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Hadronization and (de)confinement in hadronic collisions: what to learn from or about exotica?

Antonio Uras
CNRS/IN2P3 IP2I-Lyon

Introduction

First dozen of years in the 21st century: starting point of the hadronic renaissance. Hadrons traditionally explained as $q\bar{q}$ or $qqq/\bar{q}\bar{q}\bar{q}$ composites, many of the hadron masses well described in the quark model. **This common understanding of hadrons became doubtful in the last years**

- Exotic hadrons include **multiquark states, hybrid mesons and baryons, and glueballs**
- **Multiquark states can be further divided into compact multiquarks and hadronic molecules according to how the (anti)quarks are grouped together**
- For hadronic molecules, the quarks and antiquarks first form color-singlet hadrons, which then interact with each other through the residual strong force to form composite hadron systems; in this sense, **hadronic molecules are not "exotic"** but a rather natural extension of atomic nuclei to composite systems of other hadrons
- Hadrons of such exotic structures have been proposed since the early days of bag models as **the color confinement does not rule out the existence of a multiquark configuration in a color-singlet state**

The question of whether multiquark hadrons exist is an old problem

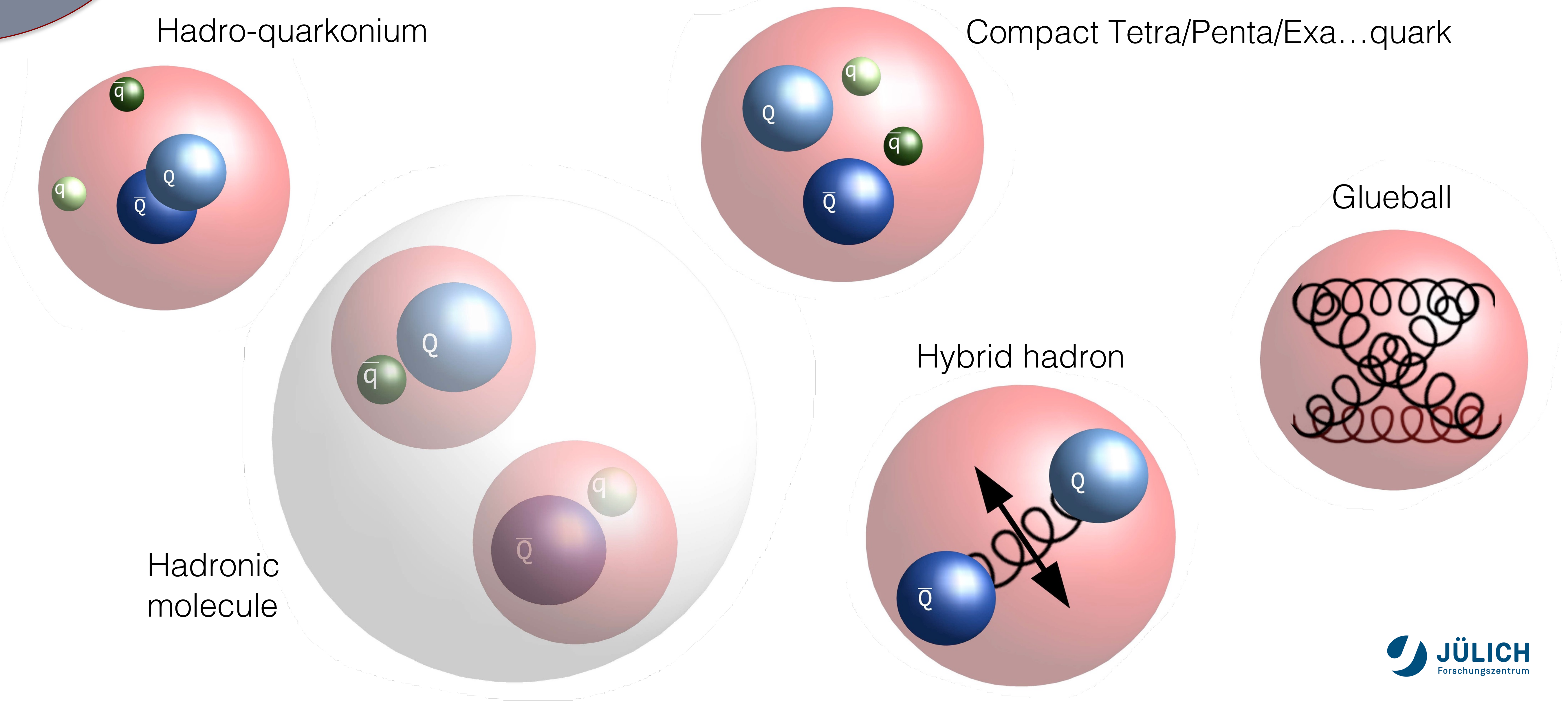
- The multiquark picture was proposed in the light hadron sector as a solution to the problem of the inverted mass spectrum of the scalar nonet: $a_0(980)$, $f_0(980)$, …

- The existence of the exotic H dibaryon (strongly bound uuddss state with mass 81 MeV lighter than the ΛΛ threshold) was speculated on the basis of the color-spin interaction, and it has been sought for in various experiments for a long time without success

- The first evidence of a tetraquark or a molecular state, X(3872), was reported by the Belle experiment at KEK only at the beginning of 2000s

- Experiments at the CERN LHC, particularly LHCb, have recently observed several new candidates for tetraquarks and pentaquarks: those candidates all involve heavy quarks, which implies that their properties can be calculated in nonrelativistic QCD

Introduction



Introduction

Understanding the structure of exotic hadrons is important to construct a new scheme over the quark model to categorize hadrons including normal and exotic ones

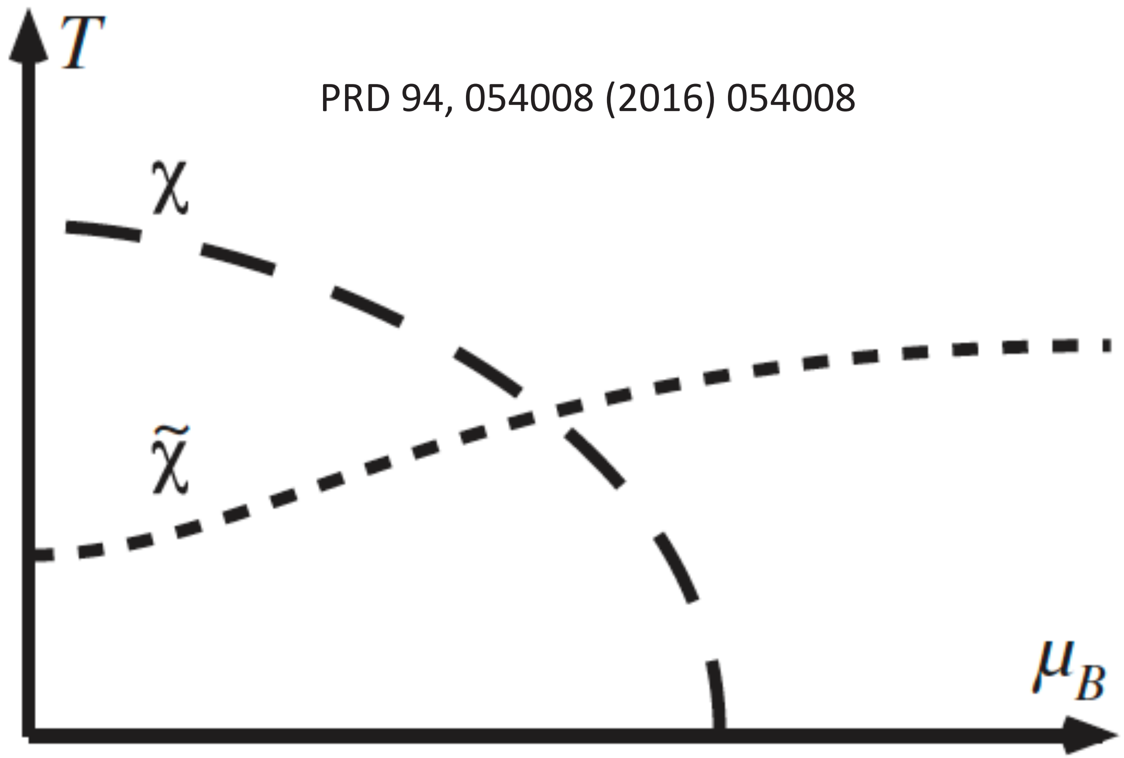
The study of how the colourful quarks and gluons are grouped inside hadrons is crucial in **gaining new insights into the mechanism of color confinement.** Key questions are:

- What kind of exotic hadrons could exist?
- What are the internal structures and properties of them?
- What are their production and decay mechanisms?

Thanks to the high statistics of the new generations of experiments, many new hadron resonances have been discovered since 2003, being good candidates for exotic hadrons. Most of them were mesonic states observed in the heavy quarkonium mass region (above the open-charm threshold), and are usually referred to collectively as XYZ states

Multi-quark states inducing a chiral phase transition

The existence of stable tetraquark configurations may lead to a second chiral phase transition, and including tetraquarks seems to be essential in using effective models to determine the position of a critical end point in the plane of T and μ



