The multiplicity of the doubly charmed state T_{cc}^{+} in heavy-ion collisions

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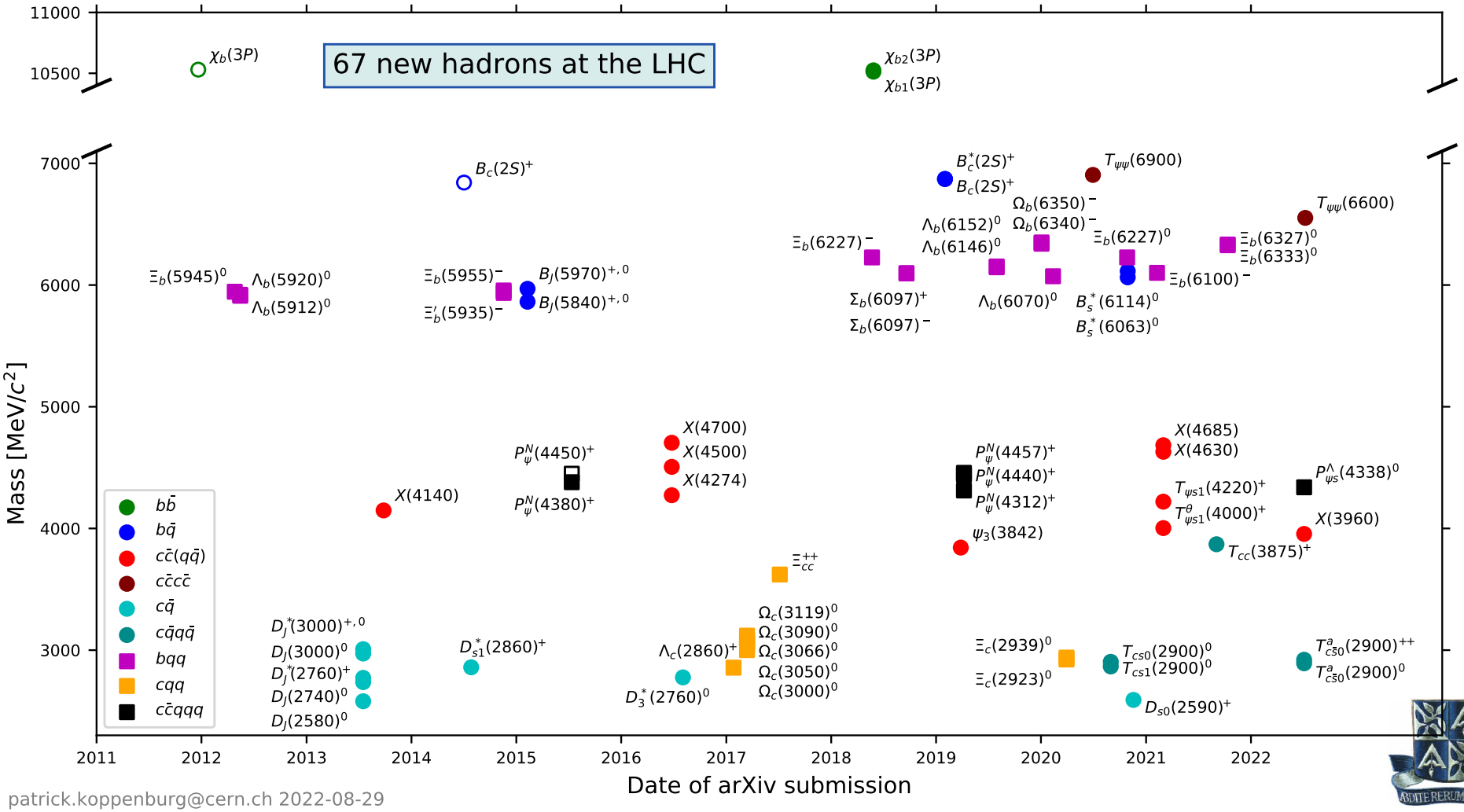
Aim

- The exotics in HICs: $X(3872)$ and T_{cc}^{+}
- Molecular and tetraquark interpretations in HICs? The coalescence model
- Interactions in the hadron gas
- Rate equation and multiplicities
- System size dependence

The heavy exotics collection

- Since 2003 [$X(3872)$]: about fifty states observed!

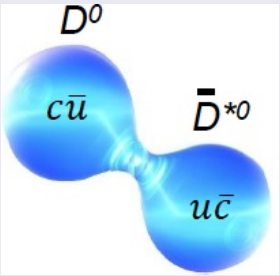


patrick.koppenburg@cern.ch 2022-08-29

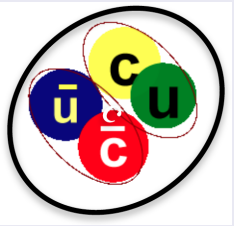
Composition and binding mechanism?

