Thursday, Sept 24, 2015, 10:30 AM (Beijing time) seminar

The 41th HENPIC seminar:Jet Quenching and Tomography in semi-Quark-Gluon-Monopole-Plasmas Produced in A+A reactions at RHIC and LHC

中国高能核物理网络论坛

Speaker： Miklos Gyulassy,Columbia University

Date：Thursday, Sept 24, 2015, 10:30 AM (Beijing time)

Download：http://pan.baidu.com/s/1sjK6iN7#path=%252F2015

abstract:

Experiments at RHIC/BNL and LHC/CERN on high energy heavy ion reactions in the past decade found that QCD matter at densities about 100 times higher than in cold nuclei exhibits near ??erfect fluid??bulk collectivity as well as ??et quenching??of high energy QCD jets. The simultaneous compatibility of these two phenomena has remained a challenge to both weakly coupled perturbative QCD based tomographic theories and also to strongly coupled AdS gravity dual based holographic theories. While perturbative QCD tomography accounts quantitatively for jet quenching, it fails to account for bulk perfect fluidity. Conversely, while AdS holography automatically explains perfect fluidity, it fails to account quantitatively for the jet quenching systematics. In this talk, I describe our recent proposal [1] to explain both phenomena simultaneously as due to competing effects related to the non-perturbative non-conformal physics of color confinement in QCD as the system cools through the critical temperature range 150-300 MeV. In this temperature range, partial confinement of quark and gluon color electric charge degrees of freedom and emergent color magnetic monopole degrees of freedom are modeled by a non-perturbative non-conformal semi-Quark-Gluon-Monopole-Plasma (sQGMP) with composition and screening properties completely constrained by lattice QCD data. Consistency and robustness of the sQGPM tomographic framework CUJET3.0 predictions compared with all current RHIC and LHC data are demonstrated. Predictions for future heavy quark jet tagged quenching observables are presented.

[1] J.Xu, J. Liao, MG, Chin.Phys.Lett. 32 (2015) 9, 092501; arXiv:1508.00552

Outline:

1) Intro to what is a sQGP
2) Experimental Heavy Ion from Bevalac 1974 to LHC today
3) Perfect Fluidity pT<2 GeV and Jet Quenching pT>10 GeV
4) The jet v2(pT>10) problem
5) Our CUJET3.0 sQGP = sQGMP solution to jet RAA and v2
6) Consistency of Jet transport field qhat(E,T) with minimal viscosity to entropy ratio of an sQGMP

Part 1: So, What is a sQGP?

sQGP is a novel form of QCD matter discovered in 2004 at RHIC in Au+Au@200 AGeV and probed since 2010 at LHC in Pb+Pb@2760 AGeV

Theoretical interpretations of sQGP include

1) strongly interacting – Quark - Gluon Plasma (sQGP)

2) Color Glass Condensate and Glasma Yang Mills Fields

3) 10D *Black Holes* in $AdS_5 \times S_5$ with strings in bulk

4) Unruh Radiation *Fields* from Accelerating SU(N) sources

5) semi-Quark-Gluon-Monopole Plasma (sQGMP)

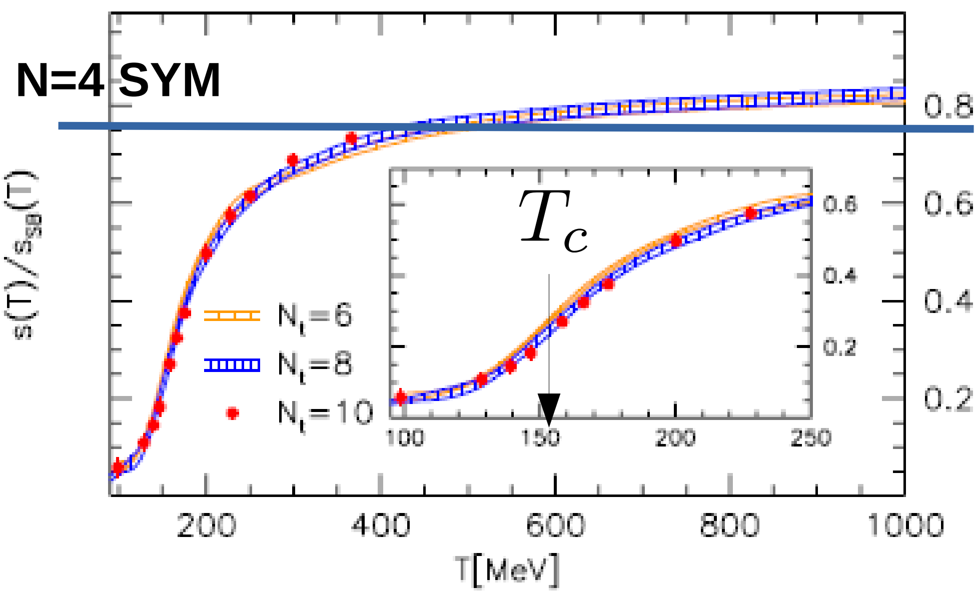
Ref 1, 2: M.G, L. McLerran, NPA750(2005).
Ref 3: S.Gubser (2007);W.Horowitz, J.Noronha, A.Ficnar, MG (2007 - 2014)
Ref 4: D.Kharzeev et al (2007); T.S. Biró, Z.Schram, MG PLB708 (2012)
Ref 5: Jiechen Xu, Jinfeng Liao, MG: 1411.3673, 1508.00552 [hep-ph]

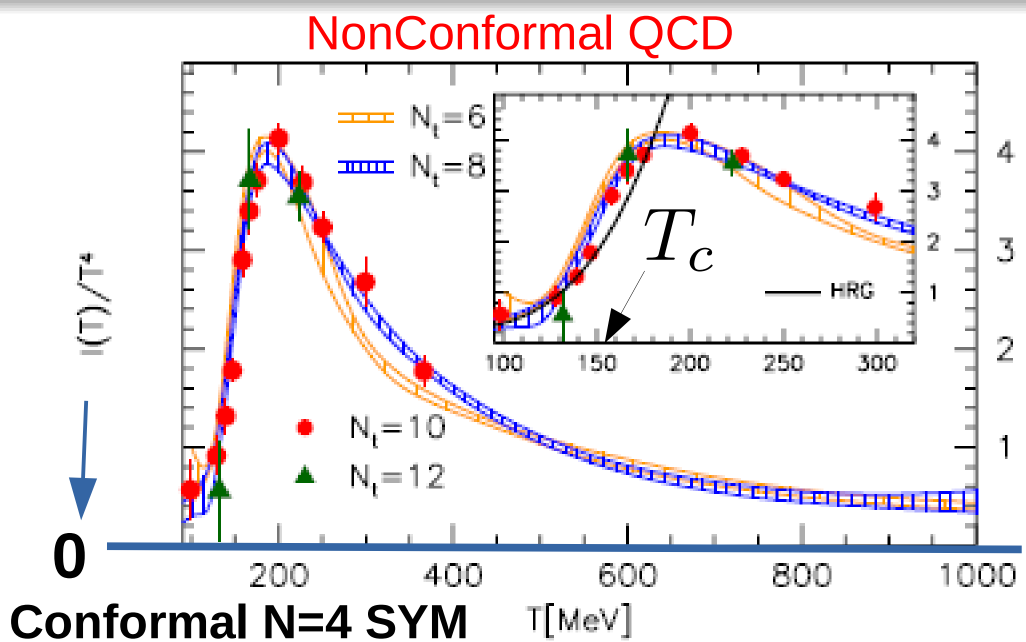
J.Liao, E.Shuryak PRC75 (2007)

Quark Gluon Plasma phase of ***Equilibrated*** QCD matter

(lattice QGP vs its conformal N=4 Supersymmetric YM cousin)

Entropy and trace anomaly $T^{\mu}_{\mu} = \epsilon(T) - 3P(T) \equiv I(T)$





good agreement with the HRG model up to the transition region

T_c can be defined as the inflection point of the trace anomaly

Inflection point of $I(T)/T^4$	154(4) MeV
T at the maximum of $I(T)/T^4$	187(5) MeV
Maximum value of $I(T)/T^4$	4.1(1)

sQGP is not a Hadron Resonance Gas beyond 150 MeV
sQGP is not a 3-loop perturbative QCD plasma below 500 MeV
sQGP is not a conformal N=4 super Yang-Mills plasma below 500 MeV

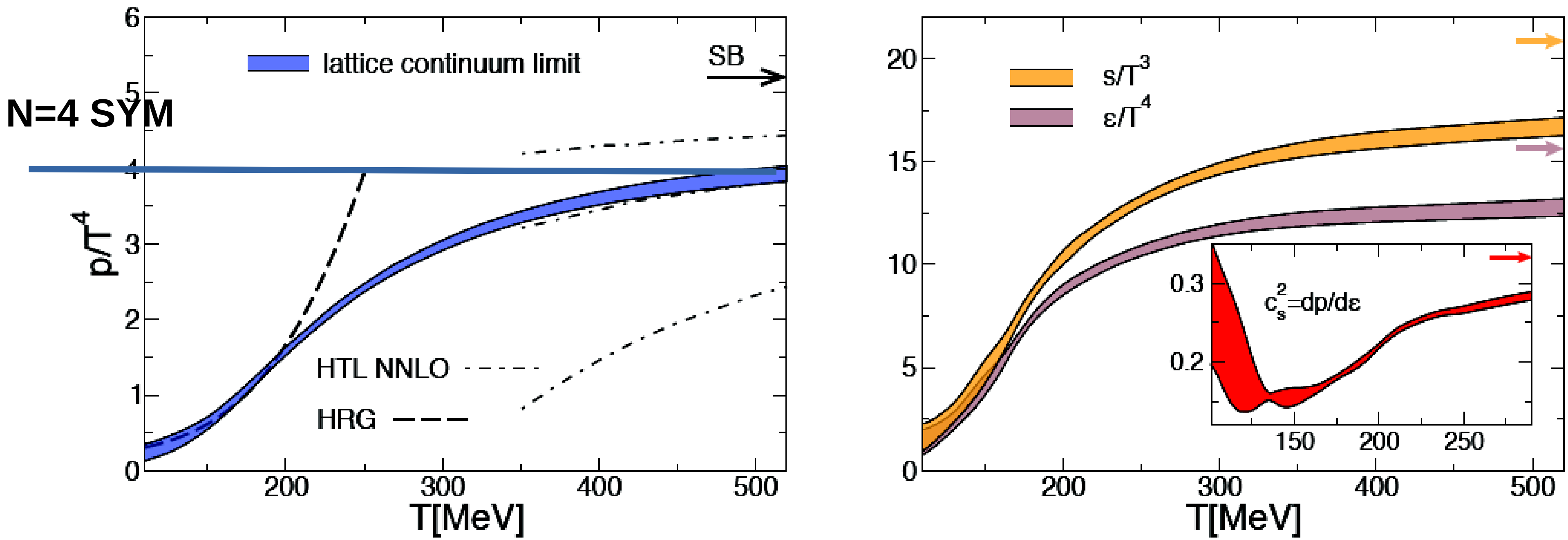


Figure 6: *Left:* continuum extrapolated result for the pressure with $N_f = 2 + 1$ flavors. The HRG prediction is indicated by the black line at low temperatures, at high temperature we show a comparison to the NNLO Hard Thermal Loop result of ref. [31] using three different renormalization scales ($\mu = \pi T$, $2\pi T$ or $4\pi T$). *Right:* entropy and energy density. The insert shows the speed of sound.

Could it be a non-conformal 5D “Black Hole” in asymptotic AdS ?
Could it be a semi-Quark-Gluon-Monopole-Plasma ?

Clearly theory needs guidance from experiment

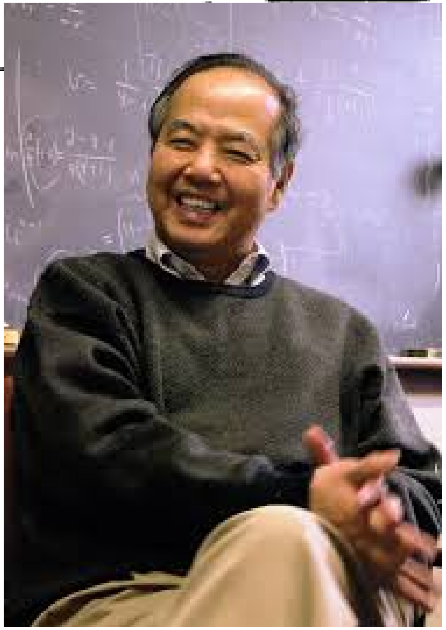
Workshop on BeV Collisions of Heavy Ions: How and Why

Nov 29 - Dec 1 1974

Bear Mountain New York

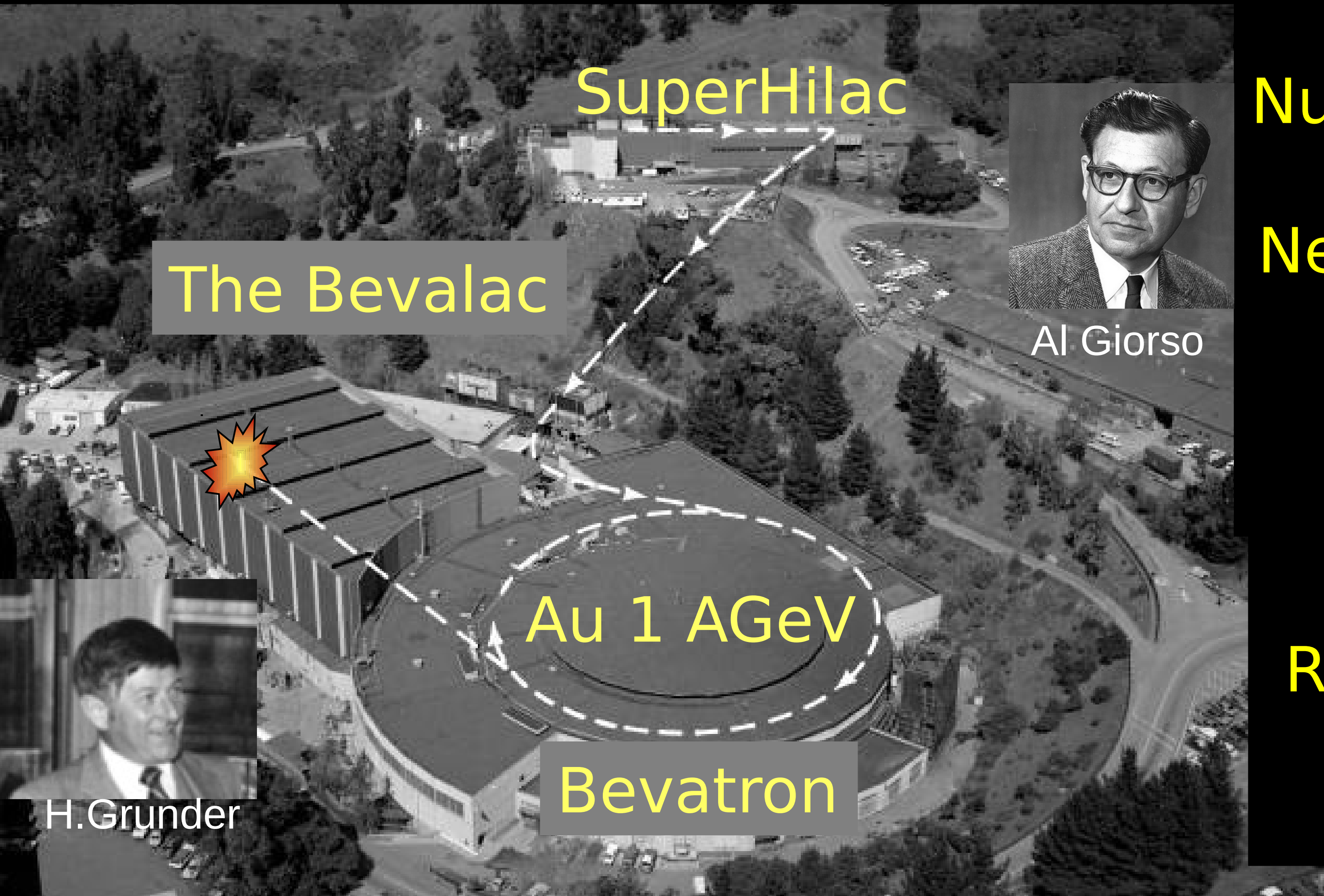
Hitherto, in high energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions. In order to study the question of "vacuum", we must turn to a different direction; we should investigate some "bulk" phenomena by distributing high energy over a relatively large volume. The fact that this direction has never been explored should, by itself, serve as an incentive for doing such experiments.

Vacuum Stability and Vacuum Excitation in a Spin 0 Field Theory
T.D. Lee, G.C. Wick , Phys.Rev. D9 **(1974)** 2291-2316



T.D Lee @ Quark Matter 1980

Lawrence Lab 1974 (the birth of experimental HeavyIons)



Nuclear Chemistry
Alchemy:
Ne +Pb -> Au + X

&

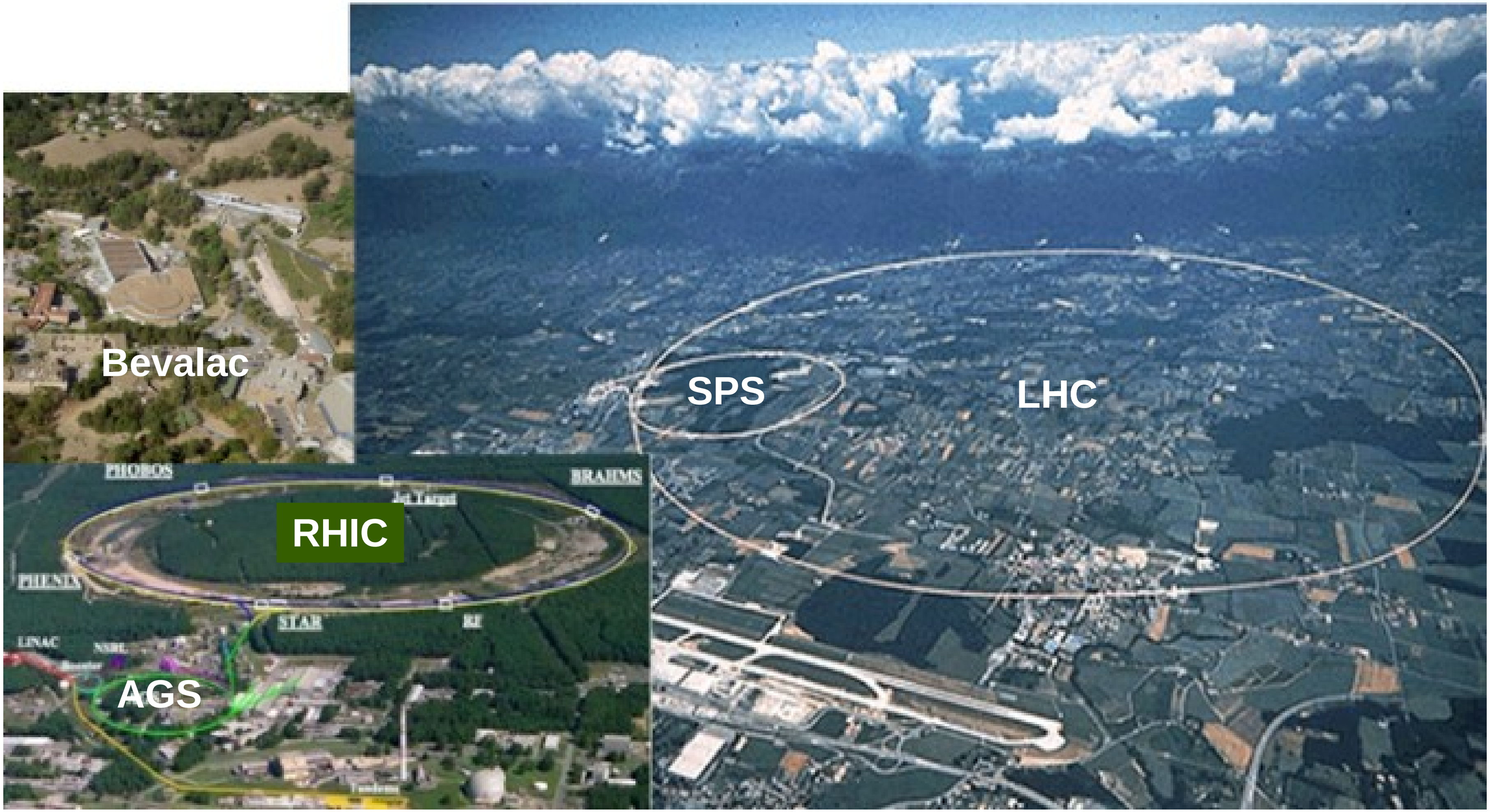
Reverse Alchemy
Au+Au -> ??

- T.D. Lee, C. Wick, “Abnormal Nuclear States and Vacuum Excitations” (74)
- W. Greiner, H.Stöcker “Nuclear Shock Waves in Heavy Ion Collisions”(74)
- J.C. Collins, M.F. Perry “Superdense Matter… Asymptotically Free Quarks?” (75)
- M. Gyulassy, W. Greiner “Pion Condensation in Heavy Ion Collisions” (76)
- E. Shuryak “Quark-Gluon Plasma and Hadronic Production of Leptons (78)
- J.D.Bjorken, L.McLerran “Explosive Quark Matter and the Centauro Event (79)
- M. Gyulassy, et al “Pion Interferometry of Nuclear Collisions” (79)

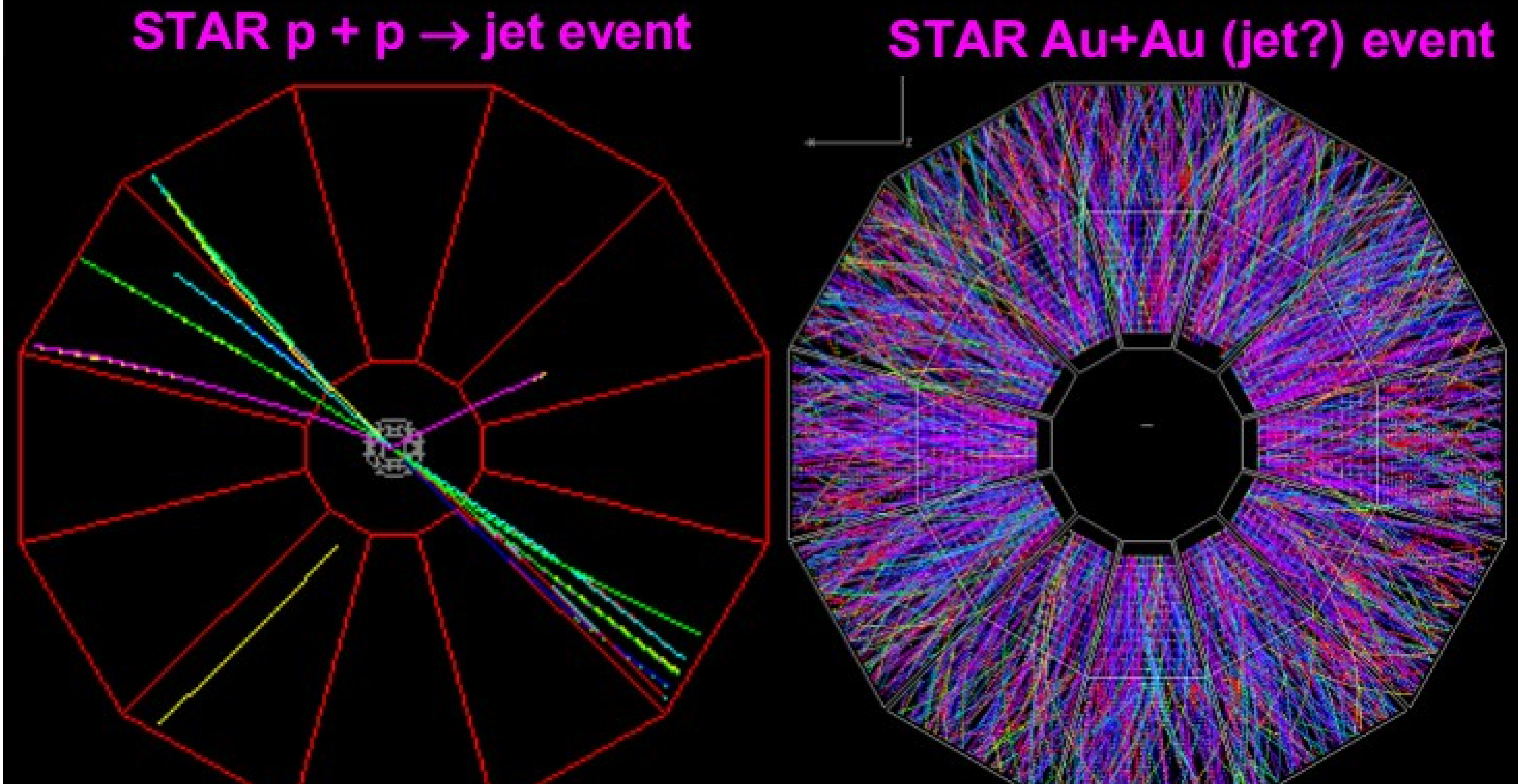
40, 000 Man Years of Exploration and Discovery of New Extreme Forms of QCD Matter

Via p+p, p+Pb, Cu+Cu, …, U+U $\sqrt{s}$ = 2 AGeV – 5 ATeV

40 years of A+A accelerator and detector development from 1974 - today



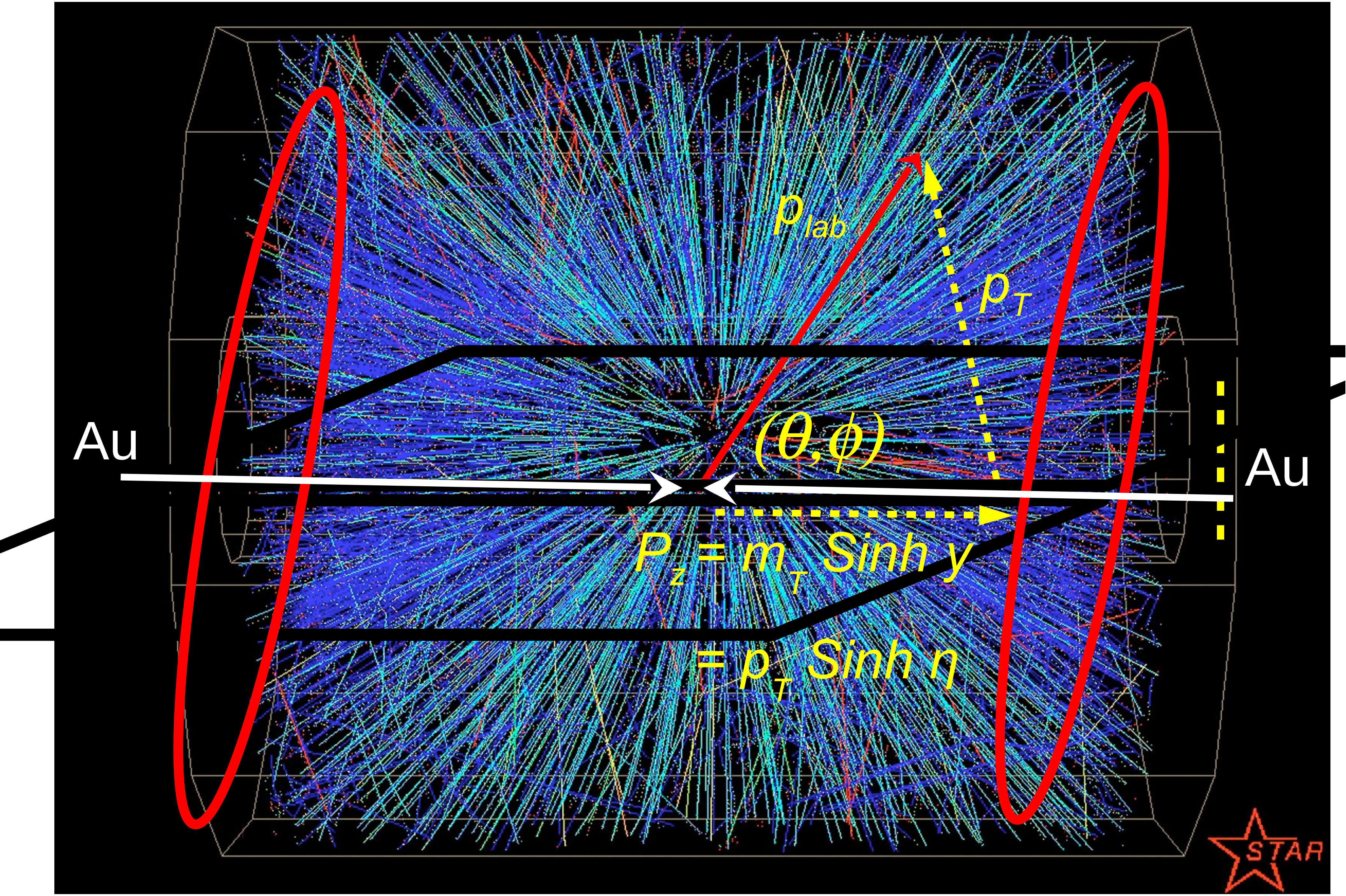
Comparing p+p to Au+Au reactions in STAR Time Projection Chamber at RHIC/BNL Ecm= 200 AGeV



How can we use ~10,000 pi, K, p, γ, ψ , ... correlations to infer properties of new phases of strongly interacting color gluon fields (CGC) and quark/gluon matter (QGP)?

