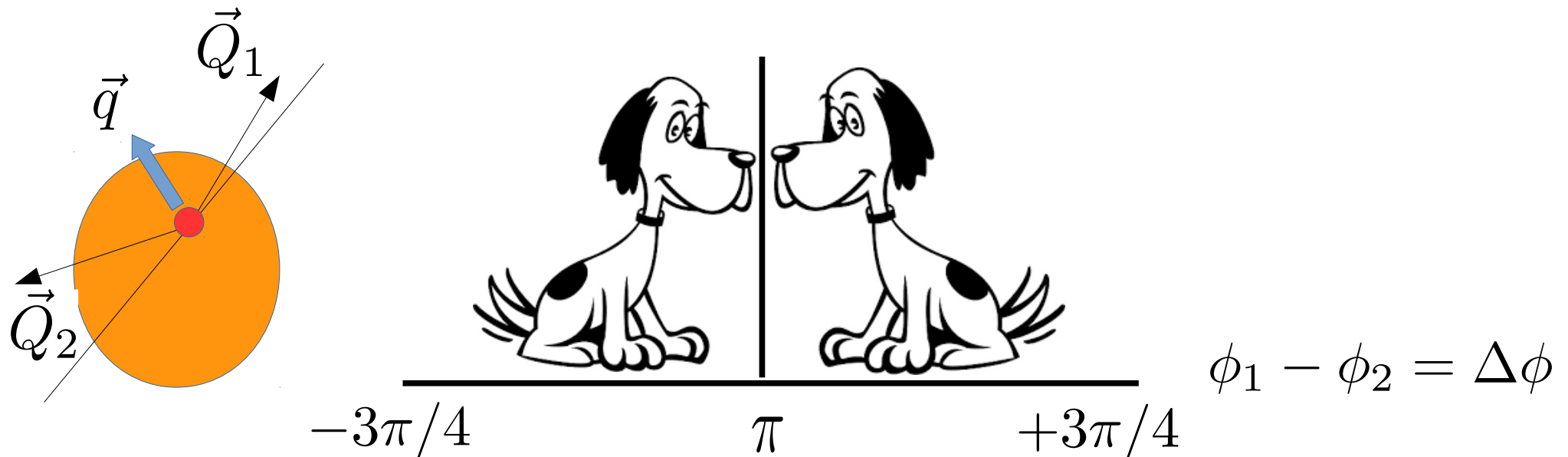




Precision Dijet Acoplanarity Tomography of the Chromo Structure of Perfect QCD Fluids

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Can we observe via A+A the QCD Landau/Rutherford scattering tails “wag” beyond the Moliere/Gaussian (BDMS Q_s) jet medium broadening approximation?



D.Appel 1986

J.P.Blaizot, L.McLerran(1986); M. Greco,(1985); V. Sudakov (1956)

Acoplanarity in
p+p is due to
Gluon radiation
from dijet antenna

In the parton model there are no bremsstrahlung effects, so we have simply $dP/dK_\eta = \delta(K_\eta)$. With perturbative QCD, multiple gluon emission from the hard scattering can be resummed in perturbation theory,¹⁴ and for the one-dimensional normal momentum density has the form

$$\frac{1}{\sigma_0(p,p_T)} \frac{1}{p_T} \frac{d\sigma}{d\phi} = \frac{dP}{dK_\eta} = \frac{1}{\pi} \int_0^\infty db \cos(K_\eta b) \exp[\tilde{B}(b)] .$$

In Double leading log
Sudakov approx

$$\tilde{B}(b) = - \int_{(b_0/b)^2}^{Q^2} \frac{dq^2}{q^2} \left[\ln \left[\frac{Q^2}{q^2} \right] A'(\alpha_s(q)) + B'(\alpha_s(q)) \right]$$

Acoplanarity in A+A arises from convolution of Sudakov and Jet-medium multiple scattering probabilities

$$F(\ell_T) \propto d\sigma/d^2\ell_T$$

$$\frac{dP}{dK_\eta} = \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} \left[\frac{1}{n!} \prod_{i=1}^n \int d^2k_{Ti} B(\mathbf{k}_{Ti}) \frac{1}{m!} \prod_{j=1}^m \int d^2l_{Tj} F(l_{Tj}) \delta \left[K_\eta - \sum_{i=1}^n (\mathbf{k}_{Ti})_\eta - \sum_{j=1}^m (l_{Tj})_\eta \right] \right]$$

$$\int_{-\infty}^{+\infty} dK_\eta \exp(iK_\eta b) \frac{dP}{dK_\eta} = \exp[\tilde{B}(b) + \tilde{F}(b)]$$

Current State of the “Acoplanarity Art”

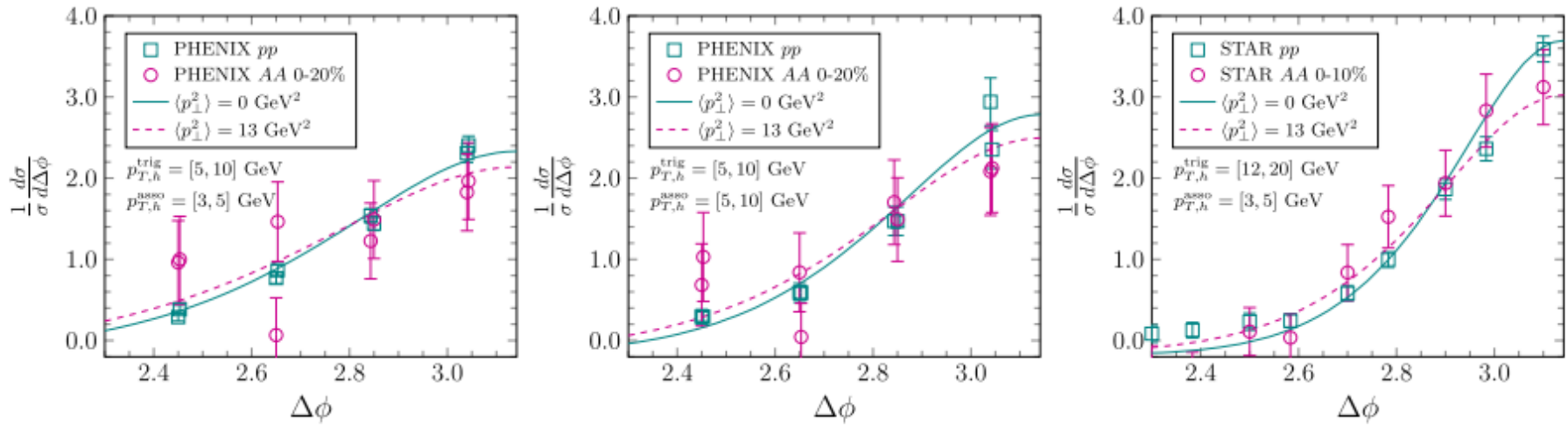


Fig. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.

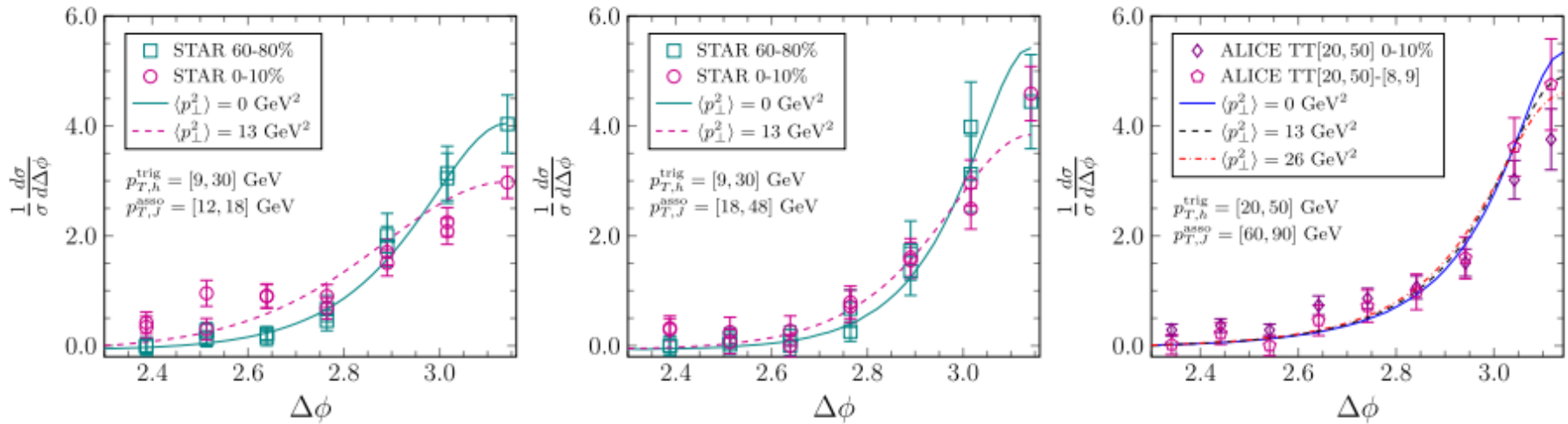


Fig. 2. Normalized hadron-jet angular correlation compared with STAR [53] and the ALICE [54] data. A factor of 3/2 is multiplied to the charged jet energy for our calculation to account for the energy carried by neutral particles. Two sets of ALICE data are shown: TT(trigger track)[20–50] (GeV) represents 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) already does. Much higher precision data in the future needed to test color dof $n_a(T)$ and $d\sigma_{ab}/dq^2$]

My interest in acoplanarity was rekindled by a Peter Jacob question after my INT 2017 talk on

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

CUJET3.0 **Jiechen Xu**, J.Liao, MG, Chin.Phys.Lett. 32 (2015) and **JHEP 1602 (2016) 169**

CUJET3.1 **Shuzhe Shi**, J.Xu, J.Liao, MG, QM17

CIBJET1.0 **Shuzhe Shi**, J.Liao, MG: **arXiv:1804.01915** and QM18

**Theme: Probing the Color Structure of the Perfect QCD Fluids via Soft-Hard-Event-by-Event
RAA and Azimuthal Harmonics**

[See also **J.Noronha-Hostler** etal, ebe vUSPH+BBMG PRL116 (2016)]

Peter's question (rephrased) :

Can **future** higher precision dijet acoplanarity measurements falsify sQGMP or pQGP or AdS-BH models of jet-medium interactions (and hopefully elucidate color confinement)?

Or are jet observables limited to the extraction of just an effective BDMS medium saturation parameter?


$$Q_s^2(a) \equiv \left\langle q_\perp^2 \frac{L}{\lambda} \right\rangle_a \equiv \int dt \sum_b \hat{q}_{ab}(x(t), t) \equiv \sum_b \int dt d^2 q_\perp q_\perp^2 \Gamma_{ab}(q_\perp, t)$$

Can acoplanarity **distribution shapes** help to extract information on the color dof in Perfect QCD fluids and constrain the microscopic differential scattering rates, Γ_{ab} , near $T \sim T_c$?

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


[Do any Γ_{ab} exhibit critical opalescence near T_c to account for perfect fluidity in AA?]

The Extra Strong Quark-Gluon Plasma
Stony Brook, Oct.2-3, 2008
A Symposium Celebrating the 60th Birthday of Edward Shuryak



Extremely Strong Magnetic Quenching of Electric Jet

— THE Physicist and the magnetic aspect of ESQGP



Jinfeng Liao
LBNL
Oct. 3, 2008

JL reported the joint work of Ed and JL (not posted yet at that time), on a novel way of resolving the issue of large jet v_2 .

[MG:Until 2014 I did not think ESQGP was needed to solve the RAA- v_2 puzzle. Sheer desperation trying many other ways to solve the RAA- v_2 puzzle led me to ask Jinfeng L to join our CUJET] 5

$$\frac{dN_{BDMS}}{dq_T^2} = \frac{e^{-q_T^2/Q_s^2}}{Q_s^2} \quad \text{versus} \quad \frac{dN_{GLV}}{dq_T^2} = f(q_T, \mu, \chi)$$

Moliere Gaussian (Qs) vs Elastic scattering opacity series $(\mu, \chi = L/\lambda, Q_s^2 = \chi\mu^2\zeta)$

