Exotic Hadrons in Heavy Ion Collisions

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Aim

- A very brief overview on the state-of-art of exotic states
- The exotics in HICs?
- Molecular, tetraquark and triangle singularities interpretations in HICs?

Summary of some of our recent results (several strategies):

- Final yields [$T_{cc}(3985)^{+}, Z_{cs}(3985)^{-}, \chi_{c1}(4274), R = \frac{N_{X(3872)}}{N_{\psi(2S)}}$...]
- Challenge: femtoscopy [$D_1(2420), D_1(2430), B\bar{B}$]
- Three-body dynamics ($K^*(4307), D^*_{1s}(2860), X(2890), \phi(2170), \ldots$
- Efimov states [$\Lambda nn, \ldots$]
- Ultrapheripherical collisions [$D\bar{D}, B\bar{B}, \ldots$]

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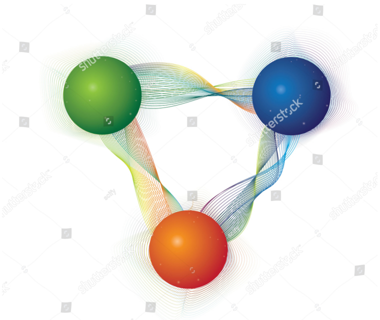
Hundreds of observed conventional hadrons

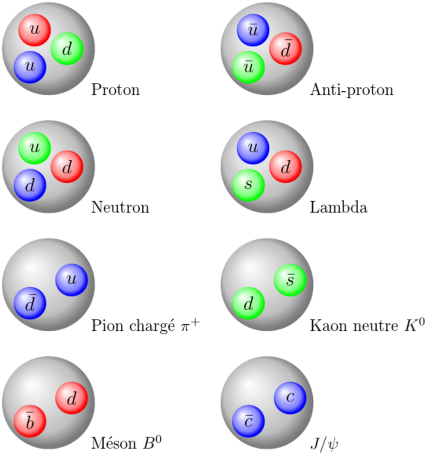
Gell-Mann (1964), ...

BARYONS: qqq $(3 \otimes 3 \otimes 3 = 1 \oplus \cdots)$

MESONS: $q\bar{q}$ $(3 \otimes \overline{3} = 1 \oplus \cdots)$

Properties $\Rightarrow$ QCD-like quark models





Unconventional Hadrons?

Question

Is it possible an unconventional hadronic structure?

QCD does not forbid more complicated combinations!!!

$$
\begin{aligned}
\text{Tetraquarks} &\Rightarrow q q \bar{q} \bar{q}\ (3 \otimes 3 \otimes \bar{3} \otimes \bar{3} = 1 \oplus \cdots) \\
\text{Pentaquarks} &\Rightarrow q q q q \bar{q}\ (3 \otimes 3 \otimes 3 \otimes 3 \otimes \bar{3} = 1 \oplus \cdots) \\
\text{Glueballs} &\Rightarrow g g \cdots g\ (8 \otimes 8 \cdots \otimes 8 = 1 \oplus \cdots) \\
\text{Hybrids} &\Rightarrow q \bar{q} g\ (3 \otimes \bar{3} \otimes 8 = 1 \oplus \cdots)
\end{aligned}
$$

If exist: new objects to study confinement mechanism;
If not exist: theory should explain why not!!!

