PLANNING A NEW GENERATION OF MULTIPARTICLE PHASE SHIFT ANALYSES IN PERIPHERAL REACTIONS

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We discuss partial wave analysis of meson resonances with emphasis on the issues relevant to the GlueX experiment at the upgraded Jefferson Laboratory accelerator. We describe the challenges in the analysis coming from the need to build theoretical models to support partial wave analysis of the experimental data. These difficulties have dogged previous experiments of this type but are counterbalanced by improved Grid-based computing environments and by the high quality of the new data.

1. Introduction

We discuss some of the phenomenological and computing principles that would be relevant in analyzing meson photoproduction with incident photon energies of about 10 GeV as envisioned in the GlueX experiment [1]. Thus we mix the old and the new; the needed understanding [2] of hadronic reactions with Regge poles, final state interactions plus S-Matrix theory and folklore hasn't changed much in 30 years. On the other hand, the Grid-based computing model [3] is still being developed with the imminent deluge of data from the LHC at CERN as a major driving force [4]. There is little doubt that the seemingly tranquil physics issues will have a far greater impact on the GlueX experiment than the "hotter" information technology (Grid). However Grids may help to produce a more powerful analysis environment than for previous such experiments and this combined with the much higher statistics and quality data will allow a more thoughtful and careful analysis of the difficult physics problems. Conversely the better data will in fact require such an improved analysis. These general issues are discussed in Sec. 2 where the next section investigates the various physics uncertainties. Sec. 4 discusses the current status of Grid and Web service technologies and their application to GlueX. The final section brings the threads together with a combined physics and computing summary.

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2. Motivation and Background

We are examining reactions like γ N $\rightarrow$ Mesons + N as shown in fig. 1 to identify new meson resonances – especially glueballs which are expected to be preferentially produced by the photon beam. The GlueX experiment aims to extract clear evidence for resonances; determine masses, widths and their decay modes; compare with theoretical models; it will focus especially in areas (exotics, glueballs) that extend our understanding of the quark model. We can summarize the characteristics of this class of experiment by:

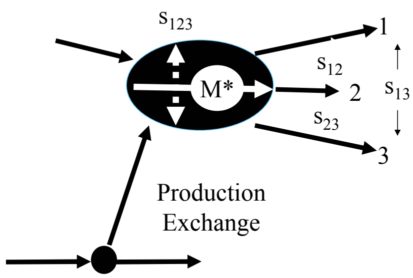


Fig. 1: Peripheral Production of a 3-body final state

- PLUS: Photon beam should excite "interesting" mesons
- PLUS: Peripheral production has reasonable cross-section at Jefferson Laboratory
- MINUS: Comparatively low spin at given mass of glueballs enhances background of "exciting" mesons compared to those we understand.
- MINUS: Need to parameterize amplitudes – cross-sections insufficient to extract resonances and parameters
- MINUS: Amplitude partial wave analysis requires model i.e. untested assumptions
- MINUS: Energy of Jefferson Laboratory lower than optimal value (20-100 GeV) for clean production mechanisms

As the high energy physics community stopped working in this general area, we do not have some key information that could have been gotten from earlier generation hadronic accelerators. For example I would consider it best to first study peripheral meson production in simple reactions like π N $\rightarrow$ π π N where clean analysis of (resonances in) π π scattering would be possible. One could then step up though reactions like π N $\rightarrow$ π π π N and systematically investigate techniques and the impact of theoretical uncertainties in the analysis. As the mesons of interest for GlueX are higher mass and lower spin than the well established states in the particle data group tables, they are not expected to be identified by simple model-independents "cuts" and plots. Rather powerful but inherently non robust partial wave analysis (PWA) must be used. It is the unclear assumptions needed in the model used for the PWA which represent the great challenge to GlueX and which in some cases could be tested in simpler (but less interesting from a resonance point of view) hadronic reactions.

