Exotic Hadron Spectroscopy

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in coll. w/ Esposito, Faccini, Maiani, Piccininini, Polosa, Riquer
Outline

• «Exotic landscape»
• $Z_c(3900)$ and $Z'_c(4025)$: tetraquarks?
• Feshbach resonances
• (Prompt production of $X(3872)$)
• Conclusions
Exotic landscape

C. Sabelli
Exotic landscape

In last ten years a lot of exotic resonances that do not fit the quarkonium model have appeared.

Nowadays, the most assessed are:
- $X(3872)$, $J^{PC} = 1^{++}$, no charged partners, huge isospin violation
- $Z_c(3900)$, $J^{PC} = 1^{+-}$, charged state
- $Y(4260), Y(4360)$, $J^{PC} = 1^{--}$, no charged partners
- $Z_b(10610)$ with $J^{PC} = 1^{+-}$, charged state
- $Z_b'(10650)$ with $J^{PC} = 1^{+-}$, charged state

A convincing comprehensive framework which includes all these states is still missing.
Proposed models

Molecule of hadrons (loosely bound)

\[ 1_c \times 1_c \in 1_c \]

Diquark-antidiquark (tetraquark)

\[ 3_c \times \bar{3}_c \in 1_c \]

Glueball & Hybrids (with valence gluons)

\[ 8_c \times 8_c \in 1_c \]

Hadrocharmonium (Van der Waals forces)

...or a superposition of all these

\[ J/\psi \]
\[ \pi \]
\[ \pi \]
$Z_c(3900)$

Found in $Y(4260) \rightarrow Z_c^\pm(3900) \pi^\mp \rightarrow J/\psi \pi^\pm \pi^\mp$

Exotic charged charmonium-like state! $I^G J^{PC} = 1^+ 1^{-+}$ (tbc)
(note that the $D D^*$ threshold is at 3876 MeV)

BESIII, PRL110 (2013) 252001

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

Belle, PRL110 (2013) 252002

$M = 3894.5 \pm 6.6 \pm 4.5$ MeV
$\Gamma = 63 \pm 24 \pm 26$ MeV
**$Z_c(3900)$**

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Exotic charged charmonium-like state! $I^G J^{PC} = 1^+ 1^{+-}$ (tbc)

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BESIII on arXiv:1310.1163

$Y(4260) \rightarrow Z_c(3885) \pi \rightarrow DD^*\pi$

$M = 3883.9 \pm 1.5 \pm 4.2$ MeV

$\Gamma = 24.8 \pm 3.3 \pm 11.0$ MeV

Is $Z_c(3900) = Z_c(3885)$?
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

$$H = -2 \sum_{i<j} \kappa_{ij} \vec{S}_i \cdot \vec{S}_j \frac{\lambda_i^a \lambda_j^a}{2} \frac{1}{2}$$
Tetraquark

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

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

- Look for a $Z_c'(3760)$ about $\sim 100$ MeV below $Z_c(3900)$
- Look for the prominent decay $Z_c(3900) \rightarrow \eta_c\rho$
Combined BES-Belle fit

Is there room for a lighter resonance?

Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 (2013) 111102

\[ Z_c \]
\[ M = 3890 \pm 6 \text{ MeV} \]
\[ \Gamma = 62 \pm 12 \text{ MeV} \]

\[ Z'_c \]
\[ M' = 3836 \pm 13 \text{ MeV} \]
\[ \Gamma' = 30 \pm 18 \text{ MeV} \]
\[ \Delta \phi = (109 \pm 30)^\circ \]

\[ \chi^2 / \text{DOF} = 41 / 65, \text{ CL} = 99.0\% \]
Combined BES-Belle fit

What about the $D^*D^*$ molecule?

Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 (2013) 111102

\[
Z_c \quad M = 3895 \pm 3 \text{ MeV} \\
\Gamma = 48 \pm 8 \text{ MeV} \\
Z'_c \quad M' = 4023 \pm 6 \text{ MeV} \\
\Gamma' = 13 \pm 26 \text{ MeV} \\
\Delta \phi = (196 \pm 77)^\circ
\]

\[
\chi^2/\text{DOF}=47/65, \text{ CL} = 95.0\%
\]

But Nature is malicious...
Z'_{c}(4020), Z'_{c}(4025)

BESIII, PRL112, 022001

Y(4260) \rightarrow Z'_{c}(4025) \pi \rightarrow D^{*}D^{*}\pi

I^{G}J^{PC} = 1^{+}1^{--}

M = 4026.3 \pm 2.6 \pm 3.7 \text{ MeV}

\Gamma = 24.8 \pm 5.6 \pm 7.7 \text{ MeV}

BESIII, PRL111, 242001

Y(4260) \rightarrow Z'_{c}(4020) \pi \rightarrow h_{c}\pi\pi

I^{G}J^{PC} = 1^{+}1^{+-}

M = 4022.9 \pm 0.8 \pm 2.7 \text{ MeV}

\Gamma = 7.9 \pm 2.7 \pm 2.6 \text{ MeV}
$Z'_c(4020), Z'_c(4025)$

$Z'_c$ decays into $h_c \pi$ ($s_{c\bar{c}} = 0$) in $P$-wave
$Z'_c$ should decay more into $\eta_c \rho$ ($s_{c\bar{c}} = 0$) in $S$-wave

If $Z'_c$ is a $D^* \bar{D}^*$ molecule, it contains a $s_{c\bar{c}} = 1$ component, it should decay into $J/\psi \pi$ in $S$-wave, where is it?

In fact, $Z_b(10610)$ and $Z'_b(10650)$ decay into both $\Upsilon(nS)$ and $h_b(nP)$

A simple PHS evaluation leads to

$$\frac{\sigma(e^+e^- \rightarrow Z'_c\pi \rightarrow \eta_c\pi\pi)}{\sigma(e^+e^- \rightarrow Z'_c\pi \rightarrow h_c\pi\pi)} \sim 270,$$
$$\frac{\sigma(e^+e^- \rightarrow Z'_c\pi \rightarrow J/\psi \pi\pi)}{\sigma(e^+e^- \rightarrow Z'_c\pi \rightarrow h_c\pi\pi)} \sim 226$$

Although precise evaluation of meson loops can severely modify these values, still $Z'_c\pi \rightarrow J/\psi \pi$ should be observed
$X, Z'_c, Z'_c$: summary

Molecule

✓ The states are near thresholds
✓ Large decay into open charm
✗ Dynamical effects make the pattern obscure
✗ How to justify bound states with positive binding energy?

Tetraquark

✓ The pattern is simple, based on $SU(3)$
✗ Many states are missing, in particular charged partners of $X(3872)$
✗ Who is $Z'_c(4025)$?
In all calculations, molecular resonances are at or below threshold. Is there a mechanism to push a bound state above threshold?
Feshbach resonances

In cold atoms there is a mechanism that occurs when two atoms can interact with two potentials, resp. with continuum and discrete spectrum.

Open charm (molecule) potential

\[ H_P \psi_P = E_P \psi_P \]

(continuum levels)

Open charm threshold

e.g. \( DD^* \)
Feshbach resonances

Papinutto, Piccinini, AP, Polosa, Tantalo arXiv:1311.7374

In cold atoms there is a mechanism that occurs when two atoms can interact with two potentials, resp. with continuum and discrete spectrum.

Closed charm (hadrocharmonium) potential

\[ H_Q \psi_Q = E_Q \psi_Q \]

e.g. \( J/\psi \rho \)

Same quantum numbers as \( DD^* \),
The operators mix under renormalization

\[ \downarrow \]

Interaction between channels
Feshbach resonances

We add an interaction Hamiltonian $H_{QP}$ so that

$$E |\psi_P\rangle = H_P |\psi_P\rangle + H_{QP} |\psi_Q\rangle$$

$$E |\psi_Q\rangle = H_Q |\psi_Q\rangle + H_{PQ} |\psi_P\rangle$$

$\nu = E_{res} - E_{th}$
Feshbach resonances

We add an interaction Hamiltonian $H_{QP}$ so that

$$a \approx a_P + C \sum \frac{|\langle \psi_i | H_{QP} | \psi_{th} \rangle|^2}{E_{th} - E_i} \approx a_{NR} - C \left( \frac{|\langle \psi_{res} | H_{QP} | \psi_{th} \rangle|^2}{\nu} \right)$$

