XYZ and $J/\psi$
photoproduction

Alessandro Pilloni

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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)

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

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

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

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

A. Pilloni – XYZ and \(J/\psi\) photoproduction
A host of unexpected resonances have appeared
decaying mostly into charmonium + light
Hardly reconciled with usual $q\bar{q}$ pheno
Exotic landscape

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

Scarce consistency between various production mechanisms

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

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

- It’s new: no XYZ state has been uncontroversially seen so far
- Rescattering mechanisms that could mimic resonances in multibody decays can be controlled better (one can change the energy beam but not the $B$ mass...)
- 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 so far not been seen in photoproduction: independent confirmation
- Not affected by 3-body dynamics: determination of resonant nature
- Experiments with high luminosity in the appropriate energy range are promising
- We study near-threshold (LE) and high energies (HE)
- Couplings extracted from data as much as possible, not relying on the nature of XYZ

VMD is used to couple the incoming photon to a vector quarkonium V
....we’ll come back to that!
Exclusive (quasi-real) photoproduction

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\[ \langle \lambda_Q \lambda'_N | T | \lambda_Y \lambda_N \rangle = \sum \frac{e f_V}{m_V} \int_{\lambda_Y=\lambda_Y, \lambda_Q} d_{\alpha_1 \cdots \alpha_j} \mathcal{P}_{\alpha_1 \cdots \alpha_j; \beta_1 \cdots \beta_j} \mathcal{B}_{\lambda_N \lambda'_N} \]

Top vertex from measured \( Q \rightarrow V \varepsilon \) decay width
Exclusive (quasi-real) photoproduction

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- We study near-threshold (LE) and high energies (HE)
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\[
< \lambda_Q \lambda'_N | T | \lambda_Y \lambda_N > = \sum_{V, \mathcal{E}} \frac{e f_V}{m_V} T_{\lambda_Y=\lambda_Y, \lambda_Q} \mathcal{P}_{\alpha_1...\alpha_j; \beta_1...\beta_j} B_{\lambda_N \lambda'_N}^{\beta_1...\beta_j}
\]

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

M. Albaladejo et al. [JPAC], PRD

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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

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

Holds at low energy, fixed spin

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

- If $\epsilon \neq iP$, $\alpha_0 < 1$, $d\sigma/dt$ 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
**X photoproduction**

- Focus on the famous $1^{++} X(3872) \rightarrow J/\psi \rho, \omega$
- $\omega$ and $\rho$ exchanges give main contributions:

Large theory uncertainty in the intermediate region
Semi-inclusive photoproduction

- Semi-inclusive cross sections are typically larger
- For small $t$ and large $x$, one can assume the process to be dominated by pion exchange
- The bottom vertex depends on the (known) pion-proton total cross section
- The pion is exchanged in the $t$-channel
- Model benchmarked on $b_1$ production

Model underestimates lower bins, conservative estimates
The model is expected to hold in the highest bin
Semi-inclusive photoproduction

- For the $Z_c^+$, the inclusive cross section is sizably larger than the exclusive process
Semi-inclusive photoproduction

- At higher energies the triple Regge regime is reached, cross sections saturate
$J/\psi$ photoproduction at threshold

The common lore is that the study of vector quarkonium photoproduction at threshold is directly related to nucleon matrix elements

**Assumptions:**

1. Factorization proof for timelike DVCS can be extended at threshold as the heavy quark mass plays the role of a hard scale
2. The top vertex contains the trivial $\gamma$-$\psi$ coupling $|\psi(0)|^2$
3. The exchange of anything but gluons is (OZI-, mass-) suppressed
4. The exchange is dynamically dominated by gluons carrying $J = 2$

Then one extracts matrix element of the energy momentum tensor $\langle p'|T_{\mu\nu}(0)|p\rangle$
The role of intermediate open charm thresholds has been pointed out, maybe «all that glitters is not glue» ....

