$X(3872)$ Production at Colliders

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Outline

Introduction

The second-most popular particle in last 10 years: $X(3872)$

Discovery of $X(3872)$

In 2003, Belle found very narrow peak $X(3872)$ in $J/\psi\pi^+\pi^-$ mass spectrum at 3872 MeV in $B^\pm \to J/\psi\pi^+\pi^-K^\pm$ decays as shown in Fig. 1 (hep-ex/0312021).

First XYZ state: $X(3872)$

The letter "X" was chosen because of its extraordinary properties. In spite of its mass just above the $D\bar{D}$ threshold, the observed decay mode is $J/\psi\pi^+\pi^-$ and there was no obvious assignment to a known charmonium.

Confirmed by all possible detector

Then it was confirmed by Babar, CLEO, CDF, D0, BESIII, CMS, ATLAS, LHCb, and so on.

Discovery of $X(3872)$ at Belle

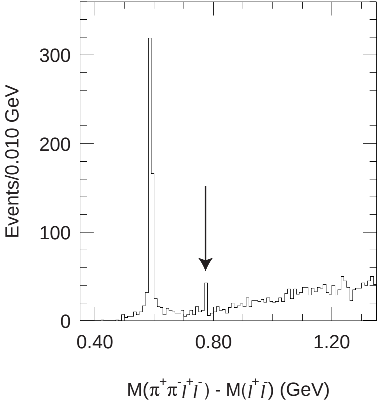

Figure: The distribution of mass difference between $J/\psi\pi^+\pi^-$ and J/ψ in $B^{\pm} \to J/\psi\pi^+\pi^- K^{\pm}$ decays(hep-ex/0312021).

Confirmed by other groups

Process (mode)	Experiment ($\#\sigma$)
$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)
$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [88–90] (np), DØ [91] (5.2)
$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)
$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)
$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)
$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)

Figure: ArXiv:1010.5827: $X(3872)$.

Mass and J^{PC} of $X(3872)$

Mass of $X(3872)$ in PDG 2014

$$M(X(3872)) - M(D^0) - M(\bar{D}^{*0}) = 0.11 \pm 0.21 MeV \tag{1}$$

$J^{PC} = 1^{++}$

A amplitude analysis was performed by LHCb collaboration (arXiv:1302.6269) for $X(3872) \to J/\psi\pi^+\pi^-$ mode and $J^{PC} = 1^{++}$ has unambiguously assigned.

Mass of $\chi_{c1}(2P)$

$$\begin{aligned} M(\chi_{c1}(2P)) &= 3925\, MeV, \quad hep-ph/0505002 \\ M(\chi_{c1}(2P)) &= 3901\, MeV, \quad arXiv:0903.5506 \end{aligned} \tag{2}$$

Mass, width, J^{PC}, and decay of $X(3872)$

$X(3872)$ $\qquad I^G(J^{PC}) = 0^+(1^{++})$

Mass $m = 3871.69 \pm 0.17$ MeV
$m_{X(3872)} - m_{J/\psi} = 775 \pm 4$ MeV
$m_{X(3872)} - m_{\psi(2S)}$
Full width $\Gamma < 1.2$ MeV, CL = 90%

$X(3872)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi^+\pi^- J/\psi(1S)$	> 2.6 %	650
$\omega J/\psi(1S)$	> 1.9 %	†
$D^0 \overline{D}^0 \pi^0$	>32 %	117
$\overline{D}^{*0} D^0$	>24 %	†
$\gamma J/\psi$	$> 6 \times 10^{-3}$	697
$\gamma \psi(2S)$	[xxaa] > 3.0 %	181
$\pi^+\pi^- \eta_c(1S)$	not seen	746
$p\overline{p}$	not seen	1693

Figure: PDG2014: Mass, width, J^{PC}, decay of $X(3872)$.

$X(3872)$: Molecule or tetraquark?

