Dijet Acoplanarity as a Probe of the Nonperturbative Color Structure of QCD Perfect Fluids with CUJET3

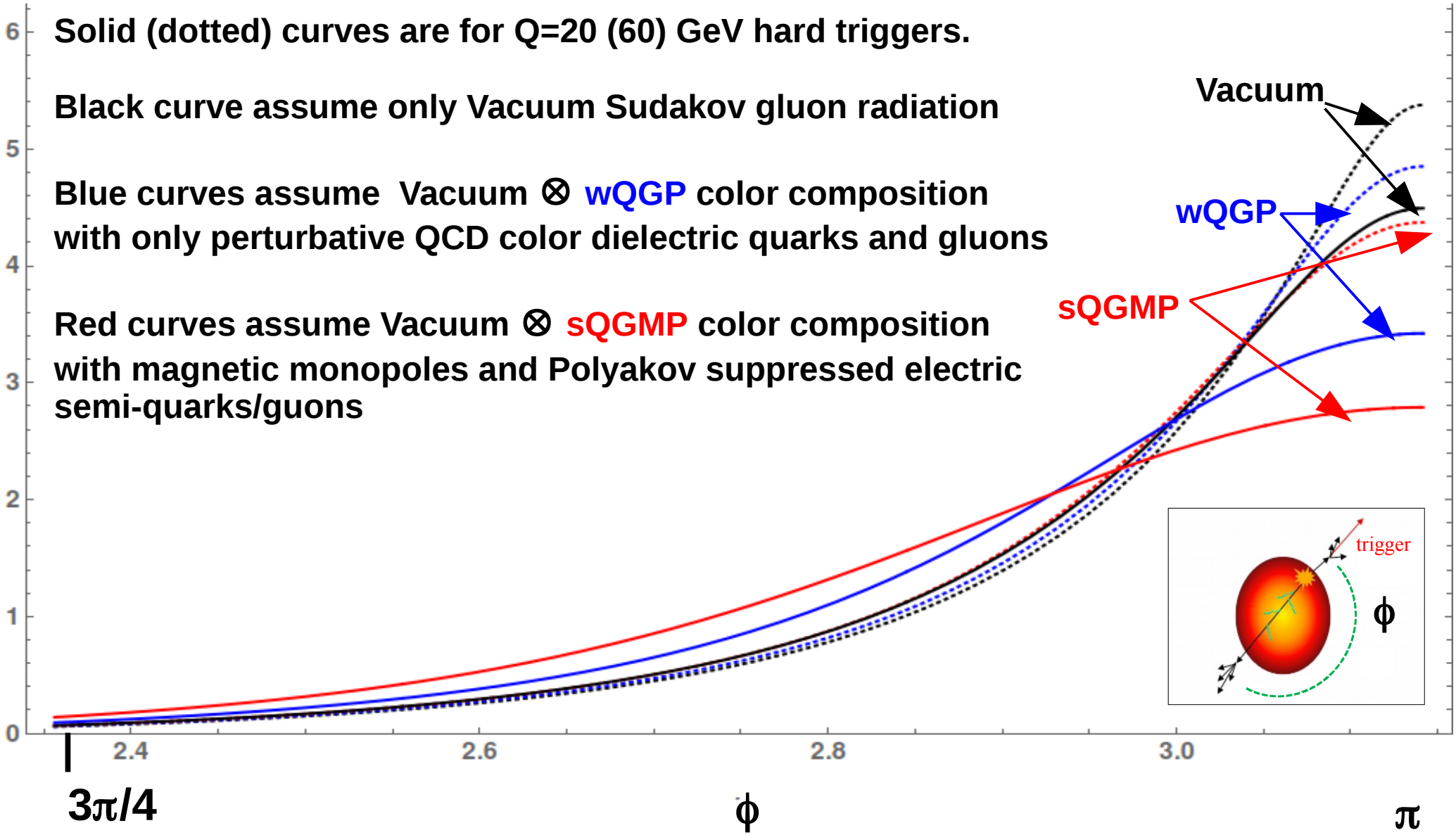
Wednesday, 6 November 2019 12:00 (20 minutes)

GYULASSY, Miklos (CCNU Wuhan)

Co-authors: JACOBS, Peter Martin (Lawrence Berkeley National Lab. (US)); LIAO, Jinfeng (Indiana University); SHI, Shuzhe (McGill University); WANG, Xin-Nian (Central China Normal University (China)) / Lawrence Berkeley Na); YUAN, Feng (LBNL)

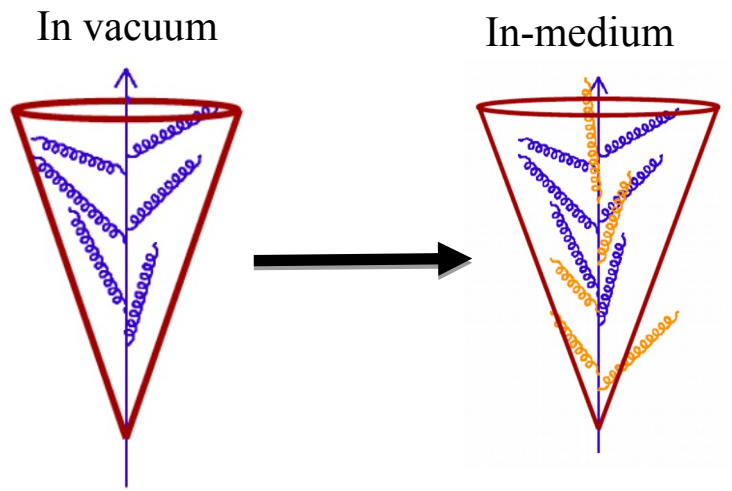
Summary: With dynamical parameters *Constrained* by RAA&v2 RHIC&LHC data , CUJET3 predicts that DiJet Acoplanarity dN/dϕ can robustly discriminate between wQGP and sQGMP color d.o.f. of the QCD fluid in the crossover T~ 150-300 MeV region

dN/dϕ



Jet quenching observables

(See P.Jacobs,Tuesday 11am)



Signatures of in-medium interactions

1. Energy transport out-of-cone → yield suppression (R_{AA}, I_{AA})
2. Jet substructure modification
3. Jet deflection → **acoplanarity**

All must occur

Different observables probe different aspects of jet quenching

- explore all three, require consistent picture

Jet quenching in high-EA pp collisions

Inclusive R_{AA}

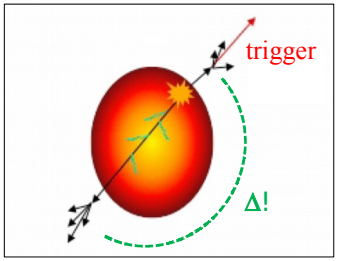
- Glauber scaling undefined, measurement not possible

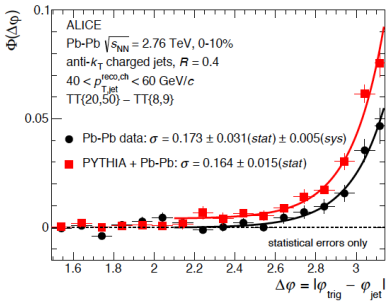
Acoplanarity

D. A. Appel, PRD 33, 717 (1986)
J.P. Blaizot and L. McLerran, PRD 34, 2739 (1986)

Experimental techniques in place

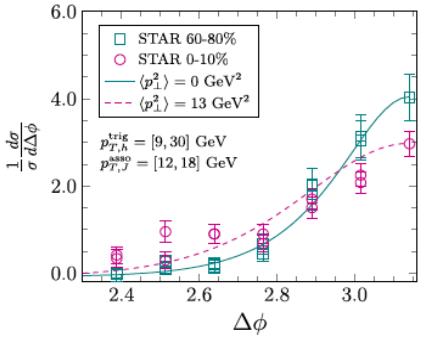
JHEP 09 (2015) 170

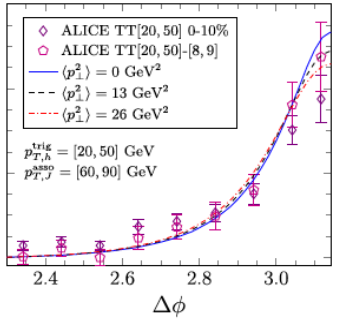




Background: initial-state (Sudakov) radiation

L. Chen et al., Phys.Lett. B773 (2017) 617





Hadron-Jet acoplanarity azimuthal distribution from Chen,Qin,Xiao,Zhang PLB773, 2017
A+A Vacuum Sudakov+ BDMS(Q_s^2) and current RHIC and LHC data

Current State of "Acoplanarity Art"

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

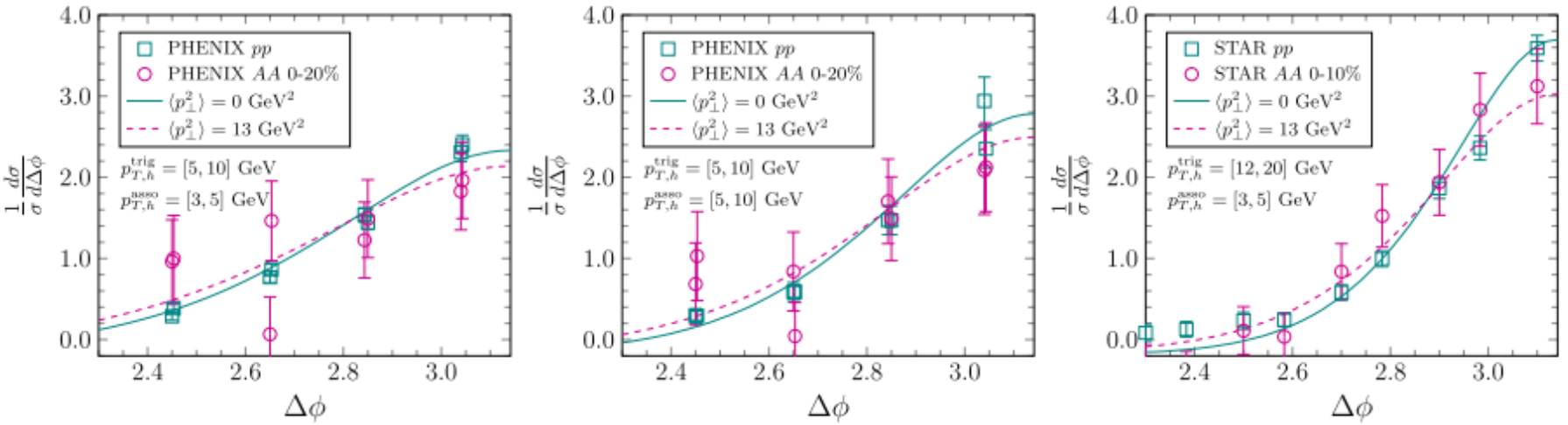
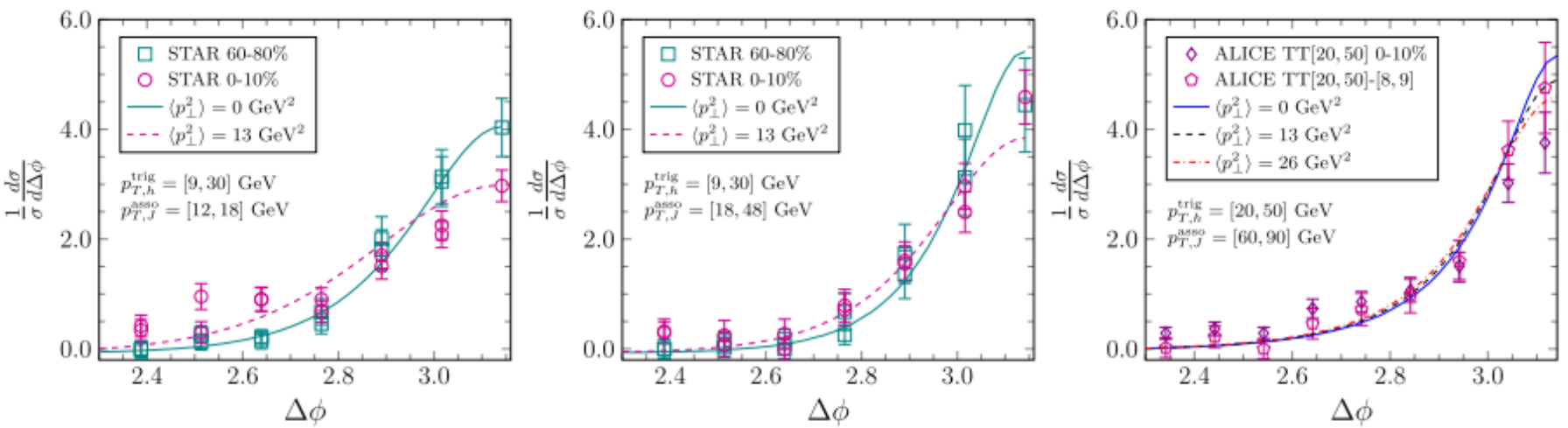


Fig. 1. Normalized dihadron angular correlation compared with PHENIX [51] and STAR [52] data.



As a stand alone observable, Acoplanarity does not constrain Q_s^2 better than RAA&v2.
However, we show below that <u>in combination with RAA&v2</u>,
Acoplanarity can greatly increases exp discriminating power to falsify dynamical models of AA

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

D. A. Appel, PhysRD33, 717 (1986); J. P. Blaizot,L. D. McLerran, PRD34, 2739 (1986)
F.~D'Eramo et al, JHEP 1305 (2013) 031; 1901 (2019) 17,MG et al , QM18 NPA982 (2019) 627.

