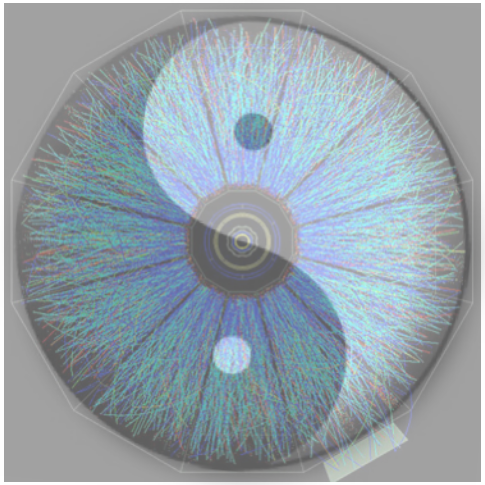
ECT* Workshop
Apr. 27, 2021

CUJET3



Jinfeng Liao

The CUJET "History"

* CUJET1: 2010~2011 (modernizing DGLV + heavy flavor)

* CUJET2: 2012~2013 (bulk, HTL, running coupling, …)

* CUJET3.0: 2014~2016 (non-perturbative medium, …)

* CUJET3.1/CIBJET: 2017~ (matured framework, global constraints, …)

Shuzhe Shi, Miklos Gyulassy, JL, Jiechen Xu

arXiV:
1411.3673;
1508.00552;

1804.01915;
1808.05461

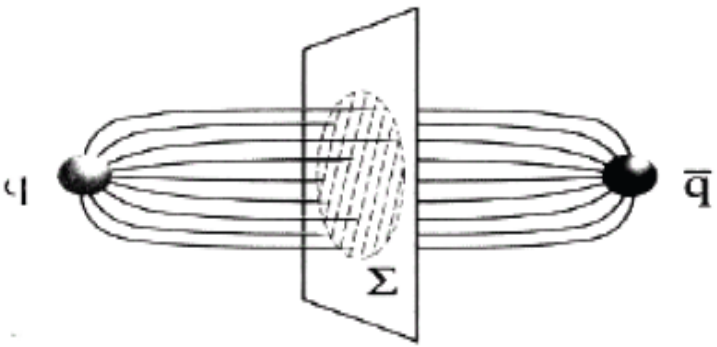
The QCD Vacuum: Confinement

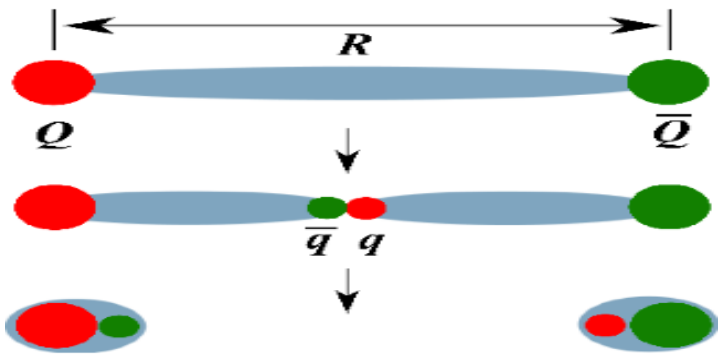
The missing particles: quarks & gluons (in the QCD lagrangian) are not seen in physically observed states.

Free Quark Searches

from Particle Data Book

All searches since 1977 have had negative results.





QCD vacuum as "dual superconductor"?!
['t Hooft, Mandelstam, Nambu, Polyakov, ...]

What Are the DoFs?

$$\mathcal{Z} = \int \mathcal{D}[A_\mu] e^{-S}$$

Two strategies:

1. Use real computers with brute force

2. Effective models that start with the right DoFs

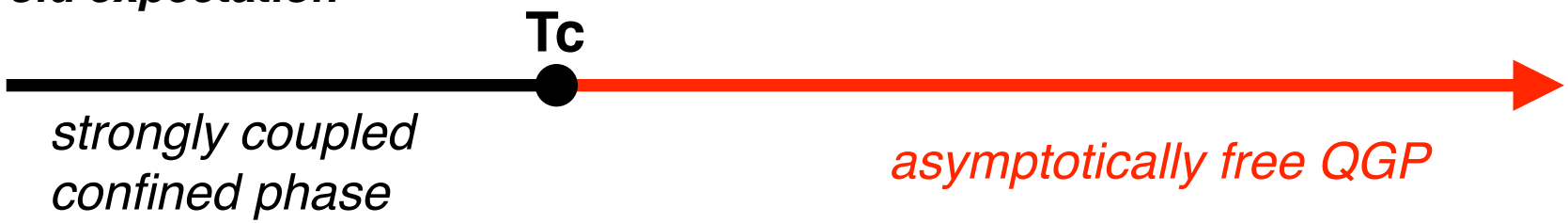
What are the most important/relevant configurations/DoFs for enforcing confinement?

S. Weiberg quote:

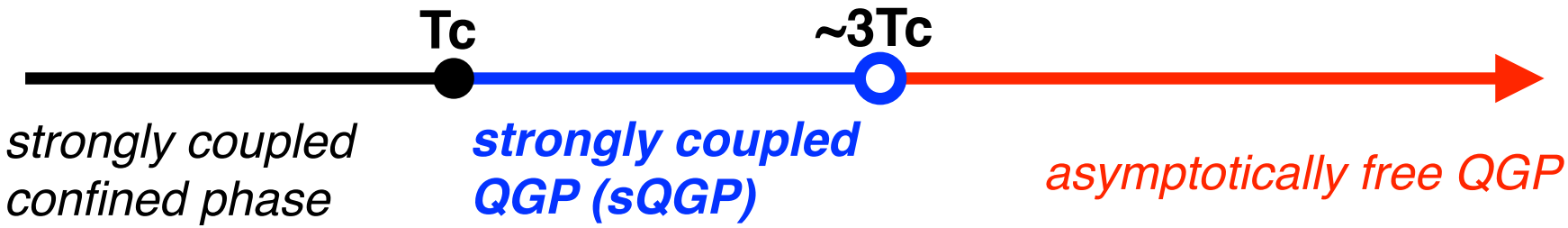
"You can use any degrees of freedom that you like to describe a physical system, but if you choose the wrong ones, you will be sorry."

So, what are the right degrees of freedom?