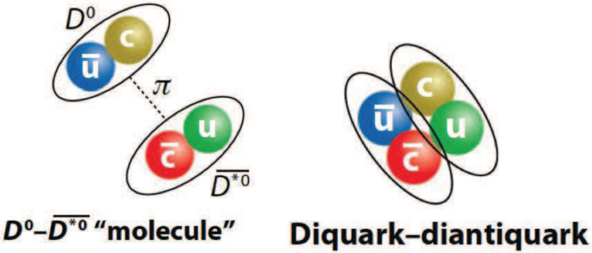

Figure: $X(3872)$: Molecule or tetraquark?

Tetraquark: $c\bar{c}u\bar{u}$ and $c\bar{c}d\bar{d}$

Mixing between $c\bar{c}u\bar{u}$ and $c\bar{c}d\bar{d}$

A mass splitting of the two mixing stests between $c\bar{c}u\bar{u}$ and $c\bar{c}d\bar{d}$ was (7 ± 2) MeV (hep-ph/0412098).

How to measure?

The difference is expected to appear as the difference in the X masses separately measured in $B^{\pm} \to XK^{\pm}$ and $B^0 \to XK^0$.

Disfavored by Belle!

The Belle result of this difference in $J/\psi\pi^+\pi^-$ mode is found to be $(-0.71 \pm 0.96 \pm 0.19)$ MeV/c^2 (arXiv:1107.0163). It strongly disfavored the tetraquark interpretation. Belle also finds no signature for the charged partner state $c\bar{c}u\bar{d}$ in $J/\psi\pi^{\pm}\pi^0$ mode.

Molecule: $D^0\bar{D}^{*0}$

Size of $D^0\bar{D}^{*0}$

The binding energy 0.11 ± 0.21 MeV would give an estimation of the molecule's size, the distance between D^0 and $\bar{D}^{*0}$ mesons to be 10 fm. And the size of $\psi(2S)$ is about 1fm.

Problem of production due to large size

The cross section of $\psi(2S)$ prompt production in the high energy $p\bar{p}$ collisions will be about a factor of 1000 larger then $X(3872)$.

$X(3872)$ production at the Tevatron (hep-ex/0612053)

$$\frac{\sigma_{prompt}(pp \to X(3872) + all) \times Br(J/\psi\pi\pi)}{\sigma_{prompt}(pp \to \psi(2S) + all)} \sim 5\% \tag{3}$$

A mixture state of molecular state and $\chi_{c1}(2P)$

Disfavors the interpretation of $X(3872)$ as pure $\chi_{c1}(2P)$

Mass of $\chi_{c1}(2P)$ is about 3900 3925 MeV. And NLO prediction of $X(3872)$ production in hadron colliders disfavors the interpretation of $X(3872)$ as pure $\chi_{c1}(2P)$ (arXiv:1303.6524).

A mixture state (hep-ph/0506222)

$X(3872)$ might be a mixture state with the $\chi_{c1}(2P)$ and the $D^0\bar{D}^{\star 0}$ components was proposed by Meng and Chao in (hep-ph/0506222). This idea is also favored the data of some other measurements and predictions (hep-ph/0508258,...).

A mixture state: production (arXiv:1304.6710)

The NLO prediction in $\alpha_s$is consistent with the CMS (arXiv:1302.3968) and the CDF data (hep-ex/0312021).

Lattice: mixture state (arXiv:1503.03257)

Mixture state of $c\bar{c}$ and $D\bar{D}$

A lattice candidate for $X(3872)$ with $I = 0$ is observed very close to the experimental state only if both $c\bar{c}$ and $D\bar{D}$ interpolators are included.

$c\bar{c}$ is necessary

The candidate is not found if diquark-antidiquark and $D\bar{D}$ are used in the absence of $c\bar{c}$.

No other neutral or charged $X(3872)$

No candidate for neutral or charged $X(3872)$, or any other exotic candidates are found in the $I = 1$ channel.

