“Sapienza” Università di Roma – INFN sez. Roma 1

On the spin of the X(3872)

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Cortona, 1 giugno 2012

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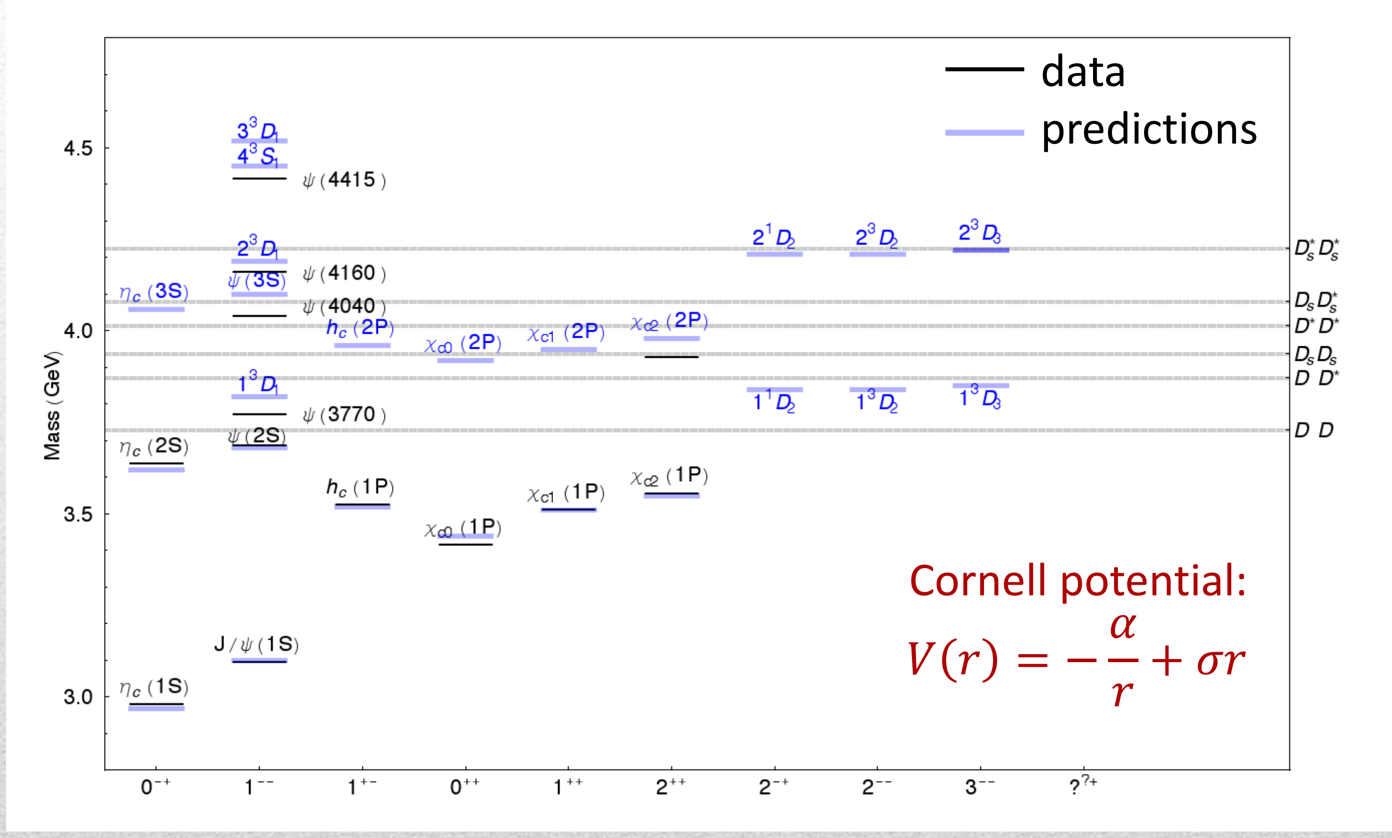
arXiv:1204.1223 [hep-ph]

Outline

- Exotic states: the X(3872)
- Main models
- The spin of the X(3872)

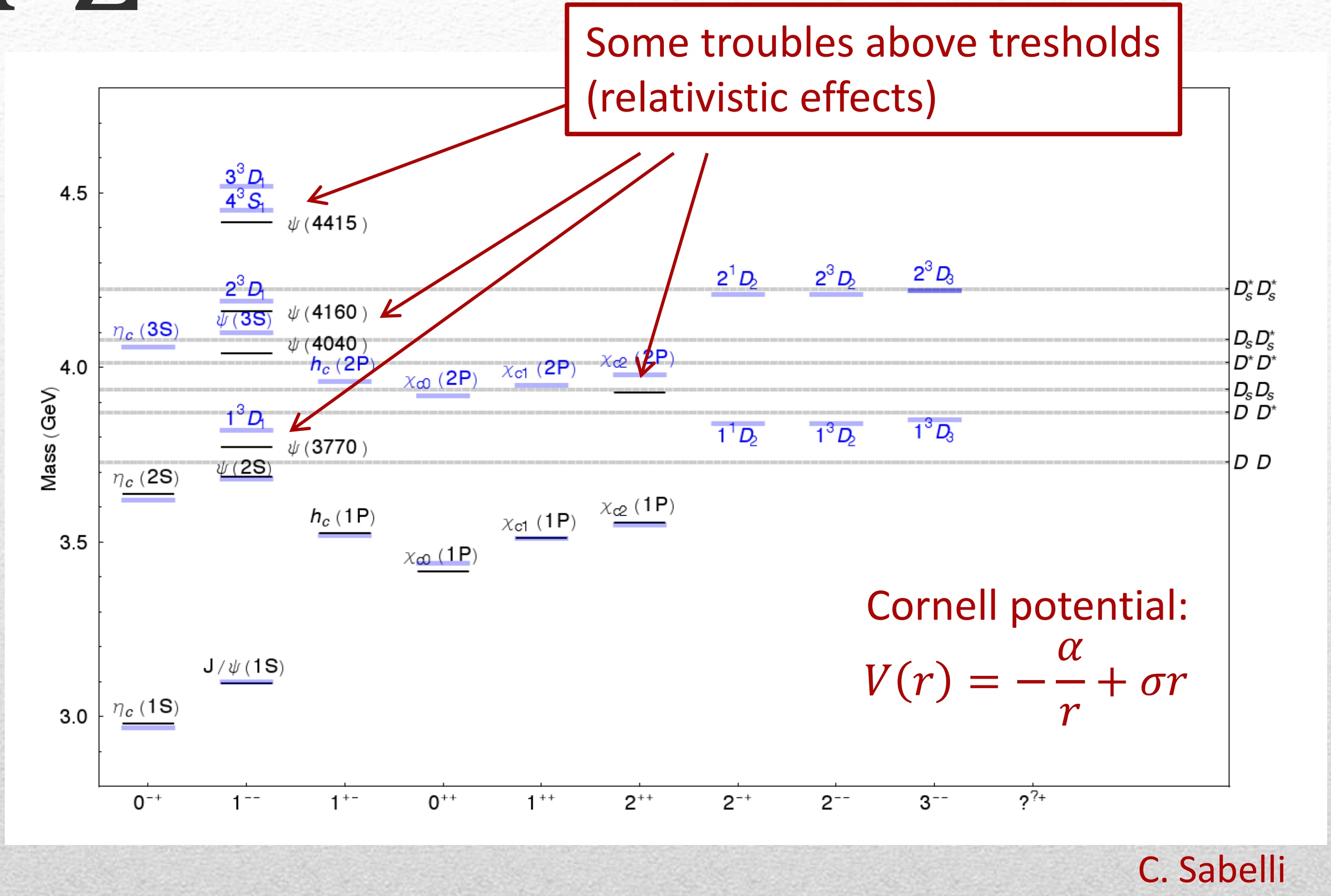
X Y Z



C. Sabelli

Before B factories, hidden charm mesons were as a $c\bar{c}$ system in a non-relativistic potential

X Y Z



Before B factories, hidden charm mesons were as a $c\bar{c}$ system in a non-relativistic potential

