

Quark Matter 2023

Sep 6, 2023

Studying Exotic Hadrons in High Energy Nuclear Collisions

Jinfeng Liao

Indiana University,
Physics Dept. & CEEM



Plan of the Talk

- *Brief introduction*
- *Volume effect for deciphering exotic structures*
- *Medium-assisted enhancement effect*
- *Summary & Outlook*

Collaborators:

*X. Guo, Y. Guo, Y Hu, E. Wang, Q. Wang, H. Xing, H. Zhang (SCNU)
A. Akridge, D. Gallimore, A. Szczepaniak, E. Passemar (IU/ExoHad)*

*To be delivered by: Alex Akridge (student)
Sorry for not being able to come...*

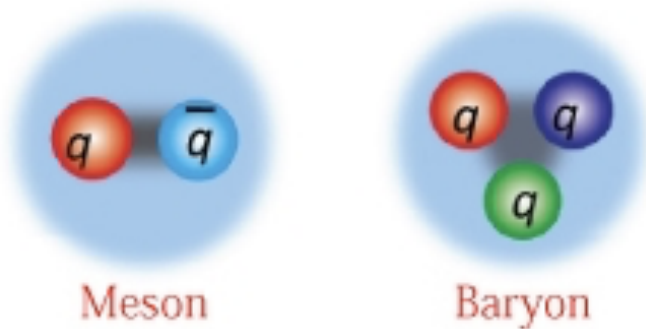
Challenging “Quark Math” for Hadrons

Quarks make hadrons:

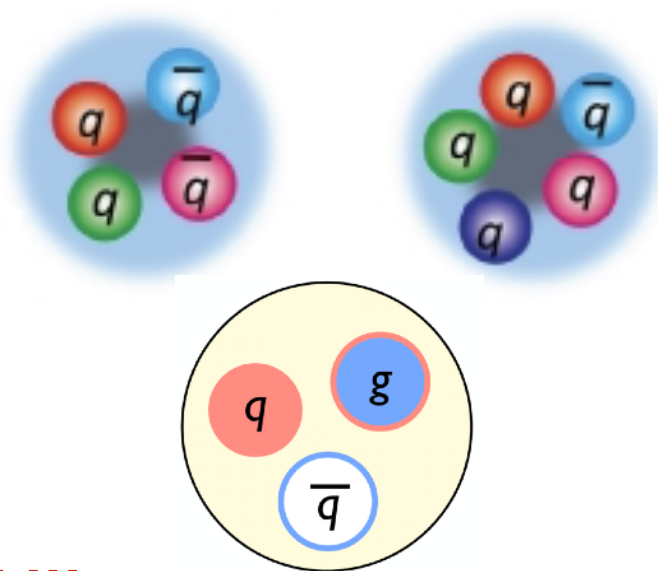
What configurations are possible and what not?

And why? — Active frontiers of hadron physics.

Standard Hadrons



Exotic Hadrons



Many experiments:
*BESIII, BaBar, Belle, CLEO,
GlueX, LHCb, ATLAS, CMS, ...*

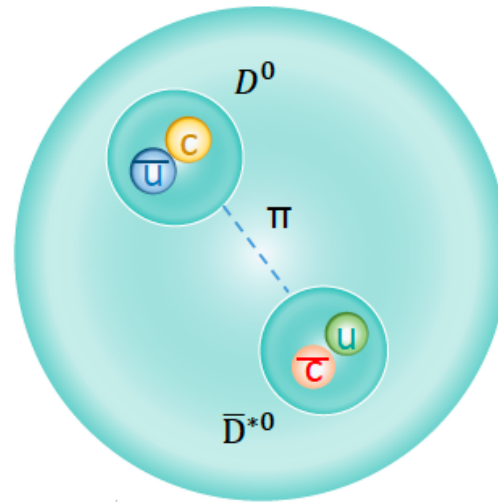
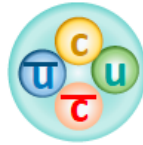
**The extreme of multi-quarks/gluons
system: quark gluon plasma (QGP)**



Structures of Exotic Hadrons

*What is the intrinsic structure of X3872
(and many other exotic hadron states)?*

*Compact
tetraquark?
 $R \sim 0.5 \text{ fm}$*



*Hadronic
molecule?
 $R \sim 5 \text{ fm}$*

*Despite ~20 years past its discovery, we still could not settle
on its basic features by an order of magnitude!*

Can we (heavy ion collisions) help?

