Production of T_{cc} in Heavy Ion Collisions at the LHC

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X(3872) and T_{cc}

Heavy ion collisions and the coalescence model

Interaction cross sections in the hadron gas

Rate equation and multiplicities

System size dependence

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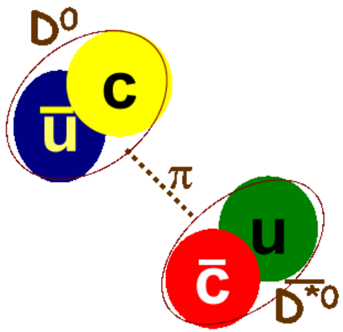
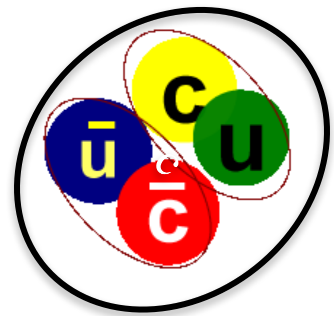
$X(3872) = (c\,\bar{c}\,q\,\bar{q}) \quad J^P = 1^+$ BELLE (2003)

Meson molecule



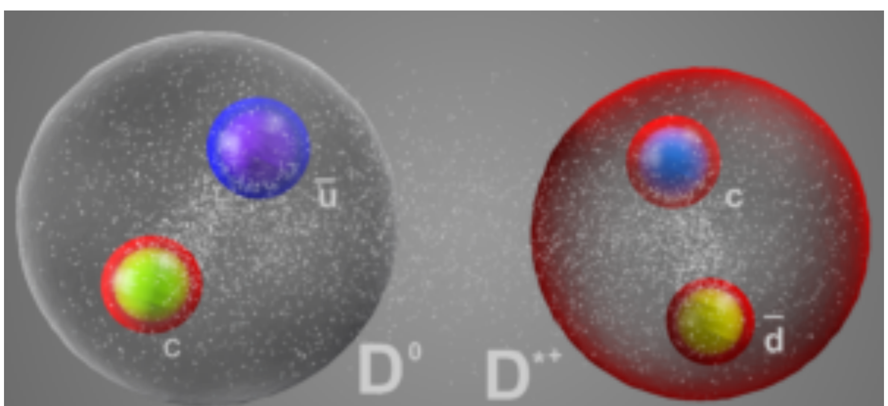
Large
~ 10 fm

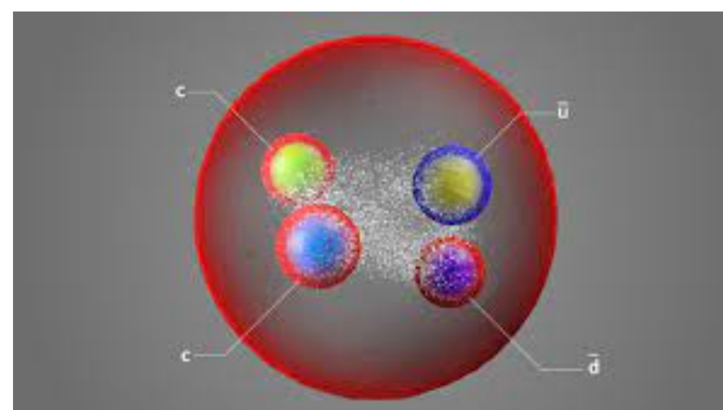
Tetraquark



Compact
~ 1 fm

$T_{cc}^{+}(3875) = (c\,c\,\bar{u}\,\bar{d}) \quad J^P = 1^+$ LHCb (2021)





Which is the correct structure ?

Use heavy ion collisions to determine the structure of the T_{cc}

Exotic Hadrons from Heavy Ion Collisions☆

Sungtae Cho[a], Tetsuo Hyodo[b], Daisuke Jido[c], Che Ming Ko[d], Su Houng Lee[e], Saori Maeda[f], Kenta Miyahara[g], Kenji Morita[b], Marina Nielsen[h], Akira Ohnishi[b], Takayasu Sekihara[i], Taesoo Song[j], Shigehiro Yasui[f], Koichi Yazaki[k], (ExHIC Collaboration)

ExHIC, Prog. Part.Nucl.Phys. (2017) arXiv:1702.00486

Why heavy ion collisions ?

