Amplitude Analysis

QCD and the role of Gluonic Excitations
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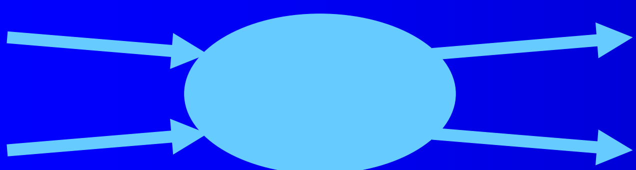

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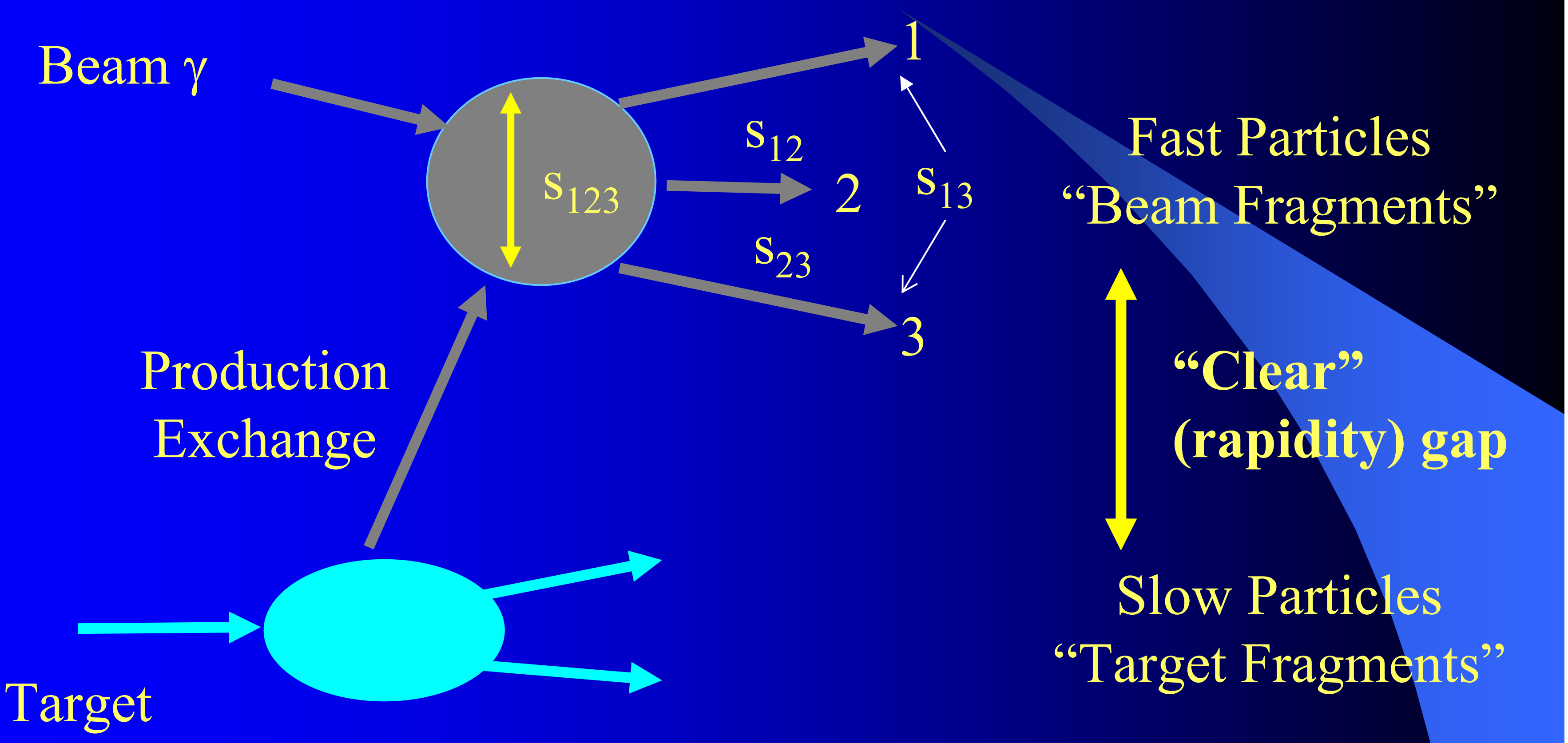
Some Lessons from the past

- **Amplitudes exhibit many features for which there is no clear formalism that expresses in an integrated "additive" fashion**
  - We found a lot of "true" results but little that was quantitative
- **Analytic Structure as in S matrix with poles and cuts**
  - Poles correspond to particles and resonances
  - Cuts to multiple exchanges (box and more complex diagrams)
  - Need to look at all channels to get full analytic structure
- **Unitarity as a well understood (but difficult in multi-particle case to implement) constraint in every direct sub-channel**
  - Constraint only strong at low channel energy when one or a few possible intermediate states and not clearly useful in production processes
- **Spin formalism (Lorenz invariance) is of course well understood and uncontroversial**
- **Complex Angular Momentum Plane: Cuts and Poles**

Prototypical Reaction

- **We are studying the sub-Reaction, Beam plus "Production Exchange" gives 1 + 2 + 3**