Calculation based on EFT and known couplings, S-wave saturates the cross section.
$J/\psi$ photoproduction at threshold

Cusp at the $\Lambda_c \bar{D}^*$ threshold

arXiv:2304.03845
Unitary reanalysis

- Differential and total cross sections are fitted with a unitary model
- In lack of polarization observables and SDME, only orbital angular momentum is considered (spinless approx.)
- Truncated sum of PWs, $\ell \leq 3$

$$F(s, t) = \sum_{\ell} (2\ell + 1) P_\ell (\cos \theta) F_\ell(s)$$

$$F_\ell(s) = f_\ell (1 + G T_\ell) = f_\ell (1 - G K_\ell)^{-1}$$

The dominant S-wave can include coupled channels, for higher waves cusps are suppressed and there is no point

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Total cross section

1. Single channel (1C): Only interactions involving the $J/\psi p$ are included;

2. Two channels (2C): We include contributions from an intermediate $D^*\Lambda_c$ channel;²

3. Three channels (3C): We include both $D^{(*)}\Lambda_c$ channels. In this case we find two classes of solutions which we discuss separately below.
Differential cross section

- This is realized with the interference of various waves,
- constructive in the forward direction
- destructive in the backward direction
because of the Legendre polynomials
Good hierarchy between waves
Contribution of open charm

Naively Wilk’s theorem says the single channel is unfavored at 3.7σ (no look elsewhere etc.), indication but not the end of the story

Contribution of open charm > 25% at 90% CL
Vector Meson Dominance

Since unitary model parametrize separately the production and scattering amplitude, one can compare with the predictions of VMD.

The value of the scattering amplitude at threshold is called scattering length. According to VMD, a small photoproduction cross sections implies a small scattering length enters with the energy dependence.

VMD: \[ F_{\psi P}^{\psi P}(s_{th}, x) = -8\pi \sqrt{s_{th}} g_{\gamma \psi} a_{\psi P} \]

1C: \[ F_{\psi P}^{\psi P}(s \rightarrow s_{th}, \theta) = n_{S}^{\psi P} (1 - i q a_{\psi P}) \]
Vector Meson Dominance

VMD badly excluded, except for the poorly constrained 3C-R model

Scattering lengths generally of $O(1\text{fm})$, but smaller ones are not excluded

Crucial to constrain better these fits by measuring open charm final states

<table>
<thead>
<tr>
<th></th>
<th>1C</th>
<th>2C</th>
<th>3C-NR</th>
<th>3C-R</th>
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<tbody>
<tr>
<td>Parameters</td>
<td>9</td>
<td>13</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>166</td>
<td>144</td>
<td>141</td>
<td>143</td>
</tr>
<tr>
<td>$\chi^2$/dof</td>
<td>1.25</td>
<td>1.12</td>
<td>1.11</td>
<td>1.13</td>
</tr>
<tr>
<td>$\zeta_{th}$ ($\theta = 0$)</td>
<td>1</td>
<td>[0.56, 0.74]</td>
<td>[0.36, 0.63]</td>
<td>[0.03, 0.62]</td>
</tr>
<tr>
<td>$R_{\text{VMD}}(\theta = 0)$</td>
<td>$[0.45, 0.73] \times 10^{-2}$</td>
<td>$[0.39, 1.62] \times 10^{-2}$</td>
<td>$[0.03, 1.74] \times 10^{-2}$</td>
<td>$[1.4 \times 10^{-2}, 0.58]$</td>
</tr>
<tr>
<td>$R_{\text{VMD}}(t = 0)$</td>
<td>$[1.3, 2.0] \times 10^{-2}$</td>
<td>$[1.3, 5.1] \times 10^{-2}$</td>
<td>$[0.08, 8.9] \times 10^{-2}$</td>
<td>$[5.4 \times 10^{-2}, 1.8]$</td>
</tr>
<tr>
<td>$a_{\psi_p}$ [fm]</td>
<td>[0.56, 1.00]</td>
<td>[0.11, 0.79]</td>
<td>$[-2.77, 0.35]$</td>
<td>$[-0.04, 0.19]$</td>
</tr>
</tbody>
</table>
Total cross section

With optical theorem one gets the total cross section $J/\psi \ p \rightarrow X$.

This has been estimated from the A-dependence of nuclear targets, 4mb at $\sqrt{s} = 6.2$ GeV.

