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

$Z_c(3900)$ as a tetraquark

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arXiv:1303.6857

Outline

- Charged $Z_c(3900)$
- Tetraquark hypothesis
- Decay channels
- Other models
- Conclusions

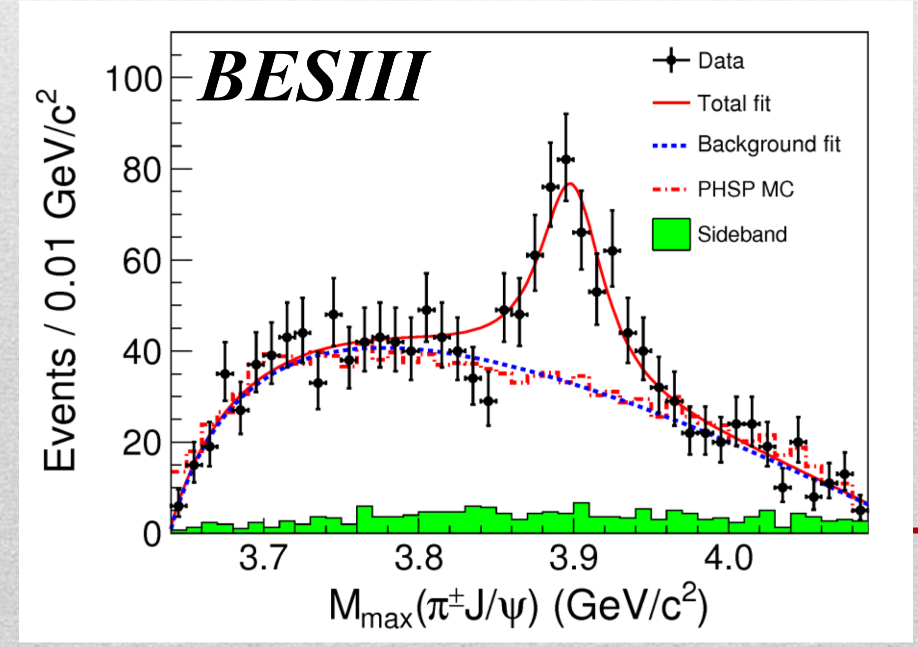
Charged $Z_c(3900)$

Found in $Y(4260) \to Z_c^{\pm}(3900)\,\pi^{\mp} \to J/\psi\,\pi^{\pm}\,\pi^{\mp}$

Exotic charged charmonium-like state!

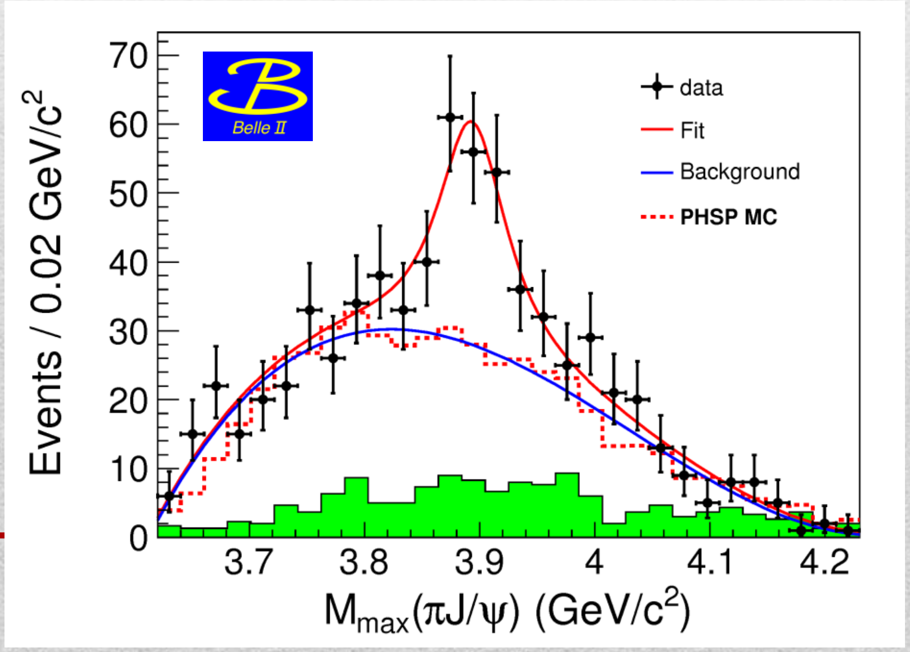
BESIII, arXiv:1303.5949

$$M = 3899.0 \pm 3.6 \pm 4.9\ \text{MeV}$$
$$\Gamma = 46 \pm 10 \pm 20\ \text{MeV}$$