3. Physics of Hadronic Amplitudes

3.1. *S-Matrix Theory*

S-Matrix theory was very popular some 30-40 years ago and we learnt a lot about scattering amplitudes coming either from study of model field theories or from general principles including symmetries, unitarity, and analyticity. Originally it was hoped that the set of overlapping nonlinear constraints might be sufficient to uniquely determine the scattering amplitude but this goal was probably not reasonable and certainly did not succeed. Rather an amazing number of "truths" were unearthed that were exhibited exactly or approximately by each amplitude. An essential aspect of this work was the overlapping nature of the "truths". They typically did not "add" like terms in a Hamiltonian but rather described amplitudes from different points of view, Thus we learnt one could not dismiss one interpretation of a feature because there was another way of describing it. Maybe these interpretations were two faces of the same coin (field theory). One example is exchanged particles and resonances; just because the low mass 3 π enhancement in diffractive $\pi\ p \rightarrow (3\ \pi)\ p$ can be caused by π exchange does not mean it is not "also" the A_1 resonance; perhaps the π exchange in $\rho\ \pi \rightarrow \pi\ \rho$ is the force that generates the A_1. One cannot "subtract" the π exchange; rather one can only perform a PWA on the full amplitude and look at phases and analyticity of individual partial wave amplitudes to discuss "background" and resonance. This may not be difficult at low masses but in regions of interest to GlueX the difference in amplitude structure between resonance and background need not be dramatic. In this case information from other reactions or some a priori prejudice may be needed to come to quantitative conclusions. Another well known example is that of "final state interactions"; as we quantify in sec. 3.5, it is not in general "correct" to subtract this off or dismiss a resonance claim because it can be explained by final state interactions. Essential problems in PWA are that

- One must parameterize amplitudes in order to able to disentangle the low spin resonances
- This parameterization must involve some assumptions which hopefully respect our current theoretical understandings as much as possible.
- One has a set of constraints on the amplitude which are incomplete and there are typically no useful ways of "guaranteeing" a given constraint without prejudicing one's expression of other issues; for example usual ways of enforcing unitarity do violence to analyticity and duality(crossing)
- Further the constraints are inherently not additive or exclusive
- We do not have enough data to be able to test either our assumptions or the uncertainties in interpretation. Partial wave analysis above threshold is only

well studied in π N elastic scattering. This is very helpful but does not address many issues that will occur in the GlueX problem.

3.2. *Defining an Amplitude*

We can assume an exchange model like fig. 1 for meson resonance production as it has been seen in essentially all such reactions above a few GeV/c beam momentum. The production exchange must be thought of as a Regge trajectory and the traditional particle exchange is only even approximately valid for π exchange. Thus one can consider these peripheral reactions as being described as a product of three terms: Bottom Vertex, Regge Propagator and Top Vertex. The amplitude of any reaction must sum over these products for each exchanged trajectory. There is insufficient data to disentangle multiple exchanges and so one would typically assume a single "effective" trajectory and one such term. Then one would normally not worry about the Regge Propagator and Bottom Vertex as due to factorization these are approximately the same for all produced states and so cancel out in any analysis. This leads to a description of the reaction in terms of a Beam (photon) scattering on a Reggeon leading to the meson final state as seen in fig. 2. We are not certain that such Reggeon amplitudes have quite the same properties as "ordinary" amplitudes like π π or π N scattering but this assumption is reasonable.

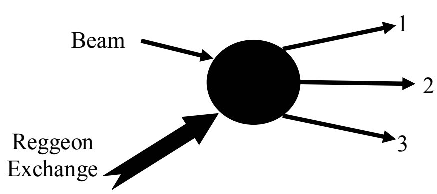


Fig. 2: Production as a Beam-Reggeon Scattering Amplitude

Density Matrices will find dominant high spin resonances and lead to analyses whose robustness will delight the statistics expert but will also robustly lead to no conclusions for the particles of interest. Thus using amplitudes is more or less essential to find any "not immediately obvious" resonances and further enforces rank and positivity conditions on density matrix. Amplitudes can then embody constraints we discuss in sec 3.3 but must be parameterized to reflect both unknowns and "what we know". This bound to be wrong at some level and the purpose of this discussion is to find ways to minimize errors in amplitude approximations and estimate their size.

