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

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References: JX, Jinfeng Liao, Miklos Gyulassy, arXiv:1411.3673, arXiv:1508.00552

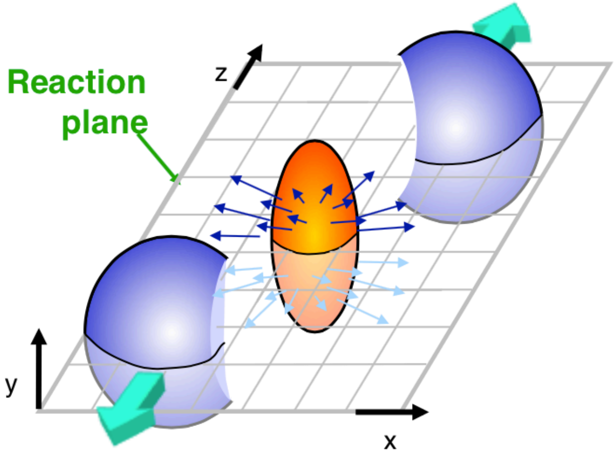
Quark Matter 2015
-- The XXV International Conference on Ultrarelativistic Nucleus-Nucleus Collisions

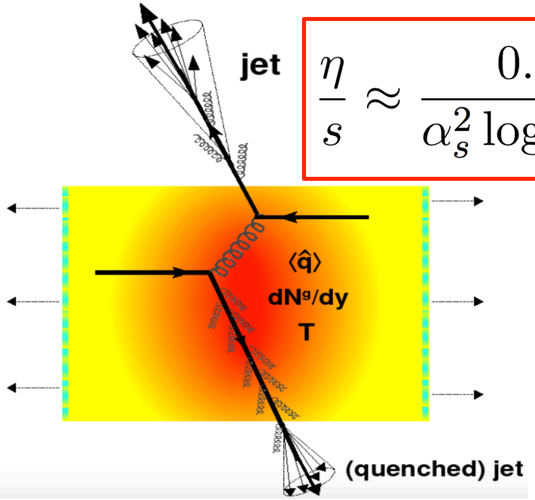
September 29, 2015 @ Kobe, Japan

Outline

- Inconsistency between soft bulk & hard jet transport properties
- Nonperturbative medium near T_c
- The CUJET3.0 jet energy loss model:
  pQCD/DGLV + sQGMP (semi-QGP + magnetic monopoles)
- Simultaneous description of high-p_T R_{AA} and v_2 at RHIC and LHC; connecting qhat/T^3(T) and η/s(T)
- Probe deconfinement using jet quenching observables?
- Jet quenching in p+A?
- Summary

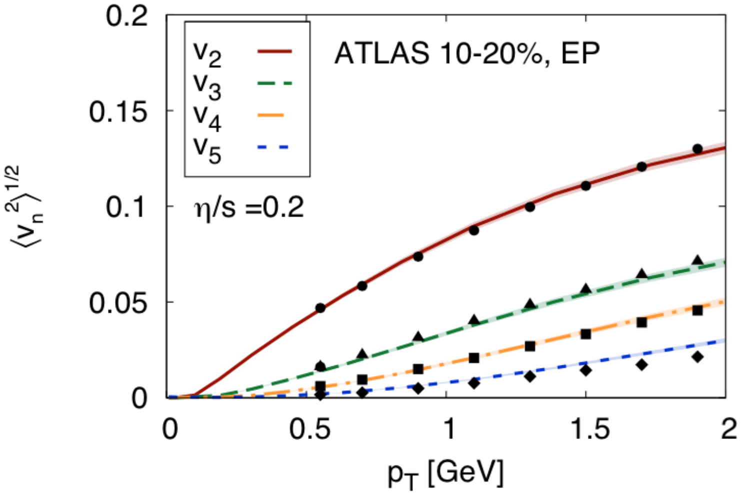
Bulk perfect fluidity vs pQCD jet quenching

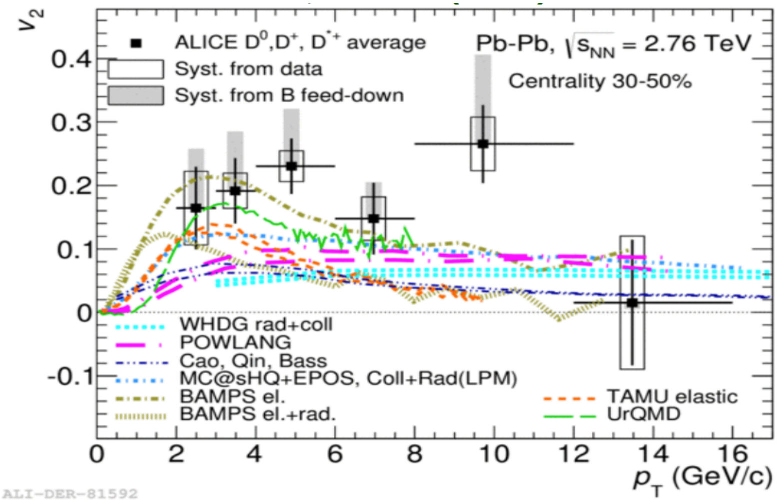




$$\frac{\eta}{s} \approx \frac{0.071}{\alpha_s^2 \log(1/\alpha_s)}$$

Bulk: nonperturbative, η/s~0.1-0.2   Jet quenching: pQCD, η/s~0.5-1.0



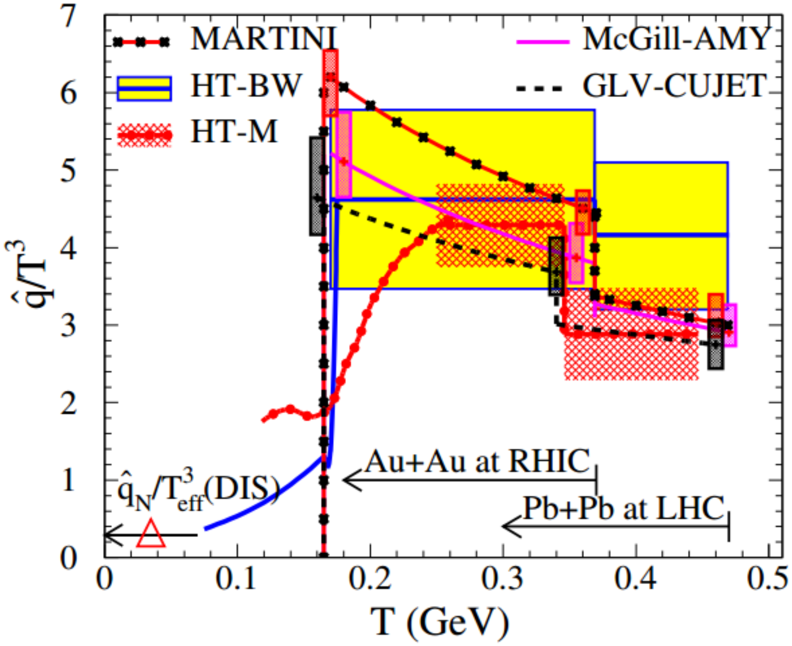


Bulk: IP-Glasma + MUSIC, Gale et al. 2013   Jet quenching: 50% underprediction of high pT v2

❖ Bulk perfect fluidity and jet quenching inconsistent?

Jet quenching parameter and η/s

$$\hat{q} = \rho \int d^2 q_\perp q_\perp^2 \frac{d\sigma}{d^2 q_\perp}$$



JET Collaboration, PRC 90, 014909 (2014)

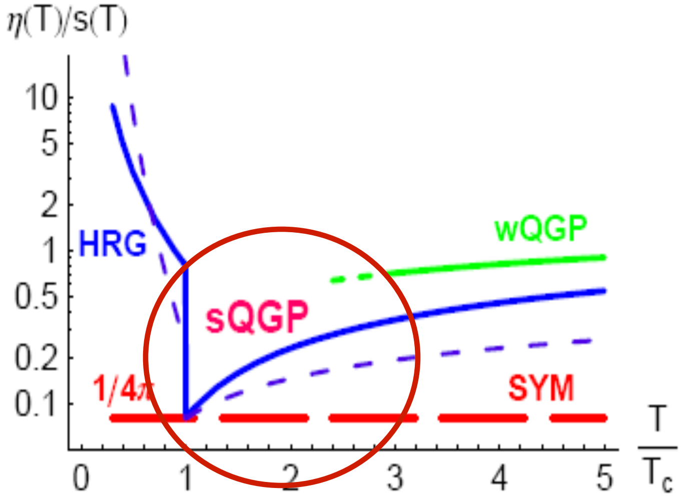
$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \quad \begin{matrix} T = 370\ \text{MeV}, \\ T = 470\ \text{MeV}, \end{matrix}$$

- ❖ Kinetic theory estimate of η/s

$$\begin{aligned} \eta/s &= \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p\rangle_a \lambda_a^{tr} \\ &= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle \mathcal{S}_{ab}\rangle/2} dq^2 \frac{4q^2}{\langle \mathcal{S}_{ab}\rangle} \frac{d\sigma_{ab}}{dq^2} \right)^{-1} \\ &= \frac{18T^3}{5s}\sum_a \rho_a/\hat{q}_a(T, E = 3T) \quad , \qquad (1 \end{aligned}$$

Danielewicz, Gyulassy, PRD 1985



Hirano, Gyulassy, NPA 2006

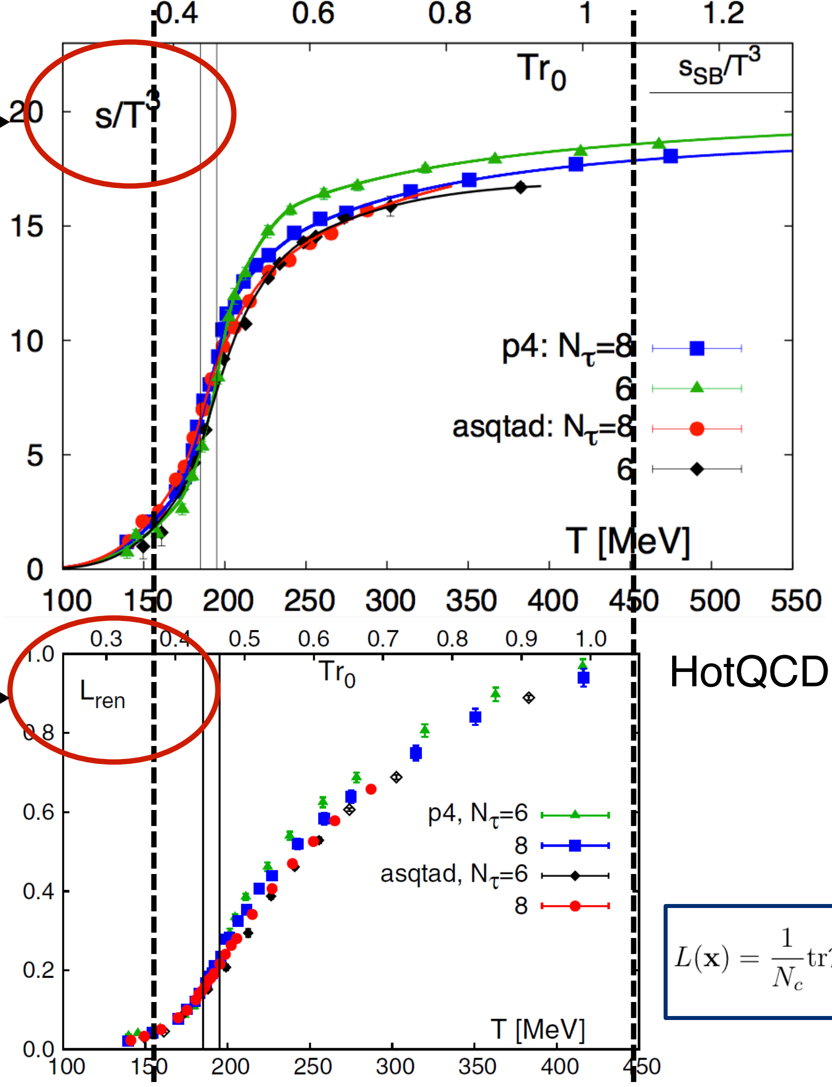
$$\frac{\eta}{s} \left\{ \begin{matrix} \approx \\ \gg \end{matrix} \right\} 1.25 \frac{T^3}{\hat{q}} \left\{ \begin{matrix} \text{for weak coupling,} \\ \text{for strong coupling.} \end{matrix} \right.$$

Majumder, Muller, Wang, PRL 2007

The nonperturbative medium near T_c from lattice

Thermal

Chromo



HotQCD Collaboration 2009

$$L(\mathbf{x}) = \frac{1}{N_c}\mathrm{tr}\mathcal{P}\exp\left[ig\int_0^{1/T} A_4(\tau,\mathbf{x})d\tau\right]$$

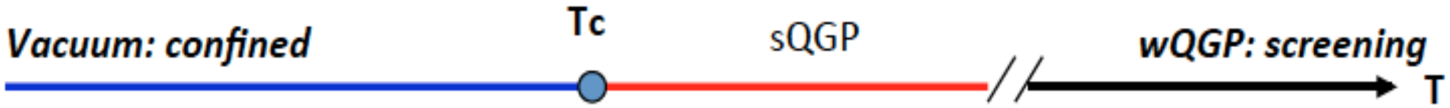
- ❖ What can be pumped out of vacuum to account for the “missing” degrees of freedom?
- ❖ What would be a lattice compatible, microscopic description of the near Tc matter?
  - ➢ Does this help reconciling the “soft” vs “hard” transport inconsistency?

Liao-Shuryak E-M Seesaw Scenario

T<< Lambda_QCD

T ~ Lambda_QCD

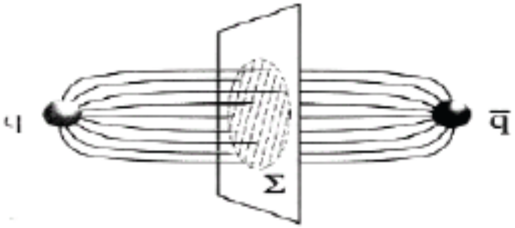
T>> Lambda_QCD



Vacuum: confined

sQGP

wQGP: screening

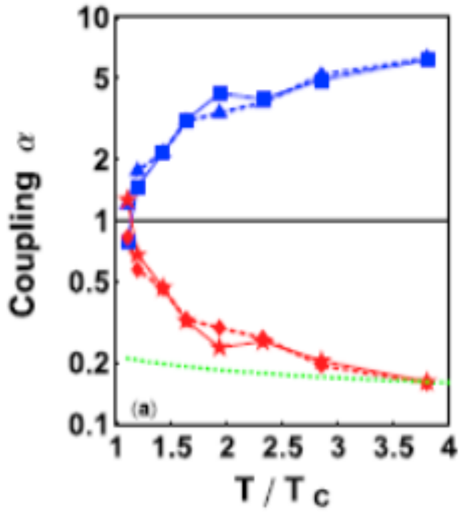


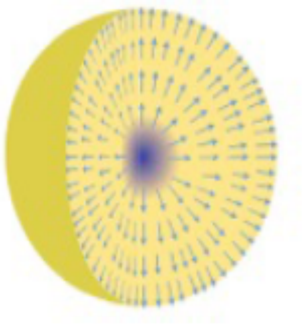
Emergent plasma with <u>E & M</u> charges:
chromo-magnetic monopoles are the "missing DoF"

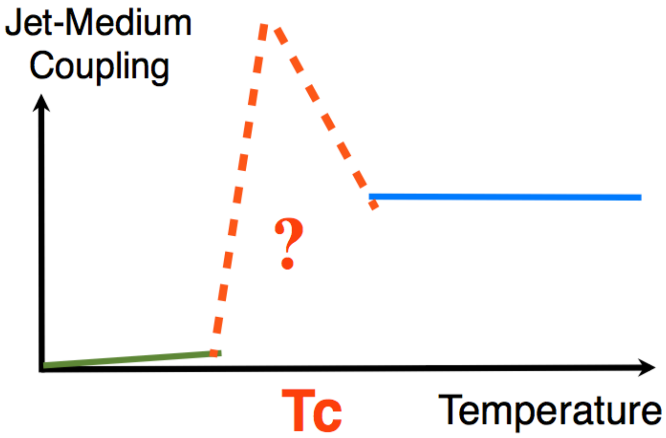
Plasma of E-charges
E-screening: g T
M-screening: g^2 T

Electric Flux Tube:
Magnetic Condensate

$$\alpha_E * \alpha_M = 1.$$







Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008; Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010; Phys.Rev.Lett.109:152001,2012.

