A Model for $\pi\eta$ and $\pi\pi$ Photoproduction

The 19th National Nuclear Physics Summer School

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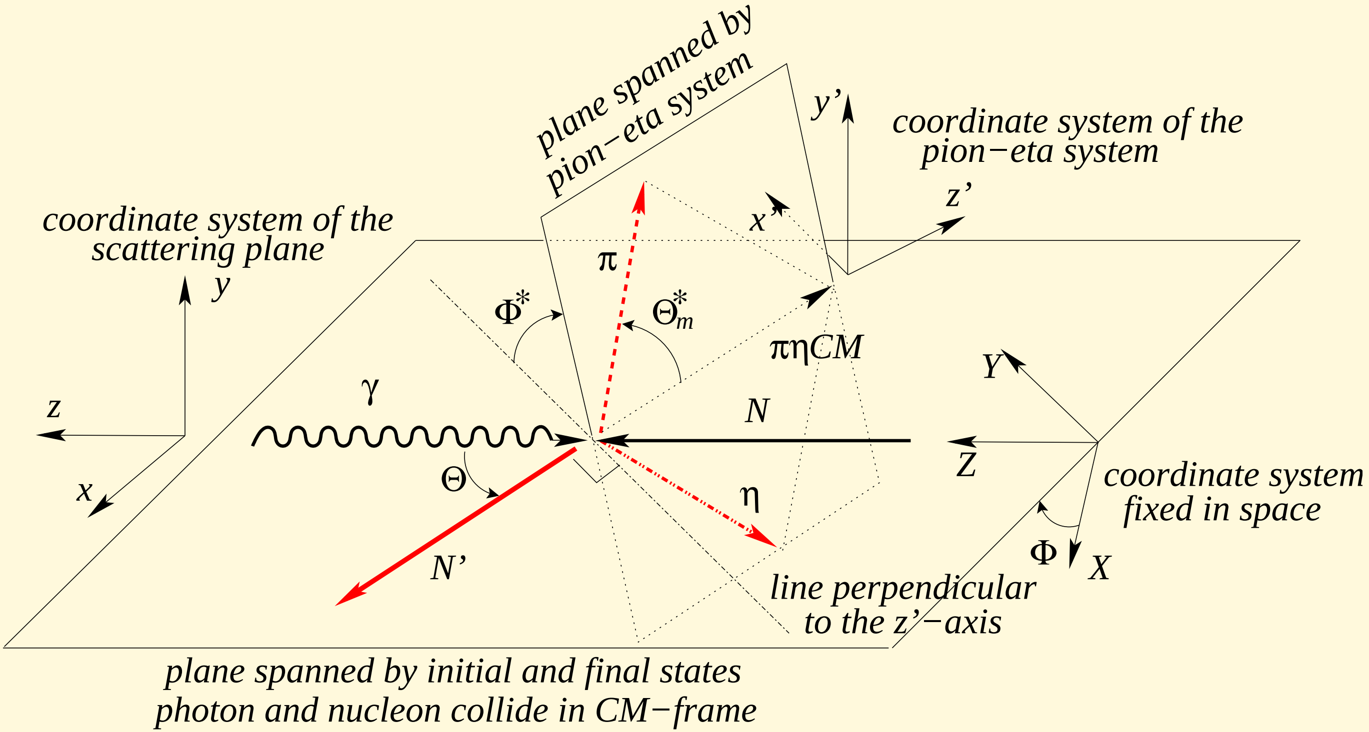
The reaction $\gamma N \to N\pi\eta$ at a glance



- For the reaction $\gamma N \to N\pi\pi$, change η to π.
- η is just like π but with **isospin zero** and **higher mass**.

Why are the reactions important?

- **Most** of our understanding of **baryon resonance properties** comes from $\pi N \to \pi N$ **reaction**.

  $\Longrightarrow$ Those resonances **not** strongly coupled to πN **channel** are difficult or even impossible to be observed using this reaction.

- Comparison between **quark models** and **PDG baryon spectra suggests** that there are **unobserved** resonances that:
  - have **masses** around **1.7 GeV** and beyond,
  - couple strongly to $\pi\eta N$ channel as well as to γN.

  $\Longrightarrow$ $\gamma N \to \pi\eta N$ is an ideal reaction to study these **supposedly existing** resonances.

- **Crystal Barrel at ELSA** (CB-ELSA), with **neutral** particle detectors is now performing experiments on $\gamma N \rightarrow N\pi\eta$ reaction.

  $\Longrightarrow$ Analysis from **Volker Credé** shows the presence of $\Delta(1232)\eta$ **decay**. Previously, **no higher resonance** is known to give this decay channel (PDG).

- We also study $\gamma N \rightarrow \pi\pi N$:
  - provides a **detailed** view into the $\gamma N \rightarrow \pi\eta N$ reaction ($\gamma N \rightarrow \pi\pi N$ reaction is **very similar** to $\gamma N \rightarrow \pi\eta N$ reaction)
  - **data** is more readily **available**
  - has been studied extensively for years but has not been studied in a **unitary** model until recently (**T.-S. H. Lee, Sato, and Matsuyama**, **Physics Reports 439 (2007) 193-253**)

Baryon spectroscopy

Understanding **baryon spectrum** is **crucial** in our efforts to study the **phenomenological interaction** between **quarks**.

