Phenomenological studies on hadronic reactions and resonance extraction

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3rd PIKIO Meeting
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Outline

- Hadron Spectroscopy and Amplitude Analysis
- JPAC work on Exotic Resonances
- Light Meson Spectroscopy
  - $\pi N \to 3\pi N$
  - $\pi N \to \eta\pi N$

Joint Physics Analysis Center (JPAC)

- JPAC is a collaboration between theorists, phenomenologists, and experimentalists to provide phenomenological and data analysis tools for hadron physics
- $\sim$ 20 active members
- $>$ 40 Research Papers (Phys.Rev., Phys.Lett, Eur.J. Phys.)
- $\mathcal{O}(10)$ ongoing analyses
- Regular lecture series on relativistic reaction theory
- Summer Workshop on Reaction Theory (2015 & 2017)

`http://www.indiana.edu/~ssrt/`

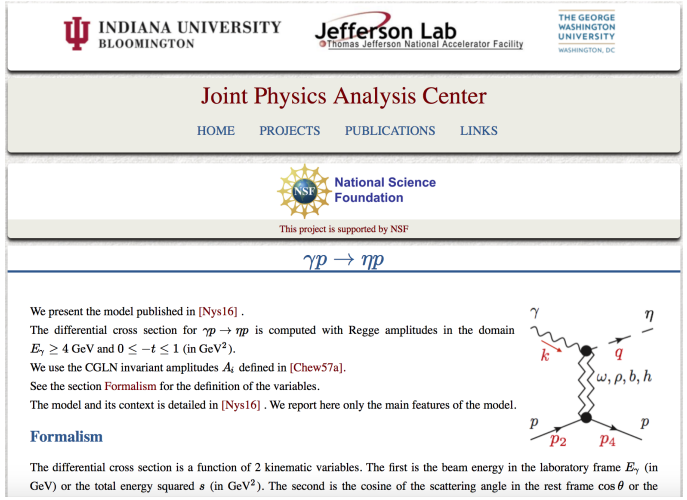
Joint Physics Analysis Center (JPAC)

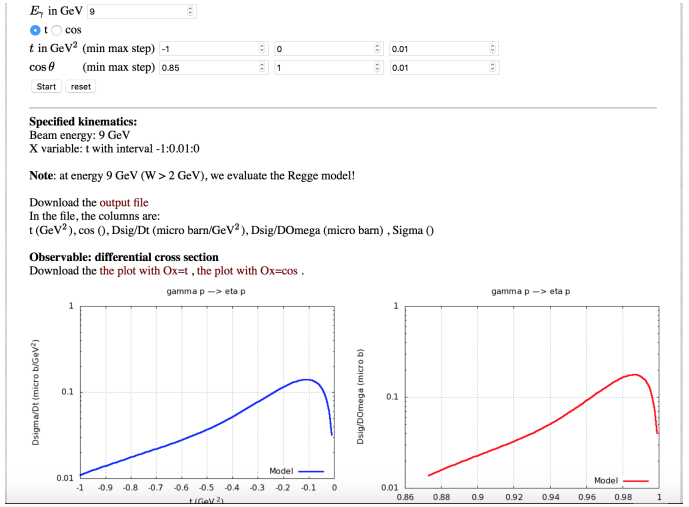
- Some JPAC work:

$Z_c(3900)$	A. Pilloni *et al.*	arXiv:1612.06490
$\gamma p \to \eta p$	J. Nys *et al.*	arXiv:1611.04658
$P_c(4450)$	A. Blin *et al.*	PRD **94**, 034002
$\eta \to \pi^+\pi^-\pi^-$	P. Guo *et al.*	PRD **92**, 054016
$\Lambda(1405)$	C. Fernández-Ramírez *et al.*	PRD **93**, 074015
$\bar{K}N \to \bar{K}N$	C. Fernández-Ramírez *et al.*	PRD **93**, 034029
$\pi N \to \pi N$	V. Mathieu *et al.*	PRD **92**, 074004
$\gamma p \to \pi^0 p$	V. Mathieu *et al.*	PRD **92**, 074013
$\omega, \phi \to \pi^+\pi^-\pi^0$	I. Danilkin *et al.*	PRD **91**, 094029
$\gamma p \to K^+K^-p$	M. Shi *et al.*	PRD **91**, 034007

Joint Physics Analysis Center (JPAC)

- 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/`



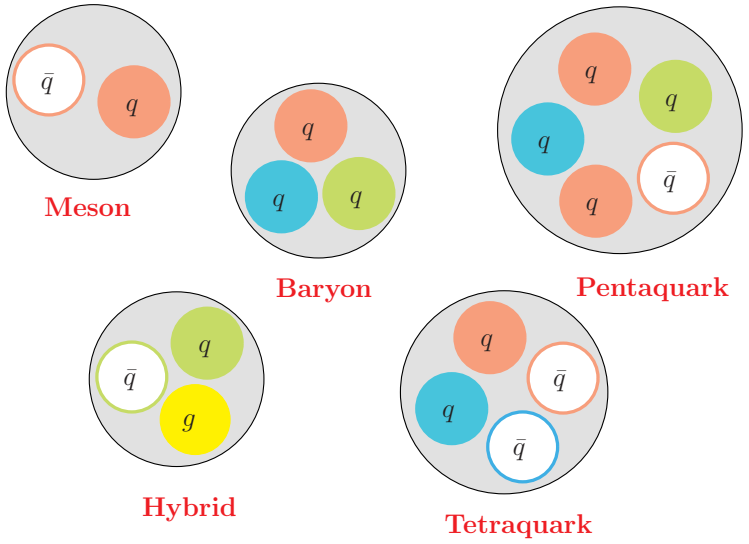


Hadron Spectroscopy

- Quantum Chromodynamics contains all information about hadrons

$$\mathcal{L}_{QCD} = \bar{q}_j(i\gamma^\mu(D_\mu)_{jk} - m_q\delta_{jk})q_k - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

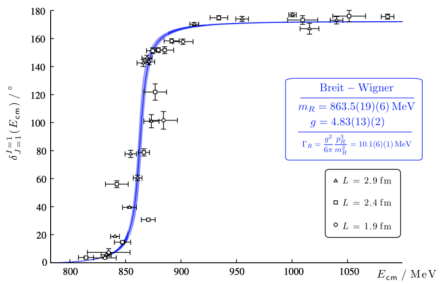
- Understand the hadron spectrum gives us clues on the nature of QCD



