The role of nucleon resonances in η' production processes

Part of a baryon spectroscopy program:

- $\gamma + N \rightarrow M + B$
- $\pi + N \rightarrow M + B$
- $N + N \rightarrow M + B + N$
- $\gamma + N \rightarrow M + M' + B$
- $\pi + N \rightarrow M + M' + B$

($M = \pi, \eta, K, \eta', \rho, \omega, K^*, \phi$)

Collaboration:

Jülich

Athens/GA

Washington/DC

Reaction Theory: MN→M'B reactions

Jülich DCC model (TOPT):

$$T = V + VGT$$

C. Schütz et al., PRC49 '94; PRC57 '98
O. Krehl et al., PRC62 '00
A. M. Gasparyan et al., PRC68 '03
M. Döring et al., NPA829 '09; NPA851 '11
D. Rönchen et al., EPJA47'13

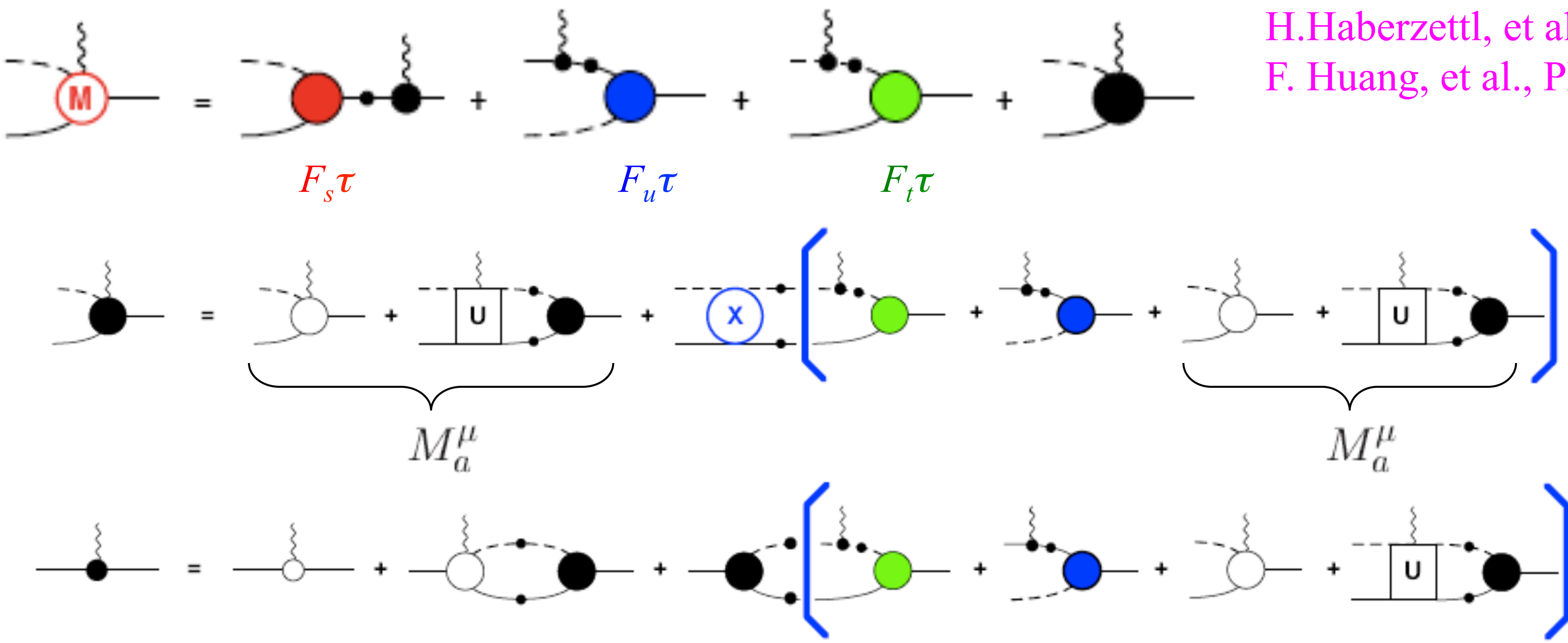
Basic features:

- Coupled channels (so far): πN, ηN, KΛ, KΣ, ππN [σN, ρN, πΔ]
- Analyticity
- 2-body unitarity & some requirements for 3-body unitarity
- Chiral Lagrangian of Wess and Zumino [PR163, '67; PR161, '88]
  - Hadron exchange provides the relevant dynamics
  - All partial waves are linked by u- and t-channel processes
  - Reaction channels are linked by SU(3) in the Lagrangian framework
  - Minimum # of explicit resonances needed due to the structured backgroung

Reaction Theory: $\gamma N \rightarrow MN$ (fully gauge invariant DCC)

$$M^\mu = M^\mu_s + M^\mu_u + M^\mu_t + M^\mu_{\rm int}$$

H.Haberzettl, PRC56, 2041, '97
H.Haberzettl, et al., PRC74,' 06
H.Haberzettl, et al., PRC83,'11
F. Huang, et al., PRC85,'12



approximated current:

generalized contact current

$$M^\mu_{\rm int} = M^\mu_c + TG\left(M^\mu_u + M^\mu_t + M^\mu_c\right)_T$$

$$k_\mu M^\mu_c = -[F_s]e_i + [F_u]e_f + [F_t]e_\pi$$

generalized Ward-Takahashi identity

$$\Gamma^\mu = \Gamma^\mu_0 + m^\mu_{KR} G[F\tau] + [F_0\tau]G\left(M^\mu_u + M^\mu_t + M^\mu_c\right)_L$$

Experimental data: *some of the issues*

- Scarcity of (2-body) hadronic reactions data:
  - → apart from the πN elastic scattering, only ~3800 data points (~24600 in photoproduction)
  - → existing data suffers from large uncertainties
  - → many of them are incompatible with each other
  - → about dozen total cross section data points for η' and φ.

HADES at GSI: πN → ωN, ρN reactions (W< 2.4 GeV); no spin observables.

J-PARC: πN → KY, ππN

EIC at Jlab in ~ 2020 ??

One of the major limitations for developing more accurate coupled-channels models.

Accurate data from CELSIUS,COSY on NN → NBM (M=π, η, K, η' ,ω, φ) help constrain model parameters.

Experimental data: *η' production reactions*

- $\gamma + N \rightarrow \eta' + N$: $d\sigma/d\Omega$ CLAS-'09, free proton
  CBELSA/TAPS-'09, free proton
  CBELSA/TAPS-'11, quasi-free neutron & proton

  Σ, E (being measured at CLAS & CBELSA/TAPS)

- $\pi + N \rightarrow \eta' + N$: σ (~15 data points with large uncertainties), '68 – '72, Baldini et al., *Total Cross-Sections for Reactions of High Energy Particles*, Landolt-Boernstein, edited by H. Schopper (Springer, Berlin, 1988), Vol. I/12a.

- $N + N \rightarrow \eta' + N + N$: σ DISTO-'98,'00, proton
  COSY11-'00,'04 proton
  COSY11-'10, neutron (upper limit)

  $d\sigma/d\Omega_{\eta'}$ DISTO-'00, proton
  COSY11-'04 proton

  $d\sigma/dM_{\eta' p}$, $d\sigma/dM_{pp}$ COSY11-'07 proton

Approach to η'/φ production reactions:

Elastic scattering (below first inelastic threshold):

$$T = \underbrace{\left\{ N^X \left| F_K \right\rangle \frac{1}{S_K^{-1} + iN^X \frac{\Gamma}{2}} \left\langle F_K \right| N^X \right\}}_{T^P} + \underbrace{N^X K^{NP}}_{X\,(=T^{NP})}$$

(full phase structure)

$$N^X = 1 - i\rho X = e^{i\delta^X} \cos\delta^X \qquad \text{(Watson's factor)}$$

$$\left| F_K \right\rangle = \left(1 + K^{NP} G^R\right) \left| F_0 \right\rangle$$

$$S_K^{-1} = S_0^{-1} - \left\langle F_0 \right| G^R \left| F_K \right\rangle = E - m_0 - \left\langle F_0 \right| G^R \left| F_K \right\rangle$$

$$\frac{\Gamma}{2} = \left\langle F_K \right| \pi\delta(E - H_0) \left| F_K \right\rangle = \left\langle F_K \right| \rho \left| F_K \right\rangle$$

$$K^{NP} = V^{NP} + V^{NP} G^R K^{NP}$$

ρ = phase-space factor

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ρ = phase-space factor

Phenomenology:

$$T = \left\{ N^X g \frac{1}{E - m_B + i N^X \frac{\Gamma_B}{2}} g N^X \right\} + N^X K^{NP}$$

(full phase structure kept)

Parameters: [g , m_B , δ^X]

Approach to η'/φ production reactions:

Full coupled-channels amplitude:

$$T_{\alpha'\alpha} = \underbrace{\sum_{r'r} \left\{ N^X_{\alpha'} \, |\hat{F}_K\rangle_{\alpha',r'} \frac{1}{S^{-1}_{K\,r'r} + i\sum_\beta N^X_\beta \frac{\Gamma_{r'r\beta}}{2}} \langle \hat{F}_K|_{\alpha,r} \, N^X_\alpha \right\}}_{T^P} + \underbrace{N^X_{\alpha'} \hat{K}^{NP}_{\alpha'\alpha}}_{X\,(=T^{NP})}$$

$$N^X_{\alpha'} \equiv 1 - i\rho_{\alpha'} X_{\alpha'\alpha'} = \frac{1}{2}\left(\eta^X_{\alpha'} e^{i2\delta^X_{\alpha'}} + 1\right) \xrightarrow{\eta^X_{\alpha'}=1} e^{i\delta^X_{\alpha'}} \cos\delta^X_{\alpha'}$$

