Status of XYZ exotics and prospects for studies at the LHC

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Charm and bottom quark production at the LHC, 3 December, 2010

Outline

Charm sector

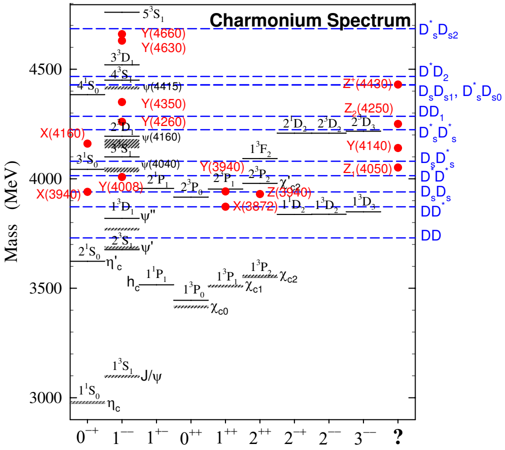
- Recent proliferation of new exotic states X, Y, Z
- Theoretical alternatives
  - molecular states
  - hybrids
  - tetraquark states (diquark - antidiquark)
  - hadrocharmonium
- the case of $X(3872)$: the oldest one and still debated

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

charmonium spectrum

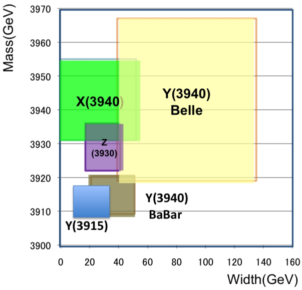


S. Godfrey, arXiv:0910.3409[hep-ph]

- all $c\bar{c}$ states below open charm threshold have been identified
- good agreement between data and theory
- something new above open charm threshold
- the theoretical picture for exotic states is far from being clear at present

very schematically, clusters of new states

- $X(3872)$, the first surprise
- the 3940 family



- the Y family (1^{--} states):
  - $Y(4260) \to J/\psi\pi\pi,\ K^+K^-$
  - $Y(4350) \to \psi(2S)\pi^+\pi^-$
  - $Y(4630) \to \Lambda_c\bar{\Lambda}_c$
  - $Y(4660) \to \psi(2S)\pi^+\pi^-$
- charged states
  - $Z(4430) \to \psi(2S)\pi^\pm$
  - $Z_1(4050),\ Z_2(4250)$ $\to \chi_{c1}(2S)\pi^\pm$
- $C = +$ states
- $X(4160) \to D^*\bar{D}^*$
- $Y(4140) \to J/\psi\phi$
- $X(4350)$

Drenska, Faccini, F.P., Polosa, Sabelli, arXiv:1006.2741 [hep-ph]

- B decays

B decays	$J/\psi\pi\pi$	$J/\psi\omega$	$J/\psi\gamma$	$J/\psi\phi$	$J/\psi\eta$	$\psi(2S)\pi\pi$	$\psi(2S)\omega$	$\psi(2S)\gamma$	$\chi_c\gamma$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	DD	DD*	D*D*	Ds(*)Ds(*)	$\gamma\gamma$
X(3872)	S	S	S	N/A	N/S	N/A	N/A	S	N/S	M/F	M/F	N/A	N/A	S	N/A	N/A	N/S
X,Y (3940)	M/F	S	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	N/S	N/A	N	N
Z(3940)	M/F	M/F	N/S	N/A	N/A	N/A	N/A	M/F	N/A	M/F	M/F	N/A	M/F	M/F	N/A	N	N
Y(4140)	M/F	M/F	N	S	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
X(4160)	M/F	M/F	N	M/F	N/A	N	N/A	N	N/A	M/F	M/F	N/A	M/F	N	N	N	N
Y(4260)	S	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
X(4350)	M/F	M/F	N	M/F	N/A	N	N	N	N/A	M/F	M/F	N/A	N	N	N	N	N
Y(4350)	M/F	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	N/A	N	N	N	N	N/A
Y(4660)	N	N/A	N/A	N/A	M/F	N	N/A	N/A	N	M/F	M/F	M/F	N	N	N	N	N/A

- production in association with ISR γ

ISR	$J/\psi\pi\pi$	$\psi(2S)\pi\pi$	$J/\psi\eta$	$\chi_c\gamma$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	DD	DD*	D*D*	Ds(*)Ds(*)
Y(4260)	S	N/S	N/S	N/S	N/S	M/F	N/A	N/S	N/S	N/S	N
Y(4350)	N/S	S	M/F	M/F	M/F	M/F	N/A	M/F	M/F	M/F	N
Y(4660)	N/S	S	M/F	M/F	M/F	M/F	S	M/F	M/F	M/F	N

status of experimental analysis at flavour factories (II)