Belle (2003): $X(3872)[J^P = 1^+]$

- Meson molecule ($\sim$ 10 fm)

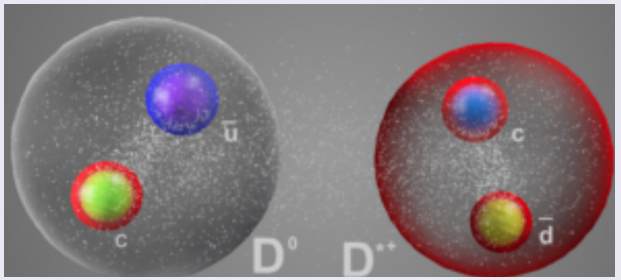


- Compact tetraquark ($\sim$ 1 fm)



LHCb (2021): $T_{cc}^+(3875)[J^P = 1^+]$

- Hadron molecule



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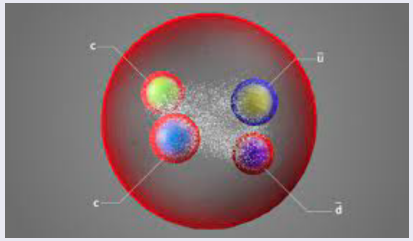

Theoretical perspective

A compelling and unified understanding has not yet emerged

Necessity of more observables to distinguish its internal structure

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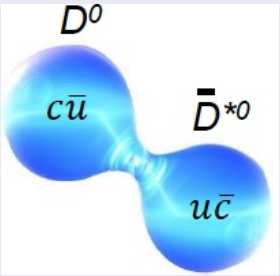

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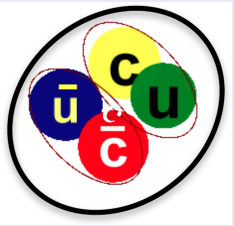

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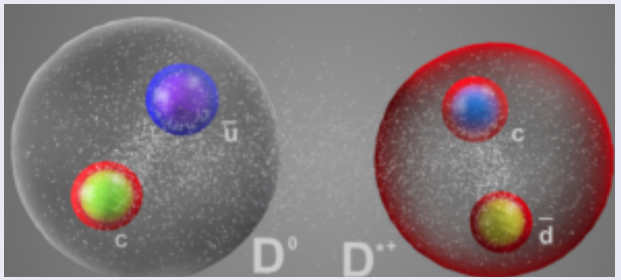

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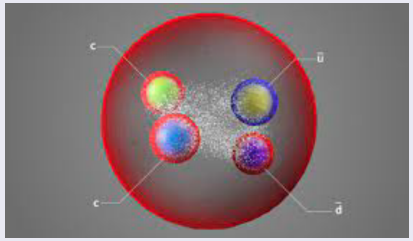

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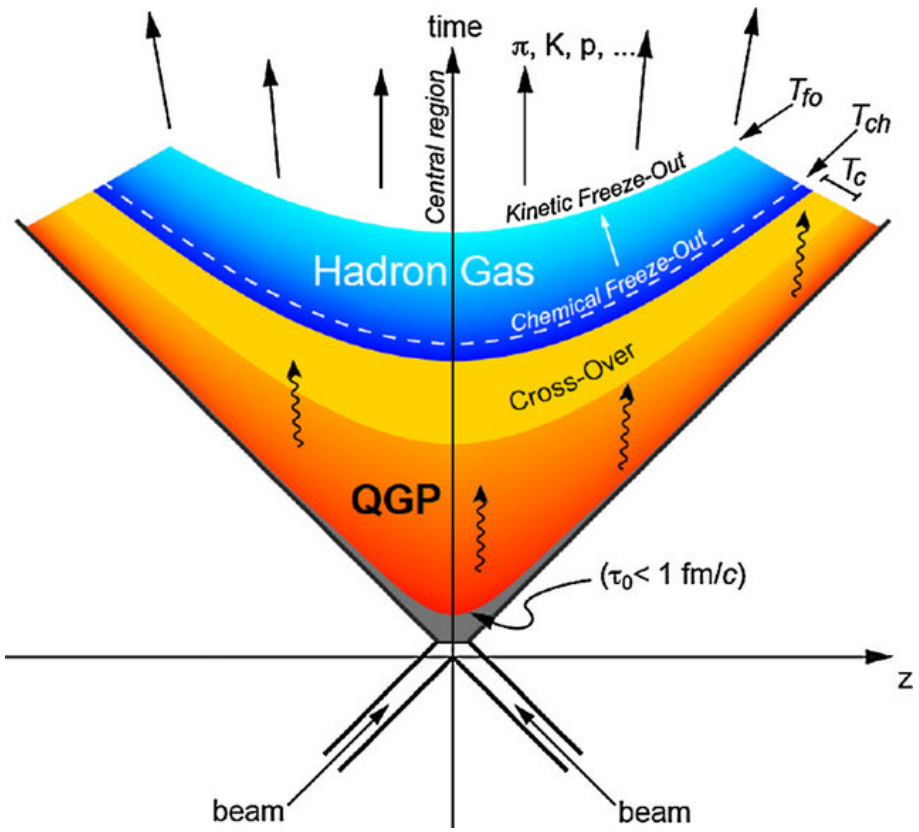
Promising alternative: exotics in HICs