Belle, arXiv:1304.0121

$$M = 3894.5 \pm 6.6 \pm 4.5\ \text{MeV}$$
$$\Gamma = 63 \pm 24 \pm 26\ \text{MeV}$$



Quantum numbers

From the decay $Y \to Z_c \pi \to J/\psi\, \pi\pi$ we know $I^G J^P = 1^+ ?^?$

For a S-wave decay, $I^G J^{PC} = 1^+ 1^{+-}$

For a P-wave decay, $I^G J^{PC} = 1^+ (0,1,2)^{--}$

C is defined for the neutral Z_c^0

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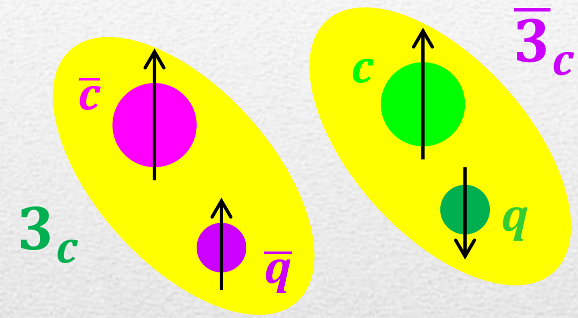
Similarly to X(3872) with $J^{PC} = 1^{++}$,
a signature $J^P = 1^+$ is favored by models

C is defined for the neutral Z_c^0

Tetraquark

One of the models for the **X(3872)** is a compact **diquark-antidiquark bound state**

$$[cq]_{S=0}[\bar{c}\bar{q}]_{S=1} + h.c.$$



Maiani *et al.* PRD71 014028

We can evaluate mass spectrum in a constituent quark model

$$H = -2\sum_{i<j}\kappa_{ij}\,\vec{S_i}\cdot\vec{S_j}\,\frac{\lambda_i^a}{2}\frac{\lambda_j^a}{2}$$

Tetraquark

$\kappa_{\bar{q}Q}$ from meson spectrum:

$\pi, \rho, D, D^*, \eta_c, J/\psi$

$\kappa_{c\bar{q}} = 17.5\ \mathrm{MeV}$
$\kappa_{c\bar{c}} = 15.0\ \mathrm{MeV}$
$\kappa_{q\bar{q}} = 77.5\ \mathrm{MeV}$

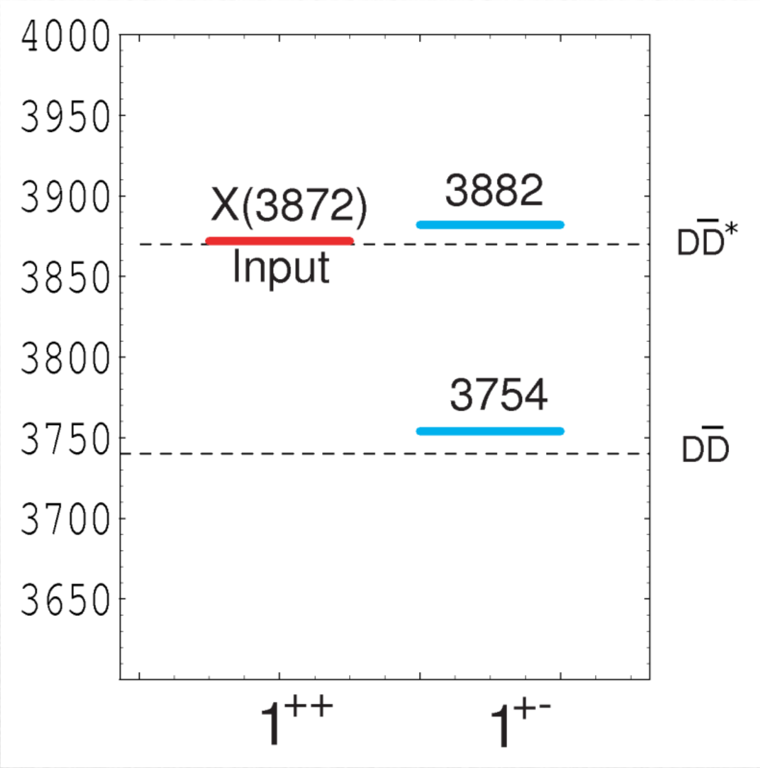
κ_{qQ} from baryon spectrum:

$\Lambda_c, \Sigma_c, p, \Delta^+$

$\kappa_{cq} = 13.5\ \mathrm{MeV}$

But the mass of constituent diquark is unknown
We impose the 1^{++} state to be the $X(3872)$
and get $m_{\mathbf{q}} = 1933\ \mathrm{MeV}$

Tetraquark



We can combine
S=0 and S=1 diquarks
to get **3 vector states:**

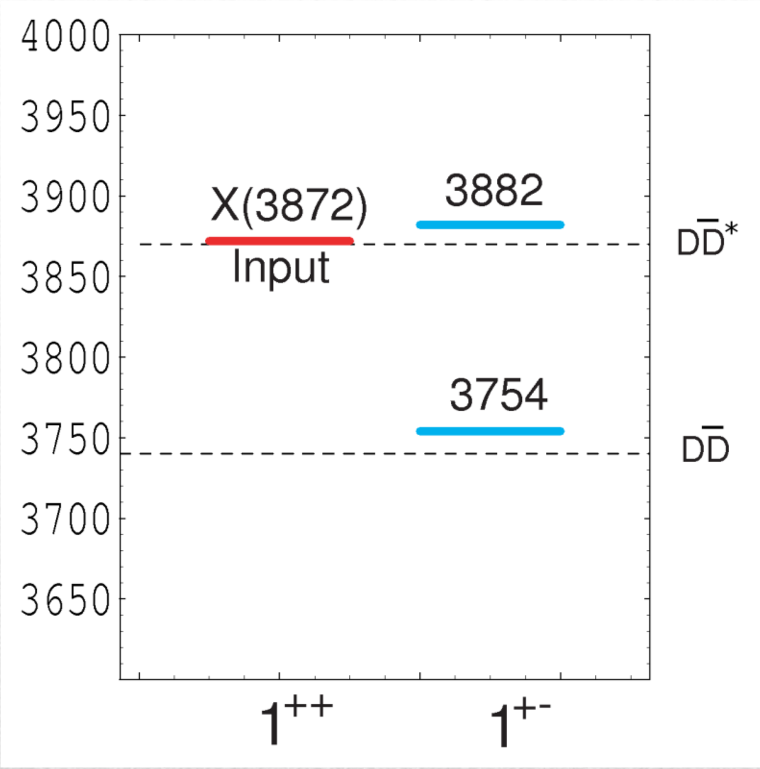
1^{++} $\frac{1}{\sqrt{2}}(|0,1\rangle + |1,0\rangle)$

1^{+-} $\frac{1}{\sqrt{2}}(|0,1\rangle - |1,0\rangle)$

1^{+-} $|1,1\rangle$

mix

Tetraquark



1^{+-} state at 3882 MeV compatible with $Z_c(3900)$!

Prevision for other states:

- Neutral $I^G = 1^+$ partner $\sim 3900\text{ MeV}$
- Neutral $I^G = 0^-$ partner $\sim 3900\text{ MeV}$
- Charged/neutral 1^{+-} states $\sim 3755\text{ MeV}$