Experiment

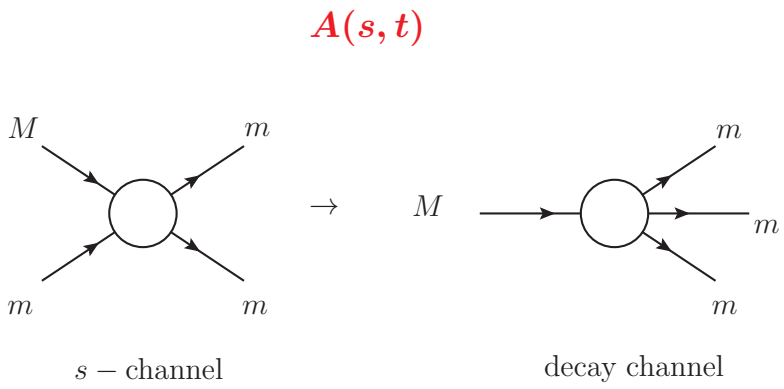
GlueX - Hall D, JLab

Lattice

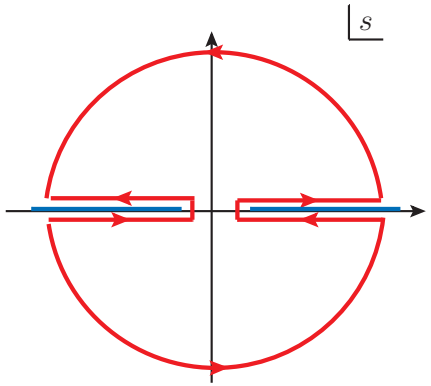


Dudek *et al.*, PRD **87**, 034505

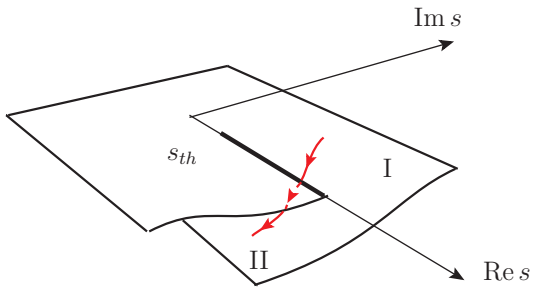
S-Matrix Princples



Crossing



Analyticity



Unitarity

$$A(s+i\epsilon,t) - A(s-i\epsilon,t) \neq 0$$

$$A(s,t) = \int \frac{ds'}{\pi} \frac{\mathrm{Im}A(s',t')}{s'-s}$$

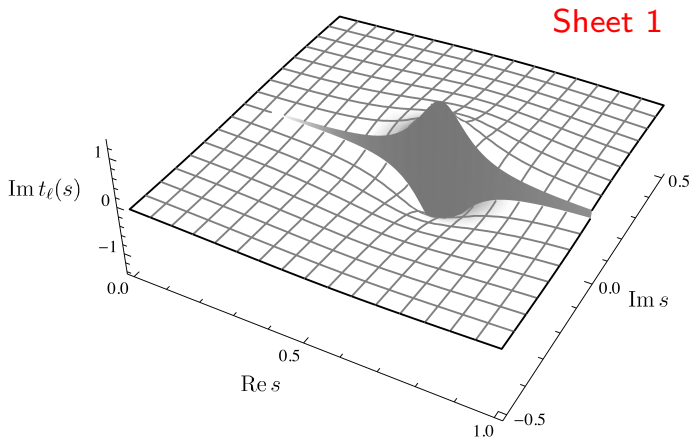
- Amplitudes must satisfy these constraints, but the constraints do not fix the dynamics
- Resonance content comes from quark models, LQCD, experiment, ...

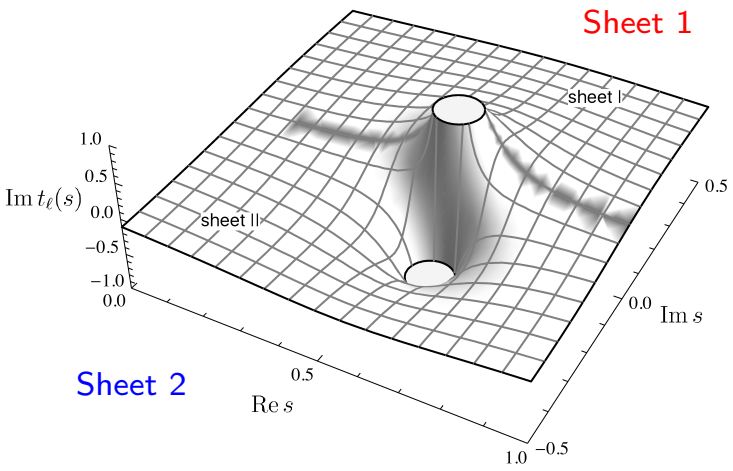
Resonances

- Resonances are associated with poles of the scattering amplitude in the complex energy plane
- Understanding of amplitude model important when continuing to complex energies
- Causality $\Longrightarrow$ poles lie on unphysical sheets
- Breit-Wigner:

$$t(s) = \frac{g^2}{m^2 - s - im\Gamma\rho(s)}$$

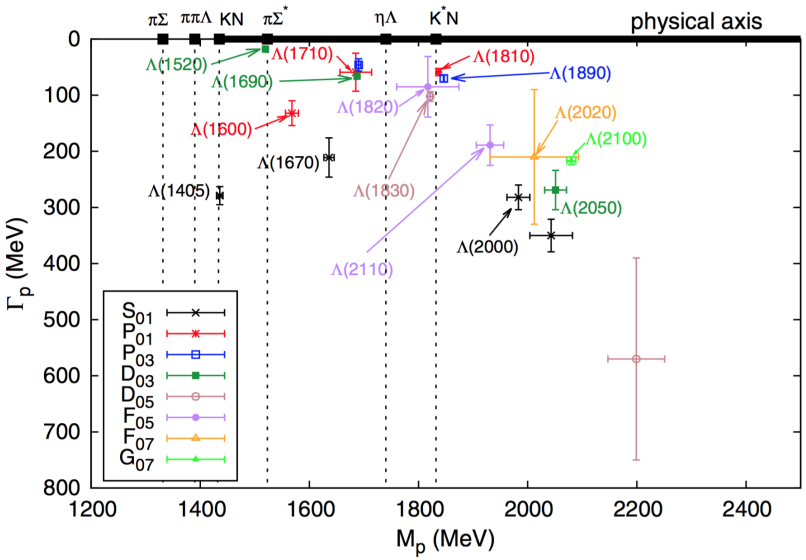
Breit-Wigner for $\pi\pi \to \rho \to \pi\pi$