- Slide courtesy of Jinfeng Liao

The semi-Quark-Gluon-Monopole Plasmas

- Near Tc: semi-QGP (Pisarski, Hidaka, Lin, Satow…)
  - Cf. Pisarski's Talk on Tue Morning
- Semi-QGP suppresses color-electric DOFs as powers of Polyakov loop

$$L(\vec{x}) \equiv \mathcal{P}\exp\left(ig\int_0^{1/T} d\tau A_0(\tau,\vec{x})\right) \qquad \ell_n(Q) \equiv \langle trL^n\rangle/N_c = \sum_{a=1}^{N_c} e^{inQ^a/T}/N_c.$$

$$n_{ab}(E) = \frac{1}{e^{(E-i(Q^a-Q^b))/T}-1} \longrightarrow \langle\sum_{ab} n_{ab}\rangle_Q \sim N_c^2T^3\ell^2$$

$$\widetilde{n}_a(E) = \frac{1}{e^{(E-iQ^a)/T}+1} \longrightarrow \langle\sum \widetilde{n}_a\rangle_Q \sim N_cT^3\ell$$

$$V^{glue}_{non-pert}(q) = \frac{4\pi^2}{3}T^2\,T^2_{deconf}\left(-\frac{c_1}{5}q(1-q)-c_2q^2(1-q)^2+\frac{c_3}{15}\right)$$

arXiv:1011.3820, 1205.0137

- "semi-QGP" + emergent chromo-magnetic monopoles = sQGMP
- Phenomenologically how can we implement such a microscopic sQGMP in a pQCD jet energy loss framework?
  - Does this simultaneously explain data of R_{AA} and v_2 at RHIC and LHC?
  - Does this provide a quantitative connenction between the perfect fluidity of QGP and pQCD jet quenching?

CUJET3.0 = pQCD/DGLV + semi-QGP + monopoles

$$\frac{dE}{dx} \propto \ldots \int_{q^2} \frac{n_e\, \alpha_s^2(q^2)\, f_E^2}{q^2(q^2+f_E^2\mu^2)} \ldots$$

Original DGLV has only quark/ gluon scattering centers

$$\frac{dE}{dx} \propto \ldots \int_{q^2} \left[\frac{n_e \boxed{(\alpha_s(q^2)\alpha_s(q^2))}\, f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m \boxed{(\alpha_s^e(q^2)\alpha^m(q^2))}\, f_M^2}{q^2(q^2+f_M^2\mu^2)} \right] \ldots$$

Now include both color-electric and color-magnetic scattering centers

$$\frac{dE}{dx} \propto \ldots \int_{q^2} \frac{n_T}{(q^2+f_E^2\mu^2)(q^2+f_M^2\mu^2)} \times \kappa(q^2,T)$$

=1, by Dirac Quantization

$$\kappa(q^2,T) \equiv \boxed{\alpha_s^2(q^2)}\chi_T \left(f_E^2 + \frac{f_E^2 f_M^2 \mu^2}{q^2} \right) + (1-\chi_T) \left(f_M^2 + \frac{f_E^2 f_M^2 \mu^2}{q^2} \right)$$

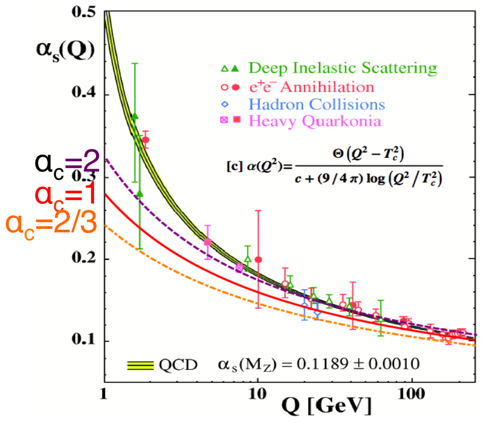
$$\chi_T = c_q\, L + c_g\, L^2$$

Polyakov Loop suppressed color-electric components

The electric scales as a power law of the Polyakov loop as in the semi-QGP model, the left over “missing” DOFs are the mag. monopoles

$$f_E = \sqrt{\chi_T} \qquad f_M = C_m g_T$$

$$\alpha_s(Q^2) = \frac{\alpha_c}{1 + \frac{9\alpha_c}{4\pi}\log\left(\frac{Q^2}{T_c^2}\right)}$$



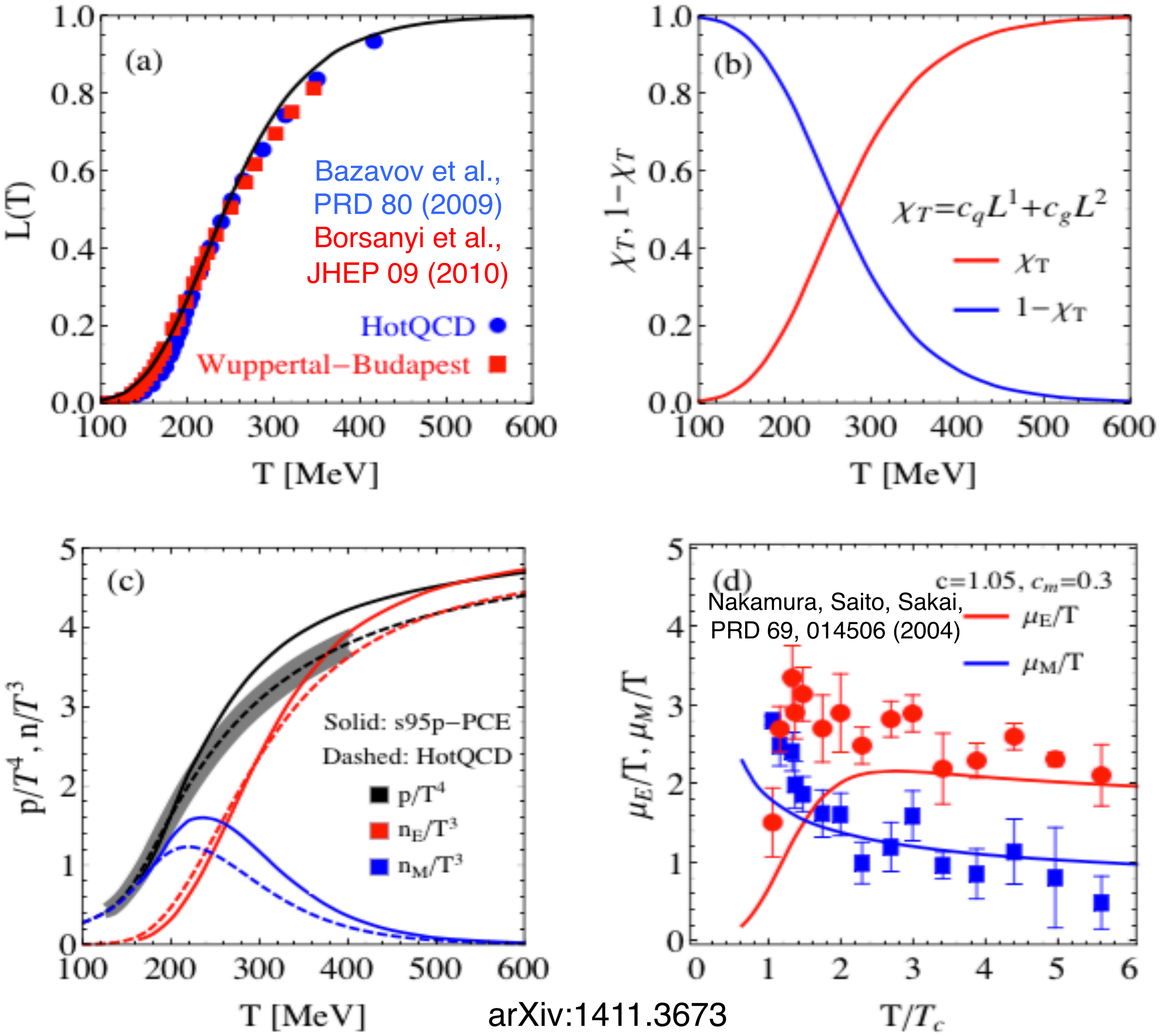
$$\Gamma(\mathbf{z}) = u_f^\mu n_\mu \qquad n = (1, \vec{\beta}_{jet})$$

Liu et al. 2007; Baier et al. 2007 $u_f^\mu = \gamma_f(1, \vec{\beta}_f)$

Relativistic flow corrections

Jiechen Xu, 09/29/2015 @ QM15

Lattice Constraints: Polyakov Loop, EOS, E & M Screening Masses



Bazavov et al., PRD 80 (2009)

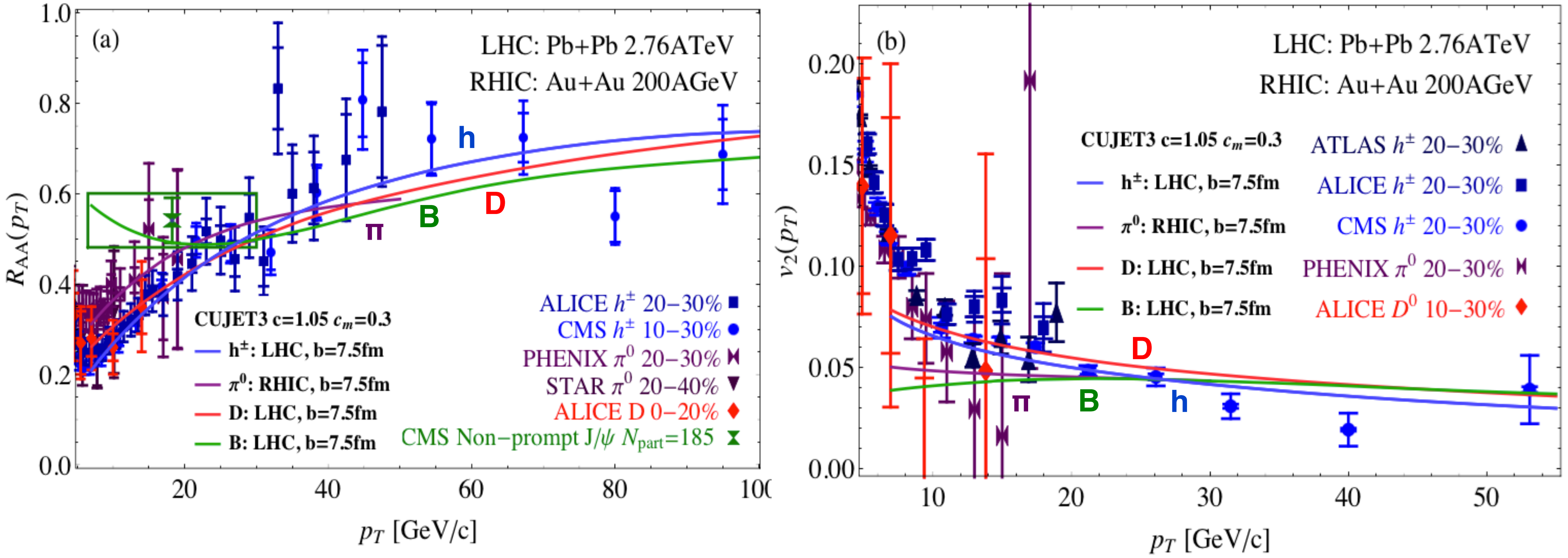
Borsanyi et al., JHEP 09 (2010)

Nakamura, Saito, Sakai, PRD 69, 014506 (2004)

arXiv:1411.3673

- The CUJET3.0 implementations of the color- electric and magnetic components are well constrained by available lattice data of Polyakov loop, EOS and E & M screening

CUJET3.0 simultaneously describes high pT $(R_{AA}+v_2)$*(light+heavy)*(RHIC+LHC)

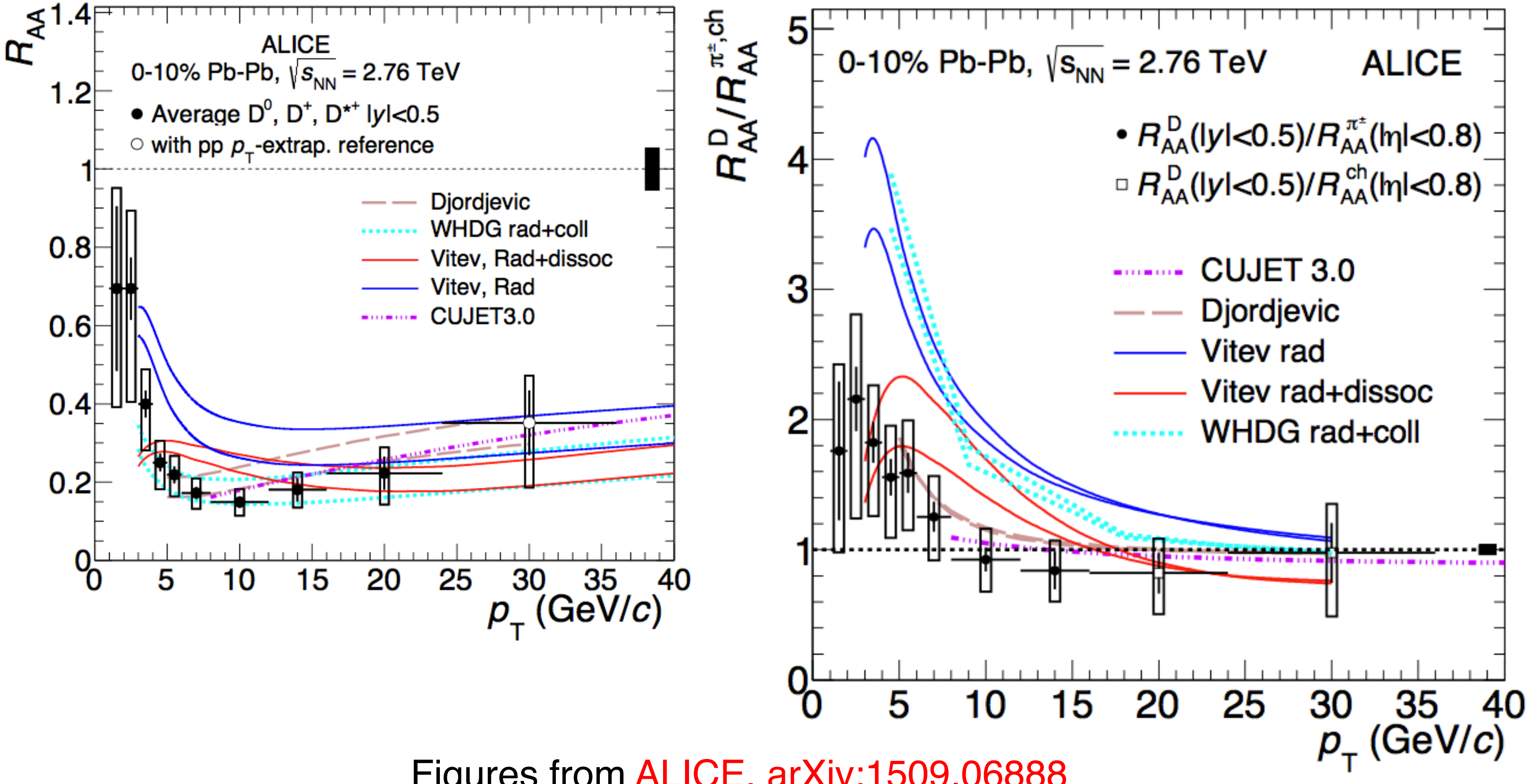


JX, J. Liao, M. Gyulassy, arXiv:1411.3673

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

The combined set of observables ***$(R_{AA}+v_2)$*(RHIC+LHC)*(pion+D+B)*** are consistently accounted for in CUJET3.0 using lattice data constrained sQGMP near Tc + pQCD jet quenching

