Hadron spectroscopy at JPAC

Alessandro Pilloni

Joint Physics Analysis Center

7th workshop of the APS Topical GHP Meeting
Washington DC, February 1st 2017

Jefferson Lab

Joint Physics Analysis Center

JPAC is a collaboration between theorists, phenomenologists, and experimentalists to provide phenomenological and data analysis tools for hadron physics

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

B. Hu, M. Mai, M. Döring, R. Workman (GWU)

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

J. Nys (Ghent U.)

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

A. Hiller-Blin (Valencia U.)

C. Fernandez-Ramirez (UNAM)

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 and 2017)
- Workshop "Future Directions in Hadron Spectroscopy" (JLab, 2014)

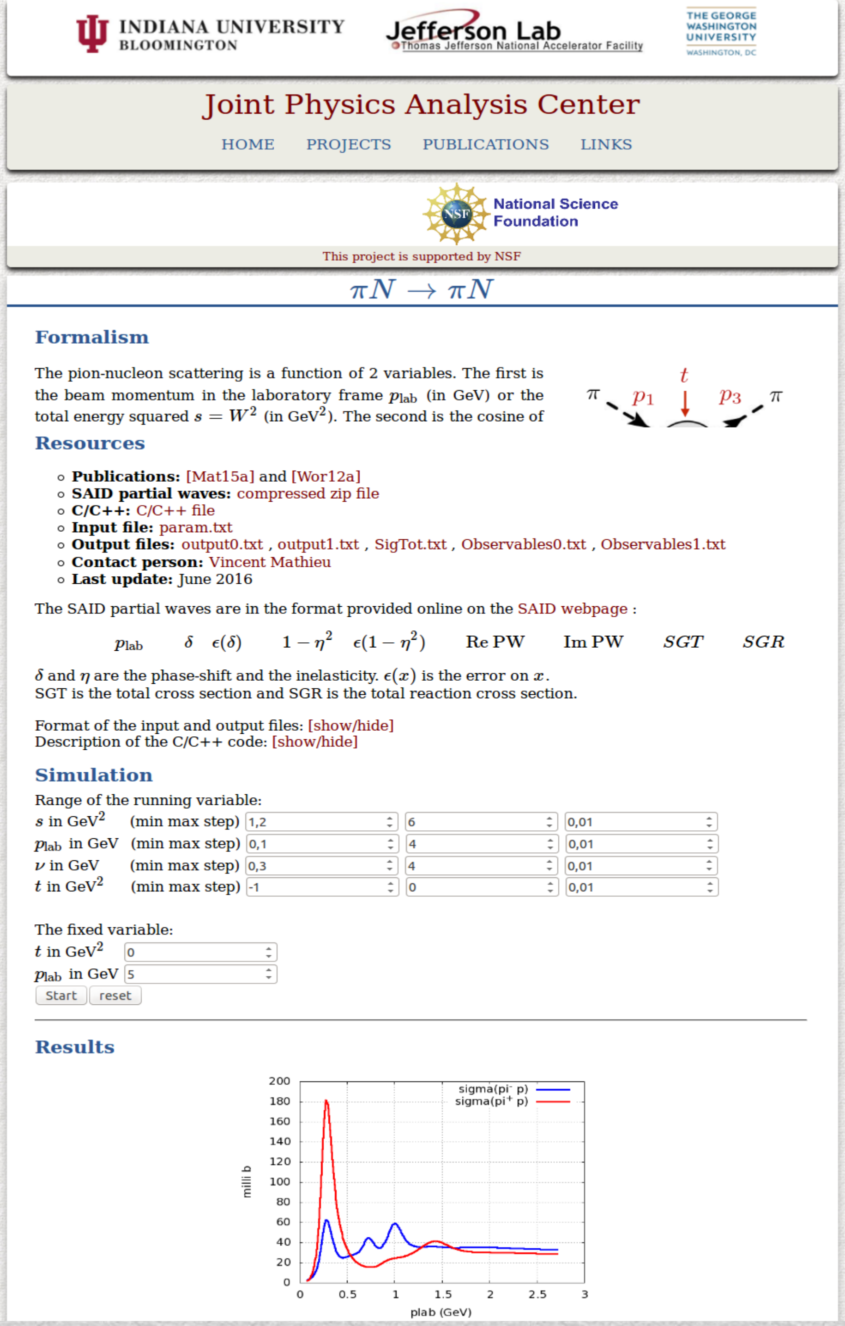
$Z_c(3900)$	AP *et al.*,	arXiv:1612.06490
$\gamma\, p \to \eta\, p$	J. Nys *et al.*,	arXiv:1611.04658
$P_c(4450)$	A. Blin *et al.*,	PRD94, 034002
$\eta \to \pi^+\, \pi^-\, \pi^0$	P. Guo *et al.*,	PRD92, 054016; arXiv:1608.01447
$\Lambda(1405)$	C. Fernandez-Ramirez *et al.*,	PRD93, 074015
$K\, N \to\, K\, N$	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
$\omega, \phi \to \pi^+\, \pi^-\, \pi^0$	I. Danilkin *et al.*,	PRD91, 094029
$\gamma\, p \to\, K^+\, K^-\, p$	M. Shi *et al.*,	PRD91, 034007

See also A. Jackura's talk on diffractive 3π production - Tomorrow, 12:05PM

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/


INDIANA UNIVERSITY BLOOMINGTON
Jefferson Lab
Thomas Jefferson National Accelerator Facility
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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 $p_{\rm lab}$ (in GeV) or the total energy squared $s = W^2$ (in GeV^2). The second is the cosine of

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 :

$p_{\rm lab}$ 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
$p_{\rm lab}$ 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

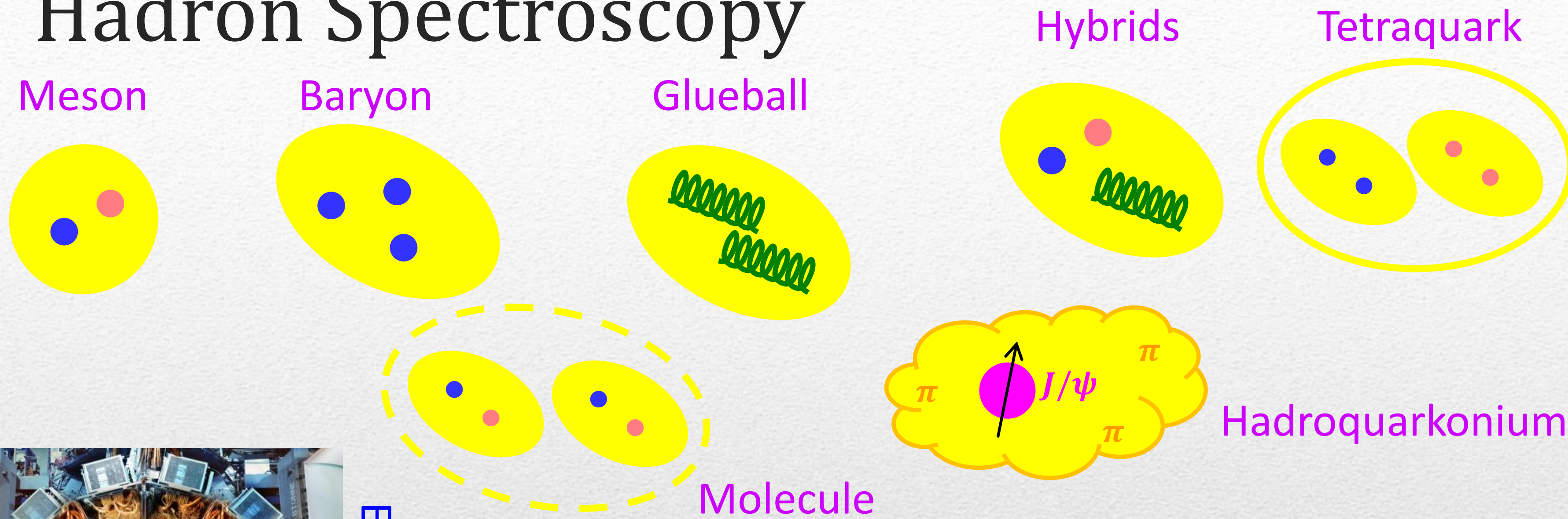
The fixed variable:

t in GeV^2	0
$p_{\rm lab}$ in GeV	5

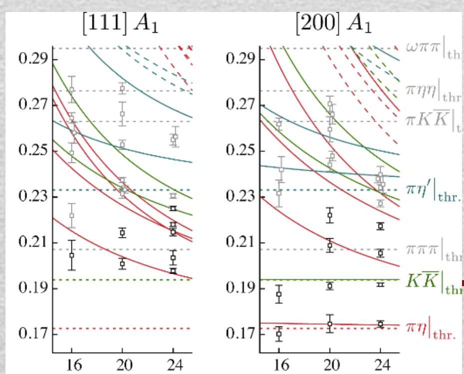
Start reset

Results

Hadron Spectroscopy



Experiment

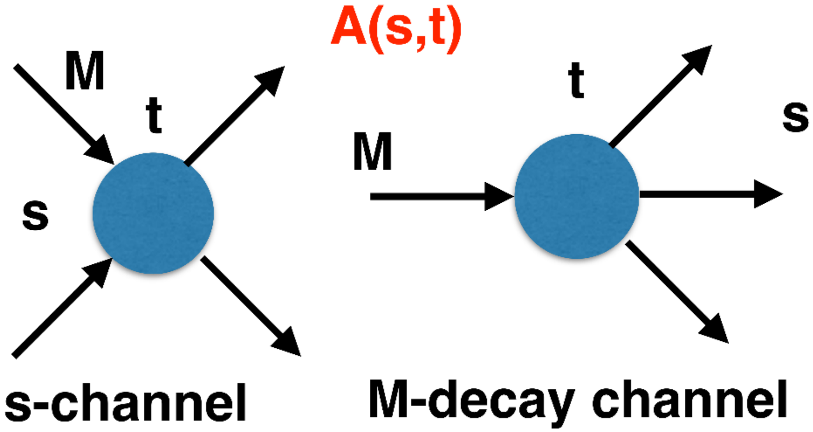


Lattice QCD

Data → Amplitude analysis (JPAC) → Properties, Model building

Interpretations on the spectrum leads to understanding fundamental laws of nature

