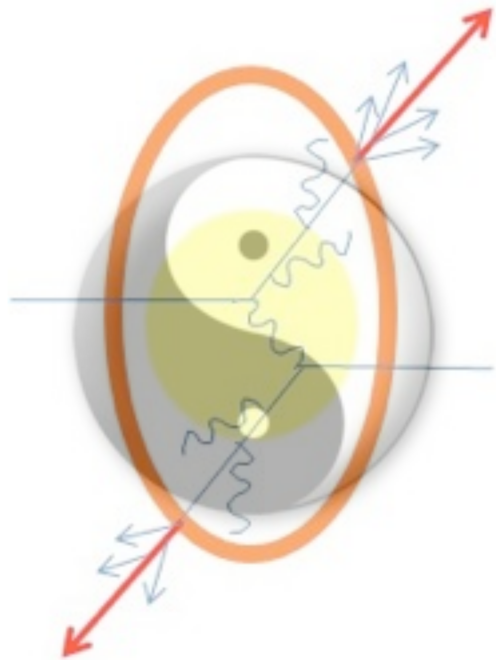
Opaqueness Evolution from Color Liberation



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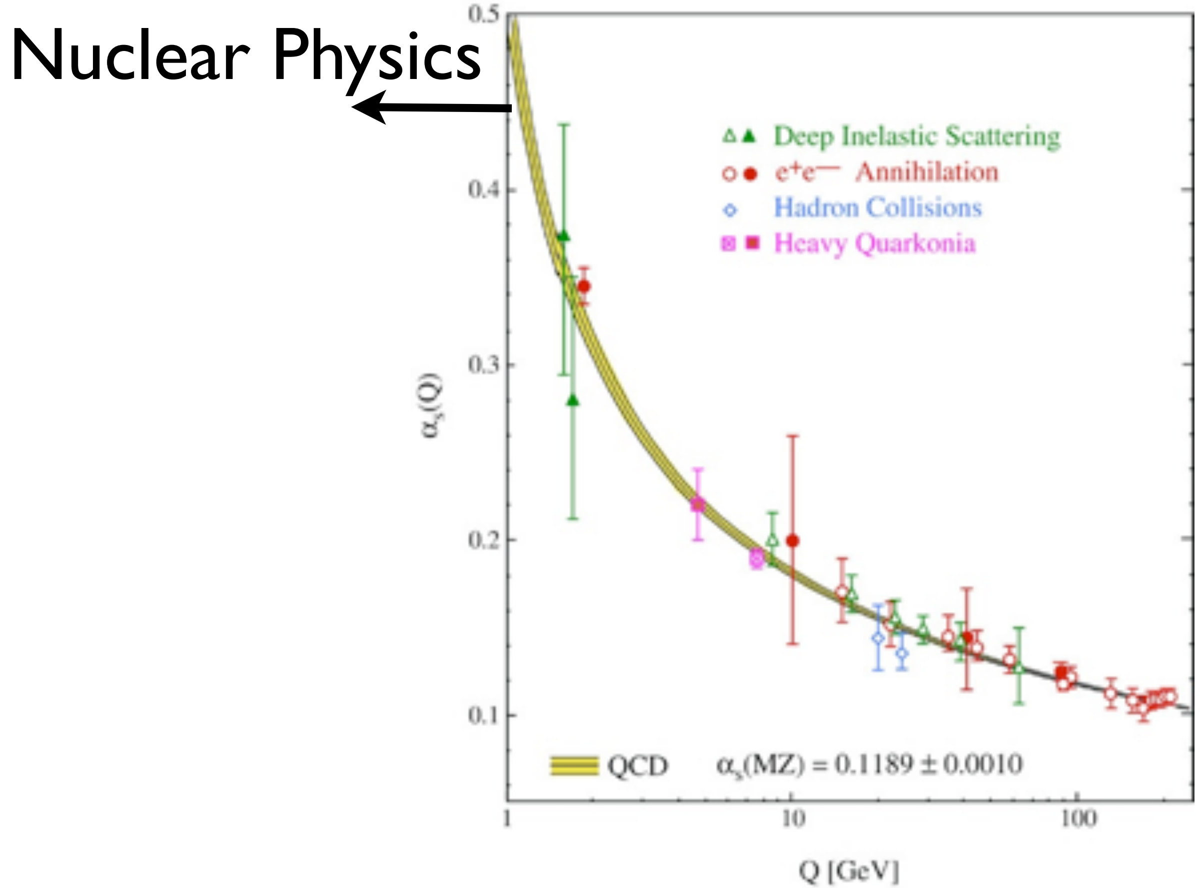
RIKEN BNL Research Center

Outline

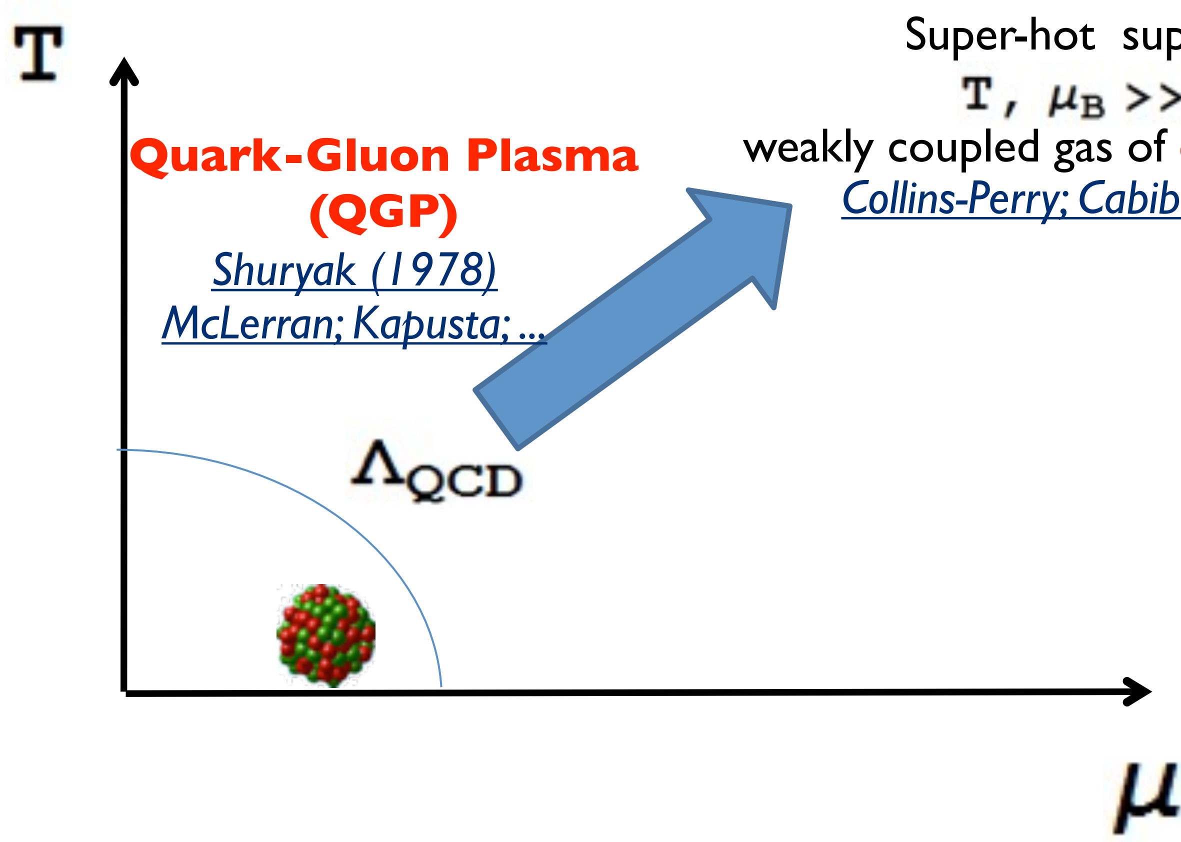
- Introduction: An Opaque QCD Plasma
- What We Learn From Geometry of Jet Quenching
- Opaqueness Evolution from RHIC to LHC
- Discussions & Summary

X. Zhang, JL, arXiv:1208.6361; 1210.1245;
JL, arXiv:1109.0271;
J.Jia, W.Horowitz, JL, Phys.Rev. C84 (2011) 034904
JL, Shuryak, Phys.Rev.Lett. 102 (2009) 202302

40 Years of Asymptotic Freedom



Asymptotically Free Matter



Super-hot super-dense:

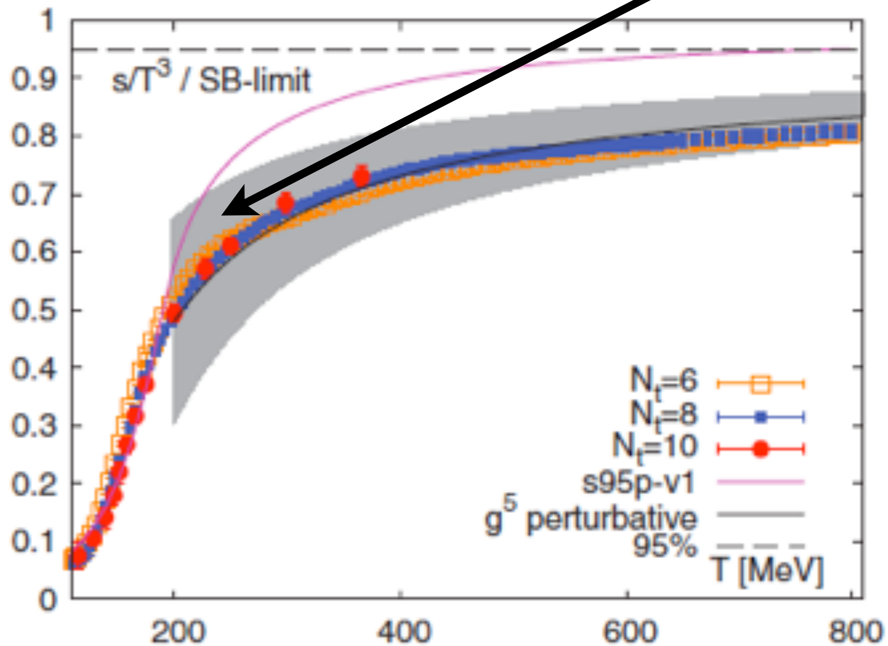
$T, \ \mu_B >> \Lambda_{QCD}$

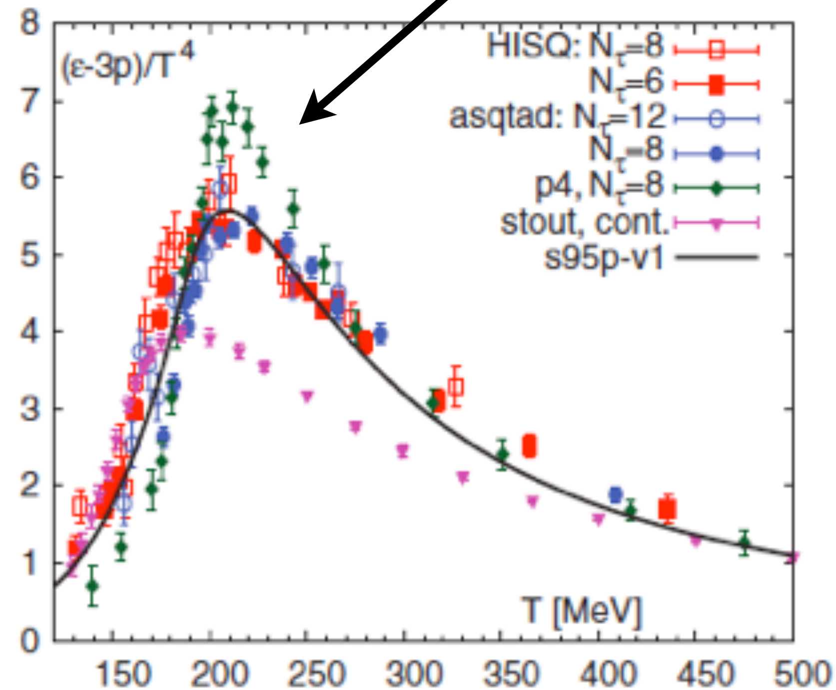
weakly coupled gas of quarks and gluons

Collins-Perry; Cabibbo-Parisi (1975)

color confined world --> color (fully) liberated world

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



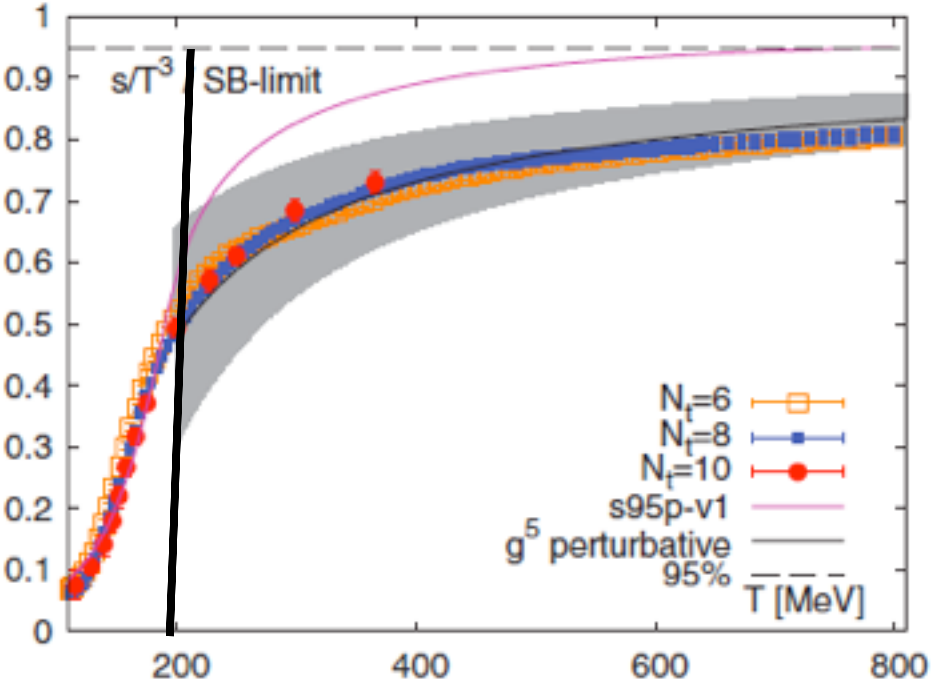


“Rapid Up” or “Rapid Down”:
pressure/energy density/entropy density/
2-nd q-susceptibilities/
chiral condensate/Q-bar-Q free energy/...

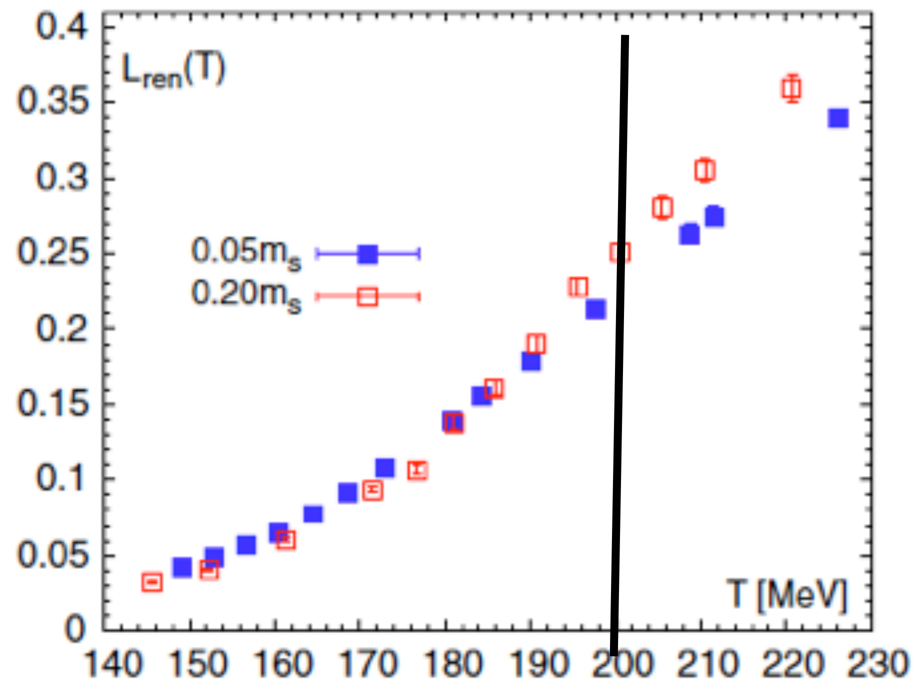
“Peak” or “Dip”:
trace anomaly/chiral susceptibility/
4-th q-susceptibilities/
Q-bar-Q internal energy/
speed of sound//...

Liberation of Color?

Degrees of freedom



Degree of color liberation



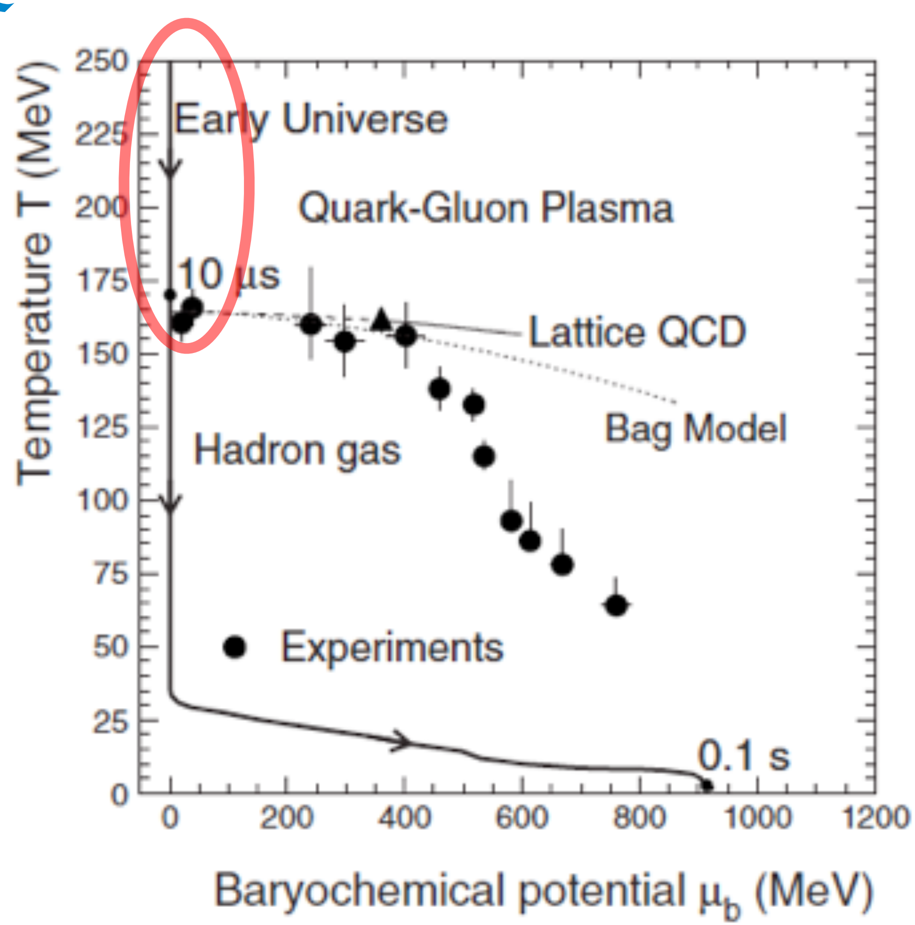
A region around Tc with liberated degrees of freedom
but only partially liberated color-electric objects.

