

Theoretical overview of (some issues on) XYZ exotic states

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- Introduction
- General features of theoretical alternatives
 - molecular states
 - hadrocharmonium
 - hybrids
 - tetraquark states (diquark - antidiquark)
- Issue of production cross sections for exotica at hadronic colliders
 - $X(3872)$ at Tevatron
 - $X(3872)$ at LHC
 - recent estimates for production cross sections of charged exotic states

What is exotics?

Restricting to the meson systems, any state not fitting the standard $q\bar{q}$ picture because of

- mass and width
- decay properties
- J^{PC} quantum numbers different from $P = (-1)^{L+1}$ or $C = (-1)^{L+S}$:
 - e.g. $0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}$ are “natural”
 - $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ are exotic

The first exotic state, $X(3872)$, dates back to ten years ago:
the oldest one and still debated

Summary of the available information on XYZ (I)

from T. Bodwin et al, arXiv:1307.7435[hep-ph]

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment ($\# \sigma$)	1 st observation
$X(3823)$	3823.1 ± 1.9	< 24	$?^{? -}$	$B \rightarrow K + (\chi_{c1} \gamma)$	Belle (3.8)	Belle 2013
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \rightarrow K + (J/\psi \pi^+ \pi^-)$ $p\bar{p} \rightarrow (J/\psi \pi^+ \pi^-) + \dots$ $B \rightarrow K + (J/\psi \pi^+ \pi^- \pi^0)$ $B \rightarrow K + (D^0 \bar{D}^0 \pi^0)$ $B \rightarrow K + (J/\psi \gamma)$ $B \rightarrow K + (\psi(2S) \gamma)$ $pp \rightarrow (J/\psi \pi^+ \pi^-) + \dots$	Belle (12.8), BaBar (8.6) CDF (np), D0 (5.2) Belle (4.3), BaBar (4.0) Belle (6.4), BaBar (4.9) Belle (4.0), BaBar (3.6) BaBar (3.5), Belle (0.4) LHCb (np)	Belle 2003
$X(3915)$	3917.5 ± 1.9	20 ± 5	0^{++}	$B \rightarrow K + (J/\psi \omega)$ $e^+ e^- \rightarrow e^+ e^- + (J/\psi \omega)$	Belle (8.1), BaBar (19) Belle (7.7), BaBar (7.6)	Belle 2004
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+ e^- \rightarrow e^+ e^- + (D\bar{D})$	Belle (5.3), BaBar (5.8)	Belle 2005
$X(3940)$	3942_{-8}^{+9}	37_{-17}^{+27}	$?^{?+}$	$e^+ e^- \rightarrow J/\psi + (D^* \bar{D})$ $e^+ e^- \rightarrow J/\psi + (\dots)$	Belle (6.0) Belle (5.0)	Belle 2007
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+ e^- \rightarrow \gamma + (D\bar{D})$	BaBar (np), Belle (np)	BaBar 2007
$Y(4008)$	4008_{-49}^{+121}	226 ± 97	1^{--}	$e^+ e^- \rightarrow \gamma + (J/\psi \pi^+ \pi^-)$	Belle (7.4)	Belle 2007
$Y(4140)$	4144.5 ± 2.6	15_{-7}^{+11}	$?^{?+}$	$B \rightarrow K + (J/\psi \phi)$	CDF (5.0), CMS (>5)	CDF 2009
$X(4160)$	4156_{-25}^{+29}	139_{-65}^{+113}	$?^{?+}$	$e^+ e^- \rightarrow J/\psi + (D^* \bar{D}^*)$	Belle (5.5)	Belle 2007