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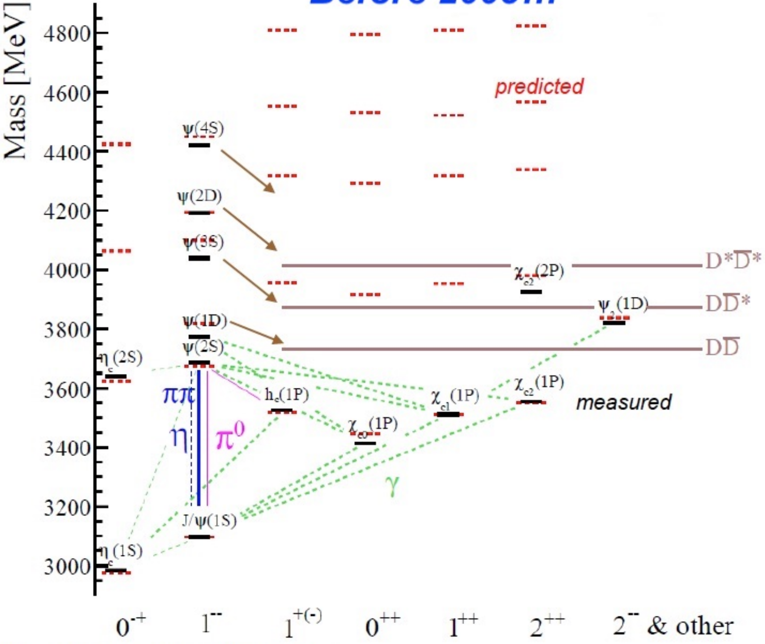
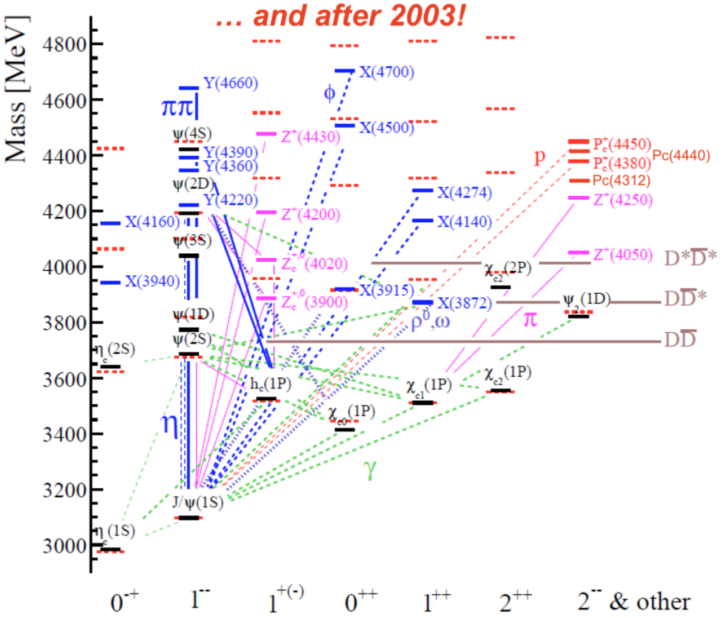
Before 2003...



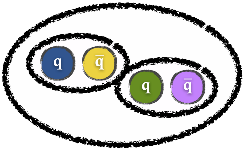
Figures from Olsen,Skwarnicki,Zieminska



(Adapted from Skwarnicki, 2018)

Intepretations for composition and binding mechanisms?

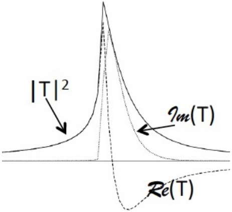
- Hadron Molecules



- Tetraquarks

- Hybrids

- Kinematical effects (TS's)



- Glueballs

- . . .

Example of the debate on prompt production of $X(3872)$

Esposito et al., EPJC (2021); 2006.15044

- Comover interaction model:

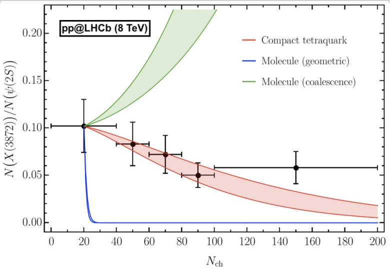
$$\tau \frac{N_{\mathcal{Q}}}{d\tau} = -\langle v\sigma \rangle_{\mathcal{Q}} \rho_c N_{\mathcal{Q}};$$

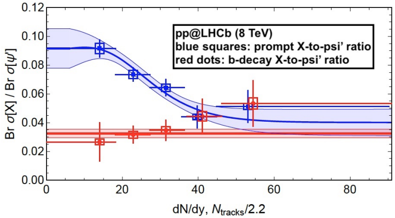
$$\langle v\sigma \rangle_{4q} \sim \pi r_{4q}^2 \simeq 11.6\,\mathrm{mb};$$
$$\langle v\sigma \rangle_{Mol} \sim \pi r_{Mol}^2 \simeq 1197\,\mathrm{mb}$$