Production of a large number of heavy quarks

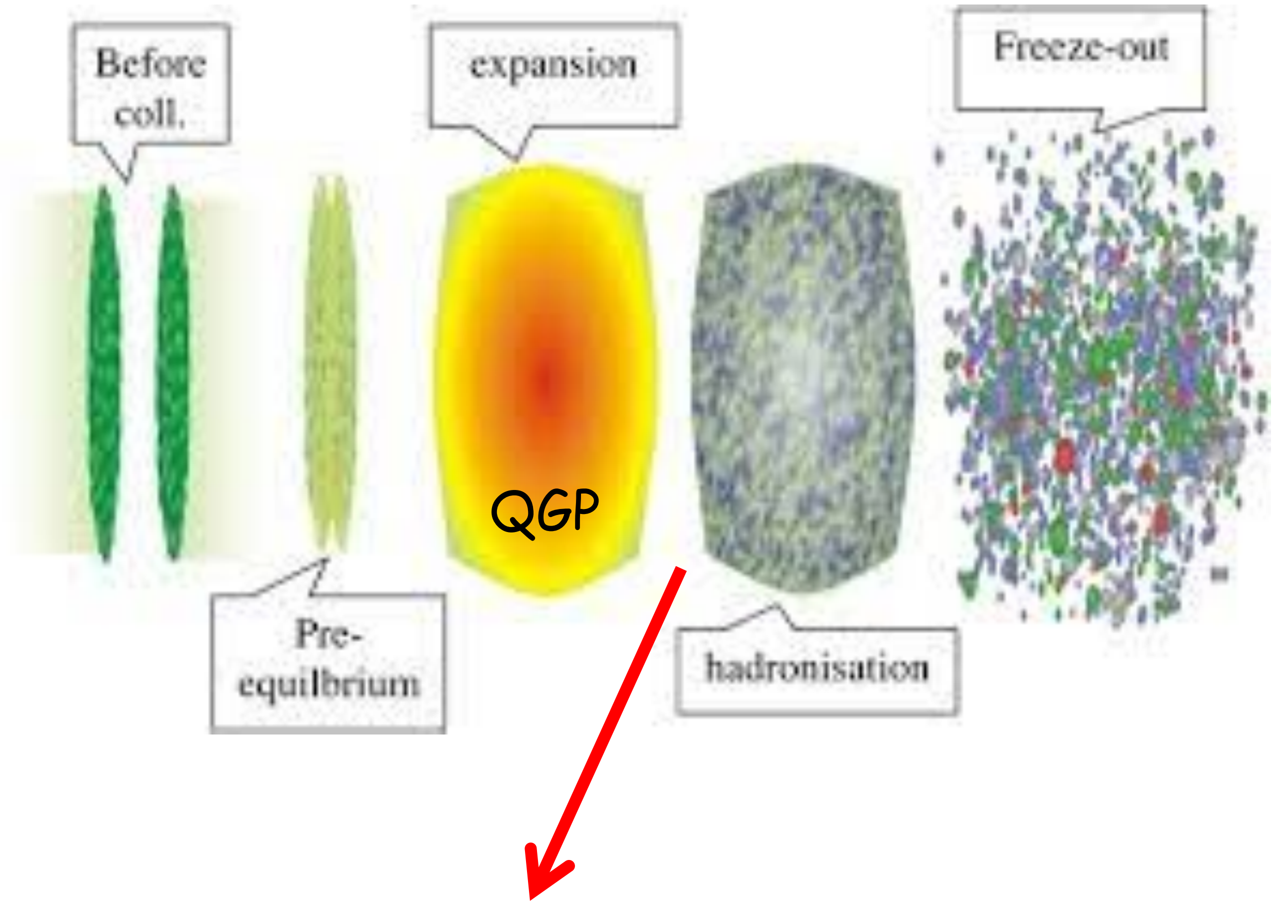
Observation is feasible:

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]

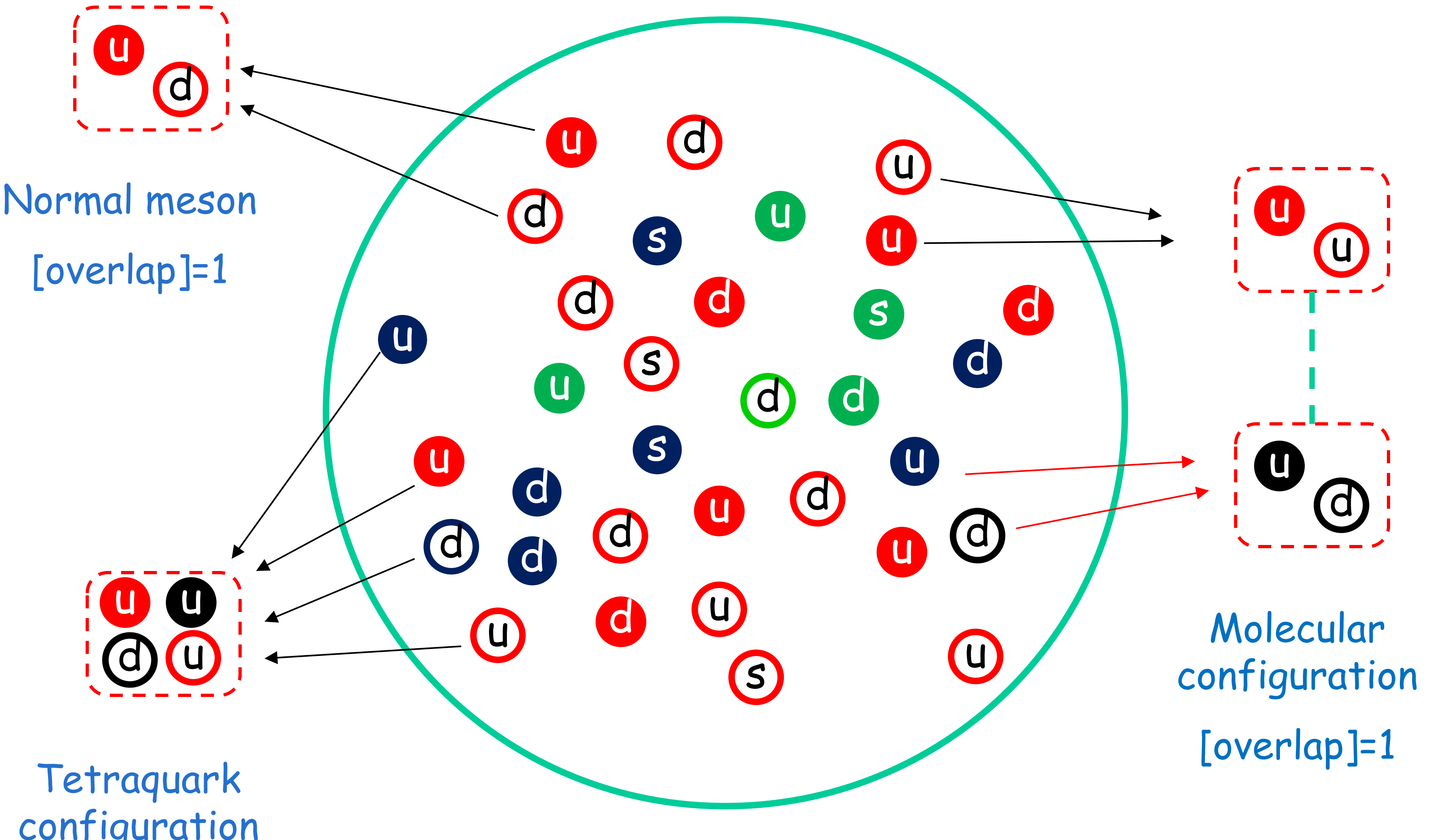
A heavy ion collision



Particles are produced during the transition from the QGP to the hadron gas

Hadron production through coalescence

(taken from S.H. Lee)



Molecular picture favored !