Open charm threshold

$\nu = E_{res} - E_{th}$
Feshbach resonances

We add an interaction Hamiltonian $H_{QP}$ so that

$$a \approx a_P + C \sum \frac{|\langle \psi_i | H_{QP} | \psi_{th} \rangle|^2}{E_{th} - E_i} \approx a_{NR} - C \frac{|\langle \psi_{res} | H_{QP} | \psi_{th} \rangle|^2}{\nu}$$

We estimate $\Gamma \propto \sqrt{\nu}$

Broad resonance ($Z_c$)

Open charm threshold

Narrow resonance ($X(3872)$)

no resonance ($X^\pm$)
Feshbach resonances

The Hadrocharmonium spectrum is unknown, it can be deduced from the mass of the resonance, otherwise one can naively expect $M_{\text{Hch}} \approx M_{c \bar{c}} + M_{\text{light}}$

We impose a cutoff on $\nu$ and $\Gamma_D < \nu$

**Charm sector**

<table>
<thead>
<tr>
<th>Open channel</th>
<th>Hadroch.</th>
<th>$M_{\text{Hch}}$ (MeV)</th>
<th>$\nu$ (MeV)</th>
<th>$I^G J^{PC}$</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^{*0} \bar{D}^0$</td>
<td>$J/\psi \rho^0$</td>
<td>3872</td>
<td>0</td>
<td>$1^- 1^{++}$</td>
<td>$X(3872)$</td>
</tr>
<tr>
<td>$D^{*+} \bar{D}^0$</td>
<td>$\psi(3770) \pi^+$</td>
<td>3900</td>
<td>24</td>
<td>$1^+ 1^{--}$</td>
<td>$Z_c(3900)$</td>
</tr>
<tr>
<td>$D^{*+} \bar{D}^0$</td>
<td>$h_c(2P) \pi^+$ (P-wave)</td>
<td>4025</td>
<td>8</td>
<td>$1^+ 1^{--}$</td>
<td>$Z'_c(4025)$</td>
</tr>
</tbody>
</table>

The vector state $Y(4260)$ does not fit this scheme $\rightarrow$ Hybrid?

Hadron Spectrum coll. JHEP 1207 (2012) 126, see also Santopinto et al. PRD78 (2008) 056003
Feshbach resonances

\(X(3872)\) should be a \(I = 1\) state, but \(M(J/\psi \rho^+) < M(D^{*+} \bar{D}^0)\)

No charged states, isospin violation!

If we assume \(\Gamma = A\sqrt{\nu}\), we can use \(Z_c(3900)\) as input
to extract \(A = 10 \pm 5 \text{ MeV}^{1/2}\)

This value is compatible for all resonances
(still large errors...)

**Bottom sector**

<table>
<thead>
<tr>
<th>Open channel</th>
<th>Hadrobo.</th>
<th>(M_{\text{Hbt}}) (MeV)</th>
<th>(\nu) (MeV)</th>
<th>(I^GJ^{PC})</th>
<th>name</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^{*+} \bar{B}^0)</td>
<td>(\chi_{b0}(1P)) (\rho^+) (P-wave)</td>
<td>10610</td>
<td>3</td>
<td>(1^+1^{+-})</td>
<td>(Z_b(10610))</td>
</tr>
<tr>
<td>(B^{*+} \bar{B}^{*0})</td>
<td>(\chi_{b0}(1P)) (\rho^+) (P-wave)</td>
<td>10650</td>
<td>1.8</td>
<td>(1^+1^{+-})</td>
<td>(Z'_b(10650))</td>
</tr>
</tbody>
</table>

We remark that \(\Gamma(Z'_b)/\Gamma(Z_b) \approx 0.63\), \(\nu(Z'_b)/\nu(Z_b) \approx 0.77\)
Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances. The most popular interpretation is a $D^0\bar{D}^{0*}$ molecule.

But the binding energy is $E_B \approx -0.14 \pm 0.22$ MeV: very small!

A simple square well model shows that $k_{\text{rel}} \approx 50$ MeV.

How many pairs can we produce at hadron colliders with such a small relative momentum?

Bignamini et al. PRL103 (2009) 162001

We obtain

$$\sigma(p\bar{p} \to DD^*) \approx 0.1 \text{ nb} \ @ \sqrt{s} = 1.96 \text{ TeV}$$

Experimentally

$$\sigma(p\bar{p} \to X(3872)) \approx 30 \text{ nb}!!!$$

Molecule challenged!!!
Prompt production of $X(3872)$

A solution can be Final State Interaction (rescattering of $DD^*$)...