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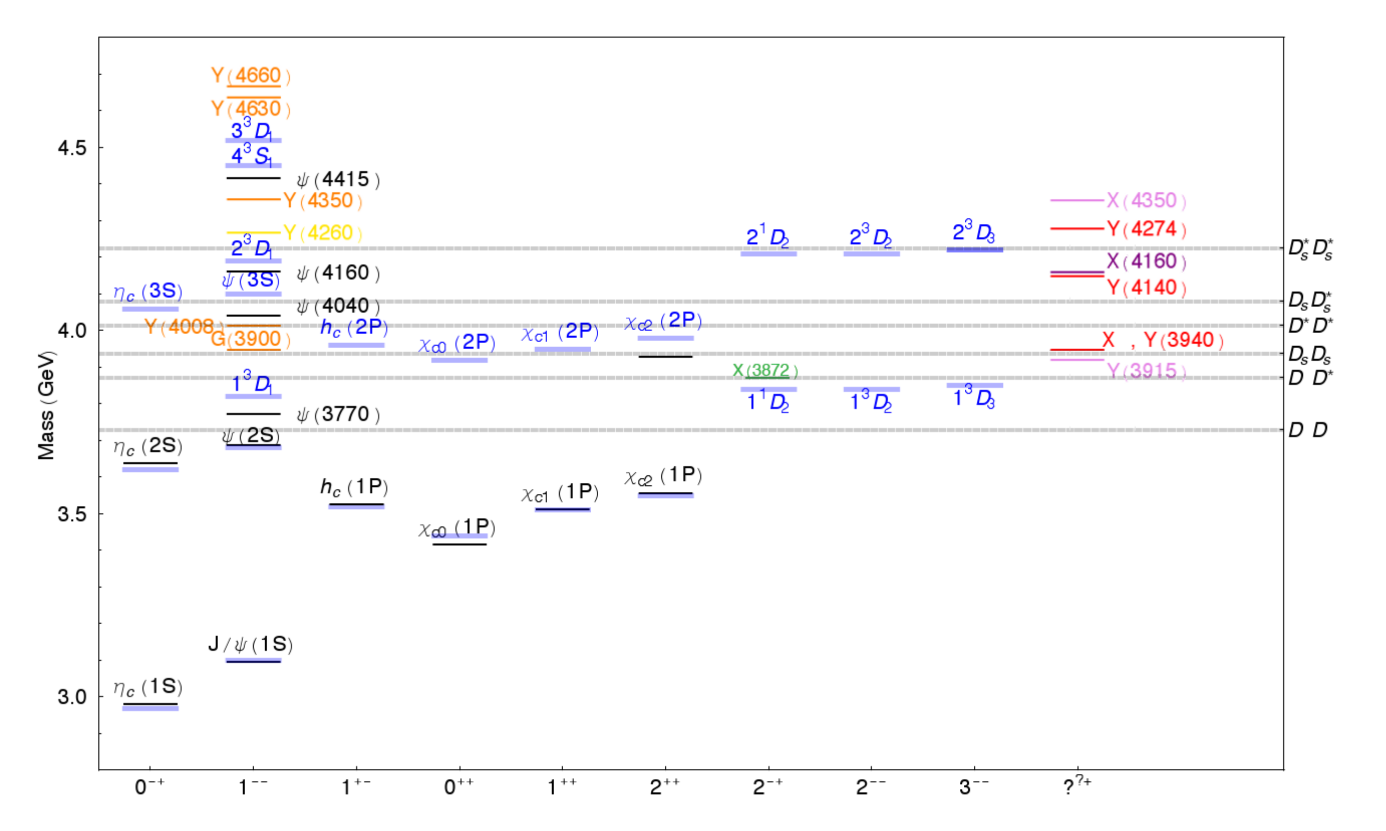
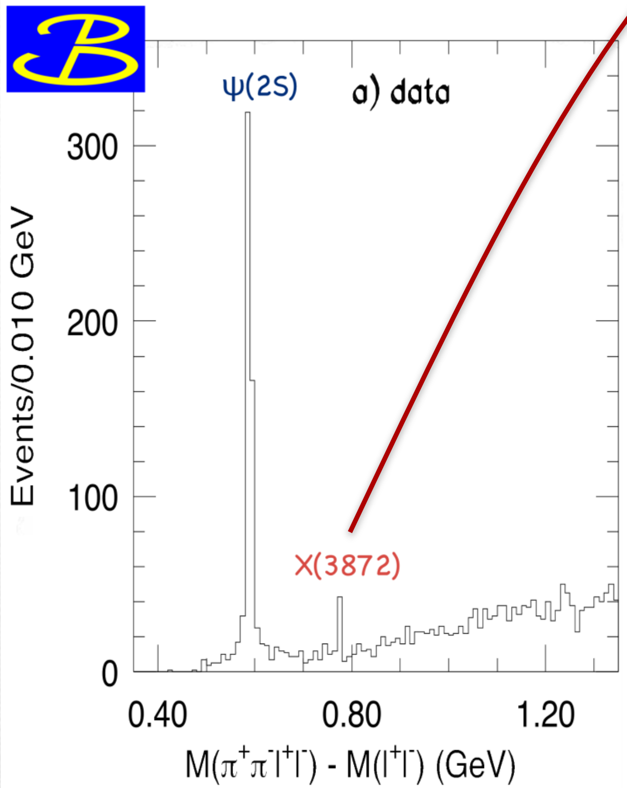


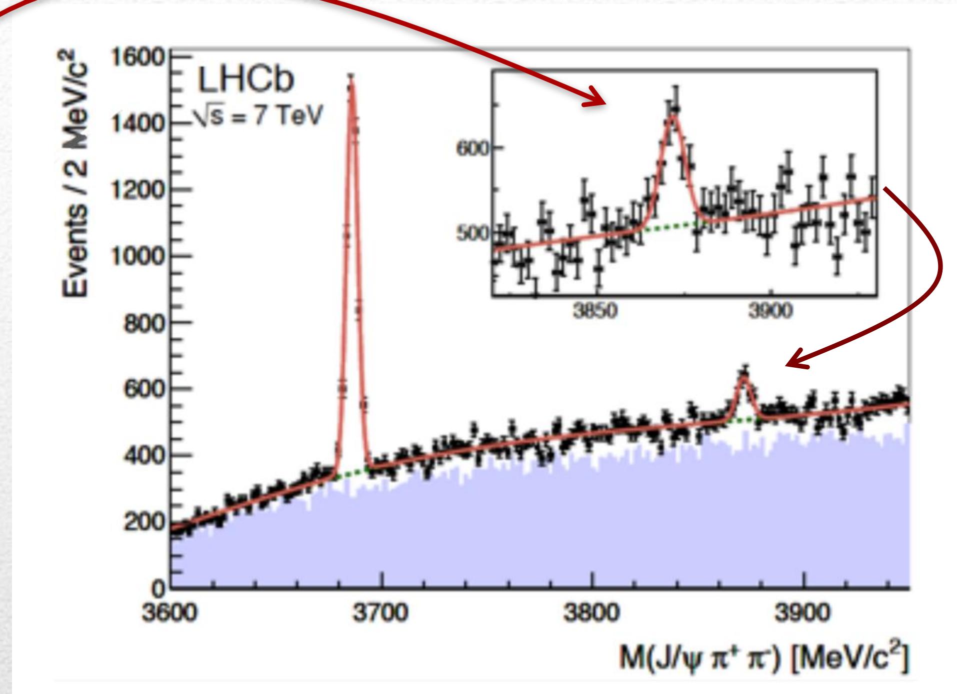
C. Sabelli

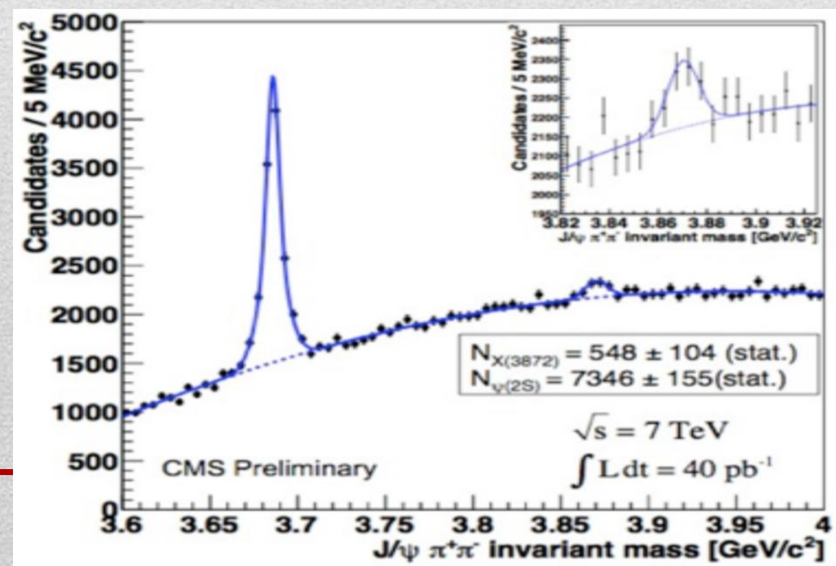
A lot of "weird" states appeared

They do not fit in the classic $c\bar{c}$ system

X(3872)







$\Gamma < 1.2$ MeV

X(3872)

- First exotic state discovered at Belle (2003)
- Too narrow ($\Gamma < 1.2$ MeV) for an above-treshold charmonium
- Radiative decay in $J/\psi\ \gamma$ too small for charmonium
- Isospin violation: $\frac{\Gamma(X\to J/\psi\ \omega)}{\Gamma(X\to J/\psi\ \rho)} \sim 0.8 \pm 0.3$ too big
- The mass cannot be predicted as a charmonium excitation (almost equal to $D^0 + D^{0*}$)

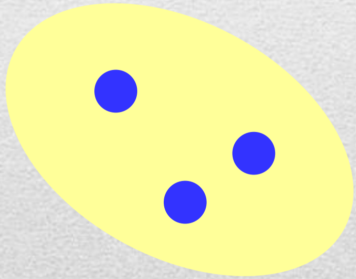
What is that?

