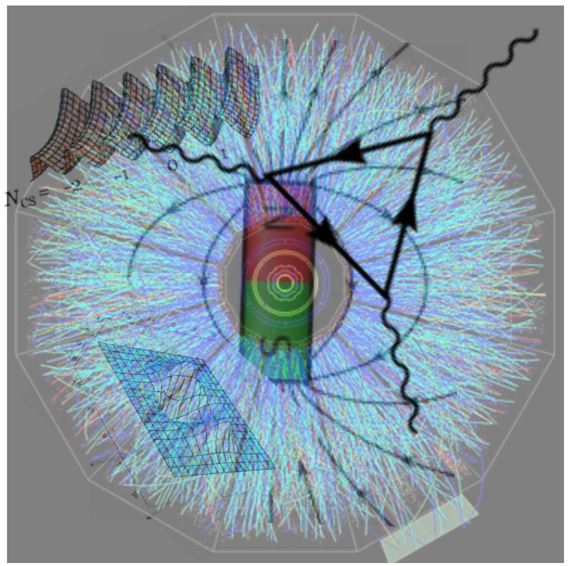
Fudan Open Seminar Series Apr. 06, 2022

Novel Phenomena in Quantum Chromo Matter

III. Cooking Exotica in a "Charming" Quark Soup



Jinfeng Liao

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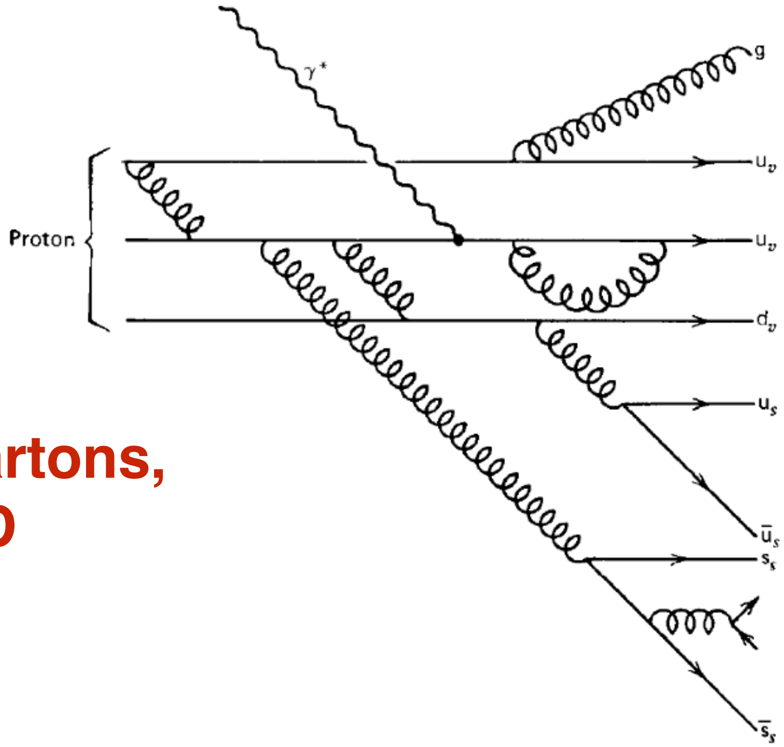
Research Supported by NSF & DOE

Introduction

From Hadrons to Quarks

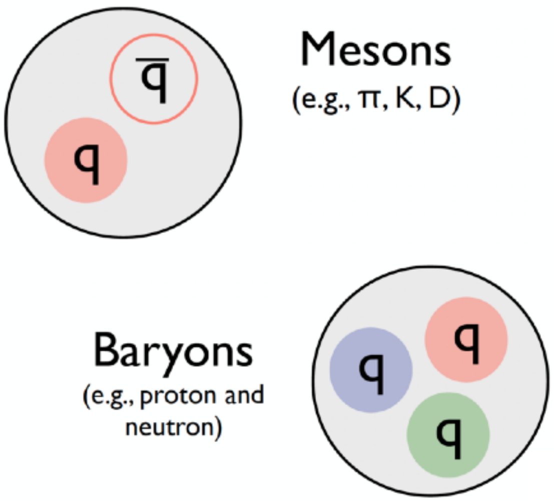
Around 1960': lots of hadrons, quark model



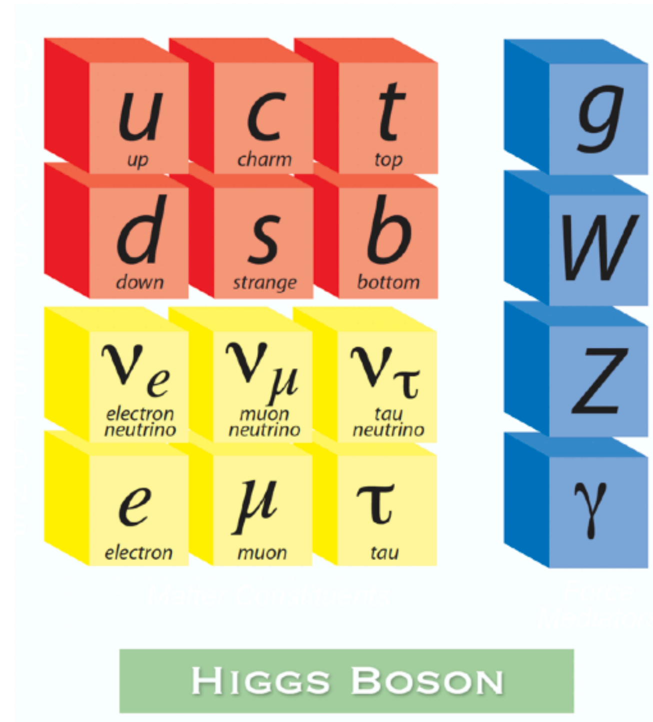
Late 60' / early 70': DIS/partons, Asymptotic freedom, QCD

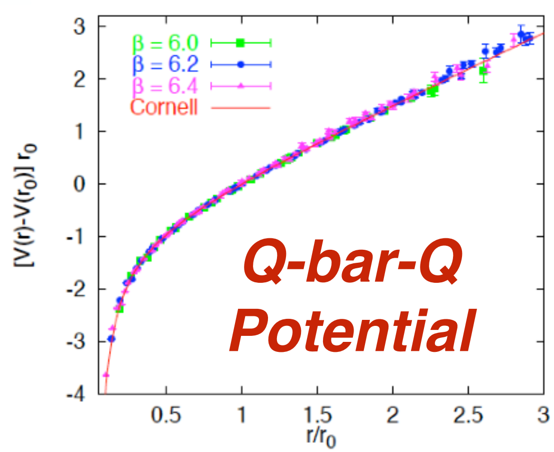
From Quarks back to Hadrons

Two typical arrangements:



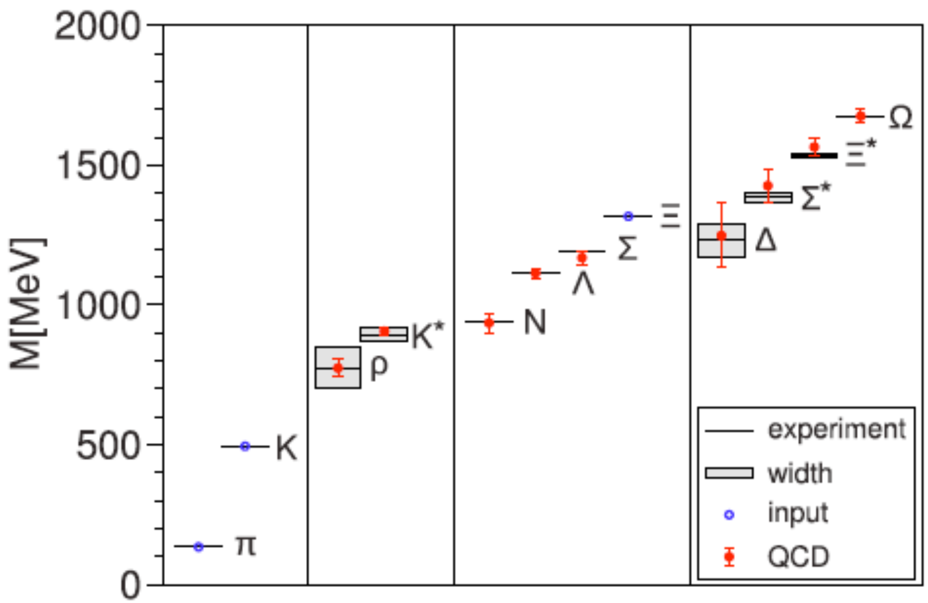
Confinement





Quark Model & Hadron Spectroscopy

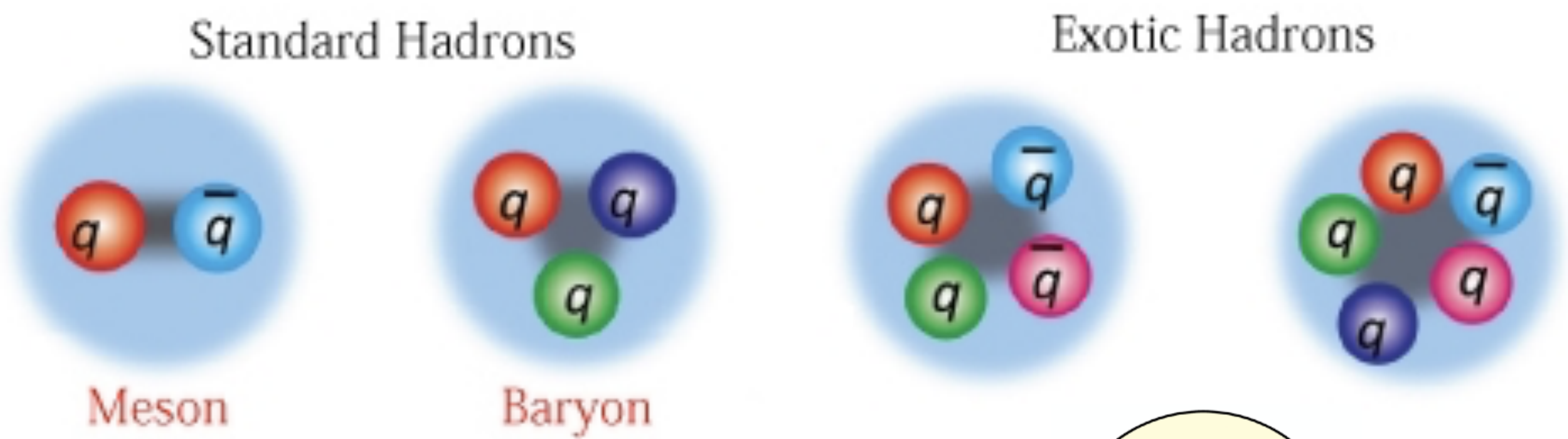
Spectra and structures of all possible hadrons
<—> A deeper understanding of QCD force.

