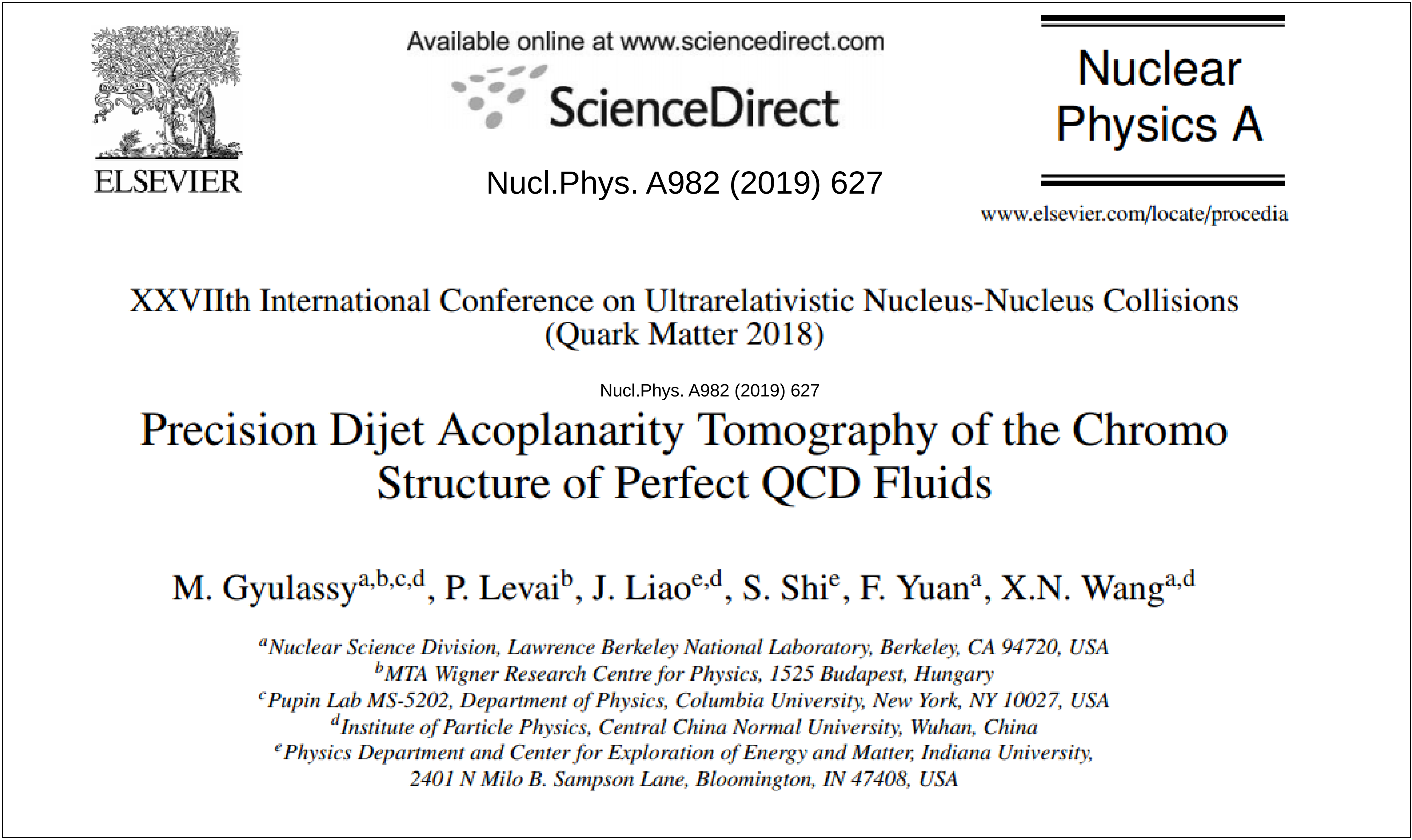
Probing the Color Structure of QCD Perfect Fluids via Jet Quenching Observables at RHIC&LHC

M. Gyulassy
Knoxville 3/19/19

Zhangjiajie

This talk has a more optimistic conclusion on Acoplanarity than my QM18 talk



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Nuclear Physics A

Nucl.Phys. A982 (2019) 627

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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

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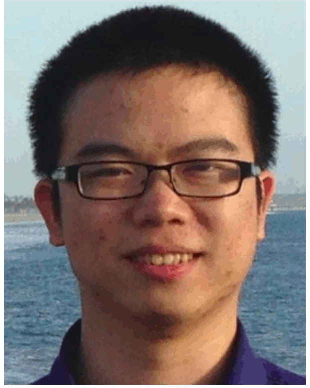
Due to new results from **Shuzhe Shi** using the CUJET3.1 framework that greatly enhances the promise of future ~ 5% precision acoplanarity (beyond my somber QM18 prognosis)

This talk owes special thanks to exceptionally talented collaborators

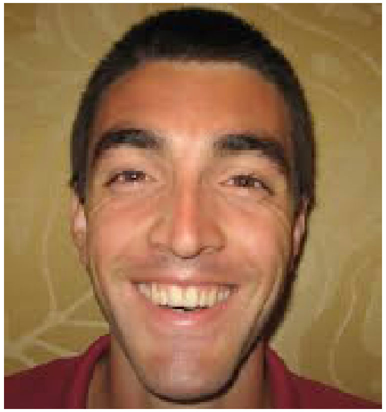

Shuzhe Shi

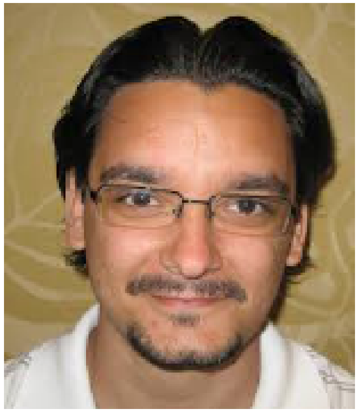

Jinfeng Liao


Jorge Noronha


Jaki Noronha-Hostler


Jiechen Xu


Alessandro Buzzatti


Andrej Ficnar


Barbara Betz

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

My interest in acoplanarity was motivated by Peter Jacob's question after my at INT 2017 talk on

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

Jiechen Xu , J.Liao, MG, Chin.Phys.Lett. 32 (2015) and JHEP 1602 (2016) 169
Shuzhe Shi, J.Xu, J.Liao, MG, Nucl.Phys. A967 (2017) 648
Shuzhe Shi, J.Liao, MG: Chin.Phys. C 42 (2018) 104104,

Global χ2 RHIC and LHC Data Constraints on Soft-Hard Transport Properties of sQGMP
[via CIBJET= EbE-VISHNU+CUJET3.1 , arXiv:1808.05461 [hep-ph] , in press CPC]

Peter Jacob's question (my paraphrase) :

Can **future** *high precision* dijet acoplanarity measurements help to falsify **sQGMP** and **wQGP** models of the color structure of QCD perfect fluids?

Can acoplanarity observables help to constrain information on the dominant color d.o.f in near perfect QCD fluids and their microscopic differential scattering rates, Γ_{ab} , near T ~ T_c ?

$$\boxed{\Gamma_{ab}(q_\perp, T) = \rho_b(T) d^2\sigma_{ab}(T)/d^2q_\perp}$$

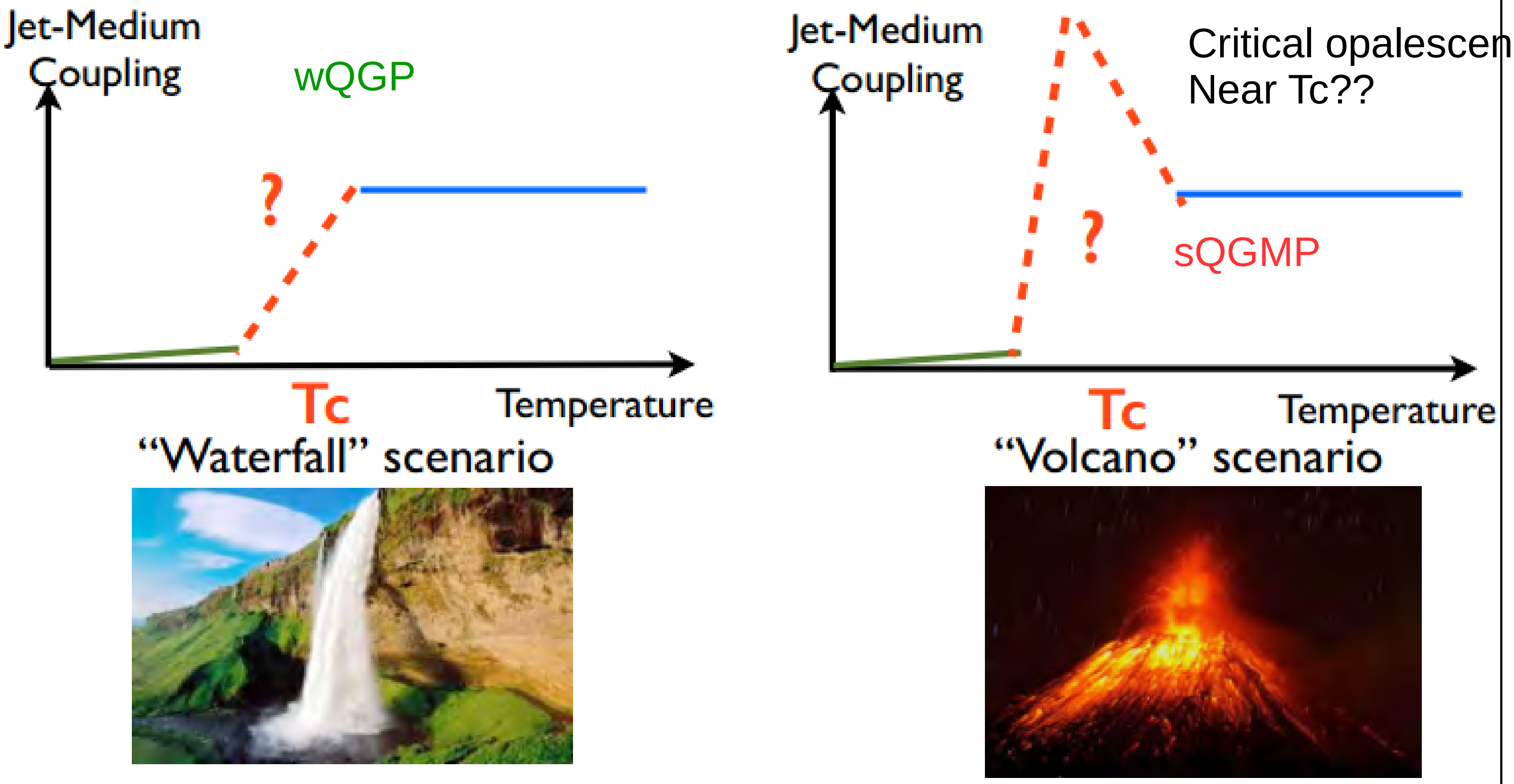
Do any Γ_{ab} lead to critical opalescence near Tc that could account for ~perfect fluidity?

Mag.Monopoles in QGMP near Tc
can account for near perfect fluidity

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

Ed Shuryak
Jinfeng Liao

From “Transparency” to Opaqueness



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

J.Liao 2015

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

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)

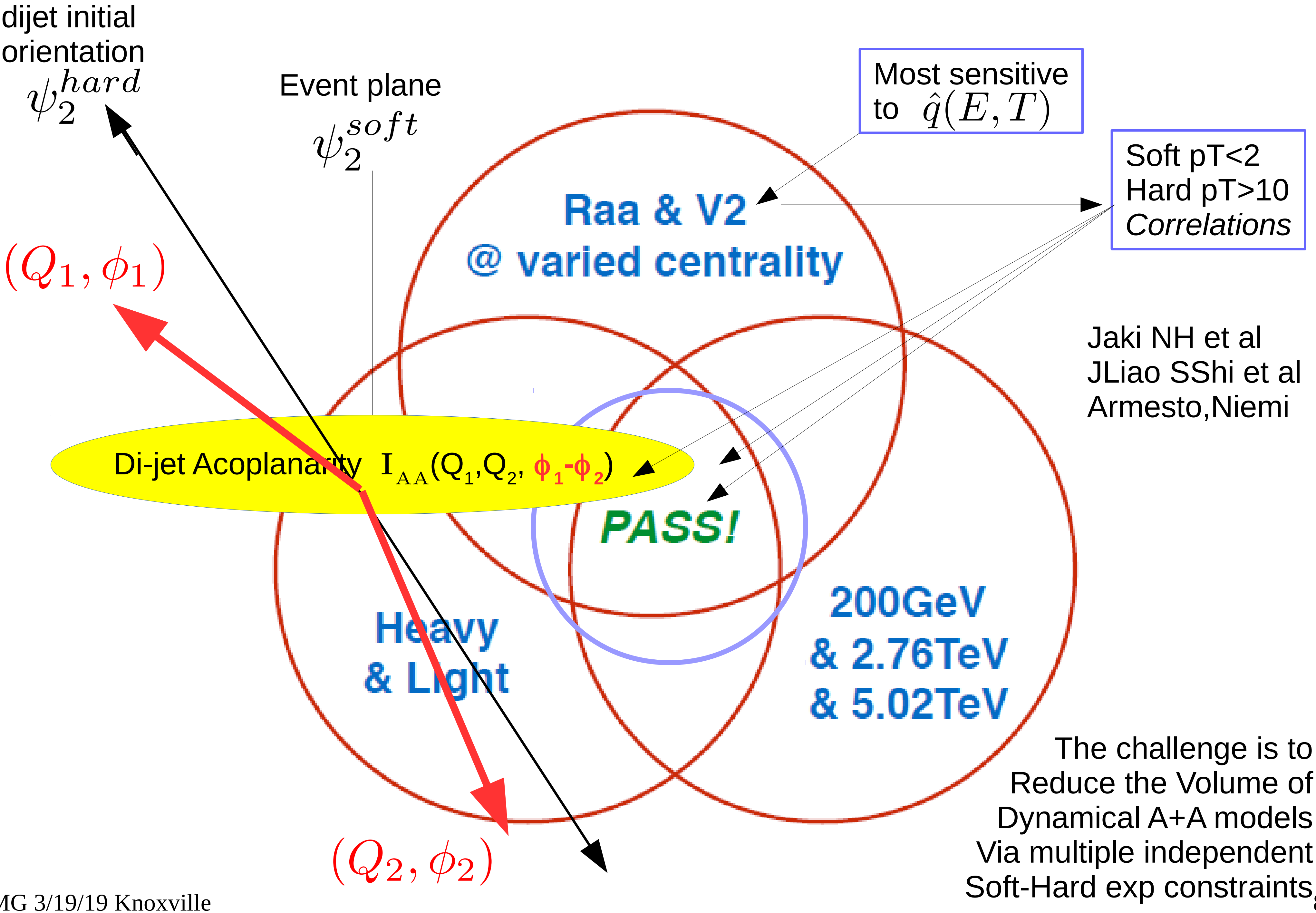
STAR Collaboration: easurements of jet quenching with semi-inclusive hadron+jet distributions in Au+Au collisions at sNN=√ 200 GeV , Phys.Rev. C96 (2017)

Outline :

Section 1: Intro and Conclusions

Section 2: Some more details of the calculation

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



dijet initial orientation ψ_2^{hard}

Event plane ψ_2^{soft}

(Q_1, ϕ_1)

(Q_2, ϕ_2)

Most sensitive to $\hat{q}(E,T)$

Soft pT<2
Hard pT>10
Correlations

Raa & V2
@ varied centrality

Di-jet Acoplanarity $I_{AA}(Q_1, Q_2, \phi_1 - \phi_2)$

PASS!