$e^+e^- \to X(3872) + \gamma$ at BESIII

1. Recently, BesIII reports the cross sections of $e^+e^- \to \gamma X(3872)$(arXiv: 1310.0280, 1310.4101)

$$
\begin{aligned}
\sigma \times \mathrm{Br}[J/\psi\pi\pi] &< 0.13\mathrm{pb} \;\; \text{at } 90\% \text{ CL.} & \sqrt{s} &= 4.009\mathrm{GeV} \\
\sigma \times \mathrm{Br}[J/\psi\pi\pi] &= 0.32 \pm 0.15 \pm 0.02\mathrm{pb} & \sqrt{s} &= 4.230\mathrm{GeV} \\
\sigma \times \mathrm{Br}[J/\psi\pi\pi] &= 0.35 \pm 0.12 \pm 0.02\mathrm{pb} & \sqrt{s} &= 4.260\mathrm{GeV} \\
\sigma \times \mathrm{Br}[J/\psi\pi\pi] &< 0.39\mathrm{pb} \;\; \text{at } 90\% \text{ CL.} & \sqrt{s} &= 4.360\mathrm{GeV}
\end{aligned}
$$

Where $\mathrm{Br}[J/\psi\pi\pi]$ means $\mathrm{Br}[X(3872) \to J/\psi\pi\pi]$.

2. NLO QCD prediction (1310.8597) is 0.12 ± 0.04 pb for $\sqrt{s} = 4.04 - 5$ GeV.

$X(3872)$ production at hadron colliders

$X(3872)$ production at the CDF (hep-ex/0612053)

$$\sigma_{prompt}(p\bar{p} \rightarrow X(3872) + all) \times Br(J/\psi\pi\pi) = 3.1 \pm 0.7nb \quad (4)$$

Molecule model give 0.085 nb (arXiv: 0906.0882)

$X(3872)$ production at the CMS (arXiv:1302.3968

$$\sigma_{prompt}(pp \rightarrow X(3872) + all) \times Br(J/\psi\pi\pi) = 1.6 \pm 0.19nb \quad (5)$$

$X(3872)$ production at the LHCb (arXiv:1302.6269)

$$\sigma_{prompt}(pp \rightarrow X(3872) + all) \times Br(J/\psi\pi\pi) = 5.4 \pm 1.5nb \quad (6)$$

Prediction of $X(3872)$ production at hadron colliders

$X(3872)$ as pure $\chi_{c1}(2P)$ (arXiv:1303.6524)

NLO prediction in both v^2 and α_s disfavour pure $\chi_{c1}(2P)$ state

$X(3872)$ as mixture states of $\chi_{c1}(2P)$ and $D\bar{D}^*$(arXiv:1304.6710)

NLO prediction consistent with CDF, CMS, and B meson decay data, but not LHCb.

The frame of Calculation

Cross sections

Hadron and Parton level cross sections

$$d\sigma(p+p\to\chi_{c1}(2P)+X) = \sum_{a,b,d}\int dx_1 dx_2 f_{a/p}(x_1) f_{b/p}(x_2)\, d\hat{\sigma}(a+b\to\chi_{c1}(2P)+d).$$

Parton level cross section

$$d\hat{\sigma}(a+b\to\chi_{c1}(2P)+f) = \sum_{n}\frac{F_n(ab)}{m_c^{d_n-4}}\langle 0|\mathcal{O}_n^{\chi_{c1}(2P)}|0\rangle.$$

Matrix elements

Fock states of $\chi_{c1}(2P)$

$$
\begin{aligned}
|\chi_{c1}(2P)\rangle &= \mathcal{O}(1)|c\bar{c}(^3P_1^{[1]})\rangle + \mathcal{O}(v)|c\bar{c}(^3S_1^{[8]})g\rangle \\
&+ \mathcal{O}(v)|c\bar{c}(^3D_{J'}^{8})g\rangle + \mathcal{O}(v^2)|c\bar{c}(^3P_J^{[1,8]})gg\rangle \\
&+ \mathcal{O}(v^2)|c\bar{c}(^1P_1^{[1,8]})g\rangle + \mathcal{O}(v^3)|c\bar{c}(^1S_0^{[8]})gg\rangle \\
&+ \ldots .
\end{aligned}
$$

