Hadron reactions and Spectroscopy Studies at JPAC

Alessandro Pilloni

Joint Physics Analysis Center

Thessaloniki, September 2nd 2016

Joint Physics Analysis Center

- JPAC was funded to support the extraction of physics results from analysis of experimental data from JLab12 and other accelerator laboratories
- This is achieved through work on theoretical, phenomenological and data analysis tools
- JPAC aims to facilitate close collaboration between theorists, phenomenologists, and experimentalists worldwide
- It is engaged in education of further generation of hadron physics practitioners

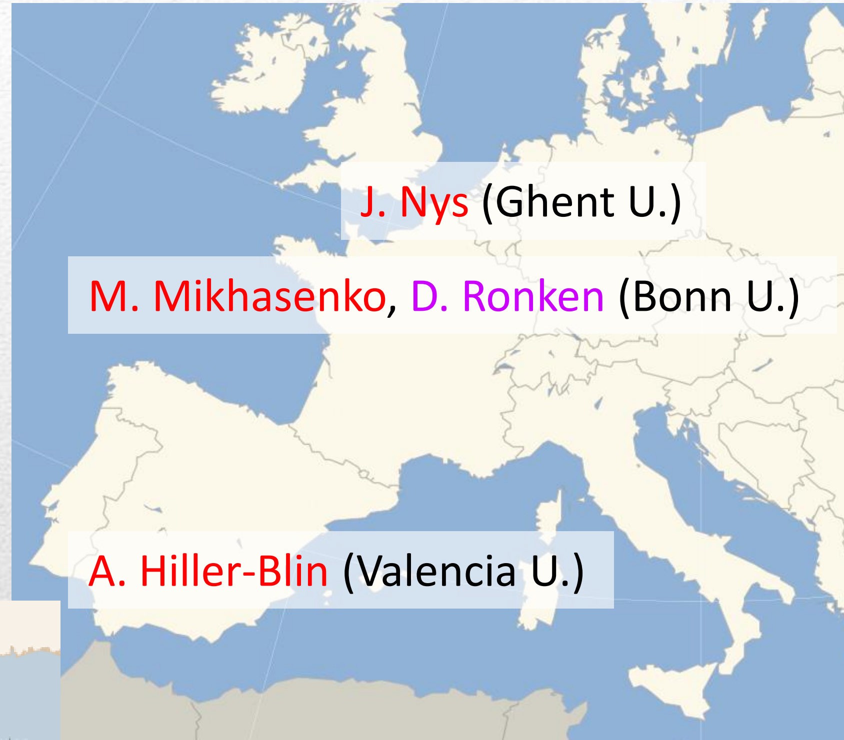
Joint Physics Analysis Center

E. Alexeev, A. Jackura, I. Lorenz,
V. Mathieu, G. Fox, T. Londergan,
E. Passemar (IU), A. Szczepaniak (IU/JLab)

B. Hu, M. Döring, R. Workman (GWU)

V. Pauk, A. Pilloni, V. Mokeev (JLab)

C. Fernandez-Ramirez (UNAM)



J. Nys (Ghent U.)

M. Mikhasenko, D. Ronken (Bonn U.)

A. Hiller-Blin (Valencia U.)

Former members:
L. Dai (Bonn), I. Danilkin (Mainz),
P. Guo (Cal. State), M. Shi (Peking)

Students, Postdocs, Faculties

Production

- $>$ 40 Research Papers (Phys.Rev., Phys.Lett, Eur.J. Phys.)
- $\sim$120 Invited Talks and Seminars
- $O(10)$ ongoing analyses
- Summer School on Reaction Theory (IU, 2015)
- Workshop “Future Directions in Hadron Spectroscopy” (JLab, 2014)

$P_c(4450)$	A. Blin *et al.*,	PRD94, 034002
$\Lambda(1405)$	C. Fernandez-Ramirez *et al.*,	PRD93, 074015
$K\, N \to K\, N$	C. Fernandez-Ramirez *et al.*,	PRD93, 034029
$\pi\, N \to \pi\, N$	V. Mathieu *et al.*,	PRD92, 074004
$\gamma\, p \to \pi^0\, p$	V. Mathieu *et al.*,	PRD92, 074013
$\eta \to \pi^+\, \pi^-\, \pi^0$	P. Guo *et al.*,	PRD92, 054016; arXiv:1608.01447
$\omega, \phi \to \pi^+\, \pi^-\, \pi^0$	I. Danilkin *et al.*,	PRD91, 094029
$\gamma\, p \to K^+\, K^-\, p$	M. Shi *et al.*,	PRD91, 034007

Interactive tools

- Completed projects are fully documented on interactive portals
- These include description on physics, conventions, formalism, etc.
- The web pages contain source codes with detailed explanation how to use them. Users can run codes online, change parameters, display results.

http://www.indiana.edu/~jpac/

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Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

National Science Foundation

This project is supported by NSF

$\pi N \to \pi N$

Formalism

The pion-nucleon scattering is a function of 2 variables. The first is the beam momentum in the laboratory frame p_{lab} (in GeV) or the total energy squared $s = W^2$ (in GeV^2). The second is the cosine of

π p_1 t p_3 π

Resources

- **Publications:** [Mat15a] and [Wor12a]
- **SAID partial waves:** compressed zip file
- **C/C++:** C/C++ file
- **Input file:** param.txt
- **Output files:** output0.txt , output1.txt , SigTot.txt , Observables0.txt , Observables1.txt
- **Contact person:** Vincent Mathieu
- **Last update:** June 2016

The SAID partial waves are in the format provided online on the SAID webpage :

p_{lab} δ $\epsilon(\delta)$ $1-\eta^2$ $\epsilon(1-\eta^2)$ Re PW Im PW SGT SGR

δ and η are the phase-shift and the inelasticity. $\epsilon(x)$ is the error on x.
SGT is the total cross section and SGR is the total reaction cross section.

Format of the input and output files: [show/hide]
Description of the C/C++ code: [show/hide]

Simulation

Range of the running variable:

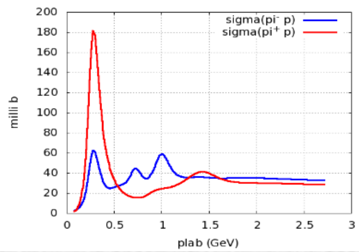
s in GeV^2	(min max step)	1,2	6	0,01
p_{lab} in GeV	(min max step)	0,1	4	0,01
ν in GeV	(min max step)	0,3	4	0,01
t in GeV^2	(min max step)	-1	0	0,01

The fixed variable:

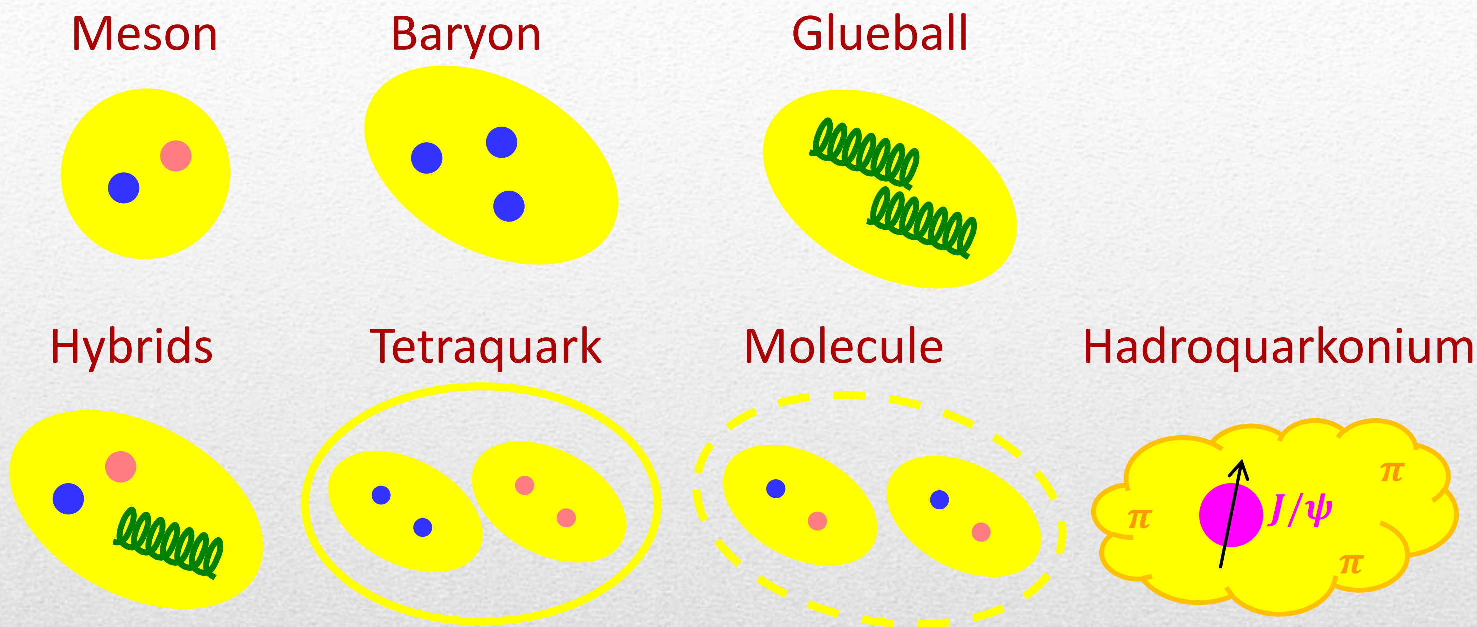
t in GeV^2 0
p_{lab} in GeV 5

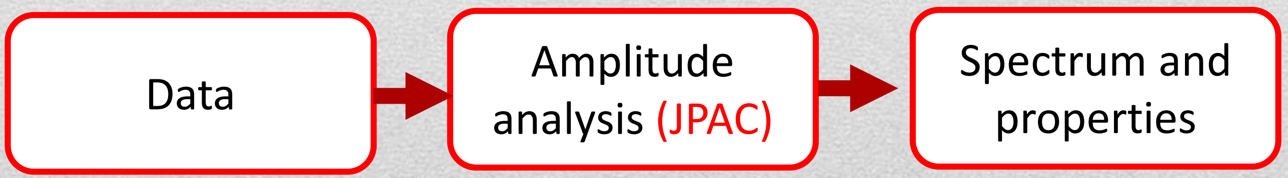
Start reset

Results



Hadron Spectroscopy



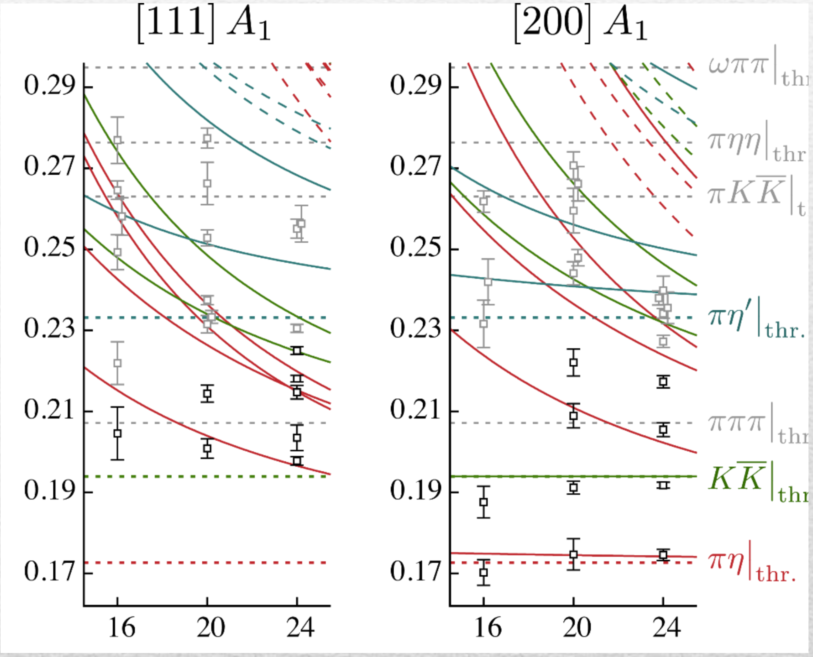


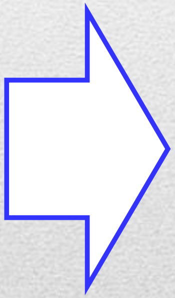
Interpretations on the spectrum leads to understanding fundamental laws of nature

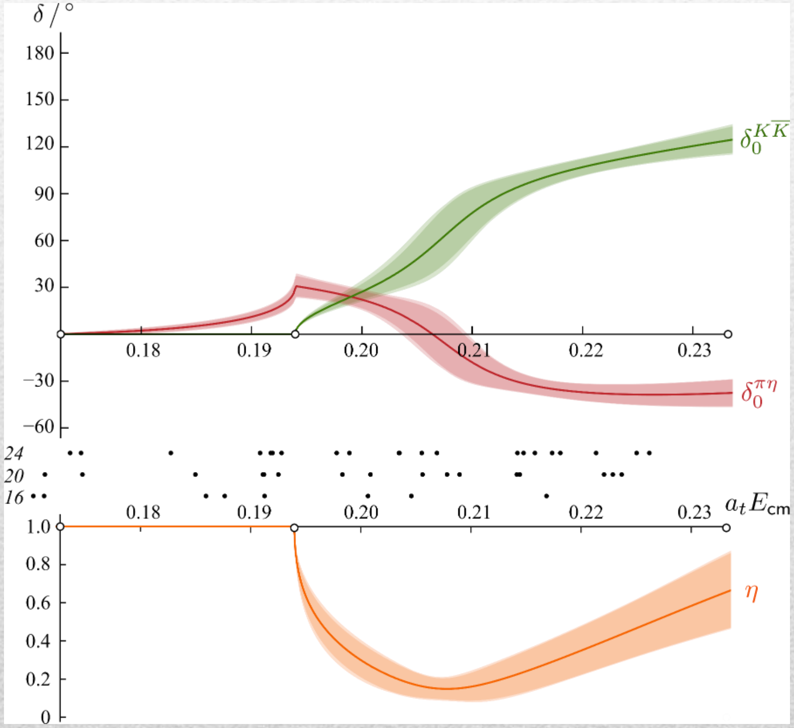
Lattice QCD and amplitude analysis

known kinematical function → $Z(E_i, L) = T(E_i)$ ← infinite volume amplitude

discrete energy spectrum of states in the lattice

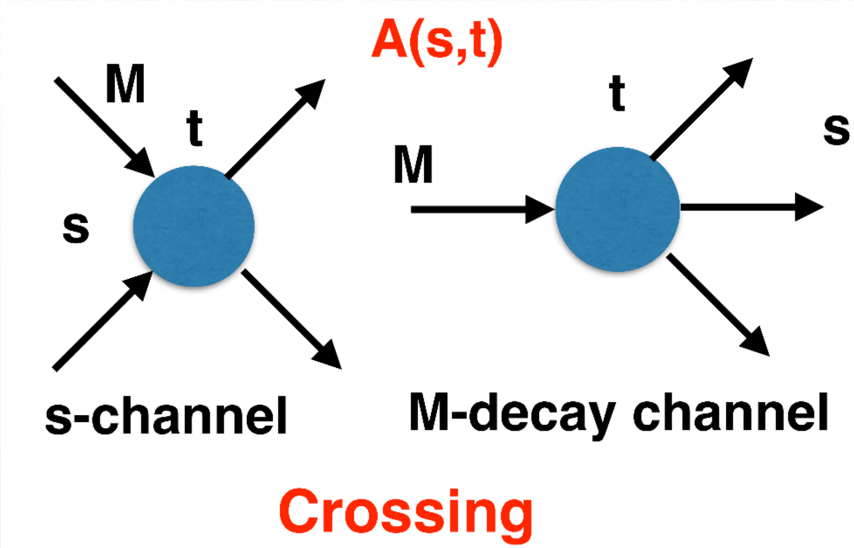






in general «solution» of the Lüscher condition requires an analytical model for T

S-Matrix principles

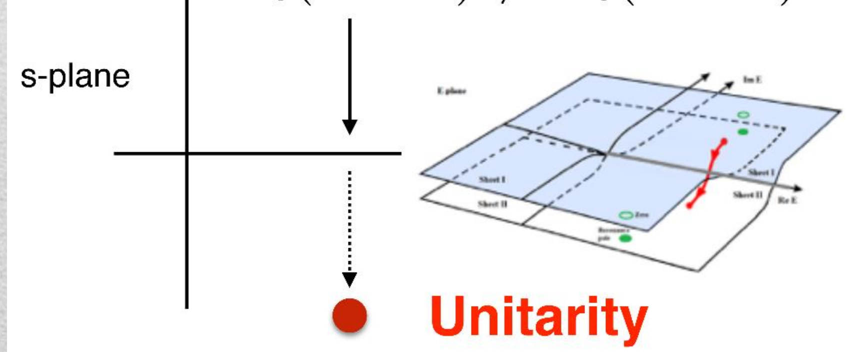


$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

Analyticity

$$A_l(s) = \lim_{\epsilon \to 0} A_l(s + i\epsilon)$$

$$A_l(s + i\epsilon) \neq A_l(s - i\epsilon)$$

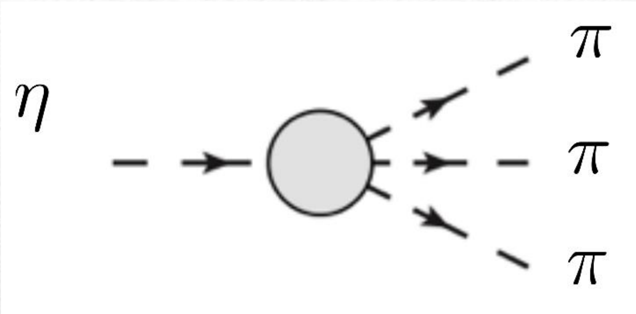


These are constraints the amplitudes have to satisfy, but do not fix the dynamics

Resonances (QCD states) are poles in the unphysical Riemann sheets

At high energies, other constraints from Regge theory (exchanges of towers of particles of any spin)

