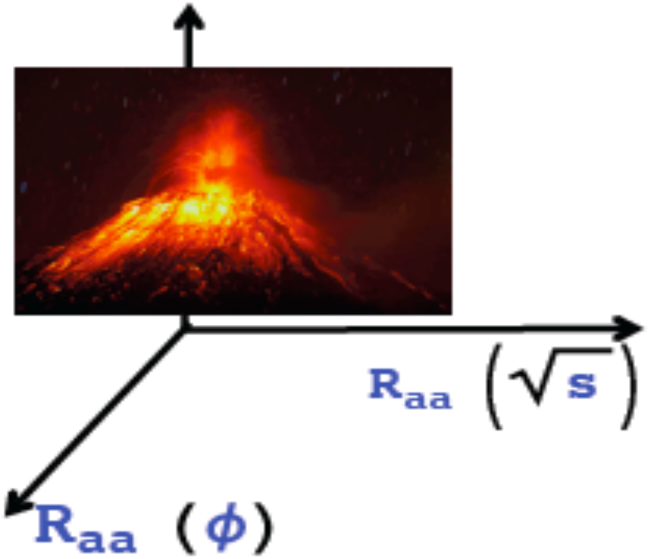
ATHIC2014 OSAKA

The 5th Asian Triangle Heavy Ion Conference 2014
In Osaka, Japan on August 5-8, 2014

ATHIC2014 @ OSAKA AUG 6, 2014

JET TOMOGRAPHY OF FLUCTUATING INITIAL CONDITIONS AND THE OPAQUENESS EVOLUTION FROM RHIC TO LHC



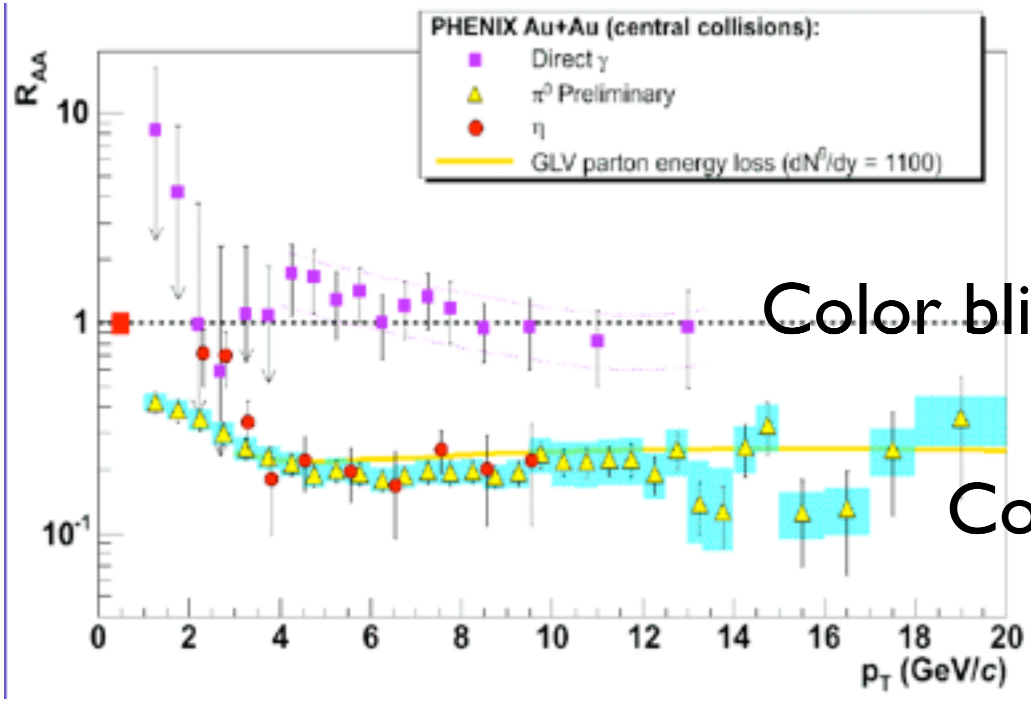
Jinfeng Liao
Indiana University, Physics Dept. & CEEM
RIKEN BNL Research Center

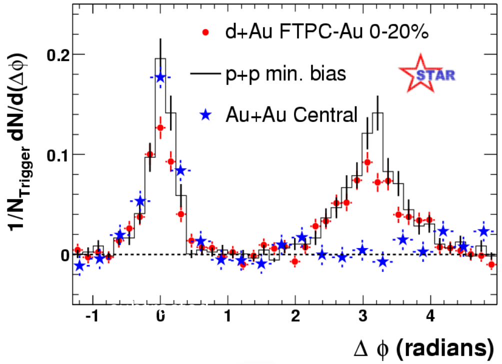
Outline

- Introduction: opaqueness evolution
- Jet tomography: What we've learned from the geometry of jet quenching with RHIC+LHC data?
- Jet tomography for the smallest QGP drop
- Opaqueness evolution from "one more dimension"
- Summary & Discussions

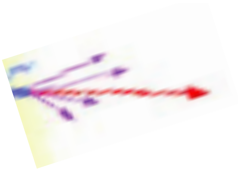
X. Zhang, JL, arXiv:1311.5463,1208.6361(PRC),
1210.1245(PRC),1202.1047(PLB);
D. Li, JL, M. Huang, arXiv:1401.2035 (PRD);
JL, arXiv:1109.0271;
JL, Shuryak, Phys.Rev.Lett. 102 (2009) 202302

A Color-Opaque Plasma



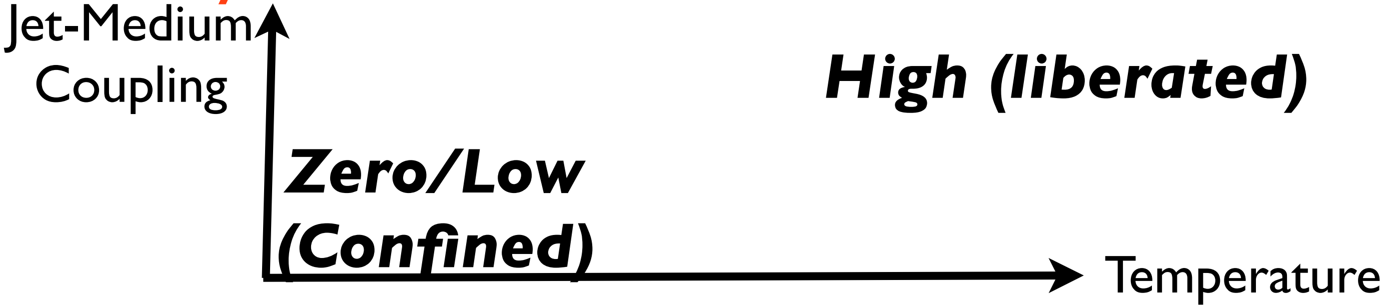


Color blind probe



Colorful probe

A qualitatively different medium



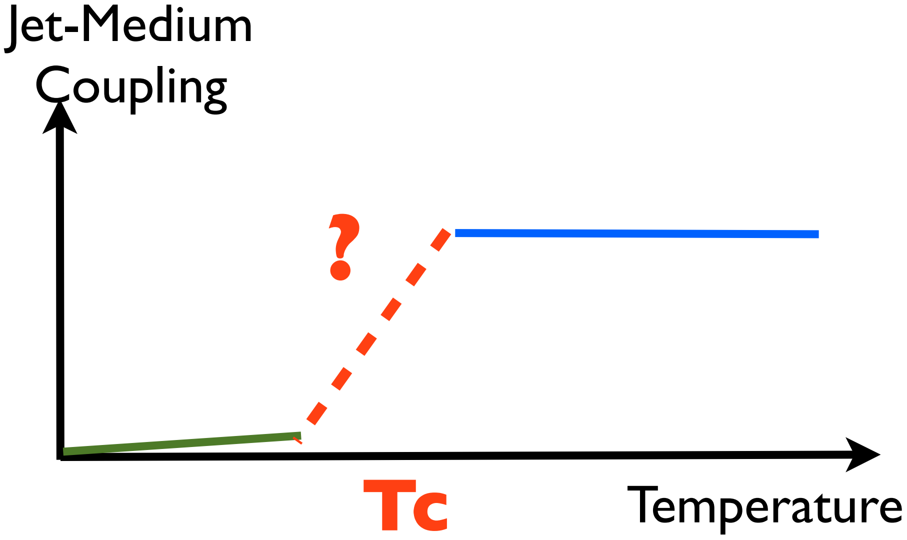
Jet-Medium Coupling

High (liberated)

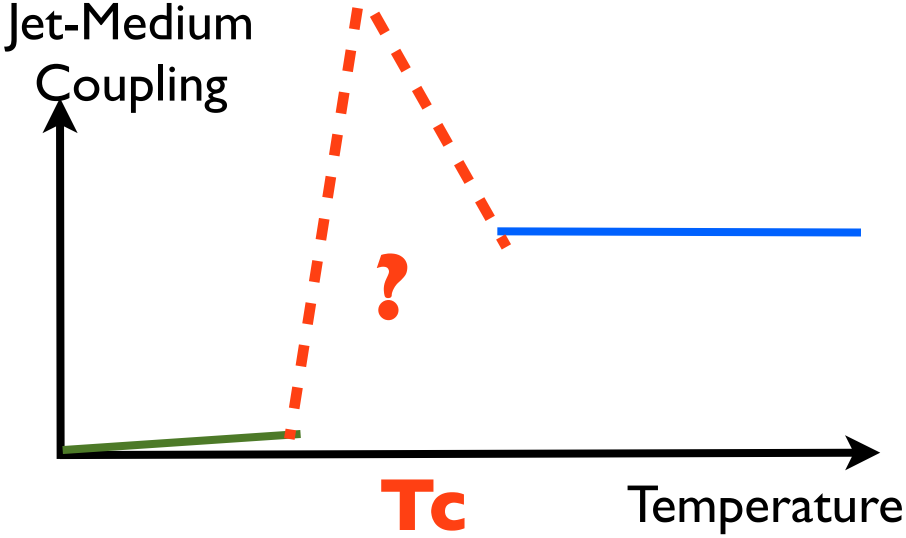
Zero/Low (Confined)

Temperature

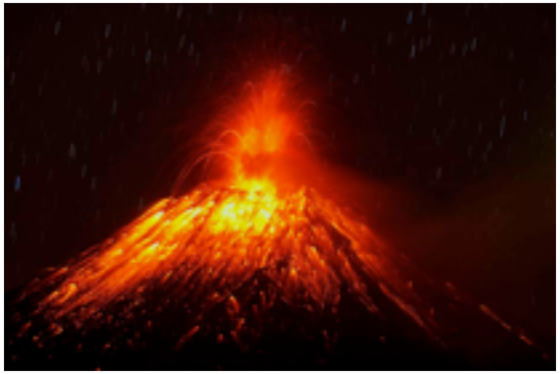
From Transparency to Opaqueness



"Waterfall" scenario

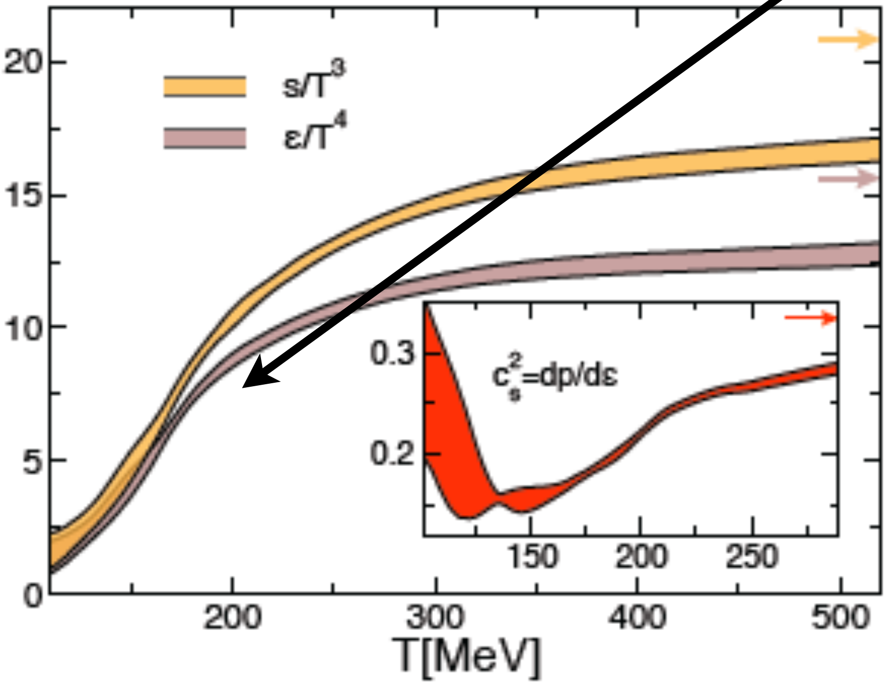


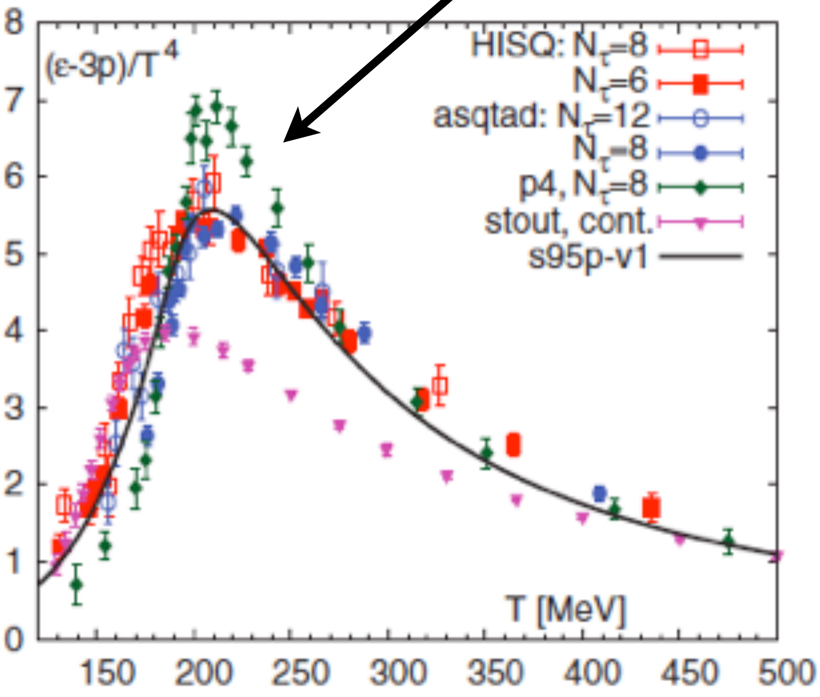
"Volcano" scenario



To me, this is a question of fundamental interest, and one we must answer for understanding of jet-quenching & of the medium itself.

Hot off the Lattice: **Crossover**, but **Rapid**

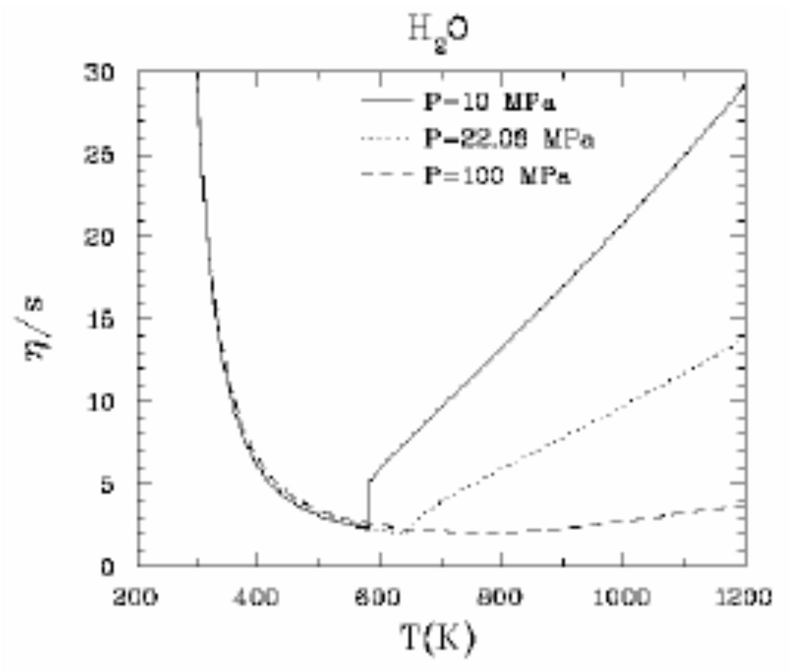




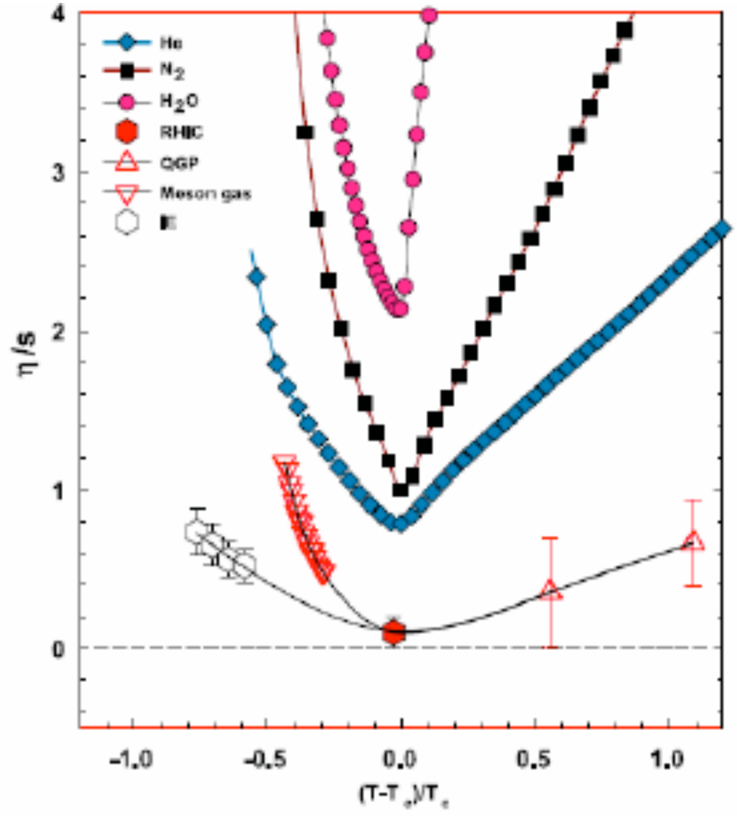
"Rapid Up" or "Rapid Down":
pressure/energy density/entropy density/
2-nd q-susceptibilities/
chiral condensate/Q-bar-Q free energy/...

"Peak" or "Dip":
trace anomaly/chiral susceptibility/
4-th q-susceptibilities/
Q-bar-Q internal energy/
speed of sound//...

How about the “Perfect-ness” of Fluid?