Hunting for X in Nuclear Collisions

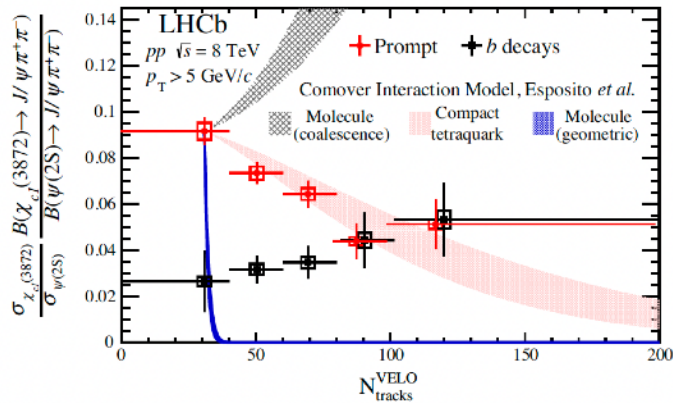
First set of X-measurements from CMS and LHCb since 2019

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

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

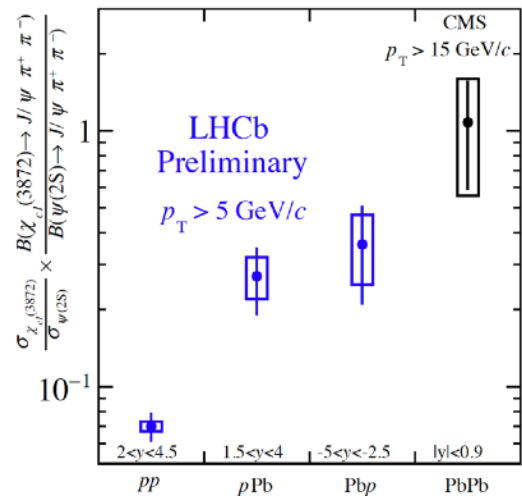
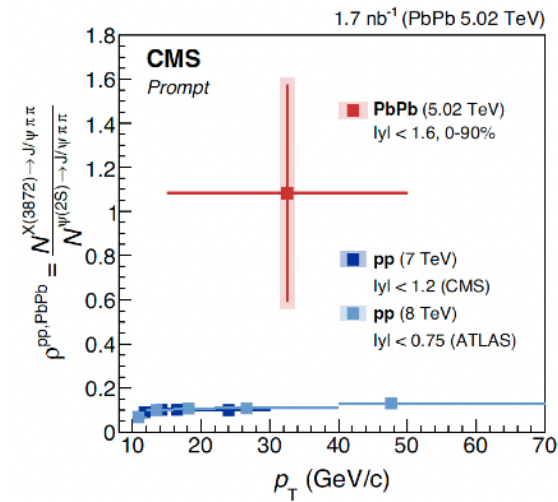
Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions

R. Aaij *et al.*^{*}
(LHCb Collaboration)



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,||}

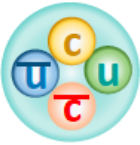
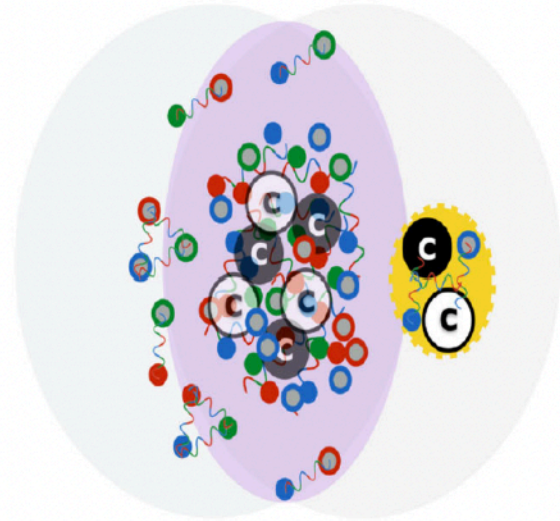
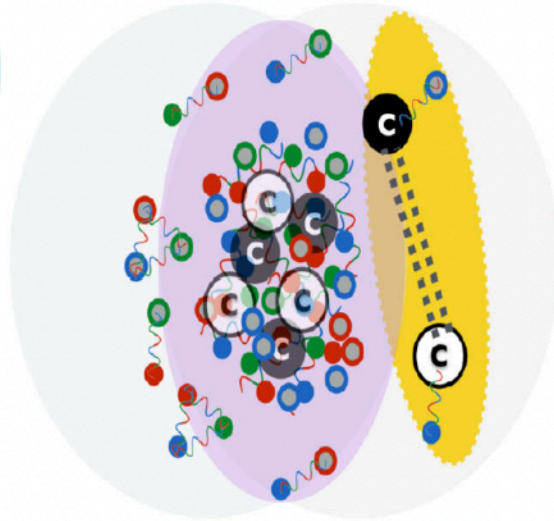
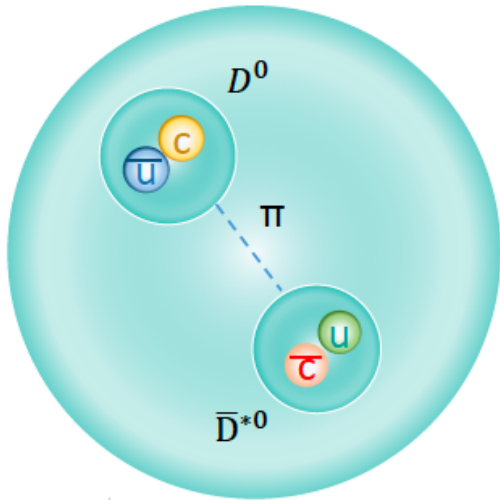
PHYSICAL REVIEW D **104**, L111502 (2021)