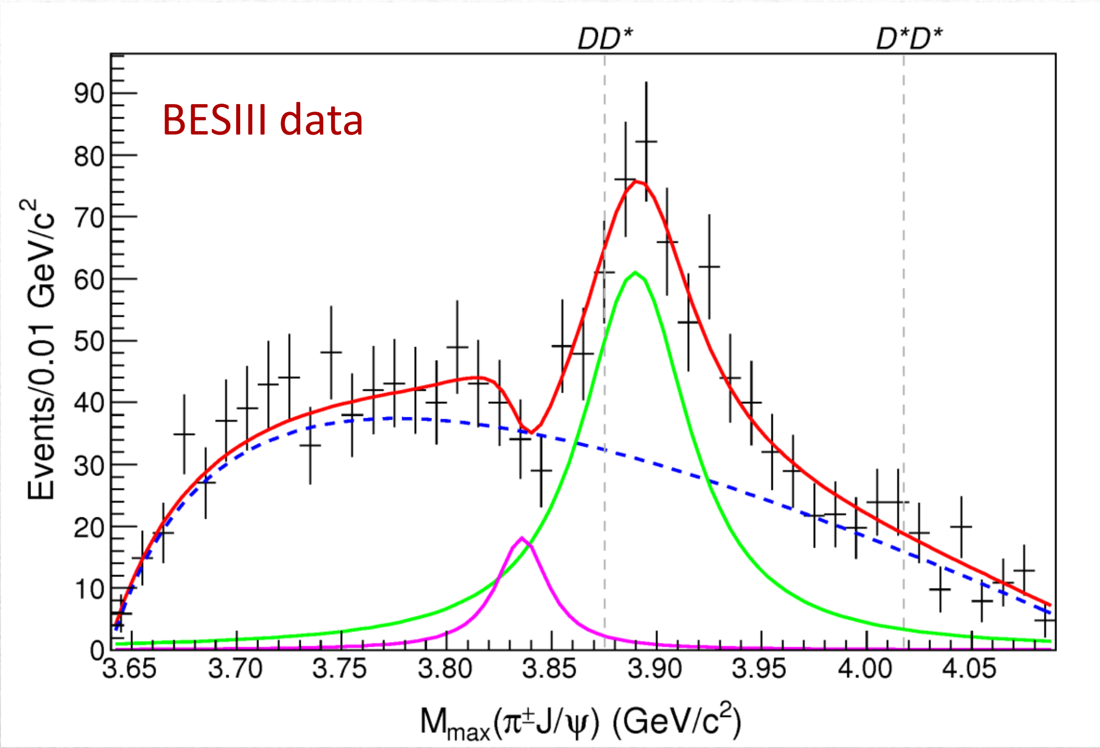
Look for a $Z_c'(3760)$ about $\sim 100\text{ MeV}$ below $Z_c(3900)$

Combined BES-Belle fit

Faccini, Maiani, Piccinini, AP, Polosa, Riquer arXiv:1303.6857

Is there room for a lighter resonance?

Combined BES-Belle fit



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Z_c	$M = 3898 \pm 6$ MeV $\Gamma = 62 \pm 12$ MeV
Z_c'	$M' = 3836 \pm 13$ MeV $\Gamma' = 30 \pm 18$ MeV
	$\Delta\phi = (109 \pm 30)^\circ$

$$\chi^2/\mathrm{DOF}=41/65,\ CL = 99.0\%$$

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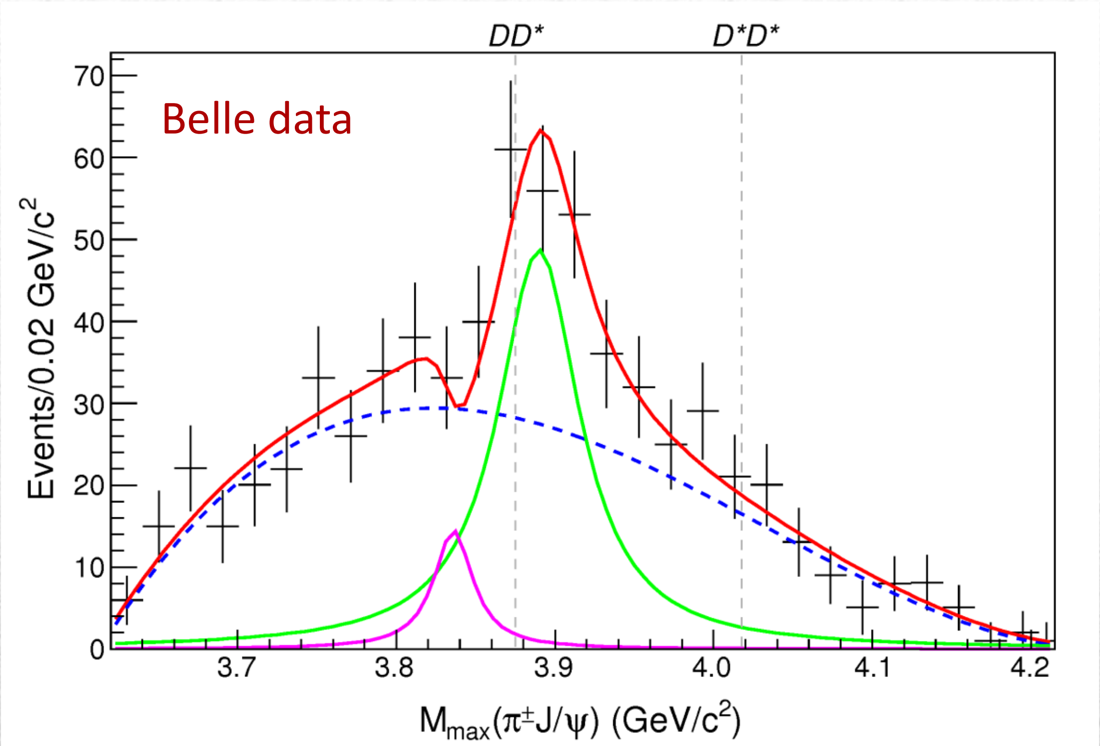