S-Matrix principles



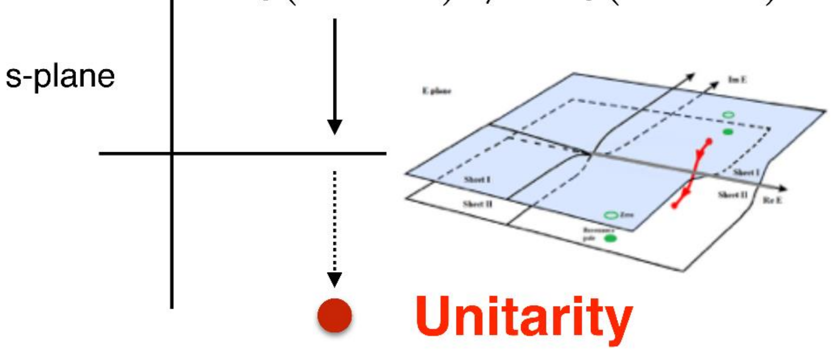
Crossing

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

Analyticity

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

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

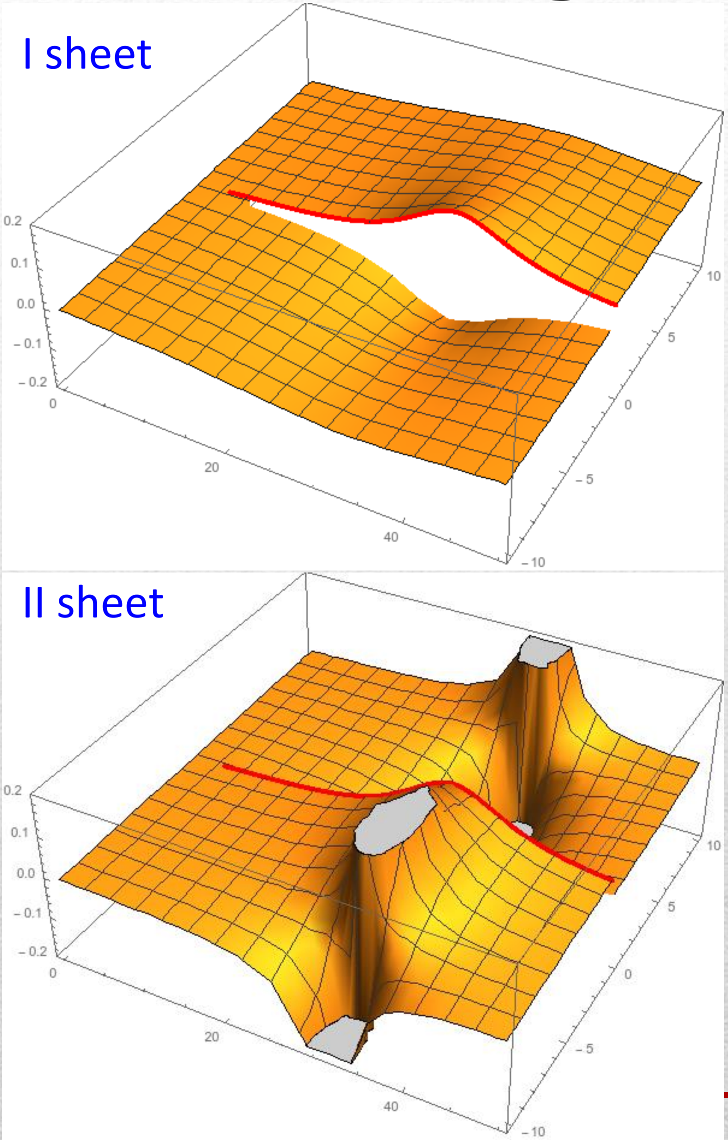


Unitarity

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

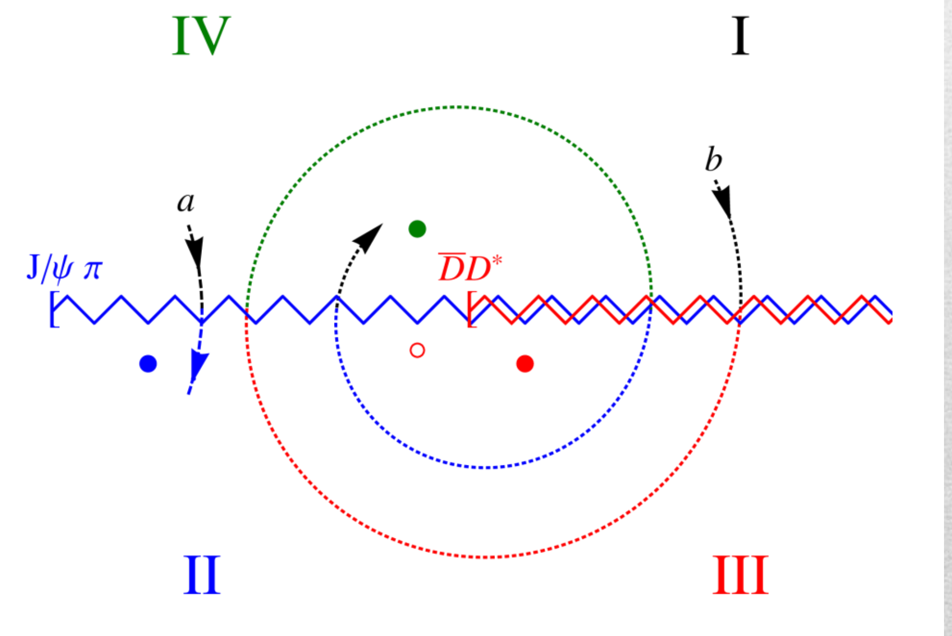
Resonances (QCD states) are poles in the unphysical Riemann sheets

Pole hunting



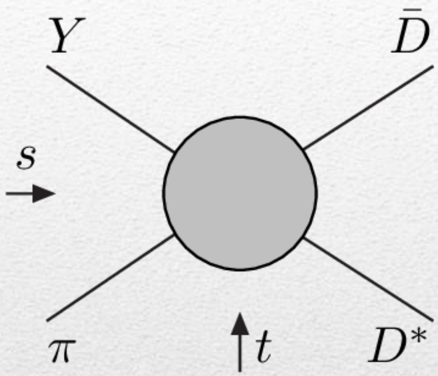
More complicated structure when more thresholds arise:
two sheets for each new threshold

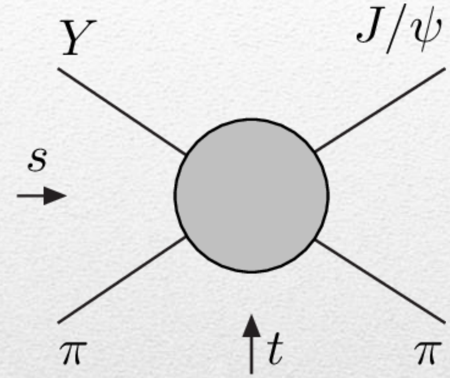
III sheet: usual resonances
IV sheet: cusps (virtual states)



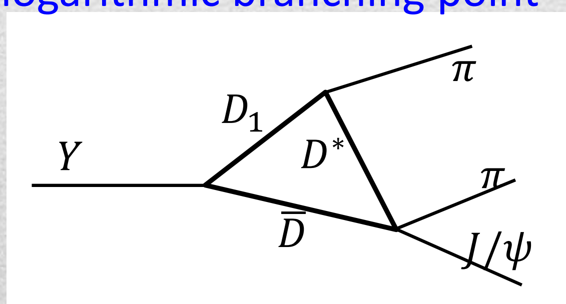
Case study, $Z_c(3900)$

One can test different parametrizations of the amplitude, which correspond to different singularities → different natures



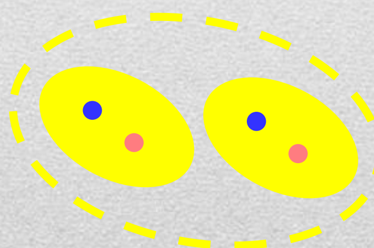


Triangle rescattering,
logarithmic branching point



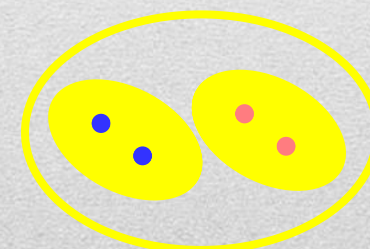
Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo *et al.* PRD92, 071502

