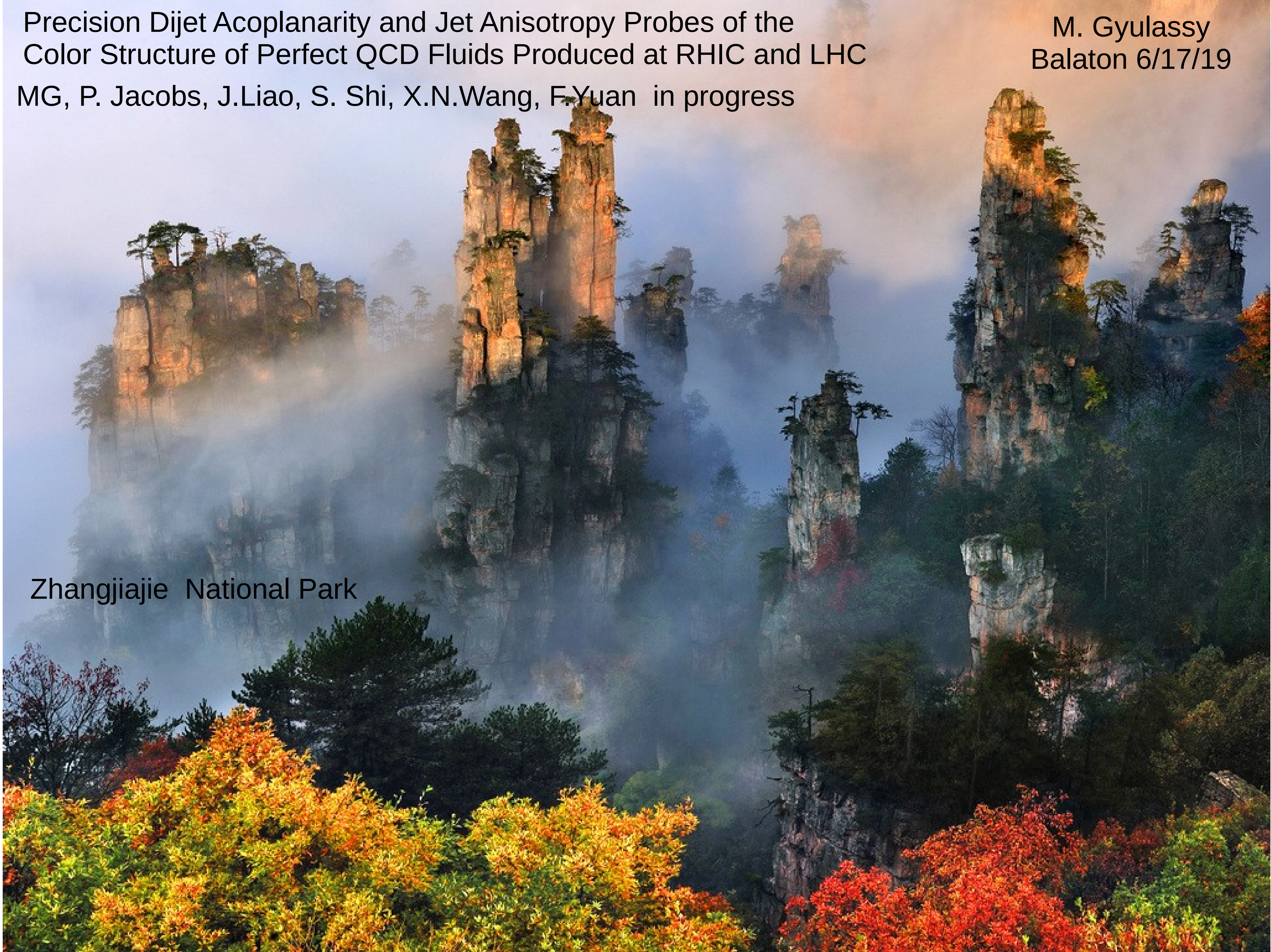
Precision Dijet Acoplanarity and Jet Anisotropy Probes of the Color Structure of Perfect QCD Fluids Produced at RHIC and LHC

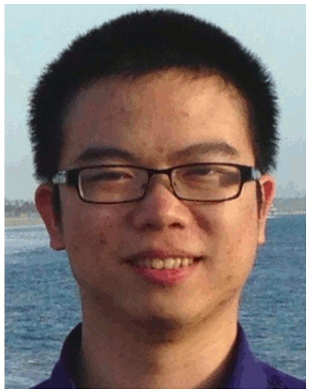
M. Gyulassy
Balaton 6/17/19

MG, P. Jacobs, J.Liao, S. Shi, X.N.Wang, F.Yuan in progress



Zhangjiajie National Park

This talk owes special thanks to
exceptionally talented collaborators



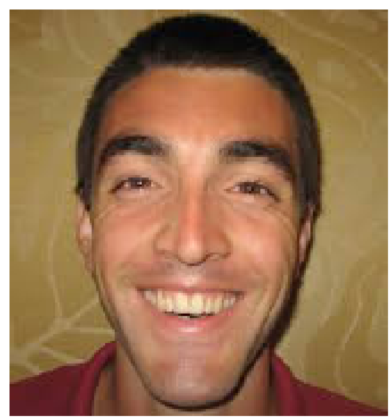
Shuzhe Shi

Jinfeng Liao

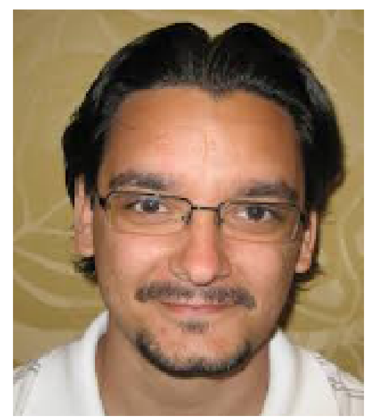
Jorge Noronha

Jaki Noronha-Hostler

Jiechen Xu



Alessandro Buzzatti



Andrej Ficnar

Barbara Betz

and F. Yuan, X.N.Wang, P.Levai, I.Vitev, M.Drordjevic, …
and the constant push by Peter Jacobs for new predictions

Outline :

Section 1: Overview of sQGMP vs wQGP Models of the Color Structure of perfect QCD fluids and the sQGMP solution of the RAA/vn puzzle

Section 2: Predictions for future high precision Di-Jet Acoplanarity Observables via CUJET3.1

Section 3: Conclusions

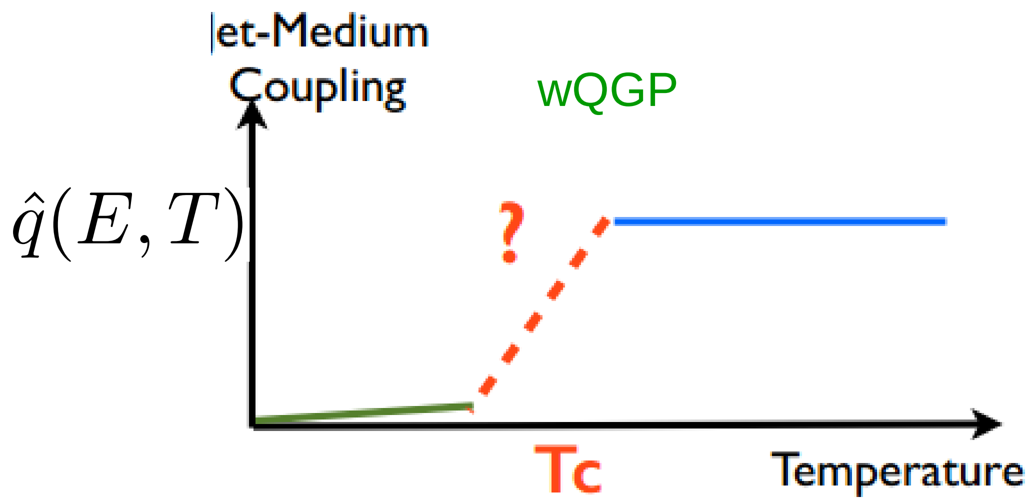
Section 4: Postscript: Old Hat, New Hat, vs Q Hat

$$\frac{d\sigma_{EE}}{dq_\perp^2} \sim \frac{\alpha_{\mathbf{E}}^{\mathbf{2}}}{q_\perp^4} \ll \frac{d\sigma_{EM}}{dq_\perp^2} \sim \frac{\mathbf{1}}{q_\perp^4}$$

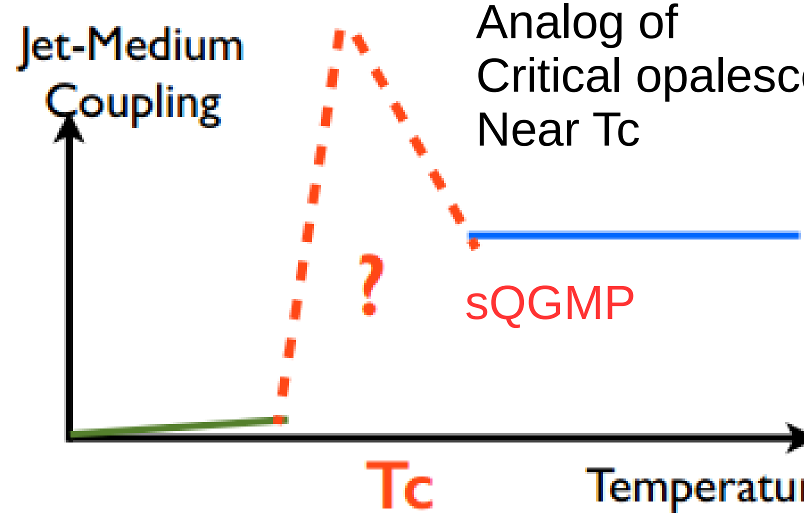
adapted from J.Liao 2008

Ed@60

From "Transparency" to Opaqueness



"Waterfall" scenario



"Volcano" scenario

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

CIBJET was developed by <u>A. Buzzatti, J.Xu, Shuzhe Shi,</u> Jinfeng Liao, MG to test quantitatively this idea with RHIC&LHC (RAA, v2, v3) Soft+Hard data

CUJET3.0

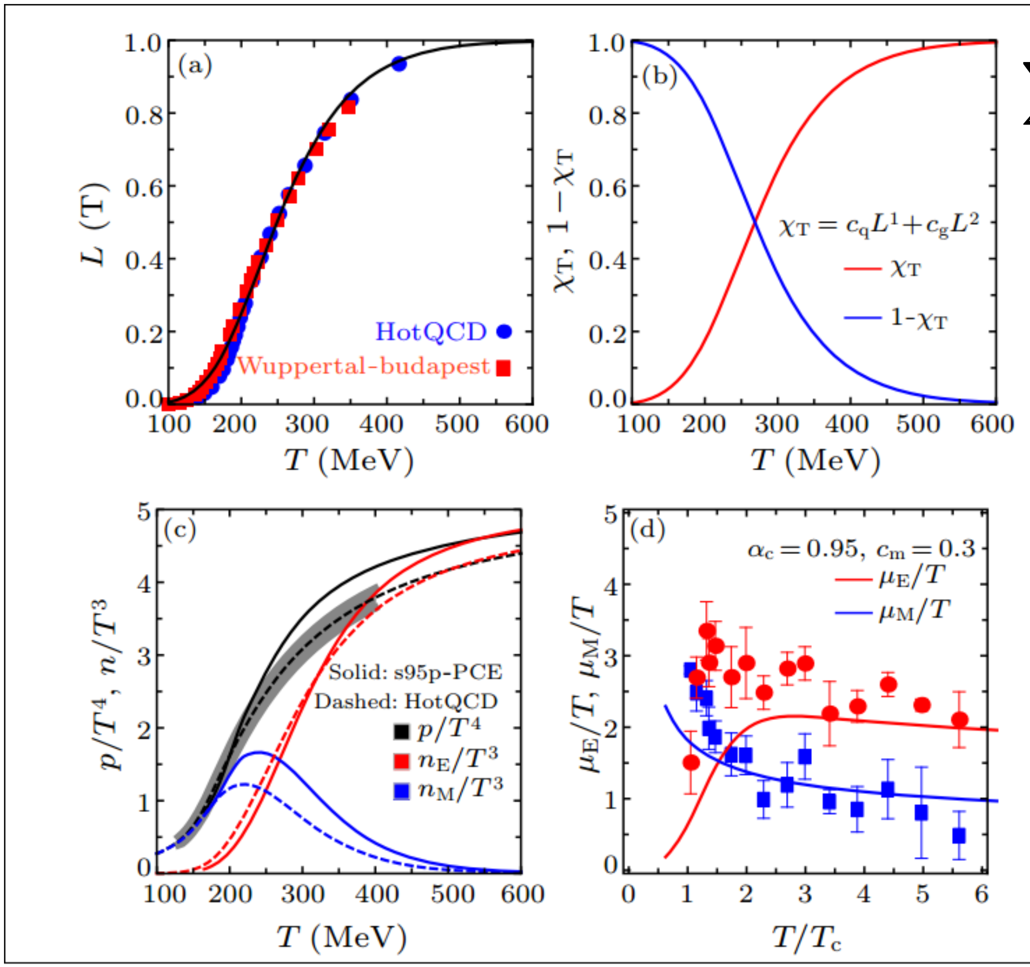
CHIN. PHYS. LETT. Vol. 32, No. 9 (2015) 092501 Letter

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

Jiechen Xu 徐杰谌)[1], Jinfeng Liao(廖劲峰)[2,3]**, Miklos Gyulassy[1]**

CUJET3.0

Lattice QCD data constraints in CUJET3



sQGMP generalization of wQGP DGLV kernel

$$\sum_b \rho_b \frac{d\sigma_{ab}}{dq^2} \propto \left[\frac{n_e(\alpha_s(q^2)\alpha_s(q^2))f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m(\alpha^e(q^2)\alpha^m(q^2))f_M^2}{q^2(q^2+f_M^2\mu^2)}\right]$$

$$f_E^2 = \chi_T = \rho_e/\rho \qquad f_M = c_m g(T)$$

The jet transport coefficient is defined as

$$\hat{q}_a(E,T) = \int dq^2\, q^2 \sum_b \rho_b \frac{d\sigma_{ab}}{dq^2}$$

Path integrals over qhat control
the transverse deflection of jets as
well as elastic and radiative jet energy loss

$$Q_s^2(a) \equiv \langle \mu^2 \chi_a \rangle \equiv \langle \int dt\ \hat{q}_a(\vec{x}_a(t),t) \rangle$$

$$\Delta\phi_{ab} \approx (Q_s^2(a) + Q_s^2(b))/Q_0^2$$

Jet Path Functionals needed to predict RAA, v2, ***and*** Acoplanarity Observables

Microscopic differential a+b scattering rates per d^2q_T given a specific model of color structure

$$\Gamma_{ab}(q_\perp,t) = \rho_b(T) d^2\sigma_{ab}(T)/d^2 q_\perp \qquad \Gamma_a(q_\perp,t) \equiv \sum_b \Gamma_{ab}(q_\perp,t)$$

Transverse diffusion Coefficient (BDMS)

$$\hat{q}_a(E,T) = \int dq_\perp^2 \; q_\perp^2 \; \Gamma_a[q_\perp] \equiv \left\langle \frac{q_\perp^2}{\lambda} \right\rangle_a$$

Medium induced transverse momentum² broadening , "saturation", scale path functional

$$Q_s^2(a) \equiv \left\langle q_\perp^2 \frac{L}{\lambda} \right\rangle_a \equiv \int dt\, t^0 \; \hat{q}_a(x(t),t) \equiv \int dt d^2 q_\perp \; \{t^0 \; q_\perp^2\} \; \Gamma_a(q_\perp,t)$$