The exchanged Reggeons are seen most cleanly at beam momenta of around 20 GeV/c and more but their essential characteristics are apparent at much lower momenta. Some backgrounds such as Regge cuts may in fact increase with increasing momenta but others like non-leading trajectories definitely decrease. The s^{α} energy dependence of the Reggeon propagator ensures that the "leading" trajectories are most important and fortunately these are well studied at GlueX energies. Very high energy data has altered our view [5] of the Pomeron which describes diffractive processes and one now suggests an intercept $\alpha(0) > 1$. However my guess is we are seeing "effective" Reggeons at GlueX and it is probably best to consider a Pomeron with $\alpha(0) = 1$ in this case. One might expect reactions with the best understood production exchanges: Pomeron, f, ω, ρ, A_2, π etc. to be most reliable. In particular the f, ω, ρ, A_2 exchange degenerate Reggeons are notable for remarkable agreement with simple ideas; one can expect analyses of reactions dominated by these exchanges to be especially reliable. π exchange is another special case due to the dominance of the "real particle" pole and one can expect to very reliably study such π target reactions by selecting small t; the π is not known to have good Regge properties and has some special features described in [2]. Pomeron production could lead to peculiar reactions with the amplitude Beam + Pomeron $\rightarrow$ Mesons perhaps exhibiting unusual features; as there is no known particle on the Pomeron trajectory, it is not so clear its amplitudes behave in the way we have understood from the Reggeons associated with "real particle" exchange.

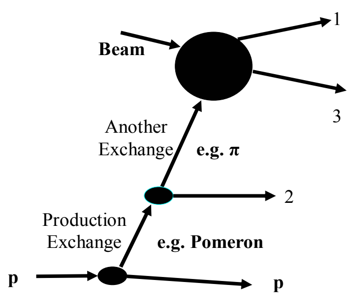


Fig 3: Multiperipheral Diagram

One identifies possible exchanges from the quantum numbers exchanged at the top vertex; amplitudes corresponding to A_1 exchange are particularly tricky. This is a low trajectory with murky properties. Further there are many possible background reactions such as those of fig. 3, which are discussed in [2].

3.3. *Properties of Amplitudes*

3.3.1. Analyticity

Analyticity tells us about the S matrix structure as poles and cuts in the s t and u complex planes. Two-body amplitudes are functions of 2 independent complex variables – say s and t with u eliminated as $s + t + u$ is equal to the sum of the particle masses. Poles as shown in fig. 4 correspond to particles and resonances while cuts to multiple exchanges (box and more complex diagrams). One needs to examine all 3 channels to get the full analytic structure. s channel partial wave amplitudes are gotten by integrating over t and u and the analyticity in these crossed channels translates into the behavior of the large angular momentum waves in s. This effect was skillfully exploited by Cutkosky in π N elastic but is not easy to use as a quantitative rule.

3.3.2. Spin and Symmetries

The consequences of Lorentz invariance for the spin structure of amplitudes is well understood but complicated as it naturally introduces one amplitude for each spin of independent particle or resonance approximated by a particle. Polarized beams in GlueX will help here. Spin formalism is well understood both for full, decay, and Regge exchange amplitudes. In particular the analytic structure of amplitudes is well defined for t-channel (Jackson-Gottfried), s-channel frame (helicity) and transversity (quantized perpendicular to production plane) amplitudes. Transversity amplitudes have nice selection rules and invariance under rotations but poor analyticity structure. The preferred s-channel frame has particularly good analyticity and well understood "zero" structure at t=0; so it should be the reference frame for amplitude studies where assumptions of "smoothness" are inevitable and so controlled with the s-channel frame.

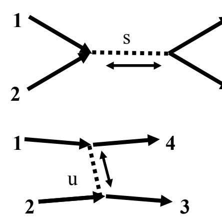


Fig. 4: 2 → 2 Scattering with ***s t*** *and* ***u*** *channel exchanges*

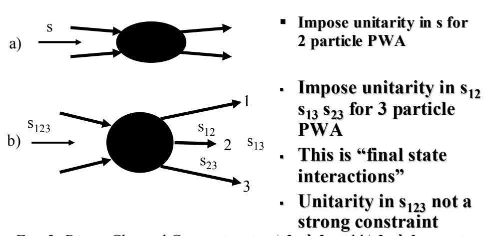


Fig. 5: Direct Channel Constraints in a) 2 → 2 and b) 2 → 3 reactions

Of course amplitudes can straightforwardly express expected structure of quantum numbers, coupling constants, symmetries, chiral limits etc.

3.3.3. Unitarity

Unitarity shown in fig. 5 as a well understood constraint in every direct sub-channel but the constraint is only strong at low channel energy when there are one or a few possible intermediate states and it is not clearly useful in production processes which are always off diagonal as shown in fig. 2. Further as we discuss later it is often wrong to add unitarity to a resonance Regge exchange model; unitarity is dual to crossed channel effects. I think the lessons from using unitarity in π N elastic and inelastic scattering are not easy to apply to the production case and many papers in this area are suspect from the duality issues discussed in the next section.

