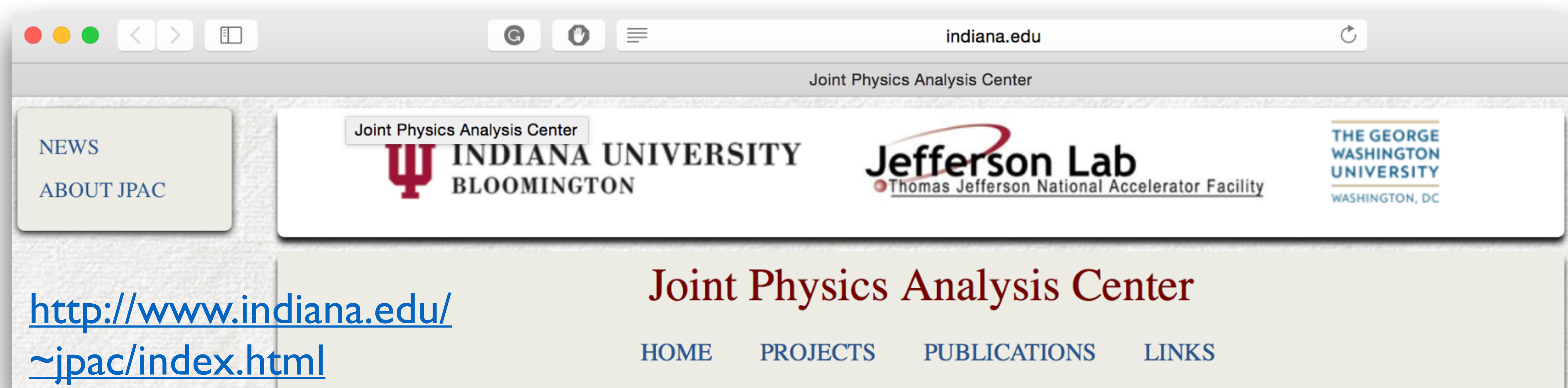
Hadron Reaction and Spectroscopy Studies at JPAC

Adam Szczepaniak
Indiana University
Jefferson Lab

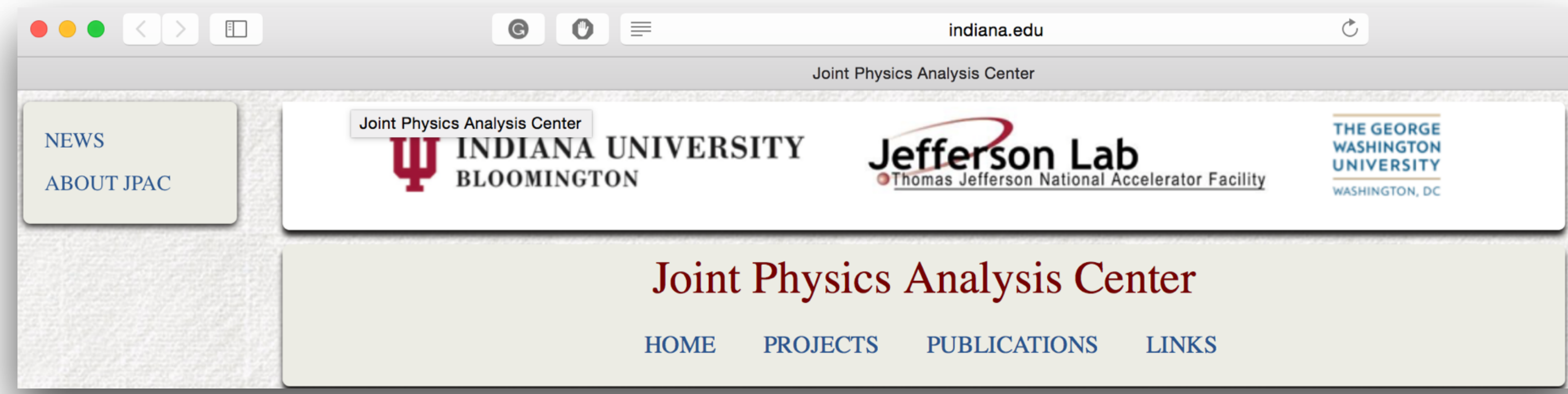
Who we are and we do

General approach: Role of reaction theory

Recent/ Current Projects



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



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

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Mike Pennington (JLab)
Tim Londergan (IU)
Geoffrey Fox (IU)
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Cesar Fernandez-Ramirez (JLab)
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Astrid Blin (Valencia)
Andrew Jackura (IU)
Lingyun Dai (IU/JLab → Valencia)
Meng Shi (JLab → Beijing)
Igor Danilkin (JLab → Mainz)
Peng Guo (IU/JLab → CSU)
…

GlueX collaboration
Matthew Shepherd (IU)
Justin Stevens (JLab)
…

CLAS collaboration
Diane Schott (GWU/JLab)
Viktor Mokeev (JLab)

HASPECT
Marco Battaglieri (Genova)
Derek Glazier (Glasgow)
Raffaella De Vita (Genoa)
…

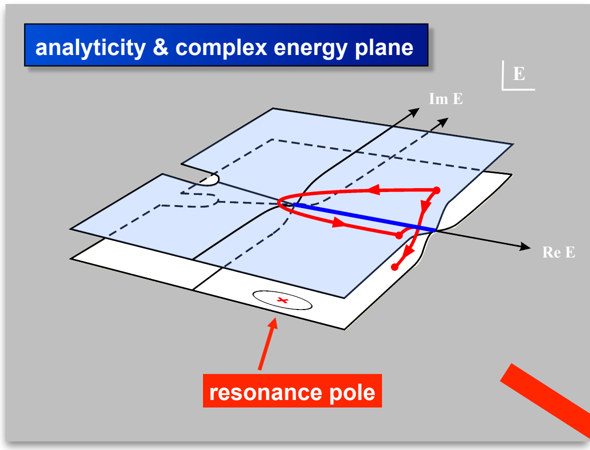
BESIII collaboration
Medina Ablikim (Beijing)
Ryan Mitchell, (IU)
…

LHCb collaboration
T.Skwarnicki (Syracuse)
J.Rademacker, (Bristol)
…

COMPASS collaboration
Mikhail Mikhasenko (Bonn)
Fabian Krinner (TUM)
Boris Grube (TUM)
…

BaBar collaboration
Antimo Palano (Bari)
…

Develop theoretical,phenomenological and computational tools for hadron experiments



- $\gamma p \to \pi^0 p$
  - Formalism
  - Model
  - Resources
  - Run

Joint Physics Analysis Center

HOME PROJECTS PUBLICATIONS LINKS

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Jefferson Lab Thomas Jefferson National Accelerator Facility
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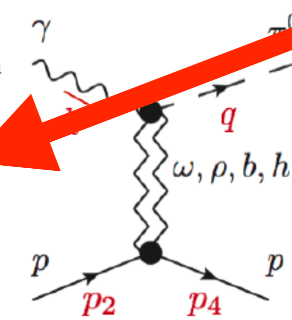
$\gamma p \to \pi^0 p$

We present the model published in [Mat15a] .
The differential cross section for $\gamma p \to \pi^0 p$ is computed with Regge amplitudes in the domain $E_\gamma \geq 4$ GeV and $0.01 \leq |t| \leq 3$ (in GeV^2).
The [illegible] as can be extrapolated outside these intervals.
We use [illegible] GLN invariant amplitudes A_i defined in [Chew57a].
See the section Formalism for the definition of the variables.
The fitting procedure is detailed in [Mat15a] . We report here only the main feature of the model.



Formalism

The differential cross section is a function of 2 variables. The first is the beam energy in the laboratory frame E_γ (in GeV) or the total energy squared s (in GeV^2). The second is the cosine of the [illegible] ng angle in the rest frame $\cos\theta$ or the momentum transfered squared t (in GeV^2).
The momenta of the particles are k (photon), q (pion), p_2 (target) and p_4 (recoil). The pion mass is μ and the proton mass is M.
The Mandelstam variables, $s=(k+p_2)^2, t=(k-q)^2, u=(k-p_4)^2$ are related through $s+t+u=2M^2+\mu^2$.

The differential cross section is expressed in term of the parity conserving helicity invariant amplitudes in the t −channel F_i

$$\frac{d\sigma}{dt} = \frac{389.4}{64\pi}\frac{k_t^2}{4M^2E_\gamma^2}\left[2\sin^2\theta_t\left(t|F_1|^2+4p_t^2|F_2|^2\right)+(1-\cos \ldots\right.$$

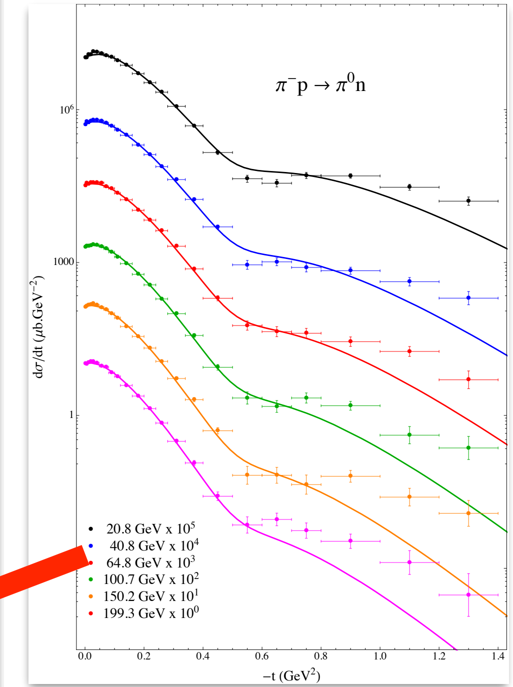
The differential cross section is expressed in μb/GeV^2. We used $(\hbar c)^2$ [illegible]
The t −channel is the rest frame of the process $\gamma\pi^0 \to p\bar{p}$.
In the t −channel, the momenta of the nucleon p_t and the pion k_t and [illegible]

$$k_t = \frac{1}{2}\sqrt{t-4M^2}, \qquad q_t = \frac{t - \ldots}{2\ldots}$$

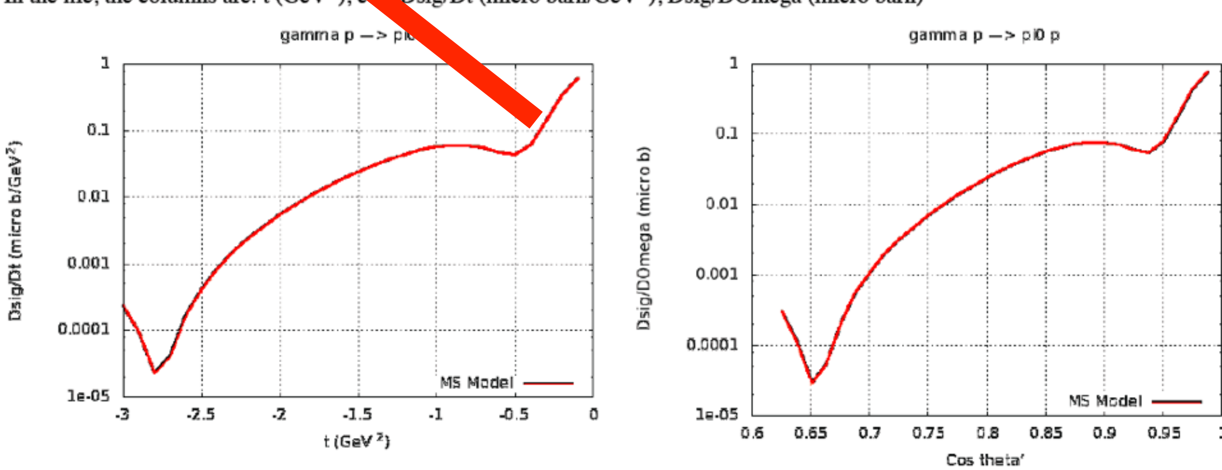
The invariant amplitudes F_i are related through the CGLN A_i amplitu[illegible]

$$F_1 = -A_1 + 2MA_4, \quad \eta \ldots$$
$$F_2 = A_1 + tA_2, \quad \eta \ldots$$
$$F_3 = 2MA_1 - tA_4, \quad \eta \ldots$$
$$F_4 = A_3 \quad \eta \ldots$$

The F_i amplitudes have good quantum numbers of the t −channel, the naturality $\eta = P(-1)^J$ and the product CP.



Download the output file, the plot [illegible] Ox=t , the plot with Ox=cos .
In the file, the columns are: t (GeV^2), [illegible] Dsig/Dt (micro barn/GeV^2), Dsig/DOmega (micro barn)




```
double complex function A(gamma,target,recoil,pip,pim,
                          ,lambda_g,lambda_t,lambda_r,
                           params)
implicit double precision (a-h,o-z)
dimension gamma(4)
dimension target(4)
dimension recoil(4)
dimension pip(4),pim(4)
dimension params(100)

 double complex Ampl

s = (gamma(4)+target(4))**2 - (gamma(1)+target(1))**2
$   - (gamma(2)+target(2))**2 - (gamma(3)+target(3))**2

s1 = (pip(4)+pim(4))**2 - (pip(1)+pim(1))**2
$    - (pip(2)+pim(2))**2 - (pip(3)+pim(3))**2

s2 = (pip(4)+recoil(4))**2 - (pip(1)+recoil(1))**2
$    - (pip(2)+recoil(2))**2 - (pip(3)+recoil(3))**2

t1 = (gamma(4)-pim(4))**2 - (gamma(1)-pim(1))**2
$    - (gamma(2)-pim(2))**2 - (gamma(3)-pim(3))**2

t1 = (target(4)-recoil(4))**2 - (target(1)-recoil(1))**2
$    - (target(2)-recoil(2))**2 - (target(3)-recoil(3))**2

call Ath(s,s1,s2,t1,t2,lambda_g,lambda_t,lambda_r,params,Ampl)

A = Ampl

return
end
```

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2015 International Summer School on Reaction Theory

INDIANA UNIVERSITY

2015 International Summer Workshop on Reaction Theory

June 8-19, 2015 @ Bloomington, Indiana, US

HOME LECTURERS PROGRAM REGISTRATION VENUE ACCOMMODATION TRANSPORTATION LOCAL INFORMATION PARTICIPANTS RESOURCES CONTACT

ABOUT THE SCHOOL

The 2015 International Summer Workshop is dedicated to theory and phenomenology of scattering theory and its application to data analysis of modern experiments in strong interactions physics. As a new frontier in particle and nuclear physics has opened up with advances in experimental, theoretical and computational techniques there is new demand for a qualitatively new level of sophistication in data analysis never before achieved. These require deep knowledge of the methods in relativistic scattering theory. For at least two decades scattering theory has essentially disappeared from the physics curriculum and generations of physicists have been educated without this basic knowledge. Few have working experience with topics ...ated to the analysis of relativistic reactions that involve aspects of Regge phenomenology, crossing relations and duali... ...ntinuations, dispersion relations, etc., and the phenomenological application of all these concepts.

...e Workshop will consist of daily lectures from faculty in the morning, followed ... lab sessions devoted to practical implementation of reaction amplitudes in data ...ing using AmpTools and ROOT. There will also be opportunities for ...rticipants to present their current research. The Workshop is dedicated ... memory of Tullio Regge who passed away on October 23, 2014. He discovered the role of complex angular momentum singularities. Named after him, Regge poles and cuts, determine asymptotic behavior of relativistic scattering amplitudes, and the discovery led to the most successful phenomenology of high energy collisions.

INDIANA UNIVERSITY

Jefferson Lab

Thomas Jefferson National Accel...

