Introduction to Charmonium and Exotic physics

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Bologna, September 8th, 2016
Outline

- Charmonium: standard and exotic
- Exotic models
- Production of exotics at LHC
- Hybridized tetraquarks
- Conclusions

Disclaimer: this is my personal, incomplete, and shamelessly biased point of view
Potential models
(meaningful when $M_Q \to \infty$)

$V(r) = -\frac{C_F\alpha_s}{r} + \sigma r$  (Cornell potential)

Effective theories
(HQET, NRQCD, pNRQCD...)

Solve NR Schrödinger eq. $\to$ spectrum

Heavy quark spin flip suppressed by quark mass,
approximate heavy quark spin symmetry (HQSS)

$\alpha_s(M_Q) \sim 0.3$
(perturbative regime)

OZI-rule, QCD multipole

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Multiscale system

Systematically integrate out the heavy scale,

\( m_Q \gg \Lambda_{QCD} \)

\[ m_Q \gg m_Q v \gg m_Q v^2 \]

Full QCD \( \rightarrow \) NRQCD \( \rightarrow \) pNRQCD

\( m_b \sim 5 \text{ GeV}, m_c \sim 1.5 \text{ GeV} \)

\( v_b^2 \sim 0.1, v_c^2 \sim 0.3 \)

Factorization (to be proved) of universal LDMEs

Good description of many production channels, some known puzzles (polarizations)
Good understanding of the spectrum, in particular below thresholds

Potential model by Radford and Repko, PRD75, 074031
A host of unexpected resonances have appeared decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

Exotic landscape

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N. Brambilla et al., EPJC74, 10, 2981
Guerrieri, AP, Piccinini, Polosa IJMJP 30, 1530002
Chen, Chen, Liu, Zhu Phys.Rept. 639, 1-121
$X(3872)$

- Discovered in $B \to K X \to J/\psi \pi \pi$
- Very close to $DD^*$ threshold
- Too narrow for an above-threshold charmonium
- Isospin violation too big
  \[ \frac{\Gamma(X \to J/\psi \omega)}{\Gamma(X \to J/\psi \rho)} \sim 0.8 \pm 0.3 \]
- Mass prediction not compatible with $\chi_{c1}(2P)$

\[ M = 3871.68 \pm 0.17 \text{ MeV} \]
\[ M_X - M_{DD^*} = -3 \pm 192 \text{ keV} \]
\[ \Gamma < 1.2 \text{ MeV @90\%, } J^{PC} = 1^{++} \]

\[ \frac{\sigma_B}{\sigma_{TOT}} = (26.3 \pm 2.3 \pm 1.6)\% \]
\[ \sigma_{PR} \times B(X \to J/\psi \pi \pi) = (1.06 \pm 0.11 \pm 0.15) \text{ nb} \]

For experimental details, wait for the talk by A.A. Alves.
Vector $Y$ states

Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR analyses (and nowhere else!)

Seen in few final states, mostly $J/\psi \pi\pi$ and $\psi(2S) \pi\pi$

Not seen decaying into open charm pairs, to compare with

\[
\frac{B(\psi(3770) \to D\bar{D})}{B(\psi(3770) \to J/\psi\pi\pi)} > 480
\]
Charged $Z$ states...

Charged quarkonium-like resonances have been found, **4q needed**

Two states $J^{PC} = 1^{+-}$ appear slightly above $D^{(*)}D^*$ thresholds

\[
e^+e^- \rightarrow Z_c(3900)^+\pi^- \rightarrow J/\psi \pi^+\pi^- \text{ and } \rightarrow (D D^*)^+\pi^- \\
M = 3888.7 \pm 3.4 \text{ MeV}, \Gamma = 35 \pm 7 \text{ MeV}
\]

\[
e^+e^- \rightarrow Z_c'(4020)^+\pi^- \rightarrow h_c \pi^+\pi^- \text{ and } \rightarrow \bar{D}^*0 D^*+\pi^- \\
M = 4023.9 \pm 2.4 \text{ MeV}, \Gamma = 10 \pm 6 \text{ MeV}
\]

Similar system in bottomonium

\[
Z(4430)^+ \rightarrow \psi(2S)\pi^+ \\
I^G J^{PC} = 1^+1^{+-}
\]

\[
M = 4475 \pm 7^{+15}_{-25} \text{ MeV} \\
\Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV}
\]

Far from open charm thresholds
Pentaquarks... and so on

LHCb, PRL 115, 072001

Two states seen in $\Lambda_b \rightarrow (J/\psi p) K^-$

$M_1 = 4380 \pm 8 \pm 29$ MeV

$\Gamma_1 = 205 \pm 18 \pm 86$ MeV

$M_2 = 4449.8 \pm 1.7 \pm 2.5$ MeV

$\Gamma_2 = 39 \pm 5 \pm 19$ MeV

Quantum numbers

$J^P = \left( \frac{3+}{2}, \frac{5\pm}{2} \right)$ or $\left( \frac{5^+}{2}, \frac{3^-}{2} \right)$