(a digression on QCD)

Quarks are the building blocks of matter
Quarks are colored particles: q $\in \mathbf{3_c}$, $\bar{q} \in \bar{\mathbf{3}}_c$

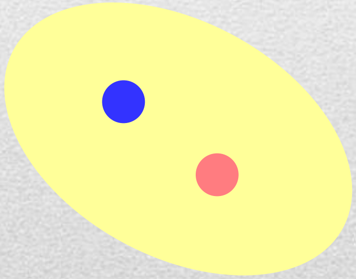
They must arrange in color neutral states

Baryons



$\mathbf{3_c} \times \mathbf{3_c} \times \mathbf{3_c} \in \mathbf{1_c}$

Mesons

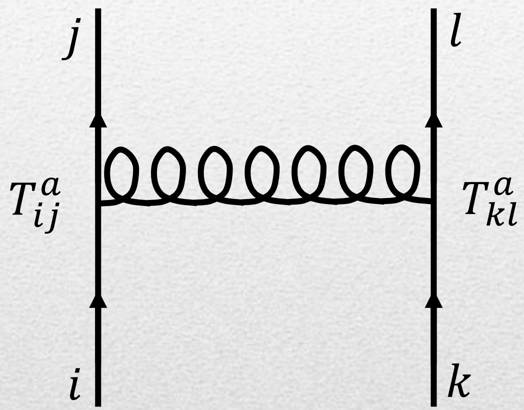


$\mathbf{3_c} \times \bar{\mathbf{3}}_c \in \mathbf{1_c}$

All hadronic matter fits in these two models (up to 2003)

(a digression on QCD)

Attraction and repulsion between electric charges is a matter product of signs.
In QCD it is more complicated than that (matrix tensor products)

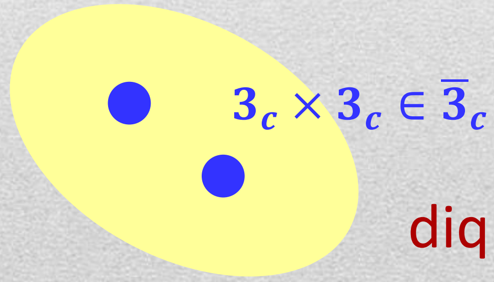


$$T^a_{R_1} \times T^a_{R_2}$$

product of representations

The singlet $\mathbf{1}_c$ is an attractive combination

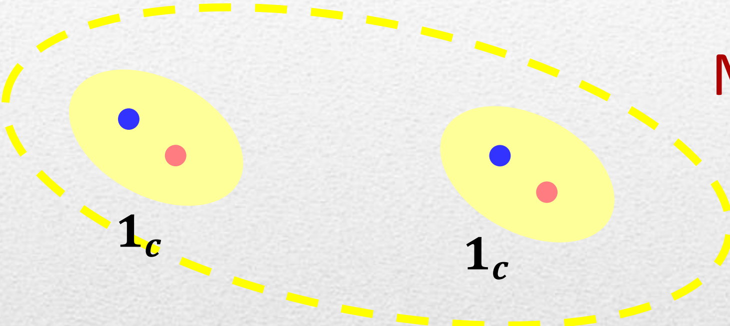
A diquark in $\bar{\mathbf{3}}_c$ is an attractive combination
A diquark is colored, so it can stay into hadrons
but cannot be an asymptotic state
We see diquarks in lattice QCD



diquark

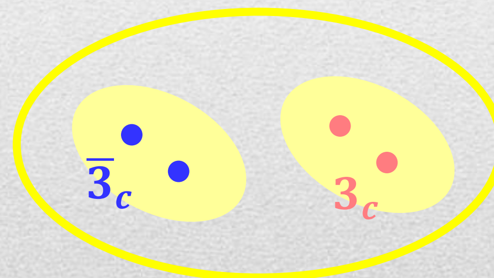
(a digression on QCD)

Can we have other neutral color states?

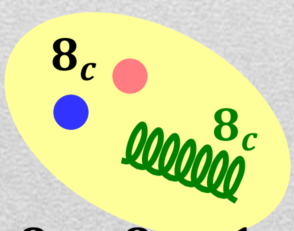


Molecule of hadrons (loosely bound)

Diquark-antidiquark (tetraquark)



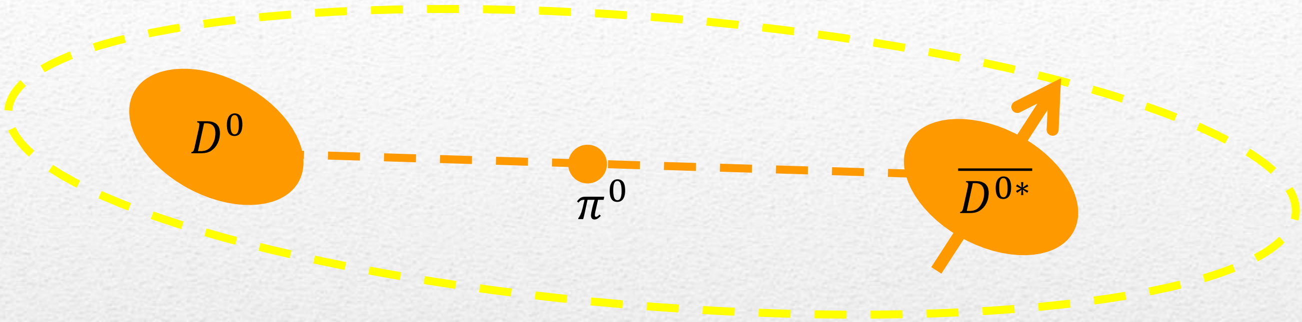
$$\mathbf{3}_c \times \overline{\mathbf{3}}_c \in \mathbf{1}_c$$



Hybrids (with valence gluons)

$$\mathbf{8}_c \times \mathbf{8}_c \in \mathbf{1}_c$$

X(3872): molecule?



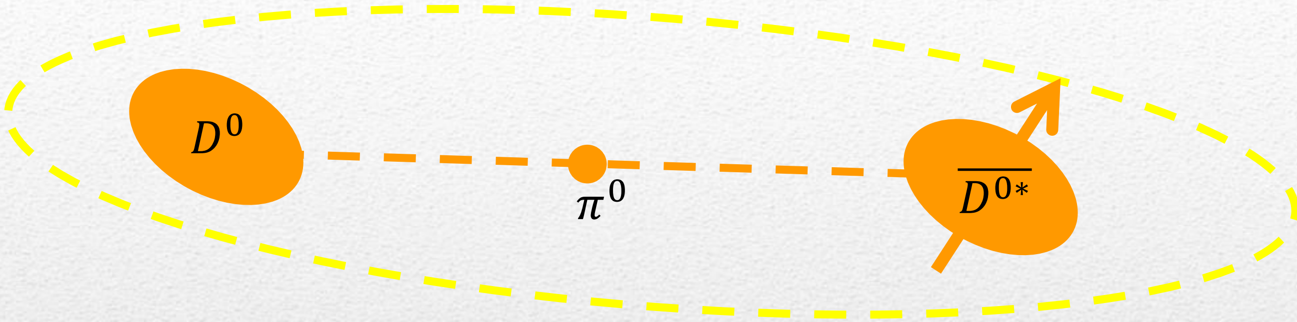
- Molecular state of $\frac{|D^0\overline{D^{0*}}\rangle+|\overline{D^0}D^{0*}\rangle}{2}$
- Small binding energy: $M_X - M_{D^0} - M_{D^{0*}} \sim (-0.25 \pm 0.40)$ MeV
- Isospin violation because of the threshold D^+D^{*-}
- Two scales:
  - $R\sim 1$ fm radius of the mesons
  - $R\sim 10$ fm radius of the molecule

Analogies with deuteron (but spins!)

1-pion exchange: $V(r) \propto \frac{e^{-m_\pi r}}{r}$

Tornqvist, Z.Phys. C61, 525 (1994)

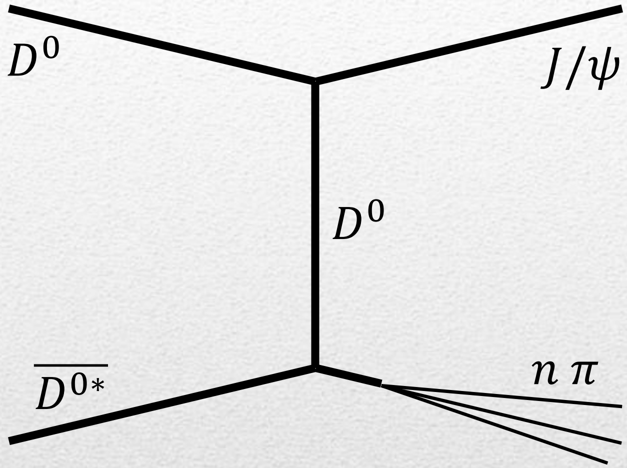
X(3872): molecule?