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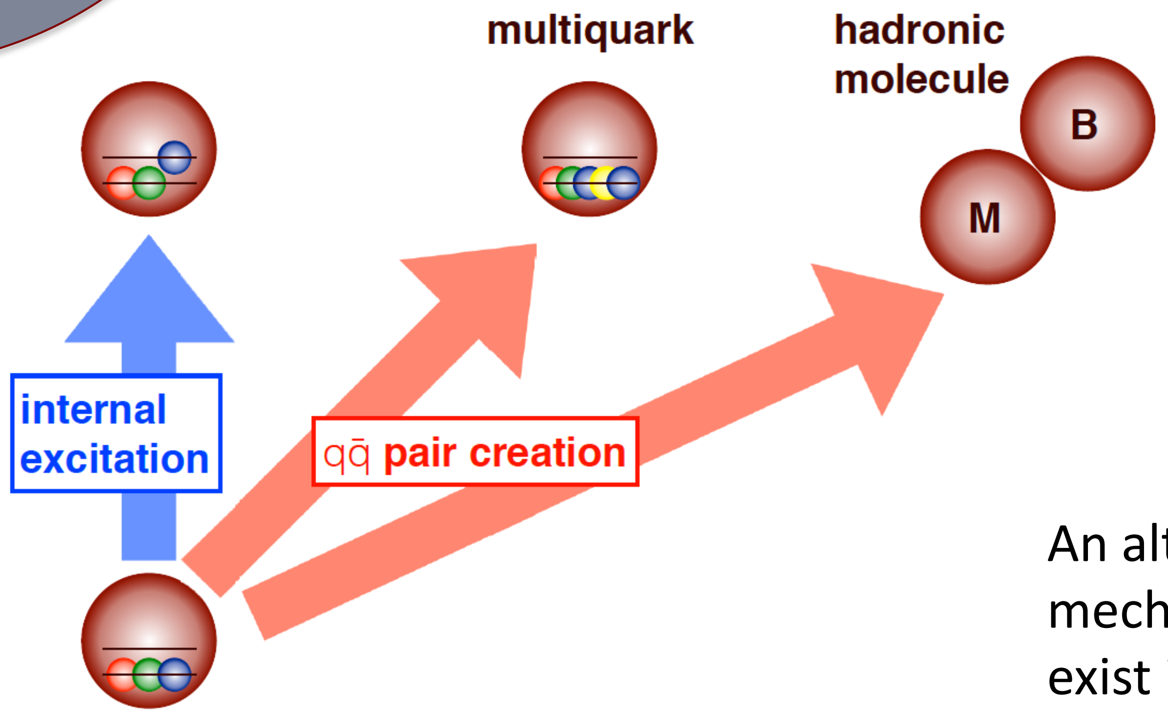
Three-flavor scenario: conjectured phase diagram in temperature T and baryo-chemical potential μ_B

The χ line is that for the chiral transition, the $\tilde{\chi}$ line is for a second transition related to the presence of the tetraquark condensate, which may connect smoothly to the transition line for color superconductivity

In a four-flavor scenario, a triquark field may combine to form hexaquarks

Exotic hadrons: size matters



It is not always possible to distinguish between an internally excited state, a compact multiquark or a molecular configuration based just on the quantum numbers of the bound system

An alternative approach to clarify the structure and the mechanisms allowing for the existence of exotic states to exist is the **estimation of their size**

- **In the case of a multi-quark state** such as a diquark pair, the confining force between the diquarks would make the system compact, with a similar size to normal hadrons
- **In the case of a hadronic molecule** such as a D*D bound state, the exotic hadron size would be determined by its binding energy or the range of the pion exchange (in the same way as the deuteron, a well-known hadronic molecule, has a much larger size than normal hadrons)

Exotic hadrons in Heavy-Ion Collisions

Another aspect of exotic hadron physics is that it is related to the knowledge of the hadron-hadron potential. Exemples: implications of the existence of $\Lambda(1405)$ below the KN thershold on the study of the KN interaction, constraint on the existence of the S = –2 dibaryon (H) through the study of the $\Lambda\Lambda$ interaction

High-energy heavy-ion collisions could provide unique information on exotic hadron structure and hadron-hadron interactions: due to the abundant number of heavy quarks and antiquarks produced in these collisions various exotic hadrons could be formed

- The dynamic of high-energy collisions is so complex that statistical arguments become valid: "we may dare to say, heavy-ion collisions are simple and clean"
- The study of the interaction of exotic hadrons with the QGP in AA collisions (or with the hadronic environment in high-multiplicity pp and p-Pb collisions) is a powerful tool to study their structure
- In addition, via hadron-hadron correlation measurements, it is in priciple possible to constrain the conditions (shape of the potential) under which a given resonance state could exist **(see previous talks)**

Exotic hadrons in HIC: statistical or coalescence?

At RHIC and LHC, abundant hadrons are produced and their yield ratio is well described by the statistical hadronization model (SHM), which assumes thermal equilibrium at chemical freeze-out

- The yields of weakly-bound hadronic states such as the light nuclei, hypernuclei, and anti-nuclei, follow the statistical model predictions with temperature and chemical potentials that are fitted to the yields of the ground-state particles
- The available observations suggest that the final abundance of ground state hadrons and light nuclei are already determined near the energy density at which quarks and gluons hadronize

However, the statistical hadronization approach has its limits:

- Limited prediction power for resonance states with large widths, less produced that the SHM prediction, suggesting that hadronic interactions and freeze-out conditions are important in determining the final yields
- Depending on their quantum numbers, the yields of excited states can be either suppressed or enhanced relative to those predicted by the SHM

➡ **How would the statistical model work for exotic hadron production?**

Exotic hadrons in HIC: statistical or coalescence?

Coalescence favors hadrons whose shape in the phase space is similar to that of the source, then a large source size at moderate T tends to favor extended hadrons in a coalescence scenario

If the coalescence is the underlying mechanism of the statistical model, the coalescence approach would give better predictions of the hadron yields including resonances and exotic hadrons, and **we can exploit high-energy heavy-ion collisions as a ruler of the hadron size:**

- Increasing sizes of the QGP would translate into smaller and larger yields for compact multi-quark states and spatially extended hadronic molecules states, respectively

- When the parameters in the coalescence model are fit to the yields of the ground-state hadrons as predicted from the statistical model, the yield of a hadron is typically an order of magnitude **smaller** when it is a compact multiquark state than that of an excited hadronic state with normal quark numbers and/or a molecular configuration

Light Hadrons

Perturbative calculations are hard to perform for hadrons built of only light quarks, as one has to use relativistic QCD in its nonperturbative regime

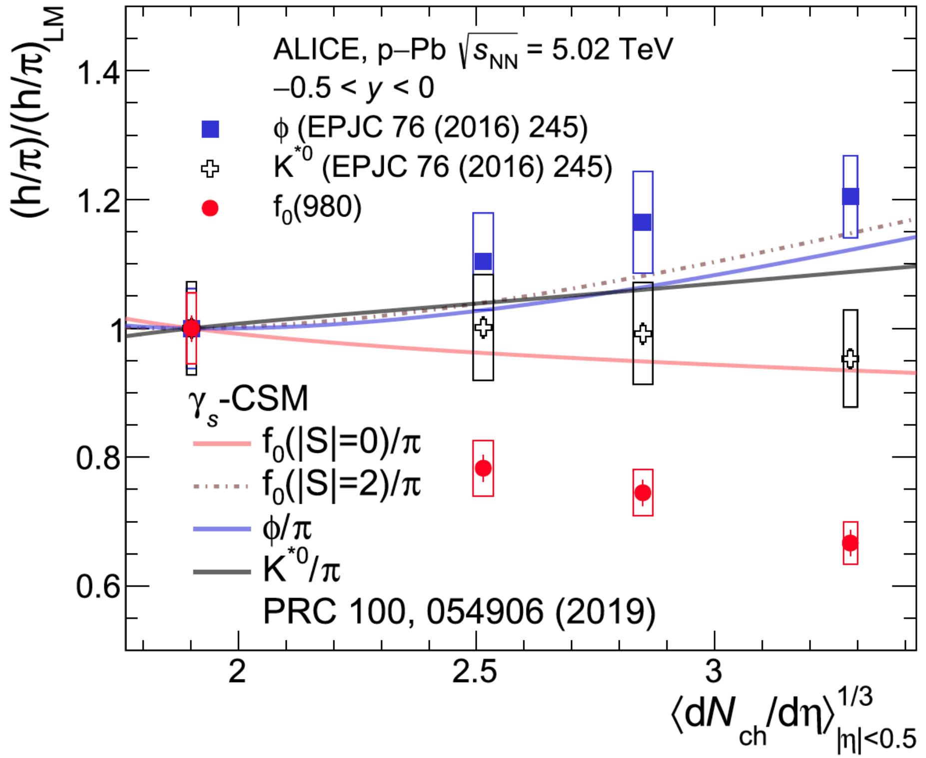
In particular, the $f_0(980)$ hadron, discovered 50 years ago has been hypothesized to be an ordinary qq meson, a tetraquark state, a KK molecule, or a qq-gluon hybrid state

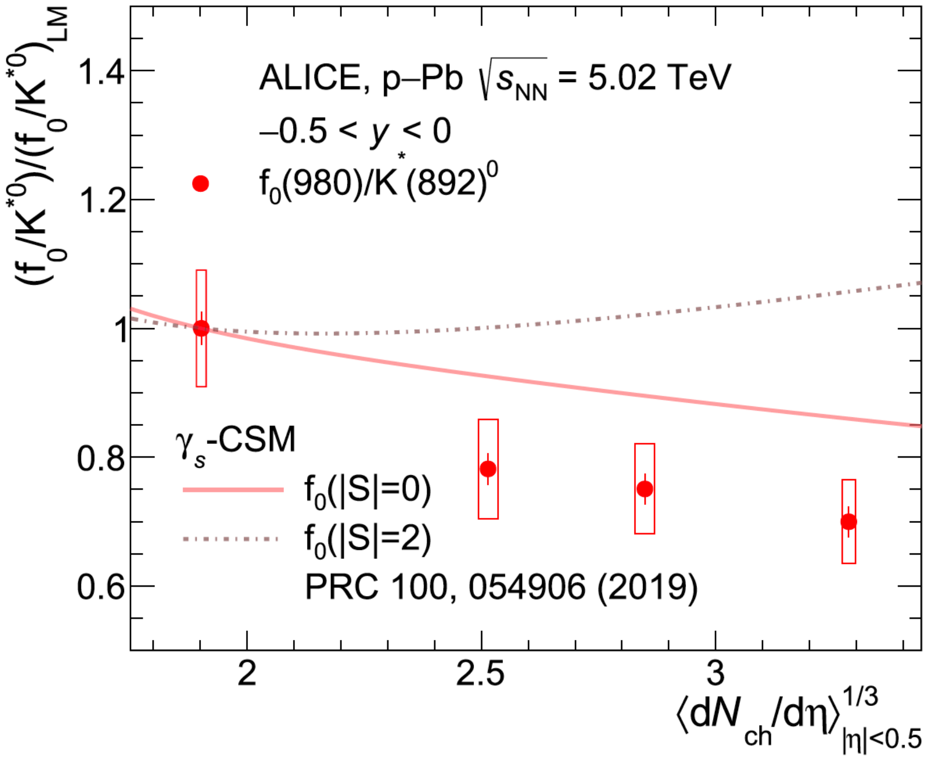
- The speculated tetraquark nature of the $f_0(980)$ hadron would have a significant impact on our understanding of QCD and color confinement
- Despite a multitude of experimental and theoretical work, the nature of the $f_0(980)$ state has not yet been established… **or maybe yes, in 2024 ☺**