The old expectation



The new paradigm thanks to discoveries at RHIC and LHC (1~3Tc):

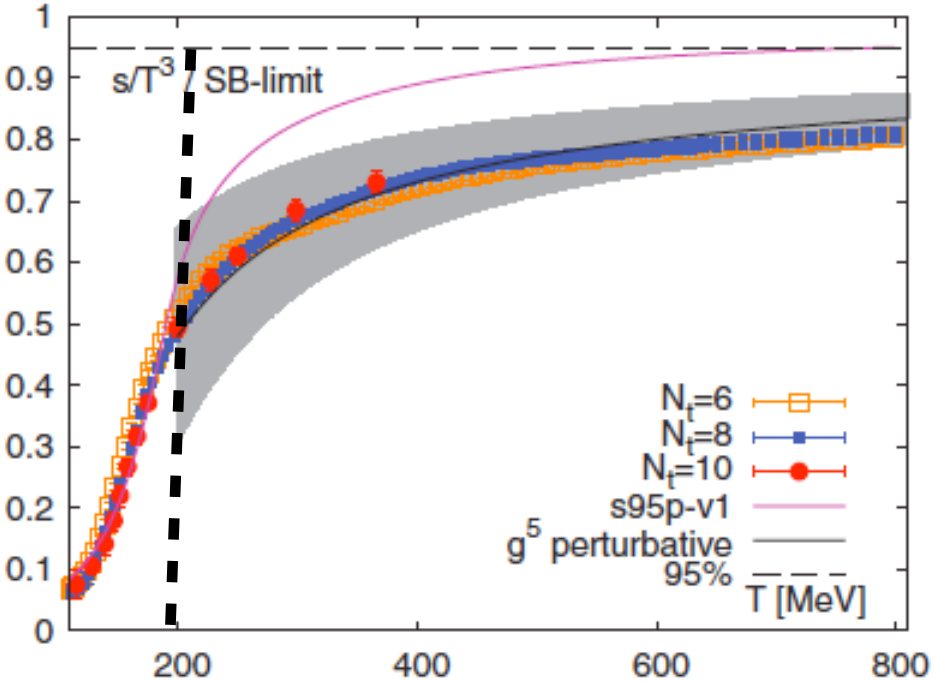


The matter just above confinement (in 1~3Tc), is more closely related to the confined world, rather than to the asymptotic QGP!

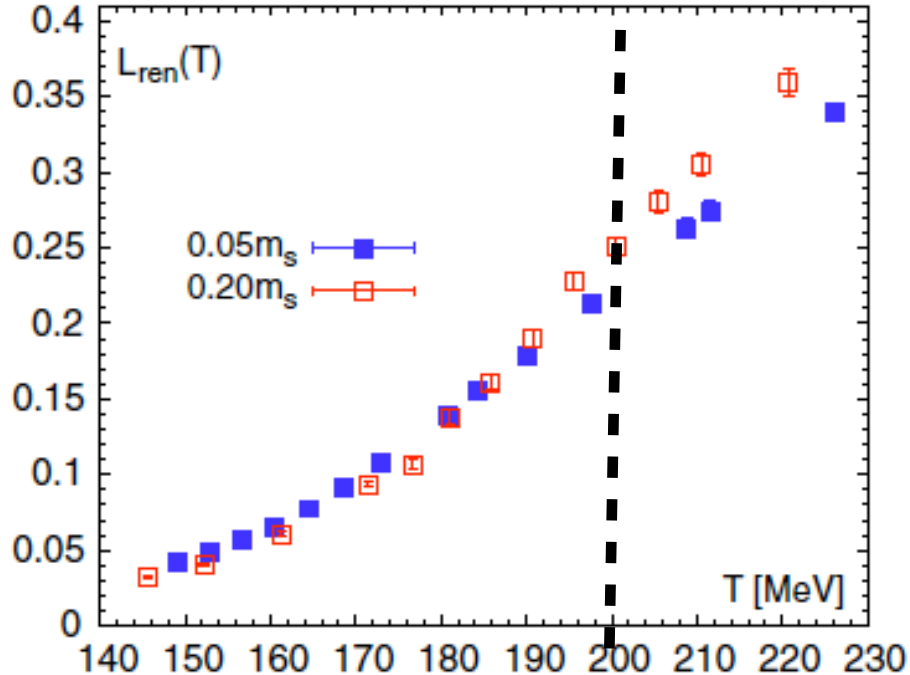
A"<u>postconfinement</u>" regime?!
What are the DoFs???

Liberation of Color? Missing DoF?

Degrees of freedom



Degree of color liberation



A region around Tc with liberated degrees of freedom but only partially liberated color-electric objects.

(Pisarski & collaborators: semi-QGP)

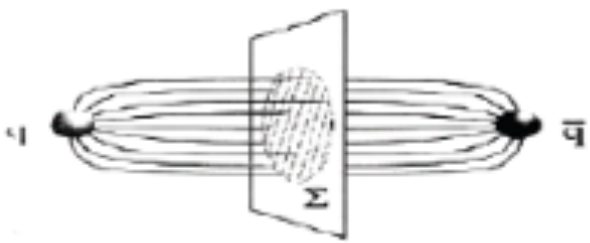
Then what are the "extra" dominant DoF here???

Thermal monopoles evaporated from vacuum condensate!

Chromo-Magnetic Monopoles in sQGP

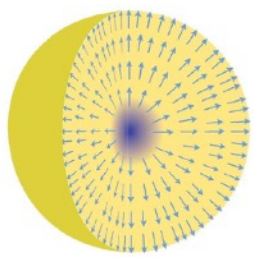
T<< Lambda_QCD | T ~ Lambda_QCD | T>> Lambda_QCD

Vacuum: confined — Tc — sQGP — *wQGP: screening* — T



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

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



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

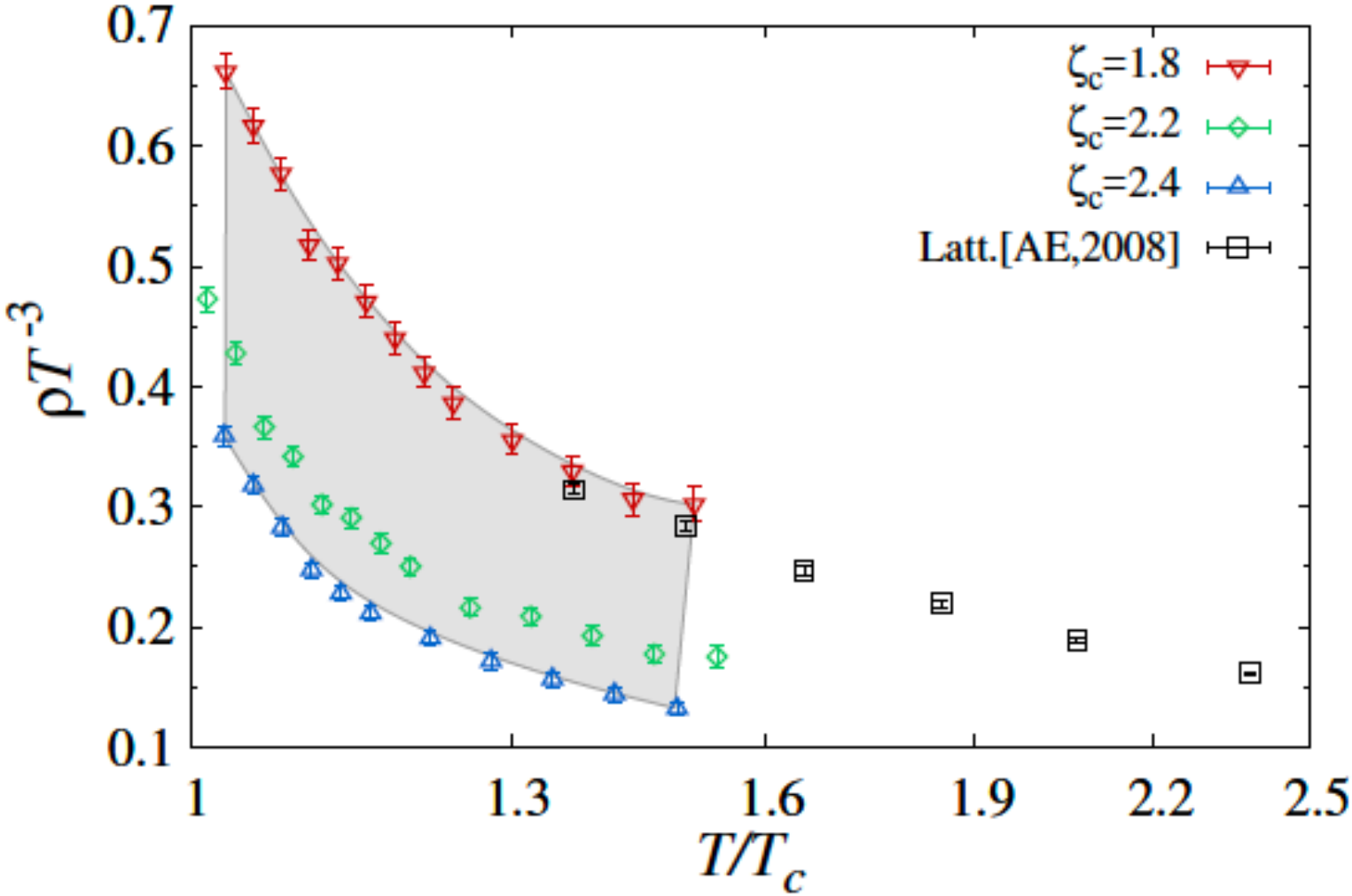
Condensate monopoles —> dense thermal monopoles near Tc: thermal monopoles play key role in this regime.