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 $\to$ interpretation



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

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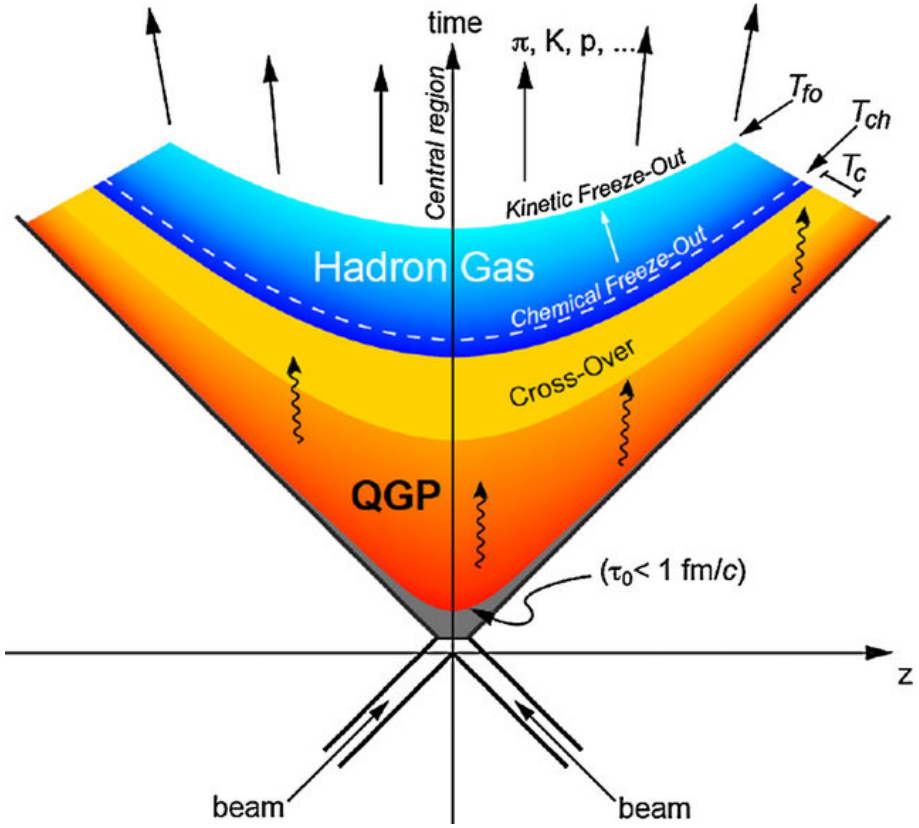


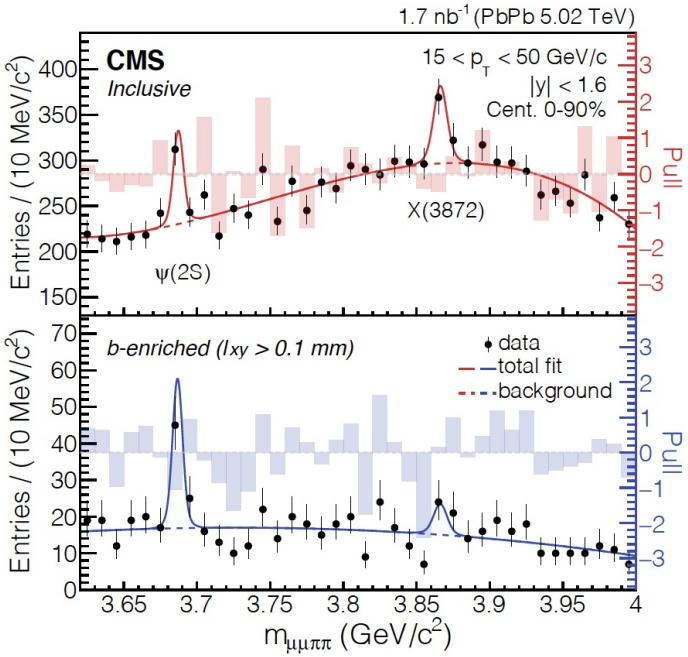
(Braun-Munzinger and Donigus, Nucl. Phys. A 987 (2019) 144)

Breaking news: first evidence of $X(3872)$ in HICs!

Evidence for X(3872) in Pb-Pb Collisions and Studies of its Prompt Production at $\sqrt{s_{NN}}$=5.02 TeV

CMS Collaboration • Albert M. Sirunyan (Yerevan Phys. Inst.) et al. (Feb 25, 2021)

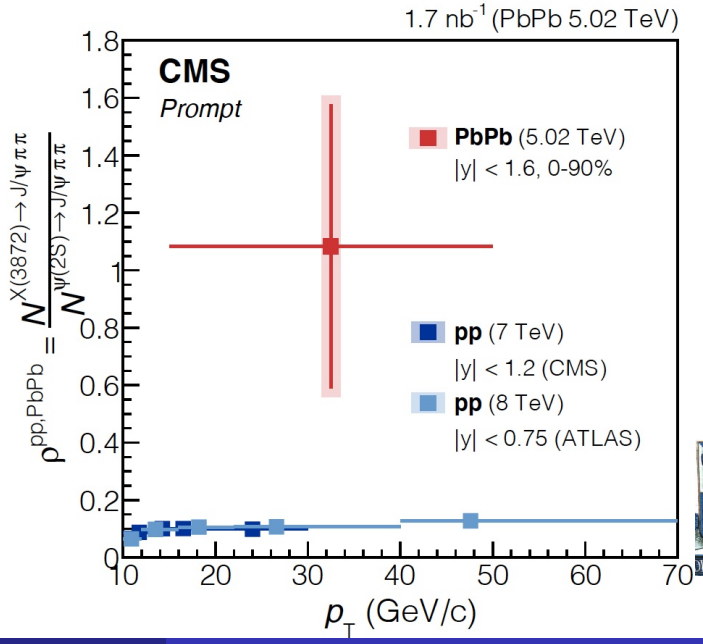
Published in: *Phys.Rev.Lett.* 128 (2022) 3, 032001 • e-Print: 2102.13048 [hep-ex]



