Photoproduction of resonances from compact and spatially extended sources

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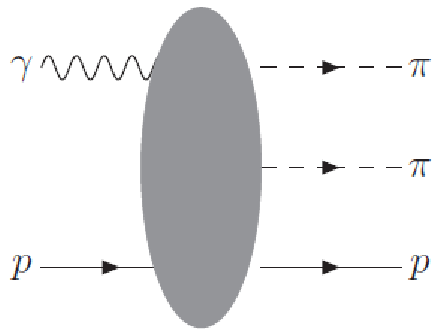
Motivation for studying meson resonances in the π+π- photoproduction

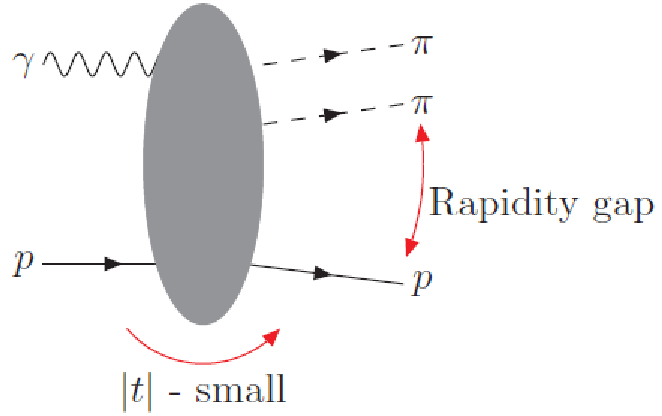
- Understanding the spectrum of resonances is directly related to fundamental features of the QCD like confinement
- Photoproduced meson systems are more likely (than eg. pion-produced) to carry exotic quantum numbers
- Reliable models are badly needed to describe the wealth of the resonance photoproduction data to be expected in near future from JLab, ELSA, MAMI, and SPring-8 experiments
- Polarized photon beams at CLAS12 and GlueX experiments allow for detailed study of production mechanisms by comparing model predictions with polarization asymmetries
- Embedding known information on πp PWA (SAID, MAID, others) in photoproduction analyses
- Immediate objective: describe the CLAS data which for a time being include the observation of the $f_0(980)$ in photoproduction

Kinematics of interest

- Out of all 3-body final states

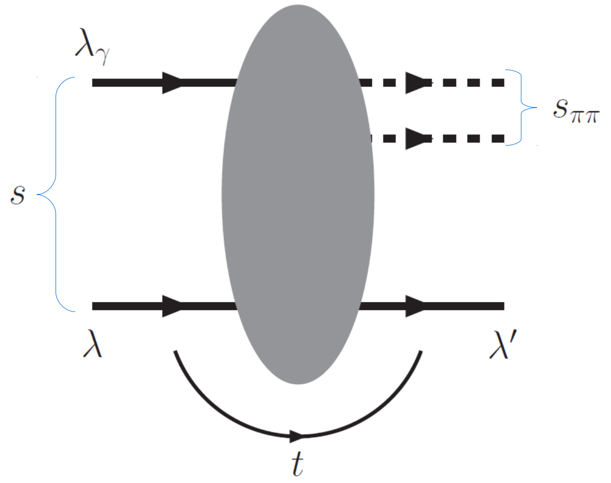


- … we are interested in those with small momentum transfer from target to recoil proton



- Such kinematics favors the production of resonances in ππ system

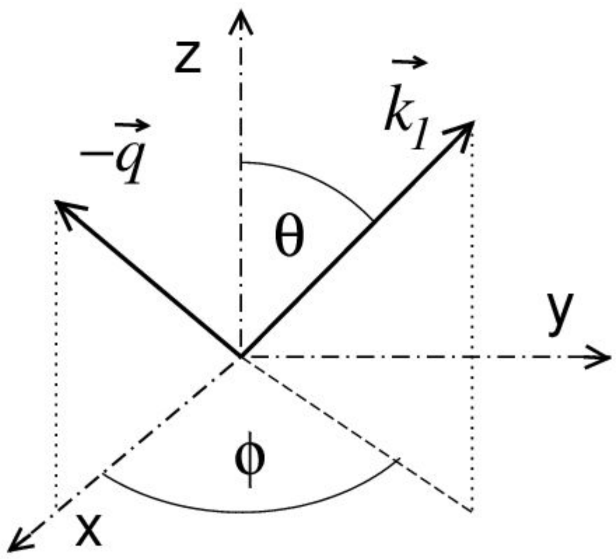
General description of the 3-particle production



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

Definition of the frame of reference



$\hat{z}$ is opposite to recoil proton momentum

$\hat{y}$ is perpendicular to production plane

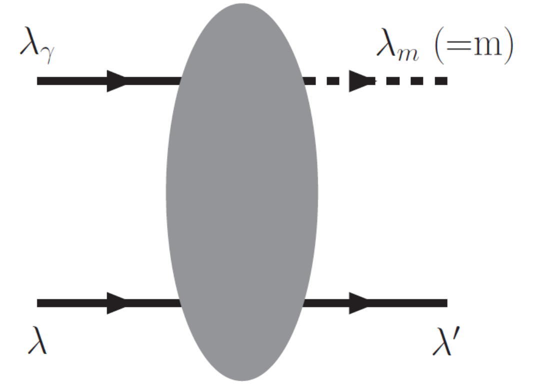
$$\hat{x} = \hat{y} \times \hat{z}$$

Assume that we analyze the ππ system with the following properties:

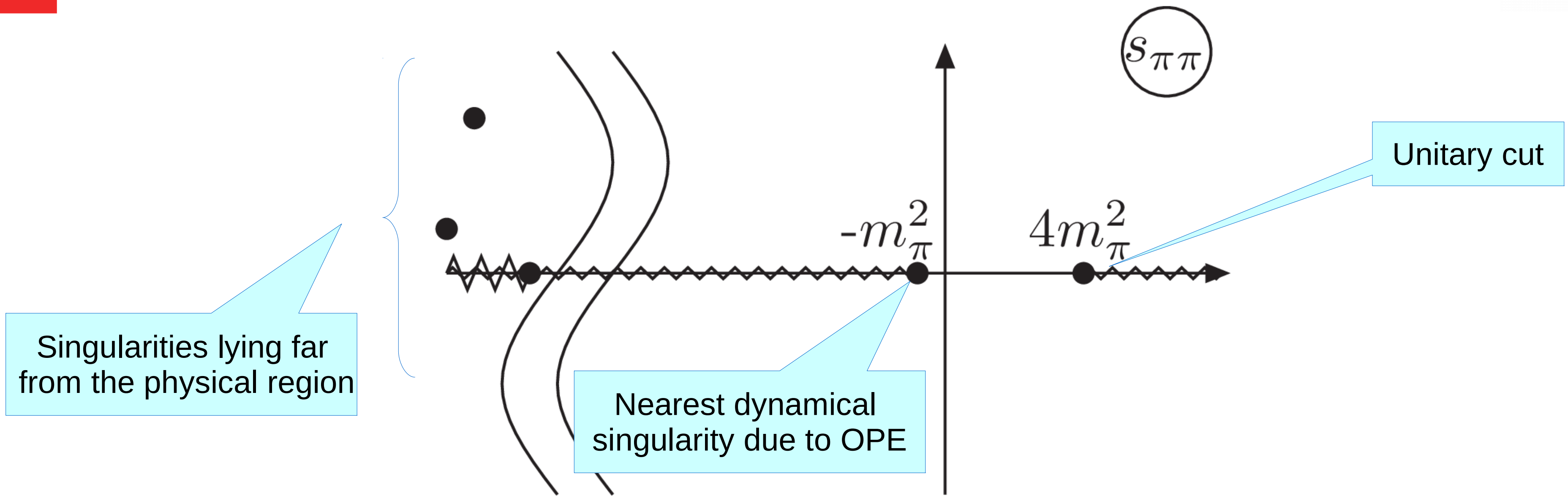
- Total CM energy $\sqrt{s}$ is “large” (~10 GeV)
- Effective mass $\sqrt{s_{\pi\pi}}$ is low – so that partial wave expansion of the amplitude is valid

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

- 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. $a_{lm}(s, s_{\pi\pi}, t) = a(s_{\pi\pi})$



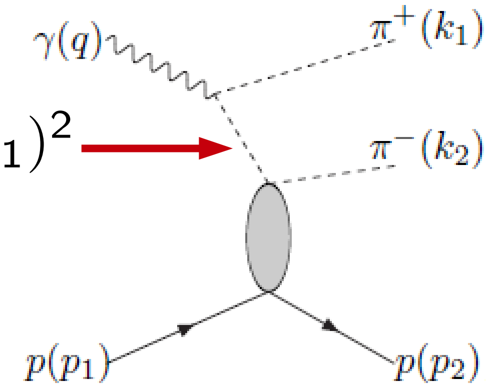
Assume the (approximate) analytical structure of $a(s_{\pi\pi})$:



1. Right hand cut of $a(s_{\pi\pi})$ is determined by unitarity (we neglect coupled channels)
2. Nearest left hand cut is due to one pion exchange and can be calculated explicitly – Deck amplitude
3. Far away singularities cannot be computed explicitly but can be reliably parameterized, eg. by low degree polynomials in $s_{\pi\pi}$

Diffuse vs compact production source

$t_1 = (q - k_1)^2$



t-channel exchange propagator	Fourier transform of propagator
$1/(t_1 - m^2)$	$\sim \frac{e^{-mr}}{r}$

