Physics with higher energy electrons

Alessandro Pilloni

GlueX Collaboration Meeting, May 25th, 2022
Exotic landscape

Estimates in
M. Albaladejo et al. [JPAC], 2008.01001

Snowmass LoI RF7_RF0_120, White paper 2203.08290

WXYZ spectroscopy at a charm photoproduction factory

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Hadron Spectroscopy in Photoproduction

Miguel Albaladejo1, Lukasz Bibrycki2, Sean Dobbs3, César Fernández-Ramírez4,5, Astrid N. Hiller Blin6, Vincent Mathieu7,8, Alessandro Pilloni9,10, Justin Stevens11, Adam P. Szczepaniak12,13,14, and Daniel Winney13,14,15,16
$X(3872)$

- 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
  \[
  \frac{\Gamma(X \to J/\psi \omega)}{\Gamma(X \to J/\psi \rho)} \approx 0.8 \pm 0.3
  \]
- Mass prediction not compatible with $\chi_{c1}(2P)$

\[
M = 3871.68 \pm 0.17 \text{ MeV}
\]
\[
M_X - M_{DD^*} = -3 \pm 192 \text{ keV}
\]
\[
\Gamma = 1.19 \pm 0.19 \text{ MeV}
\]

Sizeable prompt production at hadron colliders, $\sim 5\%$ of $\psi(2S)$

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

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

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

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

$M = 4023.9 \pm 2.4 \text{ MeV}, \Gamma = 10 \pm 6 \text{ MeV}$
Pentaquarks!

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

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

Quantum numbers

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

Higher statistics analysis revealed a two-peak structure of the narrow state, plus a new lighter one

Quantum numbers still unknown
Models

Compact

Hybrids
Containing gluonic degrees of freedom

Multiquark
Several (cluster) of valence quarks

Extended

Molecule
Bound or virtual state generated by long-range exchange forces

Hadroquarkonium
Heavy core interacting with a light cloud via Van der Waals forces

Rescattering effects
Structures generated by cross-channel rescattering, very process-dependent
Exotic landscape

Broad mesons seen in $b$ decay:
$X(4140), Z(4430), Z_{cs}(4000)\ldots$

Narrow structures seen in $b$ decay:
$X(3872), P_c, (P_{cs})$

Scarce consistency between various production mechanisms

Narrow structures seen in $e^+e^-$:
$X(3872), Y(4260), Z_c^{(r)}, Z_{c,b}$
Why photoproduction?

• It’s new: no XYZ state has been uncontroversially seen so far

• It is free from rescattering mechanisms that could mimic resonances in multibody decays

• The framework is (relatively) clean from a theory point of view

• Radiative decays offer another way of discerning the nature of the states
Exclusive (quasi-real) photoproduction

- XYZ have not been seen in photoproduction so far: independent confirmation
- Not affected by 3-body dynamics: determination of resonant nature
- Experiments in the appropriate energy range are promising
- We study near-threshold (LE) and high energies (HE)
- Couplings from data as much as possible, not relying on the nature of XYZ

\[
< \lambda_Q \lambda_N' | T | \lambda_Y \lambda_N > = \sum_{V, \mathcal{E}} \frac{e}{m_V} \frac{f_V^{\mathcal{E}}}{m_V} \, \mathcal{T}_{\lambda_V=\lambda_Y, \lambda_Q} \, \mathcal{P}_{\alpha_1...\alpha_j; \beta_1...\beta_j} \, \mathcal{B}_{\lambda_N \lambda_N'}^{\beta_1...\beta_j}
\]

M. Albaladejo et al. [JPAC], PRD

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\[ \langle \lambda_Q \lambda_N' | T | \lambda_Y \lambda_N \rangle = \sum \frac{e f V}{m_V} \int_{\lambda_V = \lambda_Y, \lambda_Q} P \alpha_1 \cdots \alpha_j \beta_1 \cdots \beta_j B^{\beta_1 \cdots \beta_j} \]