3.4. *Duality*

This was produced from a mixture of inspired theory and phenomenology in two body scattering – especially π N $\to$ π N and $\pi\ \pi \to \pi\ \pi$. It says that the 3 diagrams of fig. 4 cannot be added as we keep saying; rather if the "poles" becomes Reggeons, then the *s* channel Reggeon is created by the classical forces i.e. the *t* and *u* channel Reggeons. The remarkable Veneziano model illustrates this in a fashion that is not quantitatively useful. Consider the simple limit with exchange ρ and *f* trajectories $\alpha(t) = \alpha(0) + \alpha' t$ with $\alpha(0) \approx 0.5$ and $\alpha' \approx 1$ $(\mathrm{Gev/c})^2$. Then $\pi^+ \pi^- \to \pi^+ \pi^-$ scattering could be represented by $\Gamma(1-\alpha_\rho(s))\ \Gamma(1-\alpha_\rho(t)) / \Gamma(1-\alpha_\rho(s)-\alpha_\rho(t))$ which has no *u* channel singularities as it is exotic but shows the *s* and *t* channel Reggeons explicitly formed together and not added.

3.4.1. Two Component Duality

The above can be made more interesting by two component duality which claims that one form the full amplitude as the sum of two terms
a) The Veneziano like formula with Reggeons corresponding to traditional $q\bar{q}$ particles dual in two or three (*s,t,u*) channels.
b) A Pomeron term dual to background.
Note this formula exhibits very clearly the role of both exchange degeneracy and daughter trajectories. The latter will create of course unfortunate backgrounds for some of the non $q\bar{q}$ states GlueX is looking for. This two-component duality principle could be very powerful in meson scattering where many channels have no Pomeron at all – these should be best to look at as duality asserts that there should be much less background to hide the new states. Further the Pomeron contribution can be rather easily be estimated either from factorization and ratio of π N and N N scattering or directly from $\pi^+ \pi^+ \to \pi^+ \pi^+$ scattering. It is a pity that $\pi\ \pi$ in all its charge states was not better studied; it could tell us so much about the validity of approximations, the importance of daughters, backgrounds and extensions of ideas from meson baryon to pure meson case. Backward $\pi^+ \pi^- \to \pi^+ \pi^-$ scattering is particularly interesting as daughters in the s channel cancel the backward peaks of s-channel resonances like the ρ and as surely there will be a low cross-section for such backward scattering, study of how it is achieved in the partial wave analysis can help interpret possible new low spin resonances.

3.4.2. Finite Energy Sum Rules

In π N elastic and charge exchange scattering, duality worked well to low energies as shown by for example the persistence of Regge zeros (such as the ρ exchange "wrong signature" zero at t = -0.6 $(\mathrm{Gev/c})^2$) to low energies. Further there is the low energy suppression of backward peaks dual to nucleon and not meson or Pomeron exchange. Finite energy sum rules or FESR allow one to convert these rather sloppy arguments into precise statements. They are typified by formulae like:

$$\int_{Threshold}^{Cutoff} \nu^n \,\mathrm{Im}A(\nu,t)\,d\nu = \text{Regge Contribution} \qquad [\nu = s - u \textit{ with fixed } t]$$

Here A is the low energy amplitude to be calculated from the PWA.