(Watson's factor)

$$|\hat{F}_K\rangle_{\alpha',r'} \equiv |F_K\rangle_{\alpha',r'} - i \sum_{\beta\neq\alpha'} \rho_\beta \hat{K}^{NP}_{\alpha'\beta} \, |F_K\rangle_{\beta,r'}$$

$$\frac{\Gamma_{r'r\beta}}{2} \equiv \langle F_K|_{\beta,r'} \, \rho_\beta \, |\hat{F}_K\rangle_{\beta,r}$$

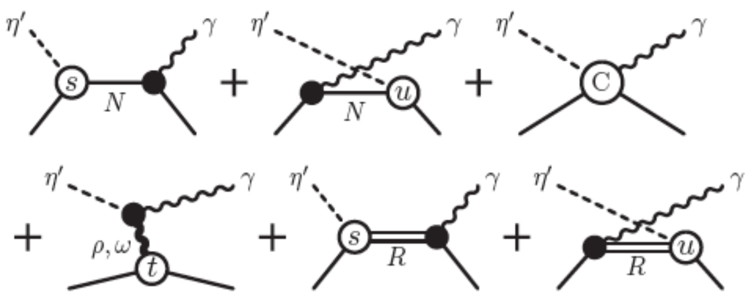
$$\hat{K}^{NP}_{\alpha'\alpha} \equiv K^{NP}_{\alpha'\alpha} - i \sum_{\beta,\beta'\neq\alpha'} K^{NP}_{\alpha'\beta'} \left((D^X)^{-1}\right)_{\beta'\beta} \rho_\beta K^{NP}_{\beta\alpha}$$

ρ_β = phase-space factor
= 0 below β threshold

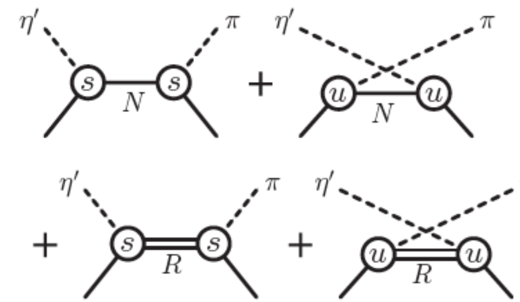
$$D^X_{\beta'\beta} \equiv \delta_{\beta'\beta} + i\rho_{\beta'} K^{NP}_{\beta'\beta}$$

Model for η' productions: *dynamical content*

$\gamma + N \to \eta' + N$



$\pi + N \to \eta' + N$



quasi-free: Fermi folding

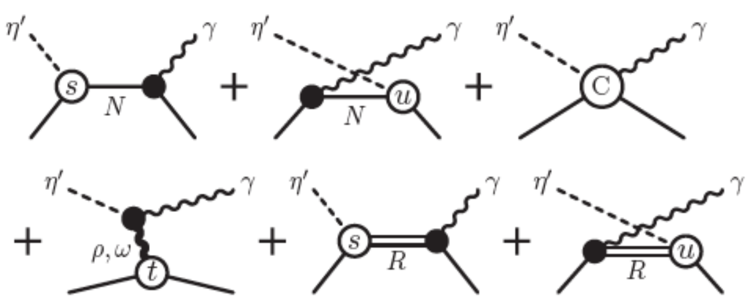
$$T_{\eta'\alpha} \cong \sum_r \left\{ N^X_{\eta'} g_{r\eta'} \frac{1}{E - m_r + i \sum_\beta N^X_\beta \frac{\Gamma_{r\beta}}{2}} g_{r\alpha} N^X_\alpha \right\} + N^X_{\eta'} V^{NP}_{\eta'\alpha} \qquad (\alpha = \gamma, \pi)$$

present calc.:

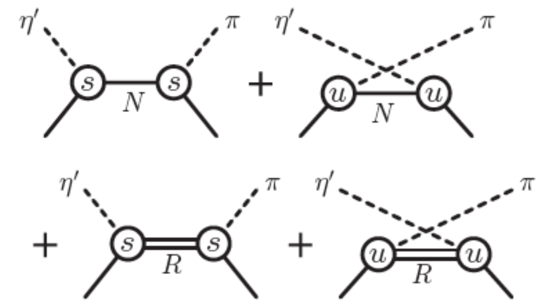
$\beta = \mathrm{M}, \eta', \gamma$
$N_\alpha^X, N_\beta^X = 1$

Model for η' productions: *effective Lagrangian approach*

γ + N → η' + N



π + N → η' + N



quasi-free: Fermi folding

present calc.:

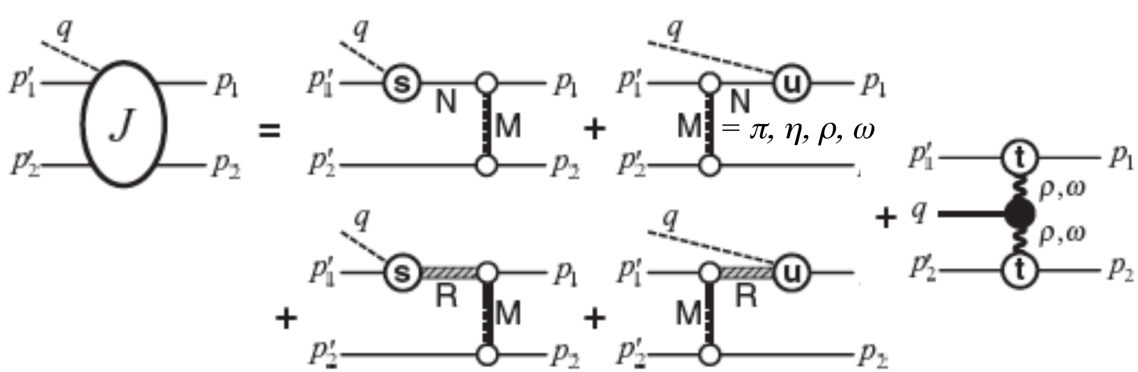
$$T_{\eta'\alpha} \cong \sum_r \left\{ N^X_{\eta'} g_{r\eta'} \frac{1}{E - m_r + i\sum_\beta N^X_\beta \frac{\Gamma_{r\beta}}{2}} g_{r\alpha} N^X_\alpha \right\} + N^X_{\eta'} V^{NP}_{\eta'\alpha} \qquad (\alpha = \gamma, \pi)$$

β = M, η', γ
$N_\alpha{}^X$, $N_\beta{}^X = 1$

N + N → η' + N + N

DWBA:

$$M = (1 + T_f G_f) J (1 + G_i T_i)$$



η' production reactions: a combined analysis

[Huang, Haberzettl, Nakayama, PRC87'13]

Res. considered: minimum number of spin-1/2 and -3/2 resonances to fit the existing data in photo- and hadron-reactions:

above threshold: $S_{11}(1925)$, $P_{13}(2050)$, $P_{11}(2130)$

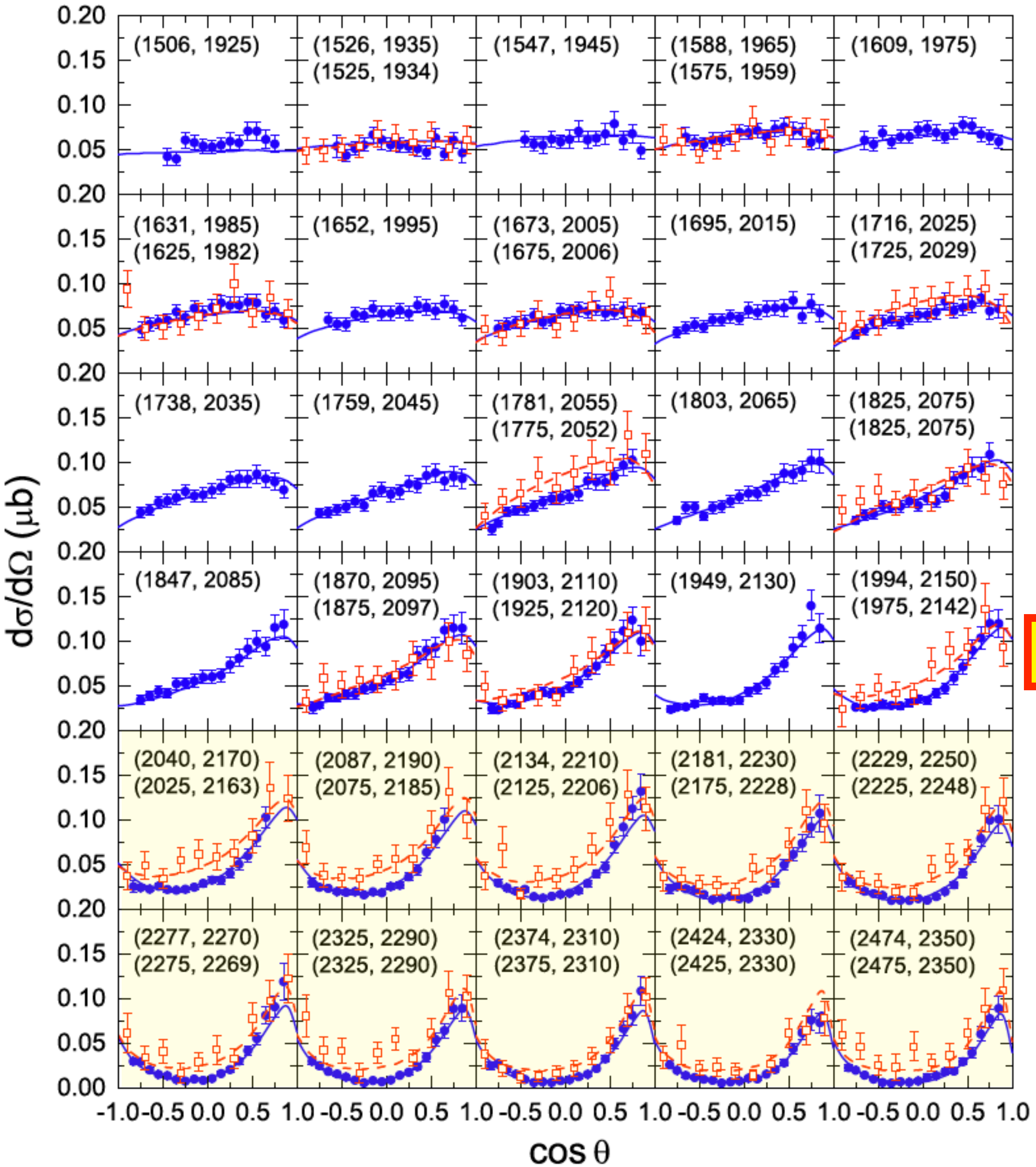
sub. threshold: $P_{13}(1720)$ (required for $d\sigma/dW$ in $pp \to \eta' pp$)