Heavy
& Light

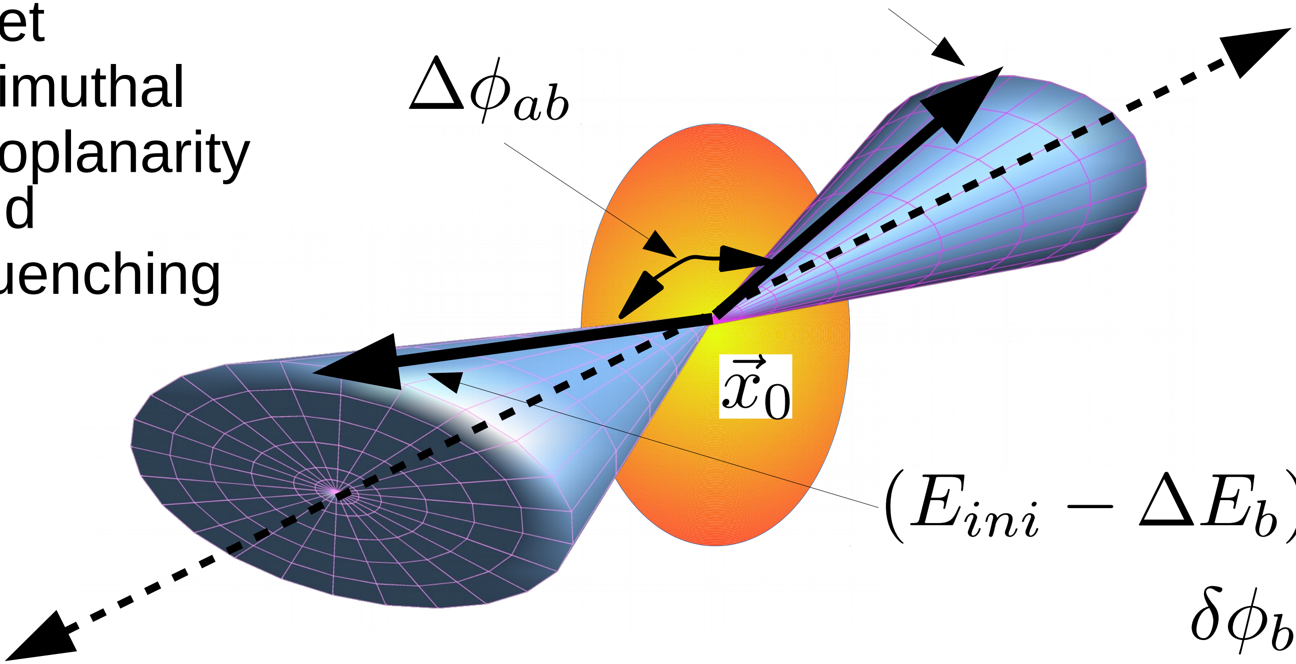
200GeV
& 2.76TeV
& 5.02TeV

Jaki NH et al
JLiao SShi et al
Armesto,Niemi

The challenge is to
Reduce the Volume of
Dynamical A+A models
Via multiple independent
Soft-Hard exp constraints

? 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



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

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

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

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

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

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

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

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

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

(see also Mike Tannenbaum, Thu 9am)

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)

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

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

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]

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

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

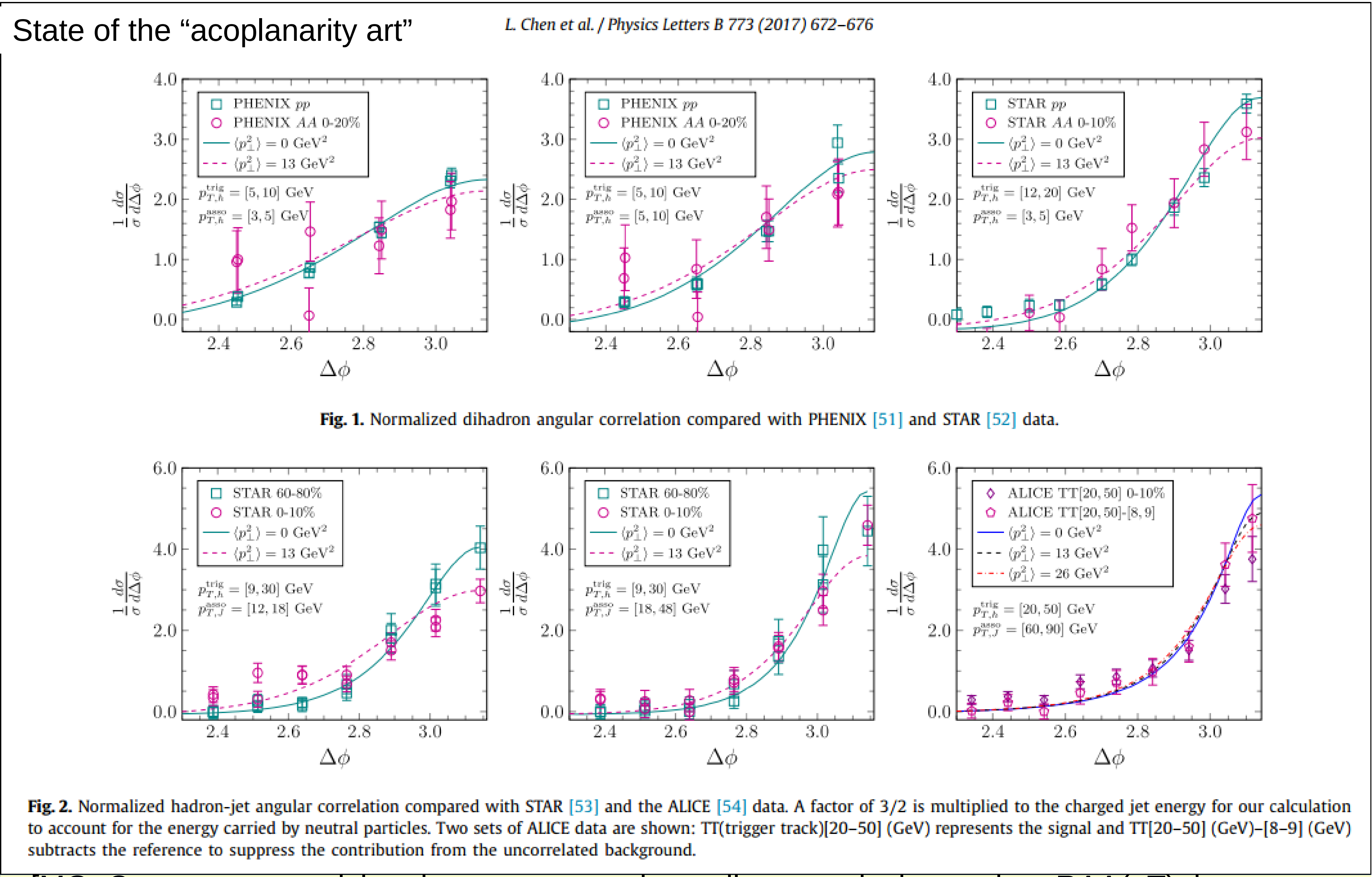
$$S_{GLV}(b;\chi,\mu) = \chi(\mu bK_1(\mu b) - 1)$$

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

Renewed interest today 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”

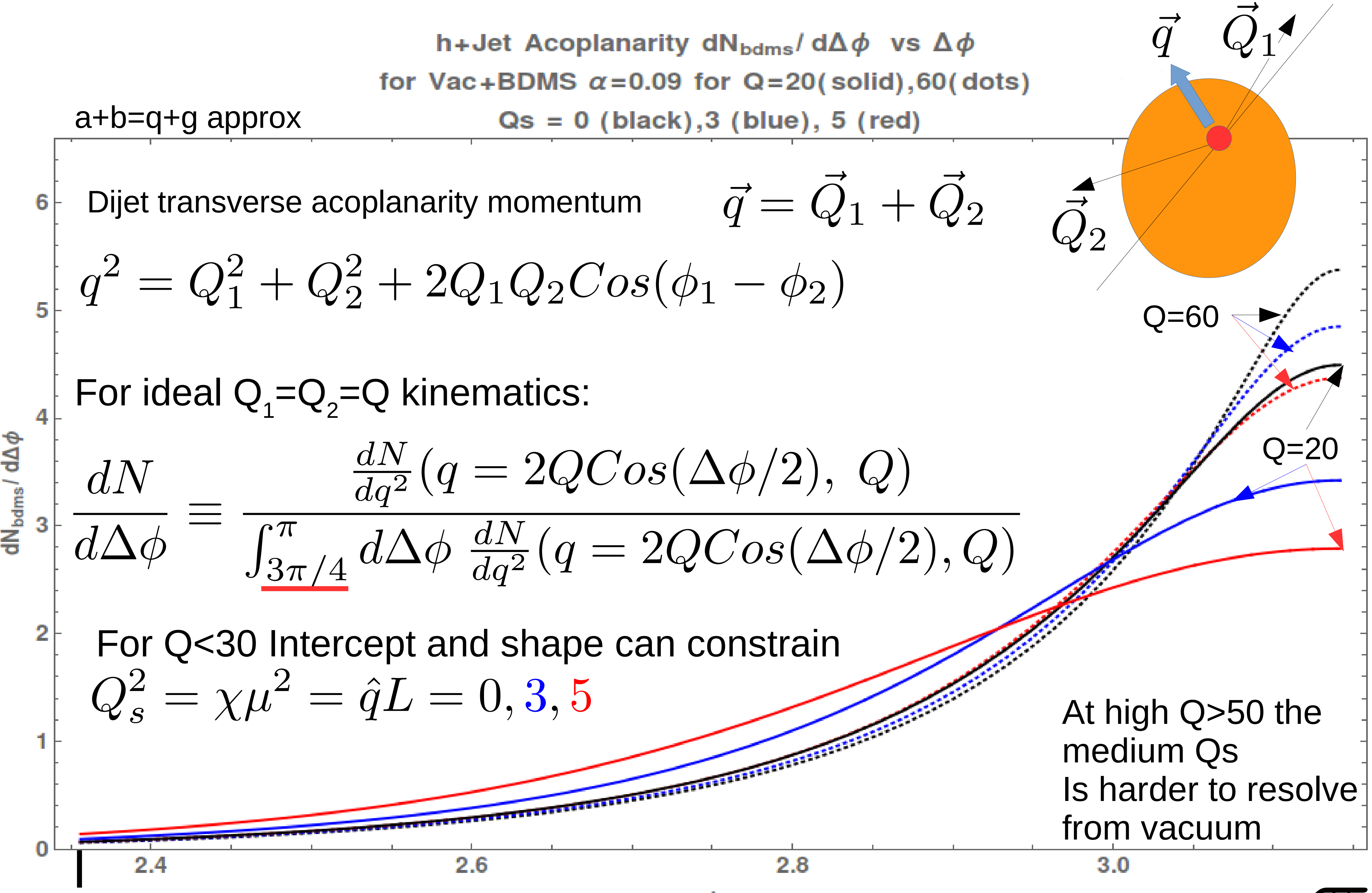


L. Chen et al. / Physics Letters B 773 (2017) 672–676

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 $d\sigma_{ab}/dq^2$]



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:

$$\frac{dN}{d\Delta\phi} \equiv \frac{\frac{dN}{dq^2}(q = 2QCos(\Delta\phi/2),\ Q)}{\int_{\underline{3\pi/4}}^{\pi} d\Delta\phi\ \frac{dN}{dq^2}(q = 2QCos(\Delta\phi/2), Q)}$$

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

$3\pi/4$

$$\Delta\phi = \pi \quad \hat{\Delta}\phi$$

π

Physics Motivation:

Lattice QCD predicts the Equation of State P(T), S(T)=dP/dT, E(T)=TS-P of QCD fluids and it revealed the gradual “bleaching” of color electric quark+gluon components for T in the broad crossover temperature range T~(1-2)Tc ~ 160 -300 MeV as measured by the Polyakov Loop and the light quark susceptibility

$$\boxed{L(T) \propto \langle tr\mathcal{P}\exp\{ig\int_0^{1/T} A_0 d\tau\}\rangle}$$

$$\chi_2^u = \frac{\partial^2(P/T^4)}{\partial(\mu_u/T)^2}$$

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

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

Fast Liberation

Slow Liberation

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

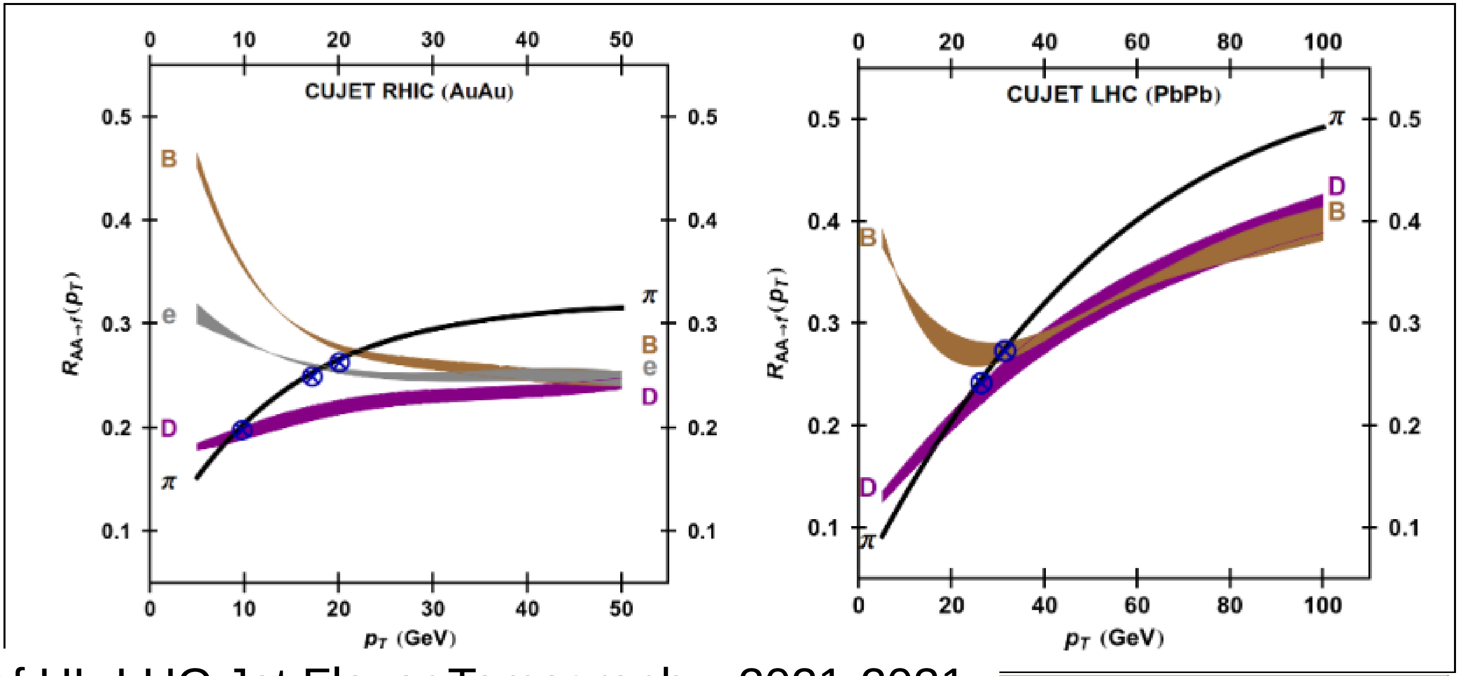
Can A+A data reveal the color structure dof and hence the mechanism of QCD confinement??

QCD Color Confinement remains the fundamental unsolved problem since 1973!