3.4.3. Applications to Partial Wave Analysis

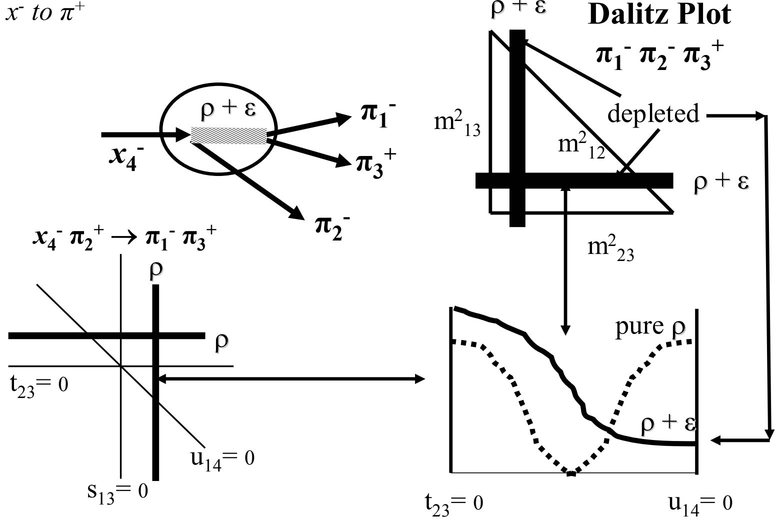
FESR were successful in π N scattering and should be also be applicable in photon (meson) scattering amplitudes as represented in fig. 2. They are especially interesting in cases like fixed u in $\pi^+ \pi^- \to \pi^+ \pi^-$ scattering where there are no Reggeon contributions. Note that FESR should work separately for Pomeron (background) and classic Regge components and for both fixed t and u. Further in π N elastic scattering one was able to use Regge exchange contributions as an approximation to high partial waves. This approach should be applicable to photon or meson induced "top vertices" including reactions like γ Pomeron $\to \pi^- \pi^- \pi^+$ with internal π exchanges sometimes giving a natural high partial wave approximation. This phenomenology suggests a PWA model that is combination of a Regge Born with low partial waves removed and parameterized low partial waves. The FESR then give constraints on the parameterized waves.

Note that two component duality gives an attractive Born term although it is obviously not rigorously justified directly by theory but unlike other approaches we do have an additive model with a clear prescription to avoid "double-counting" . Of course it might break down in the GlueX scenario with photon beams and Pomeron "targets" but it is most plausible to use methods that have worked in π N scattering than those that have failed even in that case.

3.5. *Quasi Two Body Approximations*

We will need to study final state interactions although these are partly included as duality says direct (resonances) and exchange effects (forces) are the same not different dynamics. Let us look at these issues in the context of 3 and higher particle final states at the top vertex where one will need the "quasi 2-body" approximation to do practical amplitude based partial wave analysis. Taking for example an $\pi_1^- \pi_2^- \pi_3^+$ final state at the top vertex, this would be approximated by the sum of $\pi_1^-\rho$ and $\pi_2^-\rho$ final states and this approach has proven to be reliable at least when resonances are well established like the ρ which appears to

Fig. 6: The ρ and ε must interfere coherently to suppress double charge exchange x^- to π^+



have similar dynamics to "real particles" like the π. There are some subtle effects illustrated in fig. 6. Each of the produced ρ^0 is accompanied by its spin 0^+ daughter – called here the ε – whose phenomenological status is unclear. However ρ^0 ε interference is required to remove the exotic double charge exchange $x^- \rightarrow \pi^+$ transition. As shown in fig. 6, this coherent interference between ρ and ε production would be seen in a three final state π Dalitz plot. S wave π π scattering has in simple pictures, both

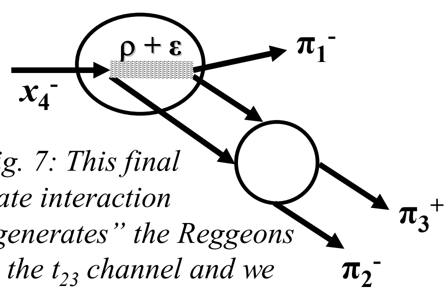
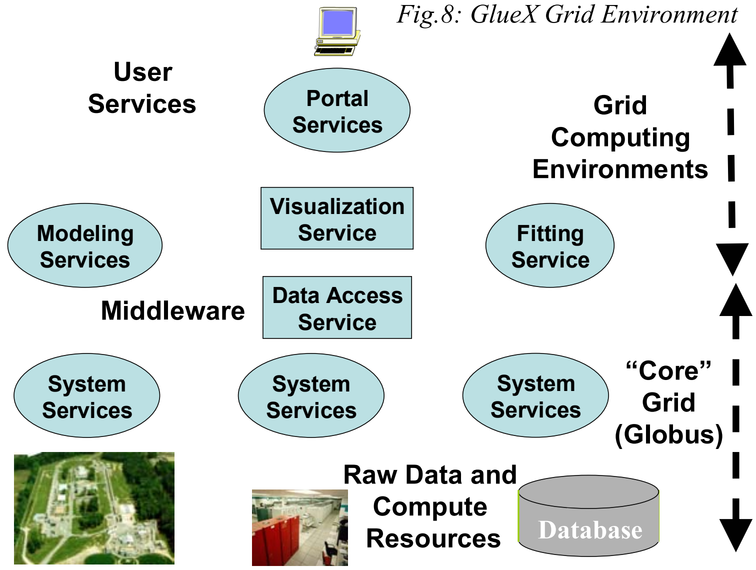