Opposite parities needed for the interference to correctly describe angular distributions

Phase motion compatible with resonant behavior (?)
Proposed models

Molecule of hadrons (loosely bound)

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

Glueball, Hybrids (with valence gluons), Born-Oppenheimer 4q

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

Diquark-antidiquark (tetraquark)

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

Hadrocharmonium (Van der Waals forces)

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

Cusp (kinematical effect)

\[ \pi \]

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**Diquarks**

Attraction and repulsion in 1-gluon exchange approximation is given by

\[
R = \frac{1}{2} \left( C_2(R_{12}) - C_2(R_1) - C_2(R_2) \right)
\]

\[
R_1 = -\frac{4}{3}, R_8 = +\frac{1}{6}
\]

\[
R_3 = -\frac{2}{3}, R_6 = +\frac{1}{3}
\]

The singlet \( \mathbf{1}_c \) is attractive

A diquark in \( \mathbf{3}_c \) is attractive

Evidence (?) of diquarks in LQCD, Alexandrou, de Forcrand, Lucini, PRL 97, 222002

H-shape with a 4 quark system

Cardoso, Cardoso, Bicudo, PRD84, 054508
Tetraquark

In a constituent (di)quark model, we can think of a diquark-antidiquark compact state

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

Maiani, Piccinini, Polosa, Riquer PRD71 014028
Faccini, Maiani, Piccinini, AP, Polosa, Riquer PRD87 111102
Maiani, Piccinini, Polosa, Riquer PRD89 114010

Spectrum according to color-spin hamiltonian
(all the terms of the Breit-Fermi hamiltonian are absorbed into a constant diquark mass):

\[ H = \sum_{dq} m_{dq} + 2 \sum_{i<j} \kappa_{ij} \vec{S}_i \cdot \vec{S}_j \frac{\lambda_i^a \lambda_j^a}{2} \]

Decay pattern mostly driven by HQSS ✓
Fair understanding of existing spectrum ✓
A full nonet for each level is expected ✗

New ansatz: the diquarks are compact objects spacially separated from each other, only \( \kappa_{cq} \neq 0 \)
Existing spectrum is fitted if \( \kappa_{cq} = 67 \text{ MeV} \)
### Tetraquark: new ansatz

**Maiani, Piccinini, Polosa, Riquer PRD89 114010**

\[
\begin{align*}
\mathcal{L} & = \lambda c \bar{c} \\
\Delta H & = \frac{B_c \vec{L}^2}{2} - 2a \vec{L} \cdot \vec{S}
\end{align*}
\]

\[
egin{array}{|c|c|c|c|c|}
\hline
J^{PC} & c \bar{c} q \bar{q} & c \bar{c} q \bar{q} & \text{Resonance Assig.} & \text{Decays} \\
\hline
0^{++} & |0, 0\rangle & \frac{1}{2}|0, 0\rangle + \sqrt{3}/2|1, 1\rangle & X_0 (\sim 3770 \text{ MeV}) & \eta_c, J/\psi + \text{light mesons} \\
0^{++} & |1, 1\rangle_0 & \sqrt{3}/2|0, 0\rangle - 1/2|1, 1\rangle & X'_0 (\sim 4000 \text{ MeV}) & \eta_c, J/\psi + \text{light mesons} \\
1^{++} & 1/\sqrt{2}(|1, 0\rangle + |0, 1\rangle) & |1, 1\rangle_1 & X_1 = X(3872) & J/\psi + \rho/\omega, DD^* \\
1^{+-} & 1/\sqrt{2}(|1, 0\rangle - |0, 1\rangle) & 1/\sqrt{2}(|1, 0\rangle - |0, 1\rangle) & Z = Z(3900) & J/\psi + \pi, h_c/\eta_c + \pi/\rho \\
1^{--} & |1, 1\rangle_1 & 1/\sqrt{2}(|1, 0\rangle + |0, 1\rangle) & Z' = Z(4020) & J/\psi + \pi, h_c/\eta_c + \pi/\rho \\
2^{++} & |1, 1\rangle_2 & |1, 1\rangle_2 & X_2 (\sim 4000 \text{ MeV}) & J/\psi + \text{light mesons} \\
\hline
\end{array}
\]

**Radial excitations**

\[
\begin{align*}
Z(2S) & = Z(4430) \\
Y_1(2P) & = Y(4360) \\
Y_2(2P) & = Y(4660)
\end{align*}
\]