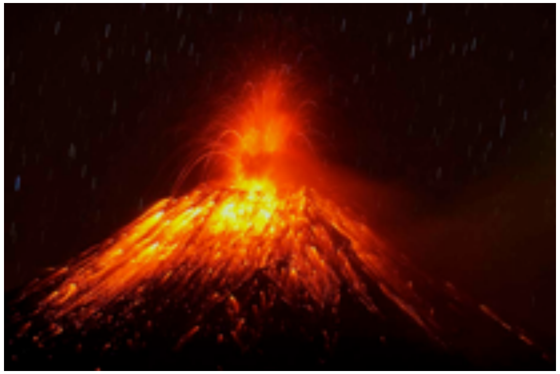


Csernai,Kapusta,McLerran, PRL(2006)



Lacey, et al, PRL(2007)

V.S.



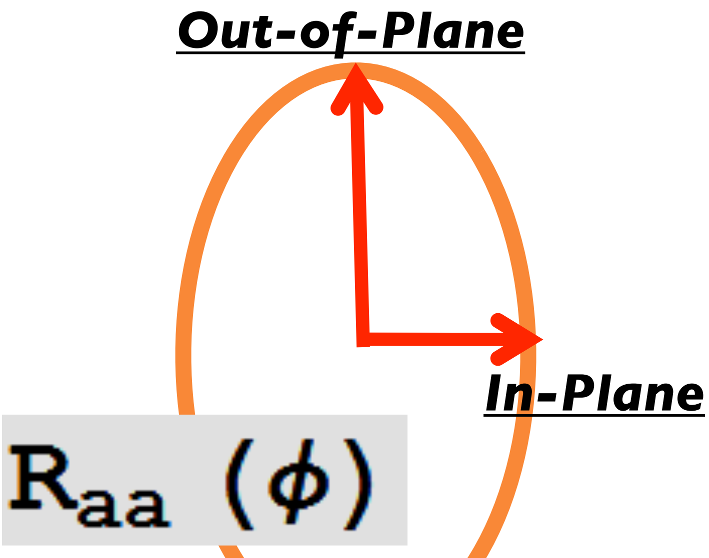
How can we get the answer about the T-dependence of jet-medium interaction?

Do we even have a chance
to find out the answer?

Luckily, we seem to be able to:

Geometric Anisotropy of Jet Quenching

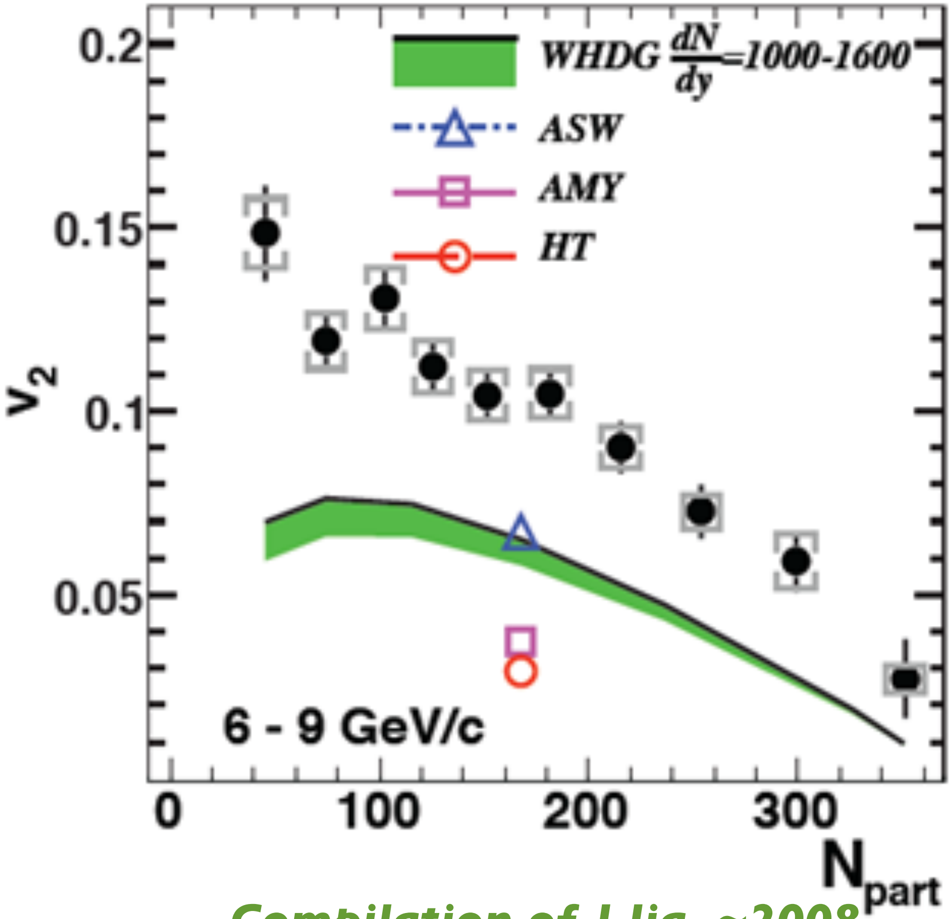
Geometric tomography(~2001): Gyulassy,Vitev,Wang,...
Geometric limit of high-pt v2: Shuryak; Drees,Feng,Jia;...
Till ~2008: clear discrepancy between data / any model



$R_{aa}\ (\phi)$

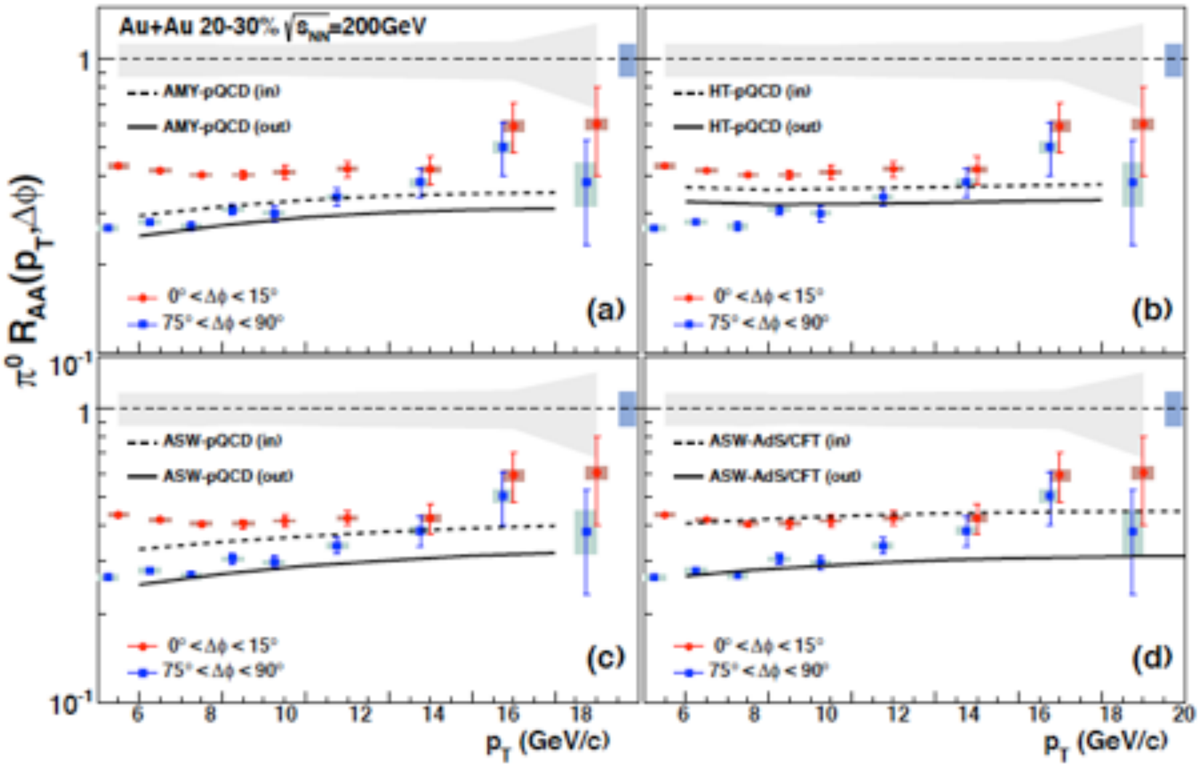
$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$

Positive v2 for high Pt hadrons

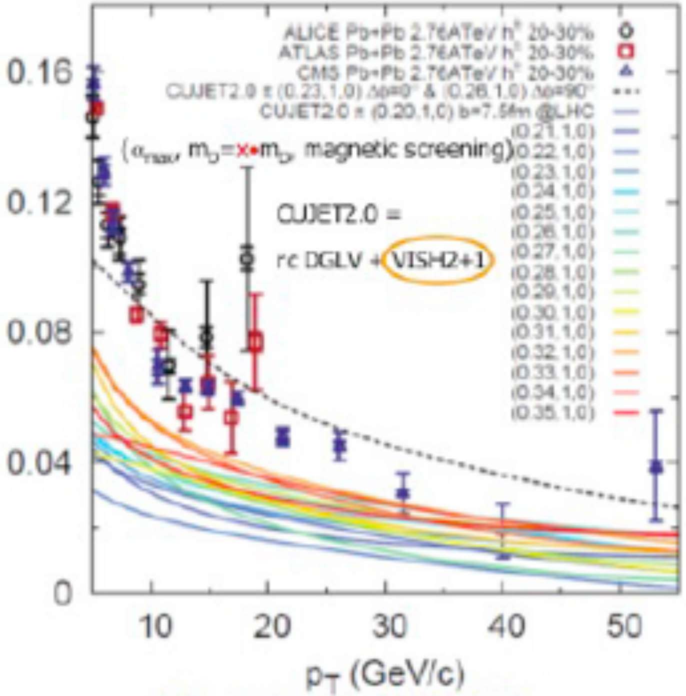


Compilation of J.Jia, ~2008

Differential Data Examples

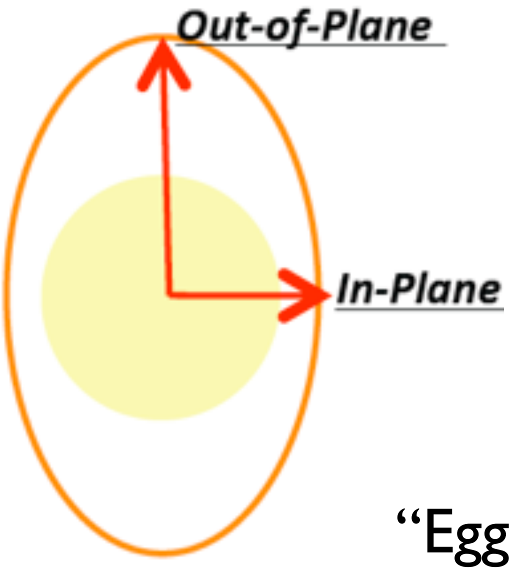


from PHENIX pi0



J. Xu et al., arXiv:1402.2956

Where Are Jets Quenched (More Strongly)?

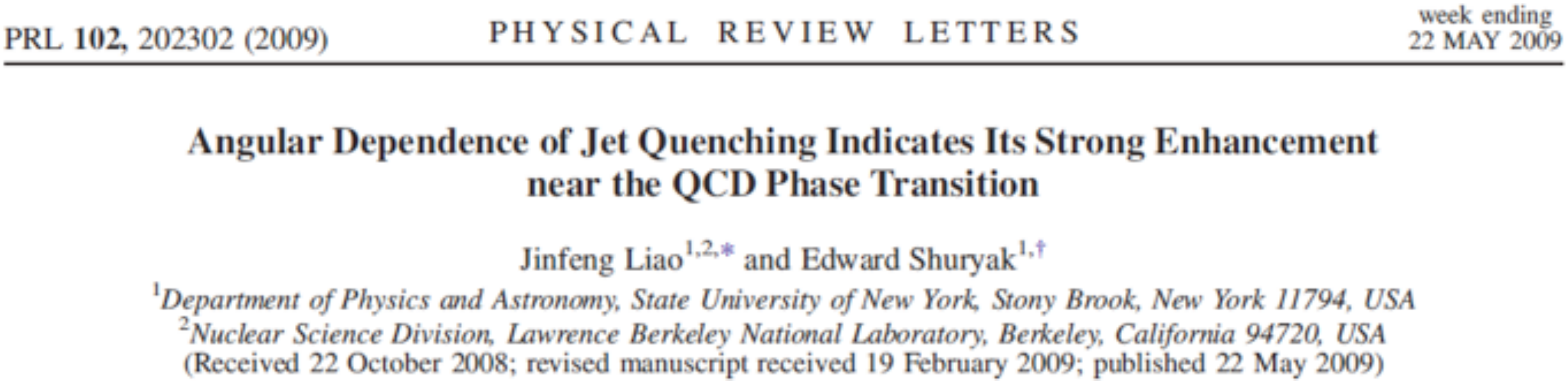


Taken for granted in all previous models: "waterfall" scenario.

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.



PRL **102**, 202302 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

Jinfeng Liao[1,2,*] and Edward Shuryak[1,†]

[1]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

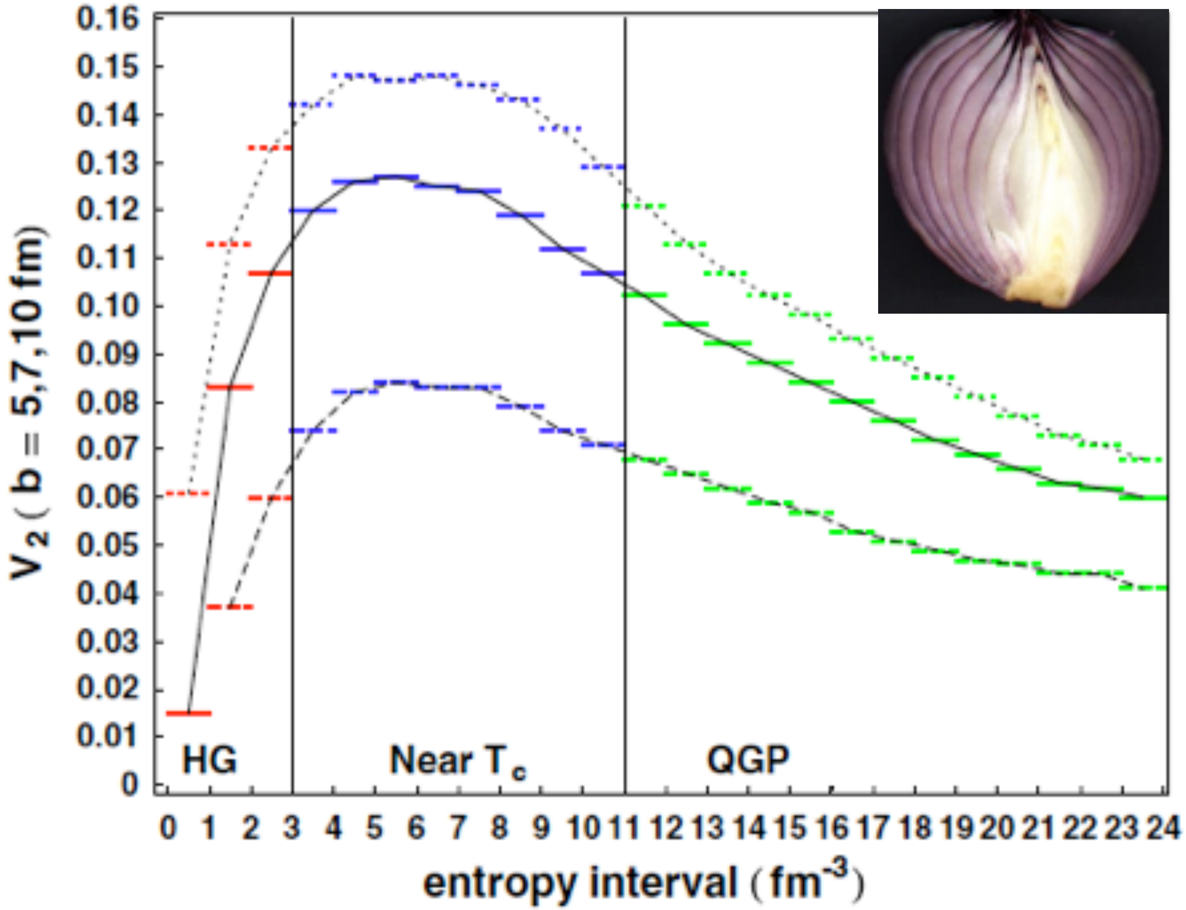
Layer-wise Jet Quenching

$$f_P = exp\left\{-\int_P \kappa[s(l)]\, s(l)\, l^m dl\right\}$$

$$R_{AA}(\phi) = <(f_P)^{n-2}>_{P(\phi)}$$

scan the jet quenching geometry layer by layer in density

$$\boxed{\kappa[s] = \kappa_c * \theta[s - s_a] * \theta[s_b - s]}$$



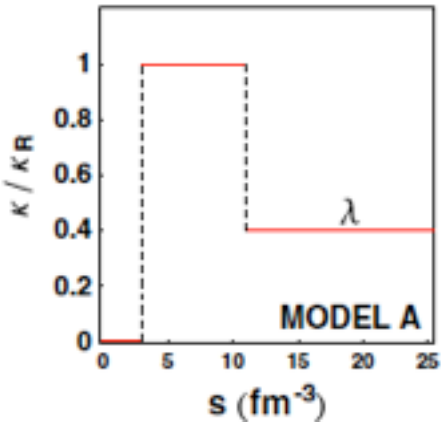
Assume jet quenching occurs only in a specific density interval with constraint from overall Raa

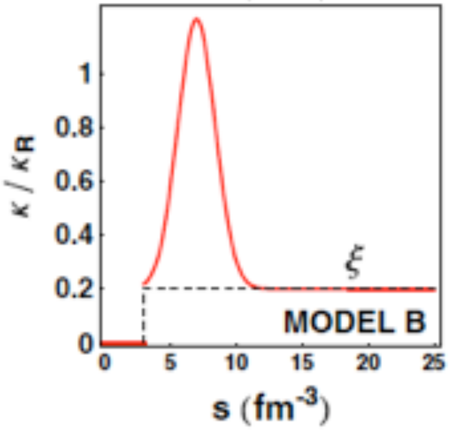
-->

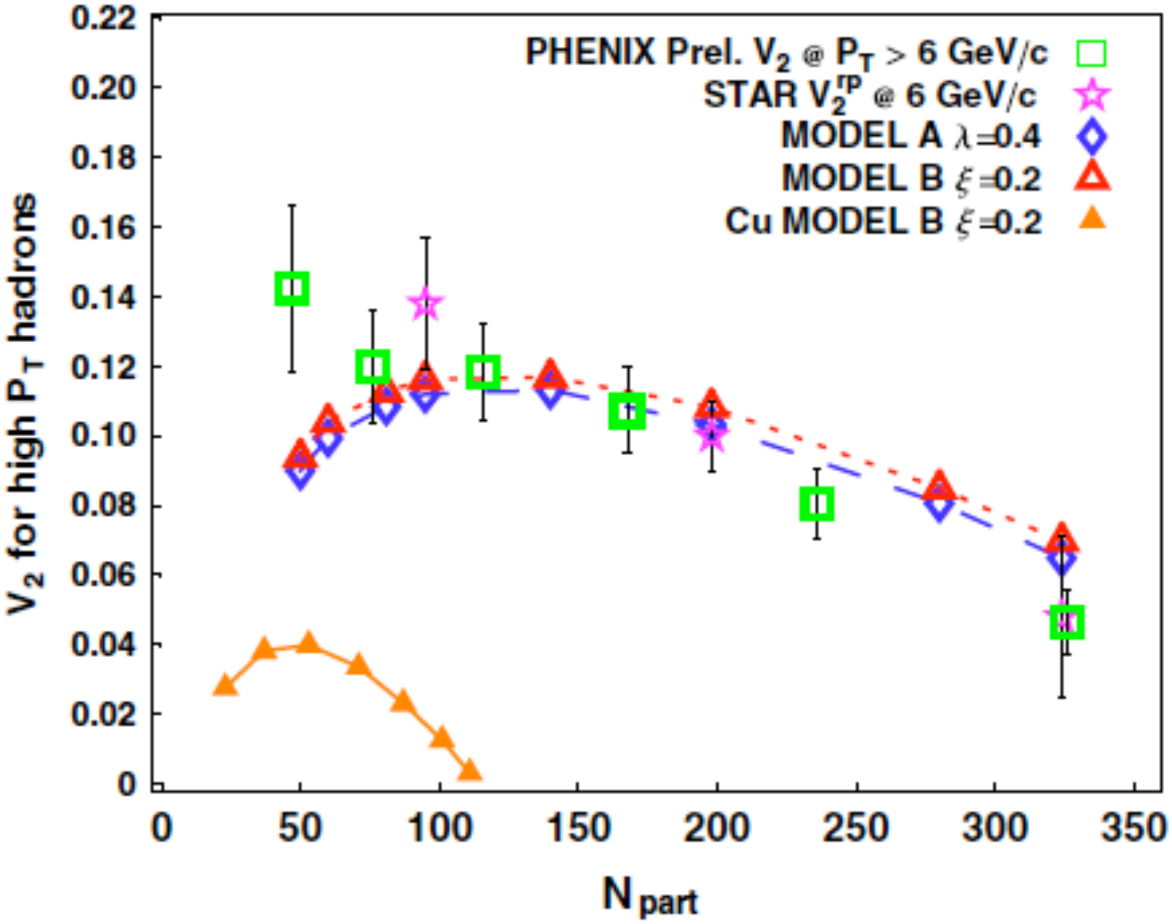
look at v2 from that layer:

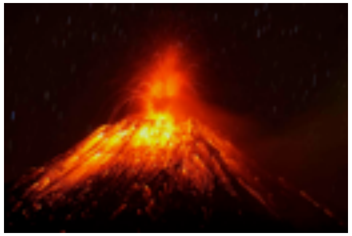
Near-Tc layers give the strongest anisotropy!

