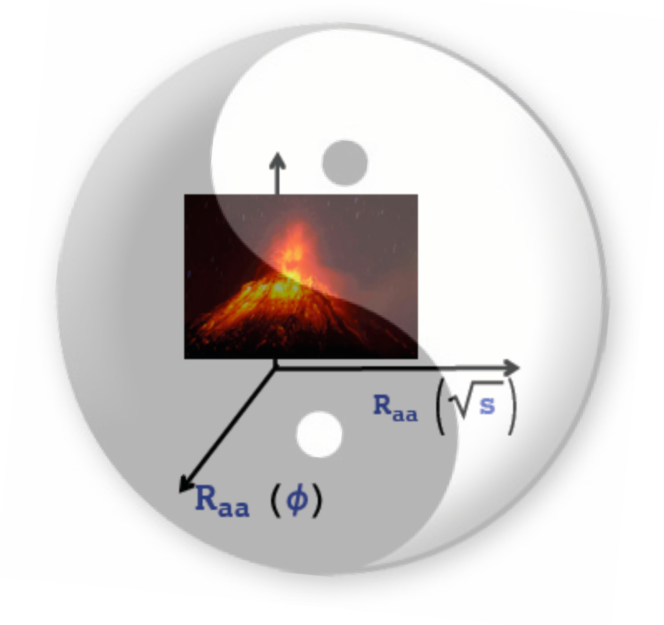
CPOD2017 @ Stony Brook Aug. 8, 2017

Understanding Confinement from Deconfined Phase



Jinfeng Liao

Indiana University, Physics Dept. & CEEM

Research Supported by NSF & DOE

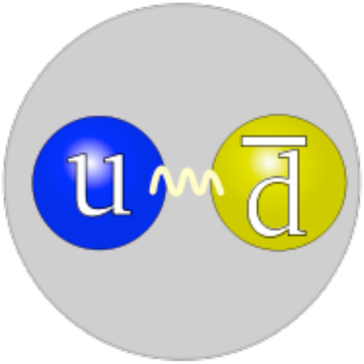
Outline

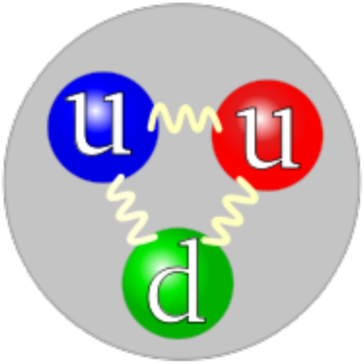
- Introductory Discussions
- Understanding Confinement from Above
- Confinement in Correlated Instaton-Dyon Ensemble
- Jet Energy Loss in CUJET3
- Summary

References:
JL & Shuryak,PRC2007,2008;NPA2006;PRD2010;PRL2008, 2009, 2012.
J. Xu, JL, M. Gyulassy, CPL2015; JHEP2016.
D. Li, JL, M. Huang, PRD2014.
X. Zhang, JL, PRC2013,2014;PLB2012.
M.LopezRuiz, J. Jiang, JL, arXiv:1611.02539.
S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1704.04577; to appear soon.

Introductory Discussions

“The Missing Particles"





from PDG

Mesons	
Light unflavored (π, ρ, a, b) (η, ω, f, ϕ, h)	619
Other light unflavored	735
Strange (K, K^*)	740
Charmed (D, D^*)	803
Charmed, strange (D_s, D_s^*, D_{sJ})	856
Bottom (B, V_{cb}/V_{ub}, B^*, B_J^*)	877
Bottom, strange (B_s, B_s^*, B_{sJ}^*)	1031
Bottom, charmed (B_c)	1039
$c\bar{c}$ (η_c, $J/\psi(1S)$, χ_c, ψ)	1040
$b\bar{b}$ (Υ, χ_b)	1109
Non-$q\bar{q}$ candidates	1131
Baryons	
N	1135
Δ	1178
Exotic	1199
Λ	1201
Σ	1217
Ξ	1241
Ω	1254
Charmed (Λ_c, Σ_c, Ξ_c, Ω_c)	1257
Doubly charmed (Ξ_{cc})	1277
Bottom (Λ_b, Σ_b, Σ_b^*, Ξ_b, b-baryon admixture)	1278

“The Missing Particles"

Free Quark Searches

All searches since 1977 have had negative results.

from PDG

This null result is by itself
a remarkable FACT of Nature.

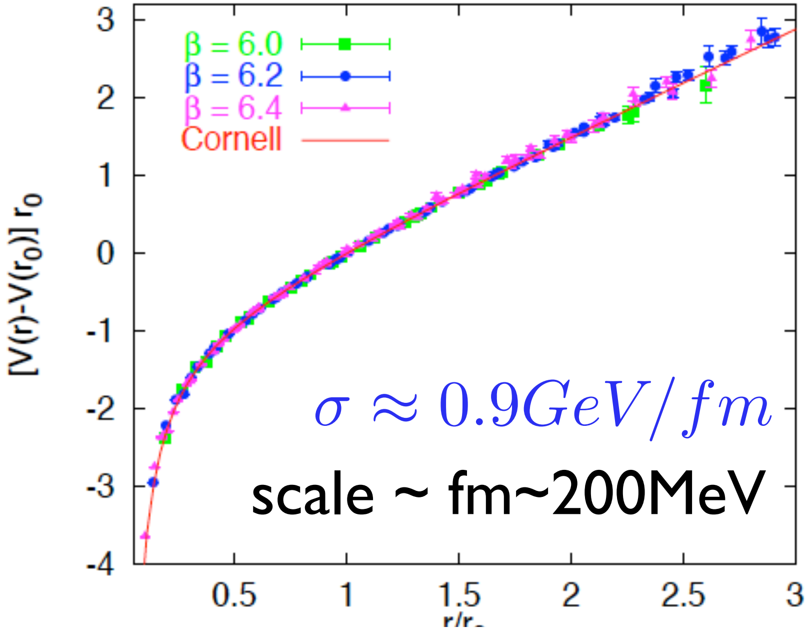
To understand the mechanism of confinement
in QCD (and QCD-like theories), remains
one of the biggest challenges within the Standard Model.

A Plausible Picture of Confining Force

$$V(r) = -\frac{\alpha_s}{r} + \sigma r$$

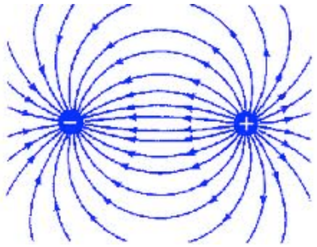
linear potential at large distance
~ 1 fm ~ 1/Lambda_QCD:
it costs infinite energy to
separate Q-bar-Q

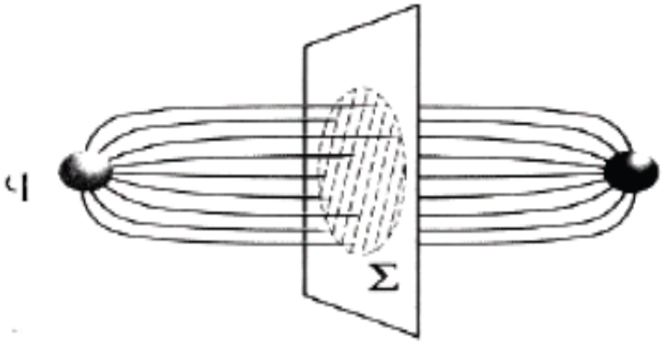
Origin of linear potential:
flux tube of chromo-E field



$\sigma \approx 0.9 GeV/fm$

scale ~ fm~200MeV



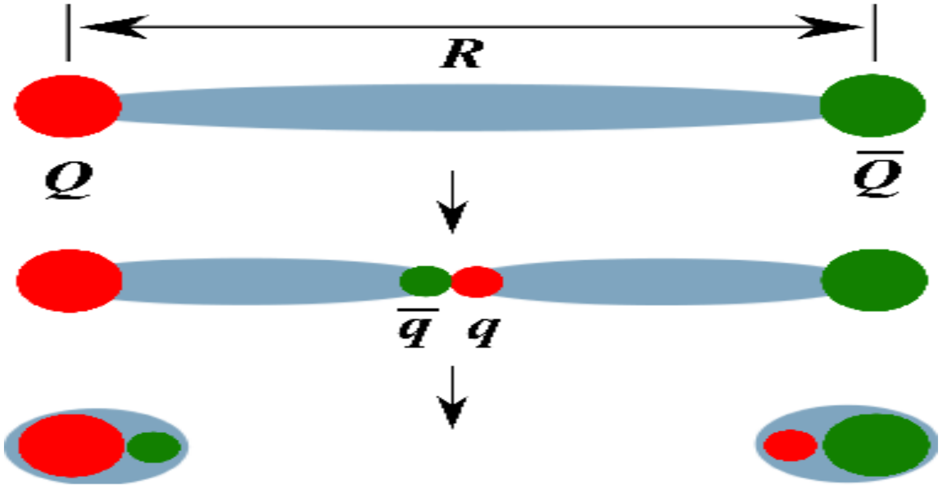


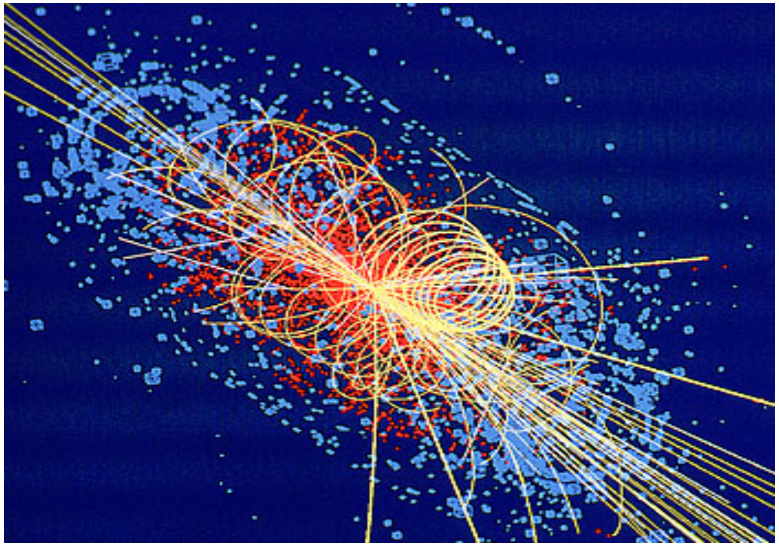
QED dipole field $V \sim \frac{1}{r}$

QCD dipole field $V \sim r$

Emergent stringy behavior!

Stringy Behavior Is Real: String Fragmentation





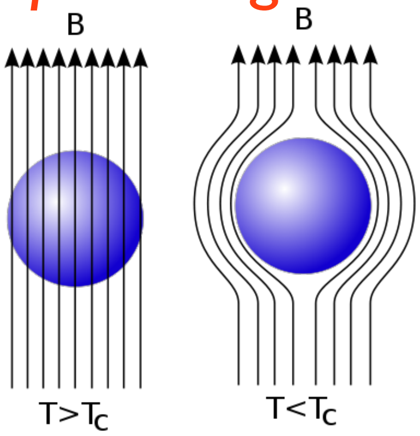
String fragmentation is widely perceived to be an important mechanism for multi-particle production (of soft hadrons) in high energy collider experiments.

It is necessarily implemented in many event generator/simulation tools, e.g. *HIJING, AMPT, PYTHIA,…*

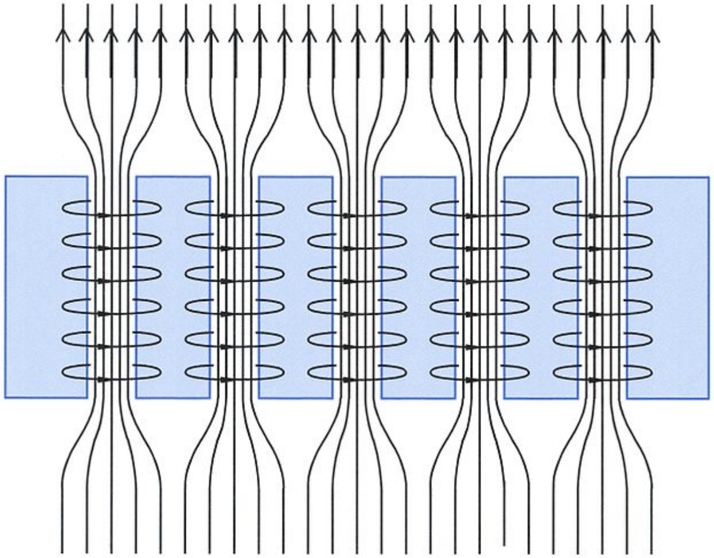
"Who orders that stringy behavior?"
Non-trivial **QCD vacuum** holds the string together!

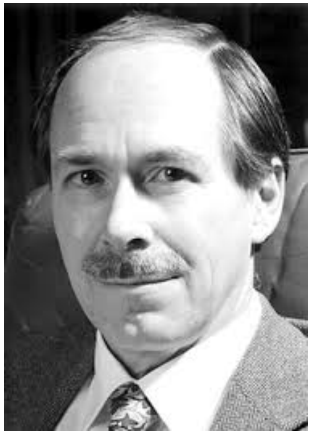
Meissner Effect in Superconductor

Meissner effect: electric (cooper-pair) condensate expels magnetic fields, and squeezes them into flux tube.



$$B_z(x) = B_0 e^{-x/\lambda}.$$

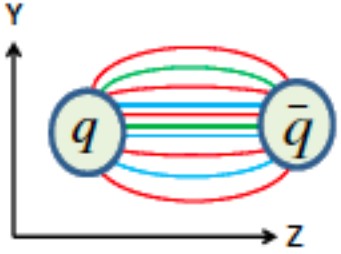


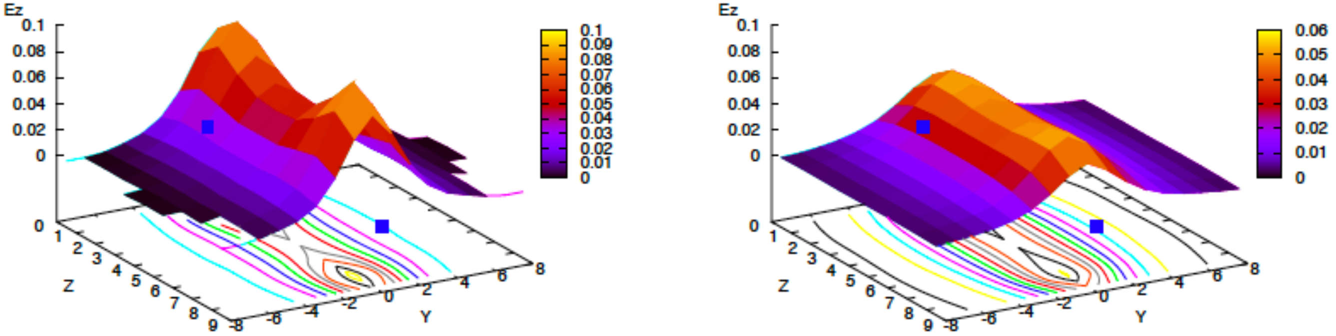


’t Hooft, Mandelstamm, Nambu —> transforming this insight into QCD

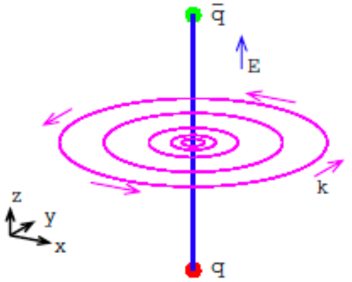
QCD Vacuum as Dual Superconductor

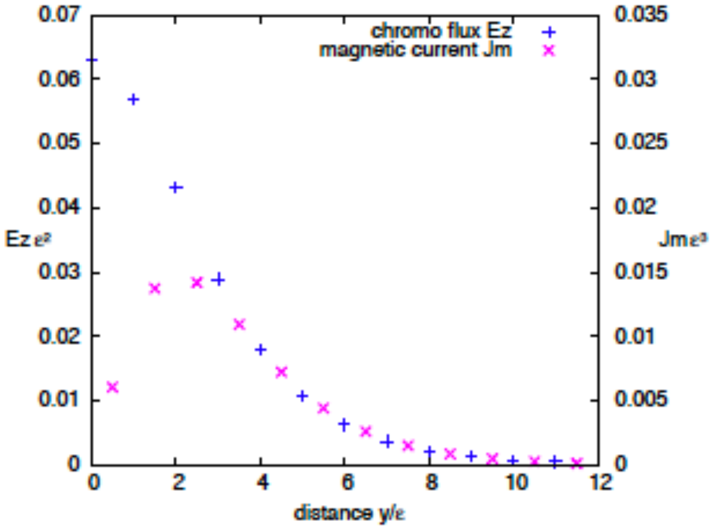
Lattice gauge theory shows the formation of flux tube.





