Production of enigmatic $X(3872)$ in proton-proton collisions and its structure

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Contents

Introduction

- $X(3872)$ was discovered by the Belle collaboration.
- We do not know what is the structure of this state.
- We know at present it is $J^{\pi} = 1^{+}$, $C = +1$ state, similarly as the well known $\chi_c(1^+)$ quarkonium.
- Different scenarios were proposed:
  (a) $c\bar{c}$ state
  (b) DD^* molecular state
  (c) tetraquark $c\bar{c}q\bar{q}$
  (d) hybrid approaches
- Can the production of $X(3872)$ in proton-proton collisions provide new information ?

Introduction

- k_t-factorization gives good description of inclusive D-meson distributions (Maciula-Szczurek).
  Higher orders are needed in collinear approach.
- k_t-factorization gives good description of $D^0 - \bar{D}^0$ correlation observables (Maciula-Szczurek).
- k_t-factorization gives good description of $\eta_c(1S)$ production (Babiarz-Schäfer-Szczurek).
- Here we shall consider production of $X(3872)$ taking into account three different approaches for its structure, within the k_t-factorization approach.
- We shall use modern unintegrated gluon distributions.
- A. Cisek, W. Schäfer and A. Szczurek, arXiv:2203.07827, "Structure and production mechanism of the enigmatic X(3872) in high-energy hadronic reactions".

Formalism, structure

- $c\bar{c}$ state, R'(0) extracted from the Eichten-Quigg study (Schrödinger equation)
- DD^* molecule

$$|X(3782)\rangle = \frac{1}{\sqrt{2}}\left(|D\bar{D}^*\rangle + |\bar{D}D^*\rangle\right) \ . \tag{1}$$

- hybrid approach (Coito, Rupp, van Beveren 2013)

$$|X(3782)\rangle = \alpha|c\bar{c}\rangle + \frac{\beta}{\sqrt{2}}\left(|D\bar{D}^*\rangle + |\bar{D}D^*\rangle\right) \ . \tag{2}$$

Quarkonium spectra

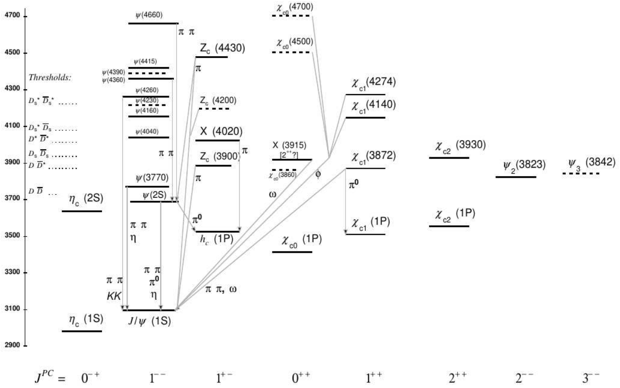


Figure: Mass spectrum of charmonia.

Formalism, production mechanism

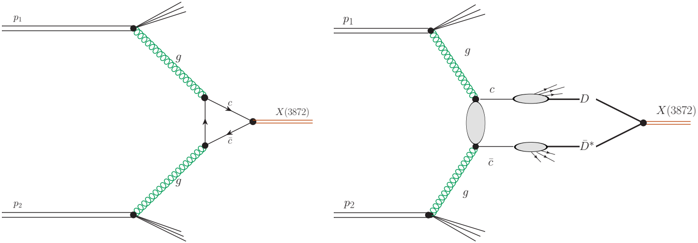


Figure: Generic diagrams for the inclusive process of $X(3872)$ production in proton-proton scattering via two gluons fusion.

adequate for the k_T-factorization calculations

Formalism, production of $c\bar{c}$ state

The inclusive cross section for $X(3872)$-production via the $2 \to 1$ gluon-gluon fusion mode is obtained from

$$\frac{d\sigma}{dyd^2\boldsymbol{p}} = \int \frac{d^2\boldsymbol{q}_1}{\pi \boldsymbol{q}_1^2}\mathcal{F}(x_1, \boldsymbol{q}_1^2, \mu_F^2) \int \frac{d^2\boldsymbol{q}_2}{\pi \boldsymbol{q}_2^2}\mathcal{F}(x_2, \boldsymbol{q}_2^2, \mu_F^2) \, \delta^{(2)}(\boldsymbol{q}_1 + \boldsymbol{q}_2 - \boldsymbol{p}) \times \frac{\pi}{(x_1 x_2 s)^2}\overline{|\mathcal{M}_{g^*g^*\to X(3872)}|^2} \quad (3)$$