The coalescence model

ExHIC, Prog. Part.Nucl.Phys. (2017) arXiv:1702.00486

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

Pb - Pb collisions at $\sqrt{s} = 5.02\ \mathrm{TeV}$

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}

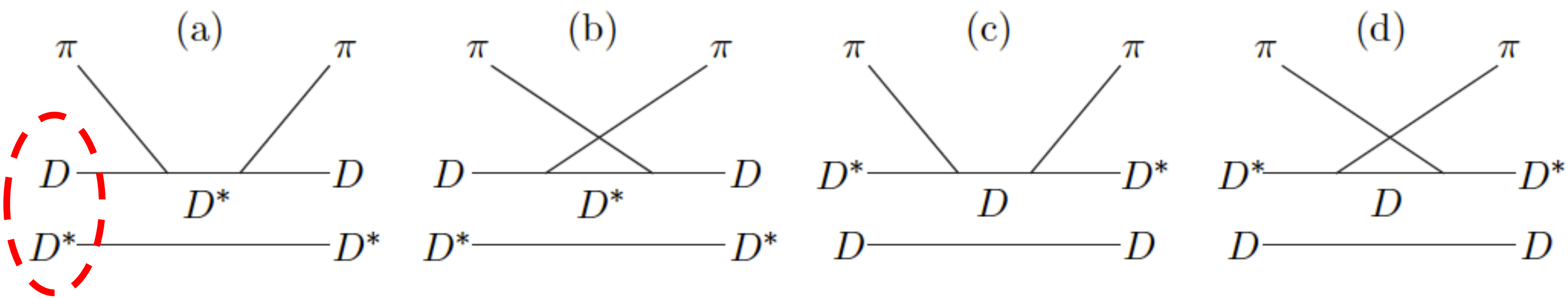
Hundred times more molecules !

Initial multiplicity changes in interactions in the hadron gas !

Tetraquarks and molecules interact differently !

Molecules: “quasi-free” model

Ho, Cho, Song, Lee,   PRC (2018), arXiv:1702.00486



$$\mathcal{L}_{\pi DD^*} = i g_{\pi DD^*} D^{*\mu} \boldsymbol{\tau} \cdot (\bar{D} \partial_\mu \boldsymbol{\pi} - \partial_\mu \bar{D} \boldsymbol{\pi}) + \text{h.c.}$$

$$F = \frac{\Lambda^2}{\Lambda^2 + \vec{q}^2},$$

Tcc is not a degree of freedom !

Vertices multiplied by form factors

Tetraquarks: interactions given by effective Lagrangians

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

$$\mathcal{L}_{\pi D D^*} = i g_{\pi D D^*} D^*_\mu \vec{\tau} \cdot \left(\bar{D} \partial^\mu \vec{\pi} - \partial^\mu \bar{D} \vec{\pi} \right)$$

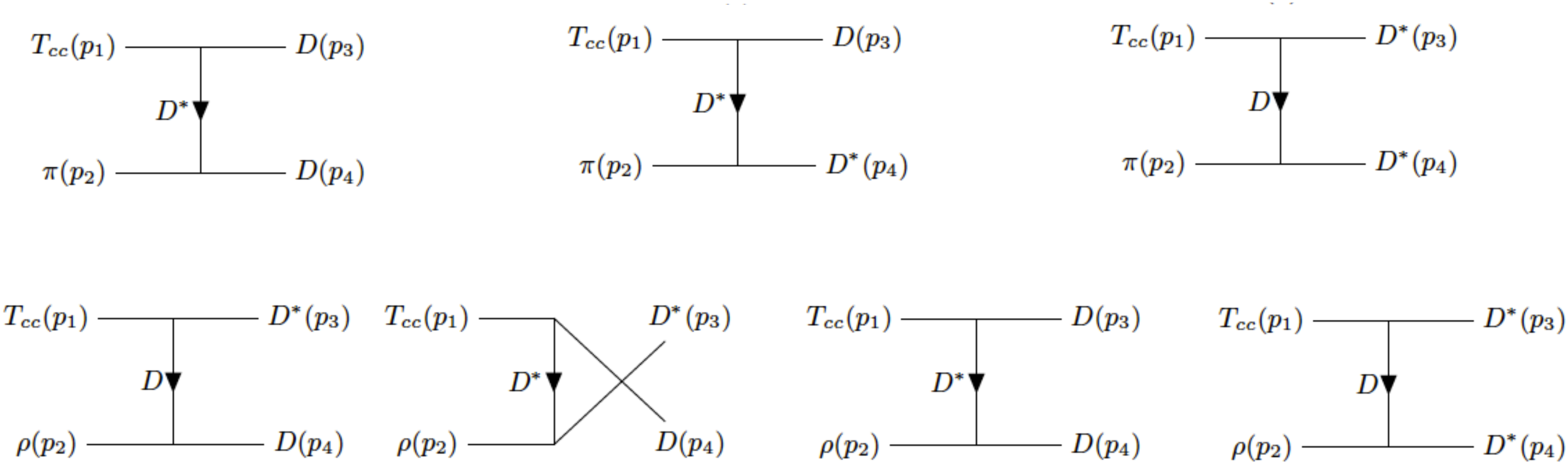
$$\mathcal{L}_{\rho D D} = i g_{\rho D D} \left(D \vec{\tau} \partial_\mu \bar{D} - \partial_\mu D \vec{\tau} \bar{D} \right) \cdot \vec{\rho}^\mu ,$$

$$\mathcal{L}_{\rho D^* D^*} = i g_{\rho D^* D^*} \left[\left(\partial_\mu D^{*\nu} \vec{\tau} \bar{D}^*_\nu - D^{*\nu} \vec{\tau} \partial_\mu \bar{D}^*_\nu \right) \cdot \vec{\rho}^\mu + \left(D^{*\nu} \vec{\tau} \cdot \partial_\mu \vec{\rho}_\nu - \partial_\mu D^{*\nu} \vec{\tau} \cdot \vec{\rho}_\nu \right) \bar{D}^{*\mu} + D^{*\mu} \left(\vec{\tau} \cdot \vec{\rho}^\nu \partial_\mu \bar{D}^*_\nu - \vec{\tau} \cdot \partial_\mu \vec{\rho}^\nu \bar{D}^*_\nu \right) \right] ,$$

$$\mathcal{L}_{\pi D^* D^*} = -g_{\pi D^* D^*} \varepsilon^{\mu\nu\alpha\beta} \partial_\mu D^*_\nu \pi \partial_\alpha \bar{D}^*_\beta ,$$

$$\mathcal{L}_{\rho D D^*} = -g_{\rho D D^*} \varepsilon^{\mu\nu\alpha\beta} \left(D \partial_\mu \rho_\nu \partial_\alpha \bar{D}^*_\beta + \partial_\mu D^*_\nu \partial_\alpha \rho_\beta \bar{D} \right),$$