Light Hadrons: $f_0(980)$

PLB 853 (2024) 138665

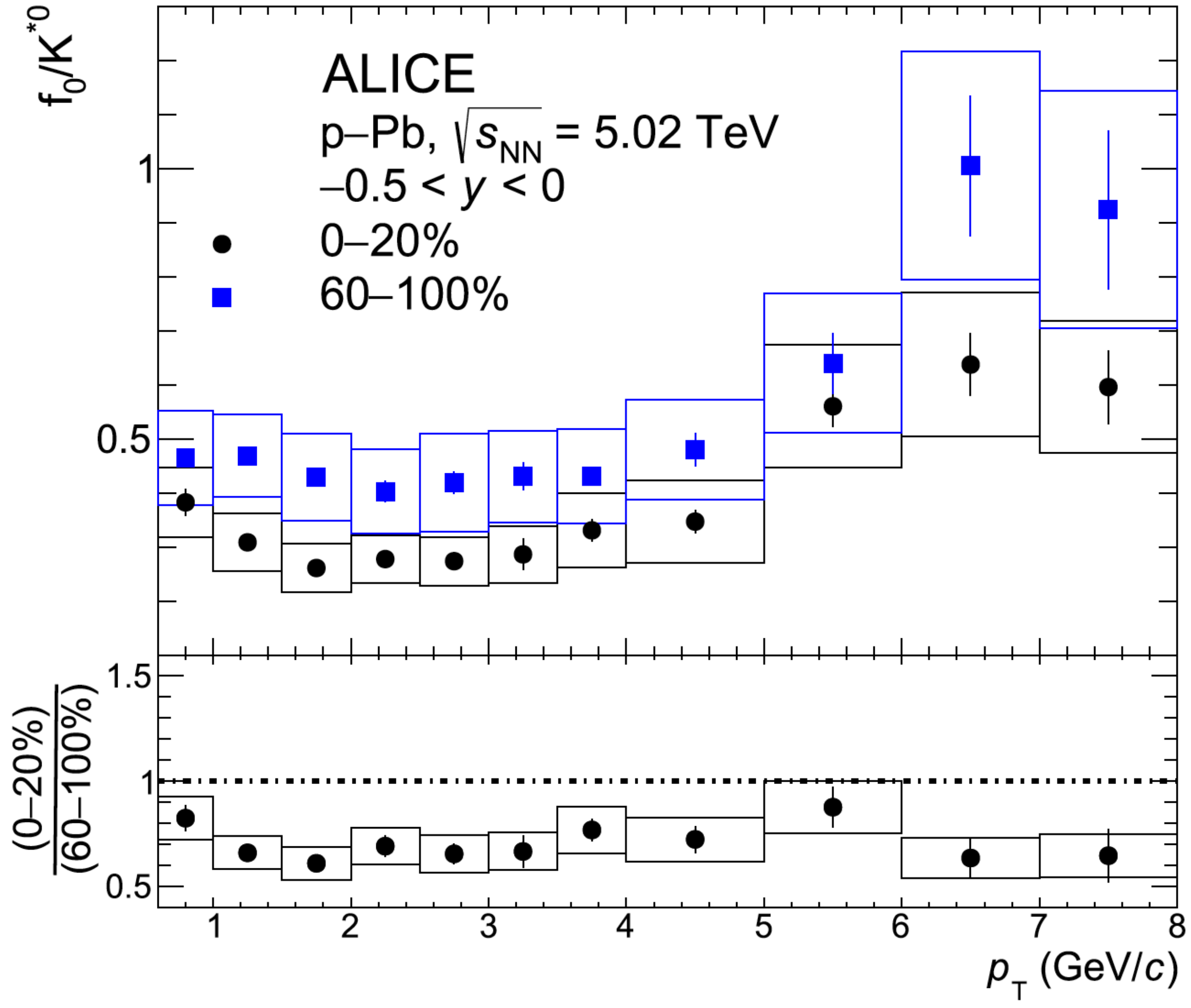
The measured double ratios of $f_0(980)$ over pions and kaons measured by ALICE shows a decreasing trend with increasing multiplicity, which is qualitatively described with the zero-hidden-strangeness assumption for $f_0(980)$ and can be explained by the strangeness enhancement of the $K^{*0}(892)$ yield





The measurement is at odds with the predictions of the canonical statistical model which predicts a mild increasing as the multiplicity increases under the assumption of two hidden strange quarks in the $f_0(980)$ composition

Light Hadrons: $f_0(980)$



- **The p_T-differential $f_0(980)/K^{*0}(892)$ ratio** does not exhibit the characteristic enhancement of baryon-to-meson ratios towards more central events, **suggesting a structure with two constituent quarks for the $f_0(980)$ resonance**
- **The abnormal suppression in terms of multiplicity and p_T relative to other particles** sheds light on the internal structure of $f_0(980)$ suggesting that it is a **conventional meson with no hidden strange quarks** and may provide insight into the properties of the late hadronic phase in p-Pb collisions

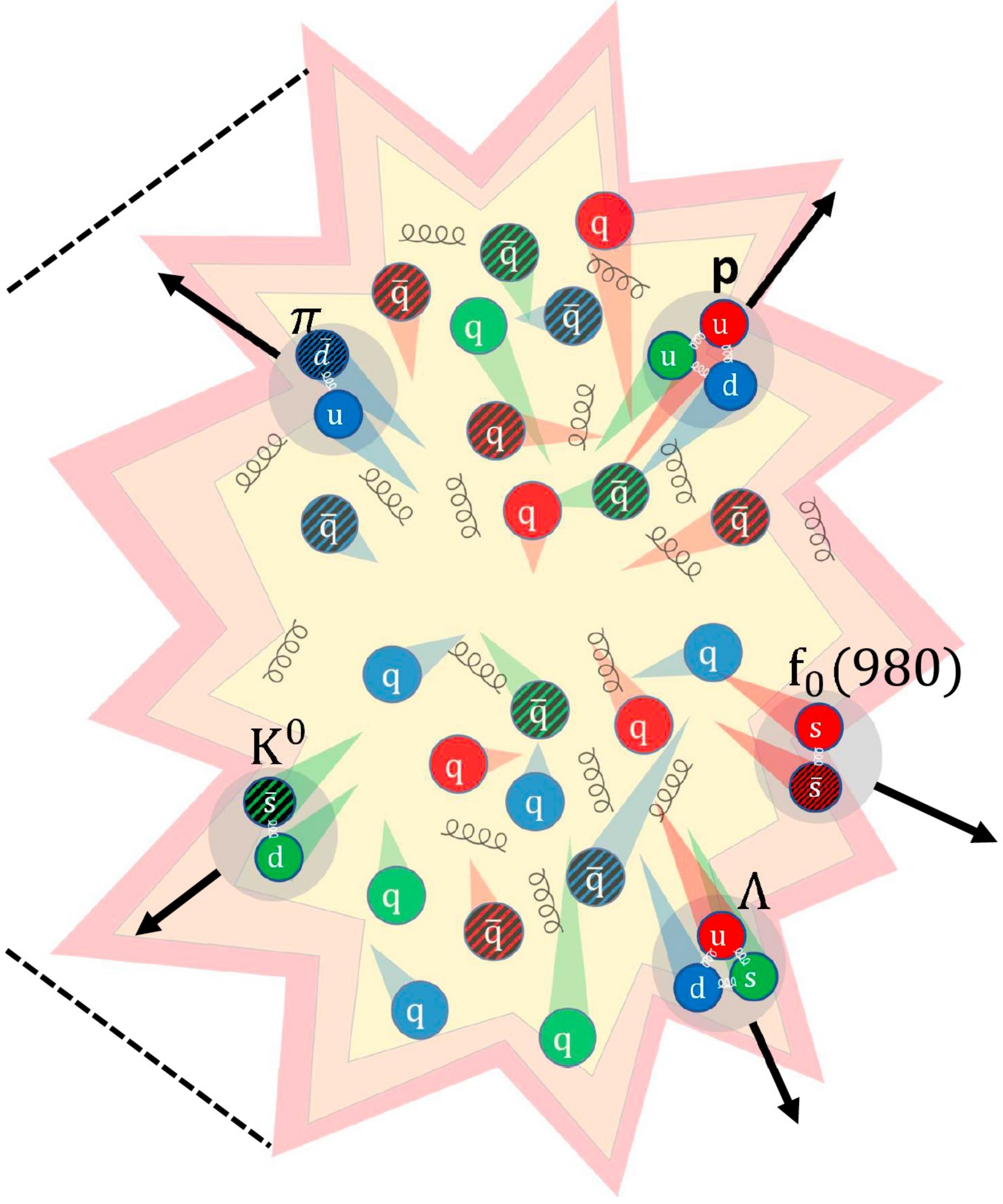
Azimuthal distributions of produced particles can be described by a Fourier series:

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi_n)]$$

- **In the coalescence picture,** quarks with close spatial positions and momenta are more likely to combine and, therefore, the anisotropic flow coefficients v_n of the formed hadron inherit those of the parent quarks ($v_{n,q}$)