PHYSICAL REVIEW C 75, 054907 (2007)

Strongly coupled plasma with electric and magnetic charges

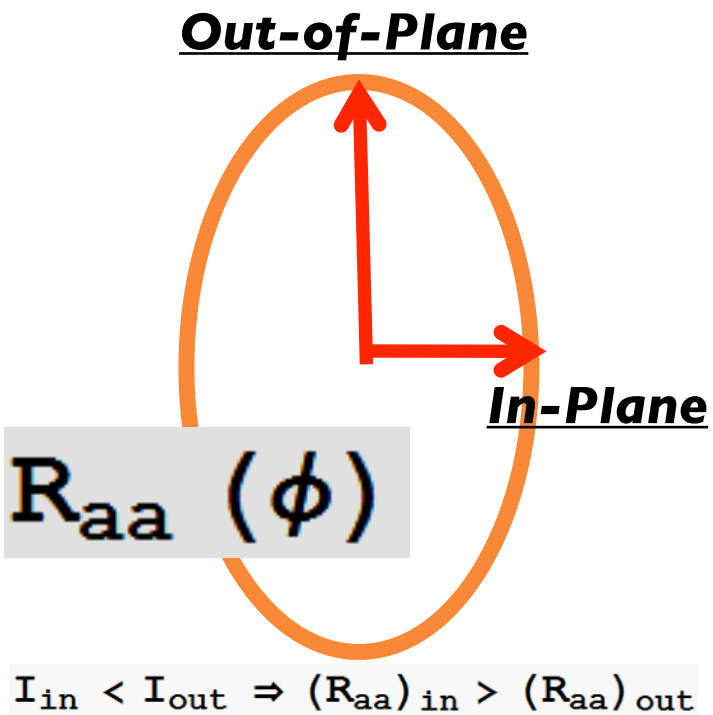
Jinfeng Liao and Edward Shuryak

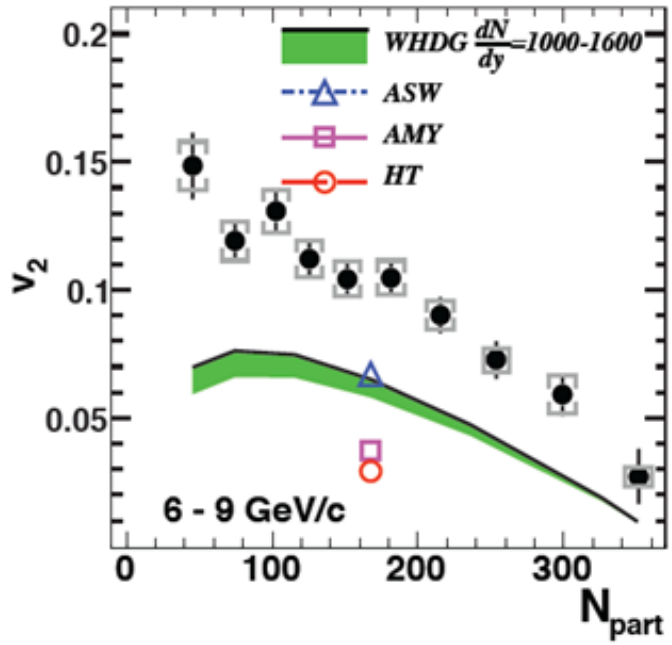
Density of Monopoles (SU(2) Pure gauge)



Magnetic Quenching of (Electric) q/g Jets

Magnetic component helps resolve a puzzle in jet energy loss!





Compilation of J.Jia, ~2008

PRL 102, 202302 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

Jinfeng Liao[1,2,*] and Edward Shuryak[1,†]
[1]*Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794, USA*
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

