Photoproduction of light-quark resonances through one-pion exchange

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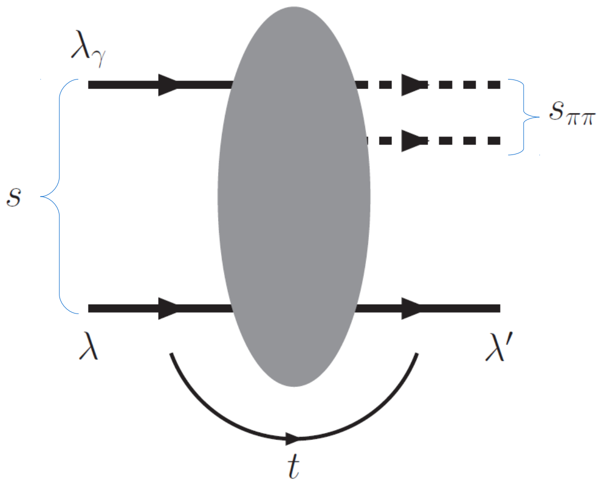
Motivation of studying the ππ photoproduction

- ππ is the simplest (spinless particles, amplitudes highly constrained by crossing symmetry) but feature reach two meson system
- It is a laboratory of methods which can be applied in more complex systems, ie. containing a few mesons or spinning mesons
- 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
- The model discussed here can be "easily" applied to eg. $\gamma p \rightarrow K^+ K^- p$

General description of the 3-particle production



The system is described in terms of 5 kinematic variables:

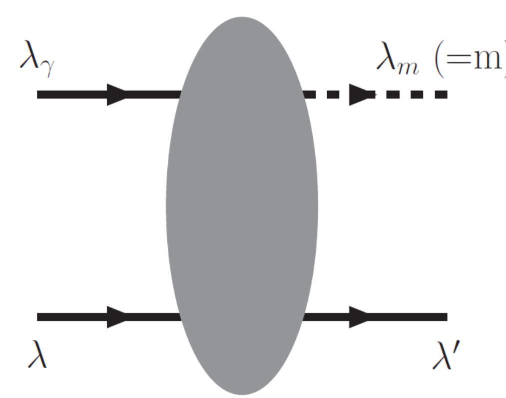
- 3 Lorentz invariants – *s*, $s_{\pi\pi}$, *t*
- φ, θ – angles, which describe the outgoing pions direction (in their CM system), with respect to z-axis directed opposite to the recoil proton momentum (helicity system)
- and 3 spins

Assume that we analyze the system with the following properties:

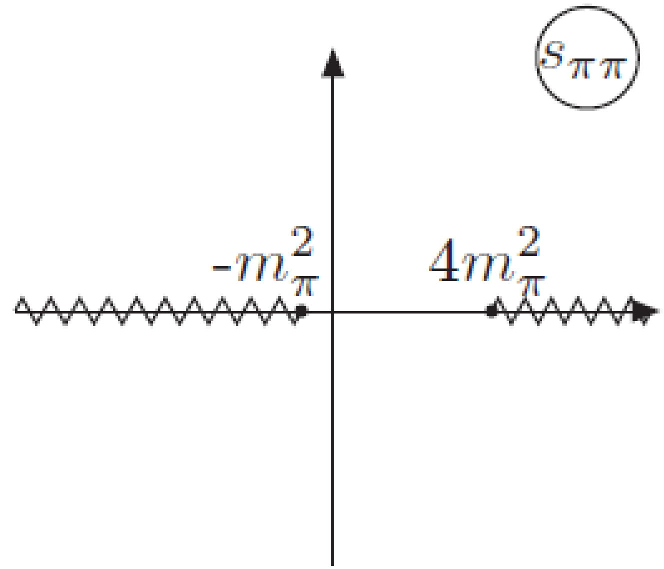
- Total CM energy $\sqrt{s}$ is “large” (~10 GeV)
- Effective mass $\sqrt{s_{\pi\pi}}$ is low – so partial wave expansion of the amplitude is valid

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

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



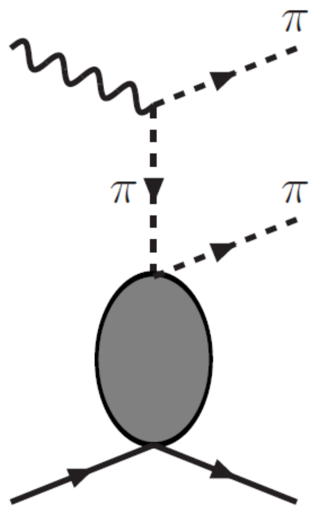
Now assume that (approximate) analytical structure of $a(s_{\pi\pi})$ is the following:



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) 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 left hand cut nearest to the physical region is due to 1-pion exchange
- So schematically we write:

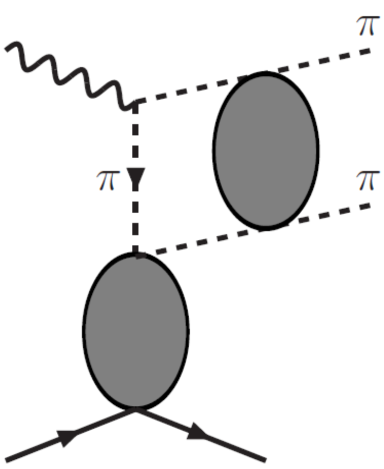
$a_L(s_{\pi\pi}) \approx$



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

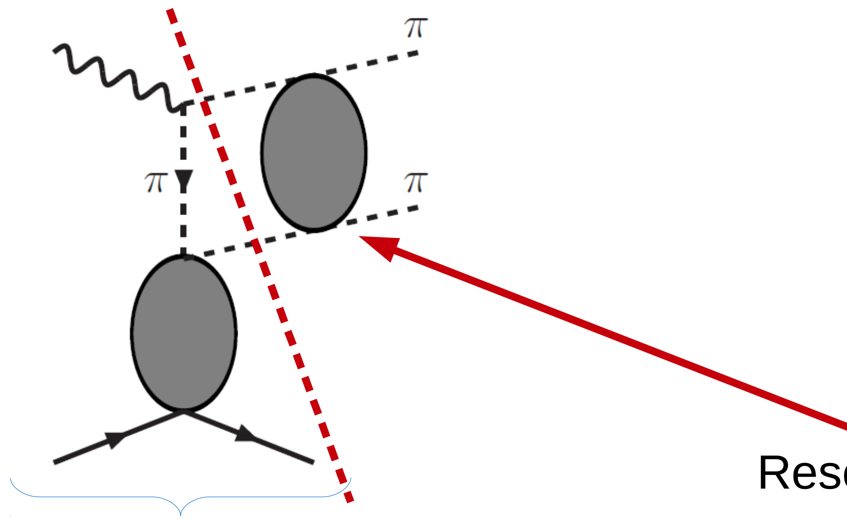
$\pi p \to \pi p$ elastic amplitude we need to parametrize (we use the SAID parametrization)

- Where are meson resonances ?
- Meson resonances arise due to final state interaction
- In principle such amplitude can be calculated by **solving** the 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



$$A_{\pi\pi} = V_{\pi\pi} + \langle \pi\pi | \hat{t}_{FSI} | m'n' \rangle G_{m'n'}(\kappa') V_{m'n'}$$

or in integral form

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

where:

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

$V_{\pi\pi}$ - initial state amplitude,

t_{FSI} -rescattering amplitude

Approximations used and limitations of the model

- In the present form of the model we take into account only the on shell part of the amplitude
- We use single ($\pi^+\pi^-$) channel approach – in particular we neglect the coupling to the $K\bar{K}$ channel (this is well justified for the D-wave, see below for details)
- So, the amplitudes used in actual calculations read:

$$T^{LM}_{\lambda\lambda_1\lambda_2} = (1 + i r_\pi (\frac{2}{3} T^L_0 + \frac{1}{3} T^L_2)) M^{LM}_{\lambda\lambda_1\lambda_2}$$

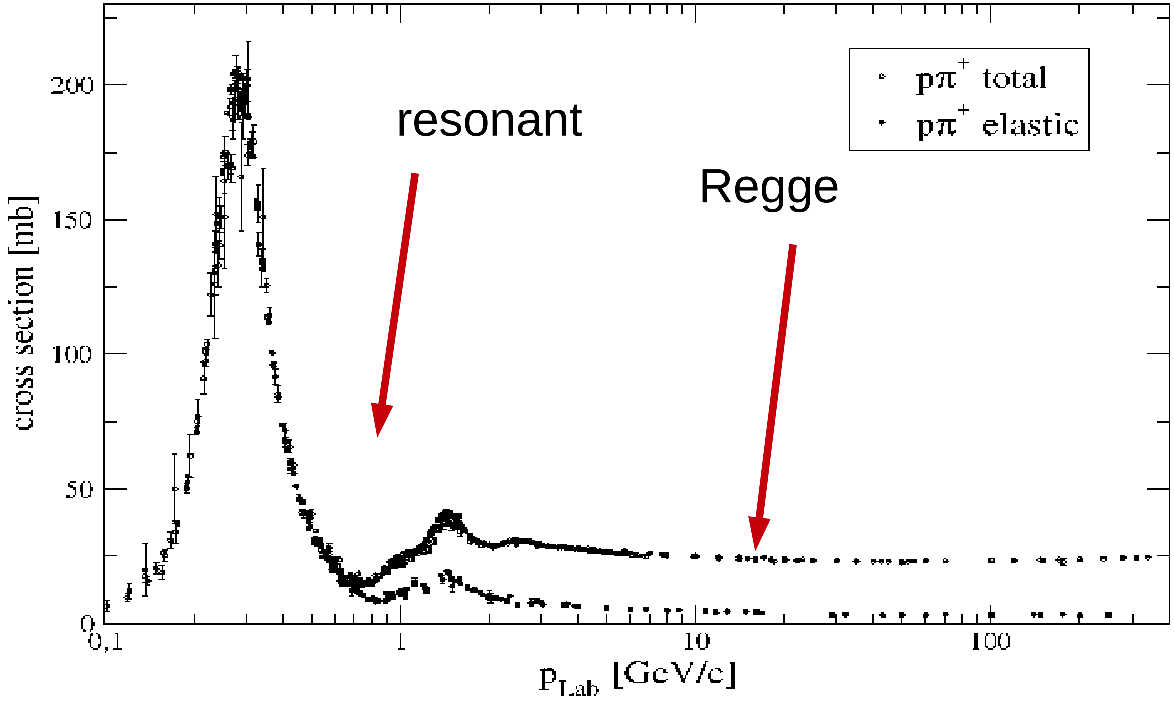
$$T^{LM}_{\lambda\lambda_1\lambda_2} = (1 + i r_\pi T^L_1) M^{LM}_{\lambda\lambda_1\lambda_2}$$

for even and odd partial waves respectively.

