The Quest for Exotic States

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CINVESTAV, Mexico City, November 17th, 2017
Prologue

Why we do care about hadron spectroscopy?

• Because it allows us to understand how the QCD degrees of freedom manifest in nature. The role of models is crucial.

• Because we need a better understanding of hadron amplitudes if we want to reduce the «hadronic uncertainties» in precision physics (e.g. $\tau$ EDM, $g_\mu - 2$, CPV in hadronic $B$ decays...)

• (the honest answer would be «because we are nerds and we like it», but we cannot reply like this to funding agencies)
Outline

• The exotic landscape

• Amplitude analysis
  • The $S$-matrix principles
  • Case study for the $Z_c(3900)$
  • Three-body unitarity
  • Pentaquark photoproduction

• Modeling
  • Diquark-antidiquark & Molecules
  • Production at colliders
  • Hybridized tetraquarks
Interpretations on the spectrum leads to understanding fundamental laws of nature.
Quarkonium orthodoxy

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

OZI-rule, QCD multipole

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

Potential models
(meaningful when \( M_Q \to \infty \))

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

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

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

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

$m_b \sim 5$ GeV, $m_c \sim 1.5$ 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)
A host of unexpected resonances have appeared decaying mostly into charmonium + light

Hardly reconciled with usual charmonium interpretation

Esposito, AP, Polosa, Phys.Rept. 668
**X(3872)**

- Discovered in $B \to K X \to K J/\psi \pi \pi$
- Quantum numbers $1^{++}$
- 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 $\chi_{c1}(2P)$
  \[
  M = 3871.68 \pm 0.17 \text{ MeV}
  \]
  \[
  M_X - M_{DD^*} = -3 \pm 192 \text{ keV}
  \]
  \[
  \Gamma < 1.2 \text{ MeV @90%}
  \]
Large prompt production at hadron colliders

\[ \sigma_B / \sigma_{TOT} = (26.3 \pm 2.3 \pm 1.6)\% \]

\[ \sigma_{PR} \times B(X \to J/\psi \pi \pi) = (1.06 \pm 0.11 \pm 0.15) \text{ nb} \]

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### Table

<table>
<thead>
<tr>
<th>B decay mode</th>
<th>X decay mode</th>
<th>product branching fraction ((\times 10^3))</th>
<th>(B_{fit})</th>
<th>(R_{fit})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K^+ X)</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>0.86 ± 0.08</td>
<td>(0.081^{+0.019}_{-0.031})</td>
<td>1</td>
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<tr>
<td>(K^0 X)</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>0.41 ± 0.11</td>
<td>(0.061^{+0.024}_{-0.036})</td>
<td>0.77^{+0.28}_{-0.35}</td>
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<tr>
<td>((K^+ \pi^-)_{NR} X)</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>0.81 ± 0.20^{+0.11}_{-0.14}</td>
<td>(0.614^{+0.169}_{-0.074})</td>
<td>8.2^{+2.3}_{-2.8}</td>
</tr>
<tr>
<td>(K^{*-} X)</td>
<td>(X \to \pi \pi J/\psi)</td>
<td>&lt; 0.34, 90% C.L.</td>
<td>(0.019^{+0.006}_{-0.009})</td>
<td>0.24^{+0.05}_{-0.06}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \omega J/\psi)</td>
<td>R = 0.8 ± 0.3</td>
<td>(0.10^{+0.02}_{-0.03})</td>
<td>0.04^{+0.02}_{-0.05}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \pi \pi^0 J/\psi)</td>
<td>0.6 ± 0.3 ± 0.1</td>
<td>(0.08^{+0.05}_{-0.04})</td>
<td>0.23^{+0.04}_{-0.02}</td>
</tr>
<tr>
<td>(K^0 X)</td>
<td>(X \to \pi \pi^0 J/\psi)</td>
<td>R = 1.0 ± 0.4 ± 0.3</td>
<td>(0.05^{+0.02}_{-0.03})</td>
<td>0.1^{+0.05}_{-0.04}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to D^{*0} B^0)</td>
<td>8.5 ± 2.6</td>
<td>(0.61^{+0.16}_{-0.07})</td>
<td>8.2^{+2.3}_{-2.8}</td>
</tr>
<tr>
<td>(K^0 X)</td>
<td>(X \to D^{*0} B^0)</td>
<td>12 ± 4</td>
<td>(0.019^{+0.006}_{-0.009})</td>
<td>0.24^{+0.05}_{-0.06}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>0.202 ± 0.038</td>
<td>(0.019^{+0.006}_{-0.009})</td>
<td>0.24^{+0.05}_{-0.06}</td>
</tr>
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<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>0.28 ± 0.08 ± 0.01</td>
<td>(0.28^{+0.05}_{-0.03})</td>
<td>0.28^{+0.05}_{-0.03}</td>
</tr>
<tr>
<td>(K^0 X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>0.178^{+0.048}_{-0.044} ± 0.012</td>
<td>(0.178^{+0.048}_{-0.044} \text{ (LO NRQCD)})</td>
<td>0.23^{+0.05}_{-0.04}</td>
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<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>0.26 ± 0.18 ± 0.02</td>
<td>(0.178^{+0.048}_{-0.044} \text{ (LO NRQCD)})</td>
<td>0.23^{+0.05}_{-0.04}</td>
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<tr>
<td>(K^0 X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(0.124^{+0.076}_{-0.061} \text{ (LO NRQCD)})</td>
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<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(0.083^{+0.109}_{-0.083} \text{ (LO NRQCD)})</td>
<td>0.23^{+0.05}_{-0.04}</td>
<td>0.23^{+0.05}_{-0.04}</td>
</tr>
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<td>(K^0 X)</td>
<td>(X \to \gamma J/\psi)</td>
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<td>(0.124^{+0.076}_{-0.061} \text{ (LO NRQCD)})</td>
<td>0.23^{+0.05}_{-0.04}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(R' = 2.46 \pm 0.64 \pm 0.20)</td>
<td>(0.124^{+0.076}_{-0.061} \text{ (LO NRQCD)})</td>
<td>0.23^{+0.05}_{-0.04}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>1.14 ± 0.55 ± 0.10</td>
<td>(0.124^{+0.076}_{-0.061} \text{ (LO NRQCD)})</td>
<td>0.23^{+0.05}_{-0.04}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(0.112^{+0.290}_{-0.057} \text{ (LO NRQCD)})</td>
<td>0.23^{+0.05}_{-0.04}</td>
<td>0.23^{+0.05}_{-0.04}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(&lt; 9.6 \times 10^{-3})</td>
<td>(&lt; 1.0 \times 10^{-3})</td>
<td>0.014</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(&lt; 0.016)</td>
<td>(&lt; 1.7 \times 10^{-3})</td>
<td>0.024</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \gamma J/\psi)</td>
<td>(&lt; 4.5 \times 10^{-3})</td>
<td>(&lt; 4.7 \times 10^{-4})</td>
<td>6.6 \times 10^{-3}</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \eta J/\psi)</td>
<td>(&lt; 1.05)</td>
<td>(&lt; 1.0 \times 10^{-3})</td>
<td>0.11</td>
</tr>
<tr>
<td>(K^+ X)</td>
<td>(X \to \eta J/\psi)</td>
<td>(&lt; 9.6 \times 10^{-4})</td>
<td>(&lt; 1.6 \times 10^{-4})</td>
<td>2.2 \times 10^{-3}</td>
</tr>
</tbody>
</table>

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CMS, JHEP 1304, 154
Vector $Y$ states

Lots of unexpected $J^{PC} = 1^{--}$ states found in ISR/direct production (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
Large HQSS violation
New BESIII data show a peculiar lineshape for the $Y(4260)$
The state appear lighter and narrower, compatible with the ones in $h_c \pi \pi$ and $\chi_{c0} \omega$
A broader old-fashioned $Y(4260)$ is appearing in $\bar{D}D^*\pi$, maybe indicating a $\bar{D}D_1$ dominance
Charged $Z$ states: $Z_c(3900), Z'_c(4020)$

Charged quarkonium-like resonances have been found, \textit{4q needed}

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

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

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

$e^+e^- \rightarrow Z'_c(4020)^+\pi^- \rightarrow h_c \pi^+\pi^-$ and $\rightarrow D'^0D^\ast+\pi^-$

$M = 4023.9 \pm 2.4$ MeV, $\Gamma = 10 \pm 6$ MeV
Charged $Z$ states: $Z_b(10610), Z'_b(10650)$

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!
Pentaquarks!