- Two classes for decay:
  - Long range: $X \to D^0\overline{D^{0*}}$ mesons simply split up
  - Short range: $X \to J/\psi\ \ n\pi$ proportional to $|\psi(0)|^2$

We need a S-wave bound state to have $|\psi(0)|^2 \neq 0$
Also, too little binding energy for a P-wave state

X(3872): molecule?



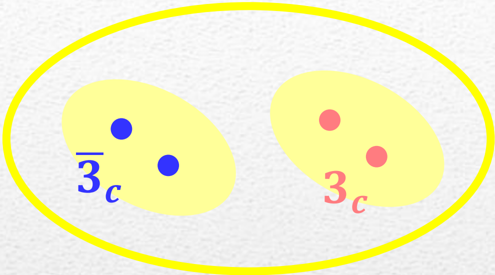
$$R \sim \frac{1}{m_c} \sim 0.2 \text{ fm}$$

Very small radius!

- Short range: $X \rightarrow J/\psi\ \ n\pi$ proportional to $|\psi(0)|^2$

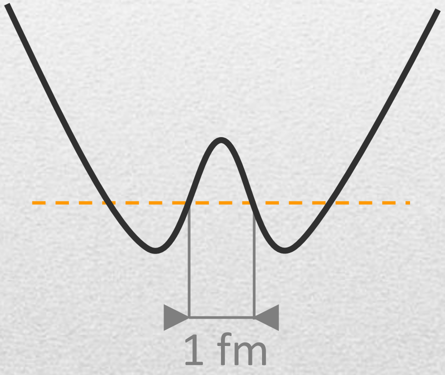
We need a S-wave bound state to have $|\psi(0)|^2 \neq 0$
Also, too little binding energy for a P-wave state

X(3872): tetraquark?



$[Cq][\bar{C}\bar{q}]$

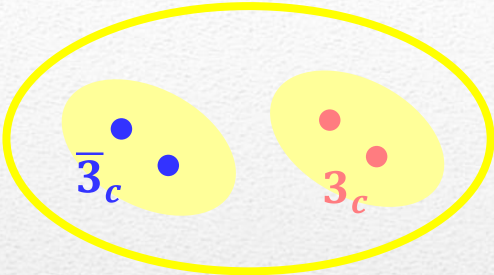
- Large binding energy: non-perturbative effects
- Double well models to describe $X \to J/\psi\ n\pi$
- One scale:
  - $R \sim 1$ fm radius of the meson



Tetraquarks prefer to decay in baryon-antibaryon, but
$M_X < M(\Lambda_c \overline{\Lambda_c}) \to$ narrowness

Maiani, Piccinini, Polosa, Riquer, PRD71, 014028 (2005)

X(3872): tetraquark?



$[Cq][\bar{C}\bar{q}]$

We can have both $[Cu][\bar{C}\bar{u}]$ and $[Cd][\bar{C}\bar{d}]$

Mass eigenstates could be a mixing: big isospin violation

Maiani, Piccinini, Polosa, Riquer, PRD71, 014028 (2005)

String model for P-wave state: Wilczek arXiv:hep-ph/0409168

Where are charged partners?

X(3872): résumé

Molecule

- ✓ $M_X = M_{D^0} + M_{D^{0*}}$
- ✓ Isospin violation
- ✓ Large decay into DD^*
- ✗ Too small prompt production cross section in $p\bar{p} \to X + \text{all}$
- ✗ Not possible in P-wave

Tetraquark

- ✓ Isospin violation
- ✓ Narrowness (below $M(\Lambda_c\Lambda_c)$)
- ✓ Models in P-wave
- ✗ Charged partners?

The measure of the spin is no matter of taxonomy, it is important to test exotic models

$J_X = 1$ → S-wave state → **Molecule** and **Tetraquark**

$J_X = 2$ → P-wave state → ~~**Molecule**~~ and **Tetraquark**

The spin of the X(3872)

We explore two channels:

$B \rightarrow K\, X$, $X \rightarrow J/\psi\ \rho$, $J/\psi \rightarrow l^+ l^-$, $\rho \rightarrow \pi^+ \pi^-$

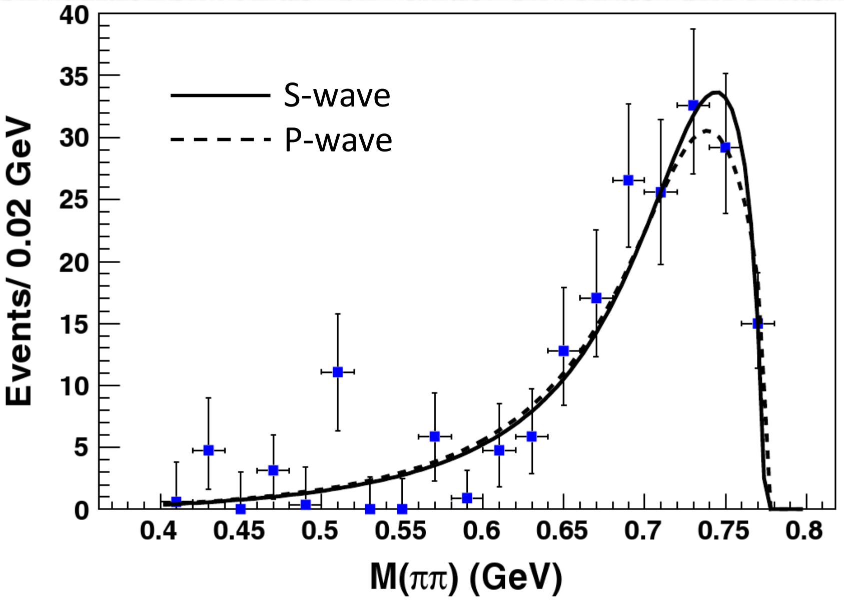
$B \rightarrow K\, X$, $X \rightarrow J/\psi\ \omega$, $J/\psi \rightarrow l^+ l^-$, $\omega \rightarrow \pi^+ \pi^- \pi^0$

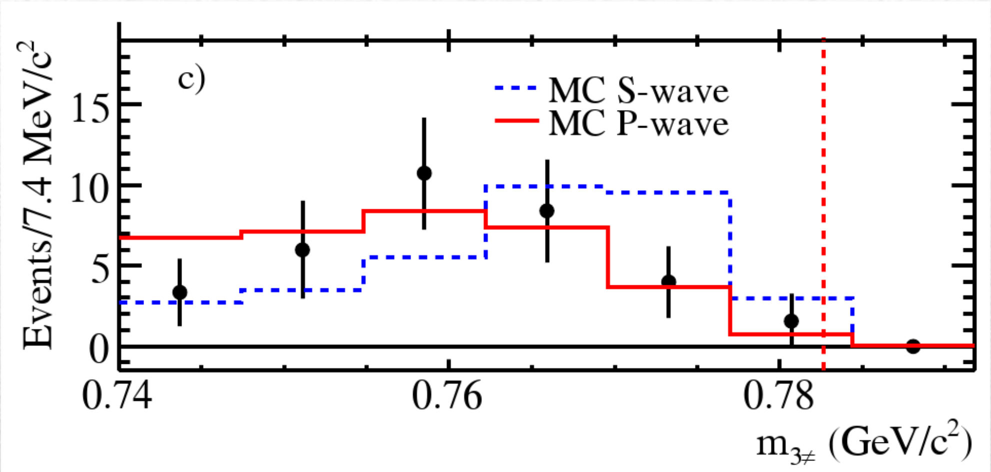
- Invariant mass of 2π, 3π system
- Angular correlations

$V = \rho, \omega$

$X \rightarrow J/\psi\ V$
- is a **S-wave** decay if $J_X = 1$
- is a **P-wave** decay if $J_X = 2$

The spin of the X(3872)

