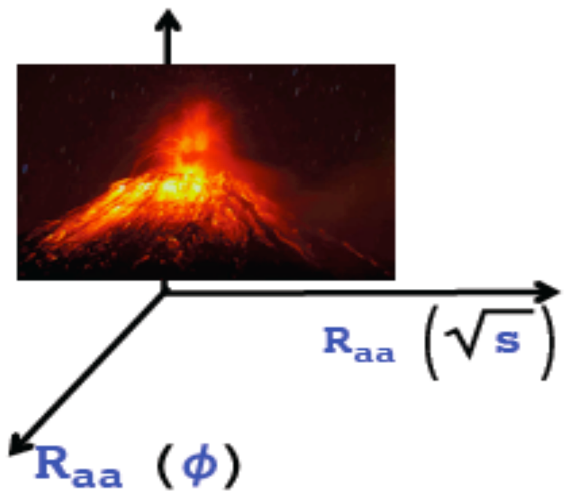
Jets Workshop @ Wuhan   Jun. 12, 2018

Probing the Color Structure of the Perfect QCD Fluids via Soft-Hard-Event-by-Event Azimuthal Correlations



Jinfeng Liao

Indiana University & CCNU & CTGU

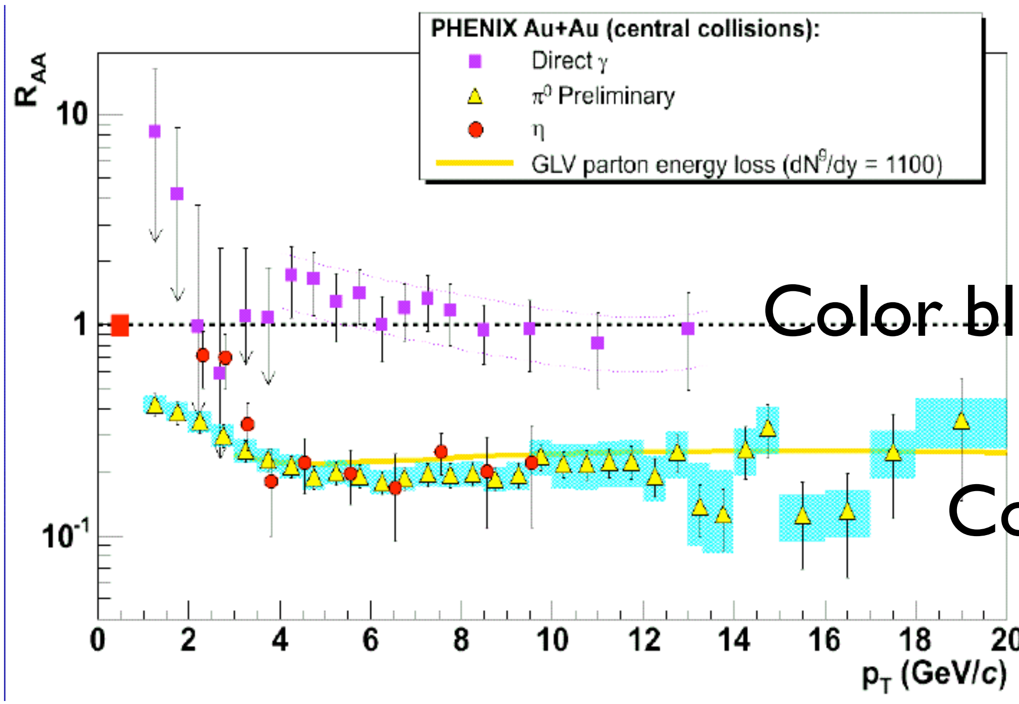
Research Supported by NSF & DOE & by NSFC

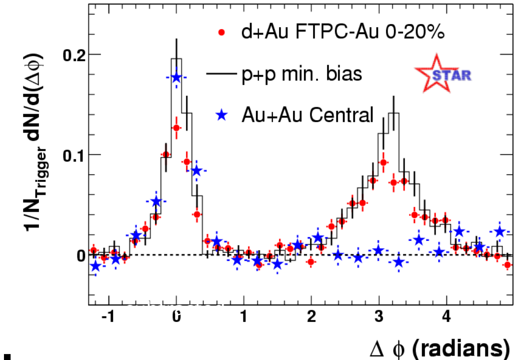
INDIANA UNIVERSITY

NSF

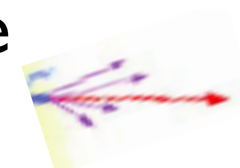
BEST COLLABORATION

A Color-Opaque Plasma



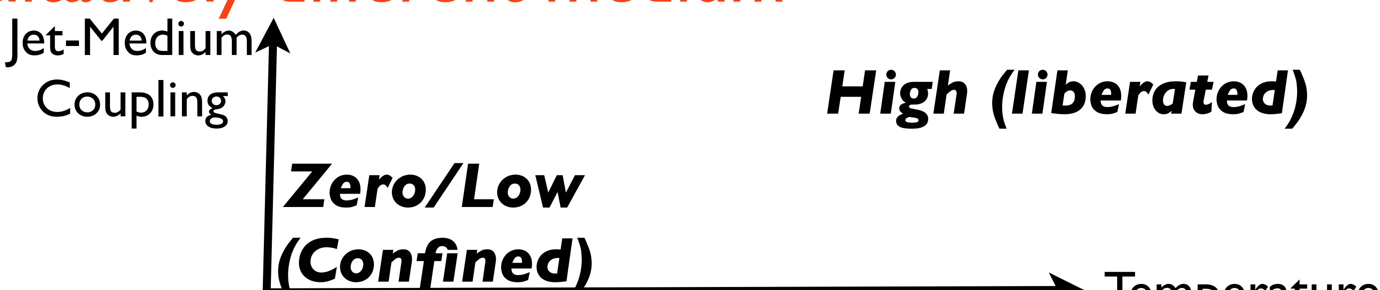


Color blind probe



Colorful probe

A qualitatively different medium



Soft-Hard Consistency for the sQGP

**** Soft and hard phenomenology studies are often computed separately (e.g. v2 at low and high Pt):***

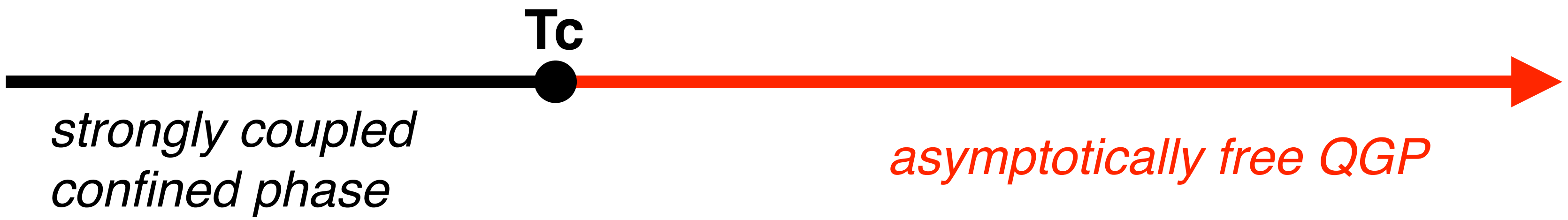
Can they be consistently described in one and same modeling?

**** Soft and hard transport properties (e.g. shear viscosity and jet transport coefficient):***

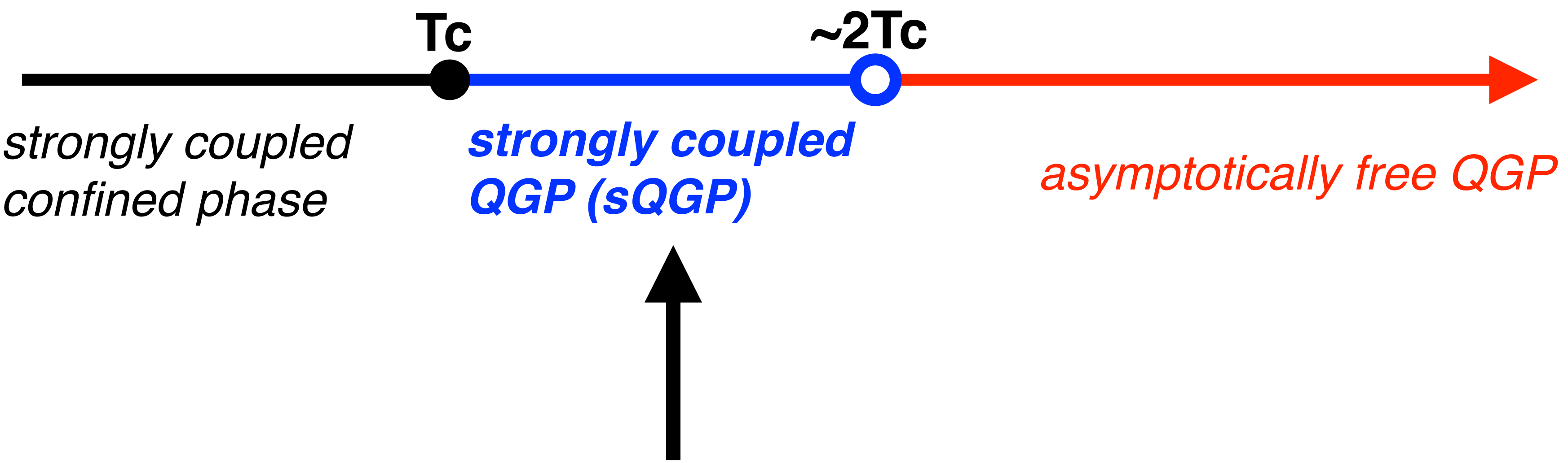
Are they consistent with each other within the same microscopic picture of the QCD medium?

sQGP: What's the Matter?

The old dream



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

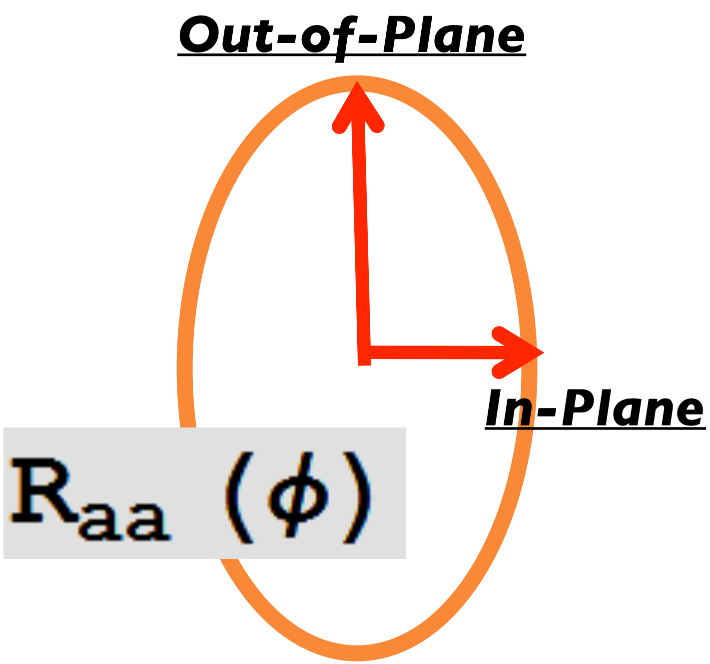


What are the relevant degrees of freedom in sQGP???
Hadrons? Quarks/gluons? Or something else?

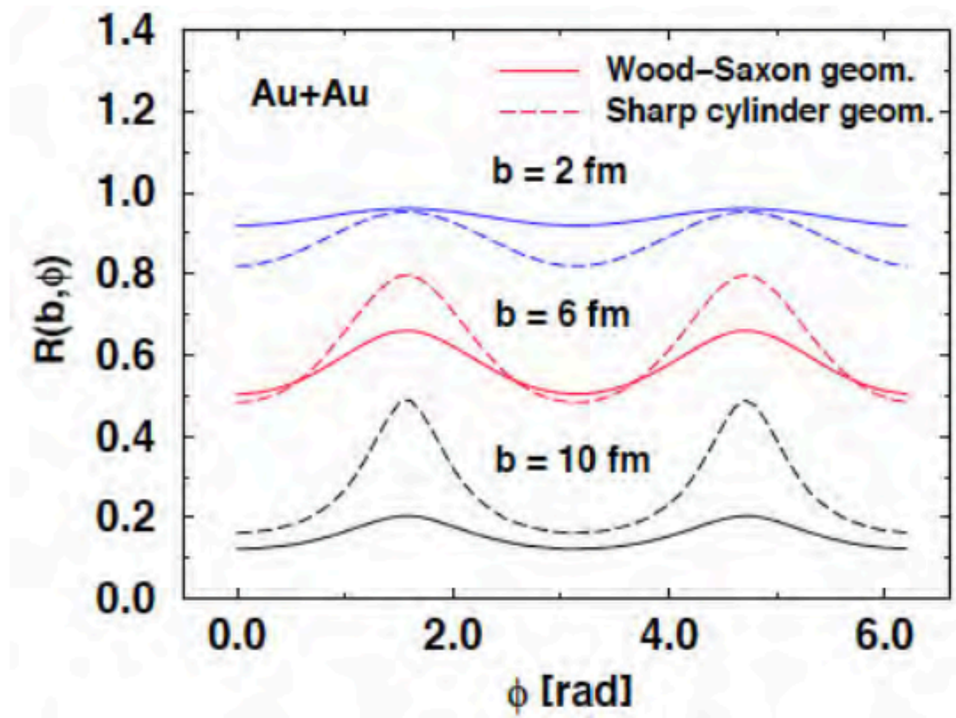
Historical Prelude

Geometric Tomography

Geometric tomography(~2000)
[Gyulassy, Vitev, Wang, arXiv:nucl-th/0012092

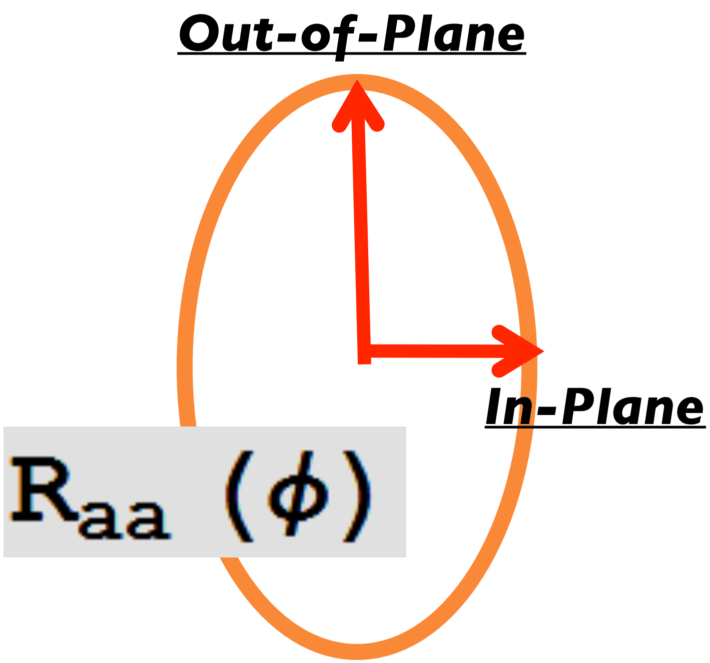


$$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$$

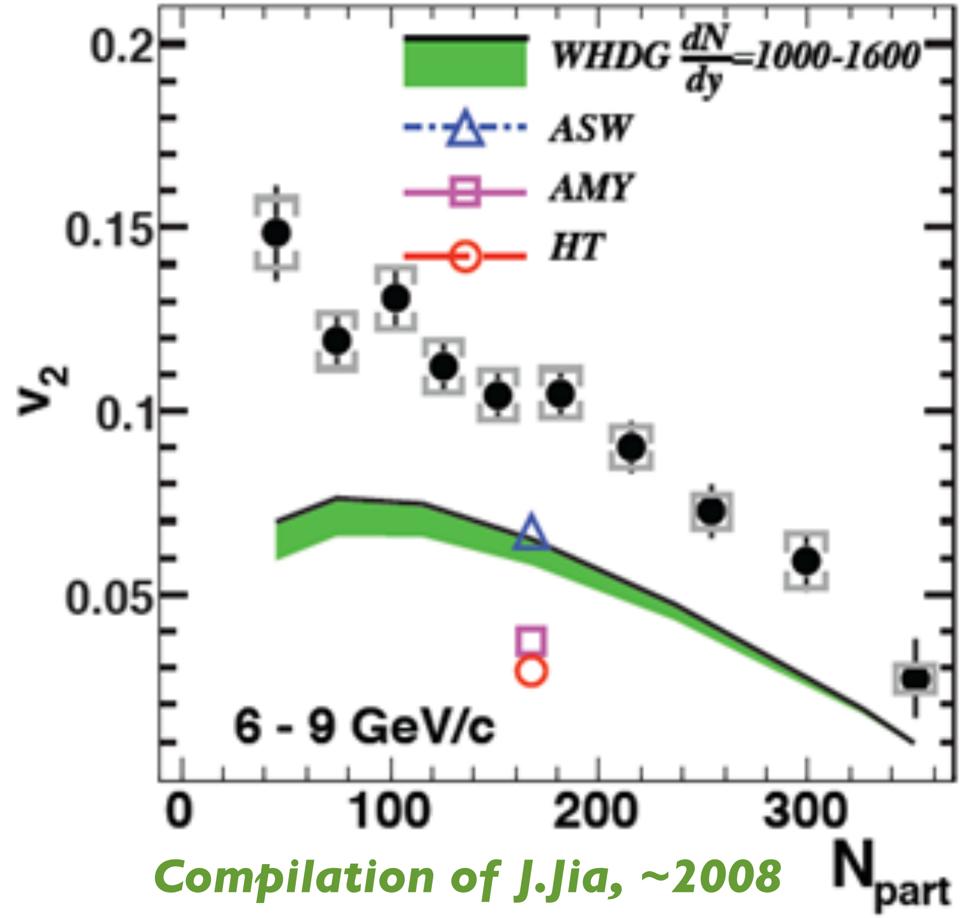


However: exp. data showed much larger anisotropy?!
Geometric model analysis: Shuryak; Drees-Feng-Jia;…