- production in $\gamma\gamma$ fusion

γγ	J/ψππ	J/ψω	J/ψγ	J/ψφ	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*	Ds(*) Ds(*)
X(3872)	N	N/F	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	M/F	N	N/A	N/A
X,Y (3940)	N	S	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	S?^	N	N/A	N
Z(3940)	N	S?^	N/F	N/A	N/A	N/A	N/F	M/F	M/F	N/A	S	N	N/A	N
Y(4140)	N	M/F	N/F	N/S	N	N/A	N/F	N	N	N/A	M/F	N	N	N
X(4160)	N	M/F	N/F	N/S	N	N/A	N/F	N	N	N/A	M/F	N	N	N
X(4350)	N	N	N/F	S	N	N	N/F	N	N	N	N	N	N	N

- production in association with J/ψ

J/Psi recoil	J/ψππ	J/ψω	J/ψγ	J/ψφ	ψ(2S)ππ	ψ(2S)ω	ψ(2S)γ	χcγ	pp	ΛΛ	ΛcΛc	DD	DD*	D*D*
X(3872)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	N/A
X,Y (3940)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	S	M/F	N/A
Z(3940)	N/F	N	N/F	N/A	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	N/A
Y(4140)	N/F	N	N/F	N	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	M/F	M/F
X(4160)	N/F	N	N/F	N	N/F	N/A	N/F	N/F	N/F	N/F	N/A	M/F	S	M/F
X(4350)	N/F	N	N/F	N	N/F	N	N/F	N/F	N/F	N/F	N/F	M/F	M/F	M/F

status of searches at Tevatron

$p\bar{p}$ incl	$J/\psi\pi\pi$	$J/\psi\omega$	$J/\psi\gamma$	$J/\psi\phi$	$J/\psi\eta$	$\psi(2S)\pi\pi$	$\psi(2S)\omega$	$\psi(2S)\gamma$	$\chi_c\gamma$	$p\bar{p}$	$\Lambda\bar{\Lambda}$	$\Lambda_c\bar{\Lambda}_c$	$D\bar{D}$	DD^*	D^*D^*	$D_s(^*)D_s(^*)$
X(3872)	S	N	N/F	N/A	N/A	N/A	N/A	N/F	N/A	N	N	N/A	N/A	N	N/A	N/A
X,Y (3940)	N/S	N	N/F	N/A	N/A	N/A	N/A	N/F	N/A	N	N	N/A	N	N	N/A	N
Z(3940)	N/S	N	N/F	N/A	N/A	N/A	N/A	N/F	N/A	N	N	N/A	N	N	N	N
Y(4140)	N	N	N/F	N	N/A	N	N/A	N/F	N/A	N	N	N/A	N	N	N	N
X(4160)	N	N	N/F	N	N/A	N	N/A	N/F	N/A	N	N	N/A	N	N	N	N
Y(4260)	N	N/A	N/A	N/A	N	N	N/A	N/A	N/F	N	N	N/A	N	N	N	N
X(4350)	N	N	N/F	N	N/A	N	N	N/F	N/A	N	N	N/A	N	N	N	N
Y(4350)	N	N/A	N/A	N/A	N	N	N/A	N/A	N/F	N	N	N/A	N	N	N	N
Y(4660)	N	N/A	N/A	N/A	N	N	N/A	N/A	N/F	N	N	N	N	N	N	N

Tevatron data can still contain large amount of undisclosed information

hopefully the upcoming LHC data will allow to cover the whole table

general features of most popular theoretical models

- hadronic molecules
  - masses close to thresholds
  - being typically loosely bound systems the molecules can decay easily through the independent decay of their constituents
  - difficult to make predictions (in principle any pair of mesons at threshold can rescatter and form a loosely bound state)
- 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
- diquark-antidiquarks
  - masses not necessarily close to threshold
  - many states, charged and neutral, 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-charmonium ($c\bar{c}$ embedded in light hadronic matter)
  - natural explanation for $Y's \to J/\psi^{(\prime)}+$light hadrons and not to open charm