[From Kei-Ichi Kondo, et al, Phys. Rep.579(2015)1-226]



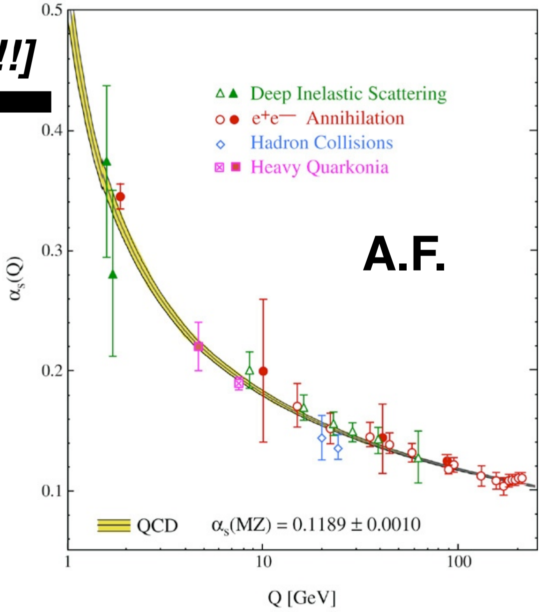


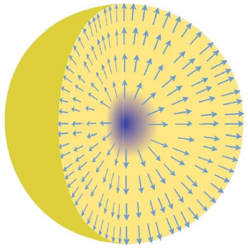
Dual Abelian-Higgs Model was developed as effective description of QCD vacuum, see e.g. review by Ripka arXiv:hep-ph/0310102

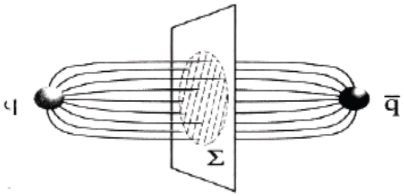
A Plausible Magnetic Scenario for QCD Vacuum

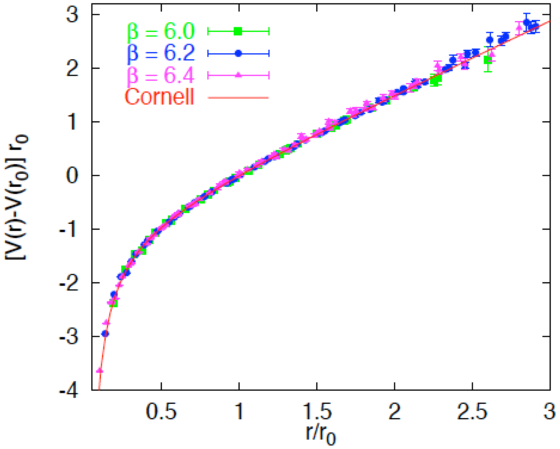
very strong coupling
at low energy
—> emergent magnetic monopoles
—> vacuum mag. condensate

[hard to workout!!!]





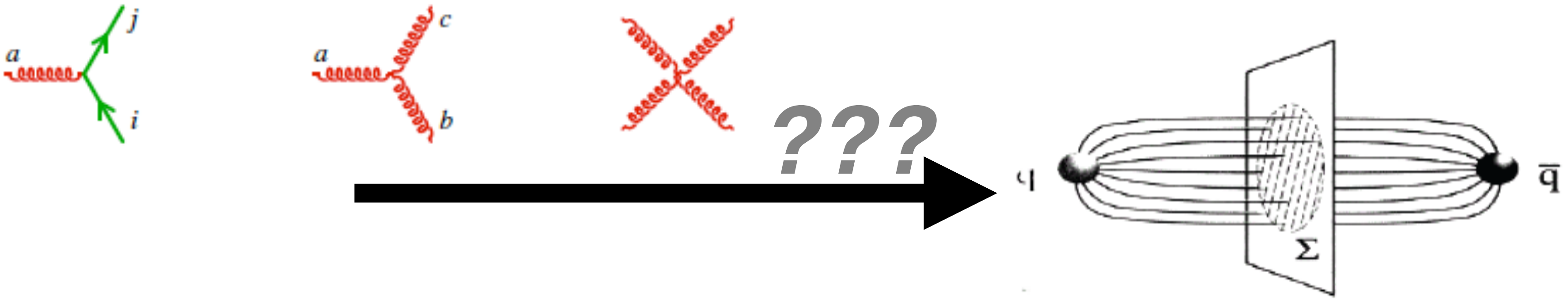




Regge phenomena;
Veneziano amplitudes;
Lund model,
string fragmentation;
…

flux tube, linear potential,
and stringy hadrons

Significant Missing Link



Clearly there is a significant link that has been missing —— for over four decades by now!

However new hopes and new directions have been developed in the past two decades about confinement:

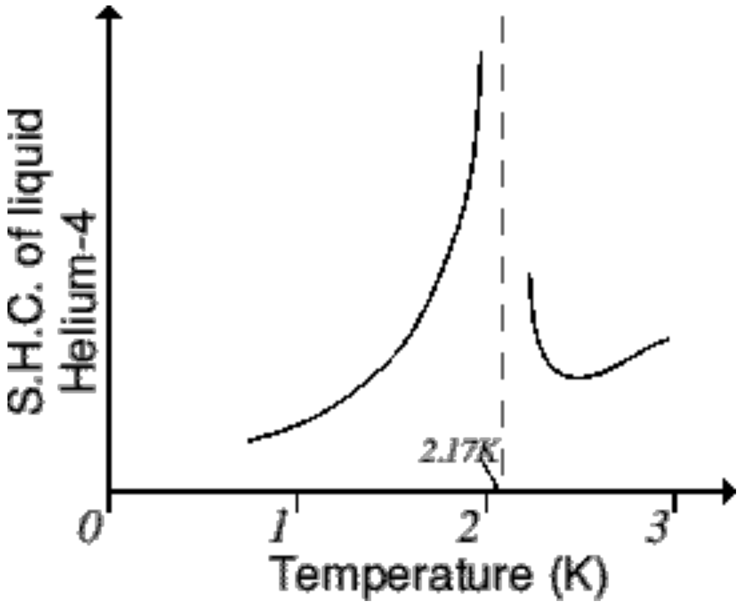
*** Unprecedented lattice computational power, that yields vast amount of precise, 1st principle information.**

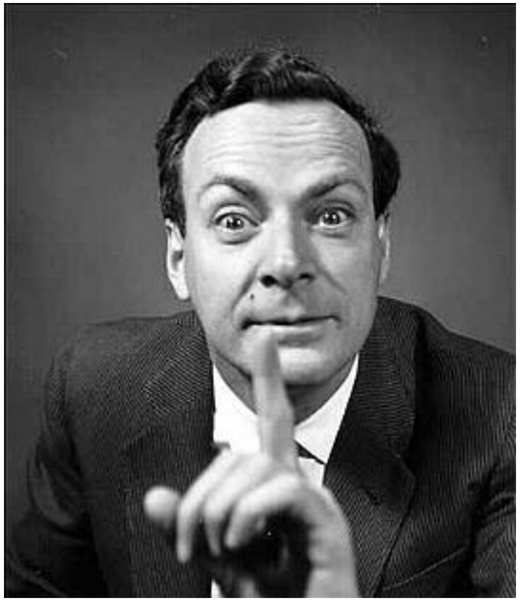
*** Explicit constructions of new topological objects (KvBLL calorons, instanton-monopoles) and their ensembles.**

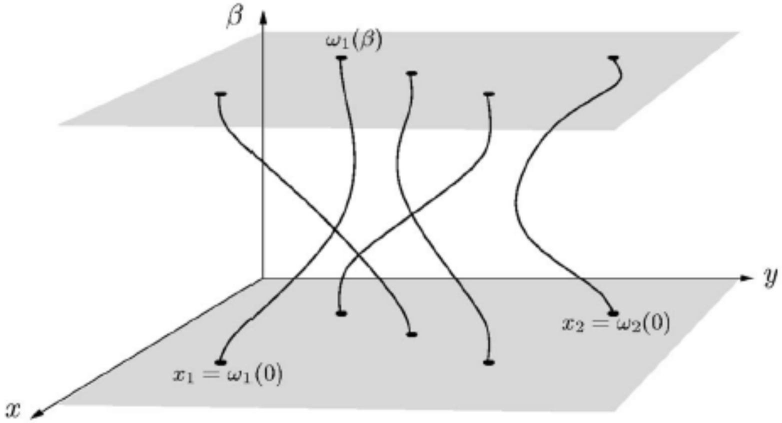
*** Thanks to heavy ion experiments, we now know A LOT about the properties of QCD matter *just about to become confining!***

Understanding Confinement from Above

Feynman's Wisdom about Helium-4







Feynman cycles for bosons

The "super" side is hard, and let's attack the lambda point from the "right side", when the system is just about to condense!

So, what about the “right side” of confinement?

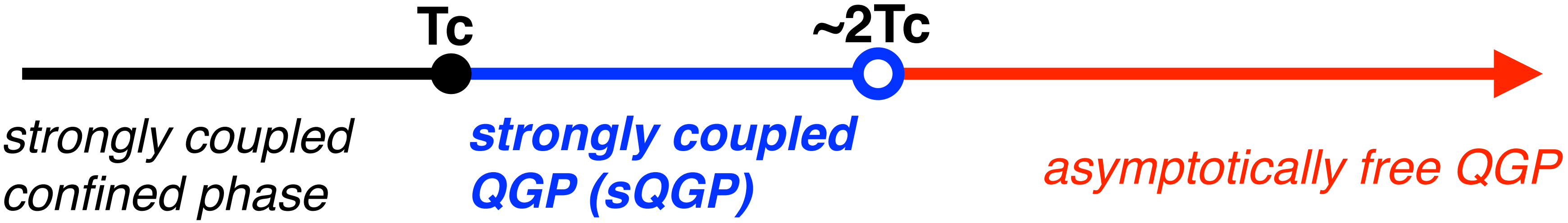
The old belief

Tc

strongly coupled
confined phase

asymptotically free QGP

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



Tc

~2Tc

strongly coupled
confined phase

strongly coupled
QGP (sQGP)

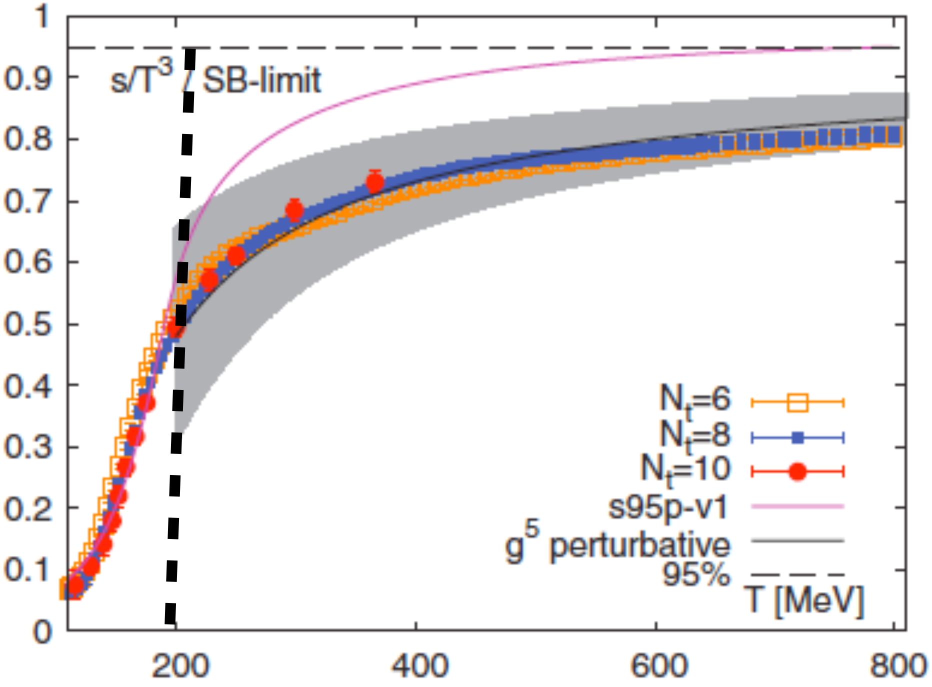
asymptotically free QGP

The matter just above confinement (in 1~2Tc),
is more closely related to the confined world, rather
than to the faraway place of asymptotic QGP!

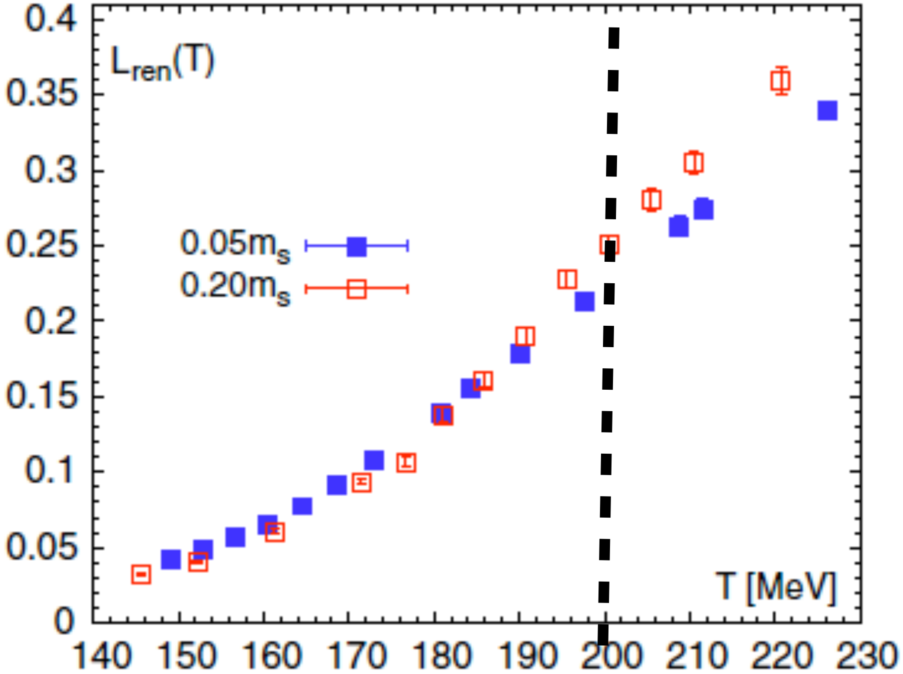
This is to say, the confinement physics (whatever it is),
must continue robustly into this region
— we call it “postconfinement” regime!

Liberation of Color? Missing DoF?

Degrees of freedom



Degree of color liberation

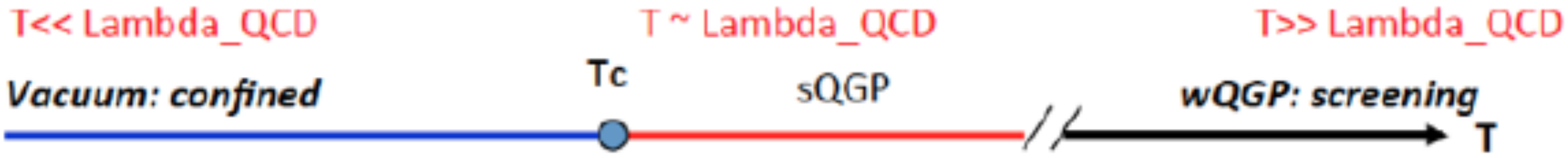


A region around Tc with liberated degrees of freedom but only partially liberated color-electric objects.