Geometric Tomography



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

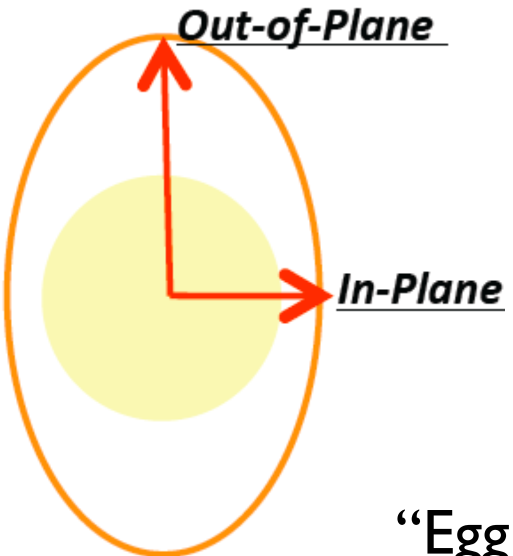


Compilation of J.Jia, ~2008

Till ~ 2008: clear discrepancy between accurate data and model predictions.

High Pt v2 became a long standing challenge

Where Are Jets Quenched (More Strongly)?



Taken for granted in all previous models:
Jet-medium coupling is T-independent.

We realized the puzzle may concern
more radical questions:

Where are jets quenched (more strongly)?

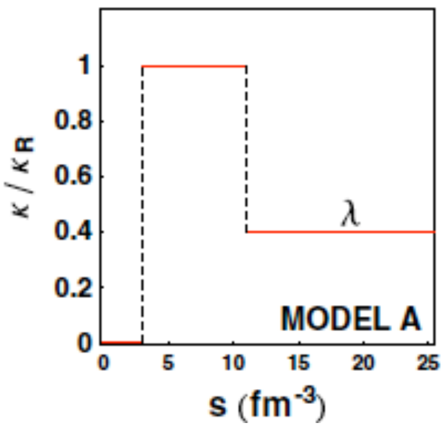
Geometry is a sensitive feature:
“Egg yolk” has one geometry, “Egg white” has another.

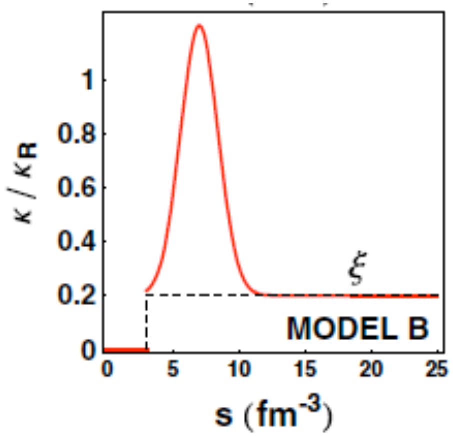
PRL **102**, 202302 (2009) PHYSICAL REVIEW LETTERS week ending 22 MAY 2009

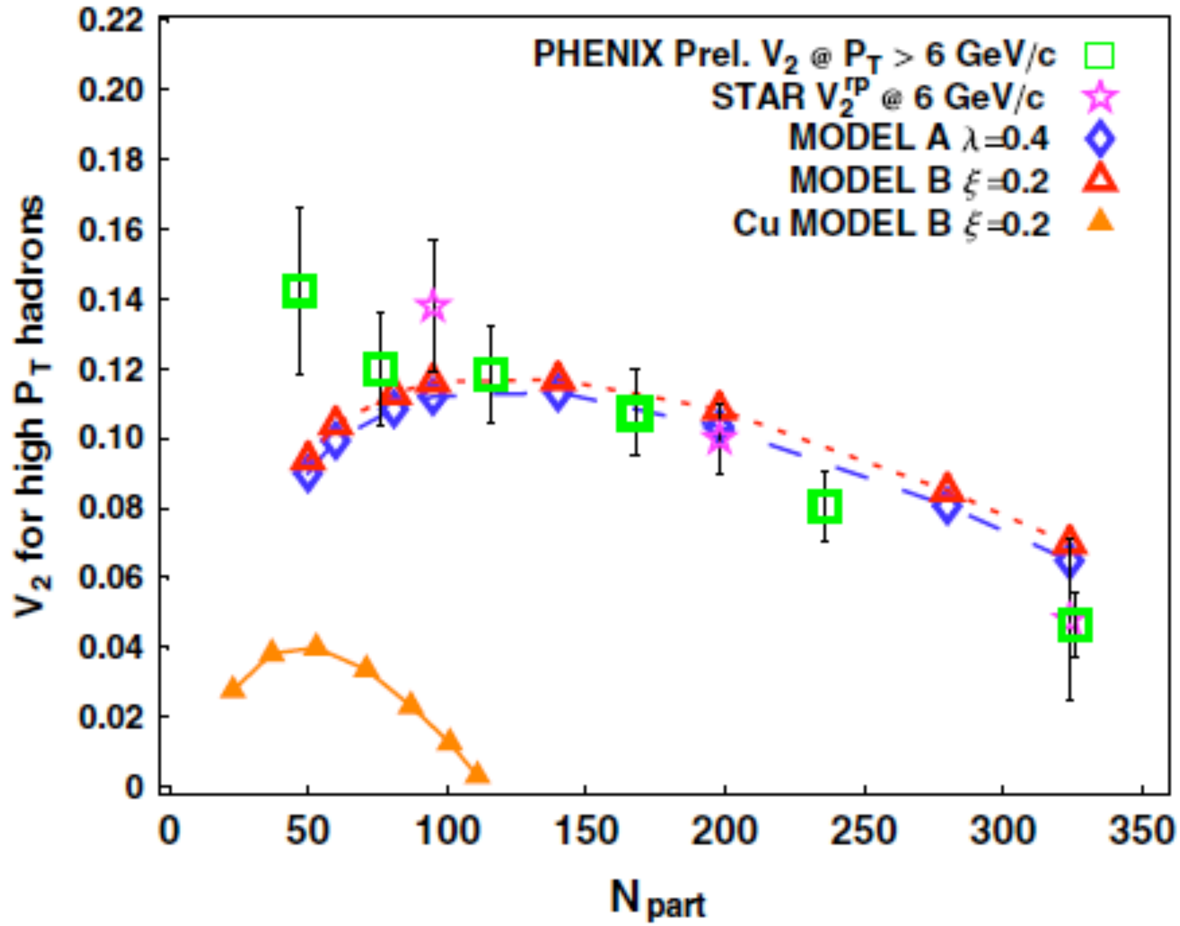
Angular Dependence of Jet Quenching Indicates Its Strong Enhancement near the QCD Phase Transition

Jinfeng Liao[1,2,*] and Edward Shuryak[1,†]
[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)

Near-Tc Enhancement (NTcE)



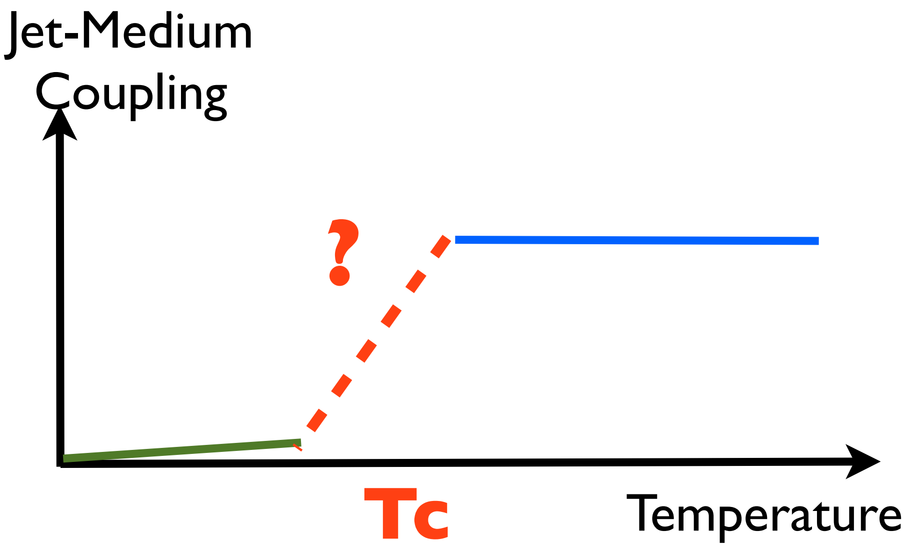




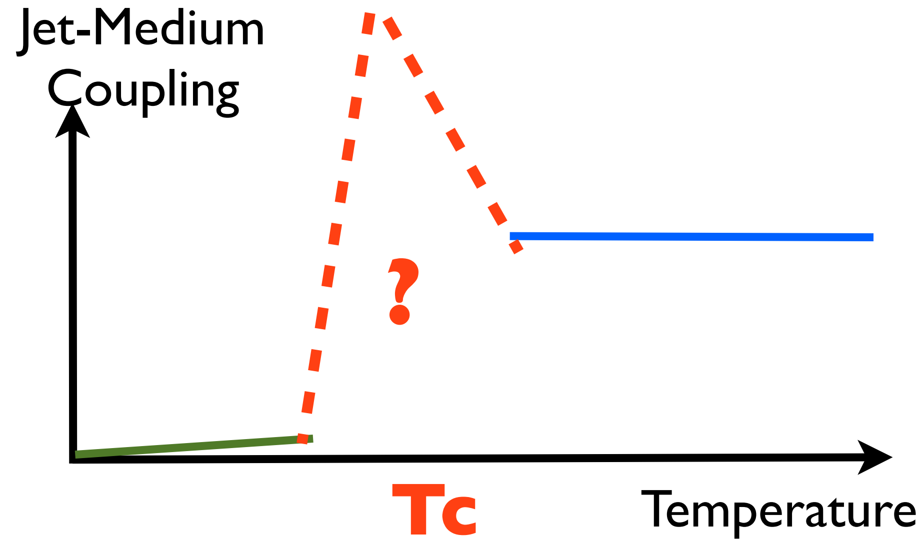
In the paper PRL(2009) we concluded:

"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."

From Transparency to Opaqueness



"Waterfall" scenario

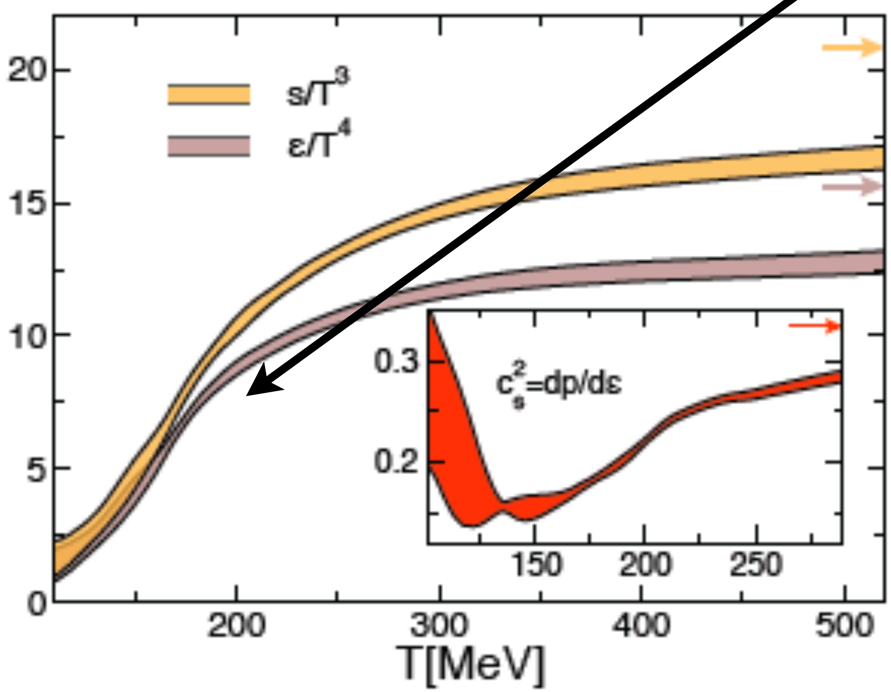


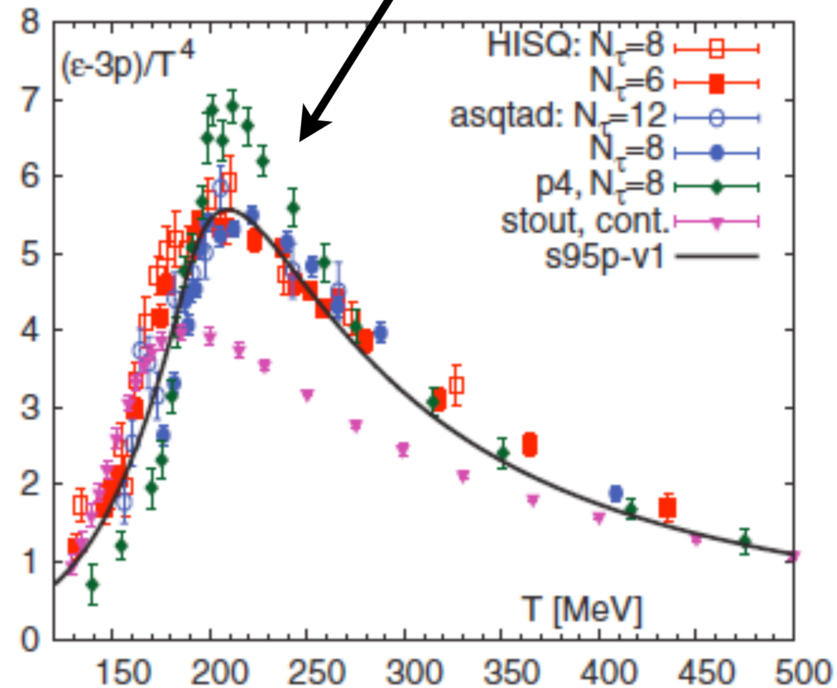
"Volcano" scenario

The temperature dependence of the QCD matter opaqueness is by itself a question of great interest!

(We were perhaps the earliest to ask & attempt to answer it.)