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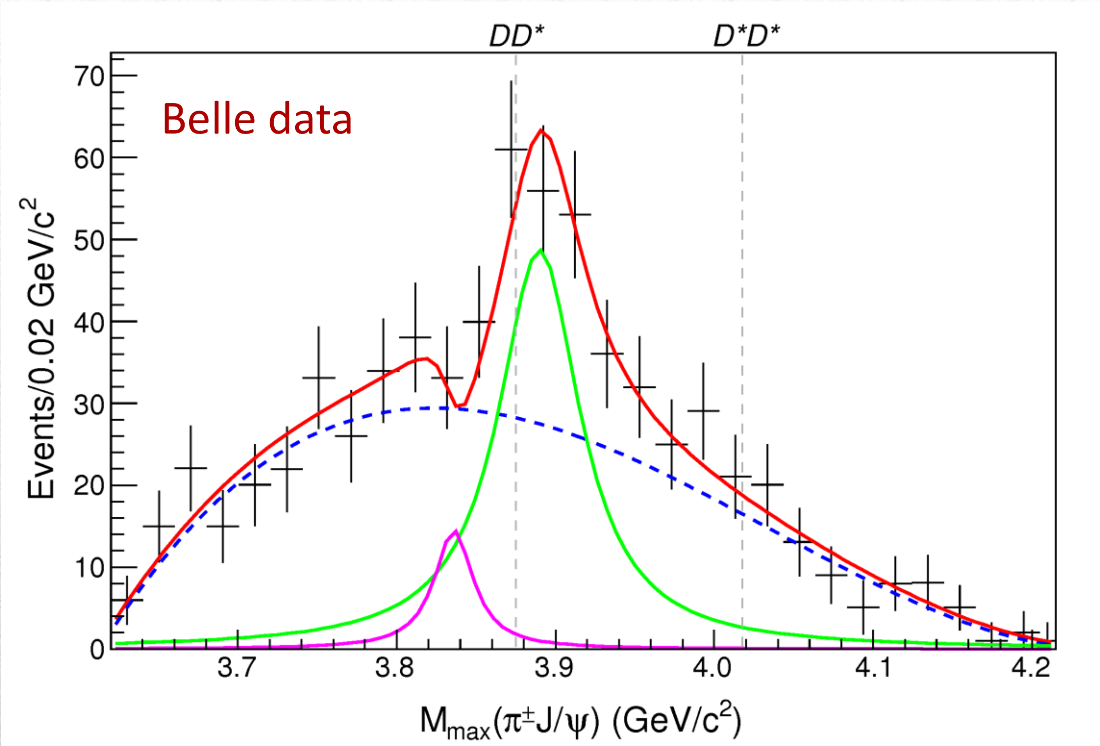

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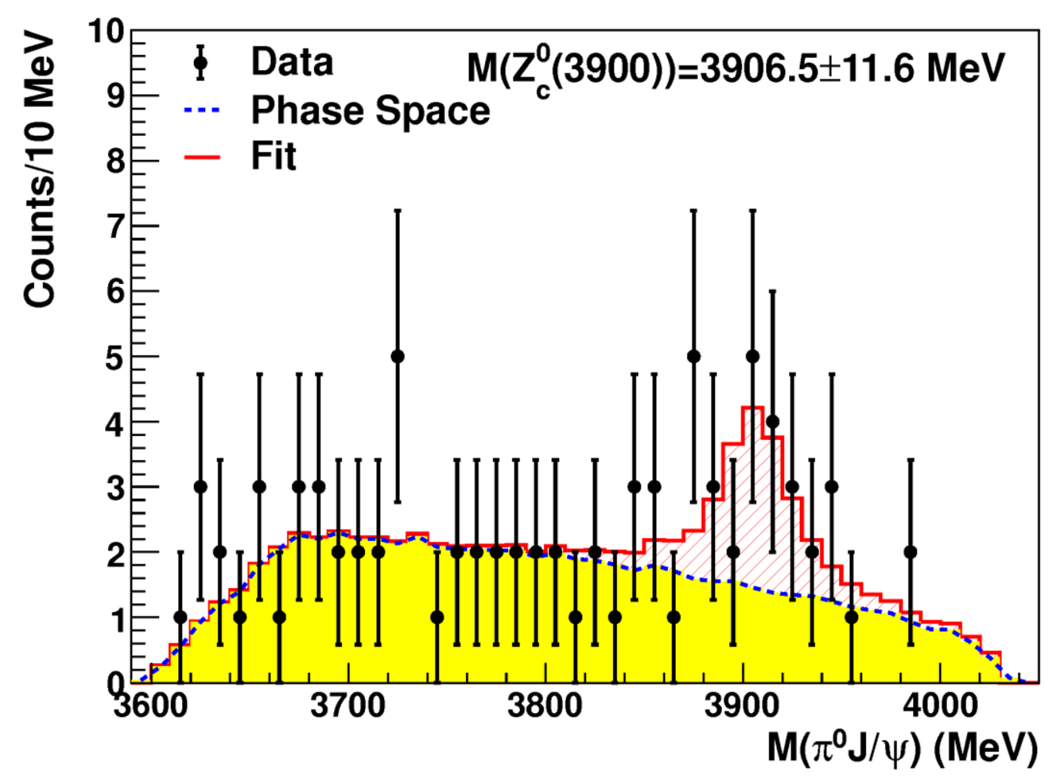
Just a hint, but… could it be the $Z_c'(3760)$?