John Harris (Yale) LNF Spring School, Frascati 12 – 16 May 2008

RHIC Au+Au → 1000 pi, K, … 200 AgeV event in STAR TPC



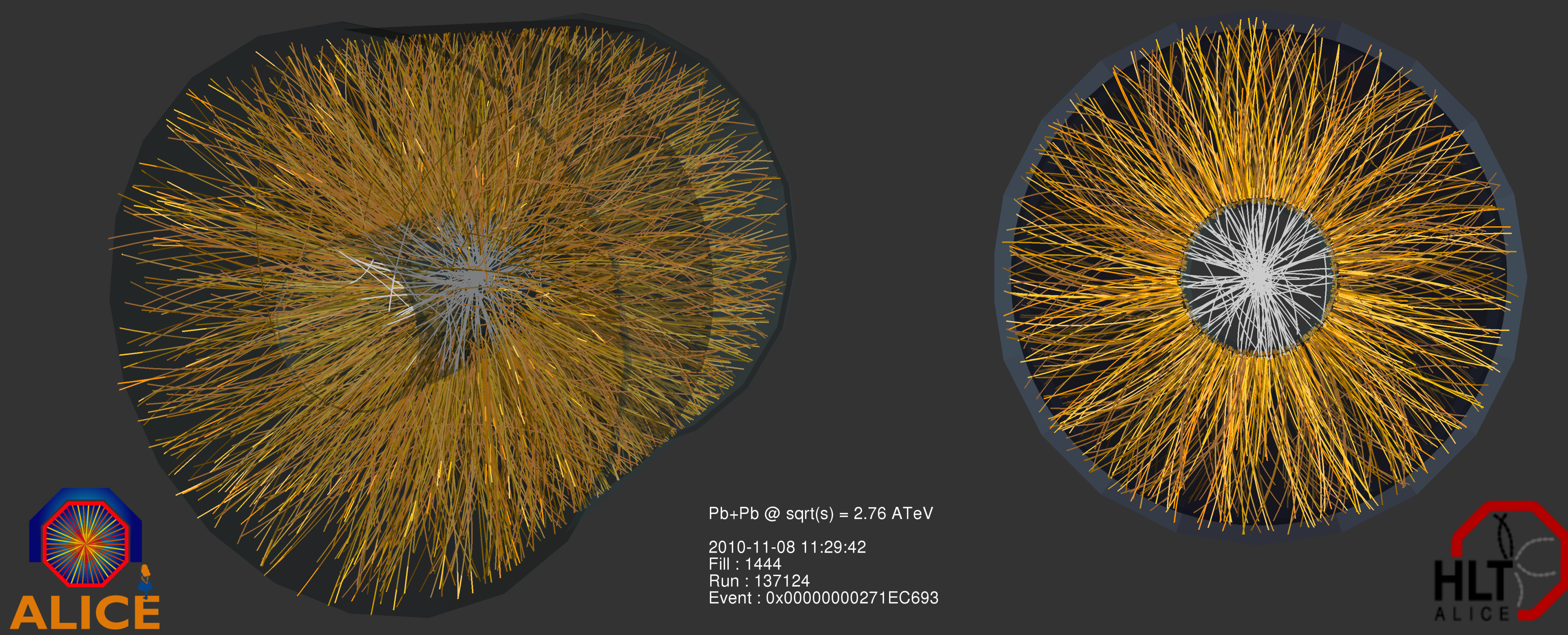
Twice density of sQGP at LHC compared to RHIC

Pb+Pb LHC

Au+Au RHIC

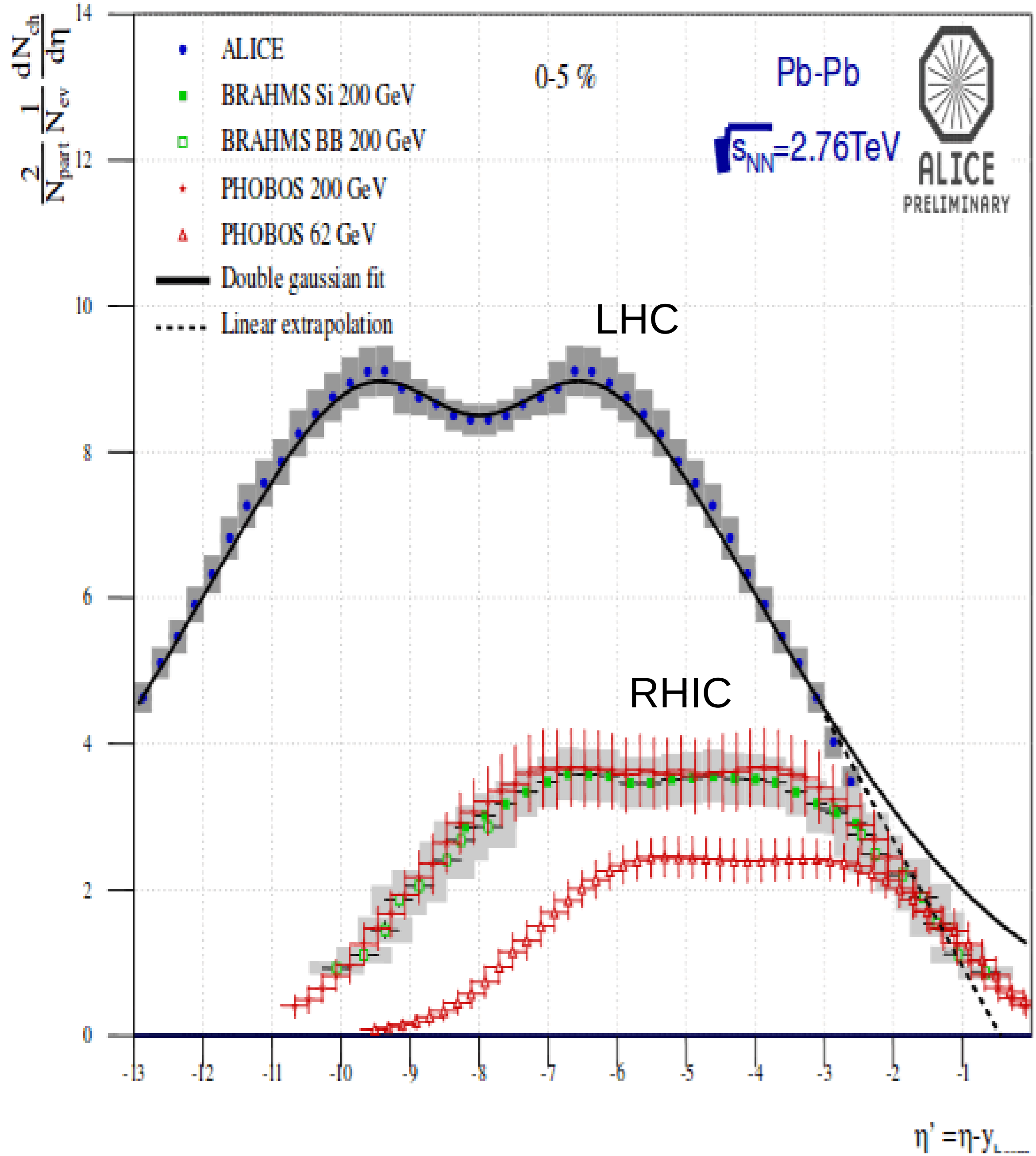
$\Delta N_{ch} / \Delta y \sim 2000$

$\Delta N_{ch} / \Delta y \sim 1000$

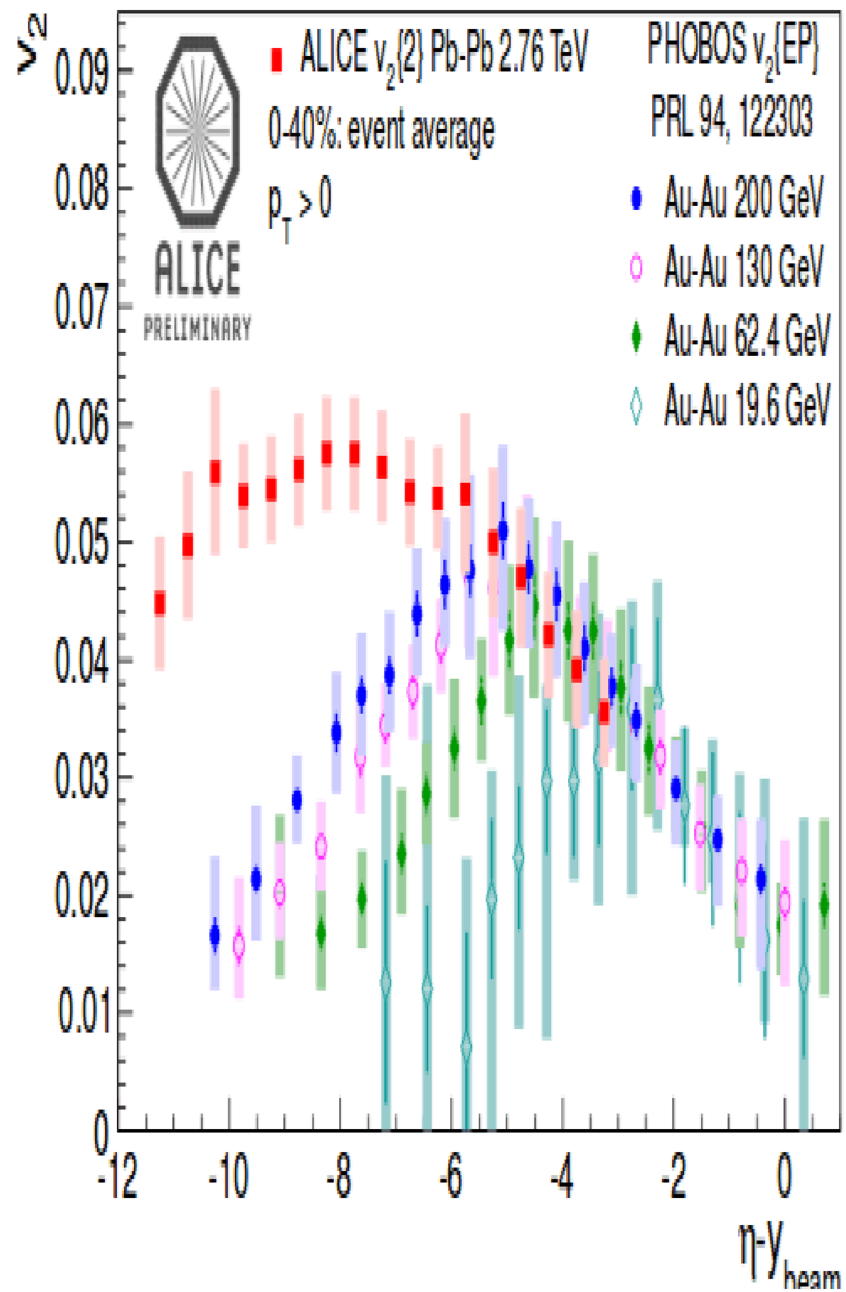


At LHC energies the QGP density doubles relative to RHIC

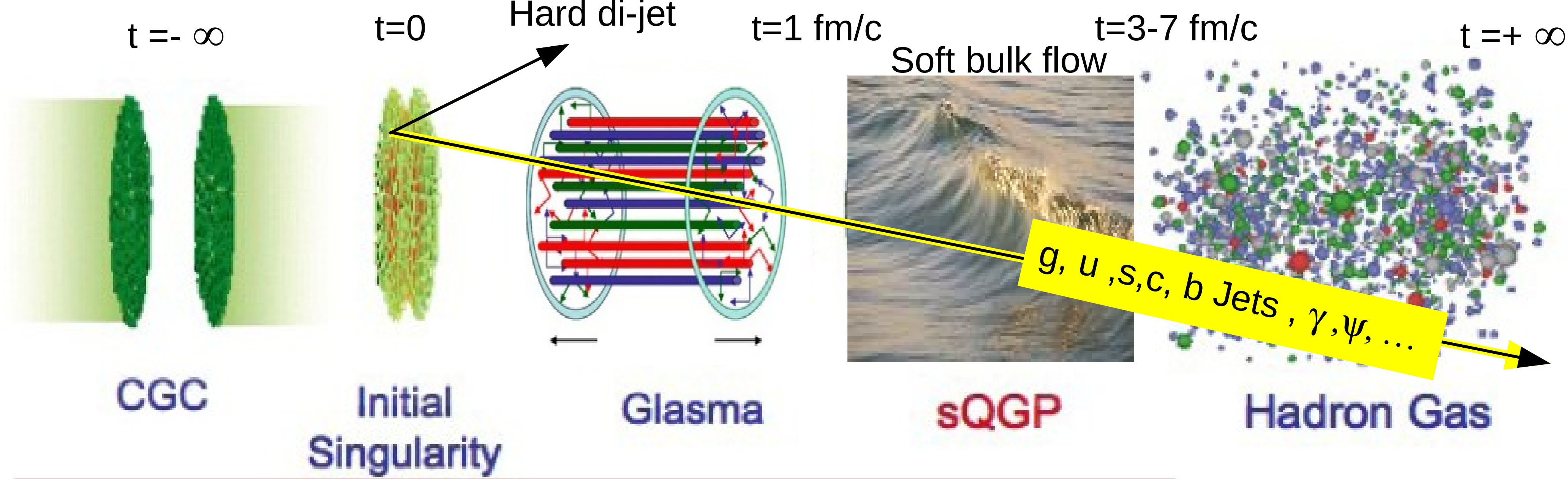
The view from Mt. LHC and its Mt.RHIC and Mt. SPS foothills



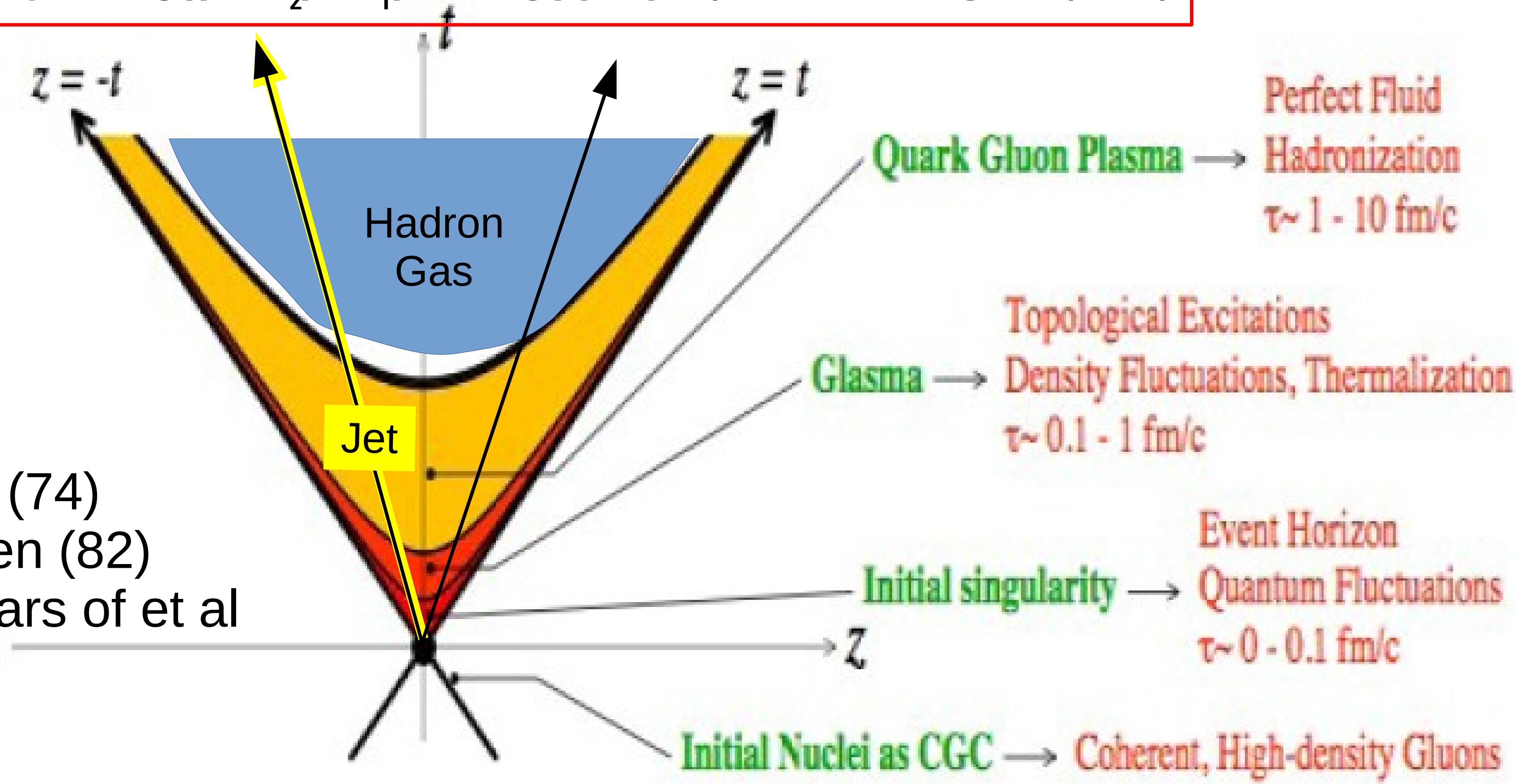
Elliptic Flow Moment



Bjorken (82) Parton Density of the QGP = dN/dy / (t pi R^2) is twice higher at LHC than RHIC



Rapidity $y = \mathrm{Log}((E+P_z)/\, m_T) \simeq \mathrm{Log}(\,(t+z)/\,\tau) \sim \eta \;=\; -\;\log\tan(\,\theta/\,2)$

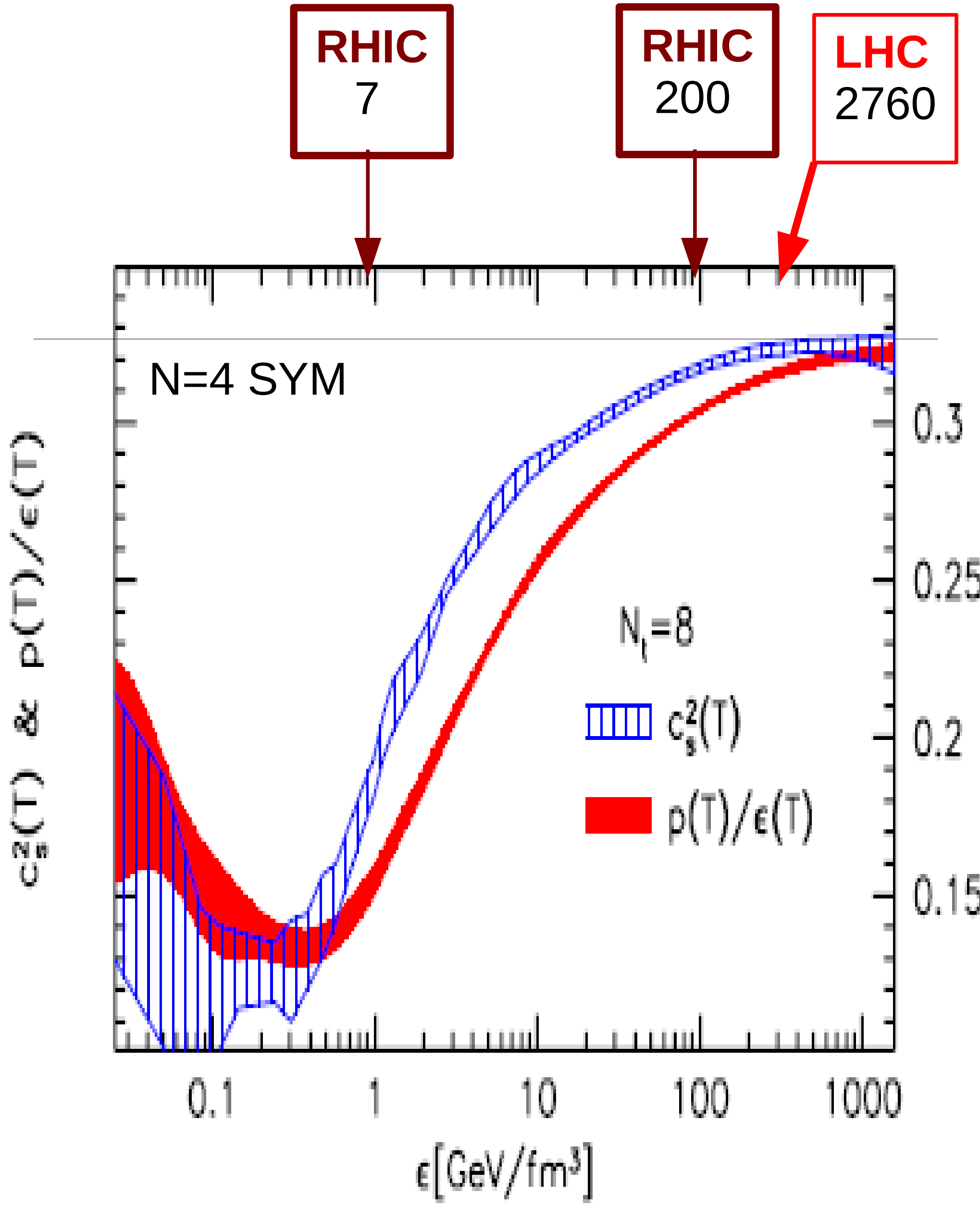


TD Lee (74)
+ Bjorken (82)
+ 41 years of et al

Why both RHIC and LHC A+A exp are needed in the future?

Wide Beam Energy Scan capability makes RHIC ideal to study Non-Conformal QCD cross-over transition T physics

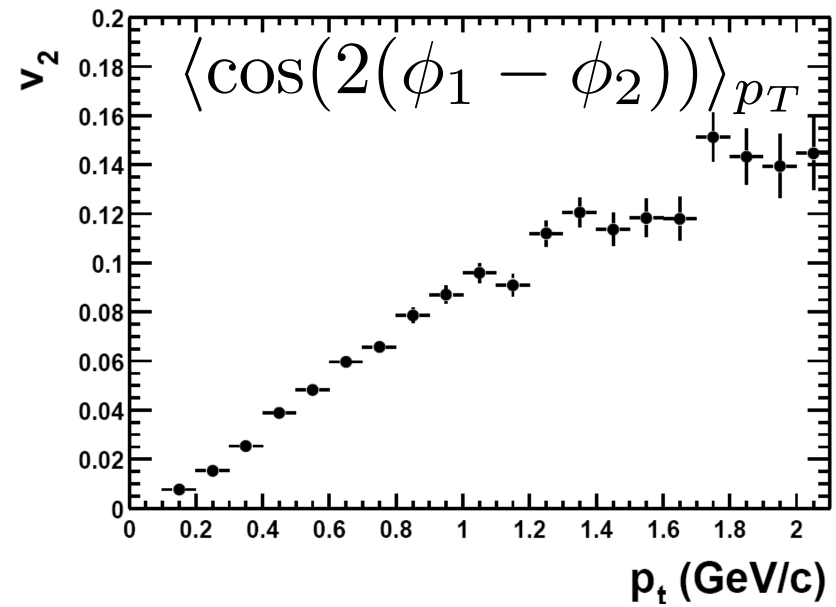
Highest energy LHC makes it ideal to measure high pT> 20 GeV u,c,b Jet Quenching probes and also To probe Color Glass gluon saturation at small x



Part 3: Discoveries @ RHIC from 2000

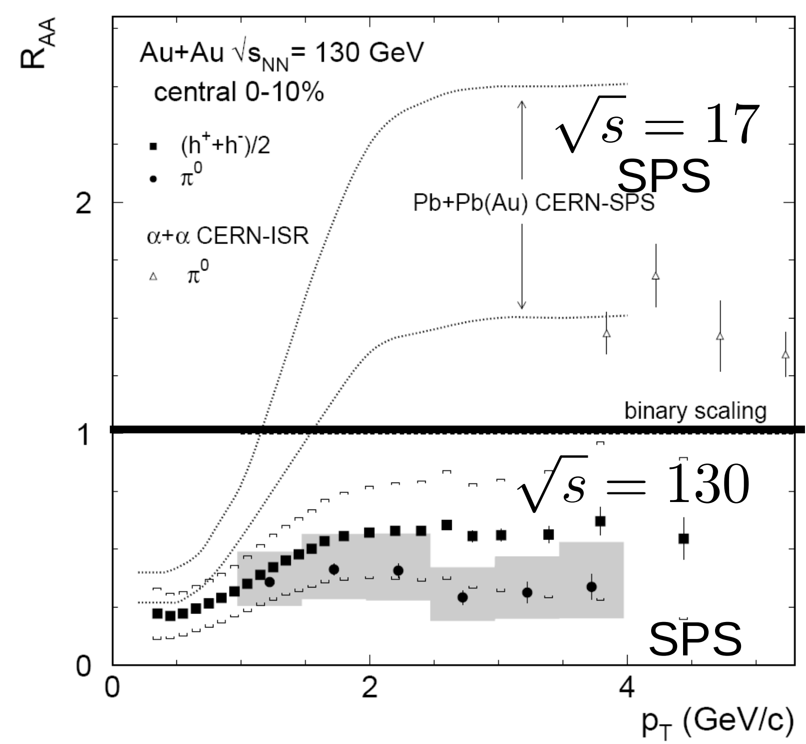
- "Bulk Elliptic Flow" pT<1GeV:

Elliptic flow in Au + Au collisions at
$\sqrt{s_{NN}}$= 130 GeV,
STAR Collaboration, Sept. 2000
Phys.Rev.Lett.86:402-407,2001
587 citations



- "Jet Quenching" pT>3 GeV

Suppression of hadrons with large transverse momentum in central Au+Au collisions at $\sqrt{s_{NN}}$ = 130 GeV,
PHENIX Collaboration Sept. 2001
Phys.Rev.Lett.88:022301,2002
854 citations



Bulk Collective Flow of QCD matter

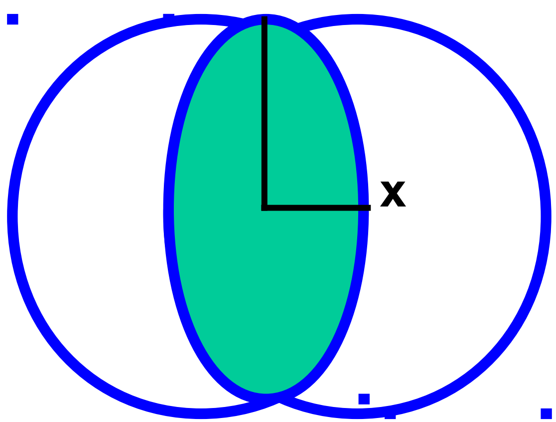
$$\partial \mu T^{\mu\nu} = \partial_\mu((e+P)u^\mu u^\nu) - P g^{\mu\nu} + \pi^{\mu\nu}) = 0$$

QCD Pressure

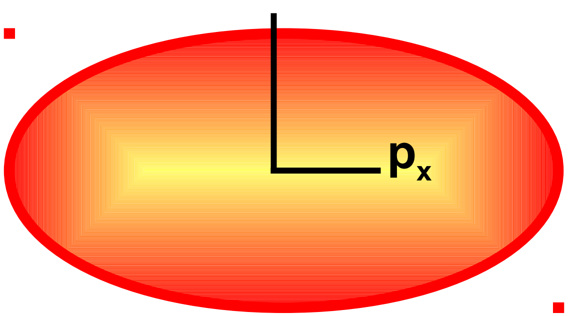
Bulk and shear Dissipation

W. Greiner, H. Stocker(1974)
P.Kolb, U. Heinz et al (2000)
D.Teany, E. Shuryak
T. Hirano, Y. Nara, ...

Initial *spatial* anisotropy ⇒ **Final *momentum* anisotropy**



$$\partial_\mu T^{\mu\nu} = 0$$



"Elliptic Flow" + harmonics

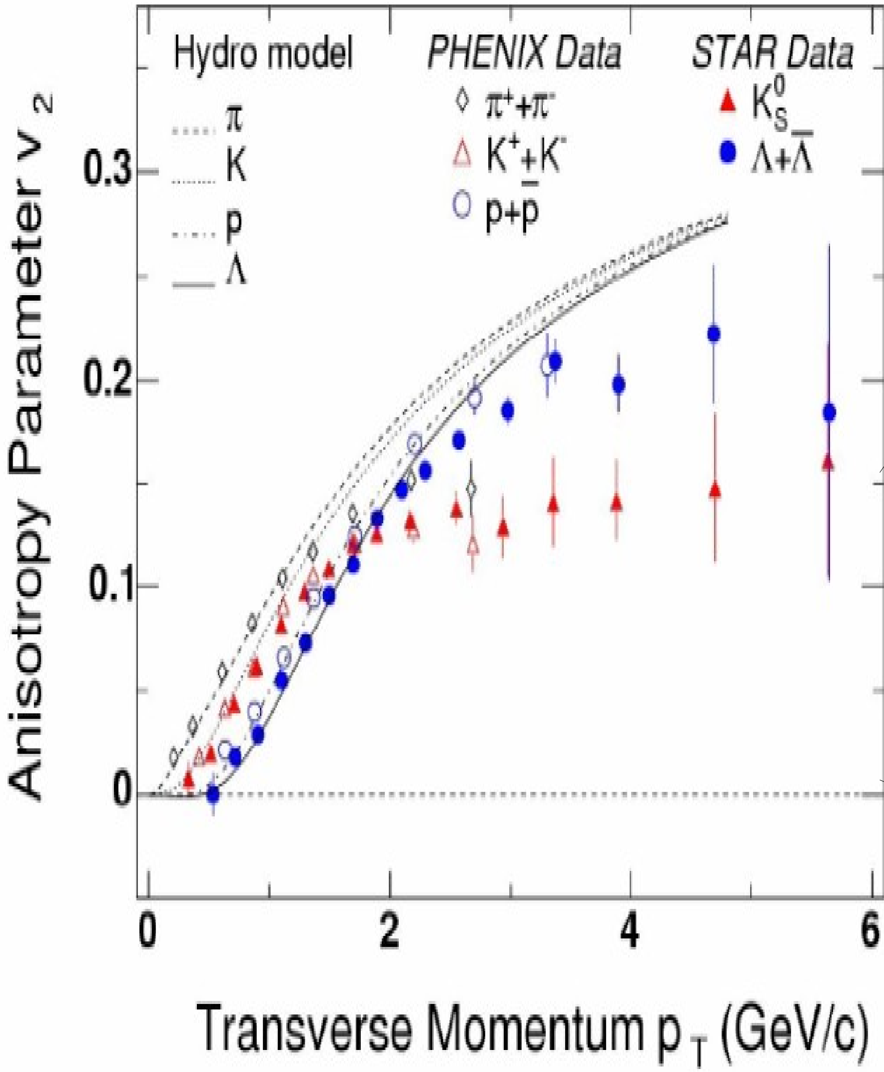
$$\frac{dN}{dy\,dp_T^2\,d\phi} = \rho(y,p_T)\left\{1 + 2 v_2(p_T)\cos(2\phi) + \cdots\right\}$$

$$v_n(\eta, p_T) = \int d\phi\ \rho(\eta, p_T, \phi)\ \cos(n(\phi - \Phi_{EP}))$$

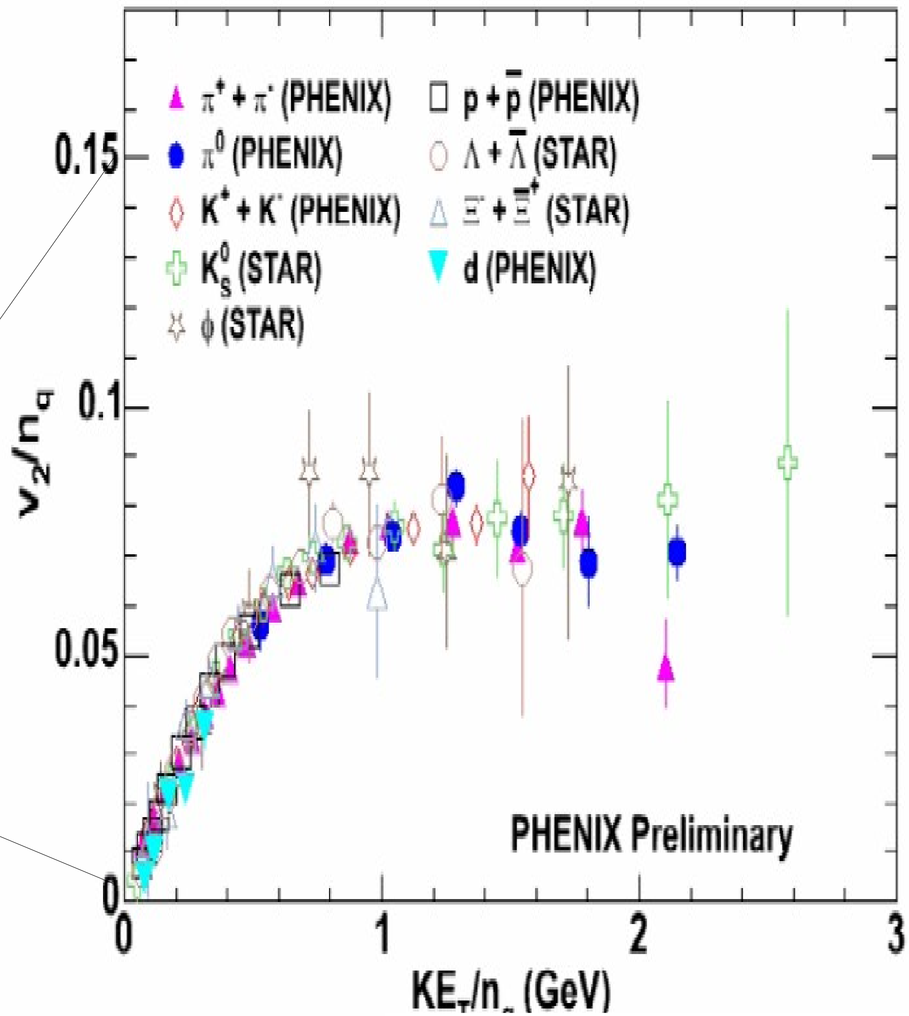
Discovery of “Perfect Fluidity” of Constituent Quarks at RHIC ?

