Probing the color structure of QCD fluids via Soft-Hard-Event-Engineering

M. Gyulassy
CCNU 10/18/17

Lecture 2

Summary of Lecture 1:

Lattice QCD Thermodynamics Equation of State P(T), S(T)=dP/dT, E(T)=TS-P
shows gradual “bleaching” of color electric q+g component of the QGP
As T decreases toward Tc ~ 170 MeV from above

Polyakov Loop L(T) and quark susceptibility $\chi_2^u = \frac{\partial^2(P/T^4)}{\partial(\mu_u/T)^2}$ Lead to different possibilities

The semi-QGP model of color electric composition near Tc depends on

Color liberation schemes

$$\chi_T = \frac{\rho_e}{\rho_{tot}} = \frac{\rho_e}{\rho_e + \rho_m} = \begin{cases} \chi_T^u = c_q \chi_2^u + c_g L^2 \\ \chi_T^L = c_q L + c_g L^2 \end{cases}$$

Fast q, Slow^2 g

Slow q, Slow^2 g

The missing “m” density is fixed by a choice of Liberation Scheme and relation of ρ to EOS

$$\rho_m(T) = (1 - \chi(T))\rho_{tot}(T) = (1 - \chi(T)) \begin{cases} P(T)/T \\ S(T)/4 \end{cases}$$

The2008 AA v2(pT>5 GeV) puzzle challenged perturbative dEdx models of jet dEdx.
But can be “solved” in various ways.

Is interpreted as density

Most provocative interpretation by J.Liao&E.Shuryak is to interpret ρ_m as density of emergent color magnetic monopoles near Tc leading to “volcano scenario” for dEdx

In Lecture 2 I review recent progress with CIBJET S.Shi,J.Liao,MG to quantify the above model

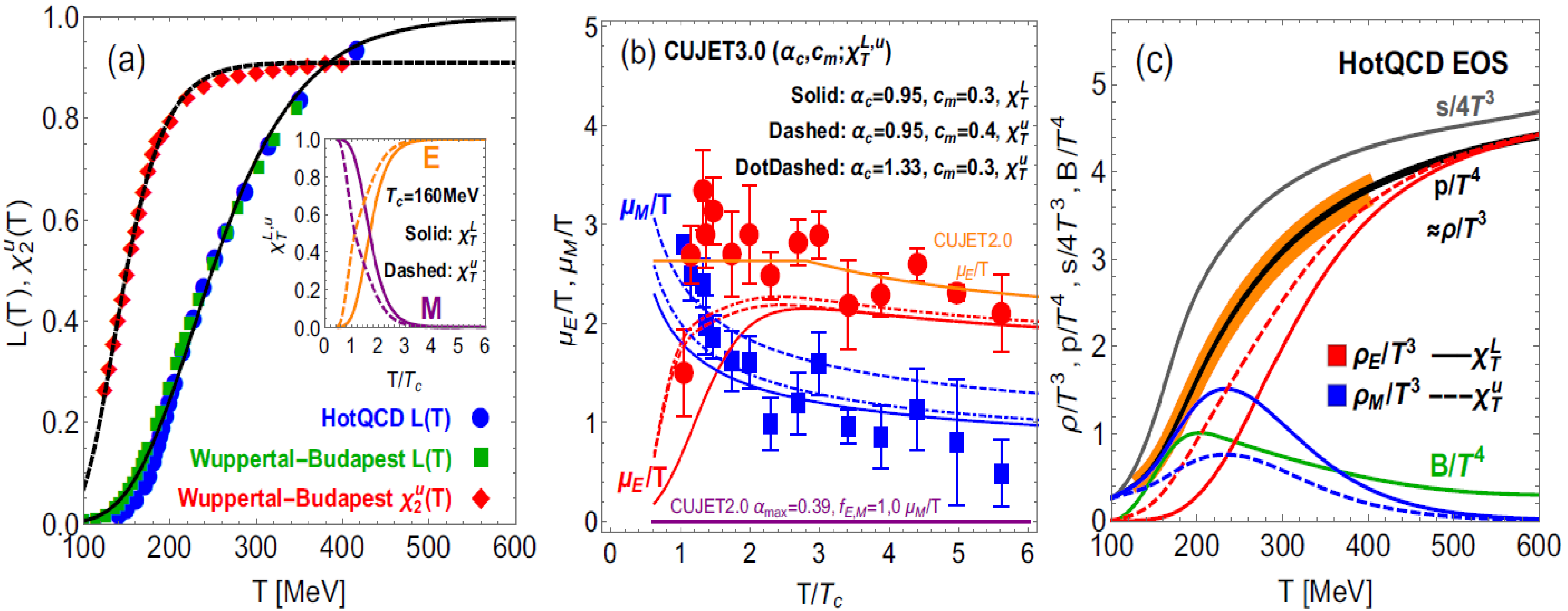
P.Petreczky proposed light quark susceptibility data =>semi-Quark dof may be liberated more quickly as T increases than suggested by Polyakov loop suppressed semi-Quarks

To estimate the sensitivity CUJET3 fits to the assumed color structure of the sQGMP we compare results with <u>Slow quark liberation</u>

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

to <u>Fast quark liberation</u>

$$\chi_T^u = c_q \chi_2^u(T)/\chi_2^u(\infty) + c_g L^2$$



The goal with CIBJET = ebeIC+VISNU+CUJET3.1 and SHEJET= ebeIC+vUSPH+BBMG is to try to put experimental constraints (via RAA,v2,v3) Chi^2 bands on Lattice “data” on the chromo composition/structure of sQGMP (quasi-quarks, gluon, gluons,monopoles, dyons) dof consistent with
(1) lattice EOS P(T) (2) screening masses, and (3) eta/s~T^3/qhat soft-hard correlations

In CUJET3 we tested 4 models of sQGMP composition compatible with Lattice QCD thermo

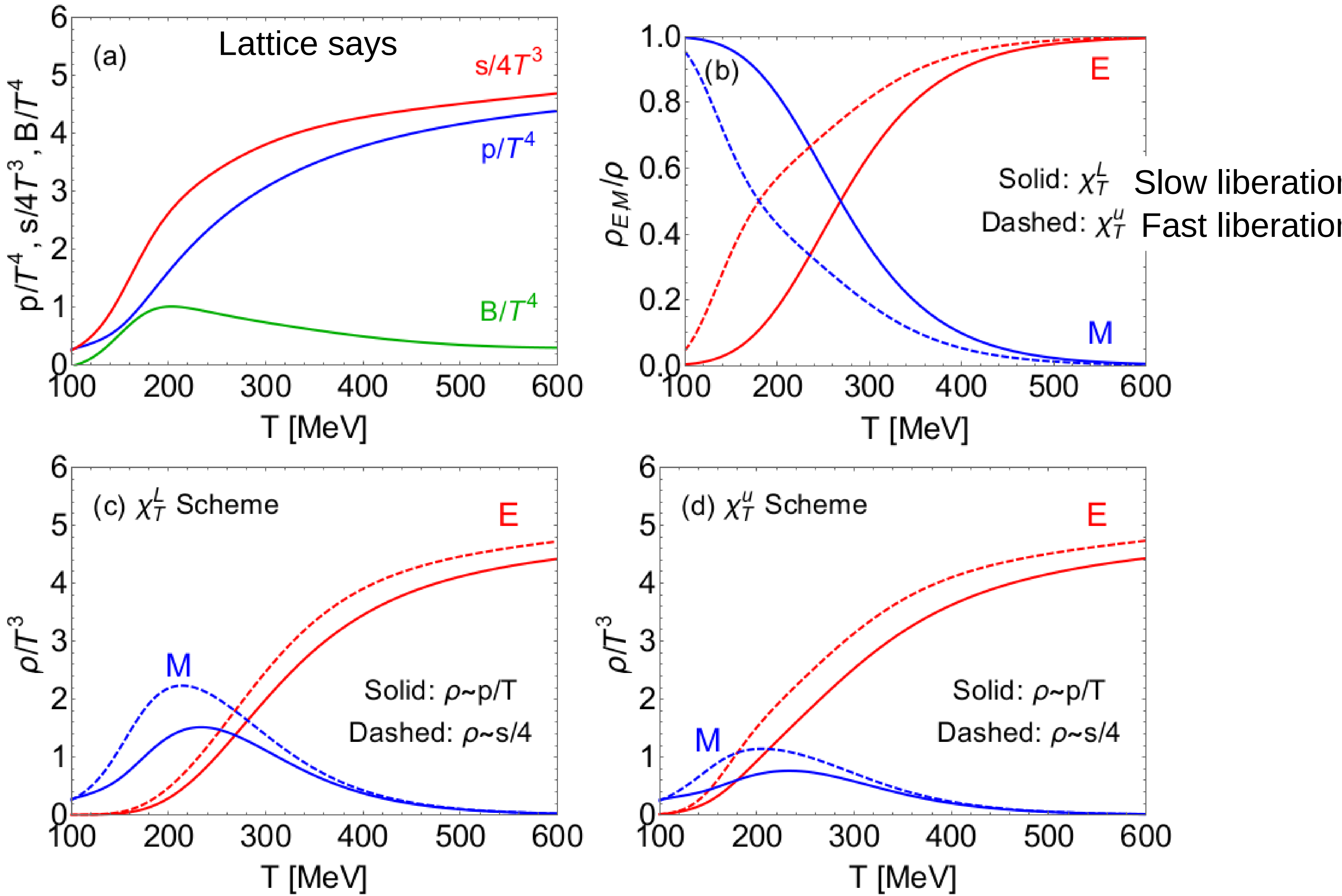
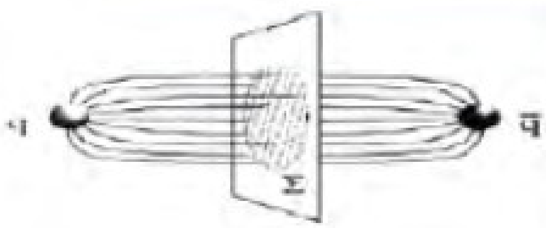


Figure 6. (Color online) (a) The effective ideal quasiparticle density, $\rho/T^3 = \xi_p P/T^4$, in the Pressure Scheme (PS, Blue) is compared with effective density, $\rho/T^3 = \xi_p S/4T^3$, in the Entropy Scheme (ES, Red) based on fits to lattice data from HotQCD Collaboration [56]. The difference is due to an interaction "bag" pressure $-B(T)/T^4$ (Green) that encodes the QCD conformal anomaly

Magnetic Scenario of Near-Tc Plasma

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

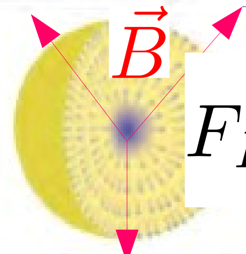
Vacuum: confined | Tc | sQGP | *wQGP: screening* | T



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

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

Dirac $\boxed{\alpha_E * \alpha_M = 1.}$



$\vec{v} = c\hat{z}$

$$F_{EM} \propto \frac{\sqrt{\alpha_E \alpha_M}}{r^2} \gg \frac{\alpha_E}{r^2}$$

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

PHYSICAL REVIEW C 75, 054907 (2007)

Strongly coupled plasma with electric and magnetic charges

Jinfeng Liao and Edward Shuryak

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Magnetic Monopole dual superconductor model of color electric confinement

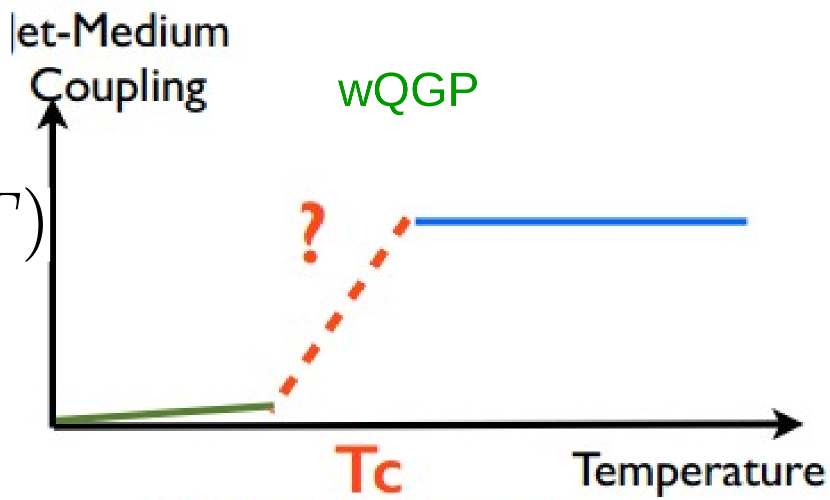
T'Hooft, Polyakov, Mandelstam 40 years ago ?Is the v2 puzzle the first experimental signature?

$$\frac{d\sigma_{EM}}{dq_\perp^2} \sim \frac{1}{q_\perp^4} \gg \frac{d\sigma_{EE}}{dq_\perp^2} \sim \frac{\alpha_E^2}{q_\perp^4}$$

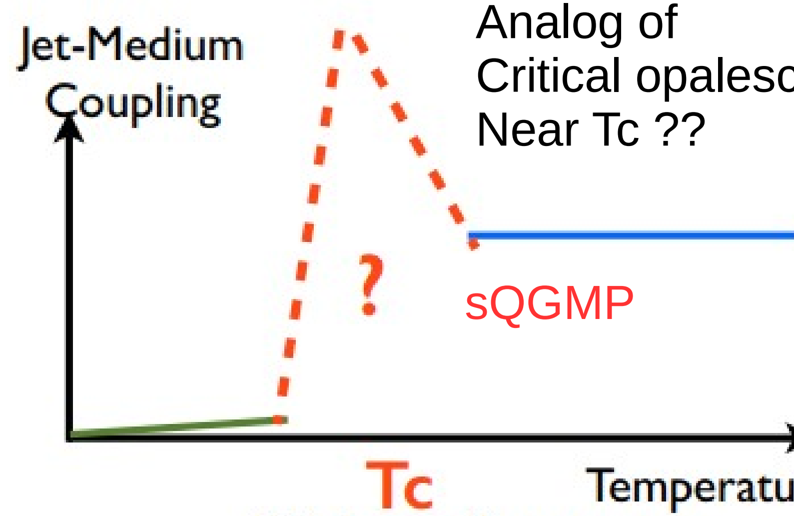
adapted from JLiao's CCNU 2015 talk slide 15