We utilized the formalism of

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

$$\frac{dN}{dq^2} \approx \frac{1}{Q^2}\frac{dN}{d\Delta\phi} = \int b db J_0(|q(Q,\Delta\phi)|b) e^{-S_{vac}(Q,b)-S_{med}(Q,b)}$$

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

The medium induced broadening in **one parameter** multi soft Gaussian BDMS approx

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

$$Q_s^2 = \int dt\ \hat{q}(T(\vec{r}(t),t)),Q)$$

The **two parameter** opacity **χ=L/λ** and screening **μ** multiple Yukawa scatt approx

$$S_{GLV}(b;\chi,\mu) = \chi(\mu b K_1(\mu b) - 1) \approx b^2 \log[1/(b\mu)^2](\chi\mu^2)/4$$

Part 2 : CUJET3 example of

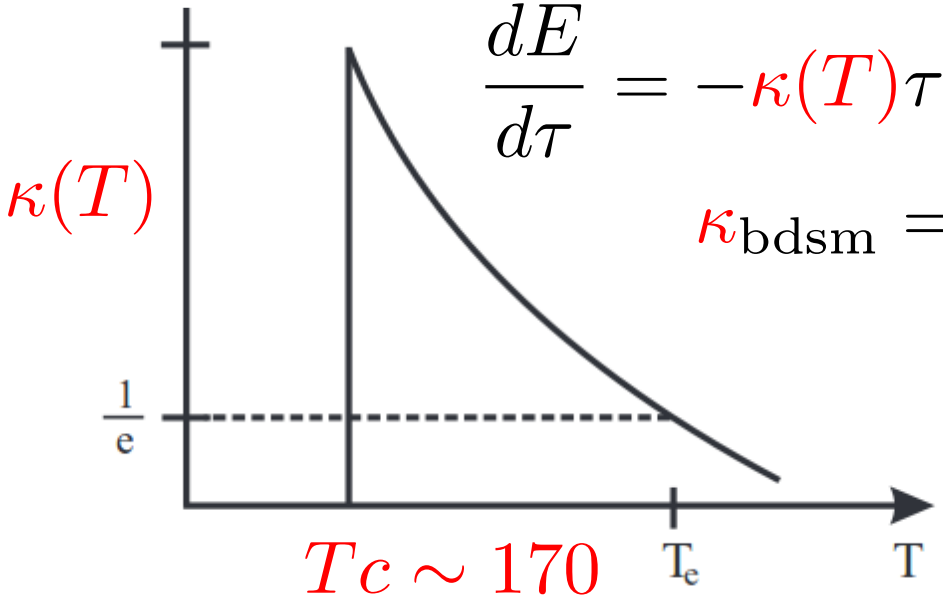
RAA Constrained Dijet Acoplanarity Tomography

Refs: Shuzhe Shi, Jinfeng Liao , M.G. :

`Probing the Color Structure of the Perfect QCD Fluids via Soft+Hard Event-by-Event Azimuthal Correlations," Chin.Phys.C42, 104104 (2018)

``Global constraints from RHIC and LHC on transport properties of QCD fluids in CUJET/CIBJET framework," Chin.Phys.C43, 044101 (2019)

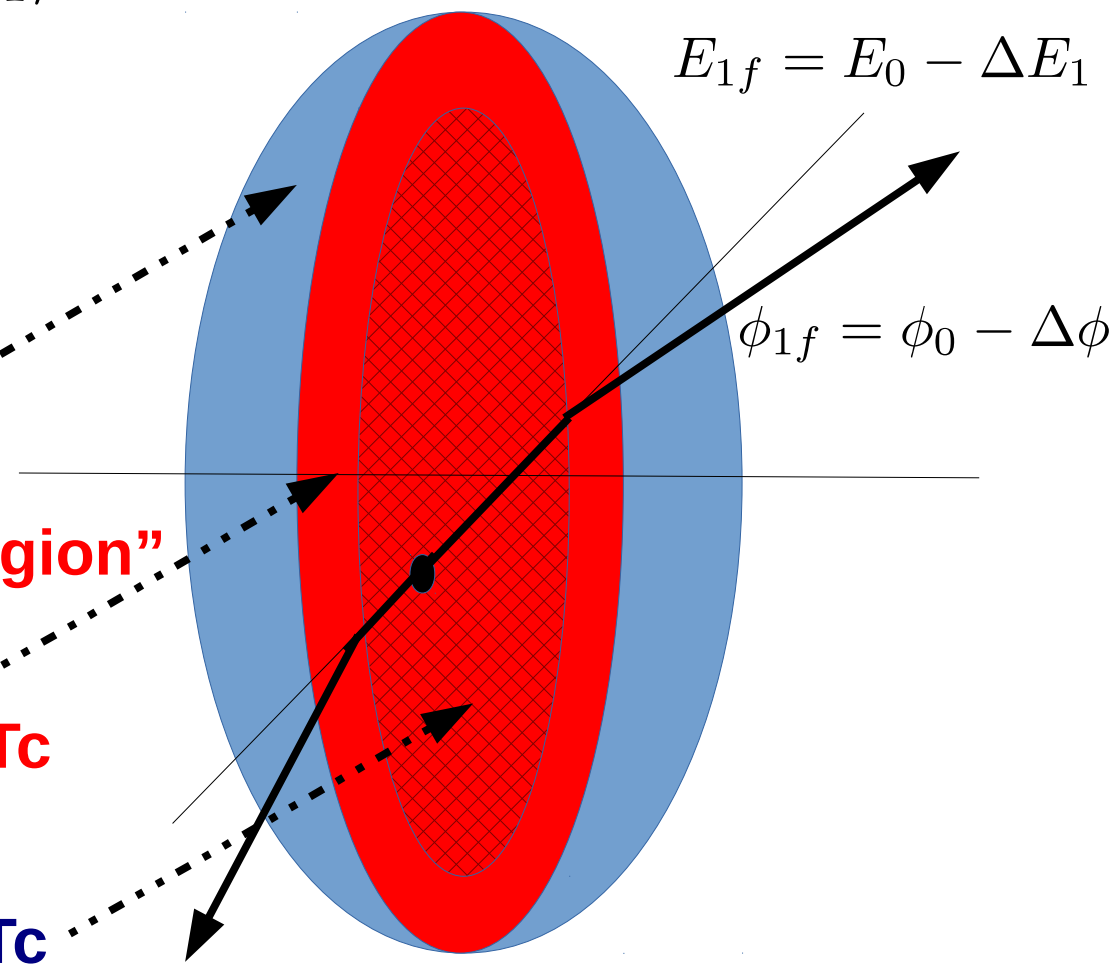
J. Liao and E. Shuryak, Angular Dependence of Jet Quenching Indicates Its Strong Enhancement Near the QCD Phase Transition ,**PRL102 (2009); Shuryak PRC66 (2002)**



$$\frac{dE}{d\tau} = -\kappa(T)\tau^b T^{2+b}$$

$$\kappa_{\rm bdsm} = \hat{q}/T^3$$

$$\frac{d\Delta\phi^2}{d\tau} = +\kappa(T)\frac{T^3}{E^2}$$



The Idea:
Emergent Color Magnetic Monopole d.o.f near Tc enhances jet ΔE and v_2 due to jet- monopole Dirac constraint:

$$\alpha_E \alpha_M = 1$$

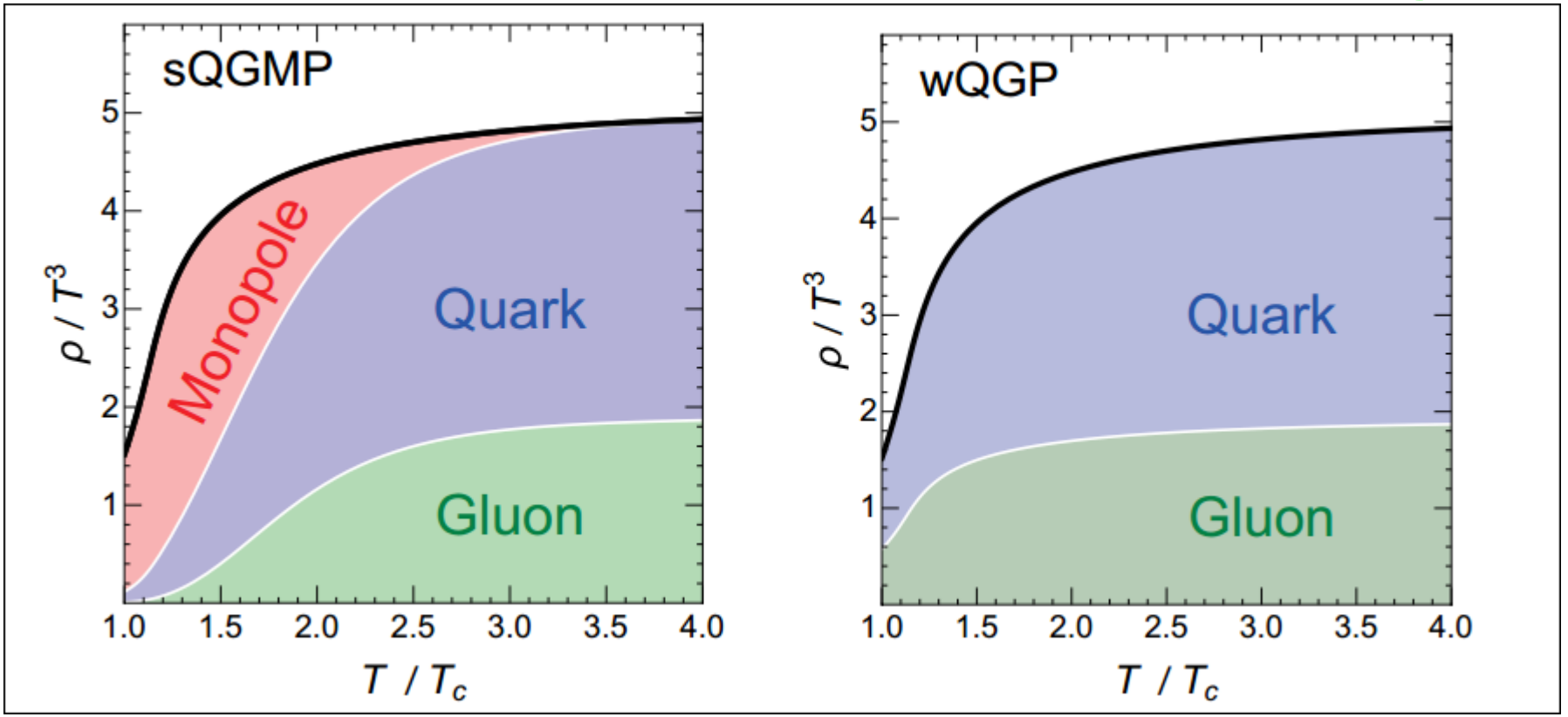
=> κ peak near (1-2) Tc enhances dijet azimuthal acoplanarity !

Chinese Physics C Vol. 42, No. 10 (2018) 104104

Probing the color structure of the perfect QCD fluids via soft-hard-event-by-event azimuthal correlations*

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

$P/T = \rho_q + \rho_g + \rho_m$ vs $P/T = \rho_q + \rho_g$



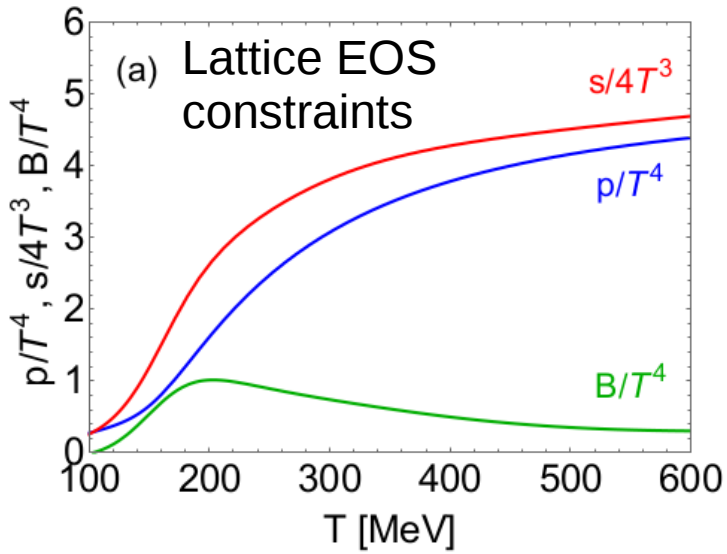
CUJET3 = (OSU VISHNU)(soft hydro) + DGLV(hard jets) + sQGMP

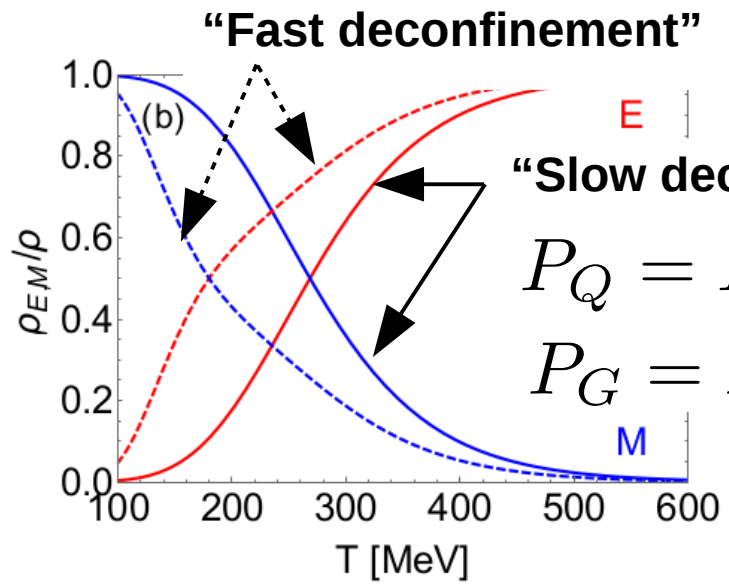
CIBJET = event-by-event CUJET3

Jiechen Xu et al

Shuzhe Shi et al

CUJET3 **sQGMP** composition constrained by Lattice QCD thermo P(T), L(T), $\chi^u(T)$, μ_E,(T), μ_M(T)