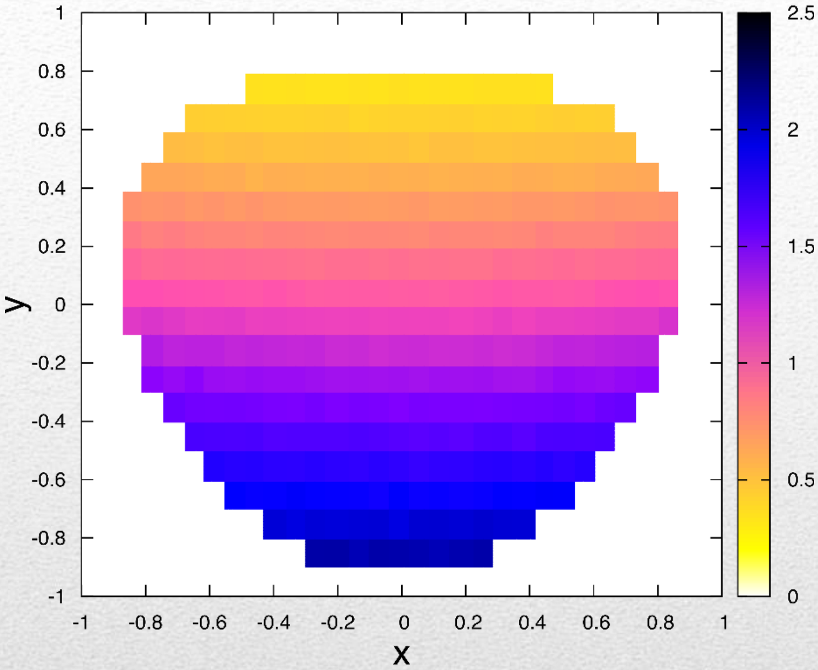
$\eta \to 3\pi$



Isospin violating decay,
sensitive to quark mass difference

Dispersive analysis (Khuri-Treiman eq.)
+ fitting to data
+ matching to NLO χPT @ Adler zero

$$Q = \frac{m_s^2 - (m_d + m_u)^2/4}{m_d^2 - m_u^2} \sim 21.6 \pm 0.4$$



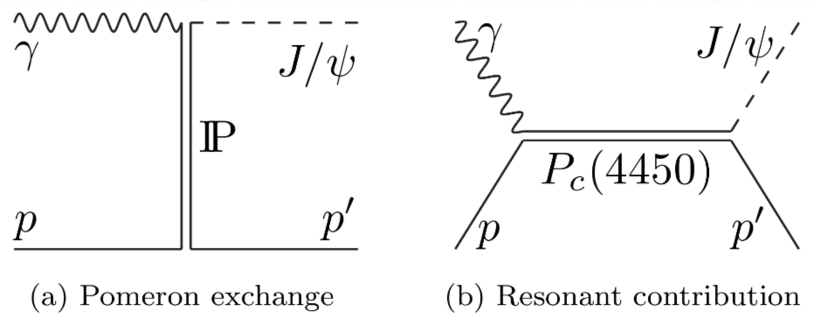
Data from
WASA-at-COSY PRC90, 045207
KLOE-2 JHEP 05, 019

P. Guo *et al.* (JPAC), PRD92, 054016
P. Guo *et al.* (JPAC), arXiv:1608.01447

Pentaquark photoproduction

We propose to search the $P_c(4450)$ state in photoproduction

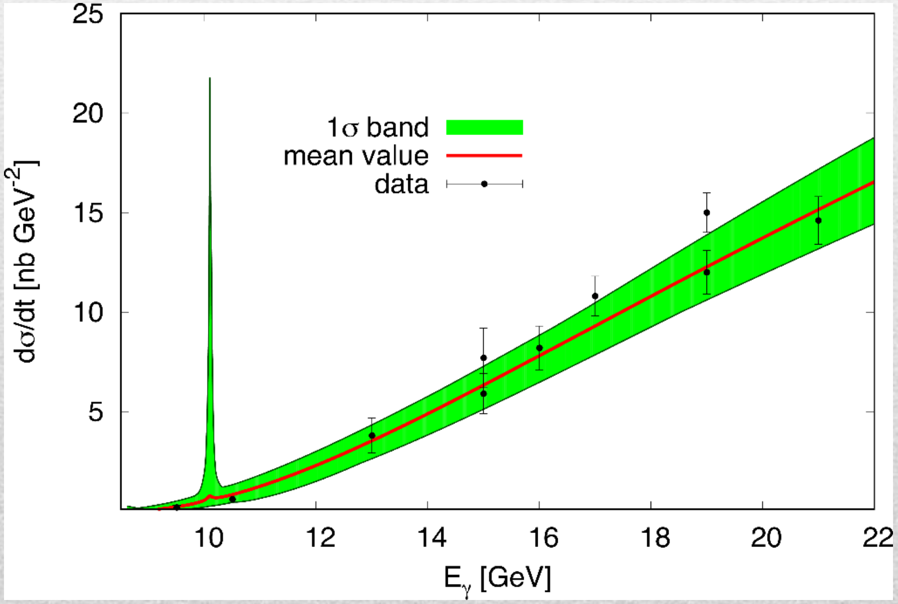
Q. Wang *et al.* PRD92, 034022
M. Karliner *et al.* PLB752, 329-332
Kubarovsky *et al.* PRD92, 031502



We use the (few) existing data and
VMD + pomeron inspired bkg
to estimate the cross section

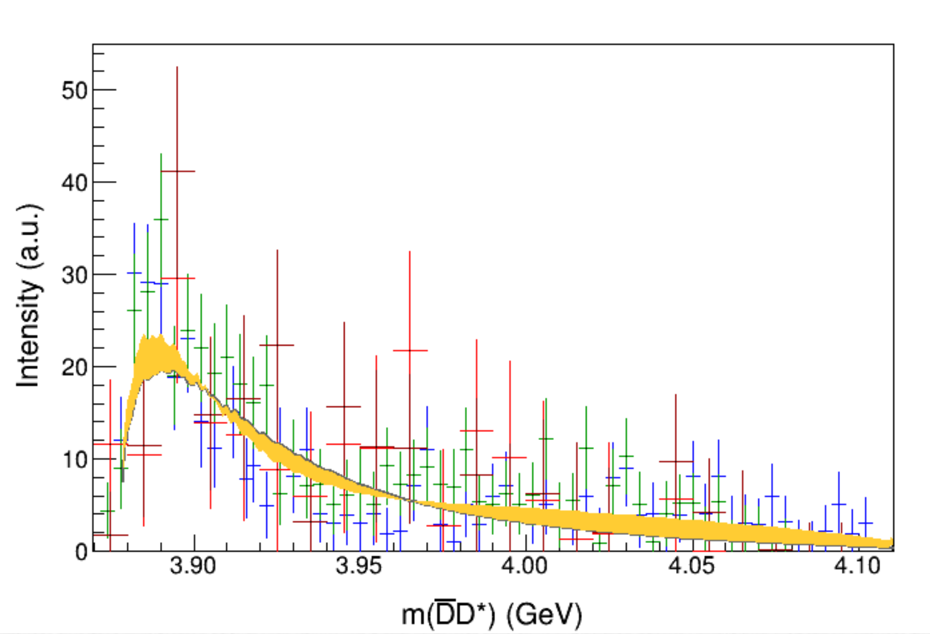
$J^P = (3/2)^-$

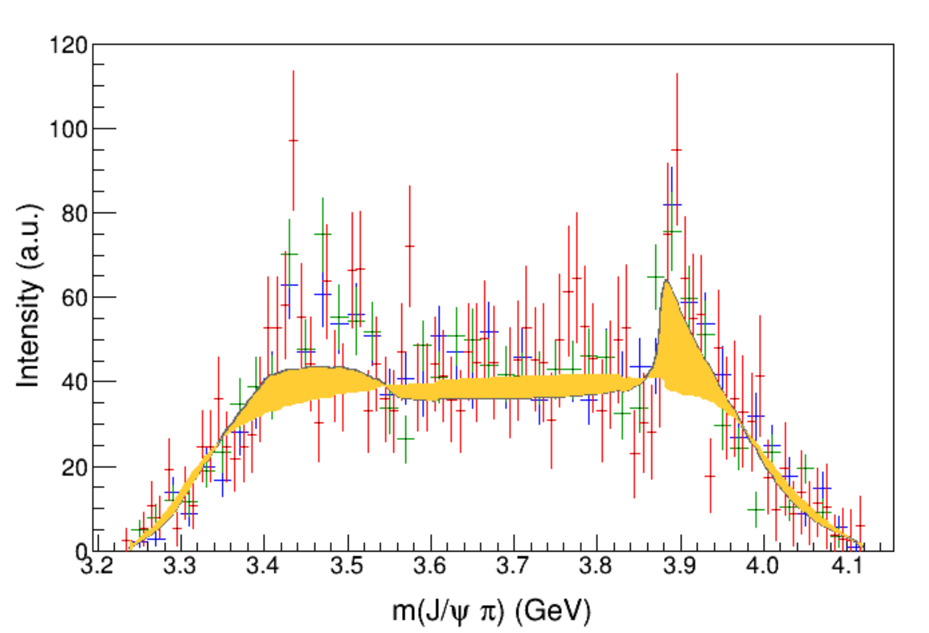
σ_s (MeV)	0	60	120
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$	$0.157^{+0.037}_{-0.022}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$	$1.150^{+0.015}_{-0.023}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$	$0.111^{+0.038}_{-0.054}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$	$16.9^{+2.0}_{-1.1}$
b_0 (GeV^{-2})	$1.01^{+0.47}_{-0.29}$	$1.02^{+0.61}_{-0.32}$	$1.03^{+0.49}_{-0.31}$
$\mathcal{B}_{\psi p}$ (95% CL)	≤ 29 %	≤ 30 %	≤ 23 %