- Data $\Rightarrow$ tetraquark nature

Braaten et al., PRD (2021); 2012.13499

- $\langle v\sigma \rangle_{Mol}$: probability-weighted sum of $\langle v\sigma \rangle(\pi D^{(*)})$
- non-relativistic XEFT
- Assumption: $f_{out,\mathcal{Q}}^{(prompt)}$ out of reach of comoving pions
- Data $\Rightarrow$ molecular picture





Theoretical perspective

A compelling and unified understanding has not yet emerged

- No single theoretical framework explains the exotics collection
- Candidates: different interpretations (hadron molecule, diquark-antidiquark, kinematic effects, ...)
- (m, Γ) can be explained by different models or even superposition of them

- Necessity of more observables to distinguish their internal structure

- Let us focus on a promising scenario

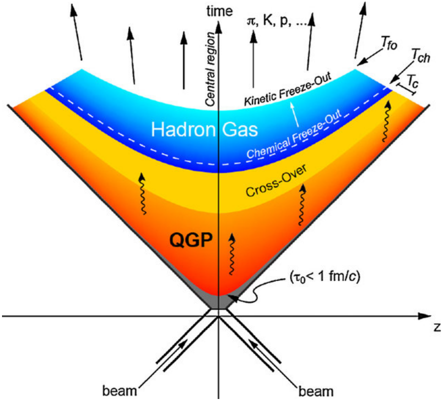
Promising alternative: exotics in HICs

Early stages of HIC's

- Large number of Q's produced
- Q's coalesce to form multiquarks

Hadron gas phase

- Multiquarks: interact with other hadrons
- Absorption / production
- Ex. $X\pi \to D^{(*)}\bar{D}^{(*)}$ or $D^{(*)}\bar{D}^{(*)} \to X\pi$
- Properties → interpretation



(Braun-Munzinger and Donigus, Nucl. Phys. A 987 (2019) 144)

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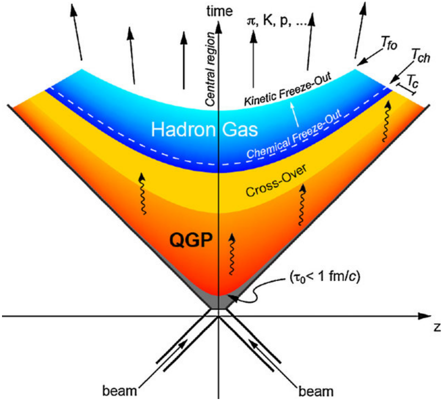


(Braun-Munzinger and Donigus, Nucl. Phys. A 987 (2019) 144)

First evidence for $X(3872)$ in HICs

CMS-LHC, Phys. Rev. Lett. 128 (2022) 032001

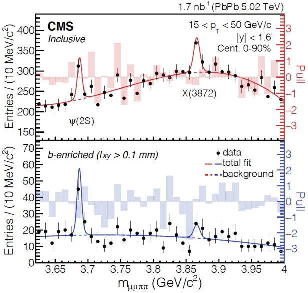
- Prompt $X(3872)$-production in *PbPb* collisions, $\sqrt{s} = 5.02$ TeV

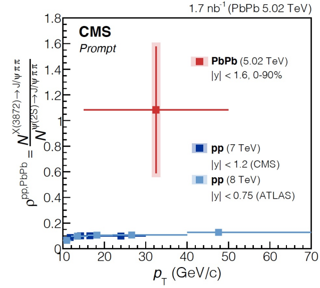
$$\begin{aligned} X(3872) &\rightarrow J/\psi \pi^+ \pi^- \\ &\rightarrow \mu^+ \mu^- \pi^+ \pi^- \end{aligned}$$

- $\rho^{(PbPb)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} = 1.08 \pm 0.9 \pm 0.52$

$\rho^{(PbPb)} \simeq 10\, \rho^{(pp)}$

Unique experimental input to investigate the properties and nature of multiquark systems





