X(3872) and Its Production at Hadron Colliders

Ce Meng Peking University
In Collaboration with H. Han & K.T. Chao

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Outline

- Mini review of X(3872)
- X production at hadron colliders
- Summary

Experimental information

- 1st observed by Belle Collaboration in

  $B \to J/\psi\pi^+\pi^- K$ Belle'03

- Mass, width and quantum numbers:

- $m_X = 3871.68 \pm 0.17$ MeV PDG'12

  $m_X - m_{D^0 D^{*0}} = -0.142 \pm 0.220$ MeV Tomaradze *et al.*'12

- $\Gamma < 1.2$ MeV CL $= 90\%$ PDG'12

- $J^{PC} = 1^{++}$ or 2^{-+}

✓ $J^{PC} = 2^{-+}$ is favored by the $\omega \to \pi^+\pi^-\pi^0$ mass spectrum in $B \to X(3872)K \to J/\psi\omega(\pi^+\pi^-\pi^0)K$ [BaBar'10], but is excluded by the recent analysis on the angular correlations in $B \to X(3872)K \to J/\psi\rho(\pi^+\pi^-)K$ by LHCb [arXiv:1302.6269, see Bressieux's talk]

Experimental information

- Decay pattern:
- Well-established decay modes:

$$J/\psi\rho(\pi^+\pi^-), J/\psi\omega(\pi^+\pi^-\pi^0), D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}/D\bar{D}\pi, J/\psi\gamma$$

Relative ratios of these 4 modes: $1:1:10:0.3$ PDG'12

✓ Large isospin violations

$$\mathrm{R}_{\rho/\omega} = \mathrm{Br}(X \to J/\psi\rho)/\mathrm{Br}(X \to J/\psi\omega) \approx 1$$

✓ $\mathrm{Br}(X \to J/\psi\rho) = \mathrm{Br}(X \to J/\psi\pi^+\pi^-) \equiv \mathrm{Br}_0 < 9\%$

- B-production:

$1 \times 10^{-4} < \mathrm{Br}(B \to X(3872)K) < 3.2 \times 10^{-4}$ BaBar'05

$\mathrm{Br}(B \to X(3872)K)\mathrm{Br}_0 = (8.6 \pm 0.8) \times 10^{-6}$ PDG'12

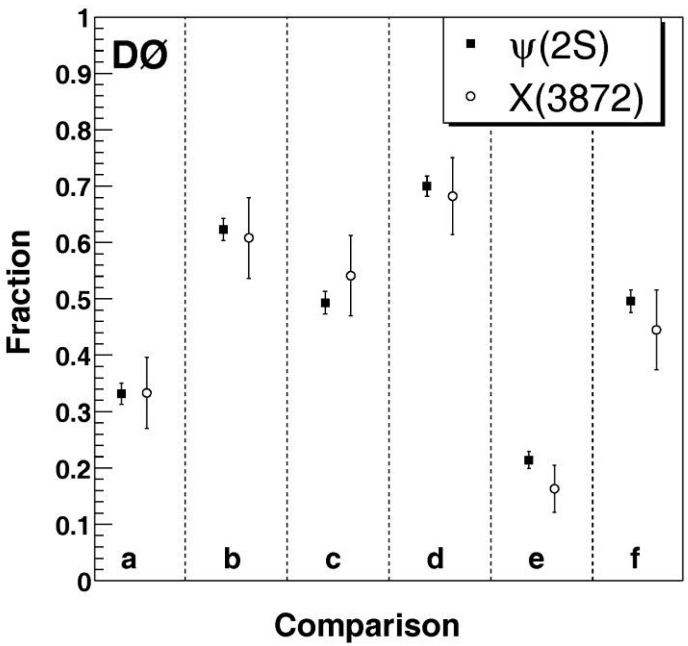
$$2.6\% < \mathrm{Br}_0 < 9\%$$

Experimental informations

- ➢ Hadro-production
- Large production rate: $\frac{\sigma(p\bar{p}\to X)\mathrm{Br}_0}{\sigma(p\bar{p}\to\psi\prime)}\frac{\epsilon_{\psi\prime}}{\epsilon_X} = (4.8 \pm 0.8)\%$ CDF'04
- Similar behaviors to ψ' production in p_T distribution and …

