Structure and production mechanism of $X(3872)$ in high-energy hadronic reactions

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Madrid, November 14-18 2022, MPI@LHC 2022

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 state
- 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, in print in Eur.Phys.J.C
  "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)

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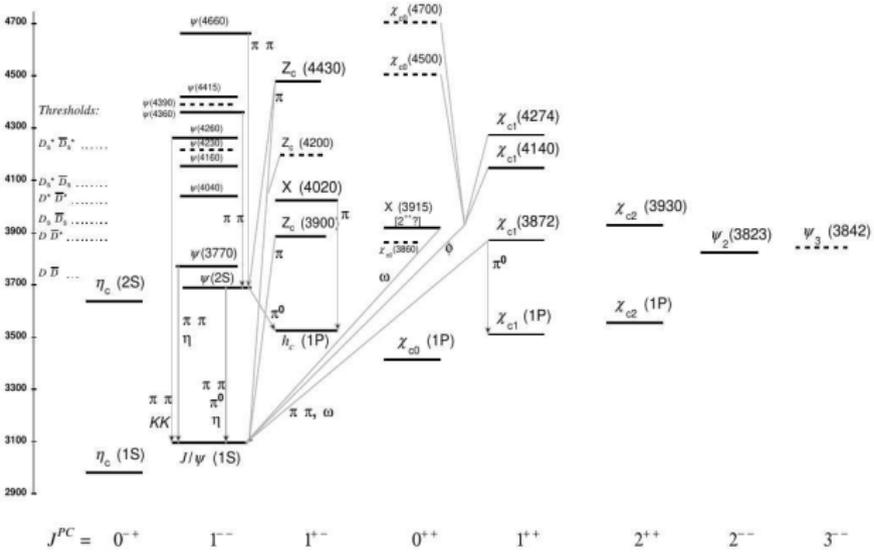
Quarkonium spectra

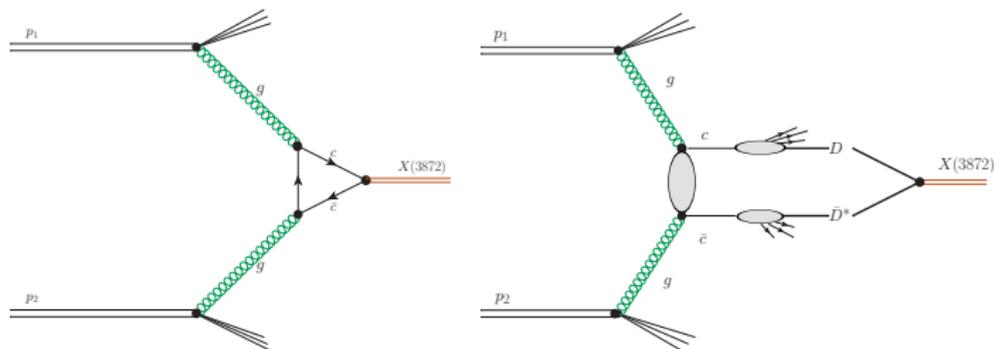

Figure: Mass spectrum of charmonia.

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

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

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):

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

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:

$$\frac{d\sigma(pp \to Q\bar{Q}\,X)}{dy_1\,dy_2\,d^2\boldsymbol{p}_1\,d^2\boldsymbol{p}_2} = \int \frac{d^2\boldsymbol{k}_1}{\pi\boldsymbol{k}_1^2}\,\mathcal{F}(x_1,\boldsymbol{k}_1^2,\mu_F^2)\int \frac{d^2\boldsymbol{k}_2}{\pi\boldsymbol{k}_2^2}\,\mathcal{F}(x_2,\boldsymbol{k}_2^2,\mu_F^2)$$

$$\times\,\delta^{(2)}\left(\boldsymbol{k}_1 + \boldsymbol{k}_2 - \boldsymbol{p}_1 - \boldsymbol{p}_2\right)\,\frac{1}{16\pi^2(x_1 x_2 s)^2}\,\overline{|\mathcal{M}^{\text{off}-\text{shell}}_{g^*g^*\to c\bar{c}}|^2}. \qquad (7)$$

where $\mathcal{M}^{\text{off}-\text{shell}}_{g^*g^*\to Q\bar{Q}}$ 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:

$$
\begin{aligned}
x_1 &= \frac{m_{T1}}{\sqrt{s}} \exp(+y_1) + \frac{m_{T2}}{\sqrt{s}} \exp(+y_2) , & (8) \\
x_2 &= \frac{m_{T1}}{\sqrt{s}} \exp(-y_1) + \frac{m_{T2}}{\sqrt{s}} \exp(-y_2), & (9)
\end{aligned}
$$

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.

