# Dipion resonance photoproduction on nucleons


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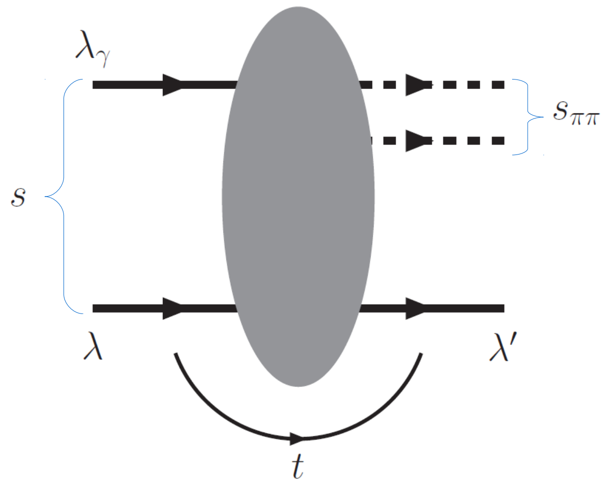
Work inspired by discussions with Adam Szczepaniak @HASPECT

# Motivation of studying the ππ photoproduction

- ππ is the simplest (spinless particles) but feature reach two meson system
- Final state ππ interaction is quite well understood due to works of Madrid-Kraków and Bern groups
- Many resonances observed in this system, whose production mechanisms are still poorly known
- ππ system is a laboratory of methods which can be applied in more complex systems, ie. containing a few mesons or spinning mesons
- Photoproduction of well known ππ resonances like ρ(770) can be used to test models

# General description of the 3-particle production




The system is described in terms of 5 kinematic variables:

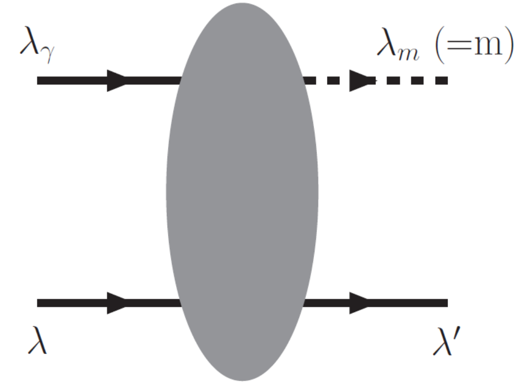
- 3 Lorentz invariants – $s$, $s_{\pi\pi}$, $t$
- φ, θ – angles, which describe the outgoing pions direction (in their CM system), with respect to z-axis directed opposite to the recoil proton momentum (helicity system)
- and 3 spins

Assume that we analyze the system with the following properties:

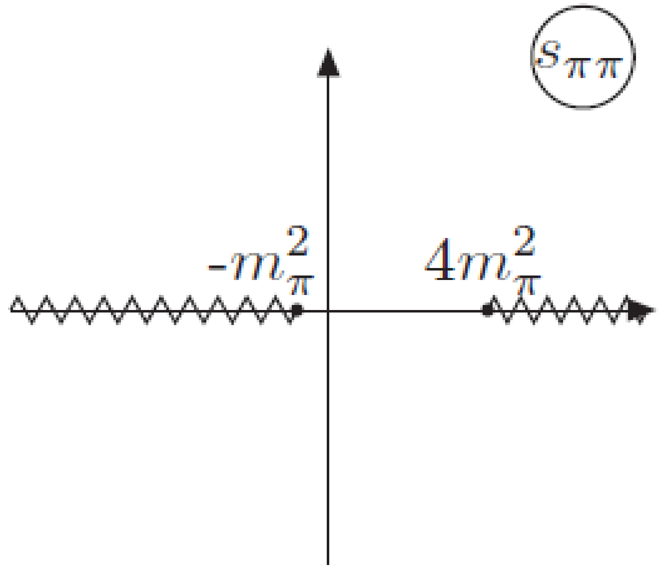
- Total CM energy $\sqrt{s}$ is "large" (~10 GeV)
- Effective mass $\sqrt{s_{\pi\pi}}$ is low – so partial wave expansion of the amplitude is valid

$$A(s, s_{\pi\pi}, t, \theta, \varphi) = \sum_{l=0}^{l_{max}} \sum_{m=-l}^{l} a^l_m(s, s_{\pi\pi}, t) Y^l_m(\theta, \varphi)$$

- For any given partial wave, we can think about the reaction as of the quasi 2→2 scattering
- For fixed $s$, $t$, $\lambda$, $\lambda'$, $\lambda_m$ we can treat the partial wave amplitude as a function of only $s_{\pi\pi}$, ie. $a_{lm}(s,s_{\pi\pi},t)=a(s_{\pi\pi})$



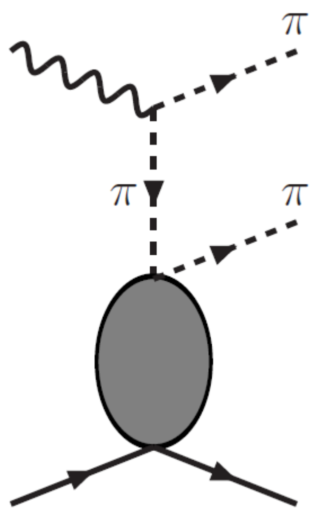
Now assume:




1. Right hand cut of *$a(s_{\pi\pi})$* is only due to elastic scattering (or one can develop a coupled channel formalism: ππ, KK,...)
2. Left hand cut is close to physical region (to be explicitly calculated) and but there may be other dynamical singularities far from the physical region, which can be parametrized (eg. by polynomials)

- For the $\gamma p \to \pi\pi p$ reaction the nearest left hand cut to the physical region is due to 1-pion exchange
- So schematically we write:

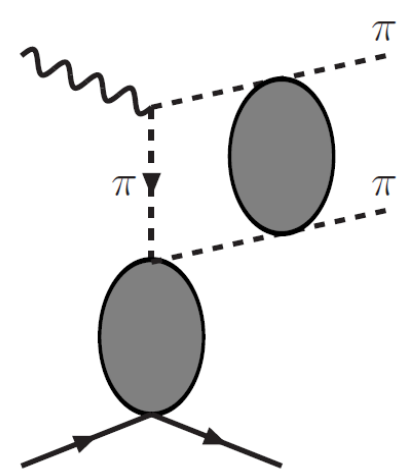
$a_L(s_{\pi\pi}) \approx$




Part of the amplitude dominated by the nearest left hand cut singularity – pion exchange

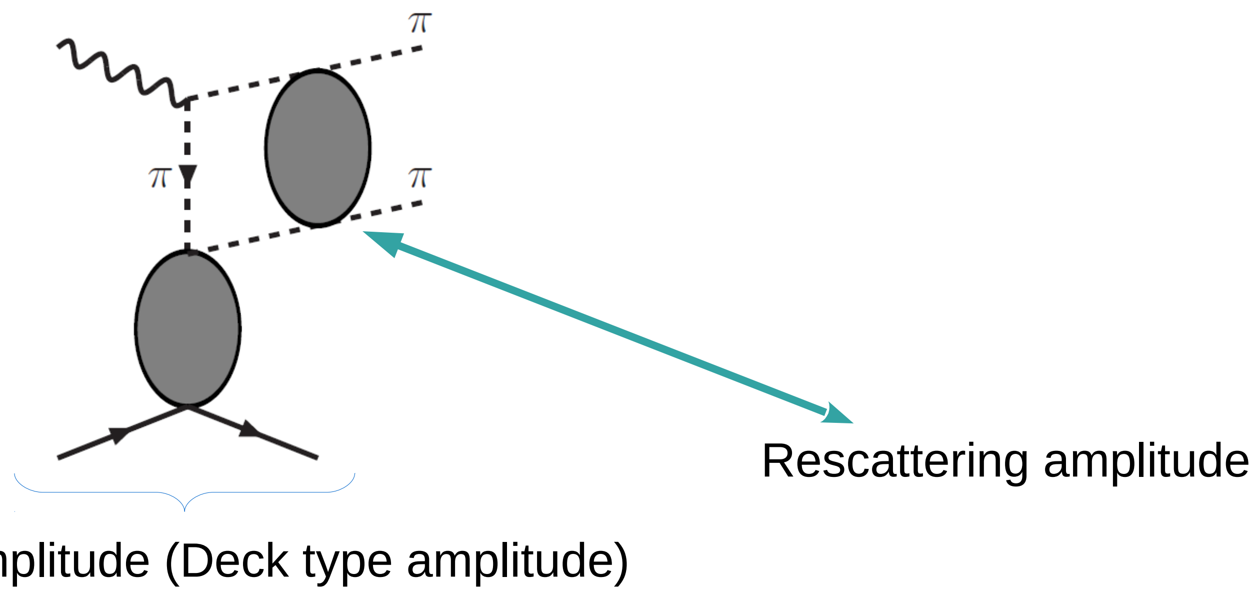
$\pi p \to \pi p$ elastic amplitude we need to parametrize (we use SAID parametrization)

- Where are meson resonances ?
- Meson resonances arise due to final state interaction
- The amplitude can be calculated by **solving** dynamical equation
- We take the different approach however. We assume that we know the ππ elastic amplitude from elsewhere and plug it into the definition of the production amplitude.



# Translating diagrams into amplitude structure

- Structure of the production amplitude




$$A_{mn} = V_{mn} + 4\pi \sum_{m'n'} \int_0^\infty \frac{\kappa'^2 d\kappa'}{(2\pi)^3} F(\kappa, \kappa') \langle mn | \hat{t}_{FSI} | m'n' \rangle G_{m'n'}(\kappa') V_{m'n'}$$

Where:

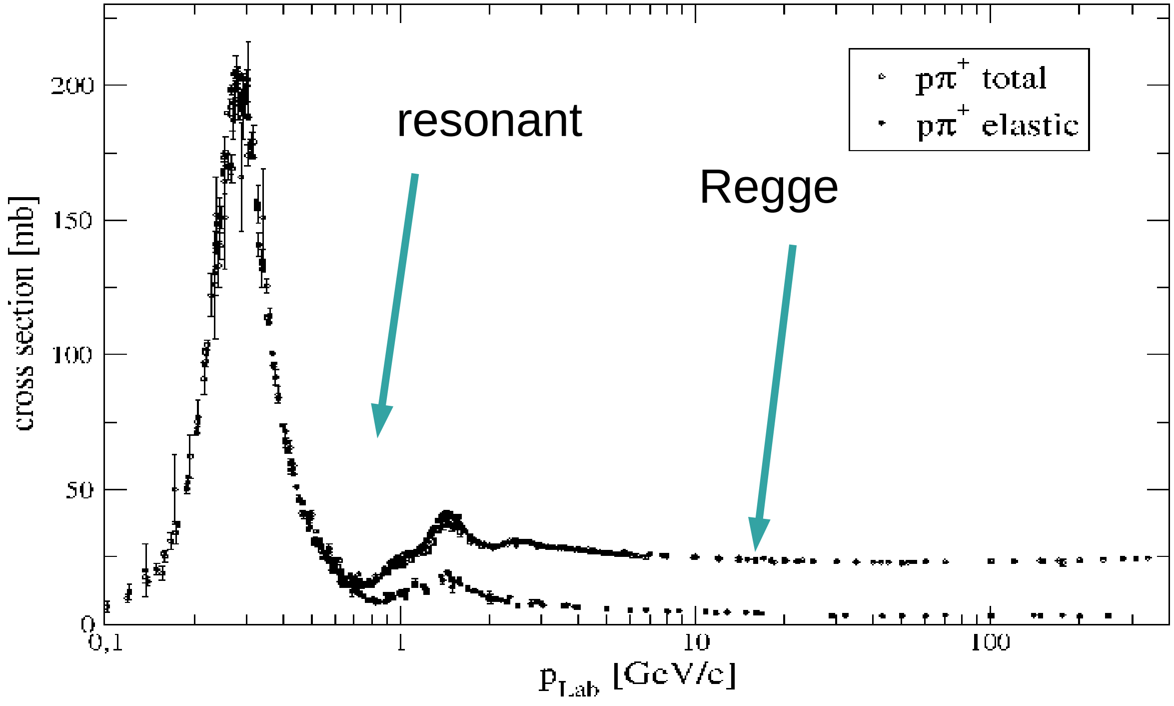
$A_{mn}$ – photoproduction amplitude of the meson pair *mn*,

$V_{mn}$ - initial state amplitude,

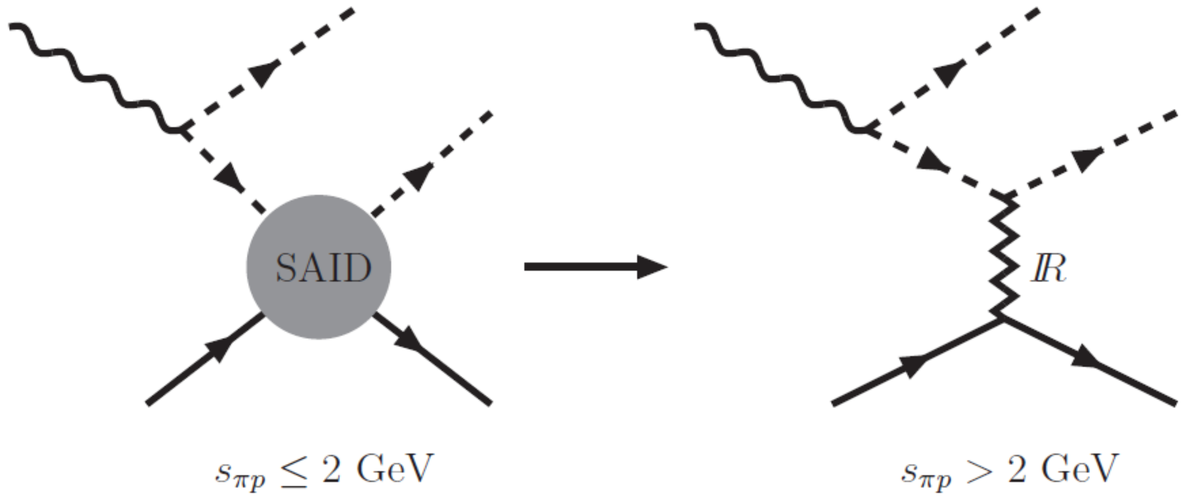
$t_{FSI}$ -rescattering amplitude

# Dipion photoproduction at upgraded JLab energies

- In previous JLab run the photon energy was ~3,5 GeV
- The SAID parametrisation covers the $M_{p\pi}$ values up to 2 GeV
- This was just enough for low photon energies but at $E_\gamma$~10 GeV we need the $\pi p \to \pi p$ amplitude parametrisation for $M_{p\pi}$>2 GeV



- Regge extrapolation is used for $M_{p\pi}$>2 GeV, where SAID amplitudes are not applicable




