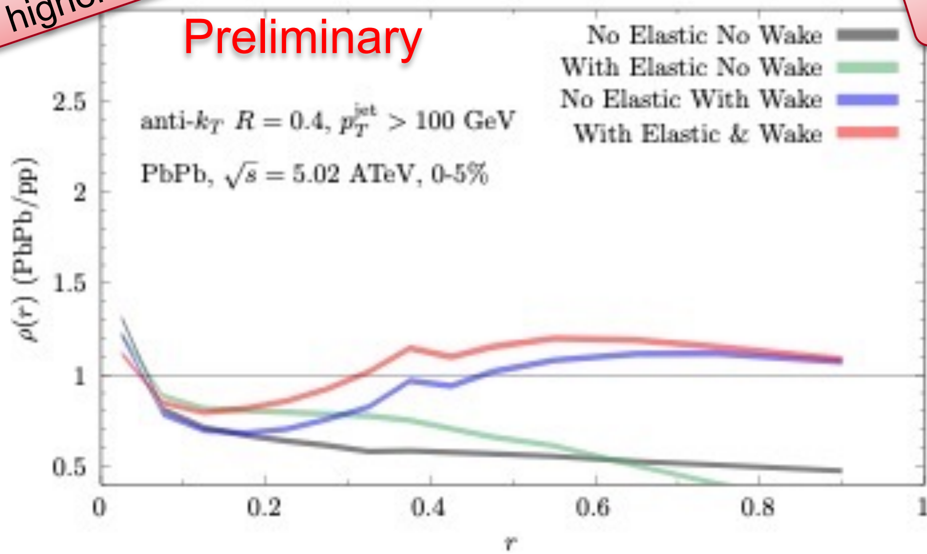
- κ_{sc} previously fit with jet and hadron suppression data from ATLAS+CMS at 2.76+5.02 TeV
- Elastic scatterings lead to slight additional suppression; refit κ_{sc} . That means red is on top of blue in this plot by construction. (Addition of the elastic scatterings yields only small change to value of κ_{sc}.)
- Adding the hadrons from the wake allows the recovery of part of the energy within the jet cone; blue and green slightly below red and blue.
- All results, here on, are Preliminary.

Preliminary

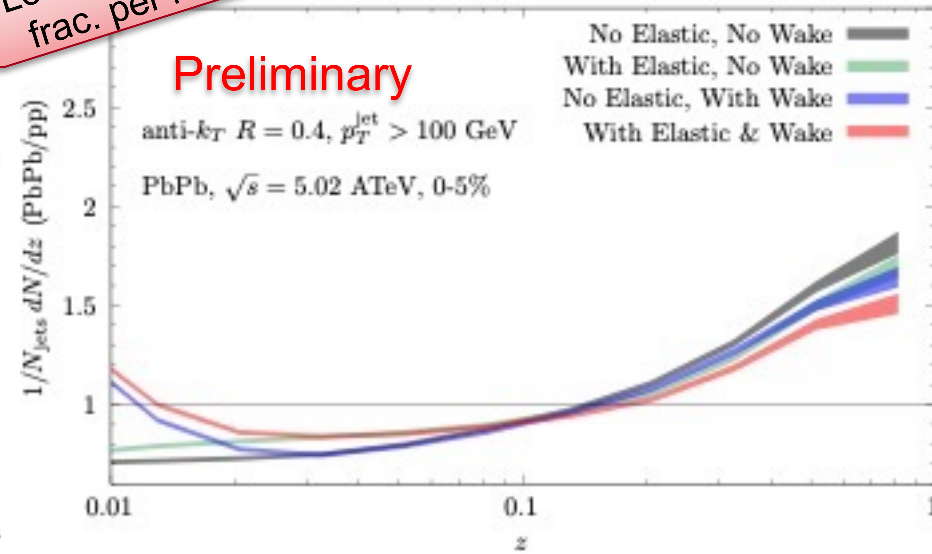


Jet Shapes and Fragmentation Functions

More energy at higher radius



Lower momentum frac. per hadron



→ Elastic scattering effects look very similar to wake effects, but smaller.

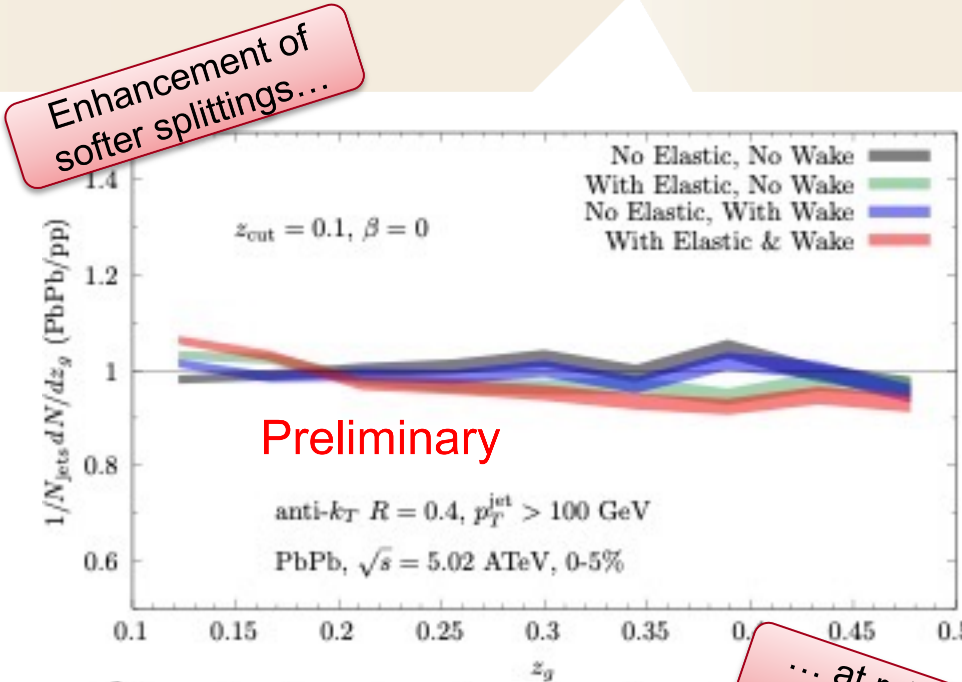
- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In these observables, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not at all.
- What if we look at groomed observables? Less sensitive to wake…

