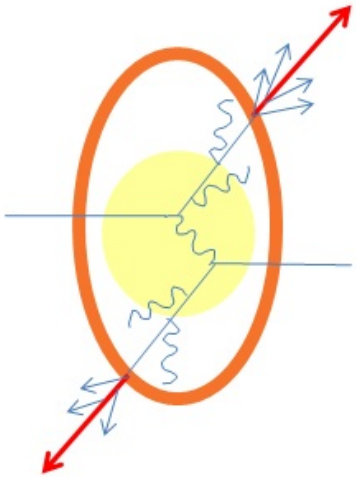
19th Particles & Nuclei International Conference, MIT JUL.25, 2011

Non-Perturbative Jet Quenching from Geometric Data



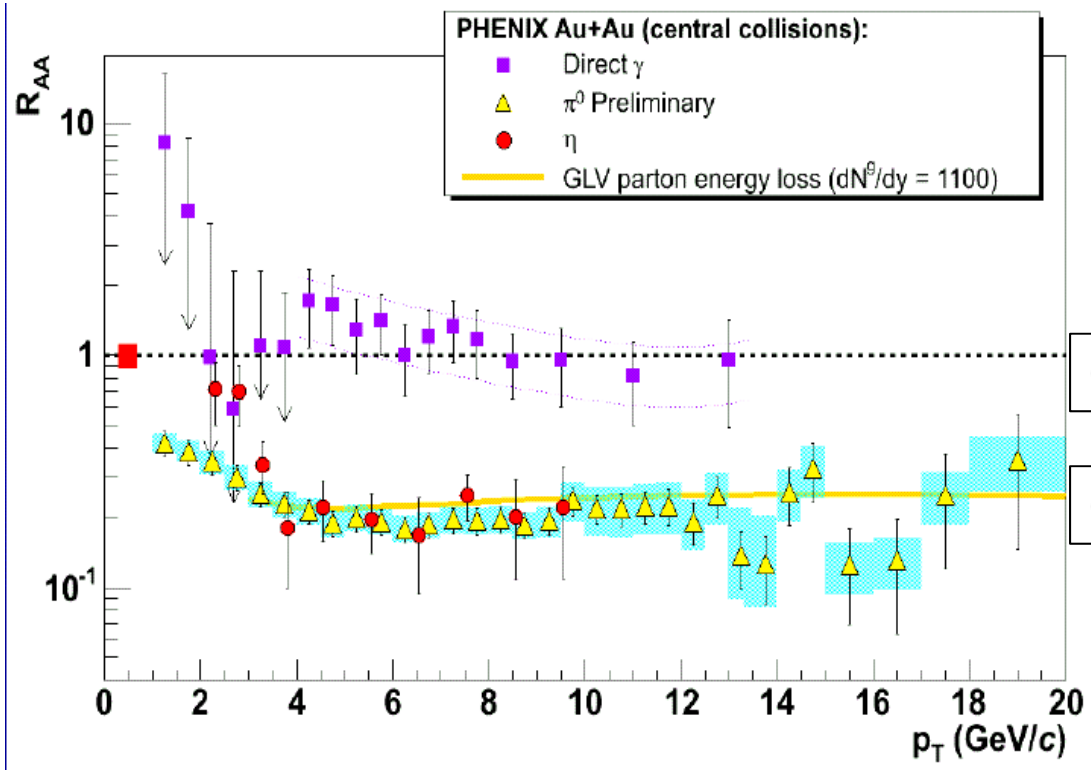
Jinfeng Liao
Brookhaven National Laboratory

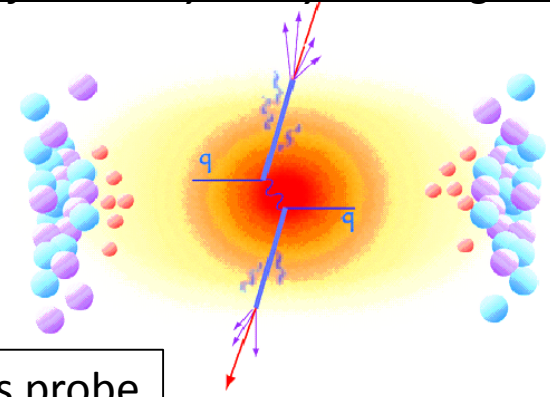
Outline

- Brief Introduction: Jet Quenching & Geometric Tomography
- Strong Enhancement of Jet Quenching Near Transition
- Geometric Data and Modeling from RHIC to LHC
- Summary

Strong Jet Quenching

Bjorken; Gyulassy & Wang; ……





Colorless probe

Colorful probe

$$R_{A\text{-}A}(p_t) \equiv \frac{d^2N^{A\text{-}A}/dp_t d\eta}{T_{A\text{-}A}\, d^2\sigma^{N\text{-}N}/dp_t d\eta}$$

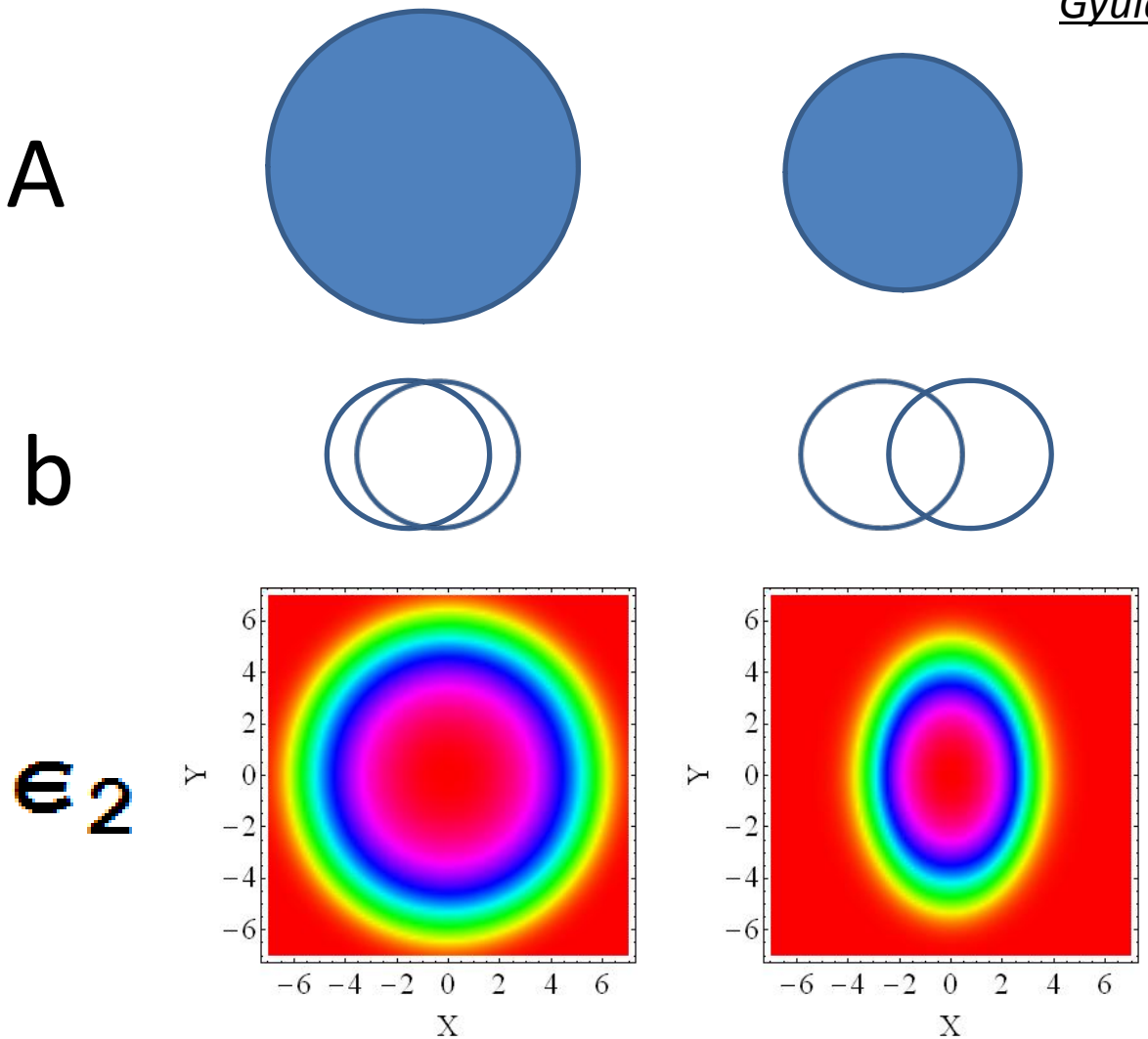
Significant energy loss → color-opaque medium
(high Pt yield (Raa), di-hadron correlation,……)

Strong jet quenching at LHC too: see recent talks at QM2011 and this conference

Geometric Tomography

Geometry of nuclei and geometry of collisions play essential roles in jet quenching.