Lattice: **Crossover**, but **Rapid**

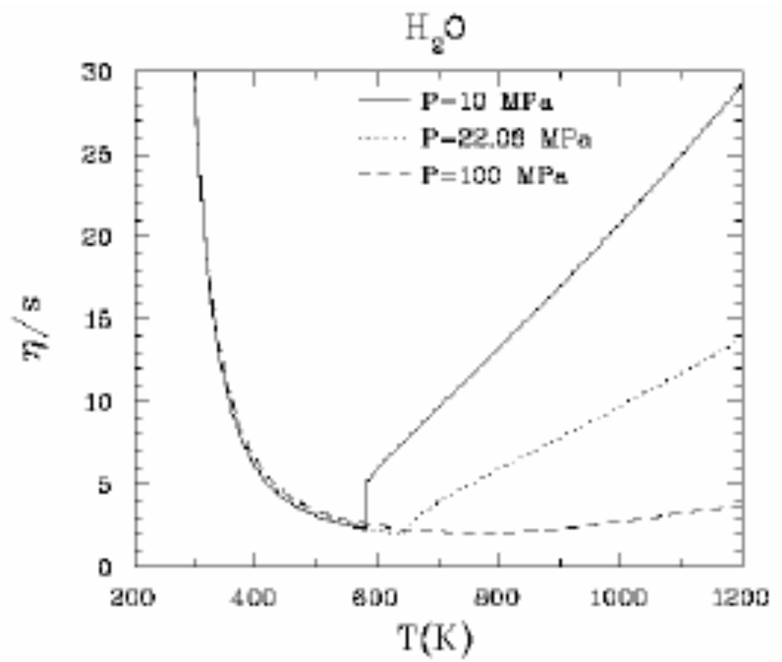




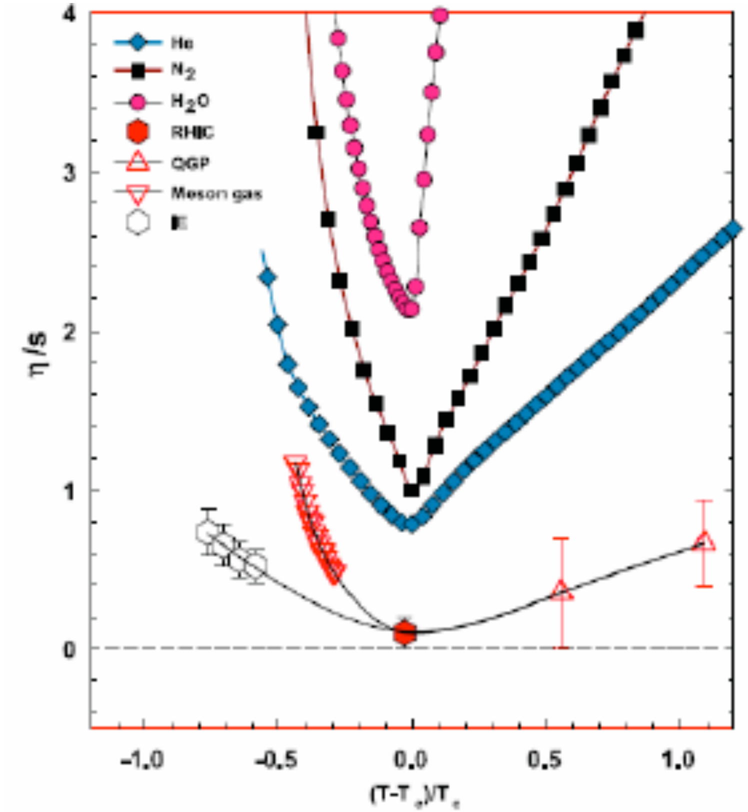
"Rapid Up" or "Rapid Down":
pressure/energy density/entropy density/
2-nd q-susceptibilities/
chiral condensate/Q-bar-Q free energy/...

"Peak" or "Dip":
trace anomaly/chiral susceptibility/
4-th q-susceptibilities/
Q-bar-Q internal energy/
speed of sound//...

How about the "Perfect-ness" of Fluid?



Csernai,Kapusta,McLerran, PRL(2006)



Lacey, et al, PRL(2007)

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.

Over time, these points were confirmed by many later studies.

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

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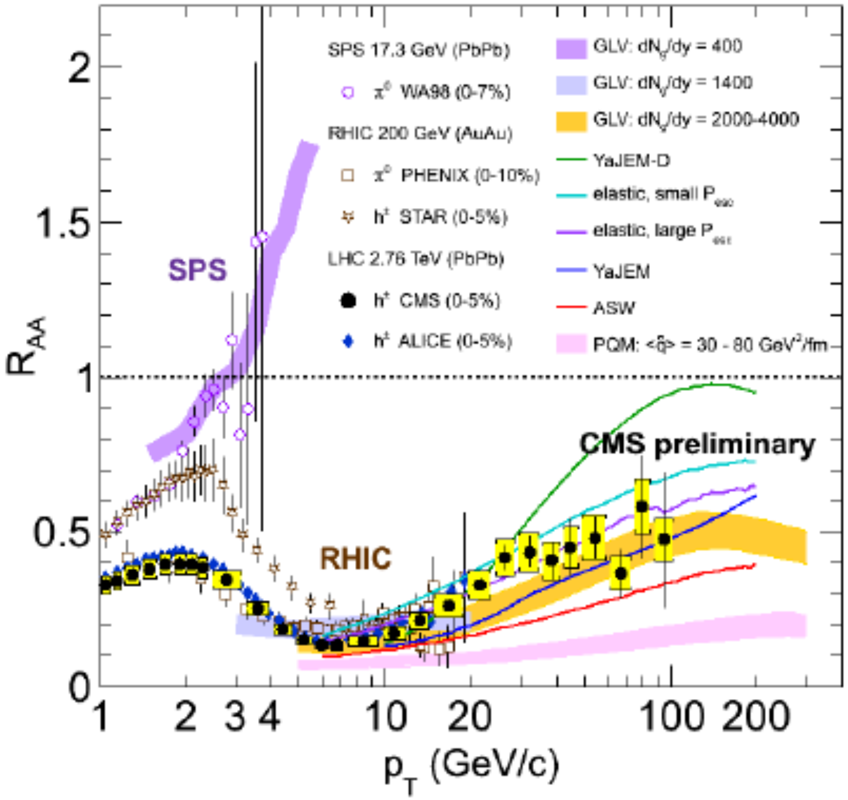
(Received 22 October 2008; revised manuscript received 19 February 2009; published 22 May 2009)

The RHIC+LHC Era

Raa(RHIC)~Raa(LHC)



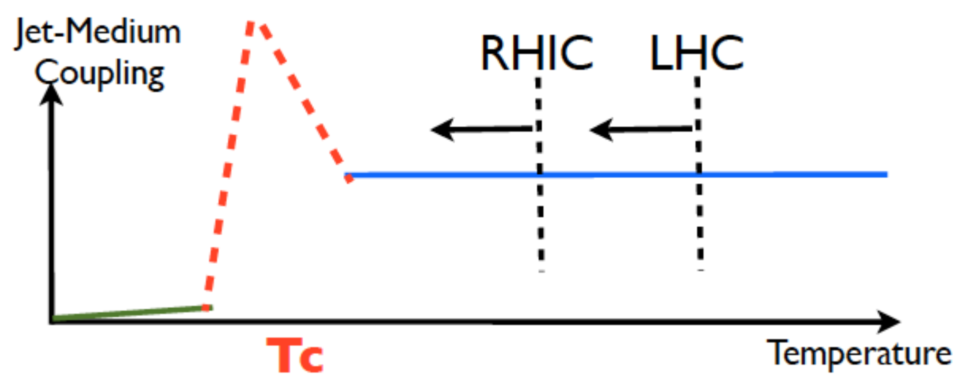
Already a clear hint of LESS OPACITY: similar R_aa, despite twice the density!

— "surprising transparency" (Horowitz & Gyulassy, QM11)

— naturally expected if the "volcano scenario" is indeed true (Liao PANIC11)

$$< \kappa >_{\rm RHIC} : < \kappa >_{\rm LHC} \approx 1 : 0.72$$

JL, arXiv:1109.0271;
Zhang & JL, arXiv: 1208.6361;
arXiv:1210.1245



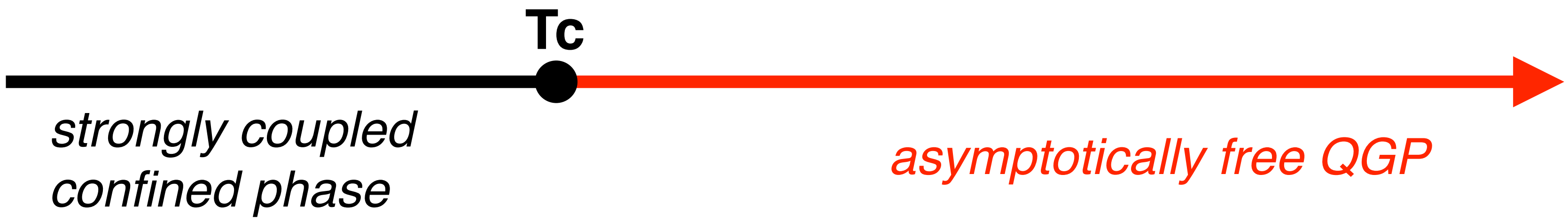
(RHIC+LHC) & (Raa+V2): a highly constraining set of observables for jet energy loss models!

The CUJET3

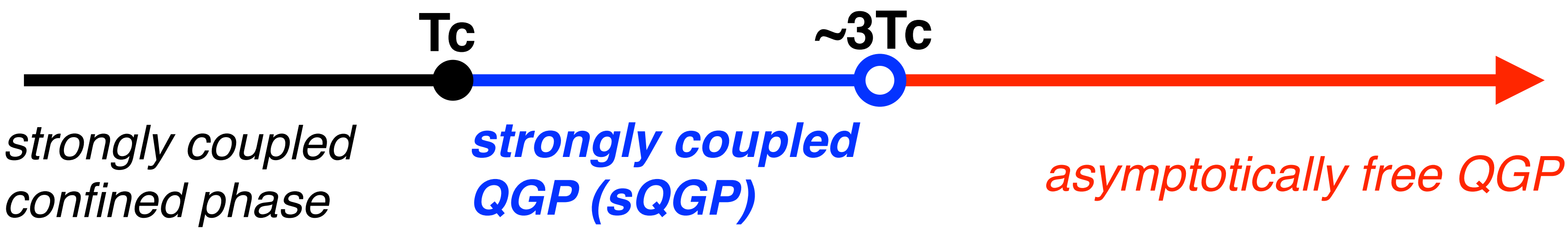
CUJET1: Buzzatti, Gyulassy [arXiv:1106.3061]
CUJET2: Jiechen Xu, Buzzatti, Gyulassy [arXiv:1402.2956]

sQGP: The Matter Just About to Confine Color

The old belief



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

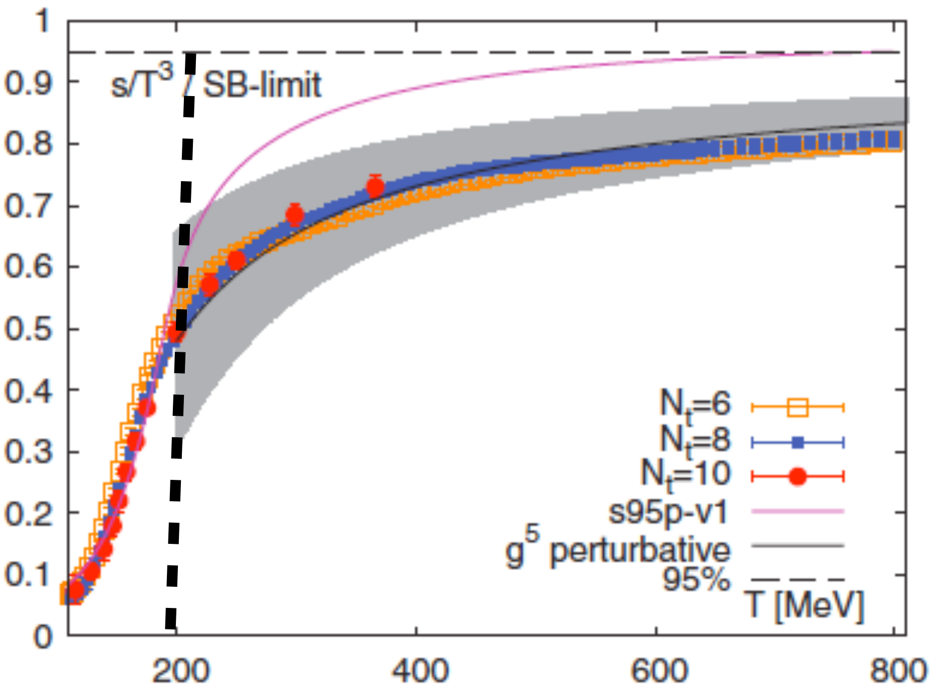


The matter just above confinement,
is more closely related to the confined world, rather
than to the faraway place of asymptotic QGP!

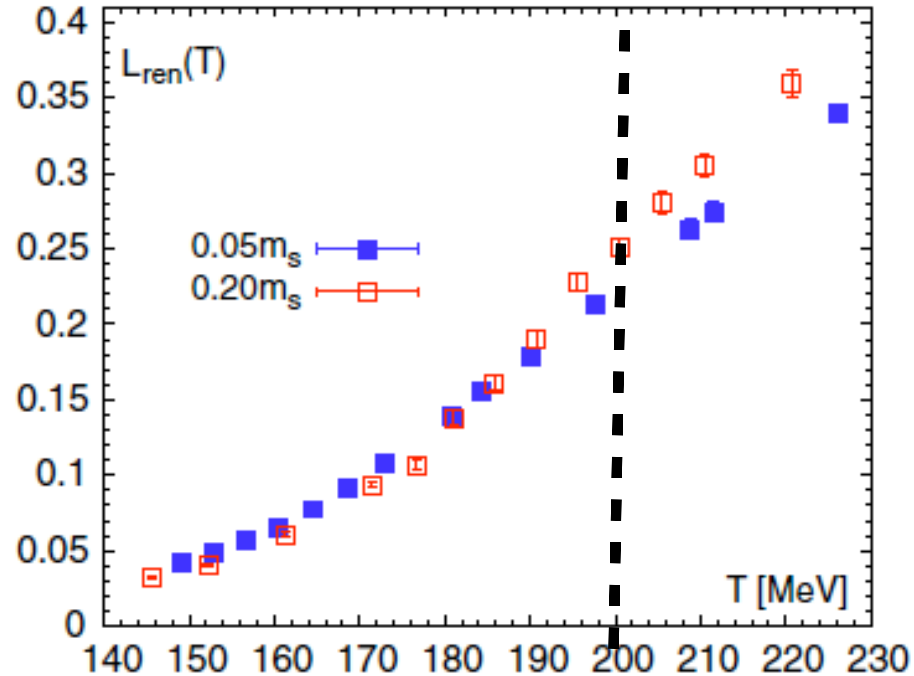
This is to say, the confinement physics (whatever it is),
must continue robustly into this region
— we call it "<u>postconfinement</u>" regime!

Liberation of Color? Missing DoF?

Degrees of freedom



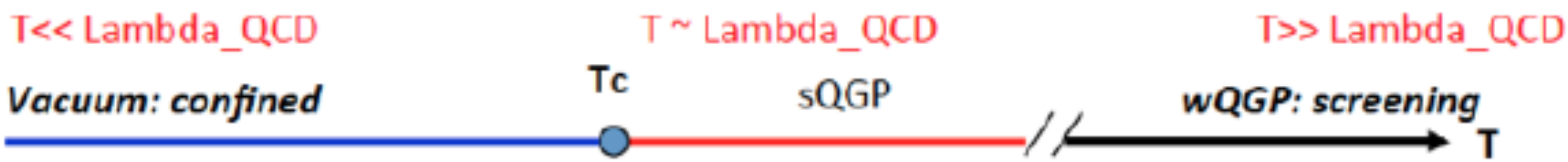
Degree of color liberation

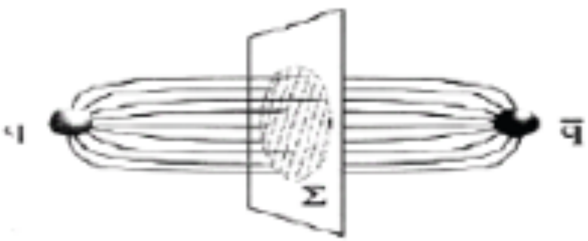


A region around Tc with liberated degrees of freedom
but only partially liberated color-electric objects.
(Pisarski & collaborators: semi-QGP)

Then what are the "extra" dominant DoF here???
Chromo-magnetic monopoles from confining vacuum!

