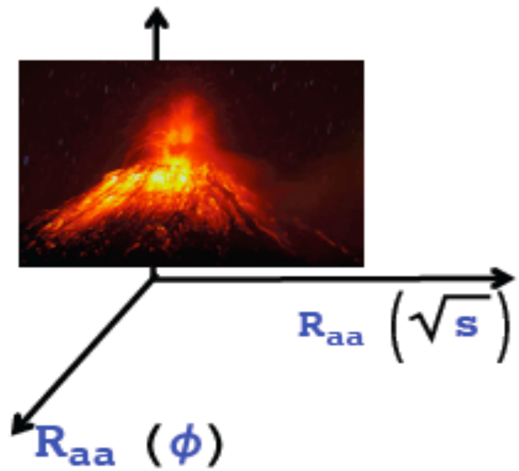
Quark Matter 2017
The 26th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
February 6-11, 2017, Chicago

Jet Quenching in a semi-Quark-Gluon Monopole Plasma: Light & Heavy Flavors Raa & V2 at RHIC & LHC



Jinfeng Liao
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Research Supported by NSF & DOE

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BEST COLLABORATION

The Making of CUJET3

Shuzhe Shi, Jiechen Xu, Jinfeng Liao, Miklos Gyulassy

Raa from RHIC to LHC

High Pt V2 Puzzle

Heavy Flavor Puzzle (CUJET1)

Monopole scenario

Semi-QGP

CUJET3: a simulation framework based on a microscopic picture of Semi-quark-gluon monopole plasma

The Making of CUJET3

Heavy Flavor Puzzle (CUJET1)

CUJET1: Buzzatti & Gyulassy 1106.3061
Including E & M screening; elastic+inelastic;
...

The Making of CUJET3

Raa from RHIC to LHC

Heavy Flavor Puzzle (CUJET1)

Surprising transparency: Horowitz-Gyulassy; Betz-Gyulassy; Zhang-Liao; …

CUJET2: Xu, Buzzatti, Gyulassy, 1402.2956
Including strong running coupling from RHIC to LHC; realistic bulk viscous hydro; …

The Making of CUJET3

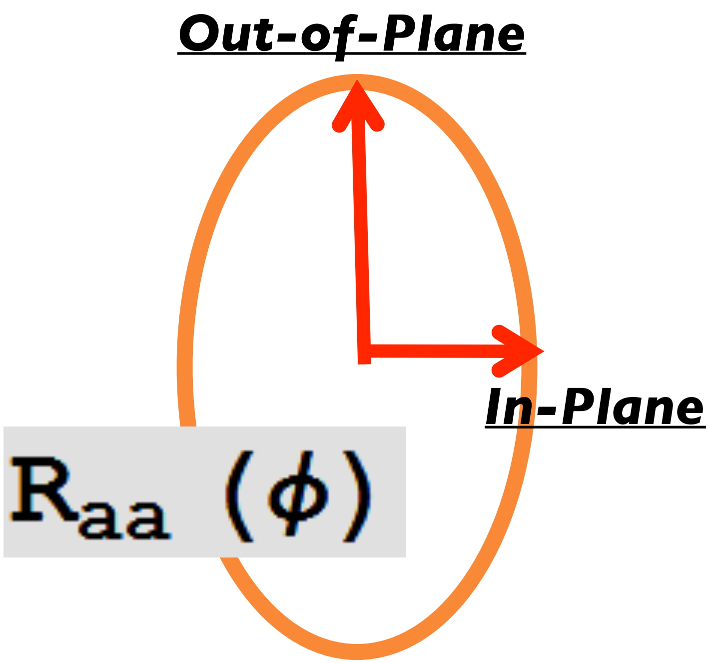
Raa from RHIC to LHC

High Pt V2 Puzzle

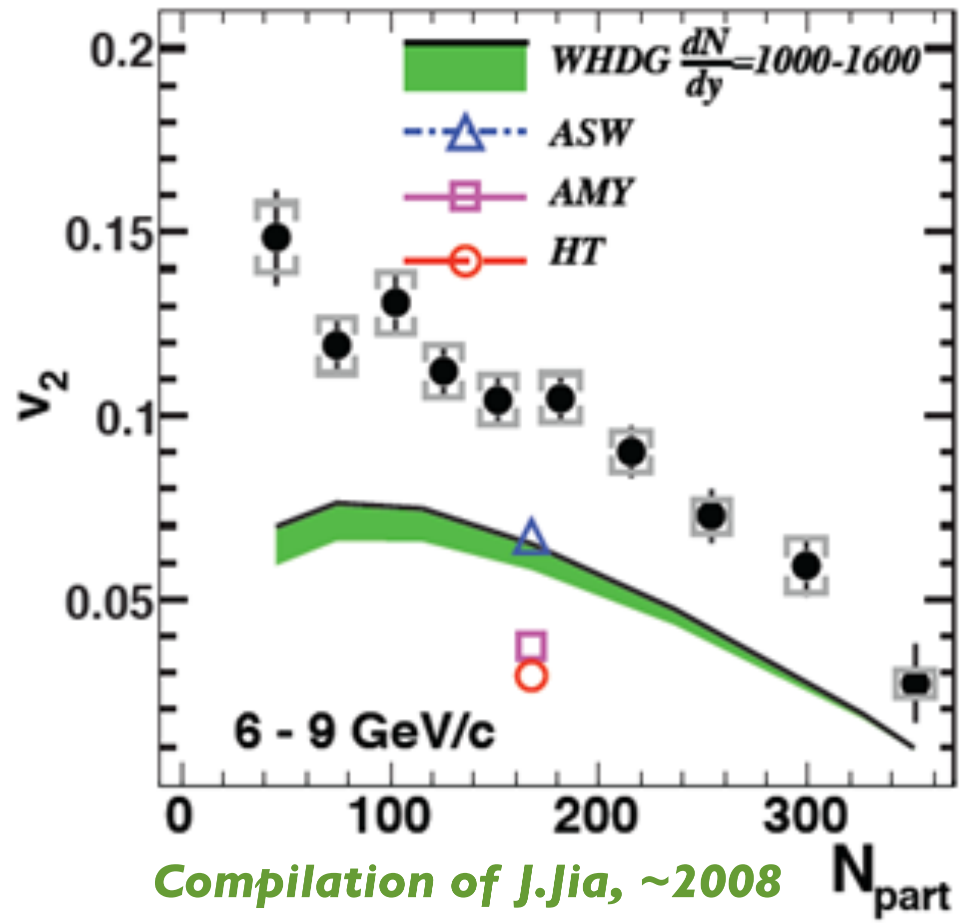
Heavy Flavor Puzzle (CUJET1)

High Pt V2 was a long standing challenge for nearly all models (including CUJET1 and CUJET2)

Geometric Tomography

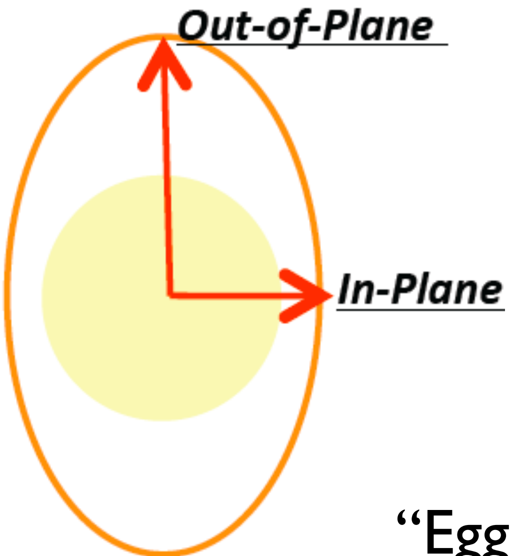


$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$



Till ~ 2008, there was clear discrepancy between accurate data and model predictions.

Where Are Jets Quenched (More Strongly)?



Taken for granted in all previous models: "waterfall" scenario.

We realized the puzzle may concern more radical questions:

Where are jets quenched (more strongly)?

Geometry is a sensitive feature:
"Egg yolk" has one geometry, "Egg white" has another.

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,†]
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[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)

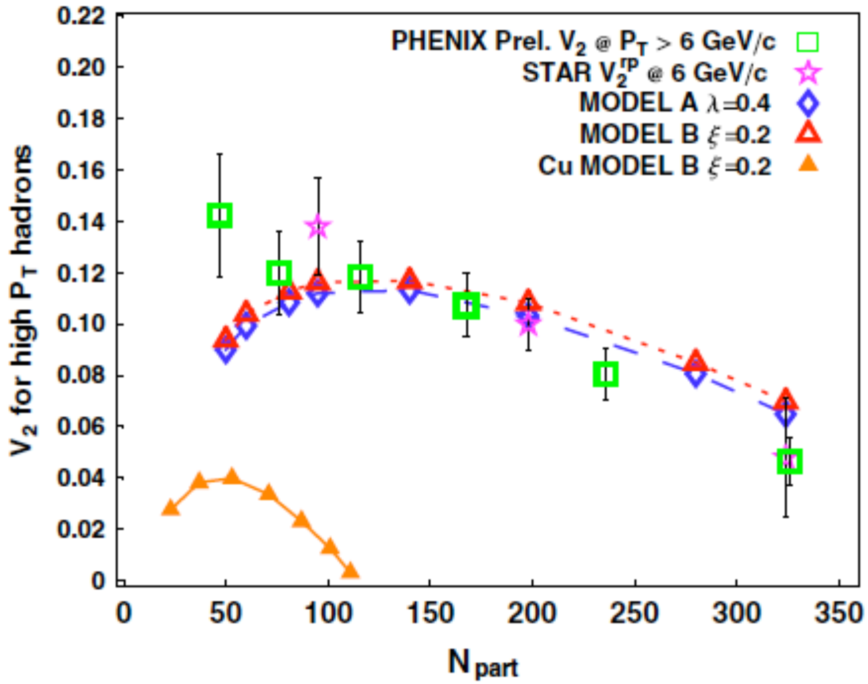
Near-Tc Enhancement of Jet-Medium Coupling

Three major findings:

(1) With fixed Raa, the jet v2 is VERY sensitive to the T-dependence of jet-medium coupling;

(2) Energy loss around Tc region enhances the jet v2;

(3) RHIC data suggests a very strong enhancement near Tc.



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."

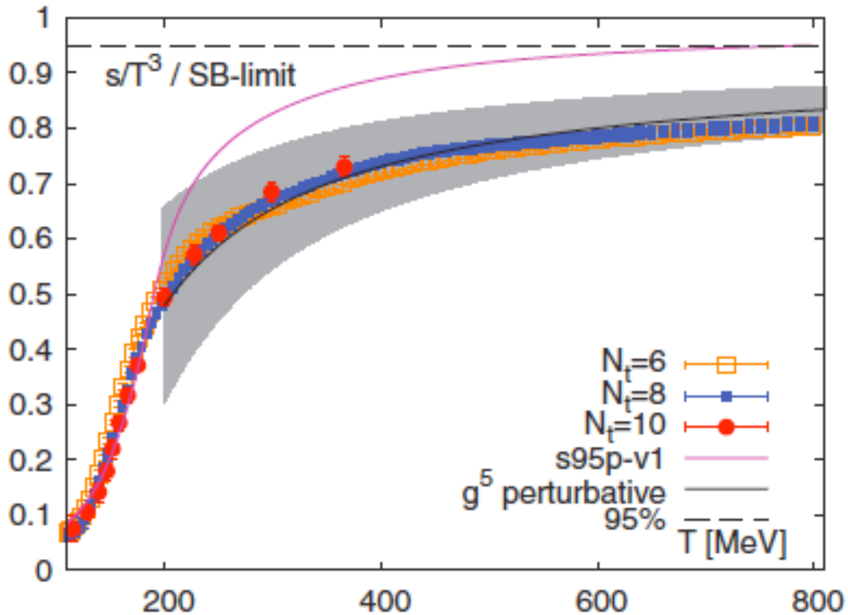
— Confirmed by many studies later!