The BDMS multi-soft pQCD radiative energy loss functional is proportional to

$$\Delta E_s(a) \equiv \frac{1}{4} \left\langle q_\perp^2 \frac{L^2}{\lambda} \right\rangle_a \equiv \frac{1}{2} \int dt\, t^1 \; \hat{q}_a(x(t),t) \equiv \int dt d^2 q_\perp \; \{t^1 \; q_\perp^2\} \; \Gamma_a(q_\perp,t)$$

The GLV pQCD medium elastic opacity functional

$$\chi(a) \equiv \left\langle q_\perp^0 \frac{L^1}{\lambda} \right\rangle_a \equiv \int dt/\lambda_a(t) \equiv \int dt d^2 q_\perp \; \{t^0 \; q_\perp^0\} \; \Gamma_a(q_\perp,t)$$

Qualitatively, for an ideal Blorken plasma brick of length L and initial time tau0

$$Q_s^2 = \hat{q}(\tau_0)\tau_0 \log(L/\tau_0) \qquad \Delta E_s = \hat{q}(\tau_0)\tau_0(L - \tau_0))$$

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)**

The extrapolation of $\hat{q}_a(E,T)$ down to the thermal scale E~3T can test consistency of viscous hydro with specific color structure of the QCD fluid assumed for jet quenching !

$$\eta/s = \frac{1}{s}\frac{4}{15}\sum_a \rho_a \overbrace{\langle p\rangle}^{3T}_a \lambda_a^{tr}$$

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

$$= \frac{18T^3}{5s}\sum_a \rho_a/\hat{q}_a(T,E=3T)\ . \qquad (9)$$

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

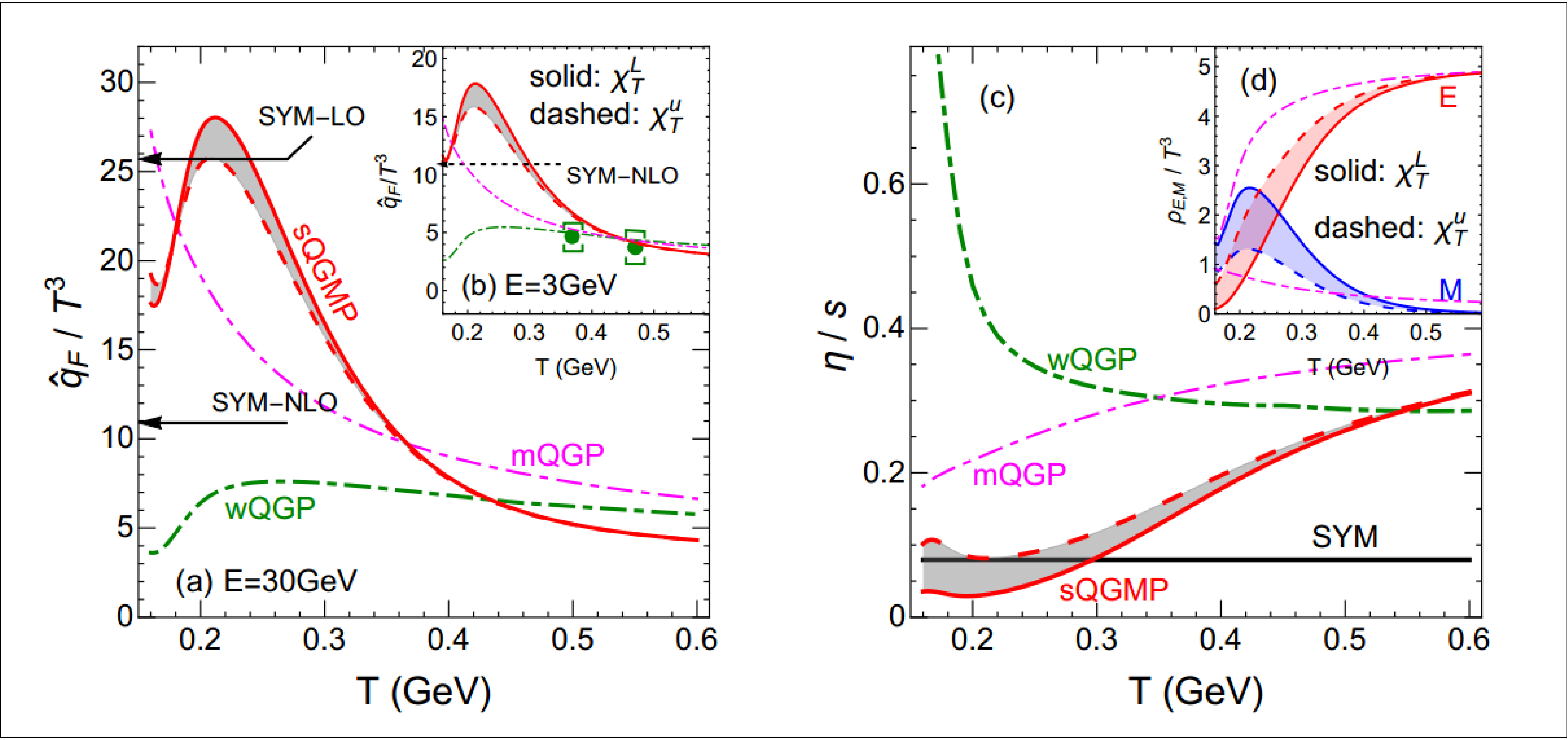
[5] T. Hirano and M. Gyulassy, Nucl. Phys. A **769**, 71 (2006).

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

Shuzhe Shi, J.Liao, MG: arXiv:1804.01915 and 1808.05461

Quantitative constraint on $\hat{q}_F(E,T)$ jet transport field ***and*** $\eta/s(T)$ via CIBJET

The q+g suppressed semi-QGP components of **sQGMP** require large monopole density near Tc to compensate the loss of color electric dof and still fit the lattice Eq of State: P/T or S(T)



Lattice constrained sQGMP color composition model accounts not only for global RHIC&LHC RAA, v2, v3 data but uniquely accounts for bulk perfect fluidity due to Near unitary bound q+m and g+m scattering rate near Tc !

VISHNU ⊗ **CUJET3.1**

Chinese Physics C Vol. 43, No. 4 (2019) 044101

VISHNU ⊗ **CUJET3.1**

ArXiv 1804.01915, 1808.05461

Global constraints from RHIC and LHC on transport properties of QCD fluids in CUJET/CIBJET framework*

Shuzhe Shi(施舒哲)[1;1)] Jinfeng Liao(廖劲峰)[1;2)] Miklos Gyulassy[2,3,4;3)] (许乐世 :-)[4]

[1] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[2] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
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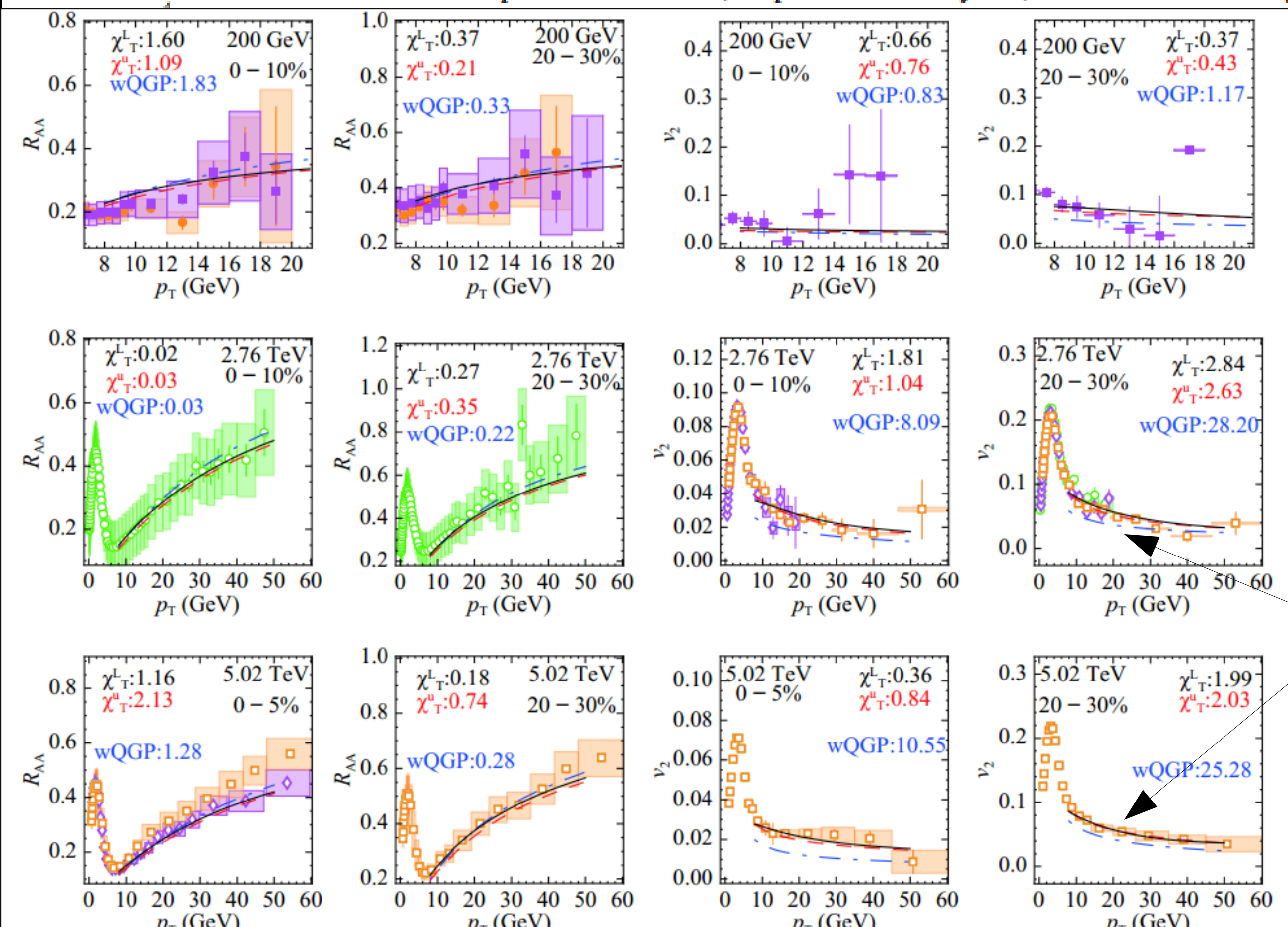
ral China Normal University, Wuhan, 430079, China [4]



Semi-QGP+MagMonopoles

Global χ^2(sQGMP) < 2 !!

RHIC+LHC1+LHC2

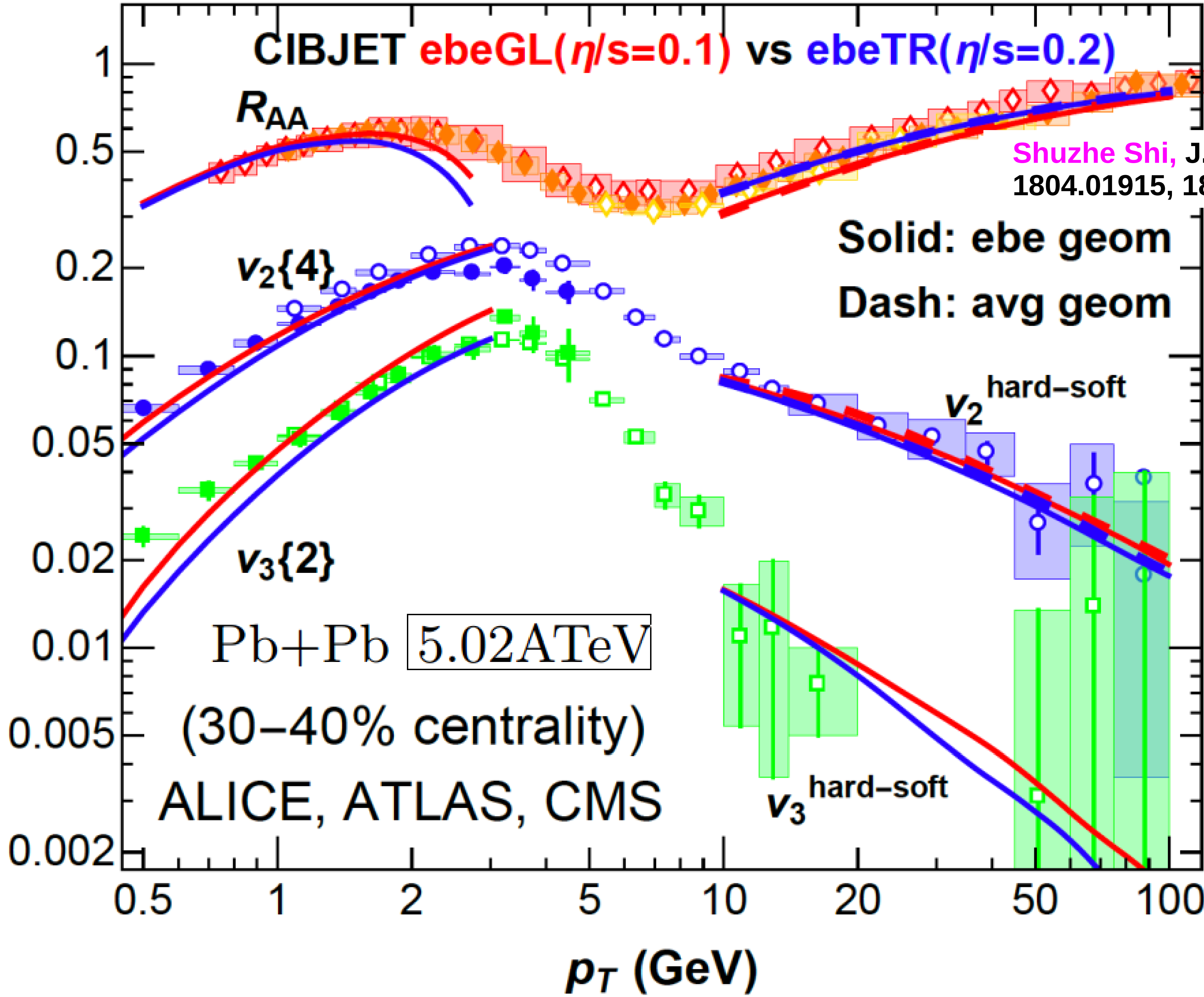
RAA & v2 !