- We take into account the ρ, ω and pomeron trajectories
- Matching procedure is used at $M_{p\pi}$=2 GeV so that

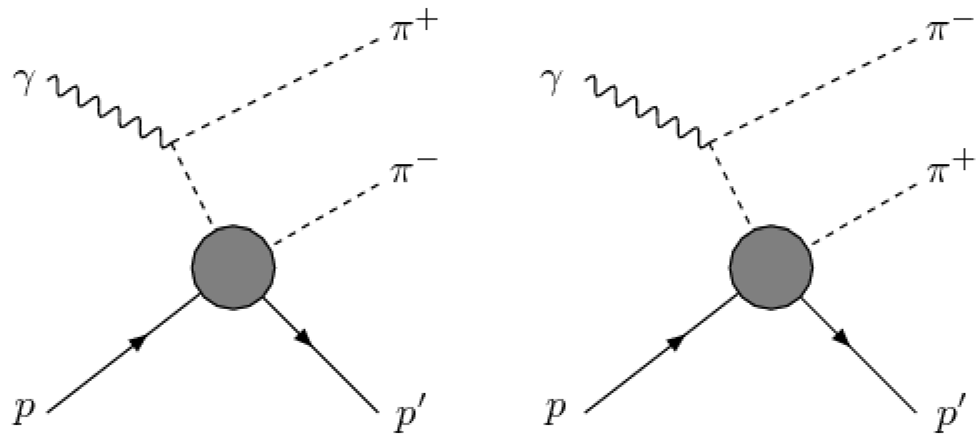
$$A_{\gamma p \to \pi\pi p} = \begin{cases} A_{res} & , M_{\pi p} \leq 2\text{GeV}, \\ A_{Regge} & , M_{\pi p} > 2\text{GeV}. \end{cases}$$

where

$$M^2_{\pi p} = m^2_{\pi} + \frac{s + m^2 - M^2_{\pi\pi}}{2} + 2|k||p'|\cos\theta$$

- $M_{p\pi}$ depends on cosθ, so partial wave projection must be done **after** matching complete amplitudes

# Deck amplitude




- **General form of the Deck amplitude** [Pumplin 1970]

$$\mathcal{M}_{\lambda_2\lambda_1} = \frac{-1}{\sqrt{4\pi}}\Big\{ e\varepsilon \cdot [\frac{\hat{\boldsymbol{\kappa}}}{|\boldsymbol{q}|}\frac{1}{x+\hat{\boldsymbol{q}}\cdot\hat{\boldsymbol{\kappa}}} + \frac{\boldsymbol{p_1}+\boldsymbol{p_2}}{q\cdot(p_1+p_2)}]{T^{+}}_{\lambda_2\lambda_1} + e\varepsilon \cdot [\frac{\hat{\boldsymbol{\kappa}}}{|\boldsymbol{q}|}\frac{1}{x-\hat{\boldsymbol{q}}\cdot\hat{\boldsymbol{\kappa}}} - \frac{\boldsymbol{p_1}+\boldsymbol{p_2}}{q\cdot(p_1+p_2)}]{T^{-}}_{\lambda_2\lambda_1}\Big\}$$

- **The amplitude is gauge invariant**

# $\gamma p \rightarrow \pi^+\pi^- p$ amplitude in high $M_{p\pi}$ limit - pomeron exchange

- Simple parametrisation of the high energy $\pi p$ scattering based on optical theorem:

$$T^{\pm}_{\lambda_1\lambda_2} = (\alpha_\pm + i)\sigma_\pm \sqrt{[s_\pm - (m+m_\pi)^2][s_\pm - (m-m_\pi)^2]}\, e^{B_\pm t/2}\theta(\pm\cos\theta)\delta_{\lambda_1\lambda_2}$$

- Denote: $\xi_\pm = (\alpha_\pm + i)\sigma_\pm exp[B_\pm t]$

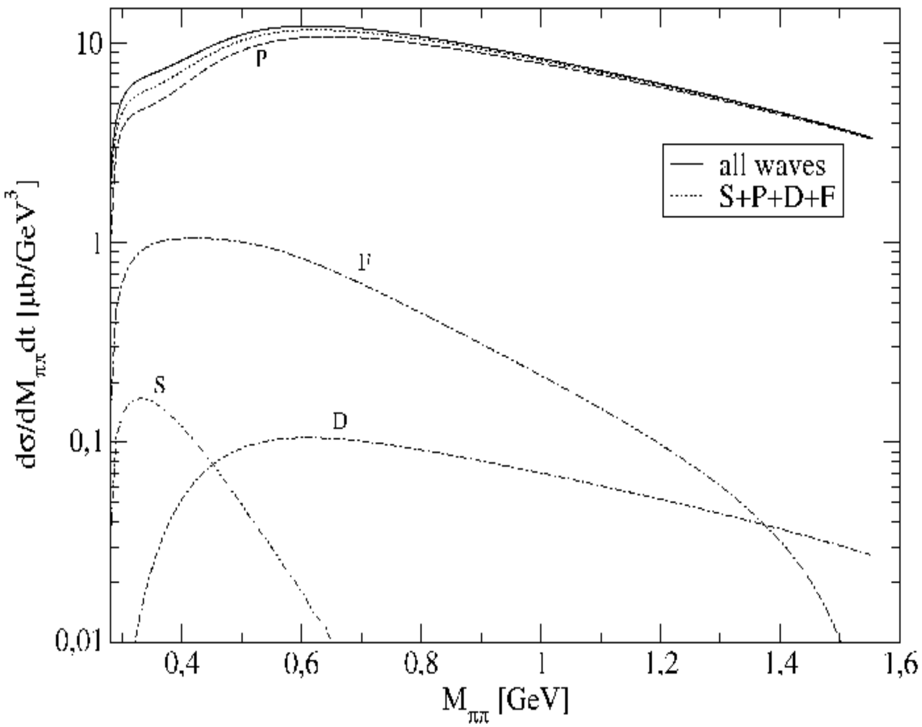
  and $h_+(\cos\theta) = \sqrt{[s_+ - (m+m_\pi)^2][s_+ - (m-m_\pi)^2]}.$