(anti)bound state,
II/IV sheet pole



Tornqvist, Z.Phys. C61, 525
Swanson, Phys.Rept. 429
Hanhart *et al.* PRL111, 132003

Compact QCD state,
III sheet pole

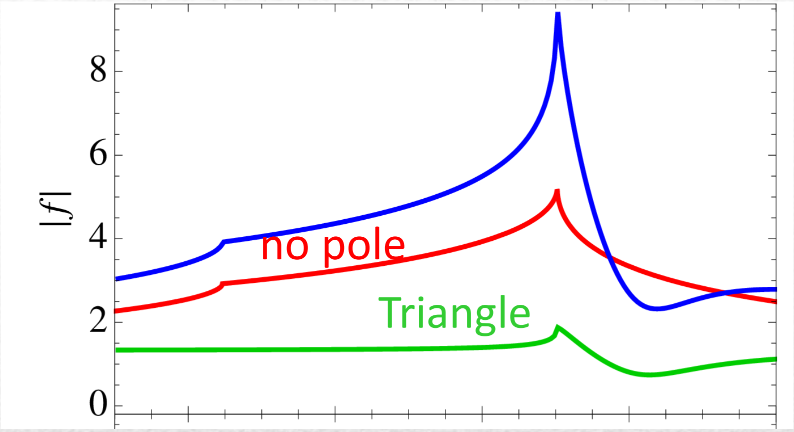


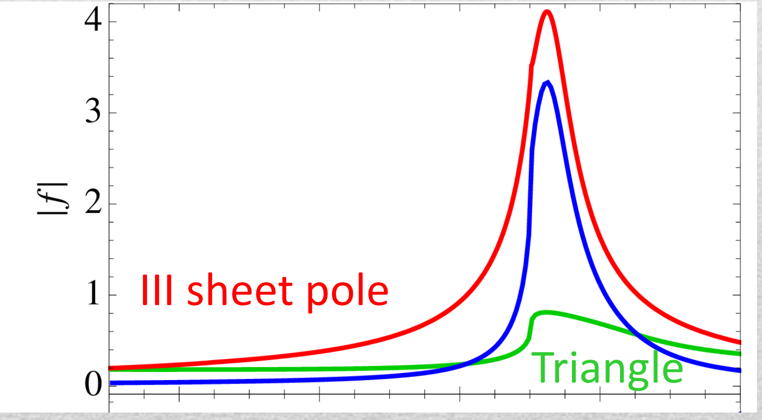
Maiani *et al.*, PRD71, 014028
Maiani *et al.*, PRD87, 111102
AP *et al.*, Phys.Rept. 668

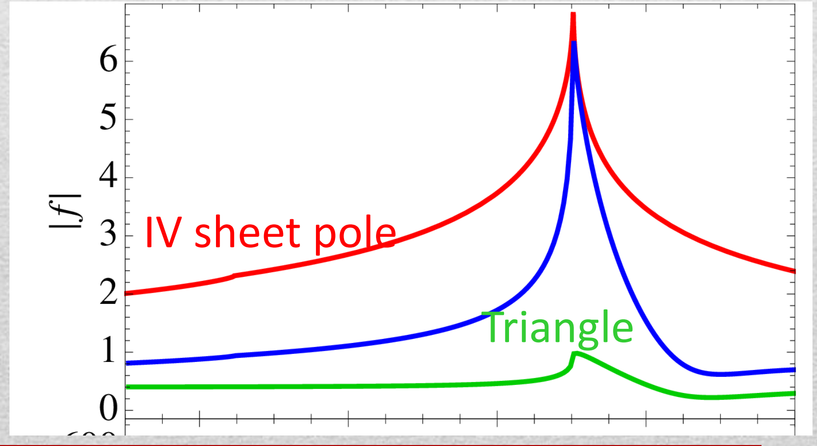
Singularities and lineshapes

Different lineshapes according to different singularities

AP *et al.* (JPAC), arXiv:1612.06490





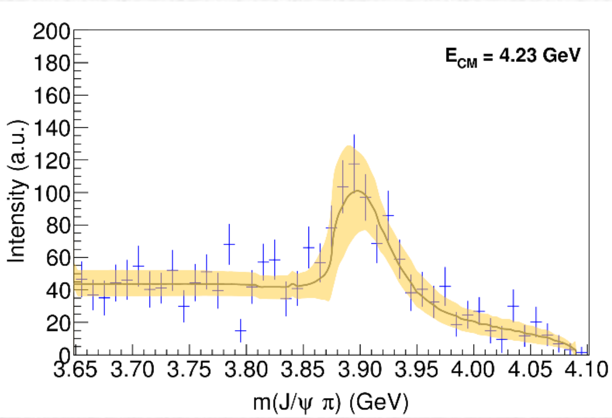


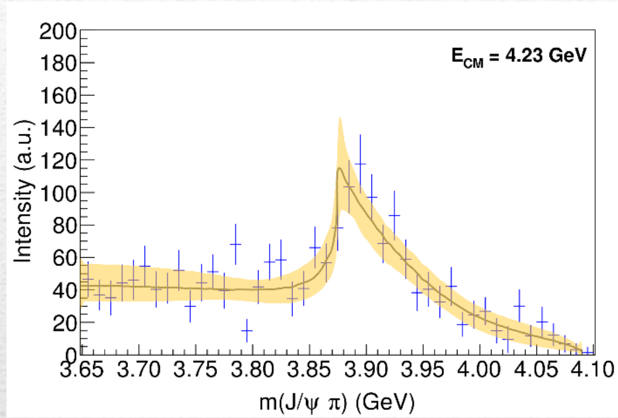
Pole extraction

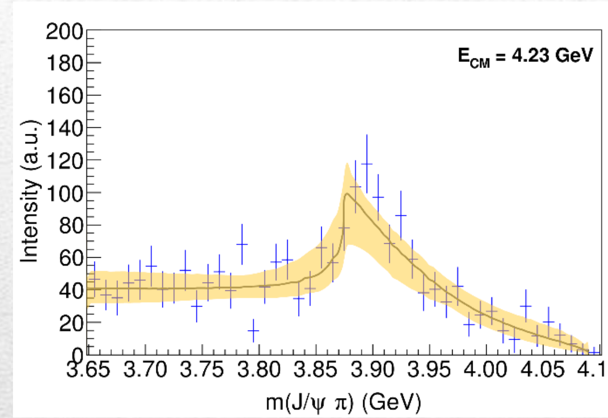
III sheet pole
(QCD state, tetraquark)

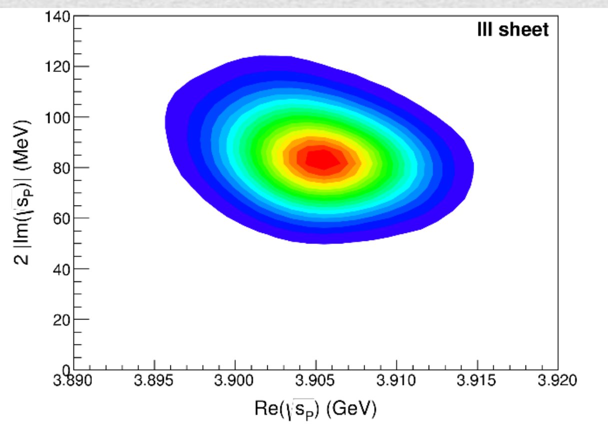
IV sheet pole
(unbound molecule)

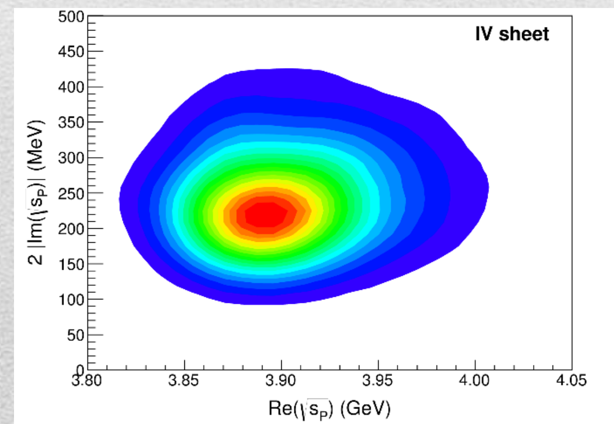
Log. branch point
(rescattering effect)