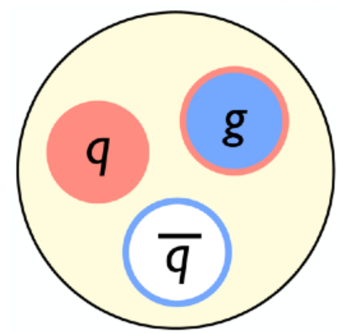


Example of light flavor (u,d,s) hadrons

Exotic Hadrons?!

Are their other ways of making hadrons?
What are possible and what are not? And why?
This is a very active frontier of hadron physics.



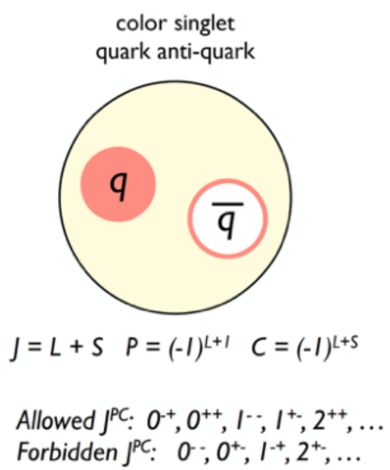


Many experiments:
BESIII, BaBar, Bell, CLEO,
GlueX, LHCb, ATLAS, CMS, …

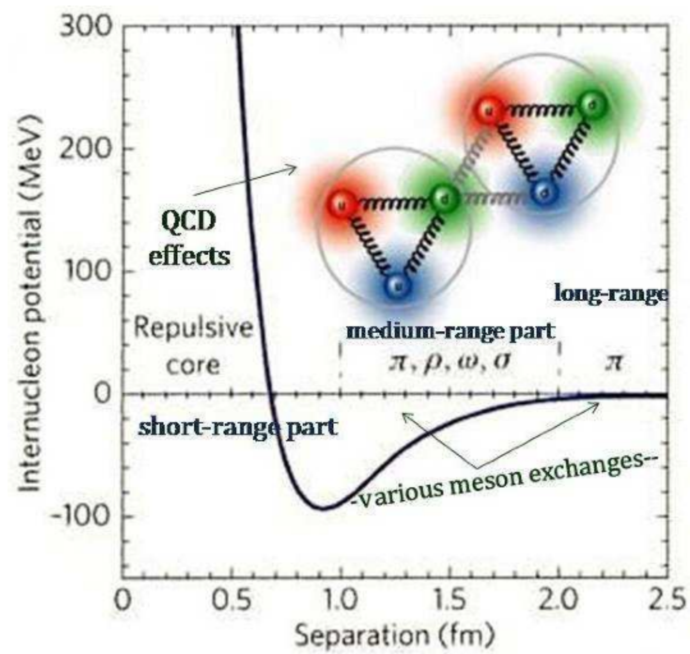
Exotic Hadrons

Exotic hadrons do not fit into the regular quark/antiquark arrangements: Quantum numbers and properties are possible only with multiple q/qbar/g

e.g. hybrids with J^PC=1^-+

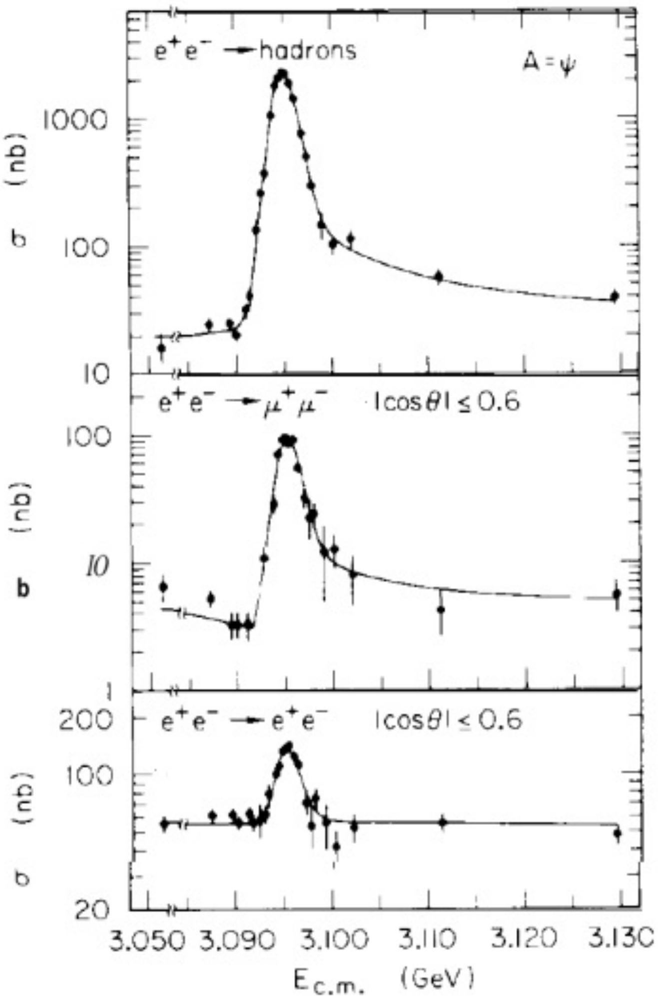


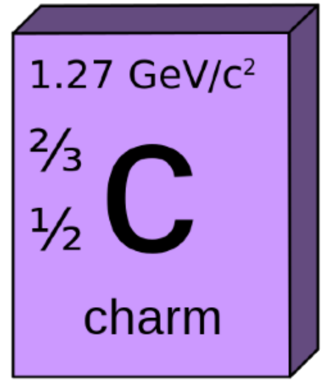
However, multiple quarks could also be not-so-exotic, e.g. deutron



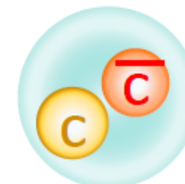
Heavy Quarks

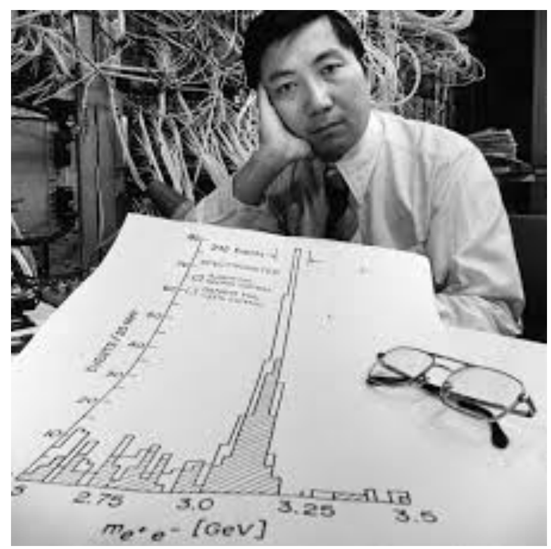
Let us focus on the so-called charm quark sector





Charmonium

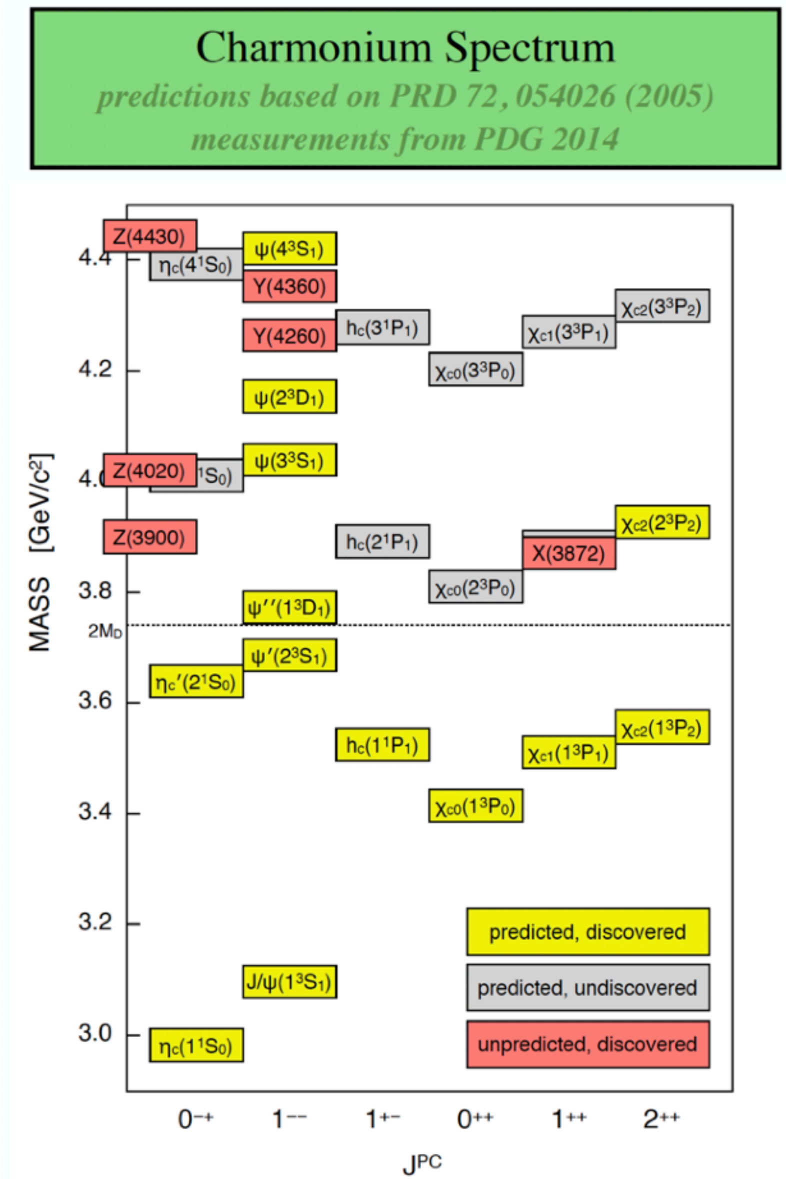




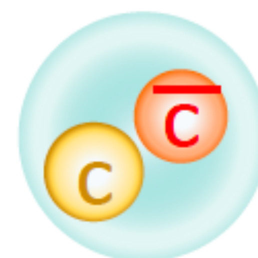
J/Psi discovery: Nov revolution (1974)

Charmonium Spectrum

The c-c-bar system offers unique opportunities for exotic hadrons!



