

X(3872) production in heavy ion collisions

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Introduction

X production

Nucleus-nucleus collisions

Hadronic effects on X production

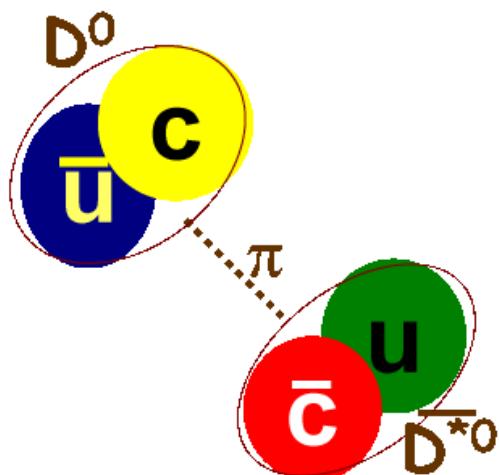
Summary

Martinez Torres, Khemchandani, FSN, Nielsen, Abreu, arXiv:1405.7583 ; 1604.07716



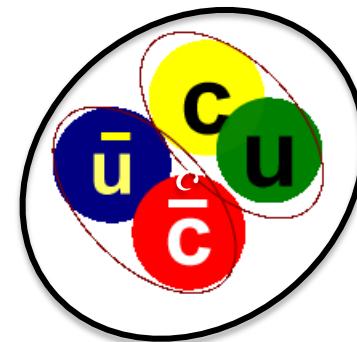
The $X(3872)$ structure

Meson molecule



large
loosely bound
meson exchange

Tetraquark



compact
color exchange

Mixture?

$$\left\{ \begin{array}{l} X = a |c\bar{c}\rangle + b |c\bar{c}q\bar{q}\rangle \\ X = a |\chi'_{c1}\rangle + b |D\bar{D}^*\rangle \end{array} \right.$$

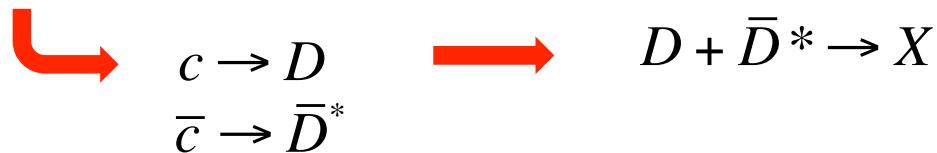
The $X(3872)$ production

B decays : $e^+ + e^- \rightarrow B^+ + B^-$



Proton-proton: $g + g \rightarrow c + \bar{c}$

(prompt production)

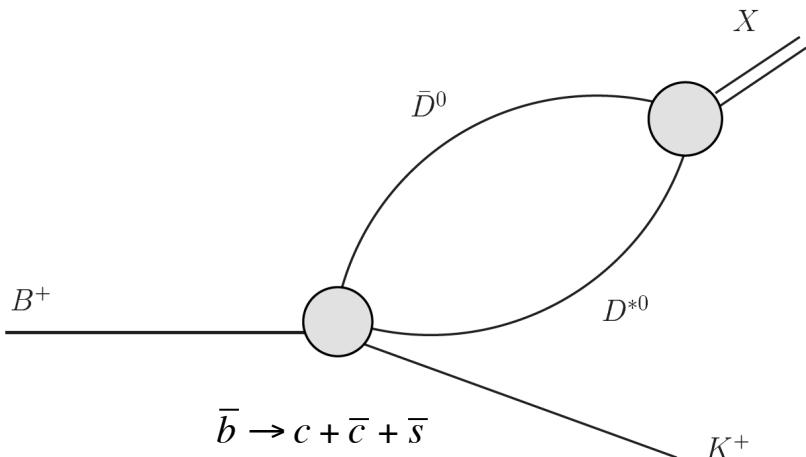


Nucleus-nucleus: ?

ExHIC Collab., Cho et al., PRL 106, 212001 (2011) ; PRC 84, 064910 (2011).

B decays

Meson Molecule

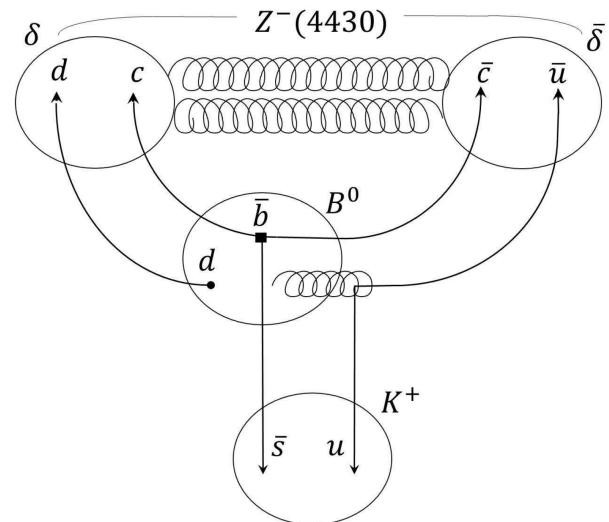


Meson coalescence

Small binding energy

E. Braaten, M. Kusunoki, hep-ph/0404161

Tetraquark



Diquark-antidiquark picture

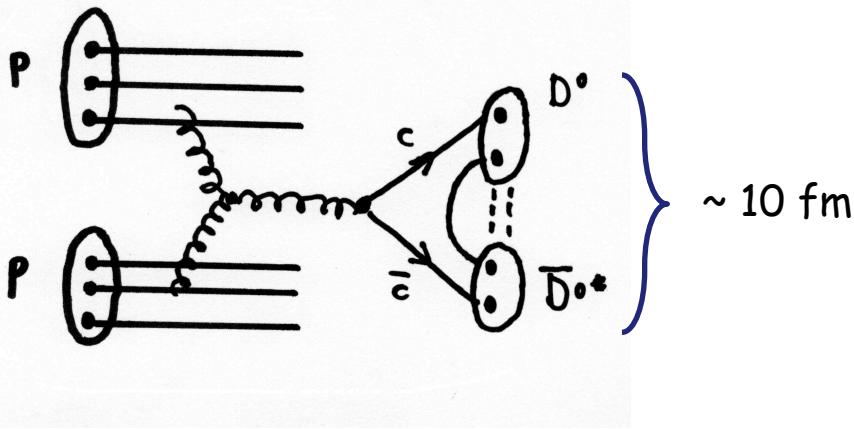
Non-relativistic potential

S.J. Brodsky, D.S. Hwang, R.F. Lebed,
arXiv:1406.7281

Both approaches work !

Proton-proton

Meson molecule



Charm quark pairs generated with PYTHIA

Fragmentation into D and D*

Model for binding D and D*

$$\sigma_{\text{th}} \simeq 0.01 \sigma_{\text{exp}} \quad (\text{CDF})$$

Bignamini et al., arXiv:0906.0882

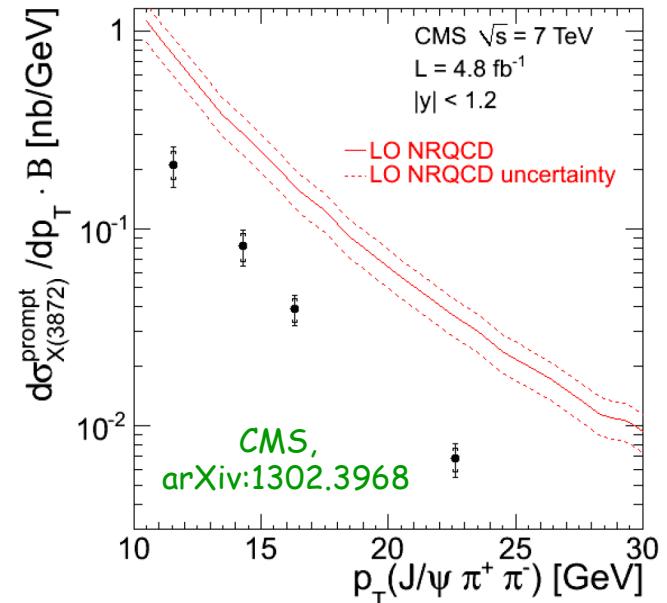
Bignamini et al., arXiv:09012.5064

Guerrieri et al., arXiv:1405.7929

NRQCD

D D* rescattering

Relative momentum \sim pion mass



Artoisenet, Braaten, arXiv:0911.2016

Artoisenet, Braaten, arXiv:1007.2868

Dall'Osso et al., POS (Beauty 2013) 066

Charmonium - Molecule Mixture

$$X = a |\chi'_{c1}\rangle + b |D\bar{D}^*\rangle$$

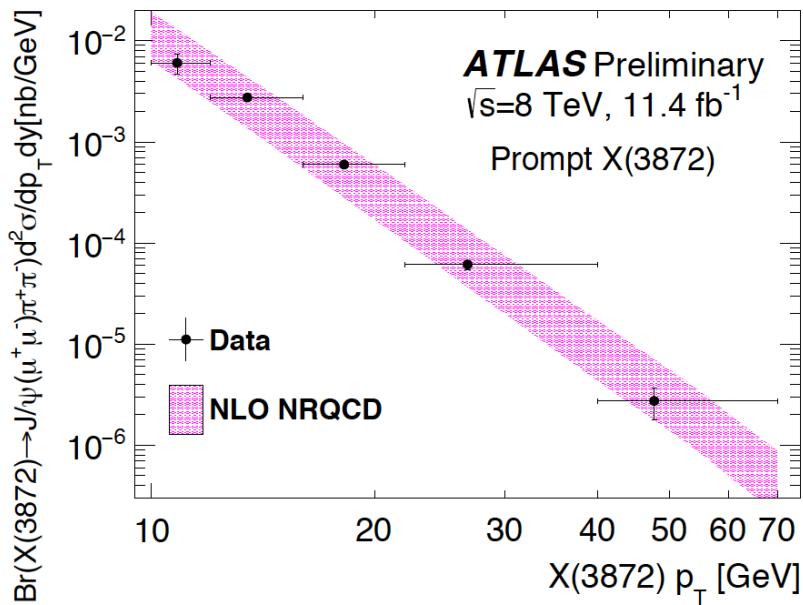
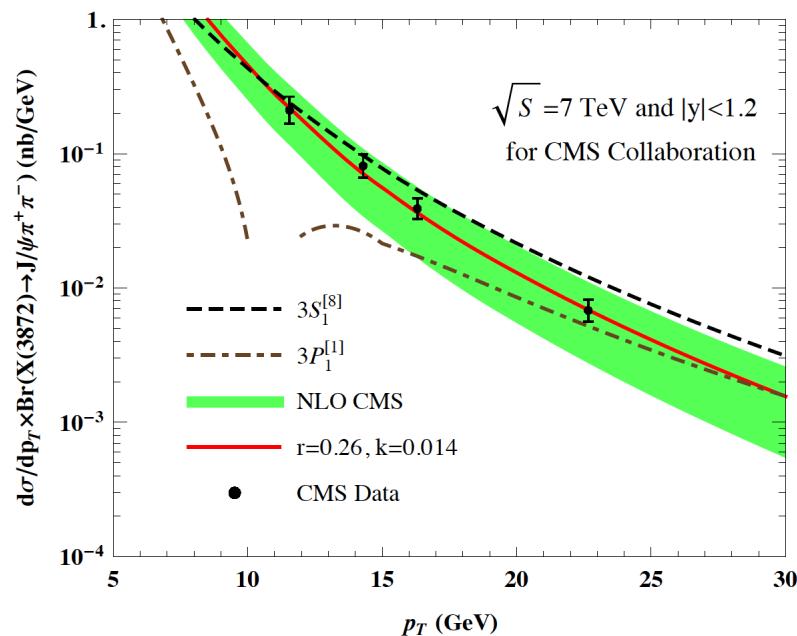
NRQCD

Meng, Han, Chao, arxiv:1304.6710

Pure D D* molecule ruled out !

ATLAS - CONF - 2016 - 028

K. Toms, ICHEP 2016 Chicago

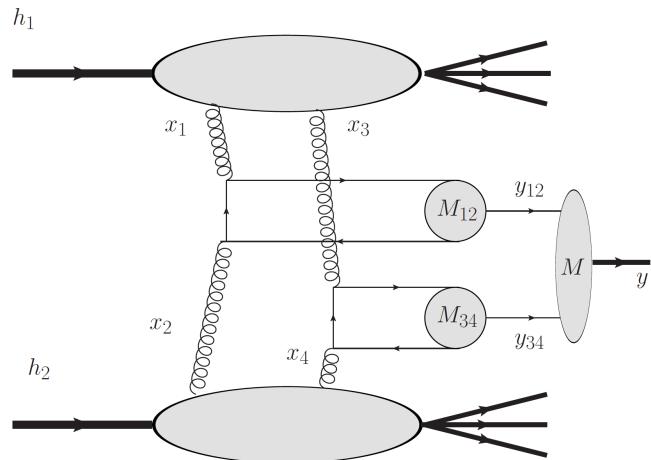


Tetraquark

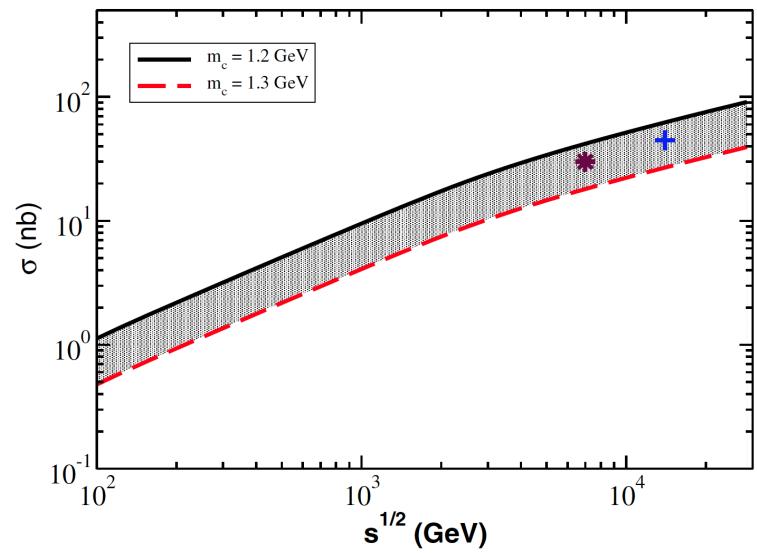
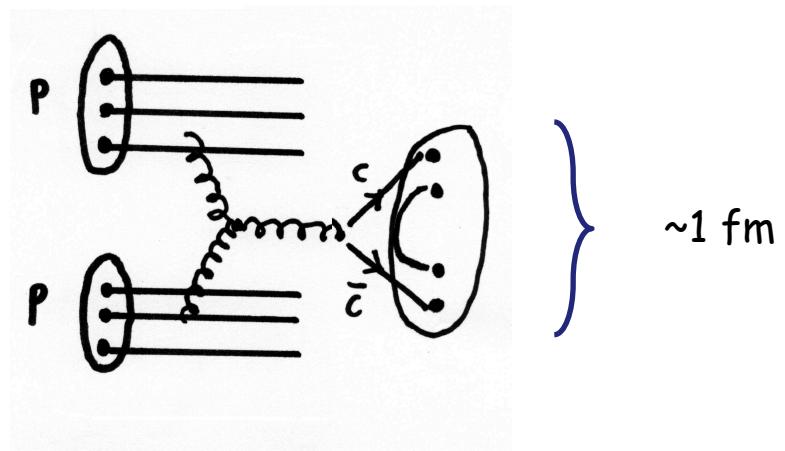
Short distance interactions