- We do not try to calculate the P-wave amplitude which is dominated by **diffractive** ρ photoproduction
- There is the undetermined relative phase between the Deck amplitude and FSI amplitude which we fix by introducing one parameter -this is the **only** parameter in the model !

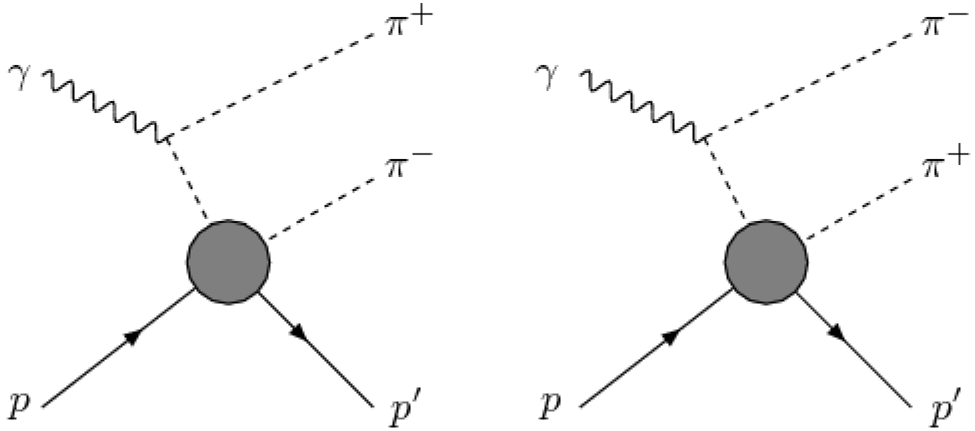
Dipion photoproduction at upgraded JLab energies

- 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 is just enough for low photon energies but at E_γ~10 GeV we will need the $\pi p \to \pi p$ amplitude parametrisation for $M_{p\pi}$>2 GeV



- In what follows the model will be compared with CLAS data taken at E_γ=3.3 GeV (max $M_{\pi p}$≈2 GeV)
- This region is entirely covered by SAID parametrisation so that we don’t need the Regge extrapolation

Drell amplitude



- **General form of the 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**

πp → πp amplitude – partial wave expansion

- 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

- **Our recipe:**

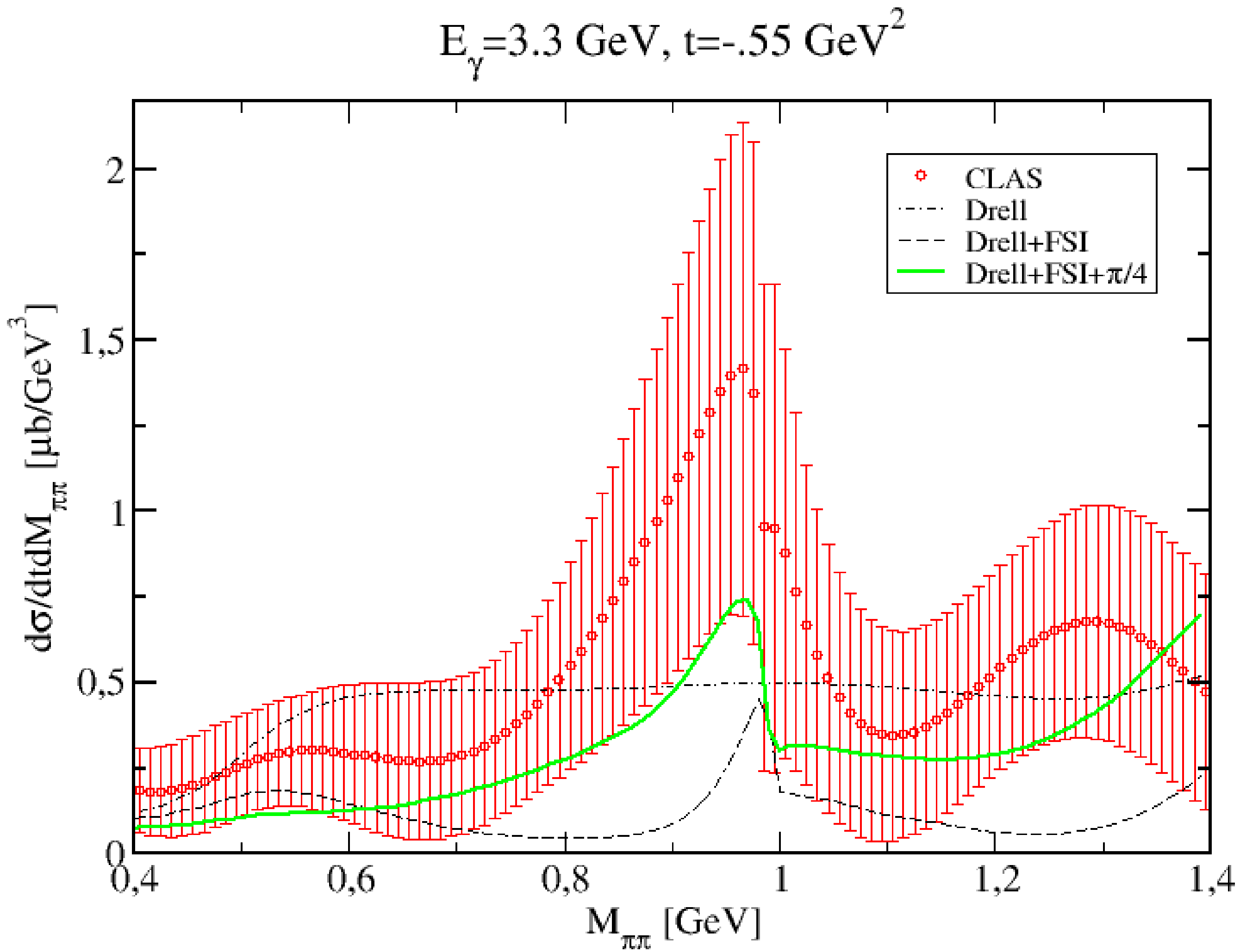
0. Take the SAID parametrisation of the πp ampitudes defined in terms of phase shifts and inelasticities and produce partial wave amplitudes
1. Reconstruct the (Lorentz invariant) πp scattering amplitude in the resonance region
2. Embed the πp amplitude into (Lorentz invariant) $\gamma p \to \pi^+\pi^- p$ amplitude
3. Rewrite it in the $\pi^+\pi^-$ rest system
4. Make a partial wave expansion of the $\pi^+\pi^-$ photoproduction amplitude