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



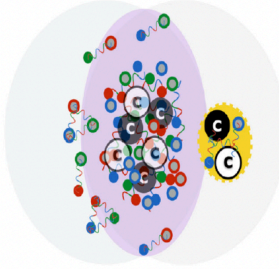
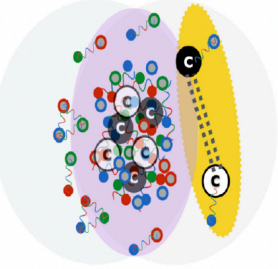
The bulk fireball has its own SIZE scale and can be controlled.

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.

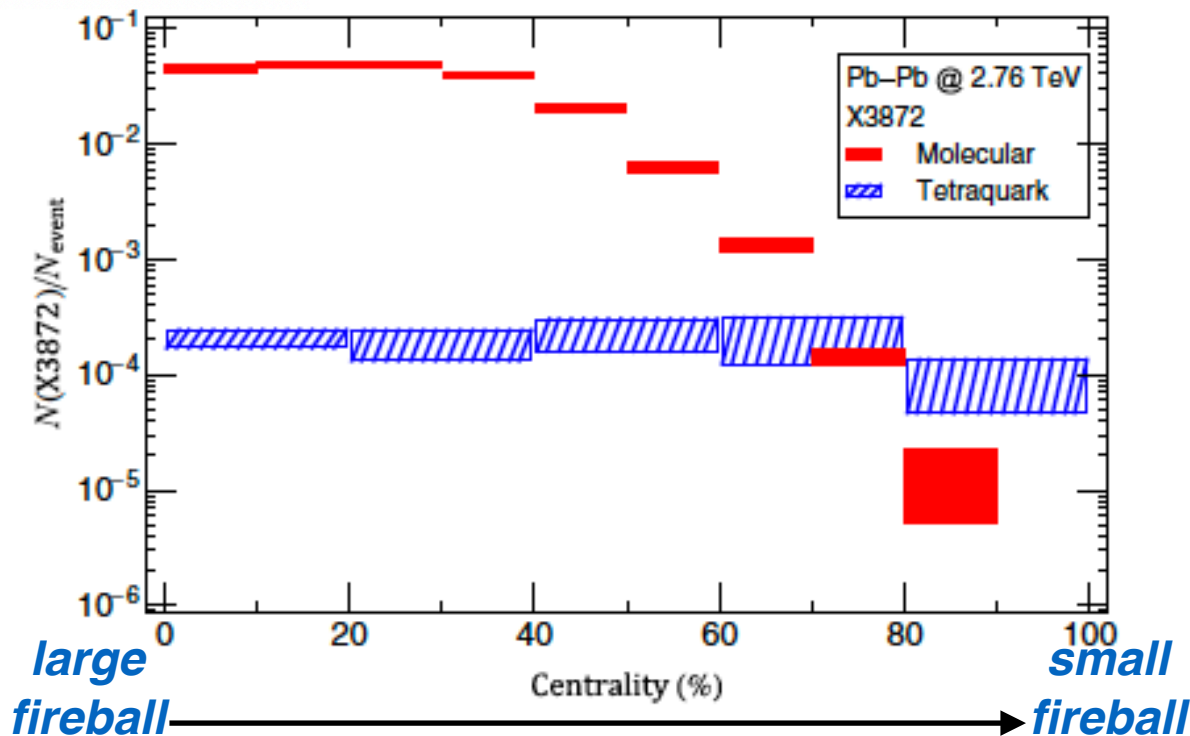
[Similar sensitivity for deuteron production to source volume was known and observed.]

