Exotic Hadron Spectroscopy

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Outline

- "Exotic hadron landscape"
- Tetraquark picture
- Prompt production
- Feshbach resonances
- Conclusions
Quarkonium orthodoxy

Heavy quarkonium sector is extremely useful for the understanding of QCD

\[ \alpha_s(M_Q) \sim 0.3 \] (perturbative regime)

OZI-rule, QCD multipole

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

Solve NR Schrödinger eq. \( \rightarrow \) spectrum

Effective theories (HQET, NRQCD...)

Integrate out heavy DOF \( \downarrow \) (spectrum), decay & production rates

Spin flip suppressed by heavy quark mass, approximate heavy quark spin symmetry (HQSS)
A host of unexpected resonances have appeared decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

Quarkonium orthodoxy?
A host of unexpected resonances have appeared decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

Quarkonium orthodoxy?
**X(3872)**

- Discovered in $B \rightarrow K X \rightarrow J/\psi \pi \pi$
- Very close to $DD^*$ threshold
- Too narrow for an above-threshold charmonium
- Isospin violation too big
  \[ \frac{\Gamma(X \rightarrow J/\psi \omega)}{\Gamma(X \rightarrow J/\psi \rho)} \sim 0.8 \pm 0.3 \]
- Mass prediction not compatible with $\chi_{c1}(2P)$
  \[ M = 3871.68 \pm 0.17 \text{ MeV} \]
  \[ M_X - M_{DD^*} = -3 \pm 192 \text{ keV} \]
  \[ \Gamma < 1.2 \text{ MeV @90\%} \]

Large prompt production, comparable to $\psi(2S)$

BaBar data in $X \rightarrow J/\psi \omega$ favor $J^{PC} = 2^{-+}$, but LHCb in $X \rightarrow J/\psi \rho$ measures $1^{++}$ at 8$\sigma$

Faccini, AP, Piccinini, Polosa PRD 86, 054012

LHCb, PRL 110, 222001
Charged $Z$ states

Notes from the Editors: Highlights of the Year

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Physics looks back at the standout stories of 2013.

As 2013 draws to a close, we look back on the research covered in Physics that really made waves in and beyond the physics community. In thinking about which stories to highlight, we considered a combination of factors: popularity on the website, a clear element of surprise or discovery, or signs that the work could lead to better technology. On behalf of the Physics staff, we wish everyone an excellent New Year.

Matteo Rini and Jessica Thomas

Four-Quark Matter

Quarks come in twos and threes—or so nearly every experiment has told us. This summer, the BESIII Collaboration in China and the Belle Collaboration in Japan reported they had sorted through the debris of high-energy electron-positron collisions and seen a mysterious particle that appeared to contain four quarks. Though other explanations for the nature of the particle, dubbed $Z_{c}(3900)$, are possible, the “tetraquark” interpretation may be gaining traction: BESIII has since seen a series of other particles that appear to contain four quarks.
**Charged Z states**

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

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

\[ e^+ e^- \rightarrow Z_c (3900)^+ \pi^- \rightarrow J/\psi \pi^+ \pi^- \text{ and } (DD^\ast)^+ \pi^- \]

\[ M = 3888.7 \pm 3.4 \text{ MeV}, \Gamma = 35 \pm 7 \text{ MeV} \]

\[ e^+ e^- \rightarrow Z'_c (4020)^+ \pi^- \rightarrow h_c \pi^+ \pi^- \text{ and } \bar{D}^0 D^{\ast+} \pi^- \]

\[ M = 4023.9 \pm 2.4 \text{ MeV}, \Gamma = 10 \pm 6 \text{ MeV} \]

Far from open charm thresholds

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

\[ I^G J^{PC} = 1^+ 1^{+\ast} \]

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

\[ \Gamma = 172 \pm 13^{+37}_{-34} \text{ MeV} \]
Pentaquarks!