Contribution to NLO in v^2

$\mathcal{O}(v^5)$ $\langle\mathcal{O}(^3P_1^{[1]})\rangle$, $\langle\mathcal{O}(^3S_1^{[8]})\rangle$

$\mathcal{O}(v^7)$ $\langle\mathcal{P}(^3P_1^{[1]})\rangle$, $\langle\mathcal{P}(^3S_1^{[8]})\rangle$, $\langle\mathcal{O}(^3S_1^{[8]},{}^3D_1^{[8]})\rangle$

The amplitudes

In the NRQCD factorization framework, the amplitude in the rest frame of H as

$$\begin{aligned}
& \mathcal{M}(a(k_1)b(k_2) \to H_{c\bar{c}}(^{2S+1}L_J)(2p_1) + f) \\
= & \sum_{L_z S_z} \sum_{s_1 s_2} \sum_{jk} \int \mathrm{d}^3\vec{q}\,\Phi_{c\bar{c}}(\vec{q}) \langle s_1; s_2 \mid SS_z \rangle \langle 3j; \bar{3}k \mid 1 \rangle \\
& \times \mathcal{M}\left[ab \to c_j^{s_1}(p_1+q) + \bar{c}_k^{s_2}(p_1-q) + f\right], \qquad (7)
\end{aligned}$$

where $\langle 3j; \bar{3}k \mid 1 \rangle = \delta_{jk}/\sqrt{N_c}$, $\langle s_1; s_2 \mid SS_z \rangle$ is the color CG coefficient for $c\bar{c}$ pairs projecting out appropriate bound states, and $\langle s_1; s_2 \mid SS_z \rangle$ is the spin CGp coefficient.
$\mathcal{M}\left[ab \to c_j^{s_1}(p_1+q) + \bar{c}_k^{s_2}(p_1-q) + f\right]$ is the quark level scattering amplitude.

The expand of quark-level amplitudes

1. S wave

$$\mathcal{M}[(c\bar{c})(^3S_1^{[8]})] = \epsilon_\rho(s_z)\mathcal{M}_t^\rho\Big|_{q=0} + \epsilon_\rho(s_z)\frac{1}{2}q^\alpha q^\beta \frac{\partial^2(\sqrt{\frac{m_c}{E_q}}\mathcal{M}_t^\rho)}{\partial q^\alpha \partial q^\beta}\Big|_{q=0}$$

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2. P wave

$$\mathcal{M}[(c\bar{c})(^3P_J^{[1]})] = \epsilon_\rho(s_z)q_\sigma(L_z)\Big(\frac{\partial \mathcal{M}_t^\rho}{\partial q^\sigma}\Big|_{q=0} + \frac{1}{6}q^\alpha q^\beta \frac{\partial^3(\sqrt{\frac{m_c}{E_q}}\mathcal{M}_t^\rho)}{\partial q^\alpha \partial q^\beta \partial q^\sigma}\Big|_{q=0}\Big) + \mathcal{O}(q^5).$$

$X(3872)$ as a mixture state

In the sight of the mixture state of $\chi_{c1}(2P)$ and $D^0\bar{D}^{\star 0}$ molecule, the cross sections of $X(3872)$ at hadron collides can be expressed as (hep-ph/0506222, arXiv: 1304.6710)

$$d\sigma[X(3872) \to J/\psi\pi^+\pi^-] = d\sigma[\chi_{c1}(2P)]\times k, \qquad (8)$$

where $k = Z_{c\bar{c}}^{X(3872)}\times Br[X(3872) \to J/\psi\pi^+\pi^-]$.
$Br[X(3872) \to J/\psi\pi^+\pi^-]$ is the branching fraction for $X(3872)$ decay to $J/\psi\pi^+\pi^-$. $Z_{c\bar{c}}^{X(3872)}$ is the possibility of the $\chi_{c1}(2P)$ component in $X(3872)$.

