Heavy Flavor Transport and Exotic Hadron Production in Heavy Ion Collisions

Jinfeng Liao

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Plan of the Talk

– ***Brief introduction***

– ***Extracting heavy quark transport coefficient***

– ***Production of heavy flavor exotic hadrons***

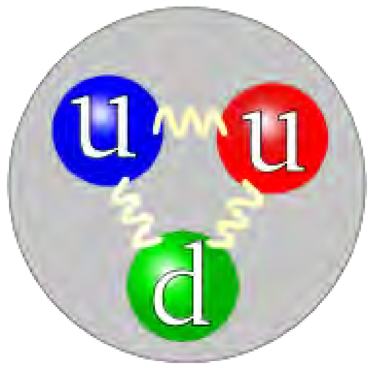
– ***Summary***

Collaborators:
A. Akridge, A. Bandyopadhyay, D. Gallimore, X. Guo, Y. Guo, Y Hu, S. Li, G.-Y. Qin, A. Szczepaniak, E. Wang, Q. Wang, H. Xing, H. Zhang, S.-L. Zhang

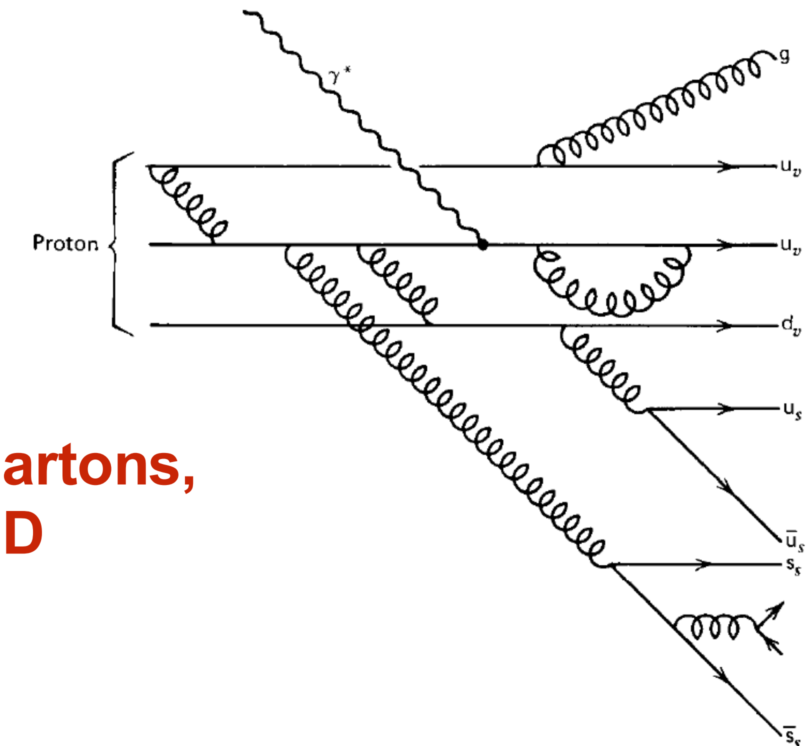
Introduction

From Hadrons to Quarks

Around 1960': lots of hadrons, quark model

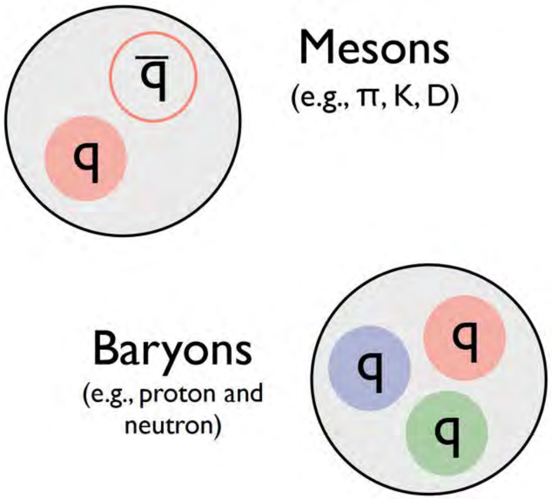


Late 60' / early 70': DIS/partons, Asymptotic freedom, QCD

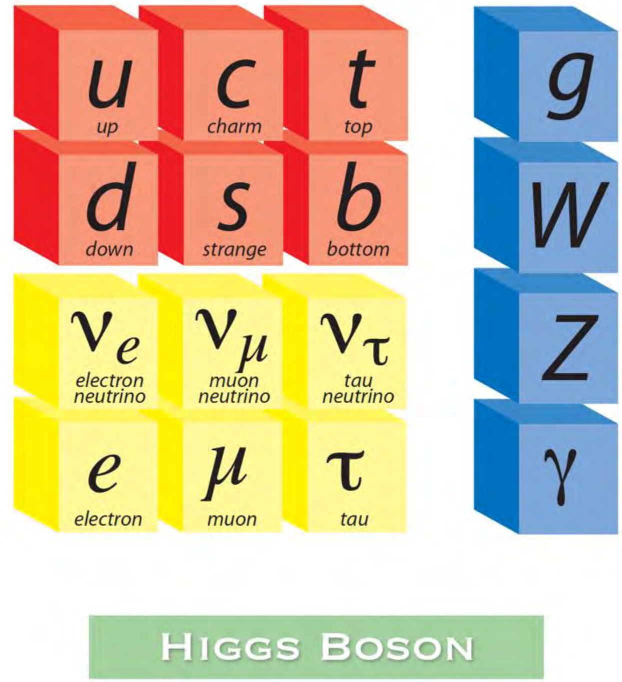


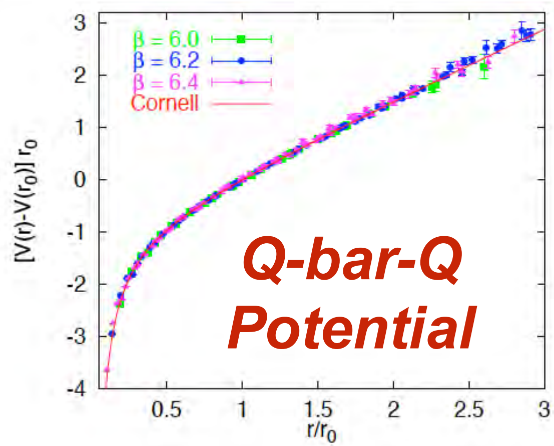
From Quarks back to Hadrons

Two typical arrangements:



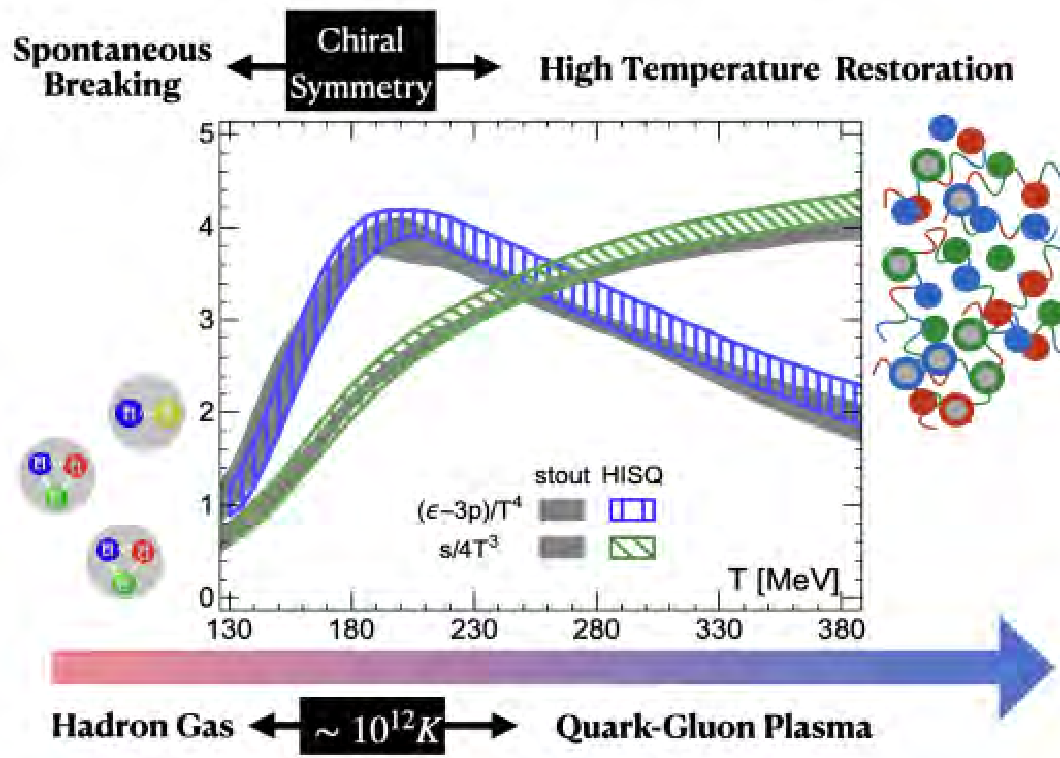
Confinement





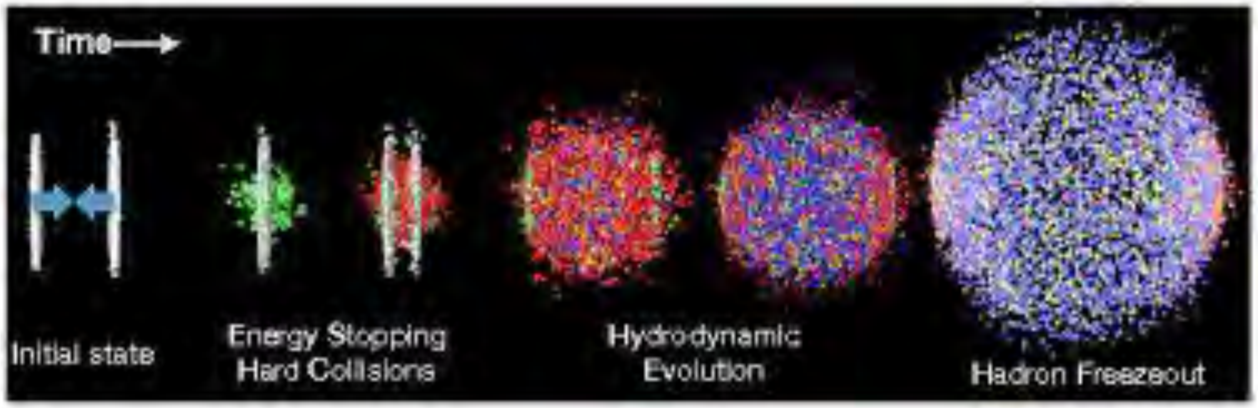
Q-bar-Q Potential

Quark-Gluon Plasma and Heavy Ion Collisions



Hadrons turn into quark-gluon plasma at high temperature.

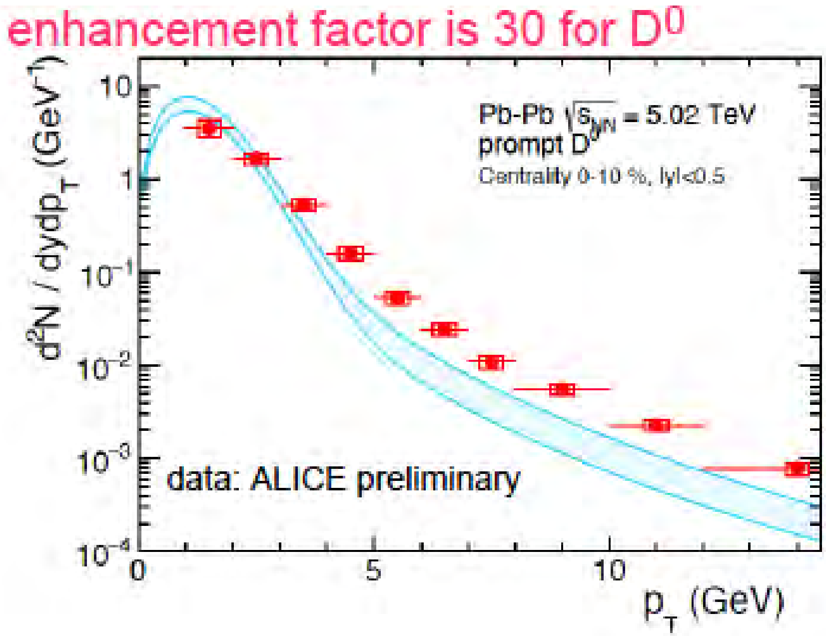
What a Heavy Ion Collision Has to Offer

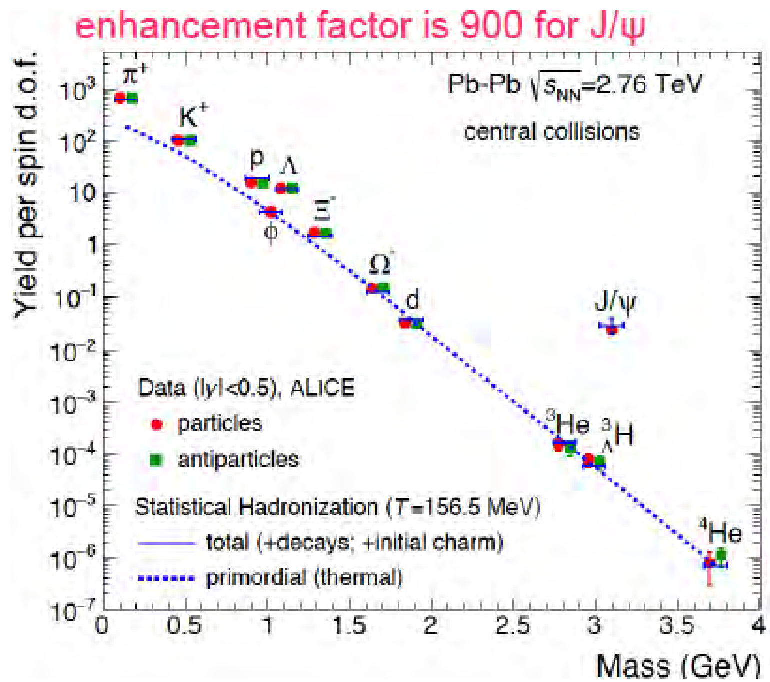


- ***A hot and dense partonic medium of many quarks/gluons***
- ***A bulk fireball with a "large", controllable size & geometry***
- ***Many hard processes at the beginning***
- ***Hadron formation from partons***
- ***A hot hadronic gas***

A versatile environment for the production and study of heavy flavor!

A “Charming” Quark Soup at O(~1000) GeV

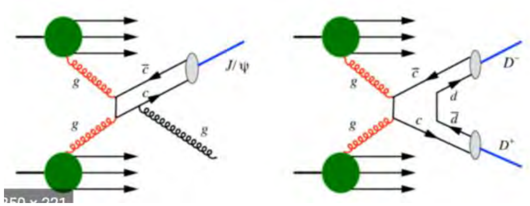


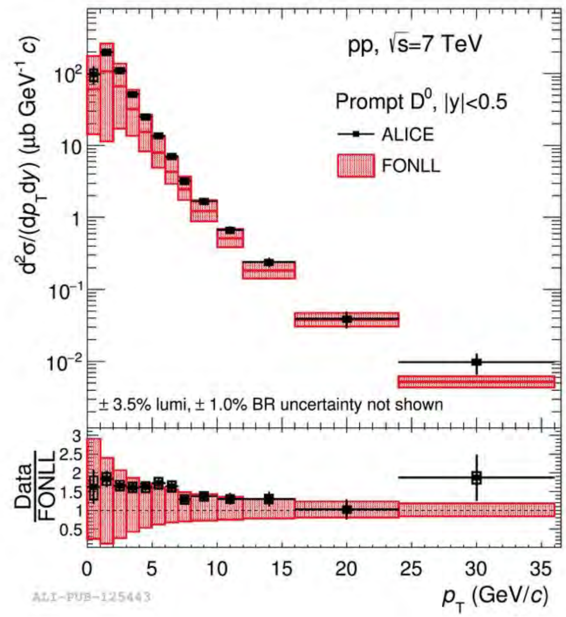


The QGP produced @ LHC O(~1000) GeV collisions, is a “charming” quark soup, with a “large” number of charms —> ideal environment for heavy flavor study!!!

Initial Charm Production

The charms are nearly all produced from initial hard scatterings that can be well described by pQCD calculations.

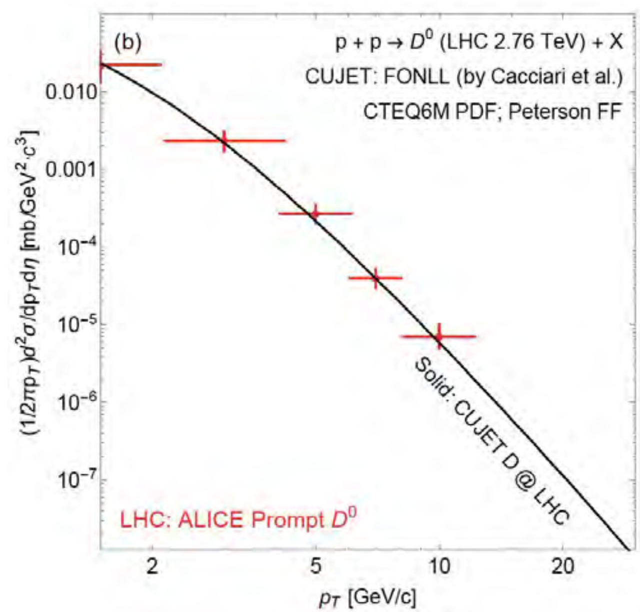




LHC is particularly advantageous:
x_RHIC ~ 0.01
x_LHC ~ 0.001

2Mc ~ 2.55 GeV >> Lambda_QCD ~ T

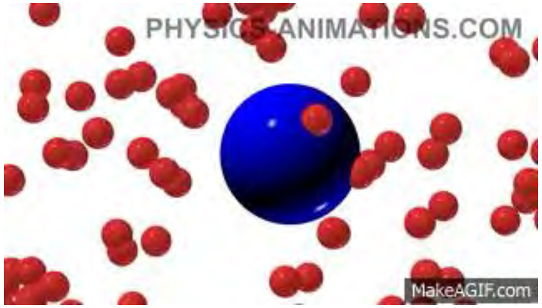
exp(-10) ~ 0.000045



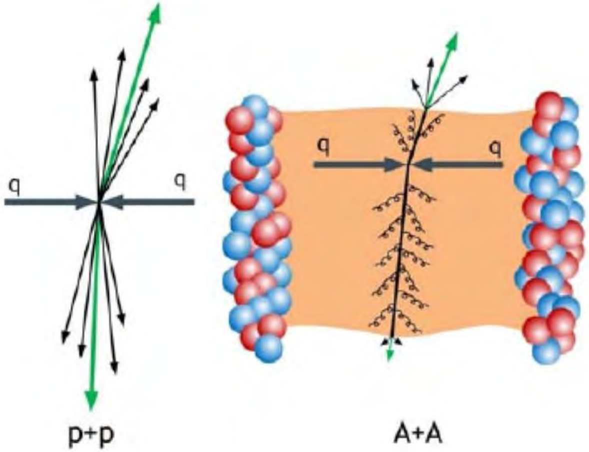
We have a pretty good idea of how many c/cbar there are in the QGP.