(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

QGP from the "Little Bangs"

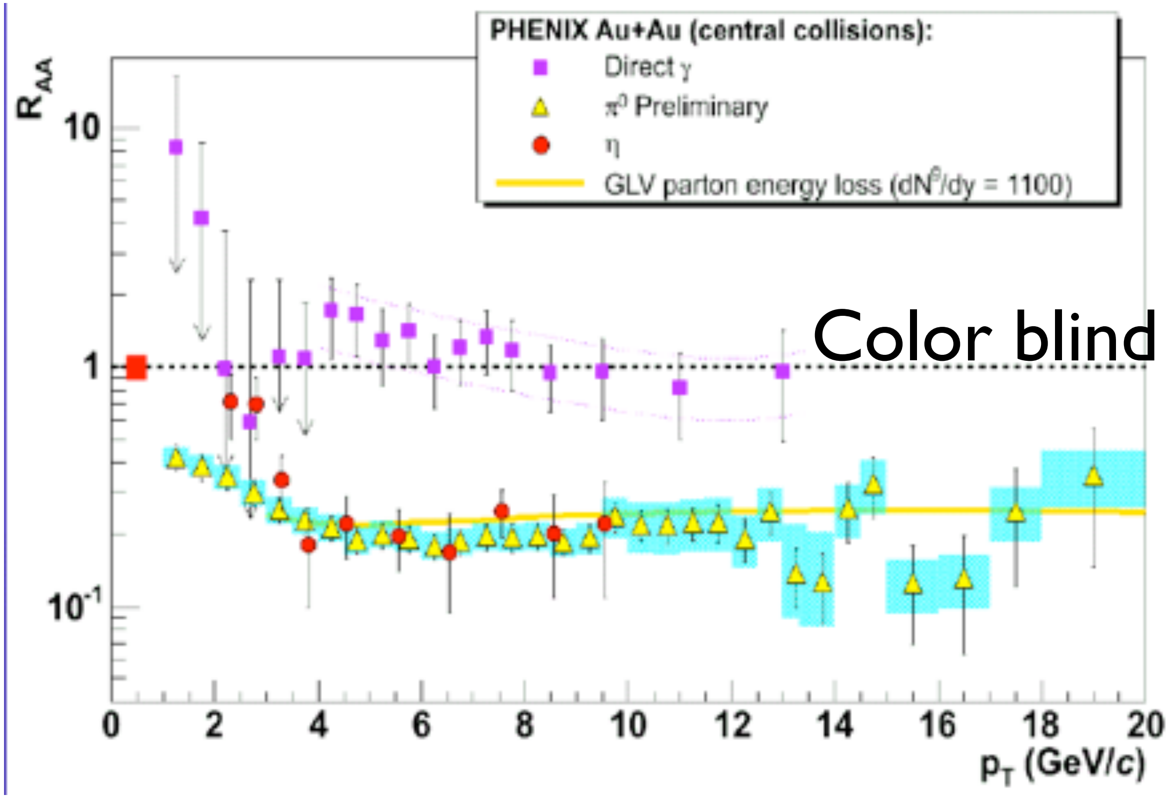


Surprising QGP: nearly perfect fluid; color opaque; ....

It is not the Asymptotically Free Matter yet!

(not unrelated to the partial liberation of color)

A Color-Opaque Plasma



Color blind probe

Colorful probe

A qualitatively different medium

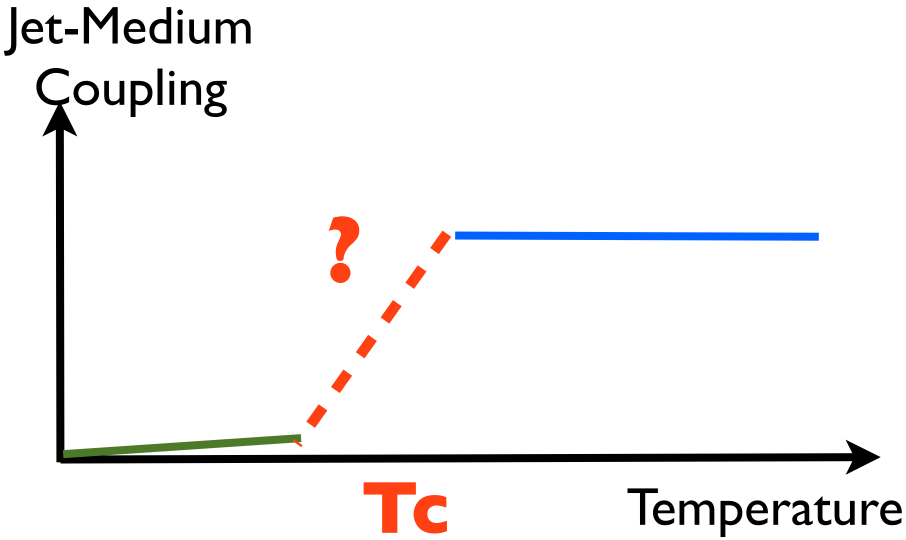
Jet-Medium Coupling

High (liberated)

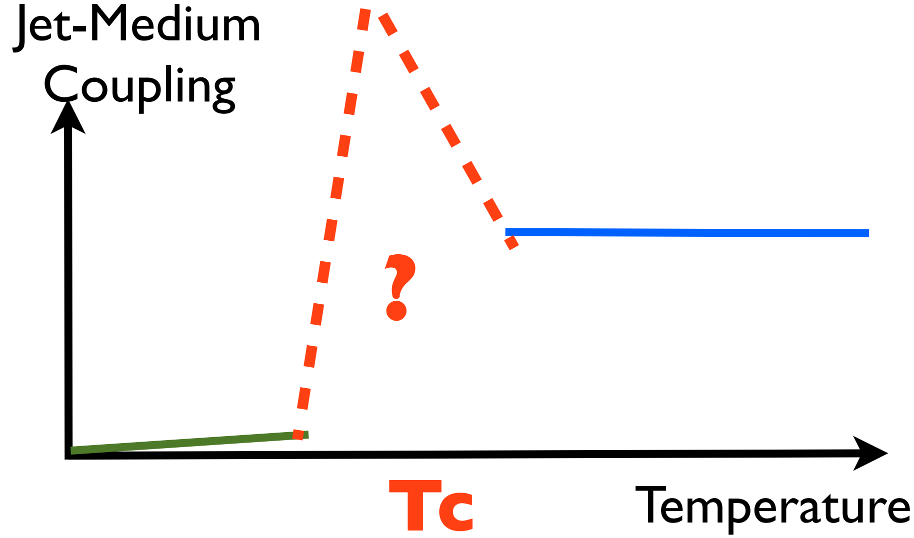
Zero/Low (Confined)

Temperature

From Transparency to Opaqueness



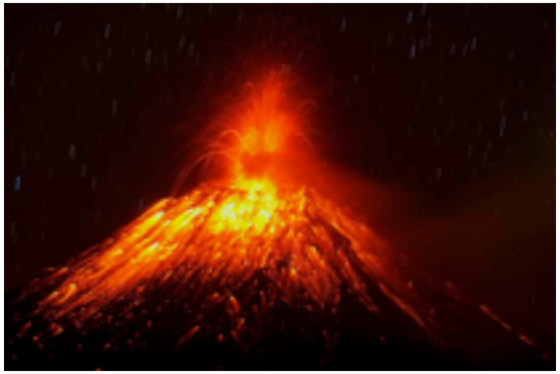
“Waterfall” scenario



“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.

V.S.



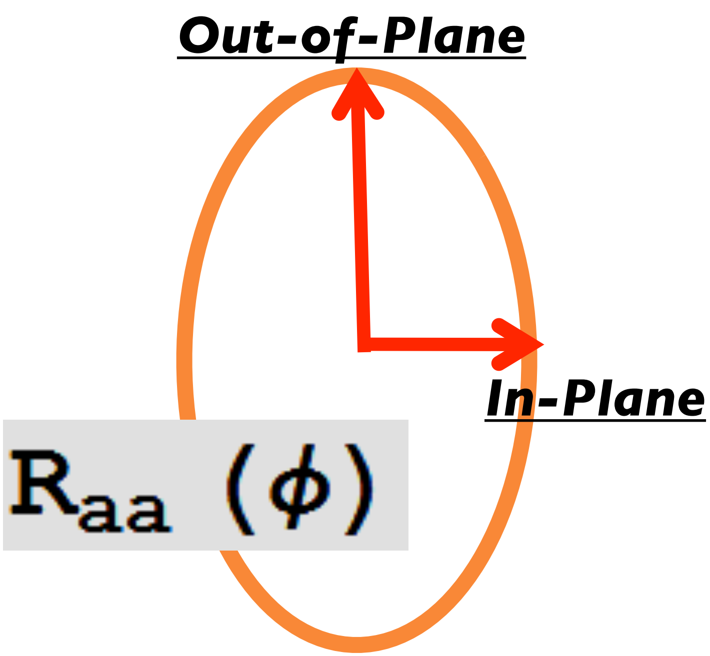
How can we get the answer?