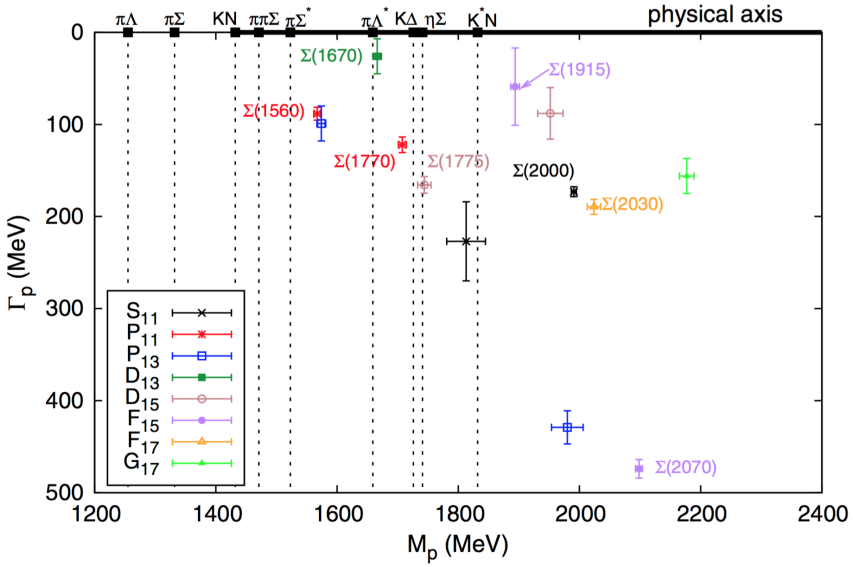


Example: Hyperon Spectrum

- Example: $\bar{K}N \to \bar{K}N$, $\bar{K}N \to \pi\Lambda$, and $\bar{K}N \to \pi\Sigma$
- Analytic multichannel model fitted to data
- Λ^* and Σ^* resonances located
- Amplitudes can be used in subsequent analyses which require these resonance



Λ^* Resonances

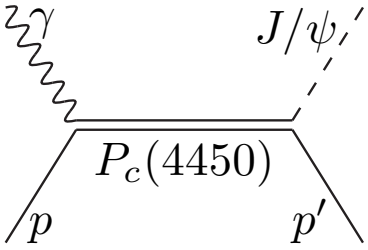


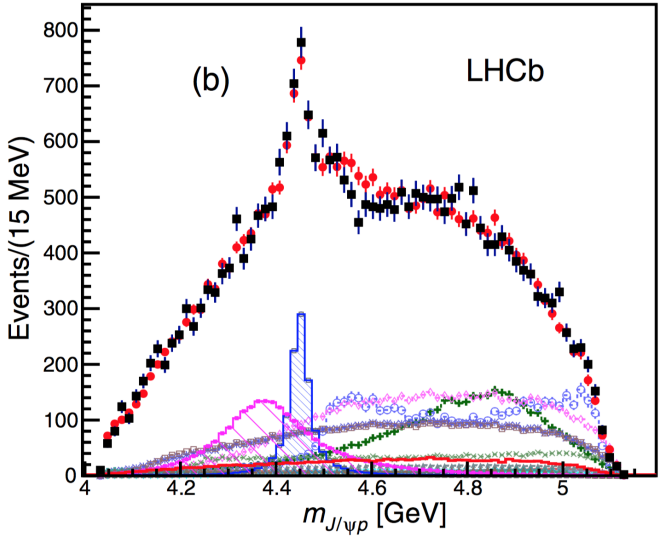
Σ^* Resonances

C. Fernandez-Ramirez *et al.* (JPAC), PRD **93**, 034029

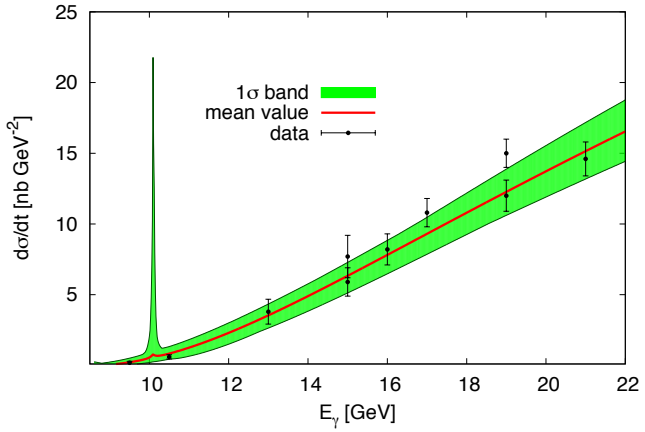
LHCb Pentaquark

- LHCb claim discovery of pentaquarks $P_c(4450)$ and $P_c(4380)$ in $\Lambda_b \to KJ/\psi p$
- Proposal to search for $P_c(4450)$ in photoproduction at JLab
- Combined JPAC-LHCb analysis on Λ_b decay using JPAC hyperon spectrum





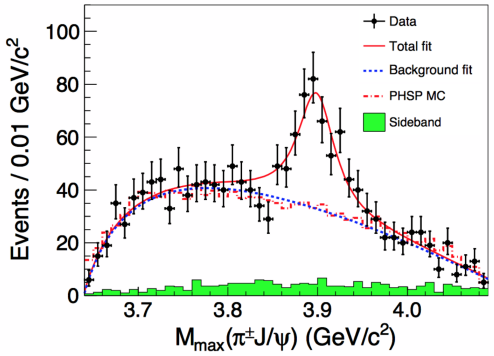
R. Aaij *et al.*, PRL **115**, 072001



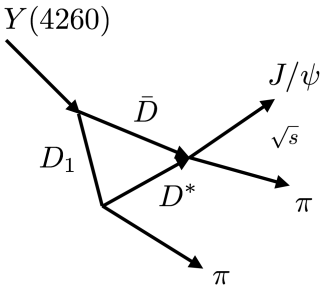
A. Blin *et al.* (JPAC), PRD **94**, 034002