A “Intrinsic Size Scan” for X3872



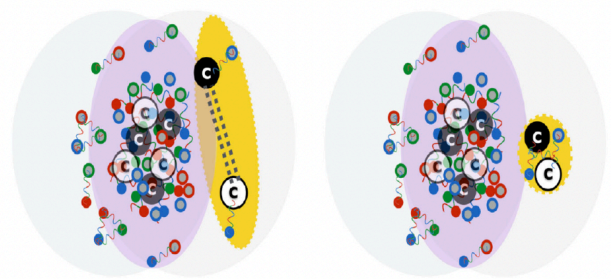
*Hadron molecule v.s. tetraquark:
Two orders of magnitude difference in the yield;
Drastically different centrality dependence.*

See framework details in PRL 126(012301)2021.

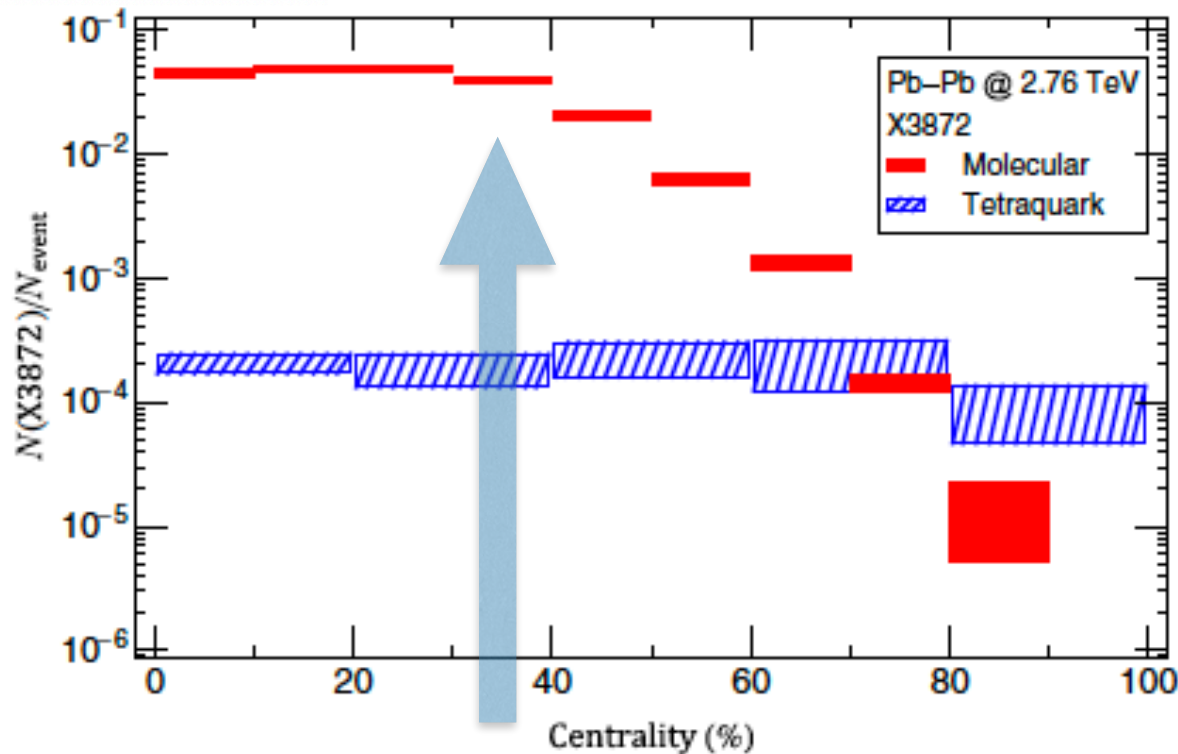


Strong volume dependence of hadron molecules: this scenario would hint at $R_{AA}(X) > 1$ (maybe even $\gg 1$)

