$a_0(980)$ photoproduction in the coupled channel model

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Outline

- Scalar resonances in the πη channel
- Justification of the coupled channel final state interaction model (+some past results)
- Structure of the FSI photoproduction amplitudes
- Model predictions for the πη photoproduction in the S-wave
- Summary

Scalar resonances in the $\pi\eta$ channel

Scalar resonances in the πη channel

$a_0(980)$

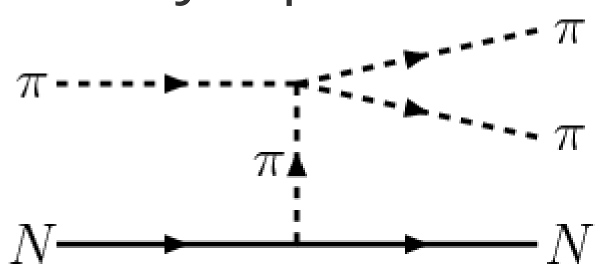
- mass around 980 MeV rather firmly established
- width known with large uncertainty: 50-100 MeV
- most likely a tetraquark system
- hadronic decay channels: $\pi\eta, K\overline{K}$

$a_0(1450)$

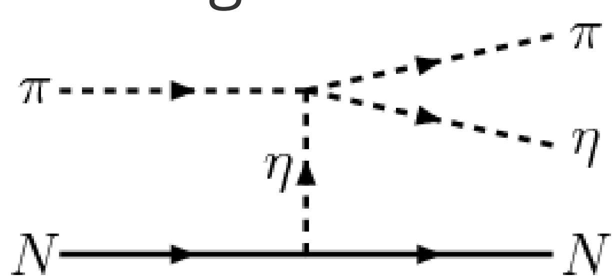
- M=1474 MeV, Γ=265 MeV
- usually treated as a member of standard $\overline{q}q$ nonet
- hadronic decay channels: $\pi\eta, \pi\eta', K\overline{K}, \omega\pi\pi, a_0(980)\pi\pi$
- branching ratios unknown – various experiments give contradictory results

Main source of difficulty

- Experimental scattering data for the πη channel are difficult to obtain
- So far we have no phase shifts and no inelasticities
- In the ππ channel, one can exploit the fact that $\pi p \to \pi\pi p$ reaction is dominated by 1-pion exchange

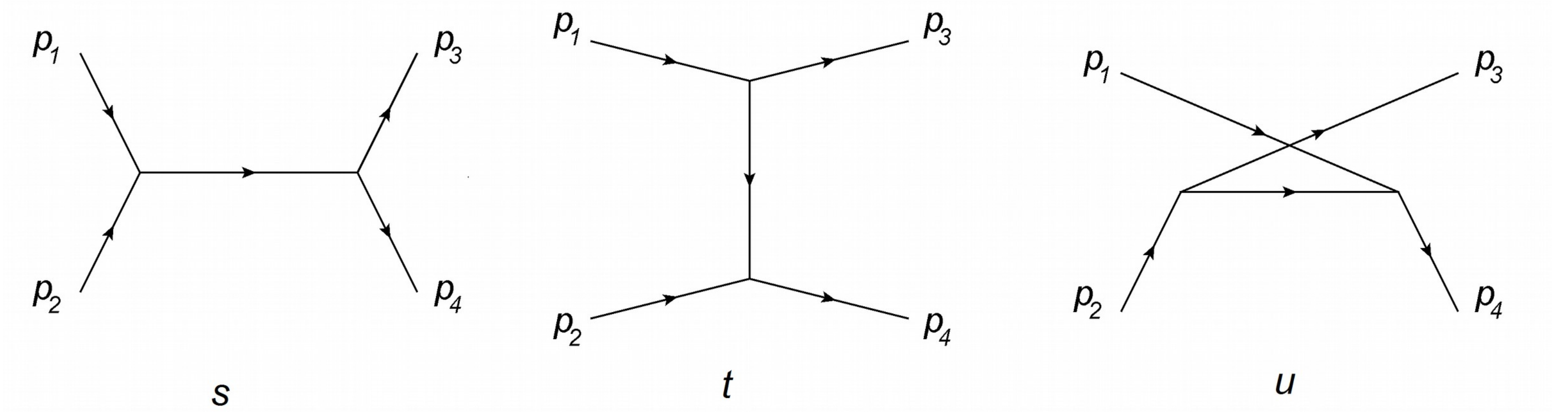


- This enables the extraction of the $\pi\pi \to \pi\pi$ amplitudes from production data
- There is no 1-eta exchange dominance in the πη production



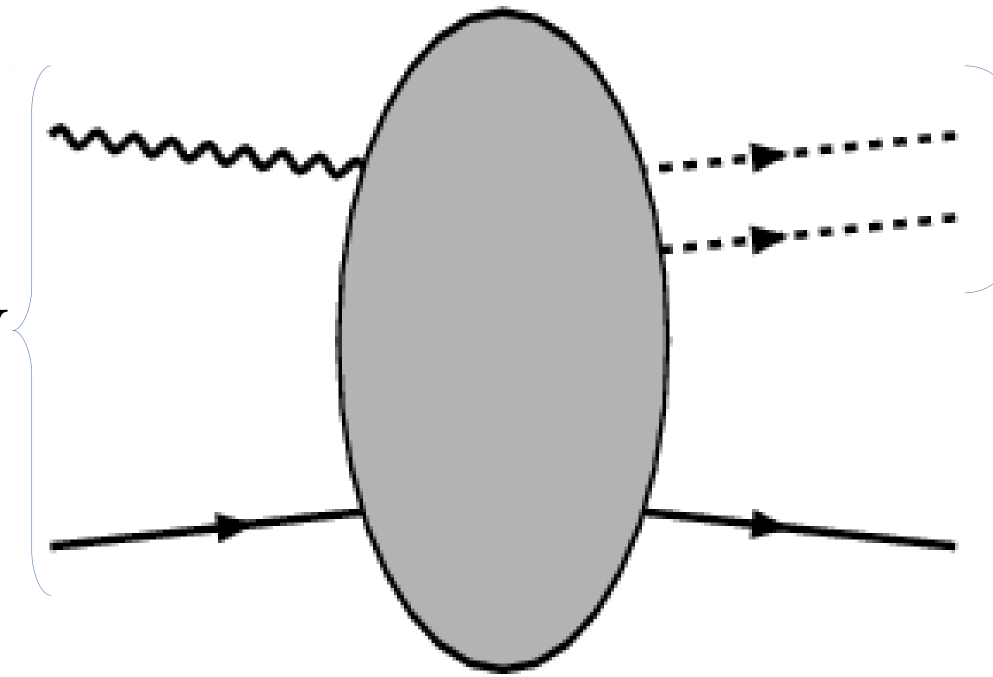
Justification of the FSI model

- One can observe a “duality” among crossing related amplitudes originating from QFT:



- Namely, that for given energy only some of them can be dominant
- In particular:
  - Low energy regime is dominated by s-channel amplitudes
  - High energy regime is dominated by t-channel exchange amplitudes

- Now assume that we photoproduce a 3 particle system consisting of nucleon and 2 (eg. pseudoscalar) mesons