Looking Under the Hood of sQGP

Some of us started a while ago to ask:
What makes the sQGP nearly prefect liquid?
In particular, what are the relevant degrees of freedom?

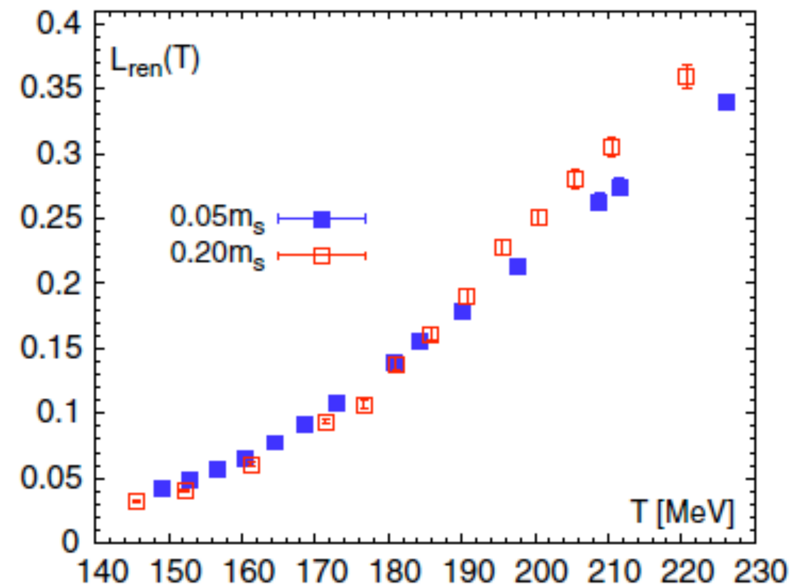
sQGP: A Plasma of Chromo E & M Charges

Liberation of Thermal DoF



Shuryak, Liao,...: this is a chromo-magnetic monopole plasma!

Degree of color liberation



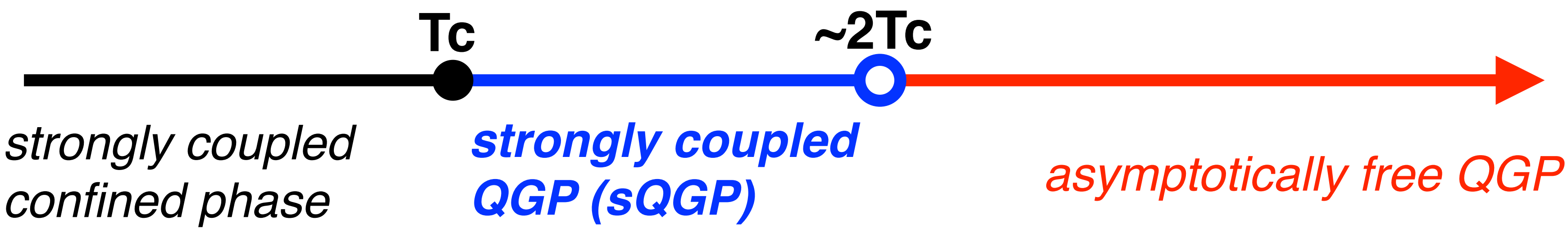
Pisarski, Hidaka, ...: this is a semi-QGP!

The two pictures are in complement, from Electric or Magnetic language respectively, and reconciled into one coherent picture.

sQGP: The Matter Just About to Be Confining

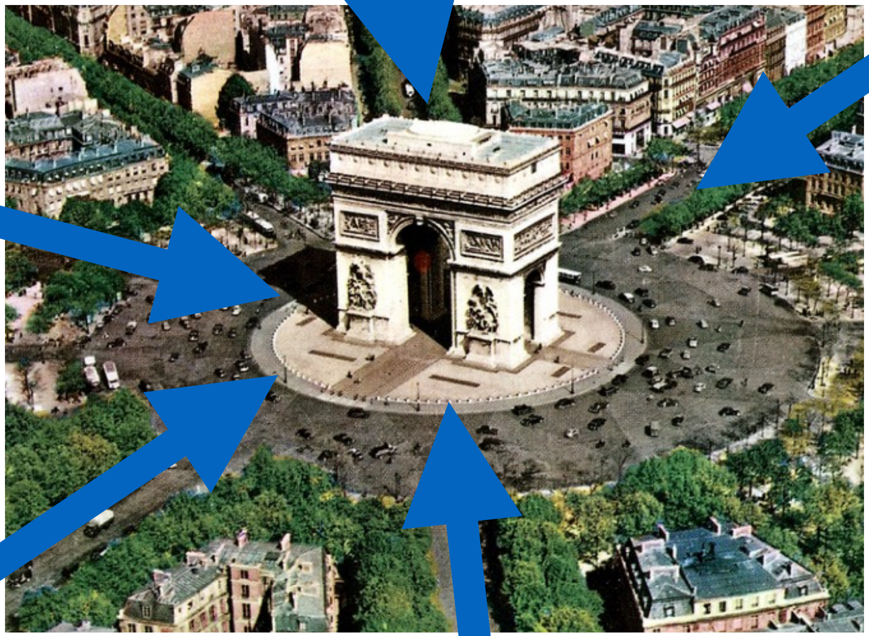
The old dream

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



The sQGP is a new emergent phase of QCD matter, with suppressed quarks/gluons and a significant monopole component: It naturally bridges the confined phase and wQGP!

The Making of CUJET3



CUJET3: a simulation framework based on a microscopic picture of Semi-quark-gluon monopole plasma

CUJET3: Semi-Quark-Gluon Monopole Plasma

CHIN. PHYS. LETT. Vol. 32, No. 9 (2015) 092501 Express Letter

Consistency of Perfect Fluidity and Jet Quenching in Semi-Quark-Gluon Monopole Plasmas *

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[1]*Department of Physics, Columbia University, New York 10027, USA*

[2]*Physics Department and CEEM, Indiana University, Bloomington 47408, USA*

[3]*RIKEN BNL Research Center, Bldg. 510A, Brookhaven National Laboratory, New York 11973, USA*

(Received 31 July 2015)

We utilize a new framework, CUJET3.0, to deduce the energy and temperature dependence of the jet transport parameter, $\hat{q}(E > 10\ \mathrm{GeV}, T)$*, from a combined analysis of available data on nuclear modification factor and azimuthal asymmetries from high energy nuclear collisions at RHIC/BNL and LHC/CERN. Extending a previous perturbative-QCD based jet energy loss model (known as CUJET2.0) with (2+1)D viscous hydrodynamic bulk evolution, this new framework includes three novel features of nonperturbative physics origin: (i) the Polyakov loop suppression of color-electric scattering (aka 'semi-QGP' of Pisarski et al.), (ii) the enhancement of jet scattering due to emergent magnetic monopoles near* T_c *(aka 'magnetic scenario' of Liao and Shuryak), and (iii) thermodynamic properties constrained by lattice QCD data. CUJET3.0 reduces to v2.0 at high temperatures* $T > 400$ *MeV, while greatly enhances* $\hat{q}$ *near the QCD deconfinement transition temperature range. This enhancement accounts well for the observed elliptic harmonics of jets with* $p_T > 10$ *GeV. Extrapolating our data-constrained* $\hat{q}$ *down to thermal energy scales,* $E \sim 2$ *GeV, we find for the first time a remarkable consistency between high energy jet quenching and bulk perfect fluidity with* $\eta/s \sim T^3/\hat{q} \sim 0.1$ *near* T_c*.*

PACS: 25.75.−q, 12.38.Mh, 24.85.+p, 13.87.−a DOI: 10.1088/0256-307X/32/9/092501

Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0

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[b]*Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 North Milo B. Sampson Lane, Bloomington, IN 47408, U.S.A.*

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JHEP02(2016)169

A Sophisticated Simulation Framework

DGLV-CUJET framework for describing multi-parton scattering:

$$x_E \frac{dN_g^{n=1}}{dx_E} = \frac{18C_R}{\pi^2} \frac{4+N_f}{16+9N_f} \int d\tau \; n(\mathbf{z})\Gamma(\mathbf{z}) \int d^2k$$
$$\times \alpha_s\left(\frac{\mathbf{k}^2}{x_+(1-x_+)}\right) \int d^2q \frac{\alpha_s^2(\mathbf{q}^2)}{\mu^2(\mathbf{z})} \frac{f_E^2\mu^2(\mathbf{z})}{\mathbf{q}^2(\mathbf{q}^2+f_E^2\mu^2(\mathbf{z}))}$$
$$\times \frac{-2(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})} \left[\frac{\mathbf{k}}{\mathbf{k}^2+\chi^2(\mathbf{z})} - \frac{(\mathbf{k}-\mathbf{q})}{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}\right]$$
$$\times \left[1-\cos\left(\frac{(\mathbf{k}-\mathbf{q})^2+\chi^2(\mathbf{z})}{2x_+E}\tau\right)\right] \left(\frac{x_E}{x_+}\right) \left|\frac{dx_+}{dx_E}\right| \; . \quad ($$

Original DGLV formalism has only quark/gluon scattering centers

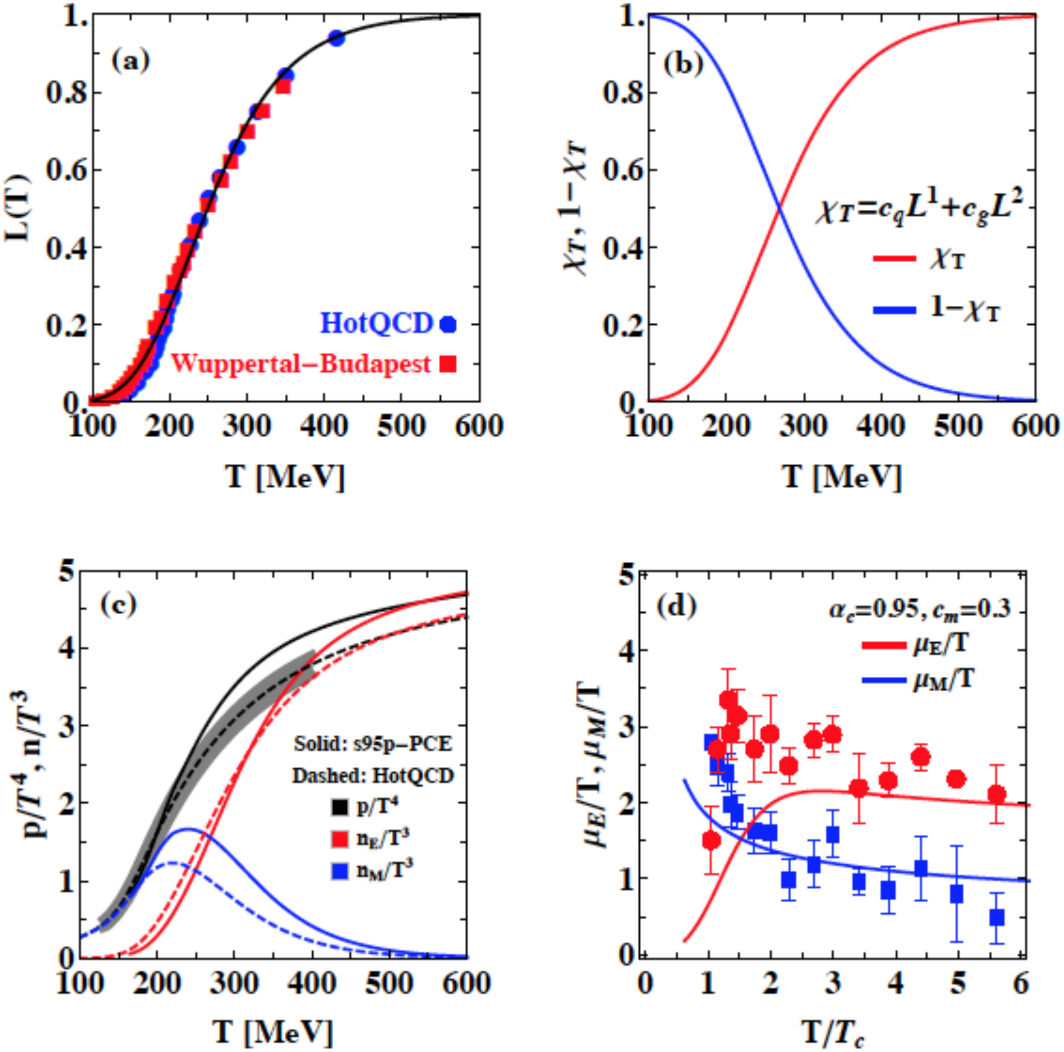
We now include both color-electric and color-magnetic scattering centers.