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

$M_1 = 4380 \pm 8 \pm 29 \text{ MeV}$
$\Gamma_1 = 205 \pm 18 \pm 86 \text{ MeV}$
$M_2 = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$
$\Gamma_2 = 39 \pm 5 \pm 19 \text{ MeV}$

Quantum numbers

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

No obvious threshold nearby
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), Born-Oppenheimer 4q

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

Hadrocharmonium (Van der Waals forces)

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

Cusp (kinematical effect)
Tetraquark – Type I

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

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

Maiani, Piccinini, Polosa, Riquer PRD71 014028

Spectrum according to color-spin hamiltonian:

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

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

\[ \kappa_{q\bar{q}} = 315 \text{ MeV}, \quad \kappa_{c\bar{c}} = 59 \text{ MeV}, \quad \kappa_{cq} = 22 \text{ MeV}, \quad \kappa_{c\bar{q}} = 72 \text{ MeV} \]
But later on a $Z'_c(4020)$ was discovered decaying into $h_c \pi$
Tetraquark: new ansatz

Maiani, Piccinini, Polosa, Riquer PRD89 114010

New ansatz: the diquarks are compact objects spacially separated from each other, only $\kappa_{cq} \neq 0$, existing spectrum is fitted if $\kappa_{cq} = 67$ MeV

\[
\mathcal{L} = H = 2m_{dq} - 2\kappa_{cq} \left( \vec{S}_c \cdot \vec{S}_q + \vec{S}_c' \cdot \vec{S}_q' \right) + \frac{B_c \vec{L} \cdot \vec{L}}{2} - 2a \vec{L} \cdot \vec{S}
\]
A state apparently breaking HQSS has been observed

Compatible to be the $Y_3$ state

Faccini, Filaci, Guerrieri, AP, Polosa, PRD 91, 117501
$$Z_c(3900) \rightarrow \eta_c \rho$$

If tetraquark

Kinematics with PHS and HQSS
Dynamics estimated according to Brodsky, Hwang, Lebed, PRL113, 112001

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

Non-Relativistic Effective Theory
HQET and Hidden gauge Lagrangian

$$\frac{BR(Z_c \rightarrow \eta_c \rho)}{BR(Z_c \rightarrow J/\psi \pi)} = (4.6^{+2.5}_{-1.7}) \times 10^{-2} ; \quad \frac{BR(Z'_c \rightarrow \eta_c \rho)}{BR(Z'_c \rightarrow h_c \pi)} = (1.0^{+0.6}_{-0.4}) \times 10^{-2}.$$
Doubly charmed states

We explored the phenomenology of doubly charmed states, which in tetraquark model are $[cc]_{s=1}[\bar{q}q]_{s=0,1}$.

The doubly charged $cc\bar{d}\bar{d}$ partner could not be interpreted as a molecule.

These states might be observed in $B_c$ decays @LHC and sought on the lattice.

Esposito, Papinutto, AP, Polosa, Tantalo, PRD88 (2013) 054029

Preliminary results on spectrum for $m_{\pi} = 490$ MeV, $32^3 \times 64$ lattice, $a = 0.075$ fm

Guerrieri, Papinutto, AP, Polosa, Tantalo, PoS LATTICE2014 106
Prompt production of $X(3872)$

The most popular interpretation of the $X(3872)$ 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 $k_{\text{rel}}$?

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001

$$\sigma(p\bar{p} \rightarrow X(3872)) \sim \int d^3 k \left| \langle X|D\bar{D}^*\rangle\langle D\bar{D}^*|p\bar{p}\rangle \right|^2 < \int_{k<k_{\text{max}}} d^3 k \left| \langle D\bar{D}^*|p\bar{p}\rangle \right|^2$$

We obtain with MC simulations

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

Experimentally

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

Molecule challenged!!!
Estimating $k_{\text{max}}$

A solution can be FSI (rescattering of $DD^*$), which allow $k_{\text{max}}$ to be as large as $5m_\pi \sim 700$ MeV

$$\sigma(p\bar{p} \rightarrow DD^* | k < k_{\text{max}}) \approx 230 \text{ nb}$$