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

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

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

Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by $\Lambda^*$ (model dependence?)

No obvious threshold nearby
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Opposite parities needed for the interference to correctly describe angular distributions, low mass region contaminated by $\Lambda^*$ (model dependence?)

No obvious threshold nearby

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$X(3872)$ on the lattice

There is only evidence (?) for the $X(3872)$ in the $I^G J^{PC} = 0^+ 1^{++}$ channel

Caveats:
- Small lattices, large artifacts
- Three body dynamics may play a role
- Interpretation of the overlap coefficients is questionable

Status of other XYZ on the lattice is even less clear

S. Prelovsek, L. Leskovec, PRL111, 192001
Interpretations on the spectrum leads to understanding fundamental laws of nature.
S-Matrix principles

A(s,t) = \sum_l A_l(s) P_l(z_s)

Analyticity

A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)

These are constraints the amplitudes have to satisfy, but do not fix the dynamics.

Resonances (QCD states) are poles in the unphysical Riemann sheets.
Pole hunting

Bound states on the real axis 1st sheet
Not-so-bound (virtual) states on the real axis 2nd sheet

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Pole hunting

More complicated structure when more thresholds arise: two sheets for each new threshold

III sheet: usual resonances
IV sheet: cusps (virtual states)
Example: The charged $Z_c(3900)$

A charged charmonium-like resonance has been claimed by BESIII in 2013.

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

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

Such a state would require a minimal 4q content and would be manifestly exotic.
Amplitude analysis for $Z_c(3900)$

One can test different parametrizations of the amplitude, which correspond to different singularities $\rightarrow$ different natures

Triangle rescattering, logarithmic branching point

(anti)bound state, II/IV sheet pole («molecule»)

Resonance, III sheet pole («compact state»)

AP et al. (JPAC), PLB772, 200

Swanson, Phys.Rept. 429

Hanhart et al. PRL111, 132003

Maiani et al., PRD71, 014028

Faccini et al., PRD87, 111102

Esposito et al., Phys.Rept. 668

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Amplitude model

\[ f_i(s, t, u) = 16\pi \sum_{l=0}^{L_{\text{max}}} (2l + 1) \left( a_{l,i}^{(s)}(s) P_l(z_s) + a_{l,i}^{(t)}(t) P_l(z_t) + a_{l,i}^{(u)}(u) P_l(z_u) \right) \]

for \( l > 0 \).

\[ f_{0,i}(s) = \frac{1}{32\pi} \int_{-1}^{1} dz_s f_i(s, t(s, z_s), u(s, z_s)) = a_{0,i}^{(s)} + \frac{1}{32\pi} \int_{-1}^{1} dz_s \left( a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) \right) = a_{0,i}^{(s)} + b_{0,i}(s) \]

\[ f_{l,i}(s) = \frac{1}{32\pi} \int_{-1}^{1} dz_s P_l(z_s) \left( a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) \right) = b_{l,i}(s) \]

Khuri-Treiman

\[ f_i(s, t, u) = 16\pi \left[ a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) + \sum_j t_{ij}(s) \left( c_j + \frac{s}{\pi} \int_{s_j}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' (s' - s)} \right) \right], \]
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 effects cancels in Dalitz projections, no peaks (Schmid, Phys.Rev. 154, 1363)

\[ f_{0,i}(s) = b_{0,i}(s) + \frac{t_{ij}}{\pi} \int_{s_i}^{\infty} ds' \frac{\rho_{j}(s') b_{0,j}(s')}{s' - s} \]

...but the cancellation can be spread in different channels, you might still see peaks in other channels only!

Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo, Meissner, Wang, Yang PRD92, 071502
Testing scenarios

- We approximate all the particles to be scalar – this affects the value of couplings, which are not normalized anyway – but not the position of singularities. This also limits the number of free parameters.

\[
f_i(s, t, u) = 16\pi \left[ a_{0,i}^{(t)}(t) + a_{0,i}^{(u)}(u) + \sum_j t_{ij}(s) \left( c_j + \frac{s}{\pi} \int_{s_j}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' (s' - s)} \right) \right],
\]

The scattering matrix is parametrized as \((t^{-1})_{ij} = K_{ij} - i \rho_i \delta_{ij}\)

Four different scenarios considered:

- «III»: the K matrix is \(\frac{g_i g_j}{M^2 - s'}\), this generates a pole in the closest unphysical sheet. The rescattering integral is set to zero.
- «III+tr.»: same, but with the correct value of the rescattering integral.
- «IV+tr.»: the K matrix is constant, this generates a pole in the IV sheet.
- «tr.»: same, but the pole is pushed far away by adding a penalty in the \(\chi^2\)
Singularities and lineshapes

Different lineshapes according to different singularities

- Triangle
- IV sheet pole
- III+tr.
- III sheet pole
- IV+tr.
- IV sheet pole
- tr.
- no pole
- Full

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Fit: III

\[ E_{\text{CM}} = 4.26 \text{ GeV} \]

\[ E_{\text{CM}} = 4.23 \text{ GeV} \]

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Fit: III+tr. 

\( E_{CM} = 4.26 \text{ GeV} \)

\( E_{CM} = 4.23 \text{ GeV} \)
Fit: IV+tr.

$E_{CM} = 4.26\; GeV$

$E_{CM} = 4.23\; GeV$

$E_{CM} = 4.23\; GeV$

$E_{CM} = 4.26\; GeV$
Fit: tr.
Fit summary

Naive loglikelihood ratio test give a $\sim 4\sigma$ significance of the scenario III+tr. over IV+tr., looking at plots it looks too much – better using some more solid test
Pole extraction

### Pole extraction

<table>
<thead>
<tr>
<th>Scenario</th>
<th>III+tr.</th>
<th>IV+tr.</th>
<th>tr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>1.5σ (1.5σ)</td>
<td>1.5σ (2.7σ)</td>
<td>“2.4σ” (“1.4σ”)</td>
</tr>
<tr>
<td>III+tr.</td>
<td>–</td>
<td>1.5σ (3.1σ)</td>
<td>“2.6σ” (“1.3σ”)</td>
</tr>
<tr>
<td>IV+tr.</td>
<td>–</td>
<td>–</td>
<td>“2.1σ” (“0.9σ”)</td>
</tr>
</tbody>
</table>

Not conclusive at this stage
Three-Body Unitarity

Original study by Amado, Aaron, Young (1968)

- 3-dimensional integral equation from unitarity constraint & BSE ansatz
- valid below break-up energies ($E < 3m$)
- Analyticity constraints unclear

\[ \hat{T} = S + \hat{T}_c + \hat{T}_d \]