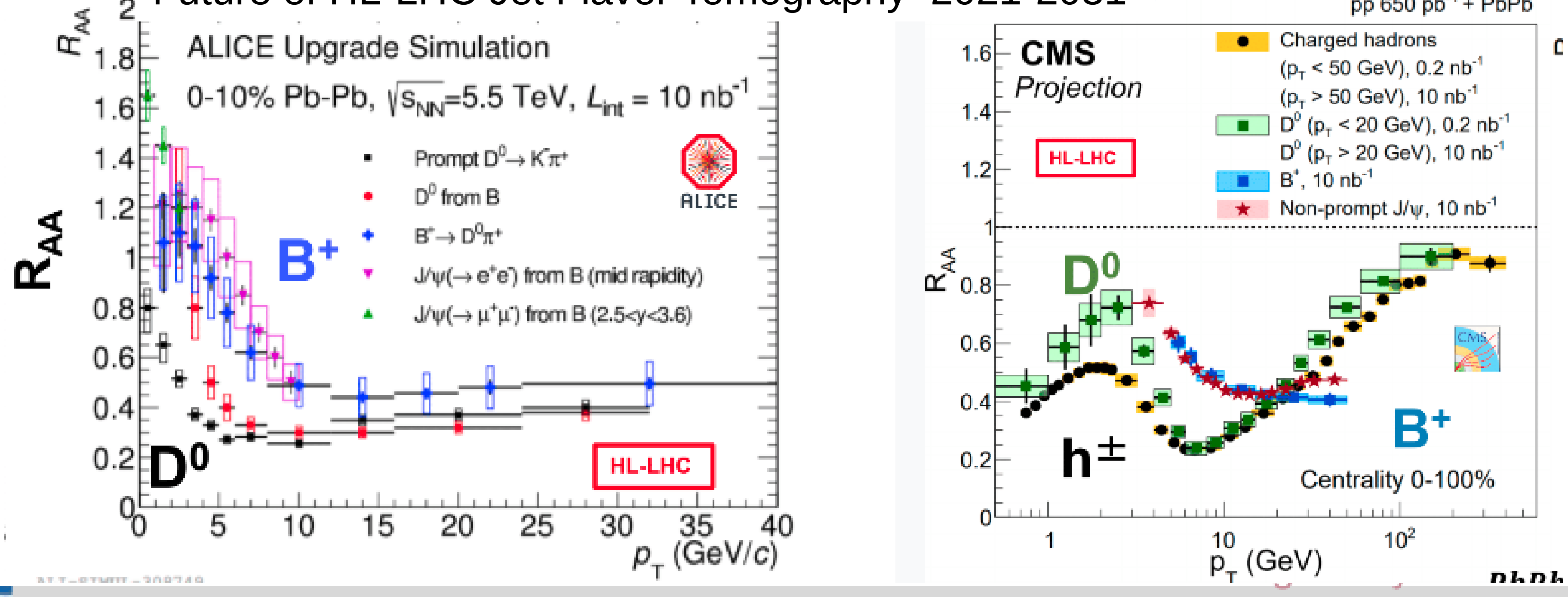
DGLV Jet Flavor Tomography

CUJET1: A.Buzzatti, MG, PRL108(2012)

Predicted
RAA level
Crossing
“fine structure”

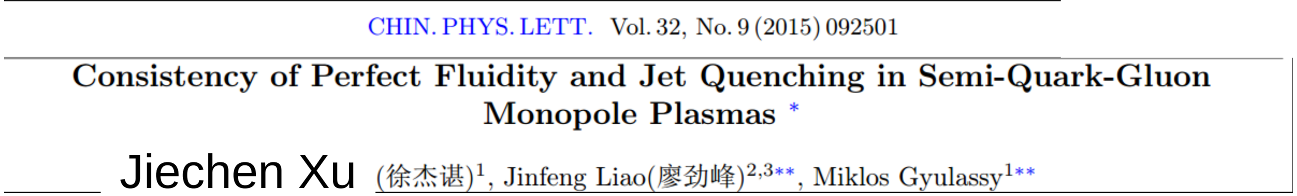


Future of HL-LHC Jet Flavor Tomography 2021-2031



Yen-Jie Lee High Density QCD in HL-LHC 22

CUJET3

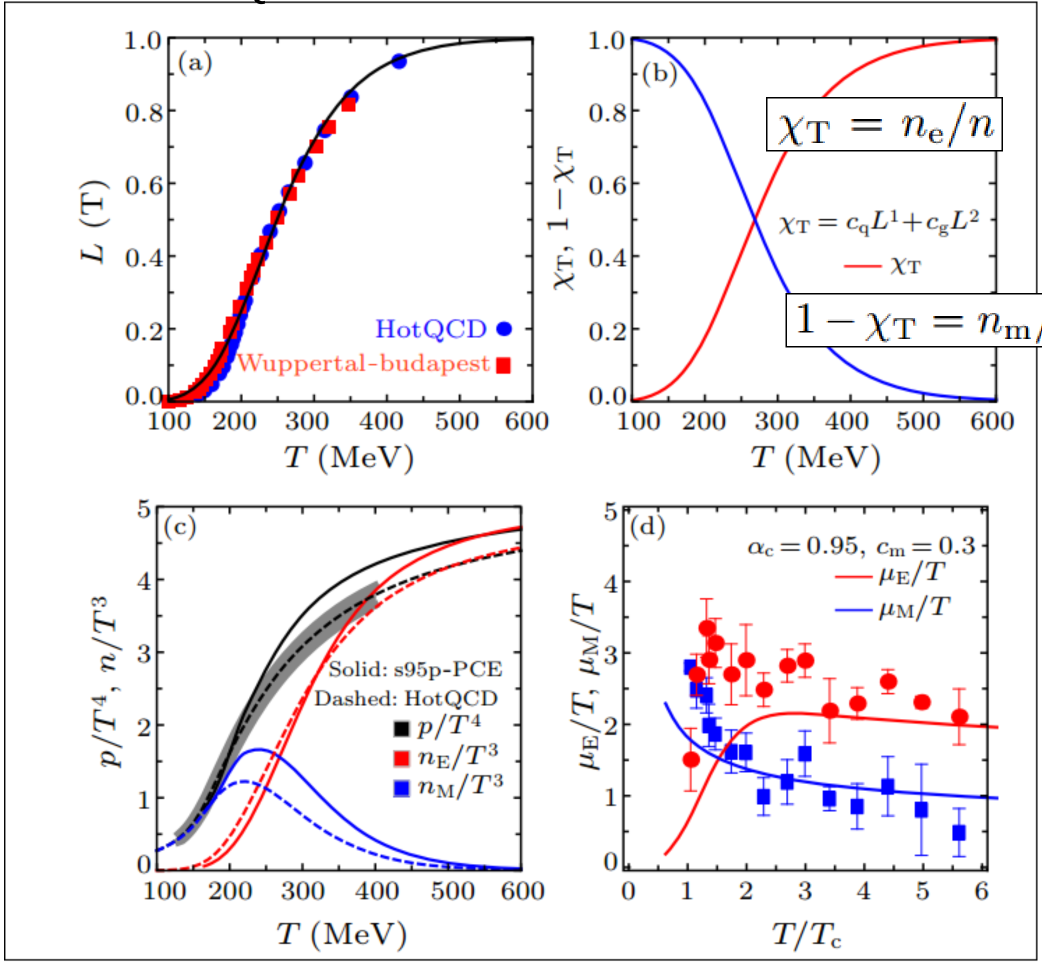

CHIN. PHYS. LETT. Vol. 32, No. 9 (2015) 092501

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

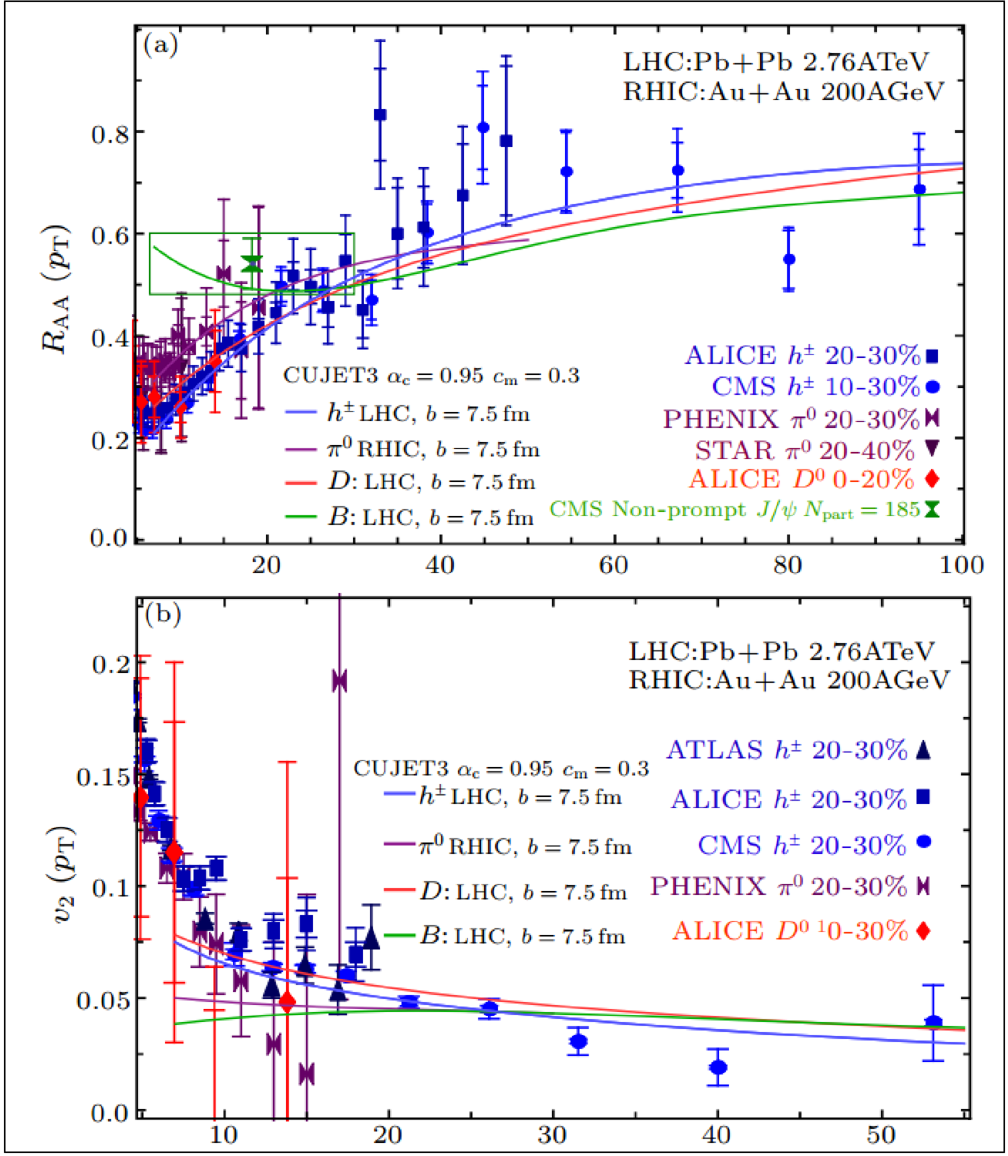
Jiechen Xu (徐杰谌)[1], Jinfeng Liao(廖劲峰)[2,3]**, Miklos Gyulassy[1]**

CUJET3

Lattice QCD data included in CUJET3.0



Quark Flavor Tomography at RHIC&LHC



sQGMP generalization of wQGP DGLV kernel

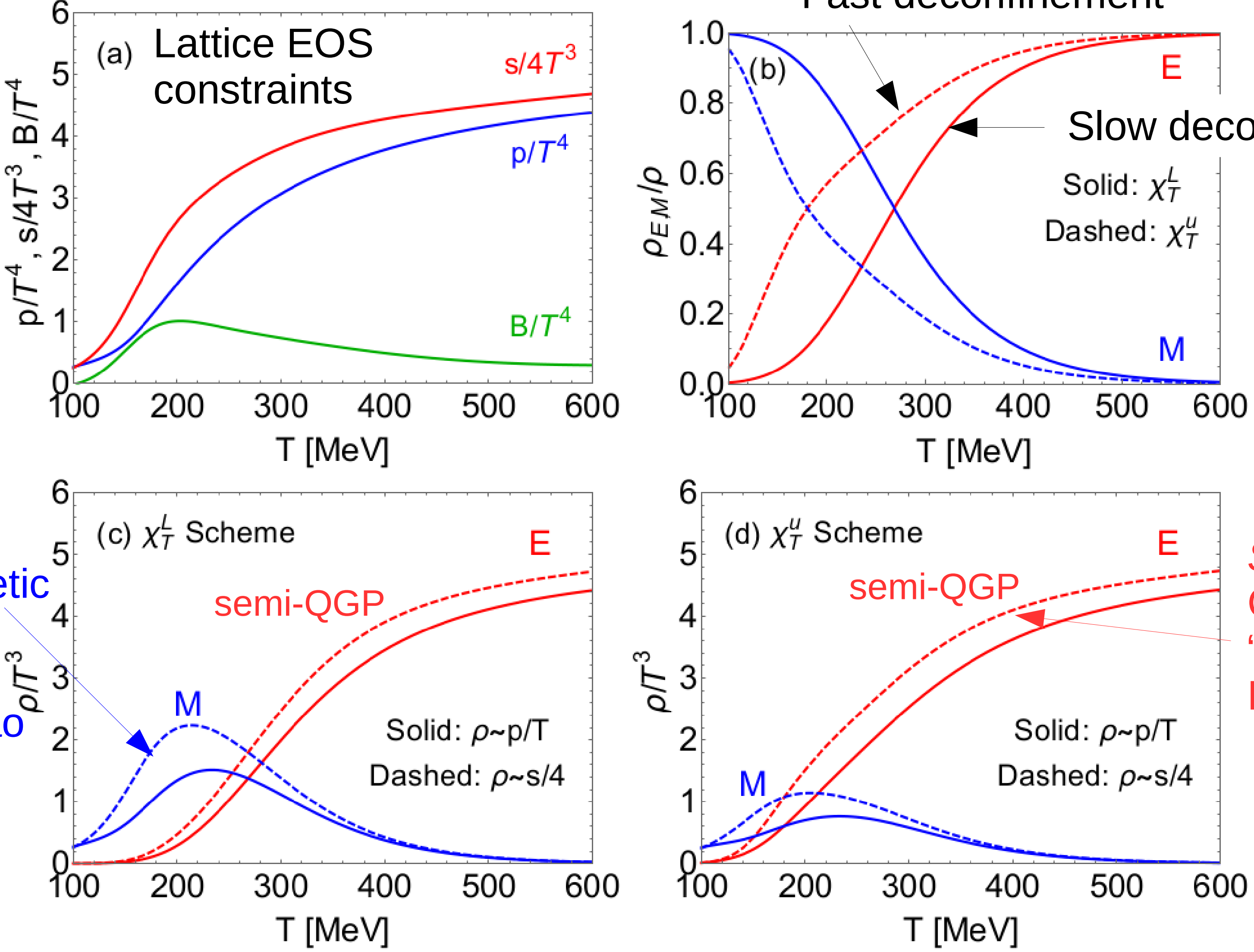
$$\sum_b \rho_b \frac{d\sigma_{ab}}{dq^2} \propto \left[\frac{n_e(\alpha_s(q^2)\alpha_s(q^2))f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m(\alpha^e(q^2)\alpha^m(q^2))f_M^2}{q^2(q^2+f_M^2\mu^2)}\right]$$

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

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

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

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 $\rho_m = 0$!



Fast deconfinement

Slow deconfinement

Emergent
Color Magnetic
Monopole
Dof
Shuryak, Liao

Suppressed
Color Electric
"*Semi*-QGP"
Hidaka,Pisarski

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)

S.Shi et al, in prep

Bottom Line message of this talk:

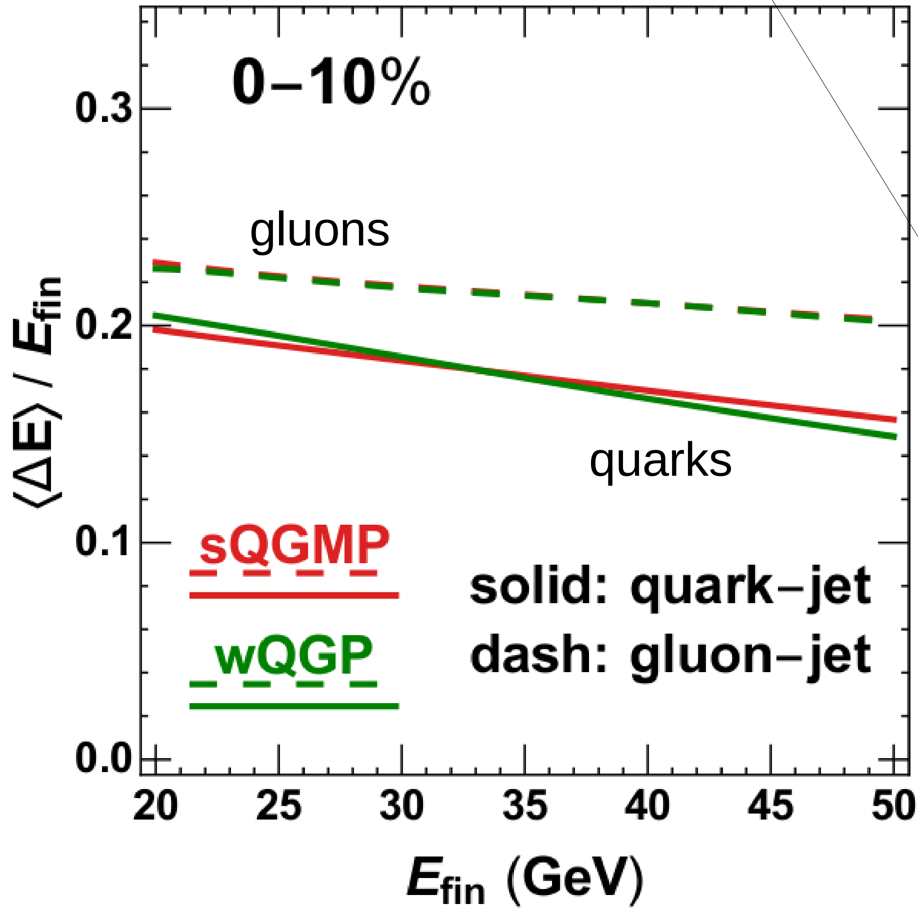
Main new result is that when parameters of both models are fixed to minimize data fit error wrt to all the single jet nuclear modification factor data on RAA(p_T,ϕ;cent,sqrt s),

