Study of N* in χQM via η productions

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Why we study the η production

- N*: Nonperturbative QCD

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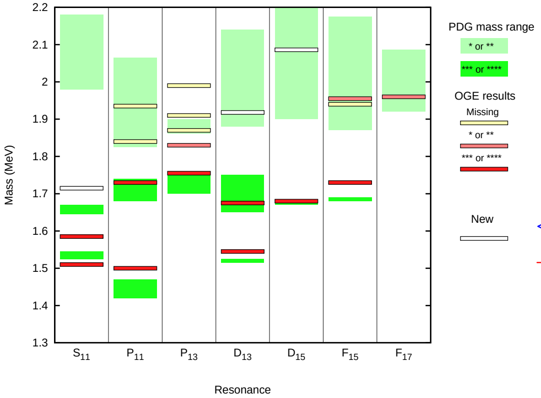
- The problems about N* spectrum compared with CQM.



- "missing" resonances
- new resonances
- The lowest resonances: $S_{11}(1535)$, $P_{11}(1440)\ldots$

$$< qqq > + < qqqq\bar{q} > + < qqqg > + \cdots$$

Why we study the η production

- N*: Nonperturbative QCD
- The problems about N* spectrum compared with CQM.
- Ways to deepen our understanding of N*
  - Photo-/electroproduction: CLAS,ELSA,MAMI...
  - π N scattering: CB...
  - NN collision: COSY,HPLUS@CSR...
  - J/ψ decay in e^+e^- collision: BES
  - ......

Why we study the η production

- N*: Nonperturbative QCD
- The problems about N* spectrum compared with CQM.
- Ways to deepen our understanding of N*
- Merit of ηN channel
  - No Δ: $I_\eta + I_N \to 1/2$, no 3/2
  - "η-mesic nuclei"
  - Important $S_{11}(1535)$

Why we study the η production

- N*: Nonperturbative QCD
- The problems about N* spectrum compared with CQM.
- Ways to deepen our understanding of N*
- Merit of ηN channel

We will study N* through two η production processes
$\gamma p \to \eta p$ and $\pi^- p \to \eta n$

Extracting information of resonances from data

Extracting the information of resonances, such as, mass, decay width, from the observables

- SAID
- MAID
- EBAC
- Bonn-Gatchina groups
- Geissen group
- . . . . . .

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Do not reach the subnucleonic degrees of freedom!

Reach the subnucleonic degrees of freedom

Approaches with the subnucleonic degrees of freedom

Reach the subnucleonic degrees of freedom

Approaches with the subnucleonic degrees of freedom

- Approaches based on fundamental theory QCD
  - Lattice QCD: great technical difficulties for resonances.
  - QCD sum rule: low energy ones, $\Delta(1232)$, $S_{11}(1535)$. . . .

Reach the subnucleonic degrees of freedom

Approaches with the subnucleonic degrees of freedom

- Approaches based on fundamental theory QCD
  - Lattice QCD
  - QCD sum rule
- Constituent quark model
  - spectrum: $SU(6) \otimes U(3)$.
  - transition amplitudes: $A_{1/2}$, $A_{3/2}$, $\Gamma_{R \to MB}$

Reach the subnucleonic degrees of freedom

Approaches with the subnucleonic degrees of freedom

- Approaches based on fundamental theory QCD
  - Lattice QCD
  - QCD sum rule
- Constituent quark model
  - spectrum
  - transition amplitudes

Those approaches did not investigate reaction mechanisms.

Our approach: study of η productions in constituent quark model

Starting Point: effective chiral Lagrangian,

$$\mathcal{L} = \bar{\psi}[\gamma_\mu(i\partial^\mu + V^\mu + \gamma_5 A^\mu) - m]\psi + \cdots,$$

where $V^\mu = \frac{1}{2}(\xi\partial^\mu\xi^\dagger + \xi^\dagger\partial^\mu\xi)$, $A^\mu = \frac{1}{2i}(\xi\partial^\mu\xi^\dagger - \xi^\dagger\partial^\mu\xi)$ with $\xi = \exp(i\phi_m/f_m)$.