$\alpha_c = \alpha(T_c) = 0.9 \pm 0.1$

$$c_m = \mu_M/(g^2 T) = 0.25 \pm 0.03$$

v2 data rule out weakly coupled (HTL) quark gluon plasma structure of perfect QCD fluids

Quantitative Test of sQGMP color structure of QCD fluids with CIBJET sQGMP

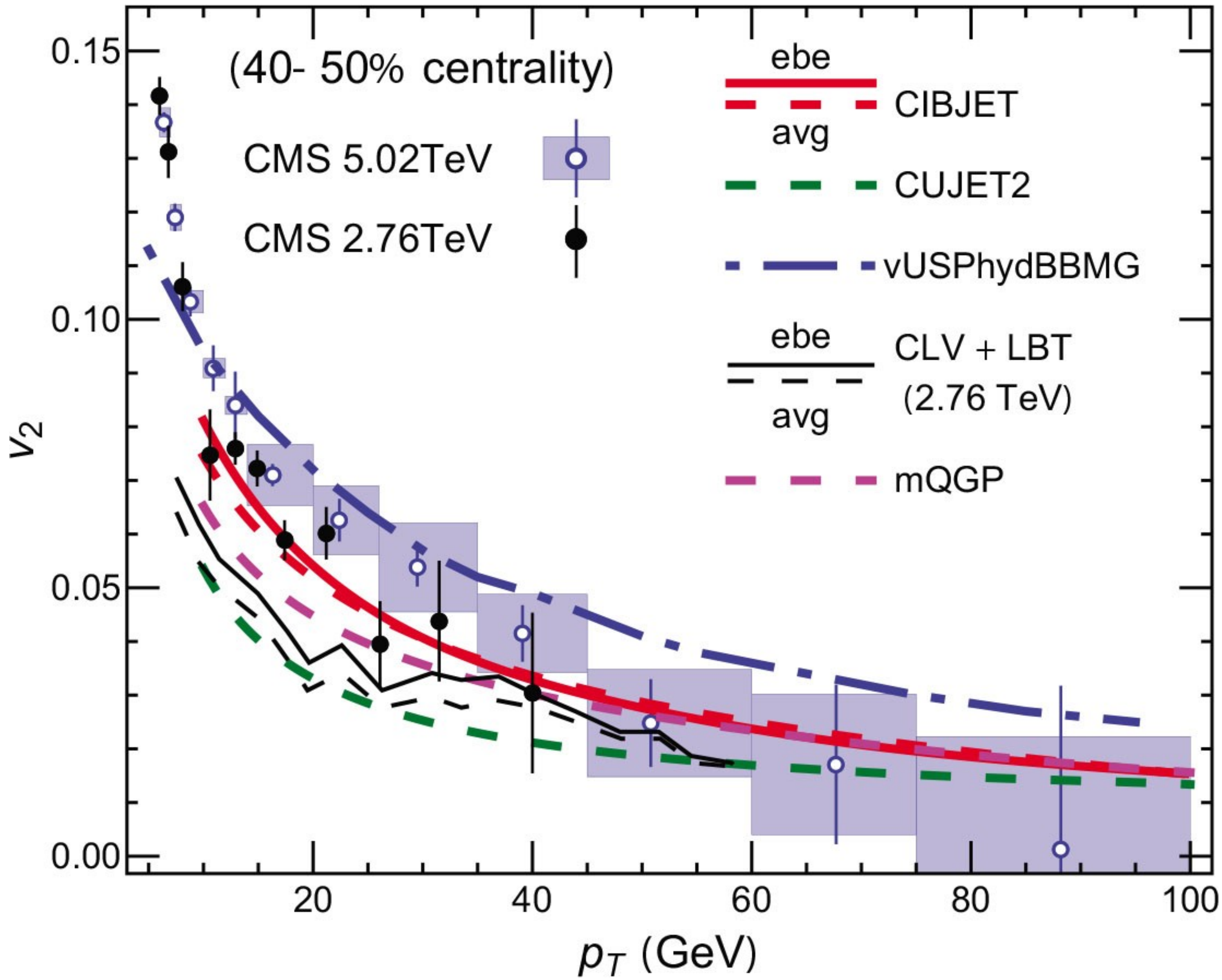


Shuzhe Shi, J.Liao, MG: 1804.01915, 1808.05461

An open problem is that our global soft+hard ebe CUJET3 sQGMP solution to the RAA-v2 puzzle in not unique !

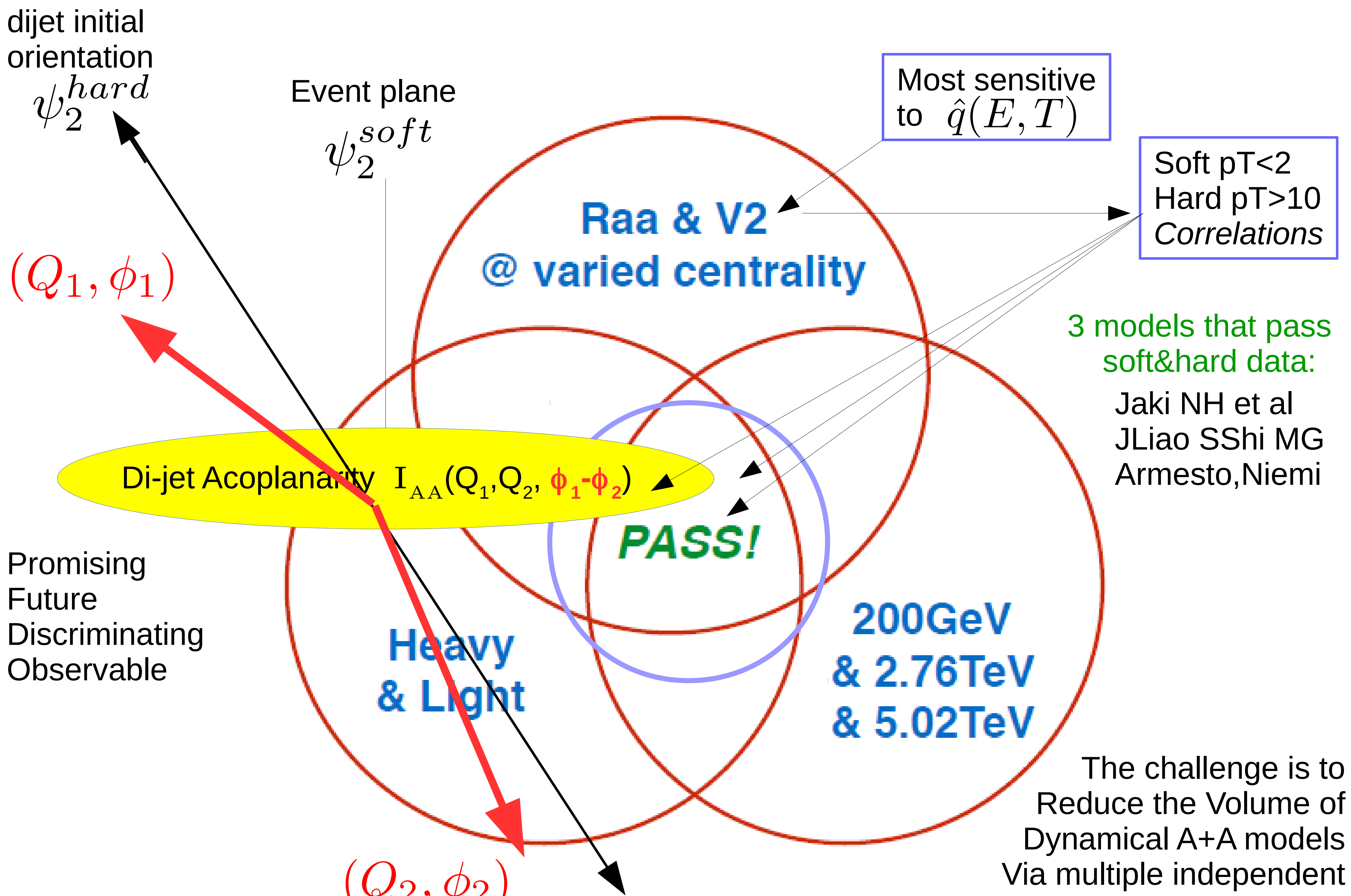
We need independent observables to break current theory degeneracy

Jaki Noronha-Hostler PRL (2016) can also explain RAA&v2
With her (vUSPhydro + dE/dx= k x T^3) hydro+en loss model



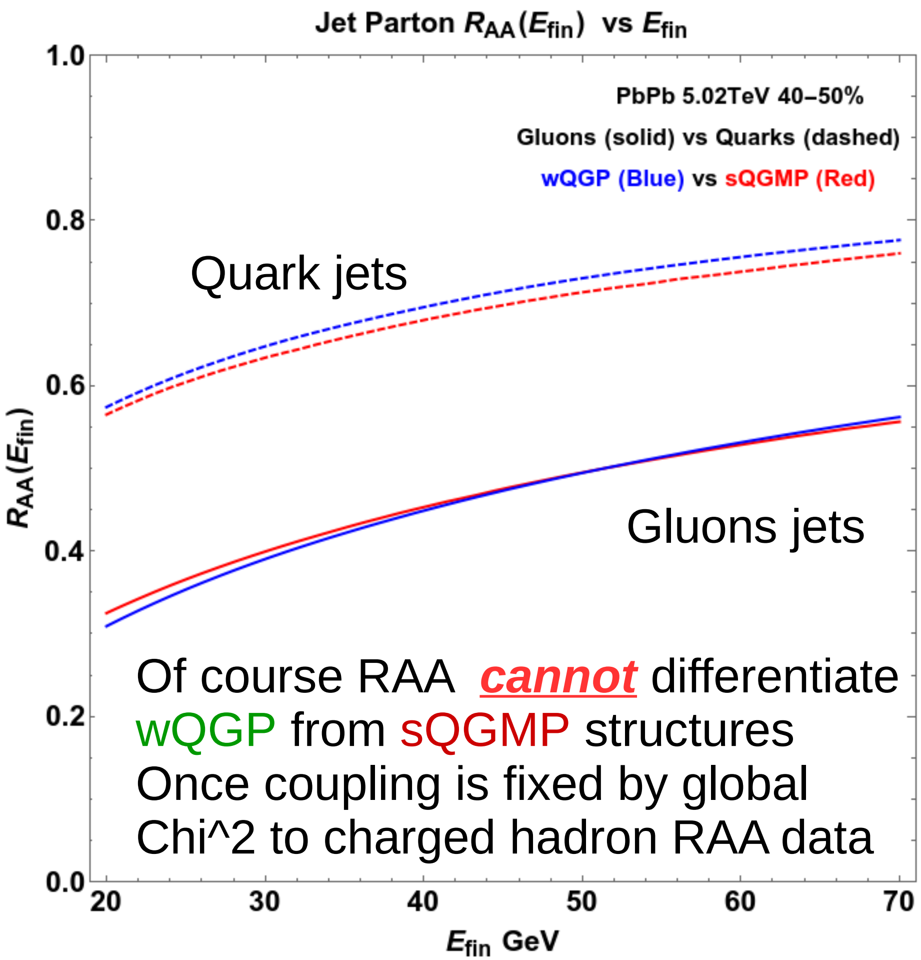
Armesto et al found a third soft/hard solution involving two independent time scales
arXiv:1902.07643

Dijet acoplanarity is a future A+B observable that could to help falsify models of the color structure of QCD perfect fluids produced at RHIC and LHC

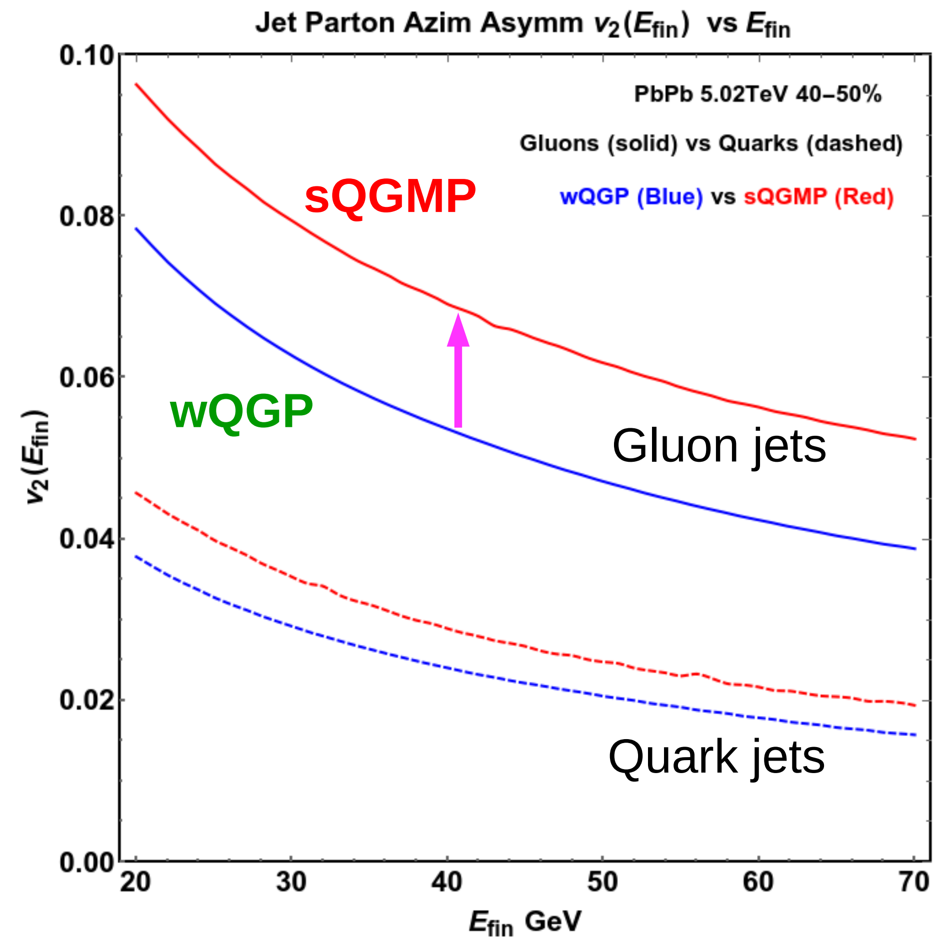


Single Jet Tomography of the Color Structure of Perfect QCD Fluids

With CUJET3.1 jet-medium coupling global Chi^2 constrained to charged hadron RHIC and LHC data on RAA data



Of course RAA ***cannot*** differentiate wQGP from sQGMP structures Once coupling is fixed by global Chi^2 to charged hadron RAA data



But 20-30% Enhancement in sQGMP of High pT azimuthal asymmetry v2(pT>20) agrees well with data but rules out wQGP structure in CUJET framework

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? Can Acoplanarity help to break thecurrent 3 fold degeneracy of AA modeling that account for both soft and hard RAA and v2 data at RHIC and LHC ?

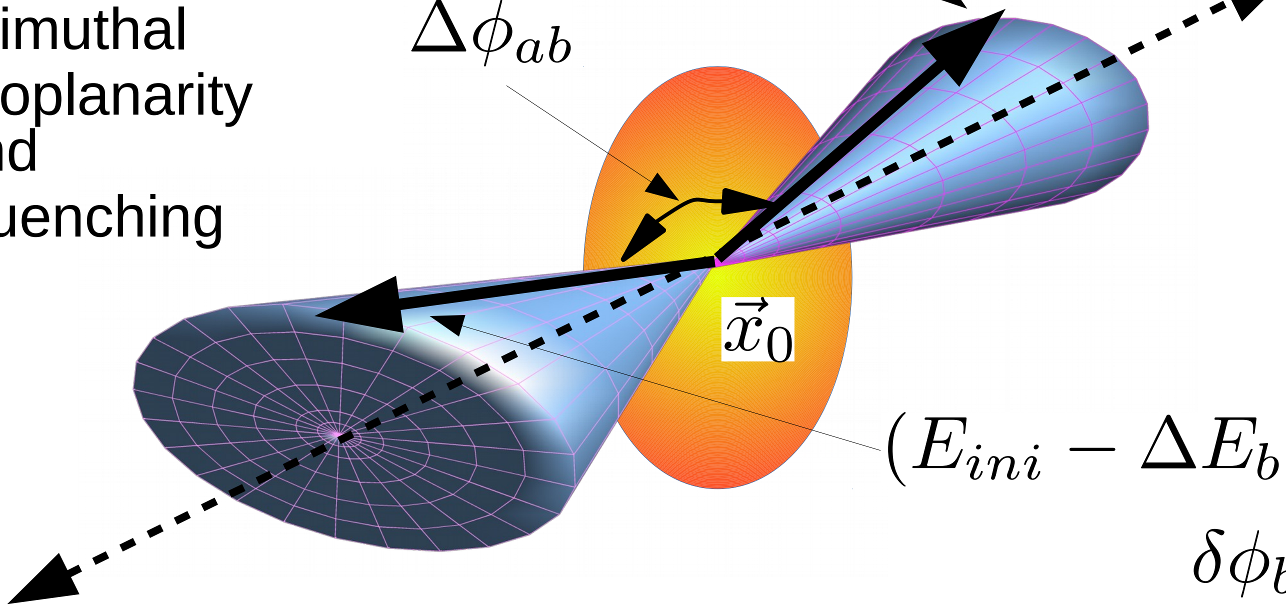
Dijet Azimuthal Acoplanarity and Quenching

$$(E_{ini} - \Delta E_a)\ \hat{n}(\phi_0 + \delta\phi_a)$$

$$E_{ini}\ \hat{n}(\phi_0)$$

$$\delta\phi_a(E_{ini}, \vec{x}_0, \phi_0)$$

$$\Delta E_a(E_{ini}, \vec{x}_0, \phi_0)$$



$$(E_{ini} - \Delta E_b)\ \hat{n}(\pi + \phi_0 + \delta\phi_b)$$

$$\delta\phi_b(E_{ini}, \vec{x}_0, \pi - \phi_0)$$

$$\Delta E_b(E_{ini}, \vec{x}_0, \pi - \phi_0)$$

$$E_{ini}\ \hat{n}(\pi + \phi_0)$$

$$\delta\phi_a = \delta\phi_a^{vac} + \delta\phi_a^{med}$$

The Acoplanarity distribution is a convolution of **Vacuum Sudakov** and **Medium** induced transverse deflection distributions (and has been proposed as QGP signal 33 years ago!)