Single Meson Photoproduction

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

physics

s-channel quantum numbers: N^* and Δ resonances

t-channel quantum numbers:

vector meson: $(1,3,\ldots)^{--}$ ω, ρ

axial-vector meson: $(1,3,\ldots)^{+-}$ b, h

$(0,2,\ldots)^{-+}$

Primakoff effect at very low t

dip at $|t| \sim 0.5$ GeV2 in $d\sigma/dt$

data

all Durham data: http://hepdata.cedar.ac.uk/search/re_gamma_p_--$003e_pi0_p_/all

High energy data:

Anderson et al: http://inspirehep.net/record/67154

$d\sigma/dt$ for Eg = 6, 9, 12, 15 GeV and |t| between 0.1 and 1.4 GeV^2

References

Mathieu et al: http://arxiv.org/abs/1505.02321

Regge

Worden: https://inspirehep.net/record/75321

FESR and Regge

Additional material:

- E. Predazzi Regge Poles (Part I) ; Regge Poles (Part II) ; Regge Poles (Part III)
- V. Mathieu Lectures on Dispersion Relations, Regge Theory and Finite Energy Sum Rules

Monday June 8

Morning session:

- M. Wright Welcome Remarks
- M. Pennington School Introduction talk (slides)
- D. Horn Birth of Hadron Duality (slides)
- G. Fox The Past and the Future (slides) ; Picture book
  Excerpts from Ph231 Particle Physics Phenomenology course as taught ~1983 at Caltech

Afternoon session:

- M. Sheperd Current Experiments (slides)
- T. Londergan Lectures 1 on Dalitz plots (slides)

Tuesday June 9

Morning session

- M. Pennington: Light-by-light Scattering Part I (slides)
- J. Rosner Lectures on Scattering and S-Matrix (slides including the 3 lectures)
- D. Horn Birth of Hadron Duality (slides)

Afternoon session:

- T. Londergan Lectures 2 on Van Hove plots (slides)
- V. Mathieu Dalitz and Van Hove plots examples:
  Events Plab = 3 GeV plain text ROOT format
  Events Plab = 6 GeV plain text ROOT format
  Events Plab = 9 GeV plain text ROOT format
  Events Plab = 12 GeV plain text ROOT format
  ROOT files:
  - The model: BreitWigner.cc

mypage.iu.edu

2015 International Summer School on Reaction Theory | References in QCD and Relativistic Hadron Scattering

References in QCD and Relativistic Hadron Scattering

Relativistic Hadron Scattering
Quantum Chromodynamics

Relativistic Hadron Scattering

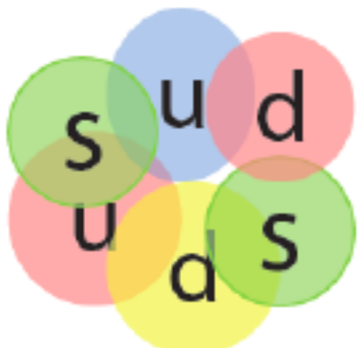
1950s

Analytic Properties of Scattering Amplitudes as Functions of Momentum Transfer - Lehmann - 1958
Decay of the Pi Meson - Goldberger - 1958
Determination of the Pion-Nucleon Scattering Amplitude from Dispersion Relations and Unitarity. General Theory - Mandelstam - 1958
On the General Theory with of Collisions Spin for Particles - Jacob - 1959
The Poles of the S-Matrix of a Rectangular Potential Well or Barrier- Nussenzveig - 1959
Uniqueness of Solutions to Dispersion Relations for Potential Scattering - Gasiorowicz - 1957

1960s

Theory of the low-energy Pion-Pion interaction - Chew and Mandelstam - 1960
Three-Body ND Scattering I Integral Angular Momenta -- Mandelstam 1965
Three-Particle Unitarity Condition for Complex Angular Momenta and the Mandelstam Branching Points - Azimov, Gribov - 1964
Three-Pion Decays of Unstable Particles - Zemach - 1964
Topics on regge-pole theory of high-energy scattering - Van Hove - 1968
Unified Approach to High- and Low-Energy Strong Interactions on the Basis of the Mandelstam Representation - Chew, Frautschi - 1960
Universal rho Coupling and the Adler-Weisberger Theorem for p(-)r() and p(-)A_{1}() in the Veneziano Model - Mckay, Wada - 1969
Unstable-Particle Scattering and the Strip Approximation - Ryan - 1963
Veneziano Model for pion-pion to pion S , Where S Has Arbitrary Spin and, Parity - GOEBEL - 1969
Zeros of Hankel Functions and Poles of Scattering Amplitudes - KELLER- 1963
A NOVEL APPLICATION OF REGGE TRAJECTORIES - Lovelace - 1968
A REGGE DAUGHTER TRAJECTORY FOR I=l, I'=0 BOSON RESONANCES - Spector- 1967
A Theoretical Approach to High-Energy Pion Phenomena - Amati - 1961
Analysis of Partial-Wave Dispersion Relations - Frye, Warnock - 1968
Analytic Properties of Radial Wave Functions - Newton - 1960
Approximation Techniques in Three-Body Scattering Theory - Rosenberg - 1961
Asymptotic Behavior of Partial-Wave Amplitudes -- Omnes 1963
Asymptotic behaviour of the scattering amplitude at high energies - Gribov - 1961
Asymptotic Projections of Scattering Models - Barger, Olsson, Reeder - 1968
ASYMPTOTIC PROPERTIES OF SCATTERING AND MULTIPLE PRODUCTION - Amati, Fubini - 1962
Bootsrap of pion-pion Scattering in the Unitarized Strip Approximation -- Collins 1969
Bootstrap of Meson Trajectories from Superconvergence - Ademollo et al. - 1968
Bootstrap of Pion-Pion Scattering in the Unitarized Strip Approximation - Collins, Johnson - 1969
Bound States and Regge Trajectories in a Vector Meson Exchange Model. I. Application to the KKover System - Arnold - 1963
Can a Scalar Meson Boostrap itself -- Collins 1964
CERN Easter Shool for Physicsts - Using the CERN Proton Synchrotron and Synchro-Cyclotron - 1964
CERN Easter Shool for Physicsts - Using the CERN Proton Synchrotron and Synchro-Cyclotron - 1965
CERN Easter Shool for Physicsts - Using the Nuclear Emulsion Technique in Conjunction with the CERN Proton Synchrotron and Synchro-Cyclotron - 1963
CERN Proceedings of the 1964 Easter School for Physicists Using the CERN proton synchrotron and synchro-cyclotron - 1964
CERN Proceedings of the 1965 Easter school for Physicists - Using the CERN Proton Synchrotron and Syncro-Cyclotron - Kreuznach - 1965
Collins-Johnson Bootstrap Calculation of the J - Lyth - 1969
Complex Angular Momenta and the Relation Between the Cross Sections of Various Processes at High Energies - Gribov, Pomeranchuk - 1962
Compton Scattering and Regge Cuts - Venturi - 1969
Crossing Relations for Helicity Amplitudes - Trueman - 1964
Crossing-Symmetric Rising Regge Trajectories - Chu, Epstein, Kaus, Slansky, Zachariasen - 1968
Dalitz-Plot Analysis Including Duality - Altarelli, Rubinstein - 1969
Data on particles and resonant States - Price et al. - 1967
Determination of Subtraction Terms in S-Matrix Theory - Jones - 1965
Determination of the pion-pion Scattering phase shift up to 1.3 GeV CM energy - Wolf - 1965
DISPERSION SUM RULES AND HIGH ENERGY SCATTERING - Logunov, Soloviev, Tavkhelidze - 1967
Dolen-Horn-Schmid duality and the deck effect - Chew, Pignotti - 1968

before we can address the following question…

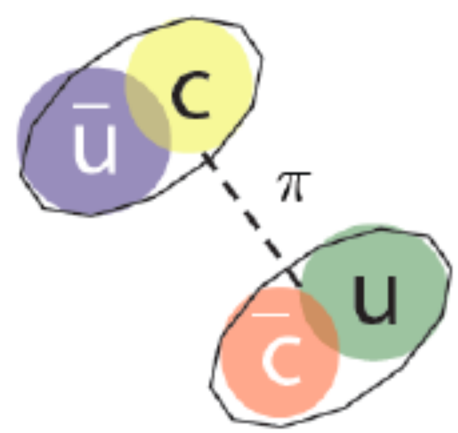


dibaryon

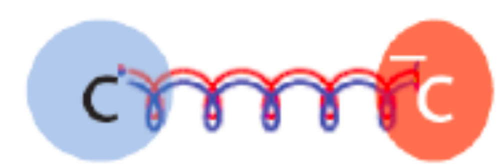
pentaquark

glueball

diquark + di-antiquark

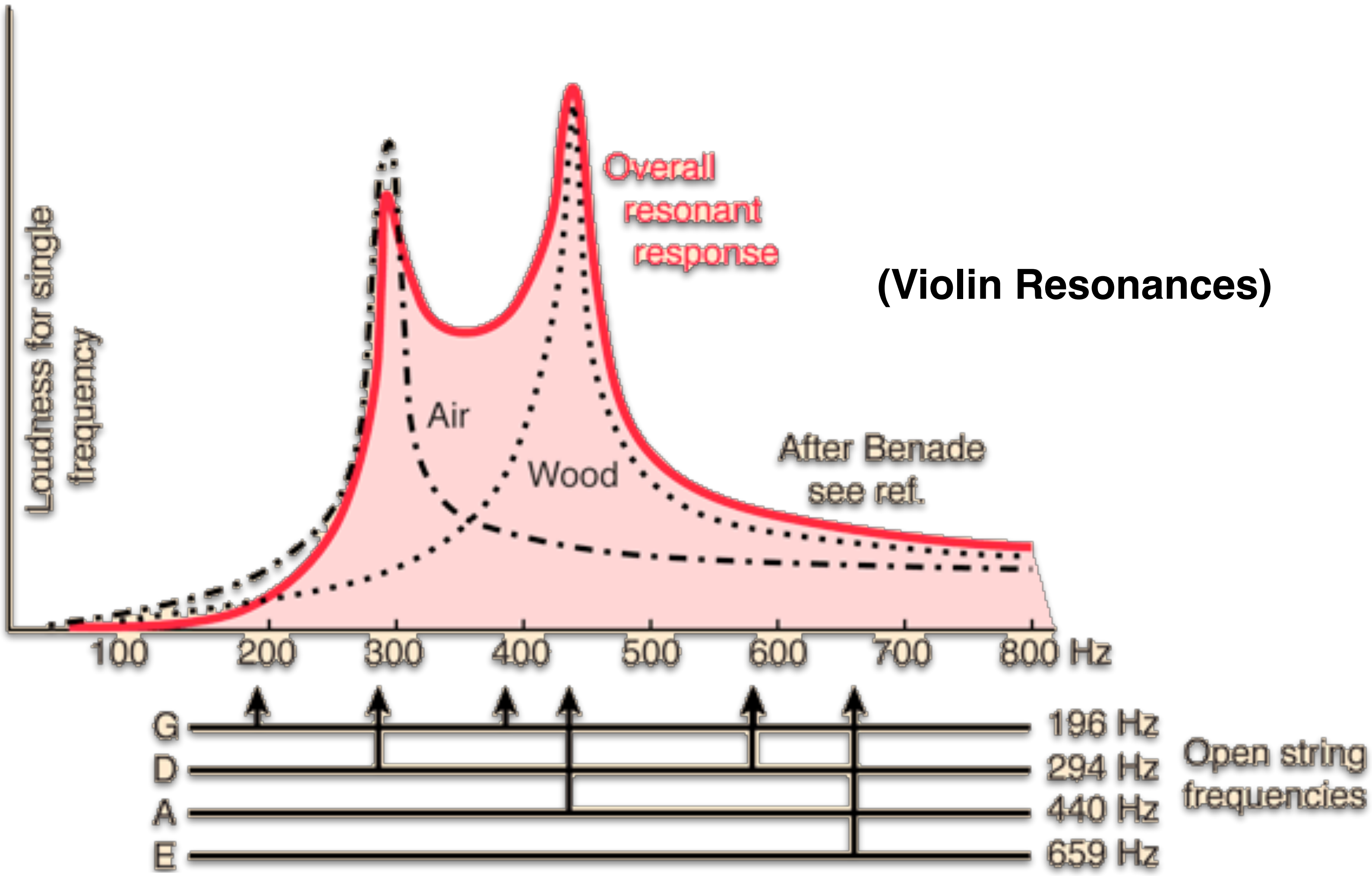


dimeson molecule

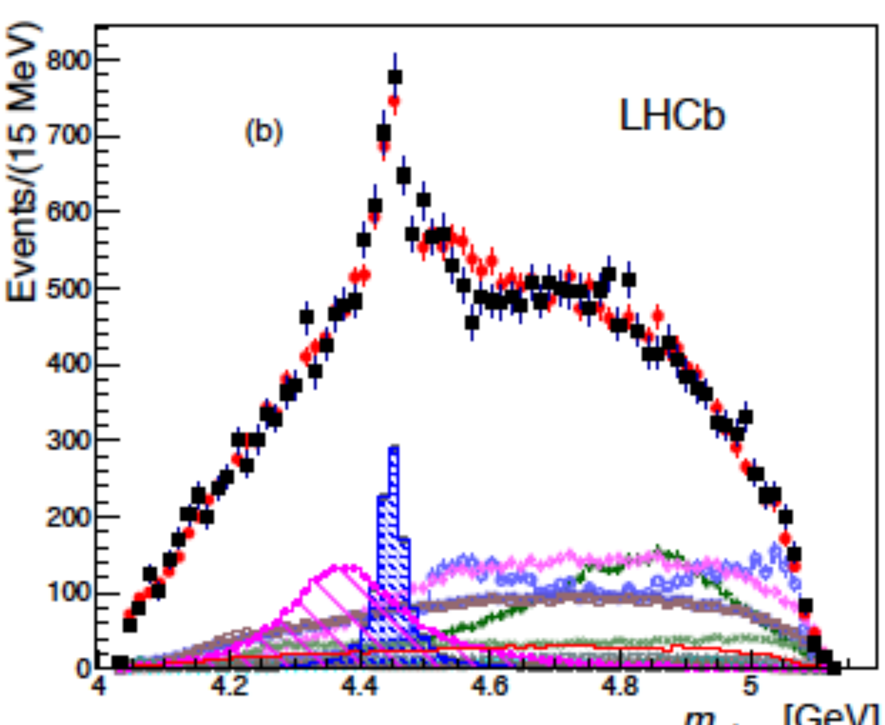


$q\,\bar{q}\,g$ hybrid

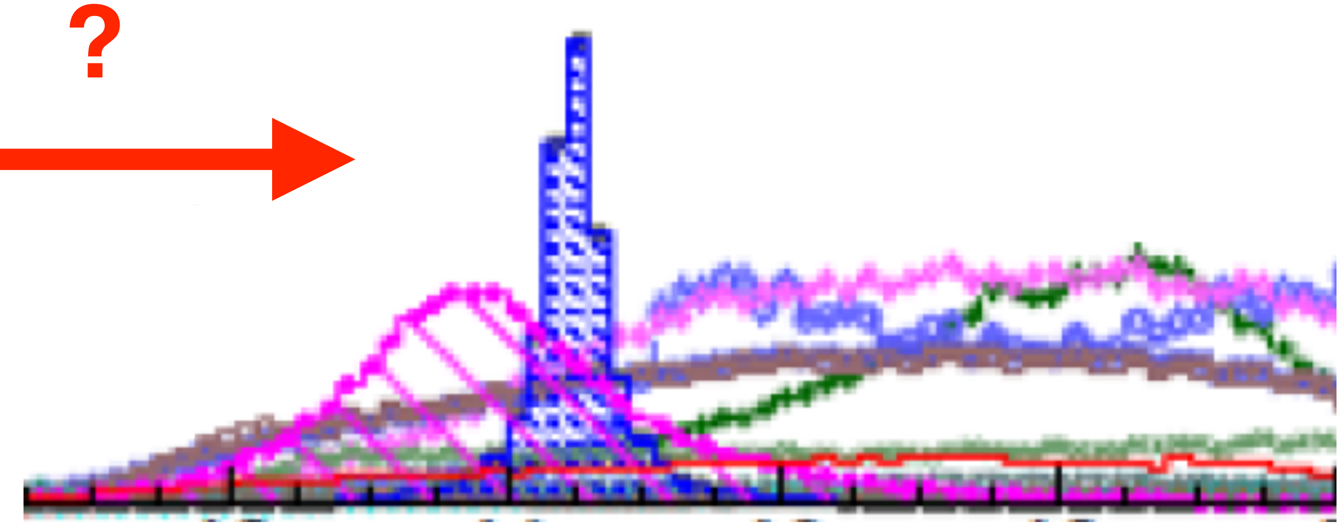
…we need to know how to interpret "peaks"