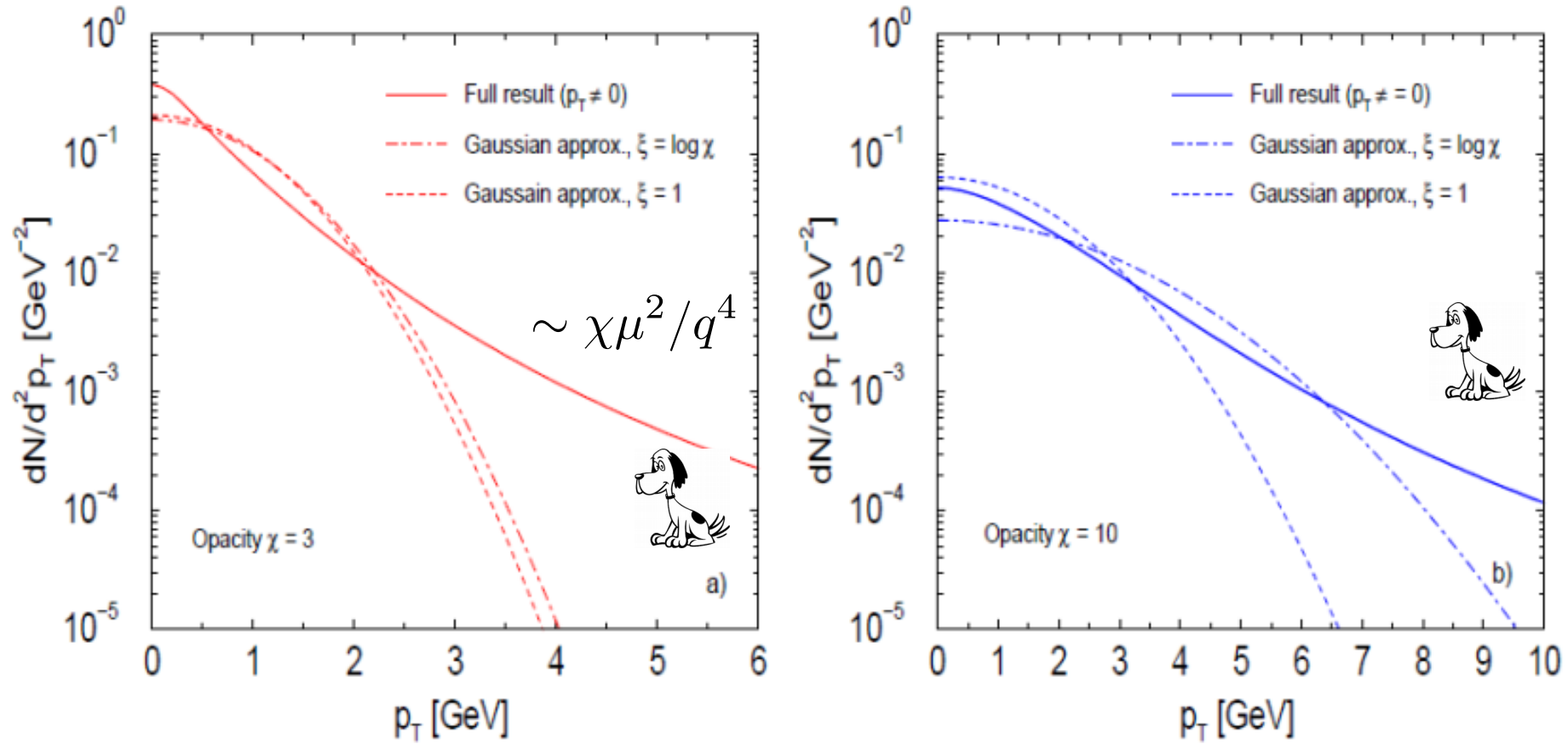
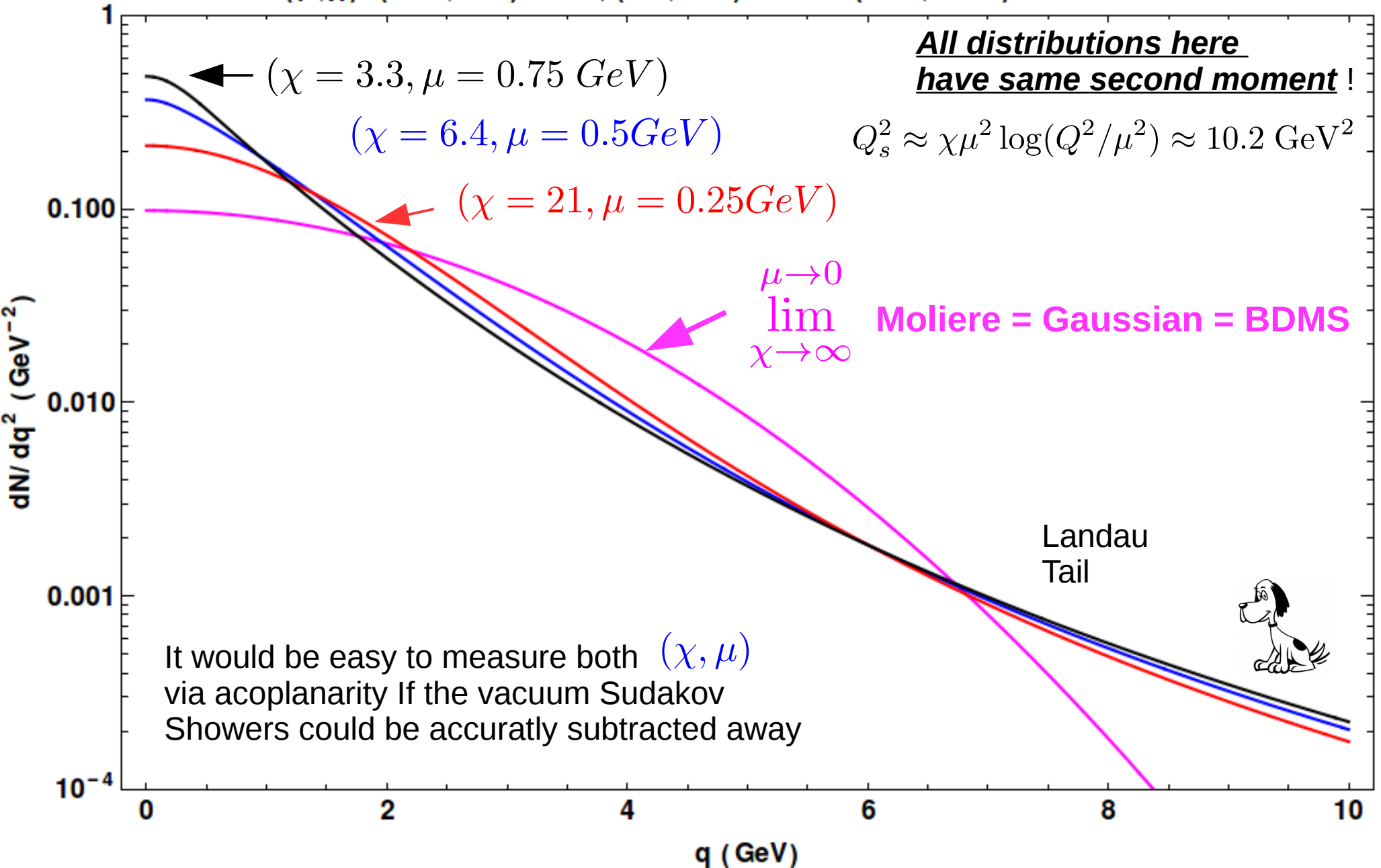


FIG 3. The final jet p_T distribution is shown versus p_T for two different opacities $\chi = 3$ (Fig. 3a) and $\chi = 10$ (Fig. 3b). We compare the full result (without the delta function contribution at $p_T \sim 0$) to the Moliere Gaussian approximation with $\xi = 1$ and $\xi = \log \chi$. In this example we use $\mu^2 = 0.25$ GeV 2 .

(See also poster Cor-45 by Hanzhon Zhang)

Conclusion 1:

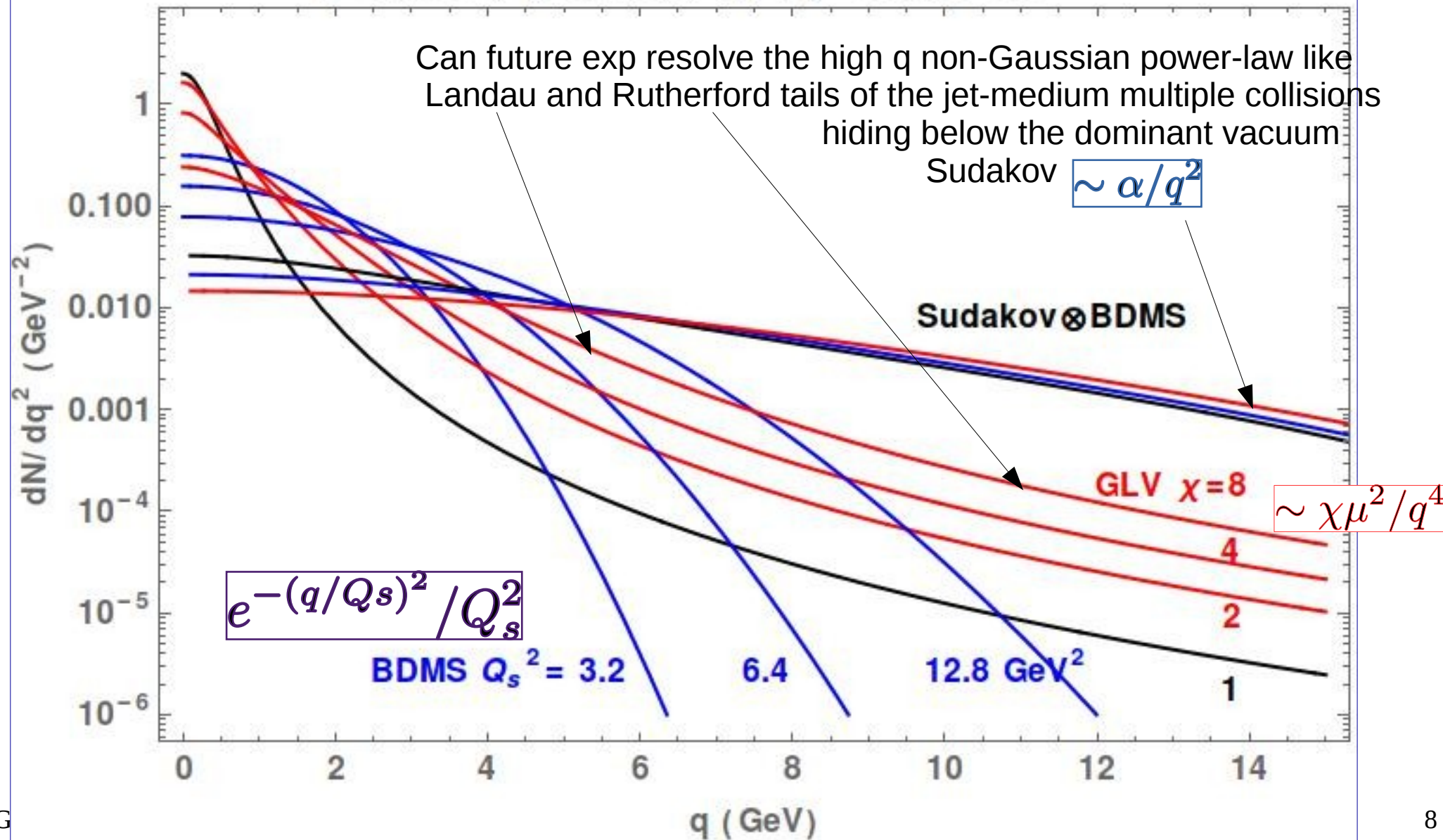
$Q=20$ dN/dq^2 Gauss(Q_s) (magenta) vs GLV(μ, χ) shapes for fixed $Q_s^2 = 10.19$
 $(\mu, \chi) = (0.75, 3.25)$ black, $(0.5, 6.38)$ blue vs $(0.25, 20.99)$ red



Conclusion 2: Unfortunately Vacuum Sudakov dominates over medium induced dijet acoplanarity

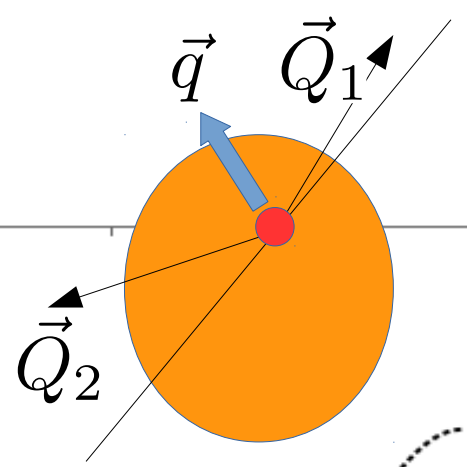
Percent level precision needed to resolve BDMS Q_s into (χ, μ)

$Q=20$ dN/dq^2 Gauss(Q_s^2) blue, GLV(μ, χ) orange, Yukawa(μ) black
 $\mu=0.5$ GeV ; $\chi=1,2,4,8$; $Q_s^2/\chi=1.59575$ GeV²



Conclusion 3:

h+Jet Acoplanarity $dN_{\text{bdms}}/d\Delta\phi$ vs $\Delta\phi$
for Vac+BDMS $\alpha=0.09$ for $Q=20$ (solid),60(dots)
 $Q_s = 0$ (black),3 (blue), 5 (red)



Dijet transverse acoplanarity momentum

$$\vec{q} = \vec{Q}_1 + \vec{Q}_2$$

$$q^2 = Q_1^2 + Q_2^2 + 2Q_1Q_2\cos(\phi_1 - \phi_2)$$

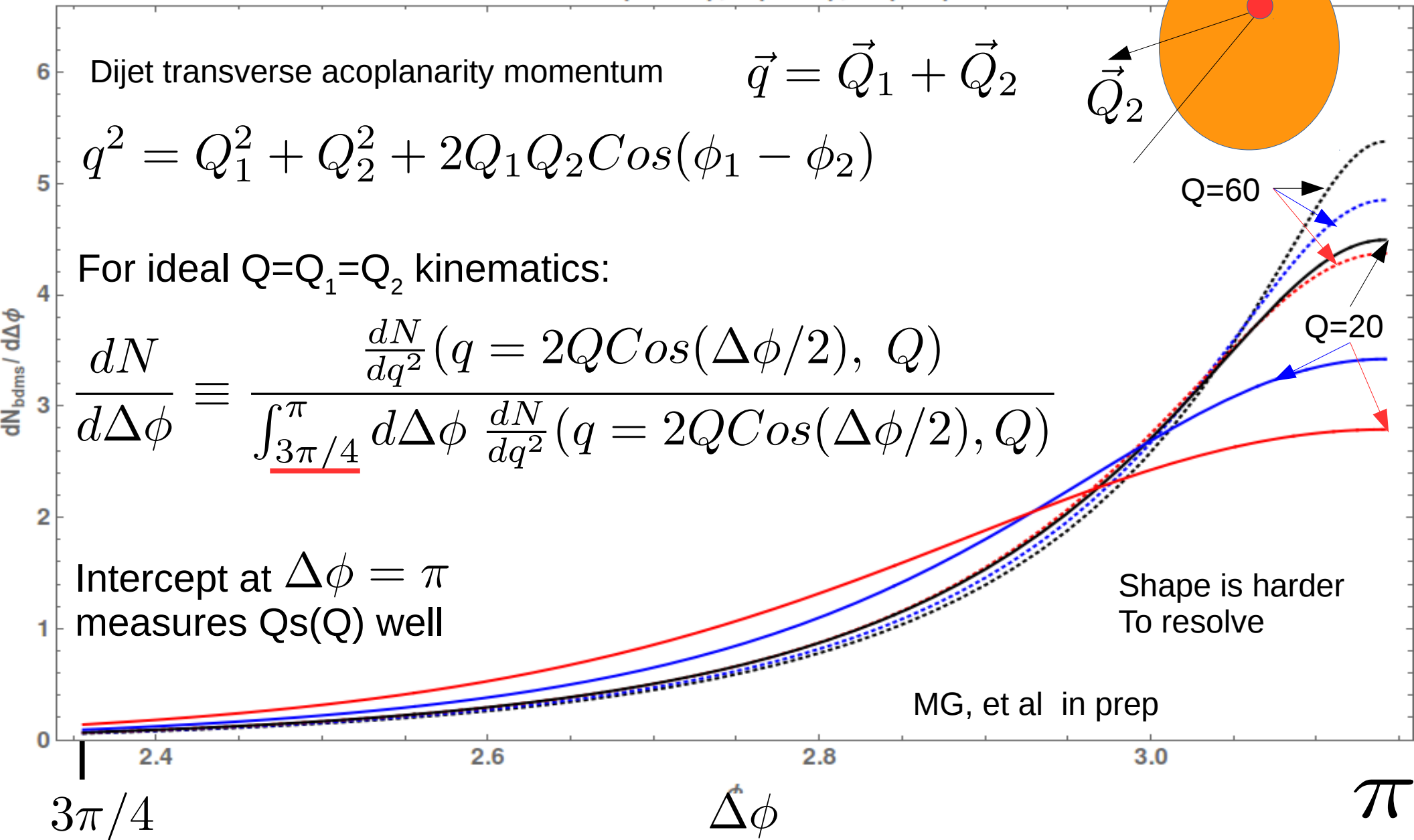
For ideal $Q=Q_1=Q_2$ kinematics:

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

Intercept at $\Delta\phi = \pi$
 measures $Q_s(Q)$ well

Shape is harder
 To resolve

MG, et al in prep



In CIBJET we tested 4 models of sQGP compatible with Lattice QCD thermo
(also tested HTL/QGP models without magnetic monopoles)