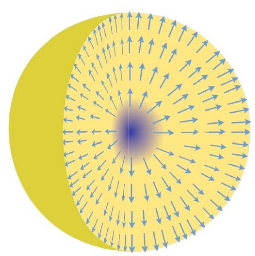
Understanding Confinement from the Above



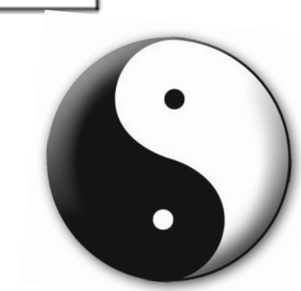


Emergent plasma with E & M charges:
chromo-magnetic monopoles are the "missing DoF"

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



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



Condensate monopoles —> dense thermal monopoles 1-2Tc: thermal monopoles play key role in this regime.

PHYSICAL REVIEW C **75**, 054907 (2007)

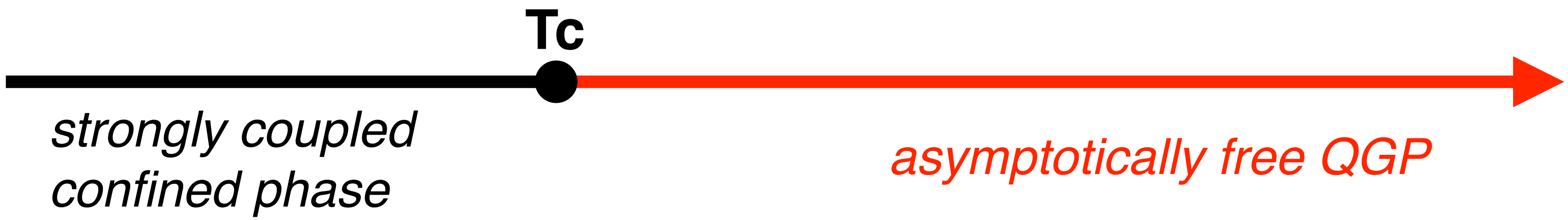
Strongly coupled plasma with electric and magnetic charges

Jinfeng Liao and Edward Shuryak

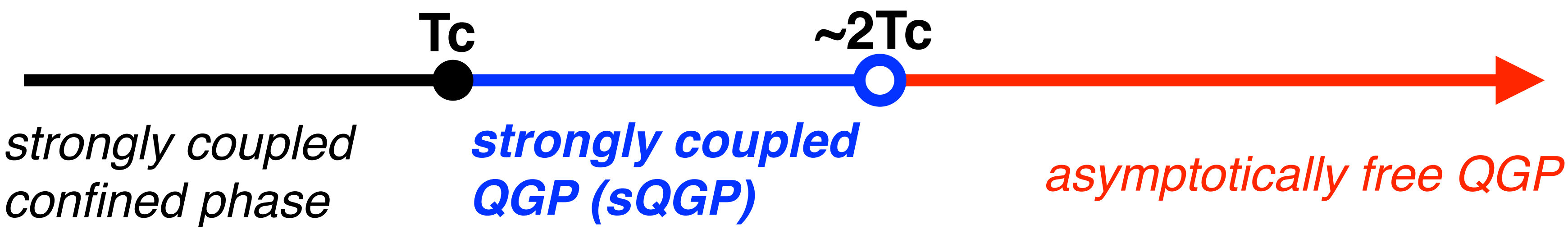
JL & Shuryak, PRC2007;PRL2008

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!

To implement this picture in a sophisticated jet energy loss model —> CUJET3!

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 *

Jiechen Xu(徐杰谌)[1], Jinfeng Liao(廖劲峰)[2,3**], Miklos Gyulassy[1**]

[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

[reported at QM15]

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

Jiechen Xu,[a] Jinfeng Liao[b,c] and Miklos Gyulassy[a]

[a]*Department of Physics, Columbia University, 538 West 120th Street, New York, NY 10027, U.S.A.*
[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.*
[c]*RIKEN BNL Research Center, Brookhaven National Laboratory, Building 510A, Upton, NY 11973, U.S.A.*

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JHEP02(2016)169

CUJET3: Semi-Quark-Gluon Monopole Plasma

A Unified Description for Comprehensive Sets of Jet Energy Loss Observables with CUJET3

Shuzhe Shi[a], Jiechen Xu[a,c], Jinfeng Liao[a,d], Miklos Gyulassy[b,c,d]

[a]*Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*
[b]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[c]*Pupin Lab MS-5202, Department of Physics, Columbia University, New York, NY 10027, USA*
[d]*Institute of Particle Physics, Central China Normal University, Wuhan, China*

arXiv: 1704.04577
[reported at QM17]

Precision Jet Tomography with the CUJET3

(Dated: May 29, 2018)

We report results of a comprehensive new global χ^2 analysis of nuclear collision data from RHIC(0.2ATeV), LHC1(2.76ATeV), and recent LHC2(5.02ATeV) energies. We use the updated CUJET3.1 framework to evaluate jet energy loss distributions in various models of the color structure of the QCD fluids produced in such reactions. The framework combines consistently viscous hydrodynamic fields predicted by VISHNU2+1 (validated with soft $p_T < 2$ GeV bulk observables) and the DGLV theory of jet elastic and inelastic energy loss generalized to sQGMP fluids with color structure including effective semi-QGP color elec-

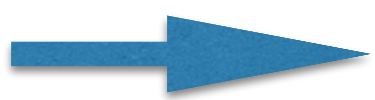
A Sophisticated Simulation Framework

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

$$x\frac{dN}{dx} \propto \ldots \int_{q^2} \left[\frac{n\,\alpha_s^2(q^2)\, f_E^2}{q^2(q^2+f_E^2\mu^2)}\right] \ldots$$



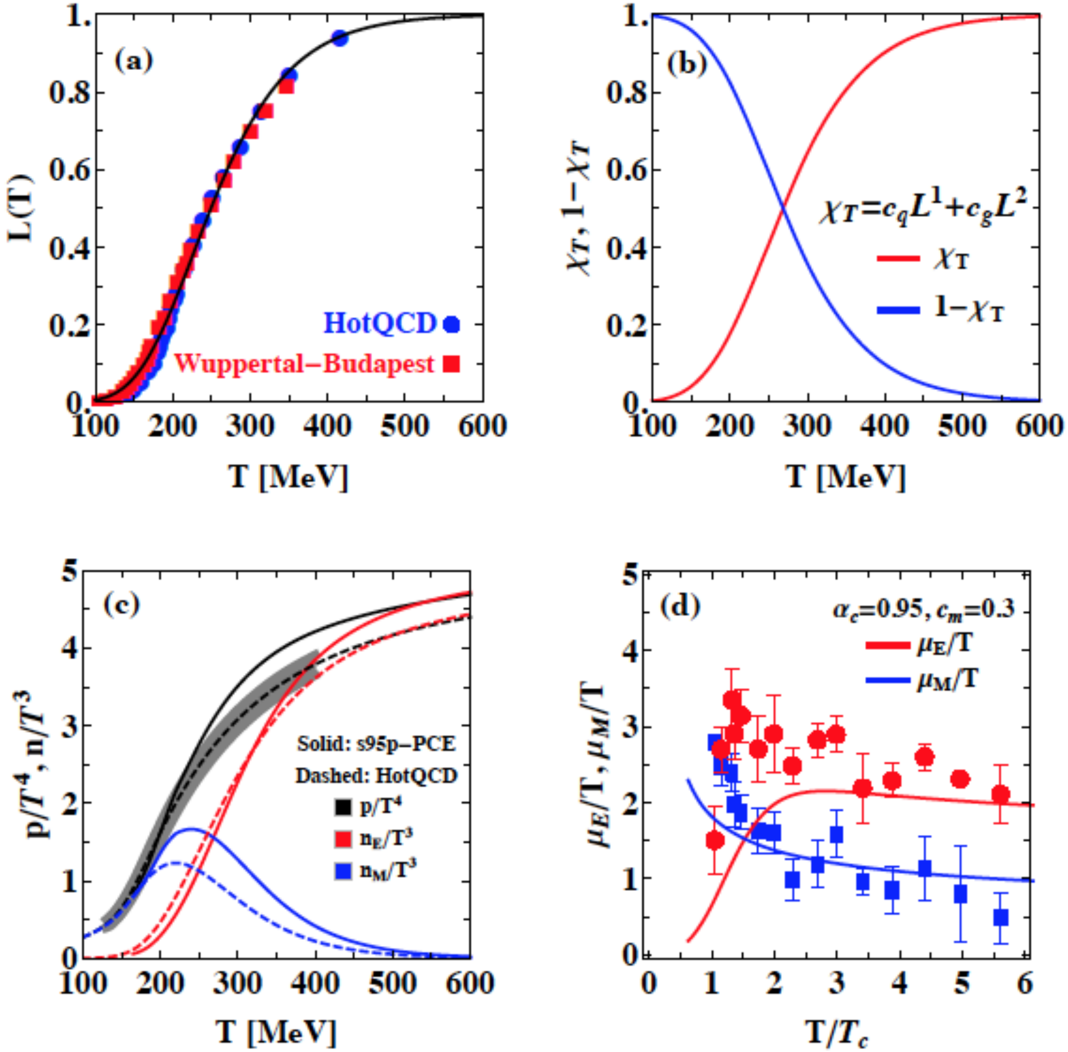
We now include both color-electric and color-magnetic scattering centers.

$$\left[\frac{n_e\left(\alpha_s(q^2)\alpha_s(q^2)\right) f_E^2}{q^2(q^2+f_E^2\mu^2)} + \frac{n_m\left(\alpha^e(q^2)\alpha^m(q^2)\right) f_M^2}{q^2(q^2+f_M^2\mu^2)}\right]$$

Bulk evolution: VISH2+1

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:*

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

* *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

We constrain the two key parameters of sQGMP by a global chi-square analysis of ALL light hadron data.

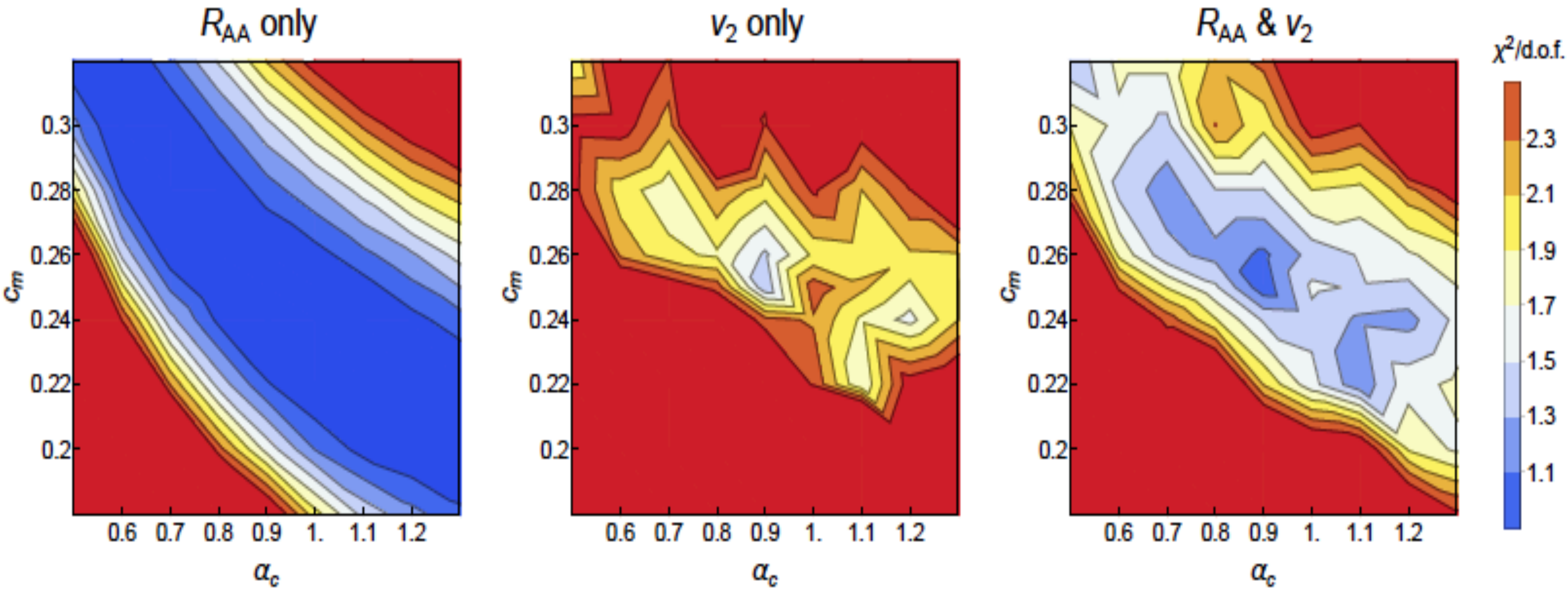
We compute χ^2/d.o.f. for each of the following 12 data sets:

- 200 GeV Au-Au Collisions, 0-10% Centrality Bin, $R_{AA}(\pi^0)$: PHENIX [33, 34];
- 200 GeV Au-Au Collisions, 0-10% Centrality Bin, $v_2(\pi^0)$: PHENIX [34];
- 200 GeV Au-Au Collisions, 20-30% Centrality Bin, $R_{AA}(\pi^0)$: PHENIX [33, 34];
- 200 GeV Au-Au Collisions, 20-30% Centrality Bin, $v_2(\pi^0)$: PHENIX [34];
- 2.76 TeV Pb-Pb Collisions, 0-10% Centrality Bin, $R_{AA}(h^\pm)$: ALICE [35];
- 2.76 TeV Pb-Pb Collisions, 0-10% Centrality Bin, $v_2(h^\pm)$: ATLAS [36], CMS [37];
- 2.76 TeV Pb-Pb Collisions, 20-30% Centrality Bin, $R_{AA}(h^\pm)$: ALICE [35];
- 2.76 TeV Pb-Pb Collisions, 20-30% Centrality Bin, $v_2(h^\pm)$: ALICE [38], ATLAS [36], CMS [37];
- 5.02 TeV Pb-Pb Collisions, 0-5% Centrality Bin, $R_{AA}(h^\pm)$: ATLAS-preliminary [39], CMS [31];
- 5.02 TeV Pb-Pb Collisions, 0-5% Centrality Bin, $v_2(h^\pm)$: CMS [32];
- 5.02 TeV Pb-Pb Collisions, 10-30% Centrality Bin, $R_{AA}(h^\pm)$: CMS [31];
- 5.02 TeV Pb-Pb Collisions, 20-30% Centrality Bin, $v_2(h^\pm)$: CMS [32];

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

Systematic Calibration of CUJET3

We constrain the two key parameters of sQGMP by a global chi-square analysis of ALL light hadron data.