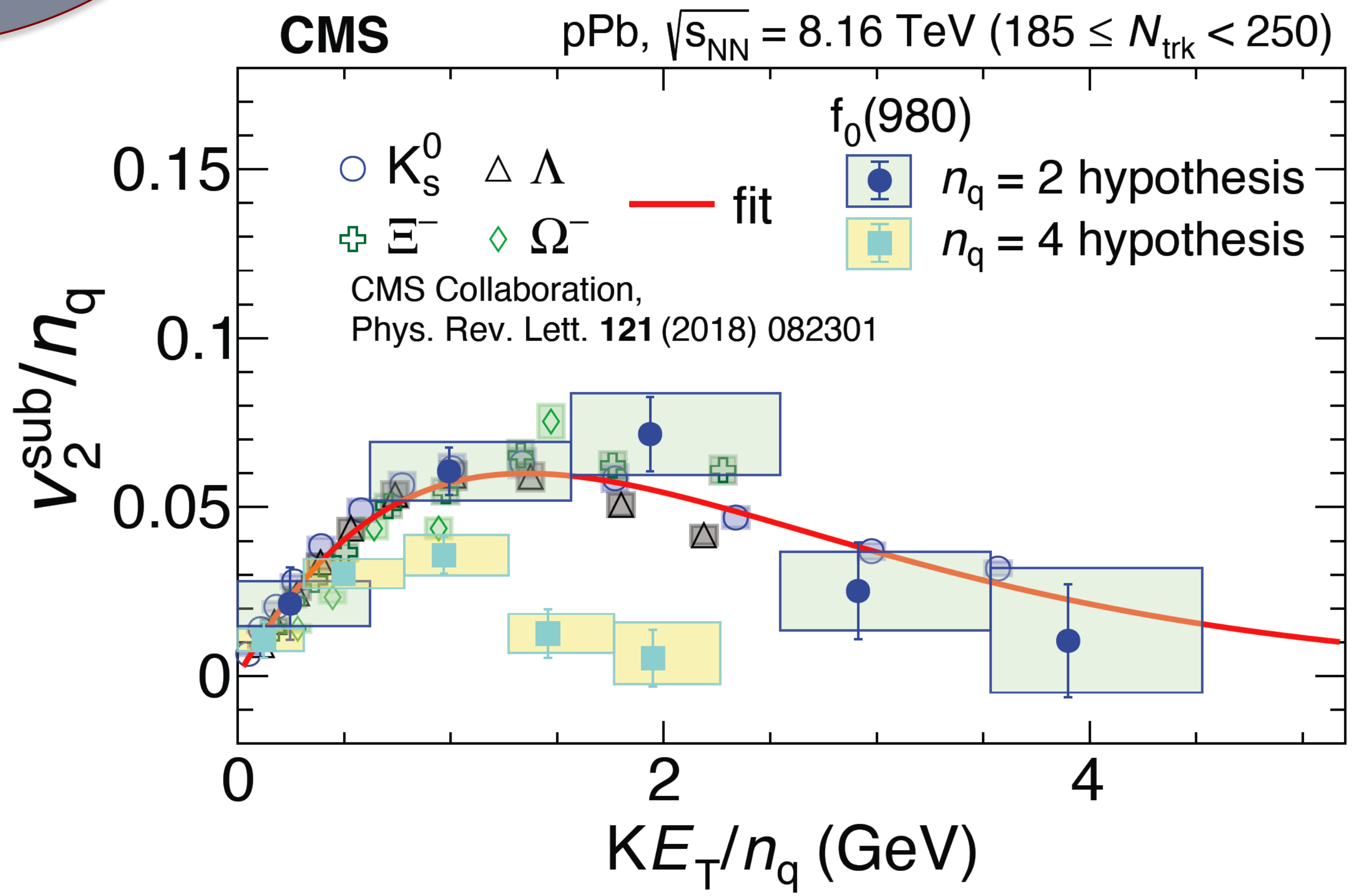
- **If n_q quarks with approximately equal momenta combine to form a hadron,** and for small values of the v_n of the formed hadron, the following p_T dependence approximately stands:

$$v_n(p_T) \approx n_q v_{n,q}(p_T/n_q)$$



Light Hadrons: $f_0(980)$

arXiv:2312.17092



$$v_n(p_T) \approx n_q v_{n,q}(p_T/n_q)$$

This expression is commonly referred to as the number of constituent quarks (NCQ) scaling of the anisotropic flow

The anisotropic flow of hadrons formed in heavy ion collisions can therefore reveal the number of constituent quarks n_q contained in a hadron, conventional or exotic

CMS data are found to disfavor a quark-antiquark-gluon hybrid state at 3.5 standard deviations.
The number of constituent quarks of the f0(980) state is consistent with the value of 2, characteristic of an ordinary meson: **strong evidence that the f0(980) hadron is a normal quark-antiquark state**

Heavy Hadrons

Above the open-charm threshold, tens of unexpected states with properties inconsistent with expectations from the traditional quark model have been observed since 2003

- The first hidden-charm state that triggered studies of the exotic states is the X(3872), also known as χ_{c1}(3872), observed by the Belle experiment in 2003
- Besides the X(3872), the Z_c(4430) and Z_b(10610/10650), which are the first charged charmonium-like and bottomonium-like states with obvious exotic characteristics, were also observed by Belle
- The first vector charmonium-like state Y (4260) and pentaquark states Pc(4450) and Pc(4380) were observed by BaBar and LHCb experiments respectively

- **Owing to the significant numbers of charm and bottom quarks produced at the TeV scale**, some of the proposed heavy exotic hadrons **can be produced in heavy-ion collisions at the LHC** with sufficient abundance for detection, making it possible to study these new exotic hadrons in the QGP

Heavy Hadrons

- **A specific difficulty in the production of a T_{QQ} state in ee collisions** is that two heavy-quark pairs produced in hard scatterings must rearrange into diquarks before reaching the tetraquark configuration, which makes it a much rarer event than the production of hadrons with $Q\overline{Q}$ content
  - Despite these difficulties, the recent estimates for the production cross sections of T_{bb} and T_{bc} tetraquarks based on Monte Carlo event generators point towards an **excellent discovery potential in ongoing and forthcoming proton-proton collisions at the LHC**

- An alternative that circumvents those rare rearrangement processes is the **production of multi-quark states by coalescence in the QGP environment** produced in heavy-ion collisions at ultrarelativistic energies, since the number of heavy quarks available for producing such structures is appreciable

- Production of exotic hadrons in the QGP also offers **new tools in the quest to understanding their structure and the properties of the QCD potential and the QGP itself**, exploiting the interaction of such hadrons with the deconfined medium (dissociation, recombination, flow…)

Heavy Hadrons

Studying the production of exotic hadrons in the medium also allows one to address the important question of how a partial restoration of chiral symmetry affects the coalescence process

- Since the coalescence happens at nonzero temperature, at which the coalescing (light) constituent quarks have properties different from those in vacuum, the tetraquark wave function is expected to be modified

- In the context of exotic hadron production in the QGP, this issue becomes particularly relevant for the stability of the produced tetraquark against two-hadron decays, as not only the tetraquark mass is changed from its vacuum value, but the threshold energy, which is given by the sum of the masses of two hadrons, is also modified

- The in-medium stability of a heavy exotic hadron is of central importance for assessing the effects of its interactions with other particles during the expansion of the system before kinetic freeze-out

Heavy Hadrons: T_{cc} and T_{bb}

PRD 99, 094037 (2019)

TABLE II. Number of b and c quarks per unit rapidity at midrapidity in 0%–10% central collision at RHIC and LHC taken from Ref. [29]. In the last two columns, under Extrapolation, we give the estimates for N_b and N_c at higher energies, obtained from a linear extrapolation of the data at the three lower energies.

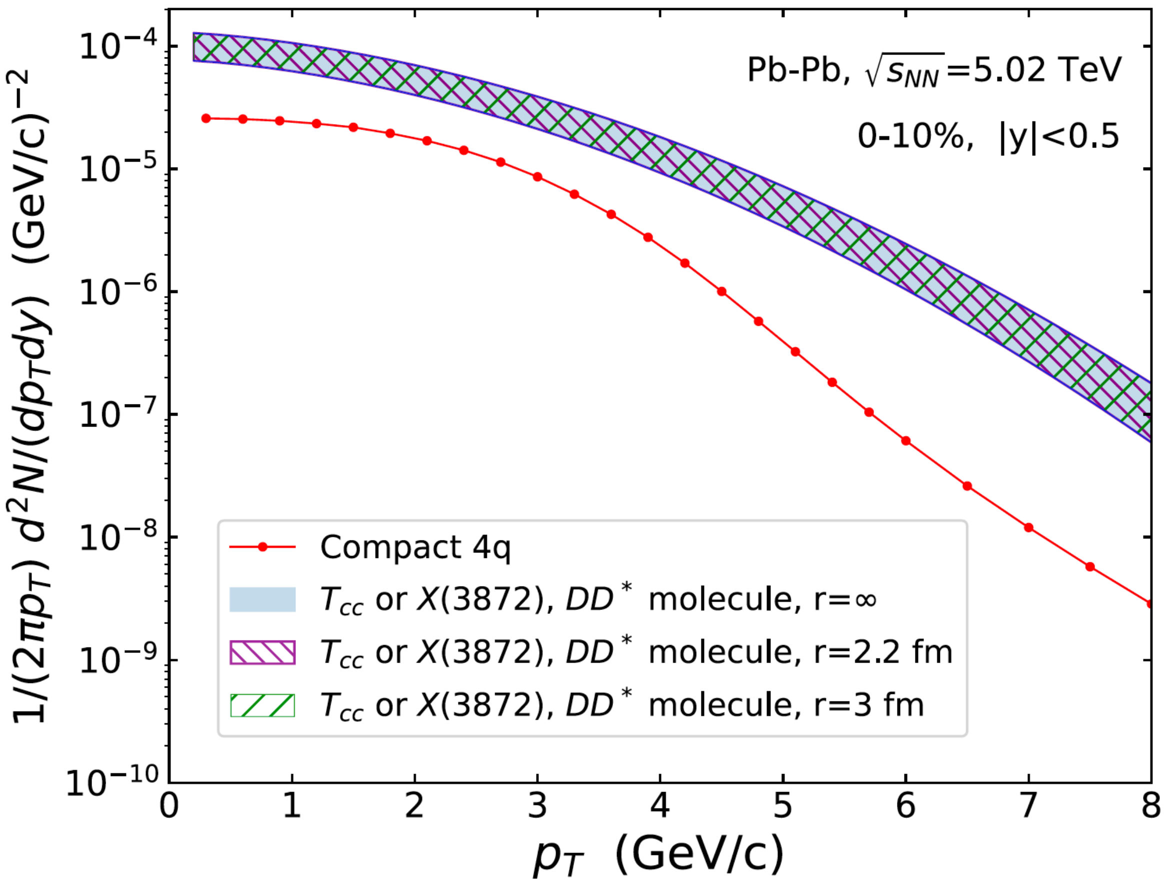
	RHIC	LHC		Extrapolation	
	0.2 TeV	2.76 TeV	5.02 TeV	10 TeV	15 TeV
N_b	0.031	0.44	0.71	1.43	2.14
N_c	4.1	11	14	25	35

TABLE III. Tetraquark yields for central Pb + Pb collisions at LHC energies $\sqrt{s_{NN}} = 2.76$ TeV and $\sqrt{s_{NN}} = 5.02$ TeV. Results in the two columns under Extrapolation are the estimates at higher energies, using for N_b and N_c the corresponding values shown in Table II. The temperature used in the Boltzmann distribution and for the chiral symmetry restoration effects is $T = 156$ MeV.