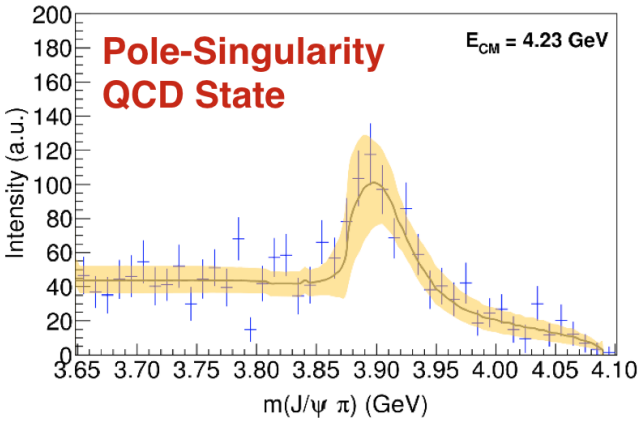
$Z_c(3900)$

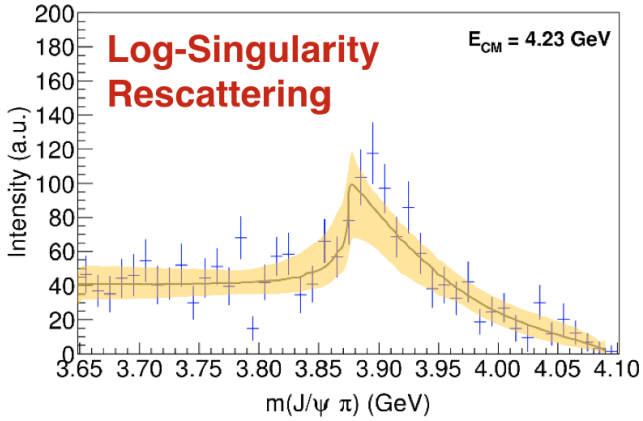
- XYZ states (discovered 2003) are non-$q\bar{q}$ mesons
- $Z_c(3900)$ is a tetraquark candidate discovered by BES and Belle
- Look into rescattering models to explain peak



M. Ablikim *et al.* (BESIII), PRL **110**, 252001

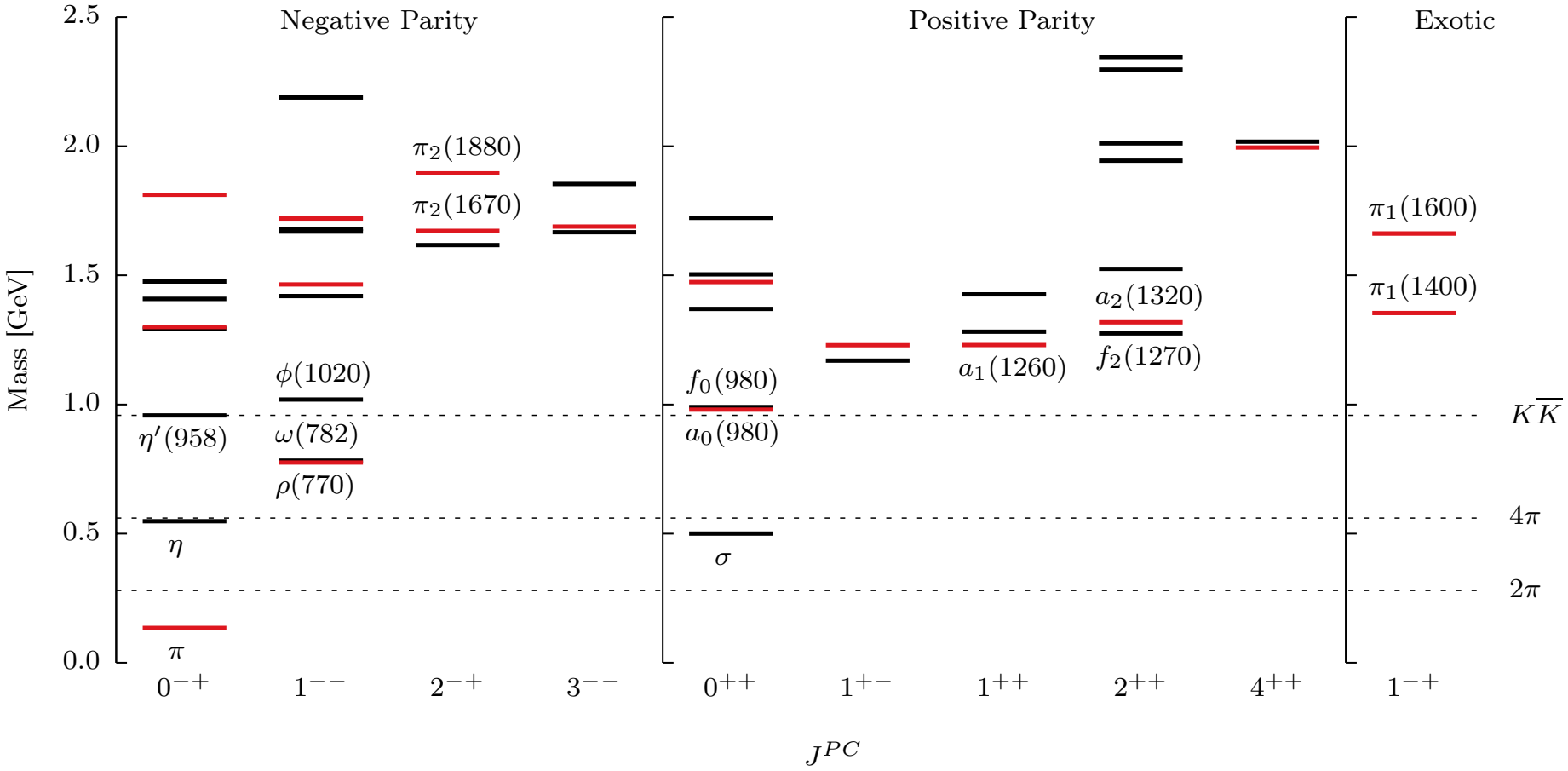






A. Pilloni, AJ *et al.* (JPAC), arXiv:1612.06490

Light Meson Spectroscopy



Amplitude Analysis at COMPASS

- COMPASS and JPAC are working together on diffractive resonance production in the 3π and $\eta^{(\prime)}\pi$ channels

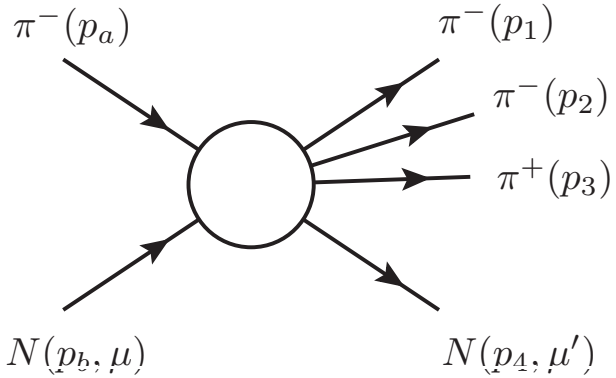
$$\pi^- N \to \pi^-\pi^-\pi^+ N \qquad \text{and} \qquad \pi^- N \to \eta^{(\prime)}\pi^- N$$