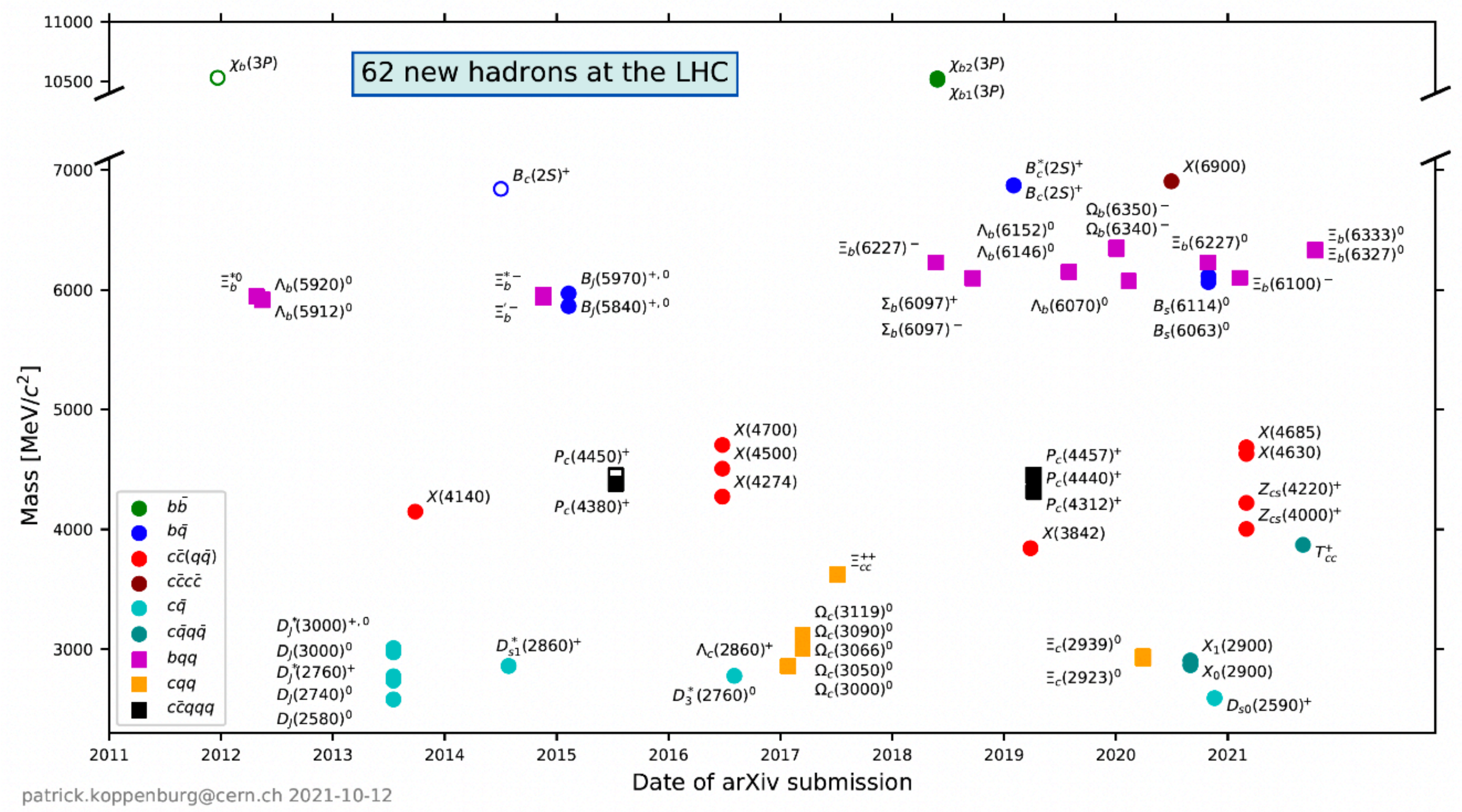
Charmonium



We are still far from fully understanding the secrets of QCD forces.

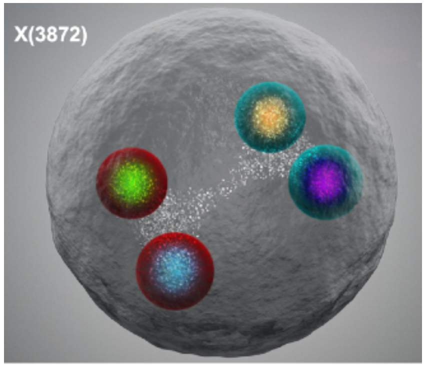
Heavy Exotica

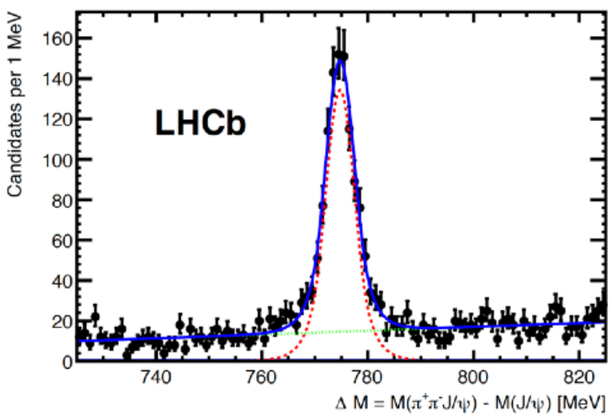
Example of heavy exotica found at LHC



Many exotic states found at other experiments as well, e.g. Zcs@BESIII, …

X3872 (aka Chi_c1)





- Mass = **3871.69 ± 0.17 MeV**
- Width < **1.2 MeV**
- $M(D^0) + M(D^{0*})$ - Mass = **0.11 ± 0.23 MeV**
  (using $M(D^0)$ = 1864.84 +- 0.07 MeV and $M(D^{0*}) - M(D^0)$ = 142.12 +- 0.07 MeV)
- $J^{PC} = 1^{++}$
- too light and too narrow to be the $\chi_{c1}(2P)$
- also seen in other decay modes
- a popular interpretation: DD* molecule or tetraquark

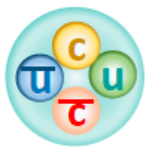
First observed in 2003 by Belle, later seen by many other experiments

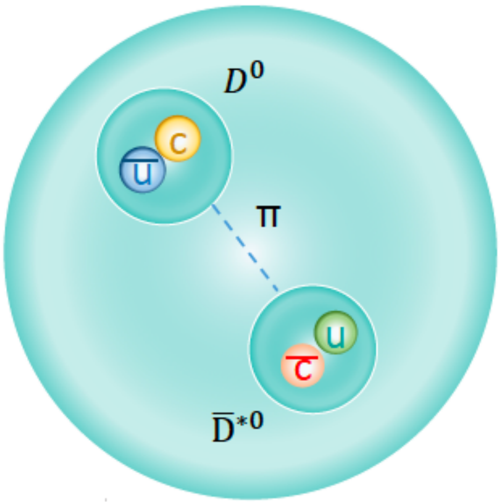
Quark content: c-cbar-u-ubar ?

X3872 (aka Chi_c1)

What is the intrinsic structure of X3872?

Compact tetra quark?
R ~ 0.5 fm



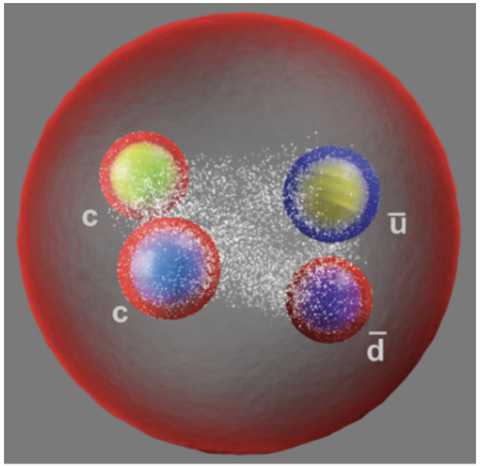


Hadron molecule?
R ~ 5 fm

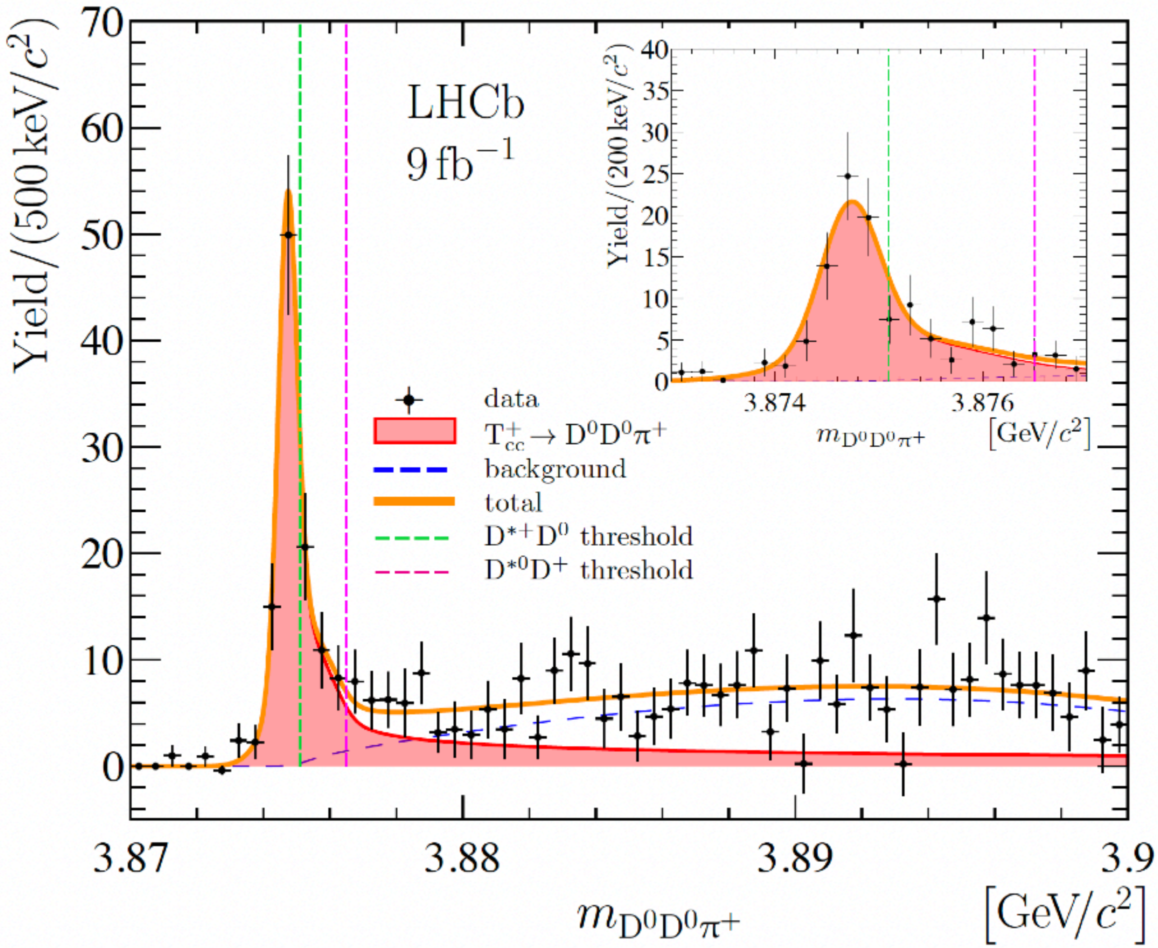
Despite nearly 20 years past its discovery, we still could not decide on the final answer of its intrinsic structure.