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

Our goal is to implement the nonperturbative NEAR-Tc Physics
—> CUJET3.0

Xu, JL, Gyulassy, arXiv:1411.3673

The Making of sQGP in CUJET3.0



* *Electric density:*
L-loop suppression

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

* *Magnetic density:*
constrained by total pressure

$$(1 - \chi_T)$$

* *Running coupling:*

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

* *Screening:*

$$f_E(T) = \sqrt{\chi_T} \quad , \quad f_M(T) = c_m\, g$$

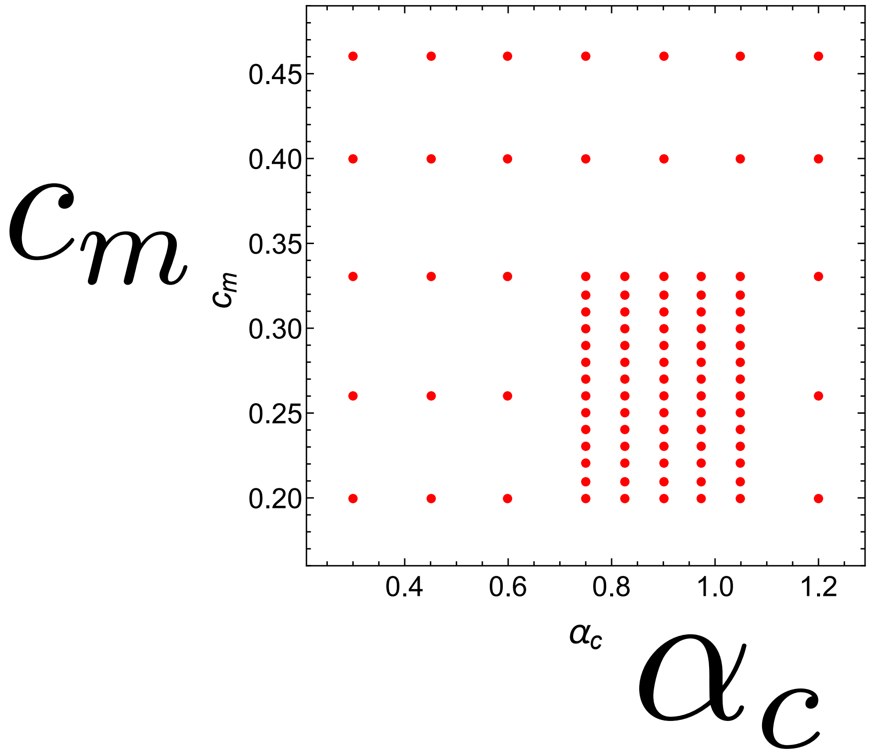
The model implementations of electric and magnetic components are carefully **constrained by available lattice data.**

[Xu, JL, Gyulassy, arXiv:1411.3673(CPL); 1508.00552(JHEP)]

Systematic Calibration of CUJET3

Using light hadron Raa and v2
at RHIC200GeV, LHC2.76TeV, LHC5.02TeV
with central and semi-central collisions.

We constrain the two key parameters of sQGMP
by a chi-square analysis.

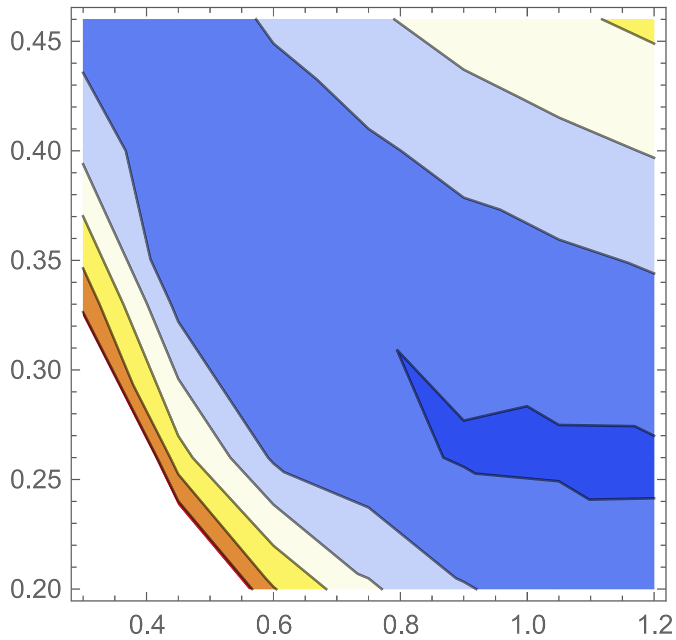


[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

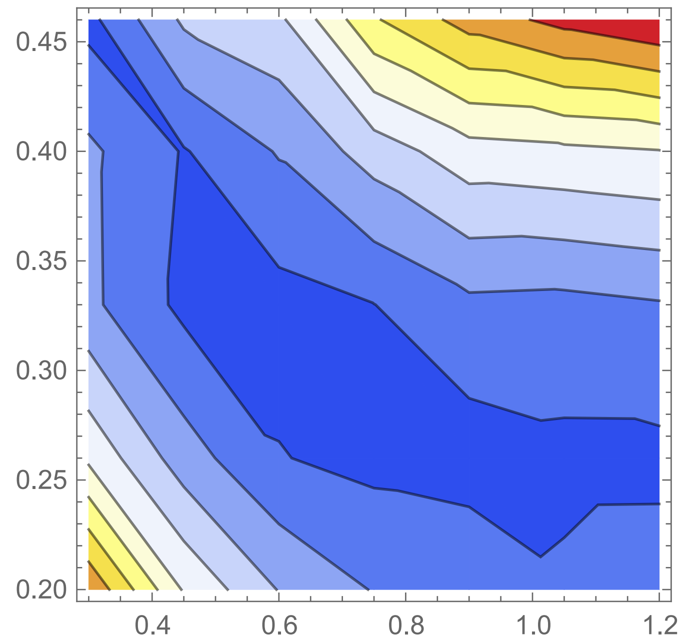
Systematic Calibration of CUJET3

Chi-square map on the parameter plane

Only central Raa



plus semi-central Raa and v2



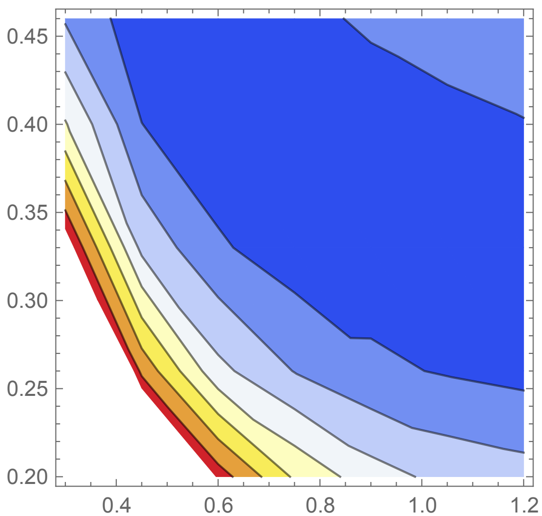
Different set of data show different sensitivity in constraining parameters.

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

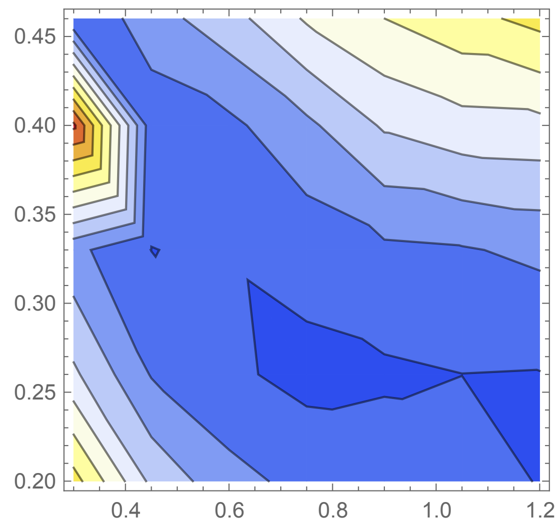
Systematic Calibration of CUJET3

Chi-square map on the parameter plane

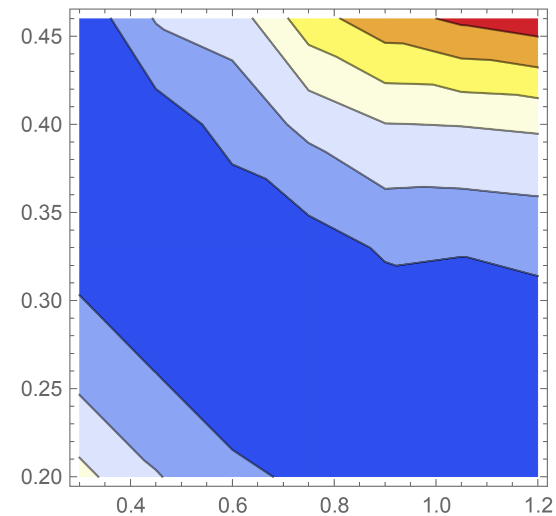
Only RHIC



Only LHC2.76TeV



Only LHC5.02TeV

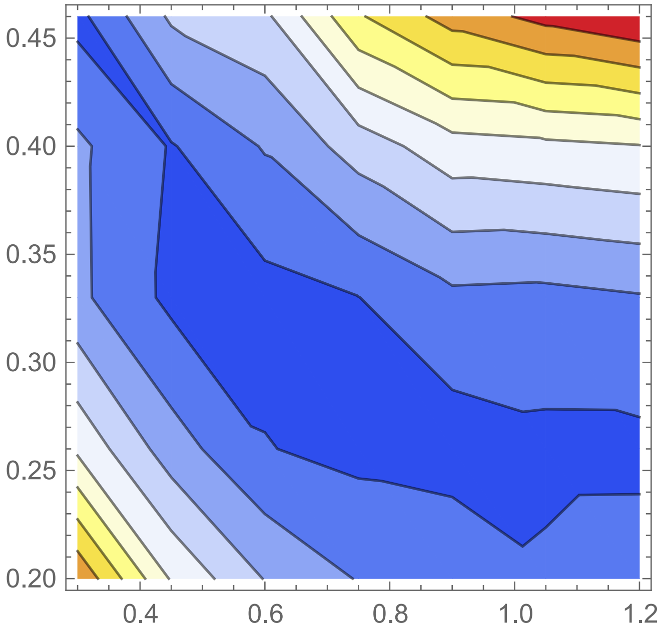


Different set of data show different sensitivity in constraining parameters.