- Interested in many J^{PC} sectors: 2^{-+}, 1^{-+}, 1^{++}, ...
- JPAC model includes unitarized analytic amplitudes
- High-energy behavior, $s \to \infty$ (190 GeV/c π^- beam at COMPASS) $\Longrightarrow$ Exchange process dominated by pomeron

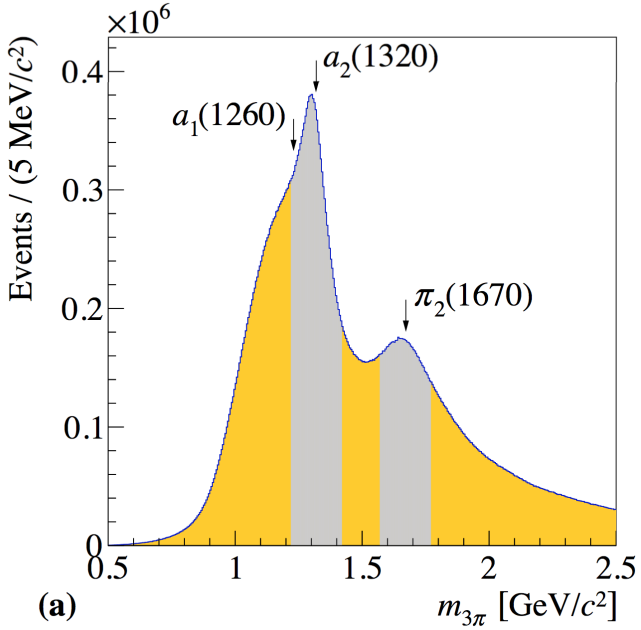
$\pi N \to 3\pi N$ at COMPASS

- Assume isobar structure in model $\Longrightarrow$ quasi-two-body process
- Focus on 2^{-+} sector
  - Understand π_2 puzzle
  - Look of hybrid states

$$A_{\mu'\mu} = \sum_{JMLS\epsilon} F^{JM\epsilon}_{LS,\mu'\mu} \sum_{\lambda} \langle J\lambda | L0S\lambda \rangle \left(\frac{2J+1}{4\pi}\right)^{1/2} D^{J\epsilon\,*}_{M\lambda}(\Omega) \left(\frac{2S+1}{4\pi}\right)^{1/2} D^{S\,*}_{\lambda 0}(\Omega')$$



C. Adolph et al. (COMPASS Collaboration), PRD **95**, 032004



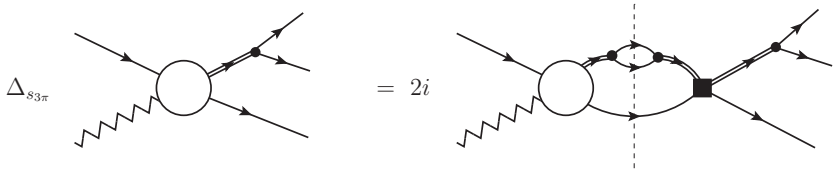
Amplitude Model: Unitarity and Analyticity

- Assume elastic rescattering only in unitarity equation

$$S = 1 + iT \ , \ S^\dagger S = 1 \implies T - T^\dagger = iT^\dagger T$$

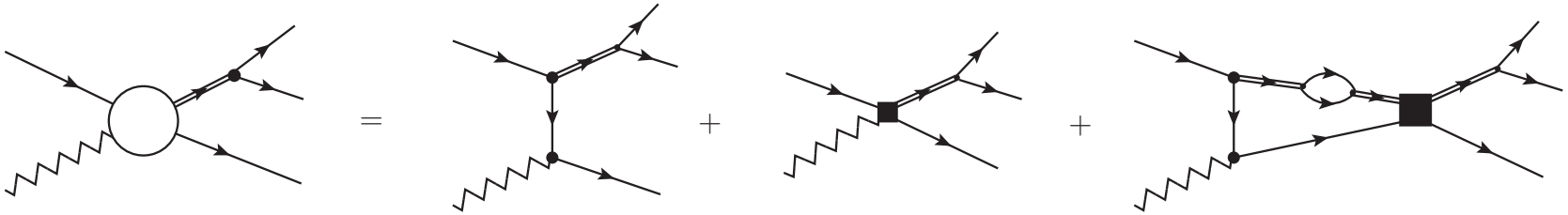
- Unitarity condition on partial wave amplitudes

$$\text{Disc}\, F_i(s_{3\pi}) = 2i \sum_j t^*_{ij}(s_{3\pi})\rho_j(s_{3\pi})F_j(s_{3\pi})$$