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



Tetraquarks: interactions given by effective Lagrangians

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

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

Ling, Liu, Geng, Wang, Xie, PLB (2022), arXiv:2108.00947

Coupling constant and form factor from QCD sum rules

$$\Pi_{\alpha\mu}(p,p',q) = \int d^4x \; d^4y \; e^{ip'.x} \; e^{iq.y} \; \langle 0|T[j^{D^*}_{\alpha}(x) j^{D}_{5}(y) j^{\dagger}_{\mu}(0)]|0\rangle$$

$$j_\mu = i(c_a^T C\gamma_\mu c_b)(\bar{u}_a \gamma_5 C \bar{d}_b^T) \qquad j^D_5 = i\bar{u}_a\gamma_5 c_a \qquad j^{D^*}_\alpha = \bar{d}_a \gamma_\alpha c_a$$

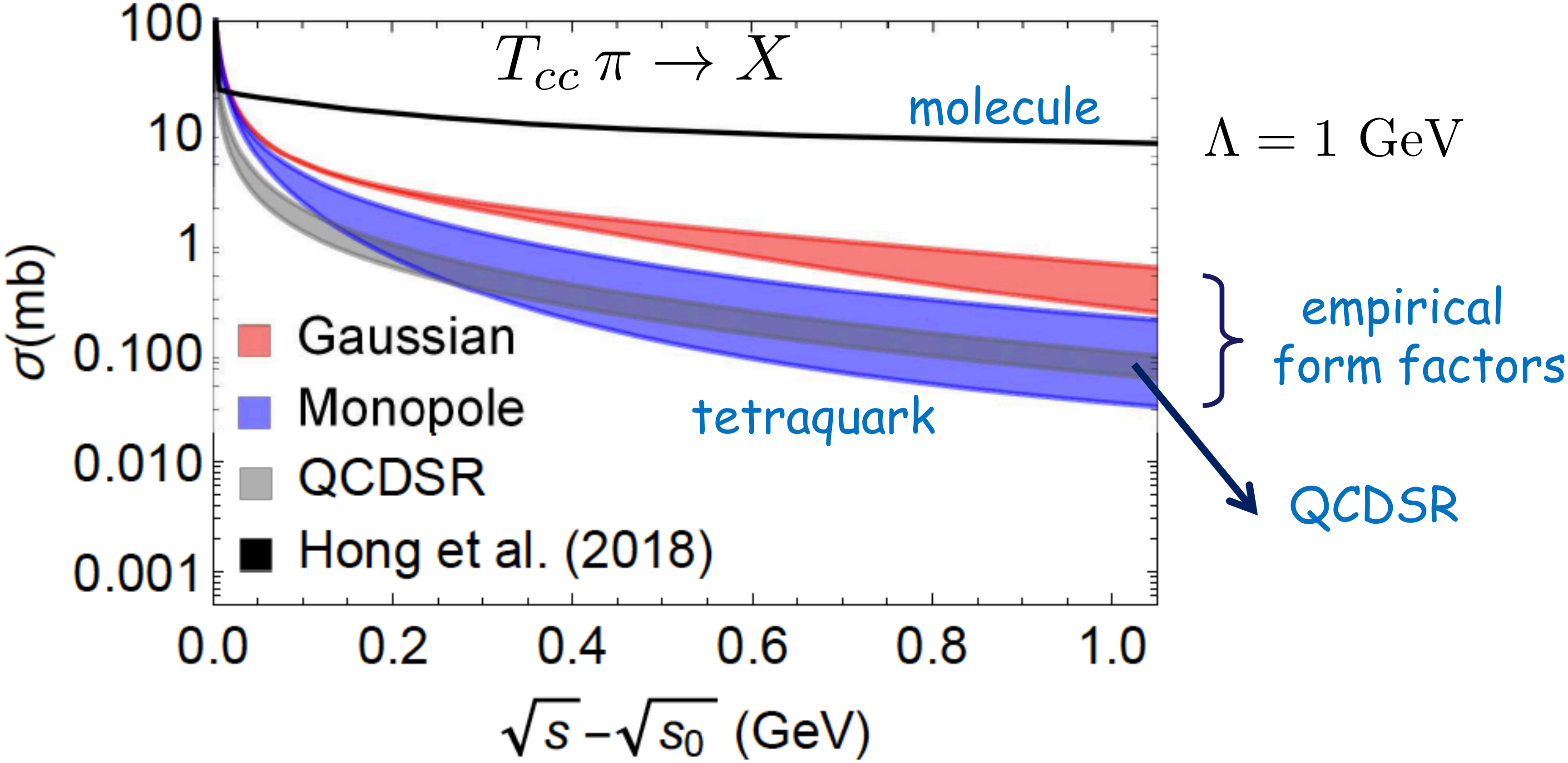
$$g_{T_{cc}DD^*}(Q^2) = g_{T_{cc}DD^*} \, e^{-g(Q^2+m_D^2)} \qquad g = 0.076 \;\; \mathrm{GeV}^{-2}$$

$$g_{T_{cc}DD^*} = g_{T_{cc}DD^*}(-m_D^2) = (1.7 \pm 0.2) \;\; \mathrm{GeV}$$

Lagrangians -> Amplitudes -> Cross Sections

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

$$\sigma_{ab\to cd} = \frac{1}{64\pi^2 s}\frac{|\vec{p}_{cd}|}{|\vec{p}_{ab}|}\int d\Omega \overline{\sum_{S,I}}|\mathcal{M}_{ab\to cd}|^2$$



QCDSR reduces the uncertainties !