A. Blin *et al.* (JPAC), PRD94, 034002

$Z_c(3900)$





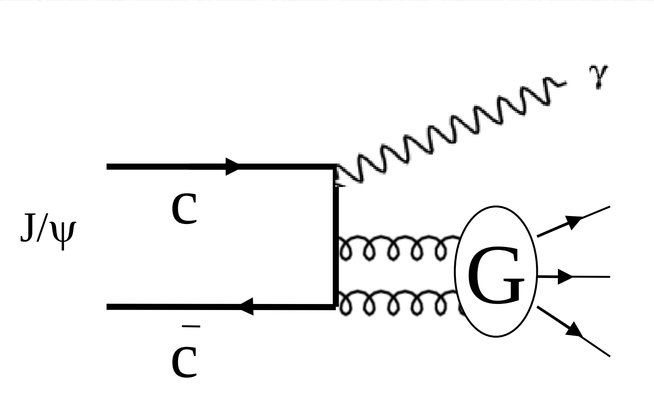
Exploring different K-matrix parametrizations for the coupled channel analysis

Precise determination of pole parameters (mass, width, Riemann sheet) might give insight on the nature of the state

AP and A. Szczepaniak (JPAC), in progress

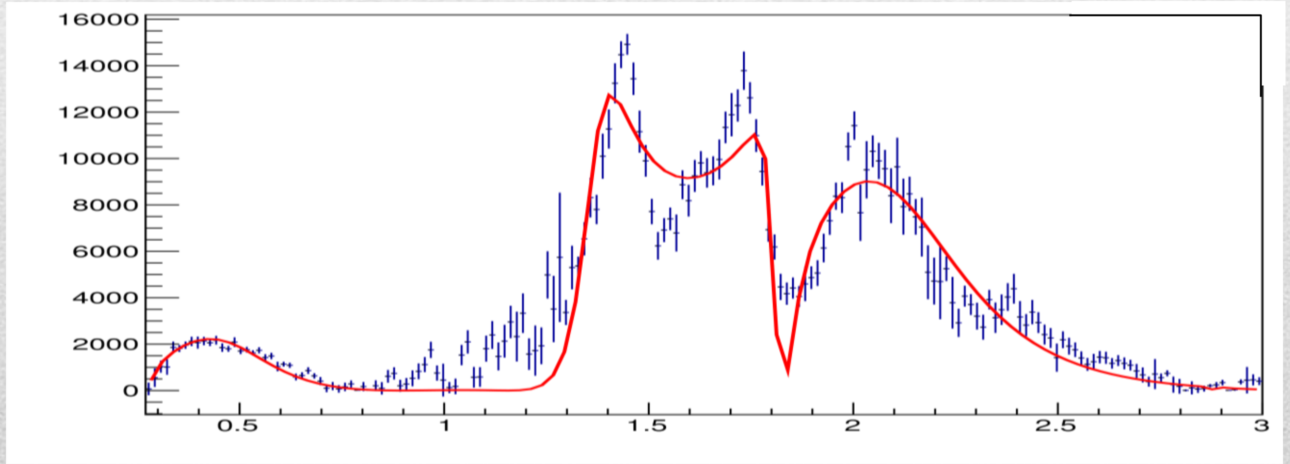
$J/\psi \to \gamma\, \pi^0\pi^0$

This is a gluon-rich process, expected to be one of the golden channels for the search of the scalar glueball



Omnès function + left hand cut parametrization (ρ/ω exchange)

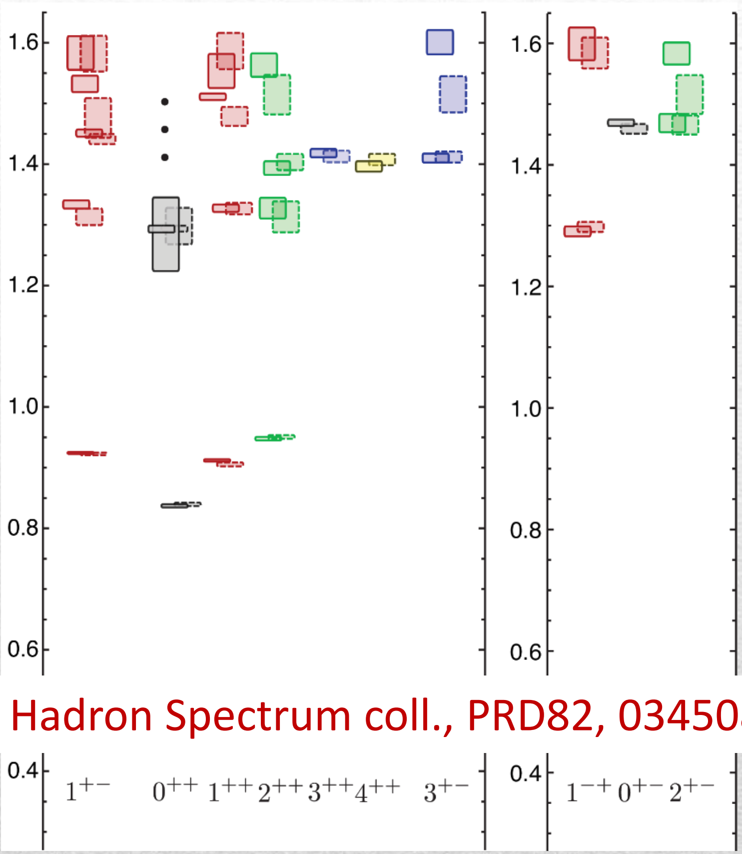
$$f^J_\mu(s) = v^J_\mu(s) + \Omega(s)\left(P_k(s) + \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{v^J_\mu(s')e^{i\delta_J(s')}\sin\delta_J(s')\Omega^{-1}(s')}{(s')^k(s'-s)}\right)$$



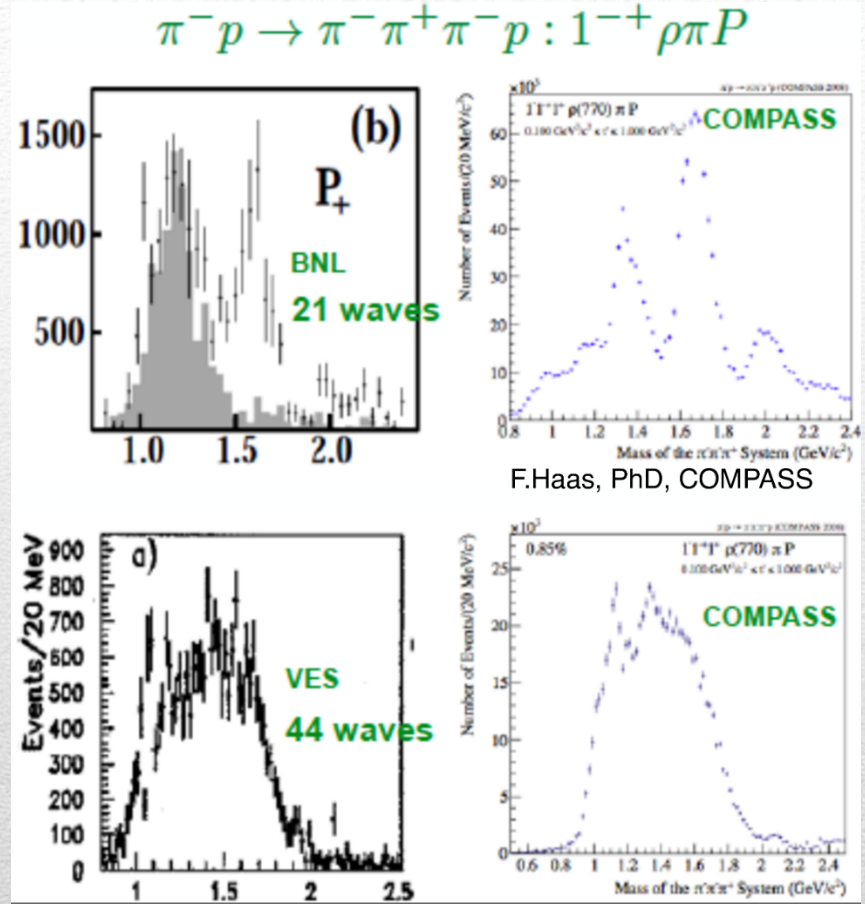
The preliminary fit qualitatively reproduces the σ region and the higher resonances

A. Pilloni (JPAC), in progress

Hybrids



Hadron Spectrum coll., PRD82, 034508



Signatures as $J^{PC} = 1^{-+}$ are not allowed in the quark model, Coulomb gauge QCD and flux tube predict glue excitation to be a quasi-particle with $J^{PC} = 1^{+-}$, $q\bar{q}g$ states expected

Need some constraint to draw robust conclusions about the existence of exotic states