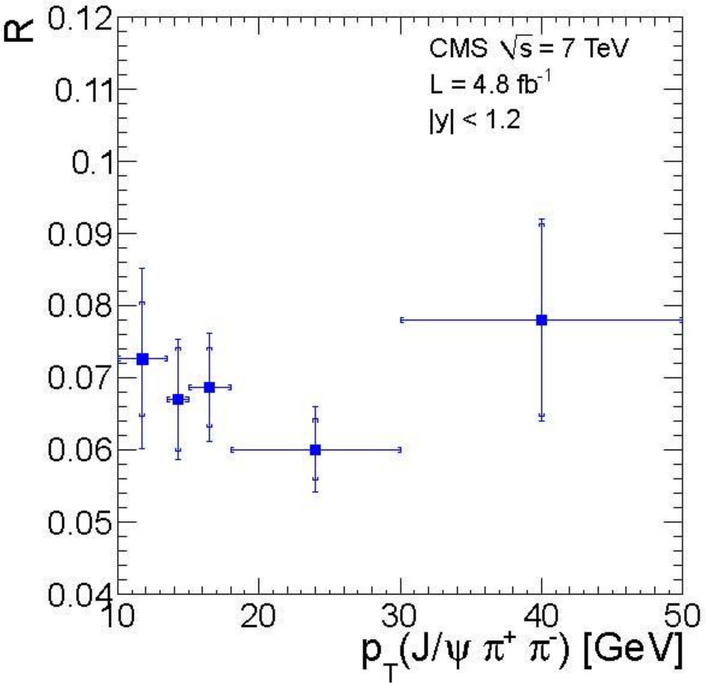
D0 PRL'04

a. $p_T > 15$ GeV b. …



CMS arXiv:1302.3968, see Yi's talk

Ratio to ψ' is not depend on p_T



$D^0\bar{D}^{*0}$ molecule models

[Tornqvist'04, Voloshin'04, Swanson'04, Braaten'04, ...]

- X(3872) is a loosely bound state of $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$
  - The mass, quantum numbers and the large isospin violation can be understood naturally.
  - The large production rate seems to be questionable
- ✓ Naively, $\sigma(X) \sim k_0^3$, where the relative momentum of $D^0\bar{D}^{*0}$ in the bound state $k_0 = \sqrt{2\mu_{DD^*}|E_b|} < 40\ \mathrm{MeV}$
- ✓ Explicit calculations [Bignamini *et al*, PRL'09]:

$$\sigma_{\mathrm{CDF}}^{\mathrm{th}}(X) < 0.085\ \mathrm{nb} \quad v.s. \quad \sigma_{\mathrm{CDF}}^{\mathrm{ex}}(X)\mathrm{Br}_0 = 3.1 \pm 0.7\ \mathrm{nb}$$

- ✓ Artoisenet and Braaten [PRD'10] proposed that the rescattering effects of $D^0\bar{D}^{*0}$ may enhance the rate to values consistent with the CDF data if the upper bound of the relative momentum of $D^0\bar{D}^{*0}$ in the rescattering is as large as $3m_\pi \approx 400\ \mathrm{MeV}$

$\chi'_{c1} - D^0\bar{D}^{*0}$ mixing model

Meng, Gao and Chao, hep-ph/0506222, to appear in PRD

- $X(3872)$ is a mixing state of χ'_{c1} and $D^0\bar{D}^{*0}/\bar{D}^0 D^{*0}$ continuum
- Both the two components are substantial, and they may play different roles in the dynamics of $X(3872)$.