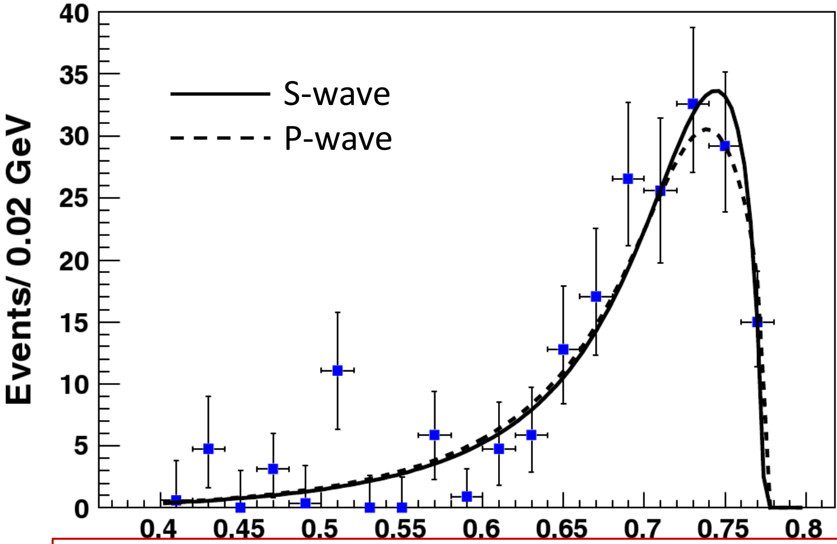


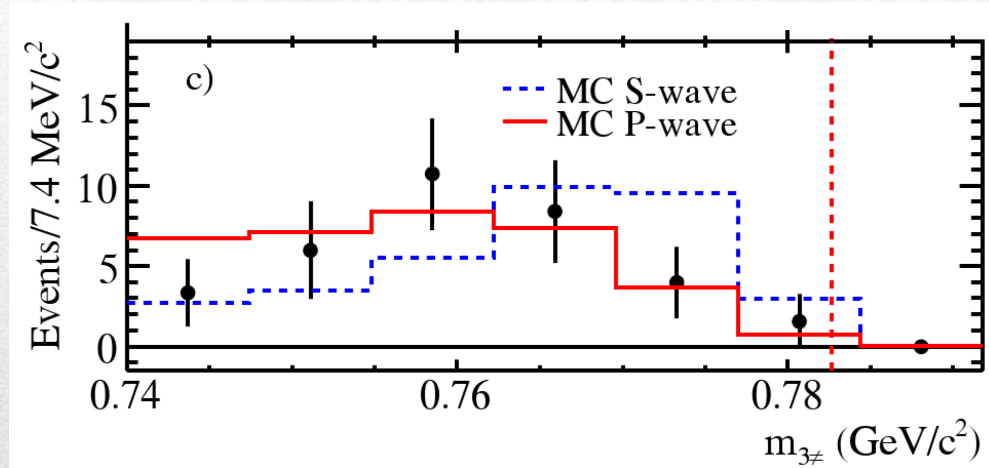


Belle, PRD84, 052004 (2011)
$X \rightarrow J/\psi\ \pi^+\pi^-$

Babar, PRD82, 011101 (2010)
$X \rightarrow J/\psi\ \pi^+\pi^-\pi^0$

The spin of the X(3872)





History

- Belle (2005) estimated $J^{PC} = 1^{++}$
- CDF (2007) ruled out all but $J^{PC}=1^{++}$ and 2^{-+}
- Babar (2010) prefered $J^{PC} = 2^{-+}$ in 3 π channel
- Belle (2011) both $J^{PC}=1^{++}$ and 2^{-+}

Exact approach

The imposing of Lorentz, parity and gauge invariance allows us to write the **exact tensorial structure**

If $J_X = 1$ $\quad \langle \psi(\varepsilon, p)\, V(\eta, q) \mid X(\lambda, P)\rangle = g_{1V}\, \varepsilon^{\mu\nu\rho\sigma}\, \lambda_\mu(P)\, \varepsilon^*_\nu(p)\, \eta^*_\rho(q)\, P_\sigma$

If $J_X = 2$

$$\langle \psi(\varepsilon, p)\, V(\eta, q) \mid X(\pi, P)\rangle$$
$$= g_{2V}\, \varepsilon^{\mu\nu\rho\sigma}\, \pi_{\alpha\mu}(P)\big(\varepsilon^{*\alpha}(p)\, \eta^*_\sigma(q)\, p_\nu q_\rho - \eta^{*\alpha}(q)\, \varepsilon^*_\sigma(p)\, q_\nu p_\rho\big)$$
$$+ g'_{2V}(p-q)^\alpha \pi_{\alpha\mu}(P)\, \varepsilon^{\mu\nu\rho\sigma}\, \epsilon^*_\rho(p)\, \eta^*_\sigma(q)$$

Faccini, Piccinini, AP, Polosa, arXiv:1204.1223 [hep-ph]

Exact approach

Our ignorance is in the effective couplings

We parametrize them with **polar form factors**

$$g \to g\left(k^*\right) = g\,\frac{1}{1 + R^2 k^{*2}}$$

$k^* =$ decay 3-momentum in X rest frame

Actually this R can be extracted from data as a free fit parameter.

We can learn some indications on the model by the size of R

Exact approach

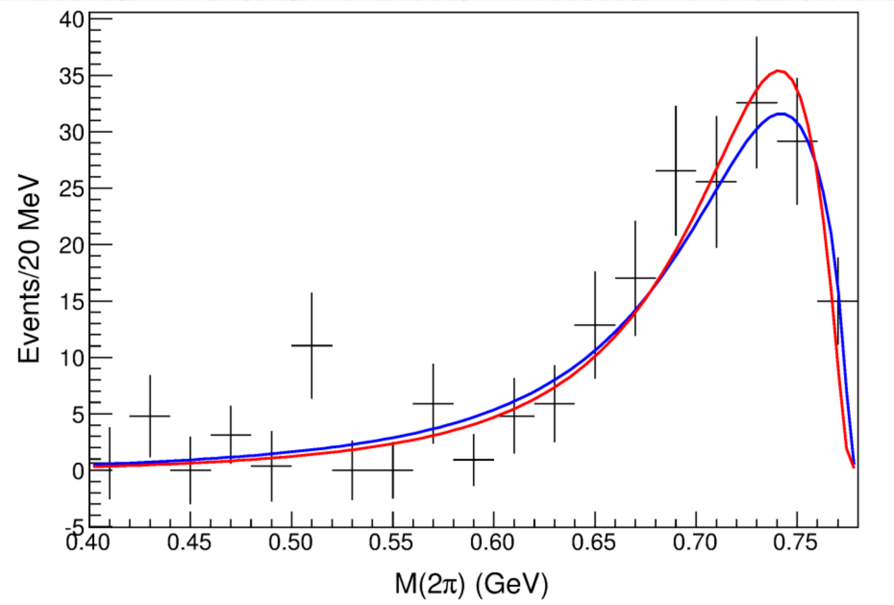
We do not need any assumption
We only simplify matrix elements with
Narrow Width Approximation

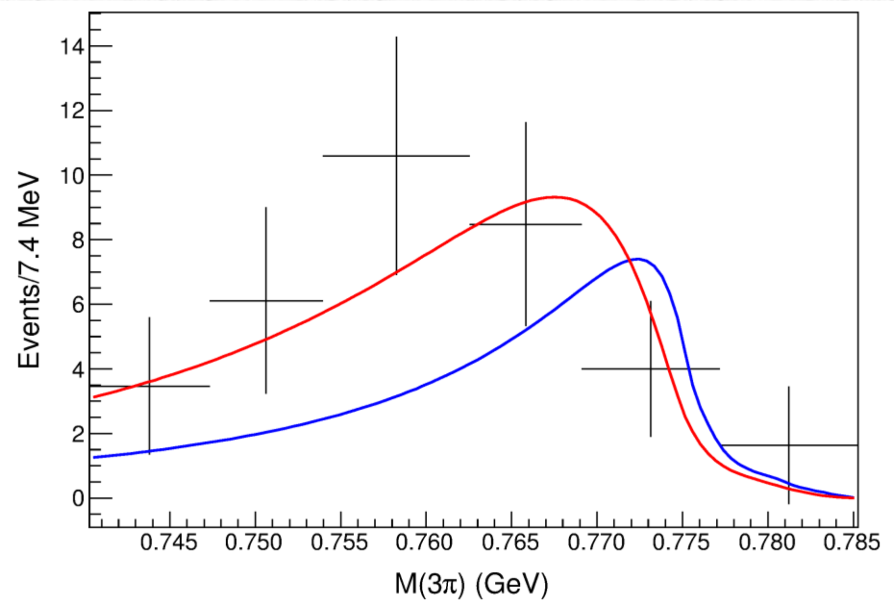
$$\sum_{\text{spin}} |\langle \psi \, n\pi \mid X \rangle|^2 \sim \sum_{\text{spin}} |\langle \, n\pi \mid V \rangle|^2 \frac{1}{|M_{n\pi}^2 - M_V^2 + iM_V\Gamma_V|^2} \frac{1}{3} \sum_{\text{spin}} |\langle \psi \, V \mid X \rangle|^2$$

In practice we neglect the angular correlations between the X and the pions

Good for invariant mass spectra
impossible for angular analysis

Combined fit





Faccini, Piccinini, AP, Polosa arXiv:1204.1223 [hep-ph]

1^{++}:

χ^2 / DOF = 25.2 / 22

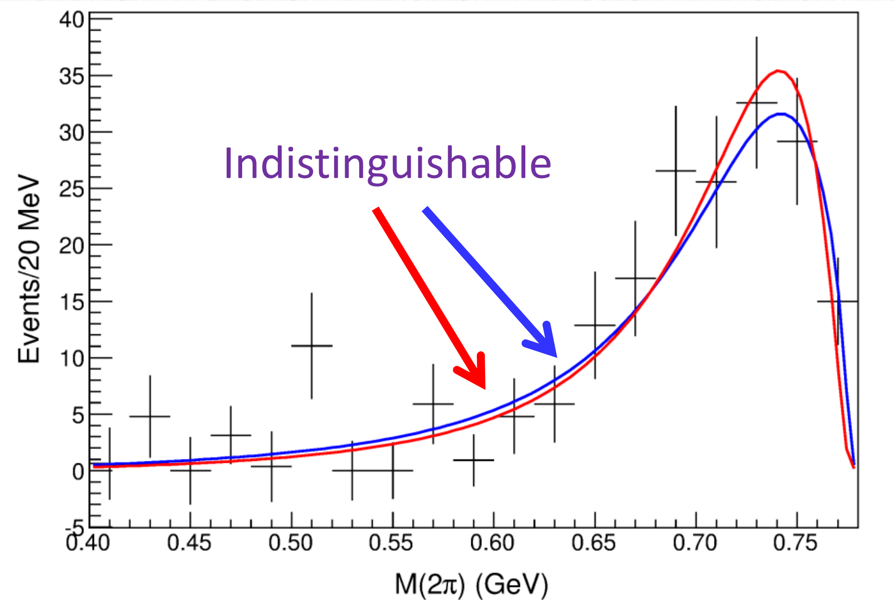
R = 1.6 GeV^{-1}

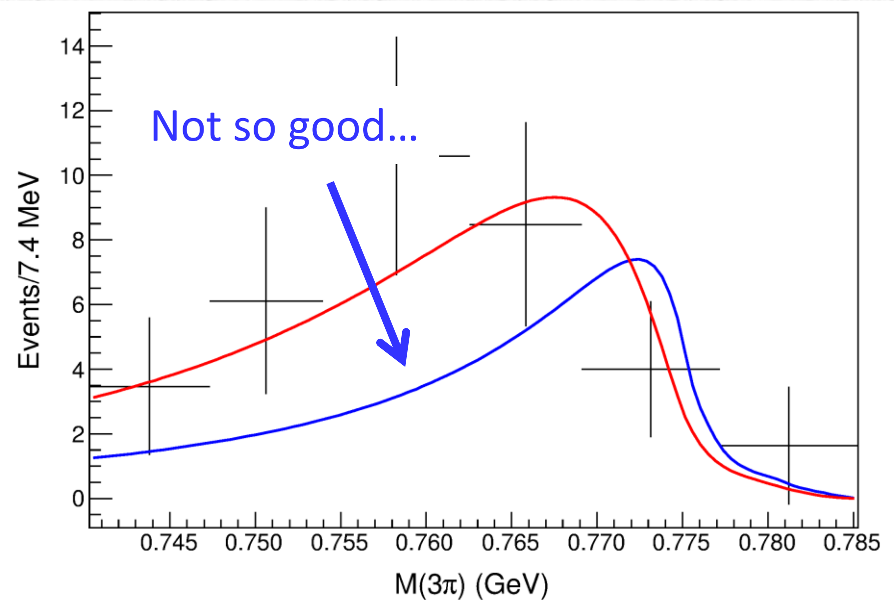
2^{-+}:

χ^2 / DOF = 17.7 / 20

R = 5.6 GeV^{-1}

Combined fit

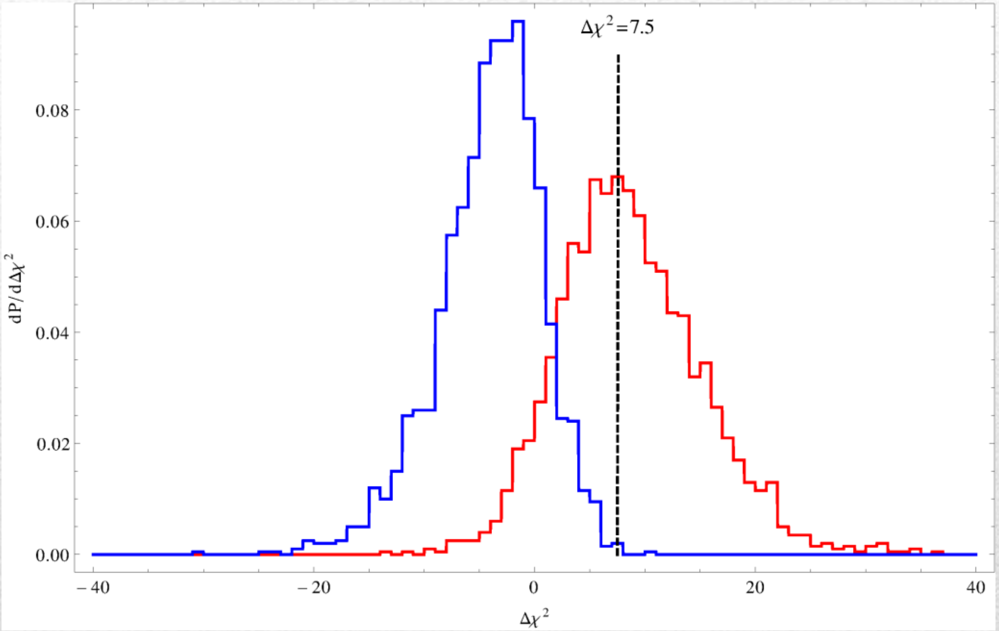




Faccini, Piccinini, AP, Polosa arXiv:1204.1223 [hep-ph]

Both χ^2 are very good because of the rich useless statistics of the 2π channel
Can we do it better?

Combined fit



A Toy MC allows us to separate the two spin hypotheses

$P(1^{++}) \sim 0.2\%$

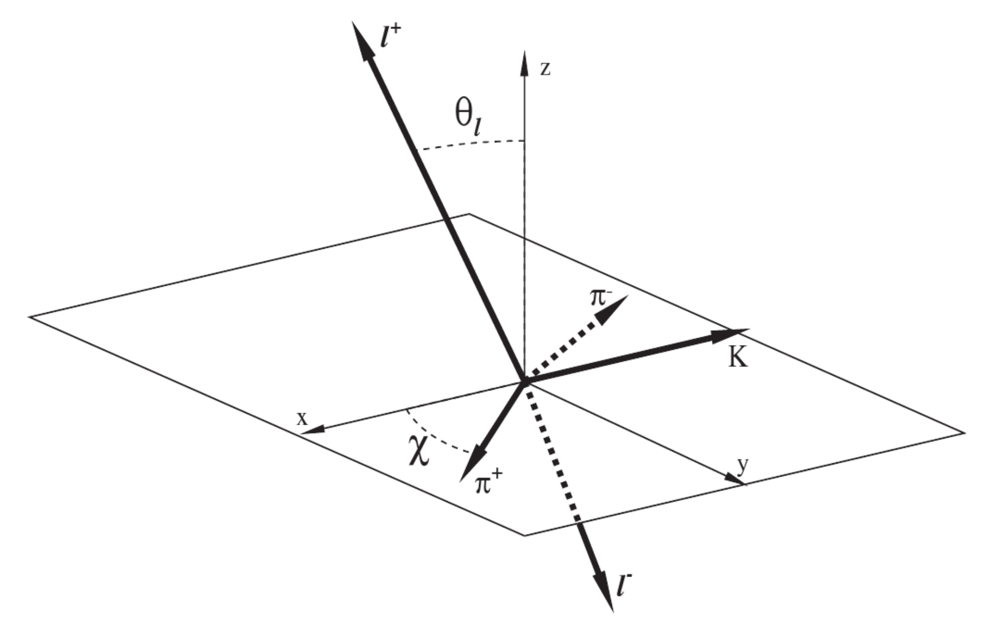
$P(2^{-+}) \sim 46\%$

Strong support for 2^{-+}

Moreover, the molecular hypothesis is challenged by $R = 1.3 \text{ fm} \gg 0.2 \text{ fm}$

Angular correlations

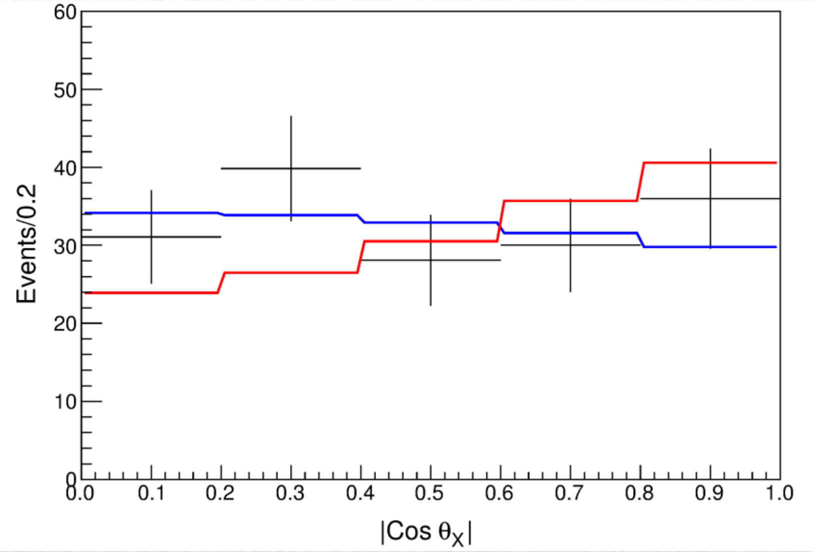
We can get over the narrow width approximation
and explore angular correlations
Same architecture, but MC approach (too big matrix elements & phase space)

