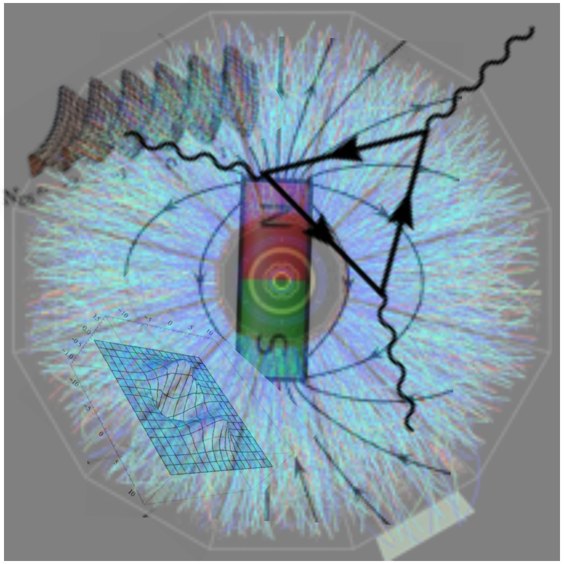
EMMI RRTF @ GSI Dec. 12th, 2016

Updates from CUJET3



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Research Supported by NSF & DOE

Outline

- Jet (geometric) tomography, and how I came into this
- CUJET3: What It Is & What It Does
- HF Tests from CUJET3
- Summary & Discussions

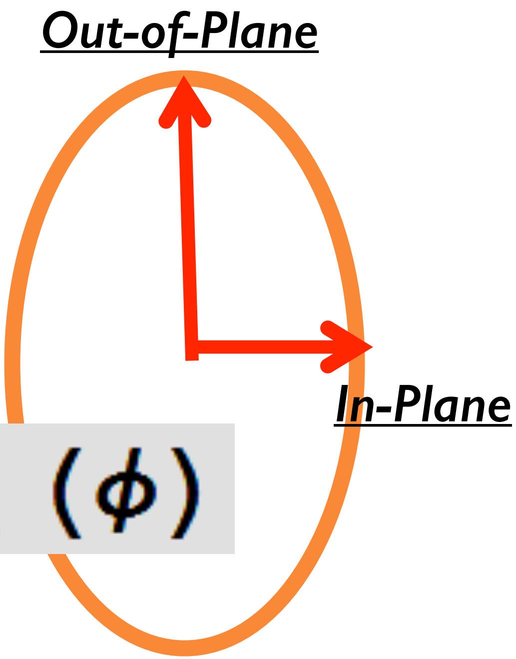
References:
Shi, Xu, JL, Gyulassy, in preparation;
Xu, JL, Gyulassy, arXiv:1411.3673[CPL2015]; arXiv:1508.00552[JHEP2016].

Li, JL, Huang, PRD89,126006(2014).
X. Zhang, JL, PRC2013; PRC2014; PLB2012; arXiv:1311.5463.
JL, arXiv:1109.0271[PANIC11 proceedings].
JL, Shuryak, Phys.Rev.Lett. 102 (2009) 202302.

Geometric Anisotropy of Jet Quenching

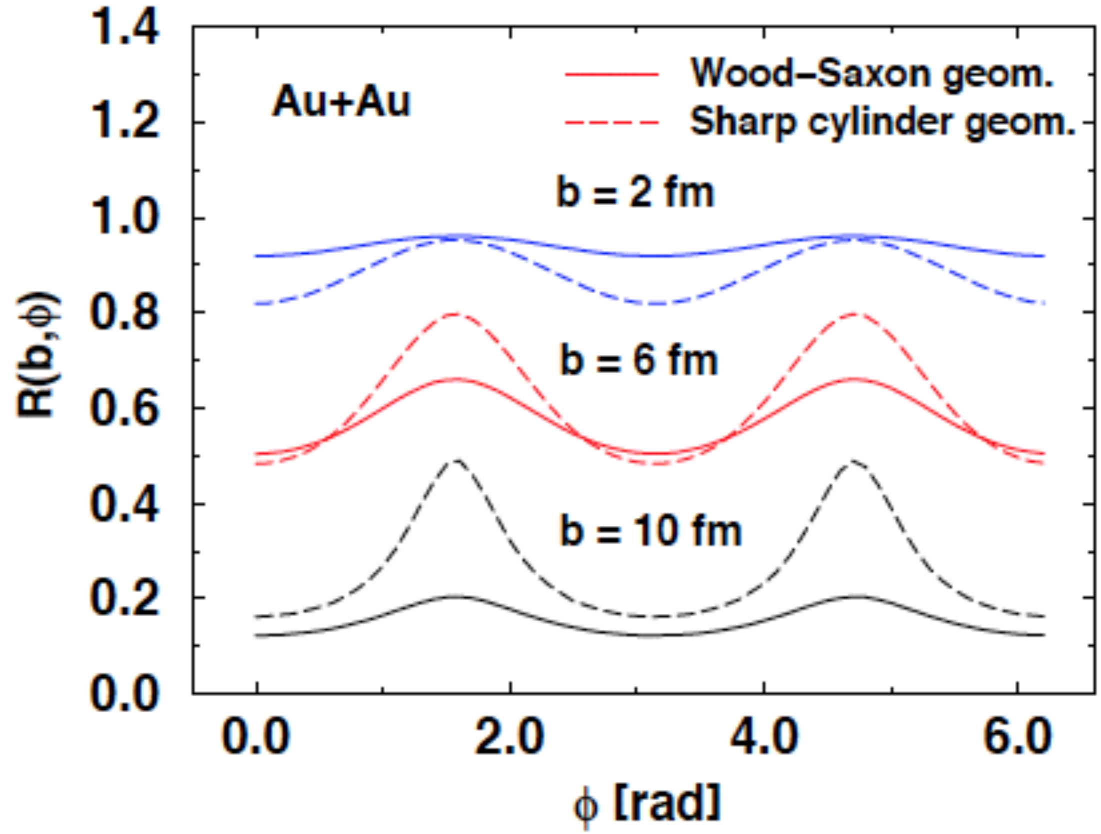
Geometric tomography(~2000)

[Gyulassy, Vitev, Wang, arXiv:nucl-th/0012092



$$R_{aa}\ (\phi)$$

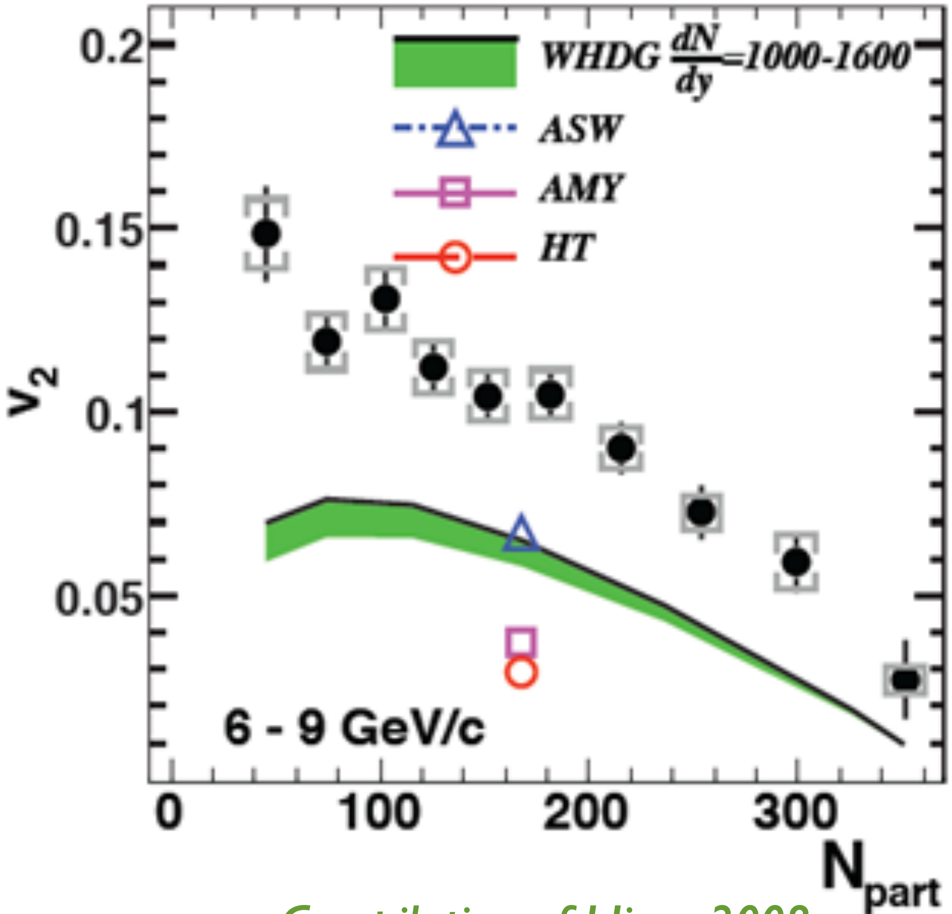
$$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$$



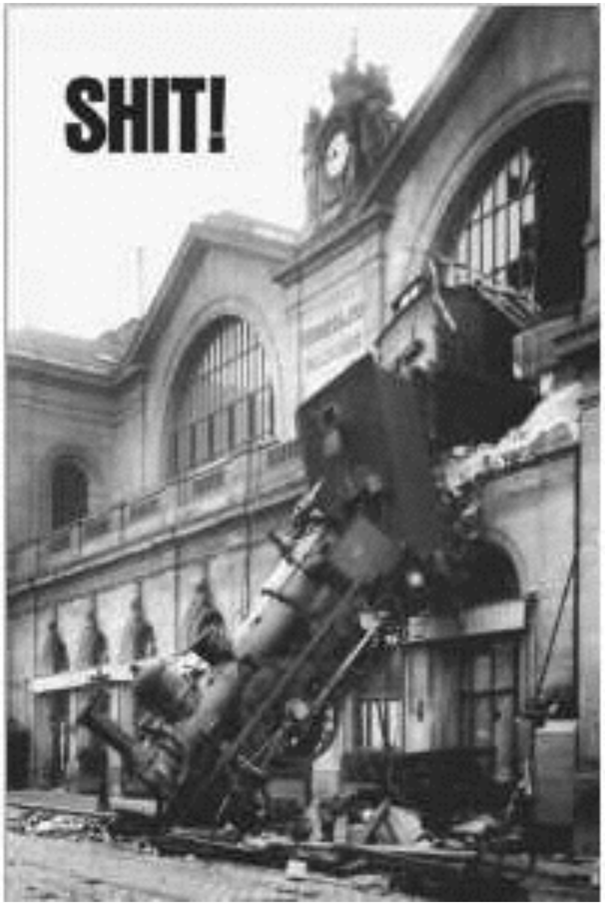
Positive v2 for high Pt hadrons — beautiful idea!

It could be a “crowning” confirmation of jet energy loss model.

Maybe Sometimes We Got Too Ambitious…



Compilation of J.Jia, ~2008



Till ~2008: clear and significant discrepancy between data / any model.
That was the situation when I dived into this water…

Magnetic Component of sQGP

Magnetic Component of Strongly Coupled Quark-Gluon Plasma

A Dissertation Presented

by

Jinfeng Liao

to

The Graduate School

in Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

in

Physics

Stony Brook University

August 2008

There is the strongly coupled QGP, in the 1~2Tc regime.

What is the making of sQGP?

What is the connection to the vacuum confinement?

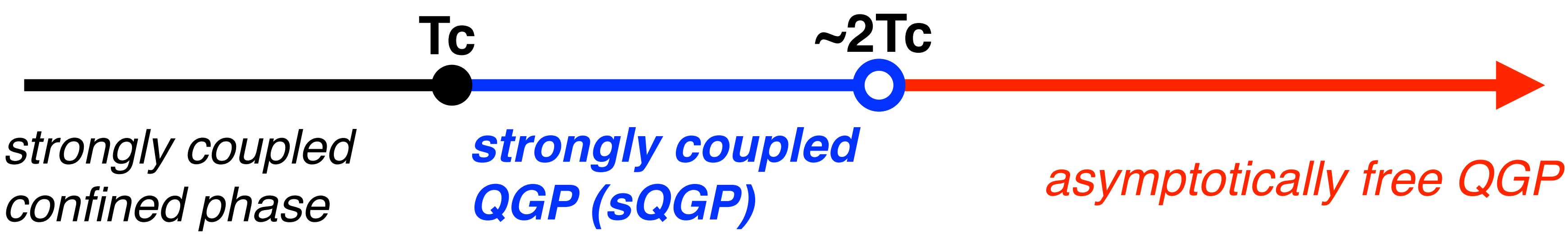
How the knowledge about sQGP helps us understand confinement?

"Magnetic Component"

sQGP: The Matter Just About to Be Confining

The old dream

The new paradigm thanks to discoveries at RHIC and LHC (1~3Tc):

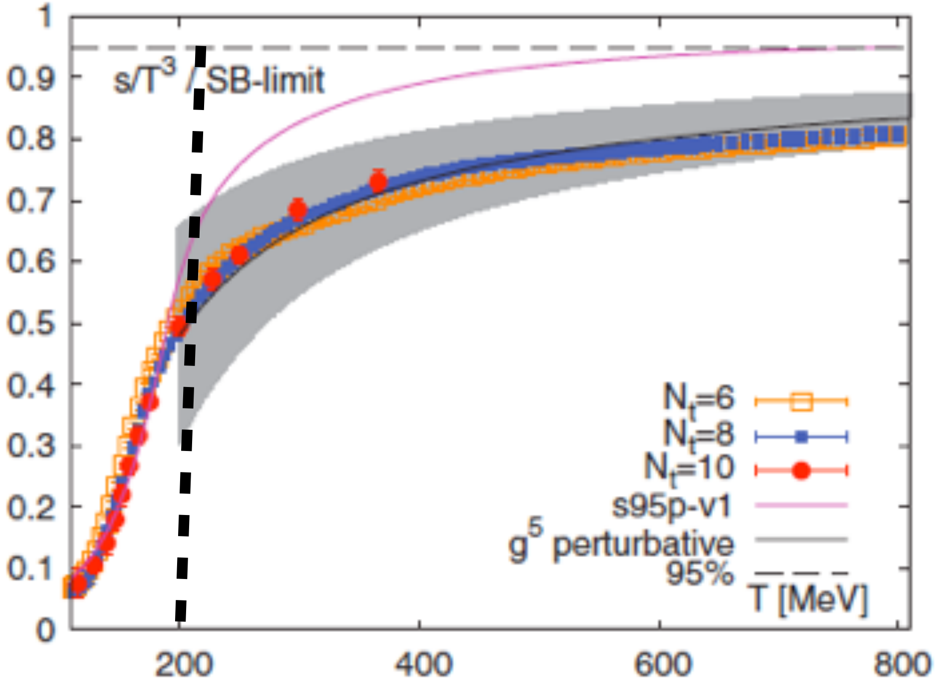


A few of us, quickly came to realize:
The matter just above confinement (in 1~2Tc),
is more like the confined world, rather than like
the far-far-away place of asymptotic QGP!

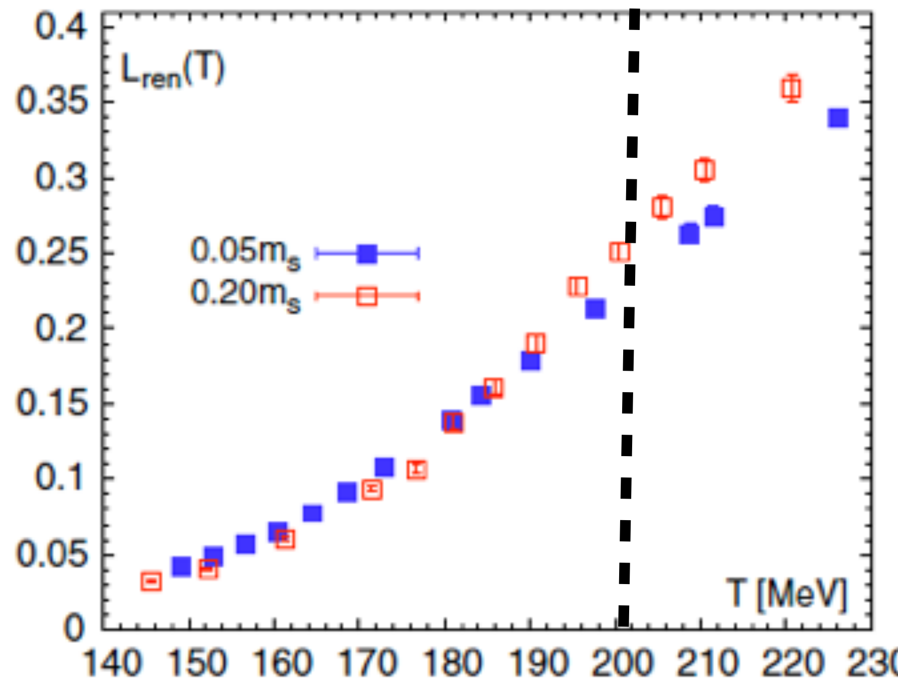
This is to say, the confinement physics (whatever it is),
must continue robustly into this region
— we call it "<u>postconfinement</u>" regime!