From "Transparency" to Opaqueness

$\hat{q}(E,T)$



"Waterfall" scenario



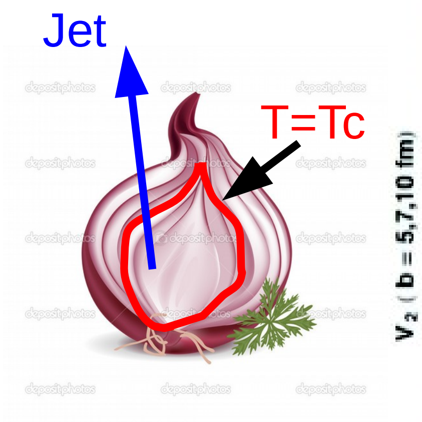
"Volcano" scenario

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

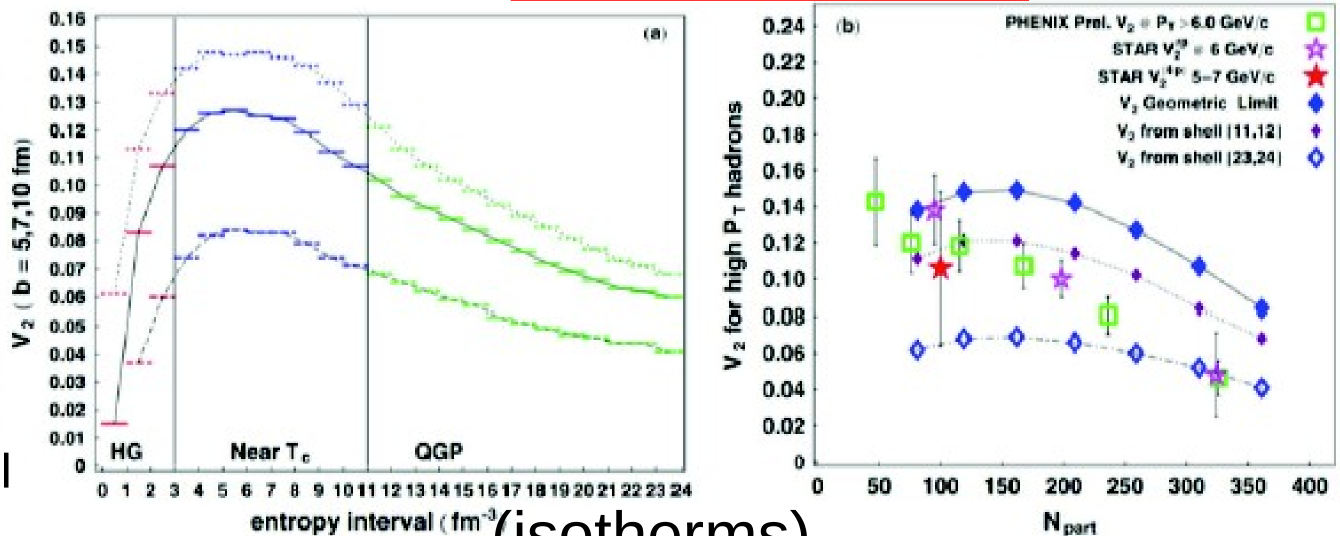
[MG:Test with wide beam energy SPS, RHIC and LHC with RAA, v2, v3 soft-hard correl]

A qualitative solution to the high-p_T v_2 puzzle

Proposed by Shuryak and Liao assuming maximal qhat near Tc due to mag monopole condensation



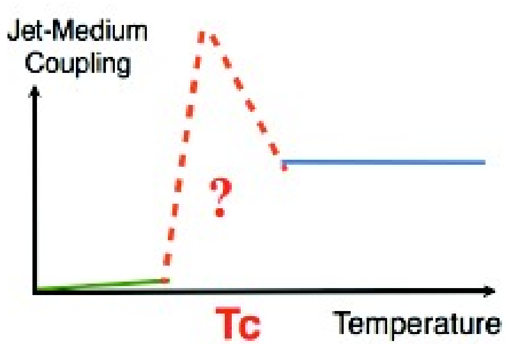
A Tc “onion” model with dEdx peak near T=Tc isotherm which has higher Eccentricity than the average

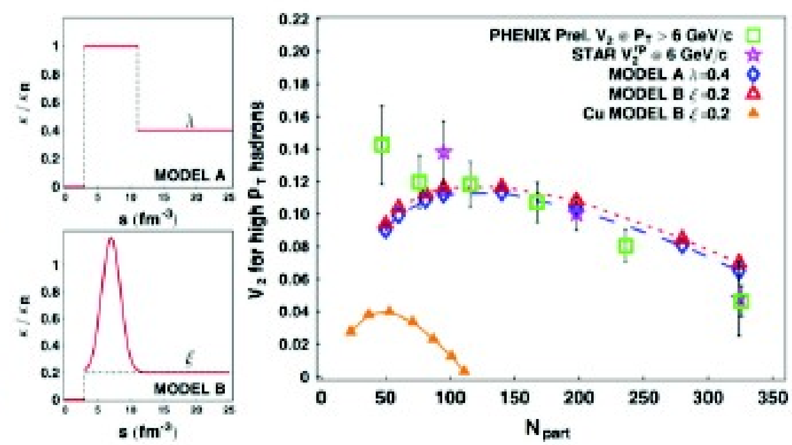


(isotherms)

Figure 3.17: *Left: The v2 obtained for each entropy shell at different centralities. Right: v_2^{max} for high p_T hadrons calculated at different N_{part} compared with available RHIC data.*

Postulate that jet medium coupling peaks near Tc





Liao & Shuryak, PRL 2009

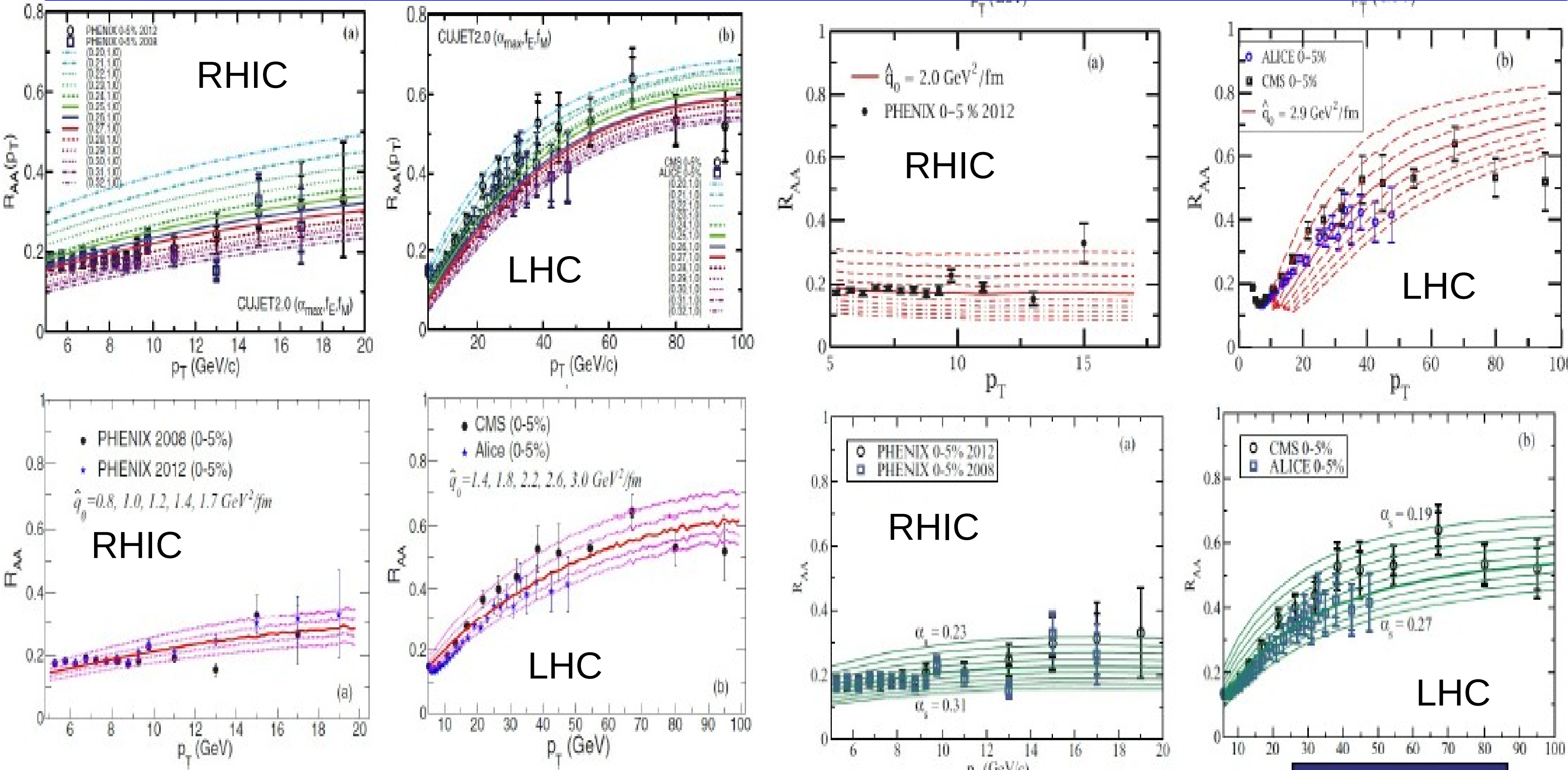
Simple optical model estimate Solve the v2 puzzle

[BBMG verified This claim In 2014]

Analog of 1868 “Critical Opalescence” liquid-gas transition in carbon dioxide

On the other hand, the v2 puzzle frustrated more quantitative pQCD based model attempts

JET collaboration : 5 pQCD based quenching models robustly fitl RAA (RHIC+LHC) but
All failed to get high pT jet elliptic anisotropy v2(pT>7 GeV) without extra assumptions



PRC90 (2014) no.1, 014909

arXiv:1511.00790 [pdf, other]

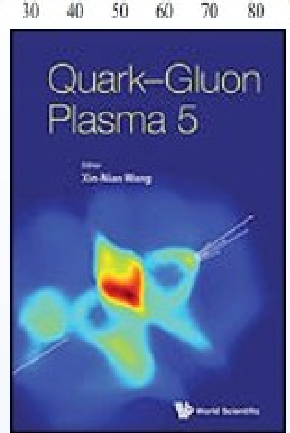
Jet quenching in high-energy heavy-ion collisions

Guang-You Qin, Xin-Nian Wang

Comments: review for QGP5, 68 pages, 34 figures

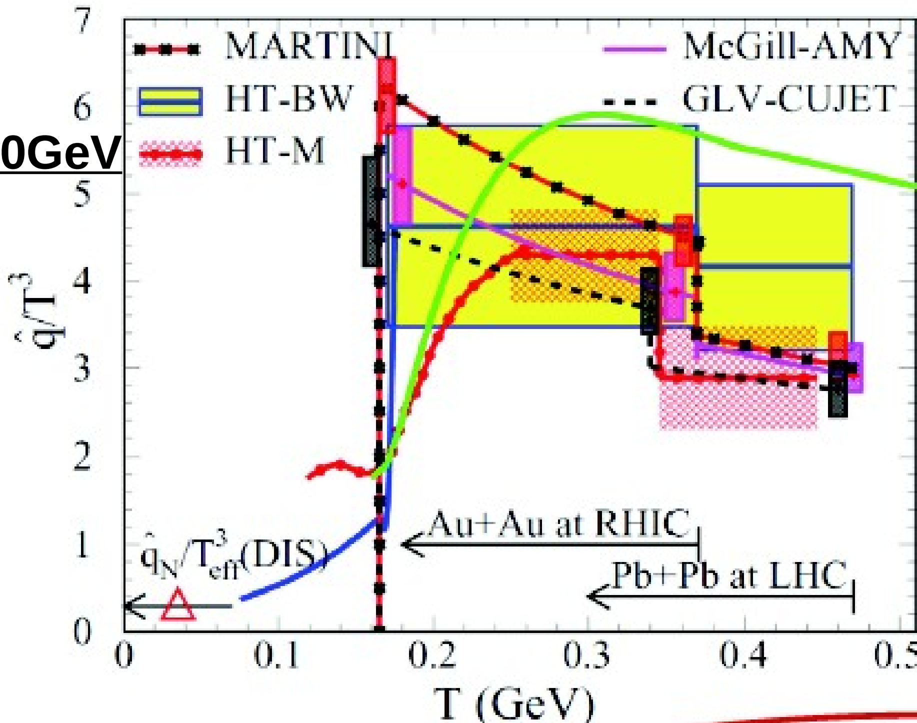
March 2016

$161



$\hat{q}(E,T)$: jet quenching parameter and η/s

E=10GeV



The Hard-Soft Consistency Problem

$$\boxed{\hat{q} = \rho \int_{g^2T^2}^{3ET} d^2q_\perp q_\perp^2 \frac{d\sigma}{d^2q_\perp}}$$

Decreases With E

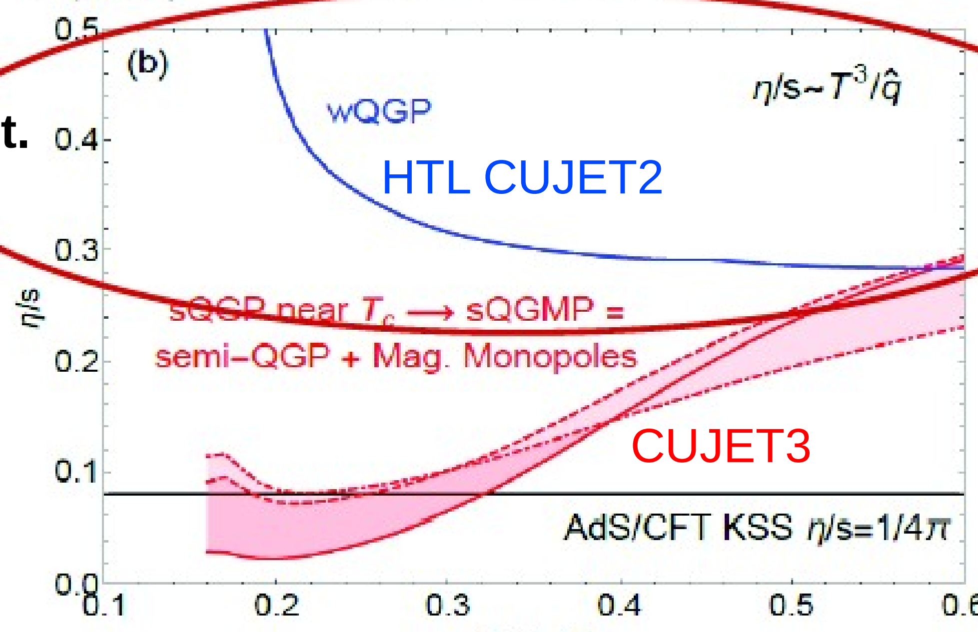
For E=10GeV . (But need E→ 1GeV for eta)

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

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

JET Collaboration, PRC 90, 014909 (2014)

JET collab assume HTL pQCD color struct.
RAA OK but not v2!
and Predict qhat extrapolated
down to E~1 GeV
thermal scales
=> eta/s predicted is too large to support perfect fluidity!