Near-Tc Enhancement (NTcE)









In the paper PRL(2009) 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."

NTcE as a Generic Mechanism

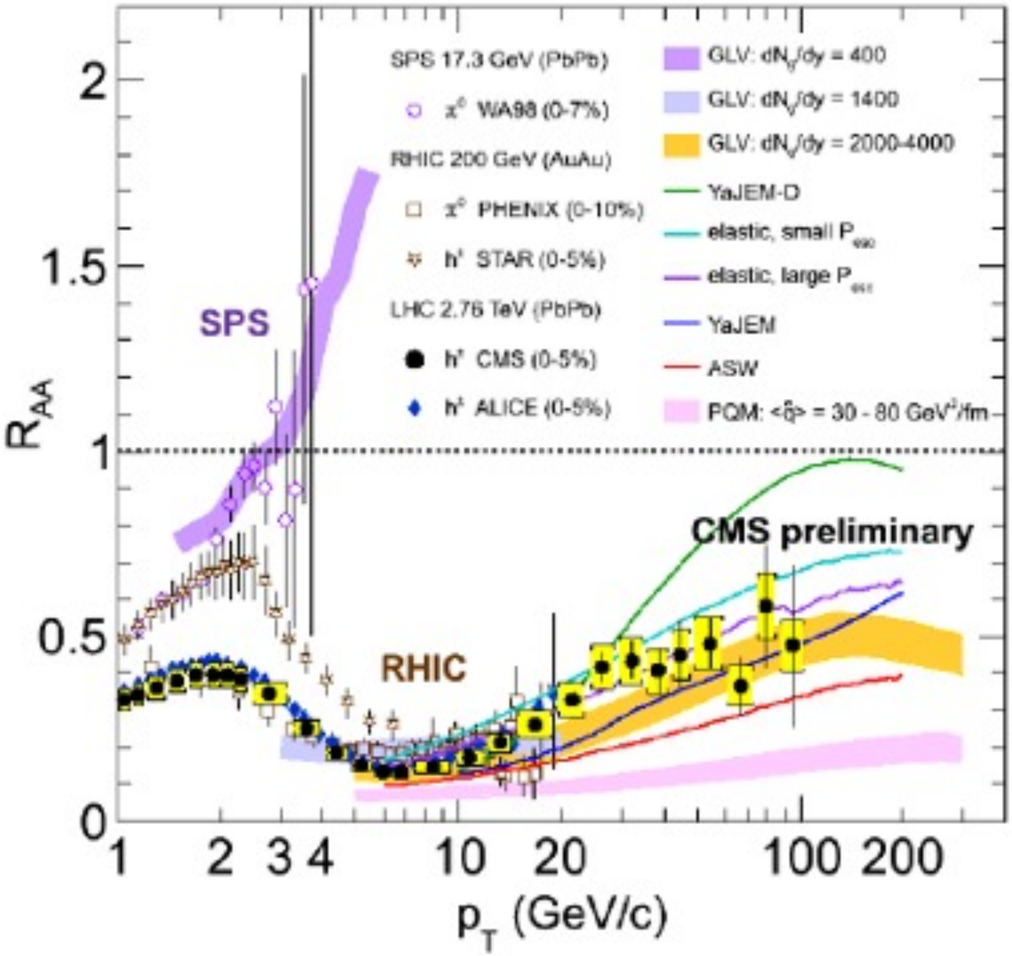
Near Tc Enhancement (the "volcano") generically increases the contribution to jet quenching from later stage and outer layer of the fireball, and gives **more anisotropy.**

* relatively insensitive to detailed shape of "volcano"

* works in jet quenching modelings with varied implementations (e.g. geometric models, or GLV/WHDG/CUJET, or ASW, with/without fluctuations/transverse expansions)

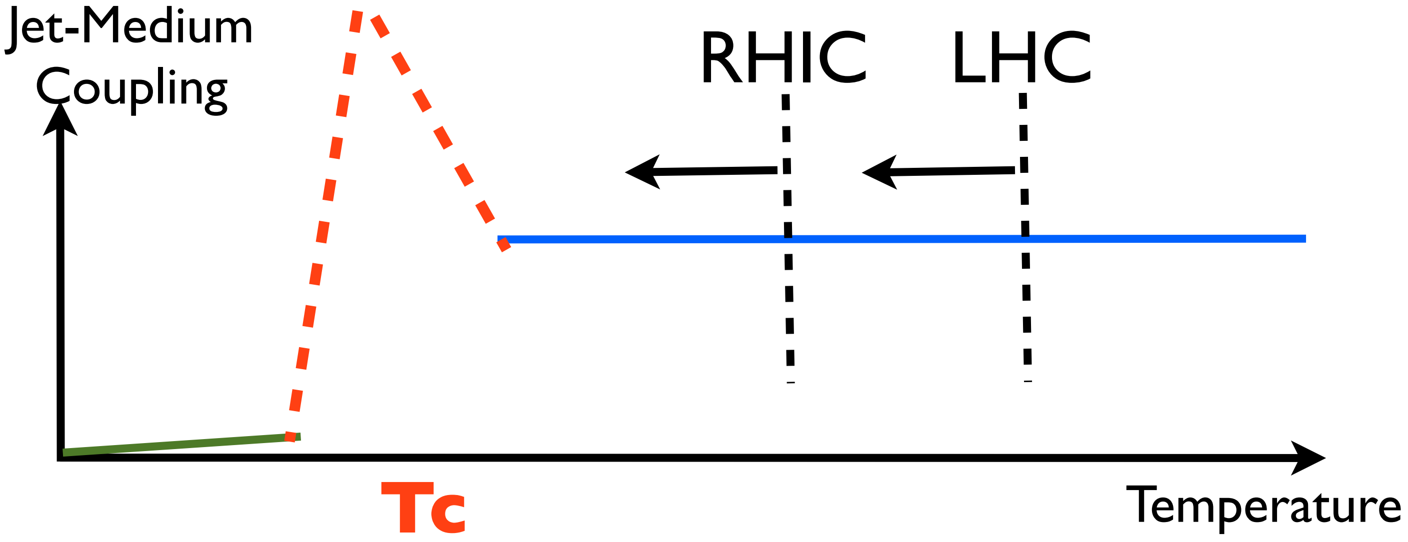
Francesco-Di Toro-Greco
Renk-Holopainen-Heinz-Shen
Gyulassy,Buzzatti,Bezt
Fries & students
Marquet & Renk
Jia & Wei

The RHIC+LHC Era



Beautiful jet quenching measurements from ALICE,ATLAS,CMS

NTcE: Shift to Less Opaque Medium at LHC



LHC compared with RHIC:

* high T QGP occupies more space-time evolution

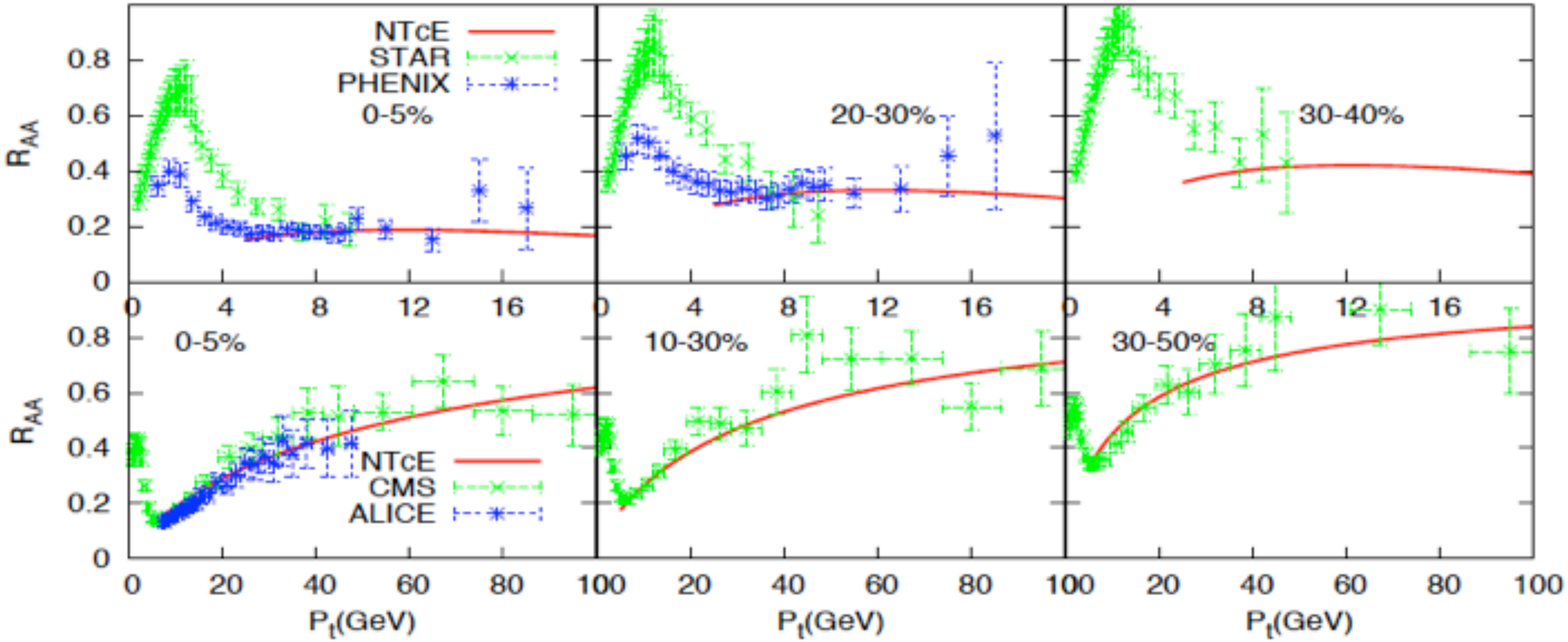
* the near-Tc will weigh less, with "volcano" effect reduced

-->

* Naturally predicts a less opaque (on average) medium seen by jets (note however density doubles)

* Anisotropy from the "volcano" and "waterfall" scenarios will become closer

Raa from RHIC to LHC



Average jet-medium coupling from RHIC to LHC: reduced by ~30% due to strong T-dependence

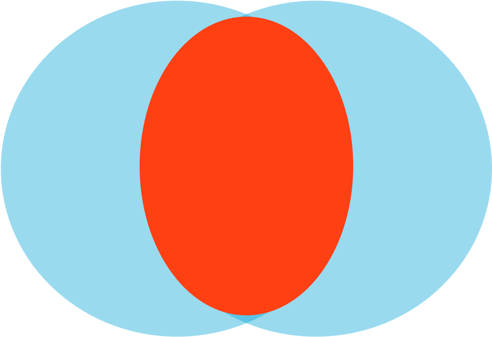
$$< \kappa[s(l)] >_P = \frac{\int_P \kappa[s(l)]\, s(l)\, l\, dl}{\int_P s(l)\, l\, dl}$$

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

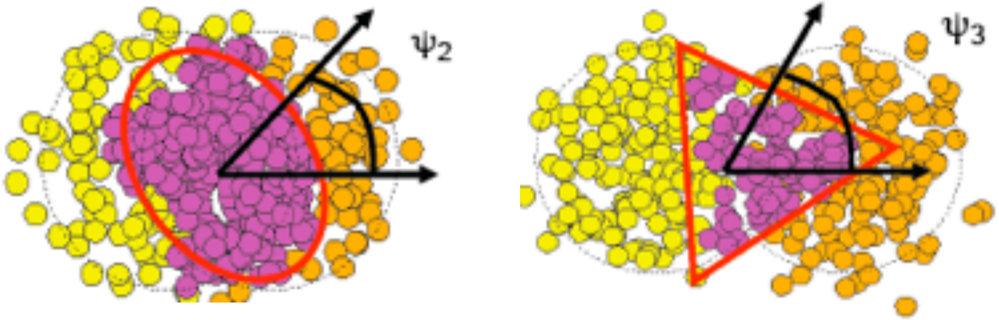
Zhang & JL, arXiv: 1311.5463; 1210.1245

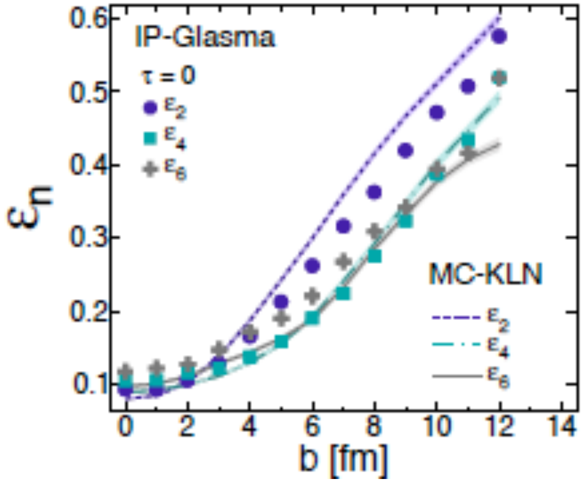
Fluctuating Initial Condition (I.C.)

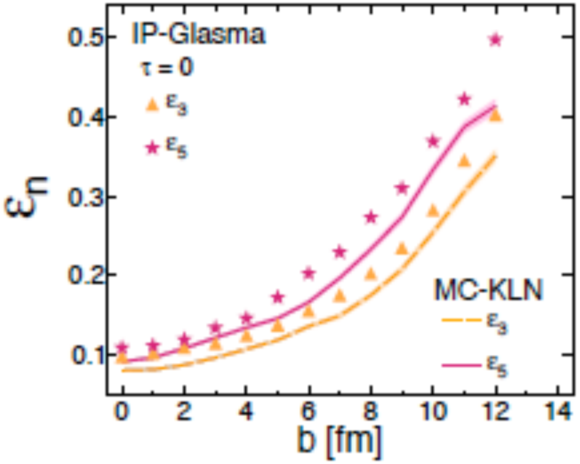
The initial condition used to be like this ...