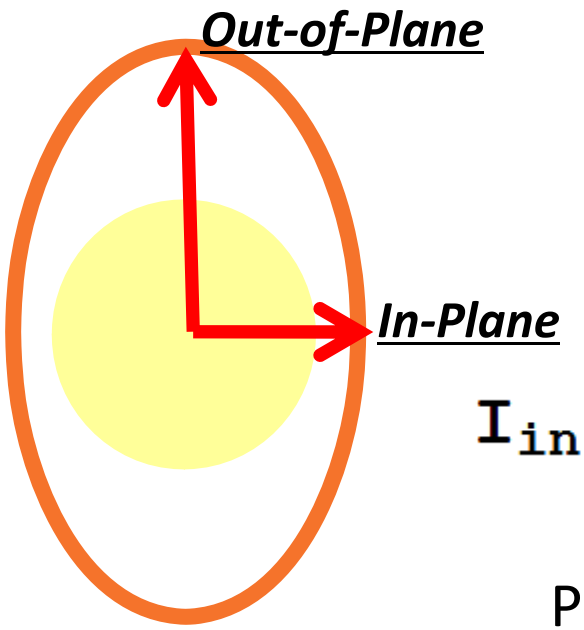
Gyulassy, Vitev, Wang; ……



Same dynamics, different geometry → predictable change in exp. outcome with geometry!

Geometric Data: V2(hard)

Non-central collision → matter spatial anisotropy → quenching anisotropy



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

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

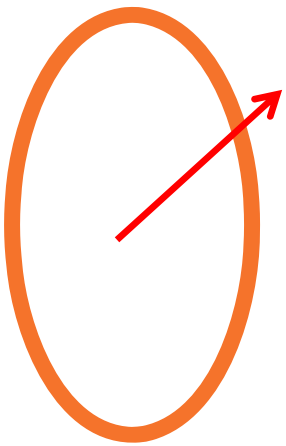
Positive v2 for high Pt particles:

$$v_2\,(\text{high } P_t) = \frac{(R_{aa})_{in} - (R_{aa})_{out}}{2\,[\,(R_{aa})_{in} + (R_{aa})_{out}\,]}$$

More sensitivity, better discriminating power

From Geometry to Dynamics

- Jet energy loss along its path through the fireball



$$\Delta E = \int_{path} F[J \mid M \mid J+M]\, dx$$

$$F[J \mid M \mid J+M] = \frac{dE}{dx} = E^{\delta}\, \kappa[s]\, s\, x^{n}$$

$$E_f = E_i \exp\left[-\int_{path} \kappa[s]\, s\, x^{n}\, dx\right]$$

The "quenching integral" is essential:

- *Initial jet spot (binary coll. profile)*
- *Jet orientation (random)*
- *Medium density (part. profile) & evolution*
- *Quenching strength*
- *Path length dependence (LPM, AdS, …)*

$$\boxed{I = \int_{path} \kappa[s]\, s\, x^{n}\, dx}$$

Using geometric data to test the dynamical features of jet quenching!

(multi-observables & their correlations: Jia,Horowitz,JL, arXiv:1101.0290)

A Bit of History

- Gyulassy-Vitev-Wang (01); Wang (01): pQCD based model predictions
- STAR preliminary data showed much larger v_2 for semi-hard Pt~4GeV
- Shuryak (01): completely opaque bulk, surface emission,

  hard sphere geometry → still considerably smaller → VERY puzzling
- More data out, till Pt~6GeV, the puzzle persisted
- Drees-Feng-Jia (05): more realistic geometric modeling, Glauber geometry,

  various path dependence, Raa as constraint → even worse
- pQCD based models continued to significantly underpredict v2
- PHENIX Run4 data, Run7 preliminary: extending to Pt~15GeV

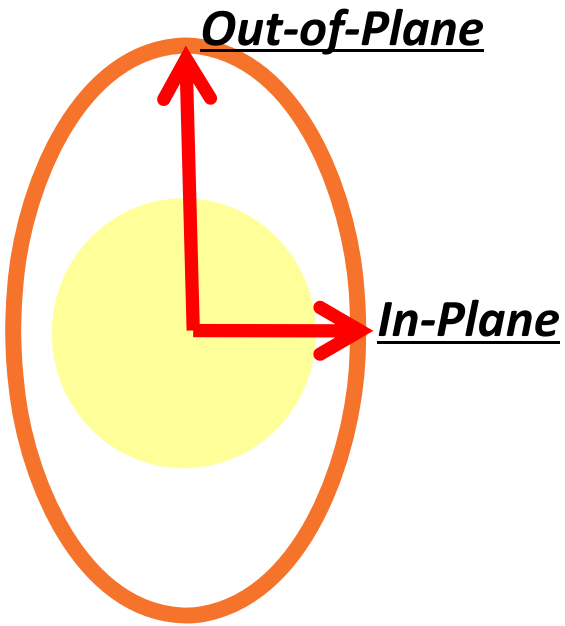
  → rather flat above 6GeV, still large compared with various models
- ??? "an area that is kind of stuck with models not quite working and lack

  of ideas how to proceed"

Till about ~ 2008:

all previous models failed to describe the (already high quality) geometric data by producing <u>too small anisotropy (V2)</u> with fixed opacity (Raa).

Pinning the Right Geometry

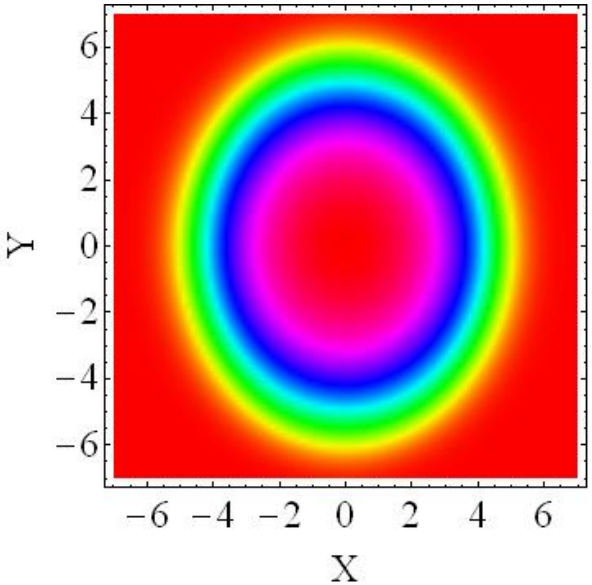


$R_{aa}(\phi)$

The puzzle may concern more radical questions:

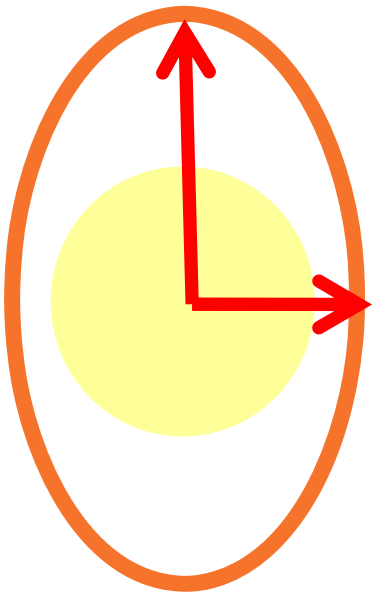
Where are jets quenched ???

JL & Shuryak, PRL102:202302,2009



"Egg yolk" has one geometry,
"Egg white" has another:
overall opacity can not tell →
measure geometry to pin physics

The "Egg Yolk v.s. White"

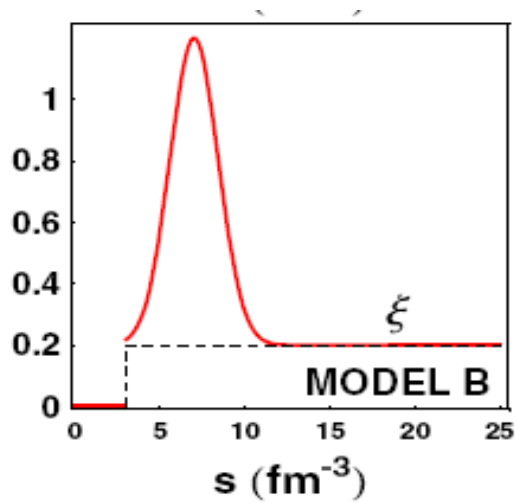


$$I = \int_{path} \kappa[s]\ s\ \ x^n\, dx$$

Taken for granted in ALL previous models:

$$\kappa[s] \Rightarrow \text{constant}$$

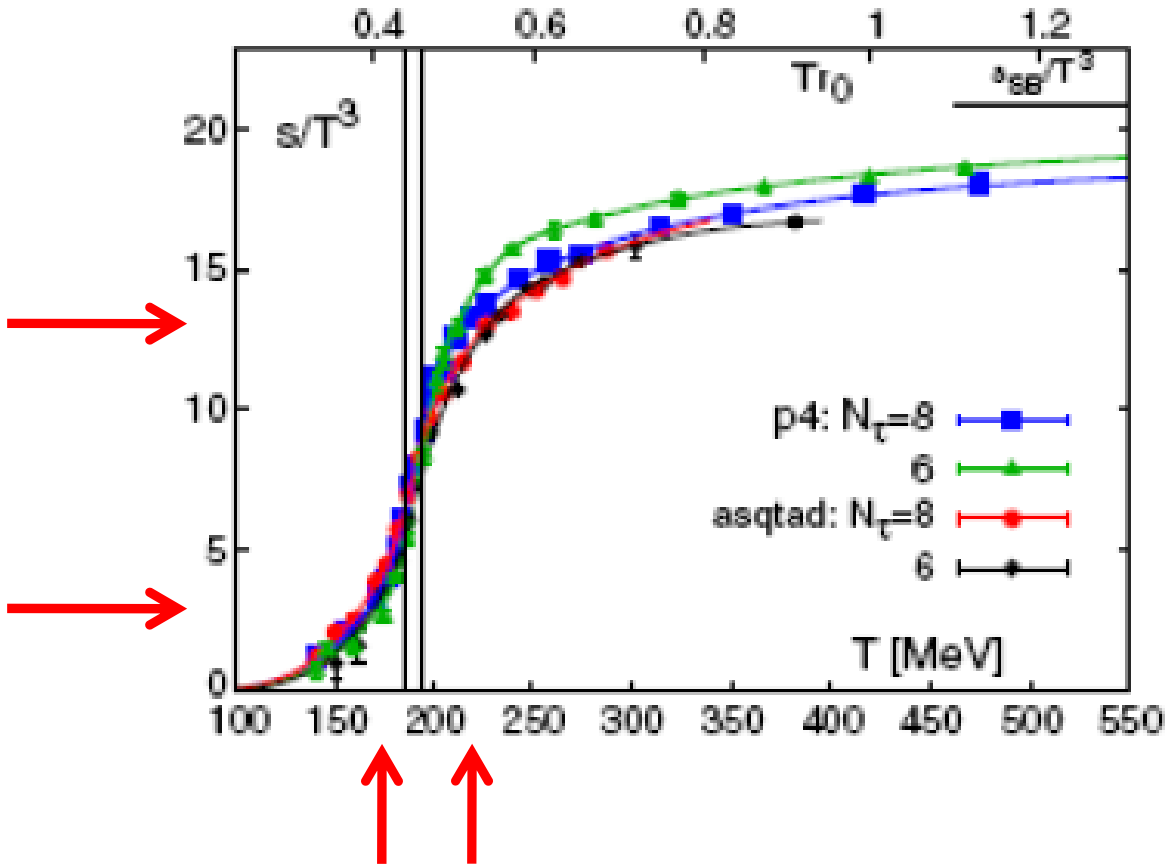
Instead, we think it shall have non-monotonic dependence, particularly enhanced near the phase boundary due to Nonperturbative dynamics related to confinement!



With such strong enhancement
→Enhance quenching at late time
→ Pick up more the "egg white" geometry

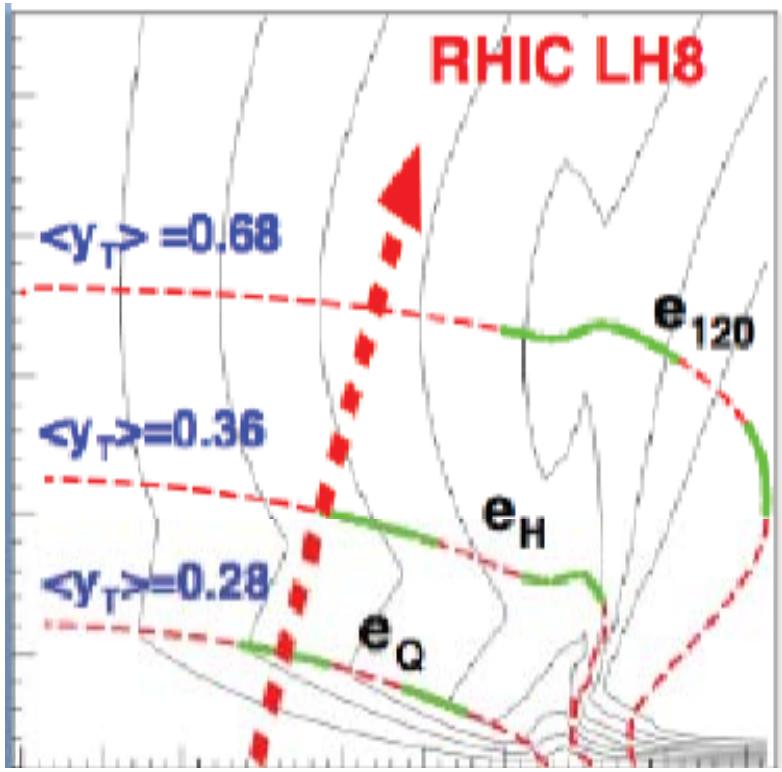
Near-Tc Matter: Thermodynamics

Near Tc is NOT a single point or narrow interval.
It is <u>a wide window</u> in terms of entropy density !