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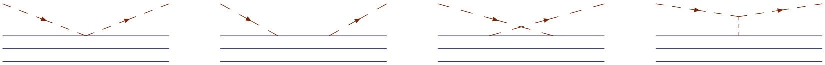
For the pseudoscalar meson productions with the Hamiltonian

$$\mathcal{M}_{fi} = \langle N_f|H_{f,i}|N_i\rangle + \sum_j \left\{ \frac{\langle N_f|H_f|N_j\rangle\langle N_j|H_i|N_i\rangle}{E_i + \omega_i - E_j} + \frac{\langle N_f|H_i|N_j\rangle\langle N_j|H_f|N_i\rangle}{E_i - \omega_j - E_j} \right\} + \mathcal{M}_T,$$



Formulism: for s-channel

Connect observables with CQM

Formulism: for s-channel

Connect observables with CQM

$\mathcal{M}^{\gamma}_{N*} \rightarrow f_{1l\pm}$

$$\mathcal{M}^{\gamma}_{N*} = if_{1l\pm}\sigma\cdot\epsilon + f_{2l\pm}\sigma\cdot\hat{\mathbf{q}}\sigma\cdot(\hat{\mathbf{k}}\times\epsilon) + if_{3l\pm}\sigma\cdot\hat{\mathbf{k}}\hat{\mathbf{q}}\cdot\epsilon + if_{4l\pm}\sigma\cdot\hat{\mathbf{q}}\epsilon\cdot\hat{\mathbf{q}},$$

$$\mathcal{M}^{m}_{N*} = f_{1l\pm} + \sigma\cdot\hat{\mathbf{q}}\sigma\cdot\hat{\mathbf{k}}f_{2l\pm}.$$

Formulism: for s-channel

Connect observables with CQM

$\mathcal{M}^{\gamma}_{N*} \longrightarrow f_{1l\pm}$

$f_{1l\pm} \longrightarrow A^{\gamma}_{3/2}, A^{m}_{1/2}$

$$f_{1l\pm} = f_0[\mp A^{\gamma}_{1/2} - \sqrt{\frac{l+1/2\mp 1/2}{l+1/2\pm 3/2}}A^{\gamma}_{3/2}]P'_{\ell\pm 1},$$

$$f_{2l\pm} = f_0[\mp A^{\gamma}_{1/2} - \sqrt{\frac{l+1/2\pm 3/2}{l+1/2\mp 1/2}}A^{\gamma}_{3/2}]P'_{\ell},$$

$$f_{3l\pm} = \pm f_0 \frac{2A^{\gamma}_{3/2}}{\sqrt{(l-1/2\pm 1/2)(l+3/2\pm 1/2)}}P''_{\ell\pm 1},$$

$$f_{4l\pm} = \mp f_0 \frac{2A^{\gamma}_{3/2}}{\sqrt{(l-1/2\pm 1/2)(l+3/2\pm 1/2)}}P''_{\ell},$$

$$f_1 = \sum_{l=0}^{\infty}[f_{l+}P'_{l+1} - f_{l-}P'_{l-1}],$$

$$f_2 = \sum_{l=0}^{\infty}[f_{l-} - f_{l+}]P'_{l}.$$

where A^{γ}_{λ} is the helicity amplitudes and $f_0 \equiv \frac{1}{(2J+1)2\pi}[\frac{M_N E_N}{M^2_{N*}}k]^{1/2}A^{m}_{1/2}$ with $A^{m}_{1/2}$ the $N^* \longrightarrow \eta N$ decay amplitude, appearing in the partial decay width

Formulism: for s-channel

Connect observables with CQM

$\mathcal{M}^{\gamma}_{N*} \longrightarrow f_{1l\pm}$

$f_{1l\pm} \longrightarrow A^{\gamma}_{3/2}, A^{m}_{1/2}$

$A^{\gamma}_{3/2}, A^{m}_{1/2} \longrightarrow \langle N|H|N^*\rangle$

$$
\begin{aligned}
A_\lambda &= \sqrt{\frac{2\pi}{k}}\langle N^*; J\lambda|H_e|N; \frac{1}{2}\lambda - 1\rangle, \\
A^m_\nu &= \langle N; \frac{1}{2}\nu|H_m|N^*; J\nu\rangle.
\end{aligned}
$$

Formulism: for s-channel

Connect observables with CQM

$\mathcal{M}^{\gamma}_{N^*} \longrightarrow f_{1l\pm}$

$f_{1l\pm} \longrightarrow A^{\gamma}_{3/2}, A^{m}_{1/2}$

$A^{\gamma}_{3/2}, A^{m}_{1/2} \longrightarrow \langle N|H|N^*\rangle$

$\langle N|H|N^*\rangle$ in CQM

- Wave function: $|N^*\rangle$ from potential model: OGE, GBE...
- Hamiltonian: H_e, H_m: χQM