Double parton scattering

Binding as in the Color Evaporation Model



Energy (TeV)	$\sigma_{c\bar{c}}$ (mb)	σ_{inel} (mb)	σ_X (nb)
7	8.5 [28]	73.2 [27]	30.0 [9]
14			44.6 ± 17.7



Carvalho, Cazaroto, Goncalves, FSN,
Phys. Rev. D93, 034004 (2016)

Nucleus - Nucleus

More charm from the initial state

Deconfined medium: quark-gluon plasma

Hadron gas phase after reconfinement



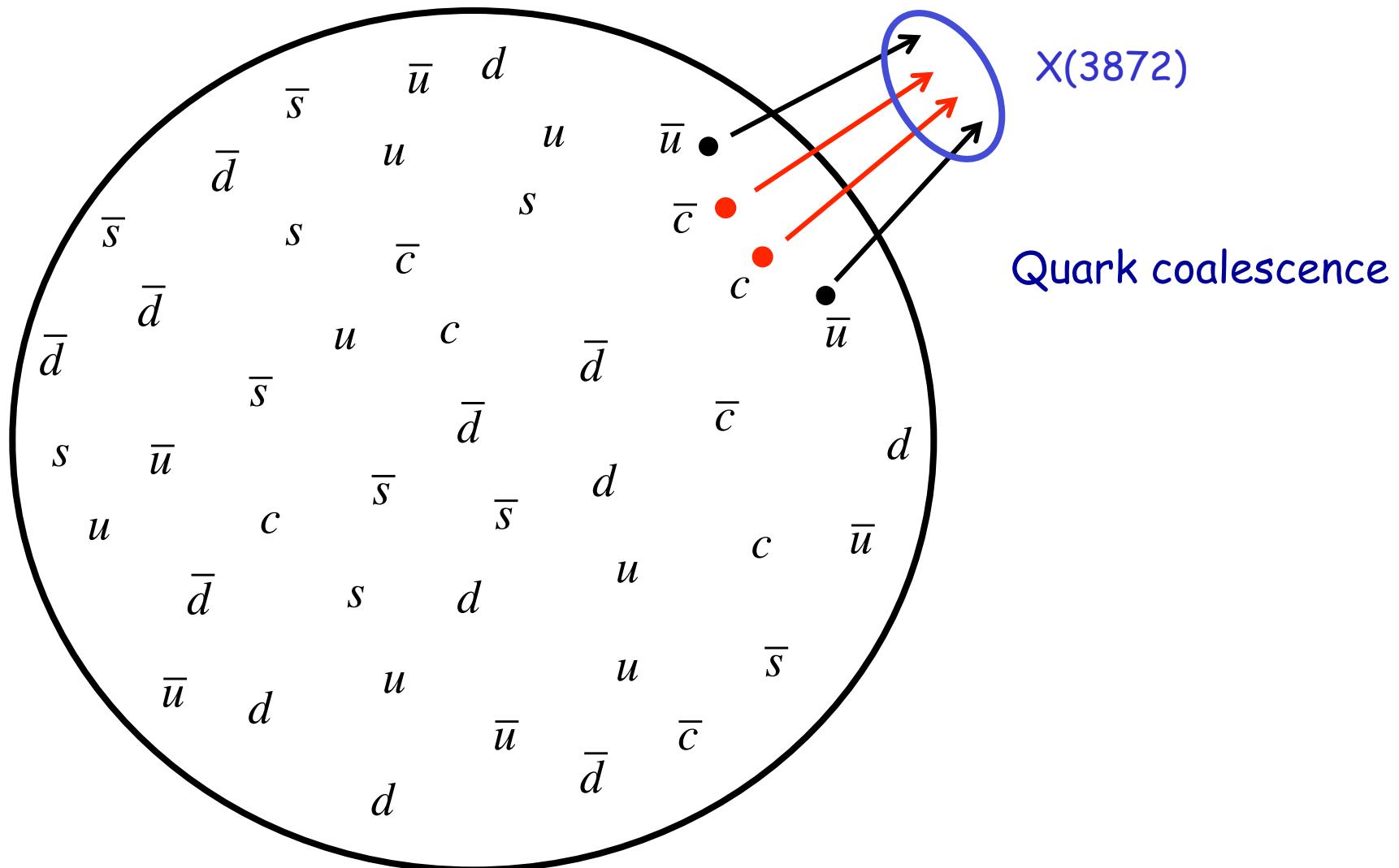
quark coalescence during the phase transition

meson-meson fusion in the hadron gas phase

meson coalescence in the end of the hadron gas phase

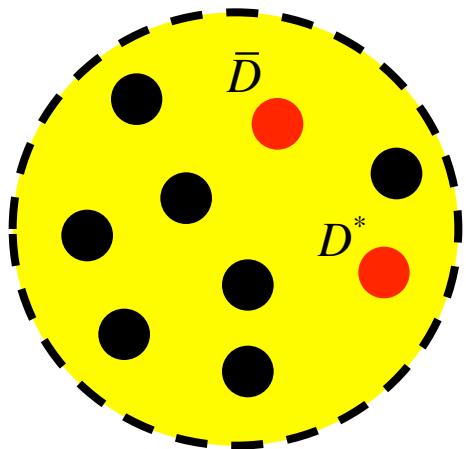
Quark coalescence during hadronization

Cho et al. ExHIC Collab., PRL 106, 212001 (2011) ; PRC 84, 064910 (2011)

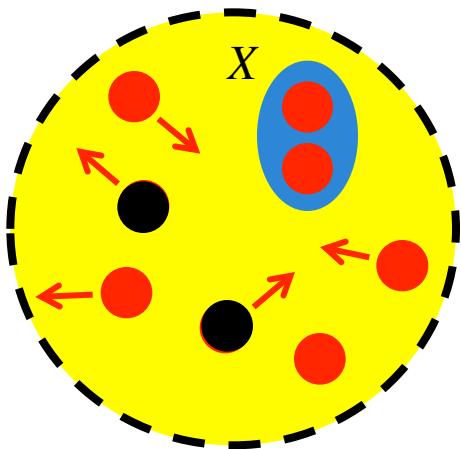


X in the hadron gas phase

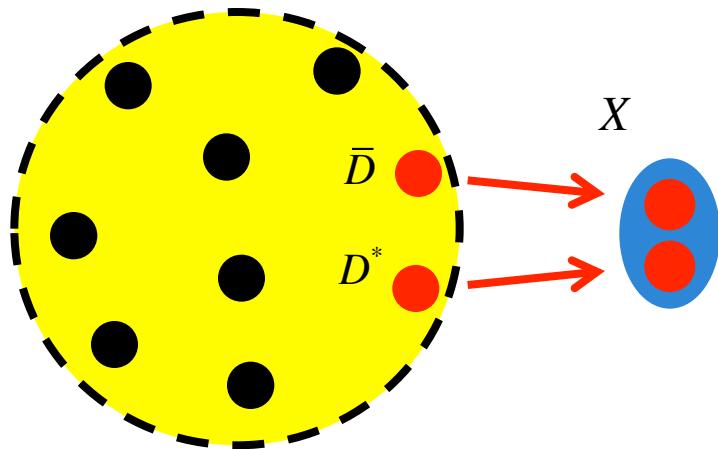
Hadron gas



X production
by meson fusion



X production
by meson coalescence



X absorption
by light hadrons

X in a hadron gas

$$\begin{array}{ll}
 \text{Production} & \left\{ \begin{array}{l} D + \bar{D} \rightarrow X + \pi \\ D + \bar{D}^* \rightarrow X + \pi \\ D^* + \bar{D}^* \rightarrow X + \pi \end{array} \right. \\
 & \qquad \qquad \qquad \text{Absorption} \left\{ \begin{array}{l} X + \pi \rightarrow D + \bar{D} \\ X + \pi \rightarrow D + \bar{D}^* \\ X + \pi \rightarrow D^* + \bar{D}^* \end{array} \right. \\
 \end{array}$$

Cross sections from SU(4) effective Lagrangians

Cho and Lee, arXiv:1302.6381, PRC (2013)

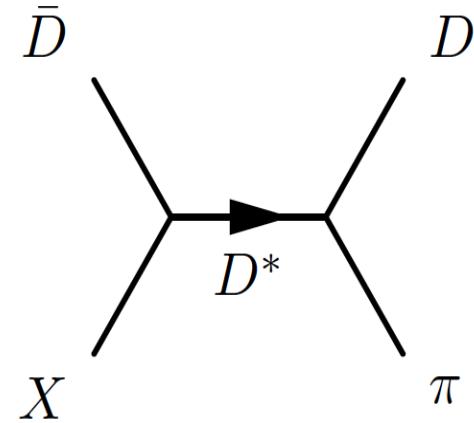
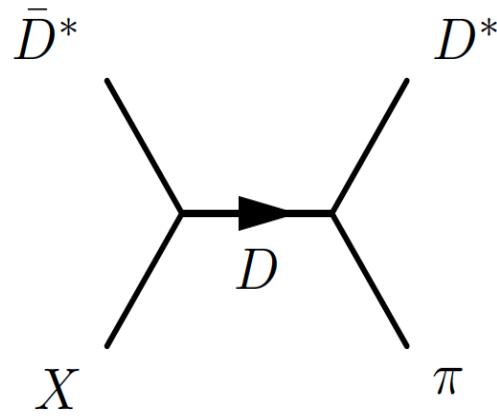
$$\mathcal{L}_{PPV} = -ig_{PPV} \langle V^\mu [P, \partial_\mu P] \rangle \quad \mathcal{L}_{VVV} = ig_{VVV} \langle (V^\mu \partial_\nu V_\mu - \partial_\nu V_\mu V^\mu) V^\nu \rangle$$

$$P = \begin{pmatrix} \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ & \bar{D}^0 \\ \pi^- & \frac{\eta}{\sqrt{3}} + \frac{\eta'}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 & D^- \\ K^- & \bar{K}^0 & -\frac{\eta}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta' & D_s^- \\ D^0 & D^+ & D_s^+ & \eta_c \end{pmatrix} \quad V_\mu = \begin{pmatrix} \frac{\omega+\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} & \bar{D}^{*0} \\ \rho^- & \frac{\omega-\rho^0}{\sqrt{2}} & K^{*0} & D^{*-} \\ K^{*-} & \bar{K}^{*0} & \phi & D_s^{*-} \\ D^{*0} & D^{*+} & D_s^{*+} & J/\psi \end{pmatrix}_\mu$$

$$\mathcal{L}_{D^* D \pi} = i g_{D^* D \pi} (D_\mu^* \partial^\mu \pi \bar{D} - D \partial^\mu \pi \bar{D}_\mu^*)$$

$$\mathcal{L}_{X D^* D} = g_{X D^* D} X^\mu \bar{D}_\mu^* D$$

Cho and Lee,
arXiv:1302.6381

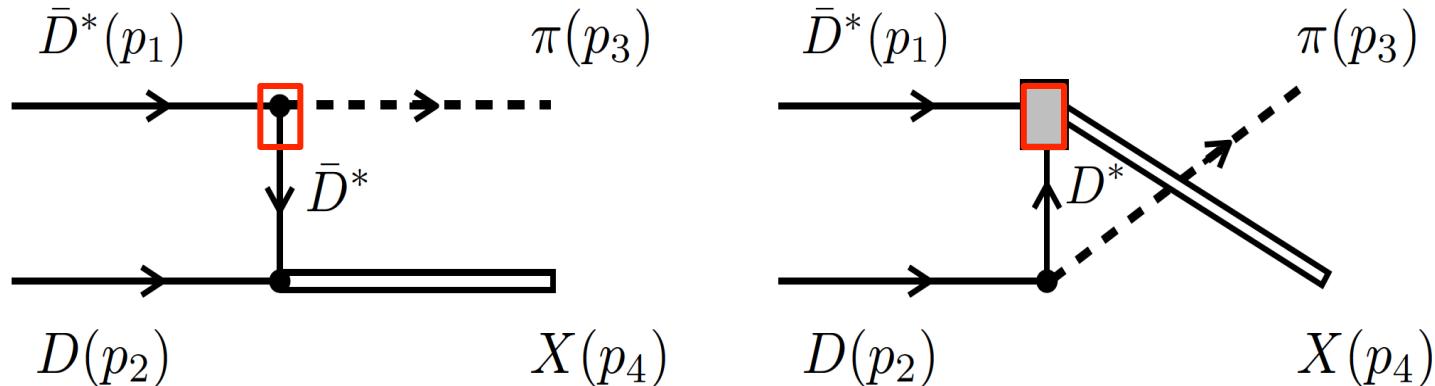


Some processes not included !