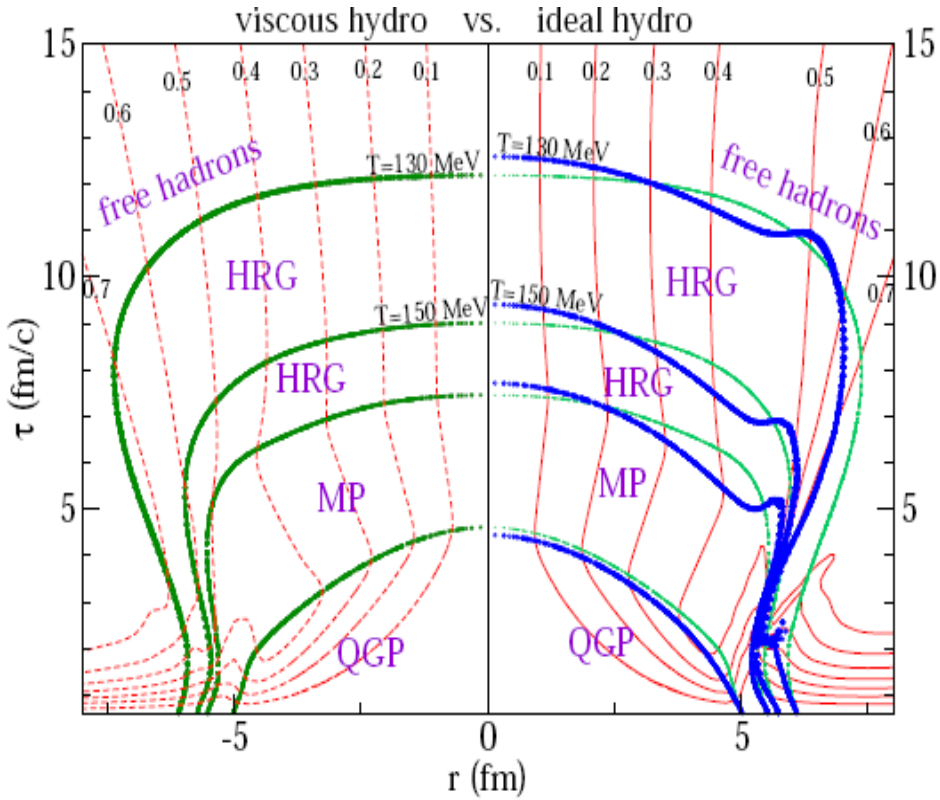


Near-Tc Matter: Hydrodynamics

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



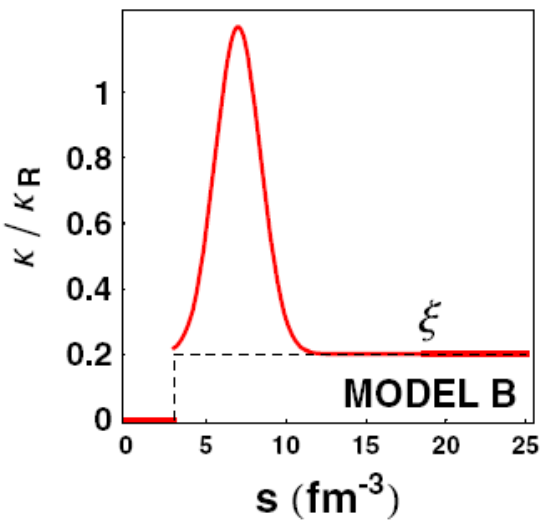
Teaney & Shuryak

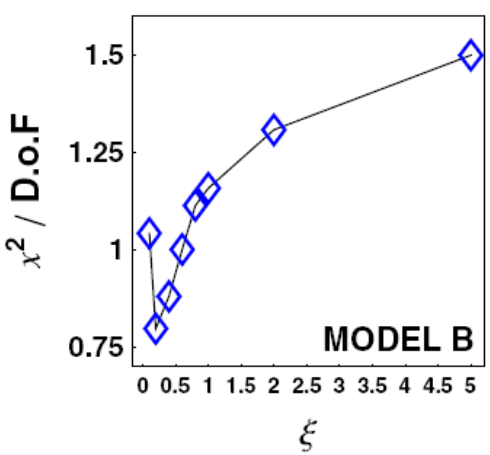


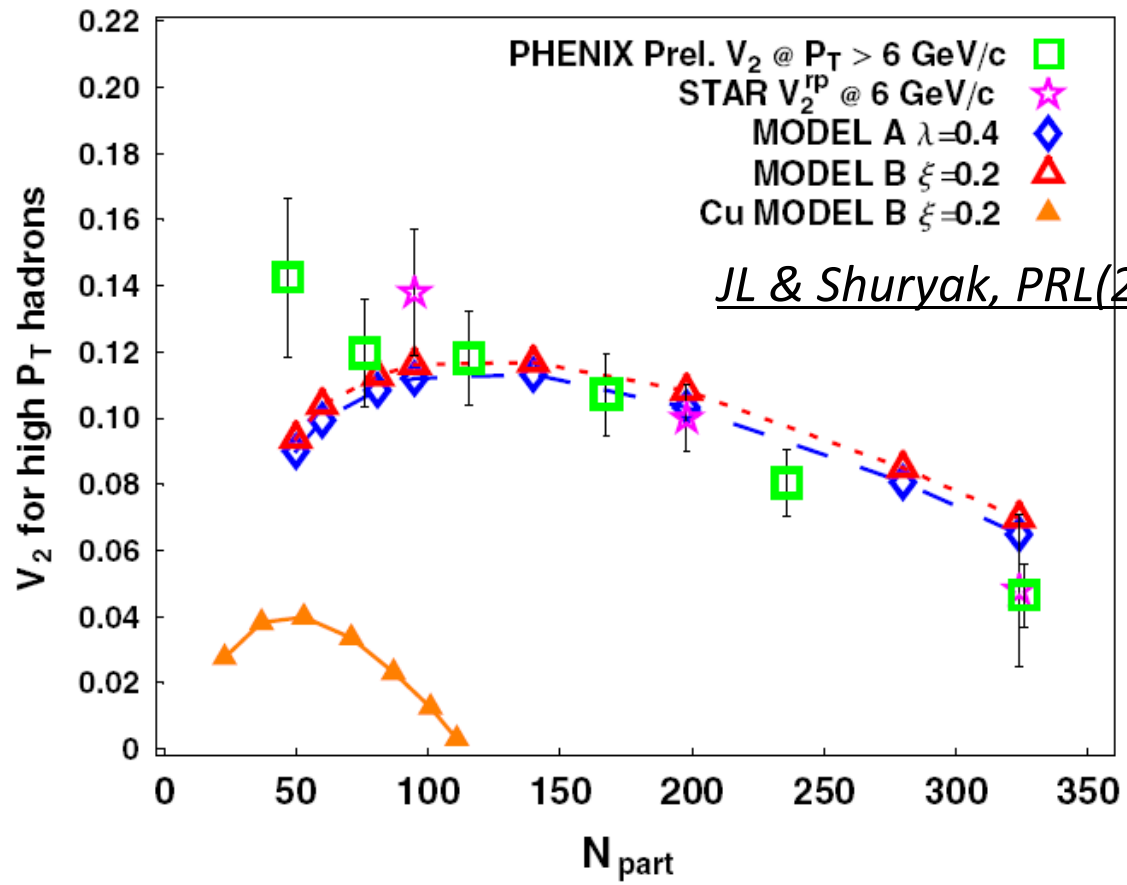
Heinz & Song

Near-Tc Enhancment Explains Geometric Data

Two components: near Tc & QGP.
Assume certain relative quenching strength \xi .
Overall quenching strength fixed by Raa.



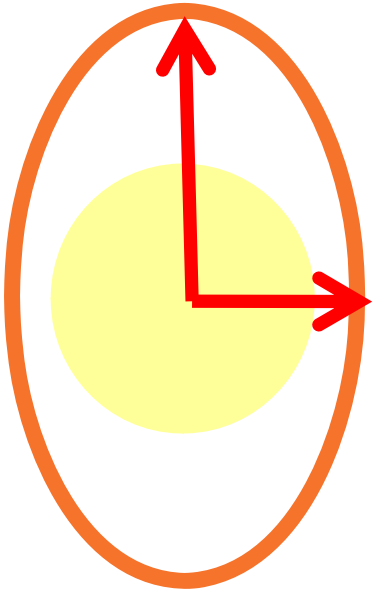




JL & Shuryak, PRL(2009)

Data favors \xi~0.2: VERY strong enhancement of jet quenching in near Tc matter !

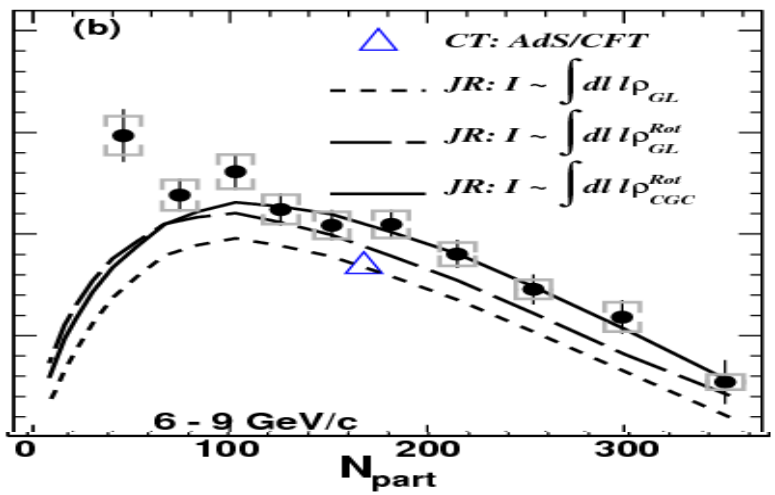
A Lately Story: L^3 Scenario



$$I = \int_{path} \kappa[s]\, s \quad x^n\, dx$$

Naïve: n=0 , linear, L
LPM: n=1 , quadratic, L^2
(some) AdS: n=2 , cubic, L^3

Larger n → stronger path-length dependence
→ amplify the in-/out-of-plane difference
→ effectively delay jet quenching to later time



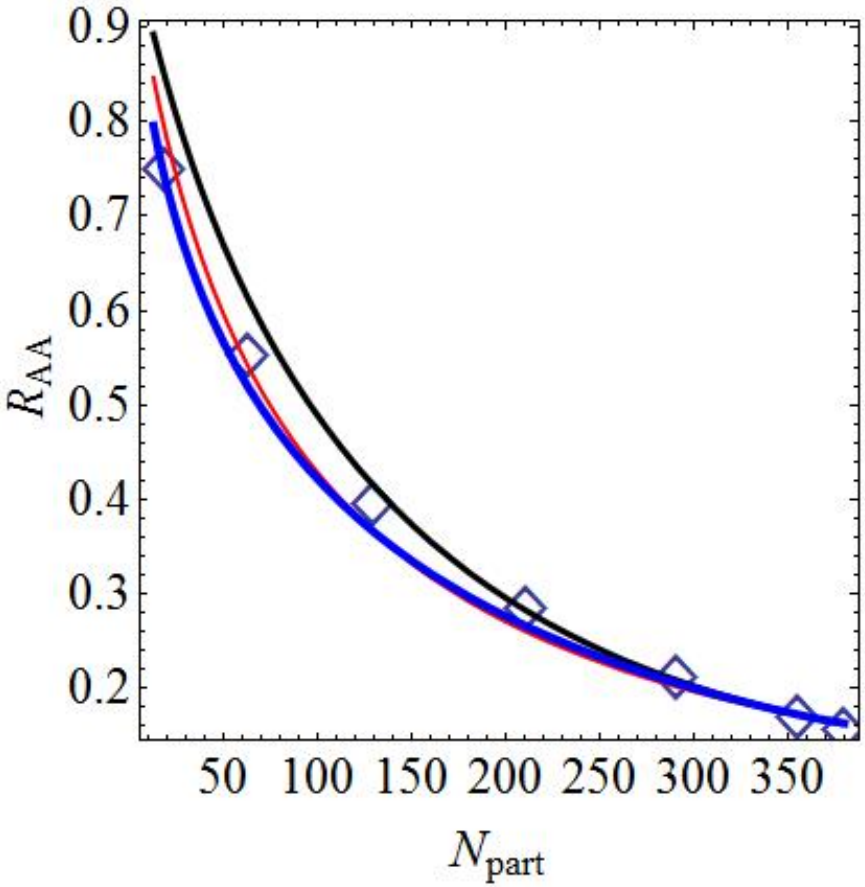
Gubser, et al; Mueller, et al; Marquet,Renk; Jia, Wei;…