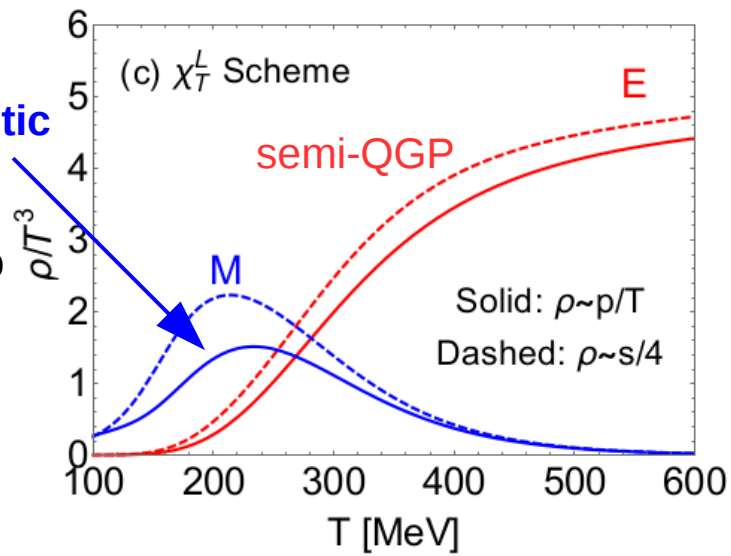


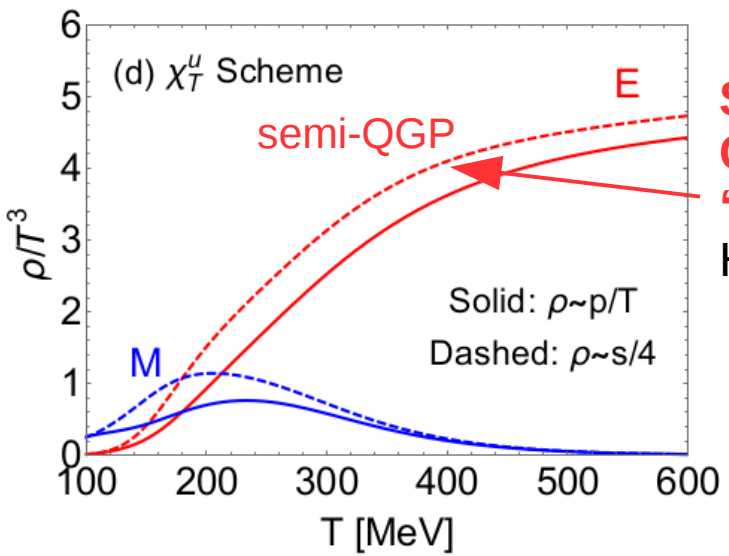
"Slow deconfinement"

$$P_Q = P_Q^{SB} L(T)$$

$$P_G = P_G^{SB} L^2(T)$$

***Emergent* Color Magnetic Monopole d.o.f.**
Shuryak, Liao



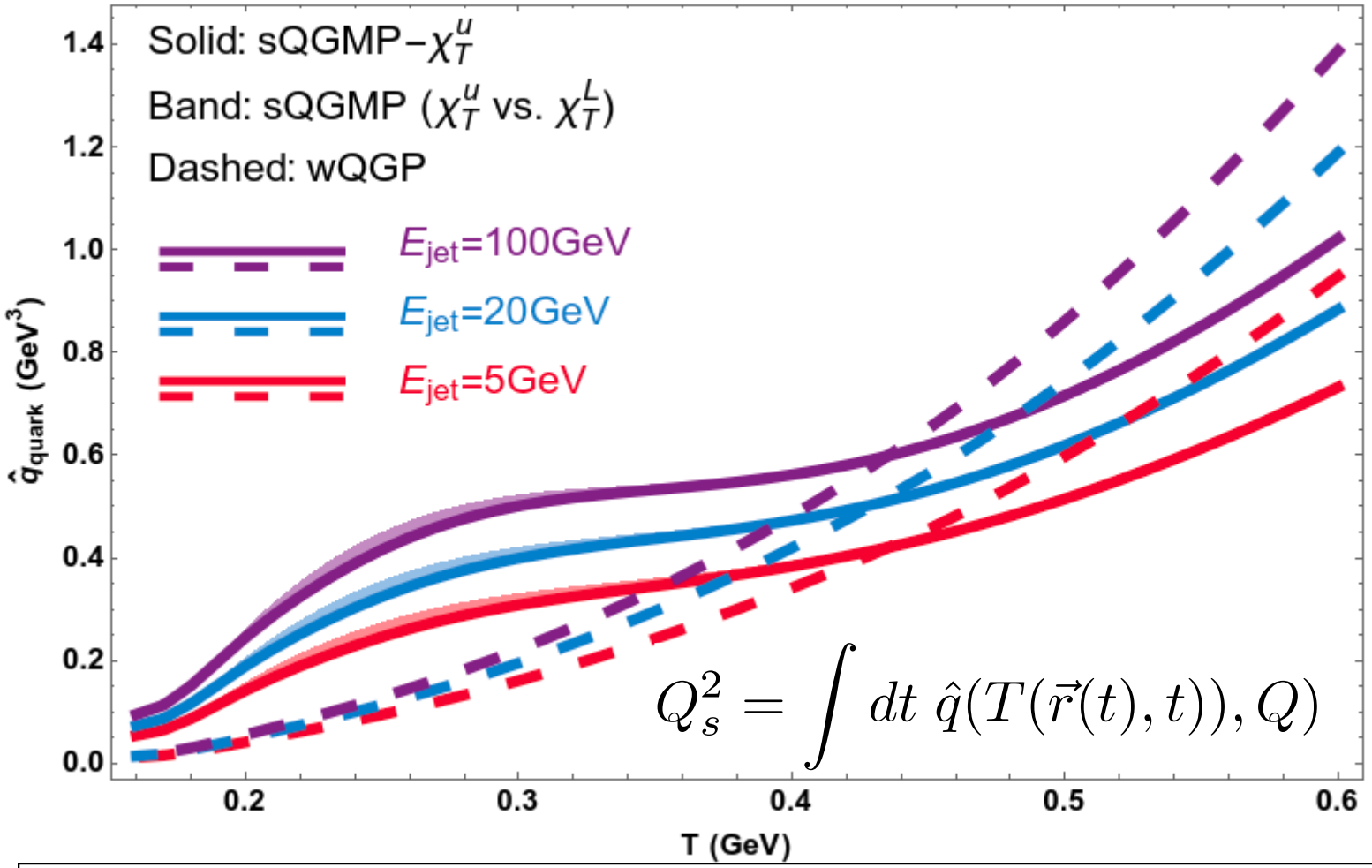


Suppressed Color Electric "semi-QGP"
Hidaka,Pisarski

sQGMP is a lattice QCD constrained model of the 1974 suggestion by **t'Hooft, Polyakov and Mandelstam** that emergent color magnetic monopole d.o.f. may play an important role in confining color electric q and g d.o.f.

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

CUJET Temperature dependence of Jet transport coeff constrained by RHIC&LHC R_{AA}



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

E+E

$$\times \left\{ [C_{qq}f_q + C_{qg}f_g] \cdot \boxed{[\alpha_s^2(\boldsymbol{q}_\perp^2)]} \cdot [f_E^2\boldsymbol{q}_\perp^2 + f_E^2 f_M^2\mu^2(\boldsymbol{z})] + \right.$$

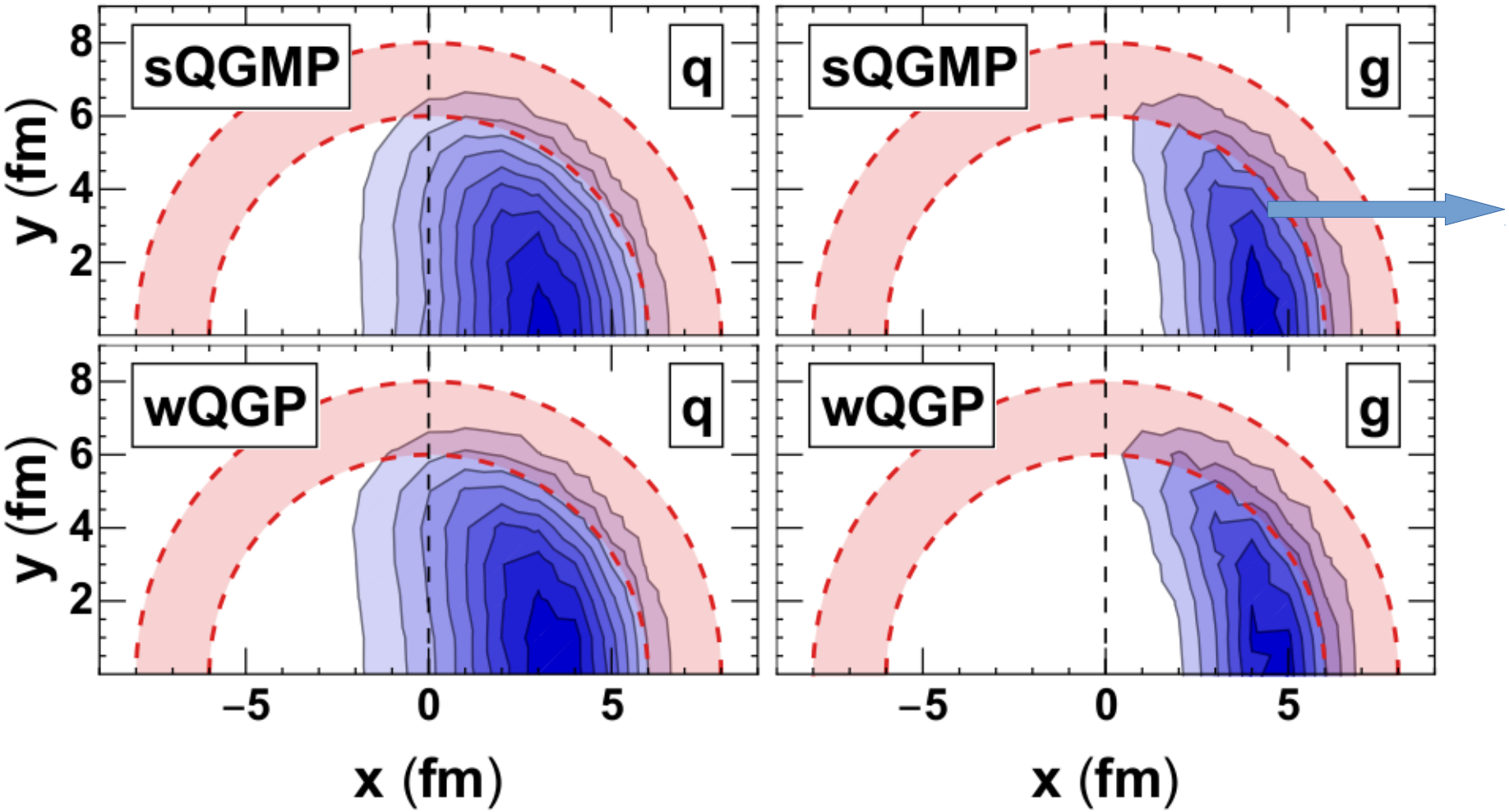
E+M

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

Spatial trigger bias of Quenched partons in wQGP and sQGP are nearly identical
Because both media couplings are **constrained** by same soft+hard RHIC&LHC data on $R_{AA}^{h^\pm}$

Example: trigger E_{fin}=20 GeV and $\phi_0 = 0$

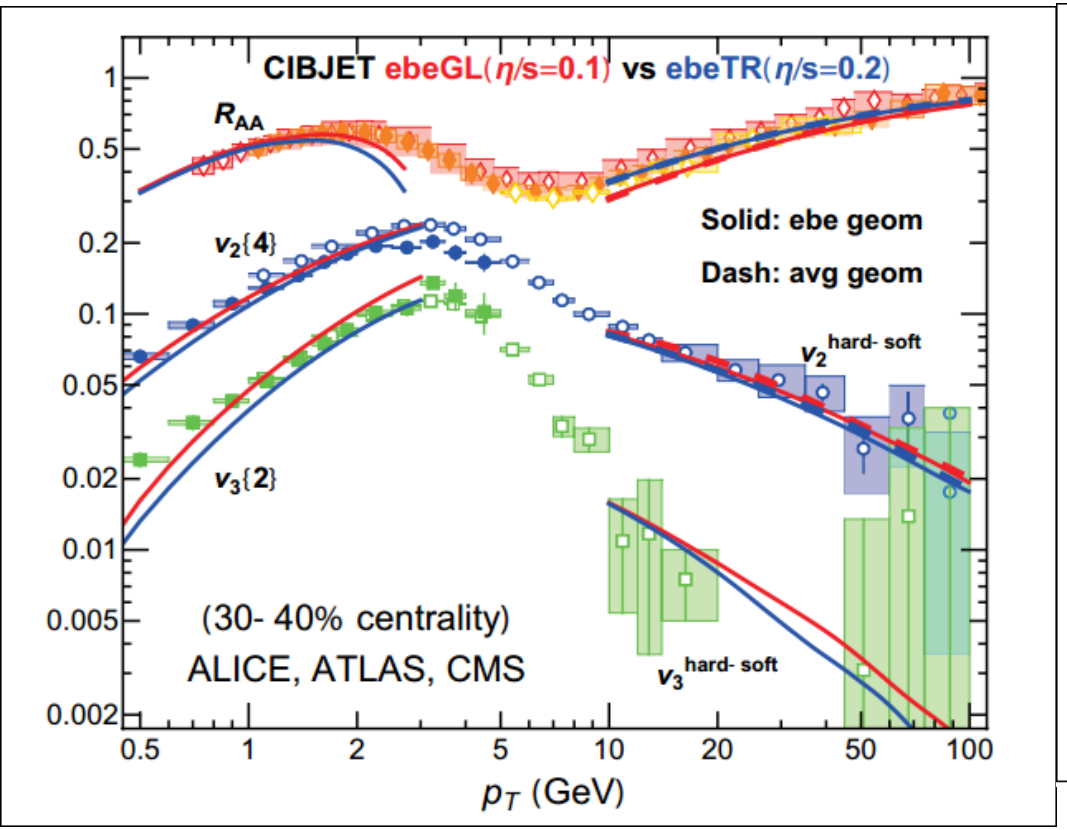
5.02 ATeV b=0 centrality geometry shown for illustration

