PROBING THE NATURE OF $Z_c^{(\prime)}$ STATES VIA THE $\eta_c \rho$ DECAY

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OUTLINE

- Introduction and motivation
- The formalism
  1. The compact tetraquark model
  2. The molecular model
- Results and comparison
- Conclusions

INTRO AND MOTIVATION

Exotic resonances

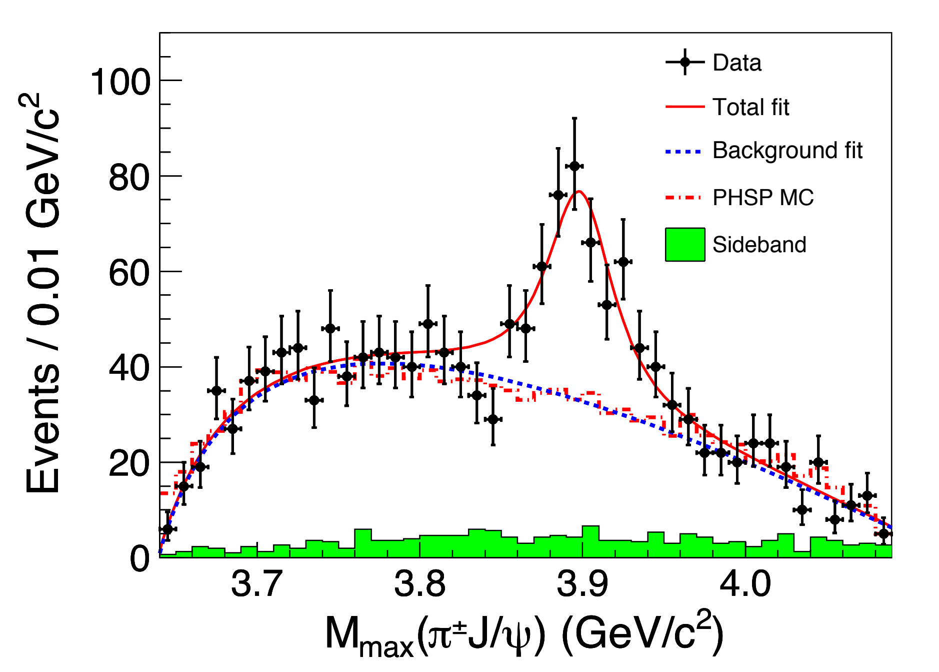
- The past 12 years witnessed the discovery of many unexpected charmonium-like resonances (and two bottomonium-like)
- Some of them are manifestly exotic **4-quark states**:
  1. $Z_c(3900)^+/Z_c'(4020)^+ \longrightarrow c\bar{c}u\bar{d}$
  2. $Z(4430)^+ \longrightarrow c\bar{c}u\bar{d}$
  3. $Z_b(10610)^+/Z_b'(10650)^+ \longrightarrow b\bar{b}u\bar{d}$
- Many phenomenological models have been developed to describe the internal structure of these states (compact tetraquark, meson molecule, hybrid, hadro-charmonium,…)
- So far, no unified/accepted description of their nature has been found
- It would be extremely useful to have a **clear discriminant** between the different ideas…