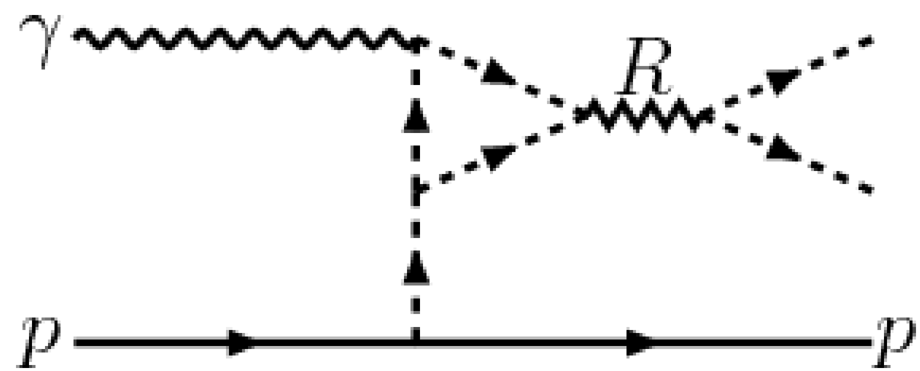
$$\text{"large"}\ \sqrt{s} \sim 10\ \text{GeV}$$

$$M_{mm'} \lesssim 2\ \text{GeV}$$

Intermediate state particles emerge due to t-channel exchange

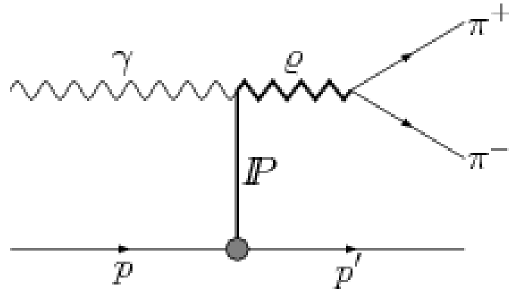
Meson-meson FSI are dominated by the s-channel intermediate resonant states

Conclusion: 2 meson states produced by new JLab experiments are ideally suited for description by FSI model



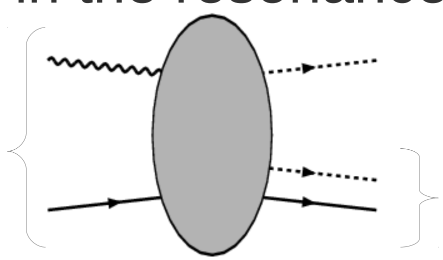
Caveats:

- (Photo-)production of $\pi^+\pi^-$, K^+K^-, $\pi^+\pi^-\pi^0$ at small 4-momentum transfers is dominated by pomeron exchange



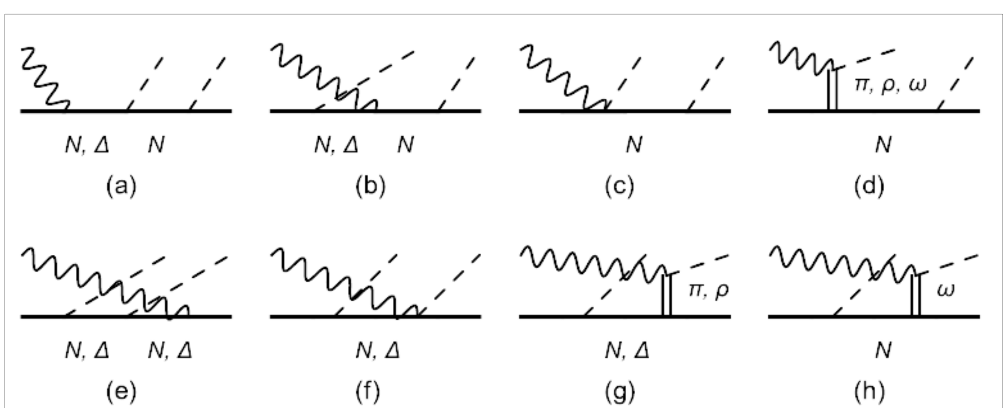
- Drell process ($M_{p\pi}$ mass in the resonance region)

$$\text{"large"}\ \sqrt{s} \sim 10\ \text{GeV}$$

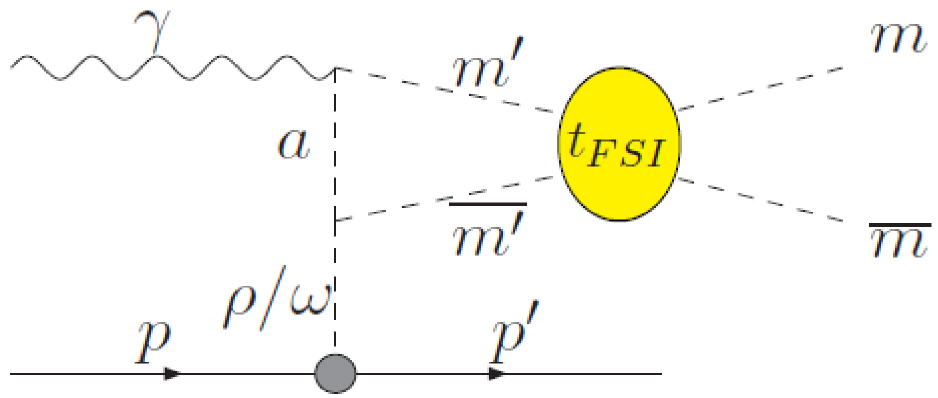


$$M_{pm'} \lesssim 2\ \text{GeV}$$

- Final state dominated by I=1/2 and I=3/2 byryonic resonances
- Low energy region is diminated by the s-channel barionic excitations



Final state resonance photoproduction



- Structure of the photoproduction amplitude:

$$\mathrm{A}_{mn}^{JM}(\lambda_\gamma,\sigma_1,\sigma_2) = V_{mn}^{JM}(\lambda_\gamma,\sigma_1,\sigma_2) +$$

$$4\pi \sum_{m'n'} \int_0^\infty \frac{\kappa'^2 d\kappa'}{(2\pi)^3} F(\kappa,\kappa') \langle mn|\hat{t}_{FSI}^J|m'n'\rangle G_{m'n'}(\kappa') V_{m'n'}^{JM}(\lambda_\gamma,\sigma_1,\sigma_2)$$

where:

$V_{mn}^{JM} = \int d\Omega Y_M^J(\Omega) V_{mn}$ -*JM* wave projected Born amplitude

