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

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中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Introduction

Baryon spectrum - N^* and Δ^*

1. Nucleon: objects with internal components and structure.
2. Baryon spectrum: excitation of internal freedom
   $\Longrightarrow$ must be wide $>$ 100 MeV (coupled strongly to πN, ηN ....)
3. Exotic&Narrow nucleon resonances?

Conventional quark model

1. More states are predicted in 3-quark models than seen in the πN scattering: misssing resonances
2. Less states are present in diquark models than seen in the πN and γN scattering: $P_{13}(1900)$ and $F_{15}(2000)$ (remedy?)
3. Problem reappears in latticeQCD and Dyson-Schwinger calculations?
   Edwards *et al.* PRD84(2011)074508 ($m_\pi = 396$ MeV) ; Eichmann *et al.* PRD94(2016)094033 (varying m_π)
4. Baryon spectrum with heavy quarks? $\Rightarrow$ Zou, Plenary talk on Wed.

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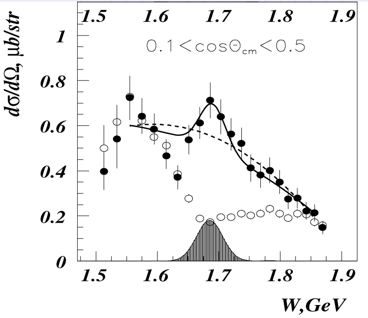
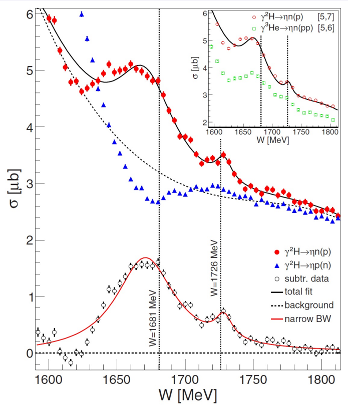
Introduction





- Graal: $\gamma n \to \eta n$

  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 $N^*(1720)$?

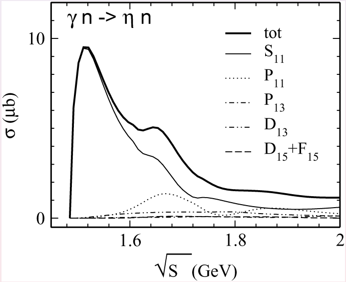
PRL111(2013)232001

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.

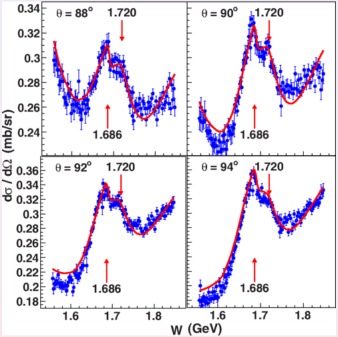


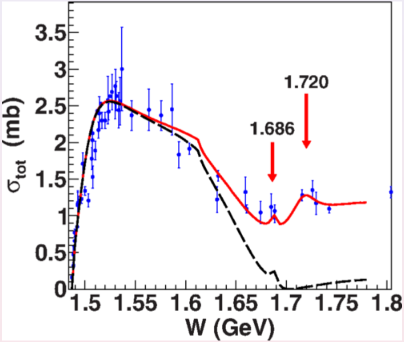
Alternative I: interference in the $1/2^-$ wave - $S_{11}(1535)$ and $S_{11}(1650)$

Bonn-Gatchina and chiral quark model

Alternative II: strangeness threshold openings Döring and Nakayama

Introduction

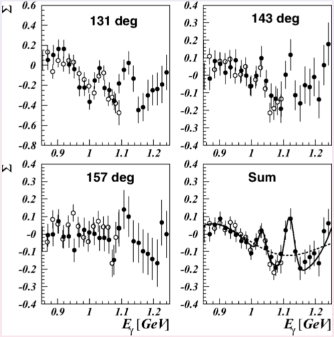


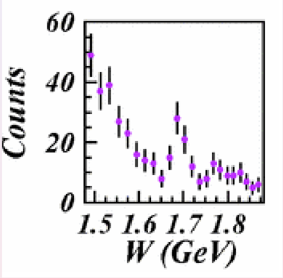


- EPECUR: $\pi^{\pm} p \to \pi^{\pm} p$
  $S_{11}(1686)$ and $P_{11}(1720)$
  PRC91(2015)025205;93(2015)062201