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

Tcc+



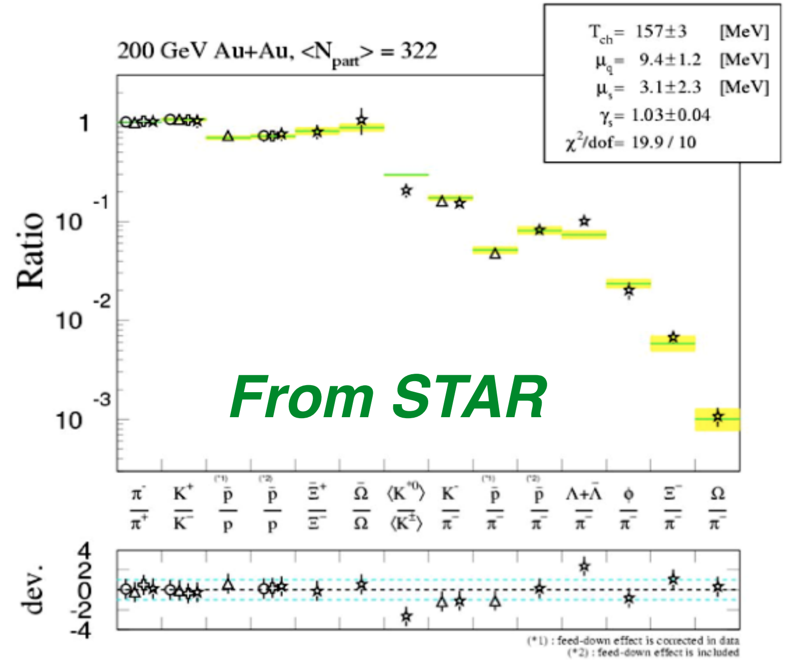
The flavor content clearly suggests the exotic nature: c-c-ubar-dbar ; Mass~3875MeV



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

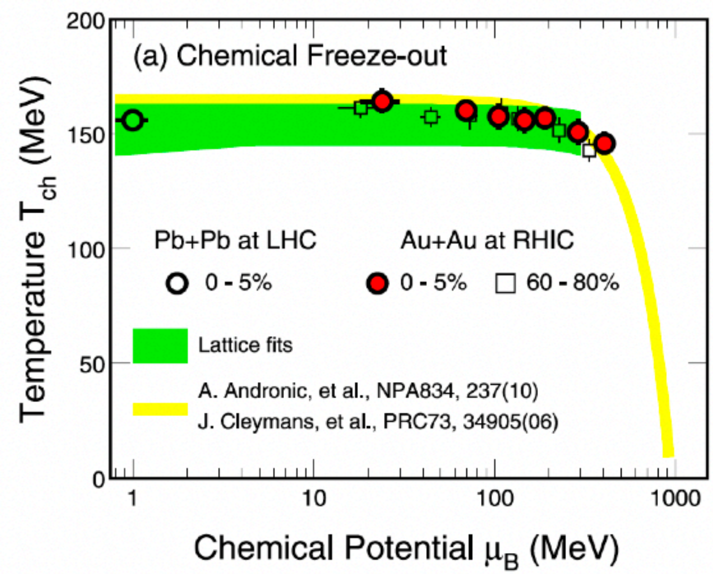
Heavy Flavor in Heavy Ion Collisions

A Hot Quark Soup in Heavy Ion Collisions



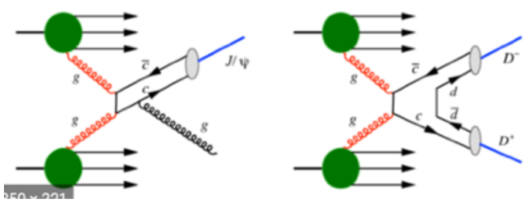
In heavy ion collisions:
We create a very hot soup of many many light quarks and gluons available for cooking hadrons!

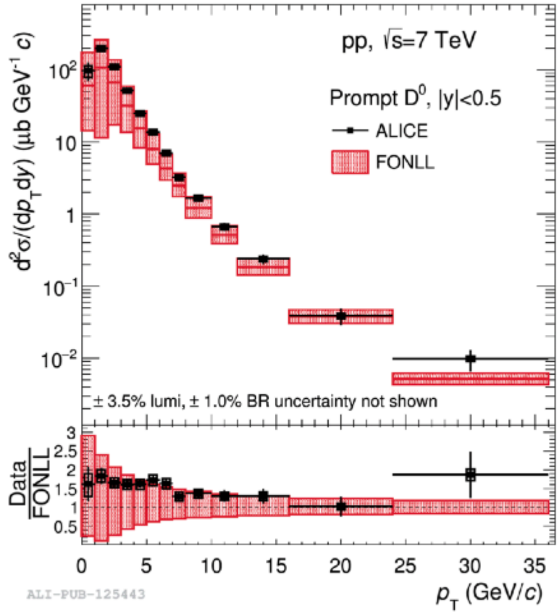
How about heavy quarks??



Initial Charm Production

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

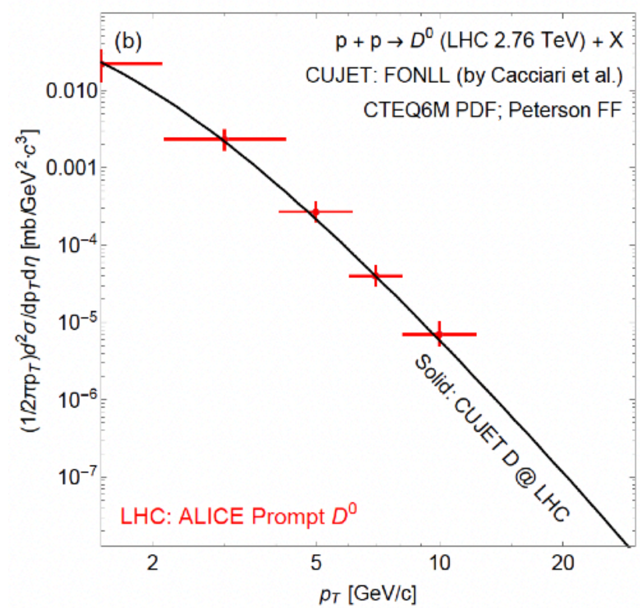




LHC is particularly advantageous:
x_RHIC ~ 0.01
x_LHC ~ 0.001

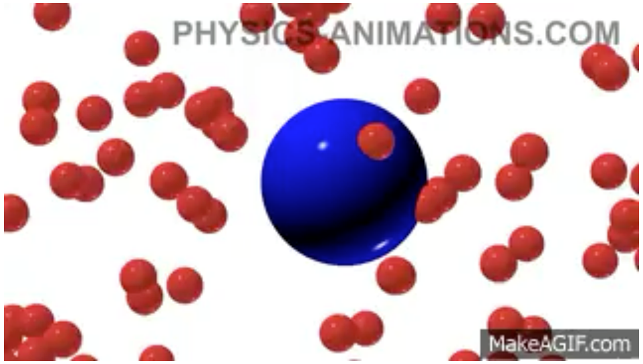
2Mc ~ 2.55 GeV >> Lambda_QCD ~ T

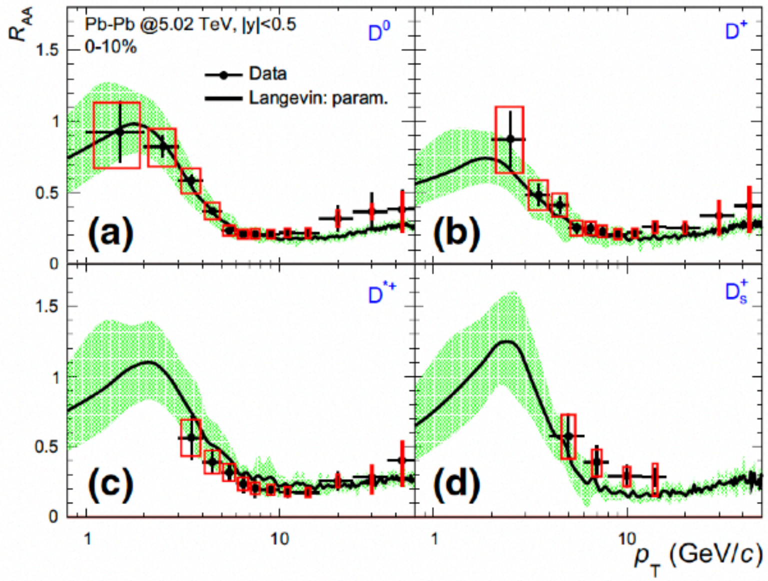
exp(-10) ~ 0.000045



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

Soft Sector: Charm Diffusion



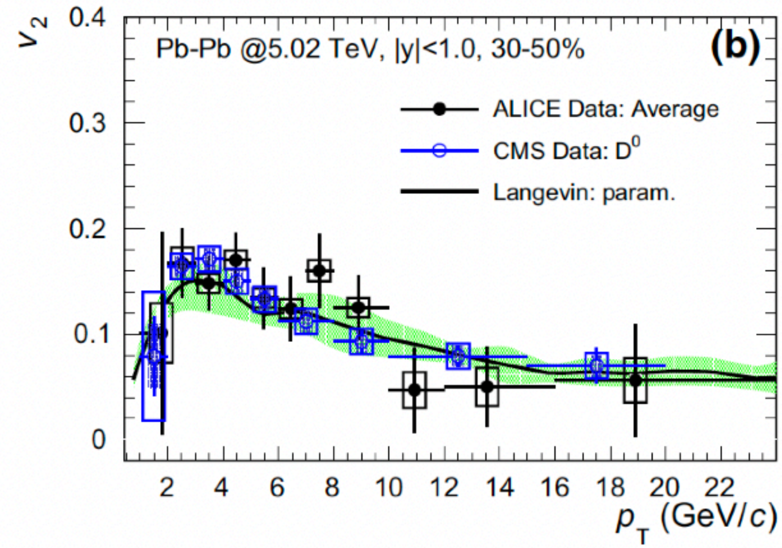


Brownian motion

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

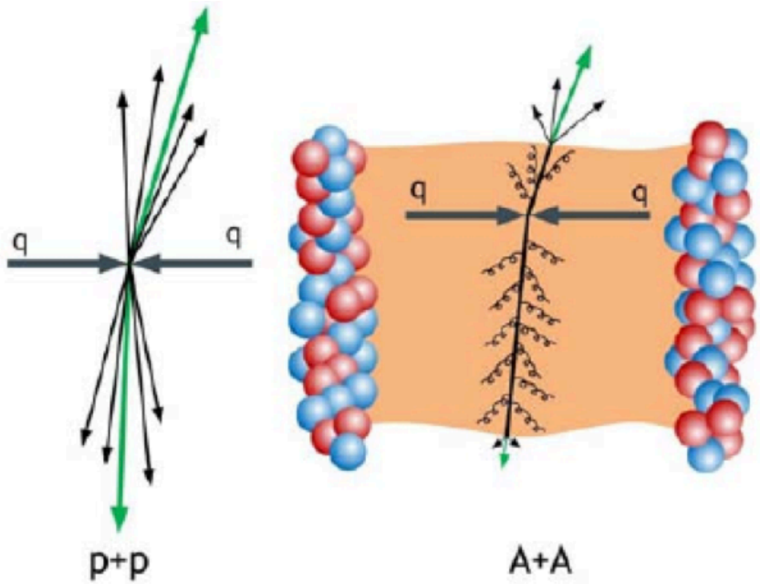
$$d\vec{p} = (\vec{F}_{\mathrm{D}} + \vec{F}_{\mathrm{T}} + \vec{F}_{\mathrm{G}})dt$$