Quark number scaling works very well for all hadron species!

Elliptic v2 moment of pions, protons, ...



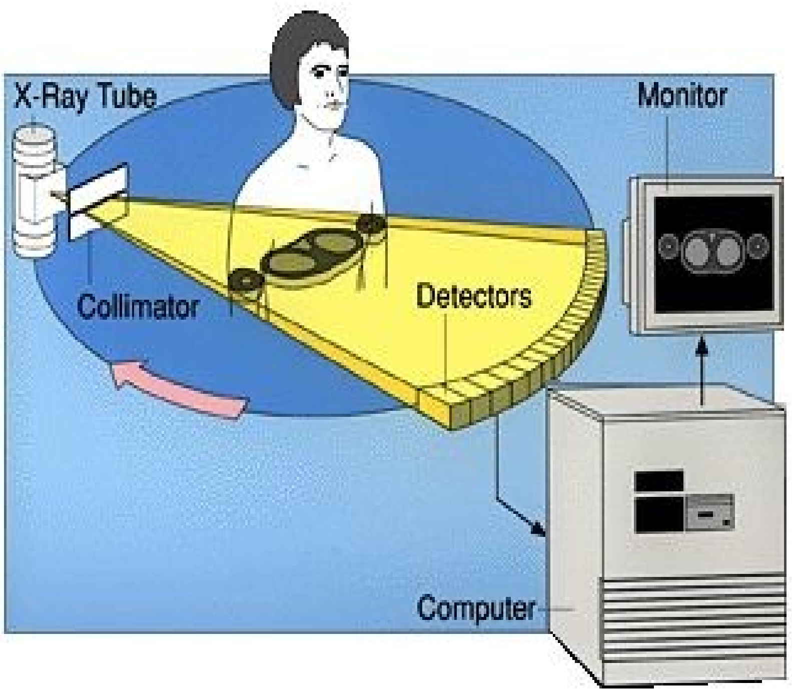
Elliptic v2 moment of **Constituent Quarks**



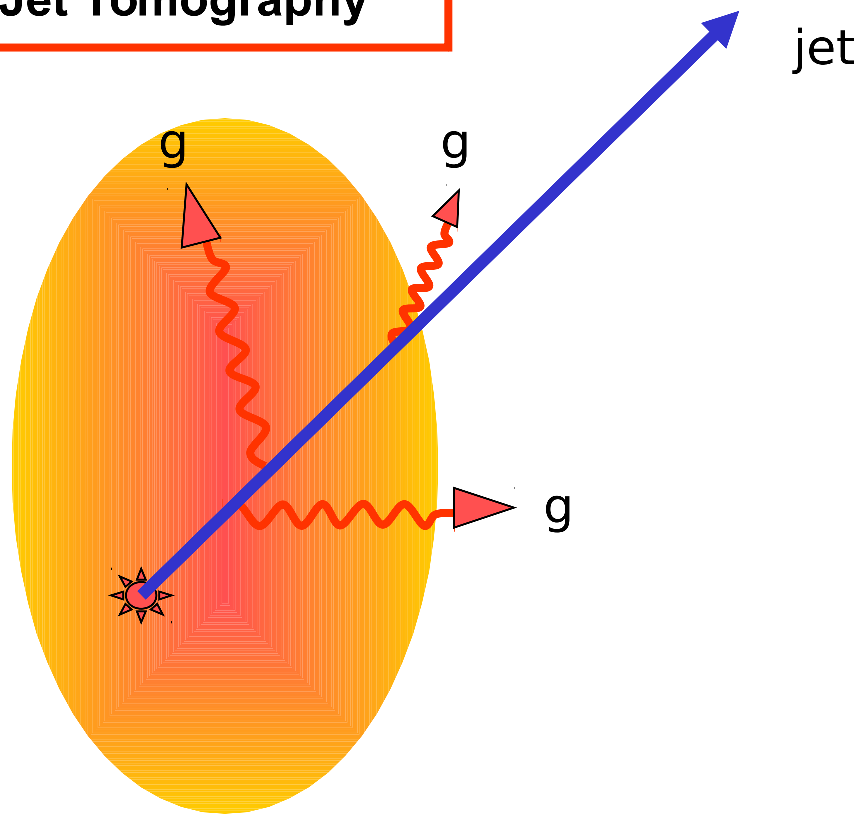
Jet Quenching and Tomography of the sQG(M)P

(X.N. Wang, M. Plumer, P. Levai, I.Vitev, M. Djordjevic, A.Adil, S. Wicks, W. Horowitz, A.Ficnar, A, Buzzatti, J. Xu, J. Liao, MG)

Medical Tomography



Jet Tomography



$$\Delta E_{GLV} \propto C_2 \alpha_s^3 \int dt\, t\, \rho(t\,,\, r(t))$$

A probe of the spacetime evolution of the plasma density and jet coupling

Nuclear Physics A538 (1992) 37c-50c
North-Holland, Amsterdam

HIGH P_T PROBES OF NUCLEAR COLLISIONS*

M. Gyulassy[1], M. Plümer[2], M. Thoma[3], and X.N. Wang[1]
Nuclear Science Division, Mailstop 70A-3307
Lawrence Berkeley Laboratory

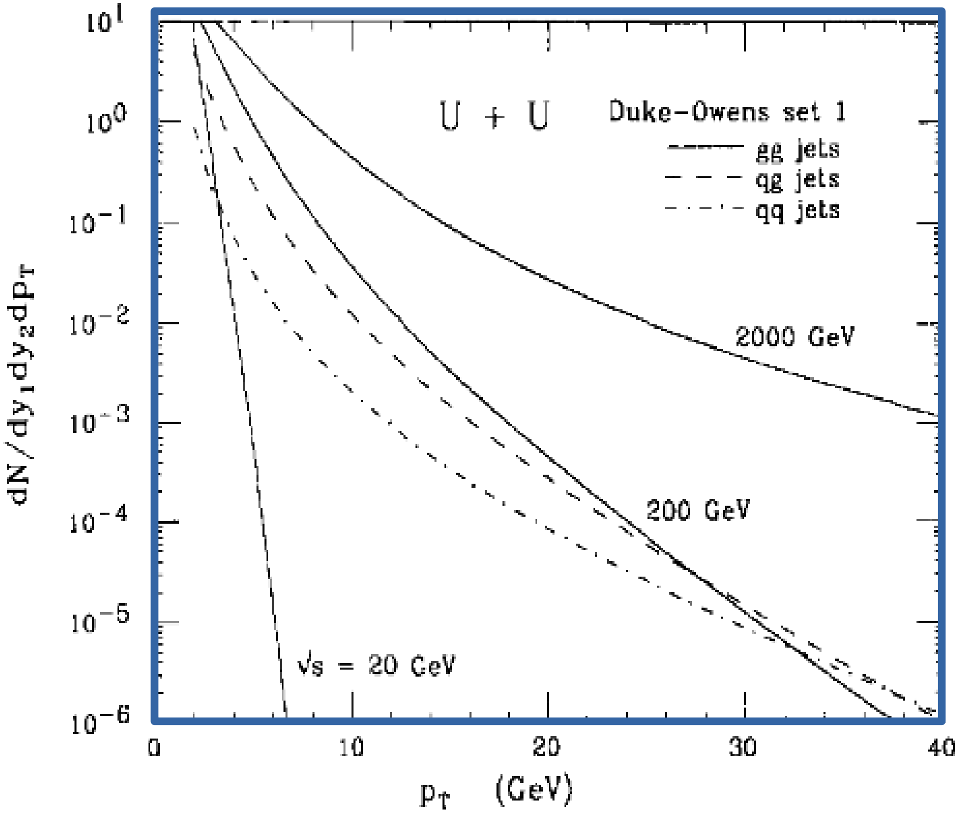
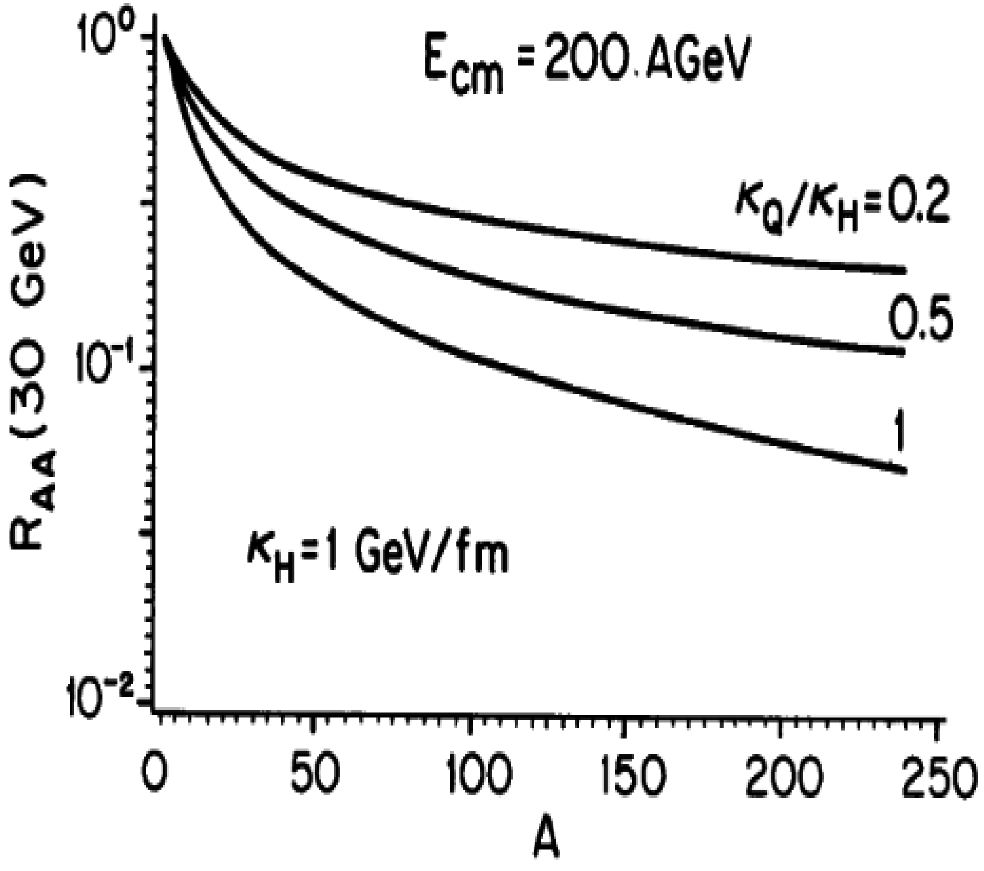


Fig. 1. The density of back-to-back jets at $y_1=y_2=0$ in central U+U collisions at various CM energies per nucleon ($\frac{1}{2}\sqrt{s}$) as a function of the jet transverse momentum p_T. Solid, dashed and dash-dotted show contributions from gg, gq, and qq jets,

Di-jet Nuclear Modification
Reduction factor

$$R_{AA}(p_T) = \frac{dN_{di-jet}(p_T,\ \Delta E(A))}{dN_{di-jet}(p_T,\ 0)}$$

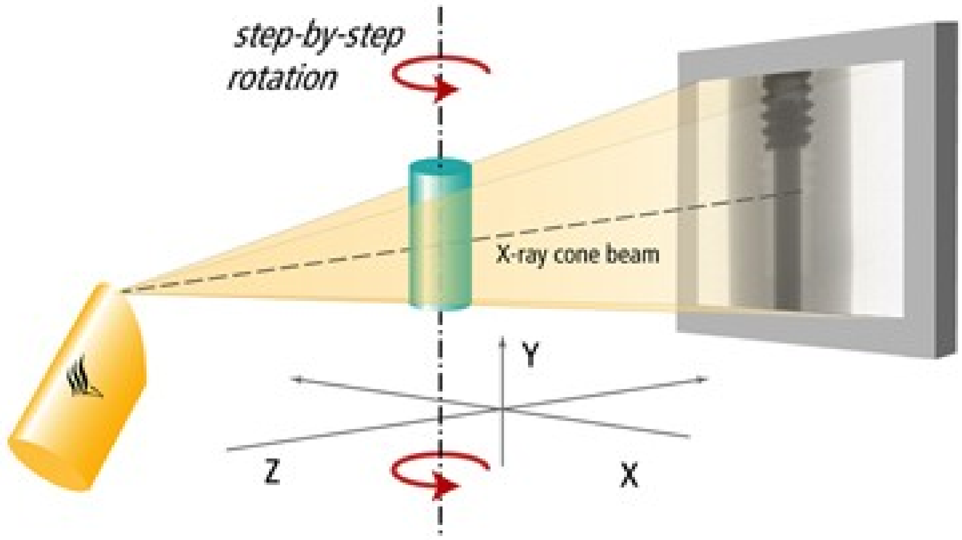


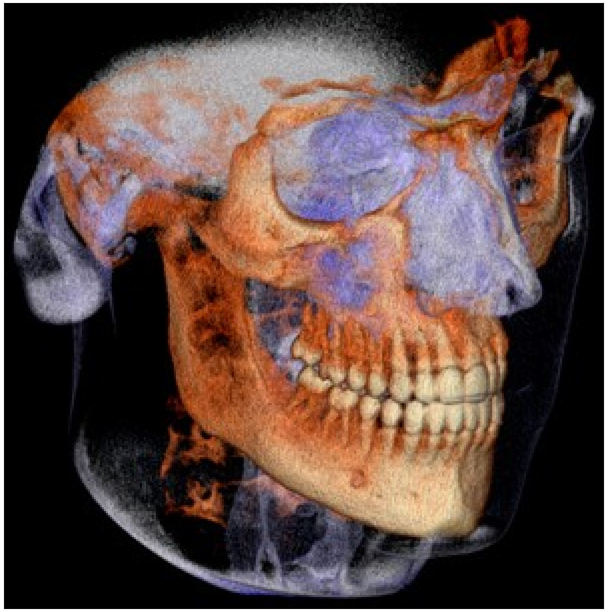
Volumetric Tomography works *only if*

1) Well known initial flux of ***penetrating probes***

2) a reliable model of ***density dependent energy loss***

3) ***AND patient is not too wiggly*** !!





e.g, Cone-Beam Volumetric Tomography (CBVT)

Low dose 3D x-ray tomography in action at your nearest dentist

Volumetric Tomography works *only if*

Are yjese conditions met
In A+A reactions ??

√ 1) Well known initial flux of ***penetrating probes***

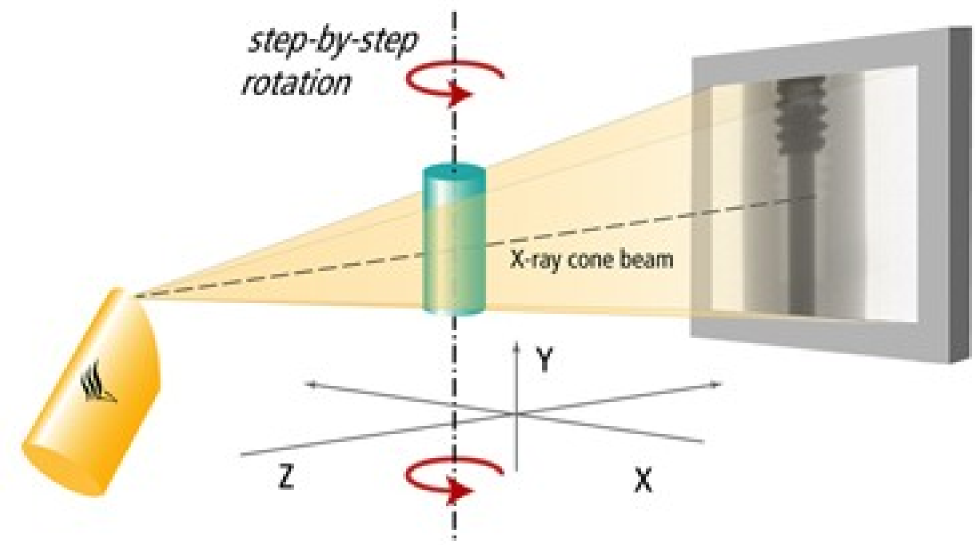
Yes, via pQCD and p+p

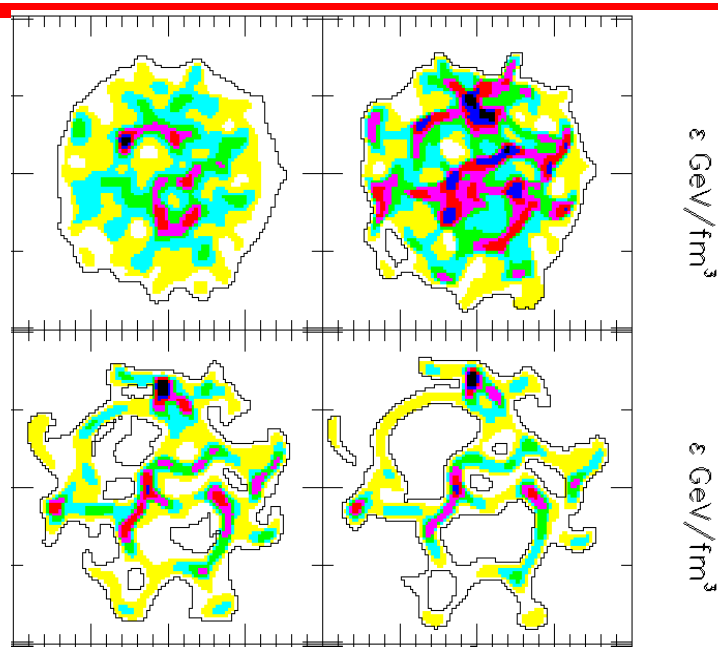
√ 2) a reliable model of ***density dependent energy loss***

Yes, via DGLV,HT,AMY

X 3) ***AND patient is not too wiggly***

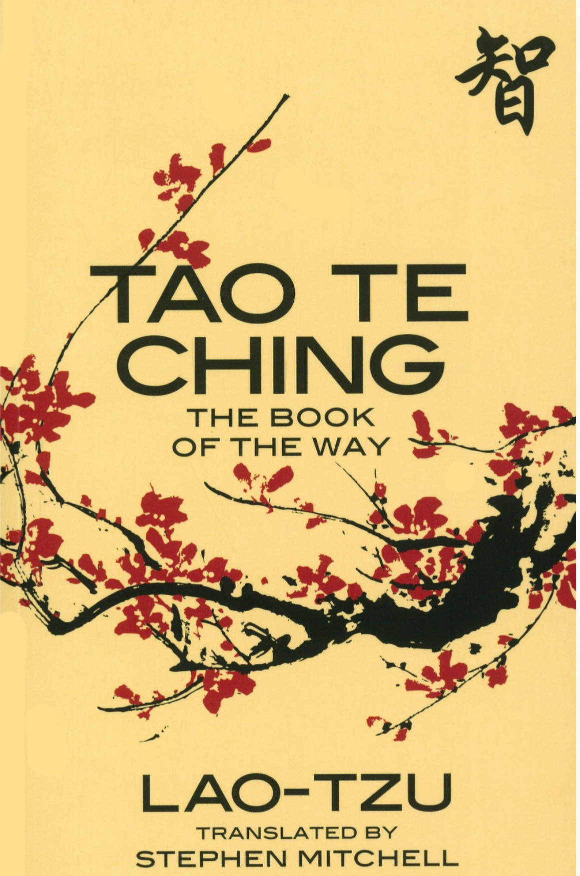
NO, we need relativistic viscous hydro to compute Bulk evolution of ensembles of fluctuating Initial Conditions !





HIJING+Hydro (97)

Nuclear modification of Jet quenching in A+A cannot be understood without Simultaneously understanding of how low pT Bulk QGP is produced and evolves



1000BC → 400 BC → 1991 AD

易經 → 道德經 → 核易經

HIJING = The Tao of A+A

(**H**eavy **I**on **J**et **IN**teraction Generator)
Monte Carlo A+B exclusive events
by X.-N. Wang and MG in 1991
emphasis on the interplay of hard pQCD
minijets and participant soft beam jets

in pp, pA and AA reactions
at collider energies $\sqrt{s} > 10\ AGeV$

<u>"I Ching</u> ([î tɕíŋ]; Chinese: 易經 ; pinyin: Yìjīng),
Is known as the Classic of Changes and uses
a type of divination called cleromancy,
<u>which produces apparently random numbers</u> "

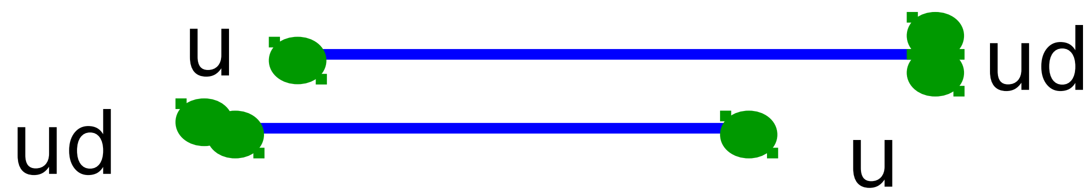
<u>HIJING</u> is a code of nuclear changes
From A+B into quarks and gluons
Then into observable hadrons via
Random numbers

HIJING A+B → ~10000 pi, K, p … Model

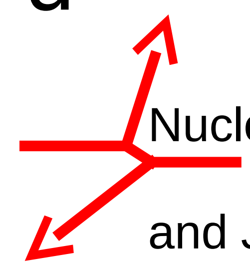
1) Soft Beam Jet Fragmentation

(string phenomenology, LUND, DPM, ATTILA)

“Pomeron”

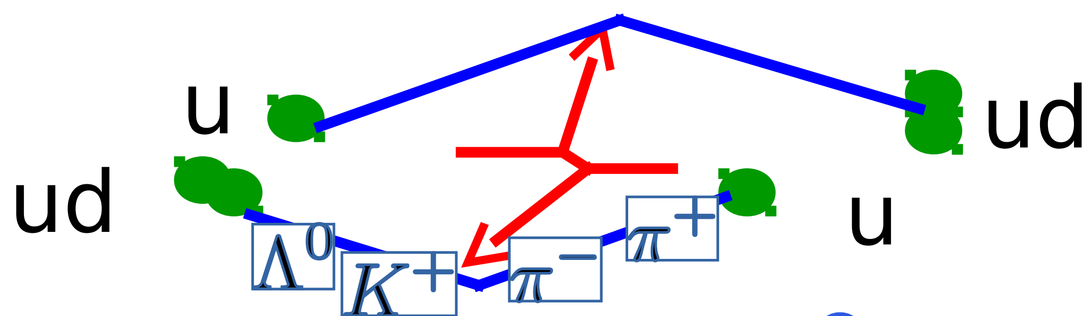


2) Hard pQCD $\boxed{p_T > p_0}$ PYTHIA

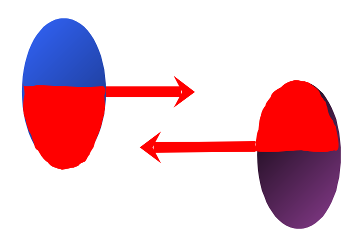


with
Nuclear shadowing
and Jet quenching

3) Hadronized via Lund String Breaking



4) A+A Glauber Geometry



Xin-Nian Wang, MG, PRD44 (1991) 3501

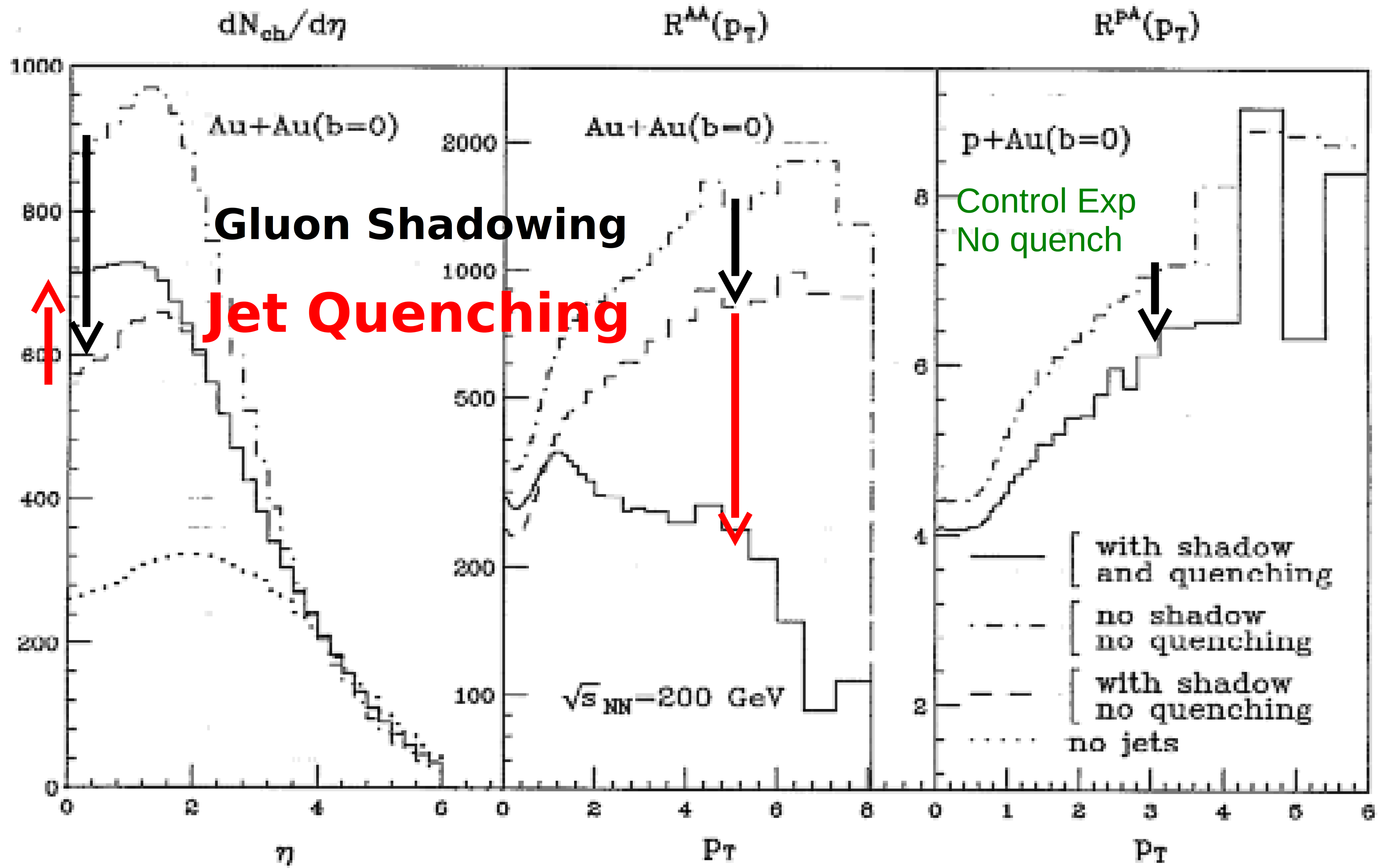
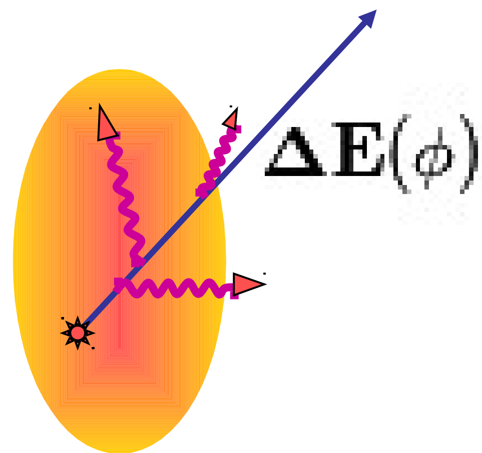


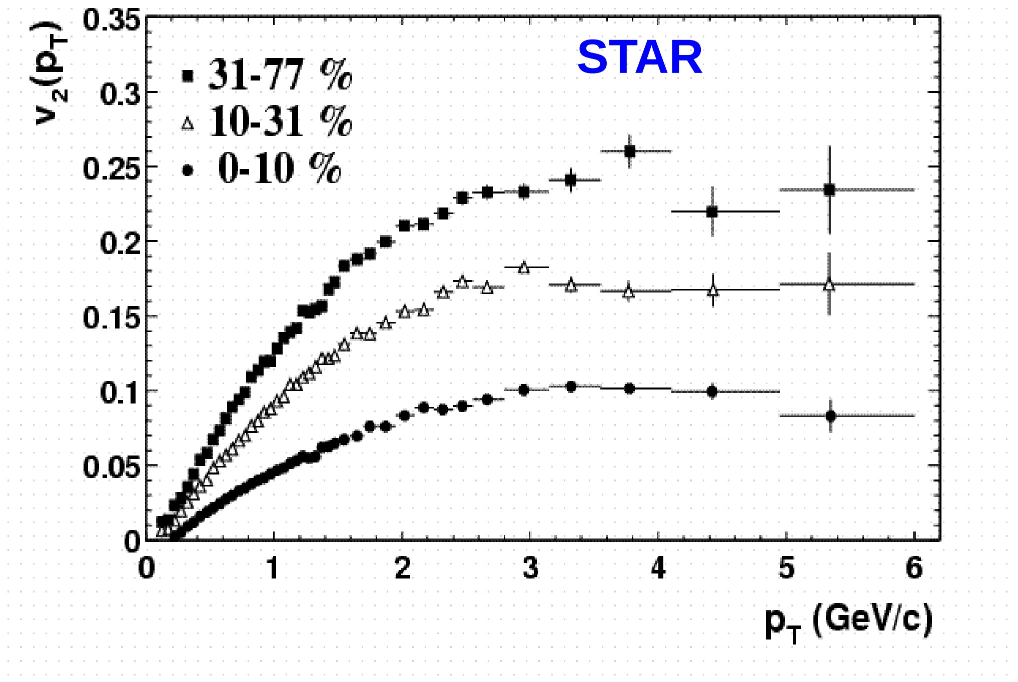
FIG. 1. Results of HIJING on the dependence of the inclusive charged-hadron spectra in central Au+Au and p+Au collisions on minijet production (dash-dotted line), gluon shadowing (dashed line), and jet quenching (solid line) assuming that gluon shadowing is identical to that of quarks and $dE/dl = 2$ GeV/fm with $\lambda_s = 1$ fm. $R^{AB}(p_T)$ is the ratio of the inclusive p_T spectrum of charged hadrons in $A+B$ collisions to that of $p+p$.