Tetraquarks: Thermal Cross Sections and Rate Equation

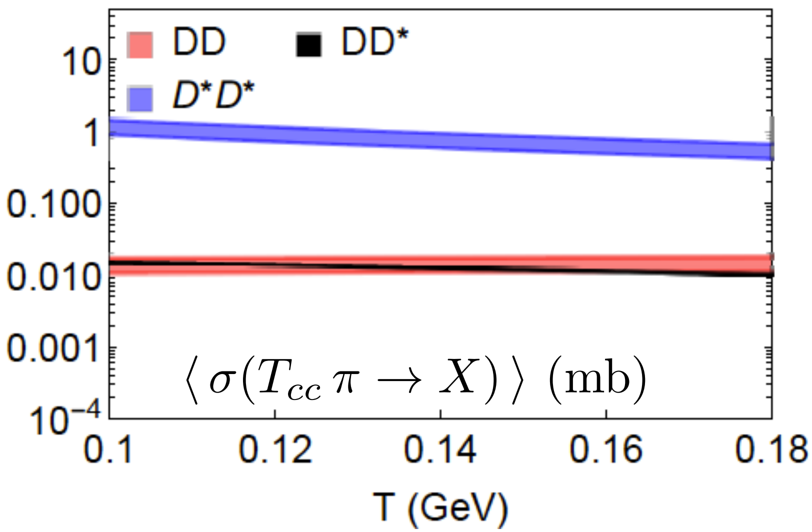
Abreu, Navarra, Vieira, PRD (2022), arXiv:2202.10882

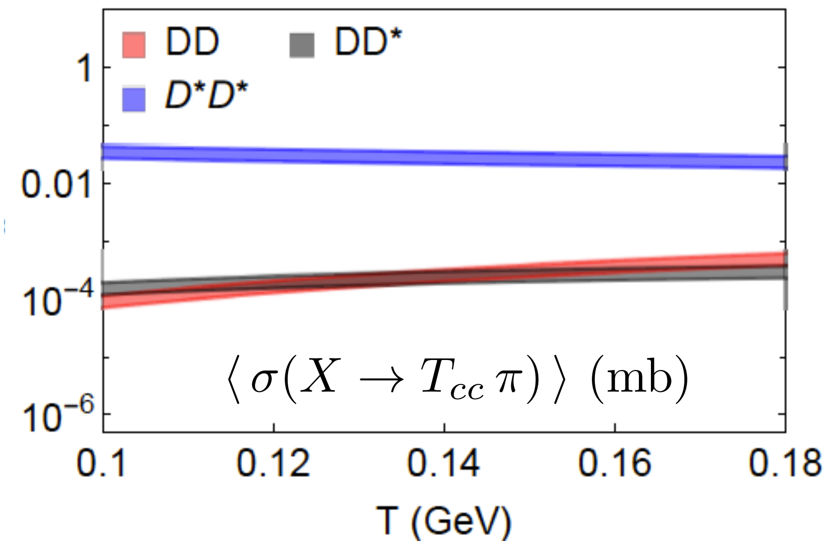
$$\langle \sigma_{ab\to cd}\, v_{ab} \rangle = \frac{\int d^3\mathbf{p}_a d^3\mathbf{p}_b\, f_a(\mathbf{p}_a)\, f_b(\mathbf{p}_b)\, \sigma_{ab\to cd}\; v_{ab}}{\int d^3\mathbf{p}_a d^3\mathbf{p}_b\, f_a(\mathbf{p}_a)\, f_b(\mathbf{p}_b)}$$

$f_i(\mathbf{p}) =$ thermal distribution

$v_{ab} =$ relative velocity

Inverse processes with detailed balance: $g_a g_b |\vec{p}_{ab}|^2 \sigma_{ab\to cd}(s) = g_c g_d |\vec{p}_{cd}|^2 \sigma_{cd\to ab}(s)$



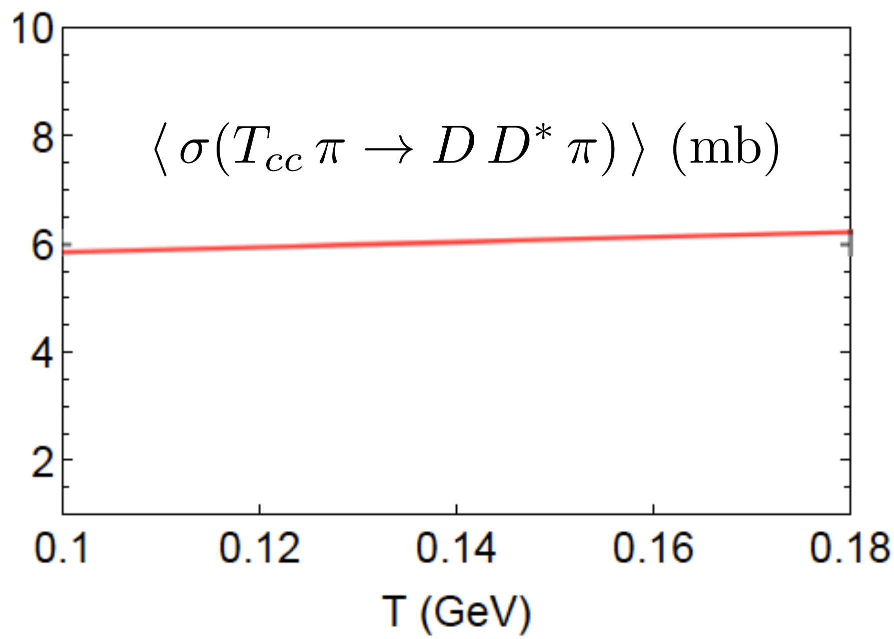


$$\frac{dN_{T_{cc}}(\tau)}{d\tau} = \sum_{\substack{c,c'=D,D^* \\ \varphi=\pi,\rho}} \left[\langle \sigma_{cc'\to T_{cc}\varphi} v_{cc'} \rangle n_c(\tau) N_{c'}(\tau) - \langle \sigma_{\varphi T_{cc}\to cc'} v_{T_{cc}\varphi} \rangle n_\varphi(\tau) N_{T_{cc}}(\tau)\right]$$