CUJET3.0's D/π suppression ratio compared with data



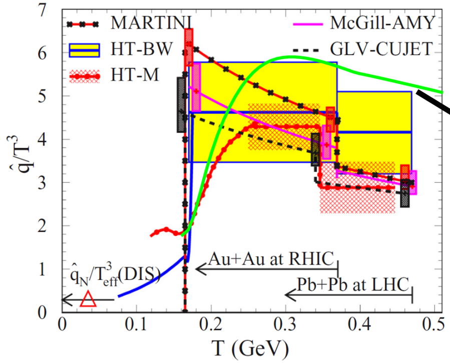
Figures from ALICE, arXiv:1509.06888

- ❖ The ratio of D and π,ch's RAA imposes further constraints on jet energy loss models
- ❖ Less than one R_{AA}^D/R_{AA}^π,ch in 10GeV<p_T<30GeV

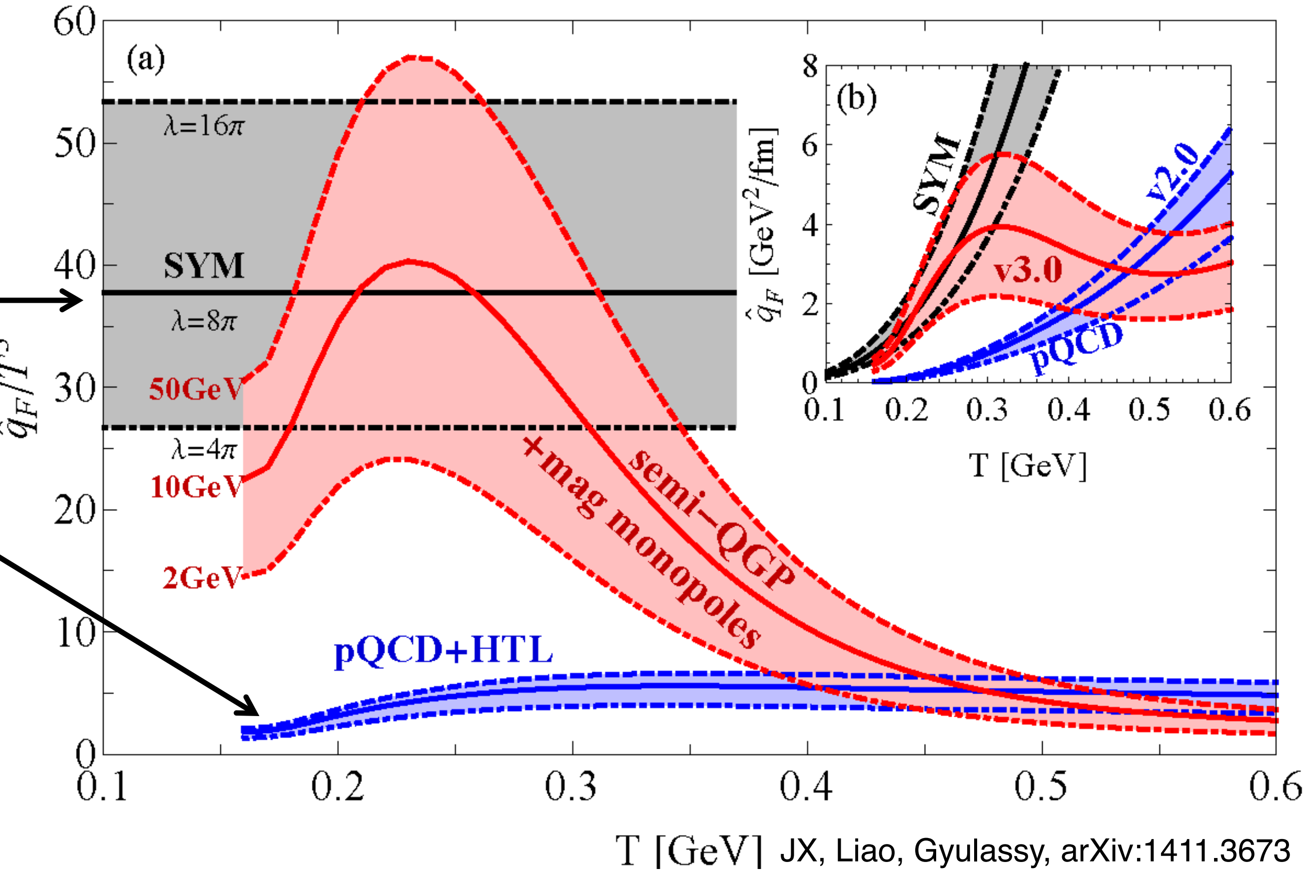
CUJET3.0: qhat(E,T) for quark jets in sQGMP

Liu et al. PRL 2006

$\hat{q} \approx 26.69\sqrt{\lambda/4\pi}T^3$



JET Collaboration, PRC 2014



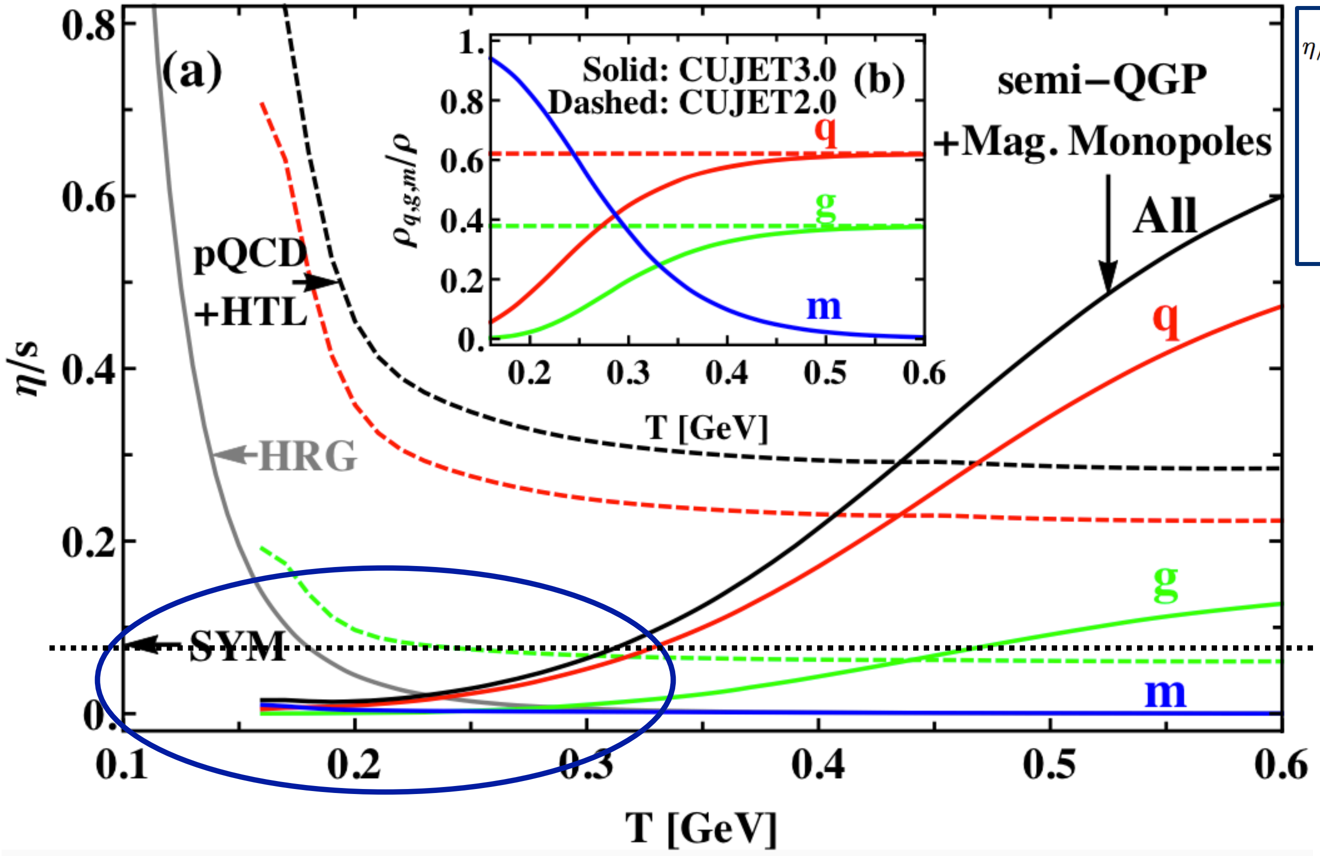
JX, Liao, Gyulassy, arXiv:1411.3673

$$\hat{q}_F = \int_0^{6ET} dq^2 \frac{2\pi q^2}{(q^2+f_E^2\mu^2)(q^2+f_M^2\mu^2)}\rho(T) \times \left[(C_{qq}f_q + C_{qg}f_g)\alpha_s^2(q^2) + C_{qm}(1-f_q-f_g)\right]$$

$f_q = c_q L(T),\ f_g = c_g L(T)^2 \quad \rho(T) \sim p(T)/T$ p(T) from s95p-v0-PCE EOS

❖ CUJET3.0 solution exhibits a “volcano” interpolation of qhat/T^3 between strong “AdS-like” sQGP at T=200-350MeV to more transparent “HTL-like” wQGP for T>400MeV

pQCD jet quenching + sQGMP: η/s(T)



$$
\begin{aligned}
\eta/s &= \frac{1}{s}\frac{4}{15}\sum_a \rho_a \langle p\rangle_a \lambda_a^{\perp} \\
&= \frac{4T}{5s}\sum_a \rho_a \left(\sum_b \rho_b \int_0^{\langle S_{ab}\rangle/2} dq_\perp^2 \frac{4q_\perp^2}{\langle S_{ab}\rangle}\frac{d\sigma_{ab}}{dq_\perp^2}\right)^{-1} \\
&= \frac{18T^3}{5s}\sum_a \rho_a/\hat{q}_a(T, E=3T)\ .
\end{aligned}
$$

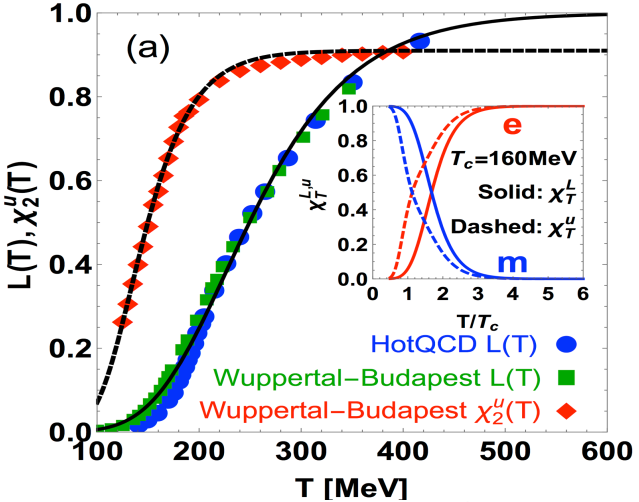
Danielewicz & Gyulassy, PRD 1985
Hirano & Gyulassy, NPA 2006
Majumder, Muller, Wang, PRL 2007

HRG η/s from:
Noronha-Hostler, Noronha, Greiner, PRL 2009, PRC 2012
Niemi, Denicol, Huovinen, Molnar, Rischke, PRL 2011

JX, Liao, Gyulassy, arXiv:1411.3673

- ❖ CUJET3.0 provides a quantitative connection between the jet transport properties controlling the hard jet quenching observables and the bulk viscous transport properties controlling the soft "perfect fluidity" of QGP observed at RHIC and LHC.
- ❖ How to make full use of this connection?

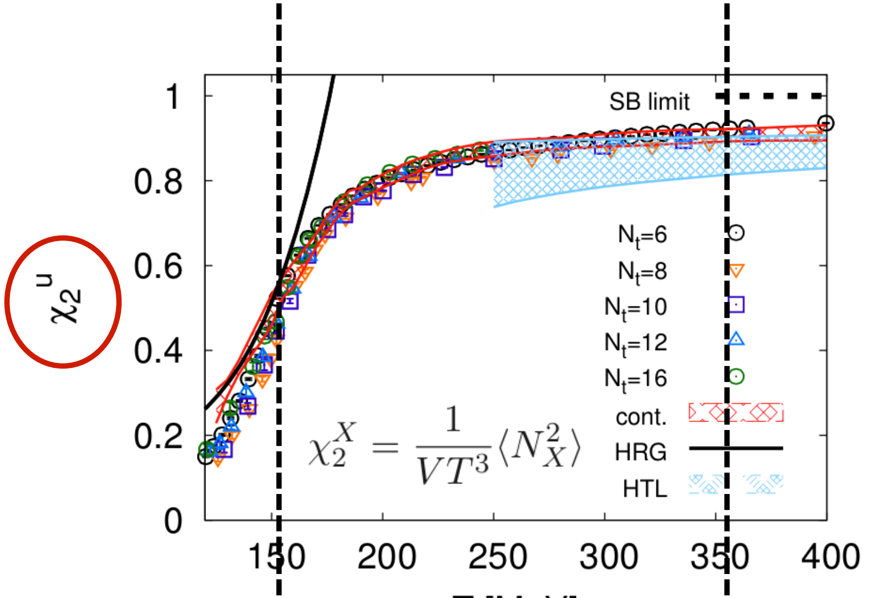
Deconfinement: Quark number susceptibility vs Polyakov loop



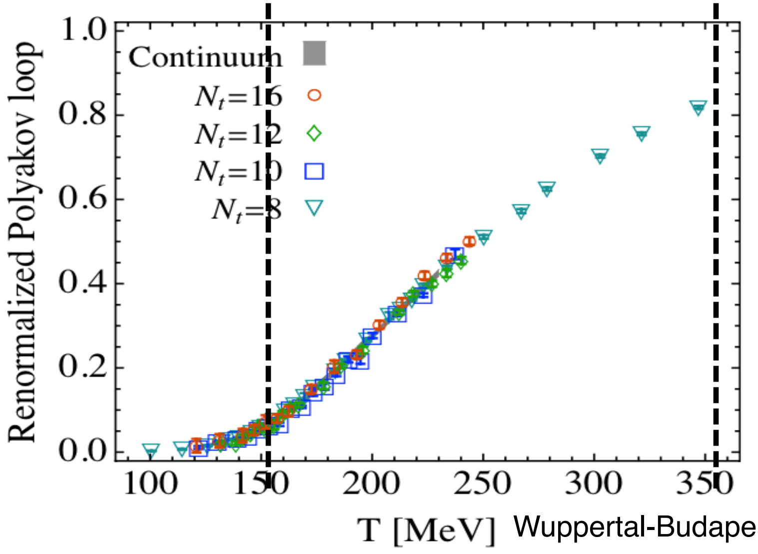
$$\chi_T(T) = c_q\,L(T) + c_g\,L^2(T)$$
$$\chi_T^u = c_q\,\tilde{\chi}_2^u + c_g\,L^2$$

JX, Liao, Gyulassy, arXiv:1508.00552

- Quark DOFs are dynamic and almost massless rather than static and massive
- Use normalized quark number susceptibility instead of Polyakov loop for the deconfinement rate of quarks near T_c