Summary of the available information on XYZ (II)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment (# σ)	1 st observation
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$e^+e^- \rightarrow \gamma + (J/\psi \pi^+ \pi^-)$ $e^+e^- \rightarrow (J/\psi \pi^+ \pi^-)$ $e^+e^- \rightarrow (J/\psi \pi^0 \pi^0)$	BaBar (8.0), CLEO (5.4) Belle (15) CLEO (11) CLEO (5.1)	BaBar 2005
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \rightarrow K + (J/\psi \phi)$	CDF (3.1)	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$e^+e^- \rightarrow e^+e^- (J/\psi \phi)$	Belle (3.2)	Belle 2009
$Y(4360)$	4361 ± 13	74 ± 18	1^{--}	$e^+e^- \rightarrow \gamma + (\psi(2S) \pi^+ \pi^-)$	BaBar (np), Belle (8.0)	BaBar 2007
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \rightarrow \gamma (\Lambda_c^+ \Lambda_c^-)$	Belle (8.2)	Belle 2007
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \rightarrow \gamma + (\psi(2S) \pi^+ \pi^-)$	Belle (5.8)	Belle 2007
$Z_c^+(3900)$	3898 ± 5	51 ± 19	1^{2-}	$Y(4260) \rightarrow \pi^- + (J/\psi \pi^+)$ $e^+e^- \rightarrow \pi^- + (J/\psi \pi^+)$	BESIII (np), Belle (5.2) Xiao <i>et al.</i> (6.1)	BESIII 2013
$Z_1^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?$	$B \rightarrow K + (\chi_{c1}(1P) \pi^+)$	Belle (5.0), BaBar (1.1)	Belle 2008
$Z_2^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?$	$B \rightarrow K + (\chi_{c1}(1P) \pi^+)$	Belle (5.0), BaBar (2.0)	Belle 2008
$Z^+(4430)$	4443^{+24}_{-18}	107^{+113}_{-71}	$?$	$B \rightarrow K + (\psi(2S) \pi^+)$	Belle (6.4), BaBar (2.4)	Belle 2007
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \rightarrow (\Upsilon(nS) \pi^+ \pi^-)$	Belle (2.0)	Belle 2010
$Z_b^+(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \rightarrow \pi^- + (\Upsilon(nS) \pi^+)$ $\Upsilon(5S) \rightarrow \pi^- + (h_b(nP) \pi^+)$	Belle (16) Belle (16)	Belle 2011
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \rightarrow \pi^- + (\Upsilon(nS) \pi^+)$ $\Upsilon(5S) \rightarrow \pi^- + (h_b(nP) \pi^+)$	Belle (16) Belle (16)	Belle 2011

general features of most popular theoretical models

• hadronic molecules

- $Q\bar{q}$ tightly bound in heavy mesons which move at distances longer than typical size of mesons
- masses close to thresholds
- typically loosely bound systems which can decay easily through the independent decay of their constituents
- isospin breaking easily accommodated
- difficult to make predictions (in principle any pair of mesons at threshold can rescatter and form a molecule)

• hybrids ($c\bar{c} +$ excited gluons)

- different quantum numbers from charmonium
- natural preference to decay to $J/\psi +$ pions
- lowest lying state predicted around 4200 MeV by LQCD $\implies Y(4260)$

• diquark-antidiquarks (tetraquarks)

- Qq tightly bound in diquarks, which interact by QCD colour force
- masses not necessarily close to threshold
- many new states (charged and neutral) foreseen (a nonet for each spin-parity)
- neutral states expected to appear in doublets
- decays include both open and hidden charm channels and (if kinematically allowed) baryonium

• hadro-quarkonium

- $Q\bar{Q}$ tightly bound as in quarkonium
- $Q\bar{Q}$ embedded in a spatially large excited state of light mesonic matter
- interactions through QCD analog of Van der Waals force
- natural suppression of decay to open charm/beauty

an example: $X(3872)$, the oldest one and still debated

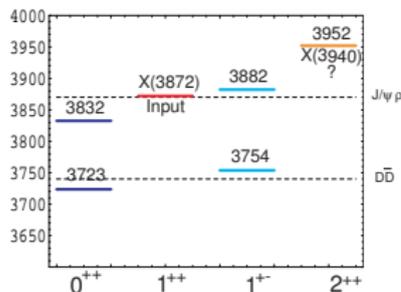
Information available for different production and decay channels

- $M(X3872) = 3871.68 \pm 0.17 \text{ MeV}$
- $M(D_0) + M(\bar{D}_0^*) = 3871.82 \pm 0.19 \text{ MeV}$
- $\Gamma_X \lesssim 1.2 \text{ MeV}$
- $M(X3872)$ in the region of $\chi_{c1}(2P)$ and $\eta_{c2}(1D)$
- $J^{PC} = 1^{++}$ (LHCb recently excluded the 2^{-+} option)
- production
 - production through B decays at e^+e^- and $p\bar{p}/pp$ colliders
 - both channels $B^\pm \rightarrow XK^\pm$ and $B^0 \rightarrow XK^0$
 - dominant prompt production at Tevatron/LHC ($p\bar{p} \rightarrow X + \text{all}$)
- decay
 - $J/\psi\rho \rightarrow J/\psi\pi^+\pi^-$
 - $J/\psi\omega \rightarrow J/\psi\pi^+\pi^-\pi^0$ (maximal isospin violation)
 - $D^0\bar{D}^{0*} \rightarrow D^0\bar{D}^0\pi^0$
 - $D^0\bar{D}^{0*} \rightarrow \bar{D}^0\gamma$
 - $J/\psi\gamma, \psi(2S)\gamma$
- first models: molecule (most popular by now) and tetraquark
- other models: $c\bar{c}$ dynamically coupled to open charm channels

see talk by E. Santopinto

$X(3872)$ as a tetraquark

- charged partners should be around (searched but not found)
- due to the spin independence of heavy quark interactions a rich structure of levels appears