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 molecules, probabilities

We now should take into account the fragmentation into D, D^*-mesons. The fragmentation fractions fulfill the sum rule:

$$\sum_i f(c \to H_i) = 1 \,. \tag{11}$$

In this formula H_i are the final (after strong decays) hadrons. Therefore the spin-1 D^* mesons should not be included here as it would lead to double counting. The final charmed particles are only those which have only weak decays: $D^+, D^0, D_s^+, \Lambda_c$, etc. The D^0 (or $\bar{D}^0$) are produced directly or come from the decays of spin-1 mesons (see PDG):

$$\mathrm{Br}(D^{*0} \to D^0) = 1 \,, \qquad \mathrm{Br}(D^{*+} \to D^0) = 0.68 \,. \tag{12}$$

$$f(c \to D^0) = 0.54 - 0.63 \,. \tag{13}$$

The total uncertainties is less than $\sim 10\%$.
The total probability can be decomposed as the sum:

$$f(c \to D^0) = f(c \to D^0)|_{\mathrm{direct}} + f(c \to D^0)|_{\mathrm{feeddown}} \,. \tag{14}$$

Production of molecules, probabilities

The direct component can be approximated as:

$$f(c \to D^0)|_{\text{direct}} \approx f(c \to D^\pm)|_{\text{direct}}, \tag{15}$$

assuming isospin symmetry.
Let us calculate therefore the feeddown probability:

$$
\begin{aligned}
f(c \to D^0)|_{\text{feeddown}} &= f(c \to D^{*0})\text{Br}(D^{*0} \to D^0) + f(c \to D^{*+})\text{Br}(D^{*+} \to D^0), \\
f(c \to D^+)|_{\text{feeddown}} &= f(c \to D^{*+})\text{Br}(D^{*+} \to D^+).
\end{aligned} \tag{16}
$$

Then the direct contributions can be calculated from

$$
\begin{aligned}
f(c \to D^0)|_{\text{direct}} &= f(c \to D^0) - f(c \to D^0)|_{\text{feeddown}}, \tag{17} \\
f(c \to D^+)|_{\text{direct}} &= f(c \to D^+) - f(c \to D^+)|_{\text{feeddown}}. \tag{18}
\end{aligned}
$$

Production of molecules, probabilities

$$f(c \to D^0) = f(\bar{c} \to \bar{D}^0) = 0.547 \,, \tag{19}$$

$$f(c \to D^+) = f(\bar{c} \to D^-) = 0.227 \,, \tag{20}$$

$$f(c \to D^{*0}) = f(\bar{c} \to \bar{D}^{*0}) = 0.237 \,, \tag{21}$$

$$f(c \to D^{*+}) = f(\bar{c} \to \bar{D}^{*-}) = 0.237 \,. \tag{22}$$

Here we have assumed that $f(c \to D^{*0}) = f(c \to D^{*+})$.
We then obtain an isospin symmetric result:

$$f(c \to D^0)|_{\mathrm{direct}} = 0.15 \,, \qquad f(c \to D^+)|_{\mathrm{direct}} = 0.15 \,. \tag{23}$$

We summarize that the direct contribution is much smaller than the total one including feeddown.
In the following we shall show results obtained from the total fragmentation fraction as well as using only the direct production fraction for D^0. The arguments are related to lifetime of D^* mesons. This will be discussed below.
The cross section for $c\bar{c}$ production are then multiplied by

$$\frac{1}{2}[f(c \to D^0)f(\bar{c} \to \bar{D}^{*0}) + f(c \to D^{*0})f(\bar{c} \to \bar{D}^0)] = \begin{cases} 0.036 \text{ direct} \\ 0.13 \text{ including feeddown.} \end{cases} \tag{24}$$

Lifetime of D^* mesons and formation of the molecule

The lifetime of D^* was estimated by theoretical calculation (not measured!) to be $c\tau \approx 2000$ fm (Henriksson et al.).