$Z_c^0(3900)$ at CLEO?

A reanalysis of CLEO data shows a 3σ neutral resonance in

$$\psi(4160) \rightarrow \pi^0 Z_c^0 \rightarrow J/\psi\, \pi^0\, \pi^0$$



Xiao et al.
arXiv:1304.3036

$$M = 3907 \pm 12\ \text{MeV}$$
$$\Gamma = 34 \pm 29\ \text{MeV}$$

Isospin violation?
Look for $Z_c^0 \rightarrow J/\psi\, \eta$

Decay channels

Two questions:

- What can $Z_c(3900)$ decay into?
- Why is $Z_c(3900)$ much broader than $X(3872)$?

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- $J/\psi\, \pi^+$
- $\psi(2S)\pi^+$
- $D^+\, \overline{D^{*0}}, D^{*+}\, \overline{D^0}$
- $\eta_c\, \rho^+$
- $h_c\, \pi^+$ in P-wave
- Radiative decays

Allowed by HQSS if $Z_c(3900)$ contains a $S = 0\; c\bar{c}$ component

suppressed

Decay channels

Two questions:

- What can $Z_c(3900)$ decay into?
- Why is $Z_c(3900)$ much broader than $X(3872)$?

- $J/\psi\,\pi^+$
- $\psi(2S)\pi^+$
- $D^+\,\overline{D^{*0}},\, D^{*+}\,\overline{D^0} \sim 4\text{ MeV}$
- $\eta_c\,\rho^+$
- $h_c\,\pi^+$ in P-wave
- Radiative decays

We suppose

$$g_{DD^*X(3872)} = g_{DD^*Z(3900)}$$

Decay channels

Two questions:

- What can $Z_c(3900)$ decay into?
- Why is $Z_c(3900)$ much broader than $X(3872)$?

- $J/\psi\,\pi^+ \sim 29\ \mathrm{MeV}$
- $\psi(2S)\pi^+ \sim 6\ \mathrm{MeV}$
- $D^+\,\overline{D^{*0}}, D^{*+}\,\overline{D^0} \sim 4\ \mathrm{MeV}$
- $\eta_c\,\rho^+ \sim 19\ \mathrm{MeV}$
- $h_c\,\pi^+$ in P-wave
- Radiative decays