	LHC		Extrapolation	
	2.76 TeV	5.02 TeV	10 TeV	15 TeV
	No chiral restoration			
$N_{T_{bb}}$	6.2×10^{-9}	1.6×10^{-8}	6.6×10^{-8}	1.5×10^{-7}
$N_{T_{cc}}$	2.4×10^{-5}	3.8×10^{-5}	1.2×10^{-4}	2.4×10^{-4}
	Chiral restoration			
$N_{T_{bb}}$	1.3×10^{-8}	3.4×10^{-8}	1.4×10^{-7}	3.1×10^{-7}
$N_{T_{cc}}$	4.0×10^{-5}	6.5×10^{-5}	2.1×10^{-4}	4.1×10^{-4}

T_{bb} expected to be a compact tetraquark, sensitive to a (partial) restoration of the chiral symmetry in the medium making it more stable and less likely to be destroyed by subsequent interactions with other hadrons → **measurable effect,** resulting in an increase in the production yields by a factor roughly equal to 2

Heavy Hadrons: T_{cc}



Approach: SHMc for D yields, coalescence to describe the formation of molecular or tetraquark configurations of T_{cc}

Expected p_T distributions for the two possible configurations of the T_{cc} significantly different in addition to the difference in the total yields → **possibility to discriminate its structure**

The model does not include possible spatial and momentum correlations of charmed mesons at the kinetic freeze-out point, in the molecular scenario

- **Compact multiquark configuration of Tcc:** coalescence model gives smaller yields than SHMc
- **Molecular configuration:** the coalescence model results (the same for X(3872) and T_{cc}) appreciably larger than those from SHMc

Heavy Hadrons: X(3872)

Various phenomenological approaches available to estimate the yield of the X(3872): statistical hadronization, coalescence, transport+coalescence. Most models based on the coalescence approach do not include the evolution effect in medium, and the statistical hadronization approach only depends the masses of hadrons, not on their internal structures

Further information to deepen the understanding of the inner structure is provided by the study of the differential yields vs centrality, rapidity and transverse momentum, as well as the elliptic flow

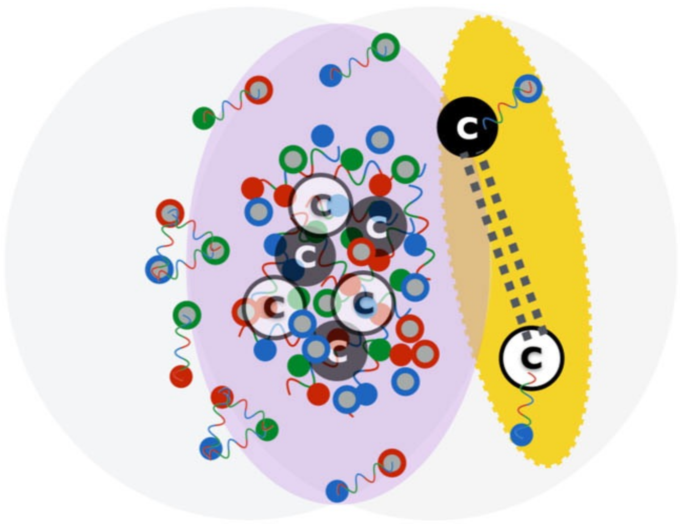
Selected recent references:

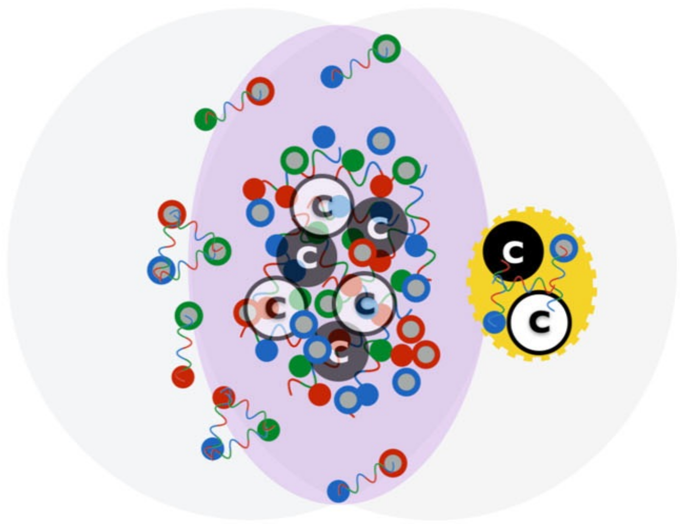
- **PRL 126, 012301 (2021)** “Deciphering the Nature of X(3872) in Heavy Ion Collisions”
- **PRC 105, 054901 (2022)** “X(3872) production in relativistic heavy-ion collisions”
- **EPJ A 57:122 (2021)** “X(3872)transport in heavy-ion collisions”
- **PRC 110, L021901 (2024)** “Medium-assisted enhancement of χ_{c1}(3872) production from small to large colliding systems”

 PRL 126, 012301 (2021)

Approach based on the AMPT model: fluctuating initial conditions, partonic scatterings modeled by parton cascade, hadronization by using coalescence, and subsequent hadronic rescattering. $c\bar{c}$ cross section calibrated by comparison with experimental data on D meson production

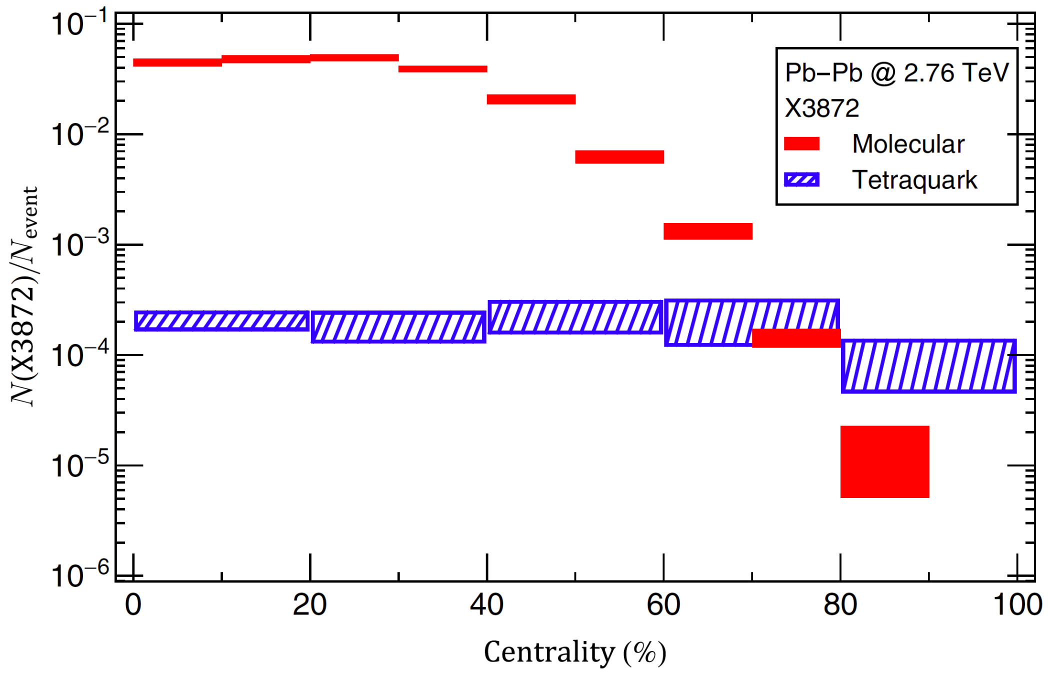
- **Tetraquark scenario:** X(3872) formed via two steps at freeze-out: (i) First diquarks and antidiquarks are created via partonic coalescence, by matching a c or $\bar{c}$ with the nearest light quark or antiquark; (ii) Then diquarks and antidiquarks form X(3872) via coalescence by matching the following quantitative constraints: relative distance < 1 fm and pair mass between the upper and lower mass limits of the heavy quark spin partners of the X(3872)

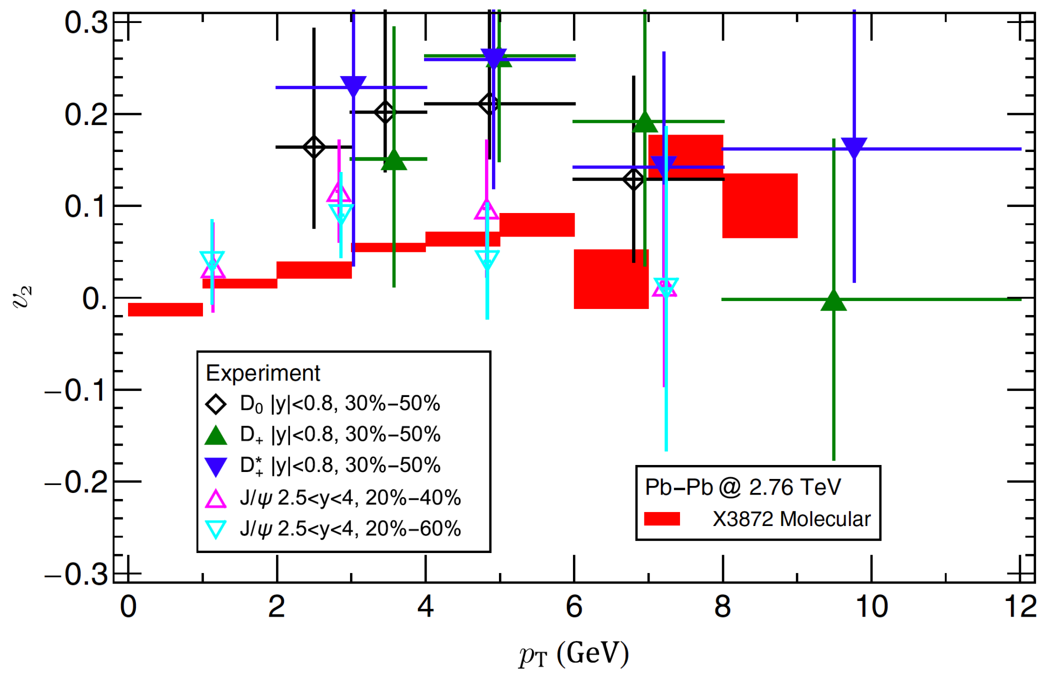




- **Molecule scenario:** X(3872) formed by the color neutral force, as analogy of deuteron, by coalescence of two charmed mesons with constraints:
  - 5 fm < relative distance < 7 fm
  - $2M_D$ < pair mass < $2M_{D*}$