$D\bar{D}$ component contributions in the molecule model

1. The parton level amplitudes may be compared with the hadron level amplitudes

$$\begin{aligned} & \mathcal{M}\left[a+b \to c\bar{c}+f\right] \\ \sim \quad & \mathcal{M}\left[a+b \to D\bar{D}+f\right]\Big|_{M_{D\bar{D}} \sim M_{c\bar{c}}} \end{aligned} \tag{9}$$

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2. But the $R^{l}_{c\bar{c}}(0) \sim v^{2l} R^{S}_{c\bar{c}}(0) \gg R_{D\bar{D}}(0)$ with the S wave $l=0$ and P wave $l=1$.

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3. For the binding energy of $c\bar{c}$ and $D\bar{D}$ are several hundreds MeV and several MeV respectively.

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3. For the binding energy of $c\bar{c}$ and $D\bar{D}$ are several hundreds MeV and several MeV respectively.
4. If $Z^{H}_{c\bar{c}} \sim Z^{H}_{D\bar{D}}$, we can consider the $c\bar{c}$ contributions only.

Numerical Result of BESIII

$X(3872)$ production at BESIII

Resonance contributions

The resonance contributions for $X(3872)$ can be estimated as:

$$\sigma_{Res}[s] = \frac{12\pi\Gamma[Res \to e^+e^-]\Gamma[Res \to \gamma X]}{(s - M^2)^2 + (M\Gamma_{tot}[Res])^2}. \tag{10}$$

The most contributions are from $\psi(4040)$ and $\psi(4160)$, the mixing of $\psi(3S)$ and $\psi(2D)$ (arXiv:1201.4155,hep-ph/0505002).

Numerical result of resonance contributions

With the parameters from (arXiv:1201.4155,hep-ph/0505002)

$$(\sigma_{\psi(4040)}[4.23] + \sigma_{\psi(4160)}[4.23]) \times k = (62 \pm 14)fb,$$
$$(\sigma_{\psi(4040)}[4.26] + \sigma_{\psi(4160)}[4.26]) \times k = (37 \pm 8)fb.$$

Cross section at BESIII

$$\sigma^{Ex}[4.23] = (0.29 \pm 0.09)pb,$$
$$\sigma^{Th}[4.23] = (0.28 \pm 0.11)pb,$$

$$\sigma^{Ex}[4.26] = (0.33 \pm 0.12)pb,$$
$$\sigma^{Th}[4.26] = (0.23 \pm 0.09)pb,$$

$$\sigma^{Ex}[4.36] = (0.11 \pm 0.09)pb,$$
$$\sigma^{Th}[4.36] = (0.10 \pm 0.04)pb,$$