Formalism, production of $c\bar{c}$ state

Here the matrix element squared for the fusion of two off-shell gluons into the $^3P_1$ color singlet $c\bar{c}$ charmonium is (see e.g. Kniehl-Saleev-Vasin for a derivation):

$$\overline{|\mathcal{M}_{g^*g^*\to X(3872)}|^2} = (4\pi\alpha_S)^2 \frac{4|R'(0)|^2}{\pi M_X^3} \frac{\boldsymbol{q}_1^2 \boldsymbol{q}_2^2}{(M_X^2 + \boldsymbol{q}_1^2 + \boldsymbol{q}_2^2)^4}$$
$$\times \quad \Big((\boldsymbol{q}_1^2 + \boldsymbol{q}_2^2)^2 \sin^2\phi + M_X^2 (\boldsymbol{q}_1^2 + \boldsymbol{q}_2^2 - 2|\boldsymbol{q}_1||\boldsymbol{q}_2| \cos\phi) \Big) , \quad (4)$$

where ϕ is the azimuthal angle between $\boldsymbol{q}_1, \boldsymbol{q}_2$.

Formalism, production of $c\bar{c}$ state

The momentum fractions of gluons are fixed as

$$x_{1,2} = m_T \exp(\pm y)/\sqrt{s}, \tag{5}$$

where $m_T^2 = \boldsymbol{p}^2 + M_X^2$.
The derivative of the radial quarkonium wave function at the origin is taken for the first radial p-wave excitation from Eichten-Quigg 2019, $|R'(0)|^2 = 0.1767\,\mathrm{GeV}^5$.
The unintegrated gluon parton distribution functions (gluon uPDFs) are normalized such, that the collinear glue is obtained from

$$xg(x,\mu_F^2) = \int^{\mu_F^2} \frac{d^2\boldsymbol{k}}{\pi\boldsymbol{k}^2}\mathcal{F}(x,\boldsymbol{k}^2,\mu_F^2)\,. \tag{6}$$

The hard scale is taken to be always $\mu_F = m_T$, the transverse mass of the $X(3872)$.

Formalism, production of the molecule

The parton-level differential cross section for the $c\bar{c}$ production, formally at leading-order, reads:

$$\frac{d\sigma(pp \to Q\bar{Q}\,X)}{dy_1 dy_2 d^2\boldsymbol{p}_1 d^2\boldsymbol{p}_2} = \int \frac{d^2\boldsymbol{k}_1}{\pi \boldsymbol{k}_1^2} \mathcal{F}(x_1, \boldsymbol{k}_1^2, \mu_F^2) \int \frac{d^2\boldsymbol{k}_2}{\pi \boldsymbol{k}_2^2} \mathcal{F}(x_2, \boldsymbol{k}_2^2, \mu_F^2)$$
$$\times \delta^{(2)}\left(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{p}_1 - \boldsymbol{p}_2\right) \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}^{\mathrm{off-shell}}_{g^* g^* \to c\bar{c}}|^2} \,. \qquad (7)$$

where $\mathcal{M}^{\mathrm{off-shell}}_{g^* g^* \to Q\bar{Q}}$ is the off-shell matrix element for the hard subprocess (Catani et al.), we use its implementation from (Maciula-Szczurek)

Formalism, production of the molecule

Here, one keeps exact kinematics from the very beginning and additional hard dynamics coming from transverse momenta of incident partons. Explicit treatment of the transverse momenta makes the approach very efficient in studies of correlation observables. The two-dimensional Dirac delta function assures momentum conservation. The gluon uPDFs are evaluated at longitudinal momentum fractions:

$$x_1 = \frac{m_{T1}}{\sqrt{s}} \exp(+y_1) + \frac{m_{T2}}{\sqrt{s}} \exp(+y_2) \,, \tag{8}$$

$$x_2 = \frac{m_{T1}}{\sqrt{s}} \exp(-y_1) + \frac{m_{T2}}{\sqrt{s}} \exp(-y_2), \tag{9}$$

where $m_{Ti} = \sqrt{p_{Ti}^2 + m_c^2}$ is the quark/antiquark transverse mass.