t_{FSI}^J - final state scattering amplitude

$G_{m'n'}(\kappa')$ - propagator of the intermediate meson pair

$F(\kappa,\kappa')$ - form-factor regularizing the meson loop

Some results based on the FSI model

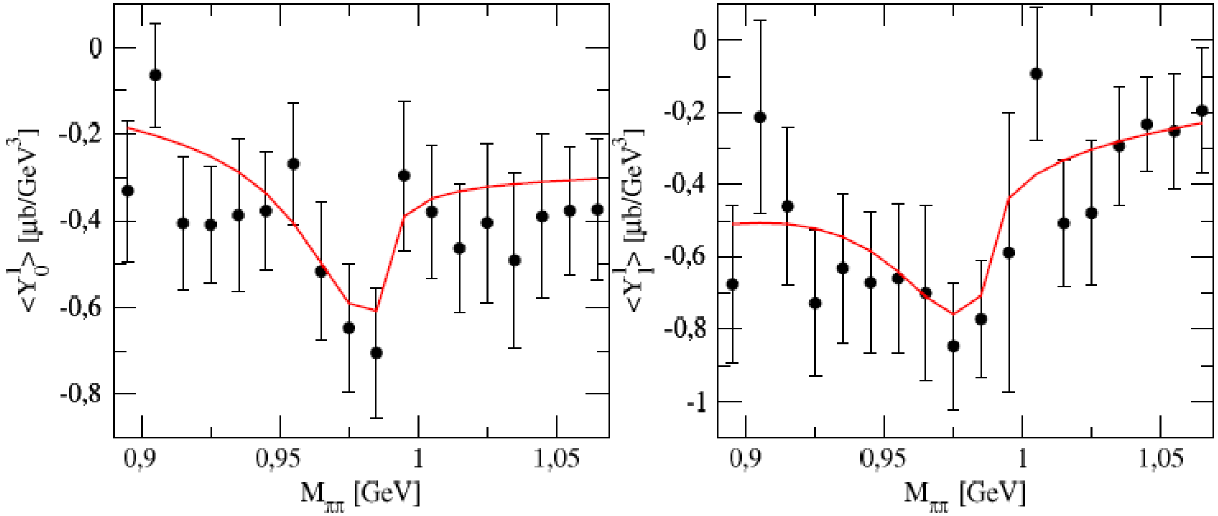
Extracting the f_0(980) signal in the $\gamma p \to \pi^+\pi^- p$ reaction (Bibrzycki, Leśniak, EPJ Web Conf. 37 (2012))

- Moments of angular distribution measured by CLAS (M. Battaglieri *et al.*, 2009. Phys.Rev. D80 (2009)) were fitted in the ππ effective mass range corresponding to f_0(980)

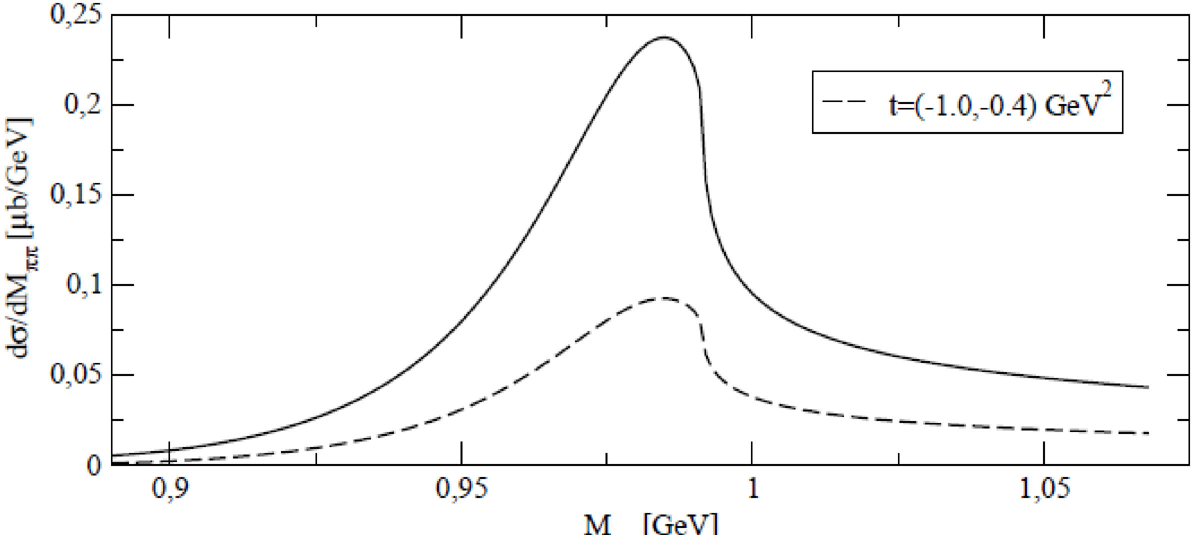
$$\langle Y_M^L(t, M_{\pi\pi})\rangle = \int d\Omega\, Y_M^L(\Omega)\, |A^P + A^\pi + A^\sigma + A^{f_2} + A^D + A^{f_0}|^2$$

- Apart from the f_0(980) photoproduction the model included:
  - ρ(770) photoproduction with the pomeron, π, σ and f_2(1270) exchange
  - Drell background