(Violin Resonances)

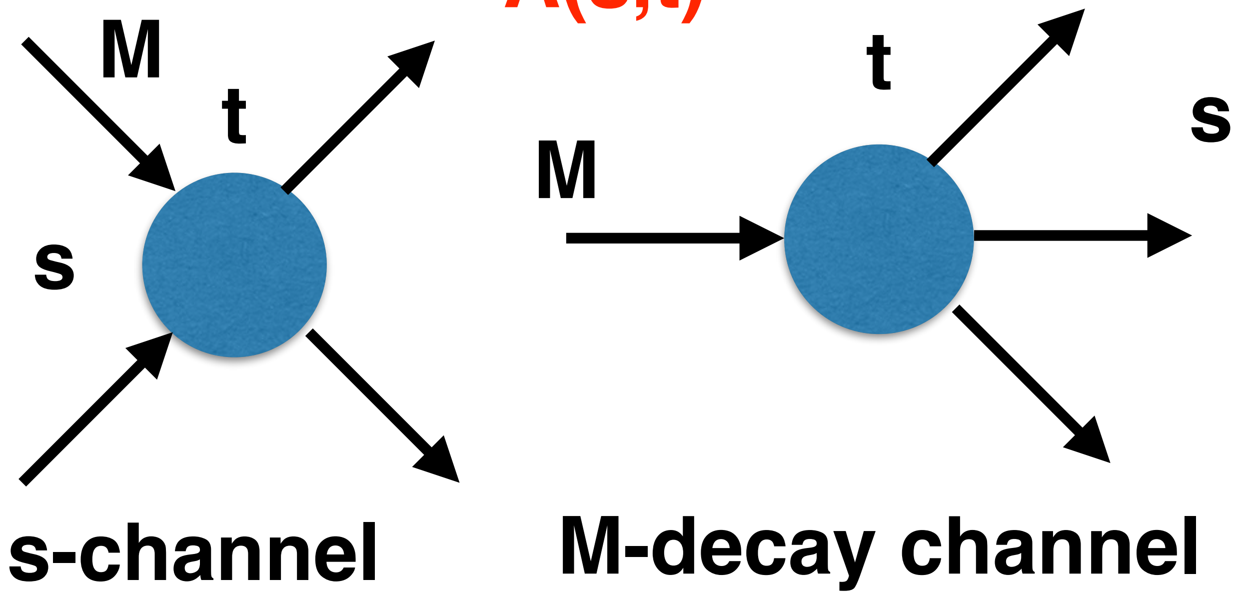


?



S-matrix principles: Crossing, Analyticity, Unitarity

$A(s,t)$



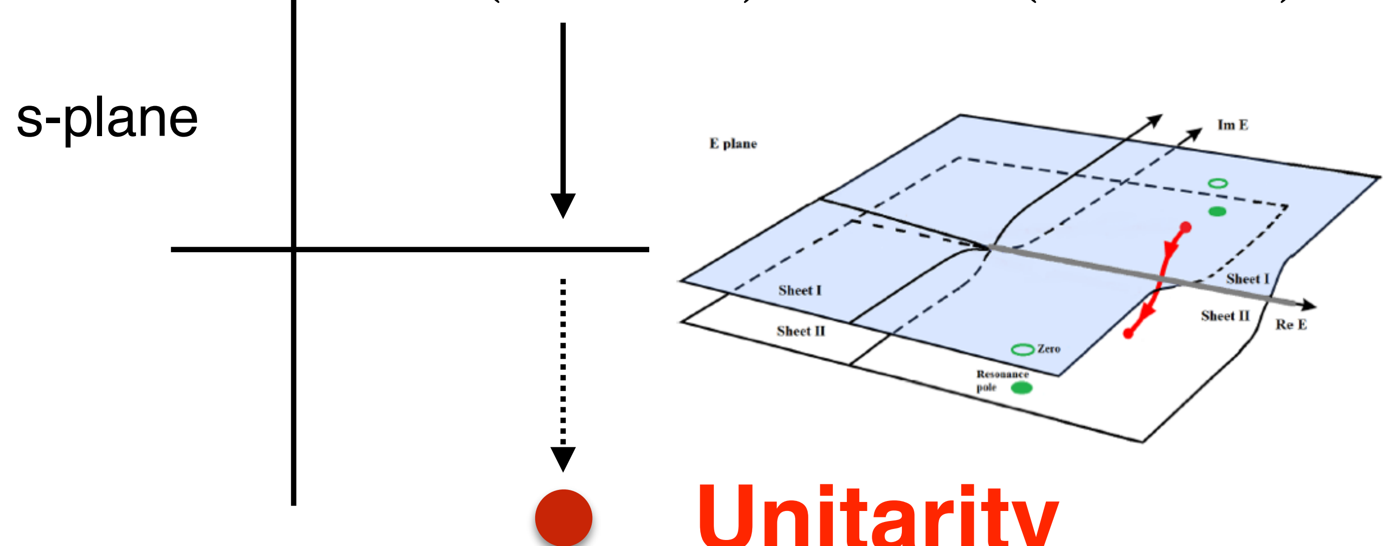
Crossing

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

Analyticity

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

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

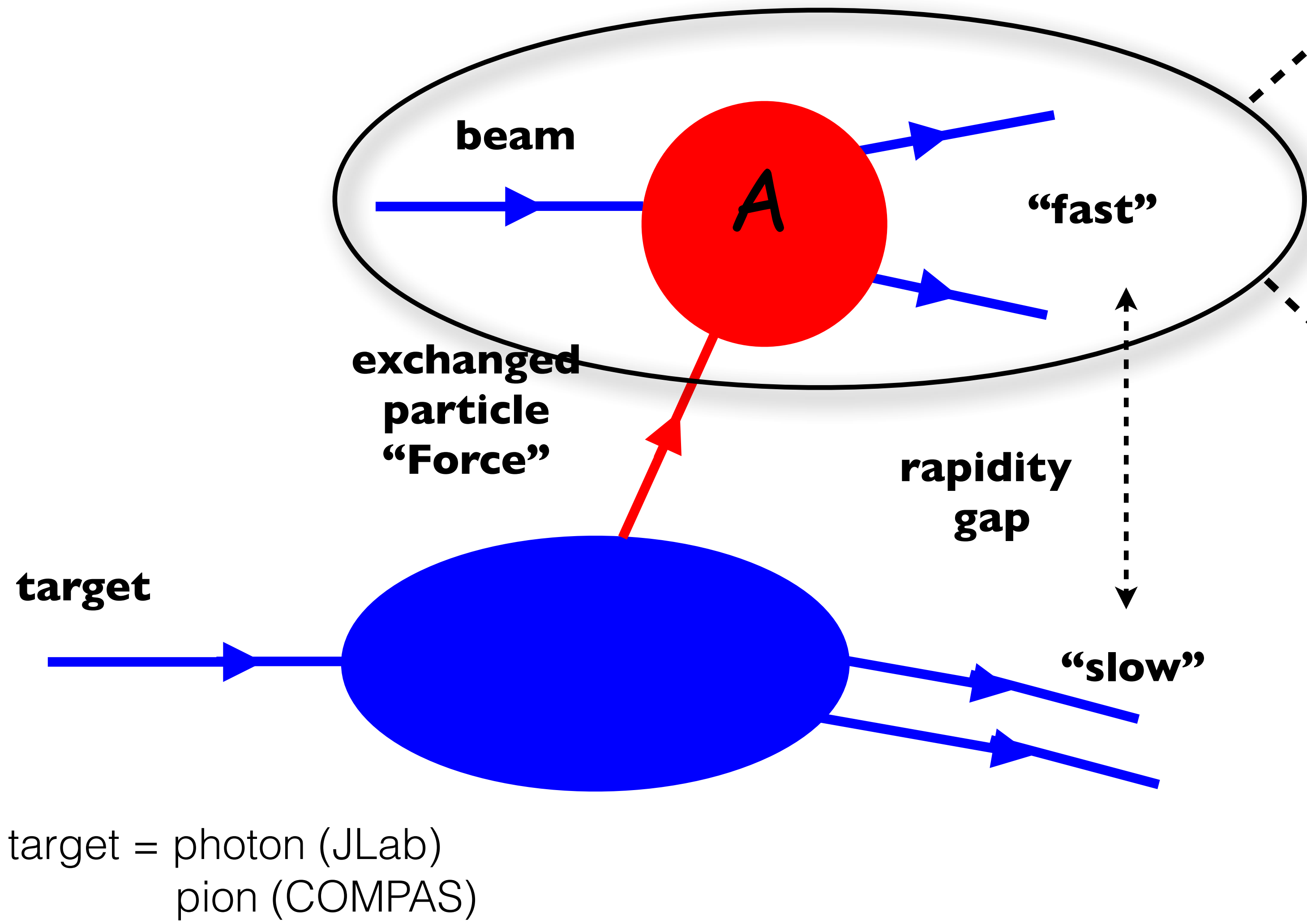


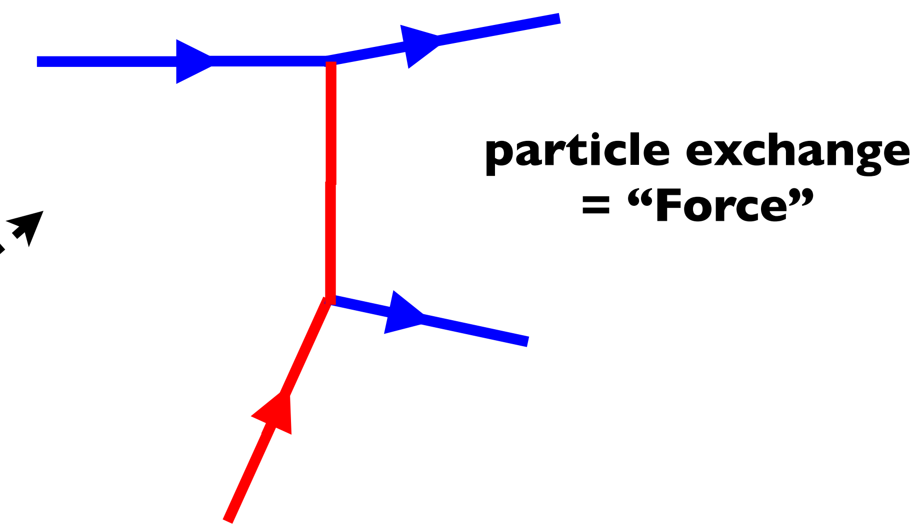
Unitarity

bumps/peaks on the real axis (experiment) come from singularities in the complex domain.

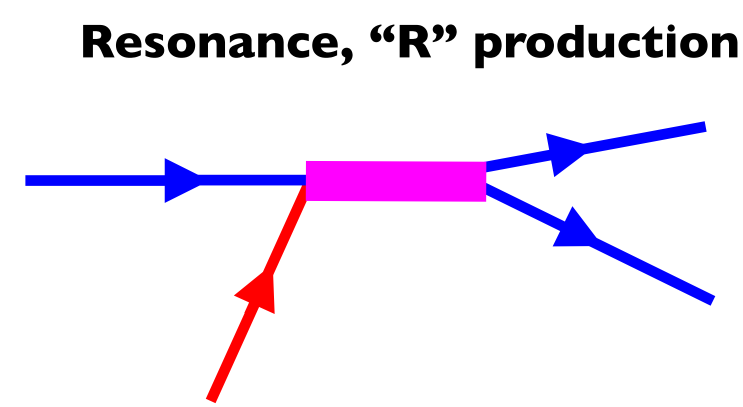
Hunting for Resonances in fixed target experiments