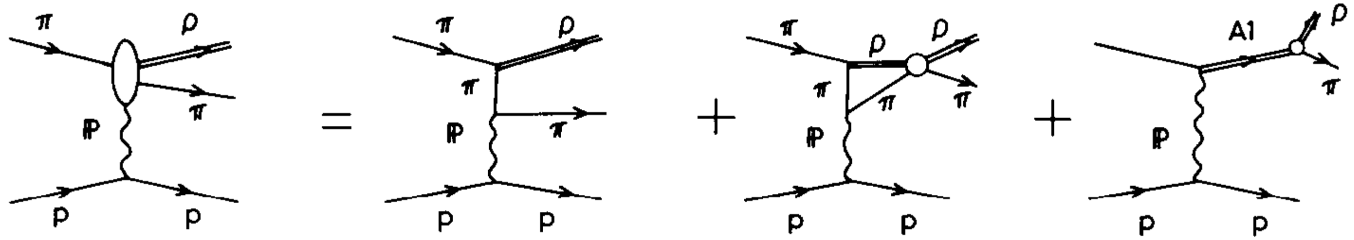
- Photoproduction of a meson pair through the exchange of:
  - Light particle (or near singularity) <==>diffuse production region
  - Heavy particle (or distant singularity)<==>compact production region
- General form of the amplitude compatible with unitarity (Aitchinson, Bowler 1978) :

$$M = M_{diffuse} e^{i\delta_{\pi\pi}} \cos\delta_{\pi\pi} + M_{compact} e^{i\delta_{\pi\pi}} \sin\delta_{\pi\pi}$$

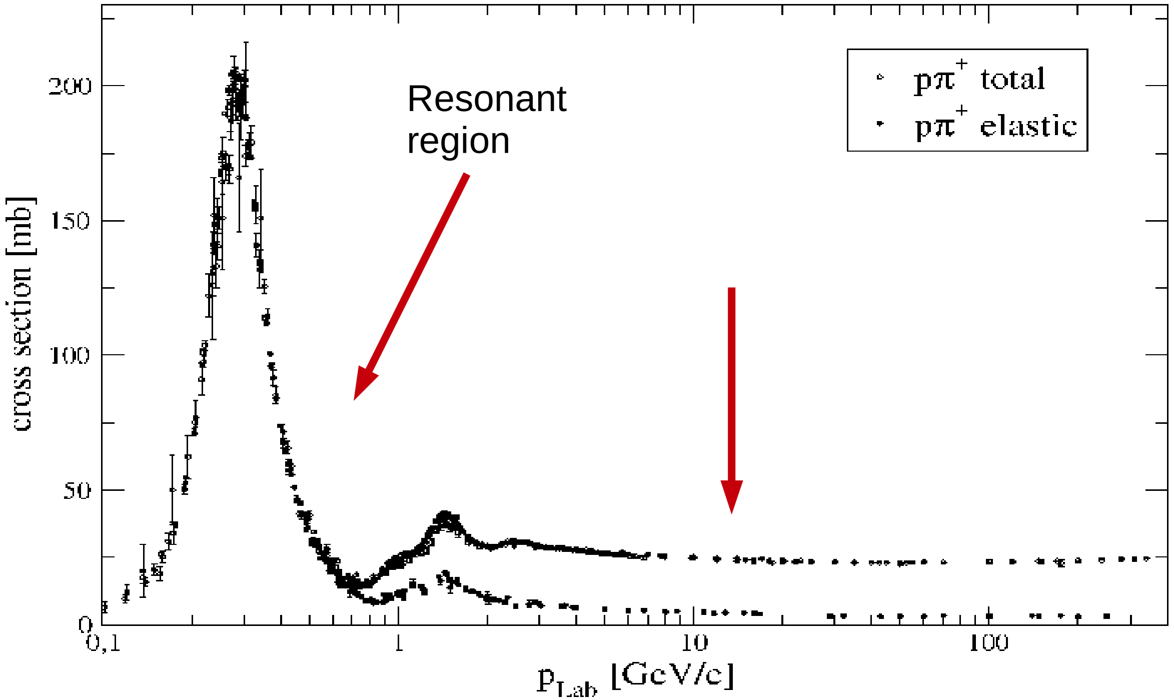
where:
$M_{diffuse}$ – one pion exchange (Deck) amplitude component
$M_{compact}$ – compact source component parameterized as: $A+B\,s_{\pi\pi}$

Generalization of the Deck amplitude

In its original form Deck model assumed diffractive πp interaction (or diffractive photon dissociation)



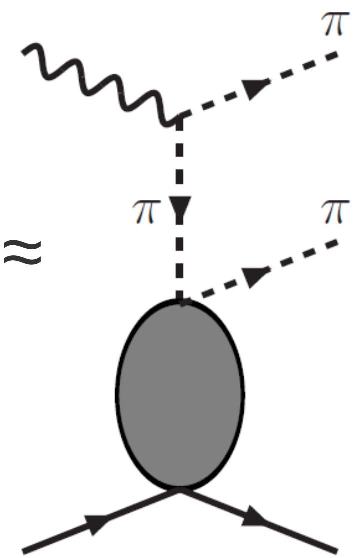
Real experiments, however, cover both diffractive and resonant regimes of πp scattering



Generalization of the Deck amplitude

… so we generalized the Deck amplitude by using SAID partial wave amplitudes which cover both the resonant and diffractive regions up to πp energy of 2.8 GeV

