10th Workshop of APS GHP Apr 13, 2023

Understanding the production of heavy flavor exotics in heavy ion collisions

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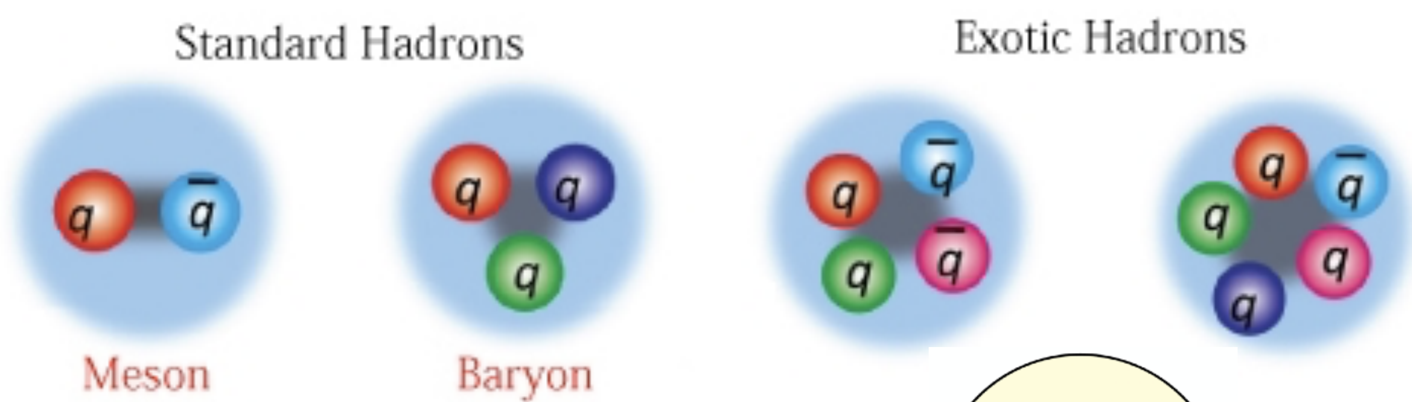
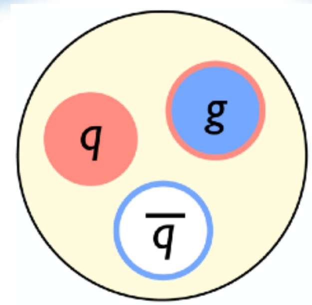
NSF

EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

Challenging "Quark Math" for Hadrons

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





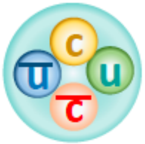
Many experiments:
BESIII, BaBar, Bell, CLEO,
GlueX, LHCb, ATLAS, CMS, …

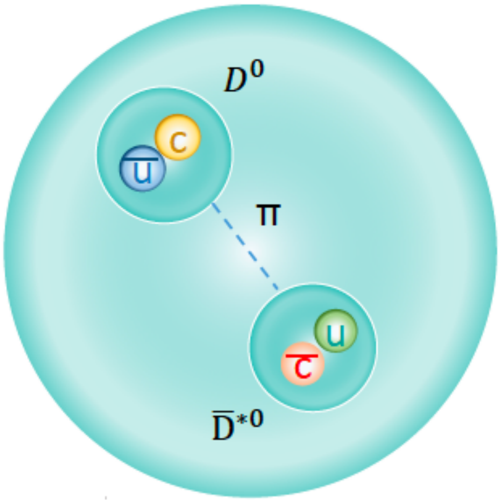
Going to the extreme of many quarks/
gluons: quark gluon plasma (QGP)

Structures of Exotic Hadrons

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

Compact tetra quark?
R ~ 0.5 fm



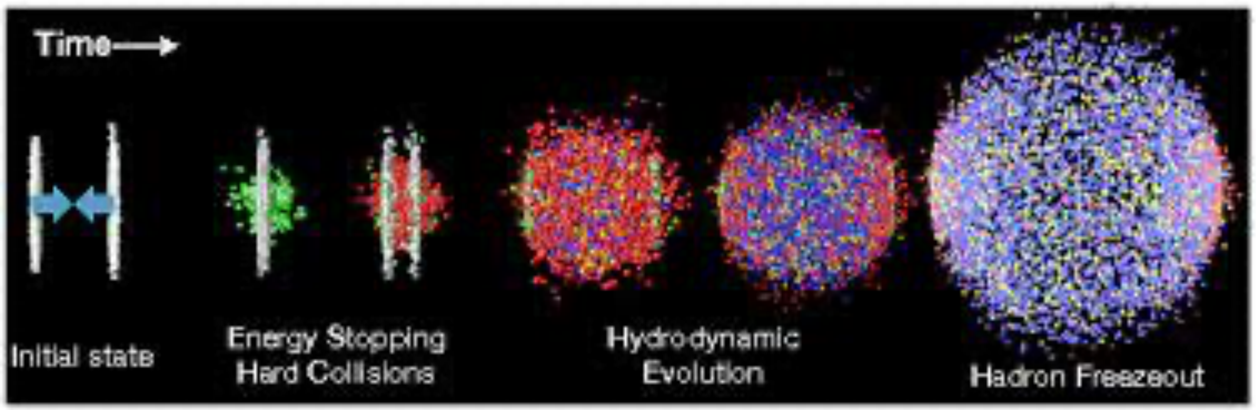


Hadron molecule?
R ~ 5 fm

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?