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$B \to K(\chi_{c1}\gamma)$	Belle (4.0)
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle (>10), BaBar (8.6)
				$p\bar{p} \to (\pi^+\pi^- J/\psi)...$	CDF (11.6), D0 (5.2)
				$pp \to (\pi^+\pi^- J/\psi)...$	LHCb (np)
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle (4.3), BaBar (4.0)
				$B \to K(\gamma J/\psi)$	Belle (5.5), BaBar (3.5)
					LHCb (> 10)
				$B \to K(\gamma \psi(2S))$	BaBar (3.6), Belle (0.2)
					LHCb (4.4)
				$B \to K(D\bar{D}^*)$	Belle (6.4), BaBar (4.9)
$Z_c(3900)^+$	3888.7 ± 3.4	35 ± 7	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III (np)
				$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III (8), Belle (5.2)
					CLEO data (>5)
$Z_c(4020)^+$	4023.9 ± 2.4	10 ± 6	1^{+-}	$Y(4260) \to \pi^-(\pi^+ h_c)$	BES III (8.9)
				$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III (10)
$Y(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(\omega J/\psi)$	Belle (8), BaBar (19)
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle (7.7), BaBar (7.6)
$Z(3930)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle (5.3), BaBar (5.8)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle (6)
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle (7.4)
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle (5.0), BaBar (1.1)
$Y(4140)$	4145.6 ± 3.6	14.3 ± 5.9	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF (5.0), Belle (1.9),
					LHCb (1.4), CMS (>5)
					DØ (3.1)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle (5.5)
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle (7.2)
$Y(4220)$	4196^{+35}_{-30}	39 ± 32	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data (4.5)
$Y(4230)$	4230 ± 8	38 ± 12	1^{--}	$e^+e^- \to (\chi_{c1}\omega)$	BES III (>9)
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle (5.0), BaBar (2.0)
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar (8), CLEO (11)
					Belle (15), BES III (np)
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar (np), Belle (np)
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III (8), Belle (5.2)
				$e^+e^- \to (\gamma\, X(3872))$	BES III (5.3)
$Y(4290)$	4293 ± 9	222 ± 67	1^{--}	$e^+e^- \to (\pi^+\pi^- h_c)$	BES III data (np)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle (3.2)
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^- \psi(2S))$	Belle (8), BaBar (np)
$Z(4430)^+$	4478 ± 17	180 ± 31	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle (6.4), BaBar (2.4)
					LHCb (13.9)
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle (4.0)
$Y(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle (8.2)
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^- \psi(2S))$	Belle (5.8), BaBar (5)
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(5S) \to \pi(\pi\Upsilon(nS))$	Belle (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle (16)
				$\Upsilon(5S) \to \pi^-(B\bar{B}^*)^+$	Belle (8)
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(5S) \to \pi^-(\pi^+\Upsilon(nS))$	Belle (>10)
				$\Upsilon(5S) \to \pi^-(\pi^+ h_b(nP))$	Belle (16)
				$\Upsilon(5S) \to \pi^-(B^*\bar{B}^*)^+$	Belle (6.8)

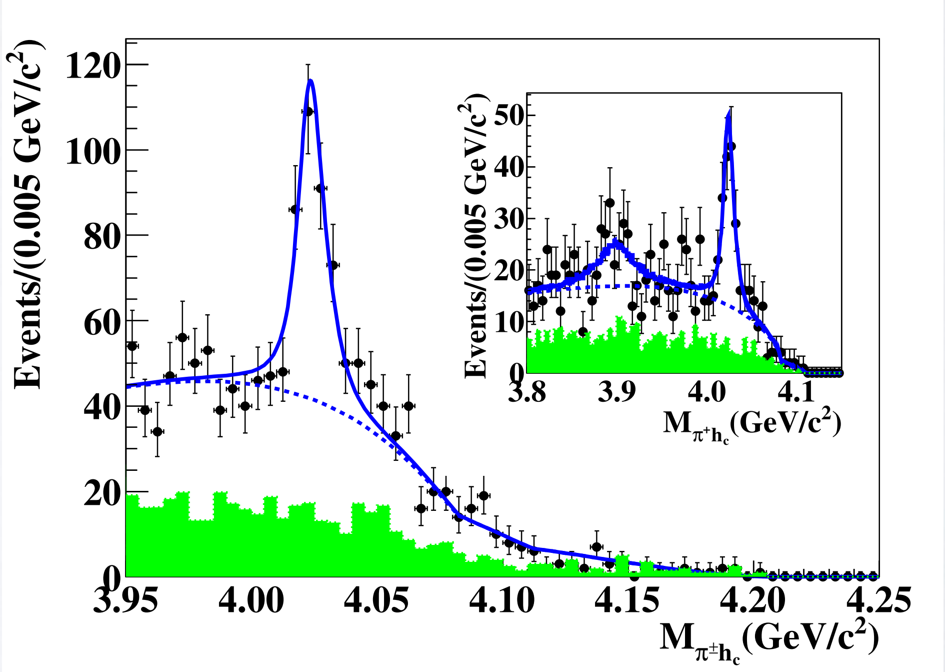
INTRO AND MOTIVATION

The $Z_c^{(\prime)} \to \eta_c \rho$ decay channel

- So far, no clear analysis of the decay of the $Z_c^{(\prime)}$ into $\eta_c \rho$ has been made
- We studied the previous processes by means of both the **compact tetraquark** (type-I and type-II paradigms) and loosely bound **meson molecule** models
- These channels might provide an essential hint to experimentally distinguish between the two models.