- $X(3872) \to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$
- $\rho^{(PbPb)} = \frac{N_{X(3872)}}{N_{\psi(2S)}} = 1.08 \pm 0.9 \pm 0.52$

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

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



Our strategy

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

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

Hadronic Interactions

$$
\begin{aligned}
\mathcal{L}_{\pi DD^*} &= i g_{\pi DD^*} D^*_\mu \vec{\tau} \cdot (\bar{D}\partial^\mu \vec{\pi} - \partial^\mu \bar{D}\vec{\pi}) + h.c., \\
\mathcal{L}_{\rho DD} &= i g_{\rho DD} (D\vec{\tau}\partial_\mu \bar{D} - \partial_\mu D\vec{\tau}\bar{D}) \cdot \vec{\rho}^\mu, \\
\mathcal{L}_{\rho D^* D^*} &= i g_{\rho D^* D^*} \left[(\partial_\mu D^{*\nu} \vec{\tau} \bar{D}^*_\nu - D^{*\nu} \vec{\tau} \partial_\mu \bar{D}^*_\nu) \cdot \vec{\rho}^\mu \right. \\
&\quad + (D^{*\nu} \vec{\tau} \cdot \partial_\mu \vec{\rho}_\nu - \partial_\mu D^{*\nu} \vec{\tau} \cdot \vec{\rho}_\nu) \bar{D}^{*\mu} \\
&\quad \left. + D^{*\mu} (\vec{\tau} \cdot \vec{\rho}^\nu \partial_\mu \bar{D}^*_\nu - \vec{\tau} \cdot \partial_\mu \vec{\rho}^\nu \bar{D}^*_\nu) \right], \\
\mathcal{L}_{\pi D^* D^*} &= -g_{\pi D^* D^*} \varepsilon^{\mu\nu\alpha\beta} \partial_\mu D^*_\nu \pi \partial_\alpha \bar{D}^*_\beta, \\
\mathcal{L}_{\rho DD^*} &= -g_{\rho DD^*} \varepsilon^{\mu\nu\alpha\beta} (D\partial_\mu \rho_\nu \partial_\alpha \bar{D}^*_\beta + \partial_\mu D^*_\nu \partial_\alpha \rho_\beta \bar{D}),
\end{aligned}
$$

Ling et al. PLB (2022), 2108.00947 :

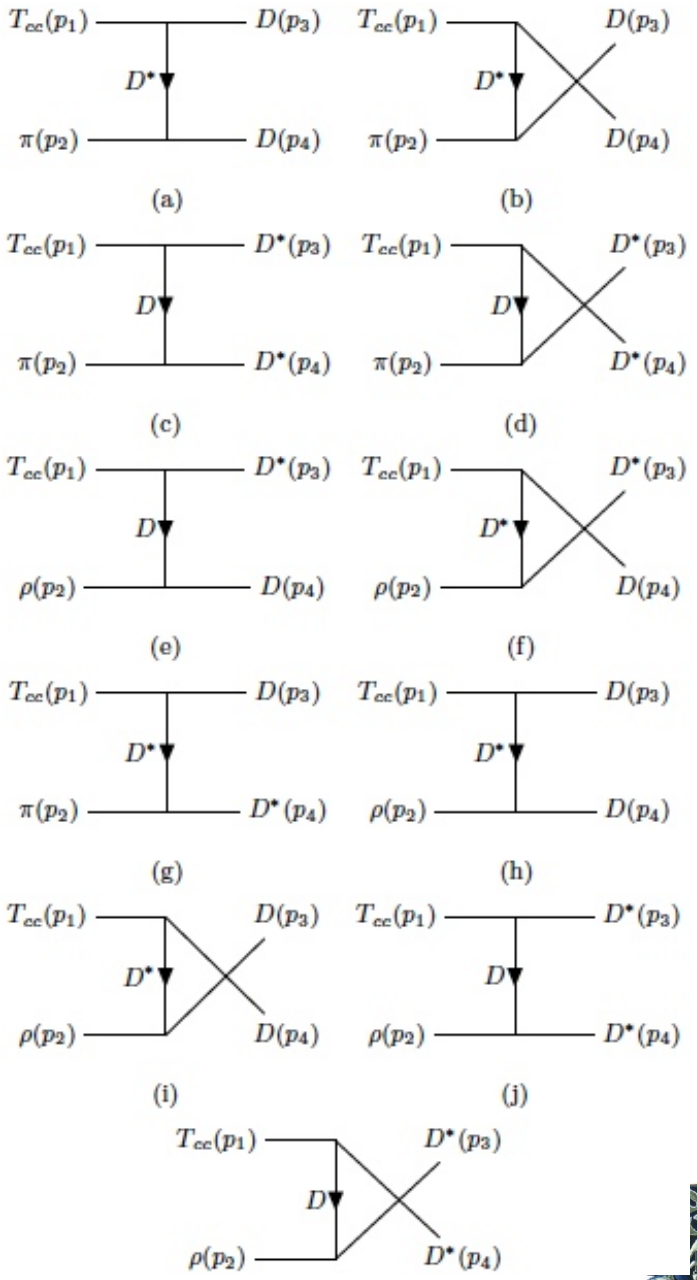
$$\mathcal{L}_{T_{cc}} = i g_{T_{cc} DD^*} T^\mu_{cc} D^*_\mu D$$