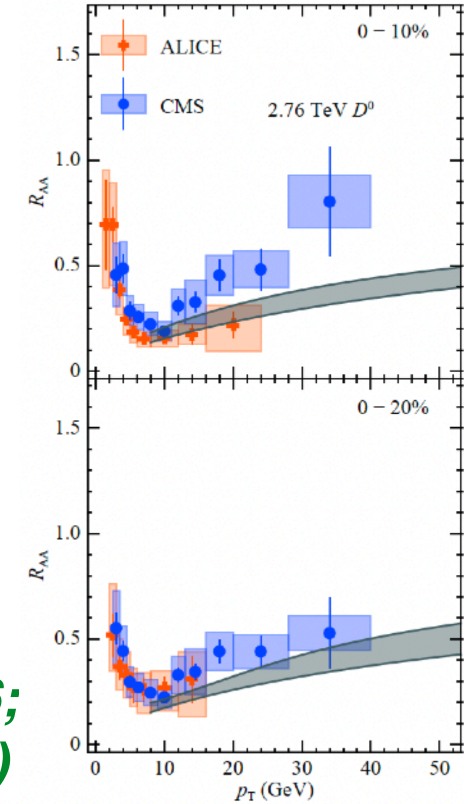
From: S. Li, JL, EPJC2020



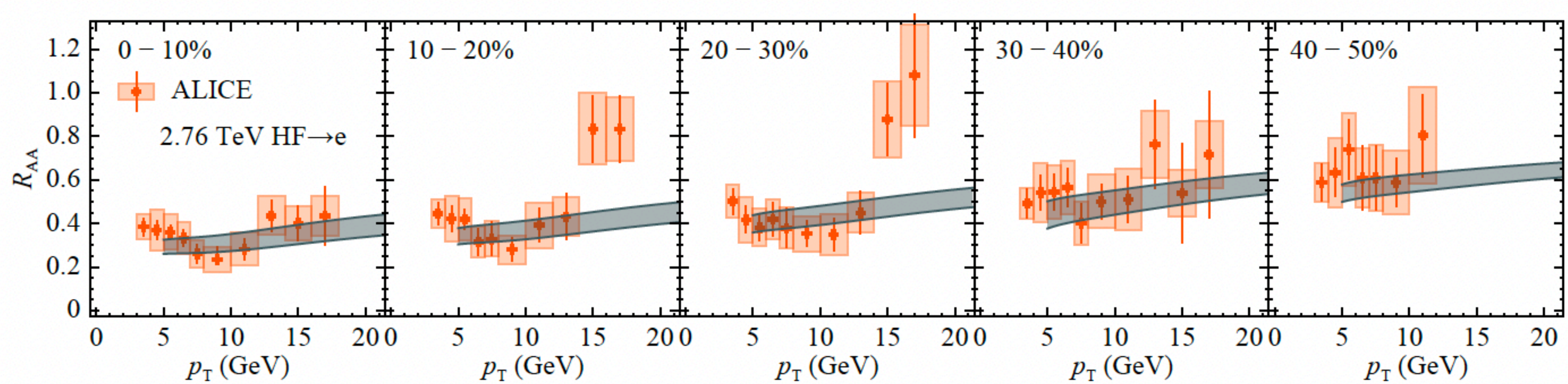
The charm quarks get carried by the bulk flow and diffuse around the whole fireball volume.

Hard Sector: Charm Energy Loss

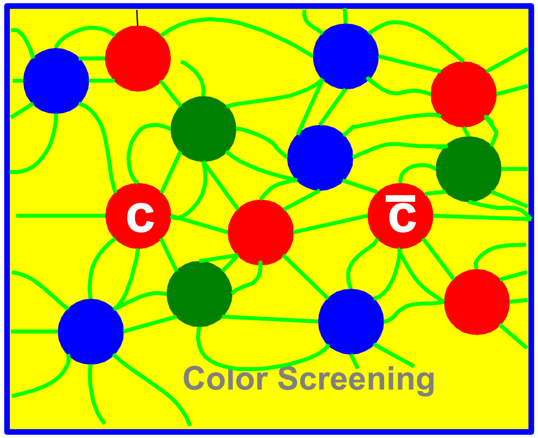


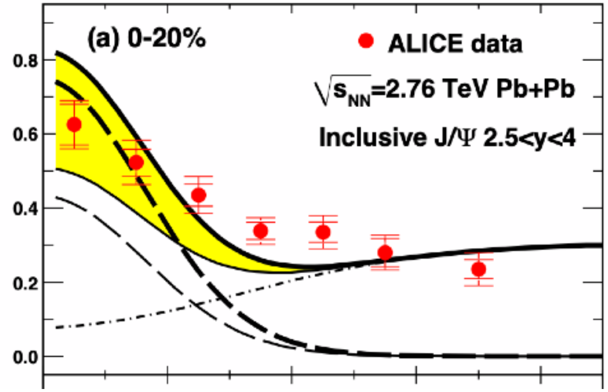


From: CUJET3
(Xu, JL, Gyulassy JHEP2016;
Shi, JL, Gyulassy, CPC2019)

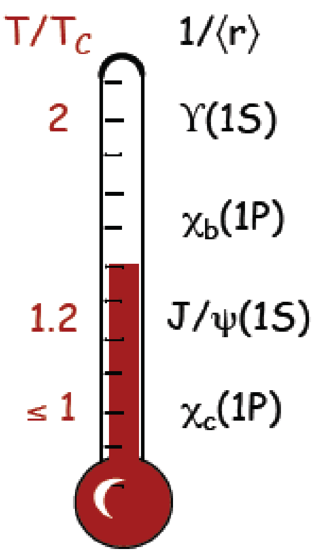


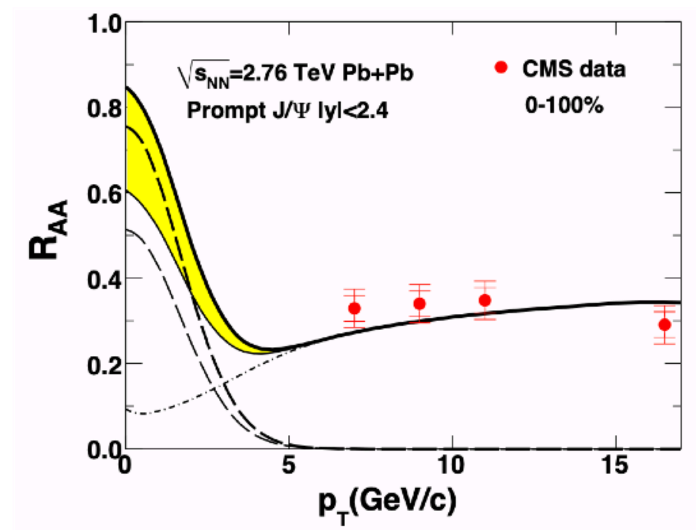
Charmonia: Melting and Regeneration





From: Zhou, Xu, Xu, Zhuang, PRC2014



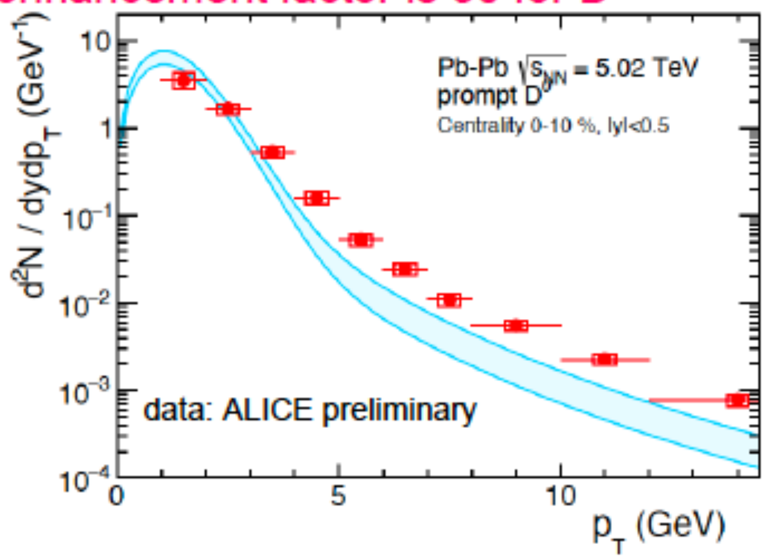


Regeneration becomes important at LHC for low to intermediate pT.

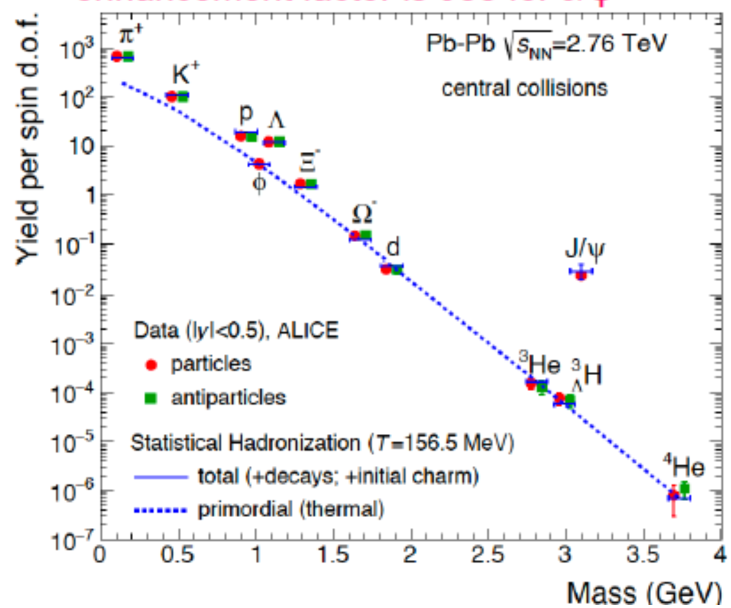
A "Charming" Quark Soup at O(~1000) GeV

Plots from Peter Braun-Munzinger

enhancement factor is 30 for D^0



enhancement factor is 900 for J/ψ



The key message here:
The QGP produced @ LHC O(~1000) GeV collisions,
is a "heavy-doping" QGP, with a "large" number of charms
—> a "charming" quark soup!
—> ideal for producing heavy exotics!!!