only photoreaction → different sets of resonances are possible

Res. masses and widths: largely constrained by photoproduction

Role of higher-spin res. : requires spin-polarization observables (Σ, T, etc)

η' photoproduction: *free proton (combined analysis)*



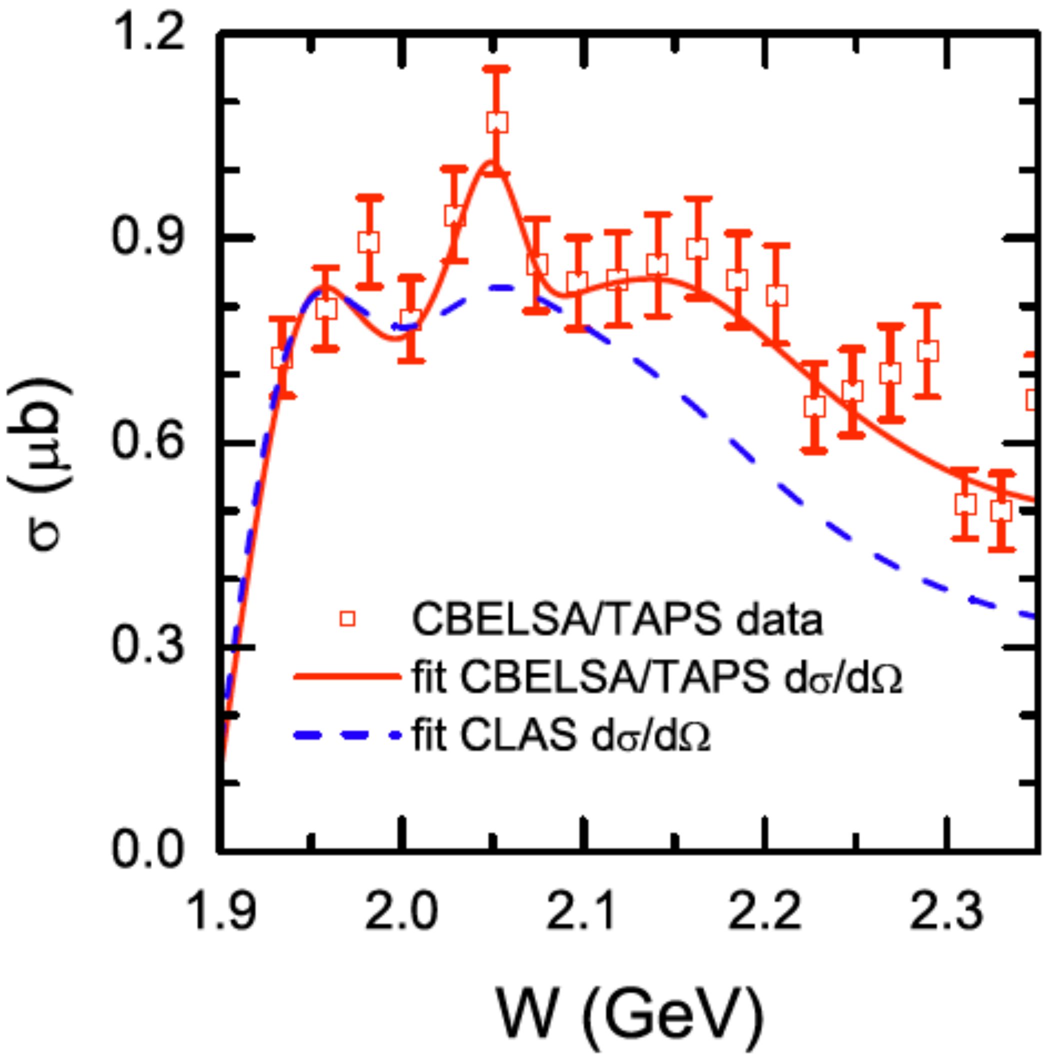
blue : CLAS-'09
[Williams et al., PRC80'09]
red : CBELSA/TAPS-'09
[Crede et al., PRC80'09]
black : CLAS-'06
[Dugger et al., PRL96'06]

blue & red curves : model results
[Huang et al., PRC87'13]

{$P_{13}(1720)$, $S_{11}(1925)$, $P_{13}(2050)$, $P_{11}(2130)$}

Discrepancy in the data:
CLAS-'09 & CBELSA/TAPS-'09

η' photoproduction: free proton (combined analysis)

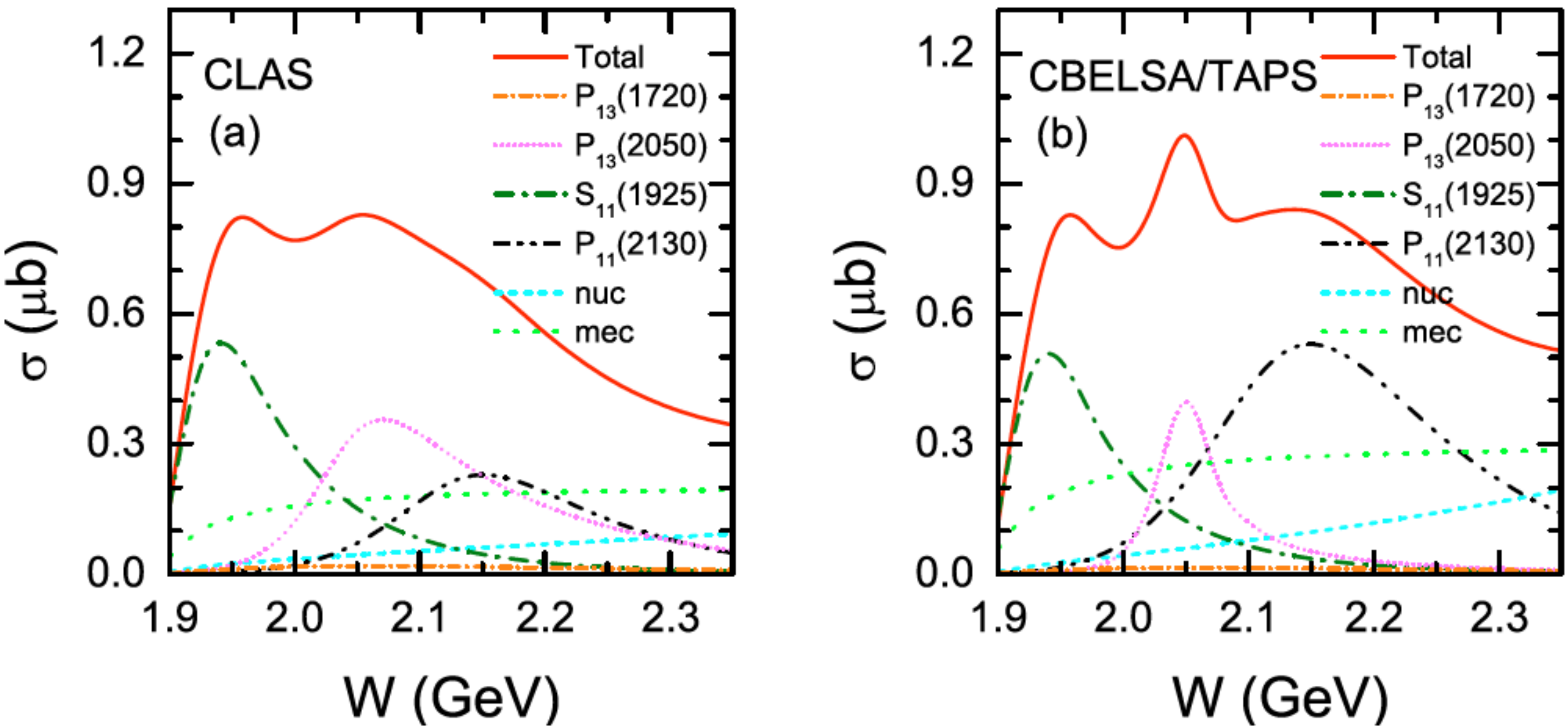


blue & red curves : model results [Huang et al., PRC87'13]