1. The short distance (the b- and $hadro$-) production and the quark annihilation decays of $X(3872)$ proceed dominantly through the χ'_{c1} component.
2. The $D^0\bar{D}^{*0}$ component is mainly in charge of the hadronic decays of $X(3872)$ into $DD\pi/DD\gamma$ as well as $J/\psi\rho$ and $J/\psi\omega$.
3. The long distance coupled-channel effects between the two components could renormalize the short distance dynamics by a product factor $Z_{c\bar{c}}$, the equivalent probability of χ'_{c1} in $X(3872)$.

$\chi'_{c1} - D^0\bar{D}^{*0}$ mixing model

- B production rate: Meng, Gao and Chao'05

$$\frac{\mathrm{Br}(B\to\chi'_{c1}K)}{\mathrm{Br}(B\to\chi_{c1}K)} = 0.75\text{–}1$$

$$\mathrm{Br}(B\to\chi'_{c1}K) = (2\text{–}4)\times 10^{-4}$$

- Rescattering of the $D^0\bar{D}^{*0}$ component: Meng and Chao, PRD'07

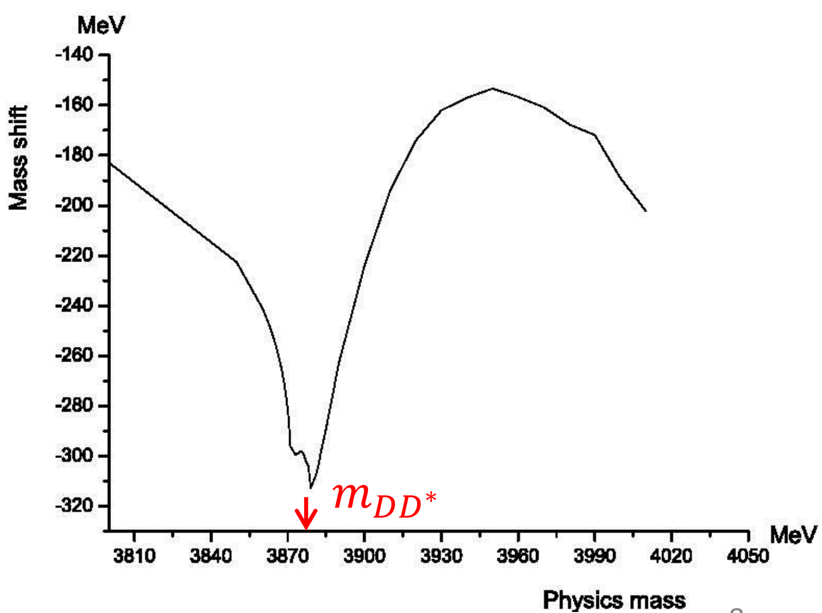
$$\frac{\mathrm{Br}(X\to J/\psi\rho)}{\mathrm{Br}(X\to J/\psi\omega)} = 0.9\text{–}1.2$$

- Mass problem:

  Coupled-channel models

  Li & Meng & Chao'09; Danilkin & Simonov'10

  The sharp mass shift curve induced by the S-wave coupling lower the "bare" mass of χ'_{c1} towards the $D^0\bar{D}^{*0}$ threshold.



X production at hadron colliders

NRQCD factorization formula

- Mixing model (χ'_{c1} production mechanism):

  [Meng & Han & Chao, arXiv:1304.6710]

- Energy scales: $p_T, m_c \gg m_c v, m_c v^2, \Lambda_{QCD} \gg E_b, \Gamma_X \sim 1\ \mathrm{MeV}$
- Factorization I:

  $$\sigma\big(pp \to X(J/\psi\pi^+\pi^-)\big) = \sigma(pp \to \chi'_{c1}) \cdot k, \qquad k = Z_{c\bar{c}}\mathrm{Br}_0$$

- Factorization II: NRQCD Bodwin & Braaten & Lepage'95

$$d\sigma(pp \to \chi'_{c1}) = \sum_n d\hat{\sigma}\big((c\bar{c})_n\big) \frac{\left\langle O_n^{\chi'_{c1}} \right\rangle}{m_c^{2L_n}}$$

$$= \sum_{i,j,n} \int dx_1 dx_2 G_{i/p} G_{j/p}\, d\hat{\sigma}(ij \to (c\bar{c})_n) \left\langle O_n^{\chi'_{c1}} \right\rangle$$