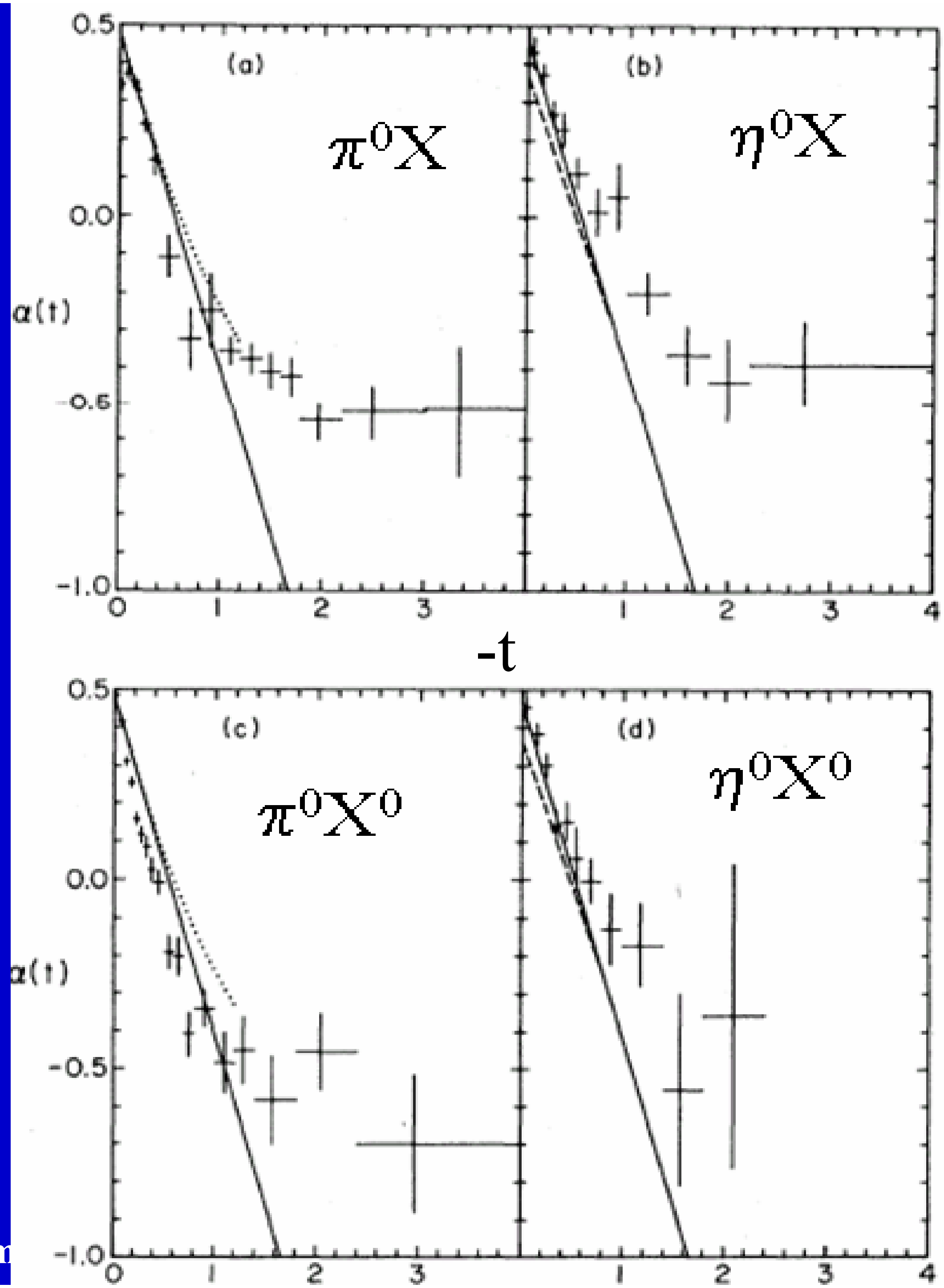


Break Amplitude Model into 2 pieces

- **1) Model for Exchange**
  - In nearly all interesting cases exchanged particle should be a well known Reggeon (possibly the Pomeron) as these have highest intercept and will dominate in high energy region and this is only place reaction clean and distinguishable from background
  - Exchange is Pomeron, ρ ω π and exchange degenerate A_2 f_2 B_1
- **2) Model for**
  Beam plus Exchange → "top vertex" final state
  - This is similar (how accurate is this?) to that for case where Exchange (Reggeon) replaced by "real particle" as critical symmetry, analyticity, duality, relevant unitarity constraints are qualitatively unchanged

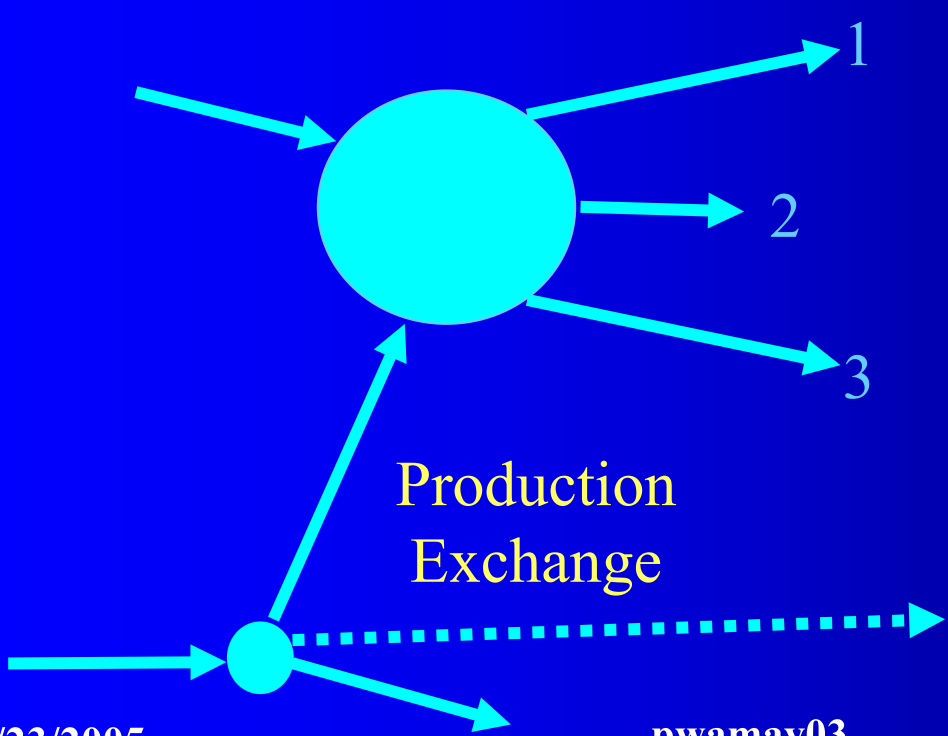
Classic Regge

- $\pi^- p \rightarrow \pi^0 \eta n$ dashed
- $\pi^- p \rightarrow \pi^0 \eta$ inclusive or all neutral (η' similar) data
- Straight lines are through 1 at $t=m_\rho^2$ or 2 at m_{A2}^2 with slope 0.95
- f and ω are equally beautiful but not so easy to measure as isospin zero with Pomeron contributions



Factorization Useful?

- **In days gone by, we got essentially identical dynamics from $\pi^- p \rightarrow \pi^0 n$; $\pi^- p \rightarrow \pi^0$ inclusive ; $\pi^- p \rightarrow \pi^0$ plus any neutral**
- **So at least in cases where clear Reggeon exchange involved, doesn't really matter if "target vertex" reaction clean**



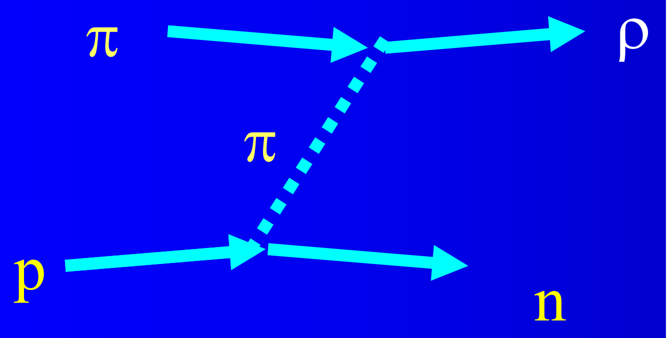
Add anything you like at bottom vertex

Classic Regge II

- ρ exchange has "wrong signature" zero at $\alpha_{\rho}(t) = 0$ which is seen even at low s from Lovelace and Donnachie phase shift analysis
- But there ought to be cuts in angular momentum plane from diagrams like that below
- If Pomeron at $\alpha = 1$ then cuts go up to $\alpha_{cut}(t) = \alpha_{\rho}(0)$
- In general cuts have smaller slope in J plane and tend to get more important at large –t
- This is not seen very convincingly although presence indicated by $\pi^- p \rightarrow \pi^0 n$ Polarization (which vanishes for a pure pole)
- Note NO real reason we can do a Regge perturbation theory

π Conspiracy/Cuts

- **Problems with double spin flip amplitudes**



OK with helicity 0 ρ but naïve factorizable π exchange vanishes when ρ helicity 1 – not seen experimentally
π p n vertex vanishes at t=0 as spin flip=0

- **Interesting to compare with Δ production at target vertex as π p Δ does not vanish at t=0**
- **Poor Man's Absorption Model:**
  - Residues at π **pole enforced in AMPLITUDEs**
  - **Simple dispersion relations (constant subject to kinematics) in t**
  - **Differs from π exchange as residues factorize; amplitude kinematic conditions violate factorization at t=0**
- Claimed to be cuts (absorption model) but little evidence