D. A. Appel, PhysRD33, 717 (1986); J. P. Blaizot,L. D. McLerran, PRD34, 2739 (1986)

$$\frac{dN}{dq^2} \approx \frac{1}{Q^2}\frac{dN}{d\Delta\phi} = \int bdbJ_0(|q(Q,\Delta\phi)|b)e^{-S_{vac}(Q,b)-S_{med}(Q,b)}$$

$$S_{vac} \approx (\alpha/2\pi)\sum_{q,g}\left\{(A_1(\log(Q^2/\mu_b^2)^2/2 + (B_1 + D_1\log(1/R^2))\log(Q^2/\mu_b^2)\right\} + S_{NP}(Q,b)$$

Mueller,Wu,Xiao,Yuan, PLB763, 208 (2016); PRD 95, 034007 (2017)
Chen,Qin,Wei,Xiao,Zhang, PLB773, 672 (2017)

(see Guang-You Qin talk Fri)

The medium induced broadening assuming the one parameter multi soft Gaussian BDMS[16]

$$|S_{BDMS}(b;Q_s) = |b^2 Q_s^2/4$$

The two parameter GLV all orders in opacity χ eikonal screened Yukawa approximation.

$$S_{GLV}(b;\chi,\mu) = \chi(\mu b K_1(\mu b) - 1)$$

GLV, Phys. Rev. D 66, 014005 (2002)

Recent interest is due to first exciting STAR and ALICE data
Phys.Rev. C96 (2017) and JHEP1509 (2015)

Jet-hadron acoplanarity azimuthal distribution from Chen,Qin,Xiao,Zhang PLB773, 2017
A+A Vacuum Sudakov+ BDMS(Qs) model compared to RHIC and LHC data

State of the “acoplanarity art”

L. Chen et al. / Physics Letters B 773 (2017) 672–676

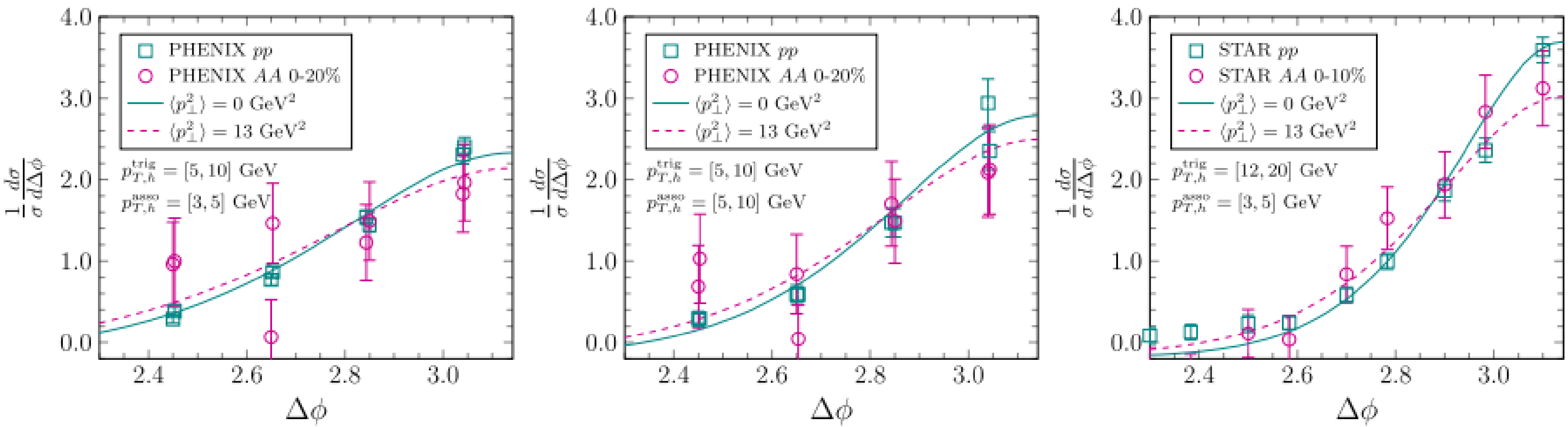


Fig. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.

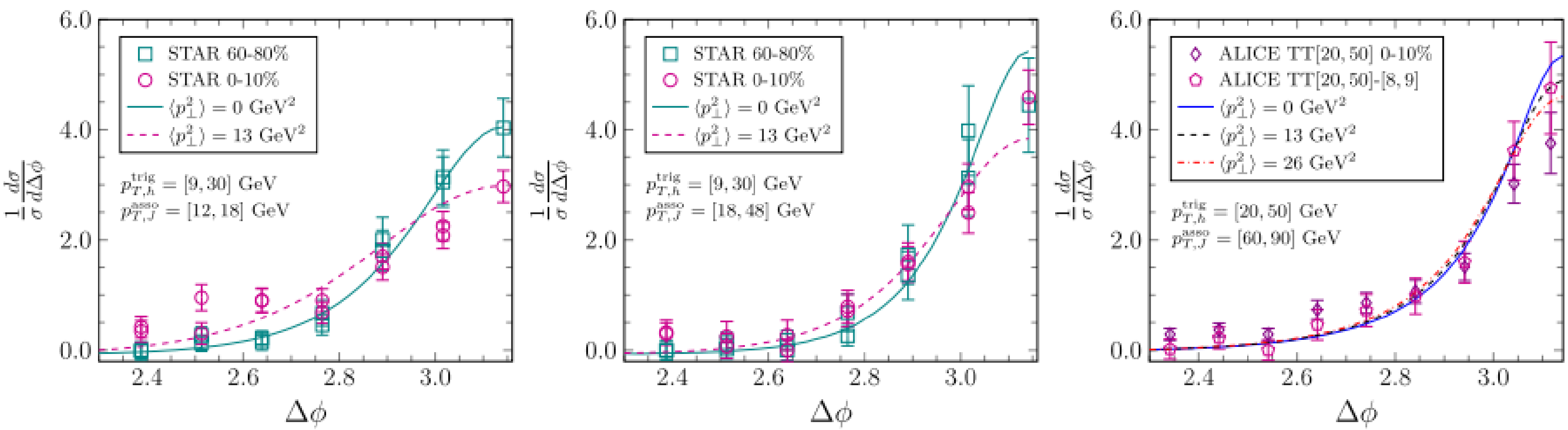


Fig. 2. Normalized hadron-jet angular correlation compared with STAR [53] and the ALICE [54] data. A factor of 3/2 is multiplied to the charged jet energy for our calculation to account for the energy carried by neutral particles. Two sets of ALICE data are shown: TT(trigger track)[20–50] (GeV) represents the signal and TT[20–50] (GeV)–[8–9] (GeV) subtracts the reference to suppress the contribution from the uncorrelated background.

[MG: Current exp precision does not constrain medium opacity better than RAA(pT), but much higher precision data in the future could perhaps test microscopic $n_a(T)$ and $d\sigma_{ab}/dq^2$]

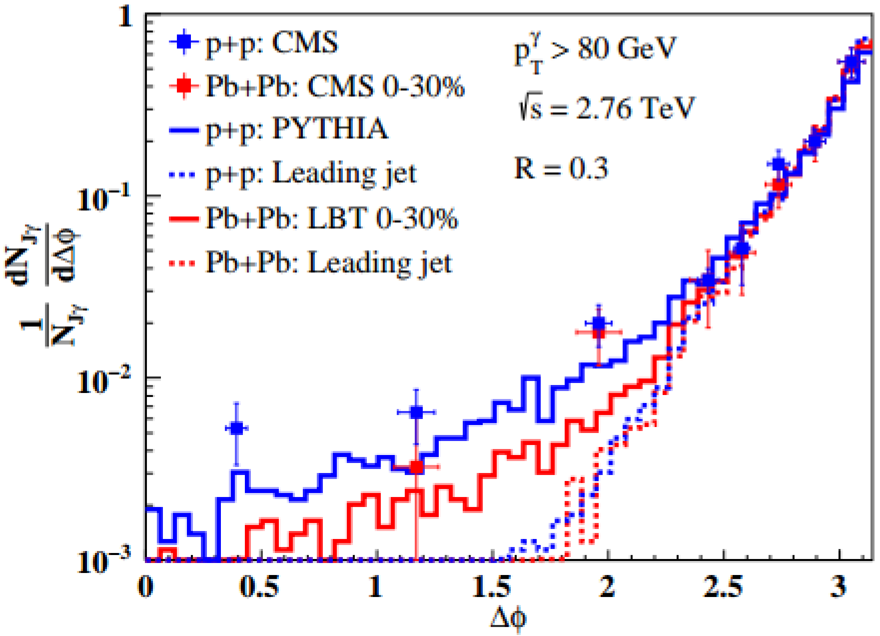


FIG. 6: (Color online) Angular distribution of γ-jet in central (0–30%) Pb+Pb (red) and p+p collisions (blue) at $\sqrt{s} = 2.76$

Multiple jets and γ-jet correlation in high-energy heavy-ion collisions

Luo,Cao,He,Wang CCNU
arXiv:1803.06785 [hep-ph]

High pT>80 GeV Sudakov makes small angle deviations from pi nearly independent

At large angles < 2, there is a predicted Suppression! of gam-jet correlations due to induced minijet suppression complementary to RAA(pT) and sensitive to qhat(E,T).

Exp should focus on the "sweet spot"

$$2.4 < \Delta\phi < \pi$$

To reduce contamination due to multiple minijets unrelated to the dijet acoplanarity

"Dominance of the Sudakov form factor in γ-jet correlation from soft gluon radiation in large pT hard processes pose a challenge for using γ-jet azimuthal correlation to study medium properties via large angle parton-medium interaction."

I reported our first results at Quark Matter 2018

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ScienceDirect

Nucl.Phys. A982 (2019) 627

Nuclear Physics A

www.elsevier.com/locate/procedia

XXVIIth International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
(Quark Matter 2018)

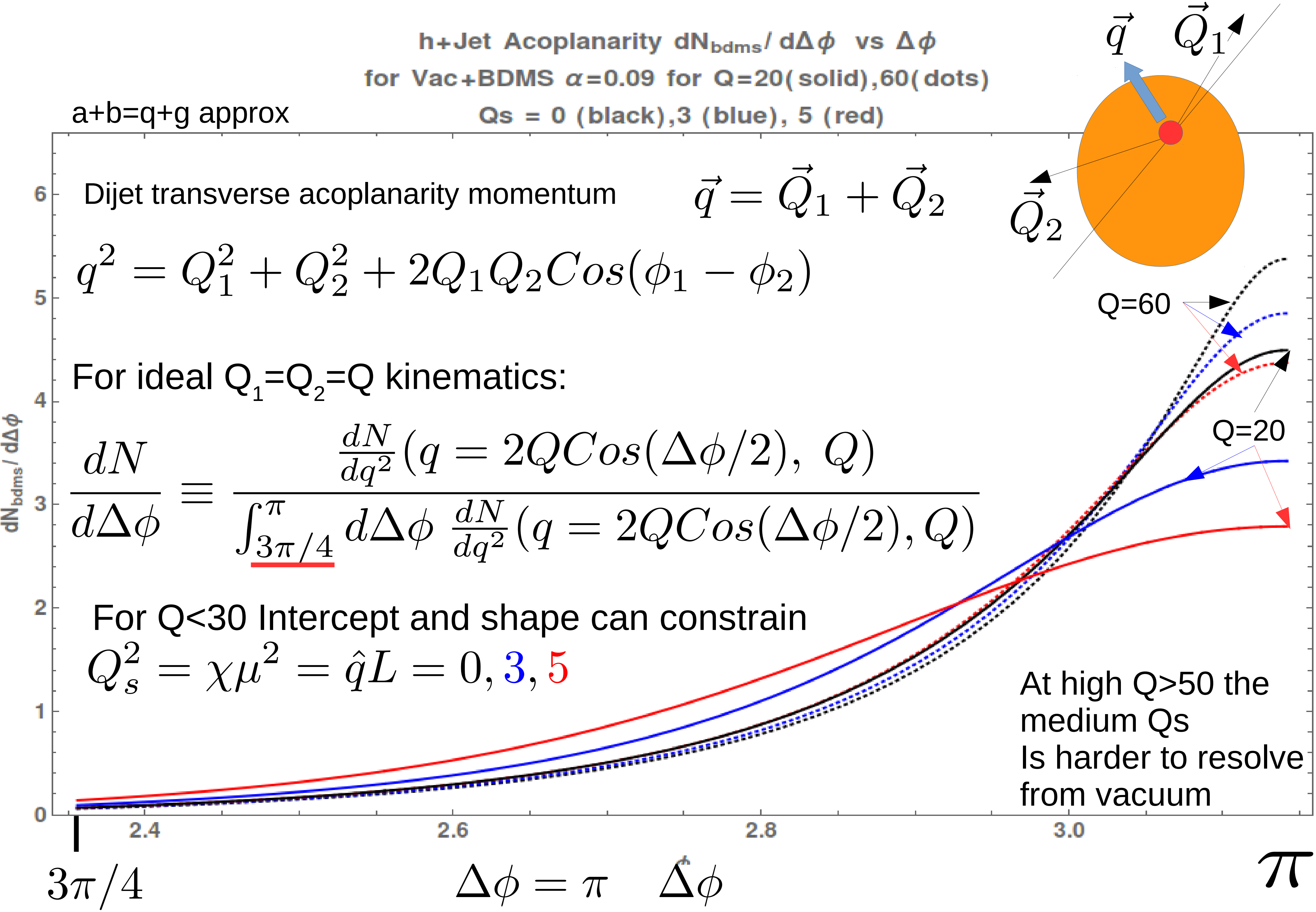
Nucl.Phys. A982 (2019) 627

Precision Dijet Acoplanarity Tomography of the Chromo Structure of Perfect QCD Fluids

M. Gyulassy[a,b,c,d], P. Levai[b], J. Liao[e,d], S. Shi[e], F. Yuan[a], X.N. Wang[a,d]

We concentrated on the problem how accurately would the shape of the acoplanarity
Distribution would have to be measured to resolve the opacity and screening mass from Qs2