"Cooking" Exotica in Heavy Ion Collisions

Early Study on Exotica in Heavy Ion Collisions

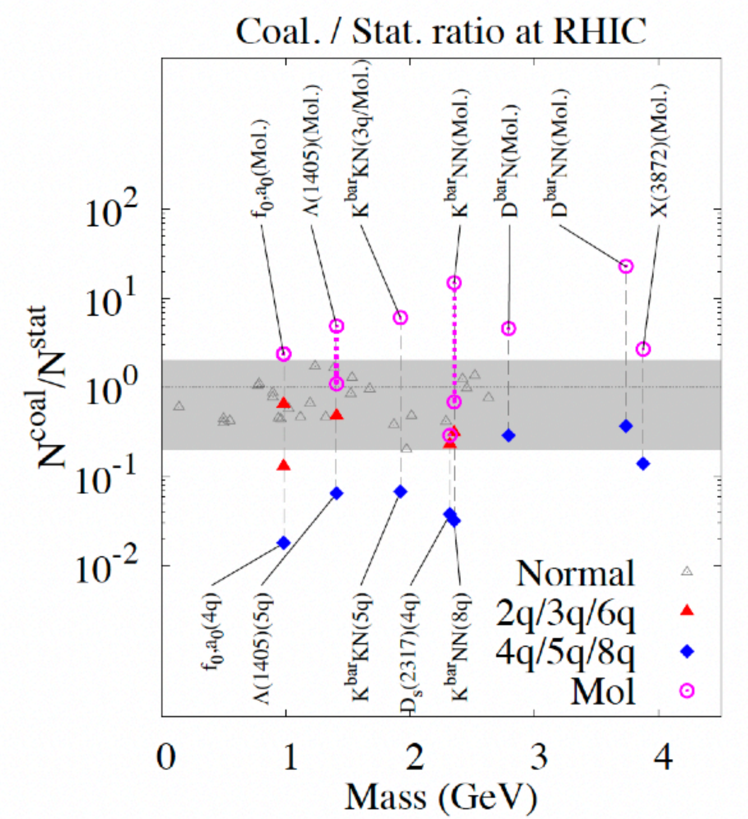
Identifying Multiquark Hadrons from Heavy Ion Collisions

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.



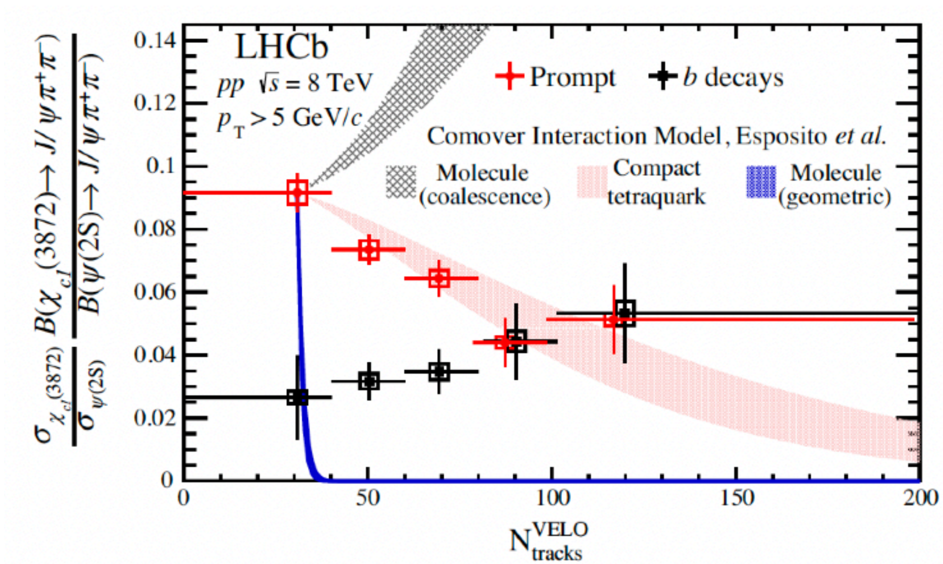
Recent Developments after the Discovery

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

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

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

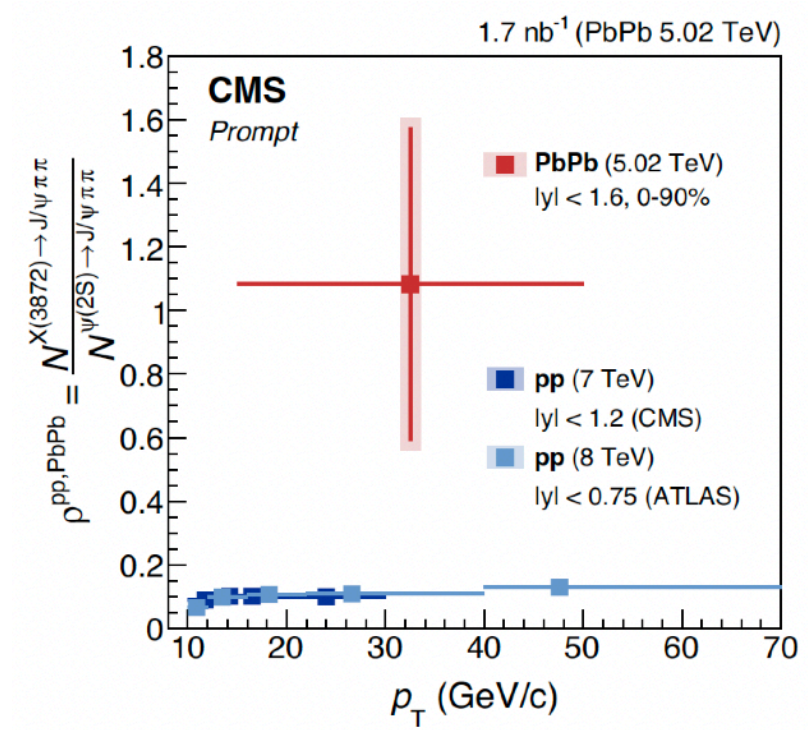
R. Aaij *et al.*[*]
(LHCb Collaboration)



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 indicate at partonic medium effect on X production!

"Cooking" Exotica in Heavy Ion Collisions

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,‖]

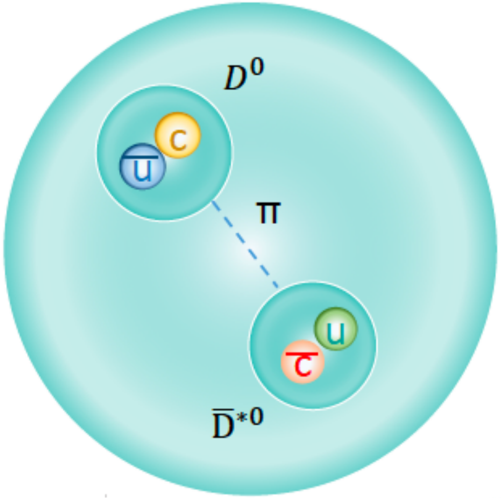
PHYSICAL REVIEW D **104,** L111502 (2021)

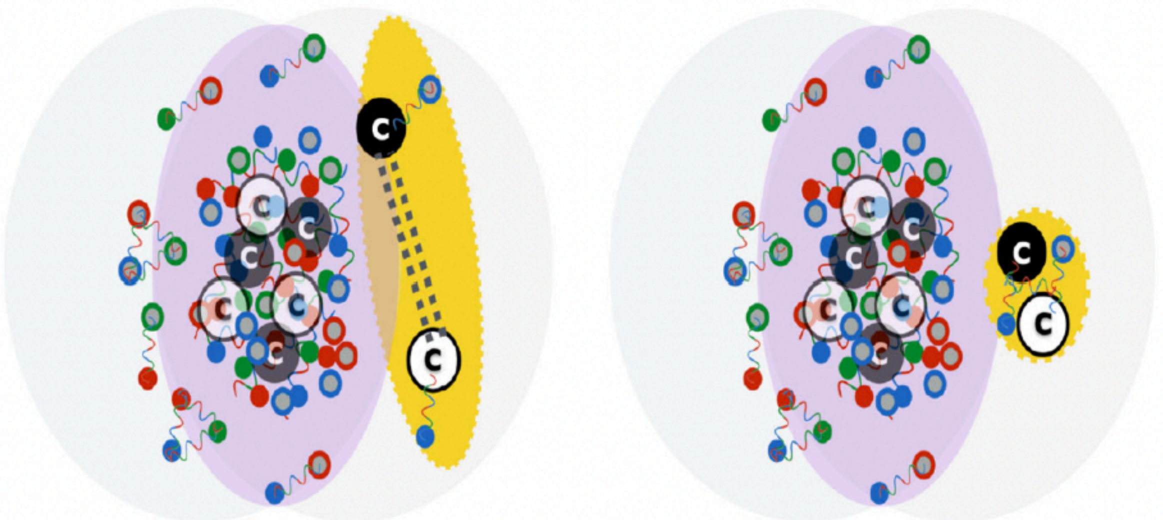
Letter

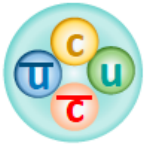
Production of doubly charmed exotic hadrons in heavy ion collisions

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.

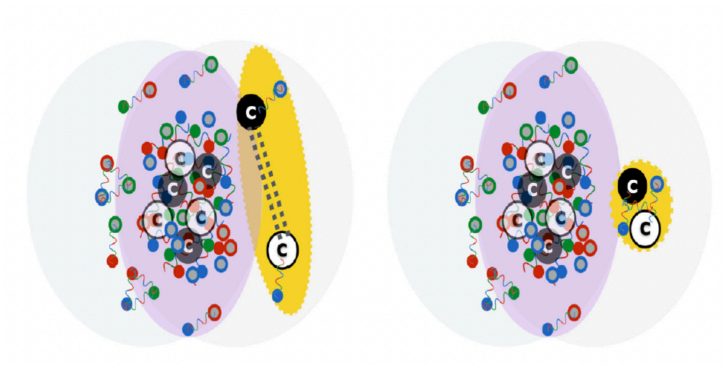
The hadronic molecule must be sensitive to the source volume.

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



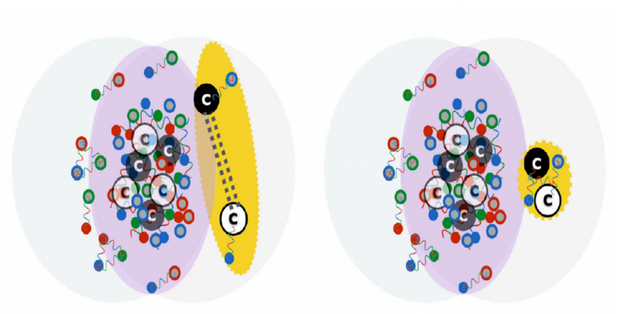
Compact tetra quark:

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!

