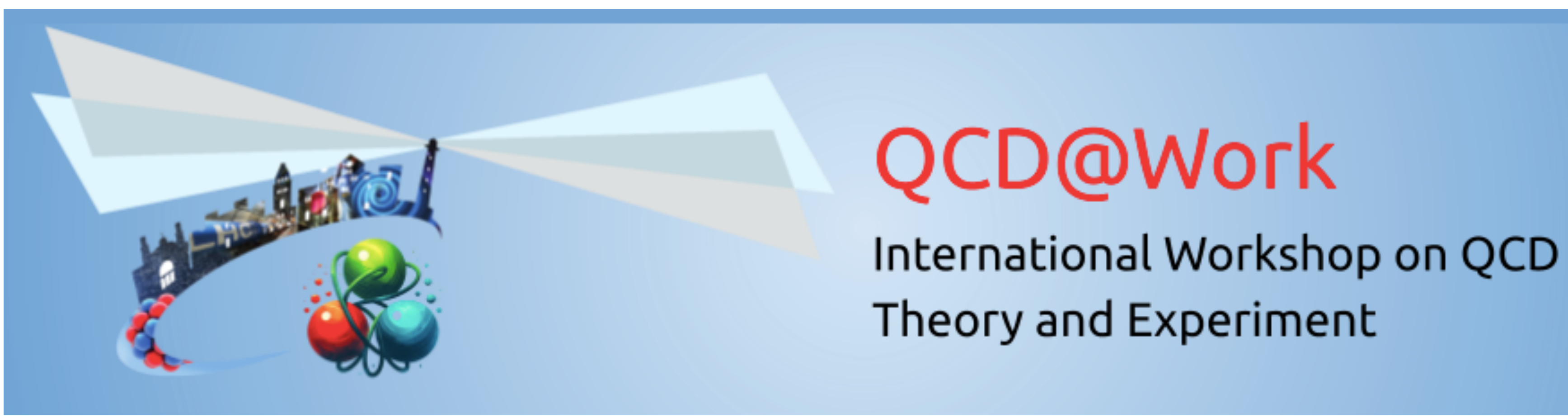
Exotic charmonium production in heavy ion collisions

F.S. Navarra

University of São Paulo

IFUSP
São Paulo
Brazil

L.M. Abreu, F.S. N, H.P.L. Vieira, arXiv:2401.11320



Exotic Charmonium

Not a state like: $c\,\bar{c}$

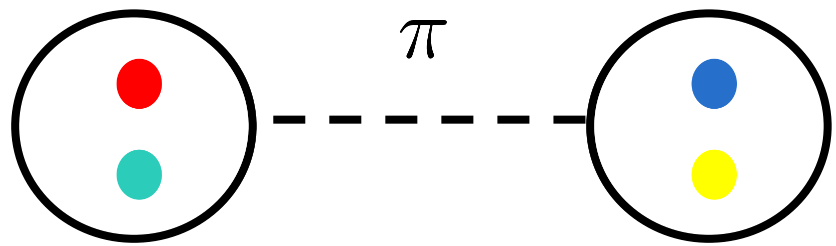
Multiquark state : $c\,\bar{c}\,q\,\bar{q}'$

Meson molecule

Large object: ~ 5 - 10 fm

Loosely bound

Meson exchange

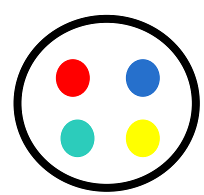


Tetraquark

Compact object: ~ 0.5 - 1 fm

Deeply bound

Color exchange



Use heavy ion collisions to determine the structure of X(3872)

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

Medium can act as a "filter" to separate different structures

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]

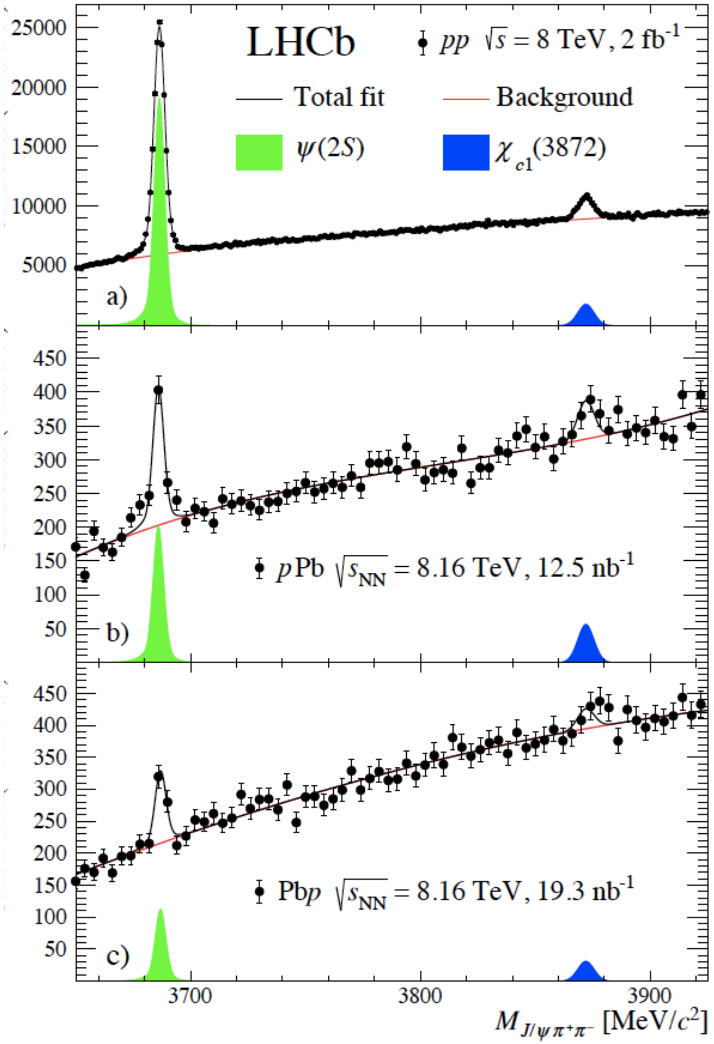
The data

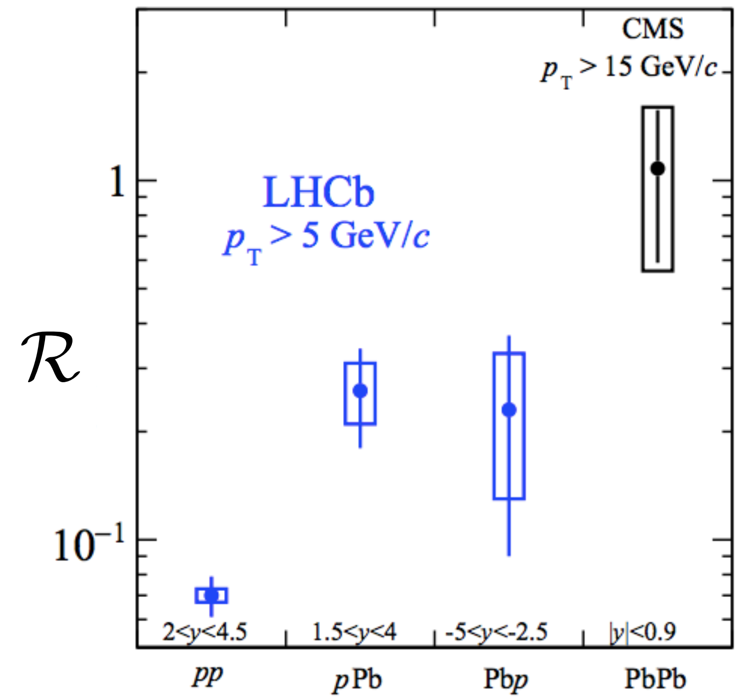
LHCb-CONF-2022-001
Quark Matter 2022

$$\psi_{2S}(3686) \to J/\psi\, \pi^+ \pi^-$$

$$X(3872) \to J/\psi\, \pi^+ \pi^-$$

$$\mathcal{R} = \frac{N_{X(3872)}}{N_{\psi(2S)}}$$



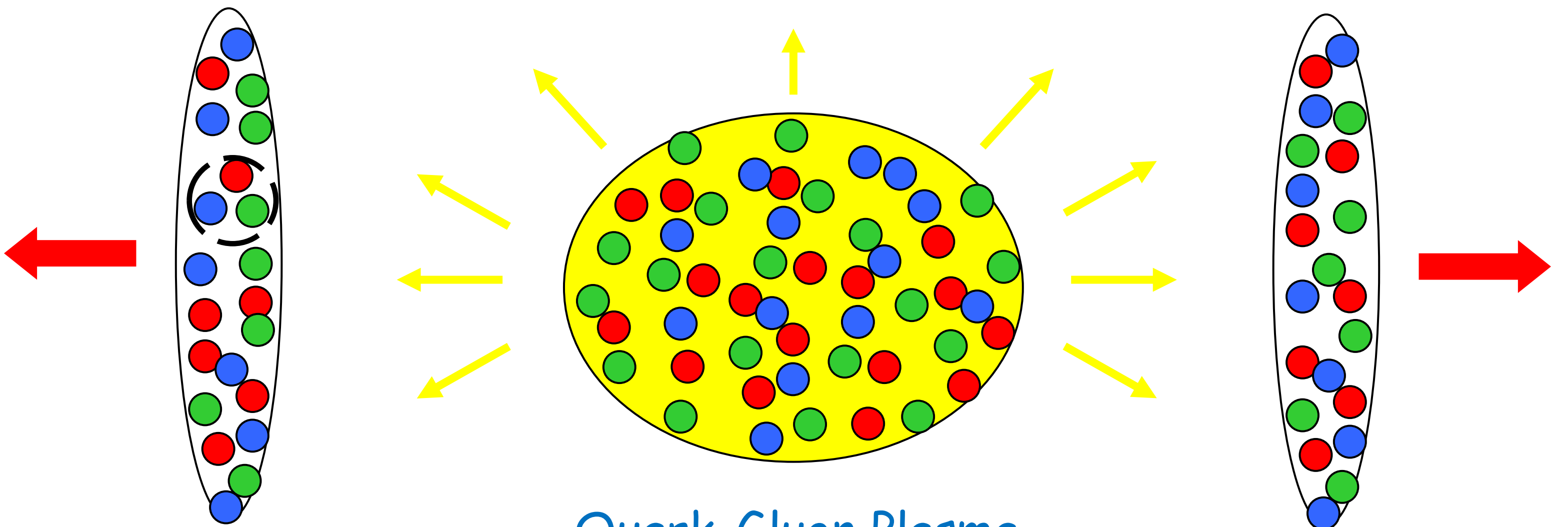


Medium effects :