- Moments at E_γ=3.3 GeV and t=-0.5 GeV2

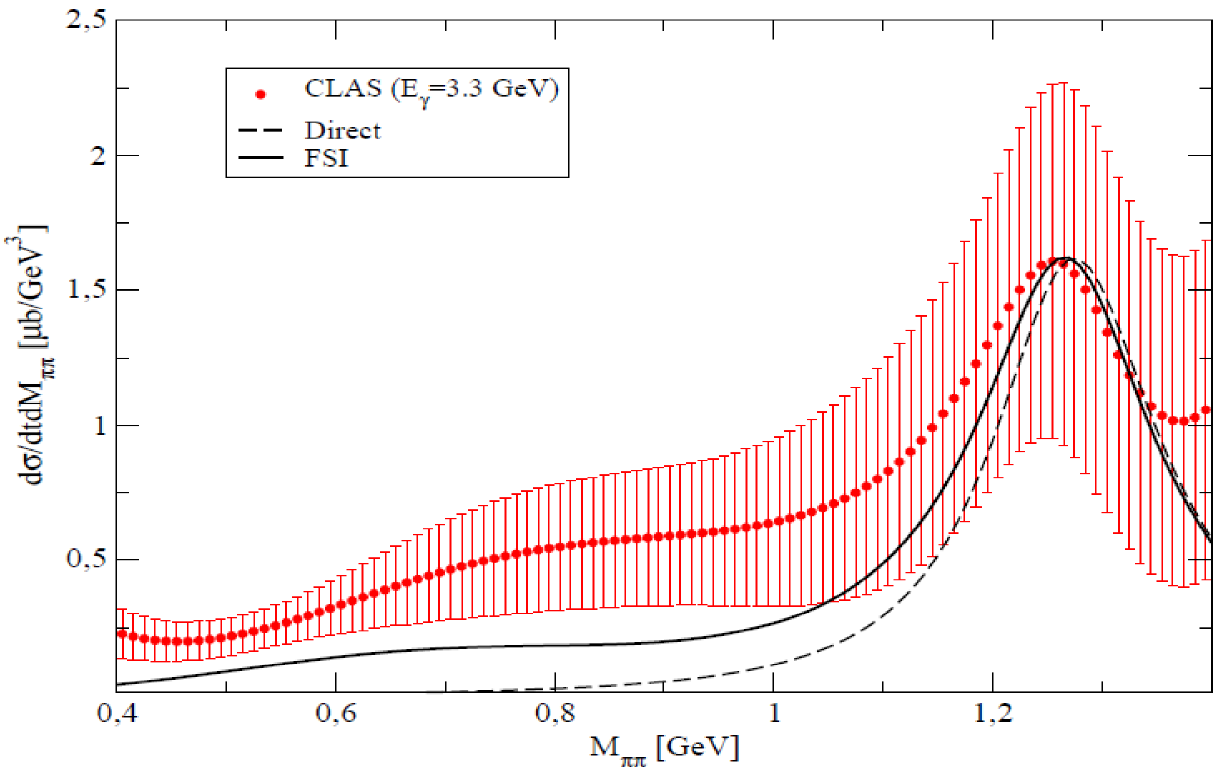


- Having constrained the resonant S-wave we calculated the mass distribution



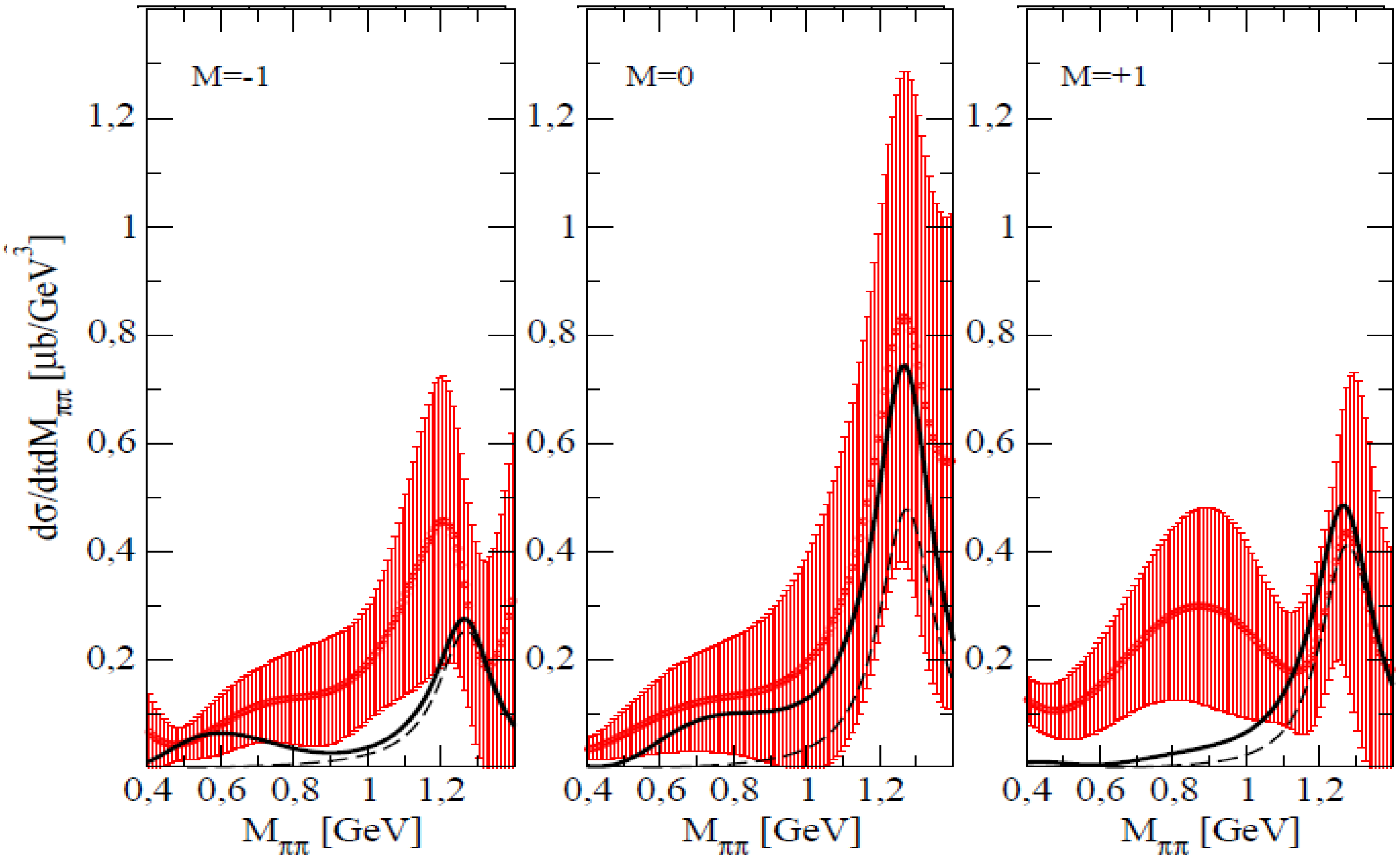
Description of the $\gamma p \to f_2(1270)p$ photoproduction at CLAS (Bibrzycki, Kamiński, Phys.Rev. D87 (2013))

- Mass distributions for direct and FSI model



- Direct and FSI photoproduction mechanisms were compared
- Although Born amplitude of the FSI model accounts for part of the background, other sources of background must be included

- Mass distributions for selected helicities +1, 0, -1 and compared them with CLAS data at E_γ=3.3 GeV



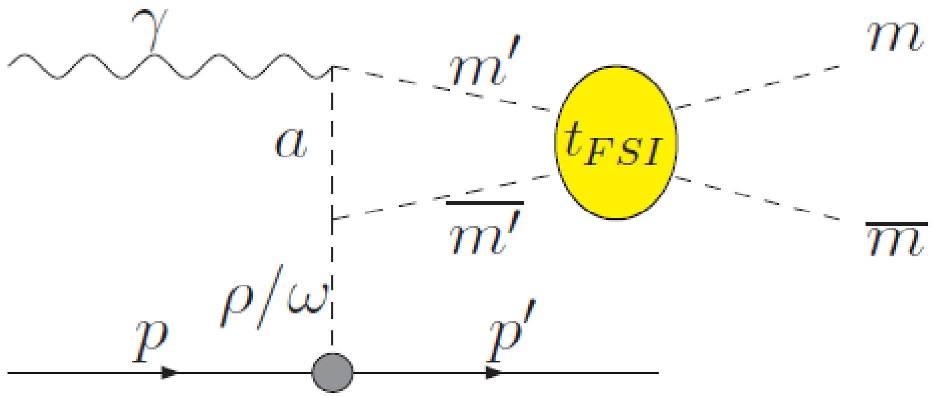
E_γ=3.3 GeV, t=-0.55 GeV

Solid line – FSI production model

Dashed line – direct production model

- With the present mass distribution measurement precision the direct and FSI photoproduction are consistent

The πη channel



- FSI amplitude structure for 2 coupled channels

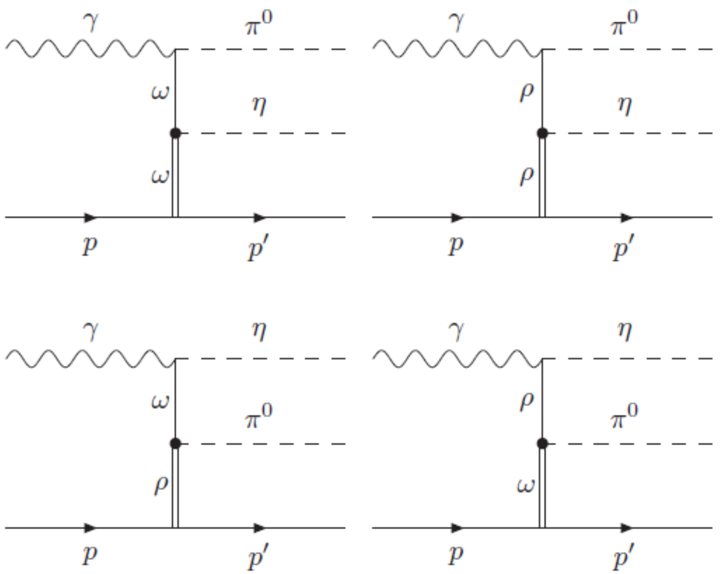
Partial wave projected Born amplitude

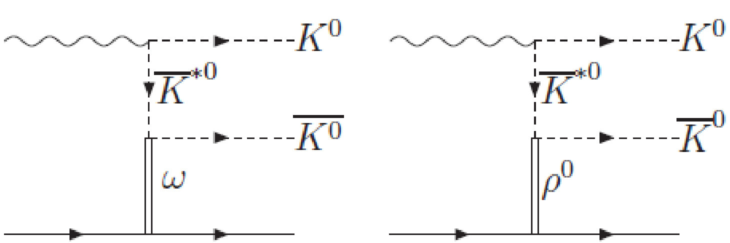
$$T^{I=1}_{\pi\eta} = \left[1 + i r_{\pi\eta} \hat{t}^{I=1}_{\pi\eta} + \hat{P}^{I=1}_{\pi\eta}\right] V_{\pi\eta} + \frac{1}{\sqrt{2}} \left[r_{K\bar{K}} \hat{t}^{I=1}_{K\overline{K};\pi\eta} + \hat{P}^{I=1}_{K\overline{K};\pi\eta}\right] \left(V_{K^+K^-} + V_{K^0\overline{K^0}}\right)$$