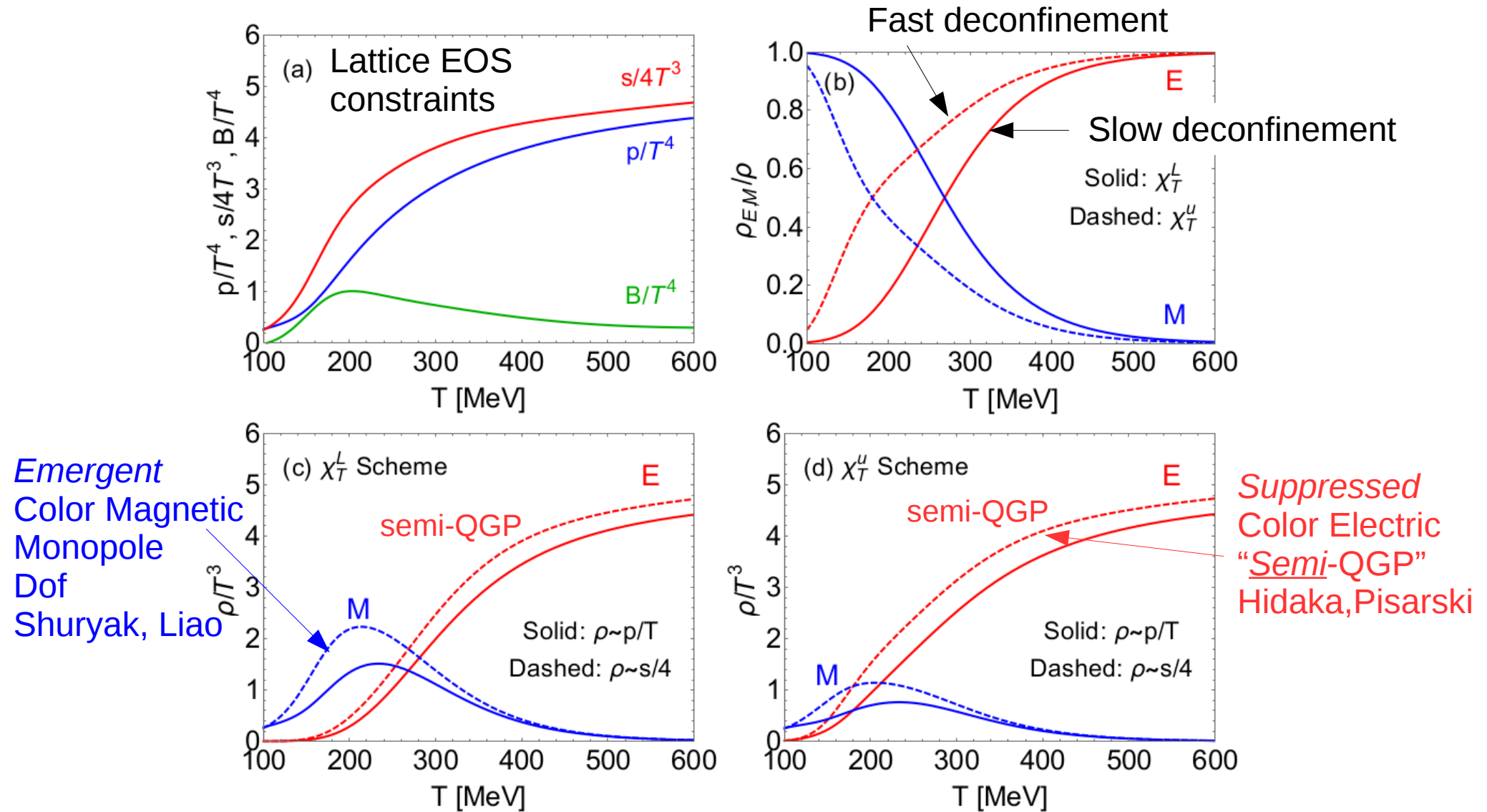
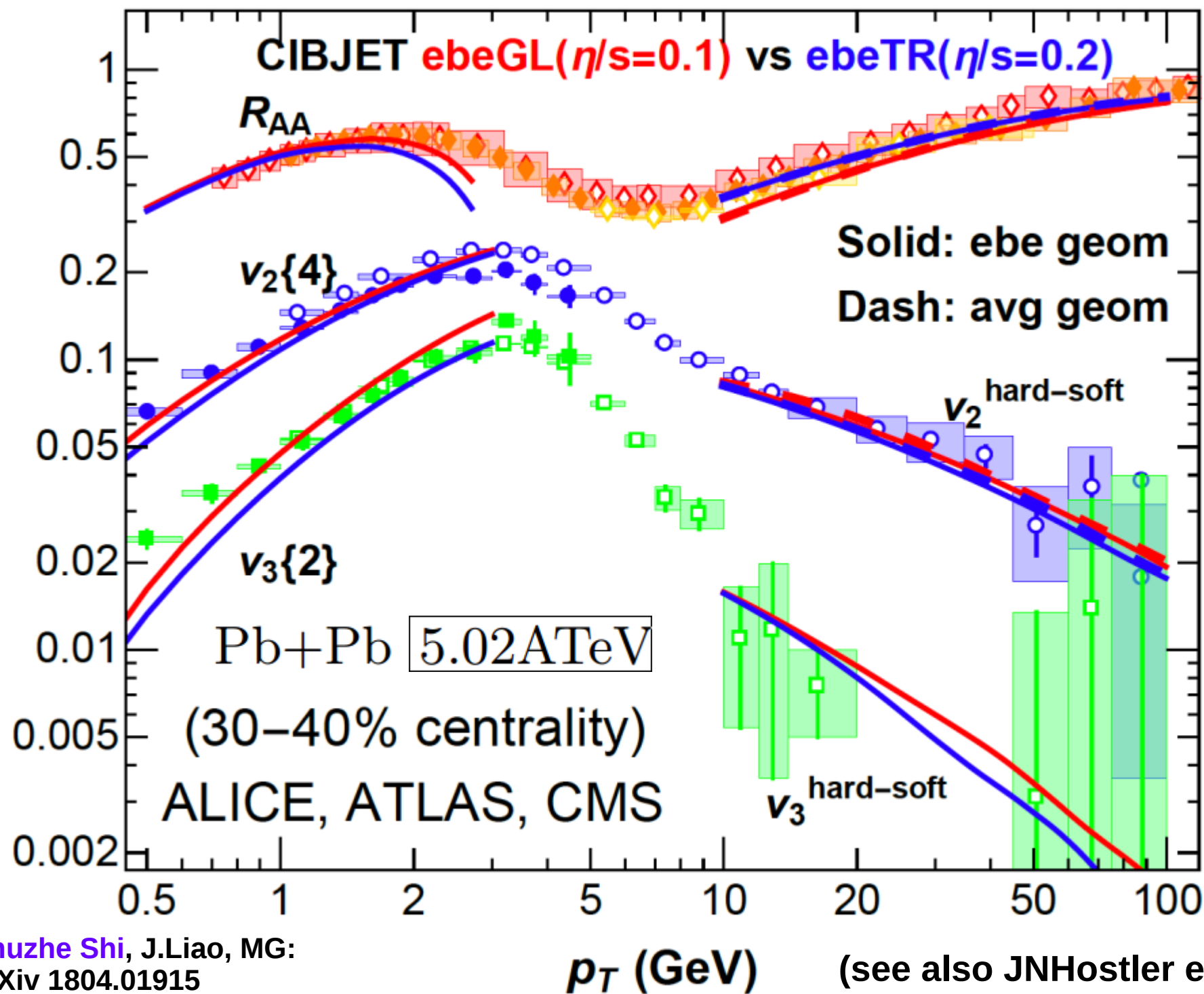


Figure 6. (Color online) (a) The effective ideal quasiparticle density, $\rho/T^3 = \xi_p P/T^4$, in the Pressure Scheme (PS, Blue) is compared with effective density, $\rho/T^3 = \xi_p S/4T^3$, in the Entropy Scheme (ES, Red) based on fits to lattice data from HotQCD Collaboration [56]. The difference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

Consistent Quantitative Soft-Hard Event Engineering with CIBJET/sQGMP



Global RHIC+LHC1+LHC2 RAA+v2 $\chi^2(\alpha_c, c_m)$ fit contours

sQGMP=(Suppressed $\chi_T^L = c_q L + c_g L^2$ elec semi-Q+G) + (Emergen(1 - χ_T^L) mag.monopoles)

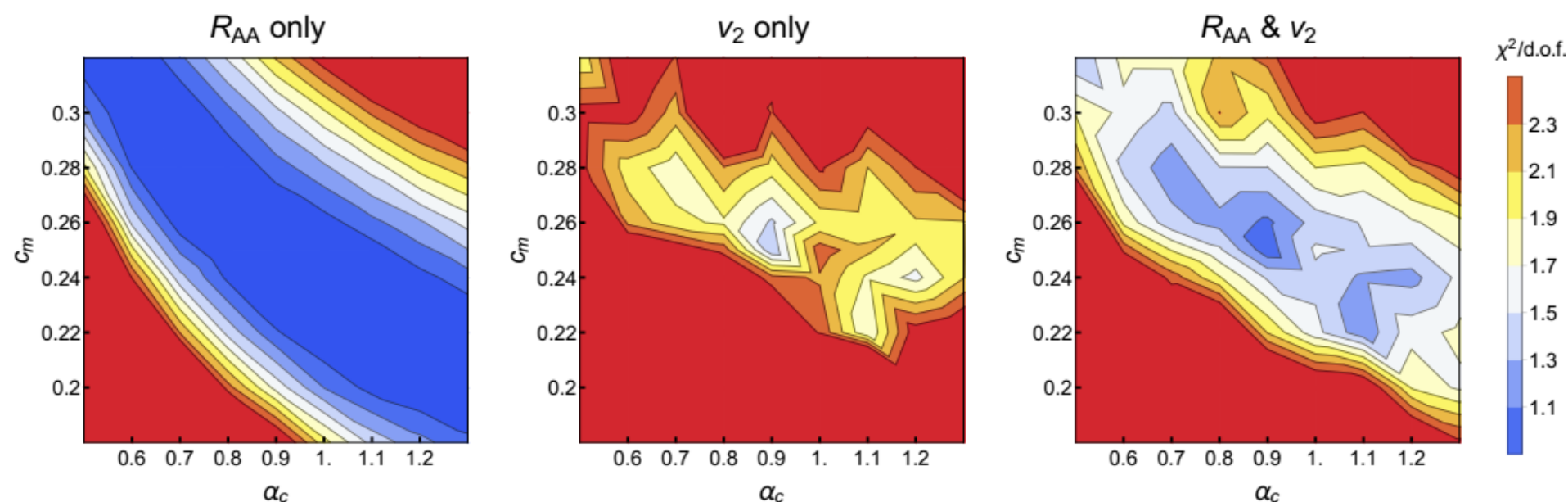


FIG. 1: (color online) $\chi^2/\text{d.o.f.}$ comparing χ_T^L -scheme CUJET3 results with RHIC and LHC data. Left: $\chi^2/\text{d.o.f.}$ for R_{AA} only. Middle: $\chi^2/\text{d.o.f.}$ for v_2 only. Right: $\chi^2/\text{d.o.f.}$ including both R_{AA} and v_2

With CIBJET = **ebe** IC+VISHNU+CUJET3.1 framework

Shuzhe Shi found that ebe only makes $\sim 10\%$ changes to hard v_2 relative using event ave geom

This creates tension between CIBJET and vUSPhydro SHEE framework interpretations.

MGyulassy QM2018 CIBJET has advantage that it interpolates between soft perfect fluidity and jets. 12

Jet Transport Coefficients = 2nd moment of $\sum_b \Gamma_{ab}(q_\perp, T)$ semiQGMP diff rates

$$\hat{q}_F(E, T) = \int_0^{6ET} dq_\perp^2 \frac{2\pi}{(\mathbf{q}_\perp^2 + f_E^2 \mu^2(z))(\mathbf{q}_\perp^2 + f_M^2 \mu^2(z))} \rho(T)$$

$$\begin{aligned} q(q+g) \\ qm \end{aligned} \quad \left\{ [C_{qq}f_q + C_{qg}f_g] \cdot [\alpha_s^2(\mathbf{q}_\perp^2)] \cdot [f_E^2 \mathbf{q}_\perp^2 + f_E^2 f_M^2 \mu^2(z)] + \right. \\ \left. [C_{qm}(1 - f_q - f_g)] \cdot [1] \cdot [f_M^2 \mathbf{q}_\perp^2 + f_E^2 f_M^2 \mu^2(z)] \right\}, \quad (14)$$

$$\hat{q}_g(E, T) = \int_0^{6ET} dq_\perp^2 \frac{2\pi}{(\mathbf{q}_\perp^2 + f_E^2 \mu^2(z))(\mathbf{q}_\perp^2 + f_M^2 \mu^2(z))} \rho(T)$$

$$\begin{aligned} g(q+g) \\ gm \end{aligned} \quad \left\{ [C_{gq}f_q + C_{gg}f_g] \cdot [\alpha_s^2(\mathbf{q}_\perp^2)] \cdot [f_E^2 \mathbf{q}_\perp^2 + f_E^2 f_M^2 \mu^2(z)] + \right. \\ \left. [C_{gm}(1 - f_q - f_g)] \cdot [1] \cdot [f_M^2 \mathbf{q}_\perp^2 + f_E^2 f_M^2 \mu^2(z)] \right\}, \quad (15)$$

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

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

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

Note that CUJET dE/dL is **not** proportional to \hat{q} but given by a generalized DGLV formula

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

The Inverse connection between hydrodynamic shear dissipation η/s and the jet transport $\hat{q}_a(T,E)$ fields in a multi-component plasma

estimate of shear viscosity per entropy density η/s can be derived from kinetic theory

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

Depends on composition and m.f.p. of all quasi-particle d.o.f. in the fluid

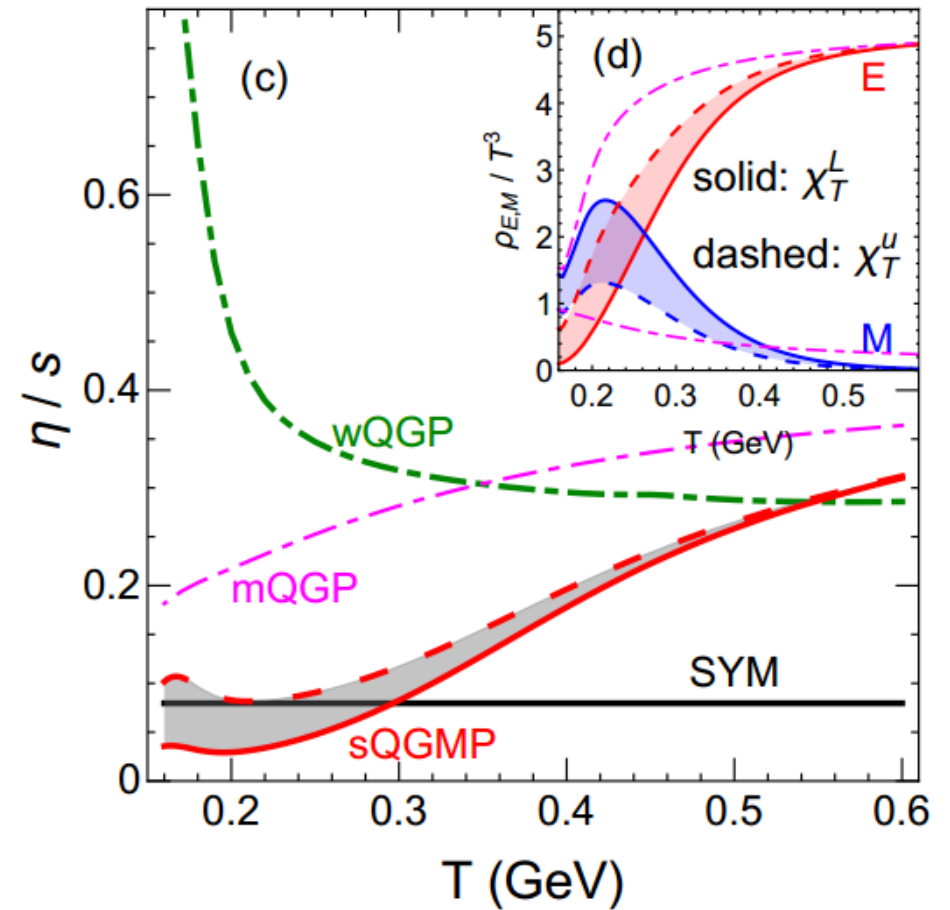
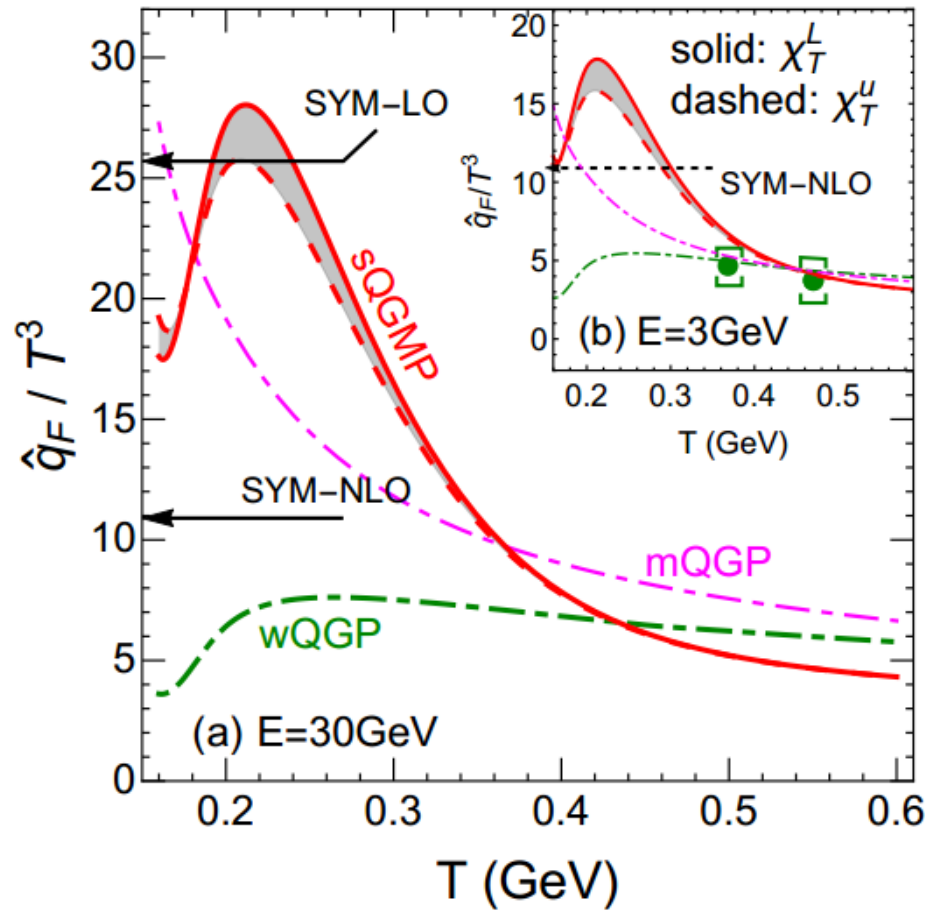
$$\begin{aligned} &= \frac{4T}{5s} \sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle S_{ab} \rangle/2} dq^2 \frac{4q^2}{\langle S_{ab} \rangle} \frac{d\sigma_{ab}}{dq^2} \right)^{-1} \\ &= \frac{18T^3}{5s} \sum_a \rho_a / \hat{q}_a(T, E = 3T) . \end{aligned}$$