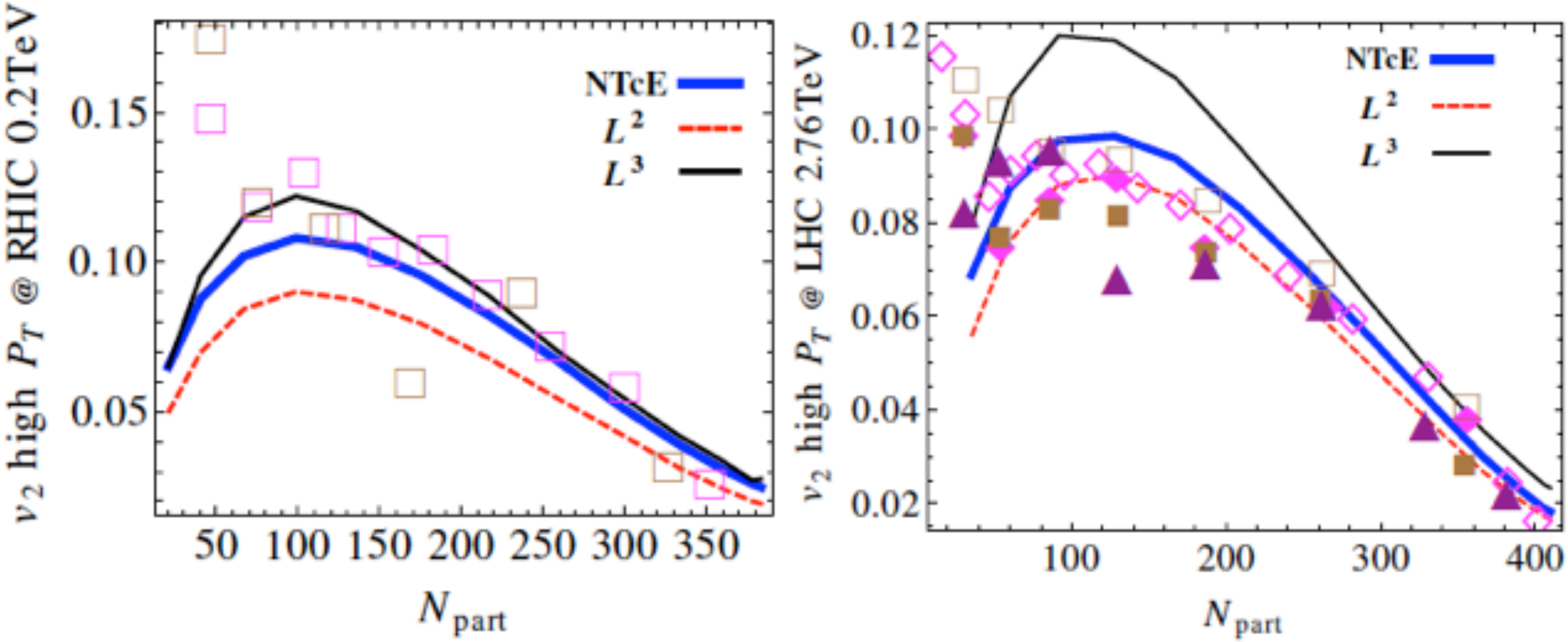
We now know it is actually like this:







V2 from RHIC to LHC



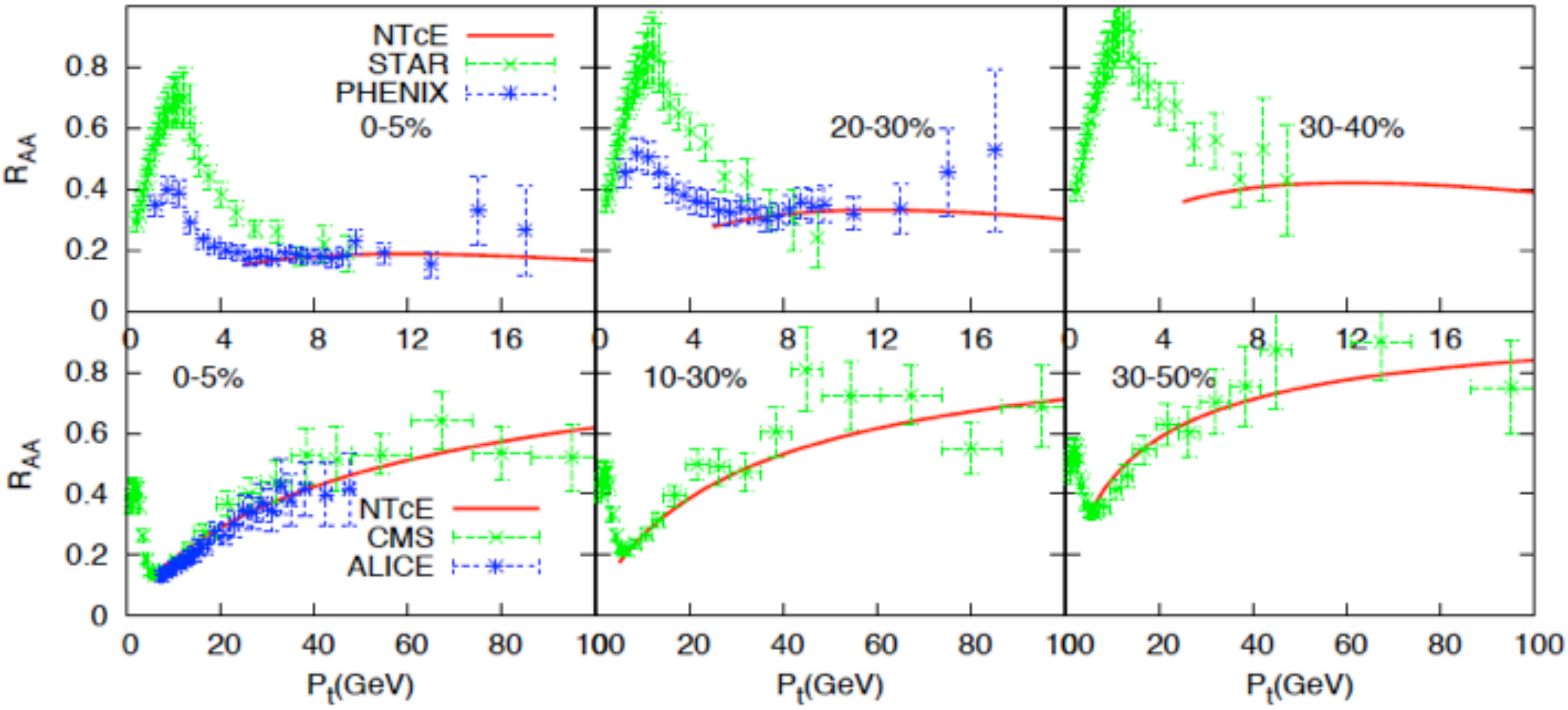
RED: L^2 model+waterfall **BLUE: L^2+volcano** **BLACK: L^3+waterfall**

* 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

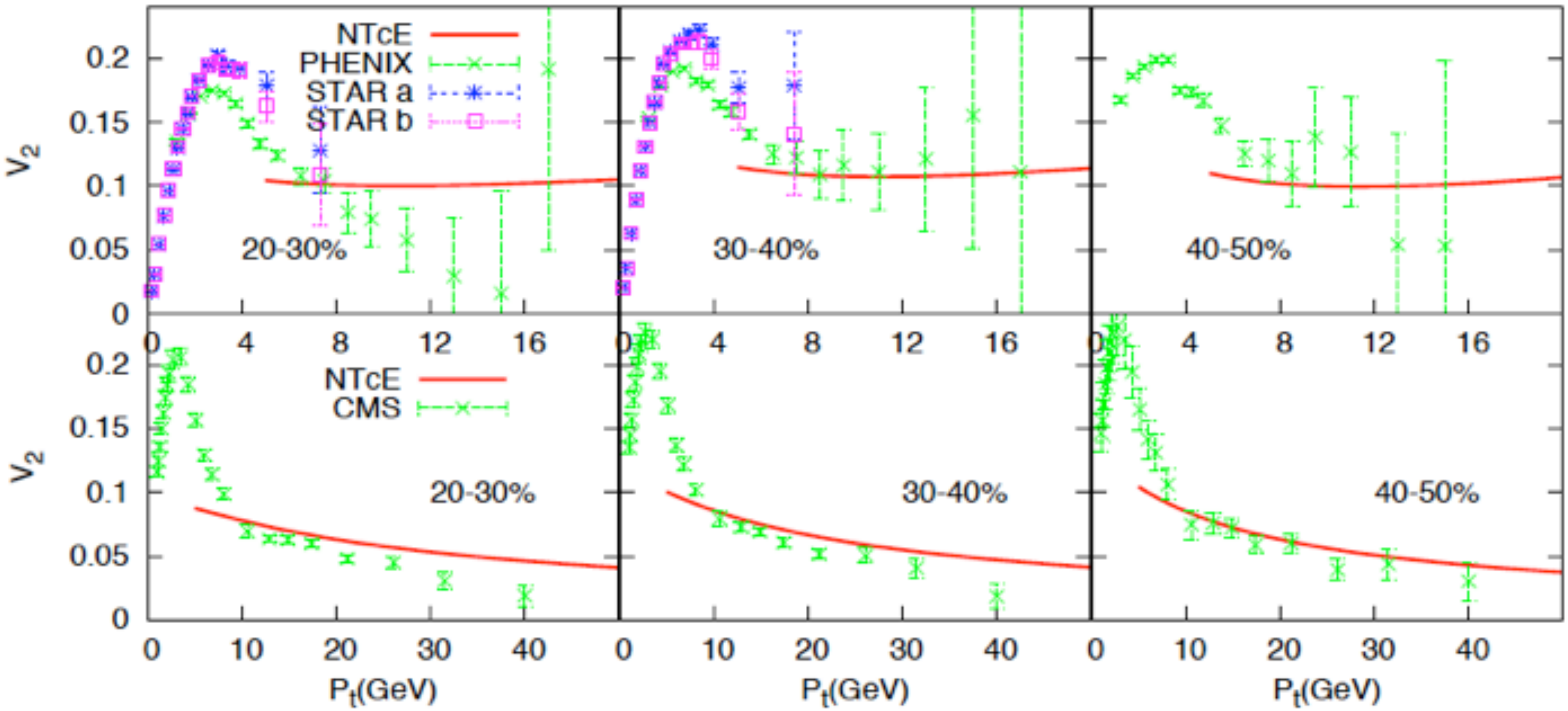
Differential R_aa from RHIC to LHC



$$\boxed{R_{AA}(\phi) = R_{AA}[1 + 2V_2 + \ldots]}$$

Zhang & JL, arXiv: 1311.5463

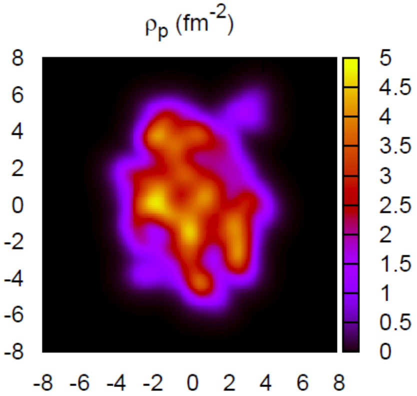
Differential V_2 from RHIC to LHC



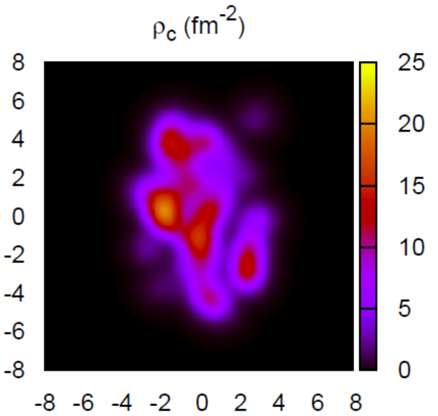
$$\boxed{R_{AA}(\phi) = R_{AA}[1 + 2V_2 + \ldots]}$$

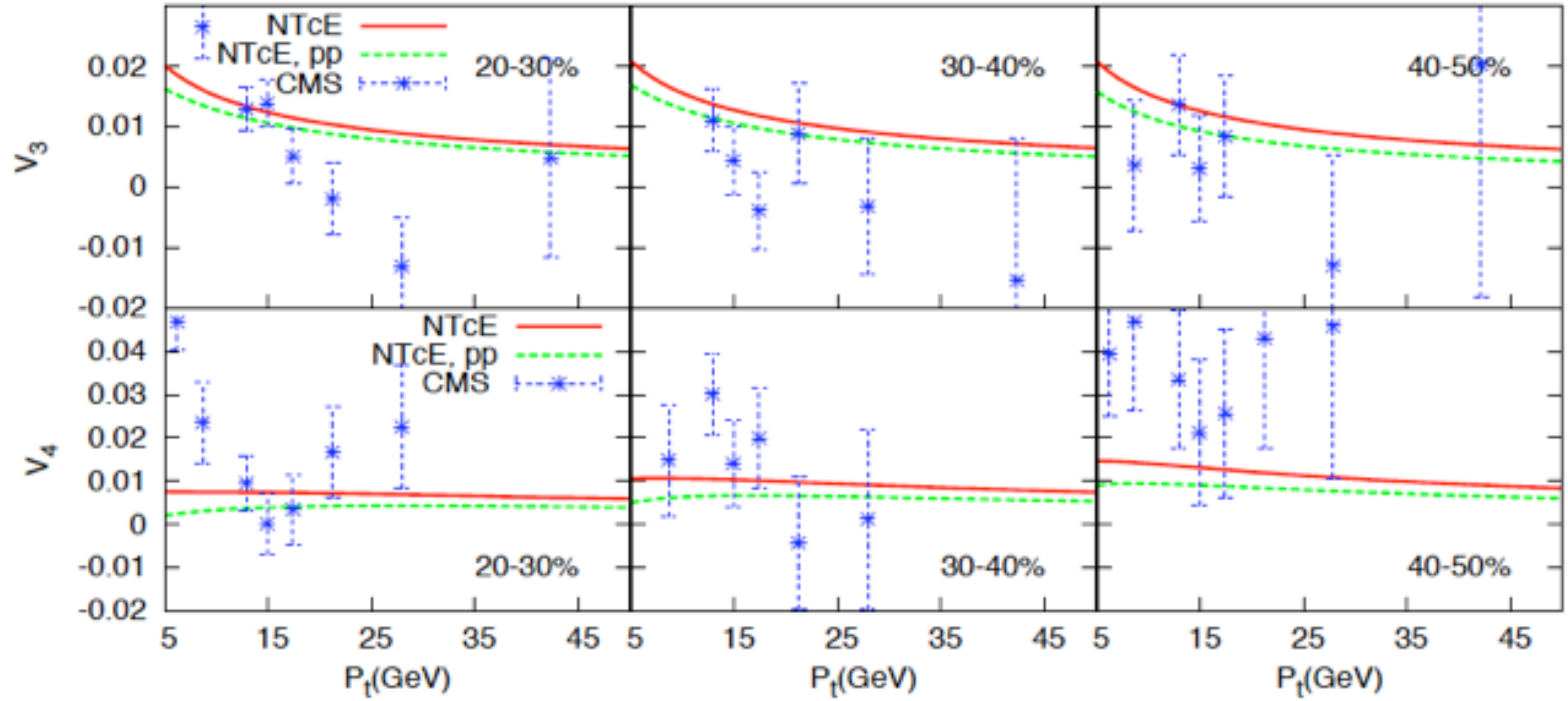
Zhang & JL, arXiv: 1311.5463

Hard Probe of Fluctuating Geometry



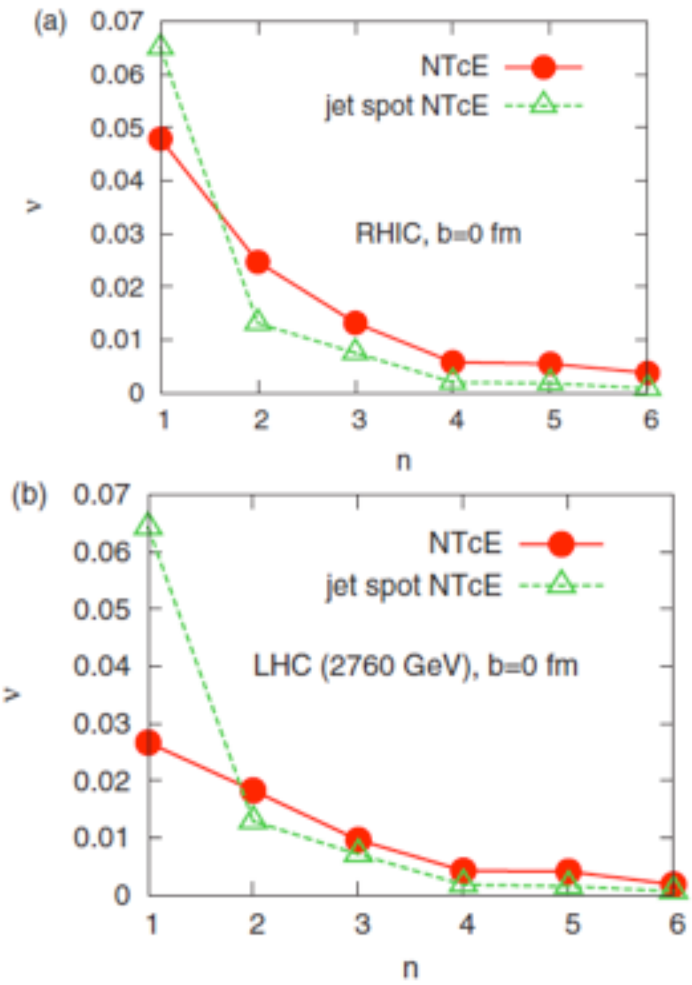
$$R_{AA}(\phi) = R_{AA}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n^J)]\right)$$





X.Zhang & JL, arXiv:1311.5463; 1210.1245; 1202.1047

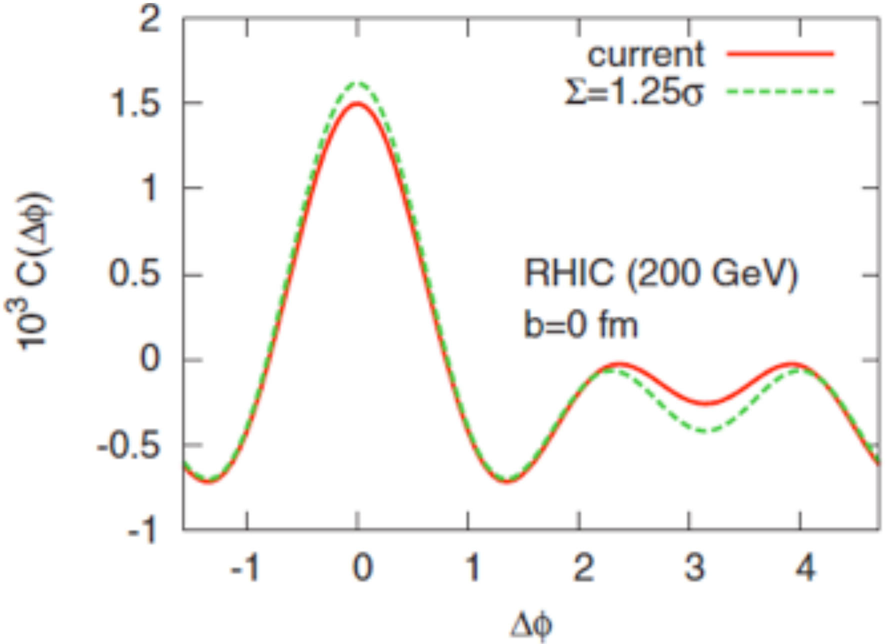
Hard-Soft Di-Hadron Azimuthal Correlations



$$\frac{dN^s}{d\phi^s} \sim 1 + 2\sum_n v_n^s \cos\left[n(\phi^s - \psi_n^S)\right],$$

$$\frac{dN^h}{d\phi^h} \sim 1 + 2\sum_m v_m^h \cos\left[m(\phi^h - \psi_m^J)\right].$$

$$C(\Delta\phi) \equiv 2 \times \left[\sum_n V_{n\Delta}\cos(n\Delta\phi)\right]$$

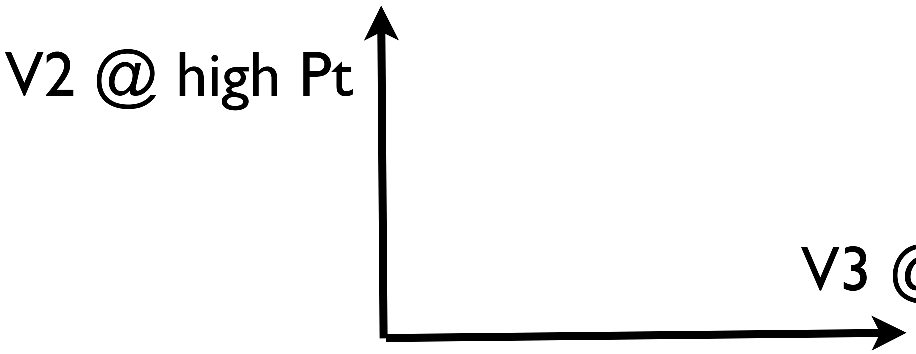


Both hard and soft sectors "see" and respond to the common fluctuating geometry --> correlations!