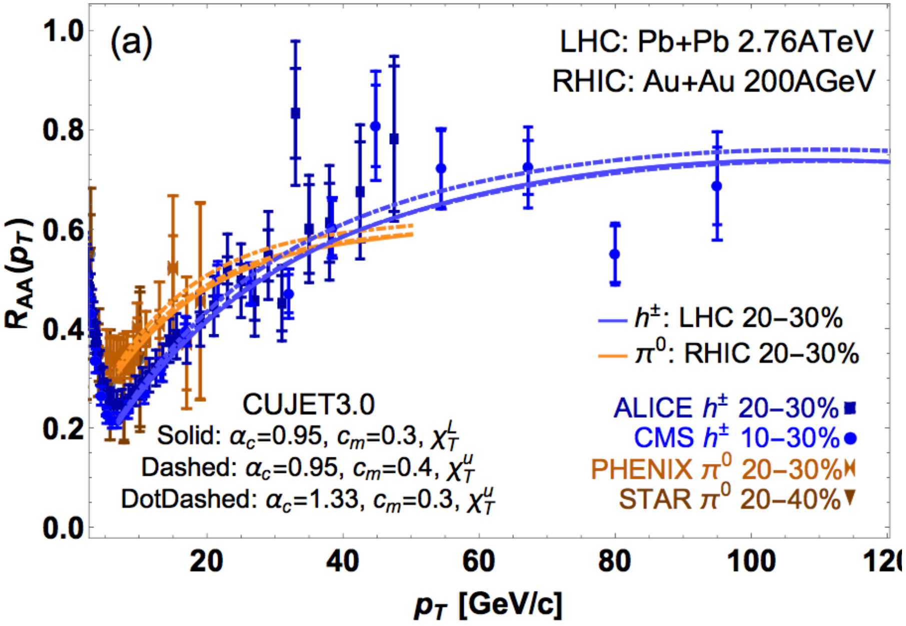


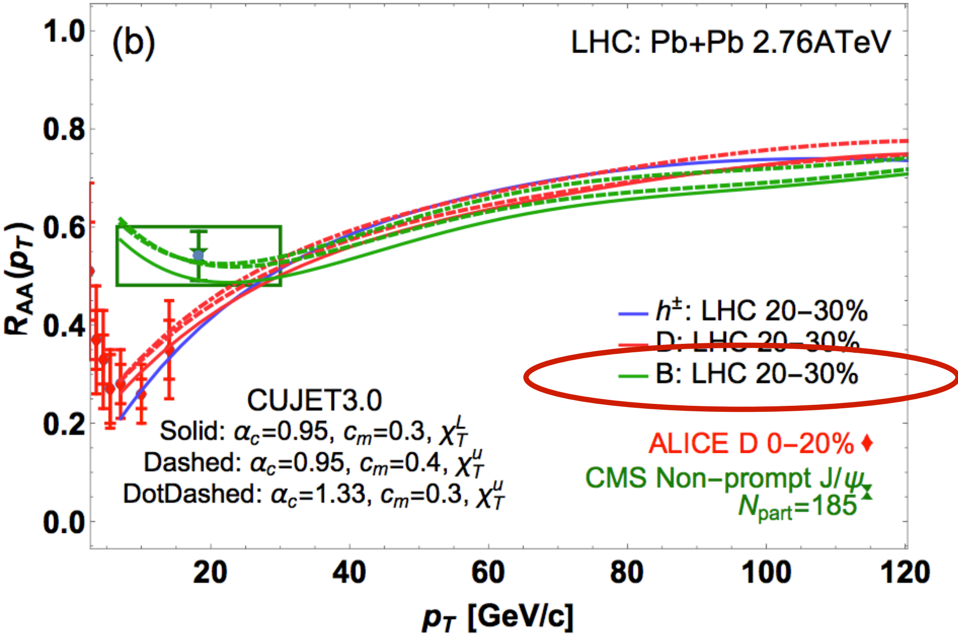
JHEP 1201, 138 (2012)

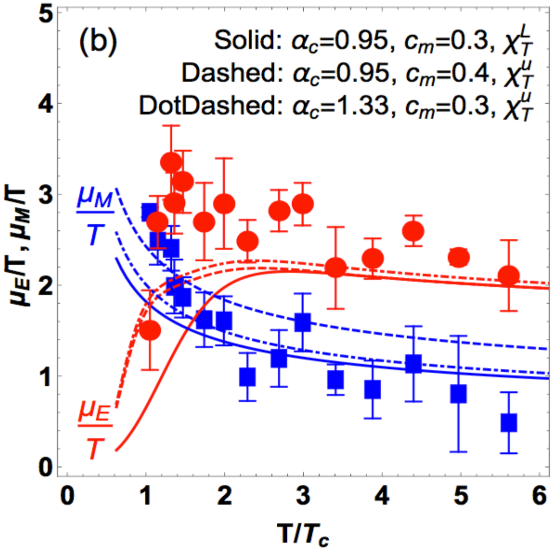


Wuppertal-Budapest 2010

Light hadron and open heavy flavor R_{AA} with “fast deconfinement”



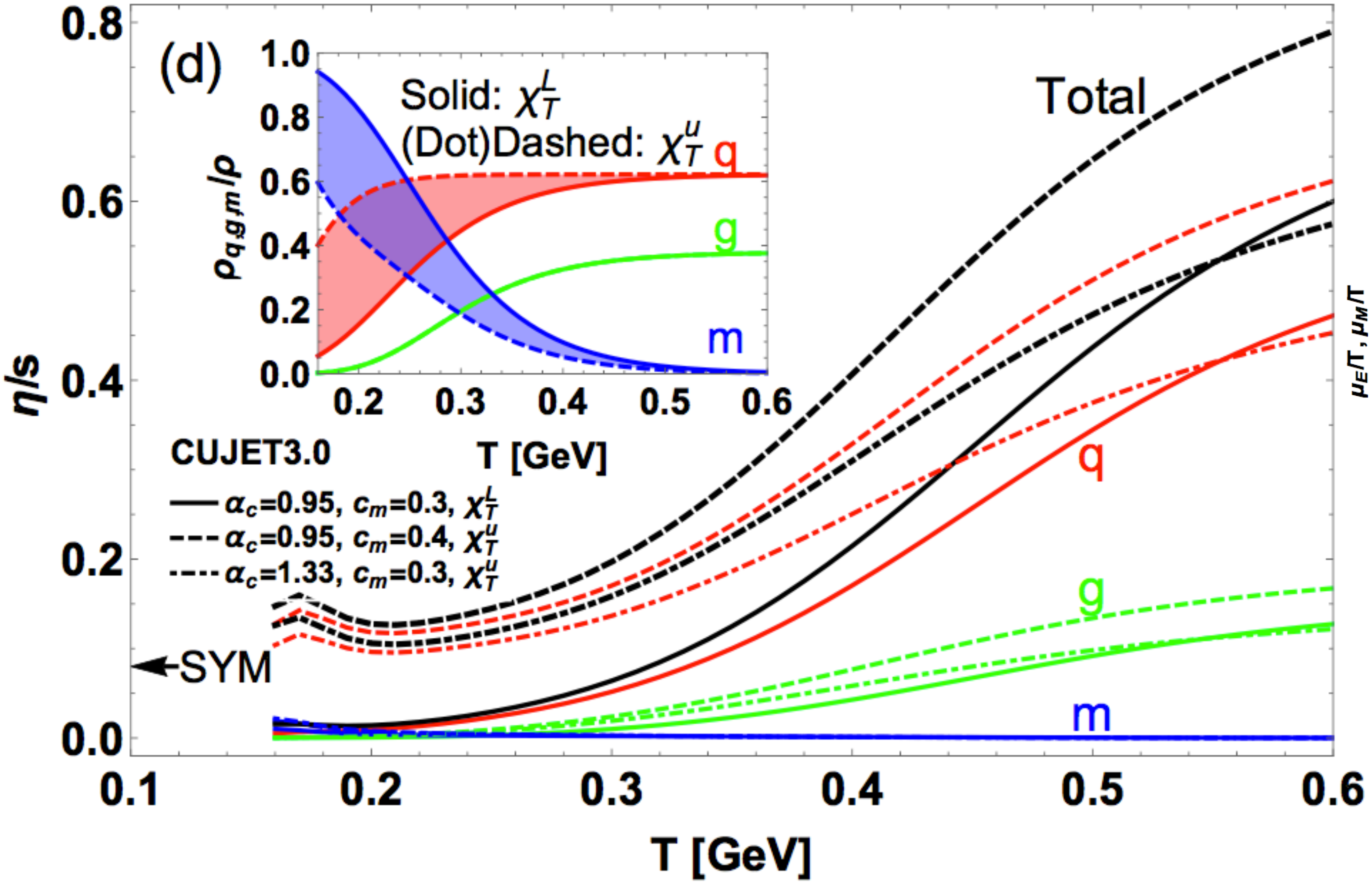


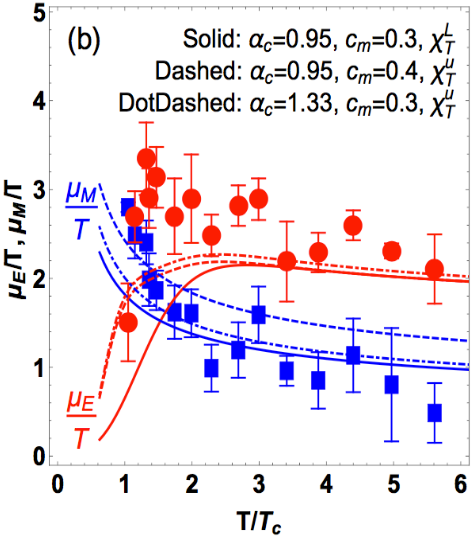


JX, Liao, Gyulassy, arXiv:1508.00552

- ❖ The parameter is adjusted to fit to LHC charged hadron R_{AA} at p_T=12.5GeV
- ❖ The beauty R_{AA} distinguishes the different liberation schemes
- ❖ The combination of light hadron and open heavy flavor R_{AA} may be used as a measure of deconfinement

The shear viscosity with “fast deconfinement”



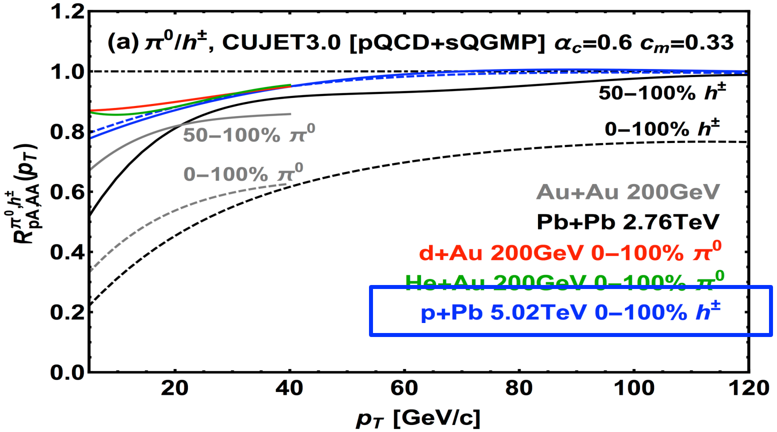


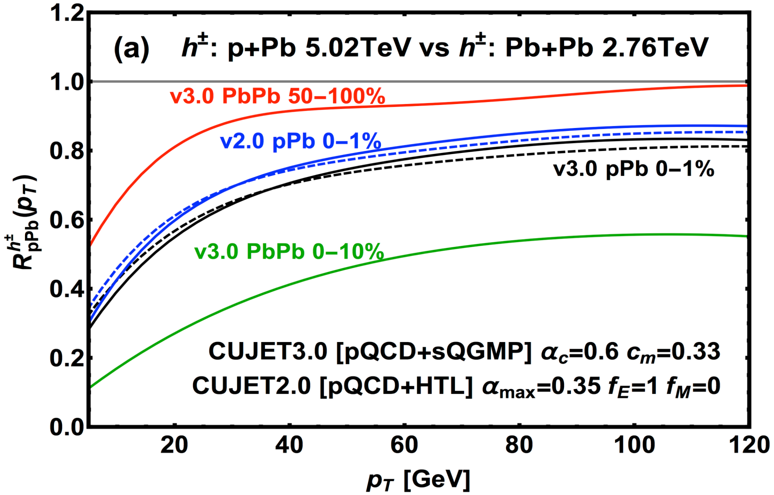
arXiv:1508.00552

- ❖ The shear viscosity minimum is sensitive to how rapidly quark DOFs are deconfined
- ❖ The slope of η/s(T) is affected mainly by the temperature dependence of E and M screening masses

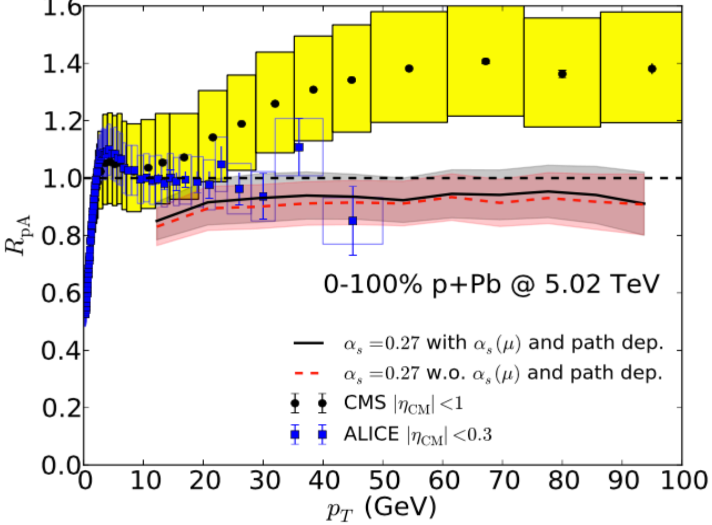
Jet quenching in p+A?

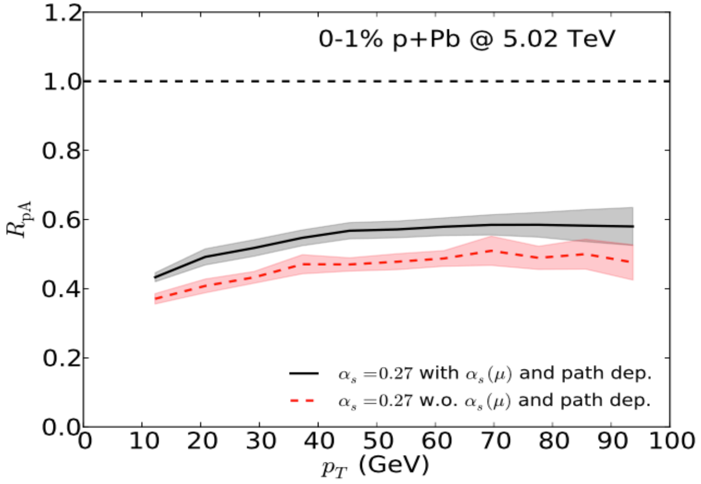
CUJET3.0/DGLV
(preliminary)