(Pisarski & collaborators: semi-QGP)

Then what are the "extra" dominant DoF here???
Thermal monopoles evaporated from vacuum condensate!

Understanding Confinement from the Above



T<< Lambda_QCD

Vacuum: confined

Tc

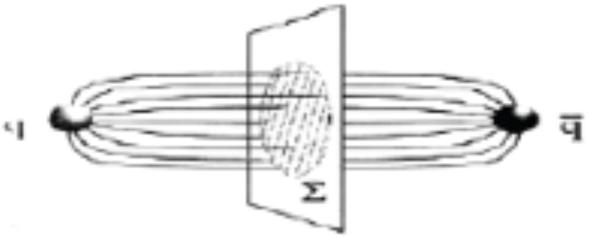
T ~ Lambda_QCD

sQGP

T>> Lambda_QCD

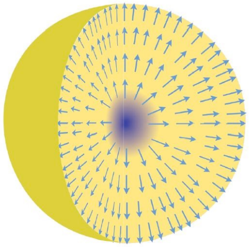
wQGP: screening

T



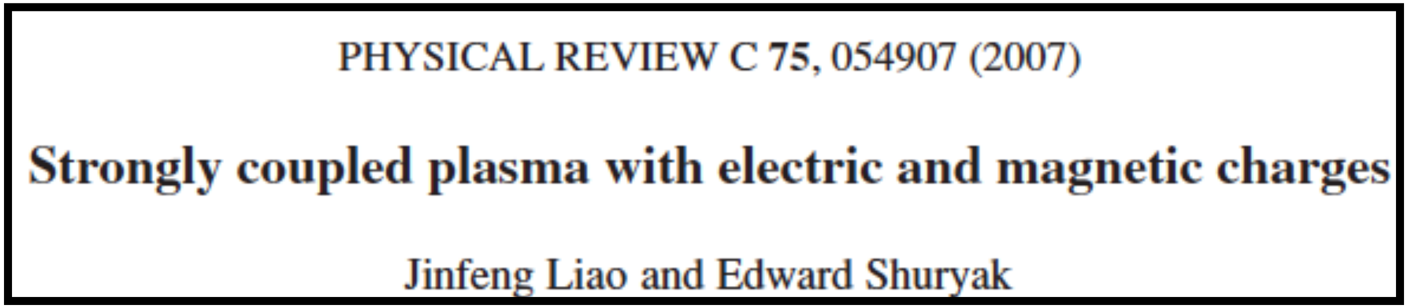
Emergent plasma
with E & M charges:
chromo-magnetic monopoles
are the "missing DoF"

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



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

Condensate monopoles —> dense thermal monopoles 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

Near-Tc Plasma Properties Are Special

The magnetic scenario of near-Tc plasma helps explain a number of highly nontrivial thermodynamic properties as computed from lattice gauge theories

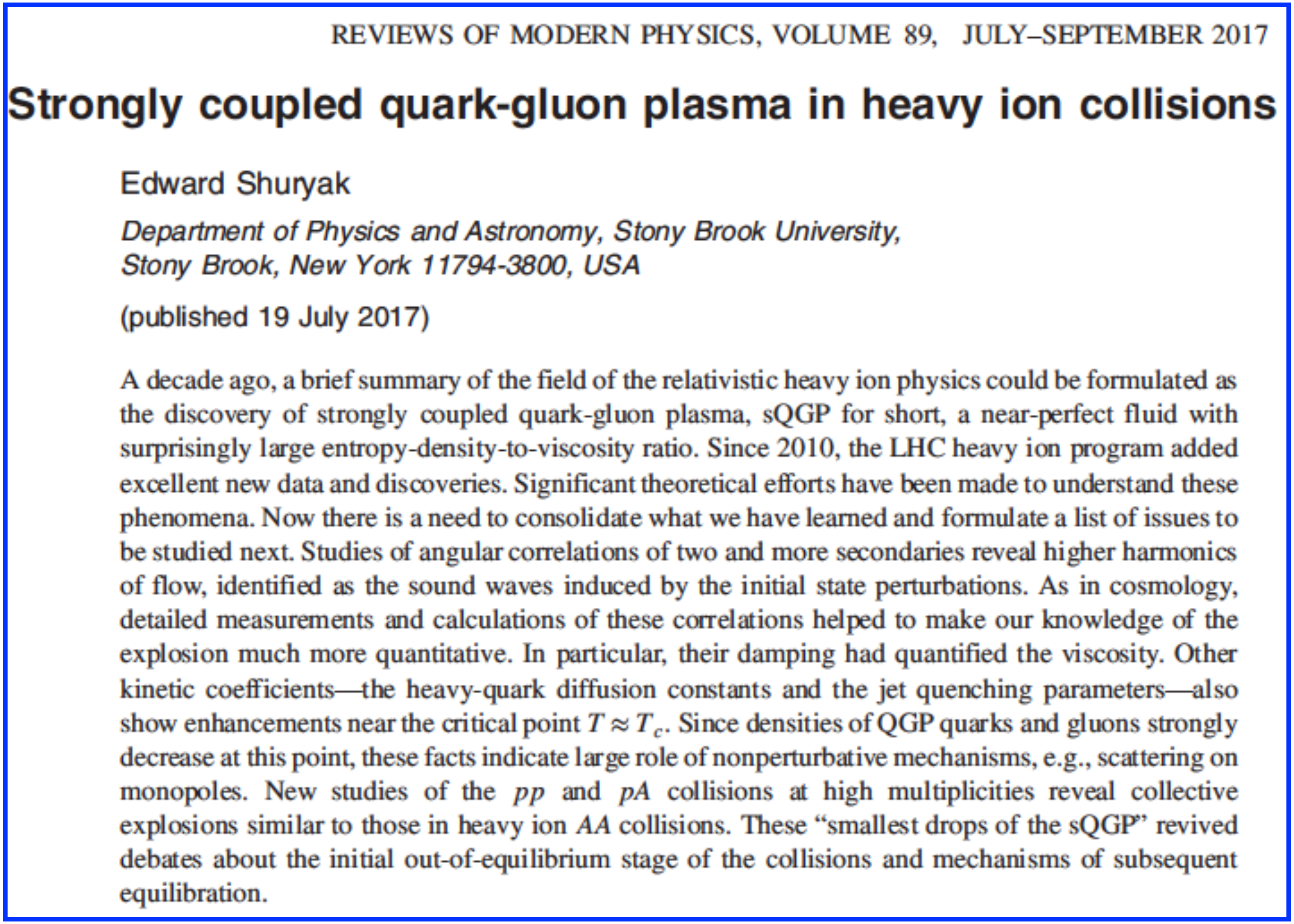
- *finite-T heavy quark potential*
- *confinement at Tc driven by ensemble of monopoles*
- *the flavor N_f dependence of transition temperature*

The magnetic scenario of near-Tc plasma helps explain a number of highly nontrivial transport properties as measured from heavy ion collision experiments

- *strong temperature dependence of transport properties*
- *nearly perfect liquid (shear viscosity, diffusion)*
- *near-Tc enhancement of jet energy loss*

In the rest of this talk: I will discuss an example of each.

A Very Nice New Review



REVIEWS OF MODERN PHYSICS, VOLUME 89, JULY–SEPTEMBER 2017

Strongly coupled quark-gluon plasma in heavy ion collisions

Edward Shuryak

Department of Physics and Astronomy, Stony Brook University,
Stony Brook, New York 11794-3800, USA

(published 19 July 2017)

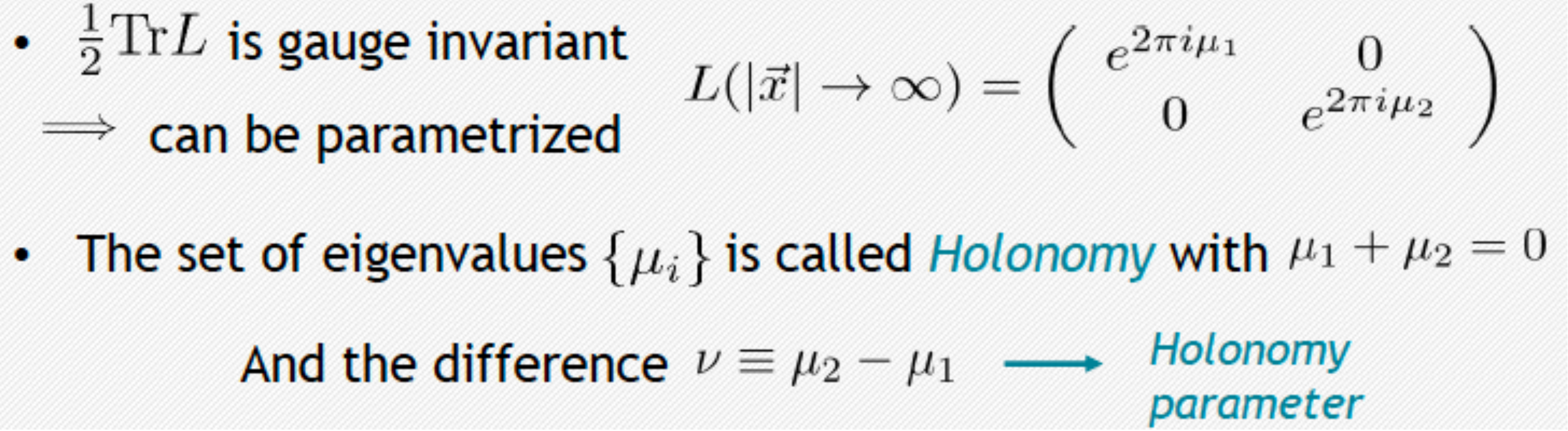
A decade ago, a brief summary of the field of the relativistic heavy ion physics could be formulated as the discovery of strongly coupled quark-gluon plasma, sQGP for short, a near-perfect fluid with surprisingly large entropy-density-to-viscosity ratio. Since 2010, the LHC heavy ion program added excellent new data and discoveries. Significant theoretical efforts have been made to understand these phenomena. Now there is a need to consolidate what we have learned and formulate a list of issues to be studied next. Studies of angular correlations of two and more secondaries reveal higher harmonics of flow, identified as the sound waves induced by the initial state perturbations. As in cosmology, detailed measurements and calculations of these correlations helped to make our knowledge of the explosion much more quantitative. In particular, their damping had quantified the viscosity. Other kinetic coefficients—the heavy-quark diffusion constants and the jet quenching parameters—also show enhancements near the critical point $T \approx T_c$. Since densities of QGP quarks and gluons strongly decrease at this point, these facts indicate large role of nonperturbative mechanisms, e.g., scattering on monopoles. New studies of the *pp* and *pA* collisions at high multiplicities reveal collective explosions similar to those in heavy ion *AA* collisions. These "smallest drops of the sQGP" revived debates about the initial out-of-equilibrium stage of the collisions and mechanisms of subsequent equilibration.

Confinement in Correlated Instanton-Monopole Ensemble [SU(2) Pure Yang-Mills Theory]

Significant developments by Stony Brook group (Shuryak, Zahed, Larsen, et al) — see their talks.

M.LopezRuiz, J. Jiang, JL, arXiv:1611.02539.
M.LopezRuiz, JL, in preparation.

Polyakov Loop & Holonomy



- $\frac{1}{2}\mathrm{Tr}L$ is gauge invariant
  $\Longrightarrow$ can be parametrized $L(|\vec{x}| \to \infty) = \begin{pmatrix} e^{2\pi i \mu_1} & 0 \\ 0 & e^{2\pi i \mu_2} \end{pmatrix}$
- The set of eigenvalues $\{\mu_i\}$ is called *Holonomy* with $\mu_1 + \mu_2 = 0$

  And the difference $\nu \equiv \mu_2 - \mu_1$ ⟶ *Holonomy parameter*

$$L_\infty = \lim_{|\vec{x}| \to \infty} \frac{1}{2} Tr \mathcal{P} e^{i \int_0^\beta d\tau A_4} = \cos(\pi\nu) \qquad \nu \in [0, 1]$$

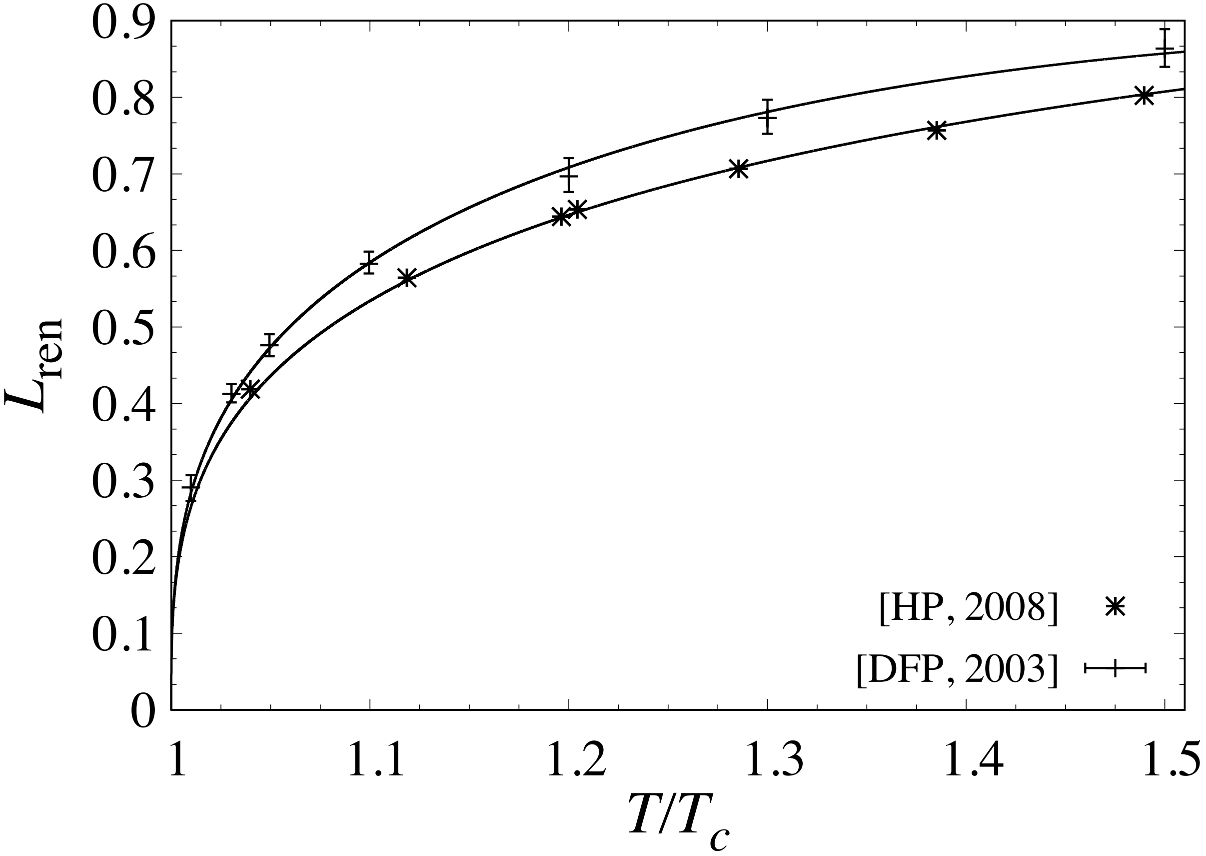
$\nu = \frac{1}{2} \to L_\infty = 0 :$ Confining, maximally nontrivial holonomy

$\nu = 0 \to L_\infty = 1 :$ Deconfined, trivial holonomy

It is holonomy that can play the role of the "Higgs" mechanism.