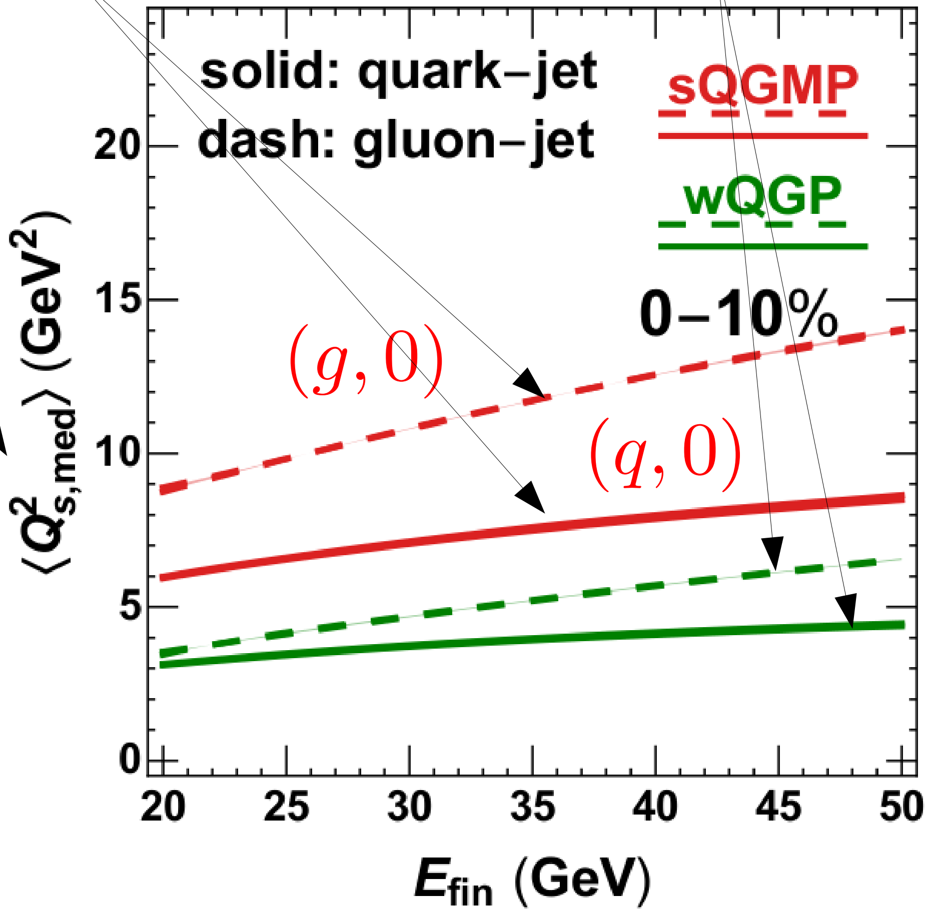
sQGMP and wQGP Energy Loss fractions are nearly identical when the jet coupling & magnetic screening in both composition models is fixed by minimizing

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

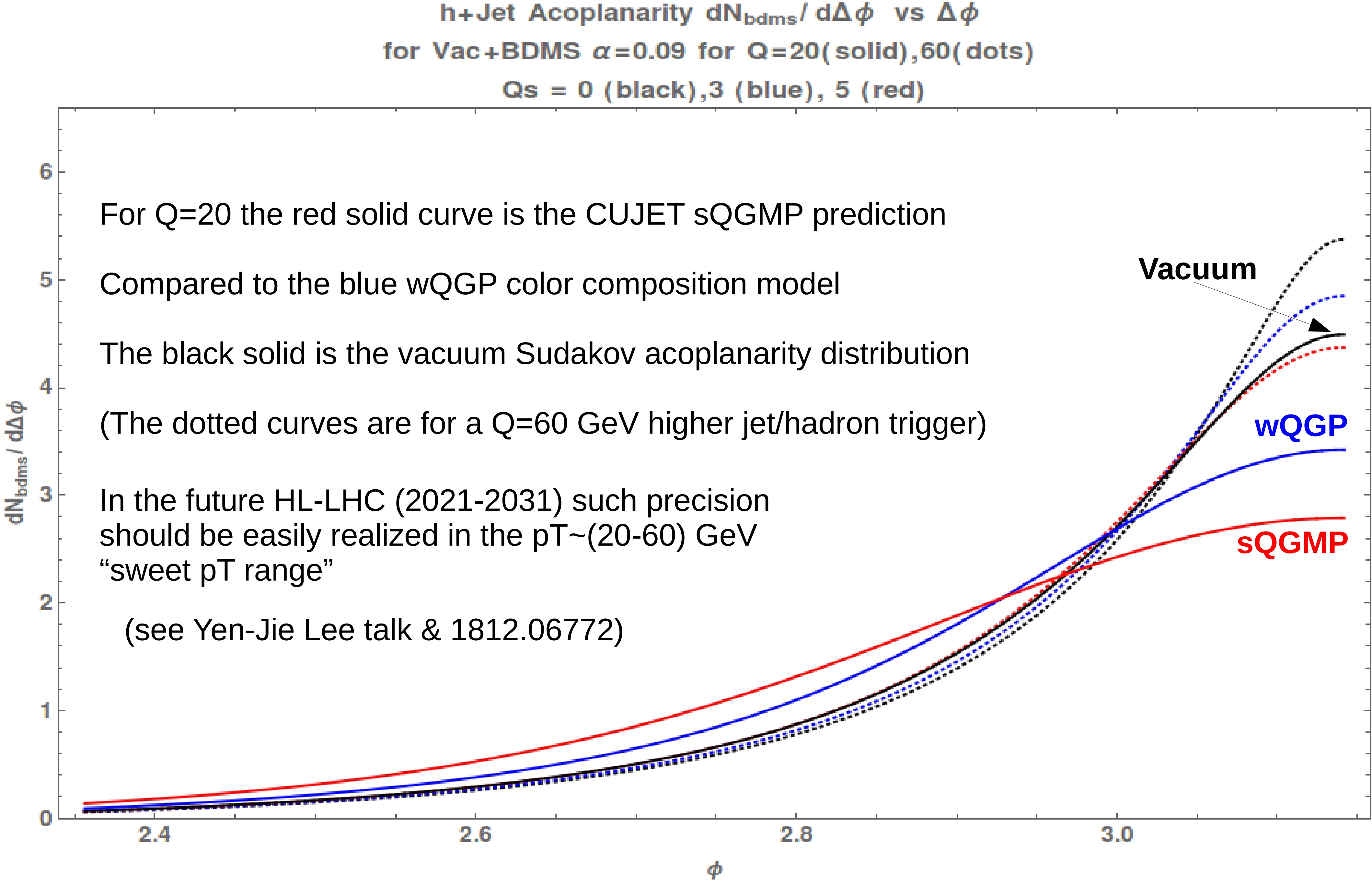
The surprise is that CUJET3 predicts a clear enhancement of sQGMP medium transverse broadening

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





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



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)

For Q=20 the red solid curve is the CUJET sQGMP prediction

Compared to the blue wQGP color composition model

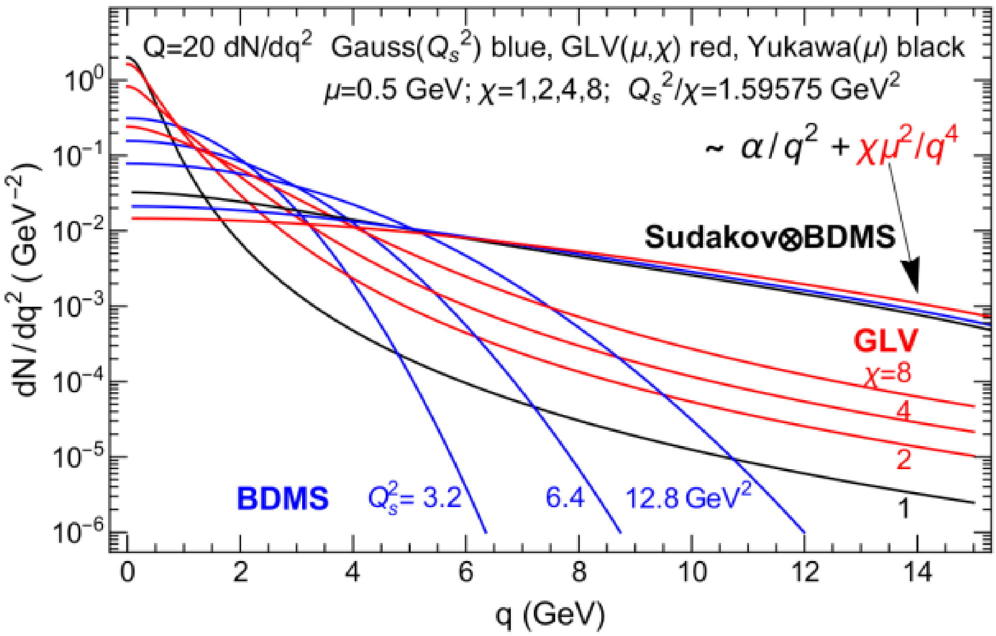
The black solid is the vacuum Sudakov acoplanarity distribution

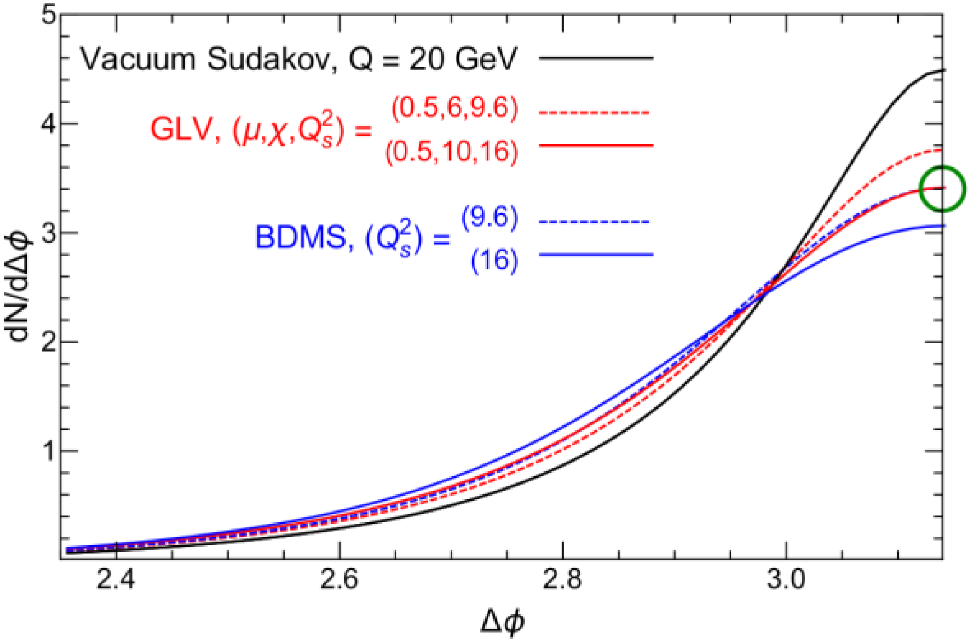
(The dotted curves are for a Q=60 GeV higher jet/hadron trigger)

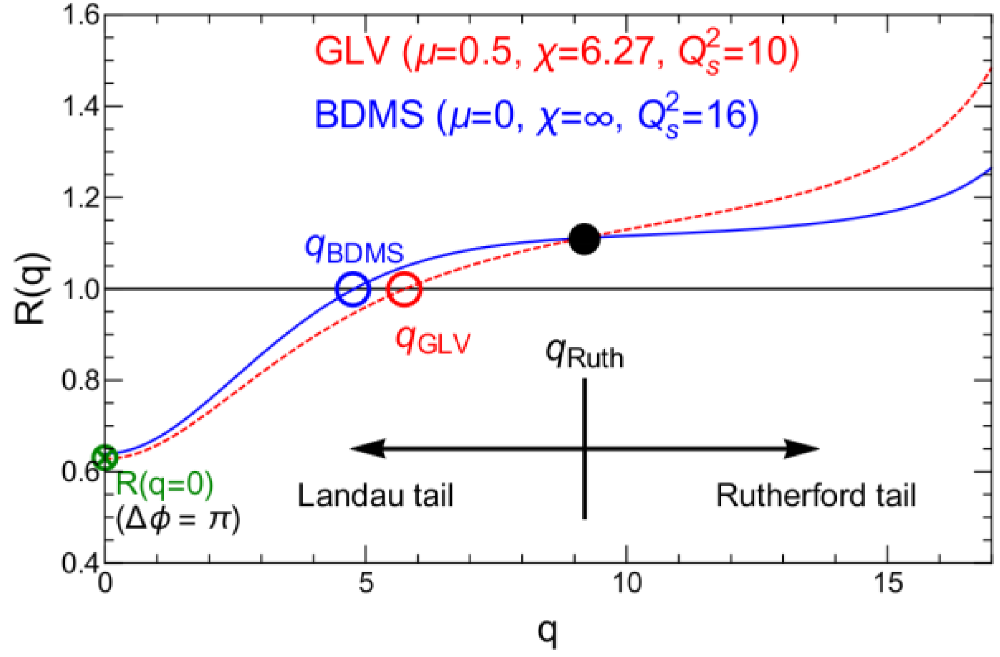
In the future HL-LHC (2021-2031) such precision
should be easily realized in the pT~(20-60) GeV
“sweet pT range”

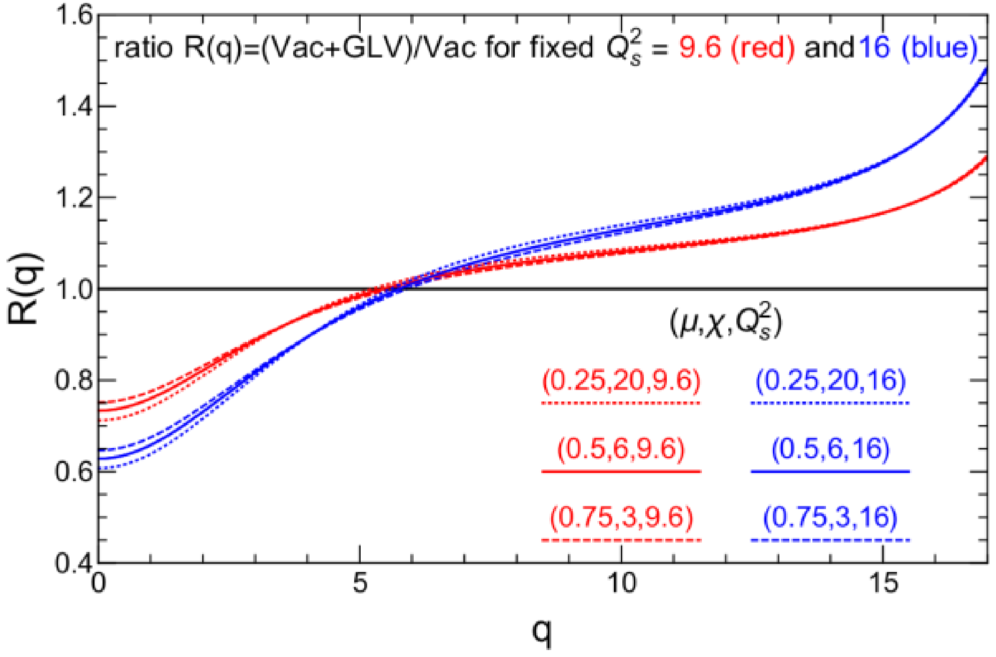
(see Yen-Jie Lee talk & 1812.06772)

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









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

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

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

$$\Gamma_{ab}(q_\perp,t)=\Gamma_{ab}(q_\perp,T(x(t),t))=\underline{\rho_b(T)d^2\sigma_{ab}(T)}/d^2q_\perp$$

$$\Gamma_a(q_\perp,t)\equiv\sum_b\Gamma_{ab}(q_\perp,t)$$

Medium induced transverse momentum² broadening , “saturation”, scale path functional

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

The BDMS multi-soft pQCD radiative energy loss functional

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

The GLV pQCD medium elastic opacity functional

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

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

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

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 in 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 $(\alpha_c \approx 0.9, c_m \approx 0.25)$

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 a clearly distinguishable prediction for dijet acoplanarity that could falsify one or both composition models

HL-LHC and sPHENIX could provide the needed level of few percent precisions needed.