Artoisenet and Braaten, PRD81, 114018

$$\mathcal{M} = -NA_{\text{prod}}^{on} \frac{e^{i\delta} \sin \delta}{k a_{NN}}$$

\begin{equation}
\sigma(p\bar{p} \rightarrow X(3872)) \rightarrow \sigma(p\bar{p} \rightarrow DD^* | k < k_{\text{max}}) \times \frac{6\pi \sqrt{2\mu E_B}}{k_{\text{max}}}
\end{equation}

However, the applicability of Watson-Migdal approach is challenged by the presence of pions that interfere with $DD^*$ propagation

Bignamini, Grinstein, Piccinini, Polosa, Riquer, Sabelli, PLB684, 228-230

FSI saturate unitarity bound? Influence of pions small?

Artoisenet and Braaten, PRD83, 014019

Guo, Meissner, Wang, Yang, JHEP 1405, 138; EPJC74 9, 3063; CTP 61 354

use $E_{\text{max}} = M_X + \Gamma_X$ for above-threshold unstable states

With different choices, 2 orders of magnitude uncertainty,

limits on predictive power
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
Light nuclei at ALICE

Recently, ALICE published data on production of light nuclei in Pb-Pb and \( pp \) collisions. These provide a benchmark for \( X(3872) \) production.

Hypertriton

Hypertriton

\[ \text{arXiv:1506.08453} \]

Deuteron

\[ \text{arXiv:1506.08951} \]

Helium-3
Nuclear modification factors

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

\[
R_{CP} = \frac{N_{coll}^P \left( \frac{dN}{dp_T} \right)_C}{N_{coll}^C \left( \frac{dN}{dp_T} \right)_P}
\]

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

Larger than 1 at $p_T > 2.5$ GeV
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.
**X, Z_c, Z'_c: summary**

- How to solve molecule production paradox?
- How to justify bound states with positive binding energy?

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 (molecule) and discrete (4q) spectrum e.g. $DD^*$ has the same quantum numbers as $[cu][\bar{c}\bar{u}]$, the operators mix under renormalization

We add an interaction Hamiltonian $H_{QP}$

$$a \simeq a_P + C \sum \frac{|\langle \psi_i | H_{QP} | \psi_{th} \rangle|^2}{E_{th} - E_i}$$

$$\simeq a_{NR} - C \frac{|\langle \psi_{res} | H_{QP} | \psi_{th} \rangle|^2}{\nu}$$

Braaten and Kusunoki, PRD69, 074005
Papinutto, Piccinini, AP, Polosa, Tantalo arXiv:1311.7374
Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

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Feshbach resonances

We impose a cutoff on $\nu < 100$ MeV
$X(3872)$ should be a $I = 0$ state, but $M(1^{++}) < M(D^{++}D^-)$
No charged component, isospin violation!

If we assume $\Gamma = A\sqrt{\nu}$, we can use $Z_c(3900)$ as input to extract $A = 10 \pm 5$ MeV$^{1/2}$
This value is compatible for all resonances (caveat: still large errors...)

| Open channel | $M_{4q}$ (MeV) | $\nu$ (MeV) | $\Gamma$ (MeV) | $I^G J^{PC}$ | name       |
|--------------|----------------|-------------|----------------|--------------|------------|
| $D^{*0}\bar{D}^0$ | 3872          | 0           | 0              | $1^-1^{++}$  | $X(3872)$ |
| $D^{*+}\bar{D}^0$ | 3900          | 24          | 53             | $1^+1^{--}$  | $Z_c(3900)$ |
| $D^{***}\bar{D}^0$ | 4025          | 8           | 24             | $1^+1^{--}$  | $Z'_c(4025)$ |
| $\eta_c(2S)\rho^+$ | 4475          | 75          | $>150$         | $1^+1^{--}$  | $Z(4430)$ |
| $B^{*+}\bar{B}^0$  | 10610         | 3           | 18             | $1^+1^{--}$  | $Z_b(10610)$ |
| $B^{**}\bar{B}^{*0}$ | 10650         | 1.8         | 11             | $1^+1^{--}$  | $Z'_b(10650)$ |

We remark that $\Gamma(Z'_b)/\Gamma(Z_b) \approx 0.63$, $\sqrt{\nu(Z'_b)/\nu(Z_b)} \approx 0.77$
Conclusions

The comprehension of strong interactions in the low energy region is tightly related to the understanding of the internal structure of hadrons. Despite a decade of efforts, the exotic charmonium sector is still puzzling. The experimental picture is still incomplete, many states are seen in one production and one decay channel only.