Lattice Results

*** 2nd order phase transition**
*** RAPID increase just above Tc**



Digal, Fortunato, Petreczky, PRD68(034008)2003
Huebner, Pica, PoS2008, arXiv:0809.3933[hep-lat]

Holonomy Potential

Classifying gauge field configurations according to holonomy:

$$\mathcal{Z} = \int \mathcal{D}[A_\mu] e^{-S} \to \int d\nu \left[\int \mathcal{D}[(A_\mu)|_\nu] e^{-S} \right]$$

Perturbative contributions

$$F_p(\nu) = \frac{(2\pi)^3 T^4}{3} \nu^2 \bar{\nu}^2$$

$$\bar{\nu} \equiv 1 - \nu$$

Nonperturbative contributions from topological sector

$$\simeq \sum_{N_{topo}} e^{-S_{N_{topo}}}$$

[But, what types of topological objects???]

$$\to \int d\nu e^{-\beta V F(\nu)}$$

Holonomy Potential

KvBLL Calorons

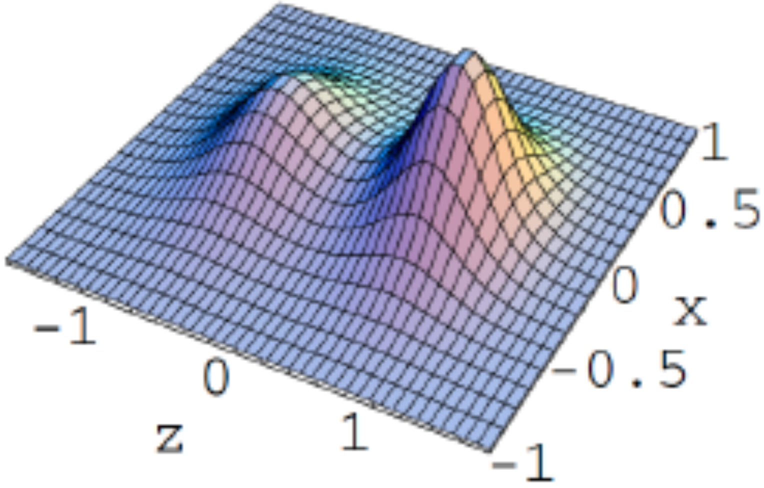
$$S_{\rm YM} = \frac{1}{2g^2}\int \mathrm{d}^4x\, \mathrm{Tr}\, F_{\mu\nu}F_{\mu\nu} \quad \text{where} \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - i[A_\mu, A_\nu]$$

$$Q_T = \frac{1}{16\pi^2}\int \mathrm{d}^4x\, \mathrm{Tr}\, F_{\mu\nu}\tilde{F}_{\mu\nu} = \pm 1 \qquad S = \frac{8\pi^2}{g^2}$$

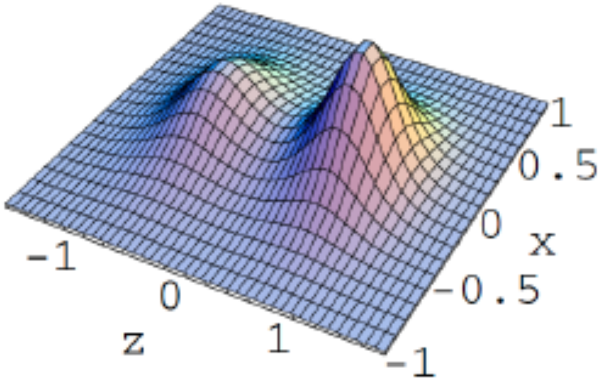
$$\boxed{A_\mu^{\rm KvBLL} = \delta_{\mu 4} v \frac{\tau^3}{2} + \frac{\tau^3}{2}\bar{\eta}^3_{\mu\nu}\partial_\nu \log\Phi + \frac{\Phi}{2}\mathrm{Re}\left[\left(\bar{\eta}^1_{\mu\nu} - i\bar{\eta}^2_{\mu\nu}\right)\left(\tau^1 + i\tau^2\right)\left(\partial_\nu + iv\delta_{\nu 4}\right)\tilde{\chi}\right]}$$

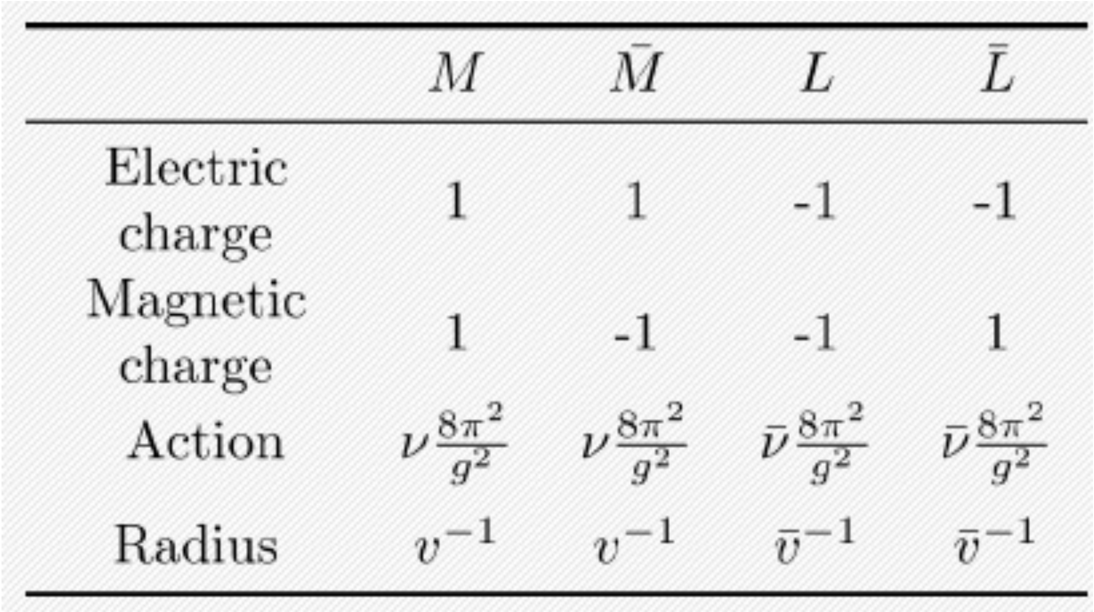
Non-trivial holonomy $v = 2\pi T\nu$ with $\nu \in [0,1]$

Most interestingly: this object is made of Nc constituent dyons (monopoles)!!!

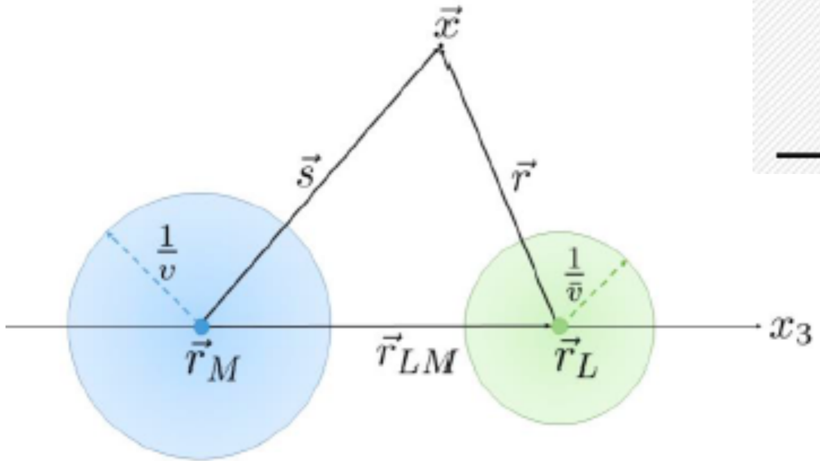


Instanton-Dyons





	M	$\bar{M}$	L	$\bar{L}$
Electric charge	1	1	-1	-1
Magnetic charge	1	-1	-1	1
Action	$\nu\frac{8\pi^2}{g^2}$	$\nu\frac{8\pi^2}{g^2}$	$\bar{\nu}\frac{8\pi^2}{g^2}$	$\bar{\nu}\frac{8\pi^2}{g^2}$
Radius	v^{-1}	v^{-1}	$\bar{v}^{-1}$	$\bar{v}^{-1}$



$$v = 2\pi T\nu \, , \; \bar{v} = 2\pi T\bar{\nu}$$

Holonomy as effective "Higgsing"

The dyons inside KvBLL instantons hold the promise of driving confinement!

Building Ensemble of Instanton-Dyons

$$\mathcal{Z} = \int \mathcal{D}[A_\mu] e^{-S} \rightarrow \int d\nu \left[\int \mathcal{D}[(A_\mu)|_\nu] e^{-S} \right]$$

$$\rightarrow \int d\nu e^{-\beta V F(\nu)}$$

$$\mathcal{Z} = e^{-VP(\nu)} \sum_{\substack{N_M, N_L, \\ N_{\bar{L}}, N_{\bar{M}}}} \frac{1}{N_L! N_M! N_{\bar{L}}! N_{\bar{M}}!} \int \prod_{l=1}^{N_L} f_L T^3 \, \mathrm{d}^3 r_{L_l} \prod_{m=1}^{N_M} f_M T^3 \, \mathrm{d}^3 r_{M_m}$$

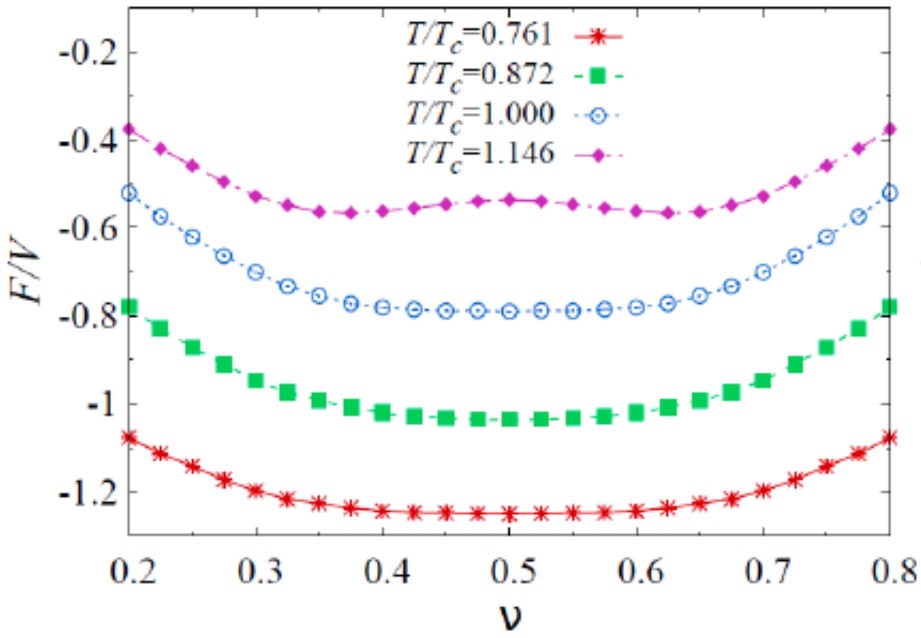
$$\times \prod_{\bar{l}=1}^{N_{\bar{L}}} f_{\bar{L}} T^3 \, \mathrm{d}^3 r_{\bar{L}_{\bar{l}}} \prod_{\bar{m}=1}^{N_{\bar{M}}} f_{\bar{M}} T^3 \, \mathrm{d}^3 r_{\bar{M}_{\bar{m}}} \det(G_D) \det(G_{\bar{D}}) \, e^{-V_{D\bar{D}}}$$

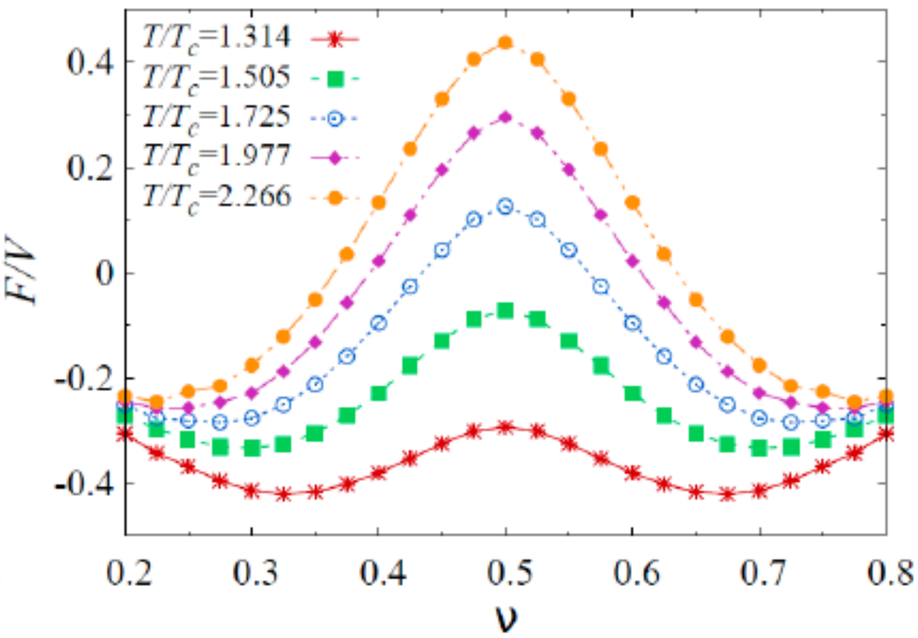
In short: sum over a statistical ensemble of many L & M Instanton-dyons with interactions (with 1-loop perturbative quantum fluctuations included)

Confinement Driven by Instanton-Dyons

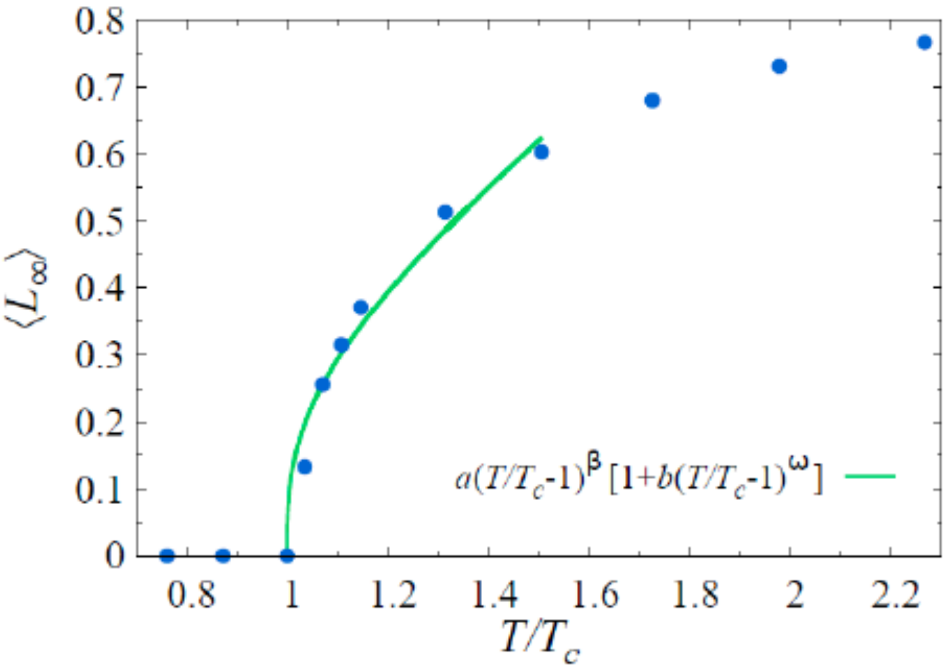
From high —> low temperatures:
Coupling increases, action decreases, dyons denser!

