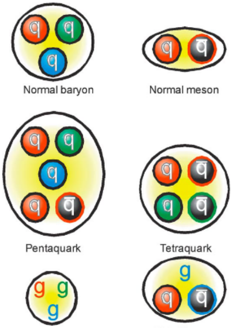
# Lecture 20
## Exotic particles in relativistic heavy ion collisions




More complicated states than mesons and baryons are not forbiden by QCD. They have been detected since 2003 (X(3872) Belle) and for the first time in heavy ion collisions in 2021 (X(3872) CMS).

In this lecture, we will discuss these particles in HIC.

# Exotic particles discovered

Table 1: Tetra- and pentaquark candidates and their plausible valence quark content.

| States | Quark content |
|---|---|
| $X_0(2900)$, $X_1(2900)$ [21,22] | $\bar{c}du\bar{s}$ |
| $\chi_{c1}(3872)$ [6] | $c\bar{c}q\bar{q}$ |
| $Z_c(3900)$ [23], $Z_c(4020)$ [24,25], $Z_c(4050)$ [26], $X(4100)$ [27], $Z_c(4200)$ [28], $Z_c(4430)$ [29–32], $R_{c0}(4240)$ [31] | $c\bar{c}u\bar{d}$ |
| $Z_{cs}(3985)$ [33], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [34] | $c\bar{c}u\bar{s}$ |
| $\chi_{c1}(4140)$ [35–38], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [38], $X(4630)$, $X(4685)$ [34], $X(4740)$ [39] | $c\bar{c}s\bar{s}$ |
| $X(6900)$ [14] | $c\bar{c}c\bar{c}$ |
| $Z_b(10610)$, $Z_b(10650)$ [40] | $b\bar{b}u\bar{d}$ |
| $P_c(4312)$ [41], $P_c(4380)$ [42], $P_c(4440)$, $P_c(4457)$ [41], $P_c(4357)$ [43] | $c\bar{c}uud$ |
| $P_{cs}(4459)$ [44] | $c\bar{c}uds$ |

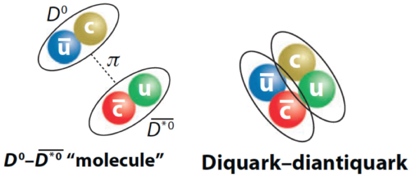
From LHCb-PAPER-2021-032.pdf. They also discovered the doubly charmed $T_{cc}^{+}(3875)$ in 2021 and three new exotics in july 2022

## What is the structure of these exotics?

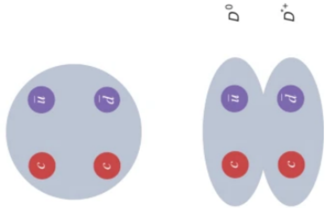
They could be molecule states (hadrons exchanging mesons or multiquarks states (quarks exchanging gluons)

Possible analogy: deuterium understood as a neutron-proton state not a compact hexaquark states

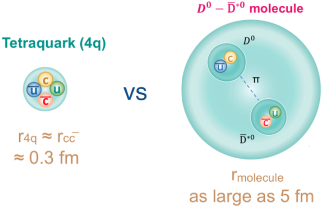
<u>Exemple:</u> X(3872) = $c\bar{c}u\bar{u}$ also known as ($\chi_{c1}$(3872))




<u>Exemple:</u> $T_{cc}^{+}$(3875) = $cc\bar{u}\bar{d}$ Long lived



These structures (molecule vs. multiquarks) have different size, so different fate in dense hot medium

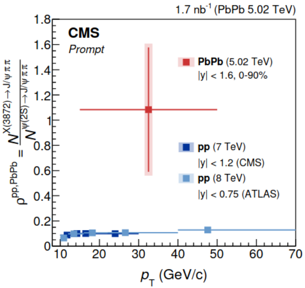



The idea then is to try to distinguish these structures in HIC. This may bring information on how quarks bind to form ordinary hadrons, confinement and the strong interaction.