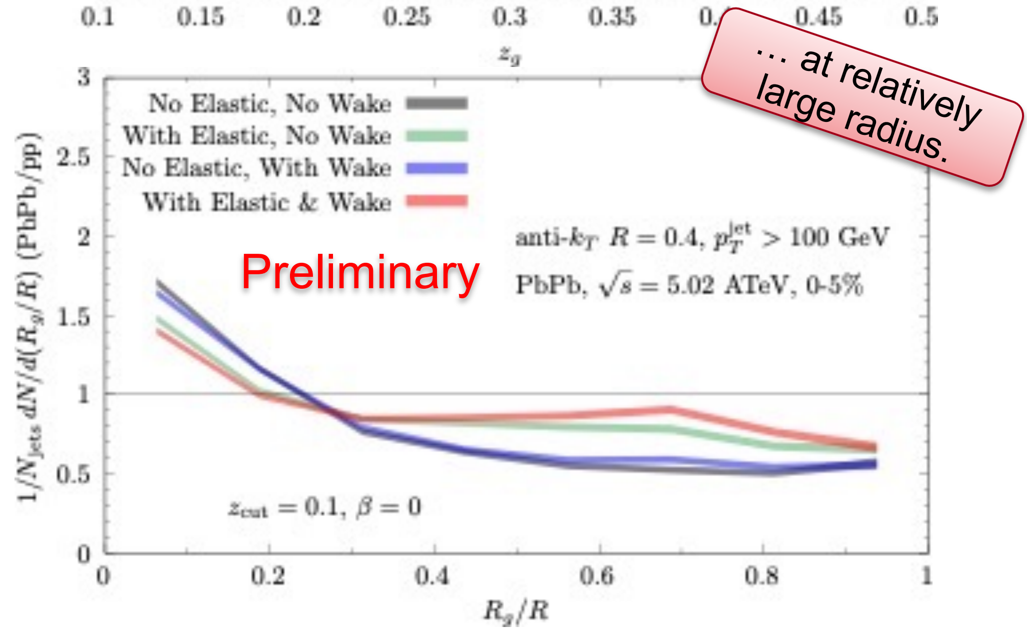
Groomed z_g and R_g

<u>**Soft Drop ($\beta = 0$)**</u>

1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2, separated by angle R_g
4. If $\frac{\min(p_{T1},p_{T2})}{p_{T1}+p_{T2}} \equiv z_g > z_{cut}$, then original jet is the final jet. Otherwise pick the harder of subjets 1 and 2 and repeat

Much less sensitivity to wake; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are dominant.