• The tetraquark model provides a comprehensive framework to describe most of the observed states
• However, it predicts much more levels than observed: dynamics (Feshbach?) is playing a crucial role
• The molecular interpretation has troubles with above-threshold states and production mechanisms
• Future experiments will need predictions which discriminate between the different models

Thank you
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

$$\frac{B(\psi(3770) \to D\bar{D})}{B(\psi(3770) \to J/\psi\pi\pi)} > 480$$
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?

A. Pilloni – Exotic Hadron Spectroscopy
$Y(4260) \to \gamma X(3872)$

F. Piccinini

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

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

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

Strong indication that $Y(4260)$ and $X(3872)$ share a similar structure
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 $\Upsilon(5S) \rightarrow h_b(nP)\pi\pi$ which violates HQSS

$\Upsilon(5S) \rightarrow Z_b(10610)^+\pi^- \rightarrow \Upsilon(nS) \pi^+\pi^-, h_b(nP) \pi^+\pi^-$ and $\rightarrow (B B^*)^+\pi^-$

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

$\Upsilon(5S) \rightarrow Z'_b(10650)^+\pi^- \rightarrow \Upsilon(nS) \pi^+\pi^-, h_b(nP) \pi^+\pi^-$ and $\rightarrow \bar{B}^*0 B^+\pi^-$

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

$X(3915)$, seen in $B \rightarrow X K \rightarrow J/\psi \omega$
and $\gamma\gamma \rightarrow X \rightarrow J/\psi \omega$
$J^{PC} = 0^{++}$, candidate for $\chi c_0(2P)$
But $X(3915) \not\rightarrow D\bar{D}$ as expected,
and the hyperfine splitting
$M(2^{++}) - M(0^{++})$ too small