An Abundance of Transport Phenomena

Open heavy flavor: soft & hard sectors

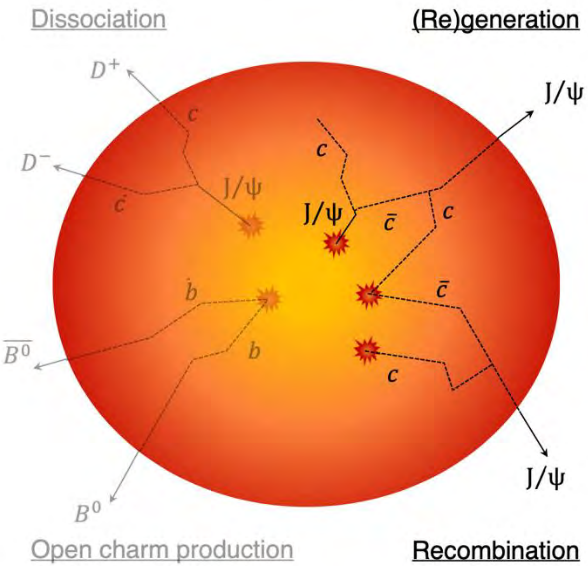


Brownian motion



Energy loss

Quarkonia

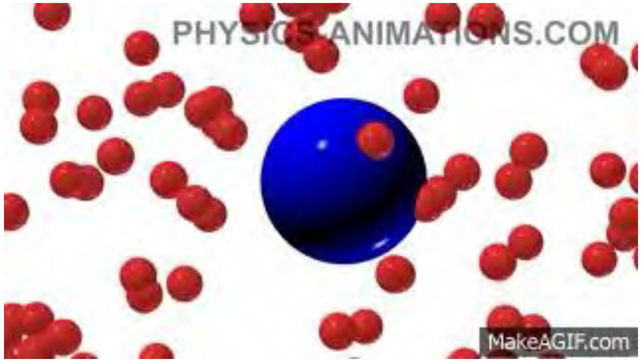


From talk by Luca Micheletti

Suppression
Regeneration
Sequential "melting"
Exotics
…

Extracting Heavy Quark Transport Coefficient

Soft Sector: Charm Diffusion



The charm quarks get carried by the bulk flow and diffuse around the whole fireball volume.

Brownian motion

Phase space evolution can bey described by a Langevin approach

$$\vec{F}_{\mathrm{D}} = -\eta_{\mathrm{D}}(\vec{p}, T) \cdot \vec{p},$$

$$d\vec{x} = \frac{\vec{p}}{E} dt$$

$$d\vec{p} = (\vec{F}_{\mathrm{D}} + \vec{F}_{\mathrm{T}} + \vec{F}_{\mathrm{G}}) dt$$

$$< \vec{F}_{\mathrm{T}}^{i}(t) \cdot \vec{F}_{\mathrm{T}}^{j}(t') > = \left[\kappa_{\parallel}(\vec{p}, T) P_{\parallel}^{ij} + \kappa_{\perp}(\vec{p}, T) P_{\perp}^{ij} \right] \delta(t - t'),$$

$$\vec{F}_{\mathrm{G}} = -\sum_{j=1}^{N_G} \frac{d\vec{p}_{\mathrm{G}}^{\,j}}{dt},$$

$$\frac{dN_G}{dz dk_{\perp}^2 dt} = \frac{2\alpha_s C_{\mathrm{A}} P(z) \hat{q}_{\mathrm{q}}}{\pi k_{\perp}^4} \left[\frac{k_{\perp}^2}{k_{\perp}^2 + (z m_{\mathrm{Q}})^2} \right]^4 sin^2\left(\frac{t - t_0}{2\tau_f} \right).$$

Heavy Quark Transport Coefficient

For HQ with high energy, E >> M

$$\hat{q}_{\mathrm{q}} = \frac{2\kappa_{\perp}}{v_{\mathrm{Q}}} \approx 2\kappa_{\perp}$$

Assuming

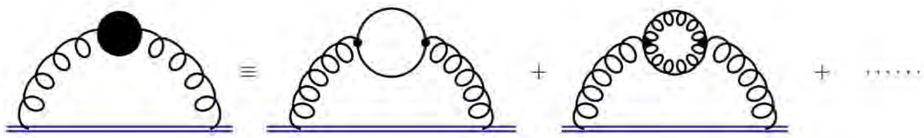
$$\kappa_{\parallel} = \kappa_{\perp} \equiv \kappa$$

$$\eta_{\mathrm{D}}(\vec{p}, T) = \frac{1}{2\pi T D_s} \cdot \frac{2\pi T^2}{E}$$

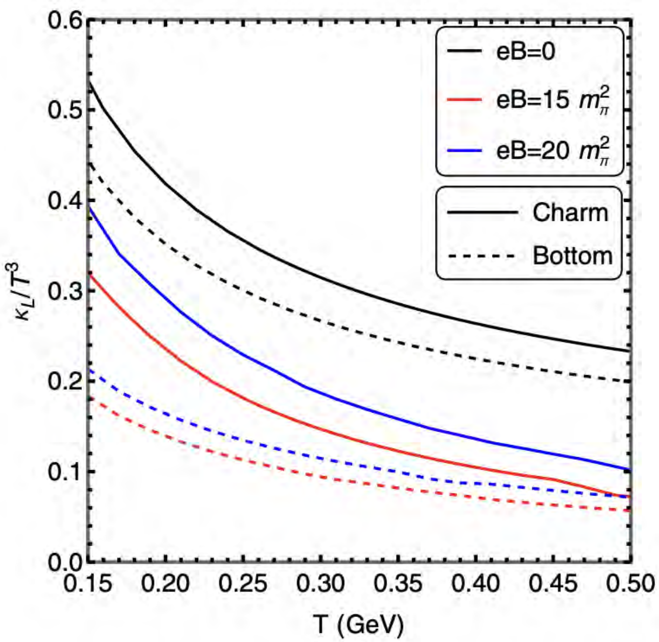
$$\kappa(T) = \frac{1}{2\pi T D_s} \cdot 4\pi T^3.$$

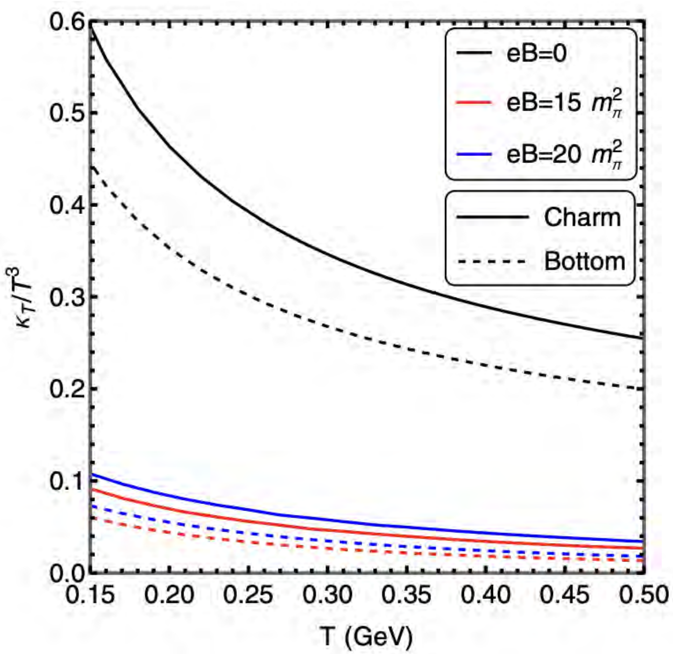
The spatial diffusion coefficient Ds becomes the key transport coefficient.

Calculating the Drag Coefficient



$$\Gamma(P \equiv E, \mathbf{v}) = -\frac{1}{2E}\frac{1}{1+e^{-E/T}}\mathrm{Tr}[(\not{P}+M)\mathrm{Im}\Sigma(p_0+i\epsilon,\vec{p})].$$





Perturbative results appear to be too small for phenomenology at relevant temperatures .

[A. Bandyopadhyay, JL, H. Xing, PRD105, 114049 (2022)]

Extraction of HF Transport Coefficients

- ***Exp. Measurements of Raa and v2 of open heavy flavor demonstrate good sensitivity for phenomenological extraction of the transport coefficients.***

- ***Average Ds controls Raa and every model could "make it" by dialing parameter.***

- ***The anisotropy v2 is trickier, and can be very sensitive to the temperature dependence.***

Extraction of Heavy-Flavor Transport Coefficients in QCD Matter

R. Rapp[*1], P.B. Gossiaux[*2], A. Andronic[*3,4], R. Averbeck[*3], S. Masciocchi[*3], A. Beraudo[5], E. Bratkovskaya[3,6], P. Braun-Munzinger[3,7], S. Cao[8], A. Dainese[9], S.K. Das[10,11], M. Djordjevic[12], V. Greco[11,13], M. He[14], H. van Hees[6], G. Inghirami[3,6,15,16], O. Kaczmarek[17,18], Y.-J. Lee[19], J. Liao[20], S.Y.F. Liu[1], G. Moore[21], M. Nahrgang[2], J. Pawlowski[22], P. Petreczky[23], S. Plumari[11], F. Prino[5], S. Shi[20], T. Song[24], J. Stachel[7], I. Vitev[25], and X.-N. Wang[26,18]

[R. Rapp, et al, Nucl. Phys. A 979 (2018) 21-86]

Data-Driven Extraction of T-Dependence

Eur. Phys. J. C (2020) 80:671
https://doi.org/10.1140/epjc/s10052-020-8243-9

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Data-driven extraction of heavy quark diffusion in quark-gluon plasma

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[3] Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan 430079, China
[4] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA

Consider Ds as a smooth function of T, with Taylor expansion:

$$D_s = d_0 + d_1 \cdot T + d_2 \cdot T^2 + \cdots$$

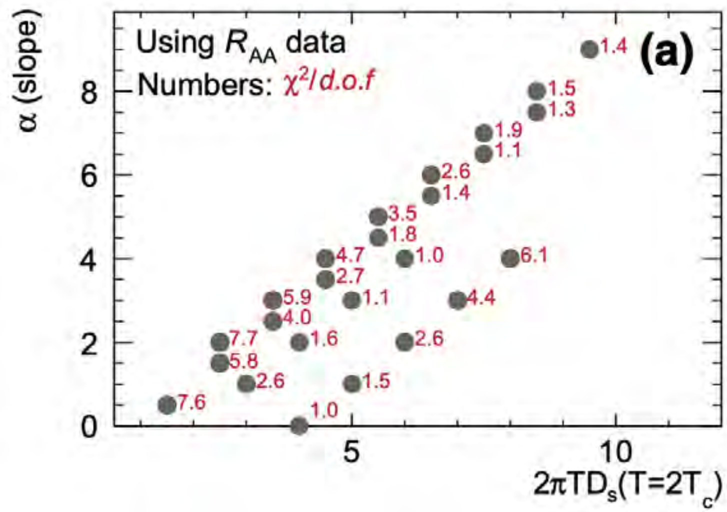
As a first step, we only expand to linear order:

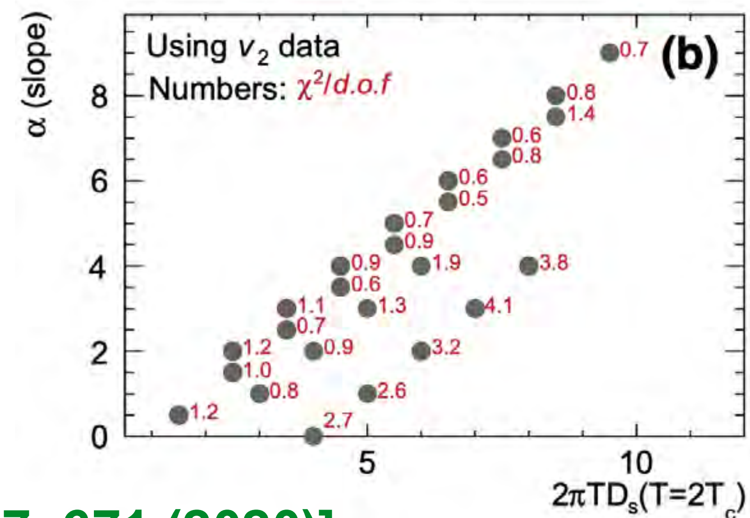
$$2\pi T D_s \approx \alpha \left(\frac{T}{T_c}\right) + \beta$$

Data-Driven Extraction of T-Dependence

We systematically scan the two parameters, and let data decide the best values.

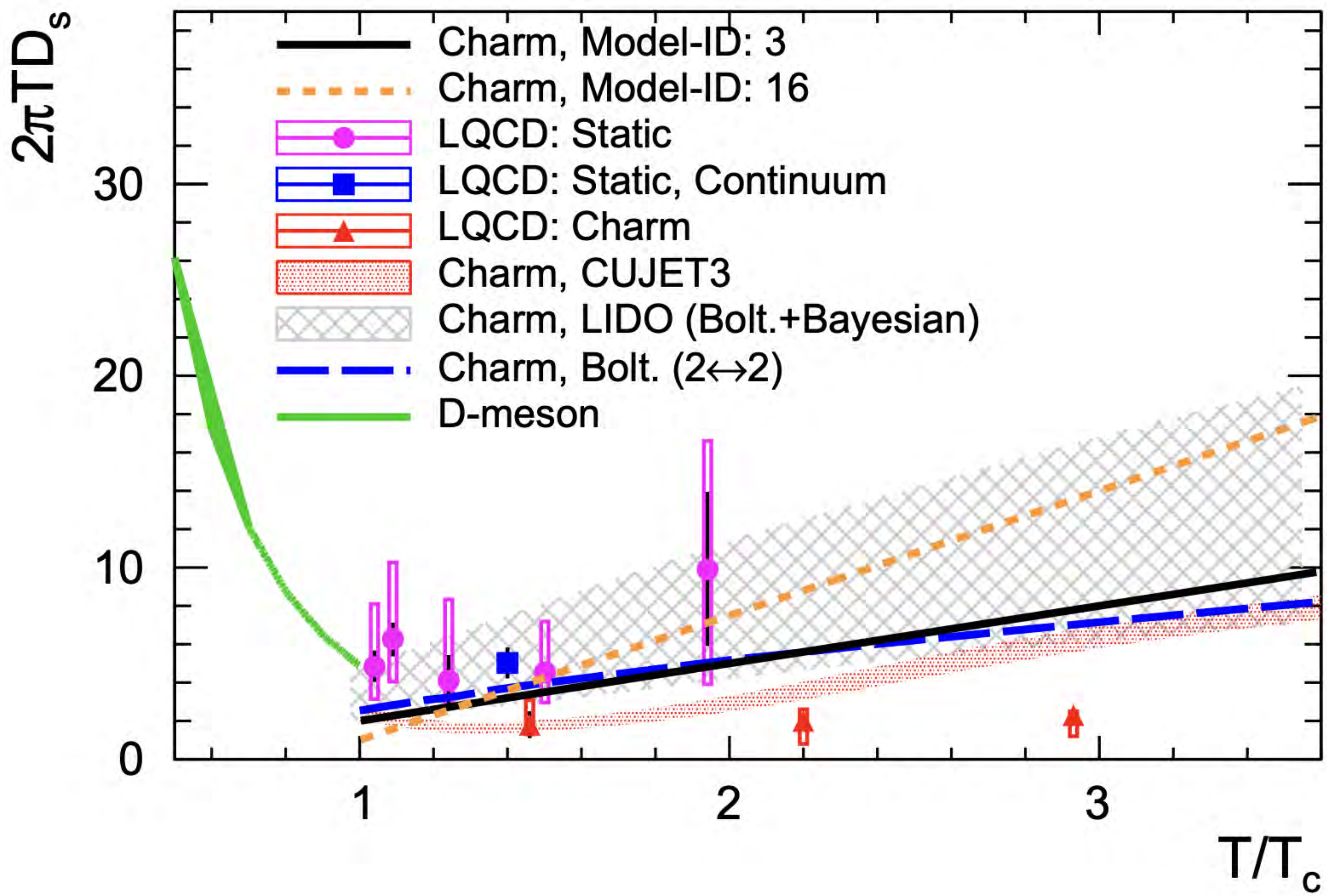
Model ID	α (Slope)	β (Intercept)	$\chi^2/d.o.f\ (R_{AA})$	$\chi^2/d.o.f\ (v_2)$	Total
1	1.00	1.00	2.61	0.85	2.37
2	2.00	0.00	1.58	0.87	1.49
3 (A)	**3.00**	**− 1.00**	**1.09**	**1.26**	**1.11**
4	4.00	− 2.00	1.03	1.86	1.14
5	0.00	4.00	1.03	2.68	1.26
6	1.00	3.00	1.55	2.64	1.70
7	2.00	2.00	2.58	3.17	2.66
8	3.00	1.00	4.45	4.06	4.40
9	4.00	0.00	6.10	3.76	5.78
10	0.50	0.50	7.61	1.17	6.73
11	1.50	− 0.50	5.77	1.04	5.12
12	2.50	− 1.50	3.95	0.70	3.51
13	3.50	− 2.50	2.68	0.58	2.39
14	4.50	− 3.50	1.84	0.90	1.71
15	5.50	− 4.50	1.44	0.53	1.32
16 (B)	**6.50**	**− 5.50**	**1.15**	**0.77**	**1.10**
17	7.50	− 6.50	1.27	1.41	1.29
18	2.00	− 1.50	7.69	1.25	6.81
19	3.00	− 2.50	5.95	1.05	5.28
20	4.00	− 3.50	4.75	0.89	4.22
21	5.00	− 4.50	3.46	0.68	3.08
22	6.00	− 5.50	2.61	0.60	2.34
23	7.00	− 6.50	1.93	0.57	1.74
24	8.00	− 7.50	1.52	0.76	1.42
25	9.00	− 8.50	1.35	0.66	1.26





[S. Li, JL, Eur. Phys. J. C 80, no.7, 671 (2020)]