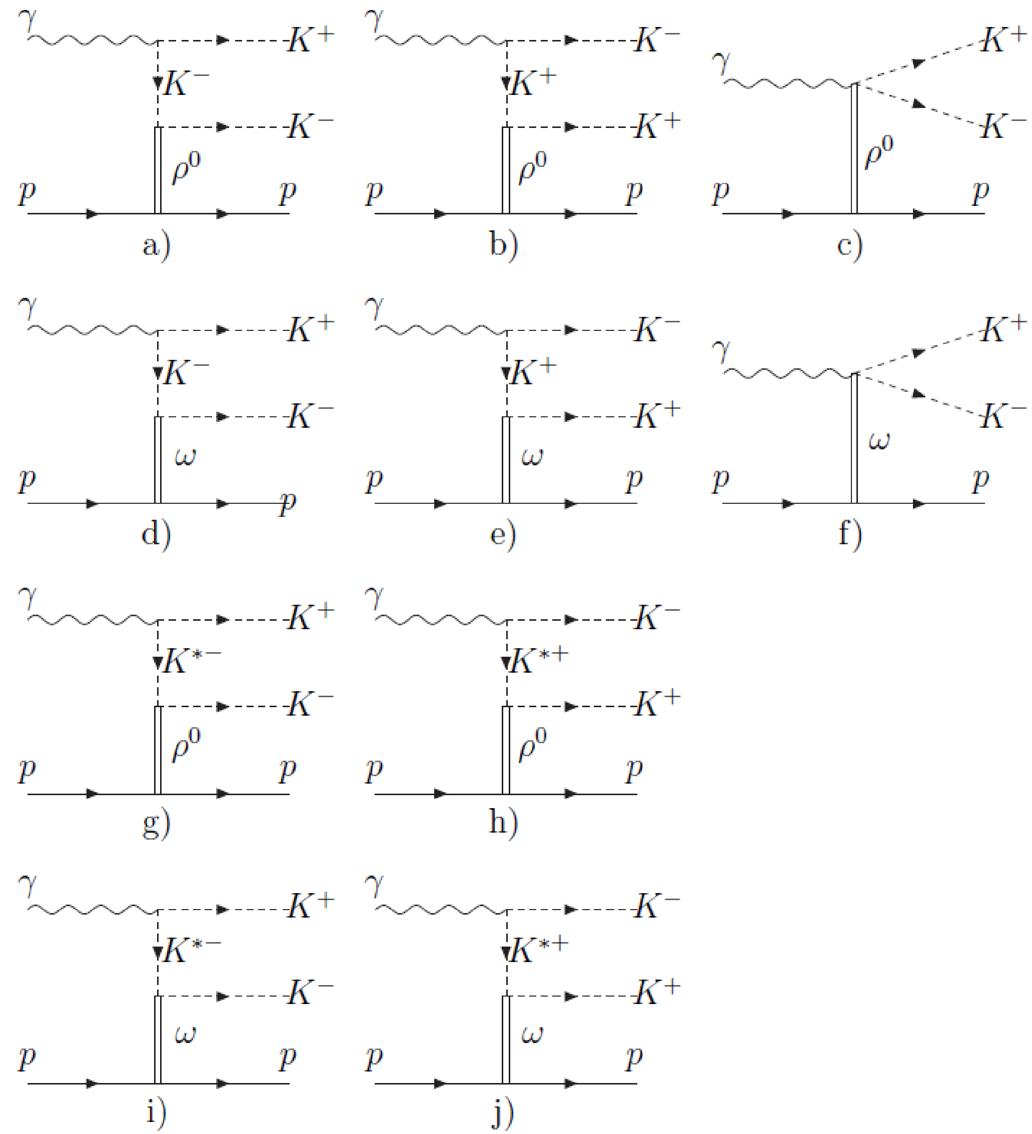
Final state scattering amplitude

- This form of the amplitude holds for all partial waves (very economical approach) !

Born amplitudes







- For energies >4 GeV we use the reggeised version of the propagator in the lower line

FSI scattering amplitude

- General structure (Leśniak, Furman Phys.Lett., B538,2002)

$$\langle p|t_{ij}|q\rangle = \langle p|V_{ij}|q\rangle + \int \frac{d^3k}{(2\pi)^3} \langle p|V_{il}|k\rangle\langle k|G_{ll}|k\rangle\langle k|t_{lj}|q\rangle$$

Lippmann-Schwinger equation

- Separable potential and couplings

$$\langle p|V_{ij}|q\rangle = \lambda_{ij} g_i(p,\beta_i) g_j(q,\beta_j),$$

where λ_{ij} -coupling matrix, β_i - range parameters (5 params. altogether)

- After "inverting" the integral equation we obtain the amplitude

$$\hat{t} = (1-\lambda\hat{I})^{-1}\lambda$$

- S- matrix parametrization

$$S = \begin{pmatrix} \eta e^{2i\delta_{\pi\eta}} & i\sqrt{1-\eta^2}e^{i(\delta_{\pi\eta}+\delta_{KK})} \\ i\sqrt{1-\eta^2}e^{i(\delta_{\pi\eta}+\delta_{KK})} & \eta e^{2i\delta_{KK}} \end{pmatrix}$$