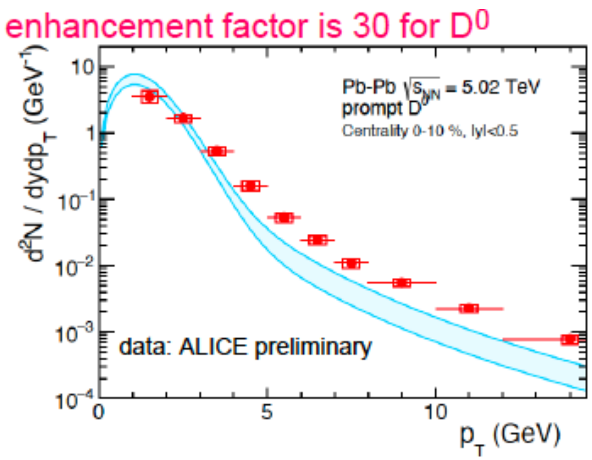
What a Heavy Ion Collision Has to Offer

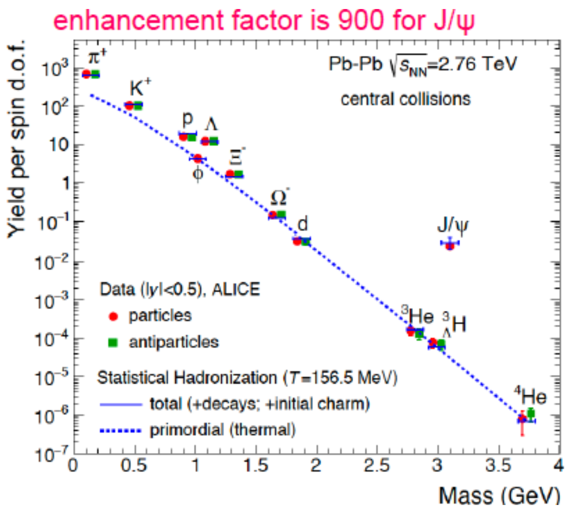


- *A hot and dense partonic medium of many quarks/gluons*
- *A bulk medium with a "large", controllable size*
- *Many hard processes at the beginning*
- *A hot hadronic gas (— see e.g. E. Braaten et al 2303.08072)*

A Charming Quark Soup

We have a nice bowl of MANY charms + numerous light quarks

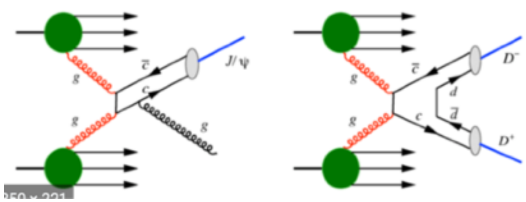


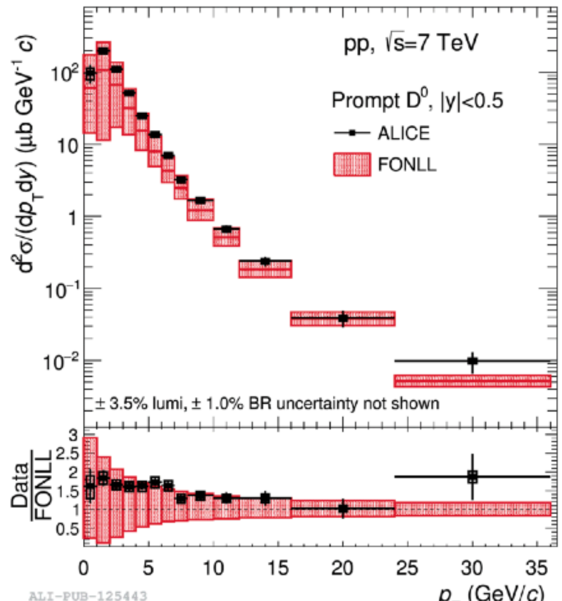


The QGP produced @ LHC O(~1000) GeV collisions, is a "charming" soup, with a "large" (~100/event) number of charms
—> ideal environment for massive production and study of heavy exotics!!!

