Photoproduction of Exotic $N^*$: from light quarks to charm and beauty

Xu CAO

in collaboration with Horst Lenske, Zhi Yang, Ju-Jun Xie, Jian-Ping Dai

The 12th International Workshop on the Physics of Excited Nucleons (NSTAR2019) 10-14 June, 2019
Introduction

Baryon spectrum - $N^*$ and $\Delta^*$

1. Nucleon: objects with internal components and structure.
2. Baryon spectrum: excitation of internal freedom
   \[ \Rightarrow \text{must be wide} > 100 \text{ MeV (coupled strongly to } \pi N, \eta N \text{ ....)} \]
3. Exotic & Narrow nucleon resonances?

Conventional quark model

1. More states are predicted in 3-quark models than seen in the $\pi N$ scattering: missing resonances
2. Less states are present in diquark models than seen in the $\pi N$ and $\gamma N$ scattering: $P_{13}(1900)$ and $F_{15}(2000)$ (remedy?)
3. Problem reappears in lattice QCD and Dyson-Schwinger calculations?
   Edwards et al. PRD84(2011)074508 ($m_\pi = 396$ MeV) ; Eichmann et al. PRD94(2016)094033 (varying $m_\pi$)
4. Baryon spectrum with heavy quarks? \[ \Rightarrow \text{Zou, Plenary talk on Wed.} \]
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4. Baryon spectrum with heavy quarks? $\Rightarrow$ Zou, Plenary talk on Wed.
Graal: $\gamma n \rightarrow \eta n$
1680 MeV, $\Gamma \sim 20$ MeV
confirmed by many exp. groups and polarized measurements
PLB647(2007)23

A2@MAMI: Werthmueller talk@Parallel B
exotic $N^*(1680)$ and $N^*(1720)$?
PRL111(2013)232001
Introduction

Shklyar et al. PLB650(2007)172

coupled-channel effects due to $S_{11}(1650)$ and $P_{11}(1710)$
key: neutron helicity amplitudes of $N^* \rightarrow$ Briscoe, talk@Parallel B on Wed.

Alternative I: interference in the $1/2^-$ wave - $S_{11}(1535)$ and $S_{11}(1650)$
Bonn-Gatchina and chiral quark model

Alternative II: strangeness threshold openings Döring and Nakayama
**EPECUR**: \( \pi^\pm p \rightarrow \pi^\pm p \)

\( S_{11}(1686) \) and \( P_{11}(1720) \)


- Old data of \( \pi^- p \rightarrow \eta n \):
- not contradictory with exotic \( N^*(1686) \) and \( N^*(1720) \)
Graal: $\gamma p \rightarrow \gamma p$

1681 MeV, $18 \pm 6$ MeV
1726 MeV, $21 \pm 7$ MeV

PRC91(2015)042201

Graal: $\gamma n \rightarrow \gamma n$

uncorrected quasifree

1685 MeV, $\Gamma < 30$ MeV

PRC83(2011)022201
Introduction

Baryon spectrum - $N_{c\bar{c}}^* (P_c)$!

Clearer signal in charm sector @ LHCb!

1. $N^*$ contain additional $c\bar{c}$: Exotic Narrow $N_{c\bar{c}}^*$
2. three $P_c$ in $\Lambda_b^0 \rightarrow J/\psi pK^-$


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Baryon spectrum - $N_{b\bar{b}}^* (P_b)$?

1. $N^*$ contain additional $b\bar{b}$: Exotic Narrow $N_{b\bar{b}}^*$?
2. Theoretically probably YES (Heavy Quark Symmetry)
3. How to search for them experimentally?

Xu CAO (IMP@CAS)
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1. $N^*$ contain additional $c\bar{c}$: Exotic Narrow $N^*_c$

2. three $P_c$ in $\Lambda^0_b \rightarrow J/\psi pK^-$


Baryon spectrum - $N^*_{bb} (P_b)$?

1. $N^*$ contain additional $b\bar{b}$: Exotic Narrow $N^*_{bb}$?