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Systematic Calibration of CUJET3

Chi-square map on the parameter plane



Optimized choice of parameters:

$$\alpha_c = 0.9 \quad c_m = 0.26$$

Model uncertainty band

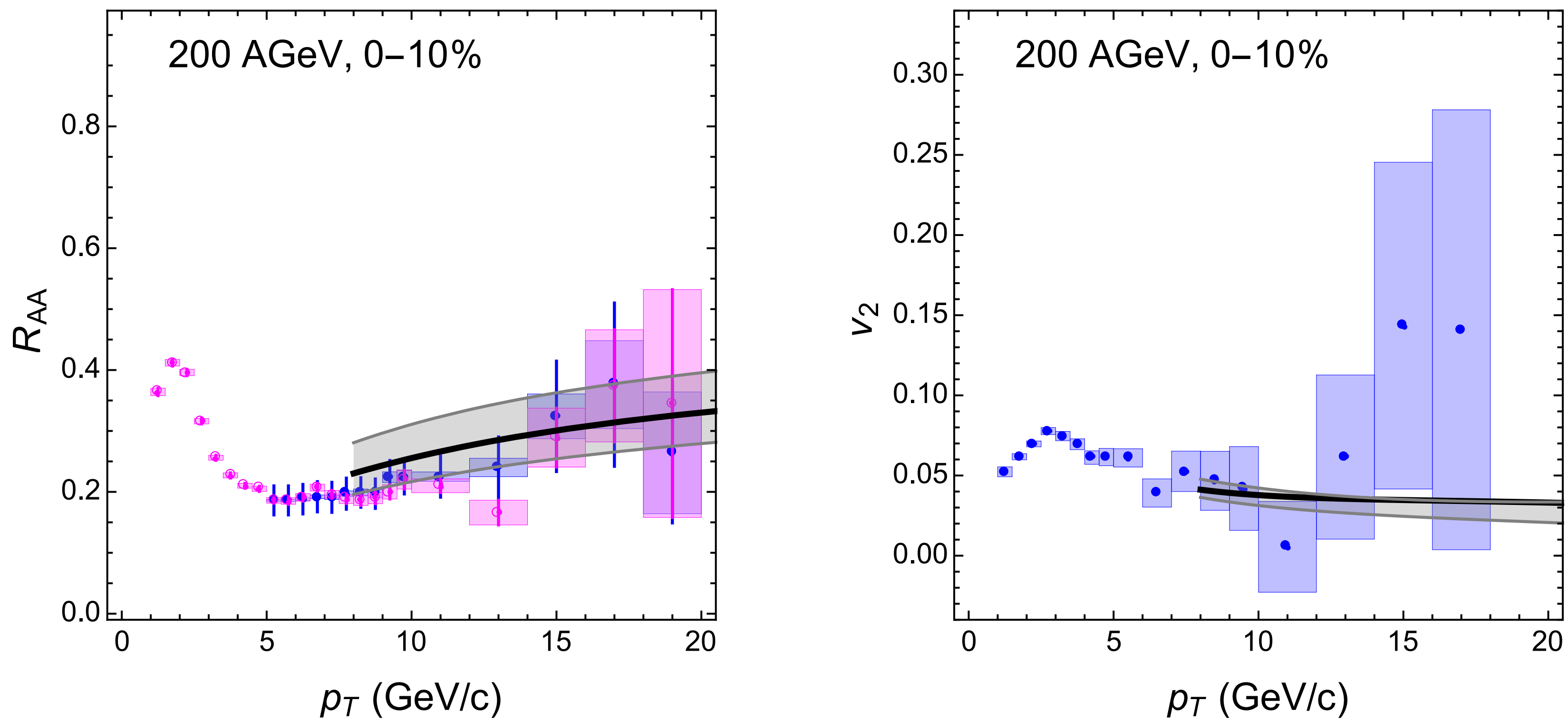
$$\alpha_c = 0.75 \quad c_m = 0.22$$

$$\alpha_c = 1.05 \quad c_m = 0.30$$

[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Systematic Calibration of CUJET3

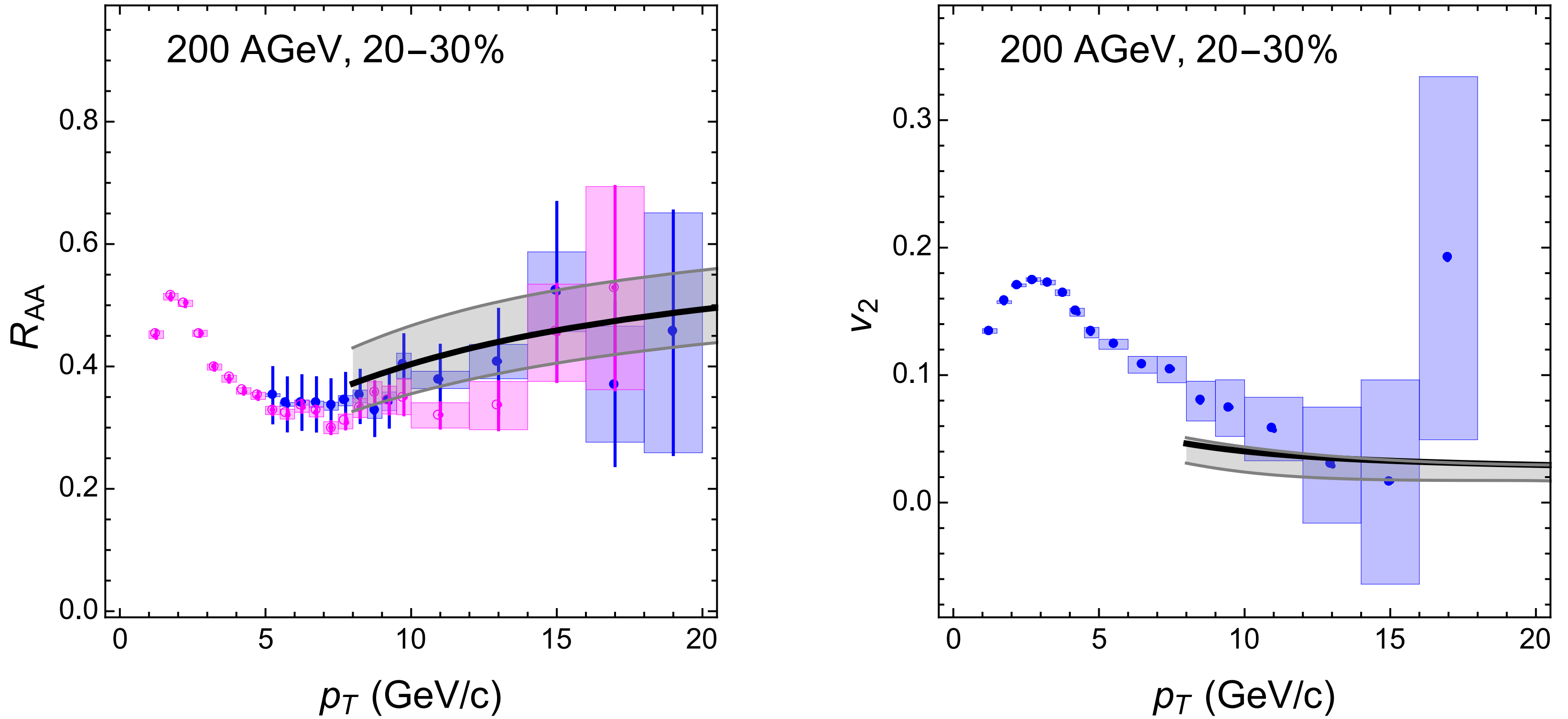
Optimized parameters: Comparison with RHIC200GeV [PHENIX data]



[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Systematic Calibration of CUJET3

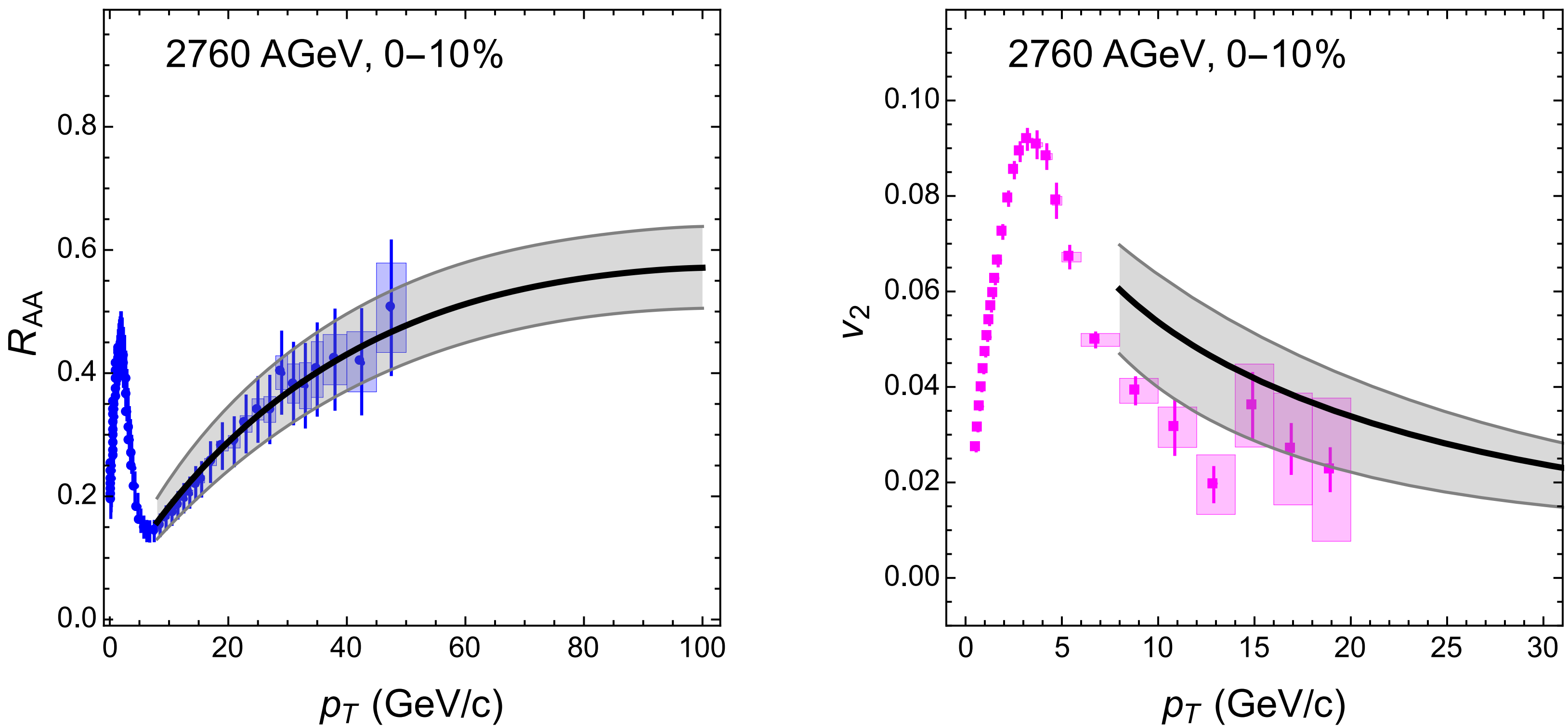
Optimized parameters: Comparison with RHIC200GeV [PHENIX data]



[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Systematic Calibration of CUJET3

Optimized parameters: Comparison with LHC2.76TeV [ALICE Raa; ATLAS V2]