Formulism: for s-channel

Connect observables with CQM

$\mathcal{M}_{N*}^{\gamma} \longrightarrow f_{1l\pm}$

$f_{1l\pm} \longrightarrow A_{3/2}^{\gamma}, A_{1/2}^{m}$

$A_{3/2}^{\gamma}, A_{1/2}^{m} \longrightarrow \langle N|H|N^*\rangle$

$\langle N|H|N^*\rangle$ in CQM

Done

Advantage: the breaking of $SU(6) \otimes O(3)$ symmetry is introduced through potential model to avoid a strength parameter (coupling constant) for each resonances

Ingredient

Channels considered

- s-channel
- u-channel
- t-channel

Data

Parmeters: 21

Results

Ingredient

Channels considered

- s-channel
  - **n=1:** $S_{11}(1535)$, $S_{11}(1650)$, $D_{13}(1520)$, $D_{13}(1700)$, and $D_{15}(1675)$;
    n=2: $P_{11}(1440)$, $P_{11}(1710)$, $P_{13}(1720)$, $P_{13}(1900)$, $F_{15}(1680)$, $F_{15}(2000)$, and $F_{17}(1990)$.
    n>2: degenerated
  - New resonances: S_{11}, D_{13}, D_{15}
- u-channel : Degenerated
- t-channel : Neglected

Data

Parmeters: 21

Results

Ingredient

Channels considered

- s-channel
- u-channel
- t-channel

Data

- η photoproduction: 1404 points
- $\pi^- p \longrightarrow \eta n$: 333 points
- Spectrum: 14 PDG resonances

Parmeters: 21

Results

Experiments: $d\sigma/d\Omega$ and Σ, T for $\gamma p \rightarrow \eta p$

Exp.	year	Obs.	Angular	P_γ	W	N_{dp}
MAMI	(1994)	$d\sigma/d\Omega$	25-154	0.716-0.790	1.49-1.54	100
CLAS	(2002)	$d\sigma/d\Omega$	45-134	0.775-1.925	1.53-2.12	190
ELSA	(2003)	$d\sigma/d\Omega$	31-138	0.775-2.900	1.53-2.51	631
LNS	(2006)	$d\sigma/d\Omega$	25-154	0.718-1.142	1.49-1.74	180
GRAAL	(2006)	$d\sigma/d\Omega$	31-160	0.714-1.477	1.49-1.91	487
ELSA	(2006)	Σ	50-148	0.843-1.343	1.57-1.84	34
GRAAL	(2006)	Σ	40-160	0.724-1.472	1.50-1.91	150
BONN	(1997)	T	33-145	0.717-1.105	1.49-1.72	50

Experiments: $d\sigma/d\Omega$ for $\pi^- p \longrightarrow \eta n$

Ref.	Year	Angular	P_π	W	δ_{sys}
Deinet	(1969)	32-123	0.718-1.050	1.51-1.70	11%
Richards	(1970)	26-154	0.718-1.433	1.51-1.90	10% to 14%
Debenham	(1975)	162-172	0.697-0.999	1.49-1.67	10% + 0.02 μb
Brown	(1975)	18-160	0.724-2.724	1.51-2.45	10% or 0.01 μb
Prakhov	(2005)	23-157	0.687-0.747	1.49-1.52	6%
Feltesse	(1975)	20-160	0.757	1.53	
Crouch	(1980)	14-167	1.395-3.839	1.88-2.85	
Morrison	(1999)	46-134	0.701-0.747	1.50-1.52	

Experiments: $d\sigma/d\Omega$ for $\pi^- p \to \eta n$

Ref.	Year	Angular	P_π	W	δ_{sys}	N_{dp}	N_{dp}
Deinet	(1969)	32-123	0.718-1.050	1.51-1.70	11%	83	80
Richards	(1970)	26-154	0.718-1.433	1.51-1.90	10% to 14%	70	66
Debenham	(1975)	162-172	0.697-0.999	1.49-1.67	10% + 0.02 μb	111	27
Brown	(1975)	18-160	0.724-2.724	1.51-2.45	10% or 0.01 μb	379	51
Prakhov	(2005)	23-157	0.687-0.747	1.49-1.52	6%	84	70
Feltesse	(1975)	20-160	0.757	1.53		16	-
Crouch	(1980)	14-167	1.395-3.839	1.88-2.85		731	-
Morrison	(1999)	46-134	0.701-0.747	1.50-1.52		34	-