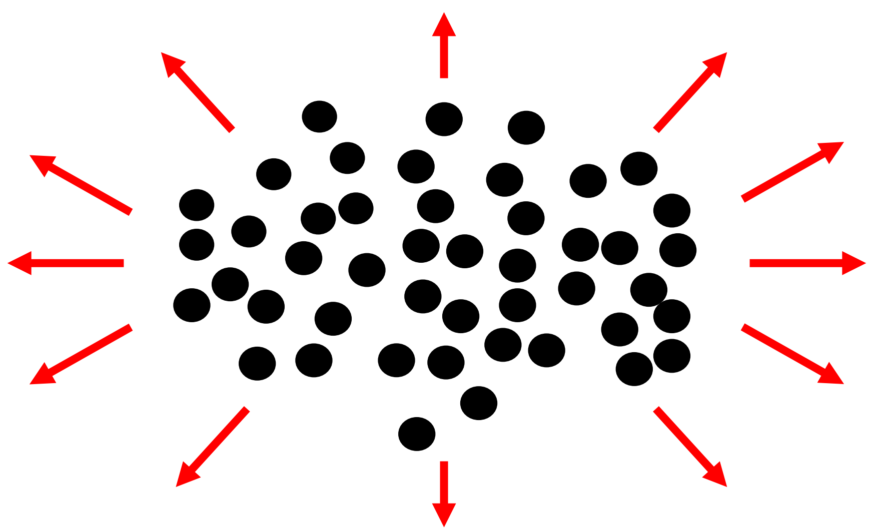
Formation at the end of QGP

Interactios in the hadron gas

Nucleus - Nucleus Collisions



Quark-Gluon Plasma



Hadron Gas

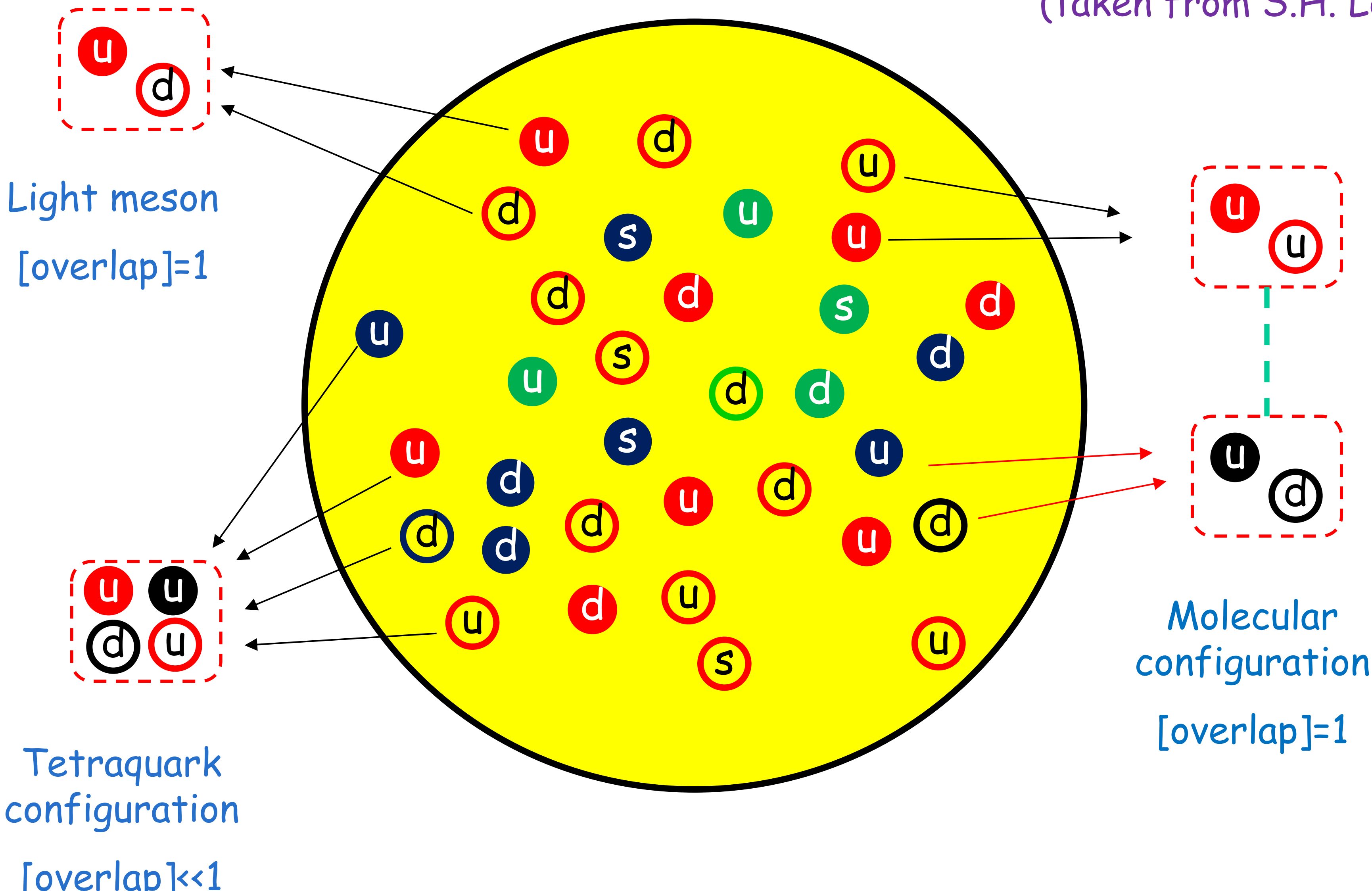
Thermal equilibrium

Hydrodynamical expansion

Lifetime ~ 10 fm

Hadron formation in the coalescence model

(taken from S.H. Lee)



Molecular configuration favored !

Coalescence model : geometry and dynamics of bound states

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

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

Pb - Pb collisions

$\sqrt{s} = 5.02$ TeV

$$\begin{cases} N_{\psi(2S)}(\tau_H) \approx 1.8 \times 10^{-4}, \\ N_X^{(4q)}(\tau_H) \approx 1.8 \times 10^{-4}, \\ N_X^{(Mol.)}(\tau_H) \approx 1.1 \times 10^{-2}, \end{cases}$$

At the end of QGP

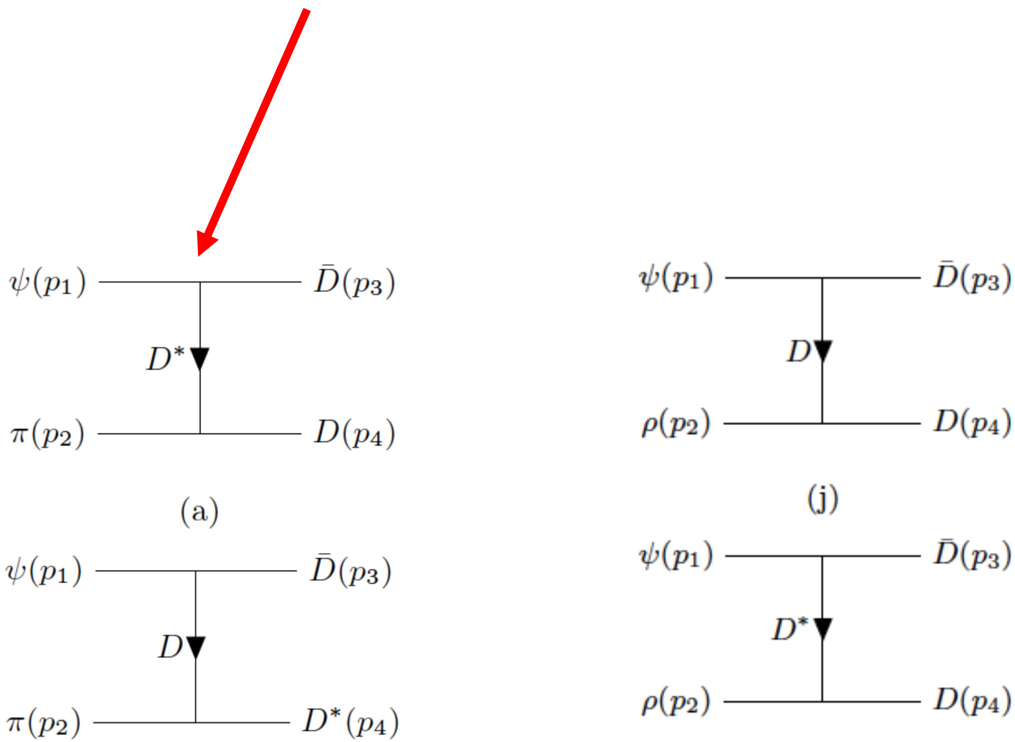
Before passing the hadron gas

$$\begin{cases} \dfrac{N_X^{(mol)}}{N_{\psi(2S)}} \simeq 50 \\ \dfrac{N_X^{(4q)}}{N_{\psi(2S)}} \simeq 1 \end{cases}$$

The interactions of J/Psi

Y.s. Oh, T. Song and S.H. Lee, arXiv:nucl-th/0010064

$$\begin{aligned}
\mathcal{L}_{\psi DD} &= g_{\psi DD}\psi_\mu(\partial^\mu D\bar{D} - D\partial^\mu\bar{D}),\\
\mathcal{L}_{\psi D^* D^*} &= -ig_{\psi D^* D^*}[\psi^\mu(\partial_\mu D^{*\nu}\bar{D}^*_\nu - D^{*\nu}\partial_\mu\bar{D}^*_\nu)\\
&\quad +(\partial_\mu\psi_\nu D^{*\nu} - \psi_\mu\partial_\nu D^{*\nu})\bar{D}^{*\mu}\\
&\quad +D^{*\mu}(\psi^\nu\partial_\mu\bar{D}^*_\nu - \partial_\mu\psi_\nu\bar{D}^{*\nu})],\\
\mathcal{L}_{\psi DD^*} &= -g_{\psi DD^*}\epsilon^{\mu\nu\alpha\beta}\partial_\mu\psi_\nu(\partial_\alpha D^*_\beta\bar{D} + D\partial_\alpha\bar{D}^*_\beta);
\end{aligned}$$



Form factors and couplings from QCD sum rules:

M.E. Bracco, M. Chiapparini, F.S. Navarra and M. Nielsen, arXiv:1104.2864

Form factors:

$$g_{abc}(Q^2) = \frac{A}{Q^2 + B}$$

$$g_{abc}(Q^2) = A\, e^{-\left(\frac{Q^2+B}{C}\right)}$$

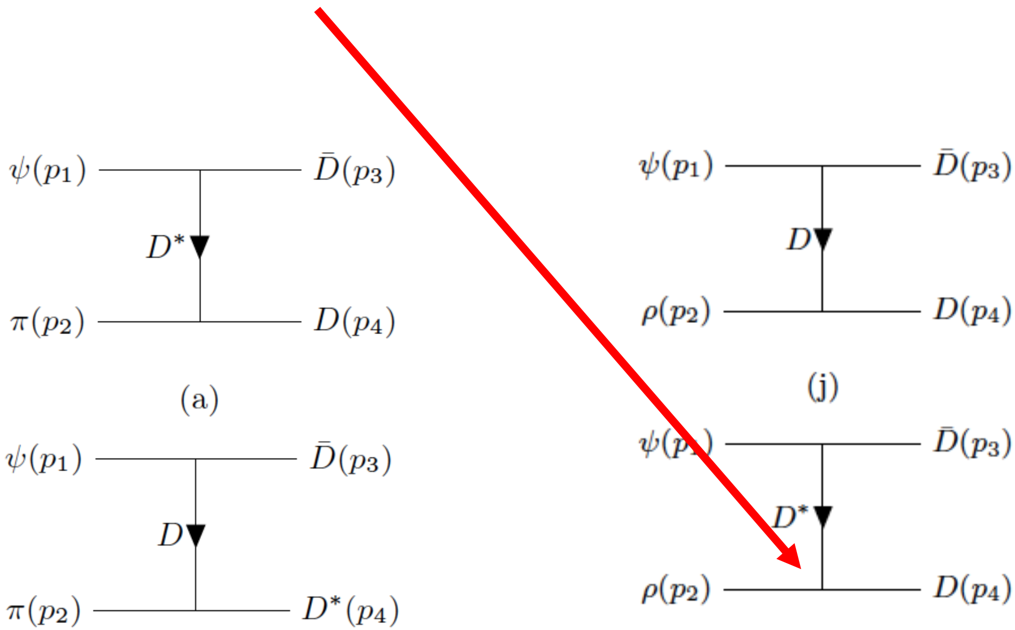
Couplings:

$$g_{abc} = g_{abc}(Q^2 = -m_c^2)$$

The interactions of J/Psi

Y.s. Oh, T. Song and S.H. Lee, arXiv:nucl-th/0010064

$$
\begin{aligned}
\mathcal{L}_{\pi D D^*} &= i g_{\pi D D^*} D^{*\mu} \vec{\tau} \cdot (\bar{D} \partial_\mu \vec{\pi} - \partial_\mu \bar{D} \vec{\pi}) + h.c., \\
\mathcal{L}_{\rho D D} &= i g_{\rho D D} (D \vec{\tau} \partial_\mu \bar{D} - \partial_\mu D \vec{\tau} \bar{D}) \cdot \vec{\rho}^{\mu}, \\
\mathcal{L}_{\rho D^* D^*} &= i g_{\rho D^* D^*} \left[(\partial_\mu D^{*\nu} \vec{\tau} \bar{D}^*_\nu - D^{*\nu} \vec{\tau} \partial_\mu \bar{D}^*_\nu) \cdot \vec{\rho}^{\mu} \right. \\
&\quad + (D^{*\nu} \vec{\tau} \cdot \partial_\mu \vec{\rho}_\nu - \partial_\mu D^{*\nu} \vec{\tau} \cdot \vec{\rho}_\nu) \bar{D}^{*\mu} \\
&\quad \left. + D^{*\mu} (\vec{\tau} \cdot \vec{\rho}^{\nu} \partial_\mu \bar{D}^*_\nu - \vec{\tau} \cdot \partial_\mu \vec{\rho}^{\nu} \bar{D}^*_\nu) \right], \\
\mathcal{L}_{\pi D^* D^*} &= -g_{\pi D^* D^*} \epsilon^{\mu\nu\alpha\beta} \partial_\mu D^8_\nu \pi \partial_\alpha \bar{D}^*_\beta, \\
\mathcal{L}_{\rho D D^*} &= -g_{\rho D D^*} \epsilon^{\mu\nu\alpha\beta} (D \partial_\mu \rho_\nu \partial_\alpha \bar{D}^*_\beta + \partial_\mu D^*_\nu \partial_\alpha \rho_\beta \bar{D})
\end{aligned}
$$



Form factors and couplings from QCD sum rules:

M.E. Bracco, M. Chiapparini, F.S. Navarra and M. Nielsen, arXiv:1104.2864

Form factors:

$$g_{abc}(Q^2) = \frac{A}{Q^2 + B}$$

$$g_{abc}(Q^2) = A\, e^{-\left(\frac{Q^2+B}{C}\right)}$$

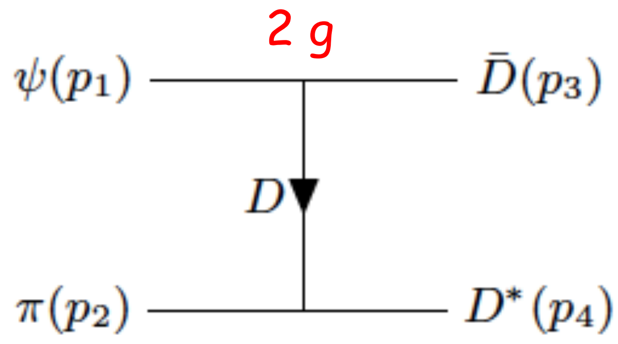
Couplings:

$$g_{abc} = g_{abc}(Q^2 = -m_c^2)$$

The interactions of Psi(2S)

$$r_{\psi(2S)} \simeq 2\, r_{J/\psi} \quad \longrightarrow \quad \sigma_{\psi(2S)} \simeq 4\, \sigma_{J/\psi}$$