- $\nu$ a general function with no right-hand singularities
- Two-body interaction is parametrized by an «isobar», i.e. a function with the correct right-hand singularities and definite quantum numbers
- $S$ and $T$ are yet unknown functions
Three-Body Unitarity

We impose the Bethe-Salpeter ansatz for the Isobar-spectator interaction \( B \) and \( \tau \) are initially unknown

\[
\langle q_1, q_2, q_3 | (\hat{T} - \hat{T}^\dagger) | p_1, p_2, p_3 \rangle = i \int_P \langle q_1, q_2, q_3 | \hat{T}^\dagger | k_1, k_2, k_3 \rangle \langle k_1, k_2, k_3 | \hat{T} | p_1, p_2, p_3 \rangle
\]

We plug the BS ansatz in the left hand side of the unitarity equation, then match!
Three-Body Unitarity

\[
\langle q_1, q_2, q_3 | (\hat{T} - \hat{T}^\dagger) | p_1, p_2, p_3 \rangle = i \int \mathcal{P} \langle q_1, q_2, q_3 | \hat{T}^\dagger | k_1, k_2, k_3 \rangle \langle k_1, k_2, k_3 | \hat{T} | p_1, p_2, p_3 \rangle
\]

BS ansatz

Product of disconnected terms are source for the connected amplitude
Three-Body Unitarity

\[ \langle q_1, q_2, q_3 | (\hat{T} - \hat{T}^\dagger) | p_1, p_2, p_3 \rangle = i \int_P \langle q_1, q_2, q_3 | \hat{T}^\dagger | k_1, k_2, k_3 \rangle \langle k_1, k_2, k_3 | \hat{T} | p_1, p_2, p_3 \rangle \]

BS ansatz

Product of disconnected terms are source for the connected amplitude
Three-Body Unitarity

Imaginary parts of $B$, $\tau$, $S$ are fixed by unitarity and matching (for simplicity $\nu = \lambda$)

$$\tau(\sigma(k)) = (2\pi)\delta^+(k^2 - m^2)S(\sigma(k))$$

$$-\frac{1}{S(P^2)} = \sigma(k) - M_0^2 - \frac{1}{(2\pi)^3} \int d^3\ell \frac{\lambda^2}{2E_\ell(\sigma(k) - 4E_\ell^2 + i\epsilon)}$$

- in the rest-frame of isobar ($\textit{Lorentz invariance}$!)
- twice subtracted dispersion relation in $\sigma(k) = (P-k)^2$

The freedom of adding real terms to $B$ allows us to use this solution as a flexible parametrization

Numerics in progress:
- D. Sadasivan, M. Mai, AP, M. Doring, A. Szczepaniak for the $a_1(1260)$ and $a_1(1420)$
- A. Jackura, AP et al. (JPAC) for the $X(3872)$
- J.M. Alarcon, E. Passemar, AP, C. Weiss for the nucleon isoscalar vector form factor
To exclude any rescattering mechanism, we propose to search the $P_c(4450)$ state in photoproduction.

Vector meson dominance relates the radiative width to the hadronic width

\[
\Gamma_\gamma = 4\pi\alpha \Gamma_{\psi p} \left( \frac{f_\psi}{M_\psi} \right)^2 \left( \frac{p_i}{p_f} \right)^{2\ell+1} \times \frac{4}{6}
\]

Hiller Blin, AP et al. (JPAC), PRD94, 034002

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The background is described via an Effective Pomeron, whose parameters are fitted to high energy data from Hera.

\[ \langle \lambda_\psi \lambda_{p'} | T_P | \lambda_\gamma \lambda_p \rangle = \]

\[ iA \left( \frac{s - s_t}{s_0} \right) ^{\alpha(t)} e^{b_0(t-t_{\text{min}})} \delta \lambda_p \lambda_{p'} \delta \lambda_\psi \lambda_\gamma \]

Asymptotic + Effective threshold

Helicity conservation

Hiller Blin, AP et al. (JPAC), PRD94, 034002
Hiller Blin, AP et al. (JPAC), PRD94, 034002

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Hadron Spectroscopy

Interpretations on the spectrum leads to understanding fundamental laws of nature.

Properties, Model building

Lattice QCD

Data

Amplitude analysis

Meson

Baryon

Glueball

Hybrids

Tetraquark

Molecule

Hadroquarkonium

Experiment

QCD
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 \(1_c\) is attractive

A diquark in \(\bar{3}_c\) 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

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

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

Maiani, Piccinini, Polosa, Riquer PRD89 114010

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$cq ar{c}q$</th>
<th>$car{c}qar{q}$</th>
<th>Resonance Assign.</th>
<th>Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^{++}$</td>
<td>$</td>
<td>0, 0\rangle$</td>
<td>$1/2</td>
<td>0, 0\rangle + \sqrt{3}/2</td>
</tr>
<tr>
<td>0$^{++}$</td>
<td>$</td>
<td>1, 1\rangle_0$</td>
<td>$\sqrt{3}/2</td>
<td>0, 0\rangle - 1/2</td>
</tr>
<tr>
<td>1$^{++}$</td>
<td>$1/\sqrt{2}(</td>
<td>1, 0\rangle +</td>
<td>0, 1\rangle)</td>
<td>$</td>
</tr>
<tr>
<td>1$^{+-}$</td>
<td>$1/\sqrt{2}(</td>
<td>1, 0\rangle -</td>
<td>0, 1\rangle)</td>
<td>$1/\sqrt{2}(</td>
</tr>
<tr>
<td>1$^{-+}$</td>
<td>$</td>
<td>1, 1\rangle_1$</td>
<td>$1/\sqrt{2}(</td>
<td>1, 0\rangle +</td>
</tr>
<tr>
<td>2$^{++}$</td>
<td>$</td>
<td>1, 1\rangle_2$</td>
<td>$</td>
<td>1, 1\rangle_2$</td>
</tr>
</tbody>
</table>

\[ H_{\text{eff}} = 2m_Q + \frac{B_Q}{2} L^2 - 3\kappa_{cq} + 2a_Y L \cdot S + b_Y \frac{\langle S_{12} \rangle}{4} \]

\[ + \kappa_{cq} \left[ 2(S_q \cdot S_c + S_{\bar{q}} \cdot S_{\bar{c}}) + 3 \right] \]

## Two different mass scenarios

| Label | $|S_Q, S_{\bar{Q}}; S, L\rangle_J$ |
|-------|----------------------------------|
| $Y_1$ | $|0, 0; 0, 1\rangle$ |
| $Y_2$ | $(|1, 0; 1, 1\rangle_1 + |0, 1; 1, 1\rangle_1)/\sqrt{2}$ |
| $Y_3$ | $|1, 1; 0, 1\rangle$ |
| $Y_4$ | $|1, 1; 2, 1\rangle$ |
| $Y_5$ | $|1, 1; 2, 3\rangle_1$ |

### Prediction for a high $Y_5$

- $M_1 = 4008 \pm 40^{+114}_{-28}$, $M_2 = 4230 \pm 8$
- $M_3 = 4341 \pm 8$, $M_4 = 4643 \pm 9$
- $M_1 = 4219.6 \pm 3.3 \pm 5.1$, $M_2 = 4333.2 \pm 19.9$
- $M_3 = 4391.5 \pm 6.3$, $M_4 = 4643 \pm 9$

\[ M_5 = \left\{ \begin{array}{ll}
6539 \text{ MeV} & \text{SI(c1)} \\
6589 \text{ MeV} & \text{SI(c2)} \\
6862 \text{ MeV} & \text{SII(c1)} \\
6899 \text{ MeV} & \text{SII(c2)} \\
\end{array} \right. \]
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 \(\gg 1/m_\pi\)
- 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

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

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 corresponds to the pure molecular interpretation of the \( X(3872) \)

Weinberg, PR 130, 776
Weinberg, PR 137, B672
Polosa, PLB 746, 248
This means that IF you can consider the pion exchange as a contact interaction, the amplitude is determined by the pole close to threshold.