JLAB 12GeV, COMPASS

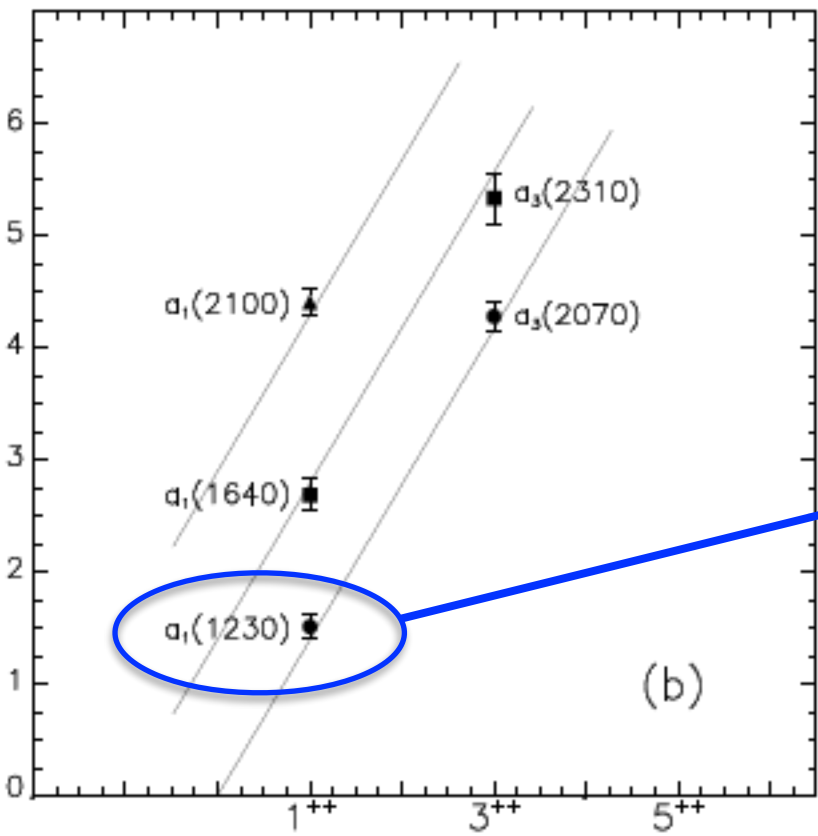


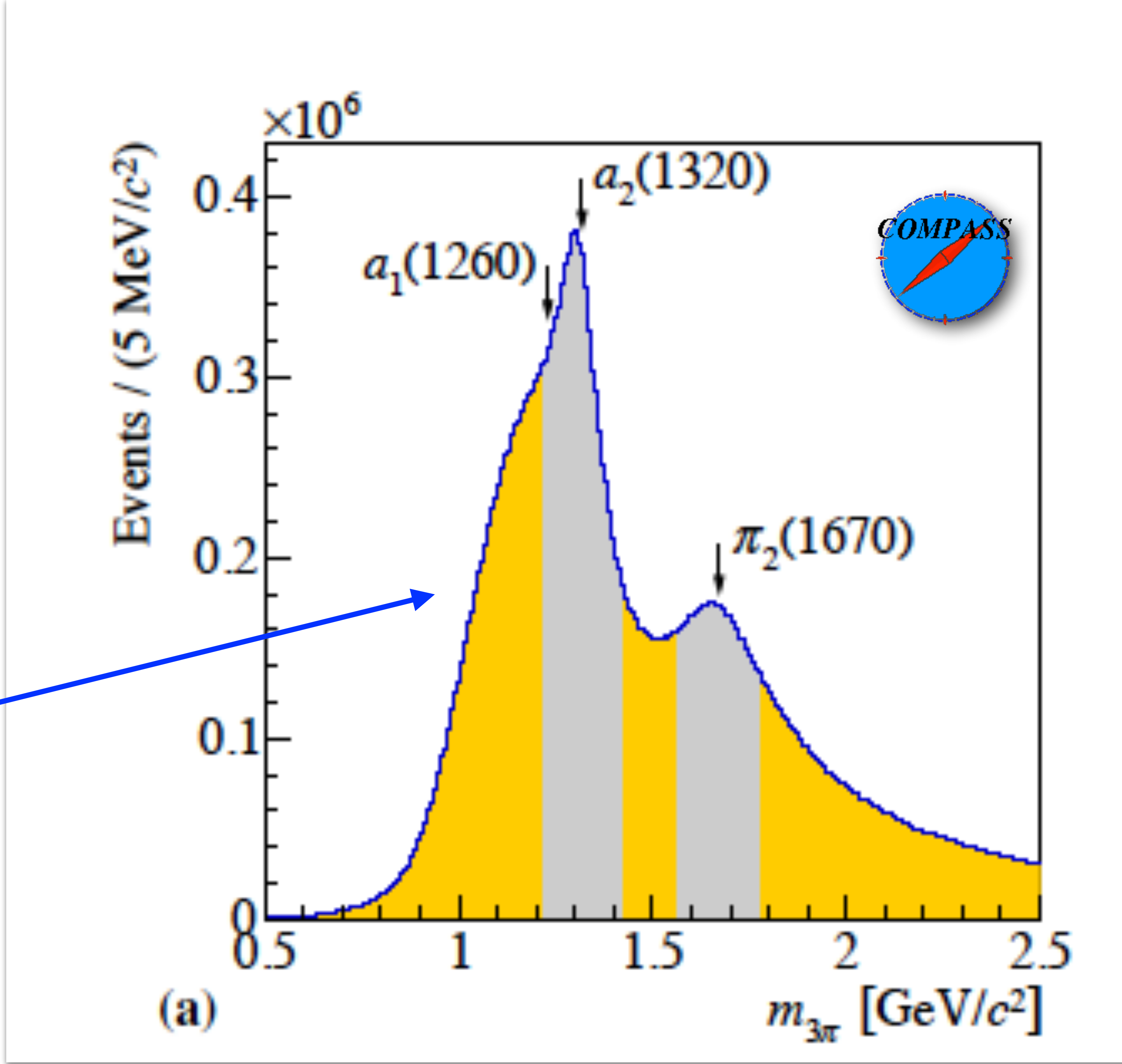


Particle ↔ Force duality



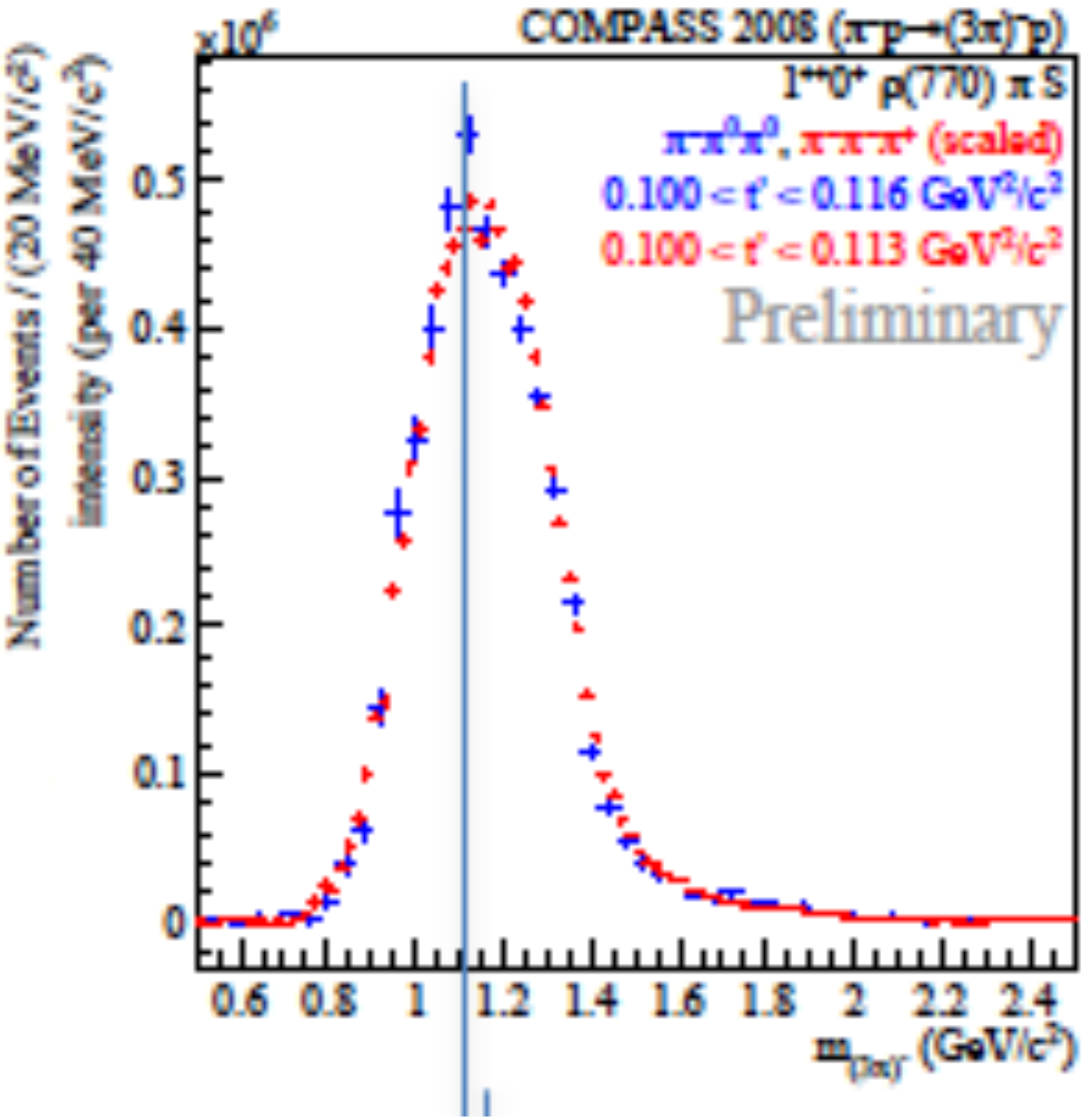
diffractive-dissociation





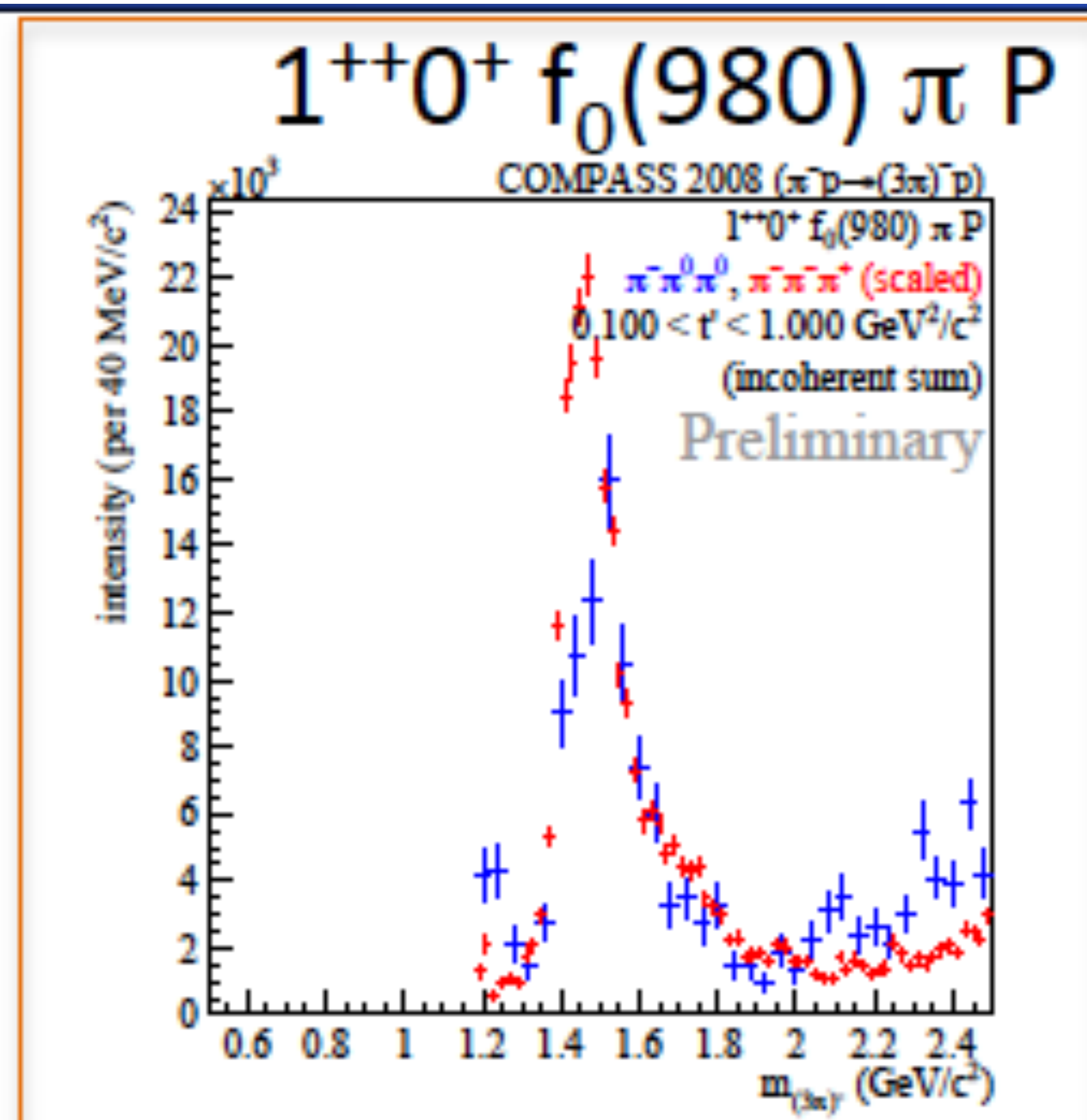
no room for another a_1

COMPASS's a_1 meson(s) $J^{PC} = 1^{++}$ (L=1,S=1)