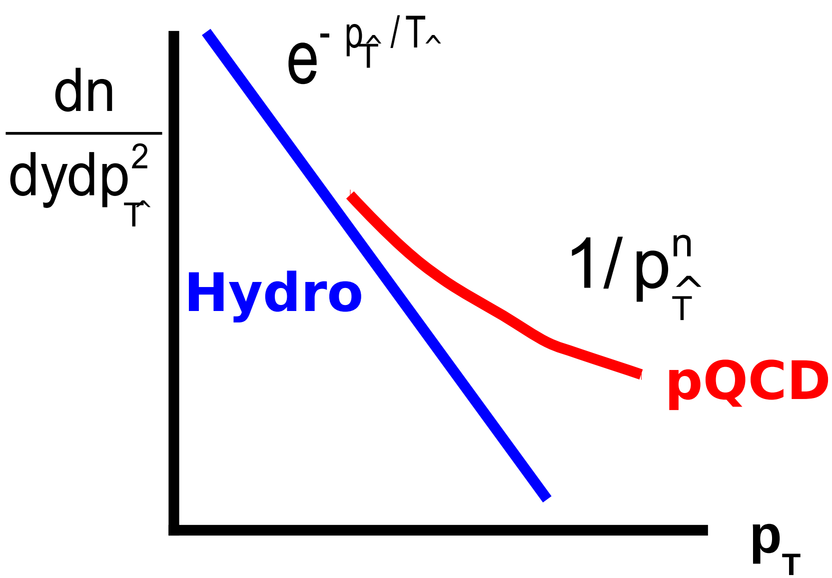
Elliptic Jet Tomography

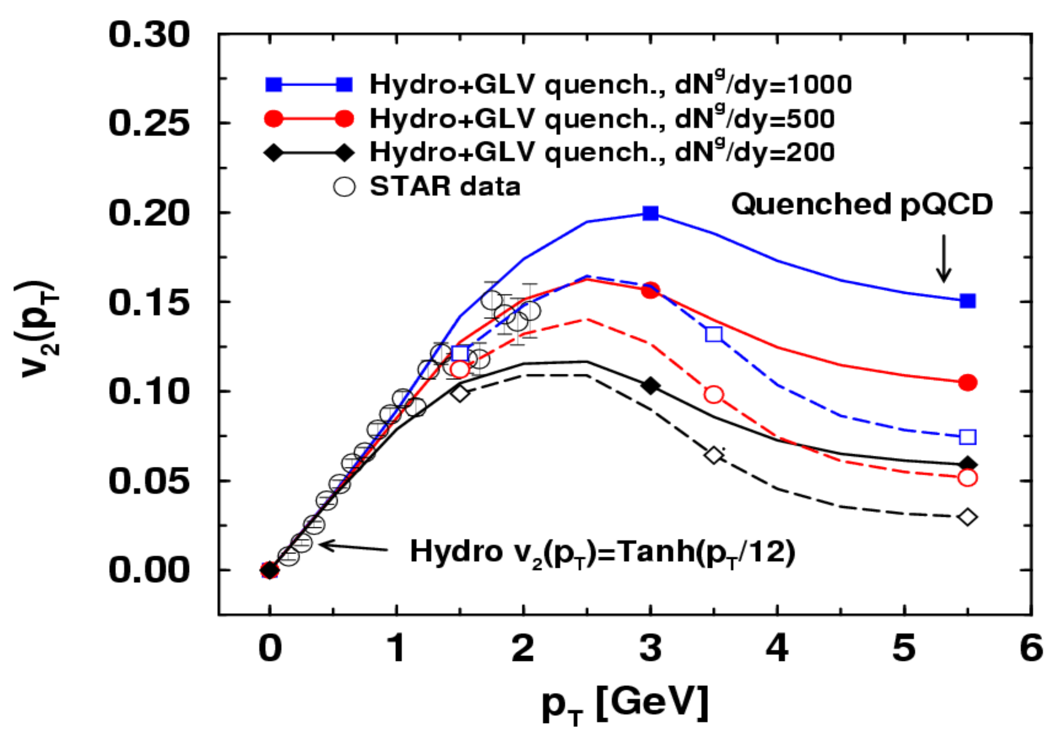
MG, I. Vitev and X.N. Wang, PRL86(01)

$$\rho_{QGP}(\tau, x_0 + \hat{n}\tau)$$



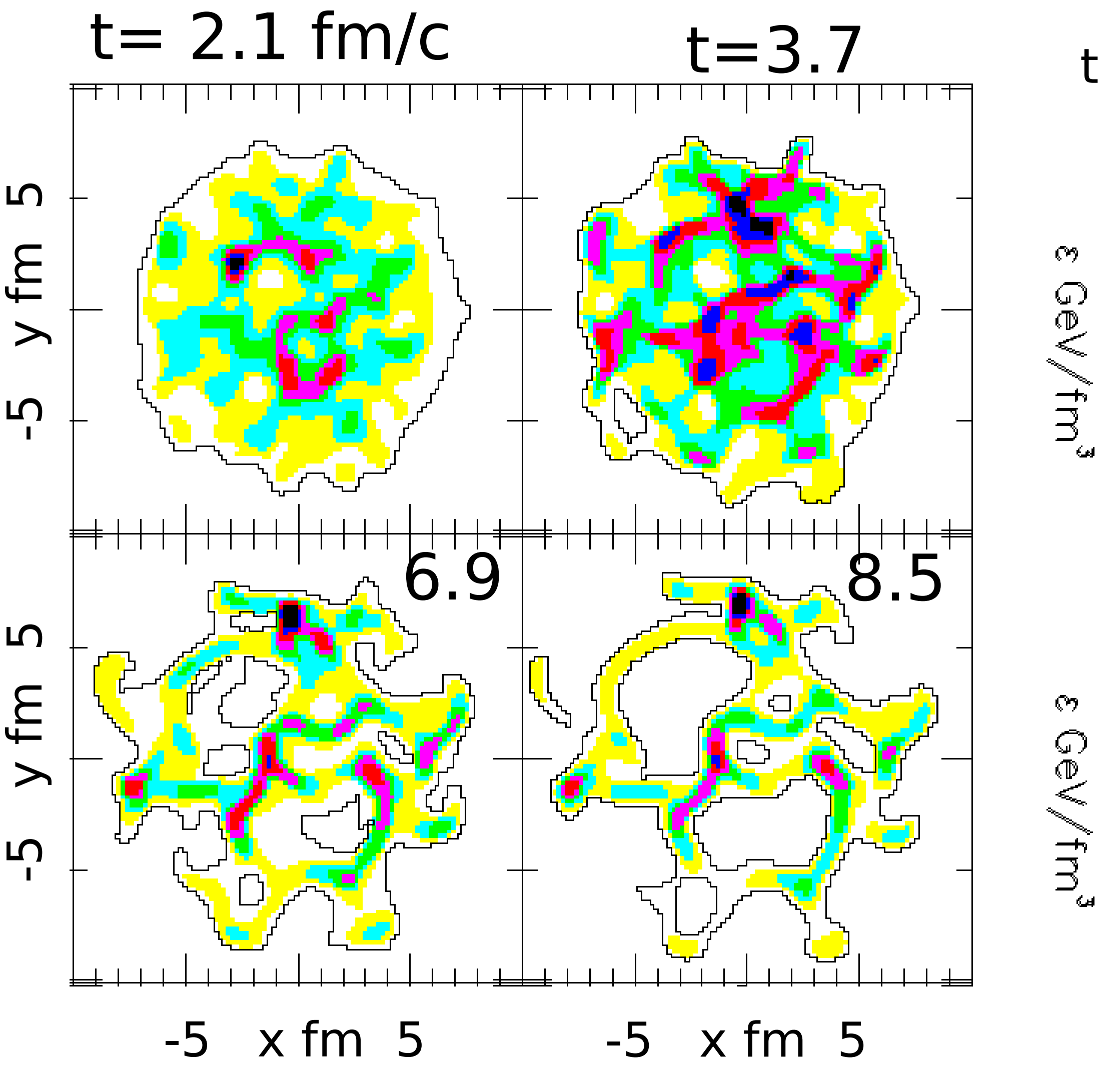




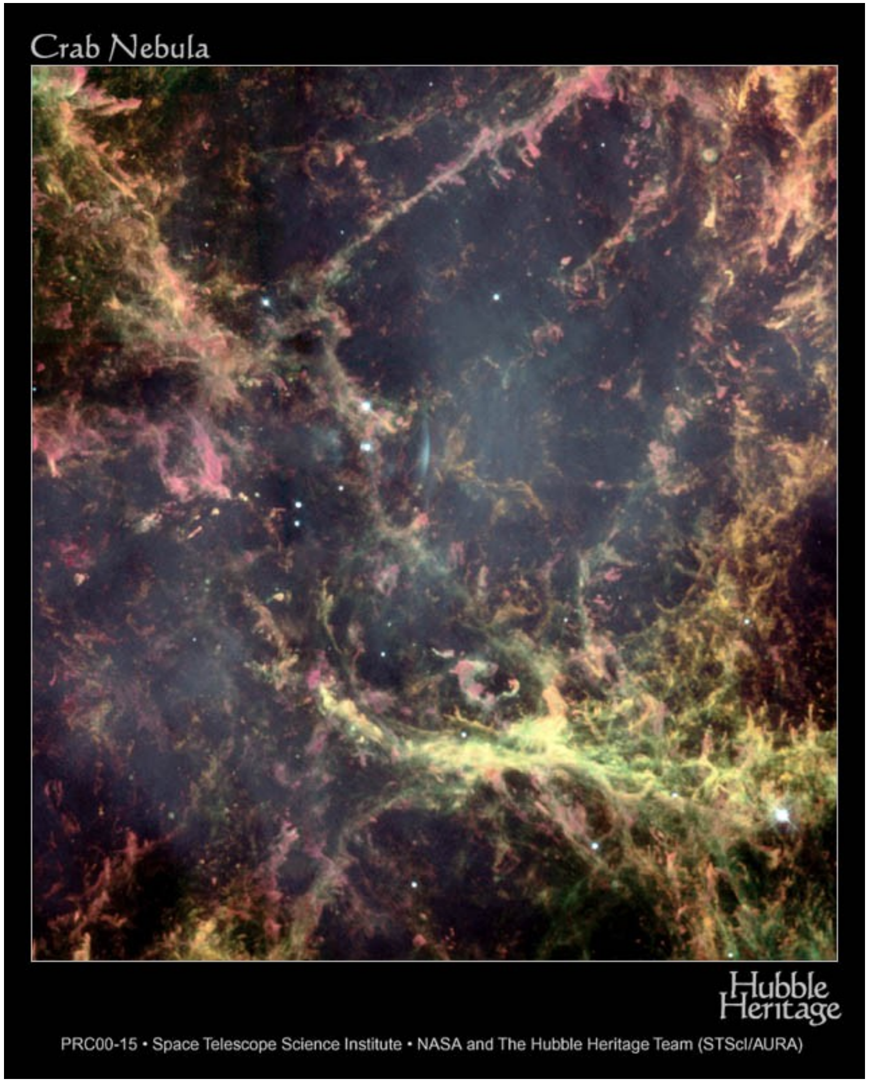


Until recently RAA *and* v2 data *could not be simultaneously fit*. This problem was solved with **sQGMP** (J.Xu, J. Liao, MG, CPL32 , 2015)

Event by event Turbulent Glue Scenario = HIJING +Hydro



t= 947 years=10^{36} fm/c, dx ~1 light year



D. Rischke, B. Zhang, MG 1997

Mini jets seed “hot spots” leading

via hydro to Filaments and Shel

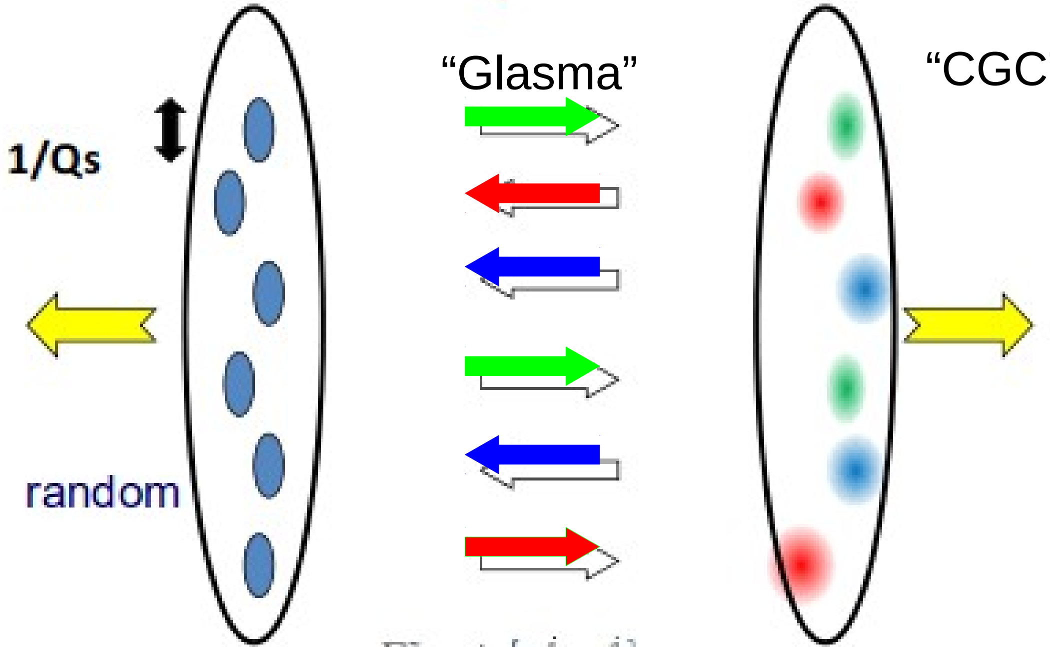
In A+A

Filaments in the Crab

supernova

Is the sQGP just a shattered Color Glass Condensate with broken bits of "Glasma" ??
(L.McLerran, R.Venugopalan 1994. ...B.Schenke et al 2012)

Heavy Ion Collisions



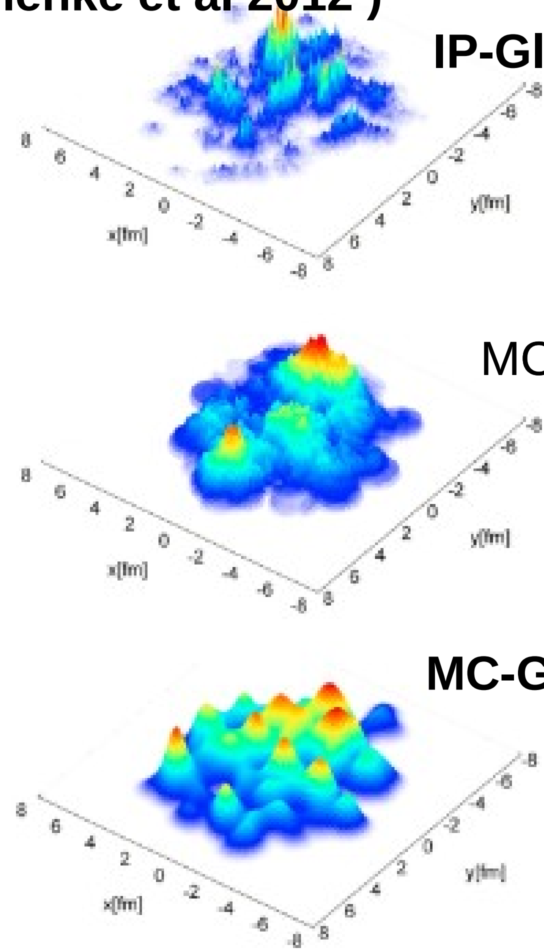
$$E^z = ig[\alpha_1^i, \alpha_2^i]$$
$$B^z = ig\epsilon^{ij}[\alpha_1^i, \alpha_2^j].$$

Typical configuration of a single event
just after the collision

IP-Glasma

MC-KLN

MC-Glauber



Highly coherent colored fields:
Stringlike in longitudinal direction
Stochastic on scale of inverse saturation momentum in transverse direction
Multiplicity fluctuates as negative binomial distribution

Longitudinal "Glasma" fields generalize Lund strings in HIJING
To both electric and magnetic and to sub nucleon scales 1/Qsat ~ 0.1 fm

Generic "abc" Models of Jet Energy Loss and RAA

For pQCD
fc: a ~ 1/3 , b~1
rc: a ~ 0 , b~1

$$\frac{dP}{d\tau} = -\kappa P^a \tau^b T^c[\vec{x}_\perp(\tau), \tau]\, \zeta_q$$

For Holographic Falling Strings (Chesler Yaffe)
Lstop ~ $E^{1/3}$
=> a = 1/3 , b=1
OR a = 0 , b=2

$$P_0(P_f) = \left[P_f^{1-a} + K \int_{\tau_0}^{\tau_f} \tau^b\, T^c[\vec{x}_\perp(\tau), \tau] d\tau\right]^{\frac{1}{1-a}},$$

For Holographic String Drag (Gubser, Herzog)
a = 1 , b=0

The new AdS "Shooting String Holography" (Ficnar,Gubser, MG)
=> a=0, b(t) interpolates between b=0 and 2, and c(t)=b(t)+2

$$R_{AA}(p_f; s, A) = \frac{\partial p_0}{\partial p_f} \frac{d\sigma(p_0(p_f))/dp}{d\sigma(p_f)/dp}$$

Spectral index From pQCD

For example,
$d\sigma \propto 1/p^n$

$$\approx \left(1 + \frac{K}{p_f^{1-a}} \int d\tau\, \tau^b T^c[\vec{x}_\perp(\tau), \tau]\right)^{\frac{a-n}{1-a}}$$

Fix κ by fit to <u>one</u> RHIC R(pf=10 GeV ,dNdy=1000) reference point.

W.Horowitz,MG, NPA872(2011); B.Betz, MG , JHEP1408(14)

Part 4: The Jet v2 versus RAA problem

a) pQCD Tomography

b) Conformal AdS string holography is not consistent with both RHIC vs LHC

c) A proposed Shuryak-Liao solution due to emergent magnetic monopole near Tc

Our A+A mini version of J, Bachall['s “10,000 STANDARD SOLAR MODELS” (2006)

. Constraints on the Path-Length Dependence of Jet Quenching in Nuclear Collisions at RHIC and LHC

Barbara Betz (Frankfurt U.), Miklos Gyulassy

Published in **JHEP 1408 (2014) 090, JHEP 1410 (2014) 043**

We compared 24 combinations of dEdx + 2+1D hydro models. One example, similar to CUJET2.0 without monopoles, is shown below

(abc)+hydro= (013) + VISH2+1

The jet RAA vs v2 puzzle

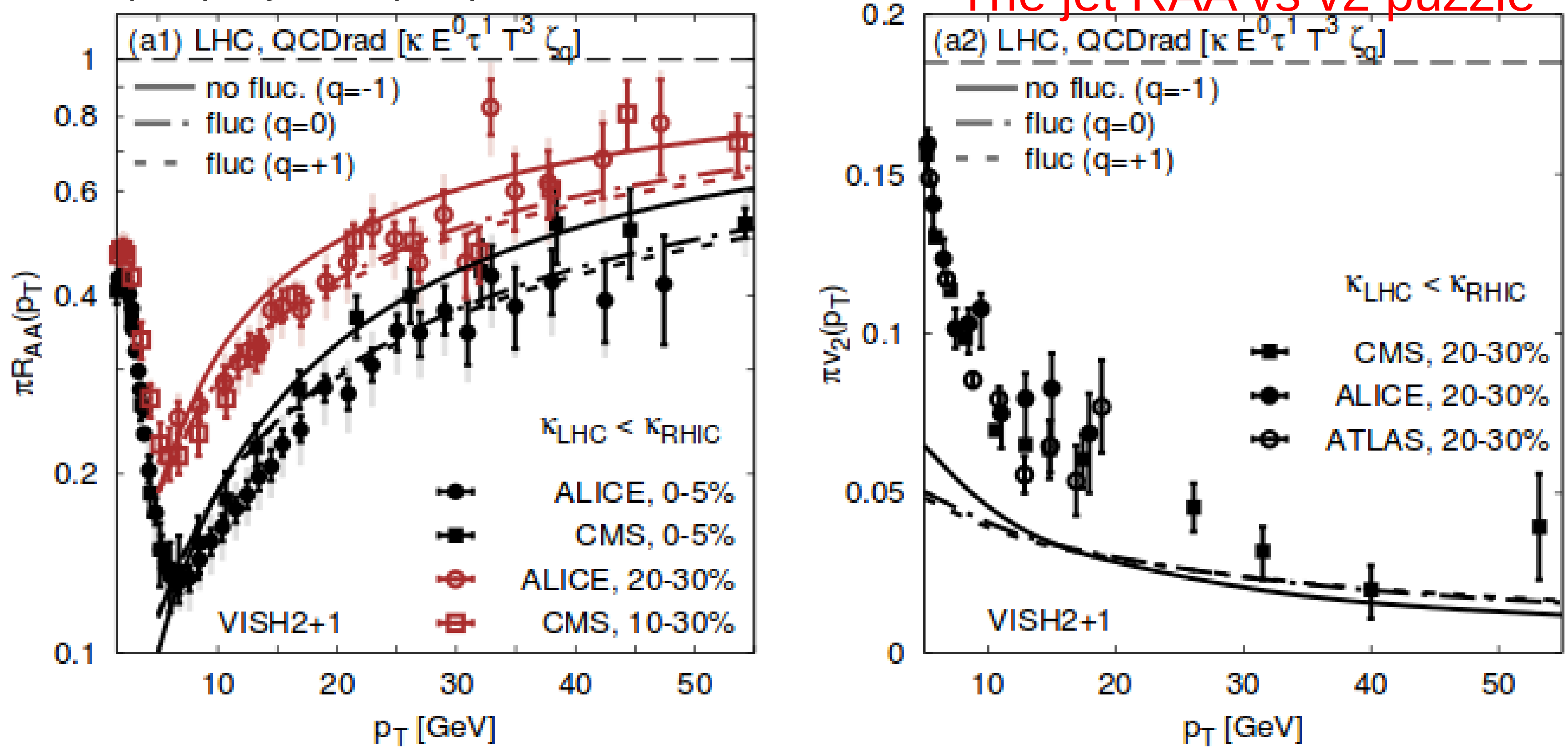


Figure 6. Azimuthal jet tomography at the LHC

This model accounts well for RAA(pT) but under predicts jet v2(pT) by factor ~2

<u>Another paradigm</u> : Look for <u>any solvable</u> field theory analogs of the analytically insoluble QCD "real world"

More Symmetry => More Constraints => Solutions are analytic

well known QM examples: SU(N) Harmonic Oscillator
O(4) Hydrogen Atom

" Hmmm "

In Field Theory it seems that SO(2,4) conformal Super-Symmetric Yang Mills may be exactly solvable in the super strongly coupling limit

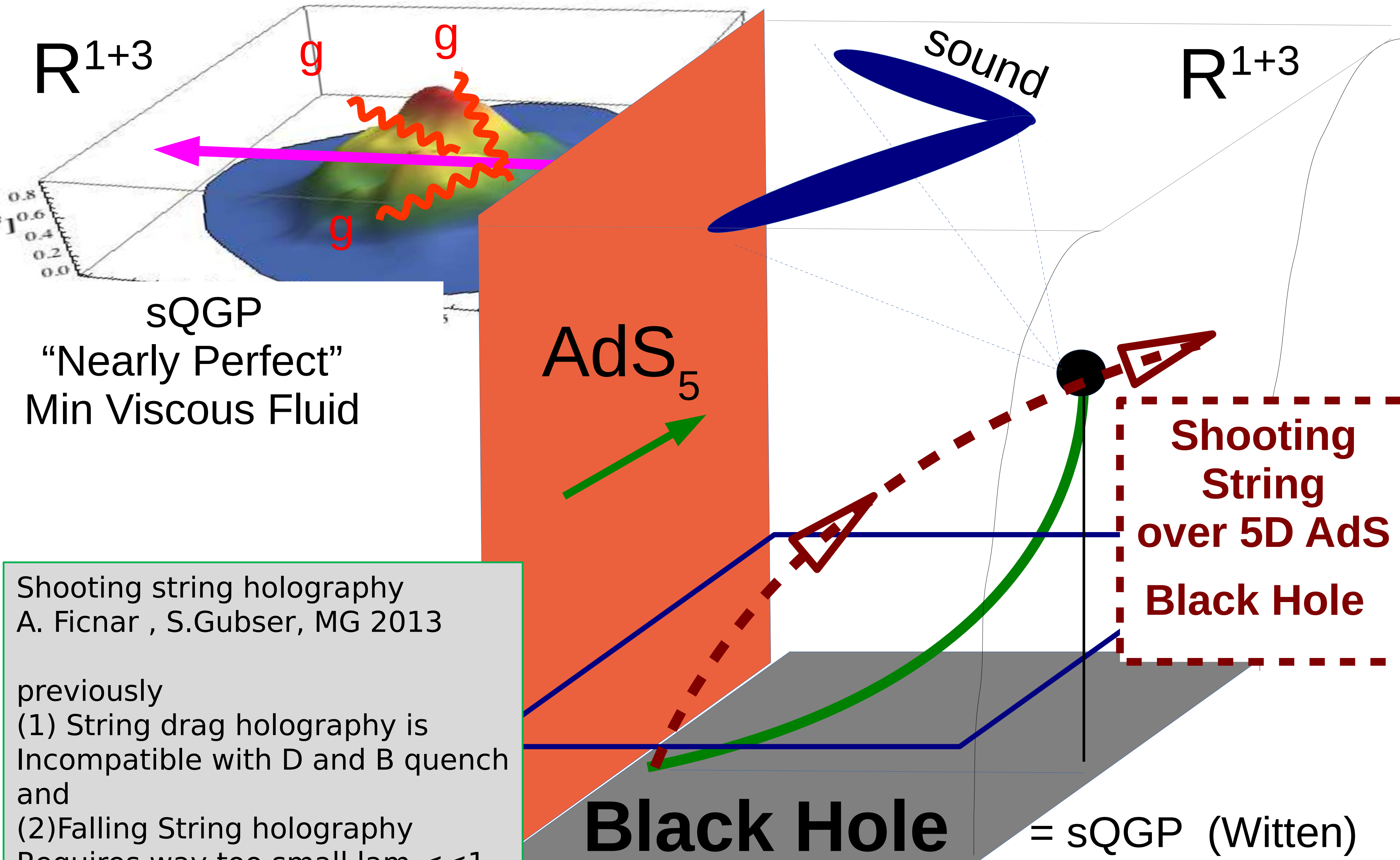
$$N_c \to \infty \quad and \quad \lambda = g^2_{YM} N_c \to \infty$$