$X(3872)$ production at BESIII

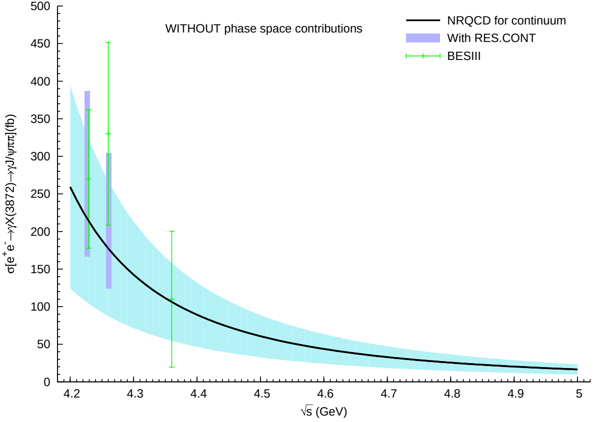


Figure: $e^+e^- \to$X(3872)$+\gamma$ at BESIII

Numerical Result of Hadron Colliders

Relativistic corrections of short distance coefficients

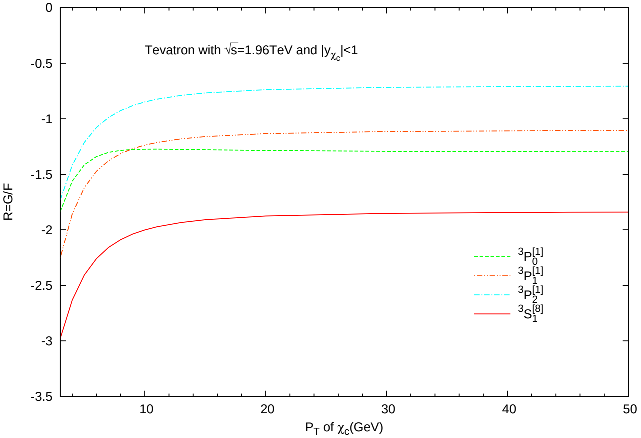
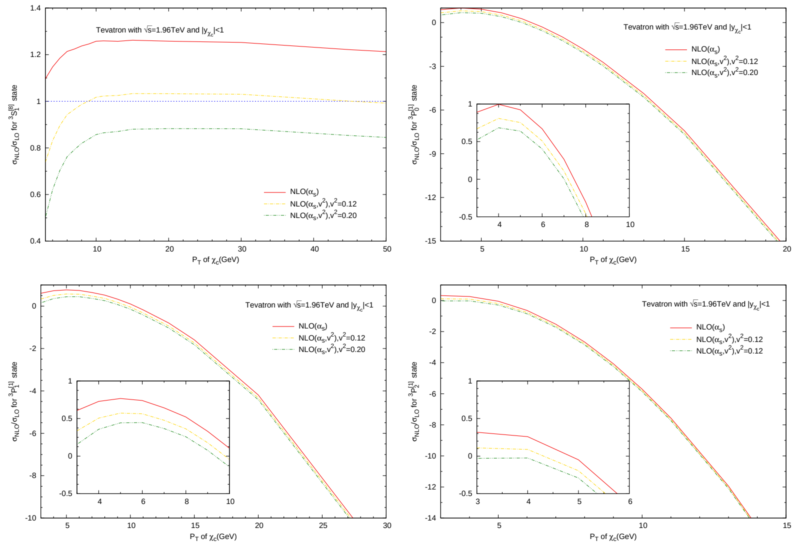


Figure:

The behavior at large p_T

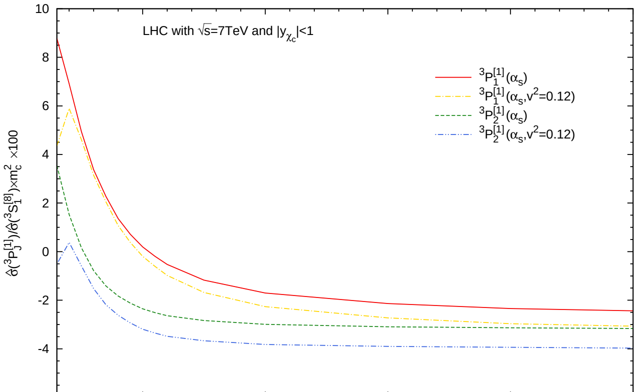
$$
\begin{aligned}
R({}^3S_1^{[8]})\Big|_{p_T \gg M} &= \frac{G({}^3S_1^{[8]})}{F({}^3S_1^{[8]})}\Big|_{p_T \gg M} &\sim& -\frac{11}{6},\\
R({}^3P_0^{[1]})\Big|_{p_T \gg M} &= \frac{G({}^3P_0^{[1]})}{F({}^3P_0^{[1]})}\Big|_{p_T \gg M} &\sim& -\frac{13}{10},\\
R({}^3P_1^{[1]})\Big|_{p_T \gg M} &= \frac{G({}^3P_1^{[1]})}{F({}^3P_1^{[1]})}\Big|_{p_T \gg M} &\sim& -\frac{11}{10},\\
R({}^3P_2^{[1]})\Big|_{p_T \gg M} &= \frac{G({}^3P_2^{[1]})}{F({}^3P_2^{[1]})}\Big|_{p_T \gg M} &\sim& -\frac{7}{10}.
\end{aligned}
$$