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

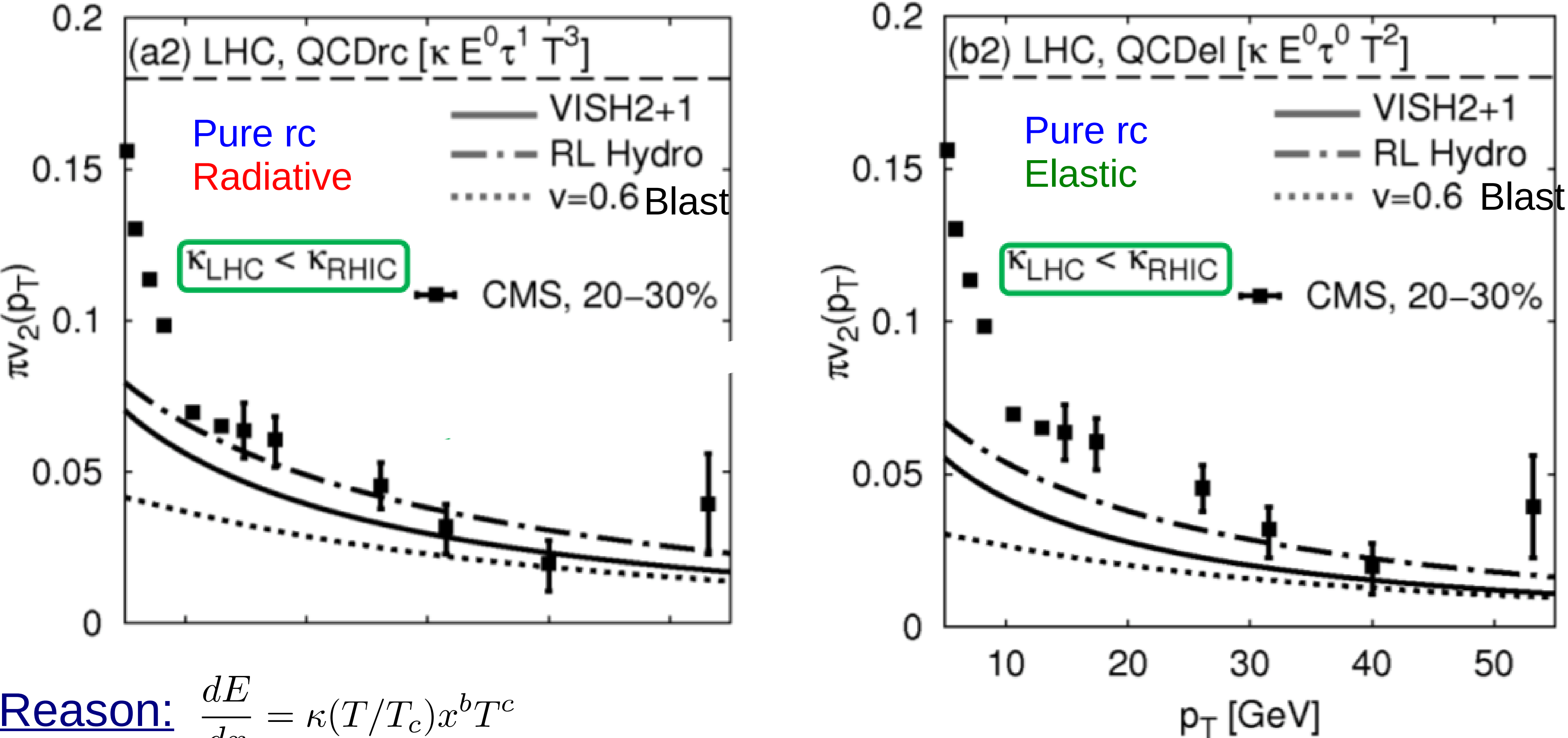
$$= \frac{18T^3}{5s}\sum_a \rho_a/\hat{q}_a(T, E=3T)$$

Majunder,Wang,Muelle Inverse eta/s and qhat Relation (2007)

Jiechen Xu, 12/15/2015 @ CU 20

Why is jet v2(pT) so difficult to predict correctly ?

Barbara Betz, MG:JHEP 1408 (2014) 090



Reason: $\frac{dE}{dx} = \kappa(T/T_c)x^bT^c$

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

Depends on a complex interplay between details of microscopic pT>10 jet dE/dx and details of 2+1D spacetime evolution {T(x), u^mu(x)} of the bulk QCD fluid that depend on ebe IC, η/s, and other transport coefficient

The azimuthal averaged RAA is less sensitive to the Hard+Soft physics corelations

A very brief history of recent heavy ion physics

(Slide from Ron Belmont's talk at Initial Stages 2017)

- 1980s and 1990s—AGS and SPS… QGP at SPS!
- Early 2000s—QGP at RHIC! No QGP at SPS? d+Au as control.
- Mid-late 2000s—Detailed, quantitative studies of strongly coupled QGP. d+Au as control.
- 2010—Ridge in high multiplicity p+p (LHC)! Probably CGC!
- Early 2010s—QGP in p+Pb!
- Early 2010s—QGP in d+Au!
- Mid 2010s and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p?? QGP in d+Au even at low energies???

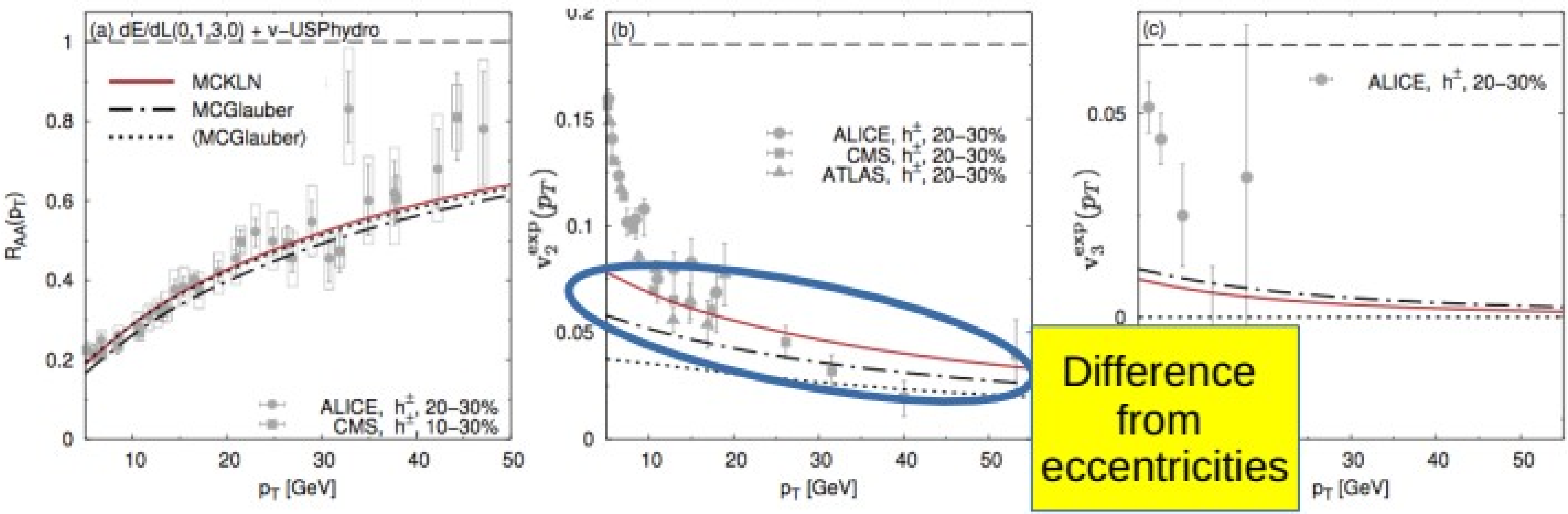
"Twenty years ago, the challenge in heavy ion physics was to find the QGP. Now, the challenge is to not find it." —Jürgen Schukraft, QM17

[MG] For this talk I assume that the QCD fluid is "Perfect" in any system where v-hydro fits Soft-***Soft***-Event-Engineered (S***S***EE) flow correlation data and then compute S***H***EE to Test different assumptions about its chromo color E and B structure of that fluid.

Last year I reviewed in 2016 the first SHEJET solution to RAA,v2, and v3 SHEE

Both R_{AA} and v_n's fit LHC $\sqrt{s_{NN}} = 2.76$TeV

Jaquelyn Noronha-Hostler, B.Betz, Jorge Noronha, MG: arXiv:1602.03788 (PRL116(2016))



The first consistent ebe-IC+vHydro+dE/dL solution consistent with Soft&Hard RAA,v2,v3

- v_3 exists due to **fluctuations**

Alver and Roland PRC81 (2010) 054905

ebe IC= MCKLN&MCGlauber ; vHydro=vUSPH ; dE/dL=BBMG pQCD like qhat L[1]

J.Noronha-Hostler, Initial Stages 2017 sld 10

DGLV-CUJET framework for describing multi-parton scattering:

ρ_{q+g}^{SB}

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

J.Xu,
A. Buzzatti,
MG 2014
JHEP1408

HTL chromo
Electric screen
Scatt Kernel

Running
coupling

Gluon formation w/ HTL
mass

Original DGLV formalism has only quark/gluon scattering centers

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

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

Idea with CUJET3 is to *deform* the DGLV HTL kernel with non-perturbative Lattice QCD data, fit (RAA,v2) data with min chi2 to fix max alpha and the ratio of magnetic/electric screen masses, and check if qhat(E->3T,T) extrapolates near 4 pi T^3 to

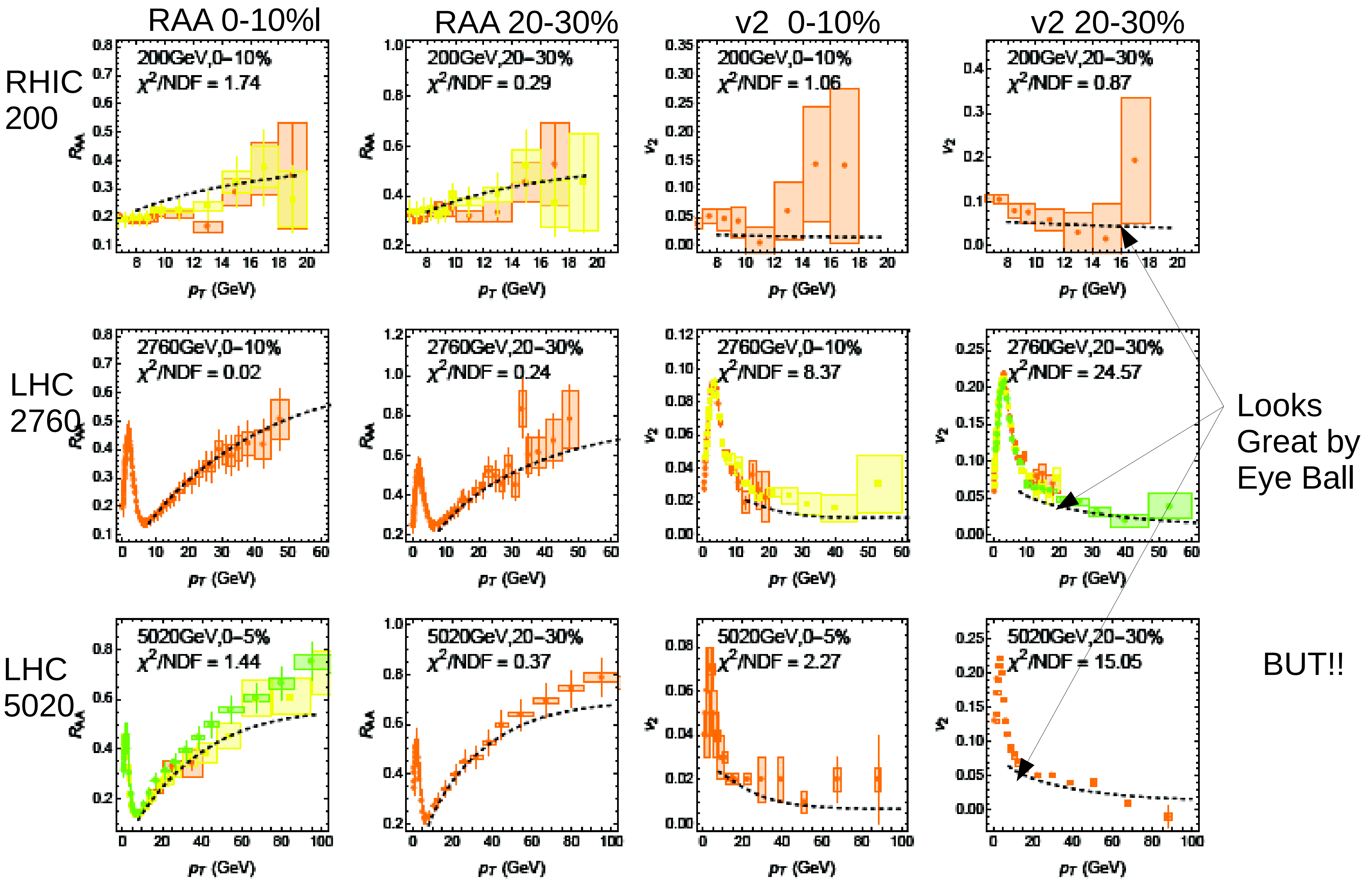
$$\boxed{\frac{\eta(T)}{s(T)} \sim \lim_{E\to 3T}\left(\frac{T^3}{\hat{q}(E,T)}\right)}$$

Shuzhe Shi 2017 test of CUJET2 in HTL QGP

Alessandro Buzzatti, J.Xu, MG, JHEP1408 (2014)

$\alpha_{max} = 0.42$

χ^2/d.o.f for VISH2+1 ⊗ CUJET2.1

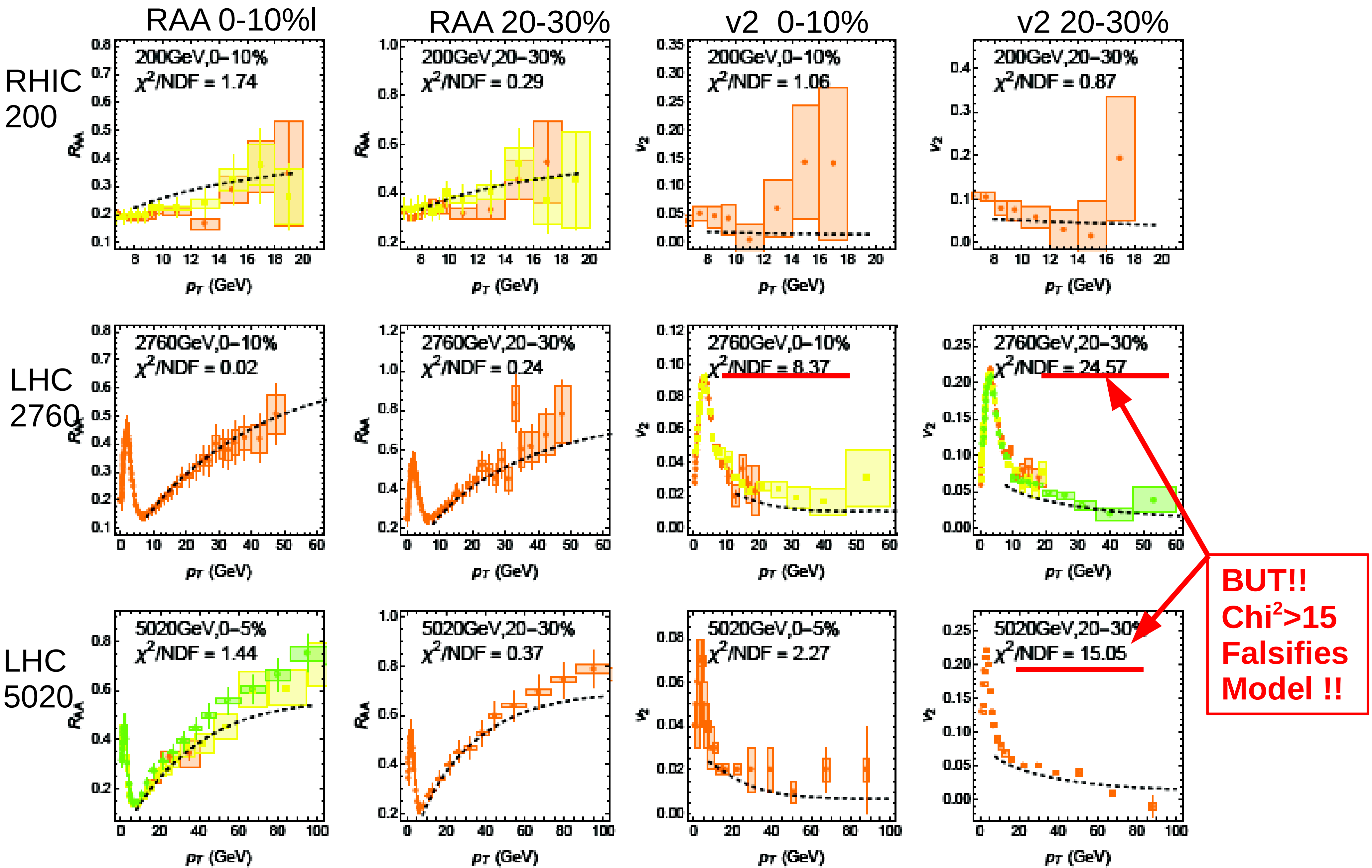


Shuzhe Shi 2017 test of CUJET2 in HTL QGP

Alessandro Buzzatti, J.Xu, MG, JHEP (2014)