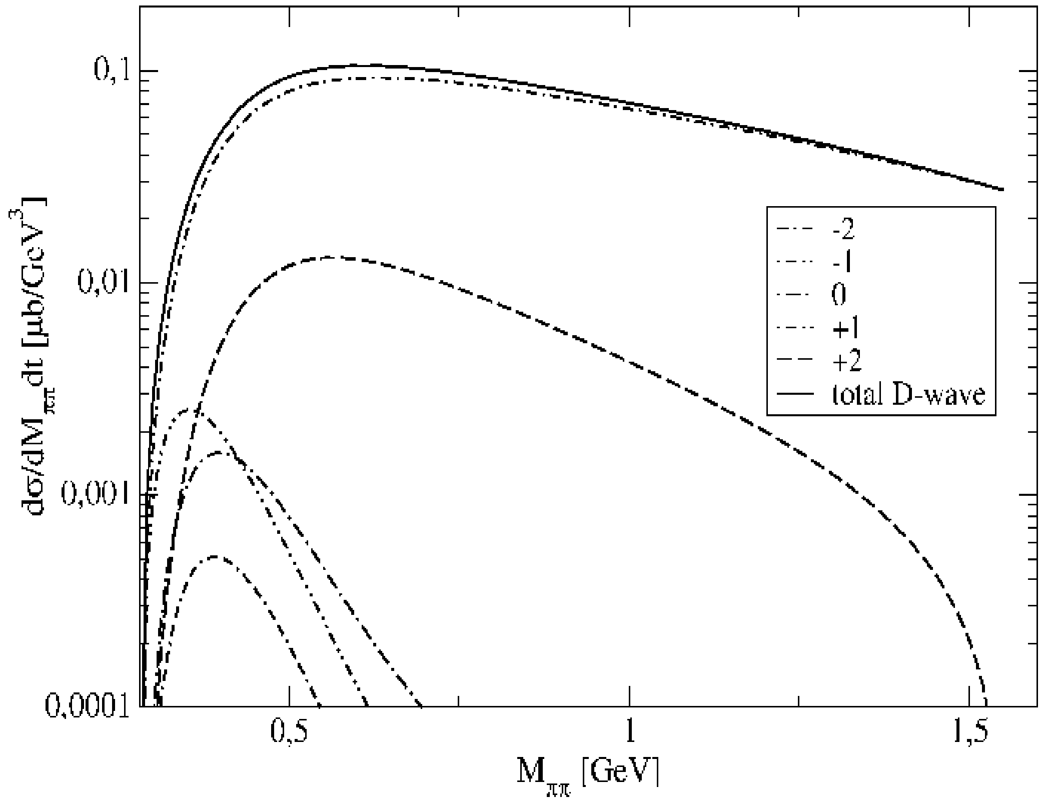
- We get the partial wave amplitude in a semi-closed form:

$$a^L_{M\,diff} = -\frac{e}{|\boldsymbol{q}|}\sqrt{\frac{4\pi}{3}}(\xi_+ - (-1)^L\xi_-)\left[\int_0^{2\pi} d\phi \int_0^{\pi} d\theta \sin\theta Y^{L\,*}_M(\theta,\phi) h_+(\cos\theta)\right.$$
$$\left.\theta(\cos\theta)\left(\frac{\sum b_m Y^1_m(\theta,\phi)}{x + \hat{\boldsymbol{q}}\cdot\hat{\boldsymbol{\kappa}}} + \sqrt{\frac{3}{4\pi}}\frac{\boldsymbol{\varepsilon}\cdot(\boldsymbol{p_1}+\boldsymbol{p_2})}{E_1 + E_2 - \hat{\boldsymbol{q}}\cdot(\boldsymbol{p_1}+\boldsymbol{p_2})}\right)\right].$$

- By Pomeranchuk theorem $\xi_+ \approx \xi_-$ for asymptotic energies, so
- Even partial waves are suppressed

# $\gamma p \to \pi^+\pi^- p$ cross sections - diffractive regime




- Mass distribution dominated by the P-wave
- Fast partial wave expansion convergence: P-wave saturates the cross section
- Even partial waves strongly suppressed