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

Luckily, we seem to be able to:
Geometry ; evolution RHIC --> LHC

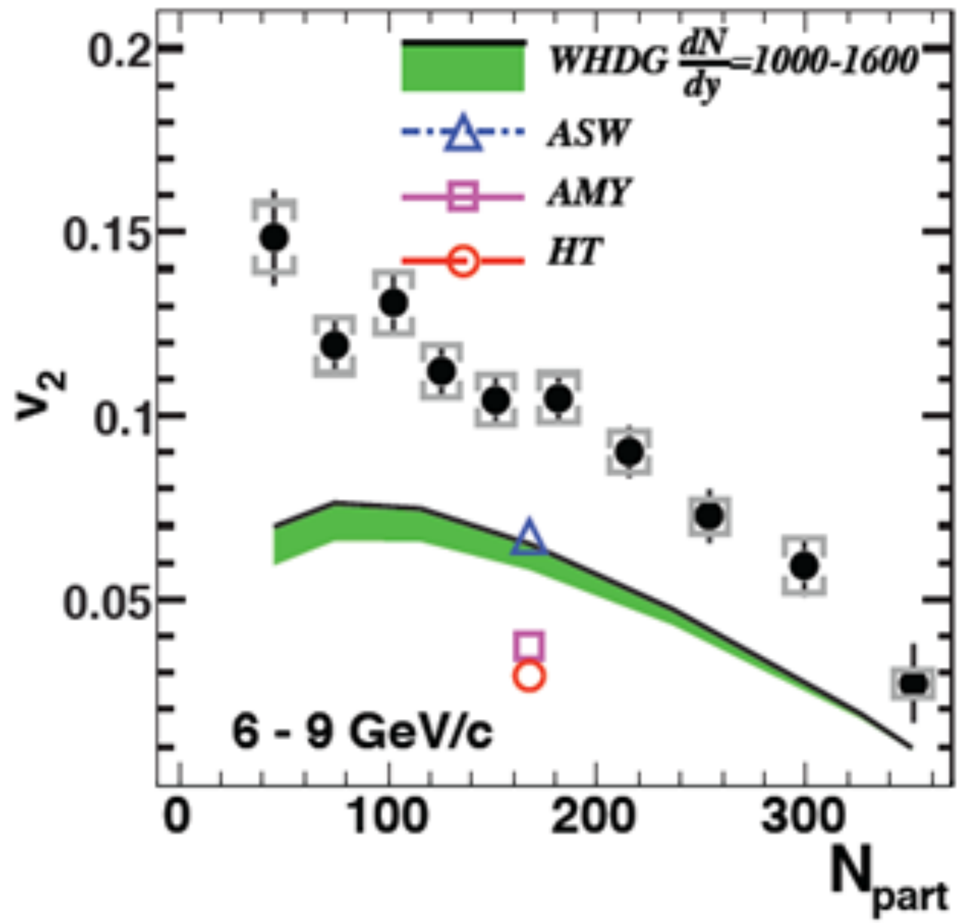
Geometric Anisotropy of Jet Quenching

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

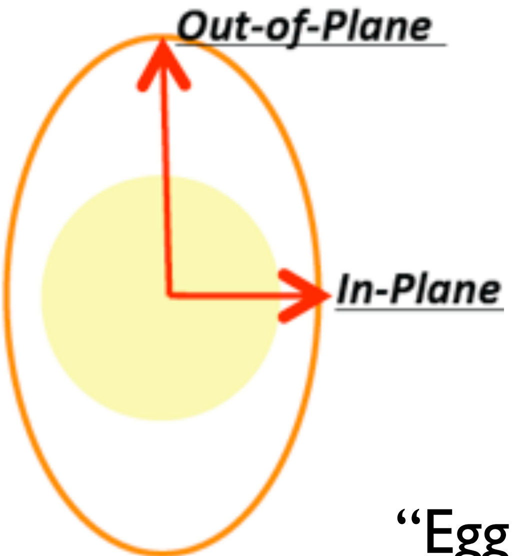


$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$

Positive v2 for high Pt hadrons



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

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(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