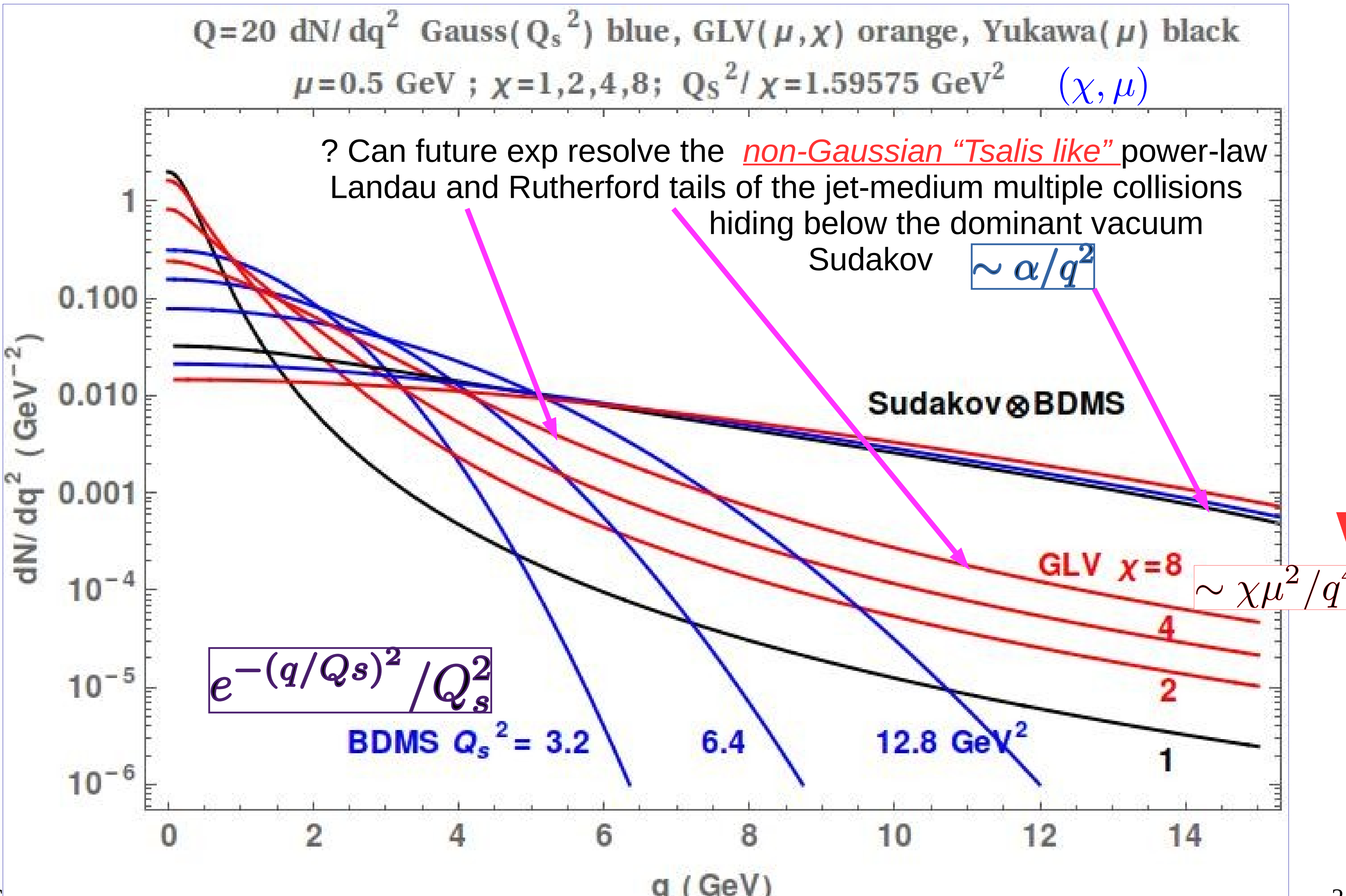
A new paper on " Discriminating Power of Dijet Acoplanarity to Probe the Color Structure
Of Perfect QCD Fluids", is in progress



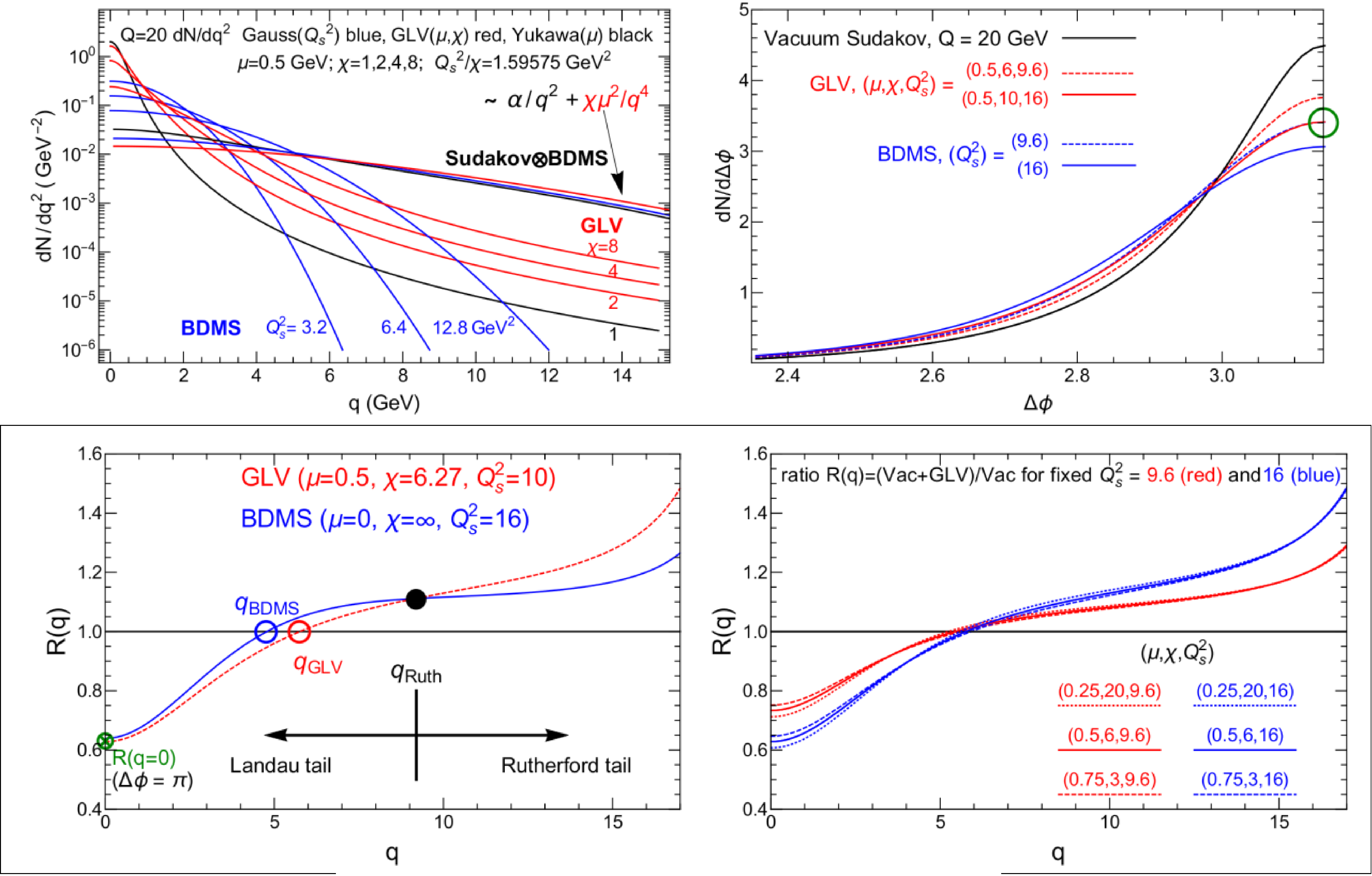
h+Jet Acoplanarity $dN_{bdms}/d\Delta\phi$ vs $\Delta\phi$
for Vac+BDMS α=0.09 for Q=20(solid),60(dots)
Qs = 0 (black),3 (blue), 5 (red)
a+b=q+g approx
Dijet transverse acoplanarity momentum $\vec{q} = \vec{Q}_1 + \vec{Q}_2$
$q^2 = Q_1^2 + Q_2^2 + 2Q_1Q_2Cos(\phi_1 - \phi_2)$
For ideal $Q_1=Q_2=Q$ kinematics:
$$\frac{dN}{d\Delta\phi} \equiv \frac{\frac{dN}{dq^2}(q = 2QCos(\Delta\phi/2),\ Q)}{\int_{3\pi/4}^{\pi} d\Delta\phi\ \frac{dN}{dq^2}(q = 2QCos(\Delta\phi/2), Q)}$$
For Q<30 Intercept and shape can constrain
$Q_s^2 = \chi\mu^2 = \hat{q}L = 0, 3, 5$
At high Q>50 the medium Qs Is harder to resolve from vacuum
Q=60
Q=20
$\vec{q}$
$\vec{Q}_1$
$\vec{Q}_2$
$dN_{bdms}/d\Delta\phi$
0
1
2
3
4
5
6
2.4
2.6
2.8
3.0
$3\pi/4$
$\Delta\phi = \pi - \phi$
π

MG, PLevai, JLiao, SShi, FYuan, XNWang QM2018

10% Percent level precision needed *even to resolve BDMS Qs* from Sudakov $\sim \alpha/q^2$



Need sub 1% ! Acoplanarity shape analysis can help decompose into separate constraints on the mean opacity $\chi =< L/\lambda >$ and mean screening scale $< \mu^2 >$ $\quad Q_s^2(\mu,\chi) = \chi\mu^2 \log(Q^2/\mu^2)$



MG et al ,QM18, Nucl.Phys. A982 (2019) 627

New Results with VISHNU+CUJET3.1 :

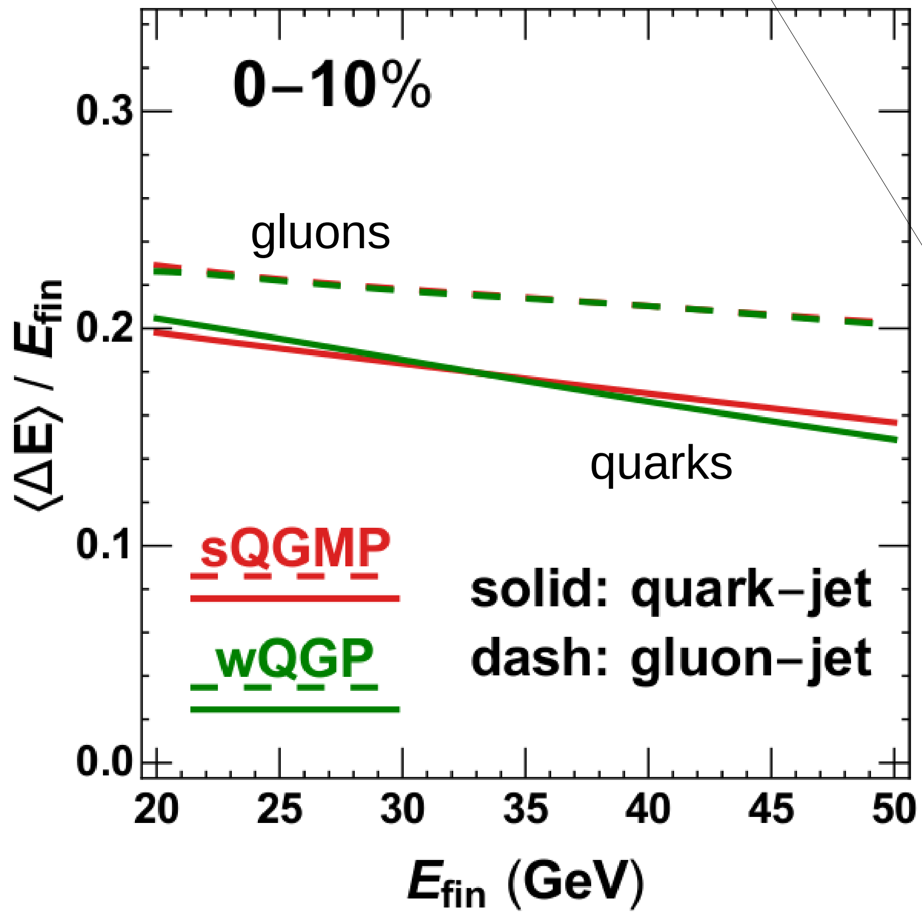
in preparation

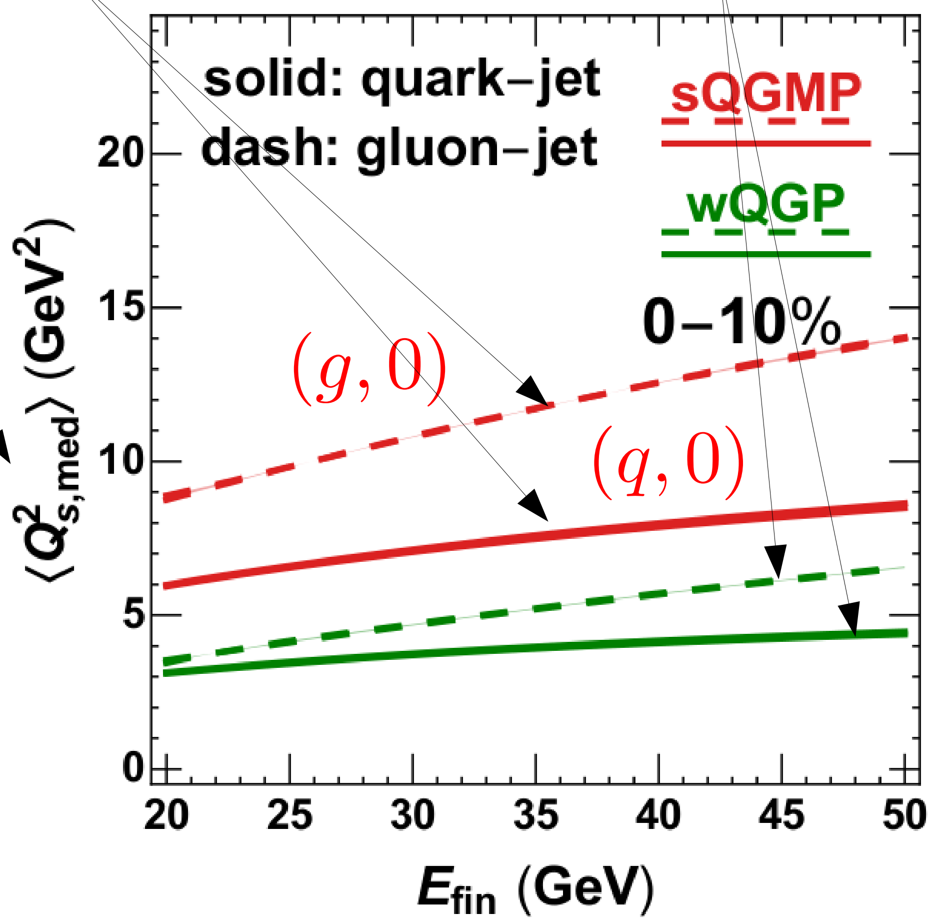
One result is that when parameters ofmodels are fixed to minimize $\chi 2$ fit to all the single jet nuclear modification factor data on RAA(p_T, ϕ ; cent, sqrt s), we find that sQGMP and wQGP Energy Loss fractions are nearly identical

$$\chi^2(\alpha_c, c_m) = \sum_{data} (R_{AA}(theo) - R_{AA}(exp))^2/(\Delta R_{AA}(exp))^2$$