Acoplanarity shape analysis at 0.1% level may even resolve $Q_s^2(a) \equiv \langle \mu_{ab}^2 \chi_a \rangle$

Into separate constraints on path ave opacities and chromo-E&M screening scales

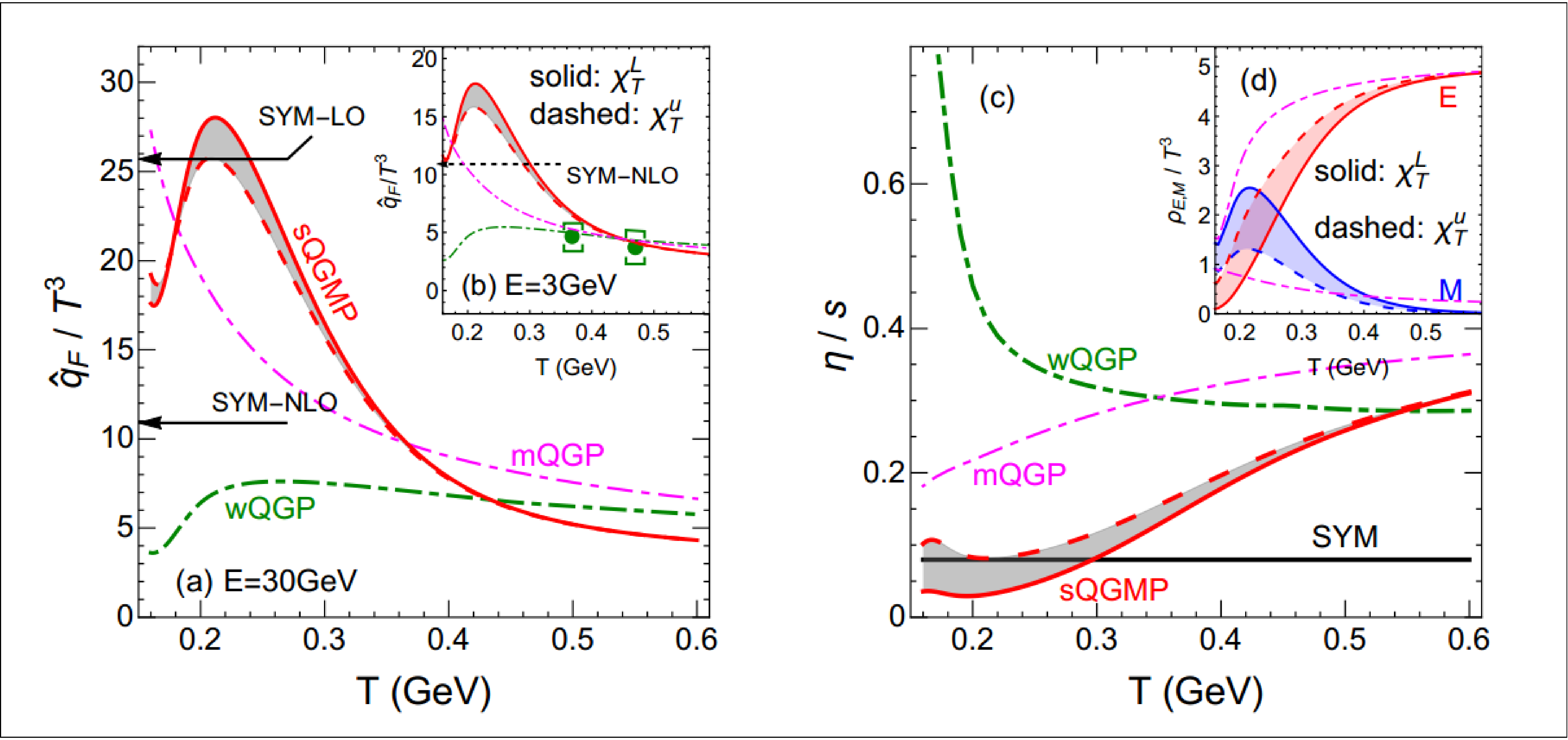
$\langle \chi_a \rangle_{b,c,u,g}$ $\langle \mu_{ab}^2 \rangle$

(my pipe dream for 2029 :-))

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 !

Section 1: Intro and Conclusions

➡ Section 2: Some more details of the calculation

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

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

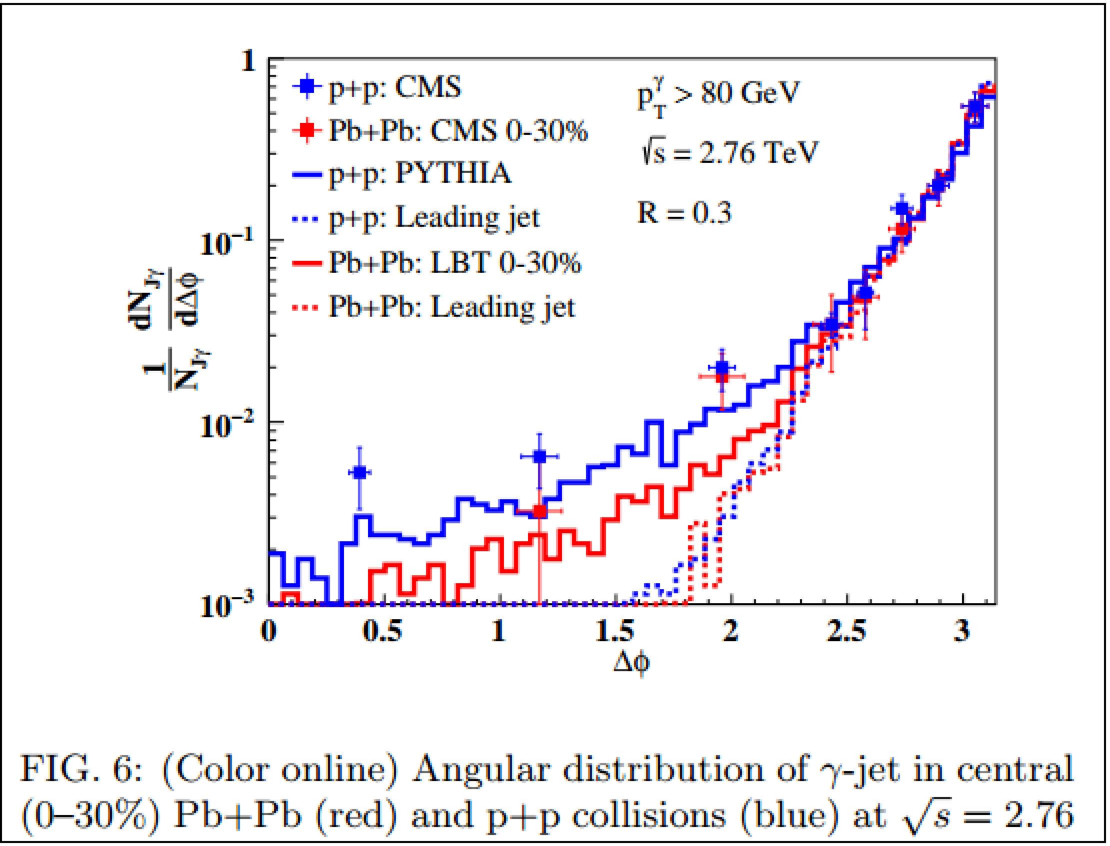


FIG. 6: (Color online) Angular distribution of γ-jet in central (0–30%) Pb+Pb (red) and p+p collisions (blue) at $\sqrt{s} = 2.76$

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).

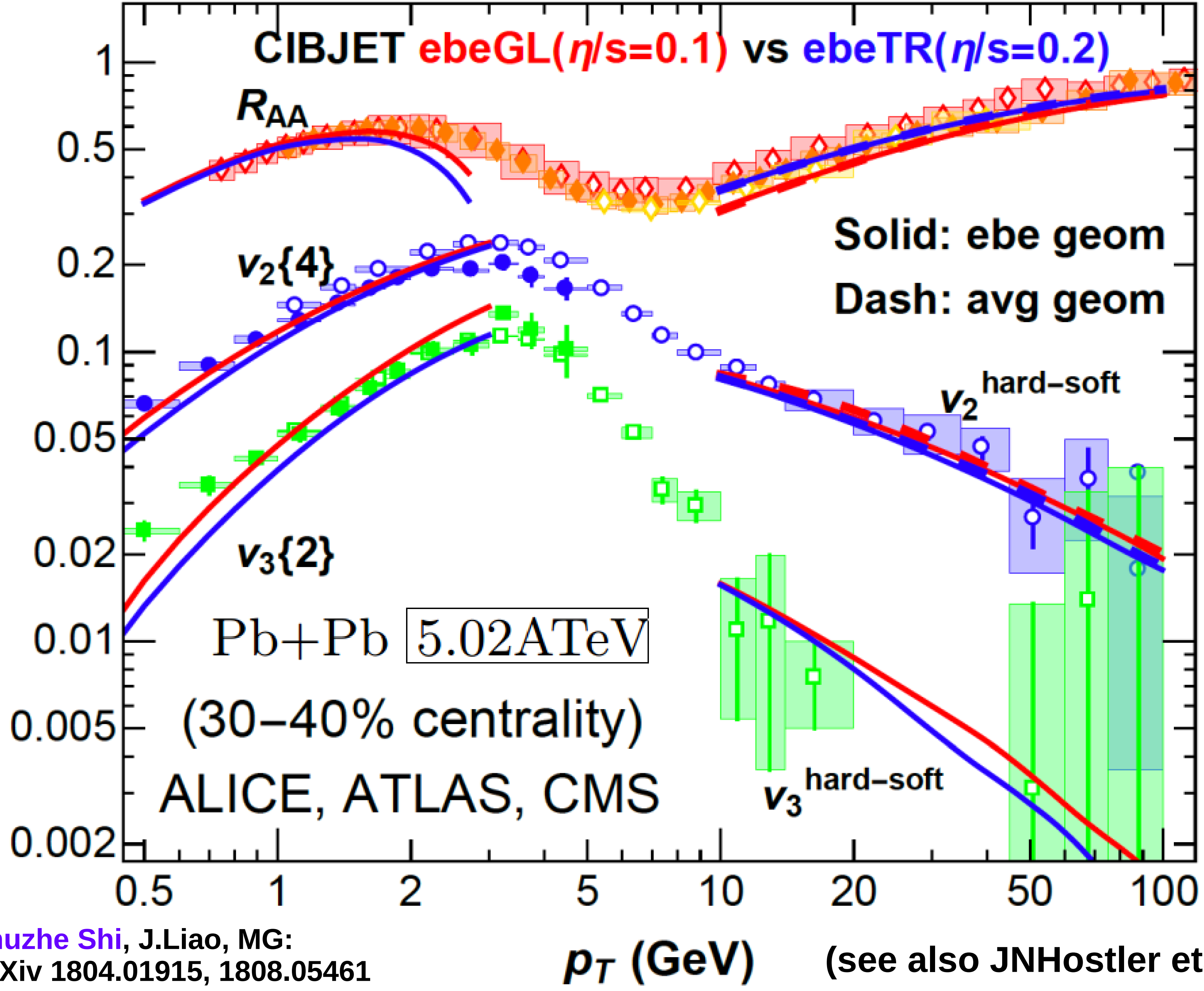
Exp should focus on the "sweet spot"

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

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."

Quantitative Test of “Volcano scenario”with CIBJET sQGMP

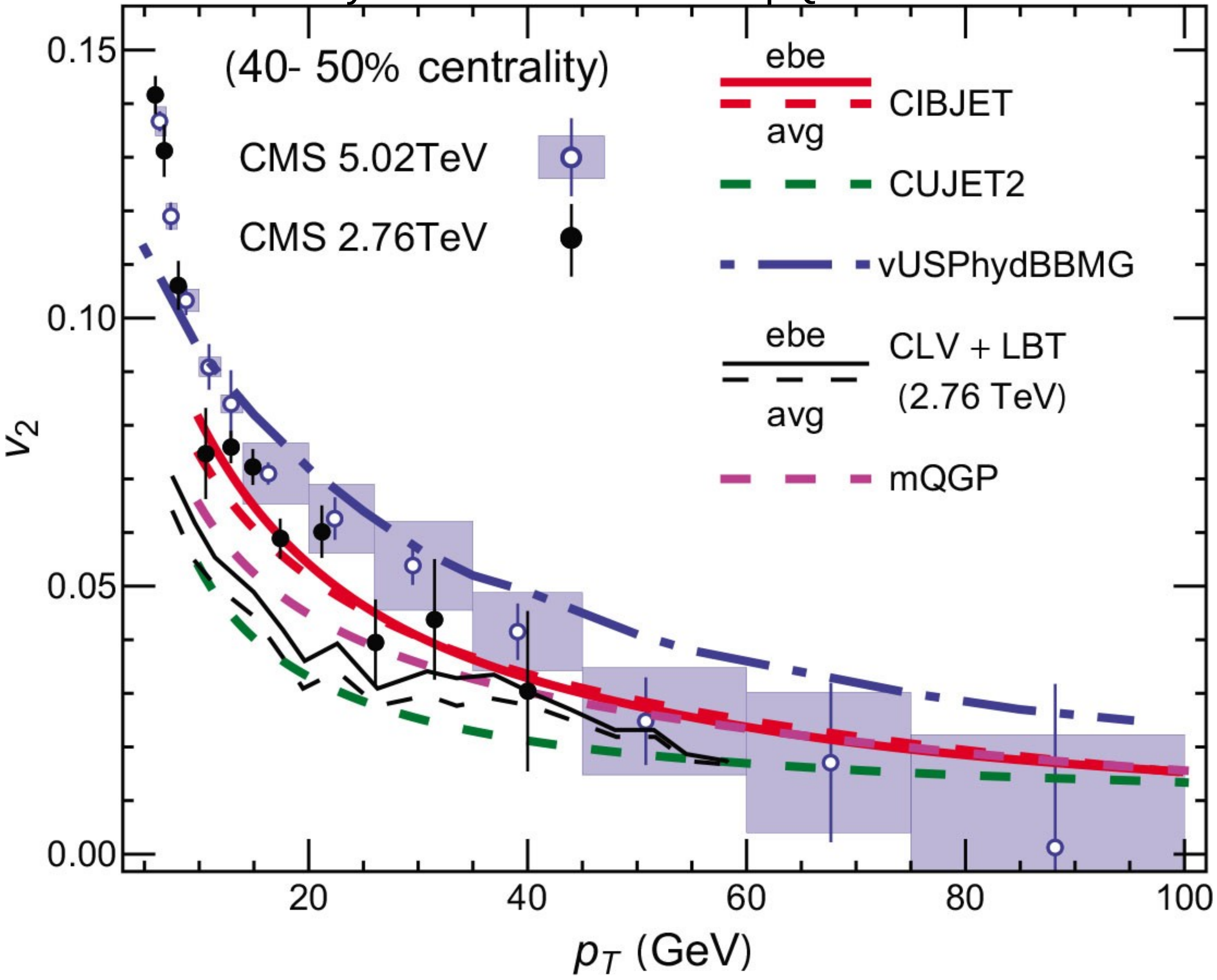


Shuzhe Shi, J.Liao, MG:
ArXiv 1804.01915, 1808.05461

(see also JNHostler etal 2016)

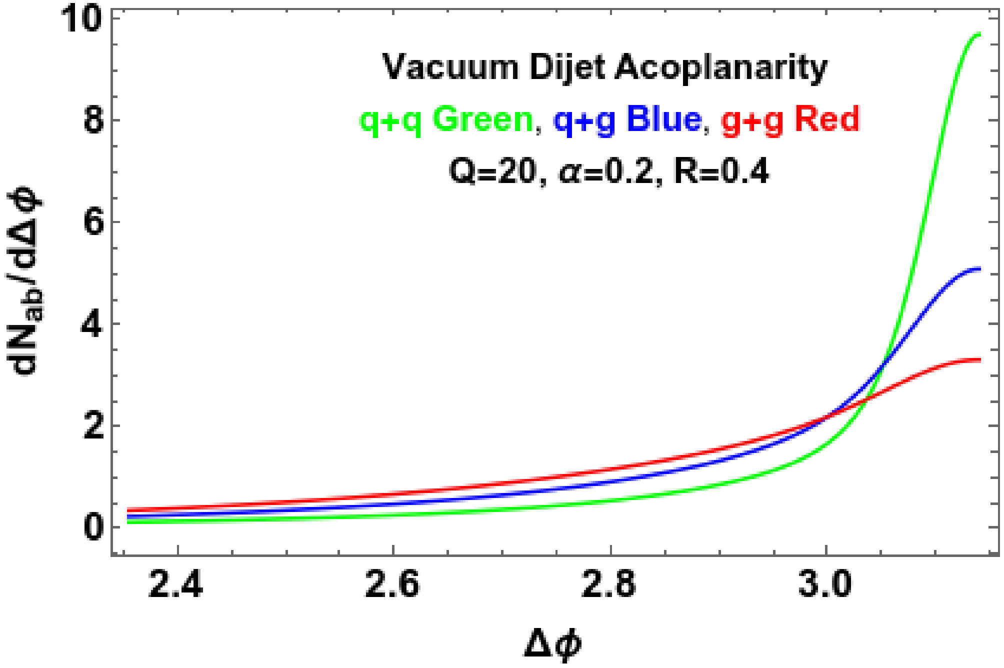
But the problem is that the CUJET3 sQGMP solution to the RAA-v2 puzzle in not unique!