A “Intrinsic Size Scan” for X3872



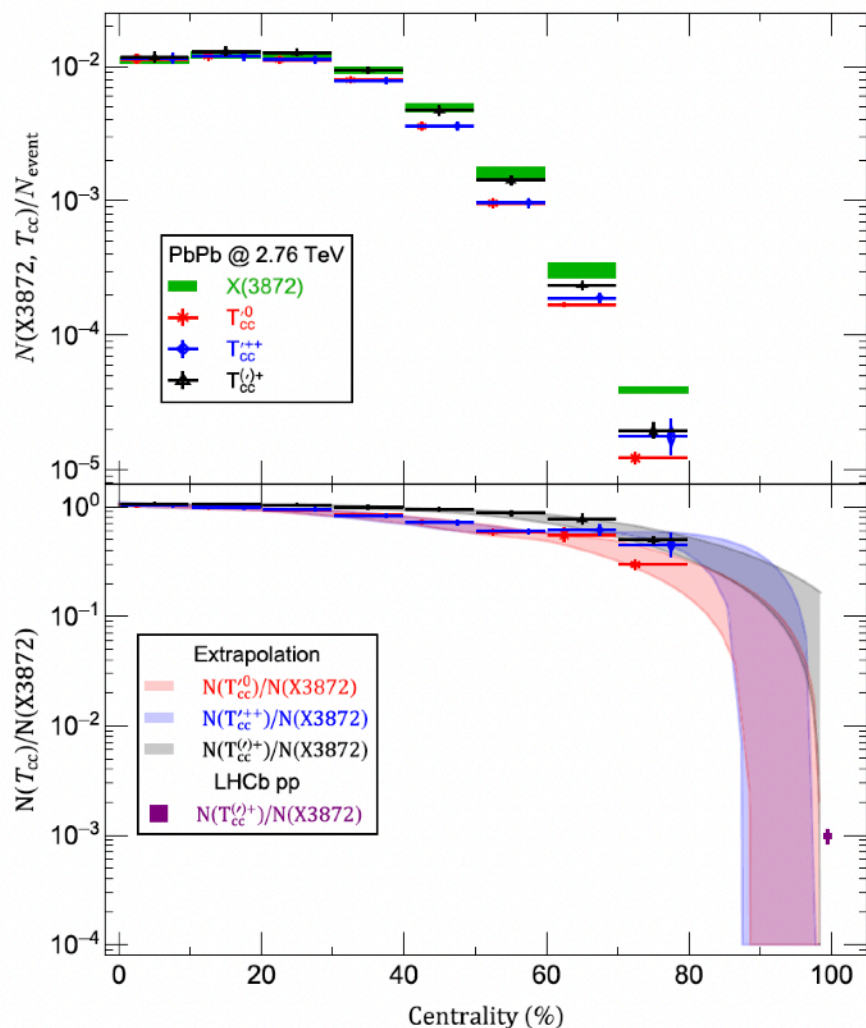
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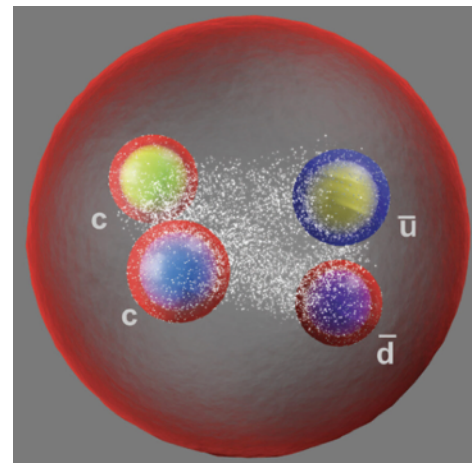
Fireball size serves as a “meter stick” for nailing X size!

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.

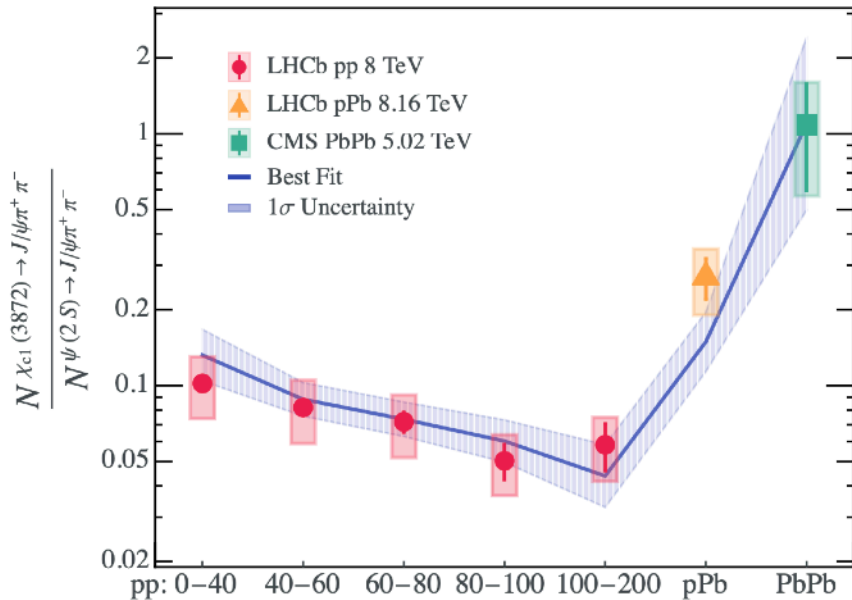


Compared with the X3872, the Tcc suffers from an even stronger threshold suppression in the peripheral collisions.