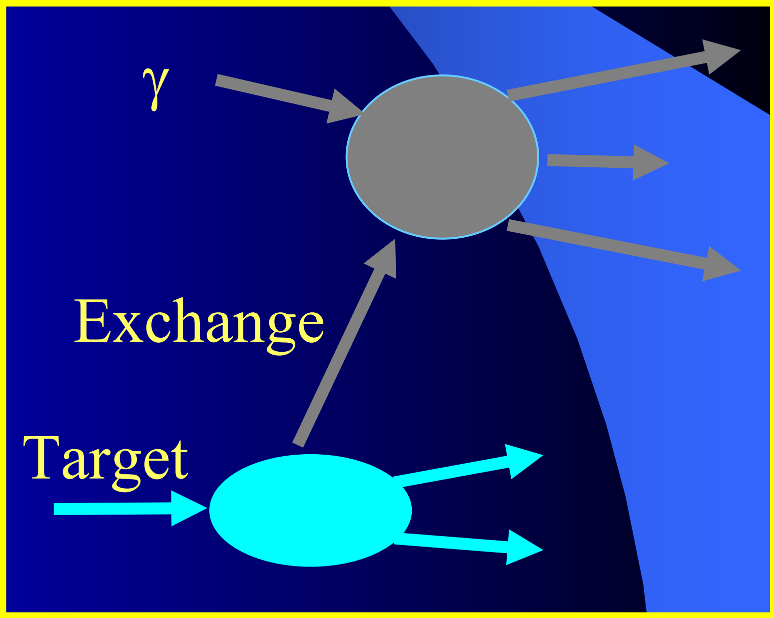
Updating what we know about Production?

- Browsing the literature, Regge phenomenology has not substantially changed in “soft” intermediate energy range
- The Pomeron sees new insights with confirmation of increasing elastic total cross-section
  - $\alpha_{Pomeron}(t) \approx 1.1 + 0.25t$
- And an even higher intercept for the hard Pomeron seen in total cross-section for $\gamma^*(Q^2)\ p(W^2)$ at large Q^2 and W^2 as discussed in book “Pomeron Physics and QCD” by Donnachie, Dosch, Landshoff and Nachtmann
  - $\alpha_{Hard\ Pomeron}(0) \approx 1.4$
- However the new Pomeron insights appear to deal with very different energy regimes than potential Jefferson laboratory experiments
  - As the exchanged Reggeons are pretty phenomenological – mixtures of multiple poles and cuts – probably best to use the older $\alpha_{Pomeron}(0) \approx 1.0$ style fits

What's the Problem Again?

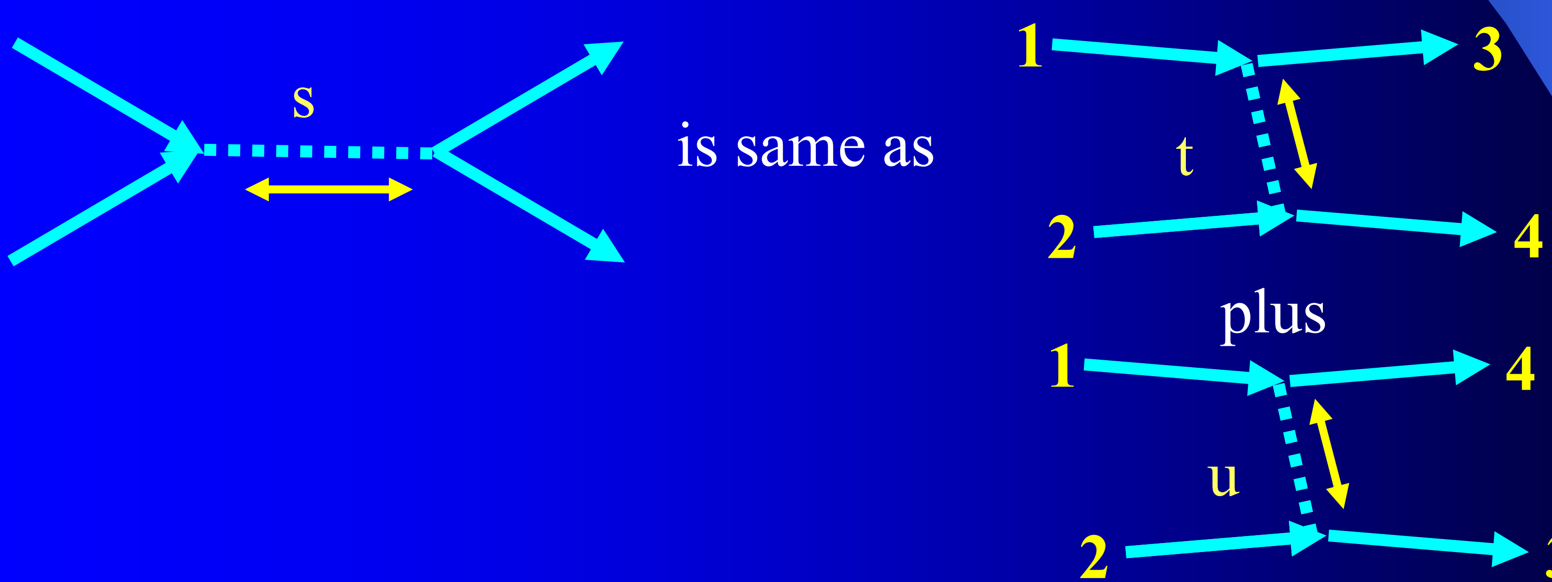
- **The understanding of exchange part is roughly right and we will use a roughly right model in PWA**
- **But we are looking at non dominant effects in γ Reggeon $\rightarrow$ 2 or 3 (or more) particles**
- **How can we sure that approximations do not affect our partial wave analysis**
- **Answer:**

Need to include all important effects and evaluate uncertainties they cause?
Lets examine other approximations



Lessons from Duality I

- t(u)-channel exchanges are "classically" the forces that create the s-channel particles
- Thus it is not trivially "wrong" that same effect (e.g. diffractively produced a_1) can be "explained from direct or cross channel point of view
- Veneziano model illustrates this in a fashion that is not quantitatively useful



Lessons from Duality II

- **It appears that $\rho\ \omega\ A_2$ f g N Δ … particles form Regge trajectories having party line characteristics**
  - Two-component duality
  - Exchange degeneracy of mesons reflecting exotic channels
  - Daughters
- **Presumably this extends to π B a_1 but I am not aware of strong evidence for this**
  - I don't know significant evidence against this either
- **Exchange Degenerate** $\alpha_\rho = \alpha_f = \alpha(0) + \alpha' t$
  Veneziano formula for $\pi^- \pi^+ \rightarrow \pi^- \pi^+$ is
  $A(s,t) = \Gamma(1-\alpha_\rho(s))\, \Gamma(1-\alpha_\rho(t)) / \Gamma(1-\alpha_\rho(s)-\alpha_\rho(t))$
- This has **Regge poles** in s and t channels, **no poles** in u channel and **residue** proportional to $\alpha(0) + \alpha' t$ at $\alpha_\rho(s)=1$
  - **$\alpha(0) + \alpha'$ t is a mixture of spin 0 and spin 1 i.e. requires** $\rho + \varepsilon$