Ingredient

Channels considered

- s-channel
- u-channel
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Data

- η photoproduction
- $\pi^- p \to \eta n$
- Spectrum

Parmeters: 21

Results

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- Spectrum

Parmeters: 21

- Coupling constant : $g_{\eta NN}$
- Parameters for OGE : m_q, α, α_s, Ω, Δ
- Higher Mass: M, Γ, C^{γ}_{N*}, C^{π}_{N*}
- New resonances: M^{γ}, Γ^{γ}, C^{γ}_{N*}
- Strength of $P_{13}(1720)$: $C^{\gamma}_{P_{13}(1720)}$, $C^{\pi}_{P_{13}(1720)}$

Results

Ingredient

Channels considered

- s-channel
- u-channel
- t-channel

Data

- η photoproduction
- $\pi^- p \to \eta n$
- Spectrum

Parmeters: 21

- Coupling constant
- Parameters for OGE
- Higher Mass
- New resonances
- Strength of $P_{13}(1720)$

Results

$\chi^2 = \sum \frac{(V_{th} - V_{ex})^2}{(E_{ex}^V)^2 + (V'_{th} E_{ex}^E)^2}$. Here V_{th}, V_{ex} E_{ex}^V and E_{ex}^E are the values from theoretical calculation and experiment and the uncertainty of observable and energy, and V'_{th} are the derivative of observable with energy.

Ingredient

Channels considered

- s-channel
- u-channel
- t-channel

Data

- η photoproduction
- $\pi^- p \longrightarrow \eta n$
- Spectrum

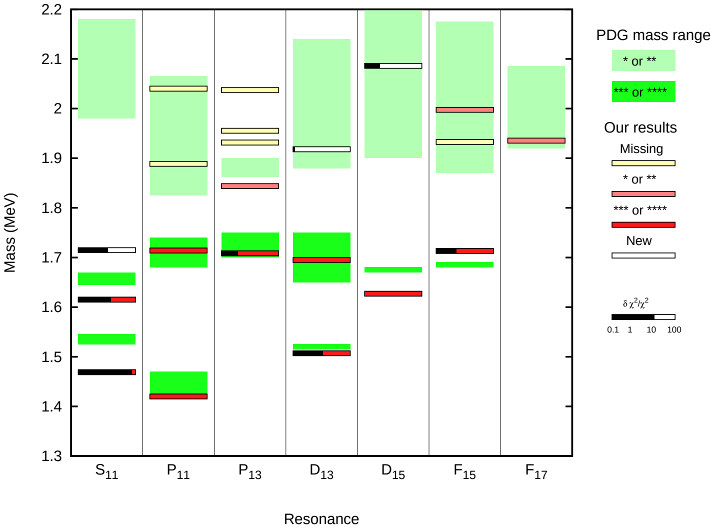
Parmeters: 21

- Coupling constant
- Parameters for OGE
- Higher Mass
- New resonances
- Strength of $P_{13}(1720)$

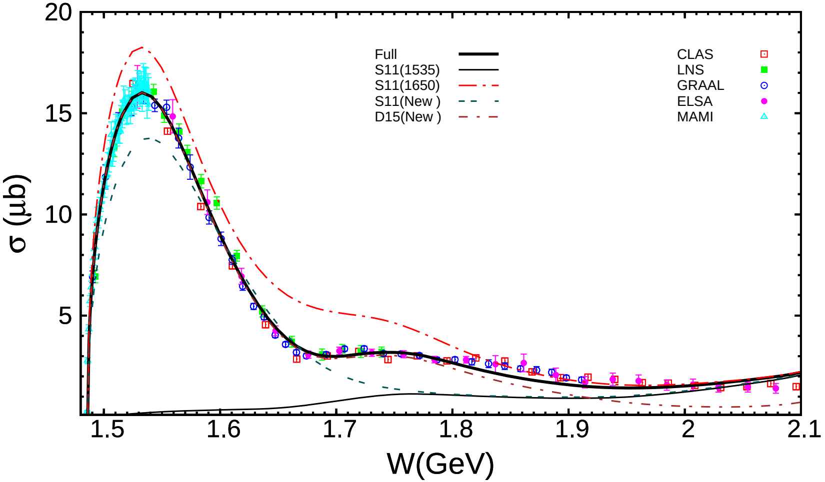
Results

- $\chi^2 = 3627/1772 = 2.05$, for total
- $\chi^2_S = 32 \quad / \quad 14 = 2.29$, for spectrum
- $\chi^2_\gamma = 3243/1404 = 2.31$, for $\gamma p \longrightarrow \eta p$
- $\chi^2_\pi = 408/\ 354 = 1.15$, for $\pi^- p \longrightarrow \eta n$, 1.99 for usual definition