This loop is now divergent, I need to renormalize the integral I can put the pole where I want.
Weinberg and amplitudes

A. Jackura, AP et al., in progress

BUT the $D^*$ actually decays into $D\pi$ and the system is constrained by 3-body unitarity

The position of the pole can be calculated given a model for the simple pion exchange

The simplest model leads to a convergent dispersion relation, the pole position is determined

One can check whether this purely molecular amplitude is consistent or not with data

Complex $s$

Short cut of real pion exchange

pole?
**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

\[
\sigma_{MC}(p\overline{p} \rightarrow DD^*|k < k_{max}) \approx 0.1 \text{ nb}
\]

\[
\sigma_{exp}(p\overline{p} \rightarrow X(3872)) \approx 30 - 70 \text{ nb!!!}
\]

_Bignamini et al. PRL103 (2009) 162001_

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

_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_
Nuclear modification factors

What happens to molecules in heavy ion collisions?
We can use deuteron data to extract the values of the nuclear modification factors

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

Larger than 1 at \( p_T > 2.5 \text{ GeV} \)
Light nuclei at ALICE vs. X(3872)

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

The X(3872) is way larger than the extrapolated cross section
Production of $Y(4260)$ and $P_c(4450)$

Given the new lineshape by BESIII, we need to rethink the binding energy of the $Y(4260)$

J. Nys and AP, to appear

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>$\bar{D}^0 D^{*0}$</td>
<td>$\sim 100$ keV</td>
<td>$\sim 50$ MeV</td>
<td>$1\pi (\sim 300$ MeV)</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>$\bar{D} D_1$</td>
<td>$\sim 70$ MeV</td>
<td>$\sim 400$ MeV</td>
<td>$2\pi (\sim 600$ MeV)</td>
</tr>
<tr>
<td>$P_c(4450)$</td>
<td>$\bar{D}^* \Sigma_c$</td>
<td>$\sim 10$ MeV</td>
<td>$\sim 150$ MeV</td>
<td>$1\pi (\sim 300$ MeV)</td>
</tr>
</tbody>
</table>

If the states are purely hadron molecule, all the properties depend on the position of the pole with respect to threshold – all the features are universal

What does the production of $X(3872)$ implies for the other states?
Production of $Y(4260)$ and $P_c(4450)$

We can use Pythia to simulate the production of event, and calculate the relative production of $Y(4260)$ and $P_c(4450)$ with respect to the $X(3872)$

We tune our MC on charm pair production CDF data, $\sqrt{s} = 1.96$ TeV $D^0, D^{*-}$: $|y| < 1.5, 5.5 < p_T < 20$ GeV

For baryons we can double check with LHCb data LHCb, $\sqrt{s} = 7$ TeV, JHEP 1206, 141 all: $2 < y < 4, 3 < p_T < 12$ GeV

A. Pilloni – The Quest for Exotic States
Production of $Y(4260)$ and $P_c(4450)$

Naively, the fragmentation function of the $D_1$ is $1/10$ of the $D^*$, but the cross section scales as $k_{\text{max}}^3$.

Pythia $p\bar{p}$, $\sqrt{s} = 1.96$ TeV

$|y| < 0.6$, $5 < p_T < 20$ GeV

The production of $Y(4260)$ is expected to be at worse comparable with the $X(3872)$

<table>
<thead>
<tr>
<th></th>
<th>No FSI</th>
<th>With FSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(4260)/X$</td>
<td>23</td>
<td>0.75</td>
</tr>
<tr>
<td>$P_c(4450)/X$</td>
<td>1.0</td>
<td>0.01</td>
</tr>
</tbody>
</table>

J. Nys and AP, to appear

A. Pilloni – The Quest for Exotic States
Hybridized tetraquarks

The absence of many of the predicted states might point to the need for selection rules.

It is unlikely that the many close-by thresholds play no role whatsoever.

All the well assessed 4-quark resonances lie close and above some meson-meson thresholds:

We introduce a mechanism that might provide “dynamical selection rules” to explain the presence/absence of resonances from the experimental data.

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 $H_{QP}$ which connects the two subspaces.
Hybridized tetraquarks

\[ \Gamma = -16\pi^3 \rho \zeta(T) \sim 16\pi^4 \rho \left| H_{PQ} \right|^2 \delta \left( \frac{p_1^2}{2M} + \frac{p_2^2}{2M} - \delta \right) \]

The expected width is the average over momenta that allow for the existence of a tetraquark \( p < \bar{p} = 50 \div 100 \text{ MeV} \)

\[ \Gamma \sim A\sqrt{\delta} \]

We therefore expect to see a level if:
- \( \delta > 0 \) the state lies above threshold
- \( \delta < \frac{\bar{p}^2}{2M} \), only the closest threshold contributes
- The states \( \psi_Q \) and \( \psi_P \) are orthogonal

\[ X(3872)^+ \text{ falls below threshold, } M(1^{++}) < M(D^{*+}\bar{D}^0) \]
\[ \delta < 0, \text{ so } a > 0 \rightarrow \text{Repulsive interaction} \]
\[ \text{No charged partners of the } X(3872)! \]
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 $[bu][\bar{s}d]$ 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 $X(4140)$.

All the resonances can be fitted with $A = (10.3 \pm 1.3) \text{ MeV}^{1/2}$, $\chi^2/\text{DOF} = 1.2/5$. 

Esposito, AP, Polosa, PLB758, 292
Conclusions & prospects

• The discovery of exotic states has challenged the well established Charmonium framework
• Experiments are (too) prolific! Constant feedback on predictions
• Thorough amplitude analyses might shed some light on the microscopic nature of the new states
• The implementation of 3-body unitarity will be a major step to understand several of these phenomena
• Some fantasy needed, many phenomenological models introduced.
• Nuclei observation at hadron colliders can give an unexpected help in testing some phenomenological hypotheses for the XYZP states
• Search for exotic states in prompt production is a necessary step to improve our understanding of the sector
• Hybridization mechanisms might be effective in reducing the number of states predicted by the tetraquark picture

Thank you

A. Pilloni – The Quest for Exotic States
Dictionary – Quark model

\[ L = \text{orbital angular momentum} \]
\[ S = \text{spin } q + \bar{q} \]
\[ J = \text{total angular momentum} \]
\[ = \text{exp. measured spin} \]

\[ I = \text{isospin} = 0 \text{ for quarkonia} \]

\[ L - S \leq J \leq L + S \]
\[ P = (-1)^{L+1}, \quad C = (-1)^{L+S} \]
\[ G = (-1)^{L+S+I} \]