- Old data of $\pi^{-} p \to \eta n$:
- not contradictory with exotic $N^{*}(1686)$ and $N^{*}(1720)$

Introduction





- Graal: $\gamma p \to \gamma p$
  1681 MeV, 18 ± 6 MeV
  1726 MeV, 21 ± 7 MeV

  PRC91(2015)042201

- Graal: $\gamma n \to \gamma n$
- uncorrected quasifree
- 1685 MeV, $\Gamma < 30$ MeV

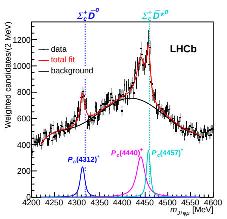
  PRC83(2011)022201

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 $\Lambda_b^0 \to J/\psi p K^-$

1904.03947;PRL115(2015)072001;Neubert,Plenary talk on Wed.



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)
   PLB709(2012)70,PRL115(2015)122001,EPJC76(2016)624,NPA980(2018)21,PRD99(2019)014035
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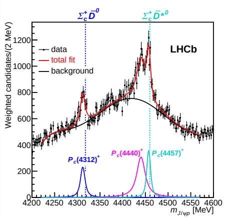

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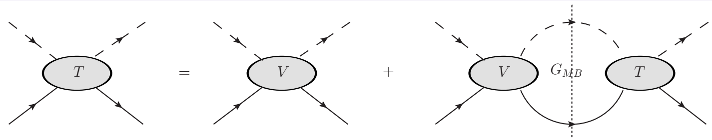
Coupled-Channel model in light quark sector

- 

$$T_{fi} = V_{fi} + V_{fa} G_{ab} T_{bi} \Longrightarrow T_{fi} = K_{fi} + iK_{fa} ImG_{ab} T_{bi}$$

K-matrix approximation

- $G_{ab} = \cancel{ReG_{ab}} + iImG_{ab} \Rightarrow T_{fi}^{J\pm,I} = \frac{K_{fi}^{J\pm,I}}{1 - iK_{fi}^{J\pm,I}}$
- 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)

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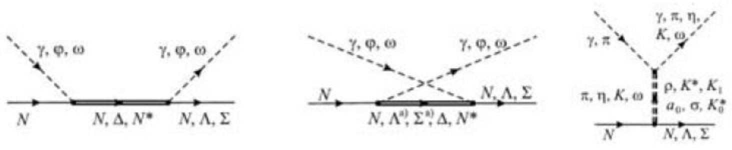
- 

$$K_{fi} = V_{fi} + \cancel{V_{fa} ReG_{ab} K_{bi}}:\ s, u, t\text{-channel}$$

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Coupled-Channel model in light quark sector

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

- The πN 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 γN state

1. initial and final vertices: electro-magnetic force
2. re-scattering between intermediate states: strong force
3. dedicate convolution of two different scales: α^2 and α_s

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

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- Compton scattering off the nucleon included perturbatively: re-scattering is only through hadronic states but ignoring the γN state

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

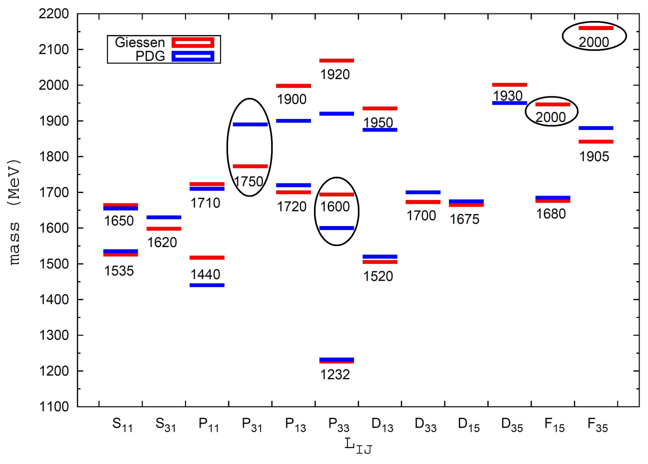
Coupled-Channel model in light quark sector