$n = {}^3P_1^{[1]}$ & ${}^3S_1^{[8]}$ at leading order in v for χ'_{c1} production

NRQCD factorization formula

- Molecule model (Molecule production mechanism):
  Artoisenet & Braaten, PRD'09

$$d\sigma(pp \to X_{D^0\bar{D}^{*0}}) = d\hat{\sigma}\left({}^3S_1^{[1]}\right)\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[1]}}\right\rangle + d\hat{\sigma}\left({}^3S_1^{[8]}\right)\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[8]}}\right\rangle$$

- Color symmetry: $\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[1]}}\right\rangle = 3\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[8]}}\right\rangle /4$
- At NLO in α_s: $d\hat{\sigma}\left({}^3S_1^{[1]}\right)/d\hat{\sigma}\left({}^3S_1^{[8]}\right) \approx 5.3 \times 10^{-4}$ for CDF widow, thus [Meng & Han & Chao, arXiv:1304.6710]

$$d\sigma(pp \to X_{D^0\bar{D}^{*0}}) = d\hat{\sigma}\left({}^3S_1^{[8]}\right)\left\langle O^{D^0\bar{D}^{*0}}_{{}^3S_1^{[8]}}\right\rangle$$

✓ The two models are different in combination of the $c\bar{c}$ channels in the factorization formula!

✓ One can compare the two models with the help of the CMS pT distribution!

NRQCD factorization formula

- NLO calculations:
  - We choose $\mu_r = \mu_f = m_T = \sqrt{p_T^2 + 4m_c^2}, \mu_{NR} = m_c = 1.5 \pm 0.1\ \mathrm{GeV}$, and vary $\mu_{r,f}$ from $m_T/2$ to m_T to estimate the errors.
  - The other details can be found in Ma & Wang & Chao'11 (MWC'11)
- To compare our following results with the available ones for χ_{c1} production [MWC'11], we parameterize the matrix elements as
  - $\left\langle O_{^3P_1^{[1]}}^{\chi'_{c1}} \right\rangle = \left\langle O_{^3P_1^{[1]}}^{\chi_{c1}} \right\rangle = \frac{9}{4\pi} |R'_{1P}(0)|^2, |R'_{1P}(0)|^2 = 0.075\ \mathrm{GeV}^5$
  - $r = m_c^2 \left\langle O_{^3S_1^{[8]}}^{\chi'_{c1}} \right\rangle / \left\langle O_{^3P_1^{[1]}}^{\chi'_{c1}} \right\rangle$ ($r_{1P} = 0.27 \pm 0.06$, MWC'11)
  - The cross section in the χ'_{c1} production mechanism is a simple function of r, k and p_T

Fit to the CMS p_T distribution

$$\sqrt{S} = 7\ \mathrm{TeV}, \qquad |y| > 1.2, \qquad 10\ \mathrm{GeV} < p_T < 30\ \mathrm{GeV}$$

- χ'_{c1} production mechanism:

$$r = 0.26 \pm 0.07, \qquad k = 0.014 \pm 0.006$$

$$\sigma^{\mathrm{fit}}_{\mathrm{CMS}}\left(p\bar{p} \to X(J/\psi\pi^+\pi^-)\right) = 1.09^{+0.08}_{-0.12}\ \mathrm{nb} \quad \left((1.06 \pm 0.19\ \mathrm{nb})_{\mathrm{ex}}\right)$$

- The central values correspond $\chi^2/2 = 0.26$
- The value of r_{2P} for χ'_{c1} is almost the same as that for $\chi_{c1}(1P)$:

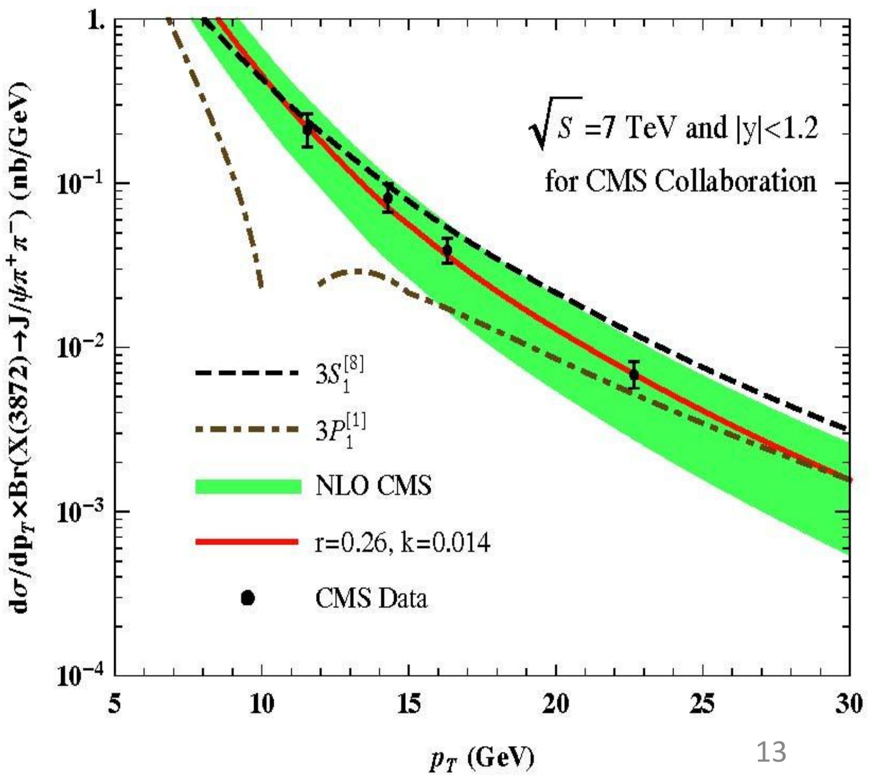
$$r_{1P} = 0.27 \pm 0.06\ [\mathrm{MWC'11}]$$

which strongly suggests that X(3872) be produced through its χ'_{c1} component at short distance

- Molecule production mechanism:

$$\left\langle O^{D^0\bar{D}^{*0}}_{^3S_1^{[8]}} \right\rangle \mathrm{Br}_0 = (6.0 \pm 0.6)10^{-5}\ \mathrm{GeV}^3$$

$$\chi^2/3 = 1.03$$



Predictions v.s. CDF data

$$\sqrt{S} = 1.96\ \text{TeV}, \qquad |y| > 0.6, \qquad p_\text{T} > 5\ \text{GeV}$$

- χ'_{c1} production mechanism:

  Inputs: $r = 0.26,\ k = 0.014$

  $\sigma_{\text{CDF}}^{\text{th}}\left(p\bar{p} \to X(J/\psi\pi^+\pi^-)\right) = 2.5 \pm 0.7\ \text{nb} \quad (v.s.\ (3.1 \pm 0.7\ \text{nb})_{\text{ex}})$