Formalism, production of the molecule

In the present analysis we employ the heavy c-quark approximation and assume that three-momenta in the pp-cm frame are equal:

$$\vec{p}_D = \vec{p}_c \ . \tag{10}$$

This approximation could be relaxed in future.
The hadronization is then included only via fragmentation branching fractions:

$$P(c \to D^0) = P(\bar{c} \to \bar{D}^0) = 0.56 \ , \tag{11}$$
$$P(c \to D^+) = P(\bar{c} \to D^-) = 0.225 \ , \tag{12}$$
$$P(c \to D^{*0}) = P(\bar{c} \to \bar{D}^{*0}) = 0.236 \ , \tag{13}$$
$$P(c \to D^{*+}) = P(\bar{c} \to \bar{D}^{*-}) = 0.236 \ . \tag{14}$$

The first number is from (Lisovyi2015) while the other numbers are from (ATLAS, D-mesons).

Formalism, production of the molecule

The cross section for $c\bar{c}$ production are then multiplied by

$$\frac{1}{2}[P(c \to D^0)P(\bar{c} \to \bar{D}^{*0}) + P(c \to D^{*0})P(\bar{c} \to \bar{D}^0)] = 0.1322(15)$$

We calculate $k_{rel} = \frac{1}{2}\sqrt{M_{c\bar{c}}^2 - 4m_c^2}$.
In the following for illustration we shall therefore assume
$k_{max} = 0.2\,\mathrm{GeV}$.
k_{max}^{DD} is then smaller.
The calculation for the SPS molecular scenario is done using the VEGAS algorithm for Monte-Carlo integration.

Production of molecule via double parton scattering

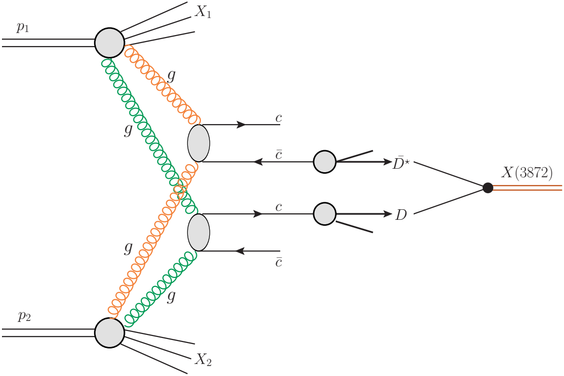


Figure: A generic diagram for the inclusive process of $X(3872)$ production in proton-proton scattering via the double parton scattering mode.

Production via double parton scattering

The corresponding cross section is calculated in the so-called factorized ansatz as:

$$\Delta\sigma = \frac{1}{2\sigma_{\rm eff}} \int \frac{d\sigma_{c\bar{c}}}{dy_1 d^2\boldsymbol{p}_1} \frac{d\sigma_{c\bar{c}}}{dy_2 d^2\boldsymbol{p}_2} \; dy_1 d^2\boldsymbol{p}_1 dy_2 d^2\boldsymbol{p}_2 \Big|_{k_{rel} < k_{max}} . \tag{16}$$

Above the differential distributions of the first and second parton scattering $\frac{d\sigma}{dy_i d^2\boldsymbol{p}_i}$ are calculated in the k_T-factorization approach as explained above. In the following we take $\sigma_{\rm eff} =$ 15 mb (Maciula,Szczurek).

The differential distributions (in p_T of the $X(3872)$ or $y_{\rm diff} = y_1 - y_2$, etc.) are obtained by binning in the appropriate variable.

Production via double parton scattering

We include all possible fusion combinations leading to $X(3872)$:

$$c_1 \longrightarrow D^0, \bar{c}_2 \longrightarrow \bar{D}^{*0} \; , \tag{17}$$

$$c_1 \longrightarrow D^{*0}, \bar{c}_2 \longrightarrow \bar{D}^0 \; , \tag{18}$$

$$\bar{c}_1 \longrightarrow \bar{D}^0, c_2 \longrightarrow D^{*0} \; , \tag{19}$$

$$\bar{c}_1 \longrightarrow \bar{D}^{*0}, c_2 \longrightarrow D^0 \; . \tag{20}$$

This leads to the multiplication factor two times bigger than for the SPS contribution.