**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,§}

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

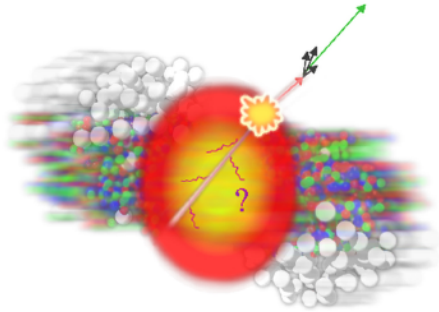
²Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Southern Nuclear Science Computing Center, South China Normal University, Guangzhou 510006, China

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

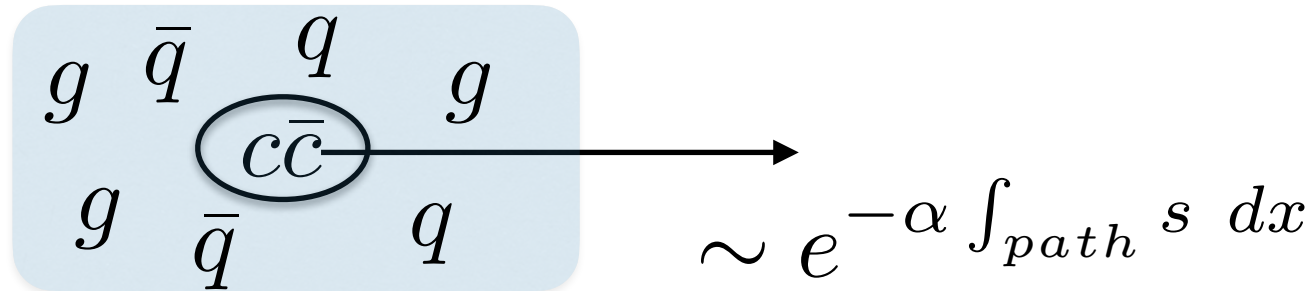
Studies of exotic hadrons such as the famous X(3872) state provide crucial insights into the fundamental force governing the strong interaction dynamics, with an emerging new frontier to investigate their production in high energy collisions where a partonic medium is present. Latest experimental measurements 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

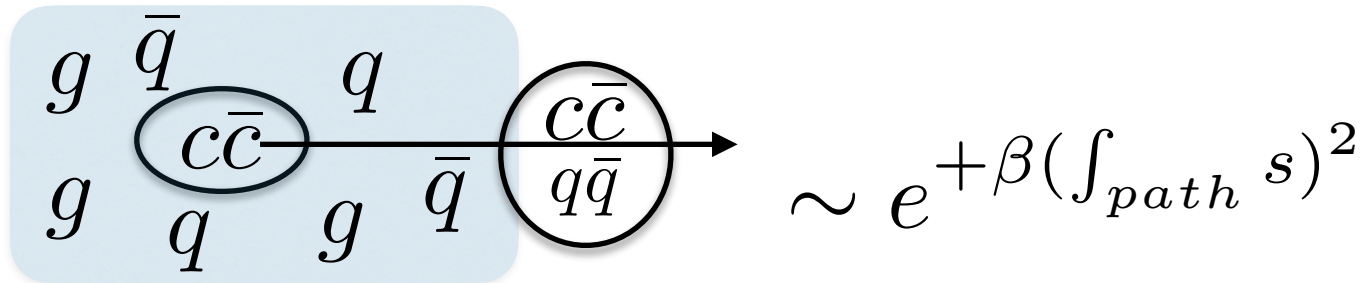
Key Idea: Medium Assisted Enhancement



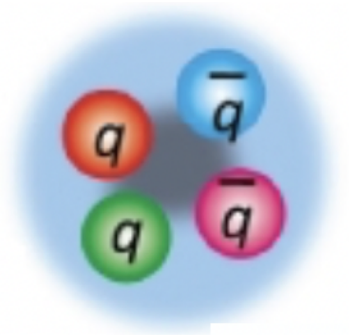
Conventional effect: suppression along path



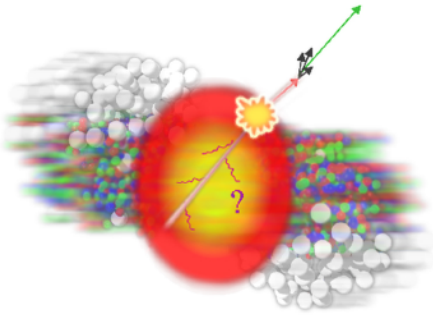
v.s.