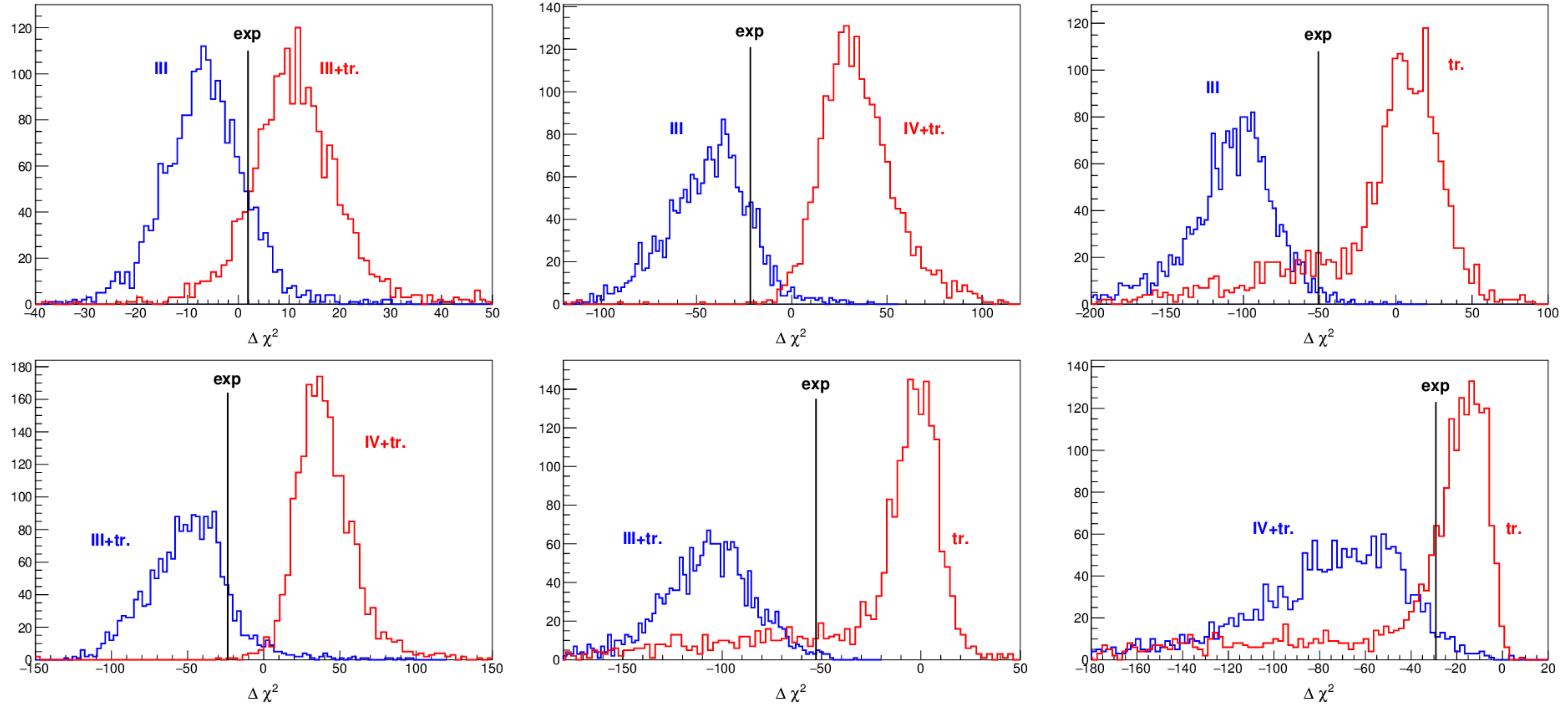




Fits to data do not give a clear preference for any model

AP *et al.* (JPAC), arXiv:1612.06490

Case study, $Z_c(3900)$



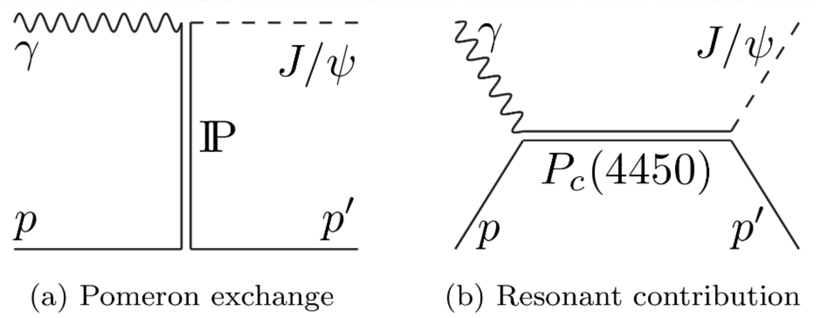
No strong conclusion can be driven yet, but we are establishing the method to use when higher statistics will be available (in particular to constrain the $D_1(2420)$ contribution)

Pentaquark photoproduction

We propose to search the $P_c(4450)$ state in photoproduction (no triangle)

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

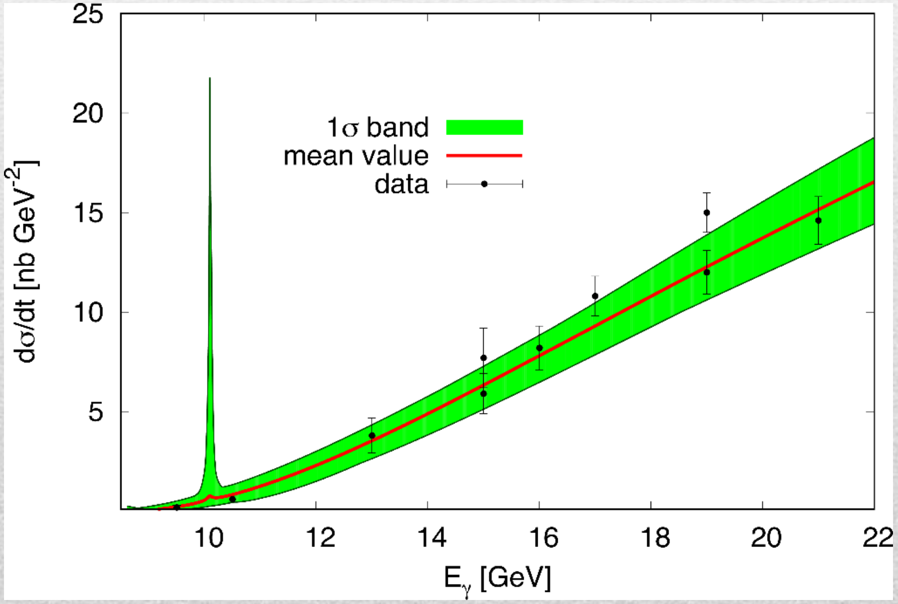
→ See talk by B. Duran!



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

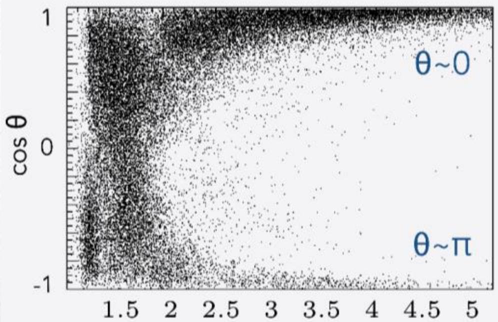
$J^P = (3/2)^-$

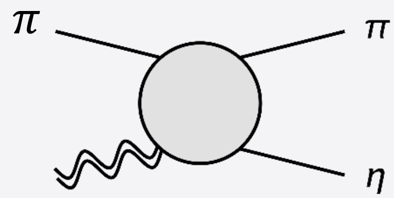
σ_s (MeV)	0	60	120
A	$0.156^{+0.029}_{-0.020}$	$0.157^{+0.039}_{-0.021}$	$0.157^{+0.037}_{-0.022}$
α_0	$1.151^{+0.018}_{-0.020}$	$1.150^{+0.018}_{-0.026}$	$1.150^{+0.015}_{-0.023}$
α' (GeV^{-2})	$0.112^{+0.033}_{-0.054}$	$0.111^{+0.037}_{-0.064}$	$0.111^{+0.038}_{-0.054}$
s_t (GeV^2)	$16.8^{+1.7}_{-0.9}$	$16.9^{+2.0}_{-1.6}$	$16.9^{+2.0}_{-1.1}$
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

Finite energy sum rules





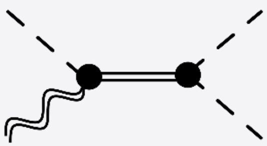
$s_1 = m(\eta\pi)^2$

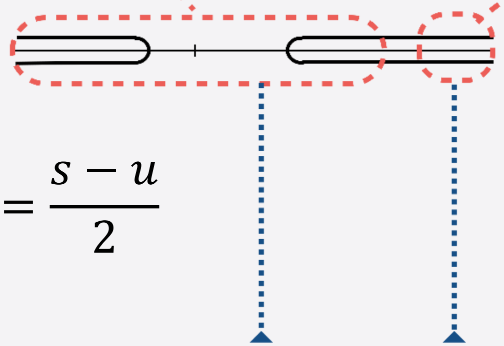
low energy

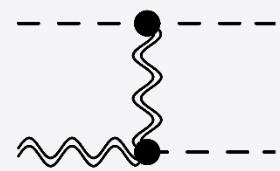
high energy

N/D

Regge pole







reconstructed from *PWA*

lhs

$$\nu = \frac{s-u}{2}$$

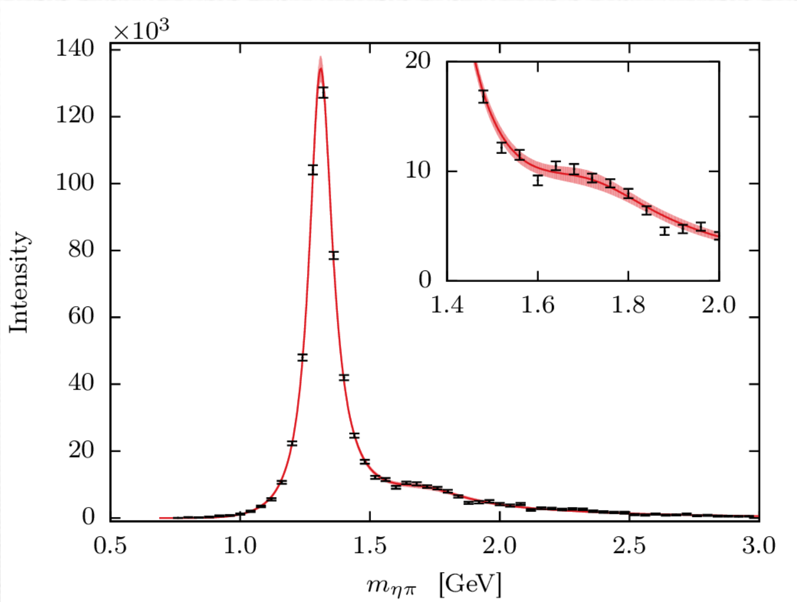
rhs

Regge parametrization

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

aim: *first systematic analysis of* ***peripheral production*** *using* ***FESR***