Final state interactions

- To describe the final state ππ interaction we use the dispersive model of the ππ scattering in the S, D and F waves by Bydzovsky, R. Kamiński and Nazari (Phys.Rev. D94 (2016) 11601)

Results

S-wave

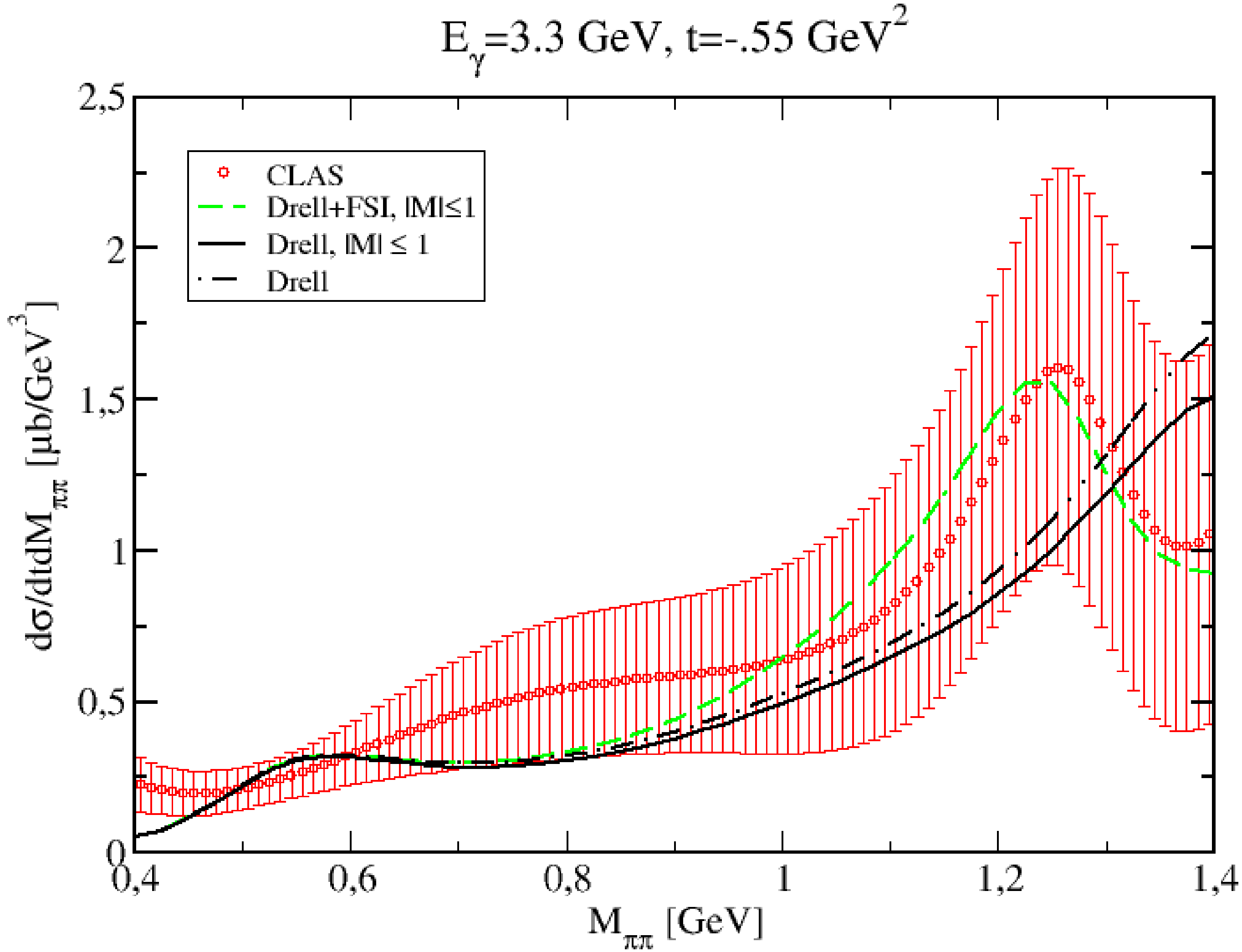


Notice:

- Very good distribution description already at the level of Drell amplitudes