$S(T) = \frac{8\pi^2}{g^2(T)} = \frac{22}{3}\log\left(\frac{T}{\Lambda}\right)$ ***At $T = T_c$, the scale parameter is defined*** $\Rightarrow \frac{\Lambda}{T_c} = \exp\left[-\frac{3}{22}S(T_c)\right]$





Confinement Driven by Instanton-Dyons

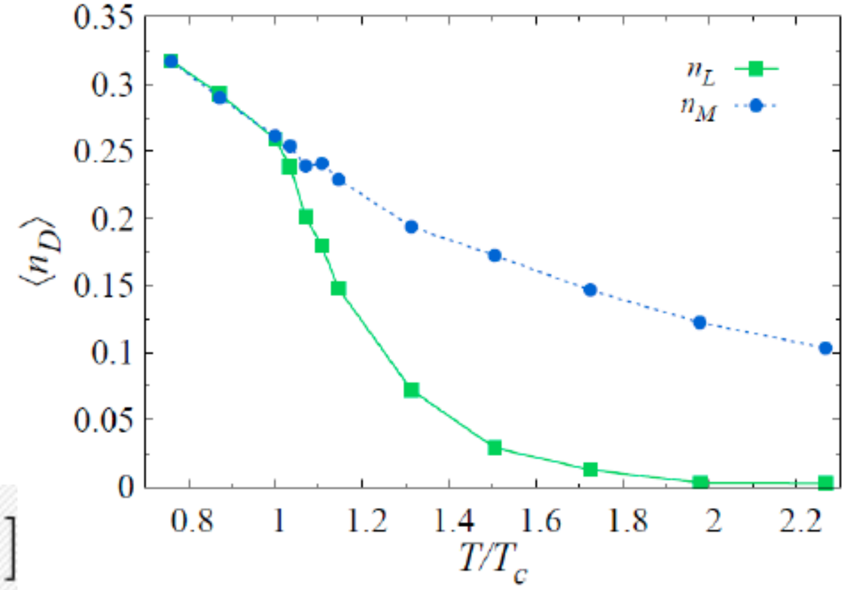


2nd order phase transition in SU(2) pure YM

$$\langle L_\infty \rangle \sim (T/T_c - 1)^\beta [1 + (T/T_c - 1)^\omega]$$

$$\beta \approx 0.3265 \qquad \omega \approx 0.84$$

Dyon density rapidly increases toward Tc from above



Dyon-anti-Dyon Correlations

“Gas” ensemble: negligible correlations;
“Liquid” ensemble: significant short range correlations
—> —> Properties of the ensemble crucially depend on such correlations!

$$\mathcal{Z} = e^{-VP(\nu)} \sum_{\substack{N_M, N_L, \\ N_{\bar{L}}, N_{\bar{M}}}} \frac{1}{N_L! N_M! N_{\bar{L}}! N_{\bar{M}}!} \int \prod_{l=1}^{N_L} f_L T^3 \, \mathrm{d}^3 r_{L_l} \prod_{m=1}^{N_M} f_M T^3 \, \mathrm{d}^3 r_{M_m}$$

$$\times \prod_{\bar{l}=1}^{N_{\bar{L}}} f_{\bar{L}} T^3 \, \mathrm{d}^3 r_{\bar{L}_{\bar{l}}} \prod_{\bar{m}=1}^{N_{\bar{M}}} f_{\bar{M}} T^3 \, \mathrm{d}^3 r_{\bar{M}_{\bar{m}}} \det(G_D) \det(G_{\bar{D}}) \, e^{-V_{D\bar{D}}}$$

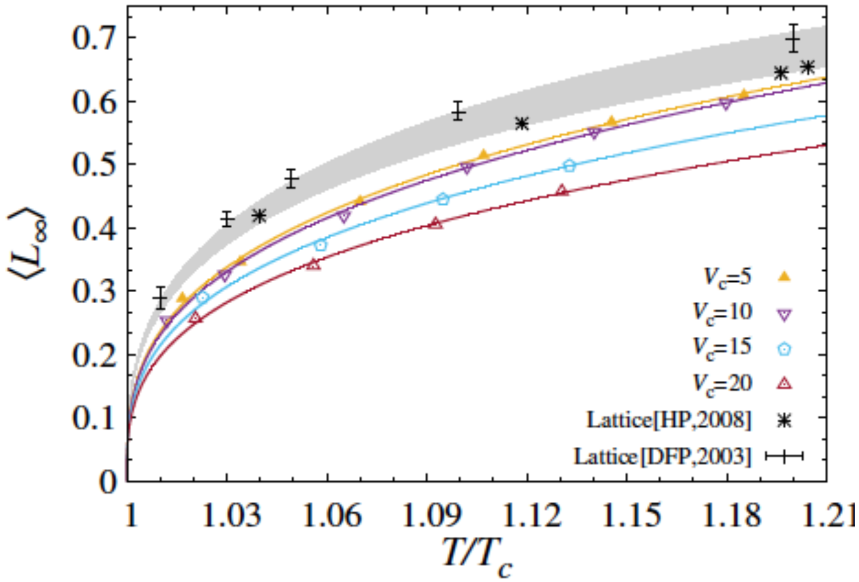
$$V_{j\bar{j}}^{C} = \frac{\nu_j V_c}{1 + e^{(\zeta_{\bar{j}} - \zeta_c)}}, \quad \zeta_j = 2\pi \nu_j T r_{j\bar{j}}$$

Implemented via interaction potential energy term

A repulsive core potential is crucial for enforcing confinement!
[first shown by Shuryak and collaborators]

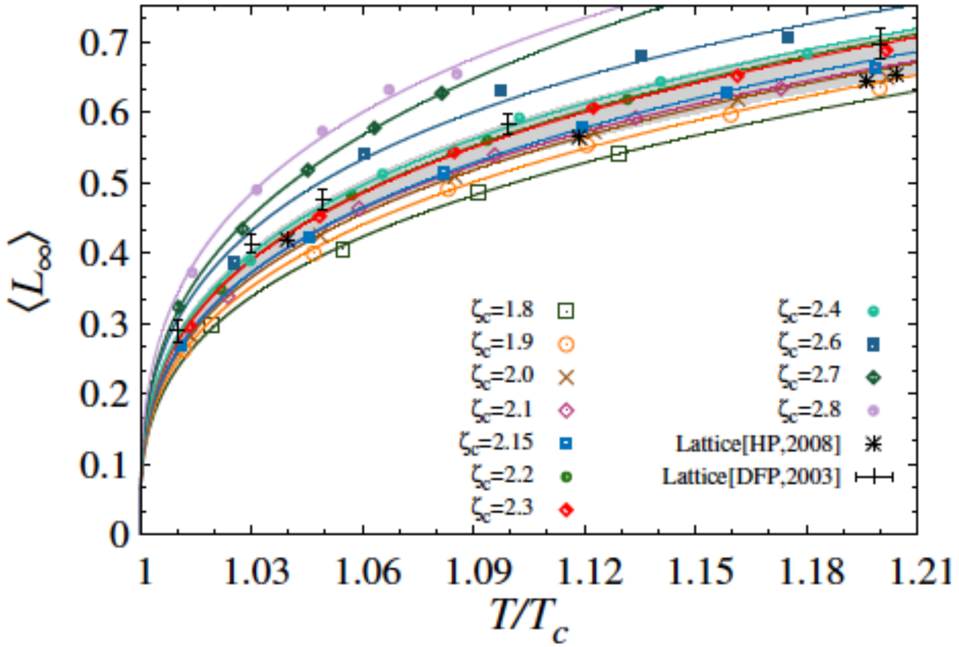
Quantitatively Constraining the Correlations

Two key parameters for the correlations: repulsive core strength and range



$$V_c \to 5$$

$$\zeta_c \to 2.3$$

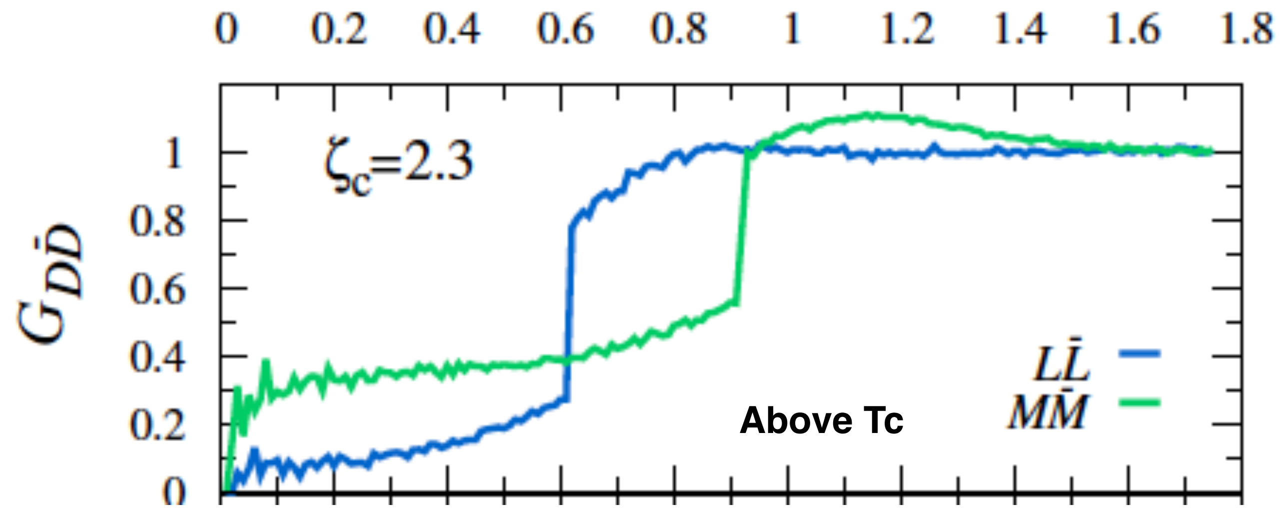


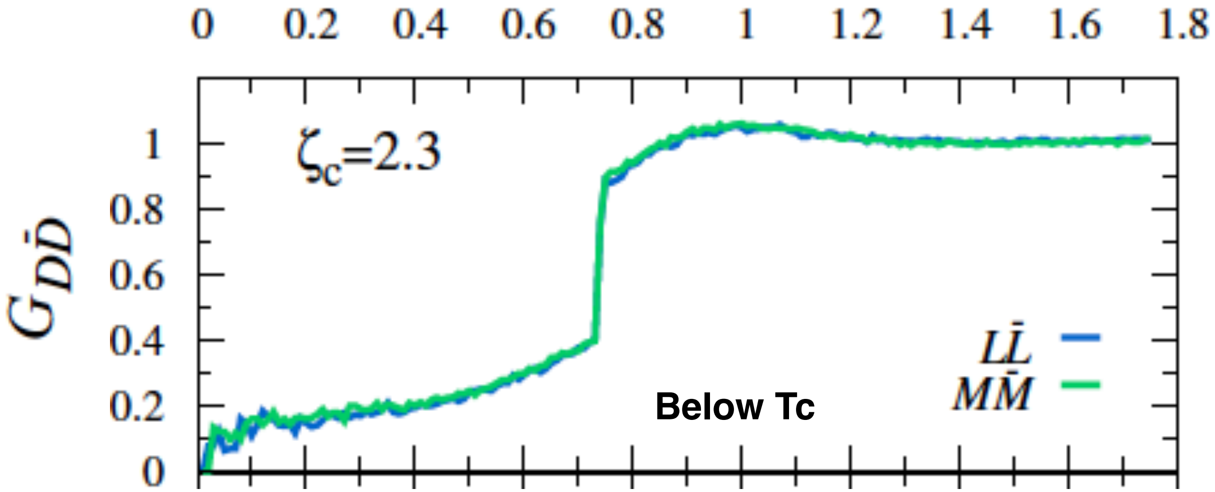
M.LopezRuiz, JL, in preparation.

A Correlated Ensemble!

*** Quantitative description for confinement transition in SU(2) YM***

*** A correlated (liquid-like) ensemble of dyons/anti-dyons***



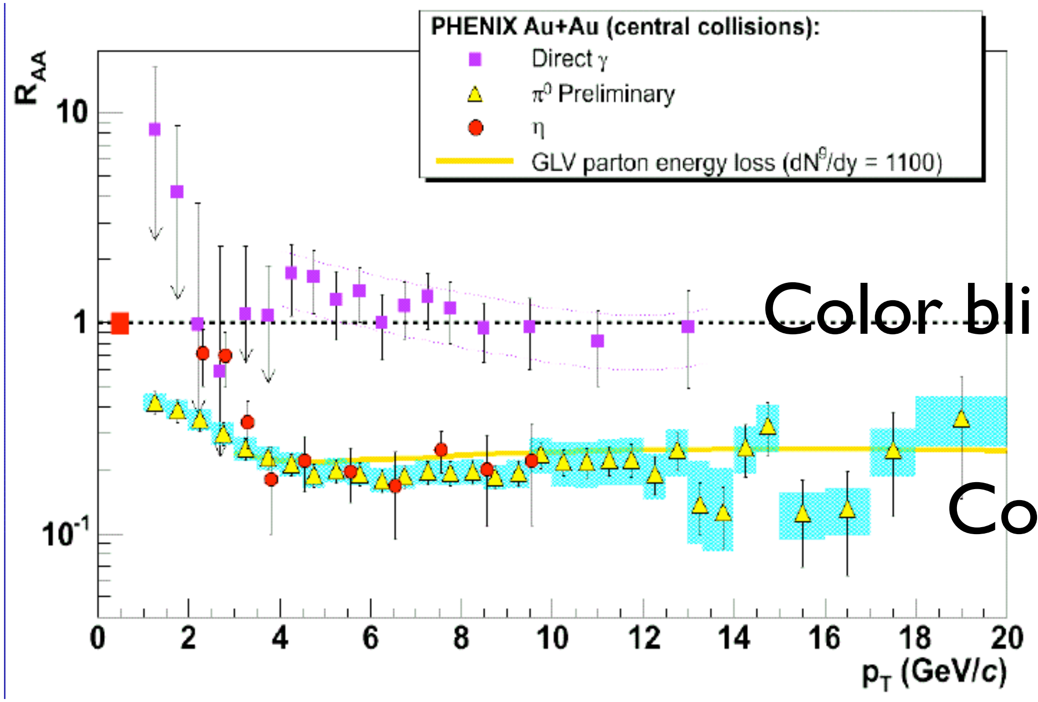


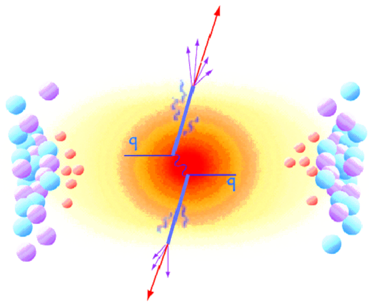
Do these magnetically charged objects manifest themselves in heavy ion collisions?
YES!

Jet Energy Loss in CUJET3

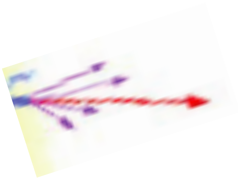
J. Xu, JL, M. Gyulassy, CPL2015; JHEP2016.
S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1704.04577; to appear soon.