MARTINI/AMY

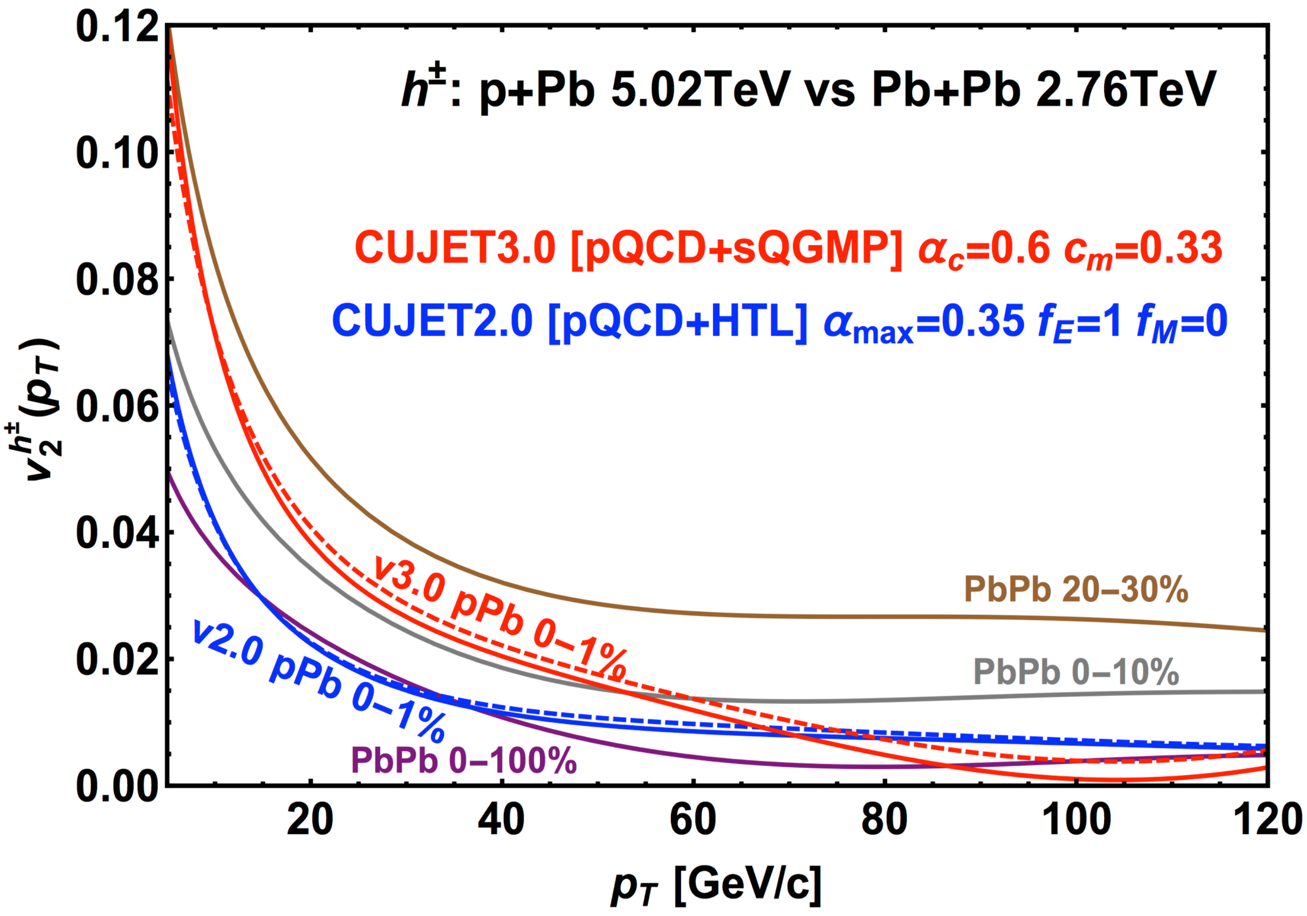


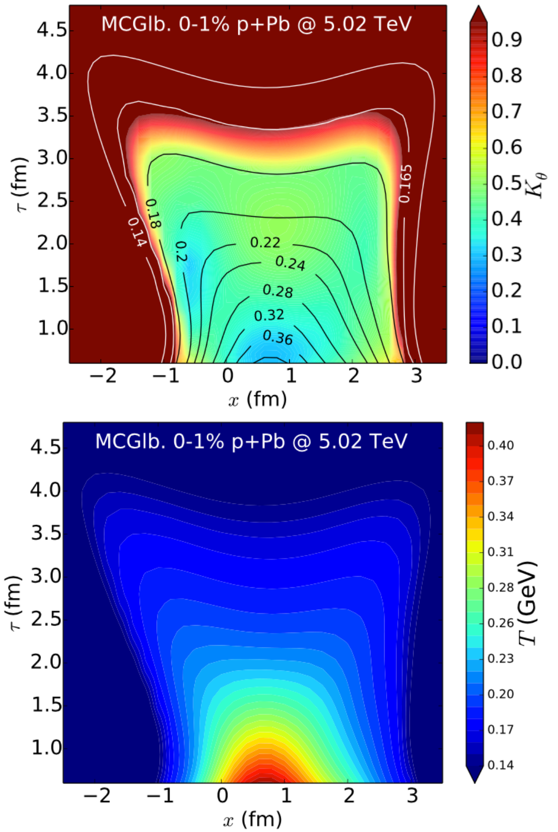


Gale, QM15 Monday Talk

- Same pA Hydro from McGill group is used, cf. Shen et al. 1504.07989 & Gale's Talk on Monday
- Min. bias see mild quenching at p_T~15GeV; Central collisions see strong jet suppressions

Azimuthal anisotropy of charged hadrons in p+A





Shen et al. arXiv:1504.07989 &
Gale's Talk on Monday

- Significant v_2 up to p_T~30GeV in central pA collisions in CUJET
- Compared with HTL QGP, in sQGMP, the monopoles contribute to a ~0.03 boost in high p_T v_2, this magnitude of enhancement is similar to the one in 20-30% AA

Summary

- Combining the pQCD jet quenching kernal and the microscopic semi-Quark-Gluon-Monopole Plasma (sQGMP) model, CUJET3.0 describes (R_{AA}+v_2) × (pion+D+B) × (RHIC+LHC) simultaneously
  - qhat bridges the AdS/CFT limit near Tc and the HTL pQCD limit at high T
  - eta/s approaches the perfect fluid ~0.1 near Tc, and rises rapidly as T rises

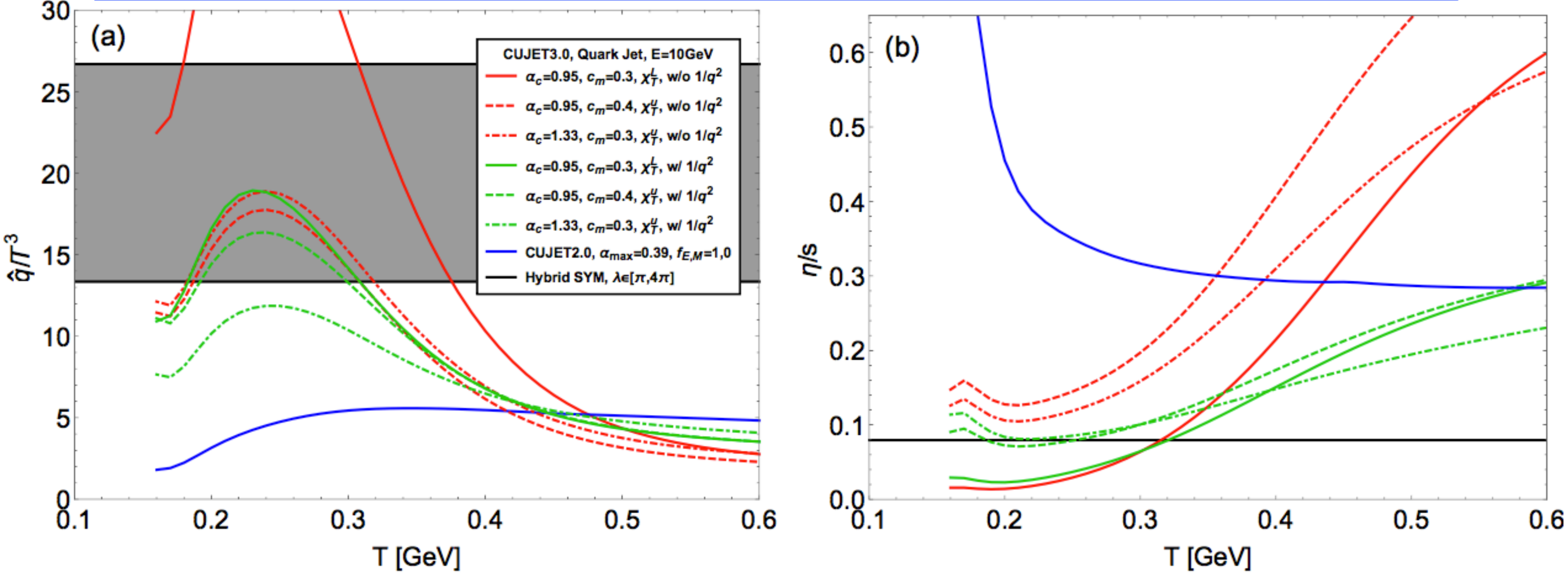
- How rapidly quark DOFs are deconfined near T_c significantly affects the suppression of open heavy flavors and the shear viscosity minimum

- Non-negligible suppressions of high-p_T light hadrons in most-central pA collisions; the high-p_T v_2 enhancement from monopoles in such system is similar to that in AA

Backup

An alternative qhat measure in sQGMP

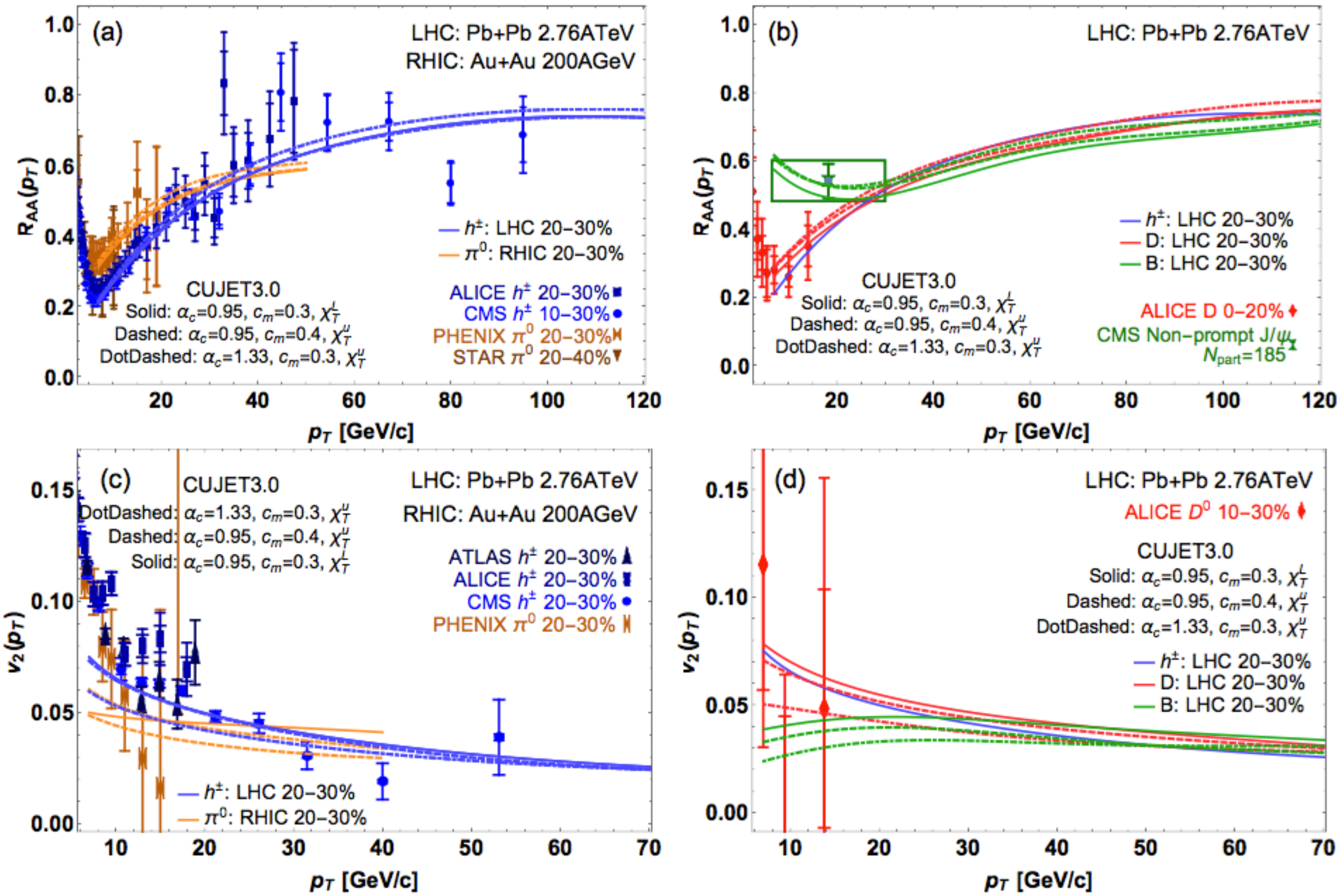
$$\hat{q}'_F(E,T) = \int_0^{6ET} d\mathbf{q}_\perp^2 \frac{2\pi}{(\mathbf{q}_\perp^2 + f_E^2\mu^2(\mathbf{z}))(\mathbf{q}_\perp^2 + f_M^2\mu^2(\mathbf{z}))}\rho(T)$$
$$\times \quad \Big\{ [C_{qq}f_q + C_{qg}f_g] \cdot [\alpha_s^2(\mathbf{q}_\perp^2)] \cdot [f_E^2\mathbf{q}_\perp^2 + f_E^2 f_M^2 \mu^2(\mathbf{z})] +$$
$$[C_{qm}(1 - f_q - f_g)] \cdot [1] \cdot [f_M^2\mathbf{q}_\perp^2 + f_E^2 f_M^2 \mu^2(\mathbf{z})] \Big\} .$$



JX, Liao, Gyulassy, arXiv:1508.00552

- The alternative qhat as well as the eta/s converges to the HTL limit at high temperature.

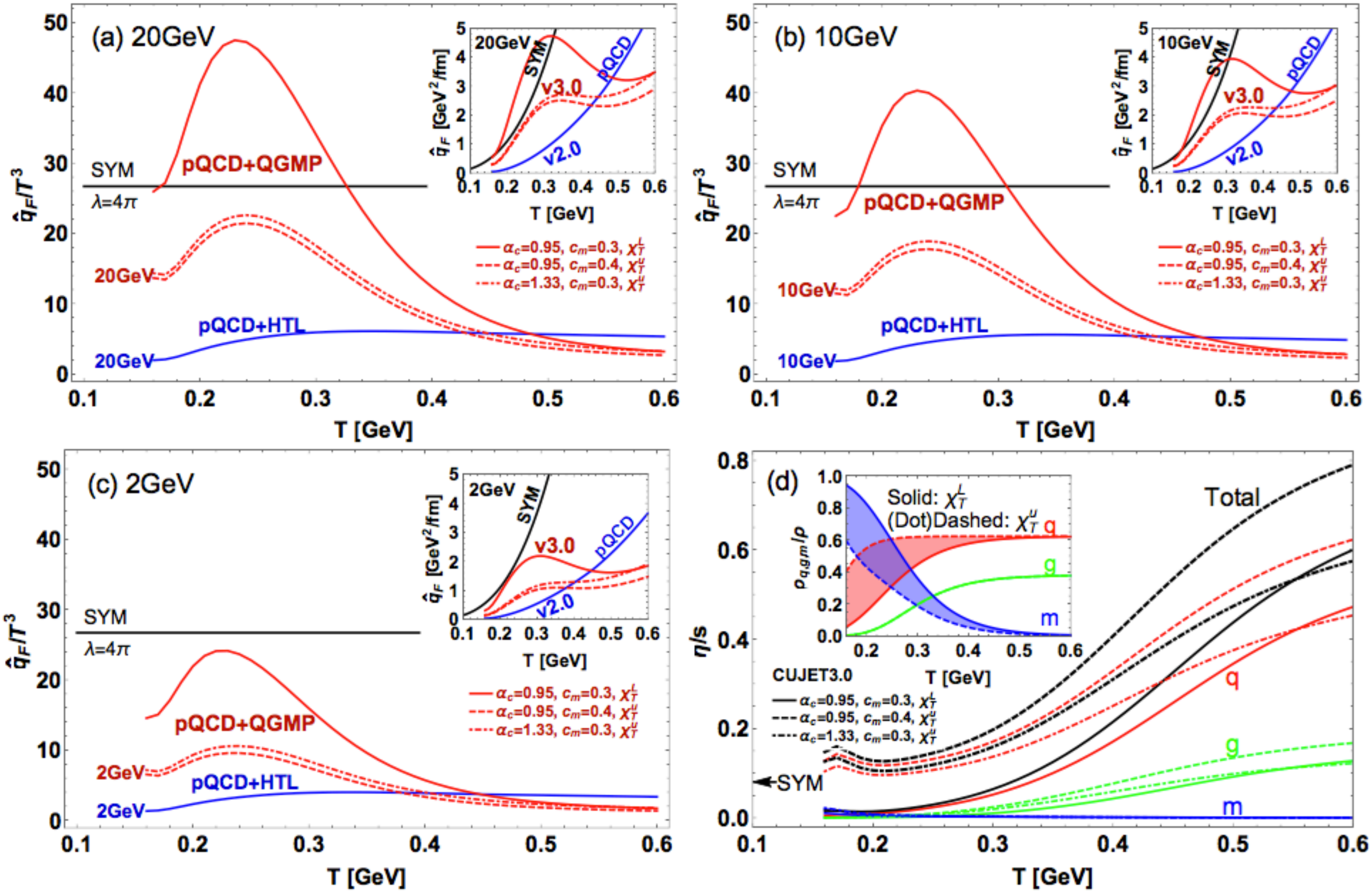
R_{AA} and v_2 in the "fast liberation" scheme