VMD estimates provide values at least 1order of magnitude smaller.
Conclusions

• Predictions for XYZ at new colliders are on the way

• However, most of them rely on Vector Meson Dominance, whose accuracy is put into question by GlueX data

• It is important to estimate open charm cross section in order to assess the validity of VMD, as well of factorization

Thank you!
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Exclusive reactions: 2008.01001

Inclusive reactions: 2209.05882

Code available on https://github.com/dwinney/jpacPhoto
https://jpac-physics.org
BACKUP
Hybrid hunting

Constituent gluon (quasiparticle excitation), \( J^{PC} = 1^{+-} \), mass \( \sim 1.0 - 1.5 \) GeV

Look for a \( \pi_1 \) state with \( J^{PC} = 1^{-+} \)

decaying into \( \eta \pi \) and \( \eta' \pi \)

\( \rho \pi \rightarrow 3\pi \)

\( b_1 \pi \rightarrow 5\pi \)

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decaying into \( \eta \pi \) and \( \eta' \pi \)

\( \rho \pi \rightarrow 3\pi \)

\( b_1 \pi \rightarrow 5\pi \)

\( m_\pi = 396 \) MeV
Amplitudes for $\eta^{(')}\pi$

We build the partial wave amplitudes according to the $N/D$ method

Jackura, Mikhasenko, AP et al. (JPAC & COMPASS), PLB
Rodas, AP et al. PRL

$$a(s) = \frac{n(s)}{D(s)}$$

The $D(s)$ contains all the Final State Interactions constrained by unitarity $\rightarrow$ universal
Amplitudes for $\eta^{(')}\pi$

We build the partial wave amplitudes according to the $N/D$ method

Jackura, Mikhasenko, AP et al. (JPAC & COMPASS), PLB
Rodas, AP et al. PRL

$$a(s) = \frac{n(s)}{D(s)}$$

The $n(s) \rightarrow$ background physics, process-dependent, smooth
Fit to $\eta^{'(i)}\pi$

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

$J^{PC} = 2^{++}$

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Pole hunting

$P$-wave $\eta \pi$ channel

$P$-wave $\eta' \pi$ channel

\[ \pi_1 \]

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Final results

Agreement with Lattice is restored

That’s the most rigorous extraction of an exotic meson available so far!
An isoscalar $\eta_1$?

There is a recent claim by BESIII in $J/\psi \rightarrow \gamma \eta \eta'$ of resonant activity in $P$-wave

Not enough information to perform a similar analysis but... stay tuned!

BW parameters:

$$M = 1855 \pm 9^{+6}_{-1} \text{ MeV},$$

$$\Gamma = 188 \pm 18^{+3}_{-8} \text{ MeV}$$
XYZ and $J/\psi$ photoproduction

The hybrid $\pi_1$

The scalar glueball

XYZ photoprod.

Hybrid Vehicle

$0^{++}$

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A. Rodas, AP et al., PRL122, 042002

A. Rodas, AP et al., EPJC82, 1, 80

M. Albaladejo et al., PRD102, 114010

D. Winney, AP et al., to appear
Glueballs

The **clearest** sign of confinement in pure Yang-Mills
The **worst** state to search in real life

Morningstar and Peardon

PRD60, 034509

<table>
<thead>
<tr>
<th>$J^P C$</th>
<th>Mass (MeV)</th>
</tr>
</thead>
</table>
| **0^-**
| Unquenched | 2590(40)(130) | 2560(35)(120) | 2250(60)(100) |
| This work | 3460(320) | 3100(30)(150) | 2780(50)(130) |
| M&P | 4490(590) | 3640(60)(180) | 3370(150)(150) |
| Ky | 5166(1000) | 3850(50)(190) | 3480(140)(160) |
| Meyer | 4130(90)(200) | 4200(45)(200) | 3942(160)(180) |
| **1^-**
| Unquenched | 3590(190) | 4010(45)(200) | 3240(130)(150) |
| This work | 4590(740) | 3930(40)(190) | 3660(130)(170) |
| M&P | 5166(1000) | 4200(45)(200) | 3480(140)(160) |
| Ky | 4130(90)(200) | 4200(45)(200) | 3942(160)(180) |
| Meyer | 4130(90)(200) | 4200(45)(200) | 3942(160)(180) |
| **2^-**
| Unquenched | 2980(30)(140) | 3600(40)(170) | 2670(65)(120) |
| This work | 3270(340) | 3550(40)(170) | 3270(90)(150) |
| M&P | 3850(350) | 3930(40)(190) | 3630(140)(160) |
| Ky | 4140(50)(200) | 4230(50)(200) | 4330(260)(200) |
| Meyer | 4140(50)(200) | 4230(50)(200) | 4330(260)(200) |
| **3^-**
| Unquenched | 2980(30)(140) | 3600(40)(170) | 2670(65)(120) |
| This work | 3270(340) | 3550(40)(170) | 3270(90)(150) |
| M&P | 3850(350) | 3930(40)(190) | 3630(140)(160) |
| Ky | 4140(50)(200) | 4230(50)(200) | 4330(260)(200) |
| Meyer | 4140(50)(200) | 4230(50)(200) | 4330(260)(200) |
| **4^-**
| Unquenched | 1710(50)(80) | 2390(30)(120) | 1475(30)(65) |
| This work | 1795(60) | 2400(25)(120) | 2150(30)(100) |
| M&P | 2620(50) | 2670(180)(130) | 2755(30)(120) |
| Ky | 3760(240) | 3690(40)(180) | 3385(90)(150) |
| Meyer | 3760(240) | 3690(40)(180) | 3385(90)(150) |
| **5^-**
| Unquenched | 1710(50)(80) | 2390(30)(120) | 1475(30)(65) |
| This work | 1795(60) | 2400(25)(120) | 2150(30)(100) |
| M&P | 2620(50) | 2670(180)(130) | 2755(30)(120) |
| Ky | 3760(240) | 3690(40)(180) | 3385(90)(150) |
| Meyer | 3760(240) | 3690(40)(180) | 3385(90)(150) |