One/two peaks seen in $B \rightarrow XK \rightarrow J/\psi \phi K$,
close to threshold
| State    | $M$ (MeV)  | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode)                       | Experiment ($\#\sigma$) |
|----------|------------|----------------|----------|-------------------------------------|--------------------------|
| $X(3823)$ | 3823.1 ± 1.9 | < 24           | $?^-_1$  | $B \to K(\chi_{c1})$                | Belle$_{exp}^{[4.0]}$    |
| $X(3872)$ | 3871.68 ± 0.17 | < 1.2           | $1^{++}$ | $B \to K(\pi^+\pi^- J/\psi)$       | CDF$_{exp}^{[1.6]}$, D0$_{exp}^{[5.2]}$, LHC$_{exp}^{[9]}$ (up) |
|          |            |                |          | $pp \to (\pi^+\pi^- J/\psi)$       |                          |
|          |            |                |          | $pp \to (\pi^+\pi^- J/\psi)$       |                          |
|          |            |                |          | $B \to K(\pi^+\pi^- J/\psi)$       | Belle$_{exp}^{[4.3]}$, BaBar$_{exp}^{[4.0]}$ |
|          |            |                |          | $B \to K(\gamma J/\psi)$           | Belle$_{exp}^{[5.5]}$, BaBar$_{exp}^{[5.5]}$ |
|          |            |                |          | $B \to K(\psi(2S))$                 | LHC$_{exp}^{[4.4]}$ (up) |
| $Z_c(3900)^+$ | 3888.7 ± 3.4 | 35 ± 7         | $1^{--}$ | $B \to K(D\bar{D}^*)$               | Belle$_{exp}^{[6.4]}$, BaBar$_{exp}^{[4.9]}$ |
| $Z_c(4020)^+$ | 4023.9 ± 2.4 | 10 ± 6         | $1^{--}$ | $Y(4260) \to \pi^-(D\bar{D}^*)$     | BES II$_{exp}^{[8.9]}$ (up) |
|          |            |                |          | $Y(4260) \to \pi^-(\pi^+\pi^- J/\psi)$ | BES III$_{exp}^{[8]}$, Belle$_{exp}^{[5.2]}$ (up) |
|          |            |                |          | $Y(4260) \to \pi^-(\pi^+\pi^- J/\psi)$ | CLEO data$_{exp}^{[5]}$ |
| $Y_{exp}(3915)$ | 3918.4 ± 1.9 | 20 ± 5         | $0^{++}$ | $B \to K(\omega J/\psi)$           | Belle$_{exp}^{[8]}$, BaBar$_{exp}^{[19]}$ (up) |
| $Z(3930)$ | 3927.2 ± 2.6 | 24 ± 6         | $2^{++}$ | $e^+e^- \to e^+e^-(\omega J/\psi)$ | Belle$_{exp}^{[7.7]}$, BaBar$_{exp}^{[7.6]}$ |
| $X(3940)$ | 3942.8 $_{-1.7}^{+2.7}$ | 130 ± 24       | $?^-_1$  | $e^+e^- \to e^+e^-(D\bar{D}^*)$     | Belle$_{exp}^{[5.3]}$, BaBar$_{exp}^{[5.8]}$ |
| $Y(4008)$ | 3891.4 ± 1.2 | 255 ± 42       | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- J/\psi)$   | Belle$_{exp}^{[7.1]}$, BaBar$_{exp}^{[7.4]}$ |
| $Z(4090)^+$ | 4051.9 $_{-10}^{+24}$ | 82 ± 34         | $?^-_1$  | $B^0 \to K^-(\pi^+\chi_{c1})$     | Belle$_{exp}^{[5.0]}$, BaBar$_{exp}^{[5.5]}$ (up) |
| $Y(4140)$ | 4145.6 ± 3.6 | 14.3 ± 5.9     | $?^-_1$  | $B^+ \to K^+(\phi J/\psi)$         | CDHF$_{exp}^{[5.0]}$, BaBar$_{exp}^{[1.9]}$, LHC$_{exp}^{[1.4]}$, CMS$_{exp}^{[5]}$ (up) |
| $X(4160)$ | 4156.9 ± 2.5 | 130.1 ± 6.8    | $?^-_1$  | $e^+e^- \to J/\psi(D^*\bar{D}^*)$  | Belle$_{exp}^{[5.5]}$ |
| $Z(4200)^+$ | 4196.9 ± 3.5 | 370 ± 110      | $1^{--}$ | $B^0 \to K^-(\pi^+\pi^- J/\psi)$  | Belle$_{exp}^{[7.2]}$ |