[BESIII Coll. PRL 111 (2013) arXiv:1309.1896]



[BESIII Coll. PRL 110 (2013) arXiv:1303.5949]

THE FORMALISM

Compact Tetraquark

- In the **(compact) tetraquark** model the four constituents are considered as being tightly bound to each other in a diquark-antidiquark configuration: $[cq_1]_{\bar{\mathbf{3}}_c}[\bar{c}\bar{q}_2]_{\mathbf{3}_c}$
- The ground state tetraquarks are taken as eigenstates of the color-spin Hamiltonian:

$$H = \sum_i m_i - 2\sum_{i<j} \kappa_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

- Two possibile *ansatz* on the κ_{ij} coefficients:
    1. **Tetraquark type-I:** the couplings are similar to those appearing in ordinary particles. All the κ_{ij} are extracted from known meson and baryon masses. [Maiani *et al.* - PRD71 (2005) arXiv:hep-ph/0412098]
    2. **Tetraquark type-II:** the dominant color-spin interactions are those within the diquarks. All the couplings are neglected except for $\kappa_{cq} = \kappa_{\bar{c}\bar{q}}$. [Maiani *et al.* - PRD89 (2014) arXiv:1405.1551]
- Depending on the chosen ansatz, the physical states will be different combinations of the Hamiltonian eigenstates
- Our interest is on the $Z_c(3900)$ and $Z_c'(4020)$ with $J^{PC} = 1^{+-}$

THE FORMALISM

Compact Tetraquark

- One relies on Heavy Quark Spin Symmetry to write the transition matrix elements to charmonia:

$$\psi_{[cq]} = \chi_c \otimes \phi_{[cq]}(\mathbf{r}_c, \mathbf{r}_q, s_q) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_c}\right)$$

$$\hat{T} = \mathbf{1}_{HS} \otimes \hat{T}_{\perp HS} + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_c}\right) \qquad \Longrightarrow \qquad \mathcal{A} = \overbrace{\langle \chi_{c\bar{c}} | \chi_c \otimes \chi_{\bar{c}} \rangle}^{\text{Clebsh-Gordard}} \underbrace{\langle \phi_{c\bar{c}} | \hat{T}_{\perp HS} | \phi[cq][\bar{c}\bar{q}] \rangle}_{\text{transition matrix element}} + \underbrace{\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_c}\right)}_{\text{theoretical error (\textasciitilde25\%)}}$$

- In our case, the <u>transition matrix elements</u> for the decays of interest are:

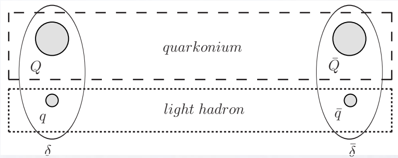
$$\langle J/\psi(\eta, p)\pi(q) | Z(\lambda, P) \rangle = g_{Z\psi\pi} \lambda \cdot \eta \qquad \langle \eta_c(p)\rho(\epsilon, q) | Z(\lambda, P) \rangle = g_{Z\eta_c\rho} \lambda \cdot \epsilon$$

$$\langle h_c(p, \eta)\pi(q) | Z(\lambda, P) \rangle = \frac{g_{Zh_c\pi}}{M_Z^2} \epsilon^{\mu\nu\rho\sigma} \lambda_\mu \eta_\nu P_\rho q_\sigma$$

- The strong couplings, g, are unknown *a-priori.*

- To test the degree of model dependence of our estimate, we used <u>two models</u>:

1. **No internal dynamics:** the spatial dependence of the wave function is ignored and the couplings to different charmonia are universal. The differences are only of kinematical nature.
2. **A model of internal dynamics included:** the tetraquark is considered as a diquark-antidiquark pair interacting with a Cornell potential and moving away from each other. The couplings squared are proportional to the charmonia probability density at the maximum diquark-antidiquark separation. **[Brodsky *et al.* - PRL113 (2014) arXiv:1406.7281]**



RESULTS

Compact Tetraquark

- We computed the decay branching ratios by using both the **type-I** and **type-II** models and both **with and without the internal dynamical description**
- Computing the maximum diquark-antidiquark separation and knowing the charmonia probability densities, **the ratios between the strong couplings** can be estimated to be:

$$g^2_{c\bar{c}} \propto |\psi_{c\bar{c}}(r_Z)|^2 \Longrightarrow g^2_{Z\eta_c\rho}/g^2_{Z\psi\pi} = 0.68^{+0.15}_{-0.12}; \quad g^2_{Z'\eta_c\rho}/g^2_{Z'h_c\pi} = \left(5.7^{+24.4}_{-4.5}\right) \times 10^{-2}$$

- The final results for the quantities of interest are:

	Kinematics only		Dynamics included	
	type I	type II	type I	type II
$\dfrac{\mathcal{BR}(Z_c \to \eta_c\,\rho)}{\mathcal{BR}(Z_c \to J/\psi\,\pi)}$	$\left(3.3^{+7.9}_{-1.4}\right) \times 10^2$	$0.41^{+0.96}_{-0.17}$	$\left(2.3^{+3.3}_{-1.4}\right) \times 10^2$	$0.27^{+0.40}_{-0.17}$
$\dfrac{\mathcal{BR}(Z'_c \to \eta_c\,\rho)}{\mathcal{BR}(Z'_c \to h_c\pi)}$	$\left(1.2^{+2.8}_{-0.5}\right) \times 10^2$		$6.6^{+56.8}_{-5.8}$	