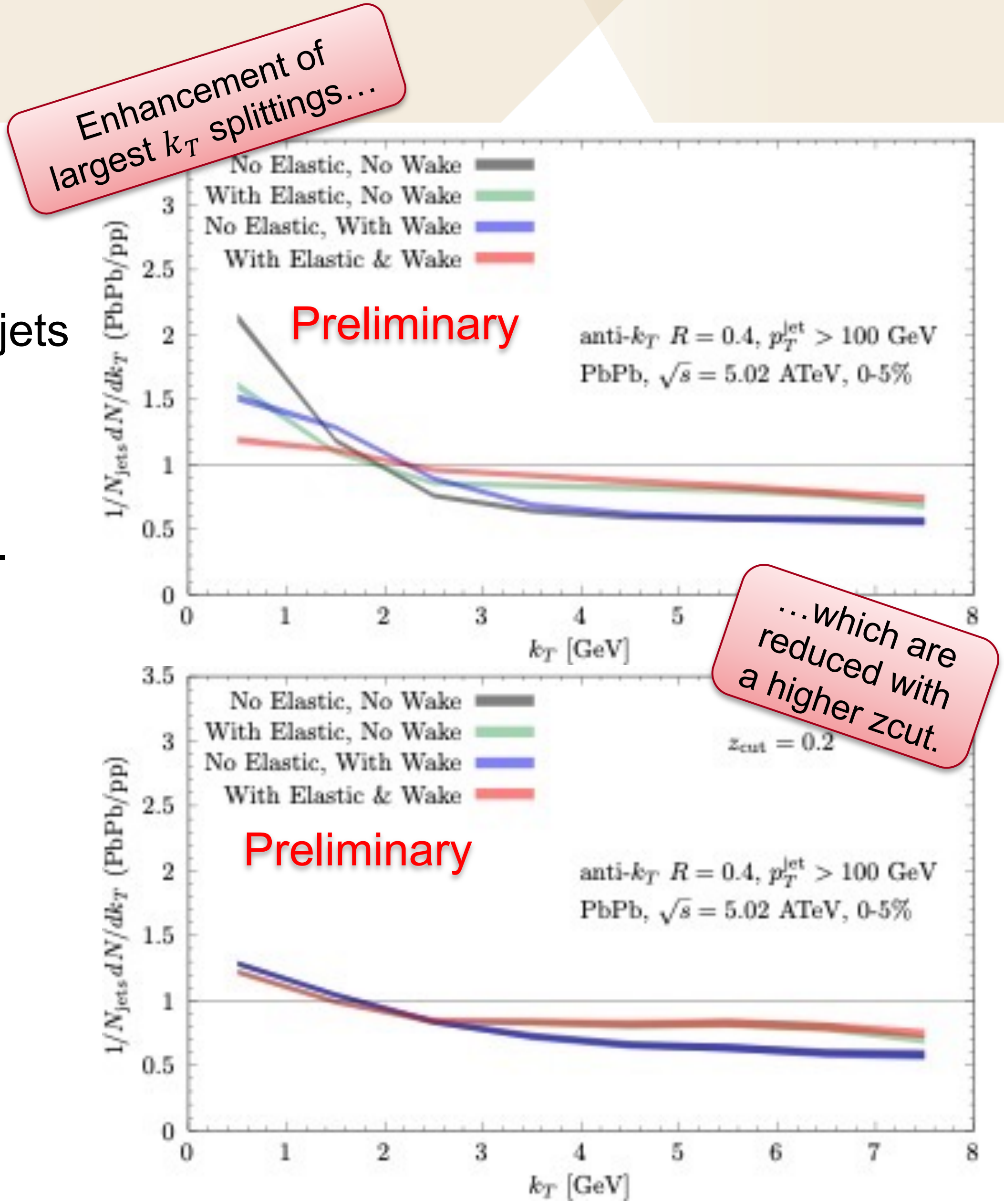


Leading k_T

1. Reconstruct jet with anti-k_T
2. Recluster with Cambridge-Aachen
3. Undo last step of 2, resulting in subjets 1 and 2
4. Note k_T of splitting
5. Follow primary branch until the end.
6. Record largest k_T

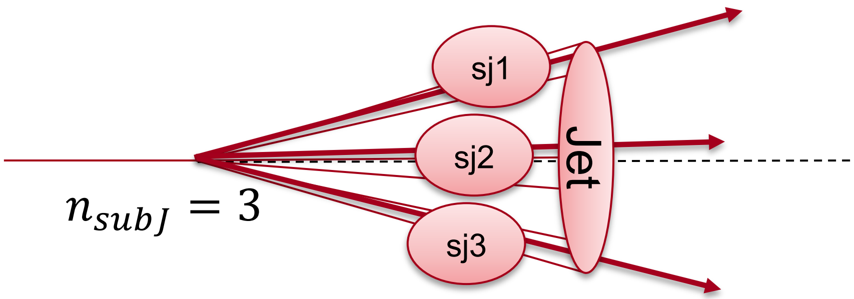
$$k_T = \min(p_{T1}, p_{T2}) \sin(R_g)$$

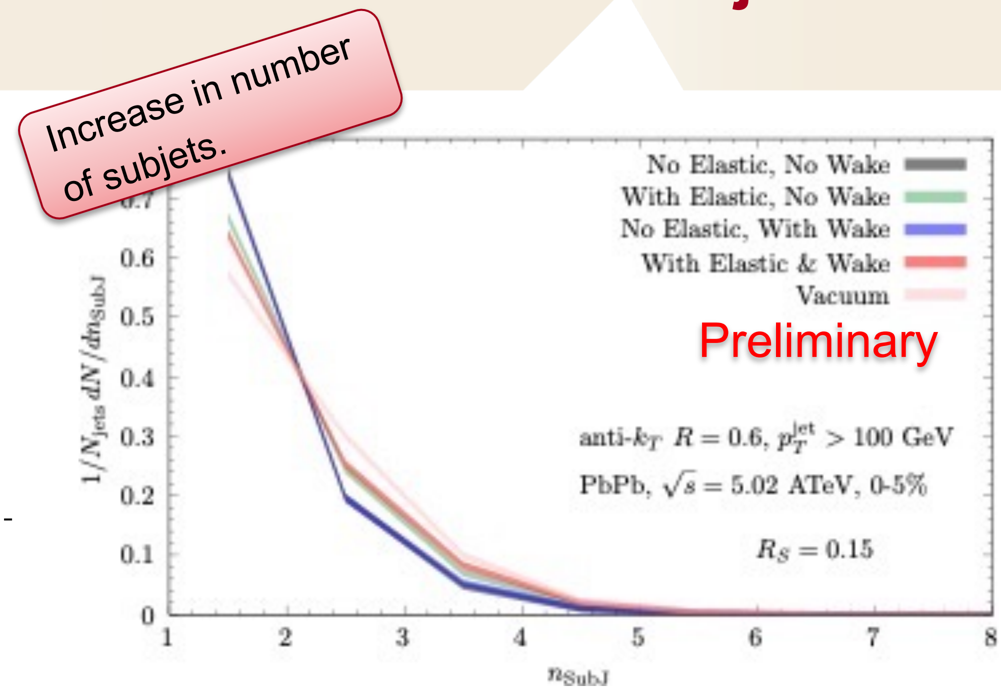
Similar message also for this groomed observable: Moliere scattering effects show up; much larger than wake effects.



Inclusive Jets within Inclusive Jets: Inclusive Subjets

1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15





Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.
Moliere scattering also yields more separated subjets…