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

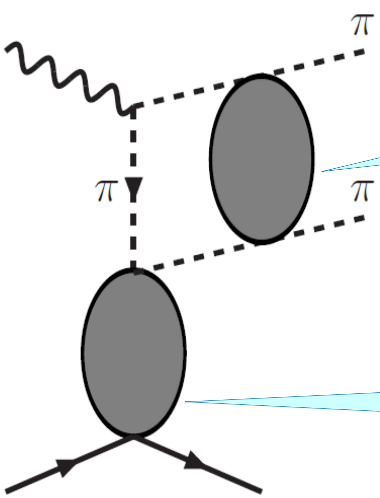


Part of the amplitude dominated by the nearest left hand cut singularity – pion exchange

SAID parametrization of the elastic $\pi p \to \pi p$ amplitude

Important: Such Deck amplitude is basically parameter free !

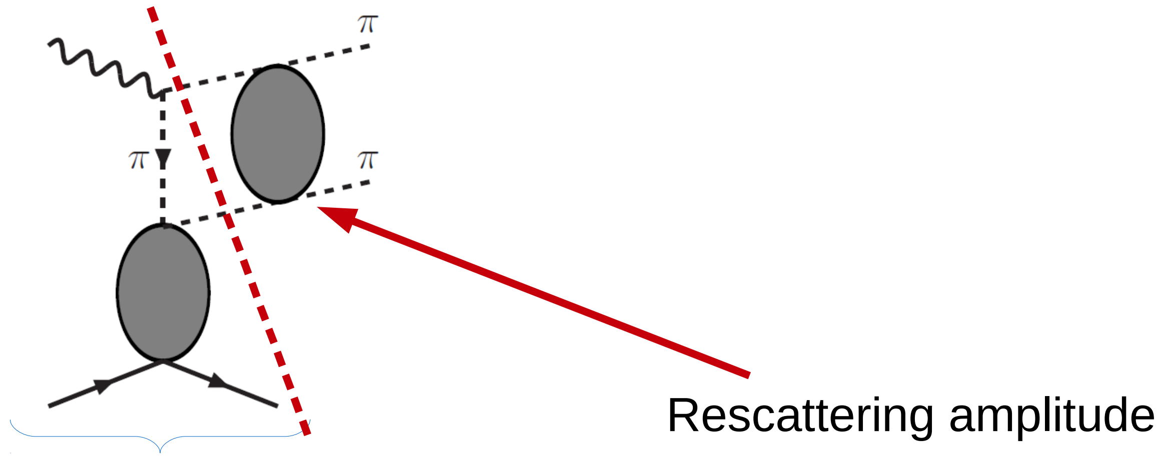
Rescattering efects or meson resonances produced in the final state



ππ FSI parametrized using dispersion amplitudes by Bydzovsky et al. (Phys.Rev. D94 (2016) 11601)

πp diffraction *and* I=1/2 and I=3/2 baryon resonances N* and Δ are encoded in SAID amplitudes

Translating diagrams into amplitude structure



Initial state amplitude (Deck type amplitude)

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

or in the explicit, partial wave projected form

$$\mathcal{T}^{lm}_{\pi^+\pi^-}(\lambda_2\,\lambda\,\lambda_1) = \left[1 + i\rho\left(\frac{2}{3}t^0_l + \frac{1}{3}t^2_l\right)\right]\mathcal{M}^{lm}_{\pi^+\pi^-}(\lambda_2\,\lambda\,\lambda_1)$$ -even partial waves

$$\mathcal{T}^{lm}_{\pi^+\pi^-}(\lambda_2\,\lambda\,\lambda_1) = \left[1 + i\rho\, t^1_l\right]\mathcal{M}^{lm}_{\pi^+\pi^-}(\lambda_2\,\lambda\,\lambda_1).$$ -odd partial waves

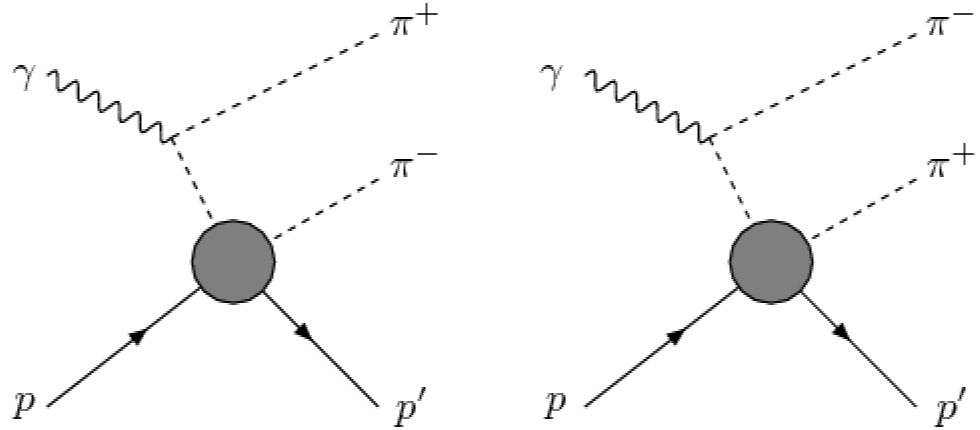
where:

$T^{lm}_{\pi+\pi-}$ – partial wave projected photoproduction amplitude of the meson pair $\pi\pi$,

$M_{\pi\pi}$- partial wave projected Deck amplitude,

t^I_l -rescattering amplitude for isospin I and spin l.