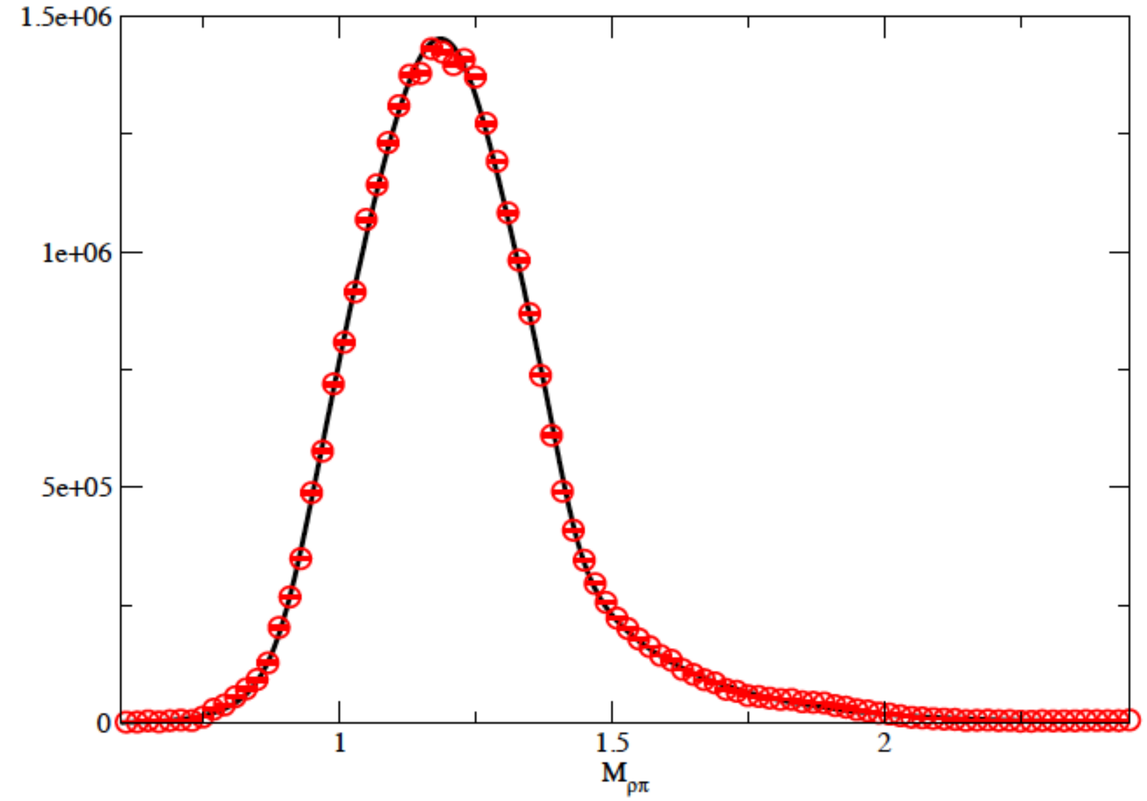
“Old” a1 in ρπ S-wave

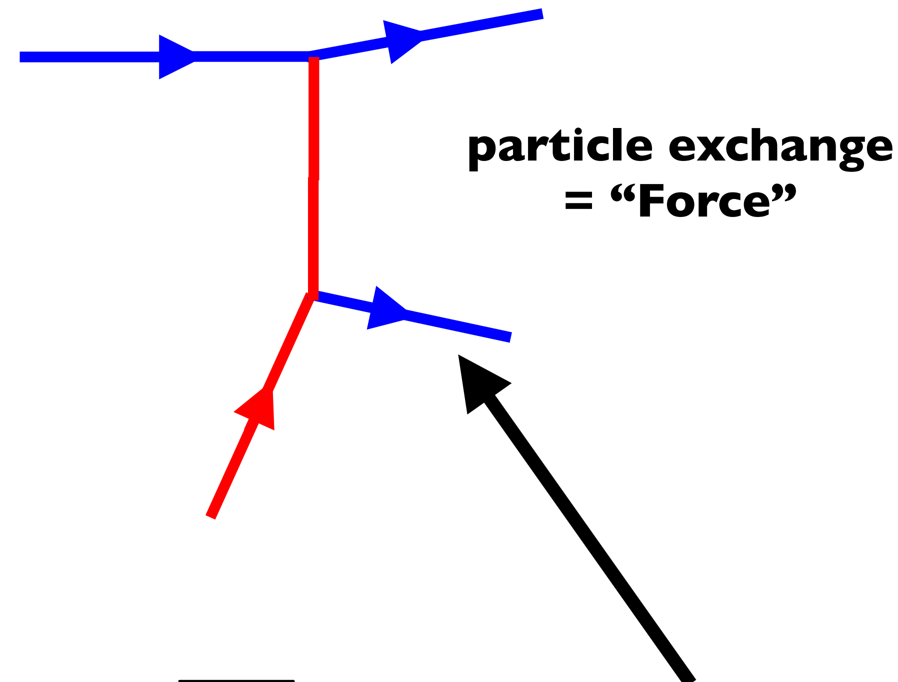
New a1 in f0 π P-wave



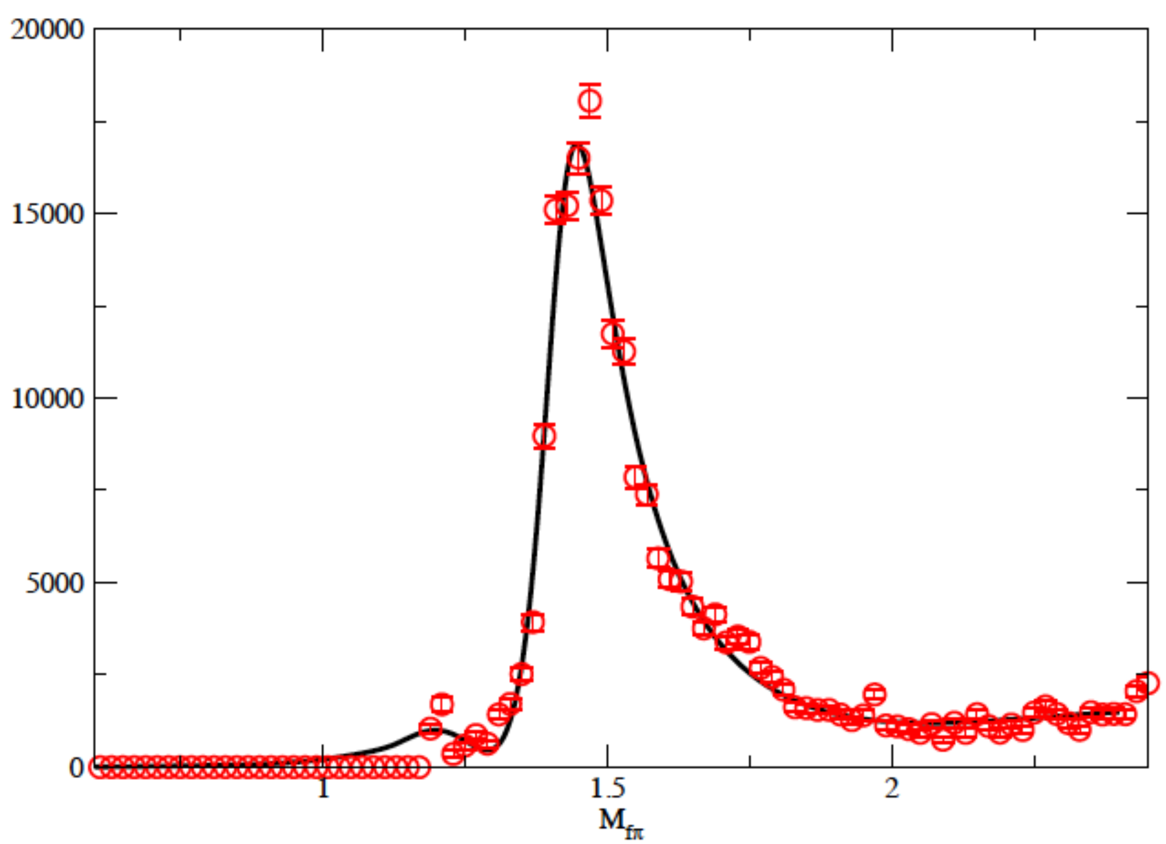
Two Breit-Wigner resonances (COMPASS)

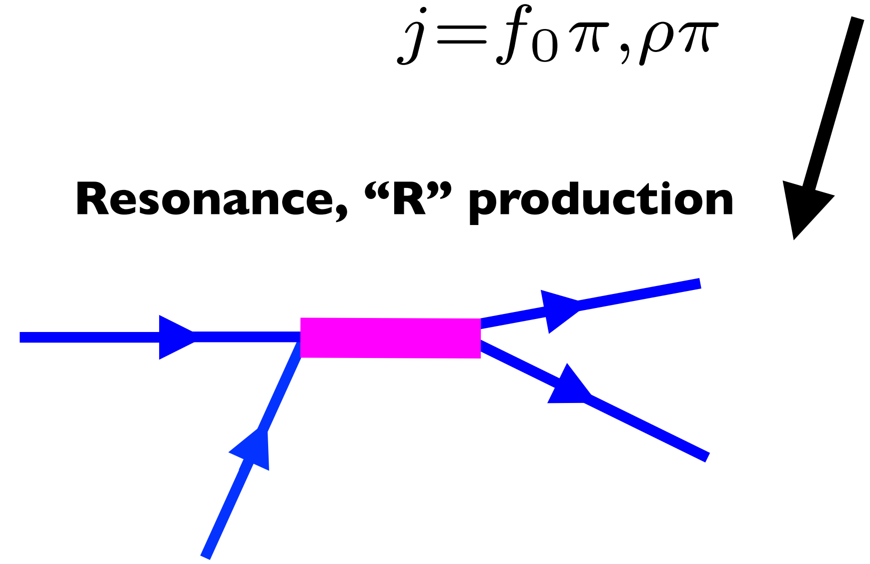
$$\Delta A_i(s) = \sum_{j=f_0\pi,\rho\pi} T^*_{ij}(s)\rho_j(s)A_j(s)$$



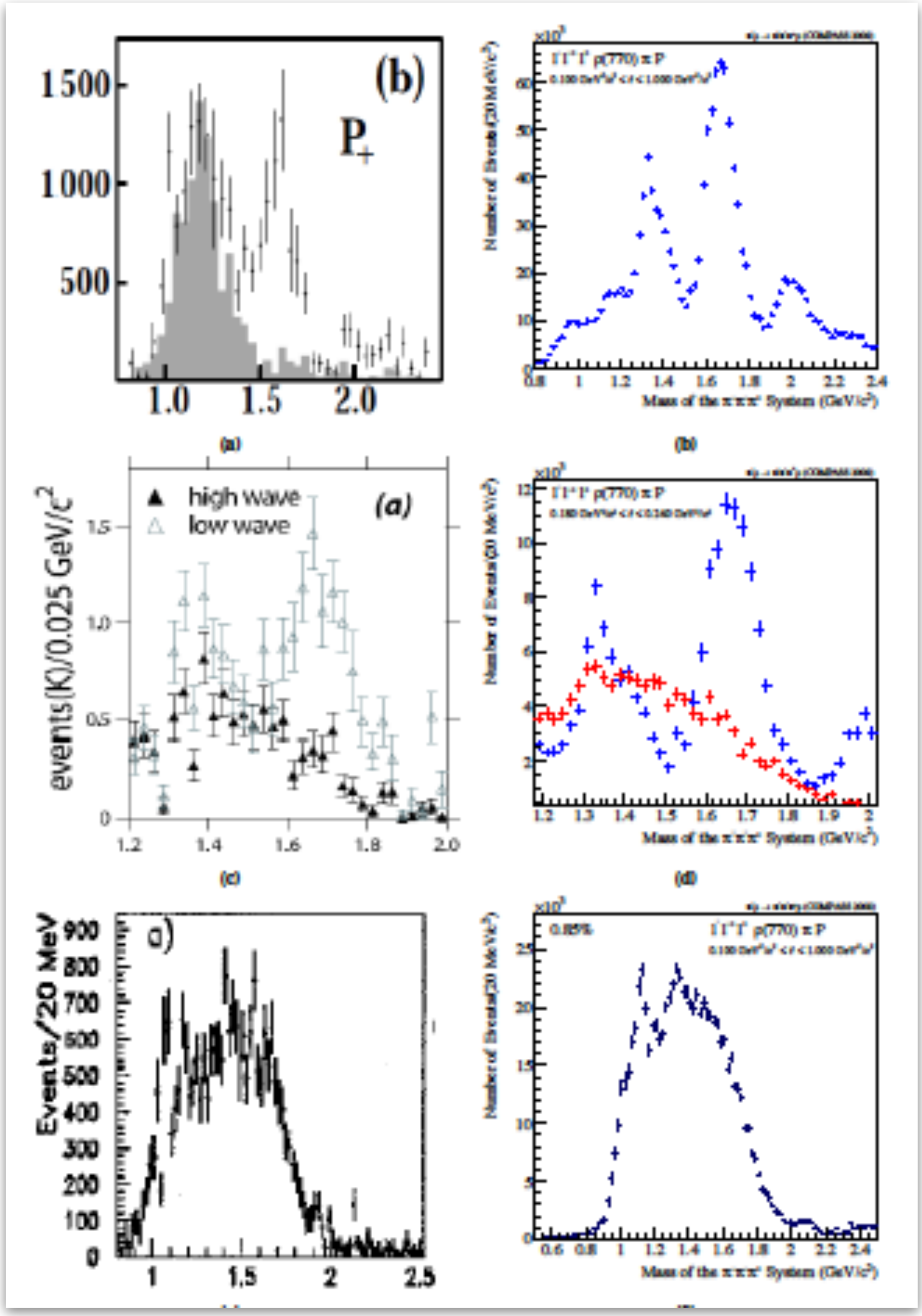


$$A_i(s) = \sum_{j=f_0\pi,\rho\pi} T_{ij}(s)P_j(s)$$

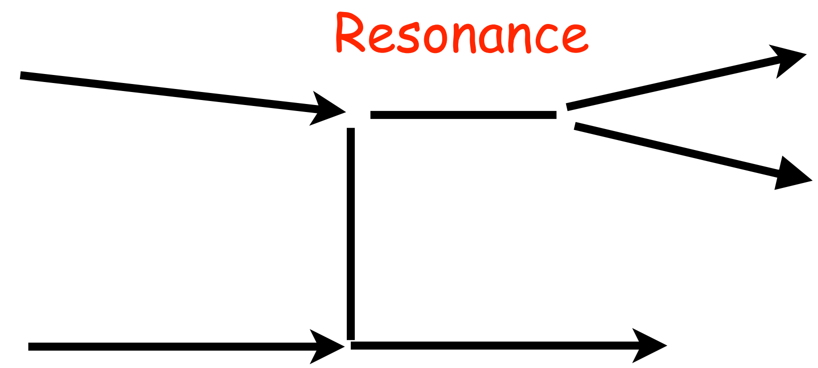




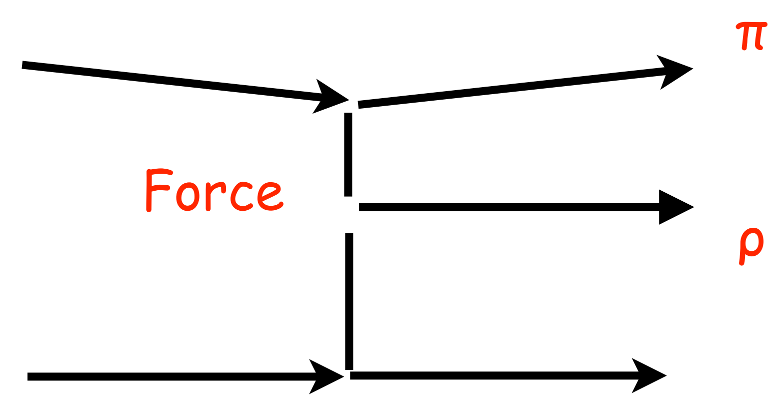
One resonance (pole) underlies both peaks



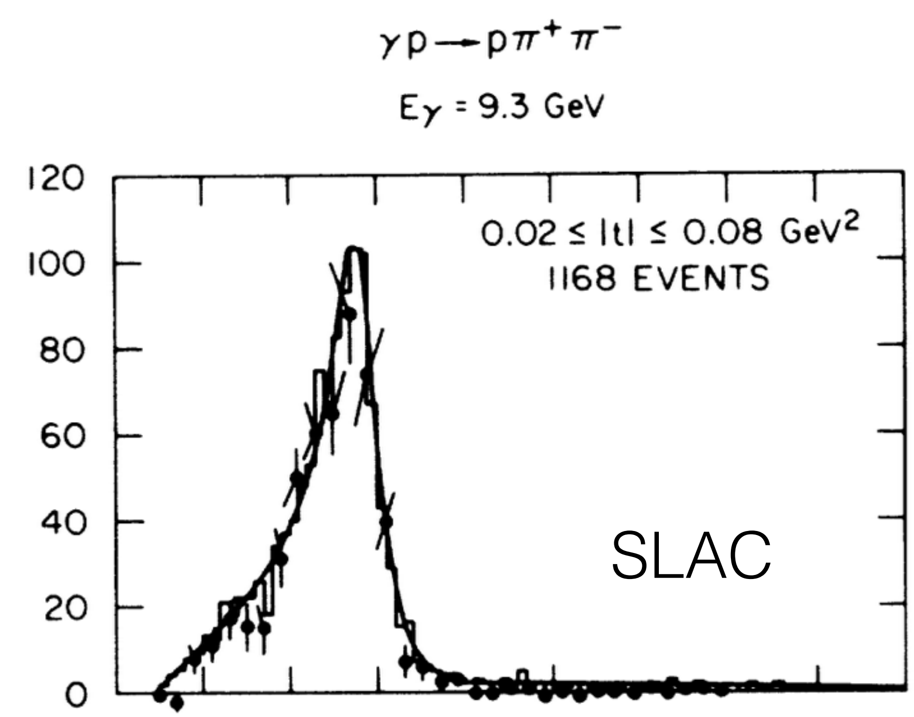
rho-pi spectrum in diffractive dissociation on hydrogen
COMPASS vs E852/BNL and VES



OPE has high partial waves



modified rho "shape" in photo-production



JPAC : Other Analyses

Light meson decays and light quark resonance

- $\omega/\phi \to 3\pi, \pi\gamma$ (dispersive)
- $\omega \to 3\pi$ (Veneziano, B4)
- $\eta \to 3\pi$, $\eta'/f1 \to \eta\pi\,\pi$, (Khuri-Treiman, B4)
- $J/\Psi \to \gamma\pi0\pi0$

Photo-production: (production models, FESR and duality)

- $\gamma p \to \pi0p$
- $\gamma p \to pK+K-$ (and Kp)
- $\gamma p \to \pi+\pi-p$, $\pi0\eta p$, ωp

Launched in the Fall of 2013
~20 papers published

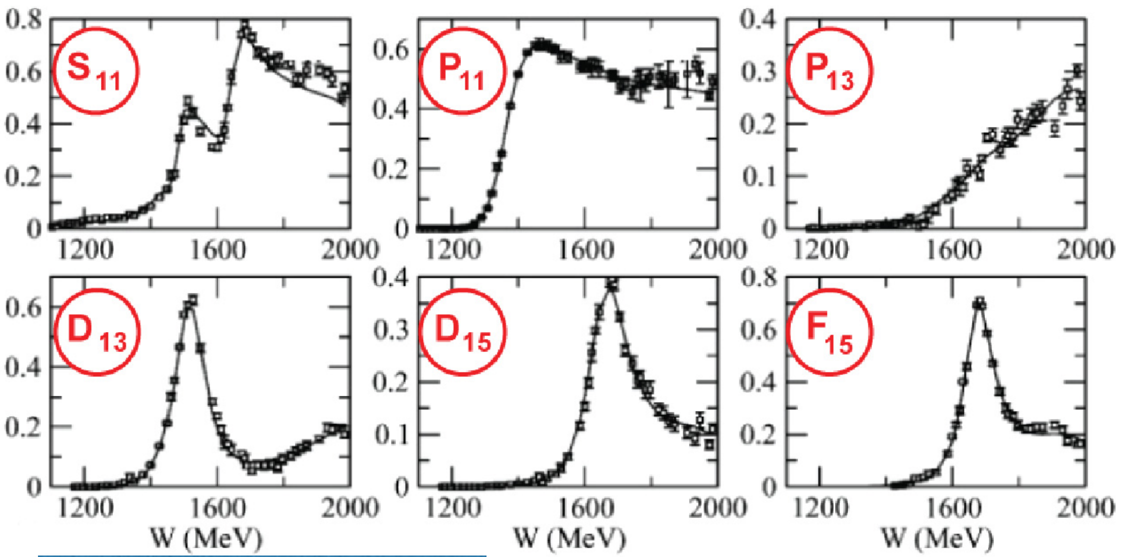
Exotica and XYZ's:

- $\pi-p \to \pi-\eta p$ & $\pi-p \to \pi-\eta' p$ (FESR)
- $B^0 \to \Psi' \pi- K^+ u$, $\Psi(4260) \to J/\Psi\ \pi+\pi-$, $\Lambda_b \to K-\ pJ/\Psi$
- $J/\Psi \to 3\pi$, $KK\pi$ (Veneziano, B4)