- 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 $I = 3/2$: Δ^*
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

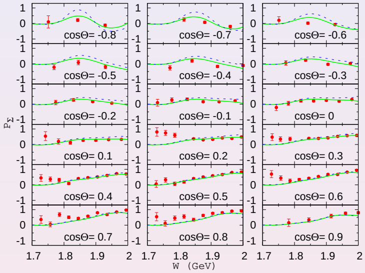
Coupled-Channel model in light quark sector

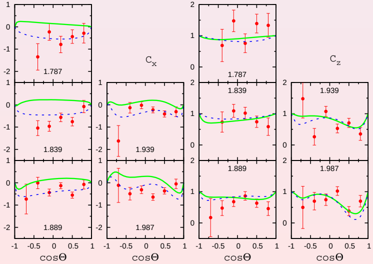
Baryon spectrum



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





- $\gamma p \to K^+\Sigma^0$: 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

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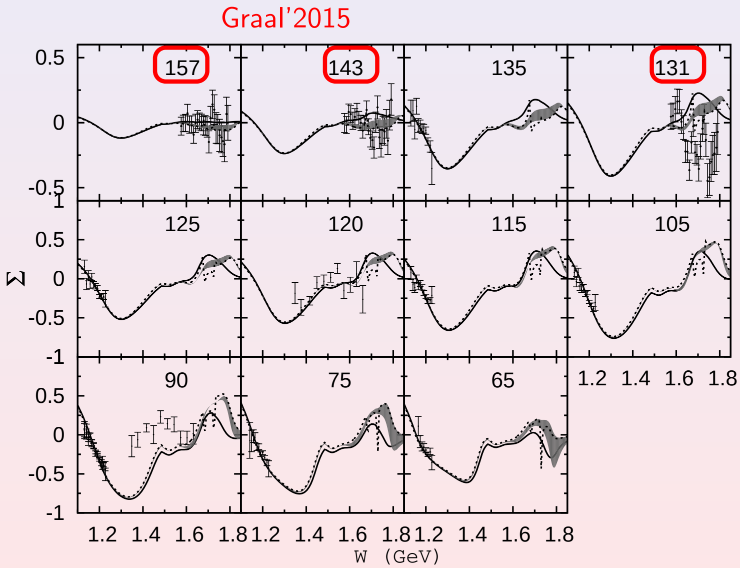

$\vec{\gamma} p \to \gamma p$ beam asymmetry: all data

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

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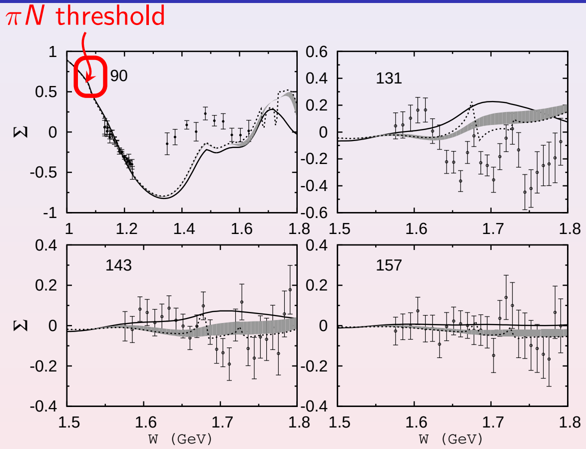

Solid lines: Fit from $K\Sigma$...

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

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

$\vec{\gamma}p \to \gamma p$ beam asymmetry: Graal data X. C., H. Lenske, PLB772(2017)274