Maiani, F.P., Polosa, Riquer, Phys. Rev. D71 014028 (2005)

- isospin breaking splits the X in two states separated by few MeV ($\sim 8 \pm 3$)
- actually the X mass measured in the $J/\psi \pi^+ \pi^-$ channel seemed to be smaller than the one measured in $D^0 \bar{D}^0 \pi^0$
- searches done at BaBar, Belle and CDF compatible with $\Delta M = 0$

$X(3872)$ as a molecule

- **binding energy: -0.14 ± 26 MeV \Rightarrow radius ~ 8 fm!**
more precise determination of m_{D^0} and $m_{D^{*0}}$ needed to determine the sign of binding energy

- $\frac{\mathcal{B}(X \rightarrow J/\psi \omega)}{\mathcal{B}(X \rightarrow J/\psi \rho)} \simeq 1$ is easily accommodated

- the radiative decays are difficult to explain

$$\frac{\Gamma(X \rightarrow \psi(2S)\gamma)}{\Gamma(X \rightarrow \psi\gamma)}_{\text{th}} \sim 4 \cdot 10^{-3} \text{ (E. Swanson, 2004) vs. } \frac{\Gamma(X \rightarrow \psi(2S)\gamma)}{\Gamma(X \rightarrow \psi\gamma)}_{\text{exp}} = 3.4 \pm 1.4$$

(BaBar 2009)

unless ad hoc admixture of $c\bar{c}$ is added to the wave function

- $\frac{\mathcal{B}(B^0 \rightarrow X K^0)}{\mathcal{B}(B^+ \rightarrow X K^+)}$
 - Belle: $0.82 \pm 0.22 \pm 0.05$ (arXiv:0809.1224)
 - BaBar: $0.41 \pm 0.24 \pm 0.05$ (Phys. Rev. D77, 111101 (2008))
 - theory: ≥ 0.06 and ≤ 0.29 (Braaten and Kusunoki, 2005; Swanson 2006)
- not easy to understand a large prompt production for a loosely bound molecule in high energy hadronic collisions (Tevatron and LHC)

Prompt production at CDF

CDF measured the fraction of *prompt* $X(3872) \rightarrow J/\psi\pi^+\pi^-$: $83.9 \pm 5.2\%$

CDF Coll. PRL **98** 132002 (2007)

Assuming the same detection efficiency for $\psi(2S)$ and $X(3872)$ and using the well measured $\mathcal{B}(\psi(2S) \rightarrow \mu^+\mu^-)$

$$\frac{\sigma(p\bar{p} \rightarrow X(3872) + \text{All})_{\text{prompt}} \times \mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)}{\sigma(p\bar{p} \rightarrow \psi(2S) + \text{All})} = 4.7 \pm 0.8\%$$

Lower experimental bound

$$\begin{aligned} \sigma(p\bar{p} \rightarrow X(3872) + \text{All})_{\text{prompt}}^{\text{min}} &> \sigma(p\bar{p} \rightarrow X + \text{All}) \times \mathcal{B}(X \rightarrow J/\psi\pi^+\pi^-) \\ &= 3.1 \pm 0.7 \text{ nb} \end{aligned}$$

for $p_{\perp}(X) > 5 \text{ GeV}$, $|y(X)| < 0.6$

Assuming conservatively $\mathcal{BR}(X \rightarrow J/\psi\pi\pi) \sim 10\%$

$$\sigma(p\bar{p} \rightarrow X(3872) + \text{All})_{\text{prompt}} \sim 30 \text{ nb}$$

Hypothesis: $X(3872)$ is an S -wave bound state of two D mesons

E.S. Swanson, E. Braaten et al.