Initial Charm Production

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



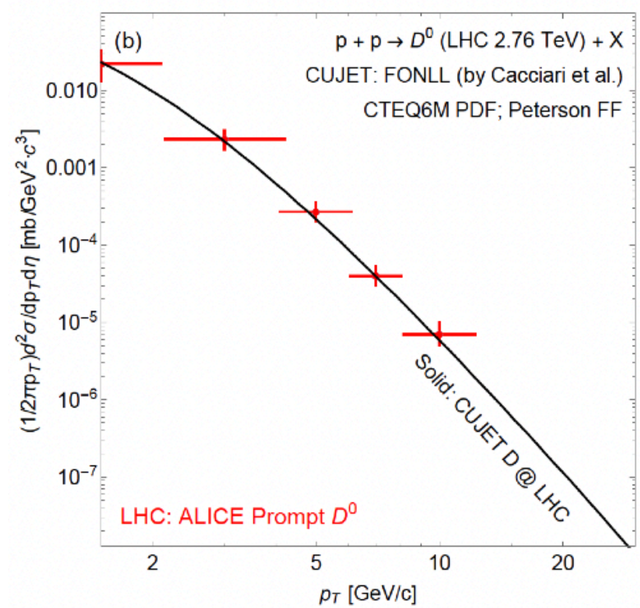


LHC is particularly advantageous:
x_RHIC ~ 0.01
x_LHC ~ 0.001

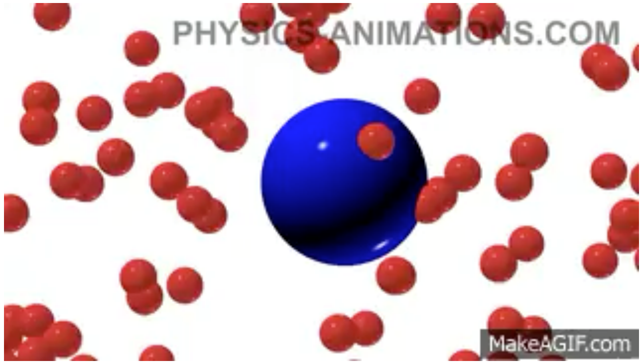
2Mc ~ 2.55 GeV >> Lambda_QCD ~ T

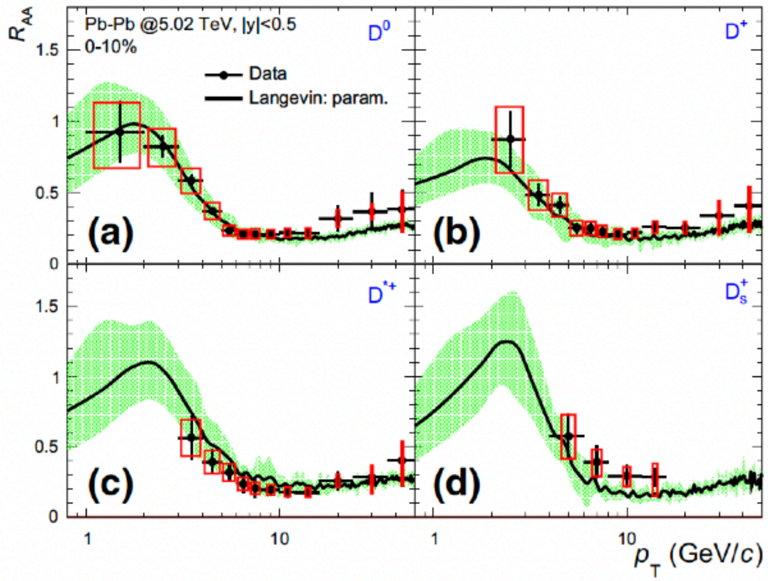
exp(-10) ~ 0.000045

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



Soft Sector: Charm Diffusion



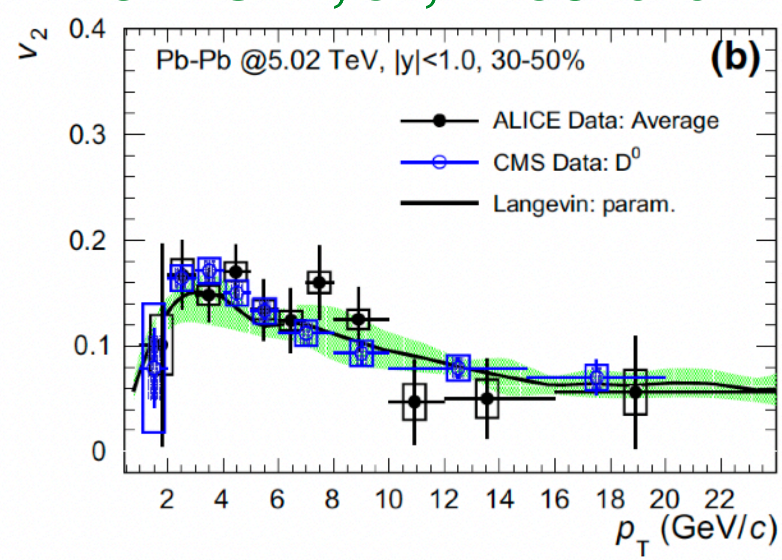


Brownian motion

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

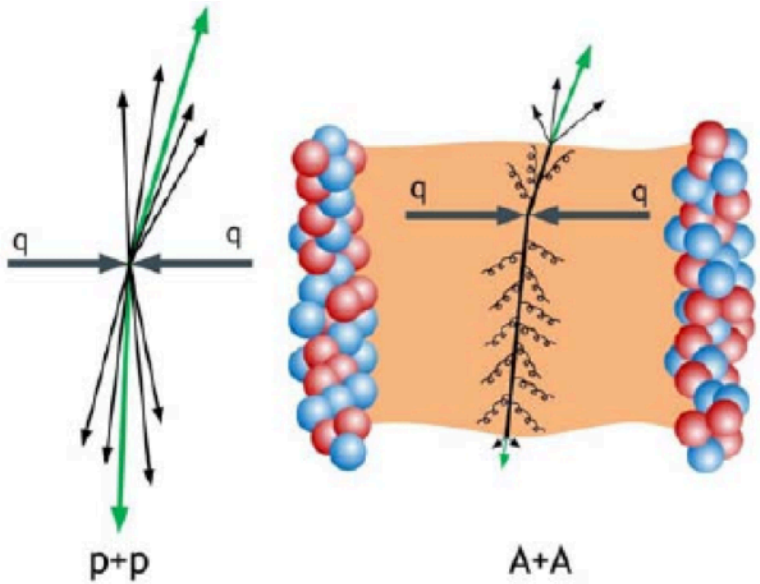
$$d\vec{p} = (\vec{F}_{\rm D} + \vec{F}_{\rm T} + \vec{F}_{\rm G})dt$$

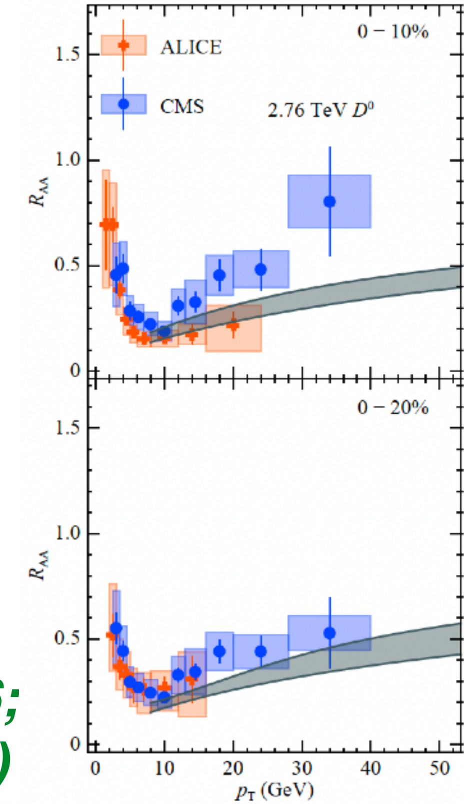
From: S. Li, JL, EPJC2020



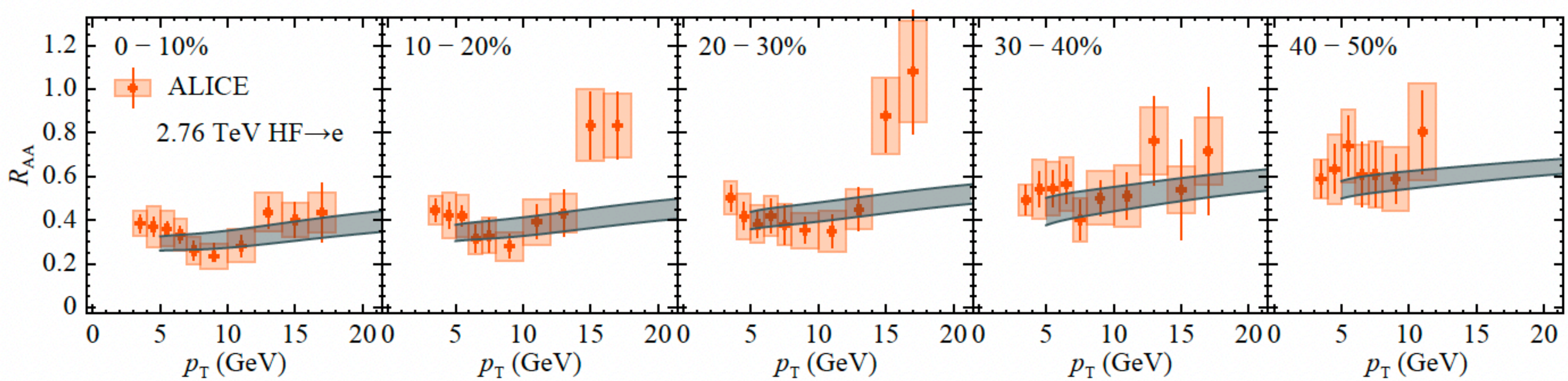
The charm quarks get carried by the bulk flow and diffuse around the whole fireball volume.