$\sigma_{\psi(2S)} \propto$ | diagram |^2 $\propto 4\, g^2$



$$g_{\psi(2S) D\bar{D}} = \left[g_{J/\psi D\bar{D}} \, , 2\, g_{J/\psi D\bar{D}} \right]$$

main source of uncertainty

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

$$\sigma_{cd\to ab}(s) = \frac{g_a g_b}{g_c g_d} \frac{|\vec{p}_{ab}|}{|\vec{p}_{cd}|} \sigma_{ab\to cd}(s)$$

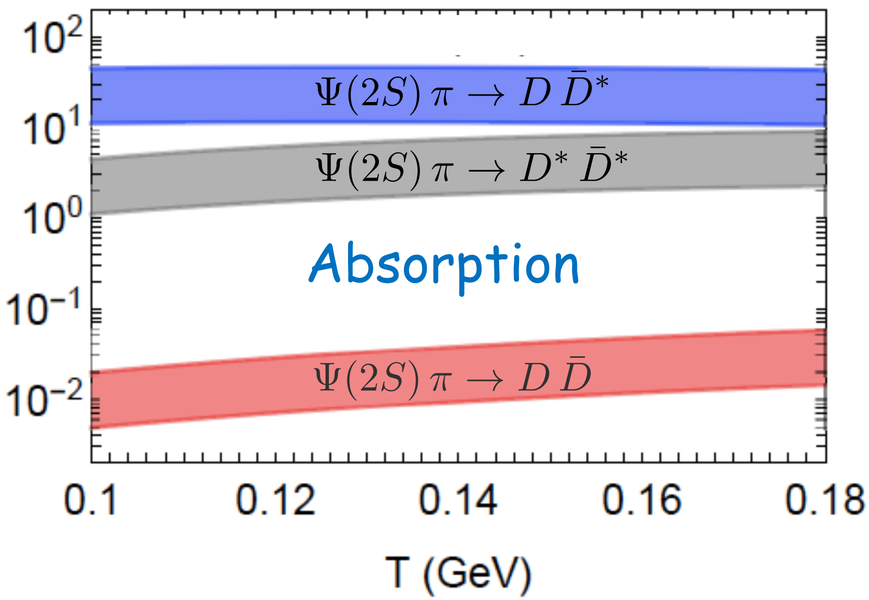
inverse reaction

In-medium "thermal" cross sections

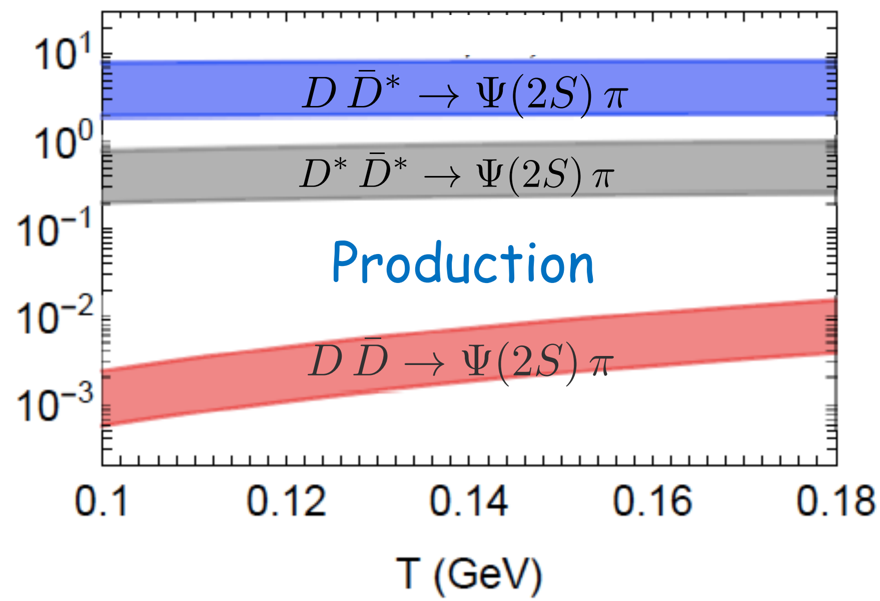
$$\langle \sigma_{ab\to cd} v_{ab} \rangle = \frac{\int d^3\mathbf{p}_a d^3\mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b) \sigma_{ab\to cd}\, v_{ab}}{\int d^3\mathbf{p}_a d^3\mathbf{p}_b f_a(\mathbf{p}_a) f_b(\mathbf{p}_b)}$$

$f_i(\mathbf{p}) =$ thermal distribution $v_{ab} =$ relative velocity

$\sigma(mb)$



$\sigma(mb)$



Time evolution of the multiplicities

$$\frac{dN_\psi}{d\tau} = < \sigma(D\bar{D} \to \Psi(2S)\pi) > \; n_D(\tau)\, N_{\bar{D}}(\tau) - \; < \sigma(\Psi(2S)\pi \to D\bar{D}) > \; n_\pi(\tau)\, N_\psi(\tau)$$

Time evolution of the multiplicities

gain loss

$$\frac{dN_h(\tau)}{d\tau} = \sum_{\substack{\bar{c}=\bar{D},\bar{D}^*;\\ c=D,D^*;\\ \varphi=\pi,\rho}} \left[\langle \sigma_{\bar{c}c\to\varphi h} v_{\bar{c}c}\rangle n_{\bar{c}}(\tau) N_c(\tau) \; - \; \langle \sigma_{\varphi h\to\bar{c}c} v_{\psi\varphi}\rangle n_{\varphi}(\tau) N_h(\tau)\right]$$

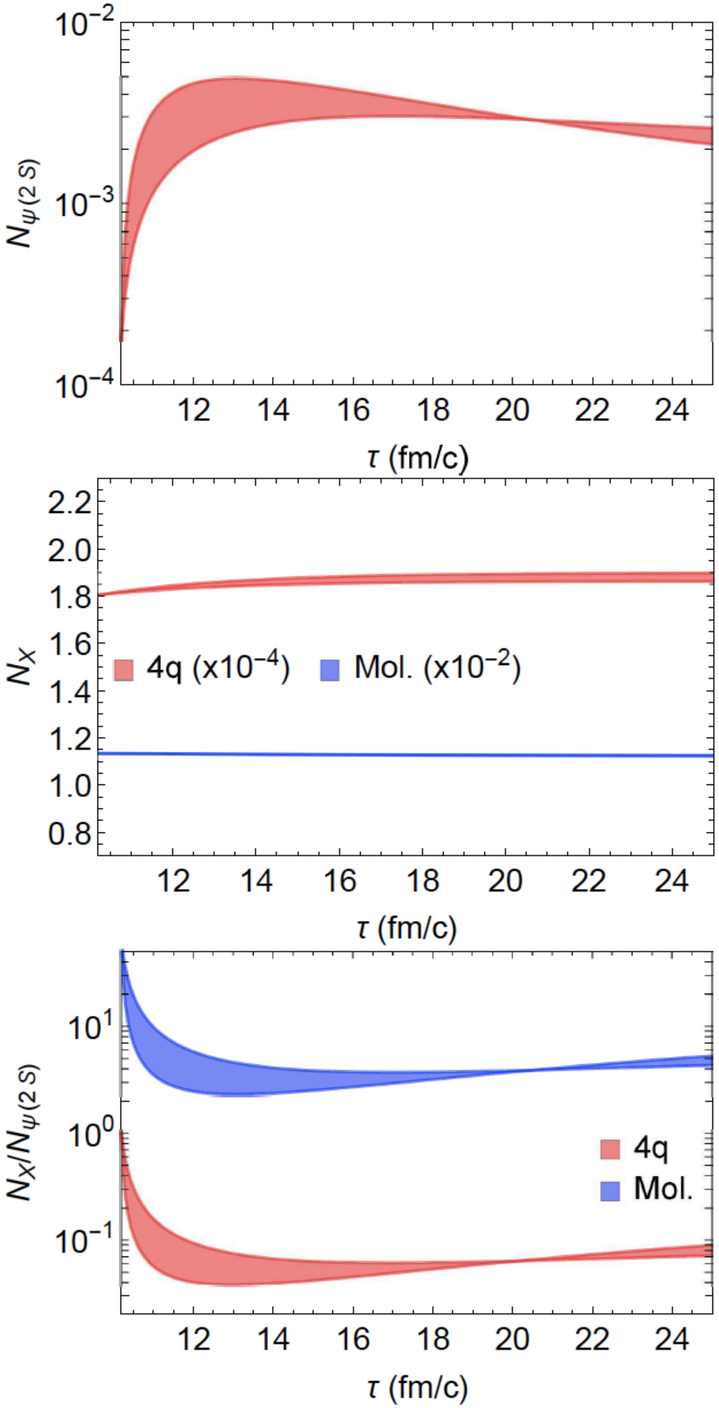
$$n_i(\tau) \approx \frac{1}{2\pi^2}\gamma_i g_i m_i^2 T(\tau) K_2\left(\frac{m_i}{T(\tau)}\right)$$

$$N_c(\tau) = n_c(\tau)\,.\,V(\tau)$$

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

Parameters fixed in:

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



grows by a factor 10 !

A. Martinez Torres et al. , arXiv:1405.7583

S. Cho and S.H. Lee arXiv:1405.7583

before the hadron gas :

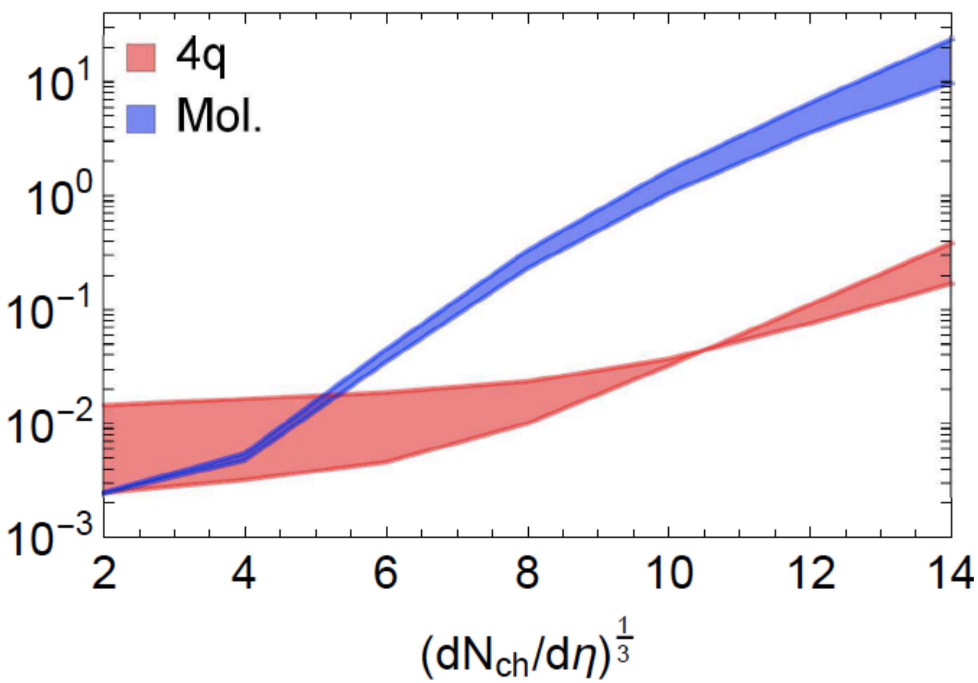
$$\frac{N_X^{(mol)}}{N_{\psi(2S)}} \simeq 5 \qquad \frac{N_X^{(mol)}}{N_{\psi(2S)}} \simeq 50$$

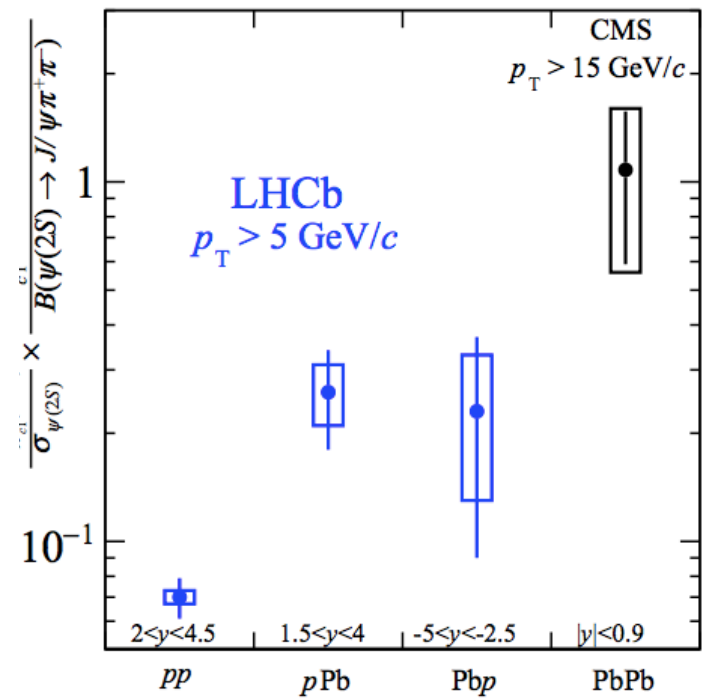
$$\frac{N_X^{(4q)}}{N_{\psi(2S)}} \simeq 1 \qquad \frac{N_X^{(4q)}}{N_{\psi(2S)}} \simeq 0.1$$