- Clear $f_0(980)$ resonance contribution
- Correction relative phase of π/4 needed to get the proper distribution behavior

- Otherwise the Drell-FSI interference is destructive and the theoretical distribution is to small
- Indication of the influence of the coupled $K\bar{K}$ channel above 1 GeV

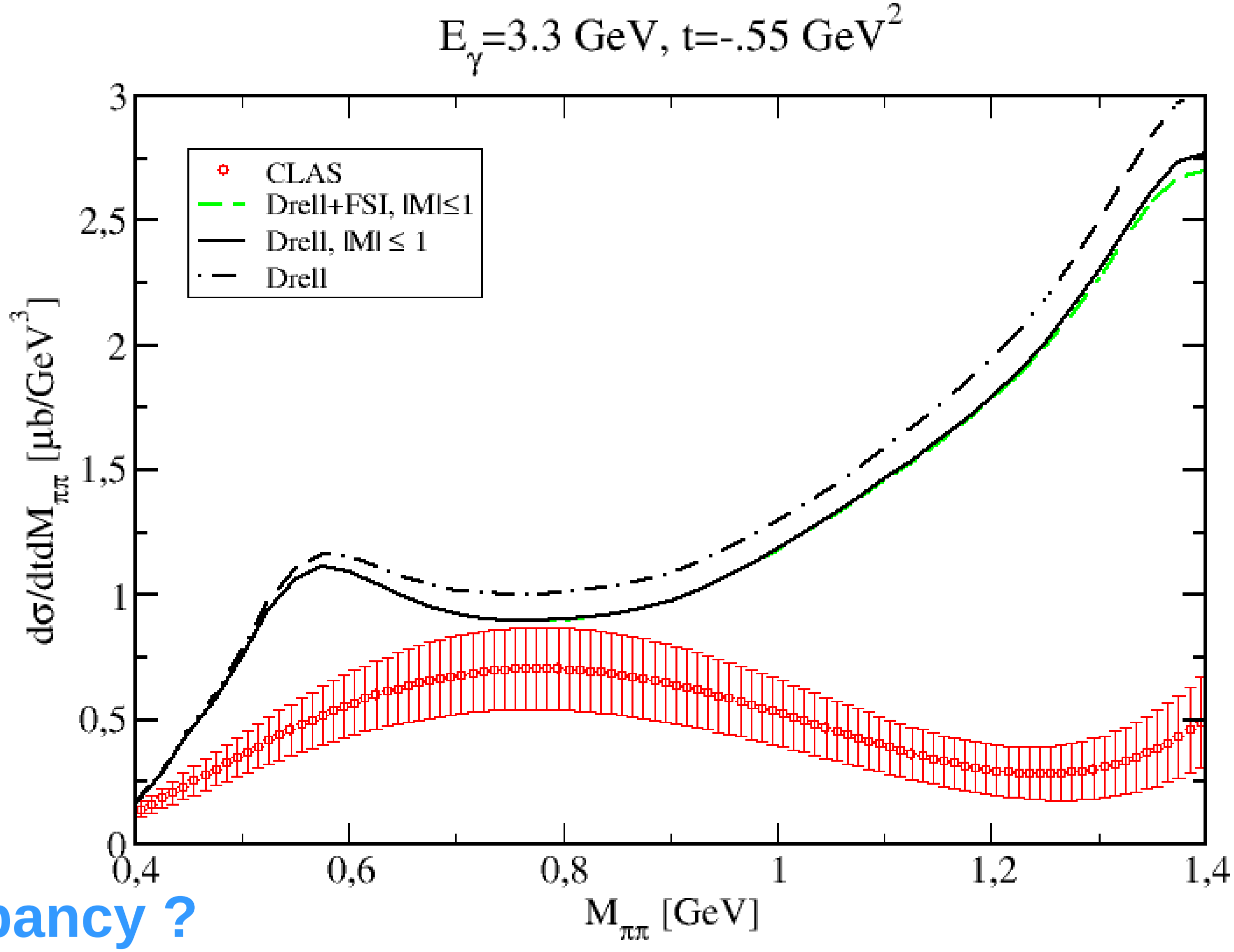
D-wave



Notice:

- Very good distribution description already at the level of Drell amplitudes
- Clear $f_2(1270)$ resonance contribution
- Correction relative phase of π/2 needed to get the proper distribution behavior
- Small contribution of helicities M=+/- 2
- No indication of the influence of the coupled $K\bar{K}$ channel – quite understandable, $f_2(1270)$ decays to $K\bar{K}$ only in <5% (84% to ππ)
- No additional background needed to describe the data

F-wave



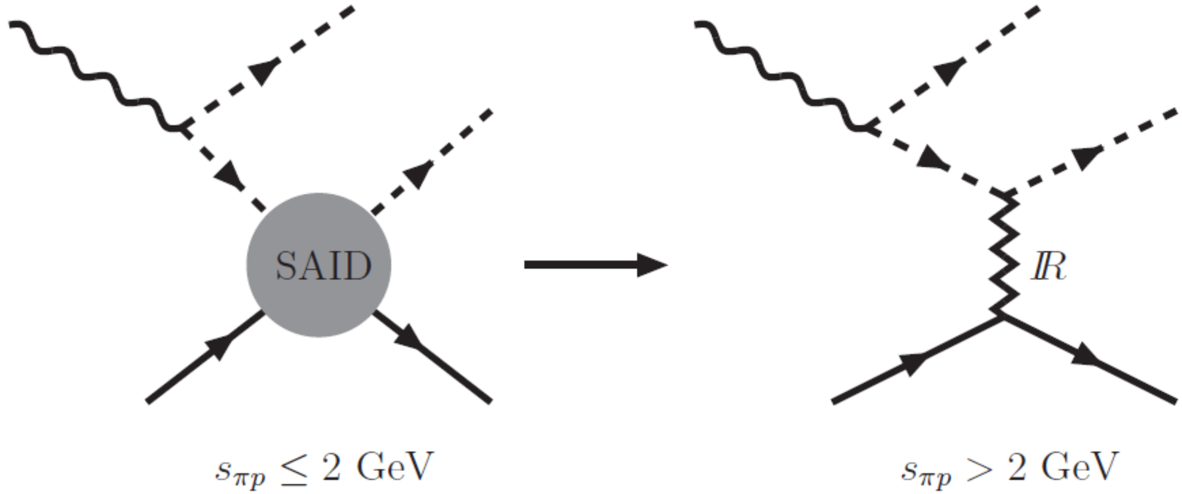
Notice:

- Model prediction is to large in almost whole mass interval
- Helicitities |M|>1 bring small contribution to the distribution
- No indication of the FSI

Can we explain the discrepancy ?

- The F-wave FSI model we use, is almost ππ elastic up to $M_{\pi\pi}$=1.5 GeV. This may be disputed given that there are many isovector channels already opened below this energy, eg. ππππ, πω, $K\bar{K}$.
- The dominant F-wave resonance ρ_3(1690) decays to ππ only in <24% while it mostly (71%) decays to ππππ/πω channel – we may expect large interchannel coupling and destructictive interference
- Higher partial waves may be affected by vector meson exchange amplitudes which may destructively interfere with one-pion-exchange amplitudes

- For $M_{\rho\pi}$>2 GeV, where SAID amplitudes are not applicable the Regge extrapolation must be used