VMD is used to couple the incoming photon to a vector quarkonium V
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\[ < \lambda_Q \lambda'_N | T | \lambda_Y \lambda_N > = \sum_{V,\mathcal{E}} \frac{e f_V}{m_V} \int_{\lambda_Y = \lambda_Y, \lambda_Q} P \alpha_1 \cdots \alpha_j; \beta_1 \cdots \beta_j \mathcal{B}^{\beta_1 \cdots \beta_j}_{\lambda_N \lambda'_N} \]

Top vertex from measured \( Q \to V \mathcal{E} \) decay width
Exclusive (quasi-real) photoproduction

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\[ < \lambda_Q \lambda'_N | T | \lambda_Y \lambda_N > = \sum_{V,E} \frac{ef_V}{m_V} T_{\lambda_V=\lambda_Y, \lambda_Q} P_{\alpha_1 \ldots \alpha_j; \beta_1 \ldots \beta_j} B_{\lambda_N \lambda'_N}^{\beta_1 \ldots \beta_j} \]

Bottom vertex from standard photoproduction pheno, exponential form factors to further suppress large t

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Threshold vs. high energy

- Fixed-spin exchanges expected to hold in the low energy region
- $t$ channel grows as $s^j$, exceeding unitarity bound, Regge physics kicks in: Reggeized tower of particles with arbitrary spin at HE

\[ s^j \rightarrow s^{\alpha_0 + \alpha't} \]

Holds at low energy, fixed spin

Holds at high energy, resummation of leading $s$ power

- If $\epsilon \neq \text{IP}$, $\alpha_0 < 1$, $d\sigma/dt$ decreases with energy
- Exchange of heavy particles further suppressed
Z photoproduction

- The Zs are charged charmoniumlike $1^{+-}$ states close to open flavor thresholds
- Focus on $Z_c(3900)^+ \rightarrow J/\psi \pi^+$, $Z_b(10610)^+$, $Z_b'(10650)^+ \rightarrow \Upsilon(nS)\pi^+$
- The pion is exchanged in the $t$-channel
Focus on the famous $1^{++} X(3872) \to J/\psi \rho, \omega$

Studying also $X(6900) \to J/\psi J/\psi$ (assumed $0^{++}$)

$\omega$ and $\rho$ exchanges give main contributions:

need to assume the existence of a OZI-suppressed $X(6900) \to J/\psi \omega$
Another $\tilde{\Xi}$?

$\tilde{\Xi}(3872)$ as a new state

$M_{\tilde{\Xi}(3872)} = (3860.0\pm10.4)\text{ MeV}/c^2$

$\Gamma_{\tilde{\Xi}(3872)} < 51\text{ MeV}/c^2 (CL=90\%)$

Significance (including systematics) is 4.1$\sigma$

$C=-1$ (?)

COMPASS claimed the existence of a state degenerate with the $X(3872)$, but with $C = 1$

Large photoproduction cross section

At COMPASS conditions:

$\sigma_{\mu N} \approx \sigma_{\gamma N} / 300$

EIC $L=10^{34}$ cm$^{-2}$ s$^{-1}$

$e^{-}N \rightarrow e^{-}[\tilde{\Xi}(3872)\pi^{\pm}N'] \rightarrow$

$\rightarrow e^{-}J/\psi \pi^{+}\pi^{-}\pi^{\pm}N' \rightarrow e^{-}\mu^{+}\mu^{-}\pi^{+}\pi^{-}\pi^{\pm}N'$

$\sim 10$ events per day

A. Guskov

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**Y (vector) photoproduction**

Diffractive production, dominated by Pomeron (2-gluon) exchange

\[
R_Y = \frac{e f_\psi}{m_\psi} \frac{g^2(Y \rightarrow \psi \pi \pi) g^2(\psi' \rightarrow \psi g g)}{\sqrt{g^2(\psi \rightarrow \gamma g g) g^2(\psi' \rightarrow \psi \pi \pi)}}
\]

