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

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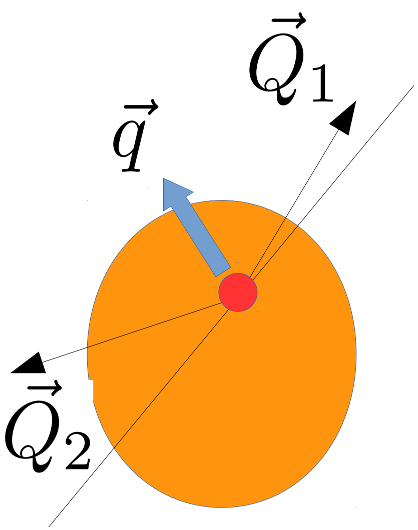
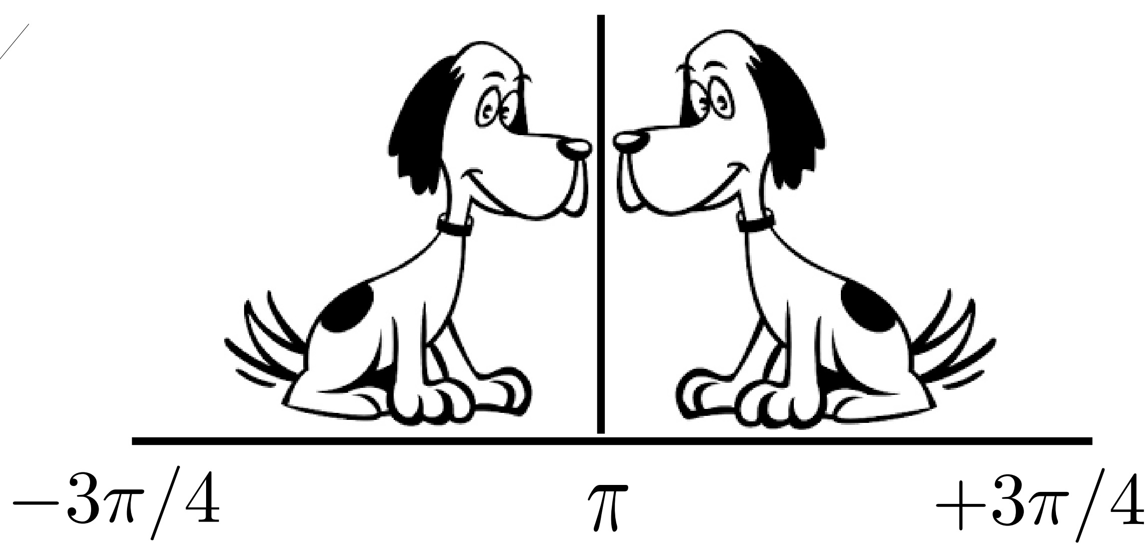
Can we observe via A+A the QCD Landau/Rutherford scattering tails "wag" beyond the Moliere/Gaussian (BDMS Q_s) jet medium broadenning approximation?





$$\phi_1 - \phi_2 = \Delta\phi$$

History of Acoplanarity : QM18 - 30 years ago

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

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

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

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

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

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Current State of the "Acoplanarity Art"

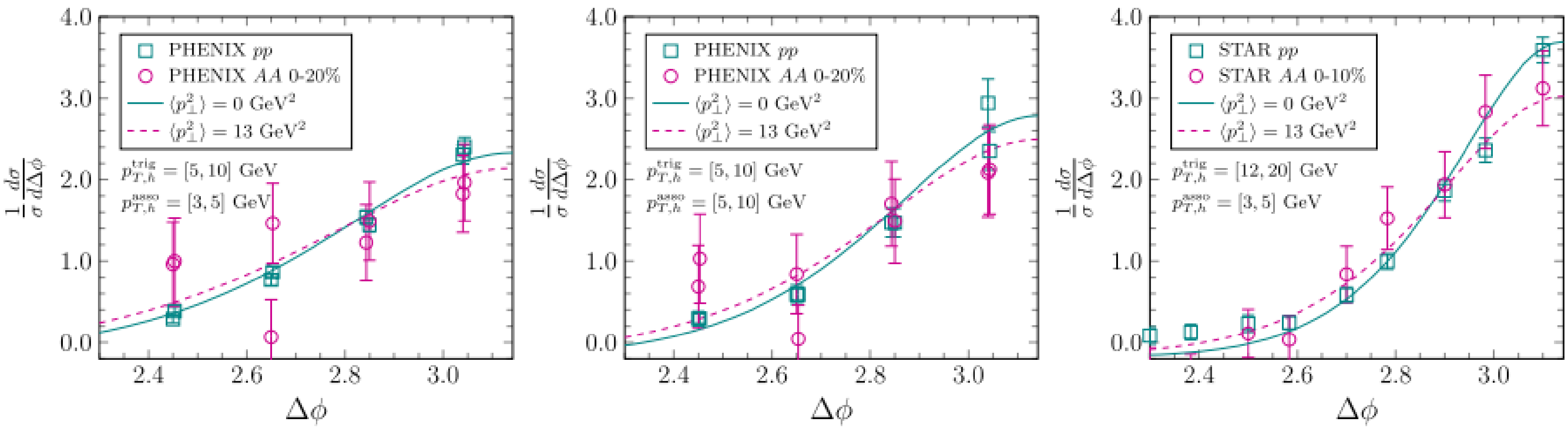


Fig. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.

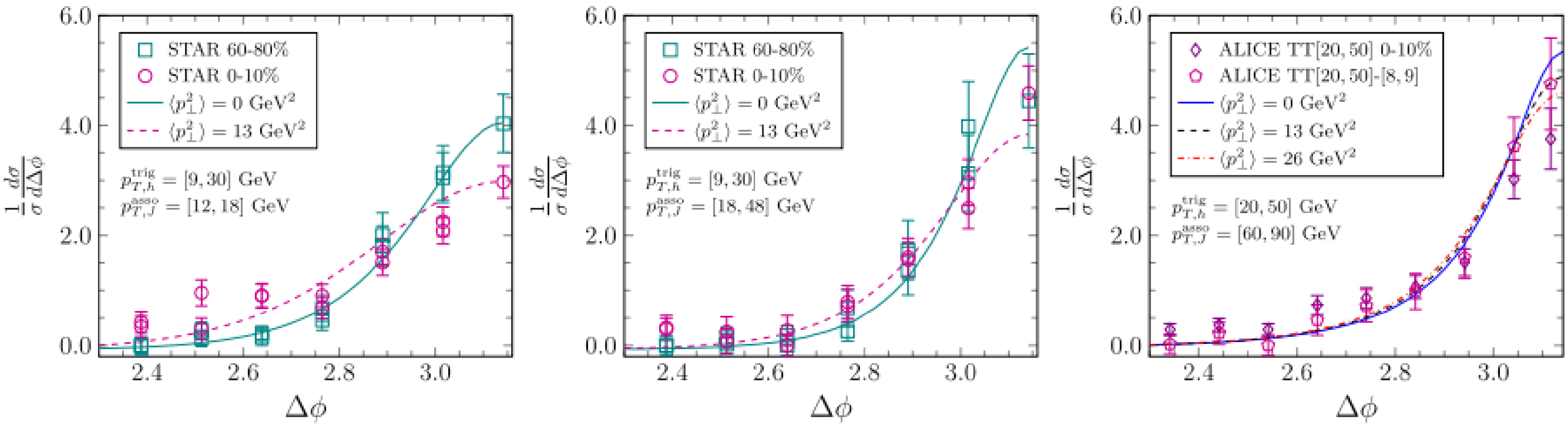


Fig. 2. Normalized hadron-jet angular correlation compared with STAR [53] and the ALICE [54] data. A factor of 3/2 is multiplied to the charged jet energy for our calculation to account for the energy carried by neutral particles. Two sets of ALICE data are shown: TT(trigger track)[20–50] (GeV) represents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

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

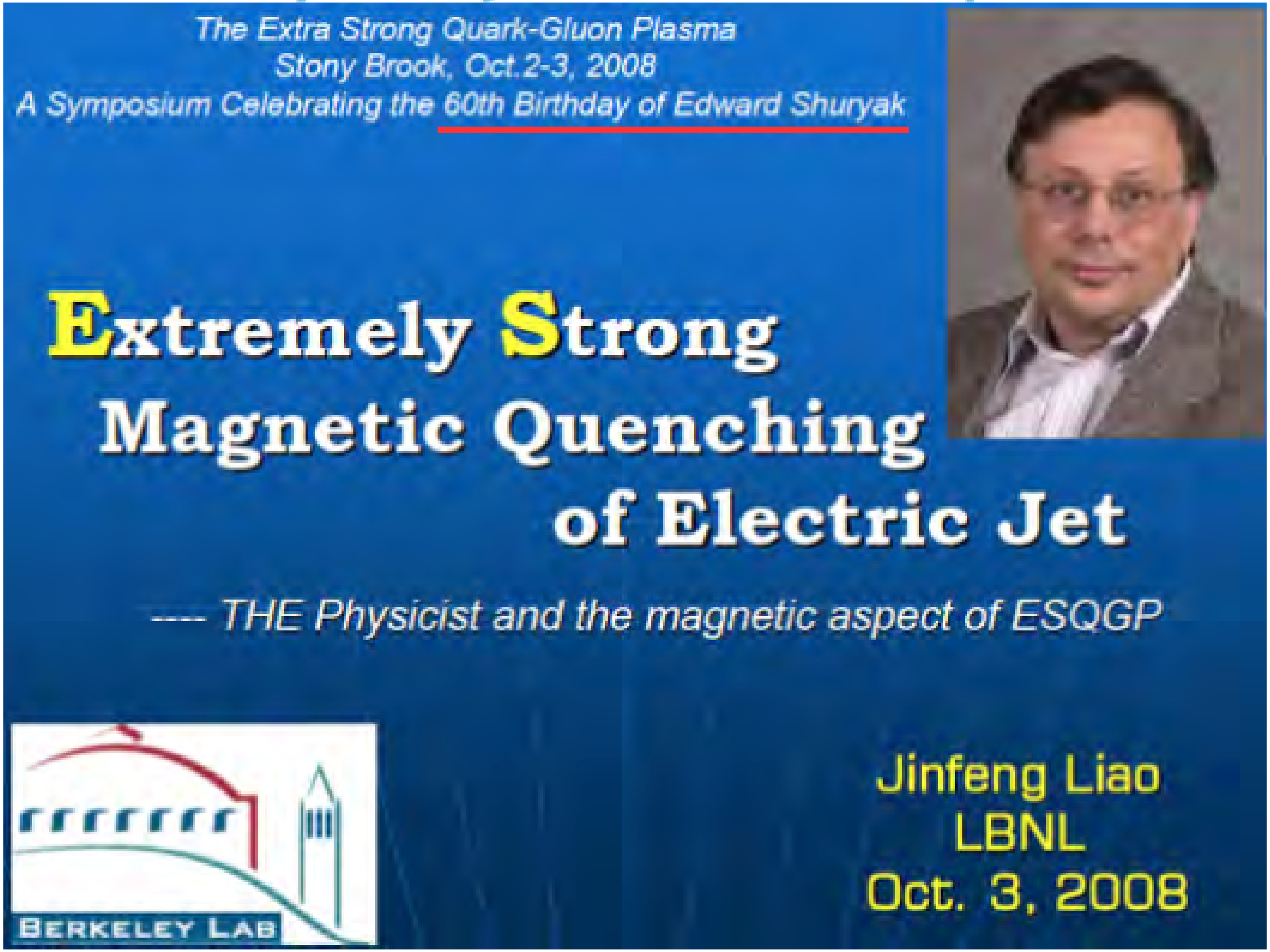
Can acoplanarity ***distribution shapes*** help to extract information on the color dof in Perfect QCD fluids and constrain the microscopic differential scattering rates, Γ_{ab} , near T ~ T_c ?

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

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

CIBJET was developed to test quantitatively
The ESQGP (EdShuryak'sQGP) proposal

Jinfeng Liao's CCNU 2015 talk slide 14



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 v2.

[MG:Until 2014 I did not think ESQGP was needed to solve the RAA-v2 puzzle. Sheer desparation trying many other ways to solve the RAA-v2 puzzle led me to ask Jinfeng L to join our CUJET]

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

GLV, PRD66, 014005 (2002)