The Special Near-Tc Matter: What are the DoF?

Liberation of Thermal DoF



Degree of color liberation



Pisarski, …: this is a semi-QGP!

Shuryak, Liao,…: this is a monopole plasma!

The two pictures are in complement, from Electric or Magnetic language respectively, and reconciled into one coherent message:

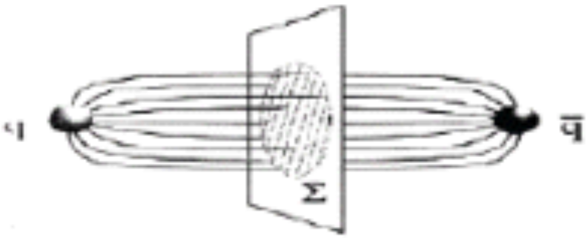
Postconfinement Regime in 1~2Tc,

with lively new manifestation of confinement physics

Magnetic Scenario of Near-Tc Plasma

T<< Lambda_QCD | T ~ Lambda_QCD | T>> Lambda_QCD

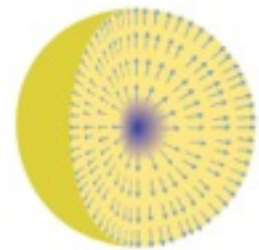
Vacuum: confined — Tc — sQGP — ***wQGP: screening*** — T



Emergent plasma
with E & M charges:
chromo-magnetic monopoles
are the "missing DoF"

Plasma of E-charges
E-screening: g T
M-screening: g^2 T

$$\alpha_E * \alpha_M = 1.$$



Condensate monopoles —> dense thermal monopoles 1-2Tc:
thermal monopoles hold together electric flux, yet with dissipation.

PHYSICAL REVIEW C 75, 054907 (2007)

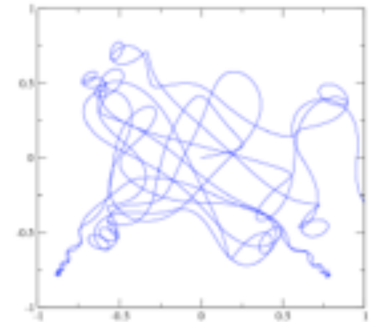
Strongly coupled plasma with electric and magnetic charges

Jinfeng Liao and Edward Shuryak

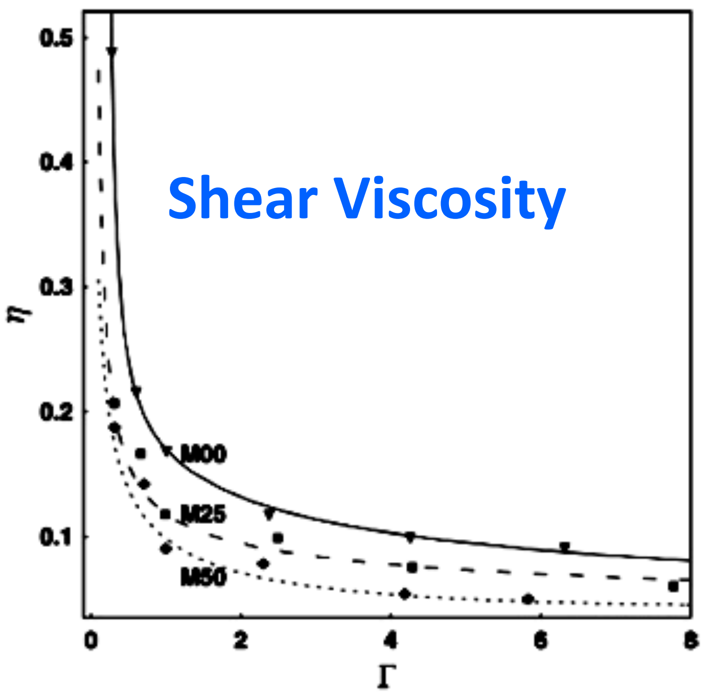
What A Magnetic Component Does?

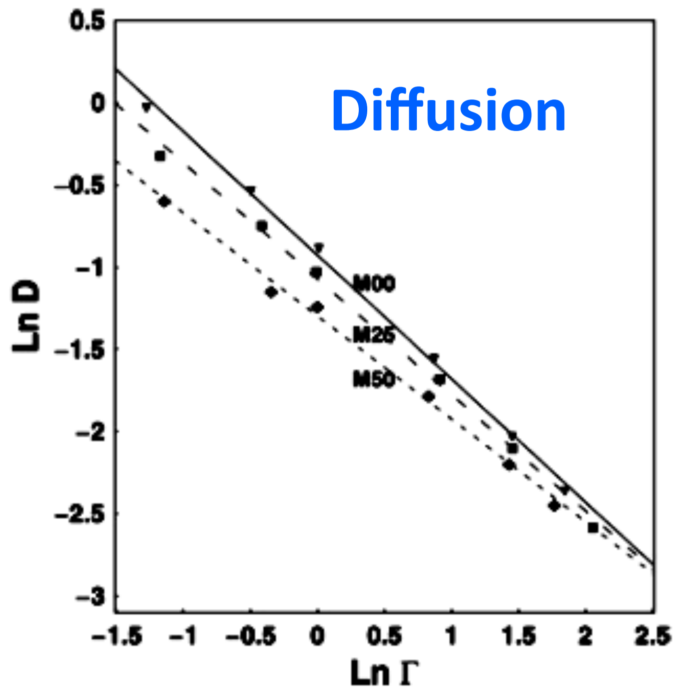
We first studied the plasma of a completely new kind: Coulomb-Lorentz Plasma!

Molecular Dynamics for 1000 particles with long range forces for varying E/M ratio:
pure electric ; 25% magnetic charges ; 50% magnetic charges



"Lorentz-Trapping Effect"



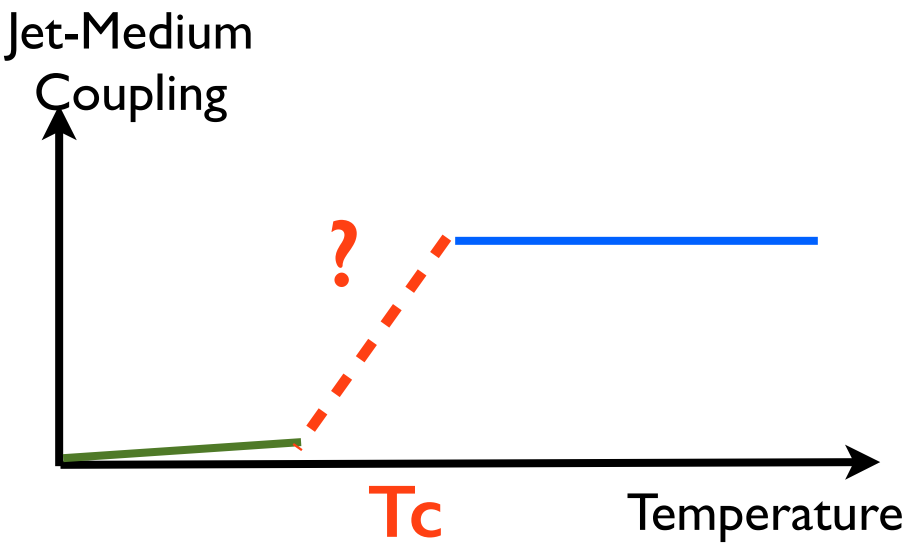


A mixture of E&M charges can help explain the "perfect fluid".

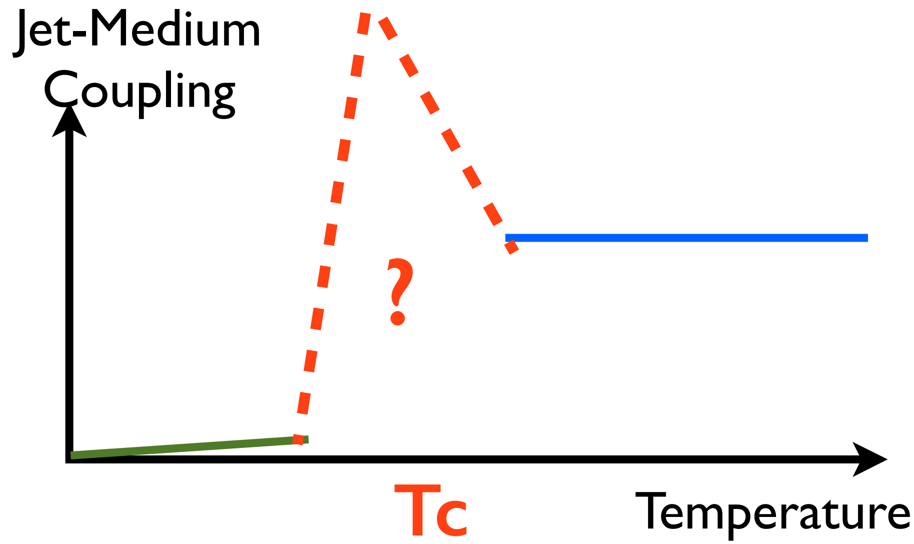
[quantum E-M scattering: Ratti, Shuryak]

What about the jets? Can they sense the M charges?
We spent a busy summer of 2008 on this problem…

From “Transparency” to Opaqueness



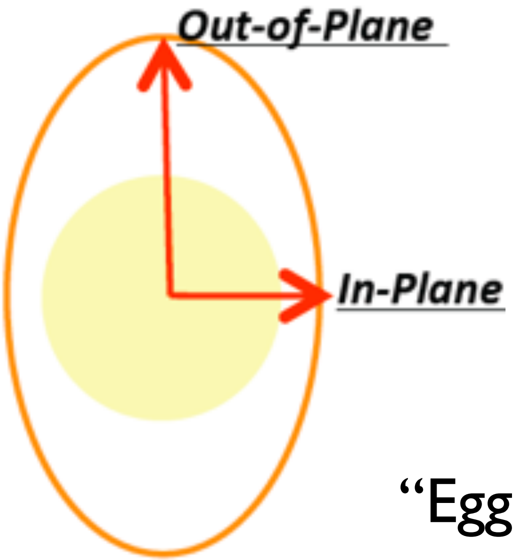
“Waterfall” scenario



“Volcano” scenario

The temperature dependence of jet-medium coupling has profound consequences!

Where Are Jets Quenched (More Strongly)?



Taken for granted in all previous models: "waterfall" scenario.

We realized the puzzle may concern more radical questions:

Where are jets quenched (more strongly)?

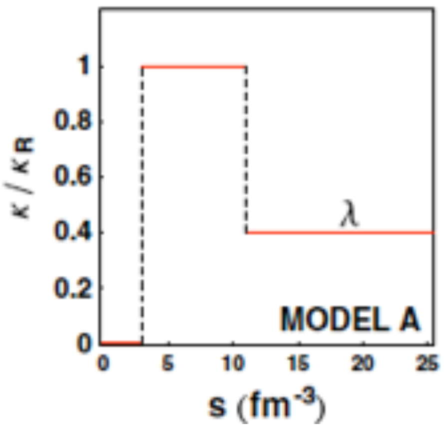
Geometry is a sensitive feature:
"Egg yolk" has one geometry, "Egg white" has another.

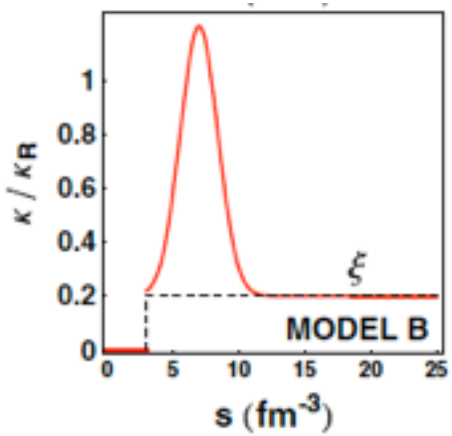
Where are jets quenched in heavy-ion collisions?

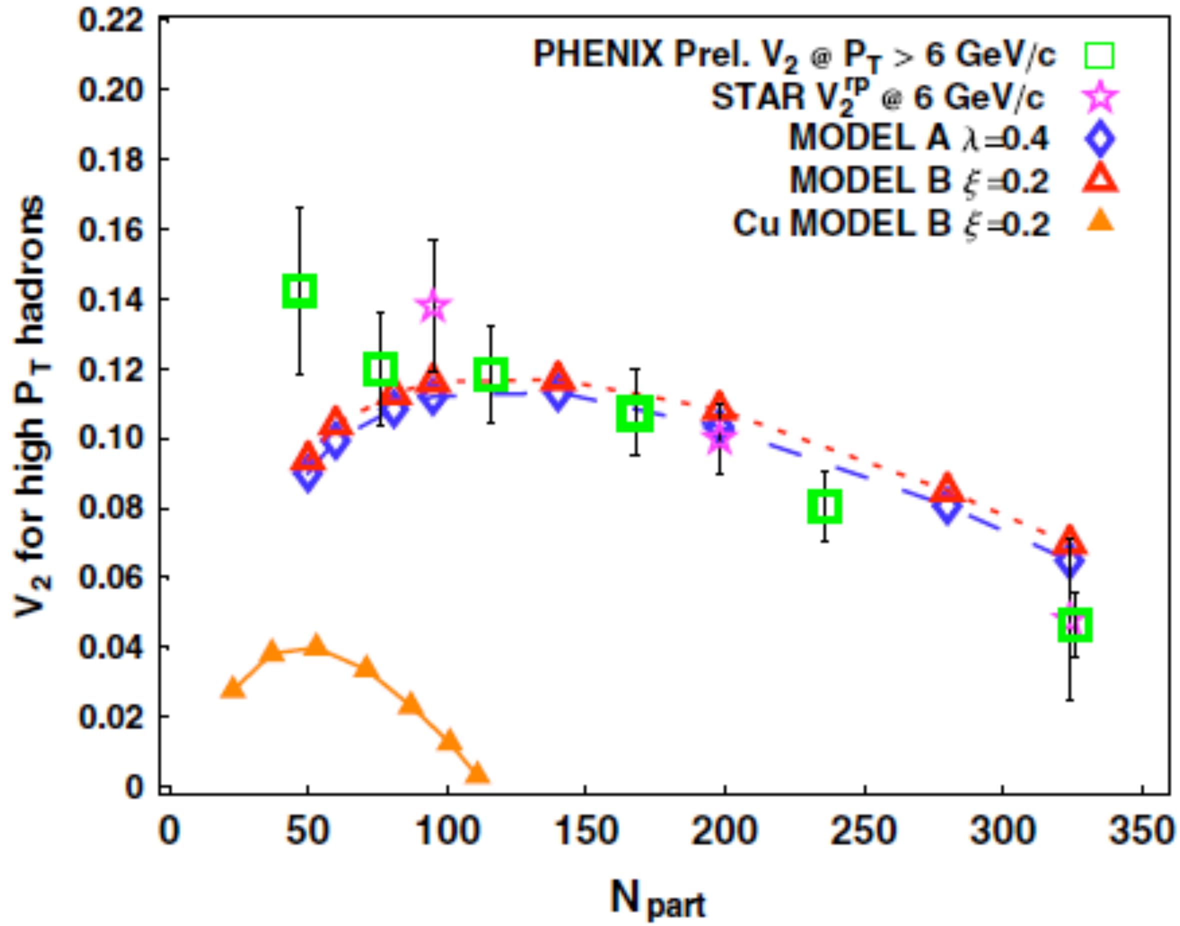
Jinfeng Liao[1,2*] and Edward Shuryak[1†]
[1]*Department of Physics and Astronomy, State University of New York, Stony Brook, NY 11794*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
(Dated: October 22, 2008)

We study dependence of jet quenching on matter density, using "tomography" of the fireball provided by RHIC data on jet azimuthal asymmetry parameter $v_2(b)$ for large p_t hadrons. Slicing the fireball into shells with constant (entropy) density, we derive a new geometrical limit for it which indeed is above the data $v_2(b) < v_2^{max}(b)$. Interestingly, the limit is reached only if quenching is dominated by a shell with the entropy density $3\,fm^{-3} < s < 11\,fm^{-3}$, exactly the near-$T_c$ region. We conclude that the data can be explained if quenching is few times stronger in the near-T_c region than in the QGP at $T > T_c$. We also argue that recent views picturing the near-T_c region as a magnetic plasma of monopoles can naturally explain that.