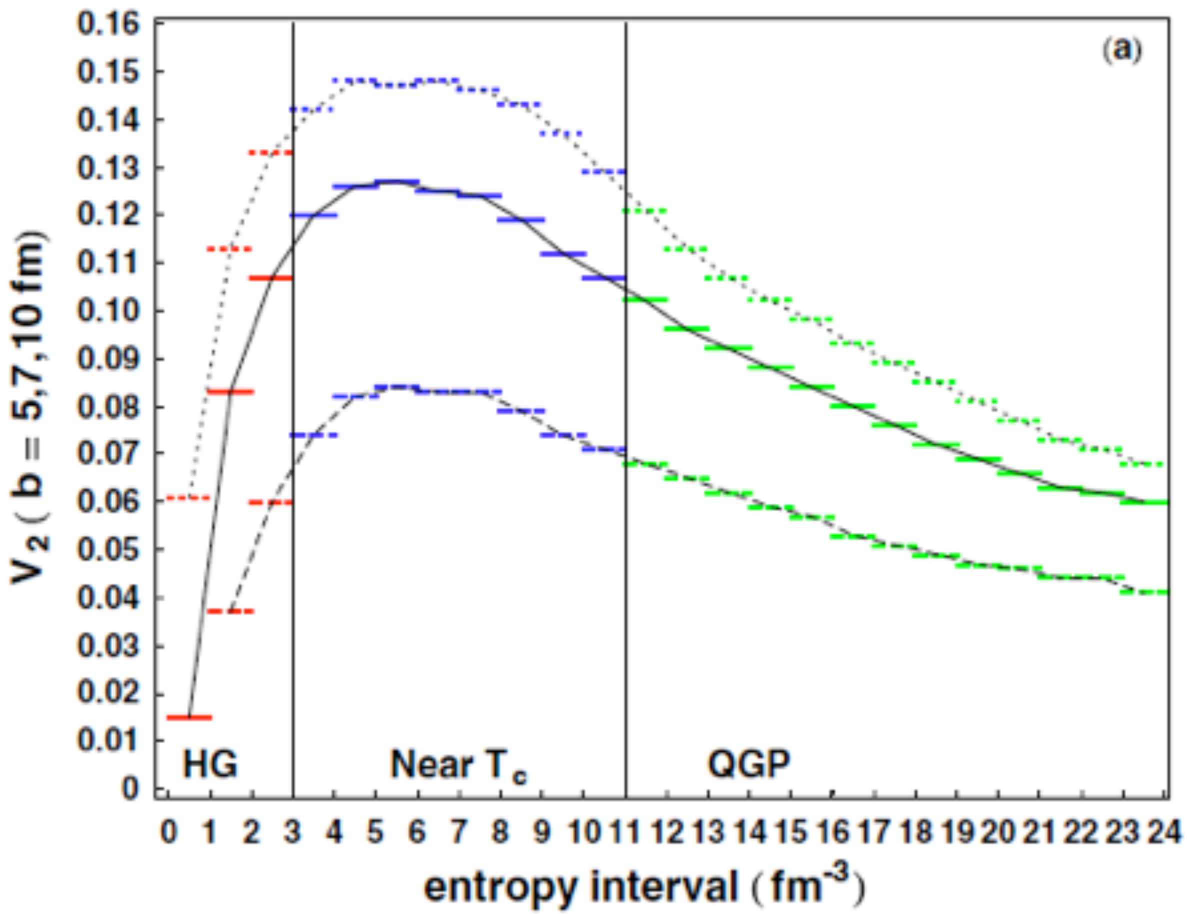
Layer-wise Jet Quenching

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

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

scan the jet quenching geometry layer by layer in density

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



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

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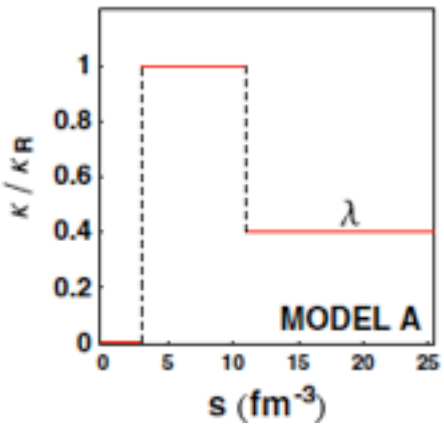
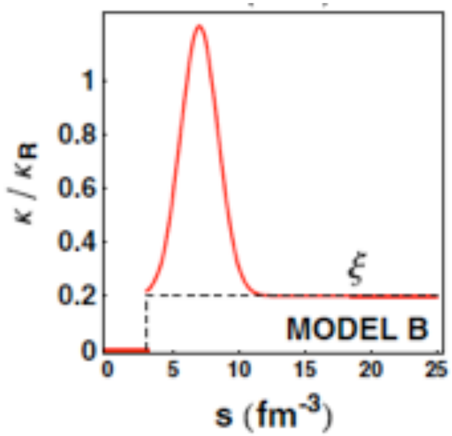
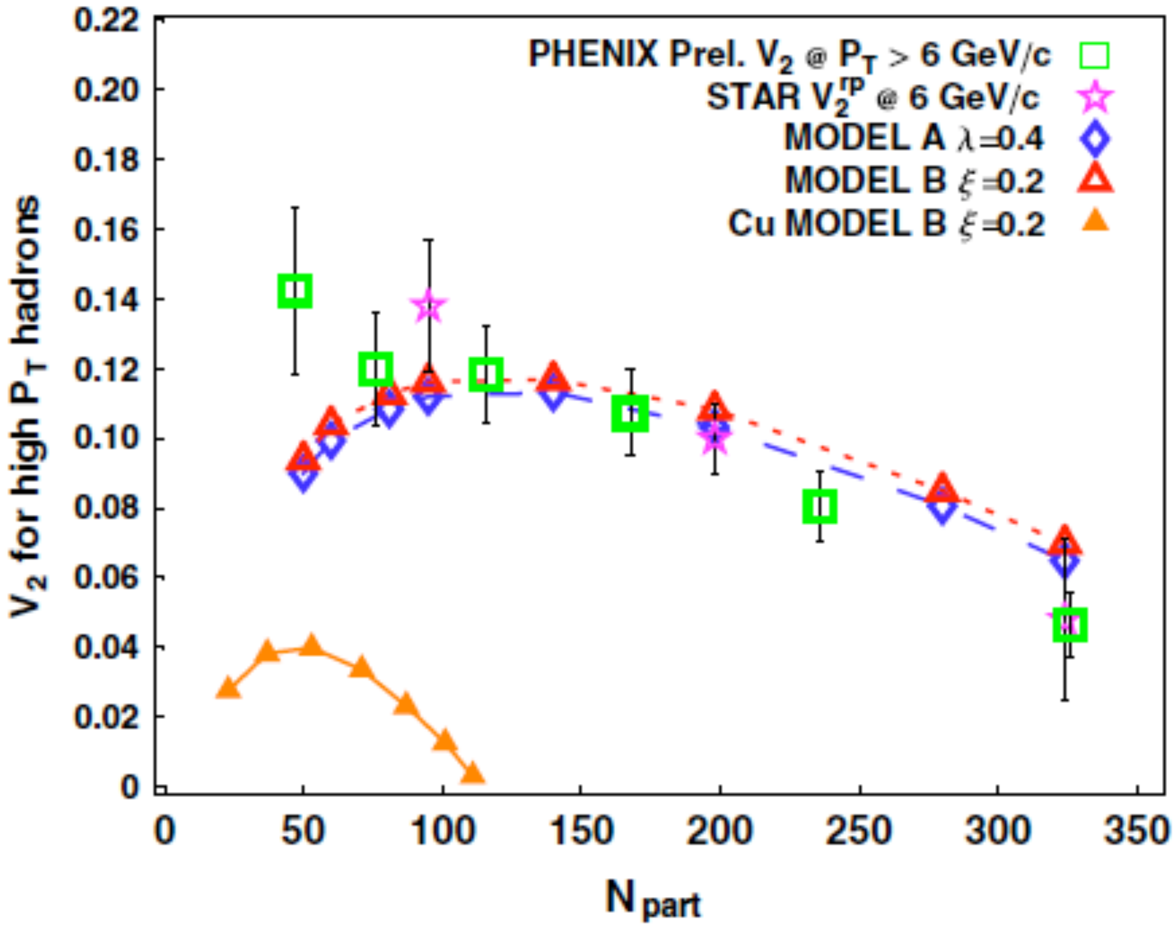
look at v2 from that layer:

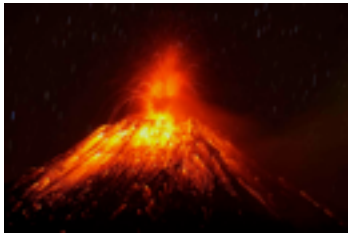
Near-Tc layers give the strongest anisotropy!

Near-Tc Enhancement (NTcE)









Models based on "volcano" scenario gave the first simultaneous description of high Pt Raa and V2 at RHIC!

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 "picks" up 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