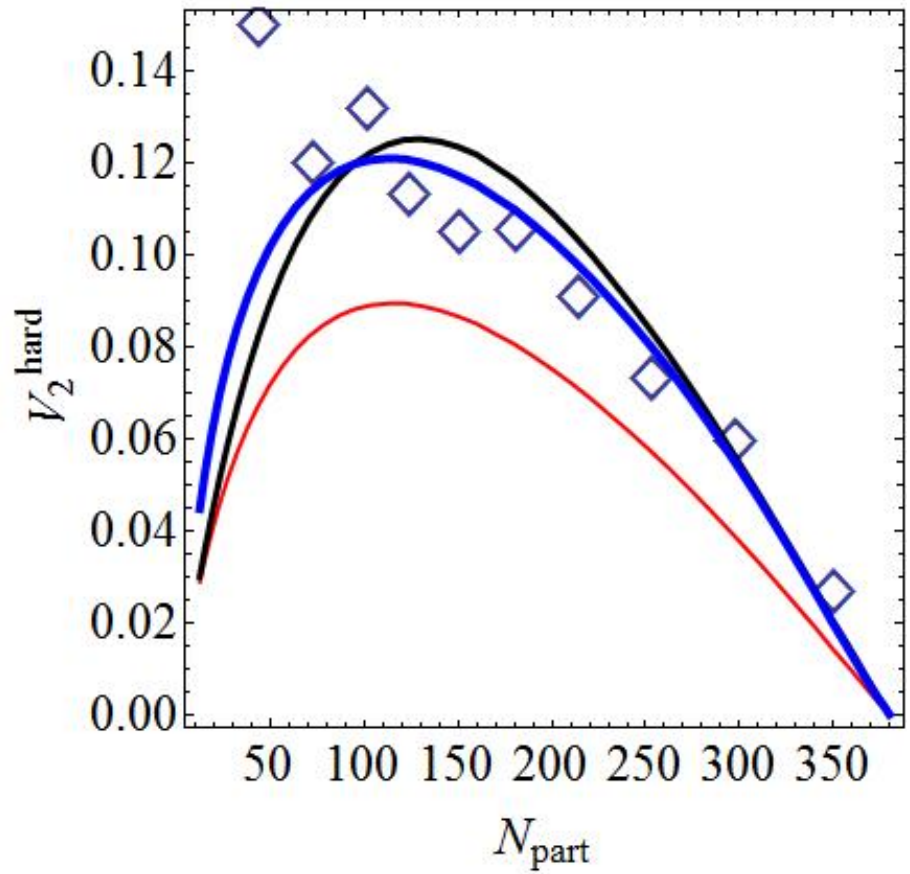
At RHIC, the bulk evolution is such that:
near Tc scenario & L^3 scenario → similar phenomenological consequence.

CAN WE FURTHER DISTINGUISH THEM, e.g. at LHC???

Geometric Data & Modeling @ RHIC

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



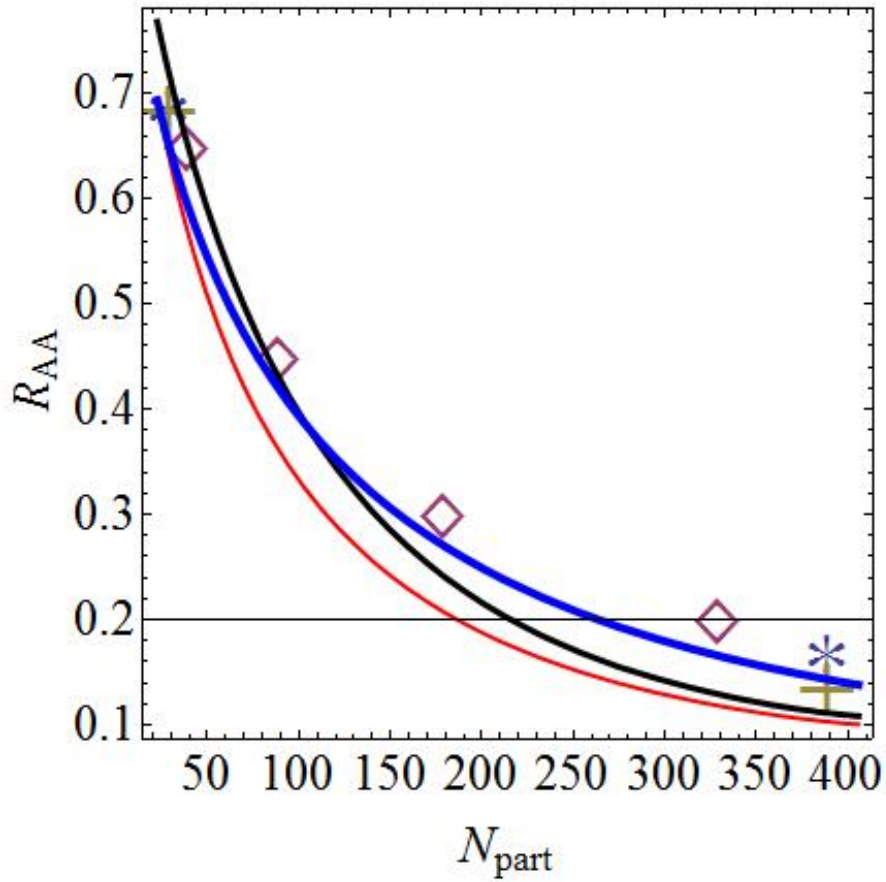


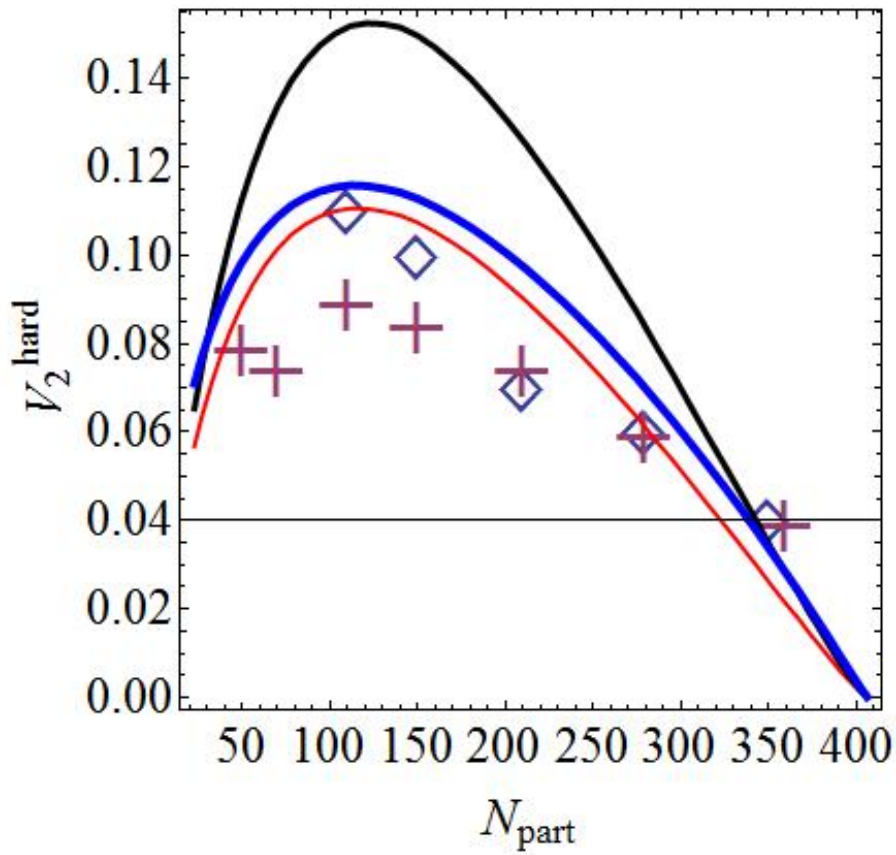
L^2 model does NOT describe v2 data across all centrality.

L^2 with near-Tc enhancement AND L^3 model both are OK
--- they both effective enhance later-stage quenching!

Geometric Data & Modeling @ LHC

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





L^2 model : *over quenching (due to strong density scaling-up); describing v2 OK.*
L^2 model : *too much anisotropy (due to strong path-length power); describing Raa OK.*

L^2 with near-Tc enhancement*: describe both Raa and V2 very well !*

Summary

◆Jet quenching: geometric data provides essential test for the dynamics of jet-medium interaction.

	Raa @RHIC	V2(hard) @RHIC	Raa @LHC	V2(hard) @LHC
L^2 model	√	×	×	√
L^2 + near-Tc	√	√	√	√
L^3 model	√	√	√	×

◆Precision RHIC data & preliminary LHC data together are much in favor of the model with

strongly enhanced jet quenching in near-Tc matter!

Post-Sumary: Physics of Near-Tc.

sQGP as an E-M SEE-SAW QGP

JL & Shuryak, PRC(07),PRL(08)

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

Magnetic:
g ~ 1

RHIC

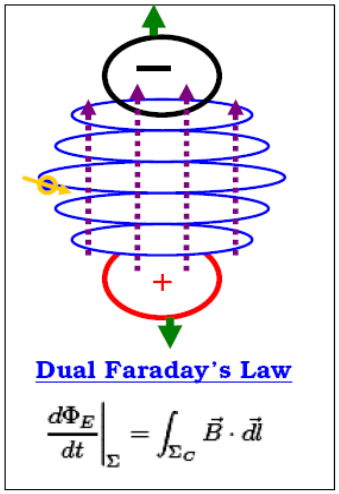
Electric:
e ~ 1

(semi-QGP)

Strongly coupled plasma with E & M charges (magnetic scenario)

Magnetic:
g<<1 , light, condensed!

Electric:
e>>1, heavy, confined!