Resonance-Regge physics in meson-baryon scattering

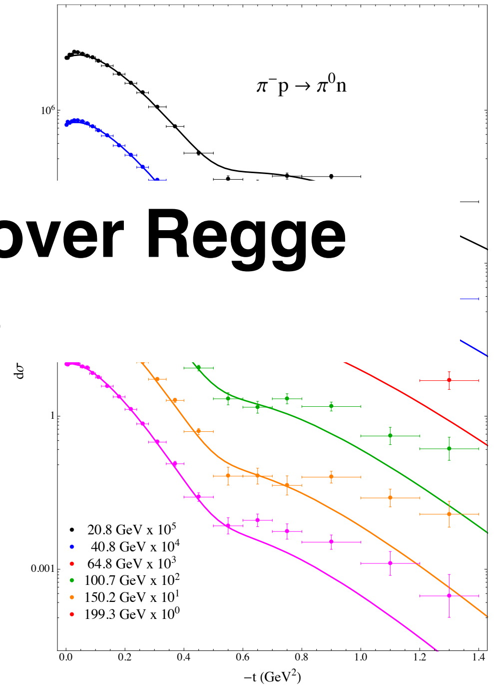
$$\int_{\nu_0}^{\Lambda} \text{Im } A^{(-)}(\nu', t)\nu'^{2k} d\nu' = \beta(t) \frac{\Lambda^{\alpha_\rho(t)+2k+1}}{\alpha_\rho(t) + 2k + 1}$$

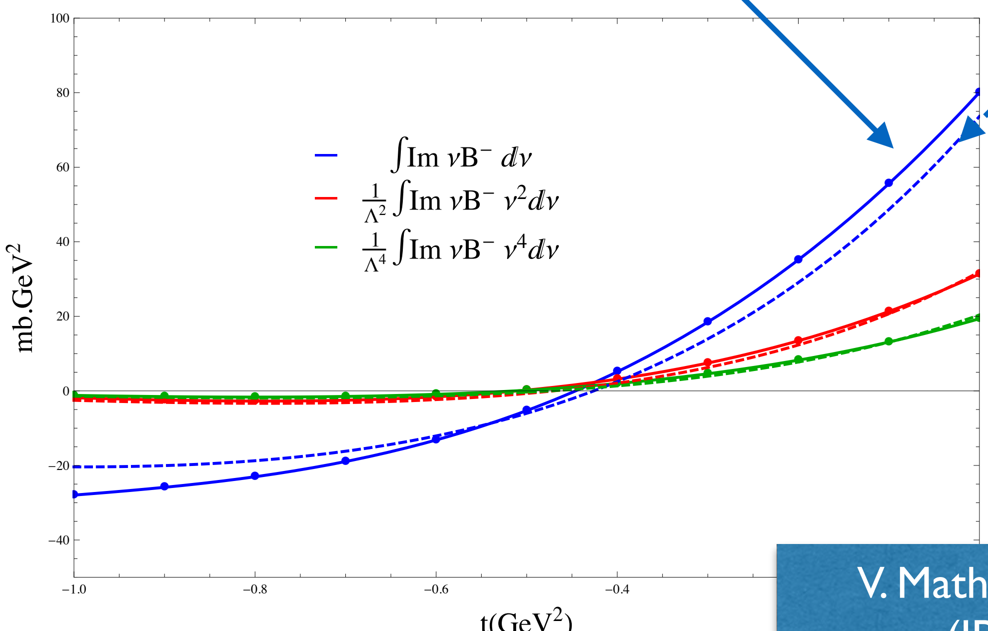
p.w. analysis

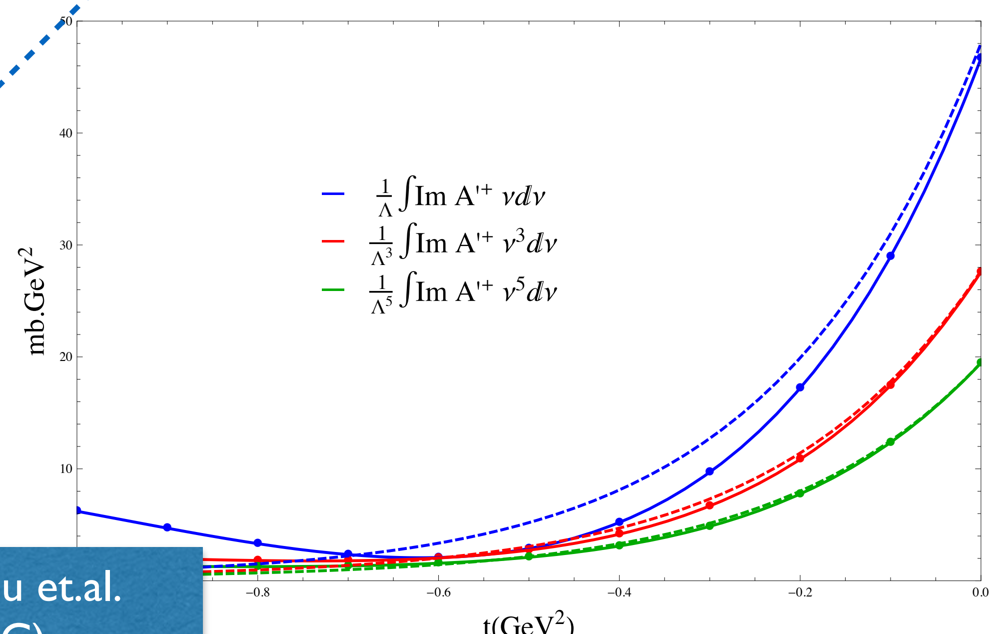


SAID, Workman et.al.

sum over Regge poles





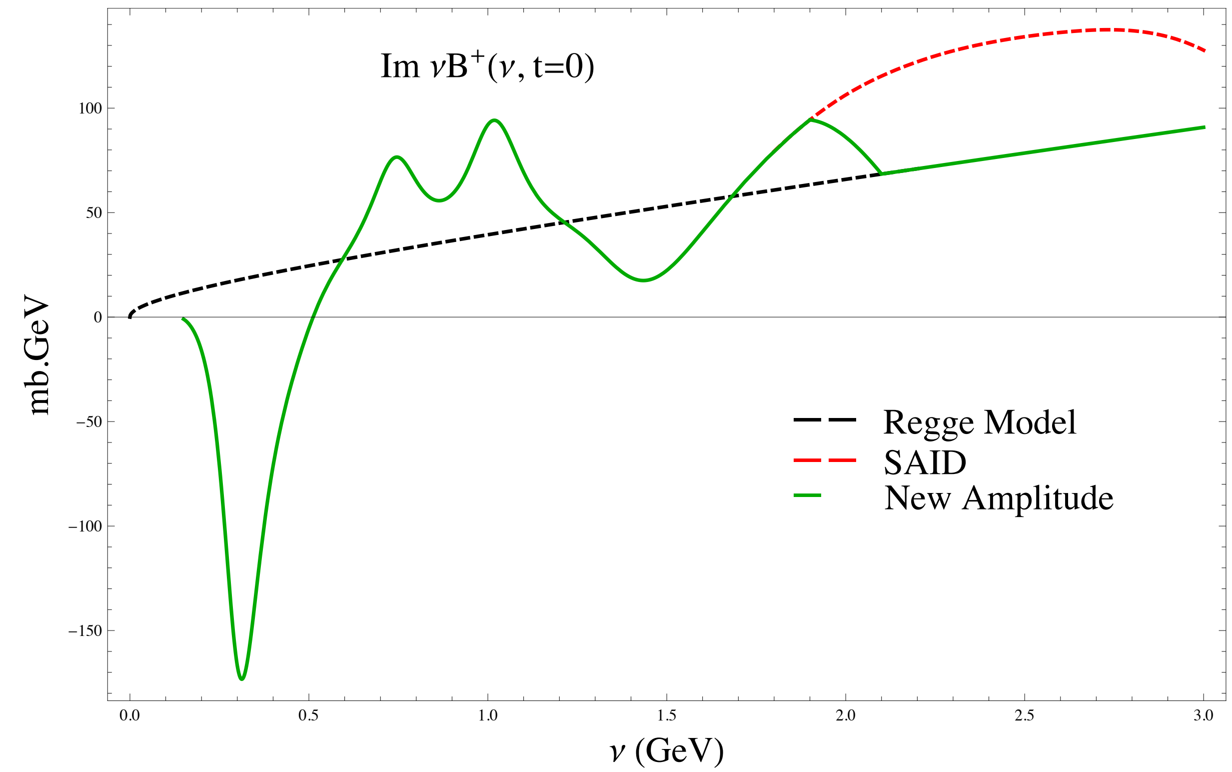


V. Mathieu et.al. (JPAC) arXiv:1506.01764

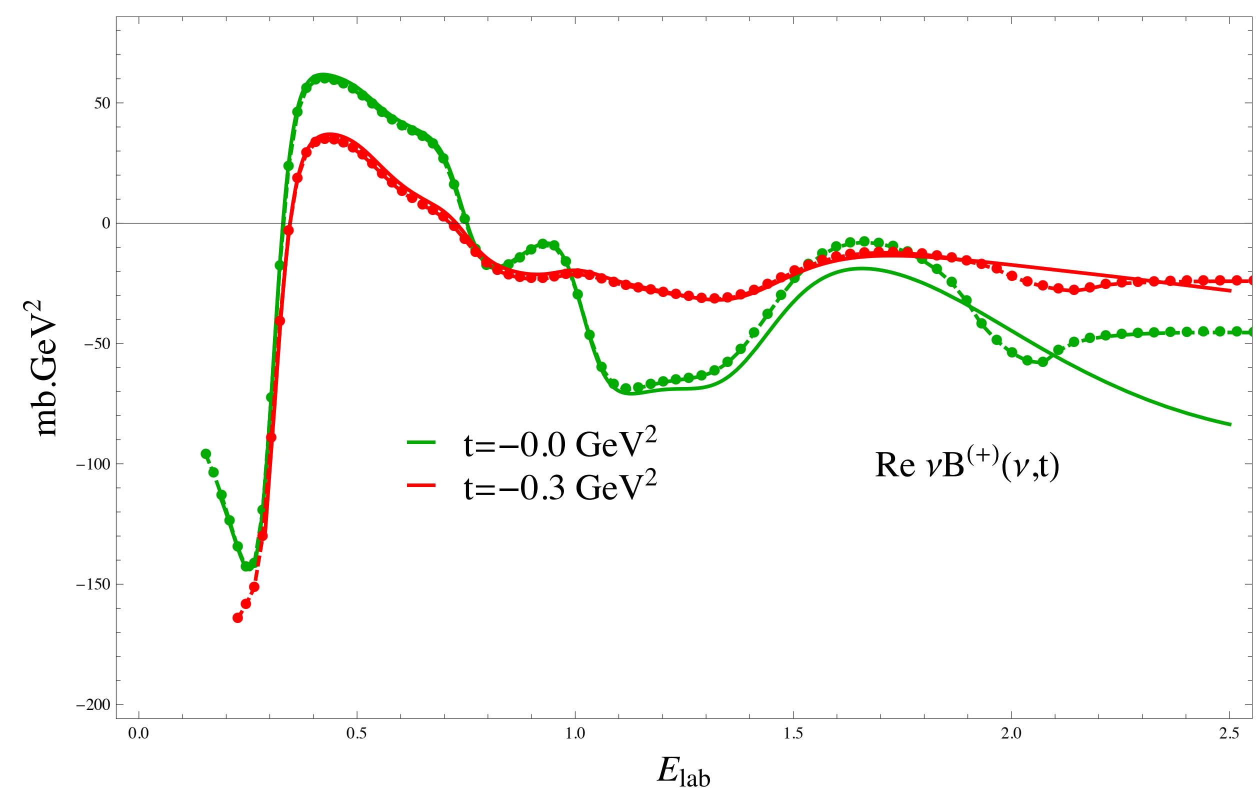
- **Construct Im(A(s,t)) from [s0, ∞] via FESR**

Reconstruct Re(A(s,t)) from dispersion relation

$$A^{(-)}(\nu,t) = \frac{2\nu}{\pi}\int_{\nu_0}^{\infty} \frac{\text{Im } A^{(-)}(\nu',t)}{\nu'^2-\nu^2} d\nu'$$



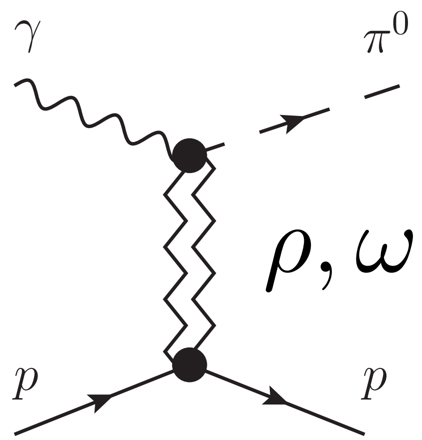
- **Excellent Match between Re(SAID) Solid lines and Re(Reconstructed) Dashed-Dotted line**



- **Building blocks to account for baryon "contamination" in dimeson production**

Resonance-Regge physics in meson-baryon scattering

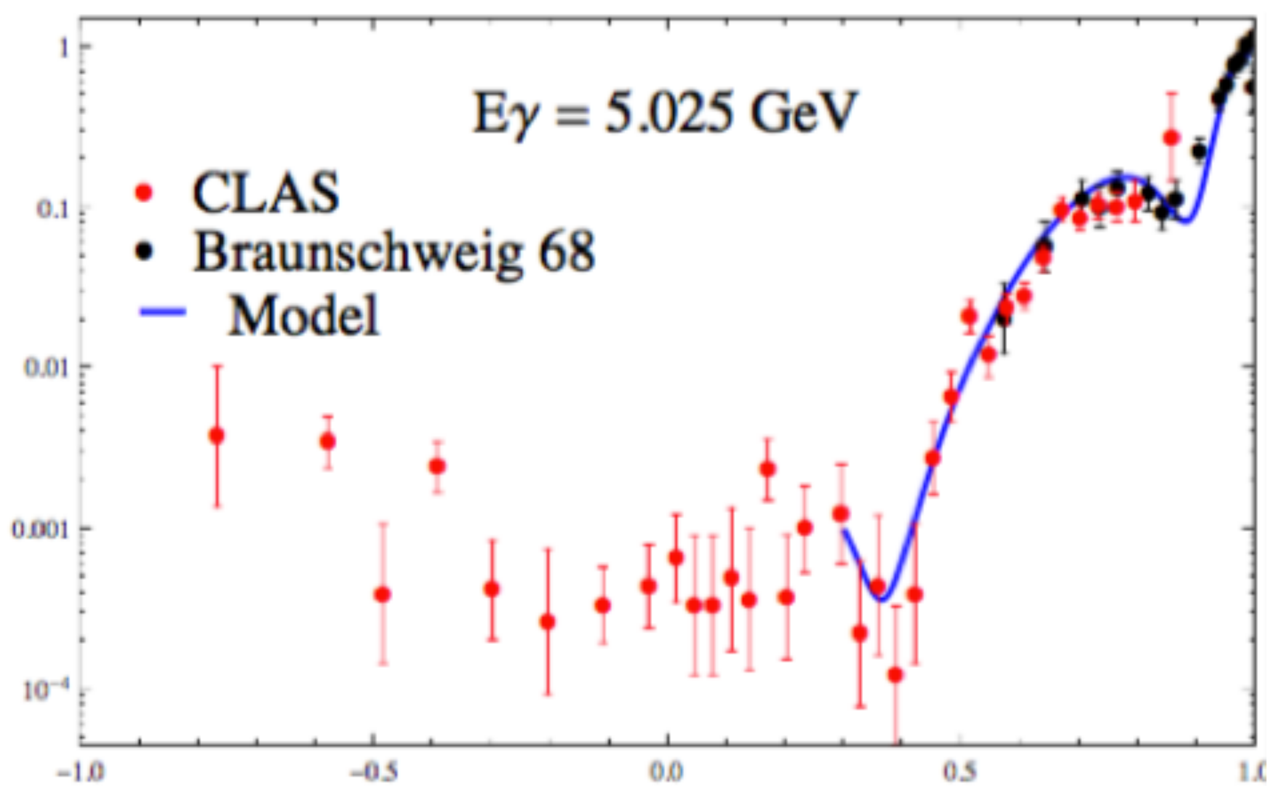
High energy regime dominated by leading t-channel exchange