Hard Sector: Charm Energy Loss

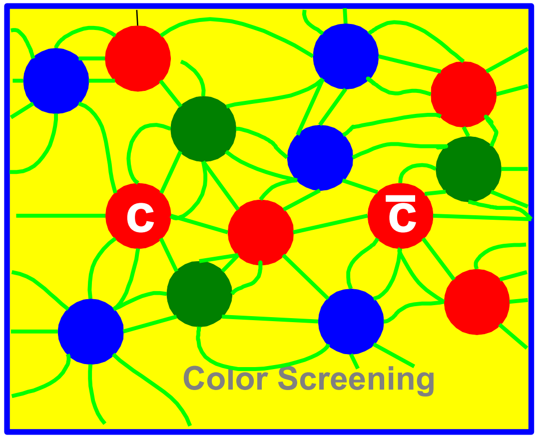


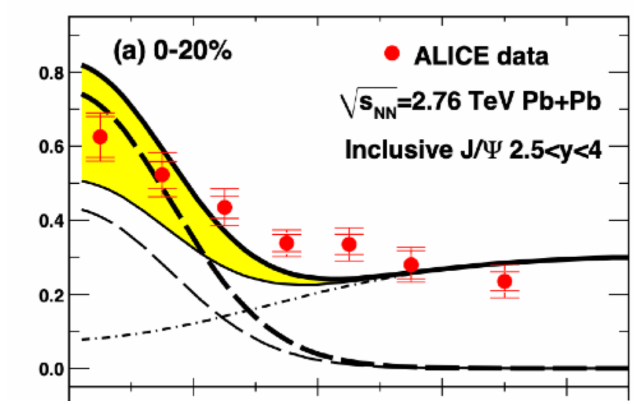


From: CUJET3
(Xu, JL, Gyulassy JHEP2016;
Shi, JL, Gyulassy, CPC2019)

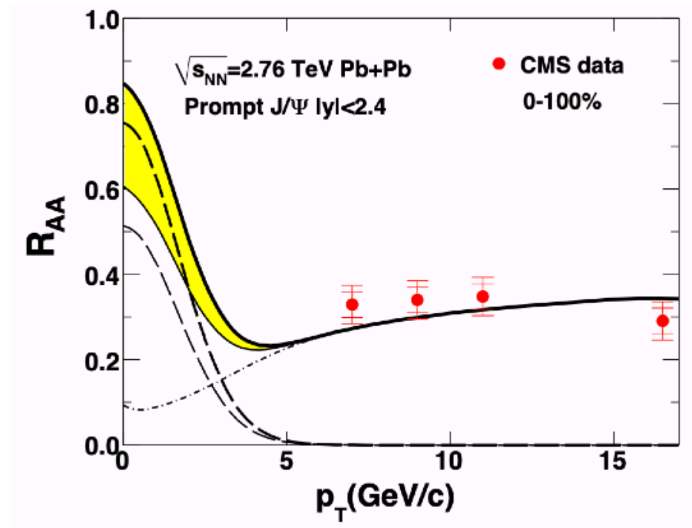


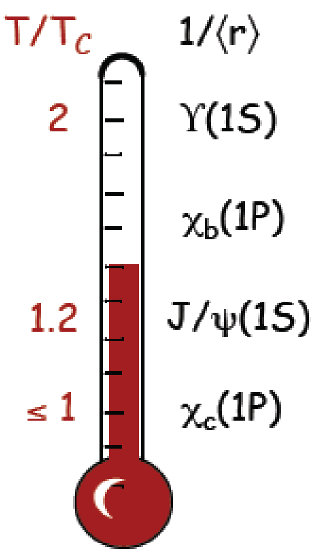
Charmonia: Melting/Regeneration/Supression





From: Zhou, Xu, Xu, Zhuang, PRC2014





Regeneration becomes important at LHC for low to intermediate pT.

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

[see e.g. arXiv:2208.08323]

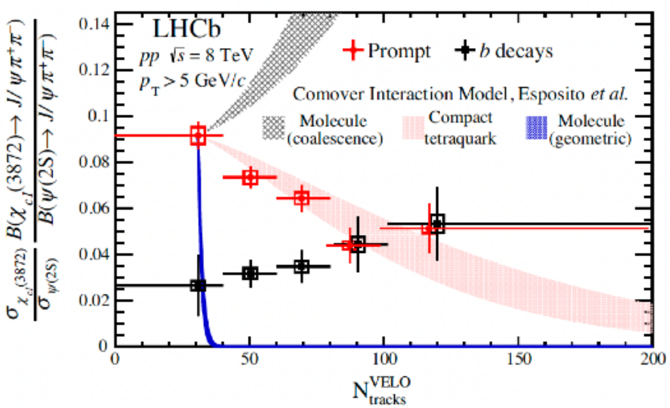
Hunting for X in Nuclear Collisions

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

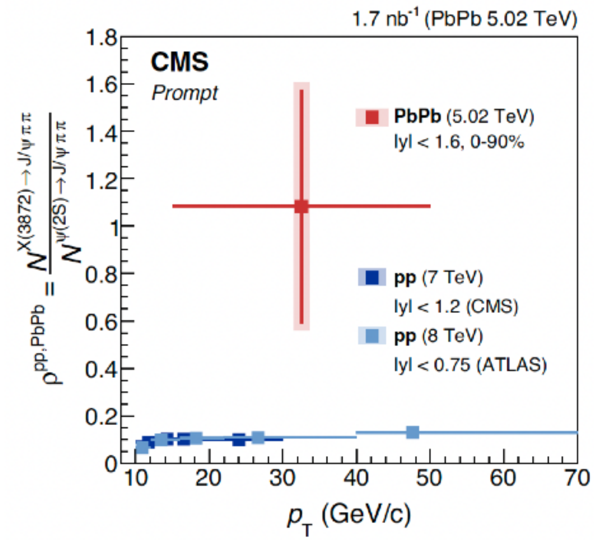
R. Aaij *et al.**
(LHCb Collaboration)