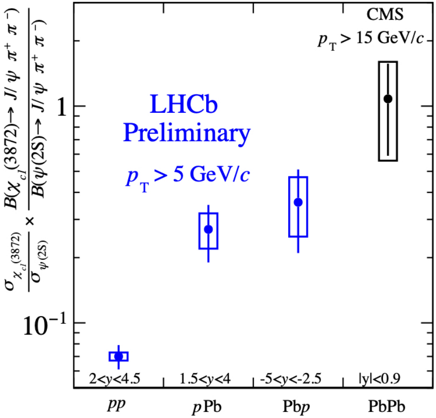
First measurement of $X(3872)$ in pPb collisions!

LHCb-LHC, LHCb-CONF-2022-001 (2022)

- Prompt $X(3872)$-production in pPb (Pbp) collisions, $\sqrt{s} = 8.16$ TeV

$$X(3872) \rightarrow J/\psi\pi^+\pi^- \rightarrow \mu^+\mu^-\pi^+\pi^-$$

- $\rho^{(PbPb)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} = 0.27 \pm 0.08 \pm 0.05$



- $X(3872)$: different dynamics in the medium!!
- Higher hadronic densities → quark coalescence as the dominant mechanism?!

Strategy 1 - Multiplicity, size dependence, ... in HICs

Hadronic Interactions $\Rightarrow$ Effective Lagrangians

$\Downarrow$

Amplitudes $\Rightarrow$ Cross Sections $\Rightarrow$ Therm. Av. Cross Sections

$\Downarrow$

Coalescence Model, Bjorken picture $\Rightarrow$ Kinetic (rate) equation

$\Downarrow$

Time Evolution and size dependence of $N_{T_{cc}}, N_X$

$\Downarrow$

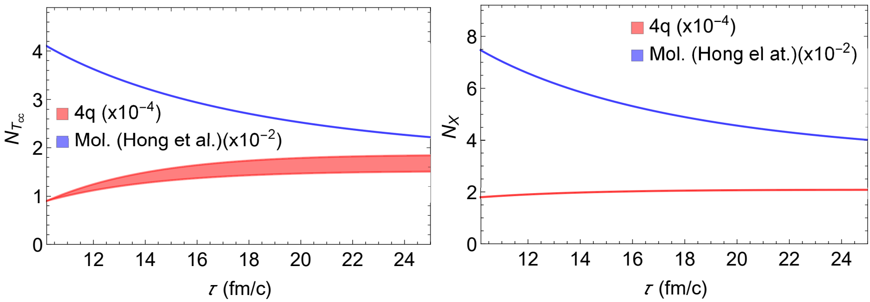
Diff. spatial configuration $\Rightarrow$ diff. hadronic interactions $\Rightarrow$ diff. final yields

$$N_X^{(4q)} \neq N_X^{(Mol)}$$

Time Evolution of T_{cc} Multiplicity - Results

Abreu, Navarra, Vieira, PRD (2022); 2202.10882

Pb - Pb at $\sqrt{s_{NN}} = 5.02$ TeV

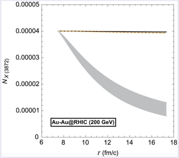


Difference between $N^{(4q)}$ and $N^{(Mol)}(\tau_H)$ decreases but remains large!

Other states

Collaboration USP-UFBA: Navarra, Nielsen, Torres, Kamchandani, LMA, Vasconcellos, Vieira ...

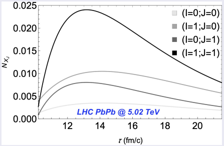
$X(3872)$ $[(cq\bar{c}\bar{q}); 0(1^{++})]$



[PRD **90**, 114023 (2014); PTEP **2016**, 103B01 (2016)

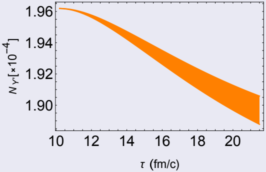
PLB **761**, 303 (2016); IJMPA **33**, 1850180 (2018), ...]