2. Theoretically probably YES (Heavy Quark Symmetry)


3. How to search for them experimentally?
Coupled-Channel model in light quark sector

\[ T_{fi} = V_{fi} + V_{fa} G_{ab} T_{bi} \implies T_{fi} = K_{fi} + iK_{fa} \text{Im}G_{ab} T_{bi} \]

**K-matrix approximation**

- \[ G_{ab} = \text{Re}G_{ab} + i\text{Im}G_{ab} \Rightarrow T_{fi}^{J\pm,I} = \frac{K_{fi}^{J\pm,I}}{1 - iK_{fi}^{J\pm,I}} \]

- **Unitarity** holds easily with technical simplicity and flexibility but at the cost of analyticity.

- final states: \( \gamma N, \pi N, \pi \pi N, \eta N, \omega N, K \Lambda, K \Sigma \)

- Feuster & Penner & Shklyar & CAO & Lenske & Mosel:
  
  PRC58,457;59,460(1999);PRC66,055211;055212(2002);EPJA21,445(2004); PRC71,055206;72,015210(2005);
  
  PLB650,172(2007);PRC80,058201(2009);87,015201(2013);88,055204(2013),PLB772,274(2017);PRC93,045206(2016)
Coupled-Channel model in light quark sector

\[ K_{fi} = V_{fi} + V_{fa} \text{Re}G_{ab}K_{bi} : s, u, t\text{-channel} \]

K-matrix approximation

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A Coupled-Channel Analysis with $J \leq 5/2$ and $\sqrt{s} < 2.0$ GeV.

- The $\pi N$ and $K \Sigma$ production: isospin $I = 1/2$ and $I = 3/2$ resonances
- Compton scattering off the nucleon included perturbatively: re-scattering is only through hadronic states but ignoring the $\gamma N$ state

1. initial and final vertices: electro-magnetic force
2. re-scattering between intermediate states: strong force
3. dedicate convolution of two different scales: $\alpha^2$ and $\alpha_s$
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- The $\pi N$ and $K \Sigma$ production: isospin $I = 1/2$ and $I = 3/2$ resonances
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1. Coupled-channel (T-matrix) equation is first solved for $\pi N \to MN$
2. In an independent second step, the $\gamma N \to MN$ can be extracted
3. Finally, the Compton scattering amplitudes are calculated without free parameters
The associate strangeness $K\Sigma$ production in photo-induced reactions: Data from CBELSA, LEPS, CLAS, Graal and SAPHIR groups.

Compton scattering off the nucleon: Graal data

1. Resonances with isospin $I = 3/2$: $\Delta^*$

2. Most of the models are based on the old database before 2000.

3. The current inconclusive status of the old isobar models:
   - New resonances?

4. The coupled-channel analysis of the $K\Sigma$ photoproduction:
   - Juelich-Bonn
   - Bonn-Gatchina
   - The Excited Baryon Analysis Center (EBAC@JLab): ANL-Osaka
Coupled-Channel model in light quark sector

Baryon spectrum

I (1075 MeV < \( W \) < 1350 MeV); II (1350 MeV < \( W \) < 1600 MeV); III (1600 MeV < \( W \) < 1800 MeV); IV (1800 MeV < \( W \) < 2250 MeV).
Coupled-Channel model in light quark sector

\[ \gamma p \rightarrow K^+ \Sigma^0: \]
polarization observables (CLAS)

X.C., V.Shklyar, H.Lenske PRC88(2013)055204

- \( C_z \): determined by the Born term with additional small structures from resonances
- \( C_x \): \( D_{33}(1700) \) important in \( d\sigma/d\Omega \), however bad for \( C_x \)
- \( F_{35}(1905) \) and \( F_{15}(1680) \) are seen
Coupled-Channel model in light quark sector

Graal’2015

$\vec{\gamma}p \to \gamma p$ beam asymmetry: all data

X. C., H. Lenske, PLB772(2017)274

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Coupled-Channel model in light quark sector

\[ \pi N \text{ threshold} \]

Solid lines: Fit from \( K\Sigma \ldots \)

Shaded area: new \( D_{33}(1700), F_{35}(1905) \)

Dotted lines: exotic \( S_{11}(1680), P_{11}(1720) \)