Magnetic Quenching of (Electric) q/g Jets

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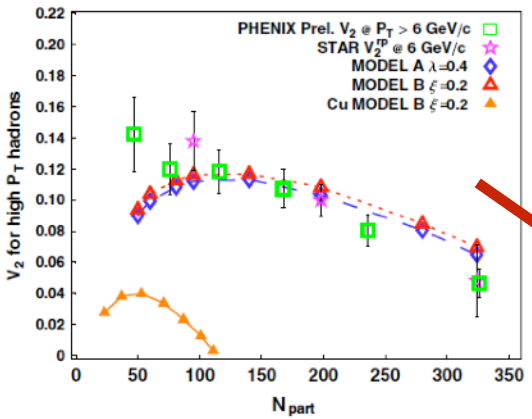
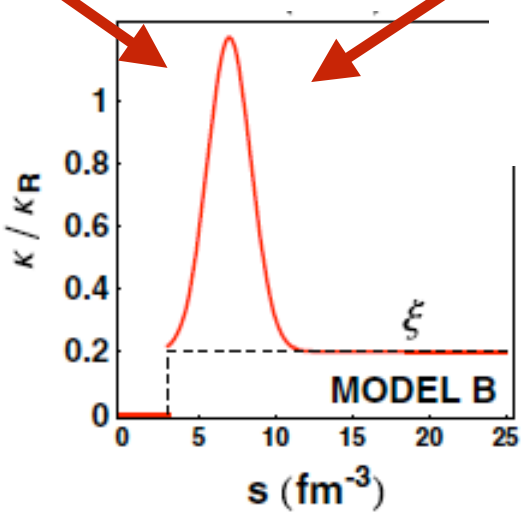
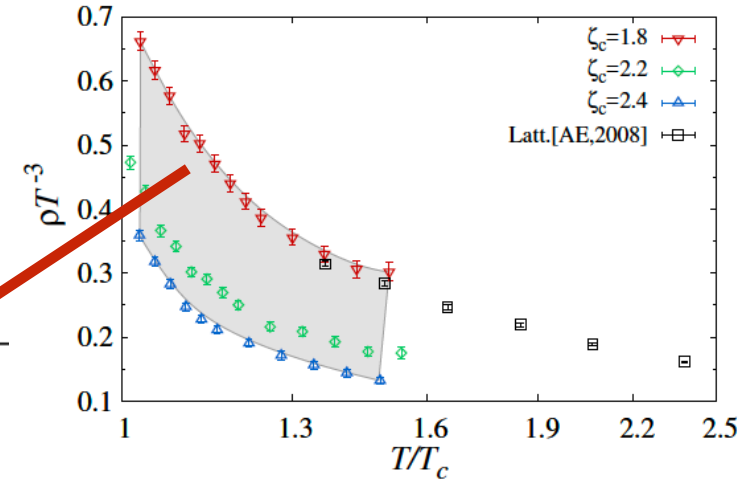






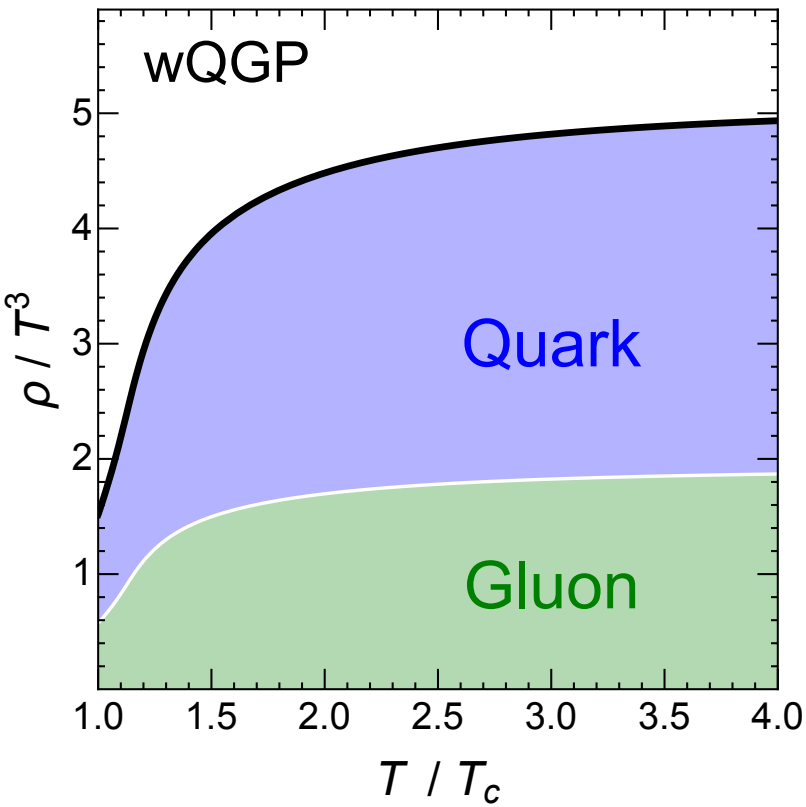
In the paper PRL(2009) we concluded:

"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

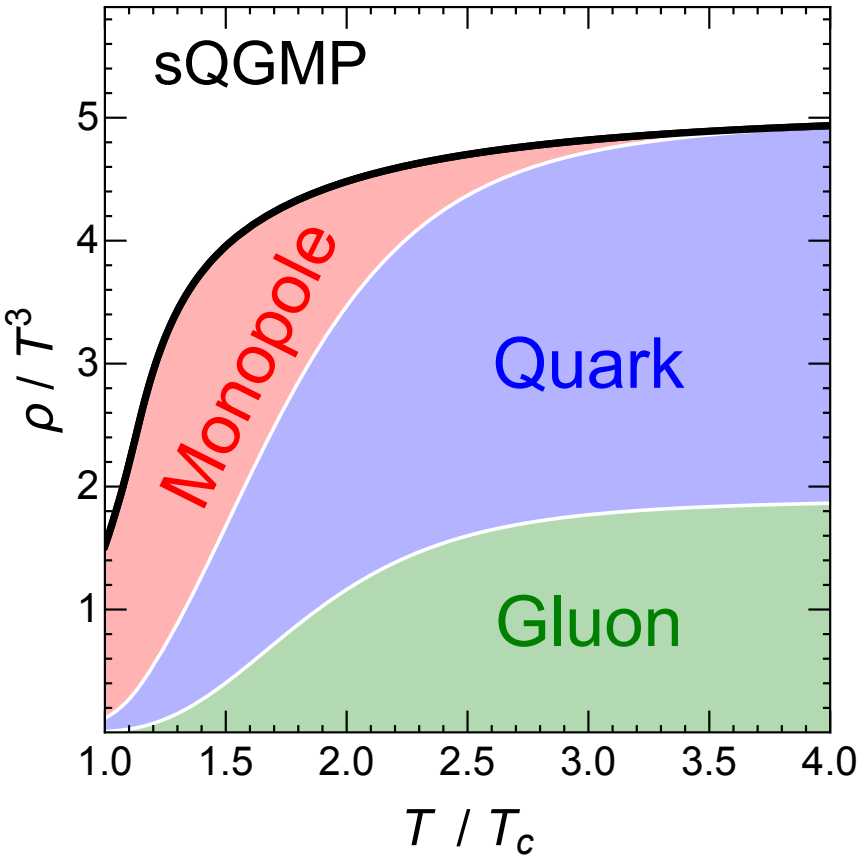
— Evidence for Magnetic DoFs!

sQGMP & CUJET3

CUJET3 based on semi-Quark-Gluon-Monopole Plasma (sQGMP)