Molecules: Thermal Cross Sections and Rate Equation

Ho, Cho, Song, Lee, PRC (2018), arXiv:1702.00486

$$\langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle(\tau) = c_1 \langle \sigma_{D\pi \to D\pi} v_{T_{cc}\pi} \rangle(\tau) + c_1 \langle \sigma_{D^*\pi \to D^*\pi} v_{T_{cc}\pi} \rangle(\tau) \qquad c_1 = 1$$



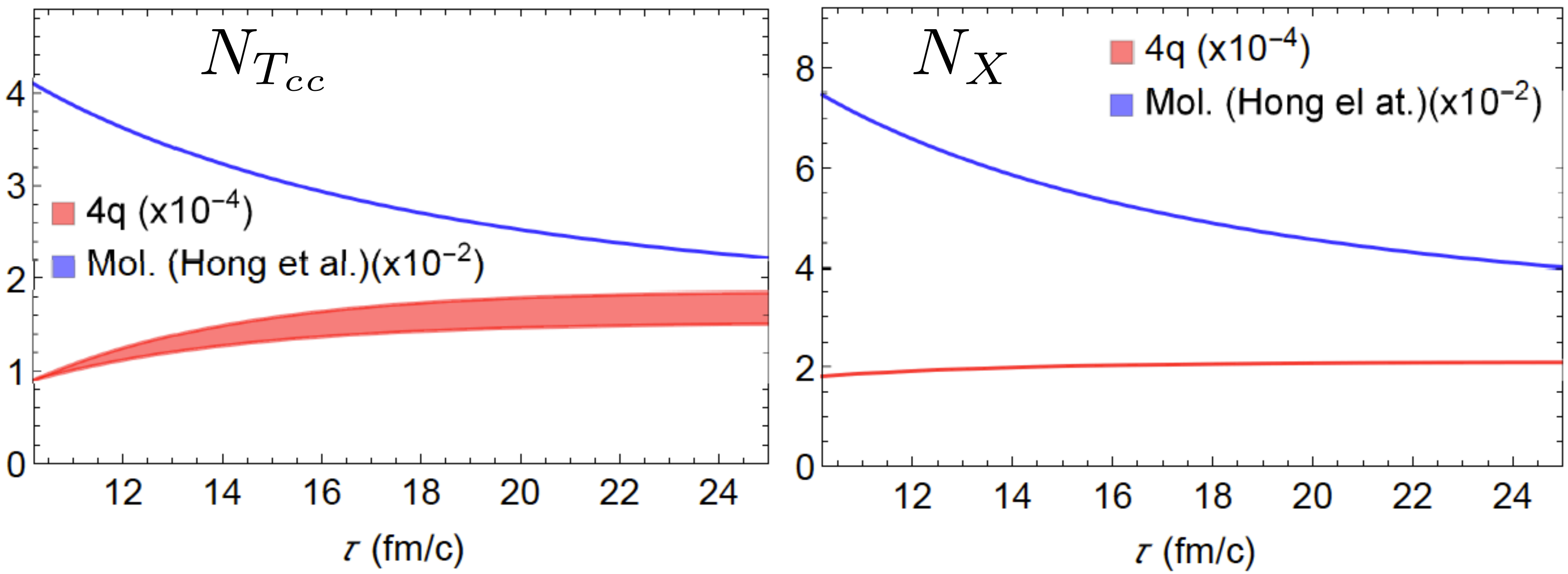
$$\frac{dN_{T_{cc}}(\tau)}{d\tau} = \langle \sigma_{T_{cc}\pi \to DD^*\pi} v_{T_{cc}\pi} \rangle(\tau)\, n_\pi(\tau) \left[-\, N_{T_{cc}}(\tau) \,+\, N^{eq}_{T_{cc}}(\tau) \frac{N_D(\tau)\, N_{D^*}(\tau)}{N^{eq}_D(\tau)\, N^{eq}_{D^*}(\tau)} \right]$$