JX, Liao, Gyulassy, arXiv:1508.00552

- Open heavy flavor R_{AA} distinguishes the different liberation schemes

qhat and eta/s in the “fast liberation” scheme

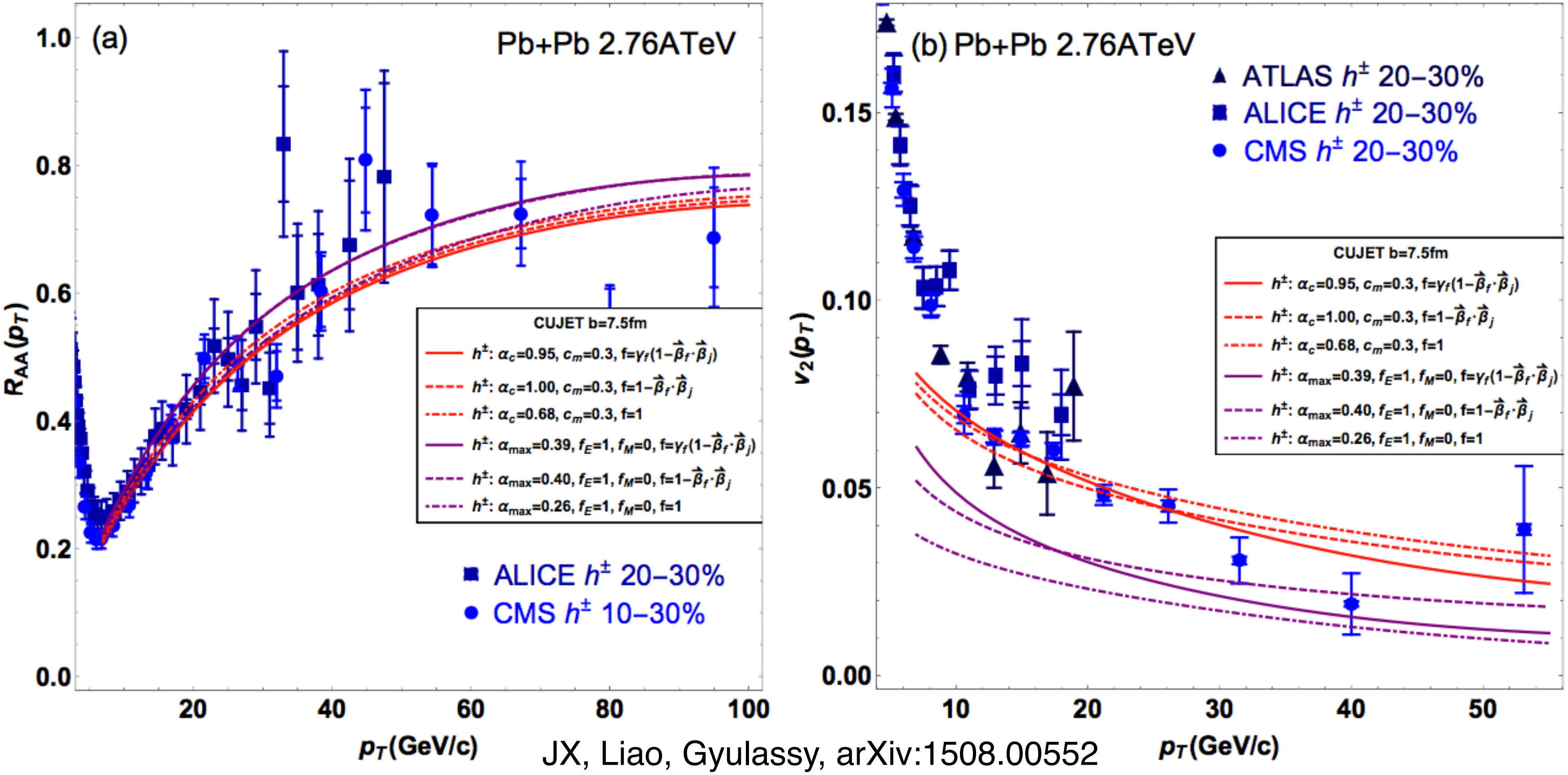


JX, Liao, Gyulassy, arXiv:1508.00552

- The shear viscosity near T_c is sensitive to how fast quark DOFs are deconfined

Relativistic corrections to jet quenching from transverse flow

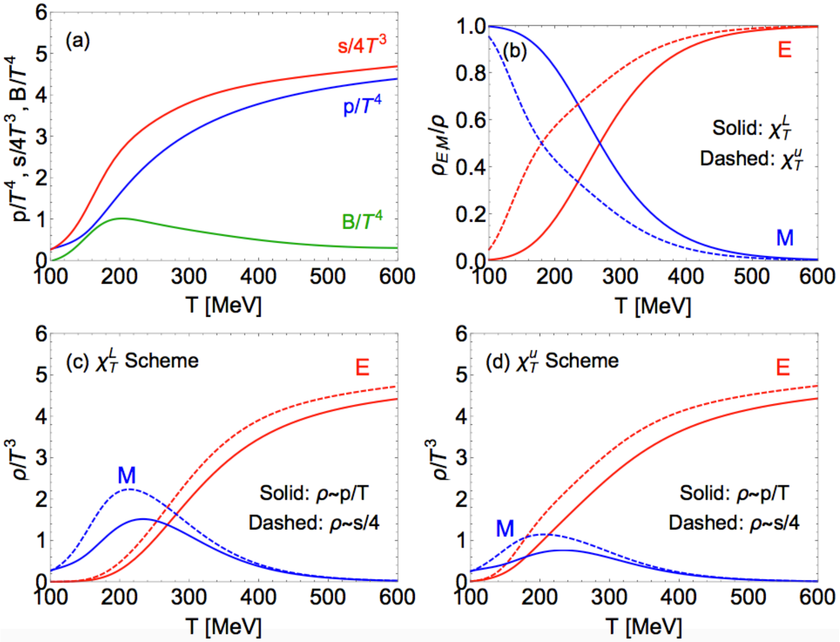
$$\Gamma(\mathbf{z}) = u_f^\mu n_\mu \quad n = (1, \vec{\beta}_{jet}) \quad u_f^\mu = \gamma_f(1, \vec{\beta}_f)$$ Liu et al. 07'; Baier et al. 07'

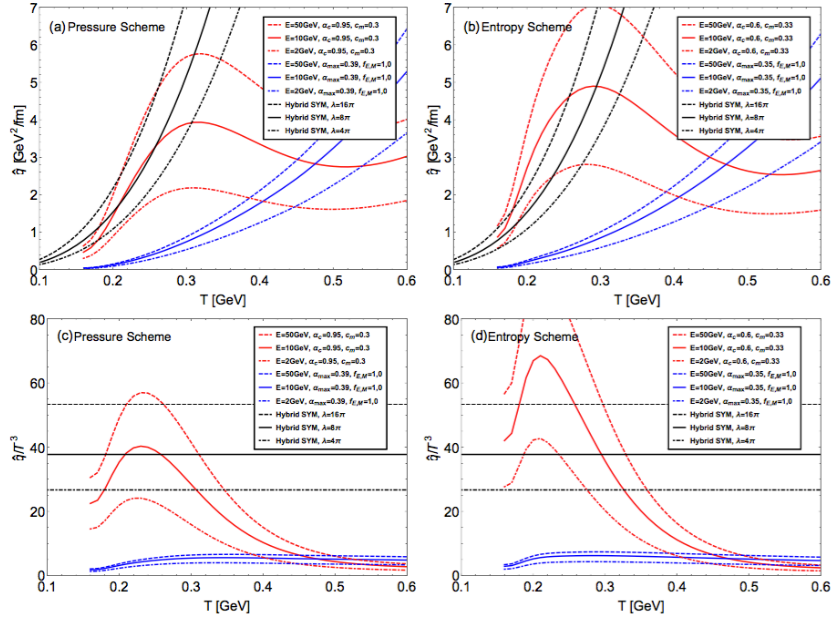


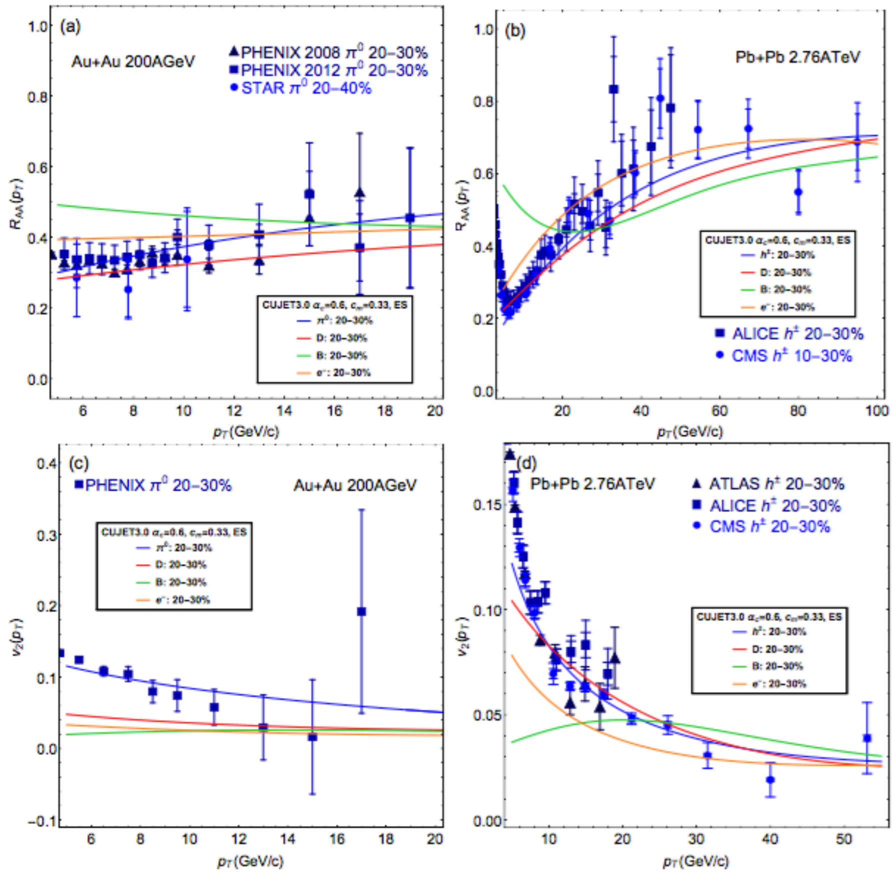
JX, Liao, Gyulassy, arXiv:1508.00552

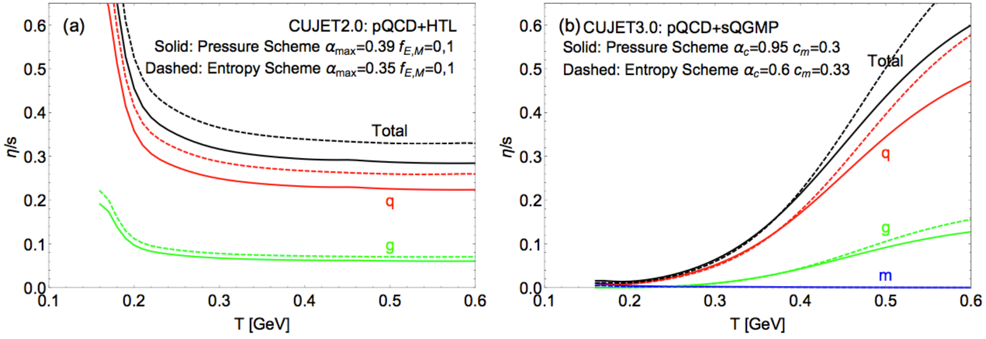
- Both RAA and v2 are surprisingly insensitive to the form of the relativistic flow corrections in both CUJET2.0 (pQCD+HTL) and CUJET3.0 (semi-QGP + magnetic monopoles)

Pressure Scheme (PS) vs Entropy Scheme (ES)









JX, Liao, Gyulassy, arXiv:1508.00552

Convergence of the DGLV opacity series

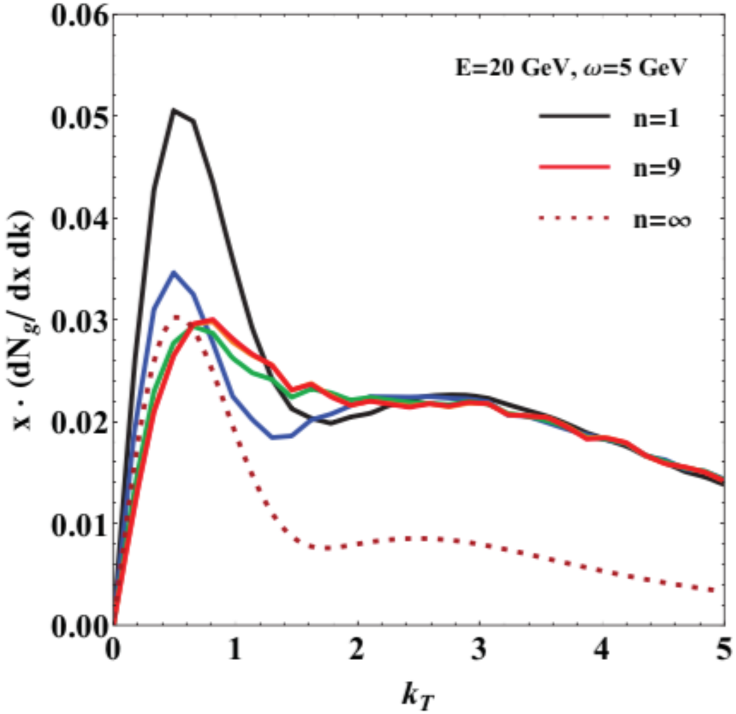
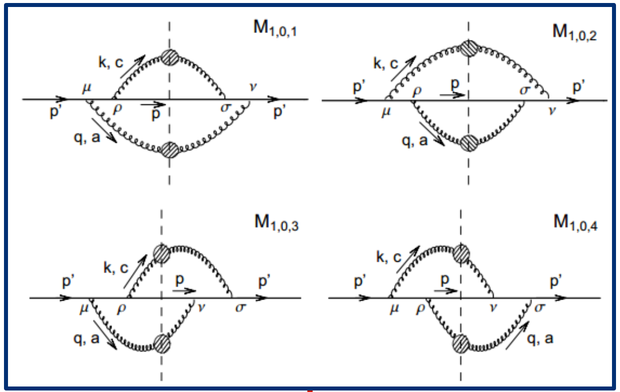


Figure 15. Radiated gluon transverse momentum distribution for a heavy quark jet with energy $E = 20\,\mathrm{GeV}$ traversing a brick plasma of size $L = 5\,\mathrm{fm}$ emitting a gluon with energy $\omega = 5\,\mathrm{GeV}$. The mass of the quark $M = 4.75\,\mathrm{GeV}$. The DGLV opacity series calculated up to n=1 (black), 3 (blue), 5 (green), 7 (orange), 9 (red) are shown in the figure. The opacity expansion computed up to ninth order is shown to converge to the ASW multiple soft scattering limit (maroon, dashed) for small $k_\perp \lesssim \hat{q}L \approx 1\,\mathrm{GeV}$. At large $k_\perp$, differs from the ASW limit, DGLV has a robust Laudau tail. Other parameters used in the simulation are: $\lambda = 1.16\,\mathrm{fm}$, $\mu = 0.5\,\mathrm{GeV}$, $m_g = 0.356\,\mathrm{GeV}$, $T = 0.258\,\mathrm{GeV}$, $n_f = 0$, $\alpha_s = 0.3$.