Near-Tc Enhancement (NTcE)







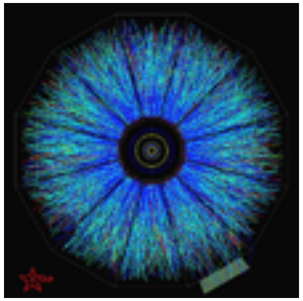
In the paper we concluded:

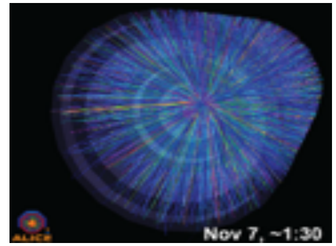
"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

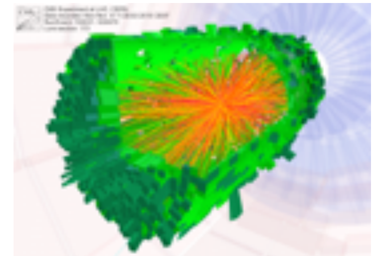
Hot QCD Matter from RHIC to LHC

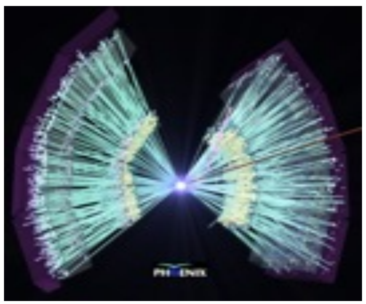
RHIC Events

LHC Events

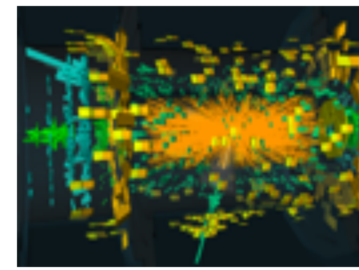








From RHIC to LHC:
Capability of shifting
QGP Temperature!



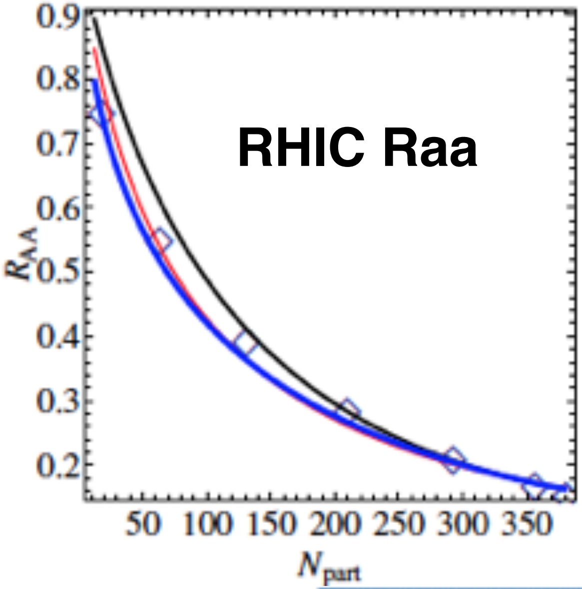
The Surprising Transparency of the sQGP at LHC

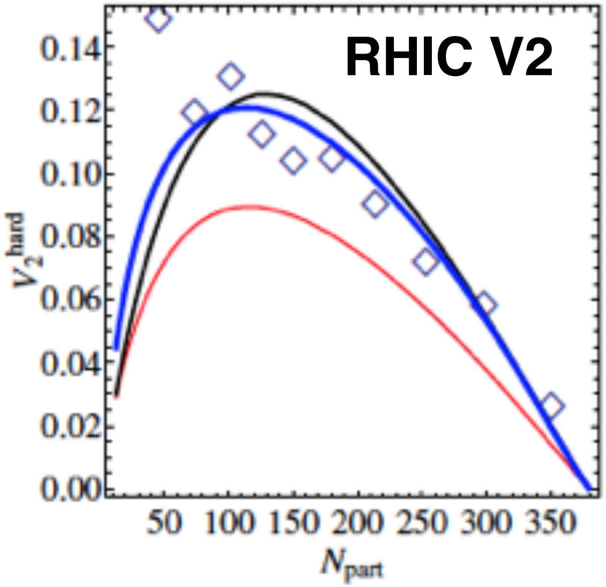
W. A. Horowitz*
Department of Physics, University of Cape Town,
Private Bag X3, Rondebosch 7701, South Africa

Miklos Gyulassy
Department of Physics, Columbia University,
538 West 120^{th} Street, New York, NY 10027, USA

(Dated: April 27, 2011)

Jet Tomo vs Mono vs Holo -graphy

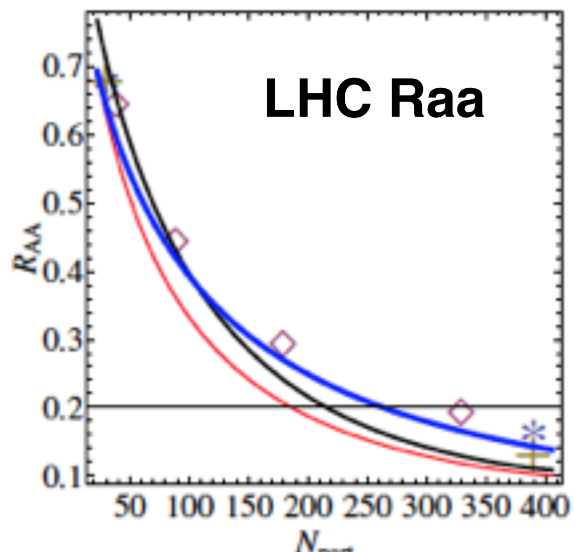


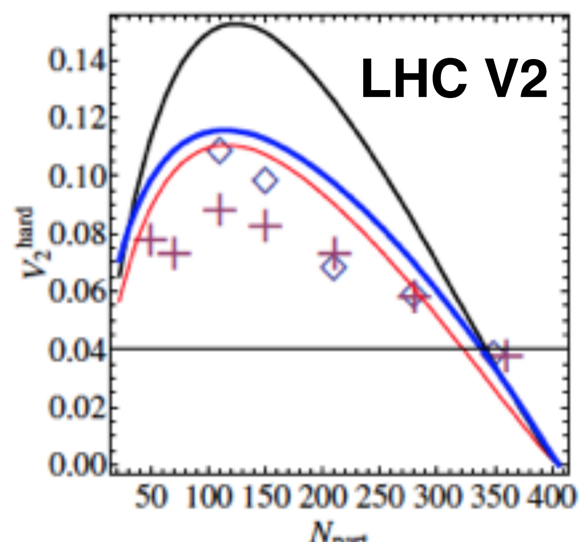


My calculation results were reported at PANIC2011, July @MIT

RED: L^2 model BLUE: L^2 + Near-Tc BLACK: L^3 model

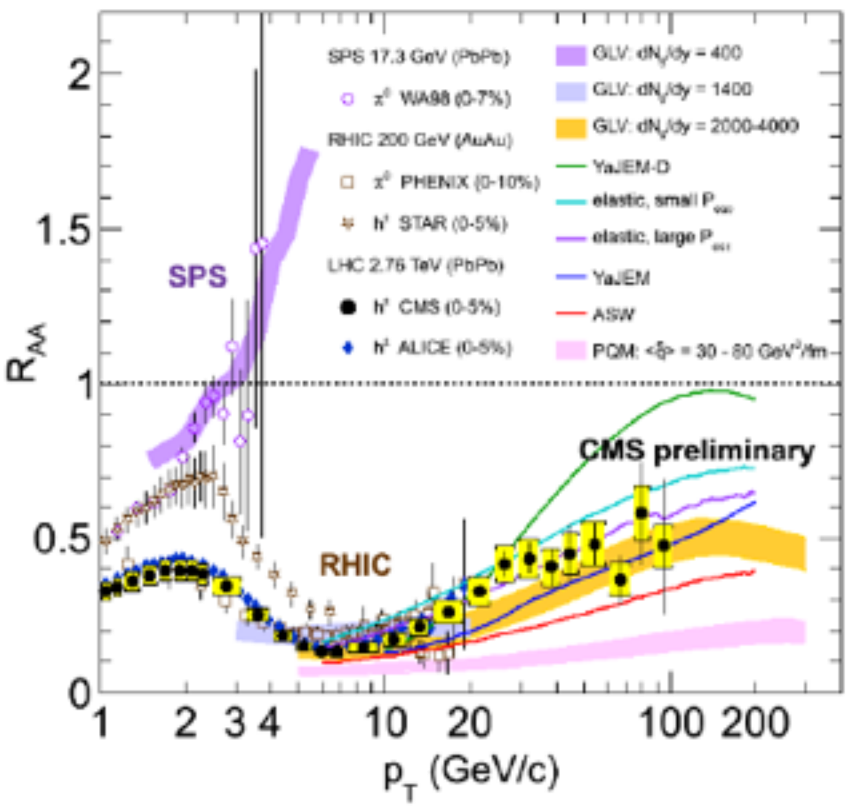
Liao, "Nonperturbative Jet Quenching from Geometric Data" arXiv:1109.0271[nucl-th]





The Opaqueness Does Shift!

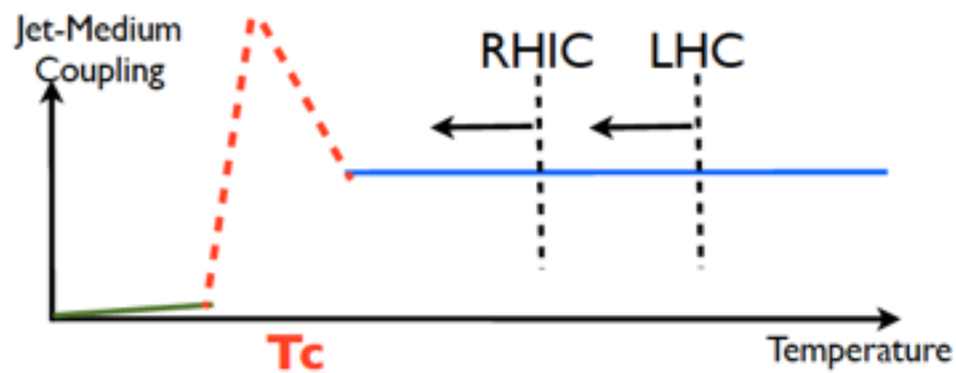
Beautiful jet quenching measurements from all collaborations



Already a clear hint of LESS OPACITY: similar R_aa, despite twice the density!

— "surprising transparency" (Horowitz & Gyulassy, QM11)

— naturally expected if the "volcano scenario" is indeed true (Liao PANIC11)



Quantifying the Reduction of Opaqueness

Examining a reduced jet-medium coupling in Pb+Pb collisions at the Large Hadron Collider

Barbara Betz[a] and Miklos Gyulassy[b]
[a] *Institute for Theoretical Physics, Johann Wolfgang Goethe-University, 60438 Frankfurt am Main, Germany*
[b] *Department of Physics, Columbia University, New York, 10027, USA*

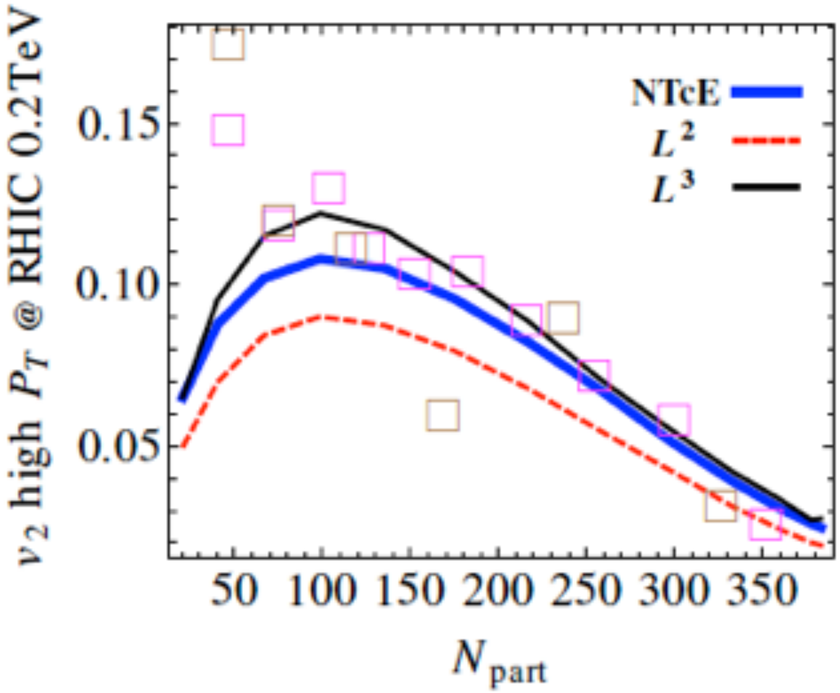
Effective Coupling κ assuming $\tau_0 = 0.01$ fm/c			
$\sqrt{s}$	Glauber z=1	dcgc1.2 z=1	Glauber z=2
0.20	0.60	0.58	0.44
2.76	0.45	0.43	0.26
LHC/RHIC	0.75	0.74	0.59

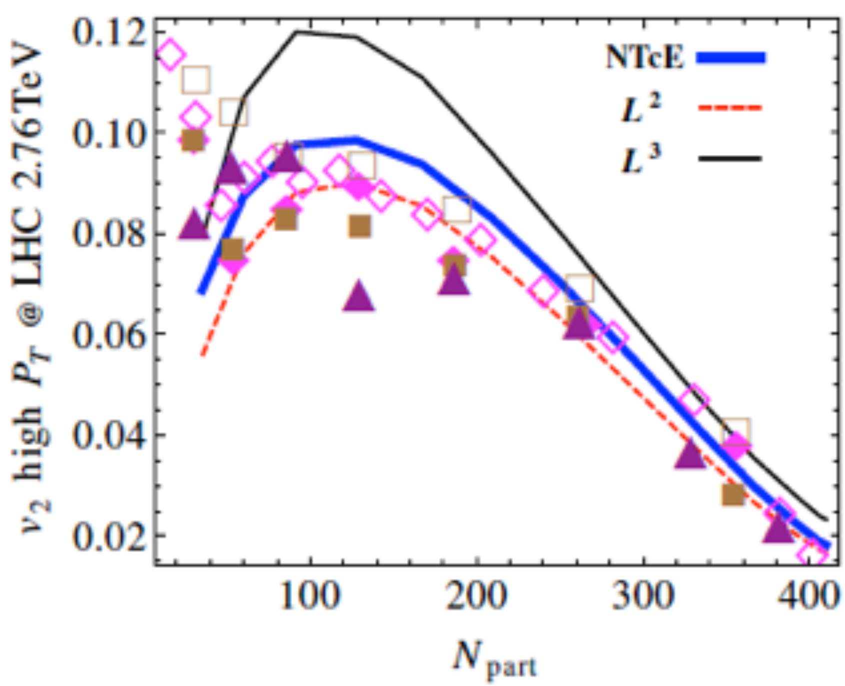
Analysis by me and student came to the same conclusion.
Zhang & JL, arXiv: 1208.6361,1210.1245.

$$< \kappa >_{RHIC} : < \kappa >_{LHC} \approx 1 : 0.72$$

Let me emphasize: this reduction is naturally born out from near-Tc enhancement !