$\eta\pi$ production



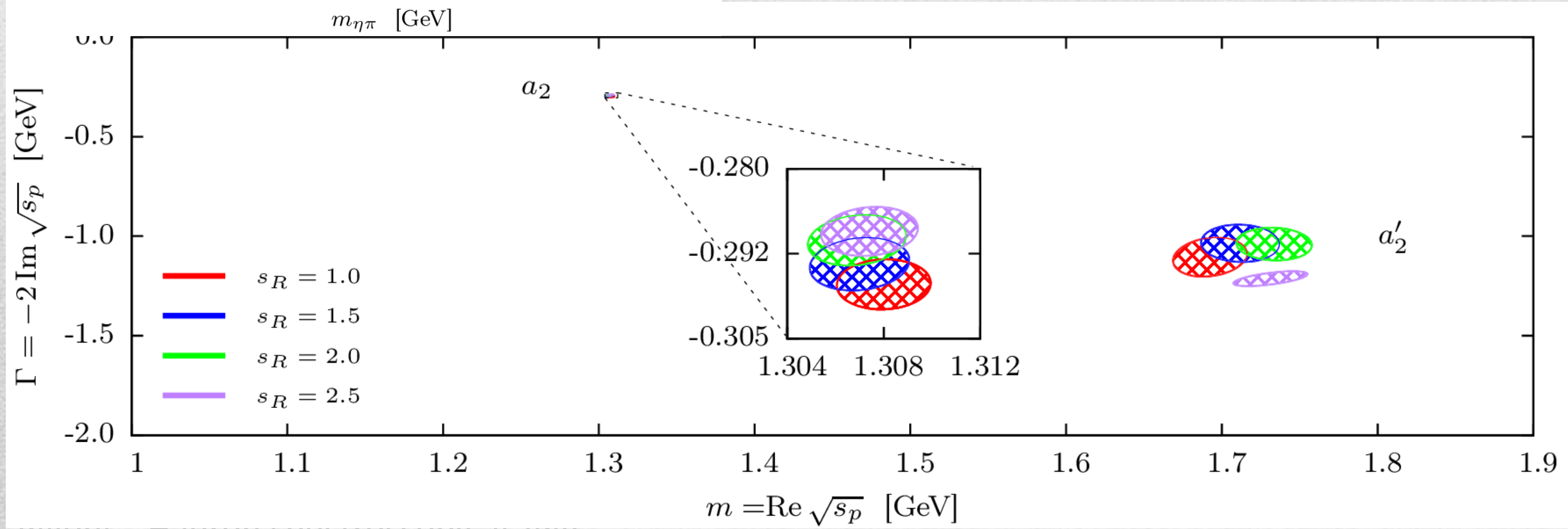
The $\eta\pi$ system is one of the golden modes for hunting hybrid mesons

We build the partial waves amplitude according to the N/D technique

We test the method on the D-wave data, where the a_2 and the a_2' show up

The coupled channel analysis to extract the parameters of the exotic P-wave is ongoing

A. Jackura, V. Pauk (JPAC), in progress

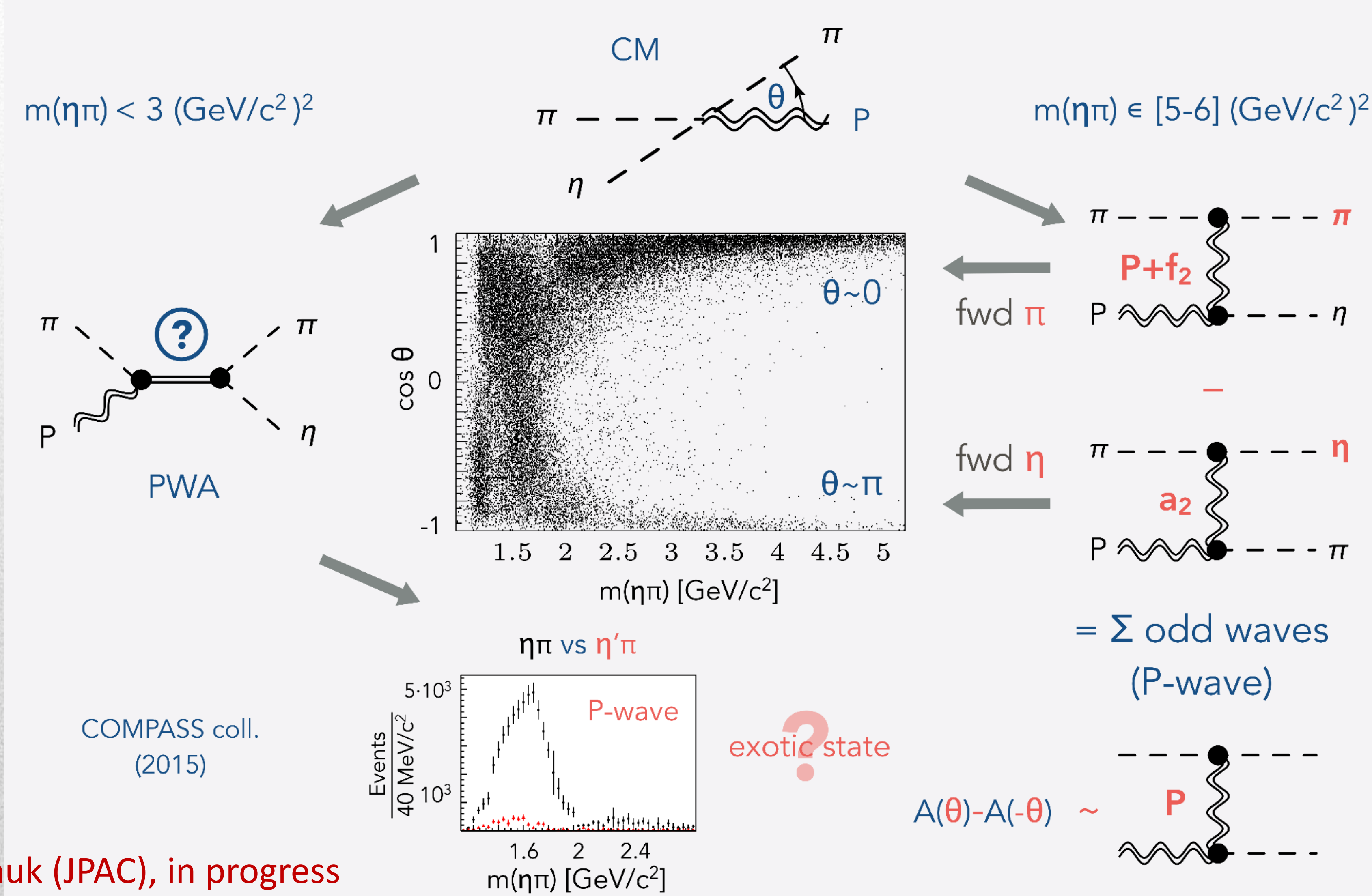


Summary

- 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

$\eta\pi$ production



V. Pauk (JPAC), in progress

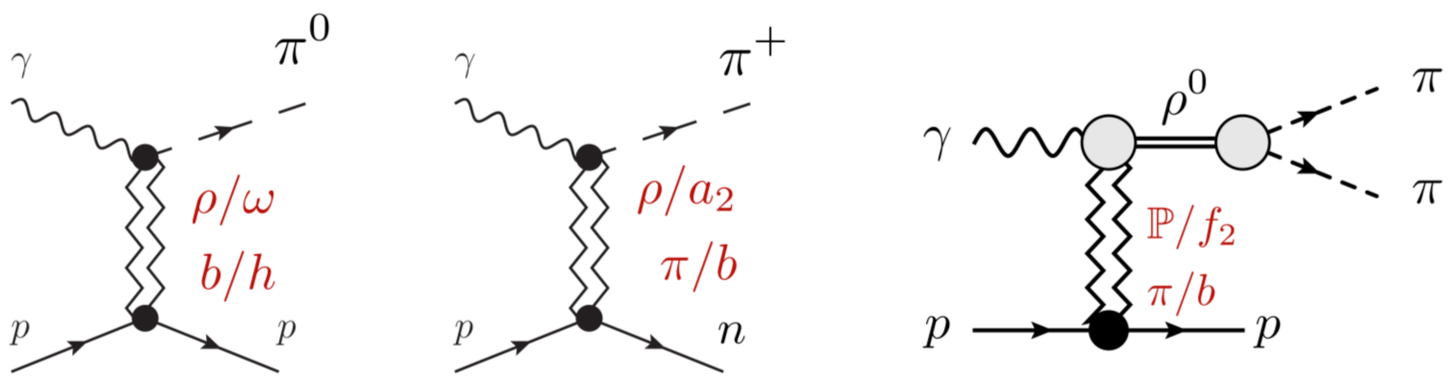
Joint Physics Analysis Center

- 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

π, ρ photoproduction

Test factorization on the simplest cases

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



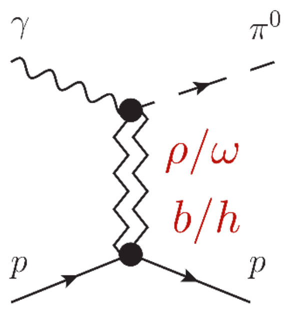
natural exchanges: $\rho/\omega/f_2/a_2/\mathbb{P}$ $\quad P = (-)^J$

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

special ?