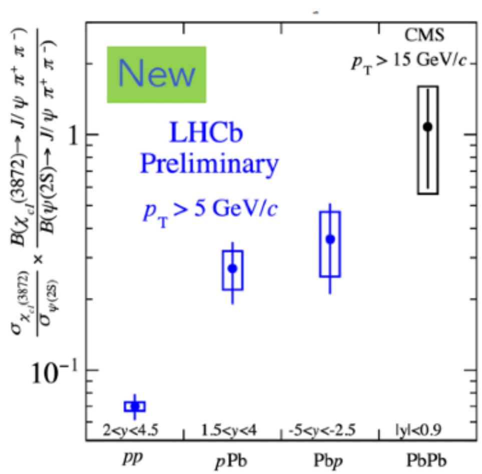
PHYSICAL REVIEW LETTERS **128,** 032001 (2022)

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



QM2022



Measurements already hint at partonic medium effect on the X production!

More and better measurements are anticipated from LHC.

"Cooking" Exotica in the Quark Soup

Heavy ion collisions as 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,∥]

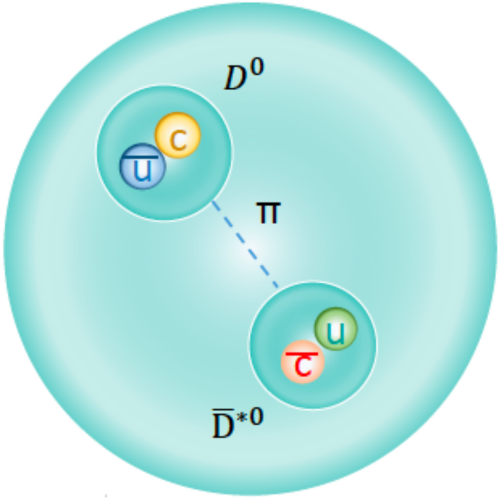
PHYSICAL REVIEW D **104,** L111502 (2021)

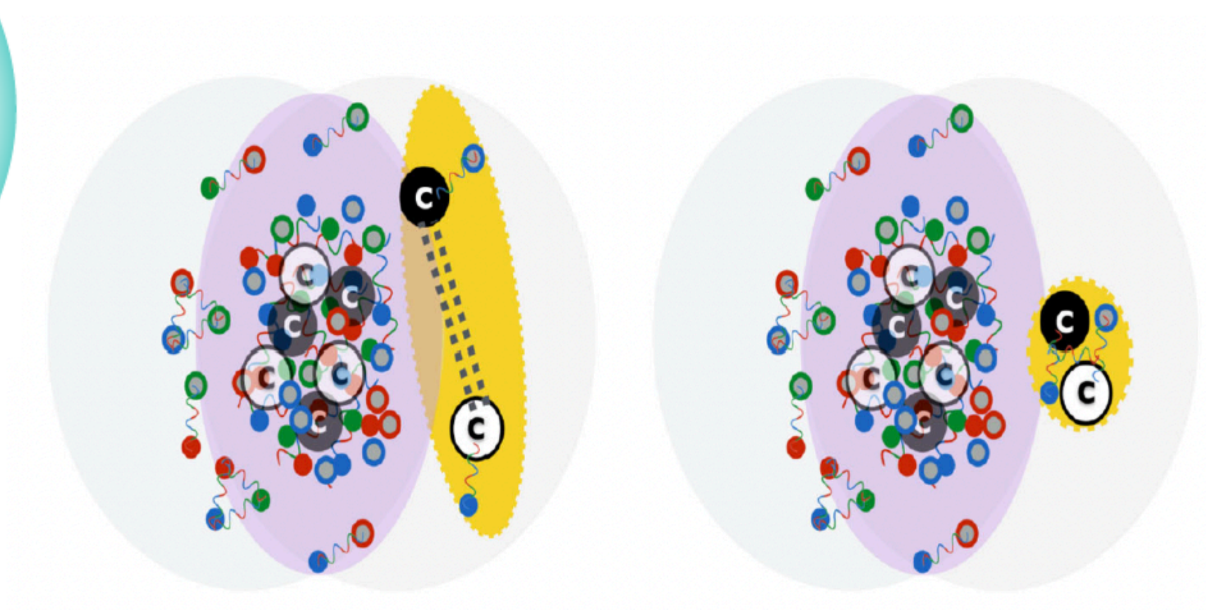
Letter

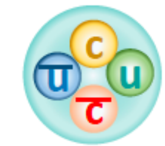
Production of doubly charmed exotic hadrons in heavy ion collisions

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.

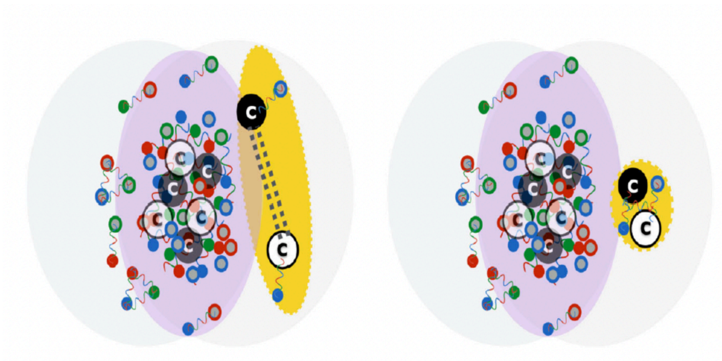
The hadronic molecule must be sensitive to the source volume.

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



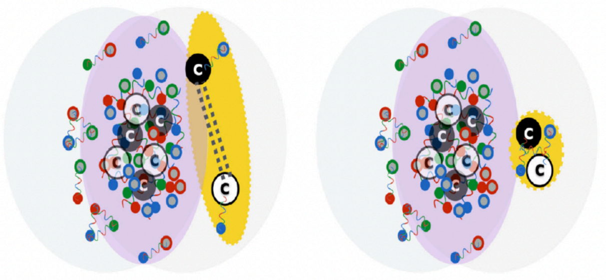
Compact tetra quark:

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!