$X_J(2900)$ $[\bar{c}\bar{s}ud); 1(0, 1^{+})]$



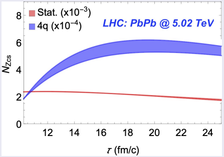
[PRD **103**, 036013 (2021); PoS 012 (2022)]

$\chi_{c1}(4274)$ $[(cs\bar{c}\bar{s}); 0^{+}(1^{++})]$



[2306.07446 [hep-ph]; another paper to appear]

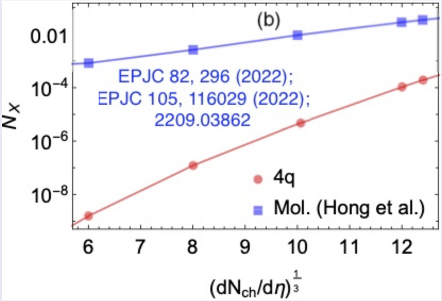
$Z_{cs}(3985)^{-}$ $[(cs\bar{c}\bar{u})\frac{1}{2}(1^{+})]$



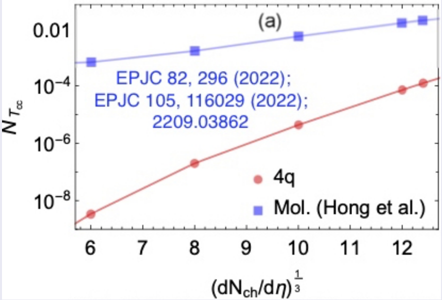
[PRD **106**, 076001 (2022); PRD **107** (2023)]

System size dependence

$X(3872)$ $[(cq\bar{c}\bar{q}); 0(1^{++})]$

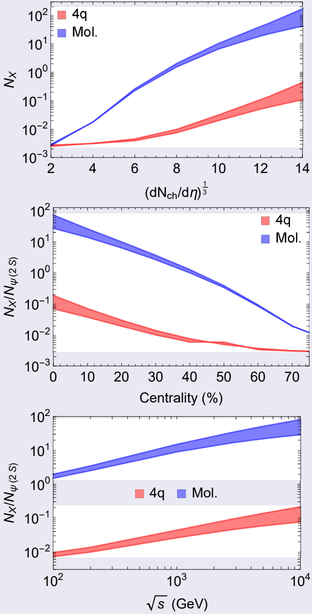


$T_{cc}(3875)^+$ $[(cc\bar{q}\bar{q}; J^P = 1^+]$

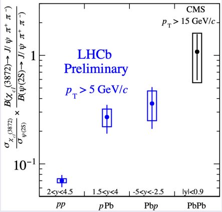


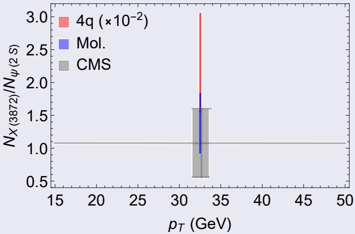
- Multiplicities grow fast with the system size!
- Molecules and tetraquarks: in the same way!

Preliminary results for $R = N_X / N_{\Psi(2S)}$



LHCb-CONF-2022-001 (2022)





Strategy 2 - a challenge: femtoscopy

- Definition - Correlation Function

$$C(\vec{p}_1, \vec{p}_2) = \frac{N(\vec{p}_1, \vec{p}_2)}{N(\vec{p}_1)N(\vec{p}_2)} \simeq \int d^3\vec{r} S_{12}(\vec{r}) |\Psi(\vec{r}, \vec{p})|$$

$S_{12}(\vec{r})$: source function (usually a Gaussian function)
$\Psi(\vec{r}, \vec{p})$: relative outgoing wave function of the two particles
$\vec{p}$: relative momentum

- Using Bethe–Salpeter approach:

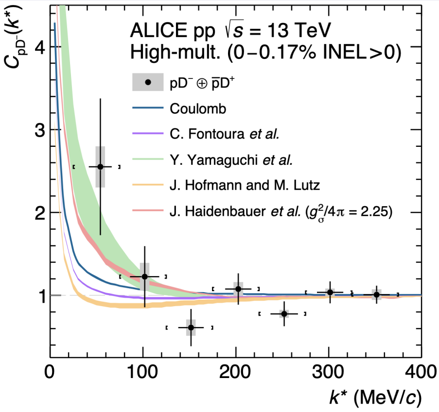
$$C_i(\vec{p}) = 1 + 4\pi \int_0^\infty r^2 dr S_{12}(r) \left(\sum_J |\omega_{ji} \tilde{\Psi}_{ji}(r, \vec{p})|^2 - j_0^2(pr) \right)$$

where

$$\tilde{\Psi}_{ji}(r, \vec{p}) = \delta_{ji} j_0(pr) + T_{ji} \int d^3\vec{q} \frac{j_0(qr)}{E - w_1^{(j)}(\vec{q}) - w_2^{(j)}(\vec{q}) + i\eta}$$

T_{ji} : transition-matrix elements

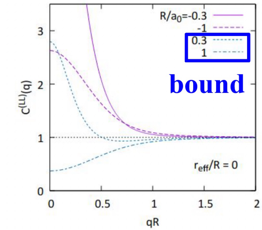
ALICE (2201.05352)



First study of the two-body scattering involving charm hadrons

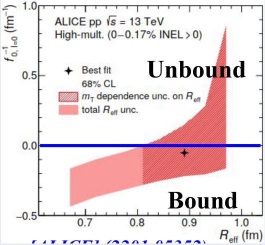
$$k\,\cot\delta = -\frac{1}{a_0} + \frac{1}{2}r_{\rm eff}k^2 + \mathcal{O}(k^3)$$

(Nuclear and atomic phys. convention.)

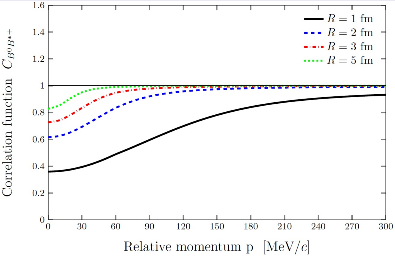


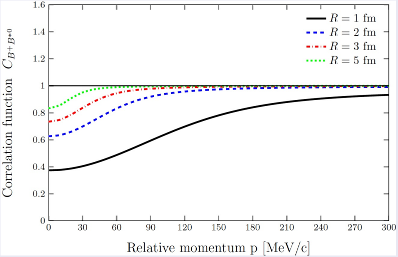
$$k\,\cot\delta = +\frac{1}{f_0} + \frac{1}{2}r_{\rm eff}k^2 + \mathcal{O}(k^3)$$

(High-E. phys. convention.)

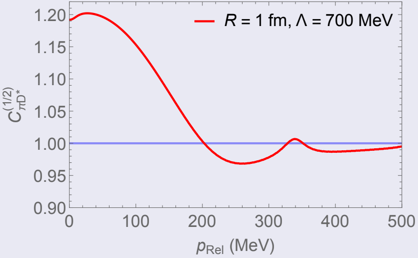


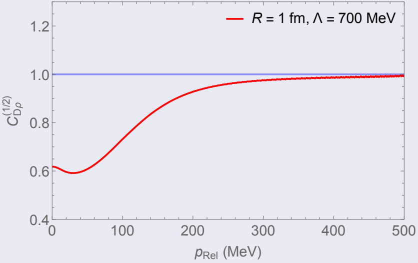
T_{bb} (UFBA-U. Valencia [Feijoo, Molina, Oset], U. Huzhou [Dai]) 2309.00444 [hep-ph]





Preliminar results: $D_1(2420)$ (UFBA-USP [Alberto, Kanchan])





Summary

- Hadron Spectrum: richer than what we expected
- New particle zoo near $D^{(*)}\bar{D}^{*}, B^{(*)}\bar{B}^{*}$ thresholds: not $(\bar{q}q, qqq)$

General description of exotic states?

- It remains a great challenge!!!
- More experimental and theoretical investigations are necessary to shed light into their dynamics
- HICs: promising testing ground for their structure

Thank You!!!

Partial financial support:

CNPq Conselho Nacional de Desenvolvimento Científico e Tecnológico

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fapesb Fundação de Amparo à Pesquisa do Estado da Bahia

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