Implementing the e-m current conservation in the Deck amplitude



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

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

- **The amplitude is gauge invariant**

$\pi p \rightarrow \pi p$ 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):

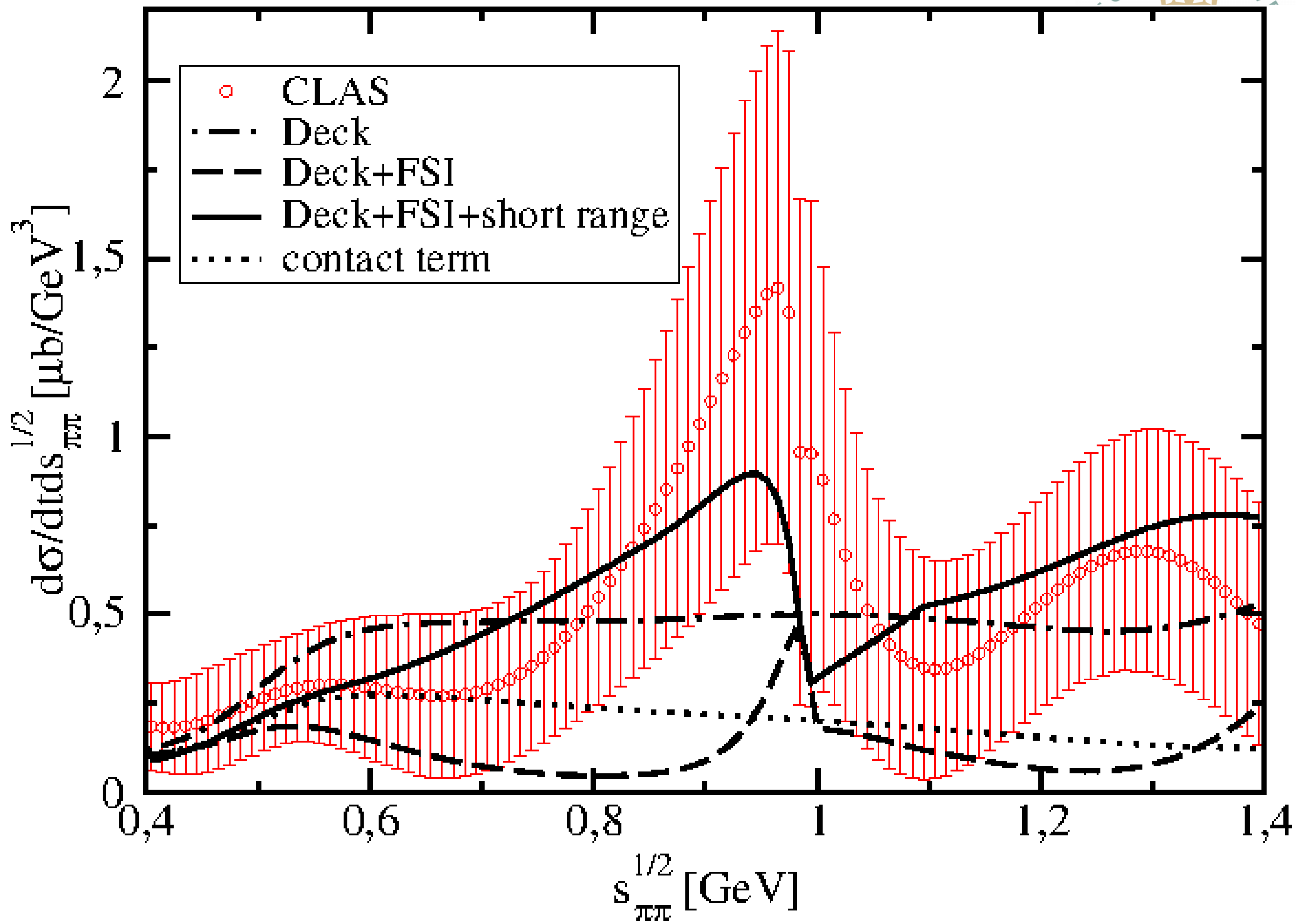
$$f_1 = \sum_{l=0}^{\infty} f_{l+} P'_{l+1}(\cos\theta^*) - \sum_{l=2}^{\infty} f_{l-} P'_{l-1}(\cos\theta^*),$$
$$f_2 = \sum_{l=1}^{\infty} (f_{l-} - f_{l+}) P'_{l}(\cos\theta^*),$$