\( \vec{\gamma} p \rightarrow \gamma p \) beam asymmetry: Graal data

X. C., H. Lenske, PLB772(2017)274
Coupled-Channel model in light quark sector

\[ \frac{d\sigma}{d\Omega} \text{ (nb/sr)} \]

S\textsubscript{11}(1680)  \hspace{1cm} P\textsubscript{11}(1720)
### Coupled-Channel model in light quark sector

<table>
<thead>
<tr>
<th>$\Delta^*$</th>
<th>Ref.</th>
<th>BW mass</th>
<th>$\Gamma_{tot}$</th>
<th>$A_{1/2}$ or $A_{1/2}^p$</th>
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<tbody>
<tr>
<td>$P_{33}(1232)$</td>
<td>our</td>
<td>1227</td>
<td>110</td>
<td>-128 ± 6</td>
<td>-253 ± 8</td>
</tr>
<tr>
<td></td>
<td>PDG</td>
<td>1232</td>
<td>117</td>
<td>-135 ± 6</td>
<td>-255 ± 5</td>
</tr>
<tr>
<td>$D_{13}(1520)$</td>
<td>our</td>
<td>1505</td>
<td>103</td>
<td>-15 ± 1</td>
<td>146 ± 1</td>
</tr>
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<td></td>
<td>new</td>
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<td>142 ± 12</td>
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<td>$F_{35}(1905)$</td>
<td>our</td>
<td>1842</td>
<td>619</td>
<td>54</td>
<td>-127</td>
</tr>
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<td></td>
<td>new</td>
<td>1842</td>
<td>619</td>
<td>61 ± 10</td>
<td>-78 ± 15</td>
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<td>1880</td>
<td>330</td>
<td>22 ± 5</td>
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<td>$S_{11}(1680)$</td>
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$\diamond$: in MeV; $\heartsuit$: in $10^{-3}$ GeV$^{-1/2}$; $\dagger$: sign is not determined.
Exotic $N^{*}_{c\bar{c}} (P_c)$ in $\gamma p \rightarrow J/\psi p$

- $P_r$ production x-section in $\gamma p \rightarrow Vp$:

$$\sigma_r = \frac{2 J + 1}{(2 s_1 + 1)(2 s_2 + 1) k_{in}^2} \frac{4 \pi \Gamma^2}{4} \frac{B(P_r \rightarrow \gamma p) B(P_r \rightarrow Vp)}{(W - M_r)^2 + \Gamma_r^2/4}$$

- Assuming $P_r \rightarrow \gamma p$ is dominated by the vector meson (VMD)

$$B(P_r \rightarrow \gamma p) = \frac{3 \Gamma(V \rightarrow e^+ e^-)}{\alpha M_{J/\psi}} \left( \frac{k_{in}}{k_{out}} \right)^{2L+1} B_L(P_r \rightarrow Vp)$$

- resulting into

$$\sigma_r \propto B^2(P_c \rightarrow Vp)$$

absence of triangle singularity!
Exotic $N_{c\bar{c}}^*$ ($P_c$) in $\gamma p \rightarrow J/\psi p$

- LHCb has given,

$$\mathcal{R} = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow P_c^+ K^-) \mathcal{B}(P_c^+ \rightarrow J/\psi p)}{\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-)}$$

independent of the spin and parity of $P_c$.

- LHCb also measured: $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi p K^-) = (3.2^{+0.6}_{-0.5}) \times 10^{-4}$

- So we expect that $\mathcal{B}(\Lambda_b^0 \rightarrow P_c^+ K^-) \mathcal{B}(P_c^+ \rightarrow J/\psi p) \sim 10^{-6}$

- GlueX&HALL-C@JLab found $\mathcal{B}(P_c^+ \rightarrow J/\psi p) < $ several percentage

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Exotic $N^{*}_{c\bar{c}} (P_c)$ in $\gamma p \rightarrow J/\psi p$

- We conjecture accordingly,

$$2\% > \mathcal{B}(P^+_c \rightarrow J/\psi p) > 0.05\%$$
$$10^{-3} > \mathcal{B}(\Lambda_b \rightarrow P^+_c K^-) > 10^{-5}$$

This loose bound in fact puts strong constraint on various models.