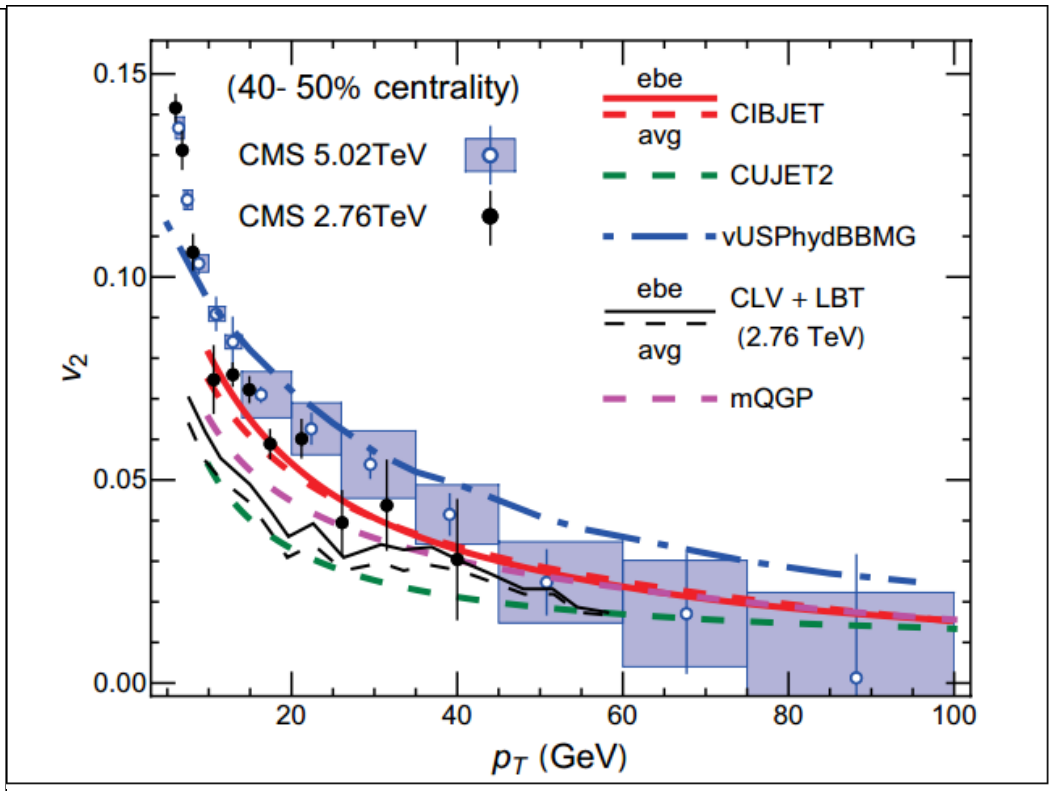


Red band shows initial VISHNU "crossover" 160< T(x,y,t=0.6) < 320 MeV region where

$\hat{q}_{sQGMP} / \hat{q}_{wQGP}$ ~ 2-4

CIBJET (sQGMP) provides a $\chi^2/dof < 2$ solution to all RAA, v2, v3 data at RHIC and LHC





However other globally consistent RHIC+LHC RAA&v2 solutions also exist:

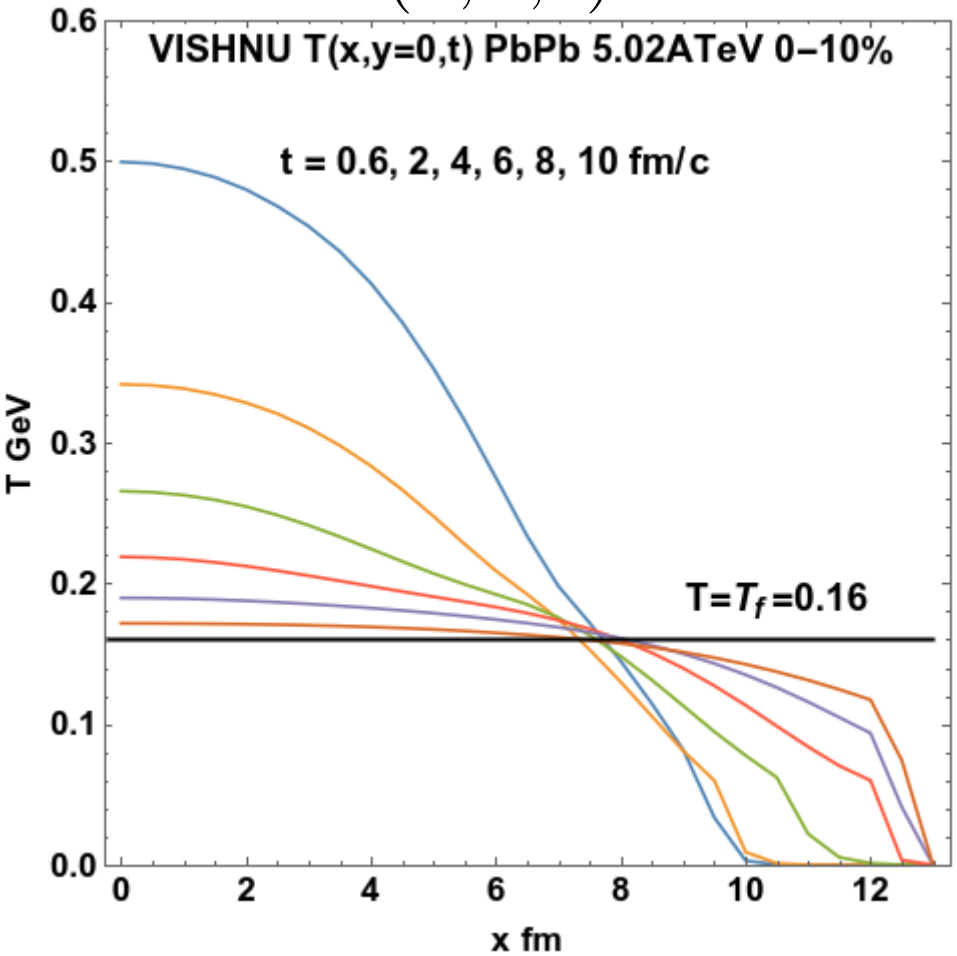
1. J. Noronha Hostler et al, PRL116,252301 (2016)
   "Event-by-Event Hydro +Jet Energy Loss: A Solution to the RAA⊗v2 Puzzle"

2. C. Andres et al, PoS HardProbes2018 (2019) 070
   "Constraining energy loss from high-T azimuthal asymmetries"

→ **We need other observables to break theoretical degeneracies !**
Constrained **Dijet AcoplanarityTomography can help**

VISHNU Temperature field Evolution For 0-10% PbPb 5.02 ATeV

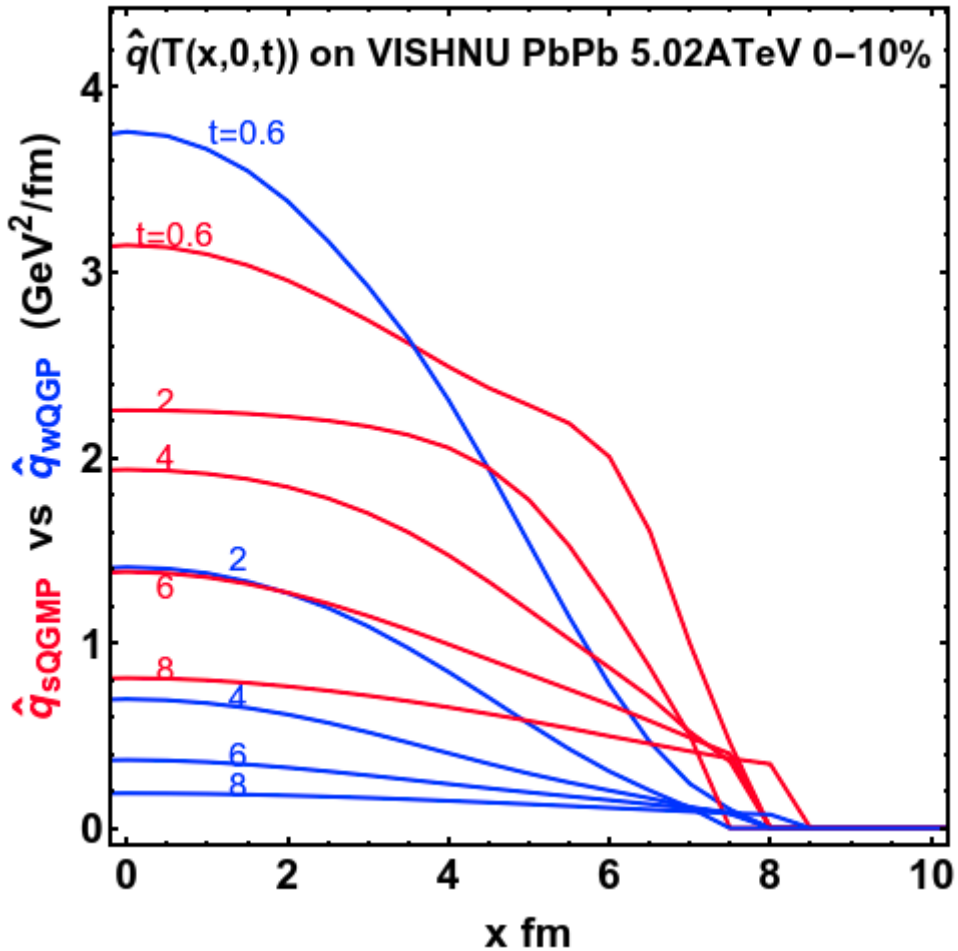
$$T(x,0,t)$$



CUJET3 qhat Evolution

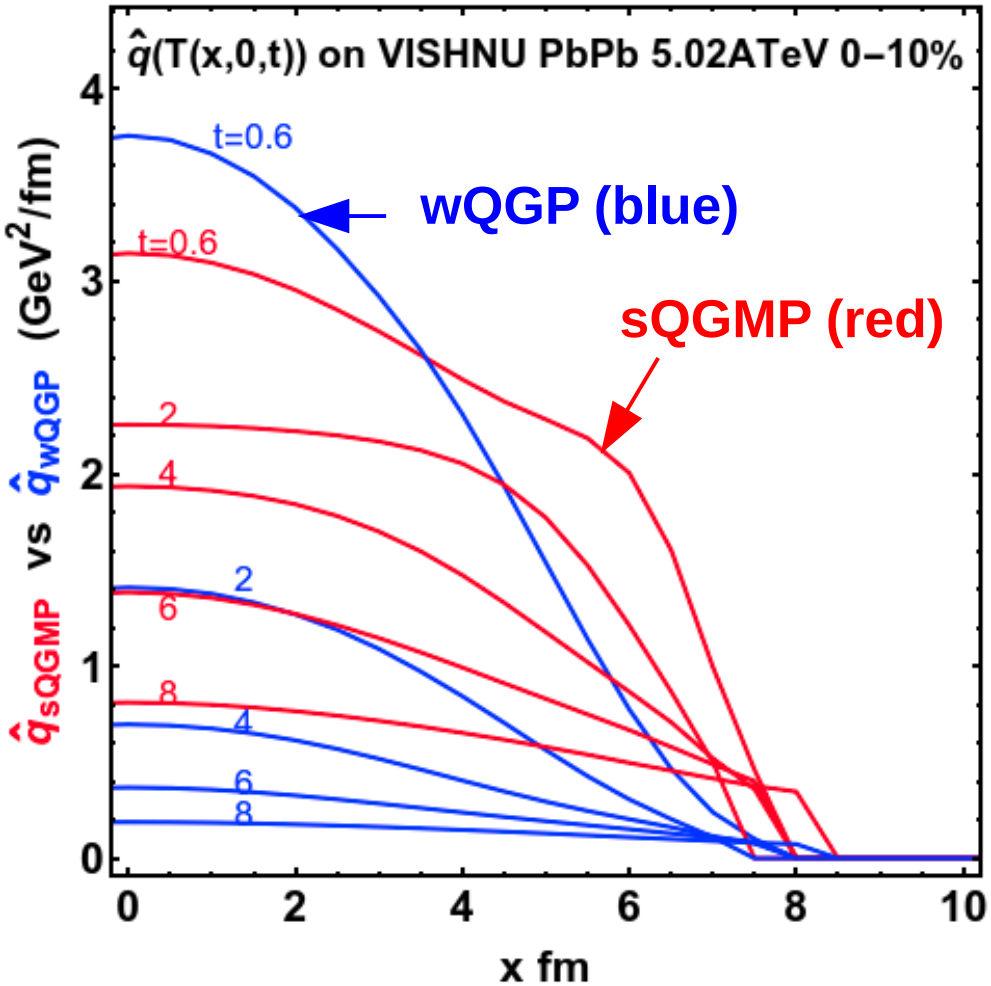
wQGP (blue) vs **sQGMP (red)**

$$\hat{q}(T(x,0,t),E=20)$$



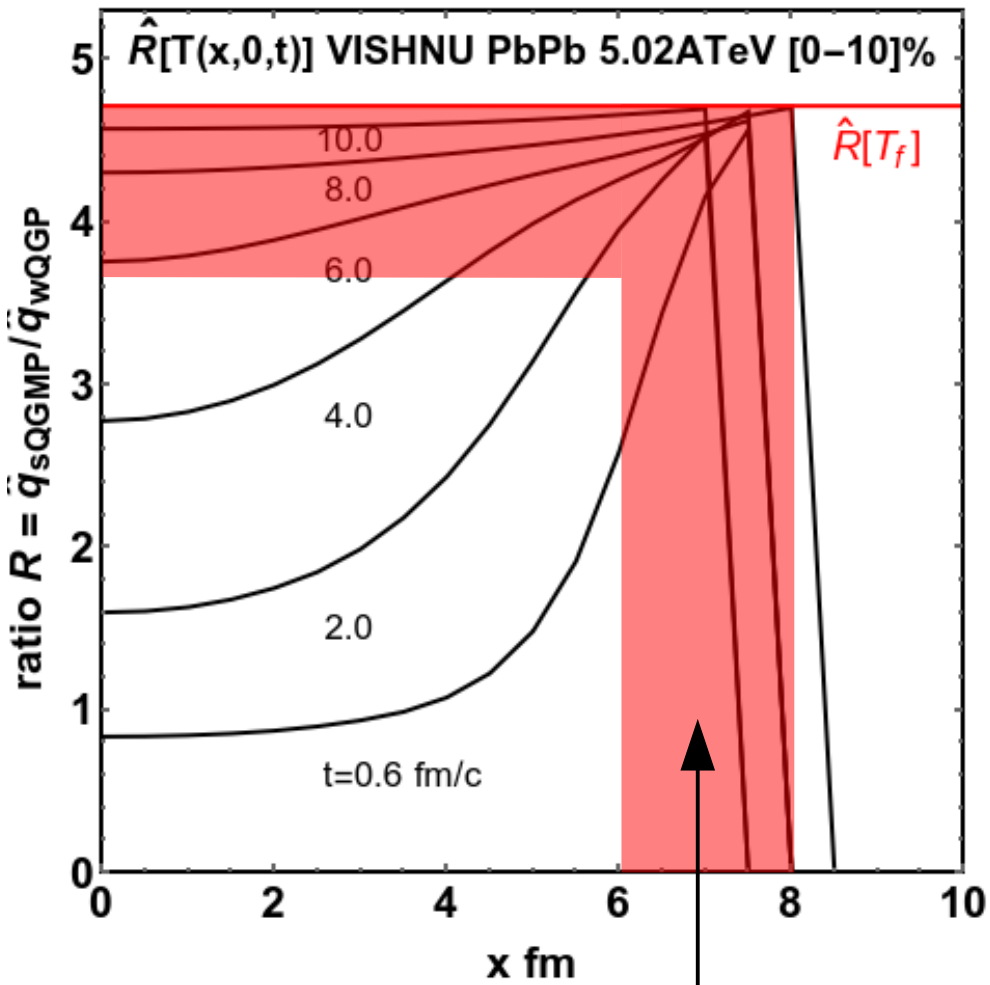
CUJET3 $\hat{q}$ Evolution

$$\hat{q}(T(x,0,t), E = 20)$$



CUJET3 Evolution of $\hat{q}$ Ratio

$\hat{q}_{sQGMP}$ (red) / $\hat{q}_{wQGP}$ (blue)