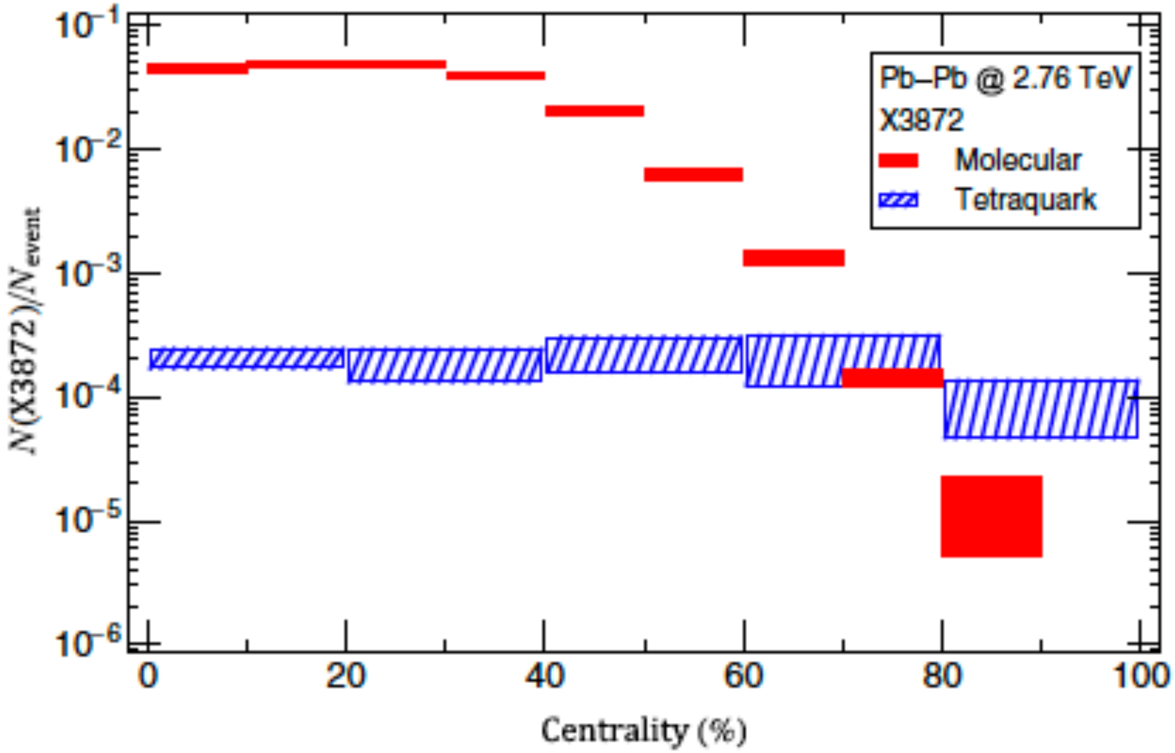
See framework details in PRL126(012301)2021.

A "Intrinsic Size Scan" for X3872



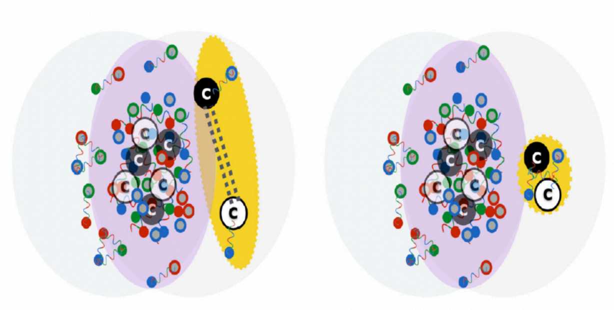
Hadron molecule v.s. tetraquark:
Two orders of magnitude difference in the yield;
Drastically different centrality dependence.

See framework details in PRL126(012301)2021.