\[ \begin{array}{c}
\text{4.00} & \text{4.25} & \text{4.50} & \text{4.75} & \text{5.00} \\
\sqrt{s} (\text{GeV}) & \sigma^{\gamma p \rightarrow J/\psi p} (\text{nb}) & 10^{-2} & 10^{-1} & 10^{0} \\
\end{array} \]

X. C. & J.-P. Dai, 1904.06015: polarization observables?
update to coupled-channel calculation?
\(\eta_c p & \bar{D}\Lambda_c & \bar{D}^{*}\Lambda_c & \bar{D}\Sigma_c & \bar{D}^{*}\Sigma_c: 110 \text{ MeV away at least} \)
Exotic $N_{b\bar{b}}^* (P_b)$ in $\gamma p \rightarrow \Upsilon p$

- It can be reached by the planned Electron-ion collider in China (EicC)
  - Energy: $3.5(e) \times 20(p) \text{ GeV}$
  - Luminosity: $2 \sim 4 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- We know little about $\Upsilon$-photoproduction.

non-resonant background within various models depends weakly on virtuality of photon due to large $M_{\Upsilon}$

X. C. et al. in preparation:
Exotic $N_{b\bar{b}}^*(P_b)$ in $\gamma p \rightarrow \Upsilon p$

- non-resonant Upsilon production: $\sim 20$ pb $\sim 0.05$M/month.
- The $P_b @$ peak $\sim 0.3$ nb $\sim 0.78$M/month.
- The two-body phase space would introduce a reduction factor of about five for near-threshold background events.
- virtual photon flux reduce electroproduction by two orders
Exotic $N_{bb^-}^*(P_b)$ in $\gamma p \rightarrow \gamma p$

- production is enhanced if ion beam is used,
  - $e^+{^{3}}$He: 3.5 GeV × 40 GeV
- Designed Polarization of beams: $e = 80\%$, $p = 70\%$
  - noticeable if $2\% > B(P_r^+ \rightarrow Vp) > 0.05\%$
  - quantum number: $J^P$
  - EM form factor?

---

Planned EicC-I

- Racetrack ERing polarized electron 3.5–5 GeV
- Figure-8 PRing polarized proton 20–25 GeV
- Energy Recovery Linac ERL electron 10–15 MeV
- Booster Ring: Accumulation 600m, 34–86 Tm
- Polarized $H^+$ Ion source
- Polarized $H^-$ Ion source

12th 5-year plan: 1.5B&1.2B CNY
Conclusion

- Compton scattering off the proton up to the third resonance region
  - \( \Delta \) states are largely determined in \( K\Sigma \) production
    - \( P_{33}(1232) \) and \( D_{13}(1520) \) resonances below 1.6 GeV
    - \( D_{33}(1700) \) and \( F_{35}(1930) \) above 1.6 GeV
  - no cusps are generated by the \( K\Lambda \) and \( \omega N \) threshold effect
    - narrow \( S_{11}(1680) \) and \( P_{11}(1720) \)
  - the model is readily extended to \( \gamma n \rightarrow \gamma n \) reaction
  - rare photoproduction data off the neutron
    - GRAAL \( \gamma n \rightarrow \gamma n \) data uncorrected by the detector efficiency

- \( \gamma p \rightarrow J/\psi p \) from constrained 2\% > \( B(P_c^+ \rightarrow J/\psi p) > 0.05\%: \)
  - differential \( \times \) section and polarization observables?
  - a coupled-channel model?

- Searching for \( P_b \) in \( \gamma p \rightarrow \Upsilon p \) in future EicC?

- Thanks for your attention!!!
Compton scattering off the proton up to the third resonance region

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\( \gamma p \rightarrow J/\psi p \) from constrained 2% > \( B(P_c^+ \rightarrow J/\psi p) > 0.05\%:

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Compton scattering off the proton up to the third resonance region

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Searching for $P_b$ in $\gamma p \rightarrow Y p$ in future EicC?