Jiechen Xu, Jinfeng Liao, MG JHEP02(2016)

- [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).

Compare **sQGMP** and Zakharov's **mQGP** JETP Lett.(2015), where $q+g$ were not suppressed

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



Lattice constrained sQGMP color composition model accounts not only for global RHIC&LHC RAA, v_2 , v_3 data but uniquely accounts for bulk perfect fluidity due to Near unitary bound $q+m$ and $g+m$ scattering rate near T_c !

5-dimensional **Einstein-Maxwell-Dilaton** modeling of perfect fluids with $\eta/s = 1/4\pi$

Energy loss, equilibration, and thermodynamics of strongly coupled supersymmetric cousins of quark-gluon-monopole plasmas

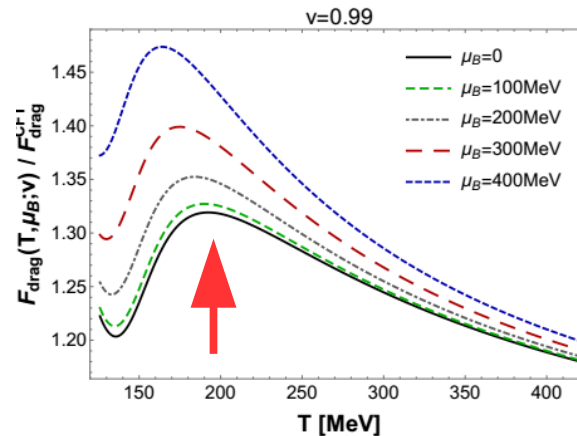
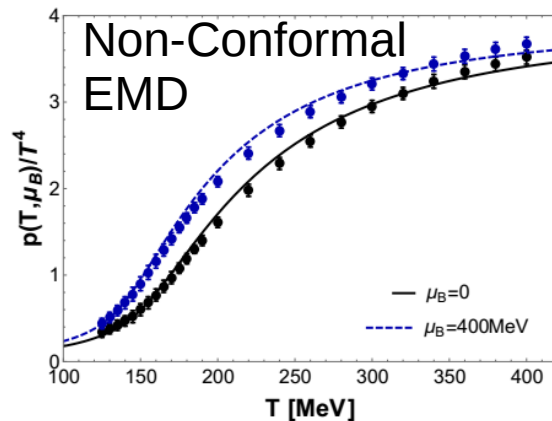
Rougemont, R., Ficnar, A., Finazzo, S.I., Noronha, J., JHEP04(2016)102

$$S = \frac{1}{16\pi G_5} \int_{\mathcal{M}_5} d^5x \sqrt{-g} \left[\mathcal{R} - \frac{1}{2} (\partial_\mu \phi)^2 - V(\phi) - \frac{f(\phi)}{4} F_{\mu\nu}^2 \right]$$

O. DeWolfe, S.S. Gubser and C. Rosen, PRD83 (2011) 086005

Ansatz for the bulk gravity fields

$$ds^2 = e^{2A(r)} [-h(r)dt^2 + d\vec{x}^2] + \frac{e^{2B(r)}dr^2}{h(r)}, \quad \phi = \phi(r), \quad A = A_\mu dx^\mu = \Phi(r)dt,$$



$$\frac{dE^{CFT}}{dx} = T^2 \sqrt{\lambda_{tH}} (\pi \gamma \beta / 2)$$

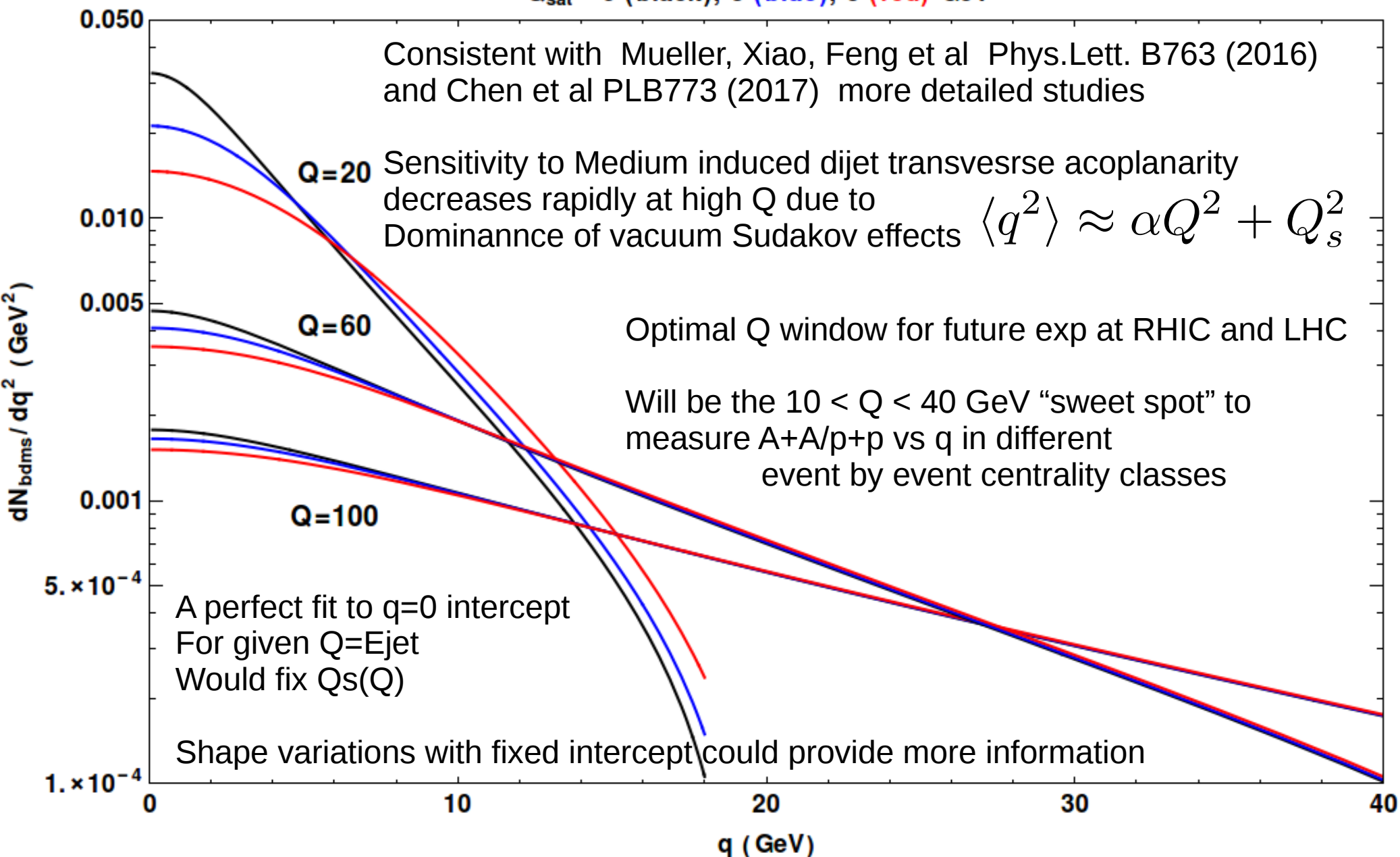
But Non-Conformal geometry
=> non-trivial **enhancement**
of string drag force near
 $T \sim (1-2) T_c$

EMD also predicts enhancement of dE/dx and q_{hat} near cross over but less than sQGMP fits.
Quantitative χ^2 tests of such holographic models with RAA & v_2 data have yet to be performed

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

Hadron-Jet Vac \otimes BDMS dN_{bdms}/dq^2 vs q for $Q=20, 60, 100$ GeV

$Q_{\text{sat}} = 0$ (black), 3 (blue), 5 (red) GeV

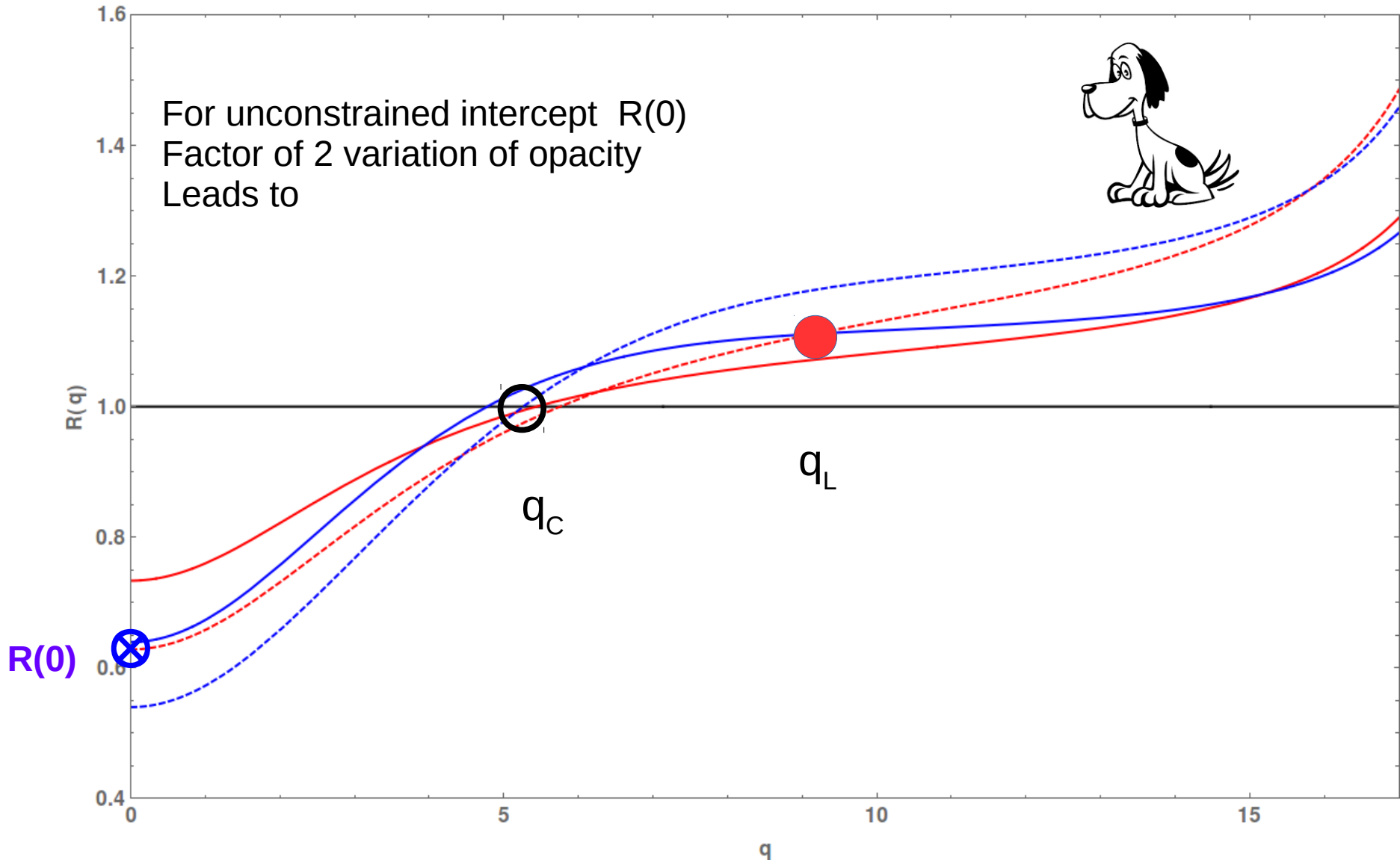


For realistic Sudakov fits to p+p need lower $\alpha \approx 0.09$

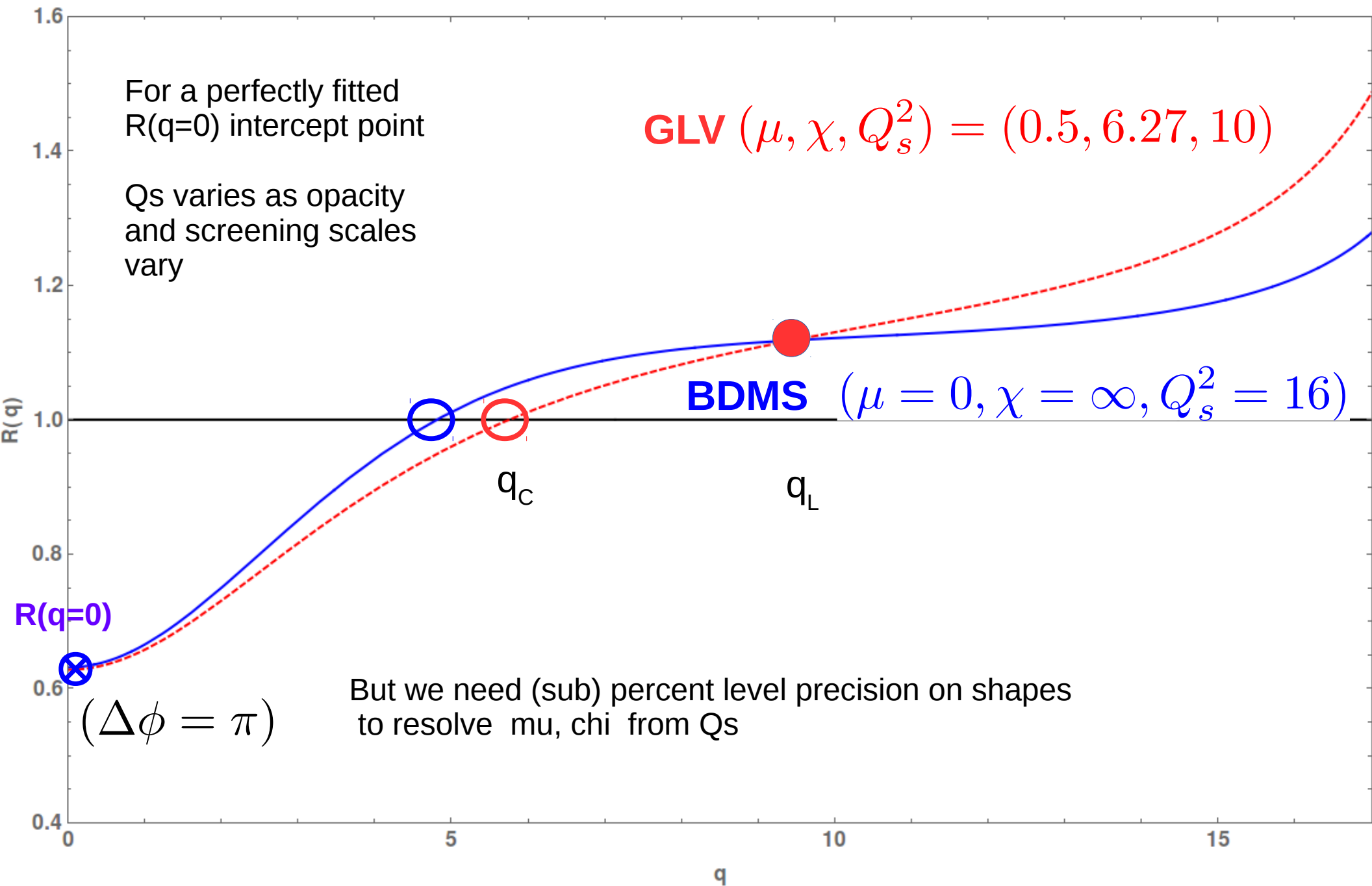
Requires much higher precision to resolve GLV finite (χ, μ) from BDMS(Q_s)