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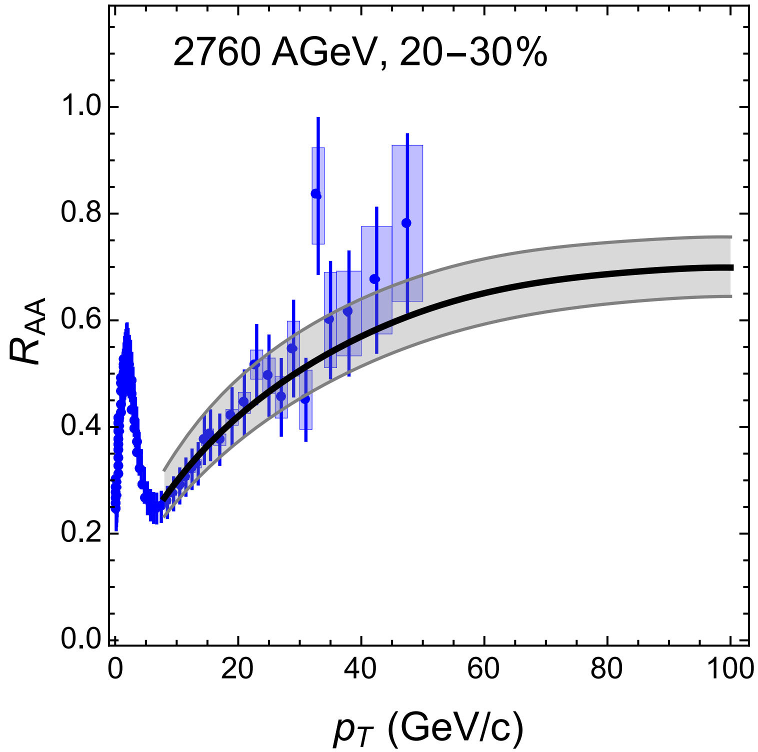
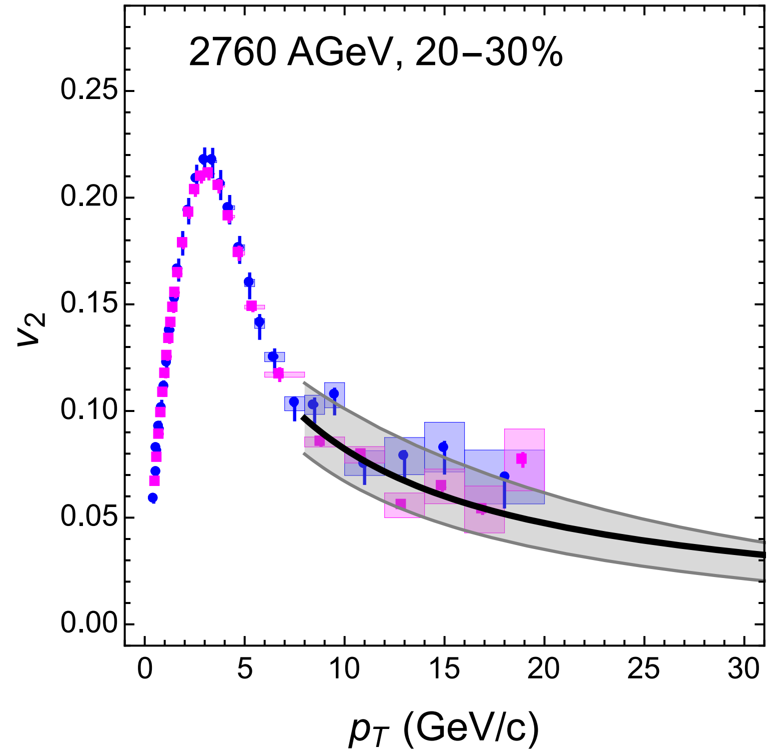
Systematic Calibration of CUJET3

Optimized parameters: Comparison with LHC2.76TeV [ALICE Raa; ATLAS V2]

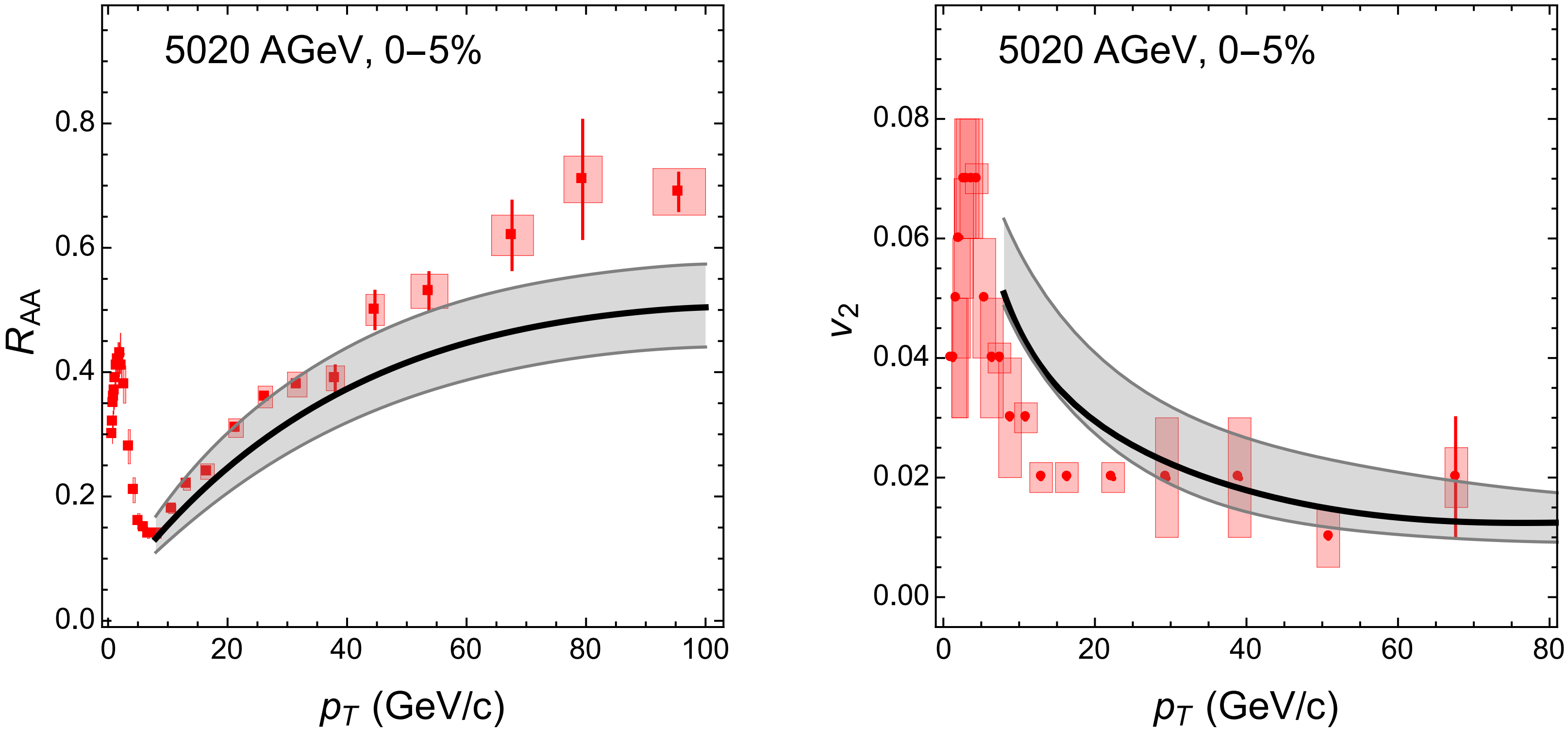




[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Systematic Calibration of CUJET3

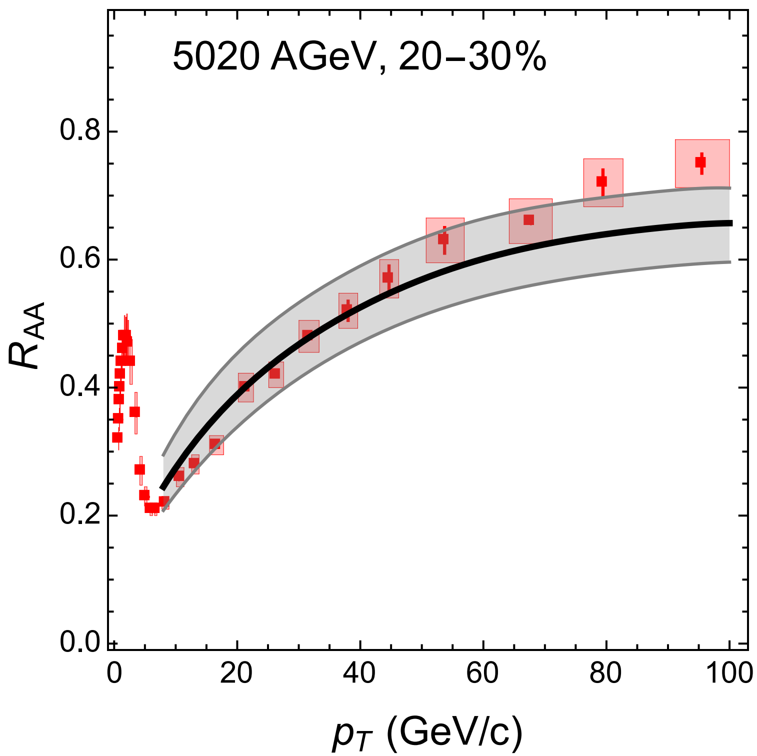
Optimized parameters: Comparison with LHC5.02TeV [CMS data]

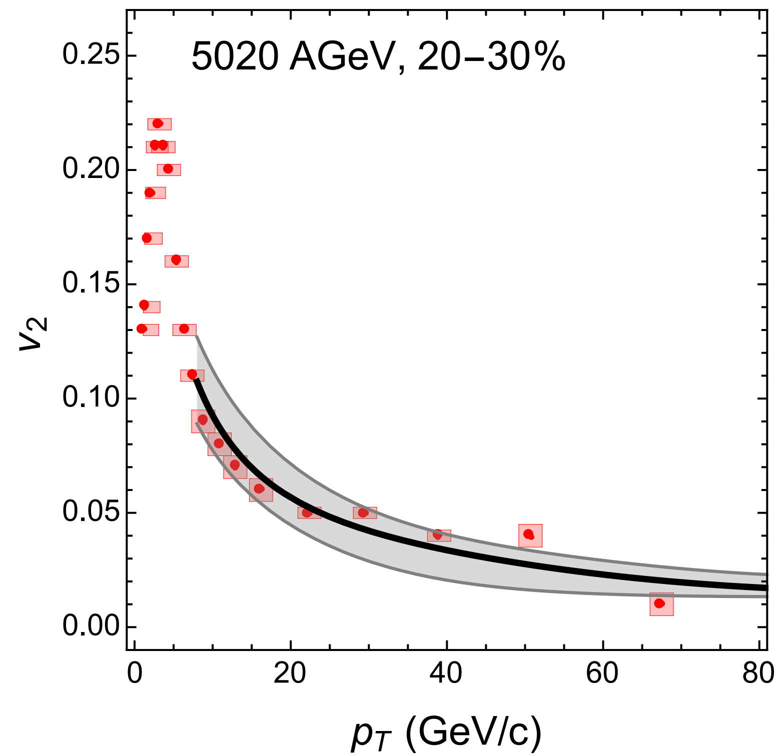


[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Systematic Calibration of CUJET3

Optimized parameters: Comparison with LHC5.02TeV [CMS data]