Large enhancement of $\hat{q}$ (sQGMP) in "crossover" Tc<T<2T$_c$ hyper-surface due to emergent jet-monopole interactions with (Dirac) $\alpha_E \alpha_M = 1 \gg \alpha_E \alpha_E \sim 0.1$

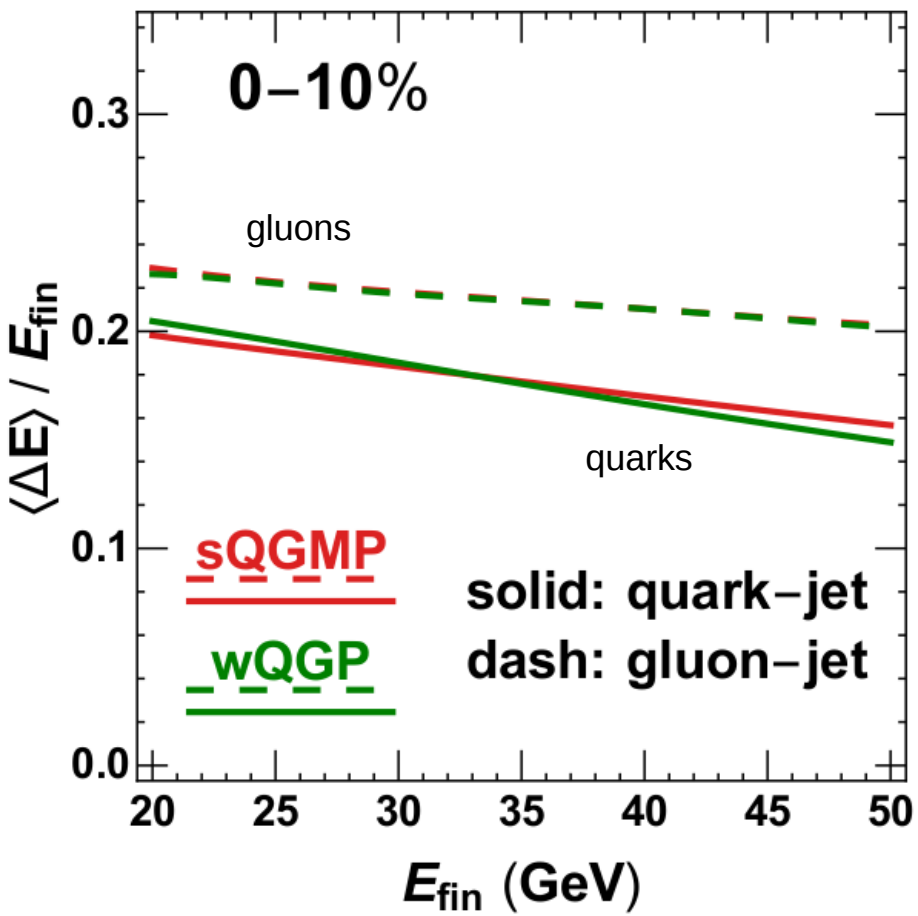
Our Latest Results with CUJET3.1

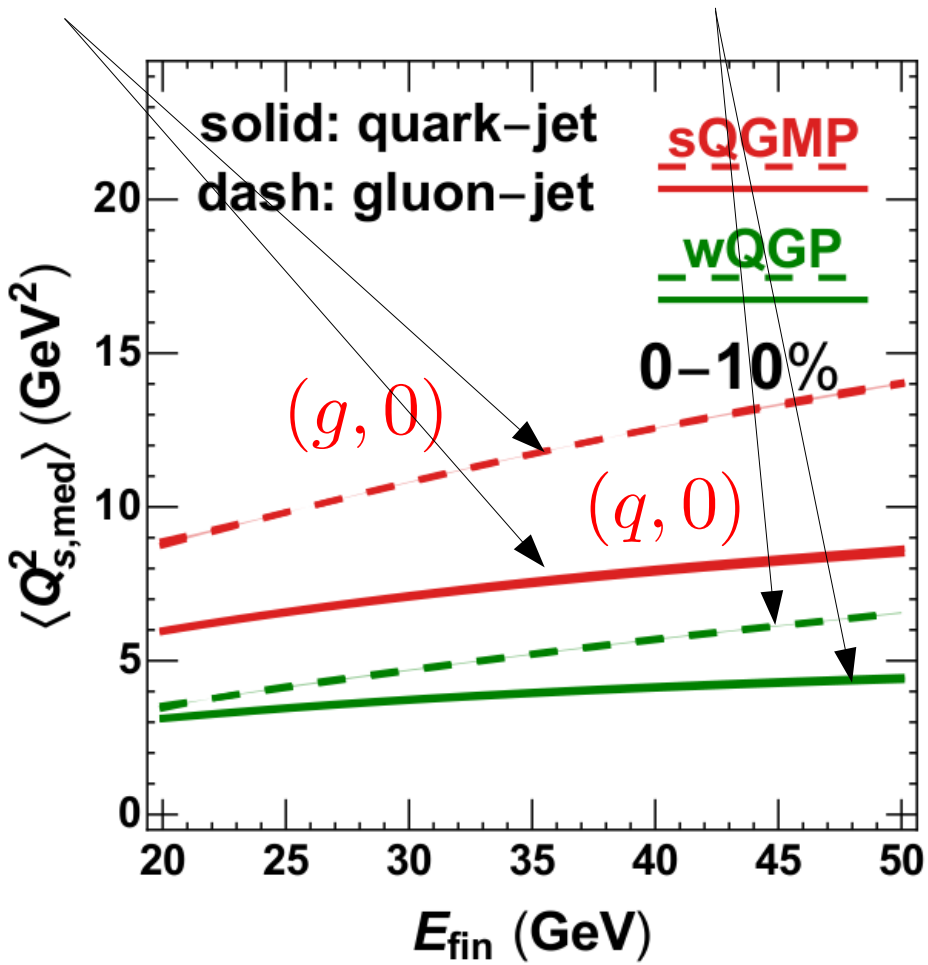
施舒哲　廖劲峰　许乐世

Using global $\chi^2[\alpha_c, c_m;\ R_{AA}\ \&\ v_2]/d.o.f. < 2$

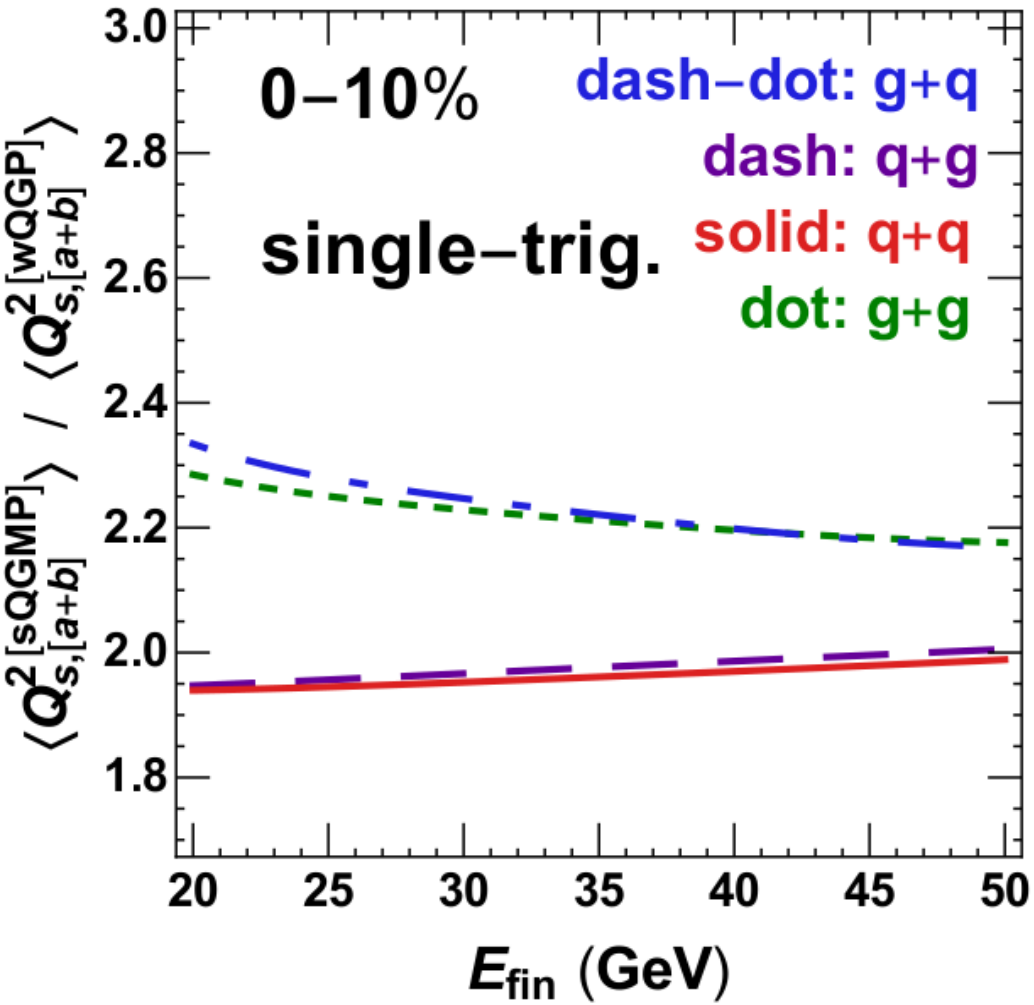
Shuzhe Shi found that
RAA&v2 constrained CUJET3.1
Predicts ~2 enhancement of
saturation scale in **sQGMP** **vs** **wQGP**

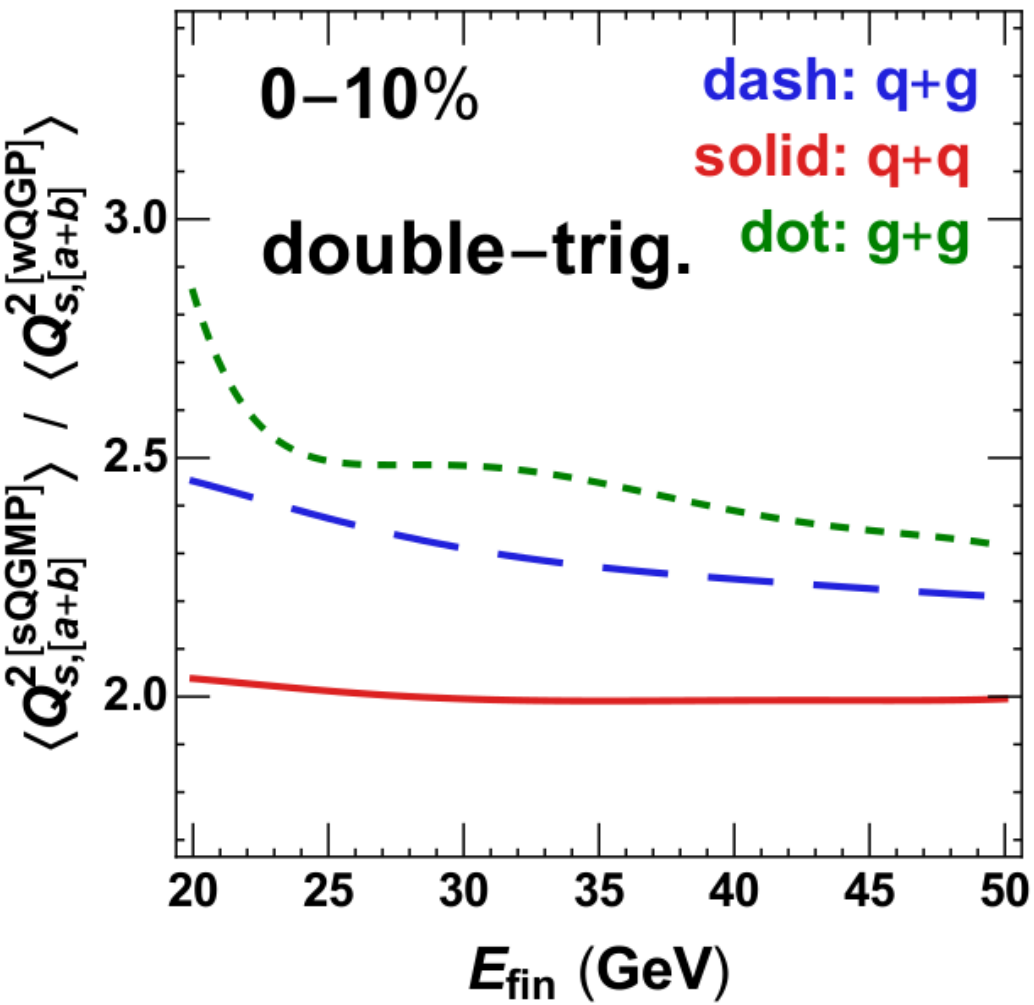
$$\langle Q_s^2 \rangle_{\mathrm{sQGMP}} \approx 2 \times \langle Q_s^2 \rangle_{\mathrm{wQGP}}$$