Gregory et al.

JHEP1210, 170
How to identify a glueball

You don’t. Since it mixes with light isoscalars, there is no model-independent way of saying which state is (mostly) the glueball. Only suggestions:

• There is one too many wrt QM. Indeed, $f_0(1370), f_0(1500), f_0(1710)$
• A glueball couples to photons only throughout mixing, so radiative widths should be small
• Their production is enhanced in gluon-rich processes, as $J/\psi$ radiative decays
• It couples equally to mesons of all flavors (?)

However, an argument based on chiral symmetry claims the coupling proportional to quark mass
\[ J/\psi \rightarrow \gamma \pi^0 \pi^0 \text{ and } \rightarrow \gamma K_S^0 K_S^0 \]

We consider the $S$ and $D$ wave by BESIII to use the information about their relative phase. Fit quality and local description improve when a third $\rho\rho$ channel is added.
Pole extraction

\[ \Gamma = 2 \text{Im} \mathcal{F} (\text{GeV}) \]

\[ M = \text{Re} \mathcal{F} (\text{GeV}) \]

\[ f_{\delta}(1500) \]

\[ f_{\delta}(1710) \]

\[ f_{\delta}(2020) \]

\[ f_{\delta}(2330) \]

\[ f_{\delta}(1270) \]

\[ f_{\delta}(1525) \]

\[ f_{\delta}(1950) \]
Looking at the residues

Despite the large systematics, the $f_0(1710)$ couples to kaons more than the $f_0(1500)$

Also, the $f_0(1710)$ couples to the initial gluon-rich state more than the $f_0(1500)$

Both these fact suggest a sizeable glueball component for the $f_0(1710)$
JLab vs. EIC

- ✓ Variety of target species, polarization
- ✓ Detectors well known (zero-angle cal required)
- ✓ High intensity
- ✗ Smaller acceptance

- ✓ Variety of beam species, polarization
- ✗ Big «if» on timescale, accelerator and detector performances
- ✗ Low intensity
- ✓ High acceptance
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 $Z^2$

\begin{equation}
\gamma^* \rightarrow q \rightarrow T \rightarrow X \rightarrow \gamma \gamma^* \rightarrow k \rightarrow p \rightarrow W \rightarrow N' \rightarrow N
\end{equation}
**Y (vector) photoproduction**

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

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

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

Assuming previous formula, one gets:

- $\Gamma_{ee}^Y = 930 \text{ eV}$
  (cfr. hep-ex/0603024, 2002.05641)
- $BR(Y \rightarrow J/\psi \pi \pi) = 0.96\%$
- $R_Y = 0.84$
Y (vector) photoproduction

- Focus on the $1^{-+} \ Y(4260) \to J/\psi \ \pi^+\pi^-$, check with $\psi' \to J/\psi \ \pi^+\pi^-$
- 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 $\psi'$?

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

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

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

$R_Y = 0.84$
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

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Semi-inclusive $X$ production

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

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

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

Artoisenet and Braaten, PRD81, 114018 from Tevatron data

If one consider the first term only, it leads to

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