PRL 126, 012301 (2021)





- **Significant difference in the expected X(3872) inclusive yields for the two scenarios**
- **Meaningful insight on the size of X(3872) in the molecular scenario formed via coalescing two D mesons:**
  - Small molecular size: the two constituents would be from nearby fluid cells with their flow effect added coherently into the X(3872), in a way similar to the well-known constituent quark scaling
  - Large molecular size: the constituent scaling would break down for X(3872), with the two D mesons originating from remote patches of the fluid (scenario preferred by the calculations)

 PRC 105, 054901 (2022)

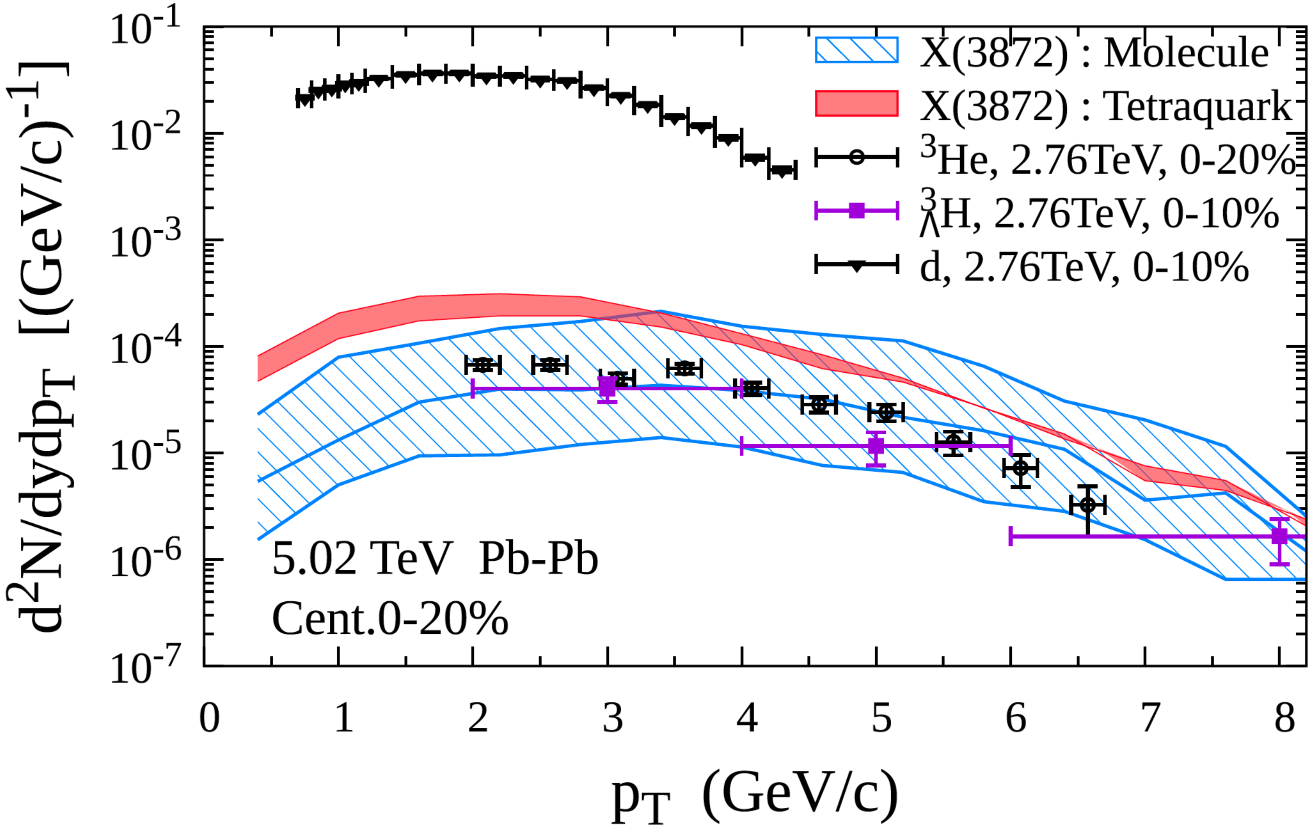
Approach: (1) Langevin equation to simulate Brownian motion of charm quarks in QGP and D mesons in a hadronic medium, (2) combination of heavy and light quarks to form D mesons, charmonia, tetraquarks in the QGP, (3) combination of D mesons to form hadronic molecules in a hadronic medium. The formation processes are described with the instantaneous coalescence model (ICM)

- **Time and spatial dependence of the temperatures and velocities of the hot medium characterized via a hydrodynamic model with the MUSIC package.** EoS: interpolation between lattice EoS for the deconfined phase and the hadron resonance gas EoS for the hadron phase, the two phases connected with a crossover phase transition
- The final production yield mainly depends on two factors: **the charm quark spatial and momentum distributions in the medium, and the size of the formed particle.** Due to the significant difference between the geometric sizes of a compact tetraquark (mean radius ≈ 0.3 - 0.5 fm) and a loosely bound hadronic molecule (mean radius ≈ 2.5 - 22 fm), their production is expected to become distinguishable in the two scenarios

Tetraquark scenario: a charm quark combines with a light quark to form a diquark, then the diquark and an antidiquark combine to form a tetraquark at the coalescence temperature (close to the J/ψ one due to the similar size). As light quarks are abundant in QGP, tetraquark production is mainly determined by the density of charm pairs and size of the tetraquark state. Most primordially produced tetraquarks may melt in QGP

Molecular scenario: D mesons form at the QCD phase boundary, then diffuse in the hadronic phase. Due to the low binding energy of the molecular state, the molecular X(3872) state cannot survive in the hadronic medium above the temperature T_{kin} of the kinetic freeze-out

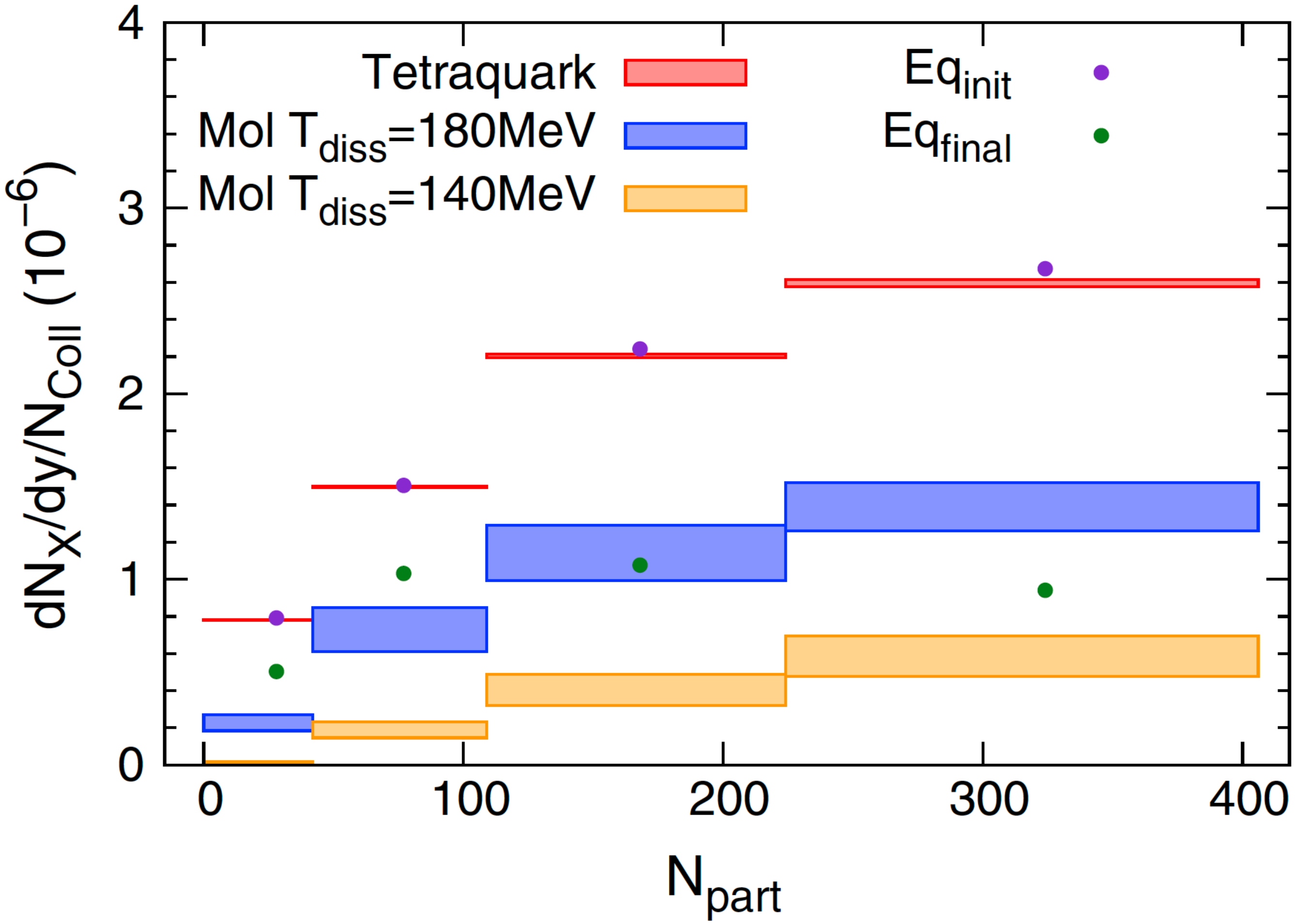
Yield for the molecular state depends on the size (3.0, 5.5, 9.0 fm in the plot). Low p_T best discriminates between the two scenarios