Multiplicities

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

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

Pb - Pb collisions at $\sqrt{s} = 5.02$ TeV

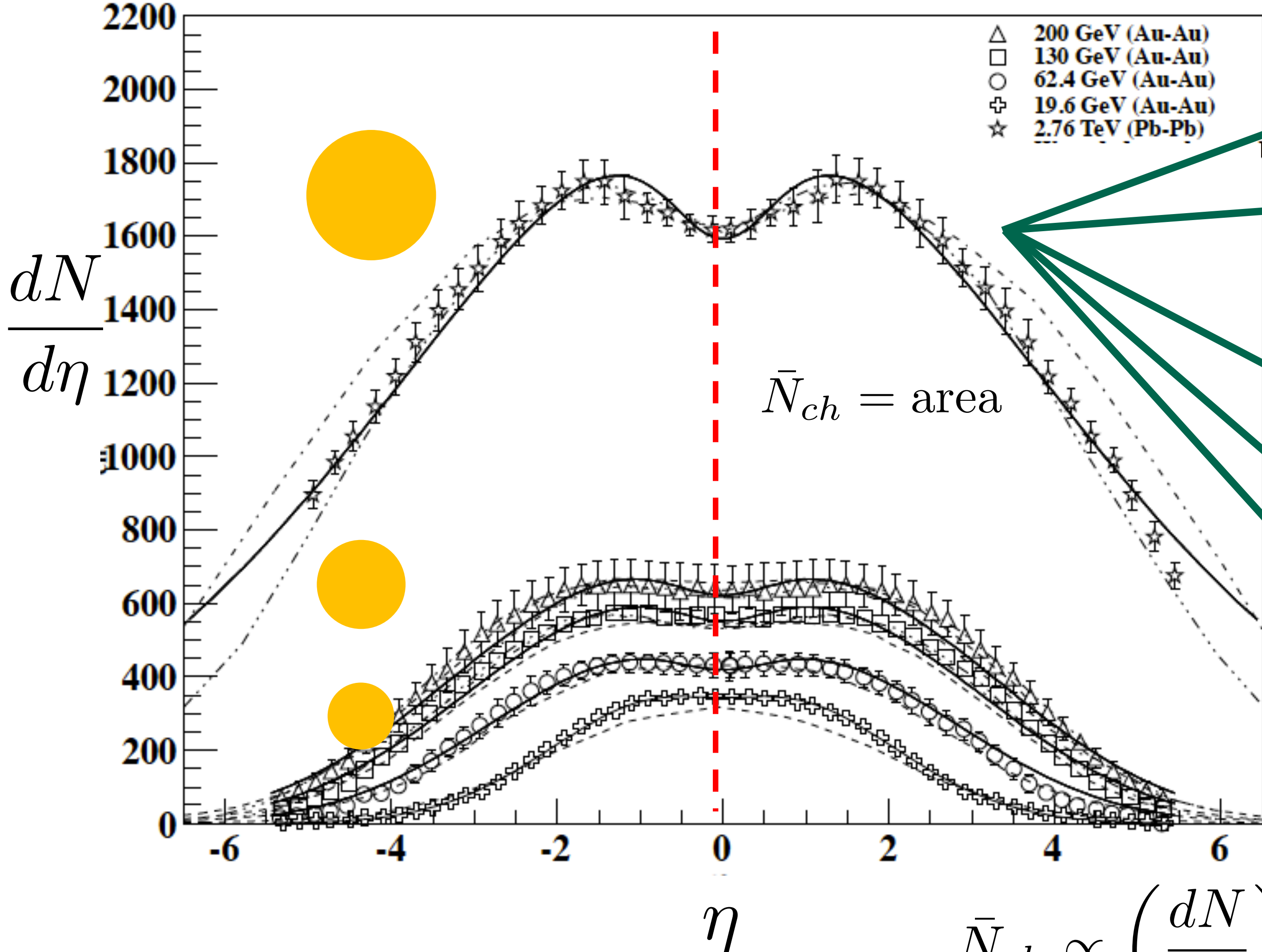


Difference of multiplicities decreases but remain large !

Estimating the
system size dependence

System size and number of charged particles

$$\left(\frac{dN}{d\eta}\right)_{\eta=0} \qquad \mathcal{N} = \left[\left(\frac{dN}{d\eta}\right)_{\eta=0}\right]^{1/3}$$



Larger volume

More charged particles

Lives longer

More charm quarks

More charm mesons

$$\bar{N}_{ch} \propto \left(\frac{dN}{d\eta}\right)_{\eta=0}$$

$$N_q \propto \mathcal{N}^3$$

System size and freeze-out time

Le Roux, Navarra, Abreu, PLB (2022), arXiv:2101.07302

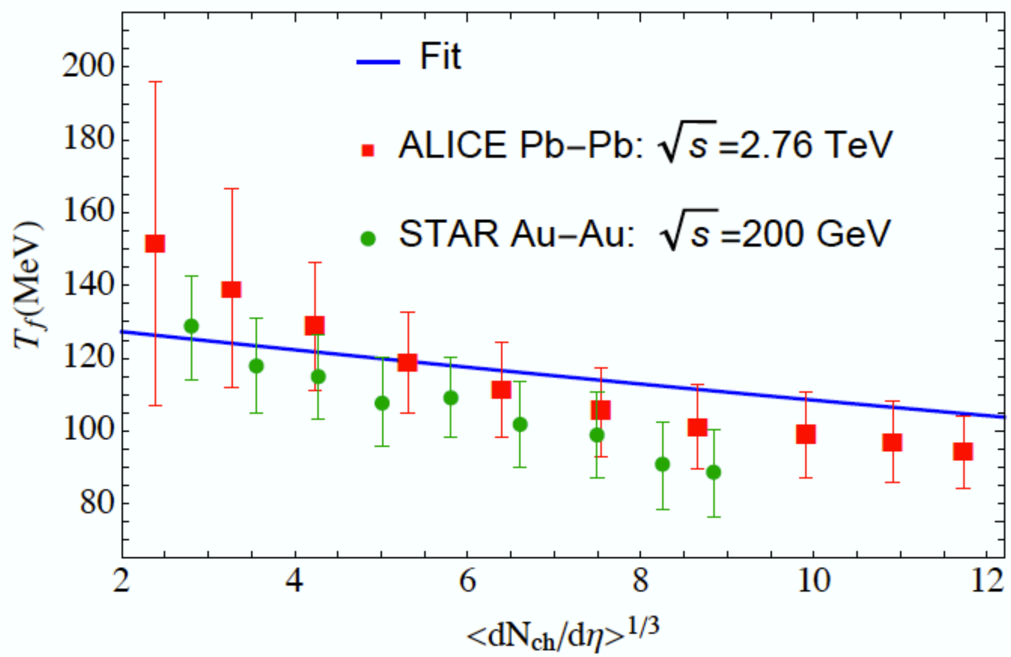
$$T_F = T_{F0}\, e^{-b\mathcal{N}}$$

$$\tau_F = \tau_H \left(\frac{T_H}{T_F}\right)^3$$

Bjorken cooling

$$\tau_F = \tau_H \left(\frac{T_H}{T_{F0}}\right)^3 e^{3b\mathcal{N}}$$

Larger systems live longer !