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

Resonances in the $\pi\pi$ partial waves

Mass distributions

S-wave



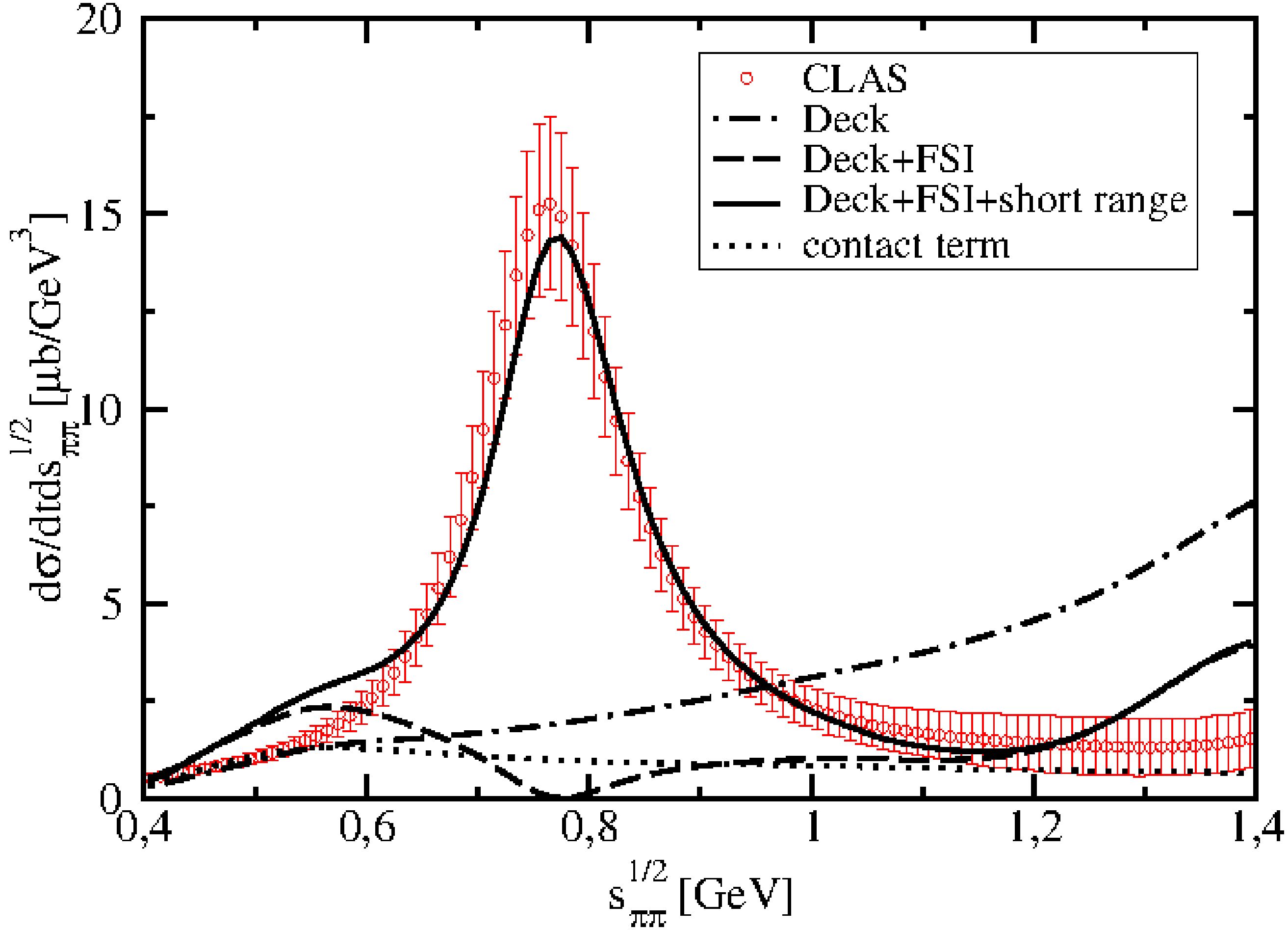
Notice:

- Very good distribution description already at the level of Deck amplitudes
- Clear $f_0(980)$ resonance contribution
- Sizable contribution from the contact term
- Drell+FSI interference is destructive and the theoretical distribution is too small
- Inclusion of the short range component with parameters A=-15 GeV^{-1} and B=3 GeV^{-3} makes the overall fit satisfactory
- Indication of the influence of the coupled $K\bar{K}$ channel above 1 GeV

P-wave

Notice:

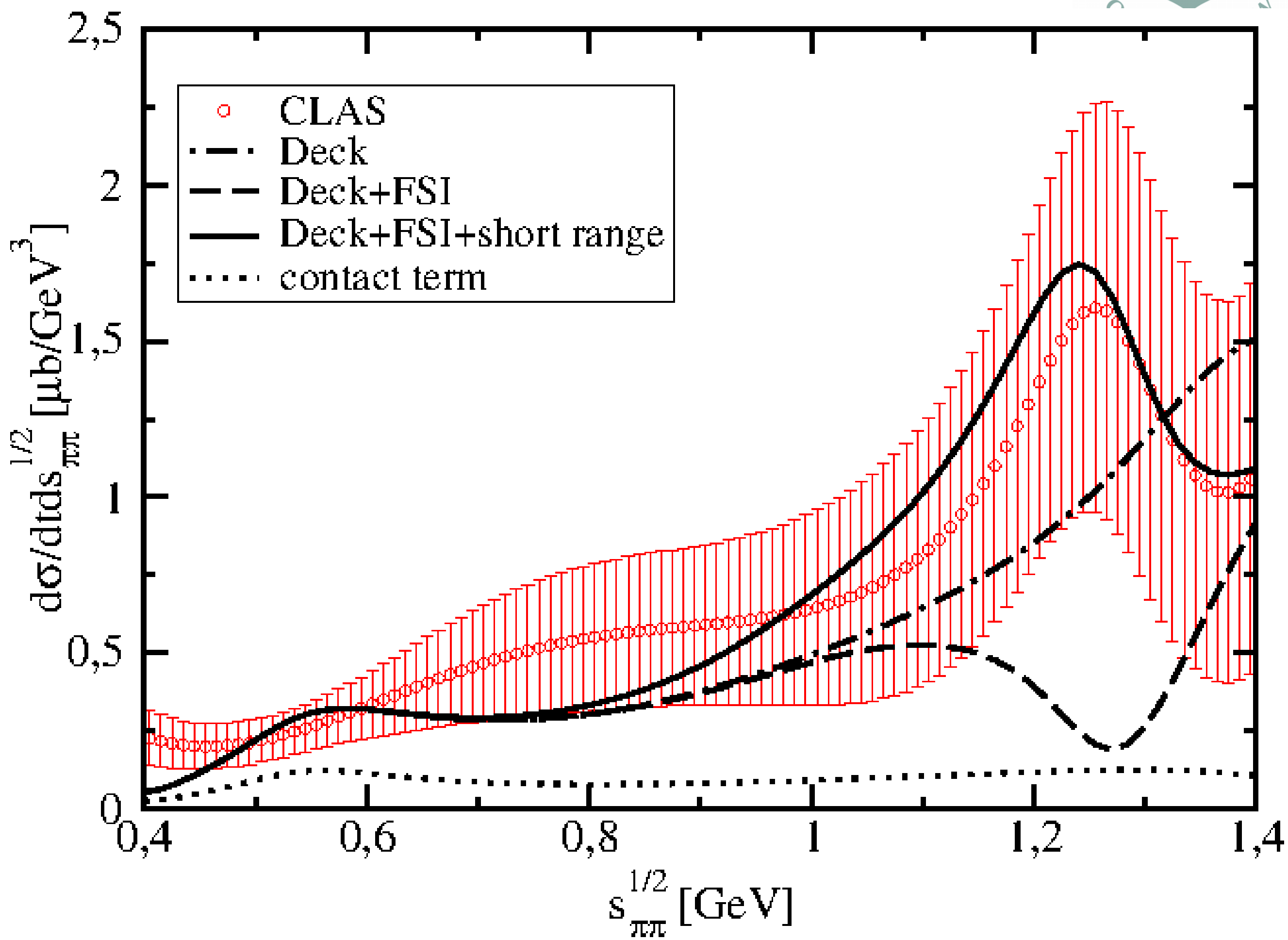
- Very good overall fit to the ρ(770) line
- Deck overshoots the data for masses above 1 GeV but destructive interference with short range component makes the fit better
- Deck+FSI results in minimum rather than maximum at resonance mass
- Fit of the short range component results in good resonance description with parameters: A=49 GeV^{-1} and B=-24 GeV^{-3}



D-wave

Notice:

- Very good distribution description already at the level of pure Deck amplitudes
- Deck+FSI results in minimum rather than maximum at resonance mass (same as ρ)
- Fit of the short range component results in good resonance description with parameters: A=-24 GeV^{-1} and B=11 GeV^{-3}