Electric:
e<<1 , light, dense

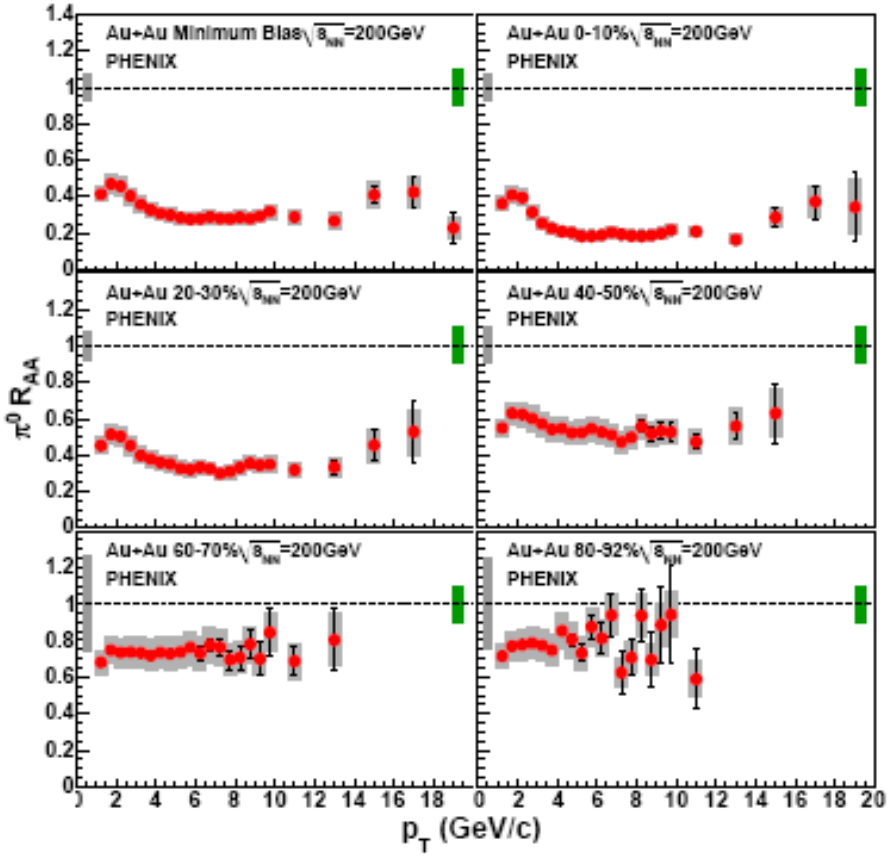
Magnetic:
g>>1 , heavy,dilute

BACKUP SLIDES

An Opaque Medium

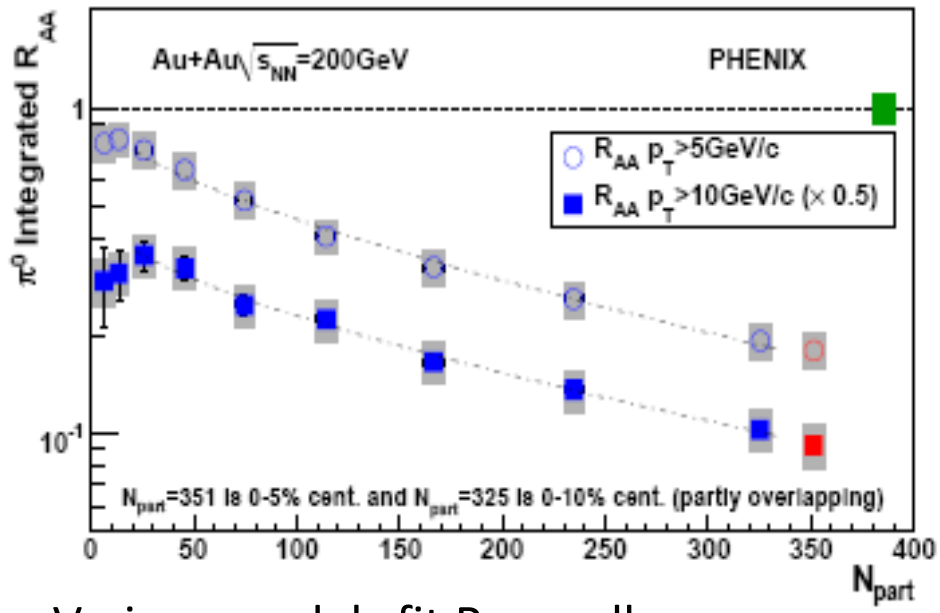
Raa characterizes the ***overall medium opacity.***

Directly related to average of quenching integral.



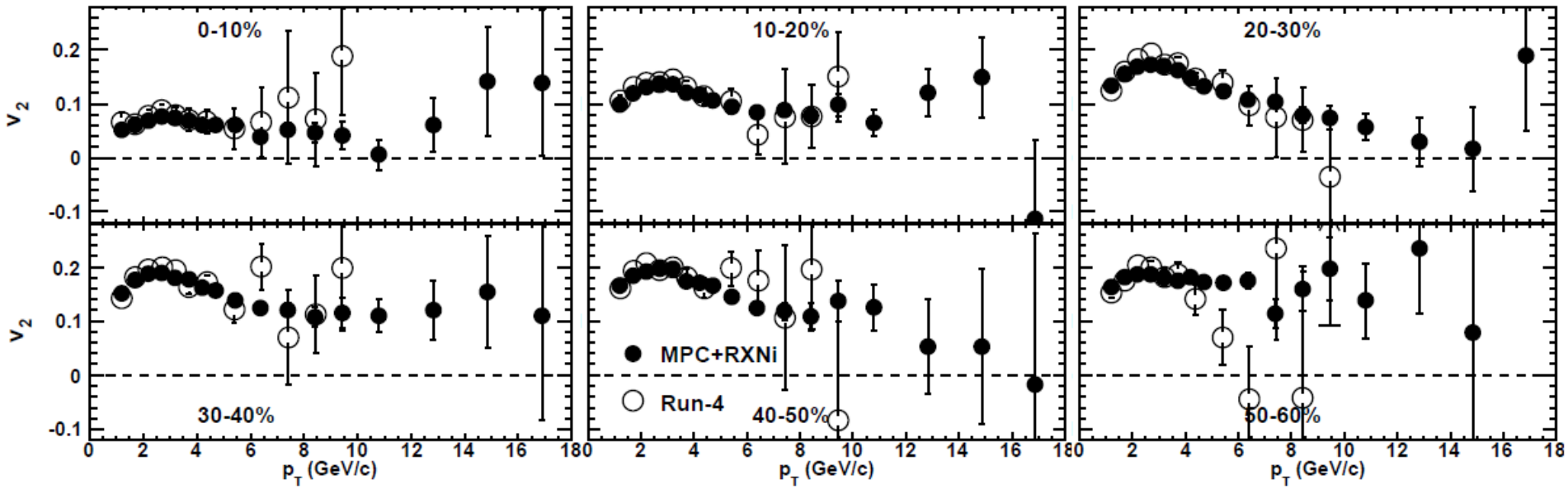
PHENIX (08)

$$R_{aa} = \langle e^{-6.1*I} \rangle$$

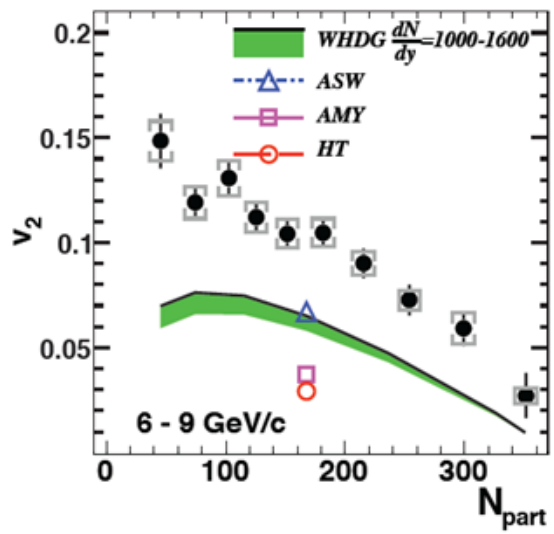


Various models fit Raa well;
Four pQCD-based models require
very different, but all large values of q-hat.