Heavy Hadrons: X(3872)

EPJ A 57:122 (2021)

Approach: transport calculations of the X(3872) through the fireball formed in nuclear collisions, based on a kinetic-rate equation previously used for charmonium

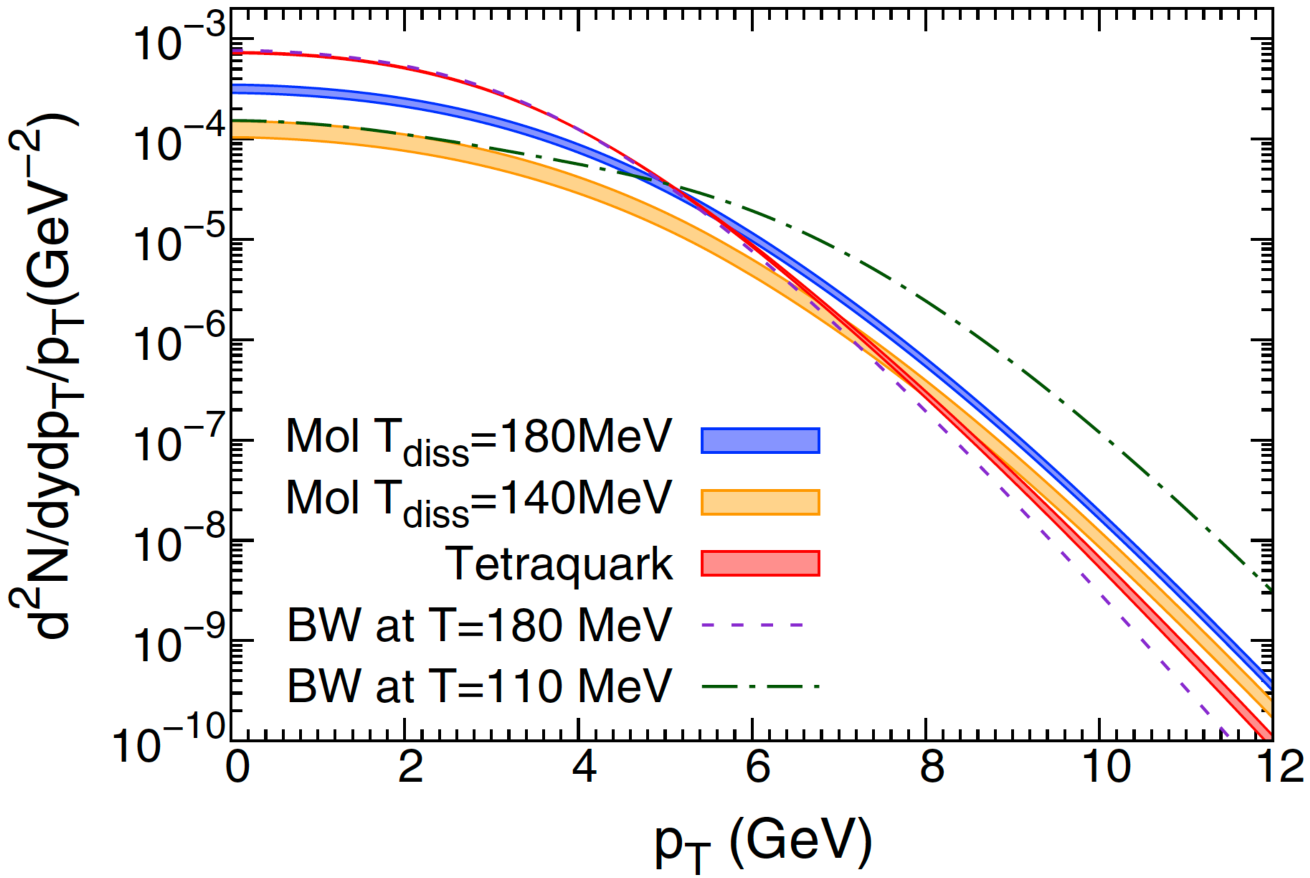


The formation and dissociation of the X(3872) is controlled by two transport parameters, i.e., its inelastic reaction rate and thermal-equilibrium limit in the evolving hot QCD medium

- **Production yields show a significant rise with increasing centrality**
- **Ratio of tetraquark over molecule scenarios of about 2** (factor 4 for peripheral collisions), significantly less than the 2 orders of magnitude predicted by coalescence models

 EPJ A 57:122 (2021)

The formation of a molecular X(3872) is due to a large but finite reaction rate in the hadronic phase, driving the abundance toward the equilibrium limit. For the tetraquark configuration, the main production occurs at an earlier stage, i.e., in the sQGP close to the "transition" temperature

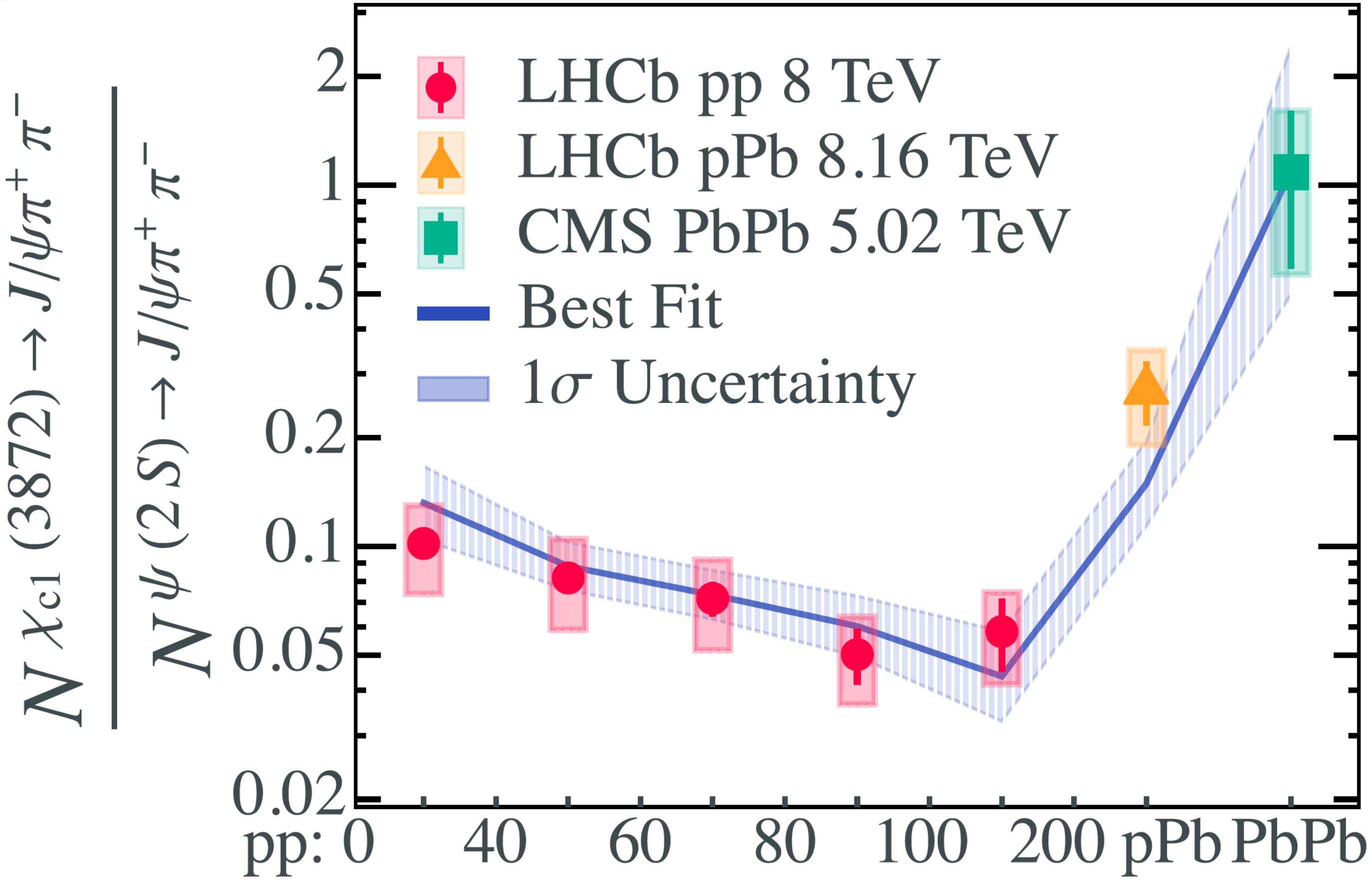


p_T spectra are found to provide additional constraints on the production time in the fireball evolution

Harder spectra expected for the molecular scenario because of the later production: **the later decoupling time leads to harder spectra caused by the blue-shift inherited from the expanding fireball**

Heavy Hadrons: X(3872)

PRC 110, L021901 (2024)