System size dependence

L.M. Abreu, F.S. N, H.P.L. Vieira, arXiv:2401.11320

$$\mathcal{R} = \frac{N_{X(3872)}}{N_{\psi(2S)}}$$



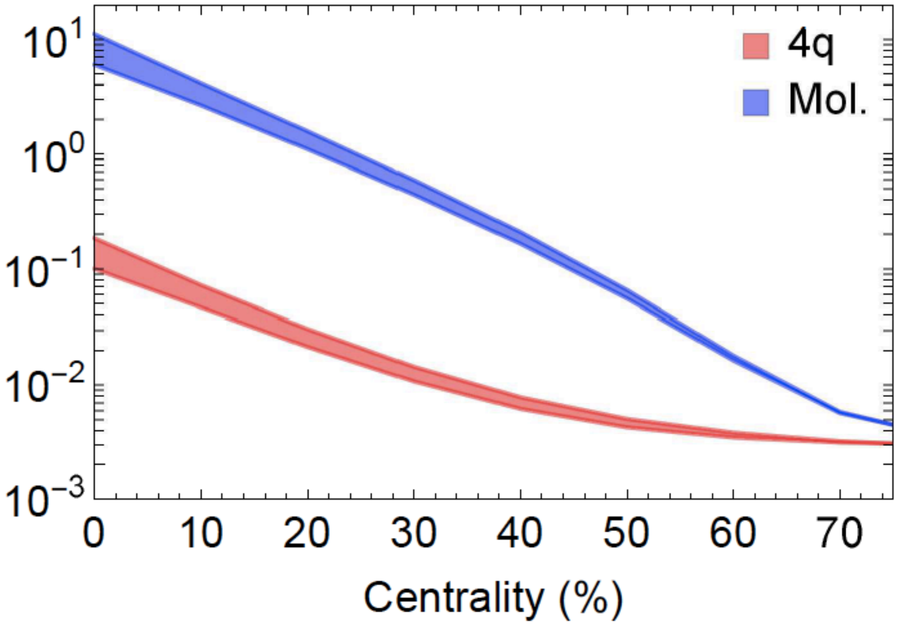


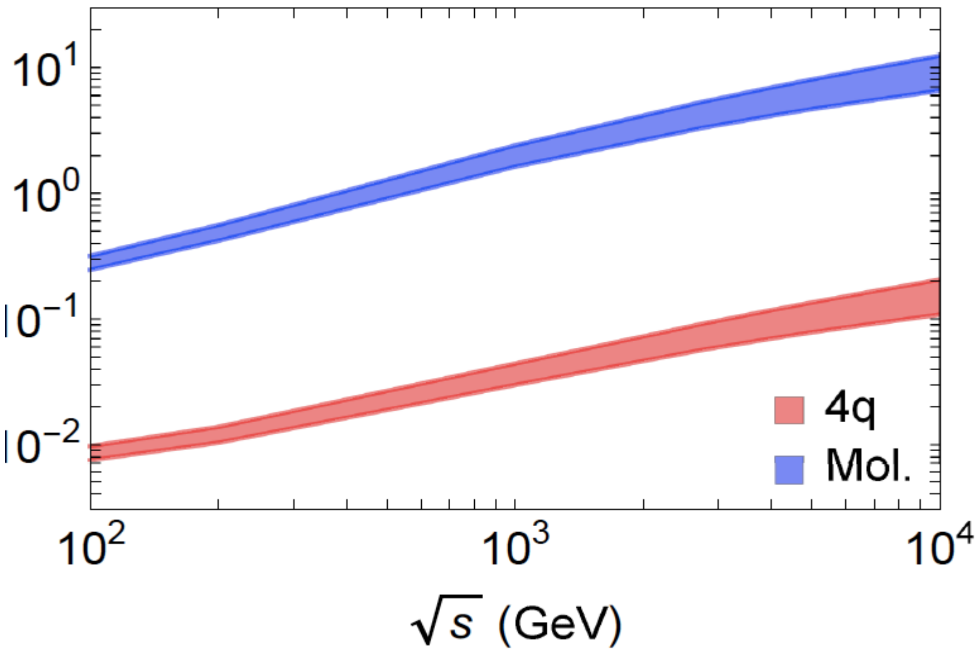
Centrality and energy dependence

L.M. Abreu, F.S. N, H.P.L. Vieira, arXiv:2401.11320

$$\mathcal{R} = \frac{N_{X(3872)}}{N_{\psi(2S)}}$$

Pb-Pb collisions





Summary

Production and absorption of X(3872) and Psi(2S) in a hadron gas

Initial conditions from QGP given by the Coalescence Model

Effective Lagrangians for the interactions

Thermal cross sections to solve rate equations

Multiplicities change with time.

$$\mathcal{R} = \frac{N_{X(3872)}}{N_{\psi(2S)}}$$

- Increases with time
- Increases with system size
- Increases with energy
- Decreases with centrality

Prediction for ALICE:

$$\frac{N_X}{N_{\psi(2S)}} \simeq 5$$ molecules

$$\frac{N_X}{N_{\psi(2S)}} \simeq 0.1$$ tetraquarks

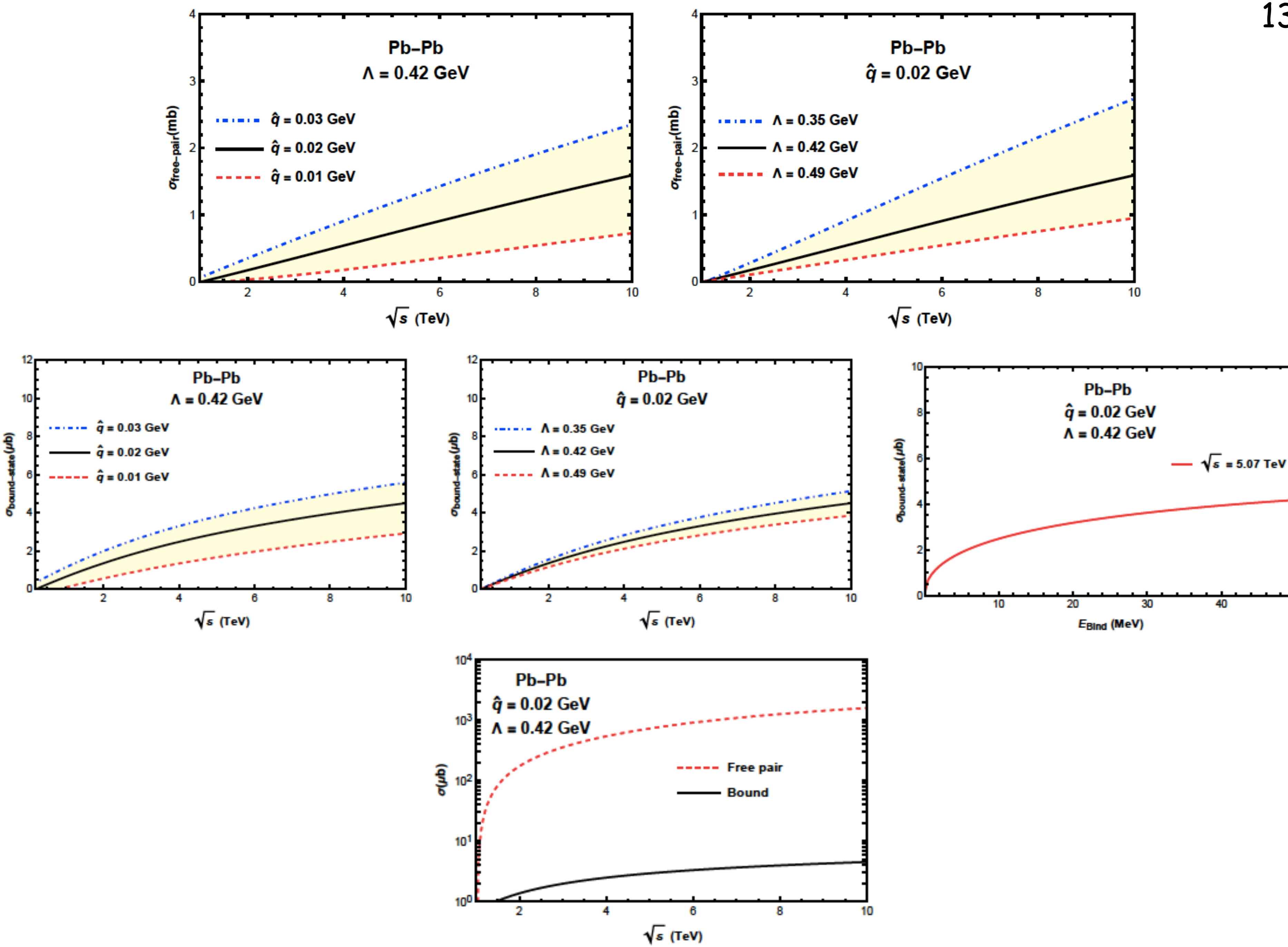

Thank you !

Prediction for ALICE:

(which includes low transverse momenta)

$$\frac{N_X}{N_{\psi(2S)}} \simeq 5 \qquad \text{for molecules}$$

$$\frac{N_X}{N_{\psi(2S)}} \simeq 0.1 \qquad \text{for tetraquarks}$$


Pb–Pb
Λ = 0.42 GeV
q̂ = 0.03 GeV
q̂ = 0.02 GeV
q̂ = 0.01 GeV
σfree–pair(mb)
√s (TeV)
Pb–Pb
q̂ = 0.02 GeV
Λ = 0.35 GeV
Λ = 0.42 GeV
Λ = 0.49 GeV
σfree–pair(mb)
√s (TeV)
Pb–Pb
Λ = 0.42 GeV
q̂ = 0.03 GeV
q̂ = 0.02 GeV
q̂ = 0.01 GeV
σbound–state(μb)
√s (TeV)
Pb–Pb
q̂ = 0.02 GeV
Λ = 0.35 GeV
Λ = 0.42 GeV
Λ = 0.49 GeV
σbound–state(μb)
√s (TeV)
Pb–Pb
q̂ = 0.02 GeV
Λ = 0.42 GeV
√s = 5.07 TeV
σbound–state(μb)
EBind (MeV)
Pb–Pb
q̂ = 0.02 GeV
Λ = 0.42 GeV
Free pair
Bound
σ(μb)
√s (TeV)

$$\sigma(Pb\,Pb \to Pb\,Pb\,D^+D^-) = 0.75^{+0.4}_{-0.4}\ \mathrm{mb}$$

$$\sigma_{exclusive}(Pb\,Pb \to Pb\,Pb\,c\bar{c}) = 1.5^{+0.4}_{-0.4}\ \mathrm{mb}.$$

$$\sigma_{QED}(Pb\,Pb \to Pb\,Pb\,c\,\bar{c}\,X) \approx \sigma_{QCD}(p\,p \to p\,p\,c\,\bar{c}\,X)$$

$$\sigma_{inclusive}(p\,p \to c\,\bar{c}\,X) = 8.43^{+1.05}_{-1.16}\ \mathrm{mb}$$

$$\sigma(Pb\,Pb \to Pb\,Pb\,B) = 3.0^{+0.8}_{-1.2}\ \mu\mathrm{b}$$

$$5 \leq \sigma(Pb\,Pb \to Pb\,Pb\,R) \leq 11\ \mu b$$

$$I)\quad g_{M_1 M_2 M_3} = \frac{A}{Q^2 + B},$$

$$II)\quad g_{M_1 M_2 M_3} = A\, e^{-\left(\frac{B+Q^2}{C}\right)}$$

M_1 M_2 M_3	Form	A	B	C
ψDD	II	5.8	20	15.8
$\psi D^* D$	II	20	27	18.6
$\psi D D^*$	II	13	26	21.2
$\psi D^* D^*$	II	6.2	0	3.55
$\pi D D^*$	I	126	11.9	-
$\pi D^* D$	I	126	11.9	-
ρDD	I	37.5	12.1	-
$\rho D^* D^*$	II	4.9	0	13.3
$\pi D^* D^*$	II	4.8	0	6.8
$\rho D D^*$	I	234	44	-
$\rho D^* D$	I	234	44	-

System size dependence

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

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

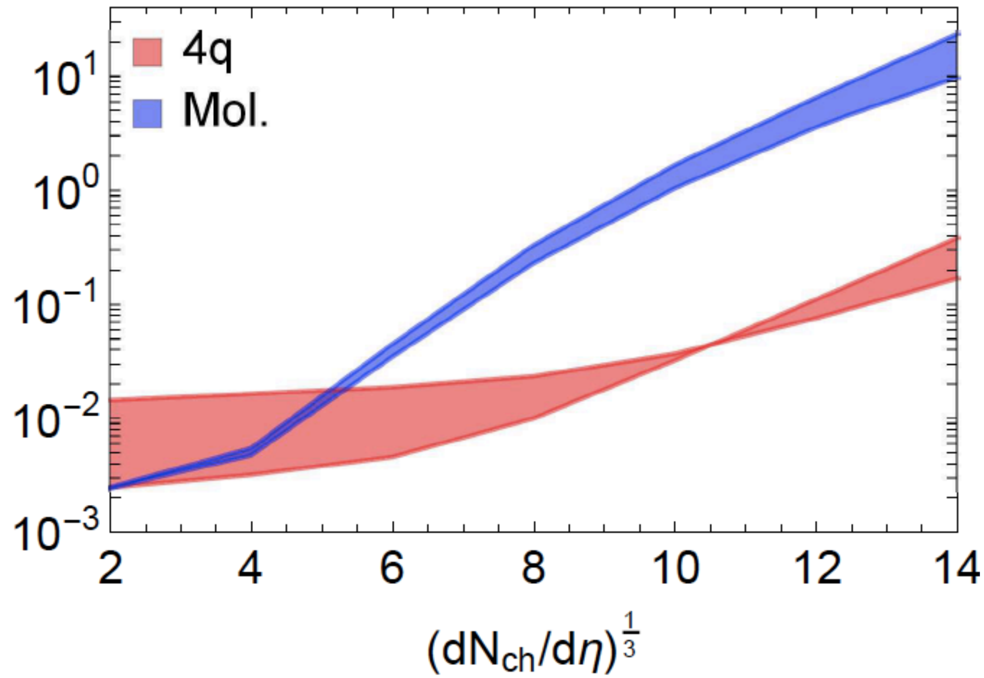
$$\tau_F = \tau_H \left(\frac{T_H}{T_{F0}}\right)^3 e^{3b\mathcal{N}}$$