A Color-Opaque Plasma



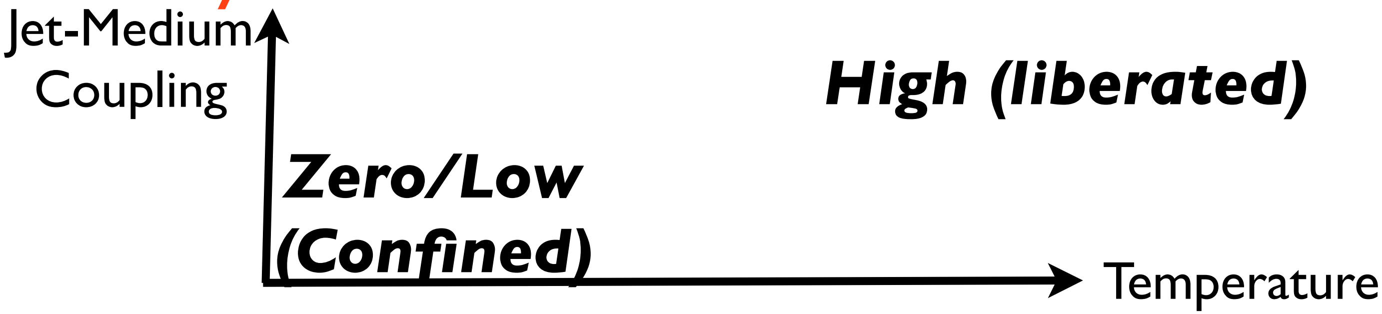


Color blind probe



Colorful probe

A qualitatively different medium



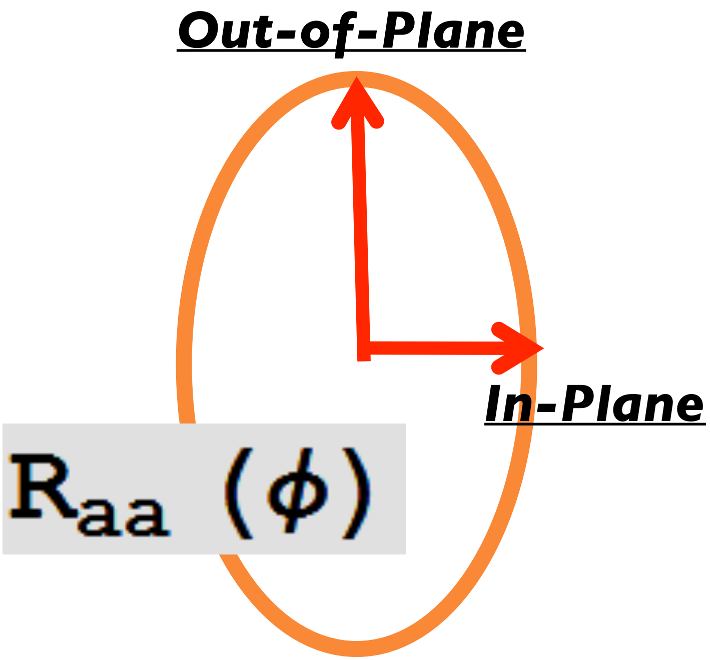
Jet-Medium Coupling

High (liberated)

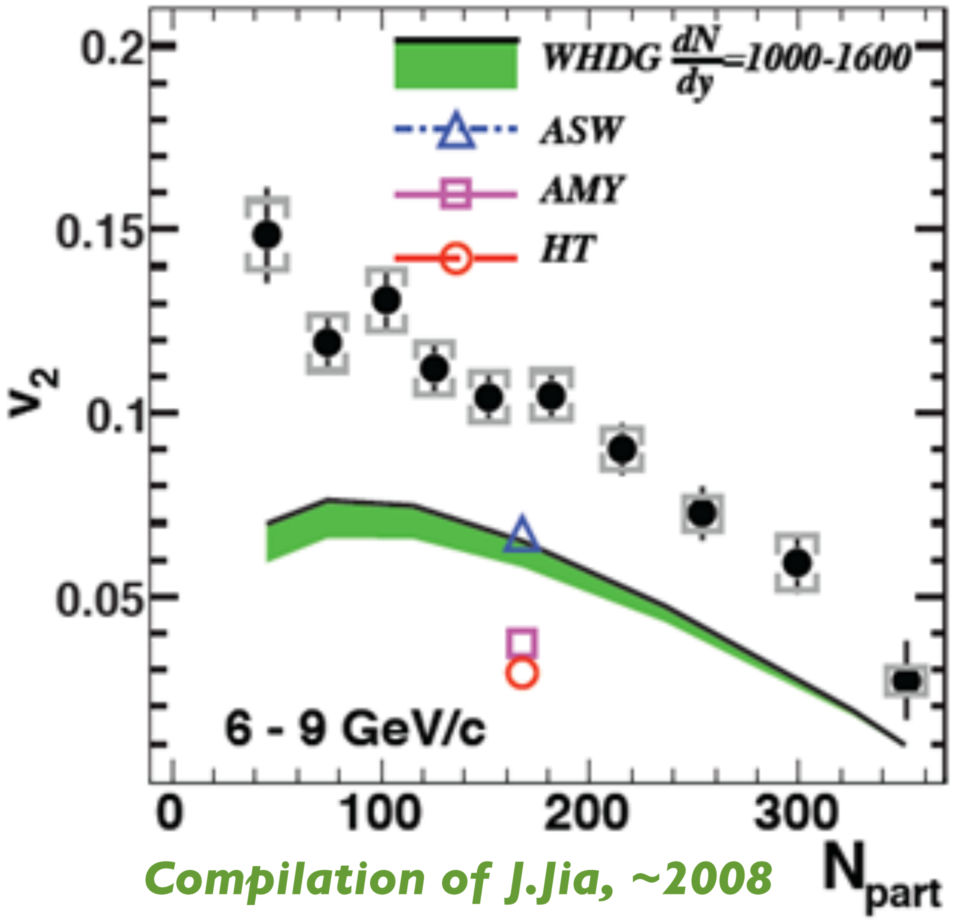
Zero/Low (Confined)

Temperature

Geometric Tomography



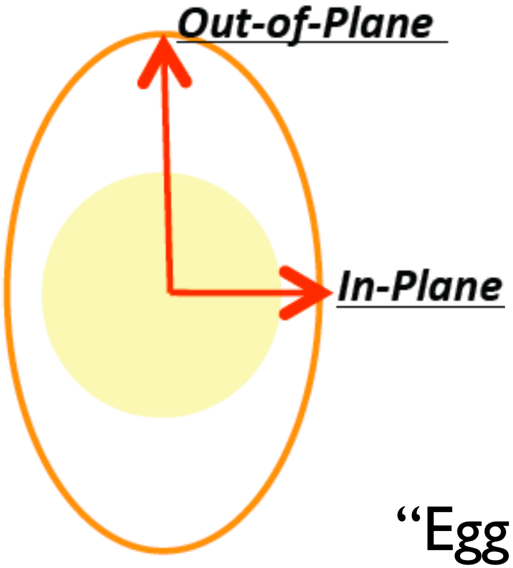
$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$



Compilation of J.Jia, ~2008

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

Where Are Jets Quenched (More Strongly)?

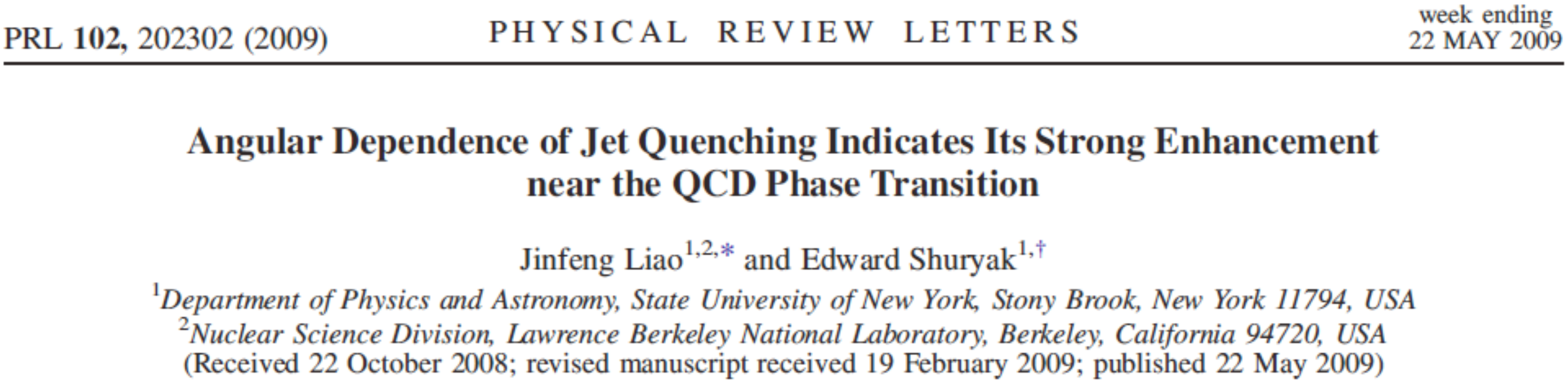


Taken for granted in all previous models:
"waterfall" scenario.

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,†]

[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)

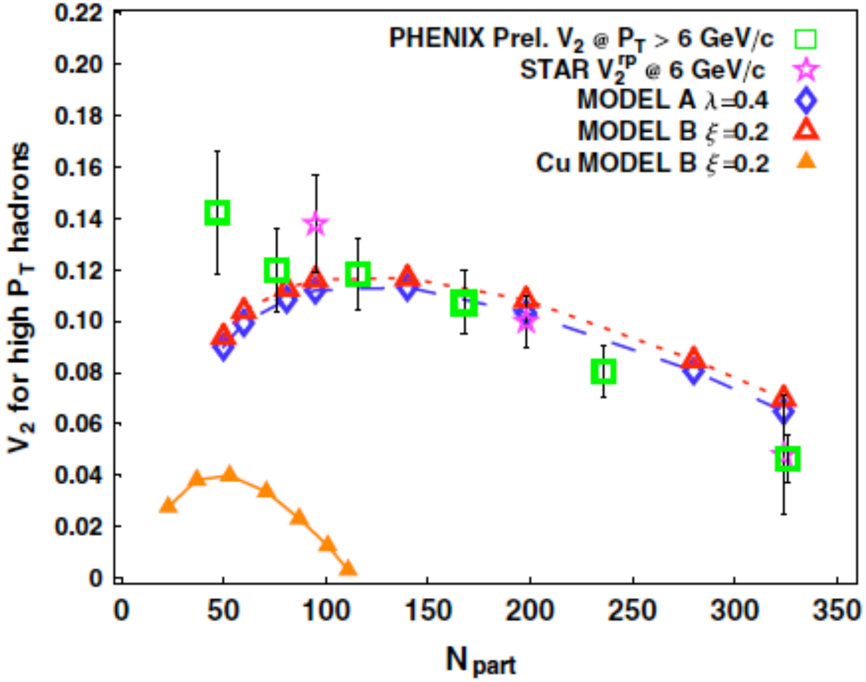
Near-Tc Enhancement of Jet-Medium Coupling

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:

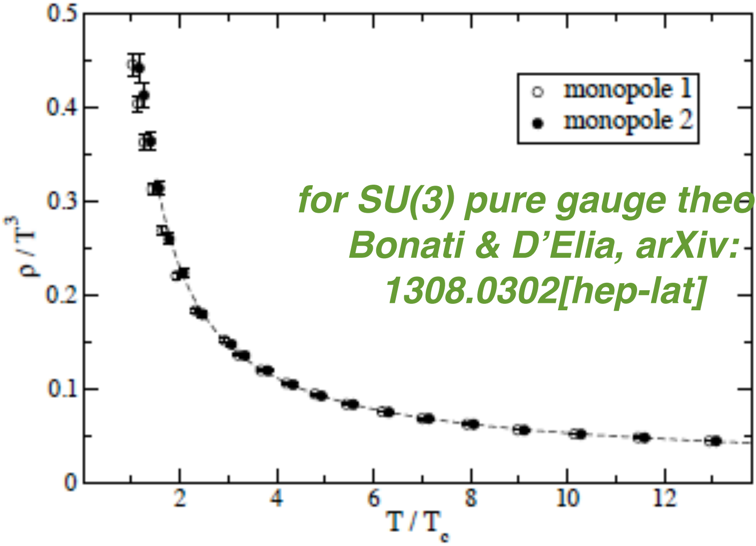
"In relativistic heavy ion collisions the jets are quenched about **2--5 times stronger** in the near-Tc region than the higher-T QGP phase."

— Confirmed by many studies later!

Near-Tc Enhancement from Monopoles

Electric and magnetic charges always scatter strongly with each other!

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



for SU(3) pure gauge theory Bonati & D'Elia, arXiv: 1308.0302[hep-lat]

Magnetic charges become copious in the plasma near Tc

Recently we've successfully implemented the magnetic scenario into a sophisticated jet modeling framework —> CUJET3

J. Xu, JL, M. Gyulassy, CPL2015; JHEP2016.
S. Shi, J. Xu, JL, M. Gyulassy, arXiv:1704.04577; to appear soon.

A Sophisticated Simulation Framework

DGLV-CUJET framework for describing multi-parton scattering:

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

Original DGLV formalism has
only quark/gluon scattering centers

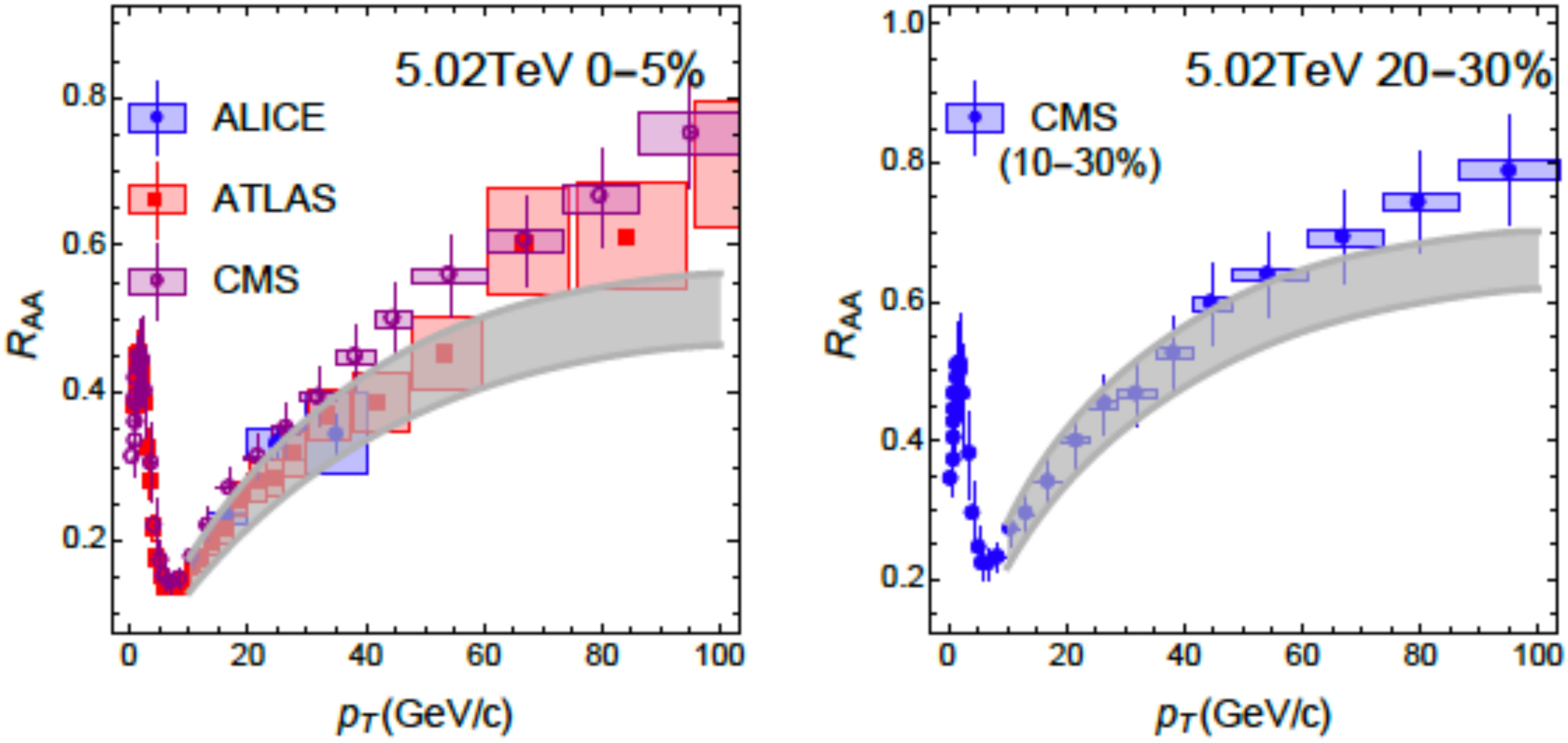
We now include both color-electric
and color-magnetic scattering centers.