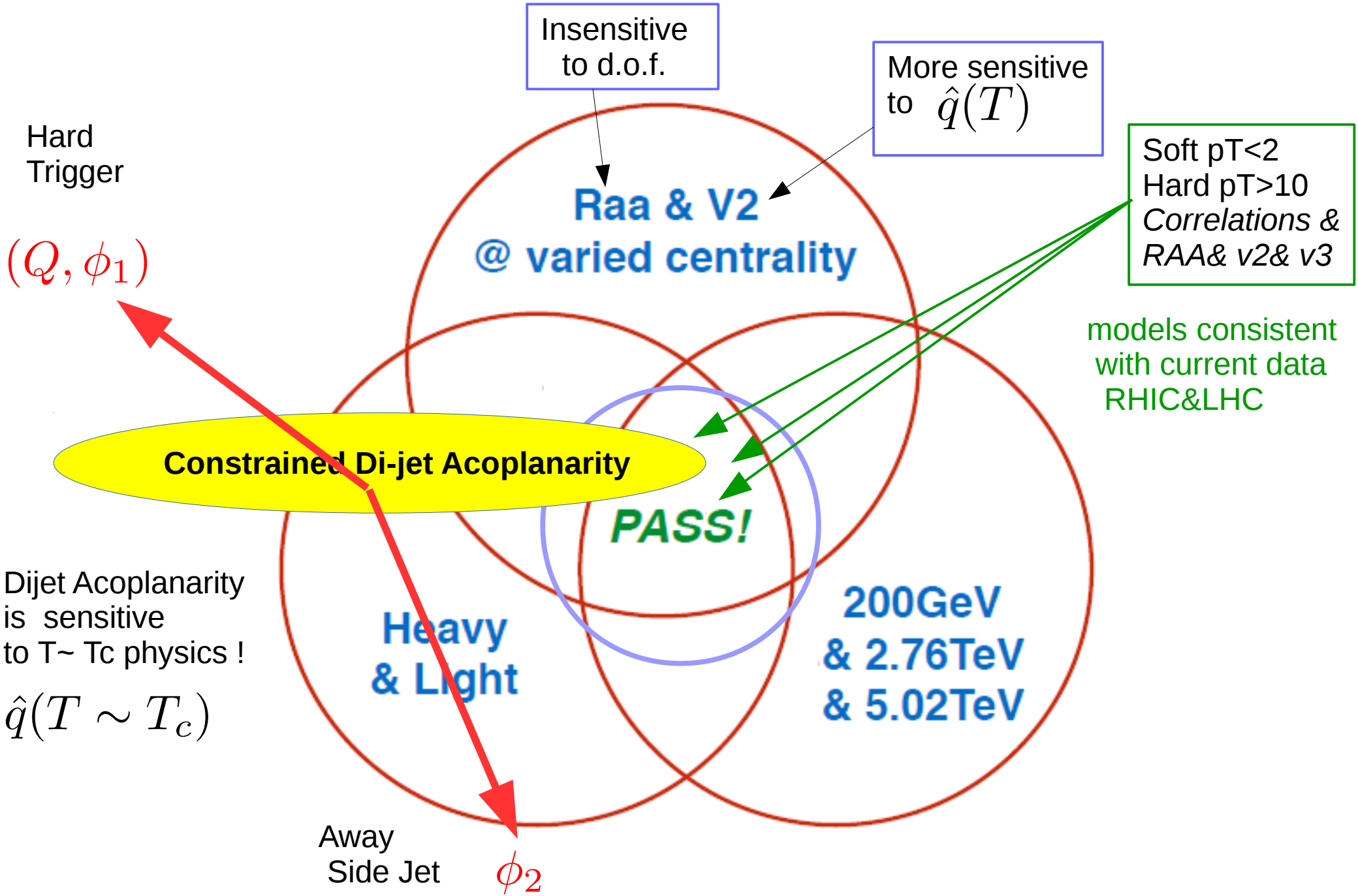


Robustness of $\frac{Q_s^2[a+b](sQGMP)}{Q_s^2[a+b](wQGP)} \sim 2$ To single or double trigger





Summary 2:
RAA&v2 *Constrained* Dijet Acoplanarity Tomography can help to falsify competing models of the color d.o.f. in perfect QCD fluids produced at RHIC and LHC



Extra Slides:

In CUJET3 DGLV Radiative energy loss is generalized to sQGMP fluids

$$\Gamma_a(\tau,\mathbf{q}_\perp) = \Sigma_b \rho_b(z^\mu(\tau)) d^2\sigma_{ab}(z^\mu(\tau))/d^2\mathbf{q}_\perp$$

$$\Delta E_a[z^\mu(\tau)]/E \propto C_a \int d\tau\, \rho(\mathbf{z})\Gamma(\mathbf{z}) \int d^2\mathbf{q}_\perp \boxed{\frac{1}{\mathbf{q}_\perp^2}\left[\frac{\alpha_s^2\chi_T f_E^2}{\mathbf{q}_\perp^2 + f_E^2\mu^2(\mathbf{z})} + \frac{(1-\chi_T)f_M^2}{\mathbf{q}_\perp^2 + f_M^2\mu^2(\mathbf{z})}\right]}$$

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

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

Interference between vacuum And medium "Antennas"

The HT/CCNU qhat approx follows from expanding dxd²k integrand in powers of $\mathbf{q}_\perp^n$ **and keeping only the quadratic $\mathbf{q}_\perp^2$ term. However all $q^{n>2}$ terms all DIVERGE as E→∞ !!**

$$\Delta E_a^{HT}/E \propto \int d\tau \left\{\hat{q}(\tau) = \int d^2q_\perp\, q_\perp^2\, d\Gamma_a(\tau,\mathbf{q}_\perp) = dQ_s^2(\tau)/d\tau\right\}$$

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

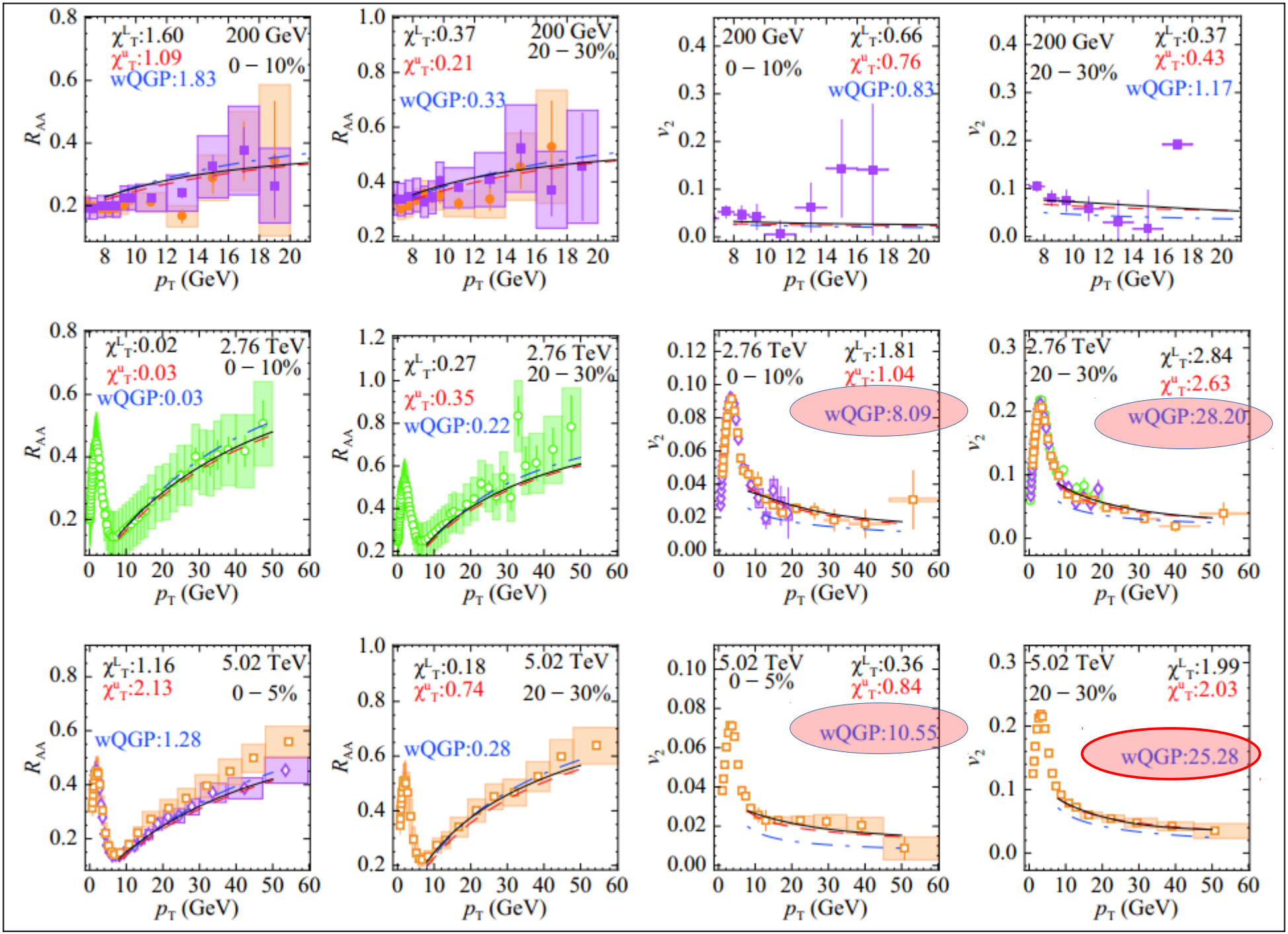
This qhat factorization of integrand is valid for E → ∞ but for E<100 GeV and T<400 MeV the numerical CUJET energy loss is not well approximated by the HT approx.

While, $$\Delta E_s^{DGLV} \neq \int dt\, t^1\, \hat{q}_a(x(t),t)$$

$$Q_s^2 = \int dt\, \hat{q}(x(t),t)$$ Holds by definition

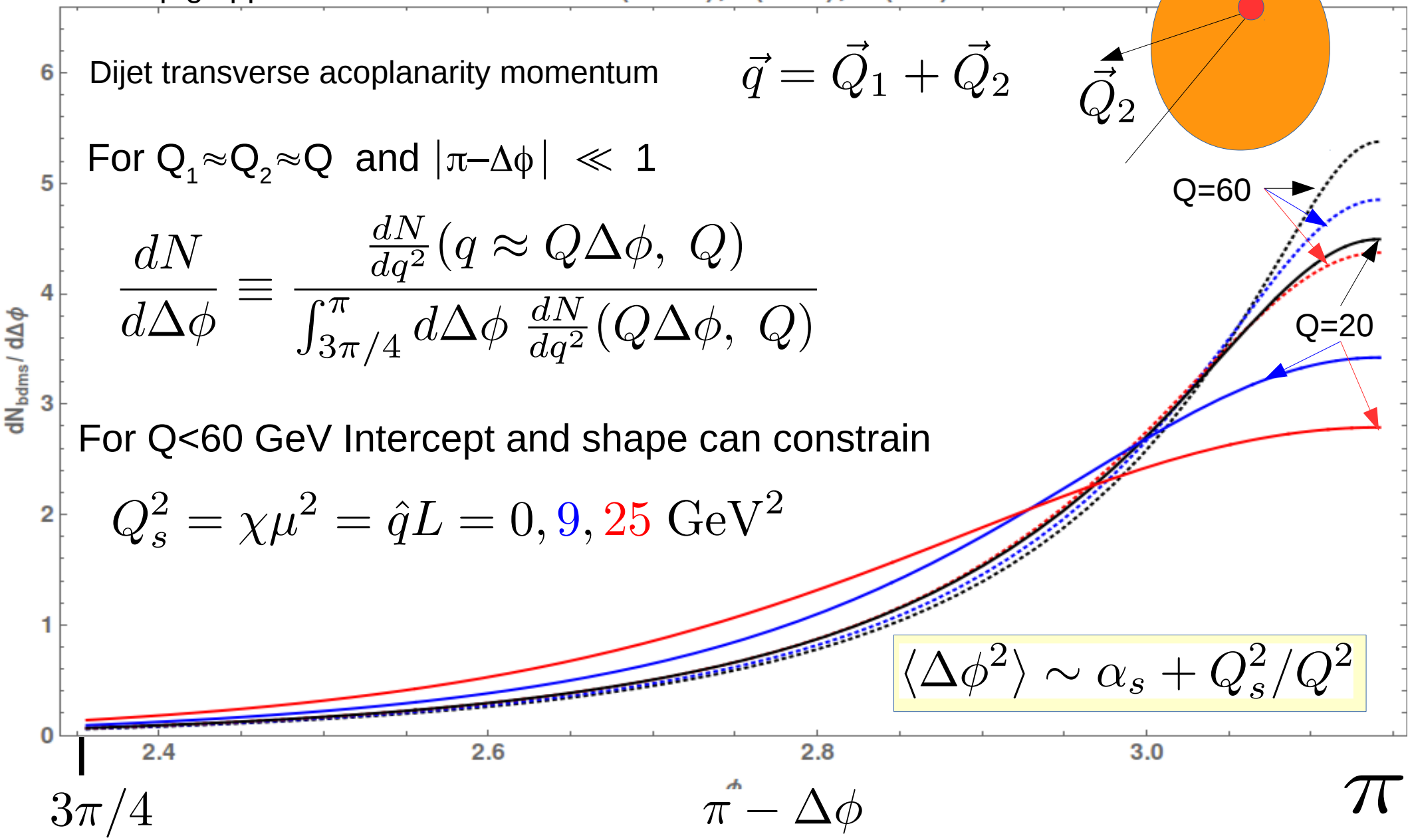
Chinese Physics C　Vol. 43, No. 4 (2019) 044101