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

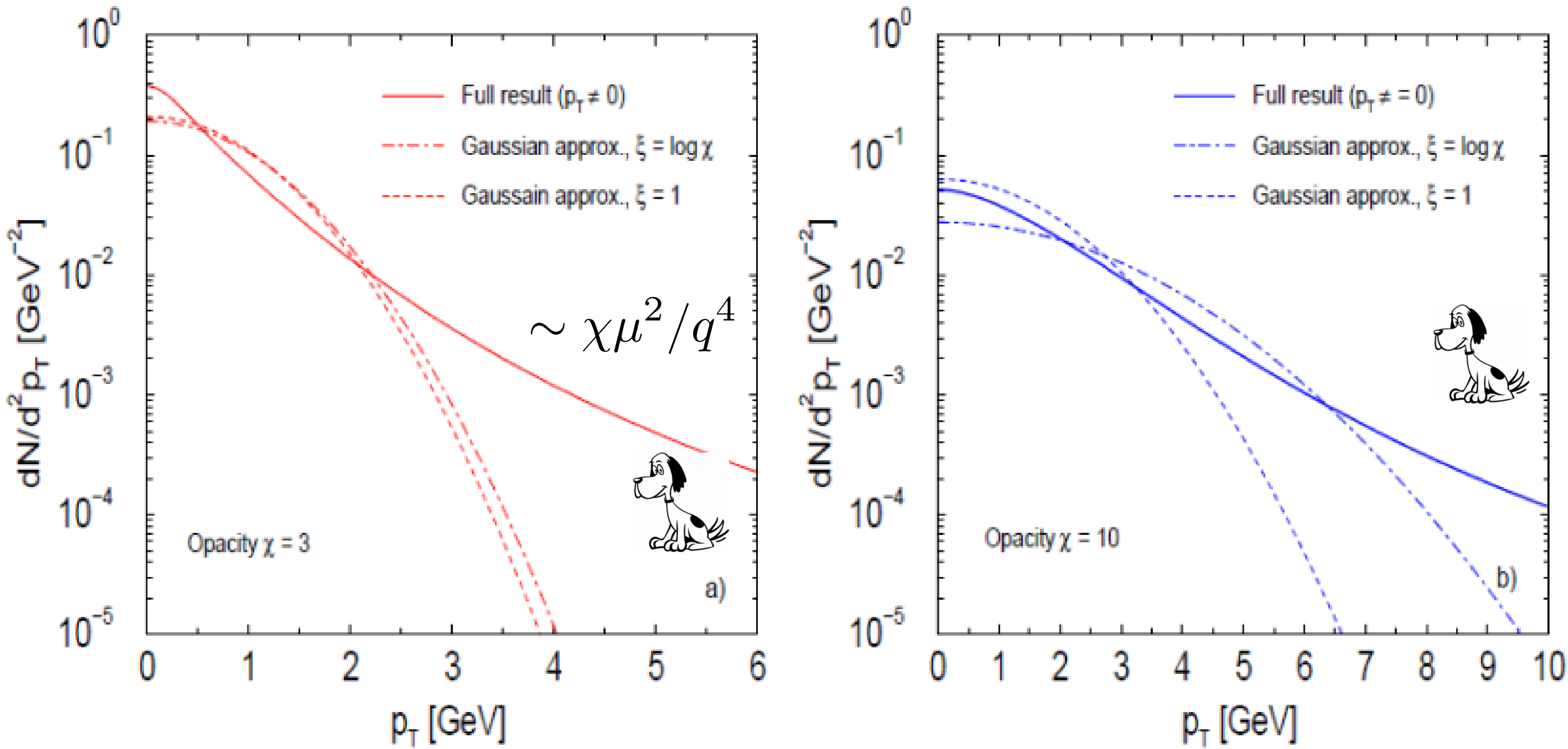
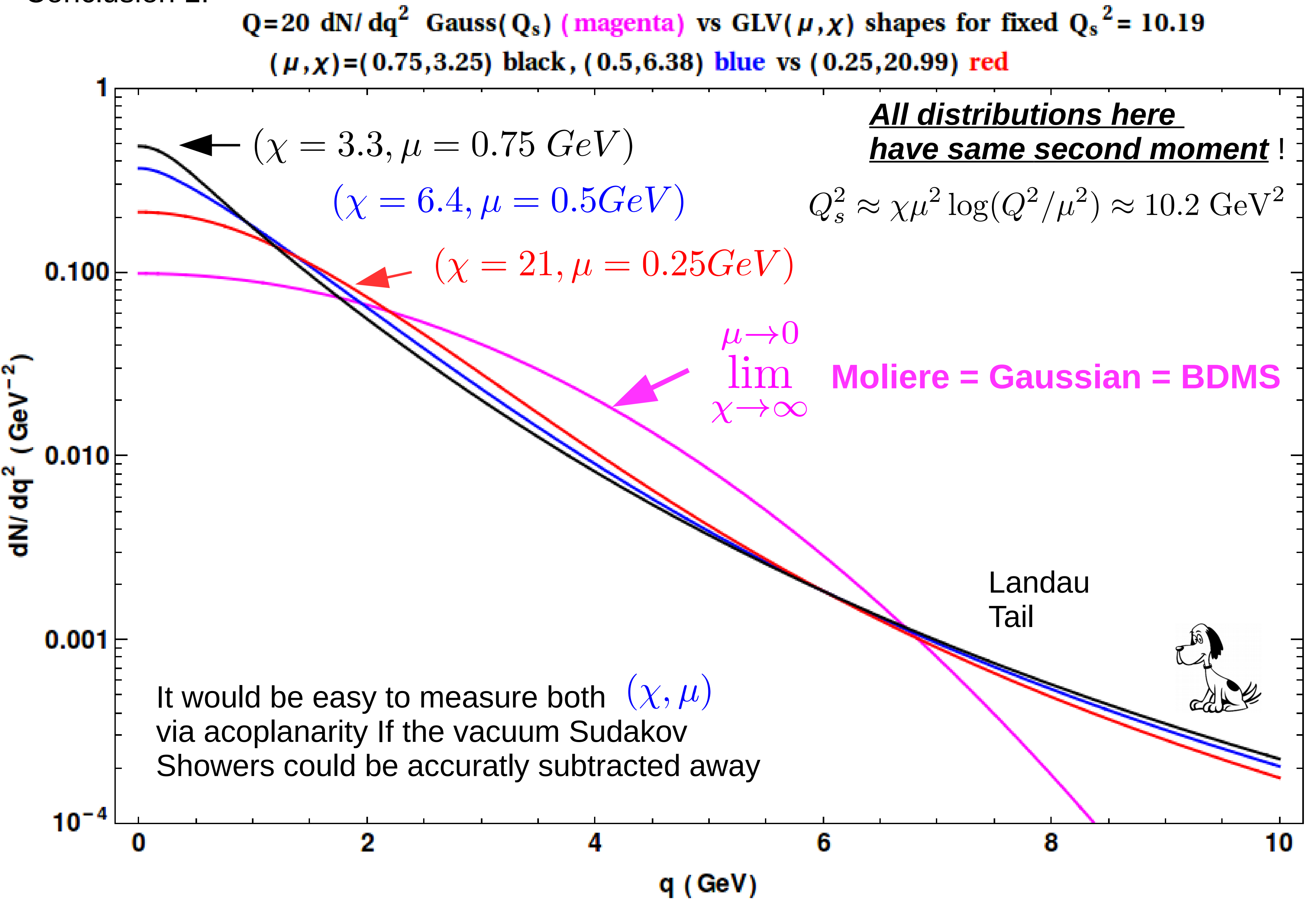


FIG 3. The final jet p_T distribution is shown versus p_T for two different opacities $\chi = 3$ (Fig. 3a) and $\chi = 10$ (Fig. 3b). We compare the full result (without the delta function contribution at $p_T \sim 0$) to the Moliere Gaussian approximation with $\xi = 1$ and $\xi = \log\chi$. In this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

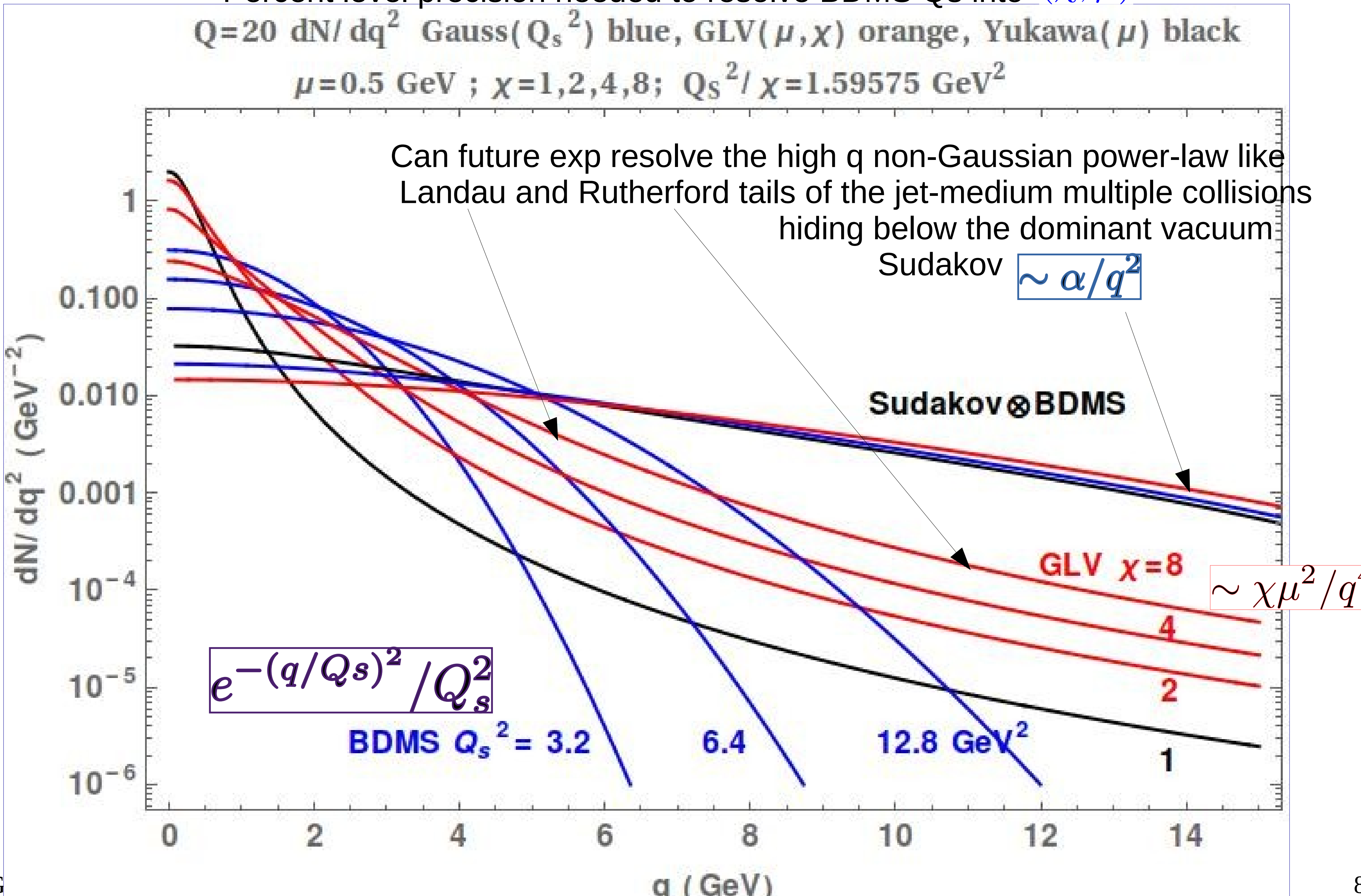
(See also poster Cor-45 by Hanzhon Zhang)

Conclusion 1:

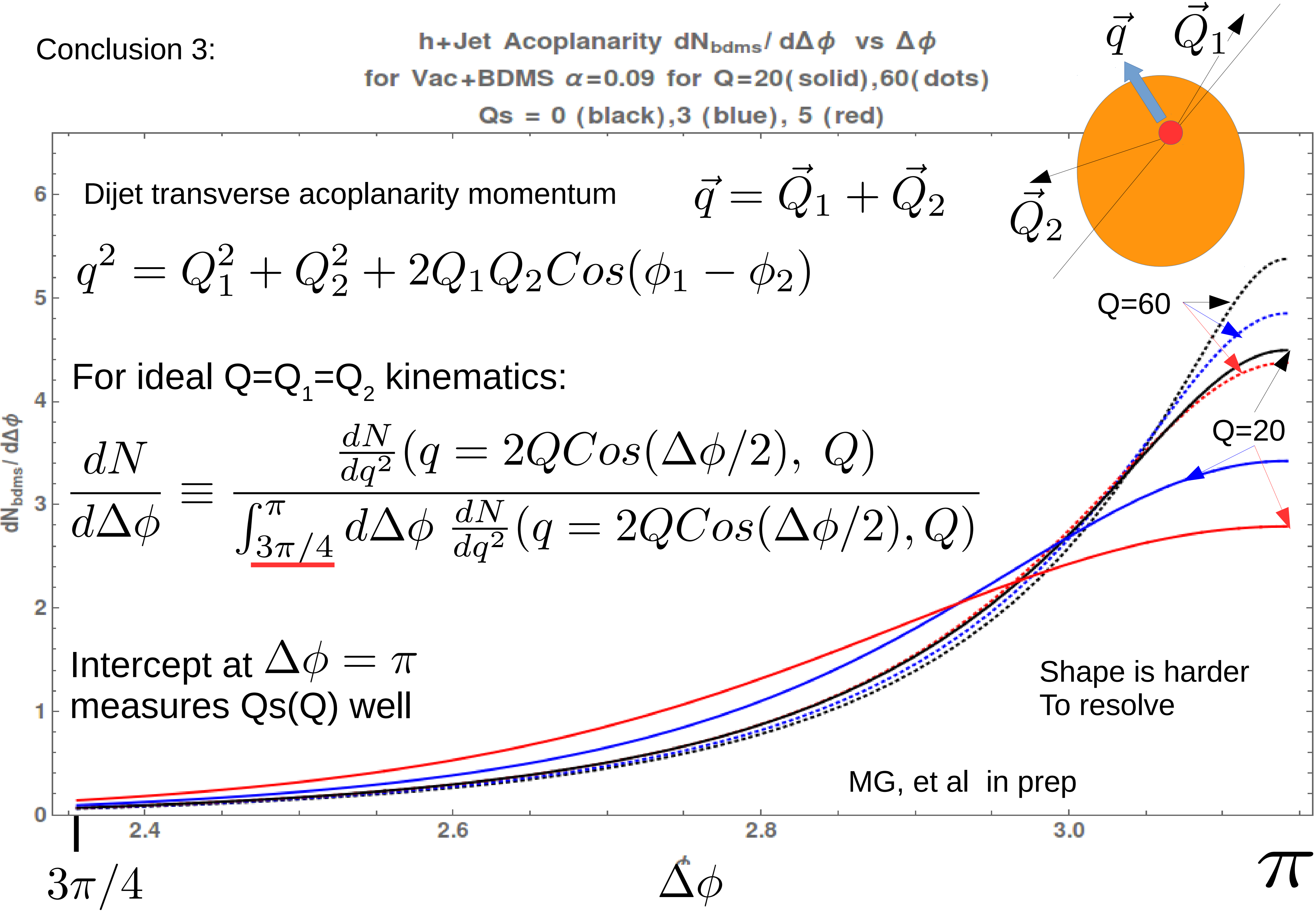


Conclusion 2: Unfortunately Vacuum Sudakov dominates over medium induced dijet acoplanarity

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



Conclusion 3:



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 $Q=Q_1=Q_2$ kinematics:

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

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

Shape is harder
To resolve

MG, et al in prep

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

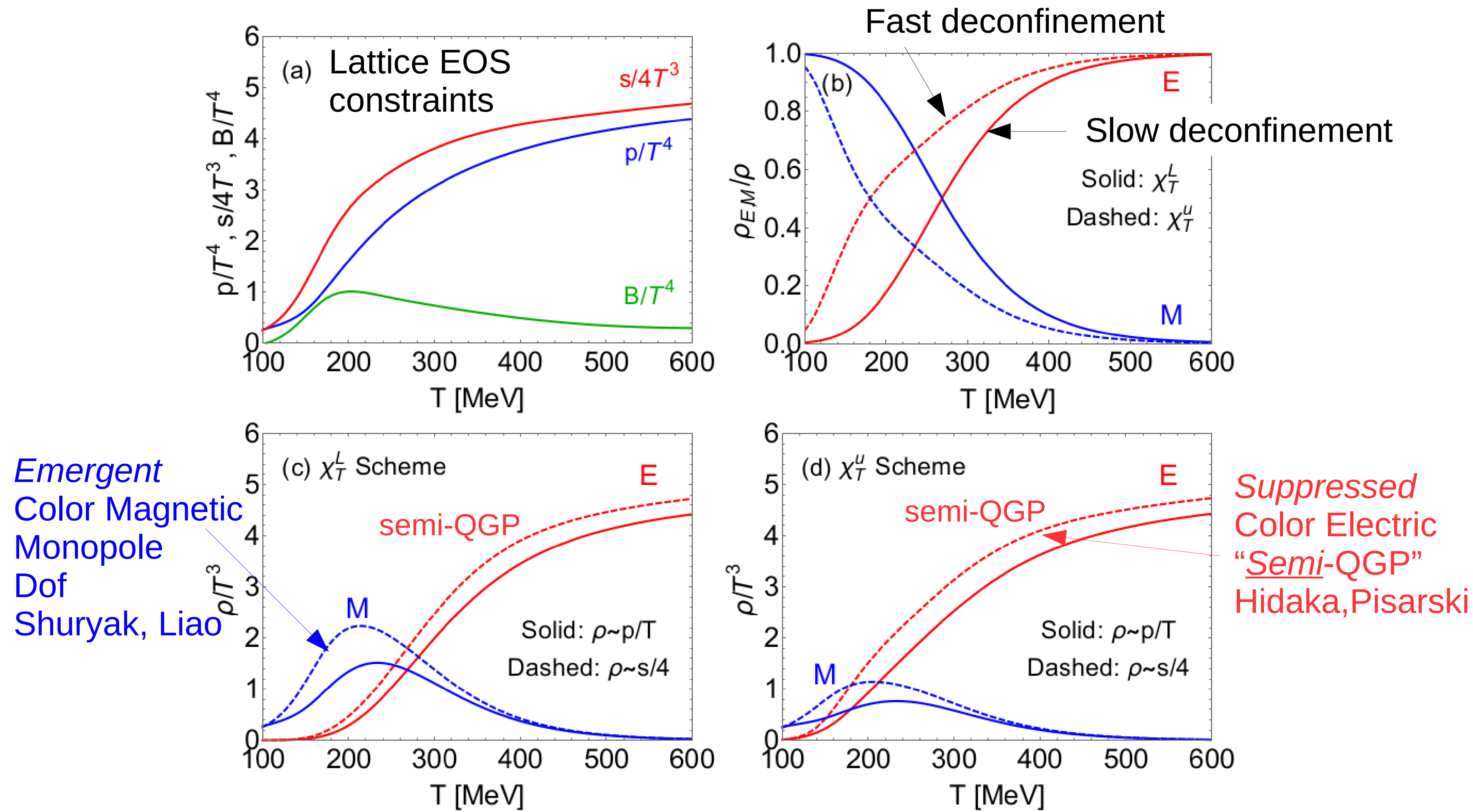
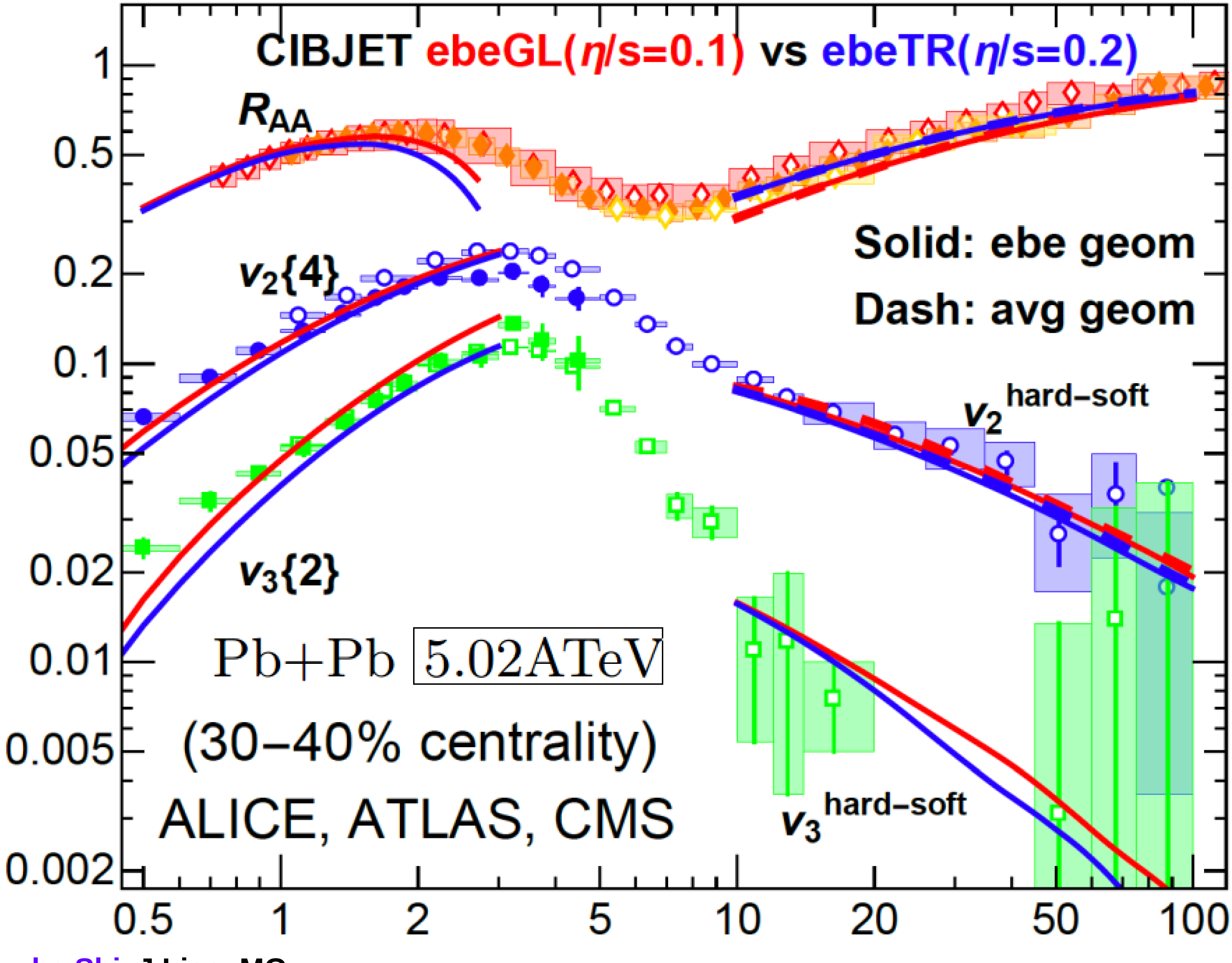


Figure 6. (Color online) (a) The effective ideal quasiparticle density, $\rho/T^3 = \xi_p P/T^4$, in the Pressure Scheme (PS, Blue) is compared with effective density, $\rho/T^3 = \xi_p S/4T^3$, in the Entropy Scheme (ES, Red) based on fits to lattice data from HotQCD Collaboration [56]. The difference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

(See also Ramamurti, Shuryak, Zahed, arXiv:1802.10509)

Consistent Quantitative Soft-Hard Event Engineering with CIBJET/sQGMP



Shuzhe Shi, J.Liao, MG:
arXiv 1804.01915

(see also JNHostler etal)

Shuzhe Shi etal arXiv:1804.01915 and in prep

VISHNU ⊗ CUJET3.1

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) + (Emergent $(1-\chi_T^L)$ mag.monopoles)

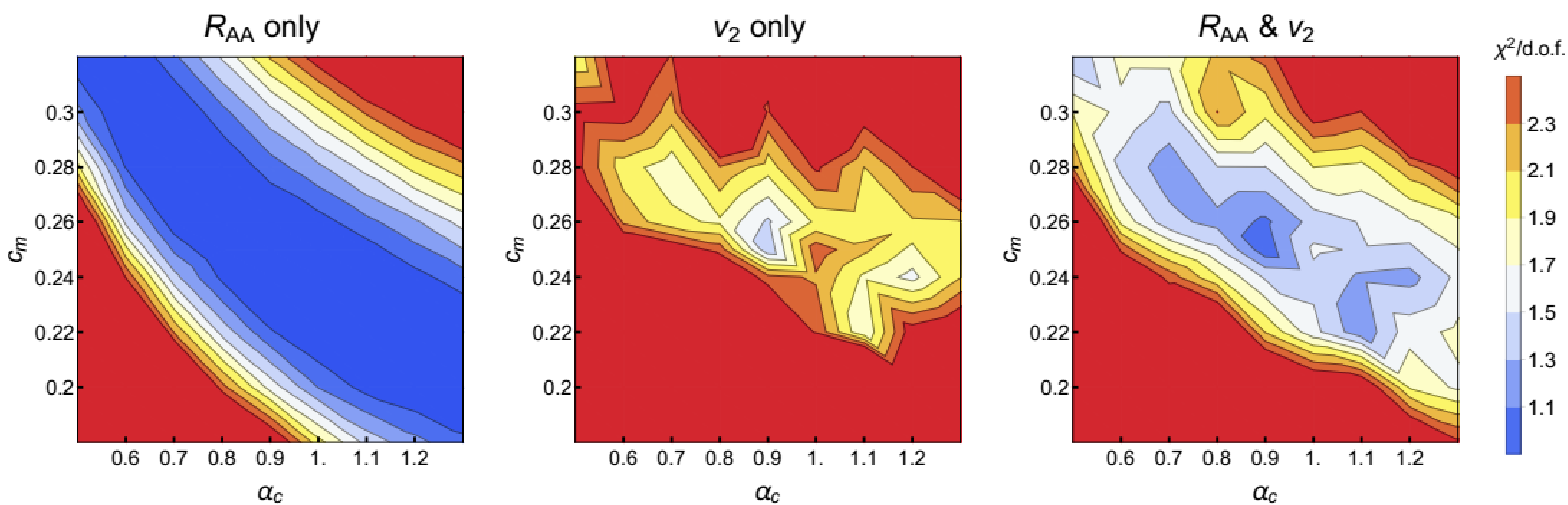


FIG. 1: (color online) χ^2/d.o.f. comparing χ_T^L-scheme CUJET3 results with RHIC and LHC data. Left: χ^2/d.o.f. for R_{AA} only. Middle: χ^2/d.o.f. for v_2 only. Right: χ^2/d.o.f. including both R_{AA} and v_2

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

Shuzhe Shi found that ebe only makes ~10% changes to hard v2 relative using event ave geom

This creates tension between CIBJET and vUSPhydro SHEE framework interpretations.

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

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

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

$$q(q+g) \quad \Big\{ [C_{qq}f_q + C_{qg}f_g] \cdot \boxed{[\alpha_s^2(\boldsymbol{q}_\perp^2)]} \cdot [f_E^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] +$$

$$qm \quad [C_{qm}(1-f_q-f_g)] \cdot \boxed{[1]} \cdot [f_M^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] \Big\}, \tag{14}$$

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

$$g(q+g) \quad \Big\{ [C_{gq}f_q + C_{gg}f_g] \cdot \boxed{[\alpha_s^2(\boldsymbol{q}_\perp^2)]} \cdot [f_E^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] +$$

$$gm \quad [C_{gm}(1-f_q-f_g)] \cdot \boxed{[1]} \cdot [f_M^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] \Big\}, \tag{15}$$

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

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)

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

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

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

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

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

<u>Jiechen Xu, Jinfeng Liao, MG JHEP02(2016)</u>

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

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

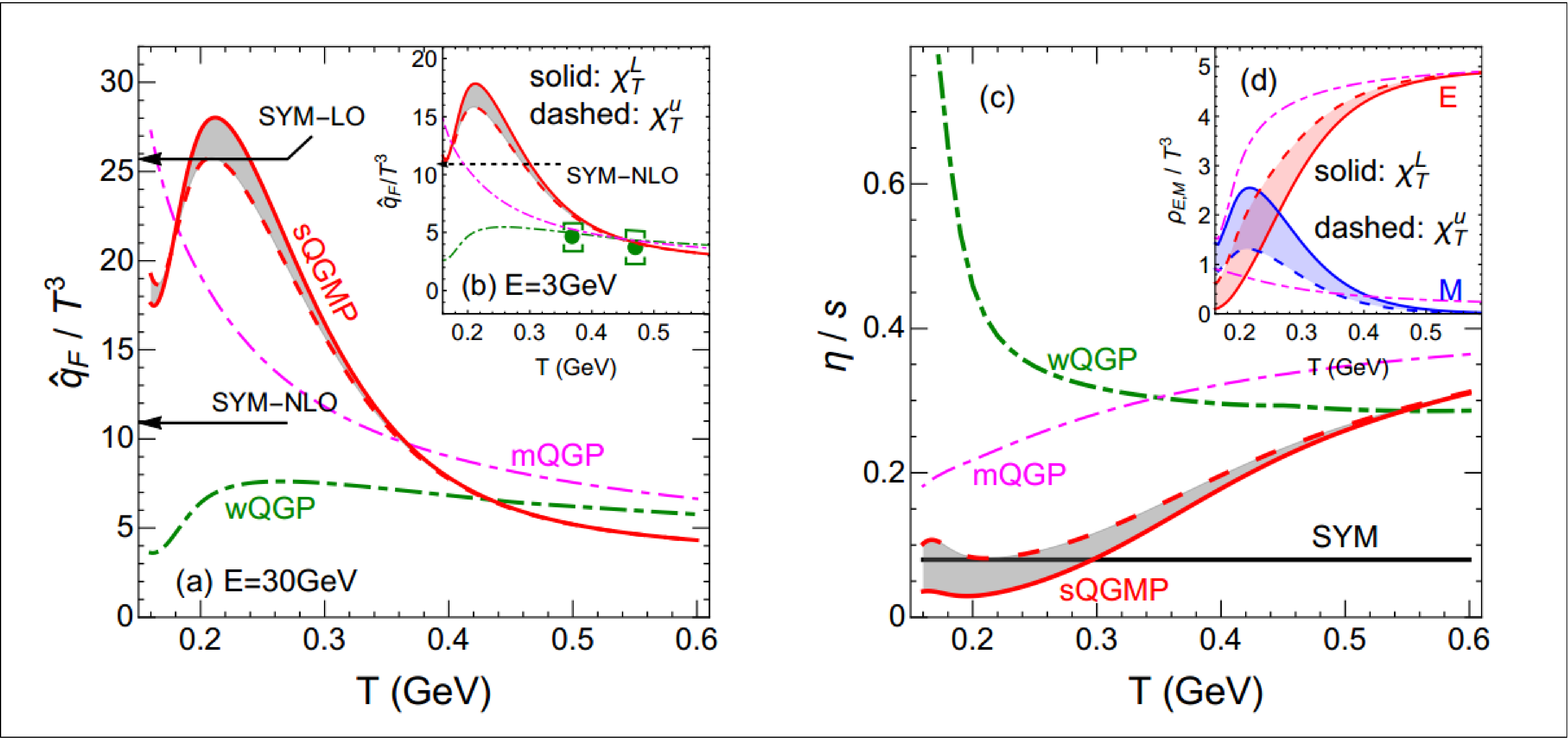
[6] A. Majumder, B. Muller, and X. N. Wang, Phys. Rev. Lett. **99**, 192301 (2007).