Inclusive Subjets

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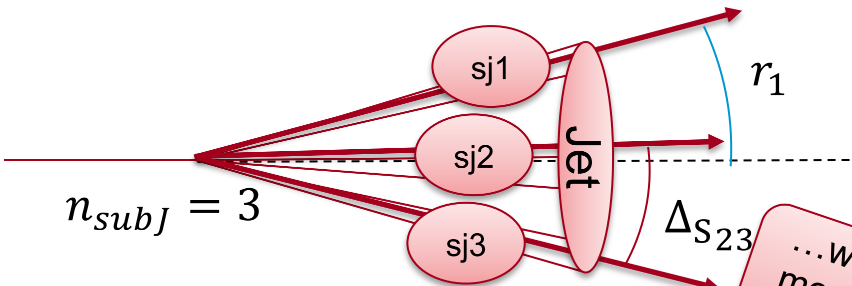
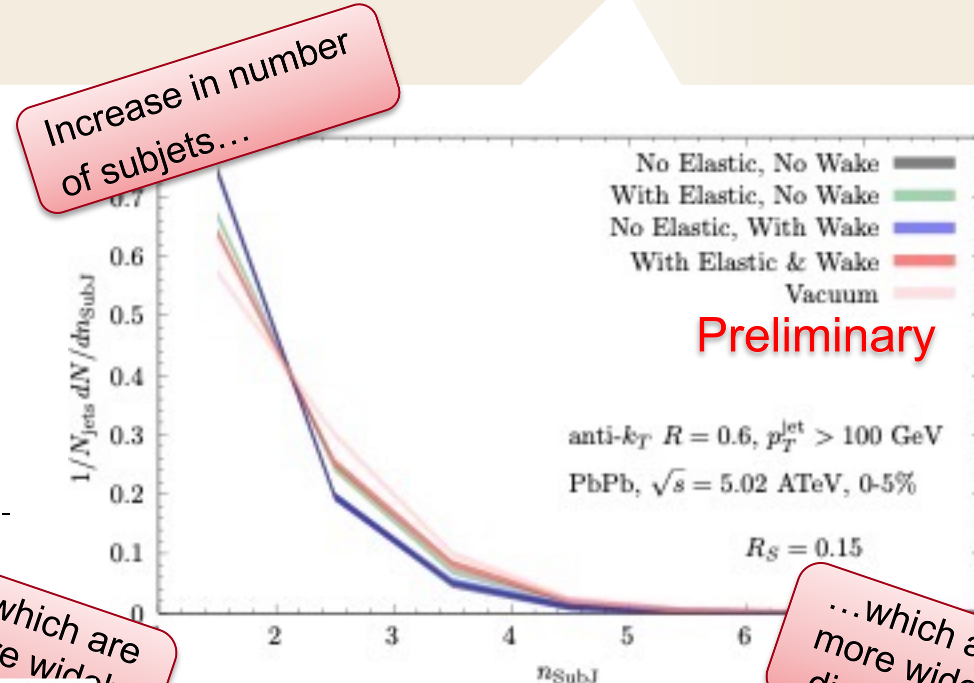
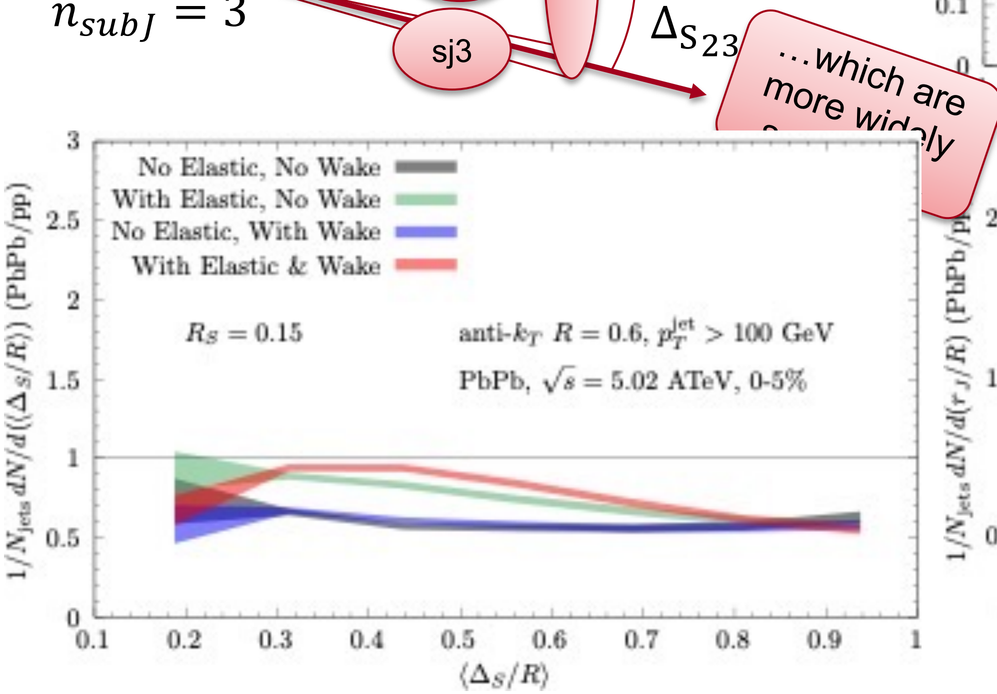
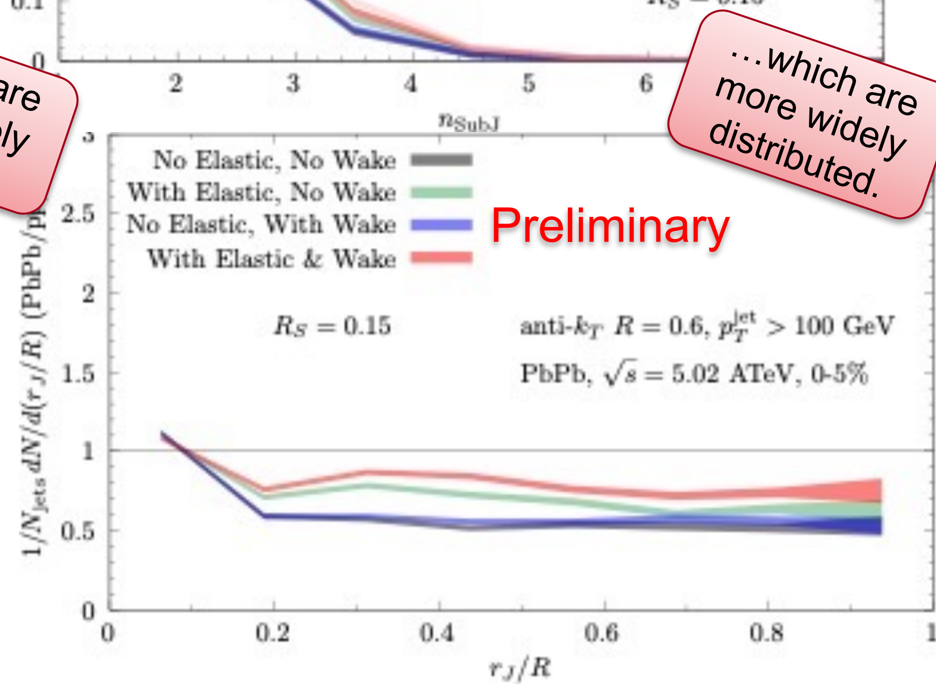
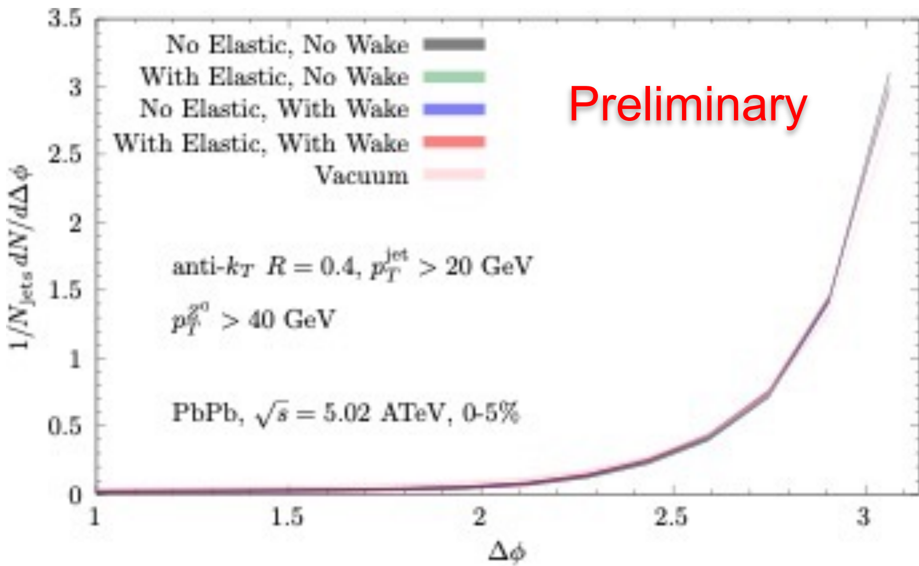