**Decay in \( \psi(2S) \) preferably**

**Assignment**

\[
\begin{align*}
Y_1 & : 3:1 \quad Y(4008) & \gamma + X_0 \\
Y_2 & : 1:0 \quad Y(4260) & \gamma + X \\
Y_3 & : 1:3 \quad Y(4290)/Y(4220) & \gamma + X'_0 \\
Y_4 & : 1:0 \quad Y(4630) & \gamma + X_2
\end{align*}
\]

**Comparison**

\[
M_{Z(4430)} - M_{Z_c} = 586^{+17}_{-16} \text{ MeV}
\]

to compare with charmonium

\[
\psi(2S) \quad 589 \text{ MeV}
\]

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Good description of the spectrum but one has to assume the axial assignment for the $X(4274)$ to be incorrect (two unresolved states with $0^{++}$ and $2^{++}$).
Triangle singularity (kinematics)

Logarithmic branch points due to exchanges in the cross channels can simulate a resonant behavior, only in very special kinematical conditions (Coleman and Norton, Nuovo Cim. 38, 438). However, this effect cancels in Dalitz projections, no peaks (Schmid, Phys.Rev. 154, 1363).

...but the cancellation can be spread in different channels, You should observe peaks and dips roughly compensating each other.

Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo, Meissner, Wang, Yang PRD92, 071502
A deuteron-like meson pair, the interaction is mediated by the exchange of light mesons

- Some model-independent relations (Weinberg’s theorem, shallow states theory)
- Good description of decay patterns (mostly to constituents) and $X(3872)$ isospin violation
- States appear close to thresholds (but $Z(4430)$)
- Lifetime of constituents has to be $\gg 1/m_\pi$
- Binding energy varies from $-70$ to $-0.1$ MeV, or even positive (repulsive interaction)
- Unclear spectrum (a state for each threshold?) – depends on potential models

$$V_\pi(r) = \frac{g_{\pi NN}^2}{3} \left(\bar{\tau}_1 \cdot \bar{\tau}_2\right) \left\{3(\hat{\sigma}_1 \cdot \hat{r})(\hat{\sigma}_2 \cdot \hat{r}) - (\hat{\sigma}_1 \cdot \hat{\sigma}_2)\right\} \left(1 + \frac{3}{m_\pi r^2} + \frac{3}{m_\pi r^2} + (\hat{\sigma}_1 \cdot \hat{\sigma}_2)\right) \frac{e^{-m_\pi r}}{r}$$

Needs regularization, cutoff dependence
Weinberg theorem

Resonant scattering amplitude

\[ f(ab \rightarrow c \rightarrow ab) = -\frac{1}{8\pi E_{CM}} g^2 \frac{1}{(p_a + p_b)^2 - m_c^2} \]

with \( m_c = m_a + m_b - B \), and \( B, T \ll m_{a,b} \)

\[ f(ab \rightarrow c \rightarrow ab) = -\frac{1}{16\pi (m_a + m_b)^2} g^2 \frac{1}{B + T} \]

This has to be compared with the potential scattering for slow particles \((kR \ll 1, \text{ being } R \sim 1/m_\pi \text{ the range of interaction})\) in an attractive potential \( U \) with a superficial level at \(-B\)

\[ f(ab \rightarrow ab) = -\frac{1}{\sqrt{2\mu}} \frac{\sqrt{B} - i\sqrt{T}}{B + T}, \quad B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2} \]

This has to be fulfilled by EVERY molecular state, but:

- \( X(3872), B = 0, g \neq 0 \)
- \( Zs, B < 0, \text{ repulsive interaction!} \)
- \( Y(4260), kR \sim 1.4 \)
Prompt production of $X(3872)$

$X(3872)$ is the Queen of exotic resonances, the most popular interpretation is a $D^0\overline{D}^{0*}$ molecule (bound state, pole in the 1st Riemann sheet?) but it is copiously promptly produced at hadron colliders

\[ \sigma_{MC}(p\bar{p} \rightarrow DD^*|k < k_{max}) \approx 0.1 \text{ nb} \]
\[ \sigma_{exp}(p\bar{p} \rightarrow X(3872)) \approx 30 - 70 \text{ nb}!!! \]

Bignamini et al. PRL103 (2009) 162001

A solution can be FSI (rescattering of $DD^*$), which allow $k_{max}$ to be as large as $5m_\pi$,
\[ \sigma(\bar{p}p \rightarrow DD^*|k < k_{max}) \approx 230 \text{ nb} \]

Artoisenet and Braaten, PRD81, 114018

However, the rescattering is flawed by the presence of pions that interfere with $DD^*$ propagation. Estimating the effect of these pions increases $\sigma$, but not enough

Bignamini et al. PLB684, 228-230
Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003
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$\sigma_{exp}(p \bar{p} \to X(3872)) \approx 30 - 70 \text{ nb}!!$

Bignamini et al. PRL103 (2009) 162001

Also, a comparison to light nuclei does not favor the $X(3872)$ to share the same nature.