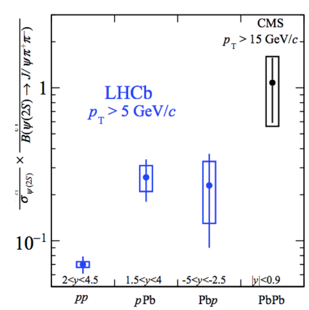
$$V = 2.82\mathcal{N}^3$$

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

$$N_u = N_d = 0.37\mathcal{N}^3.$$

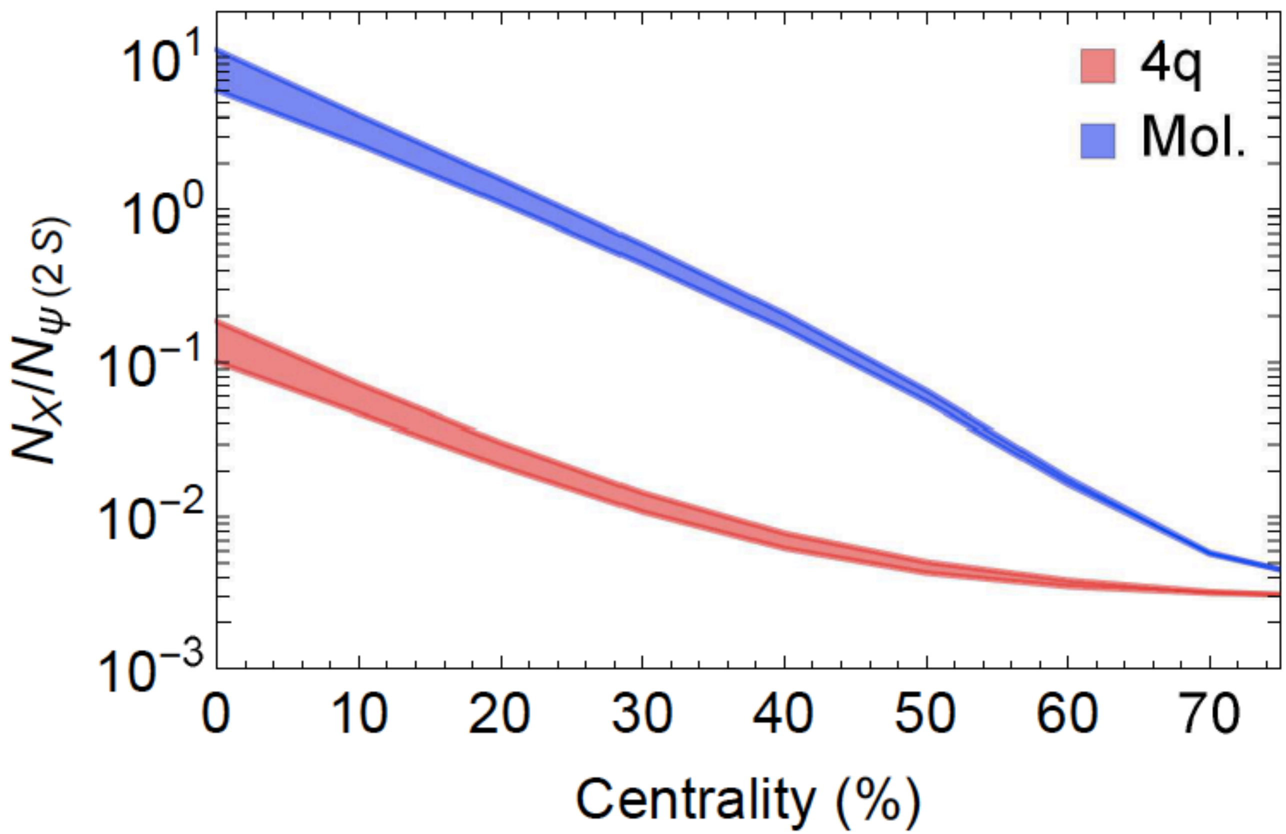
$$\mathcal{R} = \frac{N_{X(3872)}}{N_{\psi(2S)}}$$





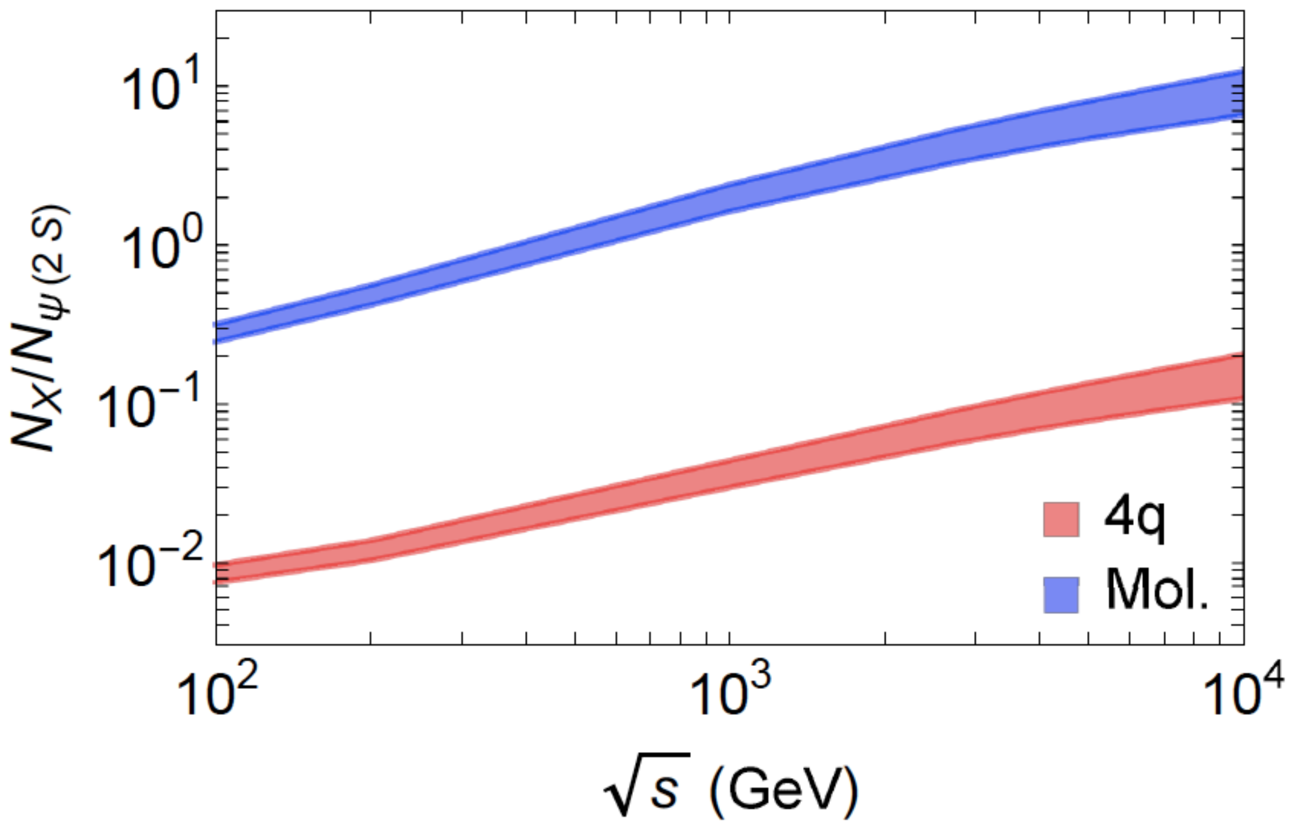
Centrality dependence

$$\frac{dN_{ch}}{d\eta}\bigg|_{|\eta|<0.5} = 2142.16 - 85.76x + 1.89x^2 - 0.03x^3 + 3.67\times10^{-5}\ x^4 - 2.24\times10^{-6}\ x^5 + 5.25\times10^{-9}\ x^6, \quad (17)$$

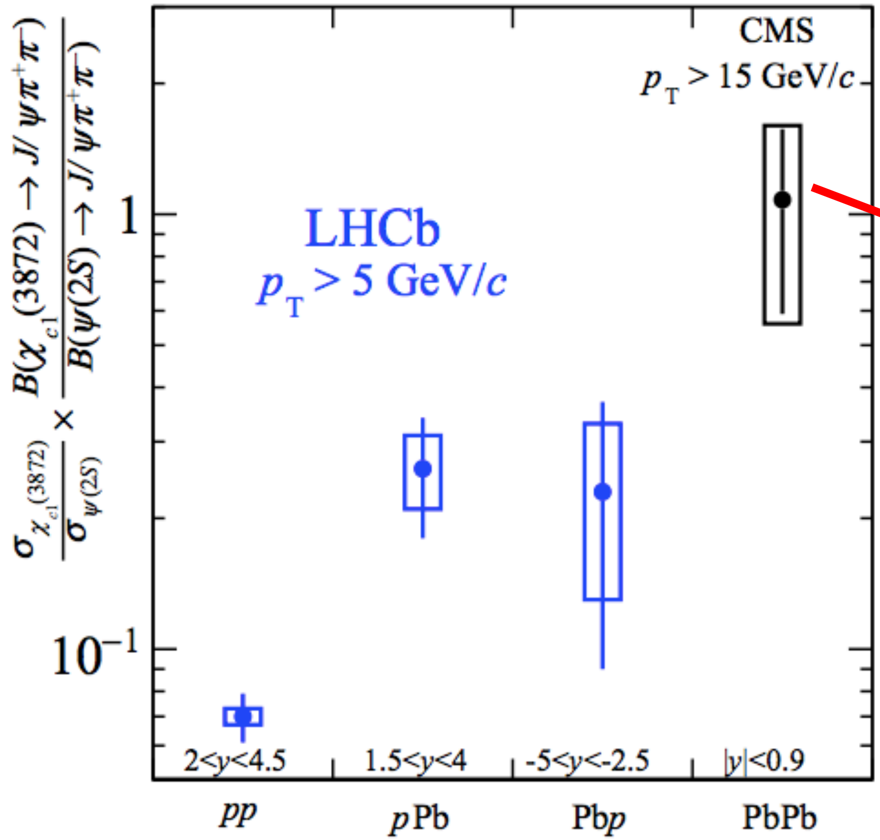


Energy dependence

$$\left.\frac{dN_{ch}}{d\eta}\right|_{|\eta|<0.5} = -2332.12 + 491.69\,\log(220.06 + \sqrt{s})$$



$$\mathcal{R} = \frac{N_{X(3872)}}{N_{\psi(2S)}}$$



Medium effects !