CUJET3 (sQGMP) is one solution to the RAA vs v2 puzzle



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

a+b=q+g approx



Dijet transverse acoplanarity momentum $\vec{q} = \vec{Q}_1 + \vec{Q}_2$

For $Q_1 \approx Q_2 \approx Q$ and $|\pi - \Delta\phi| \ll 1$

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

For Q<60 GeV Intercept and shape can constrain

$$Q_s^2 = \chi\mu^2 = \hat{q}L = 0, 9, 25\ \mathrm{GeV}^2$$

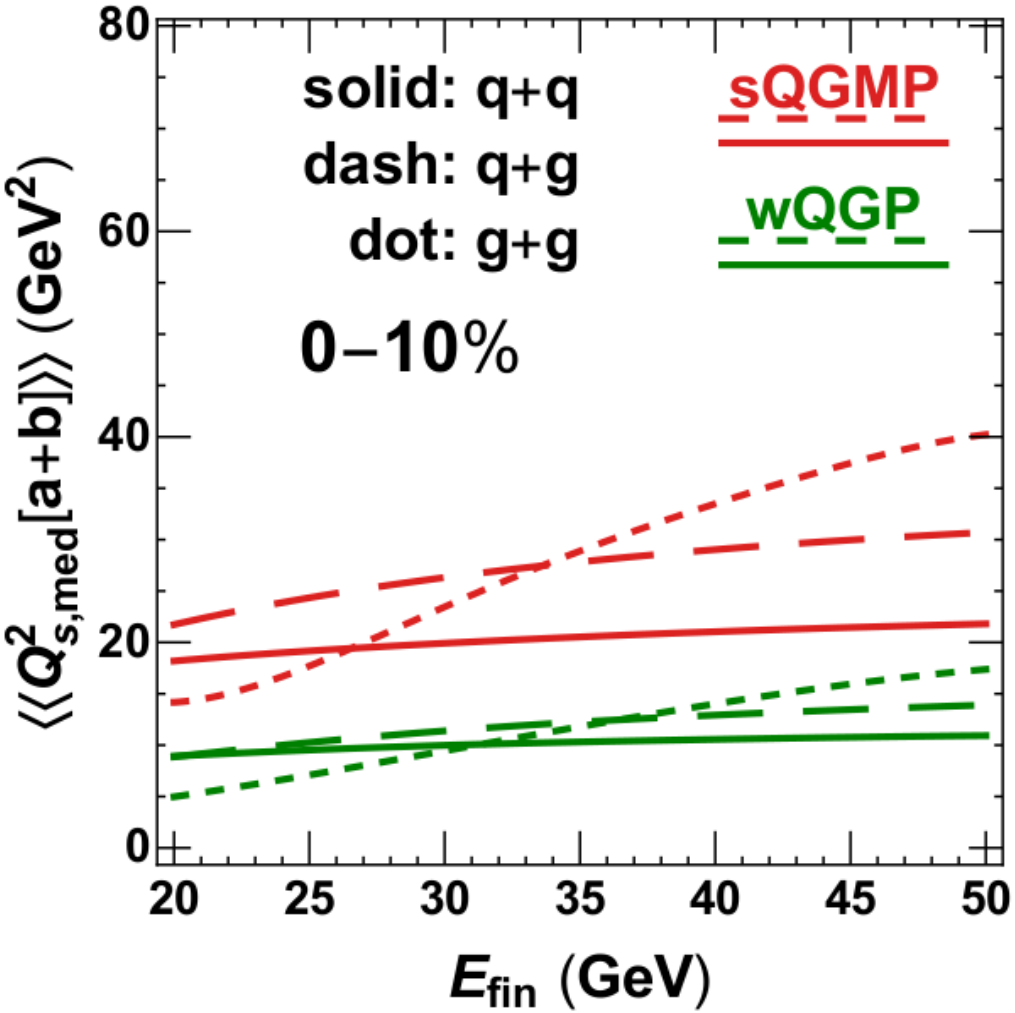
$$\langle \Delta\phi^2 \rangle \sim \alpha_s + Q_s^2/Q^2$$

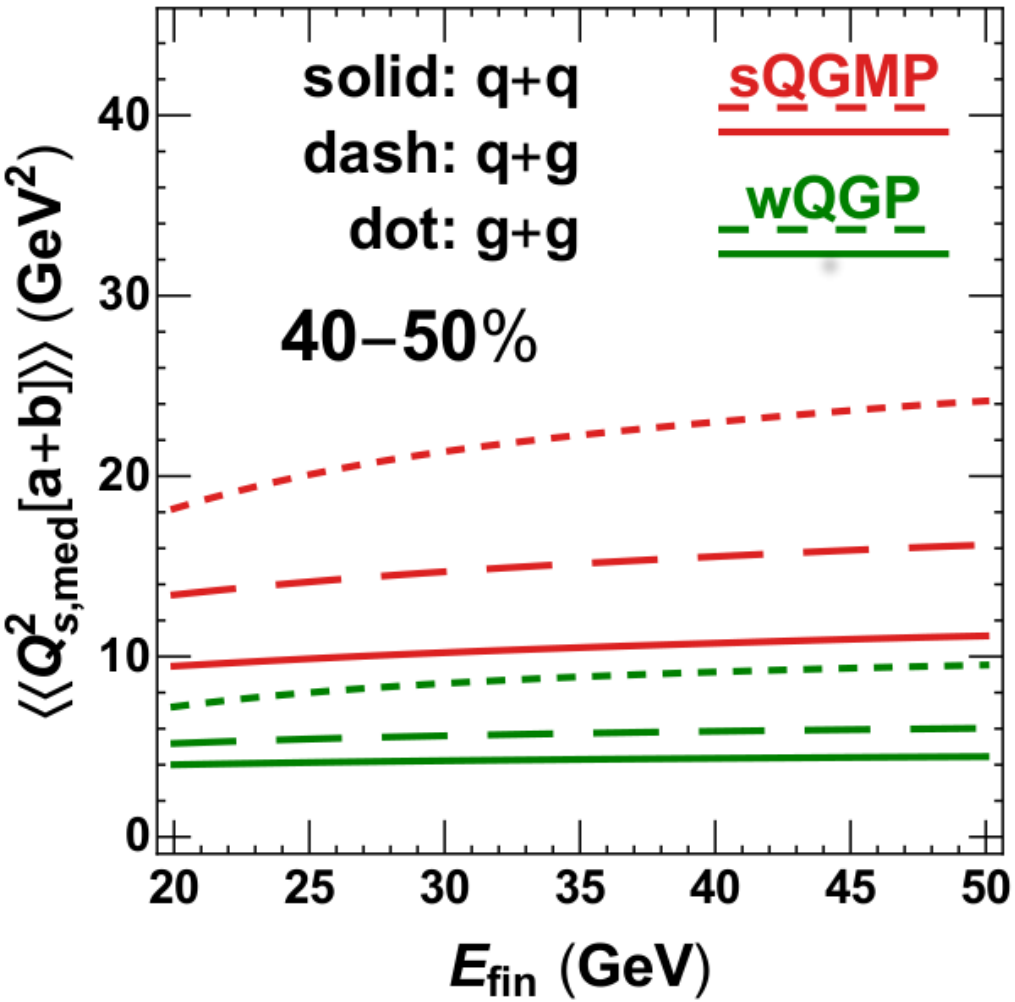
M.Gyulassy, P.Levai, J.Liao, S.Shi, F.Yuan, X.N.Wang, ``Precision Dijet Acoplanarity Tomography of the Chromo Structure of Perfect QCD Fluids,'' NPA 982 (2019) 627

Enhancement approx
Independent of
dijet {a,b} channels

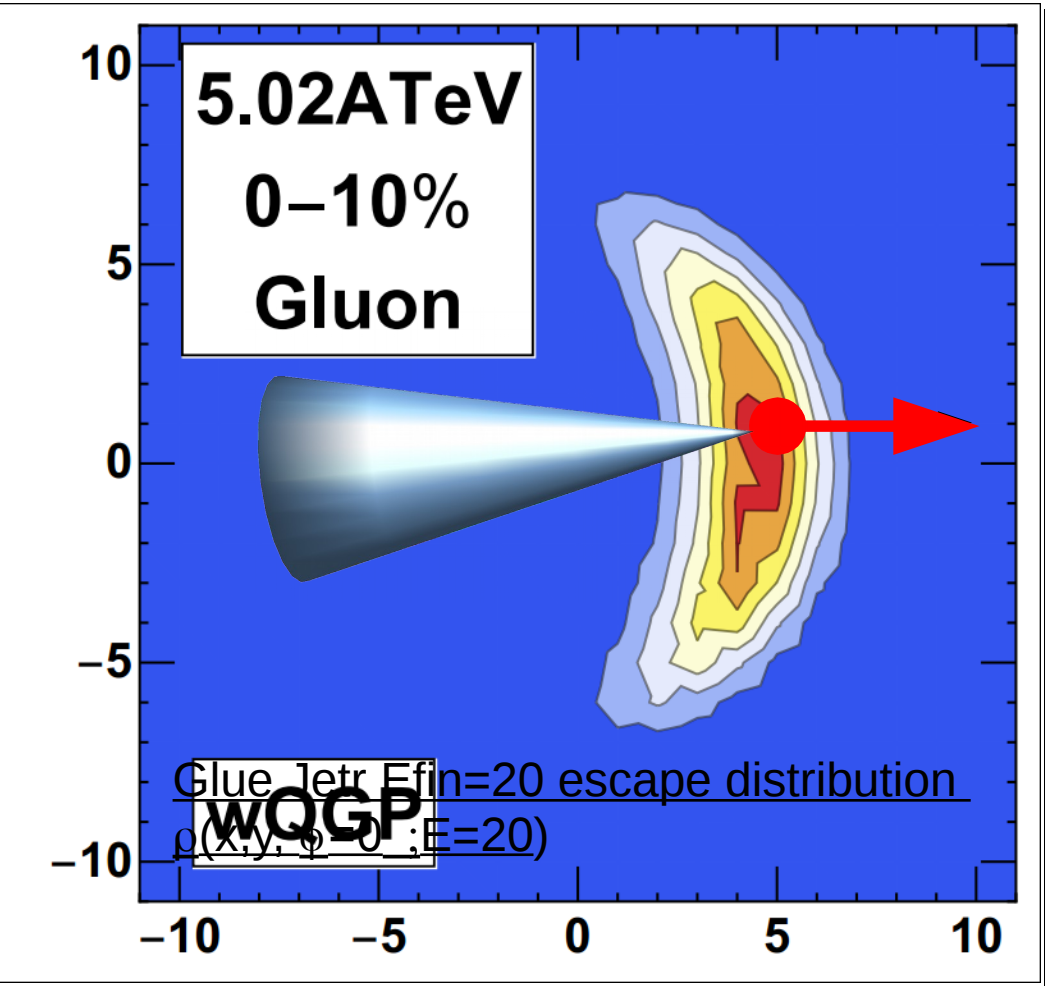
$$\frac{Q_s^2[a+b](sQGMP)}{Q_s^2[a+b](wQGP)} \sim 2$$

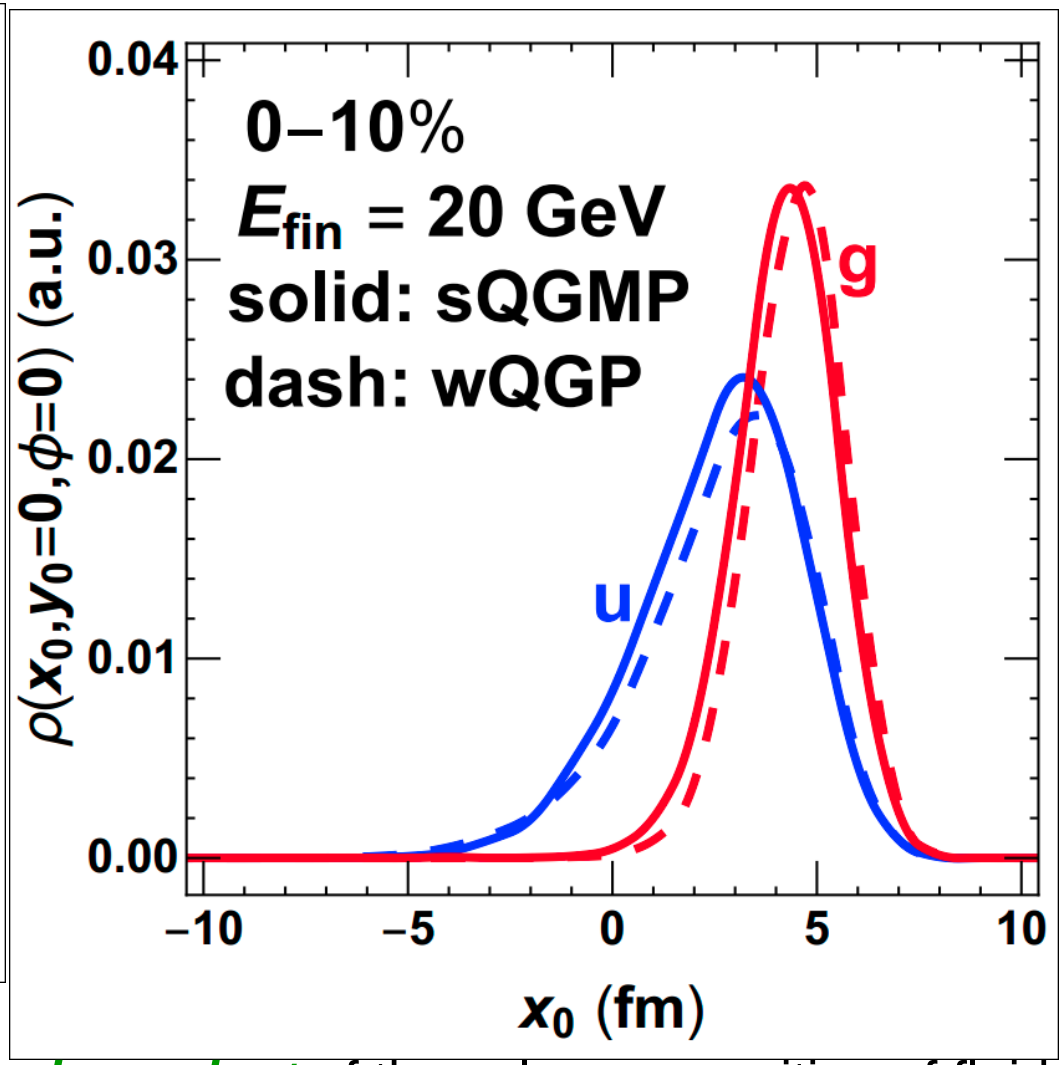
Also weak
Dependence on
trigger Efin





Single Jet trigger surface bias depends on jet Casimir q=4/3 or g=3





However, CUJET shows that the bias is ***independent*** of the color composition of fluid