Esposito, Guerrieri, Maiani, Piccinini, AP, Polosa, Riquer, PRD92, 034028
Hybridized tetraquarks

Feshbach mechanism occurs when two atoms can interact with two potentials, resp. with continuum ("molecule") and discrete (4q) spectrum → hybridization

Let \( P \) and \( Q \) be orthogonal subspaces of the Hilbert space

\[
H = H_{PP} + H_{QQ}
\]

We have the (weak) scattering length \( a_P \) in the open channel.

We add an off-diagonal \( H_{QP} \)

\[
a = a_P - C \sum \left| \langle \psi_n | H_{QP} | \psi_P \rangle \right|^2 \frac{E_n - E + i\epsilon}{\kappa}
\]

\[
\approx a_P \left( 1 - \frac{\kappa}{\delta - E + i\epsilon} \right)
\]
Hybridized tetraquarks

\[ X(3872) \] should be a \( I = 0 \) state, but \( M(1^{++}) < M(D^{++}D^-) \)
\[ \delta < 0, \] so \( a > 0 \) → Repulsive interaction
No charged component, isospin violation!

\[
d\Gamma = \rho \nu \sigma_{inel} \sim \delta(E - \delta)|\kappa a_p| \frac{d^3p}{m} \\
\Gamma \sim \sqrt{2m}|\kappa a_p| \sqrt{\delta} \equiv A\sqrt{\delta}
\]

\( E < E_{max} \), with \( E_{max} \) estimated by diquarkonium potential to be
• \( \sim 20 \) MeV for charmonium
• \( \sim 40 \) MeV for bottomonium

The closest threshold below the state dominates the interaction
Hybridized tetraquarks

The model works only if no direct transition between closed channel levels can occur. This prevents the straightforward generalization to $L = 1$ and radially excited states (like the $Y_s$ or the $Z(4430)$).

In this picture, a $[bu][\bar{s}\bar{d}]$ state with resonance parameters of the $X(5568)$ observed by D0 is not likely.

Also, one has to ensure the orthogonality between the two Hilbert subspaces $P$ and $Q$. This might affect the estimate for the $X(4140)$. 

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Production & Feshbach?

Going back to $pp(\bar{p})$ collisions, we can imagine hadronization to produce a state

$$|\psi\rangle = \alpha|qQ[\bar{q}\bar{Q}]\rangle_c + \beta|\bar{q}q)(\bar{Q}Q)\rangle_o + \gamma|\bar{q}Q)(\bar{Q}q)\rangle_o$$

If $\beta, \gamma \gg \alpha$, an initial tetraquark state is not likely to be produced.

The open channel mesons fly apart (see MC simulations).

If Feshbach mechanism is at work, an open state can resonate in a closed one.

No prompt production without Feshbach resonances!

Note that only the $X(3872)$ has been observed promptly so far...

...and a narrow $X(4140)$ not compatible with the LHCb one $\Rightarrow$ needs confirmation.
Conclusions & prospects

- Charmonium is a golden system to probe our understanding of strong interactions
- The discovery of exotic states has challenged a well established framework
- Some fantasy needed, many phenomenological models introduced.
- Experiments are very prolific! Constant feedback on predictions
- Nuclei observation at hadron colliders can give an unexpected help in testing some phenomenological hypotheses for the XYZ states
- Search for exotic states in prompt production is a necessary step to improve our understanding of the sector
- Feshbach mechanism might be effective in reducing the number of states predicted by the tetraquark picture

Thank you
BACKUP
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\[ X(3872) \]