<table>
<thead>
<tr>
<th>( J^{PC} )</th>
<th>( L )</th>
<th>( S )</th>
<th>Charmonium ((c\bar{c}))</th>
<th>Bottomonium ((b\bar{b}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0^{--}</td>
<td>0 ((S\text{-wave}))</td>
<td>0</td>
<td>( \eta_c(nS) )</td>
<td>( \eta_b(nS) )</td>
</tr>
<tr>
<td>1^{--}</td>
<td>( 0 \text{ (S-wave)} )</td>
<td>1</td>
<td>( \psi(nS') )</td>
<td>( \Upsilon(nS) )</td>
</tr>
<tr>
<td>1^{+-}</td>
<td>( 0 \text{ (P-wave)} )</td>
<td>0</td>
<td>( h_c(nP) )</td>
<td>( h_b(nP) )</td>
</tr>
<tr>
<td>0^{++}</td>
<td>( 1 \text{ (P-wave)} )</td>
<td>1</td>
<td>( \chi_{c0}(nP) )</td>
<td>( \chi_{b0}(nP) )</td>
</tr>
<tr>
<td>1^{++}</td>
<td>( 1 \text{ (P-wave)} )</td>
<td>1</td>
<td>( \chi_{c1}(nP) )</td>
<td>( \chi_{b1}(nP) )</td>
</tr>
<tr>
<td>2^{++}</td>
<td>( 1 \text{ (P-wave)} )</td>
<td>1</td>
<td>( \chi_{c2}(nP) )</td>
<td>( \chi_{b2}(nP) )</td>
</tr>
</tbody>
</table>

But \( J/\psi = \psi(1S), \quad \psi' = \psi(2S) \)
Charged Z states: Z(4430)

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

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

Far from open charm thresholds

If the amplitude is a free complex number, in each bin of \( m_{\psi'\pi^-}^2 \), the resonant behaviour appears as well.
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 \( \chi_{c0}(2P) \)

But \( X(3915) \nrightarrow D\bar{D} \) 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
$Y(4260) \rightarrow \bar{D}D_1$?

$e^+e^- \rightarrow Y(4260) \rightarrow \pi \bar{D}^0D^{**}$

$Z_c(3900) \rightarrow \bar{D}^0D^{**}$

$\mathcal{A} = \frac{N_{|\cos\theta|>0.5} - N_{|\cos\theta|<0.5}}{N_{|\cos\theta|>0.5} + N_{|\cos\theta|<0.5}}$

<table>
<thead>
<tr>
<th>$\bar{D}D_1$ MC</th>
<th>$Z_c^{+} ps$ MC</th>
<th>data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.43±0.04</td>
<td>0.02±0.02</td>
<td>0.12±0.06</td>
</tr>
</tbody>
</table>

Not a lot of room for $\bar{D}D_1(2410)$
Flavored $X(5568)$

- A flavored state seen in $B_s^0 \pi$ invariant mass by D0 (both $B_s^0 \to J/\psi \phi$ and $\to D_s \mu \nu$),
- not confirmed by LHCb or CMS
- (different kinematics? Compare differential distributions)

Controversy to be solved
Tetraquark: the $c\bar{c}s\bar{s}$ states

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 $2^{++}$)

Maiani, Polosa and Riquer, PRD 94, 054026

Much narrower than LHCb! Look for prompt!
<table>
<thead>
<tr>
<th>State</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (mode)</th>
<th>Experiment ($#\sigma$)</th>
<th>State</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (mode)</th>
<th>Experiment ($#\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3823)$</td>
<td>$3823.1 \pm 1.9$</td>
<td>$&lt; 24$</td>
<td>$?^{+}$</td>
<td>$B \to K'(\chi_c1')$</td>
<td>Belle(4.0)</td>
<td>$Y(4220)$</td>
<td>$4196^{+35}_{-30}$</td>
<td>$39 \pm 32$</td>
<td>$1^{--}$</td>
<td>$e^{+}e^{-} \to (\pi^{+}\pi^{-}h_c)$</td>
<td>BES III data(8.4)</td>
</tr>
<tr>
<td>$X(3872)$</td>
<td>$3871.68 \pm 0.17$</td>
<td>$&lt; 1.2$</td>
<td>$1^{++}$</td>
<td>$B \to K(\pi^{+}\pi^{-}J/\psi)$</td>
<td>Belle(8.6)</td>
<td>$Y(4230)$</td>
<td>$4230 \pm 8$</td>
<td>$38 \pm 12$</td>
<td>$1^{--}$</td>
<td>$e^{+}e^{-} \to (\chi_{c0}\omega)$</td>
<td>BES II(9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$pp \to (\pi^{+}\pi^{-}J/\psi)$</td>
<td>CDH(1.6), D0(5.2)</td>
<td>$Z(4240)^{+}$</td>
<td>$4248^{+185}_{-135}$</td>
<td>$177^{+241}_{-121}$</td>
<td>$?^{+}$</td>
<td>$\bar{B}^{0} \to K^{+}(\pi^{+}\chi_{c1})$</td>
<td>Belle(5.0), Babar(2.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K(\pi^{+}\pi^{-}0_{J/\psi})$</td>
<td>Belle(3.5), Babar(3.5)</td>
<td>$Y(4260)$</td>
<td>$4250 \pm 9$</td>
<td>$108 \pm 12$</td>
<td>$1^{--}$</td>
<td>$e^{+}e^{-} \to (\pi J/\psi)$</td>
<td>Babar(11), CLEO(11)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K(\gamma J/\psi)$</td>
<td>Belle(3.5), Babar(3.5)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \to K(\gamma(2S))$</td>
<td>Belle(3.5), Babar(3.5)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{c}(3900)^{+}$</td>
<td>$3888.7 \pm 3.4$</td>
<td>$35 \pm 7$</td>
<td>$1^{--}$</td>
<td>$B \to K(D\bar{D}^{*})$</td>
<td>Belle(6.4), Babar(4.9)</td>
<td>$Z_{c}(4020)^{+}$</td>
<td>$4023.9 \pm 2.4$</td>
<td>$10 \pm 6$</td>
<td>$1^{--}$</td>
<td>$Y(4260) \to \pi^{-}(D\bar{D}^{*})$</td>
<td>BES II(8.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(4260) \to \pi^{-}(\pi^{+}h_c)$</td>
<td>Belle(10)</td>
<td>$Y(4350)$</td>
<td>$4350.6^{+4.4}_{-5.1}$</td>
<td>$13^{+18}_{-10}$</td>
<td>$0/2^{+}$</td>
<td>$e^{+}e^{-} \to \pi^{+}e^{-}(\phi J/\psi)$</td>
<td>Belle(3.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(4360)$</td>
<td>$4354 \pm 11$</td>
<td>$78 \pm 16$</td>
<td>$1^{--}$</td>
<td>$e^{+}e^{-} \to (\pi^{+}\pi^{-}h_c)$</td>
<td>BES II(8.2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Z(4340)^{+}$</td>
<td>$4178 \pm 17$</td>
<td>$180 \pm 31$</td>
<td>$1^{--}$</td>
<td>$\bar{B}^{0} \to K^{-}(\pi J/\psi)$</td>
<td>BES III(19)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(4630)$</td>
<td>$4634^{+9}_{-11}$</td>
<td>$92^{+41}_{-32}$</td>
<td>$1^{--}$</td>
<td>$e^{+}e^{-} \to (\pi^{+}\pi^{-}J^{PC}=2S)$</td>
<td>Belle(4.0)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(4660)$</td>
<td>$4665 \pm 10$</td>
<td>$53 \pm 14$</td>
<td>$1^{--}$</td>
<td>$e^{+}e^{-} \to (\pi^{+}\pi^{-}h_c)$</td>
<td>BES III(19)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Z_{b}(10610)^{+}$</td>
<td>$10607.2 \pm 2.0$</td>
<td>$18.4 \pm 2.4$</td>
<td>$1^{--}$</td>
<td>$Y(5S) \to \pi(\pi^{+}\pi^{-}h_c)$</td>
<td>Belle(4.0)</td>
<td>$Z_{b}(10650)^{+}$</td>
<td>$10652.2 \pm 1.5$</td>
<td>$11.5 \pm 2.2$</td>
<td>$1^{--}$</td>
<td>$Y(5S) \to \pi(\pi^{+}\pi^{-}h_c)$</td>
<td>Belle(4.0)</td>
</tr>
</tbody>
</table>

A. Pilloni – The Quest for Exotic States

Guerrieri, AP, Piccinini, Polosa, IJMPA 30, 1530002
Joint Physics Analysis Center

- **Joint effort** between **theorists** and **experimentalists** to work together to make the best use of the next generation of very precise data taken at JLab and in the world.
- Created in 2013 by JLab & IU agreement.
- It is engaged in **education** of further generations of hadron physics practitioners.