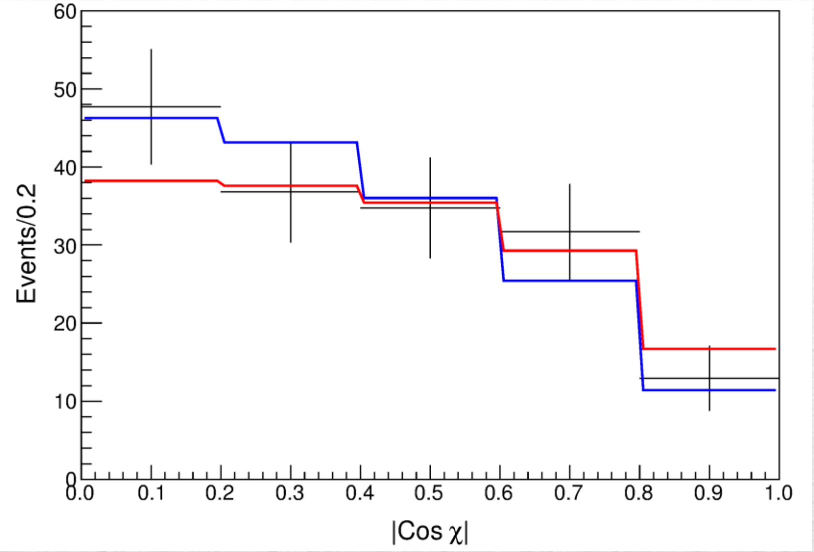


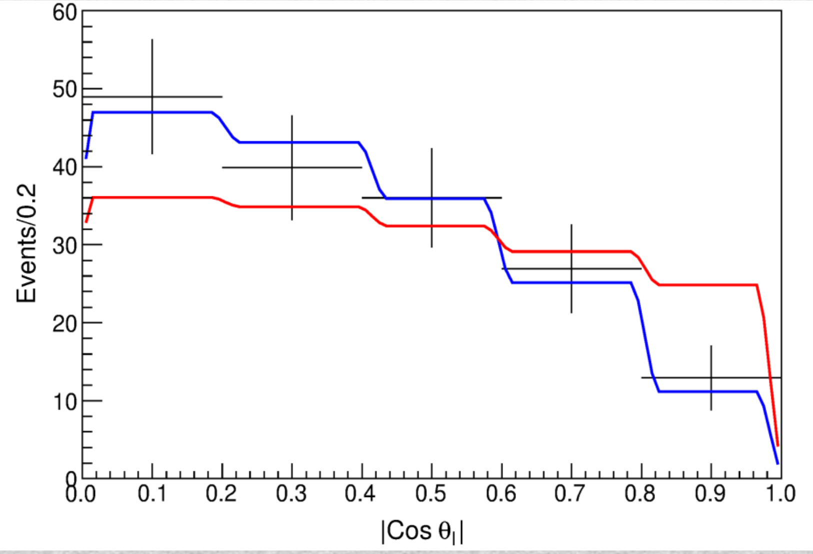
Some data published by Belle (2011) in the 2π channel

Low statistic, but some indications

Angular correlations







1^{++}: χ^2 / DOF = 6.6 / 14 CL 95%

2^{-+}: χ^2 / DOF = 20.6 / 12 CL 5.57%

This is at odds with the former result

What happens?

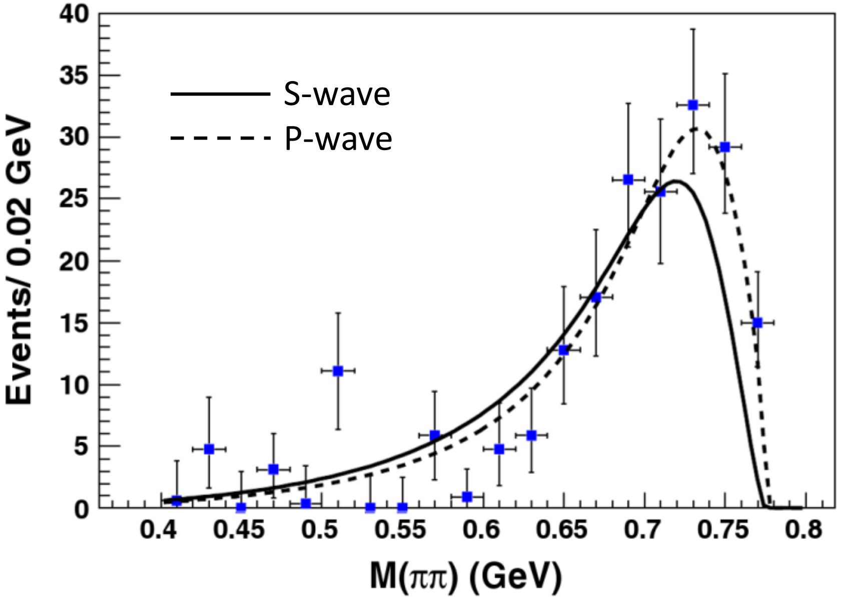
Conclusions?

- The X(3872) puzzle still has no solution!
- Invariant mass in 3π channel suggests 2^{-+}
- Angular correlations in 2π channel suggest 1^{++}
- Different particles? (with same mass???)
- Our MC tools will repeat the analysis when new data by Belle and LHCb will be available

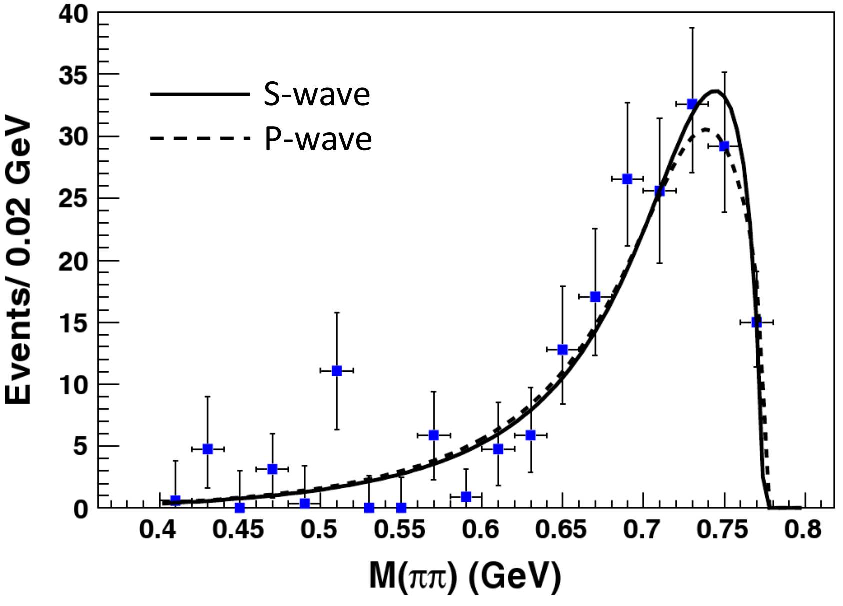
Thank you

BACKUP

The spin of the X(3872)



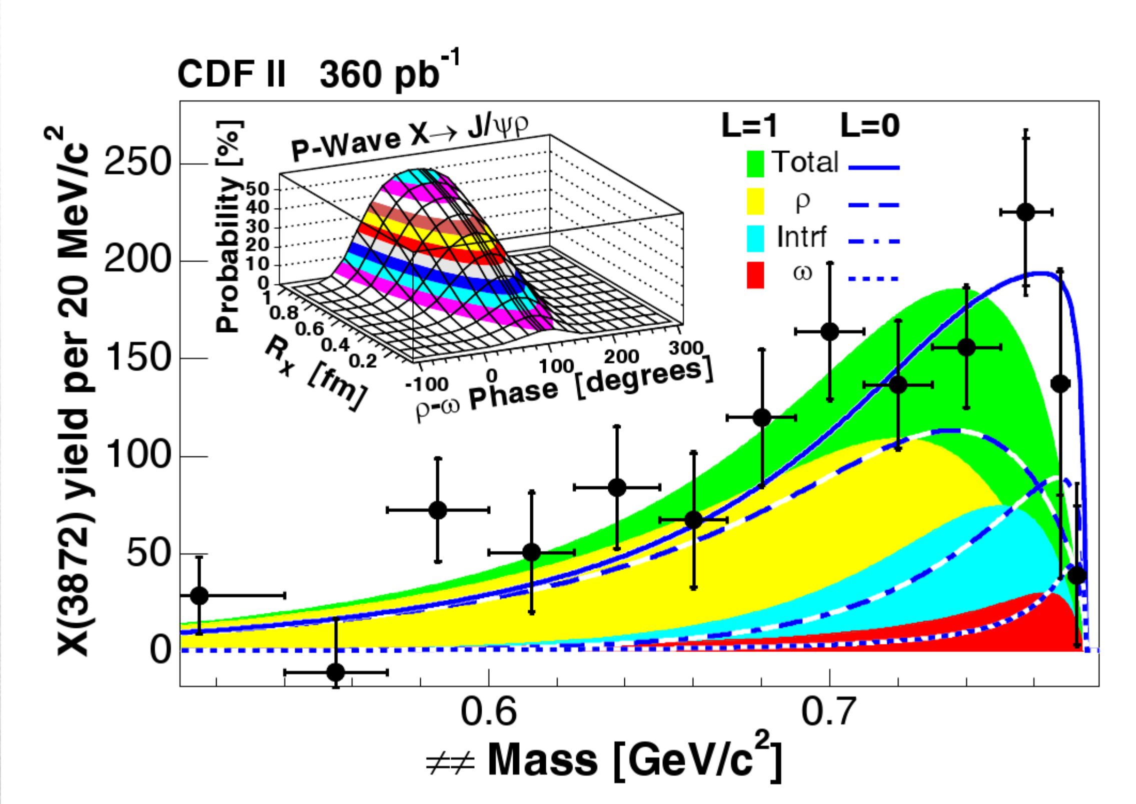
without ρ-ω mixing



with ρ-ω mixing

In particular for the P-wave, we need a big interference term
This can be constrained and ruled out by the 3π channel