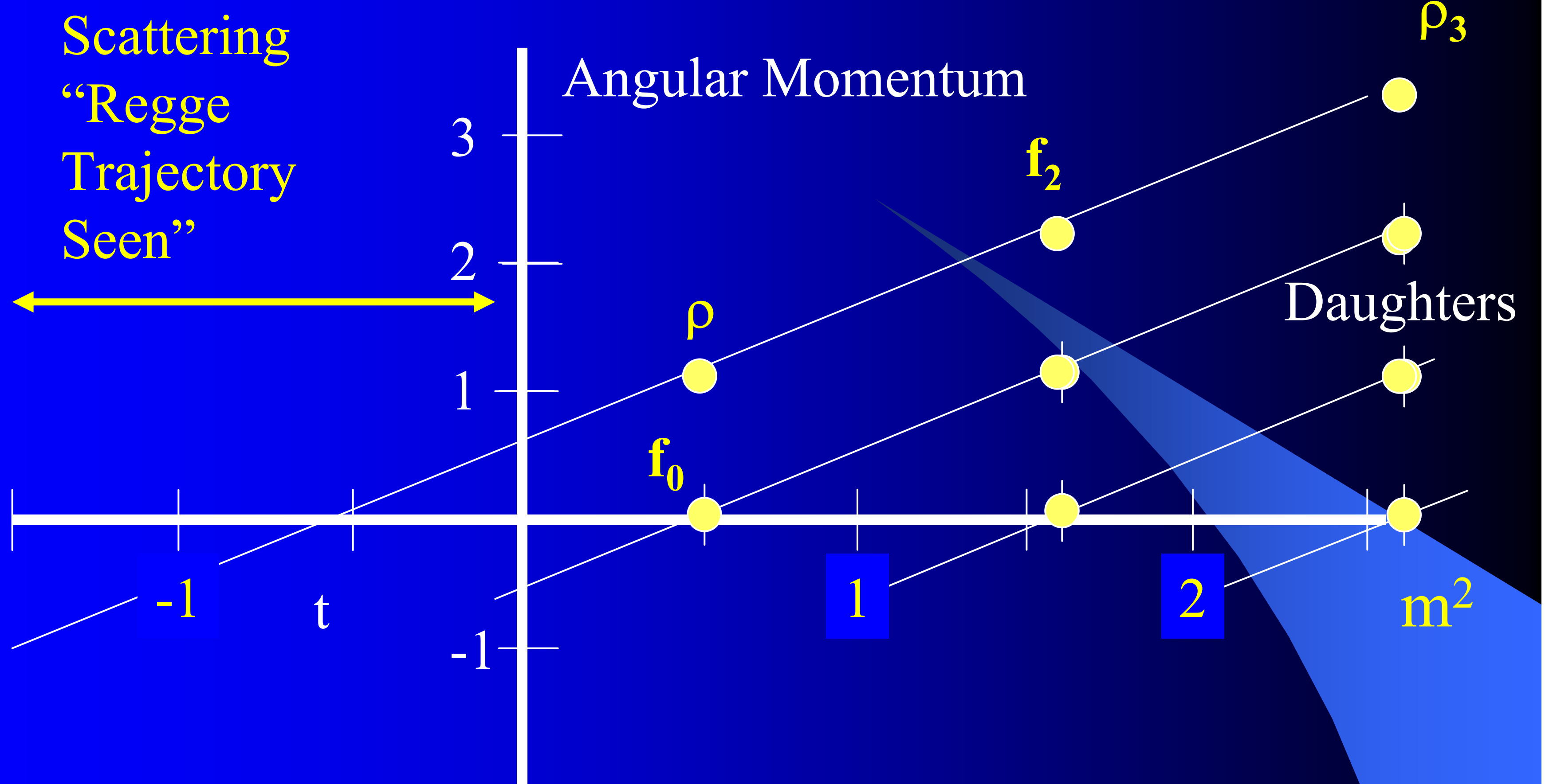
Lessons from Duality III

- **Partial Wave Analyses of π N elastic scattering suggested an important additive model of two component duality**
  - $A_{\pi N \to \pi N}(s,t,u) = A_{\text{Particle Regge}}(s,t,u) + A_{\text{Pomeron}}(s,t,u)$
- **The classic nucleon resonances in the s channel sum to an amplitude $A_{\text{Particle Regge}}(s,t,u)$ corresponding to the classic meson Reggeons in t channel plus classic nucleon Reggeons in u channel**
- **The background in the s channel corresponds to an amplitude $A_{\text{Pomeron}}(s,t,u)$ corresponding to the Pomeron in the t channel**
  - Pomeron component in meson scattering can be estimated from $\pi^+ \pi^+ \to \pi^+ \pi^+$?

Consequences of Duality

- **One should see (non exotic) daughter mesons for all the well known meson resonances**
- **The Pomeron component in meson – meson scattering is comparatively small (compared to baryon case) and easy to estimate from factorization (or counting quarks)**
- **There are of course many meson-meson scattering amplitudes where there is no Pomeron contribution and hence should not have ANY background**
- **There are several interesting cases such as $\pi^- \pi^+ \rightarrow \pi^- \pi^+$ where there are NO exchanges as u channel has exotic quantum numbers**
  - **One surely will see such suppression as all dynamics will suppress transitions like $\pi^{--} \Rightarrow \pi^+$**
  - **But duality shows that suppression implies daughter resonances which can be broad of course but can't be way off and still cancel backward peak**