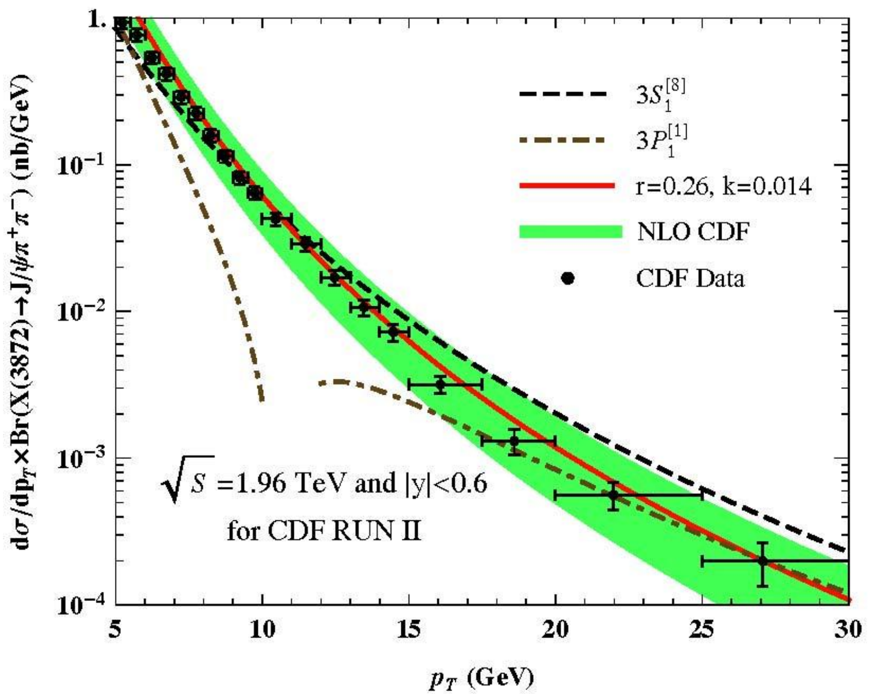
  The predicted p_T distribution of $X(3872)$ is compared with that of ψ' [CDF, PRD'09] (see the diagram)

- Molecule production mechanism:

  $$\sigma_{\text{CDF}}^{\text{molecule}} = 1.1 \pm 0.4\ \text{nb}$$

  2.6 σ deviation from data

- Both the CMS and the CDF data favor the χ'_{c1} production mechanism, but a little bit disfavor the molecule production mechanism.



Predictions v.s LHCb data

$\sqrt{S} = 7\ \text{TeV}, \qquad 2.5 < y < 4.5, \qquad 5\ \text{GeV} < p_T < 20\ \text{GeV}$

- χ'_{c1} productionmechanism:

Inputs: $r = 0.26, \quad k = 0.014;$

$$\sigma_{\text{LHCb}}^{\text{th-prompt}}(p\bar{p} \to X(J/\psi\pi^+\pi^-)) = 9.4 \pm 2.2\ \text{nb}$$

$$v.s.\ \ \sigma_{\text{LHCb}}^{\text{inclusive}} = 5.4 \pm 1.4\ \text{nb}$$ LHCb, PRL'11

- About 20% of data come from non-prompt contributions, thus our prediction is about 2 times larger than the data.
- Both the theoretical and the experimental uncertainties are large.
- More available data are expected to be analyzed [see Bressieux's talk]

- Molecule production mechanism:

$$\sigma_{\text{LHCb}}^{\text{molecule}} = 4.0 \pm 1.3\ \text{nb}$$

Better than ours, but seems to be less meaningful since the predicted pT distribution at CMS is almost inconsistent with the data.

Single parameter fit

- Fitting k to the CMS data with fixed r

  $(3.1 \pm 0.7\ \text{nb})^{\text{ex}}_{\text{CDF}}$

  $(5.4 \pm 1.4\ \text{nb})^{\text{ex}}_{\text{LHCb}} \cdot 80\%$

r	k	$\chi^2/3$	$\sigma^{\text{th}}_{\text{CDF}}(\text{nb})$	$\sigma^{\text{th}}_{\text{LHCb}}(\text{nb})$
0.20	0.021	0.39	3.26	12.2
0.25	0.015	0.17	2.63	9.87
0.30	0.012	0.20	2.28	8.56
0.35	0.010	0.27	2.06	7.72
0.40	0.008	0.34	1.90	7.14