THE FORMALISM

Meson Molecule

- In the **molecular model** the exotic states are seen as loosely bound states of two open-charm mesons.
- Predictions on decay rates can be made using the so-called Non Relativistic Effective Field Theory (NREFT). It describes the interaction between the charmonia, exotic, light and heavy mesons by means of Heavy Quark Effective Theory and Chiral Effective Theory **[see *e.g.* Cleven *et al.* - PRD87 (2013) arXiv:1301.6461 [hep-ph]]**
- The terms of the effective Lagrangian that we are going to need are:

Unknown

$$\mathcal{L}_{Z_c^{(\prime)}} = \frac{z^{(\prime)}}{2} \left\langle \mathcal{Z}^{(\prime)}_{\mu,ab} \bar{H}_{2b} \gamma^\mu \bar{H}_{1a} \right\rangle + h.c. \longrightarrow \text{Exotic + Heavy Mesons}$$

$$\mathcal{L}_{c\bar{c}} = \frac{g_2}{2} \left\langle \bar{\Psi} H_{1a} \gamma^\mu \overleftrightarrow{\partial}_\mu H_{2a} \right\rangle + \frac{g_1}{2} \left\langle \bar{\chi}_\mu H_{1a} \gamma^\mu H_{2a} \right\rangle + h.c. \longrightarrow \text{Charmonia + Heavy Mesons}$$

$$\mathcal{L}_{\rho D D^*} = i\beta \left\langle H_{1b} v^\mu \left(\mathcal{V}_\mu - \rho_\mu \right)_{ba} \bar{H}_{1a} \right\rangle + i\lambda \left\langle H_{1b} \sigma^{\mu\nu} F_{\mu\nu}(\rho)_{ba} \bar{H}_{1a} \right\rangle + h.c. \longrightarrow \text{Heavy Mesons + Light Mesons}$$

$$g_1 = (-2.09 \pm 0.16)\ \text{GeV}^{-1/2}; \quad g_2 = (1.16 \pm 0.04)\ \text{GeV}^{-3/2}; \quad \beta = 0.9 \pm 0.1 \quad \lambda = (0.56 \pm 0.07)\ \text{GeV}^{-1}$$

[Colangelo *et al.* - PRD69 (2004) arXiv:hep-ph/0310084] [Isola *et al.* - PRD68 (2003) arXiv:hep-ph/0307367]

- **Key ingredient:** Assuming the exotic mesons to be molecular bound states implies that they only couple to their open-charm constituents: $Z_c \to DD^*; \quad Z_c' \to D^* D^*$
- **Consequence:** The decays of meson molecules into final states different from their constituents can only proceed via heavy meson loops