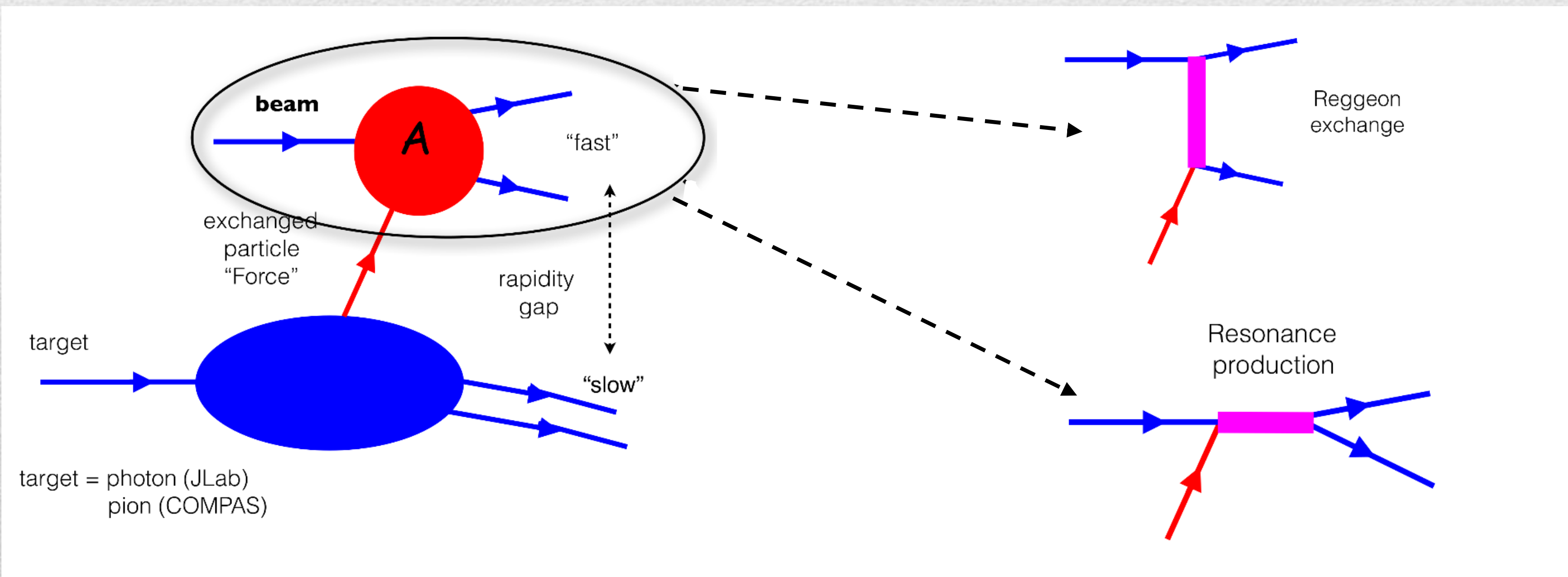
Regge exchange

Resonances are poles in s for fixed l
dominate low energy region

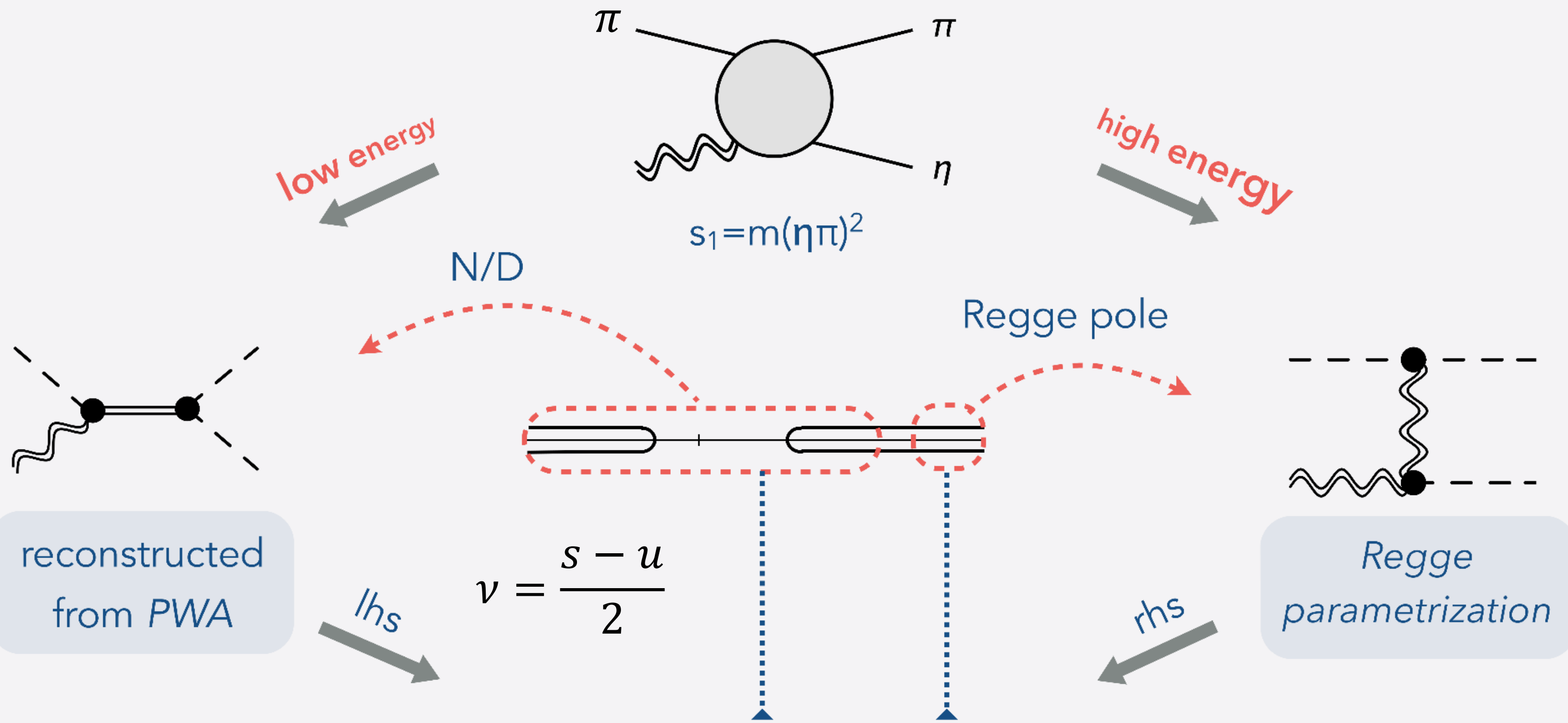
$$A_l \sim \frac{g_1 g_2}{s_p - s}$$

Reggeons are poles in l for fixed s
dominate high energy region

$$A \sim \sum s^l \sim g_1(t) g_2(t) \left((-s)^{\alpha_\pm(t)} \pm s^{\alpha_\pm(t)} \right) \left(-\frac{e^{i\pi\alpha^\pm(t)} \pm 1}{\sin \pi\, \alpha^\pm(t)} \right)$$



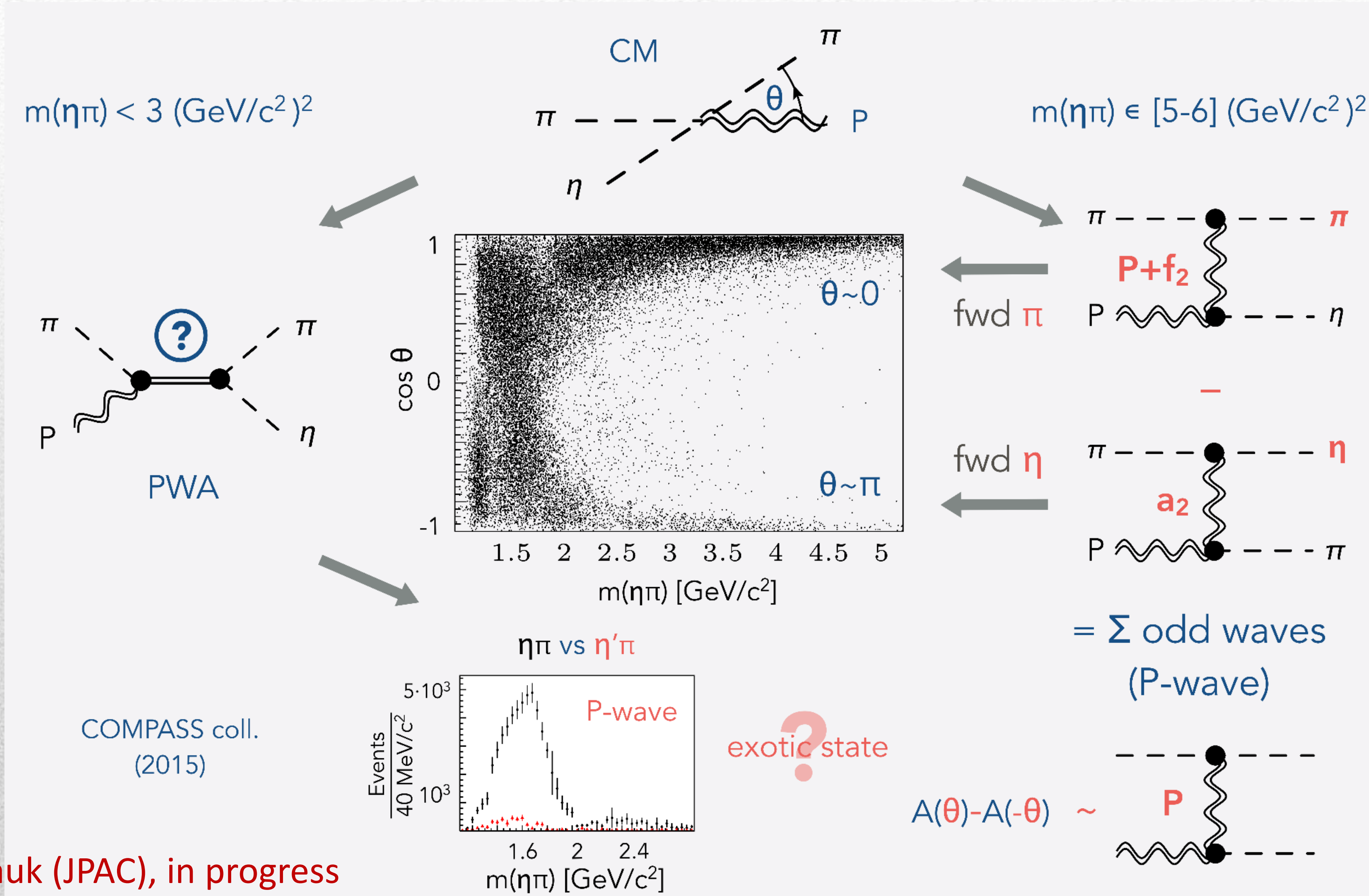
Finite energy sum rules



$$\frac{1}{\Lambda^n}\int_{\nu_{th}}^{\Lambda} Im\ A(\nu,t)\ \nu^n d\nu = \frac{\beta(t)\Lambda^{\alpha(t)+1}}{\alpha(t)+n+1}$$