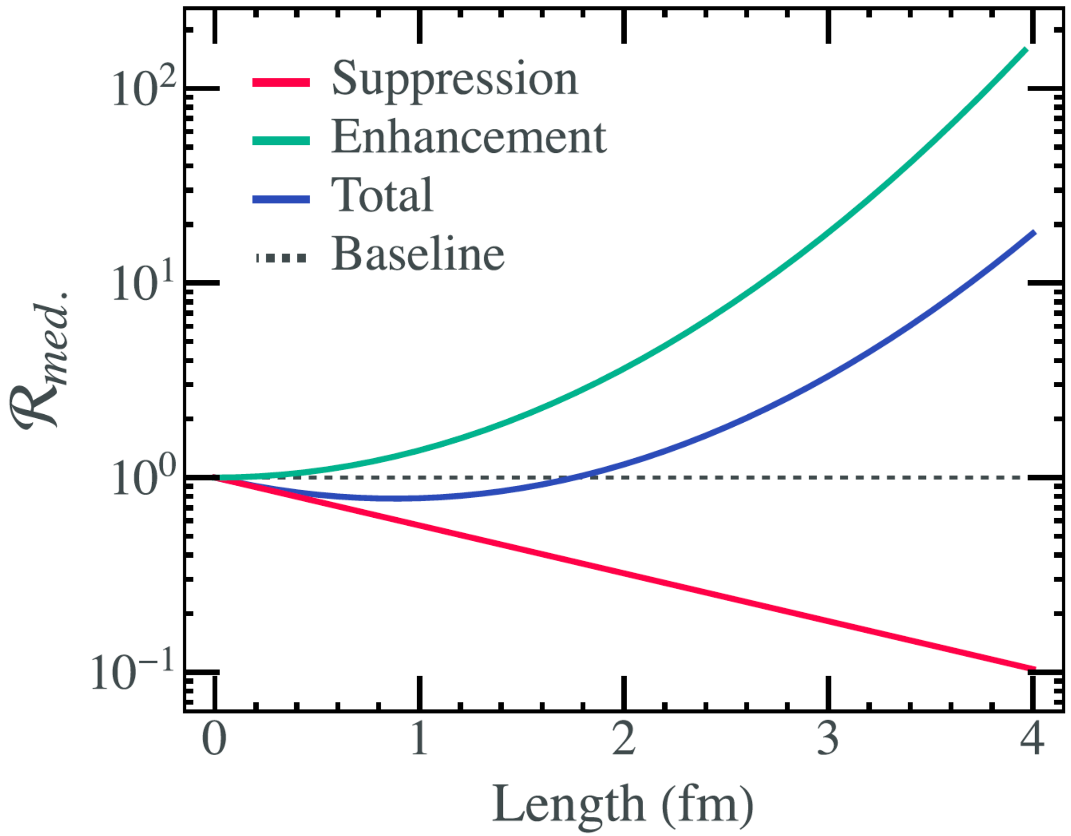
- **LHC data:** intriguing evolution pattern of the X(3872)-to-ψ(2S) yield ratio (same decay channel, similar masses) from pp collisions with increasing multiplicities toward p-Pb and Pb-Pb collisions

- **Model:** absorption-induced suppression in pp collisions followed by a medium-assisted enhancement for the X(3872) production, resulting in a non-monotonic trend from small to large colliding systems

Realistic simulations based on the competition between enhancement and suppression offer a quantitative description of all available data

PRC 110, L021901 (2024)

In the high p_T region where recent CMS and LHCb measurements were made, the production of ψ(2S) and X(3872) should dominantly come from virtual $c\bar{c}$ pairs generated in the initial hard scatterings. **These pairs will travel through the partonic medium before producing those final hadrons**



First effect: medium absorption. Random collisions with quarks and gluons from the medium result in the dissociation of the correlated comoving $c\bar{c}$ pairs, also responsible of charmonium suppression observations. **Linear dependence with the medium parton density and the path length**

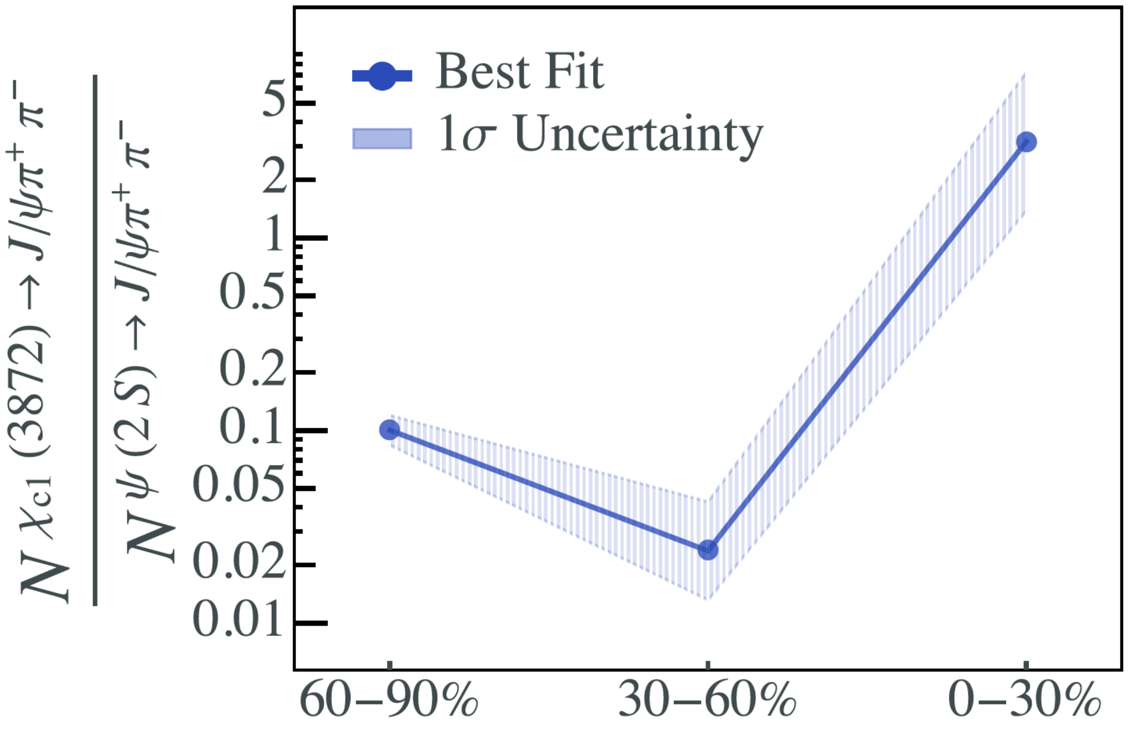
Second effect: the "picking up" of light quarks (antiquarks) through scatterings of the $c\bar{c}$ pairs with the partonic medium, which serves as a reservoir of light flavors. The light quarks (antiquarks) then comove with the $c\bar{c}$ pairs, enhancing the production of X(3872). **Quadratic dependence with the parton density and path length**

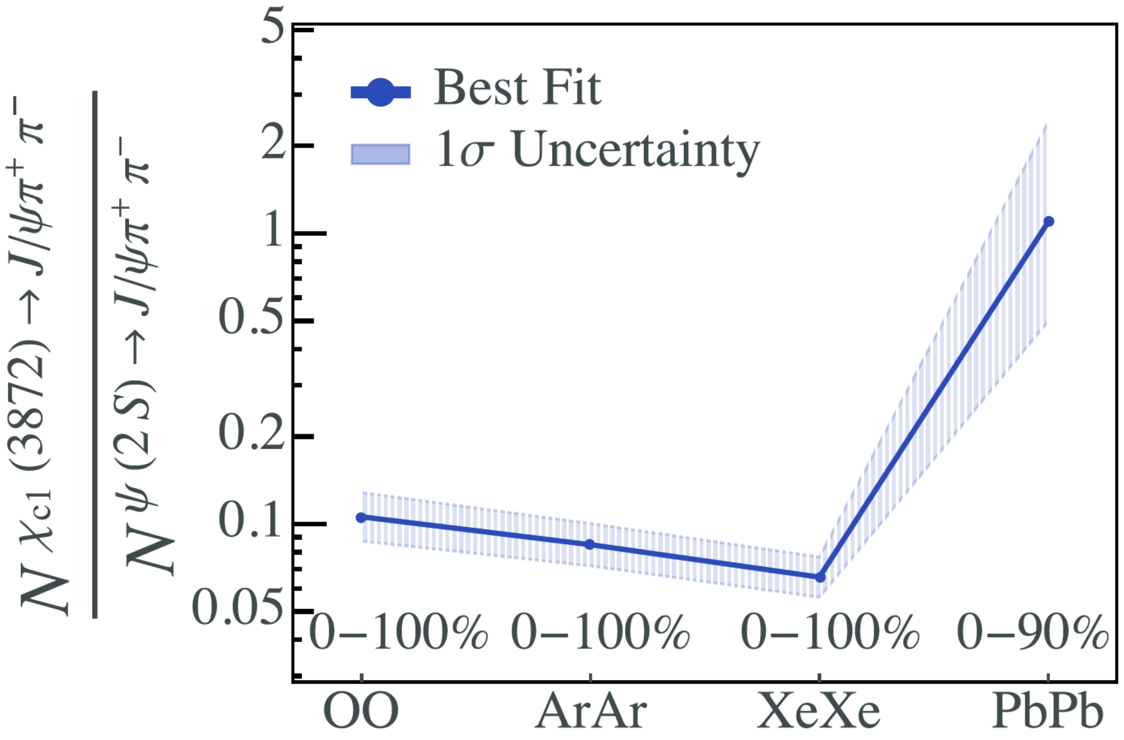
Heavy Hadrons: X(3872)

PRC 110, L021901 (2024)

- **For relatively low medium density and/or small medium size,** the linear term will dominate and therefore the overall medium effect would be a suppression of X(3872) relative to ψ(2S)

- **For relatively high medium density and large medium size,** the quadratic term will dominate and therefore the overall medium effect would be an enhancement of X(3872) relative to ψ(2S)





Conclusions

- **The study of the existence and the nature of "exotic" states is a very active and challenging field in hadron physics**, which aims at answering fundamental questions about how quarks arrange themselves in bound states

- **Heavy-ion collisions provide the only available tool to study the formation and interaction of exotic hadronic states inside a medium filled with deconfined color charges**, putting new constraints on the properties of the states, the characterization of their binding potential, and the details of their hadronization mechanisms

- **Implications of the existence of multi-quark states on the structure of the QCD phase diagram**

- **Recent evidence of the relevance of observations in heavy-ions:**
  - In the light-flavor sector, strong constraints on the nature of f0(980), probably the end of a 50 year puzzle
  - In the heavy-flavor sector, characterization of the interaction of X(3872) inside a hadronic medium

Backup Slides

Exotic hadrons in HIC: statistical or coalescence?

Various coalescence models and the statistical hadronization model (SHM) were used to estimate the yields of the X(3872) in the hadronic molecular and compact tetraquark pictures

- **The coalescence model** depends on a suitable wave function in coordinate space to encode the structure information, but relies on several unclear parameters, for instance the volume size at which coalescence occurs and the available light quark number at the hadronization temperature

- **The SHM** assumes that hadrons are in a thermal and chemical equilibrium, and the predicted yields only depend on its mass but not on its internal structure