$\alpha_{max} = 0.42$ $\quad \chi^2$/d.o.f for

VISH2+1 ⊗ CUJET2.1



CUJET3.0 status at QM15 (J.Xu, J Liao, mg, NPA956 (2016)) is a second consistent solution

To v2 puzzle

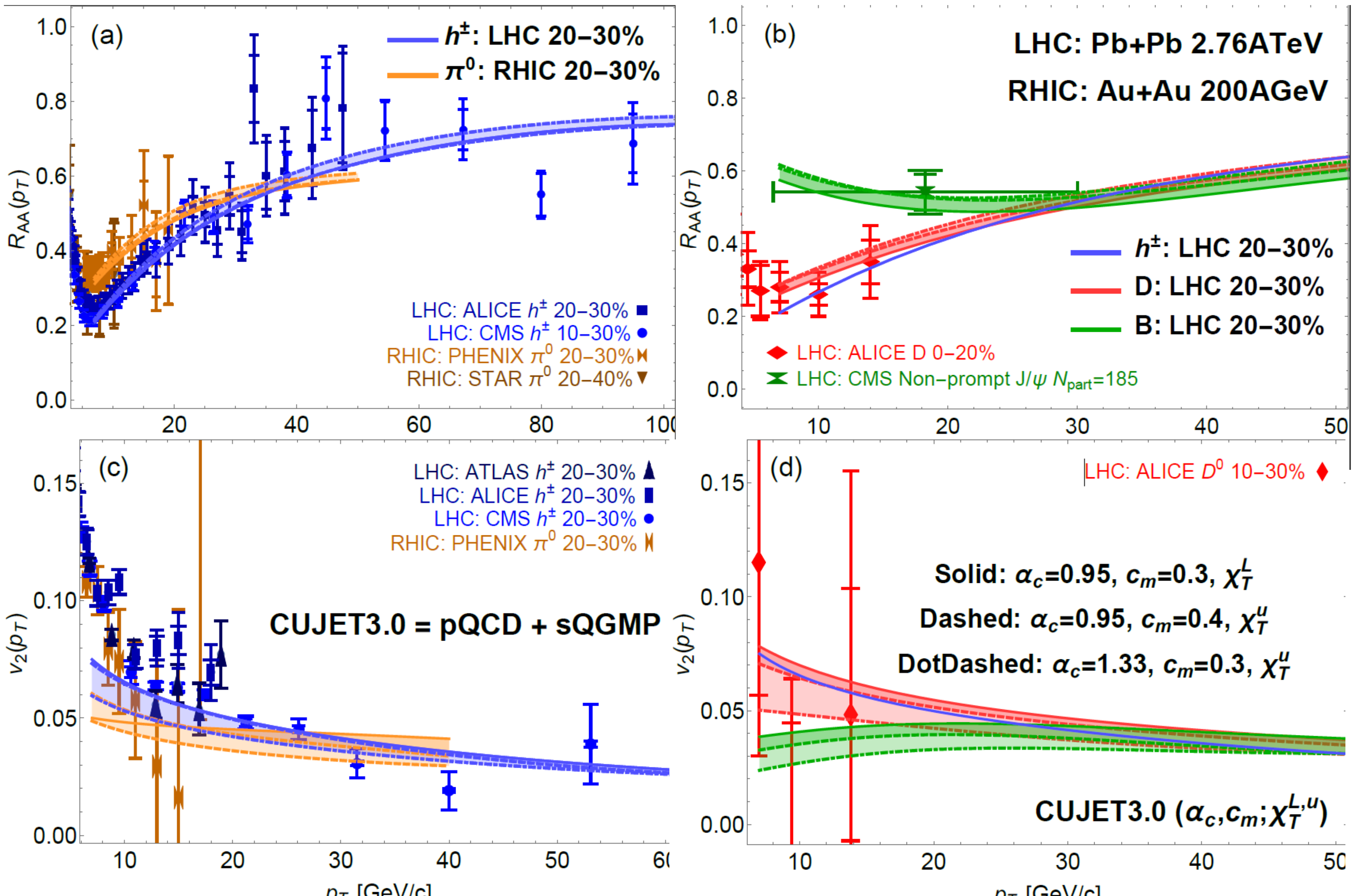
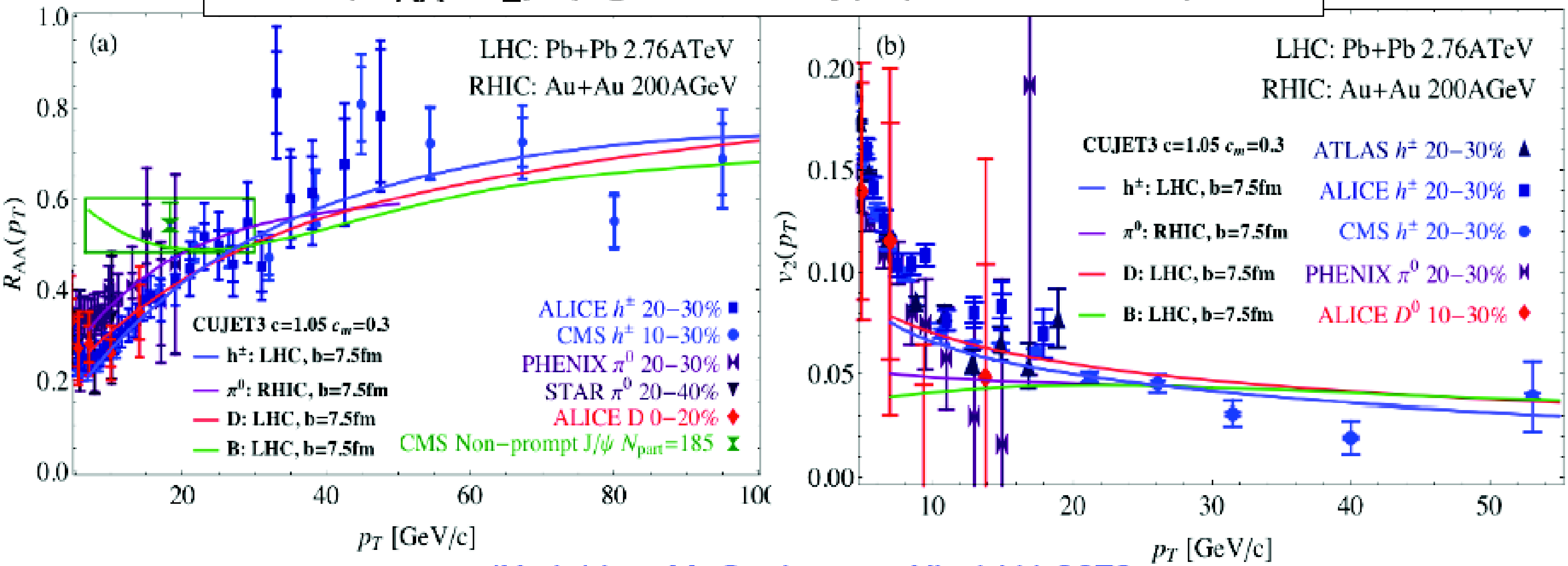


Fig. 2. (Color online) CUJET3.0 results of (a) light hadron (LH, neutral pion π^0 and charge particle $h^{\pm}$)'s R_{AA}, (b) open heavy flavor (HF, B meson and prompt D meson)'s R_{AA}, (c) LH's v_2, and (d) HF's v_2, at high $p_T > 8$GeV in semi-peripheral A+A collisions, compared with data from RHIC and LHC [2]. The variations of predicted jet quenching observables from different schemes within CUJET3.0 suggest that data on high p_T leading hadron R_{AA} and v_2 in heavy-ion collisions can rigorously constrain the nonperturbative chromo-electric and chromo-magnetic structure of the QCD matter near T_c, and provide critical information about color confinement.

Last year I also reviewed our ***smooth*** IC +VISHNU+CUJET3 successfully sQGMP modeling

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



JX, J. Liao, M. Gyulassy, arXiv:1411.3673

The combined set of observables

($R_{AA}+v_2$)*(RHIC+LHC)*(pion+D+B)

are consistently accounted for in CUJET3.0 using lattice data constrained sQGMP near Tc + pQCD/DGLV jet quenching

In 2017 however new CMS LHC2 5.05ATeV data falsified predictions sQGMP/CUJET3 while data verified J.Noronha-Hostler ebe-vUSPH/wQGP correct predictions!

CUJET3.0 qhat at QM15 shown consistent with Perfect fluiidty near Tc (J.Xu, J Liao, MG (2016))