...FSI scattering amplitude

- Relation between the S-matrix and the amplitude

$$S_{ij} = \delta_{ij} - \frac{i}{\pi}\sqrt{k_i k_j \alpha_i \alpha_j} t_{ij}$$

- Amplitude definition in terms of the Jost function

$$t_{ij} = \frac{[cofactor]_{ij}}{det(\hat{1} - \hat{\lambda}\hat{I})}$$

Jost function

$$D(k_1, k_2) = det(\hat{1} - \hat{\lambda}\hat{I})$$

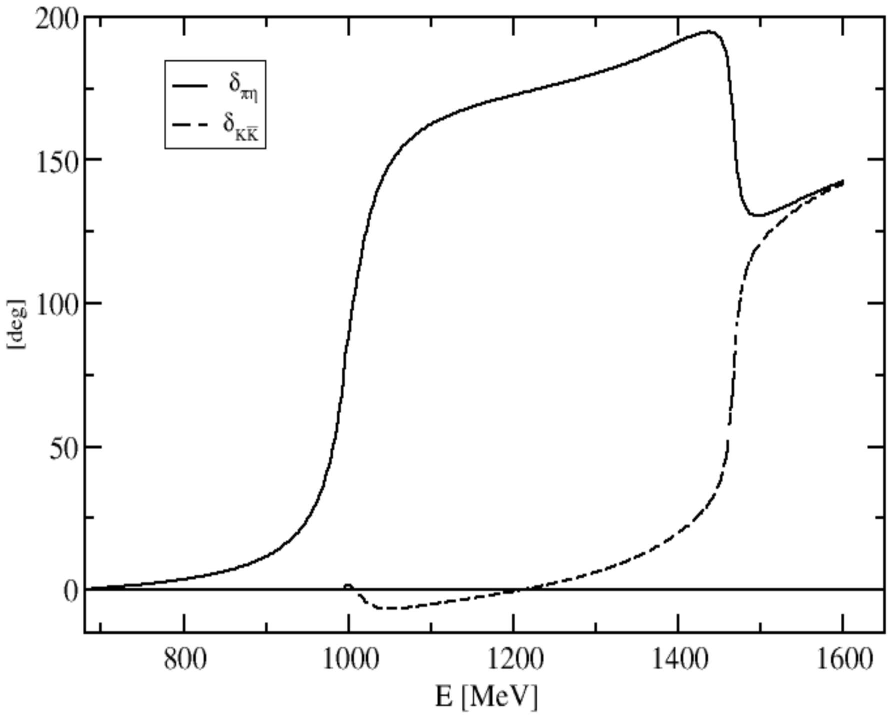
In 2 channel case:

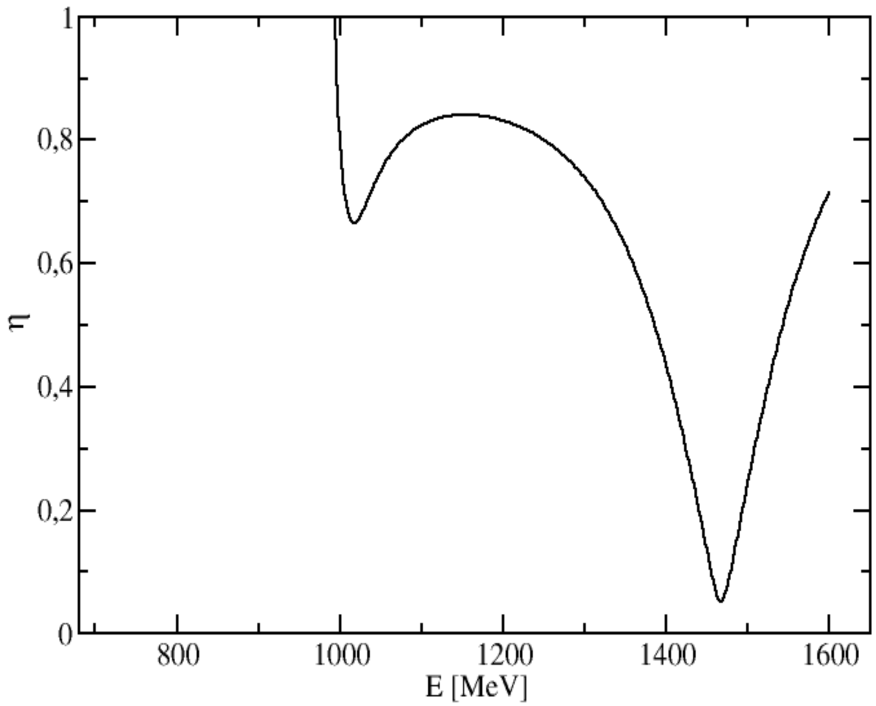
- Resonanaces are determined by poles in the amplitude – thus zeroes of the Jost function

- For 2 resonances a_0(980) and a_0(1450) we can constrain model parameters by using 2 complex (4 real) equations:

$$D(k_1^r, k_2^r) = 0 \qquad D(k_1^R, k_2^R) = 0$$

Inelasticity and phase shifts



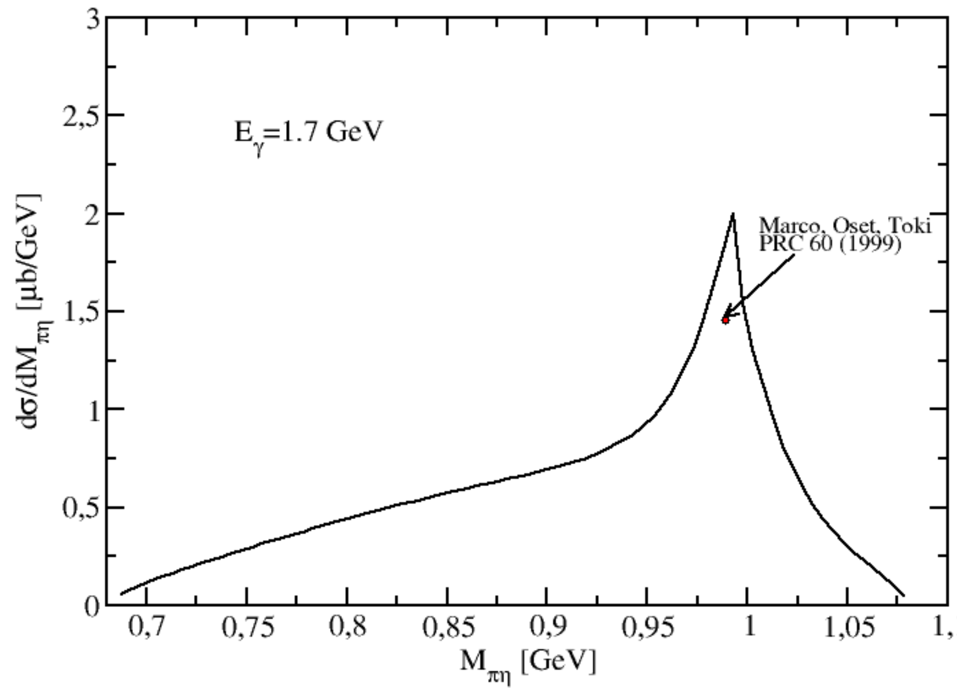


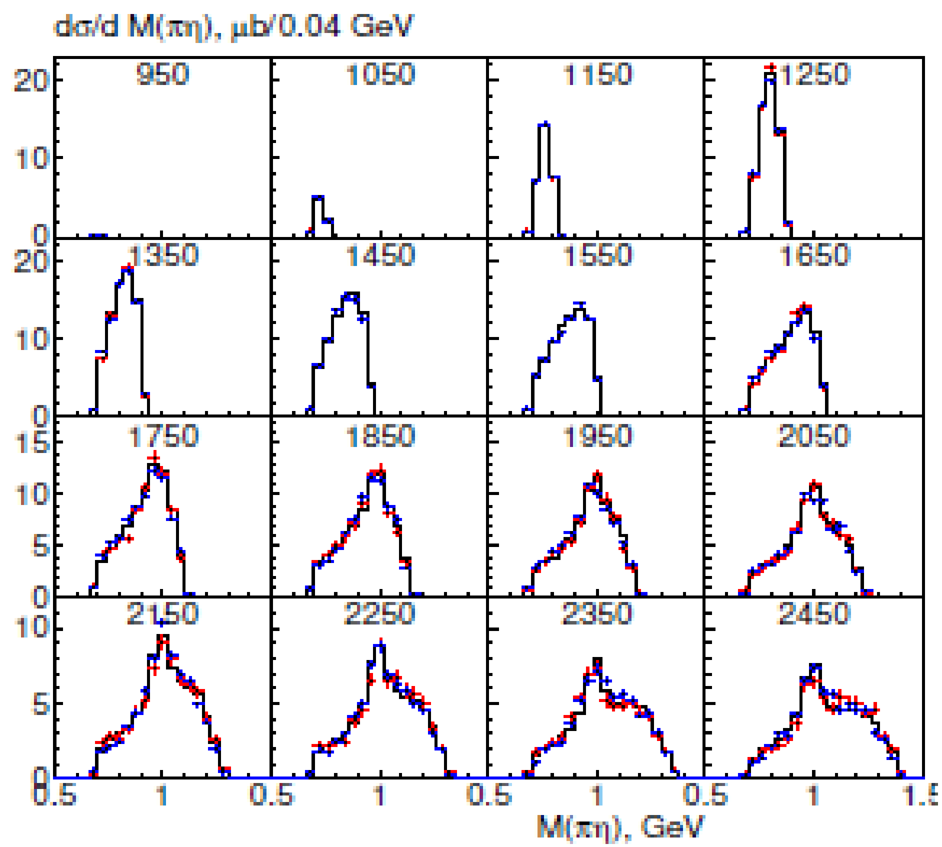
Unusual behavior of the $\delta_{\pi\eta}$ phase shift is due to the interplay of the poles and zeroes of the amplitude