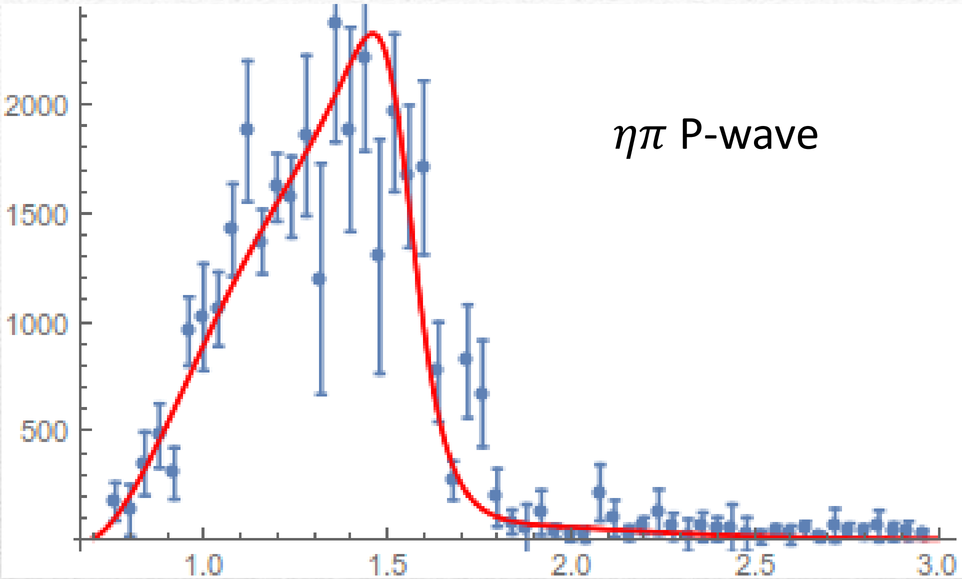
<u>aim</u>: *first systematic analysis*
*of **peripheral production** using **FESR***

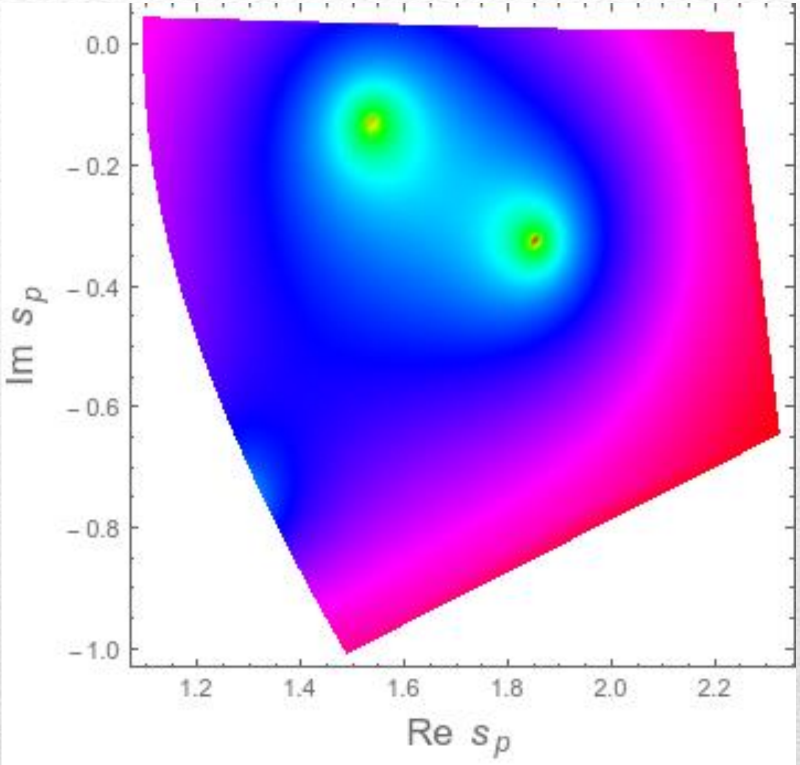
$\eta\pi$ production



V. Pauk (JPAC), in progress

$\eta\pi$ production



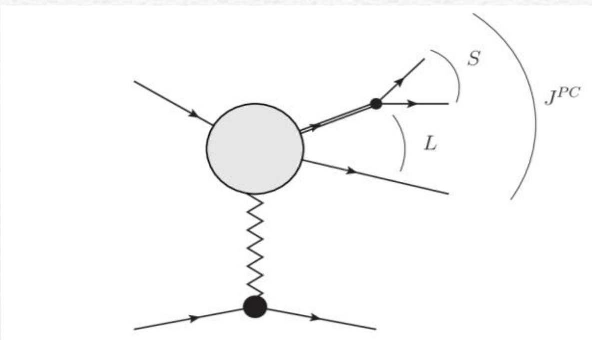


Low energy region saturated by a small number of partial waves, K matrix parametrization
Constrained with Regge asymptotic to be implemented later on

V. Pauk (JPAC), in progress

PWA of 3π sytem

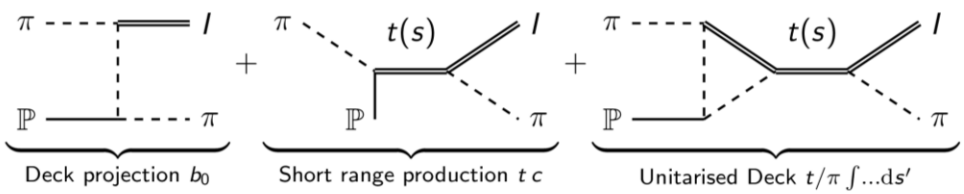
We start from 2^{-+}, long standing puzzle about $\pi_2(1670) - \pi_2(1880)$ interplay

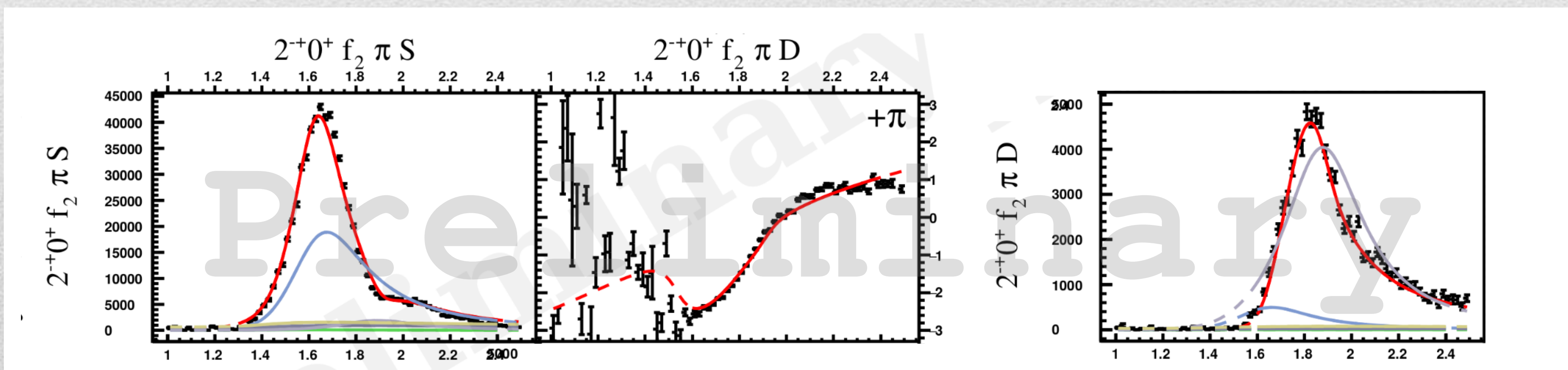


Now use unitarized Deck amplitude developed for this analysis

$$F_i(s) = b_i(s) + \sum_j t_{ij}(s) c_j + \frac{1}{\pi} \sum_j t_{ij}(s) \int_{s_j}^{\infty} ds' \frac{\rho_j(s') b_j(s')}{s' - s}$$