$$\begin{aligned}\sigma(p\bar{p} \rightarrow X(3872)) &\sim \left| \int d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\ &\simeq \left| \int_{\mathcal{R}} d^3\mathbf{k} \langle X | D\bar{D}^*(\mathbf{k}) \rangle \langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle \right|^2 \\ &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\psi(\mathbf{k})|^2 \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \\ &\leq \int_{\mathcal{R}} d^3\mathbf{k} |\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2 \sim \sigma(p\bar{p} \rightarrow X(3872))_{\text{prompt}}^{\text{max}}\end{aligned}$$

- \mathbf{k} is the rest-frame relative 3-momentum between the D and D^*
- $|\langle D\bar{D}^*(\mathbf{k}) | p\bar{p} \rangle|^2$ can be computed with MC simulations
- \mathcal{R} has to be given with a reasonable conservative Ansatz for the bound state wave function (we use a simple gaussian form)

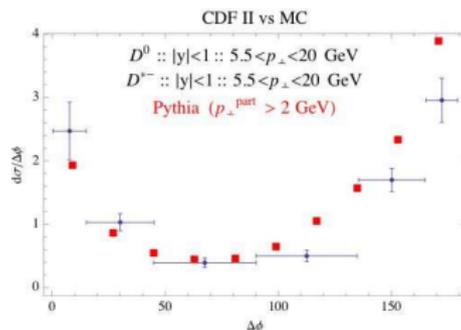
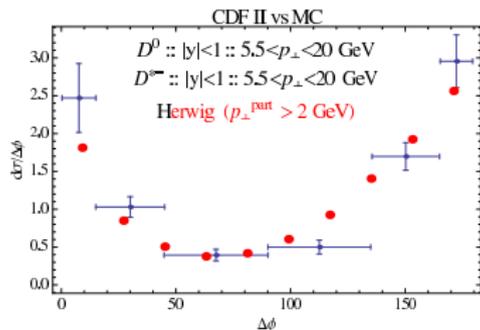
$$|\langle D \bar{D}^*(\mathbf{k}) | p \bar{p} \rangle|^2$$

- we expect the **bulk** of the contribution from events with a **gluon recoiling against an almost collinear $c\bar{c}$ pair**
- the standard Parton Shower MC Event Generators (like Herwig and Pythia) describe well the events with gluons radiated at small p_T , which are enhanced by collinear logarithms
- contributions from large p_T gluons are expected to be suppressed. We checked this numerically with ALPGEN finding a totally negligible contribution

We used both Herwig and Pythia for the simulations, since they include two completely different hadronization schemes, to have an estimate of the uncertainty introduced by the hadronization model

Herwig and Pythia tuning on CDF data for $D^0 D^{*-}$ pairs

We generated two samples of $2 \rightarrow 2$ QCD processes with parton showering and hadronization (with loose partonic cuts)



The $\Delta\phi$ shape is well reproduced once an overall k-factor is applied to the MC predictions, $\simeq 1.8$ for Herwig and $\simeq 0.7$ for Pythia

Estimate of \mathcal{R}

We need an estimate of the momentum and its spread in the gaussian. Assuming a Yukawa potential between the D mesons

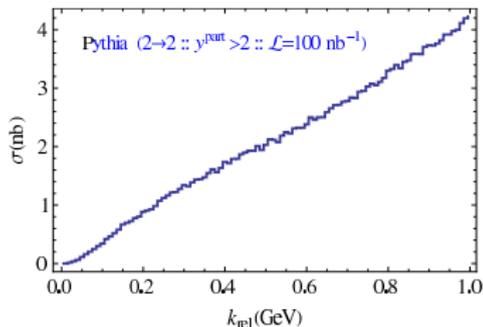
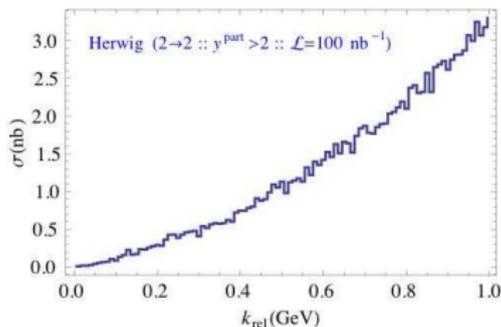
$$\frac{\hbar^2}{\mu r_0^2} - \frac{g^2}{4\pi} \frac{e^{-\frac{m_\pi c}{\hbar} r_0}}{r_0} = \mathcal{E}_0 \sim M_X - M_D - M_{D^*}$$

Solving for r_0 we find $r_0 \sim 10$ fm

- minimal uncertainty relation gives $\Delta k \simeq 12$ MeV
- $k \simeq \sqrt{\lambda(m_X^2, m_D^2, m_{D^*}^2)}/2m_X \simeq 27$ MeV