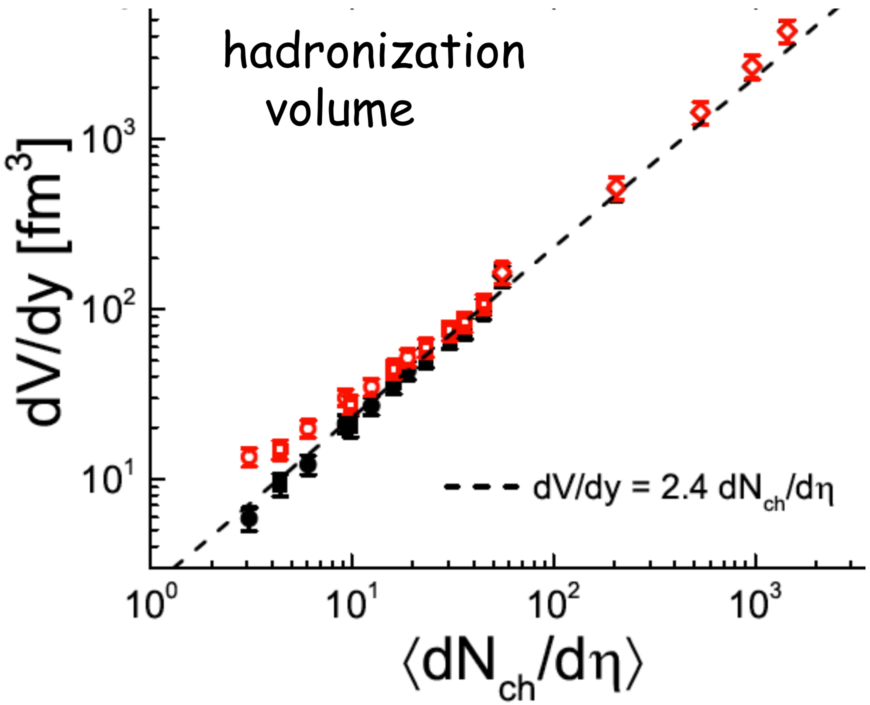


ALICE, PRC (2013), arXiv:1303.0737

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

Evolution stops later !

System size and the volume for the initial production



Vovchenko, Dönigus and Stoecker, PRC (2019)
arXiv:1906.03145

Statistical Hadronization Model

$$\frac{dV}{dy} = 2.4\,\frac{dN_{ch}}{d\eta}(|\eta| < 0.5) = 2.4\,\mathcal{N}^3$$

Assume that:

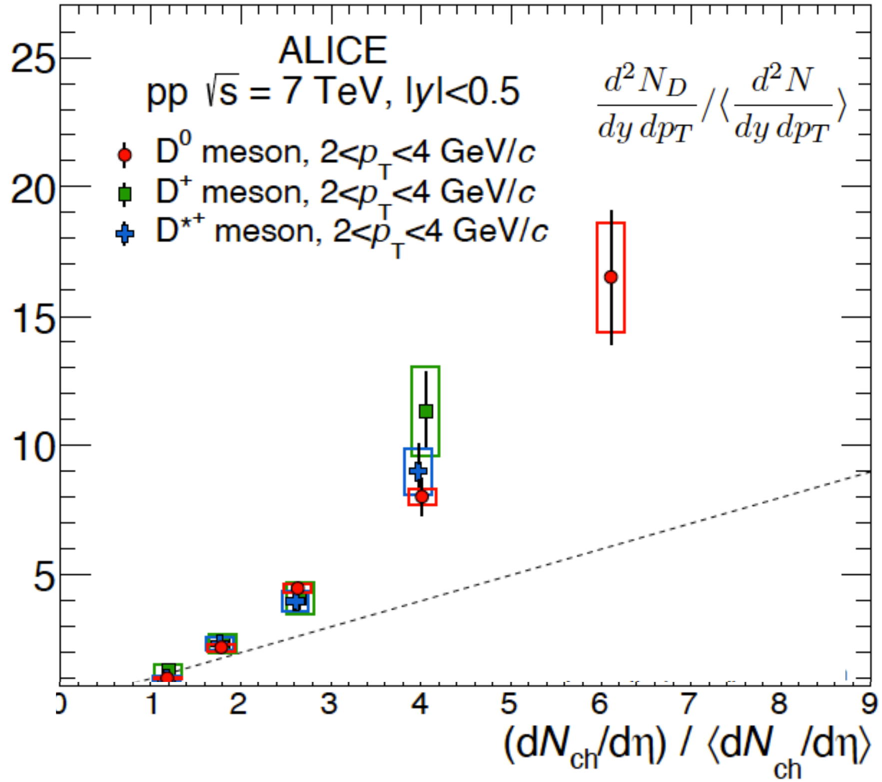
$$V \;=\; const\,\mathcal{N}^3$$

Fix the constant using EXHIC estimates:

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

System size and number of charm quarks

$$\frac{\frac{d^2N_D}{dy\,dp_T}}{\langle\frac{d^2N}{dy\,dp_T}\rangle}$$



ALICE, JHEP (2015), arXiv:1505.00664

$$\frac{d^2N_D}{dy\,dp_T}/\langle\frac{d^2N}{dy\,dp_T}\rangle = \alpha' \left(\frac{dN_{ch}}{d\eta}/\langle\frac{dN_{ch}}{d\eta}\rangle\right)^{\beta}$$

$$\beta = 1.6$$

Assume that:

$$N_D \propto (\mathcal{N}^3)^{\beta}$$

$$N_c \propto (\mathcal{N}^3)^{\beta}$$

Fix the constant
using EXHIC estimates:

$$N_c = 7.9 \times 10^{-5}\,\mathcal{N}^{4.8}$$

Initial multiplicities

$$N_{4q} = \frac{N_c\, N_c\, N_u\, N_d}{V^3} \frac{g_{T_{cc}}}{g_c\, g_c\, g_u\, g_d} \prod_{i=1}^{3} \frac{(4\pi\sigma_i^2)^{3/2}}{(1 + 2\mu_i T\sigma_i^2)}$$

$$N_m = \frac{N_D\, N_{D^*}}{V} \frac{g_{T_{cc}}}{g_D\, g_{D^*}} \frac{(4\pi\sigma^2)^{3/2}}{(1 + 2\mu T\sigma^2)}$$

These factors depend on the size

Using: $N_c \propto \mathcal{N}^{4.8}$ $\quad N_D \propto \mathcal{N}^{4.8}$ $\quad V \propto \mathcal{N}^3$ $\quad N_q \propto \mathcal{N}^3$

We find: $N_{4q} \propto \mathcal{N}^{6.6}$ $\quad N_m \propto \mathcal{N}^{6.6}$

Multiplicties grow fast with the system size !

In the same way for molecules and tetraquarks !

Conclusions

"Pure" molecules versus "pure" tetraquarks

QCDSR are effective in reducing the uncertainties

At hadronization the difference of multiplicities is large (~ 100)

After the hadron gas phase the difference of multiplicities remains large !

Difference seems to remain the same for smaller systems !