<table>
<thead>
<tr>
<th>(B) decay mode</th>
<th>(X) decay mode</th>
<th>product branching fraction ((\times 10^6))</th>
<th>(R_{fit})</th>
<th>(R_{fit}^{\text{err}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ X)</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>(0.86 \pm 0.08)</td>
<td>(BABAR(^{20}), Belle(^{25}))</td>
<td>0.081(^{+0.019}_{-0.031})</td>
</tr>
<tr>
<td>(K^0 X)</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>(0.84 \pm 0.15 \pm 0.07)</td>
<td>BABAR(^{20})</td>
<td>0.021(^{+0.024}_{-0.036})</td>
</tr>
<tr>
<td>(K^+ \pi^-)_{NRX}</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>(0.35 \pm 0.19 \pm 0.04)</td>
<td>BABAR(^{20})</td>
<td>(0.10)</td>
</tr>
<tr>
<td>(K^+)_{NRX}</td>
<td>(X \to \pi J/\psi)</td>
<td>(0.43 \pm 0.12 \pm 0.04)</td>
<td>Belle(^{29})</td>
<td>(0.10)</td>
</tr>
<tr>
<td>(K X)</td>
<td>(X \to \omega J/\psi)</td>
<td>(6.7 \pm 3.5 \pm 4.7)</td>
<td>BABAR(^{83})</td>
<td>0.164(^{+0.166}_{-0.174})</td>
</tr>
<tr>
<td>(K X)</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>(7.7 \pm 1.6 \pm 1.0)</td>
<td>BABAR(^{83})</td>
<td>0.164(^{+0.166}_{-0.174})</td>
</tr>
<tr>
<td>(K X)</td>
<td>(X \to D^* \pi^0 J/\psi)</td>
<td>(2.2 \pm 10 \pm 4)</td>
<td>BABAR(^{31})</td>
<td>0.164(^{+0.166}_{-0.174})</td>
</tr>
<tr>
<td>(K X)</td>
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<td>(9.7 \pm 4.6 \pm 1.3)</td>
<td>Belle(^{37})</td>
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</tr>
<tr>
<td>(K X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(0.202 \pm 0.038)</td>
<td>(BABAR(^{30}), Belle(^{31}))</td>
<td>0.019(^{+0.005}_{-0.009})</td>
</tr>
<tr>
<td>(K X)</td>
<td>(X \to \gamma\psi(2S))</td>
<td>(0.44 \pm 0.12)</td>
<td>BABAR(^{33})</td>
<td>(0.040)(^{+0.015}_{-0.020})</td>
</tr>
<tr>
<td>(K X)</td>
<td>(X \to \gamma\chi_{c1})</td>
<td>(0.083 \pm 0.108 \pm 0.044)</td>
<td>Belle(^{33})</td>
<td>(0.083)(^{+0.108}_{-0.183})</td>
</tr>
<tr>
<td>(K X)</td>
<td>(X \to \gamma\chi_{c2})</td>
<td>(1.14 \pm 0.55 \pm 0.10)</td>
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<td>(1.14)(^{+0.55}_{-0.10})</td>
</tr>
<tr>
<td>(K X)</td>
<td>(X \to D^* \chi_{c1})</td>
<td>(0.112 \pm 0.357 \pm 0.057)</td>
<td>Belle(^{33})</td>
<td>(0.112)(^{+0.357}_{-0.290})</td>
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</tbody>
</table>

\(R_{fit}\) and \(R_{fit}^{\text{err}}\) values are given for comparison.
**Vector $Y$ states**

A component $Y(4260) \rightarrow J/\psi f_0(980)$ might explain why $Y(4260) \rightarrow \psi(2S)\pi\pi$

The lineshape in $h_c \pi\pi$ looks pretty different
Different states contributing?

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Charged $Z$ states: $Z(4430)$

$Z(4430)^+ \rightarrow \psi(2S) \pi^+$

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

$M = 4475 \pm 7^{+15}_{-25} \text{ MeV}$

$\Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV}$

Far from open charm thresholds

If the amplitude is a free complex number, in each bin of $m_{\psi'\pi^-}$, the resonant behaviour appears as well.
Charged $Z$ states: $Z_c(3900), Z'_c(4020)$

Charged quarkonium-like resonances have been found, 4q needed

Two states $J^{PC} = 1^{+-}$ appear slightly above $D(\ast)D^\ast$ thresholds

\[
e^+e^- \rightarrow Z_c(3900)^+\pi^- \rightarrow J/\psi \pi^+\pi^- \text{ and } \rightarrow (DD^\ast)^+\pi^- \\
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M = 4023.9 \pm 2.4 \text{ MeV, } \Gamma = 10 \pm 6 \text{ MeV}
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Two states $J^{PC} = 1^{+-}$ appear slightly above $D(*)D^*$ thresholds

$e^+ e^- \rightarrow Z_c(3900)^+ \pi^- \rightarrow J/\psi \pi^+ \pi^-$ and $\rightarrow (DD^*)^+ \pi^-$

$M = 3888.7 \pm 3.4$ MeV, $\Gamma = 35 \pm 7$ MeV

$e^+ e^- \rightarrow Z'_c(4020)^+ \pi^- \rightarrow h_c \pi^+ \pi^-$ and $\rightarrow \bar{D}^*0 D^*+ \pi^-$

$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV
Charged Z states: $Z_b(106010), Z'_b(10650)$

Anomalous dipion width in $\Upsilon(5S)$, 2 orders of magnitude larger than $\Upsilon(nS)$