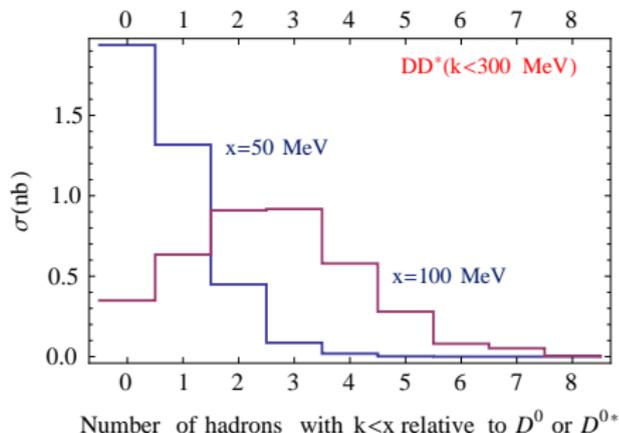
We consider the region within a sphere of radius $\mathcal{R} = 35$ MeV

$D^0 \bar{D}^{0*} k_{\text{rel}}$ distributions



- To integrate 30 nb we need k_{rel} up to several hundreds MeV
- in the region of relative momentum R Herwig and Pythia integrate 0.071 nb and 0.11 nb respectively, **too low by more than two order of magnitude!**
- According to Artoisenet and Braaten (PRD81 (2010) 114018) we didn't consider final state interactions, which can enhance the cross section by orders of magnitude
 - because of rescattering effects the effective maximum k_{rel} can reach ~ 400 MeV

- FSI relies on the Migdal-Watson theorem, which assumes no additional hadronic activity between the two particles which undergo FSI
- we estimated this activity by means of MC event generators



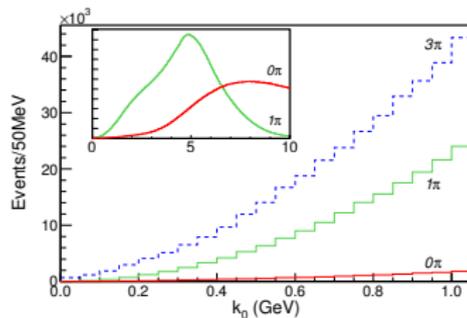
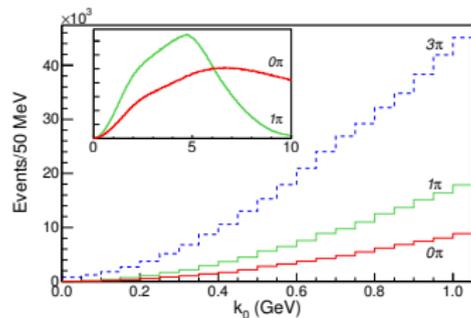
- this hadronic activity (mainly pions) could give an handle for an alternative mechanism of molecule formation

- additional pions close to $D^{0(*)}$ in momentum space can interact elastically and change the relative momentum between D^0 and D^{0*}
- the interactions are regulated by the matrix elements

$$\begin{aligned}\langle \pi(p)D(q)|D^*(P, \eta)\rangle &= g_{\pi D D^*} \eta \cdot p \\ \langle \pi(p)D^*(q, \lambda)|D^*(P, \eta)\rangle &= \frac{g_{\pi D^* D^*}}{M_{D^*}} \epsilon_{\alpha\beta\gamma\delta} \lambda^\alpha \eta^\beta p^\gamma q^\delta\end{aligned}$$

- given the initial asymmetric distribution in k_{rel} there could be a feed-down process from larger relative momenta to lower ones
- assuming D^0 and D^{0*} are under an attractive potential (modelled by a square well), the above interaction can bring D pairs from positive to negative energies (bound state)

preliminary results @ Tevatron



- from a simulation of $p\bar{p} \rightarrow c\bar{c}$ the gain in the first bin $k_{\text{rel}} < 50$ MeV ranges from a factor of 2 (Herwig) to 7 (Pythia)
- the simulation should be completed with all possible QCD processes, where $c\bar{c}$ pairs can originate from the last splitting $g \rightarrow c\bar{c}$
- including the above simulation, very small differences between Herwig and Pythia
- even if the mechanism enhances the cross section, the inclusion of one pion scattering is not enough to explain the data