| State    | $M$ (MeV)  | $\Gamma$ (MeV) | $J^{PC}$ | Process (mode)                       | Experiment ($\#\sigma$) |
|----------|------------|----------------|----------|-------------------------------------|--------------------------|
| $Y(4220)$ | 4196.8 ± 3.5 | 39 ± 32       | $1^{--}$ | $e^+e^- \to (\pi^+(\pi^- J/\psi)$  | BES III$_{dat}^{[6]}$, BaBar$_{exp}^{[4.5]}$ (4.5) |
| $Y(4230)$ | 4230 ± 8   | 38 ± 12       | $1^{--}$ | $e^+e^- \to (\chi_{c0}\omega)$     | BES II$_{exp}^{[9]}$ (up) |
| $Z(4240)^+$ | 4248.4 ± 45 | 177 ± 32      | $?^-_1$  | $B^0 \to K^-(\pi^+\chi_{c1})$     | Belle$_{exp}^{[5.0]}$, BaBar$_{exp}^{[2.0]}$ |
| $Y(4260)$ | 4250 ± 9   | 108 ± 12      | $1^{--}$ | $e^+e^- \to (\pi\pi J/\psi)$       | BaBar$_{exp}^{[8.9]}$ (8), LHC$_{exp}^{[9]}$ (up) |
|          |            |                |          | $e^+e^- \to (f_0(980)J/\psi)$      | Belle$_{exp}^{[7]}$ (up), Belle$_{exp}^{[1]}$ (up) |
|          |            |                |          | $e^+e^- \to (\pi^- Z_c(3900)^+)$   | BES II$_{exp}^{[8]}$, Belle$_{exp}^{[5.2]}$ |
|          |            |                |          | $e^+e^- \to (\gamma X(3872))$      | BES III$_{exp}^{[5.3]}$, BES III$_{dat}^{[6]}$ |
| $Y(4290)$ | 4293 ± 9   | 222 ± 67      | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- J/\psi)$   | BES III$_{exp}^{[6]}$ (up) |
| $X(4350)$ | 4350.6 ± 1.1 | 13.7 ± 10     | $0/2^{++}$ | $e^+e^- \to e^+e^-(\phi J/\psi)$   | Belle$_{exp}^{[8]}$ (3.2) |
| $Y(4360)$ | 4354 ± 11  | 78 ± 16       | $1^{--}$ | $e^+e^- \to (\pi^+\pi^- J/\psi)$   | Belle$_{exp}^{[8]}$, BaBar$_{exp}^{[2]}$ (up) |
| $Z(4390)^+$ | 4175 ± 17  | 180 ± 31      | $1^{--}$ | $B^0 \to K^-(\pi\pi J/\psi)$       | Belle$_{exp}^{[6.4]}$, BaBar$_{exp}^{[2.4]}$ (up) |
| $Y(4630)$ | 4634.1 ± 1.1 | 92 ± 3 ± 32   | $1^{--}$ | $e^+e^- \to (\Lambda^+_c \Lambda^-_c)$ | Belle$_{exp}^{[8.2]}$ |
| $Y(4660)$ | 4665 ± 10  | 53 ± 14       | $1^{--}$ | $e^+e^- \to (\pi^+(\pi^- J/\psi)$  | Belle$_{exp}^{[8]}$, BaBar$_{exp}^{[2]}$ (5) |
| $Z_0(10610)^+$ | 10607.2 ± 2.0 | 18.4 ± 2.4   | $1^{--}$ | $\Upsilon(5S) \to \pi(\pi Y(nS))$  | Belle$_{exp}^{[10]}$ (10) |
|          |            |                |          | $\Upsilon(5S) \to \pi^- (\pi^+ h_0(nP))$ | Belle$_{exp}^{[16]}$ |
| $Z_0(10650)^+$ | 10652.2 ± 1.5 | 11.5 ± 2.2   | $1^{--}$ | $\Upsilon(5S) \to \pi^-(B \bar{B}^*)^+$ | Belle$_{exp}^{[10]}$ (10) |
|          |            |                |          | $\Upsilon(5S) \to \pi^- (\pi^+ h_0(nP))$ | Belle$_{exp}^{[16]}$ |
|          |            |                |          | $\Upsilon(5S) \to \pi^- (B \bar{B}^*)^+$ | Belle$_{exp}^{[10]}$ (10) |

Guerrieri, AP, Piccinini, Polosa, IJMPA 30, 1530002

A. Pilloni – Exotic Hadron Spectroscopy
Diquarks

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

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

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

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

The singlet \( 1_c \) is an attractive combination

A diquark in \( 3_c \) is an attractive combination

A diquark is colored, so it can stay into hadrons but cannot be an asymptotic state

Evidence (?) of diquarks in lattice QCD, Alexandrou, de Forcrand, Lucini, PRL 97, 222002
Baryonium

A structure $[cq][\bar{c}q]$ can explain the dominance of baryon channel

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

$$B(Y(4660) \rightarrow \Lambda_c^+\Lambda_c^-) = 25 \pm 7$$

Cotugno, Faccini, Polosa, Sabelli, PRL 104, 132005
Tetraquark: radial excitations

Radial excitations
\[ Z(2S) = Z(4430) \]
\[ Y_1(2P) = Y(4360) \]
\[ Y_2(2P) = Y(4660) \]

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

\( \chi_c J(2P) - \chi_c J(1P) \approx 437 \text{ MeV} \)
\( \chi_b J(2P) - \chi_b J(1P) \approx 360 \text{ MeV} \)