Discrepancy in data: CLAS-'09 & CBELSA/TAPS-'09

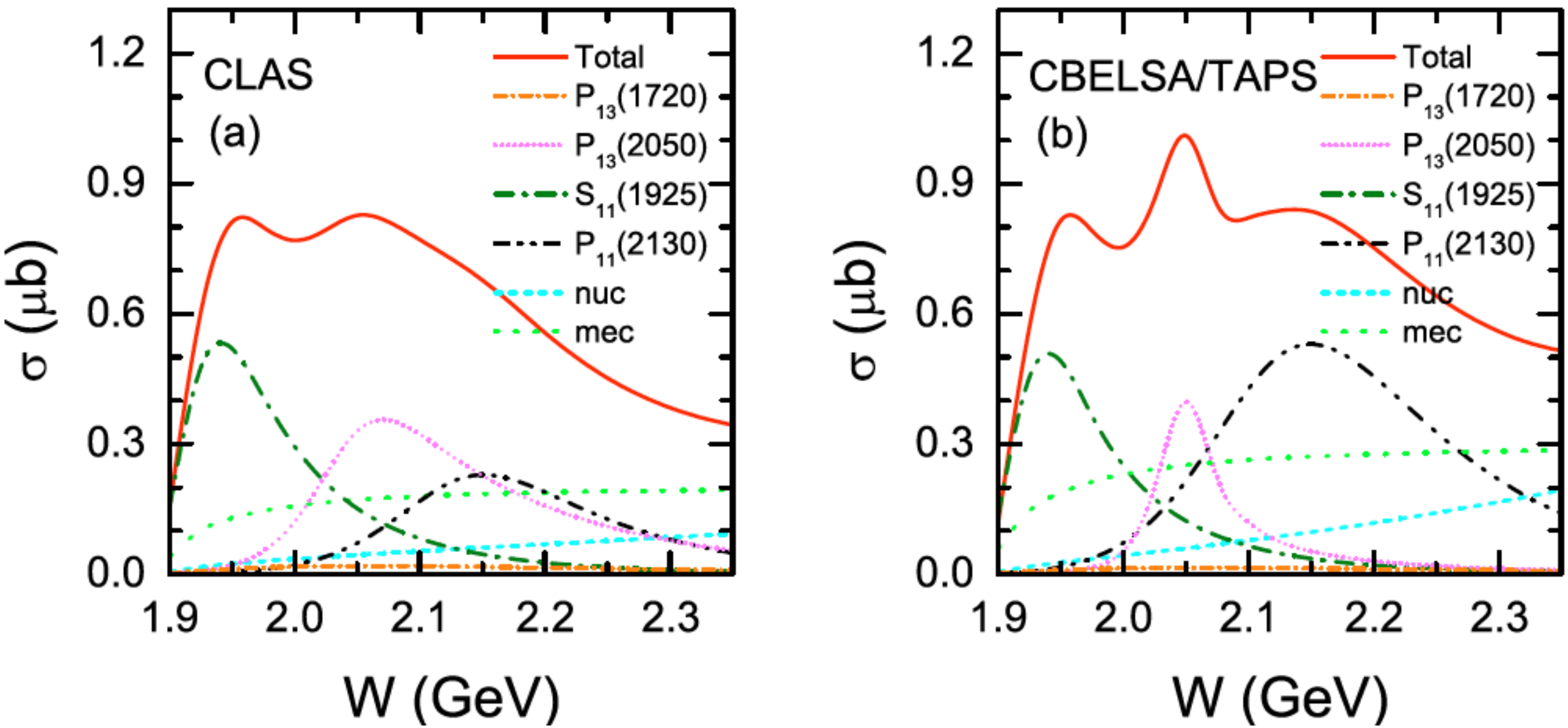
How would this affect the extracted resonance parameters?

η' photoproduction: dynamical content



{$P_{13}(1720)$, $S_{11}(1925)$, $P_{13}(2050)$, $P_{11}(2130)$}

η' photoproduction: dynamical content



{$P_{13}(1720)$, $S_{11}(1925)$, $P_{13}(2050)$, $P_{11}(2130)$}

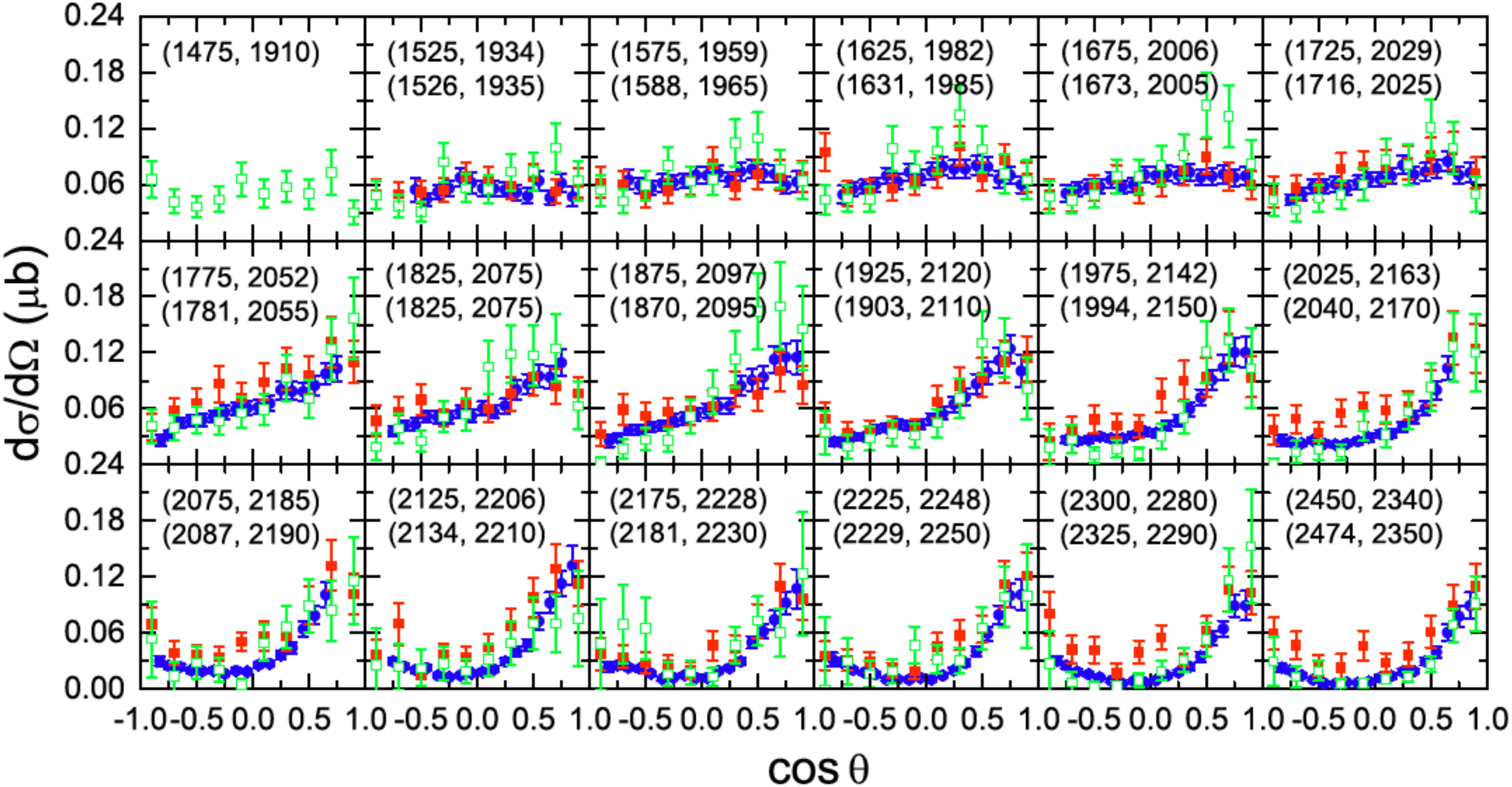
PDG: $P_{13}(1720)$****, $S_{11}(1895)$**, $P_{13}(2040)$*, $P_{11}(2110)$*

η' photoproduction: resonance parameters (combined analysis)

	free p		quasi-free p
	CLAS	CBELSA/TAPS	
χ^2/N	0.65	0.53	0.77
$g_{NN\eta'}$	1.00 ± 0.06	1.17 ± 0.31	1.00 ± 0.24
$\lambda_{NN\eta'}$	0.53 ± 0.06	0.44 ± 0.22	0.64 ± 0.24
Λ_v [MeV]	1183 ± 5	1244 ± 35	1221 ± 28
$\hat{h}$	3.89 ± 0.18	5.37 ± 1.57	4.27 ± 0.89
$P_{13}(1720)$			
M_R [MeV]	**1720**	**1720**	**1720**
Γ_R [MeV]	**200**	**200**	**200**
$\sqrt{\beta_{N\eta'}}A_{1/2}$ [10^{-3} GeV$^{-1/2}$]	0.09 ± 0.03	0.09 ± 0.06	0.06 ± 0.11
$\sqrt{\beta_{N\eta'}}A_{3/2}$	-0.16 ± 0.05	-0.13 ± 0.09	-0.03 ± 0.06
$P_{13}(2050)$			
M_R	2050 ± 4	2045 ± 7	**2048**
Γ_R	140 ± 10	52^{+184}_{-52}	51^{+241}_{-51}
$\sqrt{\beta_{N\eta'}}A_{1/2}$	-5.71 ± 0.17	-2.02 ± 0.26	-3.14 ± 0.43
$\sqrt{\beta_{N\eta'}}A_{3/2}$	9.89 ± 0.30	7.31 ± 0.93	5.75 ± 0.79
$S_{11}(1925)$			
M_R	1924 ± 4	1926 ± 10	**1925**
Γ_R	112 ± 7	99 ± 23	145 ± 45
λ	$1.00^{+0.00}_{-0.06}$	$1.00^{+0.00}_{-0.98}$	$1.00^{+0.00}_{-0.95}$
$\sqrt{\beta_{N\eta'}}A_{1/2}$	-11.84 ± 0.41	-11.07 ± 1.43	-19.93 ± 1.56
$P_{11}(2130)$			
M_R	2129 ± 5	2123 ± 23	**2126**
Γ_R	205 ± 12	246 ± 54	170 ± 178
λ	$1.00^{+0.00}_{-0.04}$	$1.00^{+0.00}_{-0.61}$	$1.00^{+0.00}_{-0.95}$
$\sqrt{\beta_{N\eta'}}A_{1/2}$	-11.34 ± 0.62	-18.80 ± 0.90	-7.45 ± 0.94