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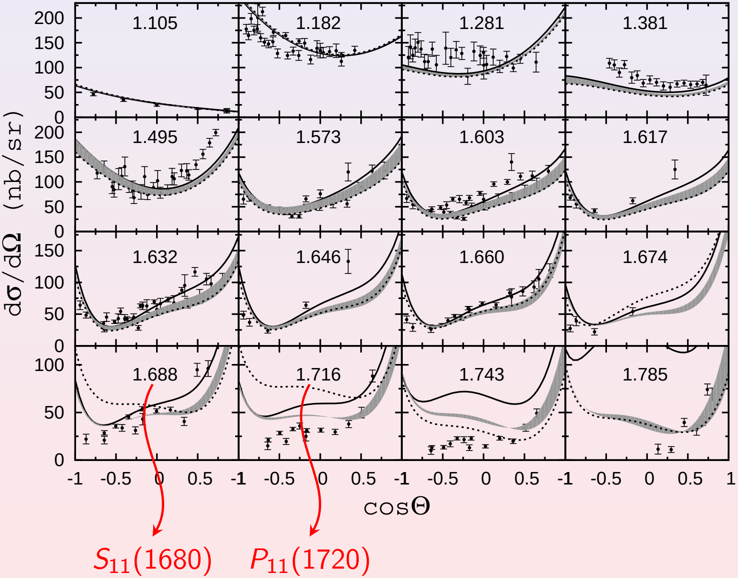

Coupled-Channel model in light quark sector

Δ^*	Ref.	BW mass$^\diamond$	$\Gamma_{tot}{}^\diamond$	$A_{\frac{1}{2}}$ or $A^p_{\frac{1}{2}}$ $^\heartsuit$	$A_{\frac{3}{2}}$ or $A^p_{\frac{3}{2}}$ $^\heartsuit$
$P_{33}(1232)$	our	1227	110	-128 $\pm$ 6	-253 $\pm$ 8
	PDG	1232	117	-135 $\pm$ 6	-255 $\pm$ 5
$D_{13}(1520)$	our	1505	103	-15 $\pm$ 1	146 $\pm$ 1
	PDG	1515	115	-20 $\pm$ 5	140 $\pm$ 10
$D_{33}(1700)$	our	1673	766	97	147
	new	1673	766	106 $\pm$ 5	142 $\pm$ 12
	PDG	1700	300	140 $\pm$ 30	140 $\pm$ 30
$F_{35}(1905)$	our	1842	619	54	-127
	new	1842	619	61 $\pm$ 10	-78 $\mp$ 15
	PDG	1880	330	22 $\pm$ 5	-45 $\pm$ 10
$S_{11}(1680)$	new	1681	2 $\pm$ 1	32 $\pm$ 10†	—
$P_{11}(1720)$	new	1726	2 $\pm$ 1	35 $\pm$ 10†	—

- $^\diamond$: in MeV; $^\heartsuit$: in 10^{-3} GeV$^{-1/2}$; †: sign is not determined.

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

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

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

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

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

- resulting into

$$\sigma_r \propto \mathcal{B}^2(P_c \to Vp)$$

!absence of triangle singularity!

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

- LHCb has given,

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

independent of the spin and parity of P_c.

- LHCb also measured: $\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-) = (3.2^{+0.6}_{-0.5}) \times 10^{-4}$
- So we expect that $\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) \sim 10^{-6}$
- GlueX&HALL-C@JLab found $\mathcal{B}(P_c^+ \to J/\psi p) <$ several percentage

state	Mass [MeV]	Width [MeV]	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	$0.53 \pm 0.16^{+0.15}_{-0.13}$

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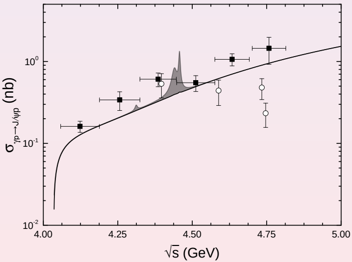
Exotic $N^*_{c\bar{c}}$ (P_c) in $\gamma p \to J/\psi p$

- We conjecture accordingly,

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

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



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 MeV away at least

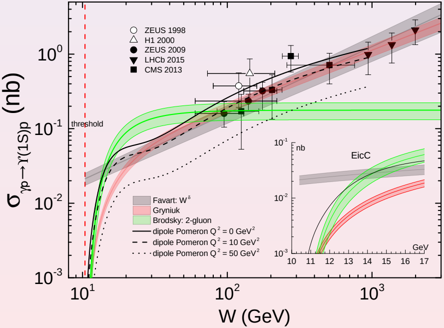
Exotic $N^*_{b\bar{b}}$ (P_b) in $\gamma p \to \Upsilon p$

- It can be reach by the planned Electron-ion collider in China (EicC)

Energy: 3.5(e) $\times$ 20(p) GeV

Luminosity: $2 \sim 4 \times 10^{33}$ cm^{-2} s^{-1}

- We know little about Υ-photoproduction.