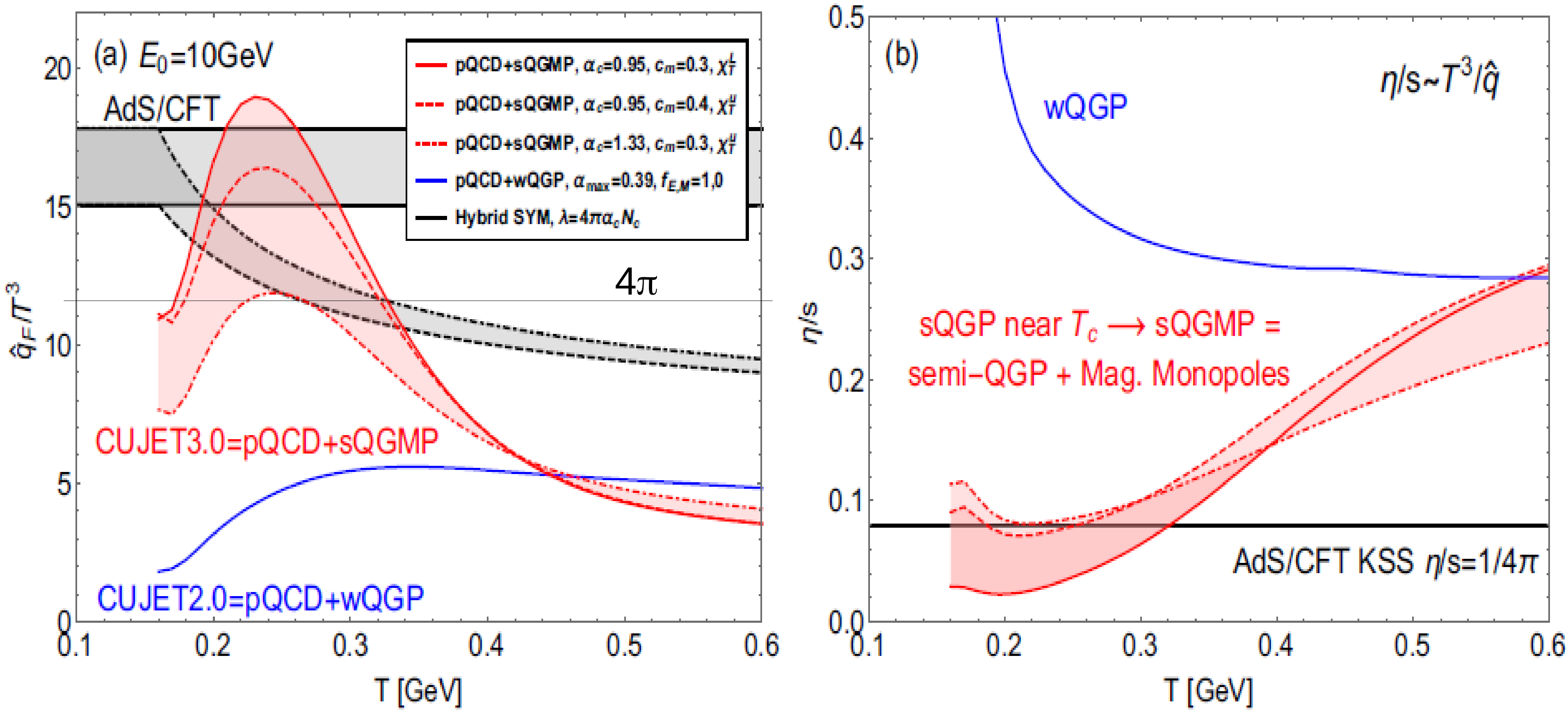


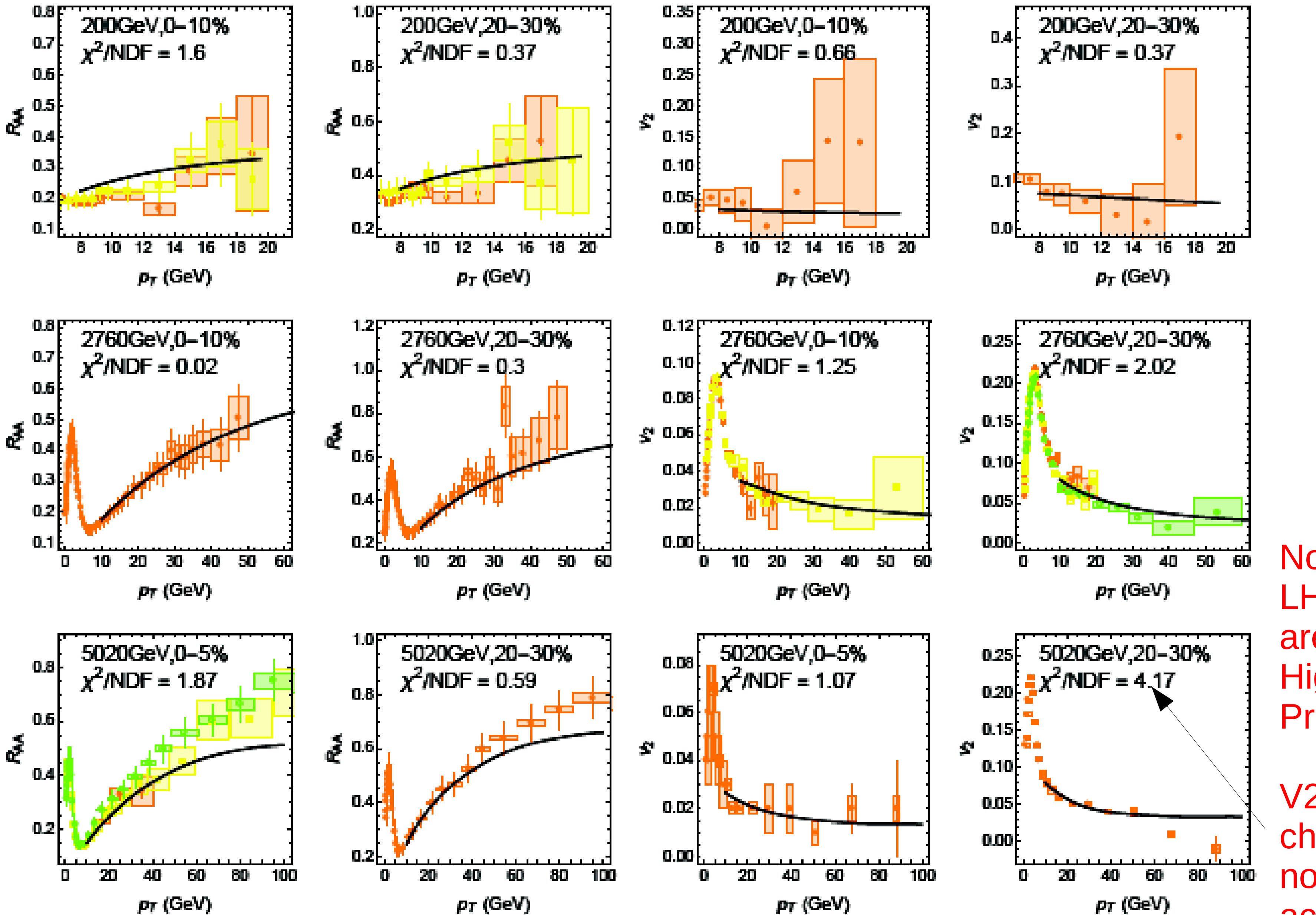
Fig. 3. (Color online) (a) The temperature dependence of the scaled jet transport parameter $\hat{q}/T^3$ for a quark jet (in the fundamental representation F of SU(N_c=3)) with initial energy E_0 = 10 GeV in various schemes within the CUJET3.0 framework, compared with the CUJET2.0 counterpart, as well as $\mathcal{N}$ = 4 Supersymmetric Yang-Mills (SYM) $\hat{q}_{\rm SYM}$ results from leading order (LO) AdS/CFT calculations ($\hat{q}_{\rm SYM} = [\pi^{3/2}\Gamma(3/4)/\Gamma(5/4)]\sqrt{\lambda}T^3_{\rm SYM}$) [15]. Note that $3T^3_{\rm SYM} \approx T^3$ because of different number of degrees of freedom in N_c = 3 SYM and three-flavor QCD [16]. The gray band with dashed black edges corresponds to using 't Hooft coupling $\lambda = 12\pi\alpha_s(Q^2)$. (b) The shear viscosity to entropy density ratio η/s estimated in the kinetic theory extrapolation $\eta/s \sim T^3/\hat{q}$ from jet quenching parameters in panel (a). Note that T_c = 160 MeV. In CUJET3.0, a $(\hat{q}_F/T^3)_{\rm max}$ and $(\eta/s)_{\rm min}$ appear at $T \sim 1.4T_c$ where the scaled number density of emergent chromo-magnetic monopoles near T_c peaks. The $(\eta/s)_{min}$ is influenced by the EM fractions. Its value in both $\chi_T^{L,u}$ schemes converge to approximately the KSS quantum bound $\eta/s = 1/4\pi$ [4]. At high T, the η/s from sQGMP and weakly-coupled QGP (wQGP) coincide because of similar color screening structures.

Shuzhe Shi 2017

χ^2/d.o.f for VISH2+1 ⊗ CUJET3.1

$(\alpha_c, c_m) = (0.9, 0.25)$

Global RHIC+LHC1+LHC2 Fit



Note LHC2 data are much Higher Precision !

V2 CMS challenge now to 1% accuracy?!

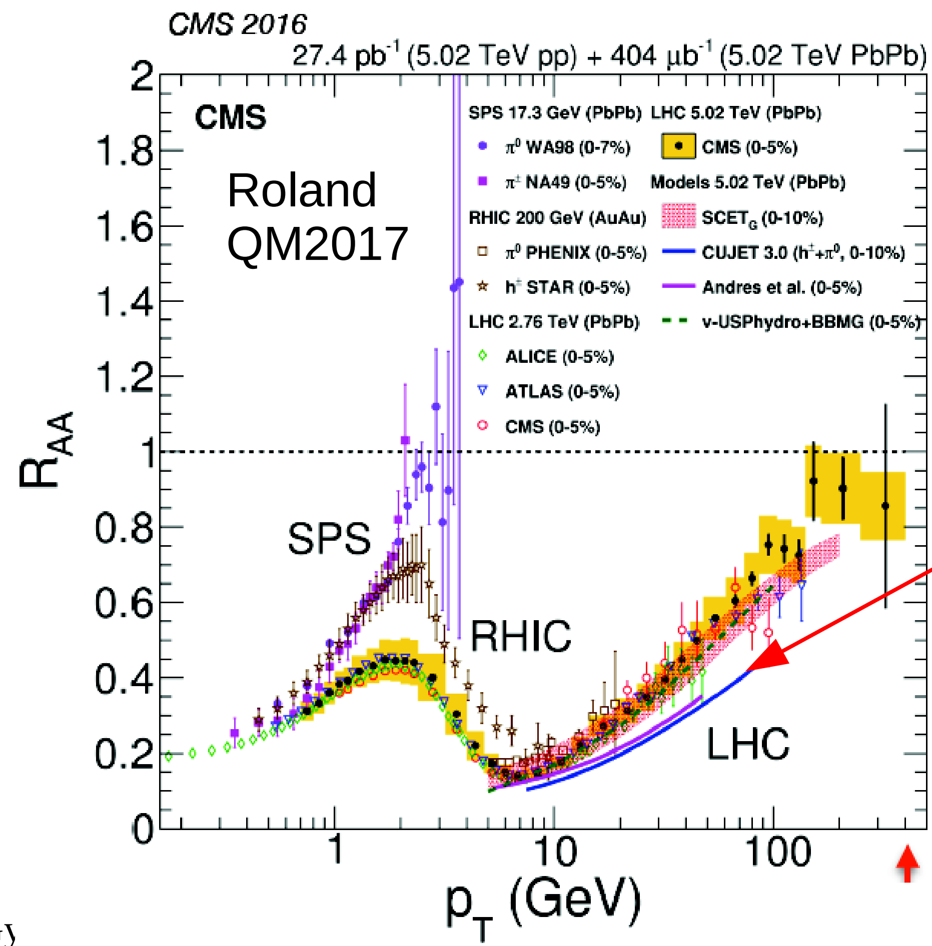
At IS16 and QM17 CMS LHC2 discrepancies of CUJET3.0
Were seen for for 5ATeV RAA and v2

Shuzhe Shi found 3 bugs in CUJET3.0 now corrected in CUJET3.

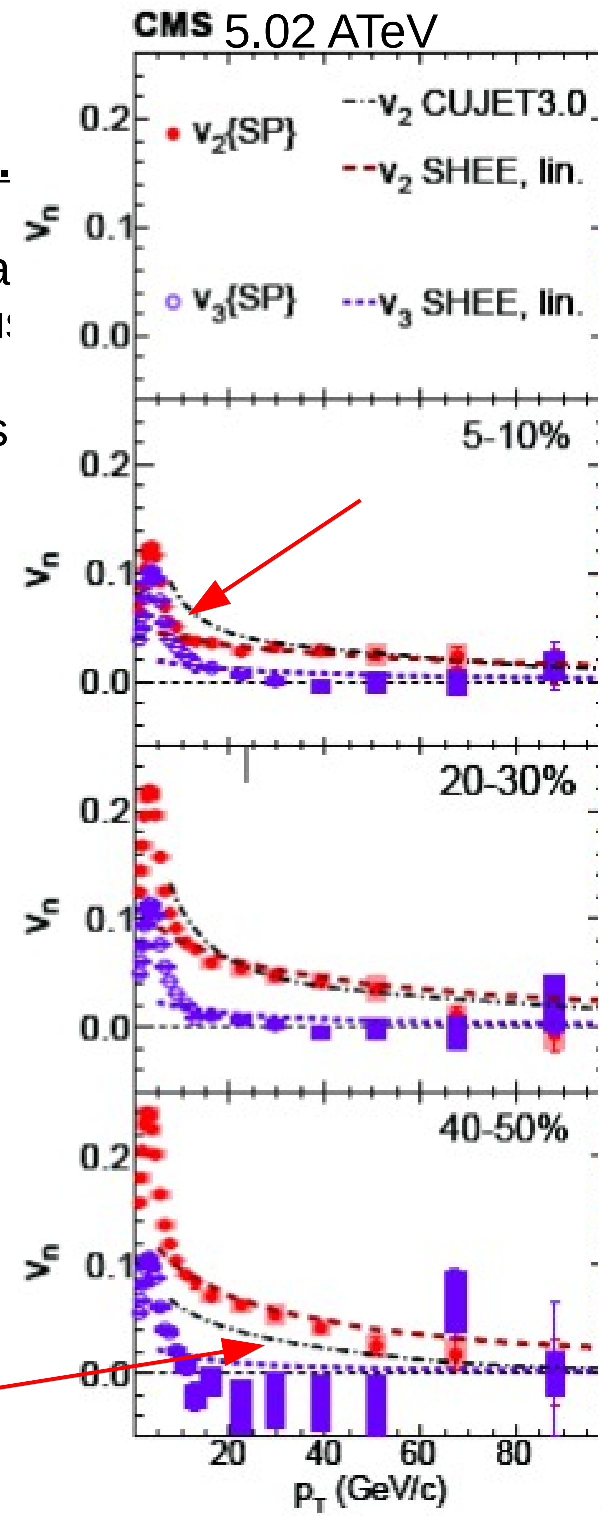
1) Initial parton spectra for 5.02 ATeV were erroneously read in from a Pythia file rather taken from pQCD LO Wang code as used previou

2) VISHNU hydro fluid grid was misread into CUJET3.0 path integrals

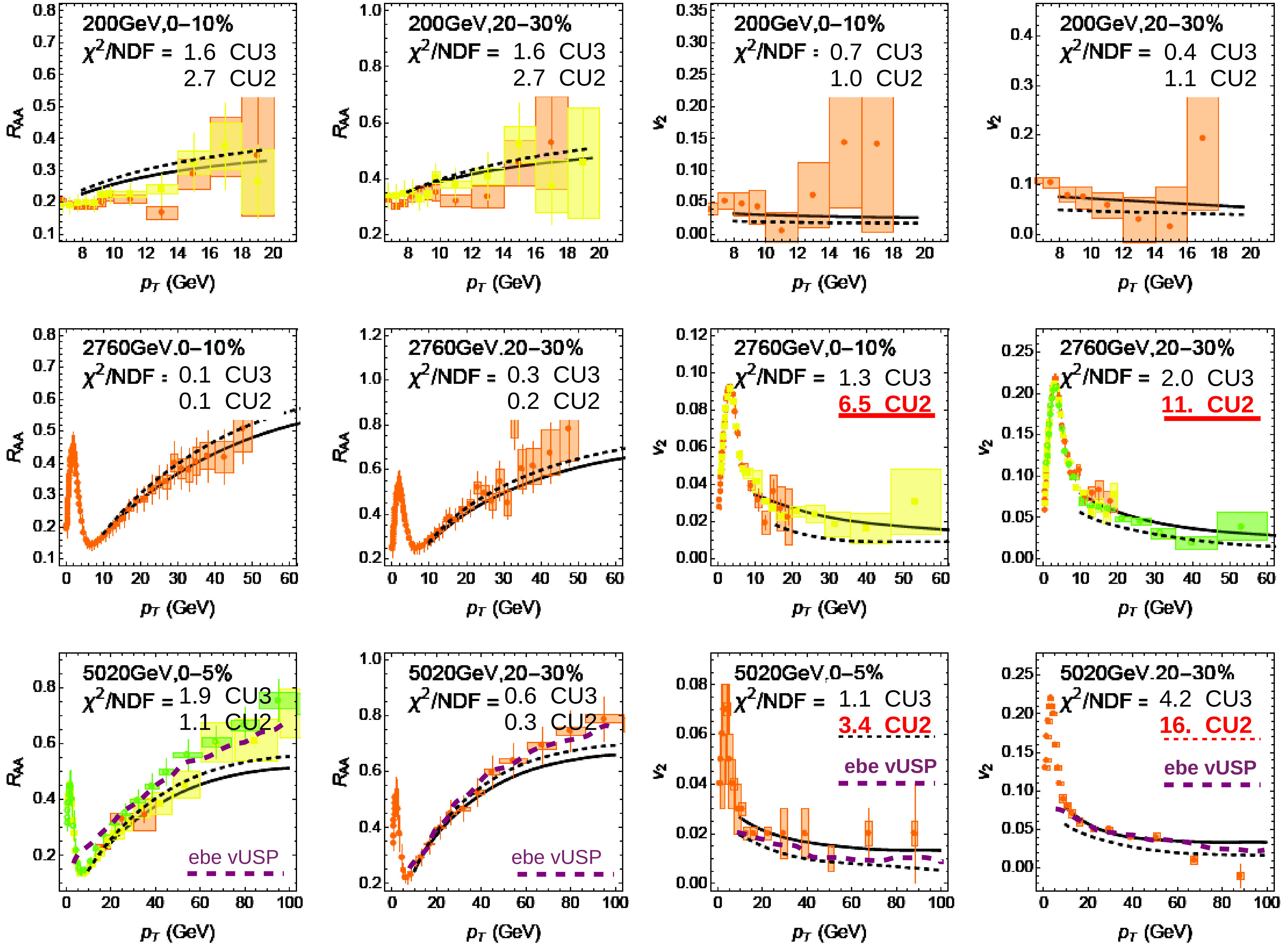
3) Initial parton spectra cut off set too low 200 instead of 400 GeV



Bugs in CUJET3.0
led at 5TeV LHC2 to
1) overquench RAA
2) predict wrong
Centrality dep of v2



pQGP/CUJET2.1 vs sQGMP/CUJET3.1 vs RHIC&LHC vs ebe/vUSP+BBMG (J.Noronha-Hostler PRC95 (2017)



Shuzhe Shi et al QM 2017
1704.04577 hep-ph

$\chi^2/\mathrm{d.o.f}$ for

VISH2+1 $\otimes$ **CUJET3.1**

Combined RHIC+LHC1+LHC2 data RAA+v2 fit Chi^2(α_c, c_m)

Assuming slow Polyakov color electric semi-q+g liberation $\chi_T^L = c_q L + c_g L^2$