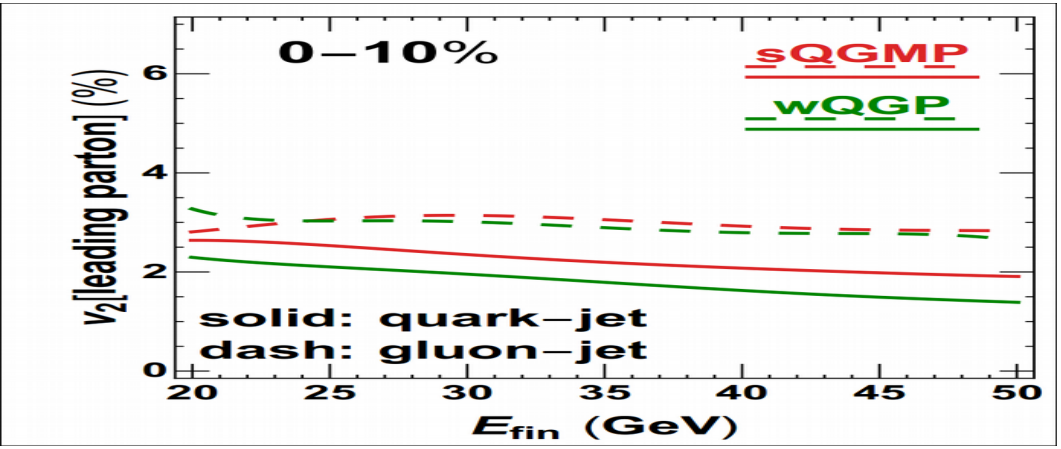
IF coupling is constrained by global Chi^2 fit to RHIC+LHC data on **RAA**(pT; s, cent%)

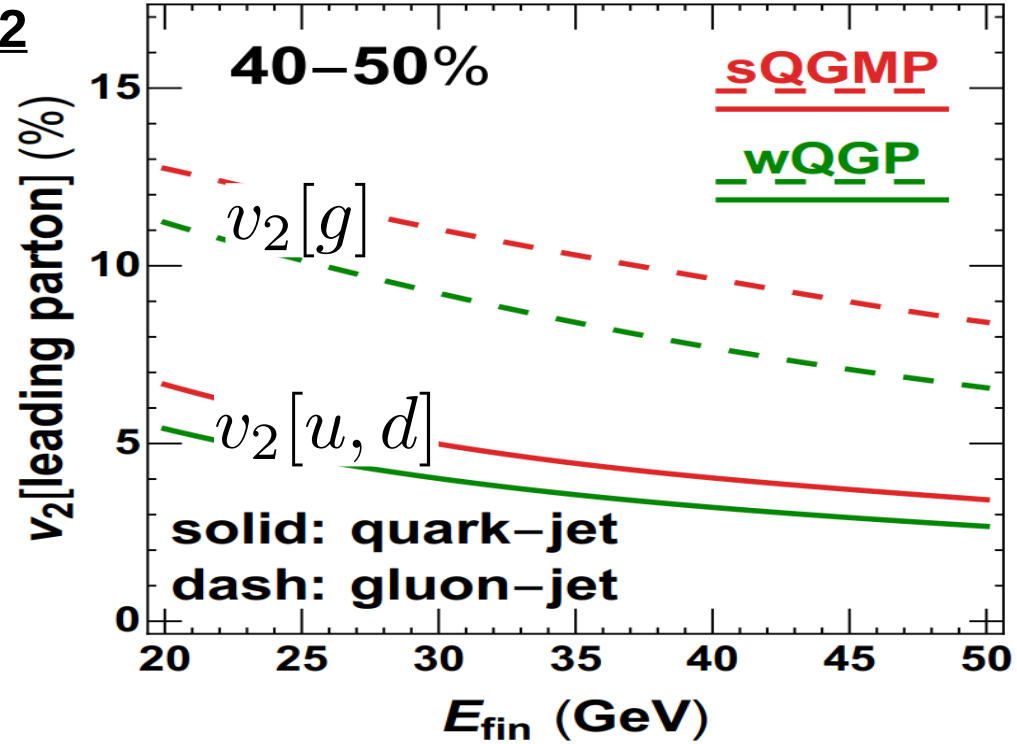
Implies that Jet Acoplanarity is mostly sensitive to T(x,t) ~ (1-2)Tc hypersurface

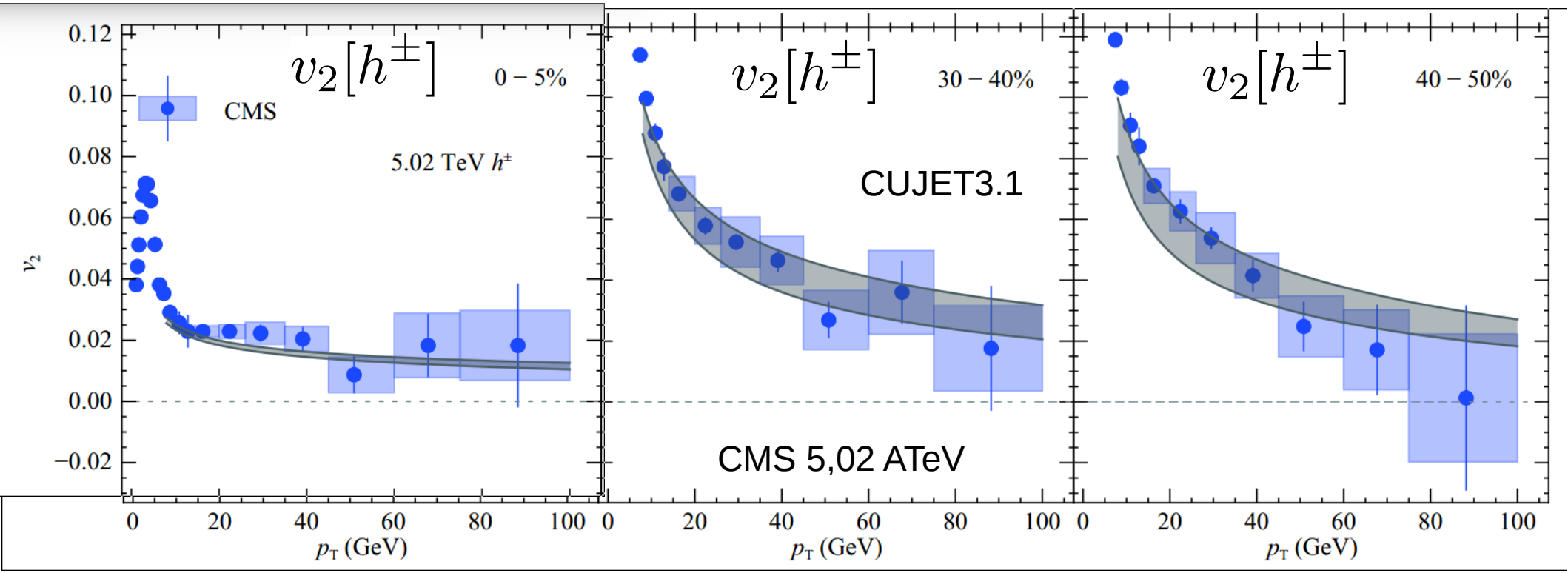
CUJET3.1 PbPb 5.02 ATeV Partonic Level **v2**

Constrained by

Charged Hadronic level **RAA** and **v2**



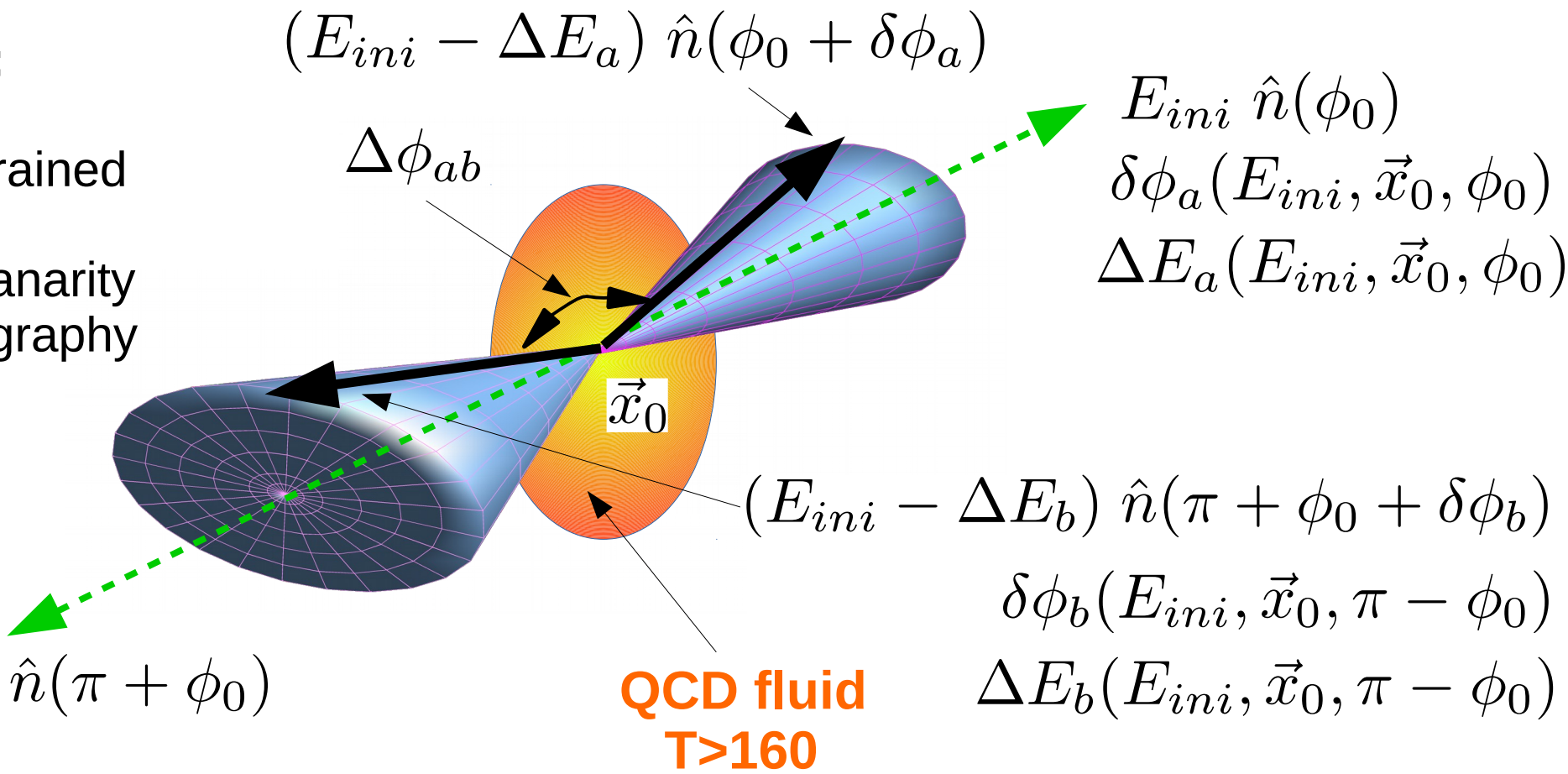




Can **Constrained** Acoplanarity help to break the current degeneracy of AA dynamical models that account at χ2<2 level for **soft&hard** **RAA&v2&v3** **light&heavy** **RHIC & LHC** data ?

CDAT:

Constrained
Dijet
Acoplanarity
Tomography

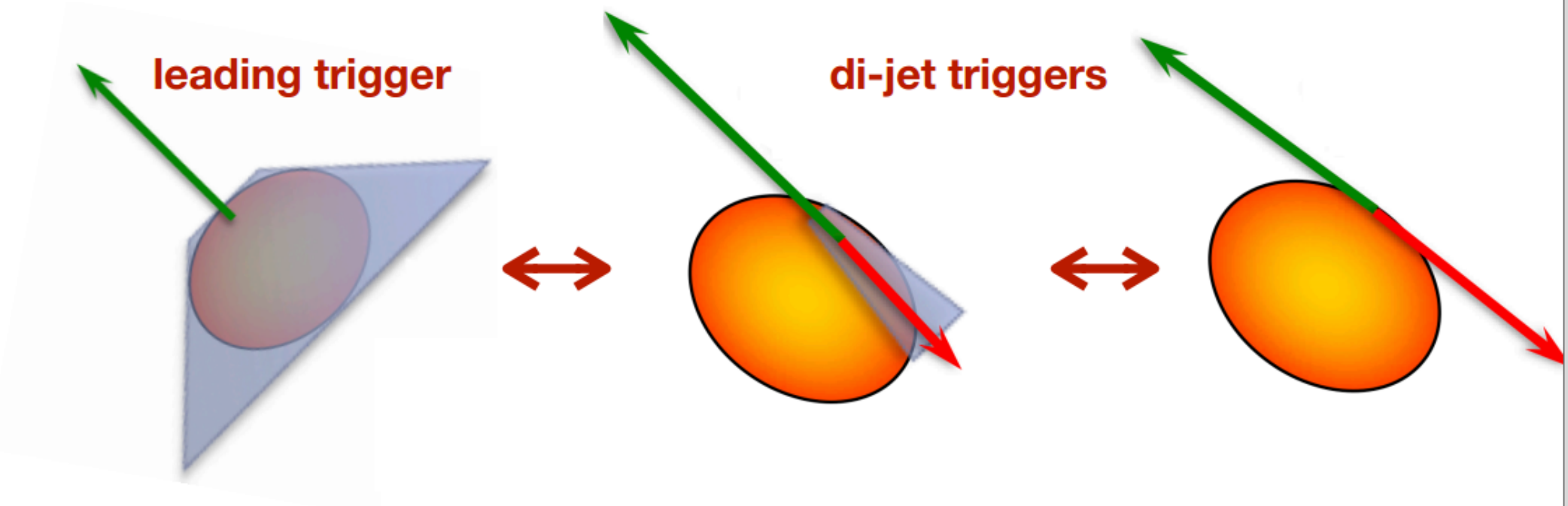


$$\delta\phi_a = \delta\phi_a^{vac} + \delta\phi_a^{med}$$

Jet trigger bias

(Nick Elsey, STAR, High pT 2019)

this bias can be helpful - opportunity to use jet definition (R, p_T^{const}) to select jet production vertex and di-jet orientation - **jet geometry engineering**



jet+hadron correlations, hadron+jet spectra

STAR, PRL 112, 122301 (2014)

STAR, PRC 96, 024905 (2017)

di-jet imbalance, di-jet hadron correlations

STAR, Phys. Rev. Lett. 119, 062301 (2017)

2+1 correlations

STAR, PRC 83 061901 (2011)

STAR, PRC 87 44903 (2013)