V2 from RHIC to LHC





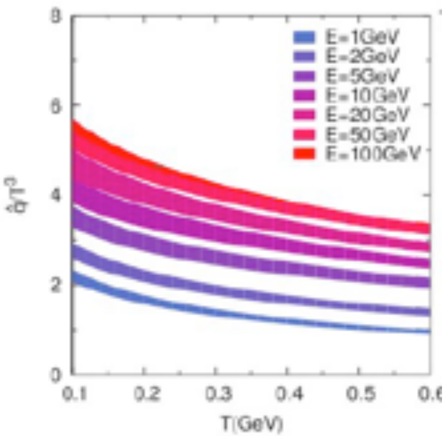
RED: L^2 model+waterfall BLUE: L^2+volcano BLACK: L^3+waterfall

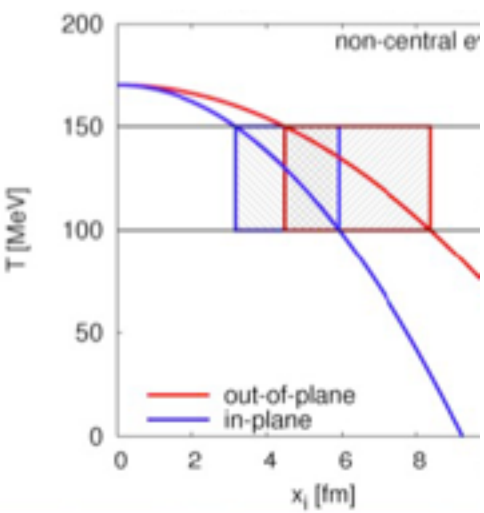
* We do see big difference between waterfall/volcano at RHIC, and this difference becomes much smaller at LHC
* RHIC + LHC data are in favor of the L^2 + Volcano scenario

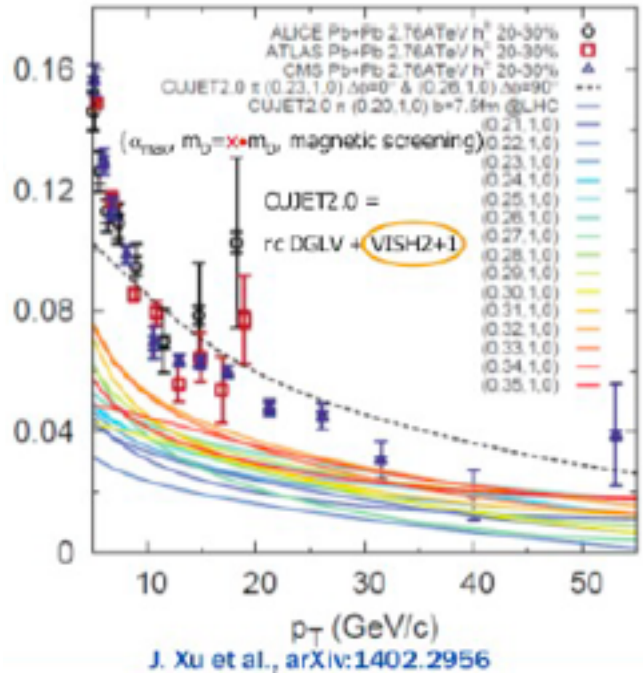
Zhang & JL, arXiv: 1208.6361

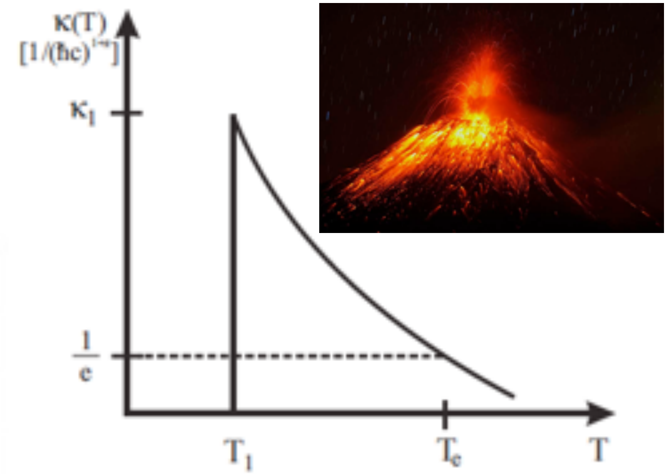
Detailed Analysis from Earlier CUJET

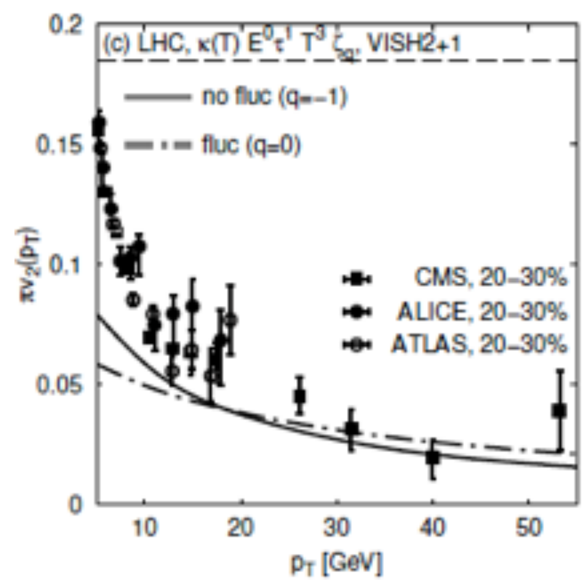
Xu, Buzzatti, Gyulassy, 1402.2956;
Betz, Gyulassy, 1404.6378









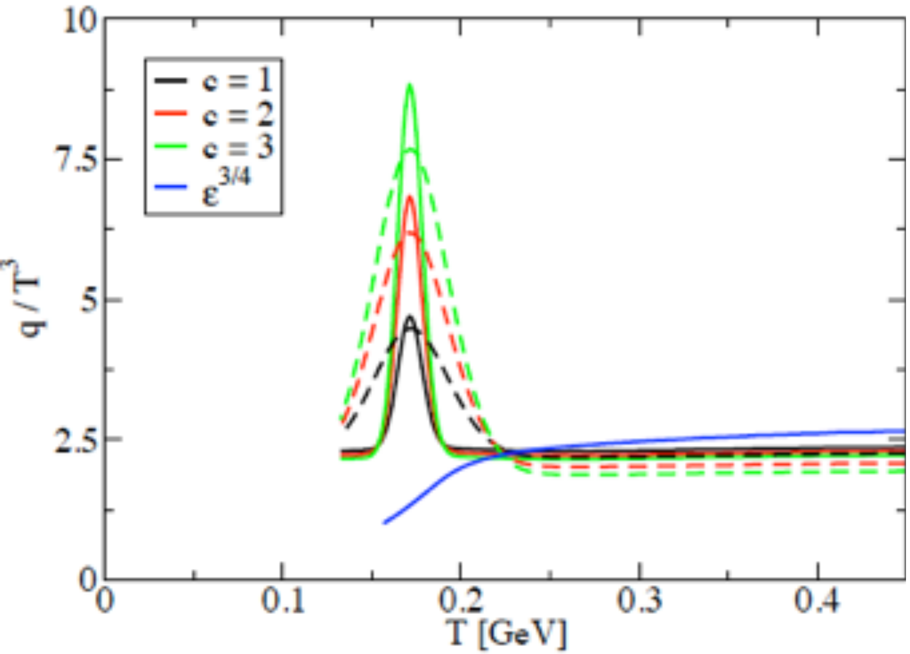


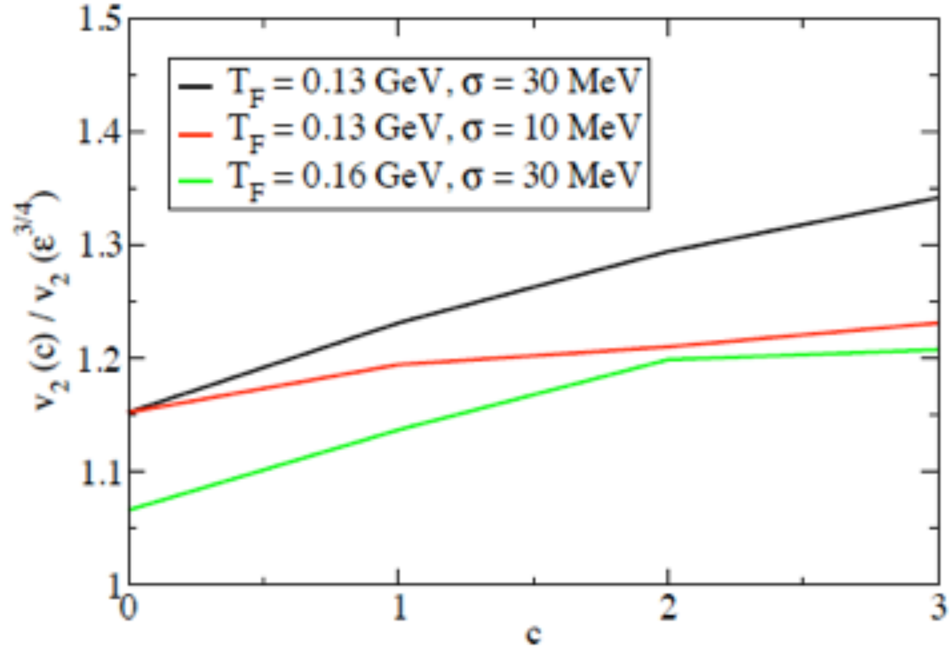
effectively:
kappa_out > kappa_in

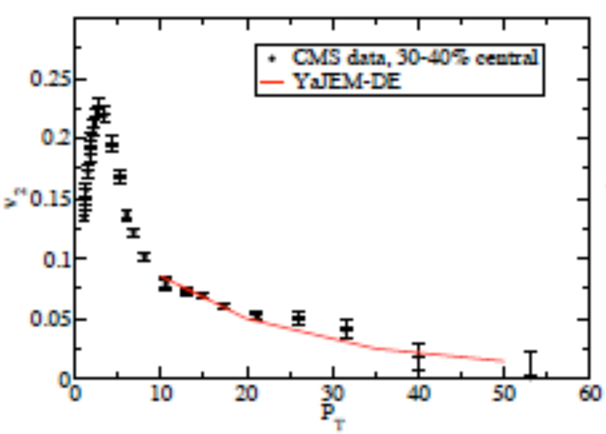
Results from Renk's Simulations

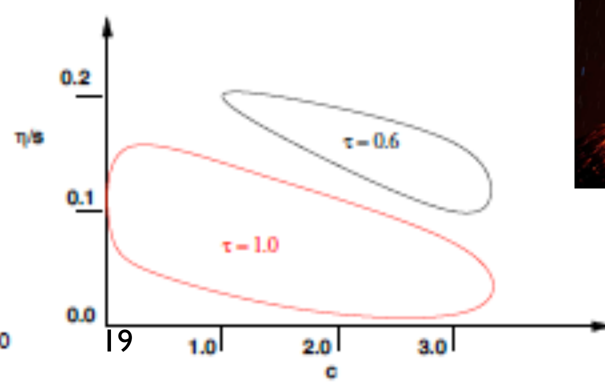
Renk, 1402.5798 & QM14

model	ASW	YDE 3d	YDE 2d
NTC/$\epsilon^{3/4}$	1.17	1.22	1.20



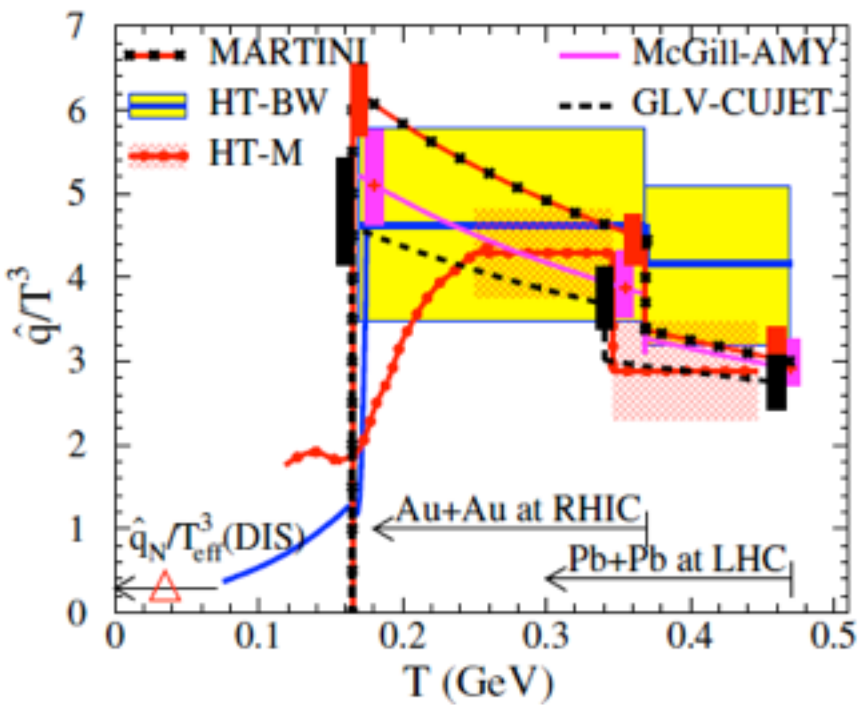




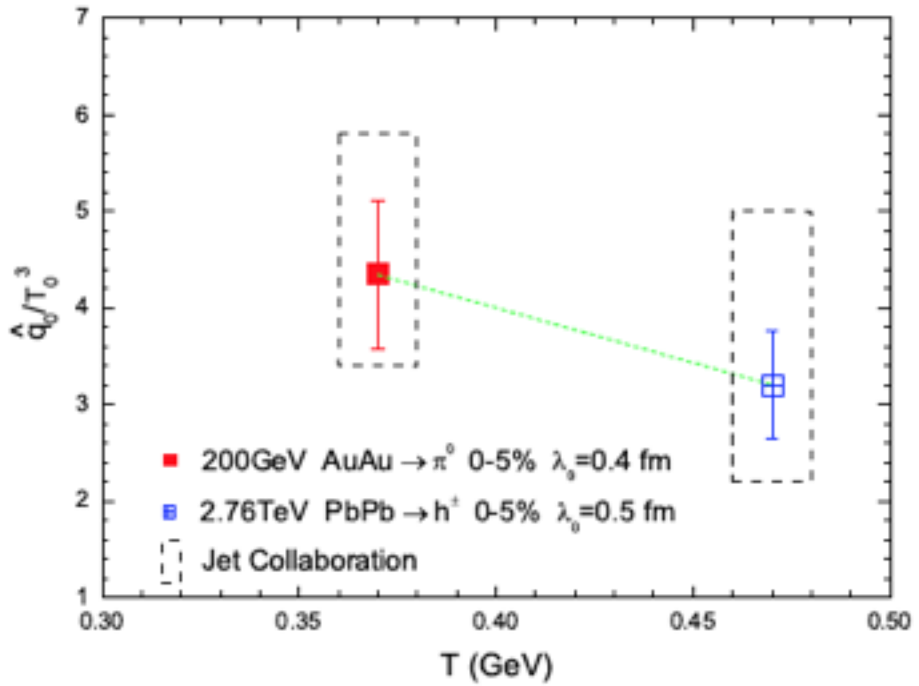


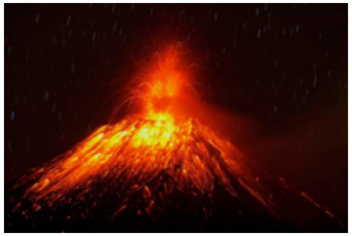
Extractions at RHIC vs LHC

JET Collaboration, arXiv: 1312.5003



Liu, Zhang, Zhang, Wang, arXiv: 1506.02840

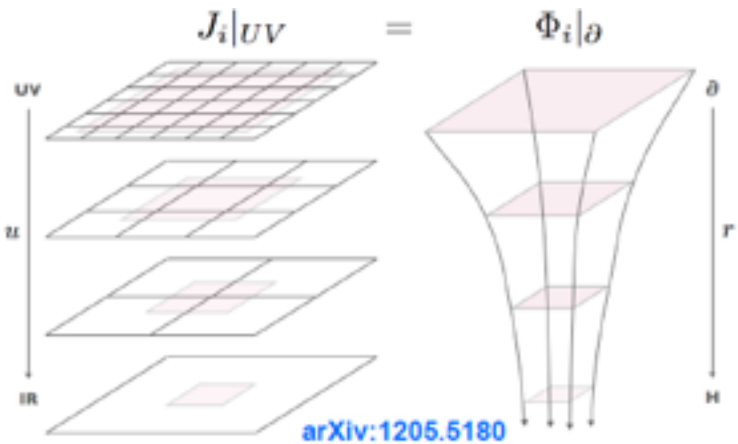




In the paper PRL(2009) we (Liao&Shuryak) concluded:

"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

Message from One More Dimension

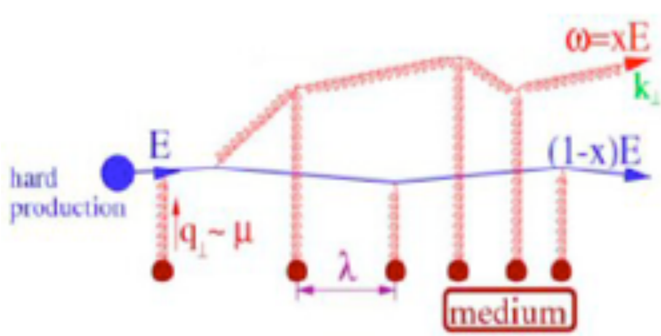


Deforming the conformal-AdS to
introduce non-conformal dynamics:
using graviton-dilaton system in the bulk

$$S_G = \frac{1}{16\pi G_5}\int d^5x\sqrt{g_s}e^{-2\Phi}\left(R_s + 4\partial_M\Phi\partial^M\Phi - V_G^s(\Phi)\right)$$

$$\Phi(z) = \mu_G^2 z^2 \tanh(\mu_{G^2}^4 z^2/\mu_G^2)$$

$$ds_5^2 = e^{2A_s}\left(-f(z)dt^2 + \frac{dz^2}{f(z)} + dx^i dx^i\right)$$

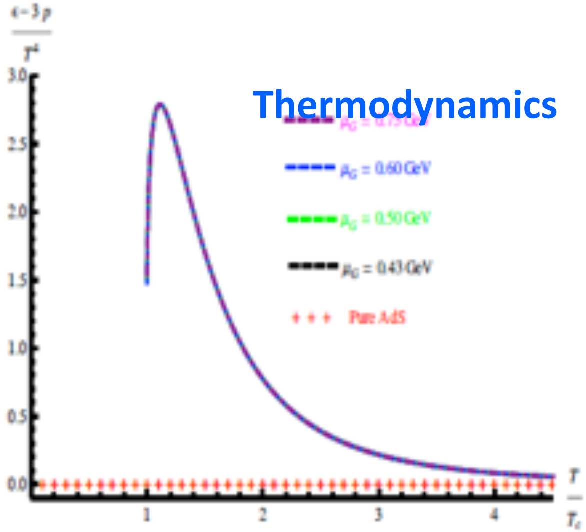


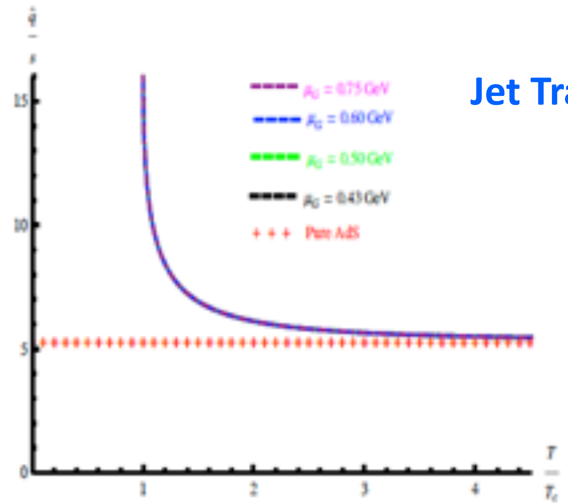
We use the Liu-Rajagopal-Wiedemann scheme
to compute q-hat

$$\hat{q} = \frac{\sqrt{2}\sqrt{\lambda}}{\pi\int_0^{z_h} dz\sqrt{g_{zz}/(g_{22}^2 g_{--})}},$$

D. Li, JL, M. Huang, arXiv:1401.2035

Results from Non-Conformal Holo-QCD



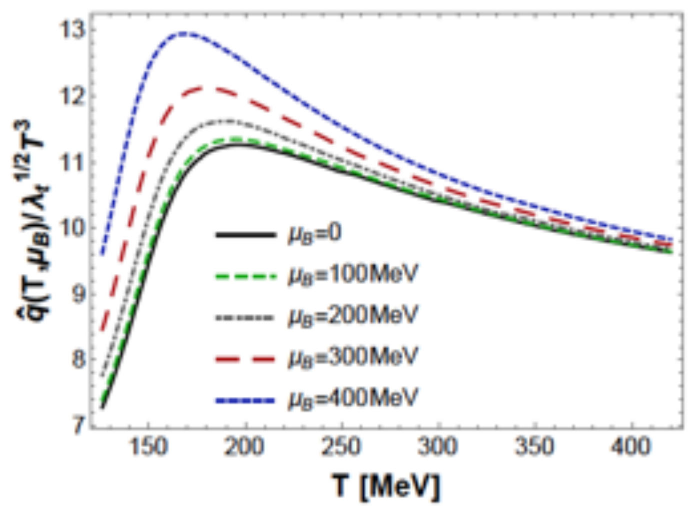


D. Li, JL, M. Huang, arXiv:1401.2035

Same non-conformal, non-monotonic, non-perturbative dynamics
---> shows up in trace anomaly and in jet transport parameter

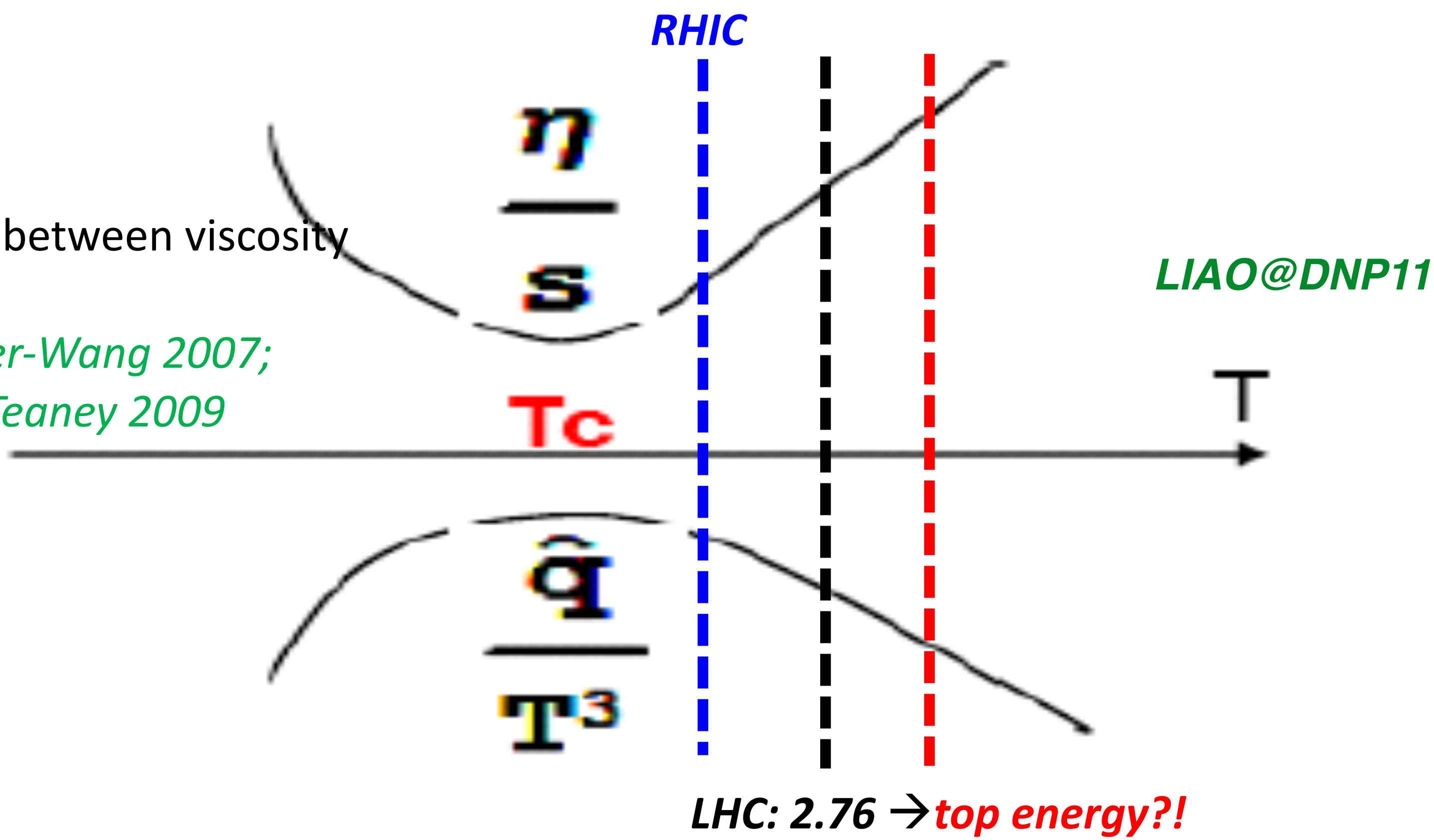
Rougemont, Ficnar, Finazzo, Noronha, arXiv:1507.06556

Quite different holo setup, but showing the same robust connection as above!



Near-Tc Matter is Special

Inverse relation between viscosity and opacity
Majumder-Muller-Wang 2007;
Dusling-Moore-Teaney 2009



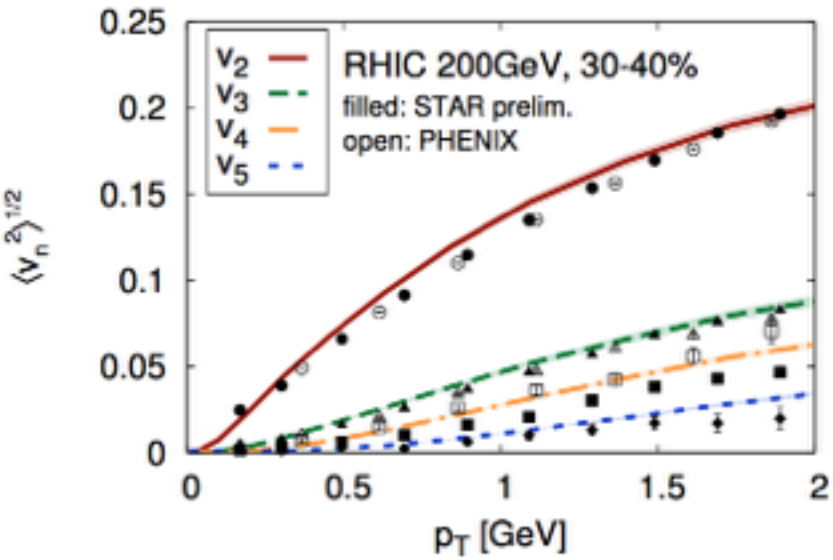
Will we see a systematic deviation from RHIC to LHC? Yes!

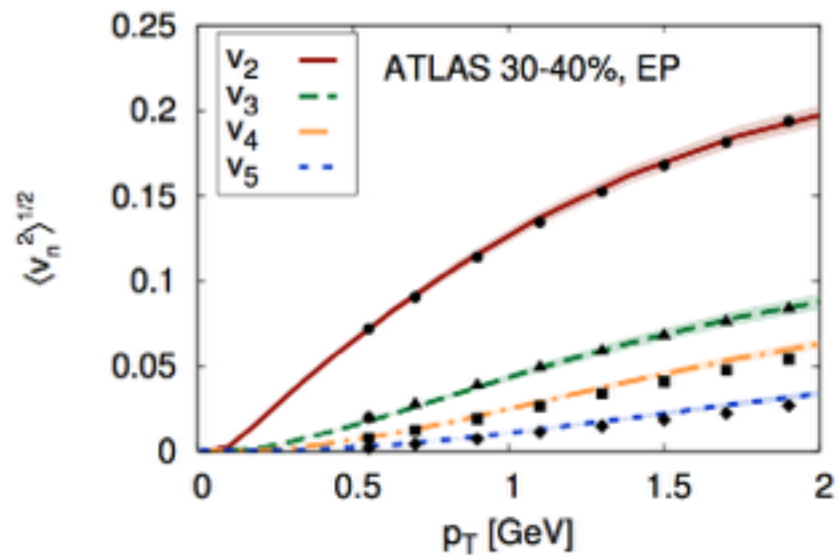
The "see-saw"-QGP expects such a picture to occur in a narrow regime 1-3Tc.

A kind of "critical opalescence"!

Reminiscence of a phase transition underlying the crossover

The QGP Liquidity is Shifting Too!





$\eta/s \approx 0.12 \longrightarrow \eta/s \approx 0.2$

Works of multiple groups (BNL-McGill, Frankfurt, Scalay, OSU) consistently suggest a visible increase, ~40%, of average eta/s from RHIC to LHC.

To be in context: the temperature is increased only by ~30% from RHIC to LHC.

Such rapid change is an indication of near-Tc phenomenon.

Toward Microscopic Making of sQGP!

There are a number of outstanding challenges in understanding how the QGP does what it does:

** We know that there are nonperturbative dynamics and emergent degrees of freedom in sQGP — how to implement such physics?*

** Experimental & lattice data validation/constraints?*

** Perfect fluidity v.s. Jet quenching — how to reconcile the two key properties of the sQGP?*

Xu, JL, Gyulassy, arXiv:1411.3673; arXiv:1508.00552

CUJET3: Semi-Quark-Gluon Monopole Plasma

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Consistency of Perfect Fluidity and Jet Quenching in Semi-Quark-Gluon Monopole Plasmas *

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We utilize a new framework, CUJET3.0, to deduce the energy and temperature dependence of the jet transport parameter, $\hat{q}(E > 10\,\mathrm{GeV}, T)$, from a combined analysis of available data on nuclear modification factor and azimuthal asymmetries from high energy nuclear collisions at RHIC/BNL and LHC/CERN. Extending a previous perturbative-QCD based jet energy loss model (known as CUJET2.0) with (2+1)D viscous hydrodynamic bulk evolution, this new framework includes three novel features of nonperturbative physics origin: (i) the Polyakov loop suppression of color-electric scattering (aka 'semi-QGP' of Pisarski et al.), (ii) the enhancement of jet scattering due to emergent magnetic monopoles near T_c (aka 'magnetic scenario' of Liao and Shuryak), and (iii) thermodynamic properties constrained by lattice QCD data. CUJET3.0 reduces to v2.0 at high temperatures $T > 400$ MeV, while greatly enhances $\hat{q}$ near the QCD deconfinement transition temperature range. This enhancement accounts well for the observed elliptic harmonics of jets with $p_T > 10$ GeV. Extrapolating our data-constrained $\hat{q}$ down to thermal energy scales, $E \sim 2$ GeV, we find for the first time a remarkable consistency between high energy jet quenching and bulk perfect fluidity with $\eta/s \sim T^3/\hat{q} \sim 0.1$ near T_c.

PACS: 25.75.−q, 12.38.Mh, 24.85.+p, 13.87.−a DOI: 10.1088/0256-307X/32/9/092501

Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0

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A Sophisticated Simulation Framework

DGLV-CUJET framework for describing multi-parton scattering:

$$x_E \frac{dN_g^{n=1}}{dx_E} = \frac{18C_R}{\pi^2} \frac{4+N_f}{16+9N_f} \int d\tau\, n(\mathbf{z})\Gamma(\mathbf{z}) \int d^2k$$
$$\times\, \alpha_s\left(\frac{\mathbf{k}^2}{x_+(1-x_+)}\right) \int d^2q \frac{\alpha_s^2(\mathbf{q}^2)}{\mu^2(\mathbf{z})} \frac{f_E^2\mu^2(\mathbf{z})}{\mathbf{q}^2(\mathbf{q}^2+f_E^2\mu^2(\mathbf{z}))}$$
$$\times\, \frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\left[\frac{\mathbf{k}}{\mathbf{k}^2+\chi^2(\mathbf{z})} - \frac{(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\right]$$
$$\times \left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}{2x_+E}\tau\right)\right]\left(\frac{x_E}{x_+}\right)\left|\frac{dx_+}{dx_E}\right| . \quad ($$