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

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

Xu, JL, Gyulassy, arXiv:1411.3673

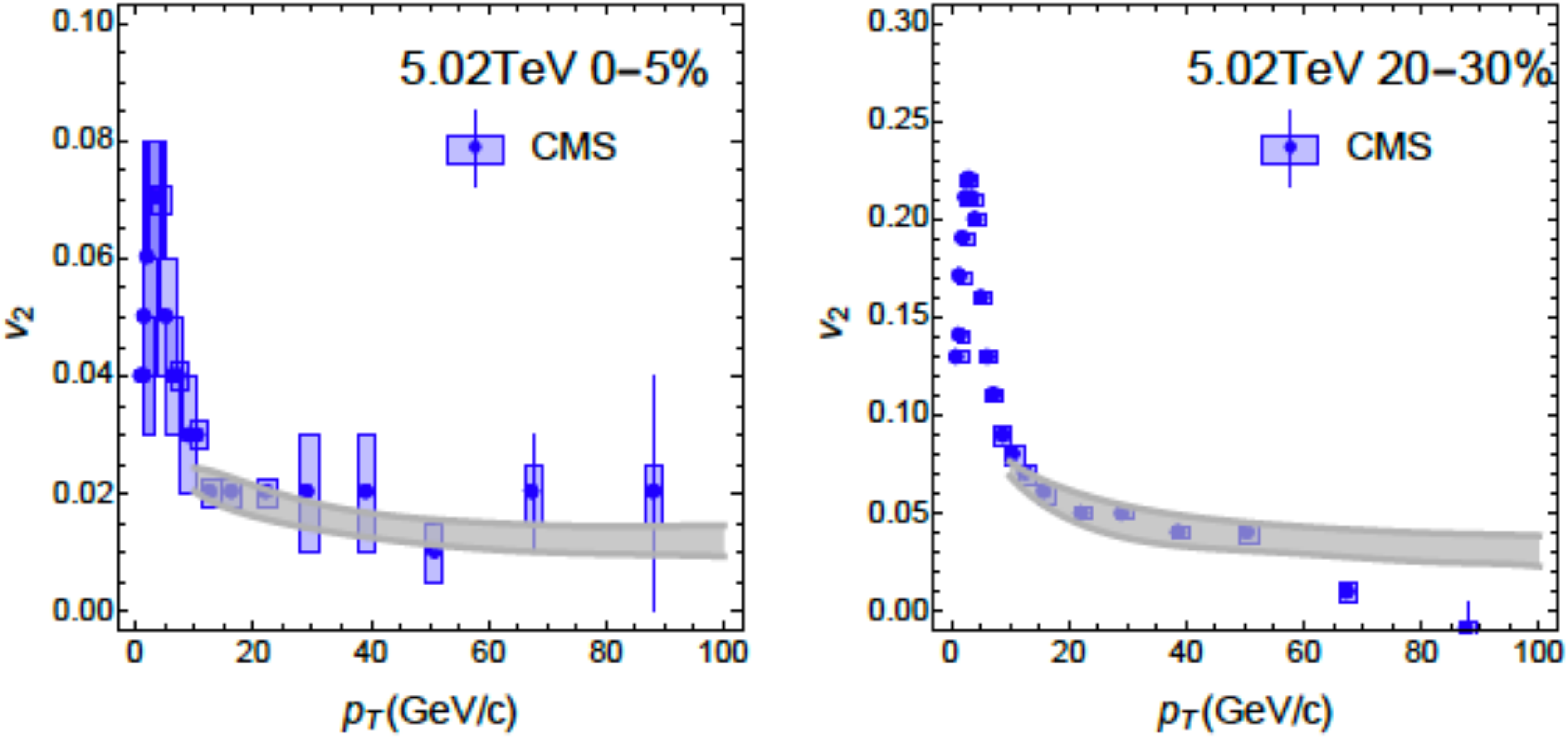
Comparison for Light Hadrons



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

[Successful comparison with RHIC200GeV and LHC2.76TeV already reported in: J. Xu, JL, M. Gyulassy, CPL2015; JHEP2016.]

Comparison for Light Hadrons



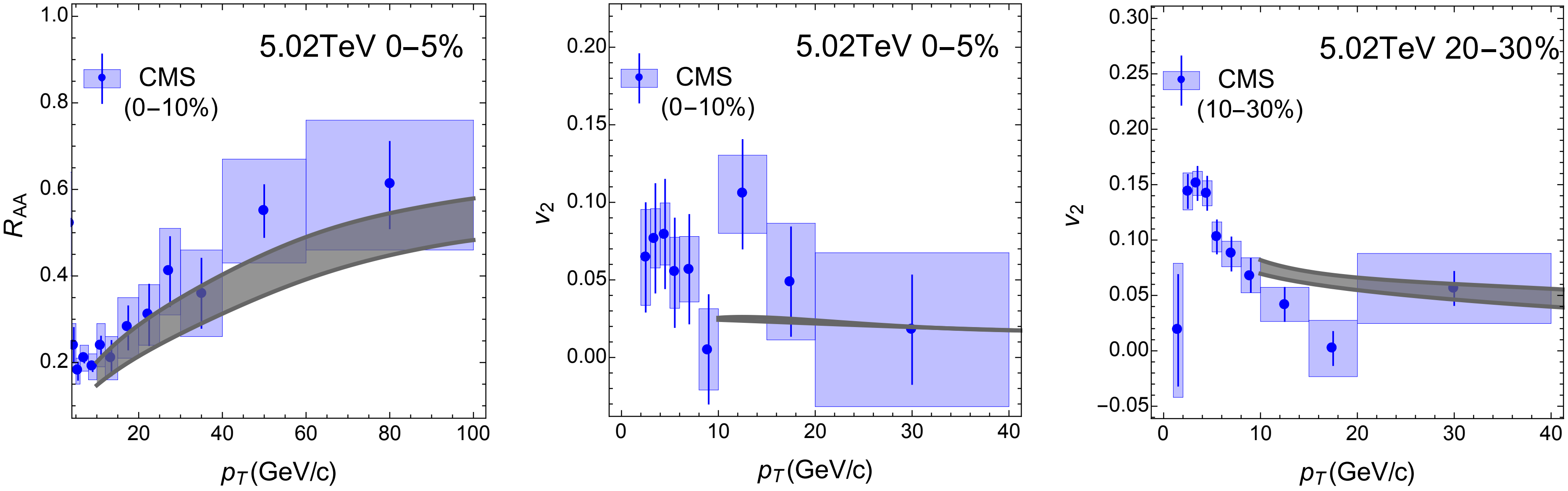
[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

[Successful comparison with RHIC200GeV and LHC2.76TeV already reported in: J. Xu, JL, M. Gyulassy, CPL2015; JHEP2016.]

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

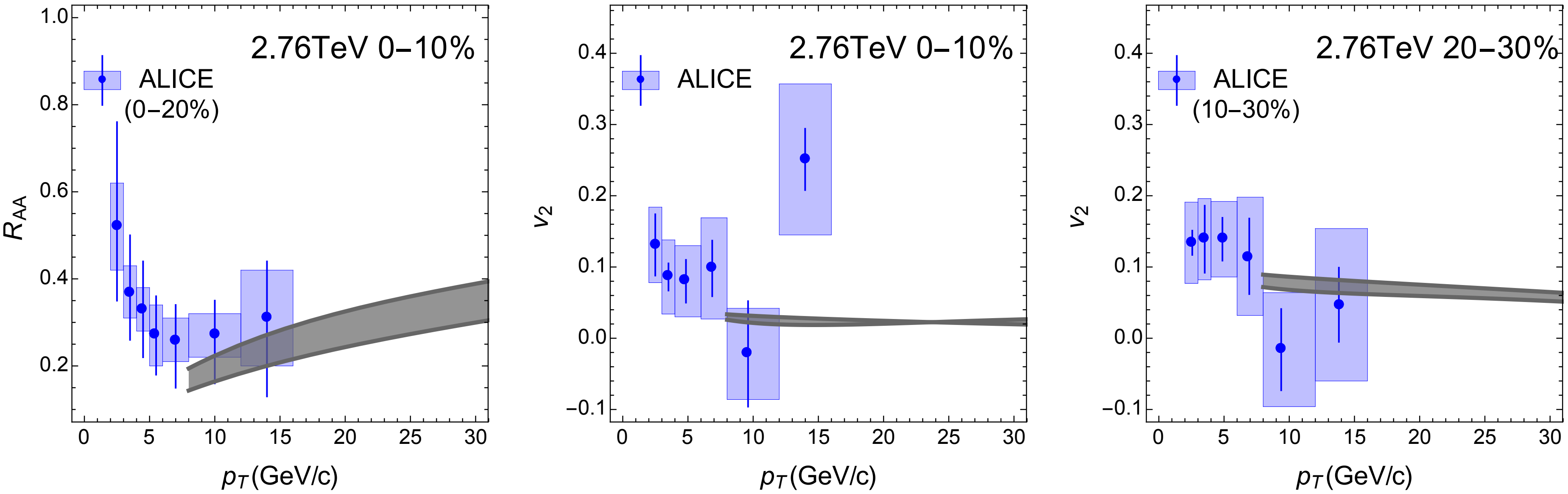


[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Independent Test with Heavy Flavor

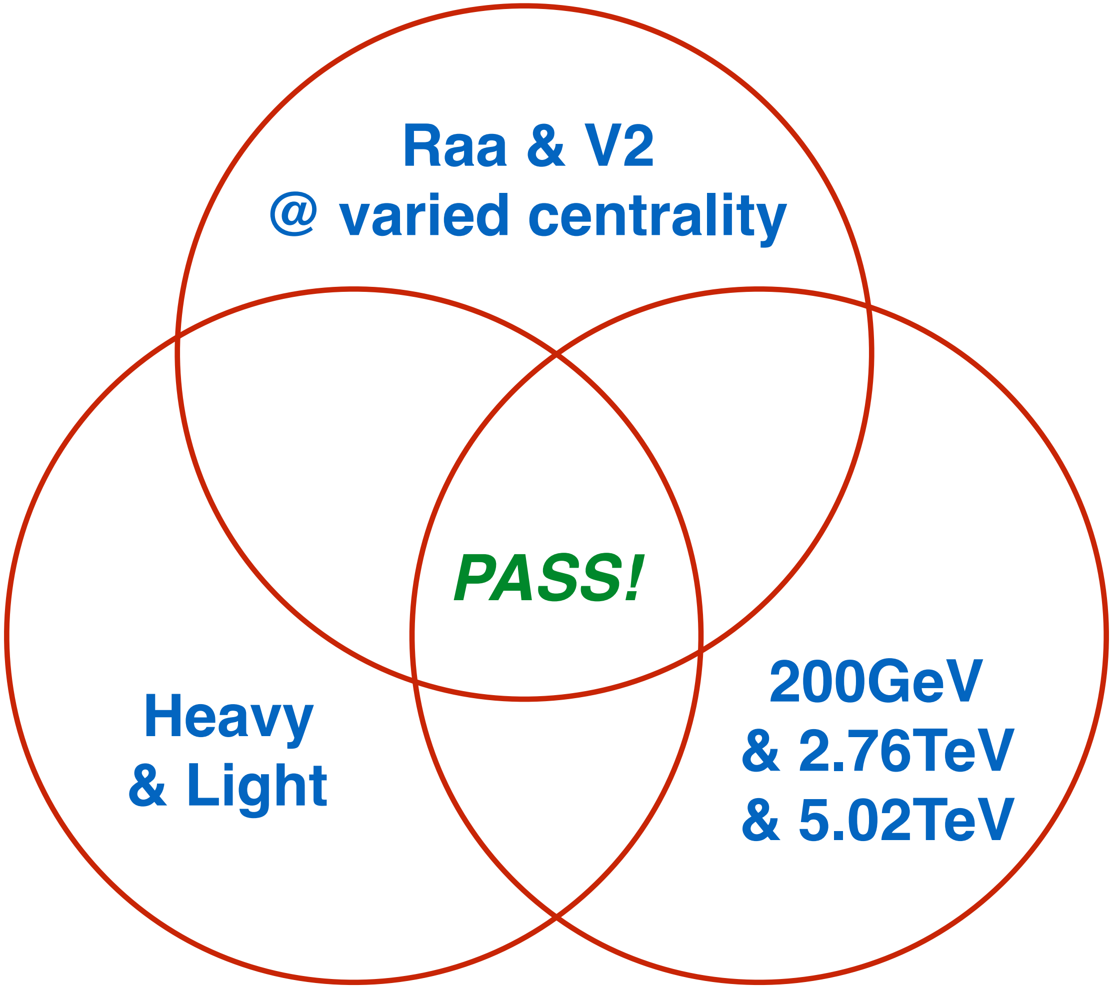
The HF serves as an independent test:
These data are NOT part of model parameter calibration.

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



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

The Challenge to Every Model



Raa & V2
@ varied centrality

PASS!

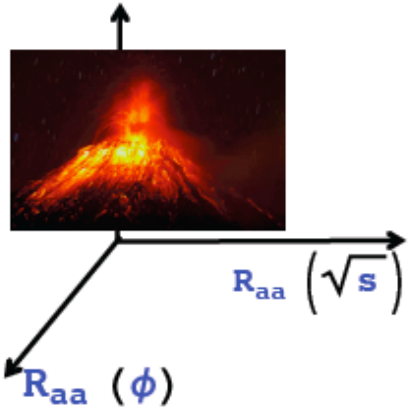
Heavy
& Light

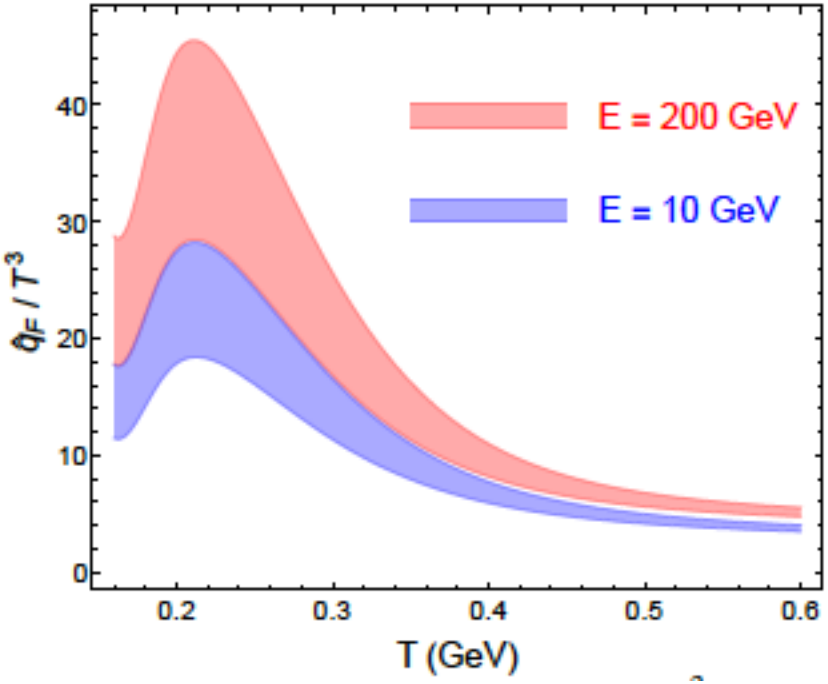
200GeV
& 2.76TeV
& 5.02TeV

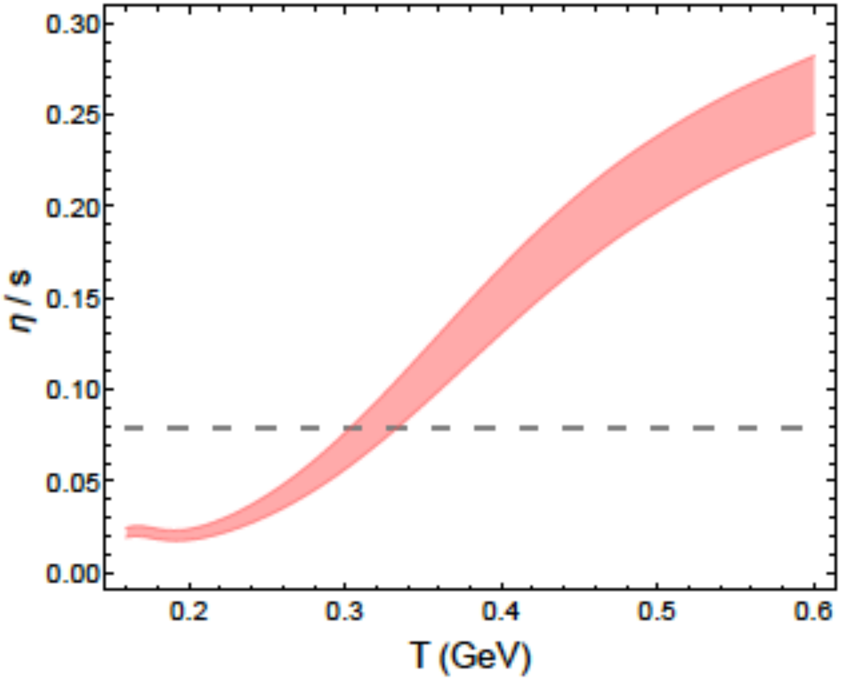
CUJET3 has taken up and passed this quantitative challenge.