Abreu, Navarra, Nielsen, Vieira, EPJC (2022), 2110.11145 $\Rightarrow$ QCD sum rules

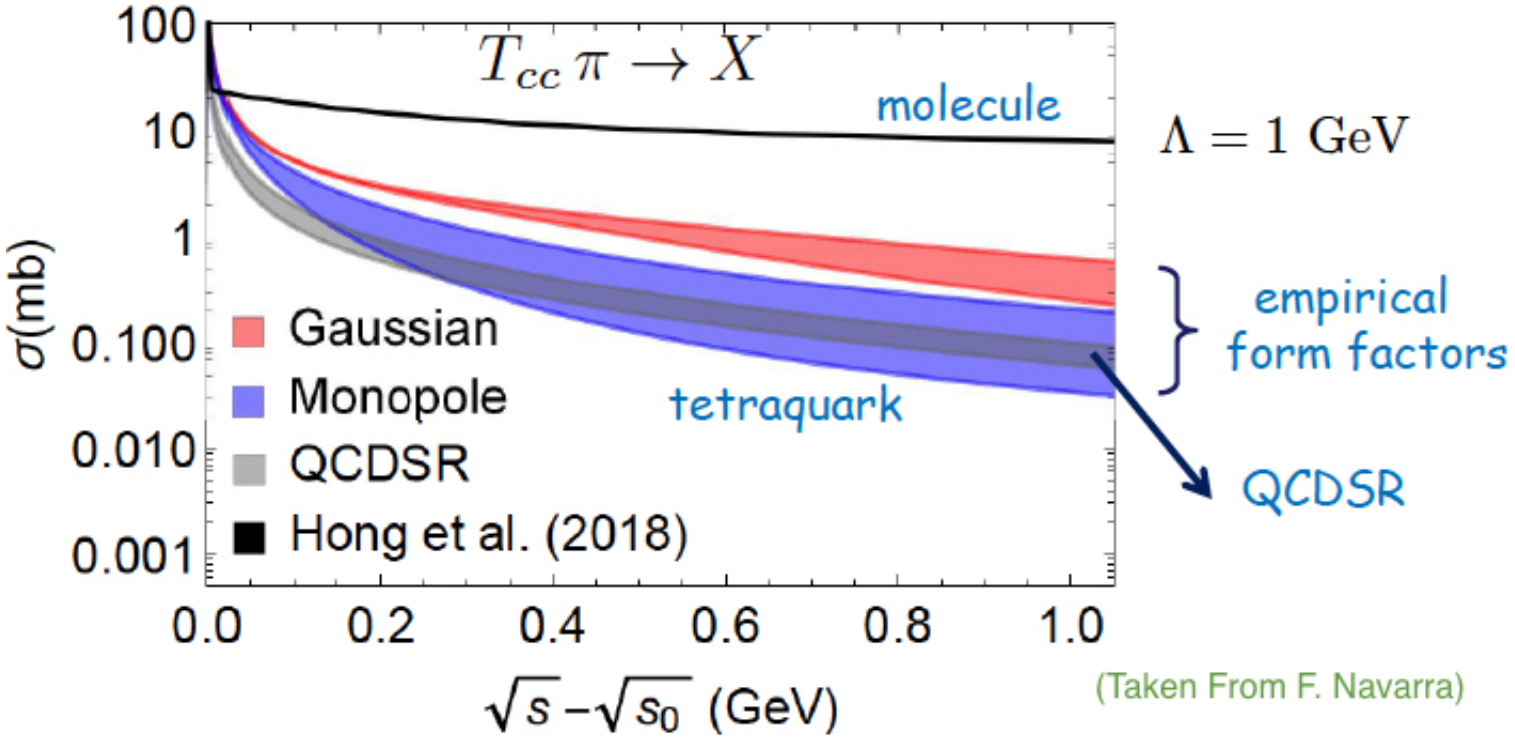
$$\Pi^{(phen)}_{\alpha\mu} \propto \left\langle 0 | T[j^{D^*}_\alpha(x) j^D_5(y) j^\dagger_\mu(0)] | 0 \right\rangle ;$$

$$g_{T_{cc} DD^*}(Q^2) = g_{T_{cc} DD^*} \, e^{-g(Q^2 + m_D^2)},$$

$$g_{T_{cc} DD^*} = (1.7 \pm 0.2) \ \text{GeV}.$$



Abreu, Navarra, Nielsen, Vieira, EPJC (2022), arXiv:2110.11145



(Taken From F. Navarra)