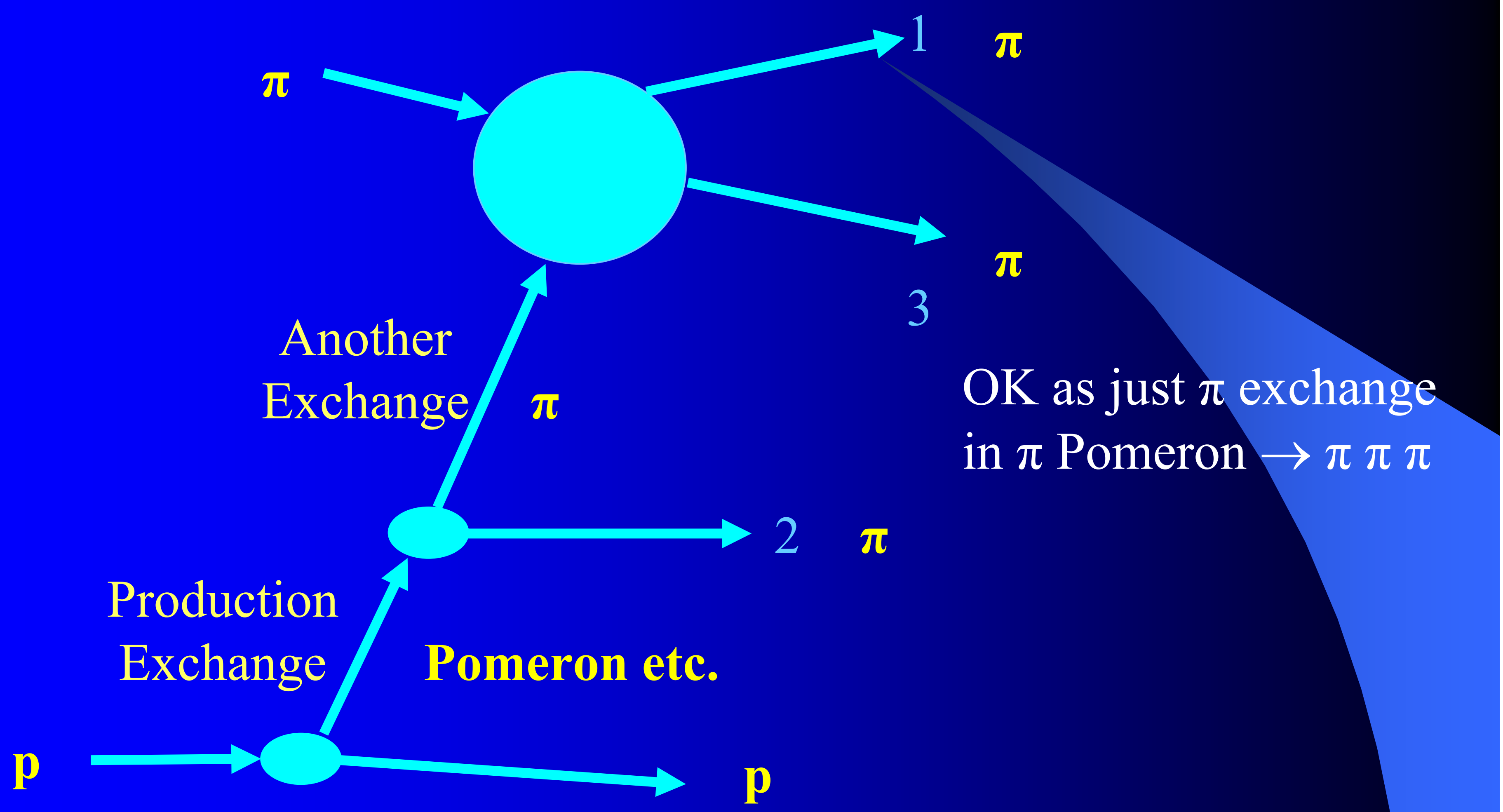
More on Duality and Daughters



- $\pi\ \pi$ scattering looks "wrong" as **f_0 does cancel** ρ **backward peak but has wrong mass nowadays**
- Should redo $\pi\ \pi$ scattering PWA

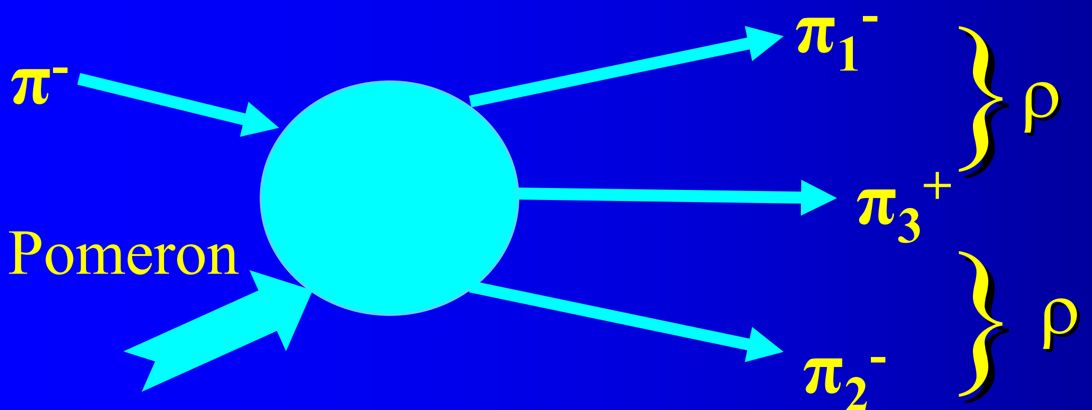
Multiperipheral Diagrams

- **As in Deck model**

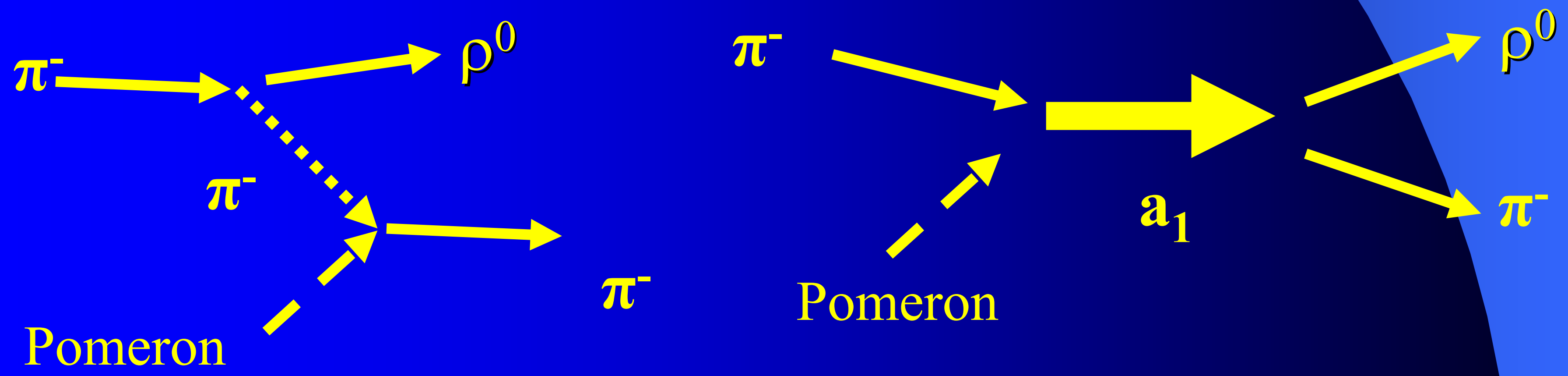


Deck Models I

- **These are low mass enhancements due to exchanges in Beam (Reggeon Exchange) → Fast Decay Particles**

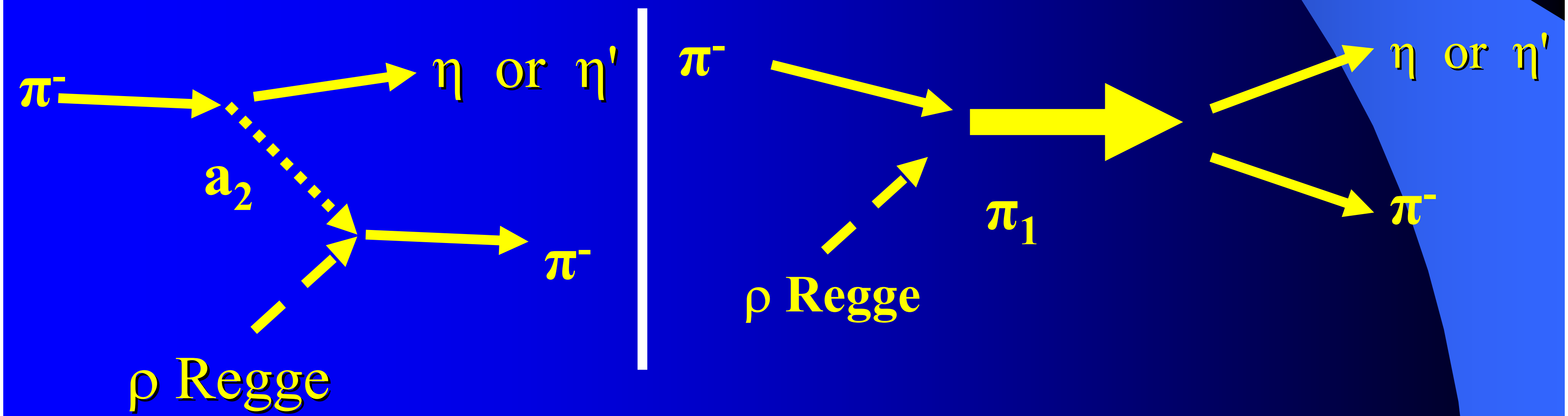


π exchange is force that produces a_1 resonance



Deck Models II

- Obviously there are exchanges in ALL Beam (Reggeon Exchange) → Fast Decay Particles reactions where exchanged forces are ambiguous with produced resonance
- Low spin direct resonances are "hardest"
- Both resonances and exchanges should exist and should be put into model