Relative momenta as large as $\Lambda \sim O(m_\pi) \sim 300$ MeV
rescatter into momenta of order $\sqrt{-2\mu E_B} \sim 50$ MeV

Artoisenet and Braaten PRD81 (2010) 114018

Migdal-Watson theorem
Prompt production of \( X(3872) \)

A solution can be Final State Interaction (rescattering of \( DD^* \))...

Artoisenet and Braaten PRD81 (2010) 114018

...but the application of Watson Theorem is spoiled by the presence of pions that interfere with \( DD^* \) propagation, Bignamini et al. PLB684 (2010) 228-230

(FSI have been used also by Meissner et al. arXiv:1308.0193 to estimate \( Z_c \) and \( Z_b \) prompt xsects, but the application to above-threshold states is unclear)
A new mechanism?

However, these pions can elastically interact with $D(D^*)$, and slow down the pairs $DD^*$

The mechanism also implies: $D$ mesons actually “pushed” inside the potential well (the classical 3-body problem!)

$X(3872)$ is a real, negative energy bound state (stable)
It also explains a small width $\Gamma_X \sim \Gamma_{D^*} \sim 100$ keV

Esposito, Piccinini, AP, Polosa JMP 4, 1569
A new mechanism?

Low $k_0$ bins are refilled by the interaction with $n$ pions
A new mechanism?

| $k_0^{max}$ | HERWIG | | | PYTHIA | | |
| | 50 MeV | 100 MeV | 50 MeV | 100 MeV | | |
| No. of events | | | | | | |
| 0 scatt. | 52 | 253 | 240 | 1560 | | |
| 1 scatt. | 44 | 299 | 283 | 1984 | | |
| 3 scatt. | 843 | 2069 | 4843 | 11679 | | |
| 4 scatt. | 1166 | 2802 | 6489 | 14916 | | |
| 5 scatt. | 1689 | 4167 | 7770 | 18284 | | |
| $\sigma$ [nb] | | | | | | |
| 0 scatt. | 0.10 | 0.50 | 0.13 | 0.83 | | |
| 1 scatt. | 0.09 | 0.59 | 0.15 | 1.05 | | |
| 3 scatt. | 1.67 | 4.10 | 2.57 | 6.20 | | |
| 4 scatt. | 2.31 | 5.55 | 3.44 | 7.92 | | |
| 5 scatt. | 3.34 | 8.25 | 4.12 | 9.71 | | |

Striking increase of $\sigma$ after each scattering!

Down by a factor 5-7 wrt $\sigma_{exp} \approx 30$ nb,
A new mechanism?

The mechanism proposed is not sufficient to explain all the experimental cross section, but could be a component of the real mechanism.

A study of the effect of $\pi$ interactions on known differential production cross section of open charm mesons is ongoing.
Conclusions

The study of exotic resonances in heavy quark sector is still puzzling

- The tetraquark picture predicts $Z_c(3900)$, but misses $Z'_c(4025)$
- The molecular picture has troubles with above-threshold states and production mechanisms
- Look for missing states and decay modes who can help in excluding models
- Explore new production mechanisms to take into account at- and above-threshold states
- Propose and search new states who can falsify some models

Thank you
BACKUP
Doubly charmed states

Another approach to choose among models, is to predict states who fit only in one model

For example, we proposed to look for doubly charmed states, which in tetraquark model are $[cc]_{S=1} [\bar{q}q]_{S=0,1}$

These states could be observed in $B_c$ decays @LHC

Esposito, Papinutto, AP, Polosa, Tantalo, PRD88 (2013) 054029
Doubly charmed states

Another approach to choose among models, is to predict states who fit only in one model

The doubly charged state $T_{s}^{++} = [cc]_{s=1} [d\bar{s}]_{s=0}$

could not be explained in the molecular picture because of the Coulombian repulsion.

If $M(T_{s}^{++}) > 3979$ MeV the state could decay into $D^{*+} D_{s}^{+}$ and could be seen @LHC

This state is particularly well-defined on the lattice, because no disconnected diagrams are involved.