Maldecena *<u>Conjecture</u>*:
In this limit, strongly coupled quantum conformal SYM in 4D is dual to *<u>classical weak gravity</u>* in the 5D curved space time: AdS_5

Conformal SO(2,4) group in 4D ~ Isometry SO(2,4) group of 5Dim AdS

Jet Tomography vs Jet Holography of “sQGP”

pQCD+Hydro(2+1)   an AdS View



sQGP
“Nearly Perfect”
Min Viscous Fluid

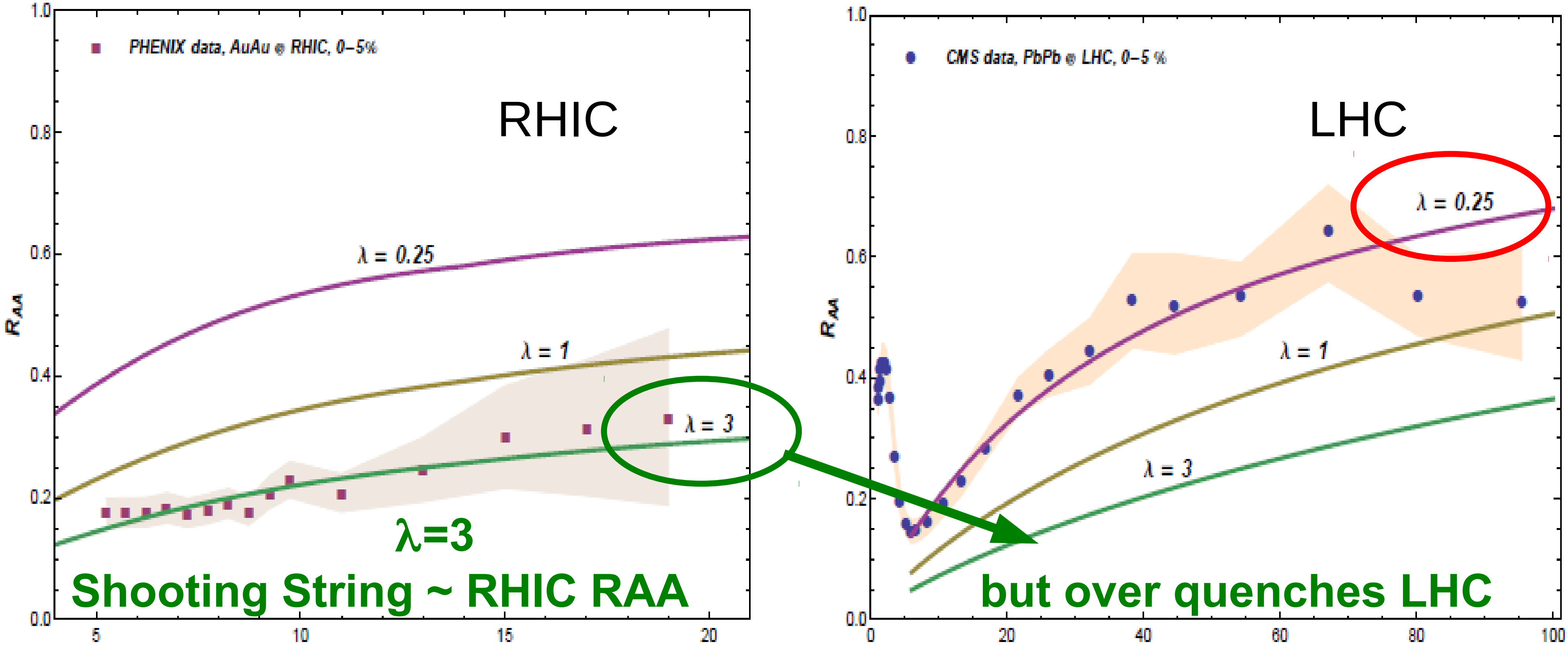
Shooting string holography
A. Ficnar , S.Gubser, MG 2013

previously
(1) String drag holography is Incompatible with D and B quench
and
(2)Falling String holography Requires way too small lam <<1

A. Ficnar , S.Gubser, MG 2013

While "reasonable" λ=3 >> 1 t'Hooft coupling can account for RHIC RAA

<u>Conformal</u> AdS holography even with shooting strings
requires **tiny λ=0.25 ~~>>~~ 1 to fit LHC RAA**

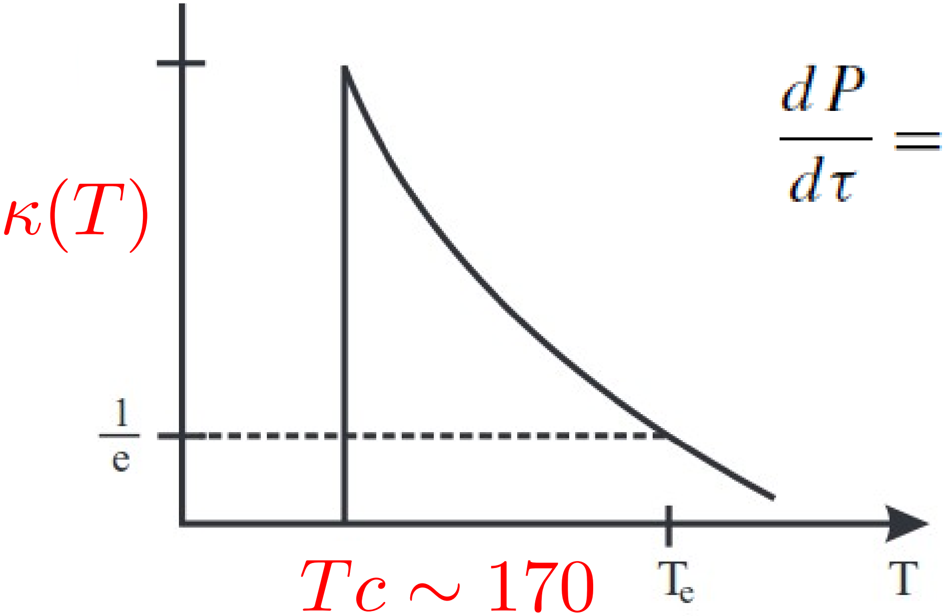


$$\frac{R^4}{\ell_s^4} \sim \lambda = 4\pi\alpha_{YM}N_c$$ should be >> 1 for classical gravity limit to hold

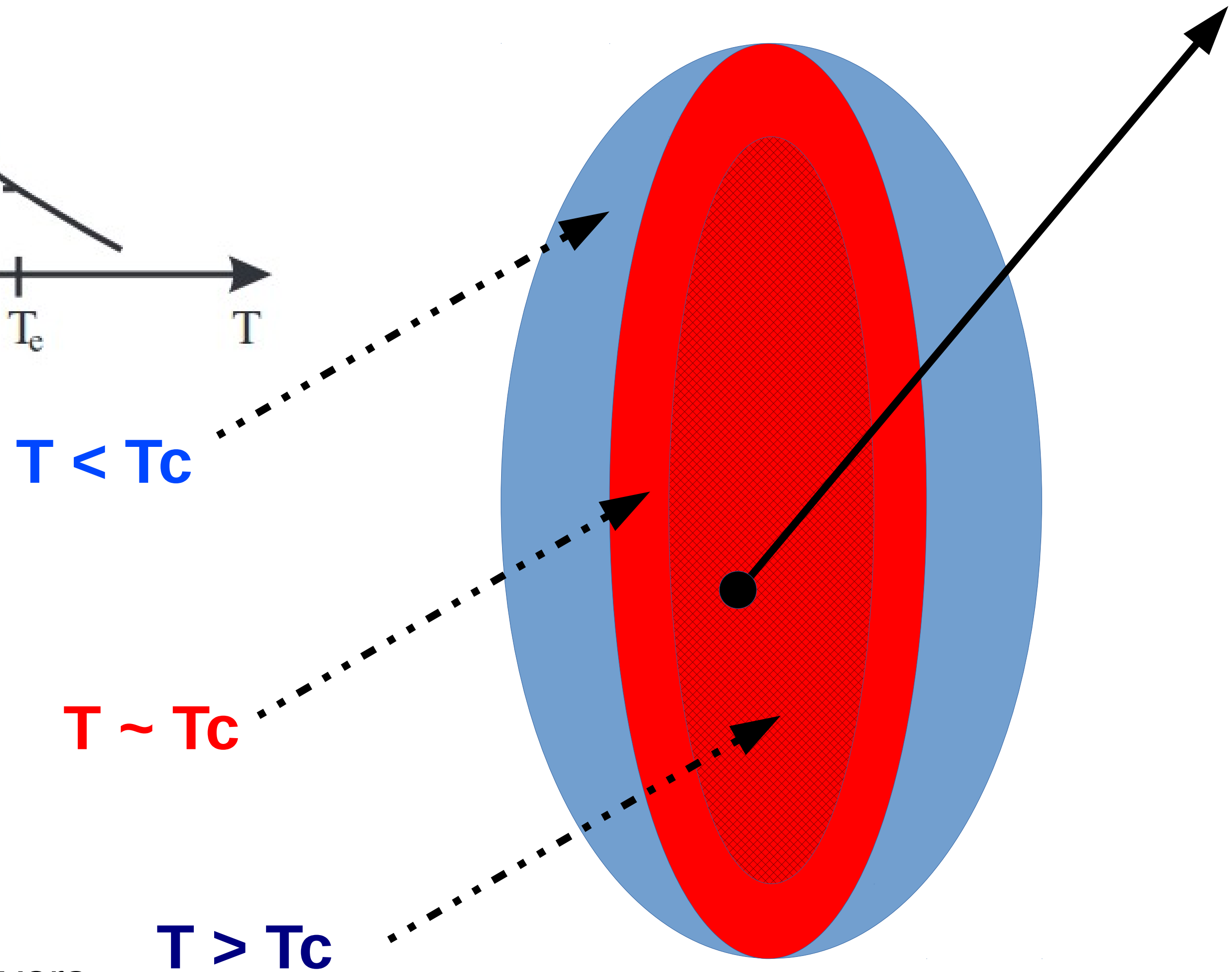
Current work in progress is to add effective bulk dilaton V(ϕ) to break the Conformal invariance of 5D AdS spacetime in a way consistent with 4D lattice QCD

A. Ficnar , S.Gubser, MG 2013

J. Liao and E. Shuryak, Angular Dependence of Jet Quenching Indicates Its Strong Enhancement Near the QCD Phase Transition ,PRL102 (2009); Shuryak PRC66 (2002)



$$\frac{dP}{d\tau} = -\kappa P^a \tau^b T^c \rightarrow -\kappa(T) P^a \tau^b T^c$$

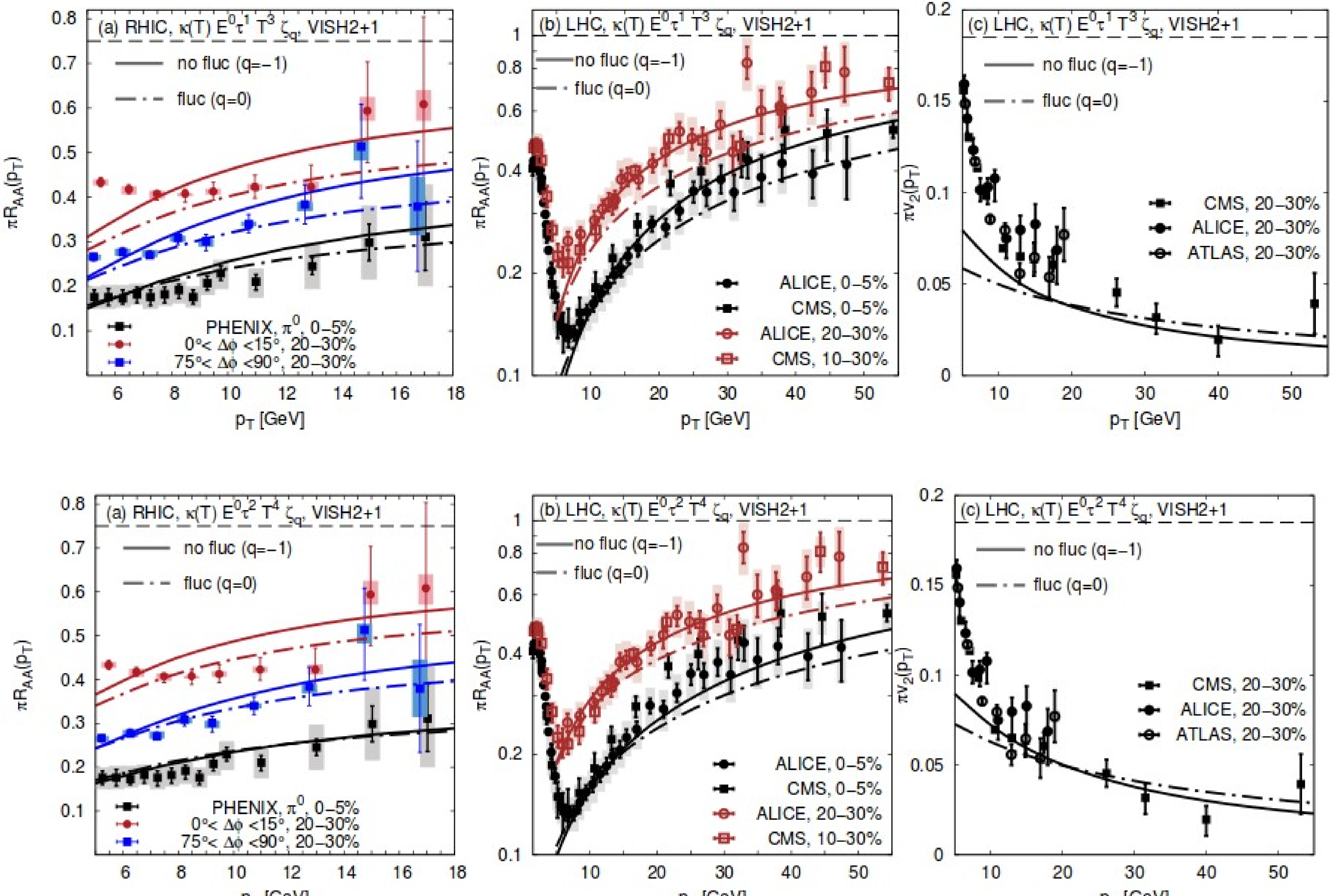


The Idea:
Emergent
Color magnetic
Monopole d.o.f
Near Tc may explain
Enhanced v2
due to
Dirac constraint

$$\alpha_E \alpha_M \geq 1$$

=> dEdx peaked near Tc favors
more azimuthal asymmetric part od sQGP

Non-Perturbative Tc enhanced k(T) BBMG generalizations of Shuryak-Liao dE/dx model can solve v2 puzzle independent of assumed path length dependence b=0-2



BBetz,MG(14) **Can SL Tc modeling be made consistent with pQCD ??**

PQCD Theory of Non-abelian Radiative Energy Loss

QCD Bethe-Heitler

- G. Bertsch, F. Gunion, Phys. Rev. **D25** 746 (1982)

QGP Multiple Collision

- M. Gyulassy, X.-N. Wang, Nucl. Phys. **B420** 583-614 (1994); Phys. Rev. **D51** 3436-3446 (1995)

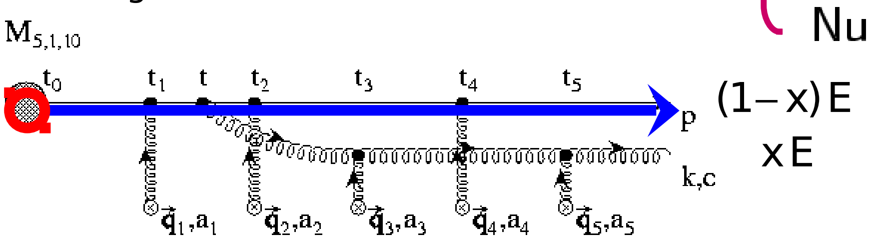
"Thick" Plasma Limit

- R. Baier, Yu. Dokshitzer, A. Mueller, S. Peigne, D. Schiff, Nucl. Phys. **B483** 291-320 (1997); Phys. Rev. **C58** 1706-1713 (1998)
- B. Zakharov, JETP Lett. **65** 615-620 1997, JETP Lett. **73** 49-52 (2001)

"Thin" Plasma Limit

- M. Gyulassy, P. Levai, Ivan Vitev, NPB 595 371-419 (2001); Phys. Rev. Lett. **85** 5535-5538 (2000)
- U. Wiedemann, Nucl. Phys. **B588** 303-344 (2000), Nucl. Phys. **B582** 409-450 (2000)

L/λ_g Opacity Expansion



Analytic to all orders $(L/\lambda)^n$

$$\boxed{q + QGP \to q + QGP + \mathbf{g}} \qquad x\frac{dN}{dx\,d^2\mathbf{k}_T^2}$$

P.Levai

I.Vitev

Part 4: CUJET2.0 = rc DGLV + VISH2+1 at RHIC and LHC and

VISH is bulk flow pT<2 GeV constrained viscous 2+1 D hydro U.Heinz

$$x\frac{dN_{Q->Q+g}}{dx}(\mathbf{x},\phi) = \int d\tau\, \rho_{QGP}(\mathbf{x}+\hat{\mathbf{n}}(\phi)\tau,\tau) \int \frac{d^2\mathbf{q}}{\pi} \frac{\alpha_s^2(\mathbf{q}^2)}{(\mathbf{q}^2+f_E^2\mu^2(\tau))(\mathbf{q}^2+f_M^2\mu^2(\tau)} \int \frac{d^2\mathbf{k}}{\pi}\alpha_s(k_T^2/(x(1-x))$$
$$\times \frac{12(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)} \cdot \left(\frac{(\mathbf{k}+\mathbf{q})}{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)} - \frac{\mathbf{k}}{\mathbf{k}^2+\chi(\tau)}\right)\left(1-\cos\left[\frac{(\mathbf{k}+\mathbf{q})^2+\chi(\tau)}{2x_+E}\,\tau\right]\right) .$$

where $\mu^2(\tau) = 4\pi\alpha_s(4T^2)$ is the local HTL color electric Debye screening mass squared in a pure gluonic plasma with local temperature $T(\tau) \propto \rho_{QGP}^{1/3}(\mathbf{x},\tau)$ along the jet path $\mathbf{x}(\tau)$ through the plasma. Here $\chi(\tau) = M^2x_+^2 + f_E^2\mu^2(T(\tau))(1-x_+)/\sqrt{2}$ controls the "dead cone" and LPM destructive interference effects due to both the finite quark current mass M, and a thermal gluon $m_g = f_E\,\mu(T)/\sqrt{2}$ mass.

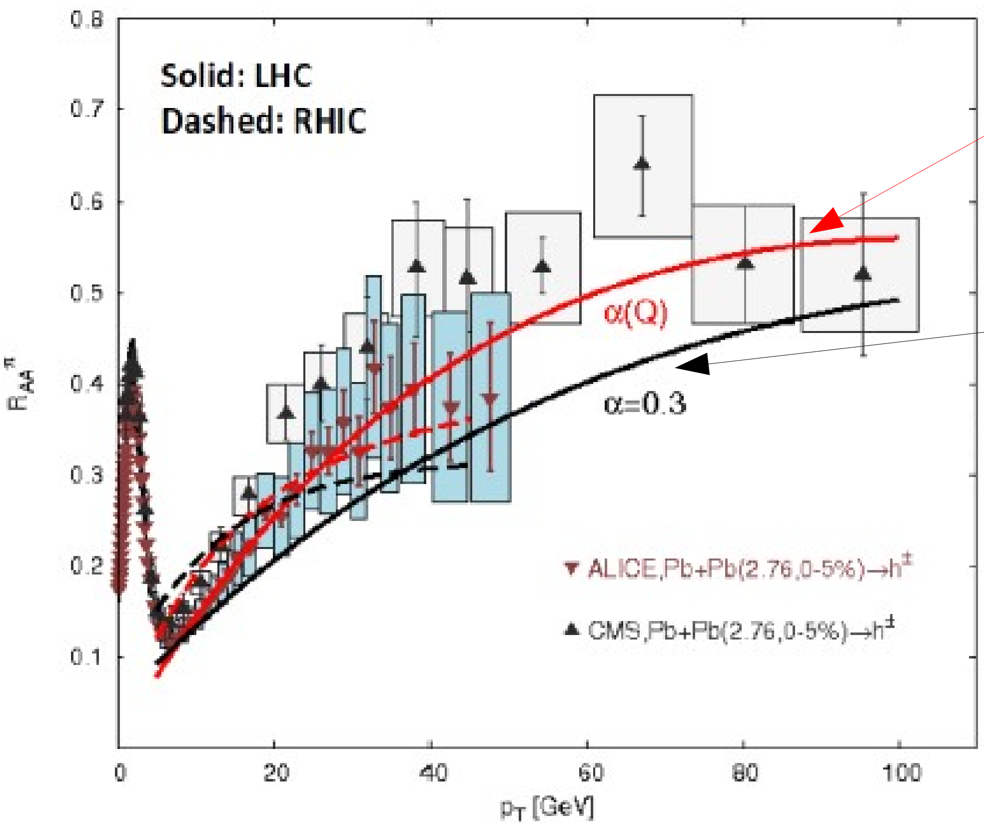
Includes effects due to bulk Radial and Elliptic transverse flow of sQGP as well as boost invariant Bjorken longitudinal flow

These suppress jet v2 by factor of 2 (as in **D. Molnar and D.Sun**, NPA932 (2014))

J.Xu, A.Buzzatti, MG, JHEP 1408 (2014)

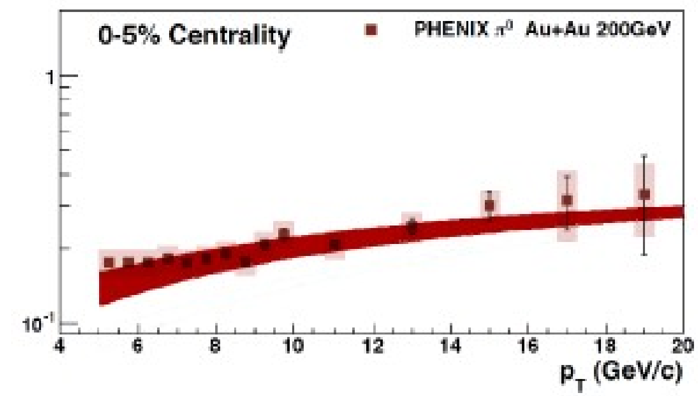
CUJET1.0 = rc DGLV (rad + el) + <u>Bj(1+1) QGP</u>

A.Buzzatti, MG, NPA 904 (2013) 779



<u>Running coupling</u> naturally explains relative transparency LHC QGP At 2 X RHIC density as well as RHIC RAA

(RHIC constrained fixed coupling Over-predicts quenching at LHC)

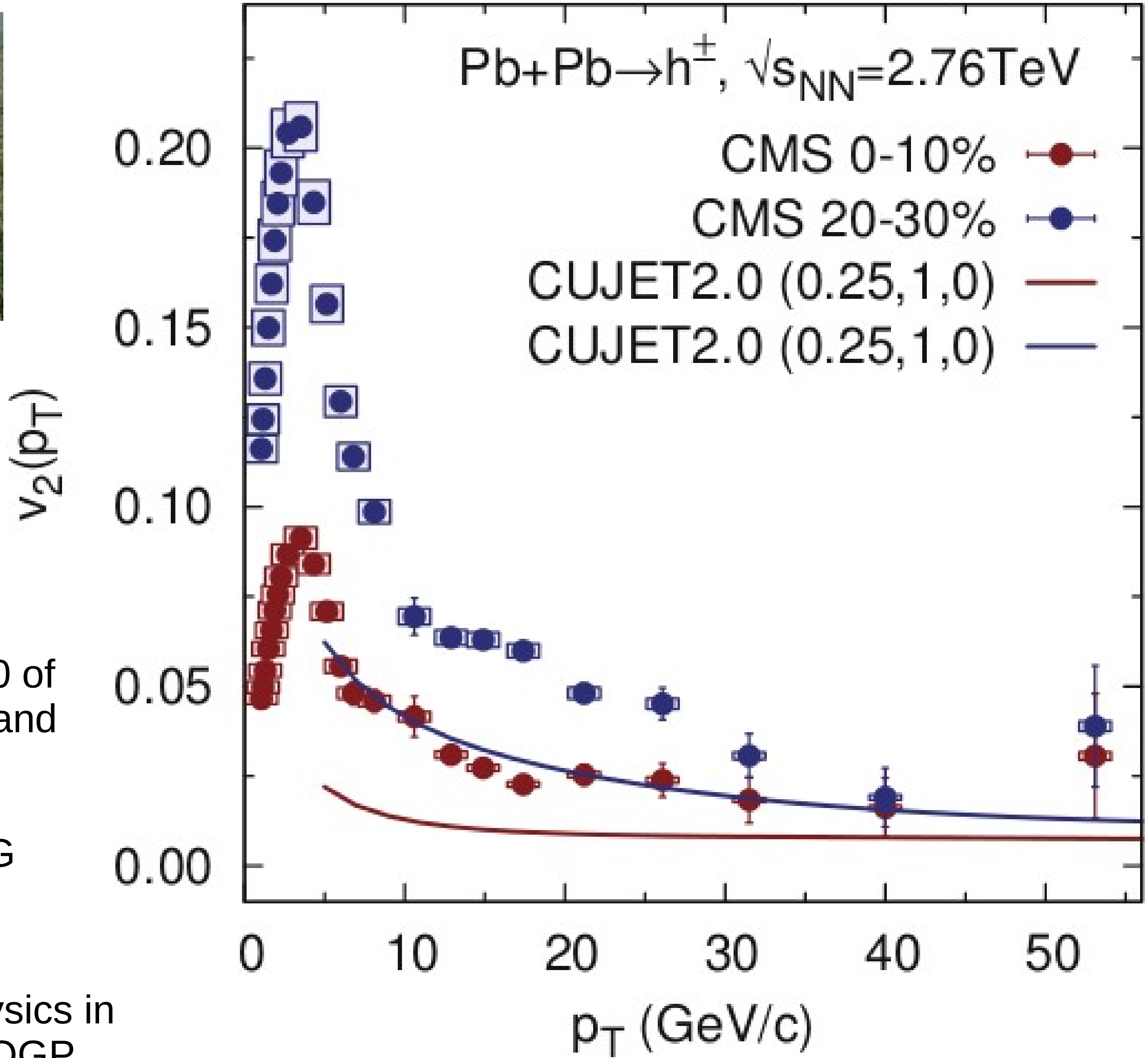


The similarity of RAA at RHIC and LHC pT<20 and the higher pT slope of RAA at LHC is due to the canceling effects of ~2 higher opacity at LHC and the less rapidly falling initial jet spectra ~1/pT^5 at LHC vs 1/pT^8 at RHIC

The LHC data also show clearly the need to include running QCD coupling effects That also weaken LHC quenching (hence raising RAA)

The persistent v2 puzzle

CUJET2.0 accounts for only half of the 5% azimuthal Asymmetry of jets observed at LHC



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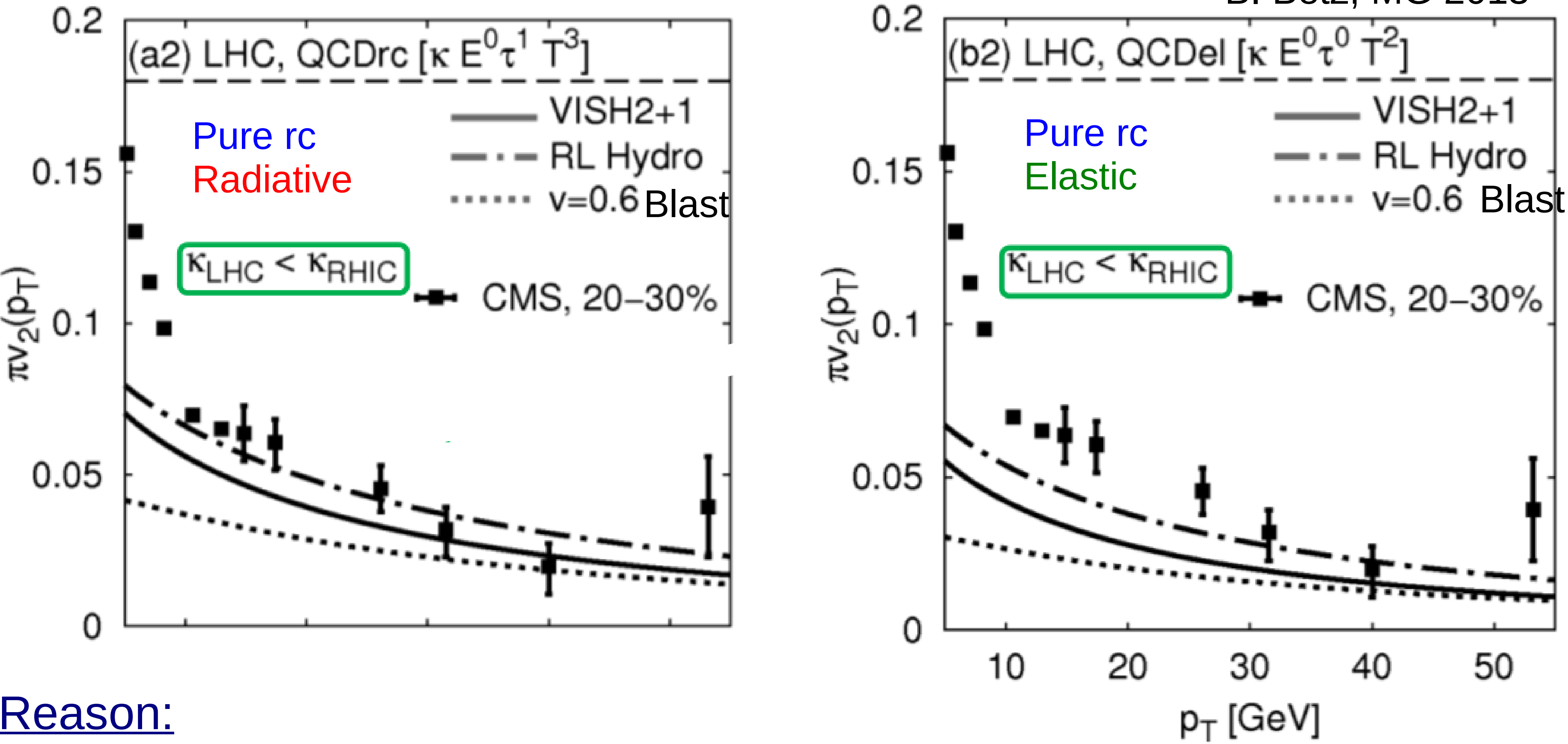
Azimuthal jet flavor tomography with CUJET2.0 of nuclear collisions at RHIC and LHC

Jiechen Xu , A Buzzatti, MG JHEP 1408 (2014) 063

There must be missing physics in The pQCD HTLmodel of sQGP

What makes jet v2(pT) so difficult to get correct ?