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

Information available for different production and decay channels

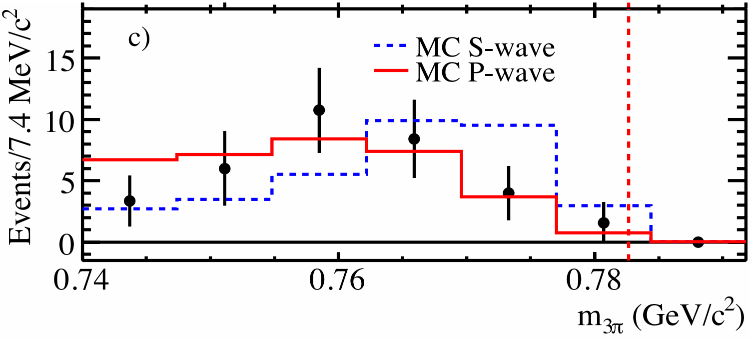
- $M(X3872) = 3871.56 \pm 0.22$ MeV
- $M(D_0) + M(\bar{D}_0{}^*) = 3871.87 \pm 0.19$ MeV
- $\Gamma_X \lesssim 3$ MeV
- production
  - production through B decays at e^+e^- and $p\bar{p}$ colliders
  - both channels $B^\pm \to XK^\pm$ and $B^0 \to XK^0$
  - dominant prompt production at Tevatron ($p\bar{p} \to X+$ all)
- decay
  - $J/\psi\rho \to J/\psi\pi^+\pi^-$
  - $J/\psi\omega \to J/\psi\pi^+\pi^-\pi^0$
  - $D^0\bar{D}^{0*} \to D^0\bar{D}^0\pi^0$
  - $D^0\bar{D}^{0*} \to \bar{D}^0\gamma$
  - $J/\psi\gamma$, $\psi(2S)\gamma$

(maximal isospin violation)

$X(3872)$: $J^{PC} = 1^{++}$ or 2^{-+}?

- 2005: Belle analysis of $X \to J/\psi\pi^+\pi^-$ “strongly favors 1^{++}”, “strongly disfavours 2^{-+}” and “2^{++} is not ruled out” (hep-ex/0505038)
- 2006: CDF analysis of $X \to J/\psi\pi^+\pi^-$: “1^{++} and 2^{-+} are the only ones consistent with the data”. “All other states are excluded at 99.7% c.l.” (hep-ex/0612053)
- 2010: BaBar analysis of $X(3872) \to J/\psi\pi^+\pi^-\pi^0$ prefers 2^{-+}

(1005.5190[hep-ex])

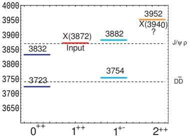


$X(3872)$ as a molecule

- binding energy: -0.35 ± 41 MeV $\Rightarrow$ radius ~ 8 fm!
- $\frac{\mathcal{B}(X \to J/\psi\omega)}{\mathcal{B}(X \to J/\psi\rho)} \simeq 1$ is easily accomodated
- the radiative decays are difficult to explain
  $\frac{\Gamma(X \to \psi(2S)\gamma)}{\Gamma(X \to \psi\gamma)}_{\rm th} \sim 4 \cdot 10^{-3}$ (E. Swanson, 2004) vs. $\frac{\Gamma(X \to \psi(2S)\gamma)}{\Gamma(X \to \psi\gamma)}_{\rm exp} = 3.4 \pm 1.4$
  (BaBar 2009)
  unless ad hoc admixture of $c\bar{c}$ is added to the wave function
- $\frac{\mathcal{B}(B^0 \to XK^0)}{\mathcal{B}(B^+ \to XK^+)}$
  - 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)

$X(3872)$ as a tetraquark

- charged partners should be around (not found until now)
- 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 (8 ± 3)
- actually the X mass measured in the $J/\psi\pi^+\pi^-$ channel seemed to be smaller than the one measured in $D^0\bar{D}^0\pi^0$
  - BaBar: $\Delta M = 2.7 \pm 1.6 \pm 0.4$ MeV (PRD77 111101 (2008))
  - Belle: $\Delta M = 0.18 \pm 0.89$ MeV (arXiv:0809.1224)
  - CDF: $\Delta M < 3.6$ MeV @ 95% C.L.

Prompt production at CDF

CDF measured the fraction of *prompt* $X(3872) \to {}_{J/\psi\pi^+\pi^-}$: 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 $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$

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

Lower experimental bound

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

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

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

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

Th. estimate of the production cross section (assuming 1^{++} molecule)

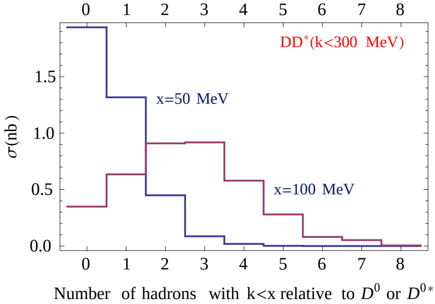
Bignamini, Grinstein, F.P., Polosa, Sabelli: Phys. Rev. Lett. 103, 162001, 2009