The calculation is ongoing...
Doubly charmed states

Just started the analysis of correlators \( \langle O_1(x)O_1^+(0) \rangle \)
where \( O_1 = \epsilon_{ABK} \bar{c}_c \gamma^i c^B \epsilon_{CDK} (\bar{d}_c \gamma^5 s_c^D - \bar{s}_c \gamma^5 d_c^D) \)
is the interpolating operator of a \( J^P = 1^+ \) tetraquark

Guerrieri, Papinutto, AP, Polosa, Tantalo, work in progress

Simulation with a \( 32^3 \times 64 \) lattice, \( n_f = 2, m_\pi \simeq 500 \) MeV

Lüscher’s method is to be implemented
$Z^0_c(3900)$ at CLEO?

A reanalysis of CLEO data shows a $3\sigma$ neutral resonance in

$$\psi(4160) \to \pi^0 Z^0_c \to J/\psi \pi^0 \pi^0$$

Xiao et al.
PLB767, 366-370

$$M = 3907 \pm 12 \text{ MeV}$$

$$\Gamma = 34 \pm 29 \text{ MeV}$$

Isospin violation?
Look for $Z^0_c \to J/\psi \eta$

Hanhart et al.
arXiv:1312.5621
Two questions:

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

- $J/\psi \pi^+$
- $\psi(2S)\pi^+$
- $D^+ D^{*0}, D^{*+} D^0 \sim 4 \text{ MeV}$
- $\eta_c \rho^+$
- $h_c \pi^+$ 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 $X(3872)$?

• $J/\psi \pi^+ \sim 29$ MeV
• $\psi(2S)\pi^+ \sim 6$ MeV
• $D^+ \overline{D^{*0}}, D^*+ \overline{D^0} \sim 4$ MeV
• $\eta_c \rho^+ \sim 19$ 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

$\Gamma \sim 60$ MeV, agrees with experimental value
Other models

Hadro-charmonium

Voloshin PRD87 9, 091501

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. PRL111 (2013) 132003

\( DD^* \) loosely bound molecule

1-\( \pi \) 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 \( 1/\alpha \) (short range decay)

Braaten et al. PRD69, 074005

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

Molecule

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

Expected with $\text{BR}(Z_c \to D D^*) \sim 70$-$80\%$
But we estimated $\Gamma(Z_c \to D D^*) \sim 4$ 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

Wang et al. arXiv:1303.6355

Tornqvist Z.Phys. C61 525-537

Voloshin
PRD 84, 031502
Other models

Molecule

$Z_c^0(3900)$ could violate isospin just like $X(3872)$

$A \ Y(4260) \rightarrow Z_c^0 \ \pi^0 \rightarrow J/\psi \ \eta \ \pi^0$ could occur

If so, it cannot be accommodated into molecular picture:

In $X(3872)$ isospin violation is due to

$\Delta = M(D^+D^{-*}) - M(D^0D^{0*}) \sim 8 \text{ MeV}$

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
Strong couplings

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

$$g_{DD^*X(3872)}^2 = BR(X \rightarrow DD^*) \Gamma_X \left( \frac{p^*}{8\pi M_X^2} \frac{1}{|M(X \rightarrow DD^*)|^2} \right)^{-1}$$

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 $M_X = 3872$ MeV and with a width $\Gamma_X = 1.2$ MeV respecting the kinematical limits

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

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

The matrix element can be evaluated in an effective theory

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

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

The D-wave component 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

\[ g \sim M_{Z_c} \sim 3900 \text{ MeV} \]
Tuning of MC

Monte Carlo simulations

- We compare the $D^0 D^{*-}$ pairs produced as a function of relative azimuthal angle with the results from CDF:

Such distributions of charm mesons are available at Tevatron
No distribution has been published (yet) at LHC

The c-cbar run underestimate the low angles (low-$k_t$) region!
The enhancement is impressive because first bins are almost empty
$T$ states production

\[ \overline{D^0}, D^-, D_s^- \]
\[ T_s^+, T_{s^+}, T_{s^2^+} \]
\[ T^0, T^+, T_s^+ \]
\[ p, n, \Lambda, \Sigma, \Xi \ldots \]
To do
Fare calcoli spazio fasi
Controlla numeri arxiv (BES e voloshin)
Aggiungi una slide backup sul ccbar