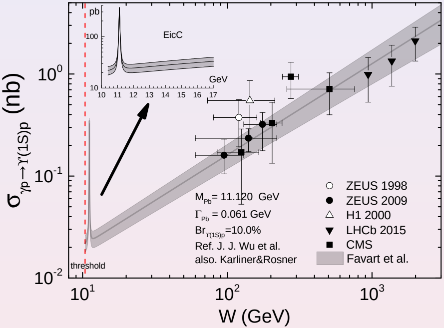


X. C. *et al.* in preparation:

non-resonant background within various models

depends weakly on virtuality of photon due to large M_Υ

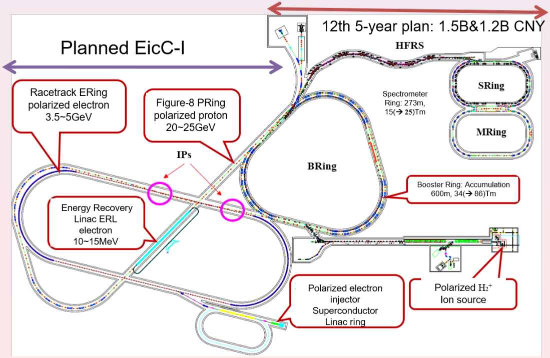
Exotic $N^*_{b\bar{b}}$ (P_b) in $\gamma p \to \Upsilon p$



- non-resonant Upsilon production: $\sim$ 20 pb $\sim$ 0.05M/month.
- The P_b @ peak $\sim$ 0.3 nb $\sim$ 0.78M/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 $N^*_{b\bar{b}}$ (P_b) in $\gamma p \to \Upsilon p$

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



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Spares: Frame

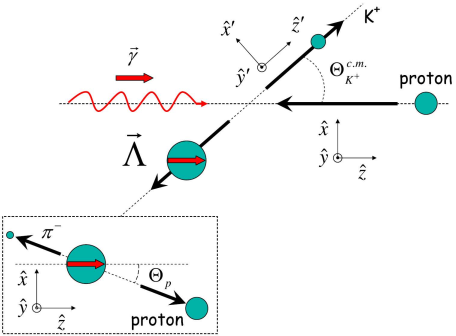


FIG. 1. (Color online) In the overall reaction center of mass, the coordinate system can be oriented along the outgoing K^+ meson $\{\hat{x}', \hat{y}', \hat{z}'\}$ or along the incident photon direction $\{\hat{x}, \hat{y}, \hat{z}\}$. The dotted box represents the rest frame of the hyperon and the coordinate system used for specifying the polarization components. The red arrows represent polarization vectors.

Spares: Observables

Observable	Required polarization		
	Beam	Target	Hyperon
	Single polarization & cross section		
A, $\frac{d\sigma}{d\Omega}$	–	–	–
Σ	linear	–	–
T	–	transverse	–
P	–	–	along y'
	Beam and target polarization		
G	linear	along z	–
H	linear	along x	–
E	circular	along z	–
F	circular	along x	–
	Beam and recoil baryon polarization		
$O_{x'}$	linear	–	along x'
$O_{z'}$	linear	–	along z'
$C_{x'}$	circular	–	along x'
$C_{z'}$	circular	–	along z'
	Target and recoil baryon polarization		
$T_{x'}$	–	along x	along x'
$T_{z'}$	–	along x	along z'
$L_{x'}$	–	along z	along x'
$L_{z'}$	–	along z	along z'

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.

Spares: isovector photon

- Assuming the photon behaves as an isoscalar particle, isospin relations between channels of pion photoproduction are violated explicitly in experiment: $\Delta \to N\gamma$
- Electromagnetic couplings are dependent on the different charge states of a particle and thus break the isospin symmetry
- For the isovector photon-isovector photon $\gamma p \to \gamma p$ 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 rescat-tering part.

Spares: Need for photoproduction data

- However....πN data is not enough for the model calculation.
- i.e. $\pi^+ p \to K^+\Sigma^+$:
  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 π beams are expected in HADES@GSI, JLab, and J-PARC.
  - Conventional πN experiment revived?
- Plenty of photoproduction data should be used.