$F_i(s) =$



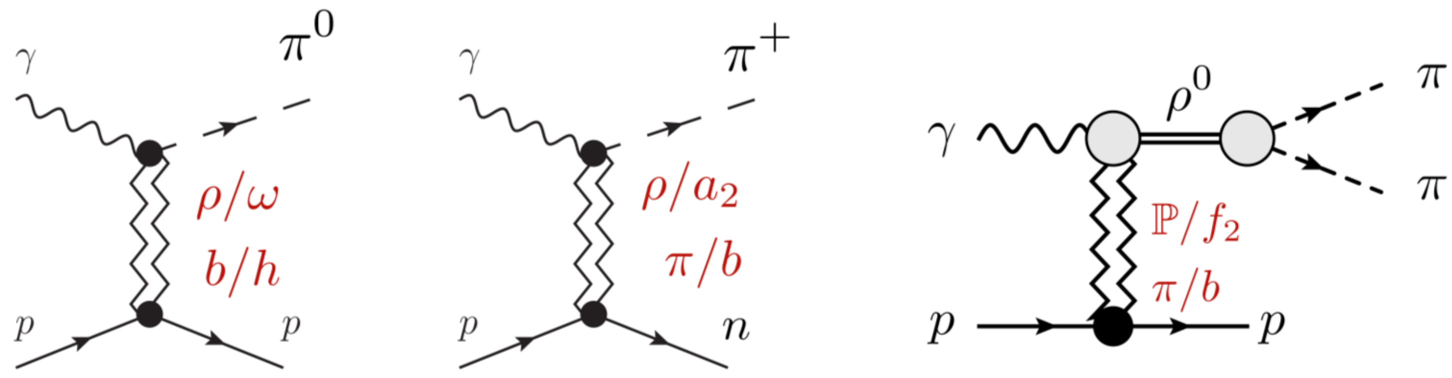


A. Jackura, M. Mikhasenko (JPAC), in progress, see M. Mikhasenko's talk on Thursday 18:30

π, ρ photoproduction

Test factorization on the simplest cases

1. Neutral pion photoproduction
2. Charged pion photoproduction
3. Rho meson photoproduction



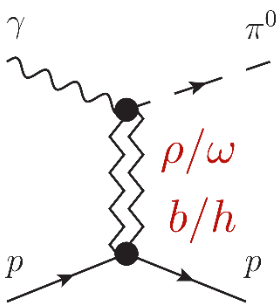
natural exchanges: $\rho/\omega/f_2/a_2/\mathbb{P}$ $\quad P = (-)^J$

unnatural exchanges: $\pi/b/h$ $\quad P = -(-)^J$

special ?

$\gamma\, p \to \pi^0\, p$

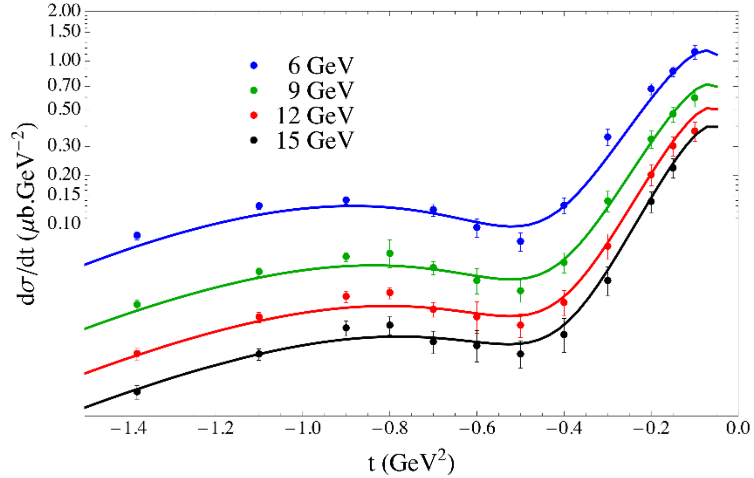
Model based on factorization
with parameters fitted

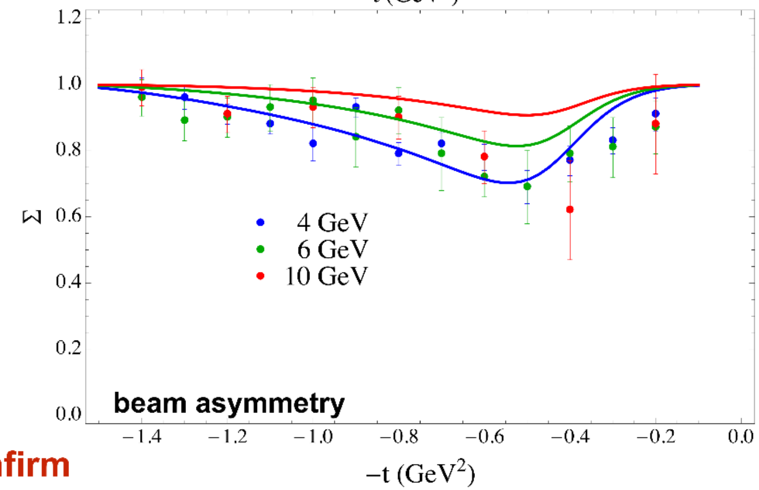


$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

axial-vector exchanges strength decreases with energy

More precise data@JLAB could confirm



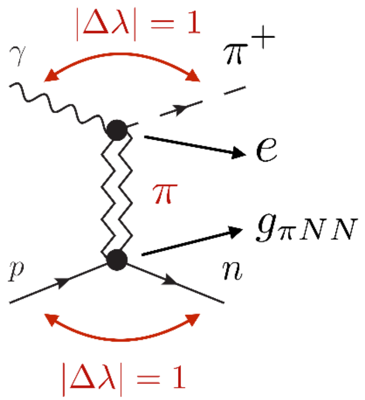


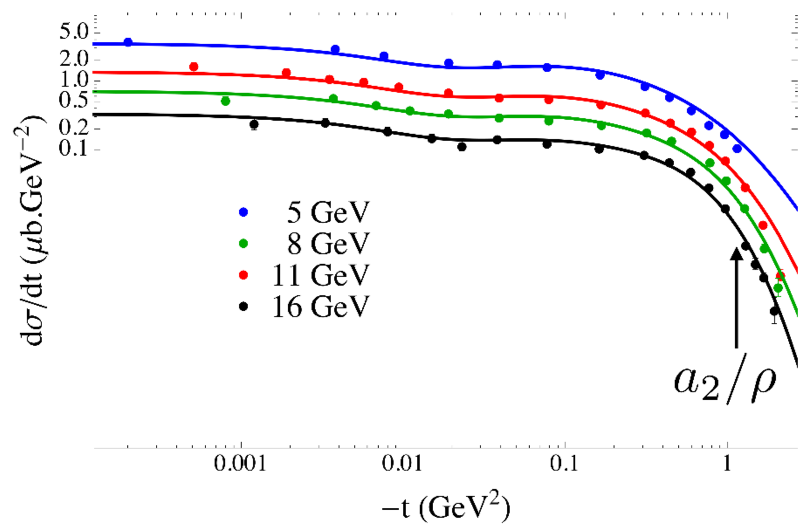
V. Mathieu *et al.* (JPAC), PRD92, 074013

$\gamma\, p \to \pi^+\, n$

Pion dominate very small |t| :

[Boyarski et al. 1968]





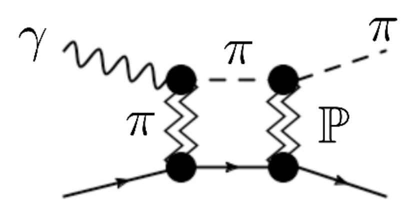
Factorization of Regge residues:
$(\lambda_\gamma, \lambda_\pi) = (1, 0)$ **and**

$$(\lambda_p, \lambda_n) = \left(-\frac{1}{2}, +\frac{1}{2}\right) \qquad A^{10}_{-\frac{1}{2}\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$$(\lambda_p, \lambda_n) = \left(+\frac{1}{2}, -\frac{1}{2}\right) \qquad A^{10}_{\frac{1}{2}-\frac{1}{2}} \propto \frac{-t}{m_\pi^2 - t}$$

$$|(\lambda_\gamma - \lambda_p) - (\lambda_\pi - \lambda_{p'})| = 0$$

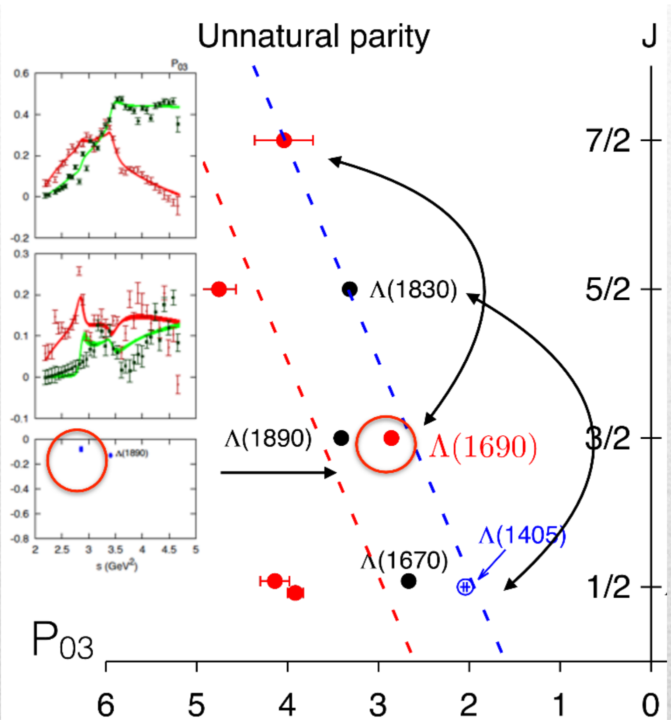
William's Poor man absorption: $\rightarrow \dfrac{-m_\pi^2}{m_\pi^2 - t}$