- Dominance of the partial wave with helicity of photon
- Partial waves with $\lambda > 1$ can be large

# $\gamma p \rightarrow \pi^+\pi^- p$ amplitude - resonant regime

- General form of the πp scattering amplitude (Chew, Goldberger, Low, Nambu (1957))

$$\mathcal{T}_{\alpha\beta} = \overline{u}(p_2)(A_{\alpha\beta} + \gamma \cdot Q B_{\alpha\beta}) u(p_1)$$

Where: $Q = \frac{1}{2}(q - k_1 + k_2)$ and

$$\frac{A}{4\pi} = \frac{W+m}{E+m} f_1 - \frac{W-m}{E-m} f_2,$$
$$\frac{B}{4\pi} = \frac{f_1}{E+m} + \frac{f_2}{E+m}.$$

Then the $f_1$ and $f_2$ functions are partial wave expanded (separately for I=1/2 and I=3/2):

$$f_1 = \sum_{l=0}^{\infty} f_{l+} P'_{l+1}(\cos\theta^*) - \sum_{l=2}^{\infty} f_{l-} P'_{l-1}(\cos\theta^*),$$
$$f_2 = \sum_{l=1}^{\infty} (f_{l-} - f_{l+}) P'_l(\cos\theta^*),$$

There are a few experimental/phenomenological analyses in order to fit data to this expansion: Bonn-Gatchina, MAID, SAID.

# $\gamma p \to \pi^+\pi^- p$ amplitude - resonant regime

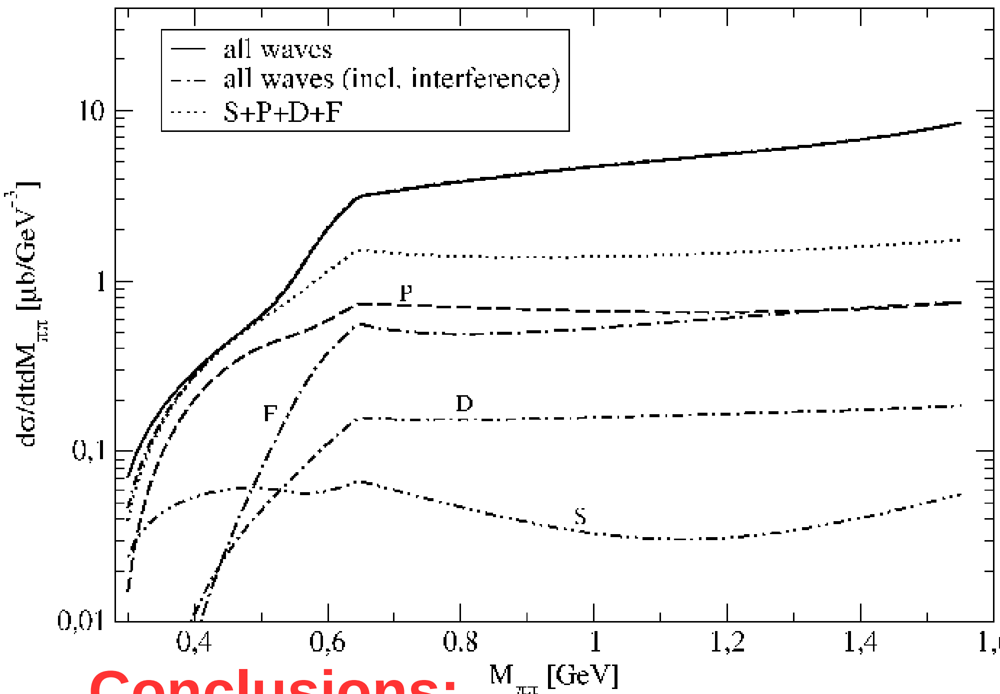
- Our idea was to get partial waves in terms of the phase shifts and inealisticities and then:

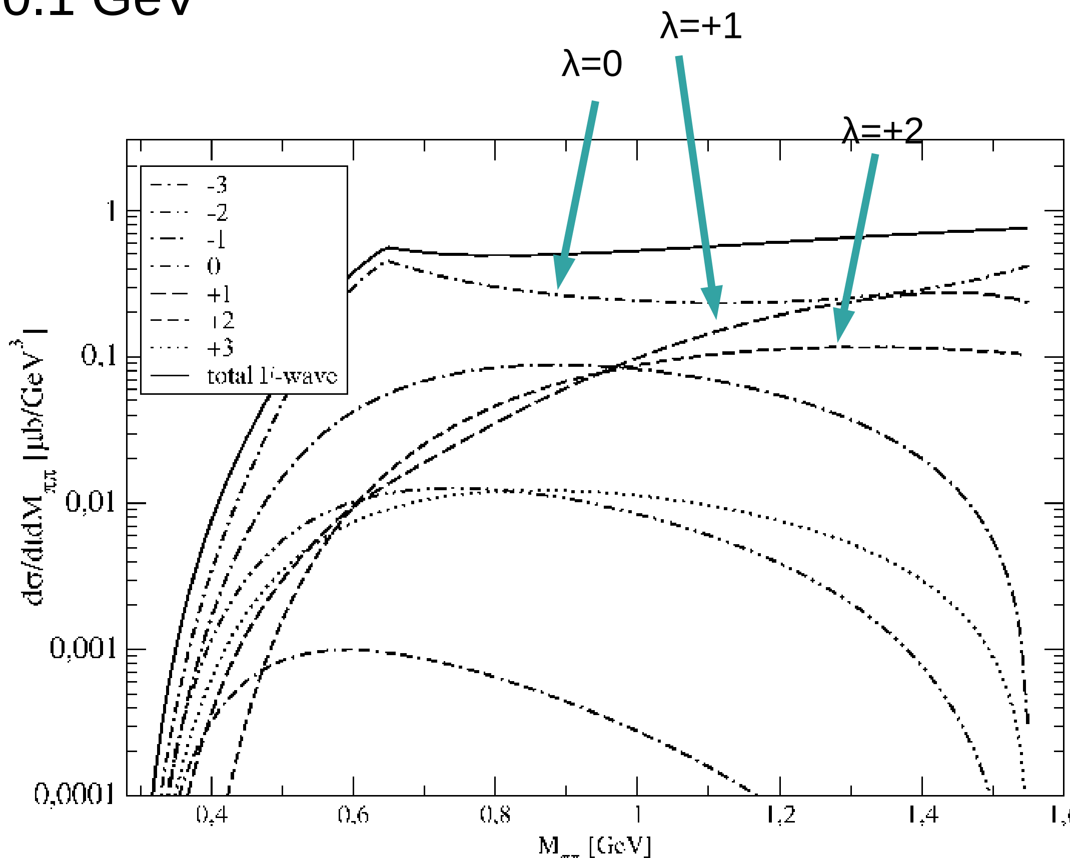
0. Take the SAID phase shifts and inelasticities and produce partial wave amplitudes

1. Reconstruct the (Lorentz invariant) $\pi p$ scattering amplitude in the resonance region
2. Embed the $\pi p$ amplitude into $\gamma p \to \pi^+\pi^- p$
3. Rewrite it in the $\pi^+\pi^-$ rest system
4. Make a partial wave expansion of the $\pi^+\pi^-$ photoproduction amplitude

# γp → π⁺π⁻p cross sections- resonant regime

Some results at $E_\gamma$=3.5 GeV and -t=0.1 GeV$^2$




**Conclusions:**

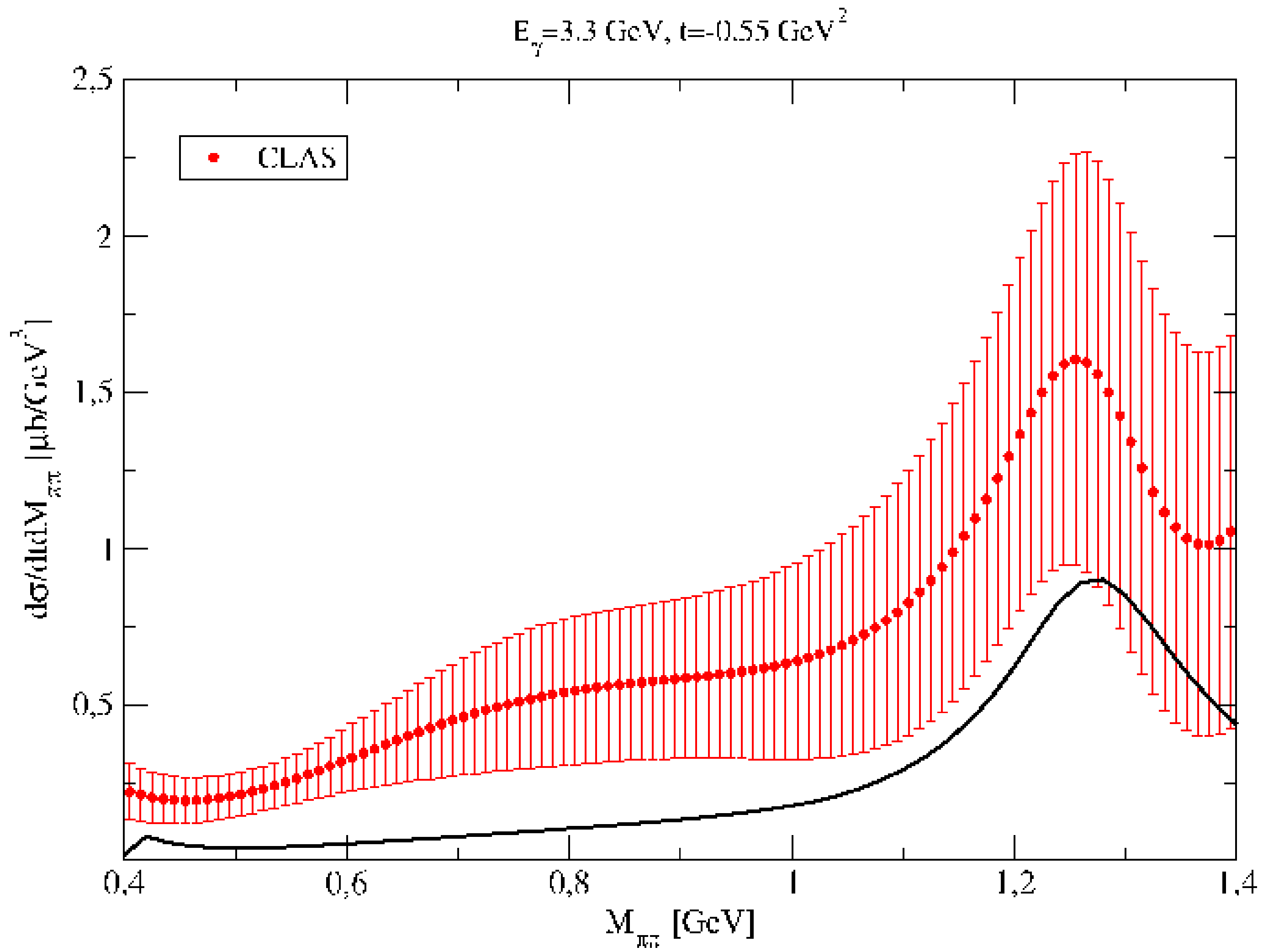
- Slow partial wave expansion convergence; S+P+D+F waves correspond to ~50% of the cross section
- Even partial waves suppressed
- One cannot neglect partial waves with large m's (like +2) – they can induce strong interferences with the ππ resonance signal
- Only taking these interferences into account one can reasonably describe individual partial waves <=> understand the behavior of the spherical harmonic moments and spin density matrix.