What de we know for multiquark system in HIC?

Very little but that should change

CMS measured $X(3872)/\Psi'$ for high $p_\perp$ (15 GeV < $p_\perp$< 50 GeV) around midrapidity ($|y|$< 1.6) at $\sqrt{s_{NN}} = 5.02$ TeV in Pb+Pb




CMS PRL 128 (2022)032001

They studied $X(3872) \to J/\Psi\pi^+\pi^-$ and similarly for $\psi'$

## Model 1: Possible thermalization of charm quarks

N.B. This is a speculative idea

Suggestion: $J/\Psi$ from recombination should inherit thermalized charm flow, precisely

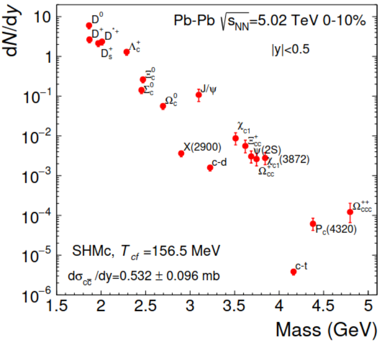
- The abundance of charm quarks is fixed at the beginning of the collision and is conserved
- Interactions in the hot fireball bring the charm quarks close to equilibrium
- Charmonia are created at hadronization in thermal equilibrium

How can this be tested?

- Prediction for $X(3872)$ yield from Statistical Hadronization Model: yield is independent of structure (cf. calculation of abundances in lecture 14) and it is $1.004\,10^{-3} \pm 3.777\,10^{-4}$

A.Andronic, P. Braun-Munzinger, M. K. Köhler, A. Mazeliauskas, K. Redlich, J. Stachel and V. Vislavicius

JHEP 07 (2021) 035 arXiv:2104.12754

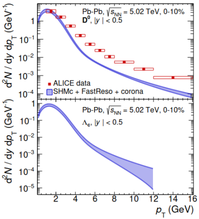


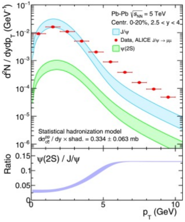
- $p_\perp$ distribution should be explained by hydrodynamics
  Predictions were made using a blast wave model (slide 8 lecture 13) and resonance decays were included

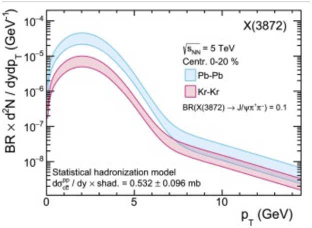
  A.Andronic, P.Braun-Munzinger,M.K.Köhler, K.Redlich, J.Stachel PLB 797 (2019) 134836 + previous

  reference

Reasonable agreement with LHC data for $\Lambda_c$, D-meson, $j/\Psi$ and prediction for $X(3872)$ at low $p_\perp$ where hydro is relevant



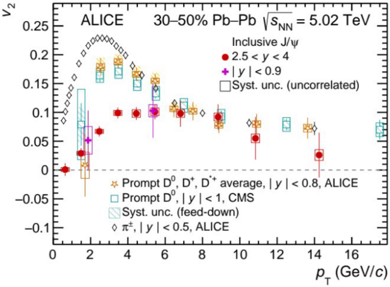



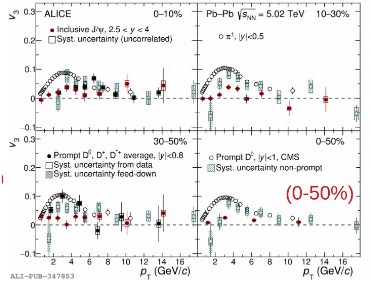

For X, no difference claimed between structures (as expected?)