X.Zhang & JL, arXiv:1210.1245; 1202.1047

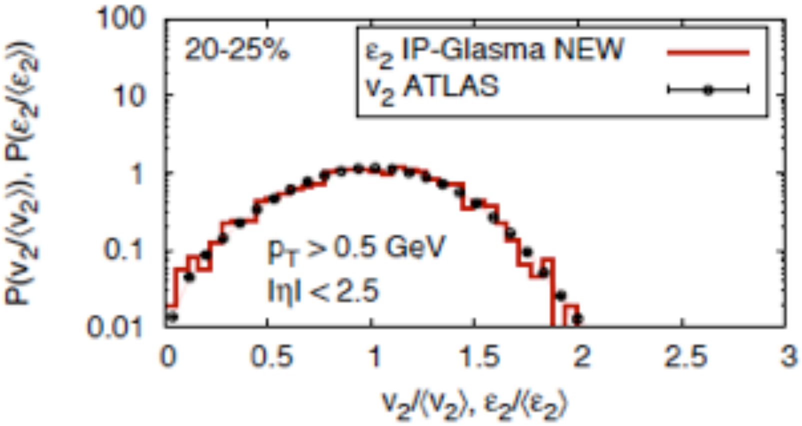
Possible Future Measurements

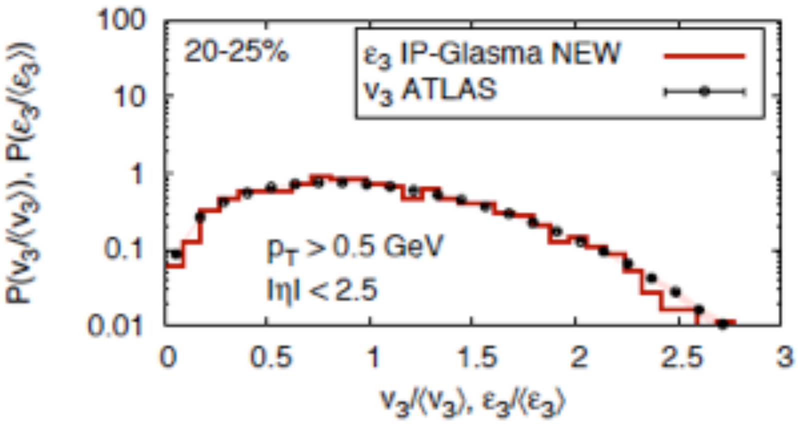
** Correlations between V2 and V3*


V2 @ high Pt

V3 @ high Pt

** Measure high Pt anisotropy with Event-Shape-Engineering*





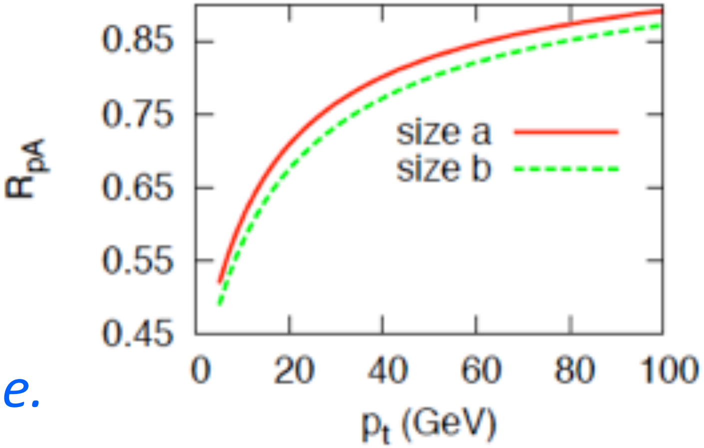
Together these can provide stringent test of jet energy loss models as well as I.C. models.

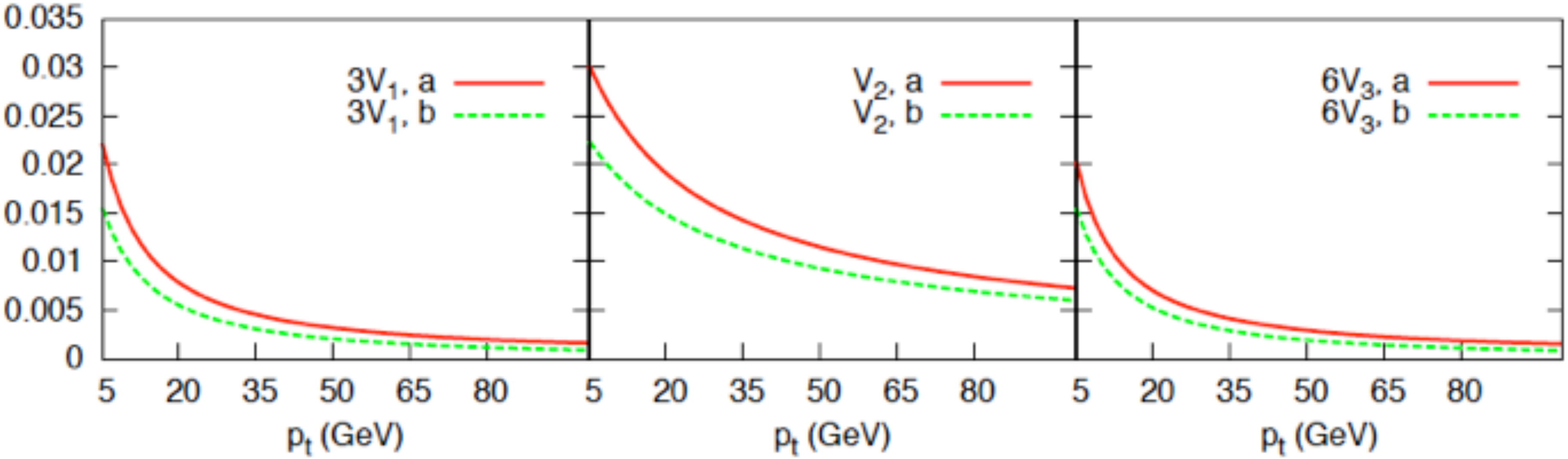
Final State Attenuation in the Mini-Bang?

High multiplicity pPb collisions at LHC (and dAu at RHIC) have generated significant interests recently:

Are they "Mini-Bangs" creating matter with significant final state interactions?

Possible jet attenuation is an independent probe.



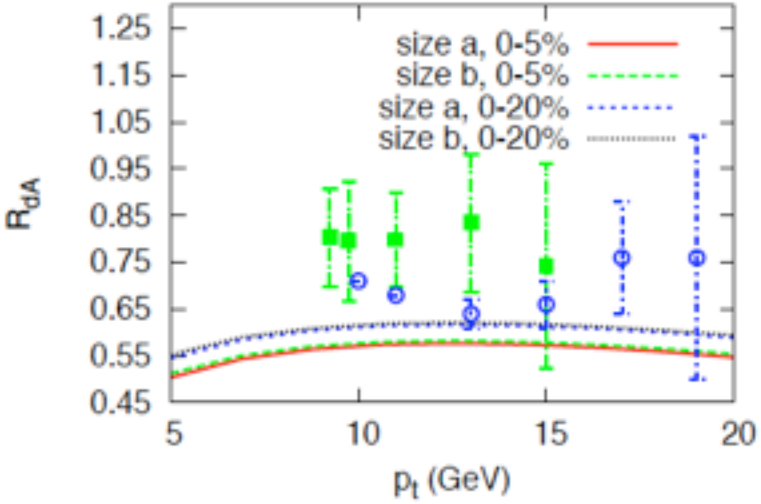


R_pA itself could be rather tricky!

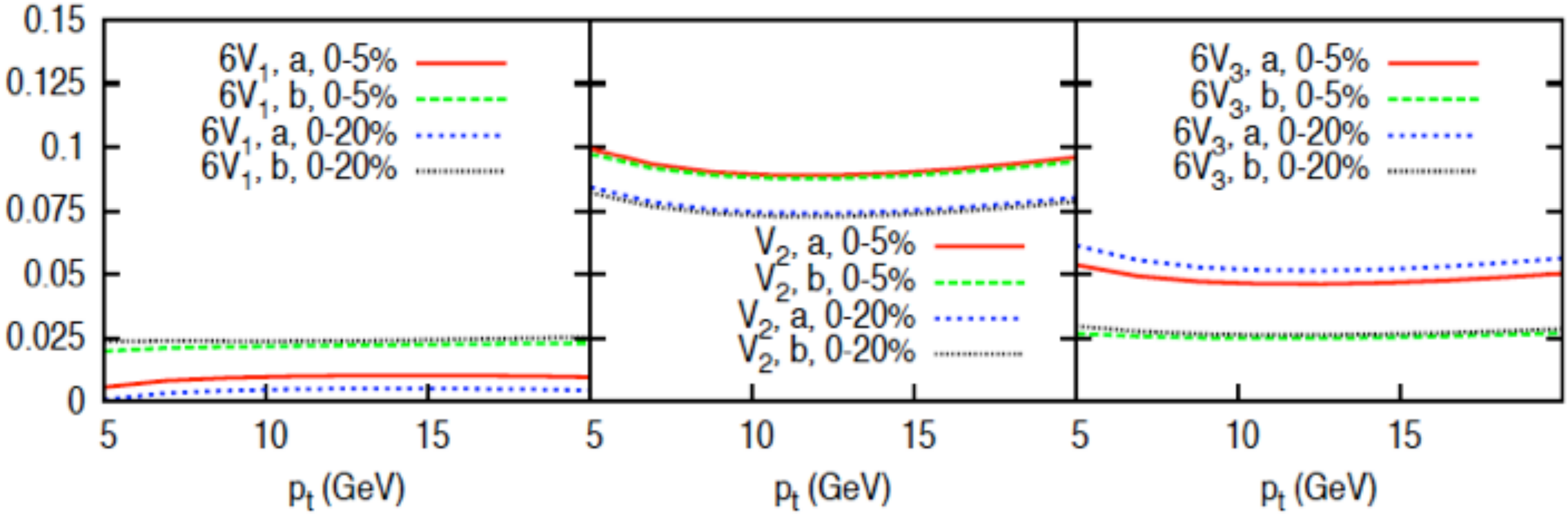
High p_t anisotropy, particularly v_2 could be a golden signal!

X.Zhang & JL, arXiv:13 11.5463

“Mini-Bangs”: High Multi. dAu at RHIC

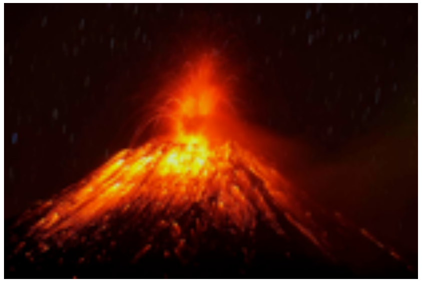


High p_t anisotropy, particularly v_2 ~ 10%
--> could be a golden signal to tell YES or NO

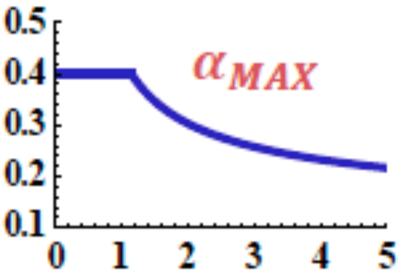


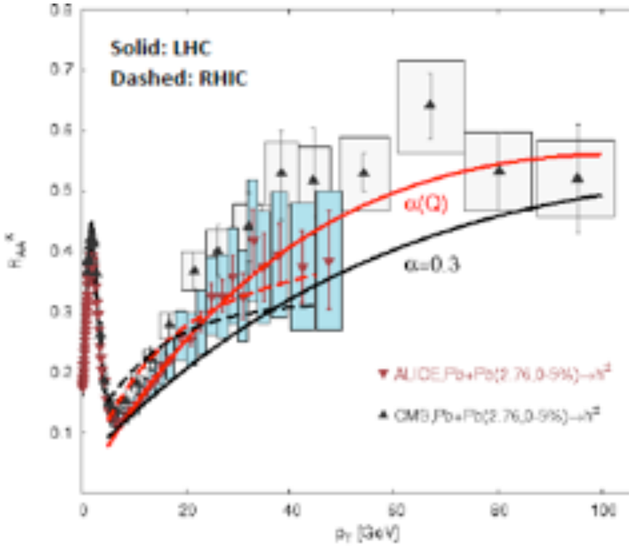
X.Zhang & JL, arXiv:13 11.5463

“Volcano” Seen from “Different Angles”



- * Horowitz & Gyulassy:
  “surprising transparency” when simply extrapolating RHIC to LHC
- * Betz & Gyulassy:
  10~30% reduction in “polytrope” model
- * Buzzatti & Gyulassy:
  Strong running coupling at T --> Tc
  (also in Zakharov calculation)

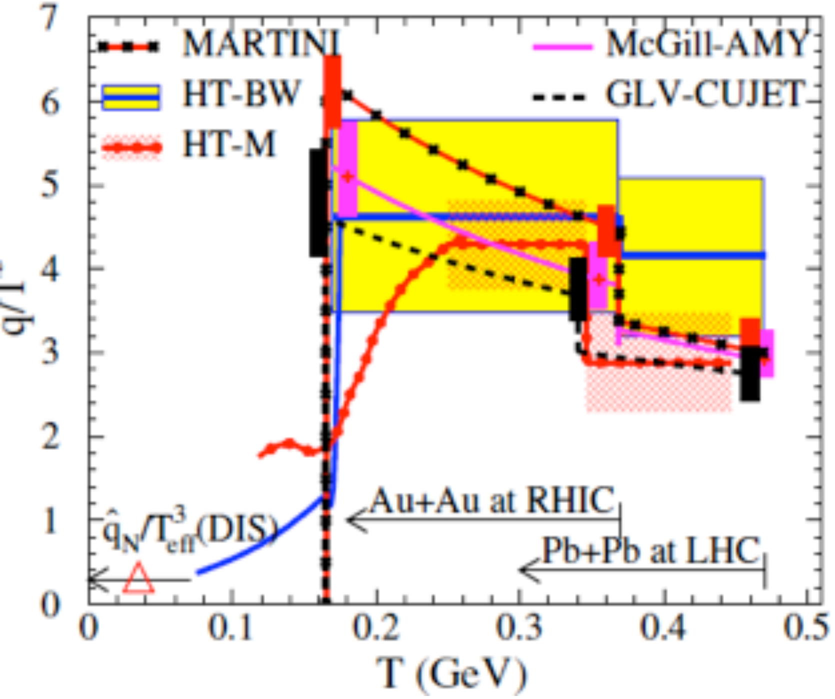


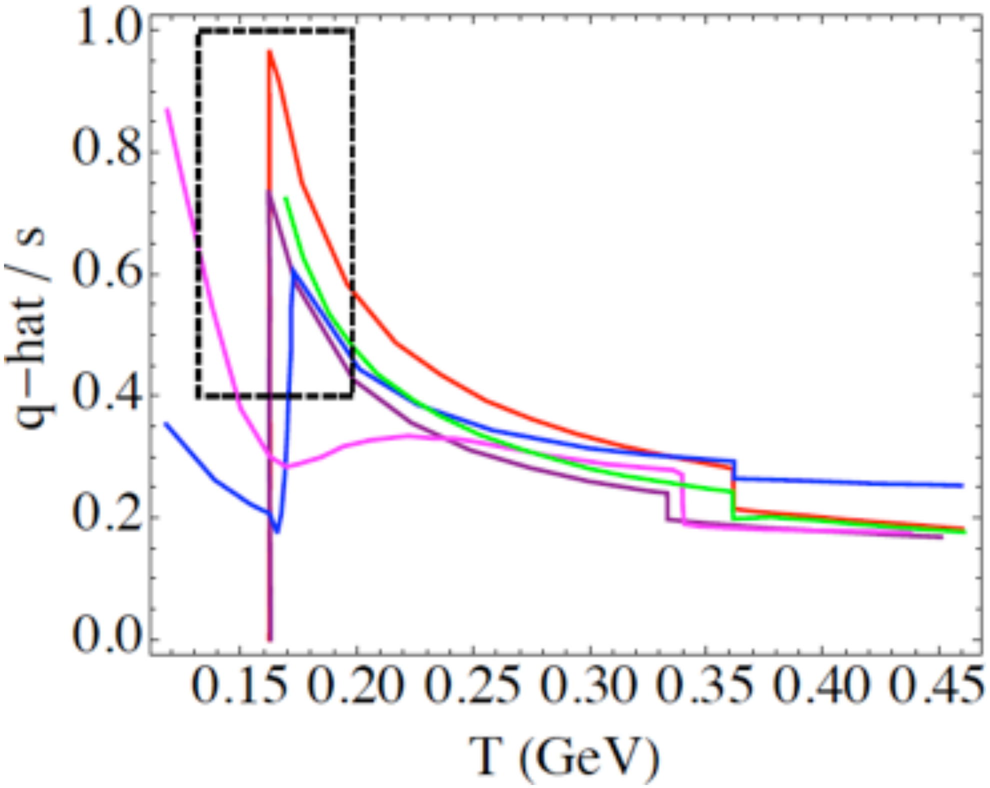


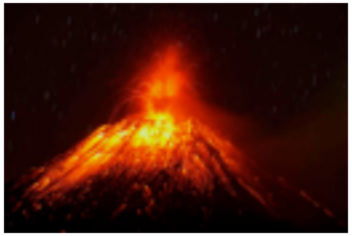
- * Lacey et al, scaling analysis: q-hat(LHC) ~ q-hat(RHIC) despite twice the density
- * Lattice QCD: Q-bar-Q internal energy shows strong peak at Tc
- * Majumder-Muller-Wang, Dusling-Moore-Teaney:
  peak in q-hat/density related with dip in \eta/s ?
- * Majumder: lattice attempt -->q-hat/density showing peak?

