Overview of theory requirements to experiments on new spectroscopy

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Outline

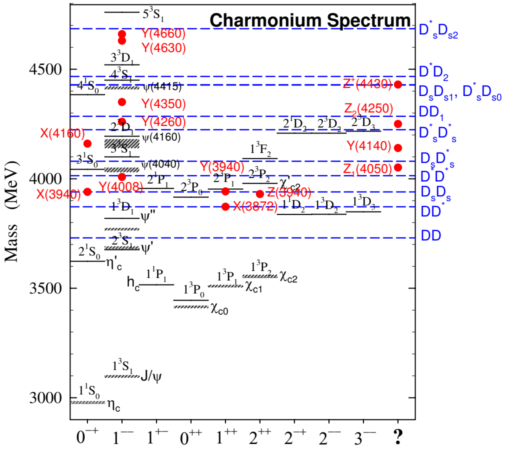
- Proliferation of new exotic states X, Y, Z
- Theoretical alternatives
  - molecular states
  - hybrids
  - tetraquark states (diquark - antidiquark)
- What will be the role of SuperB and its interplay with future hadronic colliders LHC(B) and Panda at FAIR?

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

summary of the available information on XYZ

state	M (MeV)	Γ (MeV)	J^{PC}	Seen In	Observed by:
$Y_s(2175)$	2175 ± 8	58 ± 26	1^{--}	$(e^+e^-)_{ISR}$, $J/\psi \to Y_s(2175) \to \phi f_0(980)$	BaBar, BESII, Bel
$X(3872)$	3871.4 ± 0.6	< 2.3	1^{++}	$B \to KX(3872) \to \pi^+\pi^- J/\psi$, $D\bar{D}^*$, $\gamma J/\psi$	Belle, CDF, D0, Ba
$X(3915)$	3914 ± 4	28^{+12}_{-14}	$?^{++}$	$\gamma\gamma \to \omega J/\psi$	Belle
$Z(3930)$	3929 ± 5	29 ± 10	2^{++}	$\gamma\gamma \to Z(3940) \to D\bar{D}$	Belle
$X(3940)$	3942 ± 9	37 ± 17	$0^{?+}$	$e^+e^- \to J/\psi X(3940) \to D\bar{D}^*$ (not $D\bar{D}$ or $\omega J/\psi$)	Belle
$Y(3940)$	3943 ± 17	87 ± 34	$?^{?+}$	$B \to KY(3940) \to \omega J/\psi$ (not $D\bar{D}^*$)	Belle, BaBar
$Y(4008)$	4008^{+82}_{-49}	226^{+97}_{-80}	1^{--}	$(e^+e^-)_{ISR} \to Y(4008) \to \pi^+\pi^- J/\psi$	Belle
$Y(4140)$	4143 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^?$	$B \to KY(4140) \to J/\psi\phi$	CDF
$X(4160)$	4156 ± 29	139^{+113}_{-65}	$0^{?+}$	$e^+e^- \to J/\psi X(4160) \to D^*\bar{D}^*$ (not $D\bar{D}$)	Belle
$Y(4260)$	4264 ± 12	83 ± 22	1^{--}	$(e^+e^-)_{ISR} \to Y(4260) \to \pi^+\pi^- J/\psi$	BaBar, CLEO, Be
$Y(4350)$	4324 ± 24	172 ± 33	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	BaBar
$Y(4350)$	4361 ± 13	74 ± 18	1^{--}	$(e^+e^-)_{ISR} \to Y(4350) \to \pi^+\pi^- \psi'$	Belle
$Y(4630)$	$4634^{+9.4}_{-10.6}$	92^{+41}_{-32}	1^{--}	$(e^+e^-)_{ISR} \to Y(4630) \to \Lambda_c^+\Lambda_c^-$	Belle
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$(e^+e^-)_{ISR} \to Y(4660) \to \pi^+\pi^- \psi'$	Belle
$Z_1(4050)$	4051^{+24}_{-23}	82^{+51}_{-29}	?	$B \to KZ_1^\pm(4050) \to \pi^\pm\chi_{c1}$	Belle
$Z_2(4250)$	4248^{+185}_{-45}	177^{+320}_{-72}	?	$B \to KZ_2^\pm(4250) \to \pi^\pm\chi_{c1}$	Belle
$Z(4430)$	4433 ± 5	45^{+35}_{-18}	?	$B \to KZ^\pm(4430) \to \pi^\pm\psi'$	Belle
$Y_b(10890)$	$10,890 \pm 3$	55 ± 9	1^{--}	$e^+e^- \to Y_b \to \pi^+\pi^-\Upsilon(1,2,3S)$	Belle

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

general features of 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
  - isospin breaking easily accomodated
  - 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 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) barionium

a closer look at $X(3872)$, as an example of the difficulties associated with the interpretations of exotics

After six years since its discovery it is not settled yet

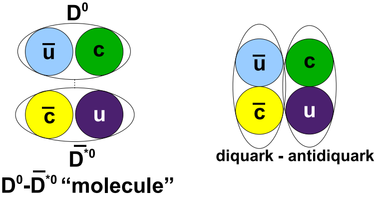
Information available for different production and decay channels