Original DGLV formalism has only quark/gluon scattering centers

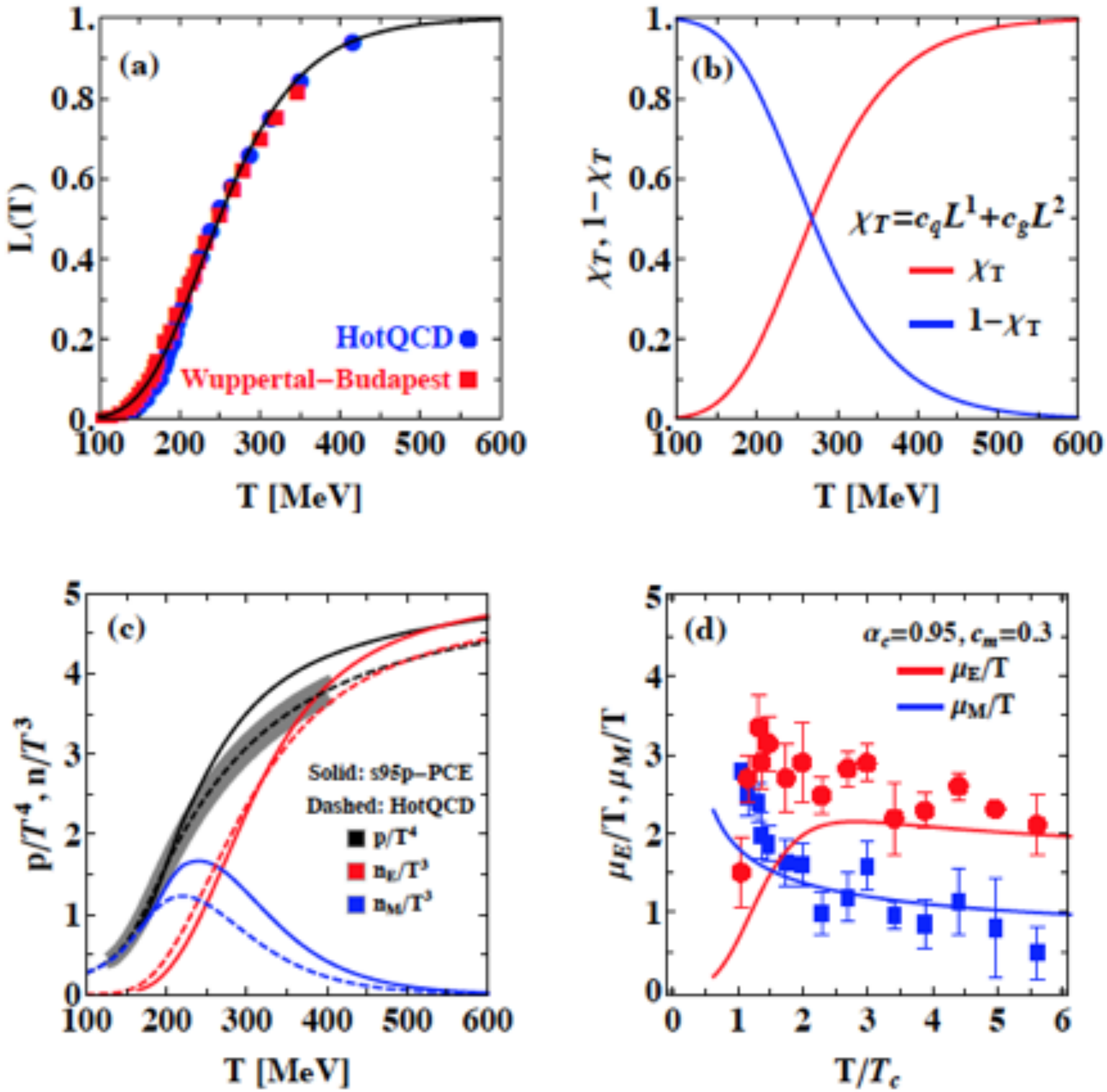
We now include both color-electric and color-magnetic scattering centers.

$$x\frac{dN}{dx} \propto \ldots \int_{q^2}\left[\frac{n\,\alpha_s^2(q^2)\,f_E^2}{q^2(q^2+f_E^2\mu^2)}\right]\ldots \longrightarrow \left[\frac{n_e\,(\alpha_s(q^2)\alpha_s(q^2))\,f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m\,(\alpha^e(q^2)\alpha^m(q^2))\,f_M^2}{q^2(q^2+f_M^2\mu^2)}\right]$$

Our goal is to implement the nonperturbative NEAR-Tc Physics —> CUJET3.0

Xu, JL, Gyulassy, arXiv:1411.3673

The Making of sQGP



** Electric density:*
L-loop suppression

$$\chi_T = c_q\, L + c_g\, L^2$$

** Magnetic density:*
constrained by total pressure

$$(1-\chi_T)$$

** Running coupling:*
L-loop suppression

$$\alpha_s(Q^2) = \alpha_c / \left[1 + \frac{9\alpha_c}{4\pi} \mathrm{Log}\left(\frac{Q^2}{T_c^2}\right)\right]$$

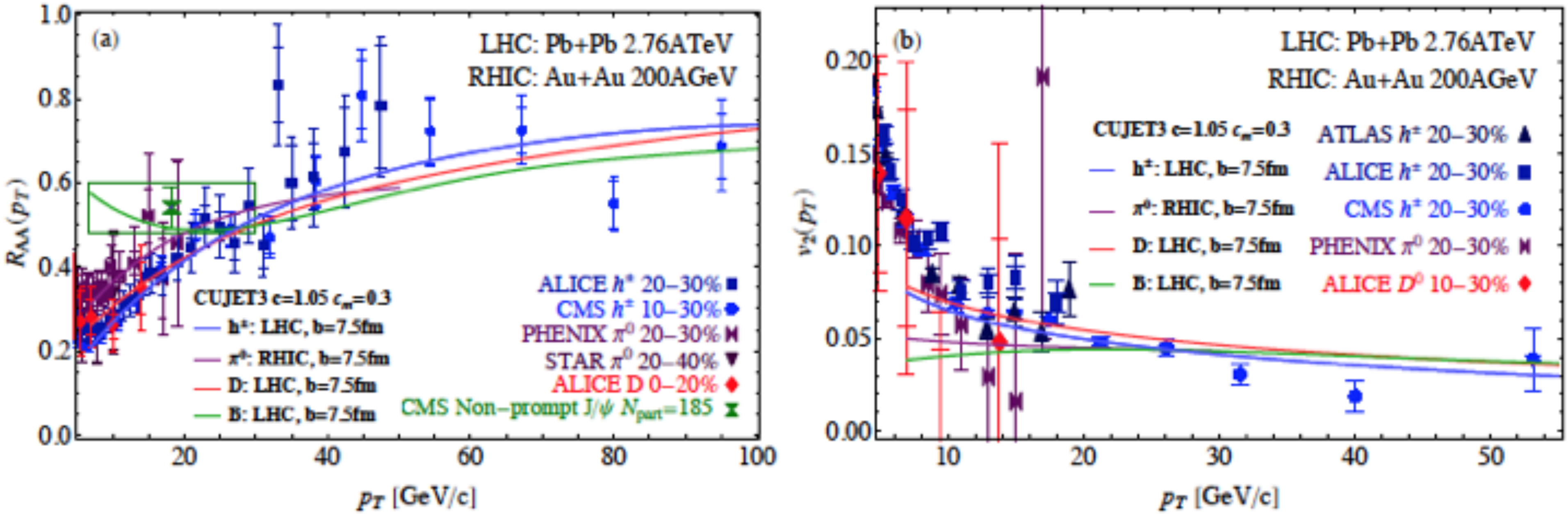
** Screening:*

$$f_E(T) = \sqrt{\chi_T} \quad , \quad f_M(T) = c_m\, g$$

The model implementations of electric and magnetic components
are **well constrained by available lattice data.**

Xu, JL, Gyulassy, arXiv:1411.3673

CUJET3.0 Explains (RHIC+LHC)*(Raa+V2)!



The SEVEN set of single hadron observables

*[(RHIC+LHC) * (RAA+V2) * (pion)]*

*+ [(LHC) * (RAA+V2) * (D)]*

*+ [(LHC) * (RAA) * (B)],*

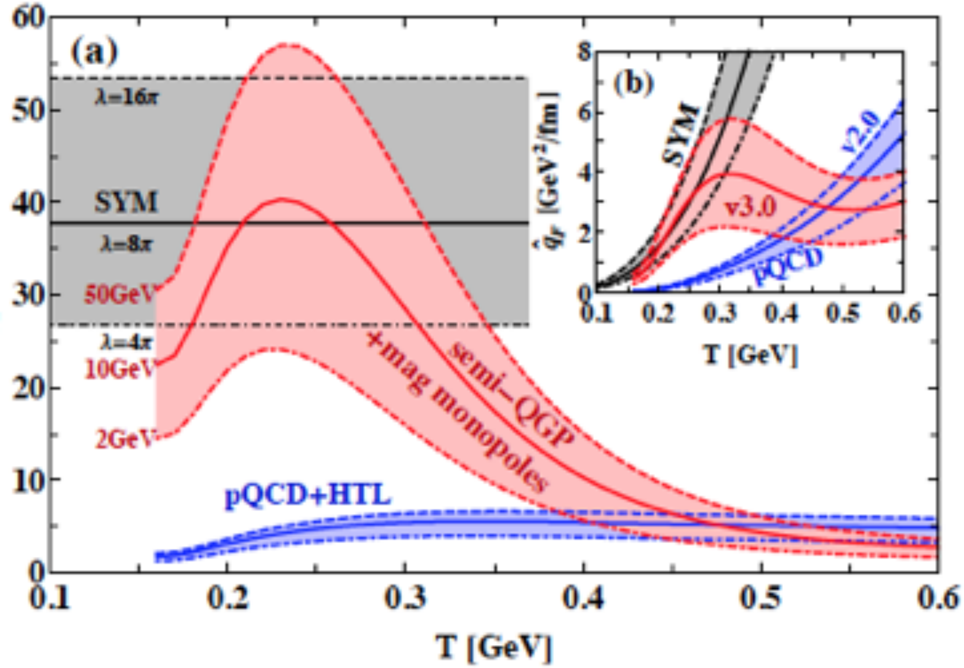
are nicely explained by CUJET3.0 framework

(with essentially ONE model parameter)

that implements the nonperturbative near-Tc physics!

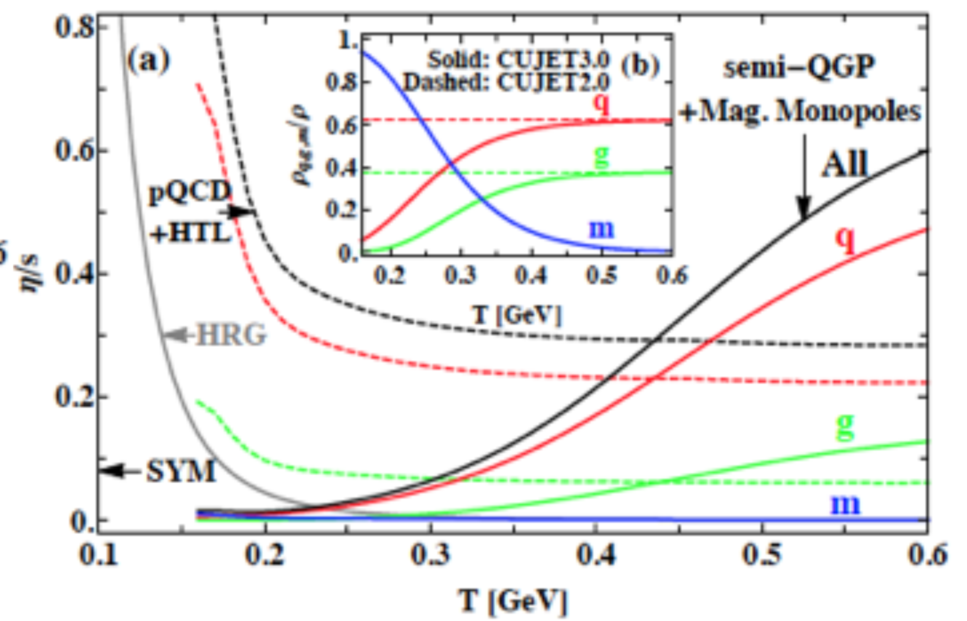
Xu, JL, Gyulassy, arXiv:1411.3673

Near-Tc Matter Properties are Special!



Jet transport coefficient q-hat/T^3 computed from CUJET3.0 shows a prominent peak near Tc!

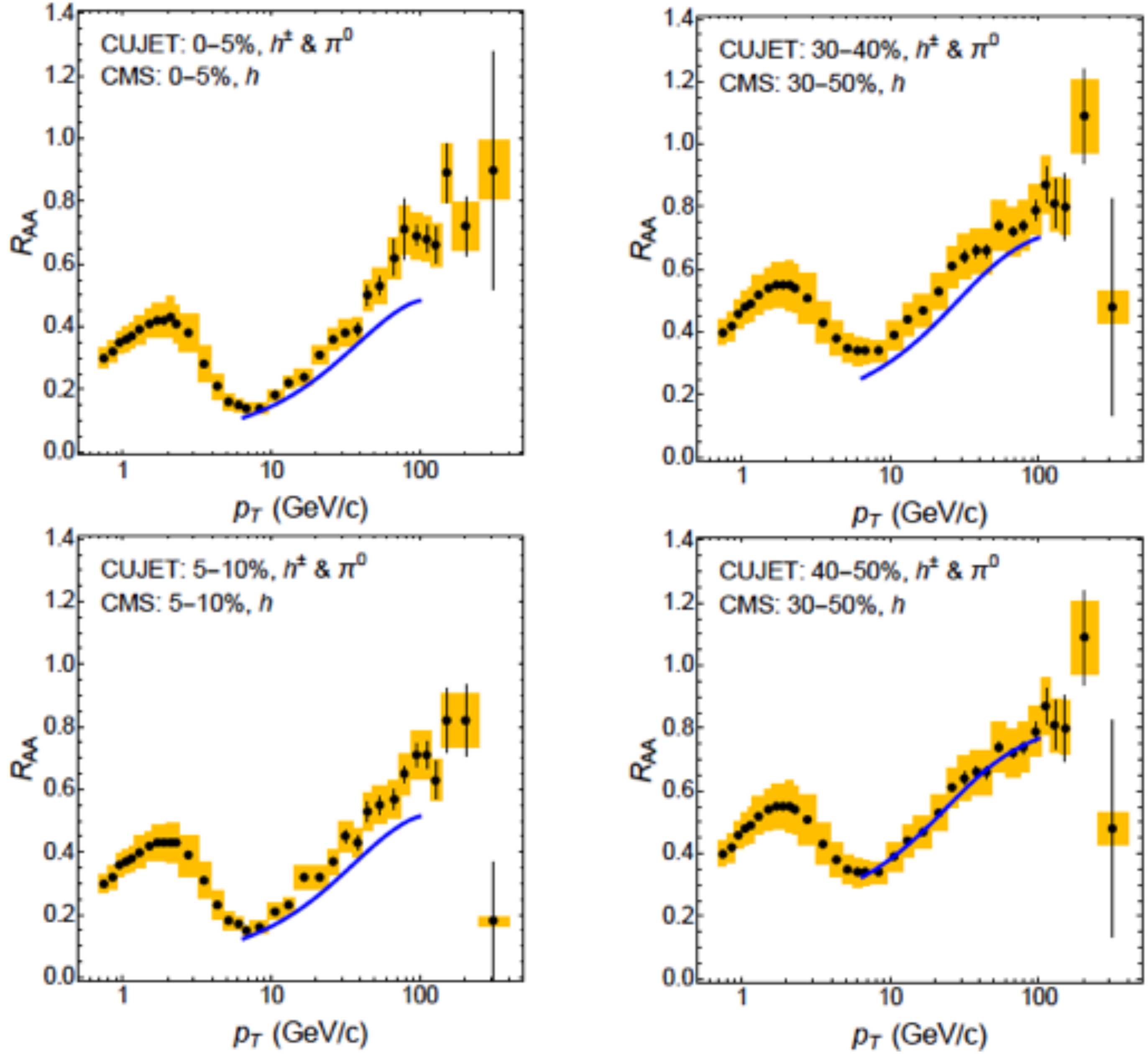
Shear viscosity, eta/s, computed from CUJET3.0 shows a clear minimum near Tc and rapid increase to high T!