Moreover, observed $\Upsilon(5S) \to h_b(nP)\pi\pi$ which violates HQSS

$\Upsilon(5S) \to Z_b(10610)^{+}\pi^- \to \Upsilon(nS)\pi^+\pi^-, h_b(nP)\pi^+\pi^-$

and $\to (B B^*)^{+}\pi^-$

$M = 10607.2 \pm 2.0$ MeV, $\Gamma = 18.4 \pm 2.4$ MeV

$\Upsilon(5S) \to Z'_b(10650)^{+}\pi^- \to \Upsilon(nS)\pi^+\pi^-, h_b(nP)\pi^+\pi^-$

and $\to \bar{B}^*0 B^+\pi^-$

$M = 10652.2 \pm 1.5$ MeV, $\Gamma = 11.5 \pm 2.2$ MeV

2 twin resonances!
\[ Y(4260) \rightarrow \gamma X(3872) \]

F. Piccinini

**BESIII:** \( e^+e^- \rightarrow Y(4260) \rightarrow X(3872)\gamma \)

With \( \mathcal{B}[X(3872) \rightarrow \pi^+\pi^- J/\psi] = 5\% \)

\[
\frac{\mathcal{B}[Y(4260) \rightarrow \gamma X(3872)]}{\mathcal{B}(Y(4260) \rightarrow \pi^+\pi^- J/\psi)} = 0.1
\]

Strong indication that \( Y(4260) \) and \( X(3872) \) share a similar structure

Chen, Maiani, Polosa, Riquer EPJC75 11, 550
X(3872) on the lattice: spectrum

Where is the \( \chi_{c1}(2P) \)?

\( J^{PC} = 1^{++} \) \( I = 0 \) channel

Baryonium

A structure $[Qq][\bar{Q}\bar{q}]$ exhibits an «H» shape, as considered by baryonium models
Rossi, Veneziano, NPB 123, 507; Phys.Rept. 63, 149; PLB70, 255

Isospin violation expected, $\alpha_s(m_c) \ll 1$

$$\frac{B(Y(4660) \to \Lambda_c^+\Lambda_c^-)}{B(Y(4660) \to \psi(2S)\pi\pi)} = 25 \pm 7$$

Cotugno, Faccini, Polosa, Sabelli, PRL 104, 132005

Cardoso, Cardoso, Bicudo, PRD84, 054508
Since this is still a $3 \leftrightarrow \bar{3}$ color interaction, just use the Cornell potential:

$$V(r) = -\frac{4 \alpha_s}{3} \frac{1}{r} + br + \frac{32\pi \alpha_s}{9m_{cq}^2} \left( \frac{\sigma}{\sqrt{\pi}} \right)^3 e^{-\sigma^2 r^2} S_{cq} \cdot S_{\bar{cq}},$$

where $\sigma = 0.16$ fm, $\alpha_s = 0.32$, and $m_{cq} = 0.7$ GeV.

Use that the kinetic energy released in $\bar{B}^0 \rightarrow K^- Z^+(4430)$ converts into potential energy until the diquarks come to rest.

Hadronization most effective at this point (WKB turning point).

$r_Z = 1.16$ fm, $\langle r_{\psi(2S)} \rangle = 0.80$ fm, $\langle r_{J/\psi} \rangle = 0.39$ fm.

$\frac{B(Z^+(4430) \rightarrow \psi(2S)\pi^+)}{B(Z^+(4430) \rightarrow J/\psi \pi^+)} \sim 72$ ($>10$ exp.)
If tetraquark

Kinematics with HQSS, dynamics estimated according to Brodsky et al., PRL113, 112001

\[
A = \langle \chi_{c\bar{c}} | \chi_{c} \otimes \chi_{\bar{c}} \rangle \langle \phi_{c\bar{c}} | \hat{T}_{\perp HLS} | \phi[cq][\bar{c}\bar{q}] \rangle + O \left( \frac{\Lambda_{QCD}}{m_c} \right)
\]

Uncertainty \sim 25\%

Reduced matrix element
- approximated as a constant
- or \( \propto \psi_{c\bar{c}}(r_Z) \)

<table>
<thead>
<tr>
<th>Kinematics only</th>
<th>Dynamics included</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>type I</td>
</tr>
<tr>
<td>( \frac{BR(Z_c \rightarrow \eta_c \rho)}{BR(Z_c \rightarrow J/\psi \pi)} )</td>
<td>((3.3^{+2.9}_{-1.4}) \times 10^2)</td>
</tr>
<tr>
<td>( \frac{BR(Z'_c \rightarrow \eta_c \rho)}{BR(Z'_c \rightarrow h_c \pi)} )</td>
<td>((1.2^{+2.8}_{-0.5}) \times 10^2)</td>
</tr>
</tbody>
</table>
Non-Relativistic Effective Theory, HQET+NRQCD and Hidden gauge Lagrangian
Uncertainty estimated with power counting at NLO

\[ Z_c(3900) \rightarrow \eta_c \rho \]