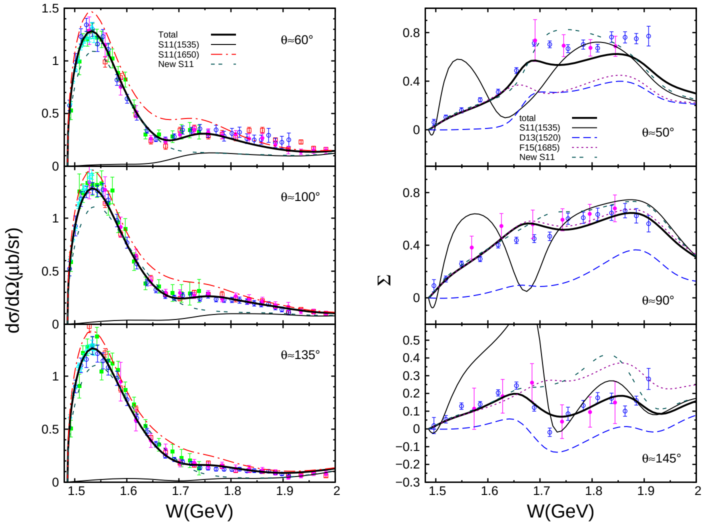
Spectrum


2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
Mass (MeV)
S11
P11
P13
D13
D15
F15
F17
Resonance
PDG mass range
* or **
*** or ****
Our results
Missing
* or **
*** or ****
New
δχ2/χ2
0.1 1 10 100

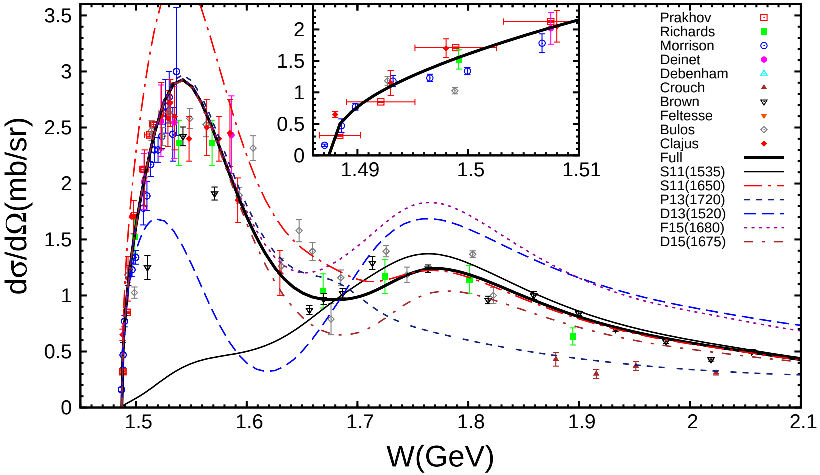
Results: σ for $\gamma p \longrightarrow \eta p$



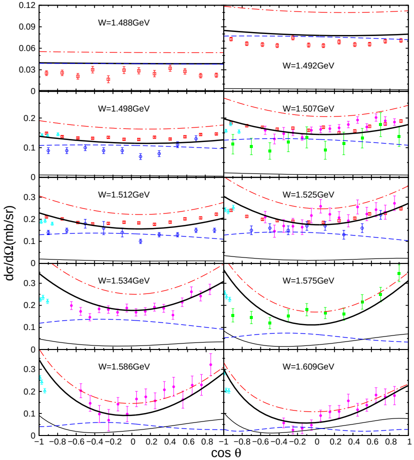
Results: $d\sigma/d\Omega$ and Σ for $\gamma p \to \eta p$