**Effective Field Theories**
- Analyticity+Unitarity
- Dispersion Relations
- Regge Theory

**Insight on QCD dynamics**
- Fundamental parameters
- Resonances, exotic states

**Experiments**
- CLAS, GlueX, BESIII, COMPASS, LHCb, BaBar, Belle II, KLOE, MAMI, Lattice
Joint Physics Analysis Center

A. Jackura, N. Sherrill, G. Fox, T. Londergan (IU), E. Passemar, A. Szczepaniak (IU/JLab)
R. Workman (GWU), M. Döring (GWU/JLab)
V. Mathieu, V. Pauk, A. Pilloni, V. Mokeev (JLab)
P. Guo (Cal. State U.)

L. Bibzrycki, R. Kaminski (Krakow)
J. Nys (Ghent U.)
M. Mikhasenko (Bonn U.)
I. Danilkin, A. Hiller Blin (Mainz U.)
A. Celentano (INFN-GE)
M. Albaladejo (Valencia U.)

Students, Postdocs, Faculties

A. Pilloni – JPAC program for Hadron Spectroscopy
Interactive tools

- Completed projects are fully documented on interactive portals
- These include description on physics, conventions, formalism, etc.
- The web pages contain source codes with detailed explanation how to use them. Users can run codes online, change parameters, display results.

http://www.indiana.edu/~jpac/
Strategy

• We fit the following invariant mass distributions:
  • BESIII PRL110, 252001 $J/\psi \pi^+, J/\psi \pi^-, \pi^+\pi^-$ at $E_{CM} = 4.26$ GeV
  • BESIII PRL110, 252001 $J/\psi \pi^0$ at $E_{CM} = 4.23, 4.26, 4.36$ GeV
  • BESIII PRD92, 092006 $D^0 D^{*+}, D^{*0} D^+$ (double tag) at $E_{CM} = 4.23, 4.26$ GeV
  • BESIII PRL115, 222002 $D^0 D^{*0}, D^{*0} D^0$ at $E_{CM} = 4.23, 4.26$ GeV
  • BESIII PRL112, 022001 $D^0 D^{*+}, D^{*0} D^+$ (single tag) at $E_{CM} = 4.26$ GeV
  • Belle PRL110, 252002 $J/\psi \pi^\pm$ at $E_{CM} = 4.26$ GeV
  • CLEO-c data PLB727, 366 $J/\psi \pi^\pm, J/\psi \pi^0$ at $E_{CM} = 4.17$ GeV

• Published data are not efficiency/acceptance corrected,
  $\rightarrow$ we are not able to give the absolute normalization of the amplitudes

• No given dependence on $E_{CM}$ is assumed – the couplings at different $E_{CM}$ are independent parameters
Strategy

- **Reducible (incoherent) backgrounds are pretty flat** and do not influence the analysis, except the peaking background in $D^0 D^{*0}$, $D^{*0} D^0$ (subtracted)

- Some information about **angular distributions** has been published, but it’s **not constraining** enough → we do not include in the fit

- Because of that, we **approximate all the particles to be scalar** – this affects the value of couplings, which are not normalized anyway – but not the position of singularities. This also limits the number of free parameters
Figure 7: Interplay of scattering amplitude poles and triangle singularity to reconstruct the peak. We focus on the $J/\psi \pi$ channel, at $E_{CM} = 4.26$ GeV. The red curve is the $t_{12}$ scattering amplitude, the green curve is the $c_1 + H(s, D_1) + H(s, D_0)$ term in Eq. (9), and the blue curve is the product of the two. The upper plots show the magnitudes of these terms, the lower plots the phases. The middle row shows the contributions to the unitarized term due to the $D_1$ (dashed) and the $D_0$ (dotted). Only for $D_1$ the singularity is close enough to the physical region to generate a large peak. (a) The pole on the III sheet generates a narrow Breit-Wigner-like peak. The contribution of the triangle is not particularly relevant. (b) The sharp cusp in the scattering amplitude is due to the IV sheet pole close by; the triangle contributes to make the peak sharper. (c) The scattering amplitude has a small cusp due to the threshold factor, and the triangle is needed to make it sharp enough to fit the data.
Lineshapes at 4230

Figure 8: Same as Figure 7, but for $E_{CM} = 4.23$ GeV.
Statistical analysis

Toy experiments according to the different hypotheses, to estimate the relative rejection of various scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>III+tr.</th>
<th>IV+tr.</th>
<th>tr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>1.5σ (1.5σ)</td>
<td>1.5σ (2.7σ)</td>
<td>“2.4σ” (“1.4σ”)</td>
</tr>
<tr>
<td>III+tr.</td>
<td>–</td>
<td>1.5σ (3.1σ)</td>
<td>“2.6σ” (“1.3σ”)</td>
</tr>
<tr>
<td>IV+tr.</td>
<td>Not conclusive at this stage</td>
<td>“2.1σ” (“0.9σ”)</td>
<td></td>
</tr>
</tbody>
</table>
Searching for resonances in \( \eta \pi \)

- The \( \eta \pi \) system is one of the golden modes for hunting hybrid mesons
- We build the partial waves amplitude according to the \( N/D \) method

A. Jackura, *et al.* (JPAC & COMPASS), 1707.02848

The denominator \( D(s) \) contains all the Final State Interactions constrained by unitarity \( \rightarrow \) universal

The numerator \( n(s) \) depends on the exchanges \( \rightarrow \) process-dependent, smooth
Searching for resonances in $\eta\pi$

The denominator $D(s)$ contains all the FSI constrained by unitarity $\rightarrow$ universal

$$D(s)_{ij} = (K^{-1})_{ij}(s) - \frac{s}{\pi} \int_{s_i}^{\infty} \frac{\rho_i(s')N_{ij}(s')}{s'(s'-s)} ds'$$

$$K_{ij}(s) = \sum_R \frac{g_i^R g_j^R}{M_R^2 - s}$$

Standard K matrix, with usual trick for vanishing determinant

The numerator $n(s)$ depends on the exchanges $\rightarrow$ process-dependent, smooth

$$\rho_i(s)N_{ij}(s) = \frac{\lambda^{(2l+1)/2}(s, m_{\pi}^2, m_\eta^2)}{(s + \Lambda)^7}$$
Searching for resonances in $\eta\pi$

Precise determination of pole position

Smooth «background»
Searching for resonances in $\eta\pi$

- The coupled channel analysis involving the $\eta\pi$ and $\eta'\pi$ for $P$- and $D$-wave is ongoing.

\[ a_2(1320) \]
\[ a_2'(1700) \]

- The extension to the GlueX production mechanism and kinematics is also ongoing.
- Same $D(s)$, different numerator.