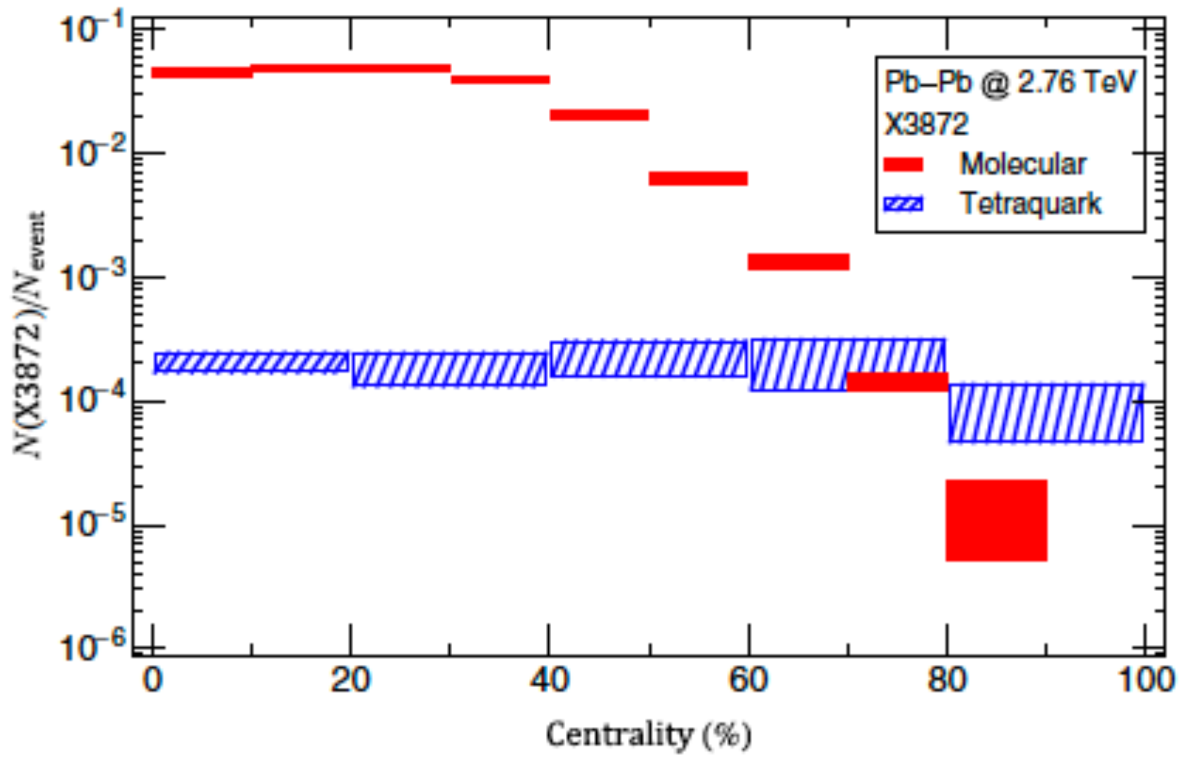
See framework details in PRL126(012301)2021.

A "Intrinsic Size Scan" for X3872



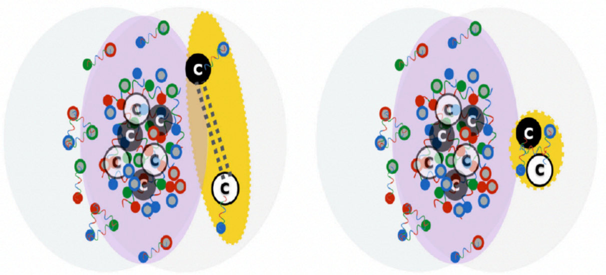
Hadron molecule v.s. tetraquark:
Two orders of magnitude difference in the yield;
Drastically different centrality dependence.

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



Hadron molecule v.s. tetraquark:
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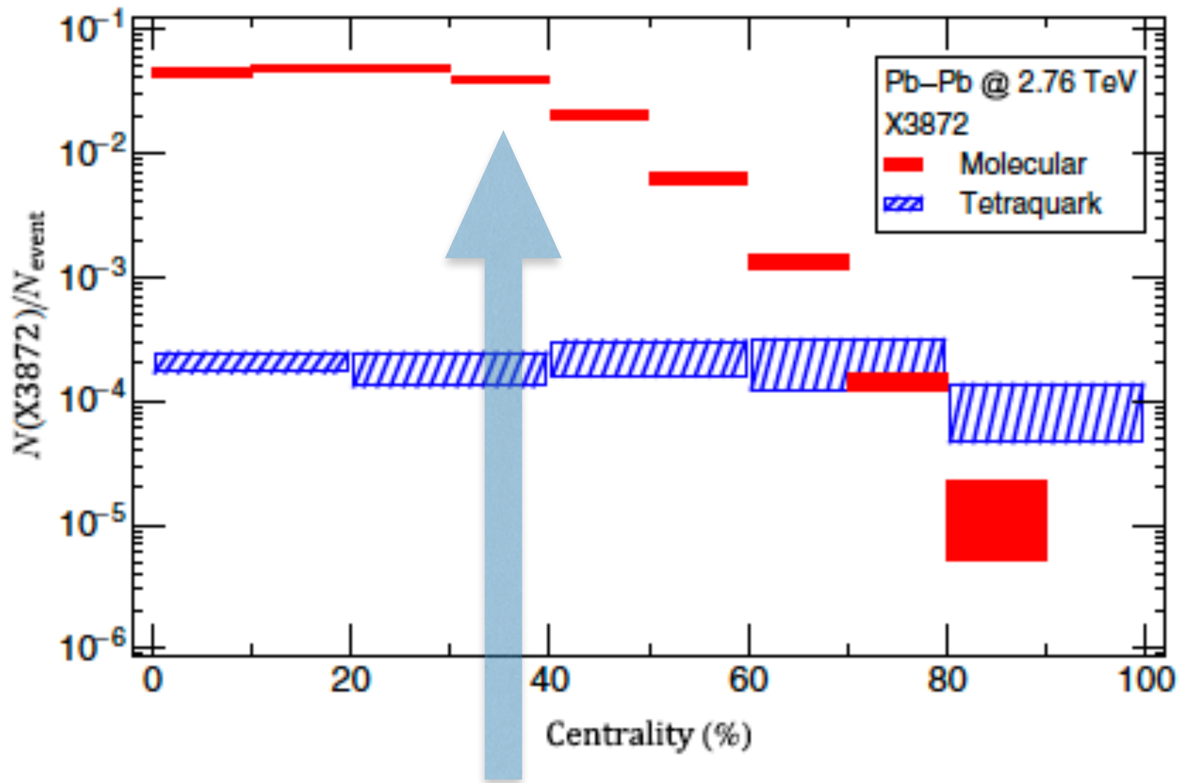
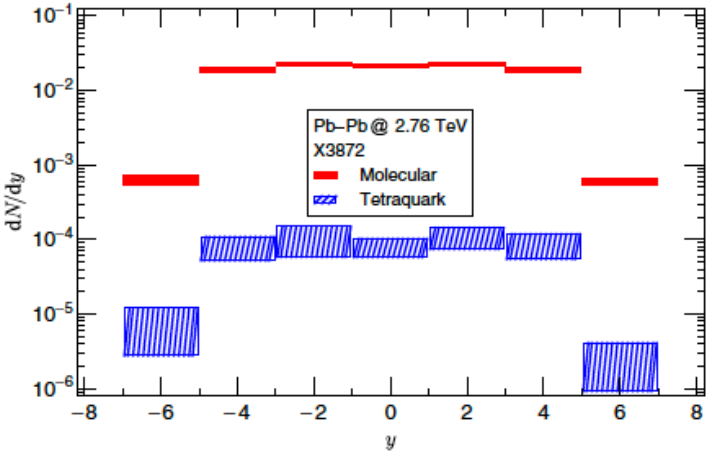
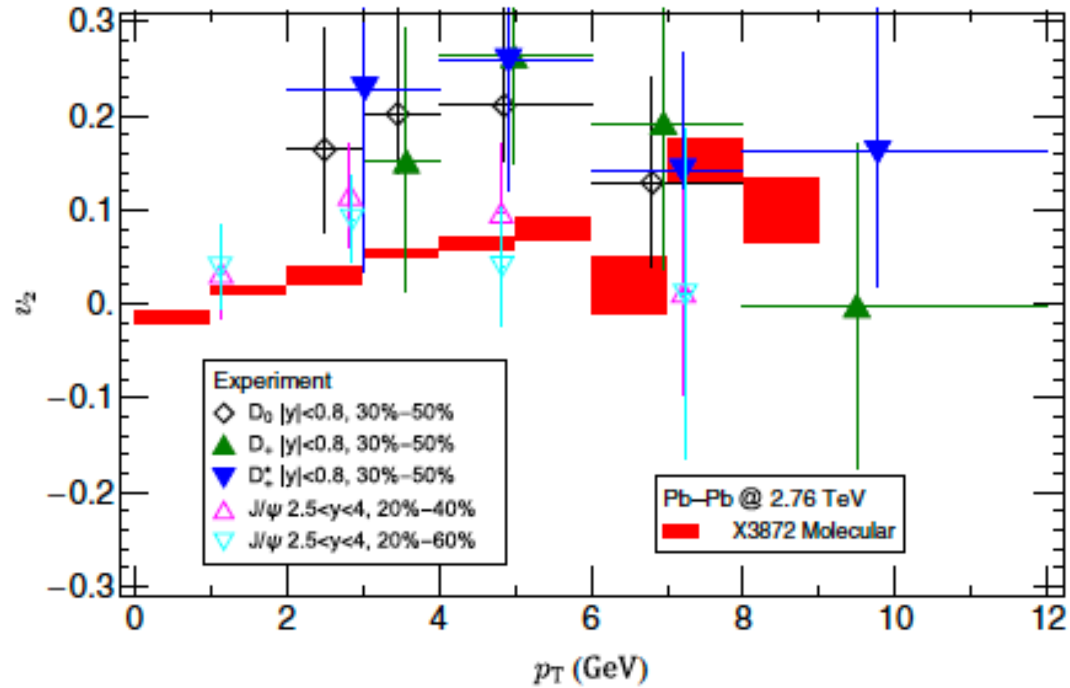
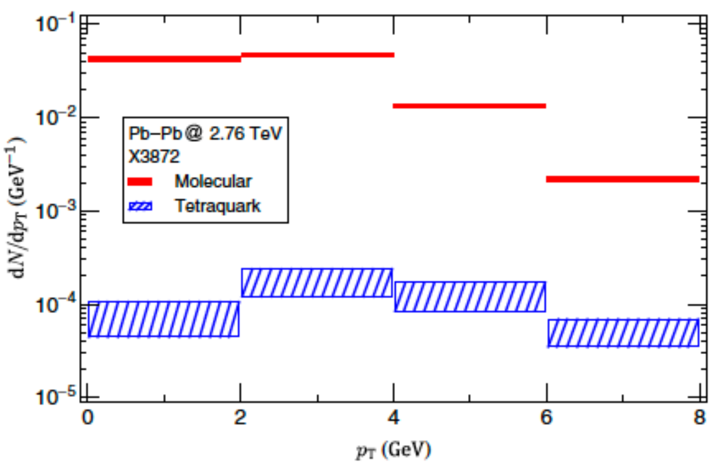


Likely where the fireball size becomes smaller than molecular size; future measurements can nail SIZE of X(3872)!