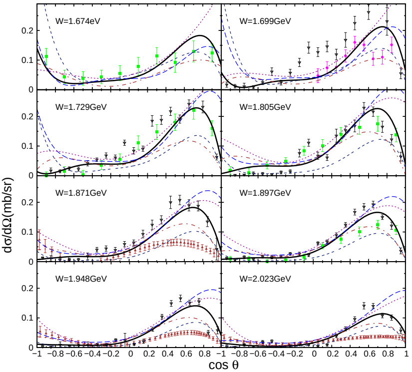


Results: σ for $\pi^- p \longrightarrow \eta n$



Results: $d\sigma/d\Omega$ for $\pi^- p \to \eta n$





Results: Helicity amplitudes and decay widths

Resonances	$A_{1/2}$	$A_{1/2}^{PDG}$	$A_{3/2}$	$A_{3/2}^{PDG}$	$\sigma\sqrt{\Gamma_{\eta N}}$	$(\sigma)\sqrt{\Gamma_{\eta N}^{PDG}}$	$\sqrt{\Gamma_{\pi N}}$	$\sqrt{\Gamma_{\pi N}^{PDG}}$
$S_{11}(1535)$	73	90 ± 30			7.18	$8.87^{+1.37}_{-1.37}$	6.78	$8.22^{+1.59}_{-1.60}$
$S_{11}(1650)$	66	53 ± 16			-2.42	$1.95^{+0.94}_{-1.57}$	8.85	$11.31^{+1.95}_{-1.98}$
$P_{11}(1440)$	-23	-65 ± 4			-2.42		17.16	$13.96^{+4.41}_{-3.48}$
$P_{11}(1710)$	-53	9 ± 22			-1.05	$2.49^{+1.75}_{-0.88}$	4.12	$3.87^{+3.20}_{-1.64}$
P_{11}	18				-2.79		6.59	
P_{11}	3				-1.20		4.51	$5.34^{+2.16}_{-2.16}$
$P_{13}(1720)$	177	18 ± 30	-69	-19 ± 20	2.91	$2.83^{+1.04}_{-0.71}$	20.15	$5.48^{+2.27}_{-1.60}$
$P_{13}(1900)$	30		2		-1.33	$8.35^{+2.11}_{-2.20}$	11.02	$11.38^{+2.20}_{-2.21}$
P_{13}	28		0		2.44		3.06	
P_{13}	12		2		0.03		5.54	
P_{13}	-3		3		-1.01		3.12	
$D_{13}(1520)$	-7	-24 ± 9	158	166 ± 5	0.44	$0.51^{+0.07}_{-0.06}$	14.77	$8.31^{+0.71}_{-0.53}$
$D_{13}(1700)$	-4	-18 ± 13	4	-2 ± 24	-0.81	$0.00^{+1.22}_{-0.00}$	4.92	$3.16^{+1.58}_{-1.58}$
$D_{15}(1675)$	-6	19 ± 8	-8	15 ± 9	-2.50	$0.00^{+1.28}_{-0.00}$	7.59	$7.75^{+0.87}_{-1.00}$
$F_{15}(1680)$	24	-15 ± 6	136	133 ± 12	0.58	$0.00^{+1.18}_{-0.00}$	13.71	$9.37^{+0.53}_{-0.54}$
F_{15}	-9		4		0.97		0.35	
$F_{15}(2000)$	-1		10		-0.47		3.60	$4.00^{+6.20}_{-2.18}$
$F_{17}(1990)$	5	1	6	4	-1.55	$0.00^{+2.17}_{-0.00}$	6.84	$4.58^{+1.55}_{-1.55}$

Conclusion

- Study of η productions in quark level (CQM).
- Study of "missing" resonances in η productions directly in CQM.
- Study of spectrum and observables simultaneously in CQM.

- For known resonances:
  - Both : $S_{11}(1535)$,$S_{11}(1650)$,$D_{13}(1520)$,$F_{15}(1680)$, $P_{13}(1720)$
  - $\pi^- p \longrightarrow \eta n$: $P_{11}(1440)$, $D_{15}(1675)$
- For "missing" resonances:
  - Both : Negligible
- For New resonances:
  - $\gamma \quad p \longrightarrow \eta p$: New $S_{11}(1715)$ and $D_{15}(2090)$
- For $\pi^- p \longrightarrow \eta n$
  - $P_{13}(1720)$: second bump for the cross section
  - Near threshold: Large $d(d\sigma/d\Omega)/\mathrm{dE}{\rightarrow}\Delta E$ is more important!