η' photoproduction: *data comparison (quasi-free proton)*

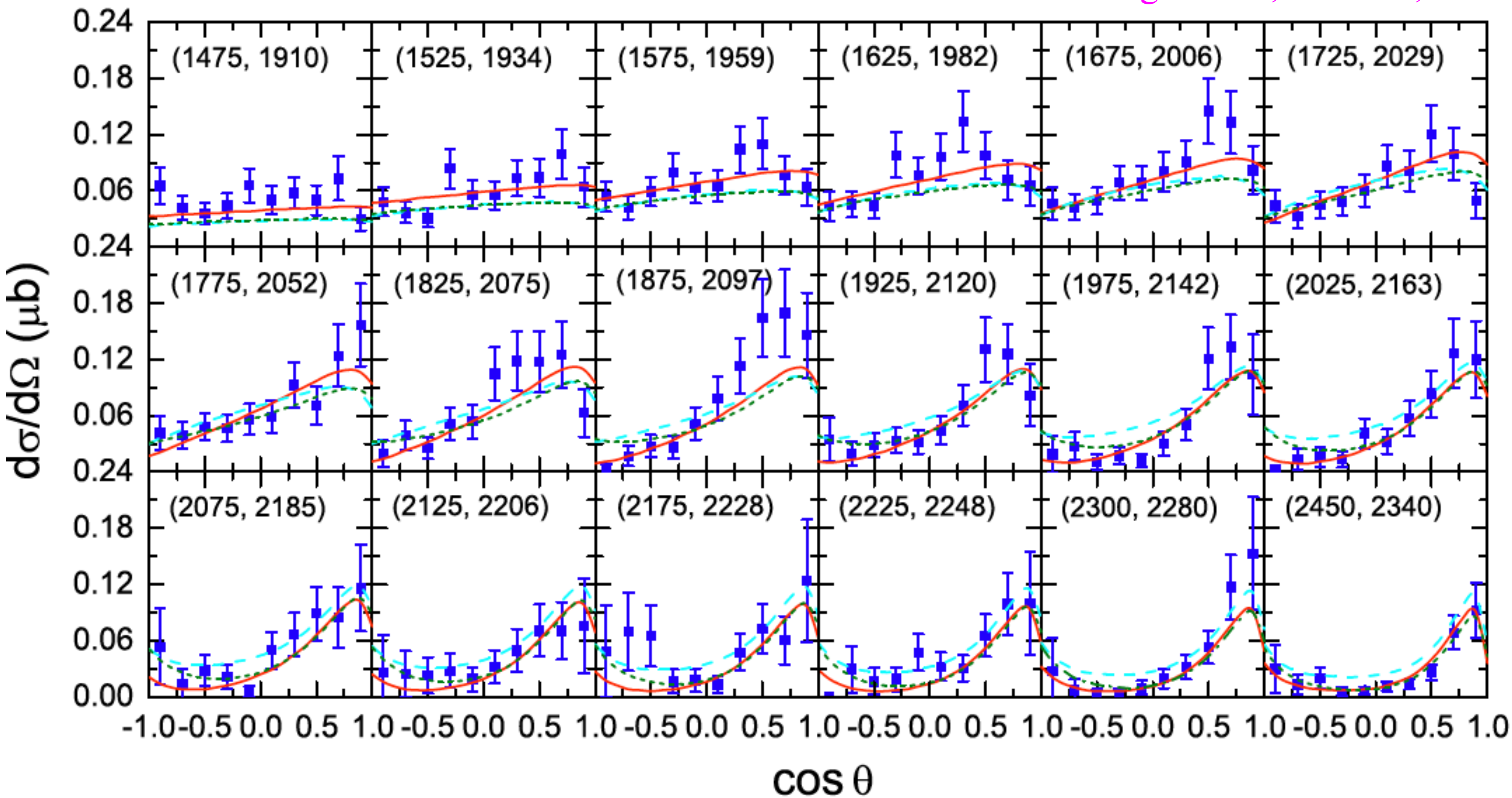
Green : CBELSA/TAPS-'11 (quasi-free proton) [Jaegle et al., EPJA47,'11]
Red : CBELSA/TAPS-'09 (free proton) [Crede et al., PRC80,'09]
Blue : CLAS-'09 (free proton) [Williams et al., PRC80,'09]



η' photoproduction: *quasi-free proton (combined analysis)*

Red : CBELSA/TAPS-'11 quasi-free proton fit
Cyan : CBELSA/TAPS-'09 free proton fit
Green : CLAS-'09 free proton fit

data: Jaegle et al., EPJA47,'11

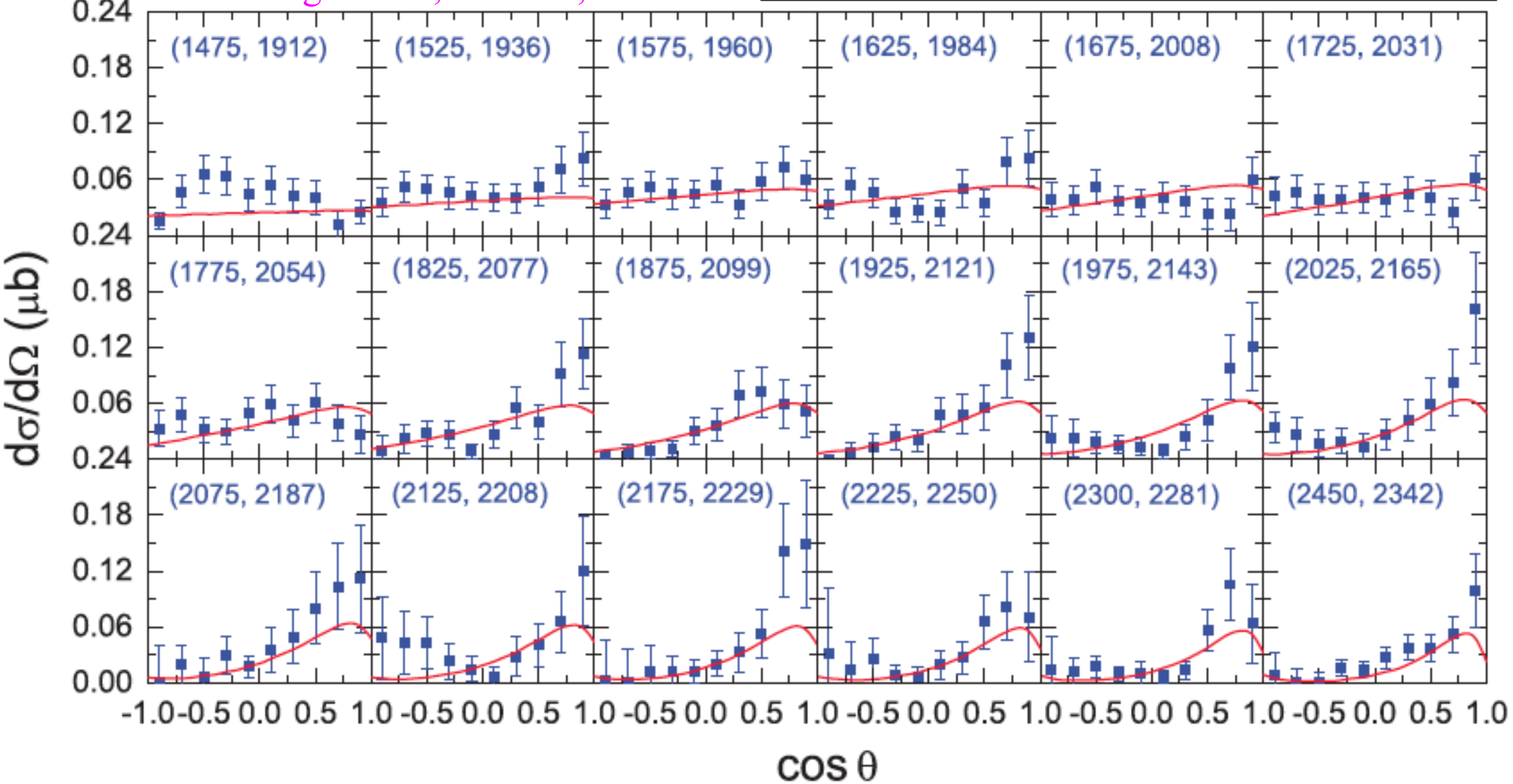


η' photoproduction: *quasi-free neutron (combined analysis)*

Red : CBELSA/TAPS-'11 quasi-free neutron fit

	$P_{13}(1720)$	$P_{13}(2050)$	$S_{11}(1925)$	$P_{11}(2130)$
$\sqrt{\beta_{N\eta'}}A_{1/2}$	0.04	0.94	15.54	7.60
$\sqrt{\beta_{N\eta'}}A_{3/2}$	−0.00	−1.64		
$\beta_{n\gamma}/\beta_{p\gamma}$	0.32	−0.09	−0.61	−3.06

data: Jaegle et al., EPJA47,'11



NNη' coupling strength:

Present analysis: $g_{NN\eta'} \sim 1.0$ (cannot much larger)

Particular interest in connection to the "nucleon-spin crisis" (EMC collaboration, PLB206, '88). NNη′ coupling constant is related to the flavor-singlet axial charge G_A through the U(1) Goldberger-Treiman relation:

$$2m_N G_A(0) \cong \underbrace{\sqrt{2N_F}F_\pi g_{NN\eta'}(0)}_{\text{quark contribution to the proton "spin"}} + \underbrace{F_\pi^{\,2} m_{\eta'}^{\,2} g_{NNG}(0)}_{\text{gluon contribution to the proton "spin"}}$$

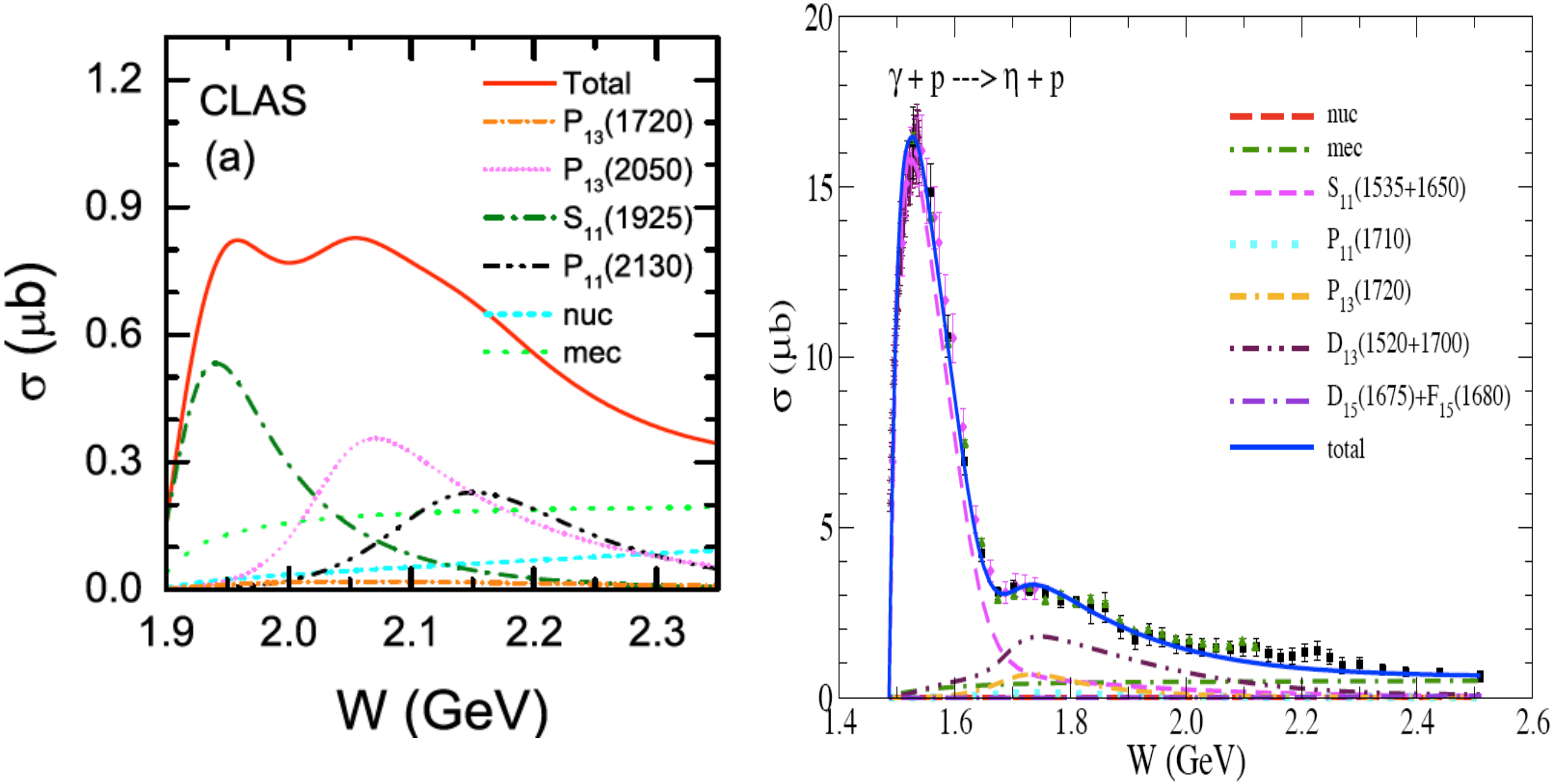
Shore&Veneziano, NPB381, '92.

$G_A(0) \approx 0.16 \pm 0.10$ (SMC collaboration, PRD56,'97)

quark contribution to the proton "spin"

gluon contribution to the proton "spin"

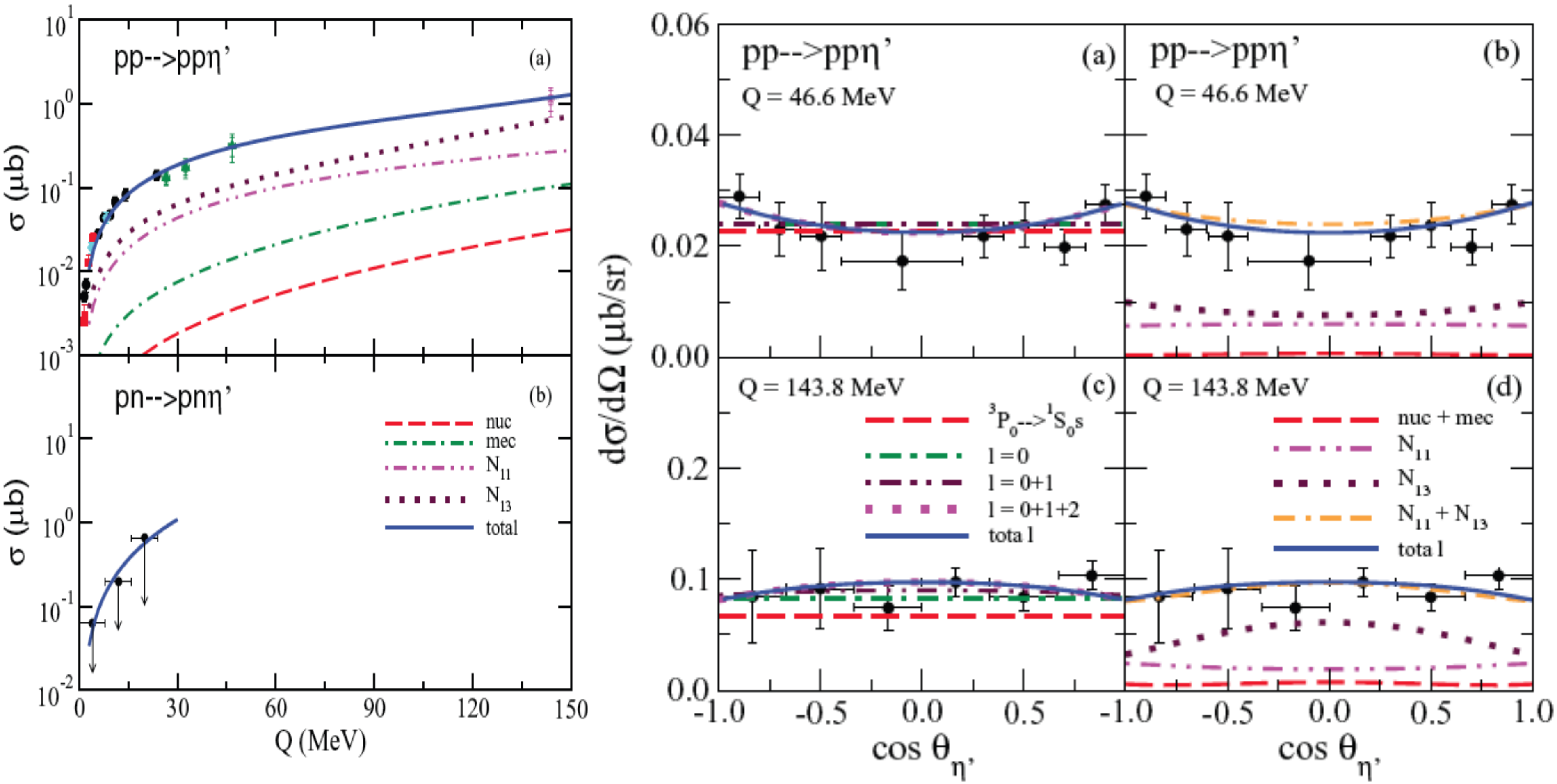
η' photoproduction: *comparison with η photoproduction*