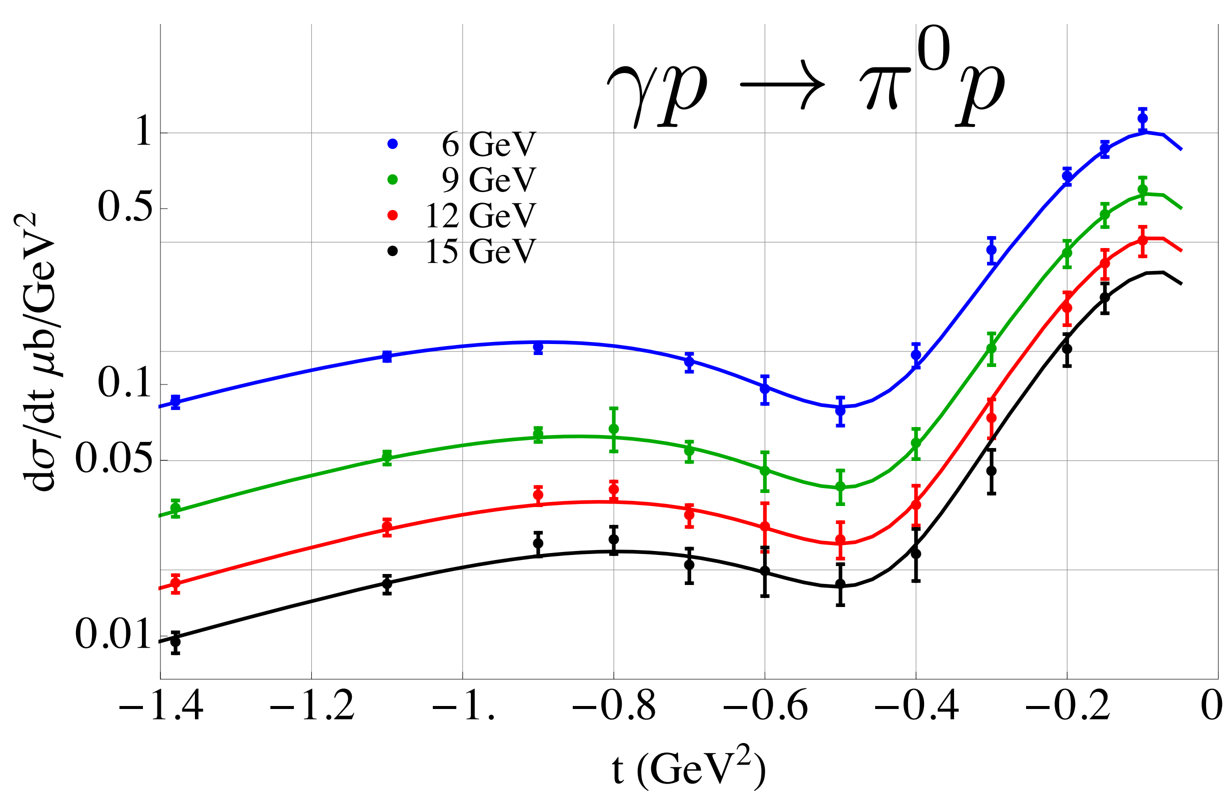
exchange contribution in term of CGLN M1,…,M4 given by t-channel Regge exchange:

$$\bar{u}(p_4,\mu_4)\,[g_1(tM_1 - M_2) + g_4 M_4]\,u(p_2,\mu_2)$$

$$\times\beta(t)\,\frac{1-e^{-i\pi\alpha(t)}}{2\sin\pi\alpha(t)}\,s^{\alpha(t)-1}$$



CLAS preliminary data
Courtesy of M.C. Kunkel et al.

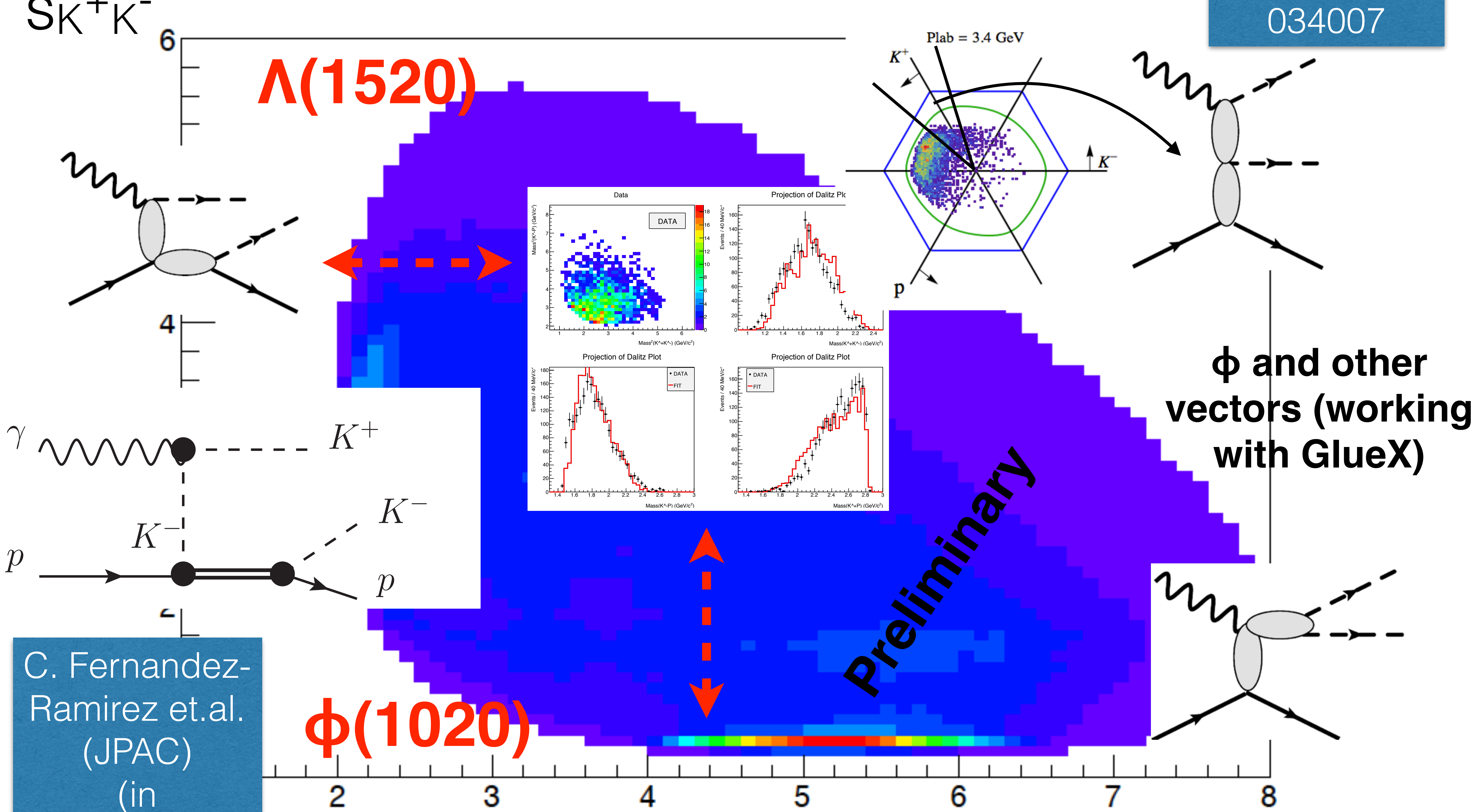


develop FESR's and extend to finite Q^2

Duality @ JLab

B_5 amplitude description

M. Shi et.al. (JPAC) PRD91 3 034007



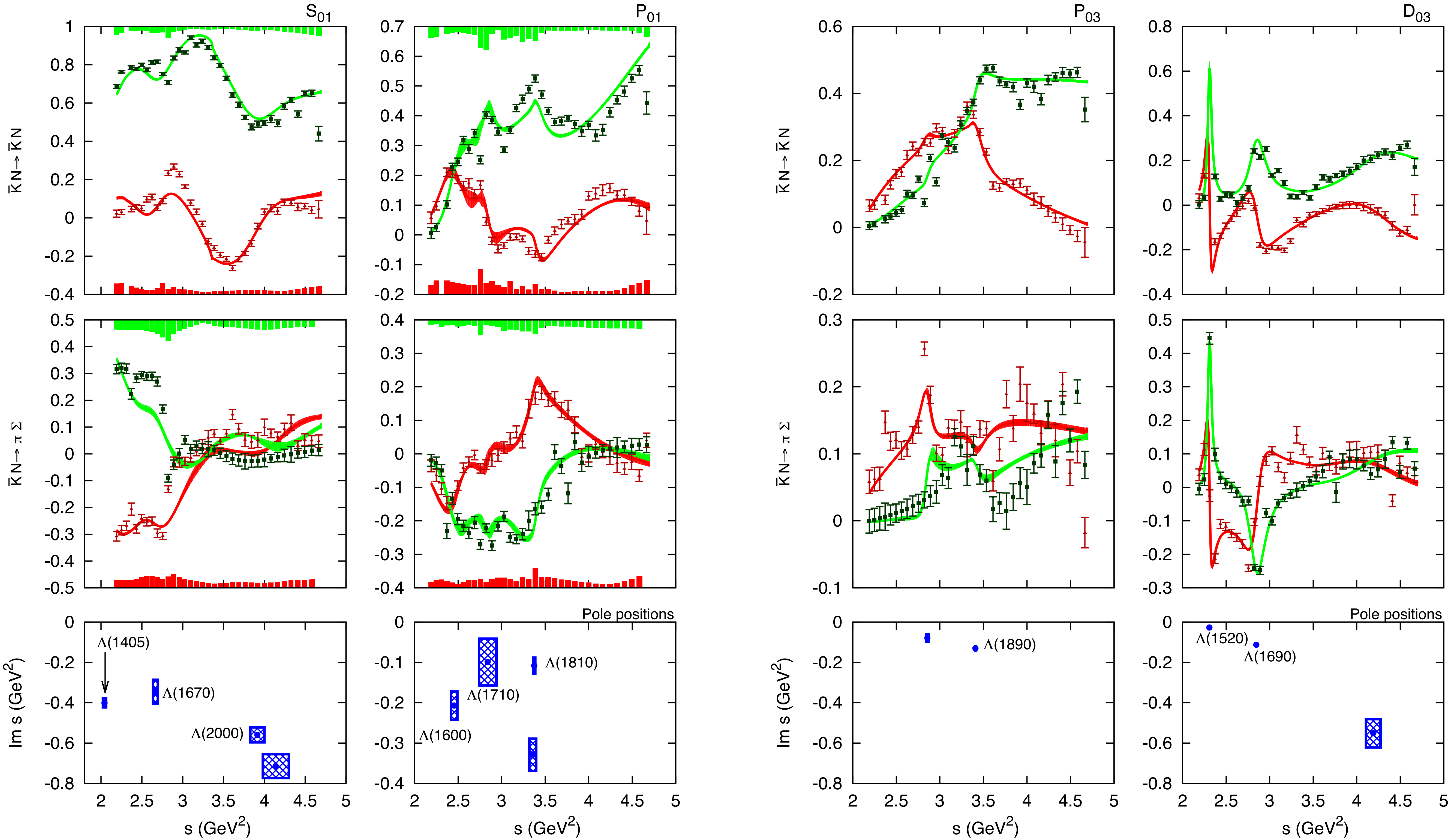
C. Fernandez-Ramirez et.al. (JPAC) (in preparation)

γp → K+K-p (g11,g12)

also see D. Glazier

KN scattering (resonance region)

$[l_{I\,2J}]$



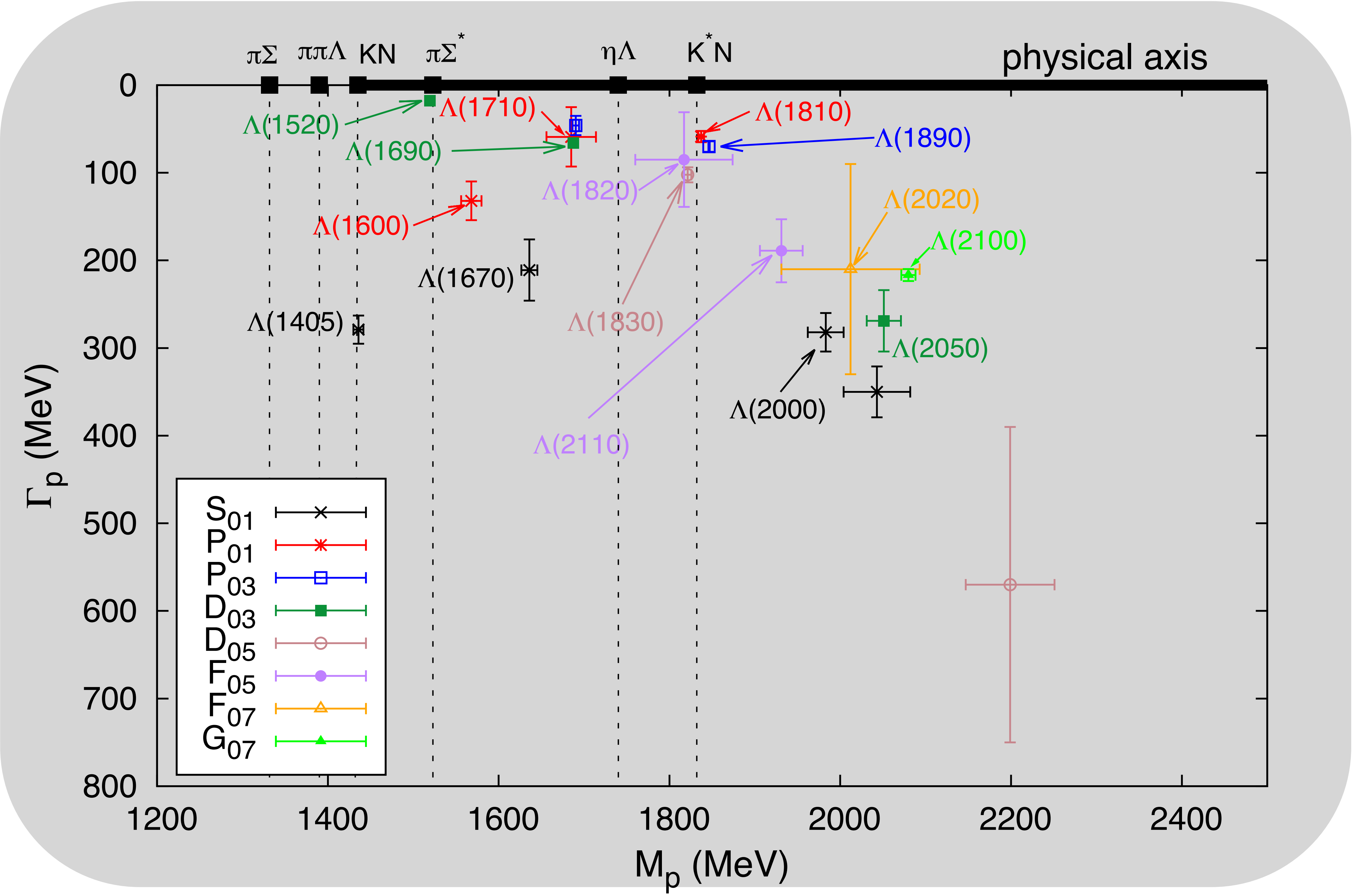
unitarity, analyticity, coupled channels.