But the surprise is that CUJET3 Then predicts a clear enhancement of sQGMP medium transverse broadening

$$\langle \mathbf{Q_s^2} \rangle_{\mathbf{sQGMP}} \approx \mathbf{2} \times \langle \mathbf{Q_s^2} \rangle_{\mathbf{wQGP}}$$





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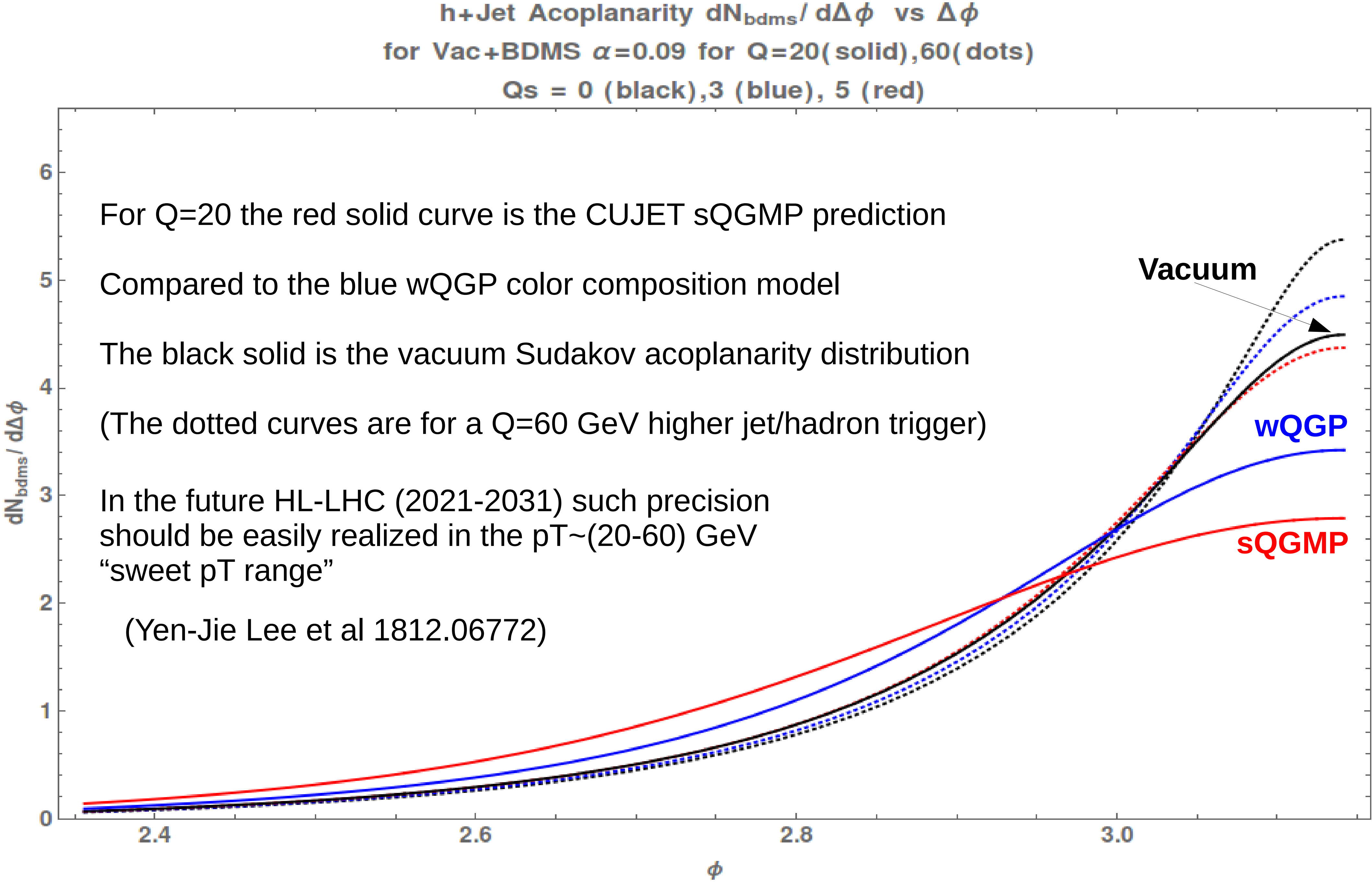
The good news is that with **RAA and v2 constrained Soft+Hard models**, Precision ~ 5-10%
Hadron-Jet Acoplanarity can discriminate between wQGP and sQGMP color structures



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→ Section 3: Conclusions

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Conclusions:

CUJET3.1/CIBJET is one of three current 2+1D ebe visc Hydro X Micoscopic Jet-Fluid frameworks

Consistent with all current RAA and v2 flavor tomography data. However,only CUJET3 / sQGMP $\hat{q}(E \to 3T, T \to T_c)$ is **consistent with perfect fluidity** hydrodynamics for pT<2 !

With global chi^2 min sQGMP parameters $(\alpha_c \approx 0.9 \pm 0.1, c_m \approx 0.25 \pm 0.03)$

CUJET3 predicts that dijet path averaged saturation scale functionals

$$Q_s^2(a) \equiv \langle \mu^2 \chi_a \rangle \equiv \langle \int dt\, t^0\ \hat{q}_a(x(t), t) \rangle$$

differ by a factor of ~2 between sQGMP and wQGP ! This can discriminate between Color structure models when 5-10% precision on dijet acoplanarity can be exp reached.

HL-LHC and sPHENIX are projected to reach level of few percent precisions needed.

Acoplanarity shape analysis requires extreme 0.1% precision to resolve $Q_s^2(a) \equiv \langle \mu_{ab}^2 \chi_a \rangle$ into separate constraints on

opacities $\langle \chi_a \rangle_{b,c,u,g}$ and chromo-E&M screening scales $\langle \mu_{ab}^2 \rangle$

(this my 70 Bday pipe dream for 2029) 

Outline :

Section 1: Overview of sQGMP vs wQGP Models of the Color Structure of perfect QCD fluids and the sQGMP solution of the RAA/vn puzzle

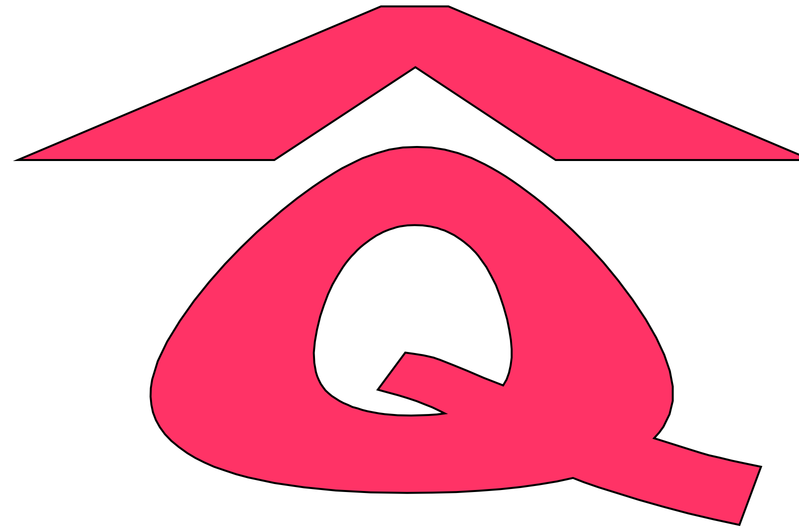
Section 2: Predictions for future high precision Di-Jet Acoplanarity Observable via CUJET3.1

Section 3: Conclusions

➡ Postscript: Old Hat, New Hat, vs Q Hat ? Beware of fairy tales

Beware of Fairy Tales

vs



Most are only half true

A qhat story: Once there was a queen called

$$\hat{q}_a(E,T) = \int dq_\perp^2 \; q_\perp^2 \; \Gamma_a[q_\perp] \equiv \left\langle \frac{q_\perp^2}{\lambda} \right\rangle_a$$

She claimed to have power over transverse broadening and controlled by a functional

$$Q_s^2(a) \equiv \left\langle q_\perp^2 \frac{L}{\lambda} \right\rangle_a \equiv \int dt\, t^0 \; \hat{q}_a(x(t),t) \equiv \int dt d^2q_\perp \; \{t^0 \; q_\perp^2\} \; \Gamma_a(q_\perp,t)$$

She also claimed power over radiative energy loss via another jet path functional

$$\Delta E_s(a) \equiv \frac{1}{4} \left\langle q_\perp^2 \frac{L^2}{\lambda} \right\rangle_a \equiv \frac{1}{2} \int dt\, t^1 \; \hat{q}_a(x(t),t) \equiv \int dt d^2q_\perp \; \{t^1 \; q_\perp^2\} \; \Gamma_a(q_\perp,t)$$

But there was a group of hobbits (CUJET) in her realm who claimed that she had power over only one of the two functionals: namely $Q_s^{2.}$. They claimed that they have the power over Jet quenching and RAA & v2 & Acoplanarity

$$\begin{aligned} x_E \frac{dN}{dx_E} &= \frac{18 C_R}{\pi^2} \frac{4+N_f}{16+9N_f} \int d\tau \; \rho(\mathbf{z}) \Gamma(\mathbf{z}) \int d^2\mathbf{k}_\perp \alpha_s\left(\frac{\mathbf{k}_\perp^2}{x_+(1-x_+)}\right) \\ &\times \int d^2\mathbf{q}_\perp \frac{1}{\mathbf{q}_\perp^2} \left[\frac{\alpha_s^2 \chi_T f_E^2}{\mathbf{q}_\perp^2 + f_E^2 \mu^2(\mathbf{z})} + \frac{(1-\chi_T) f_M^2}{\mathbf{q}_\perp^2 + f_M^2 \mu^2(\mathbf{z})} \right] \\ &\times \frac{-2(\mathbf{k}_\perp - \mathbf{q}_\perp)}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2(\mathbf{z})} \left[\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2 + \chi^2(\mathbf{z})} - \frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2(\mathbf{z})} \right] \\ &\times \left[1 - \cos\left(\frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2(\mathbf{z})}{2x_+ E} \tau \right) \right] \left(\frac{x_E}{x_+} \right) \left| \frac{dx_+}{dx_E} \right| , \end{aligned}$$

Radiative energy loss in CUJET= DGLV generalized to sQGMP

$$\frac{\Delta E_{\rm rad}}{E} = \int x_E \frac{dN}{dx_E} dx_E$$

$$\sum_b \rho_b(T) d^2\sigma_{ab}(T)/d^2 q_\perp$$

$$= \frac{18 C_R}{\pi^2} \frac{4+N_f}{16+9N_f} \int d\tau\, \rho(\mathbf{z})\Gamma(\mathbf{z}) \int d^2\mathbf{q}_\perp \frac{1}{\mathbf{q}_\perp^2} \left[\frac{\alpha_s^2 \chi_T f_E^2}{\mathbf{q}_\perp^2 + f_E^2 \mu^2(\mathbf{z})} + \frac{(1-\chi_T) f_M^2}{\mathbf{q}_\perp^2 + f_M^2 \mu^2(\mathbf{z})} \right]$$

$$\times \int_0^1 dx_+ \int d^2\mathbf{k}_\perp \alpha_s\left(\frac{\mathbf{k}_\perp^2}{x_+(1-x_+)}\right) \left[1 - \cos\left(\frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2(\mathbf{z})}{2 x_+ E} \tau \right) \right] \left(1 + \frac{\mathbf{k}_\perp^2}{4 x_+^2 E^2} \right)$$

$$\times \frac{-2(\mathbf{k}_\perp - \mathbf{q}_\perp)}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2(\mathbf{z})} \left[\frac{\mathbf{k}_\perp}{\mathbf{k}_\perp^2 + \chi^2(\mathbf{z})} - \frac{(\mathbf{k}_\perp - \mathbf{q}_\perp)}{(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + \chi^2(\mathbf{z})} \right]$$

n=0,1 Interference
“Antenna”

In order to try to derive the qhat approximation from above we must expand the 2nd *and* 3rd lines in powers of $\mathbf{q}_\perp$ **and retain only the quadratic $\mathbf{q}_\perp^2$ term !! All higher moments DIVERGE !!!**

$$\approx \frac{24}{\pi^2} \frac{4+N_f}{16+9N_f} \int d\tau\, \hat{q}(E,T)$$

$$\times \left\{ \int_0^1 dx_+ \int d^2\mathbf{k}_\perp \alpha_s\left(\frac{\mathbf{k}_\perp^2}{x_+(1-x_+)}\right) \left[1 - \cos\left(\frac{\mathbf{k}_\perp^2 + \chi^2(\mathbf{z})}{2 x_+ E} \tau \right) \right] \left(1 + \frac{\mathbf{k}_\perp^2}{4 x_+^2 E^2} \right) \frac{2(\mathbf{k}_\perp^2 - \chi^2(\mathbf{z}))^2}{(\mathbf{k}_\perp^2 + \chi^2(\mathbf{z}))^4} \right.$$

$$\left. + \int_0^1 dx_+ \int d^2\mathbf{k}_\perp \alpha_s\left(\frac{\mathbf{k}_\perp^2}{x_+(1-x_+)}\right) \left[\sin\left(\frac{\mathbf{k}_\perp^2 + \chi^2(\mathbf{z})}{2 x_+ E} \tau \right) \frac{\mathbf{k}_\perp^2 \tau}{x_+ E} \right] \left(1 + \frac{\mathbf{k}_\perp^2}{4 x_+^2 E^2} \right) \frac{\mathbf{k}_\perp^2 - \chi^2(\mathbf{z})}{(\mathbf{k}_\perp^2 + \chi^2(\mathbf{z}))^3} \right\}$$