Use the same splittings for tetraquarks

\[ M(Z(4430)) - M(Z_c(3900)) = 586^{+17}_{-26} \text{ MeV} \]
A **deuteron-like meson pair**, the interaction is mediated by the exchange of light mesons

- Some model-independent relations (**Weinberg’s theorem**) ✓
- 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 $\gg 1/m_\pi$, (but why $\Gamma_Y \gg \Gamma_{D_{-1}}$?)
- 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 ×

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

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 \( kR \ll 1 \), being \( R \sim 1/m_\pi \) the range of interaction) in an attractive potential \( U \) with a superficial level at \(-B\)

\[
f(ab \rightarrow ab) = -\frac{1}{\sqrt{2\mu}} \frac{\sqrt{B - i\sqrt{T}}}{B + T}\]

\[
B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2}\]

Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248
Weinberg theorem

\[ B = \frac{g^4}{512\pi^2} \frac{\mu^5}{(m_a m_b)^2}, \quad kR \ll 1 \]

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

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

Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248
Hadro-charmonium

Born in the context of QCD multipole expansion

\[ H_{\text{eff}} = -\frac{1}{2} a_\psi E_i^a E_i^a \]
\[ a_\psi = \langle \psi | (t_c^a - t_c^a') r_i G r_i (t_c^a - t_c^a') | \psi \rangle \]

the chromoelectric field interacts with soft light matter (highly excited light hadrons)

A bound state can occur via Van der Waals-like interactions

Expected to decay into core charmonium + light hadrons,
Decay into open charm exponentially suppressed
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:

  - CDF data
    - HERWIG :: $pp \rightarrow cc$
    - PYTHIA :: $pp \rightarrow cc$
    - $D^0$ :: $|y|<1 :: 5.5<p_T<20$ GeV
    - $D^{*-}$ :: $|y|<1 :: 5.5<p_T<20$ GeV

The $c$-cbar run underestimate the low angles (low-$k_0$) region!

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

| $k_0^{\text{max}}$ | HERWIG 50 MeV | HERWIG 100 MeV | PYTHIA 50 MeV | PYTHIA 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 $\sigma_{\text{exp}} \approx 30$ nb,
The enhancement is impressive because first bins are almost empty

| #events | Herwig | Pythia |
|---------|--------|--------|
| 0π      | 10     | 3      |
| 1π      | 19     | 21     |
| 3π      | 802    | 814    |
Light nuclei at ALICE

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

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

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

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, \( \rho = \tanh^{-1} \left( \frac{(n+2) \langle \beta \rangle}{2} \left( \frac{r}{R} \right)^n \right) \), and \( \langle \beta \rangle \) the averaged speed of the particles in the medium.
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).

No prompt production without Feshbach resonances!

For example, we compare the at-threshold $X(3872)$ with the below-threshold $Y(4260)$.

CMS $X(3872)$ data: JHEP 1304, 154

$$\frac{\sigma(pp \rightarrow X(3872)) \times BR(X(3872) \rightarrow J/\psi \pi^+\pi^-)}{\sigma(pp \rightarrow Y(4260)) \times BR(Y(4260) \rightarrow J/\psi \pi^+\pi^-)} \sim 10^2$$
$T$ states production

\[
\begin{align*}
\bar{b} & \rightarrow \lambda^2 \rightarrow \bar{c} \rightarrow D^0, D^-, D_s^- \\
& \rightarrow u, d, s \\
& \rightarrow \bar{u}, \bar{d}, \bar{s} \\
& \rightarrow c \\
\end{align*}
\]

\[
\begin{align*}
b & \rightarrow \lambda^2 \rightarrow c \rightarrow T^+, T^{++}, T_{s^{++}} \\
& \rightarrow \bar{u} \\
& \rightarrow d \\
& \rightarrow \bar{u}, \bar{d}, \bar{s} \\
& \rightarrow u, d, s \\
& \rightarrow p, n, \Lambda, \Sigma, \Xi, \ldots
\end{align*}
\]