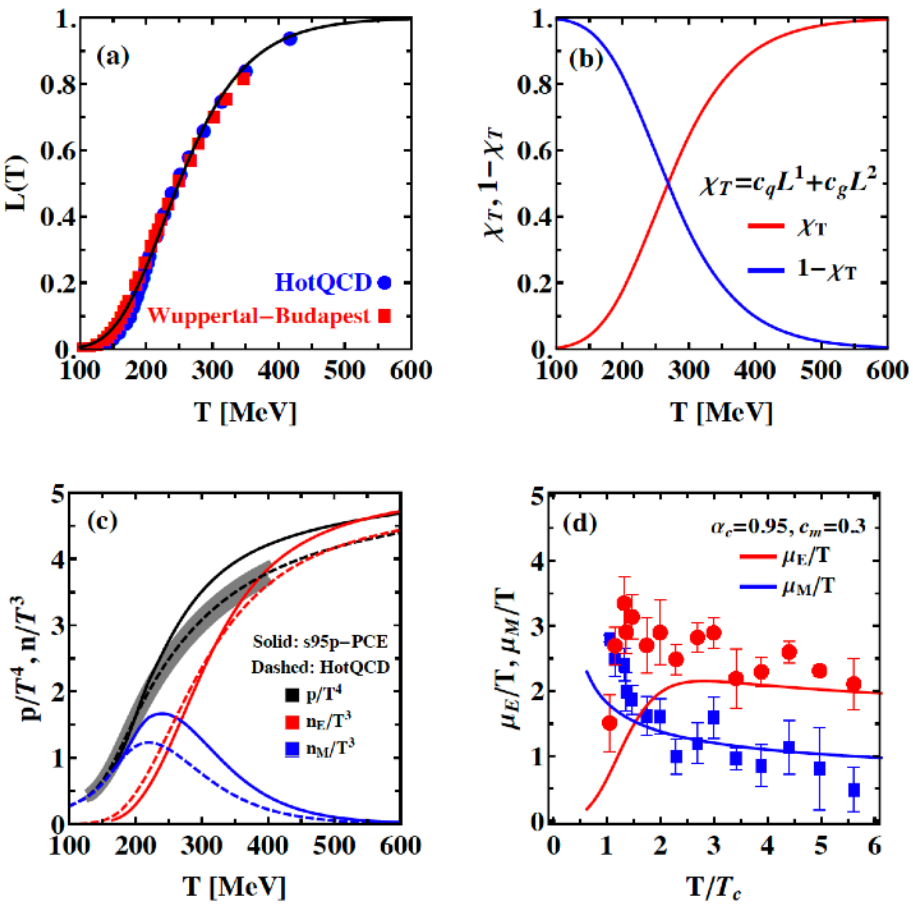
v.s.



CUJET2

CUJET3

sQGMP Construction



- E-den.: Polyakov-loop suppression

$$\rho_E/\rho = \chi_T = c_q L + c_g L^2$$

- M-den.: constrained by total entropy

$$\rho_M/\rho = 1 - \chi_T$$

- Running coupling:

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

- Screening:

$$f_E = \sqrt{\chi_T}\,, \qquad f_M = \boxed{c_m} g$$

- on top of VISHNU2+1 hydro bkg.

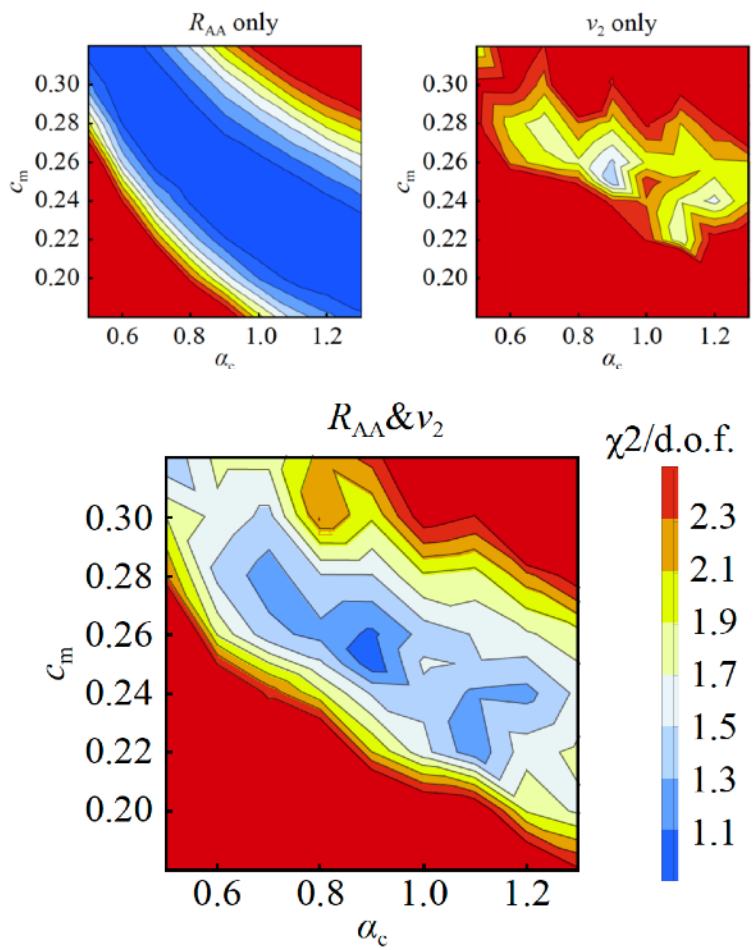
J. Xu, JL, M. Gyulassy, CPL2015; JHEP2016.
S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1804.01915; arXiv:1808.05461

Global Constraints with RHIC/LHC Data

Two key parameters in the CUJET3 model:

- α_c : running coupling $\alpha_s(q^2)$ @ $q = T_c$
- c_m : parameter for magnetic screening