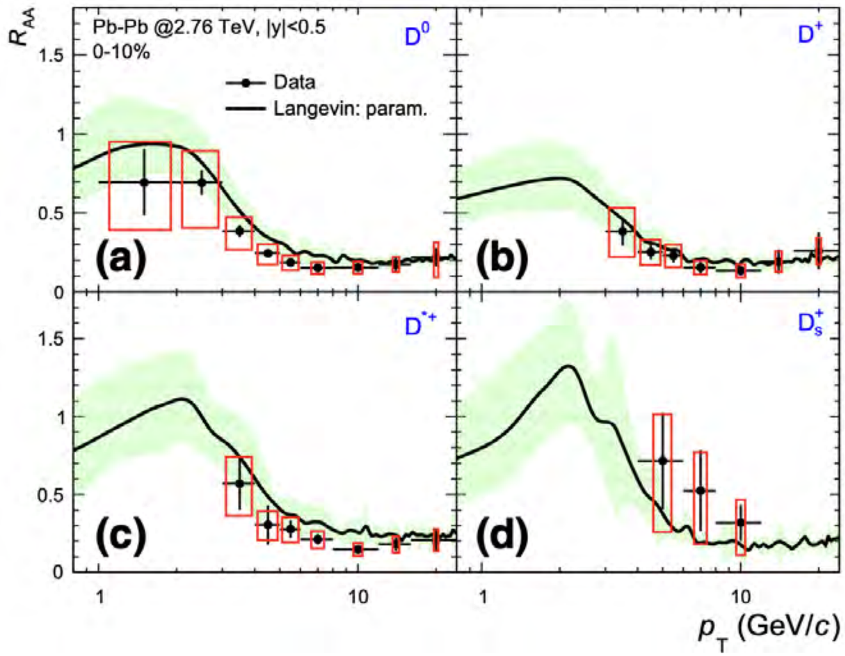
Data-Driven Extraction of T-Dependence

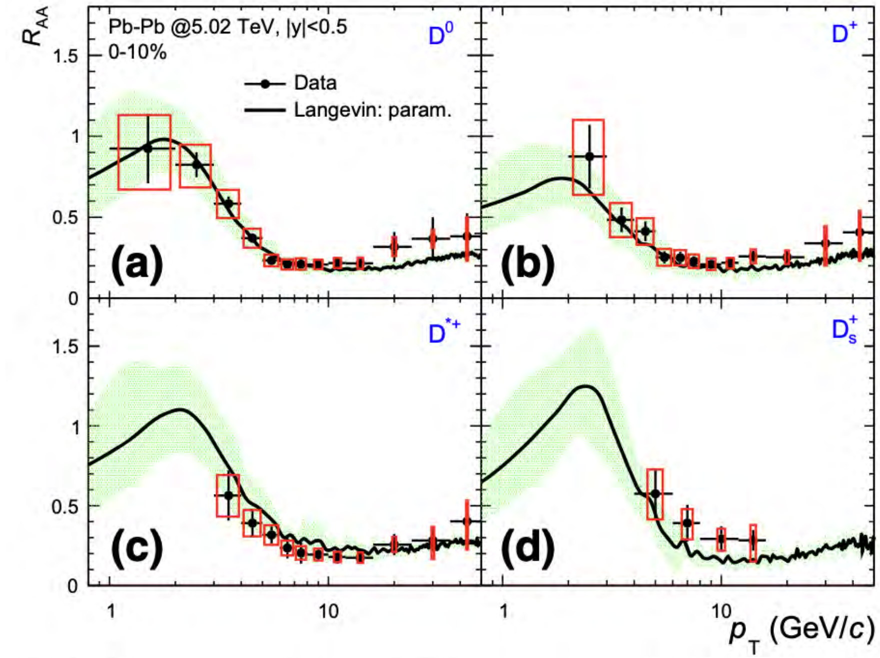


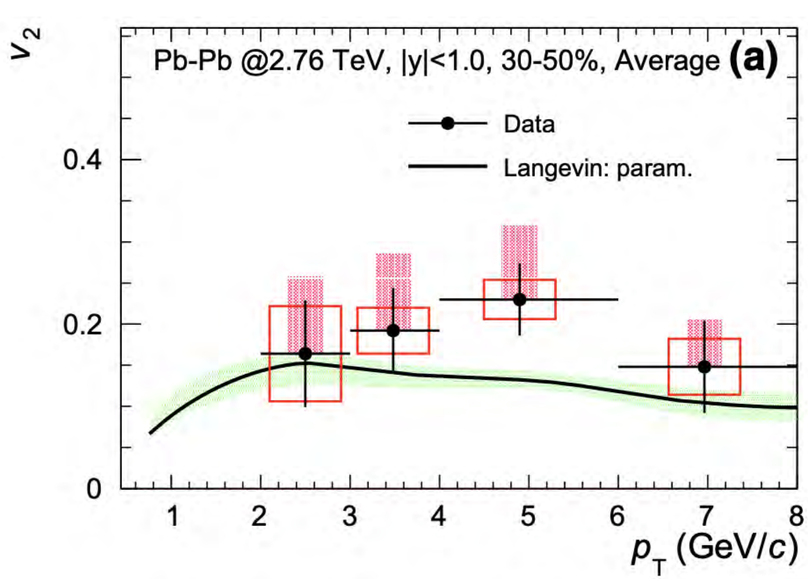
(2 pi T Ds) very small near Tc;
Strong increase toward higher temperature

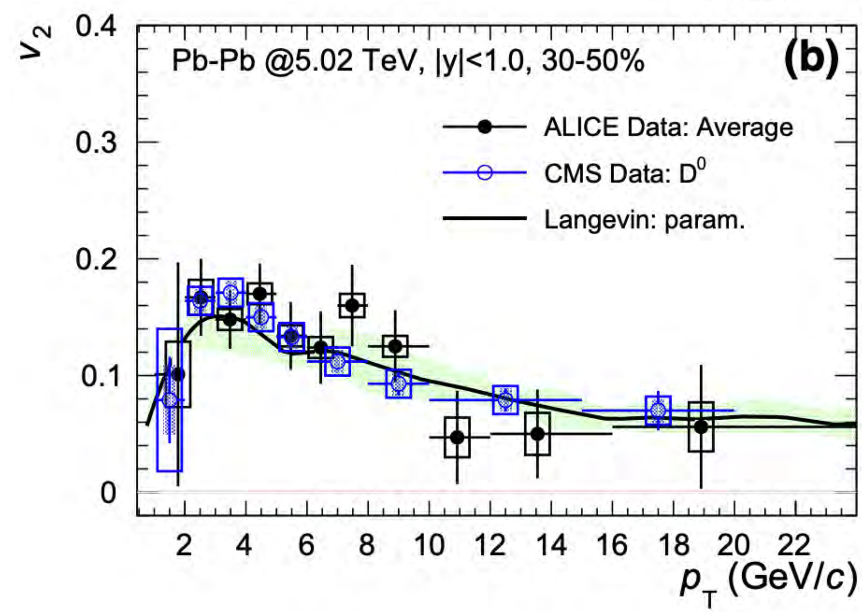
[S. Li, JL, Eur. Phys. J. C 80, no.7, 671 (2020)]

Comparison with Exp Data

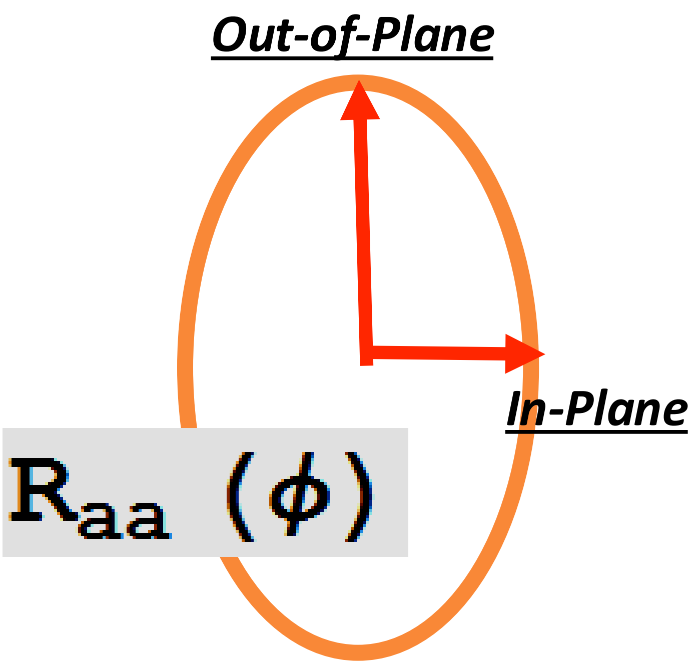




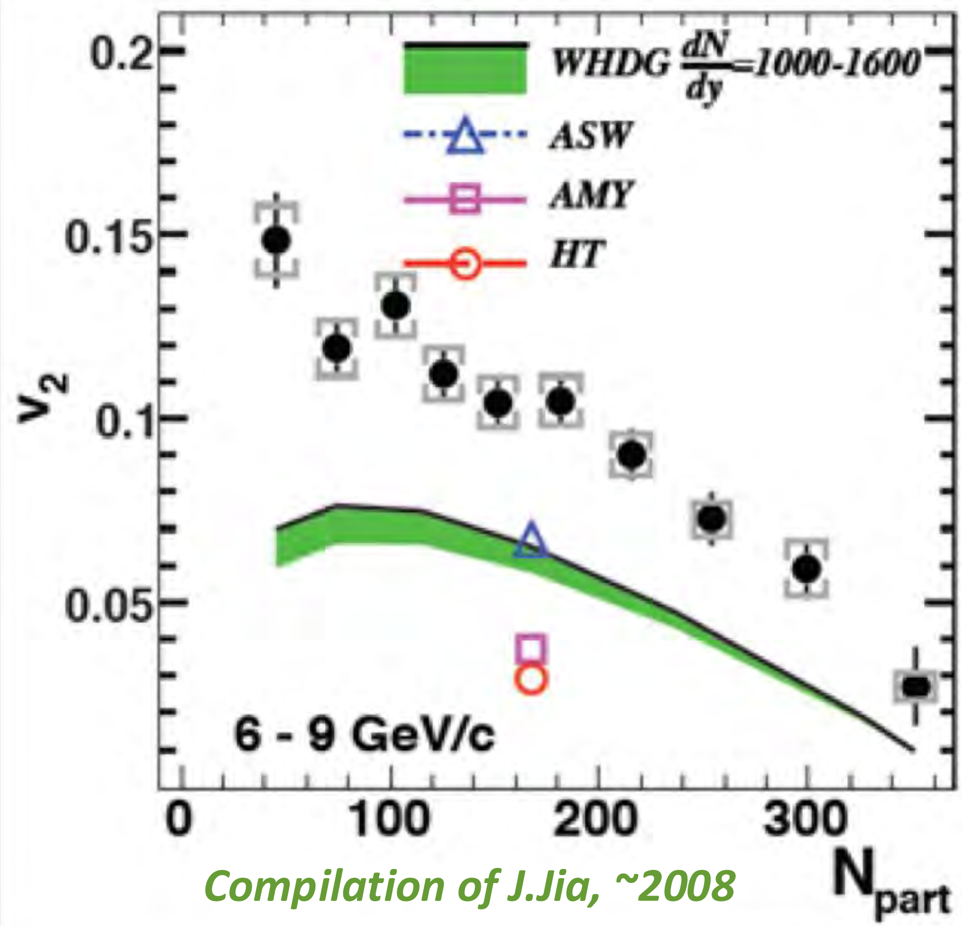




High Pt: Jet Quenching & Geometric Tomography



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



Compilation of J.Jia, ~2008

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

High Pt v2 became a long standing challenge

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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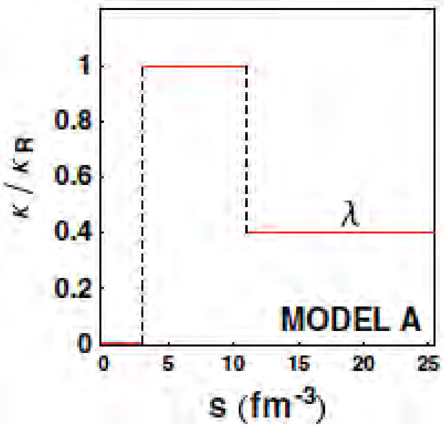
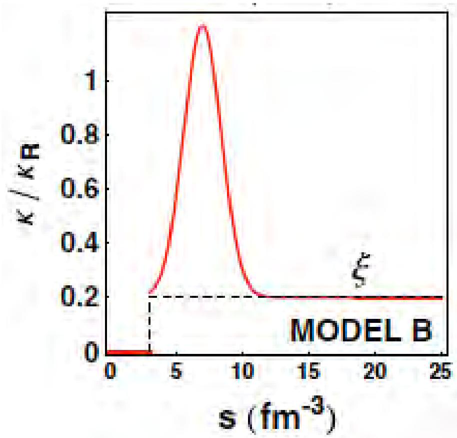
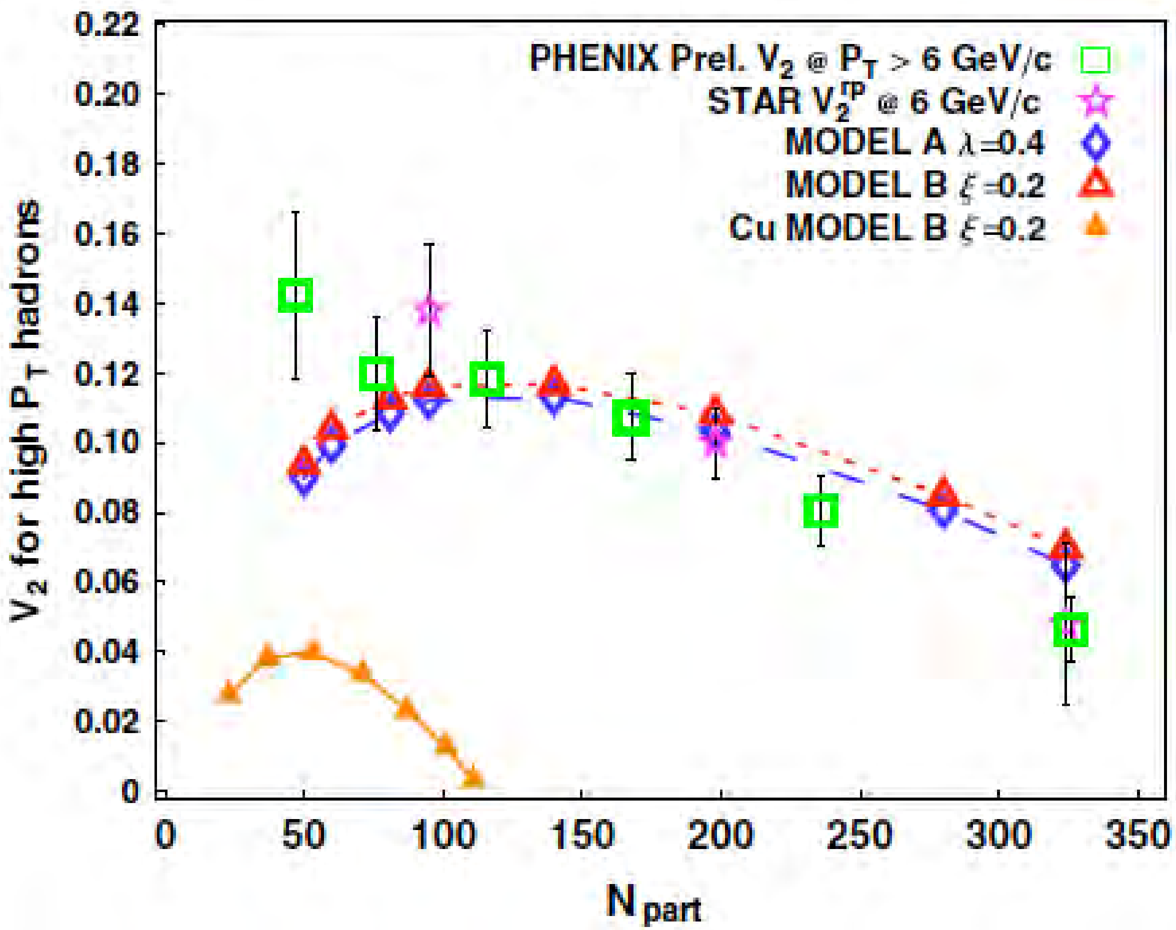
[2]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

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

Near-Tc Enhancement (NTcE)





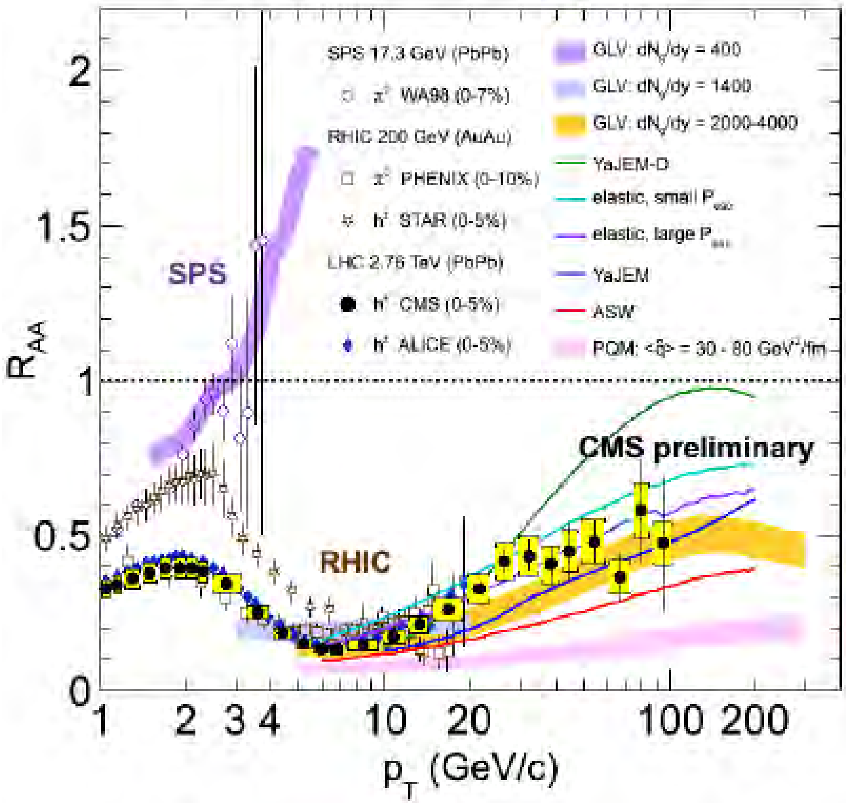


In the paper PRL(2009) we concluded:

"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."