The State-of-Art RHIC Data



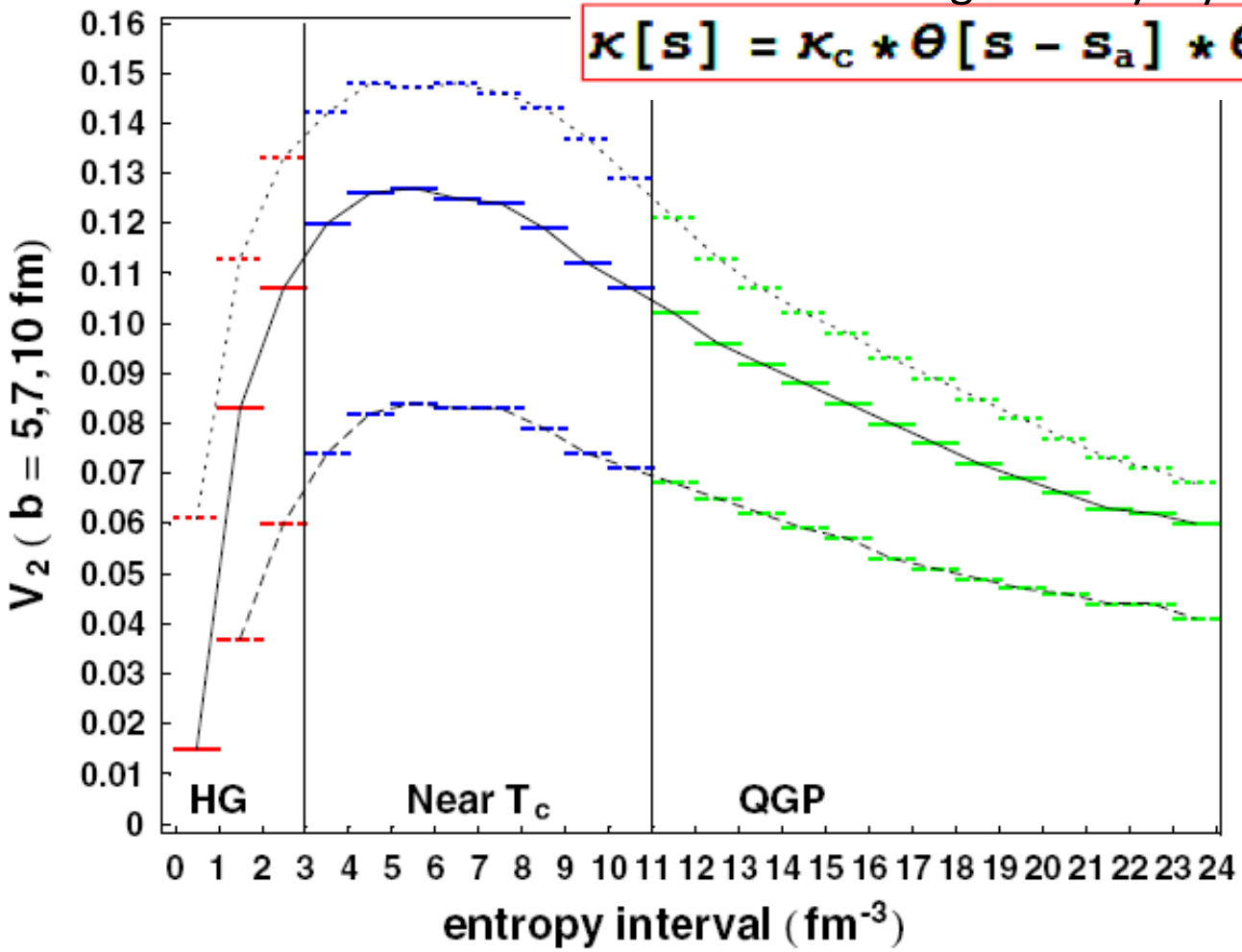
PHENIX Run4 & Run7



Layer-wise Jet Quenching

Scan the fireball geometry layer by layer

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

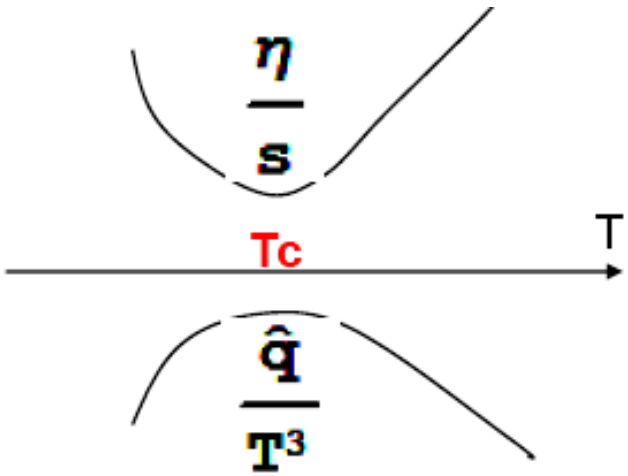


Jet quenching in the near Tc matter yields the largest geometric anisotropy!

Related Supportive Hints

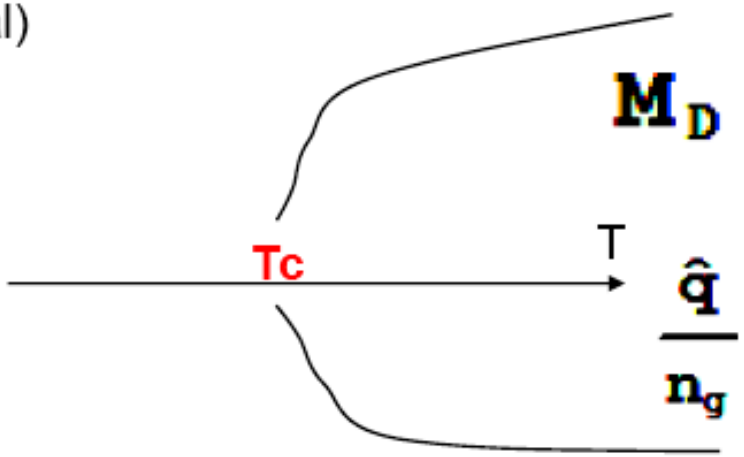
Eta/s & q-hat (Majumder,Muller,Wang,'07):

$$\frac{\eta}{s} \times \frac{\hat{q}}{T^3} \sim \text{constant}$$



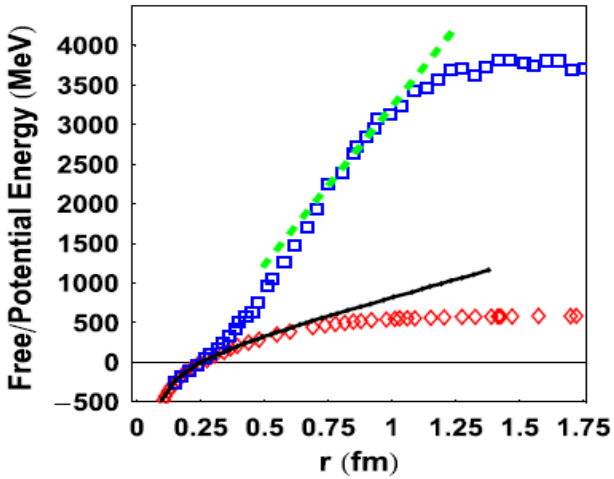
GW/GLV jet quenching model(Gyulassy, et al)

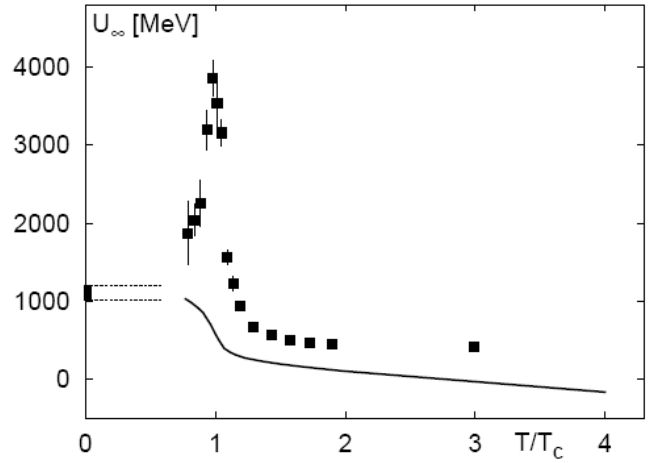
$$\frac{\hat{q}}{n_g} \sim \alpha * \mathrm{Log}\left[\frac{Q_{UV}}{M_D}\right]$$



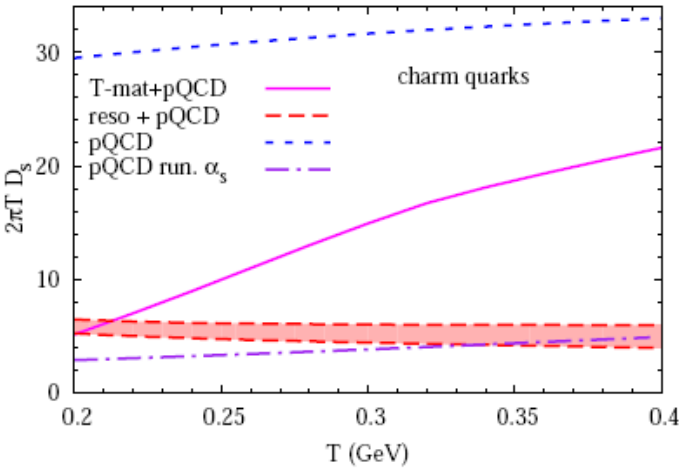
Related Supportive Hints

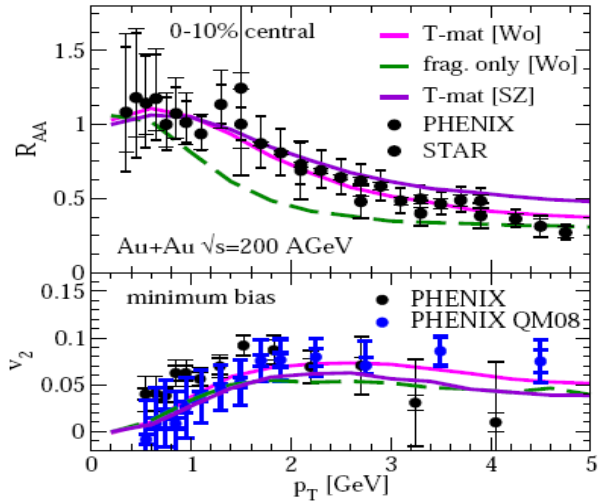
Lattice Q-bar-Q potential: significant separation energy peaked around Tc