No grounds for other couplings

We only suppose

$$g = M_{Z_c}$$

Some agreement with QCD sum rules

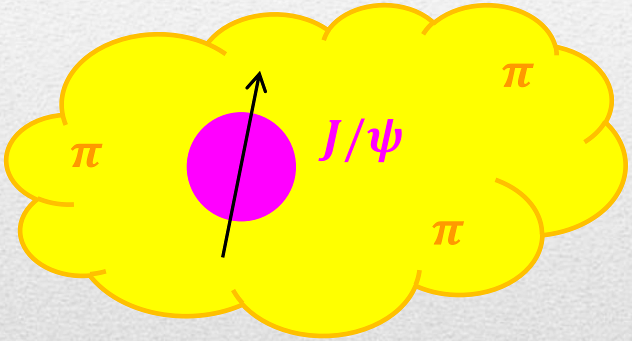
Dias *et al.* arXiv:1304.6433

$\Gamma \sim 60\ \mathrm{MeV}$, agrees with experimental value

Other models

Hadro-charmonium

Voloshin arXiv:1304.0380



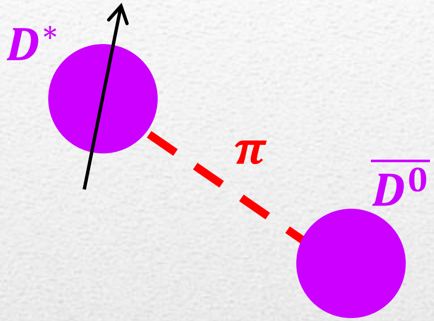
A $c\bar{c}$ state surrounded by light matter

Decay into $\eta_c\ \rho$ forbidden by HQSS

A light $Z_c'(3785)$ expected with $I^G J^{PC} = 1^- 0^{++}$
(not visible in $J/\psi\ \pi$ channel)

Other models

Molecule



Wang *et al.* arXiv:1303.6355

DD^* loosely bound molecule
1-π exchange attractive in $I^C = 1^-$ channel,
although less than in $I^C = 0^+$ ($X(3872)$)

Tornqvist Z.Phys. C61 525-537

A molecule decays mostly into its constituents
(long range decay)

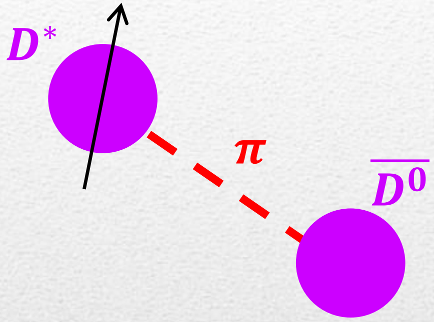
Decays into charmonium + light mesons
suppressed by $1/a$ (short range decay)

Braaten *et al.* PRD69, 074005

e.g. $BR(X(3872) \to DD^*) \sim 70\%$, $BR(X(3872) \to J/\psi\ \rho) \sim 5\%$

Other models

Molecule



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1-π exchange attractive in $I^C = 1^-$ channel,
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Expected with $\mathrm{BR}(\mathrm{Z_c} \to DD^*) \sim$ 70-80%
But we estimated $\Gamma(\mathrm{Z_c} \to DD^*) \sim 4$ MeV,
How to reach $\Gamma = 40$ MeV?

A light $Z_c'(3760)$ expected with $I^G J^{PC} = 1^- 0^{++}$
A heavy $Z_c''(4020)$ expected at $D^* D^*$ threshold

Voloshin
PRD 84, 031502

Other models

Molecule

$Z_c^0(3900)$ could violate isospin just like $X(3872)$
A $\mathrm{Y}(4260) \to Z_c^0\,\pi^0 \to J/\psi\,\eta\,\pi^0$ could occur

If so, it cannot be accomodated into molecular picture:

In X(3872) isospin violation is due to
$$\Delta = \mathrm{M}(\mathrm{D}^+\mathrm{D}^{-*}) - \mathrm{M}(\mathrm{D}^0\mathrm{D}^{0*}) \sim 8\ \mathrm{MeV}$$

Hanhart *et al.* PRD85 011501

Z_c^0 is above both thresholds, and $\Delta \ll \Gamma$

In molecular picture Z_c^0 should be a pure isovector

Conclusions

A $Z_c(3900)$ with $I^G J^{PC} = 1^+ 1^{+-}$ is compatible with different models (tetraquark, molecule, hadro-$c\bar{c}$)

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A $Z_c(3900)$ with $I^G J^{PC} = 1^+ 1^{+-}$ is compatible with different models (tetraquark, molecule, hadro-$c\bar{c}$)

To establish its nature, we need:

- Quantum numbers
- Decay channels $(DD^*, J/\psi\, \eta, \eta_c\, \rho)$
- Looking for a lighter partner $3750\text{-}3850\ \mathrm{MeV}$ in both $G = \pm$ channels
- Looking for a heavier partner at $\sim 4020\ \mathrm{MeV}$

Thank you

BACKUP

Strong couplings

How do we evaluate $g_{DD^*X(3872)}$?

$$g^2_{DD^*X(3872)} = BR(X \to DD^*)\,\Gamma_{\mathrm{X}} \left(\frac{p^*}{8\pi M_x^2} \overline{|M(X \to DD^*)|^2} \right)^{-1}$$