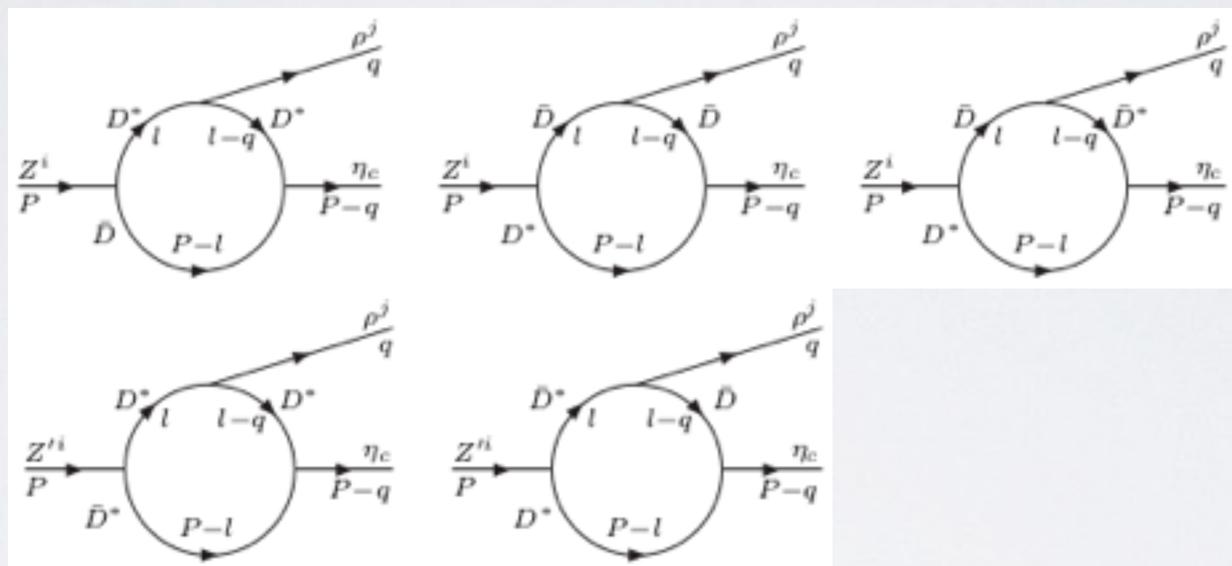
THE FORMALISM

Meson Molecule

- The **one-loop diagrams** we need to compute for our processes are:

$Z_c(3900) \to \eta_c \rho$:

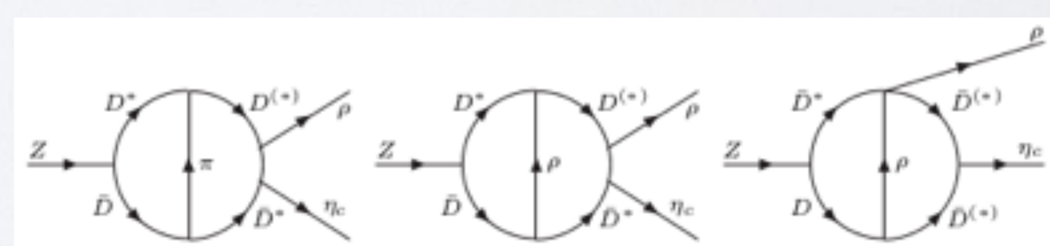
$Z_c'(4020) \to \eta_c \rho$:



And similarly for the $J/\psi\pi$ and channels $h_c\pi$

- Since these molecules are assumed to be very close to threshold, the typical velocities of the heavy mesons, $v \simeq \sqrt{|M_X - 2M_D|/M_D}$, are going to be small. This allows a power counting procedure to estimate the relevance of higher order loop diagrams. `[see e.g. Cleven et al. - PRD87 (2013) arXiv:1301.6461 [hep-ph]]`

- In our case, **higher order contributions** look like:



- We estimated a 15% theoretical uncertainty on the single amplitudes

RESULTS

Meson Molecule

1. **First result:**

$$\frac{\mathcal{BR}(Z_c \to \eta_c \rho)}{\mathcal{BR}(Z_c \to J/\psi \pi)} = \left(4.6^{+2.5}_{-1.7}\right) \times 10^{-2}; \quad \frac{\mathcal{BR}(Z_c' \to \eta_c \rho)}{\mathcal{BR}(Z_c' \to h_c \pi)} = \left(1.0^{+0.6}_{-0.4}\right) \times 10^{-2};$$

2. **Second result:**

- If we assume the decay channels for the $Z_c^{(\prime)}$ to be saturated by the $D^{(*)}D^*$, $\eta_c\rho$, $h_c\pi$, $J/\psi\pi$, $\psi(2S)\pi$ channels, then we can fit the couplings $z^{(\prime)}$ from the experimental total widths:

$$|z| = \left(1.26^{+0.14}_{-0.14}\right)\ \text{GeV}^{-1/2}; \quad |z'| = \left(0.58^{+0.22}_{-0.19}\right)\ \text{GeV}^{-1/2}.$$

- This allows to compute the following branching fractions:

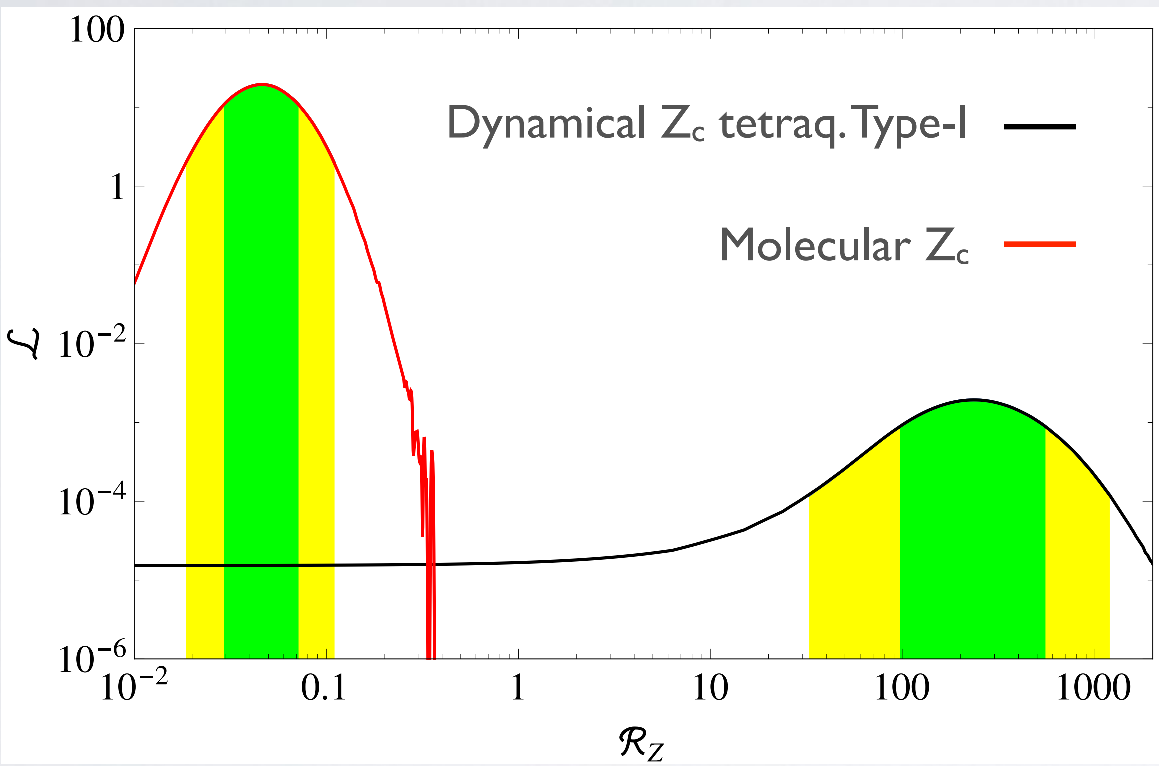
$$\frac{\mathcal{BR}(Z_c \to h_c \pi)}{\mathcal{BR}(Z_c' \to h_c \pi)} = 0.34^{+0.21}_{-0.13}; \quad \frac{\mathcal{BR}(Z_c \to J/\psi \pi)}{\mathcal{BR}(Z_c' \to J/\psi \pi)} = 0.35^{+0.49}_{-0.21}.$$

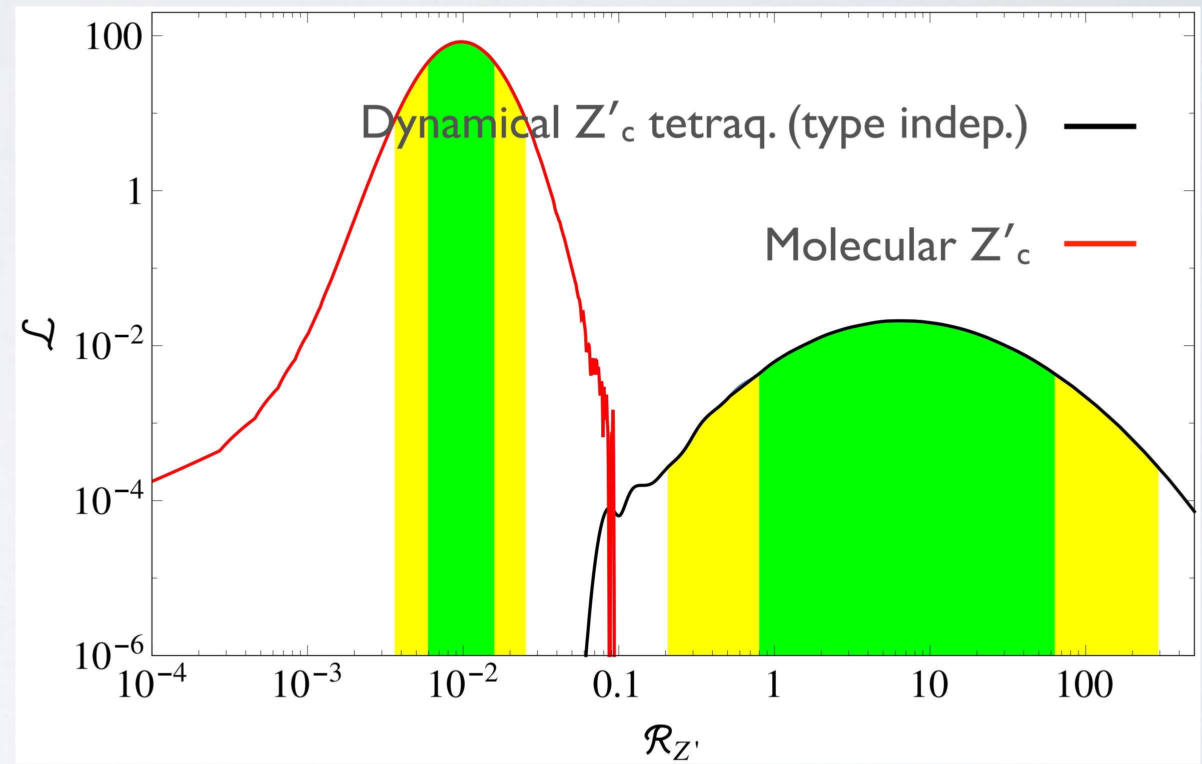
- Both these decay widths should be of the same order of magnitude for the $Z_c(3900)$ and the $Z_c'(4020)$
- It seems in contrast with the experimental data: in the $J/\psi\pi$ channel no hint of Z_c' has been observed