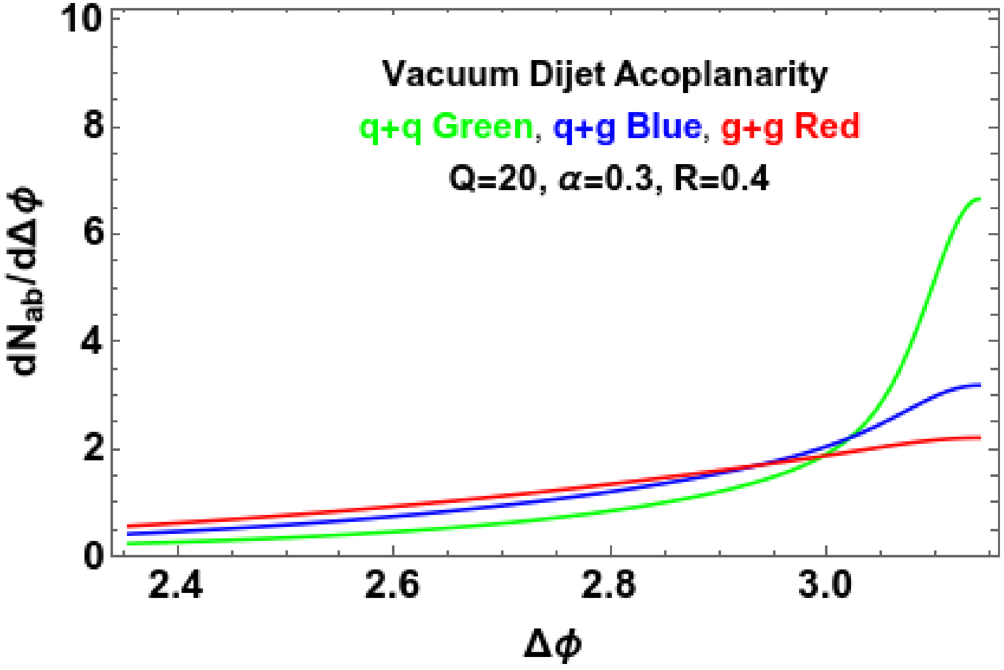
Jaki Noronha-Hostler et al PRL (2016) could explain same data
In her vUSPhydro + dE/dx= k x T^3 pQCD like en loss model



Recently Armesto, Niemi et al found a third solution arXiv:1902.07643

Multi dijet channels q+q, q+g, g+g complicate even vacuum Sudakov acoplanarity





pQCD => pp→parton ab fractions
vary with sqrt(s) and pT=Q

$$f_{pp\to ab}(vac; Q, \sqrt{s})$$

$$\frac{dN_{dijet}}{d\Delta\phi} = \sum_{ab} f_{ab} \frac{dN_{ab}}{d\Delta\phi}$$

=> a linear combination of rather different channel dependent Vacuum acoplanarity distributions

In A+A fab are modified by Quench energy losses

$$\Delta E_a \sim \int d\tau\, \hat{q}_a(x_a(\tau), \tau)\, \tau^1$$

$$\Delta E_b \sim \int d\tau\, \hat{q}_b(x_b(\tau), \tau)\, \tau^1$$

and $dN_{ab}/d\Delta\phi$ are modified by extra Medium dependent acoplanarity broadening controlled by

$$\delta(\Delta\phi)^2 \;\; (Q_s^2(a) + Q_s^2(b))/Q^2$$

$$\Delta Q_s^2[a] \sim \int d\tau\, \hat{q}_a(x_a(\tau), \tau)\, \tau^0$$

Jet Transport Coefficients = q_T^2 moment of $\sum_b \Gamma_{ab}(q_\perp, T)$. In CUJET3 sQGMP

$$\begin{array}{ll} & \hat{q}_F(E,T) = \int_0^{6ET} dq_\perp^2 \, \frac{2\pi}{(\boldsymbol{q}_\perp^2 + f_E^2\mu^2(\boldsymbol{z}))(\boldsymbol{q}_\perp^2 + f_M^2\mu^2(\boldsymbol{z}))}\rho(T) \\ q(q+g) & \Big\{ [C_{qq}f_q + C_{qg}f_g] \cdot \boxed{[\alpha_s^2(\boldsymbol{q}_\perp^2)]} \cdot [f_E^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] + \\ qm & [C_{qm}(1-f_q-f_g)] \cdot \boxed{[1]} \cdot [f_M^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] \Big\} , \end{array} \tag{14}$$

$$\begin{array}{ll} & \hat{q}_g(E,T) = \int_0^{6ET} dq_\perp^2 \, \frac{2\pi}{(\boldsymbol{q}_\perp^2 + f_E^2\mu^2(\boldsymbol{z}))(\boldsymbol{q}_\perp^2 + f_M^2\mu^2(\boldsymbol{z}))}\rho(T) \\ g(q+g) & \Big\{ [C_{gq}f_q + C_{gg}f_g] \cdot \boxed{[\alpha_s^2(\boldsymbol{q}_\perp^2)]} \cdot [f_E^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] + \\ gm & [C_{gm}(1-f_q-f_g)] \cdot \boxed{[1]} \cdot [f_M^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] \Big\} , \end{array} \tag{15}$$

Dirac

Note Γ_{qm} & Γ_{gm} => Critical Opalescence near Tc because $\alpha_E\alpha_M = 1 >> \alpha_E^2$

In wQGP $\rho_m = 0$! $\rho_q = f_q^{SB}\rho, \; \rho_g = f_g^{SB}\rho, \; f_E = 1, \; f_M = 0$ $\alpha_E\alpha_E \sim 0.1 << 1$

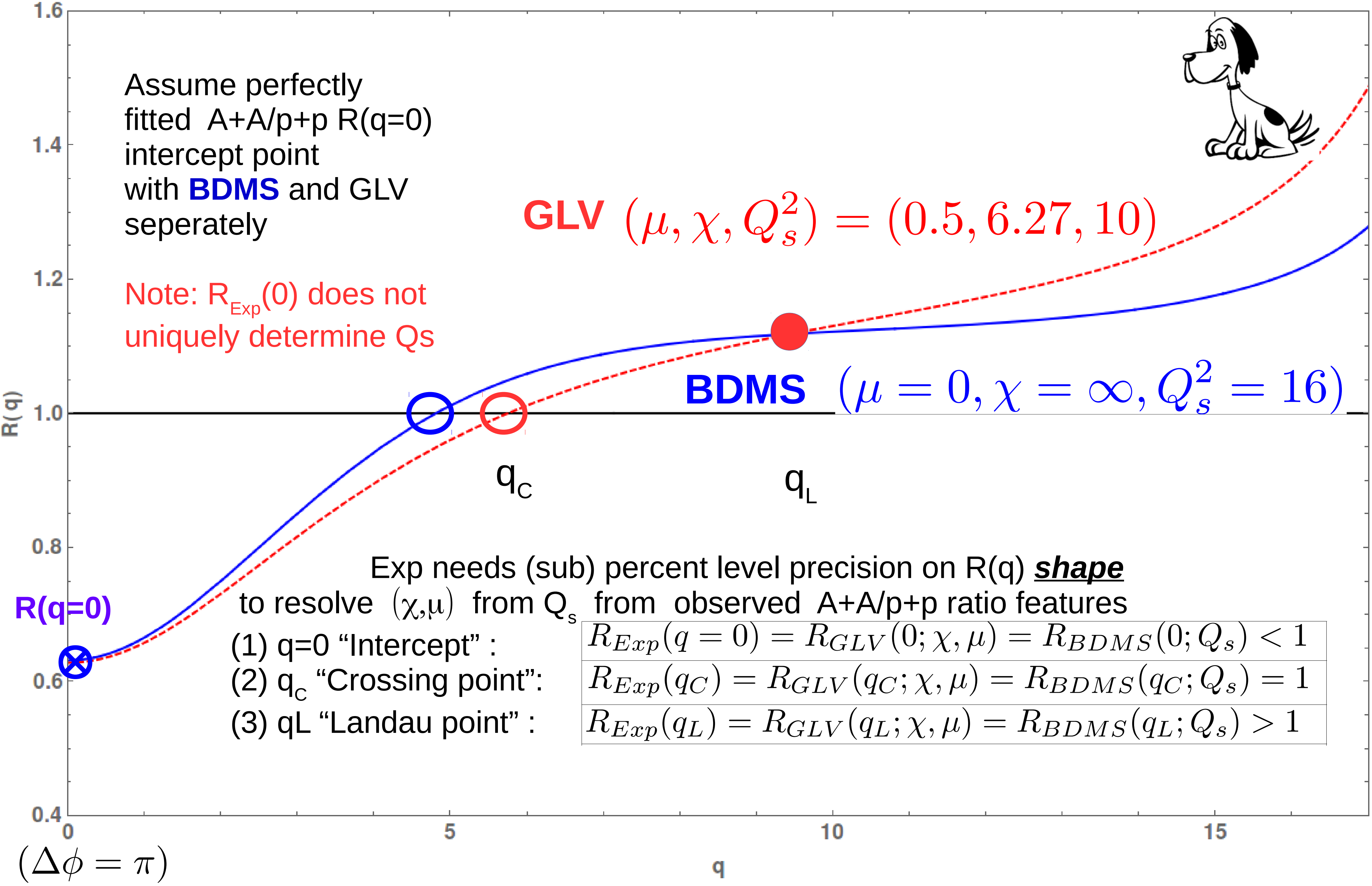
Can acoplanarity *distribution shapes test the existence of such novel color dynamics in* ≈ Perfect QCD fluids near Tc and constrain the multicomponent differential scattering rates?

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

Note that CUJET dE/dL is ***not*** proportional to qhat L but given by a generalized DGLV formula

(See eq2.23 J.Xu, J.Liao, MG, JHEP 02 (2016) 169)

Ratio dN(Vac+GLV)/dN(Vac) (red) vs dN(Vac+BDMS)/dN(Vac) (blue) vs q



Assume perfectly
fitted A+A/p+p R(q=0)
intercept point
with **BDMS** and GLV
seperately

Note: $R_{Exp}(0)$ does not
uniquely determine Qs

GLV $(\mu, \chi, Q_s^2) = (0.5, 6.27, 10)$

BDMS $(\mu = 0, \chi = \infty, Q_s^2 = 16)$

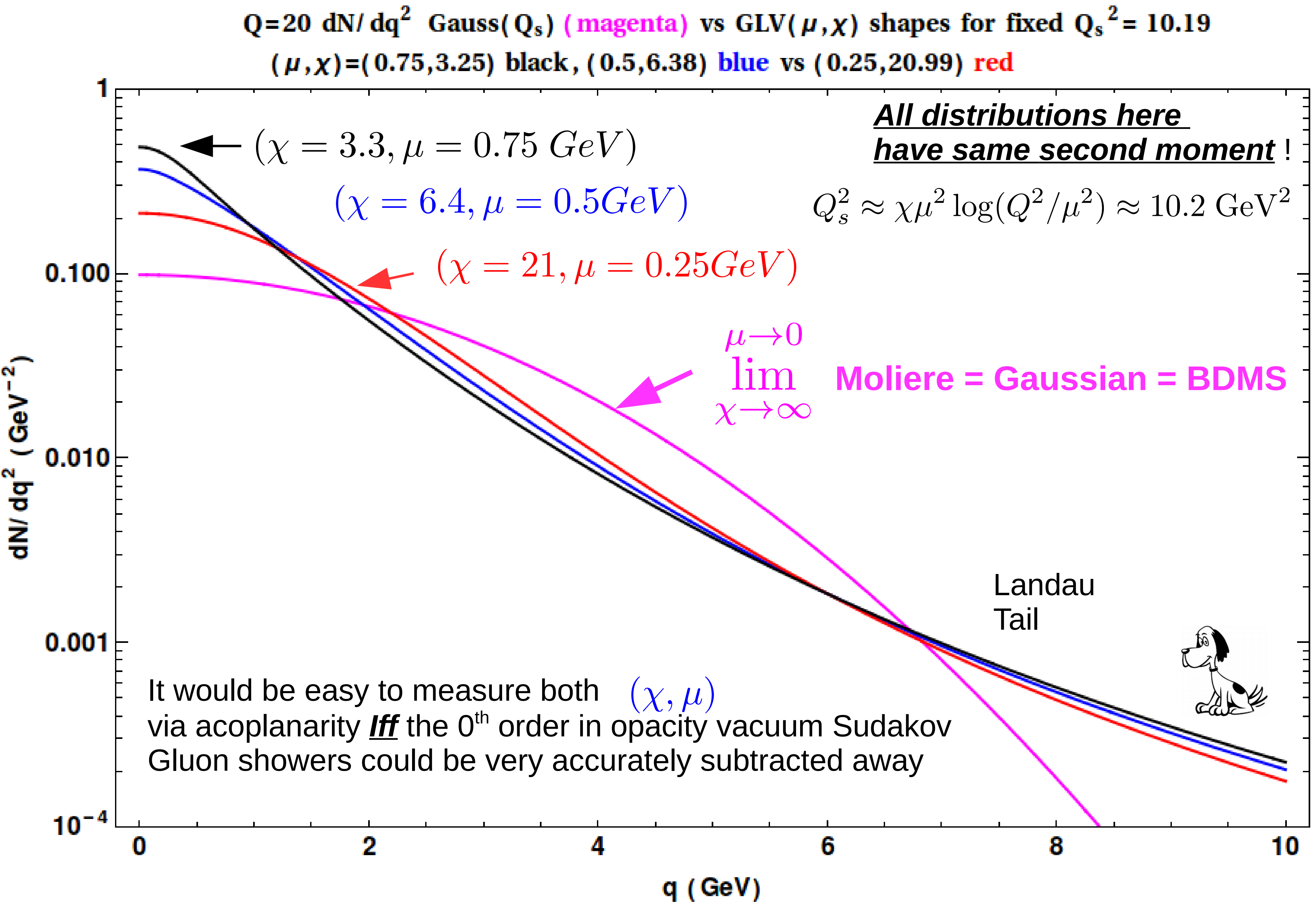
Exp needs (sub) percent level precision on R(q) ***shape***
to resolve (χ,μ) from Q_s from observed A+A/p+p ratio features

(1) q=0 “Intercept” : $R_{Exp}(q=0) = R_{GLV}(0;\chi,\mu) = R_{BDMS}(0;Q_s) < 1$

(2) q_C “Crossing point”: $R_{Exp}(q_C) = R_{GLV}(q_C;\chi,\mu) = R_{BDMS}(q_C;Q_s) = 1$

(3) qL “Landau point” : $R_{Exp}(q_L) = R_{GLV}(q_L;\chi,\mu) = R_{BDMS}(q_L;Q_s) > 1$

MG, PLevai, JLiao, SShi, FYuan, XNWang QM2018 and in prep


Q=20 dN/ dq^2 Gauss(Q$_s$) (magenta) vs GLV(μ,χ) shapes for fixed Q$_s$^{2}= 10.19
(μ,χ)=(0.75,3.25) black, (0.5,6.38) blue vs (0.25,20.99) red

All distributions here have same second moment !