JX, Buzzatti, Gyulassy, JHEP 1408, 063 (2014)

CUJET: to solve the heavy quark energy loss puzzle + to explain the surprising transparency of QGP at LHC

❖ Recoiling scattering centers



$$\lambda_{\rm dyn} \Longleftrightarrow \lambda_{\rm stat} = \frac{\lambda_{\rm dyn}}{c(n_f)}$$

$$\left[\frac{\mu^2}{\boldsymbol{q}^2(\boldsymbol{q}^2+\mu^2)}\right]_{\rm dyn} \Longleftrightarrow \left[\frac{\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}\right]_{\rm stat}$$

Djordjevic and Heinz, PRC (2008)

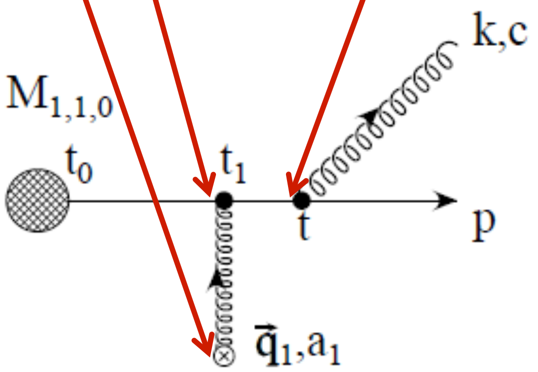
❖ Path length fluctuations: $T(\tau_{max}) = T_f$

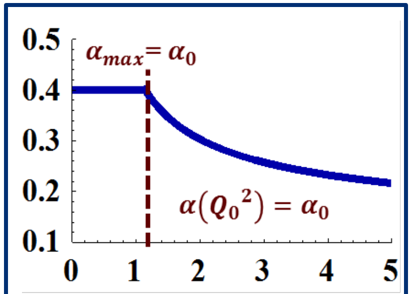
❖ Multi-scale running strong coupling

$$Q^2 = \mathbf{q}^2$$

$$Q_2^2 = q^2 - M^2 = \frac{\mathbf{k}^2}{x_+(1-x_+)} + \frac{x_+ M^2}{1-x_+} + \frac{m_g^2}{x_+}$$

$$Q^2 = (2T)^2$$





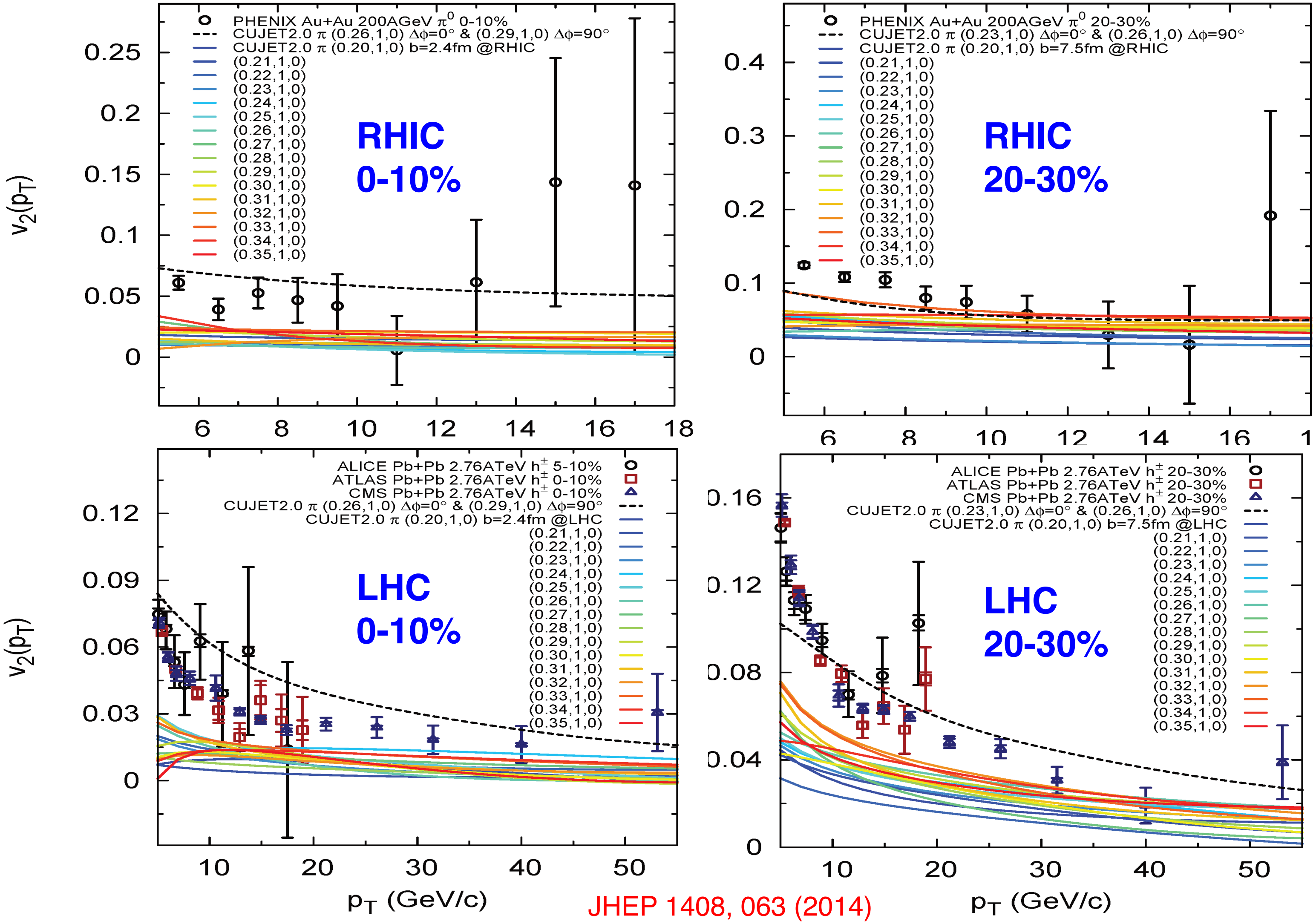
Zakharov, JETP Lett. 2008

Buzzatti, Gyulassy, 2013; JX, Buzzatti, Gyulassy, 2014

❖ Elastic: S. Peigne and A. Peshier, PRD 77, 114017 (2008)

$$\alpha_s^2 \log\frac{4ET}{\mu^2} \longrightarrow \alpha_s(\mu^2)\alpha_s(4ET)\log\frac{4ET}{\mu^2(\alpha_s(4T^2);T)}$$

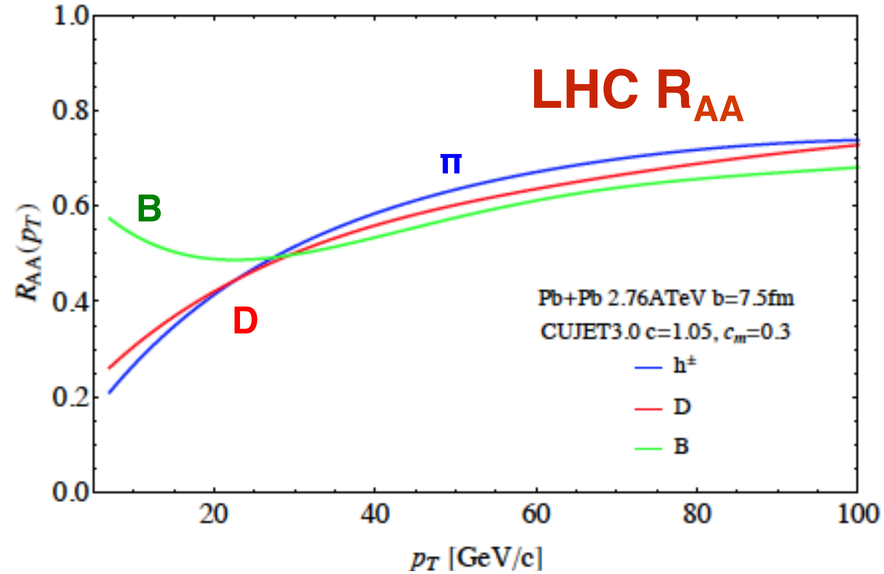
High-p_T v_2 in the pQCD energy loss model

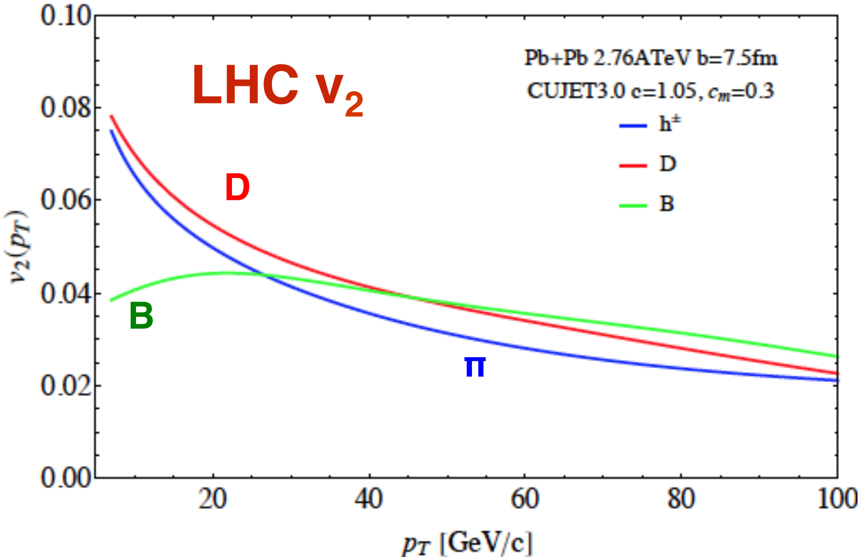


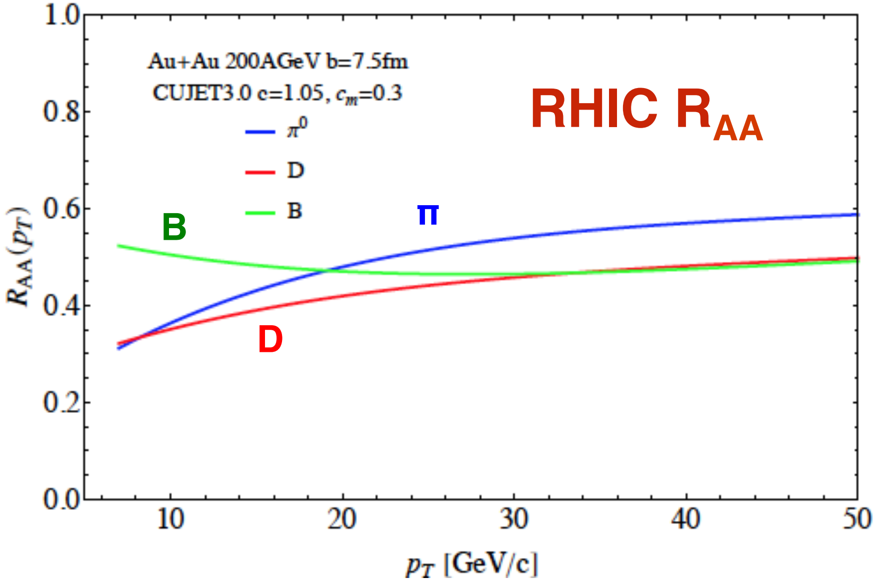
JHEP 1408, 063 (2014)

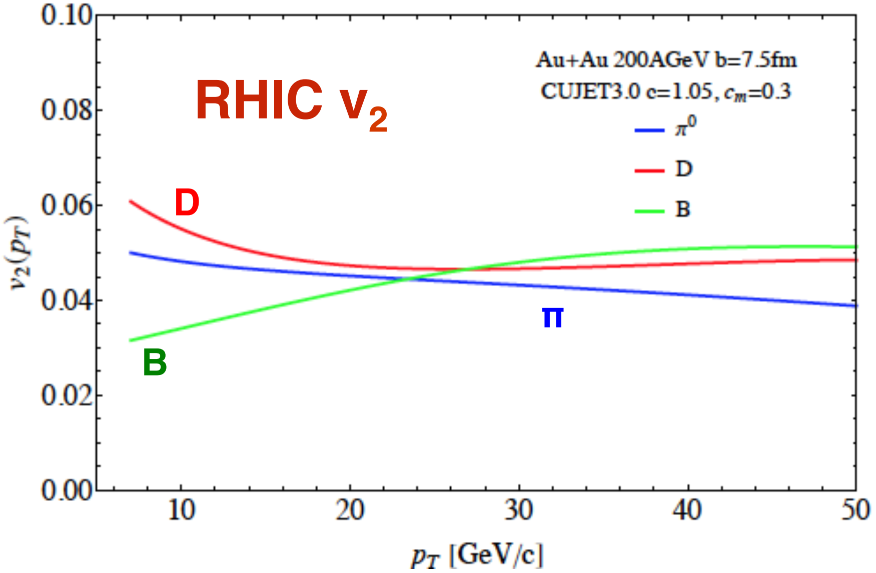
- ❖ The **50%** underestimation of v2 can be accounted for if the average coupling strength is tuned up by **10%** from in- to out-of-reaction plane paths

Open charm's and beauty's high p_T R_{AA} and v_2 at RHIC and LHC (20-30% centrality) from CUJET3.0