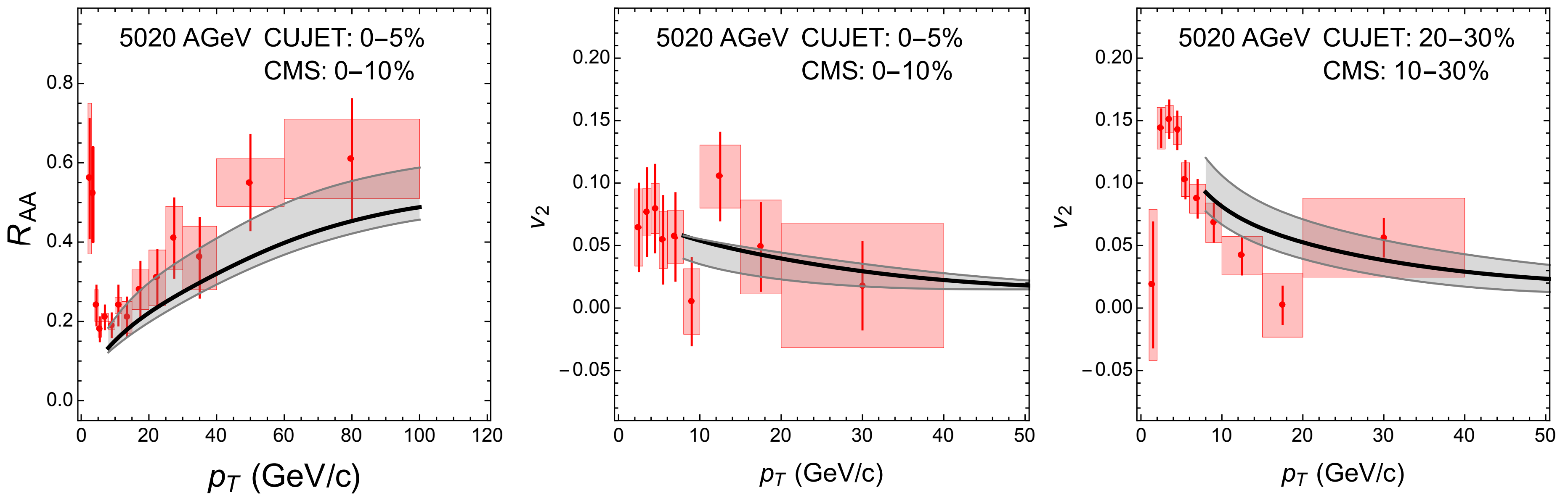


[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Independent Test with Heavy Flavor

The HF serves as an independent test:
These data are NOT part of model parameter calibration.

D0 Raa and v2 compared with CMS at LHC5.02TeV

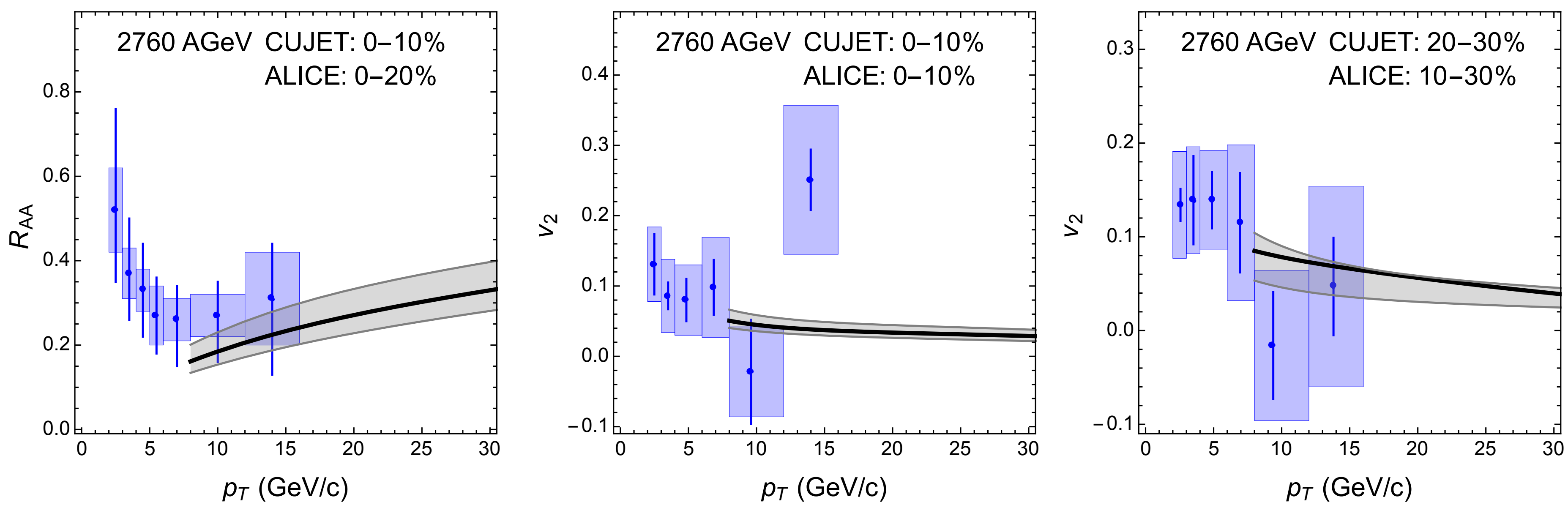


[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Independent Test with Heavy Flavor

The HF serves as an independent test:
These data are NOT part of model parameter calibration.

D0 Raa and v2 compared with ALICE at LHC2.76TeV

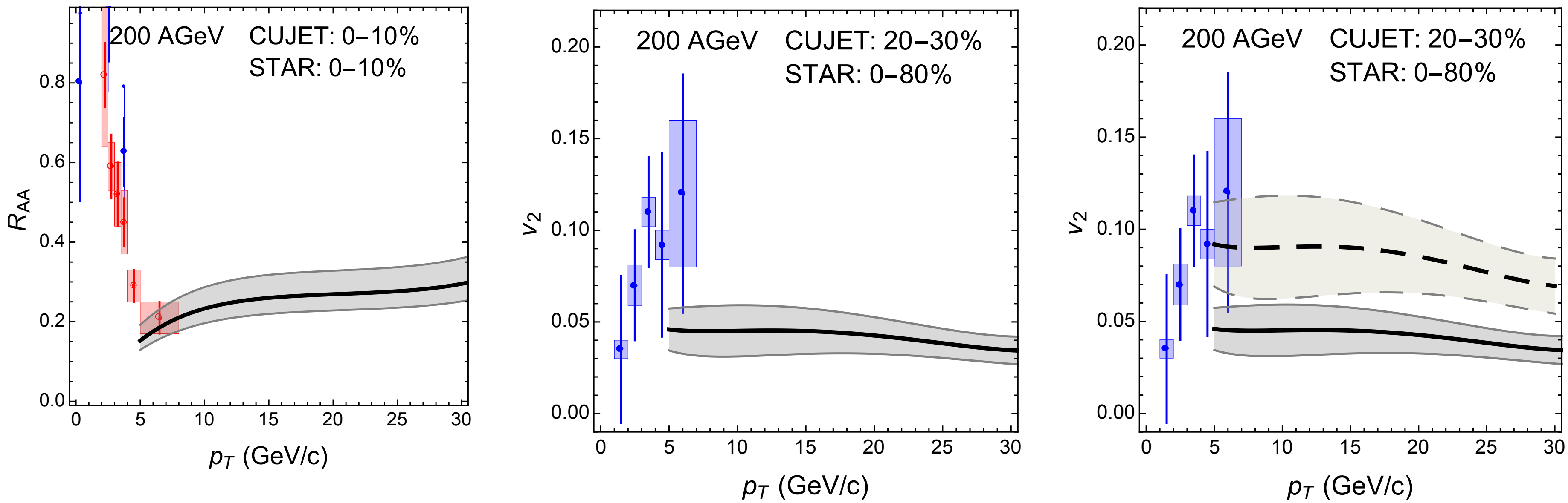


[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Independent Test with Heavy Flavor

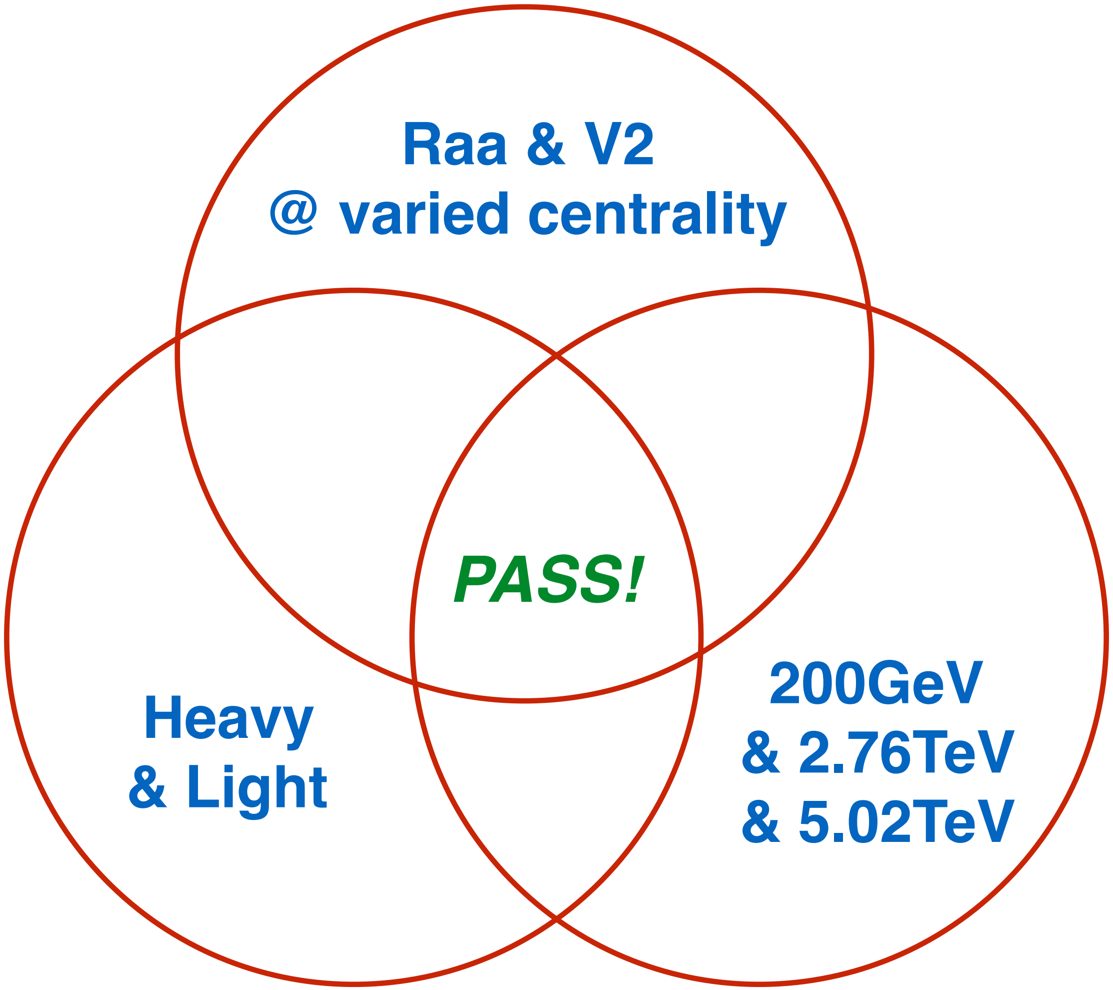
The HF serves as an independent test:
These data are NOT part of model parameter calibration.

D0 Raa and v2 compared with STAR at RHIC200GeV



[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

The Challenge to Every Model



CUJET3 has passed this challenge.