The RHIC+LHC Era

Raa(RHIC)~Raa(LHC)



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

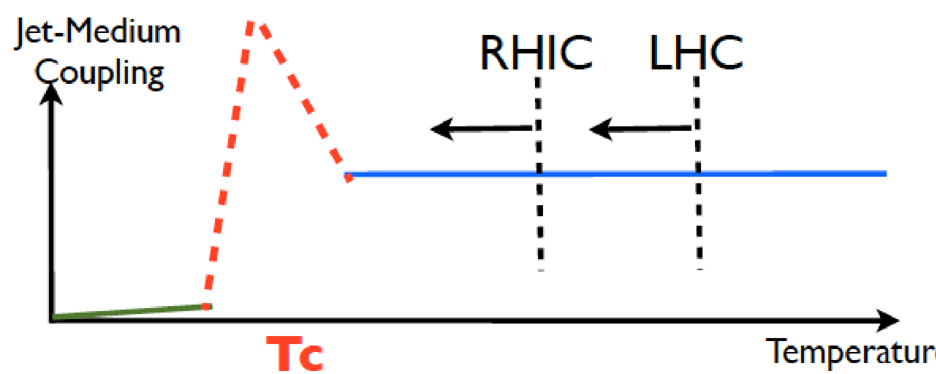
— "surprising transparency" (Horowitz & Gyulassy, QM11)

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

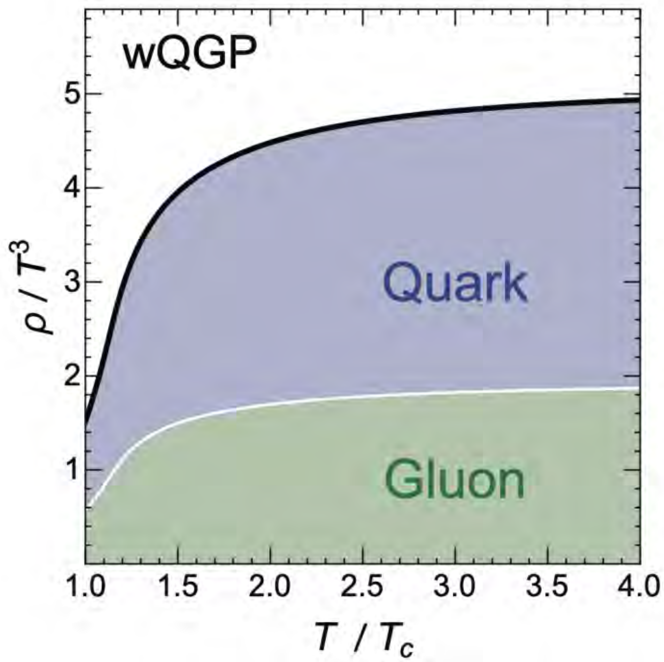
$$\boxed{<\kappa>_{\mathrm{RHIC}} : <\kappa>_{\mathrm{LHC}} \approx 1 : 0.72}$$

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

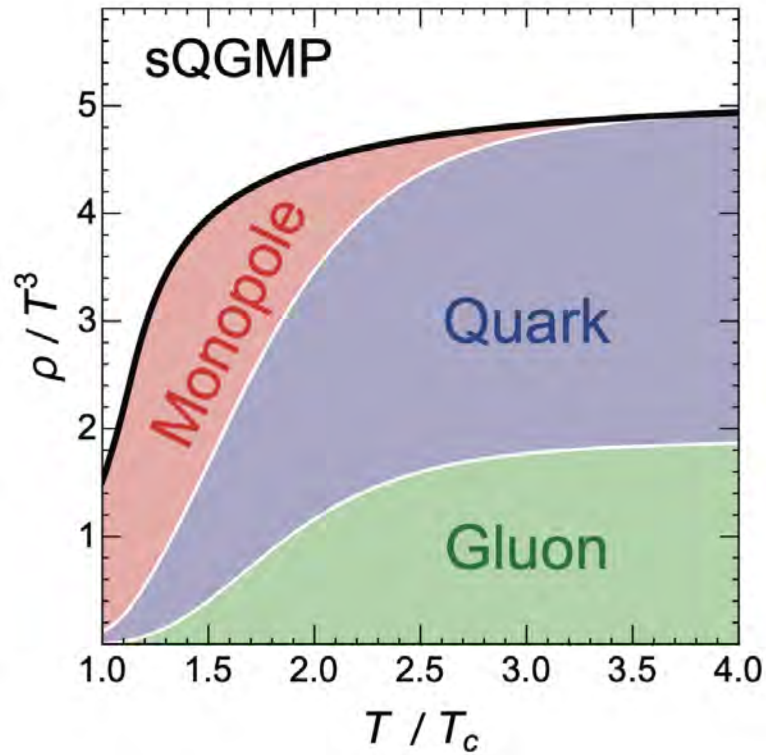
(RHIC+LHC) & (Raa+V2): a highly constraining set of observables for jet energy loss models!



The Chromo-Magnetic Component of QGP



v.s.



To implement the magnetic scenario in a sophisticated jet energy loss model —> CUJET3: It allows quantitative test of the magnetic component.

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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(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

JHEP02(2016)169

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

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CUJET3: Semi-Quark-Gluon Monopole Plasma

Chinese Physics C Vol. 42, No. 10 (2018) 104104

Probing the color structure of the perfect QCD fluids via soft-hard-event-by-event azimuthal correlations*

Shuzhe Shi[1)] Jinfeng Liao[1;1)] 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
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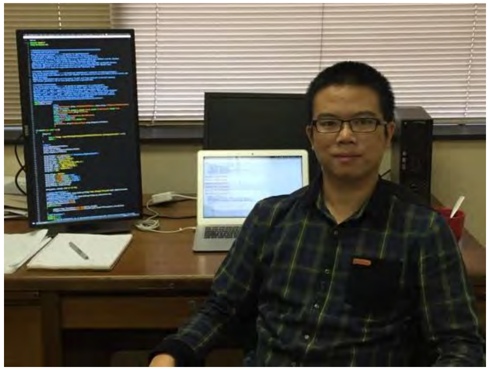


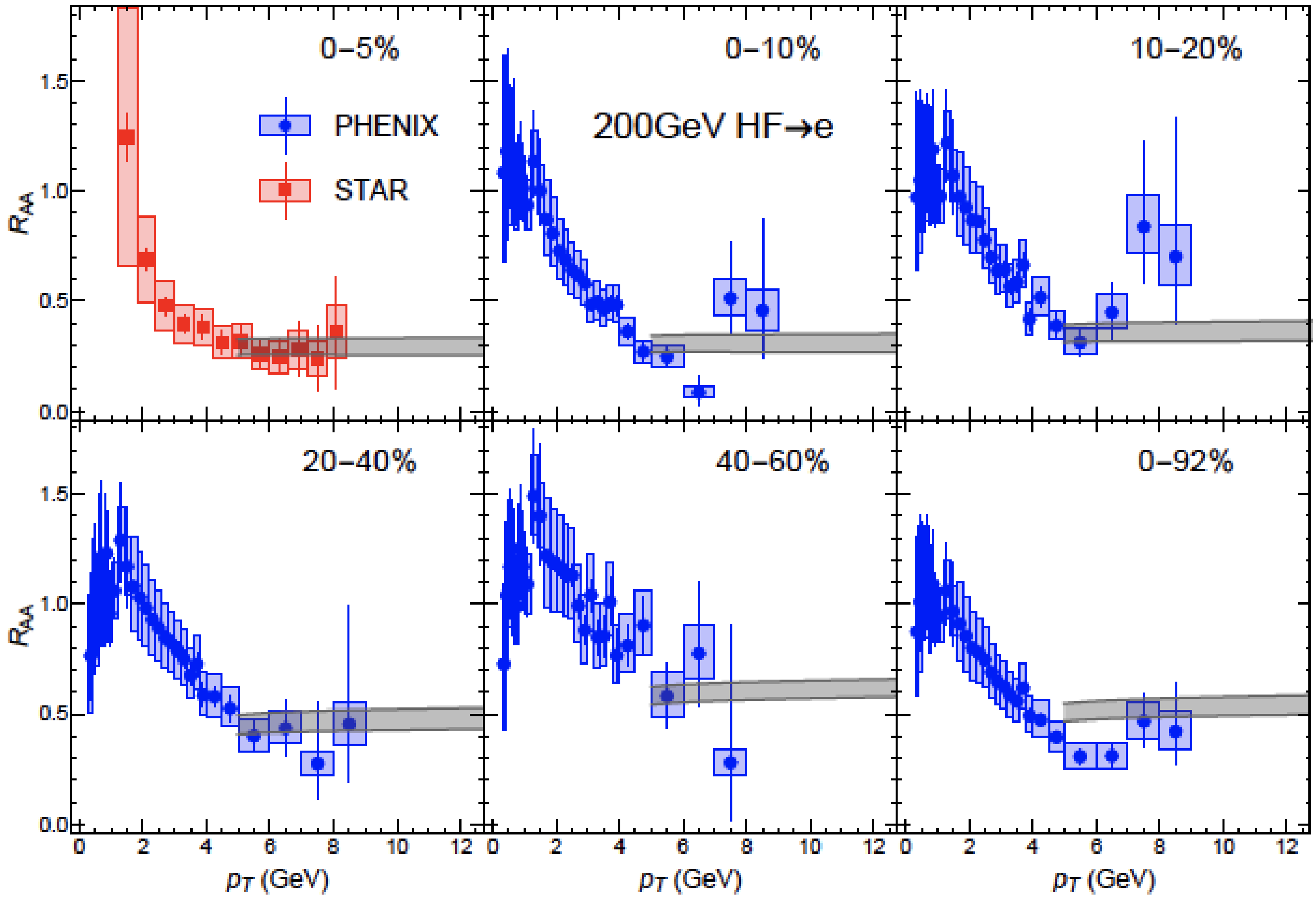
Chinese Physics C Vol. 43, No. 4 (2019) 04[illegible]101

Global constraints from RHIC and LHC on transport properties of QCD fluids in CUJET/CIBJET framework*

Shuzhe Shi(施舒哲)[1;1)] Jinfeng Liao(廖劲峰)[1;2)] Miklos Gyulassy[2,3,4;3)]

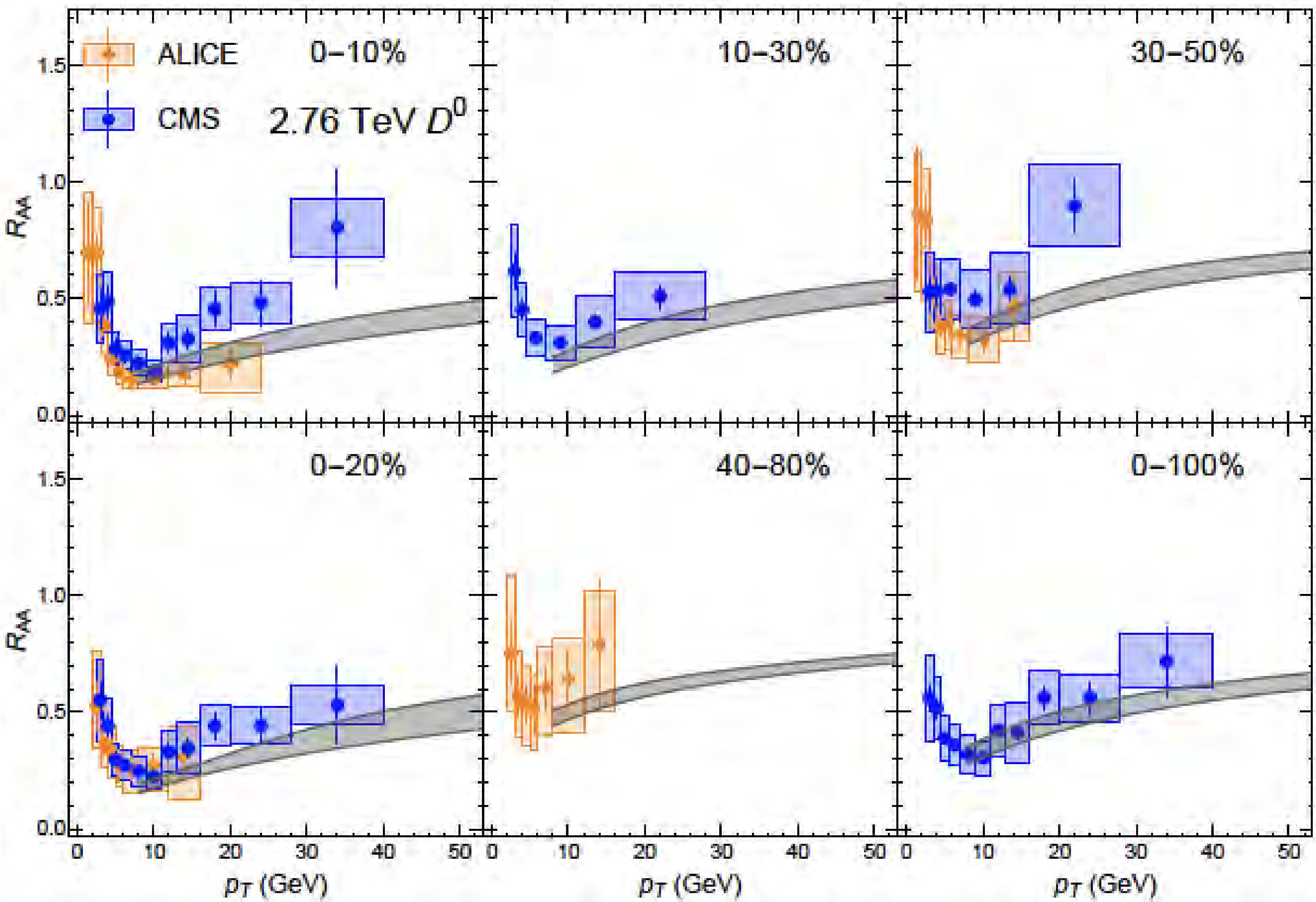
[1] Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA
[2] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[3] Pupin Lab MS-5202, Department of Physics, Columbia University, 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

Independent Test with Heavy Flavor Data



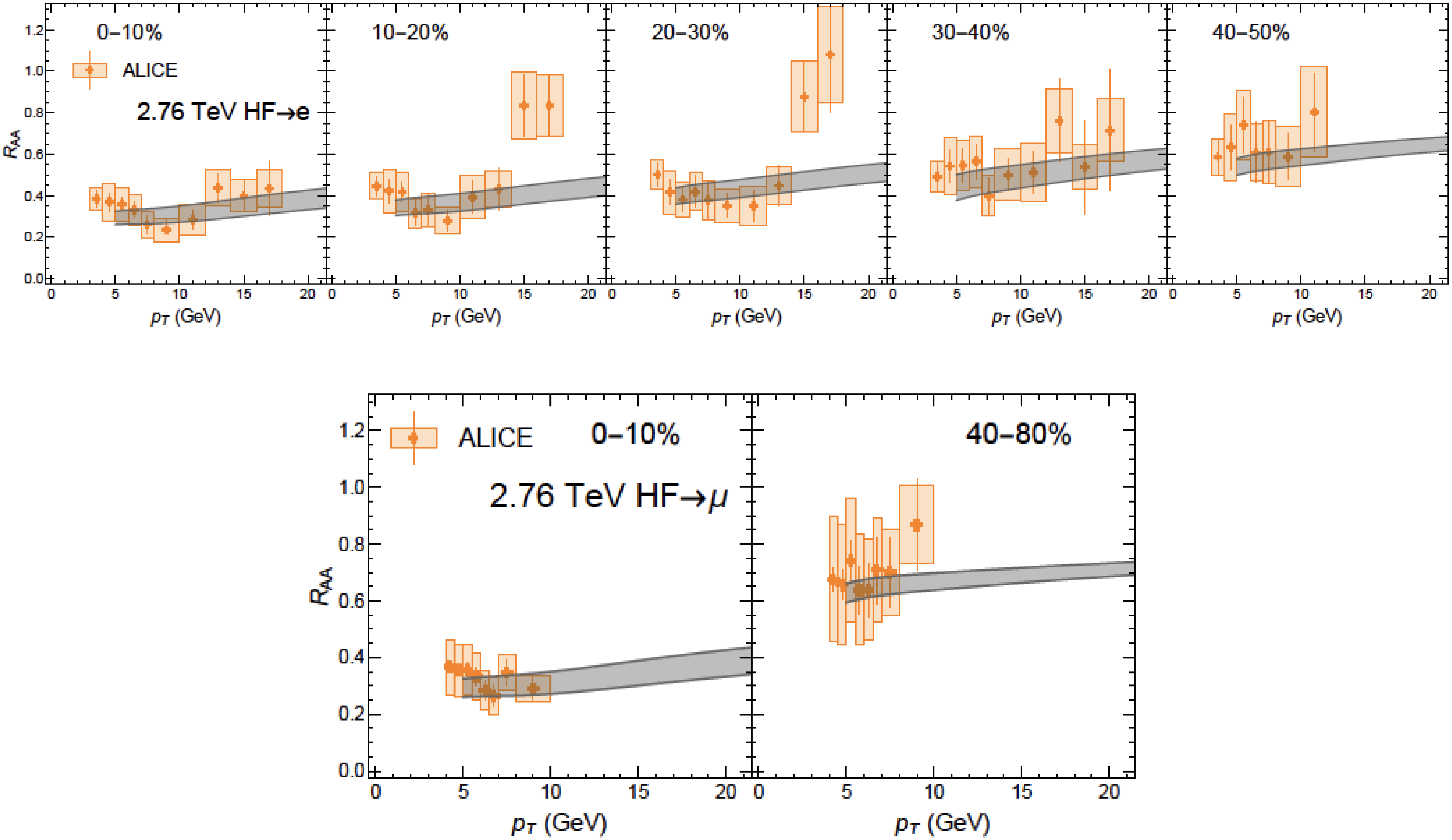
[S. Shi, J. Liao, M. Gyulassy, Chin.Phys.C 43 (2019) 4, 044101]

Independent Test with Heavy Flavor Data



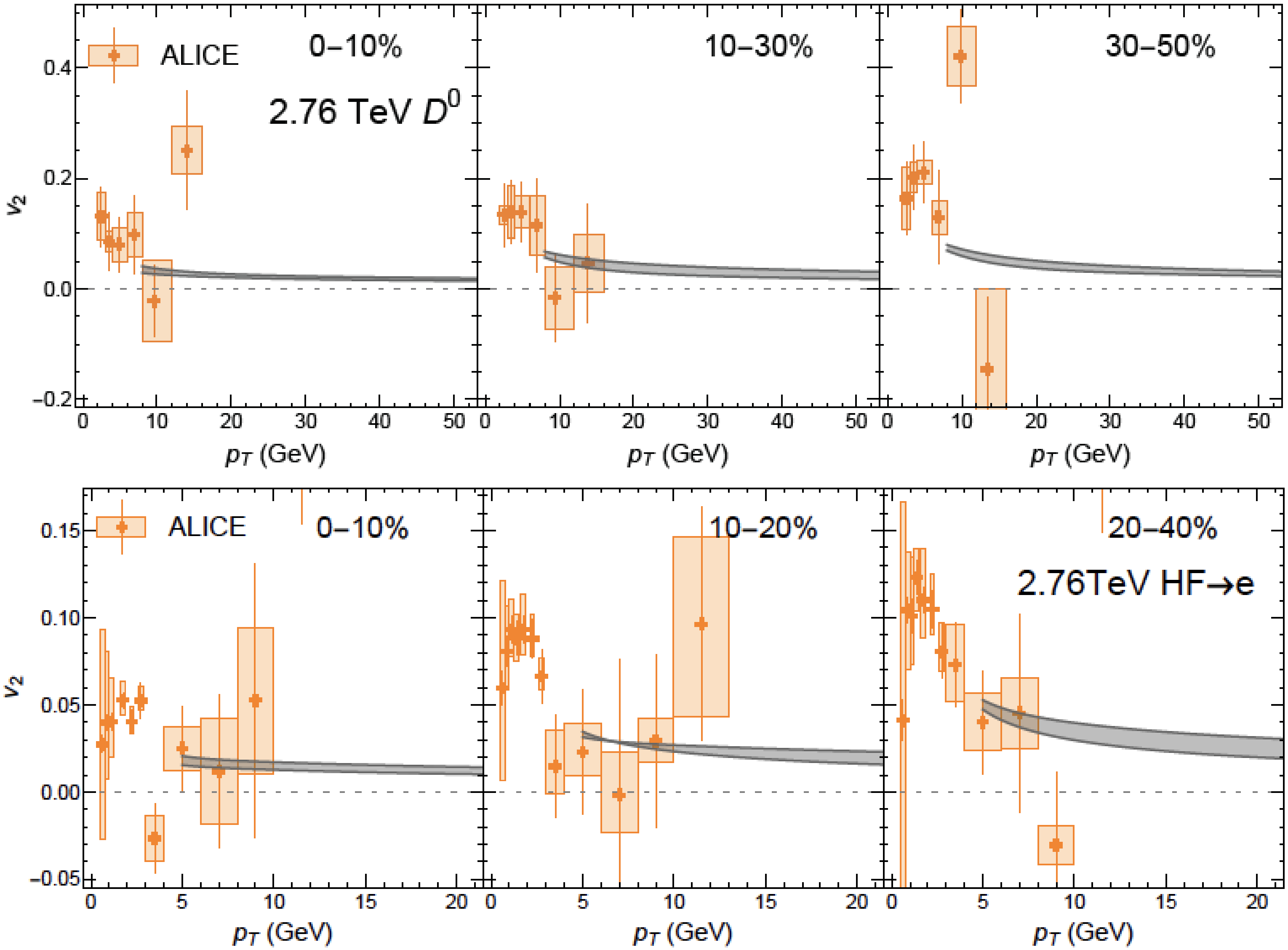
[S. Shi, J. Liao, M. Gyulassy, Chin.Phys.C 43 (2019) 4, 044101]