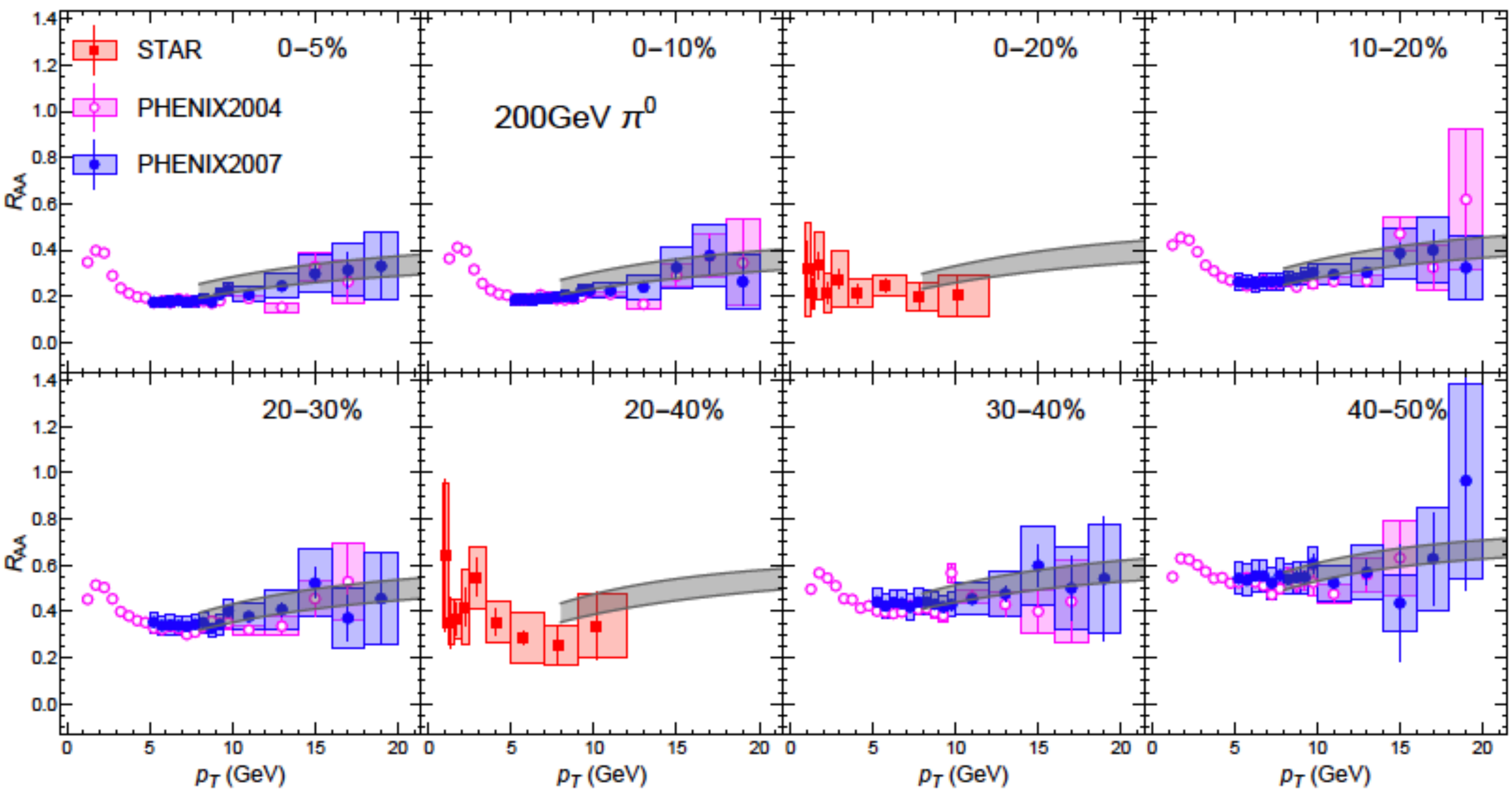


Optimal values: $\alpha_c = 0.9,\ c_m = 0.25$

[chi^2/dof =0.97]

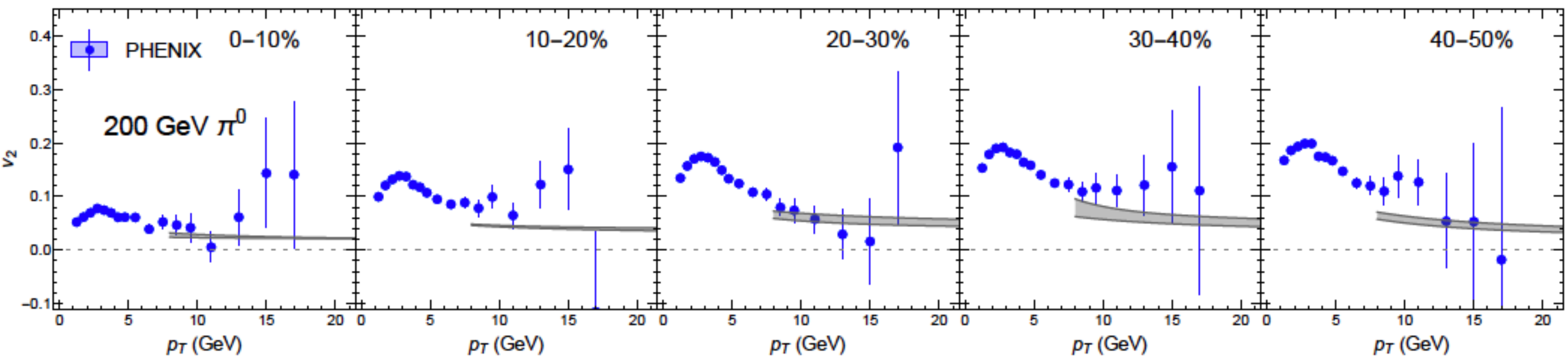
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Comparison with Light Hadron Data



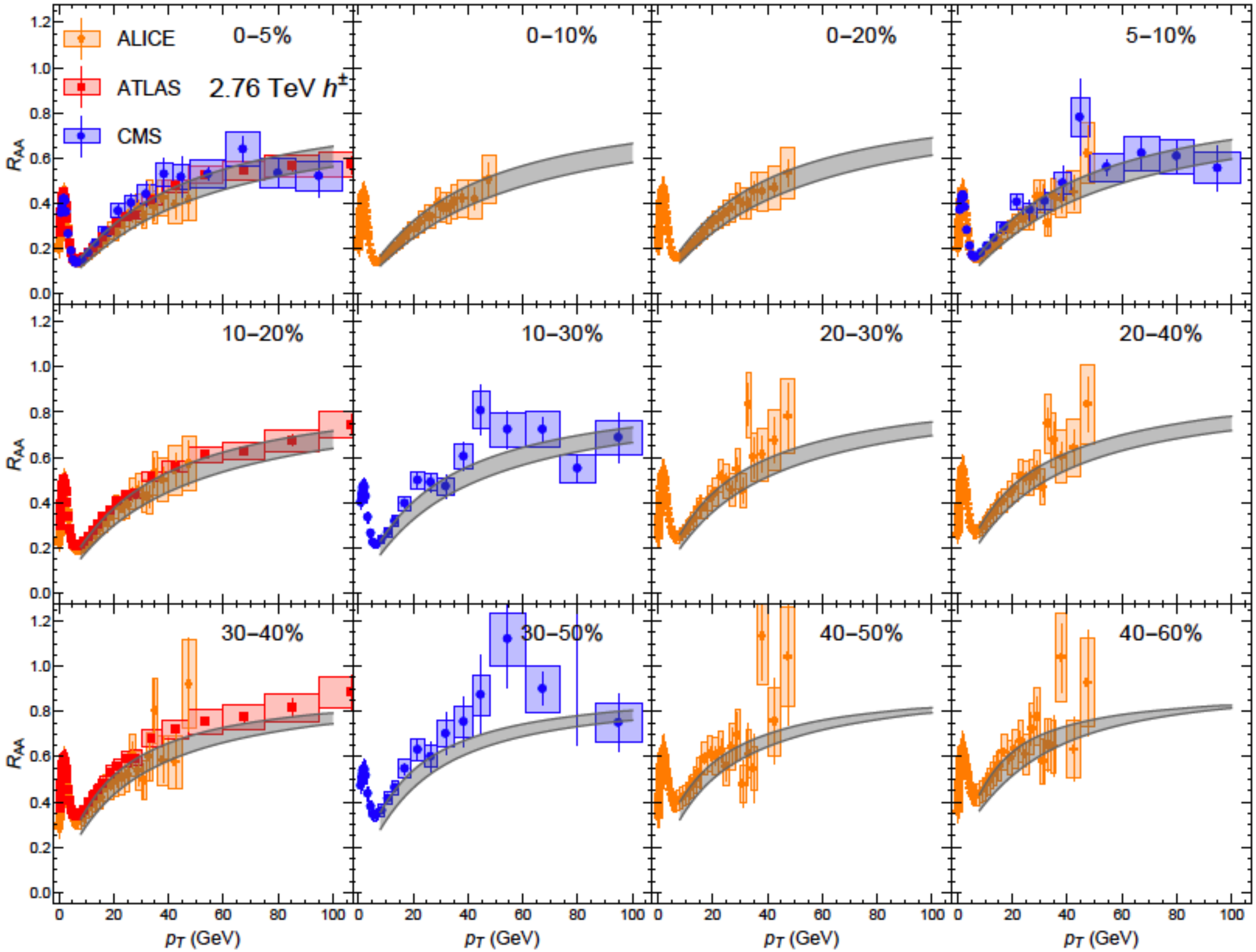
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Comparison with Light Hadron Data



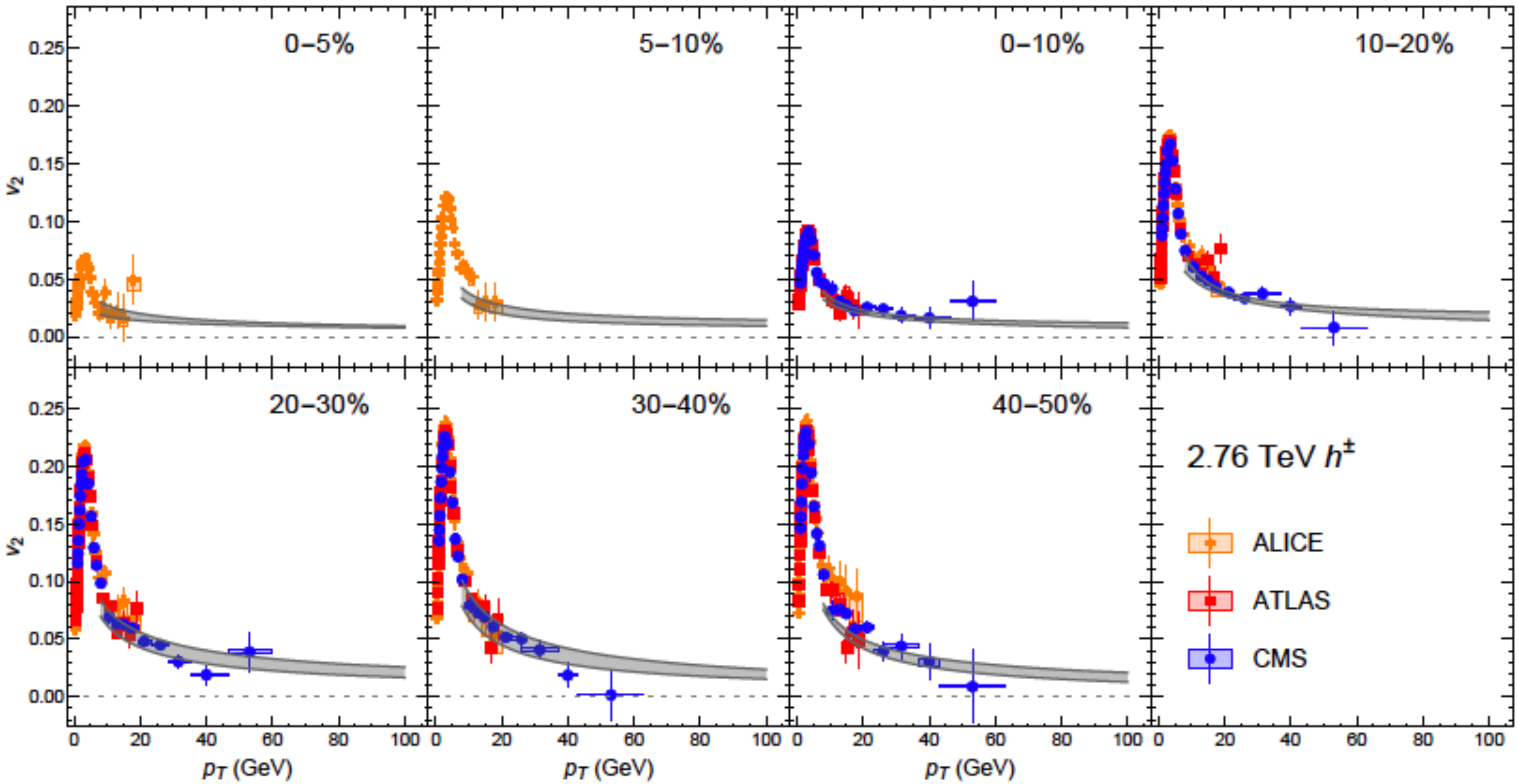
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Comparison with Light Hadron Data



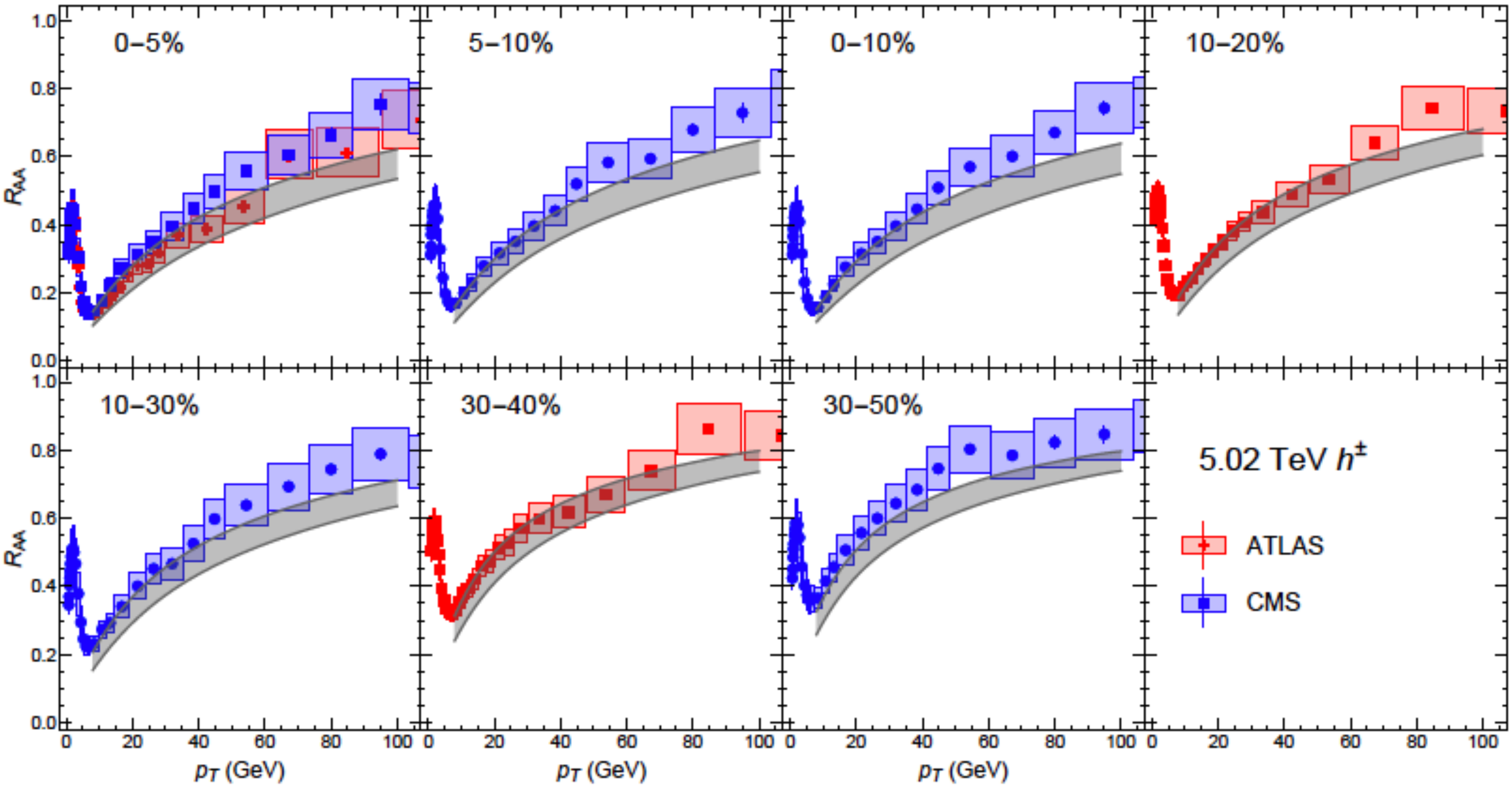
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Comparison with Light Hadron Data