Interactios in the hadron gas

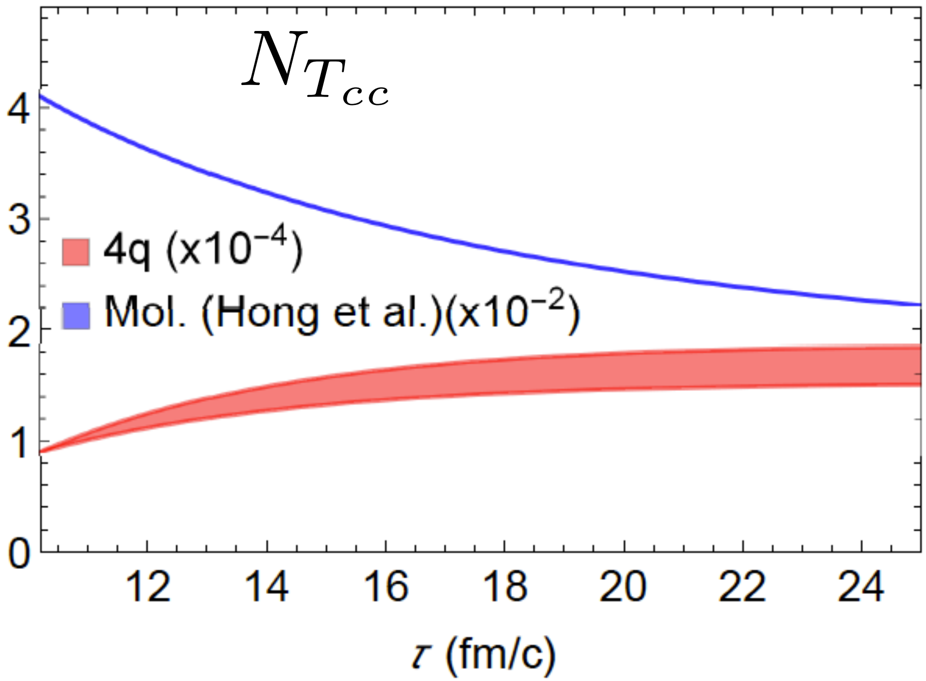
LHCb, arXiv:2402.14975

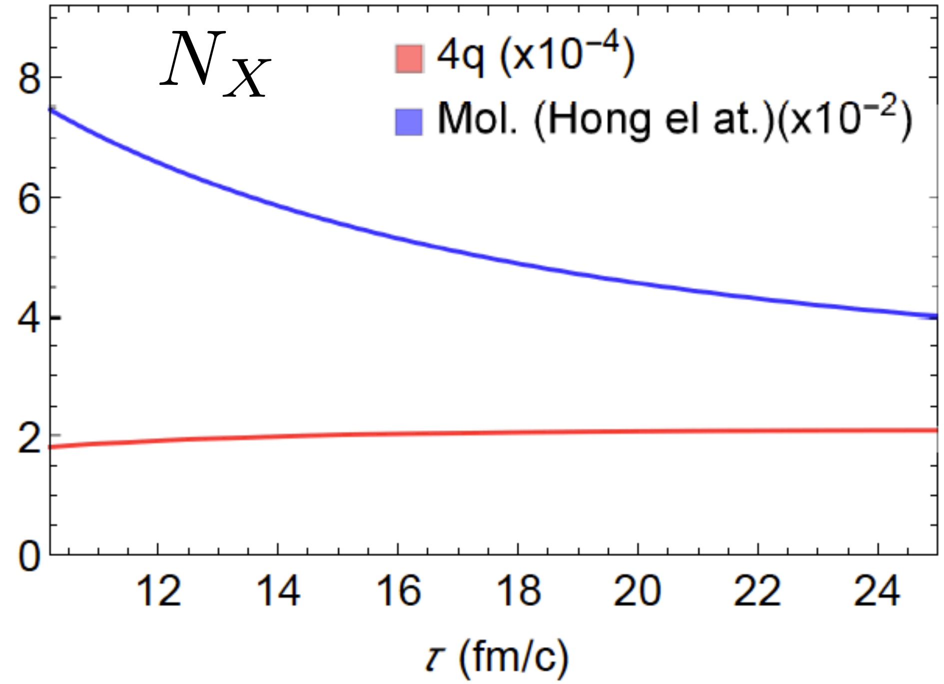
Multiplicities

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

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

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





Difference of multiplicities decreases but remain large !

Tetraquarks: Thermal Cross Sections and Rate Equation

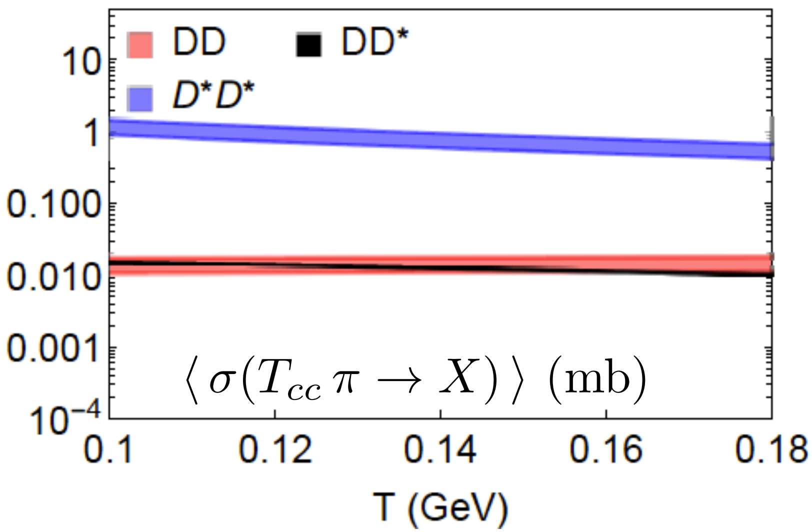
Abreu, Navarra, Vieira, PRD (2022), arXiv:2202.10882

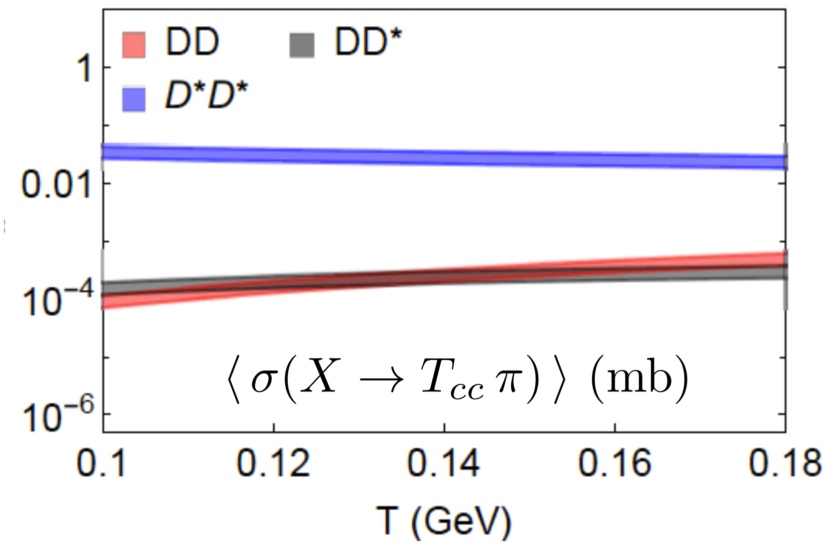
$$\langle \sigma_{ab\to cd}\, v_{ab} \rangle = \frac{\int d^3\mathbf{p}_a d^3\mathbf{p}_b\, f_a(\mathbf{p}_a)\, f_b(\mathbf{p}_b)\, \sigma_{ab\to cd}\; v_{ab}}{\int d^3\mathbf{p}_a d^3\mathbf{p}_b\, f_a(\mathbf{p}_a)\, f_b(\mathbf{p}_b)}$$

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

$v_{ab} =$ relative velocity

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





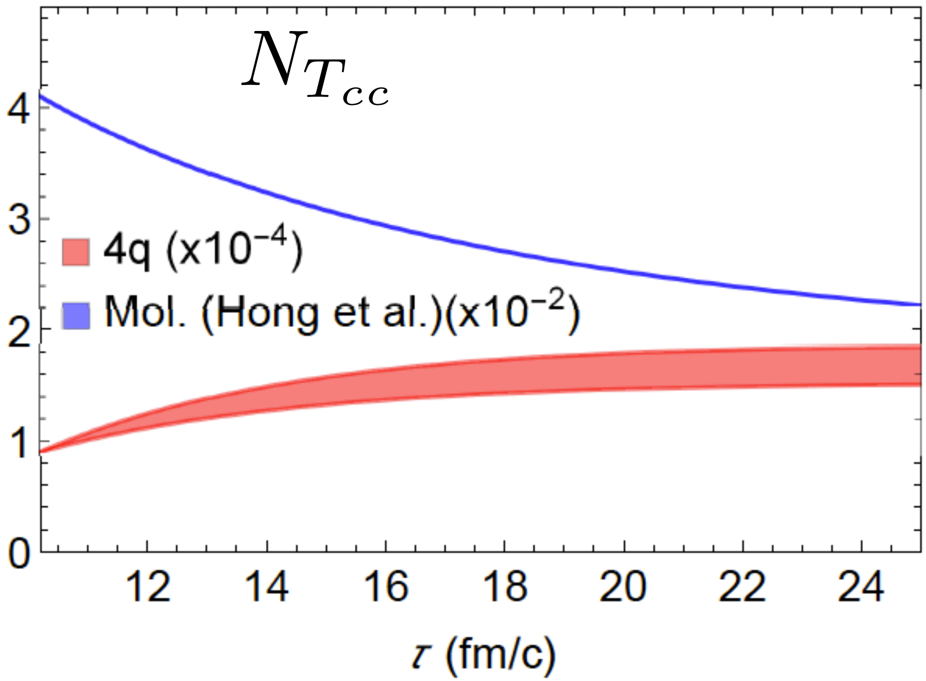
$$\frac{dN_{T_{cc}}(\tau)}{d\tau} = \sum_{\substack{c,c'=D,D^* \\ \varphi=\pi,\rho}} \left[\langle \sigma_{cc'\to T_{cc}\varphi} v_{cc'} \rangle n_c(\tau) N_{c'}(\tau) - \langle \sigma_{\varphi T_{cc}\to cc'} v_{T_{cc}\varphi} \rangle n_\varphi(\tau) N_{T_{cc}}(\tau)\right]$$

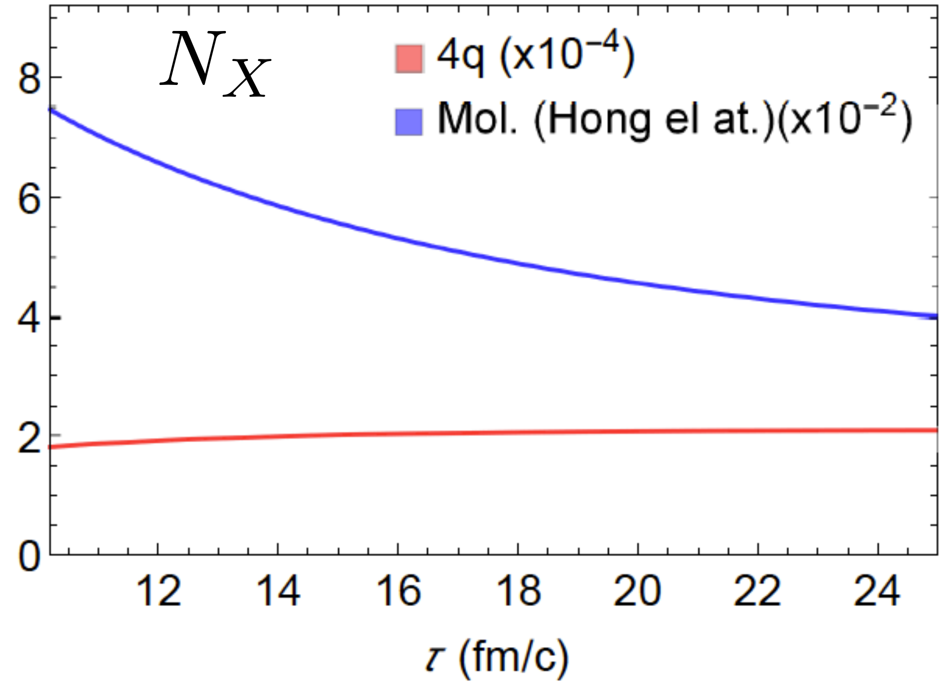
Multiplicities

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

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

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





Difference of multiplicities decreases but remain large !


Thank you !

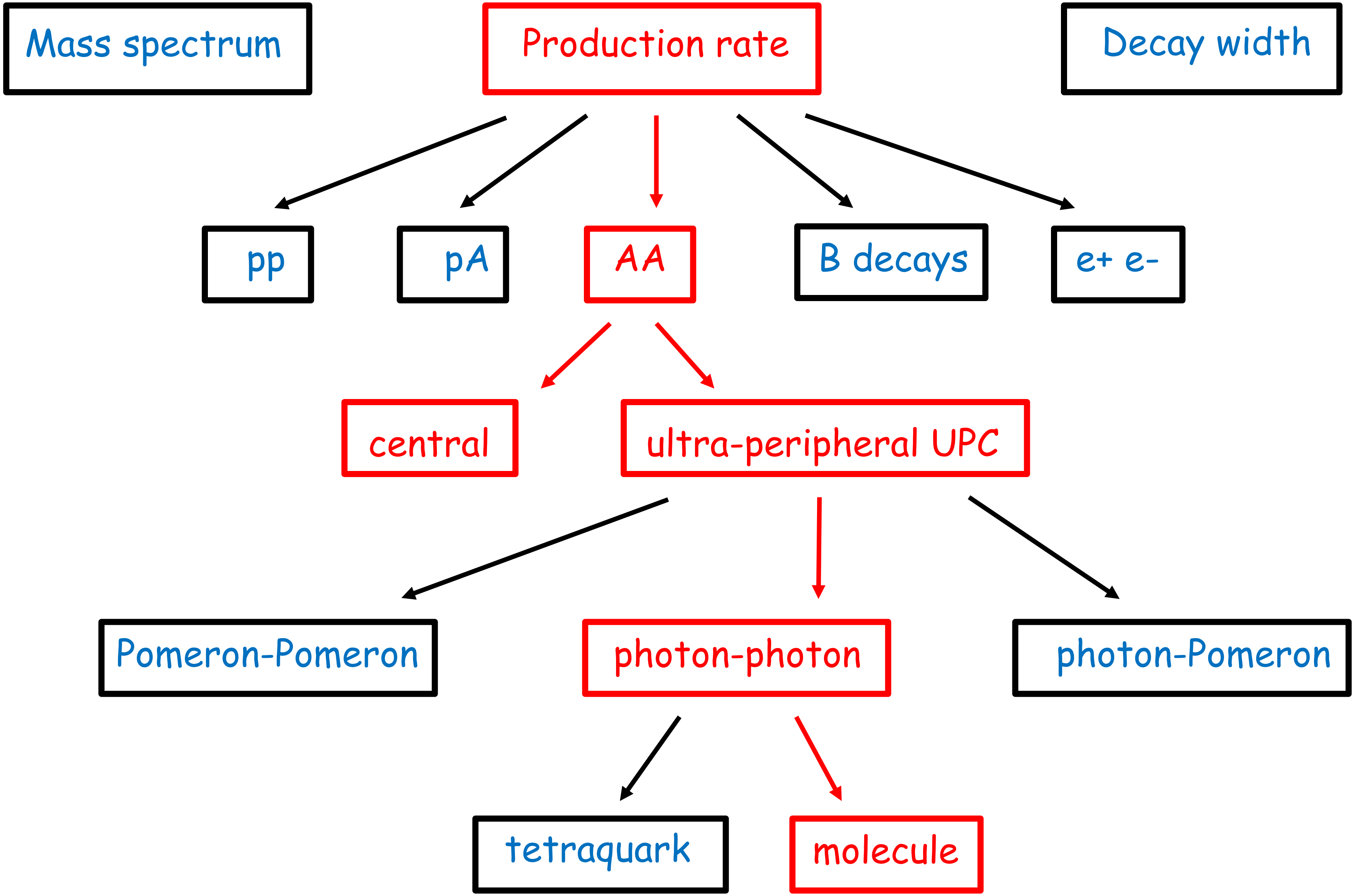
I - Production of exotic charmoniun in ultra-peripheral collisions (UPC)