Independent Test with Heavy Flavor Data



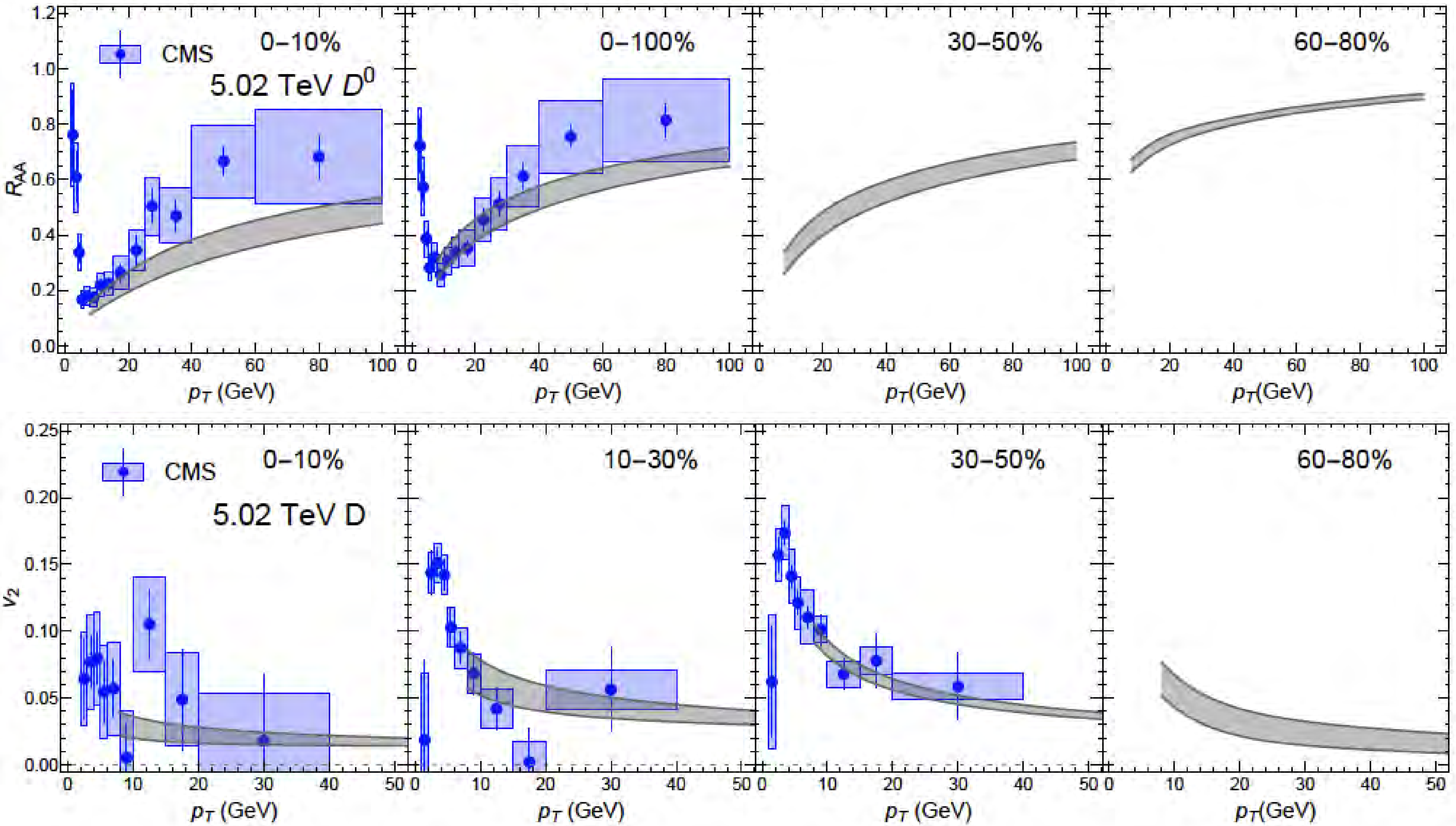
[S. Shi, J. Liao, M. Gyulassy, Chin.Phys.C 43 (2019) 4, 044101]

Independent Test with Heavy Flavor Data



[S. Shi, J. Liao, M. Gyulassy, Chin.Phys.C 43 (2019) 4, 044101]

Independent Test with Heavy Flavor Data



[S. Shi, J. Liao, M. Gyulassy, Chin.Phys.C 43 (2019) 4, 044101]

Latest Development from CUJET3

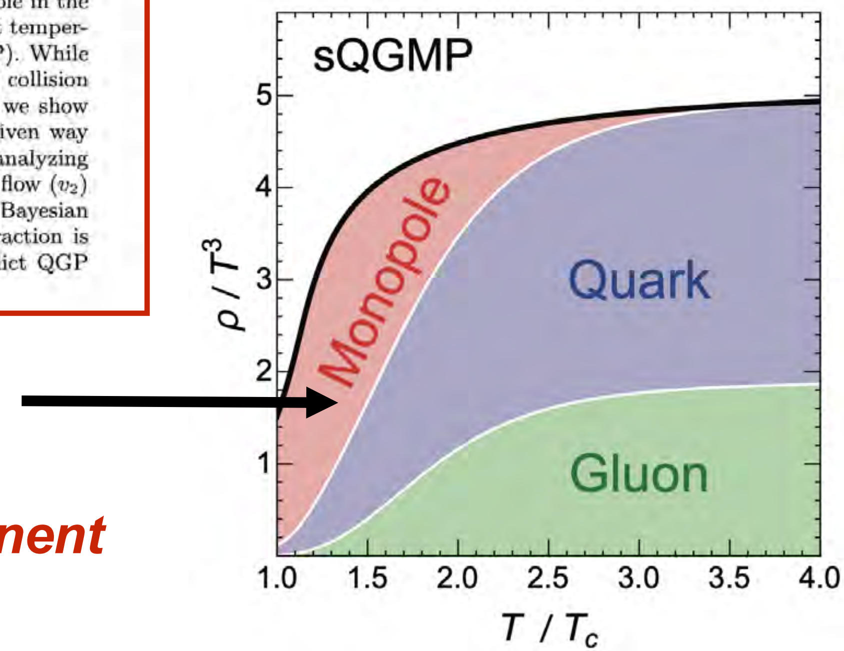
Bayesian inference of the magnetic component of quark-gluon plasma

Yu Guo,[1] Jinfeng Liao,[2,*] and Shuzhe Shi[1,3,†]

[1] *Department of Physics, Tsinghua University, Beijing 100084, China.*
[2] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA.*
[3] *State Key Laboratory of Low-Dimensional Quantum Physics, Tsinghua University, Beijing 100084, China.*

(Dated: October 21, 2025)

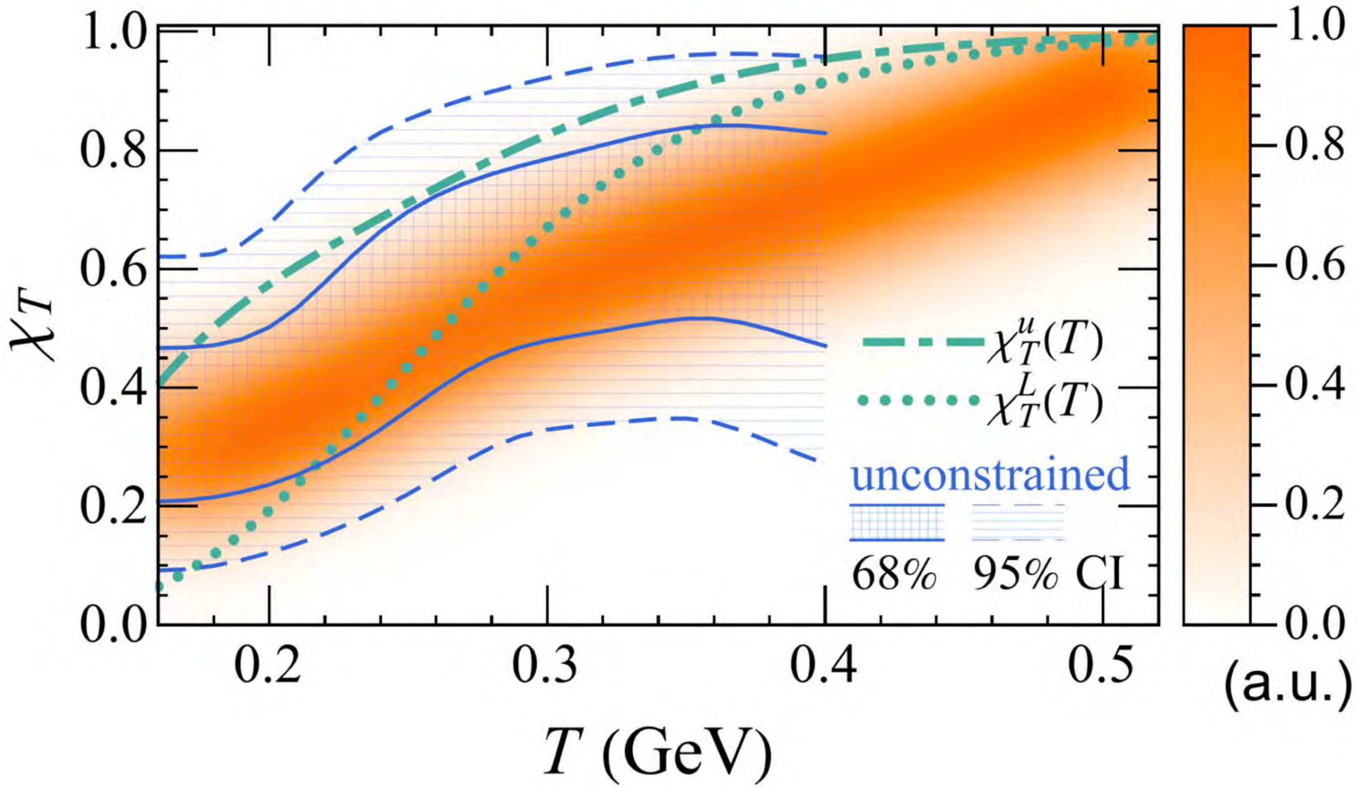
The chromo-magnetic monopoles (CMM), emergent topological excitations of non-Abelian gauge fields carrying chromo-magnetic charge, have long been postulated to play an important role in the vacuum confinement of quantum chromodynamics (QCD), the deconfinement transition at temperature $T_c \approx 160$MeV, as well as the strongly coupled nature of quark-gluon plasma (QGP). While such CMMs have been found to provide solutions for challenging puzzles from heavy-ion collision measurements, they were typically introduced as model assumptions in the past. Here we show how their very existence can be determined and their abundance extracted in a data-driven way for the first time. Using the CUJET3 framework for calculations of jet energy loss and analyzing a comprehensive experimental data set for nuclear modification factor (R_{AA}) and elliptic flow (v_2) of high-transverse-momentum hadrons, the fraction of CMMs in the QGP is obtained by Bayesian inference and is found to be substantial in the $1 \sim 2T_c$ region. The posterior CMM fraction is further validated by excellent agreement with additional data and is also shown to predict QGP transport properties quantitatively consistent with the state-of-the-art knowledge.



Is there a chromo-magnetic component in QGP? Let data decide!

[Yu Guo, JL, Shuzhe Shi, arXiv:2510.16838]

Evidence from Bayesian Inference



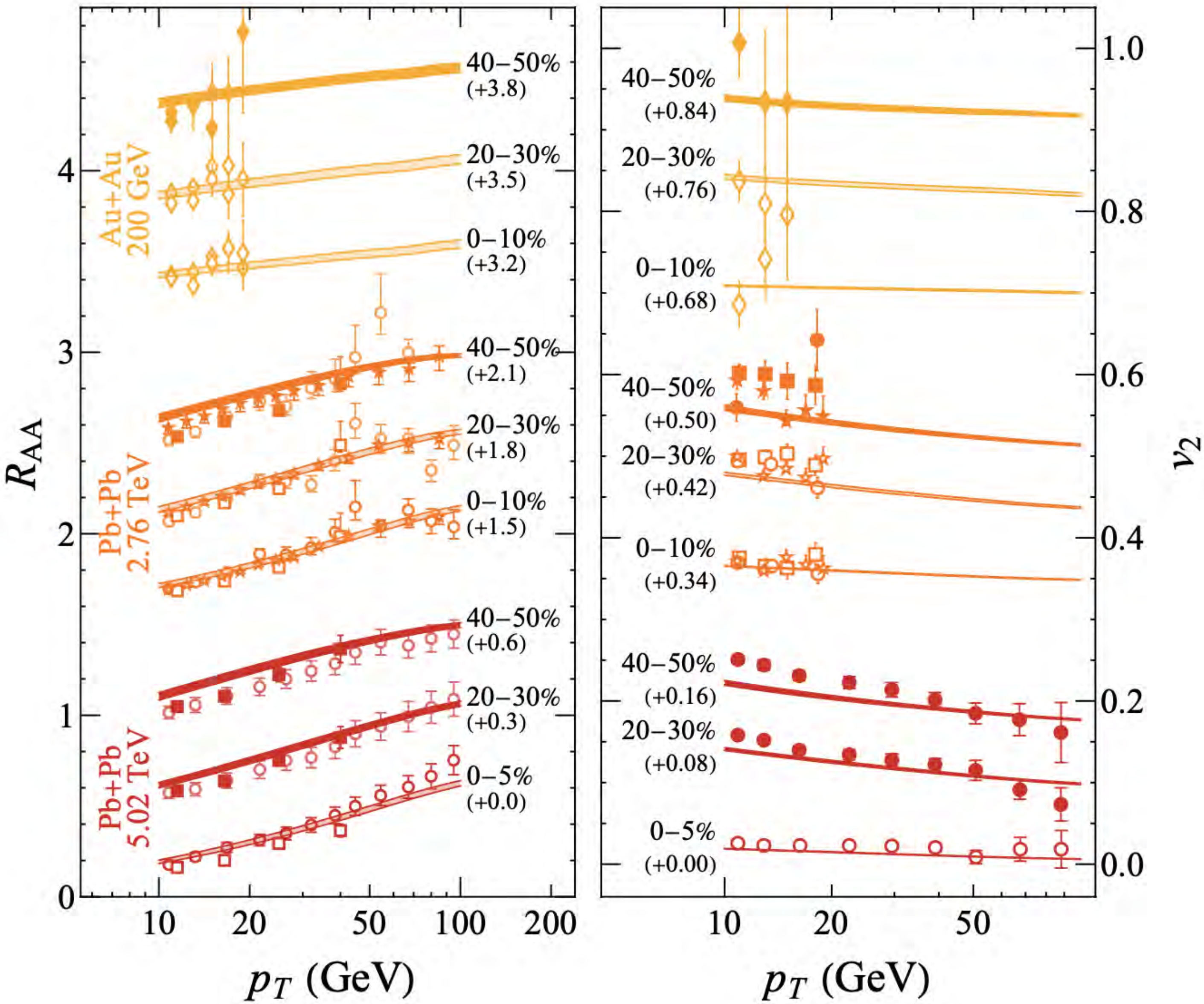
$$\rho_m = (1-\chi_T)\rho$$

$$\rho_g \equiv \left(\frac{16}{16+9N_f}\right) \chi_T \rho$$

$$\rho_q \equiv \left(\frac{9N_f}{16+9N_f}\right) \chi_T \rho$$

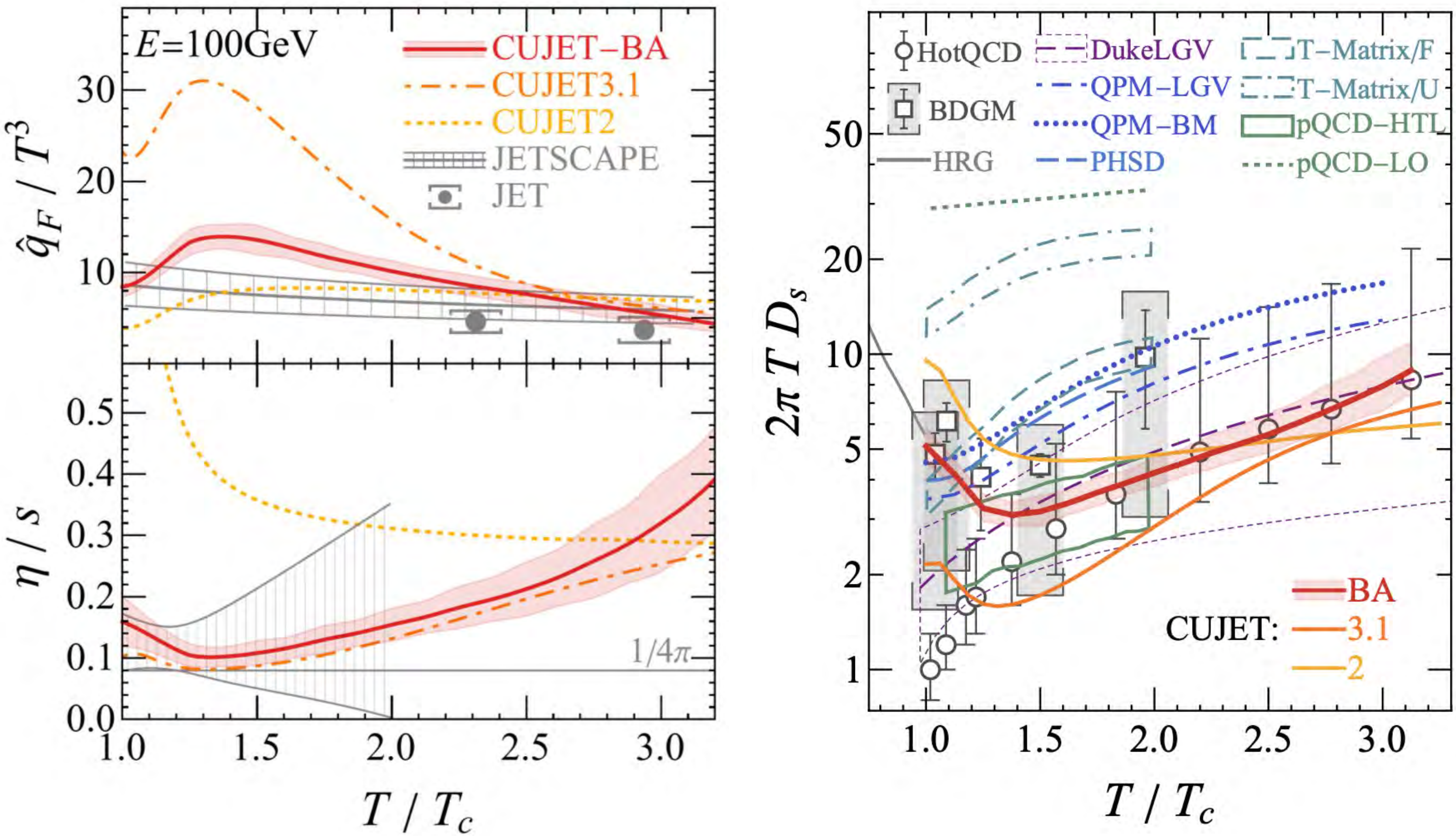
[Yu Guo, JL, Shuzhe Shi, arXiv:2510.16838]

Data Validation



[Yu Guo, JL, Shuzhe Shi, arXiv:2510.16838]