After such a long time, in general, D^0 from the decay of D^* may be far away from the associated D^{*0} – so formation of the molecule may be difficult.

However, the condition on relative momentum of D and D^* mesons selects mesons flying almost parallel to each other.

In such a system, in a somewhat naive calculation (non-interacting mesons), the probability that together with a D^0 there exists a D^{*0} that has not decayed yet to produce a $X(3872)$ at a time t can be estimated as:

$$P = (1 - \exp(-t/\tau)) \exp(-t/\tau) < 0.25. \tag{25}$$

This suggests that in reality one should rather include only directly produced D^0 (or $\bar{D}^0$). This strongly reduces the cross section and causes that the purely molecular scenario is disfavoured – the corresponding $d\sigma/dp_T$ (see results) is below the experimental data.
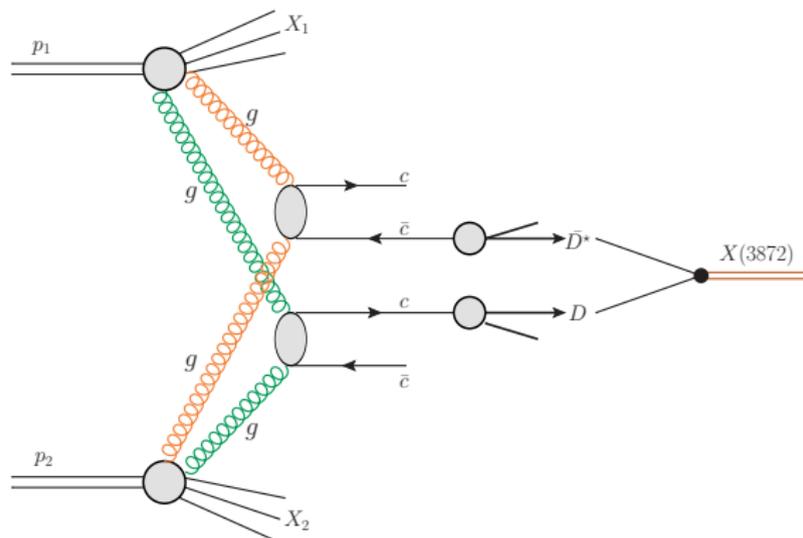
Production of molecule via double parton scattering

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:

$$\Delta\sigma = \frac{1}{2\sigma_{\text{eff}}} \int \frac{d\sigma_{c\bar{c}}}{dy_1 d^2\boldsymbol{p}_1} \frac{d\sigma_{c\bar{c}}}{dy_2 d^2\boldsymbol{p}_2} \; dy_1 d^2\boldsymbol{p}_1 dy_2 d^2\boldsymbol{p}_2 \bigg|_{k_{rel}<k_{max}} . \tag{26}$$

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 $\sigma_{\text{eff}} = 15$ mb (Maciula,Szczurek).