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

A "Intrinsic Size Scan" for X3872



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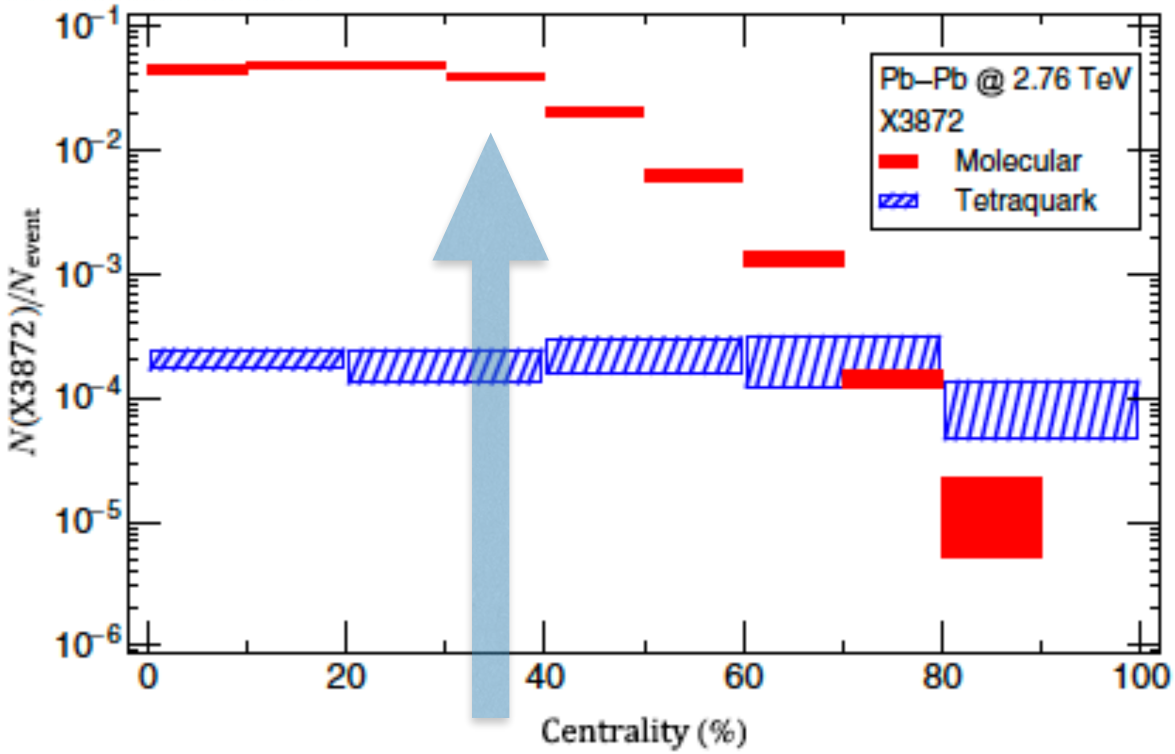
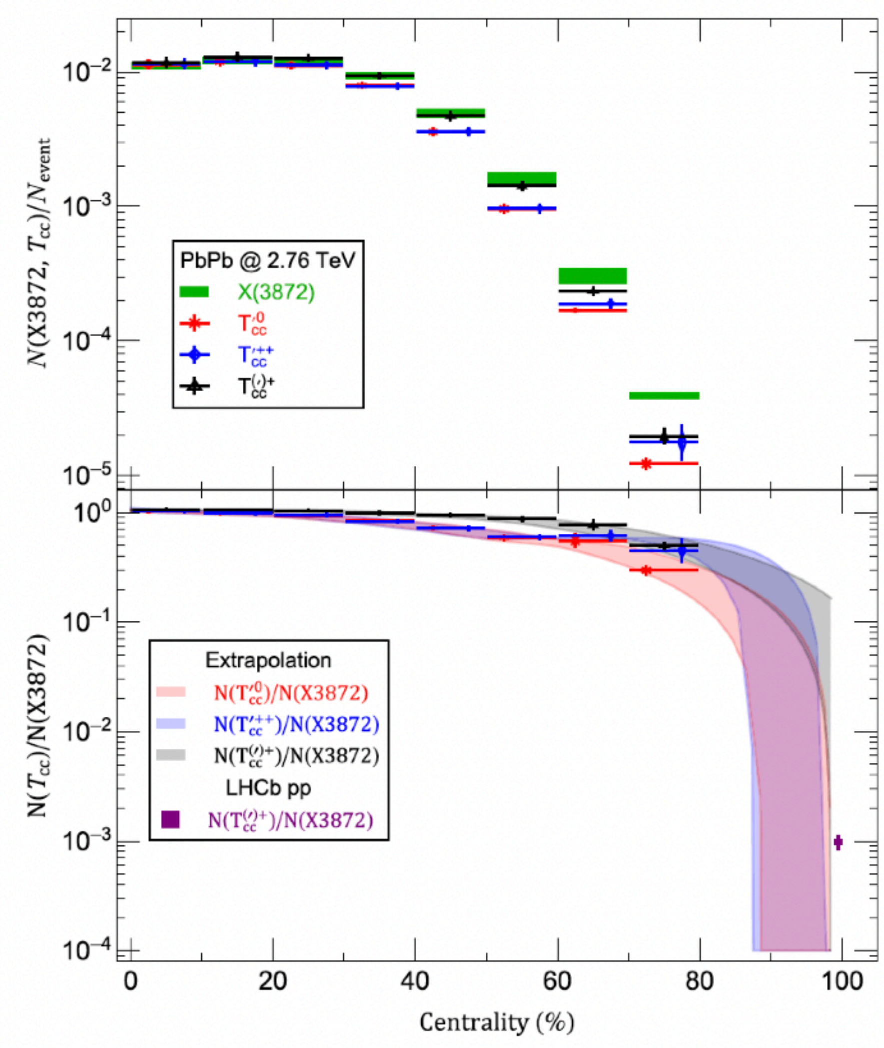


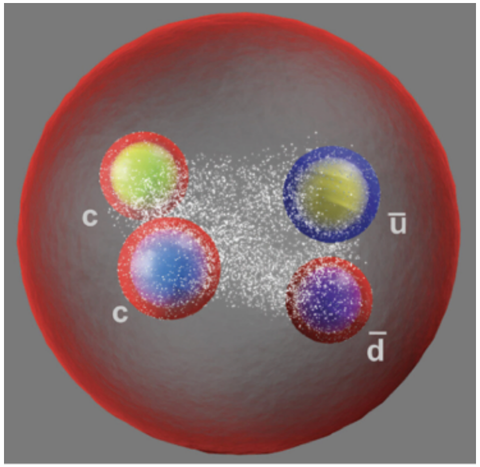
Fireball size serves as a "meter stick" for nailing X size!

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.

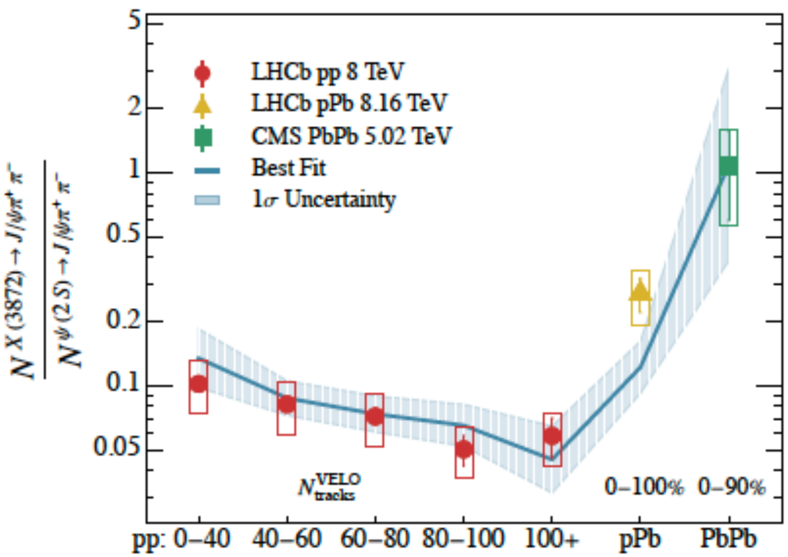


Compared with the X3872, the Tcc suffers from an even stronger threshold suppression in the peripheral collisions.

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?!



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

arXiv:2302.03828

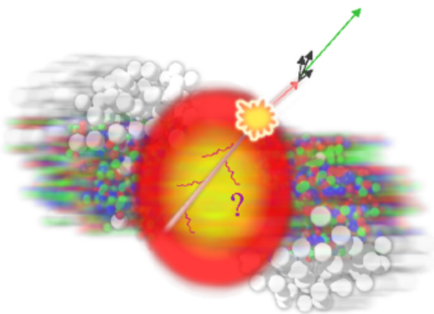
Medium-Assisted Enhancement of $X(3872)$ Production from Small to Large Colliding Systems

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.