Predictions for Transport Coefficients

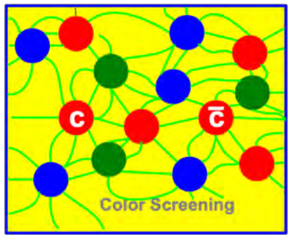


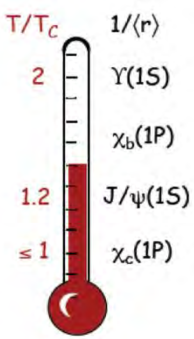
[Yu Guo, JL, Shuzhe Shi, arXiv:2510.16838]

“Cooking” the Exotica in Heavy Ion Collisions

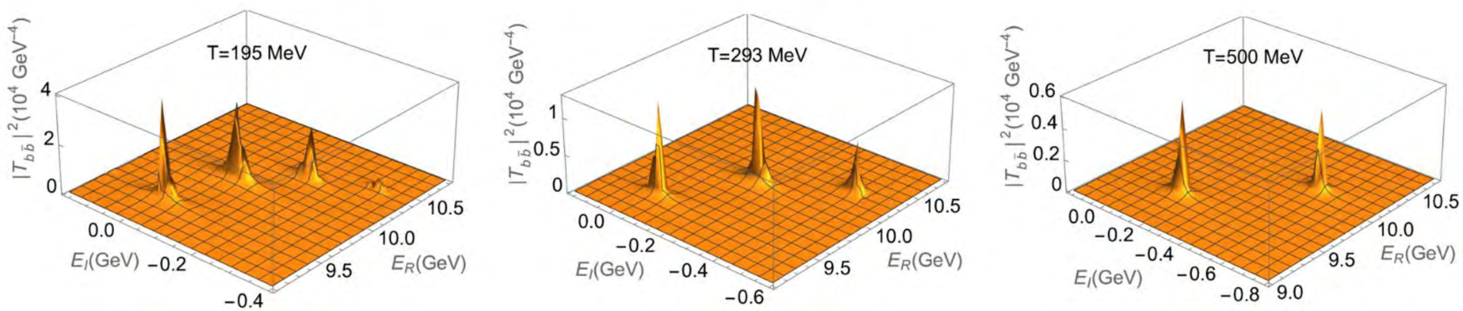
Quarkonium as Probe of QGP

At low to intermediate pT: suppression and regeneration effects compete



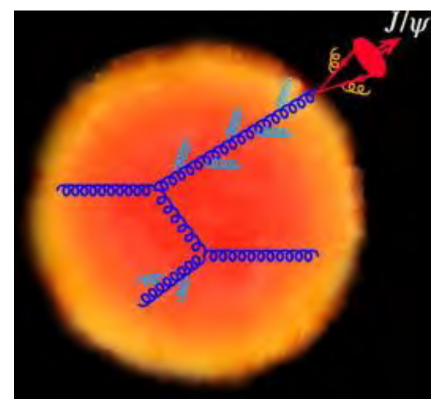


Tang, Hanlon, Mukherjee, Petreczky and Rapp, PRL 135 (2025) 1142302



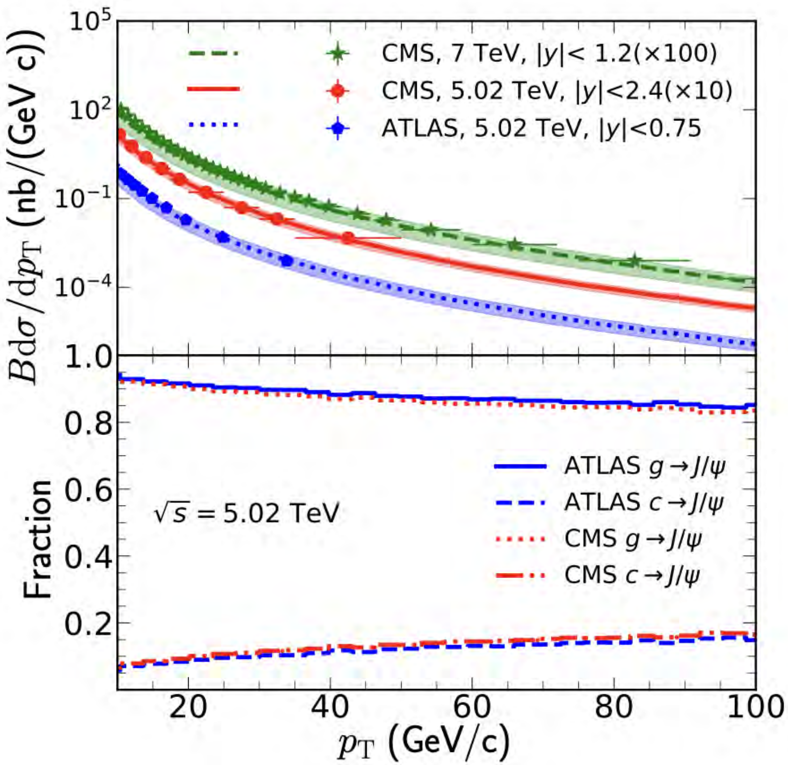
From talk by Petreczky

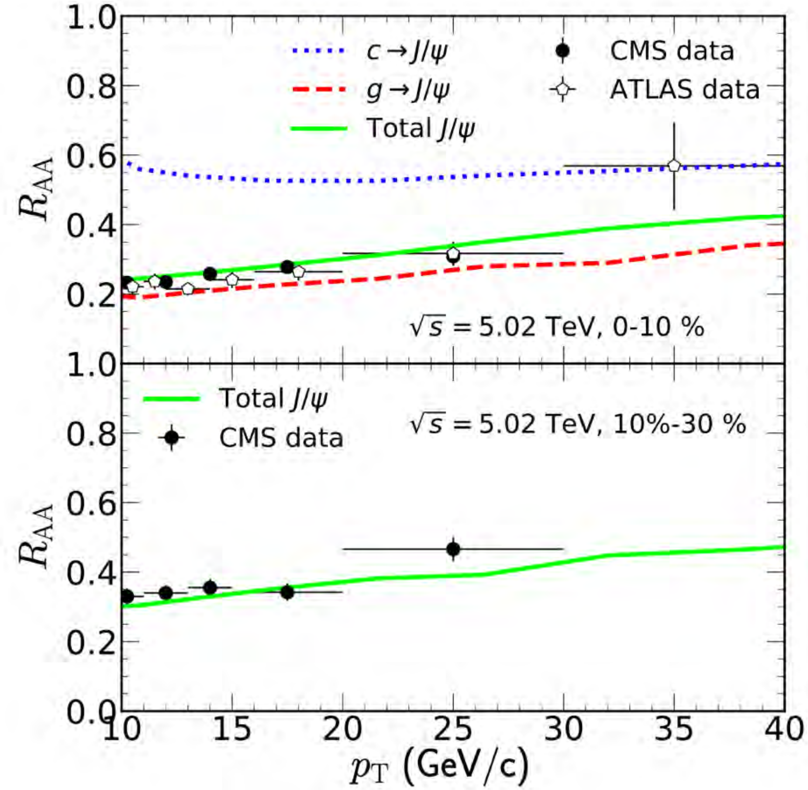
At high pT: dominated by gluon energy loss and fragmentation.



Determining Gluon Energy Loss from J/Psi

J/Psi production at high p_T is dominated by gluon fragmentation.





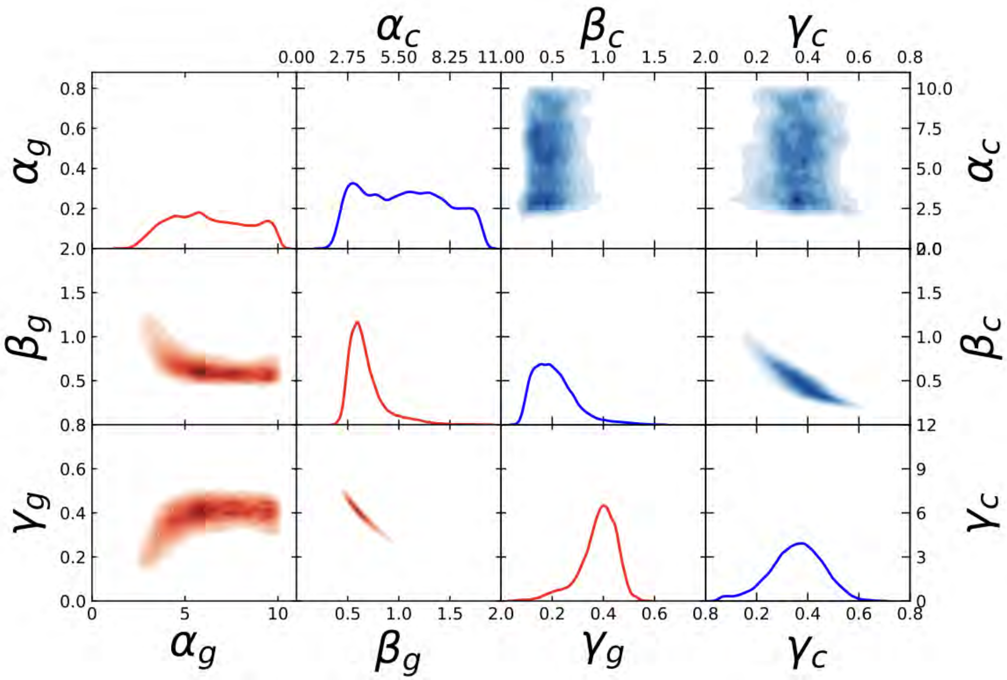
pp collision ***AA collision***

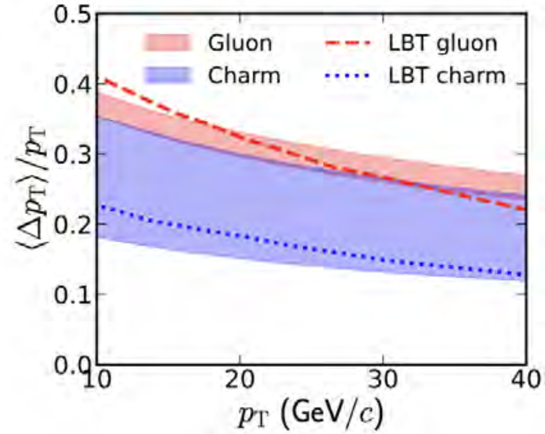
[S.L. Zhang, JL, G.Y. Qin, E. Wang, H. Xing, Sci.Bull. 68 (2023) 2003-2009]

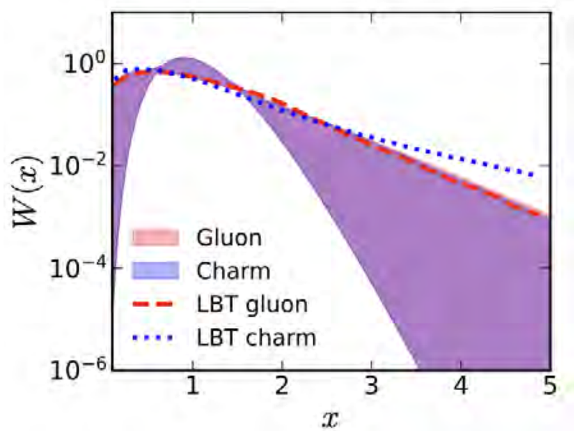
Determining Gluon Energy Loss from J/Psi

J/Psi production at high p_T is dominated by gluon fragmentation. This allows Bayesian extraction of gluon energy loss.

$$W^i(x) = \frac{\alpha_i^{\alpha_i} x^{\alpha_i - 1} e^{-\alpha_i x}}{\Gamma(\alpha_i)}$$



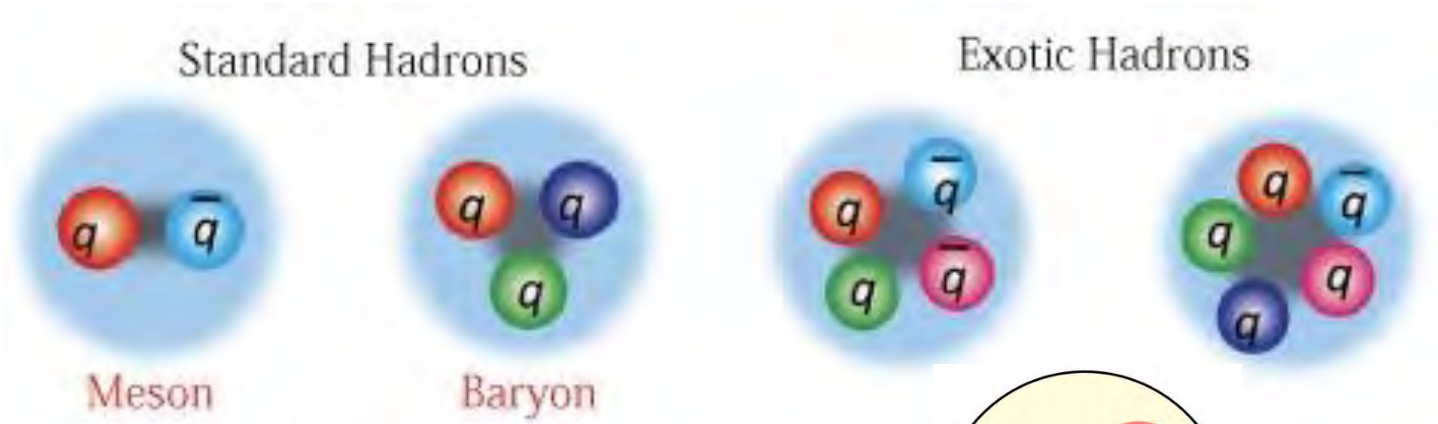


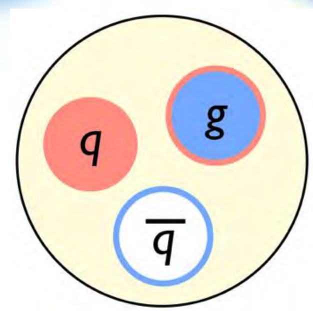


[S.L. Zhang, JL, G.Y. Qin, E. Wang, H. Xing, Sci.Bull. 68 (2023) 2003-2009]

Challenging "Quark Math" for Hadrons

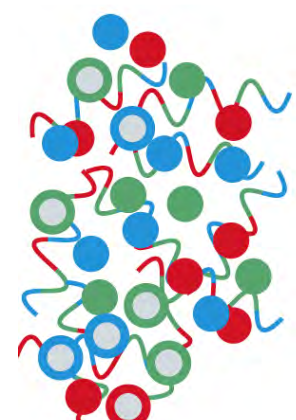
Quarks make hadrons:
What configurations are possible and what not?
And why? —- Active frontiers of hadron physics.





Many experiments:
BESIII, BaBar, Bell, CLEO,
GlueX, LHCb, ATLAS, CMS,
…

The extreme of multi-quarks/gluons
system: quark gluon plasma (QGP)

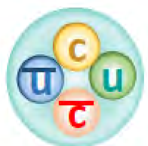


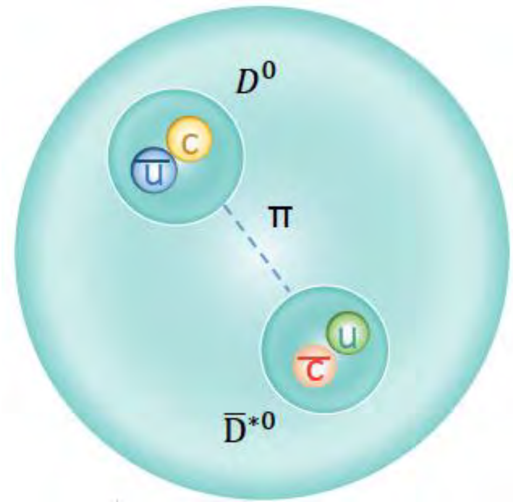
X3872 (aka Chi_c1)

First observed in 2003 by Belle, later seen by many other experiments

What is the intrinsic structure of X387??

Compact tetra quark?
R ~ 0.5 fm



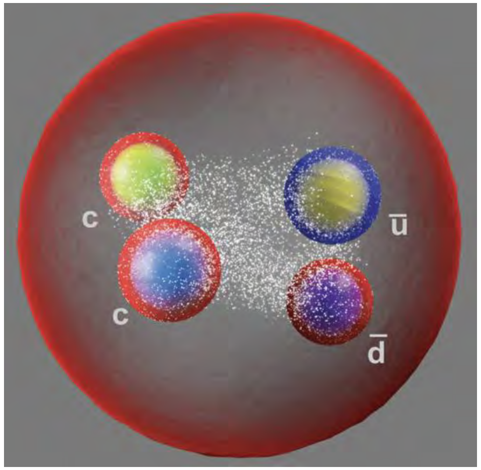


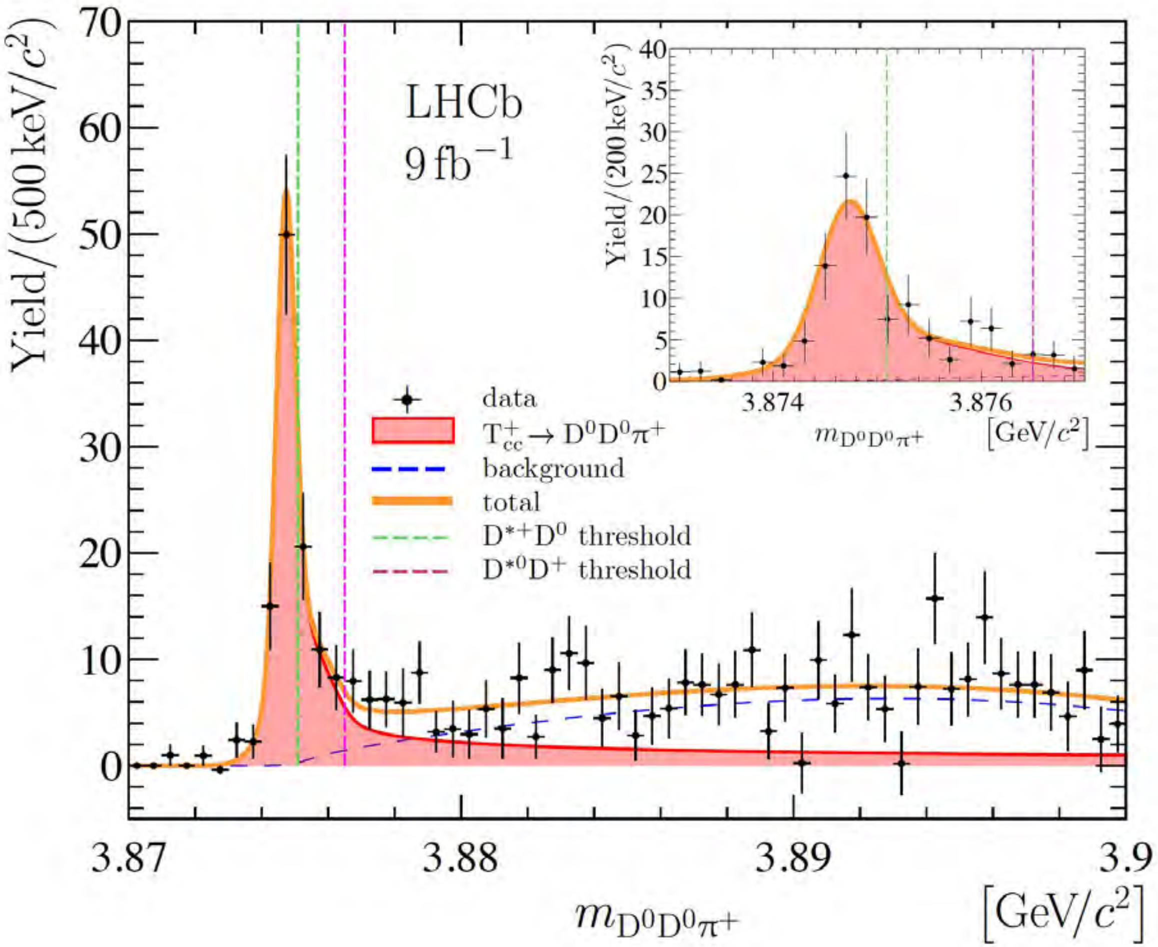
Hadron molecule?
R ~ 5 fm

Despite 20+ years past its discovery, we still could not decide on the final answer of its intrinsic structure.