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FIG. 1. (Color online) In the overall reaction center of mass, the coordinate system can be oriented along the outgoing $K^+$ meson \{\hat{x}', \hat{y}', \hat{z}'\} or along the incident photon direction \{\hat{x}, \hat{y}, \hat{z}\}. The dotted box represents the rest frame of the hyperon and the coordinate system used for specifying the polarization components. The red arrows represent polarization vectors.
Physically, $C_x$ and $C_z$ measure the transfer of circular polarization, or helicity, of the incident photon on an unpolarized target to the produced hyperon.
Assuming the photon behaves as an isoscalar particle, isospin relations between channels of pion photoproduction are violated explicitly in experiment: $\Delta \rightarrow N\gamma$

Electromagnetic couplings are dependent on the different charge states of a particle and thus break the isospin symmetry

For the isovector photon-isovector photon $\gamma p \rightarrow \gamma p$ amplitudes: When both initial and final photons are in isovector states, the total isospin could be either $I = 1/2$ or $I = 3/2$, respectively, thus being weighted differently in the rescattering part.
However…. $\pi N$ data is not enough for the model calculation.

i.e. $\pi^+ p \rightarrow K^+ \Sigma^+$:

1. Giessen model: $P_{31}$ dominates at threshold, $D_{35}$ and $P_{33}$ are important at high energies.
2. Juelich model: $S_{31}$ dominates, $F_{37}$ is seemed at high energies.
3. Bonn-Gatchina PWA: $P_{33}$ is the most essential, and high partial waves are important at high energies.

Secondary $\pi$ beams are expected in HADES@GSI, JLab, and J-PARC.

- Conventional $\pi N$ experiment revived?

- Plenty of photoproduction data should be used.
11 $N^*$ resonances with $I = 1/2$
9 $\Delta^*$ resonances with $I = 3/2$
estatic partial waves:
$\gamma N \rightarrow \pi N$ multipoles: GWU

<table>
<thead>
<tr>
<th>$\Delta^*$</th>
<th>$A^p_{1/2}$</th>
<th>$A^p_{3/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_{31}(1620)$</td>
<td>-58</td>
<td>—</td>
</tr>
<tr>
<td>$P_{31}(1750)$</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>$P_{33}(1232)$</td>
<td>-128</td>
<td>-253</td>
</tr>
<tr>
<td>$P_{33}(1600)$</td>
<td>-10</td>
<td>-17</td>
</tr>
<tr>
<td>$P_{33}(1920)$</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>$D_{33}(1700)$</td>
<td>97</td>
<td>147</td>
</tr>
<tr>
<td>$D_{35}(1930)$</td>
<td>-66</td>
<td>1</td>
</tr>
<tr>
<td>$F_{35}(1905)$</td>
<td>54</td>
<td>-127</td>
</tr>
<tr>
<td>$F_{35}(2000)$</td>
<td>18</td>
<td>-23</td>
</tr>
</tbody>
</table>

$\Re$ and $\Im$ of $E^{1/2}$, $M^{1/2}$, and $E^{3/2}$.
Spares: $\pi^+ p \rightarrow K^+ \Sigma^+$

- $\pi^+ p \rightarrow K^+ \Sigma^+$: differential cross section
- Full model vs the calculation with the $P_{31}(1750)$ turning off
Spares: $\gamma p \rightarrow K^0\Sigma^+$

- $\gamma p \rightarrow K^0\Sigma^+$: CBELSA EPJA35(2008) CLAS thesis(2003)
  less accurately reproduced, becoming worse above 1.9 GeV

- problem in the $d\sigma/d\omega$: non-resonant contribution

- recoil polarization $P_\Sigma$: data with large error bars:
  role of $D_{15}(1675)$
Spares: Born couplings

<table>
<thead>
<tr>
<th></th>
<th>$g_{NK\Sigma}$</th>
<th>$g_{NK_0^*\Sigma}$</th>
<th>$g_{NK^*\Sigma}$</th>
<th>$\kappa_{NK^*\Sigma}$</th>
<th>$g_{NK_1\Sigma}$</th>
<th>$\kappa_{NK_1\Sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>new</td>
<td>-5.41</td>
<td>-32.94</td>
<td>0.83</td>
<td>-1.71</td>
<td>3.67</td>
<td>-2.58</td>
</tr>
<tr>
<td>old</td>
<td>2.48</td>
<td>-26.15</td>
<td>4.33</td>
<td>-0.86</td>
<td>22.80</td>
<td>2.40</td>
</tr>
</tbody>
</table>

Table: Born couplings in the model.