Fig. 7: This final state interaction "generates" the Reggeons in the t_{23} channel and we include these in ρ + ε ansatz in s_{13} channel

"background" dual to the Pomeron and the ε dual to *f* and ρ exchange in the *t* channel. It would be important to clarify these basic duality related dynamics as soon as possible as they underlie much analysis needed by GlueX. The best place to start would be the simplest two and three π final states produced in a π beam. Here FESR can be important in distinguishes what is background and what is ($q\bar{q}$) resonance. Fig. 7 returns to the $\pi_1^- \pi_2^- \pi_3^+$ final state, and points out that the final state interactions in the 23 channel generate the Reggeons in this channel which are then dual to the ρ^0 and ε in the 13 channel. This glib assertion is complicated by the Pomeron in the 23 channel which is dual to the 13 background which we try not to include – although given confused situation with the ε this may be difficult to achieve. GlueX needs to build a sophisticated modeling framework that can incorporate these complicated effects and estimate uncertainties that they produce.

4. Grid Computing

Fig.8: GlueX Grid Environment



Grids address "Internet Scale Distributed Computing" and can also be considered as supporting the electronic communities (virtual organizations) that have become common in e-Science and were in many ways pioneered in particle physics. One expects the LHC data processing infrastructure LCG to be the largest scientific Grid and major projects such as EDG (European Data Grid [6] and its follow-on EGEE - Enabling Grids for E-science in Europe [7]) in Europe and the US PPDG, GriPhyn and iVDGL (collectively Trillium) projects have been centered on this problem. These projects have been built on major computer science activities such as Globus [8] and the Global Grid Forum [9] developing respectively core Grid software and standards [3,4,10]. The current particle physics Grid technology is focused on the management of the core data, its initial analysis passes and the support of the multi-tiered computing infrastructure that will be used to process the data. Currently the Grid community is moving from the older Globus 2 technology to Web Service/OGSA (Open Grid Service Architecture [11]) based approaches such as GT3 [12]. GlueX will presumably make as much use as possible of this infrastructure and focus new activities on the special requirements of the PWA problem. We expect that as shown in fig. 8, GlueX will use Web and Grid Services systematically and adopt a modern portal architecture [13]. GlueX should for example build database support on the evolving OGSA-DAI approach which will support a rich collection of data storage and access options (files, relational and XML queries) [14].

The key physics modules should be designed as Grid services with well defined input and output ports for their data and user interaction; this will require developing XML schema to define the PWA data structures and using them in the WSDL (Web Service Definition Language) interfaces. Capabilities such as define model, calculate model predictions, perform (parallel) fit, access data and visualize results will be separate Grid services defined by standard Grid and PWA specific meta-data. These services will be linked together by evolving Grid workflow systems. All system capabilities (visualize, run Monte-Carlo, examine job status etc.) will be available as portlets [15]. This portal approach is based currently on Apache open source Jetspeed technology and allows easy re-use of both Grid services and their interfaces. The PWA work will access the growing library of general portlets which cover essentially all core Grid services as well as useful capabilities such as collaboration including the Access Grid. We further expect that good management and data-mining (visualization) tools will be essential to cope with the large datasets and challenging physics.

5. Possible Plan for GlueX Physics Analysis

We have discussed the Physics and Computing issues underlying the GlueX analysis. We suggest an approach that starts with a formalism that allows the inclusion of all relevant effects. These include Regge production mechanisms and Regge models inside the “top vertex”. The latter should be used for high partial waves, two-component duality and FESR. Sophisticated spin formalisms should be used. Unitarity should be “worried about” but not blindly added.

GlueX should encourage related studies with meson beams to study both interesting resonances and assumptions in a more controlled environment. We hope that the good experimental data combined with the powerful computing environment will allow interactive analysis to analyses the inevitable uncertainties and biases in the analysis so that authoritative results will be possible. Sources of error include:

- Unitarity (final state interactions)
- Errors in the two-component duality picture.
- Exotic particle production, Pomeron exchange, photon beams, π exchange or some other "classic effect" not present in original πN analyses behave unexpectedly and are inconsistent with current folklore.
- Failure of quasi two body approximation
- Regge cuts which are present but impossible to study quantitatively
- Background from other channels

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