$$D + \bar{D}^* \rightarrow X + \pi \quad X + \pi \rightarrow D + \bar{D}^*$$

Anomalous coupling terms

Martinez Torres, Khemchandani, FSN, Nielsen, Abreu, arXiv:1405.7583



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

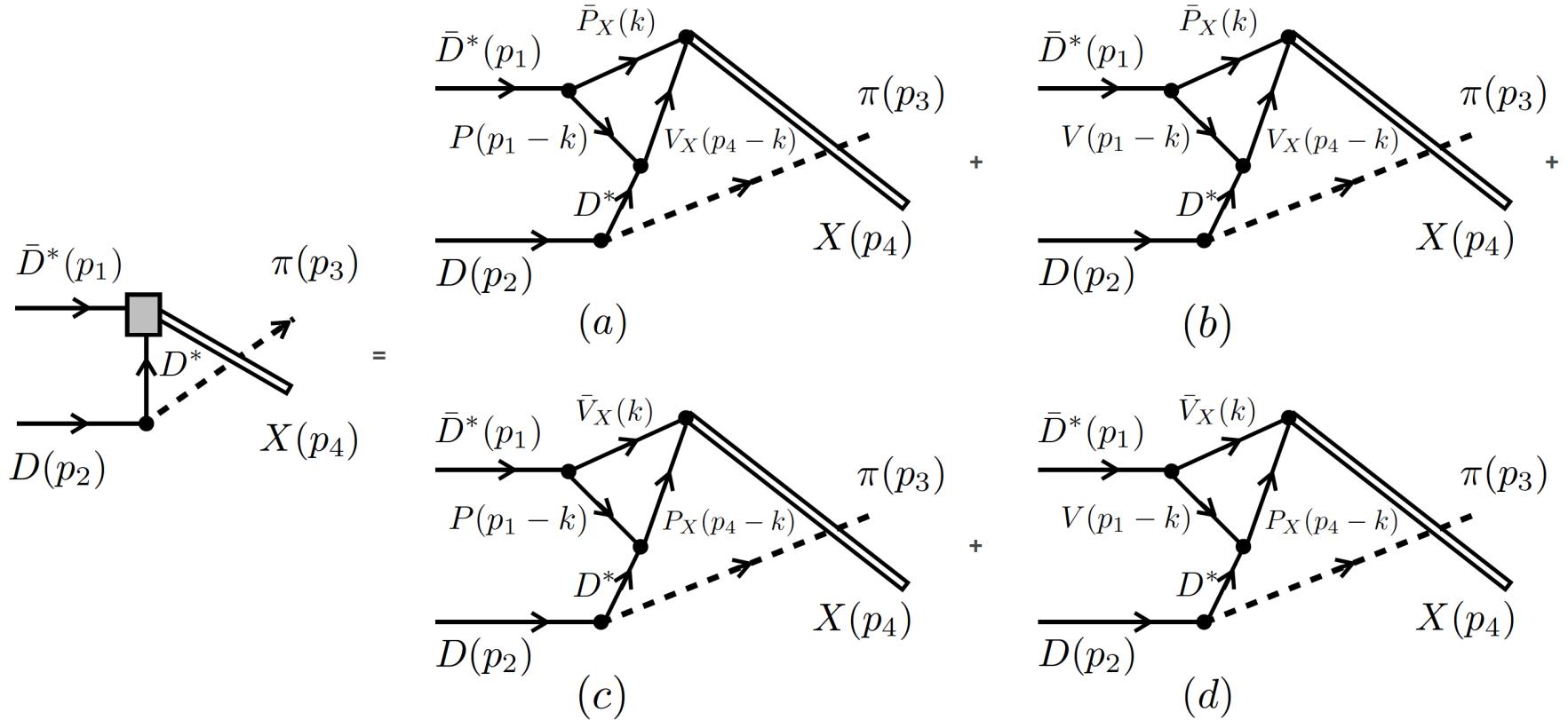
$$\mathcal{L}_{X D^* D^*} = i g_{X D^* D^*} \epsilon^{\mu\nu\alpha\beta} \partial_\mu X_\nu \psi^\mu \bar{D}_\alpha^* D_\beta^*$$

L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, PRD 71 (2005) 014028

$g_{D^* D^* \pi}$ from QCD sum rules

Bracco, Chiapparini, FSN, Nielsen, arXiv:1104.2864, Prog. Part. Nucl. Phys. (2012)

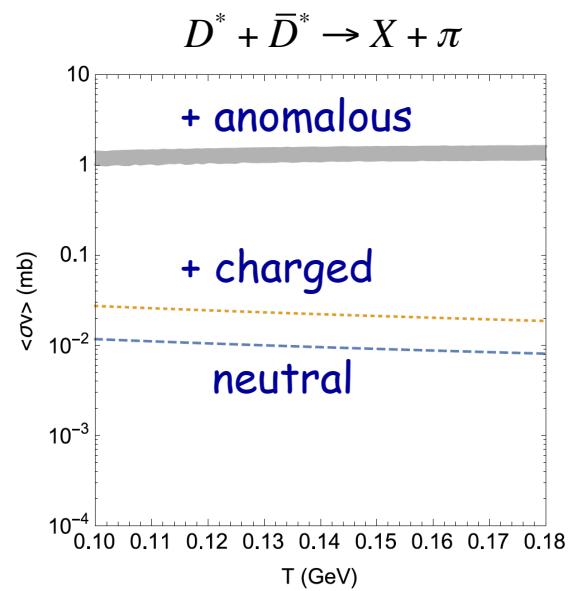
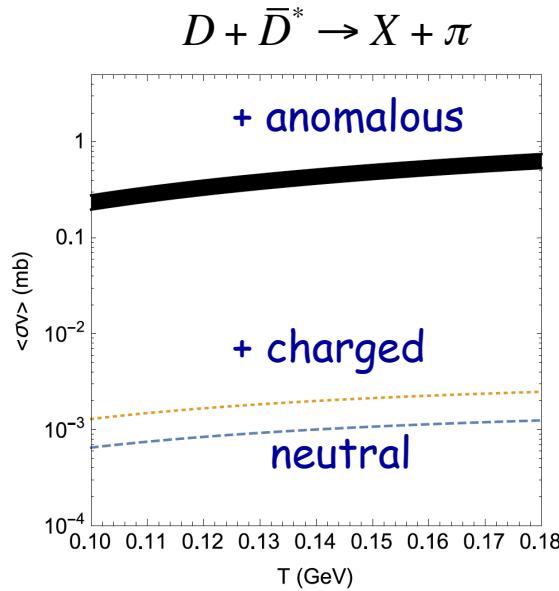
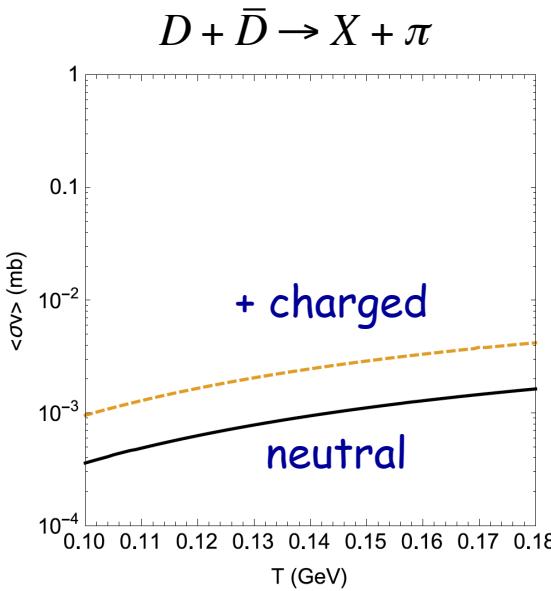
Loop diagrams to calculate the $\bar{D}^* D^* \rightarrow \pi X$ coupling



Divergences regularized by a cut-off: 700 - 1000 MeV

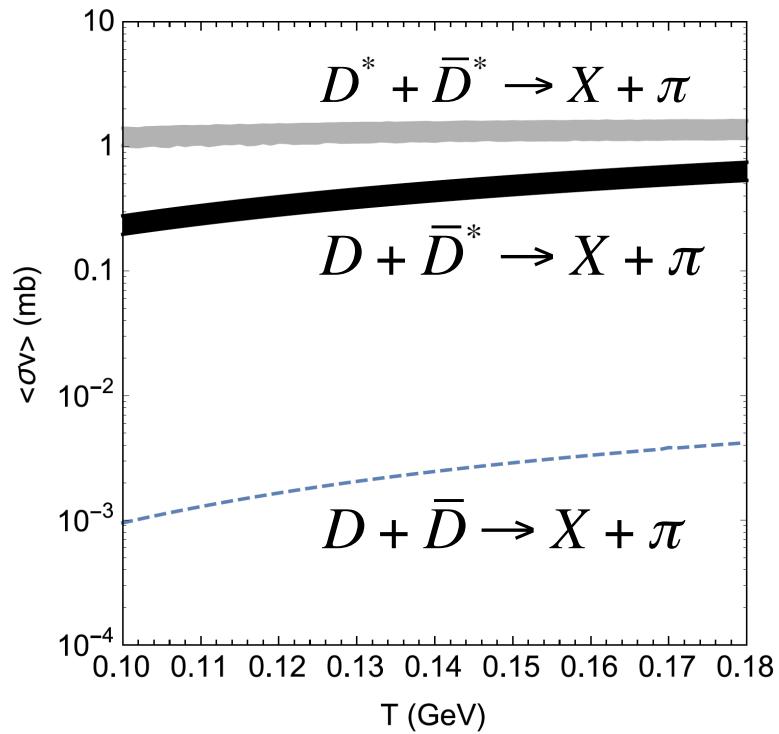
Thermally averaged cross sections

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

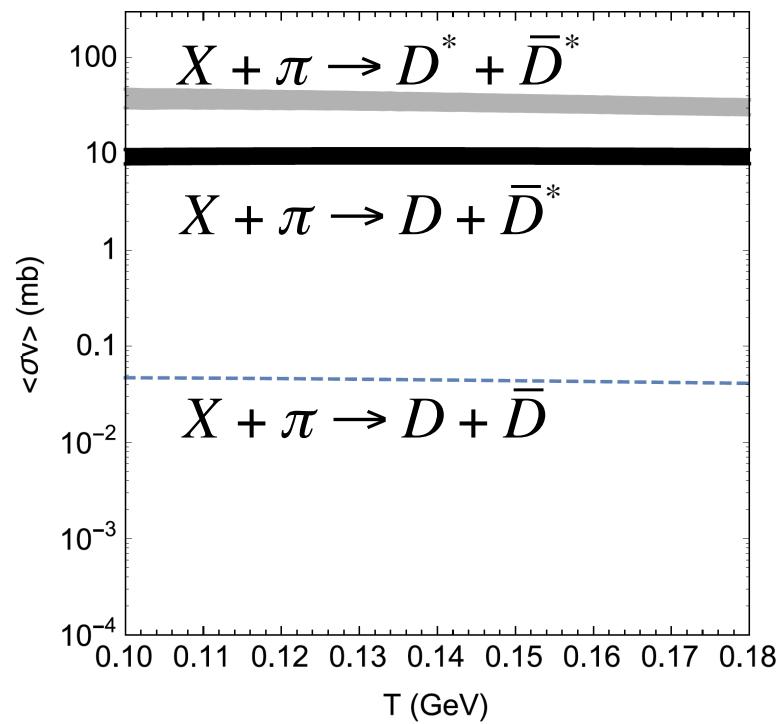


Corrections are very large !

Production



Absorption



Absorption MUCH stronger than production !

Time evolution of the X abundance

$$\frac{dN_X(\tau)}{d\tau} = R_{QGP}(\tau) + \sum_{l,c,c'} \left(\begin{array}{c} \langle \sigma_{cc' \rightarrow lX} v_{cc'} \rangle n_c(\tau) N_{c'}(\tau) \\ \text{gain} \end{array} - \begin{array}{c} \langle \sigma_{lX \rightarrow cc'} v_{lX} \rangle n_l(\tau) N_X(\tau) \\ \text{loss} \end{array} \right)$$

Cooling and expansion

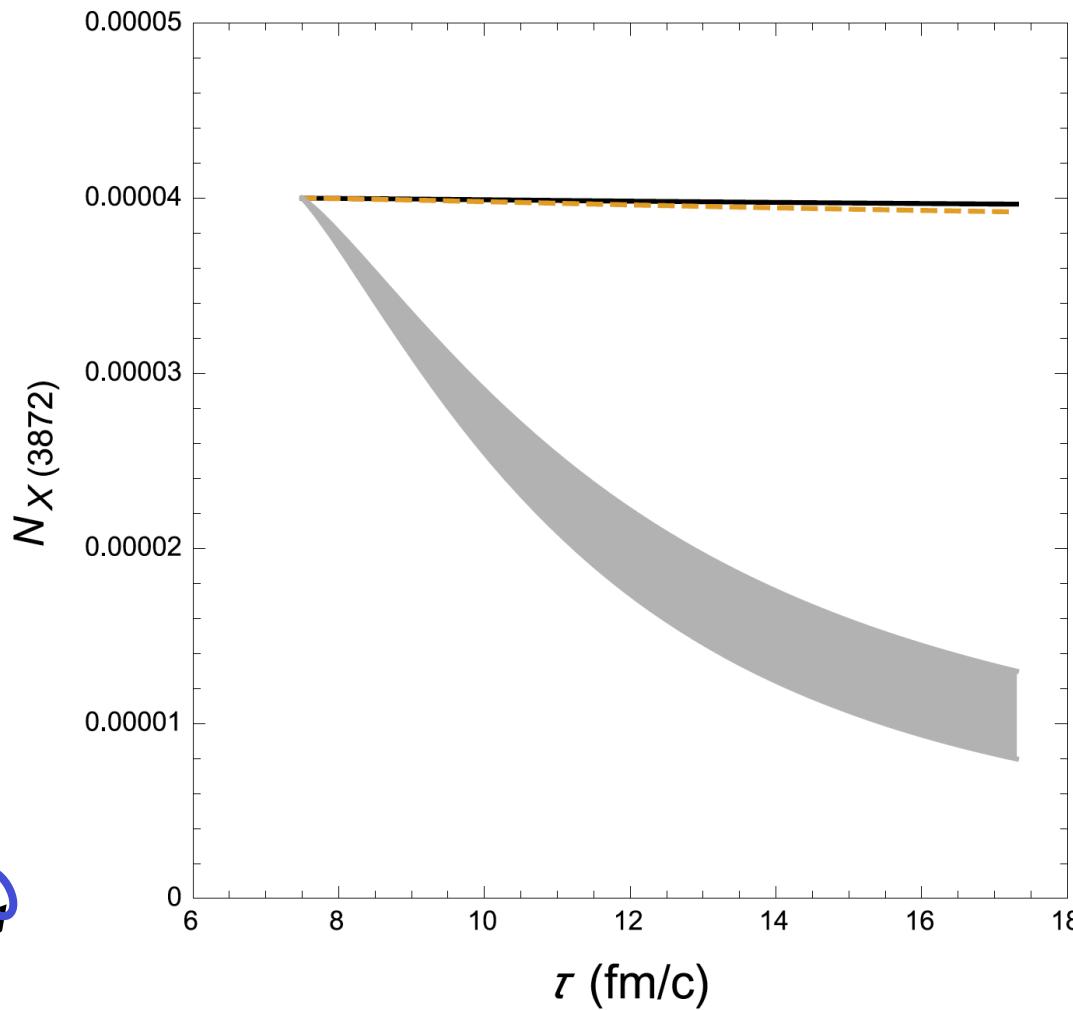
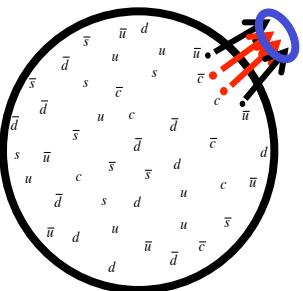
$$\left\{ \begin{array}{l} T(\tau) = T_C - (T_H - T_F) \left(\frac{\tau - \tau_H}{\tau_F - \tau_H} \right)^{\frac{4}{5}}, \\ V(\tau) = \pi \left[R_C + v_C (\tau - \tau_C) + \frac{a_C}{2} (\tau - \tau_C)^2 \right]^2 \tau_C. \end{array} \right.$$