Can we help resolving the challenge of "quark math" with heavy ion collisions?

Tcc+





The flavor content clearly suggests the exotic nature: c-c-ubar-dbar ; Mass~3875MeV

Can we help resolving the challenge of "quark math" with heavy ion collisions?

Early Study on Exotica in Heavy Ion Collisions

Identifying Multiquark Hadrons from Heavy Ion Collisions

Sungtae Cho, Takenori Furumoto, Tetsuo Hyodo, Daisuke Jido, Che Ming Ko, Su Houng Lee, Marina Nielsen, Akira Ohnishi, Takayasu Sekihara, Shigehiro Yasui, and Koichi Yazaki (ExHIC Collaboration)

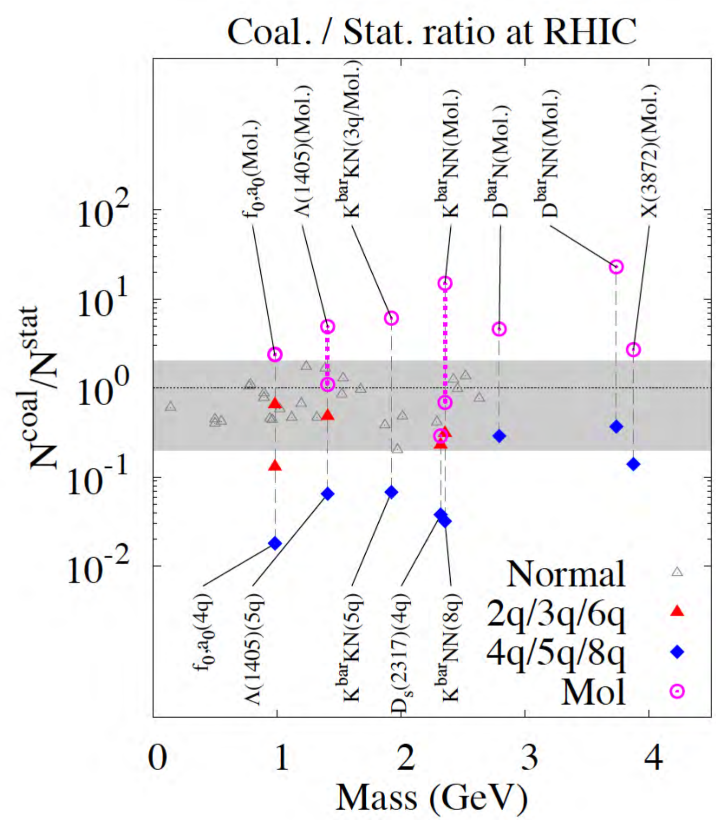
Phys. Rev. Lett. **106**, 212001 – Published 24 May 2011

Exotic hadrons in heavy ion collisions

Sungtae Cho, Takenori Furumoto, Tetsuo Hyodo, Daisuke Jido, Che Ming Ko, Su Houng Lee, Marina Nielsen, Akira Ohnishi, Takayasu Sekihara, Shigehiro Yasui, and Koichi Yazaki (ExHIC Collaboration)

Phys. Rev. C **84**, 064910 – Published 14 December 2011

What one can learn from these studies:
The internal structure influences the yield;
hadron molecules are more easily formed.



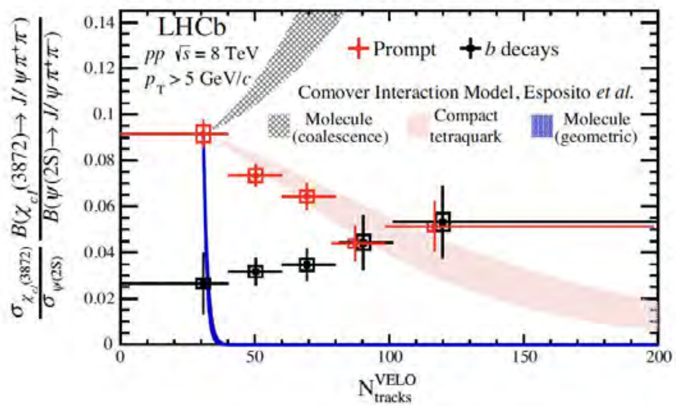
Hunting for X in Nuclear Collisions

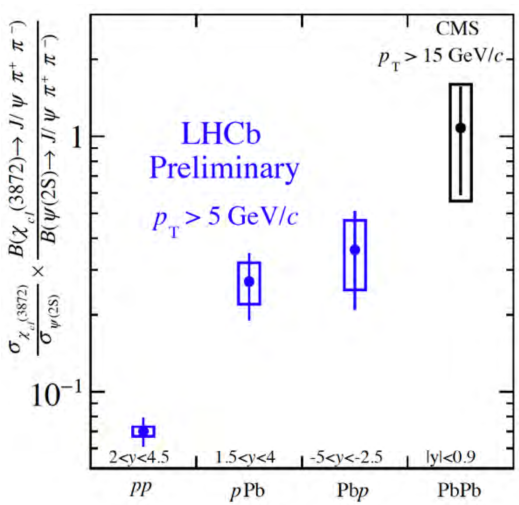
First set of X-measurements from CMS and LHCb since 2019

PHYSICAL REVIEW LETTERS **126,** 092001 (2021)

Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions

R. Aaij *et al.**
(LHCb Collaboration)

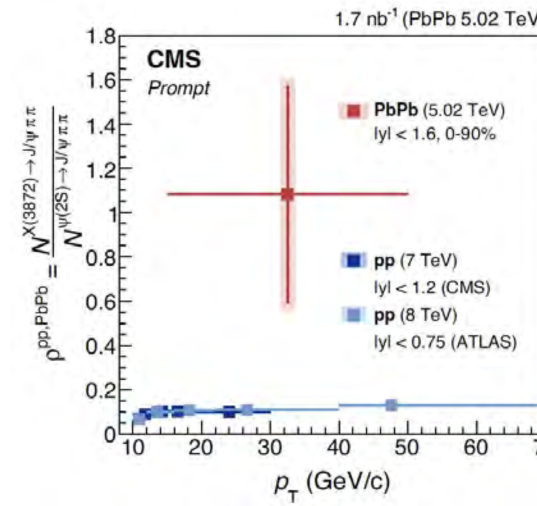




PHYSICAL REVIEW LETTERS **128,** 032001 (2022)

Evidence for X(3872) in Pb-Pb Collisions and Studies of its Prompt Production at $\sqrt{s_{NN}} = 5.02$ TeV

A. M. Sirunyan *et al.**
CMS Collaboration



Measurements already hint at partonic medium effect on exotic production!

The intriguing patterns require theoretical understanding!

"Cooking" Exotica in the Quark Soup

Heavy ion collisions provide a powerful venue for the massive production and detailed study of exotica existence and structures!

PHYSICAL REVIEW LETTERS **126,** 012301 (2021)

Deciphering the Nature of X(3872) in Heavy Ion Collisions

Hui Zhang,[1,2,*] Jinfeng Liao,[3,†] Enke Wang,[1,2,‡] Qian Wang,[1,2,4,§] and Hongxi Xing[1,2,‖]

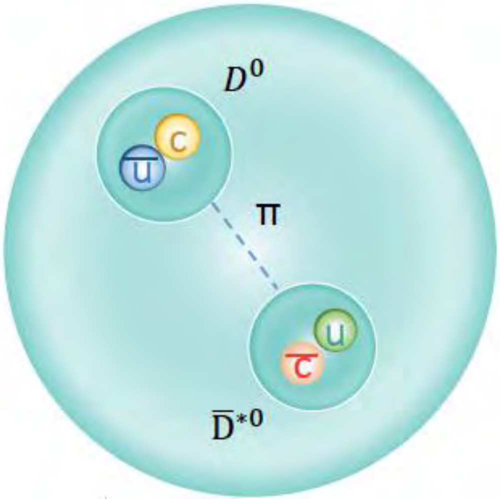
PHYSICAL REVIEW D **104,** L111502 (2021)

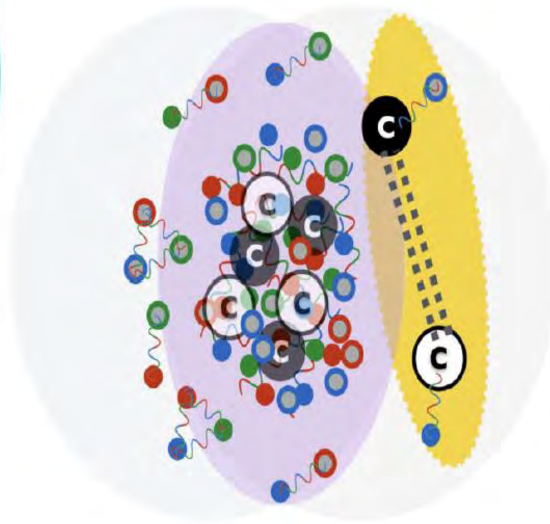
Letter

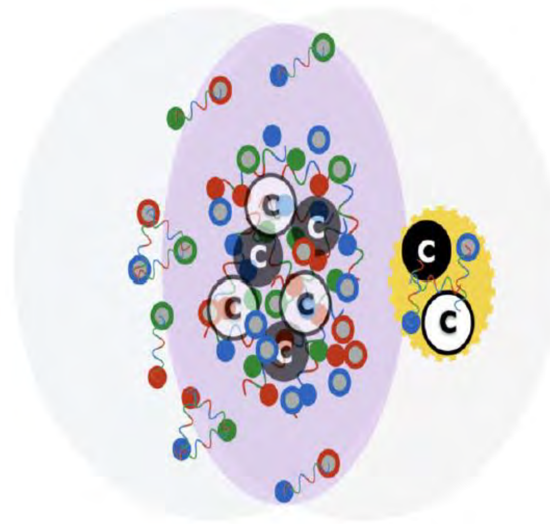
Production of doubly charmed exotic hadrons in heavy ion collisions

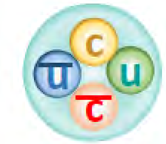
Yuanyuan Hu,[1,2] Jinfeng Liao,[3,*] Enke Wang,[1,2,†] Qian Wang,[1,2,‡] Hongxi Xing,[1,2,§] and Hui Zhang[1,2,‖]

Nailing Down X(3872) Structure









The bulk fireball has its own SIZE scale and can be controlled.

The compact tetra quark would be insensitive to overall size but sensitive to the c and cbar distribution in the fireball.

The hadronic molecule must be sensitive to the source volume.

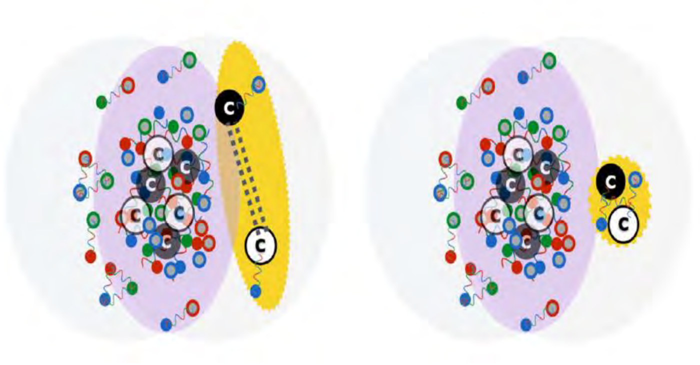
[Similar sensitivity for deuteron production to source volume was known and observed.]

Implementing X Production in Dynamical Heavy Ion Modeling

Dynamical bulk evolution: AMPT
Initial charm: calibrated with D meson production

Hadron molecules:

First form D mesons at freeze out;
*Then use coalescence of D-D*bar, etc;*
Mass matching;
Size matching 5~7fm



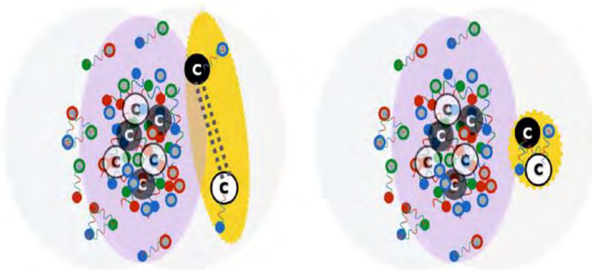
Compact tetra quark:

First form diquark and antidiquark at freeze out;
Then use coalescence of diquark-anti-diquark;
Mass matching;
Size matching <1fm

The hope is to reveal simple yet robust features that distinguish the two intrinsic structures!

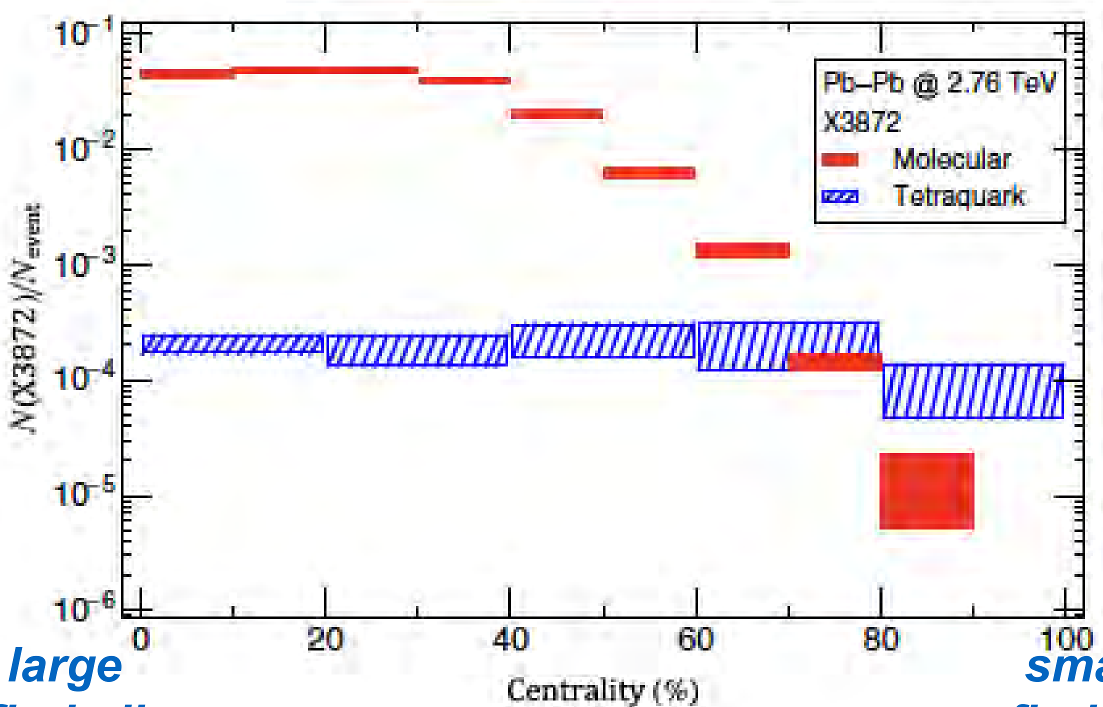
See framework details in PRL126(012301)2021.

A “Intrinsic Size Scan” for X3872



Hadron molecule v.s. tetraquark:
Two orders of magnitude difference in the yield;
Drastically different centrality dependence.

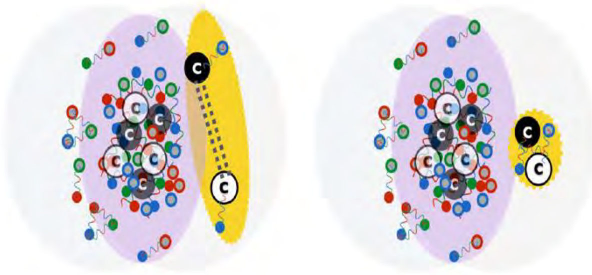
See framework details in PRL126(012301)2021.



large fireball → ***small fireball***

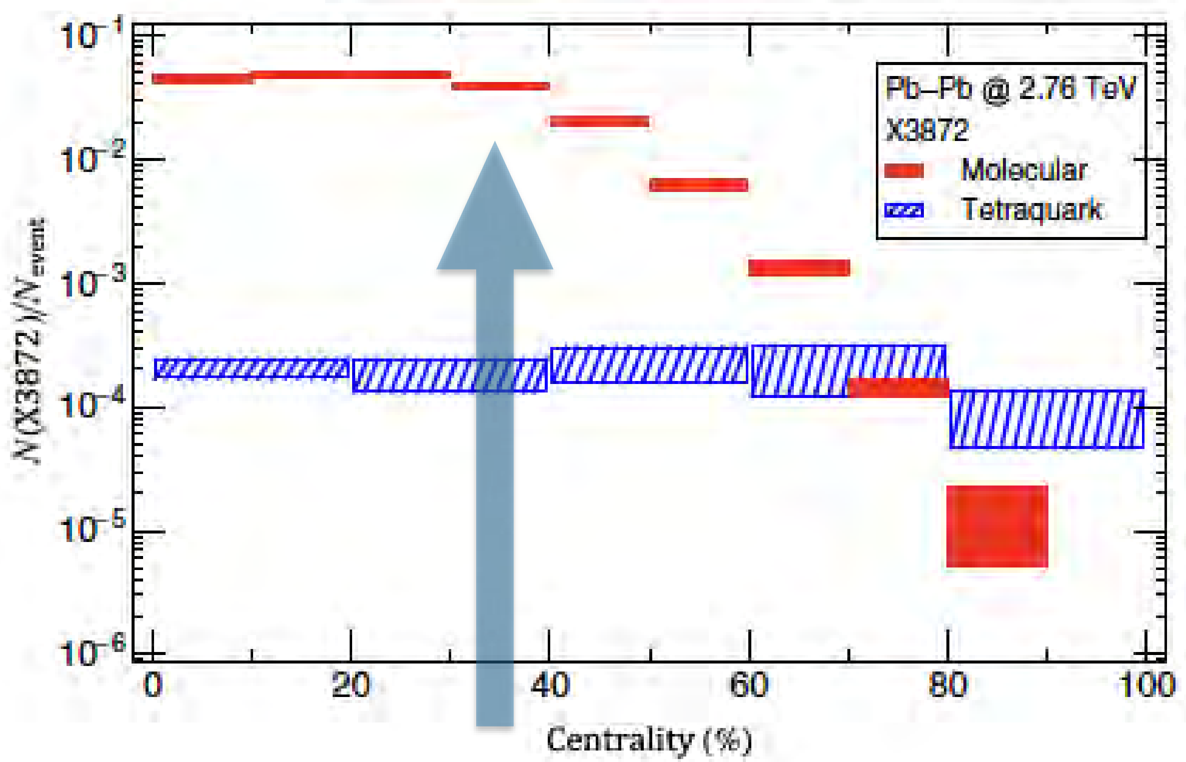
Strong volume dependence of hadron molecules: this scenario would hint at R_AA(X) > 1 (maybe even >>1)

A “Intrinsic Size Scan” for X3872



Hadron molecule v.s. tetraquark:
Two orders of magnitude difference in the yield;
Drastically different centrality dependence.