- Estimate of an upper theoretical bound for the production cross section using MC event generators, tuned to CDF data for $D^0 D^{*-}$ pairs
- Results
  - Consider a region in relative momentum given by a sphere with $R \sim 35$ 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 orders 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

hadronic activity close to $D^0 \bar{D}^{0*}$ pairs

Bignamini, Grinstein, F.P., Polosa, Riquer, Sabelli, PLB684 (2010) 228

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



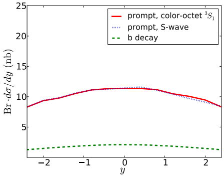
- this hadronic activity could be measured on the real data

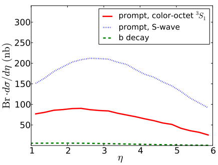
testable predictions for the LHC

- 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

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

- Assuming $S-$wave dominance, the results are stable (in the scenario of spin-triplet or color-octet dominance) in the central region (a factor of 4 in the cross section w.r.t. Tevatron) while the predictions are less stables in the forward LHCb kinematical configurations





What if $J^{\mathrm{PC}} = 2^{-+}$?

- The $X(3872)$ can not be a loosely bound molecule
- It could be a standard charmonium $({}^1D_2)$ but...
  - The mass is too large. Several potential model predictions give values smaller by about 70 MeV
  - The measured $\mathcal{BR}(X \to J/\psi\gamma)$ and $\mathcal{BR}(X \to J/\psi'\gamma)$ (especially the latter) are much larger than theoretical predictions, even orders of magnitude

    Ja, Sang, Xu, 1007.4541 [hep-ph]
  - the production cross section is proportional to the fragmentation function, which starts at $\mathcal{O}(v^7)$ in NRQCD. It has been calculated several years ago in the colour singlet approx (which is leading)

    Cho, Wise, PRD51 (1995) 3351
  - according to this, we calculated the inclusive production cross section for the CDF event selection

    Burns, F.P., Polosa, Sabelli, PRD82 (2010) 074003

$$\sigma(p\bar{p} \to 1^1D_2) \simeq 0.6\,\mathrm{nb}$$

too small by two orders of magnitude!

Could it be a tetraquark?

Yes but:

- The fitted diquark $[cq]$ mass results to be smaller w.r.t. the case 1^{++} by about 200 MeV, so the spectrum is shifted downwards
- To give $J^{PC} = 2^{-+}$ we need one unit of orbital momentum between the diquarks, so that a new set of lighter states $(L = 0)$ should be present

	0^{++}	1^{++}	2^{++}	0^{-+}	1^{-+}	2^{-+}		1^{+-}	0^{--}	1^{--}	2^{--}
$\eta_c\pi^0$	S		[D]		(P)		$J/\psi\pi^0$	S,D	(P)	(P)	(P,F)
$\eta_c\eta$					(P)		$J/\psi\eta$		(P)	(P)	(P,F)
$J/\psi\rho$				(P)	(P,F)	(P,F)	$\eta_c\rho$		[P]	(P)	[P,F]
$J/\psi\omega$				(P)	(P,F)	(P,F)	$\eta_c\omega$		[P]	(P)	[P,F]
$\eta_c'\pi^0$					(P)		$\psi'\pi^0$		(P)	(P)	(P,F)
$D\bar{D}$					(P)		$D\bar{D}$			P	
$D^*\bar{D}$				P	P	P	$D^*\bar{D}$		P	P	P
$\eta_c\sigma$		[P]	[P]	S		D	$J/\psi\sigma$	(P)		S,D	D
$\chi_0\pi$				S		D	$h_c\pi$			S,D	[D]
$\chi_1\pi$					S,D	D	$\chi_0\gamma$	(P)		S,D	D
$\chi_2\pi$				D	D	S,D	$\chi_1\gamma$		S,D	S,D	S,D
$J/\psi\gamma$	S,D	S,D	S,D	(P)	(P,F)	(P,F)	$\chi_2\gamma$			S,D	S,D
$\psi'\gamma$				(P)	(P,F)	(P,F)	$\eta_c\gamma$	S,D	[P]	(P)	[P,F]
$h_c\gamma$				S,D	S,D	S,D	$\eta_c'\gamma$		[P]	(P)	[P,F]

(Burns, F.P., Polosa, Sabelli, PRD82 (2010) 074003)

Summary

- the discovery of new particles at flavour factories gave revival and excitement to hadron spectroscopy
- this triggered searches (and findings) at Tevatron
- after six years of theoretical and experimental activity the situation is not clear yet, also for the best known $X(3872)$, even though often new resonances are coming out from the data
- LHC will be necessary to have a clear picture on the new particles and their nature
- having clarified the models for the charm sector, we can use the B sector future data at LHC as an additional testing ground of theoretical predictions, where we have now indications of something new from the anomalous rates for $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1, 2)$ around the $\Upsilon(5S)$ resonance at flavour factories