D, D* and pion abundancies

$$\left\{ \begin{array}{l} N_{c'}(\tau) \approx \frac{1}{2\pi^2} \gamma_C g_D m_{D^{(*)}}^2 T(\tau) V(\tau) K_2 \left(\frac{m_{D^{(*)}}}{T(\tau)} \right), \\ n_c(\tau) \approx \frac{1}{2\pi^2} \gamma_C g_D m_{D^{(*)}}^2 T(\tau) V(\tau) K_2 \left(\frac{m_{D^{(*)}}}{T(\tau)} \right), \\ n_\pi(\tau) \approx \frac{1}{2\pi^2} \gamma_\pi g_\pi m_\pi^2 T(\tau) V(\tau) K_2 \left(\frac{m_\pi}{T(\tau)} \right), \end{array} \right.$$

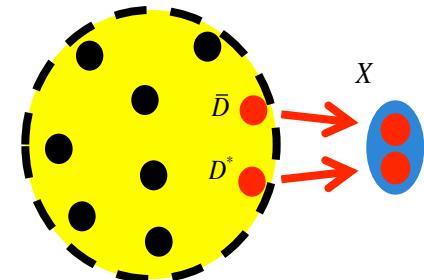
Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV

Tetraquark =
 4×10^{-5}

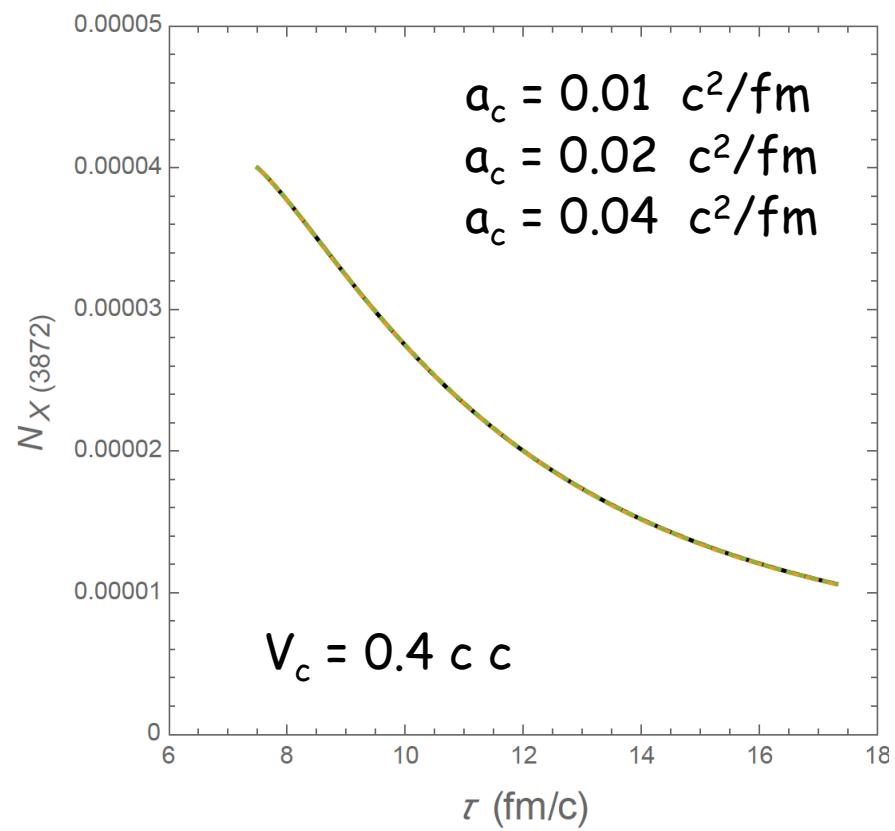
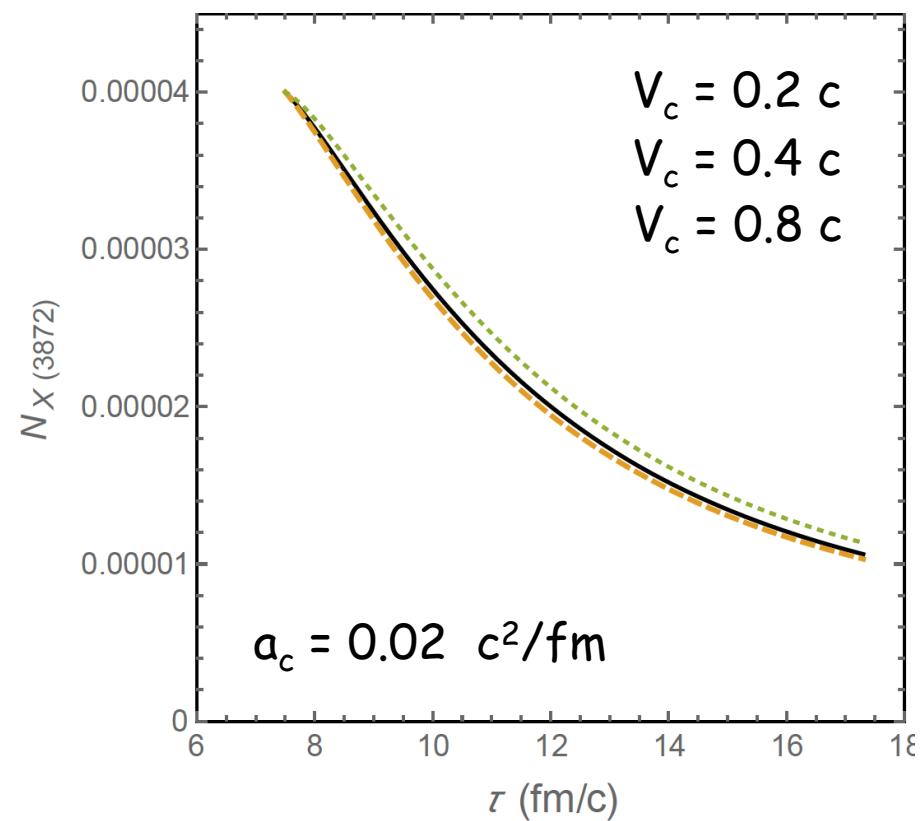


Cho and Lee,
arXiv:1302.6381

Meson coalescence
 8×10^{-4}



Dependence on the expansion model



Summary

We want to use HIC to know the structure of the X

X tetraquark is produced at the end of the plasma phase by quark coalescence

In the hadron phase X can be produced and destroyed

This is described by Effective Lagrangians.

Here we have introduced terms with anomalous couplings

Cross sections much larger

Significant reduction of the X abundance

X molecule is produced at the end of the hadron phase by meson coalescence

Conjecture: if we see any X in HIC, then it is a molecule !

Back ups

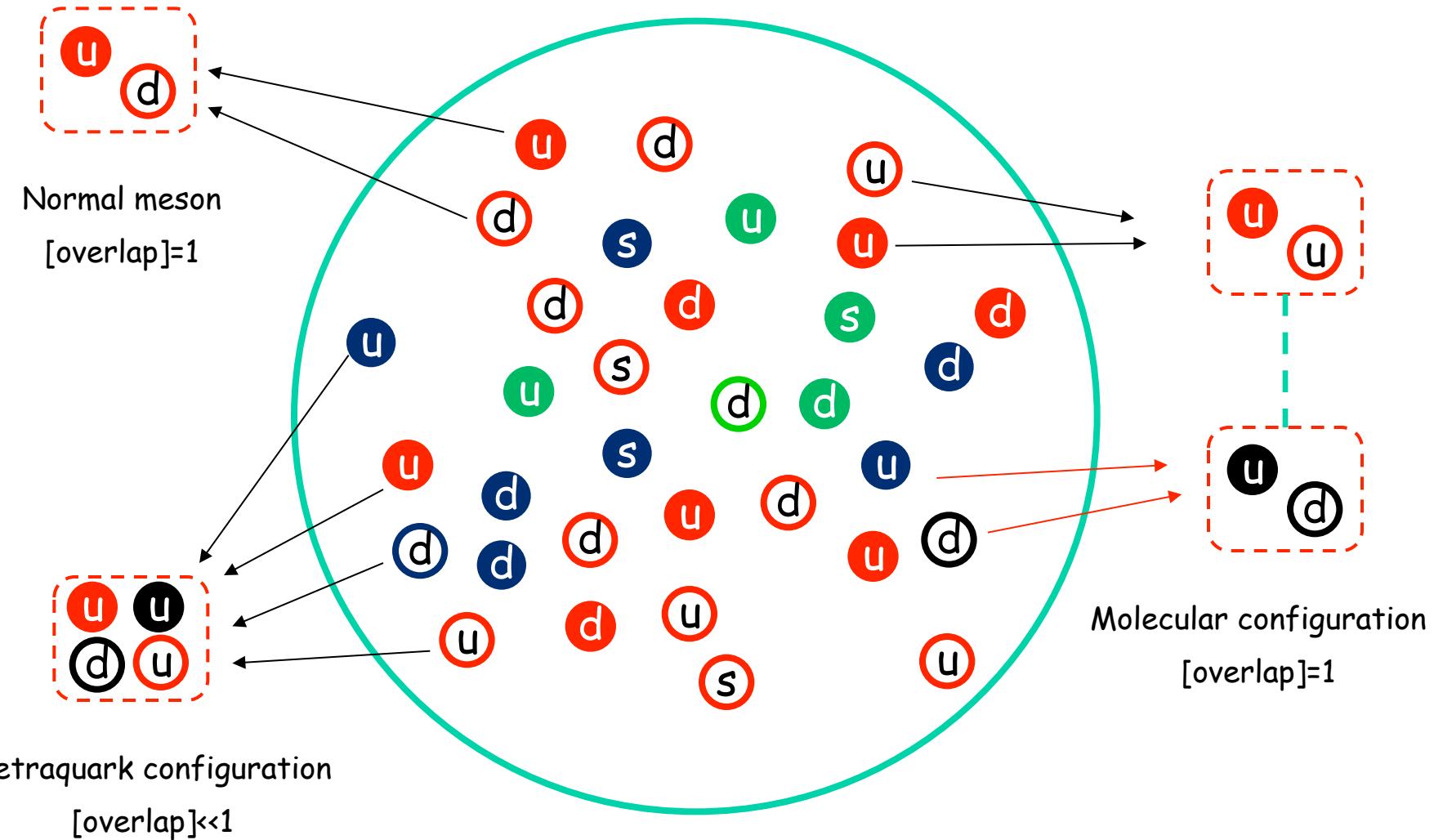
Temp.(MeV) Time (fm/c)		
$R_C = 8.0$ fm	$T_C = 175$	$\tau_C = 5.0$
$v_C = 0.4c$	$T_H = 175$	$\tau_H = 7.5$
$a_C = 0.02c^2/\text{fm}$	$T_F = 125$	$\tau_F = 17.3$

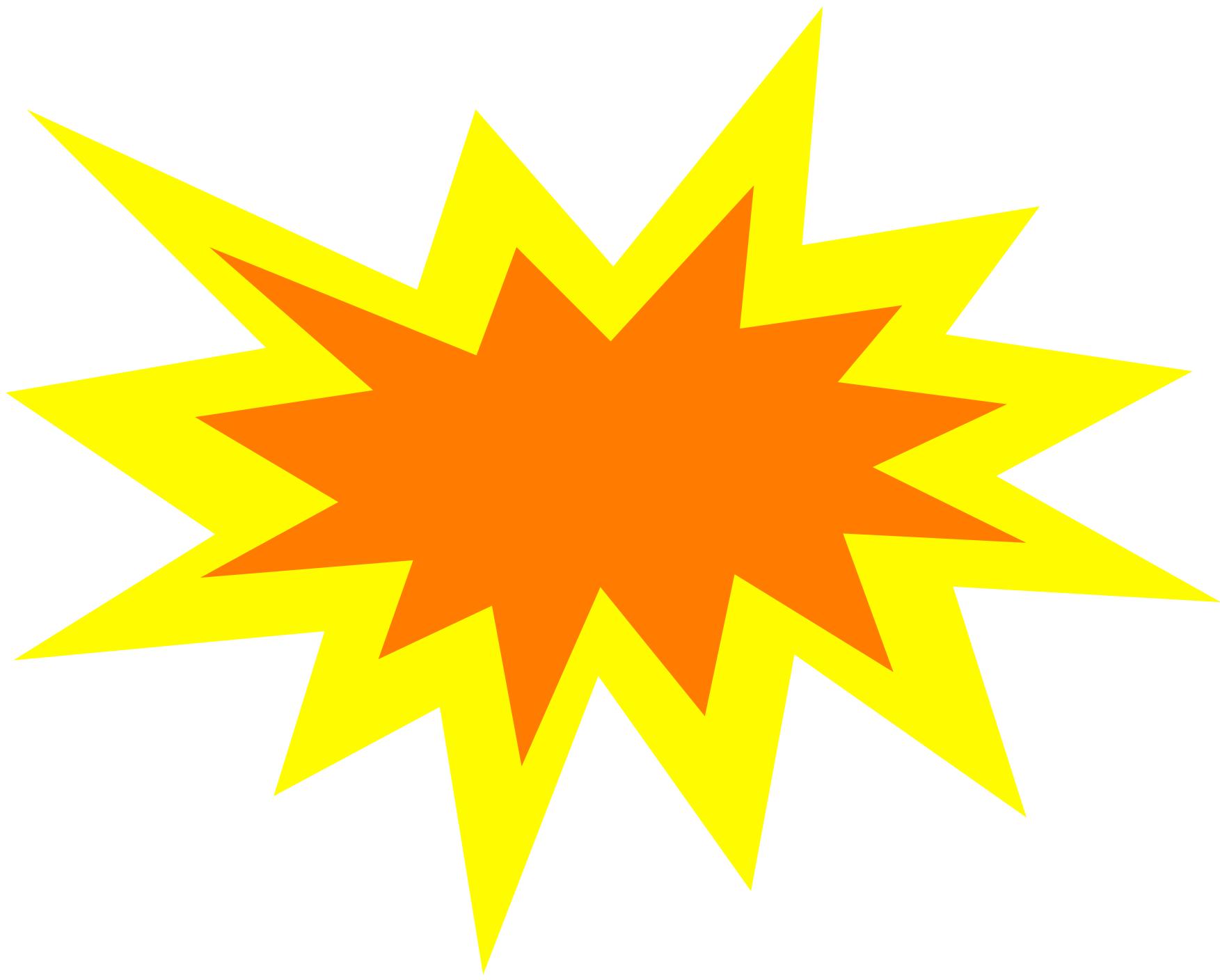
	$J^p = 1^+$	$J^p = 2^-$
$g_{X_J D^* D}$	3.5 ± 0.7 GeV	189 ± 36
$g_{X_J \psi \rho}$	0.14 ± 0.03	-0.29 ± 0.08 GeV^{-1}
$g'_{X_J \psi \rho}$		0.28 ± 0.09 GeV^{-1}

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

$$R_{QGP}(\tau) = \begin{cases} N_X^0 / (\tau_H - \tau_C), & \tau_C < \tau < \tau_H \\ 0, & \text{otherwise} \end{cases}$$

Hadron production through coalescence $\rightarrow c \times \exp\left(-\frac{M}{T}\right) \times [\text{overlap}]$



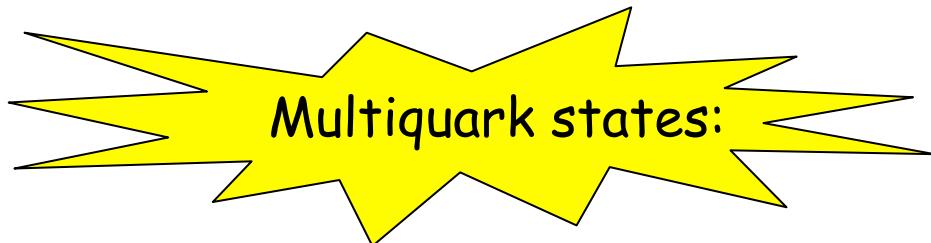


Introduction

New charmonium states

- 2003 Observation of $X(3872)$ by BELLE $X \rightarrow J/\psi + \pi^+ + \pi^-$
(CDF, CMS, ATLAS...)
- 2008 Observation of $Z^+(4430)$ by BELLE $Z \rightarrow \psi' + \pi^+$
- 2016 More than 20 confirmed states !