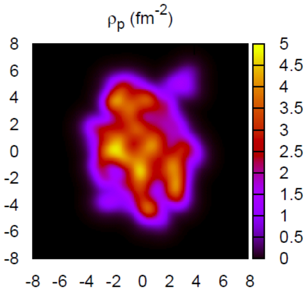
Look forward to every model taking up this challenge.

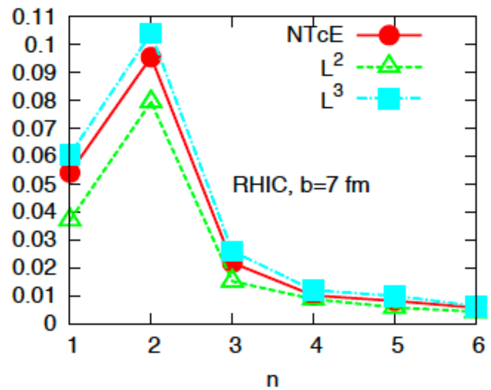
Event-by-Event Jet Quenching

Harmonic Jet Tomography

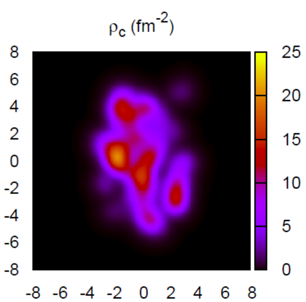
Event-by-event azimuthal anisotropy of jet quenching in relativistic heavy ion collisions

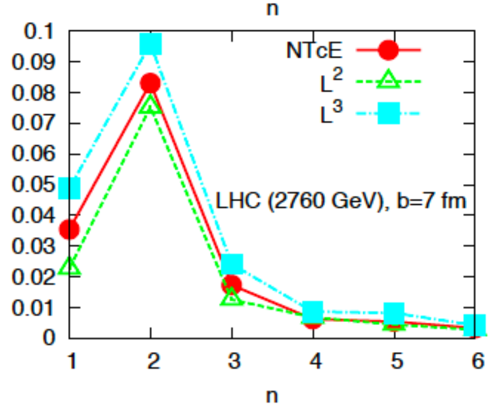
Xilin Zhang[1,3*] and Jinfeng Liao[1,2†]

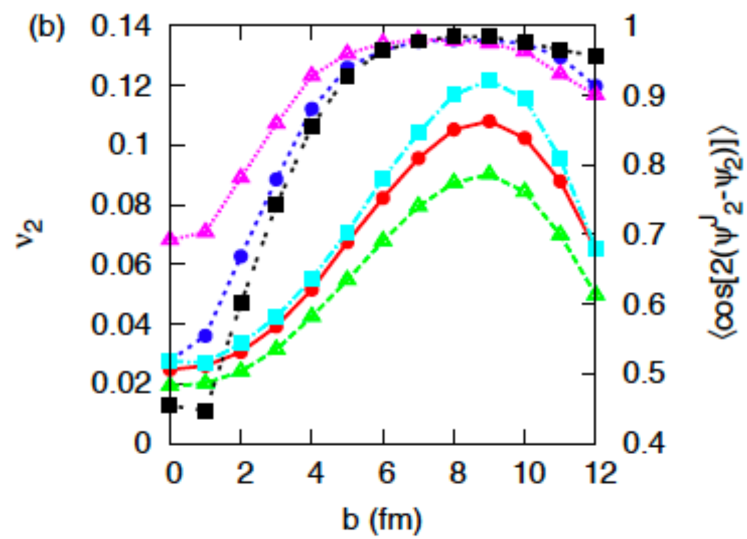




$$R_{AA}(\phi) = R_{AA}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \psi_n^J)]\right)$$



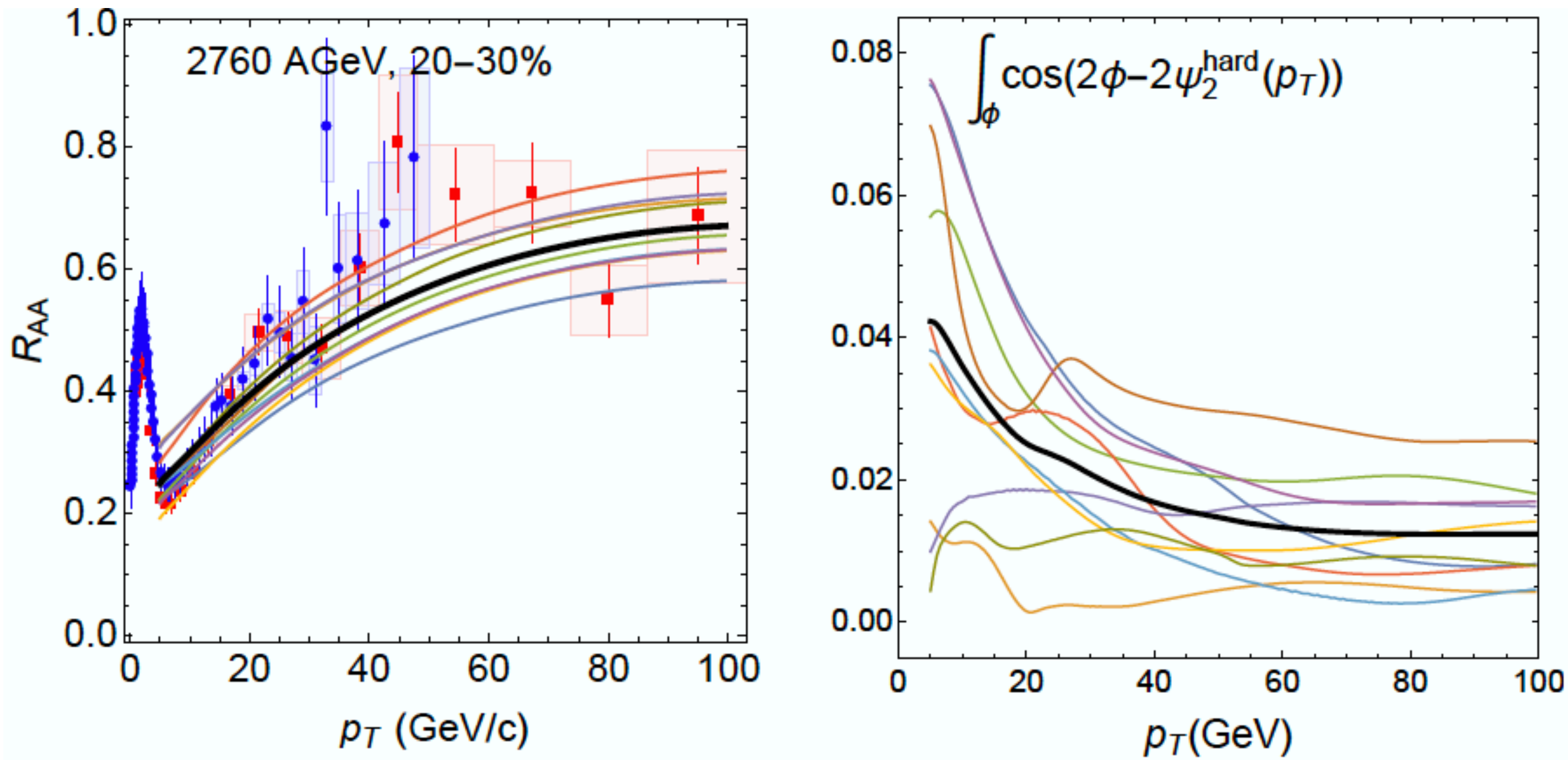




[X. Zhang, J. Liao, 1202.1047; 1208.6361; 1210.1245; 1311.5463]

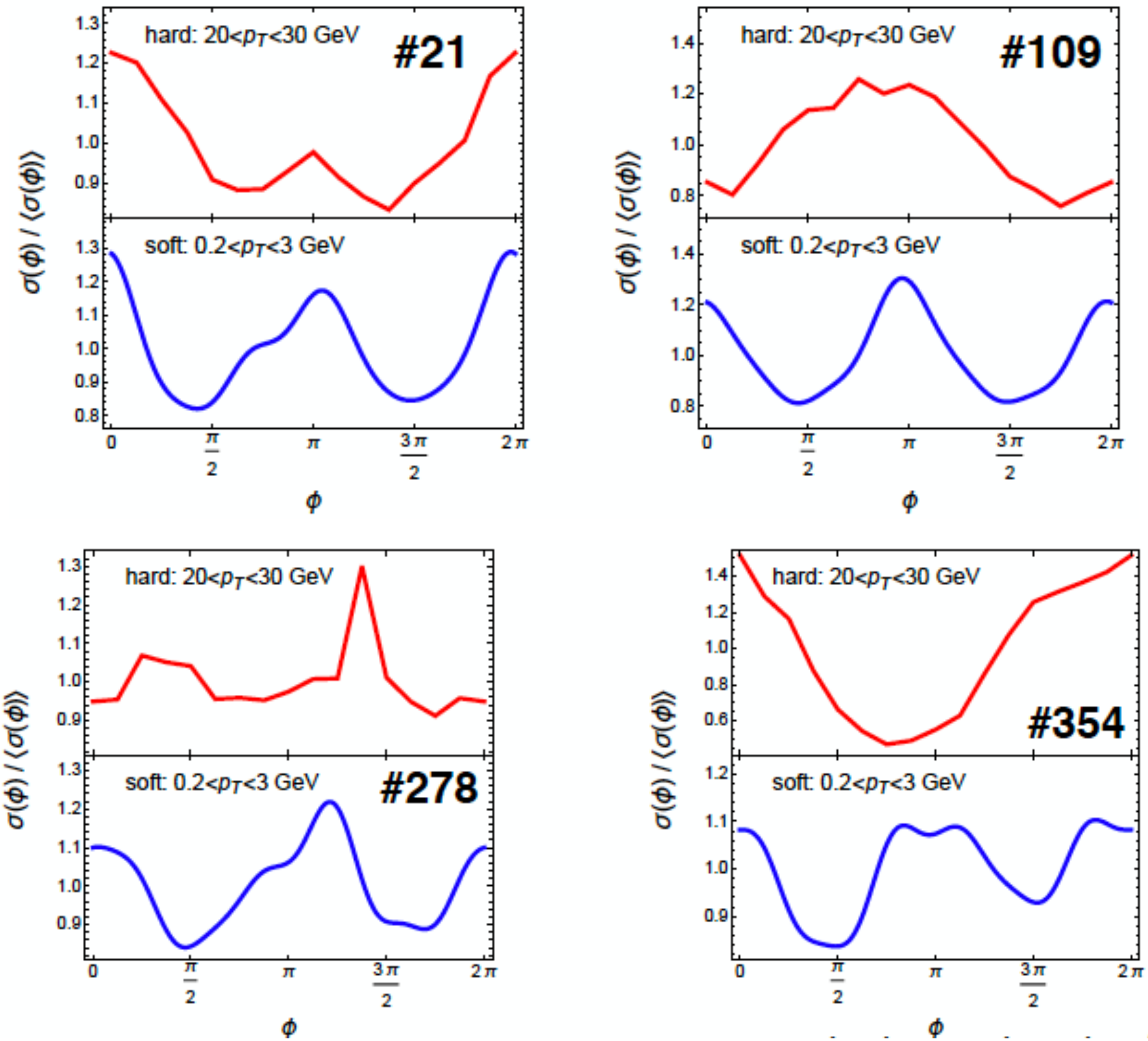
Event-By-Event Jet Quenching

A first try of e-by-e CUJET3 exercise
(for 10 events —computationally expensive!)