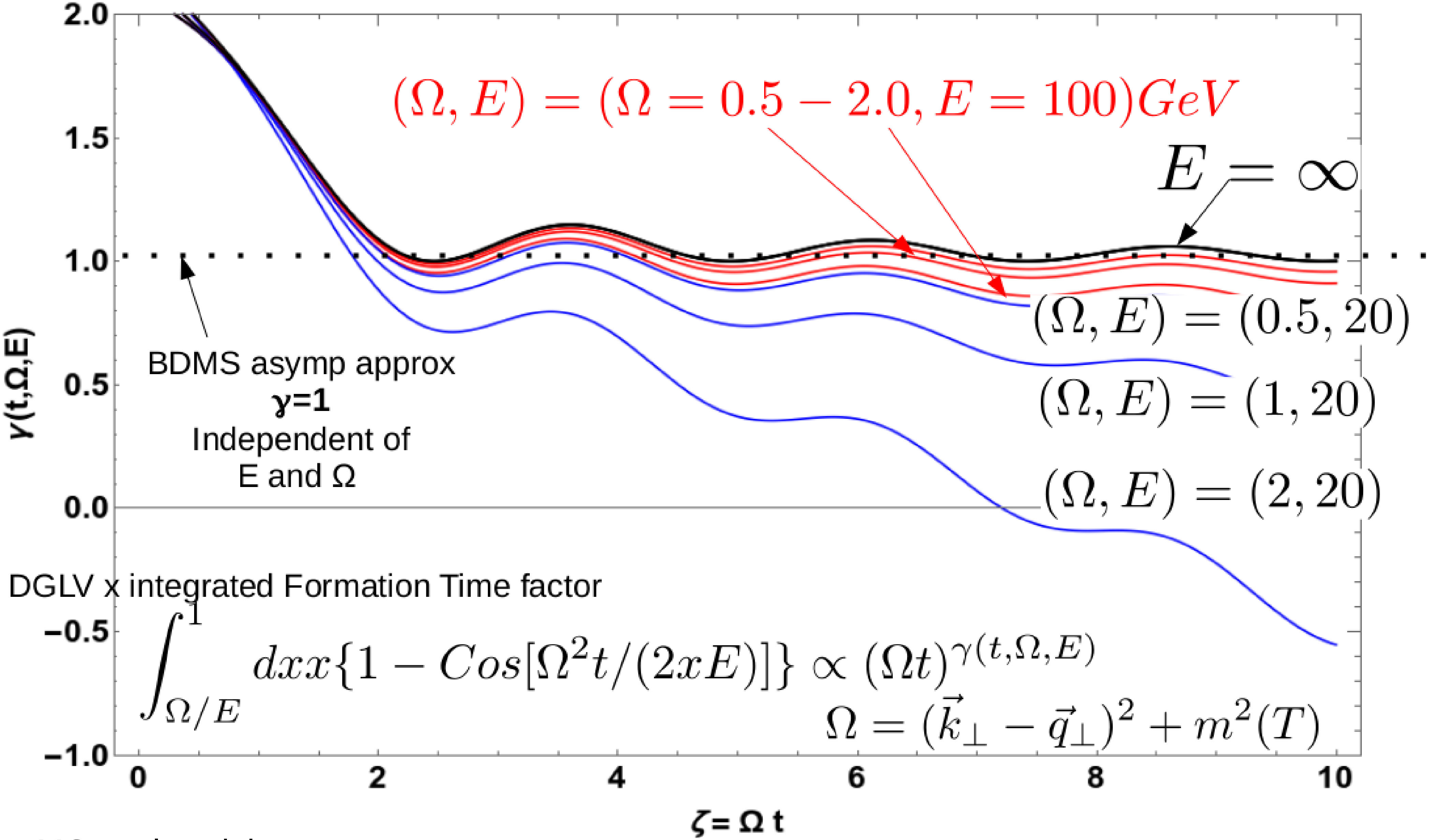
We found that the integrals of 2nd *and* 3rd lines of this unstable asymptotic series behave approximately linearly in path time only in the formal $E \to \infty$ limit ! For E<100 GeV and T<400 MeV CUJET energy loss cannot be reduced to BDMS form

$$\Delta E_s(CUJET) \neq \Delta E_s(BDMS) \propto \int dt\, t^1\, \hat{q}_a(x(t),t)$$

GLV $\gamma(t,\Omega,E) = d\text{Log}\left(\int_{\Omega/E}^{1} dx\, x\, F\right)/d\text{Log}(\Omega\, t)$ = x integrated Formation time index vs $\zeta = \Omega t$

Cases shown are Ω = 0.5, 1, 2 GeV (highest, mid, lowest)

and E=20, 100, Infty (blue, red, black)



MG et al work in progress

Our analysis calls into question the leading q=0 approximation in HT model

Physics Letters B 782 (2018) 707–716

CCNU Wuham Qhat Model

HE, CAO, CHEN, LUO, PANG, AND WANG PHYSICAL REVIEW C **99**, 054911

In the above linear Boltzmann transport equation, the inelastic processes include only induced gluon radiation accompanying elastic scattering in the current version of LBT. The radiative gluon spectrum is simulated according to the high-twist approach [63–66],

$$\frac{dN_g^a}{dz dk_\perp^2 d\tau} = \frac{6\alpha_s P_a(z) k_\perp^4}{\pi (k_\perp^2 + z^2 m^2)^4} \frac{p \cdot u}{p_0} \hat{q}_a(x) \sin^2 \frac{\tau - \tau_i}{2\tau_f}, \tag{3}$$

where m is the mass of the propagating parton a, z and $k_\perp$ are the energy fraction and transverse momentum of the radiated gluon, $P_a(z)$ the splitting function, $\tau_f = 2p_0 z(1-z)/(k_\perp^2 + z^2 m^2)$ the gluon formation time and τ_i is the time of the last gluon emission. The jet transport parameter,

$$\hat{q}_a(x) = \sum_{bcd} \rho_b(x) \int d\hat{t} q_\perp^2 \frac{d\sigma_{ab\to cd}}{d\hat{t}}, \tag{4}$$

is defined as the transverse momentum transfer squared per mean-free-path in the local comoving frame, where $\rho_b(x)$ is the parton density (including the degeneracy). The Debye screen mass μ_D is used as an infrared cut-off for the energy of the radiated gluons.

Extra Slides

Key references on which this work was built

A. H. Mueller, B. Wu, B. W. Xiao and F. Yuan,
Probing Transverse Momentum Broadening in Heavy Ion Collisions
Phys. Lett. B 763, 208 (2016)

Probing Transverse Momentum Broadening via Dihadron and Hadron-jet Angular Correlations in Relativistic Heavy-ion Collisions
Phys. Rev. D 95, 034007 (2017)

L. Chen, G. Y. Qin, S. Y. Wei, B. W. Xiao and H. Z. Zhang,
Probing Transverse Momentum Broadening via Dihadron and Hadron-jet Angular Correlations in Relativistic Heavy-ion Collisions
Phys. Lett. B 773, 672 (2017) [arXiv:1607.01932 [hep-ph]]

ALICE Collaboration: Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb-Pb collisions at sNN = √2.76 TeV, JHEP1509 (2015)

STAR Collaboration: easurements of jet quenching with semi-inclusive hadron+jet distributions in Au+Au collisions at sNN=√ 200 GeV , Phys.Rev. C96 (2017)

Physics Motivation:

Lattice QCD predicts the Equation of State P(T), S(T)=dP/dT, E(T)=TS-P of QCD fluids and it has revealed the **gradual "*bleaching*" of color electric quark+gluon d.o.f.** in the broad crossover temperature range T~(1-2)Tc ~ 160 -300 MeV as measured by the **Polyakov Loop** and the **Light Quark Susceptibility**

$$L(T) \propto \langle tr\mathcal{P} \exp\{ig \int_0^{1/T} A_0 d\tau\}\rangle \qquad \chi_2^u = \frac{\partial^2 (P/T^4)}{\partial(\mu_u/T)^2}$$

The ***semi*-QGP** (Hidaka-Piszarski) model of color electric bleaching near Tc is described by

$$\chi_T = \frac{\rho_e}{\rho_{tot}} = \frac{\rho_q + \rho_g}{\rho_q + \rho_g + \rho_m} = \begin{cases} \chi_T^u = c_q \chi_2^u + c_g L^2 & \text{Fast Liberation} \\ \chi_T^L = c_q L + c_g L^2 & \text{Slow Liberation} \end{cases}$$

Where the **missing "m" density** is fixed by a constituent relation of ρ_{tot} to QCD/EOS P or S

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

The RAA-v2 (pT>10 GeV) puzzle challenged perturbative dEdx models of jet dEdx. and has been "solved" in various ways in 3 consistent Soft-Hard frameworks to date

Most provocative interpretation by J.Liao&E.Shuryak 2007 was to interpret ρ_m as the density of **emergent color magnetic monopoles** near Tc leading to **"volcano scenario"** for dEdx

Can A+A data reveal the color structure dof and hence the mechanism of QCD confinement??

QCD Color Confinement remains the fundamental unsolved problem since 1973!

CUJET3.0

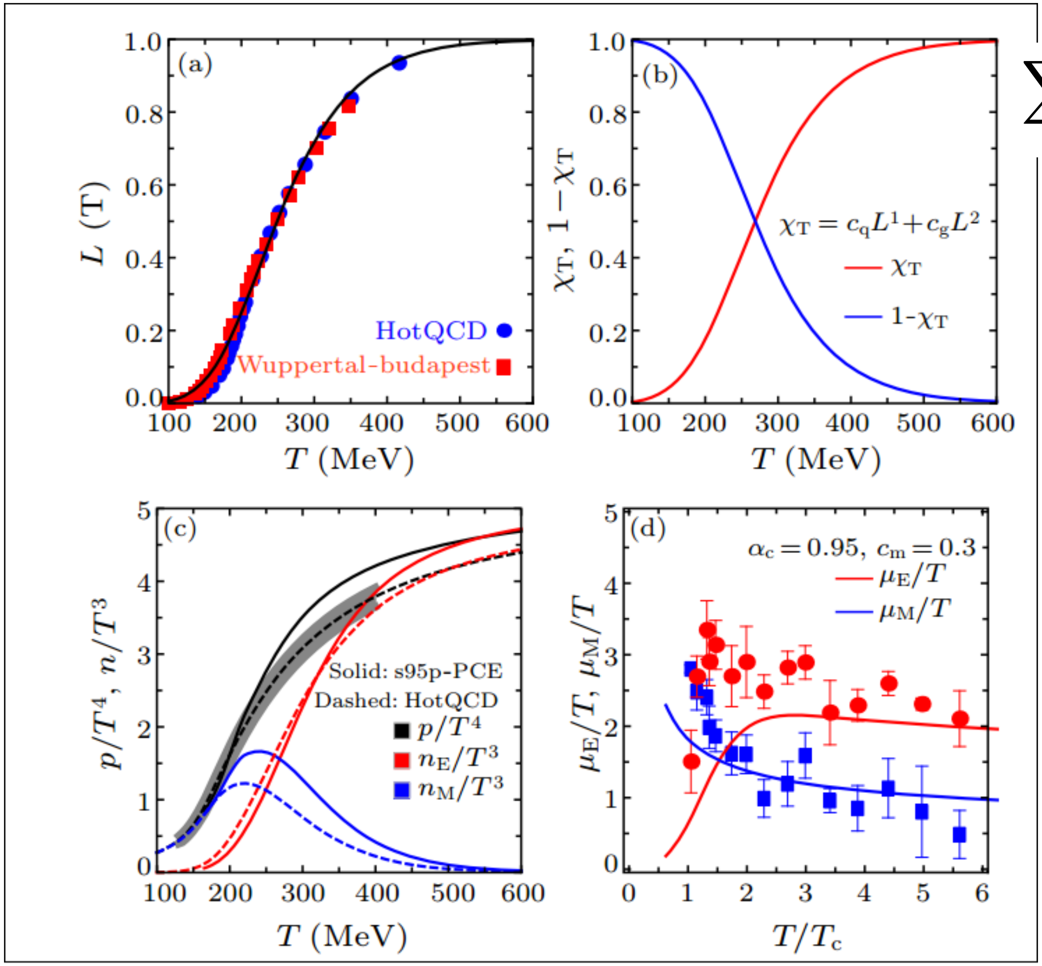
CHIN. PHYS. LETT. Vol. 32, No. 9 (2015) 092501 Letter

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

Jiechen Xu 徐杰谌)[1], Jinfeng Liao(廖劲峰)[2,3]**, Miklos Gyulassy[1]**

CUJET3.0

Lattice QCD data constraints in CUJET3



sQGMP generalization of wQGP DGLV kernel

$$\sum_b \rho_b \frac{d\sigma_{ab}}{dq^2} \propto \left[\frac{n_e(\alpha_s(q^2)\alpha_s(q^2))f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m(\alpha^e(q^2)\alpha^m(q^2))f_M^2}{q^2(q^2+f_M^2\mu^2)}\right]$$

$$f_E^2 = \chi_T = \rho_e/\rho \qquad f_M = c_m g(T)$$

The jet transport coefficient is defined as

$$\hat{q}_a(E,T) = \int dq^2\, q^2 \sum_b \rho_b \frac{d\sigma_{ab}}{dq^2}$$

Path integrals over qhat control the transverse deflection of jets as well as elastic and radiative jet energy loss

$$Q_s^2(a) \equiv \langle \mu^2 \chi_a \rangle \equiv \langle \int dt\, \hat{q}_a(\vec{x}_a(t),t) \rangle$$

$$\Delta\phi_{ab} \approx (Q_s^2(a) + Q_s^2(b))/Q_0^2$$

CUJET3.0

CHIN. PHYS. LETT. Vol. 32, No. 9 (2015) 092501

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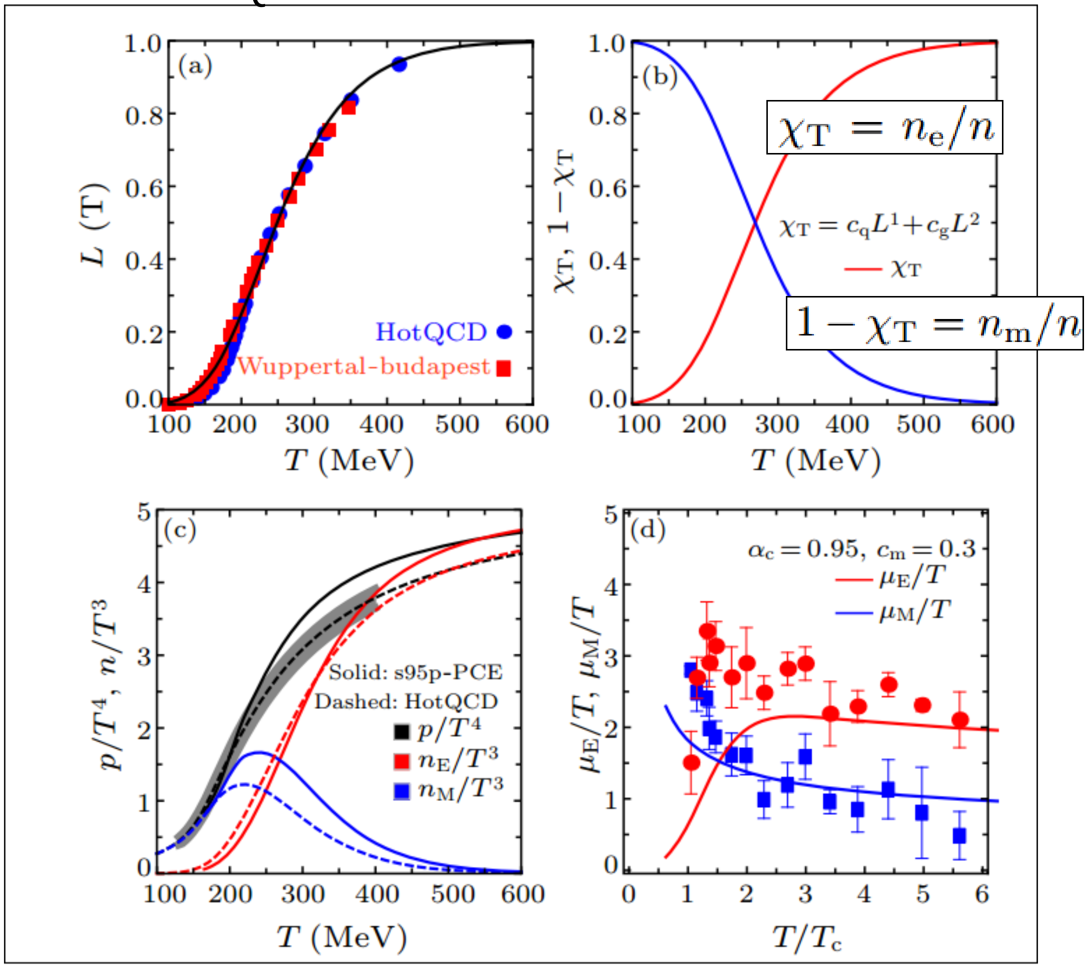
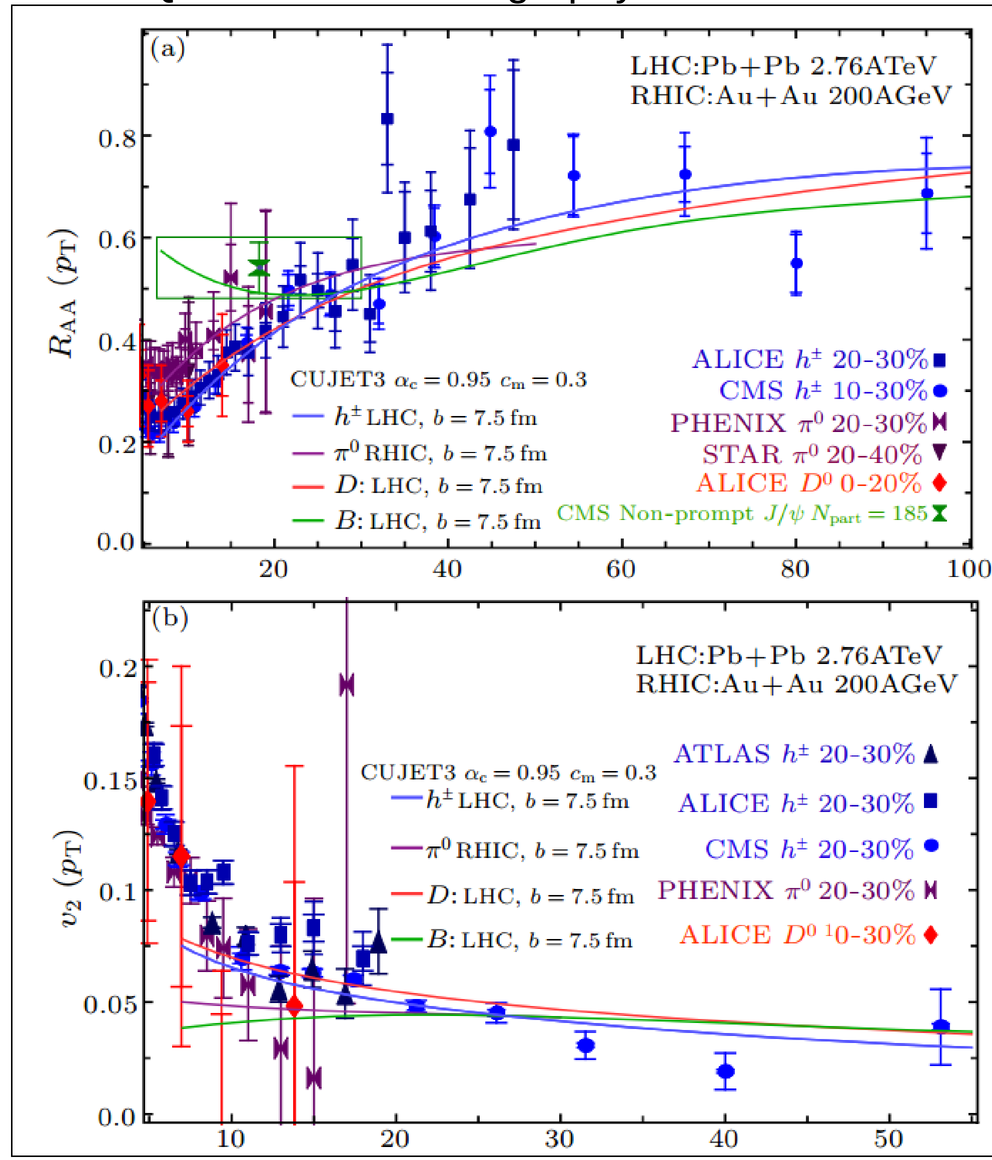
CUJET3.0