Ratio $dN(\text{Vac}+\text{GLV})/dN(\text{Vac})$ (red) vs $dN(\text{Vac}+\text{BDMS})/dN(\text{Vac})$ (blue) vs q

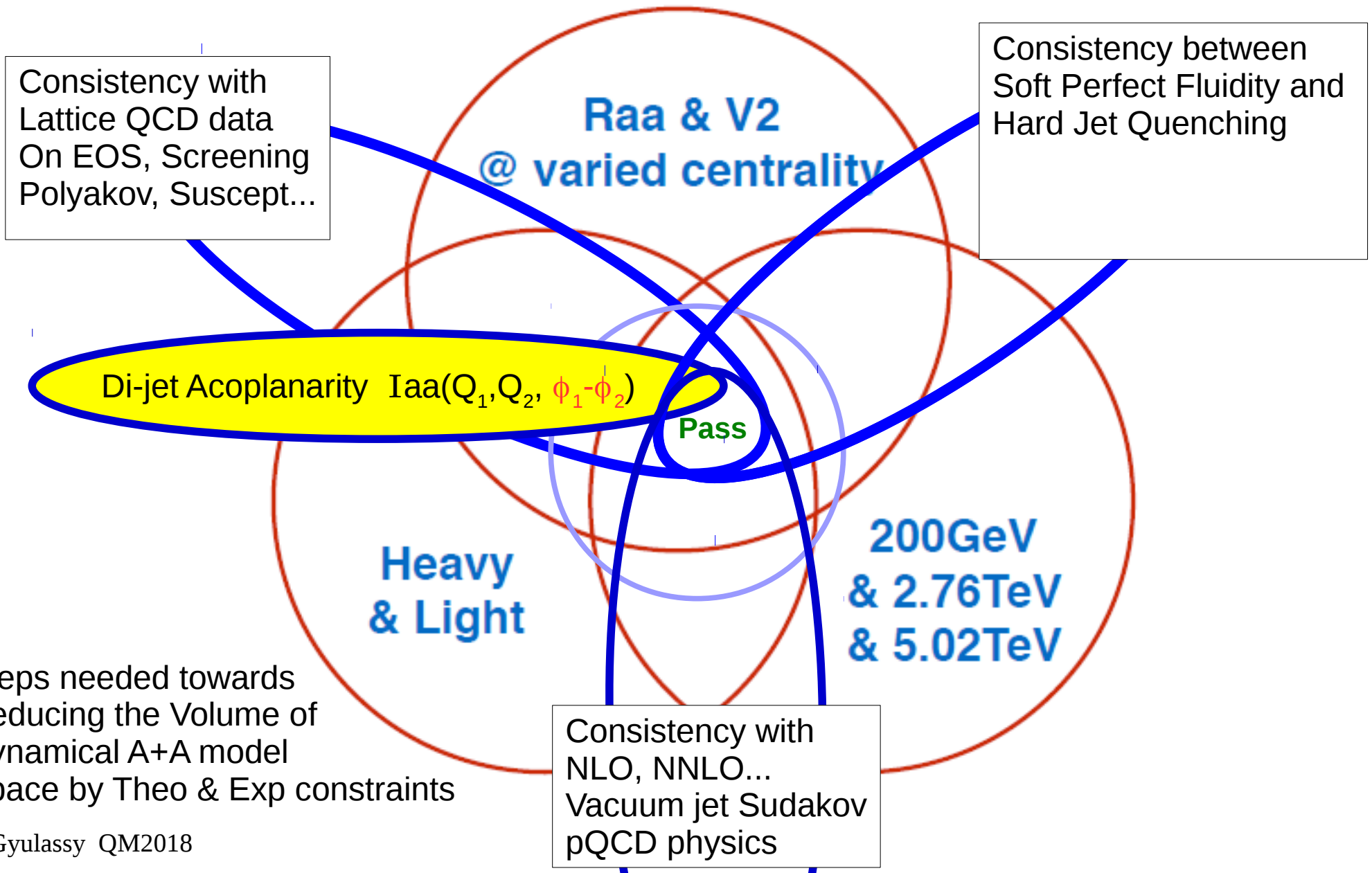
for $Q=20$, $\alpha=0.09$, GLV $\mu=0.5$ $\chi=6, 10 \iff$ BDMS $Q_s^2=9.57449$ (solid), 15.9575 (dash)



Ratio $dN(\text{Vac}+\text{GLV})/dN(\text{Vac})$ (red) vs $dN(\text{Vac}+\text{BDMS})/dN(\text{Vac})$ (blue) vs q
 for $Q=20$, $\alpha=0.09$, **GLV** $\mu=0.5$ $\chi=6, 10 \Leftrightarrow$ **BDMS** $Q_s^2=10$. (solid), 16. (dash)



The Challenge to Every Model



Final remarks:

Is the extra experimental and theoretical effort needed to try to extract dynamical information such as $\Gamma_{ab}(q_\perp, T) = \rho_b(T) d^2 \sigma_{ab}(T) / d^2 q_\perp$ from the *very tiny* medium modifications of azimuthal acoplanarity observables worth it?

Yes, because we need new ways to falsify competing microscopic dynamical mechanisms such as critical opalescence in sQGMP or non-conformal holography to gain insight into the novel chromodynamics responsible for the observed perfect fluidity of the bulk in A+A and rich jet quenching patterns in the hard sector.

Italy is a great place to study acoplanarity. Thanks to QM18 organizers



Appendix: extra slides and links to longer lectures

<http://www.columbia.edu/~mg150/Talks/2017/MGyulassy-Lec2-CCNU-101817.pdf>

<http://www.columbia.edu/~mg150/Talks/2017/MGyulassy-Lec2-CCNU-101817.pdf>

distribution in the Sudakov resummation formalism as follows

$$\frac{d\sigma}{d\Delta\phi} = \sum_{a,b,c,d} \int p_{\perp\gamma} dp_{\perp\gamma} \int p_{\perp J} dp_{\perp J} \int dy_{\gamma} \int dy_J \int db \times x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b) \frac{1}{\pi} \frac{d\sigma_{ab \rightarrow cd}}{d\hat{t}} b J_0(|\vec{q}_{\perp}|b) e^{-S(Q,b)}, \quad (1)$$

where J_0 is the Bessel function of the first kind, q_{\perp} is the transverse momentum imbalance between the photon and the jet $\vec{q}_{\perp} \equiv \vec{p}_{\perp\gamma} + \vec{p}_{\perp J}$, which takes into account both initial and final transverse momentum kicks from vacuum Sudakov radiations and medium gluon radiations. Here we define $x_{a,b} = \max(p_{\perp\gamma}, p_{\perp J})(e^{\pm y_{\gamma}} + e^{\pm y_J})/\sqrt{s_{NN}}$ as

The vacuum Sudakov factor $S_{pp}(Q, b)$ is defined as

$$S_{pp}(Q, b) = S_P(Q, b) + S_{NP}(Q, b) \quad (2)$$

where the perturbative S_P Sudakov factor depends on the incoming parton flavour and outgoing jet cone size. The perturbative Sudakov factors can be written as [35–37]

pQCD Vacuum Shower
$$S_P(Q, b) = \sum_{q,g} \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[A \ln \frac{Q^2}{\mu^2} + B + D \ln \frac{1}{R^2} \right] \quad (3)$$

At the next-to-leading-log (NLL) accuracy, the coefficients can be expressed as $A = A_1 \frac{\alpha_s}{2\pi} + A_2 (\frac{\alpha_s}{2\pi})^2$, $B = B_1 \frac{\alpha_s}{2\pi}$ and $D = D_1 \frac{\alpha_s}{2\pi}$, with the value of individual terms given by the following table, where both A and B terms are summed over the corresponding incoming parton flavours.

	A_1	A_2	B_1	D_1
quark	C_F	$K \cdot C_F$	$-\frac{3}{2}C_F$	C_F
gluon	C_A	$K \cdot C_A$	$-2\beta C_A$	C_A

Here C_A and C_F are the gluon and quark Casimir factor, respectively. $\beta = \frac{11}{12} - \frac{N_f}{18}$, and $K = (\frac{67}{18} - \frac{\pi^2}{6})C_A - \frac{10}{9}N_f T_R$. $R^2 = \Delta\eta^2 + \Delta\phi^2$ represents the jet cone-size, which is set to match the experimental setup. The implementation of the non-perturbative Sudakov factor $S_{NP}(Q, b)$ follows the prescription given in Refs [61, 62]. In the Sudakov resummation formalism, following the usual b^* prescription, the factorization scale is set to be $\mu_b \equiv \frac{c_0}{b_{\perp}} \sqrt{1 + b_{\perp}^2/b_{max}^2}$,

Logarithmic approximations, quark form factors, and quantum chromodynamics

S. D. Ellis, N. Fleishon, and W. J. Stirling

1394

S. D. ELLIS, N. FLEISHON

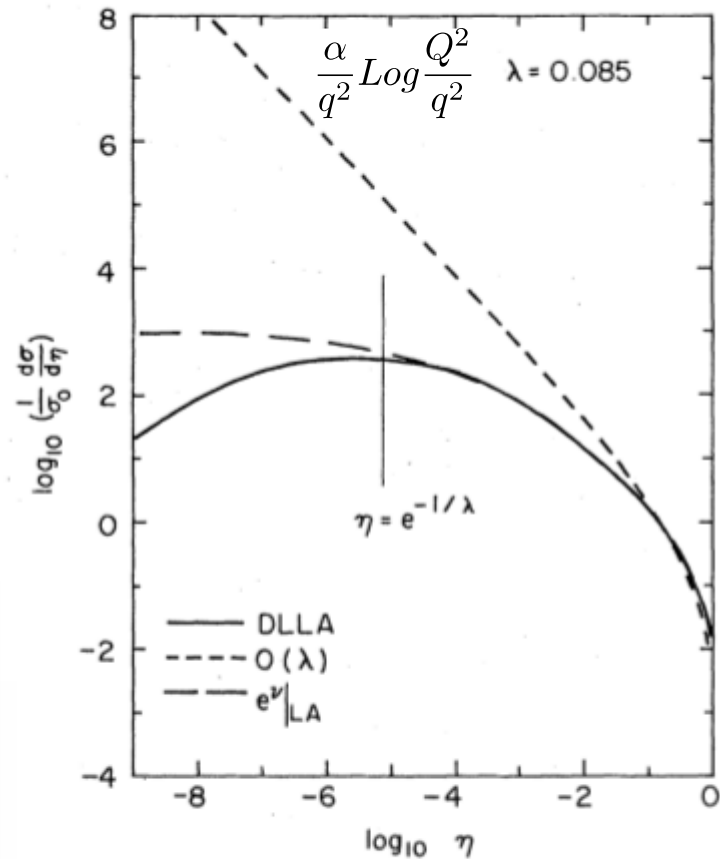


FIG. 4. Theoretical approximations to the cross section defined in the text. The long-dashed line is the soft logarithmic approximation [LA, (1), (2), (3)]. The solid line is the DLLA Eq. (2.12). The dashed line is the corresponding one-gluon contribution.

It is convenient to return to the general notation of the Introduction and define $\eta = Q_T^2/s$ and $\lambda = \alpha_s C_F/\pi$. Thus Eq. (2.11) can be written as

$$\begin{aligned} \frac{1}{\sigma_0} \frac{d\sigma}{d\eta} \Big|_{\text{DLLA}} &= \frac{\lambda}{\eta} \ln \frac{1}{\eta} \exp\left(-\frac{\lambda}{2} \ln^2 \eta\right) \theta(1-\eta) \\ &= \frac{d}{d\eta} F_{\text{DLLA}}(\eta) \theta(1-\eta) \end{aligned} \quad (2.12)$$

with $F_{\text{DLLA}}(\eta)$ identified from Eq. (1.1).

with $C_F = 4/3$, $T_R = 1/2$ and $N = 3$. It is instructive to see how the logarithms in b -space generate logarithms in q_T -space. For illustration, we take only the leading coefficient $A^{(1)} = 2C_F$ to be non-zero in $e^{S(b, Q^2)}$, and assume a fixed coupling α_s . This corresponds to

$$\frac{d\sigma}{dq_T^2} = \frac{\sigma_0}{2} \int_0^\infty b db J_0(q_T b) \exp\left[-\frac{\alpha_s C_F}{2\pi} \ln^2\left(\frac{Q^2 b^2}{b_0^2}\right)\right]. \quad (6)$$

The expressions are made more compact by defining new variables $\eta = q_T^2/Q^2$, $z = b^2 Q^2$, $\lambda = \alpha_s C_F/\pi$, $z_0 = 4 \exp(-2\gamma_E) = b_0^2$. Then

$$\frac{1}{\sigma_0} \frac{d\sigma}{d\eta} = \frac{1}{4} \int_0^\infty dz J_0(\sqrt{z\eta}) e^{-\frac{\lambda}{2} \ln^2(z/z_0)} \quad (7)$$

and we encounter the same expression as in [6], which describes the emission of soft and collinear gluons with transverse momentum conservation taken into account. The result

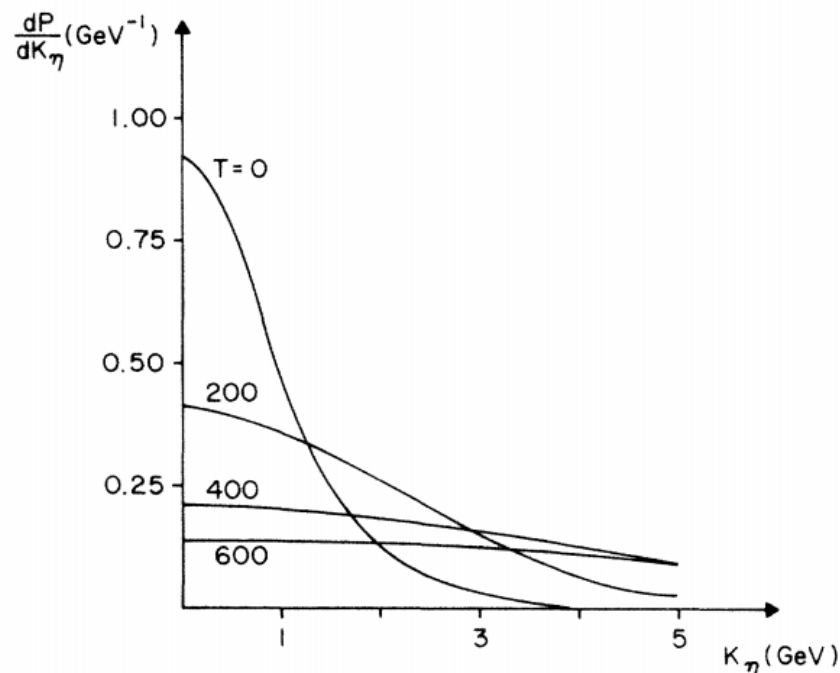
The conclusion is then that the *subleading logarithms* which arise from a correct treatment of transverse-momentum conservation can play a major role in filling in the zero at $\eta=0$ and obscuring the maximum which was present near $\ln 1/\eta \sim 1/\lambda$ in the DLLA. It is informative to di-

For $F(l_T)$, the probability density for scattering elastically off the plasma constituents with transverse-momentum transfer l_T , we propose the following form:

$$F(l_T) = \sum_x n_x R \frac{d^2 \sigma_x}{d^2 l_T}, \quad (11)$$

where x runs over the different particle types comprising the plasma ($x = g, q_i, \bar{q}_i$), with n_x their number density. This equation essentially relates the plasma mean free path to the available distance for scattering (R) for each particular l_T .