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



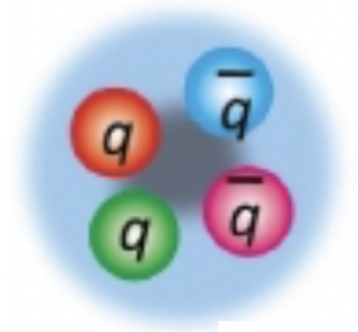
Key Idea: Medium Assisted Enhancement



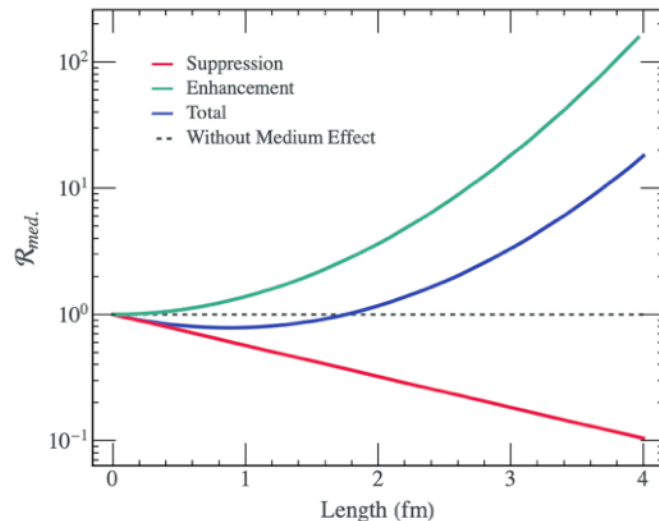
Conventional effect: suppression along path

V.S.

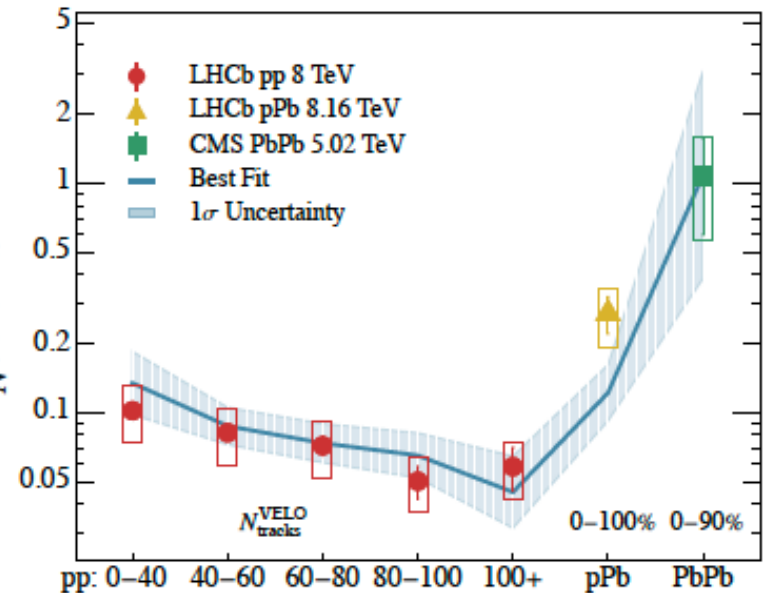
**Novel effect for exotics:
Medium-assisted enhancement
squarely along path**



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



$$\frac{N^X(3872) \rightarrow J/\psi \pi^+ \pi^-}{N^{\psi(2S)} \rightarrow J/\psi \pi^+ \pi^-}$$