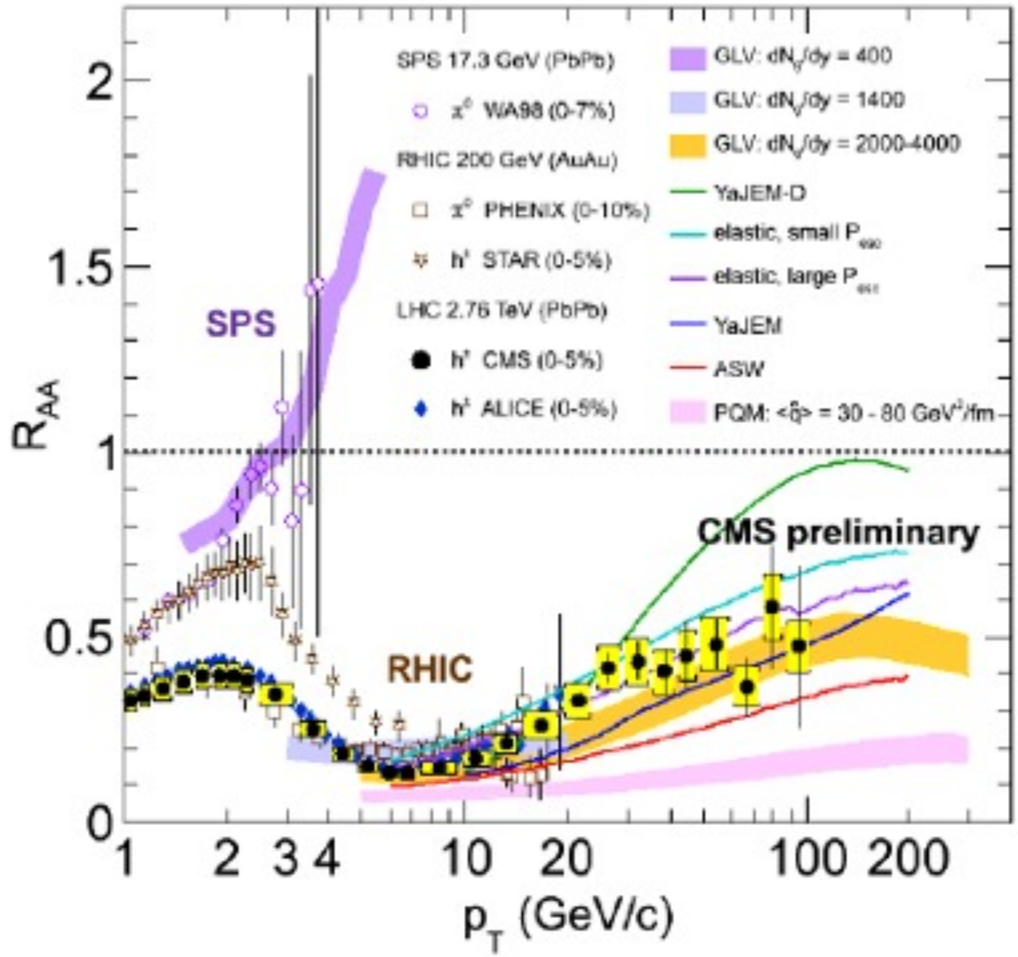
Gyulassy,Buzzatti,Bezt

Fries & students

Marquet & Renk

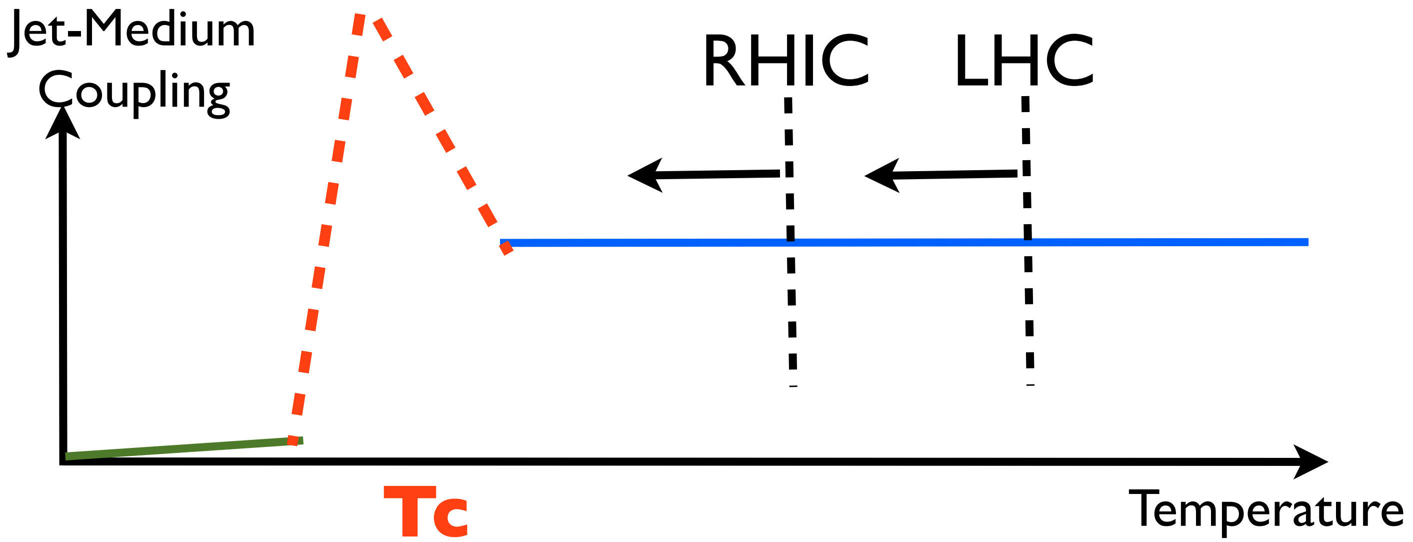
Jia & Wei

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

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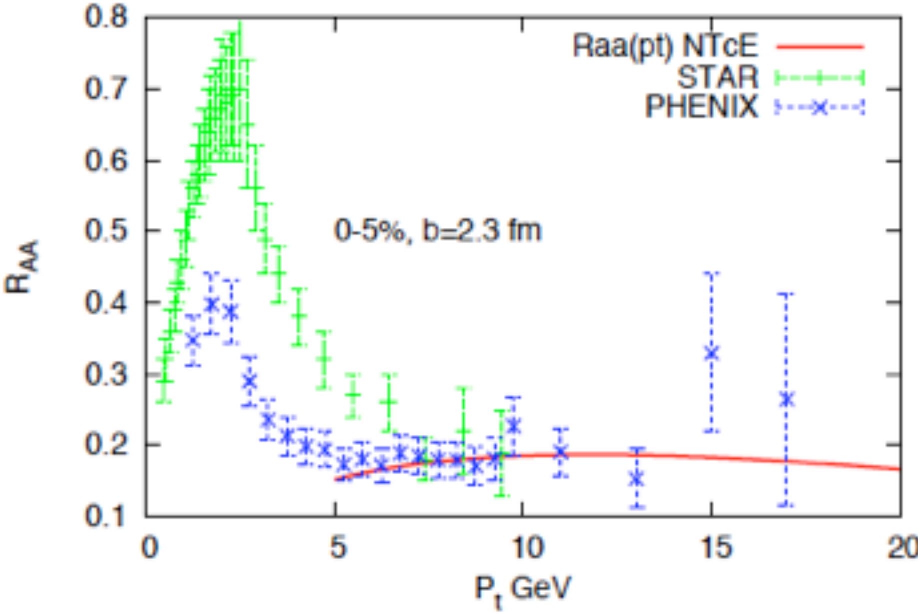
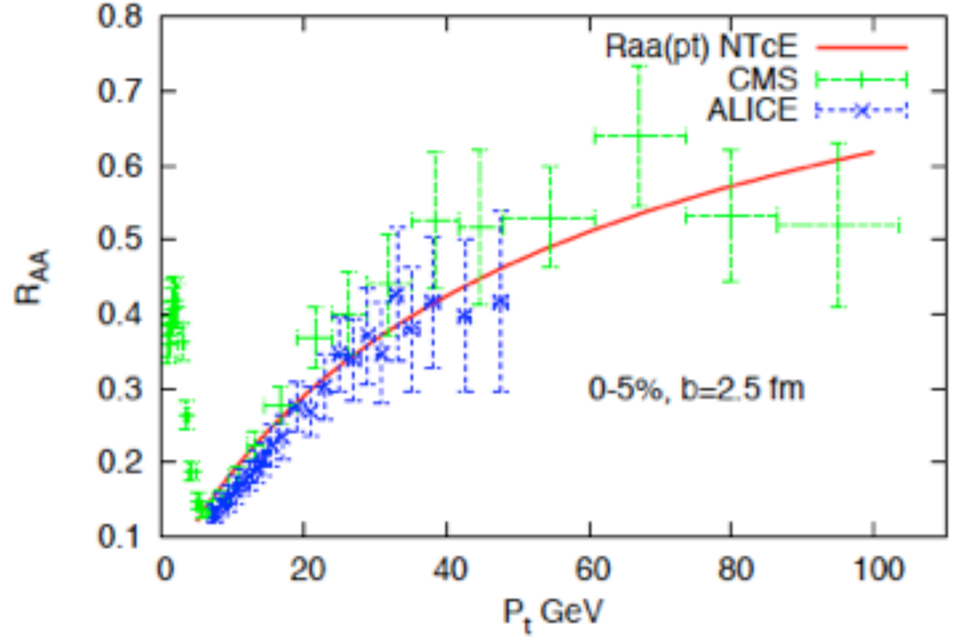
* Naturally predicts a less opaque (on average) medium seen by jets (note however density doubles)

* Anisotropy from the “volcano” and “waterfall” scenarios will become closer

Raa from RHIC to LHC



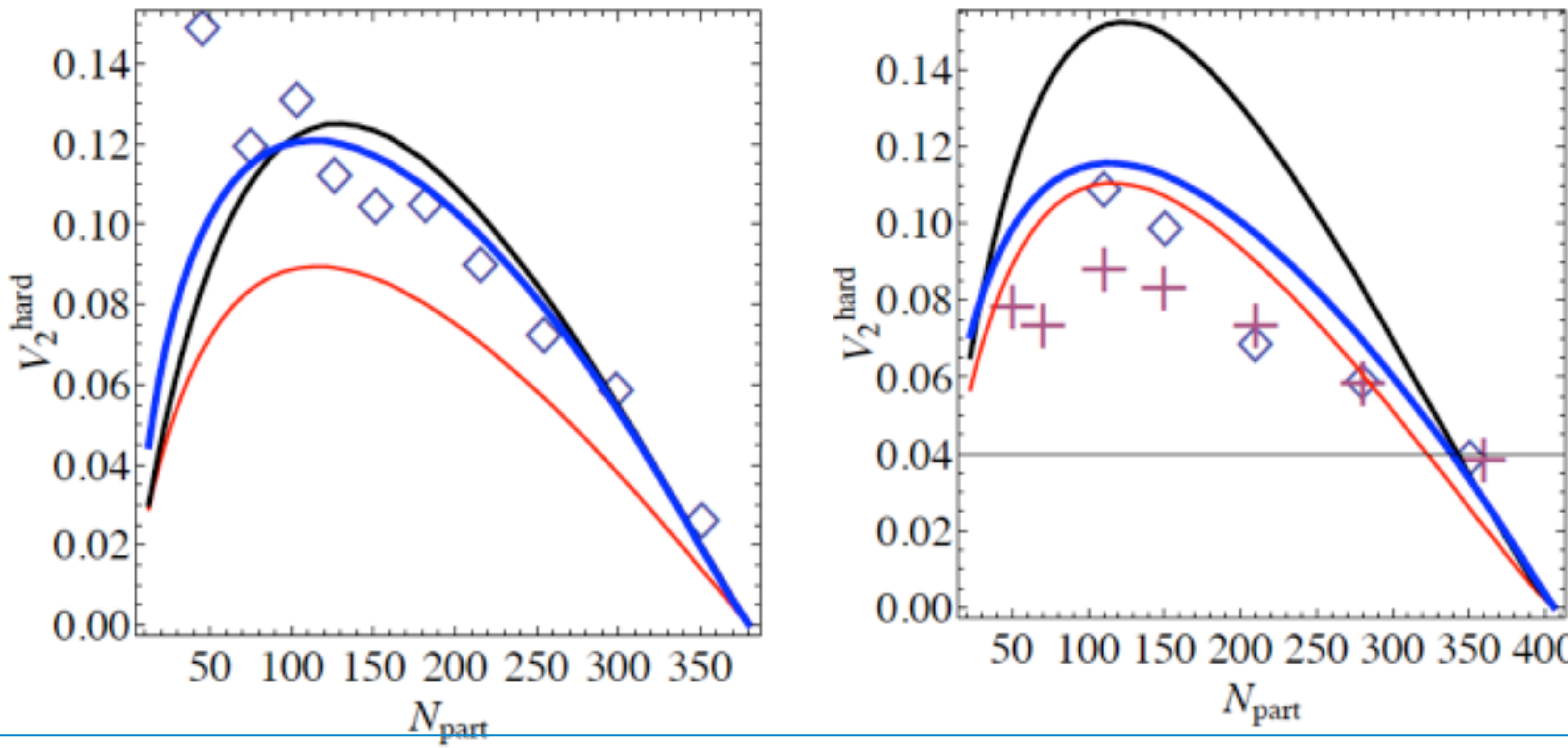


Average jet-medium coupling from RHIC to LHC: reduced by ~30%

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

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

V2 from RHIC to LHC



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

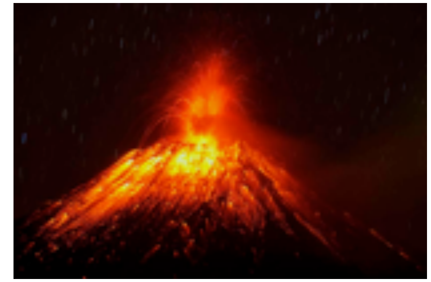
* We do see big difference between waterfall/volcano at RHIC, and this difference becomes much smaller at LHC