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

Production via double parton scattering

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

$$c_1 \to D^0, \bar{c}_2 \to \bar{D}^{*0} , \tag{27}$$

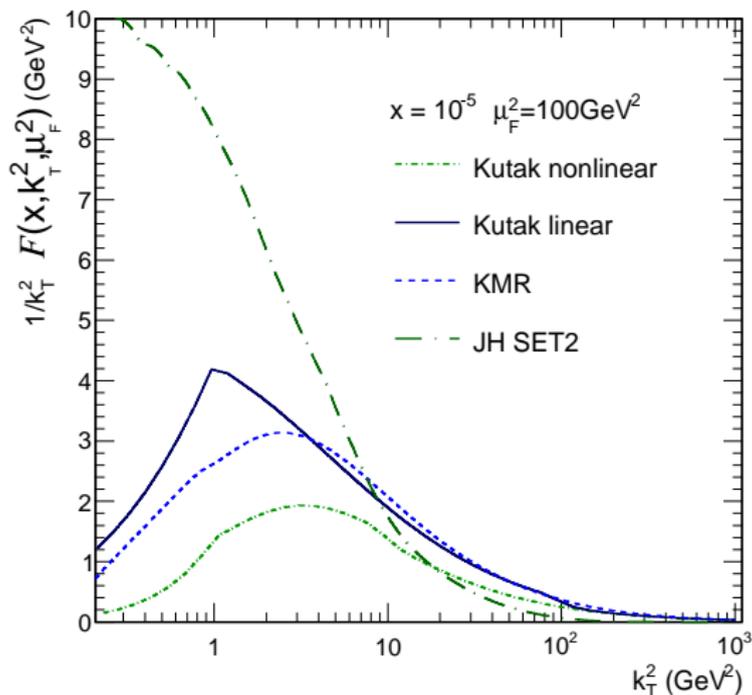$$c_1 \to D^{*0}, \bar{c}_2 \to \bar{D}^0 , \tag{28}$$

$$\bar{c}_1 \to \bar{D}^0, c_2 \to D^{*0} , \tag{29}$$
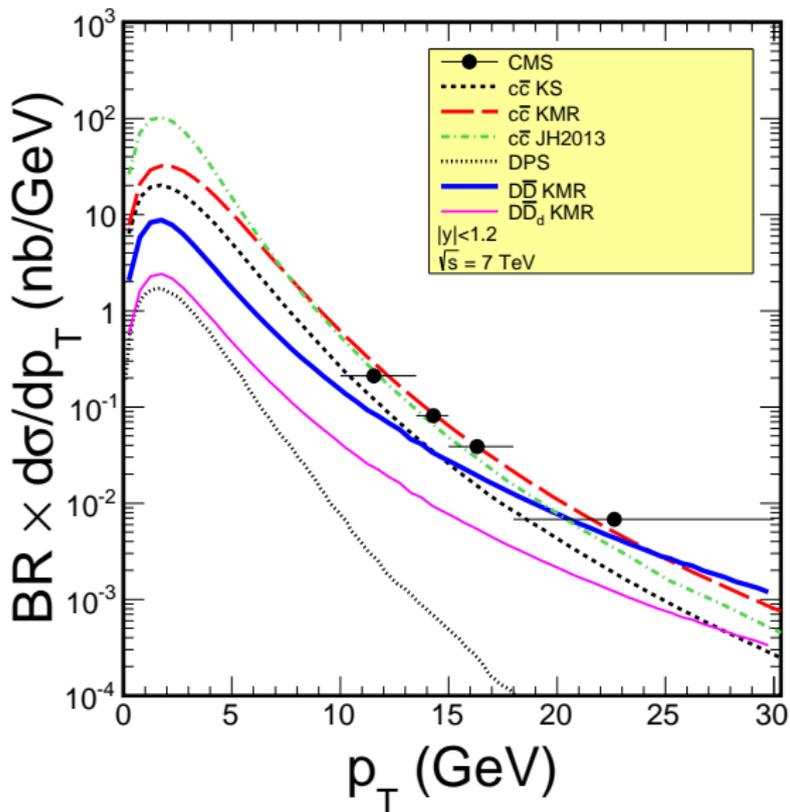
$$\bar{c}_1 \to \bar{D}^{*0}, c_2 \to D^0 . \tag{30}$$