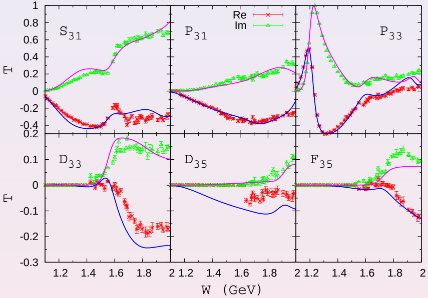
Spares: PWA

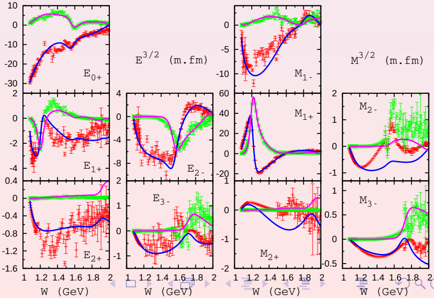
- 11 N^* resonances with $I = 1/2$
- 9 Δ^* resonances with $I = 3/2$

elastic πN partial waves:

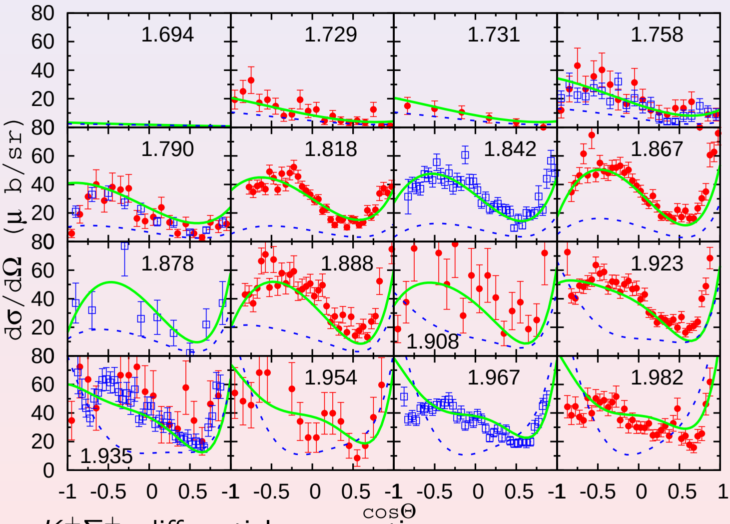
$\gamma N \to \pi N$ multipoles: GWU

Δ^*	$A^p_{\frac{1}{2}}$	$A^p_{\frac{3}{2}}$
$S_{31}(1620)$	-58	—
$P_{31}(1750)$	1	—
$P_{33}(1232)$	-128	-253
$P_{33}(1600)$	-10	-17
$P_{33}(1920)$	21	25
$D_{33}(1700)$	97	147
$D_{35}(1930)$	-66	1
$F_{35}(1905)$	54	-127
$F_{35}(2000)$	18	-23



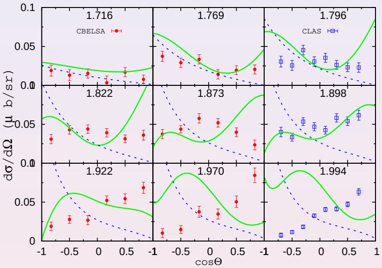


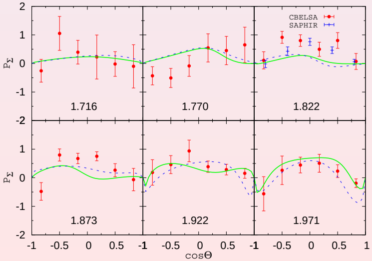
Spares: $\pi^+ p \to K^+\Sigma^+$



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

Spares: $\gamma p \to K^0\Sigma^+$





- $\gamma p \to K^0\Sigma^+$:
  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_Σ:
  data with large error bars:
  role of $D_{15}(1675)$