- $t$-channel $K_1$ and $K_0^*$ meson exchange: small
- $K\Lambda$ production, PRC72,015210(2005): $g_{NK\Lambda} = -6.04$ (CLAS) or $-4.70$ (SAPHIR)
  $\Rightarrow$ SU(3) symmetry: the relative sign of $NK\Sigma$ and $NK\Lambda$ is negative
  $\Rightarrow$ confirmed by the Bonn-Gatchina (EPJA)
- $D_{13}(1520)$, $D_{15}(1675)$, $D_{35}(1930)$ and $F_{15}(1680)$ states, have large couplings to the $K\Sigma$ channel.
A clean isospin filter: $P_{31}(1750)$, $P_{31}(1910)$, and $S_{31}(1620)$

but a challenge to experiment: neutron in three final states

Spares: Fit quality

<table>
<thead>
<tr>
<th>$\chi^2/\text{num.}$</th>
<th>data num.</th>
<th>Solid</th>
<th>Shaded</th>
<th>Dotted</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma p \rightarrow \gamma p: d\sigma/d\Omega$</td>
<td>95*</td>
<td>92.2</td>
<td>25.9</td>
<td>60.2</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \gamma p: \Sigma$</td>
<td>78*</td>
<td>1.5</td>
<td>2.5</td>
<td>1.7</td>
</tr>
<tr>
<td>$\gamma p \rightarrow K\Sigma: \text{all}$</td>
<td>909</td>
<td>2.0</td>
<td>2.8</td>
<td>3.1</td>
</tr>
</tbody>
</table>

*: only data between 1.6 - 1.8 GeV are included.

- Solid: from the $K\Sigma$ solution
- Shaded: refit by including Compton scattering
- Dotted add $S_{11}(1680)$, $P_{11}(1720)$, only 1$\sigma$ significance!
The total cross section of non-resonant Upsilon photo-production can be read as

\[ \sigma_V = N \mathcal{W}^{\delta(Q^2)} = N \mathcal{W}^{\alpha + \beta \ln(Q^2 + M_v^2)} \]

The merit of this simple parameterization is that it is applicable to all DVMP with proper \( Q^2 \) dependence. The parameters \( \alpha \) and \( \beta \) have been determined by the data of DVMP to be \( \alpha = 0.31 \pm 0.02 \) and \( \beta = 0.13 \pm 0.01 \). The corresponding \( \delta(Q^2 = 0) \approx 0.89 \), confronted with the perturbative QCD prediction \( \delta \sim 1.7 \). The normalization \( N \) is determined by the data of \( \gamma p \to \Upsilon p \) at high energies to be \( 2.62 \pm 0.38 \) nb. The production of exotic state candidate \( P_b \) in \( \gamma p \to \Upsilon p \) can be written as

\[ \sigma_R = \frac{2J + 1}{(2s_1 + 1)(2s_2 + 1)} \frac{4\pi \Gamma^2}{k_{in}^2} \frac{\mathcal{B}(P_b \to \gamma p) \mathcal{B}(P_b \to \Upsilon(1S)p)}{4(X - M)^2 + \Gamma^2/4} \]
2. R. Aaij et al. [LHCb Collaboration], JHEP 1509, 084 (2015)
Photoproduction of Exotic $N^*$: From light quarks to charm and beauty

We explore the photo-production of possible exotic $N^*$, which are narrow pentaquark candidates containing light quarks or charm or beauty. The latter two are also known as $P_c$ and $P_b$ states in literatures. We analyzed the Compton scattering off the proton in the third resonance region in a coupled-channel effective Lagrangian model with K-matrix approximation. The evidence of exotic $N^*$ with light quarks are found to be weak at present. Motivated by the $P_c$ observed by LHCb, we discussed the possible signal of $P_c$ and $P_b$ states in $\gamma p \rightarrow J/\psi p$ and $\gamma p \rightarrow \Upsilon p$, respectively at an Electron-Ion Collider (EIC) in order to disentangle the nature of these states.