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

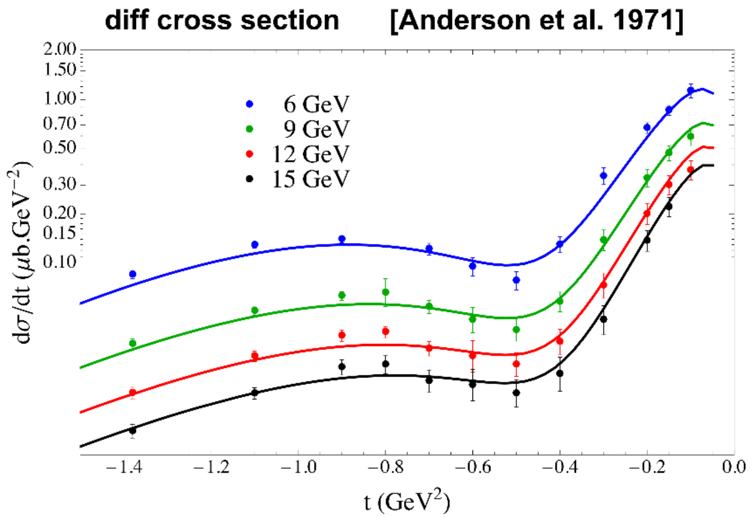
Model based on **factorization**
with parameters fitted

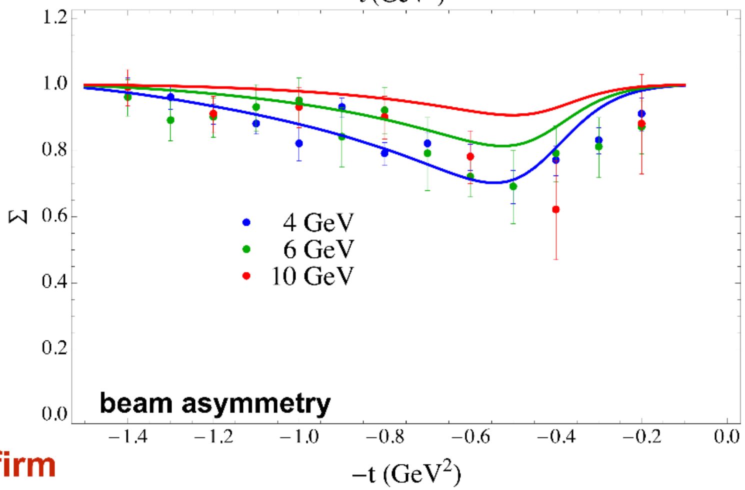


$$\Sigma = \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{|\rho+\omega|^2 - |b+h|^2}{|\rho+\omega|^2 + |b+h|^2}$$

axial-vector exchanges strength decreases with energy

More precise data@JLAB could confirm



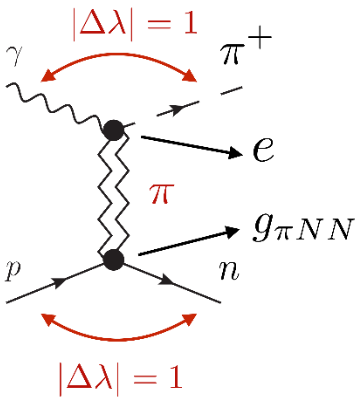


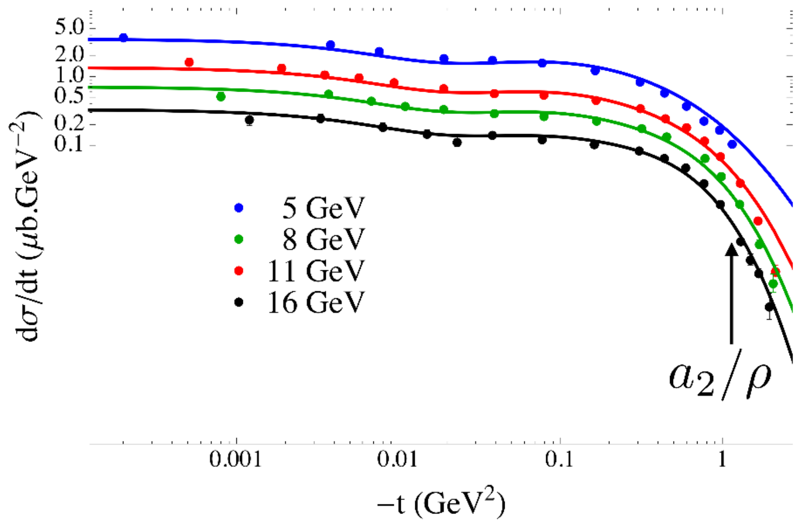
V. Mathieu *et al.* (JPAC), PRD92, 074013

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

Pion dominate very small |t| :

[Boyarski et al. 1968]





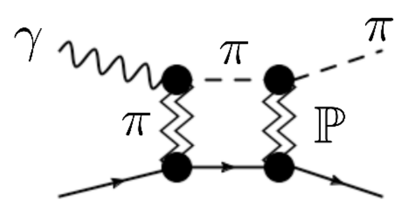
Factorization of Regge residues:
$(\lambda_\gamma, \lambda_\pi) = (1, 0)$ **and**

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

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

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

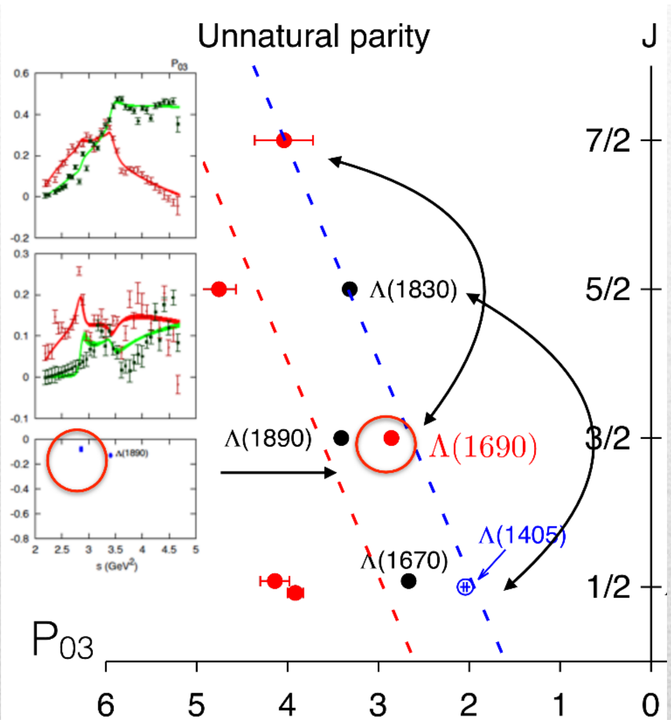
William's Poor man absorption: $\rightarrow \dfrac{-m_\pi^2}{m_\pi^2 - t}$