(See eq3.14 J.Xu, J.Liao, MG, JHEP 02 (2016) 169)

Shuzhe Shi, J.Liao, MG: arXiv:1804.01915 and in prep

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

The suppressed semi-QGP components of **sQGMP** require large monopole density near Tc 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, v2, v3 data but uniquely accounts for bulk perfect fluidity due to Near unitary bound q+m and g+m scattering rate near Tc !

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

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

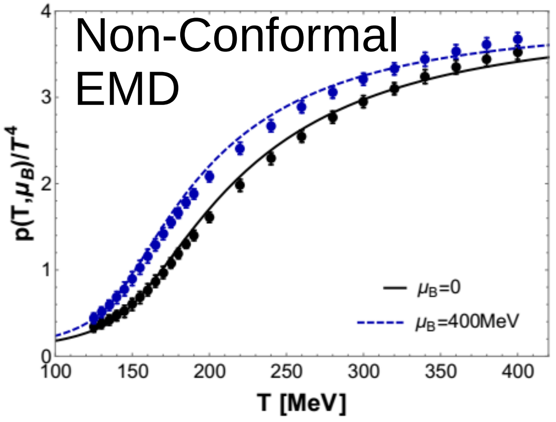
Rougemont, R., Ficnar, A., Finazzo, S.I., Noronha, J., JHEP04(2016)102

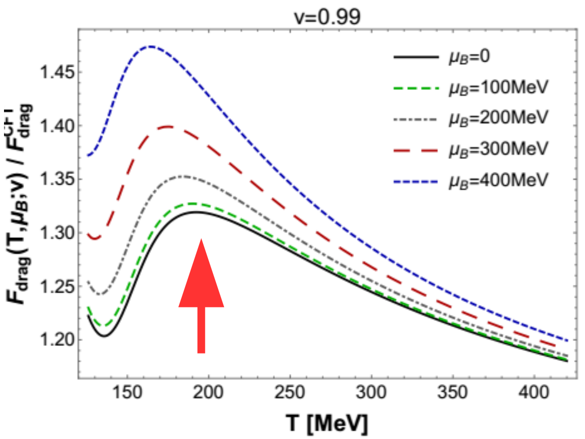
$$S = \frac{1}{16\pi G_5}\int_{\mathcal{M}_5} d^5x\sqrt{-g}\left[\mathcal{R} - \frac{1}{2}(\partial_\mu\phi)^2 - V(\phi) - \frac{f(\phi)}{4}F_{\mu\nu}^2\right]$$

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

Ansatz for the bulk gravity fields

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



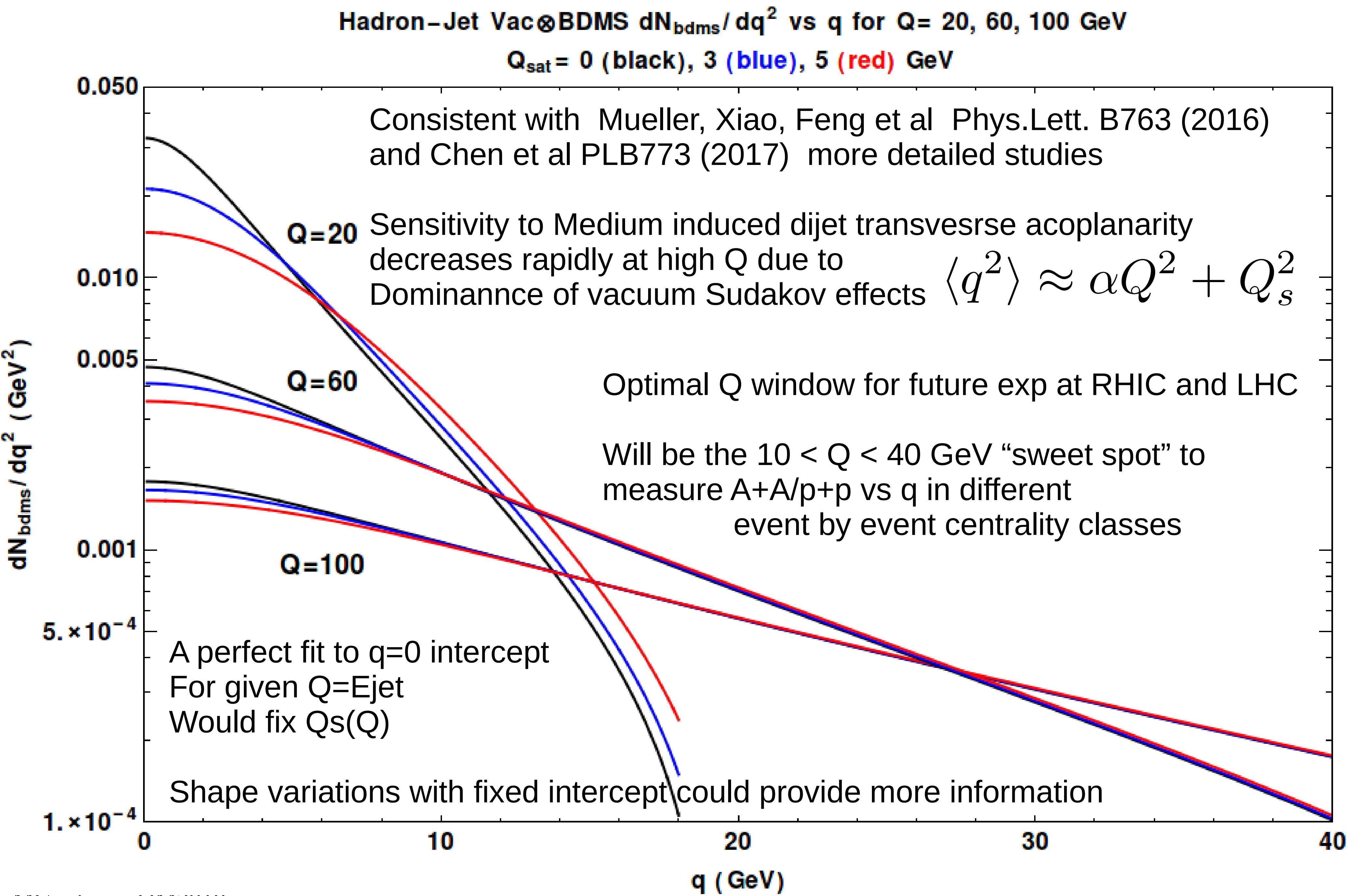


$$\frac{dE^{CFT}}{dx} = T^2\sqrt{\lambda_{tH}}(\pi\gamma\beta/2)$$

But Non-Conformal geometry
=> non-trivial **enhancement**
of string drag force near
T~ (1-2) Tc

EMD also predicts enhancement of dE/dx and qhat near cross over but less than sQGMP fits.
Quantitative chi^2 tests of such holographic models with RAA & v2 data have yet to be performed

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) more detailed studies

Sensitivity to Medium induced dijet transvesrse acoplanarity decreases rapidly at high Q due to Dominannce 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

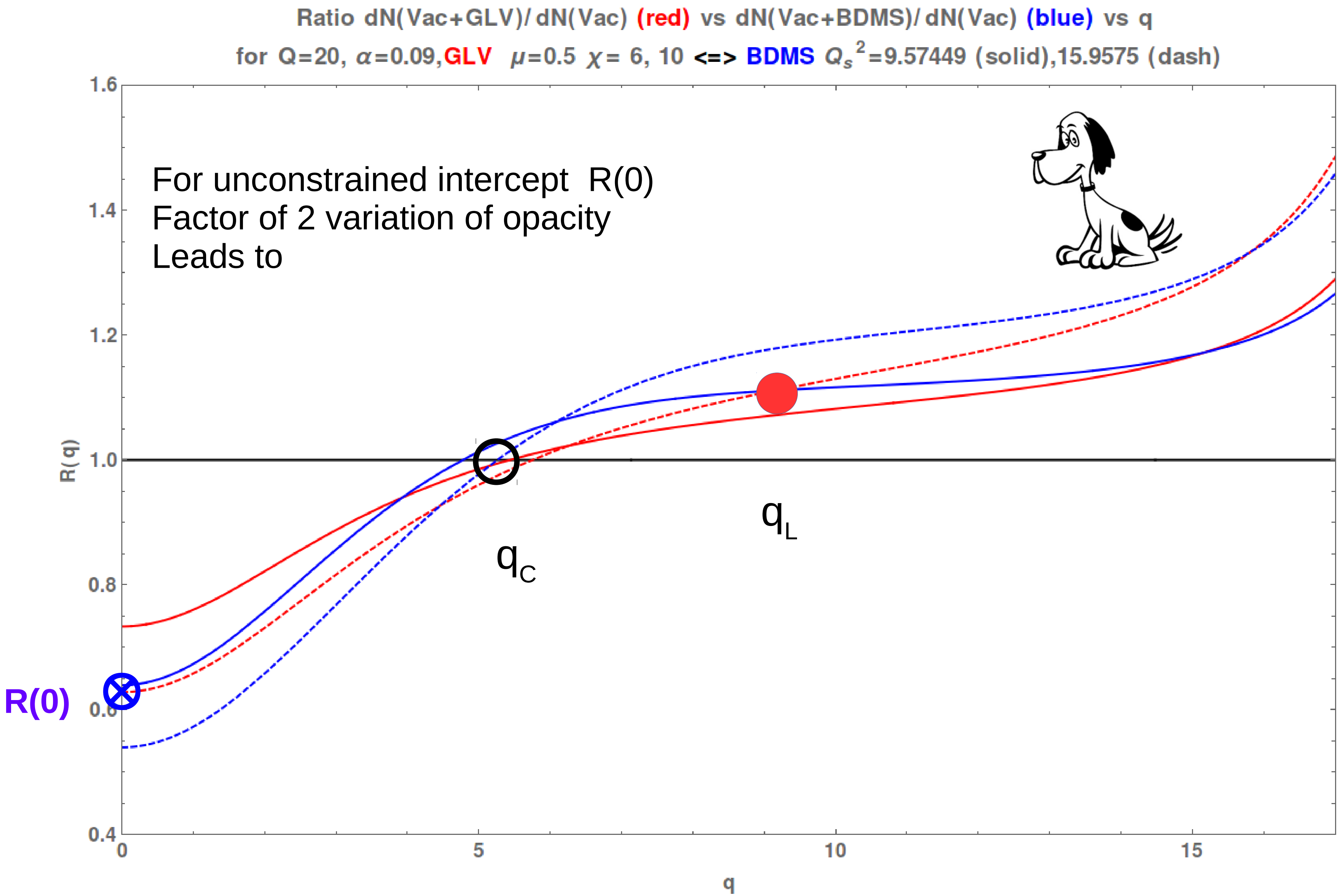
Will be the 10 < Q < 40 GeV “sweet spot” to measure A+A/p+p vs q in different event by event centrality classes

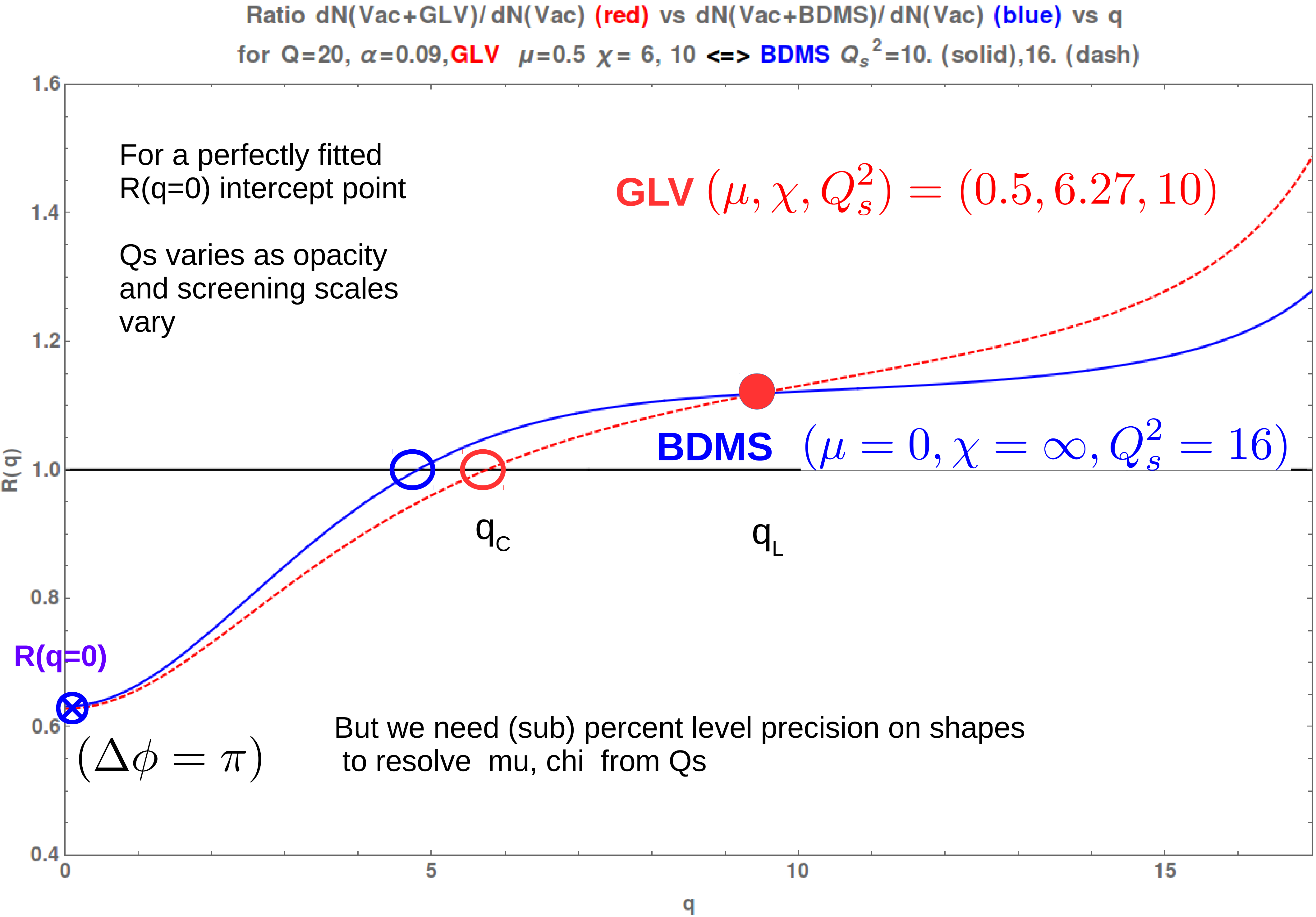
A perfect fit to q=0 intercept
For given Q=Ejet
Would fix Qs(Q)