New “exotic” charmonium states : not just $c\bar{c}$



$c\bar{c}q\bar{q}$

Summary I

Study X production to understand the X structure

In B decays all models work

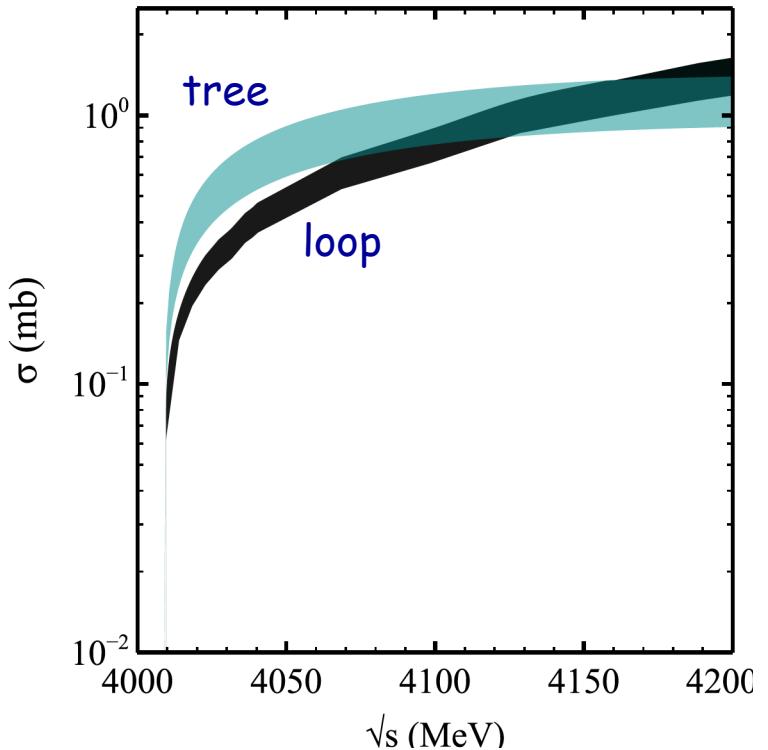
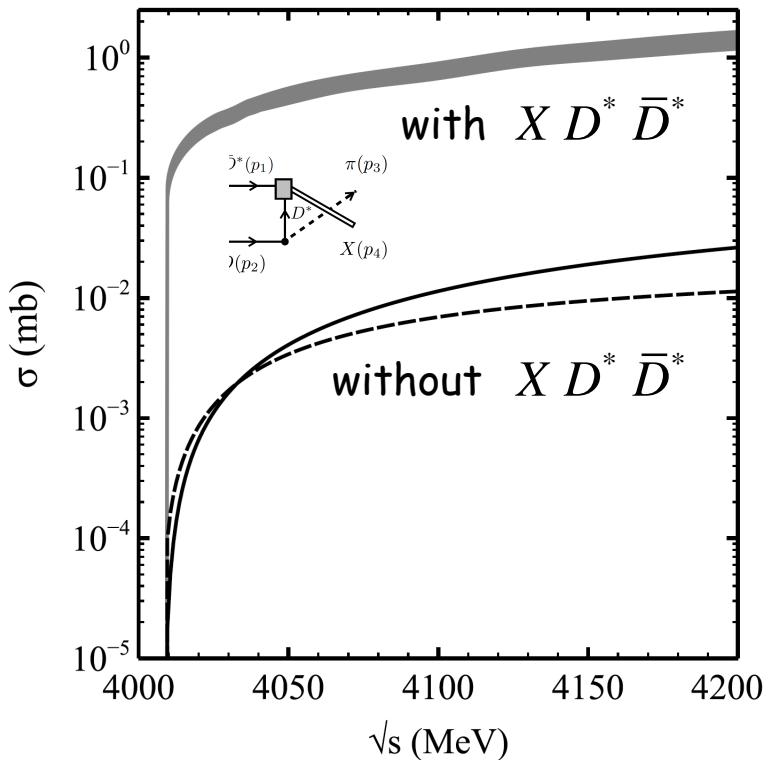
In pp a pure molecular approach is disfavored

Charmonium - molecule mixture seems to work

Tetraquarks not fully explored yet

Double parton scattering may be very important !

$$D + \bar{D}^* \rightarrow X + \pi$$

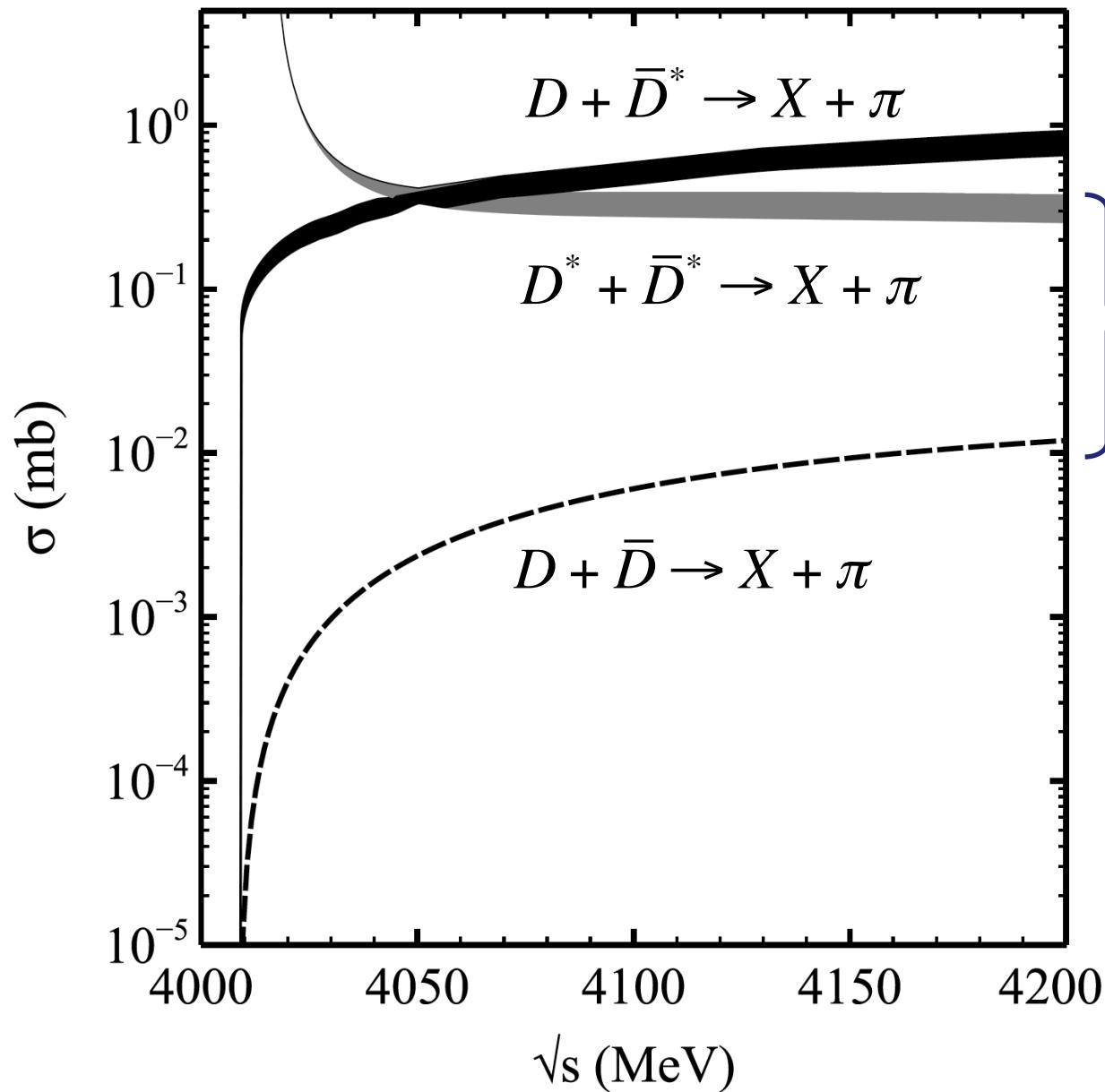


$$D + \bar{D}^* \rightarrow X + \pi$$

$X D^* \bar{D}^*$ vertex is very important

Fit the tree level calculation
to the loop calculation and
extract the coupling :

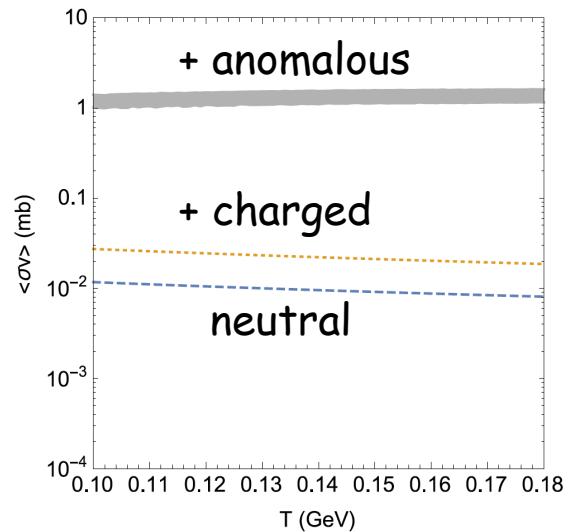
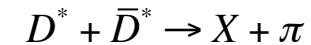
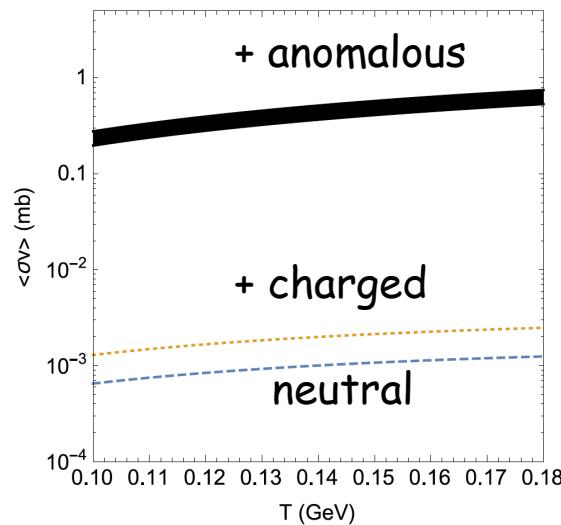
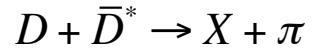
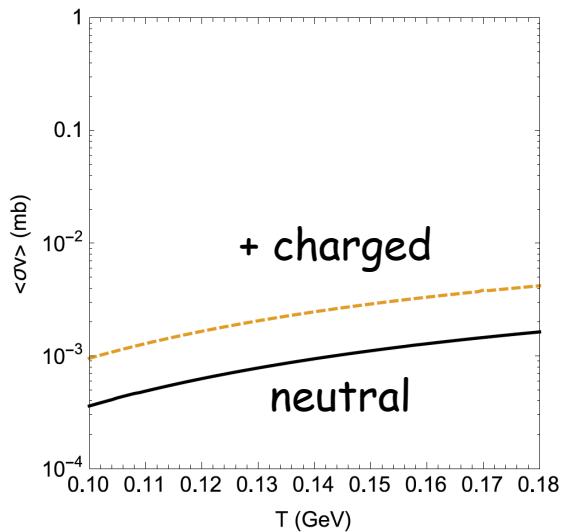
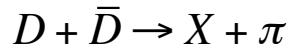
$$g_{XD^*D^*} = 1.95 \pm 0.22$$



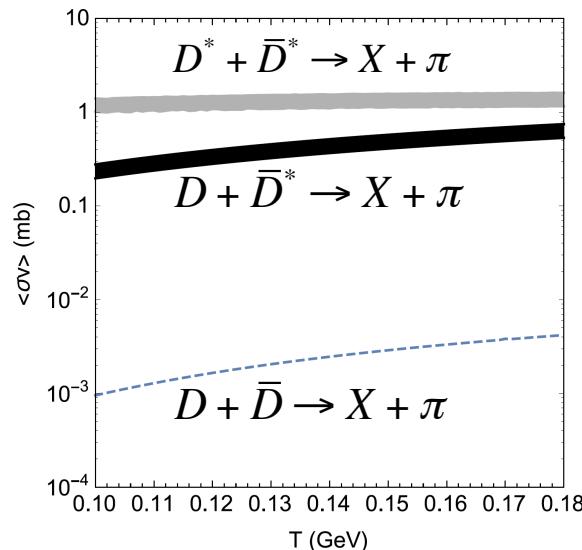
new

Cho and Lee,
arXiv:1302.6381

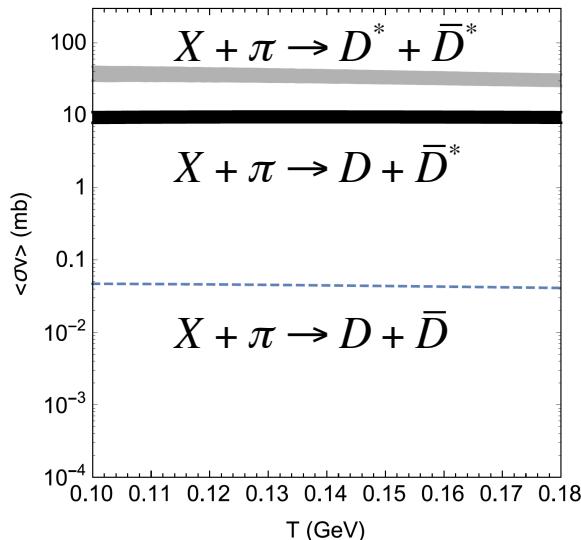
$D + \bar{D}^* \rightarrow X + \pi$ is the most important process !



Production



Absorption



Dependence on the cooling

Behavior of T ?