Fit single-energy p.w. up to J=7/2 and 2.15 GeV

$\bar{K}N, \pi\Sigma, \pi\Lambda, \eta\Lambda, \eta\Sigma, \pi\Sigma(1385), \pi\Lambda(1520), \bar{K}\Delta(1232), \bar{K}^*N, \sigma\Lambda, \sigma\Sigma$

KN scattering (resonance region)

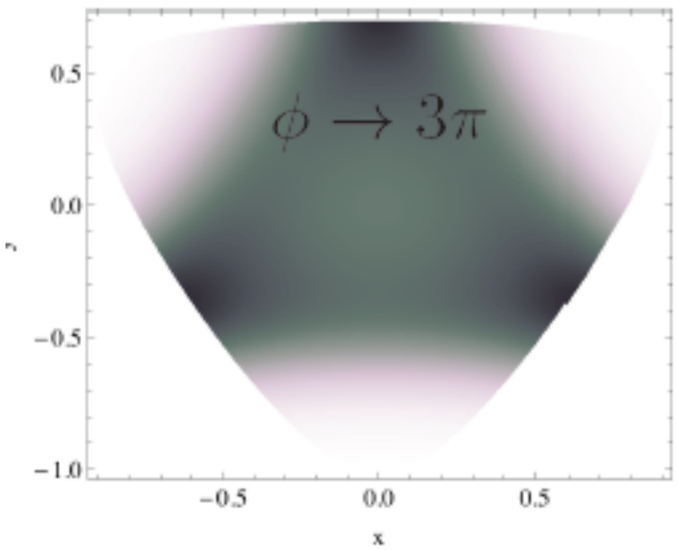
$[l_{I\,2J}]$

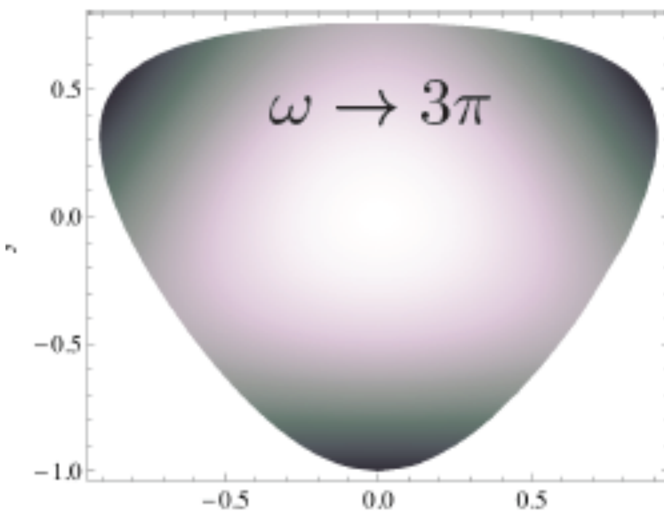


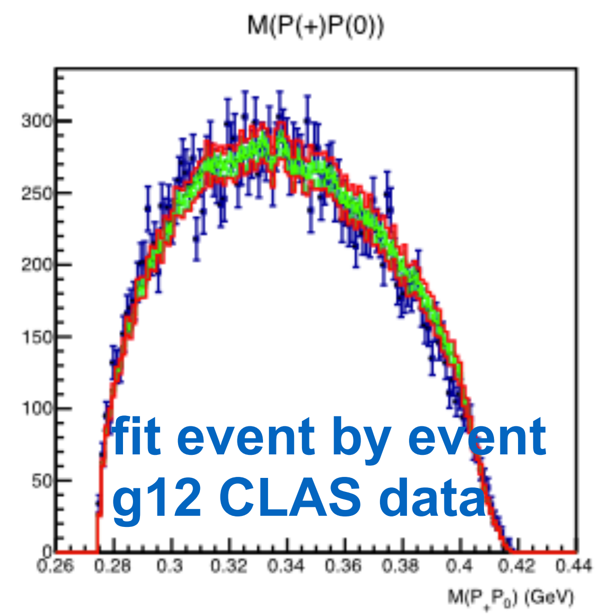
Light meson decays

$\eta \to 3\pi \quad \omega \to 3\pi \quad \phi \to 3\pi$

- **Constrained phase space,**
- **Effective (chiral) dynamics,**
- **Small number of partial waves,**
- **Amendable to dispersive methods**







$\eta \to 3\pi^0$ $\left(Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \right)$

$$A(s,t,u) = -\frac{1}{Q^2}\frac{M_K^2}{M_\pi^2}\frac{M_K^2 - M_\pi^2}{3\sqrt{3}F_\pi^2}M(s,t,u)$$

$\alpha = -0.022 \pm 0.004$

WASA@COSY

Predictions

$Q = 21.4 \pm 0.4$

CLAS@CEBAF in preparation

KLOE@DAPHNE in preparation

$\eta \to 3\pi^+\pi^+\pi^0$

TABLE II: Dalitz plot parameters for $\eta \to \pi^+\pi^-\pi^0$. Set 1 and Set 2 correspond to $(I,L) = (0,0), (1,1)$ and $(I,L) = (0,0), (2,0), (1,1)$ cases respectively (see Table I).

	a	b	d	f
WASA-at-COSY [11]	-1.144 ± 0.018	$0.219 \pm 0.019 \pm 0.037$	$0.086 \pm 0.018 \pm 0.018$	0.115 ± 0.037
KLOE [15]	$-1.090 \pm 0.005^{+0.008}_{-0.019}$	$0.124 \pm 0.006 \pm 0.010$	$0.057 \pm 0.006^{+0.007}_{-0.016}$	$0.14 \pm 0.01 \pm 0.02$
CBarrel [13]	-1.22 ± 0.07	0.22 ± 0.11	0.06 ± 0.04 (fixed)	–
Layter *et al.* [47]	-1.080 ± 0.014	0.03 ± 0.03	0.05 ± 0.03	–
Gormley *et al.* [48]	-1.17 ± 0.02	0.21 ± 0.03	0.06 ± 0.04	–
Theory				
Set 1	-1.116 ± 0.030	0.188 ± 0.010	0.047 ± 0.005	0.093 ± 0.004
Set 2	-1.117 ± 0.035	0.188 ± 0.014	0.079 ± 0.003	0.090 ± 0.003
NLO [21]	-1.371	0.452	0.053	0.027
NNLO [22]	-1.271 ± 0.075	0.394 ± 0.102	0.055 ± 0.057	0.025 ± 0.160
Kambor *et al.* [23]	-1.16	0.24...0.26	0.09...0.10	–
NREFT [28]	-1.213 ± 0.014	0.308 ± 0.023	0.050 ± 0.003	0.083 ± 0.019

More to come
stay tuned

Resonance + Regge analysis of $\pi^- (\gamma)p \to \pi^-\eta p$

Vector meson photo production (GlueX)

Resonance in 3 body systems

Comprehensive analysis of 2-to-2 Regge phenomena

B4 amplitudes for 1-to-3

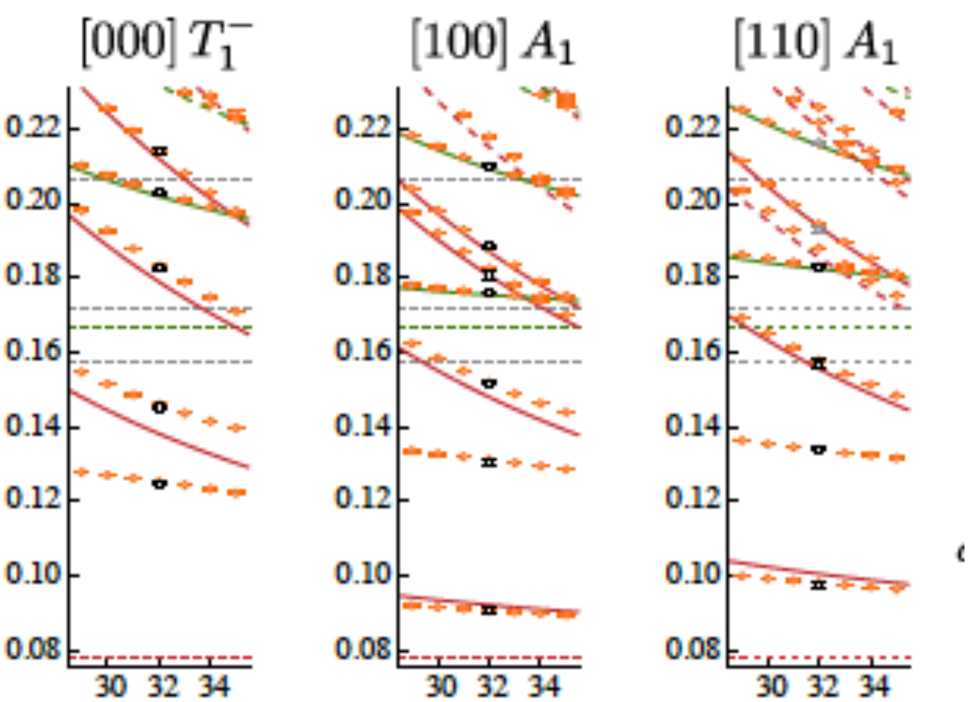
QCD on the Lattice : simulated scattering experiment

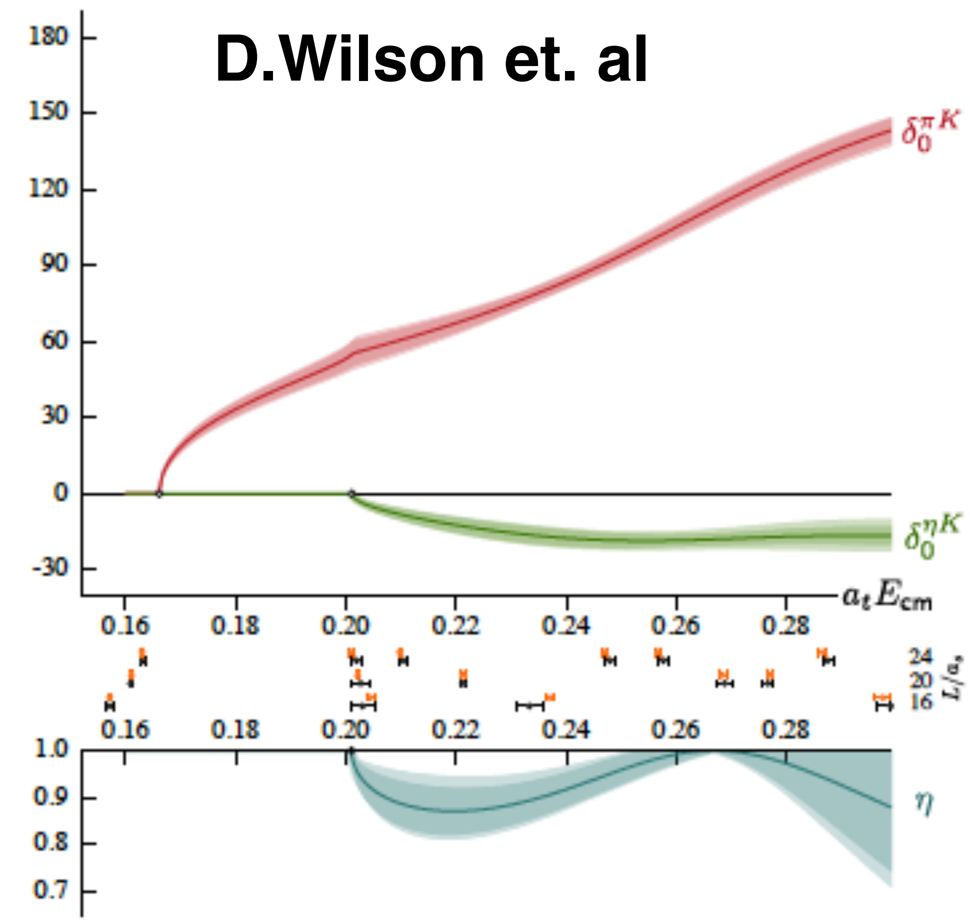
(known kinematical function)

$Z(E_i) = T(E_i)$

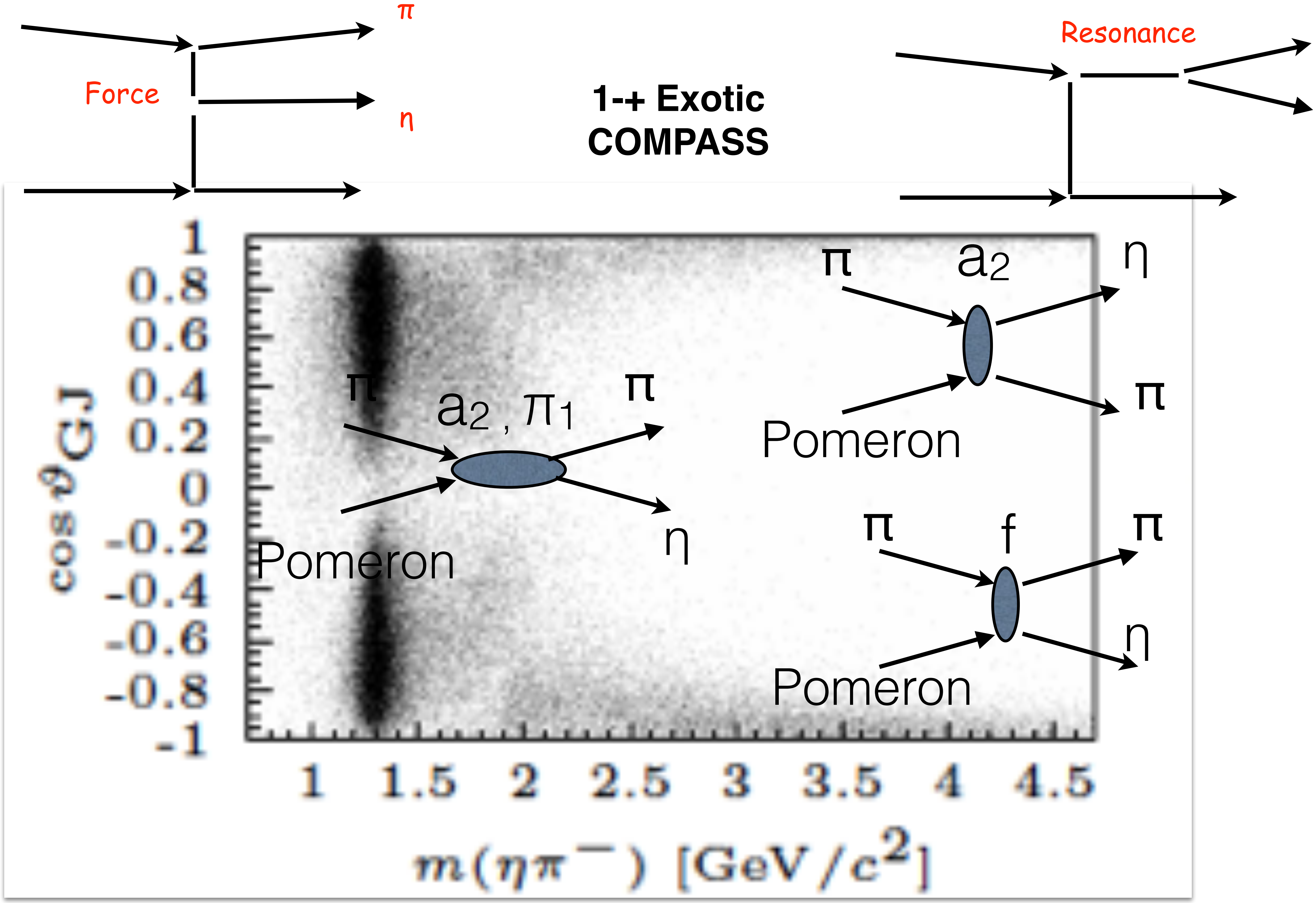
(infinite volume amplitude)

E_i = discrete energy spectrum of states in the lattice





in general “solution” of the Lusher condition requires an analytical model for T



duality —> the production channel is dominated by spin-even partial waves. What is the exotic (P-wave) dual to ?