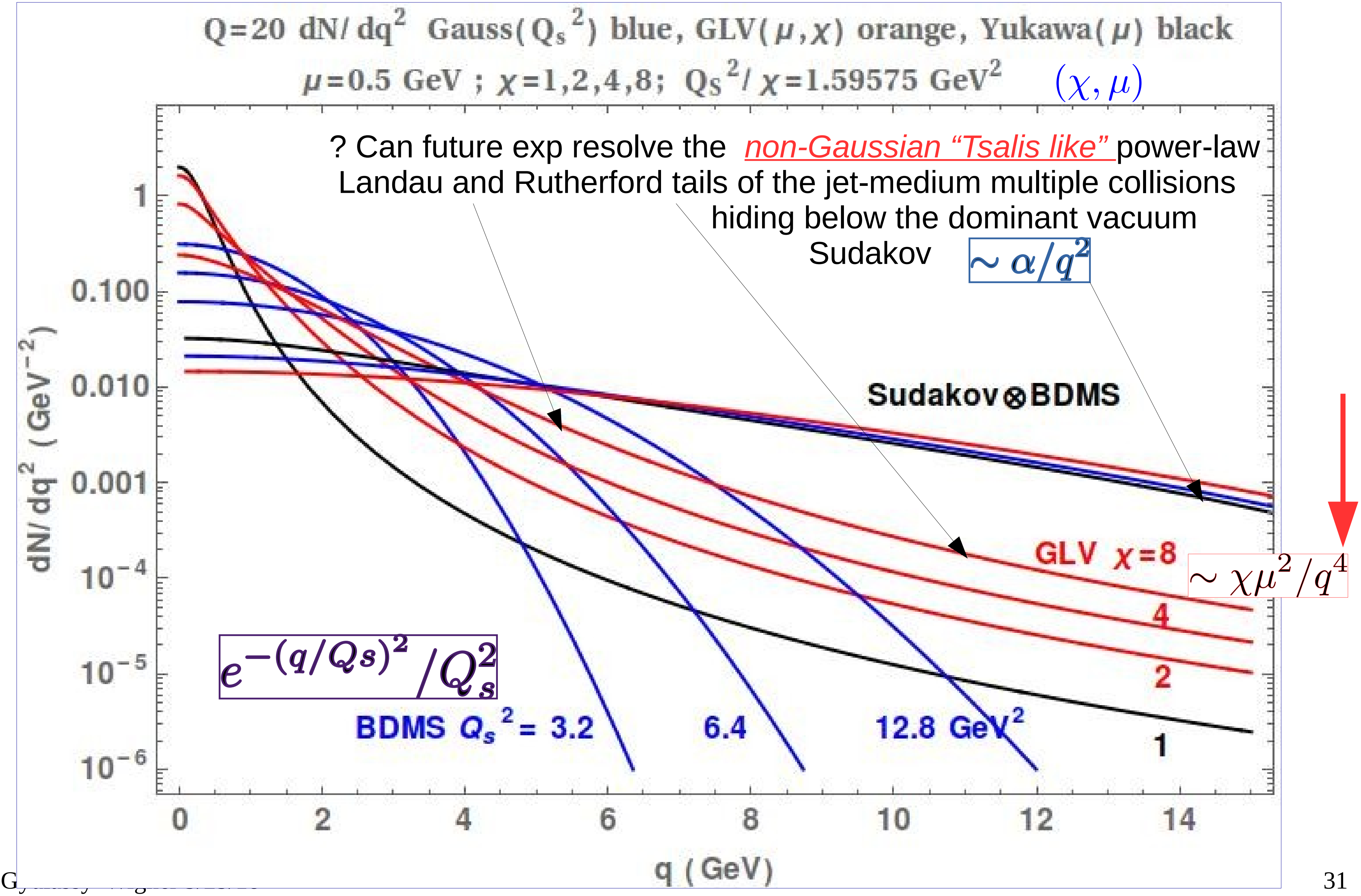
$$Q_s^2 \approx \chi\mu^2 \log(Q^2/\mu^2) \approx 10.2\ \mathrm{GeV}^2$$

Moliere = Gaussian = BDMS

It would be easy to measure both (χ, μ)
via acoplanarity ***Iff*** the 0th order in opacity vacuum Sudakov
Gluon showers could be very accurately subtracted away

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

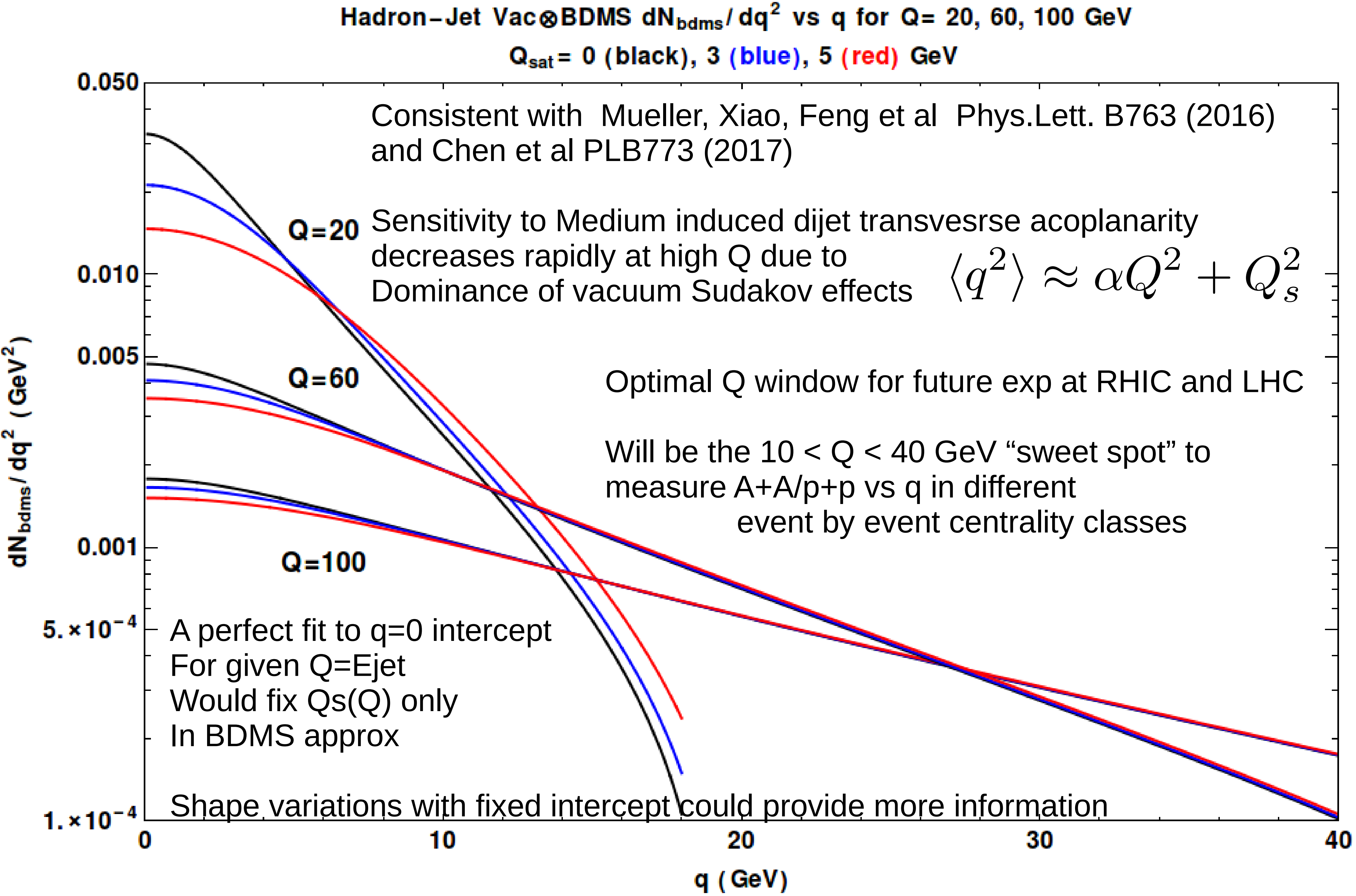
10% Percent level precision needed *even to resolve BDMS Qs* from Sudakov $\sim \alpha/q^2$



? Can future exp resolve the *non-Gaussian "Tsalis like"* power-law Landau and Rutherford tails of the jet-medium multiple collisions hiding below the dominant vacuum Sudakov $\sim \alpha/q^2$

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

One parameter, Q_s, BDMS medium convoluted with Sudakov dijet transverse distributions



Consistent with Mueller, Xiao, Feng et al Phys.Lett. B763 (2016) and Chen et al PLB773 (2017)

Sensitivity to Medium induced dijet transvesrse acoplanarity decreases rapidly at high Q due to Dominance of vacuum Sudakov effects

$$\langle q^2\rangle \approx \alpha Q^2 + Q_s^2$$

Optimal Q window for future exp at RHIC and LHC

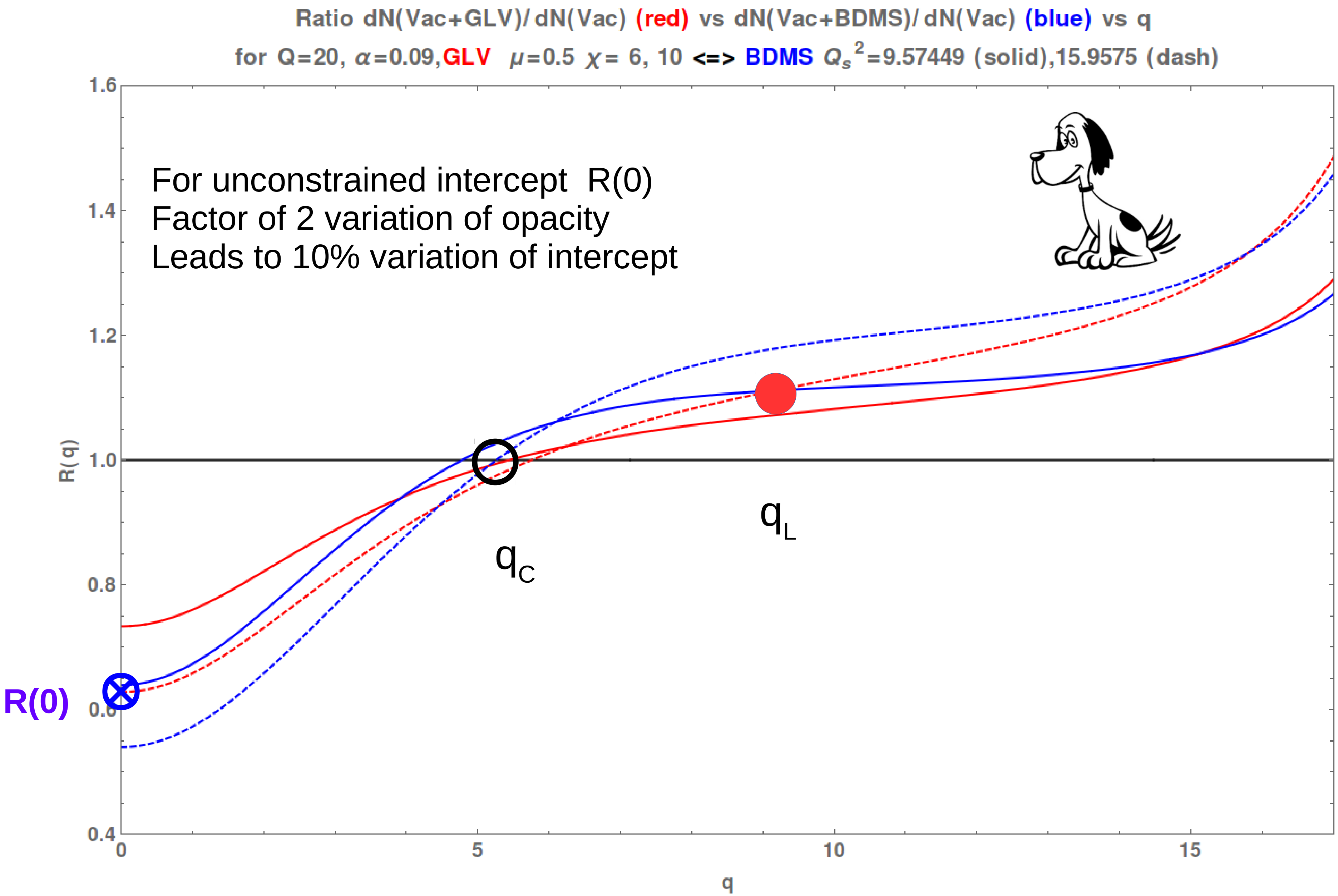
Will be the 10 < Q < 40 GeV “sweet spot” to measure A+A/p+p vs q in different event by event centrality classes

A perfect fit to q=0 intercept
For given Q=Ejet
Would fix Qs(Q) only
In BDMS approx

Shape variations with fixed intercept could provide more information

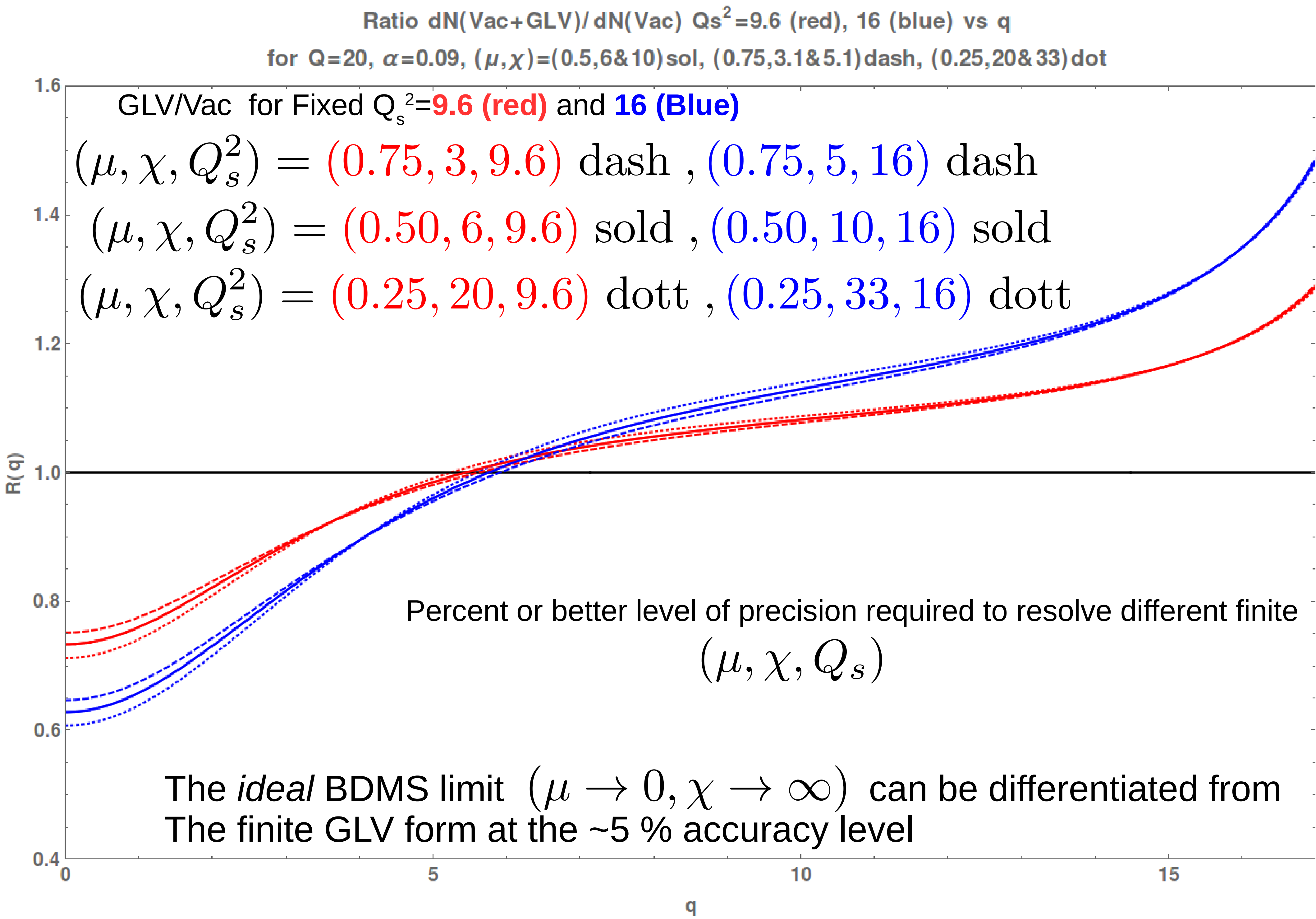
MG, PLevai, JLiao, SShi, FYuan, XNWang QM2018 and in prep

For realistic Sudakov fits to p+p need lower $\alpha \approx 0.09$ and next to leading corr.
Requires very high precision to resolve GLV finite (χ,μ) from BDMS(Qs) medium effects



Ratio dN(Vac+GLV)/dN(Vac) (red) vs dN(Vac+BDMS)/dN(Vac) (blue) vs q
for Q=20, α=0.09,GLV μ=0.5 χ= 6, 10 <=> BDMS Q_s^2=9.57449 (solid),15.9575 (dash)

For unconstrained intercept R(0)
Factor of 2 variation of opacity
Leads to 10% variation of intercept