* RHIC + LHC data are in favor of the L^2 + Volcano scenario

(See Xilin Zhang talk tomorrow for newest results with initial fluctuations and higher harmonics)

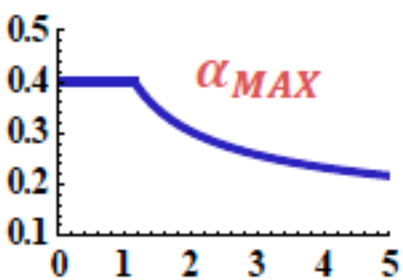
"Volcano" Seen from "Different Angles"

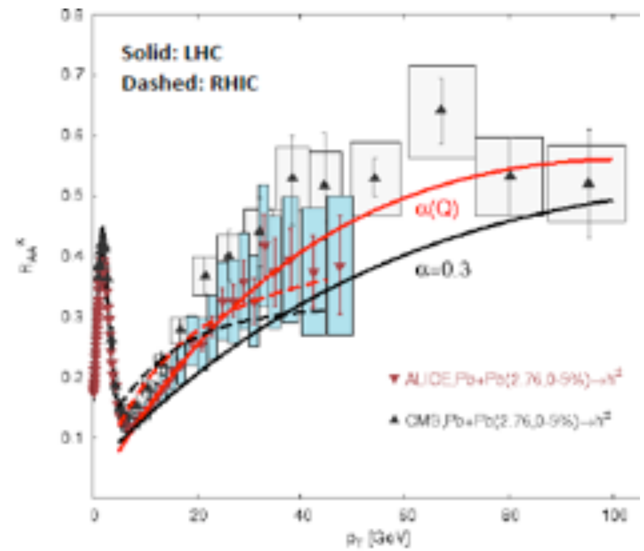
* Horowitz & Gyulassy:
  "surprising transparency" when simply extrapolating RHIC to LHC



* 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

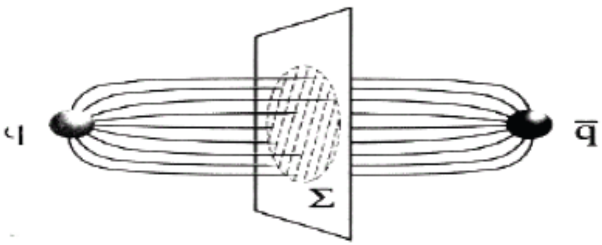
* Lattice QCD: Q-bar-Q internal energy shows strong peak at Tc

* Muller-Majumder-Wang, Dusling-Moore-Teaney:
  peak in q-hat/density related with dip in \eta/s ?
* Majumder: lattice attempt -->q-hat/density showing peak?

What are Underlying the "Volcano"?

T<< Lambda_QCD — T ~ Lambda_QCD — T>> Lambda_QCD

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



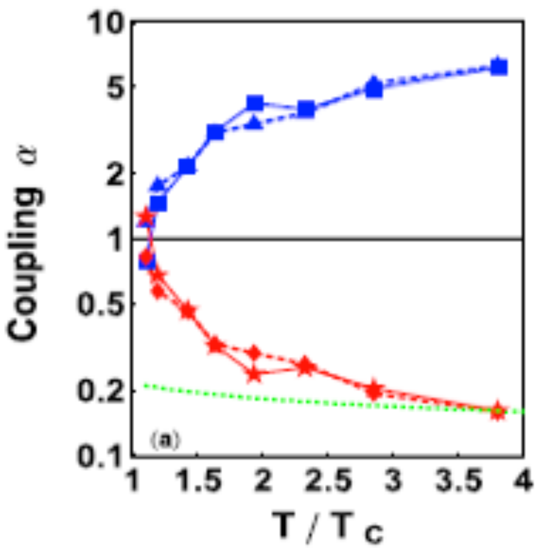
Emergent plasma with <u>E & M</u> charges:
chromo-magnetic monopoles are the "missing DoF"

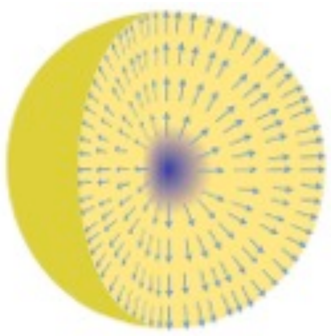
Plasma of E-charges
E-screening: g T
M-screening: g^2 T

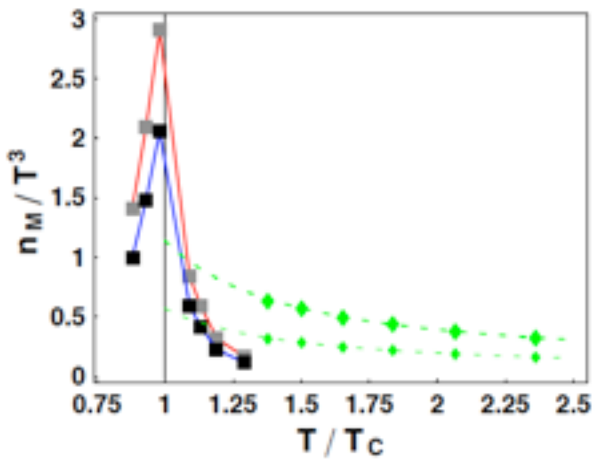
Electric Flux Tube:
Magnetic Condensate

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

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







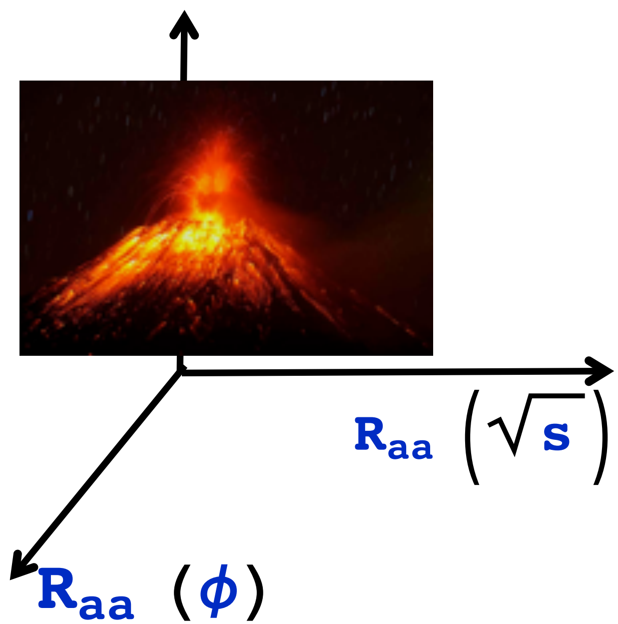
JL & Shuryak:
Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008; Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010; Phys.Rev.Lett.109:152001,2012.

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 fascinating midland between the confined world and the asymptotically free matter.



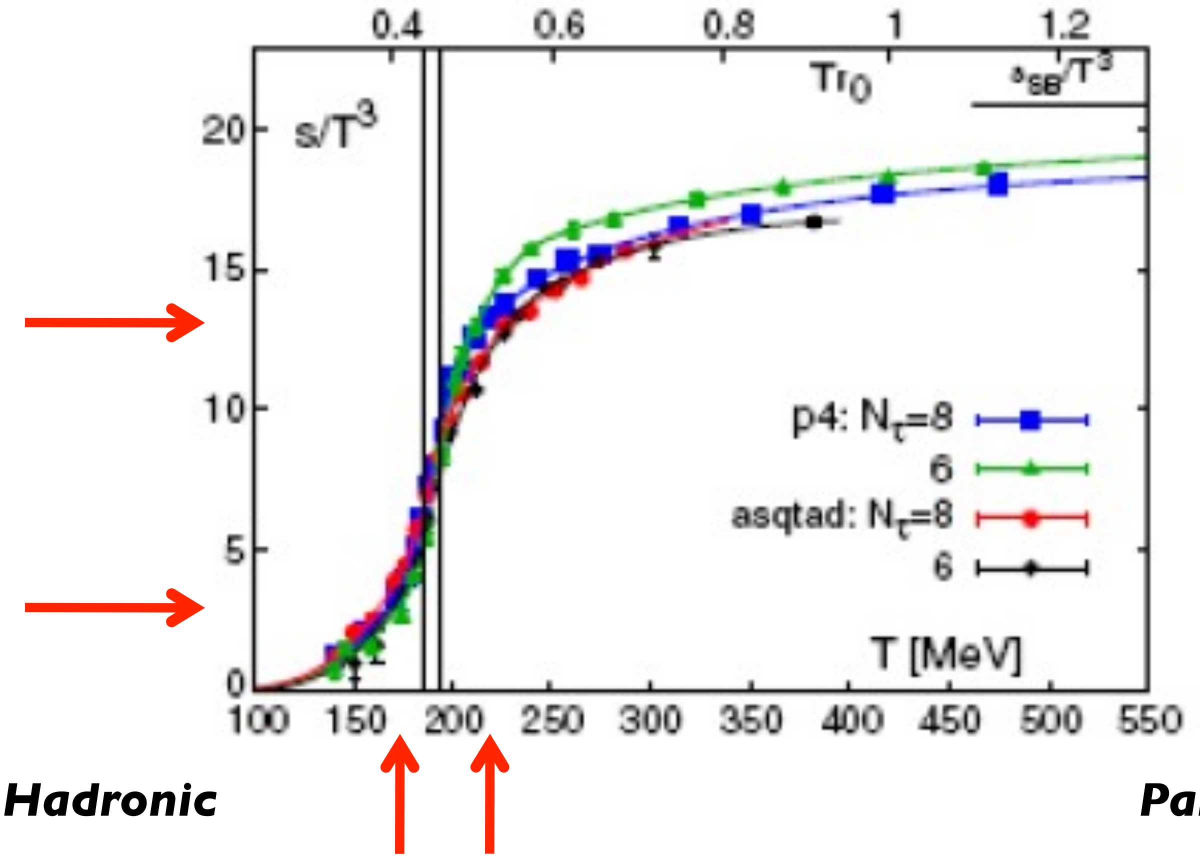
BACKUP SLIDES

Near-Tc Matter: Thermodynamics

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

What is the nature of confinement transition?