Latest Analysis from JET Collaboration

JET Collaboration, arXiv: 1312.5003







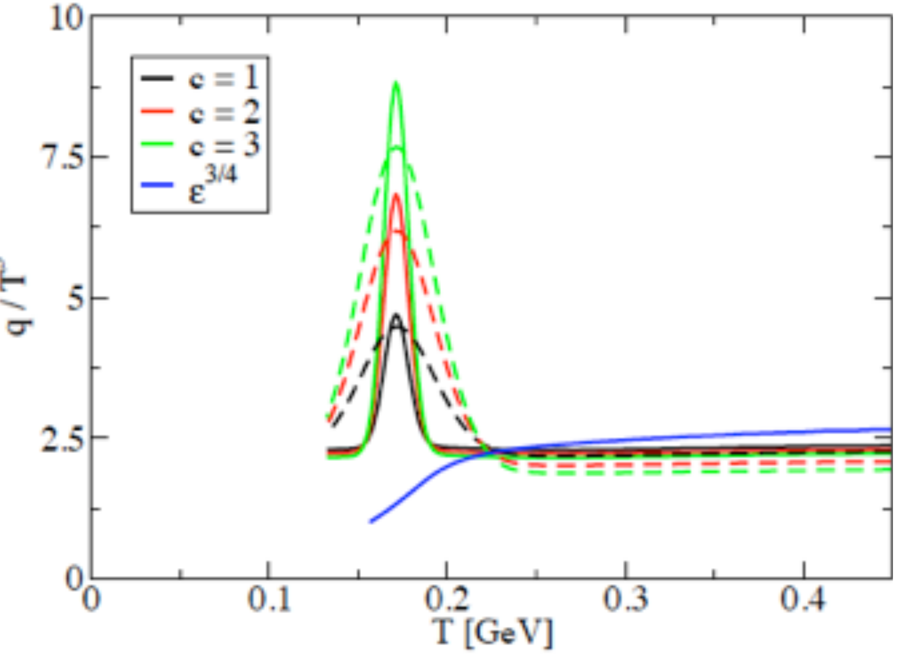
In the paper PRL(2009) we concluded:

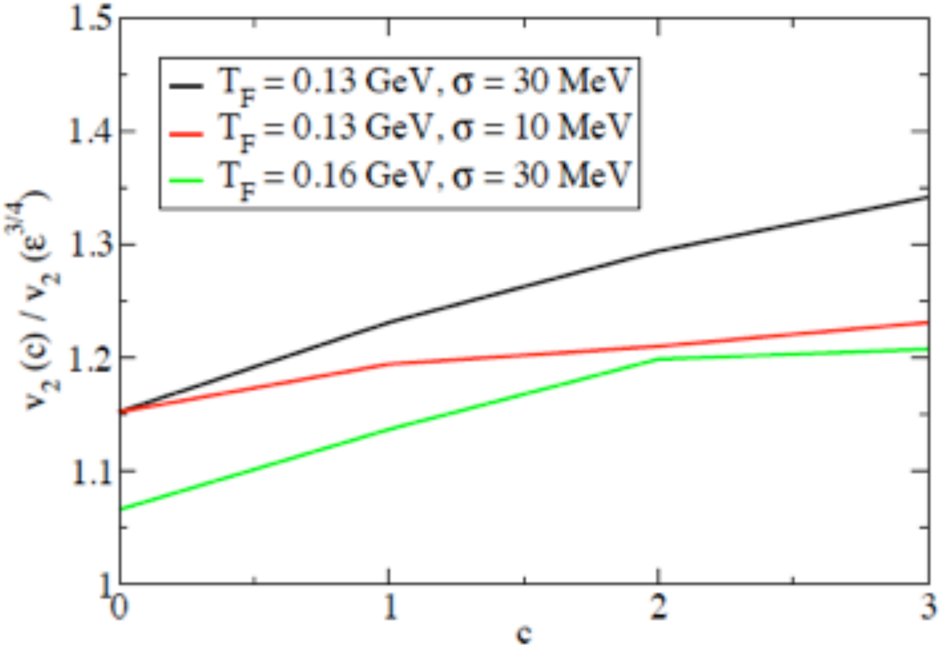
"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

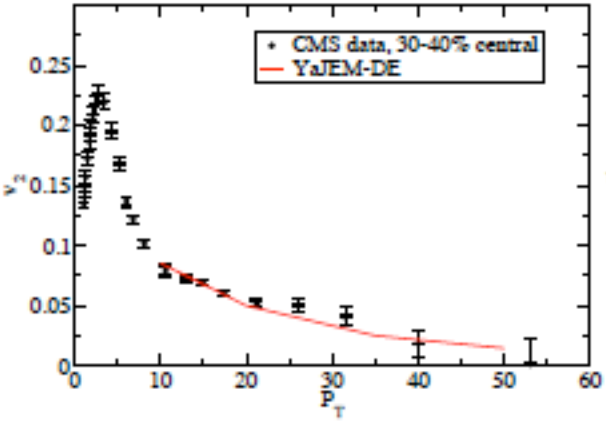
Latest Results from State-of-Art Simulations

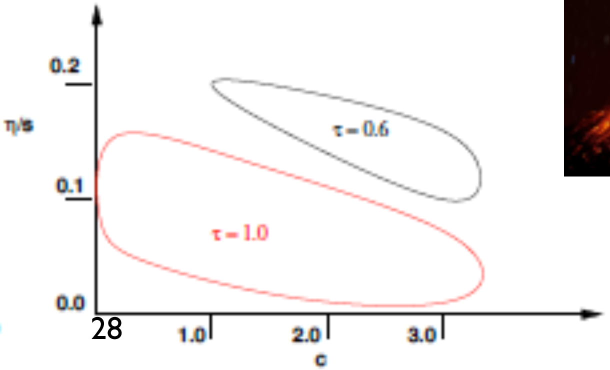
Renk, 1402.5798 & QM14

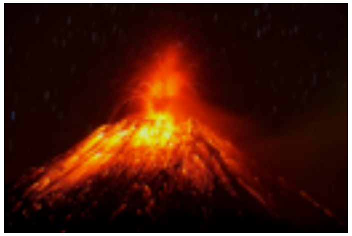
model	ASW	YDE 3d	YDE 2d
$NTC/\epsilon^{3/4}$	1.17	1.22	1.20



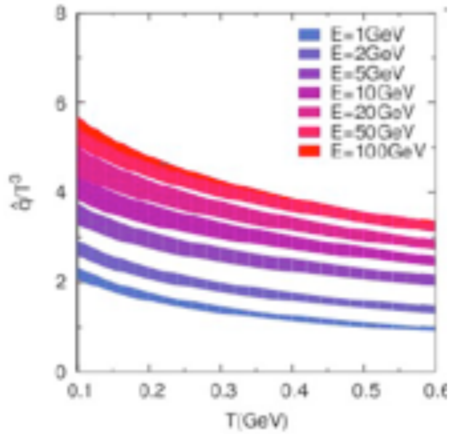


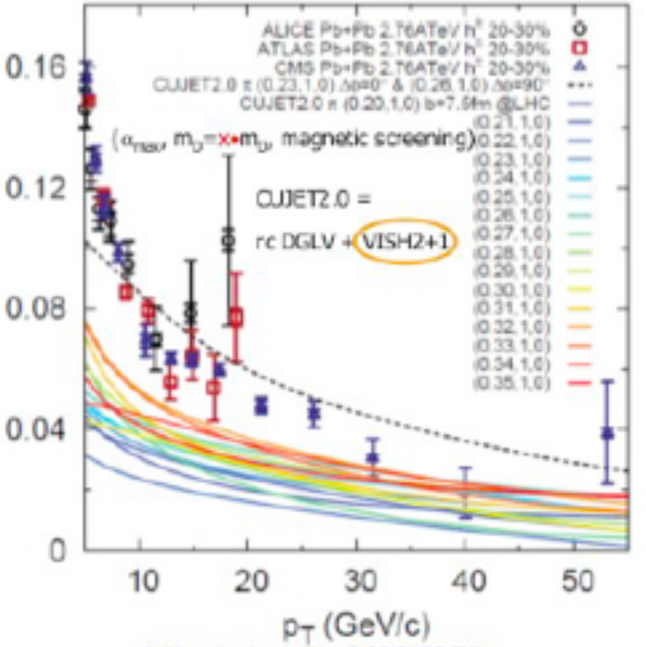




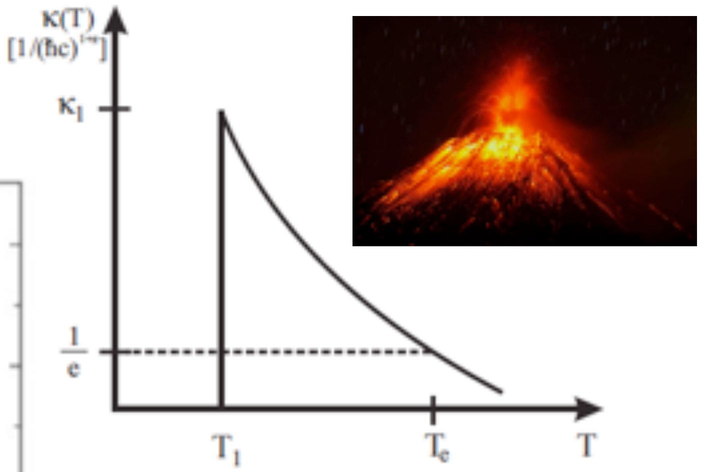


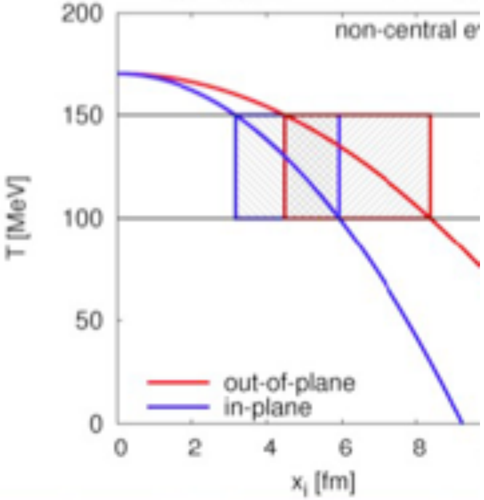
Latest Analysis from CUJET & Models

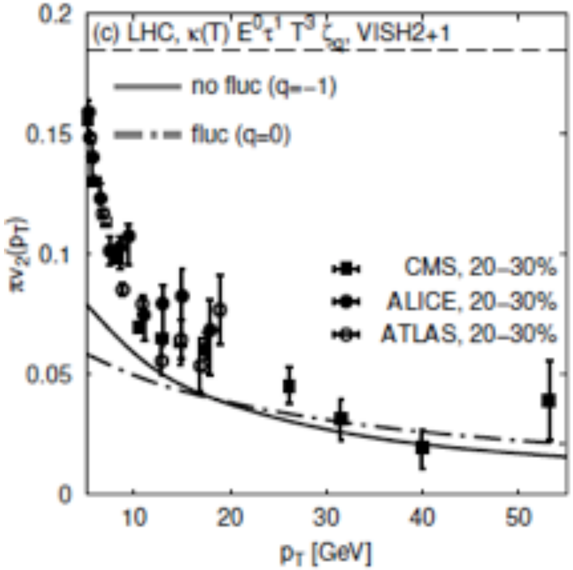




J. Xu et al., arXiv:1402.2956







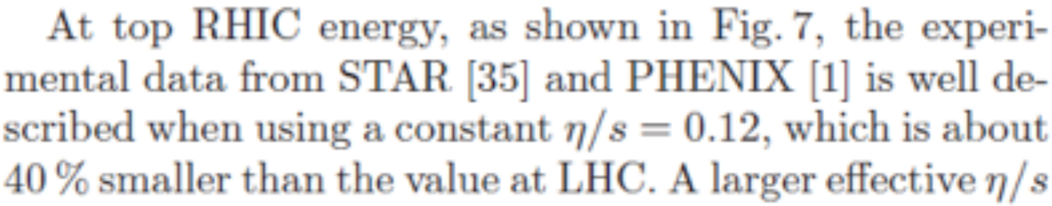
effectively:
kappa_out > kappa_in

Xu, Buzzatti, Gylassy, 1402.2956;
Betz, Gylassy, 1404.6378

Near-Tc Matter is Special!

* Harmonic flows from RHIC to LHC:

hydro simulations suggest a clear increase of ~40% in eta/s



At top RHIC energy, as shown in Fig. 7, the experimental data from STAR [35] and PHENIX [1] is well described when using a constant $\eta/s = 0.12$, which is about 40 % smaller than the value at LHC. A larger effective η/s

Gale,Jeon,Schenke,Tribedy,Venugopalan
arXiv:1209.6330

Also earlier analysis by Frankfurt group and OSU group

* Raa + Geometry + Evolution from RHIC to LHC:

strong evidences for Near-Nc Enhancement

--> predicts a less opaque medium at LHC!

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

X.Zhang & JL, PLB(2012), arXiv:1208.6361,1210.1245(PRC2013)

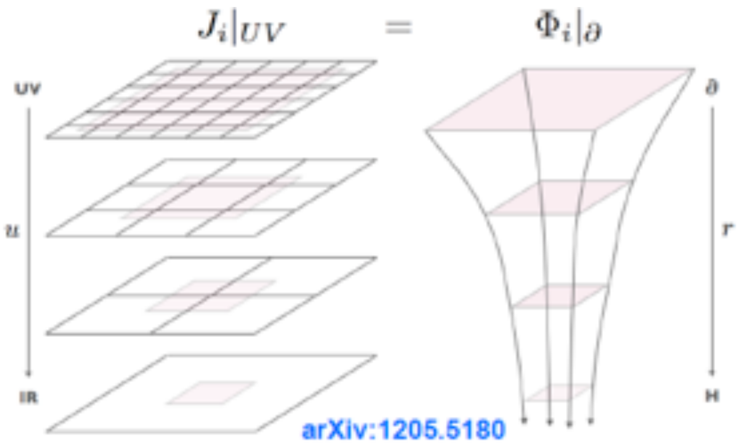
Consistent messages from independent analysis by

Horowitz&Gyulassy; Betz & Gyulassy; Lacey, et al; B. Zakharov

RHIC+LHC: E-M "See-Saw" Scenario at work

---> anticipating critical test at LHC top energy!

Going to One More Dimension

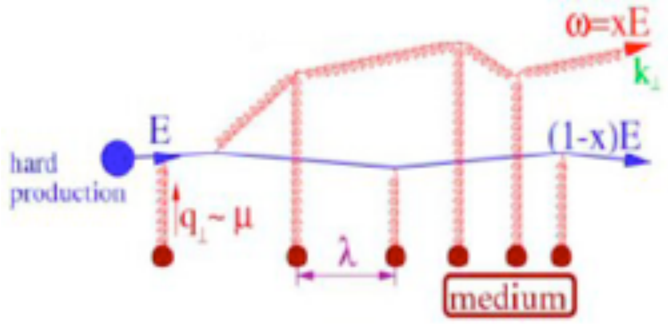


Deforming the conformal-AdS to
introduce non-conformal dynamics:
using graviton-dilaton system in the bulk

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

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

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

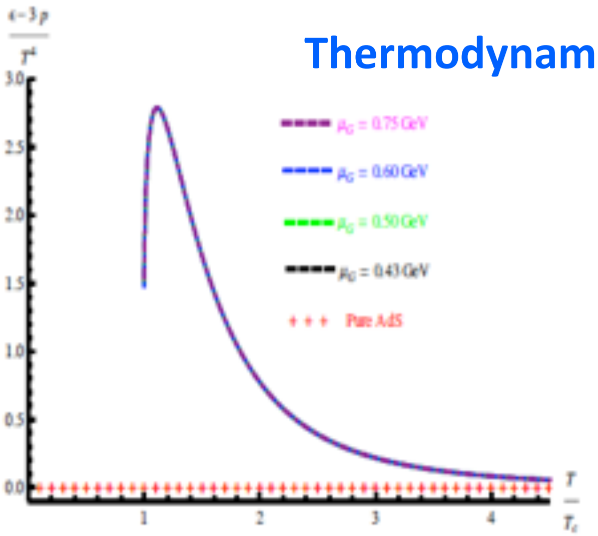


We use the Liu-Rajagopal-Wiedemann scheme
to compute q-hat

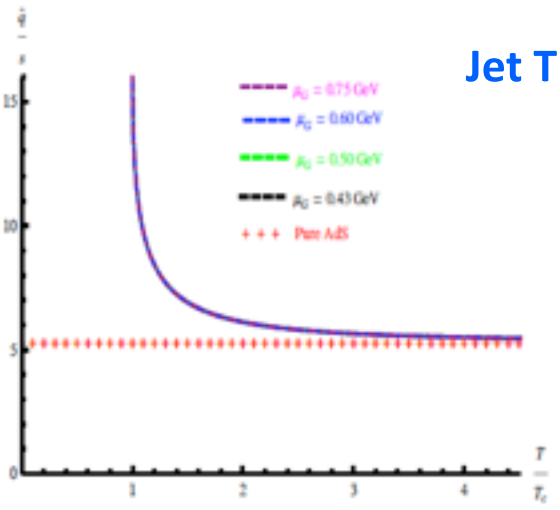
$$\hat{q} = \frac{\sqrt{2}\sqrt{\lambda}}{\pi\int_0^{z_h} dz\sqrt{g_{zz}/(g_{22}^2 g_{--})}},$$

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

Results from Non-Conformal Holo-QCD

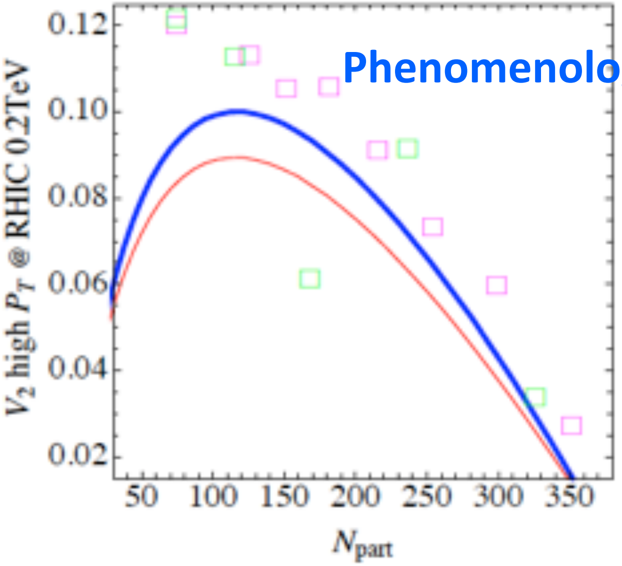


Thermodynamics



Jet Transport

Same non-conformal, non-monotonic, non-perturbative dynamics --> shows up in trace anomaly and in jet transport parameter --> considerably increases jet anisotropy toward data as compared with conformal case



Phenomenology

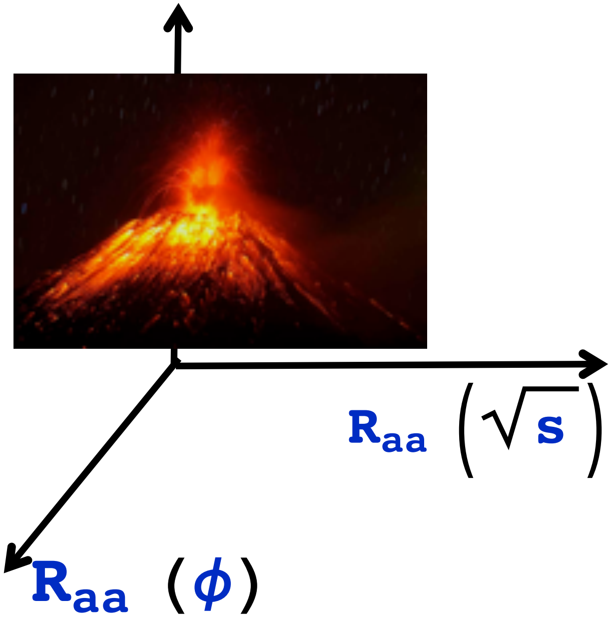
D. Li, JL, M. Huang, arXiv:1401.2035

Summary

- * An exciting problem: determine and understand the temperature dependence of jet-medium coupling

- * Geometry + Evolution from RHIC to LHC: strong evidences for Near-Nc Enhancement

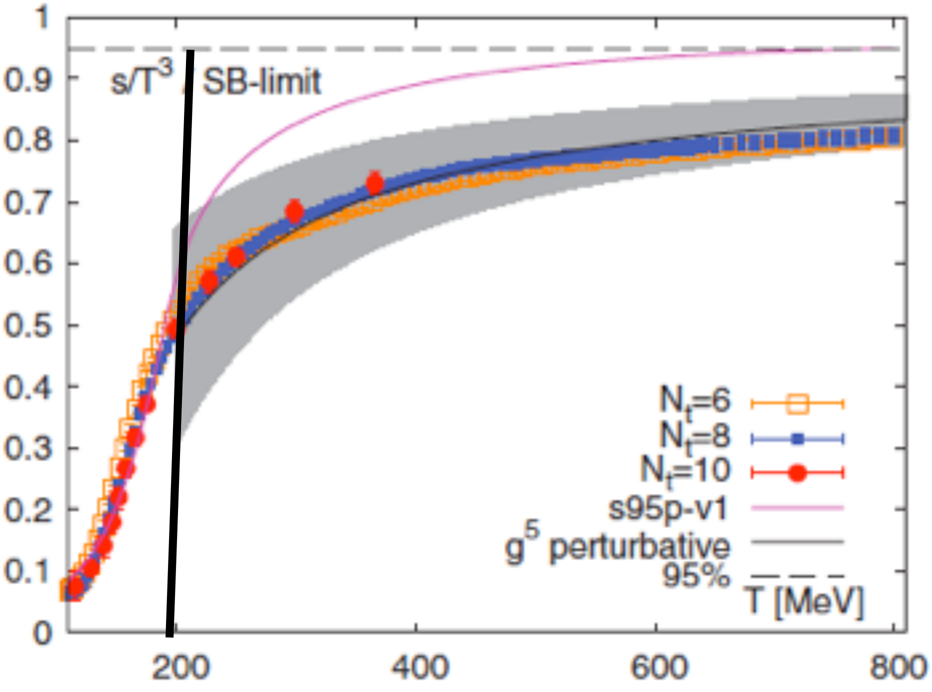
- * RHIC + LHC together provide unique opportunities for mapping out the detailed shape of the "volcano" and for probing the transition zone between the confined world and the asymptotically free matter.