- Fitting k to B decay data

$$\text{Br}(B \to X(J/\psi\pi^+\pi^-)K) = \text{Br}(B \to \chi'_{c1}K) \cdot k$$

$$= (8.6 \pm 0.8) \times 10^{-6}$$ PDG'12

$$\text{Br}^{\text{fit}}(B \to \chi'_{c1}K) = (3.7\text{–}5.7) \times 10^{-4}$$ Kalashnikova & Nefediev PRD'09

$$\therefore k = Z_{c\bar{c}}\text{Br}_0 = 0.018 \pm 0.004$$

- ✓ Window in the table: $r = 0.20\text{-}0.26$
- ✓ With a modest value $\text{Br}_0 = 5\% \quad \in (2.6\%\text{–}9\%)$

$$Z_{c\bar{c}} = 28\%\text{–}44\%$$

Summary

- Within the framework of NRQCD factorization formula, the prompt cross section of X(3872) is evaluated up to NLO in α_s in the mixing model:
  - The CMS p_T distribution can be fitted very well with $\chi^2/2 = 0.26$.
  - The obtained r_{2P} for χ'_{c1} is almost the same as r_{1P} for χ_{c1} [MWC'11], which strongly suggests that the X(3872) be produced through its χ'_{c1} component at short distance.
  - The outcomes of the fit explain the CDF total cross section very well, however, the predicted cross section for the LHCb widow is larger than the data by a factor of 2, which might due to the large uncertainties.
- By harmonizing the fit results with those in B decays, we get

  $$k = Z_{c\bar{c}}\mathrm{Br}(X \to J/\psi\pi^+\pi^-) = 0.018 \pm 0.004, \qquad r = 0.20\text{–}0.26,$$

  which could be important to understand the nature of X(3872).
- The cross section in the molecule model is also evaluated at NLO in α_s, which is disfavored by both the CMS and the CDF data to some extent.