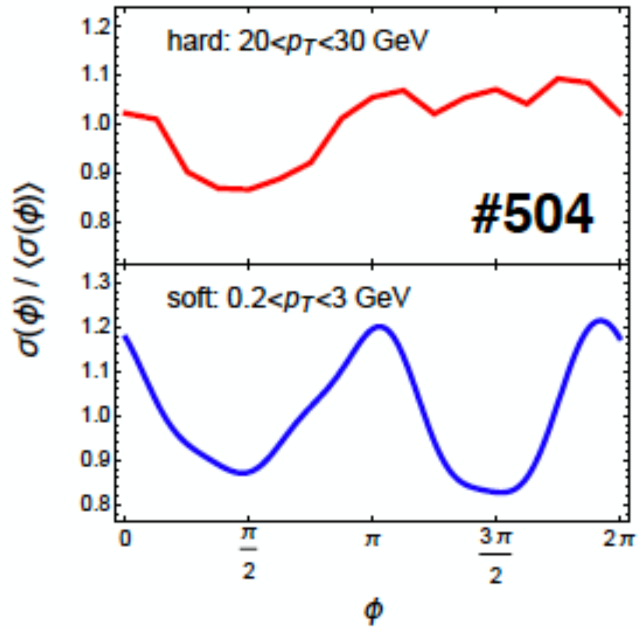
[Hydro background from Jaki Noronha-Holster]

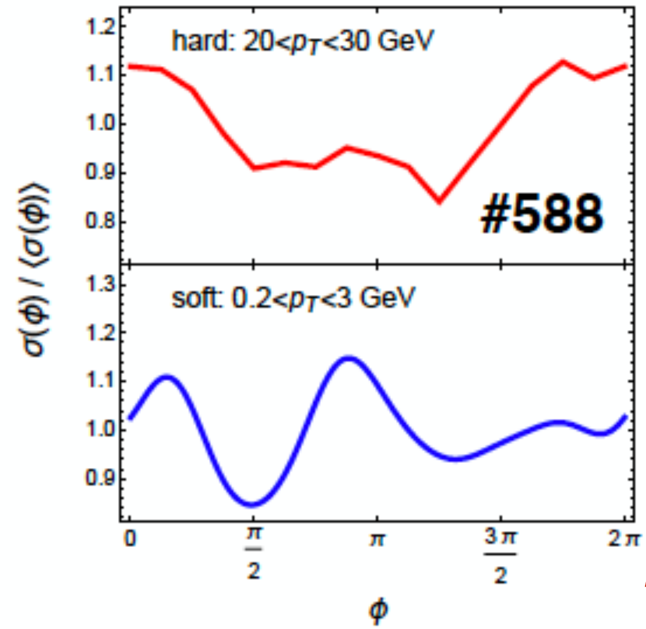
Event-By-Event Jet Quenching



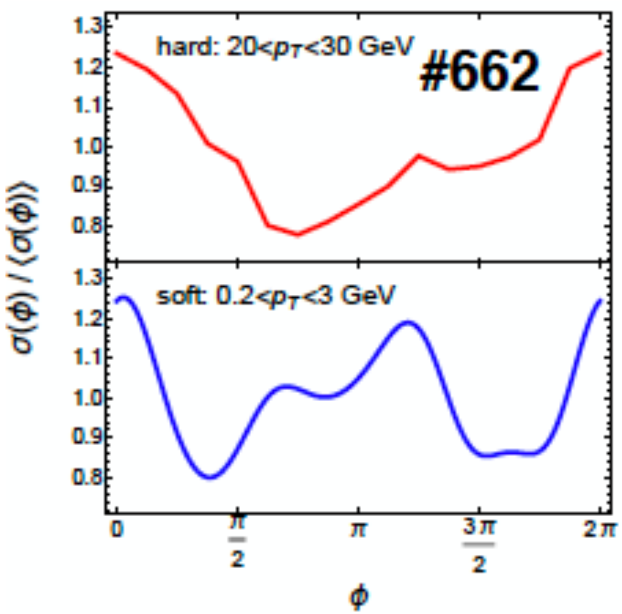
Correlated soft & hard responses to initial geometry

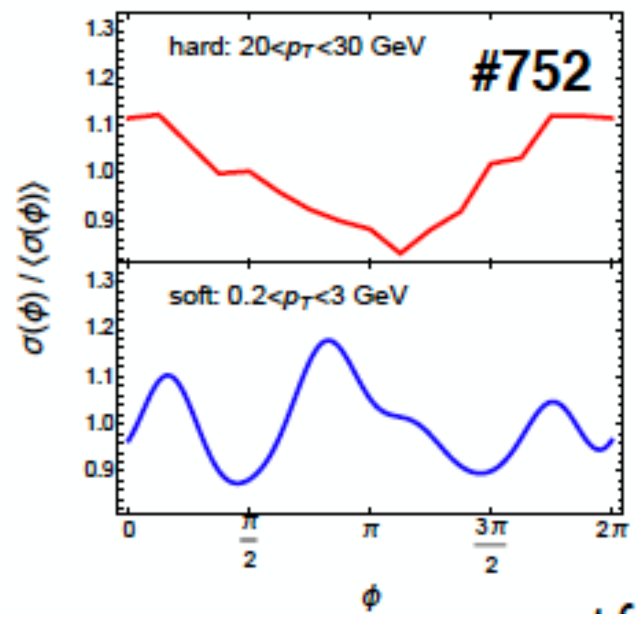
Event-By-Event Jet Quenching





Correlated soft & hard responses to initial geometry

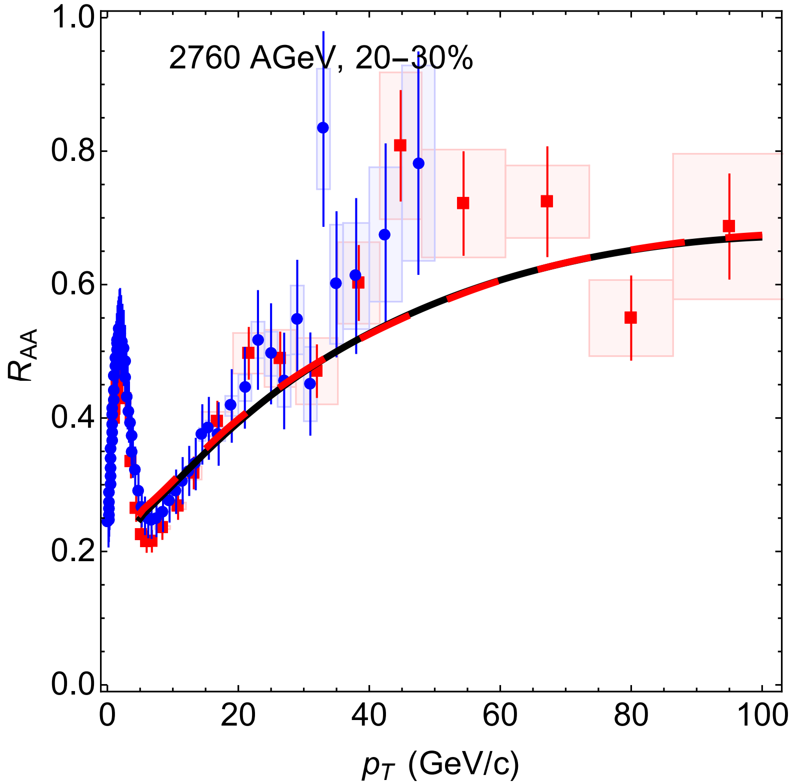


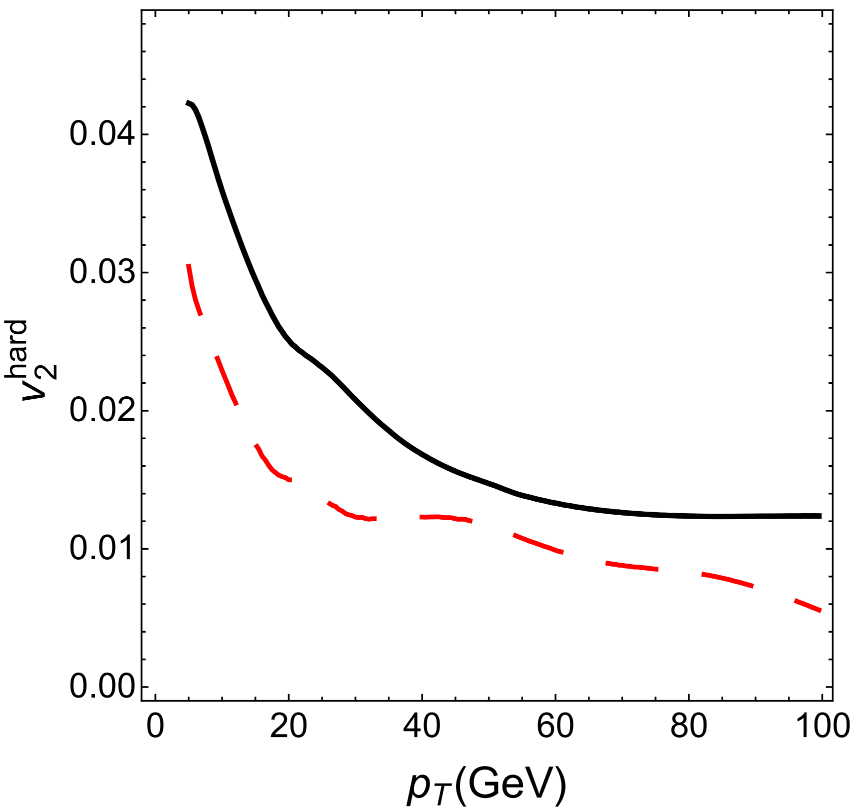


Event-By-Event Jet Quenching

High-Pt V2 gets enhanced in e-by-e simulations.

[J. Noronah-Hostler, B. Betz, J. Noronah, M. Gyulassy, PRL116, 252301 (2016)]

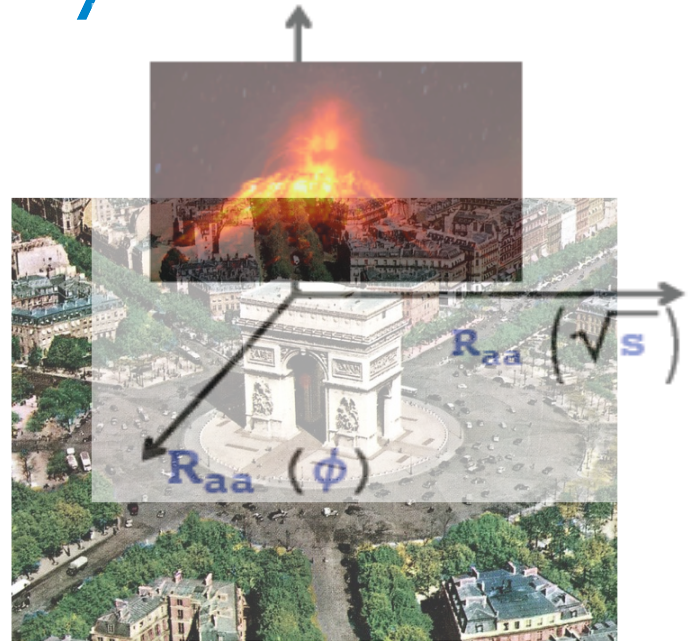




A wealth of physics to be explored in e-by-e CUJET3!

Summary

CUJET3: a simulation framework based on a microscopic picture of Semi-quark-gluon monopole plasma



**** The CUJET3 successfully describes an large set of available single-hadron data: Raa & v2 @ varied centrality & beam energies for light & heavy flavors.***

**** Preliminary event-by-event jet quenching in CUJET3 suggests enhanced v2.***

Discussions

Connecting the soft and hard physics in sQGMP