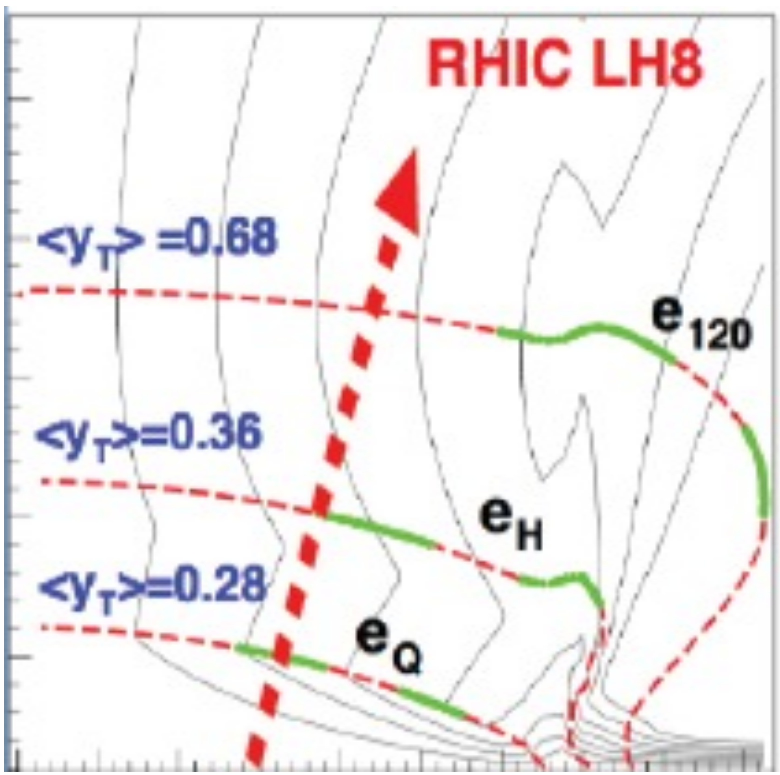
Can H.I.C. help us understand the matter just about to confine?



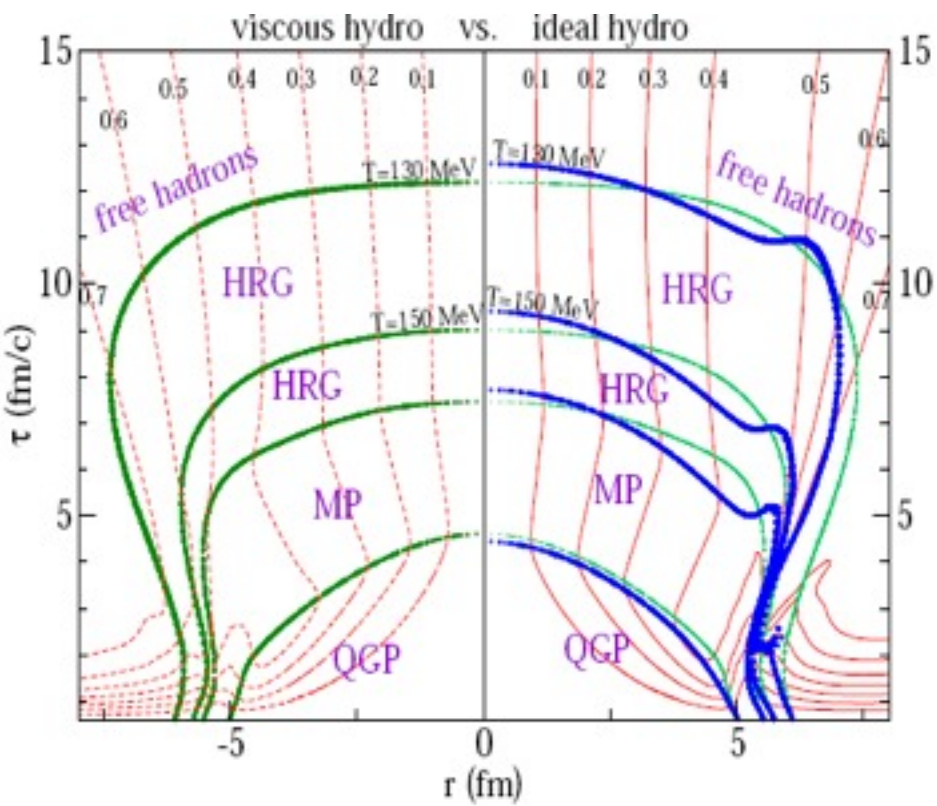
The world is much richer than just a HRG and a Stefan-Boltzmann QGP!

Near-Tc Matter: Hydrodynamics

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



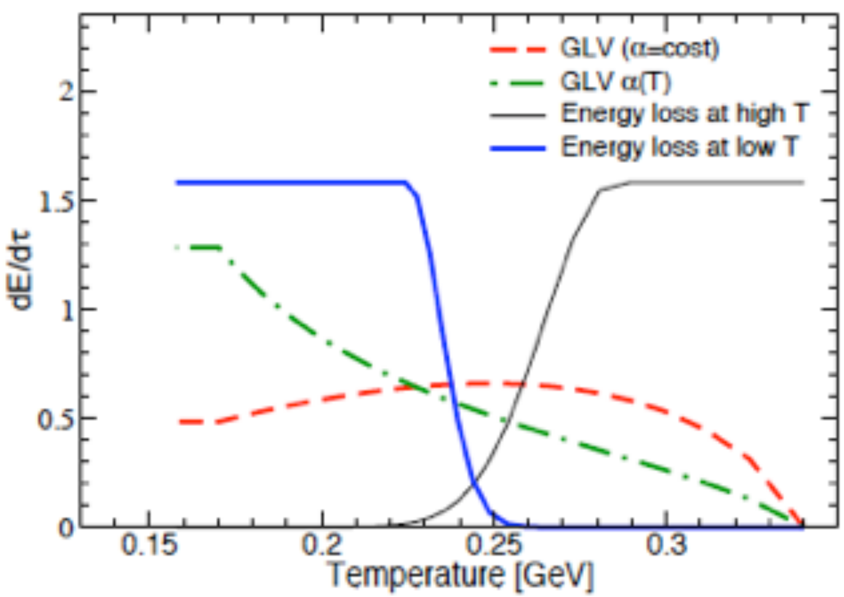
Teaney & Shuryak

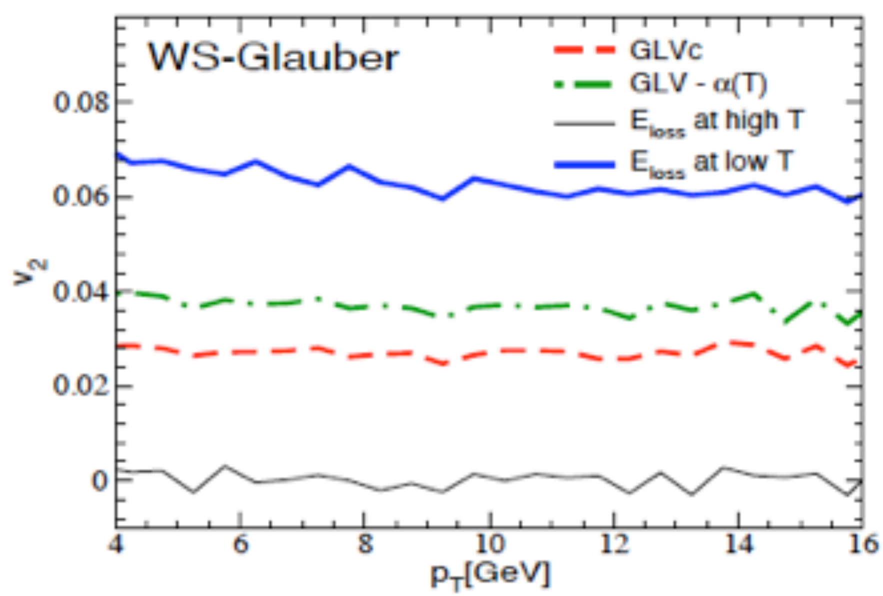


Heinz & Song

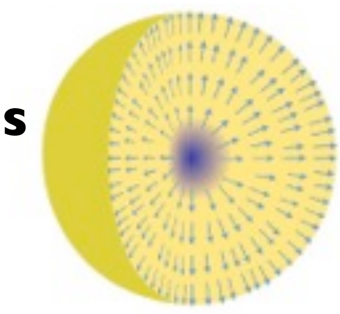
Sensitivity to T-dependence of Energy Loss

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;

<u>Dirac Quantization obeyed, mass & size ~ 1/g</u>

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.