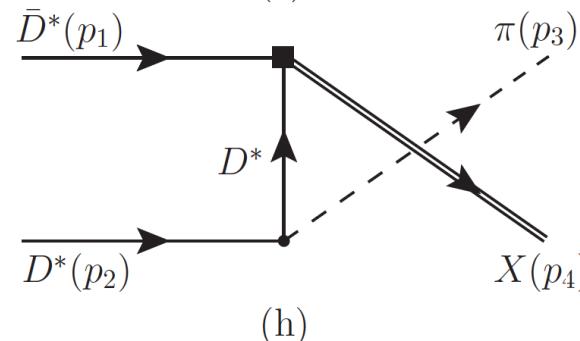
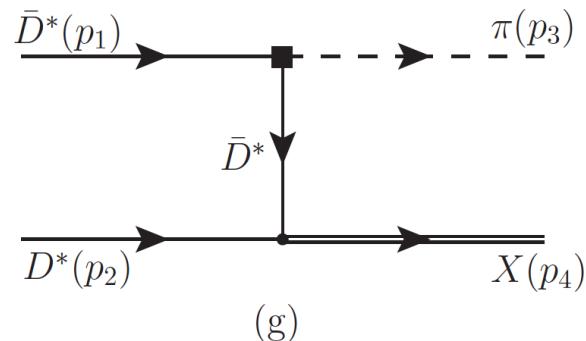
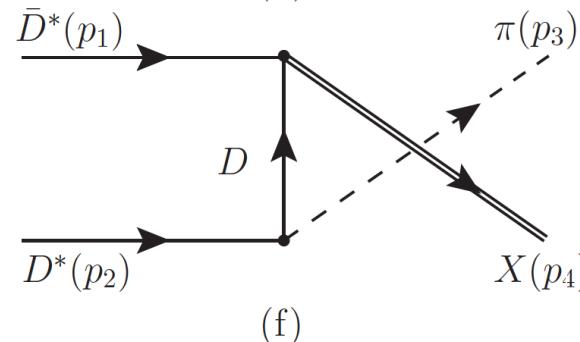
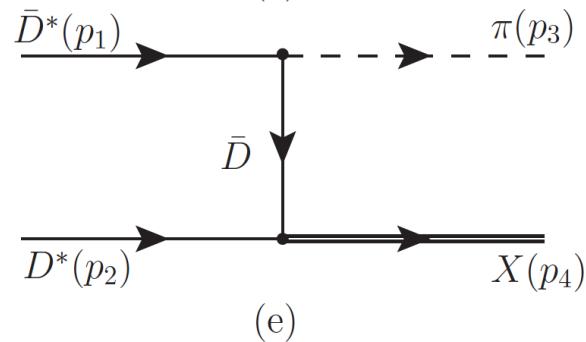
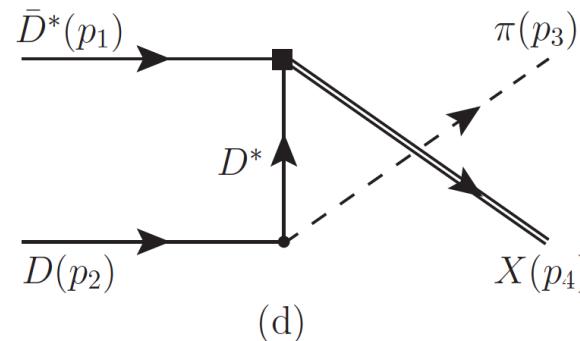
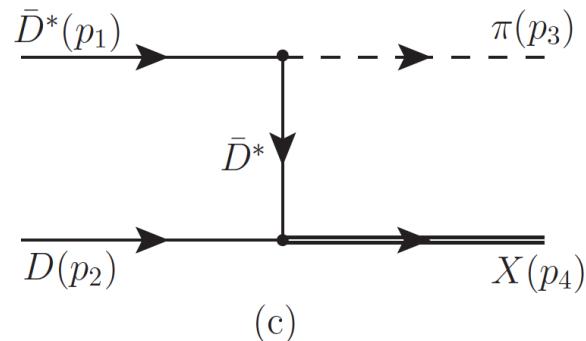
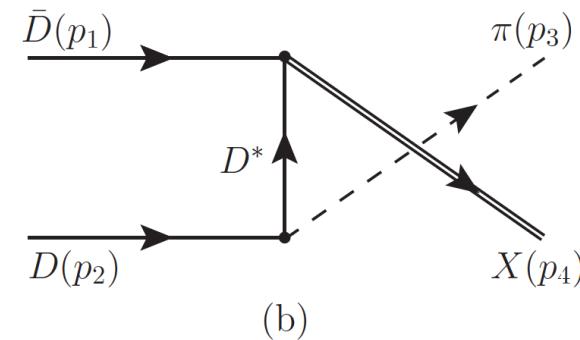
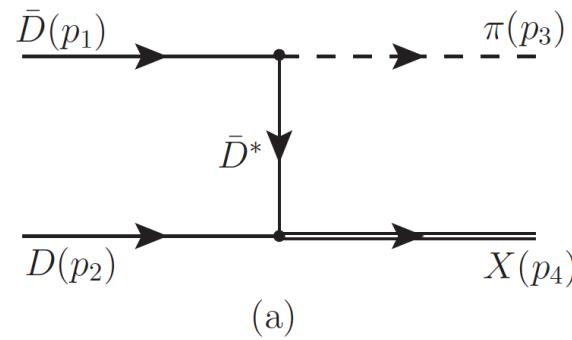
Production in all phases

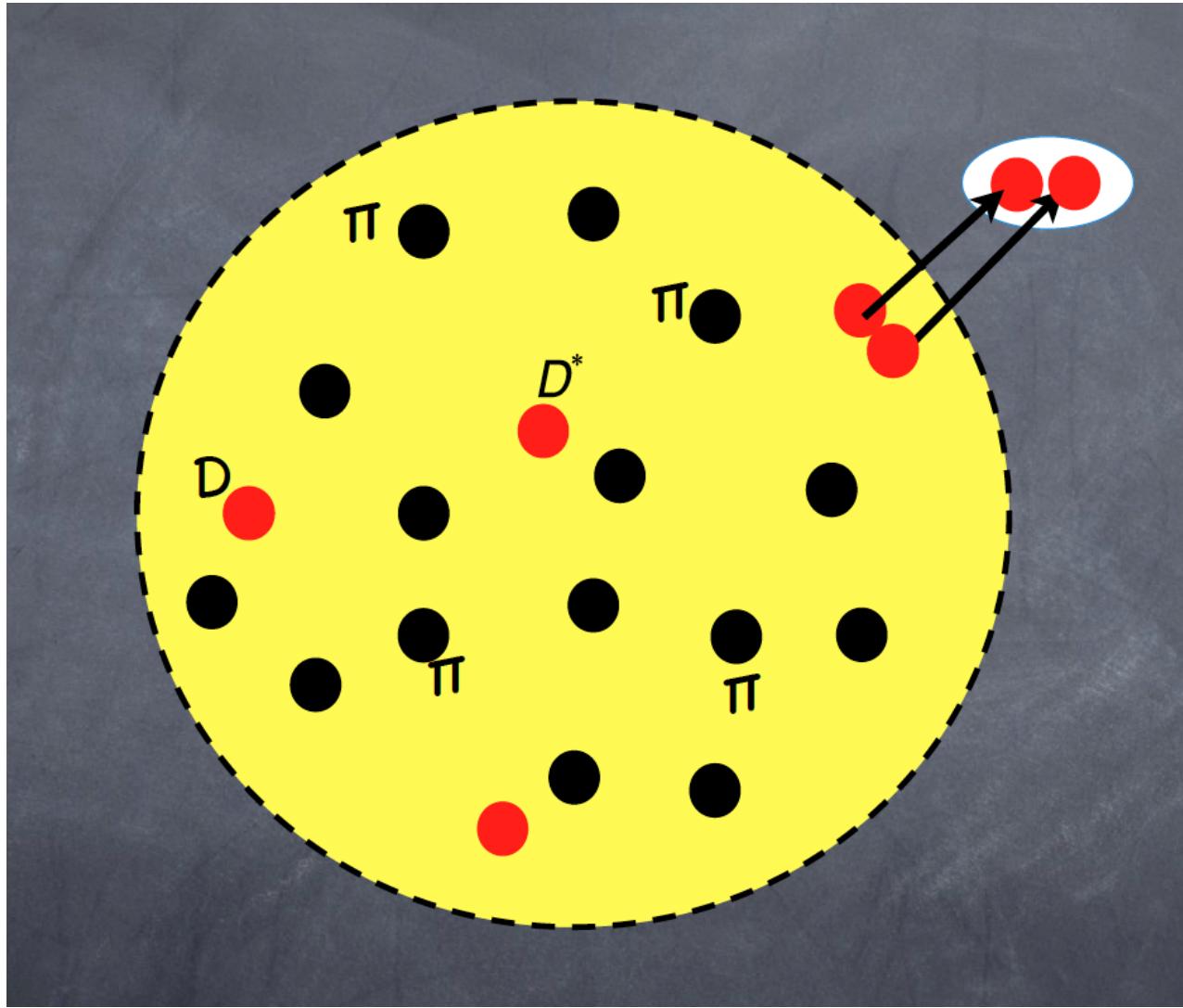
SU(4) matrices

Detailed balance

Molecula X tetraquark nas diversas fases

Citar exhic





M.Nielsen, F.S. Navarra and S.H. Lee, Phys. Rept. 497, 41 (2010) arXiv:0911.1958

M. Nielsen and F.S. Navarra, Mod. Phys. Lett. A 29, 1430005 (2014) arXiv:1401.2913

X production in nucleus - nucleus

Cho et al. ExHIC Collab., PRL 106, 212001 (2011) ; PRC 84, 064910 (2011)

Double parton scattering (DPS) in pp collisions

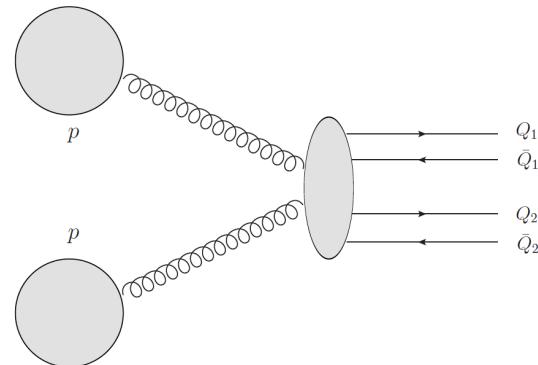
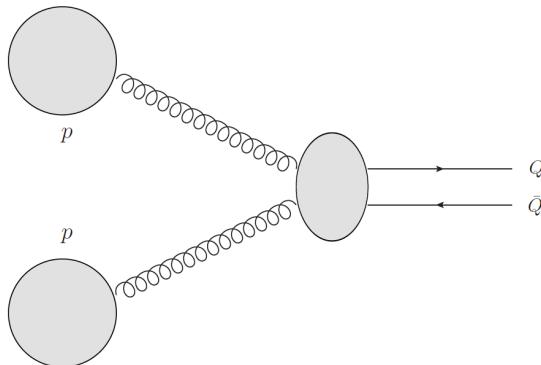
Two partons from the target scatter with two partons from the projectile

Landshoff, Polkinghorne, PRD (1978)

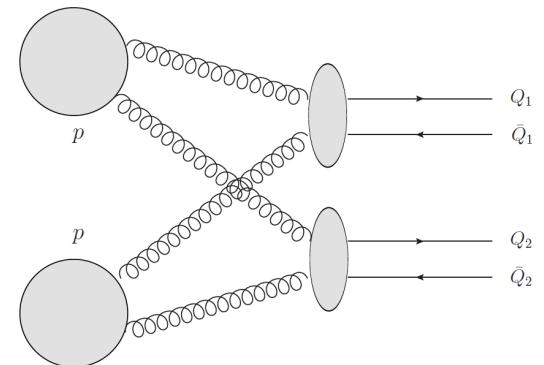


M. Diehl, arXiv:1306.6059

Single parton scattering (SPS)



Double parton scattering (DPS)

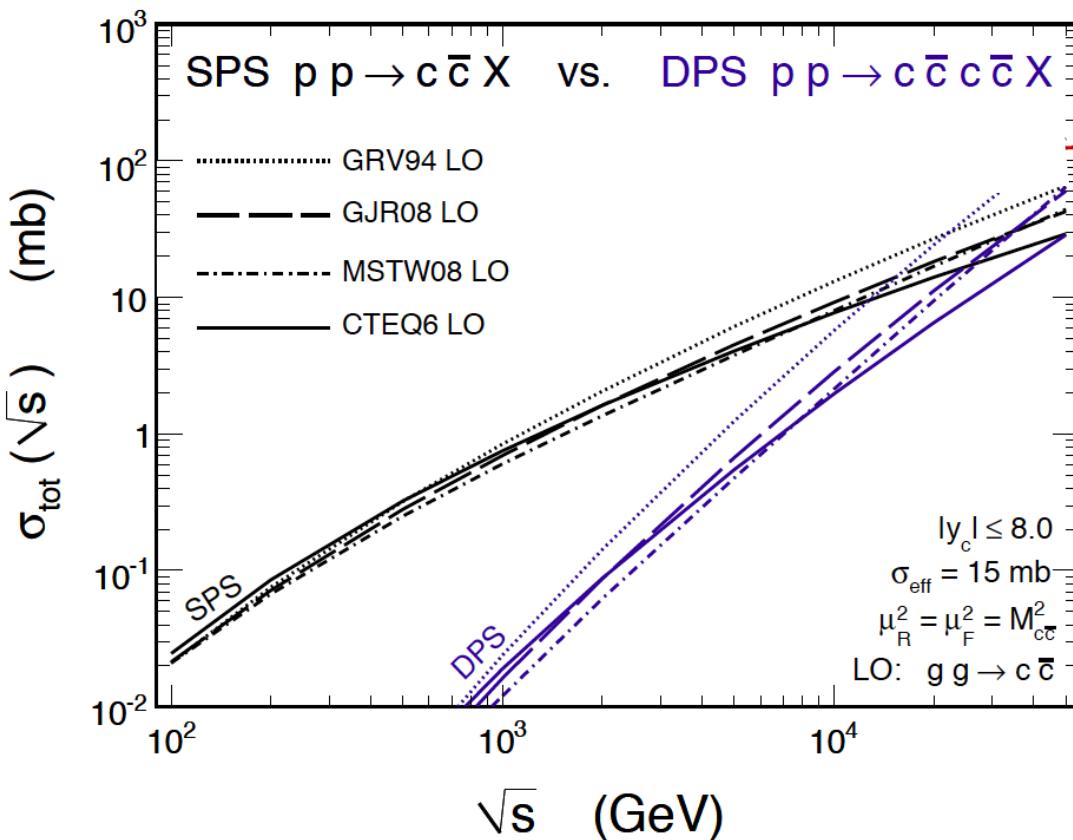


DPS is enhanced by $G(x)$ which is very large at the LHC

Double charm production in pp collisions

{ uncorrelated partons
 independent scatterings

$$\sigma_{h_1 h_2 \rightarrow Q_1 \bar{Q}_1 Q_2 \bar{Q}_2}^{DPS} = \frac{\sigma_{h_1 h_2 \rightarrow Q_1 \bar{Q}_1}^{SPS} \sigma_{h_1 h_2 \rightarrow Q_2 \bar{Q}_2}^{SPS}}{\sigma_{eff}}$$