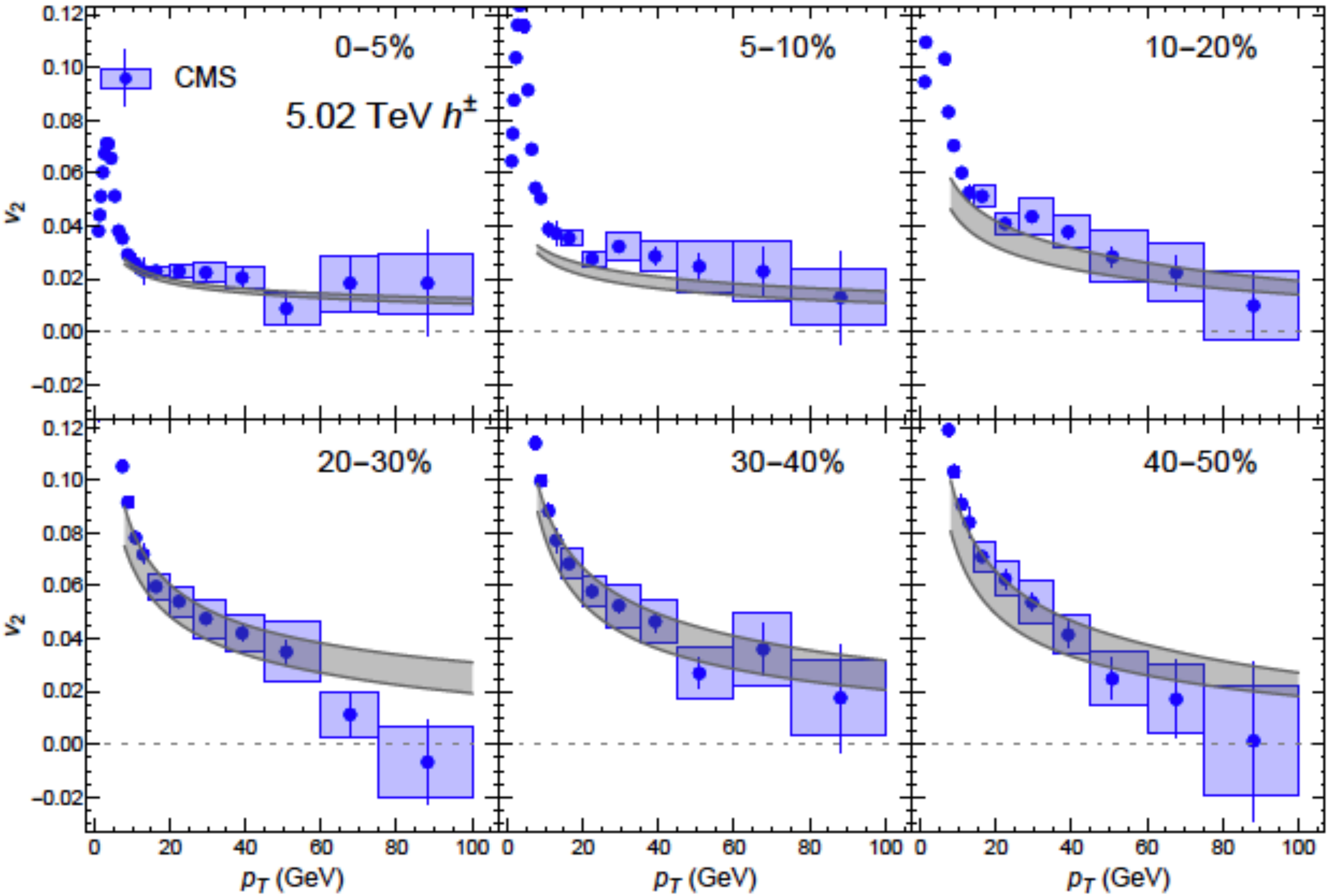
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Comparison with Light Hadron Data



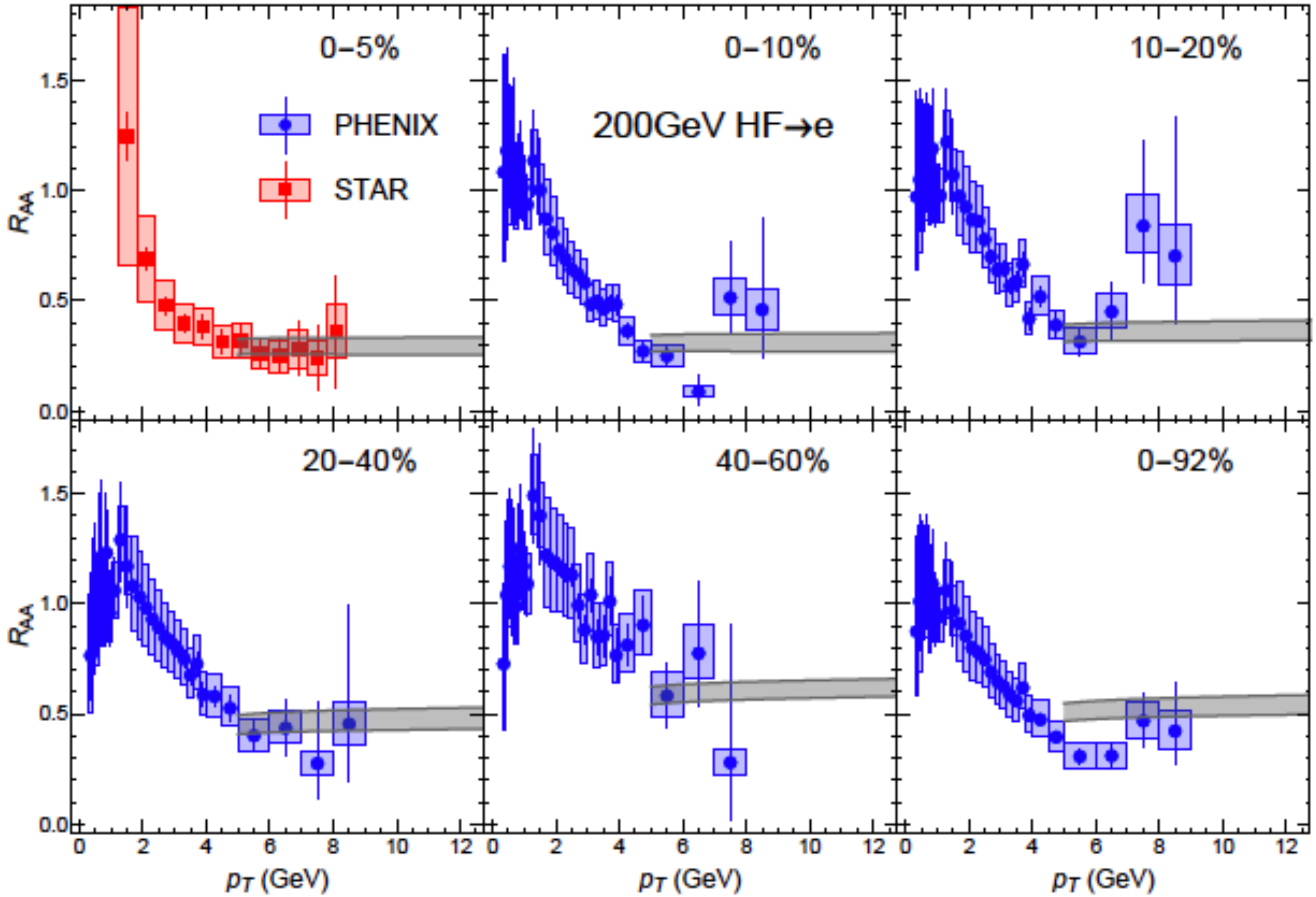
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Comparison with Light Hadron Data



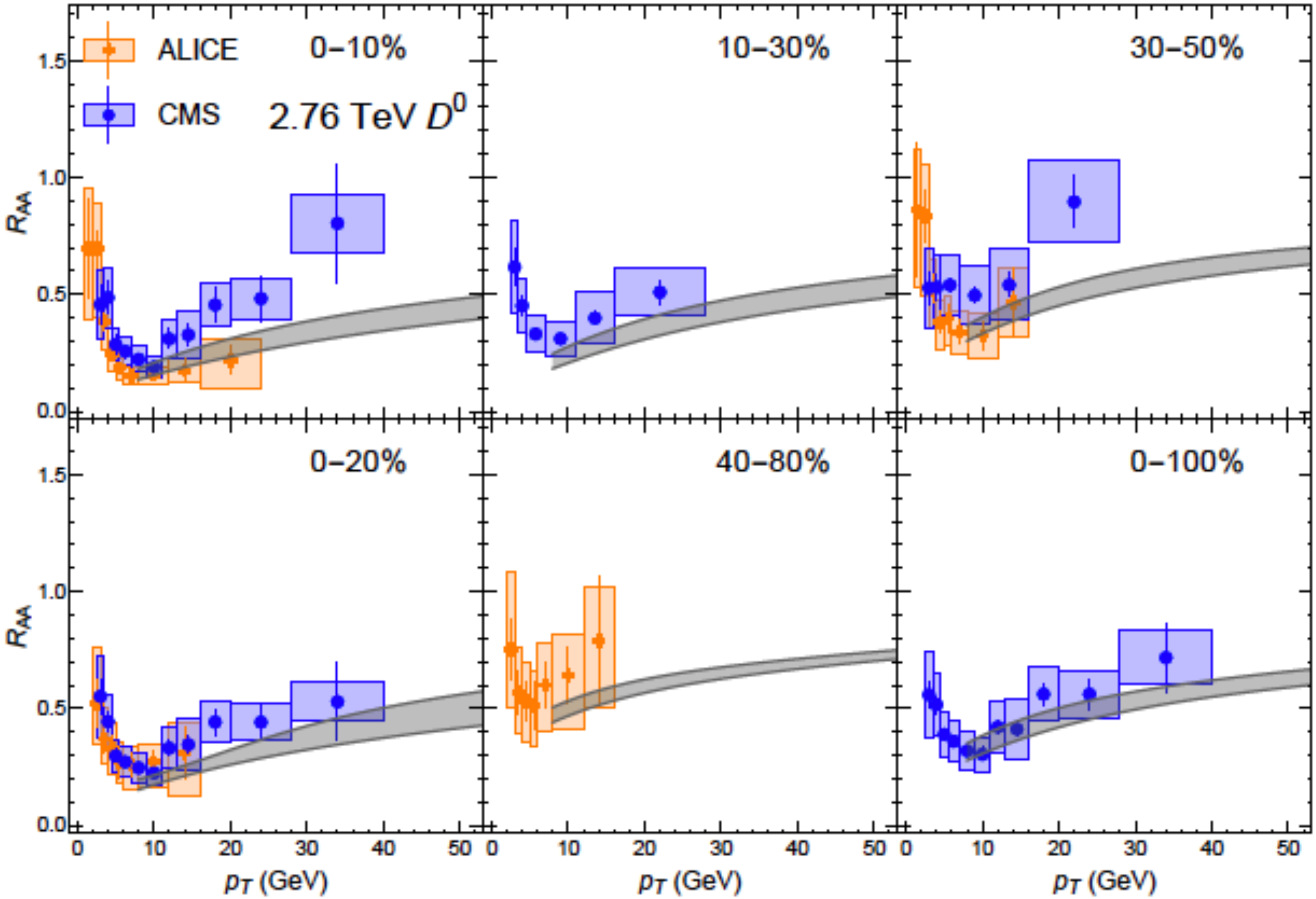
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Independent Test with Heavy Flavor Data



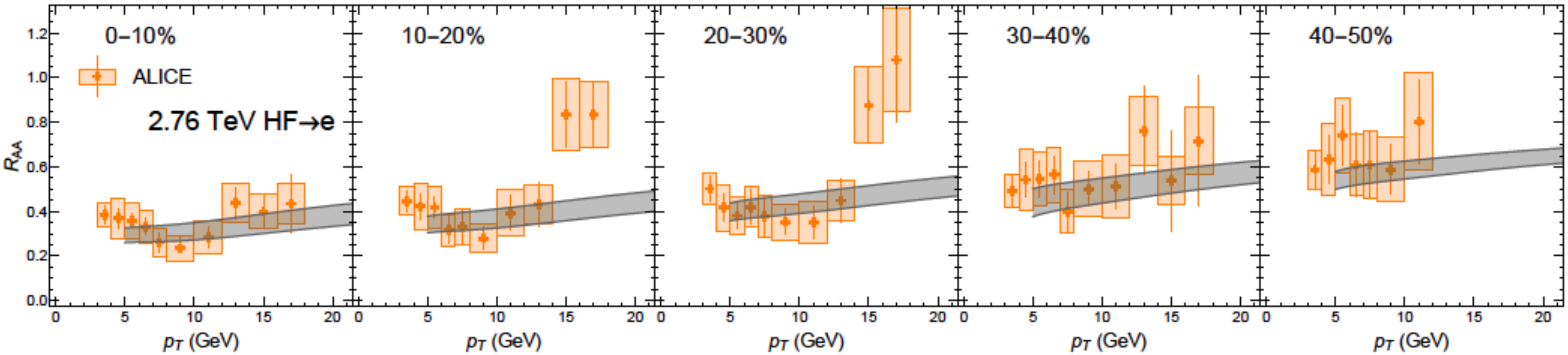
[S. Shi, J. Liao, M. Gyulassy, in preparation]