If molecule

\[ \mathcal{L}_{Z_c}^{(r)} = \frac{z^{(r)}}{2} \left( Z_{\mu a b} H_{2 b} \gamma^\mu H_{1 a} \right) + h.c., \]

\[ \mathcal{L}_{c\bar{c}} = \frac{g_2}{2} \left( \bar{\psi} H_{1 a} \phi H_{2 a} \right) + \frac{g_1}{2} \left( \bar{\chi}_\mu H_{1 a} \gamma^\mu H_{2 a} \right) + h.c., \]

\[ \mathcal{L}_{\rho DD'} = i \beta \left( H_{1 b} \gamma^\mu \left( \mathcal{V}_{ab} - \mathcal{R}_{ab} \right) H_{1 a} \right) + i \lambda \left( H_{1 b} \sigma^{\mu \nu} F_{\mu \nu}(\rho)_{ba} H_{1 a} \right) + h.c. \]

\[
\frac{\text{BR}(Z_c \rightarrow \eta_c \rho)}{\text{BR}(Z_c \rightarrow J/\psi \pi)} = (4.6^{+2.5}_{-1.7}) \times 10^{-2} ;
\frac{\text{BR}(Z_c' \rightarrow \eta_c \rho)}{\text{BR}(Z_c' \rightarrow h_c \pi)} = (1.0^{+0.6}_{-0.4}) \times 10^{-2} .
\]

\[
\frac{\text{BR}(Z_c \rightarrow h_c \pi)}{\text{BR}(Z_c \rightarrow h_c \pi)} = 0.34^{+0.21}_{-0.13} ;
\frac{\text{BR}(Z_c \rightarrow J/\psi \pi)}{\text{BR}(Z_c' \rightarrow J/\psi \pi)} = 0.35^{+0.49}_{-0.21} .
\]
Tetraquark at large-$N$

Some discussions about the existence of tetraquark poles in the large-$N$ limit have been recently raised

S. Weinberg, PRL110 261601
Kencht and Peris, PRD88, 036016
Cohen and Lebed, PRD89, 054018
Cohen and Lebed, PRD90, 016001
Maiani, Polosa, Riquer, JHEP1606, 160

The poles can appear at subleading order (nonplanar diagrams), and give rise to narrow objects
### Tetraquark: the $Y$ states

<table>
<thead>
<tr>
<th>$L = 1$</th>
<th>$P(S_{c\bar{c}} = 1) : P(S_{c\bar{c}} = 0)$</th>
<th>Assignment</th>
<th>Radiative Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_1$</td>
<td>$3:1$</td>
<td>$Y(4008)$</td>
<td>$\gamma + X_0$</td>
</tr>
<tr>
<td>$Y_2$</td>
<td>$1:0$</td>
<td>$Y(4260)$</td>
<td>$\gamma + X$</td>
</tr>
<tr>
<td>$Y_3$</td>
<td>$1:3$</td>
<td>$Y(4290)/Y(4220)$</td>
<td>$\gamma + X'_0$</td>
</tr>
<tr>
<td>$Y_4$</td>
<td>$1:0$</td>
<td>$Y(4630)$</td>
<td>$\gamma + X_2$</td>
</tr>
</tbody>
</table>

**New data on the $Y$ states are going to change this picture, waiting for a clarification.**

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A. Pilloni – Introduction to charmonium and exotic physics
Estimating $k_{max}$

The binding energy is $E_B \approx -0.16 \pm 0.31$ MeV (PDG): very small!

In a simple square well model this corresponds to:

$$\sqrt{\langle k^2 \rangle} \approx 50 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 10 \text{ fm}$$

(binding energy reported by NU, PRD91, 011102)

$E_B \approx -0.003 \pm 0.192$ MeV: $\sqrt{\langle k^2 \rangle} \approx 20$ MeV, $\sqrt{\langle r^2 \rangle} \approx 60$ fm

to compare with deuteron: $E_B = -2.2$ MeV

$$\sqrt{\langle k^2 \rangle} \approx 80 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 4 \text{ fm}$$

We assume $k_{max} \sim \sqrt{\langle k^2 \rangle} \approx 50$ MeV, some other choices are commented later
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!
A new mechanism?

In a more billiard-like point of view, the comoving pions can elastically interact with $D(D^*)$, and slow down the $DD^*$ pairs

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

By comparing hadronization times of heavy and light mesons, we estimate up to $\sim 3$ collisions can occur before the heavy pair to fly apart

We get $\sigma(p\bar{p} \rightarrow X(3872)) \sim 5$ nb, still not sufficient to explain all the experimental cross section

Esposito, Piccinini, AP, Polosa, JMP 4, 1569
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003
Light nuclei at ALICE

Recently, ALICE published data on production of light nuclei in Pb-Pb and $pp$ collisions:

These might provide a benchmark for $X(3872)$ production.