COMPARISON

A neat difference

- A direct comparison of the likelihoods for the decays in $\eta_c \rho$ for the two models is:





- The tetraquark type-I (both dynamical and non-dynamical) for the Z_c is **clearly distinguished (>2σ)** from the meson molecule for the $\mathcal{BR}(Z_c \to \eta_c \rho)/\mathcal{BR}(Z_c \to J/\psi \pi)$ ratio
- The tetraquark type-I and II (both dynamical and non-dynamical) for the Z_c' is also **clearly distinguished** from the meson molecule for $\mathcal{BR}(Z_c' \to \eta_c \rho)/\mathcal{BR}(Z_c' \to h_c \pi)$
- The type-II tetraquark for the Z_c does not provide a neat difference

CONCLUSIONS

- Searching for a clear discriminant between the possible compact tetraquark and meson molecule interpretations of the manifestly exotic $Z_c^{(\prime)}$ states we looked at their decays into the $\eta_c \rho$ final state.
- For the Z_c the predictions from tetraquark type-I and meson molecule are **different with more than 95% C.L.**
- For the Z_c' the predictions from both tetraquark type-I/II and meson molecule are **different with more than 95% C.L.**
- The same conclusions hold both with and without including a model for internal tetraquark dynamics
- The study of the $\eta_c \rho$ **final state** might provide an **essential information** to distinguish between a compact tetraquark and a loosely bound meson molecule structure
- Also, the molecular picture predicts both $Z_c^{(\prime)}$ to be similarly visible in the $J/\psi\pi$ channel. This seems at odds with experimental data

THANK YOU!

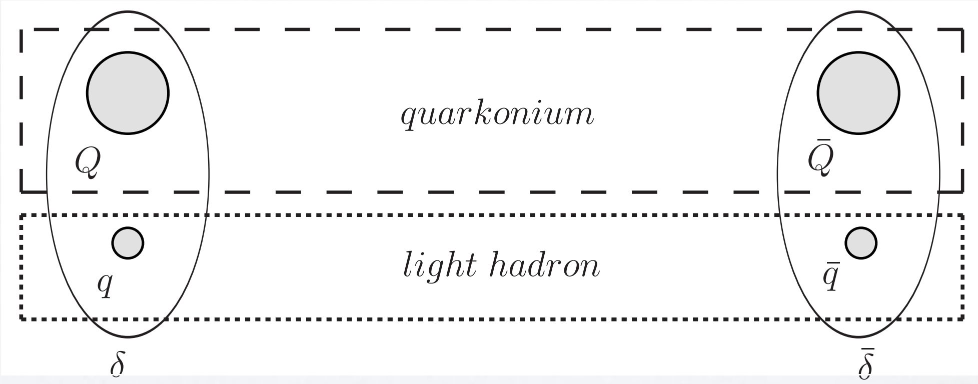
BACK UP

A POSSIBLE MODEL FOR INTERNAL 4-QUARK DYNAMICS

- In a recent paper by Brodsky, Hwang and Lebed a possible description of the internal dynamics of tetraquarks has been proposed `[Brodsky et al. - PRL113 (2014) arXiv:1406.7281]`
- In this model the fundamental constituents are the diquark and antidiquark which interact via a spinless Cornell potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br$$