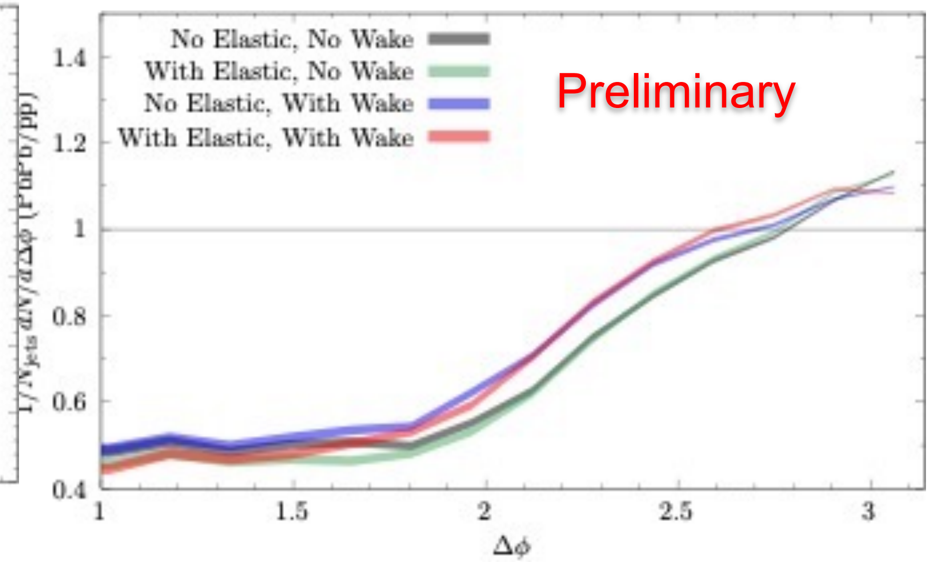






Z-Jet Acoplanarity

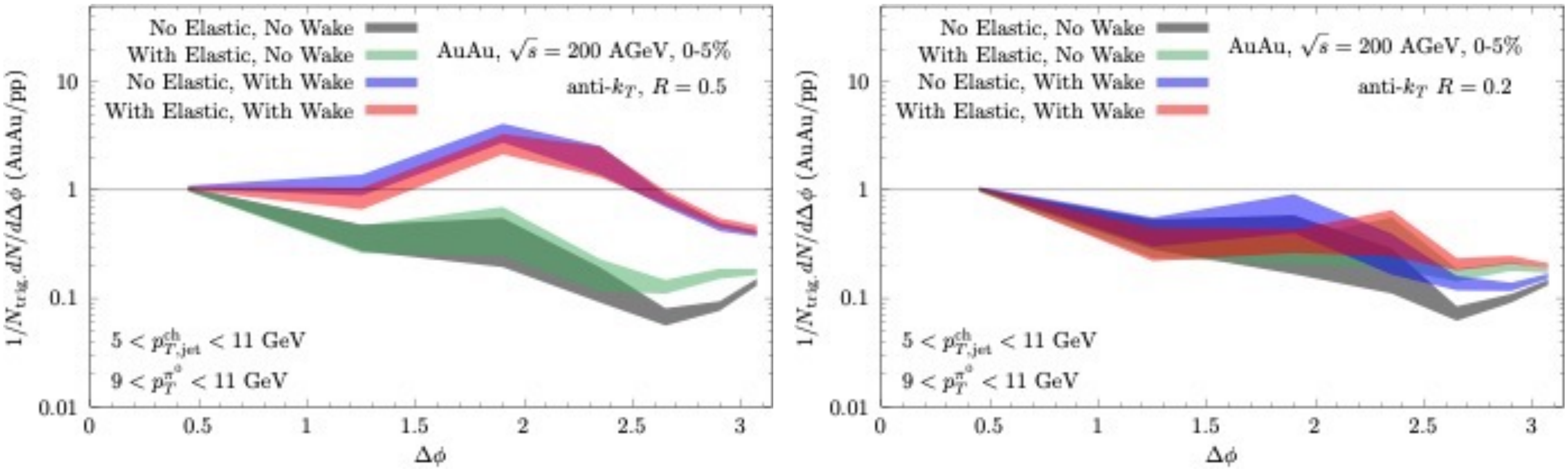




- Study acoplanarity in boson-jet system: Z-jet.
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Desirable to look into acoplanarities at even lower p_T , perhaps via single hadron correlations. And then also Gamma-D, D$\overline{\rm D}$ correlations….
- Groomed z_g and R_g , leading kT, and in particular inclusive subjet observables all more sensitive to Moliere scattering.
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron--Charge-Jet Acoplanarity, RHIC energy