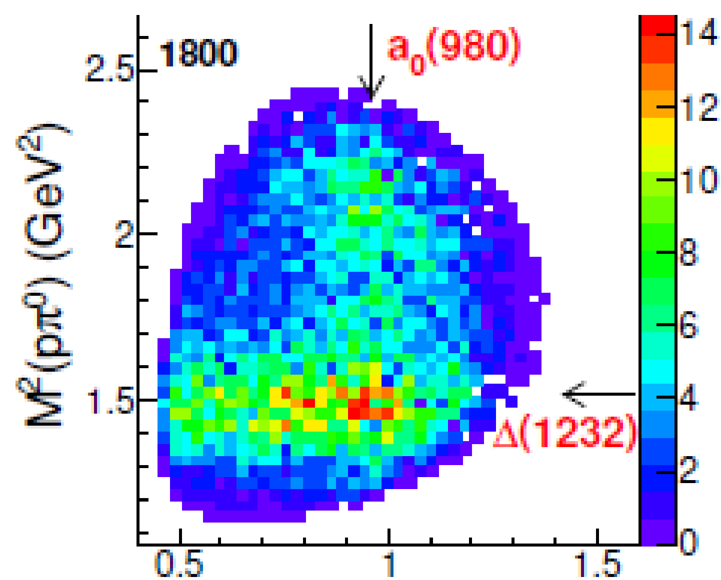
πη photoproduction results

Mass distributions for low energy photoproduction

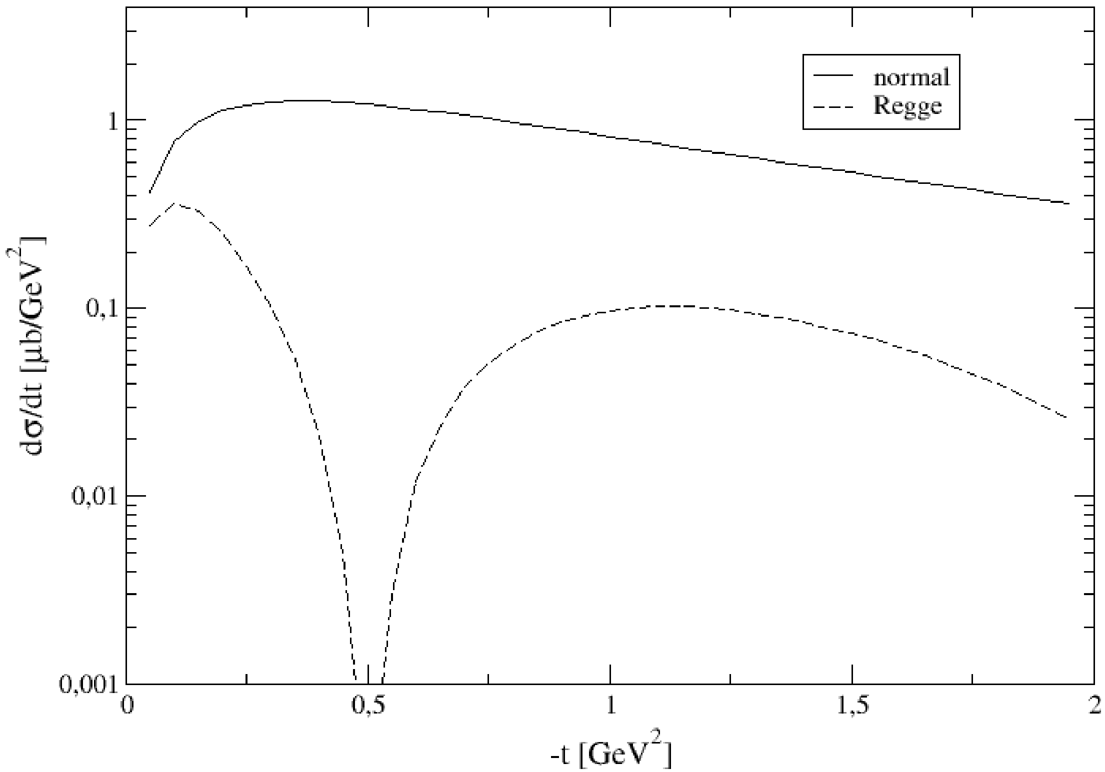
Signal of the $a_0(980)$ photoproduction sitting on a large background can be found in ELSA data (E. Gutz *et al.* Eur.Phys.J. A50 (2014)) at photon energy E_γ=1.8 GeV