BackUp

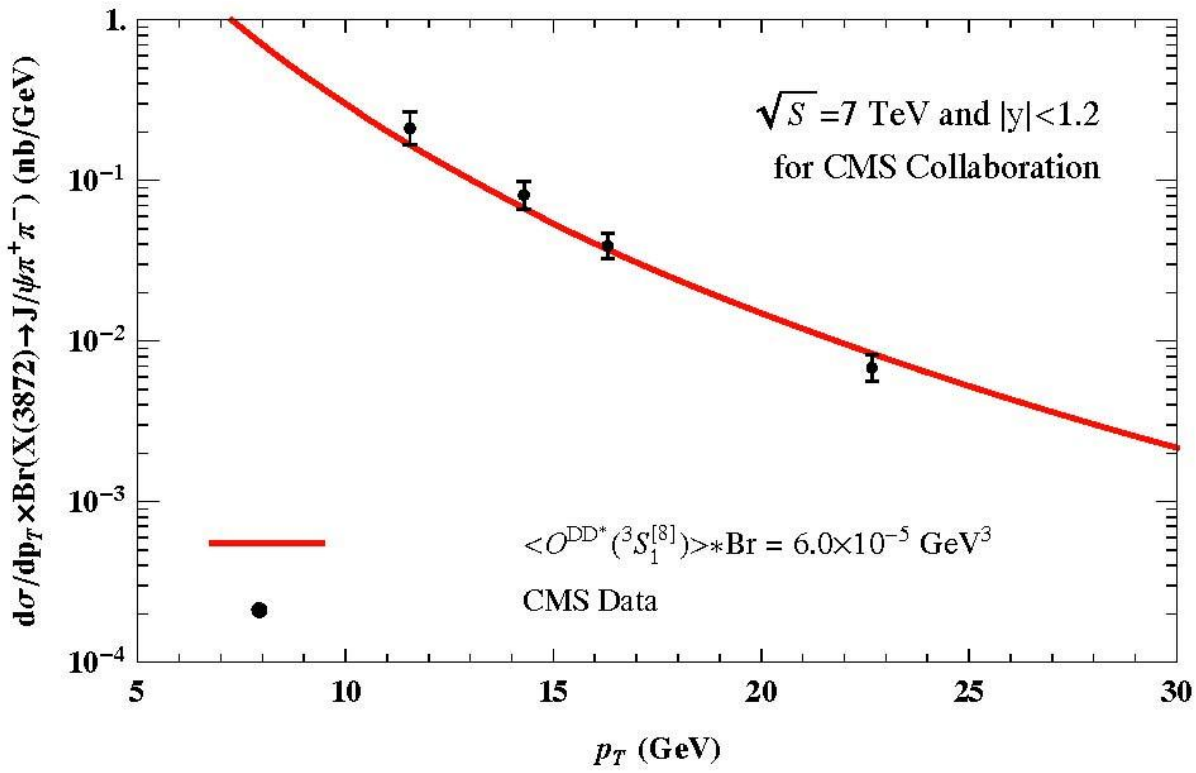
Fit to the CMS p_T data

$\sqrt{S} = 7$ TeV, $\quad |y| > 1.2, \quad 10 \text{ GeV} < p_T < 30$ GeV

- Molecule production mechanism:

$$\left\langle O^{D^0\bar{D}^{*0}}_{^3S_1^{[8]}} \right\rangle \mathrm{Br}_0 = (6.0 \pm 0.6)10^{-5}\ \mathrm{GeV}^3$$

$\chi^2/3 = 1.03$

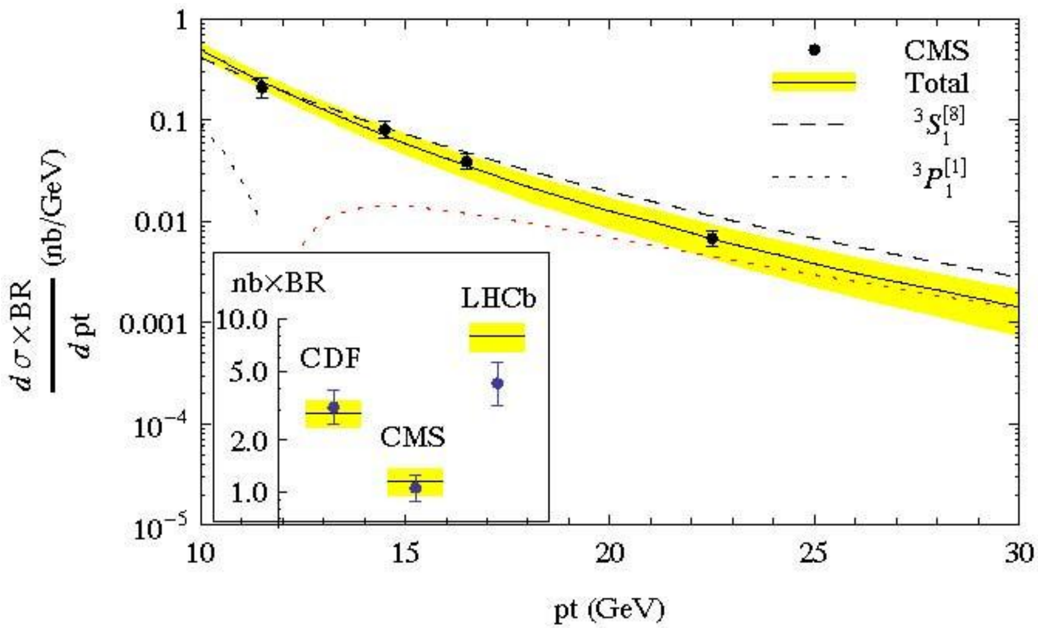


Comparison with arXiv: 1303.3524

- Butenschoen & He & Kniehl, arXiv: 1303.3524:

  Set IV: fit two matrix elements to both the CMS and CDF data

	Input	Fit values		Predictions	
	$\lvert R'_{2P}(0)\rvert^2/\mathrm{GeV}^5$	$r \times 10^2$	$k \times 10^3$	$\sigma^{\mathrm{th}}_{\mathrm{CDF}}/\mathrm{nb}$	$\sigma^{\mathrm{th}}_{\mathrm{LHCb}}/\mathrm{nb}$
BHK/set IV	0.102	24 ± 4	11 ± 5	2.9 ± 0.5	8.0 ± 1.5
Ours	0.075	26 ± 4	14 ± 6	2.5 ± 0.7	9.4 ± 2.5



Only stress that the X(3872) could not be a pure χ'_{c1} state