- We take into account the ρ, ω and pomeron trajectories

- Matching procedure is used at $M_{\rho\pi}$=2 GeV so that

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

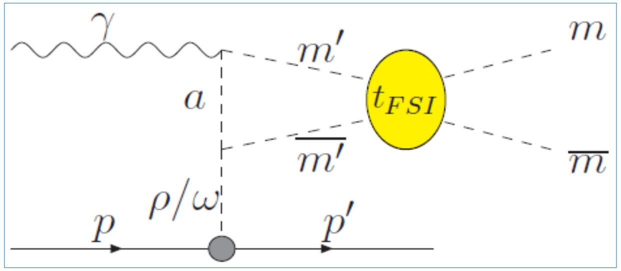
where

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

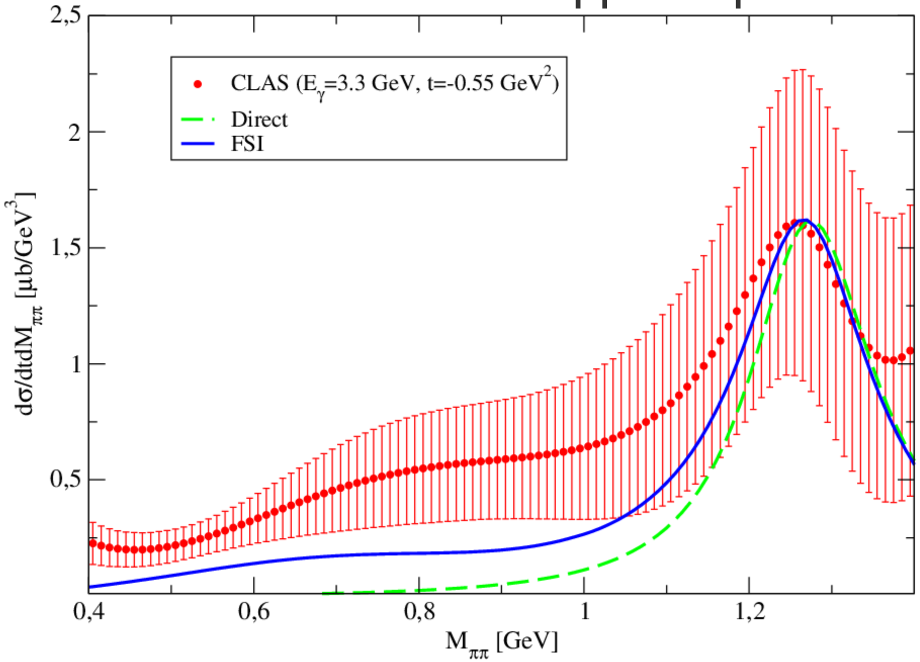
- $M_{\rho\pi}$ depends on cosθ, so partial wave projection must be done **after** matching complete amplitudes

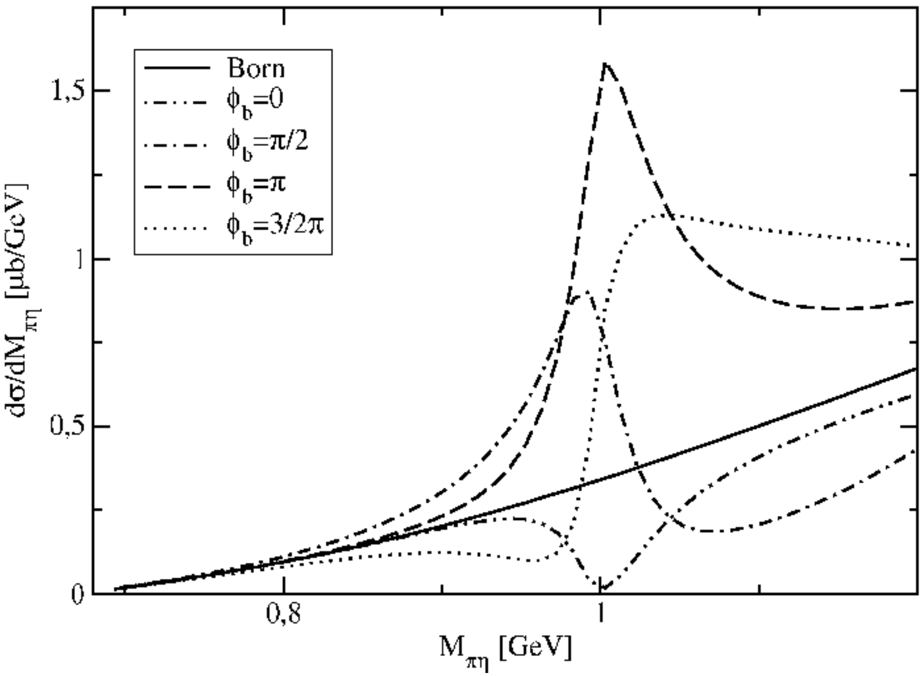
Reggeized t-channel amplitude

- Reggeized t-channel photoproduction amplitude can be treated as the high M_{mp} approximation of the Drell/Deck amplitude



- With this approximation we described the D-wave π+π- photoproduction and the S-wave πη photoproduction





- Distributions obtained from these amplitudes lack absolute normalisation, so either must be fitted or amplitudes must be matched to low energy ones.

Summary:

- Drell amplitudes with the final state ππ interaction give a very good description of the S- and D-wave photoproduction from the ππ threshold up to the resonanace region (f_0(980) and f_2(1270) respectively)
- Some qualitative deviation in the S-wave mass distribution may be attributed to influence of the as yet neglected the $K\bar{K}$ channel
- The discrepancy observed in the F-wave may be attributed to:
  - Neglected coupled channels ($K\bar{K}$, ππππ)
  - Vector (or tensor) exchanges which may strongly affect the higher partial waves
- Whether it is really the case is a matter of our further studies

Challenges:

- Unified description of πp in the resonance and Regge regions (Szczepaniak et al. Phys.Rev. D92 (2015) 074004) to be embedded in the photoproduction amplitude
- Inclusion of the important coupled channels (most notably $K\bar{K}$) – this entails the necessity to properly parametrize the pK^- and pK^+ elastic scattering amplitude up to $M_{Kp}\approx 10$ GeV – the isospin partial wave amplitude is the combination of these charge amplitudes
- Inclusion of the effects of the off-shell propagation of intermediate meson pair
- Quantifying the admixture of competing mechanisms, eg. vector meson exchange by computing beam asymmetry and comparison with data.