- Artoisenet and Braaten (PRD81 (2010) 114018), relying on CDF data, give predictions for the $X(3872)$ inclusive cross section at the LHC using the NRQCD factorization formula

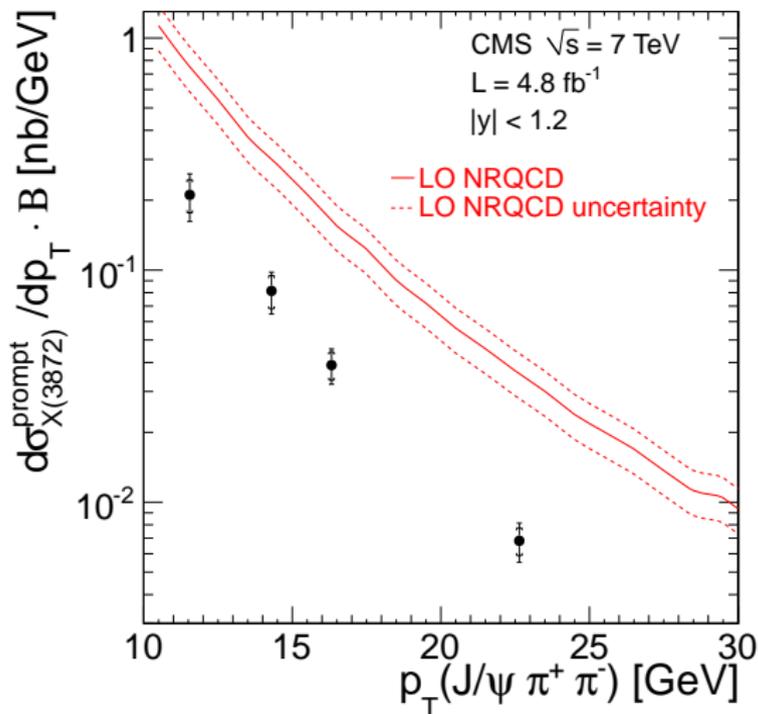
$$\sigma(X(3872)) = \sum_n \hat{\sigma}[c\bar{c}_n] \langle \mathcal{O}_n^X \rangle$$

n runs over color and angular-momentum channels of $c\bar{c}$

- four independent universal matrix elements:
 - $\langle \mathcal{O}_1^X(^3S_1) \rangle$
 - $\langle \mathcal{O}_1^X(^1S_0) \rangle$
 - $\langle \mathcal{O}_8^X(^3S_1) \rangle$
 - $\langle \mathcal{O}_8^X(^1S_0) \rangle$
- simplifying assumptions can be adopted to reduce the number of independent matrix elements, e.g. S -wave dominance, spin-triplet dominance, color-octet dominance

comparison with LHC production data

CMS Collaboration, arXiv:1302.3968[hep-ex]



- following the original idea of Bignamini et al, 2009, very recent application to production cross section prediction for charged exotic states
- since these states are above threshold

$$\sigma(Z_Q) \approx K_{H\bar{H}} \int_0^\Lambda dk \frac{d\sigma_{H\bar{H}}^{\text{MC}}(k)}{dk} \frac{|f(E)|^2}{|f(E = E_\Lambda)|^2},$$

Table: Integrated normalized cross sections (in units of nb) for the reactions $pp/\bar{p} \rightarrow Z_b(10610), Z_b(10650), Z_c(3900),$ and $Z_c(4020)$ at the LHC and the Tevatron. Results are obtained using Herwig (Pythia). The rapidity range $|y| < 2.5$ has been assumed for the LHC experiments (ATLAS and CMS) at 7, 8 and 14 TeV, respectively, for the Tevatron experiments (CDF and D0) at 1.96 TeV, we use $|y| < 0.6$; the rapidity range $2.0 < y < 4.5$ is used for LHCb.

	$Z_b(10610)$	$Z_b(10650)$	$Z_c(3900)$	$Z_c(4020)$
Tevatron	0.26(0.47)	0.06(0.17)	11(13)	1.7(2.0)
LHC 7	4.8(8.0)	1.2(3.0)	187(211)	29(31)
LHCb 7	0.76(1.3)	0.18(0.47)	33(39)	5.5(5.8)
LHC 8	5.9(9.5)	1.4(3.5)	220(240)	34(36)
LHCb 8	0.9(1.4)	0.22(0.56)	40(48)	6.3(6.9)
LHC 14	11(17)	2.6(6.5)	382(423)	61(63)
LHCb 14	1.9(3.0)	0.52(1.2)	84(88)	14(14)