Finite Energy Sum Rules

- **In π N elastic scattering, duality worked well to low energies as shown by for example**
  - Persistence of Regge zeros (such as ρ exchange zero at t = -0.6 Gev^2) to low energies
  - Suppression of backward peaks corresponding to nucleon and not meson exchange)
- **We need to convert sloppy S-matrix arguments into more precise constraints wherever possible**
- **Finite energy sum rules FESR of form**

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

were successful in π N scattering and should be also be applicable in photon (meson) scattering

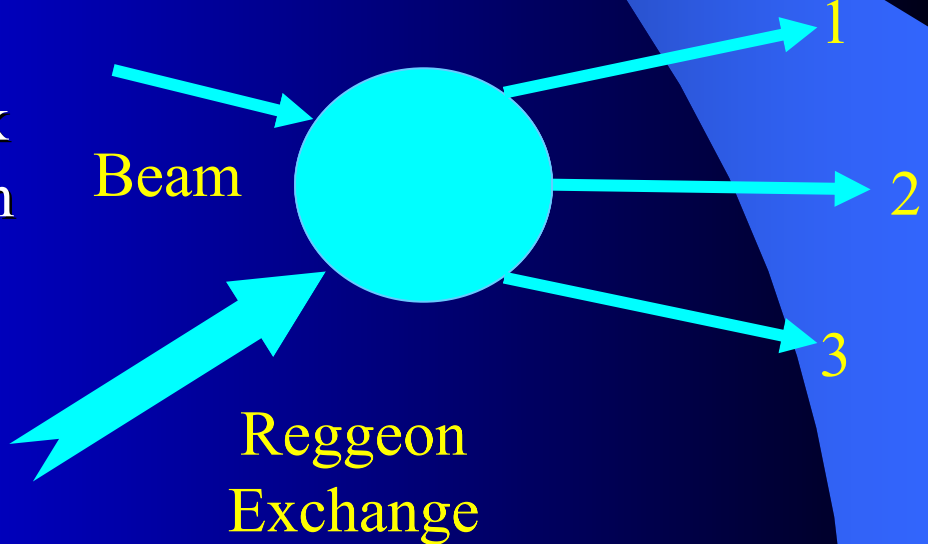
  - A is the low energy amplitude from the partial wave analysis

Duality and PWA

- **FESR should work separately for Pomeron (background) and classic Regge components and for fixed t and u.**
  – At fixed u in $\pi^- \pi^+ \rightarrow \pi^- \pi^+$ **one has zero Regge contribution**
- **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 π^- **Pomeron** $\rightarrow \pi^- \pi^- \pi^+$ **with internal π exchange**
- **This phenomenology suggests a PWA model that is combination of**
  – Regge Born with low partial waves removed and
  – Parameterized low partial waves
  – FESR constraints on parameterized waves

Using Two-component Duality

- **Strong Interactions are hard for PWA as there is**
  - No systematic approximation where one can write a model and then improve it as necessary
  - Many cases where effects are different but not additive
- **Two component duality gives an attractive Born term although it is obviously not justified directly by theory.**
- **It is attractive as has a prescription to avoid "double-counting"**
- **It might break down either because**
  - Intrinsic errors are too great
  - It could in particular not work for vertices with either photon beams (unlikely) or with an exchanged Pomeron as one of the particles

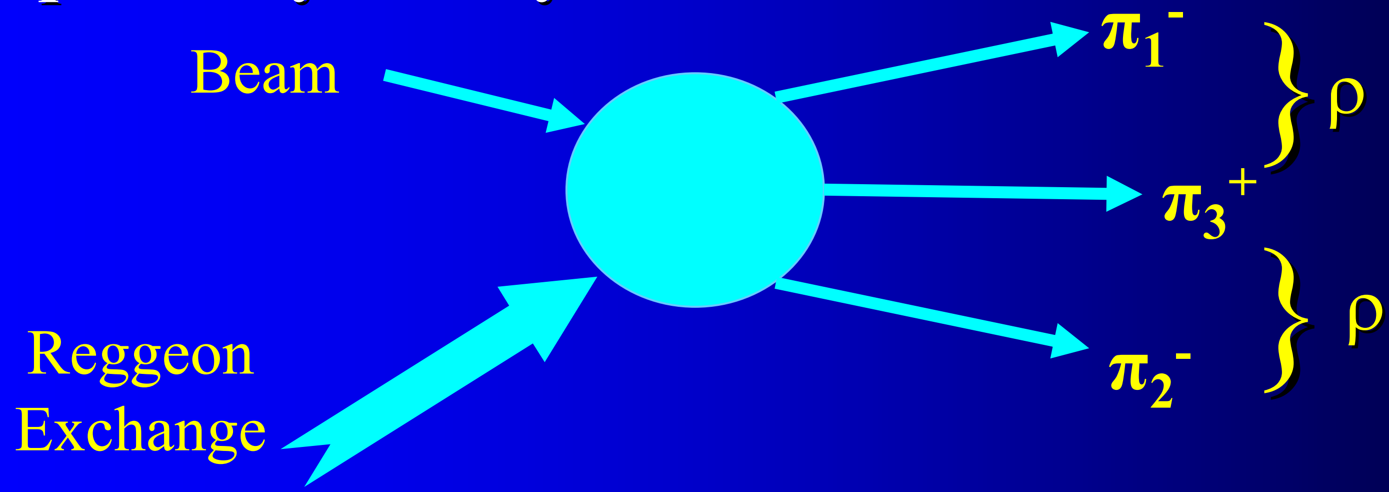


Sources of Errors in PWA

- **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**
  - An effect being "final state interactions" does not mean it is or is not a resonance ….
- **One will be looking at 2 3 and higher particle final states at the top vertex and realistically one will need the "Quasi 2-body" approximation to do a practical amplitude based partial wave analysis.**
  - This sometimes can be done reliably and independently in different sub-channels

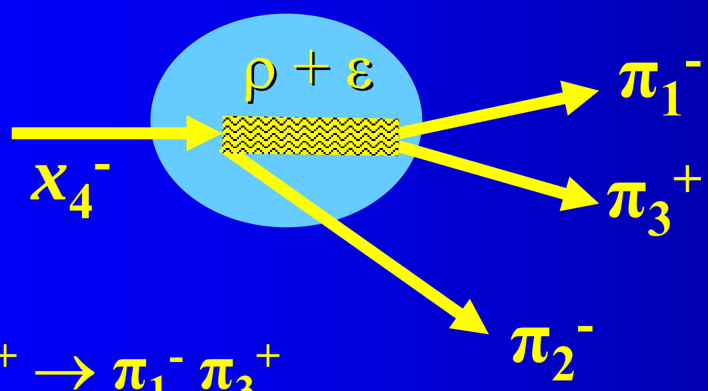
Quasi 2-body Approximation I

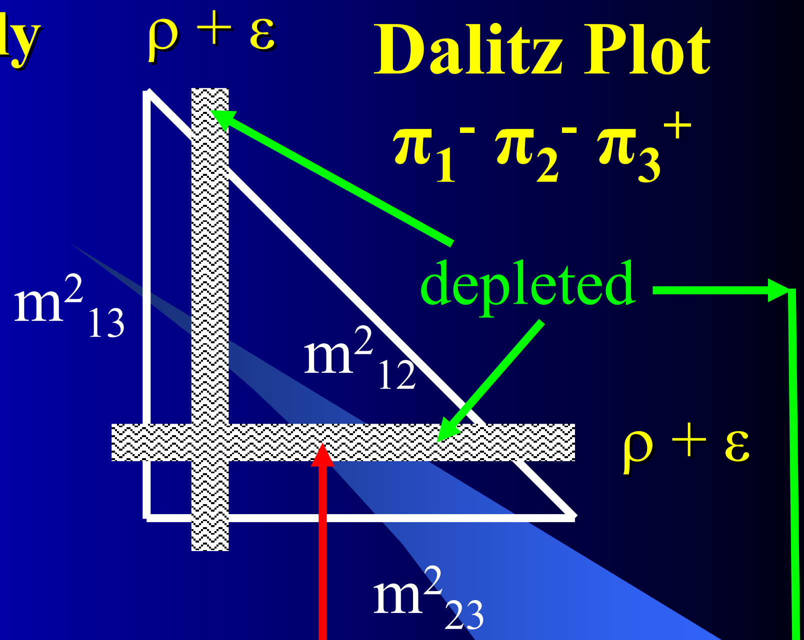
- The "Quasi 2-body" approximation says that $\pi_1^- \pi_2^- \pi^+$ final state can be thought of as $\pi_1^- \rho$ plus $\pi_2^- \rho$ and has proven to be reliable at least when resonances are well established like the ρ which appears to have similar dynamics to "real particles" like the π
- However there are subtle amplitude interference effects required by duality