12 sets of light flavor data



- 200 GeV Au-Au Collisions, 0%–10% Centrality Bin, $R_{AA}(\pi^0)$: PHENIX [40, 41];
- 200 GeV Au-Au Collisions, 0%–10% Centrality Bin, $v_2(\pi^0)$: PHENIX [41];
- 200 GeV Au-Au Collisions, 20%–30% Centrality Bin, $R_{AA}(\pi^0)$: PHENIX [40, 41];
- 200 GeV Au-Au Collisions, 20%–30% Centrality Bin, $v_2(\pi^0)$: PHENIX [41];
- 2.76 TeV Pb-Pb Collisions, 0%–10% Centrality Bin, $R_{AA}(h^\pm)$: ALICE [42];
- 2.76 TeV Pb-Pb Collisions, 0%–10% Centrality Bin, $v_2(h^\pm)$: ATLAS [43], CMS [44];
- 2.76 TeV Pb-Pb Collisions, 20%–30% Centrality Bin, $R_{AA}(h^\pm)$: ALICE [42];
- 2.76 TeV Pb-Pb Collisions, 20%–30% Centrality Bin, $v_2(h^\pm)$: ALICE [45], ATLAS [43], CMS [44];
- 5.02 TeV Pb-Pb Collisions, 0%–5% Centrality Bin, $R_{AA}(h^\pm)$: ATLAS-preliminary [34], CMS [35];
- 5.02 TeV Pb-Pb Collisions, 0%–5% Centrality Bin, $v_2(h^\pm)$: CMS [36];
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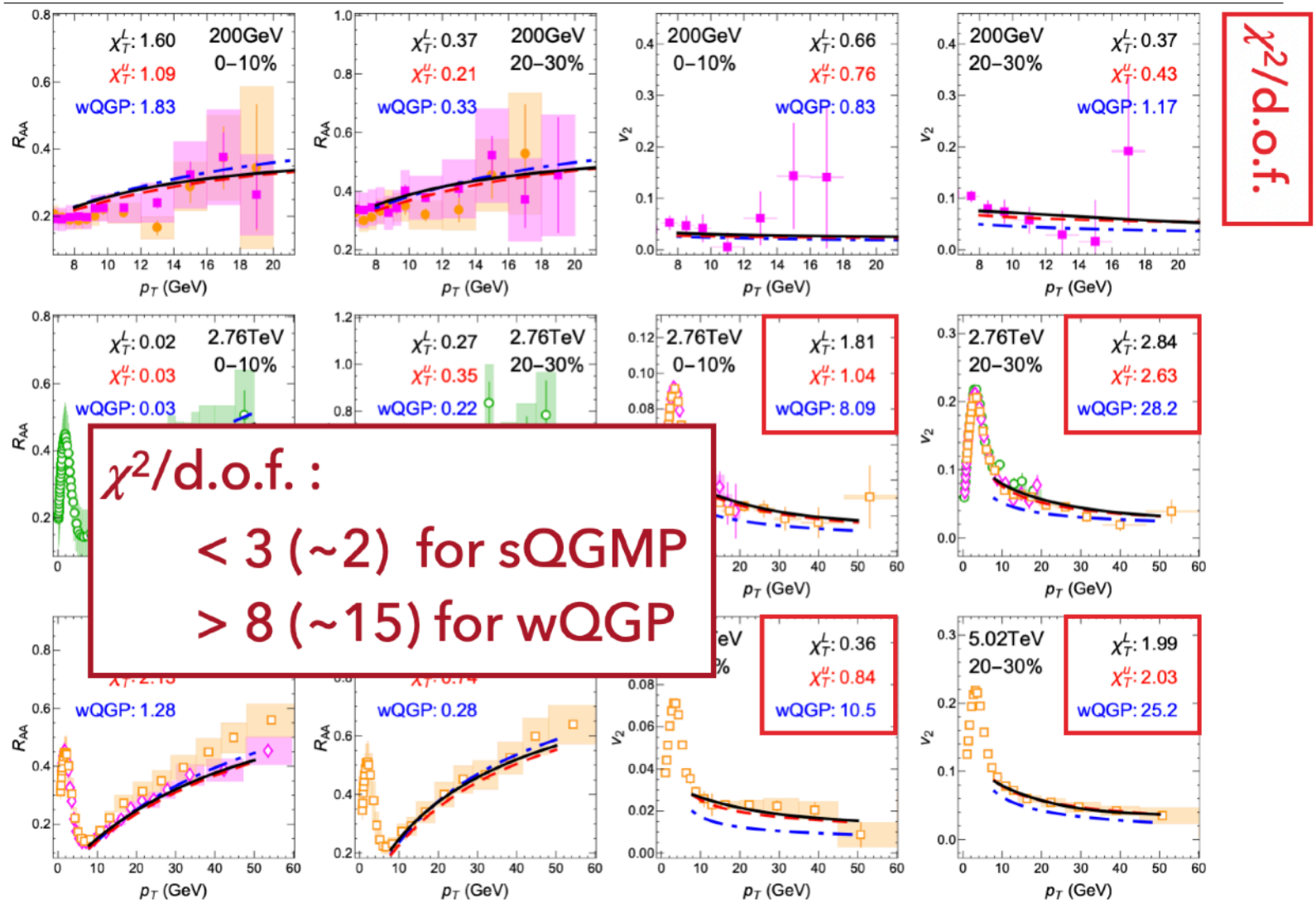
S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1804.01915; arXiv:1808.05461

Phenomenology with CUJET3



χ^2/d.o.f. :