Stefan-Boltzmann wQGP model estimates



$$F(l_T) = 9aRT^3 \left[1 + \frac{N_F}{4} \right] \frac{\alpha_s^2(l_T)}{l_T^4}$$

Cut off soft divergence below pQCD Debye mass

$$\ell_{\perp} \sim gT$$

“Based on this, one is encouraged to conjecture that someday jet behavior could be used as an effective thermometer of a QCD plasma.”

Confirmed by J.P.Blaizot, L.McLerran(1986)
In more realistic detail

Medium Induced Acoplanarity Distribution shapes due to multiple collisions depend on at least two parameters

$$(\mu, \chi)$$

e.g Yukawa $\mu \approx gT$ screened parton elastic scattering

$$\frac{d\tilde{\sigma}_{el}}{d^2\mathbf{q}}(\mathbf{b}) = \int \frac{d^2\mathbf{q}}{(2\pi)^2} e^{-i\mathbf{q}\cdot\mathbf{b}} \frac{1}{\pi} \frac{\mu^2}{(\mathbf{q}^2 + \mu^2)^2} = \frac{\mu b}{4\pi^2} K_1(\mu b)$$

Mult.coll. opacity χ^n series can be summed in b-space

$$dN(\mathbf{p}) = e^{-\sigma_{el}T(\mathbf{b}_0)} \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} e^{\tilde{\sigma}_{el}(\mathbf{b})T(\mathbf{b}_0)} dN^{(0)}(\mathbf{b})$$

$$\chi = \langle L/\lambda \rangle = \int dt \int d^2\mathbf{q} \{d\sigma_{el}(t)/d^2\mathbf{q}\} \rho(t, \mathbf{b}_0) \sim O(\alpha T L)$$

$$dN(\mathbf{p} \gg \chi\mu^2\xi) \approx (\chi\mu^2\xi)/p^4 \quad \text{Landau tail}$$

In large $\chi \gg 1$ lim, distrib. approaches Moliere form

$$dN(\mathbf{p}) = \int d^2\mathbf{b} e^{i\mathbf{p}\cdot\mathbf{b}} \frac{1}{(2\pi)^2} \frac{e^{-\chi\mu^2\xi b^2/2}}{\chi\mu^2\xi} = \frac{1}{2\pi} \frac{e^{-p^2/2\chi\mu^2\xi}}{\chi\mu^2\xi}$$

In BDMS approx this Gaussian form depends on only one "saturation scale"

$$Q_s^2 = \chi\mu^2\xi = \int dt \hat{q}(t)$$

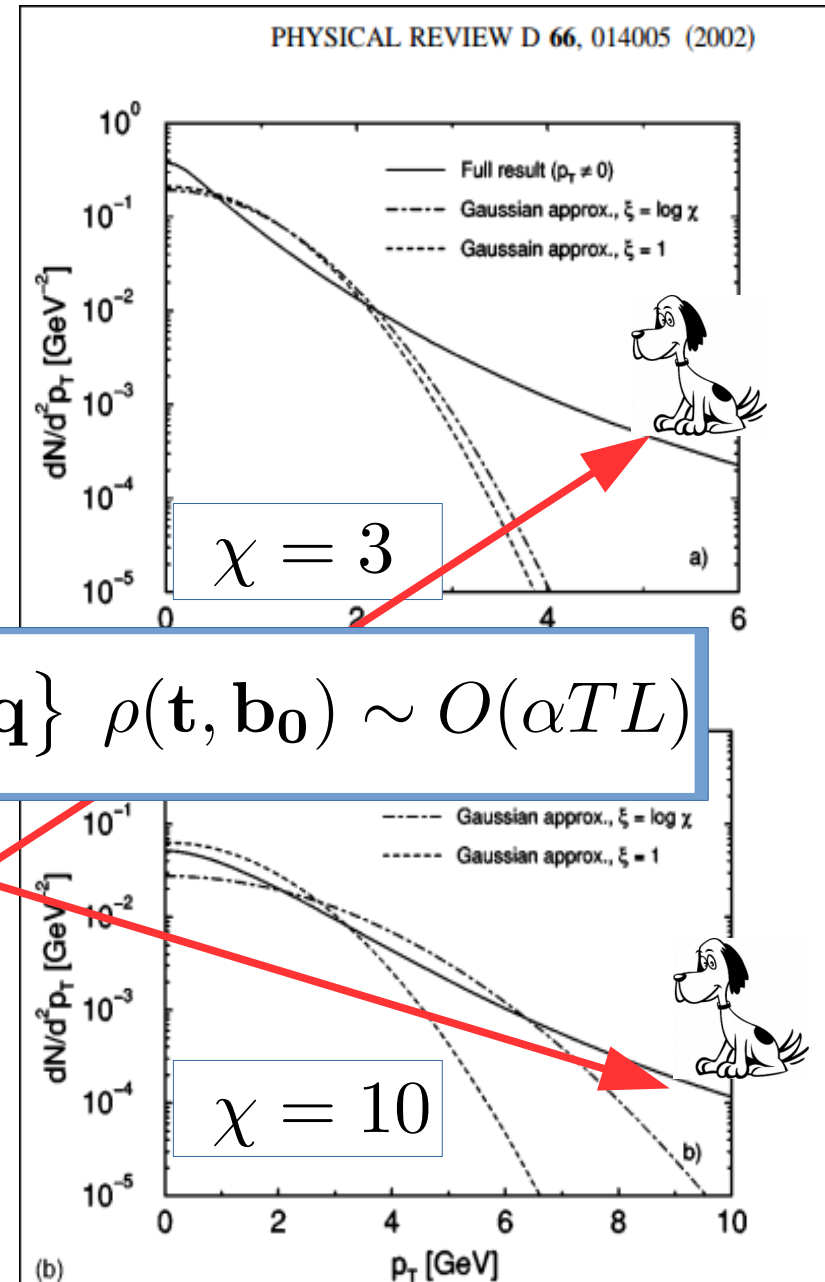
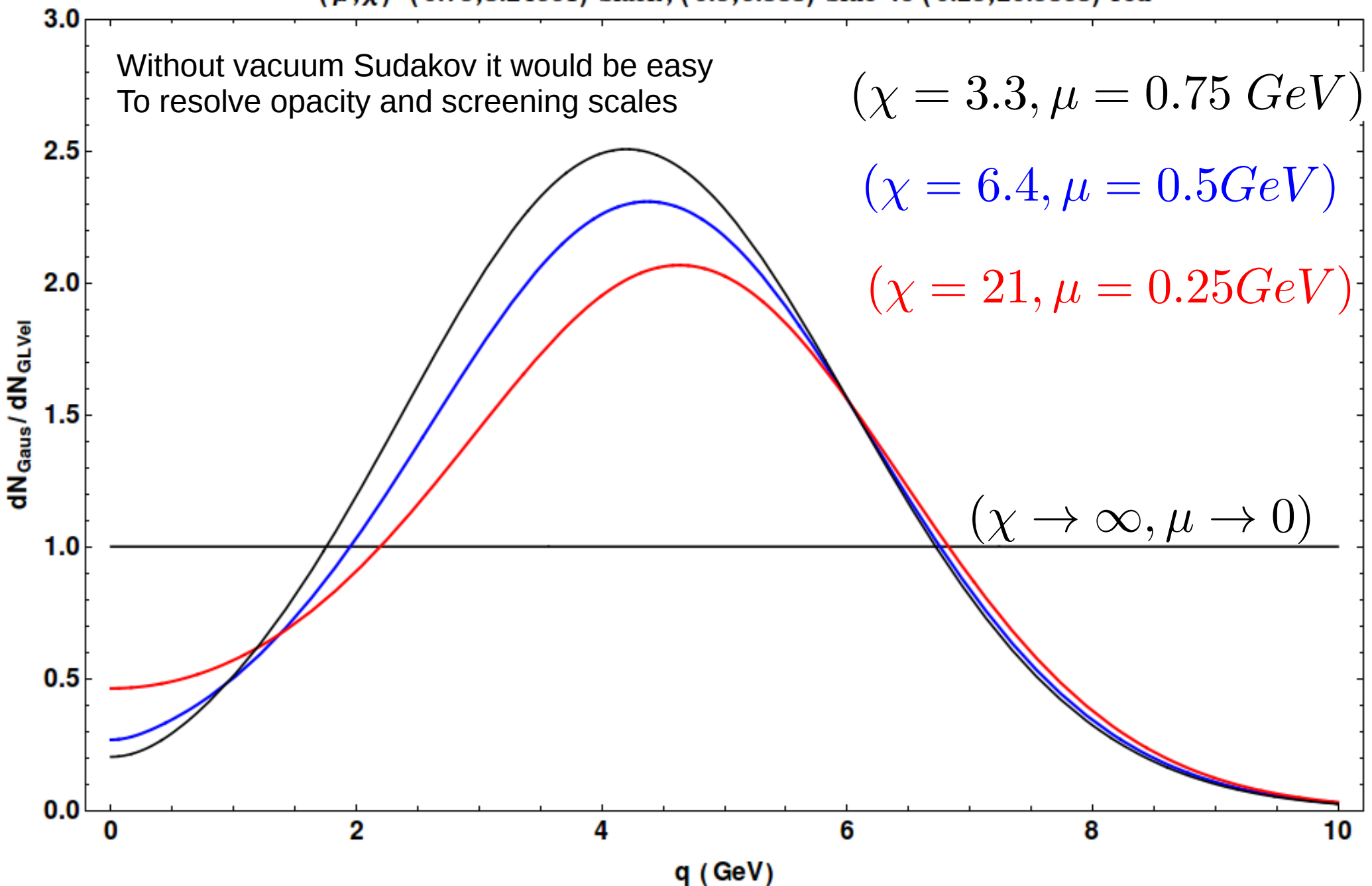


FIG. 3. The final parton p_T distribution is shown versus p_T for two different opacities $\chi=3$ (a) and $\chi=10$ (b). We compare the full result (without the delta function contribution at $p_T \sim 0$) to the Moliere Gaussian approximation with $\xi=1$ and $\xi=\log \chi$. In this example we use $\mu^2=0.25 \text{ GeV}^2$.

Conclusion 1:

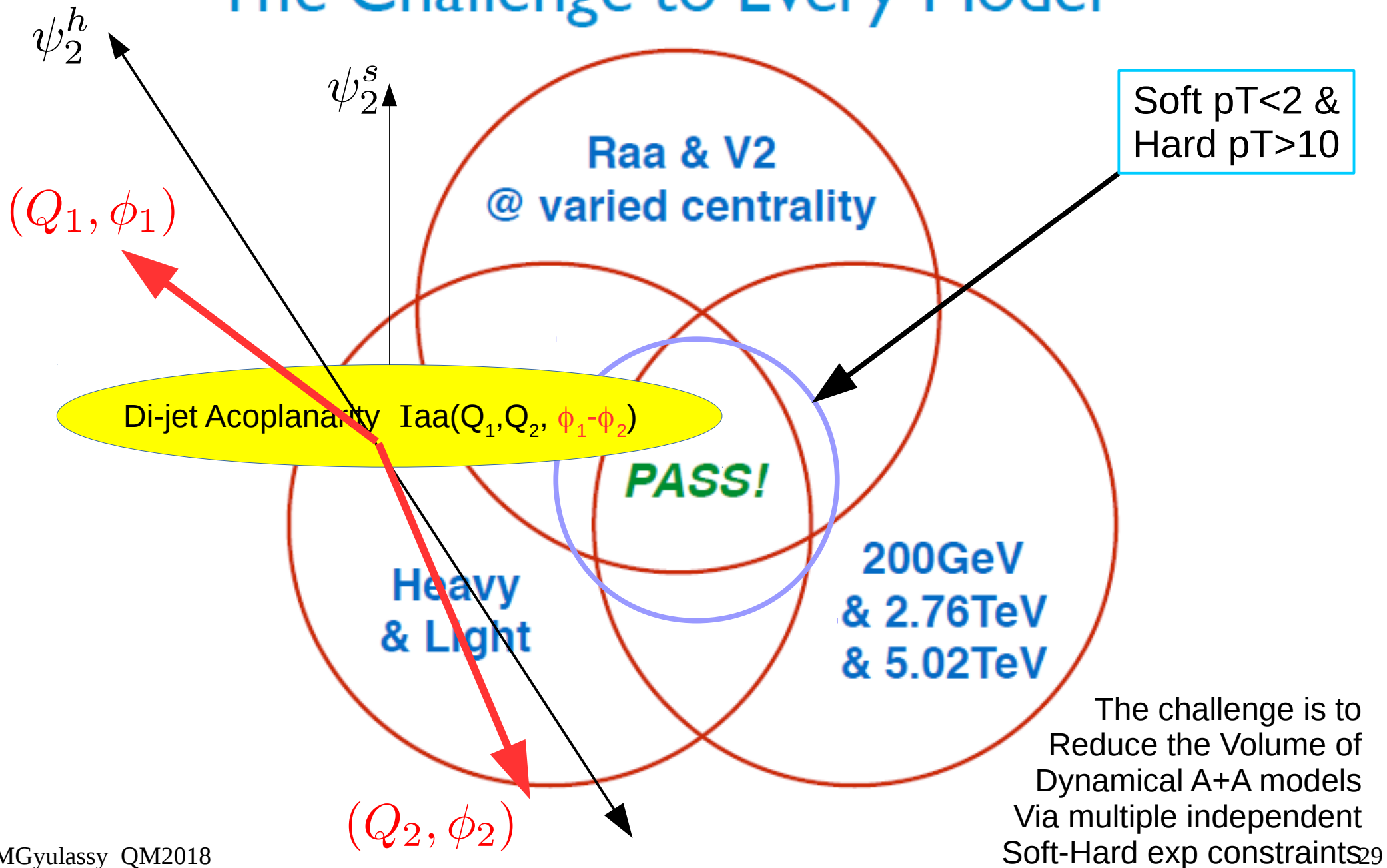
$Q=20$ Ratio $dN_{\text{Gaus}}(Q_s)/dN_{\text{GLVel}}(\mu, \chi)$ vs q for $Q_s^2 = 10.1857$