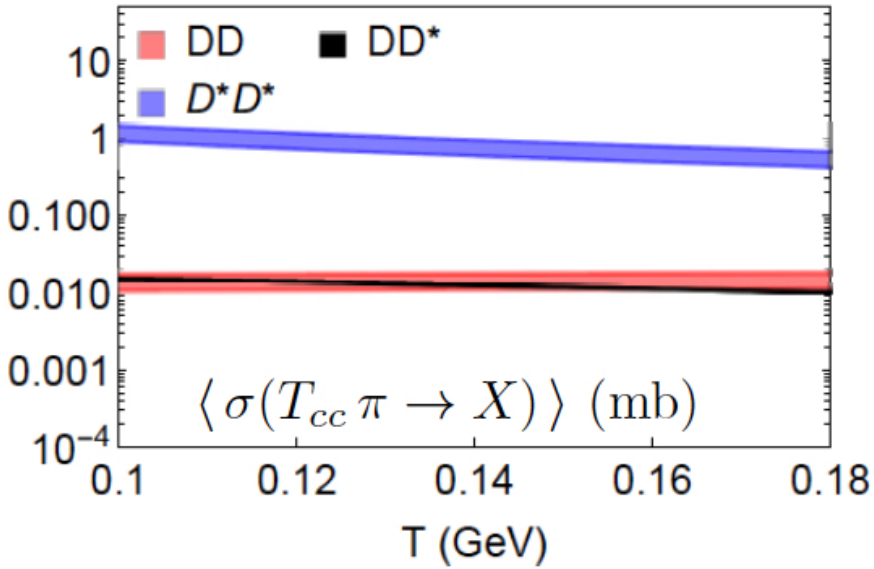
- Ho,Cho,Song,Lee, PRC (2018), 1702.00486: Monopole form factors
- "Quasi-free" model: $\sigma_{T_{cc}\pi \to DD^*\pi} = \sigma_{D\pi \to D\pi} + \sigma_{D^*\pi \to D^*\pi} \Rightarrow$ Molecules!

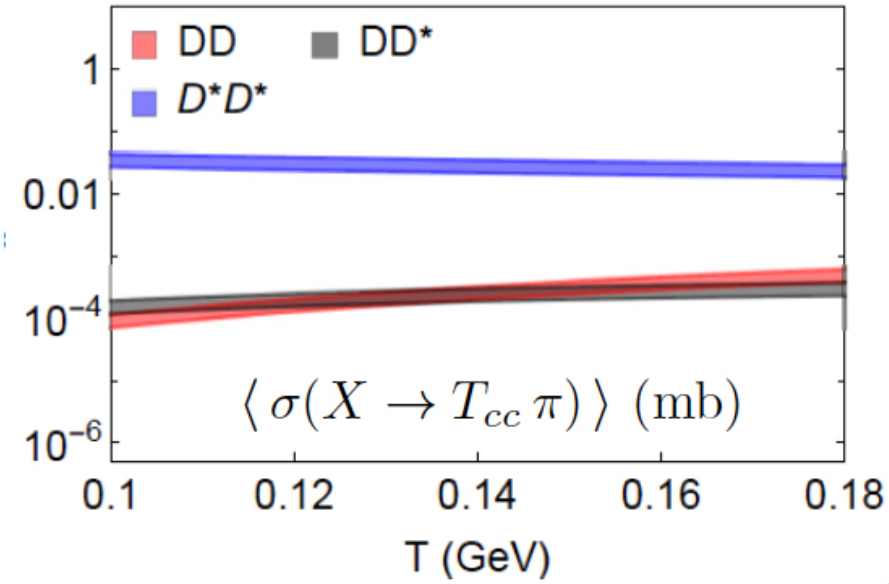
- QCDSR $\Rightarrow$ Natural description for tetraquarks!
- QCDSR $\Rightarrow$ Reduction of the uncertainties!

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

Thermally Averaged Cross Sections for tetraquarks

$$\langle \sigma_{ab\to cd} v_{ab} \rangle = \frac{\int d^3p_a d^3p_b f_a(p_a) f_b(p_b) \sigma_{ab\to cd} \; v_{ab}}{\int d^3p_a d^3p_b f_a(p_a) f_b(p_b)}$$





(Inverse processes $\Rightarrow$ detailed balance equation)

Time Evolution of T_{cc} Multiplicity

$$\frac{dN_{T_{cc}}(\tau)}{d\tau} = \sum_{\substack{c,c'=D,D^* \\ \varphi=\pi,\rho}} \left[\langle \sigma_{cc'\to T_{cc}\varphi} v_{cc'}\rangle n_c(\tau) N_{c'}(\tau) - \langle \sigma_{\varphi T_{cc}\to cc'} v_{T_{cc}\varphi}\rangle n_\varphi(\tau) N_{T_{cc}}(\tau)\right]$$

Bjorken picture:

$$T(\tau) = T_C - (T_H - T_F)\left(\frac{\tau-\tau_H}{\tau_F-\tau_H}\right)^{\frac{4}{5}}; \quad V(\tau) = \pi\left[R_C + v_C(\tau-\tau_C) + \frac{a_C}{2}(\tau-\tau_C)^2\right]^2 \tau c$$

Initial conditions $\Rightarrow$ coalescence model

$$N_{T_{cc}}^{Coal} \approx g_T \prod_{j=1}^{n} \frac{N_j}{g_j} \prod_{i=1}^{n-1} \frac{(4\pi\sigma_i^2)^{\frac{3}{2}}}{V(1+2\mu_i T\sigma_i^2)} \left[\frac{4\mu_i T\sigma_i^2}{3(1+2\mu_i T\sigma_i^2)}\right]^{l_i}$$