- production
  - production through B decays at e^+e^- and $p\bar{p}$ colliders
  - both channels $B^\pm \to XK^\pm$ and $B^0 \to XK^0$
  - also prompt production at Tevatron ($p\bar{p} \to X+$ all) (see later)
- decay
  - $J/\psi\pi^+\pi^-$ and $J/\psi\pi^+\pi^-\pi^0$
  - $D^0\bar{D}^0\pi^0$, $D^0\bar{D}^0\gamma$
  - $J/\psi\gamma$, $\psi(2S)\gamma$

a closer look at $X(3872)$ properties

- mass too low for a hybrid
- $J/\psi\rho$ and $J/\psi\omega \Rightarrow$ maximal isospin breaking
- $J/\psi\gamma$ and $\psi'\gamma \Rightarrow C = +1$
- $D\bar{D}\pi$ and $D\bar{D}\gamma$ point to a $D^0\bar{D}^{0*}$ composition
- CDF analysis of decay products favours $J^{PC} = 1^{++}$ or 2^{-+}
- Belle analysis would exclude 2^{-+}

- molecule or tetraquark?



Nielsen, Navarra, Lee, arXiv:0911.1958[arXiv:hep]

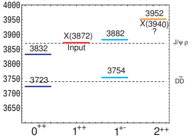
$$M(X3872) = 3871.81 \pm 0.36$$
$$M(D_0) + M(\bar{D_0}^*) = 3871.46 \pm 0.19$$

$X(3872)$ as a molecule

- binding energy: -0.35 ± 41 MeV $\Rightarrow$ radius ~ 8 fm!
- small width: the relative orbital angular momentum is at most $l \leq k/m_\pi \Rightarrow$ only S-wave resonant scattering is allowed. But attractive potentials do not generate long-lived resonances in S-wave. Bound metastable states can be formed by means of centrifugal angular barrier
- $\frac{\mathcal{B}(X \to J/\psi\omega)}{\mathcal{B}(X \to J/\psi\rho)} \simeq 1$ is easily accomodated
- the radiative decays are difficult to explain $\frac{\Gamma(X \to \psi(2S)\gamma)}{\Gamma(X \to \psi\gamma)}\Big|_{\rm th} \sim 4 \cdot 10^{-3}$ (E. Swanson, 2004) vs. $\frac{\Gamma(X \to \psi(2S)\gamma)}{\Gamma(X \to \psi\gamma)}\Big|_{\rm exp} = 3.4 \pm 1.4$ (BaBar 2009) unless ad hoc admixture of $c\bar{c}$ is added to the wave function
- $\frac{\mathcal{B}(B^0 \to X K^0)}{\mathcal{B}(B^+ \to X K^+)}$
  - 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)

$X(3872)$ 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

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

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

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

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

Upper theoretical bound

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

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

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

- $\mathbf{k}$ 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)

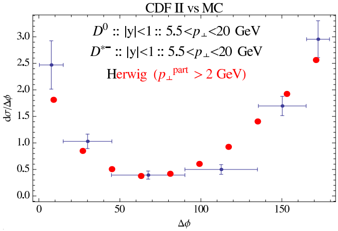
$|\langle D\bar{D}^*(\mathbf{k})|p\bar{p}\rangle|^2$

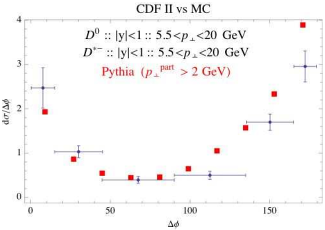
- we expect the bulk of the contribution from events with a gluon recoiling against an almost collinear $c\bar{c}$ pair
- the standard Parton Shwower MC Event Generators (like Herwig and Pythia) describe well the events with gluons radiated at small p_{T}, which are enhanced by collinear logarithms
- 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 → 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

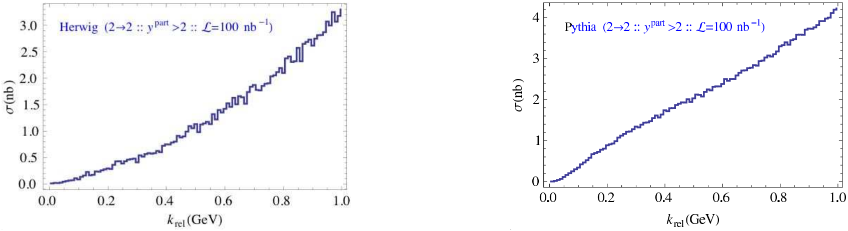
$$\frac{\hbar^2}{\mu r_0^2} - \frac{g^2}{4\pi} \frac{e^{-\frac{m_\pi c}{\hbar} r_0}}{r_0} = \mathcal{E}_0 \sim M_X - M_D - M_{D^*}$$

Solving for r_0 we find $r_0 = 8.6 \pm 1.1$ 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

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



- To integrate 3.1 ± 0.7 nb we need $k_{\rm rel}$ up to 205 ± 20 MeV for Herwig and 130 ± 15 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 one order of magnitude!

Few days ago our findings have been subject of criticism by Artoisenet and Braaten...

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
- next generation colliders such as LHC(b), PANDA and SuperB will be necessary to have a clear picture on the new particles and their nature
- to this aim it is extremely important a gain in luminosity of a factor of 10 (hopefully 100) and the possibility of studying different channels (both for production and decay) at different machines, with the highest possible mass resolution
- having clarified the models for the charm sector, we could use the B sector future data as an additional testing ground of theoretical predictions