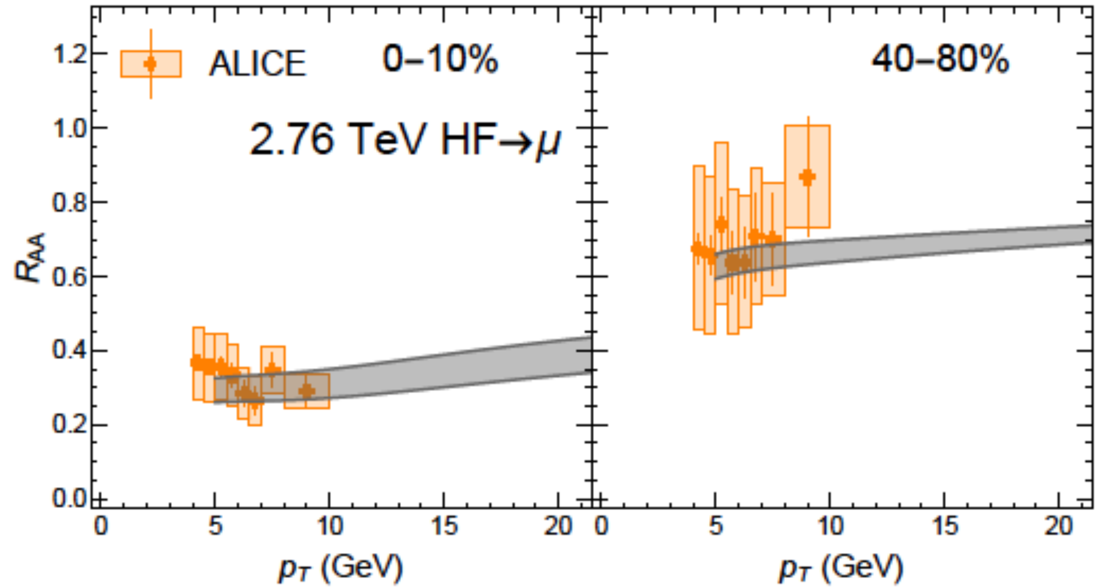
Independent Test with Heavy Flavor Data



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

Independent Test with Heavy Flavor Data





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

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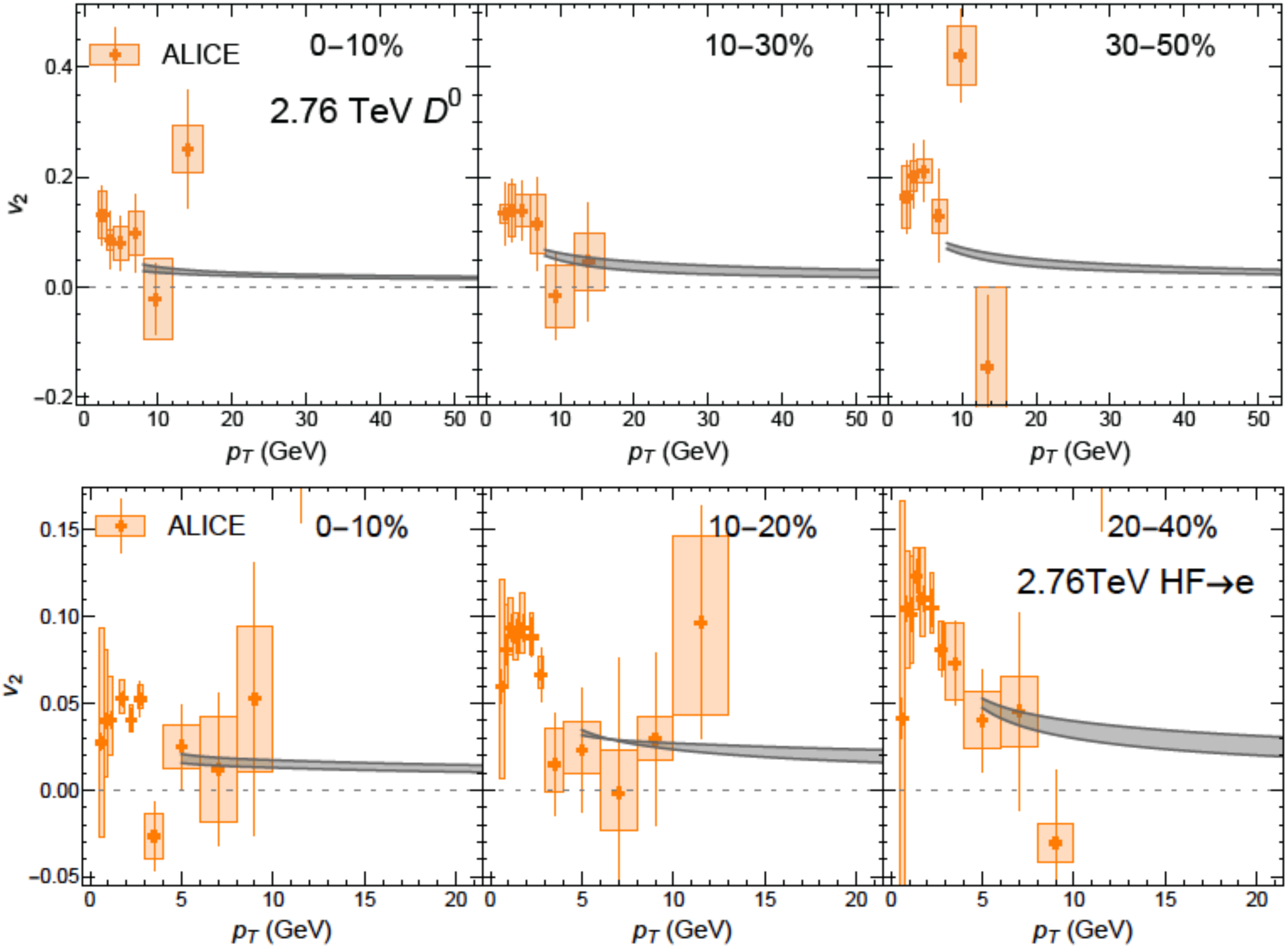
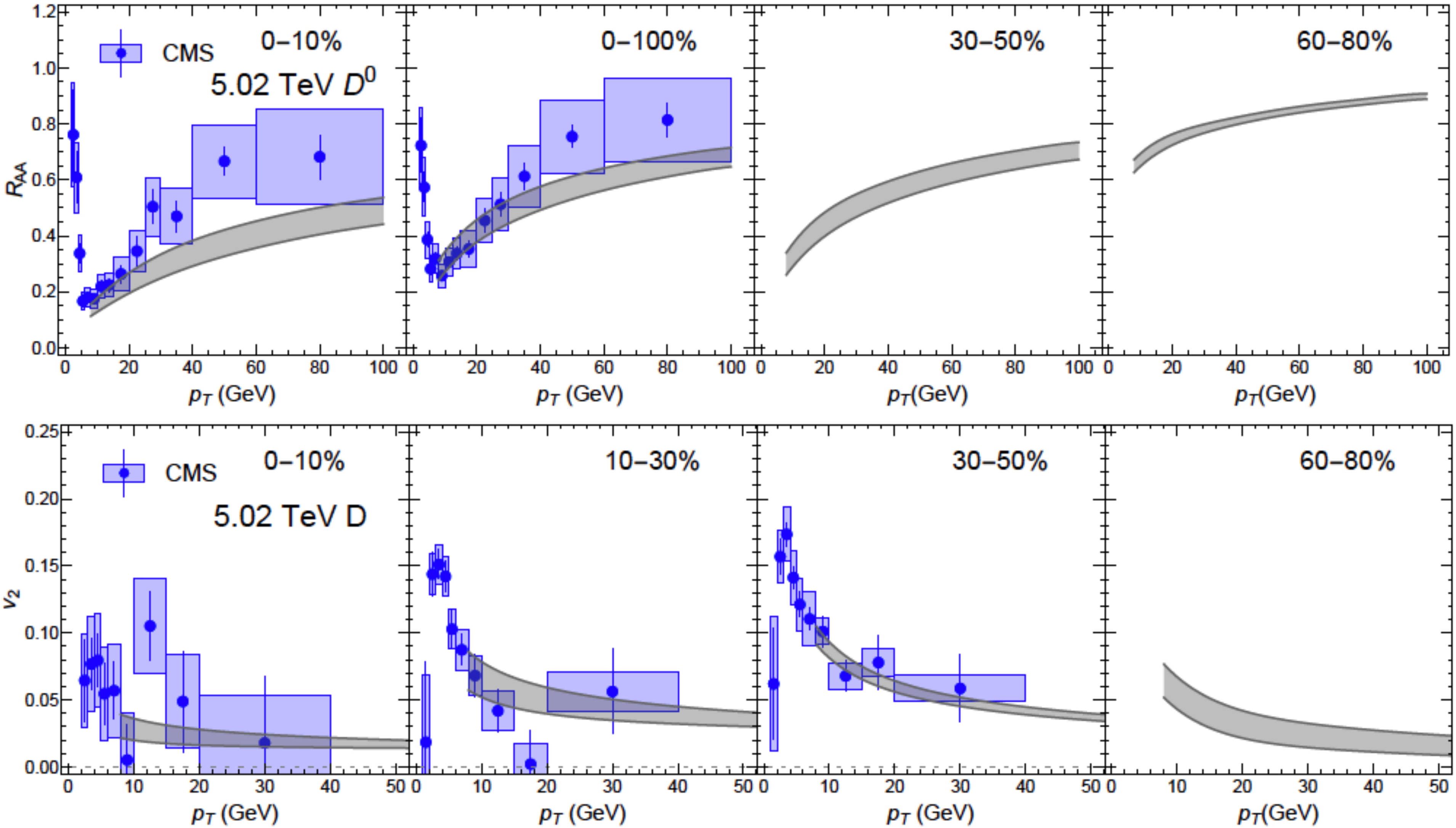


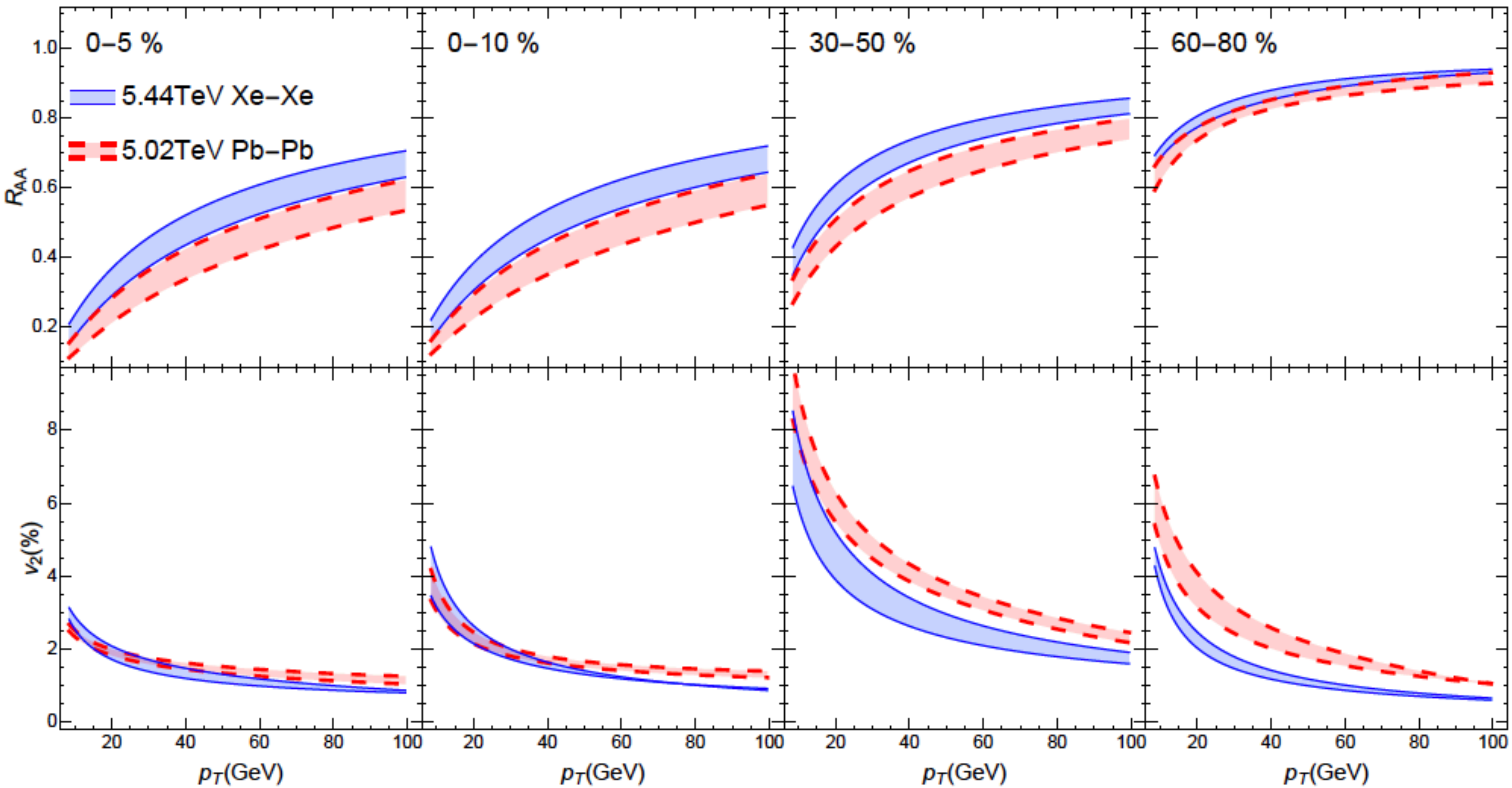
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Independent Test with Heavy Flavor Data



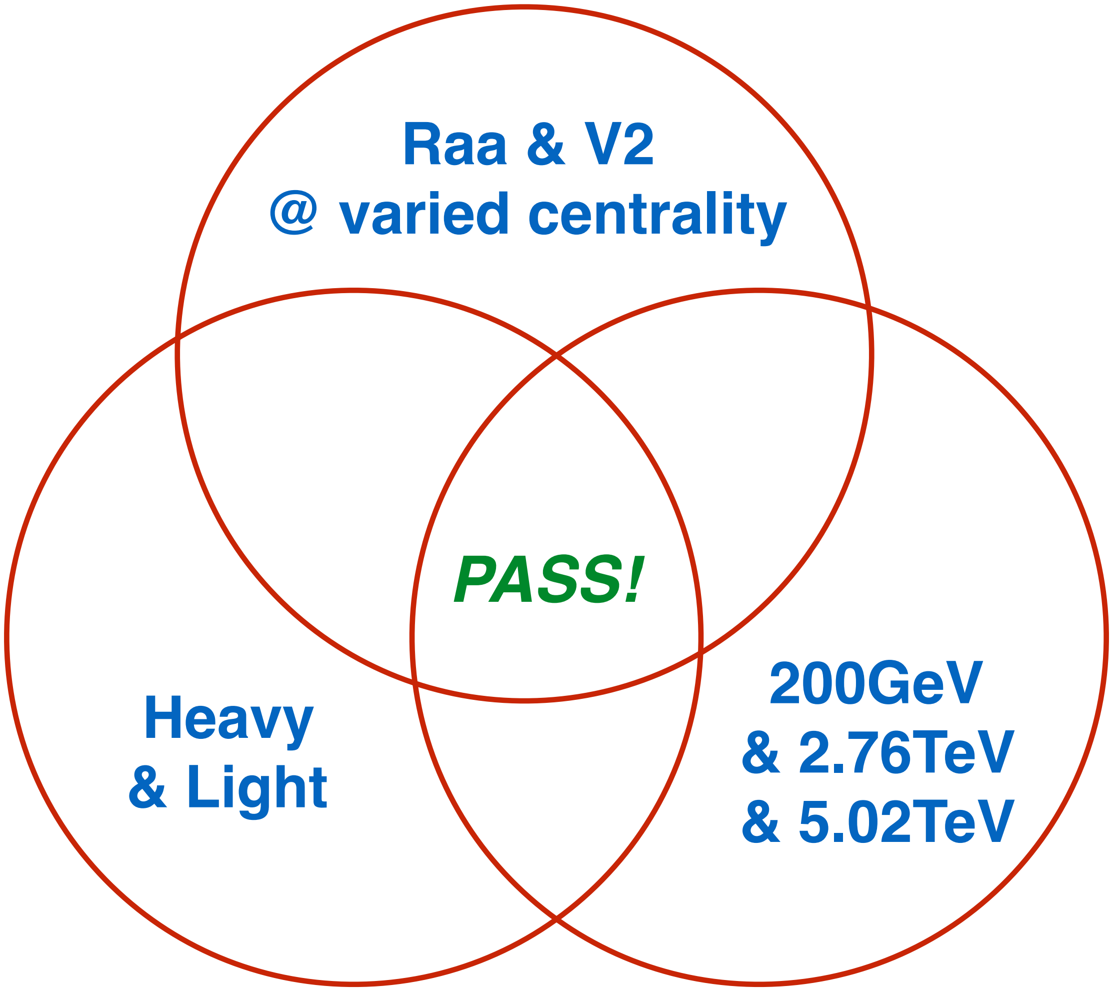
[S. Shi, J. Liao, M. Gyulassy, in preparation]

Example of Predictions: XeXe



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

The Challenge to Every Model

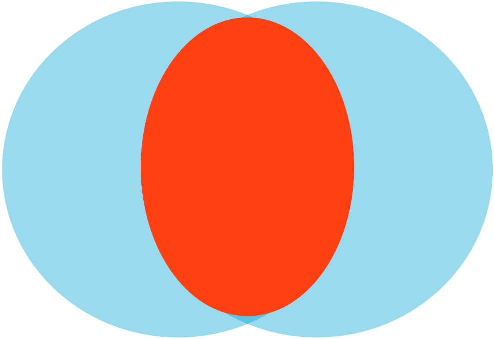


CUJET3 has passed this challenge.
Every model should take up this challenge.

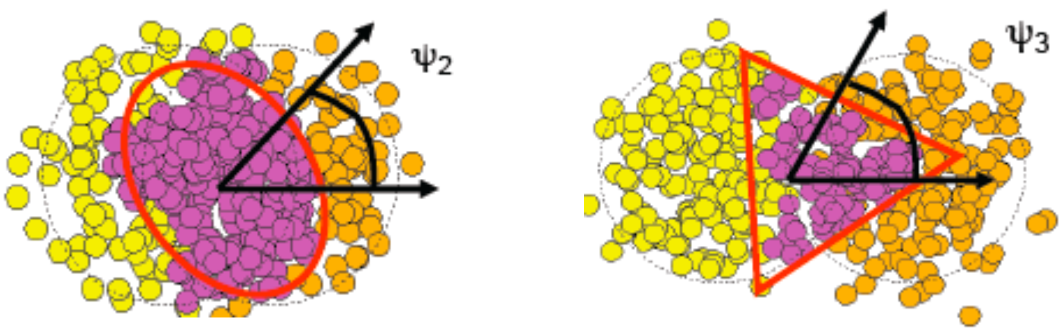
The CIBJET:
Soft-Hard-E-by-E Azimuth Correlations

Fluctuating Initial Condition (I.C.)

The initial condition used to be like this ...



We now know it is actually like this:



Influence on high Pt anisotropy? Consistency of soft-hard observables?

Soft-Hard Consistency Check!!!