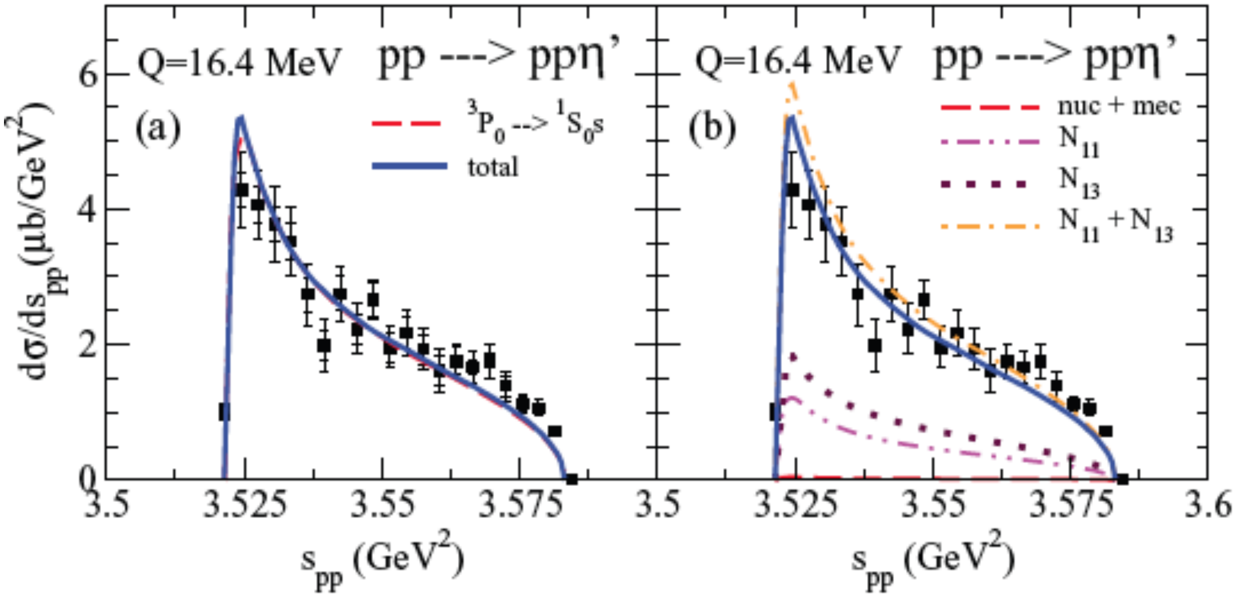
{$P_{13}(1720)$, $S_{11}(1925)$, $P_{13}(2050)$, $P_{11}(2130)$}

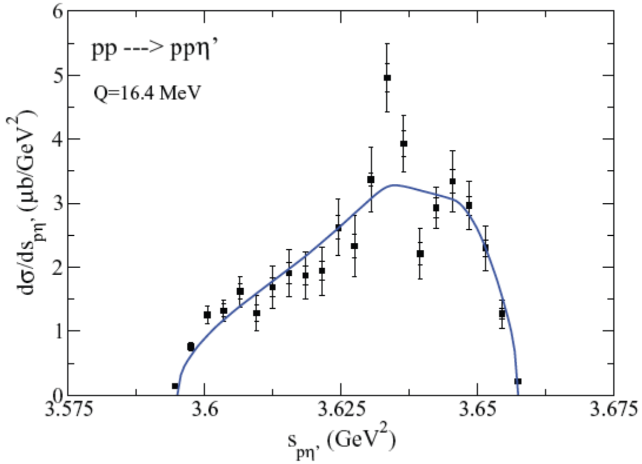
PDG: $P_{13}(1720)$****, $S_{11}(1895)$**, $P_{13}(2040)$*, $P_{11}(2110)$*

η' hadroproduction: $NN \to \eta' NN$ (combined analysis)



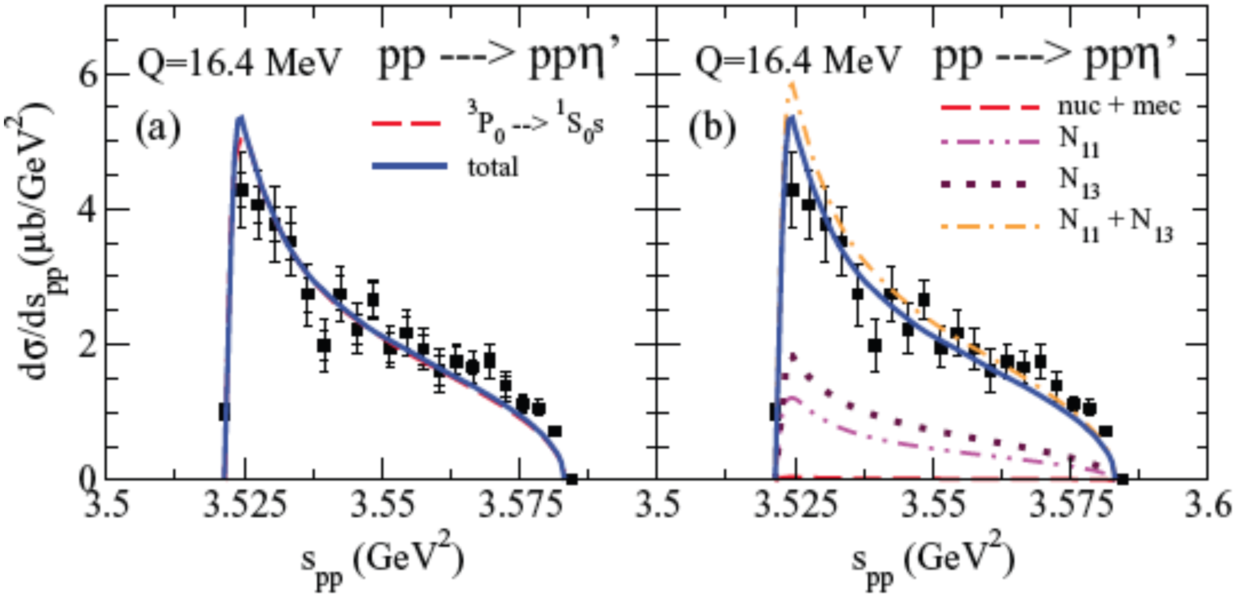
η' hadroproduction: *NN → η'NN (combined analysis)*

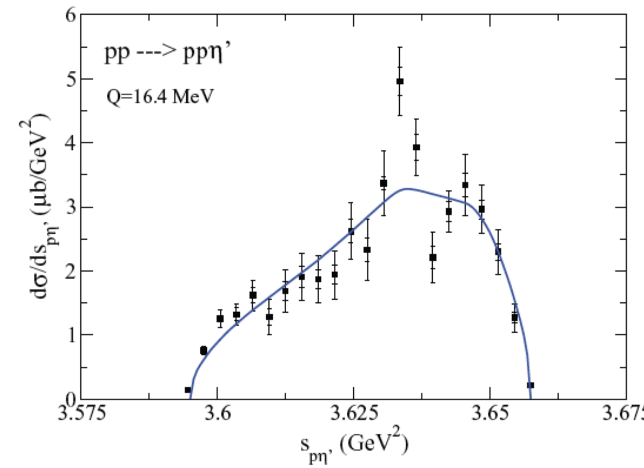




Data: COSY11,
P. Klaja et al., PLB684'07

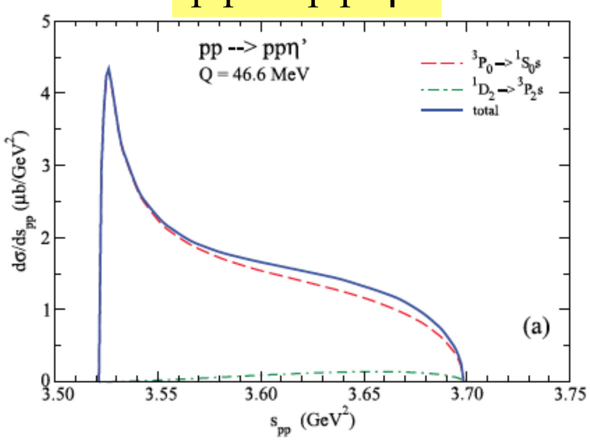
η' hadroproduction: *NN → η'NN (combined analysis)*



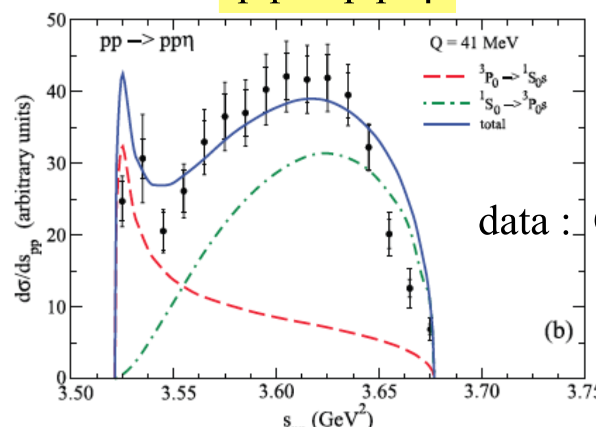


Data: COSY11,
P. Klaja et al., PLB684'07

p p → p p η'