Lattice QCD data included in CUJET3.0



Quark Flavor Tomography at RHIC&LHC



sQGMP generalization of wQGP DGLV kernel

$$\sum_b \rho_b \frac{d\sigma_{ab}}{dq^2} \propto \left[\frac{n_e(\alpha_s(q^2)\alpha_s(q^2))f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m(\alpha^e(q^2)\alpha^m(q^2))f_M^2}{q^2(q^2+f_M^2\mu^2)}\right]$$

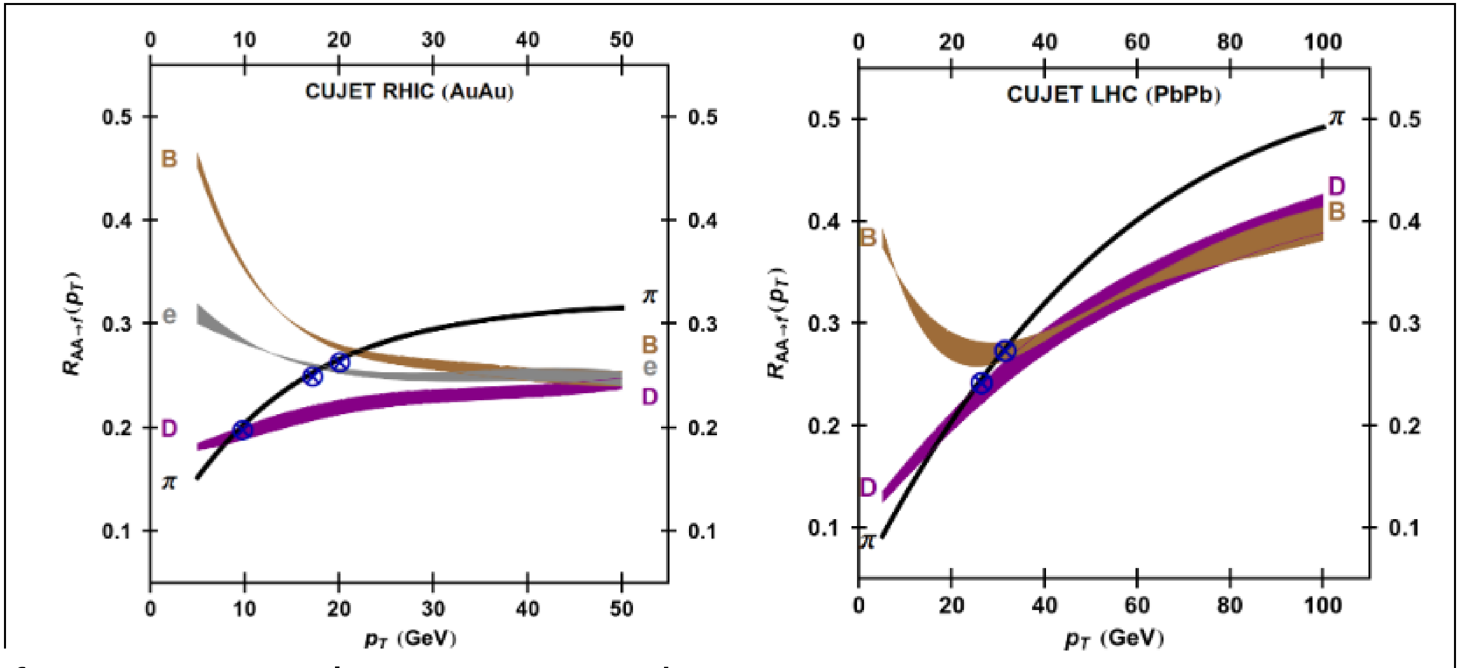
$$f_E^2 = \chi_T = \rho_e/\rho \qquad f_M = c_m g(T)$$

! Future HL-LHC needed esp. for B vs D !

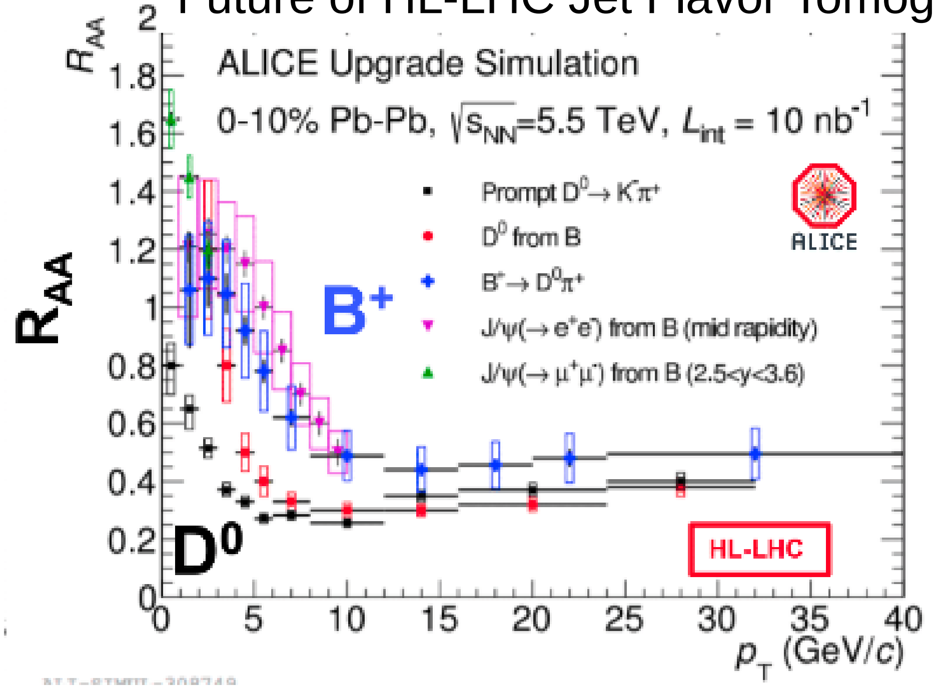
(see Shuzhe Shi talk & 1808.05461) (see Yen-Jie Lee talk & 1812.06772)

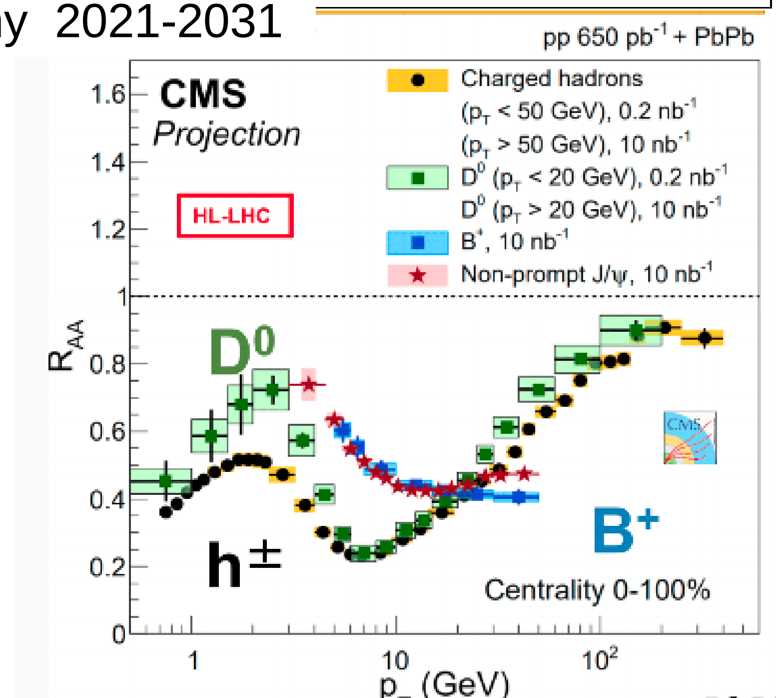
DGLV Jet Flavor Tomography CUJET1: A.Buzzatti, MG, PRL108(2012)

Predicted
RAA level
Crossing
“fine structure”



Future of HL-LHC Jet Flavor Tomography 2021-2031





CUJET3 tested 4 models of sQGMP compatible with Lattice QCD thermo, L, χ^u, μ_E,μ_M
and compared to HTL wQGP color composition by setting $\rho_q = \rho_q^{SB}, \rho_g = \rho_g^{SB}$, and $\rho_m = 0$!

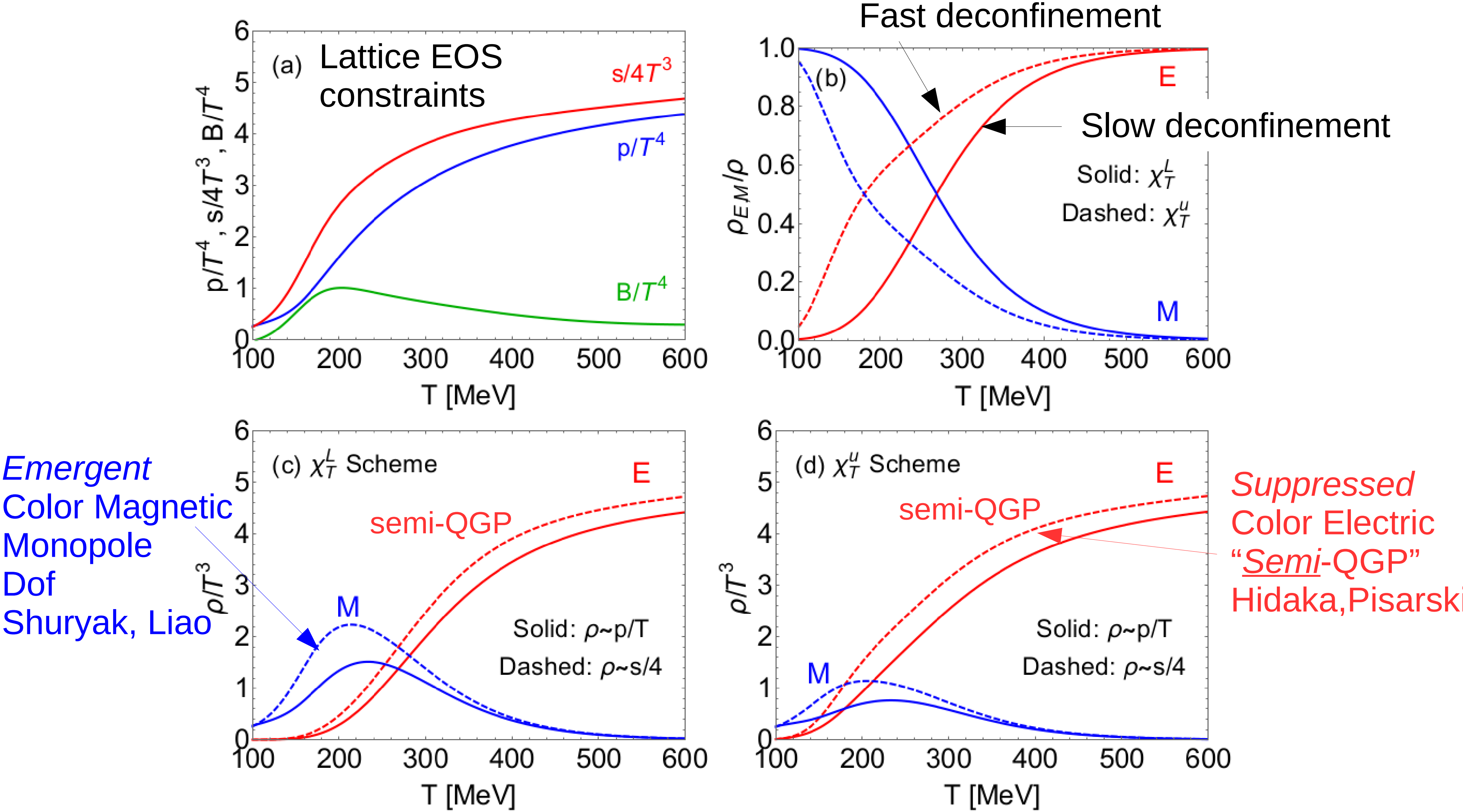


Figure 6. (Color online) (a) The effective ideal quasiparticle density, $\rho/T^3 = \xi_p P/T^4$, in the Pressure Scheme (PS, Blue) is compared with effective density, $\rho/T^3 = \xi_p S/4T^3$, in the Entropy Scheme (ES, Red) based on fits to lattice data from HotQCD Collaboration [56]. The difference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

(See also Zakharov:1412.6287; Ramamurti, Shuryak, Zahed, arXiv:1802.10509)