\[ \pi_1(1600)? \]
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
Counting rules

Brodsky, Lebed PRD91, 114025

- Exotic states can be produced in threshold regions in $e^+e^-$, electroproduction, hadronic beam facilities and are best characterized by cross section ratios

- Two examples:

1) $\frac{\sigma(e^+e^-\rightarrow Z_c^+\pi^-)}{\sigma(e^+e^-\rightarrow \mu^+\mu^-)} \propto \frac{1}{s^6}$ as $s \rightarrow \infty$

2) $\frac{\sigma(e^+e^-\rightarrow Z_c^+(\bar{c}c\bar{d}u)+\pi^-(\bar{u}d))}{\sigma(e^+e^-\rightarrow \Lambda_c(cud)+\bar{\Lambda}_c(\bar{c}\bar{u}d))} \rightarrow \text{const} \text{ as } s \rightarrow \infty$

- Ratio numerically smaller if $Z_c$ behaves like weakly-bound dimeson molecule instead of diquark-antidiquark bound state due to weaker meson color van der Waals forces

Different estimates close to thresholds, and in presence of annihilating $q\bar{q}$

Guo, Meissner, Wang, Yang, 1607.04020
Voloshin PRD94, 074042
Tetraquark: the $Y(4220)$

A state apparently breaking HQSS has been observed.

Compatible to be the $Y_3$ state.

Faccini, Filaci, Guerrieri, AP, Polosa, PRD 91, 117501
Tetraquark: the $b$ sector

Ali, Maiani, Piccinini, Polosa, Riquer PRD91 017502

\[
M(Z_b') - M(Z_b) = 2\kappa_b \\
M(Z_c') - M(Z_c) = 2\kappa_c \sim 120 \text{ MeV} \\
\kappa_b : \kappa_c = M_c : M_b \sim 0.30
\]

\[
2\kappa_b \sim 36 \text{ MeV}, \text{ vs.} 45 \text{ MeV (exp.)}
\]

\[
Z_b = \frac{\alpha |1q\bar{q}0_{b\bar{b}}\rangle - \beta |0q\bar{q}1_{b\bar{b}}\rangle}{\sqrt{2}}
\]

\[
Z_b' = \frac{\alpha |1q\bar{q}0_{b\bar{b}}\rangle + \beta |0q\bar{q}1_{b\bar{b}}\rangle}{\sqrt{2}}
\]

Data on $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi\pi$ and $\Upsilon(5S) \rightarrow h_b(nP)\pi\pi$ strongly favor $\alpha = \beta$
If tetraquark

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

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

Uncertainty \sim 25%

Clebsch-Gordan

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

<table>
<thead>
<tr>
<th></th>
<th>Kinematics only</th>
<th>Dynamics included</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>type I</td>
<td>type II</td>
</tr>
<tr>
<td>( \mathcal{BR}(Z_c \to \eta_c \rho) )</td>
<td>( (3.3^{+2.9}_{-1.4}) \times 10^2 )</td>
<td>( 0.41^{+0.96}_{-0.17} )</td>
</tr>
<tr>
<td>( \mathcal{BR}(Z_c \to J/\psi \pi) )</td>
<td>( (1.2^{+2.8}_{-0.5}) \times 10^2 )</td>
<td>( 6.6^{+56.8}_{-5.8} )</td>
</tr>
</tbody>
</table>
$Z_c(3900) \to \eta_c \rho$

If molecule

Non-Relativistic Effective Theory, HQET+NRQCD and Hidden gauge Lagrangian

Uncertainty estimated with power counting at NLO

$$\mathcal{L}_{Z_c^{(t)}} = \frac{z^{(t)}}{2} \left\langle Z_{\mu,ab}^r \tilde{H}_{2b} \gamma^\mu \tilde{H}_{1a} \right\rangle + h.c.,$$

$$\mathcal{L}_{\bar{c}c} = \frac{g_3}{2} \left\langle \bar{\psi} H_{1a} \gamma^\mu \tilde{H}_{2a} \right\rangle + \frac{g_1}{2} \left\langle \bar{\chi}_\mu H_{1a} \gamma^\mu H_{2a} \right\rangle + h.c.,$$

$$\mathcal{L}_{\bar{c}DD^*} = i \beta \left\langle H_{1b} \gamma^\mu \left( V_{\mu} - \rho_\mu \right)_{ba} \tilde{H}_{1a} \right\rangle + i \lambda \left\langle H_{1b} \gamma^\nu F_{\mu \nu}(\rho)_{ba} \tilde{H}_{1a} \right\rangle + h.c.,$$

$$\text{BR}(Z_c \to \eta_c \rho) / \text{BR}(Z_c \to J/\psi \pi) = \left(4.6^{+2.5}_{-1.7}\right) \times 10^{-2}; \quad \text{BR}(Z'_c \to \eta_c \rho) / \text{BR}(Z'_c \to h_c \pi) = \left(1.0^{+0.5}_{-0.4}\right) \times 10^{-2}.$$
Dynamical movie \( Z^+(4430) \)

- Since this is still a \( 3 \leftrightarrow \bar{3} \) color interaction, just use the Cornell potential:
  \[
  V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_{cq}^2} \left( \frac{\sigma}{\sqrt{\pi}} \right)^3 e^{-\sigma^2 r^2} \mathbf{s}_{cq} \cdot \mathbf{s}_{\bar{cq}},
  \]

  e.g. Barnes et al., PRD 72, 054026

- 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)

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

\[
\frac{B(Z^+(4430) \rightarrow \psi(2S)\pi^+)}{B(Z^+(4430) \rightarrow J/\psi \pi^+)} \sim 72
\]

(> 10 exp.)
Towards hybridized tetraquarks

The absence of many of the predicted states might point to the need for selection rules. It is unlikely that the many close-by thresholds play no role whatsoever. All the well assessed 4-quark resonances lie close and above some meson-meson thresholds: We introduce a mechanism that might provide “dynamical selection rules” to explain the presence/absence of resonances from the experimental data.

<table>
<thead>
<tr>
<th></th>
<th>Thr.</th>
<th>( \delta ) (MeV)</th>
<th>( \Delta \sqrt{\delta} ) (MeV)</th>
<th>( \Gamma ) (MeV)</th>
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<tr>
<td>( X(3872) )</td>
<td>( \bar{D}^0 D^{*0} )</td>
<td>0(^\dagger)</td>
<td>0(^\dagger)</td>
<td>0(^\dagger)</td>
</tr>
<tr>
<td>( Z_c(3900) )</td>
<td>( \bar{D}^0 D^{*+} )</td>
<td>7.8</td>
<td>27.9</td>
<td>27.9</td>
</tr>
<tr>
<td>( Z'_c(4020) )</td>
<td>( \bar{D}^{<em>0} D^{</em>+} )</td>
<td>6.7</td>
<td>25.9</td>
<td>24.8(^\ddagger)</td>
</tr>
<tr>
<td>( X(4140) )</td>
<td>( J/\psi \phi )</td>
<td>a) 31.6</td>
<td>52.7</td>
<td>28.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>b) 30.1</td>
<td>54.7</td>
<td>83.0</td>
</tr>
<tr>
<td>( Z_b(10610) )</td>
<td>( \bar{B}^0 B^{*+} )</td>
<td>2.7</td>
<td>16.6</td>
<td>18.4</td>
</tr>
<tr>
<td>( Z'_b(10650) )</td>
<td>( \bar{B}^{<em>0} B^{</em>+} )</td>
<td>1.8</td>
<td>13.4</td>
<td>11.5</td>
</tr>
<tr>
<td>( X(5568) )</td>
<td>( B_s^0 \pi^+ )</td>
<td>61.4</td>
<td>78.4</td>
<td>21.9</td>
</tr>
<tr>
<td>( X_{bs} )</td>
<td>( B^+ \bar{K}^0 )</td>
<td>5.8</td>
<td>24.1</td>
<td>—</td>
</tr>
</tbody>
</table>