K factor of Tevatron



Ratio of short distance coefficients between ${}^3P^{[1]}_{J=1,2}$ and ${}^3S^{[8]}_1$

$$R_{\chi_c} = \frac{5}{3}\frac{r + m_c^2 d\hat{\sigma}\left[{}^3P_2^{[1]}\right]/d\hat{\sigma}\left[{}^3S_1^{[8]}\right]}{r + m_c^2 d\hat{\sigma}\left[{}^3P_1^{[1]}\right]/d\hat{\sigma}\left[{}^3S_1^{[8]}\right]} + \mathcal{O}(v^2).$$



Fit the long distance matrix elements

The ration of long distance matrix elements at NLO α_s

$$r = m_c^2 \frac{\langle 0|\mathcal{O}^{\chi_{cJ}}(^3S_1^8)|0\rangle}{\langle 0|\mathcal{O}^{\chi_{cJ}}(^3P_J^1)|0\rangle} = 0.045 \pm 0.010 \sim \mathcal{O}(v^2)/(2N_c).$$

The ration of long distance matrix elements at NLO α_s, v^2

$$r_{(\alpha_s)}|_{p_T >> M} = r_{(\alpha_s, v^2)}\{1 + v^2 d\hat{\sigma}_{rc}\left[^3S_1^{[8]}\right]/d\hat{\sigma}_{NLO(\alpha_s)}\left[^3S_1^{[8]}\right]\}.$$

Fit the long distance matrix elements ration *r*

Fit the long distance matrix elements ration *r*, where in unit of 10^{-2}.

v^2	CDF,$\chi^2/2$	CMS,$\chi^2/5$	LHCb,$\chi^2/6$	All,$\chi^2/15$
0	4.0 ± 0.2,1.85	4.0 ± 0.1,1.59	5.3 ± 0.4,0.80	4.1 ± 0.1,1.82
0.12	4.8 ± 0.2,1.93	5.1 ± 0.1,1.85	6.7 ± 0.5,0.84	5.1 ± 0.1,2.21

Table:

Cross sections with fitted v^2 and r

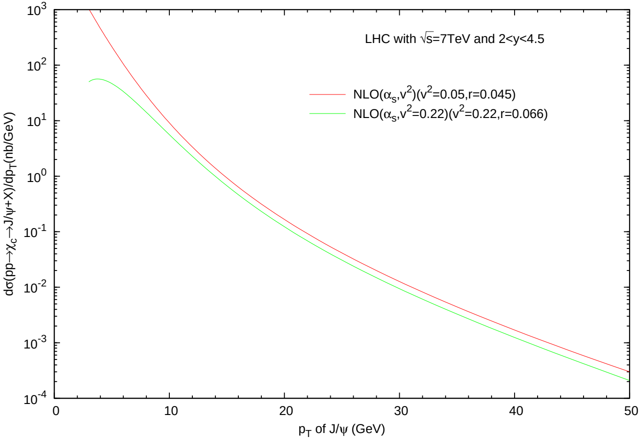


Figure:

Cross sections with fitted v^2 and r

The relativistic correction of χ_{cJ} will suppress the cross sections of J/ψ at low p_T.

Production of $X(3872)$ at CDF, CMS, and LHCb

Experimental data of $X(3872)$

$$\sigma^{CDF}[X(3872) \to J/\psi\pi^+\pi^-] = 3.1 \pm 0.7\, nb,$$
$$\sigma^{LHCb}[X(3872) \to J/\psi\pi^+\pi^-] = 5.4 \pm 1.5\, nb.$$

Table: $X(3872)$ is considered as the mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{\star 0}$. r and k is fitted through CMS data at $p_T > 10$ GeV $X(3872)$ with different v^2.

v^2	r	k	$\sigma^{th}_{CDF}(nb)$	$\sigma^{th}_{LHCb}(nb)$
0	0.044 ± 0.004	0.010	2.51 ± 0.12	9.14 ± 0.46
0.20	0.056 ± 0.004	0.015	2.70 ± 0.14	7.88 ± 0.46
0.30	0.067 ± 0.005	0.022	3.07 ± 0.18	6.37 ± 0.45
0.33	0.071 ± 0.005	0.027	3.32 ± 0.20	5.51 ± 0.46