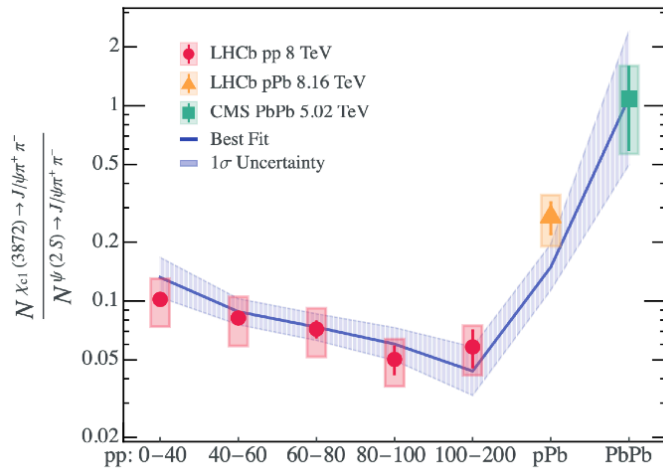
arXiv:2302.03828

System Size Scan for X-Production

Conventional effect:
suppression along path

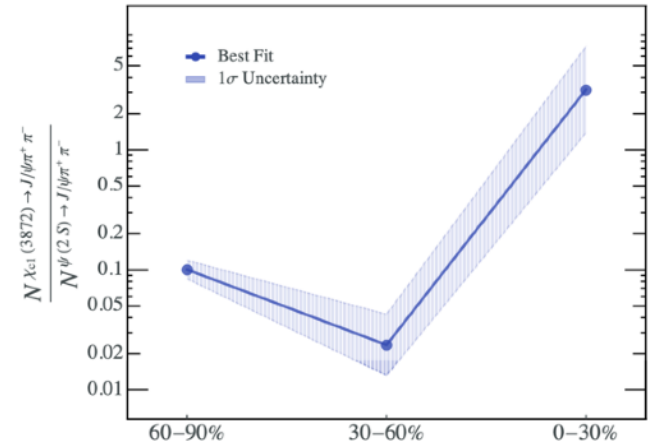
v.s.

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

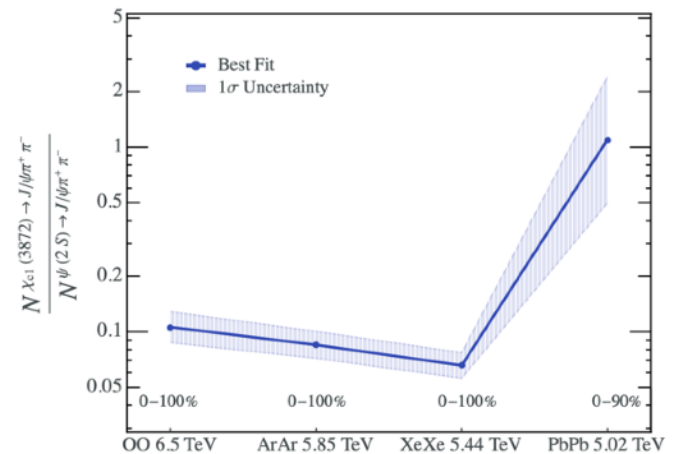


arXiv:2302.03828

**Predictions
to be tested**



Centrality dependence in PbPb



System size dependence

Summary

- *Study of exotic hadrons is an important frontier of QCD physics, with unsolved puzzles.*
- *Heavy ion collisions at very high energy provide an unparalleled factory for producing heavy exotic states and measuring their properties.*
- *Heavy ion fireball size serves as a valuable “meter-stick” for calibrating the intrinsic size of exotic states.*
- *Novel medium enhancement for exotics could lead to nontrivial system size dependence in their production.*
- *Future heavy ion measurements will provide unique insights into these exotic states.*

An Emerging Frontier at the Intersection of Hot & Cold QCD Physics



The Exo(tic) Had(ron) Collaboration started in 2023 to explore all aspects of exotic hadron physics, from predictions within lattice QCD, through reliable extraction of their existence and properties from experimental data, to descriptions of their structure within phenomenological models.

One important thrust is to integrate hadron physics inputs/constraints with heavy ion phenomenology and use heavy ion measurements to help nail down the existence and properties of exotic hadrons.

An Emerging Frontier at the Intersection of Hot & Cold QCD Physics

The Present and Future of QCD

QCD Town Meeting White Paper – An Input to the 2023 NSAC Long Range Plan

arXiv: 2303.02579

Exotic hadrons Several key detector upgrades are also currently underway that will directly improve measurements of exotic hadrons in heavy ion collisions. The entire LHCb tracking system has been replaced with detectors of higher granularity, which will enable measurements in Pb+Pb collisions up to $\sim 30\%$ centrality [1180]. An upgrade to the fixed target system at LHCb will enable high-statistics $p + A$ data sets to be collected at lower center of mass energies where coalescence effects are expected to be small [1188]. The CMS experiment is pursuing the addition of particle ID detectors which will greatly aid in rejecting combinatorial background when reconstructing hadronic decays of exotic hadrons, allowing access to states at lower p_T than currently possible at CMS [1189]. In the farther future, for Run-5, LHCb will be further upgraded to remove all centrality limitations [1182], and the ALICE3 detector, with full particle ID and a fast DAQ, will be well suited to measurements of exotics in heavy ion collisions [1170].

It is exciting time to expect tests of theoretical predictions by future measurements!