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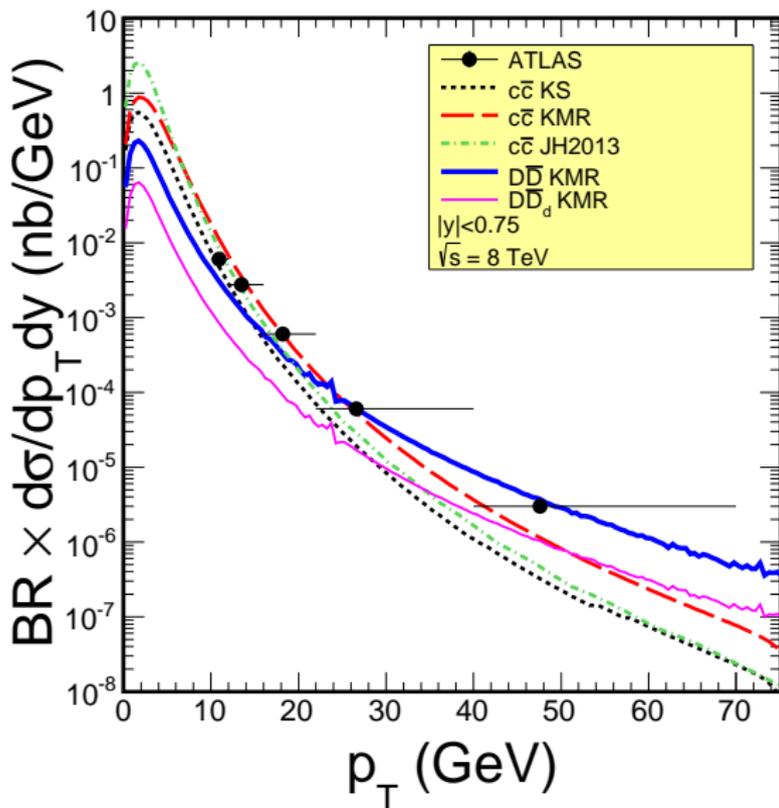
Unintegrated gluon distributions

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.
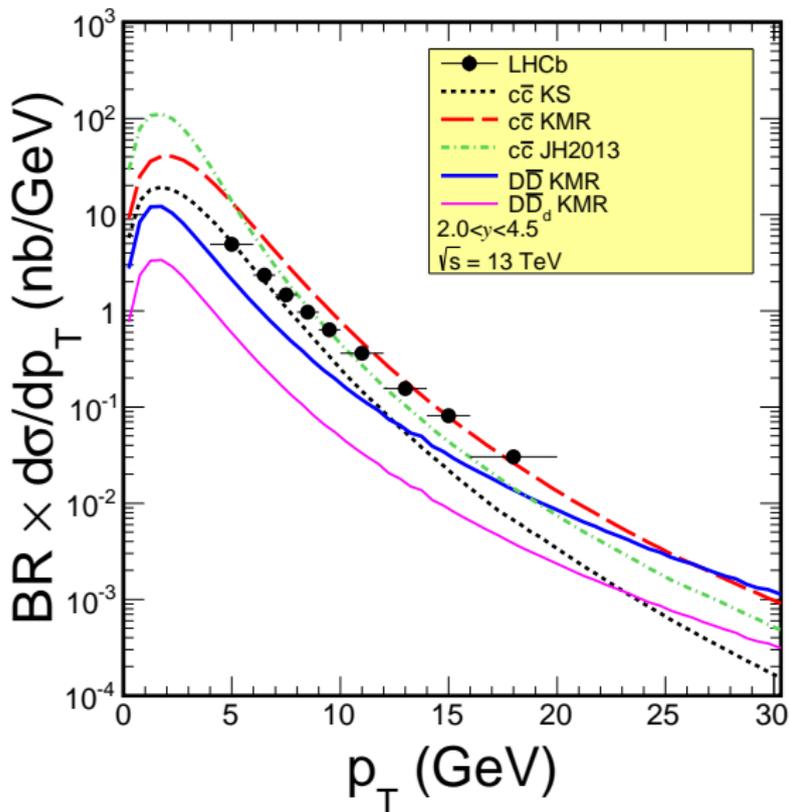
Results, X(3872) production as $c\bar{c}$ state