The spin of the X(3872)



CDF PRL96 (2006) 102002

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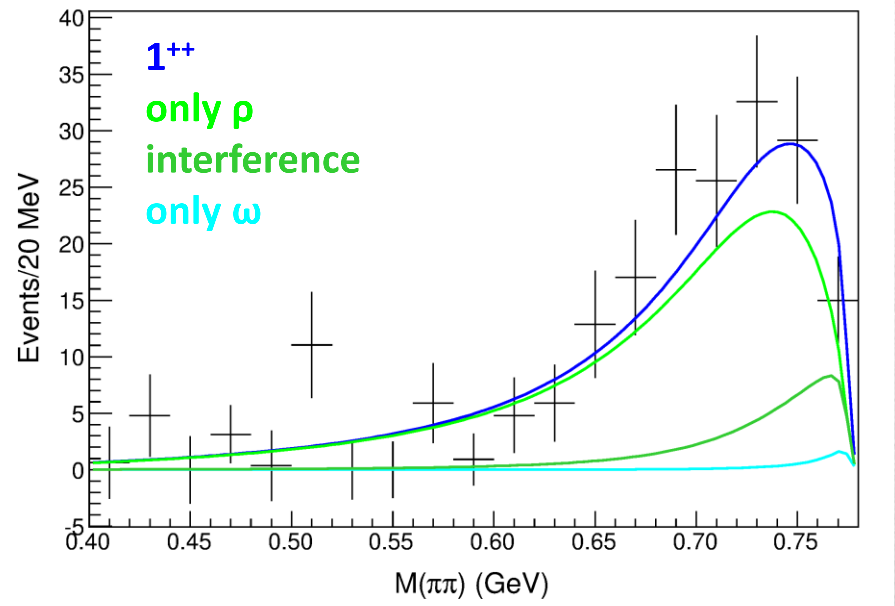
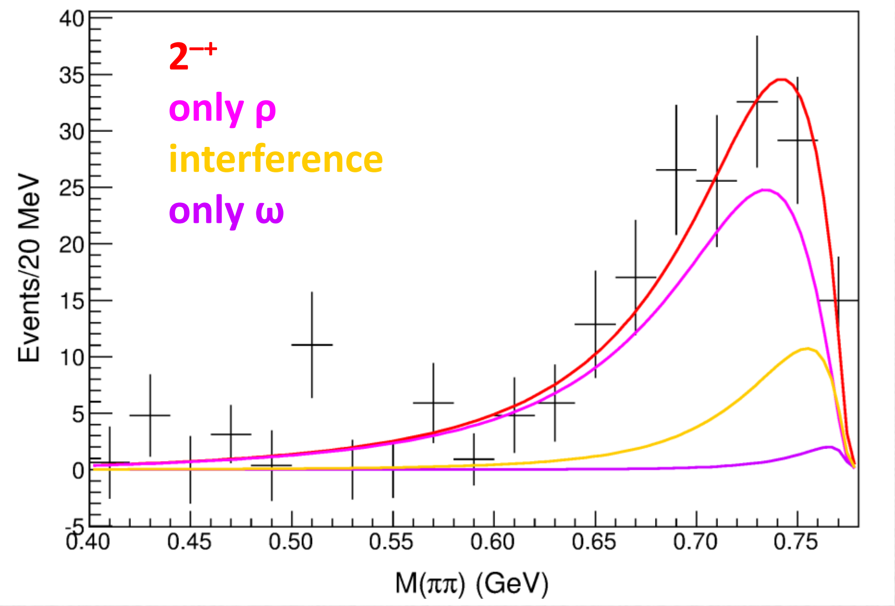
The spin of the X(3872)





With a polar form factor, the fits are good even without the mixing; we can add it and constrain with the 3π channel

Blatt-Weisskopf

Experimentalists use BW barrier factors to fit invariant mass spectra

$$\frac{dN}{dm_{n\pi}} \propto \left(k^*\right)^{2l+1} f_{lX}^2\left(k^*\right) \left|\frac{\sqrt{m_{n\pi}\Gamma_V}}{m_V^2 - m_{n\pi}^2 - i m_V \Gamma_V}\right|^2$$

$$\text{with}\,\Gamma_V = \Gamma_{0V}\left(\frac{q^*(m_{n\pi})}{q^*(m_V)}\right)^3\left(\frac{m_V}{m_{n\pi}}\right)\left(\frac{f_{lV}\left(q^*(m_{n\pi})\right)}{f_{lV}\left(q^*(m_V)\right)}\right)^2$$

BW barrier factors depend on orbital angular momentum of decay products

$f_0\left(k^*\right)=1$ for a S-wave

$f_1\left(k^*\right)=\frac{1}{\sqrt{1+R^2k^{*2}}}$ for a P-wave

BW do not depend directly on spin!

Blatt-Weisskopf

BW factors are calculated in nuclear theory

1D model of spin-0 particles (potential well + centrifugal barrier)

Problems:

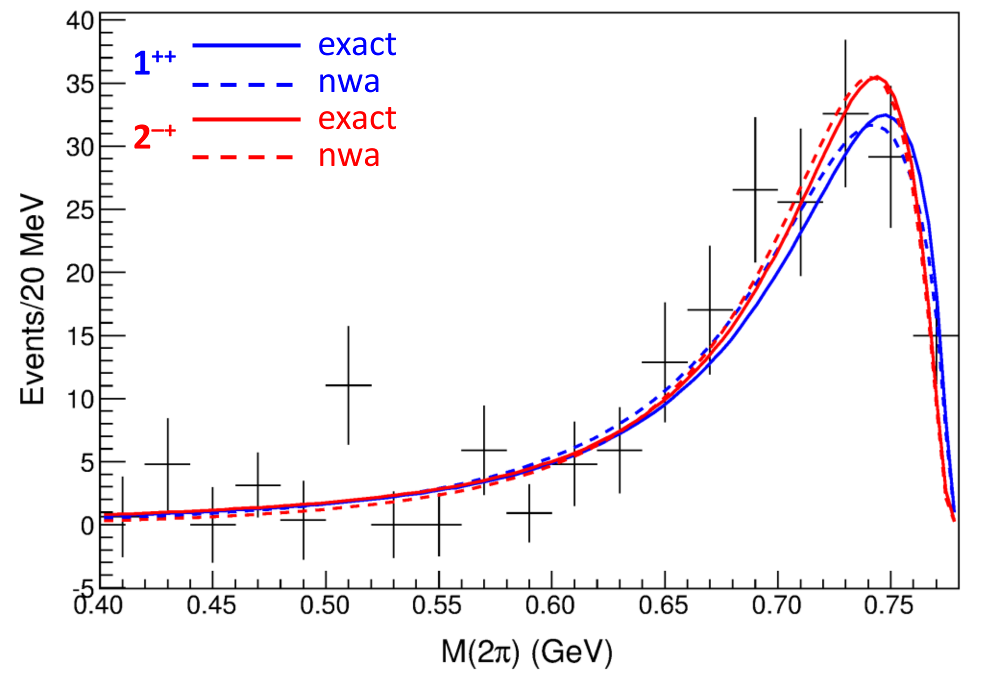
- Rough model (no spin, only orbital angular momentum)
- Analicity (the square root)
- R cannot be extracted from data, must be fixed:
  - Belle (2010): $R = 5\ \mathrm{GeV}^{-1}$: good 2^{-+}
  - Hanhart *et al.* (2011): $R = 1\ \mathrm{GeV}^{-1}$: bad 2^{-+}

Narrow width

Is narrow width approximation really good?

$\Gamma_\omega \sim 8$ MeV, very narrow

$\Gamma_\rho \sim 146$ MeV, not so narrow…



We verify *a posteriori* with a MC taking R from the approximated fit

Good, in particular for 2^{-+}