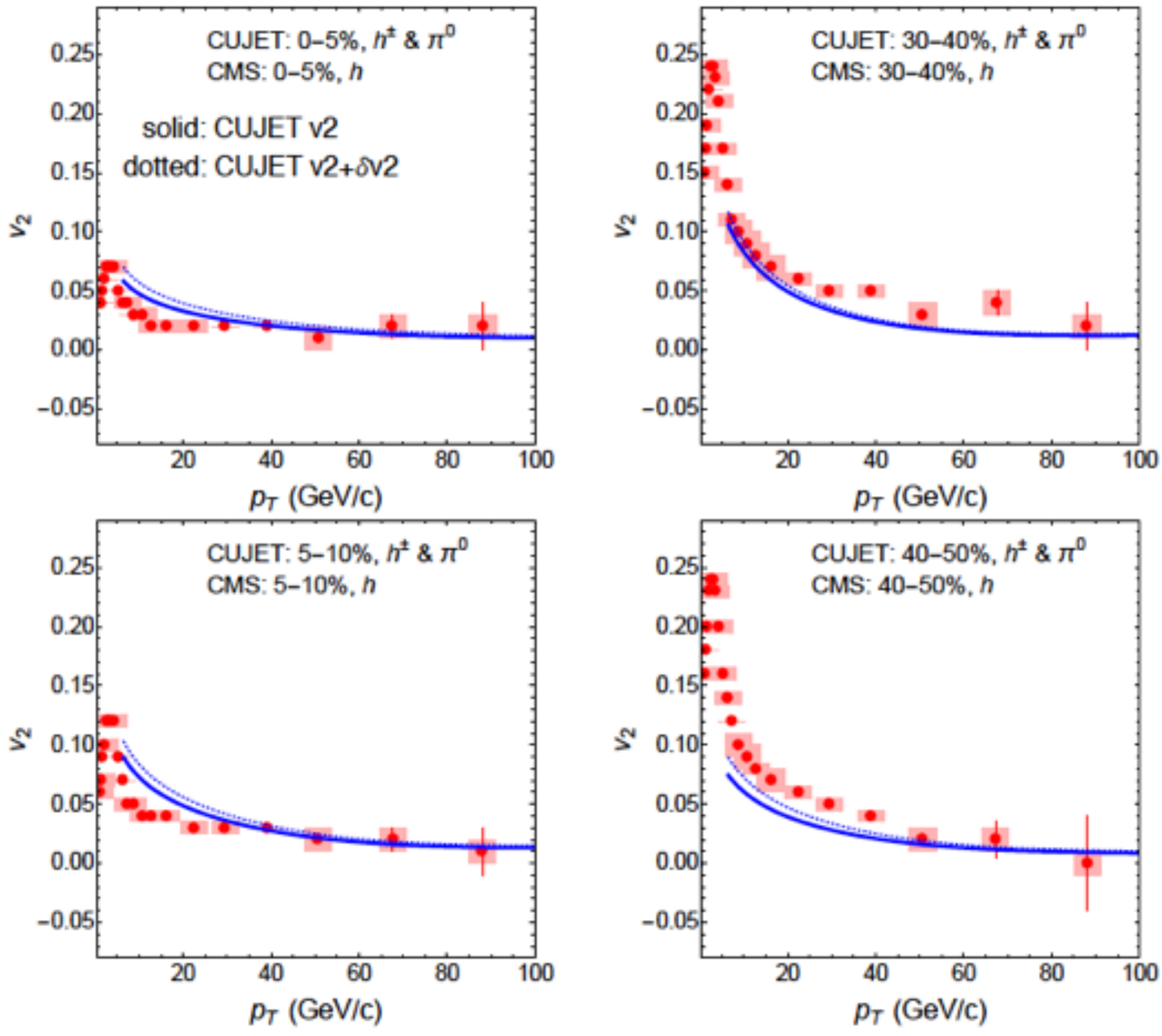
CONSISTENCY of Perfect Fluidity & Jet Quenching in the semi-quark-gluon monopole plasma (sQGMP)!

Xu, JL, Gyulassy, arXiv:1411.3673

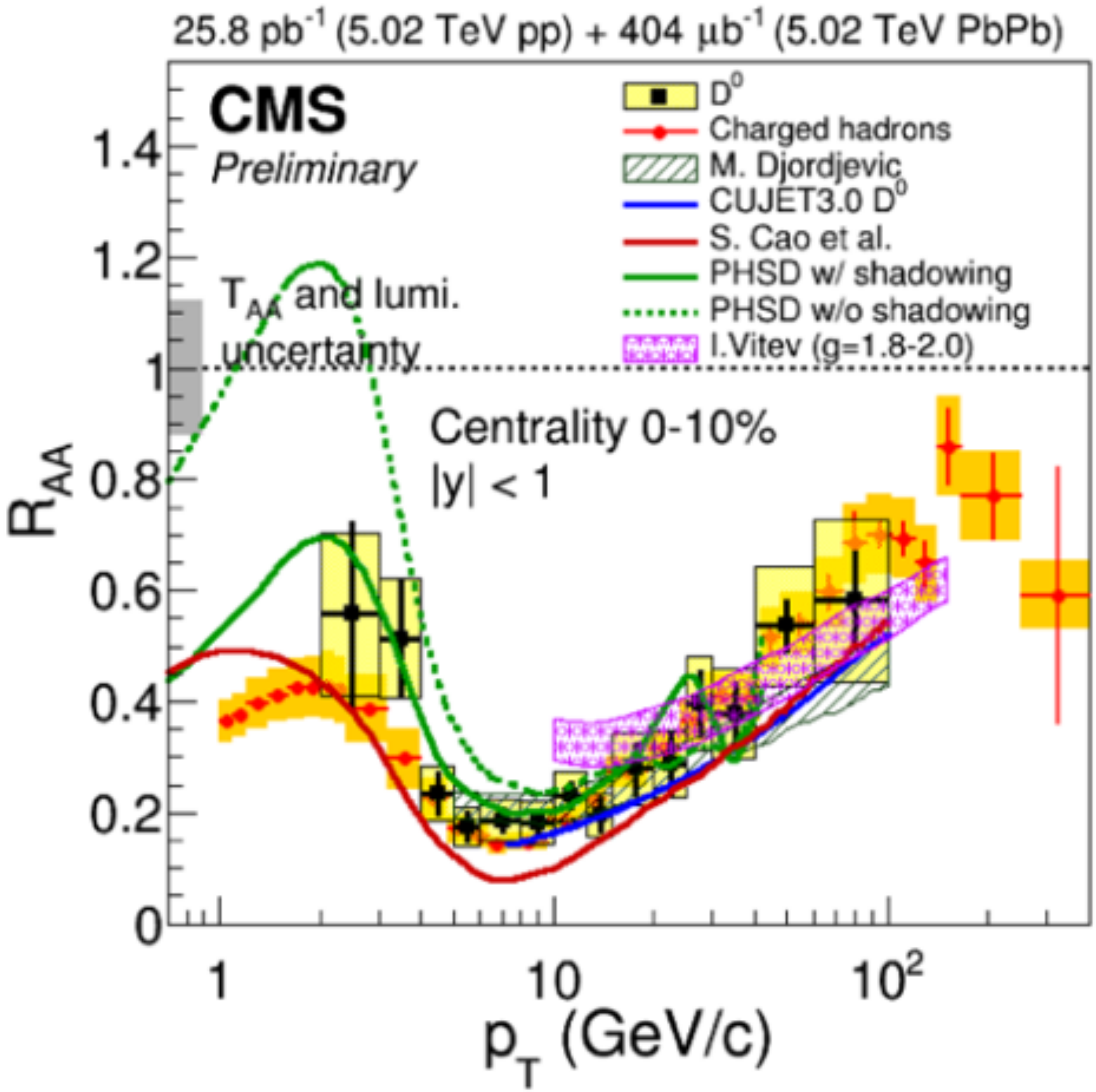
Test CUJET3 @ LHC 5TeV



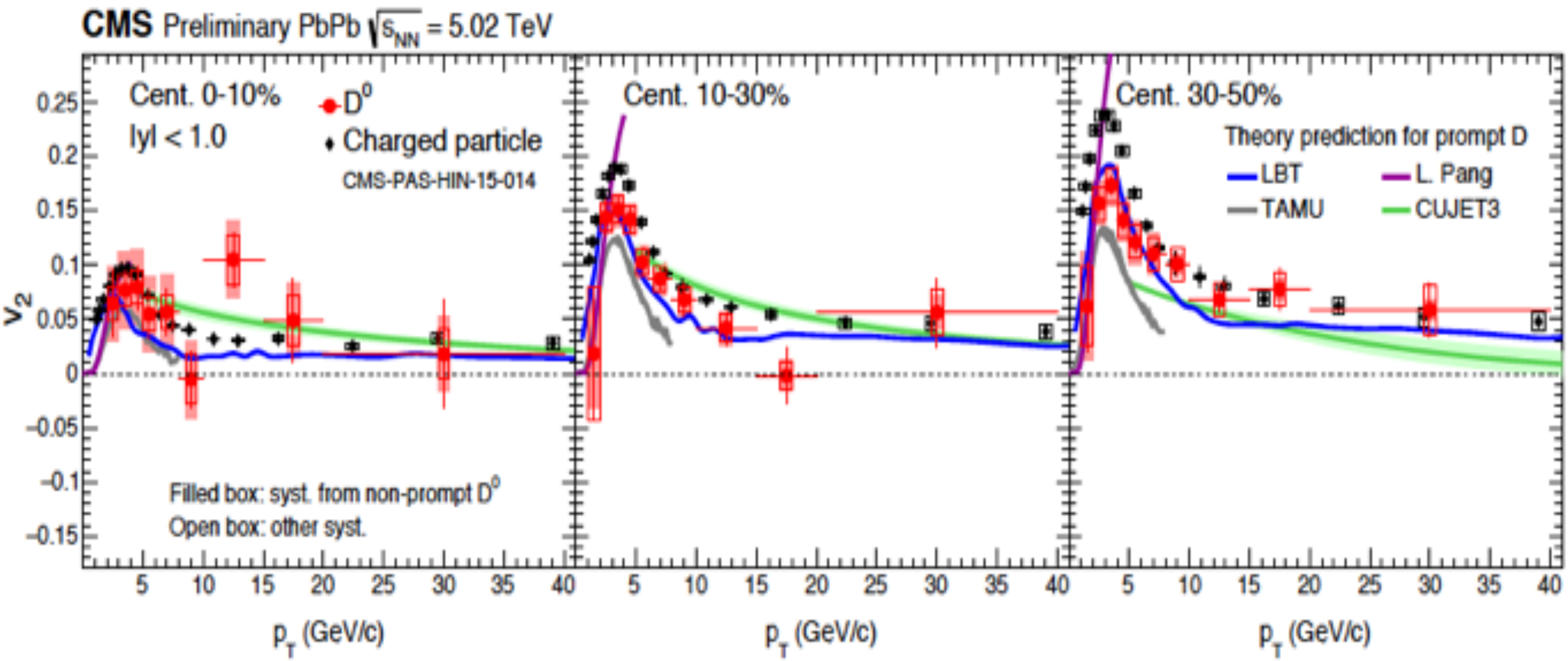
Test CUJET3 @ LHC 5TeV



Test CUJET3 @ LHC 5TeV



Test CUJET3 @ LHC 5TeV



HF Test from CUJET3 for RRTF

- Only collisional/elastic energy loss included.
  (no radiational/inelastic e.l.)

- dE/dx = - A(p^2) p , [M.Mustafa et al PRC57(1998)]
  A(p^2) obtained from file "FPcoeff-pQCD-K5.dat"

- Both input charm quark pp spectrum & fragmentation function are using "RRTF standard".

- 2+1D VISHNU hydro profile employed.

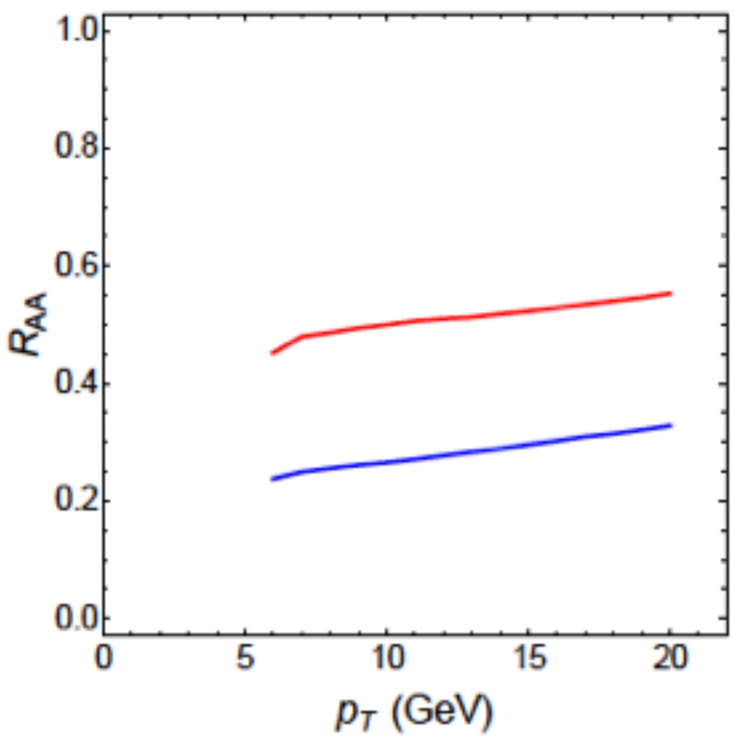
- For comparison, results using CUJET collisional energy loss kernel also attached.

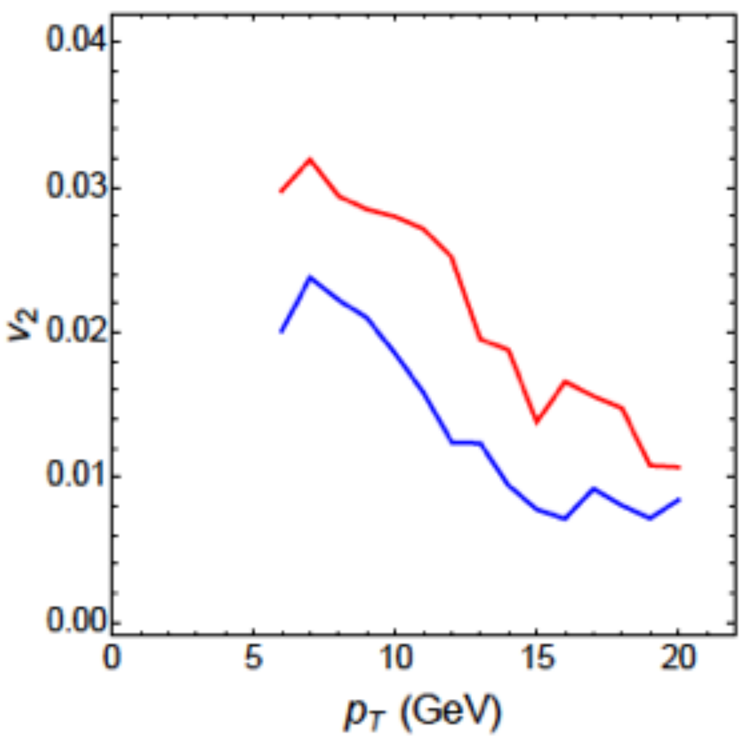
$$\frac{dE}{dx} = -C_R \pi \alpha_s^2 T^2 \left(1 + \frac{2}{6}\right) \left(\frac{1}{v} + \frac{v^2 - 1}{2v^2} \log \frac{1+v}{1-v}\right) \log\left(\frac{k_{max}}{\mu}\right)$$