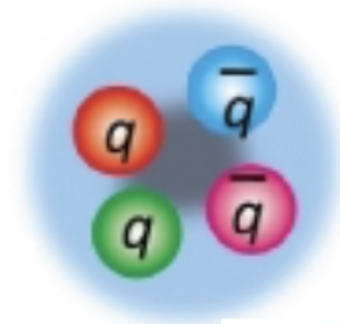
Key Idea: Medium Assisted Enhancement



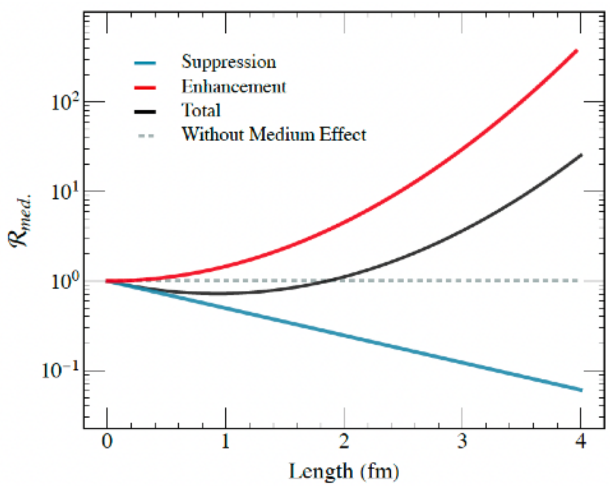
Conventional effect: suppression along path

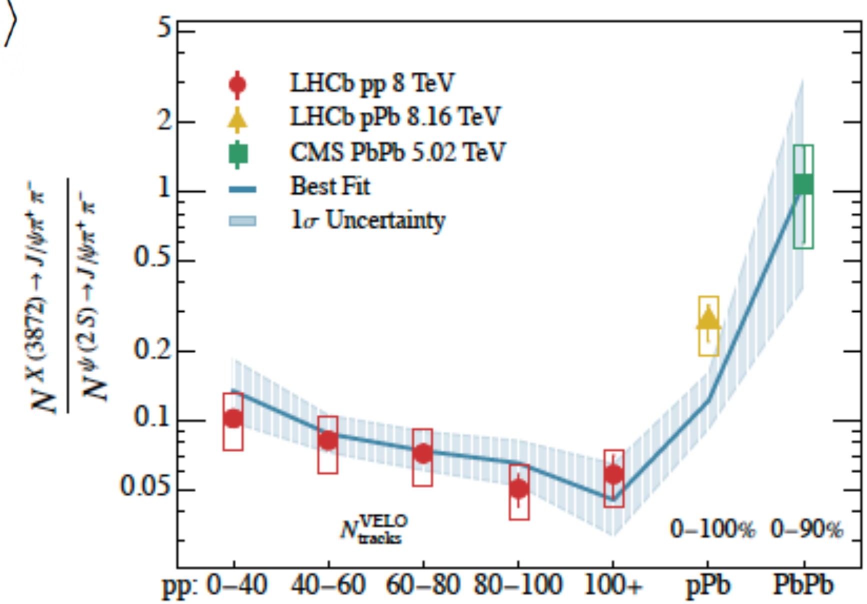
v.s.

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



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





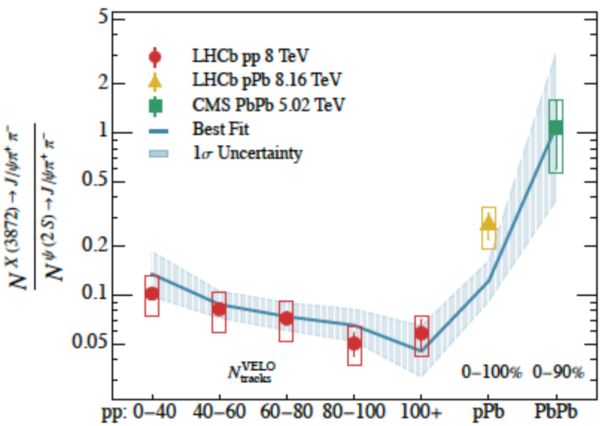
arXiv:2302.03828

System Size Scan for X-Production

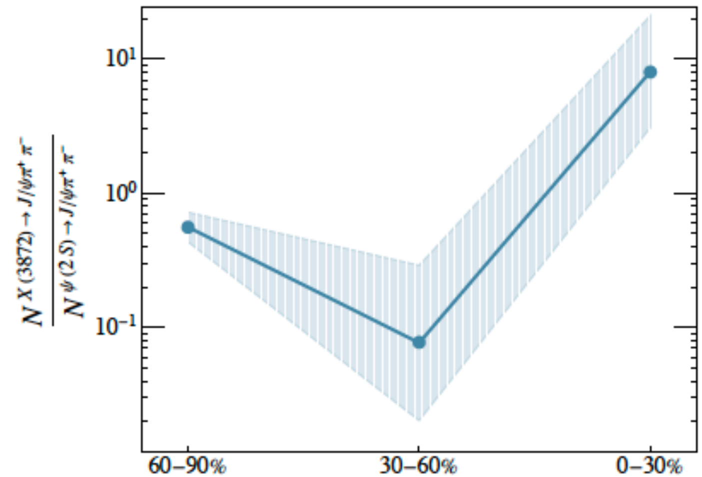
Conventional effect: suppression along path

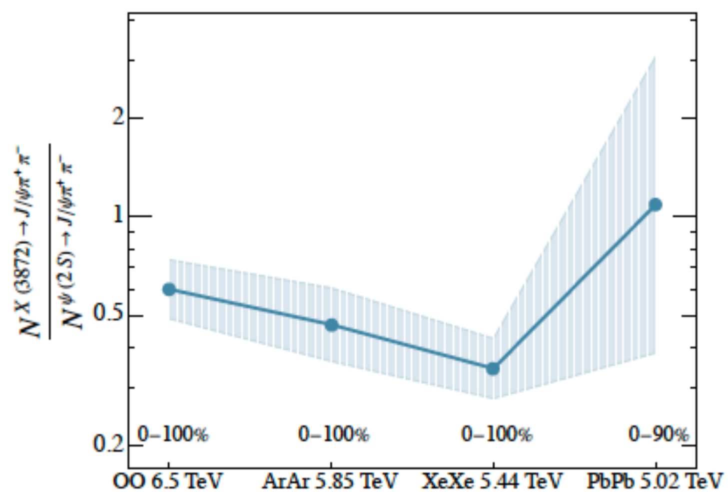
v.s.

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



Predictions to be tested





arXiv:2302.03828

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

– ***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.***