$X(3872)$ production in CMS

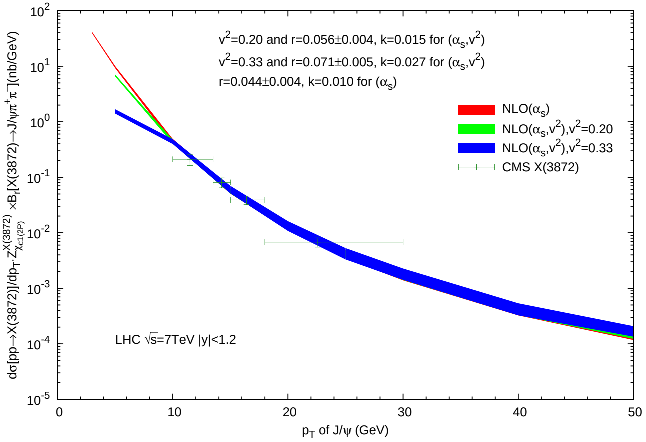


Figure: $X(3872)$ production in CMS

$X(3872)$ production in LHCb

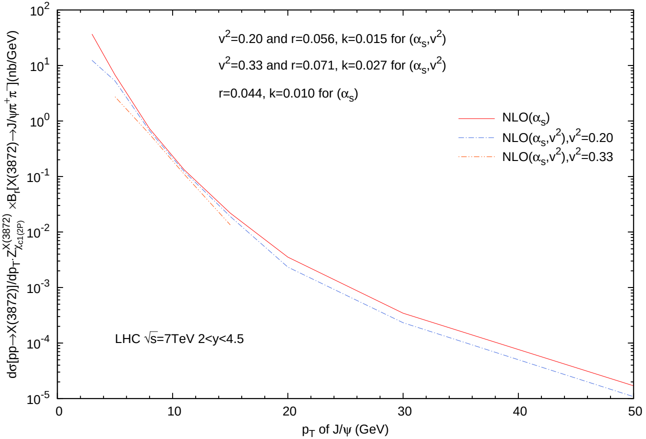


Figure: $X(3872)$ production in LHCb

$X(3872)$ production at 14 TeV LHCb

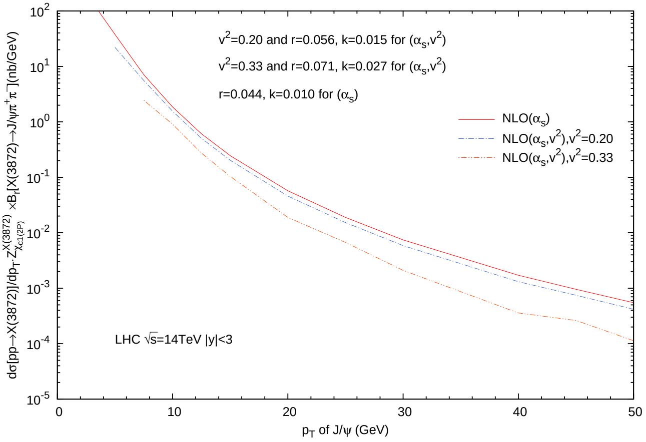


Figure: $X(3872)$ production in CMS at 14 TeV

Summary

$X(3872)$ as a mixture states of $\chi_{c1}(2P)$ and $D\bar{D}^*$

Support by production at B decay, decay, and Lattice QCD.

$X(3872)$ production in BESIII

$\mathcal{O}(\alpha_s v^2)$ corrections of $X(3872)$ production in BESIII is consistent with experimental data

$X(3872)$ production in hadron colliders

$\mathcal{O}(\alpha_s, v^2)$ corrections of $X(3872)$ production is consistent with experimental data of CDF, CMS, and LHCb.