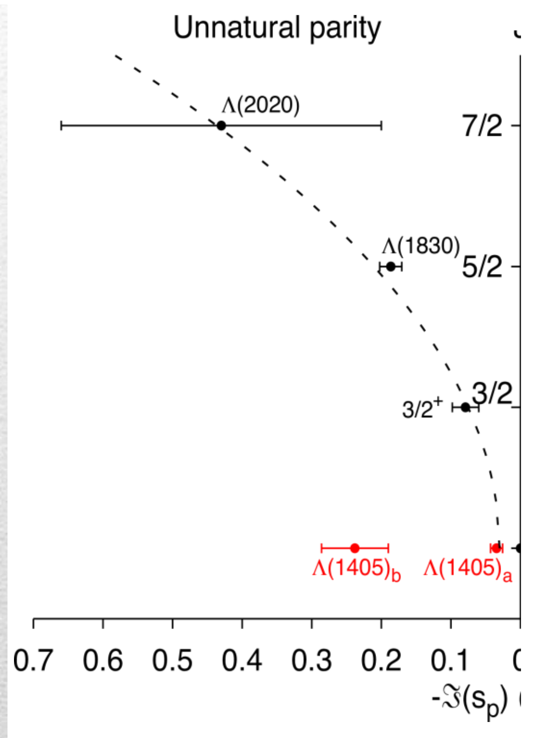


V. Mathieu (JPAC), in progress

KN 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

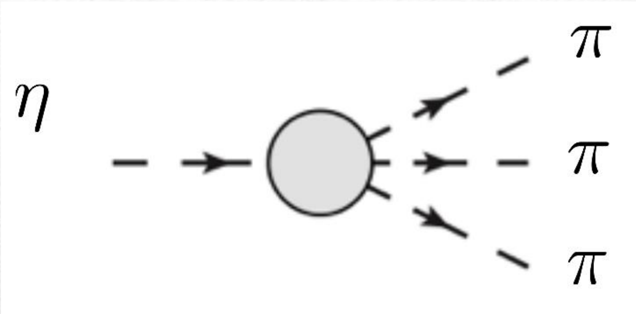




One of the $\Lambda(1405)$ poles is out of the trajectory
→ non 3-q state

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

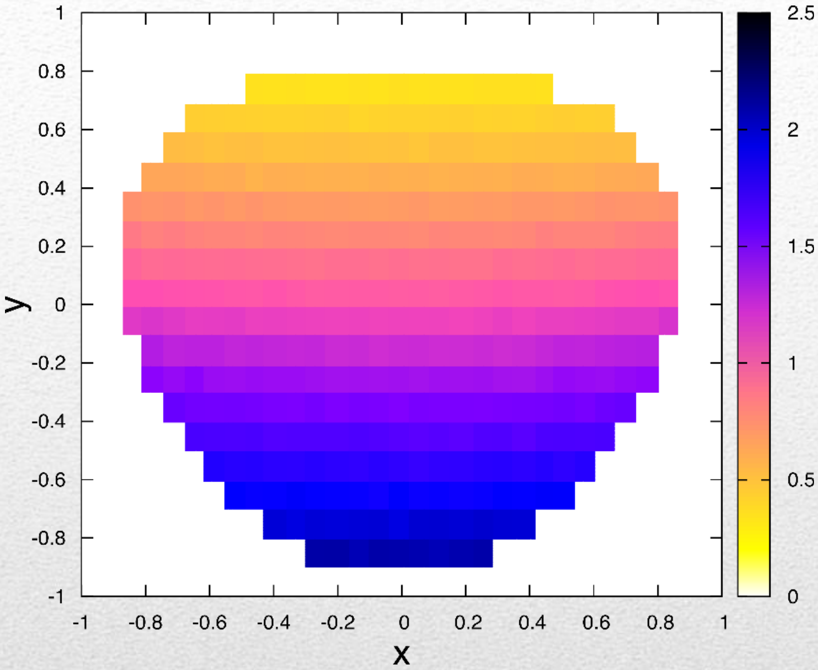
$\eta \to 3\pi$



Isospin violating decay,
sensitive to quark mass difference

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

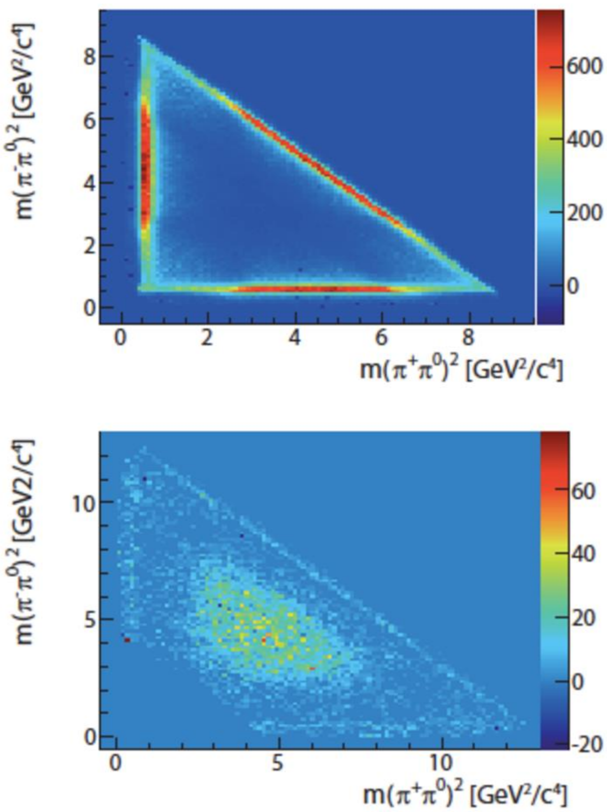
$$Q = \frac{m_s^2 - (m_d + m_u)^2/4}{m_d^2 - m_u^2} \sim 21.6 \pm 0.4$$



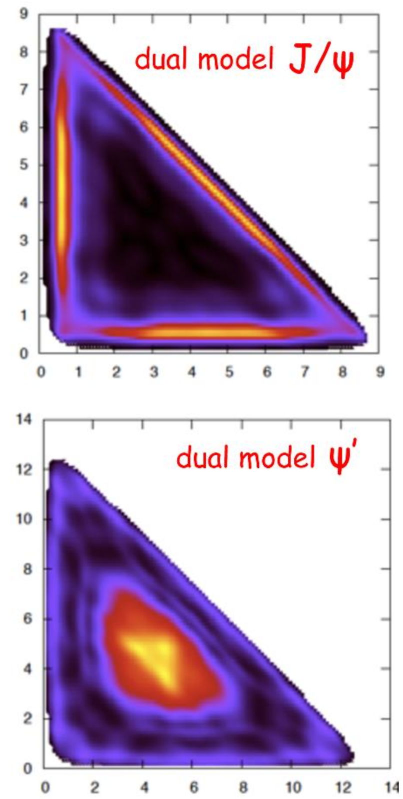
Data from
WASA-at-COSY PRC90, 045207
KLOE-2 JHEP 05, 019

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

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



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

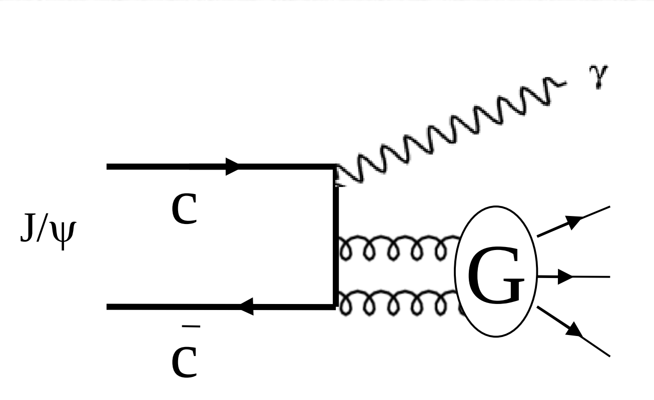


$$A(s,t) = \frac{\Gamma(-J(s))\Gamma(-J(t))}{\Gamma(-J(s)-J(t))}$$

A. Szczepaniak and M. Pennington, PLB737, 283

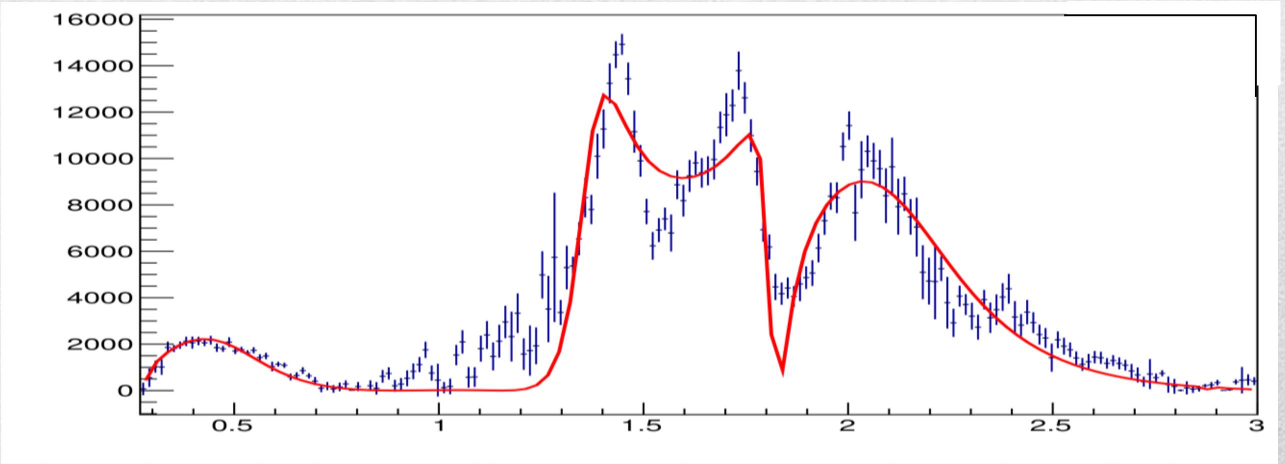
$J/\psi \to \gamma\, \pi^0\pi^0$

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

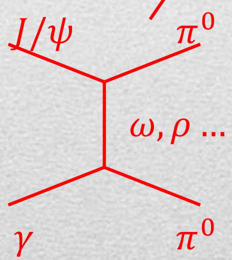
A. Pilloni (JPAC), in progress

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

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

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

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



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

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

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

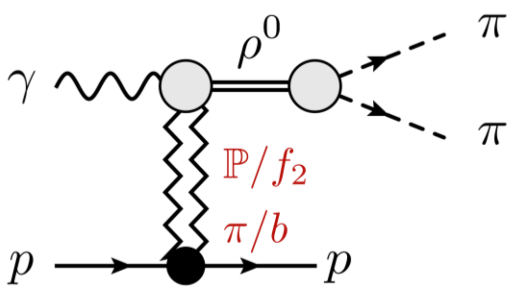
Adler zero
describes the σ region

K-matrix poles

Background terms
(effective LHC)

A. Pilloni

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



Use beam polarization to extract spin density matrix elements:

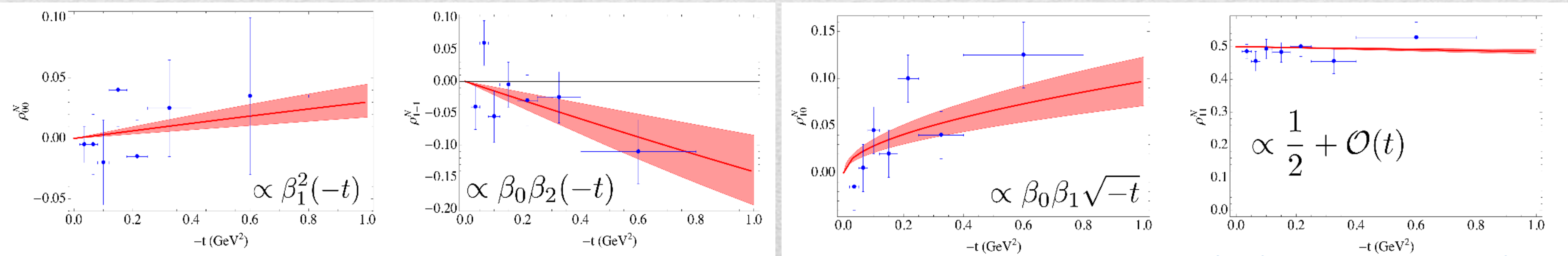
$$\rho^0_{MM'} = \frac{1}{N} \sum_{\lambda_\gamma \lambda_p \lambda_{p'}} A_{\lambda_\gamma \lambda_p \lambda_{p'}, M} A^*_{\lambda_\gamma \lambda_p \lambda_{p'}, M'}$$

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

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

At leading s, one can separate natural and unnatural exchanges

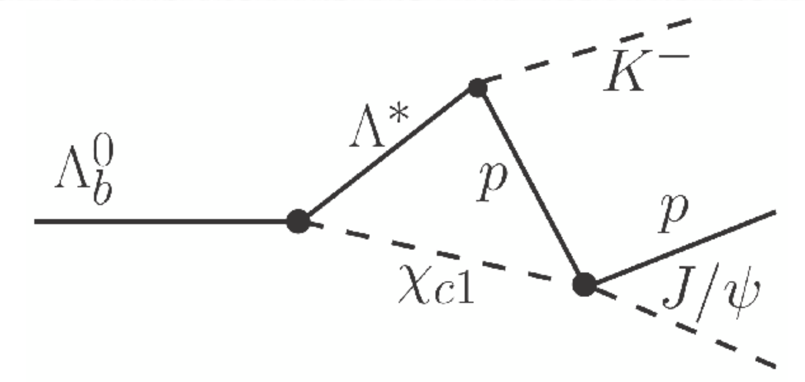
Test factorization at top vertex: non-flip $\beta_0\left(\sqrt{-t}\right)^0$, single-flip $\beta_0\left(\sqrt{-t}\right)^0$, double-flip $\beta_2\left(\sqrt{-t}\right)^2$

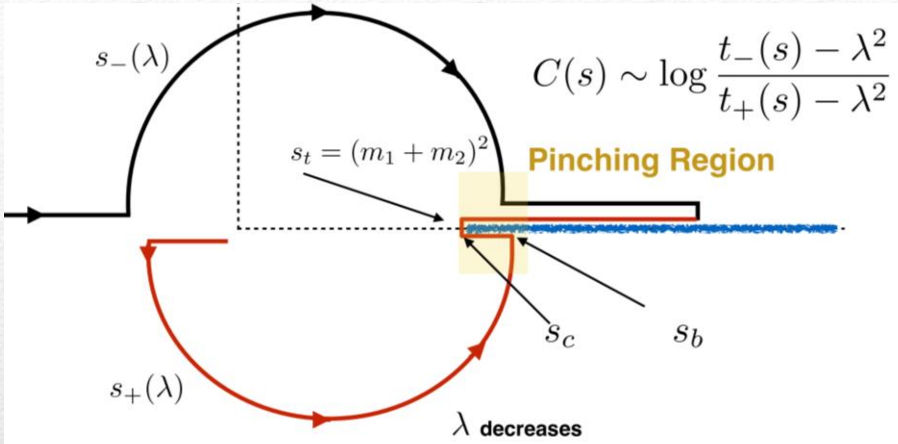


Fit gives $\beta_0 : \beta_1 : \beta_2 = 1.00 : 0.14 : -0.09$, which agrees with the expected trend

V. Mathieu

Other models: triangle singularity





Logarithmic branch points due to exchanges in the cross channels can simulate a resonant behavior, only in very special kinematical conditions (Coleman and Norton, Nuovo Cim. 38, 438), However, this effects cancels in Dalitz projections, no peaks (Schmid, Phys.Rev. 154, 1363)

$$f_{0,i}(s) = b_{0,i}(s) + \frac{t_{ij}}{\pi} \int_{s_i}^{\infty} ds' \frac{\rho_j(s') b_{0,j}(s')}{s' - s}$$

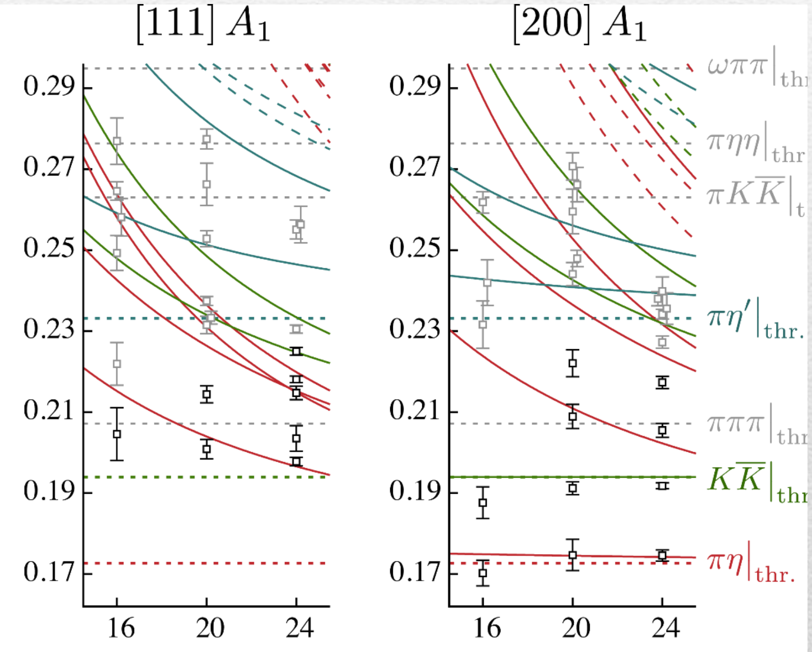
...but the cancellation can be spread in different channels, you might still see peaks in other channels only!

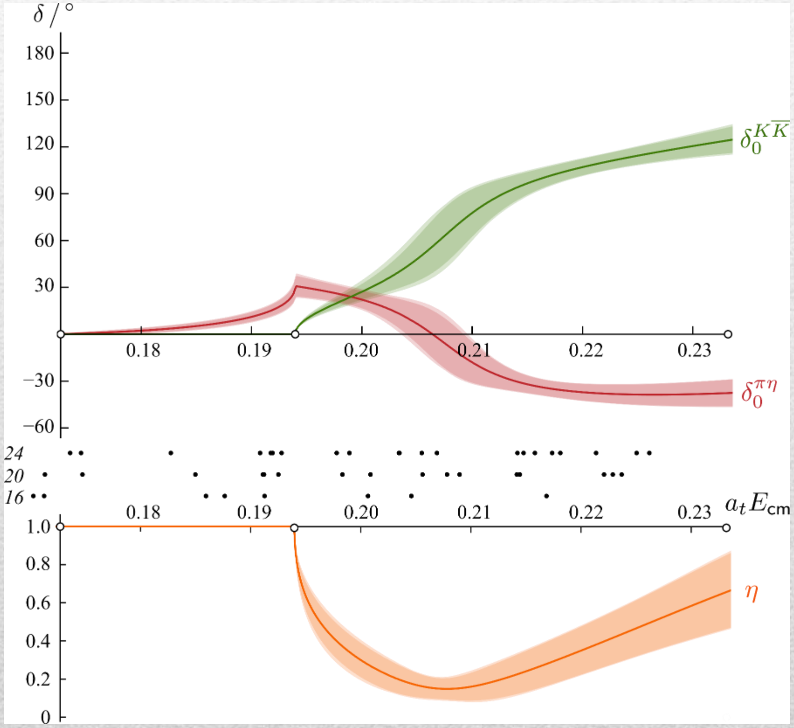
Szczepaniak, PLB747, 410-416
Szczepaniak, PLB757, 61-64
Guo, Meissner, Wang, Yang PRD92, 071502

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

- Amplitude are analytical functions of the Mandelstam variables constrained, $A(s,t)$ fundamental object
- Amplitude bumps/peaks seen on the real axis (experiment) come from singularities on unphysical sheets
- The only singularities come from physical processes (thresholds, resonances)
- The singularities on unphysical sheet are dynamical (from QCD) and are not determined by S-matrix. They can be constrained by S-matrix

$$A(s) = \sqrt{s}$$
$$A_{II}(s) = -\sqrt{s}$$

$$A(4 + i\epsilon) = \sqrt{4\, e^{i\epsilon}} = 2$$
$$A_{II}(4 + i\epsilon) = -2$$

Experiment happens here

$$A(4 - i\epsilon) = \sqrt{4\, e^{2i\pi - i\epsilon}} = -2$$
$$A_{II}(4 - i\epsilon) = 2$$