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

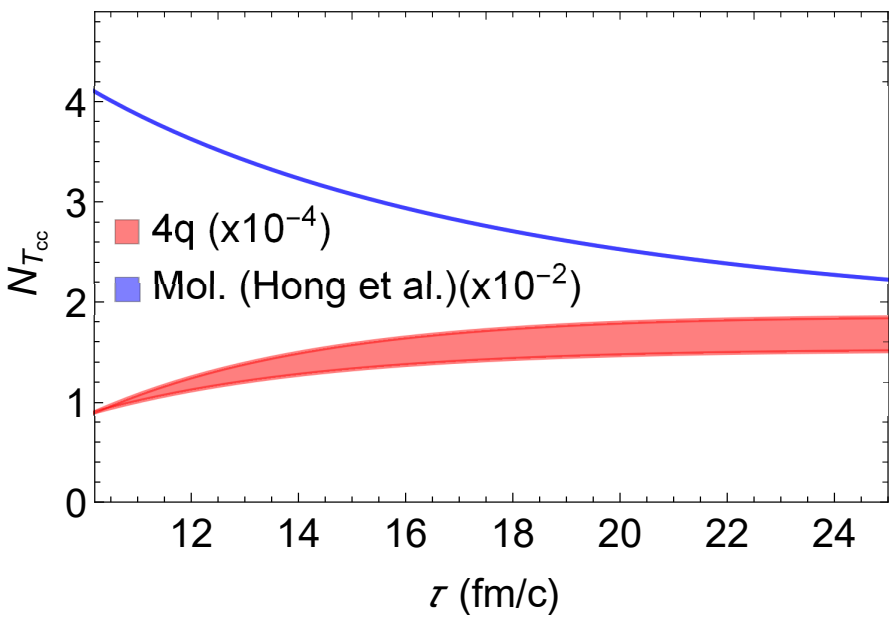
State	$N^{(4q)}(\tau_C)$	$N^{(Mol)}(\tau_H)$
T_{cc}^+	8.40×10^{-5}	4.10×10^{-2}
$X(3872)$	1.81×10^{-4}	7.50×10^{-2}

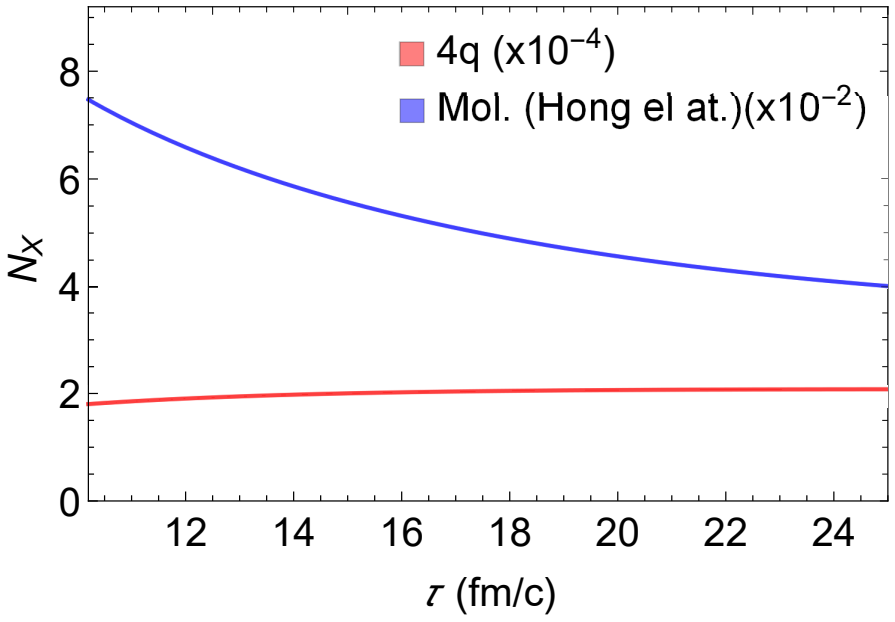
- Hundred times more molecules!
- Changes in initial multiplicity due to interactions in the hadron gas?
- Different interactions for tetraquarks and molecules?