Data at low $p_\perp$ needed to test the prediction

Elliptic flow and mass hierarchy have been observed

This a signal of collectivity (lectures 15 and 16)




I saw no calculation of this from the PBM/JS group but they should be able to do it also with a blast wave (cf. slides 8-9 in lecture 15)

Data at low $p_{\perp}$ needed

# Model 2: Transport and regeneration + blast wave

X.Du and R.Rapp NPA 943 (2015) 147; X. Du, R. Rapp, and M. He PRC 96 (2017) 054901

Their model has

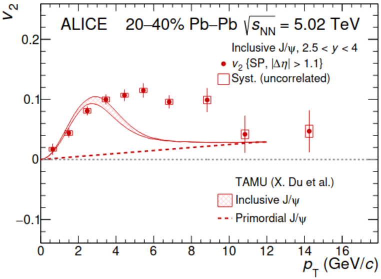
- Transport and regeneration until hadronization

The fireball evolution is modeled with $V_{FB}(\tau) = (z_0 + v_z\tau + 1/2a_z\tau^2)\pi(r_0 + 1/2a_\perp\tau^2)$ cf. X.Zhao and R.Rapp PLB 664 (2008) 253

- Blast wave at hadronization

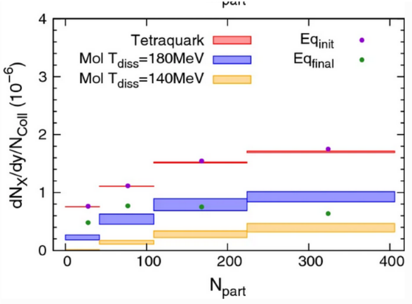
We saw that $R_{AA}$'s for $J\Psi$ and $\Psi'$ are in reasonable agreement with experiment in lecture 19.

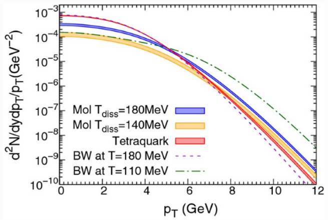
They also have reasonable agreement for $v_2(p_\perp$




ALICE JHEP 10 (2020) 141 arXiv:2005.14518

# They made predictions for X(3872): structure matters



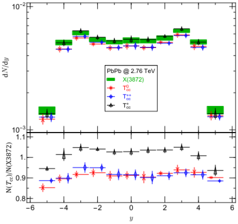

Transverse-momentum spectra of the $X(3872)$ in 0–20% central Pb-Pb collisions for the molecular (blue band for $T_{diss}$ = 180 MeV and orange band for $T_{diss}$ = 140 MeV) and tetraquark (red band) scenarios, compared to blastwave spectra at chemical (dashed line) and thermal (dash-dotted line) freezeout. The width ranges and temperature exponent are as in Fig. 4, with no nuclear shadowing on the charm cross section included

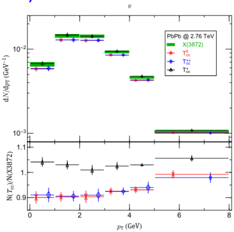
# Model 3: AMPT

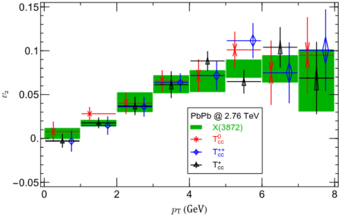
AMPT: fluctuating initial conditions+ partonic scatterings modeled by parton cascade+ hadronization by using a quark coalescence model+ subsequent hadronic rescattering. No hydro.

Widely used for other particles and observables in HIC

## Results for X(3872) and Tcc:




H. Zhang, J. Liao, E. Wang, Q. Wang, H. Xing arXiv:2004.00024 and Y.Hu, J. Liao, E. Wang, Q. Wang, H. Xing, H. Zhang arXiv:2109.07733

## Homework (or maybe challenge)

In the statistical hadronization model, the abundances of X(3872) (or $\chi_{c1}$(3872)) and $\Psi(2s)$ (or $\Psi'$) are small and very close to one another, can you think of an explanation?

Why is the $J/\Psi$ yield higher?

Other references on this topic

- https://www.origins-cluster.de/en/press-release/new-class-of-matter-long-lived-doubly-charmed-te