Unintegrated gluon distributions

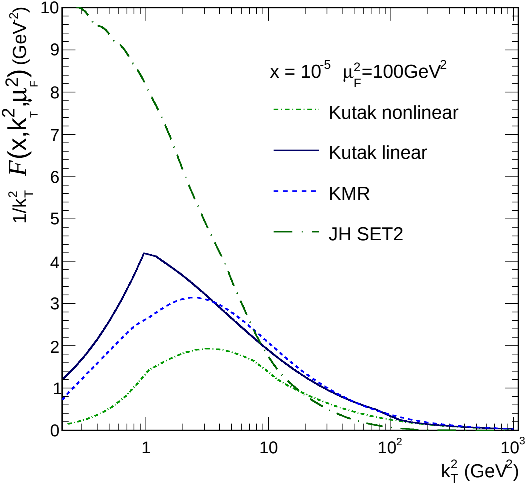
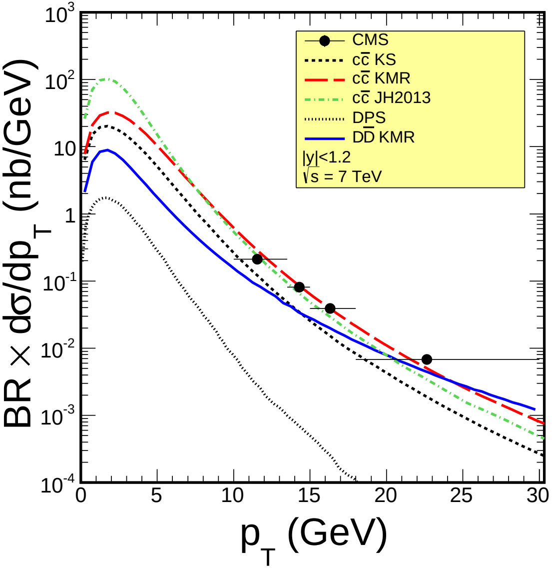
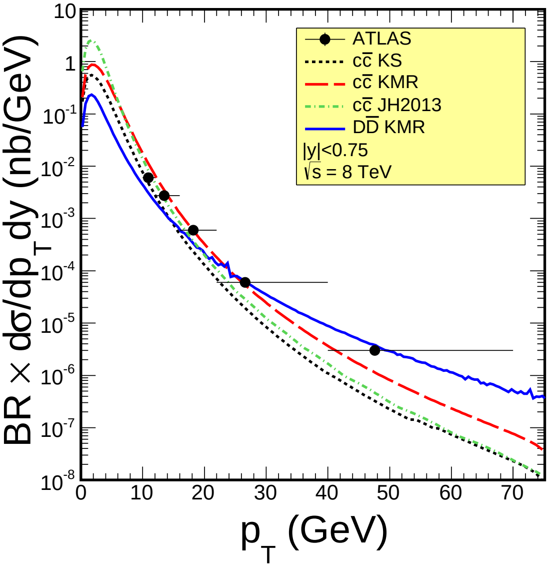


Figure: Some unintegrated gluon distributions as a function of k_t^2 for a given $x = 10^{-5}$ and factorization scale $\mu^2 = 100$ GeV^2.