B. Betz, MG 2013



Reason:

v2 Jet ≈ ½ (dE/dx Model) + ½ (spacetime bulk hydro 2+1D flow)

Depends on the complex interplay between details of microscopic pT>10 jet dE/dx
And details of 2+1D spacetime evolution of the bulk soft pT<2 GeV sQGP
Controlled by Initial Conditions and η/s and higher order transport coefficient

The azimuthal averaged RAA is much less sensitive to the Hard+Soft convolution

Part 5: Our proposed sQGP = sQGMP solution

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

Jiechen Xu,[1,*] Jinfeng Liao,[2,3,†] and Miklos Gyulassy[1,‡]

[1] *Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, USA*
[2] *Physics Dept and CEEM, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*
[3] *RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, Upton, NY 11973, USA*

(Dated: March 10, 2015)

We utilize a new framework, CUJET3.0, to deduce the energy and temperature dependence of jet transport parameter, $\hat{q}(E > 10\ GeV, T)$, from a combined analysis of available data on nuclear modification factor and azimuthal asymmetries from RHIC/BNL and LHC/CERN on high energy nuclear collisions. 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: (1) the Polyakov loop suppression of color-electric scattering (aka "semi-QGP" of Pisarski et al) and (2) the enhancement of jet scattering due to emergent magnetic monopoles near T_c (aka "magnetic scenario" of Liao and Shuryak) and (3) thermodynamic properties constrained by lattice QCD data. CUJET3.0 reduces to v2.0 at high temperatures $T > 400$ MeV, but 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.

CUJET3: Jiechen Xu, Jinfeng Liao, MG:
Chin.Phys.Lett. 32 (2015) 9, 092501 and arXiv:1508.00552
CUJET2: Jiechen Xu, A. Buzzatti, MG, JHEP 1408 (2014) 063

A key missing ingredient in both pQCD and AdS/CFT are Hadron Resonances!!

Something must confine color electric q and g degrees of freedom below Tc

The most natural candidate from analogy with condensed matter physics

is the magnetic dual of superconductivity (Nambu, Mandelstam, T'Hooft ~ 1974)

IF QCD has *emergent chromo-magnetic monopole* degrees of freedom near Tc

And *IF* they condense below Tc (like Cooper pairs do in superconductors)

Then they can provide the missing sQGMP link physics between

the T >> Tc asymptotic pQCD weakly coupled (asymp.free) QGP

and

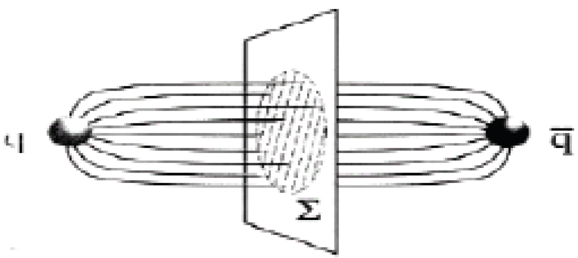
the T<< Tc confined color neutral HRG world

CUJET3 tests quantitatively if critical scattering between elec amd mag monopoles
Can explain perfect fluidity as well as jet quenching near Tc

The Liao-Shuryak sQGMP Scenario

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

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



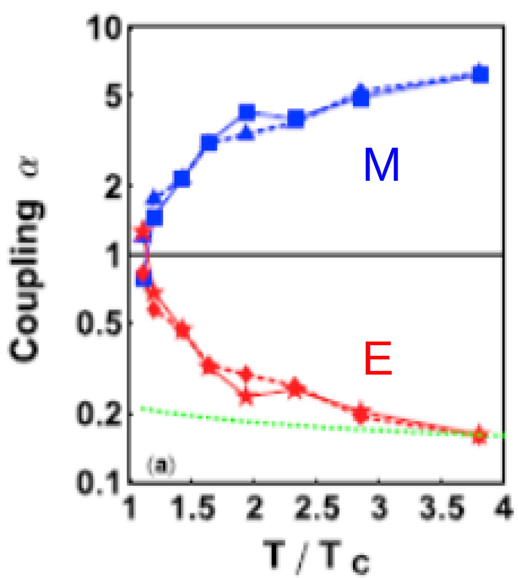
Electric Flux Tube:
Magnetic Condensate

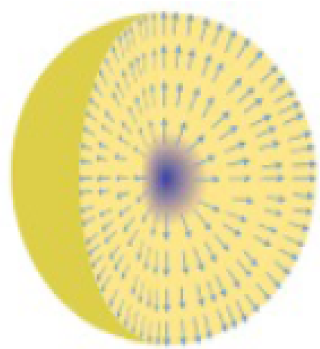
Emergent plasma with <u>E & M</u> charges:
chromo-magnetic monopoles are the "missing DoF"

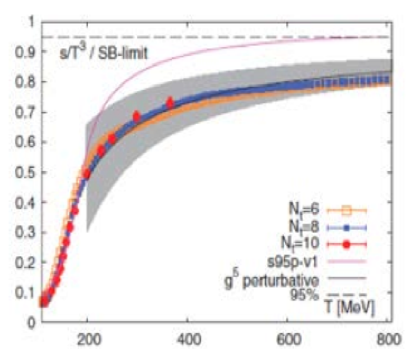
$$\alpha_E * \alpha_M = 1.$$

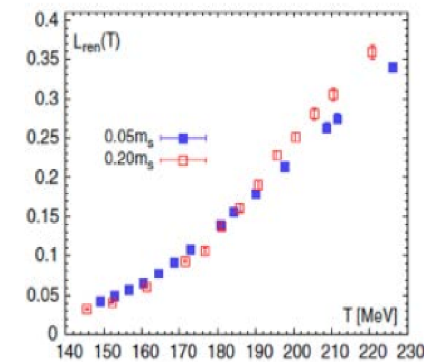
Plasma of E-charges
E-screening: g T
M-screening: g^2 T

$$L(\mathbf{x}) = \frac{1}{N_c}\mathrm{tr}\mathcal{P}\exp\left[ig\int_0^{1/T} A_4(\tau,\mathbf{x})d\tau\right]$$









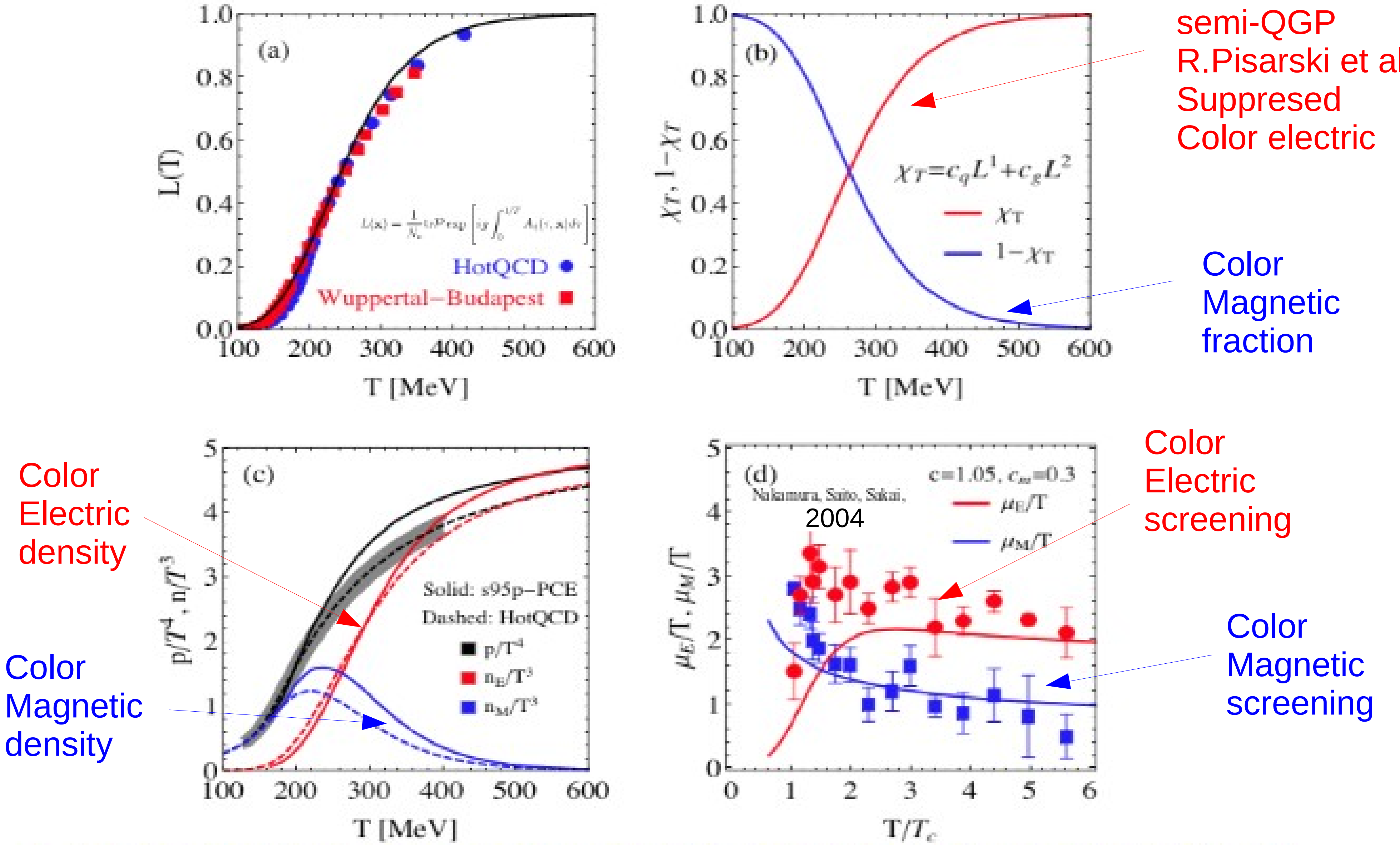
A region around Tc with liberated degrees of freedom
but only partially liberated color-electric objects—missing D.o.F.:
semi-QGP + emergent magnetic component

Jingeng Liao and Ed 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.

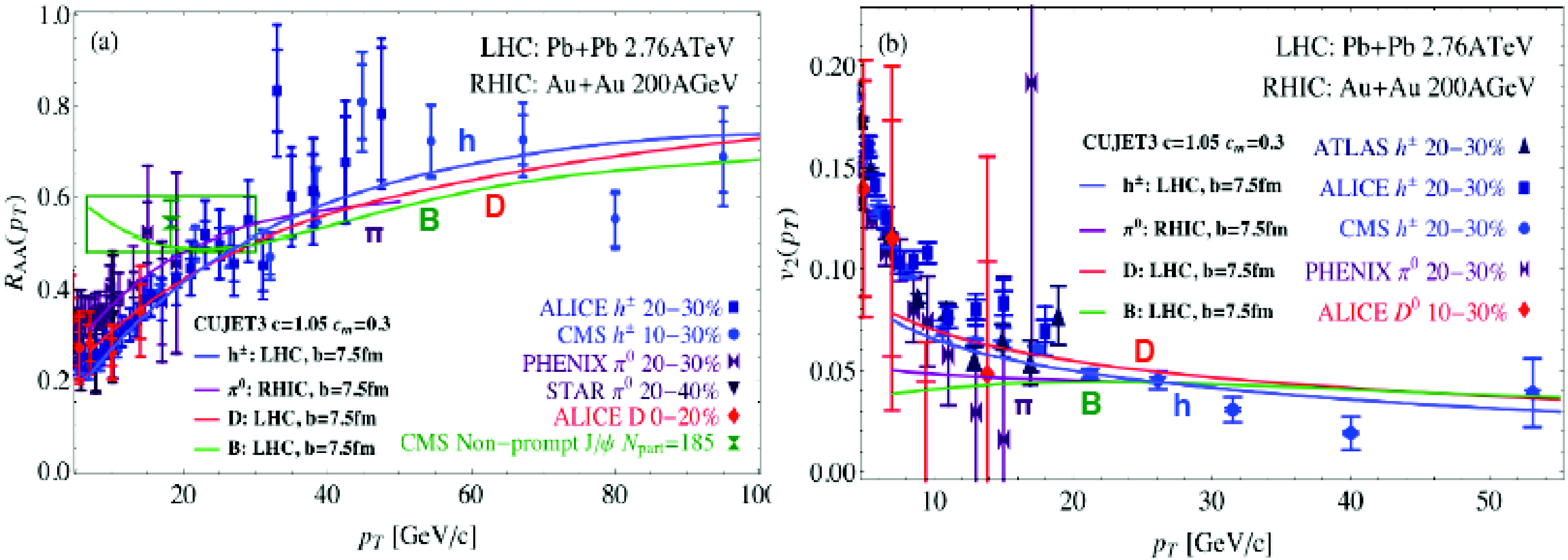
❖ Slide from Jinfeng Liao, APS DNP Hawaii 2014

Lattice Constraints: Polyakov Loop, EOS, Screening Masses



❖ The CUJET3.0 implementations of electric and magnetic components are well constrained by available lattice data. The only adjustable parameter in this model is “c”.

CUJET3.0 simultaneously describes high pT $(R_{AA}+v_2)$*(light + heavy)*(RHIC+LHC)



The combined set of observables

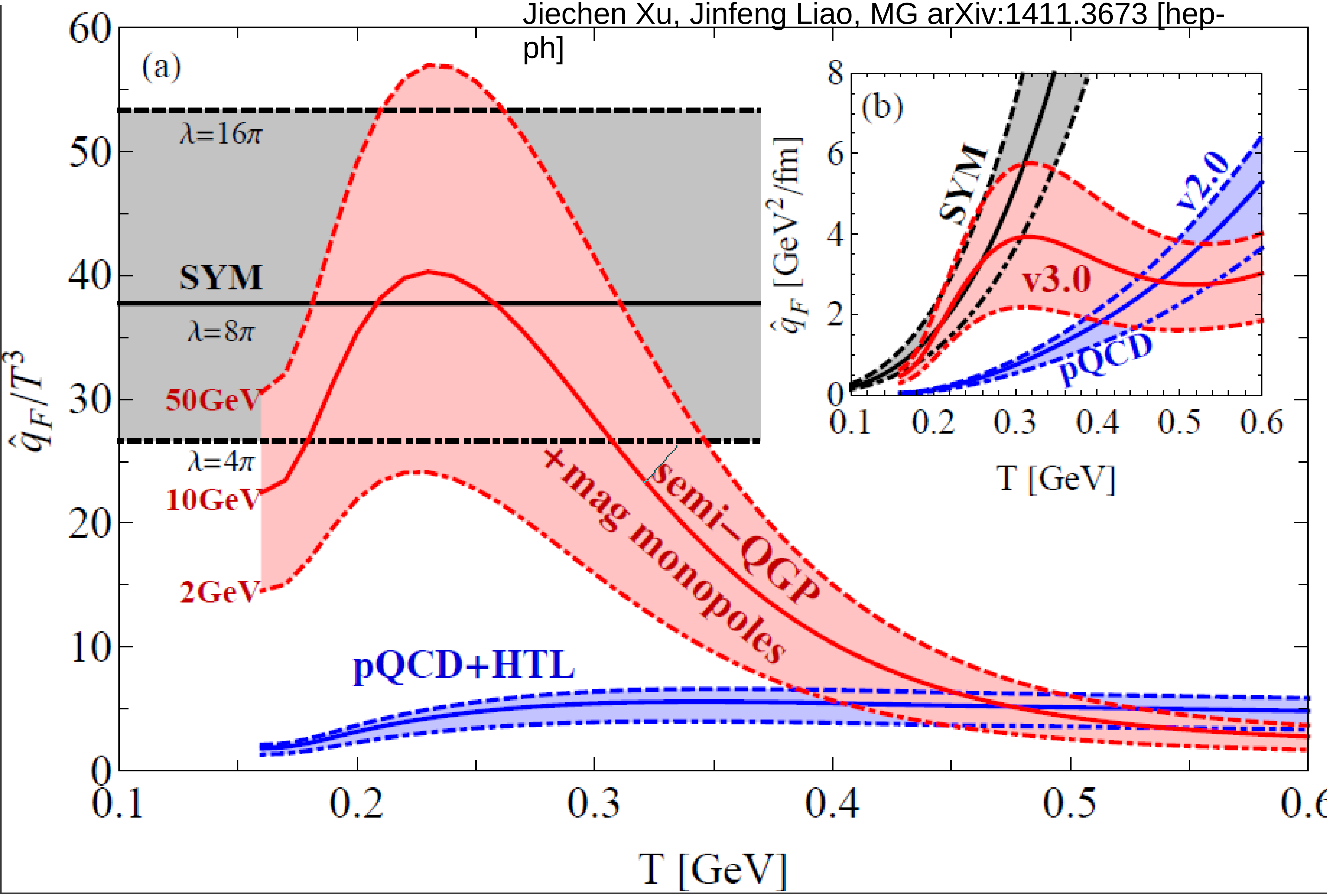
$(R_{AA}+V_2)$*(RHIC+LHC)*(pion+D+B)

are consistently accounted for (within present experimental errors) in the CUJET3.0 framework using lattice data constrained

sQGMP near Tc + pQCD jet quenching

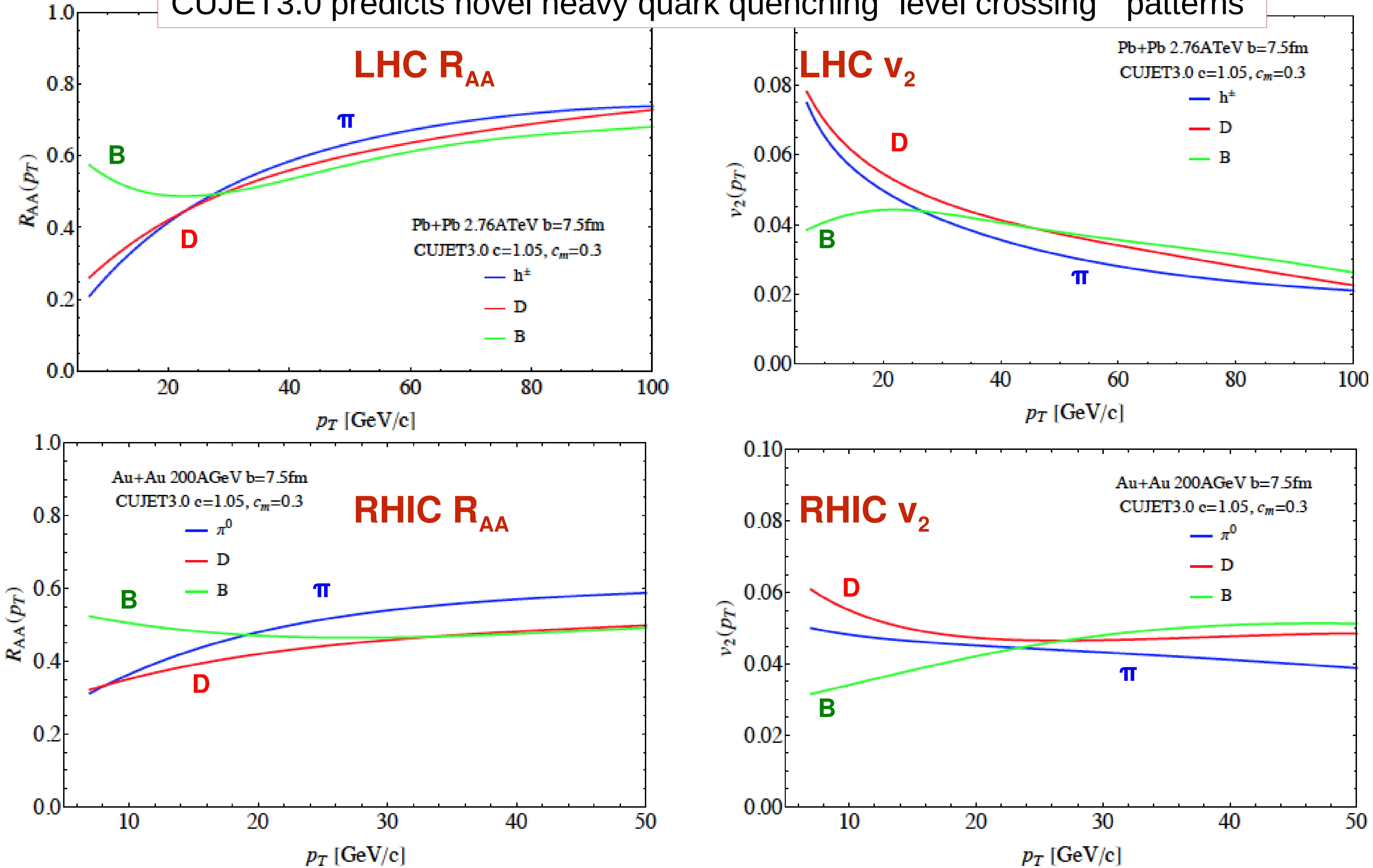
Jiechen Xu, Jinfeng Liao, MG arXiv 1411.3673 sQGMP interpolates between conformal pQCD and AdS limits Non-Conformally in T~ (1-2)Tc

Jiechen Xu, Jinfeng Liao, MG arXiv:1411.3673 [hep-ph]



Open charm and beauty at high p_T R_{AA} and v_2 at RHIC and LHC (20-30% centrality) from CUJET3.0

CUJET3.0 predicts novel heavy quark quenching “level crossing” patterns



Part 6: Consistency of Jet transport Field qhat(E,T) and
Perfect Fluidity eta/s~1/4pi in the sQGMP model

In addition to the RAA vs jet v2 problem

there is the problem of consistency and robustness of
Bulk Perfect Fluidity and Jet Quenching

In CUJET3.0 we solve both problems by including

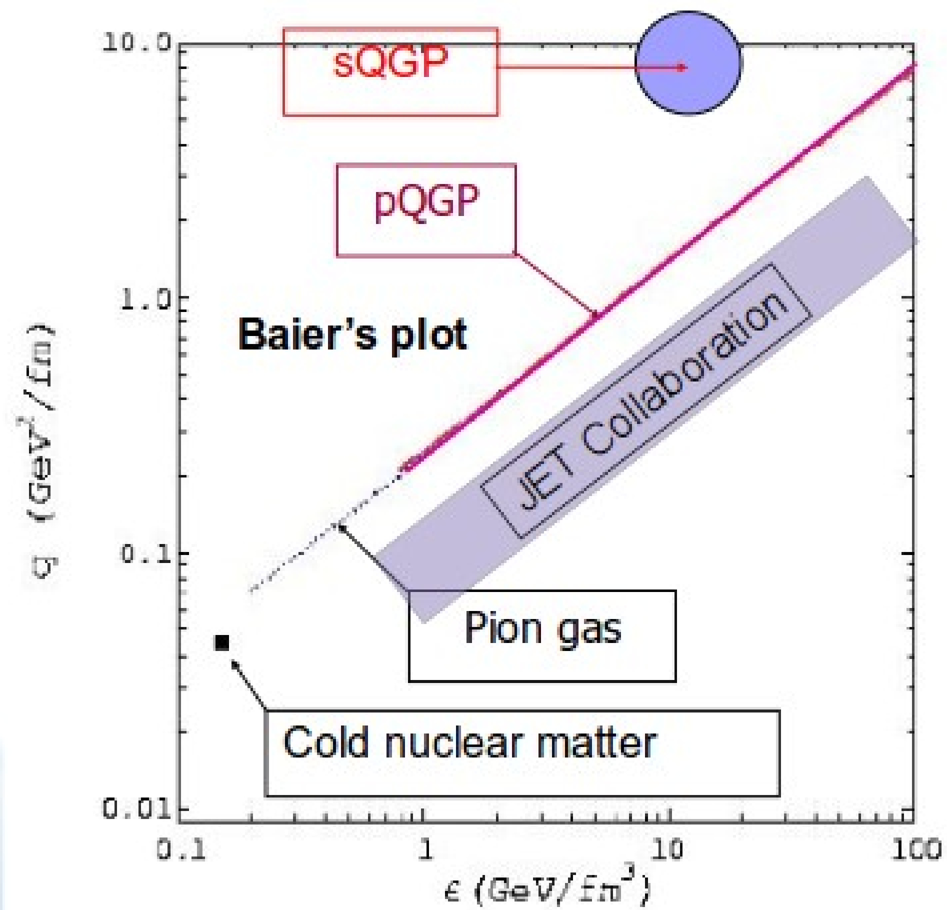
(1) emergent magnetic monopole d.o.f near Tc
(2) suppressed color elect charge q+g components near Tc
(3) lattice equation of state P(T) , L(T), chi(T), mE(T), mM(T)

CUJET3.0=CUJET2.0 + suppressed q and glue +
+ enhanced mag monopole + lattice QCD

Jet quenching vs. η/s

From B. Mueller's slide 2013

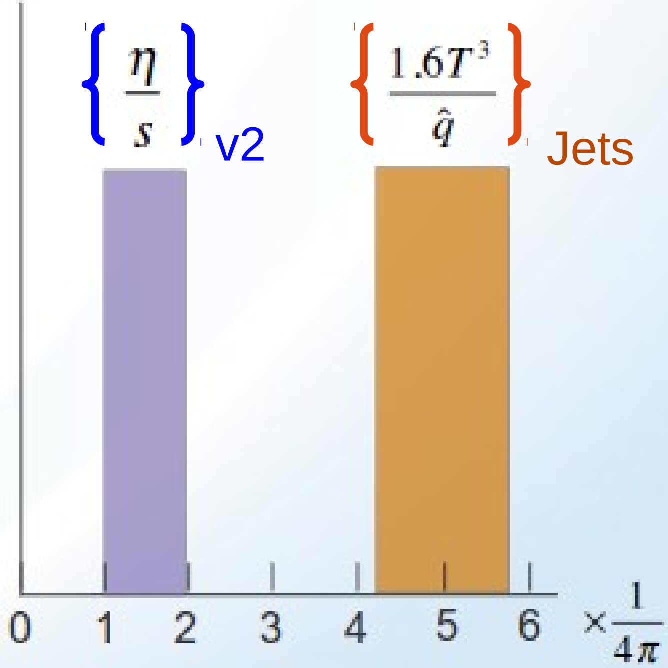
Majumder, BM, Wang



$$\eta / s \approx \frac{0.065}{\alpha_s^2 \ln(q_{\max}^2 / m_D^2)}$$

$$T^3 / \hat{q} \approx \frac{0.04}{\alpha_s^2 \ln(q_{\max}^2 / m_D^2)}$$

HTL Weakly Coupled



Brookhaven Science Associates

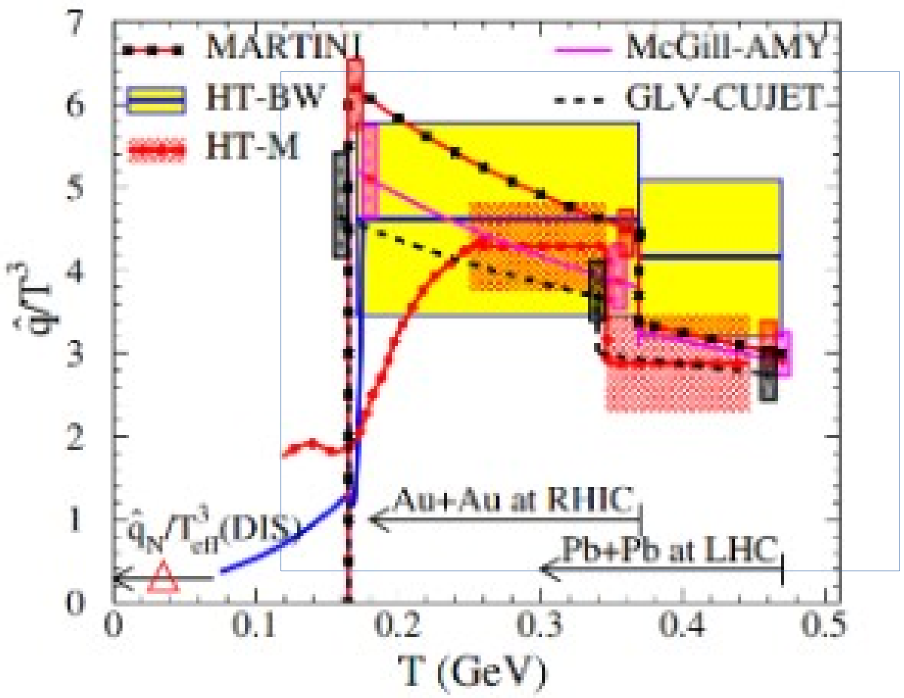
23

BROOKHAVEN NATIONAL LABORATORY

Bulk Flow suggests strongly coupled near "perfect fluidity" for pT<2 GeV
while Hard Jet probes extrapolated down to pT~ 2GeV predict factor >4 larger viscosity

Jet quenching parameter (qhat) and η/s

$$\hat{q} = \rho \int d^2 q_\perp q_\perp^2 \frac{d\sigma}{d^2 q_\perp}$$



JET Collaboration, PRC 90, 014909 (2014)

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \mathrm{GeV^2/fm} \text{ at } \begin{array}{l} T = 370 \text{ MeV,} \\ T = 470 \text{ MeV,} \end{array}$$