Very Preliminary



- Study acoplanarity in pi0 - charged jet system.
- Parameters similar to but not same as STAR
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.5 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron--Charge-Jet Acoplanarity, RHIC energy

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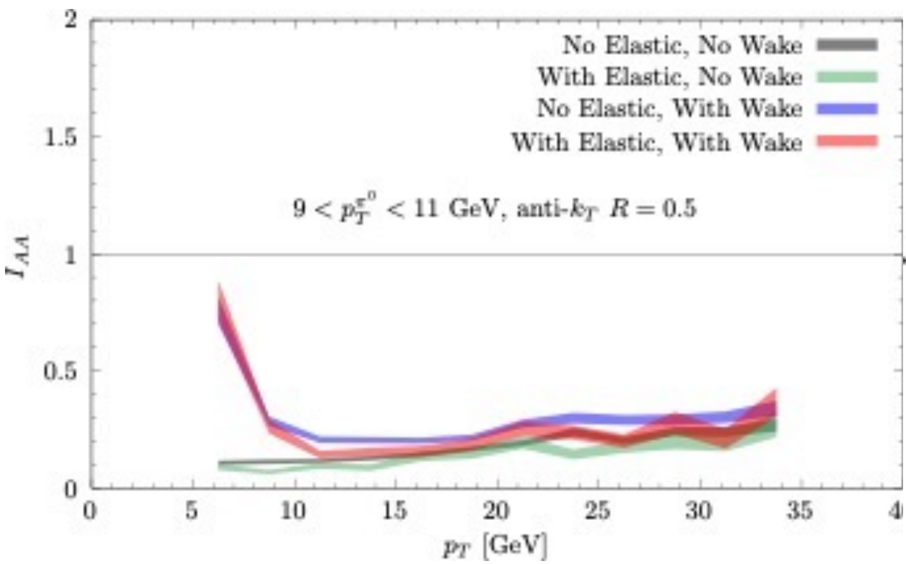