Connecting the Soft and the Hard Sectors

Strongly enhanced near-Tc jet-medium interaction!







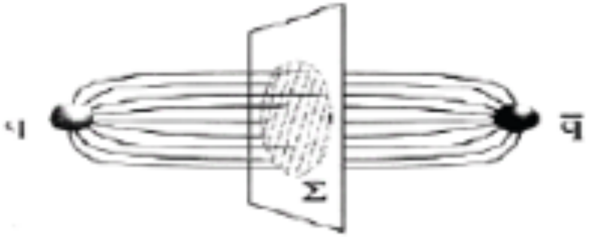
Summary

Summary: Taming Confinement from sQGP

T<< Lambda_QCD

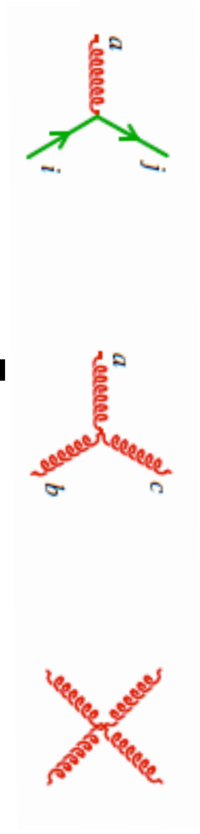
T ~ Lambda_QCD

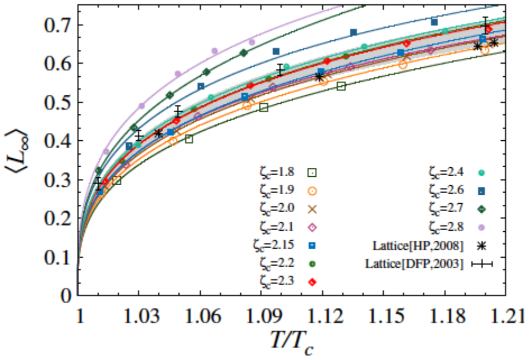
T>> Lambda_QCD

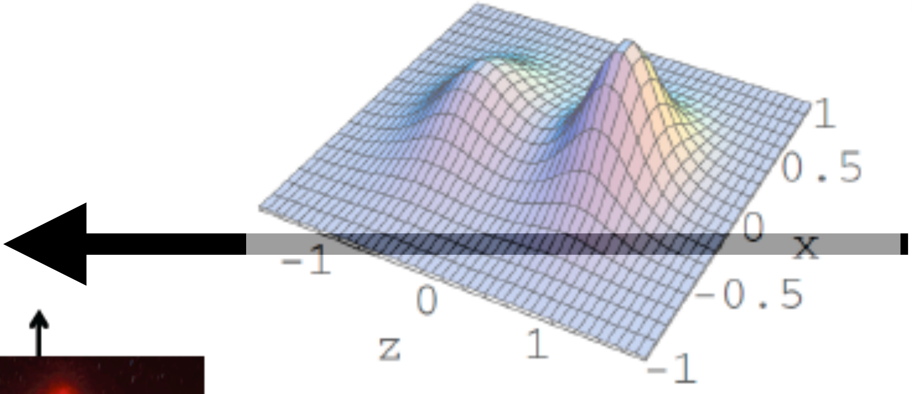


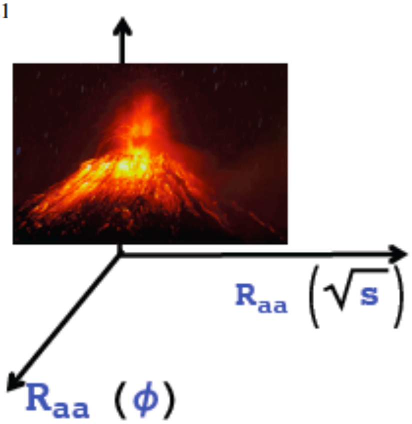
Emergent plasma with E & M charges:
chromo-magnetic monopoles are the "missing DoF"

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



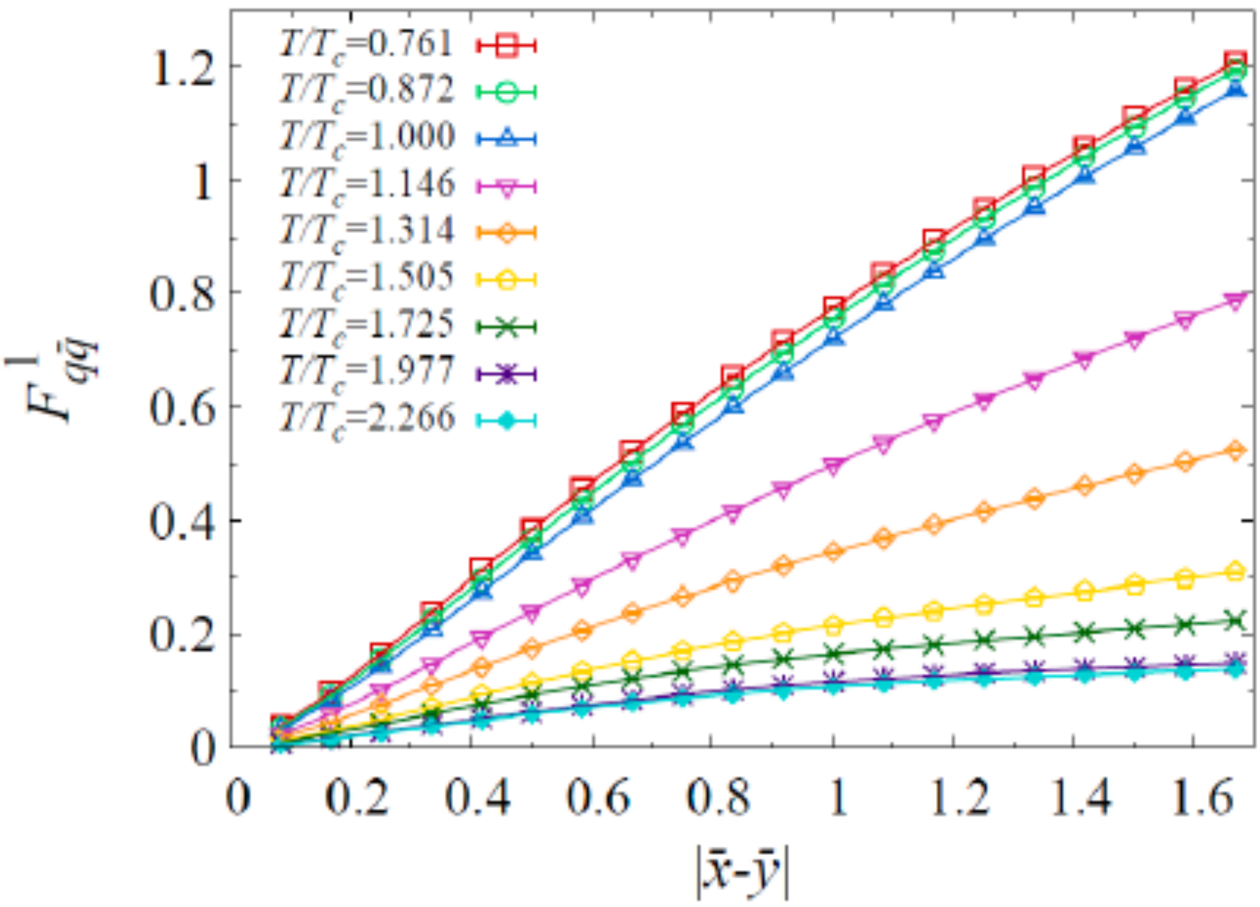






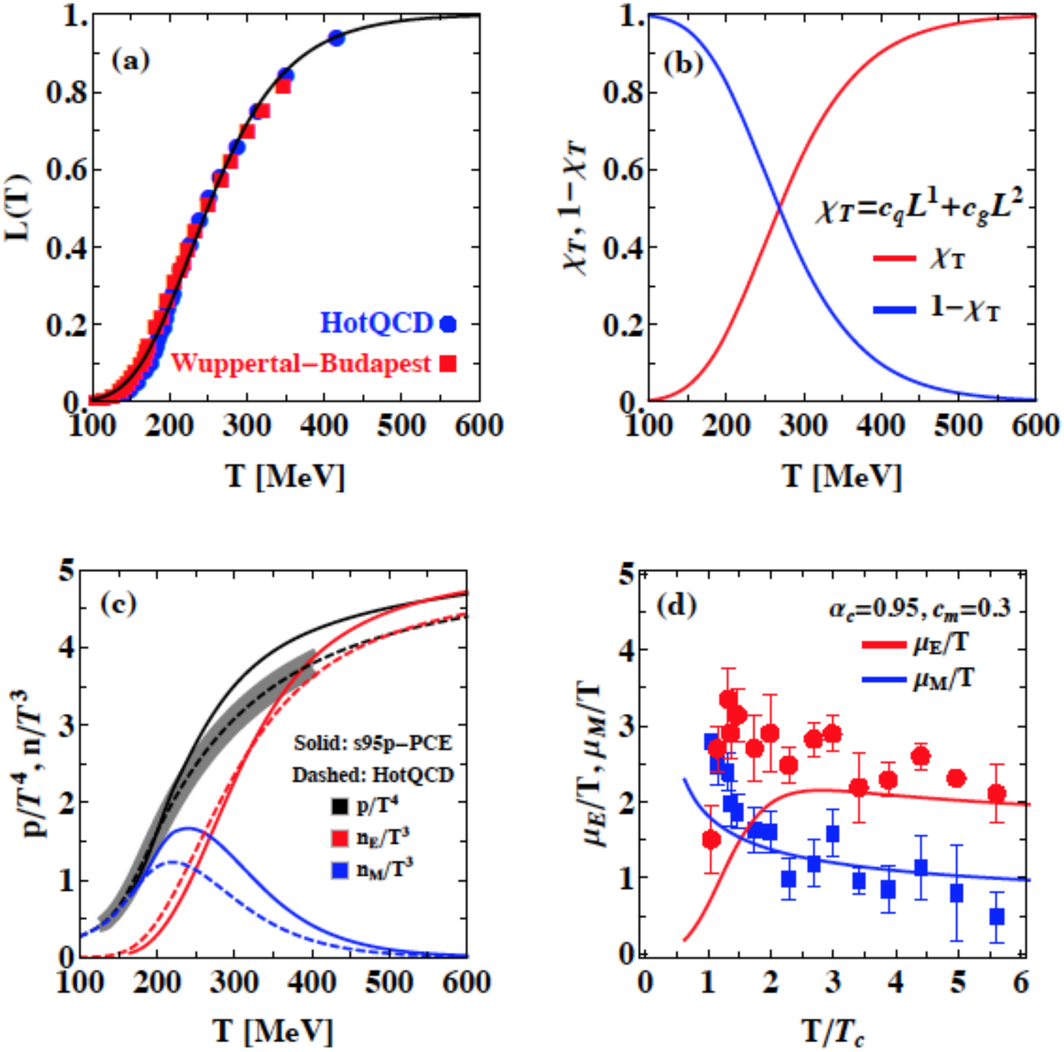
Backup

Confinement Driven by Instanton-Monopoles



Static quark-anti-quark potential: the "string" emerges!

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:*

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

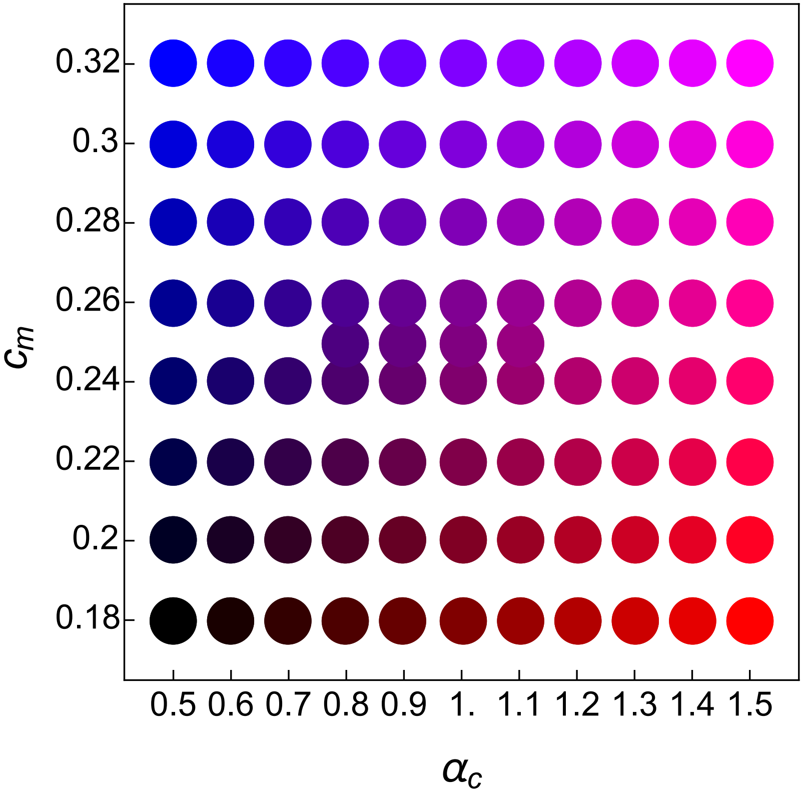
The model implementations of electric and magnetic components are carefully **constrained by available lattice data.**

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

Systematic Calibration of CUJET3

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.

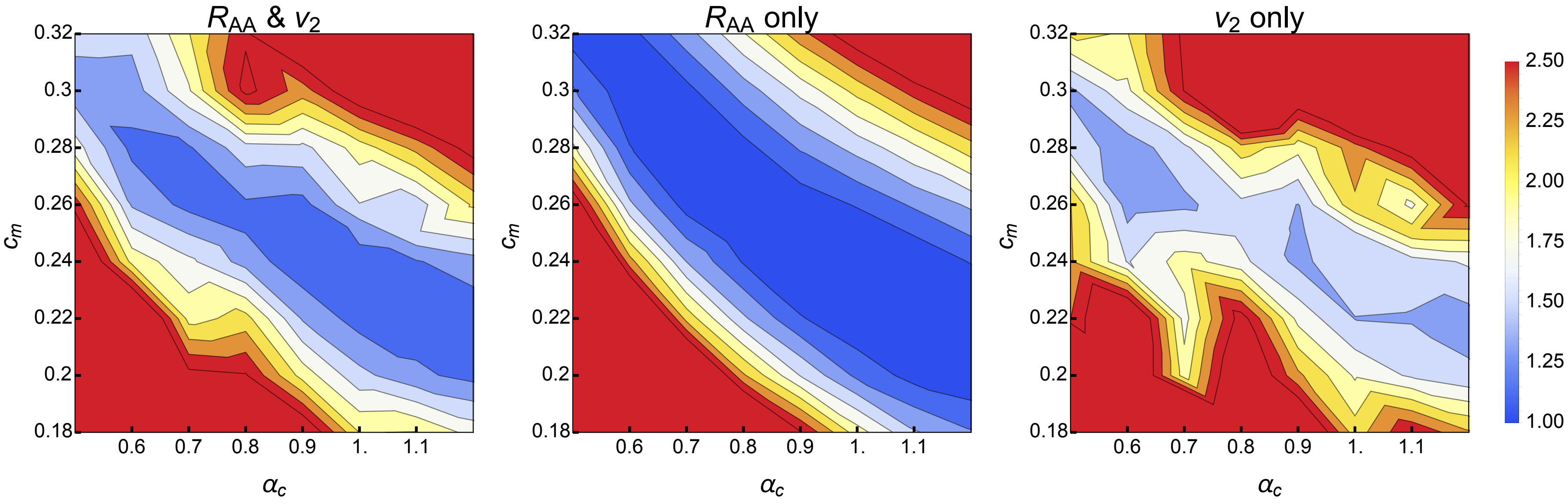


[S. Shi, J. Xu, J. Liao, M. Gyulassy, in preparation]

Systematic Calibration of CUJET3

Chi-square map on the parameter plane

Different set of data show different sensitivity in constraining parameters.



Identified optimal parameter band

$$(\alpha_c = 0.8, c_m = 0.22)$$

$$(\alpha_c = 1.0, c_m = 0.28)$$

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