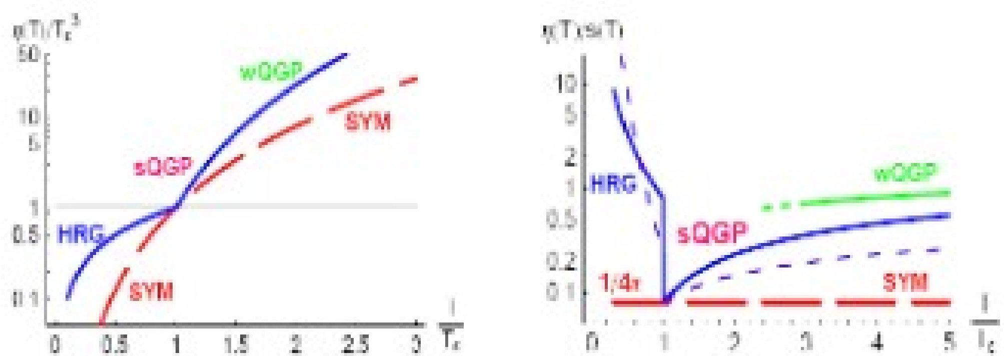
- Kinetic theory estimate of η/s from qhat

$$\begin{aligned} \eta/s &= \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p \rangle_a \lambda_a^{tr} \\ &= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle S_{ab}\rangle/2} dq^2 \frac{4q^2}{\langle S_{ab}\rangle}\frac{d\sigma_{ab}}{dq^2}\right)^{-1} \\ &= \frac{18T^3}{5s}\sum_a \rho_a / \hat{q}_a(T, E=3T) \ , \end{aligned} \quad (1$$

Danielewicz, Gyulassy, PRD 1985

$$\frac{\eta}{s}\left\{\begin{matrix} \approx \\ \gg \end{matrix}\right\} 1.25 \frac{T^3}{\hat{q}} \left\{\begin{array}{l} \text{for weak coupling,} \\ \text{for strong coupling.} \end{array}\right.$$

Majumder, Muller, Wang, PRL 2007



Hirano, Gyulassy, NPA 2006

Our proposed sQGMP solution to puzzles

sQPMP = *semi*-chomo-Electric(Q+G)+ *semi*-chromo-Magnetic Monopoles M

semi color Elect quasiparticles Q+G are suppressed by Polyloop and Polyloop^2 (aka Pisarski et el) or suppressed by Quark susceptibility (aka Petreczky et al)

semi color Magnetic quasiparticle M that are emergent d.o.f in vicinity of Tc (aka Liao and Shuryak)

Semi also in sense that the competing three Q+G+M Deg. of Freedom That evolve into a perturbative Q+G HTL DOF for T > 3 Tc

The Inverse connection between eta/s and the jet transport qhat(T,E) field

Jiechen Xu, Jinfeng Liao, MG arXiv:1411.3673 [hep-ph]

We now turn to the shear viscosity. As in [4–6], an estimate of shear viscosity per entropy density η/s can be derived from kinetic theory in the weak coupling limit:

$$\eta/s = \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p\rangle_a \lambda_a^{tr}$$

Depends of composition and m.f.p. of all quasi-particles in the QGP

$$= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle \mathcal{S}_{ab}\rangle/2} dq^2 \frac{4q^2}{\langle \mathcal{S}_{ab}\rangle}\frac{d\sigma_{ab}}{dq^2}\right)^{-1}$$

[4,5]

★

$$= \frac{18T^3}{5s}\sum_a \rho_a/\hat{q}_a(T, E=3T) \ .$$

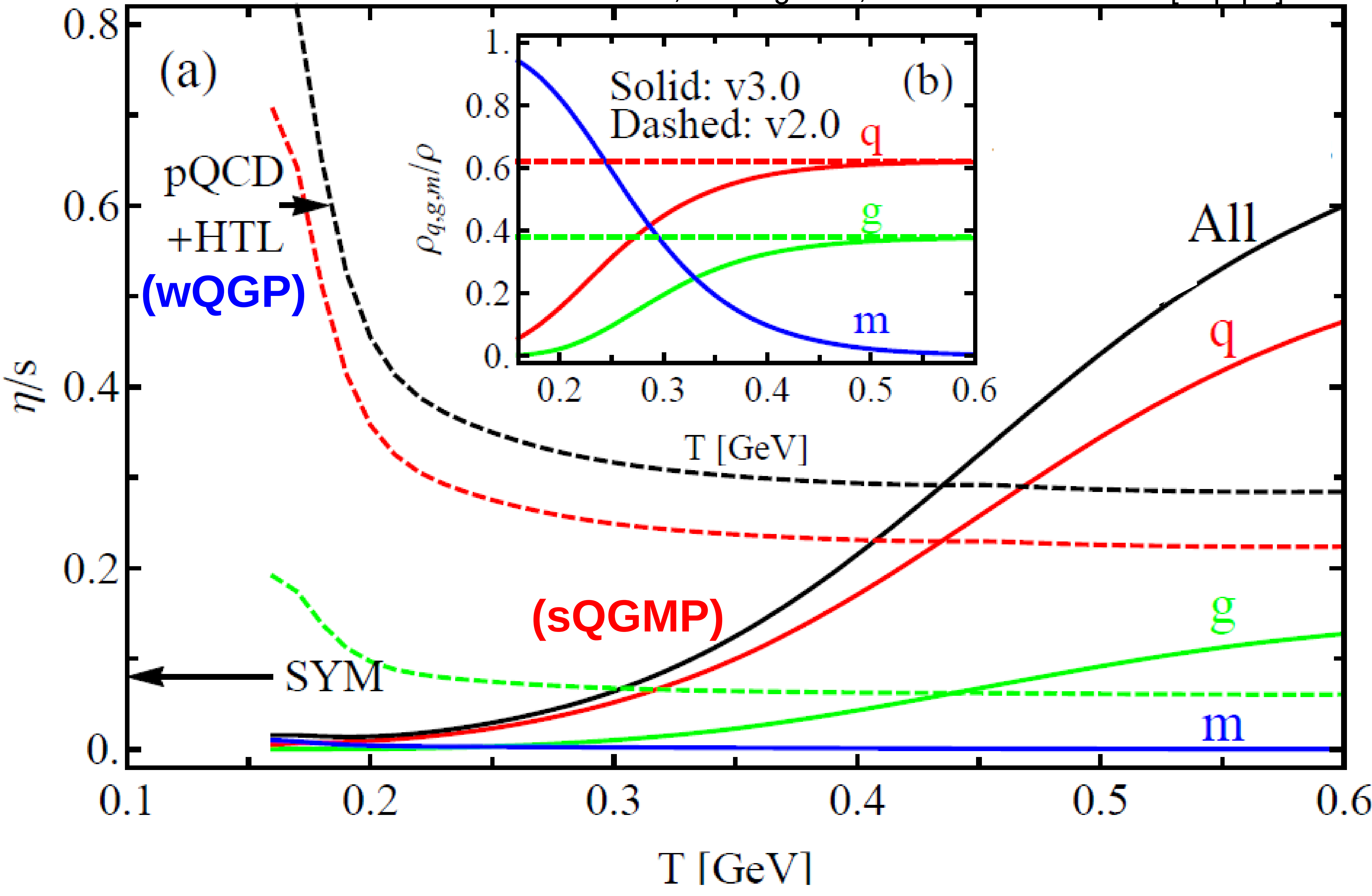
[4] P. Danielewicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985).

[5] T. Hirano and M. Gyulassy, Nucl. Phys. A **769**, 71 (2006).

★ [6] A. Majumder, B. Muller, and X. N. Wang, Phys. Rev. Lett. **99**, 192301 (2007).

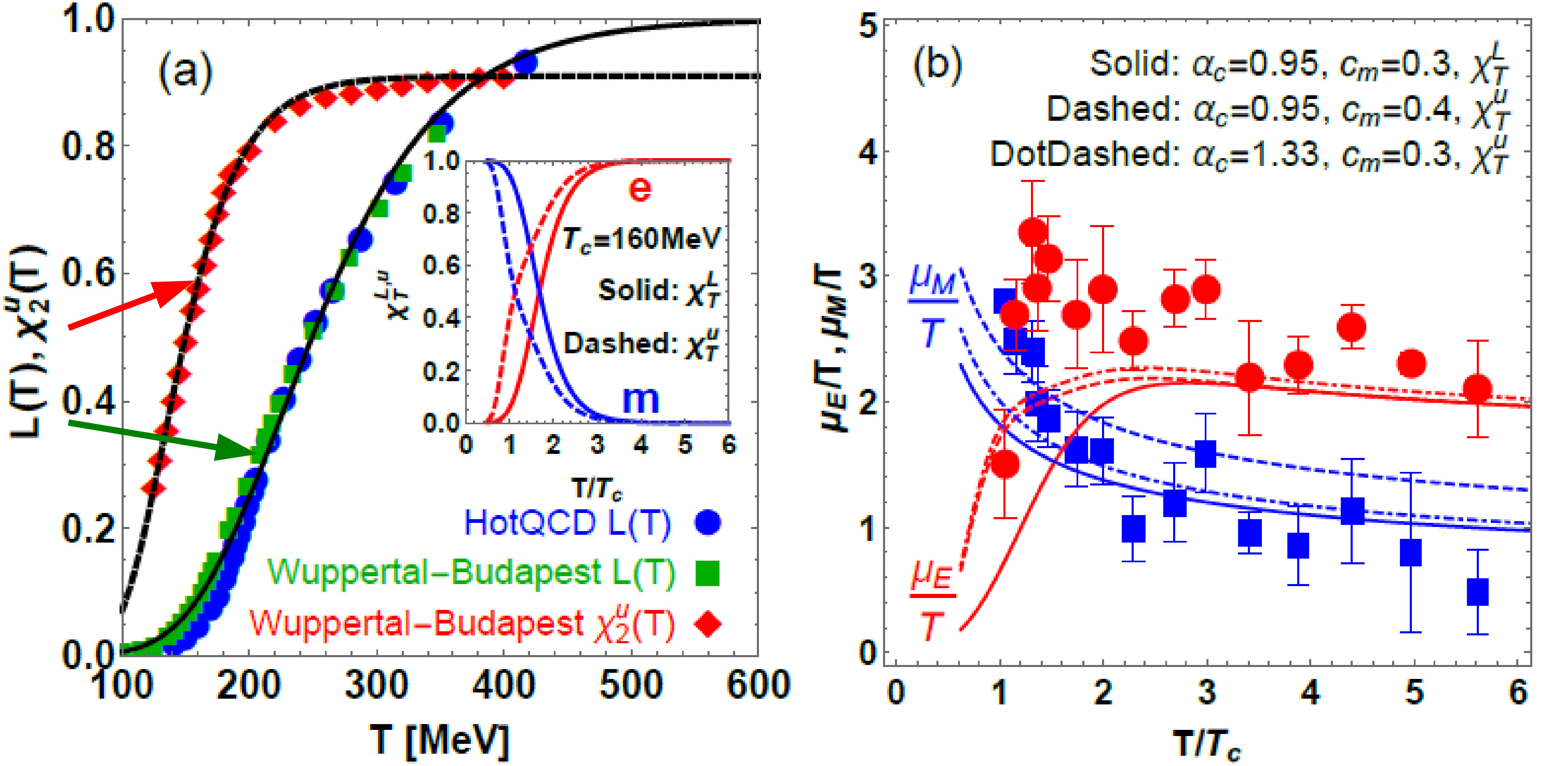
CUJET 2.0 vs 3.0 result fig 1: eta/s > 0.3 wQGP vs eta/s < 0.1 sQGMP for T< 300 MeV

Jiechen Xu, Jinfeng Liao, MG arXiv:1411.3673 [hep-ph]



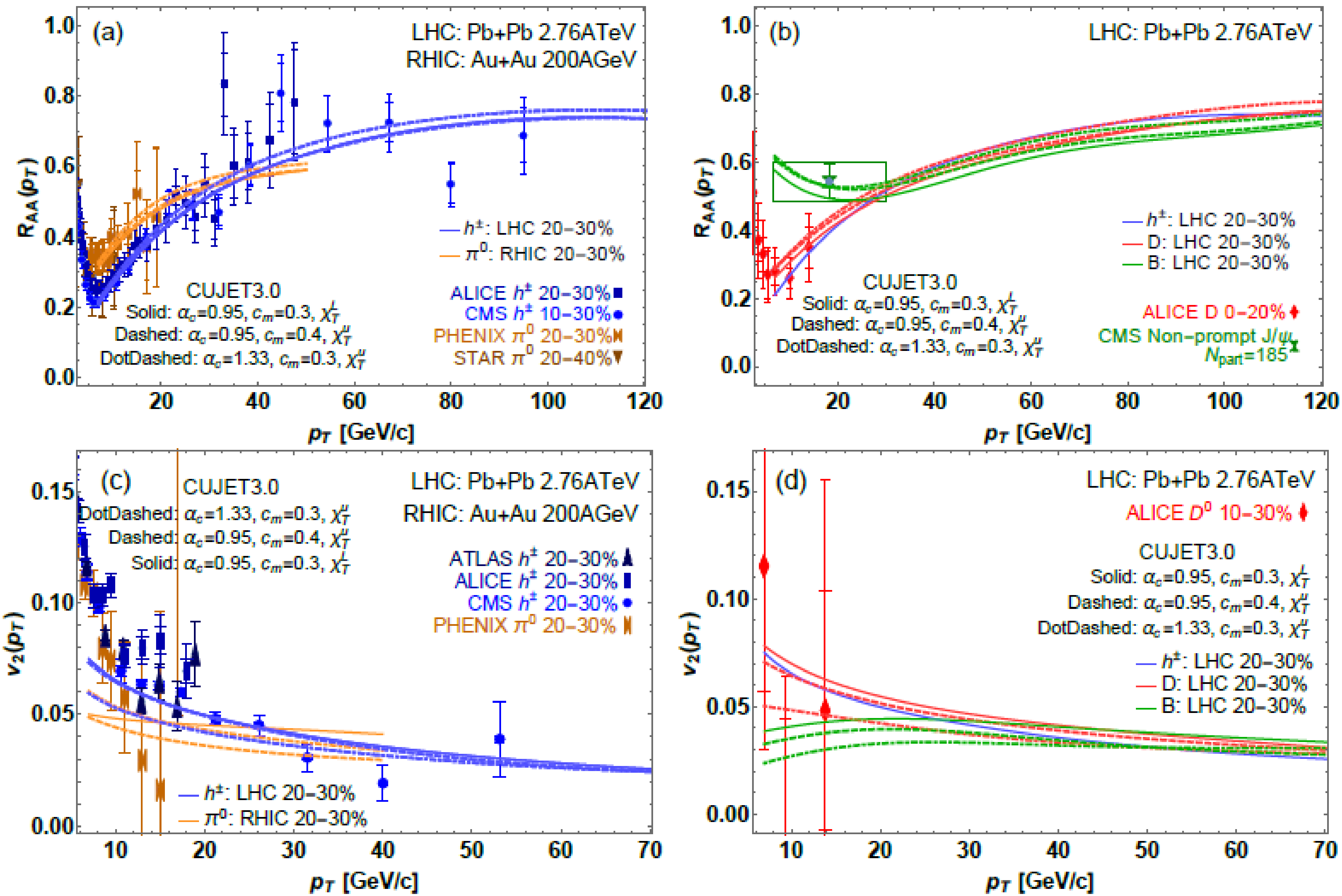
Current systematic theoretical uncertainties in semi-Quark composition

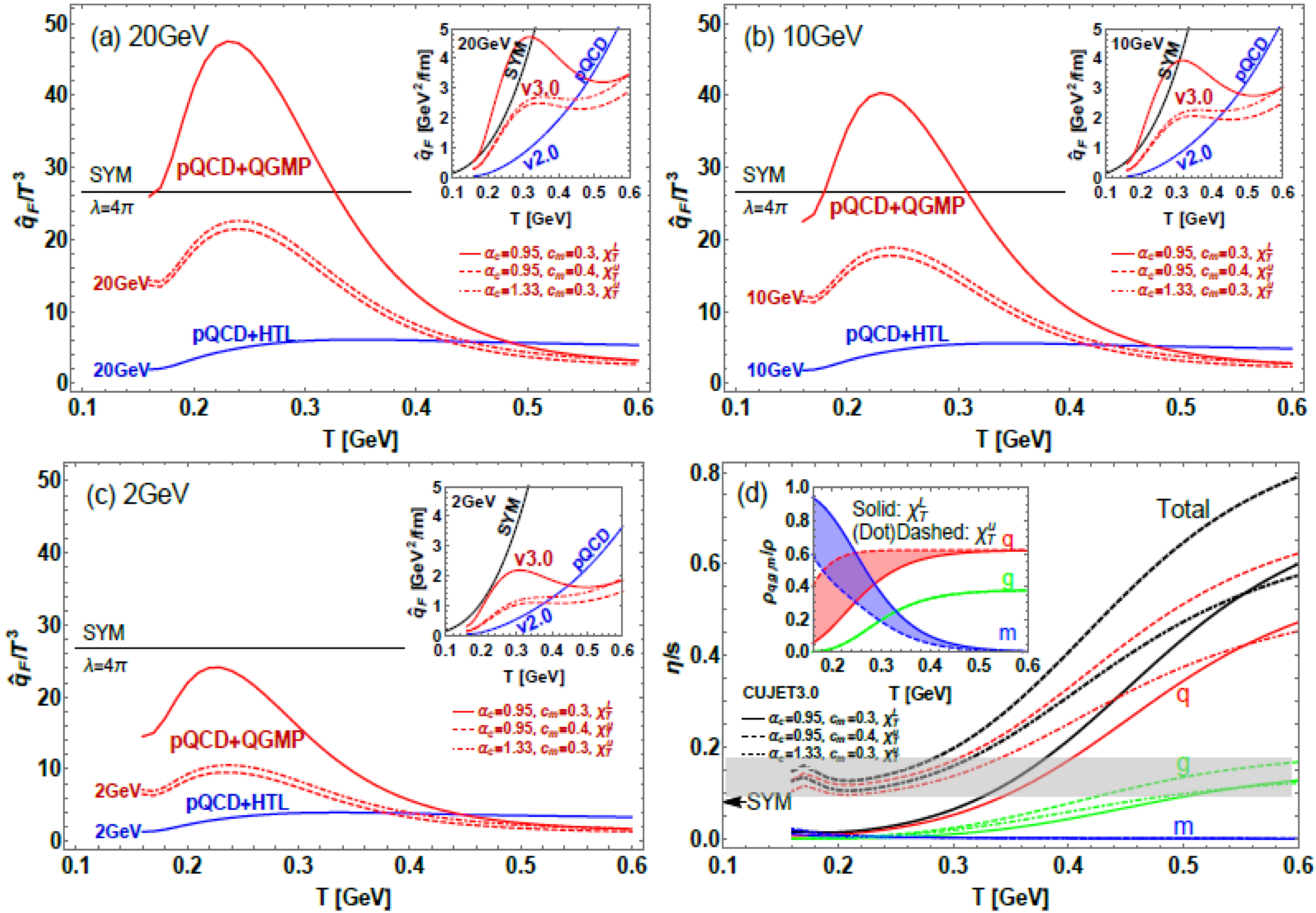
diagonal susceptibility of light quark number density $\chi_2^u(T)$
Suggest much faster light quark deconfinement
Than the slower Polyakov loop L(T) for heavy quarks



We compute RAA, v2, qhat, and eta/s with both semi-quark scenarios to gauge
Some of the yystematic errors of the sQGMP model

Robustness of CUJET3 predictions with semi-QGMP model of sQGP





Fast quark liberation with quark susceptibility stay above the unitarity bound and within the light grey band inferred from bulk pT<2 GeV harmonic flow data.
In contrast the slow Polyakov liberation scheme dives below the grey band.

Summary :

(1) The combined 12 sets of observables,

(RHIC + LHC) * (RAA + V2) * (pion + D + B),

are consistently accounted in the CUJET3.0 sQGMP framework

using a lattice QCD constrained Q, G and M decomposition

of bulk constrained VISH2+1 hydrodynamic evolved fluids.

The Perfect Fluid semi-opaque sQGP is compatible with semiQGMP

(2) Most remarkably, for the first time, the CUJET3.0 sQGMP framework

may solve the past inconsistency between perturbative QCD based high jet transport coefficient field, $\hat{q}(E > 10\ \mathrm{GeV}, T)$ deduced from RHIC & LHC,

and the small $\eta/s = \sum_a \rho_a/\hat{q}(E = 2\ \mathrm{GeV}, T) \sim 0.1 - 0.2$

required to account for bulk "Perfect Fluidity".

In sQGMP this is due to 1/alf_s enhancement of color electric interactions with emergent non-abelian color magnetic monopoles near Tc together with nonperturbative suppression of color electric components consistemt with available lattice QCD data

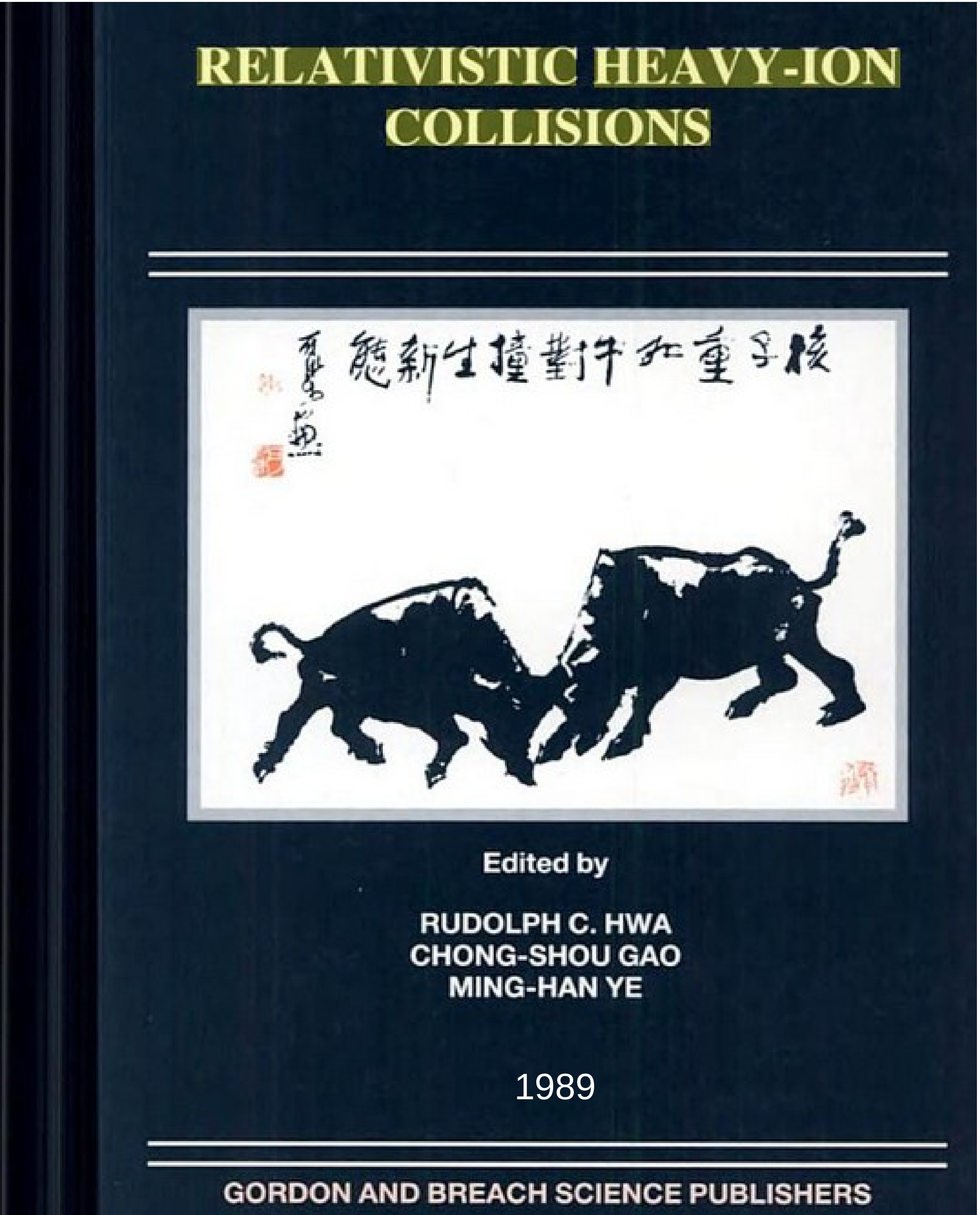
So, sQGP is system of suppressed q and g d.o.f. interacting strongly with emergent chromomagnetic monopoles that condense to confine all color below Tc ???

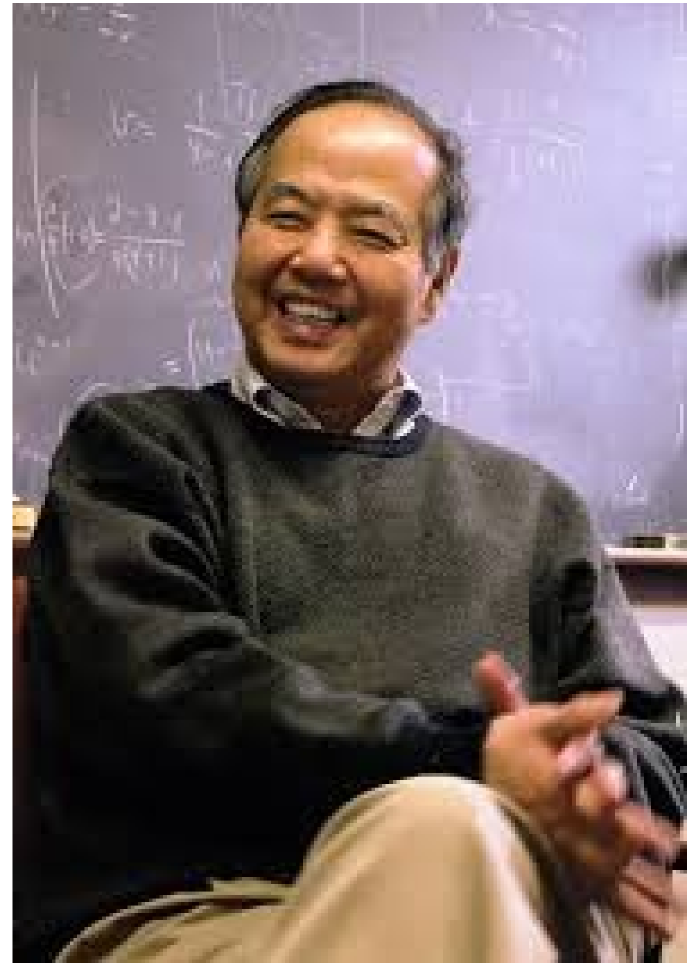
**Hmmmm!
Are you really sure it is not a broken Color Glasma
Or a 5D Black Hole ??**

What about p+p and p+A at LHC? Are they also perfect fluid sQGMP ?

We thought
pp and pA
Were supposed to
Be Null
Control Exp??

Well, that is another long story, to be continued ...





HEPNIC physics is obviously fun

“Nuclei as heavy as bulls
Through collision
Generate new states of matter”

Li Keran

The open p+p, p+A, A+A Theoretical and Experimental Landscape: CCNU is an ideal base from which to continue its exploration

Extra slides

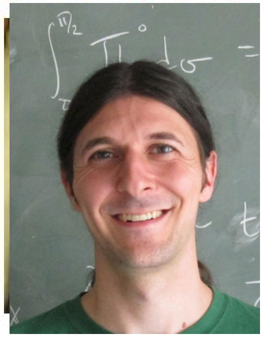
My elite Columbia Univ PhD Students with whom I enjoyed working with since 1992 on

Jet Tomography and AdS Holography



I.Vitev, M.Djordjevic, A. Adil.