$(\mu, \chi) = (0.75, 3.24661)$ black, $(0.5, 6.383)$ blue vs $(0.25, 20.9863)$ red

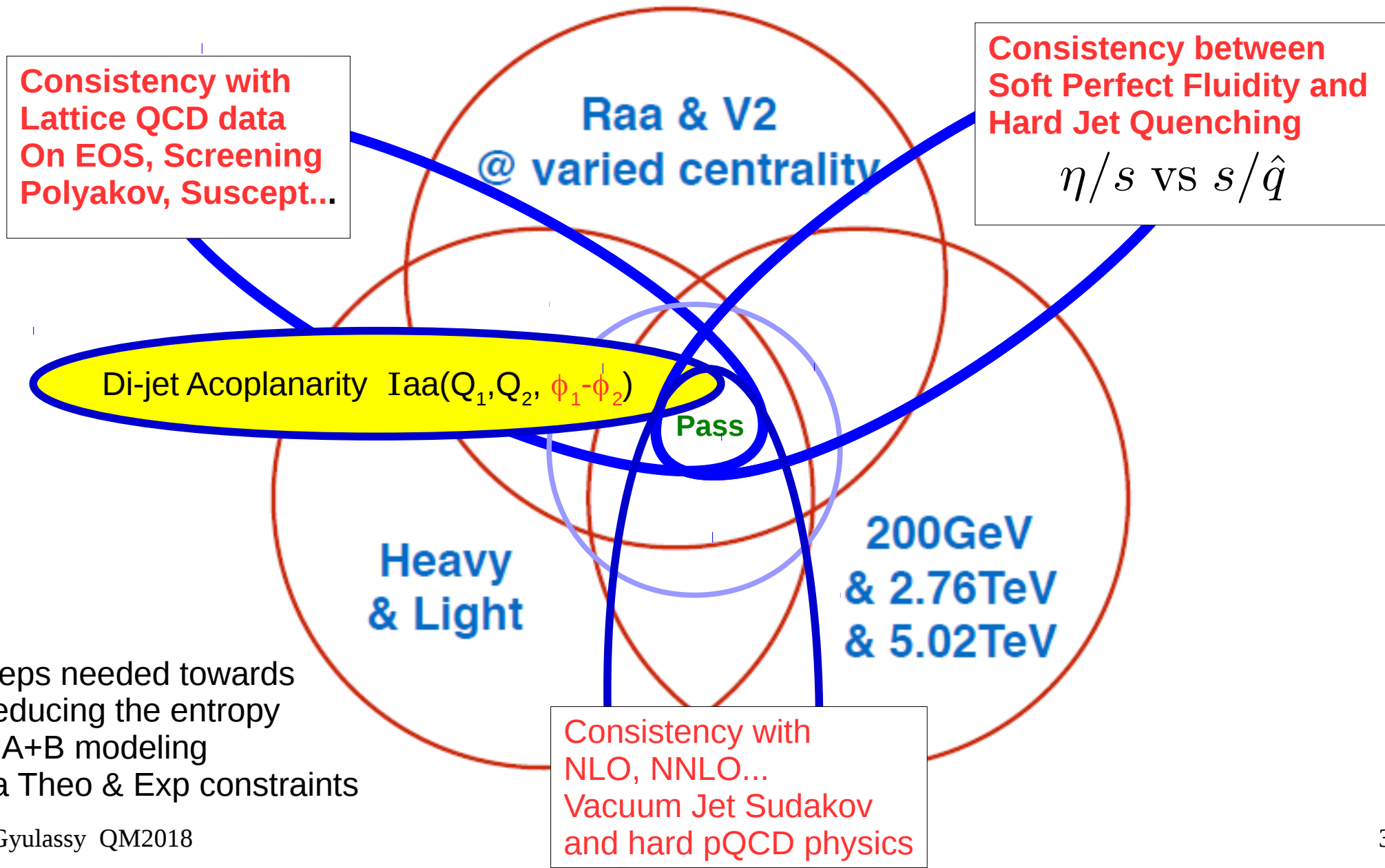


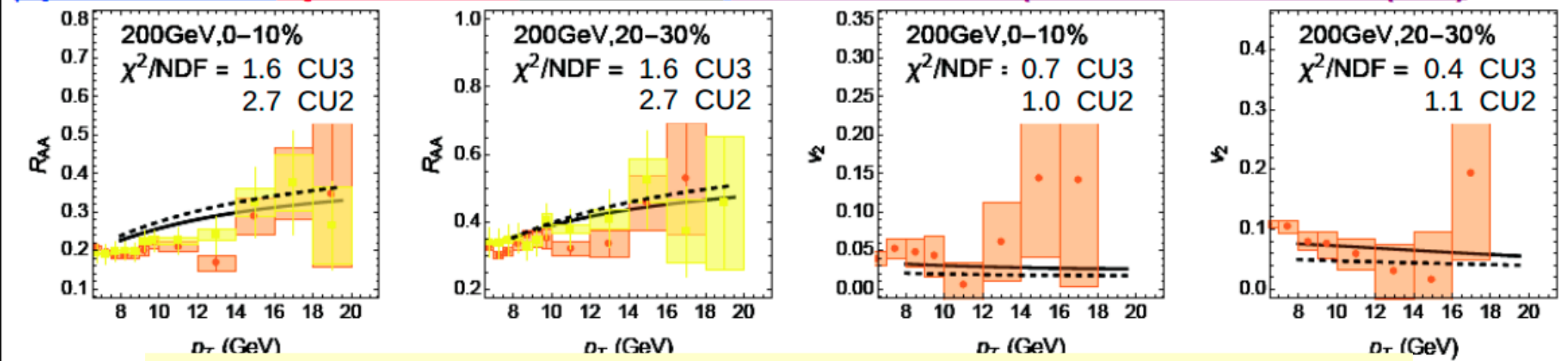
This talk focuses on adding another exp observable, dijet acoplanarity, to
Jinfeng Liao's Quark Matter 2017 theory wish list

The Challenge to Every Model

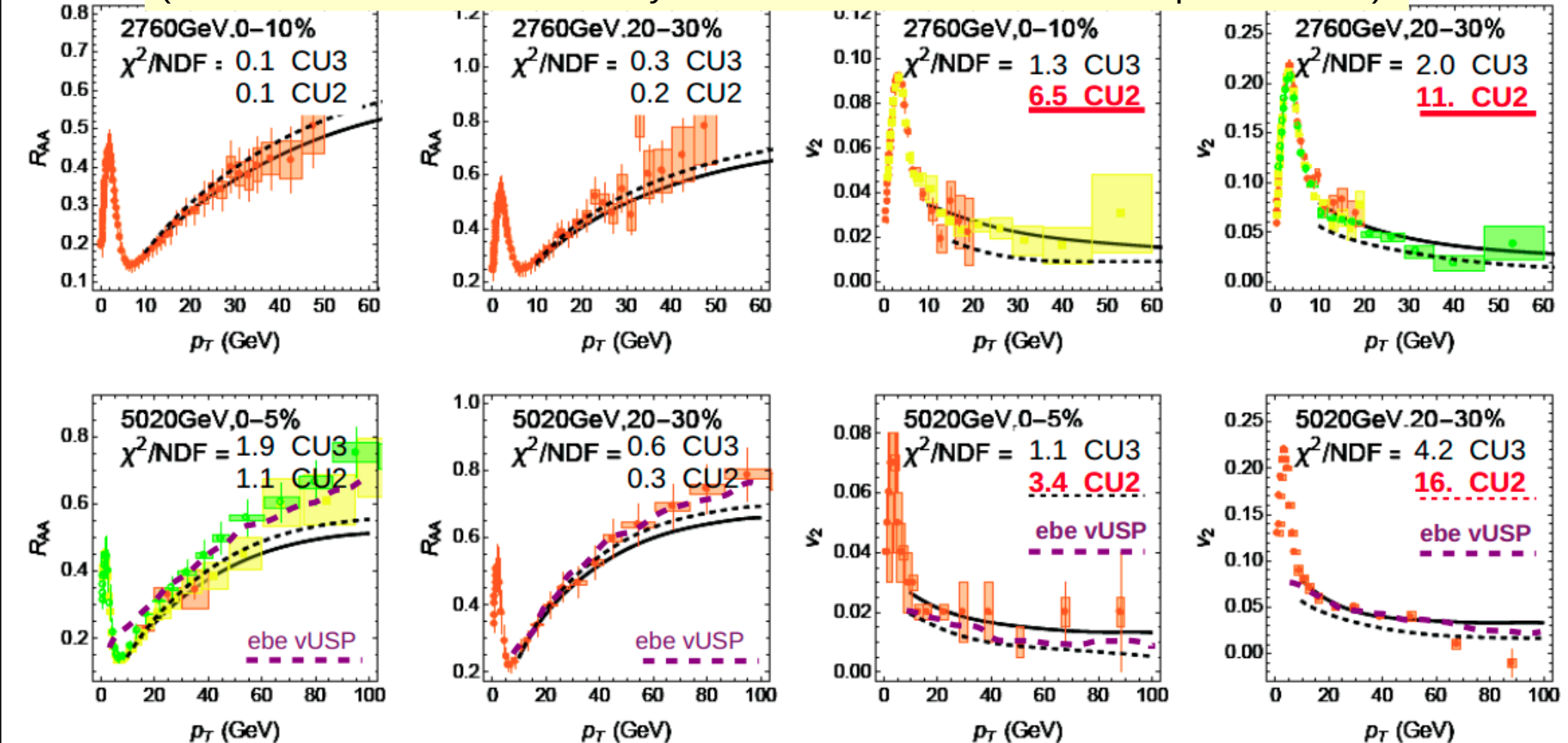


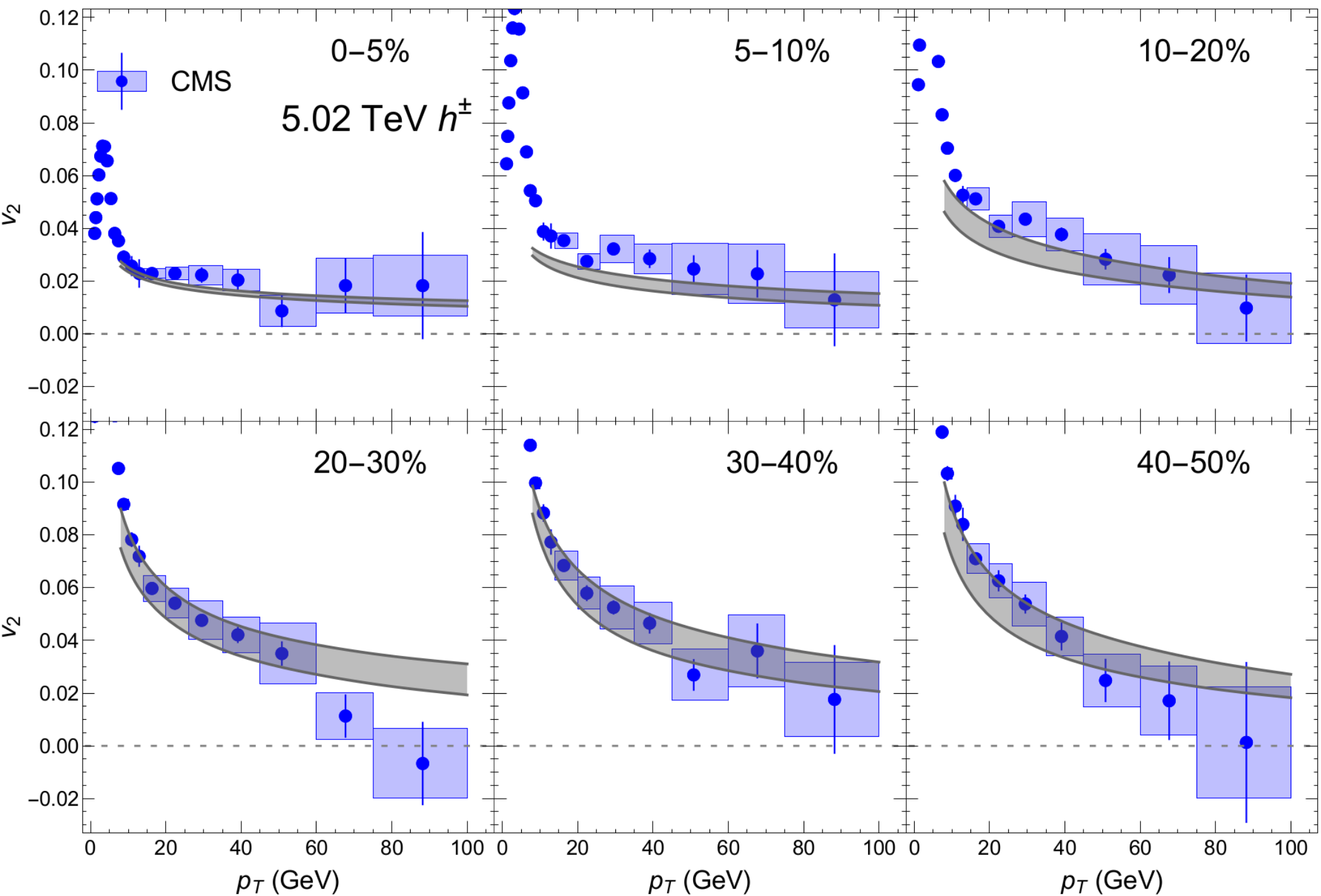
The Challenge to Every Model



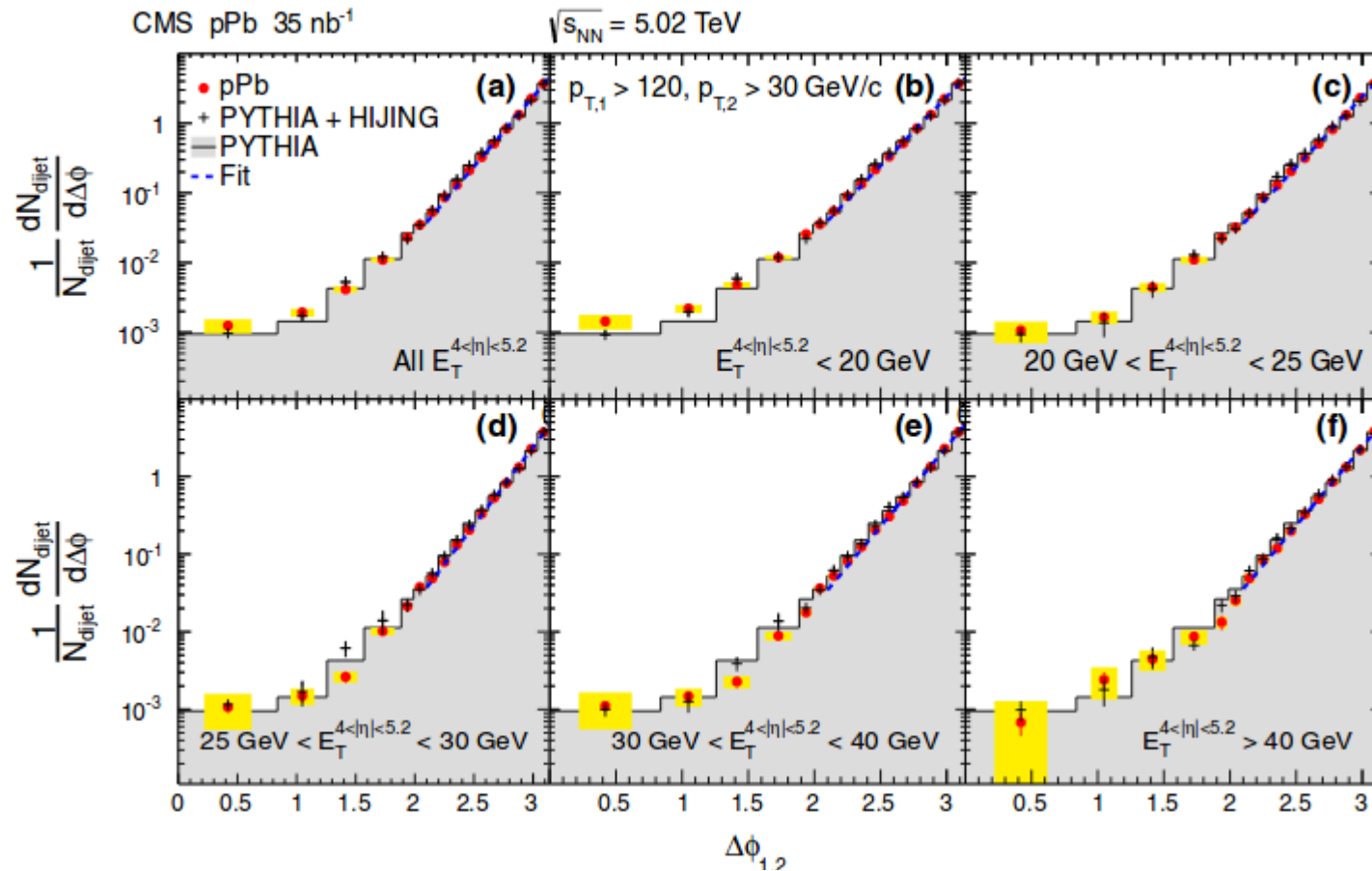


(Global RHIC&LHC Chi^2 analysis: Shuzhe Shi et al 2018 to be posted soon)