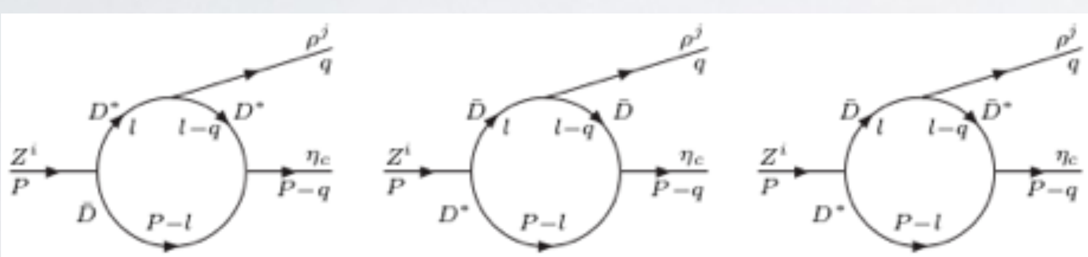
- After the diquark and antidiquark are produced they keep moving away $\longrightarrow$ at a distance r_Z the (classical turning point) the tetraquark decays into charmonium + light meson $\longrightarrow$ the decay into a certain charmonium will be more likely the larger the overlap between its wave function and the $Q\bar{Q}$ wave function in the diquark-antidiquark pair:



- To compute the max. diquark-antidiquark distance one imposes: $V(r_Z) = M_Z - 2m_{[cq]}$
- Once the distance is know one can say: $g_{c\bar{c}}^2 \propto |\psi_{c\bar{c}}(r_Z)|^2$

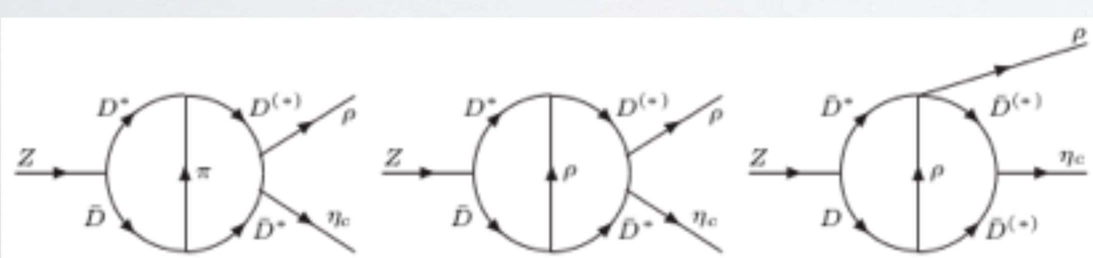
MORE ON NON-RELATIVISTIC POWER COUNTING

- The meson molecule are considered to be very near threshold $\longrightarrow$ typical velocities are small $\longrightarrow$ non-relativistic approximation
- Main ingredients:
  1. Heavy meson velocities relevant in the production/decay of some heavy particle X is: $v_X \sim \sqrt{|M_X - 2M_D|/M_D}$
  2. Meson loops count as: $v_X^5/(4\pi)^2$
  3. Substitute the heavy meson propagator with: $\dfrac{i}{p^2 - m_D^2 + i\epsilon} \longrightarrow \dfrac{1}{2m_D} \dfrac{i}{p^0 - \frac{\mathbf{p}^2}{2m_D} - m_D + i\epsilon}$
  4. The propagators then count as: $1/v_X^2$
  5. If derivative on the vertices are present we have an addition power of v_X or of the external momentum q
- In our case the one-loop diagrams count as:



$$\frac{\bar{v}^5}{(4\pi)^2}\frac{1}{\bar{v}^6}\beta g_V \frac{q}{m_\rho}\frac{q}{M_D} \simeq 1\times 10^{-2} \qquad \frac{\bar{v}^5}{(4\pi)^2}\frac{1}{\bar{v}^6}\lambda g_V q \frac{q}{M_D} \simeq 5\times 10^{-3}$$

- The two-loop diagrams, instead, are:



$$\frac{v_Z^5}{(4\pi)^2}\frac{1}{v_Z^4}\frac{v_\eta^5}{(4\pi)^2}\frac{1}{v_\eta^4}\frac{1}{M_D^2 v_\eta^2}\frac{g^2\beta g_V}{F_\pi^2 m_\rho} q^4 M_D \simeq 3\times 10^{-5}$$

$$\frac{v_Z^5}{(4\pi)^2}\frac{1}{v_Z^4}\frac{v_\eta^5}{(4\pi)^2}\frac{1}{v_\eta^4}\frac{1}{M_D^2 v_\eta^2 + m_\rho^2}\frac{\lambda\beta g_V^3}{m_\rho} q^4 M_D \simeq 7\times 10^{-6}$$

$$\frac{v_Z^5}{(4\pi)^2}\frac{1}{v_Z^4}\frac{v_\eta^5}{(4\pi)^2}\frac{1}{v_\eta^4}\frac{M_D^2}{M_D^2 v_\eta^2 + m_\rho^2}\lambda\beta g_V^3 \frac{q^2}{m_\rho} \simeq 2\times 10^{-4}$$

Conservative error on amplitudes is 15%