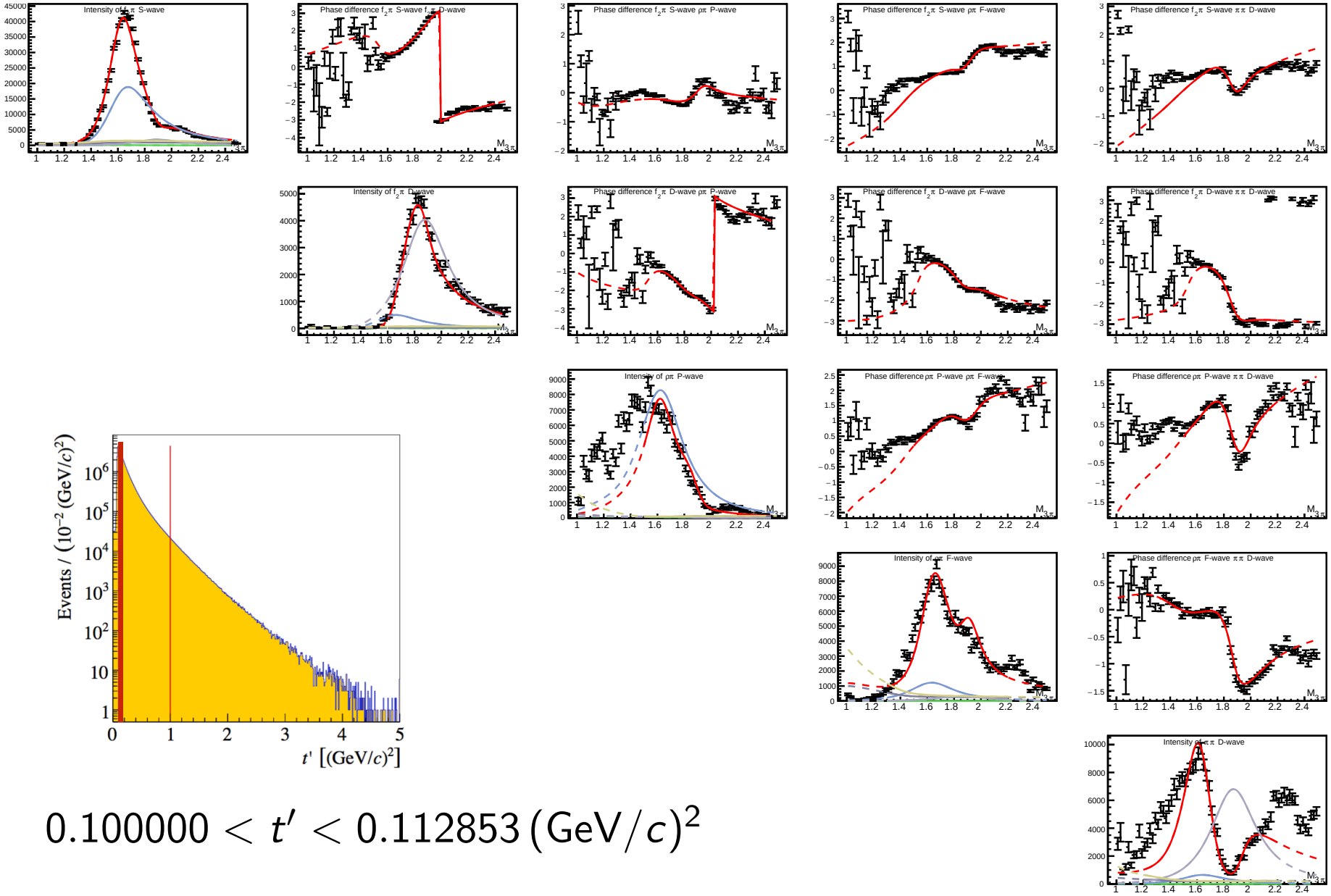


- Given rescattering t_{ij}, can write dispersive solution

$$F_i(s_{3\pi}) = b_i(s_{3\pi}) + \sum_j t_{ij}(s_{3\pi})c_j + \frac{1}{\pi}\sum_j t_{ij}(s_{3\pi}) \int_{s_j}^{\infty} ds' \frac{\rho_j(s')b_j(s')}{s' - s_{3\pi}}$$



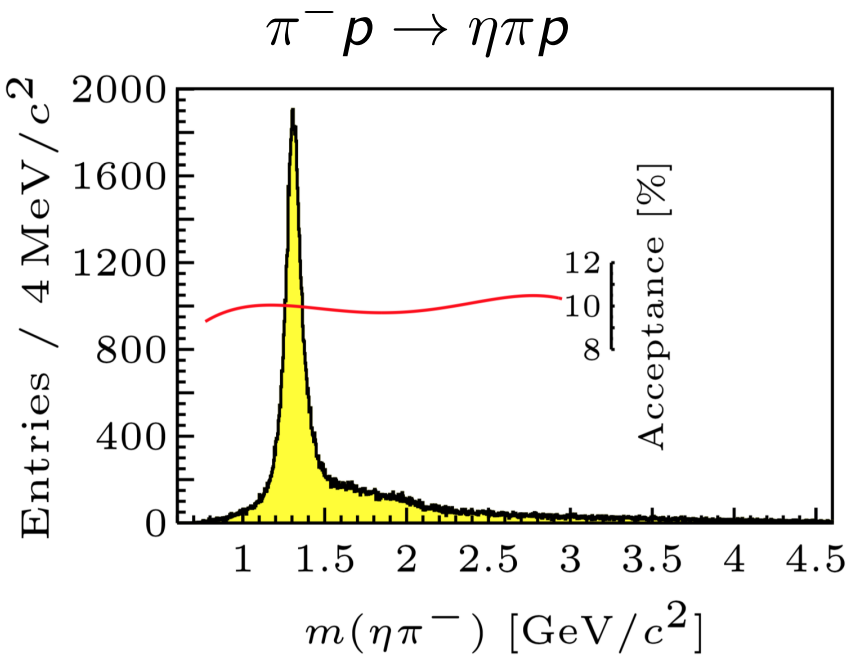
M. Mikhasenko, AJ *et al.*, in preparation



$$0.100000 < t' < 0.112853\,(\mathrm{GeV}/c)^2$$

$\pi^- p \to \eta\pi p$ at COMPASS

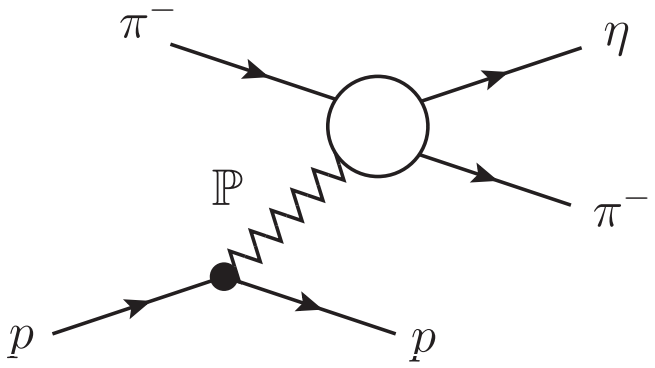
- The $\eta\pi$ system is one of the golden modes for hunting hybrid mesons
- Focus on $J^{PC} = 2^{++}$ first to test methodology
- Expect $a_2(1320)$ (Large peak) to be narrow resonance, from quark models and LQCD expect excited a_2.
- The coupled channel analysis to extract the parameters of the exotic P-wave is ongoing



C. Adolph et al. (COMPASS Collaboration), Physics Lett. B 740, 303 (2015)

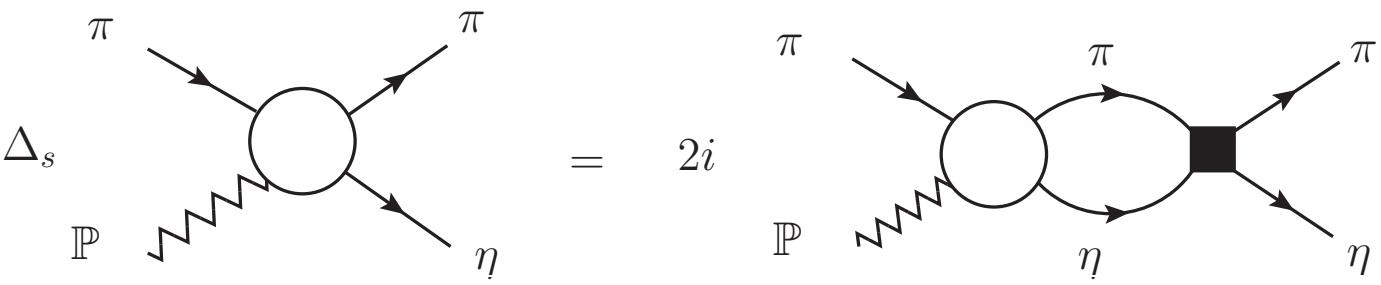
Formalism

- $\pi p \to \eta\pi p$ is high-energy peripheral process $\Longrightarrow$ pomeron dominated exchange