CMS Studies of dijet transverse momentum balance and pseudorapidity distributions in pPb collisions at 5.02 TeV have already achieved great precision



Very high precision has (after 30 years) been reached at LHC in pp and pA to test vacuum Sudakov acoplanarity due to jet gluon showers. Thus Sudakov A, B and non-perturb D factors can now be tuned to high accuracy

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

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

High $p_T \sim 100$ GeV makes small angle deviations from π nearly independent of medium effect and are dominated by vacuum Sudakov effects.

At large angles < 2 there is a predicted suppression of γ -jet correlations due to multiple induced jet suppression complementary to RAA(p_T) Sensitive to $\hat{q}(E, T)$.

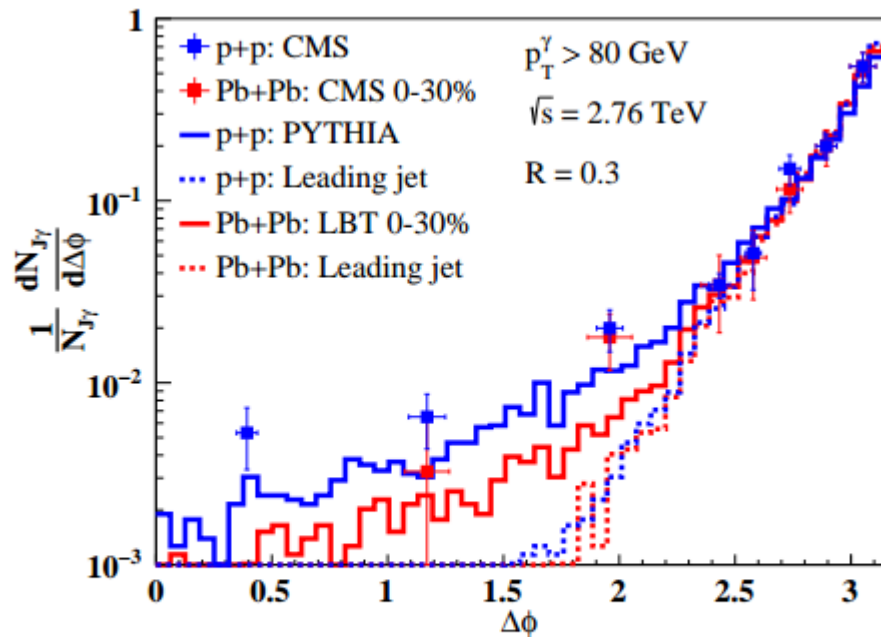


FIG. 6: (Color online) Angular distribution of γ -jet in central (0–30%) Pb+Pb (red) and p+p collisions (blue) at $\sqrt{s} = 2.76$

Exp should focus in “sweet spot”

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

To reduce large distortion due to the quenching of multiple medium minijets unrelated to the dijet

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

Hybrid: Pythia+ N=4 SYM holography model with added Gaussian transverse momentum
Distributed with BDMS Gaussian approximation controlled by a parameter K

$$Q_s^2 \equiv \langle \hat{q} L \rangle \equiv K \langle T^3 L \rangle$$

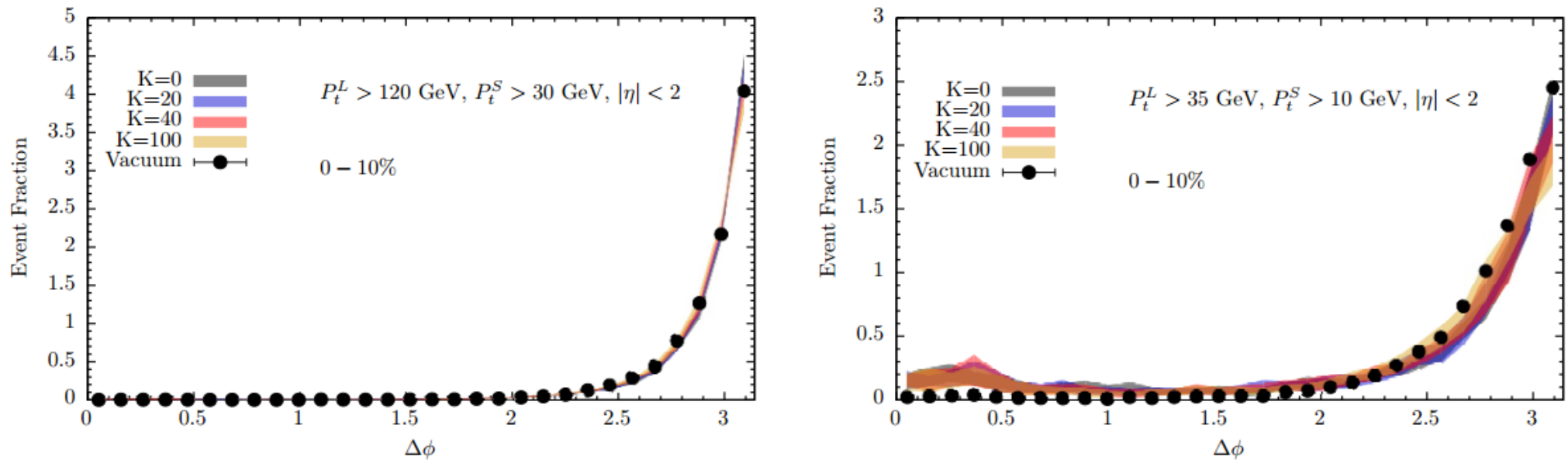


Figure 3. Dijet acoplanarity distribution for high-energy (left) and low-energy (right) dijets in LHC heavy ion collisions with $\sqrt{s} = 2.76$ ATeV for two different values of the broadening parameter K . For comparison, the black dots show the acoplanarity in proton-proton collisions as simulated by PYTHIA.

the effects of medium broadening on the acoplanarity distribution are small

For $E \sim 30$ GeV strong coupling broadening could be tested in the future to falsify

holographic or perturbative or other hybrid model combinations

This example is Exaggerated with

Ratio $R(\Delta\phi)$ of Jet Medium to Vacuum Acoplanarity

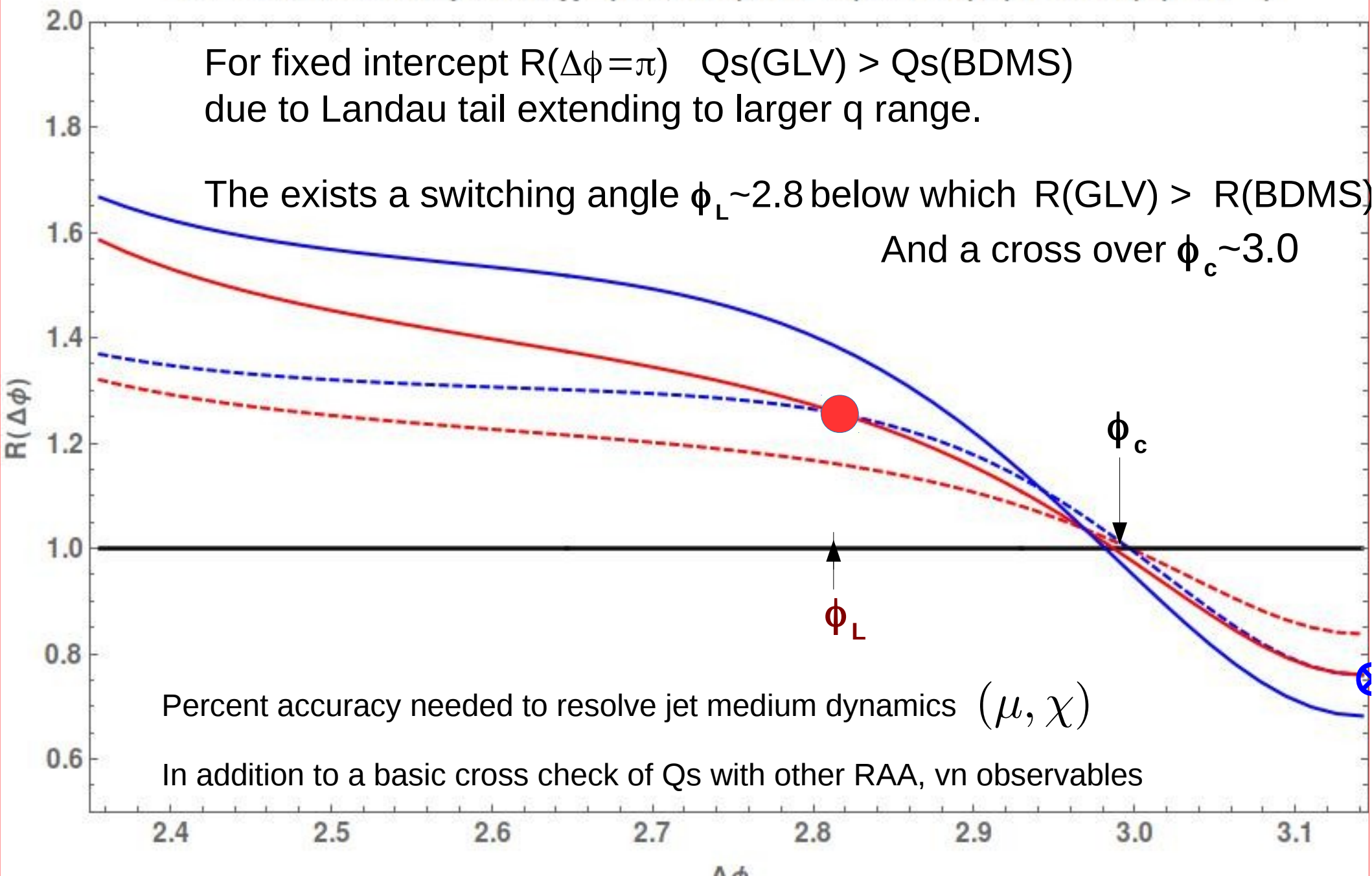
(Vac+GLV)/Vac (red) vs (Vac+BDMS)/Vac (blue)

for $Q=20$, $\alpha=0.3$, $\mu=0.5$, $\chi=(5.7, 10.2)$, $Q_s^2=(9 \text{ dash}), (16 \text{ solid}) \text{ (GeV}^2\text{)}$

For fixed intercept $R(\Delta\phi=\pi)$ $Q_s(\text{GLV}) > Q_s(\text{BDMS})$
due to Landau tail extending to larger q range.

There exists a switching angle $\phi_L \sim 2.8$ below which $R(\text{GLV}) > R(\text{BDMS})$

And a cross over $\phi_c \sim 3.0$

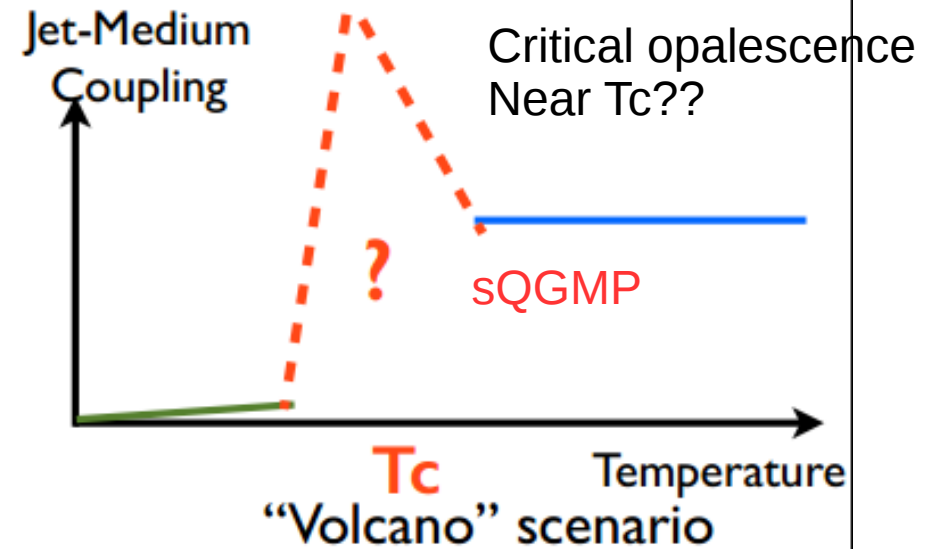
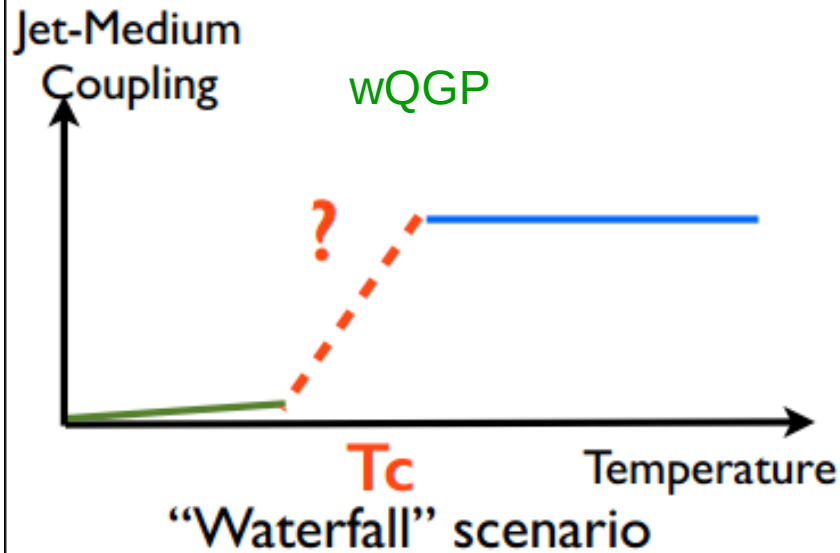


Monopole component near T_c
could account for near perfect fluidity

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

J.Liao 2015

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, and Shuzhe Shi to quantitatively test this
idea with SPS, RHIC and LHC RAA, v_2 , v_3 data?**