Existing data allow to put a 95% upper limit on the ratio of \(\psi'/Y(4260)\) yields

Assuming previous formula, one gets:

\[
\Gamma_{ee}^Y = 930 \text{ eV}
\]

\[
BR(Y \rightarrow J/\psi \pi \pi) = 0.96\% \\
R_Y = 0.84
\]

(cfr. hep-ex/0603024, 2002.05641)

![Graphs showing production cross-sections for J/\(\psi\), \(\psi(2S)\), and \(Y(4260)\)]
Primakoff X photoproduction

Using measurement of $\Gamma(X \rightarrow \gamma\gamma^*)$ from Belle, one can get predictions for Primakoff.

Makes use of ion targets, enhancement of cross sections as $Z^2$.
Diffractive semi-inclusive $Z_c$ ph.

If the target fragments are separated from the beam ones, one can invoke Regge factorization.

Quark-Regge duality allows to replace the intermediate hadrons with Pomeron, prediction reliable for $x_B \sim 1, t \ll W_{\gamma p}^2$.

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Diffractive semi-inclusive $Z_C$ ph.

\[ \sigma \text{ [nb]} \]

\[ W \text{ [GeV]} \]

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An example of yield estimate

- Example with an ideal SuperCEBAF
- \( E_{\text{lab}} \sim 20 \text{ GeV} \), photon flux \( 10^8 \gamma / \text{s} \)
- Typical target, 500 pb\(^{-1} \) /yr
- Assuming efficiency 1%

<table>
<thead>
<tr>
<th>System</th>
<th>( W_{\gamma p} ) (GeV)</th>
<th>( \sigma ) (nb)</th>
<th>( \mathcal{B}(Q \rightarrow \ell^+ \ell^- n\pi) \times 10^{-3} )</th>
<th>Counts</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>6</td>
<td>33.1</td>
<td>5.3</td>
<td>877</td>
<td>( \sim 90 ) [52]</td>
</tr>
<tr>
<td>( Z_c(3900)^+ )</td>
<td>15</td>
<td>15.9</td>
<td>12.5</td>
<td>994</td>
<td>( \sim 1300 ) [15]</td>
</tr>
<tr>
<td>( Z_b(10610)^+ )</td>
<td>15</td>
<td>2.8</td>
<td>2.6</td>
<td>36</td>
<td>( \sim 750 ) [53]</td>
</tr>
<tr>
<td>( Z_b'(10650)^+ )</td>
<td>0.66</td>
<td>2.1</td>
<td></td>
<td>7</td>
<td>( \sim 200 ) [53]</td>
</tr>
</tbody>
</table>

\( \mathcal{B}(J/\psi \rightarrow \ell^+ \ell^-)^2 \times 10^{-3} \)

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</tr>
</thead>
<tbody>
<tr>
<td>X(6900)</td>
<td>12</td>
<td>1.9</td>
<td>14</td>
<td>133</td>
<td>( \sim 800 ) [32]</td>
</tr>
</tbody>
</table>
Conclusions

• Photoproduction is a valuable tool to study exotic states
• Complementary information to other mechanisms
• Facilities to study photoproduction at low energies are very welcome to pursue this program

Thank you!
Joint Physics Analysis Center

Exclusive reactions: 2008.01001

Inclusive reactions: to appear

Code available on https://github.com/dwinney/jpacPhoto
BACKUP
**Exclusive $P_c$ photoproduction**

At Jlab12 measurements of direct $P_c$ production are being performed

Using VMD, $\text{BR}(P_c \rightarrow J/\psi p) \sim 1\%$
Polarized $P_c$ photoproduction

- s channel resonances significant at low energies:
- u channel dominates at high energies
- Main background from $N(*)$ trajectories
- Estimated $P_c$ coupling upper bound of same order of magnitude as $N(*)$ coupling
- Reggeization suppresses $P_c$ due to larger mass (smaller trajectory intercept)
- We estimate that the $P_c$ trajectories will hardly be visible at the EIC
- $P_b$ searches still possible: s channel at higher energies!