Shape variations with fixed intercept could provide more information

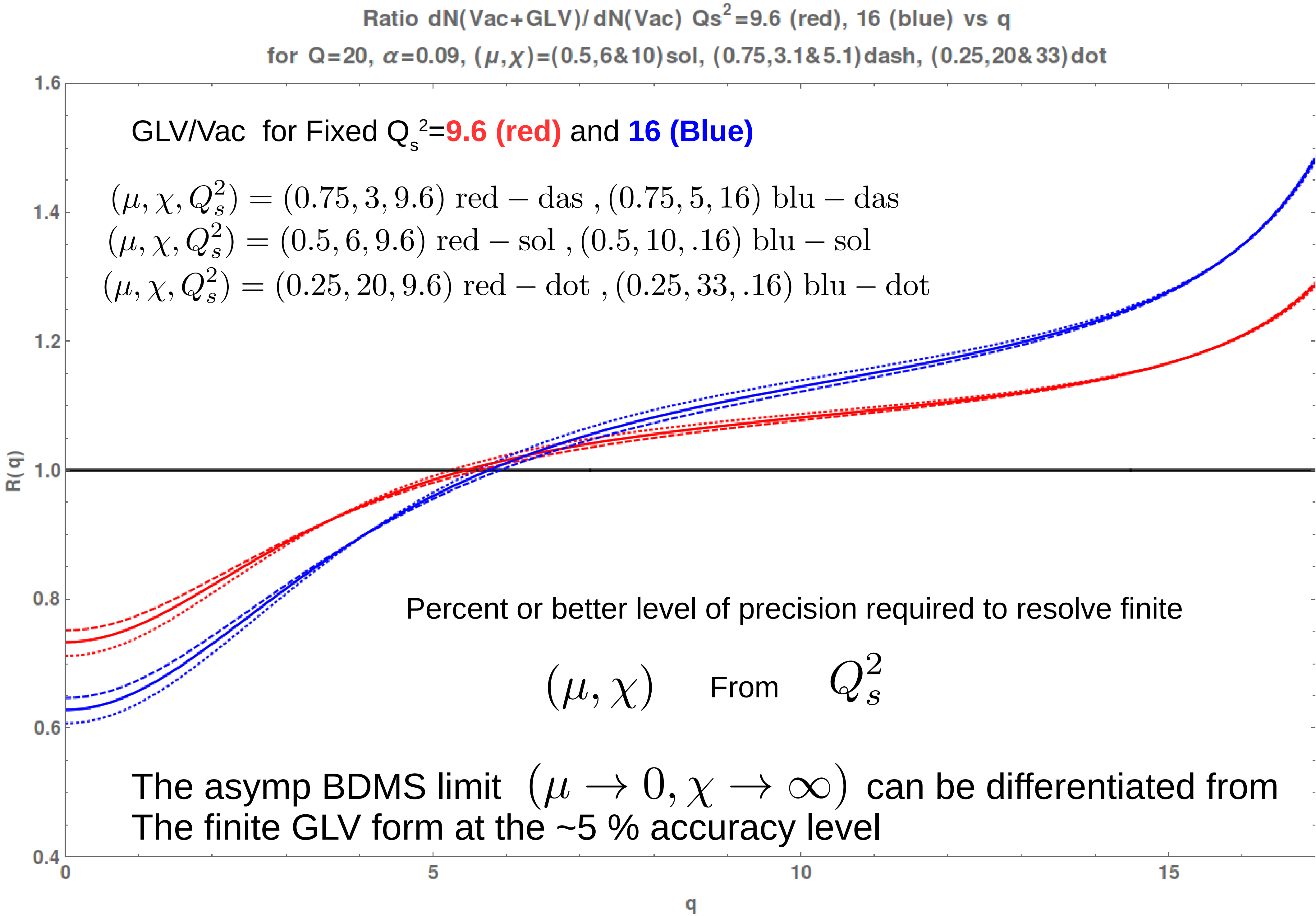
For realistic Sudakov fits to p+p need lower $\alpha \approx 0.09$

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

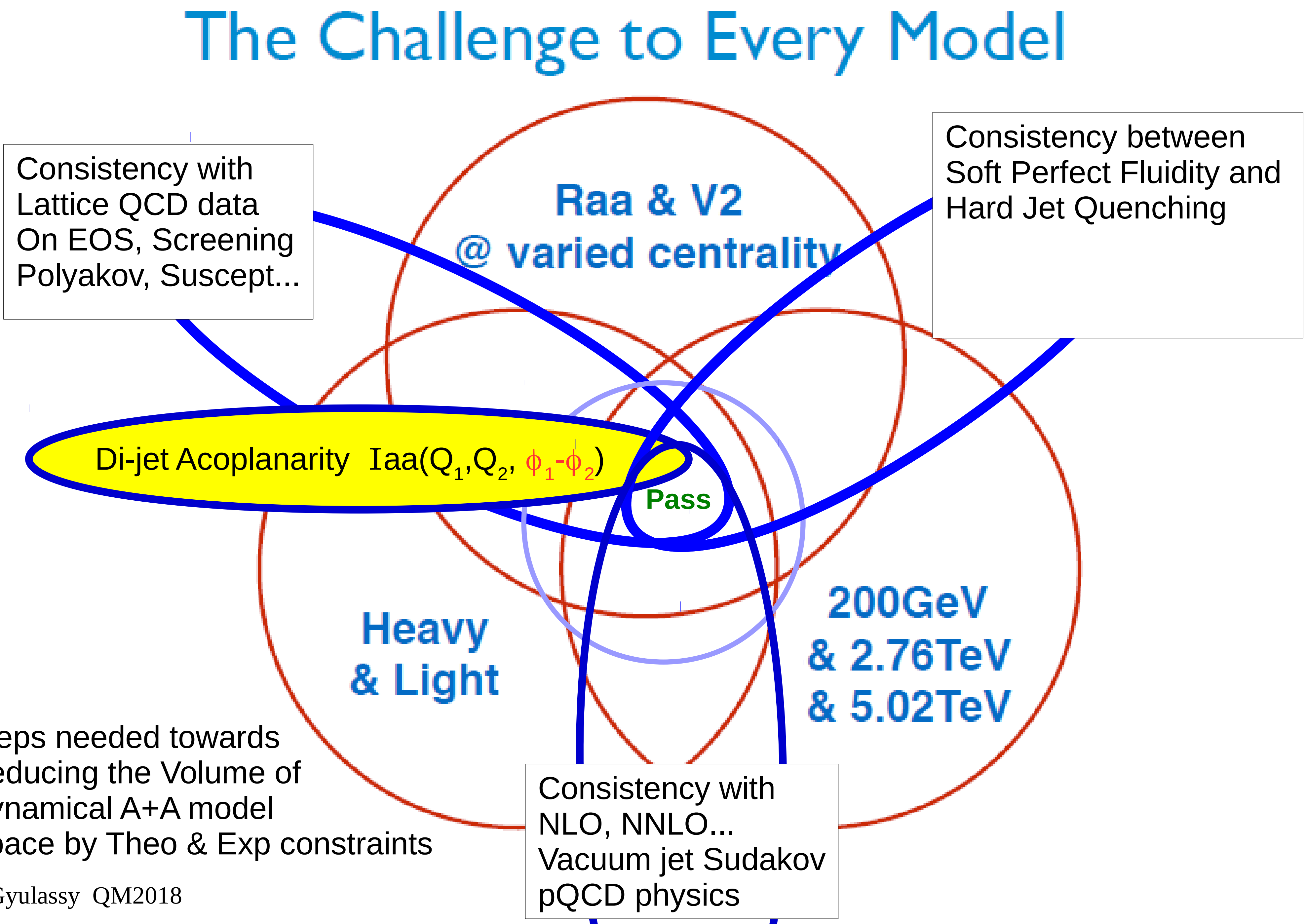




Ratio dN(Vac+GLV)/dN(Vac) (red) vs dN(Vac+BDMS)/dN(Vac) (blue) vs q
for Q=20, α=0.09,GLV μ=0.5 χ= 6, 10 <=> BDMS Q_s^2=10. (solid),16. (dash)
For a perfectly fitted
R(q=0) intercept point
Qs varies as opacity
and screening scales
vary
GLV $(\mu, \chi, Q_s^2) = (0.5, 6.27, 10)$
BDMS $(\mu = 0, \chi = \infty, Q_s^2 = 16)$
q_C
q_L
R(q=0)
$(\Delta\phi = \pi)$
But we need (sub) percent level precision on shapes
to resolve mu, chi from Qs
R(q)
q
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
5
10
15


Ratio dN(Vac+GLV)/dN(Vac) Qs^2=9.6 (red), 16 (blue) vs q
for Q=20, α=0.09, (μ,χ)=(0.5,6&10)sol, (0.75,3.1&5.1)dash, (0.25,20&33)dot
GLV/Vac for Fixed Q_s^2=9.6 (red) and 16 (Blue)
$(\mu, \chi, Q_s^2) = (0.75, 3, 9.6)$ red − das , $(0.75, 5, 16)$ blu − das
$(\mu, \chi, Q_s^2) = (0.5, 6, 9.6)$ red − sol , $(0.5, 10, .16)$ blu − sol
$(\mu, \chi, Q_s^2) = (0.25, 20, 9.6)$ red − dot , $(0.25, 33, .16)$ blu − dot
Percent or better level of precision required to resolve finite
(μ, χ) From Q_s^2
The asymp BDMS limit $(\mu \to 0, \chi \to \infty)$ can be differentiated from
The finite GLV form at the ~5 % accuracy level
R(q)
q
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0
5
10
15

Summary: My theoretical and exp wish list at QM18 updated from J.Liao's QM17 talk



Steps needed towards
Reducing the Volume of
Dynamical A+A model
Space by Theo & Exp constraints

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 chromo dynamics 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

Lin Chen, Guang-You Qin *, Shu-Yi Wei, Bo-Wen Xiao, Han-Zhong Zhang
PLB 773 (2017) 672 "Probing transverse momentum broadening...

distribution in the Sudakov resummation formalism as follows

$$\frac{d\sigma}{d\Delta\phi} = \sum_{a,b,c,d} \int p_{\perp\gamma} dp_{\perp\gamma} \int p_{\perp J} dp_{\perp J} \int dy_\gamma \int dy_J \int db$$

$$\times x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b) \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} b\ J_0(|\vec{q}_\perp|b) \boxed{e^{-S(Q,b)},} \tag{1}$$

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

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

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

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

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 $\mu_b \equiv \frac{c_0}{b_\perp}\sqrt{1 + b_\perp^2/b_{max}^2}$,

PHYSICAL REVIEW D VOLUME 24, NUMBER 5 1 SEPTEMBER 1981

Logarithmic approximations, quark form factors, and quantum chromodynamics

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

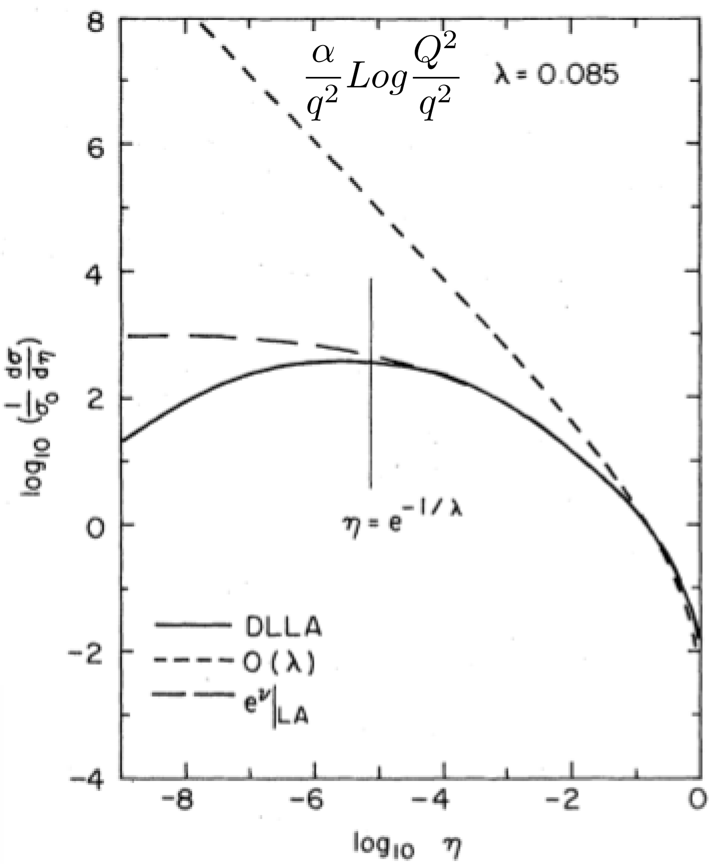


FIG. 4. Theoretical approximations to the cross section defined in the text. The long-dashed line is the soft logarithmic approximation [LA, (1), (2), (3)]. The solid line is the DLLA Eq. (2.12). The dashed line is the corresponding one-gluon contribution.