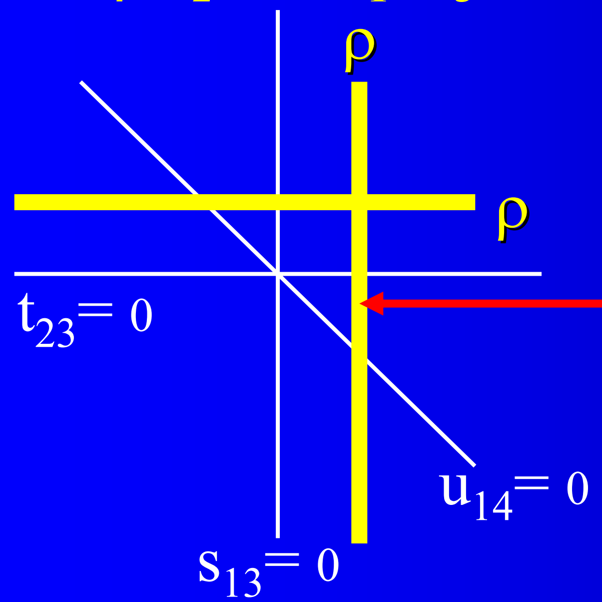
Quasi 2-body Approximation II

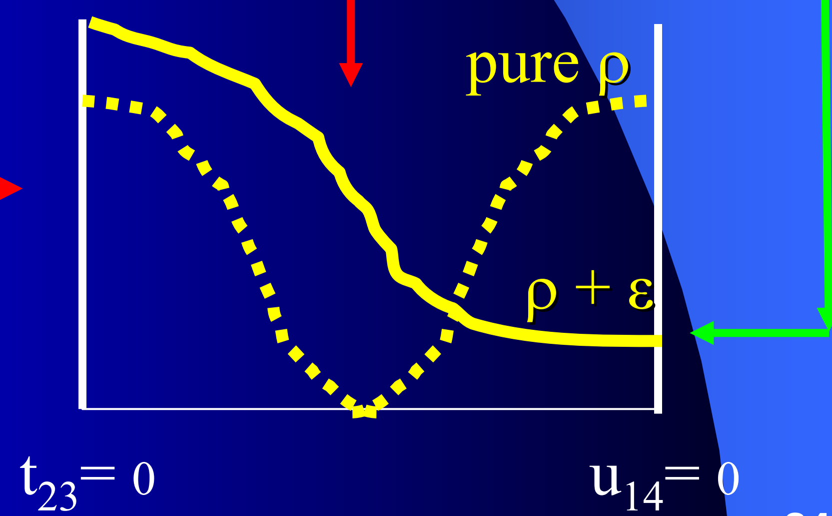
- **The ρ and ε must interfere coherently to suppress double charge exchange x^- to π^+**





$x_4^-\ \pi_2^+ \rightarrow \pi_1^-\ \pi_3^+$

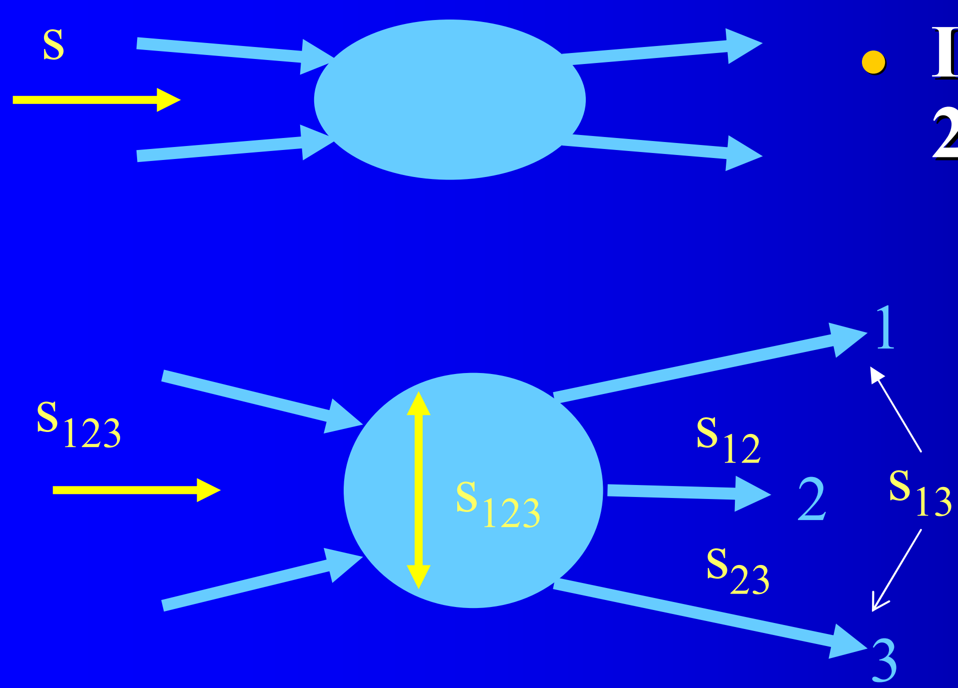




Quasi 2-body Approximation III

- Spin 0 ε is daughter trajectory to ρ and required by duality in $\pi^- \pi^+$ scattering as no u-channel exchanges
- The situation is not helped by the unclear status of $\pi\ \pi$ S-wave scattering. In a Regge model one has in S wave
  - Background dual to Pomeron exchange and
  - ε dual to f and ρ exchange in t channel
- I don't know how well these effects have been studied but it could be important to study such $\varepsilon\ \rho$ interference in the quasi 2-body reaction in final states such as
  - $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$, $\pi^- p \rightarrow \pi^- \pi^+ n$ where there might be enough data to get model independent results
- Such analyses should try to use $\pi^- \pi^+ \rightarrow \pi^- \pi^+$ finite energy sum rules to express quantitatively the lack of $\pi^+ \pi^+$ Reggeons