F.C. Sobrinho, L.M. Abreu, C. A. Bertulani, F.S. Navarra, arXiv:2405.02645

II - Production of exotic charmoniun in central collisions

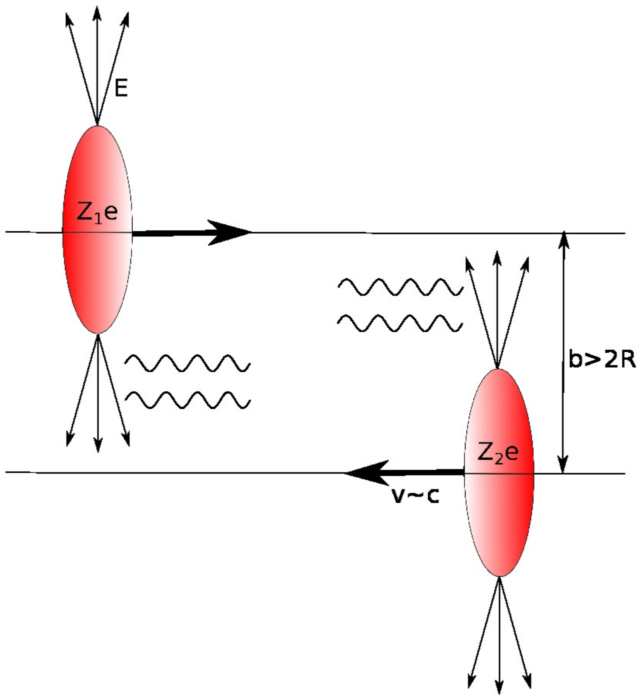
L.M. Abreu, F.S. Navarra, H.P.L. Vieira, arXiv:2401.11320

Studying Exotic Charmonium



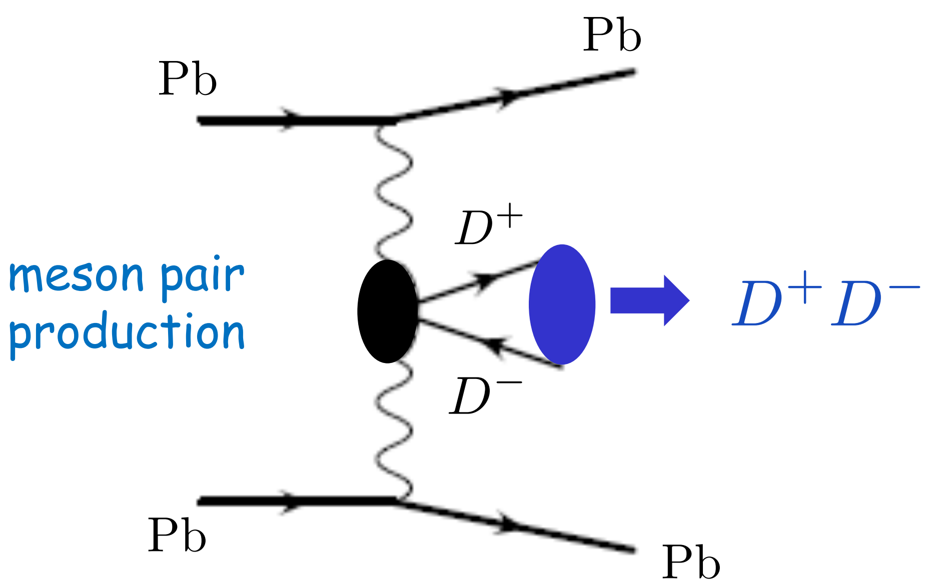
Production of charm molecules in Ultra-Peripheral Collisions

UPC:



C. A. Bertulani, S. R. Klein, and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55, 271 (2005), arXiv:nucl-ex/0502005.

The lightest charm molecule : D^+D^-



$$\sqrt{s_{NN}} = 5.02\ TeV$$

Lightest Charm Molecule : scalar D^+D^- bound state

Known as $X(3700)$ $M \approx 3723\ \mathrm{MeV}$

Predicted in:

D. Gamermann, E. Oset, D. Strottman and M. J. Vicente Vacas, Phys. Rev. D 76, 074016 (2007).

C. Hidalgo-Duque, J. Nieves and M. P. Valderrama, Phys. Rev. D 87, 076006 (2013).

J. Nieves and M. P. Valderrama, Phys. Rev. D 86, 056004 (2012).

S. Prelovsek, S. Collins, D. Mohler, M. Padmanath and S. Piemonte, JHEP 06, 035 (2021).

Experimental evidence (not conclusive) in:

S. Uehara et al. (Belle Collaboration), Phys. Rev. Lett. 96, 082003 (2006).

B. Aubert et al. (BaBar Collaboration), Phys. Rev. D81, 092003 (2010).

Recent works:

M.~Ablikim et al. [BESIII], Phys. Rev. D 108, 052012 (2023)

P. C. S. Brandao, J. Song, L. M. Abreu and E. Oset, Phys. Rev. D 108, 054004 (2023)

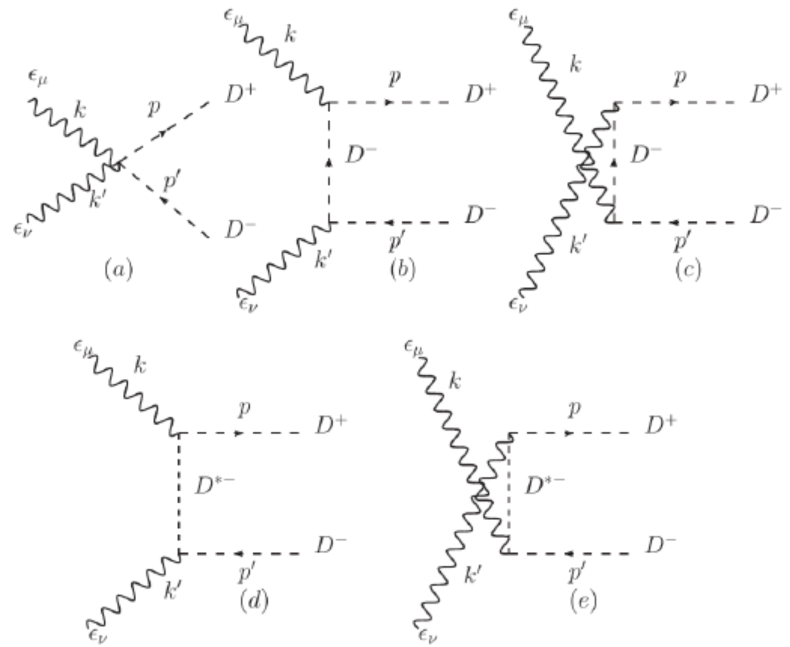
Meson Pair Production in Photon-Photon Collisions

$$\mathcal{L} = -ig_{\gamma D^+ D^{*-}} F_{\mu\nu} \epsilon^{\mu\nu\alpha\beta} (D^{*-}_\alpha \overleftrightarrow{\partial}_\beta D^+ + D^- \overleftrightarrow{\partial}_\beta D^{*+}_\alpha)$$

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - m_D^2 \phi^* \phi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$D_\mu \phi = \partial_\mu \phi + ieA_\mu \phi$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$



Form factors in the vertices:

$$F(q^2) = \frac{\Lambda^2 - m_D^2}{\Lambda^2 - q^2} \qquad F(m_D^2) = 1$$

Parameter !

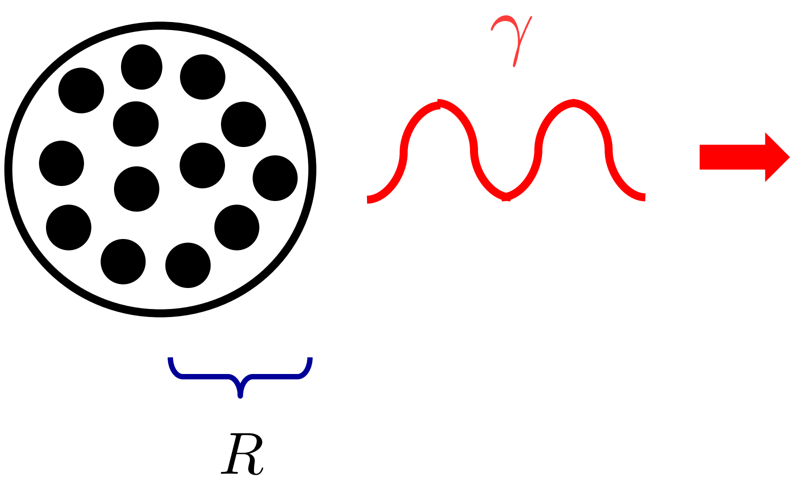
$$\sigma_P = \frac{1}{64\pi^2} \frac{1}{\hat{s}} \sqrt{1 - \frac{4m_D^2}{\hat{s}}} \int |M(\gamma\gamma \to D^+ D^-)|^2 d\Omega$$

The Number of Equivalent Photons

F.C. Sobrinho, L.M. Abreu, C. A. Bertulani, F.S. Navarra, arXiv:2405.02645

$$n(\vec{q})d^3q = \frac{Z^2\alpha}{\pi^2}\frac{(\vec{q}_\perp)^2}{\omega\, q^4}d^3q = \frac{Z^2\alpha}{\pi^2\omega}\frac{(\vec{q}_\perp)^2}{\left((\vec{q}_\perp)^2+(\omega/\gamma)^2\right)^2}d^3q$$

Coherent emission: the photon does not resolve the charges in the source



minimum wavelength : $2\,R$

maximum transverse momentum :

$$\hat{q} = \frac{1}{2R}$$

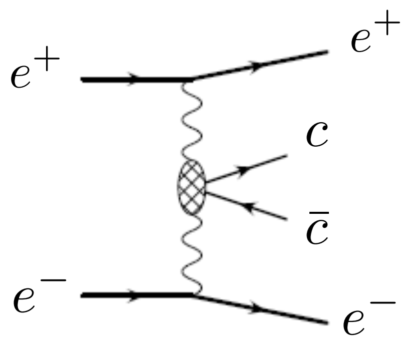
Parameter !

Pb : $\hat{q} = 0.014\,\mathrm{GeV}$

proton : $\hat{q} = 0.1\,\mathrm{GeV}$

$$n(\omega)d\omega = \frac{2Z^2\alpha}{\pi}\ln\left(\frac{\hat{q}\gamma}{\omega}\right)\frac{d\omega}{\omega}$$

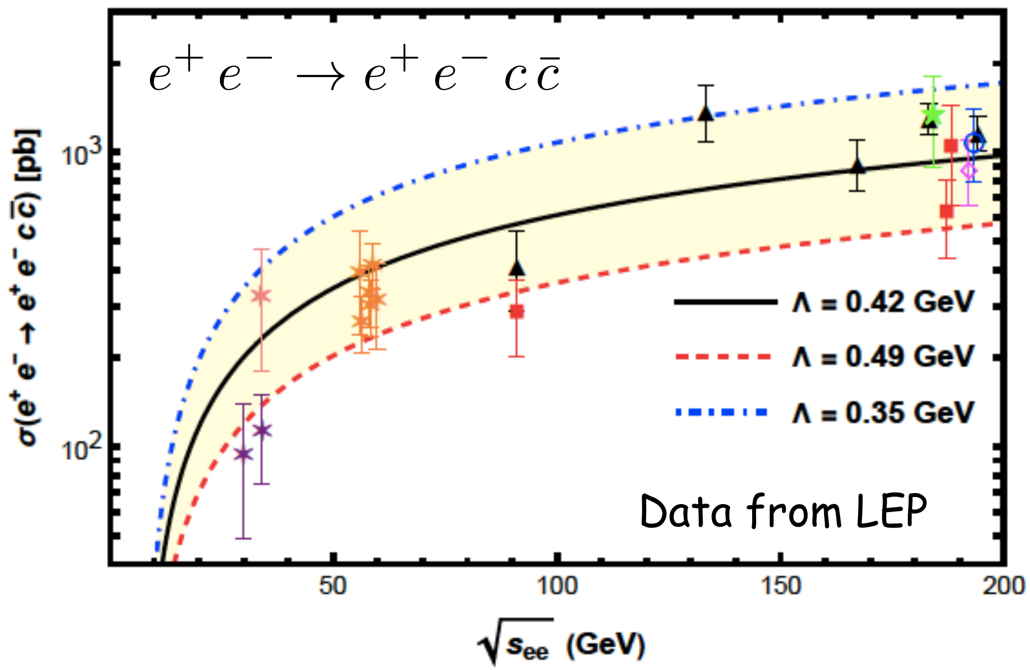
Fixing the cut-off with LEP data



$$\sigma_P = \frac{1}{64\pi^2}\frac{1}{\hat{s}}\sqrt{1-\frac{4m_D^2}{\hat{s}}}\int |M(\gamma\gamma \to D^+D^-)|^2 d\Omega$$

$$\sigma(e^+e^- \to e^+e^- D^+D^-) = \int d\omega_1\, d\omega_2\, n(\omega_1)\, n(\omega_2)\, \sigma_P$$