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

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\eta}\bigg|_{\mathrm{DLLA}} = \frac{\lambda}{\eta}\ln\frac{1}{\eta}\exp\left(-\frac{\lambda}{2}\ln^2\eta\right)\theta(1-\eta)$$
$$= \frac{d}{d\eta}F_{\mathrm{DLLA}}(\eta)\,\theta(1-\eta) \qquad (2.12)$$

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

with $C_F = \frac{4}{3}$, $T_R = \frac{1}{2}$ 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

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

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

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

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-

A. Kulesza, W.J. Stirling / Nuclear Physics B 555 (1999) 279–305

D.Appel 1986

Jet Scattering in multi-component partonic plasmas

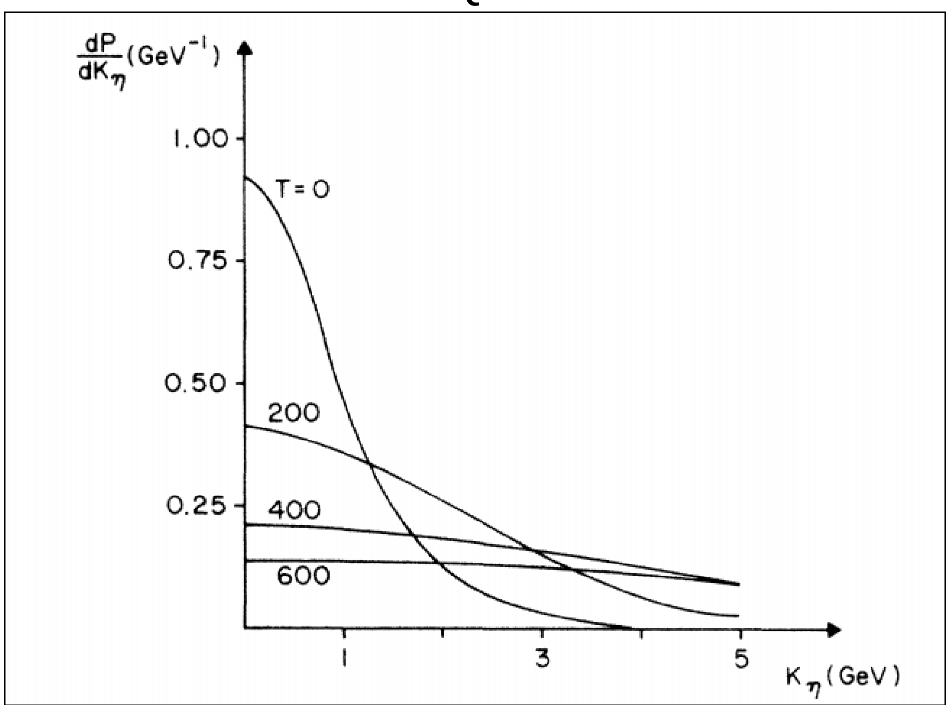
For $F(l_T)$, the probability density for scattering elastically off the plasma constituents with transverse-momentum transfer l_T, we propose the following form:

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

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.

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

Stefan-Boltzmann wQGP model estimates



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 (μ, χ)

GLV PRD66 (2002)

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

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

$$\chi = \langle L/\lambda \rangle = \int \mathbf{dt} \int \mathbf{d^2q}\ \{\mathbf{d}\sigma_{\mathbf{el}}(\mathbf{t})/\mathbf{d^2q}\}\ \rho(\mathbf{t}, \mathbf{b_0}) \sim O(\alpha T L)$$

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

Landau tail

In large χ>>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"

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

PHYSICAL REVIEW D **66**, 014005 (2002)

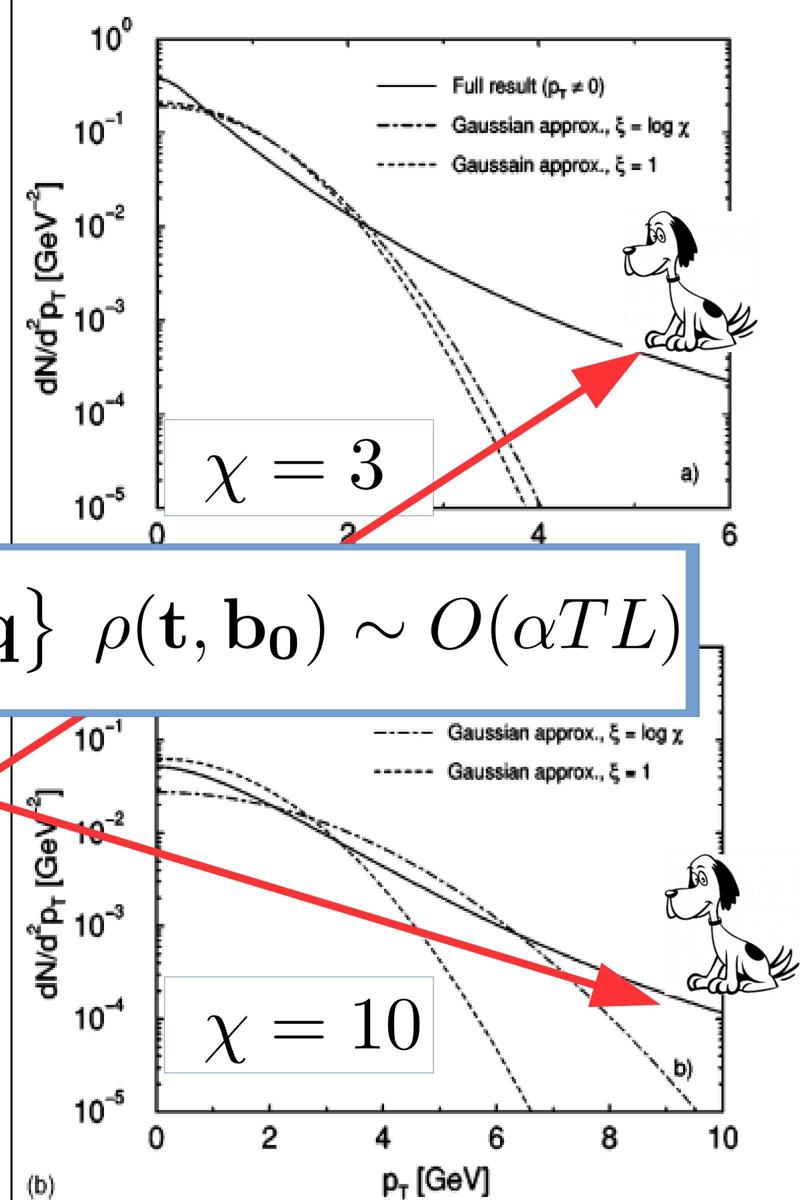
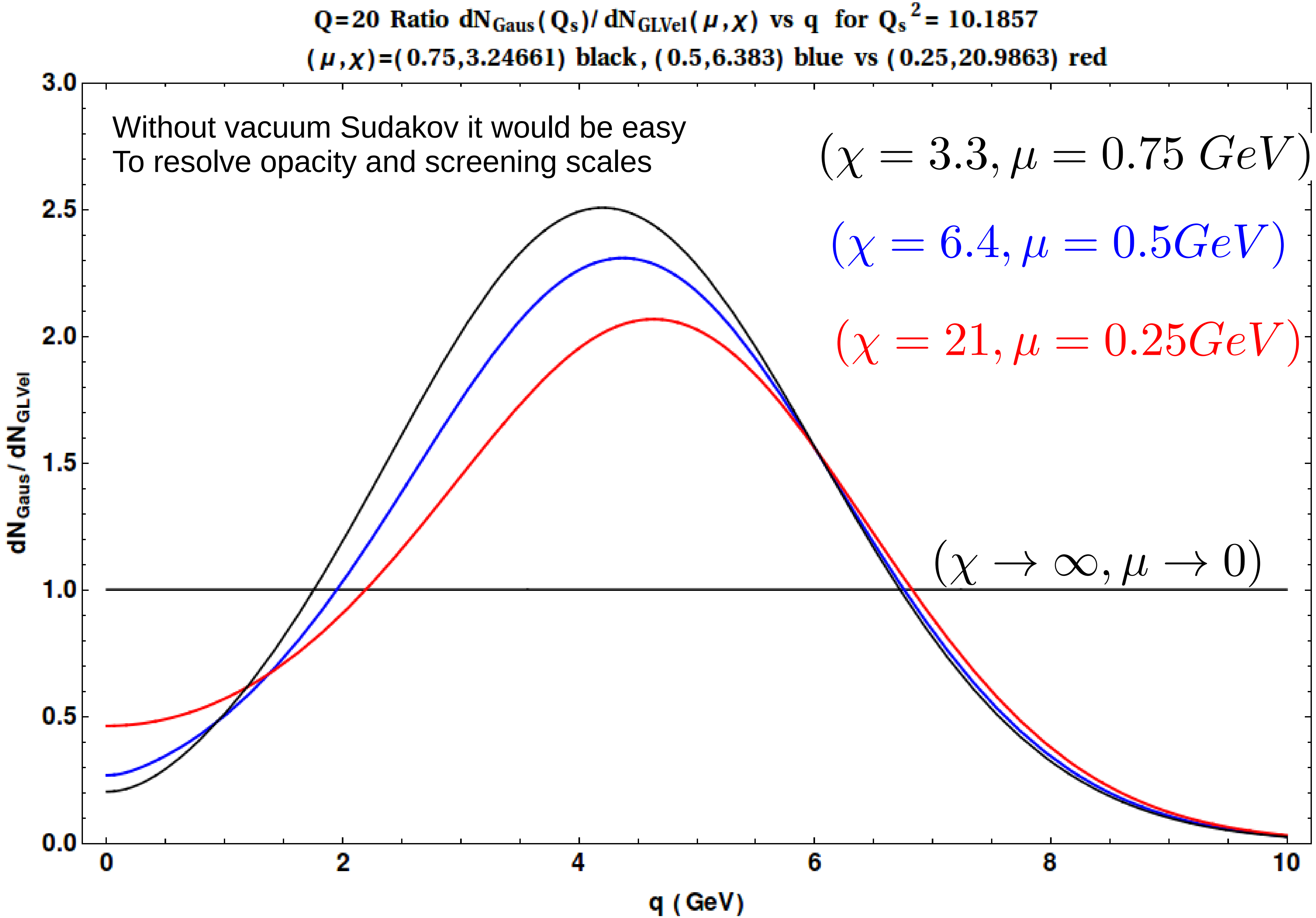


FIG. 3. The final parton p_T distribution is shown versus p_T for two different opacities $\chi=3$ (a) and $\chi=10$ (b). We compare the full result (without the delta function contribution at $p_T \sim 0$) to the Moliere Gaussian approximation with $\xi=1$ and $\xi=\log\chi$. In this example we use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

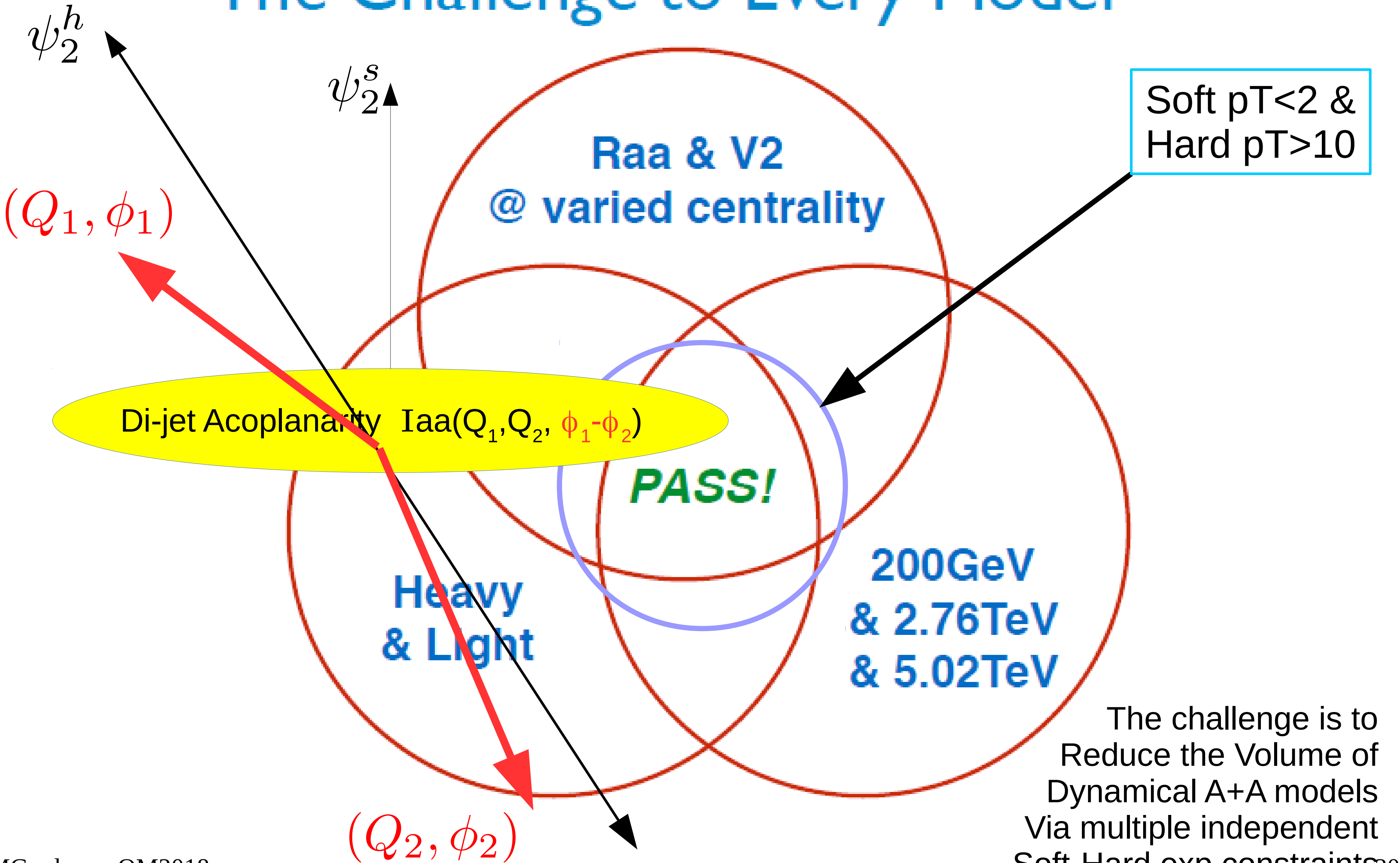
MGyulassy QM2018

Conclusion 1:



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



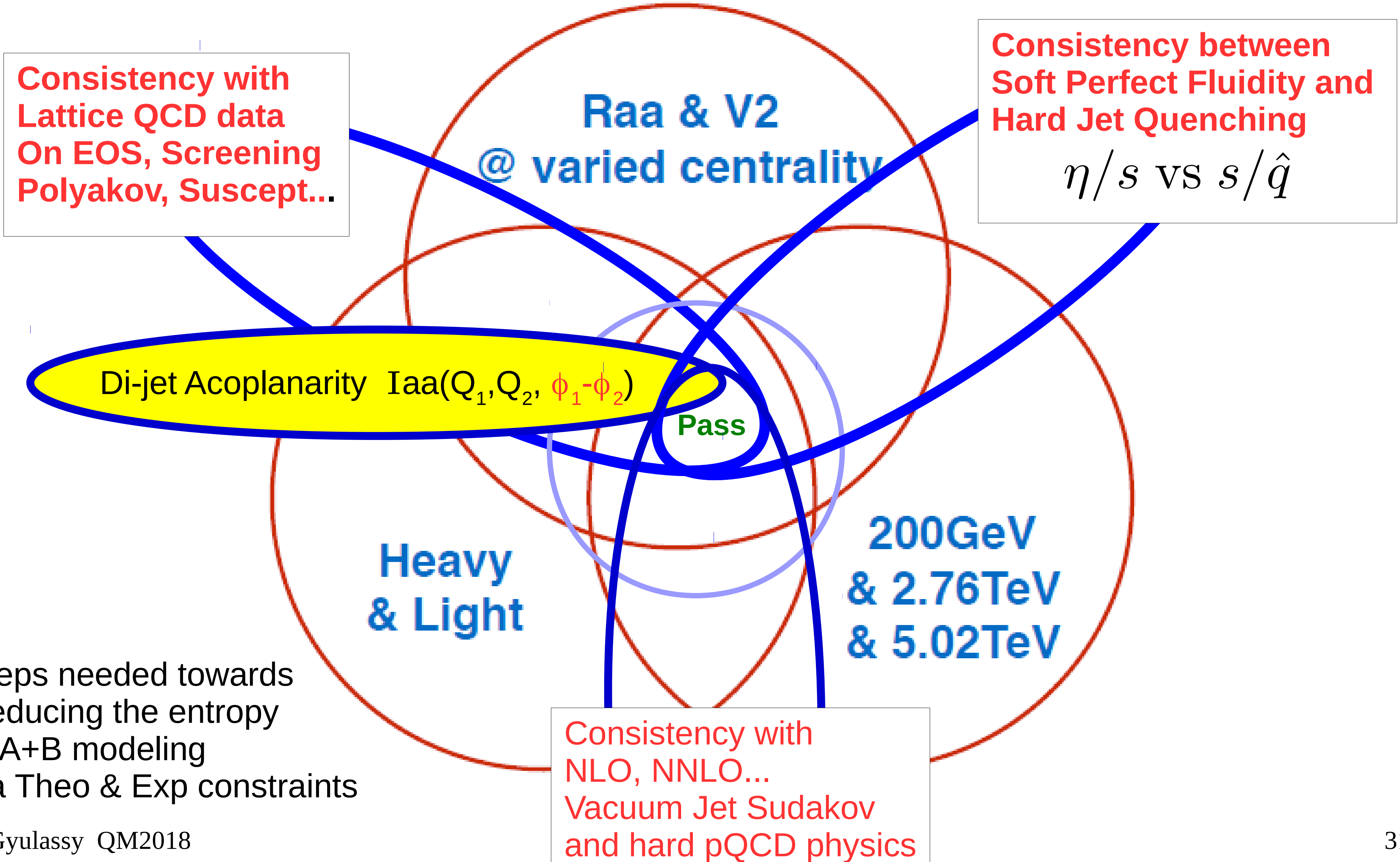
The challenge is to
Reduce the Volume of
Dynamical A+A models
Via multiple independent
Soft-Hard exp constraints

My greedier SHEE theory wish list at QM18

Simultaneous Soft+Hard Event Engineering

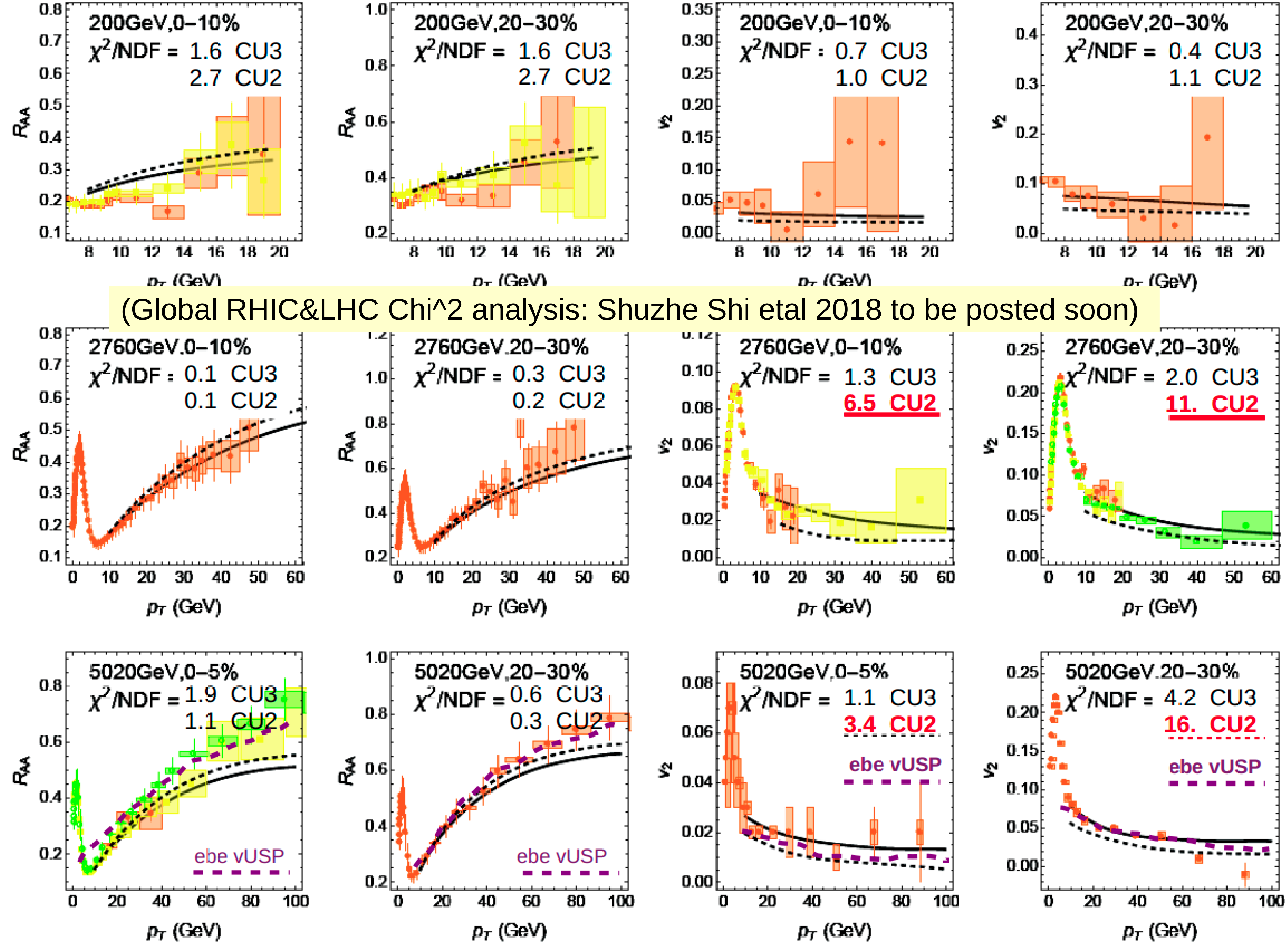
JNH etal (16)
SShi etal (17)

The Challenge to Every Model



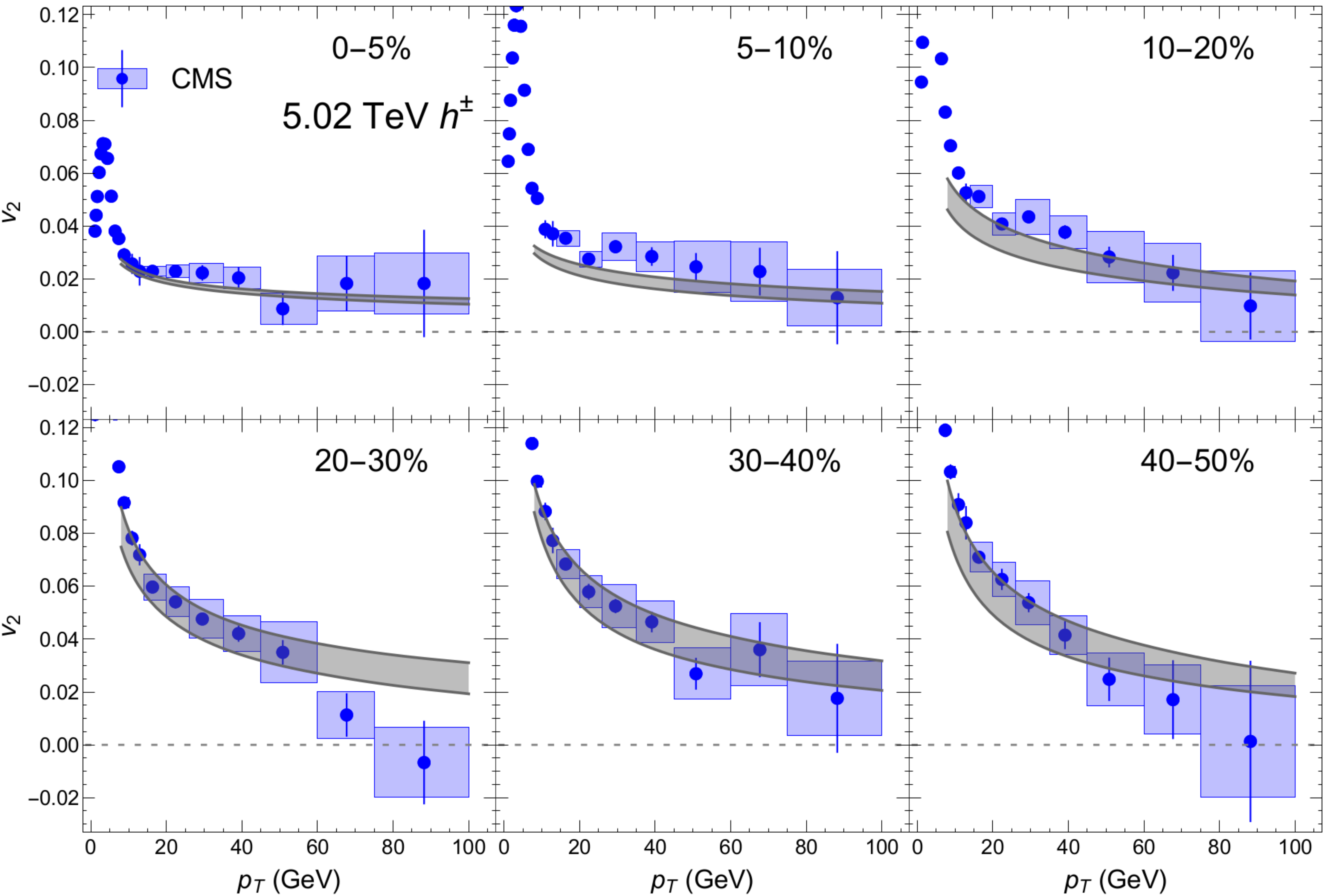
Steps needed towards
Reducing the entropy
of A+B modeling
via Theo & Exp constraints

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

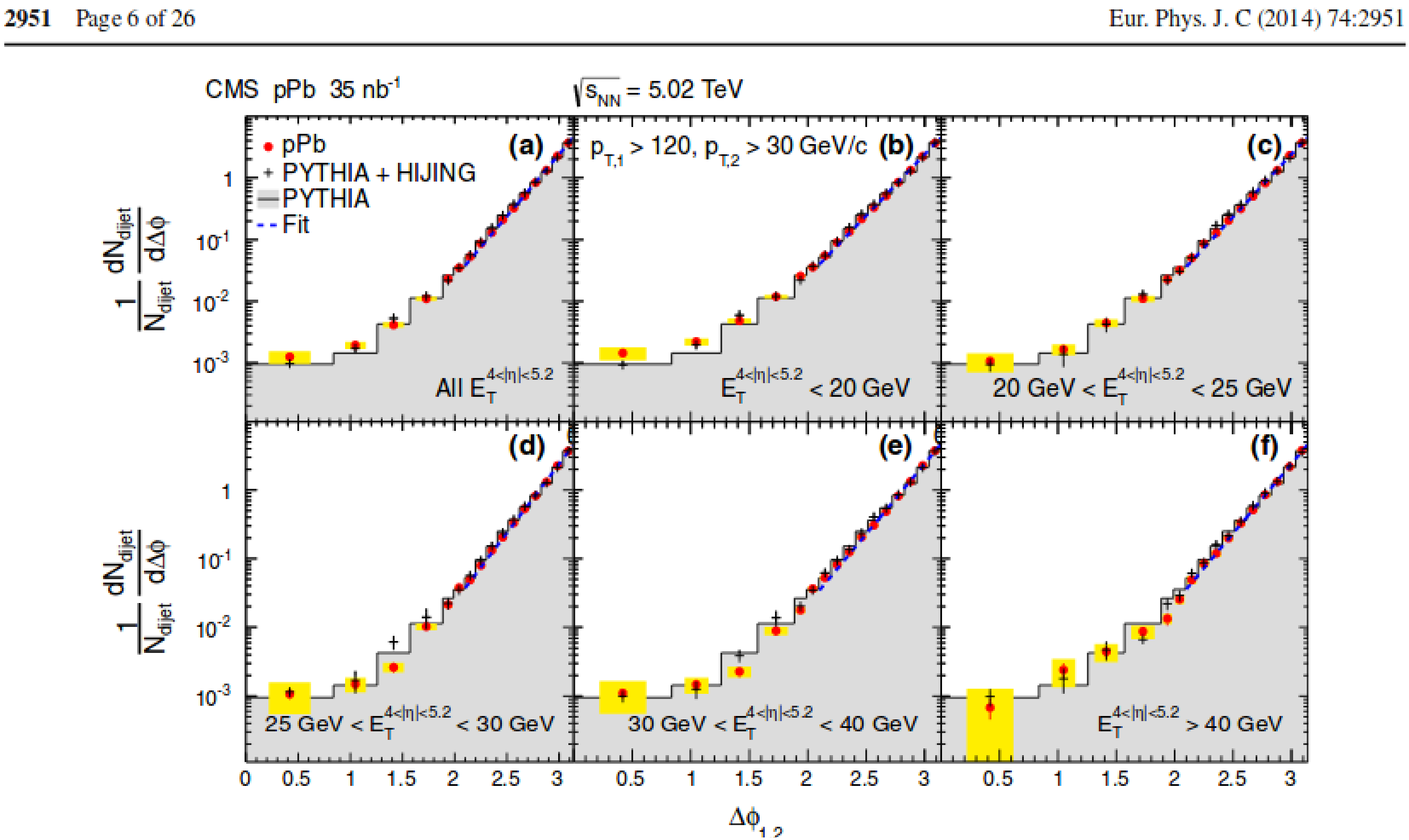


(Global RHIC&LHC Chi^2 analysis: Shuzhe Shi etal 2018 to be posted soon)