We introduce a mechanism that might provide “dynamical selection rules” to explain the presence/absence of resonances from the experimental data.
Baryonium

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

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

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

Cotugno, Faccini, Polosa, Sabelli,
PRL 104, 132005
$Y(4260) \rightarrow \gamma X(3872)$


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**
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-$k_0$) region!
Prompt production of $X(3872)$

$$\sigma(\bar{p}p \to X) \sim \left| \int d^3k \langle X| D^0 \bar{D}^{*0}(k)\rangle \langle D^0 \bar{D}^{*0}(k)|\bar{p}p \rangle \right|^2$$

$$\lesssim \left| \int_{R} d^3k \langle X| D^0 \bar{D}^{*0}(k)\rangle \langle D^0 \bar{D}^{*0}(k)|\bar{p}p \rangle \right|^2$$

$$\leq \int_{R} d^3k |\Psi(k)|^2 \int_{R} d^3k |\langle D^0 \bar{D}^{*0}(k)|\bar{p}p \rangle|^2$$

$$\leq \int_{R} d^3k |\langle D^0 \bar{D}^{*0}(k)|\bar{p}p \rangle|^2$$

The estimate of the $k_{max}$ has been brought back

Albaladejo et al. arXiv:1709.09101

The essence of the argument is that one has to look at the integral of the wave function

$$\int_{R} d^3 k \psi(k)$$

Esposito et al. arXiv:1709.09631
W. Wang arXiv:1709.10382
Prompt production of $X(3872)$

However, the integral of the wave function may not be well defined. For example, if one considers the wave function in the scattering length approximation,

$$
\psi(k) = \frac{1}{\pi} \frac{a^{3/2}}{a^2 k^2 + 1}
$$

Esposito et al. arXiv:1709.09631

it’s not integrable

A physical value should rather be based on expectation values which involve $|\psi(k)|^2$

For example, an estimate using the virial theorem gives $k \sim 100$ MeV for the deuteron.

Moreover, the wave function may change sign, which makes the integral nonmonotone. What’s the right $R$ then?
The argument is about the value of a non-normalizable wave function. Any argument about where the wave function is localized must be calculated for the modulus square:

$$\sigma(pp \to X) \sim \left| \int d^3 k \langle X | D^0 \bar{D}^{*0}(k) \rangle \langle D^0 \bar{D}^{*0}(k) | pp \rangle \right|^2$$
Tuning pions

This picture could spoil existing meson distributions used to tune MC
We verify this is not the case up to an overall $K$ factor

Guerrieri, Piccinini, AP, Polosa, PRD90, 034003

Neither at CDF...

...nor at ATLAS
Notes from the Editors: Highlights of the Year

Published December 30, 2013 | Physics 6, 139 (2013) | DOI: 10.1103/Physics.6.139

*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.
Doubly charmed states

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 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
$T$ states production

- $\bar{D}^0, D^-, D_s^-$
- $T_s^+, T_s^{++}, T_{ss}^{++}$
- $T^0, T^+, T_s^+$
- $p, n, \Lambda, \Sigma, \Xi$ ...

\[ \bar{b} \rightarrow c \]
\[ \lambda^2 \]
\[ c \]
\[ \bar{s} \]
\[ u, d, s \]
\[ \bar{u}, \bar{d}, \bar{s} \]
\[ c \]

\[ b \rightarrow c \]
\[ \lambda^2 \]
\[ \bar{u} \]
\[ d \]
\[ c \]
\[ q \]
\[ \bar{u}, \bar{d}, \bar{s} \]
\[ u, d, s \]
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 (bound state, pole in the 1$^{\text{st}}$ Riemann sheet?)

We aim to evaluate prompt production cross section at hadron colliders via Monte-Carlo simulations

**Q.** What is a molecule in MC?  
**A.** «Coalescence» model

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

This should provide an upper bound for the cross section

---

Bignamini, Piccinini, Polosa, Sabelli PRL103 (2009) 162001  
Kadastatic, Raidan, Strumia PLB683 (2010) 248
Estimating $k_{max}$

The binding energy is $E_B \approx -0.16 \pm 0.31$ MeV: 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 in Kamal Seth’s talk is $E_B \approx -0.013 \pm 0.192$ MeV:)

$$\sqrt{\langle k^2 \rangle} \approx 30 \text{ MeV}, \sqrt{\langle r^2 \rangle} \approx 30 \text{ fm}$$

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
We tune our MC to reproduce CDF distribution of $\frac{d\sigma}{d\Delta\phi} (p\bar{p} \rightarrow D^0 D^{*-})$

We get $\sigma (p\bar{p} \rightarrow DD^* |k < k_{max}) \approx 0.1 \text{ nb @ } \sqrt{s} = 1.96 \text{ TeV}$

Experimentally $\sigma (p\bar{p} \rightarrow X(3872)) \approx 30 - 70 \text{ nb}$!
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

However, the applicability of Watson theorem 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 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

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 $\sigma(p\bar{p} \to X(3872)) \sim 5$ nb, still not sufficient to explain all the experimental cross section
Hybridized tetraquarks – Selection rules

- Consider the down quark part of the $X(3872)$ in the diquarkonium picture:
  \[
  \Psi_d = X_d = [cd]_0[\bar{c}\bar{d}]_1 + [cd]_1[\bar{c}\bar{d}]_0 \sim (D^*-D^+ - D^{*+}D^-) + i(\psi \times \rho^0 - \psi \times \omega^0)
  \]
  \[\text{Fierz rearrangement}\]

- The closest threshold from below is $\Psi_m \sim \bar{D}^0 D^{*0} \quad \rightarrow \quad \Psi_d \perp \Psi_m \quad \checkmark$

- But if we consider the up quark part of the $X(3872)$:
  \[
  \Psi_d = X_u = [cu]_0[\bar{c}\bar{u}]_1 + [cu]_1[\bar{c}\bar{u}]_0 \sim (\bar{D}^{*0}D^0 - D^{*0}\bar{D}^0) - i(\psi \times \rho^0 + \psi \times \omega^0)
  \]

- But then $\Psi_d \not\perp \Psi_m \quad \chi$

- Only $X_d$ is produced via this mechanism
  \[\rightarrow \quad \text{isospin violation} \quad \rightarrow \quad \text{no hyperfine neutral doublet}\]

- $X_b$
  - (A) Diquark model predicts $M(X_b) \simeq M(Z_b) \simeq (10607 \pm 2)$ MeV
  
  (B) The closest orthogonal threshold is $M(B^0 B^{*0}) = (10604.4 \pm 0.3)$ MeV

  (C) This could either be above threshold (very narrow state) or below (no state at all)

  (D) Experimentally the diquark model overpredicts the mass of the $X$:
  
  \[M(Z_c) - M(X) \simeq 32 \text{ MeV}\]

  (E) We favor the below threshold scenario $\rightarrow$ no $X_b$ should be seen
Production of hybridized tetraquarks

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

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

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

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

$\alpha$ expected to be small in Large N limit, Maiani, Polosa, Riquer JHEP 1606, 160

No prompt production without hybridization mechanism!

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.