- Expand amplitude into partial waves, separates spectrum into J^{PC} sectors. Unitarity constrains partial wave amplitude

$$\Delta_s \, a_{\ell m_\ell}(s) = 2i \, \rho_\ell(s) t^*_\ell(s) a_{\ell m_\ell}(s)$$



Formalism

- Model for $a_{\ell m_\ell}$

$$a_{\ell m_\ell} = f_{\ell m_\ell}(s) t_\ell(s)$$

where $f_{\ell m_\ell}(s)$ is flexible model for production mechanism, given by

$$f_{\ell m_\ell}(s) = \sum_{n=0} \alpha_n \, T_n(\omega(s))$$

with

$$\omega(s) = (1 - \sqrt{s - s_R})/(1 + \sqrt{s - s_R})$$

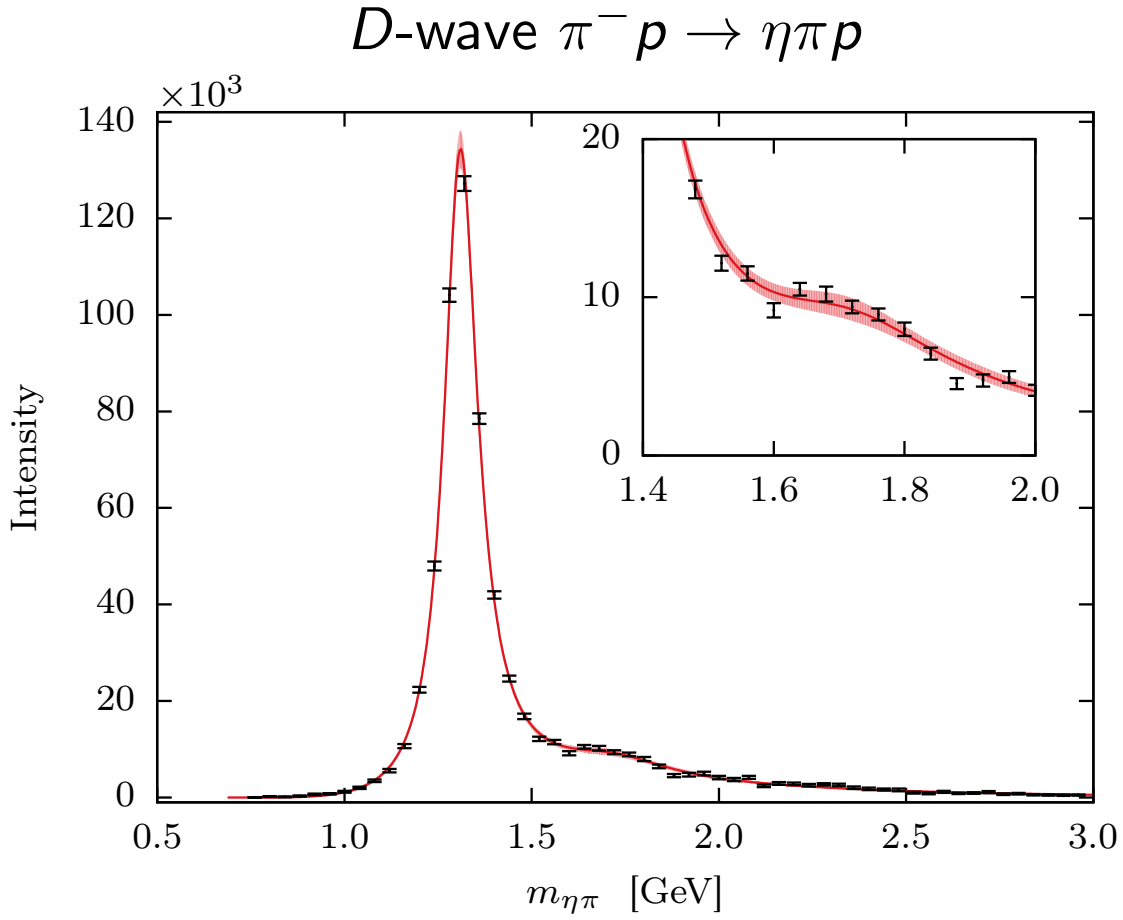
- Parameterize $t_\ell(s)$ by

$$t_\ell^{-1}(s) = M_\ell(s) - \frac{s}{\pi} \int_{s_{th}}^{\infty} ds' \frac{\rho_\ell(s')}{s'(s' - s)}$$