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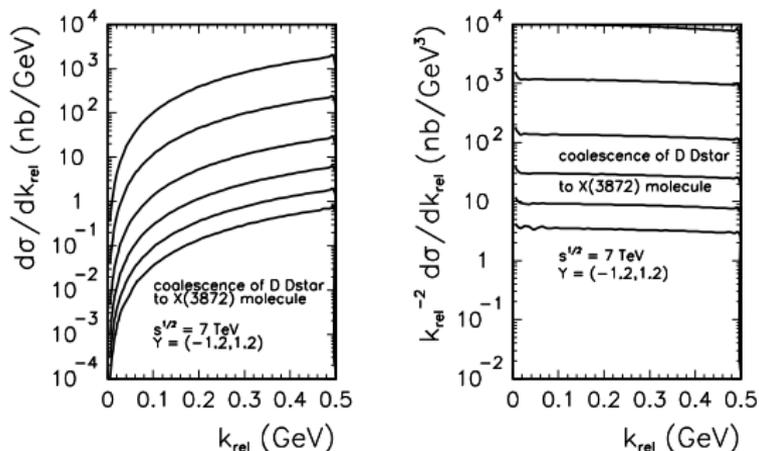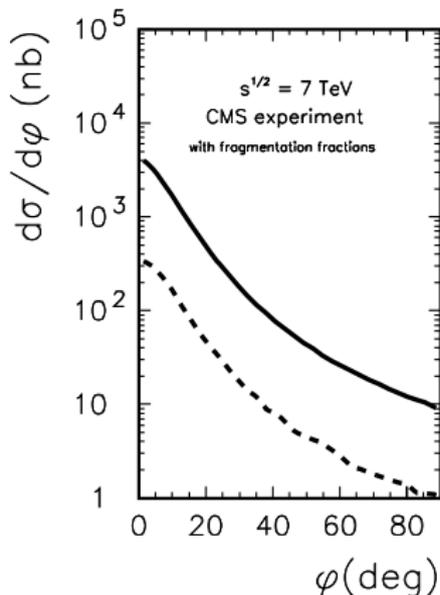
Results, molecular picture

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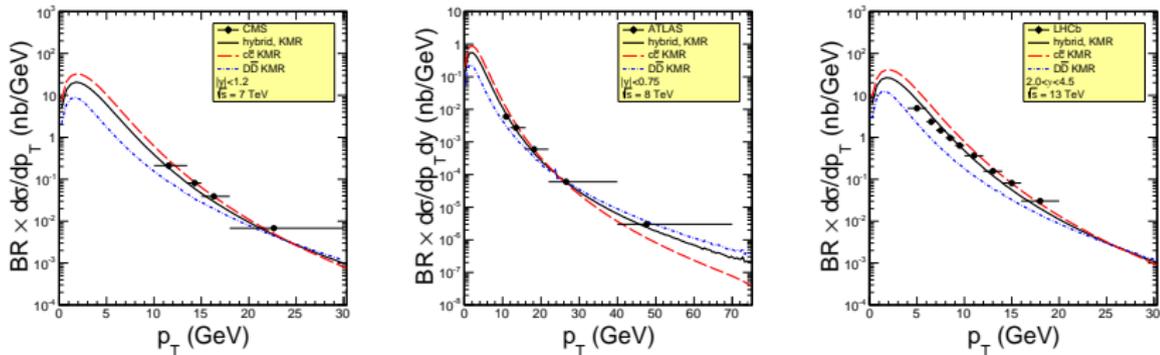
$p_{t,X}$ (GeV) = (0,5), (5,10), (10,15), (15,20), (20,25), (25,30)

Results, molecular picture

Figure: Azimuthal correlations between $c\bar{c}$ that fullfill the condition $k_{rel} < 0.2$ GeV. Here the CMS cuts were imposed. We show contribution of SPS (solid line) and DPS (dashed line). All D^0 included.

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).

Lifetime arguments suggest, however, that rather small probabilities of the molecular component are preferred.

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 $g^* g^* \rightarrow X(3872)$ 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 infinitely heavy quark approximation.
  A reasonable results have been obtained.

- Having in mind the finite lifetime of D^* mesons we have shown results for both directly produced D^0 and for all D^0, including the feeddown contribution.

Conclusions

- In addition, a hybrid model (mixture of $c\bar{c}$ and molecular component).
  A reasonable results have been obtained.

- All three (naive) approaches describe the LHC data for $pp \to X(3872)$.

- The lifetime argument discussed here for the first time suggests that in reality one should rather include rather only directly produced D^0 (or $\bar{D}^0$). This strongly reduces the cross section and causes that the purely molecular scenario is disfavoured.

- Therefore in the hybrid scenario the probability of the molecular component should not be too big.