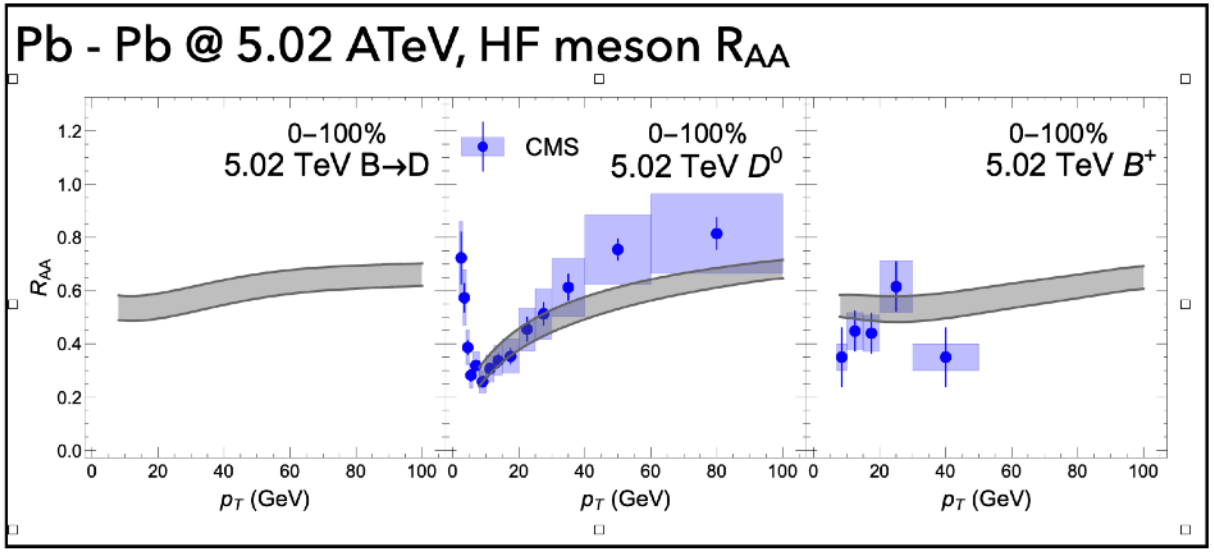
< 3 (~2) for sQGMP

> 8 (~15) for wQGP

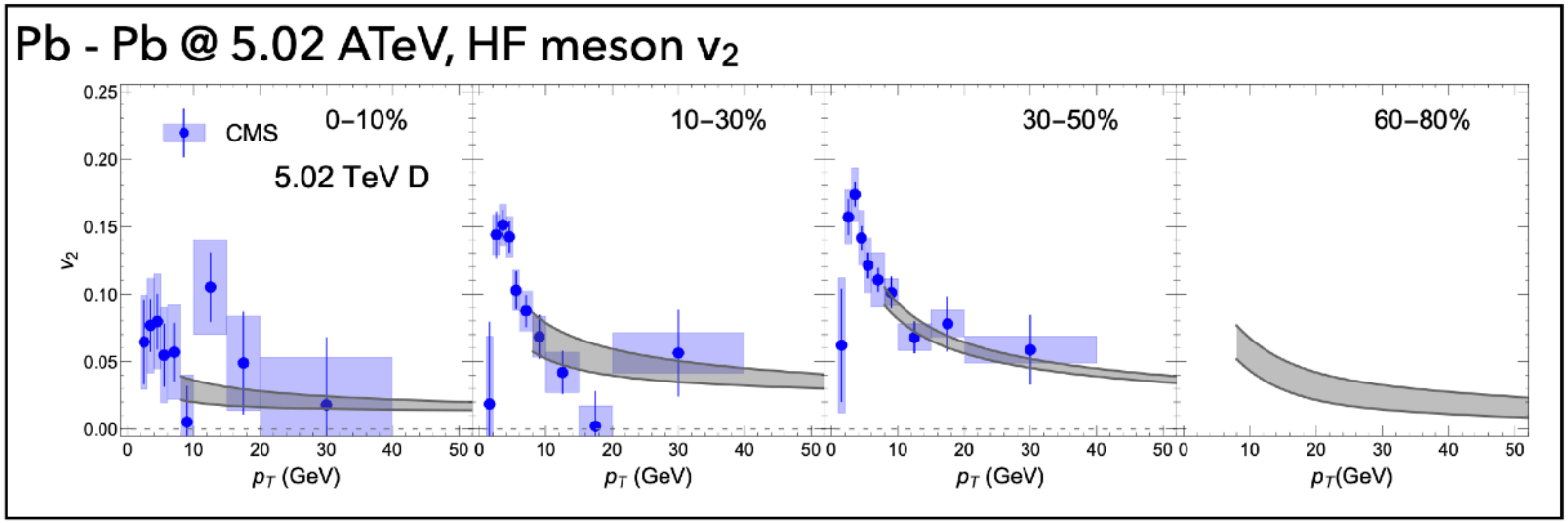
The magnetic component is crucial.

S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1804.01915; arXiv:1808.05461

Phenomenology with CUJET3

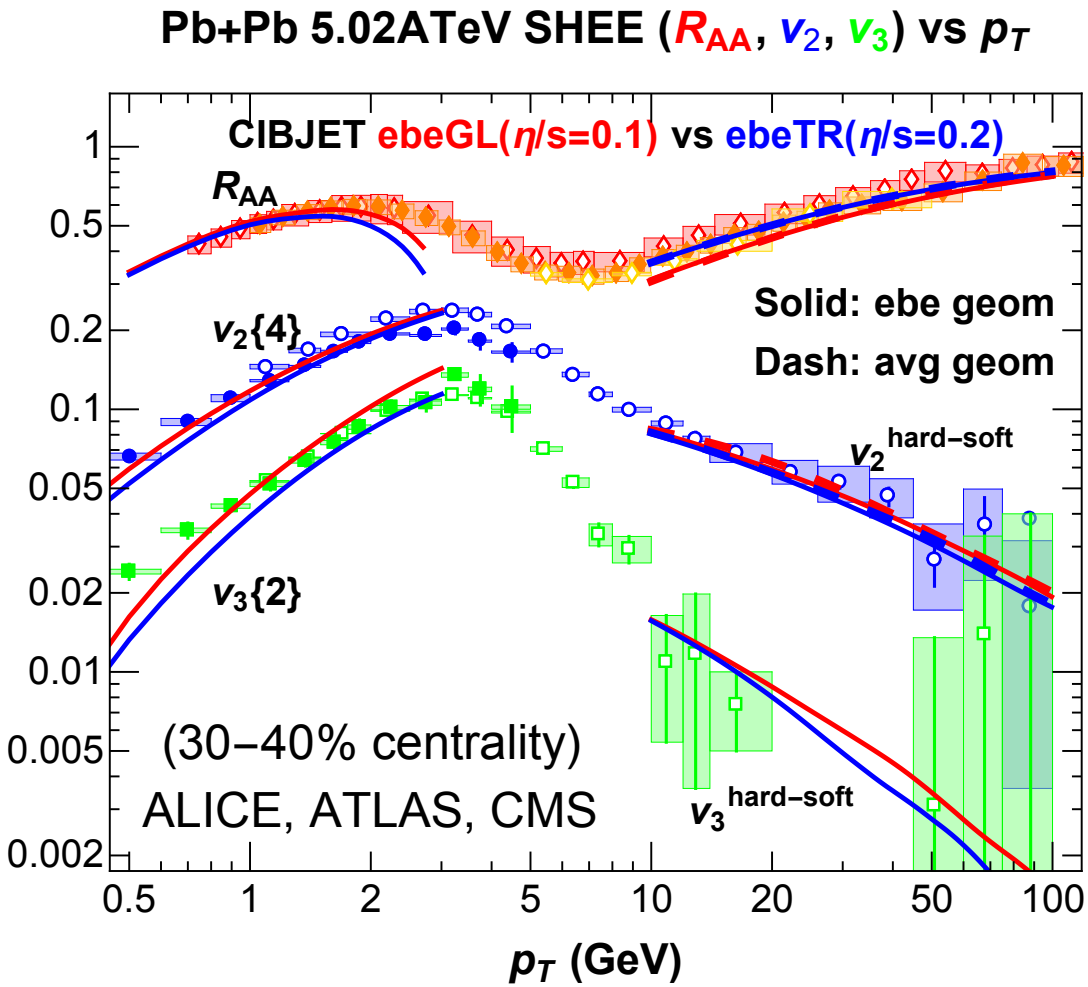


Independent test with heavy flavor observables



S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1804.01915; arXiv:1808.05461