Heavy quark phenomenology favors "valley" of diffusion constant around Tc (R Rapp & collaborators)





Recent Developments

- confirmation of near Tc scenario in e.g. GLV,ASW type of jet quenching models

  Renk-Holopainen-Heinz-Shen (arXiv:1010.1635)

  Francesco-Di Toro-Greco (arXiv:1009.1261)

  Fries & students (to appear)

- physical near-Tc mechanism (pre-hadron loss in resonance matter; radiation of Cherenkov meson)

  Pirner, et al (arXiv:1010.0134)

  [Panuev, formation time ~3fm]

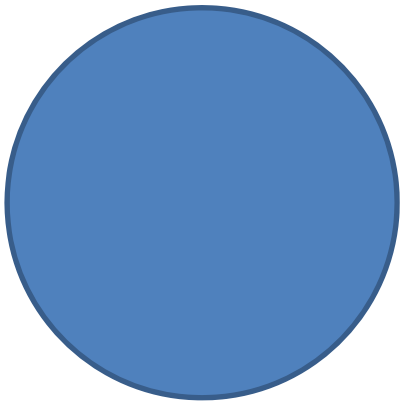
  Casalderrey-Solana, et al (arXiv:1009.5937)

- alternative late-stage jet quenching via L^3

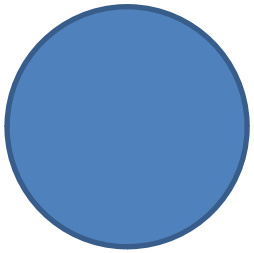
  Marquet & Renk; Jia & Wei; Renk-Heinz et al.

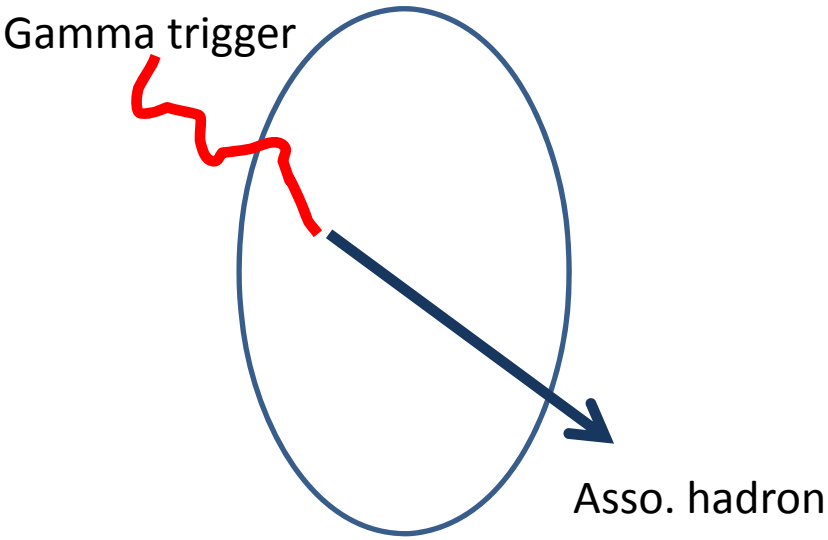
Near-Tc v.s. L^3

Can we distinguish the two different scenarios?



AuAu to CuCu:
L^3 more sensitive
to system size





Gamma-hadron correlation:
Pt fraction z tells path length;
Look at Iaa and Iaa(phi)

E-M SEE-SAW

JL & Shuryak, PRC(07),PRL(08)

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

Magnetic:
g ~ 1

RHIC

Electric:
e ~ 1

(semi-QGP)

Strongly coupled plasma with E & M charges (magnetic scenario)

Magnetic:
g<<1 , light, condensed!

Electric:
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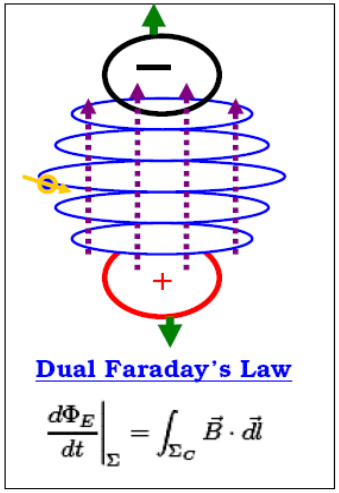
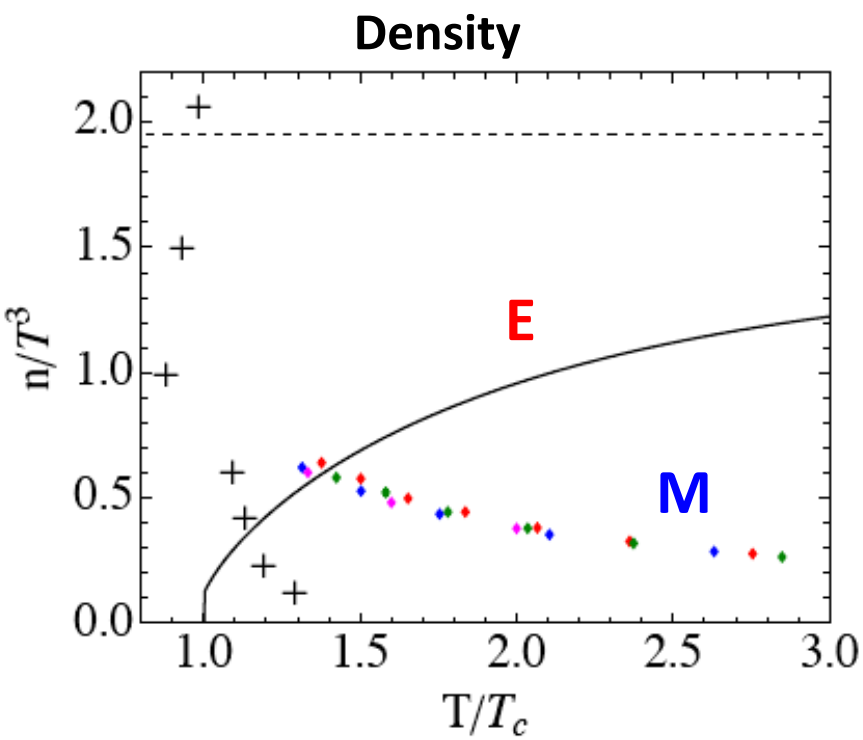
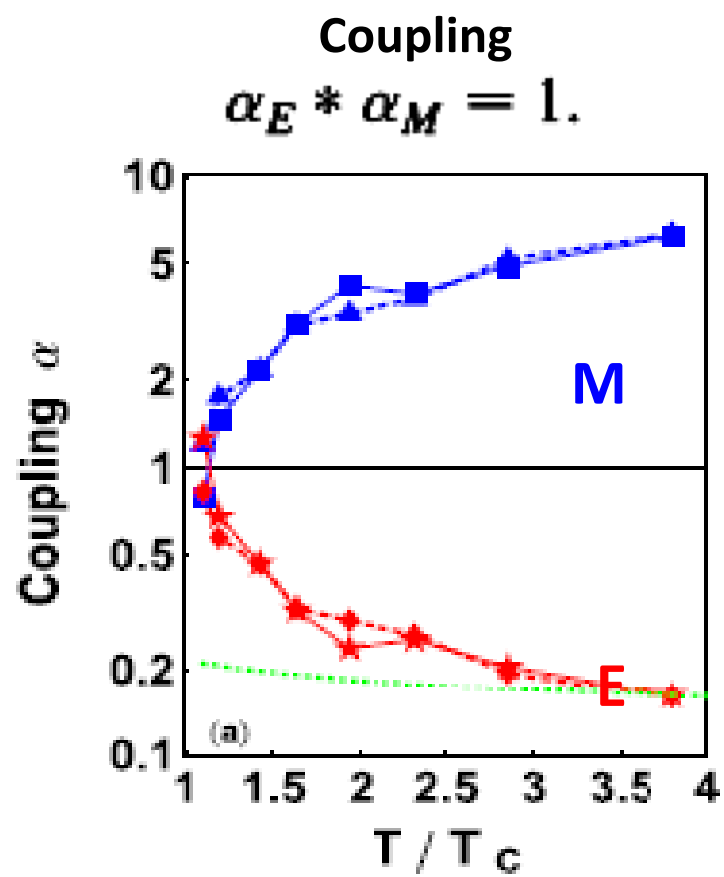


Electric:
e<<1 , light, dense

Magnetic:
g>>1 , heavy,dilute

The See-saw in Density & Coupling





See-saw at work !
Expect rapid change at higher T

JL & Shuryak, 06,07,08; Claudia & Shuryak, 08;
(Lattice) Delia, et al, 07; (semi-QGP) Pisarski, et al, 08.