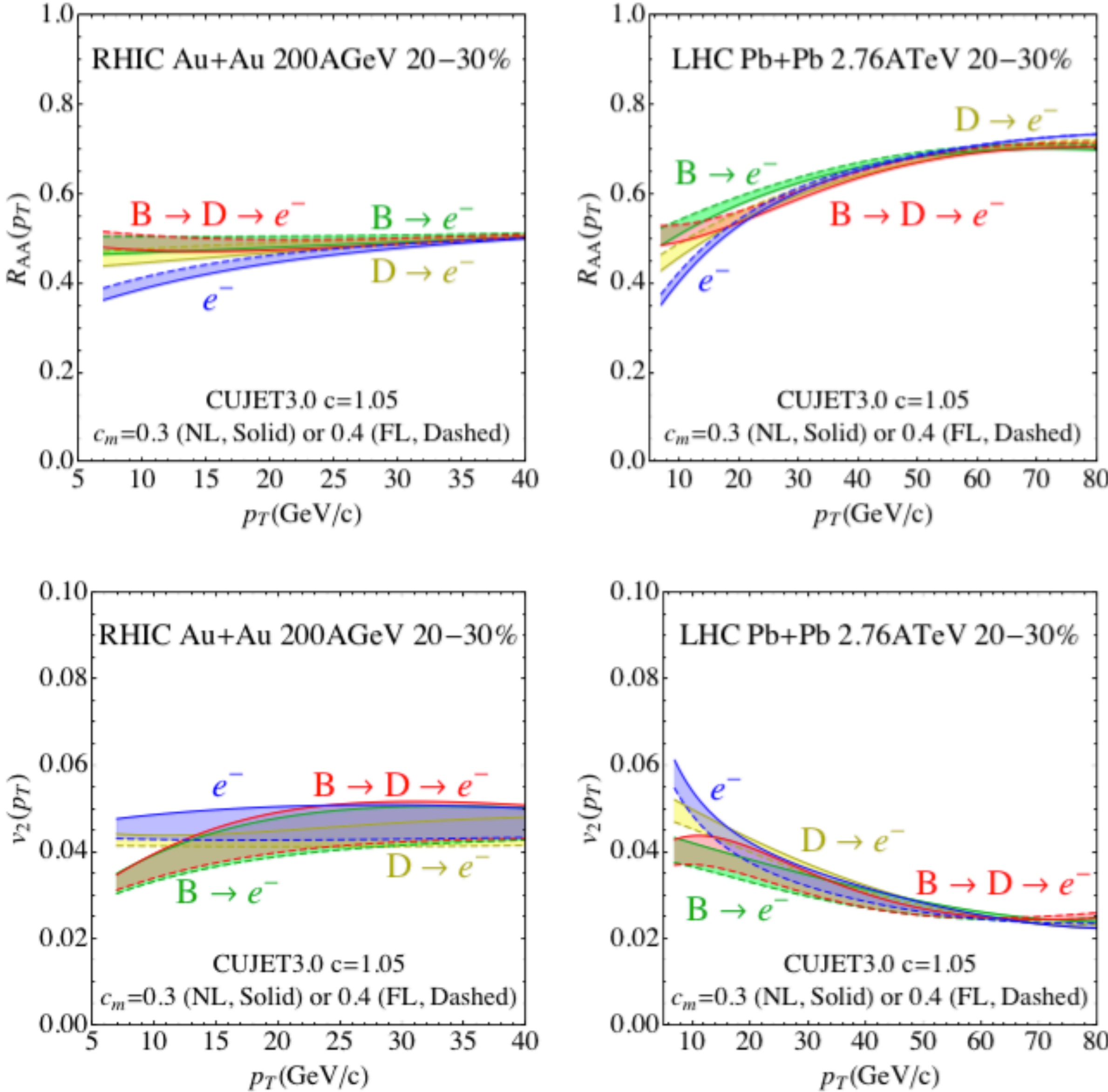


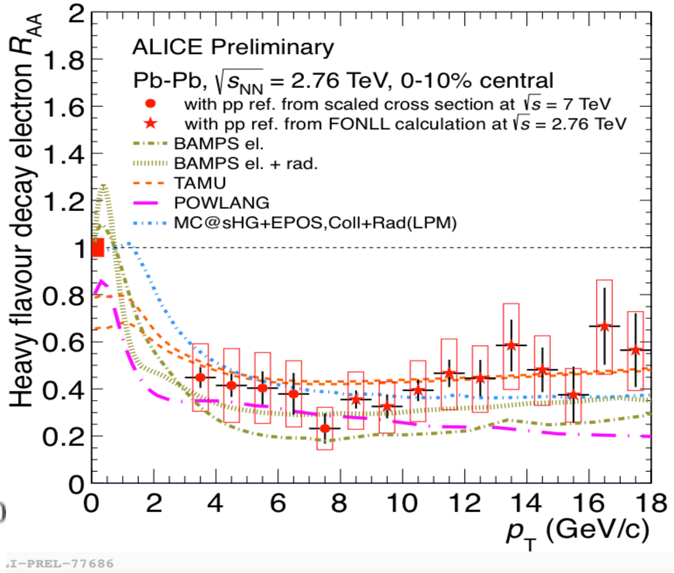


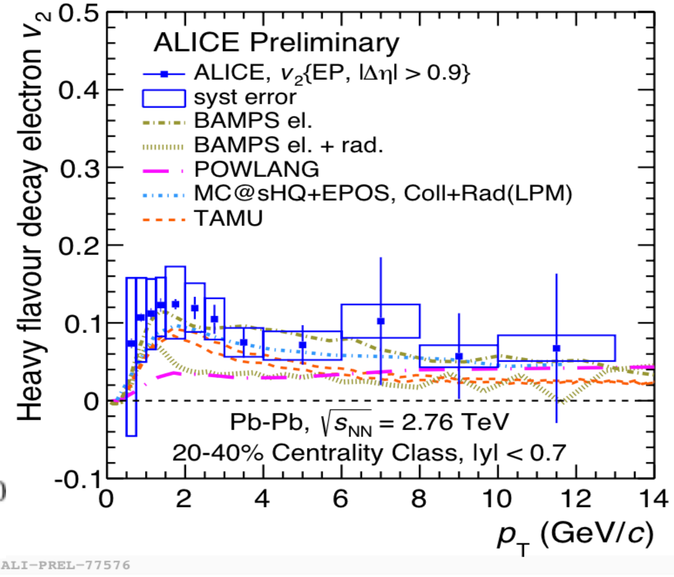




CUJET3.0: HF Decay Electron RAA & v2

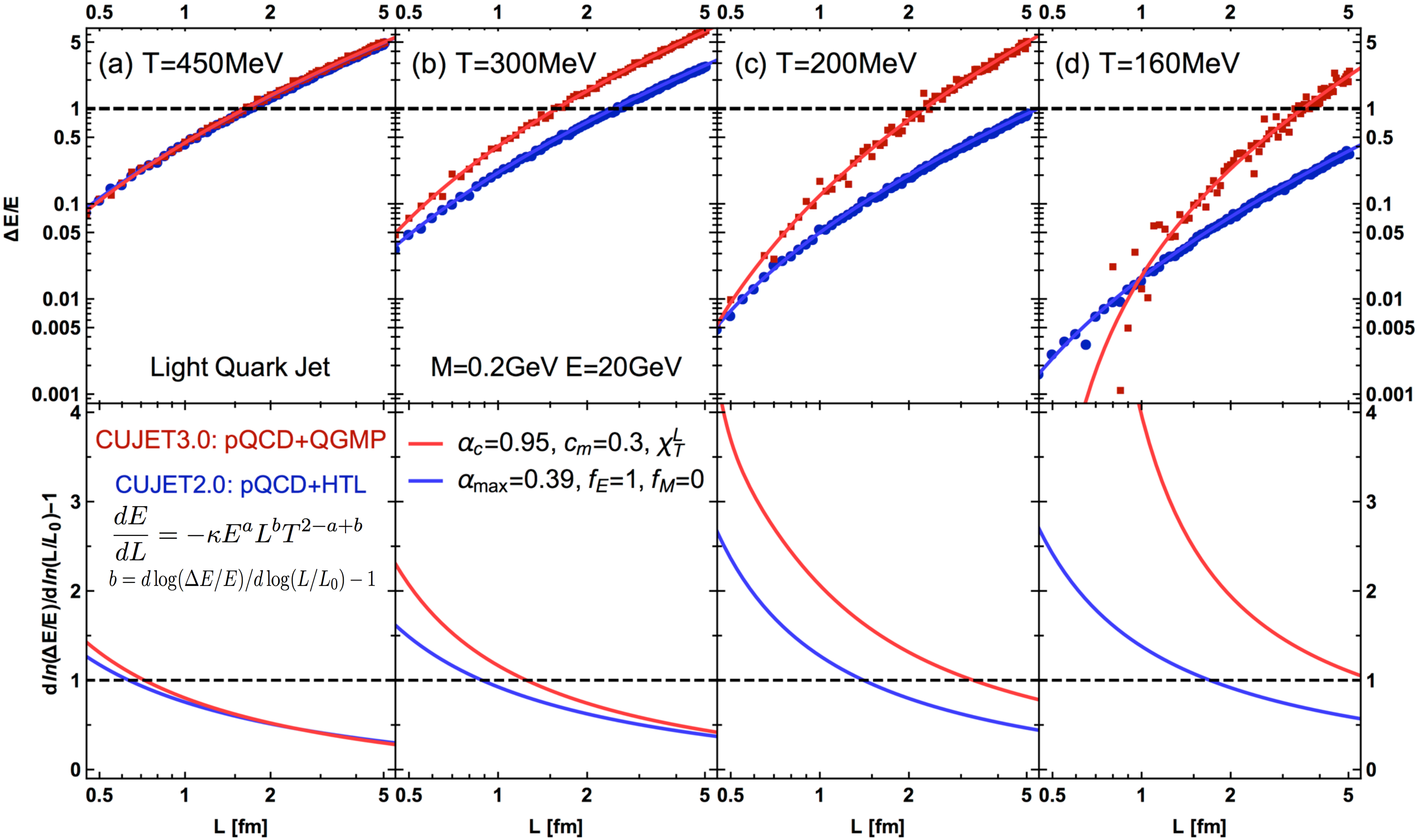






❖ To be compared with data

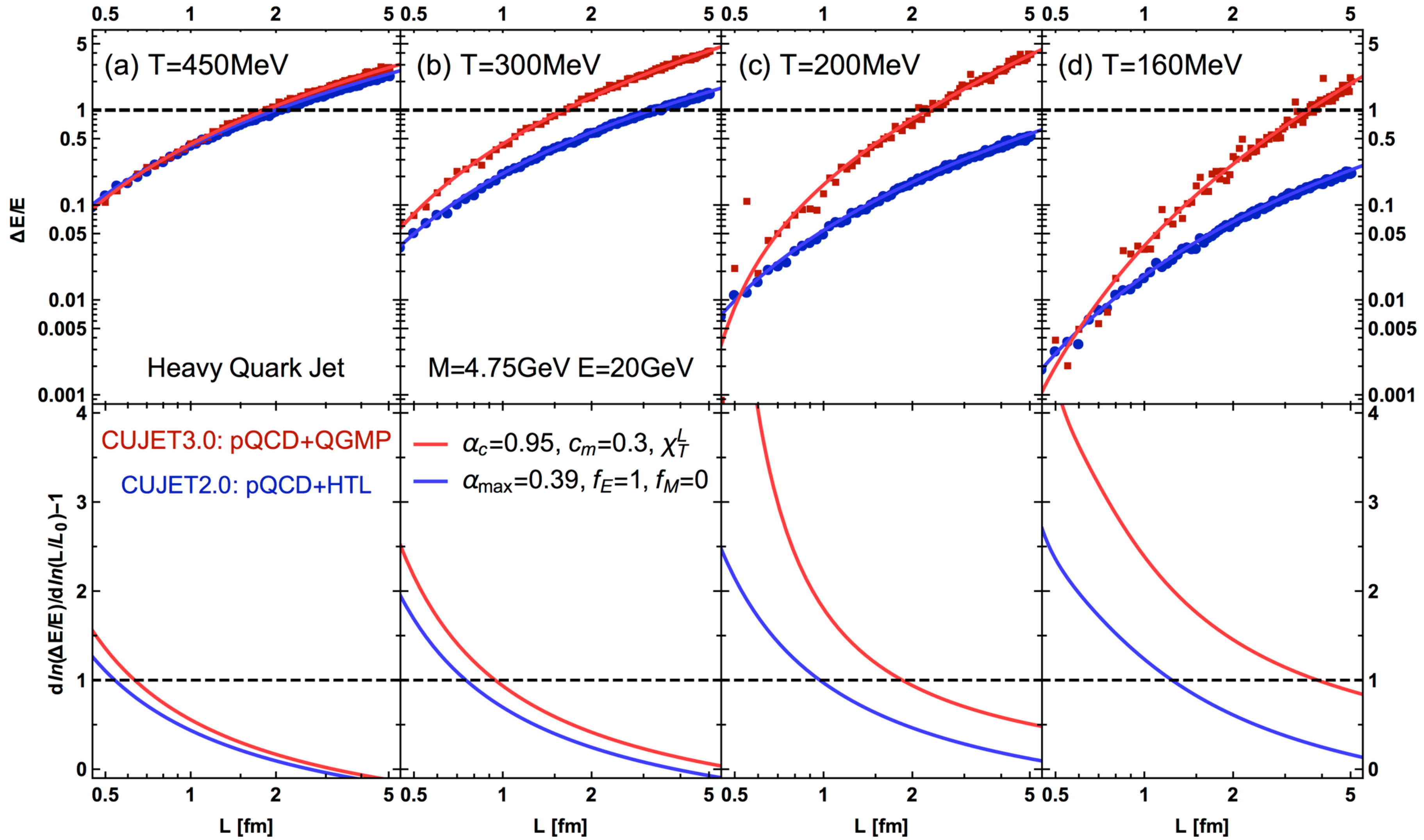
Path length dependence of jet energy loss in sQGMP



JX, Liao, Gyulassy, arXiv:1508.00552

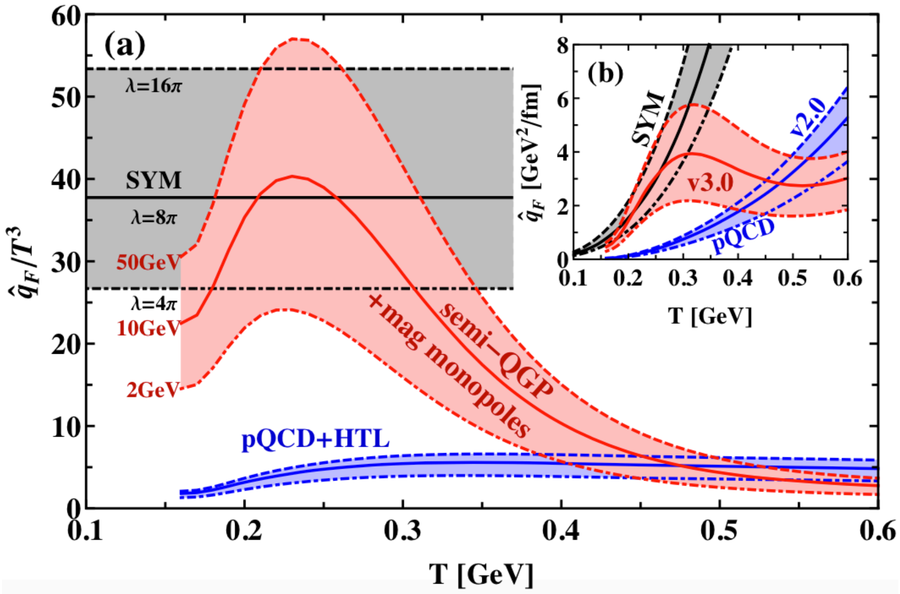
❖ Monopoles bring non-perturbative effects into the pQCD energy loss theory

Path length dependence of heavy quark energy loss in sQGMP



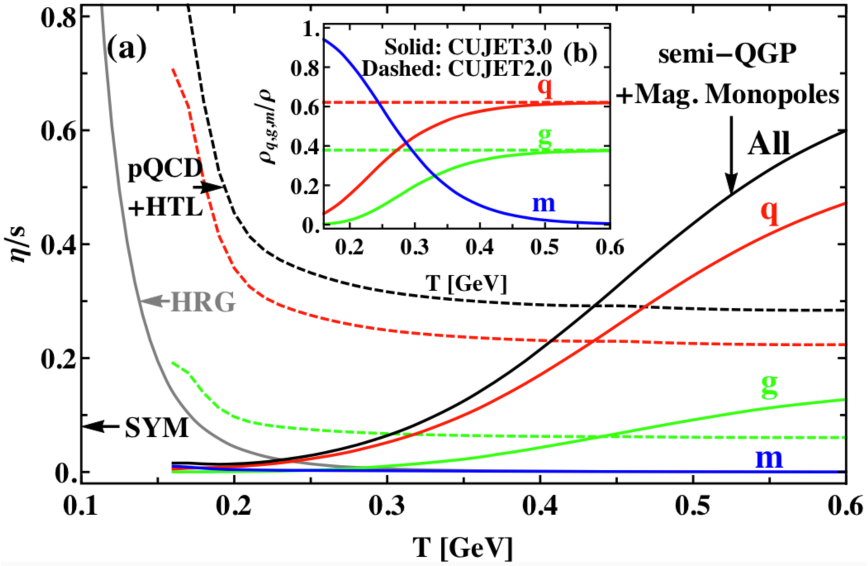
JX, Liao, Gyulassy, arXiv:1508.00552

Near-Tc properties of sQGMP are special!



Jet transport coefficient qhat/T^3
computed from CUJET3.0
shows a prominent peak near Tc!

Shear viscosity, η/s,
computed from CUJET3.0
shows a clear minimum near Tc
and a rapid rise at high T!



CUJET3.0 = [pQCD] + [semi-QGP] + [magnetic monopoles] bridges the “soft” bulk perfect fluidity and the “hard” jet quenching (η/s~T^3/qhat)

BES@RHIC and LHC are both essential to constrain and map out the strongly non-conformal QCD confinement transition physics