Time Evolution of T_{cc} Multiplicity

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

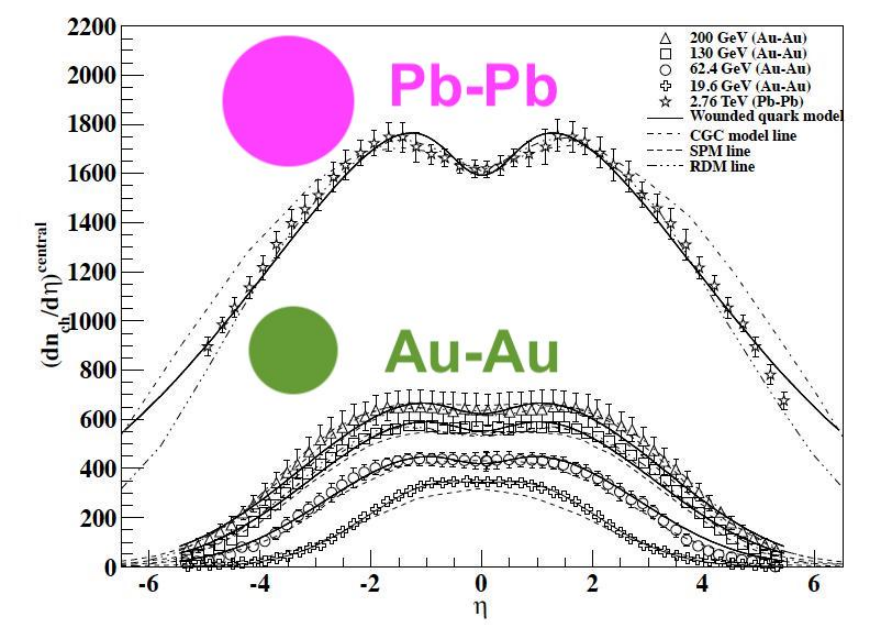
Pb - Pb at $\sqrt{s_{NN}} = 5.02$ TeV





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

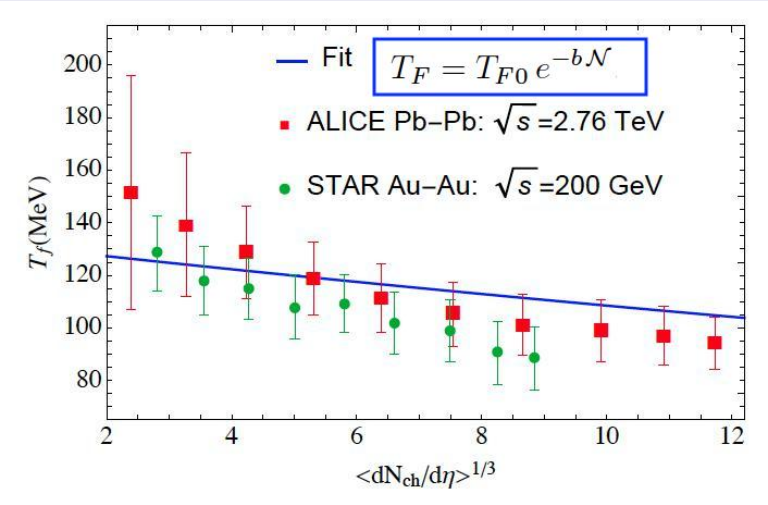
System size and number of charged particles



Larger size:

- Greater $\mathcal{N} = \left[\left(\frac{dN_{ch}}{d\eta}\right)_{|\eta|<0.5}\right]^{1/3}$
- System lives longer
- More charm quarks
- More charmed mesons

System size and freeze-out time



- Bjorken-like cooling: $\tau_F T_F^3 = \tau_H T_F^3$
- Evolution stops later: $\tau_F = \tau_H \left(\frac{T_H}{T_{F0}}\right)^3 e^{3b\mathcal{N}}$

System size and volume

- From Statistical Hadronization Model and EXHIC [Vovchenko et al. PRC (2019); 1906.03145] :

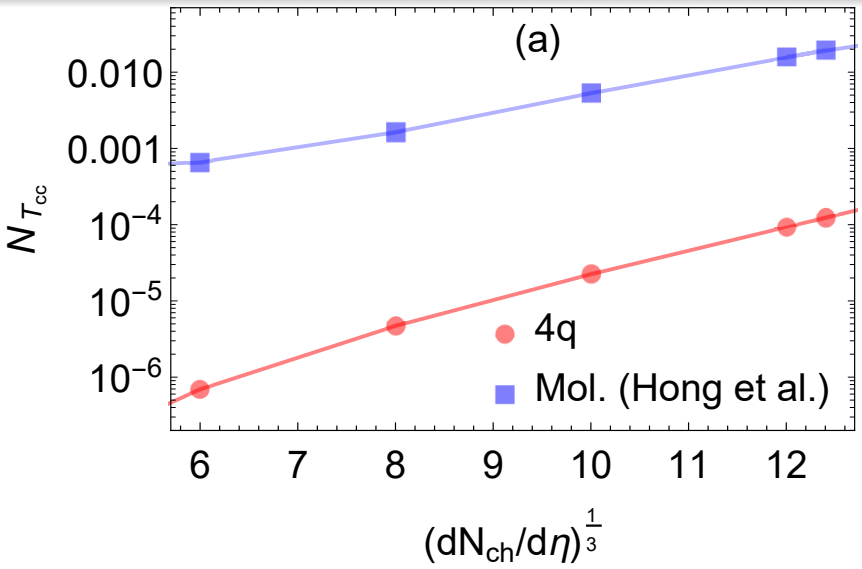
$$V = 2.82\,\mathcal{N}^3$$

System size and number of quarks

- ALICE, JHEP (2015); 1505.00664: $N_D \propto \left(\mathcal{N}^3\right)^{1.6}$
- $N_c \propto N_D \propto \mathcal{N}^{4.8}$
- ALICE, PRC (2013): $N_q \propto \mathcal{N}^3$
- Fix the constants using EXHIC

Initial multiplicities and $\mathcal{N}$

$$N_{T_{cc}}^{(4q)} \propto \frac{N_c^2 N_c^2}{V^3} \propto \mathcal{N}^{6.6} \qquad N_{T_{cc}}^{(Mol)} \propto \frac{N_D N_{D^*}}{V} \propto \mathcal{N}^{6.6}$$



- Multiplicities grow fast with the system size!
- In the same way for molecules and tetraquarks!

Conclusions

- HICs: promising testing ground for exotics
- QCDSR: useful for tetraquarks and reduces the uncertainties
- Coalescence model: much more molecules than tetraquarks
- After the hadron gas phase: difference of multiplicities remains large!
- Difference: remains the same even for smaller systems!

Thank You!!!

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