Phenomenology with CUJET3

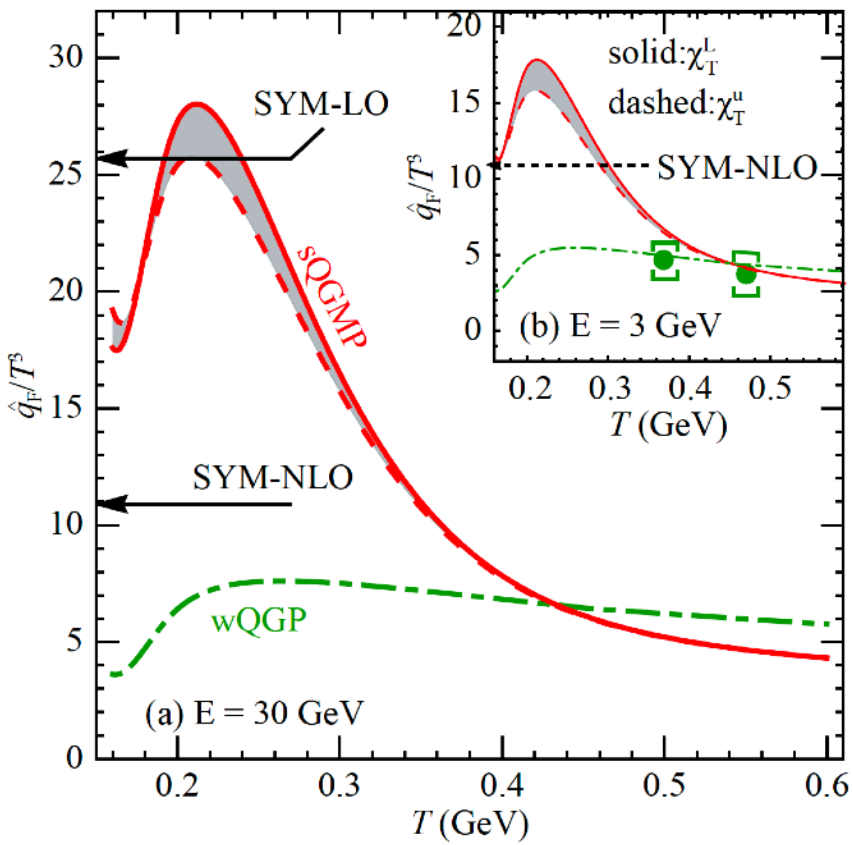


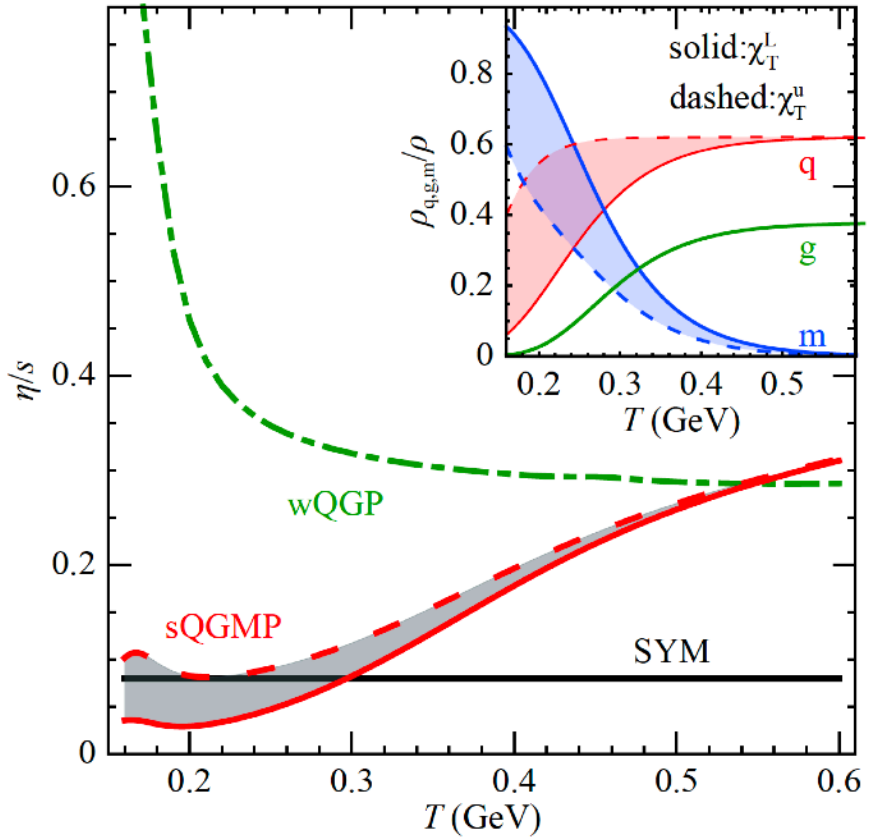
Consistent description of both soft and hard observables

S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1804.01915; arXiv:1808.05461

Transport Coefficients in CUJET3

CUJET3 based on semi-Quark-Gluon-Monopole Plasma (sQGMP)





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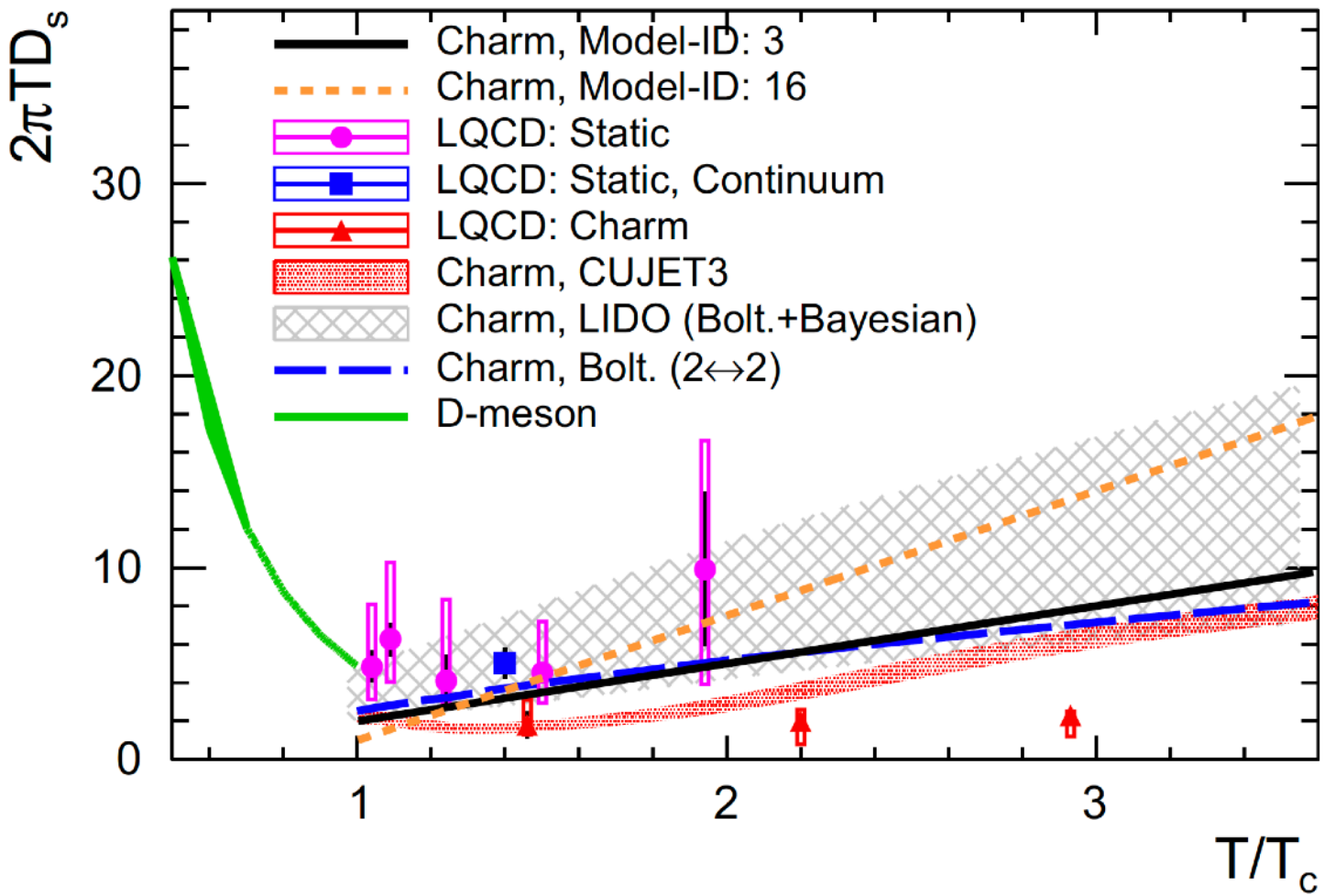

Plot taken from arXiv:1912.08965