More Heavy Ion Observables for X(3872)

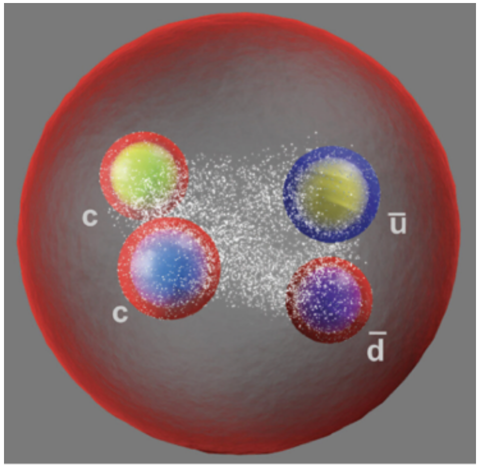






"It is tempting to envision an exciting time of vibrant and coherent theory and experiment efforts for exploring heavy ion collisions as a massive production factory of exotic hadrons to its fullest extent."

The Tcc Production in Heavy Ion Collisions



$$T'^{0}_{cc}: \quad D^0 D^{*0} \quad I = 1, \qquad I_3 = -1,$$

$$T'^{++}_{cc}: \quad D^+ D^{*+} I = 1, \qquad I_3 = 1,$$

$$T^{(\prime)+}_{cc}: \quad D^{0/+} D^{*+/0} \qquad I = 0(1), \qquad I_3 = 0.$$

$$T'^{+}_{cc} = -\frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+)$$

$$T^{+}_{cc} = -\frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+)$$

Heavy ion collisions have EVEN MORE advantage for the production of Tcc, which requires at least two pairs of c-cbar quarks!

We study its production in the hadron molecule picture.

We expect strong volume effect and an EVEN STRONGER threshold effect at peripheral collisions.

See details in PRD104(L111502)2021.

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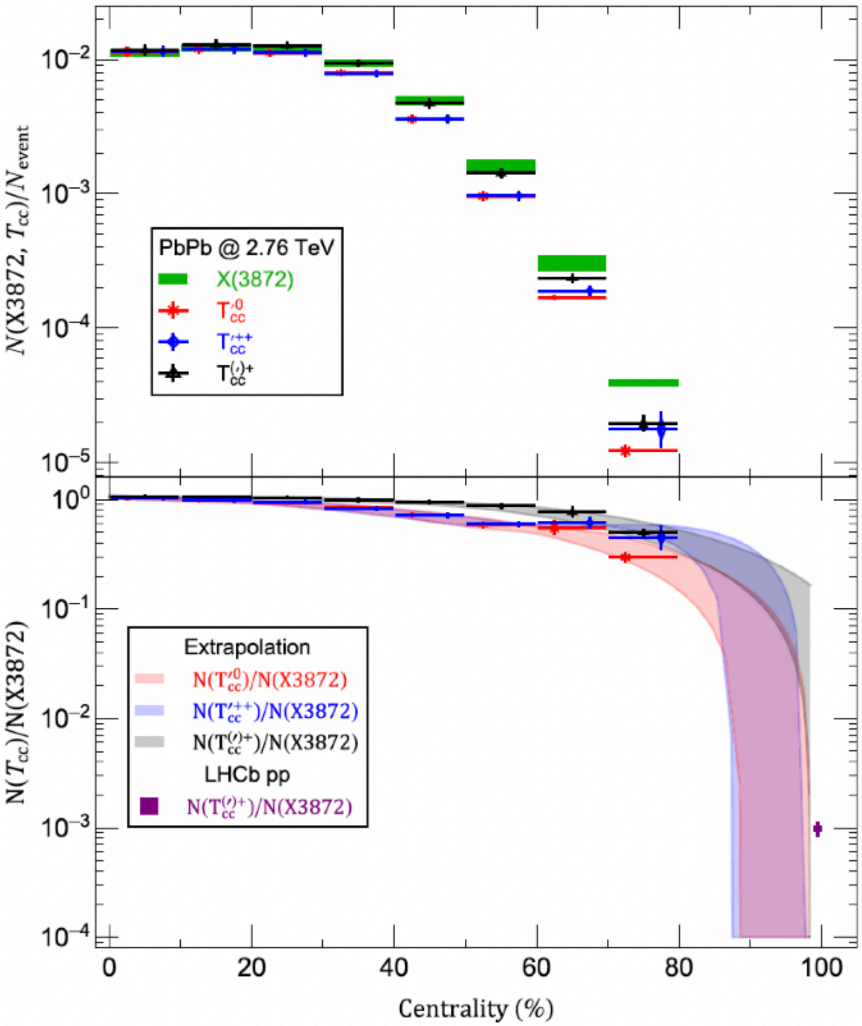
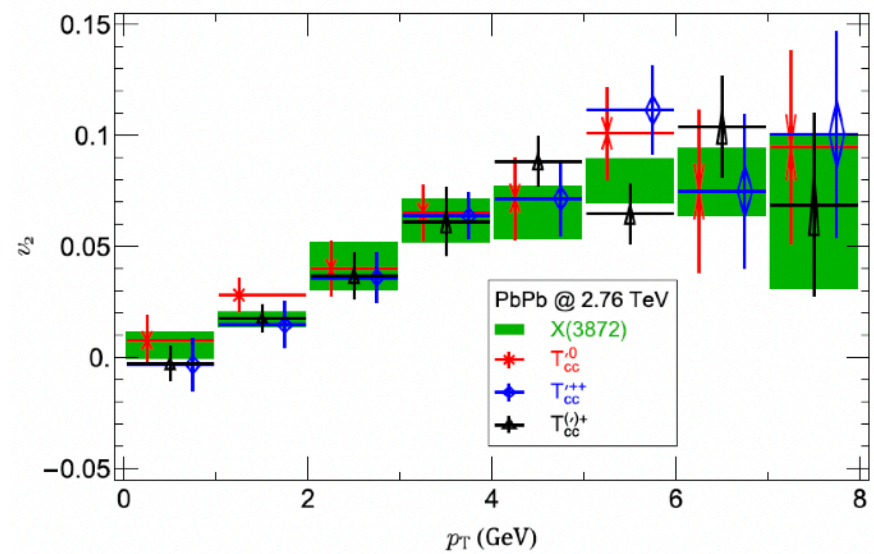


The Tcc production shows a very strong volume (i.e. centrality) dependence.

Tcc and X yields are comparable in central collisions.

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



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Summary

Cooking Exotica in a Charming Quark Soup

- ***Study of exotic hadrons is an important frontier of QCD physics, with unsolved puzzles.***

- ***Heavy ion collisions at very high energy prove to be an unparalleled factory of producing many charm quarks/antiquarks for producing heavy exotic states and measuring their properties.***

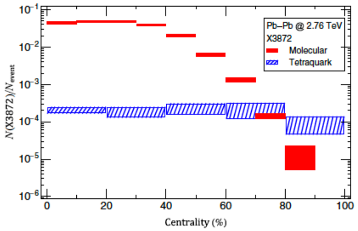
- ***Heavy ion fireball size serves as a RULER for calibrating the intrinsic size of exotic states like the X3872 and Tcc.***

- ***Future measurements of centrality dependence and collective flow will provide unique insights into these exotica.***

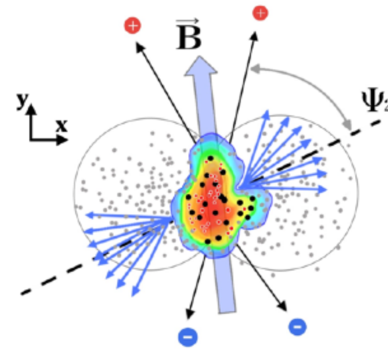
- ***This line of investigation is just starting!***

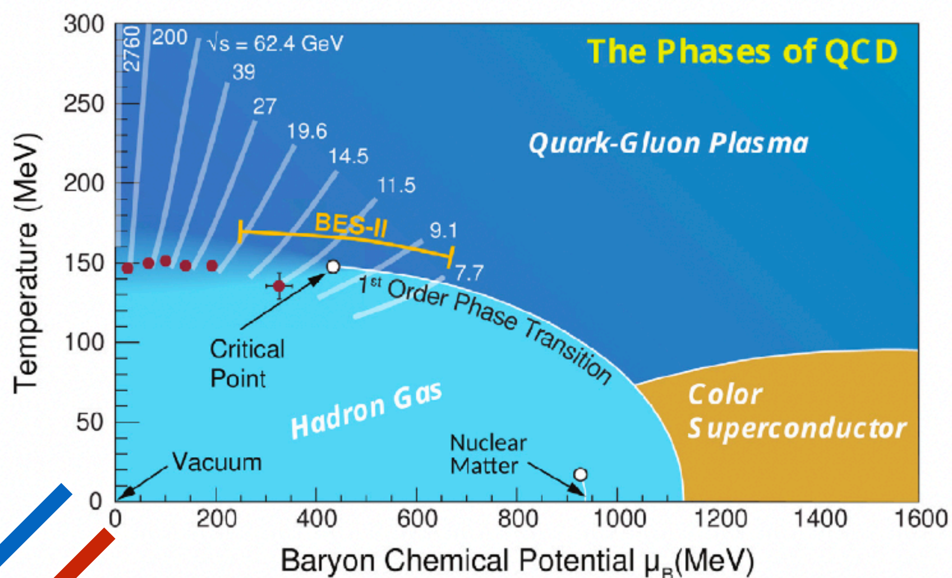
Rich and Diverse Heavy Ion Physics Onward

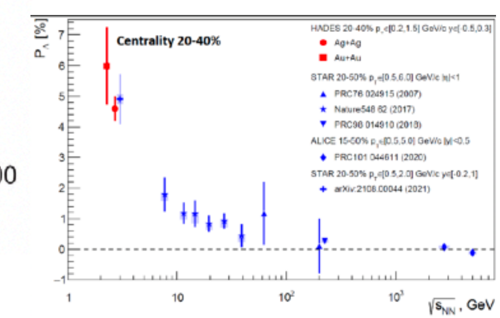
O(~1000)GeV: Charm exotica



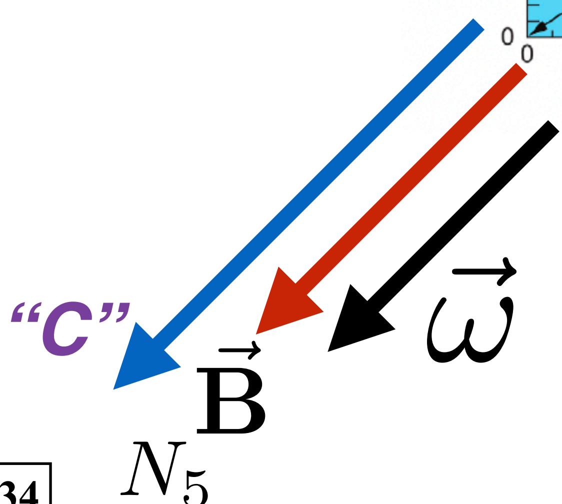
O(~100)GeV: Chiral Magnetic Effect







O(1~10)GeV: vorticity & polarization



Many novel dimensions of the QCD universe!