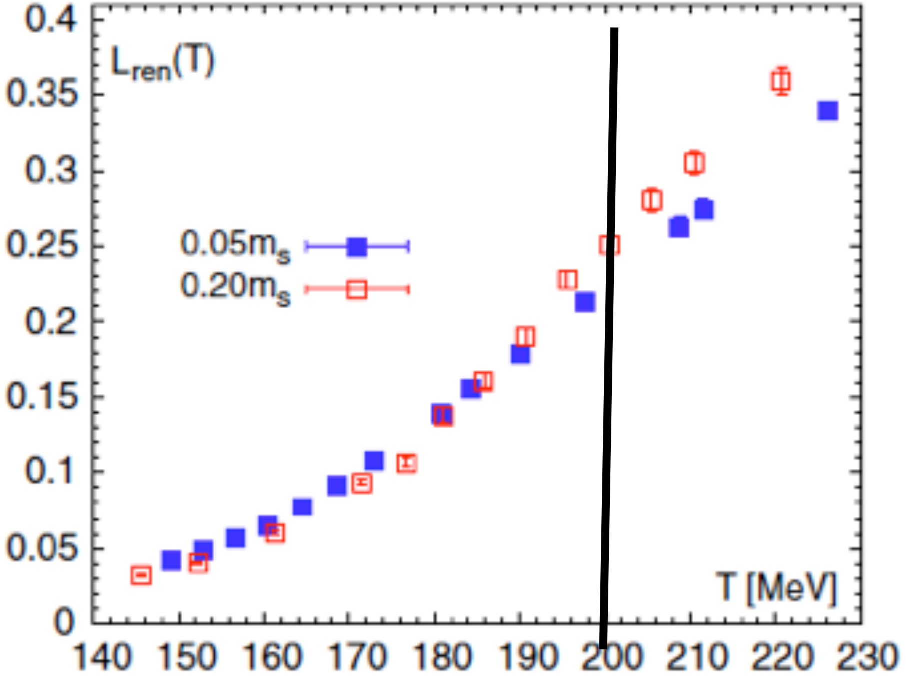
BACKUP SLIDES

Liberation of Color?

Degrees of freedom



Degree of color liberation



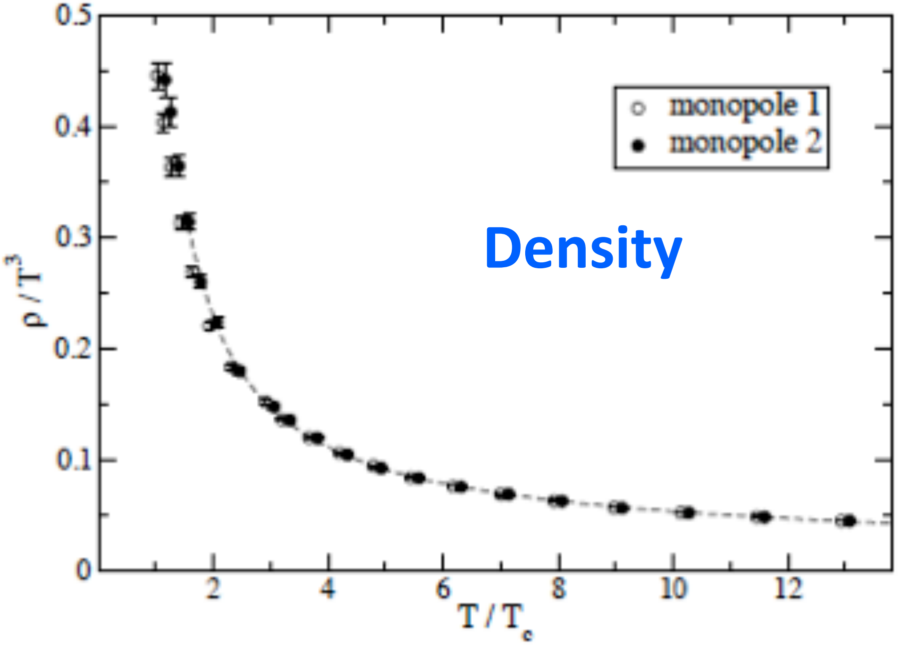
A region around Tc with liberated degrees of freedom but only partially liberated color-electric objects.

(Pisarski & collaborators: semi-QGP --- see Skokov's talk)

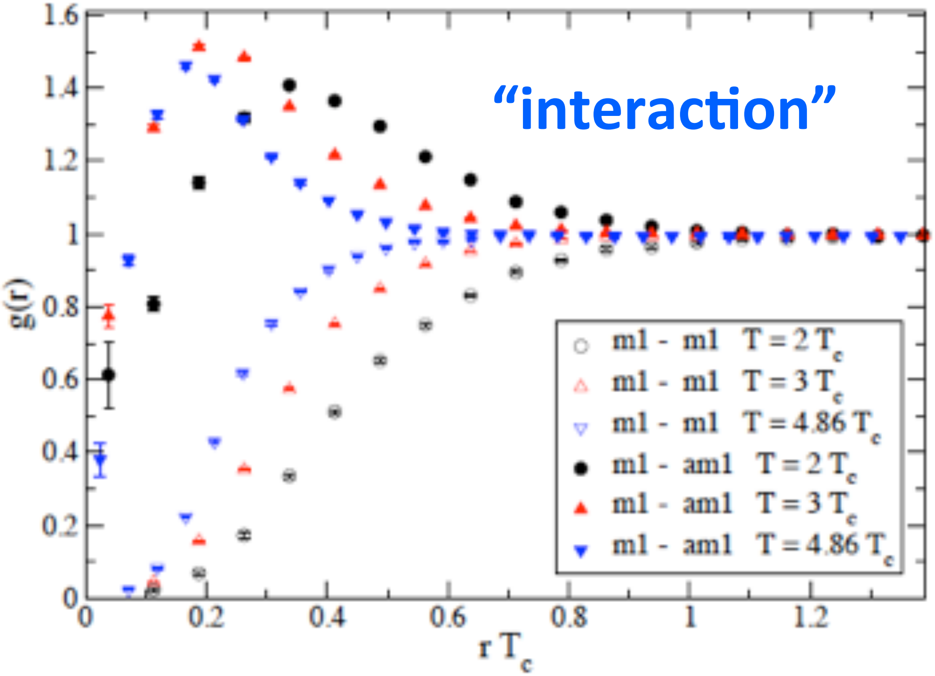
Then what are the "extra" dominant DoF here???

Let's come to this later, for the moment: sth. special Near Tc, not yet the AFM

MOST RECENT LATTICE EVIDENCE



Density



“interaction”

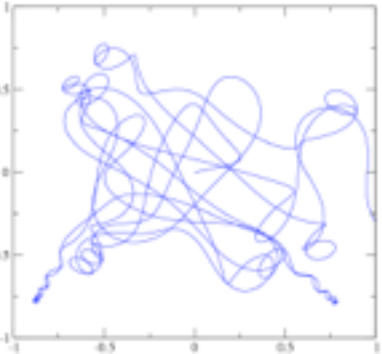
for SU(3) pure gauge theory

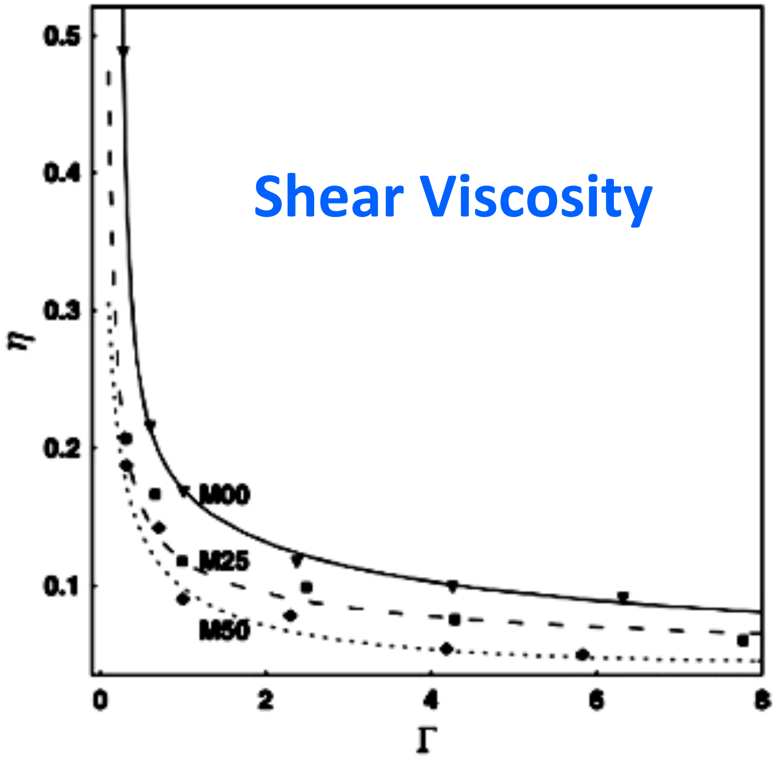
Bonati & D’Elia, arXiv:1308.0302[hep-lat]

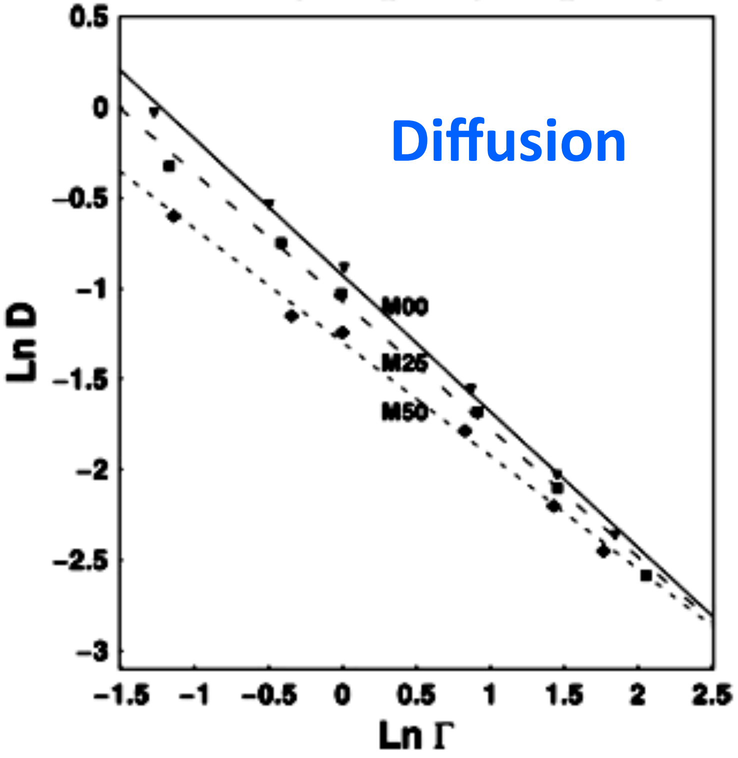
LOW SHEAR VISCOSITY OF E-M PLASMA

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




Shear Viscosity


Diffusion

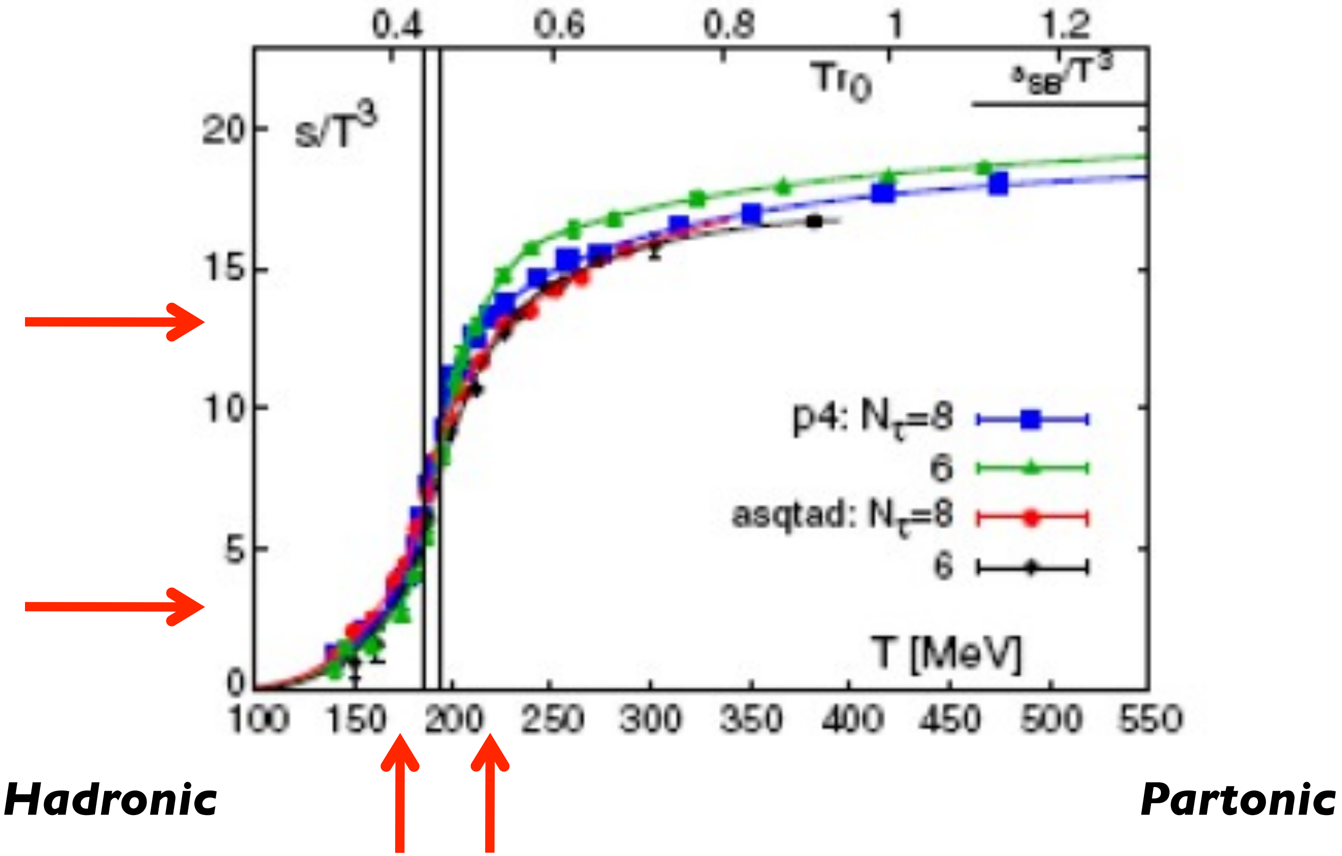
A mixture of E&M charges help explain the observed transport properties.

Near-Tc Matter: Thermodynamics

Near Tc: a wide window in terms of entropy density !

What is the nature of confinement transition?

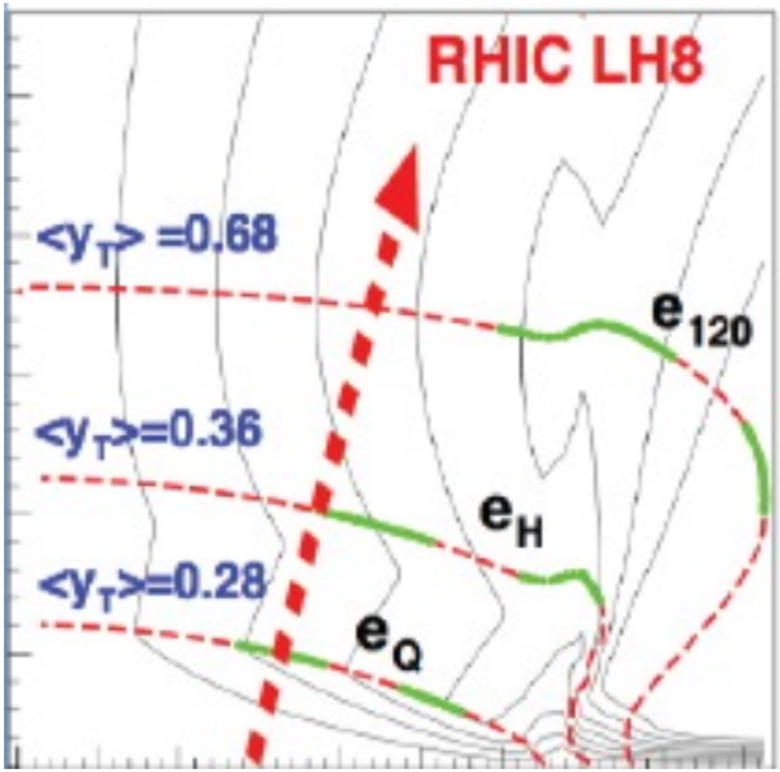
Can H.I.C. help us understand the matter just about to confine?