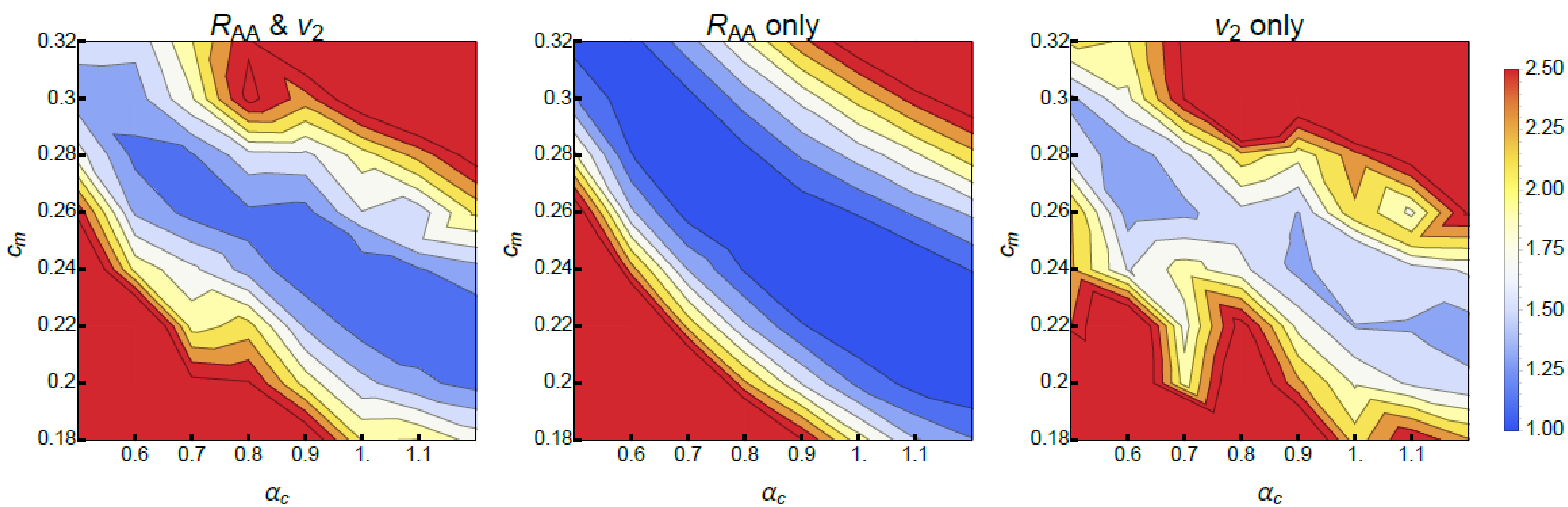
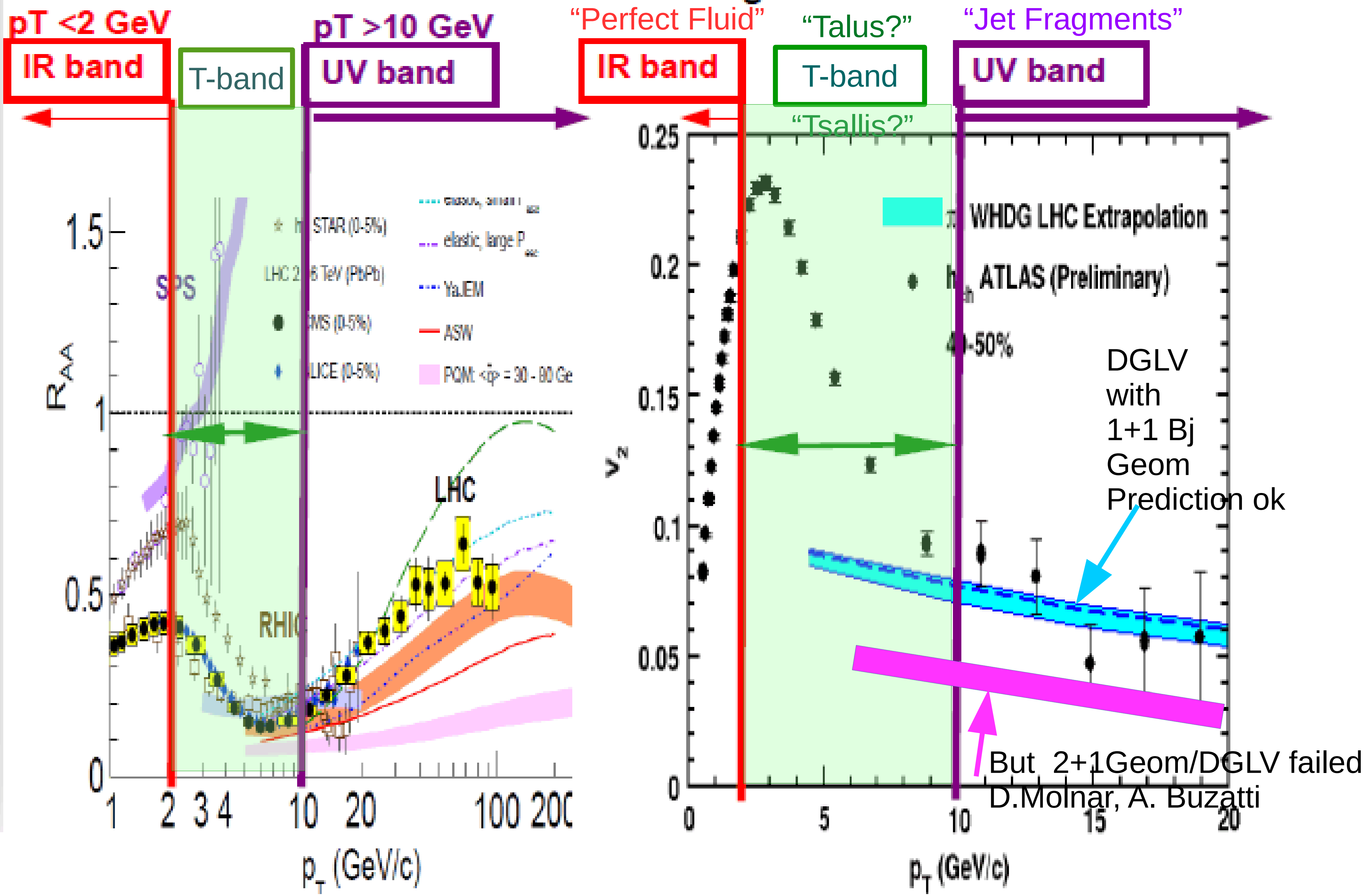


Fig. 1. (color online) The $\chi^2/d.o.f$ distribution on (α_c, c_m) parameter plane, from comparing CUJET3 results for pion high p_T observables with central and semi-central data from RHIC 200GeV, LHC 2.76TeV as well as 5.05TeV collisions: (left) including both R_{AA} and v_2 data; (middle) including only R_{aa}; (right) including only v_2.

The main question at QM17 was how large could event-by-event fluctuation Effects corrections be. J. Noronha-Hostler et al first consistent solution claimed Rather large modification due to ebe fluctuations.

S.Shi has now completed new CIBJET = ebe-CUJET3.1 predictions

30 Years of A+A Jet Quenching Data from SPS to LHC



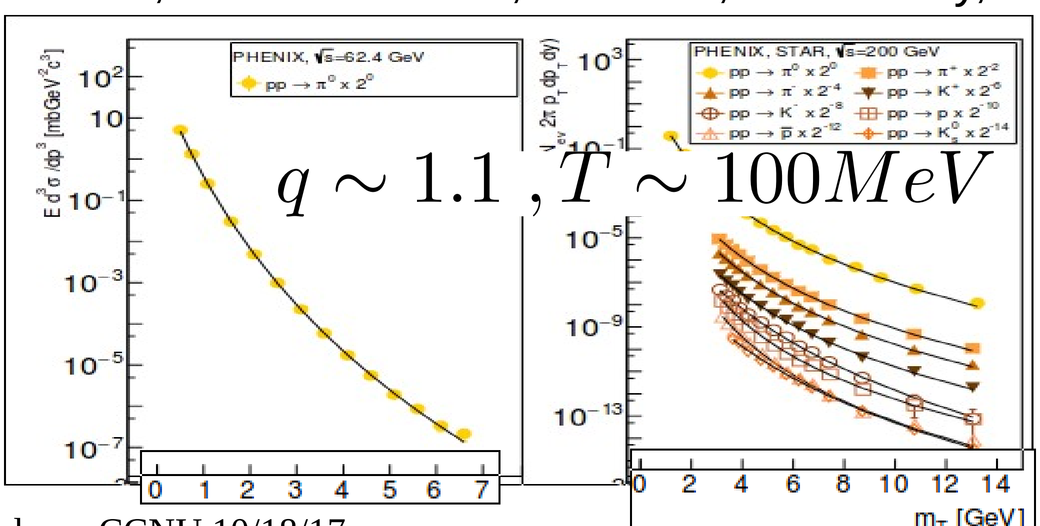
Encyclopedia of Quaternary Science, (2013), vol. 3, pp. 566-573

Figure 3 Talus slopes modified by extensive snow avalanche activity

Analog of "T-band" in A+A. The ***Talus*** distribution of rubble can be fit by **Tsallis** distribution

Non-Extensive Statistics: $e_q(E/T) \equiv (1-(q-1)E/T)^{1/(q-1)} \xrightarrow{q \to 1} e^{-E/T}$

Tsallis fits well SPS,RHIC and LHC pT distribution data down to 2GeV !
G. Biró, G.G. Barnaföldi, T.S. Biró, K.Ürmössy, arXiv:1608.0143



$q \sim 1.1\ ,\ T \sim 100 MeV$

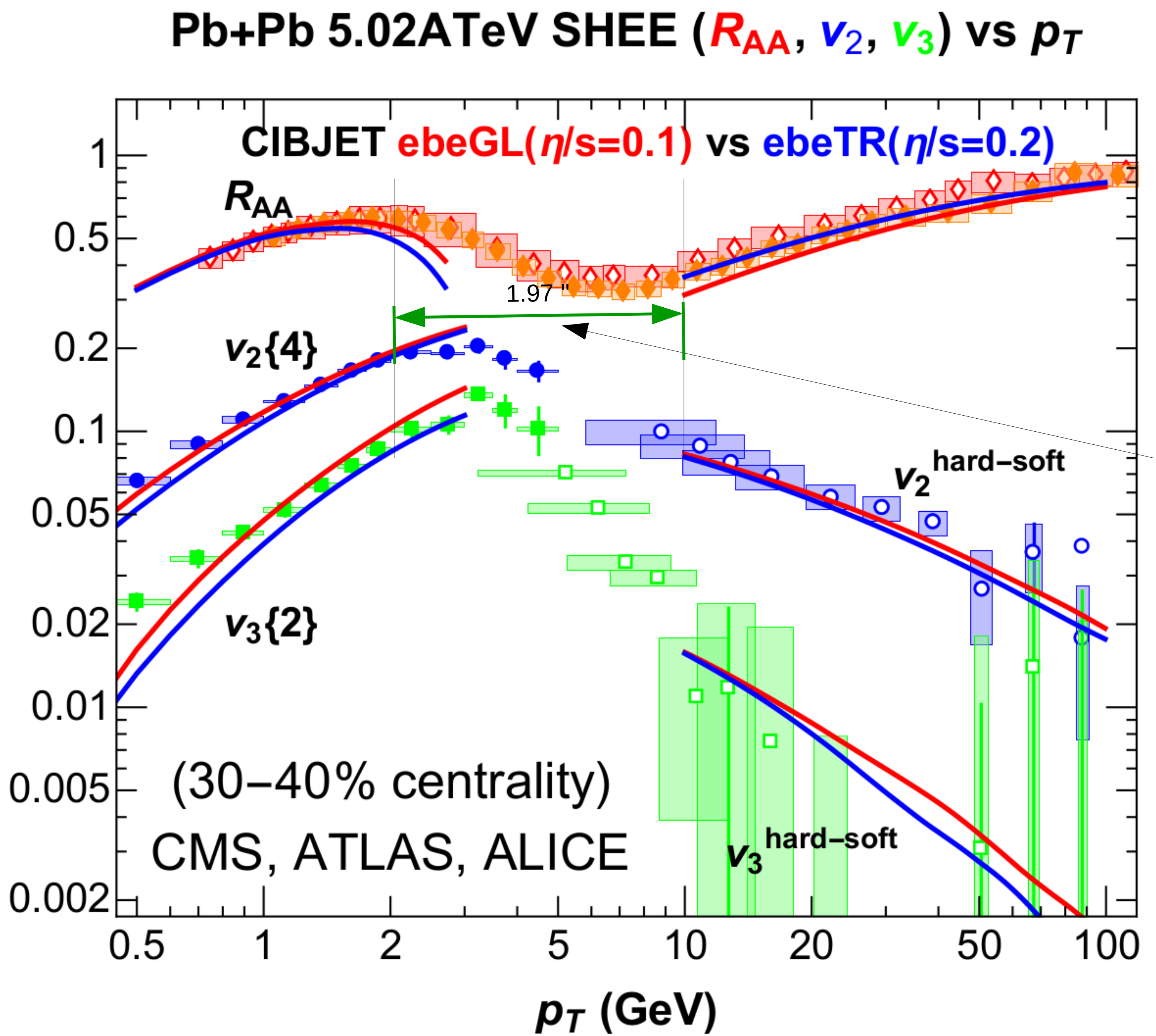
PQCD can rigorously
Predict jet fragment pT
Only above pT> 10 GeV

Tsallis interpolates between
Non-peturbative soft pT<2
Hydro-like (infrared)
And hard (ultraviolet) pT>10

[Needs detailed dynamic coalescence
Modeling along lines of R.Fries' seminar]

Summary of new results with sQGMP via CIBJET= ebe-IC+VISHNU2+1 + CUJET3.1

The new **S**oft-**H**ard-**E**vent-**E**ngineering double-log “**SHEE Plot**” shows good agreement with soft&hard RAA,v2,v3