Hypertriton

Helium-3

A. Pilloni – Introduction to charmonium and exotic physics
Light nuclei at ALICE

\begin{center}
\begin{tikzpicture}
\begin{loglogaxis}[
width=\textwidth,\height=\textwidth,
xlabel=$p_T$ (GeV/c),
ylabel=$\frac{1}{N_{ev}} \frac{d^2N}{dy dp_T}$ (GeV/c)^2,
xticklabels={0, 1, 2, 3, 4, 5},
yticklabels={10^{-8}, 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2}, 10^{-1}}
]
\addplot [red, mark=*, only marks] coordinates {
(0, 1), (1, 0.5), (2, 0.25), (3, 0.125), (4, 0.0625), (5, 0.03125)
};
\addplot [orange, mark=square, only marks] coordinates {
(0, 2), (1, 1), (2, 0.5), (3, 0.25), (4, 0.125), (5, 0.0625)
};
\addplot [yellow, mark=diamond, only marks] coordinates {
(0, 3), (1, 1.5), (2, 0.75), (3, 0.375), (4, 0.1875), (5, 0.09375)
};
\addplot [green, mark=triangle, only marks] coordinates {
(0, 4), (1, 2), (2, 1), (3, 0.5), (4, 0.25), (5, 0.125)
};
\addplot [blue, mark=pentagon, only marks] coordinates {
(0, 5), (1, 2.5), (2, 1.25), (3, 0.625), (4, 0.3125), (5, 0.15625)
};
\addplot [black, mark=star, only marks] coordinates {
(0, 6), (1, 3), (2, 1.5), (3, 0.75), (4, 0.375), (5, 0.1875)
};
\addplot [dashed, black] coordinates {
(0, 1), (1, 0.5), (2, 0.25), (3, 0.125), (4, 0.0625), (5, 0.03125)
};
\end{loglogaxis}
\end{tikzpicture}
\end{center}

Deuteron
arXiv:1506.08951
Nuclear modification factors

We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different $\sqrt{s}$)

$R_{CP} = \frac{N_{coll}^{P} \left( \frac{dN}{dp_{T}} \right)_{C}}{N_{coll}^{C} \left( \frac{dN}{dp_{T}} \right)_{P}}$

$R_{AA} = \frac{\left( \frac{dN}{dp_{T}} \right)_{Pb-Pb}}{N_{coll} \left( \frac{dN}{dp_{T}} \right)_{pp}}$
Nuclear modification factors

We can use deuteron data to extract the values of the nuclear modification factors (caveat: for RAA data have different $\sqrt{s}$)

$$R_{CP} = \frac{N^P_{coll} \left( \frac{dN}{dp_T} \right)_C}{N^C_{coll} \left( \frac{dN}{dp_T} \right)_P}$$

$$R_{AA} = \frac{\left( \frac{dN}{dp_T} \right)_{\text{Pb-Pb}}}{N_{coll} \left( \frac{dN}{dp_T} \right)_{pp}}$$

Larger than 1 at $p_T > 2.5$ GeV

A. Pilloni – Introduction to charmonium and exotic physics
Light nuclei at ALICE

We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp

\[
\left( \frac{d\sigma}{dp_{\perp}} \right)_{\text{pp}} \frac{\Delta y}{B(3\text{He }\pi)} \times \frac{\sigma_{pp}^{\text{inel}}}{N_{\text{coll}}} \left( \frac{1}{N_{\text{evt}}} \frac{d^2 N(3\text{He }\pi)}{dp_{\perp} dy} \right)_{\text{Pb-Pb}}
\]

We extrapolate this data at higher \( p_T \) either by assuming an exponential law, or with a blast-wave function, which describes the emission of particles in an expanding medium.

The blast-wave function is

\[
\frac{dN}{dp_{\perp}} \propto p_{\perp} \int_0^R r dr \; m_{\perp} I_0 \left( \frac{p_{\perp} \sinh \rho}{T_{\text{kin}}} \right) K_1 \left( \frac{m_{\perp} \cosh \rho}{T_{\text{kin}}} \right),
\]

where \( m_{\perp} \) is the transverse mass, \( R \) is the radius of the fireball, \( I_0 \) and \( K_1 \) are the Bessel functions, \( \rho = \tanh^{-1} \left( \frac{(n+2)\langle \beta \rangle}{2} (r/R)^n \right) \), and \( \langle \beta \rangle \) the averaged speed of the particles in the medium.
We assume a pure Glauber model (RAA = 1) and a value RAA = 5 to rescale Pb-Pb data to pp.

The $X(3872)$ is way larger than the extrapolated cross section.