**Y (vector) photoproduction**

- Focus on the $1^{--} Y(4260) \rightarrow J/\psi \pi^+\pi^-$, check with $\psi' \rightarrow J/\psi \pi^+\pi^-$
- Diffractive production, dominated by Pomeron (2-gluon) exchange
- Good candidates for EIC: diffractive production increases with energy!
- We have $\gamma\psi$-pomeron coupling from our analyses 1606.08912, 1907.09393

How to rescale from $J/\psi$ to $\psi'$?

$$R_{\psi'} = \sqrt{\frac{g^2(\psi' \rightarrow \gamma gg)}{g^2(\psi \rightarrow \gamma gg)}} \sim 0.55$$

$$g^2(\psi \rightarrow \gamma gg) = \frac{6m_\psi B(\psi \rightarrow \gamma gg) \Gamma_\psi}{PS(\psi \rightarrow \gamma gg)}$$
**Y (vector) photoproduction**

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**How to rescale from $J/\psi$ to $Y(4260)$?**

We assume VMD and $g^2(Y \rightarrow \psi\pi\pi) = g^2(Y \rightarrow \psi gg) \times g^2(gg \rightarrow \pi\pi)$ (Novikov & Shifman)

$$R_Y = \frac{e f_{\psi}}{m_{\psi}} \sqrt{\frac{g^2(Y \rightarrow \psi\pi\pi) g^2(\psi' \rightarrow \psi gg)}{g^2(\psi \rightarrow \gamma gg) g^2(\psi' \rightarrow \psi\pi\pi)}}$$

Caveat: $BR(Y \rightarrow \psi\pi\pi)$ only known times the leptonic width $\Gamma_{ee}^Y$
Existing data allow to put a 95% upper limit on the ratio of $\psi'/Y(4260)$ yields

Assuming previous formula, one gets:

$\Gamma_{ee}^Y = 930\, eV$

(cfr. hep-ex/0603024, 2002.05641)

$BR(Y \rightarrow J/\psi\pi\pi) = 0.96\%$

$R_Y = 0.84$
Diffractive semi-inclusive $Z_c$ ph.

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Semi-inclusive $X$ production

For large $Q^2$ one can invoke NRQCD factorization to describe quarkonium(-like) production

$$d\sigma(e^- + p \rightarrow H + X) = \sum_n d\sigma(e^- + p \rightarrow Q\bar{Q}(n) + X) \langle \mathcal{O}^H(n) \rangle$$

Perturbative partonic matrix element, calculable

Nonperturbative transition matrix element $Q\bar{Q} \rightarrow H$ fitted from data
Semi-inclusive $X$ production

One can assume the same NRQCD factorization for exotics, independent of their internal structure:

$$\sigma[X(3872)] = \sum_n \hat{\sigma}[c\bar{c}_n] \langle O_n^X \rangle,$$

$$\text{Br}[X \to J/\psi \pi^+ \pi^-] \left( \langle O_8^X (3 S_1) \rangle + 0.159 \langle O_8^X (1 S_0) \rangle + 0.085 \langle O_1^X (1 S_0) \rangle \right.$$  
$$+ 0.00024 \langle O_1^X (3 S_1) \rangle \right) = (2.7 \pm 0.6) \times 10^{-4} \text{ GeV}^3$$

Artoisenet and Braaten, PRD81, 114018 from Tevatron data

If one consider the first term only, it leads to

$$\text{Br}[X \to J/\psi \pi^+ \pi^-] \sigma(X(3872), Q^2 > 1 \text{ GeV}) \approx 2.6 \text{ pb} \quad \sqrt{s} = 100 \text{ GeV}$$

X. Yao