Outside the hadronic **“Talus”** zone between the Fuild and Jet ranges

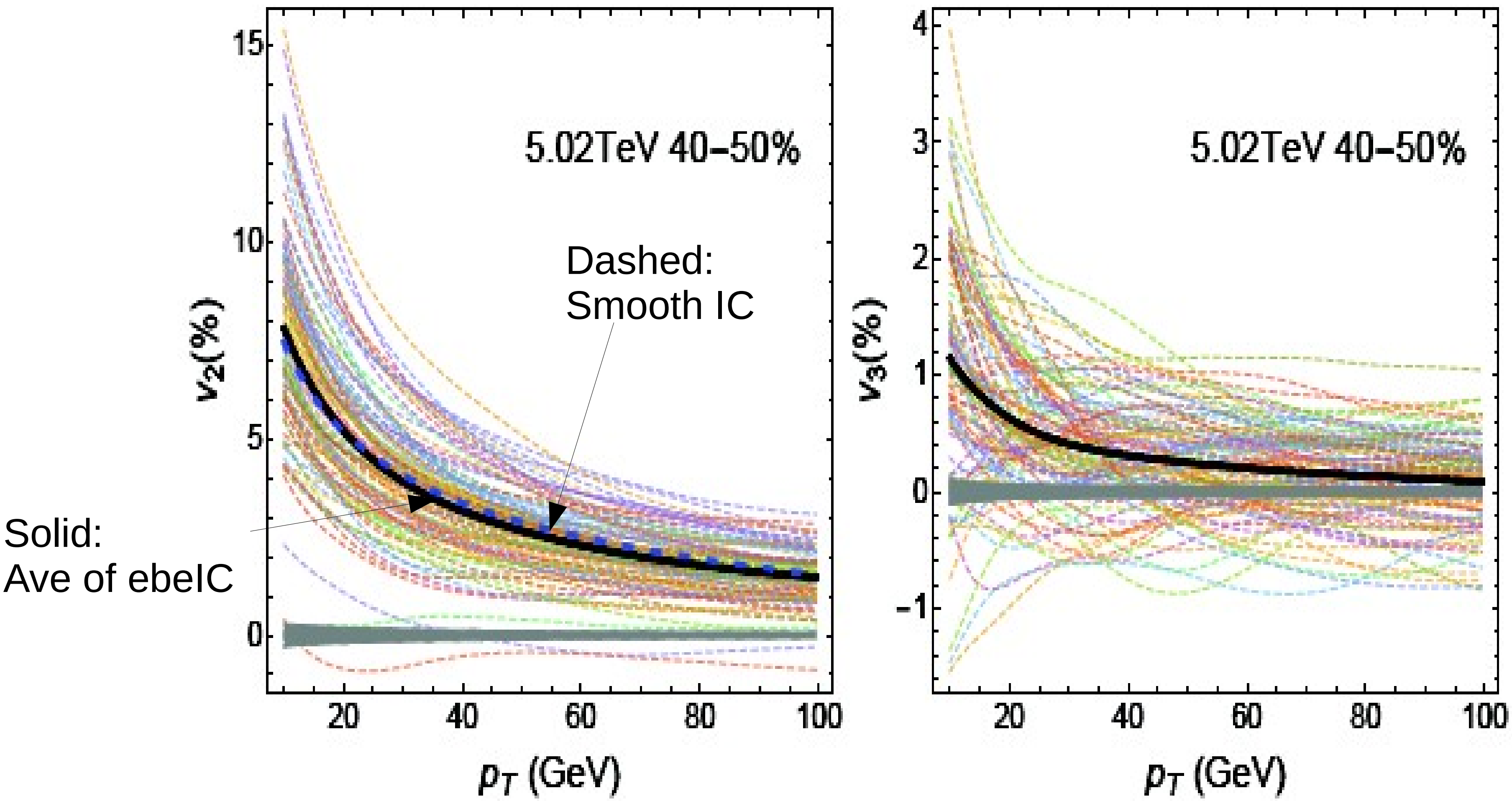
S.Shi, J. Liao, MG: “A second SHEE solution to RAA-vn Puzzle”, in prep

Comparison of ebe with smooth CIBJET= event-by-event CUJET3.1 from Shuzhe Shi

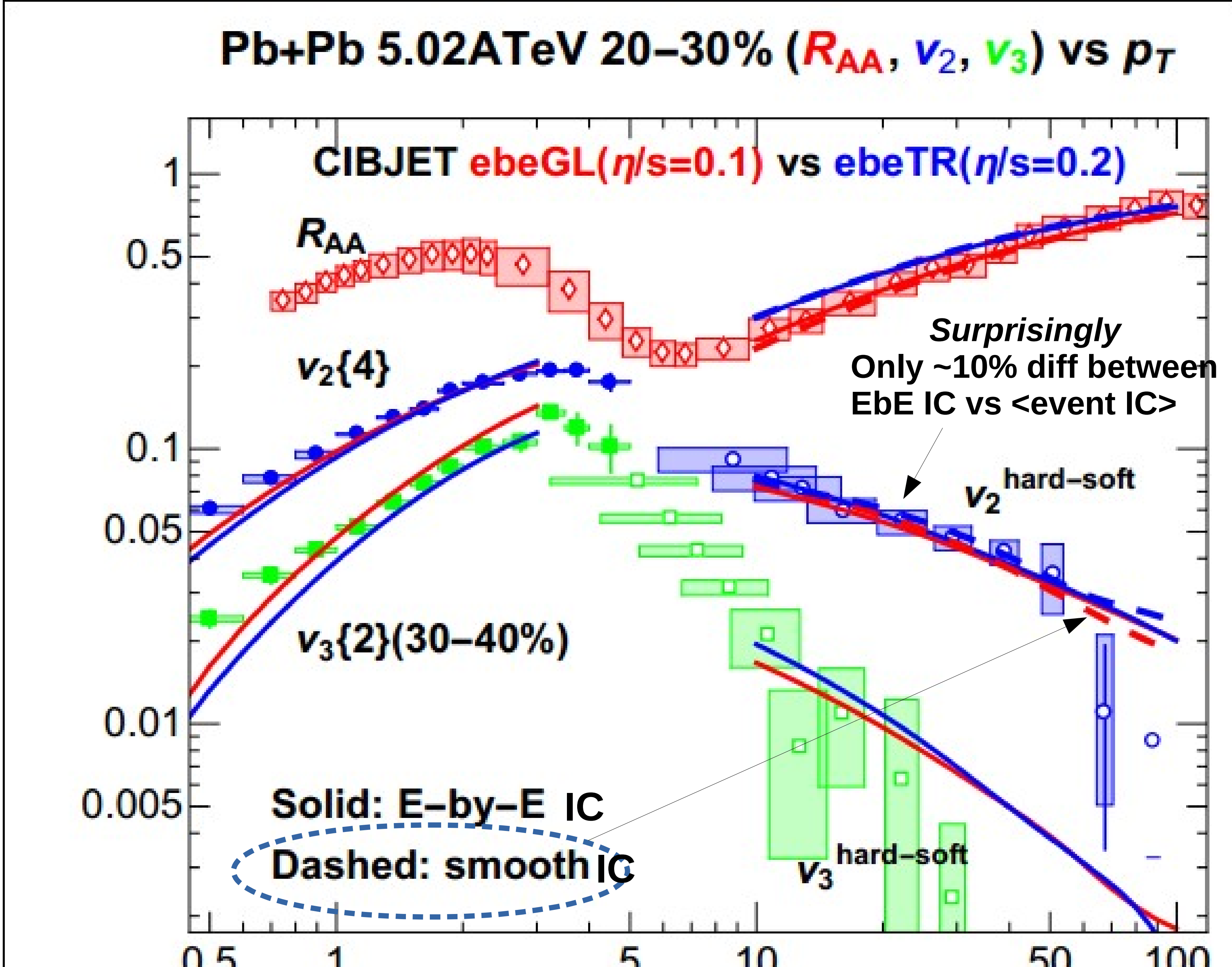
A Note for Event-by-Event CUJET simulations

(Dated: May 22, 2017)

Here is a note for the Event-by-Event CUJET simulations. It includes ~ 100 events in each of the centrality range 0-5% and 40-50% 5.02 TeV Pb-Pb collisions. As the first step of the study, (E-by-E) VISHNU hydro profile is employed. The short message is: while event-by-event fluctuation gives non-vanishing v_3, its effect on R_{AA} and v_2 are limited.



ebe does not change ave v2(pT) but essential for v3(pT)



This is one major difference between ebevUSPH/BBMG and CIBJET

ebeIC and smooth IC CIBJET results very similar

Summary so far:

After discovering and correcting three code errors in CUJET3.0 implementation,

S.Shi's corrected version CUJET3.1 with ***smooth*** event IC predictions are

found to agree with LHC1 and LHC2 data on RAA and v2 (but v3=0 for smooth IC)

Similar agreement with data as with SHEEJET == ebeIC+vUSPH+BBMG.

So there exists multiple solutions to the RAA-v2 puzzle consistently in both soft and hard sectors excluding the Talus 2<pT<10 range!

The QM17 question about effect of event by event fluctuations was solved with

CIBJET by Shizhe Shi:

Ebe-fluct IC were found to differ by only ~10% from smooth IC .

For RAA&v2 but v3 required ebe IC and was found to agree with both hard and soft data on that odd moment also.

Next we turn to internal theoretical consistency as to possible way to break the degeneracy Of interpretation of available SHEE data.

Soft bulk QCD fluid flow of course depends on equation of state , e.g. dP(T)/dT, but also on dissipative controlled by $\eta(T)/s(T)$ (and higher order IS coeff)

Lattice QCD provides precise prediction of P(T) and s(T)

But $\eta(T)$ has so far been out of reach with LQCD

Fortunately we can try constrain it not only with soft vn(pT) correlations
But also from jet quenching (hard probes) systematics via

$$\boxed{\eta(T)/s(T) \propto \lim_{E \to 3T} T^3/\hat{q}(E,T)}$$

To the extent that pT>10 GeV RAA, v2, v3 are sufficient to constrain $\hat{q}(E,T)$
To extrapolate E down to E→ 3 T thermal energy range

In any partonic quasiparticle framework, the transport parameter governing the radiative energy loss of a propagating parton in SU(3)-color representation R is [4]

$$\hat{q}_R \equiv \rho \int dq_\perp^2 q_\perp^2 \frac{d\sigma_R}{dq_\perp^2}. \quad (1)$$

A.Majumder, B.Muller, XN Wang
PRL99 (2007)

Kinetic Theory connection between $\hat{q}(E,T)$ And Viscosity in the Fluid limit:

Use transport theory relaxation time approx to estimate how phase space responds to variations of local temp and fluid velocity T(x), u(x) change f(x,p)

$$p^\mu \partial_\mu f^0(x,p) = -\frac{p\cdot u}{\tau_f(p)}\delta f(x,p),$$

$$\delta f = f - f_0 \equiv f(x,p) - (Exp[(pu(x))/T(x)] \pm 1)^{-1}$$

$$\boxed{\tau_f^{-1} = n_f\sigma_t(ff) + n_f\sigma_t(f\bar{f}) + n_b\sigma_t(fb) \approx \hat{q}(p,T)/(3pT/2)}$$

Transport Cross section

$$\sigma_t(ij) = \int \mathrm{d}\cos\theta \frac{\mathrm{d}\sigma(ij\to ij)}{\mathrm{d}\cos\theta}(1-\cos\theta) \approx \int dq_\perp^2 \frac{d\sigma_{ij}}{dq_\perp^2}\frac{4q_\perp^2}{\underbrace{s(ij)}_{6pT}} \equiv \frac{2}{3T}\frac{\hat{q}_{ij}}{n_j}$$

$$\Delta T^{\mu\nu} = -\int \mathrm{d}p\,\frac{p^\mu p^\nu}{p\cdot u}\left\{g_f\tau_f p^\alpha\partial_\alpha f^0 + g_f\tau_{\bar{f}} p^\alpha\partial_\alpha \bar{f}^0 + g_b\tau_b p^\alpha\partial_\alpha b^0\right\}$$

$$\boxed{\eta = \frac{1}{15T}\int\frac{\mathrm{d}^3p}{(2\pi)^3}\frac{\bar{p}^4}{E^2}\left\{g_f\tau_f f^0(1-f^0) + g_f\tau_{\bar{f}}\bar{f}^0(1-\bar{f}^0) + g_b\tau_b b^0(1+b^0)\right\}} \propto \frac{T^6}{\hat{q}} \propto s(T)\frac{T^3}{\hat{q}}$$

Updated from P.Danielewicz,MG (1985) & P.Hosoya, K.Kajantie (1985)
A.Majumder, B. Muller, X.N.Wang, PRL99 (2007)

For i.ne.j the shear stress correction is

$$\tau^{ij} = \left(\int \frac{d^3 p}{(2\pi)^3} \frac{(p_i\, p_j)^2}{E^2} \frac{\tau(p)}{T} f(p)\,(1 \pm f(p)) \right) \nabla^i u^j$$

for Bose + or Fermi − . From this we derive

$$\eta = \frac{1}{15} \frac{4\pi}{(2\pi)^3} \int dp\, f(p) \frac{d}{dp} \left(\overbrace{\tau(p)}^{3pT/2\hat{q}} \frac{p^5}{E} \right) \propto \frac{T^3 s(T)}{\hat{q}(p{\sim}3T, T)}$$

for off diag stress

$$\langle px^2\, pz^2 \rangle = p^4 \langle \mathrm{Cos}[\theta]^2 \mathrm{Sin}[\theta]^2 \mathrm{Cos}[\phi]^2 \rangle$$

$$= \langle px^2\, py^2 \rangle = p^4 \langle \mathrm{Sin}[\theta]^4 \mathrm{Cos}[\phi]^2 \mathrm{Sin}[\phi]^2$$

$$= p^2 / 15$$

Updated from P.Danielewicz,MG (1985) & P.Hosoya, K.Kajantie (1985)
A.Majumder, B. Muller, X.N.Wang, PRL99 (2007)

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

In a multicomponent sQGMP plasma **Jiechen Xu, Jinfeng Liao, MG JHEP02(2016)**

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:

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

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

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

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

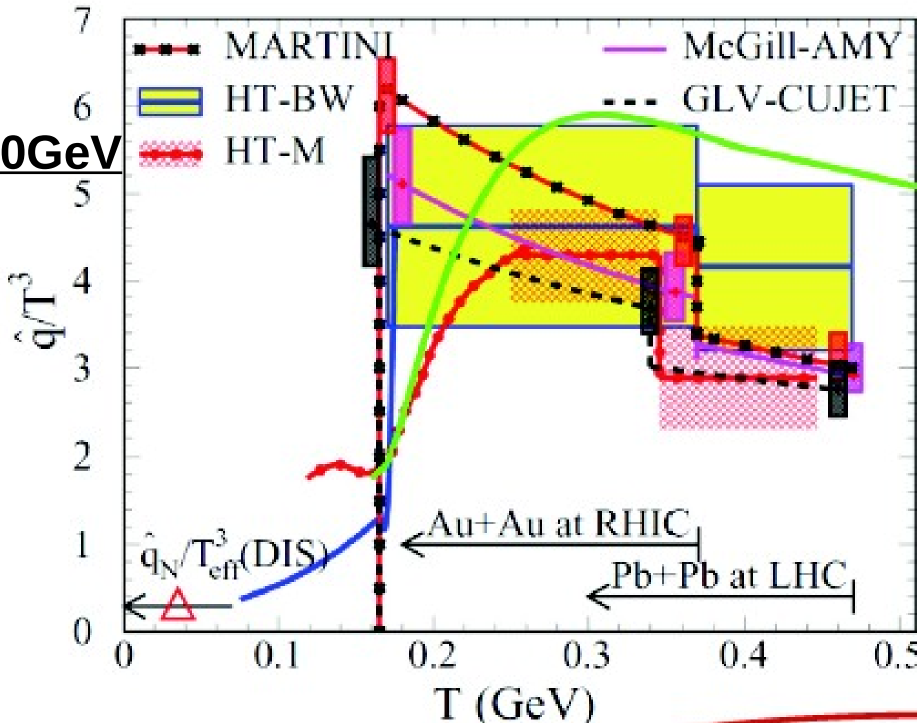
[4] P. Danielewicz and M. Gyulassy, Phys. Rev. D **31**, 53 (1985).

[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).