where M_ℓ are CDD terms, capturing resonance effects

$$M_\ell(s) = C_0 - C_1 s - \sum_r \frac{C_2^r}{C_3^r - s}$$

Results of Fit

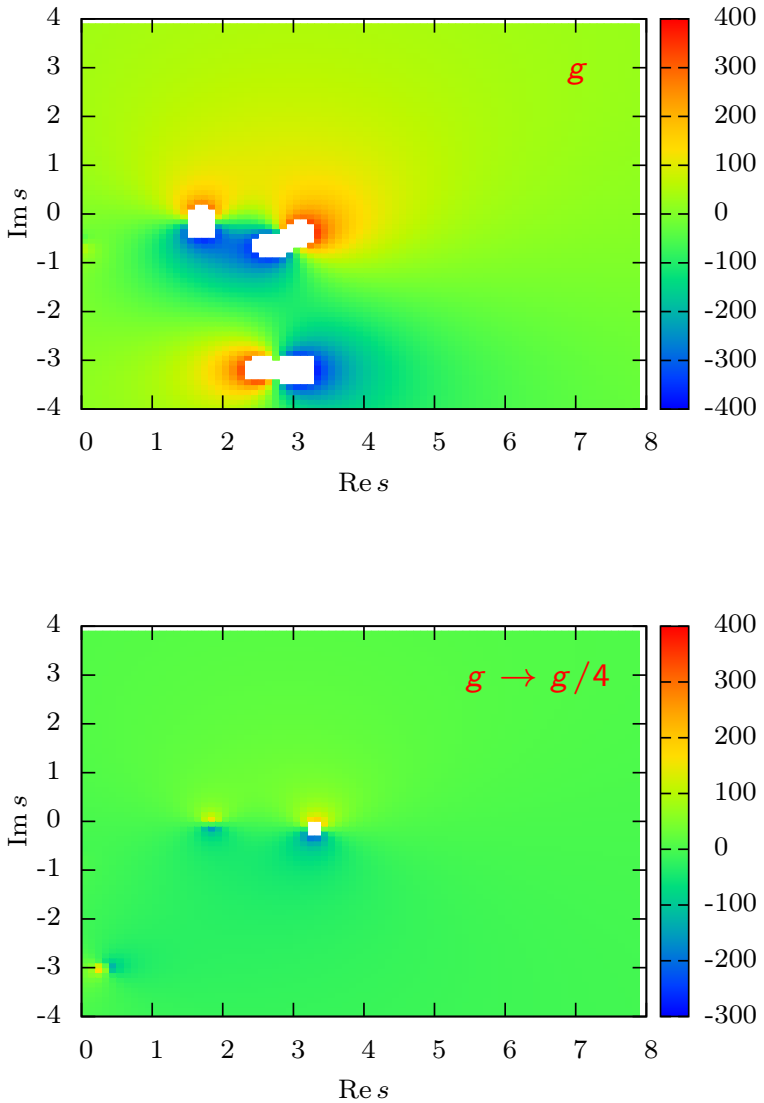


AJ *et al.*, in preparation

- Model fit to COMPASS D-wave intensity
- Tested stability of fit by changing models, number of parameters, etc.
- 3 poles found, need to understand their nature

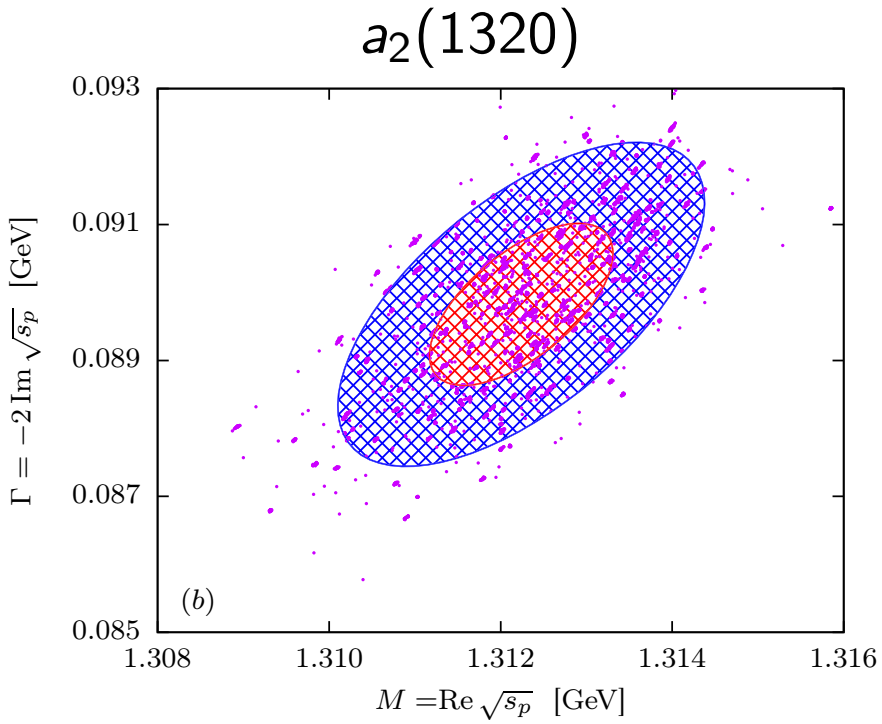
Pole Movement

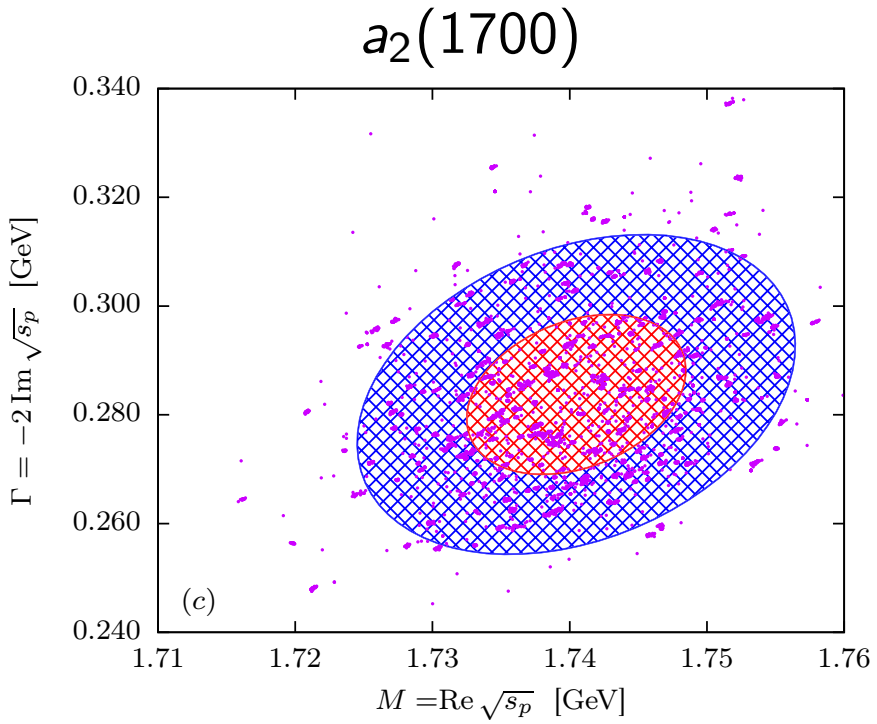
AJ *et al.*, in preparation



Poles in 2^{++}

AJ *et al.*, in preparation





- Two poles were found in the 2^{++} sector
  - $M(1320) = 1.312(1)$ GeV, $\Gamma(1320) = 0.090(1)$ GeV
  - $M(1700) = 1.740(8)$ GeV, $\Gamma(1700) = 0.28(1)$ GeV
- Statistical errors were determined from a bootstrap analysis

Summary

- JPAC provides analytic amplitudes for amplitude analyses
- Understand hadronic resonances gives us insight into nature of QCD
- Mysteries in both the heavy sector and the light sector
- Need to have robust analysis techniques in order to extract exotica
- Analyses like the 3π or $\eta\pi$ analyses serve as templates to probe further into the hadronic puzzles such as XYZ states, Pentaquarks, hybrids, ...