W.Horowitz, S. Wicks, A. Buzzatti, A. Ficnar, B. Betz, J. Noronha, J.Xu

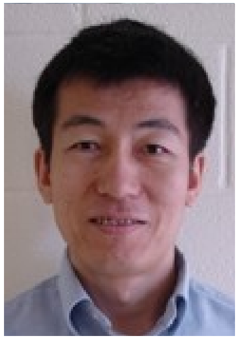


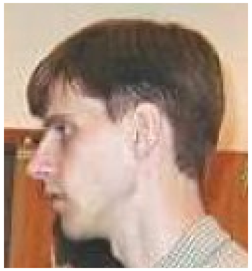




A+A Transport and Hydrodynamics

Z. Lin B. Zhang D.Molnar S.Vance



Some of my teachers and collaborators to whom I owe much thanks

Running coupling

CUJET1.0

$\alpha\left(k_T^2/(x(1-x))\right)$ $\qquad$ $\left(\alpha\left(q_i^2\right)\right)^2$

$$x\frac{dN^{(n)}}{dx\,d^2\mathbf{k}} = \frac{C_R\alpha_s}{\pi^2}\frac{1}{n!}\int\prod_{i=1}^{n}\left(d^2\mathbf{q}_i\,\frac{L}{\lambda_g(i)}\left[\bar{v}_i^2(\mathbf{q}_i)-\delta^2(\mathbf{q}_i)\right]\right)\times$$
$$\times\left(-2\,\tilde{\mathbf{C}}_{(1,\cdots,n)}\cdot\sum_{m=1}^{n}\tilde{\mathbf{B}}_{(m+1,\cdots,n)(m,\cdots,n)}\left[\cos\left(\sum_{k=2}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)-\cos\left(\sum_{k=1}^{m}\Omega_{(k,\cdots,n)}\Delta z_k\right)\right]\right)$$

$\alpha\left(9\,T^2\right)$

Soft Radiation ($E \gg \omega$, $x \ll 1$)
Soft Scattering ($E \gg q$, $\omega \gg k_T$)

Opacity series expantion $\longrightarrow$ $\left(\frac{L}{\lambda}\right)^n$

Radiation antenna $\longrightarrow$ *Cascade terms*

$$\tilde{\mathbf{C}}_{(i_1 i_2\cdots i_m)} = \frac{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})}{(\mathbf{k}-\mathbf{q}_{i_1}-\mathbf{q}_{i_2}-\cdots-\mathbf{q}_{i_m})^2+m_g^2+M^2x^2},$$

$$\tilde{\mathbf{B}}_{(i_1 i_2\cdots i_m)(j_1 j_2\cdots j_n)} = \tilde{\mathbf{C}}_{(i_1 i_2\cdots j_m)}-\tilde{\mathbf{C}}_{(j_1 j_2\cdots j_n)}\ .$$

Gunion – Bertsch $\qquad \tilde{\mathbf{B}}_i = \tilde{\mathbf{H}}-\tilde{\mathbf{C}}_i\,,$

Hard $\qquad \tilde{\mathbf{H}} = \frac{\mathbf{k}}{\mathbf{k}^2+m_g^2+M^2x^2}\,,$

$\alpha\left(9\,T^2\right)$

LPM effect $\longrightarrow$

$$\Omega_{(m,\cdots,n)} = \underbrace{\frac{(\mathbf{k}-\mathbf{q}_m-\cdots-\mathbf{q}_n)^2}{2xE}}_{Inverse\ formation\ time}+\underbrace{\frac{m_g^2+M^2x^2}{2xE}}_{Mass\ effects}$$

Scattering center distribution $\longrightarrow$ $\Delta z_k = z_k - z_{k-1} \sim L/(n+1)$

Levai, Vitev, Djordjevic, Wicks, Horowitz, Buzzatti, MG

CUJET3.0 = CUJET2.0 + semi-QGP + Mag. Monopoles

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

Original DGLV has only quark/gluon scattering centers

$$\frac{dE}{dx} \propto \cdots \int_{q^2} \frac{n_e\, \alpha_s^2(q^2)\, f_E^2}{q^2(q^2+f_E^2\mu^2)} \cdots$$

$$\frac{dE}{dx} \propto \cdots \int_{q^2} \left[\frac{n_e \boxed{\left(\alpha_s(q^2)\alpha_s(q^2)\right)} f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m \boxed{\left(\alpha_s^e(q^2)\alpha^m(q^2)\right)} f_M^2}{q^2(q^2+f_M^2\mu^2)} \right] \cdots$$

$$\frac{dE}{dx} \propto \cdots \int_{q^2} \frac{n_T}{(q^2+f_E^2\mu^2)(q^2+f_M^2\mu^2)} \times \kappa(q^2,T)$$

=1, by Dirac Quantization

$$\kappa(q^2,T) \equiv \boxed{\alpha_s^2(q^2)}\, \chi_T \left(f_E^2 + \frac{f_E^2 f_M^2 \mu^2}{q^2}\right) + (1-\chi_T)\left(f_M^2 + \frac{f_E^2 f_M^2 \mu^2}{q^2}\right)$$

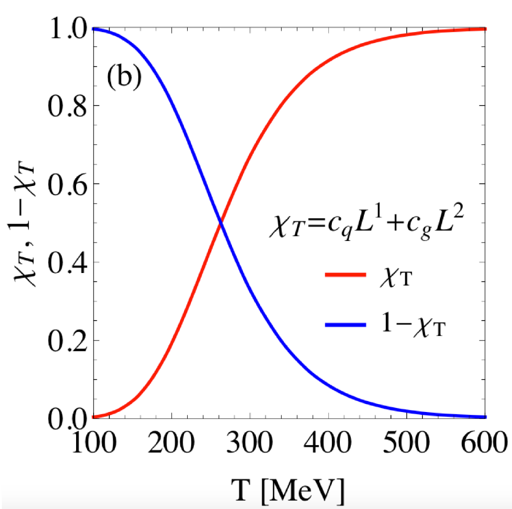
$$\chi_T = c_q L + c_g L^2$$

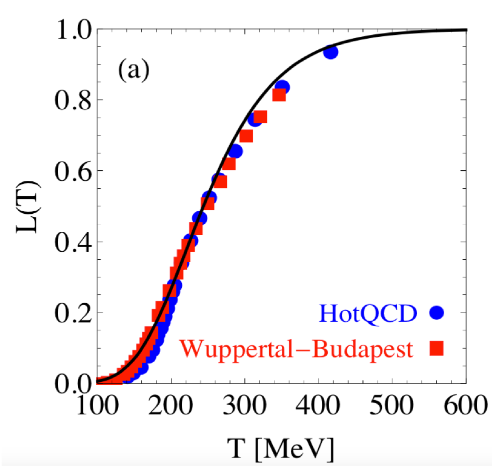
Polyakov Loop suppressed color electric component

$$f_E = \sqrt{\chi_T}$$

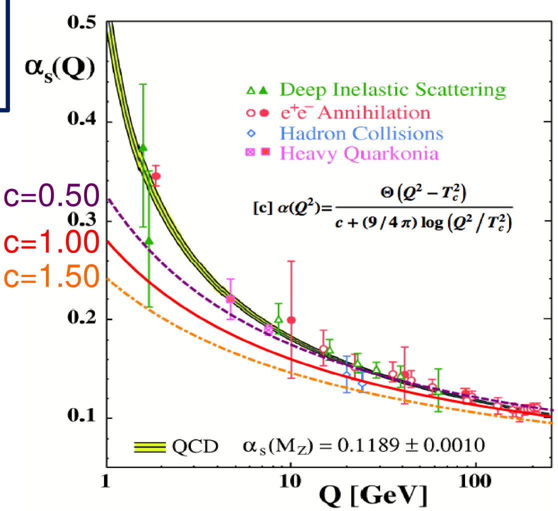
$$f_M = C_m g_T$$

$$L(\mathbf{x}) = \frac{1}{N_c} \mathrm{tr}\mathcal{P} \exp\left[ig \int_0^{1/T} A_4(\tau, \mathbf{x}) d\tau \right]$$





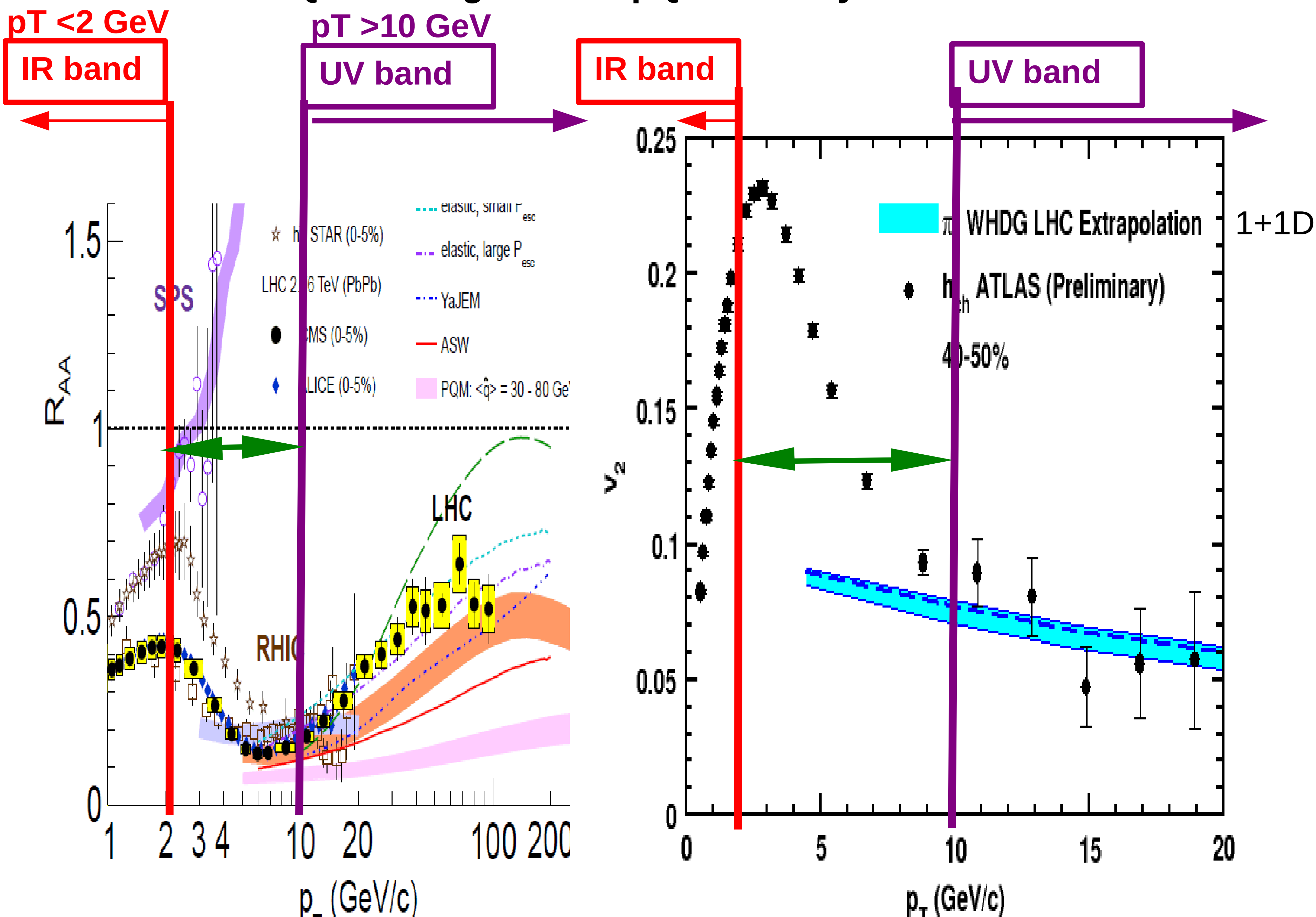
Bazavov et al., PRD 80 (2009)
Borsanyi et al., JHEP 09 (2010)



$$\alpha_s^2(q^2) \approx [1/[c + (9/2\pi)Log(q/\Lambda)]]^2$$

c = 1/alf_max is THE free param

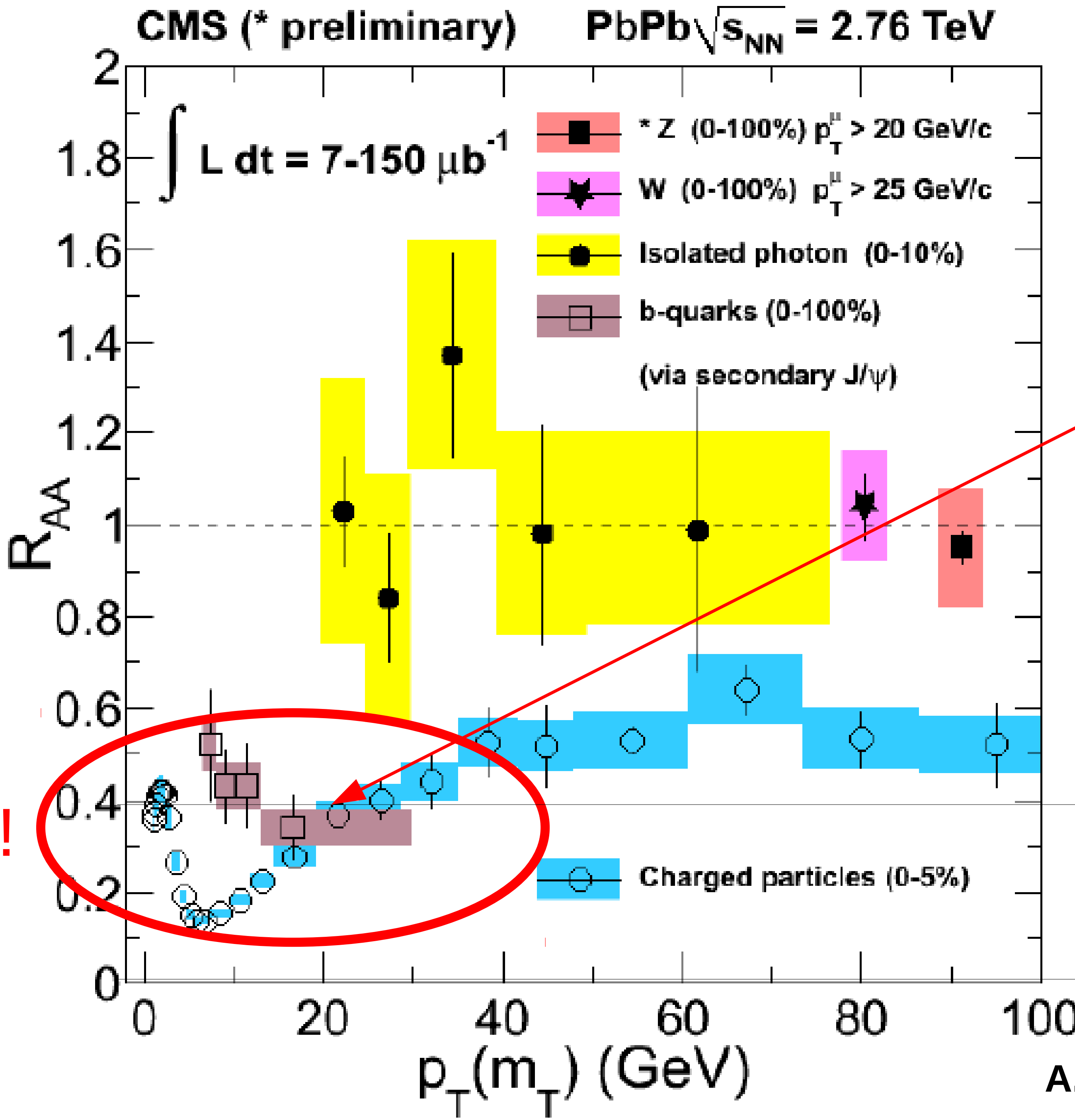
Jet Quenching data vs pQCD theory from SPS to LHC



The Perfect fluid physics in the Bulk "IR" seems very different from pQCD "UV".

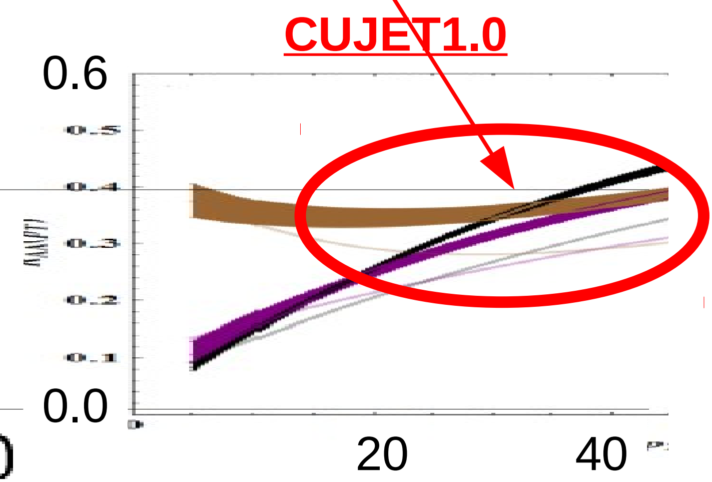
Is there a way to interpolate between long and short wavelength physics?

G.Roland QM12: First evidence for B quark quenching



!!

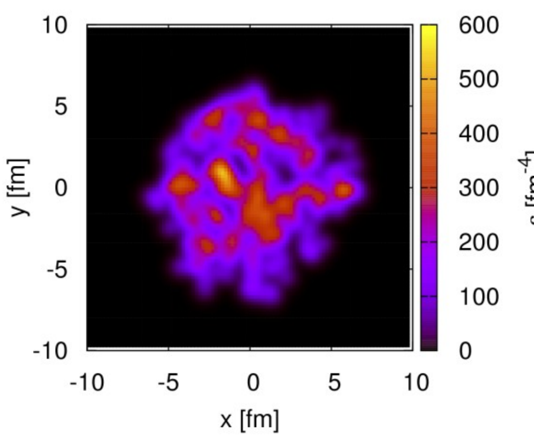
Has CMS seen
A hint of our predicted
RAA "Level Crossing"
of B and pion RAA
??

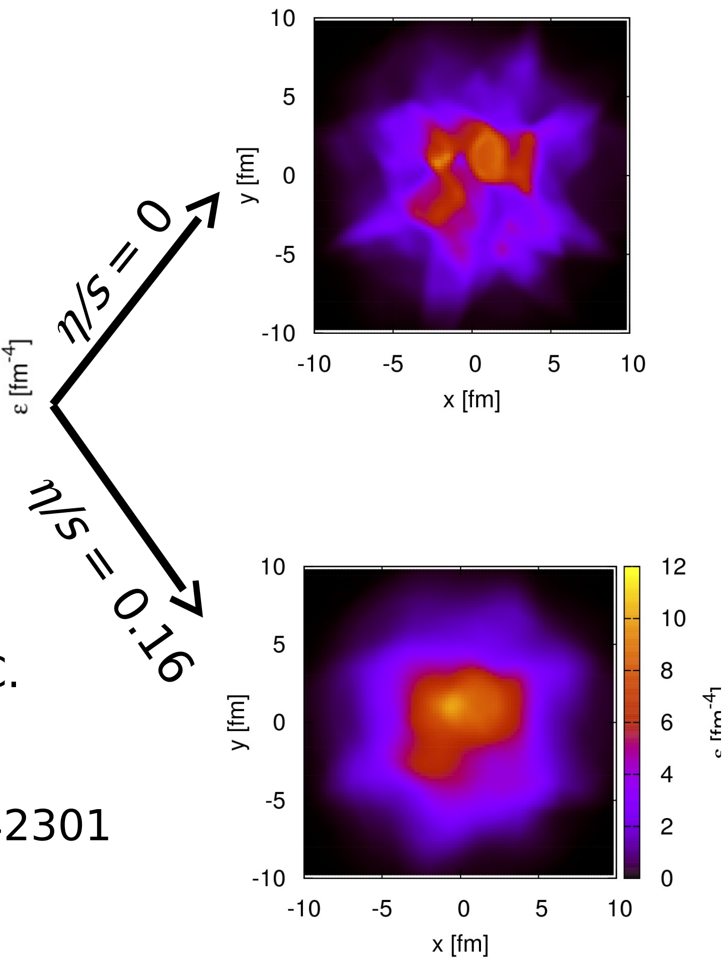


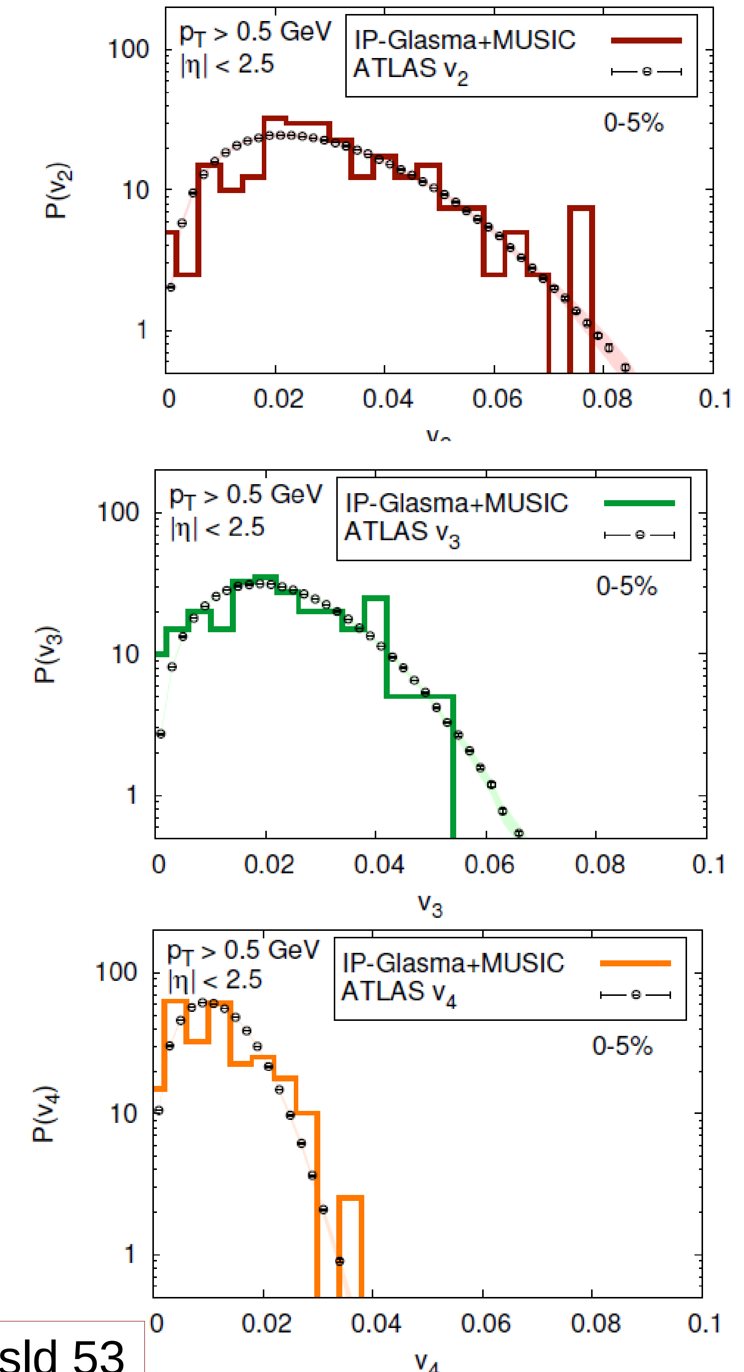
A. Buzzatti, MG, PRL 108 (2012)

State of the Art – *Event-by-Event* Flow Harmonic Distributions

- Treatment of gauge field fluctuations at sub-nucleon scales:







- B. Schenke, S. Jeon, C. Gale, Phys. Rev. C82, 014903 (2010); Phys.Rev.Lett.106, 042301 (2011)
- B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 108, 252301 (2012)

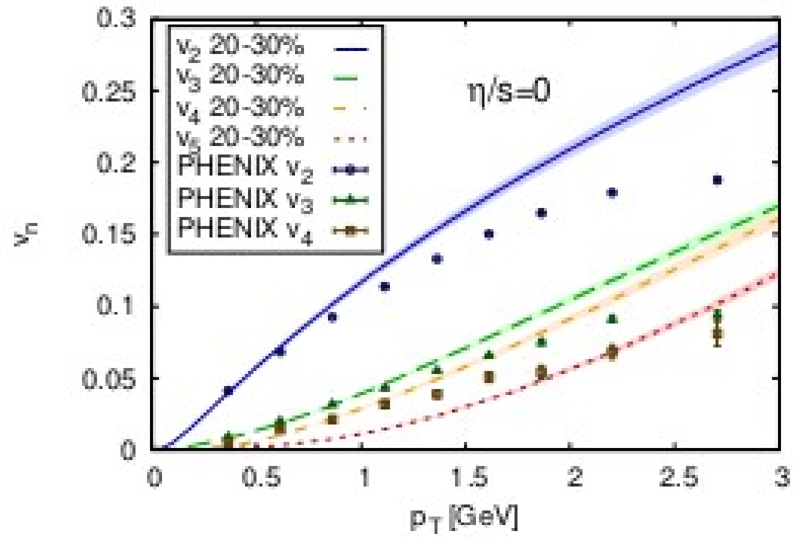
from W.Zajc Colloquium 2015 sld 53

Using higher harmonics to determine η/s

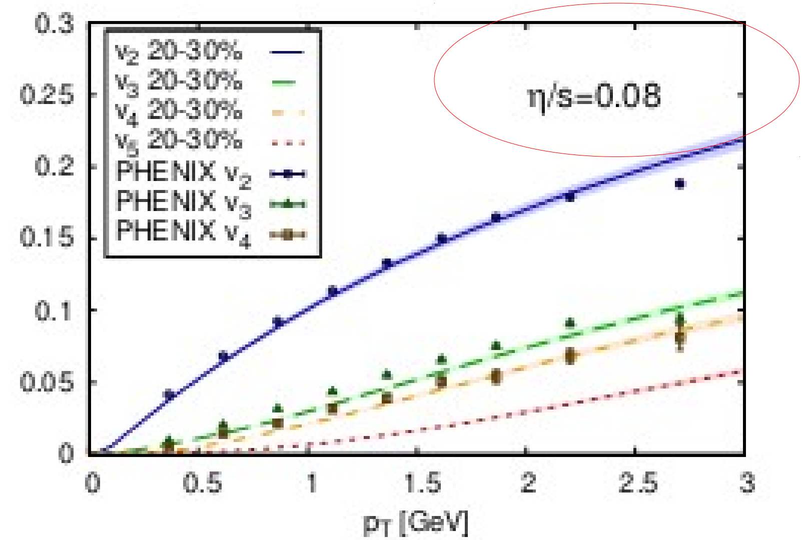
Viscocity/entropy
Of perfect fluid QGP

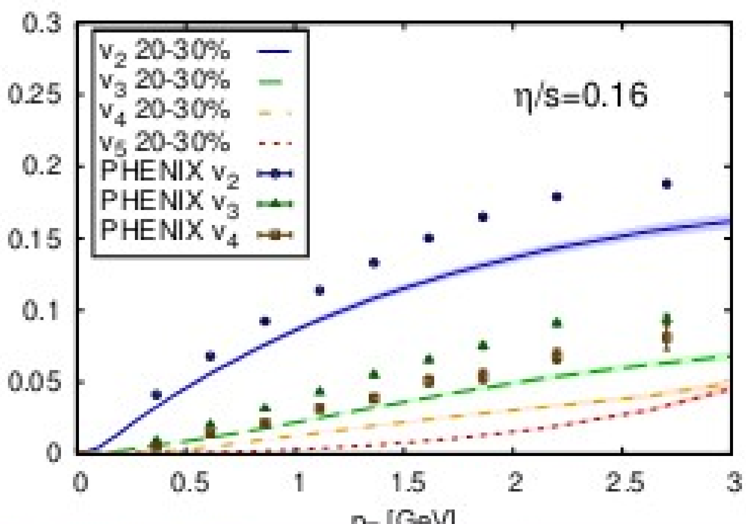
B. Schenke, S. Jeon, C. Gale, arXiv:1109.6289

Data is from event-plane method. Calculations are $\sqrt{\langle v_n^2 \rangle}$.



MC-Glauber initial conditions





Best viscous hydrodynamics fits
Favor viscosity to entropy ratio
of sQGP to be near the unitarity
Bound 1/4pi suggested by
AdS/CFT. So is sQGP a Black hole??

Björn Schenke (BNL) QM2012 37/42

New Forms of High Energy Density Matter accessible via A+A

You are here

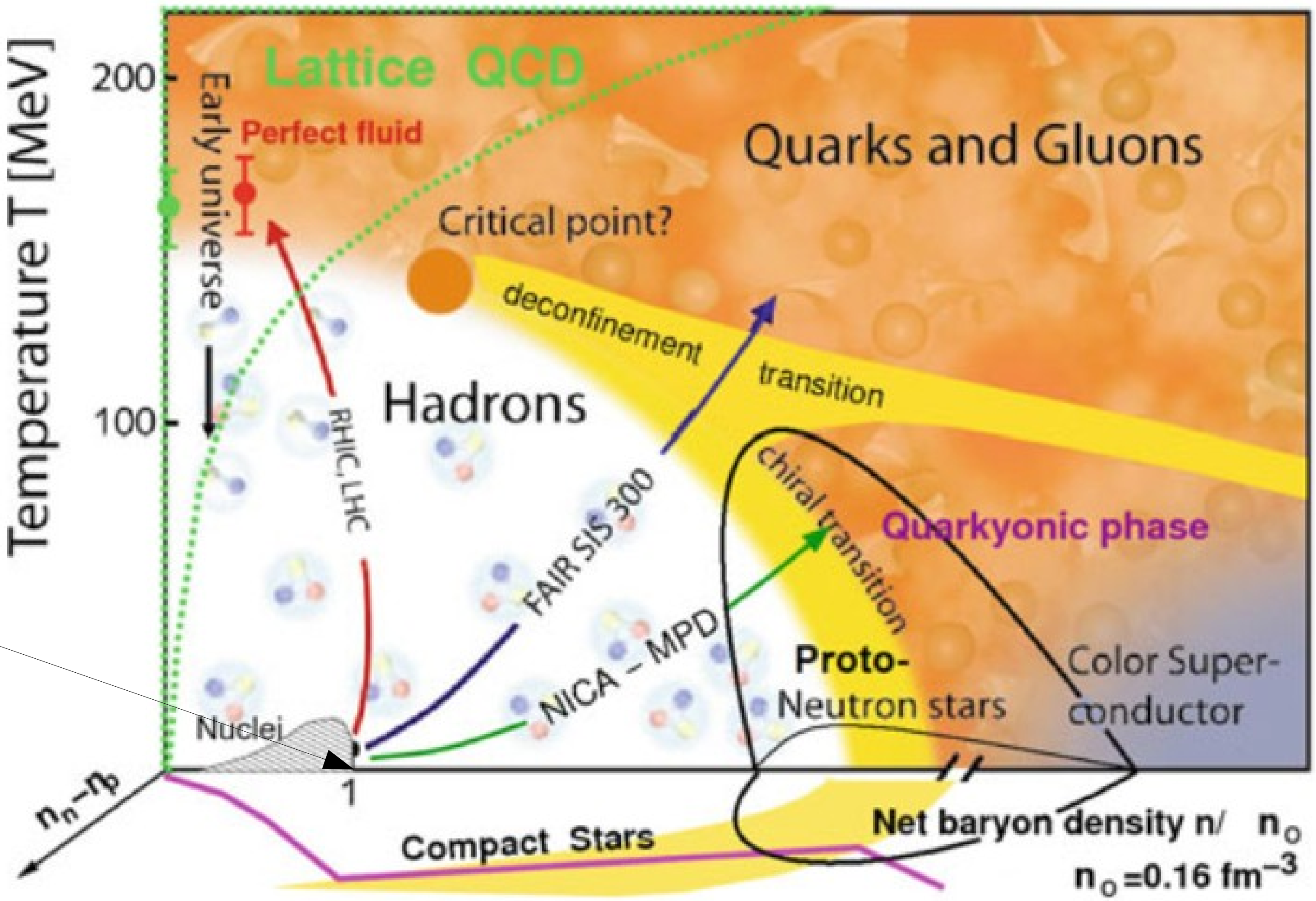


Fig. 1 A conception of the phase diagram of QCD

L.McLerran 2011