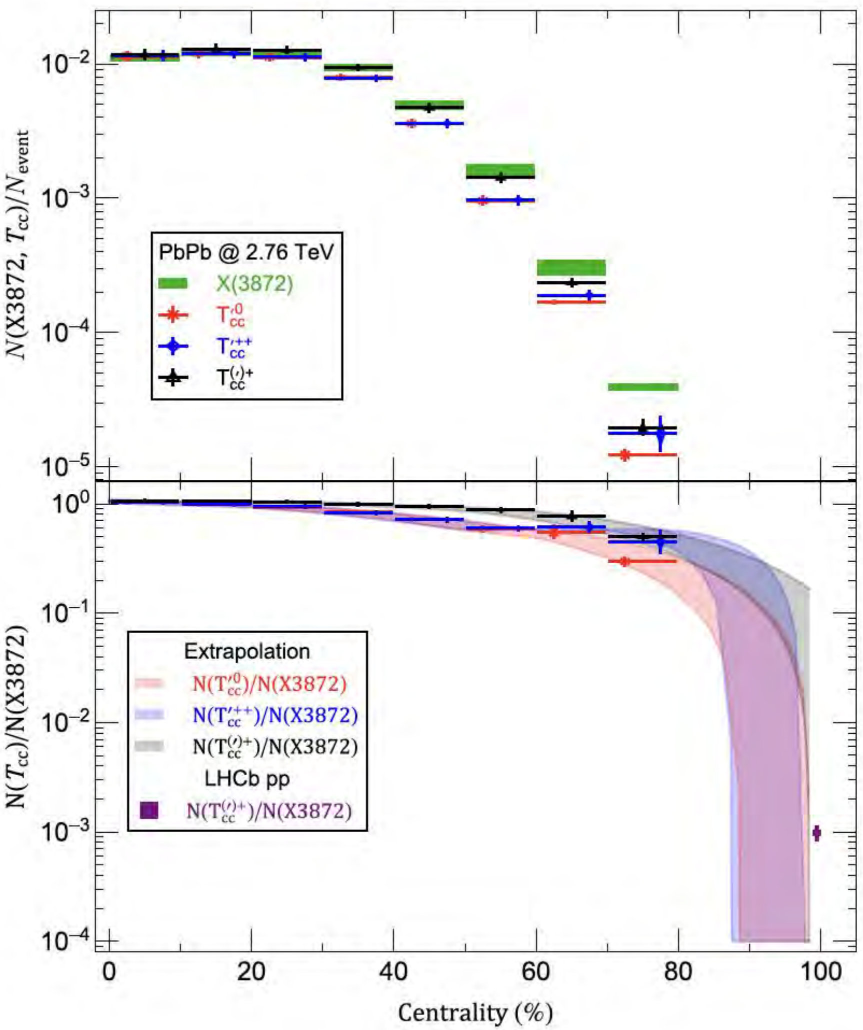
See details in PRL126(012301)2021.



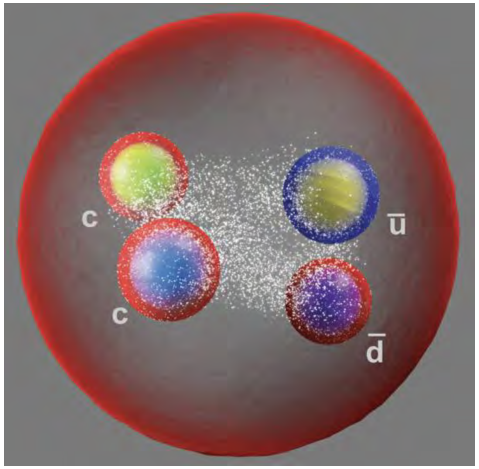
Fireball size serves as a “meter stick” for nailing X size!

Likely where the fireball size becomes smaller than molecular size; future measurements can nail SIZE of X(3872)!

The Tcc Production in Heavy Ion Collisions



The Tcc production shows a very strong volume (i.e. centrality) dependence.

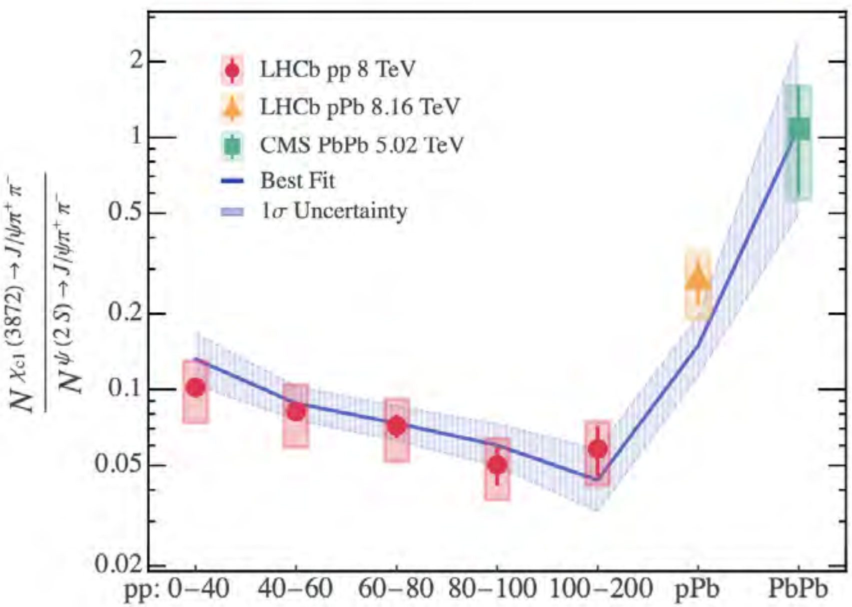


Compared with the X3872, the Tcc suffers from an even stronger threshold suppression in the peripheral collisions.

See details in PRD104(L111502)2021.

Medium Modifications on X-Production

LHCb and CMS data show intriguing non-monotonic pattern of X-production with changing partonic medium?!



First model to provide quantitative description of all these data together

Is a partonic medium (as compared with vacuum) helping to make X? Or killing the X? Or maybe both?

Medium-Assisted Enhancement of $X(3872)$ Production from Small to Large Colliding Systems

Yu Guo,[1,2] Xingyu Guo,[1,2,*] Jinfeng Liao,[3,†] Enke Wang,[1,2,‡] and Hongxi Xing[1,2,§]

[1] *Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China*

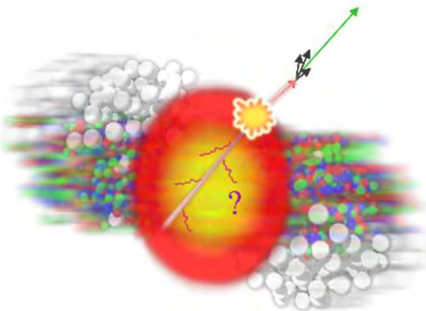
[2] *Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Southern Nuclear Science Computing Center, South China Normal University, Guangzhou 510006, China*

[3] *Physics Department and Center for Exploration of Energy and Matter, Indiana University, 2401 N Milo B. Sampson Lane, Bloomington, IN 47408, USA*

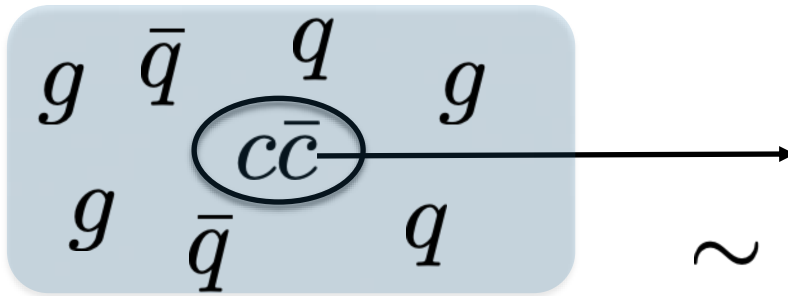
Studies of exotic hadrons such as the famous $X(3872)$ state provide crucial insights into the fundamental force governing the strong interaction dynamics, with an emerging new frontier to investigate their production in high energy collisions where a partonic medium is present. Latest experimental measurements from the Large Hadron Collider show an intriguing evolution pattern of the $X(3872)$-to-$\Psi(2s)$ yield ratio from proton-proton collisions with increasing multiplicities toward proton-lead and lead-lead collisions. Here we propose a novel mechanism of medium-assisted enhancement for the $X(3872)$ production, which competes with the more conventional absorption-induced suppression and results in a non-monotonic trend from small to large colliding systems. Realistic simulations from this model offer the first quantitative description of all available data. Predictions are made for the centrality dependence of this observable in PbPb collisions as well as for its system size dependence from OO and ArAr to XeXe and PbPb collisions. In both cases, a non-monotonic behavior emerges as the imprint of the competition between enhancement and suppression and can be readily tested by future data.

arXiv:2302.03828

Key Idea: Medium Assisted Enhancement

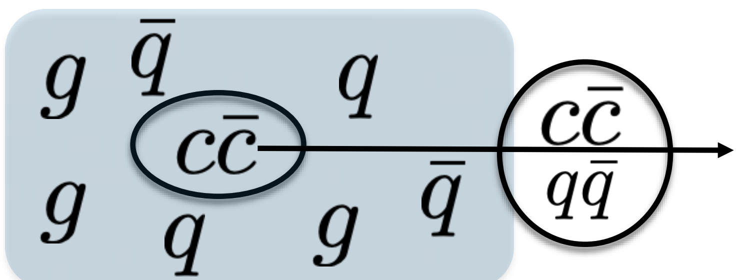


Conventional effect: suppression along path



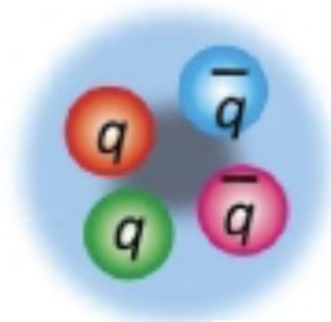
$$\sim e^{-\alpha \int_{path} s \ dx}$$

v.s.



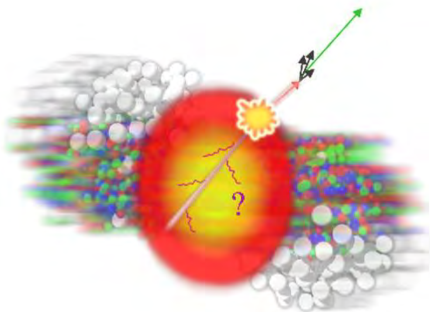
$$\sim e^{+\beta(\int_{path} s)^2}$$

Novel effect for exotics:
Medium-assisted enhancement squarely along path



arXiv:2302.03828

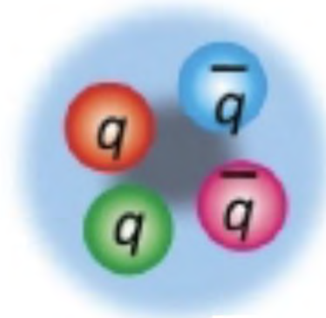
Key Idea: Medium Assisted Enhancement



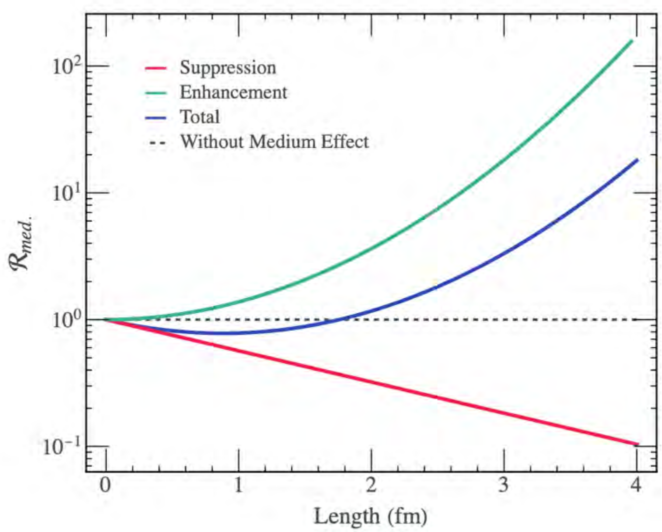
Conventional effect: suppression along path

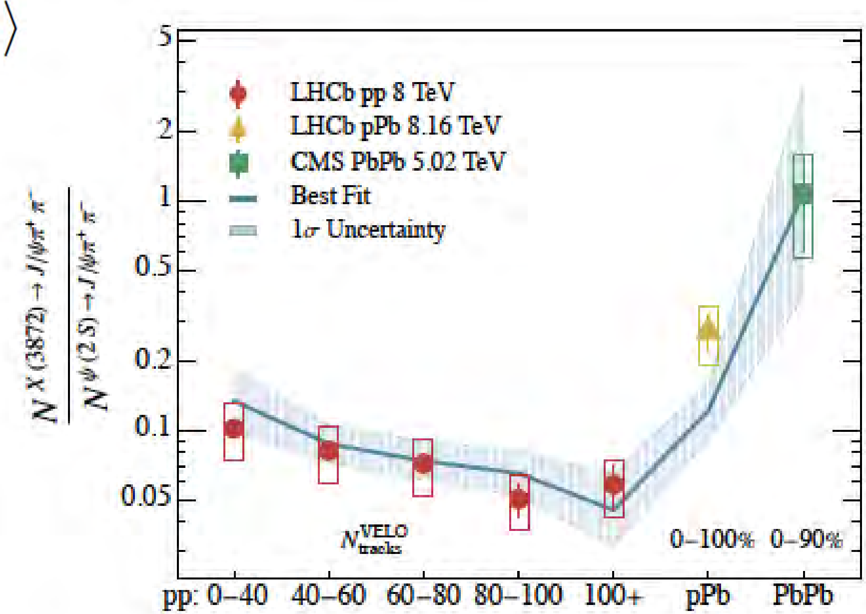
v.s.

Novel effect for exotics:
Medium-assisted enhancement
squarely along path



$$R^X = \langle\langle e^{\int_{\text{path}}[-\alpha_X n(x)+\beta_X^2 n(x)\int_0^x n(y)\mathrm{d}y]\mathrm{d}x}\rangle\rangle$$





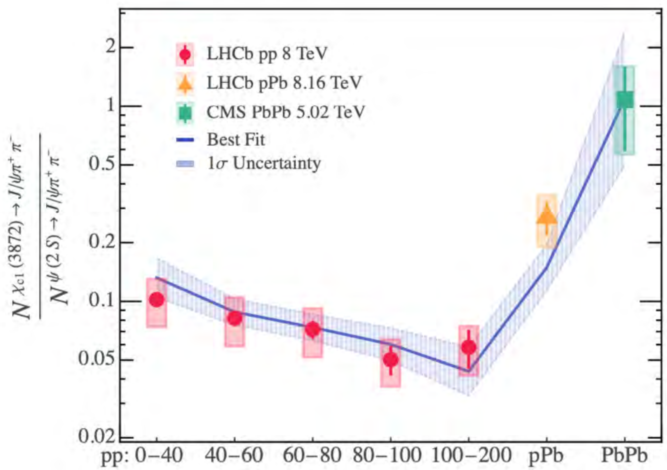
arXiv:2302.03828

System Size Scan for X-Production

Conventional effect: suppression along path

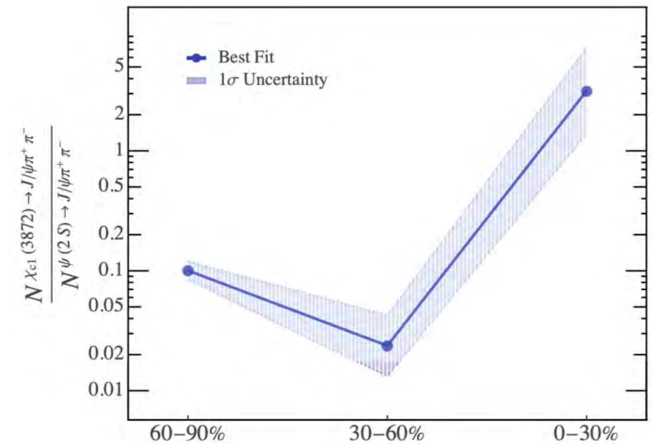
v.s.

Novel effect for exotics: Medium-assisted enhancement squarely along path

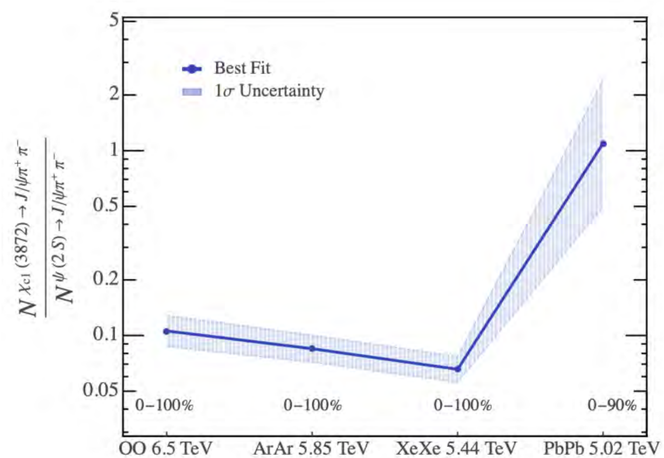


arXiv:2302.03828

Predictions to be tested



Centrality dependence in PbPb



System size dependence

Many Interesting Studies

There are many model calculations, with varied assumptions and different findings.

B. Wu, X. Du, M. Sibila and R. Rapp, Eur. Phys. J. A 57, no.4, 122 (2021)

A. Esposito, E. G. Ferreiro, A. Pilloni, A. D. Polosa and C. A. Salgado, Eur. Phys. J. C 81 (2021) no.7, 669

M. Albaladejo, J. M. Nieves and L. Tolos, Phys. Rev. C 104 (2021) no.3, 035203

B. Chen, L. Jiang, X. H. Liu, Y. Liu and J. Zhao, Phys. Rev. C \textbf{105} (2022) no.5, 054901

E. Braaten, L. P. He, K. Ingles and J. Jiang, Phys. Rev. D 106 (2022) no.3, 034033

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L. M. Abreu, F. S. Navarra and H. P. L. Vieira, Phys. Rev. D 110 (2024) no.1, 014011

B. Wu, Z. Tang, M. He and R. Rapp, Phys. Rev. C \textbf{109} (2024) no.1, 014906

……

It is certainly not a simple problem. We want to look for robust features.

Definitely need more measurements from heavy-ion collisions !

Summary

Summary

- *Heavy flavor production in heavy-ion collisions offers unique opportunities to study QGP properties and hadron formation mechanism.*

- *Open heavy flavor allows extraction of diffusion coefficient and its temperature dependence, shedding light on the strongly coupled nature of QGP.*

- *High pT charmonium production is dominated by gluon and can be used to extract gluon energy loss.*

- *Heavy ion collisions provide an interesting environment to study the exotic hadron formation and to understand their intrinsic structures. Novel medium effects ould lead to nontrivial system size dependence.*

The 10th International Symposium on Heavy Flavor Production in Hadron and Nuclear Collisions

26–29 Oct 2026
Indiana University
US/Eastern timezone

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