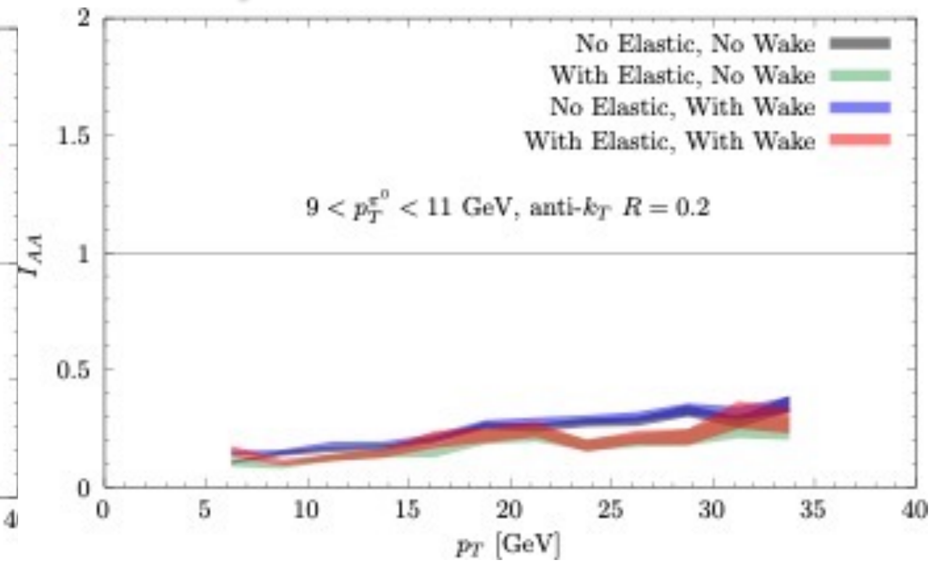

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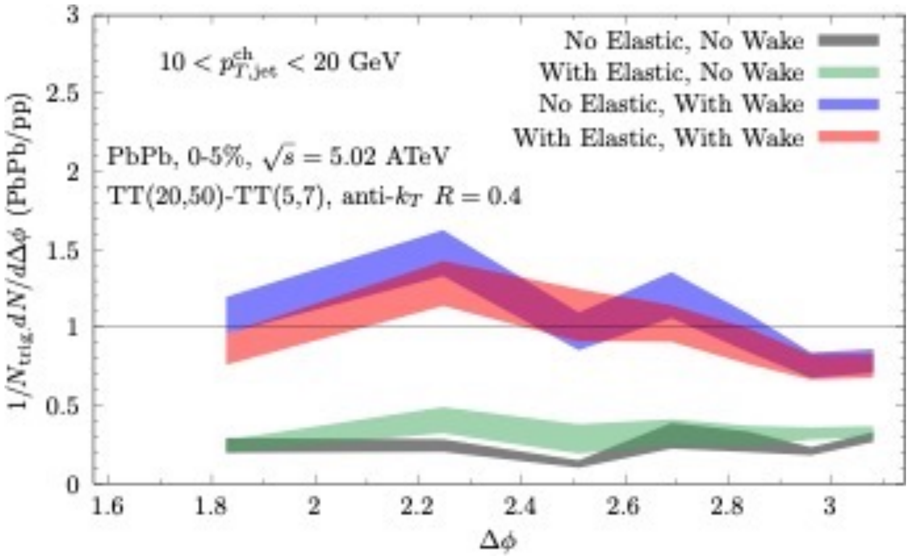
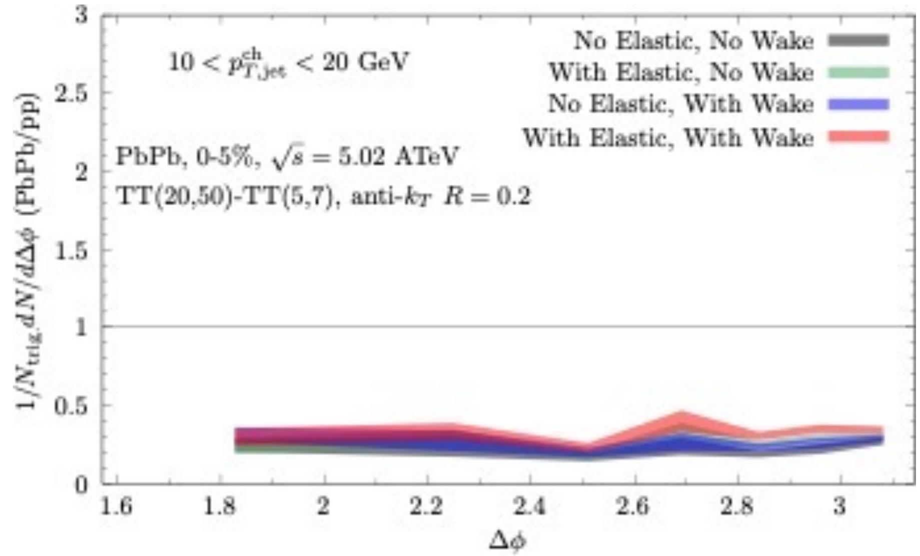
Hadron--Charge-Jet Acoplanarity, LHC energy

Very Preliminary





- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
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- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
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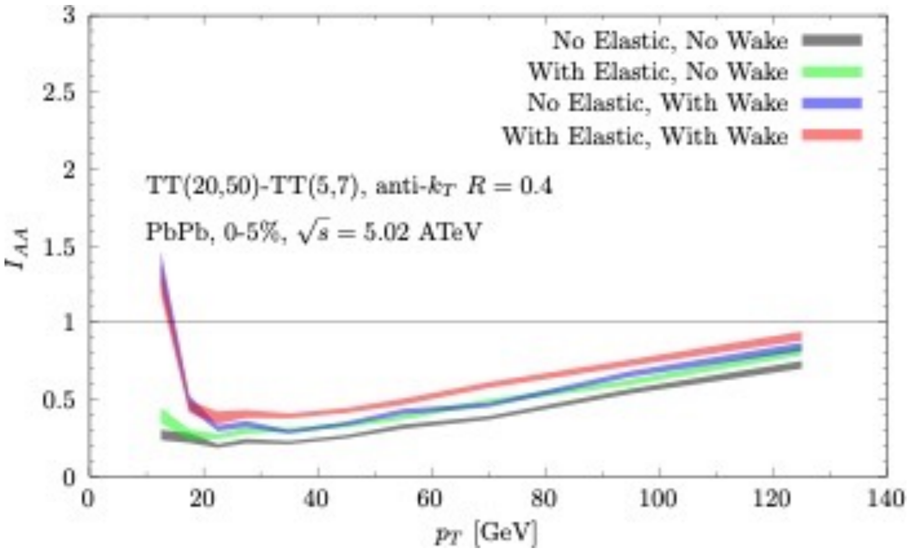
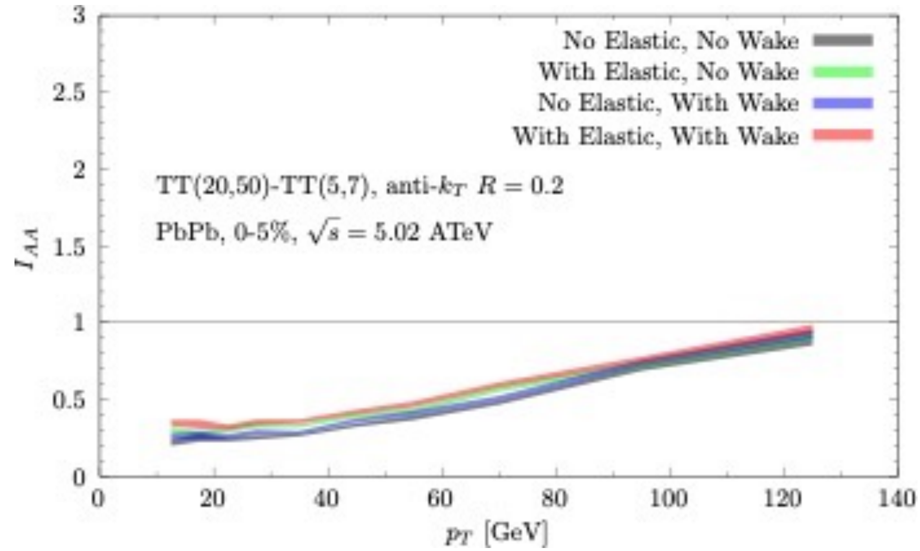
Hadron—Charge-Jet Acoplanarity, LHC energy