HF Test from CUJET3 for RRTF

R_{AA} & v_2 for charm quark

- Blue: 0-10%
- Red: 30-50%

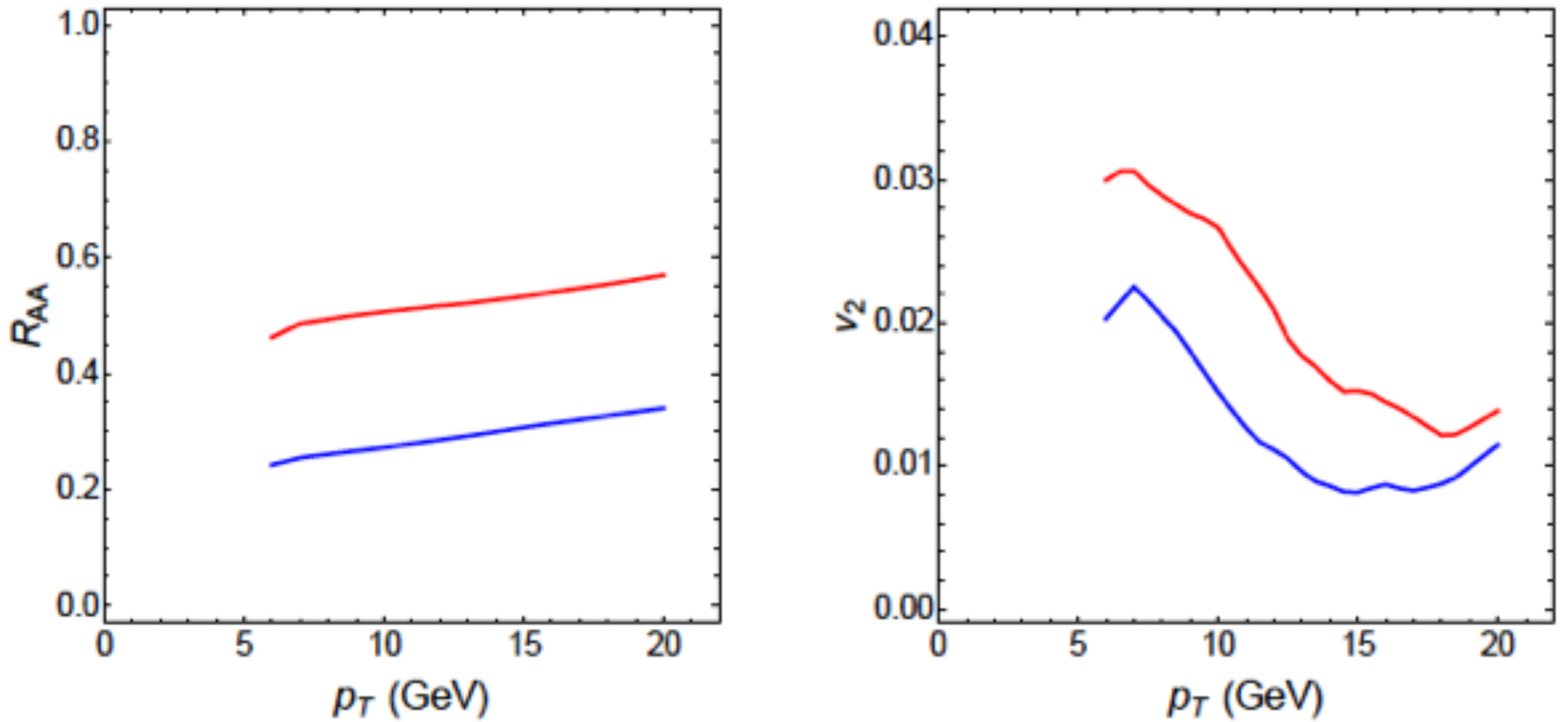




HF Test from CUJET3 for RRTF

R_{AA} & v_2 for D0

- Blue: 0-10%
- Red: 30-50%

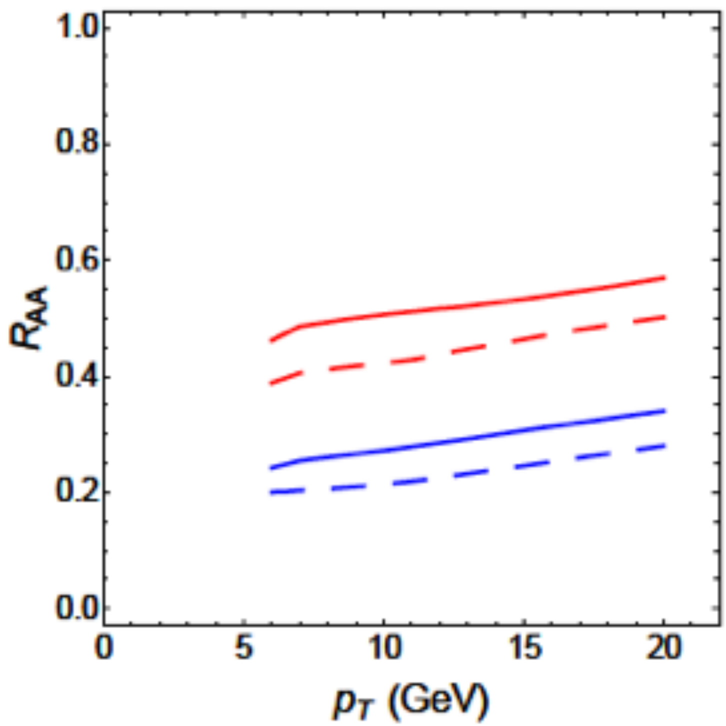


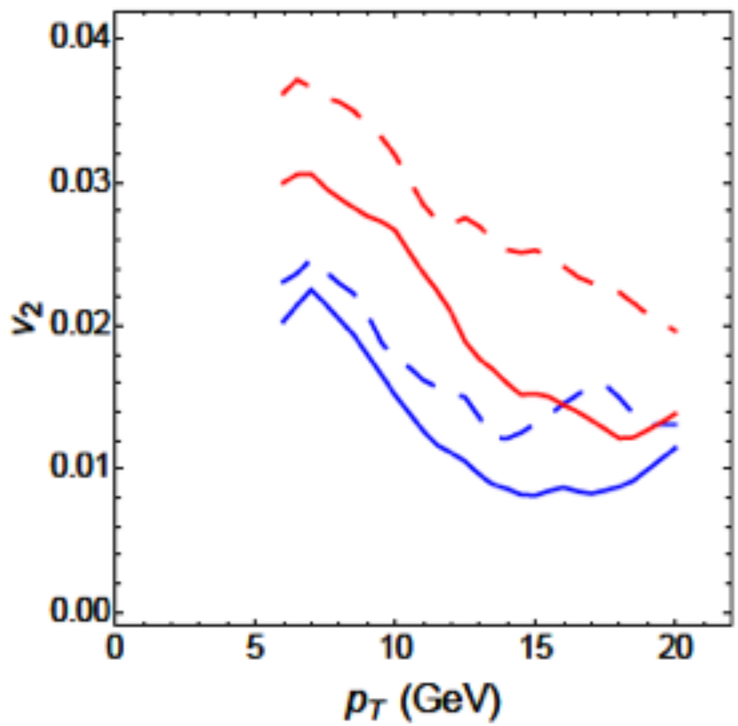
HF Test from CUJET3 for RRTF

R_{AA} & v_2 for D0 — CUJET c.e.l. kernel

for comparison

- Blue: 0-10%
- Red: 30-50%
- Solid: RRTF standard
- Dashing: CUJET with α_s = 0.4, N_f = 3, m_c = 1.5 GeV

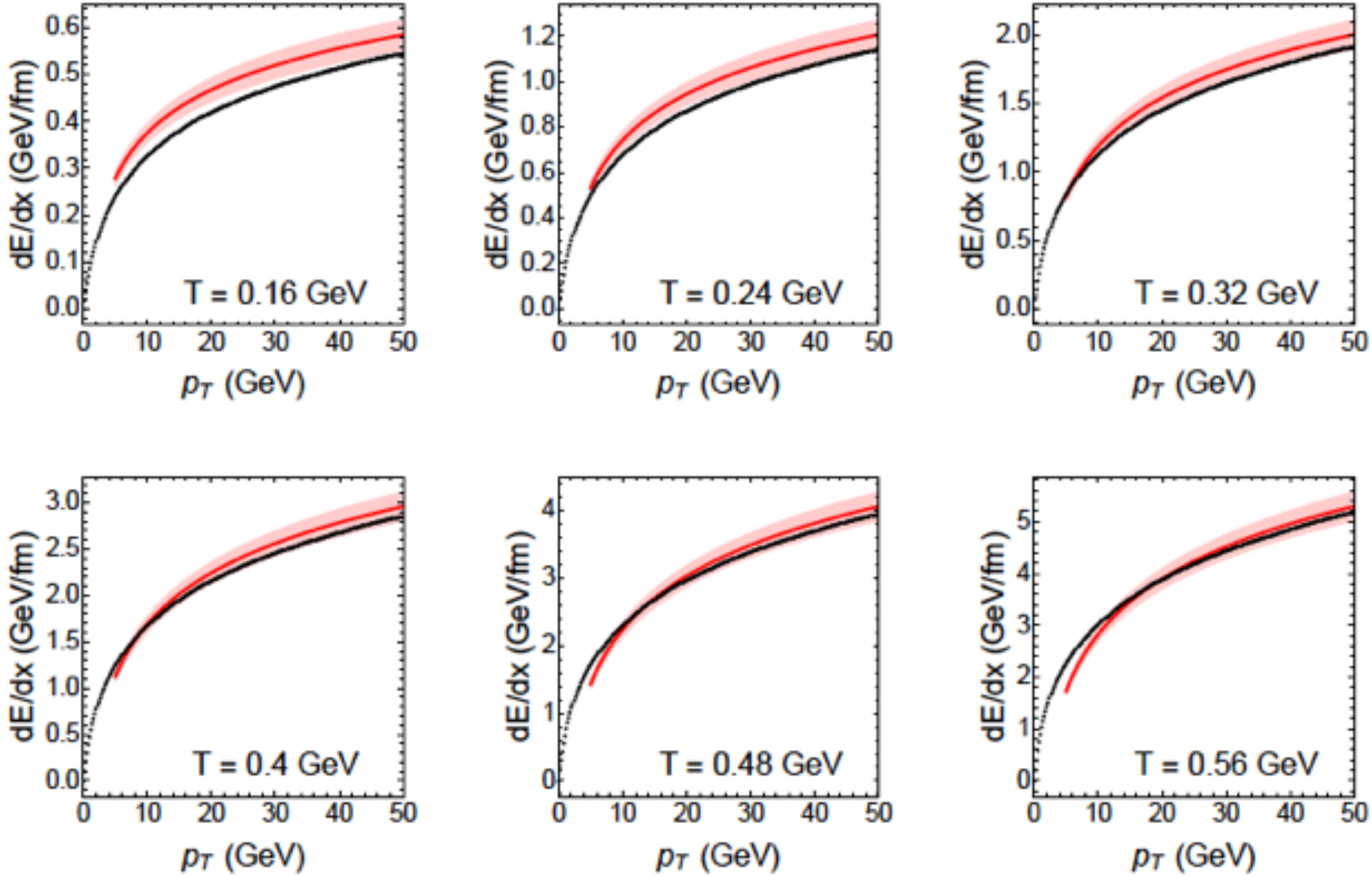




HF Test from CUJET3 for RRTF

Black dots: from "FPcoeff-pQCD-K5.dat"
Red curves: CUJET standard kernel

band: Nf = 2 ~ 3 from bottom to top
central curve: Nf = 2.5

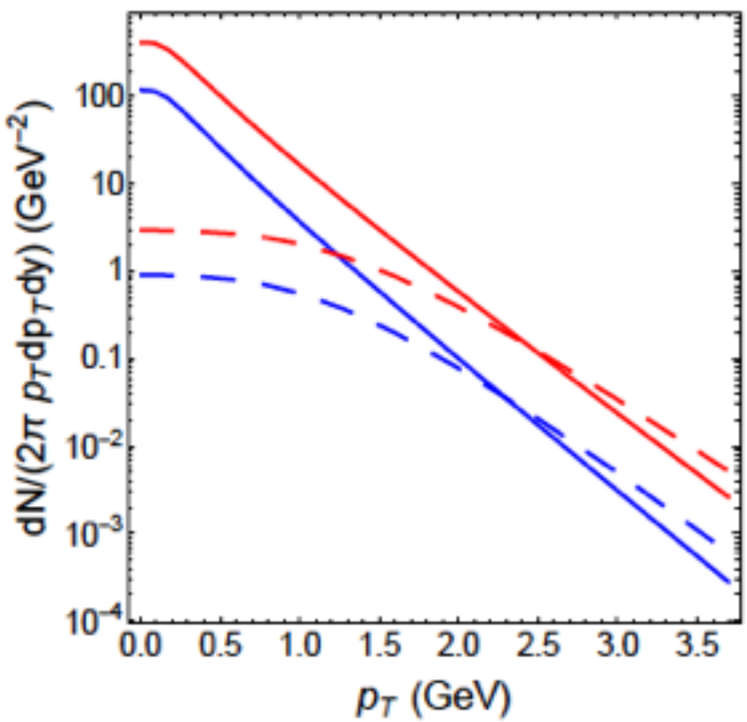


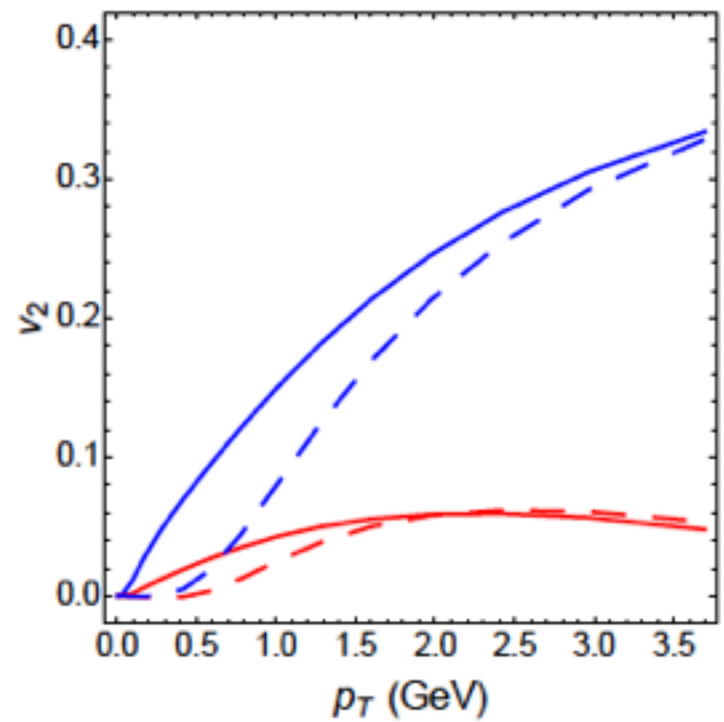
HF Test from CUJET3 for RRTF

about hydro — Spectrum & v2 **BEFORE** hadron cascade

(at the end of QGP evolution)

- Blue: 0-10%
- Red: 30-50%
- Solid: pions
- Dashed: protons

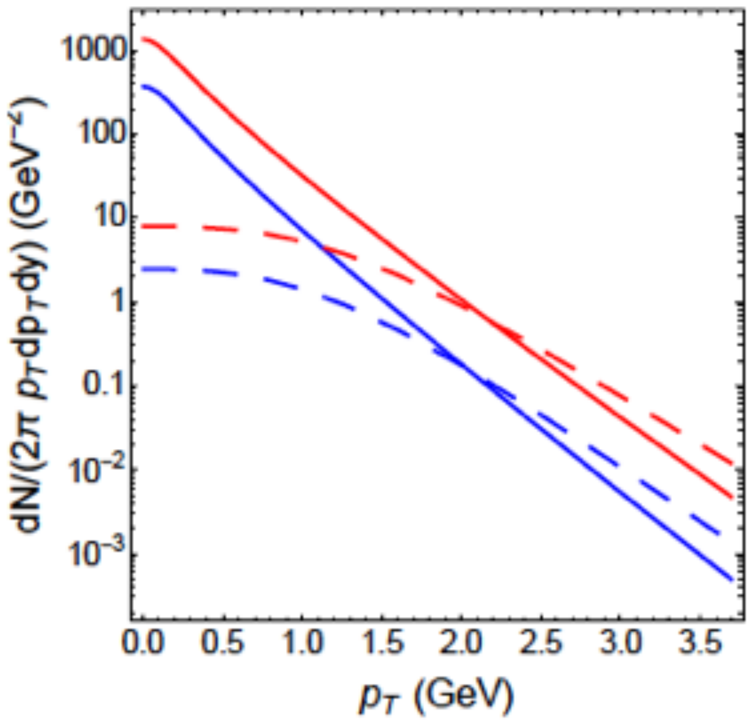


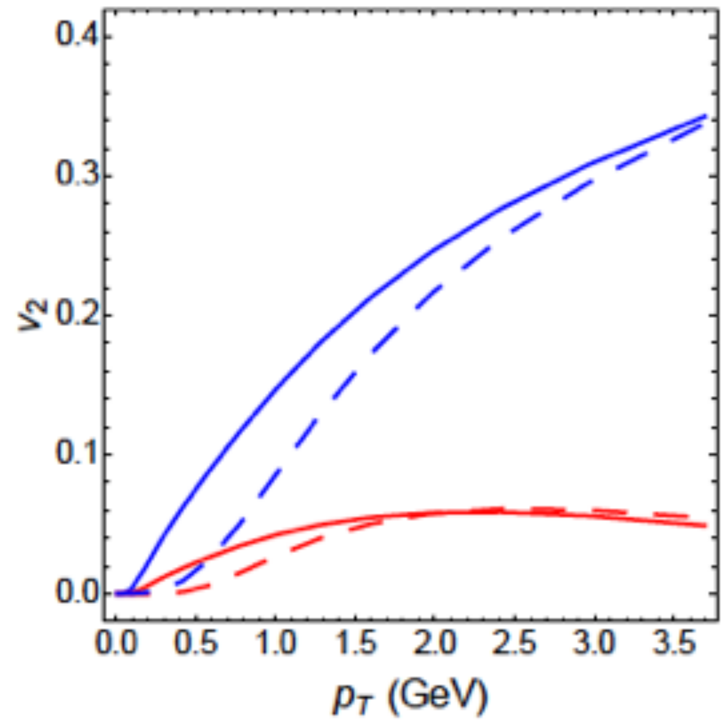


HF Test from CUJET3 for RRTF

about hydro — Spectrum & v2 **AFTER** hadron cascade

- Blue: 0-10%
- Red: 30-50%
- Solid: pions
- Dashed: protons





Summary & Discussions