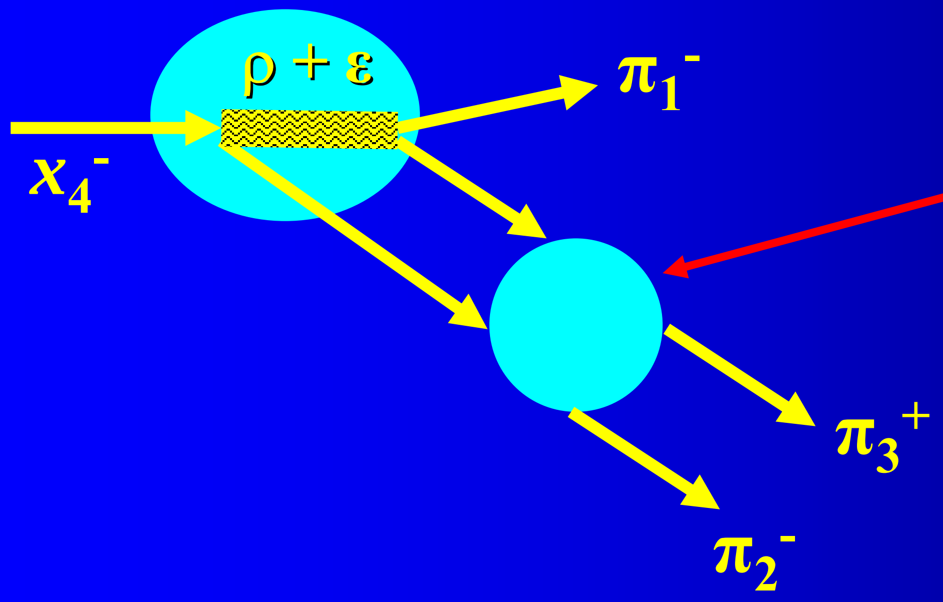
Direct Channel Constraints



- **Impose unitarity in s for 2 particle PWA**
  - **Impose unitarity in s_{12} s_{13} s_{23} for 3 particle PWA**
  - **This is "final state interactions"**
  - **Unitarity in s_{123} not usually a strong constraint**

Duality and Finite State Interactions

- Returning to $\pi^- \pi^- \pi^+$ final state we see that final state interactions are perhaps already included in quasi two body model and so should NOT be added



This final state interaction "generates" the Reggeons in the t_{23} channel and we include these in $\rho + \varepsilon$ ansatz in s_{13} channel

- Not totally clear as Pomeron component in t_{23} channel is not included in duality (it corresponds to "background in s_{13} which we try not to include)
- Unitarity (final state interactions) rigorously give a discontinuity across a t_{23} cut but not so clear this is very useful

Some lessons I

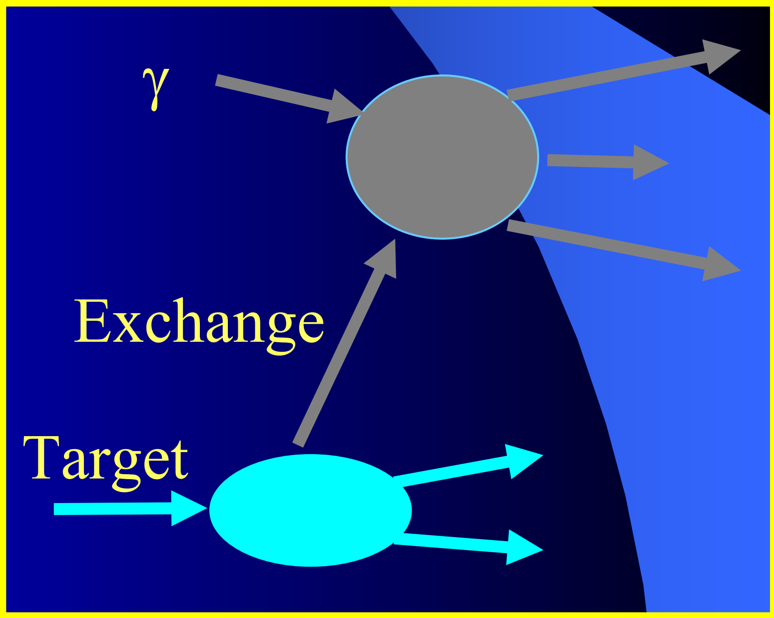
- **All confusing effects exist and no fundamental (correct) way to remove. So one should:**
  - Minimize effect of the hard (insoluble) problems such as "particles from wrong vertex", "unestimatable exchange effects" sensitive to slope of unclear Regge trajectories, absorption etc.
- **Note many of effects (exchanges) are intrinsically MORE important in multiparticle case than in relatively well studied $\pi N \Rightarrow \pi N$**
- **Try to estimate impact of uncertainties from each effect on results**
  - Need systematic very high statistic studies of relatively clean cases where spectroscopy may be less interesting but one can examine uncertainties
  - Possibilities are A_1 A_2 A_3 B_1 peripherally produced and even $\pi N \Rightarrow \pi \pi N$

Some lessons II

- **Theory failed to provide convincing parameterizable amplitudes one could use to fit/explain data**
- **Theory provided some quantitative constraints (π pole, unitarity, kinematics, …), many qualitative truths (two-component duality) which overlap and whose effect can be estimated with errors from 10 to 100%**
- **25 years ago, Rip van Winkle dozed off as not clear how to make progress**
- **Now we must take a factor of 100 or so more data to tackle problem phenomenologically**
- **First step is to clarify and test technique**
- **Next step is to use technique to do new physics**

Effects to Include I

- We need to develop reasonable Regge phenomenology for production amplitudes
- Identifying reliably quantum numbers (including naturality) of exchanged particles will be essential if we to make reliable PWA models
- We do not expect previous fits to give quantitative predictions in many cases
- However they gives some folklore which should be very valuable in building these Regge exchange models
- Ignore Regge cuts



Effects to Include II

- **Spin Formalism: Must use**
  - Amplitude Parameterization – polarization needed with photon beams to determine the different amplitudes with different photon helicities
  - With some checks using a Density Matrix Formalism – but this can't cope with explicit contributions, analyticity etc. Only likely to show clearly "blatant" effects.
  - Transversity versus helicity formalism needs to be investigated – trade-off of analyticity versus selection rules

Effects to Include III

- **Regge exchange contributions in top vertex:** **Identify all allowed (by normal Regge phenomenology) exchanges and catalog where expected to be large due to coupling constants and/or values of $\alpha(t,u)$**
- **Use usual duality type arguments to identify related s_{13} t u exchanges i.e. where you might expect the direct and crossed descriptions to be related**
- **Develop models for exchange contributions using simple phenomenological Regge theory**
  - Determine parameter either by fitting higher mass data or iteratively through finite energy sum rules
  - Identify all π exchange contributions and expect these to be reliable (with "conspirator) near t=0 but unreliable away from there -- π as a Regge pole problematic
  - Again ignore cuts

Investigate Uncertainties

- **There are several possible sources of error**
  - Unitarity (final state interactions)
  - Errors in the two-component duality picture
  - Exotic particles are produced and are just different
  - Photon beams, π exchange or some other "classic effect" not present in original πN analyses behaves unexpectedly
  - Failure of quasi two body approximation
  - Regge cuts cannot be ignored
  - Background from other channels
- **Develop tests for these in both "easy" cases (such as "old" meson beam data) and in photon beam data at Jefferson laboratory**
  - Investigate all effects on any interesting result from PWA

Effects to Include III

- **Cutkosky style Accelerated Convergence is certainly sound but possibly easier to explicitly include high partial waves rather than choose an expansion that maximizes convergence**
  - Could use Cutkosky style expansion functions
- **Dispersion Relations and other Analyticity**
  - Check FESR's and look for zeros
  - Present data and fits in a way to display effect (e.g. fixed u cross sections for reactions with no u channel exchanges) – check qualitatively reasonable
- **Multichannel analysis (at top vertex) is useful and could reduce parameters and check results**
  - but will not be as powerful as in π N case as unitarity will rarely be applicable in same fashion (as don't have any elastic amplitudes except for case of π exchange in production case)