One parameter: Λ



F.C. Sobrinho, L.M. Abreu, C. A. Bertulani, F.S. Navarra, arXiv:2405.02645

Production of Bound States in Photon-Photon Collisions

Take the average over the bound state wave function :

(QFT, Peskin, page 150)

$$\frac{M(\gamma\gamma \to B)}{\sqrt{2E_B}} = \int \frac{d^3q}{(2\pi)^3} \tilde{\psi}^*(\vec{q}) \frac{1}{\sqrt{2E_{D+}}} \frac{1}{\sqrt{2E_{D-}}} M(\gamma\gamma \to D^+D^-)$$

If relative momentum q is small: $M(\gamma\gamma \to B) = \psi^*(0)\sqrt{\frac{2}{E_B}} M(\gamma\gamma \to D^+D^-)$

$$d\sigma = \frac{1}{H} \frac{d^3p_B}{(2\pi)^3} \frac{1}{2E_B} (2\pi)^4 \delta^{(4)}(k + k' - p_B) |M(\gamma\gamma \to B)|^2$$

The Wave Function at the Origin

D. Gamermann, J. Nieves, E. Oset and E. Ruiz Arriola, Phys. Rev. D 81, 014029 (2010)

Bethe-Salpeter Equation for a two (heavy) particle system:

$$\psi(0) = \frac{g}{(2\pi)^{3/2}} G \quad \begin{cases} G = -8\mu\pi\left(\Lambda_0 - \gamma \arctan\left(\frac{\Lambda_0}{\gamma}\right)\right) \\ g^2 = \dfrac{\gamma}{8\pi\mu^2(\arctan(\frac{\Lambda_0}{\gamma}) - \frac{\gamma\Lambda_0}{\gamma^2+\Lambda_0^2})} \end{cases} \qquad \gamma = \sqrt{2\mu E_b}$$

$$\begin{cases} \Lambda_0 & \text{cut-off} \\ \mu = m_D/2 & \text{reduced mass} \\ E_b & \text{binding energy} \end{cases} \longrightarrow \quad \psi(0) = f(E_b)$$

Final Cross Sections

$$\sigma_P(A\,A \to A\,A\,D^+D^-) = \int_{m_D^2/\hat{q}\gamma}^{\hat{q}\gamma} d\omega_1 \int_{m_D^2/\omega_1}^{\hat{q}\gamma} d\omega_2\, \sigma_P(\omega_1, \omega_2)\, n(\omega_1)\, n(\omega_2)$$

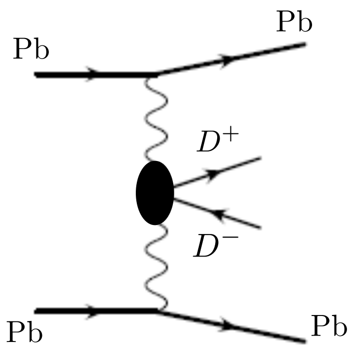
Two parameters: Λ $\hat{q}$

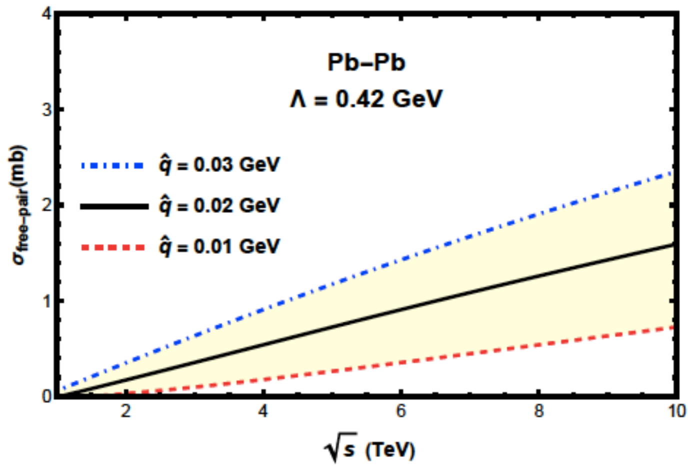
$$\sigma_B(A\,A \to A\,A\,B) = \int_{m_D^2/\hat{q}\gamma}^{\hat{q}\gamma} d\omega_1 \int_{m_D^2/\omega_1}^{\hat{q}\gamma} d\omega_2\, \sigma_B(\omega_1, \omega_2)\, n(\omega_1)\, n(\omega_2)$$

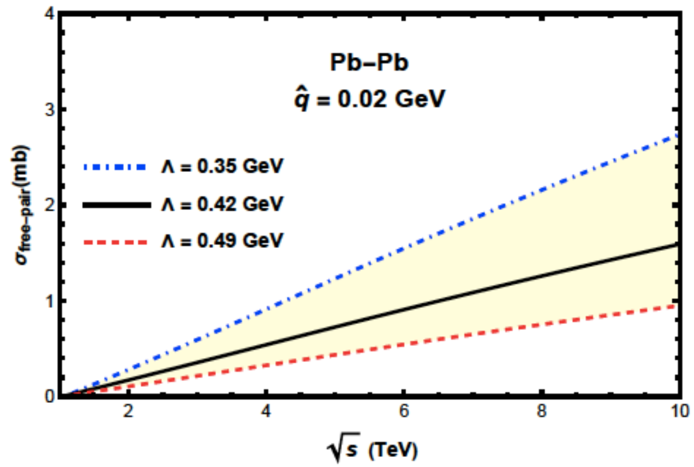
Three parameters: Λ $\hat{q}$ $\psi(0)$

Results

Free pair production



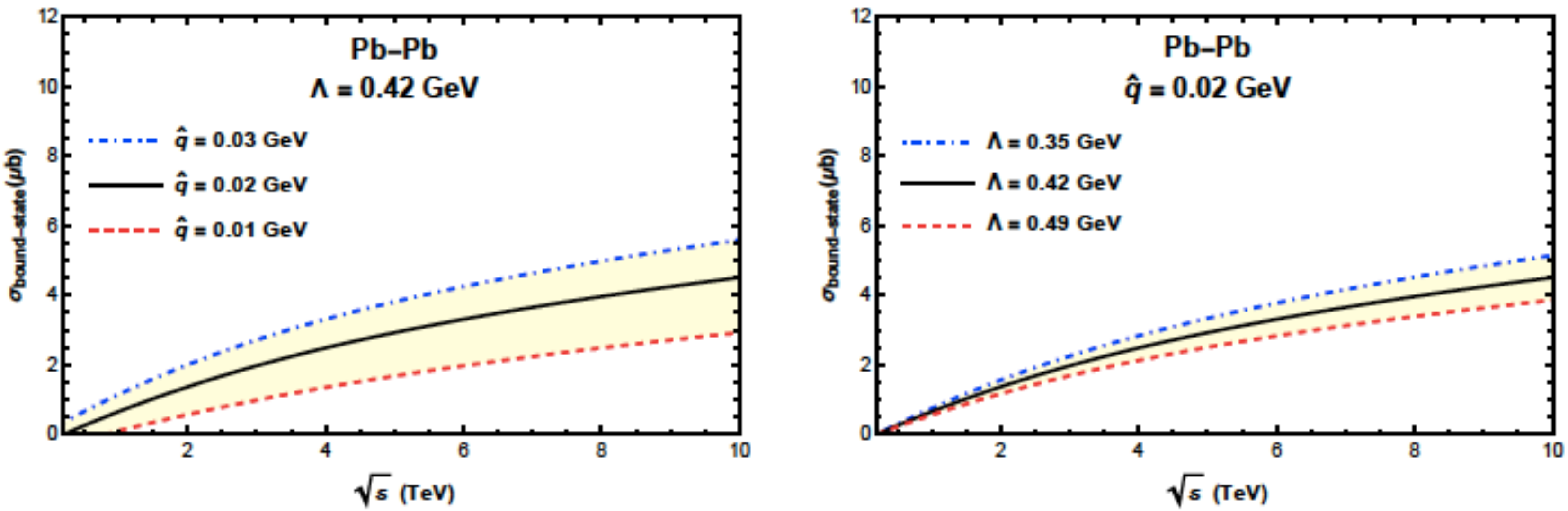




$\sqrt{s} = 5.02\ \mathrm{TeV}$ → $\sigma(Pb\,Pb \to Pb\,Pb\,D^+D^-) = 0.75^{+0.4}_{-0.4}\ \mathrm{mb}$

Bound state production in Pb Pb

$$E_b = 17 \text{ MeV} \qquad |\psi(0)|^2 \simeq 0.008 \text{ GeV}^3$$



$$\sqrt{s} = 5.02 \text{ TeV} \longrightarrow \boxed{\sigma(Pb\,Pb \to Pb\,Pb\,B) = 3.0^{+0.8}_{-1.2}\ \mu\text{b}}$$

Comparison with previous results

Two photon fusion in the impact parameter formalism

$$\sigma = \int N(\omega_1, b_1)\, N(\omega_2, b_2)\, \hat{\sigma}(\gamma\gamma \to R)\, S(b)\, d^2b_1\, d^2b_2\, d\omega_1\, d\omega_2$$

b-dependent equivalent photon spectrum

Form factor

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2 b^2 \omega} \left[\int du\, u^2 J_1(u) F\left(\sqrt{\frac{(b\omega/\gamma)^2 + u^2}{b^2}} \right) \frac{1}{(b\omega/\gamma)^2 + u^2} \right]^2$$

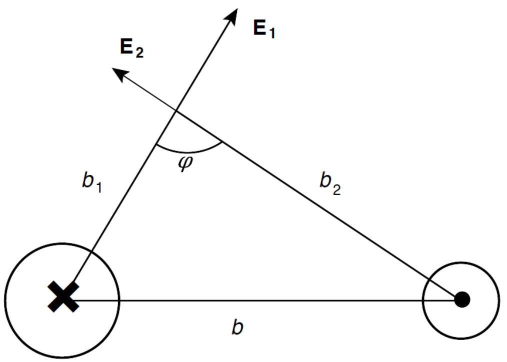
Photon fusion cross section : Low formula

Decay width

$$\hat{\sigma}(\gamma\gamma \to R) = 8\pi^2 (2J+1) \frac{\Gamma_{R\to\gamma\gamma}}{M_R} \delta(4\omega_1\omega_2 - M_R^2)$$

Geometric factor

$$S(b) = \Theta(|\mathbf{b_1} - \mathbf{b_2}| - R_1 - R_2)$$



Exotic scalar charmonium production

Klusek-Gawenda, Szczurek, arXiv:1004.5521

State	Mass	$\Gamma_{\gamma\gamma}^{theor}$(keV)	$\sigma_{b_{min}}$ (μb) pointlike			σ_F (μb) monopole			σ_R (μb)		
			2.76 TeV	5.5 TeV	39 TeV	2.76 TeV	5.5 TeV	39 TeV	2.76 TeV	5.5 TeV	39 TeV
X(3940), 0^{++}	3943	0.33	4.2	8.2	31.6	6.5	11.8	40.9	5.7	10.8	39.6
X(3915), 0^{++}	3919	0.20	2.6	5.1	19.8	4.0	7.3	25.3	3.6	6.7	24.5

Moreira, Bertulani, Gonçalves, FSN, arxiv:1610.06604

molecules

State	Mass	$\Gamma_{\gamma\gamma}$[keV]	$\sigma[\mu$b]		
			2.76 TeV	5.02 TeV	39 TeV
X(3940), 0^{++}	3943	0.33	5.5	9.7	32.5
$\chi_{c0}(3915)$, 0^{++}	3919	0.20	3.4	6.0	20.1

Fariello, Bhandari, Bertulani, F.S.N., arXiv:2306.10642

$$5 \leq \sigma \leq 11 \ \mu b$$

Summary-I

Formalism to create charm meson molecules in photon-photon collisions

Use effective Lagrangians and the bound state wave function

Three parameters: Λ $\hat{q}$ $\psi(0)$ Can be better constrained !

Production of the molecule $D^+ D^-$ $\sigma \simeq 3.0\ \mu b$

Production of similar states with a similar method $5 \leq \sigma \leq 11\ \mu b$

Production of the equivalent tetraquark $\sigma \simeq 0.18\ \mu b$

A. Esposito, C.A. Manzari, A. Pilloni, A.D. Polosa, arXiv:2109.10359

Summary-I

Formalism to create charm meson molecules in photon-photon collisions

Use effective Lagrangians and the bound state wave function

Formalism to create charm meson molecules in photon-photon collisions

Production of the molecule $D^+ D^-$ $\sigma \simeq 3.0 \ \mu b$

Production of similar states with a similar method $5 \leq \sigma \leq 11 \ \mu b$

Production of the equivalent tetraquark $\sigma \simeq 0.18 \ \mu b$

A. Esposito, C.A. Manzari, A. Pilloni, A.D. Polosa, arXiv:2109.10359