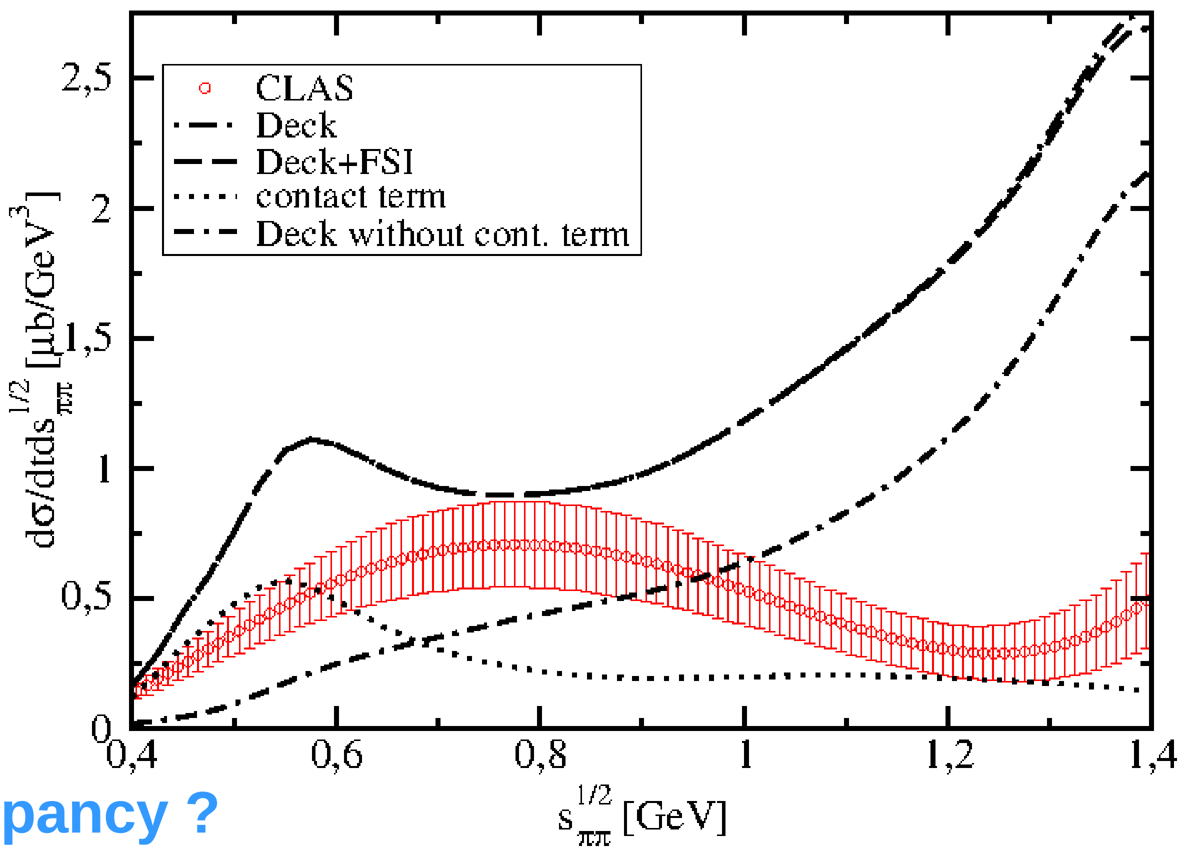


- No indication of the influence of the coupled $K\bar{K}$ channel – quite understandable, $f_2(1270)$ decays to $K\bar{K}$ only in <5% (84% to ππ)
- No additional background needed to describe the data

F-wave

Notice:

- Model prediction is too large in almost whole mass interval
- No indication of the FSI



Can we explain the discrepancy ?

- The bump below 0.6 GeV is due to particular choice of the contact term adopted from Pumplin (1970) for diffractive πp scattering – not necessarily suitable for our case
- The dominant F-wave resonance $\rho_3(1690)$ decays to ππ only in <24% while it mostly (71%) decays to ππππ/πω channel – we may expect large interchannel coupling and destructictive interference

Summary:

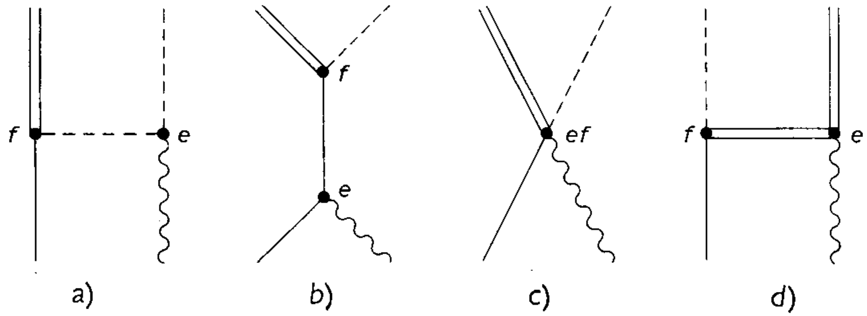
- The model which combines diffuse source (Deck) and compact source components properly describes the ππ mass distributions in *S*-,*P*- and *D*- partial waves and reproduces the dominance of the $f_0(980)$, ρ(770) and $f_2(1270)$ respectively,

Wave	A [GeV^{-1}]	B [GeV^{-3}]
S	−15±1	3±1
P	49±2	−24±2
D	−24±11	10±7

- The relative contribution of the compact source component is large for the ρ(770) and $f_2(1270)$ – in line with the $q\bar{q}$ nature of these resonances,
- The S-wave amplitude is dominated by the diffuse source component, which implies that $f_0(980)$ is a more loosely bound $qq\bar{q}\bar{q}$ object.

To do...

- Better accounting for e-m current conservation – some small (or even big) bumps can be attributed to particular choice of the contact term (suitable for t-channel dominated model)



eg. including s- and u-channel (apart from t-channel) diagrams and *different* contact term (P. Stichel, M. Scholz 1964)

- Inclusion of coupled channels – especially important in the S-wave – not so easy, because we do not have at our disposal the Kp amplitudes comparable to SAID

Thank you

for

your attention