p p → p p η

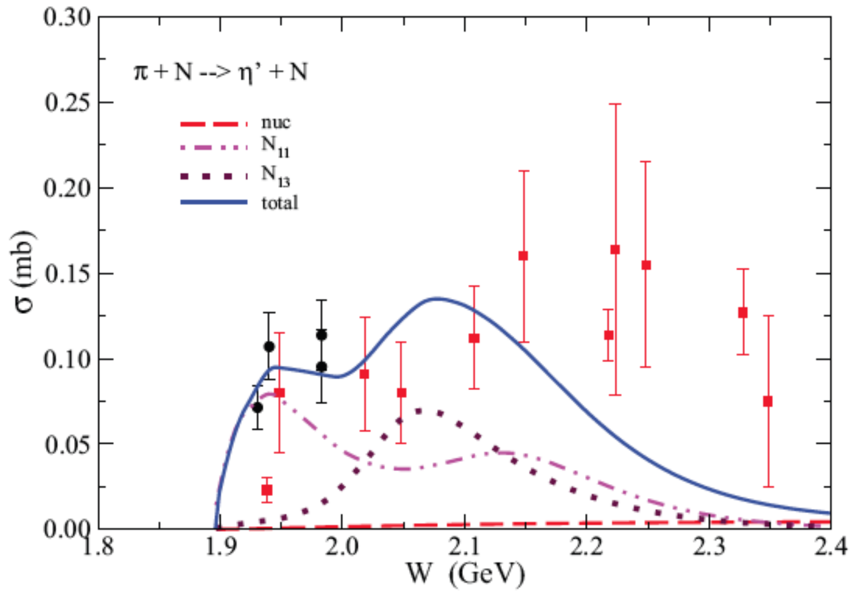


data : COSY-TOF,
M Abdel-Bary et al., EPJA16'03

η' hadroproduction: *$NN \to \eta' NN$ (combined analysis)*

Parameters	$S_{11}(1925)$	$P_{11}(2130)$	$P_{13}(1720)$	$P_{13}(2050)$
M_R (MeV)	1924	2129	**1720**	2050
Γ_R (MeV)	112	205	**200**	140
$\beta_{N\eta'}$ (%)	6	3	0.09	2
$\beta_{N\pi}$ (%)	22	25	[11 ± 3] 16	25
$\beta_{N\eta}$ (%)	4	[61 ± 60] 0.5	[4.0 ± 1.0] 9	0.03
$\beta_{N\rho}$ (%)	22	62	[70-85] 75	37
$\beta_{N\omega}$ (%)	47	13	2	36
$(g_{RN\eta'}, \lambda)$	(0.68, 1.00)	(1.77, 1.00)	(1.20, –)	(1.38, –)
$(g_{RN\pi}, \lambda)$	(−0.36, 1.00)	(−1.28, 1.00)	(−0.17, –)	(−0.12, –)
$(g_{RN\eta}, \lambda)$	(−0.28, 0.81)	(−0.35, 0.34)	(−1.50, –)	(−0.04, –)
$(g^{(1)}_{RN\rho}, g^{(2)}_{RN\rho}, g^{(3)}_{RN\rho})$	(−2.42, 0.04, –)	(2.58, −0.14, –)	(−23.63, 54.09, 16.72)	(0.50, 9.10, 28.66)
$(g^{(1)}_{RN\omega}, g^{(2)}_{RN\omega}, g^{(3)}_{RN\omega})$	(1.02, −1.70, –)	(2.47, 0.53, –)	(−27.64, 138.87, −318.85)	(−3.19, −16.75, −36.39)

η' hadroproduction: *πN → η'N (combined analysis)*

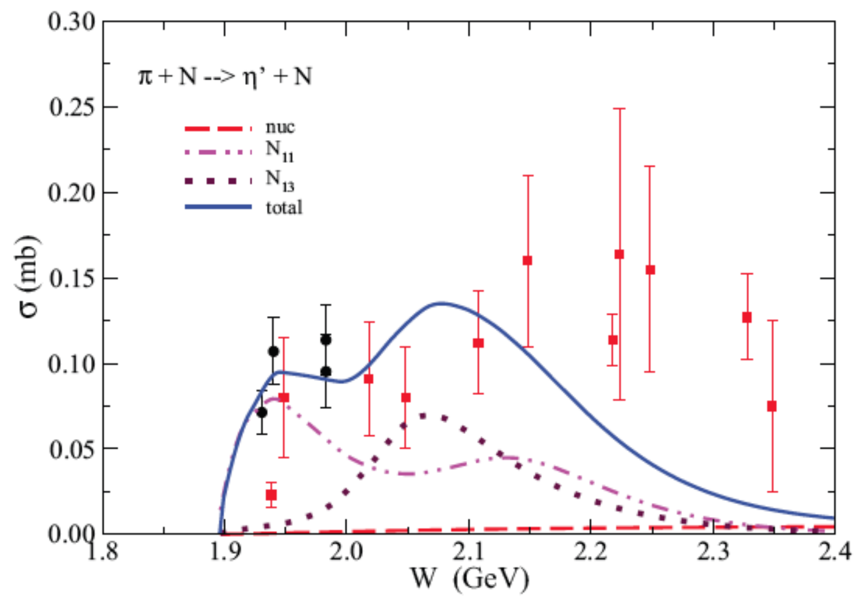


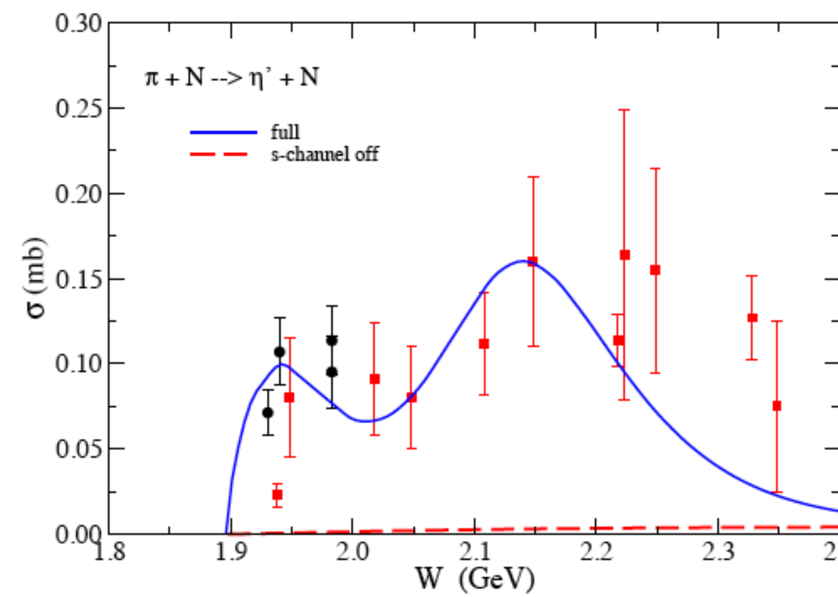
<u>Double-bump structure:</u>

- interference between $S_{11}(1925)$ and $P_{13}(2050)$
- remains to be confirmed
- if corroborated, rules out the sub-threshold resonance-dominance assumption of $S_{11}(1535)$ [Xu and Cao, PRC78'08]

[motivated by its strong coupling to η and η'
(pentaquark configuration)
[B. Zong, proc. NSTAR13, Peniscola, Spain]]

η' hadroproduction: $\pi N \rightarrow \eta' N$ (combined analysis)





Double-bump structure:

- interference between $S_{11}(1925)$ and $P_{13}(2050)$
- remains to be confirmed
- if corroborated, rules out the sub-threshold resonance-dominance assumption of $S_{11}(1535)$ [Xu and Cao, PRC78'08]

[motivated by its strong coupling to η and η'
(pentaquark configuration)
[B. Zong, proc. NSTAR13, Peniscola, Spain]]

$T = T^P(\text{s-channel}) + T^{NP}(=X)$

$X = N^X_{\eta'} K^{NP} \sim V^{NP}$,

$|X| << |T^P|$ (consistent with small FSI, $N^X_{\eta'} = 1 - i\,\rho_{\eta'} X_{\eta'\eta'} \sim 1$)

η'N scattering length: *a rough estimate*

Present phenomenology:

$a_{\eta' N} \sim (0.017 + i\,0.005)$ fm

Oset & Ramos, PLB704, 334(2011)

α	$a_{\eta p}$ [fm]	$\|a_{\eta p}\|$ [fm]	$a_{\eta' p}$ [fm]	$\|a_{\eta' p}\|$ [fm]
−0.126	0.272 + i0.246	0.367	0.073 + i0.019	0,075
0.204	0.247 + i0.233	0.340	−0.072 + i0.020	0,075
−0.193	0.276 + i0.248	0.371	0.098 + i0.020	0,1
0.256	0.241 + i0.231	0.334	−0.098 + i0.020	0,1
−0.333	0.282 + i0.251	0.378	0.149 + i0.020	0,15
0.352	0.228 + i0.225	0.320	−0.149 + i0.021	0,15

Full DCC: [D. Roenchen et al., EJPA 47, 44(2013)]

$a_{\eta N}$ = (0.49 + i 0.24) fm (model A)
= (0.55 + i 0.24) fm (model B)

Summary:

- Phenomenological approach to two-body reactions keeping the full phase structure of the reaction amplitude developed.

- Combined analysis of photo- and hadro-reactions constrain the model parameters:

  $\gamma + N \rightarrow \eta' + N$ (free and quasi-free)

  $N + N \rightarrow \eta' + N + N$

  - unique set of minimal number of spin-1/2 and -3/2 resonances obtained

    $\{P_{13}(1720), S_{11}(1925), P_{13}(2050), P_{11}(2130)\}$

  - results consistent with very small FSI

- Role of FSI : spin-polarization observables can help to learn more (sensitive to the relative phase).

- Role of higher-spin resonances: spin-polarization observables required.

- Same approach to other meson production reactions where the hadronic data are scarce to fix the FSI : e.g., ϕ production.

The End