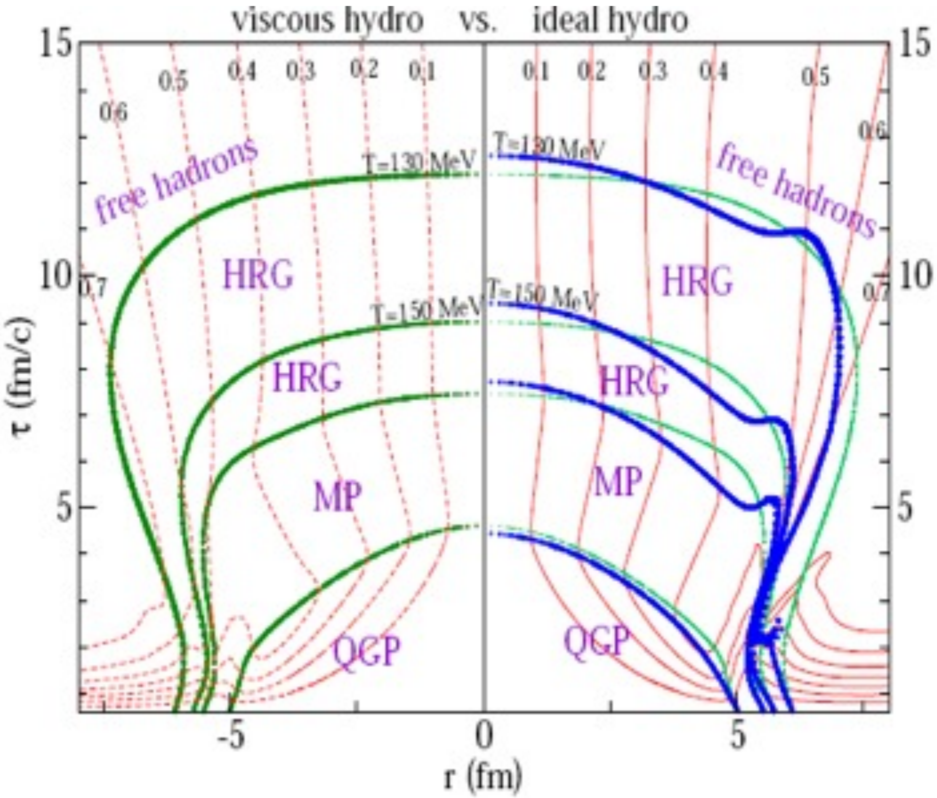
The world is much richer than just a HRG and a Stefan-Boltzmann QGP!

Near-Tc Matter: Hydrodynamics

Near Tc Matter (between HRG and QGP) occupies
large space time volume (~1/3) during the fireball evolution.



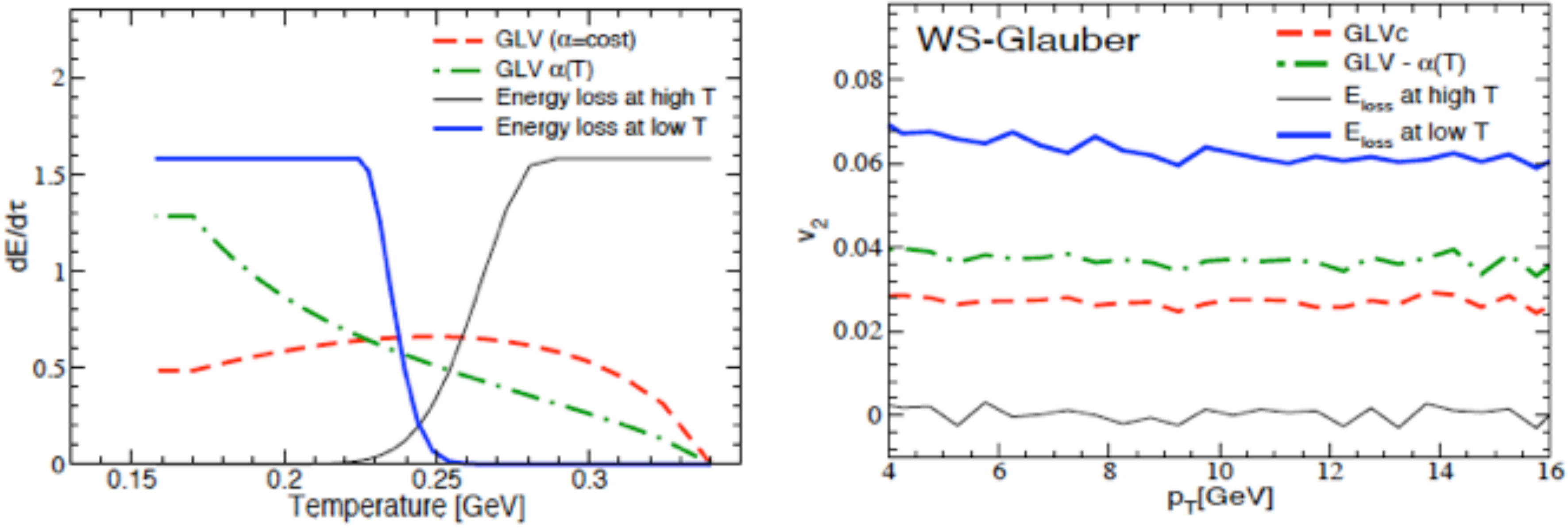
Teaney & Shuryak



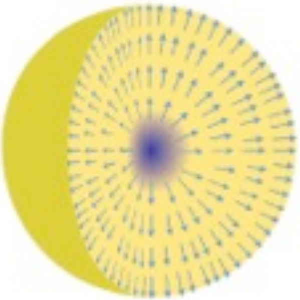
Heinz & Song

Sensitivity to T-dependence of Energy Loss

Francesco-Di Toro-Greco (arXiv:1009.1261)



Magnetic Monopoles & E-M Duality



't Hooft-Polyakov (1974):

monopoles naturally arise as topological solutions to classical EoM in non-Abelian gauge theories;

Dirac Quantization obeyed, mass & size ~ 1/g

$$\boxed{\mathtt{Dirac:}\ e^{*}g=1}$$

What happens if the gauge theory with monopoles is in strongly coupled regime?

E-M Duality: (Motonen, Olive, 1977)

strong coupling → change of D.o.F. toward emergent ones ;

Dirac condition → E and M couplings inversely related

E weakly coupled → theory in terms of E language

E strongly coupled → theory better described by Magnetic.

What are Underlying the "Volcano"?

T<< Lambda_QCD

T ~ Lambda_QCD

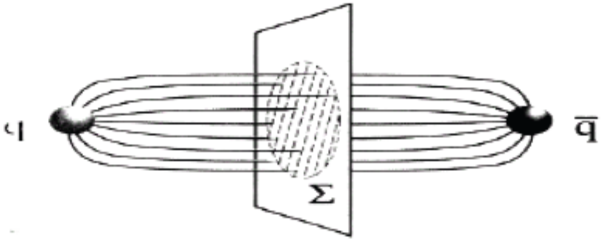
T>> Lambda_QCD

Vacuum: confined

Tc

sQGP

wQGP: screening



Emergent plasma with E & M charges:

chromo-magnetic monopoles are the "missing DoF"

Plasma of E-charges

E-screening: g T

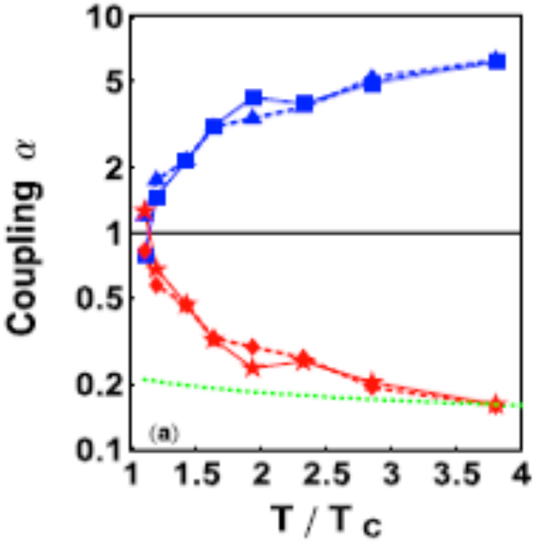
M-screening: g^2 T

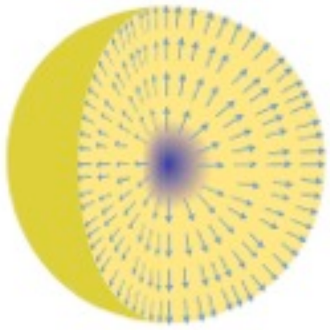
Electric Flux Tube:

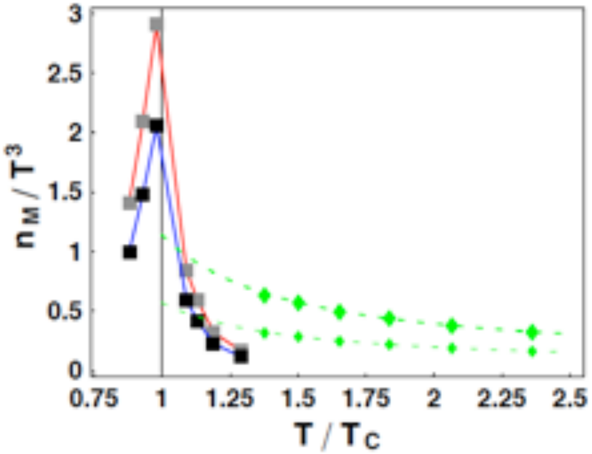
Magnetic Condensate

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

$$\kappa \sim \frac{\alpha_E(T)\alpha_M(T)n_m(T)}{s(T)} = \frac{n_m/T^3}{s/T^3}$$







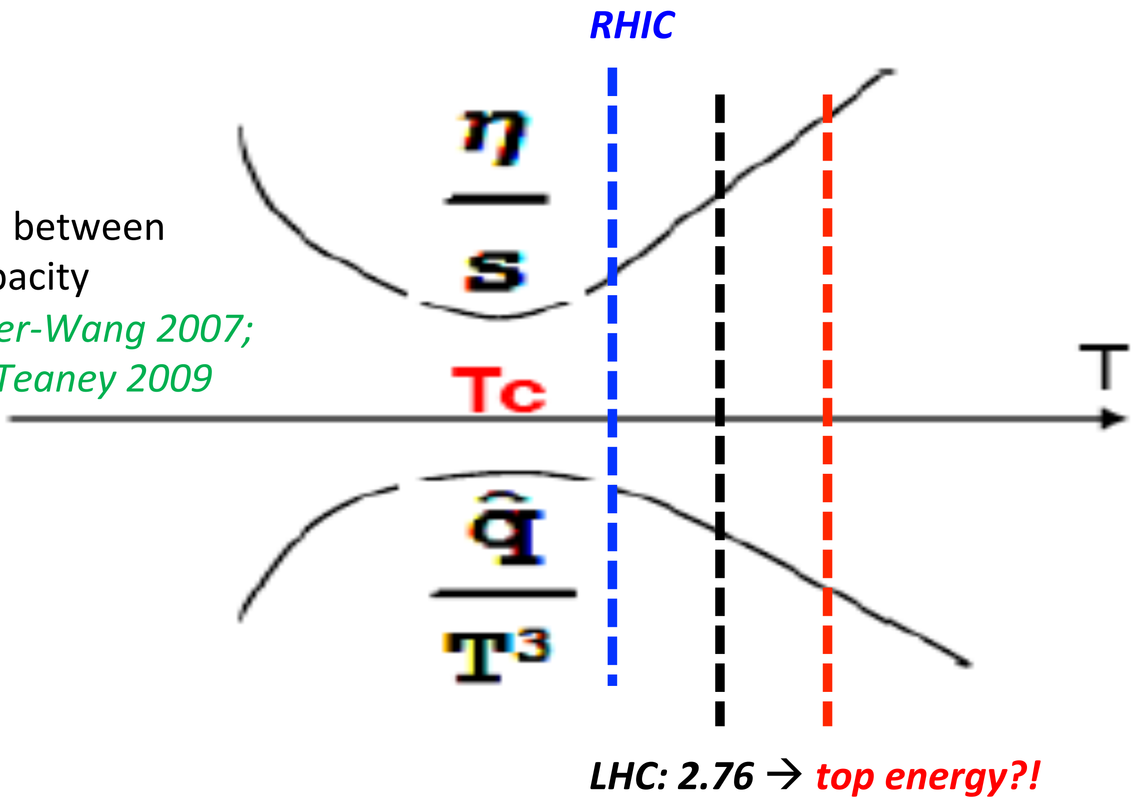
JL & Shuryak:

Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008; Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010; Phys.Rev.Lett.109:152001,2012.

FROM TALK @ DNP2011

QUENCHING & VISCOSITY LINKED-UP: FROM NEAR TC TO HIGHER T

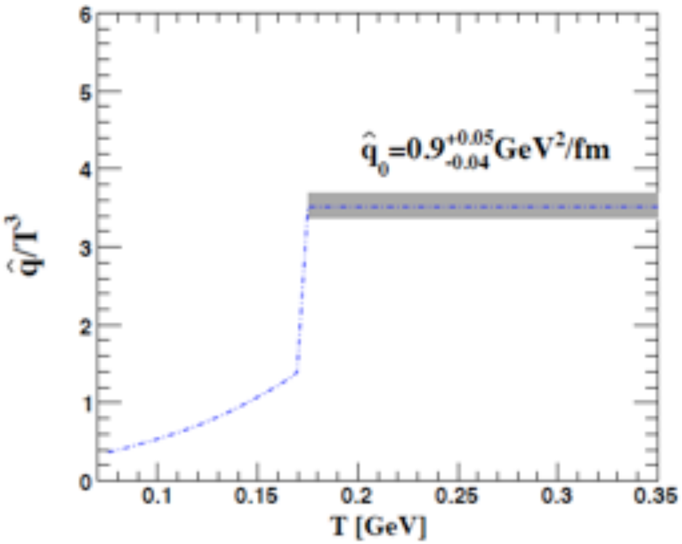
Inverse relation between viscosity and opacity
Majumder-Muller-Wang 2007;
Dusling-Moore-Teaney 2009



Will we see a systematic deviation from RHIC to LHC?

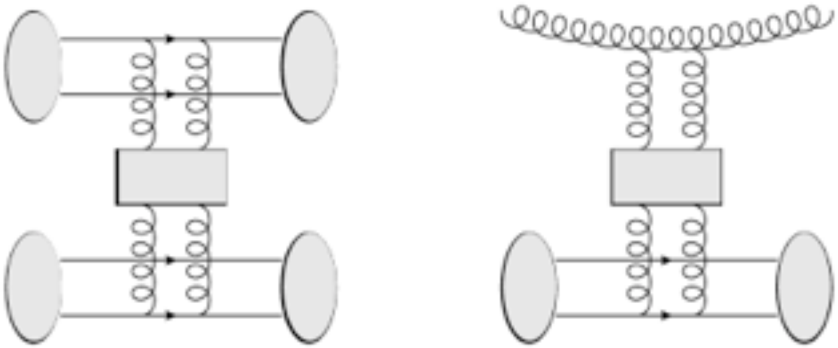
The "see-saw"-QGP expects such a picture to occur in a narrow regime 1-4Tc.

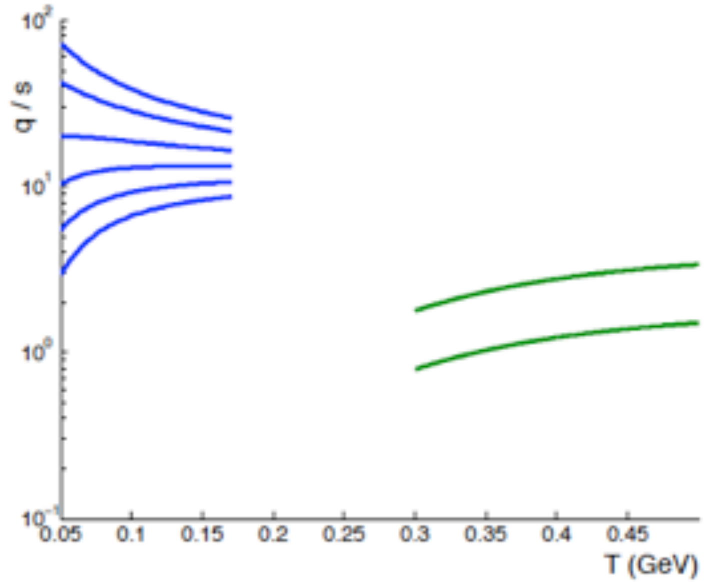
Energy Loss on the Hadronic Side



$$\hat{q}_h = \frac{\hat{q}_N}{\rho_N}\left[\frac{2}{3}\sum_M \rho_M(T) + \sum_B \rho_B(T)\right]$$

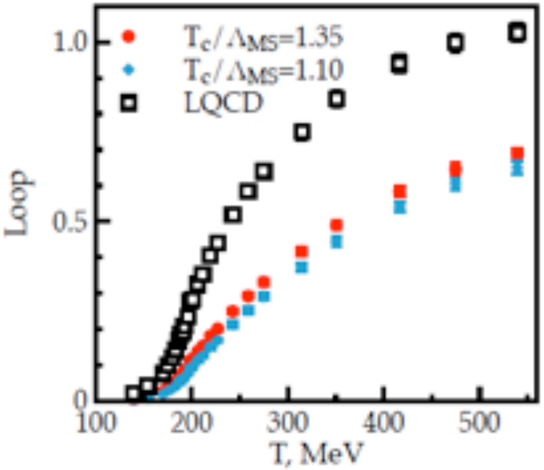
Chen, Greiner, Wang, Wang, Xu, arXiv:1002.1165





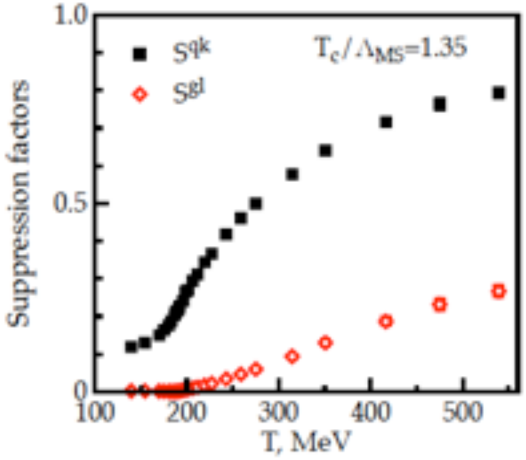
Hidalgo-Duque, Llanes-Estrada, arXiv:1309.7211

Energy Loss from the semi-QGP



$$S^{\rm qk}(Q) \sim \ell \quad ; \quad S^{\rm gl}(Q) \sim \ell^2$$

$$\frac{dE}{dx} = \left(S^{\rm qk}(Q)\, \alpha_s^2\, T^2\, \pi \frac{N_f(N_c^2-1)}{12\, N_c} \ln\left(\frac{ET}{m_D^2}\right) + S^{\rm gl}(Q) \left(\frac{(N_c^2-1)}{6} \ln\left(\frac{ET}{m_D^2}\right) + \frac{C_f^2}{6} \ln\left(\frac{ET}{M^2}\right)\right)\right)$$



Collisional energy loss of heavy quark in semi-QGP: decrease toward Tc.
(picture from the electric side)
(magnetic charges make the rise.)

Lin, Pisarski, Skokov, arXiv:1312.3340