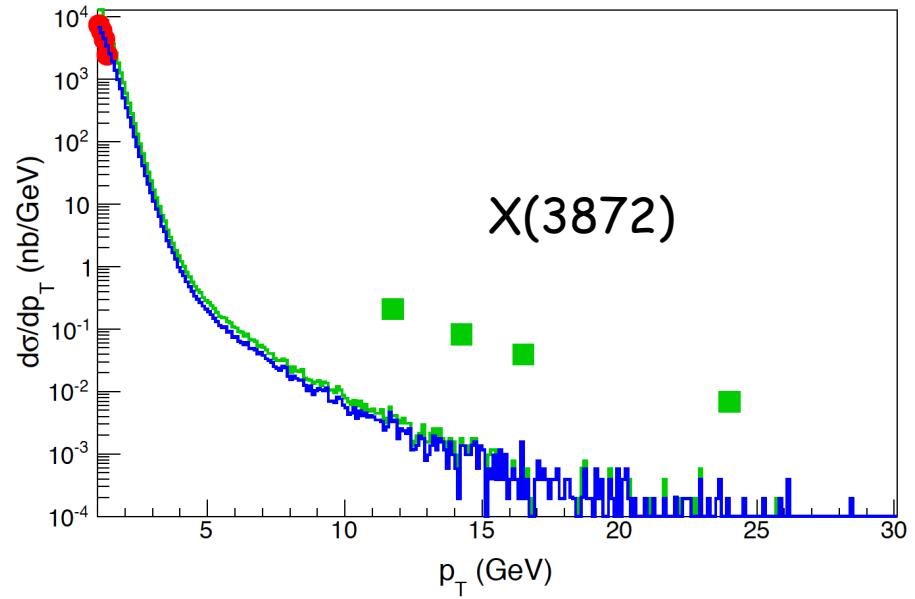
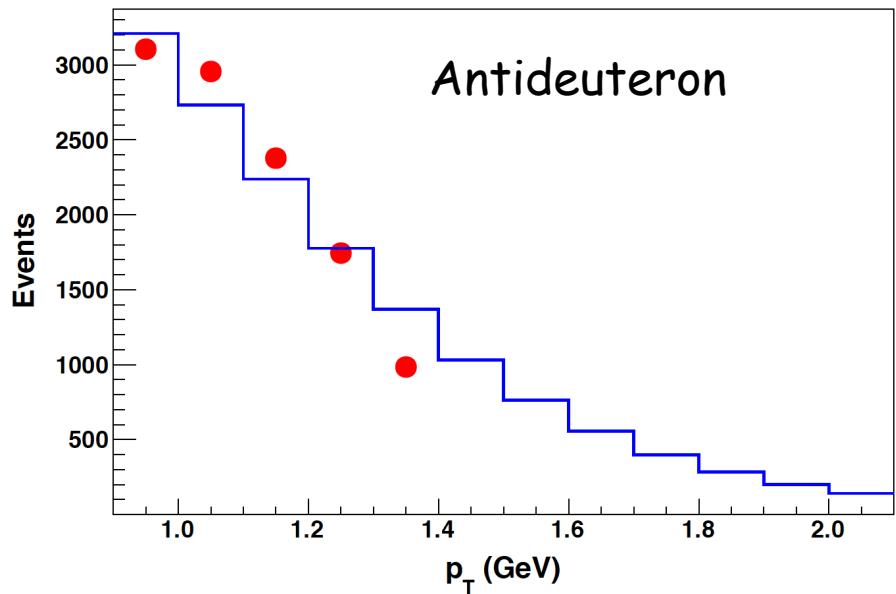
LHC: DPS = SPS !!!

Luszczak, Maciula, Szczurek,
arXiv:1111.3255

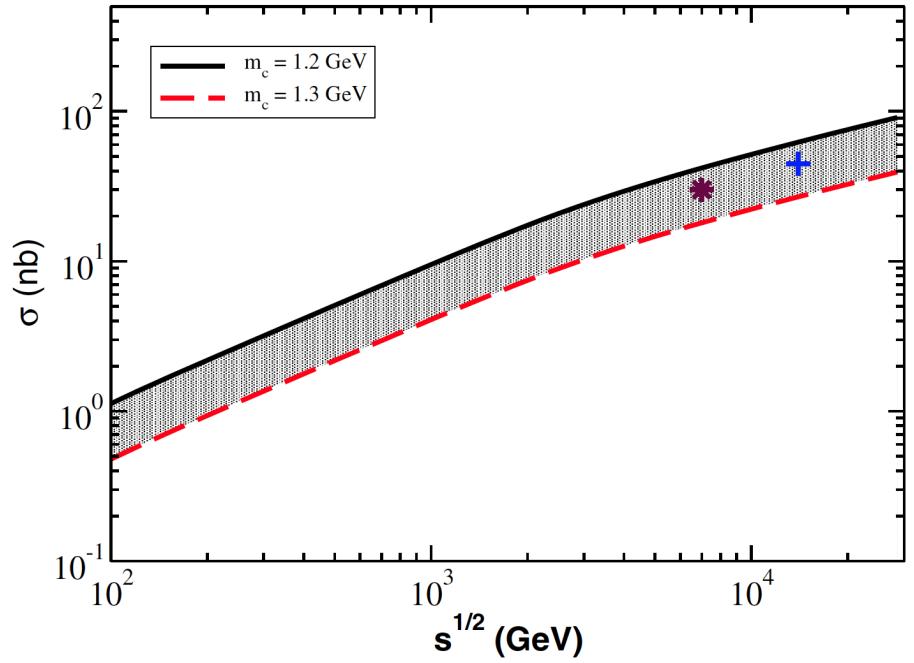
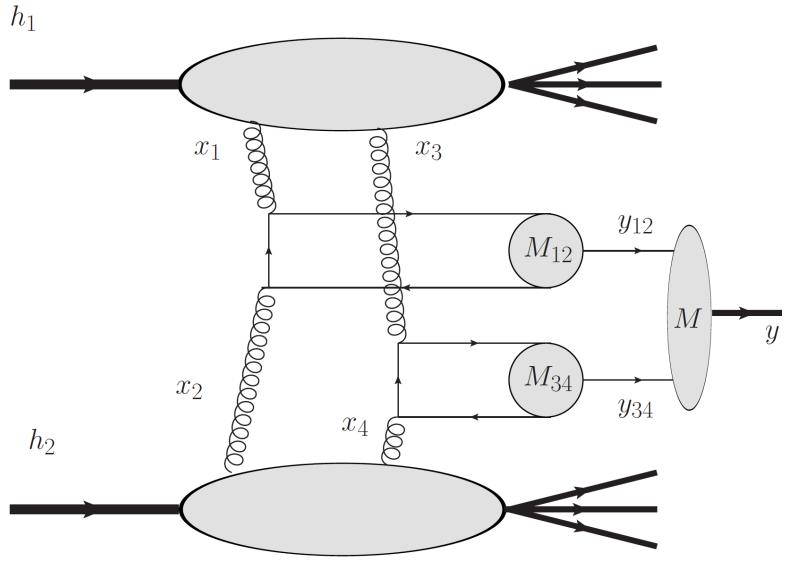
Cazaroto, Goncalves, FSN,
arXiv:1306.4169

Antideuteron production: the test of the roman model !

CMS data



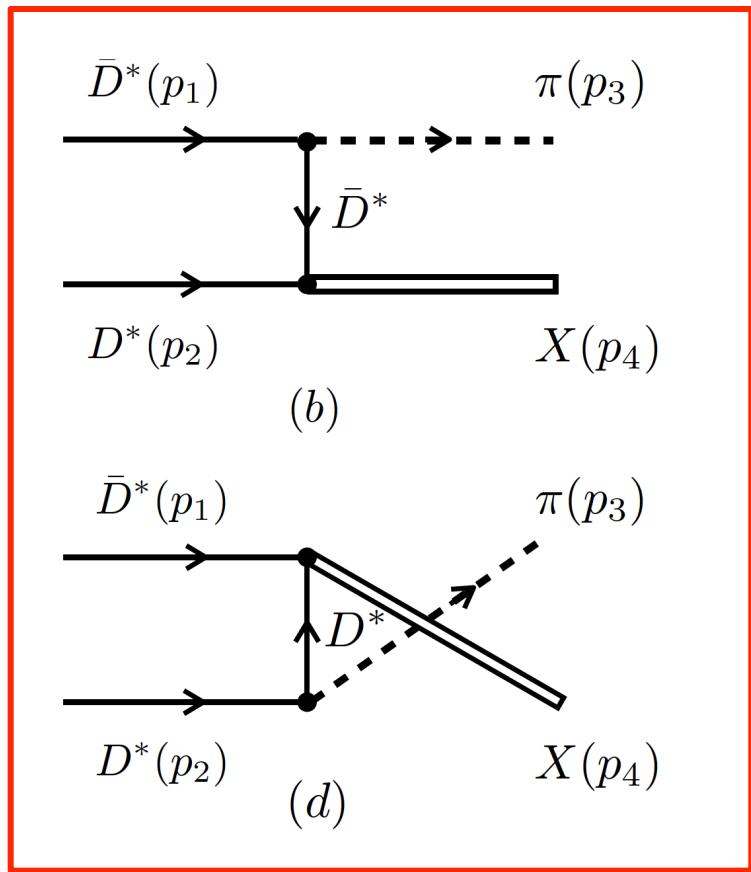
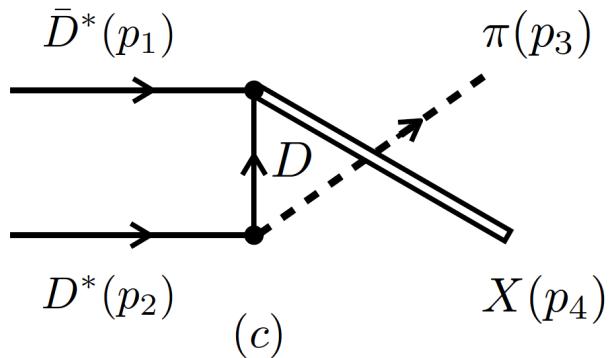
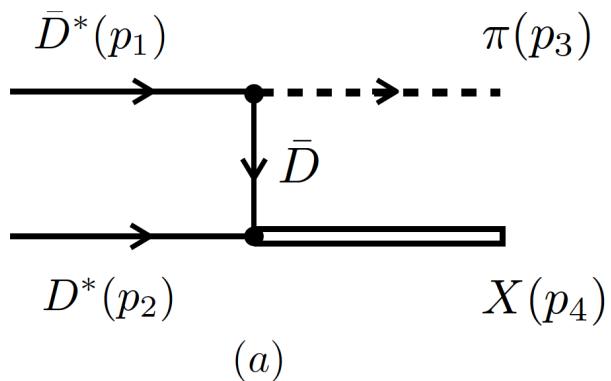
A. Guerrieri et al., arXiv:1405.7929



Energy (TeV)	$\sigma_{c\bar{c}}$ (mb)	σ_{inel} (mb)	σ_X (nb)
7	8.5 [28]	73.2 [27]	30.0 [9]
14			44.6 ± 17.7

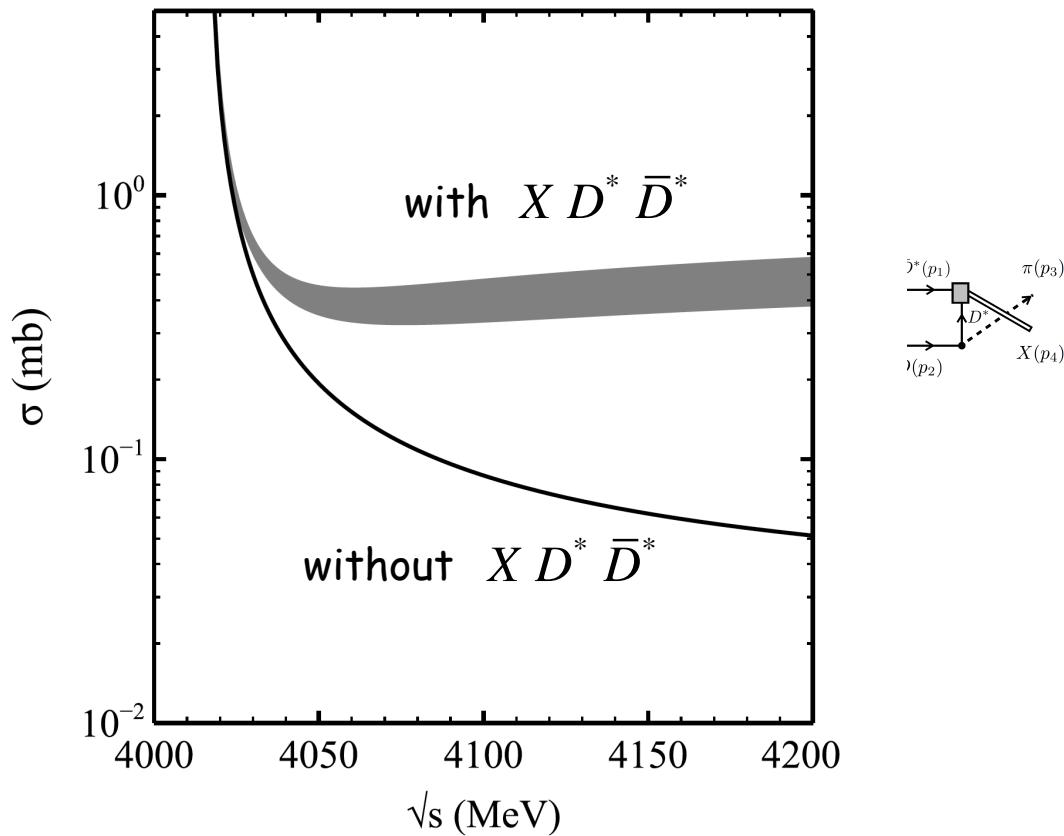
Carvalho, Cazaroto, Goncalves, FSN,
Phys. Rev. D93, 034004 (2016)