# Final state interactions

- To describe the final state $\pi\pi$ interaction we use the dispersive model of the $\pi\pi$ scattering in S, P, D and F waves by Bydzovsky, R. Kamiński and Nazari

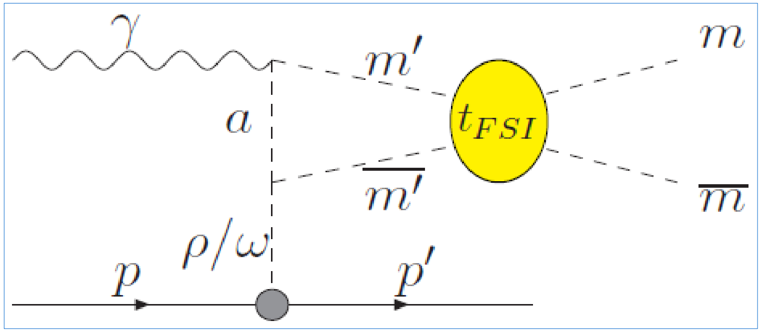
(see R.K. talk at this workshop)

# Resonant mass distribution

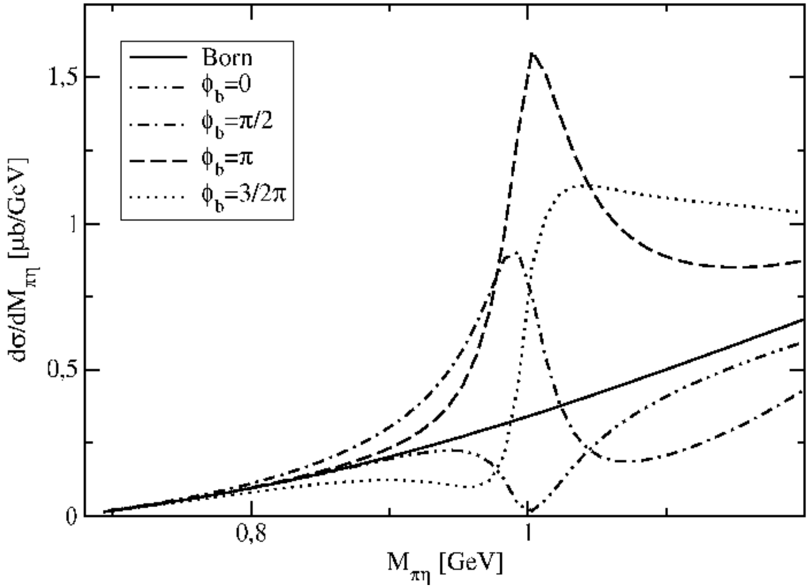


# Deck vs. reggeized t-channel production

- If the resonant final state were photoproduced through the reggeized t-channel exchange




- … then we must include additional phase in order to get resonance maximum instead of minimum



# Summary:

- Deck amplitudes with final state $\pi\pi$ interactions seem to be the main contribution to the resonant D-wave photoproduction, with $f_2(1270)$ signal clearly observable
- (Without any fits) we get the proper resonance line shape and mass distribution very close that measured by CLAS
- One can think about using this approach for description of $K\bar{K}$ and $\pi\eta$ photoproduction but the dominant left hand cut contributions arise then from kaon and $\rho/\omega$ exchange which are more distant from the physical region