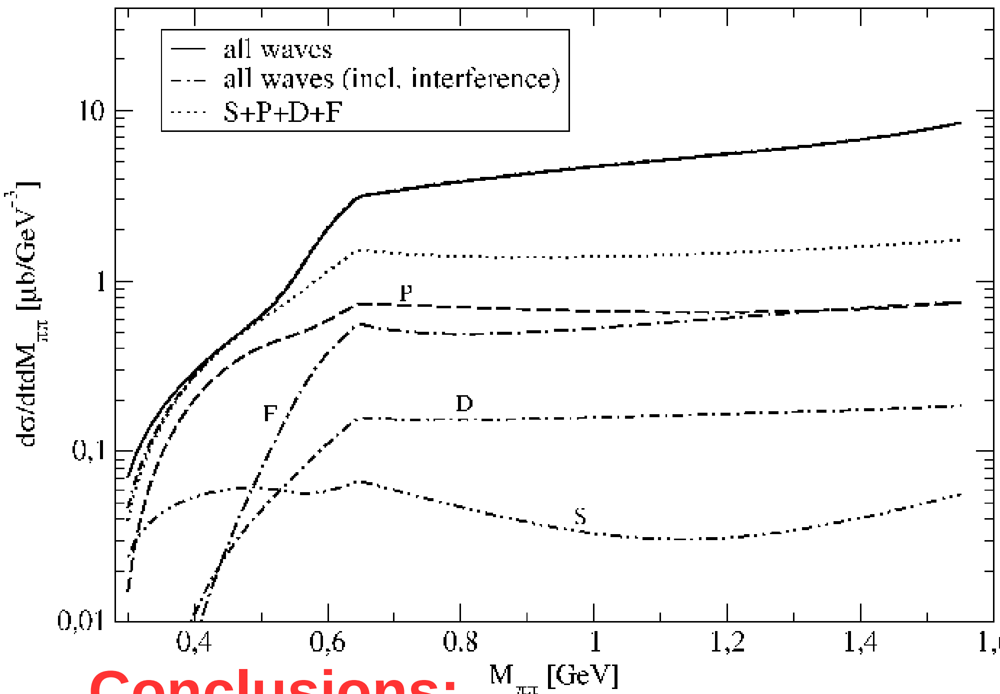
We await new CLAS12 and GlueX data.

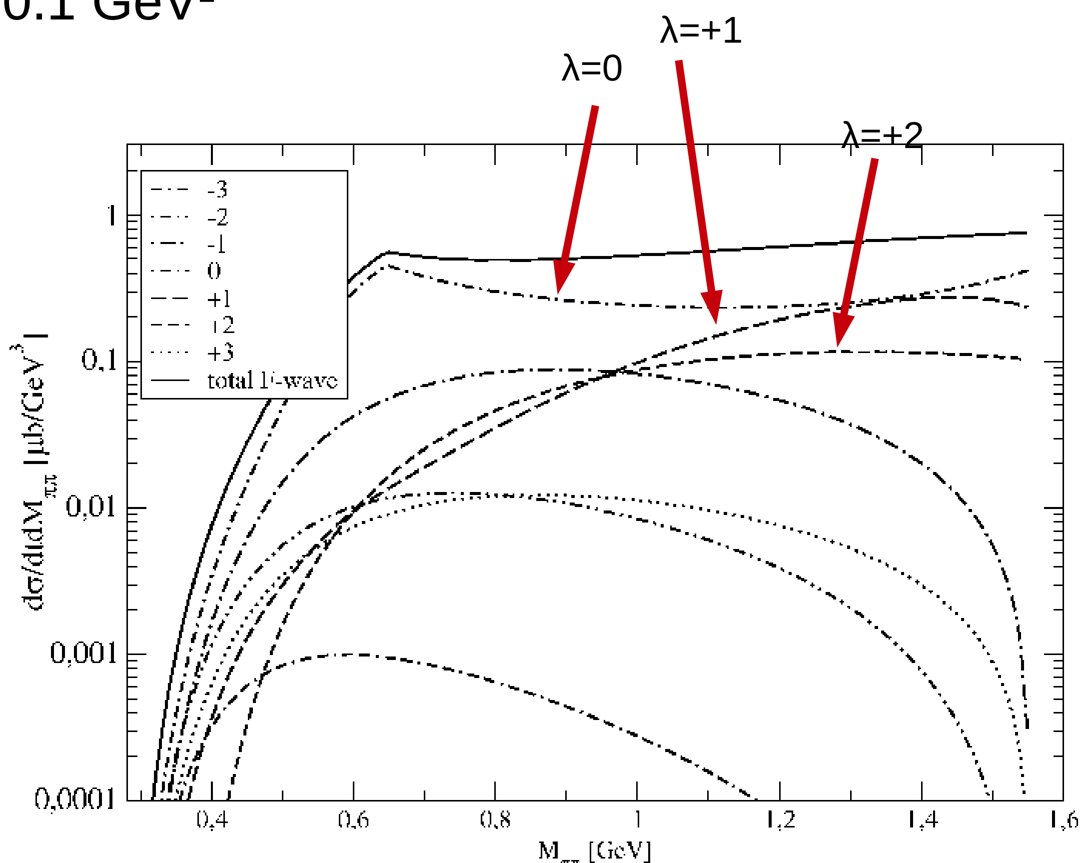
Thank you for your attention.

Back up slide

γp → $\pi^+\pi^-$p cross sections- resonant regime

Some results at E_γ=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.