Very Preliminary





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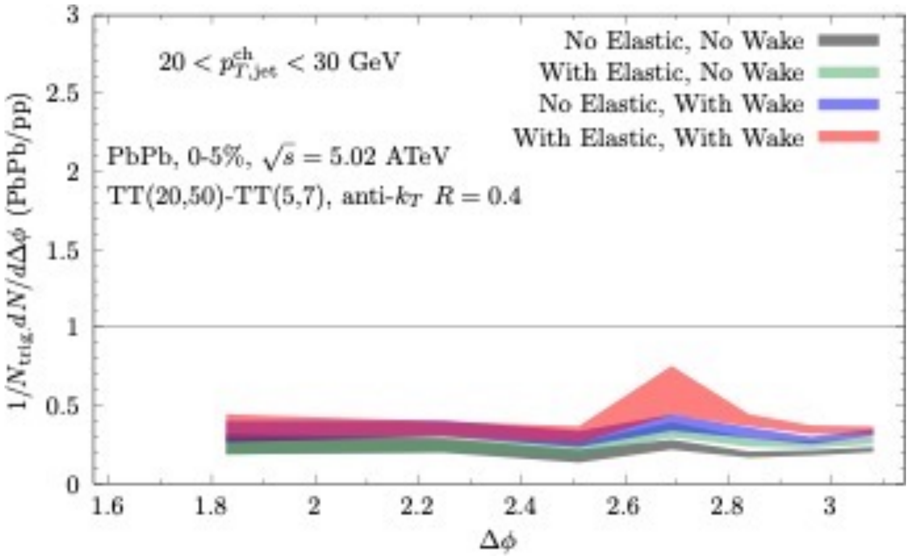

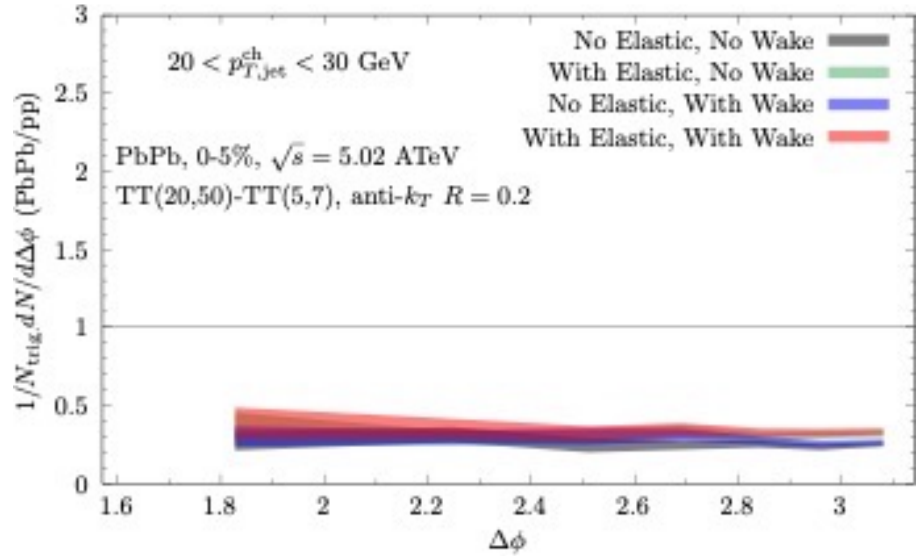

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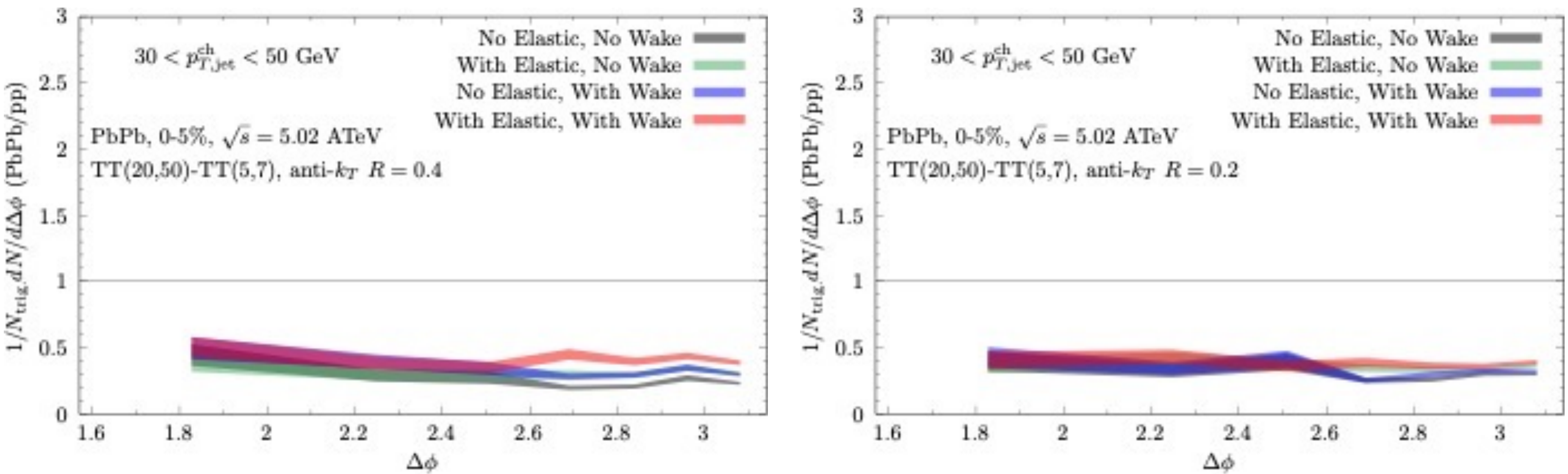

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Conclusions

- Studied the effect of power-law-rare, large-angle, scattering on jet observables in the perturbative regime.

- Moliere scattering affects many “shape observables”, but for “overall shape observables” (jet shapes; FF) effects are similar to, and smaller than, effects of wake.

- Grooming helps, by grooming away the soft particles from the wake. Effects of Moliere scattering dominate the modification of several groomed observables.

- Modification of inclusive subjet observables (number, and angular spread, of subjets) are especially sensitive to the presence of Moliere scatterings. These observables are unaffected by the wake. They reflect what it is that makes the effects of scattering different from those of the wake.

- Subjet observables may also be influenced by other ways in which jet shower partons “see” particulate aspects of the QGP. Great!

- Acoplanarity observables that we have investigated to date show little sensitivity to Moliere scattering; significant sensitivity to the wake in some cases.

- Future: studying charm observables (gamma-D, $D\overline{D}$, D within jets …)