Shuzhe Shi et al CUJET3.1 test passed CMS v2 centrality data at 5.02ATeV



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

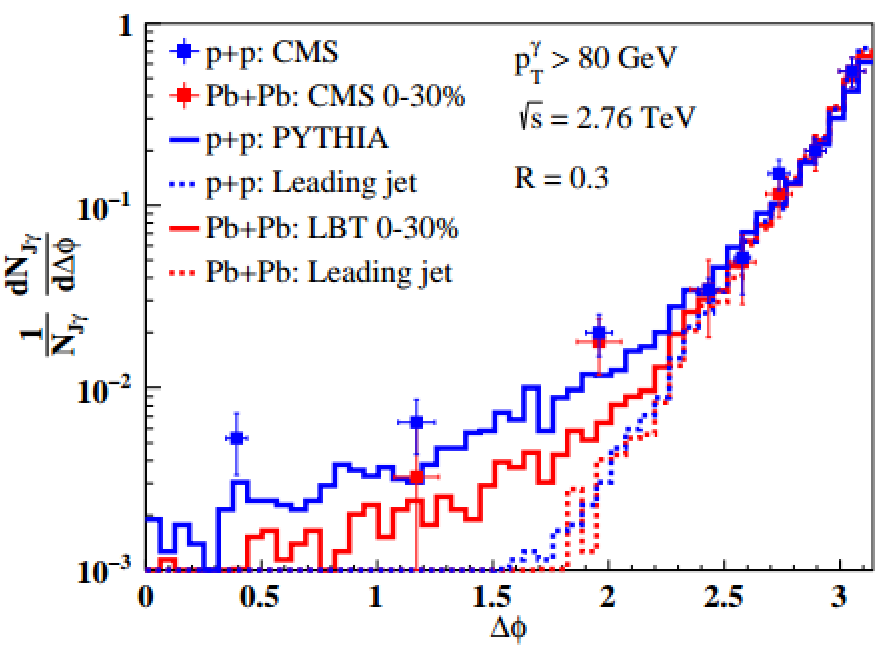


FIG. 6: (Color online) Angular distribution of γ-jet in central (0–30%) Pb+Pb (red) and p+p collisions (blue) at $\sqrt{s} = 2.76$

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

High pT~ 100 GeV makes small angle Deviations from pi nearly independent Of medium effect and are dominated by Vaccum Sudakov effects.

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

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 dijett

“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.”

Angular structure of jet quenching within a hybrid strong/weak coupling model

Jorge Casalderrey-Solana et al JHEP03 (2017) 135

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

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

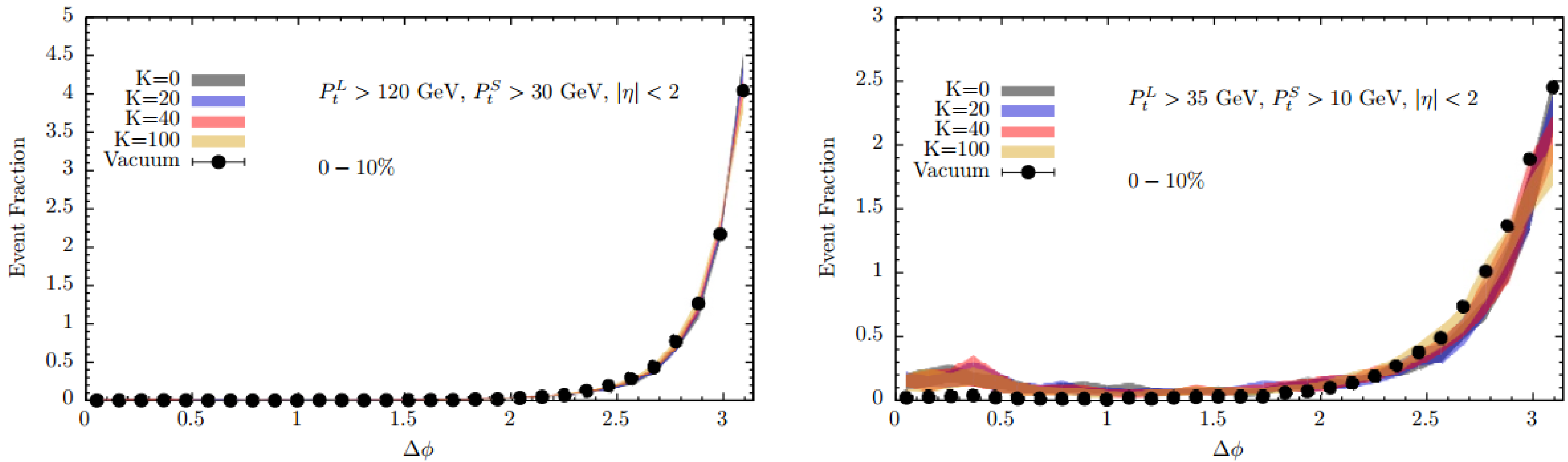
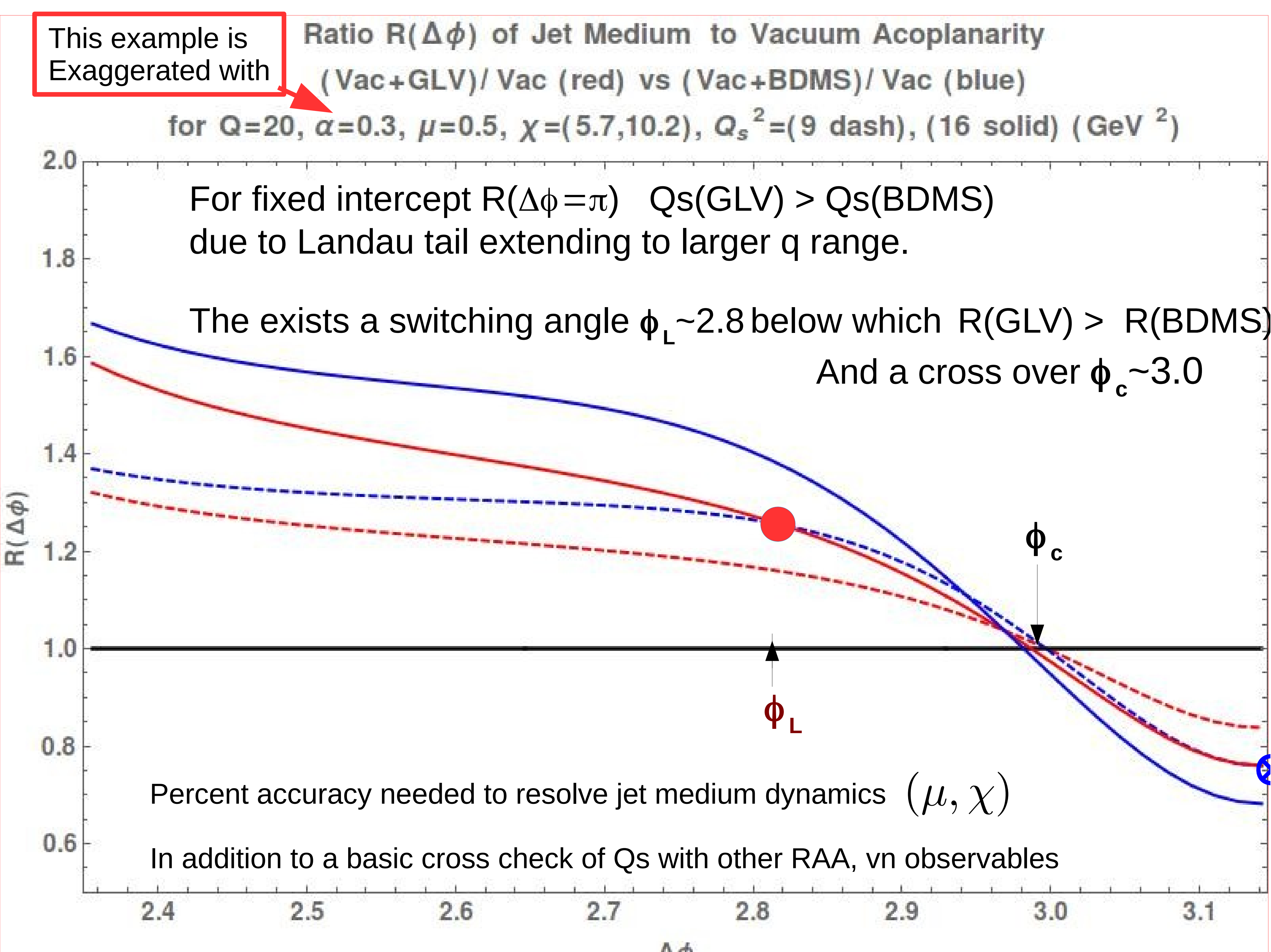


Figure 3. Dijet acoplanarity distribution for high-energy (left) and low-energy (right) dijets in LHC heavy ion collisions with $\sqrt{s} = 2.76$ ATeV for two different values of the broadening parameter K. For comparison, the black dots show the acoplanarity in proton-proton collisions as simulated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

the effects of medium broadening on the acoplanarity distribution are small

For E ~ 30 GeV strong coupling broadenning could be tested in the future to falsify holographic or perturbative or other hybrid model combinations



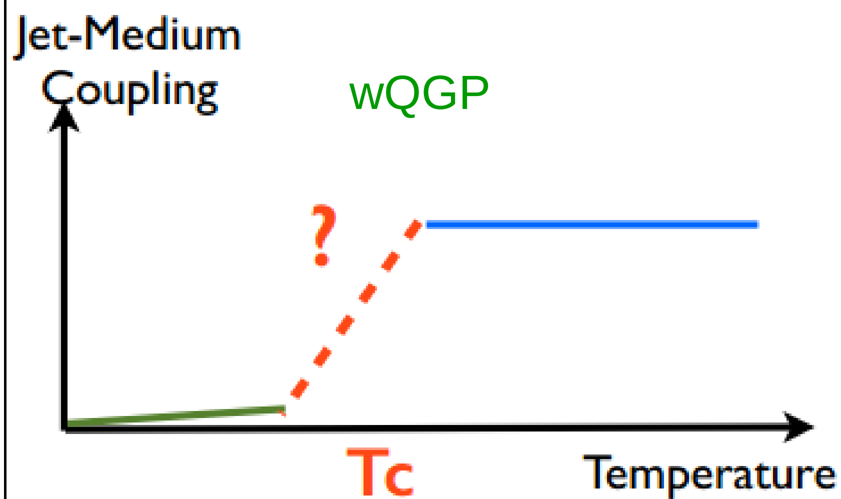
This example is Exaggerated with
Ratio R(Δφ) of Jet Medium to Vacuum Acoplanarity
(Vac+GLV)/ Vac (red) vs (Vac+BDMS)/ Vac (blue)
for Q=20, α=0.3, μ=0.5, χ=(5.7,10.2), Q_s^2=(9 dash), (16 solid) (GeV ^{2})
For fixed intercept R(Δφ=π) Qs(GLV) > Qs(BDMS)
due to Landau tail extending to larger q range.
The exists a switching angle ϕ_L~2.8 below which R(GLV) > R(BDMS)
And a cross over ϕ_c~3.0
ϕ_c
ϕ_L
Percent accuracy needed to resolve jet medium dynamics (μ, χ)
In addition to a basic cross check of Qs with other RAA, vn observables
R(Δφ)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1

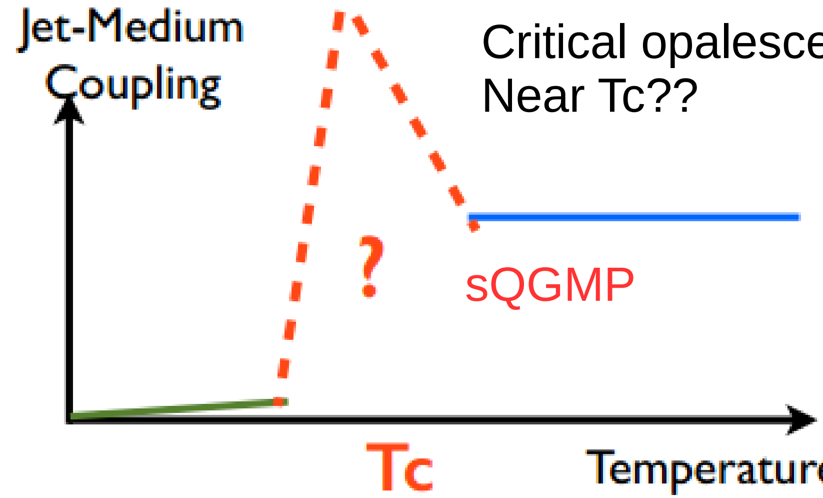
Monopole component near Tc
could account for near perfect fluidity

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

J.Liao 2015

From "Transparency" to Opaqueness





"Waterfall" scenario

"Volcano" scenario

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, v2, v3 data?