But if $M_X < M_D + M_{D^*}$ the decay momentum p^* is undefined

We average over a random set $(M_X)_i$, distributed as a Breit-Wigner, centered at $M_X = 3872\ \mathrm{MeV}$ and with a width $\Gamma_X = 1.2\ \mathrm{MeV}$ respecting the kinematical limits

$$M_D + M_{D^*} < (M_X)_i < \mathrm{M_B} - \mathrm{M_K}$$

We get $g_{DD^*X(3872)} = 2.5\ \mathrm{GeV}$

Strong couplings

The matrix element can be evaluated in an effective theory

$$\langle D(p)\, D^*(\eta, q)|X(\lambda, P)\rangle = g_{DD^*X}\, \eta \cdot \lambda$$

$$\frac{1}{3}\sum_{\text{pol}} |\langle D(p)\, D^*(\eta, q)|X(\lambda, P)\rangle|^2 = \frac{1}{3} g^2_{DD^*X} \left(3 + \frac{p^{*2}}{M_X^2}\right)$$

The D-wave componenent is negligible with respect to the S-wave one

We get $g_{DD^*X(3872)} = 2.5\ \text{GeV}$

Strong couplings

What about other couplings?

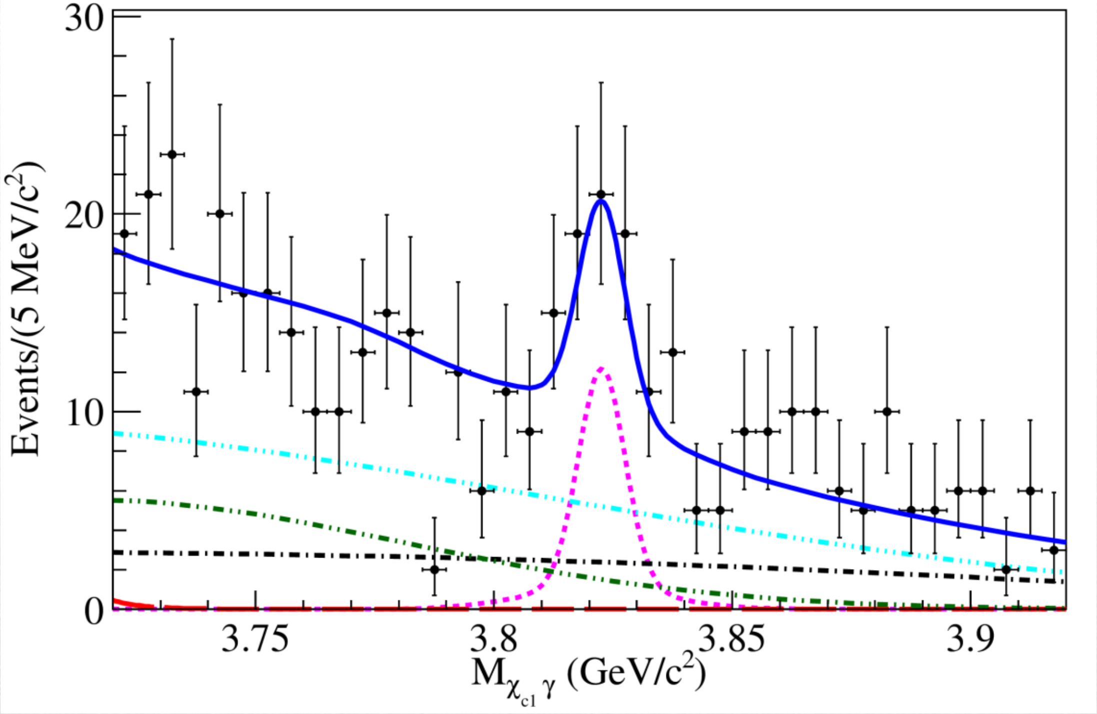
We cannot relate $g_{X\psi\rho}$ to $g_{Z_c\psi\pi}$
(no chiral symmetry or HQSS)

But we are talking about S-wave decays
and we need couplings with the dimension of a mass

The main mass scale is the mass of the $Z_c(3900)$
So we estimate

$$g \sim M_{Z_c} \sim 3900 \text{ MeV}$$

$Z_c' \to \chi_{c1}\gamma$?



Belle arXiv:1304.3975

$M = 3823.1 \pm 1.8 \pm 0.7$ MeV
$\Gamma < 24$ MeV

Proposed a 2^{--} signature (identified as $\psi_2(1D)$), but could be 1^{+-} if the decay is in P-wave

Could be the neutral partner of Z_c'?