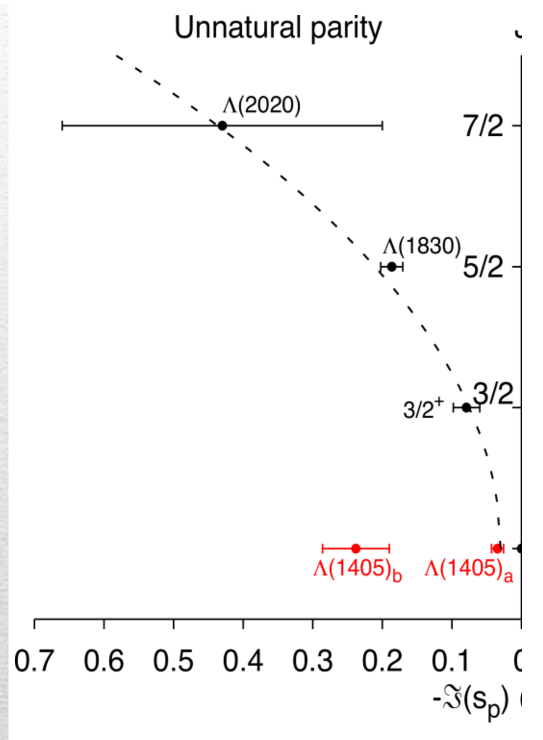


V. Mathieu (JPAC), in progress

$\bar{K}N$ scattering and the $\Lambda(1405)$

Coupled-channel K matrix model (up to 13 channels per partial wave), analyticity in angular momentum enforced, fit to KSU partial waves





One of the $\Lambda(1405)$ poles is out of the trajectory
→ non 3-q state

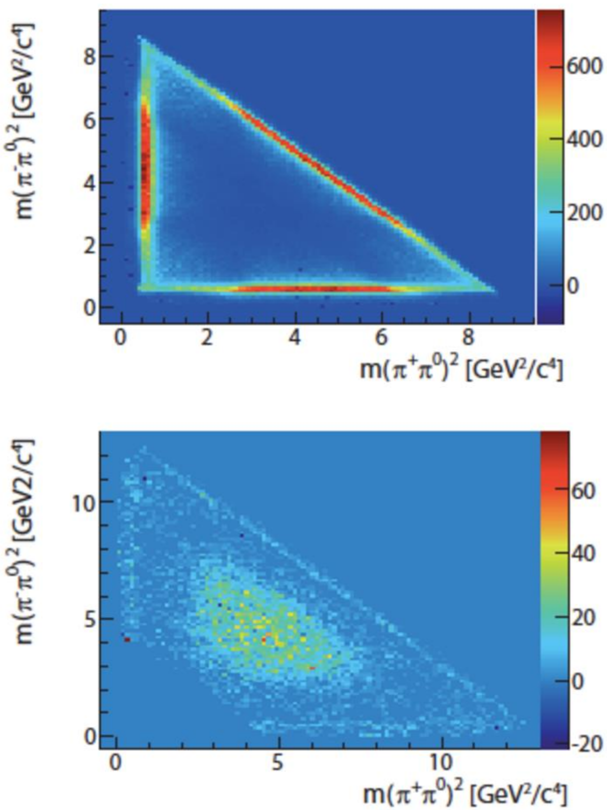
C. Fernandez-Ramirez *et al*. (JPAC), PRD93, 034029
C. Fernandez-Ramirez *et al*. (JPAC), PRD93, 074015

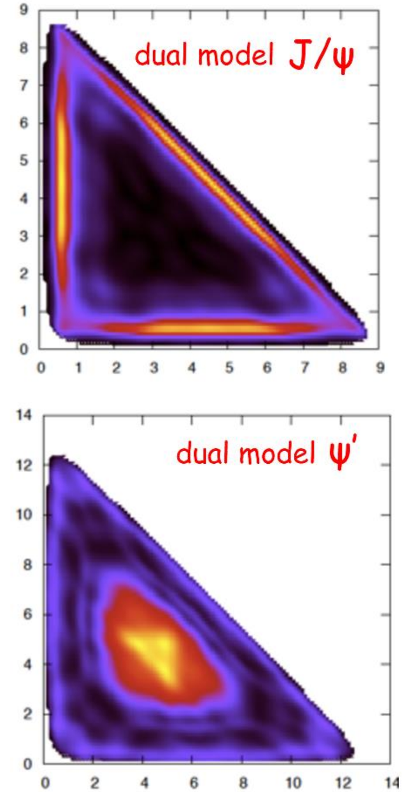
Summary

- We have established a large portfolio of research projects that directly benefit the ongoing and future analyses.
- JPAC members work directly with data analysis teams from CLAS, GlueX, COMPASS, LHCb, BES3
- There is strong institutional support to this effort from JLab, IU, GWU.
- There are numerous expansion paths, that in particular take advantage of the expertise in lattice, hadron structure, global pdf analyses, etc. that exist in the theory group
- The next ~10 years will focus on extracting physics from the new experiments (and we expect support from experimental groups).

BACKUP

$\psi^{(\prime)} \to \pi^+\pi^-\pi^0$ within dual models





$$A(s,t) = \frac{\Gamma(-J(s))\Gamma(-J(t))}{\Gamma(-J(s)-J(t))}$$

BESIII, Phys.Lett. B710 (2012) 594-599

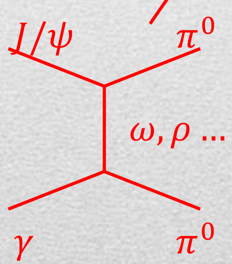
A. Szczepaniak and M. Pennington, PLB737, 283

$J/\psi \to \gamma\, \pi^0\pi^0$

We start approximating the problem to 1 channel, i.e. neglecting inelasticities.
Unitarity and dispersion relations allow us to write the solution in terms of the Omnès function

$$\mathrm{Disc}_R\, f_\mu^J = \rho(s) f_\mu^J A_{\pi\pi}^{J*} = f_\mu^J e^{-i\delta_J} \sin\delta_J$$

$$f_\mu^J(s) = v_\mu^J(s) + \Omega(s)\left(P_k(s) + \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{v_\mu^J(s') e^{i\delta_J(s')} \sin\delta_J(s')\Omega^{-1}(s')}{(s')^k(s'-s)}\right)$$



Depends on the $\pi\pi$ scattering phase, parametrized with K matrix

$$K_\pi = \frac{m_\pi^2 - 2s}{2f_\pi^2}$$

Adler zero
describes the σ region

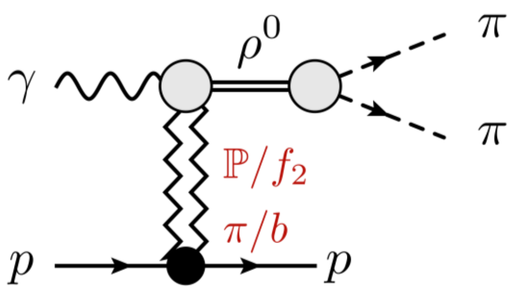
$$K_R = \sum_i \frac{g_i}{M_i^2 - s} + \sum_j \gamma_j s^j$$

K-matrix poles

Background terms
(effective LHC)

A. Pilloni

$\gamma\, p \to \rho^0\, p$



Use beam polarization to extract spin density matrix elements:

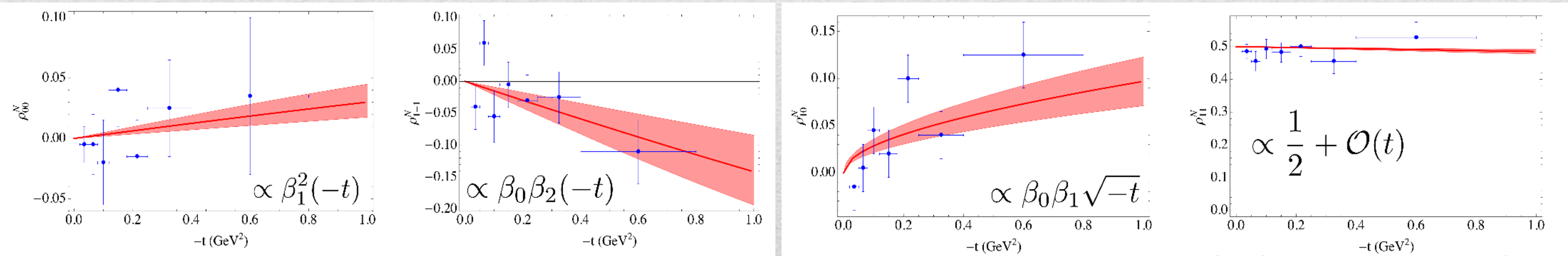
$$\rho^0_{MM'} = \frac{1}{N}\sum_{\lambda_\gamma\lambda_p\lambda_{p'}} A_{\lambda_\gamma\lambda_p\lambda_{p'},M}A^*_{\lambda_\gamma\lambda_p\lambda_{p'},M'}$$

$$\rho^1_{MM'} = \frac{1}{N}\sum_{\lambda_\gamma\lambda_p\lambda_{p'}} A_{\lambda_\gamma\lambda_p\lambda_{p'},M}A^*_{-\lambda_\gamma\lambda_p\lambda_{p'},M'}$$

$$N = \sum_\lambda |A_\lambda|^2$$

At leading s, one can separate natural and unnatural exchanges

Test factorization at top vertex: non-flip $\beta_0\left(\sqrt{-t}\right)^0$, single-flip $\beta_0\left(\sqrt{-t}\right)^0$, double-flip $\beta_2\left(\sqrt{-t}\right)^2$



Fit gives $\beta_0 : \beta_1 : \beta_2 = 1.00 : 0.14 : -0.09$, which agrees with the expected trend

V. Mathieu