$\hat{q}(E,T)$ jet quenching parameter and η/s

E=10GeV



The Hard-Soft Consistency Problem

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

$3ET$

g^2T^2

Decreases With E

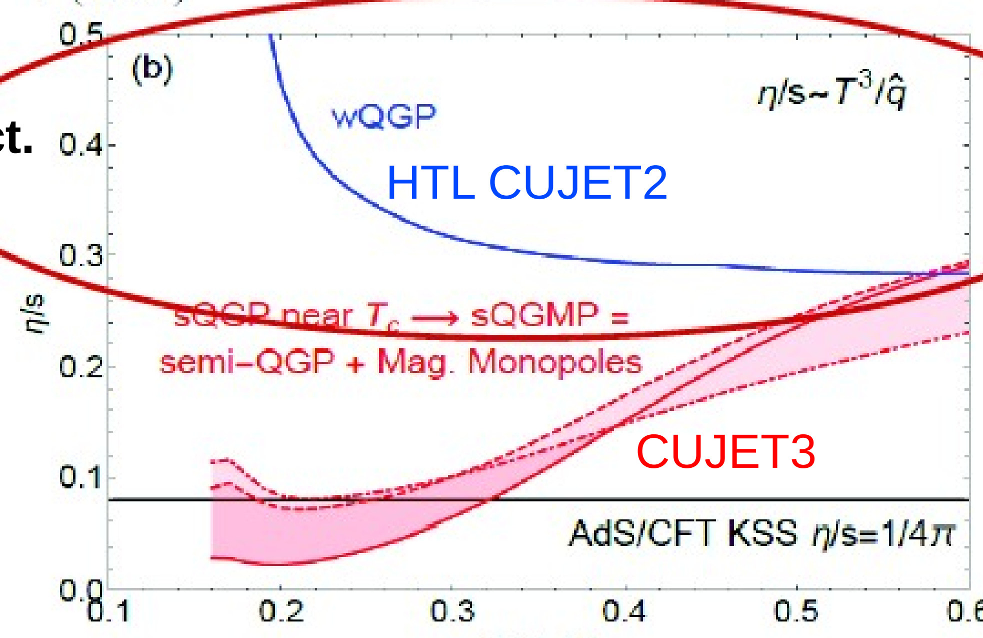
For E=10GeV . (But need E→ 1GeV for eta)

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

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

JET Collaboration, PRC 90, 014909 (2014)

JET collab assume
HTL pQCD color struct.
RAA OK but not v2!
and Predict qhat
extrapolated
down to E~1 GeV
thermal scales
=> eta/s predicted is
too large to support
perfect fluidity!

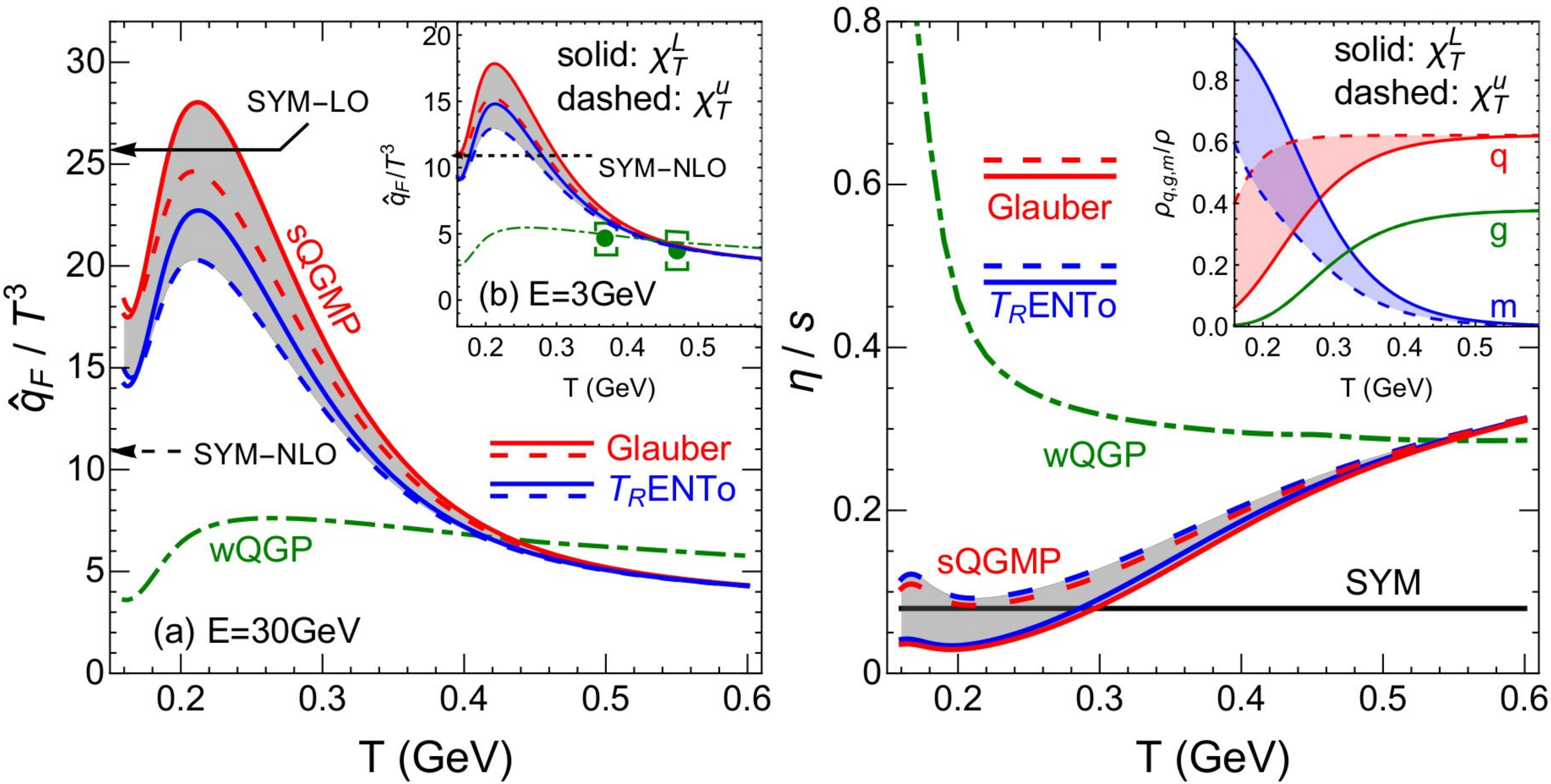


$$\eta/s = \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p \rangle_a \lambda_a^{tr}$$

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

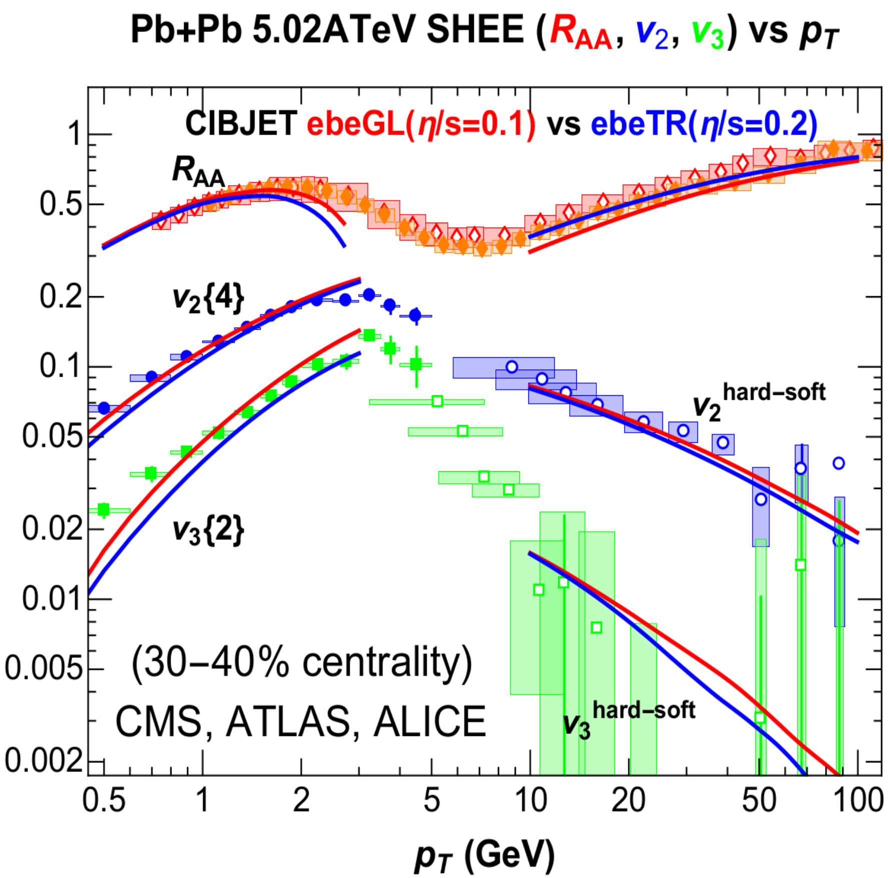
Majunder,Wang,Muelle
Inverse eta/s and qhat
Relation (2007)

2017 CIBJET $\chi^2(\alpha_c, c_m)$ fits to RHIC+LHC1+LHC2 soft and hard data
Show sQGMP transport properties are consistent with assumed “Perfect Fluidity”

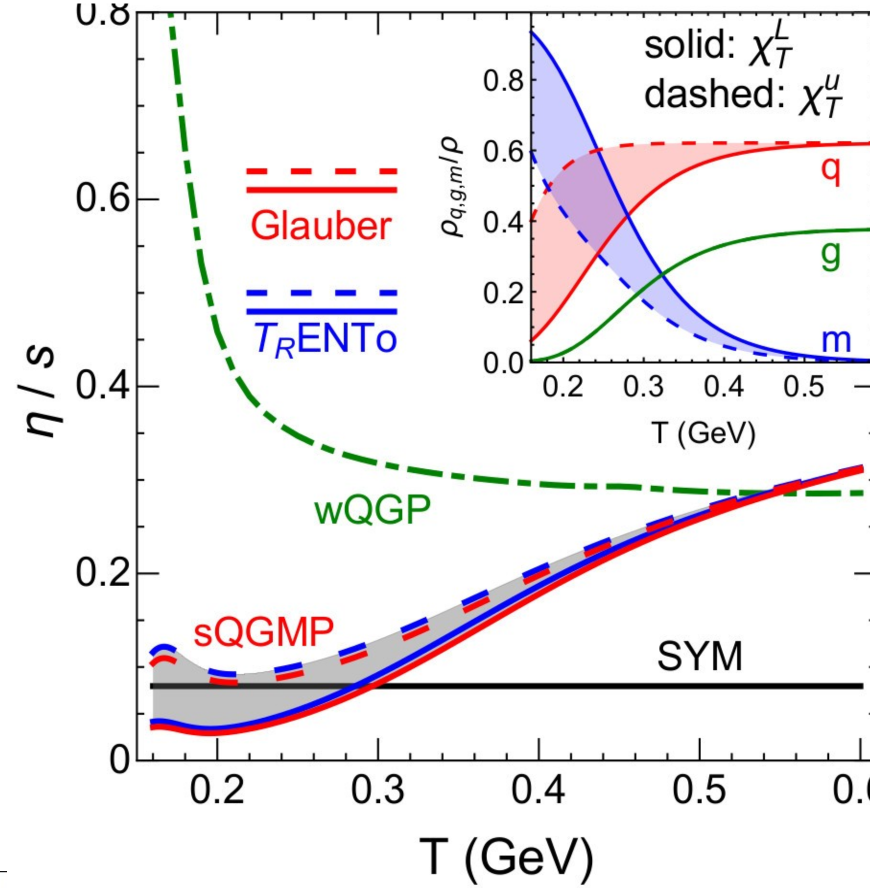


While SHEEJET assuming wQGP HTL color electric structure of the QGP fluid
And CIBJET assuming semi-QGP+mag.monopole sQGMP bleached color electric sector
Supplemented by rich color magnetic structure of the QGP fluid give comparable chi^2
Wrt data, only sQGMP is consistent with minimal viscous “Perfect Fluidity”

Summary of SHEE vs eta/s connection: CIBJET= ebe-IC + VISHNU2+1 + (“Talus0”) + CUJET3.1



SQGMP structure explains eta/s~1/4pi !

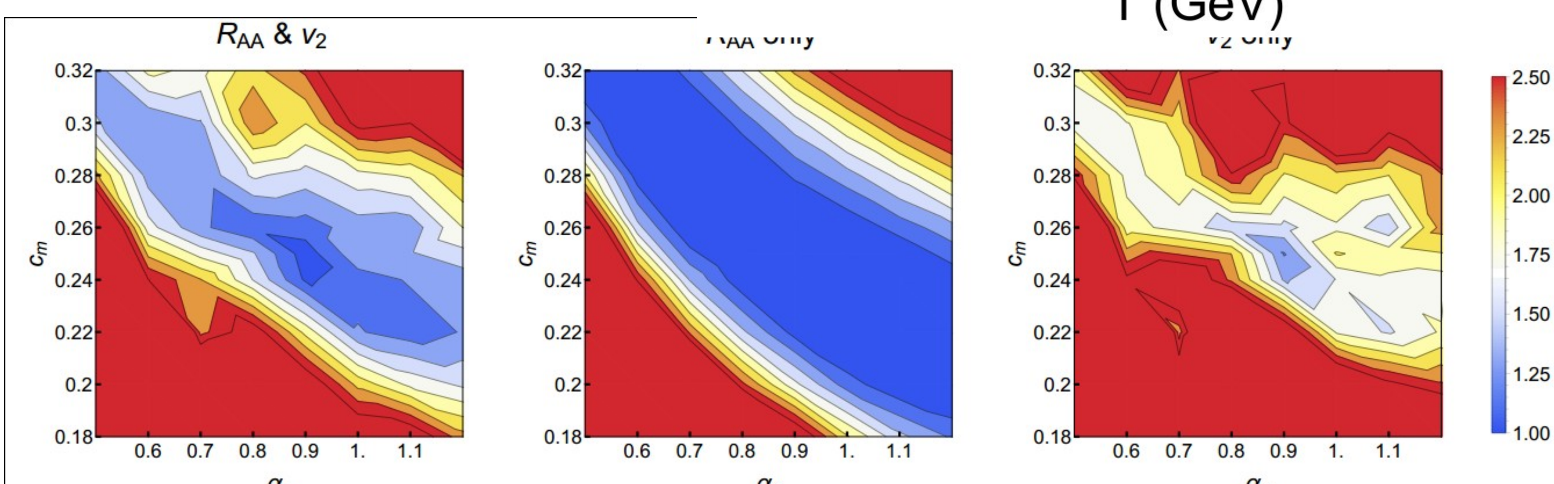


Global

$$\chi^2/dof$$

RHIC&LHC1&2

Composition of Semi-Q&G+MP is not yet well Resolved by data



S.Shi, J. Liao, MG: A second SHEE solution to RAA-vn Puzzle, in prep

My version of Jinfeng Liao's future directions slide at Quark Matter 2017

Does there exist an onthologically unique and internally consistent description of hot QCD matter?
Need exp and theo constraints to reduce the infinite volume of theory space by falsification.