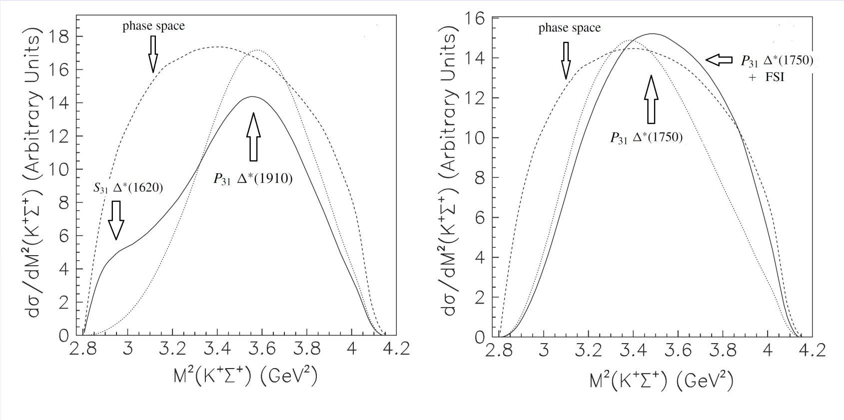
Spares: Born couplings

	$g_{NK\Sigma}$	$g_{NK_0^*\Sigma}$	$g_{NK^*\Sigma}$	$\kappa_{NK^*\Sigma}$	$g_{NK_1\Sigma}$	$\kappa_{NK_1\Sigma}$
new	-5.41	-32.94	0.83	-1.71	3.67	-2.58
old	2.48	-26.15	4.33	-0.86	22.80	2.40

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.

Spares: $pp \to nK^+\Sigma^+$



- A clean isospin filter: $P_{31}(1750)$, $P_{31}(1910)$, and $S_{31}(1620)$
- but a challenge to experiment: neutron in three final states
  see X-Y Wang, X.C.*, J-J Xie, X-R Chen, PRC92, 015202 (2015)

Spares: Fit quality

$\chi^2/num.$	data num.	Solid	Shaded	Dotted
$\gamma p \to \gamma p$: $d\sigma/d\Omega$	95*	92.2	25.9	60.2
$\gamma p \to \gamma p$: Σ	78*	1.5	2.5	1.7
$\gamma p \to K\Sigma$: all	909	2.0	2.8	3.1

- *: only data between 1.6 - 1.8 GeV are included.
- Solid: from the $K\Sigma$ solution
- Shaded: refit by including Compton scattering
- Dottedadd $S_{11}(1680)$, $P_{11}(1720)$, only 1σ significance!

Spares: Formalism

The total cross section of non-resonant Upsilon photo-production can be read as

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

The merit of this simple parameterization is that it is applicable to all DVMP with proper Q^2 dependence. The parameters α and β 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 $\delta(Q^2 = 0) = 0.89$, confronted with the perturbative QCD prediction $\delta \sim 1.7$The normalization $\mathcal{N}$ is determined by the data of $\gamma p \to \Upsilon p$ at high energies to be 2.62 ± 0.38 nb. The production of exotic state candidate P_b in $\gamma p \to \Upsilon p$ can be written as

$$\sigma_R = \frac{2J+1}{(2s_1+1)(2s_2+1)} \frac{4\pi}{k_{in}^2} \frac{\Gamma^2}{4} \frac{\mathcal{B}(P_b \to \gamma p)\,\mathcal{B}(P_b \to \Upsilon(1S)p)}{(W-M)^2 + \Gamma^2/4}$$

Spares: Reference for $\gamma p \to \Upsilon p$

1. L. Favart, M. Guidal, T. Horn and P. Kroll, Eur. Phys. J. A 52, no. 6, 158 (2016)
2. R. Aaij et al. [LHCb Collaboration], JHEP 1509, 084 (2015)
3. J. Breitweg et al. [ZEUS Collaboration], Phys. Lett. B 437, 432 (1998)
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5. C. Adloff et al. [H1 Collaboration], Phys. Lett. B 483, 23 (2000)
6. CMS Collaboration [CMS Collaboration], CMS-PAS-FSQ-13-009.
7. J. J. Wu and B. S. Zou, Phys. Lett. B 709, 70 (2012)
8. M. Karliner and J. L. Rosner, Phys. Rev. Lett. 115, no. 12, 122001 (2015)
9. M. Karliner and J. L. Rosner, Phys. Lett. B 752, 329 (2016)

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 $\gamma p \to J/\psi p$ and $\gamma p \to \Upsilon p$, respectively at an Electron-Ion Collider (EIC) in order to disentangle the nature of these states.