$$D^* + \bar{D}^* \rightarrow X + \pi$$



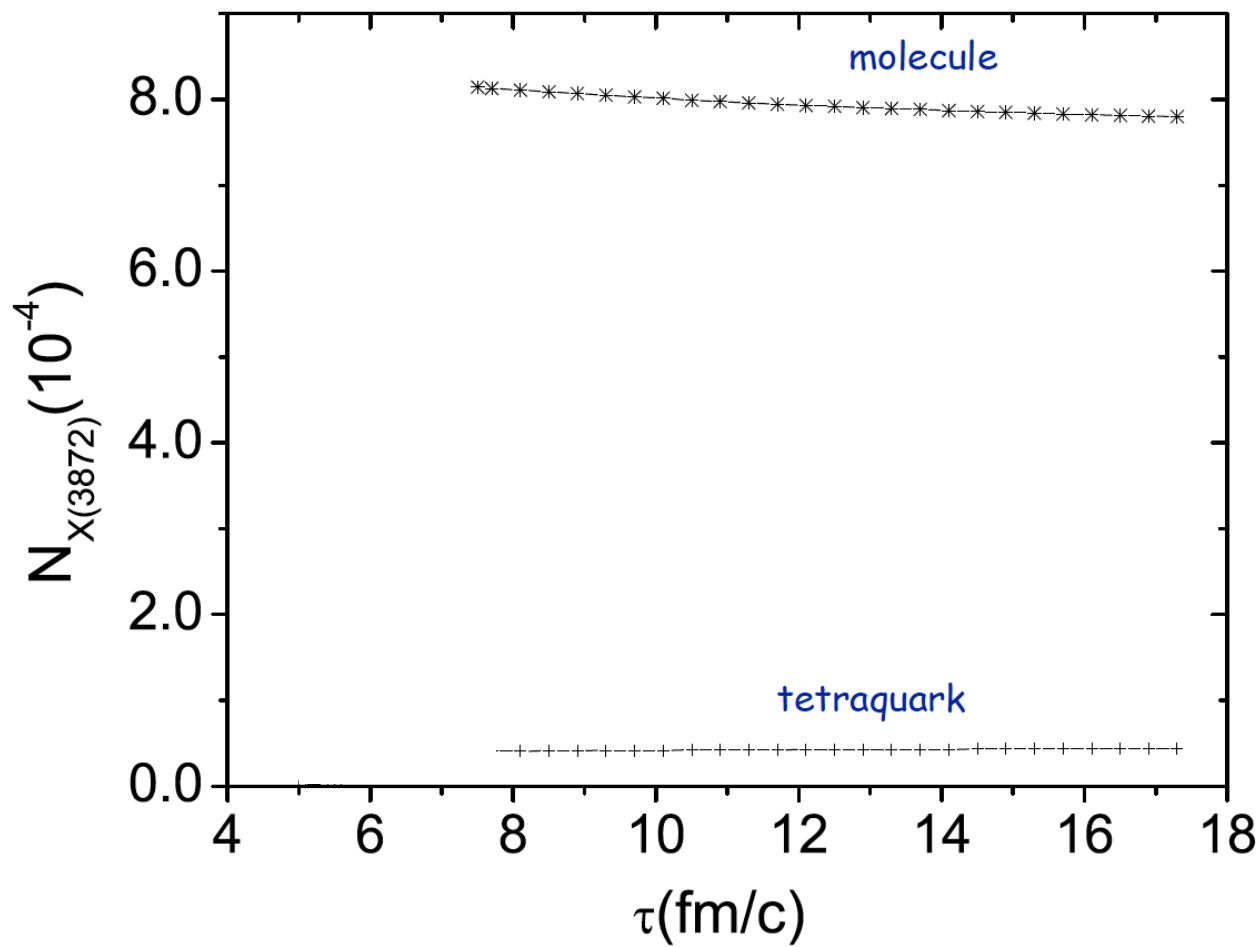
anomalous terms

$$D^* + \bar{D}^* \rightarrow X + \pi$$



$X D^* \bar{D}^*$ vertex is very important !

Time evolution of the X abundancy



Some processes not included !



Cho and Lee,
arXiv:1302.6381

Exotic hadrons :

New hadrons: which are not $q\bar{q}$ or qqq states. Multiquark systems !

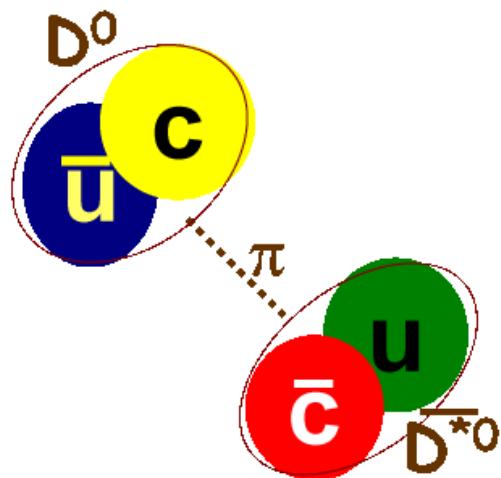
Observed in many experiments:

$e+e-$, pp , AA (?)

20 new states ! Best known: $X(3872)$ (PDG)

The X(3872) structure

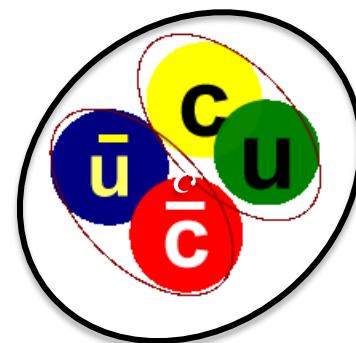
Meson molecule



large
loosely bound
meson exchange

Mixture ?

Tetraquark



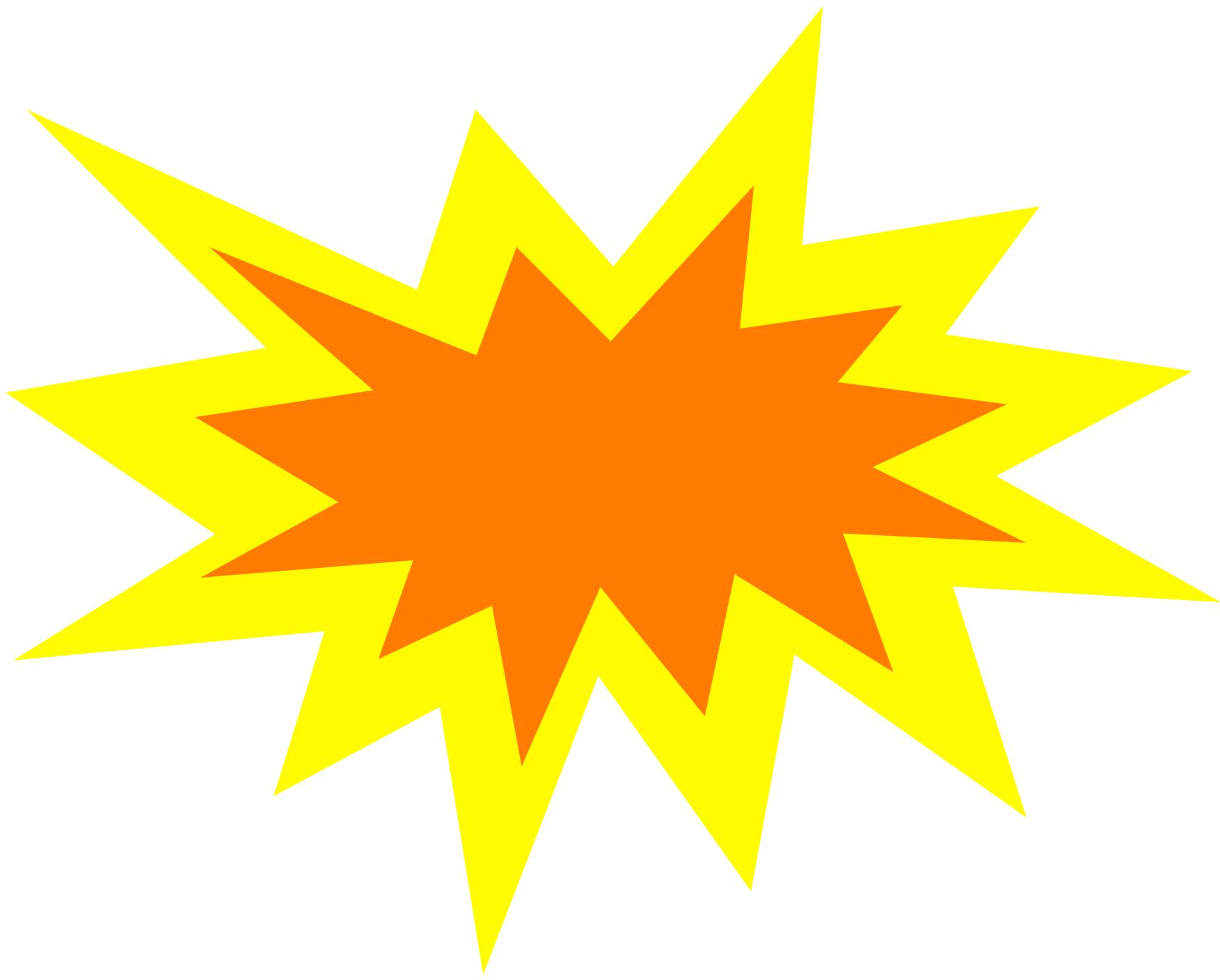
compact
color exchange

$$\left\{ \begin{array}{l} X = a |\chi'_{c1}\rangle + b |D\bar{D}^*\rangle \\ X = a |c\bar{c}\rangle + b |c\bar{c}q\bar{q}\rangle \\ X = a |c\bar{c}\rangle + b |D\bar{D}^*\rangle \\ X = a |c\bar{c}q\bar{q}\rangle + b |D\bar{D}^*\rangle \end{array} \right.$$

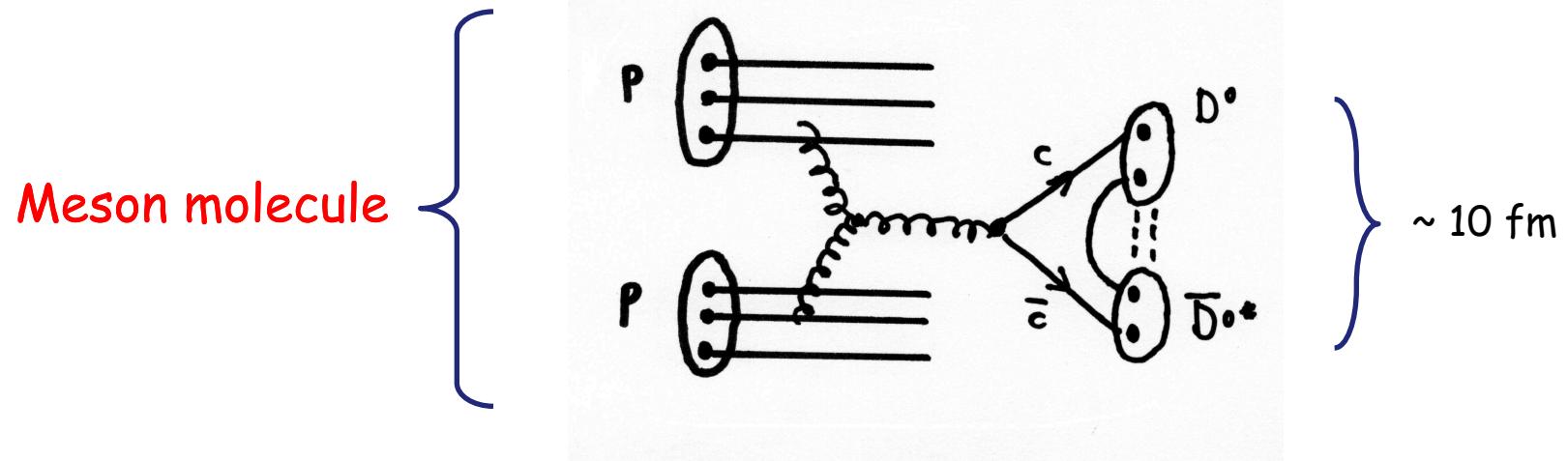
Browse: [Home](#) / Déjeuner sur l'herbe (diptych), Alain Jacquet, 1964

DÉJEUNER SUR L'HERBE (DIPTYCH), ALAIN JACQUET, 1964





Proton-proton: $\sigma_{\text{exp}} \simeq 30 \text{ nb}$ (CMS)



"Roman model"

Bignamini et al., arXiv:0906.0882

Charm quark pairs generated with PYTHIA

Fragmentation into D mesons pairs

Model for binding the D mesons

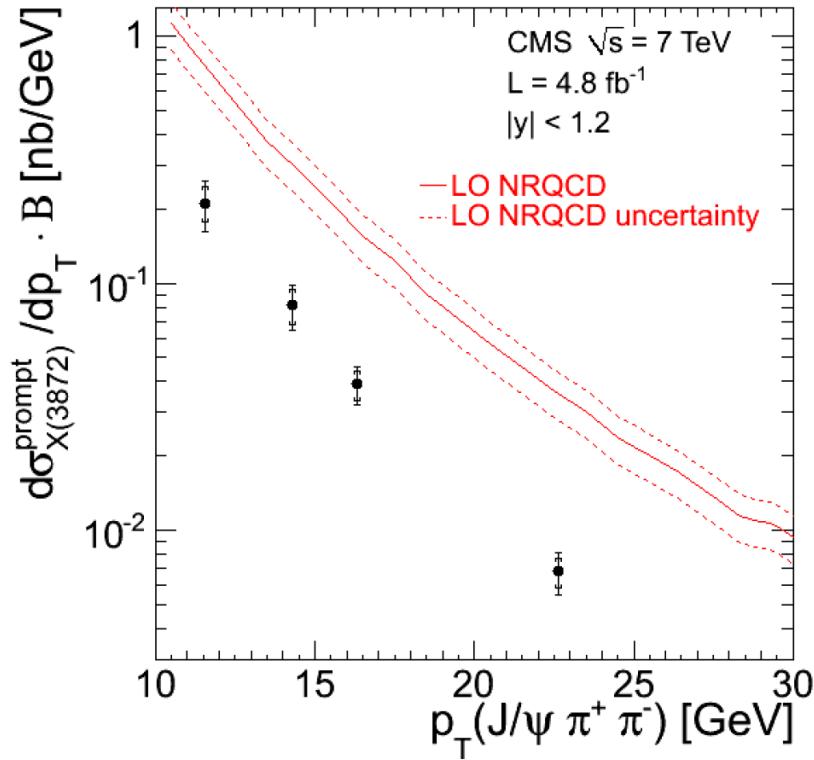
Result:

$$\sigma_{\text{th}} \simeq 0.01 \sigma_{\text{exp}}$$

Problem for the
molecular approach !

NRQCD plus rescattering in the final state:
molecular approach describes the CDF data !

Predictions for the LHC :



P. Artoisenet, E. Braaten,
arXiv:0911.2016

M. Dall'Osso et al.,
POS (Beauty 2013) 066

- The measured differential cross section (times the product of the relevant branching fractions) for prompt production of $X(3872)$ is presented on the left, and the non-prompt production is presented on the right. The $X(3872)$ is modeled as a mixture of a $\chi_{c1}(2P)$ and a $\bar{D}^0 D^{*0}$ molecular state.