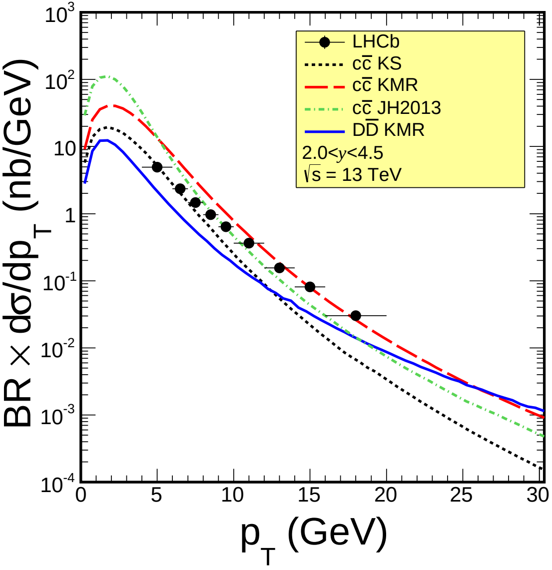
Results, $c\bar{c}$ state



Results, $c\bar{c}$ state



Results, $c\bar{c}$ state



Results, molecular picture

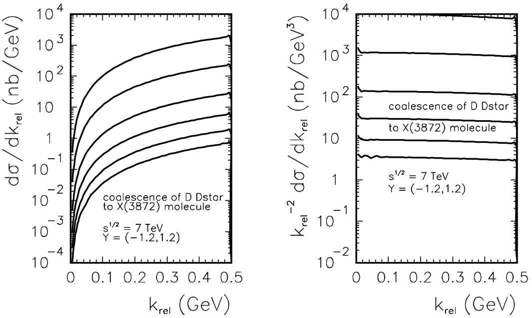
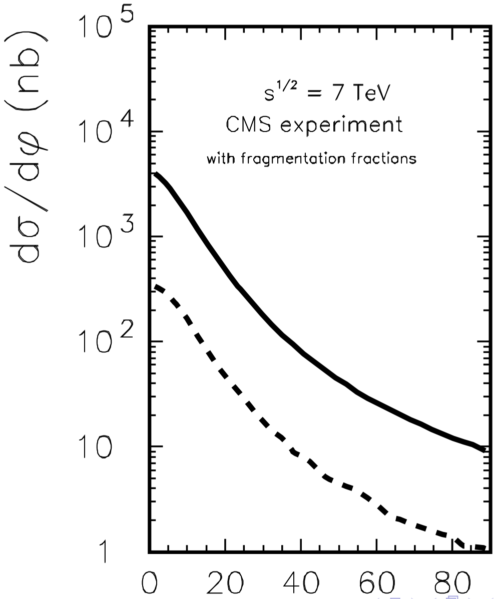


Figure: Distribution in k_{rel} for different windows of $p_{t,c\bar{c}} = p_{t,X}$ (left panel) for the CMS kinematics. In the right panel we show the cross sections divided by k_{rel}^2. In these calculations the KMR UGDF with the MMHT NLO collinear gluon distribution was used.

$p_{t,X}$ (GeV) = (0,5), (5,10), (10,15), (15,20), (20,25), (25,30)

Results, molecular picture



Results, hybrid model

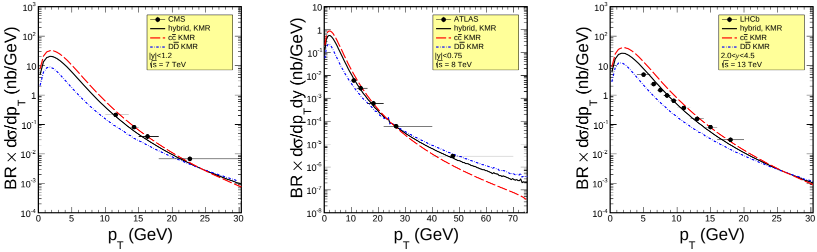


Figure: Transverse momentum distribution of $X(3872)$ for the CMS, ATLAS and LHCb experiments. Shown are results for the KMR UGDF. Here BR $= 0.038$ for CMS and LHCb, and $\mathrm{BR} = 0.038 \cdot 0.0596$ for ATLAS. We show results for different combinations of α and β: (1,0), (0,1), (0.5,0.5).

Conclusions

- The structure of famous $X(3872)$ is not known.
- Can the production of $X(3872)$ in proton-proton scattering be a new source of information ?
- We have calculated production of $X(3872)$ as the $c\bar{c}$ in the k_t-factorization approach within nonrelativistic approach for the $g^*g^* \to X(3872)$ vertex with modern unintegrated distributions.
  A reasonable results have been obtained.
- We have done similar calculation for the DD^* fusion. $c\bar{c}$ is calculated in the k_t-factorization approach. D and D^* mesons calculated in infinitly heavy quark approximation.
  A reasonable results have been obtained.
- In addition, a hybrid model (mixture of $c\bar{c}$ and molecular component).
  A reasonable results have been obtained.

Conclusions

- All free approaches describe the LHC data for $pp \longrightarrow X(3872)$.