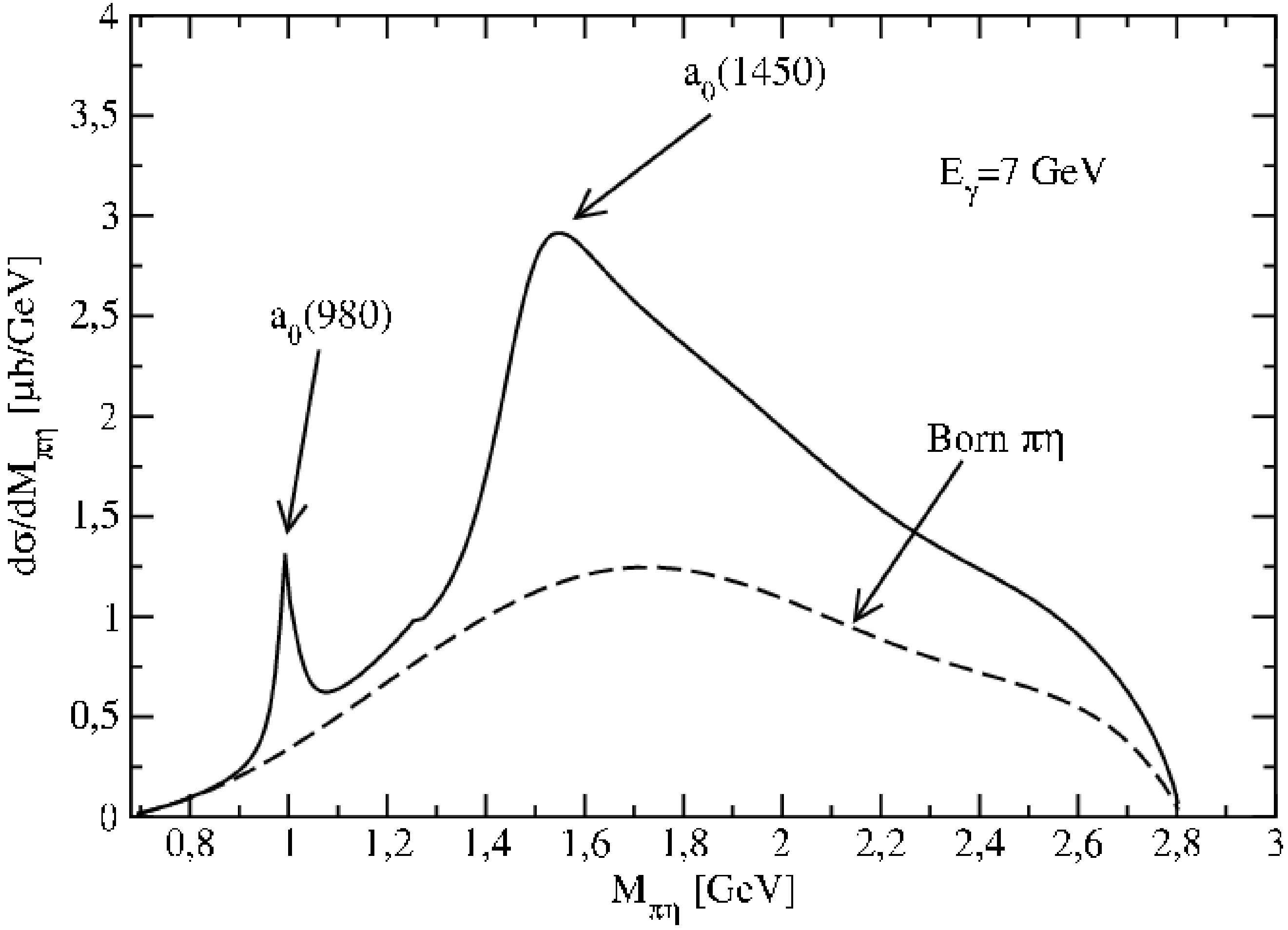


Differential cross section at E_γ=5 GeV



- For high energies the reggeised version of the model is supposed to apply (here E_γ=5 GeV)
- The minimum at t ≈ -0.5 GeV^2 can be “filled” by inclusion of Regge cuts

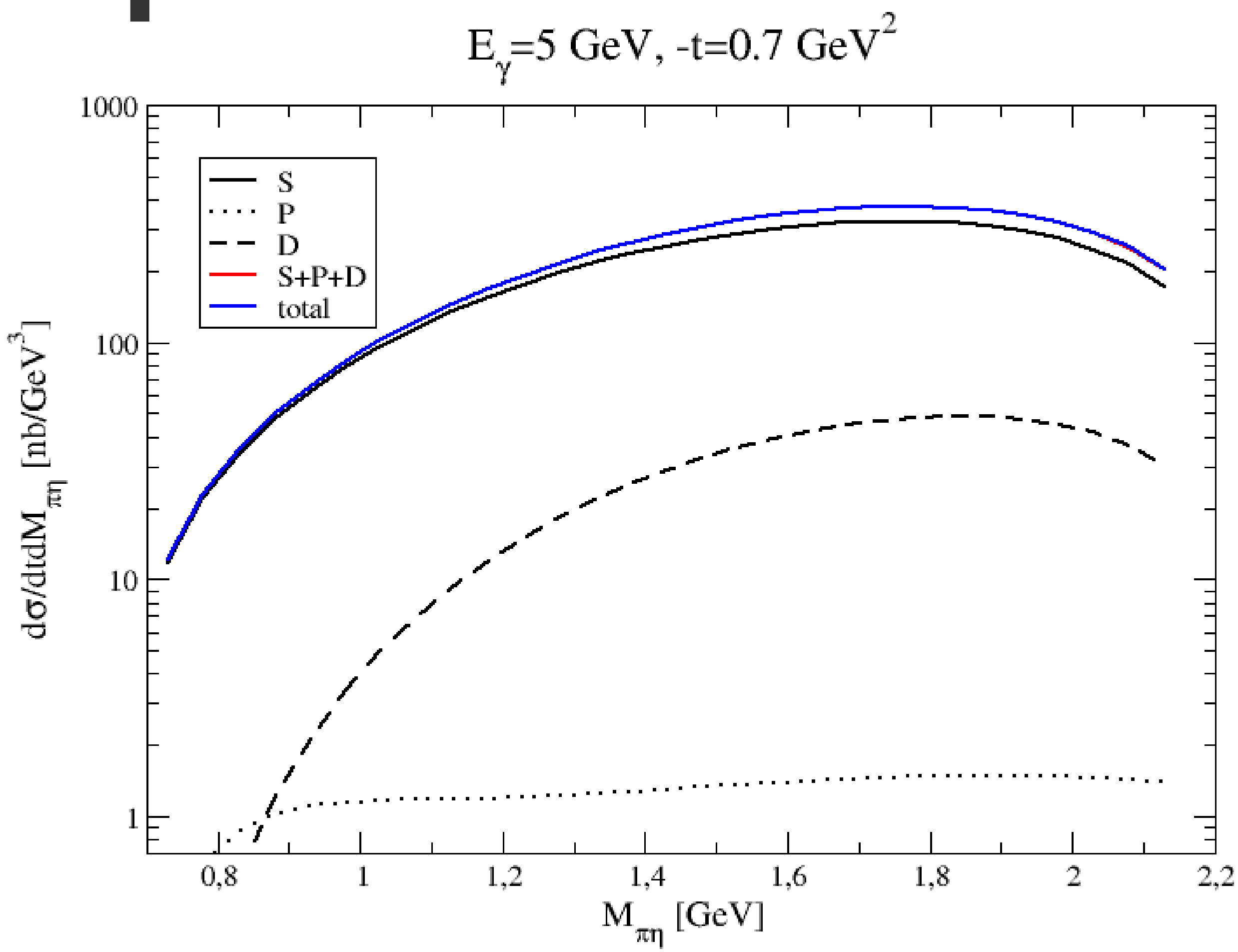
Mass distribution for CLAS12 photon energies



Warning

Discarding the πη’ and ωππ channels introduces the uncertainty to the model for $M_{\pi\eta}$>1 GeV.

Higher partial waves



- Born amplitudes are dominated by the S-wave amplitude
- P-wave smaller than the S-wave by two orders of magnitude – is this the reason why CLAS didn't see the $\pi_1(1400)$?

Summary

- We constructed the $\pi\eta$-$K\bar{K}$ coupled channel model of scalar-isovector resonance photoproduction
- $a_0(980)$ photoproduction cross section assumes values which make it possible to observe (in worst case through the PW interference effects) at CLAS12 and GlueX
- The same applies to $a_0(1450)$ but this prediction at present may be biased by incomplete treatment of open channels ($\pi\eta'$, $\omega\pi\pi$) – works underway to include the $\pi\eta'$ channel
- Isovector P-wave in the $\pi\eta$ channel is strongly suppressed at the level of Born amplitudes – so any P-wave resonances photoproduced through the FSI should be suppressed