GLV/Vac for Fixed Q_s^2=**9.6 (red)** and **16 (Blue)**

$$(\mu,\chi,Q_s^2) = (0.75,3,9.6)\ \text{dash}\ ,\ (0.75,5,16)\ \text{dash}$$

$$(\mu,\chi,Q_s^2) = (0.50,6,9.6)\ \text{sold}\ ,\ (0.50,10,16)\ \text{sold}$$

$$(\mu,\chi,Q_s^2) = (0.25,20,9.6)\ \text{dott}\ ,\ (0.25,33,16)\ \text{dott}$$

Percent or better level of precision required to resolve different finite

$$(\mu,\chi,Q_s)$$

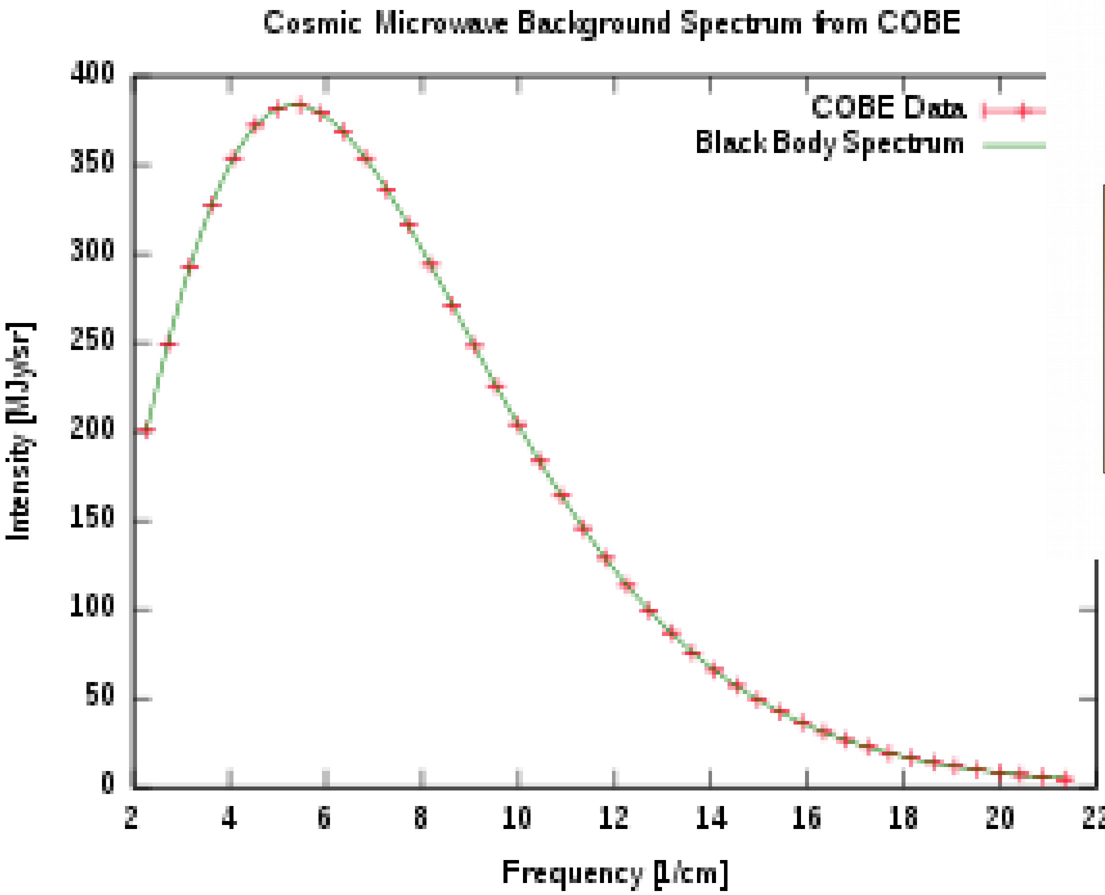
The *ideal* BDMS limit $(\mu \to 0, \chi \to \infty)$ can be differentiated from
The finite GLV form at the ~5 % accuracy level

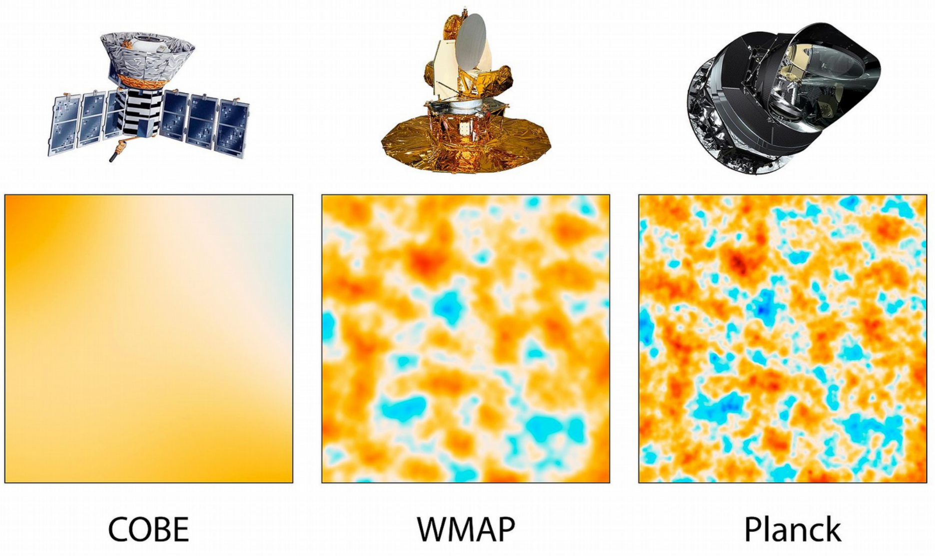
Cosmic Inspiration for pushing toward a future high precision era of A+A

1 part per 100,000 fluctuations can and have been observed to constrain cosmological models

https://en.wikipedia.org/wiki/Cosmic_microwave_background

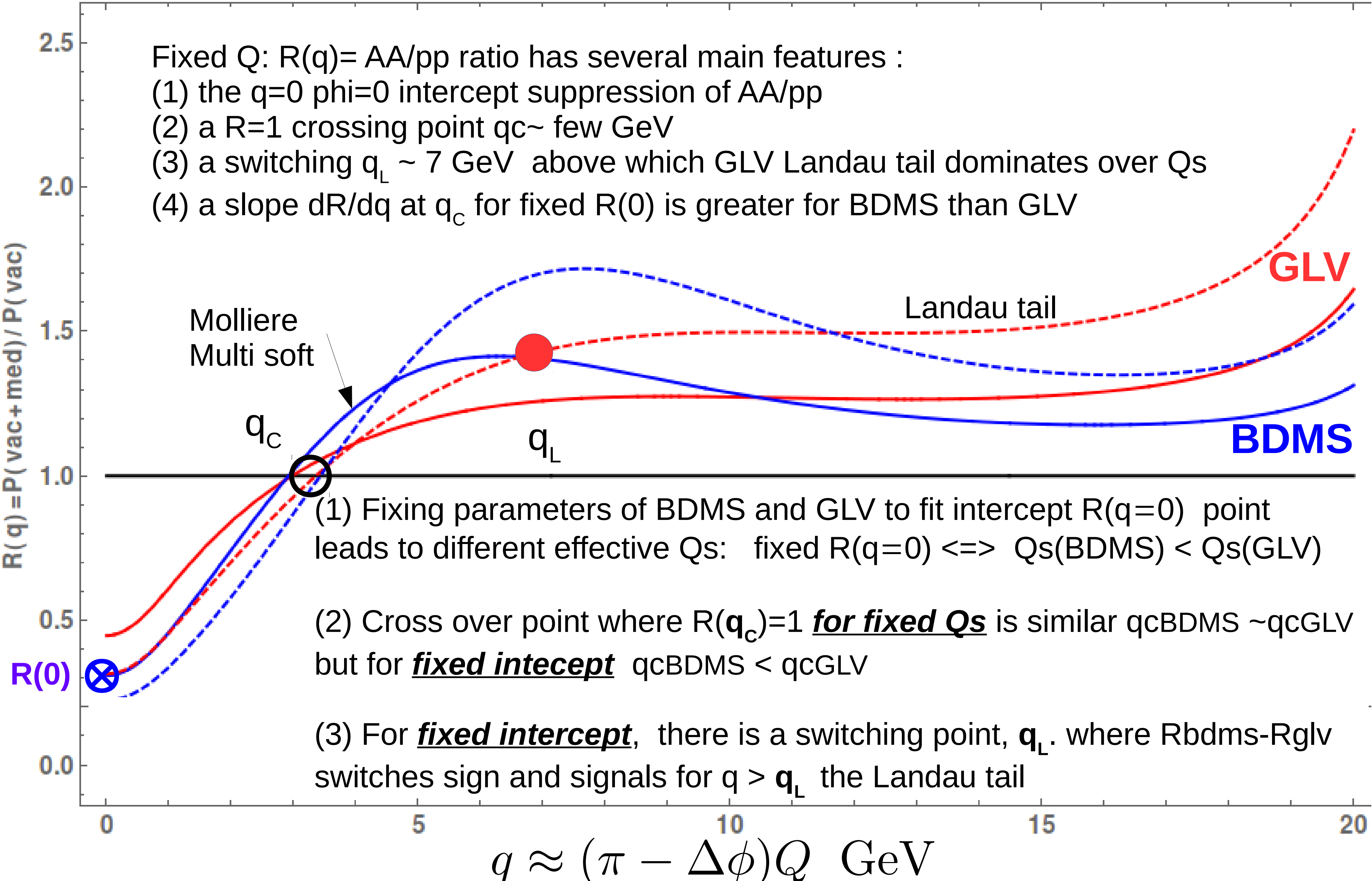
Graph of cosmic microwave background spectrum measured by the FIRAS instrument on the COBE, the most precisely measured black body spectrum in nature.[7]
The error bars are too small to be seen even in an enlarged image,
and it is impossible to distinguish the observed data from the theoretical curve.





This example is Exaggerated with

Ratio of Probalities for dijet transverse momentum q Relative to Vacuum for BDMS(blue) and GLV(Red) ($Q=20$, $\alpha=0.3$) with medium induced $Q_{med}{}^2=9$ (solid) vs 16 (dashed)



Fixed Q: R(q)= AA/pp ratio has several main features :
(1) the q=0 phi=0 intercept suppression of AA/pp
(2) a R=1 crossing point qc~ few GeV
(3) a switching q_L ~ 7 GeV above which GLV Landau tail dominates over Qs
(4) a slope dR/dq at q_C for fixed R(0) is greater for BDMS than GLV

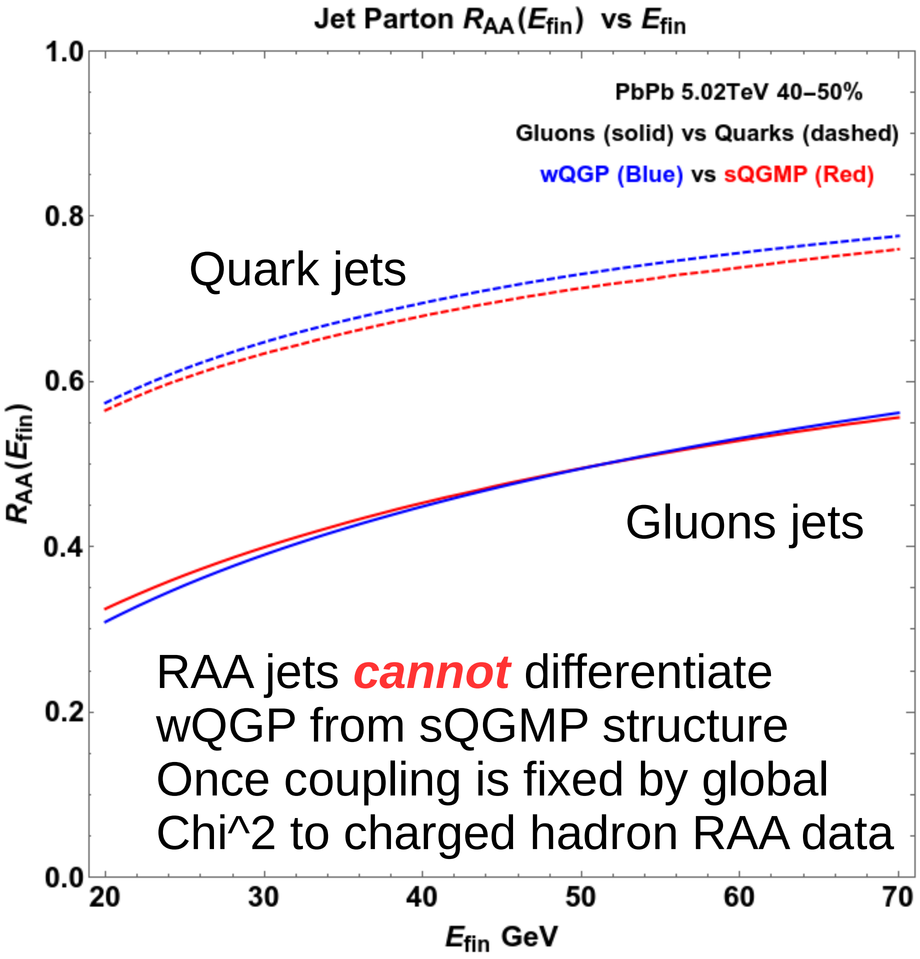
(1) Fixing parameters of BDMS and GLV to fit intercept R(q=0) point leads to different effective Qs: fixed R(q=0) <=> Qs(BDMS) < Qs(GLV)

(2) Cross over point where R(**q_C**)=1 ***<u>for fixed Qs</u>*** is similar qcBDMS ~qcGLV but for ***<u>fixed intecept</u>*** qcBDMS < qcGLV

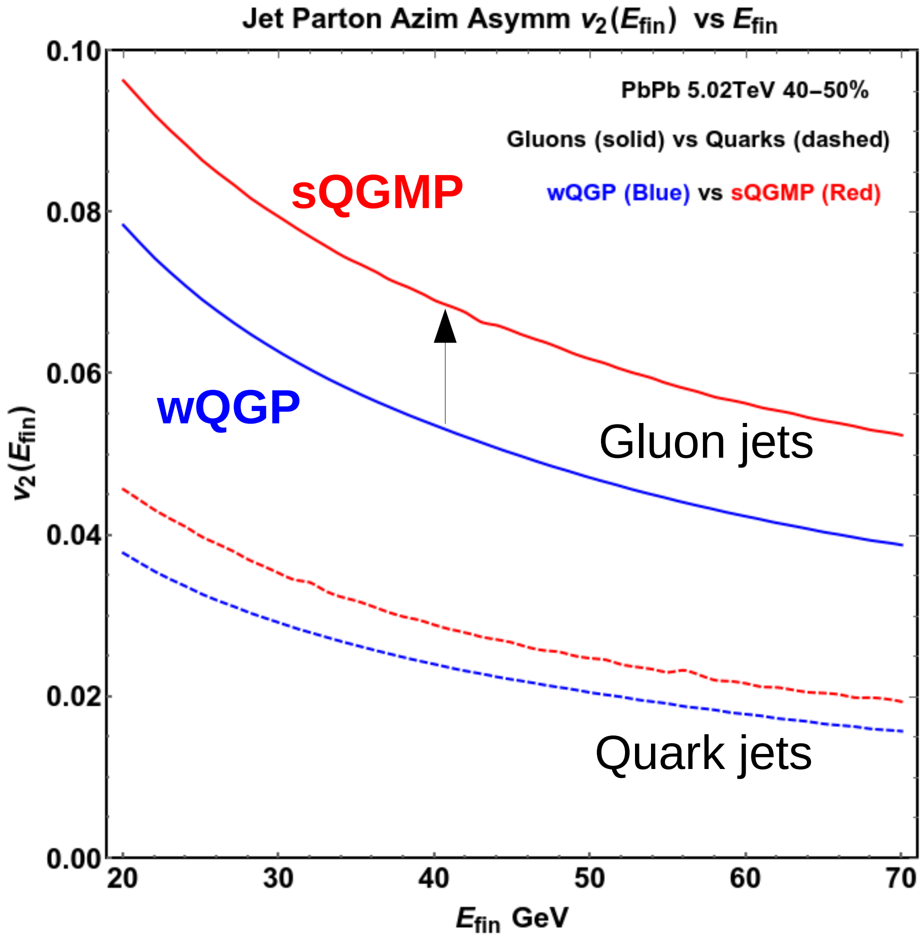
(3) For ***<u>fixed intercept</u>***, there is a switching point, **q_L**. where Rbdms-Rglv switches sign and signals for q > **q_L** the Landau tail

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



RAA jets ***cannot*** differentiate wQGP from sQGMP structure 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 that rules out wQGP structure in this particular framework

However, hadron-jet and jet-jet acoplanarity observables are sensitive
Not only to energy loss path functionals but especially to
Transverse broadening functional that CUJET3 predicts to differ significantly
Between wQGP and sQGMP structures of the QCD perfect fluid

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