Probing the Color Structure of the Perfect QCD Fluids via Soft-Hard-Event-by-Event Azimuthal Correlations

Shuzhe Shi,[1] Jinfeng Liao,[1] and Miklos Gyulassy[2,3,4]

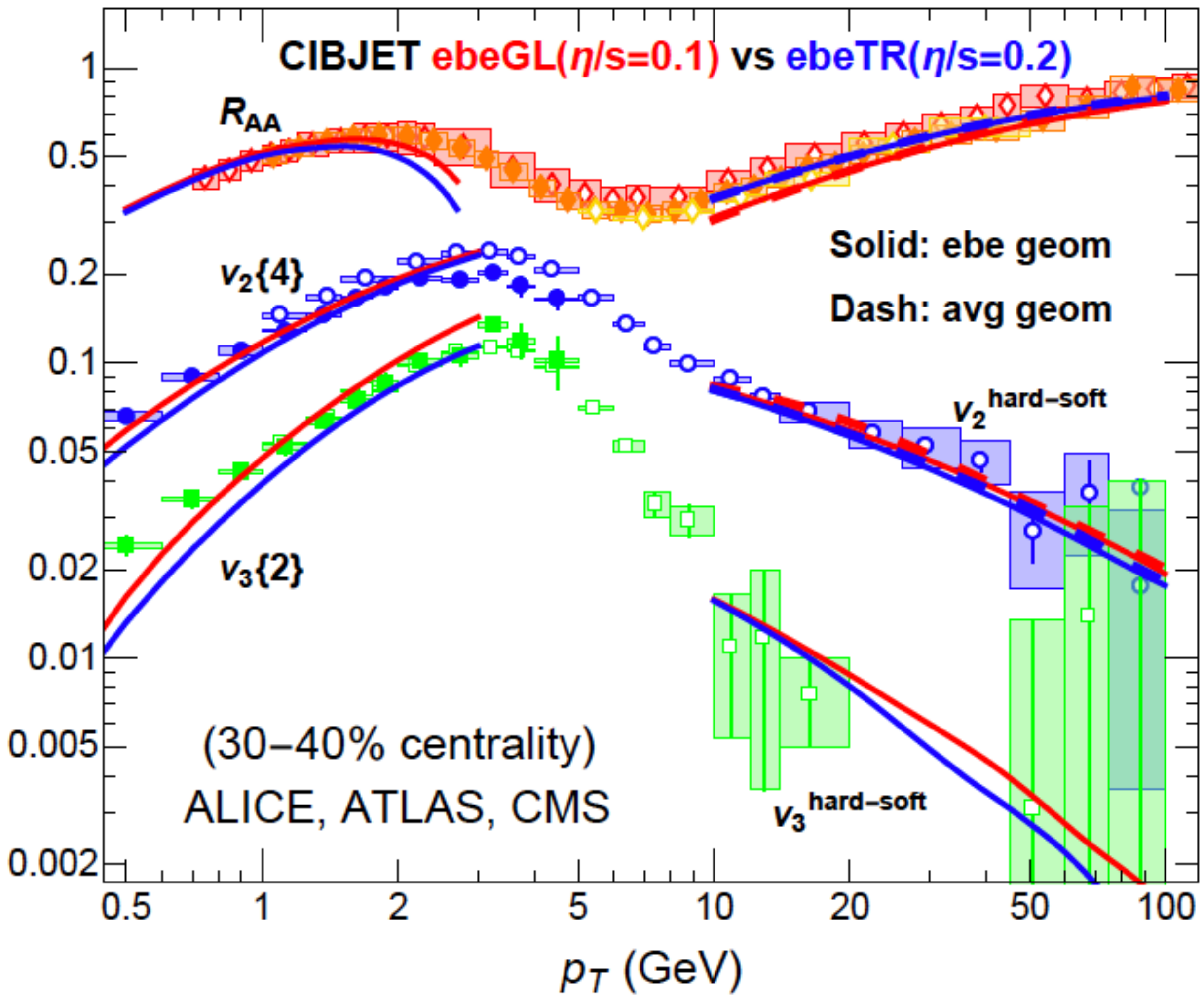
[1] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA.*
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.*
[3] *Pupin Lab MS-5202, Department of Physics, Columbia University, New York, NY 10027, USA.*
[4] *Institute of Particle Physics and Key Laboratory of Quark & Lepton Physics (MOE), Central China Normal University, Wuhan, 430079, China.*

We develop a comprehensive dynamical franework, CIBJET, to calculate on an event-by-event basis the dependence of correlations between soft ($p_T < 2$ Gev) and hard ($p_T > 10$ Gev) azimuthal flow angle harmonics on the color composition of near-perfect QCD fluids produced in high energy nuclear collisions at RHIC and LHC. CIBJET combines consistently predictions of event-by-event VISHNU2+1 viscous hydrodynamic fluid fields with CUJET3.1 predictions of event-by-event jet quenching. We find that recent correlation data favor a temperature dependent color composition including bleached chromo-electric $q(T) + g(T)$ components and an emergent chromo-magnetic degrees of freedom $m(T)$ consistent with non-perturbative lattice QCD information in the confinement/deconfinement temperature range.

[S. Shi, J. Liao, M. Gyulassy, arXiv:1804.01915]

Soft-Hard-E-by-E Azimuth Correlations

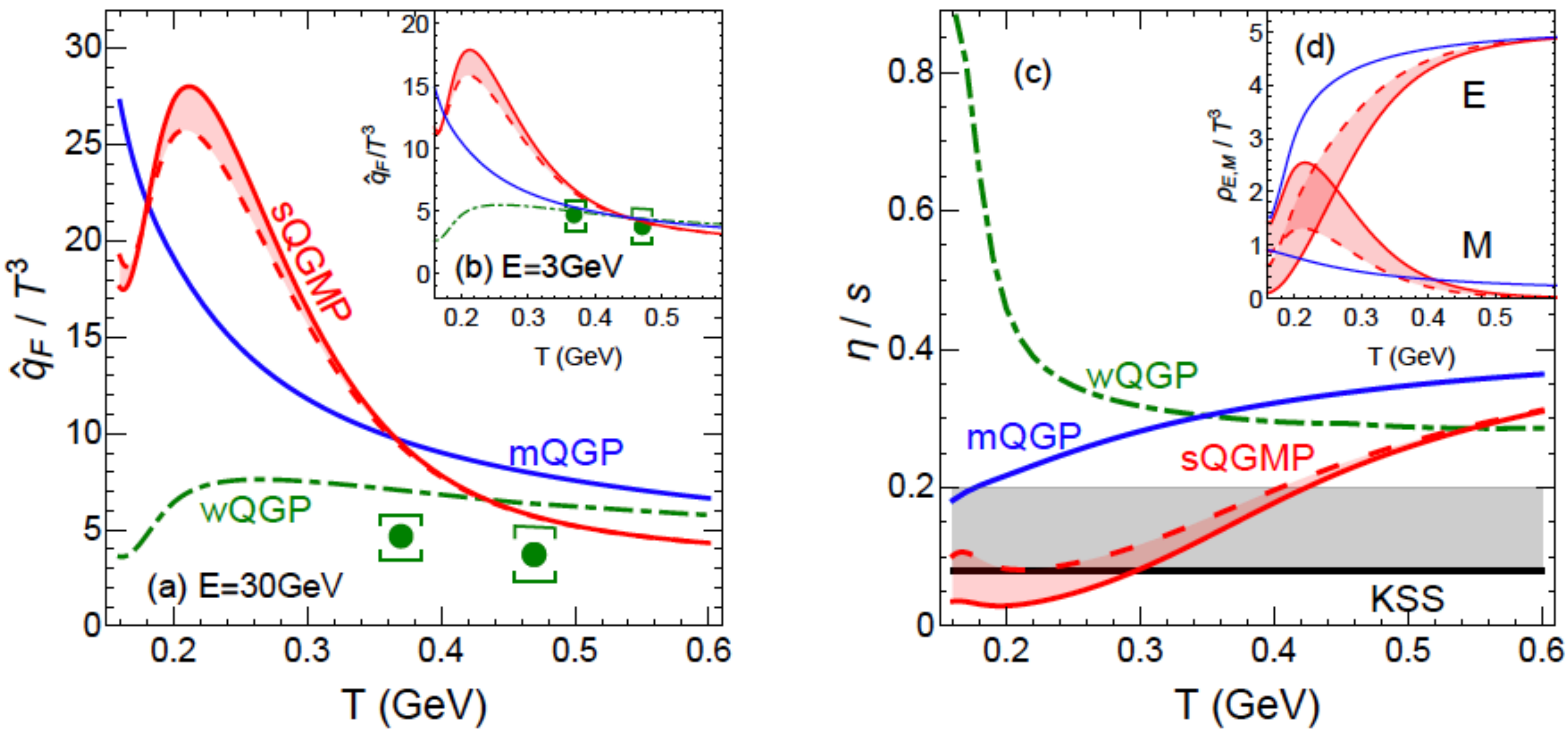
All observables computed from the same event-by-event simulations!



Our calculations show SOFT-HARD CONSISTENCY !!!

[S. Shi, J. Liao, M. Gyulassy, arXiv:1804.01915]

Transport Properties of sQGP



sQGMP: consistency between soft and hard transport properties!

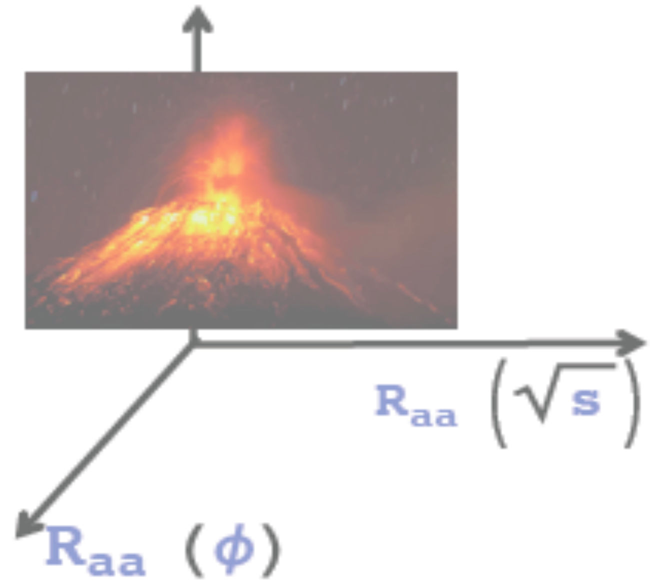
Heavy ion data —> transport properties —> color structure of sQGP!

[S. Shi, J. Liao, M. Gyulassy, arXiv:1804.01915]

Summary & Outlook

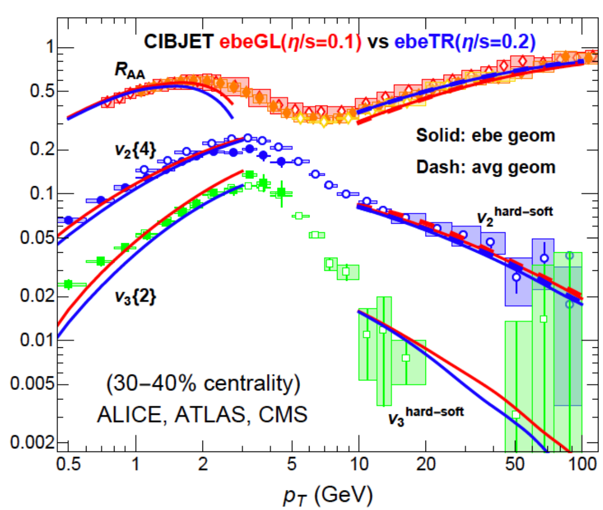
Summary

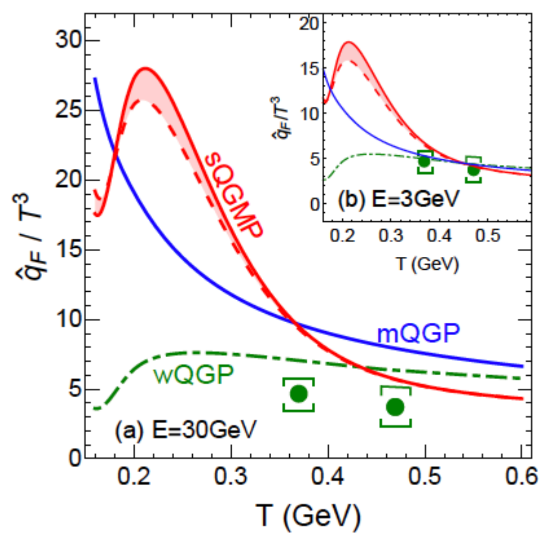
CUJET3/CIBJET:
a simulation framework based on
a microscopic picture of
Semi-quark-gluon monopole plasma
(sQGMP)

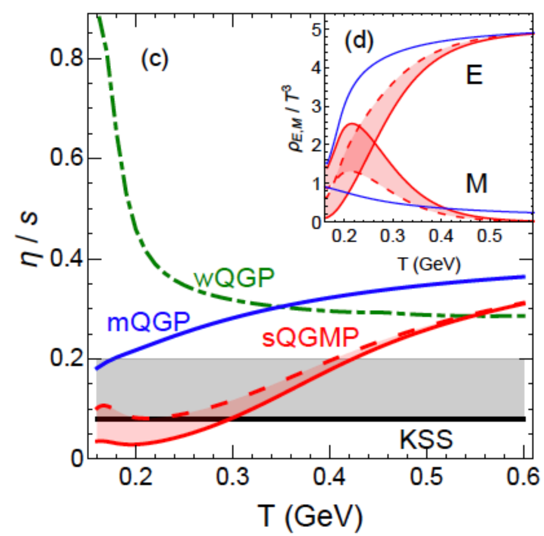


Phenomenologically it describes
all single hadron energy loss data well.

It achieves the soft-hard consistency!







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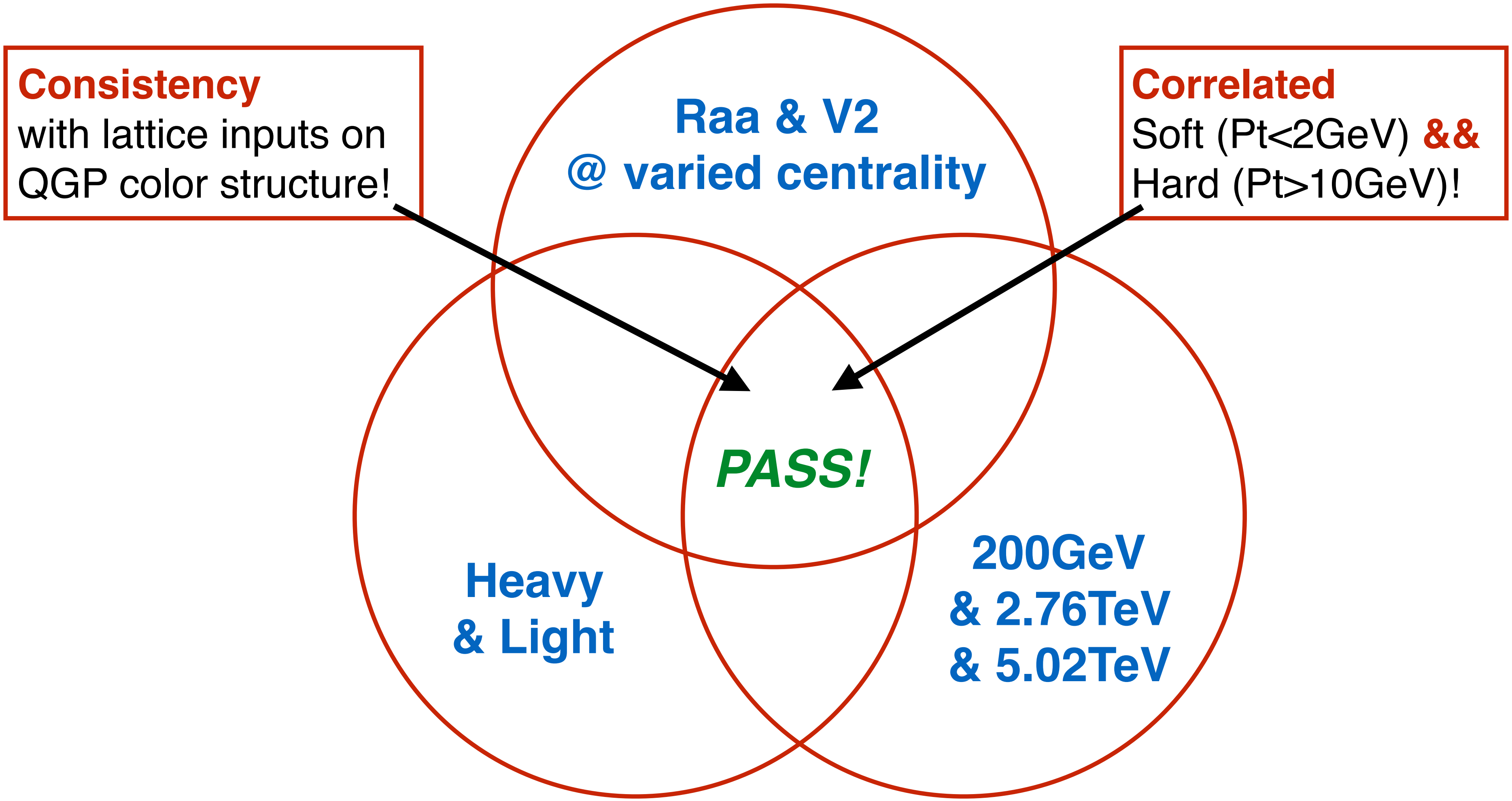

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