$\Longrightarrow$ **Phenomenological** approaches for **quark interactions** are developed since a **direct QCD** calculation is too **difficult** to do.

- **Experiment**: **Reactions** involving **hadronic** interactions like $\pi N \to \pi N$, $\gamma N \to \pi N$, $\gamma N \to \pi\pi N$, $\gamma N \to \pi\eta N$, etc.
  $\Longrightarrow$ **Data** is usually given as scattering **cross-sections** or **partial-wave amplitudes**.
- **Theory**: **Prediction** of **baryon spectrum** by using **quark model** calculations, etc.
  $\Longrightarrow$ Often given as **baryon masses** and **widths** to various channels.
- In order to **compare** the two, a **reaction model is needed**.
  $\Longrightarrow$ provides a **bridge** by interpreting experimental data in terms of baryon resonance masses and widths to various channels.

Our work is to build a reaction model to allow the comparison between experimental and theoretical results.

A proposed model

Unitary and **dynamical coupled-channel** model that includes **rescattering**:

- **Unitarity** is important for conservation of **probability**.
- **Rescattering** needs to be taken into account:
  - The system we are studying is **strongly-interacting**.
    $\Longrightarrow$ **Higher-order** terms need to be taken into account.
  - We need to **compare** the resonance parameters extracted from **fitting** the data using our model to **quark models**.
    $\Longrightarrow$ Quark models provide **bare** values for masses and coupling constants, not **dressed** ones.
  - Might **reduce** the dependence on **form-factors**.
- **Dynamical coupled-channel**

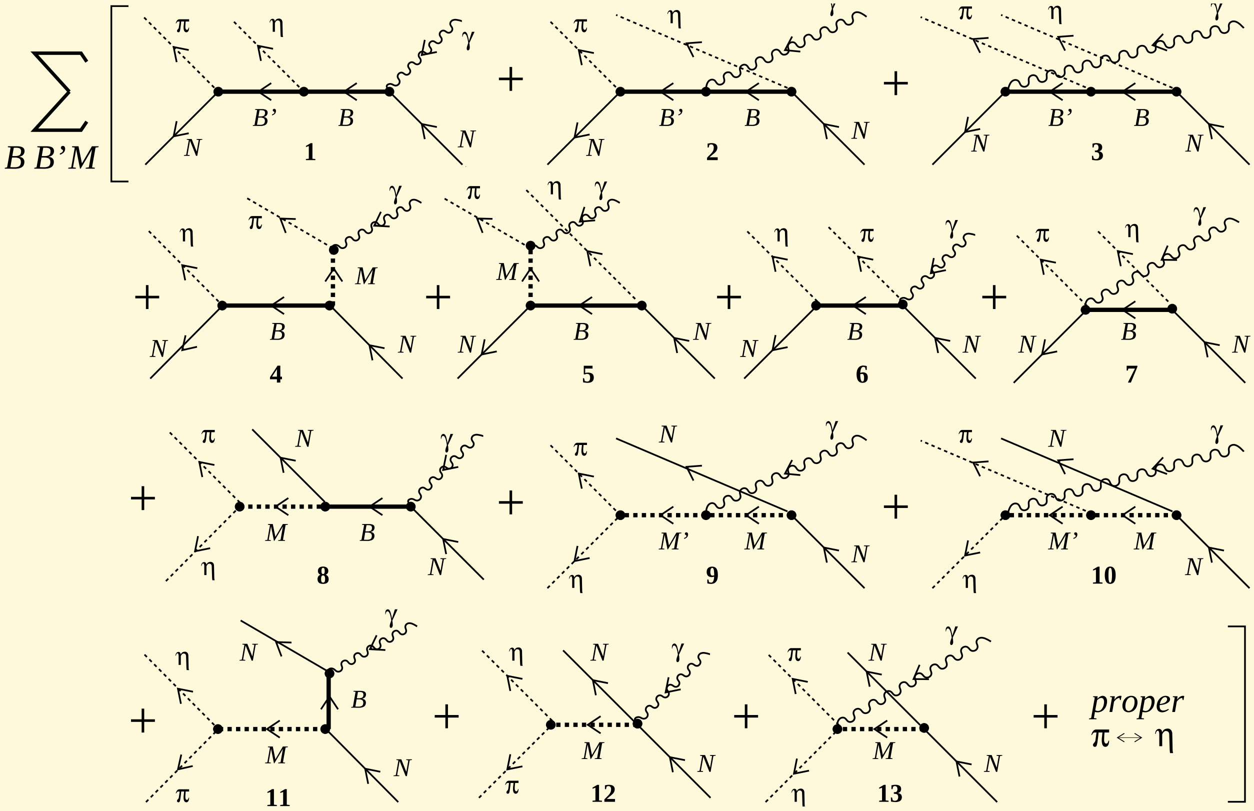
  $\Longrightarrow$ **Rescattering** is treated using the **correct** intermediate-state coupled-channel dynamics.

Calculation of the reaction amplitude

- We start from the **tree-level** **Feynman diagrams** of the reaction.
- **Unitarization** will be implemented later.
- The **vertices** is constructed by using a **phenomenological Lagrangian**.
- We can form the scattering amplitude $\mathcal{M}$ from the **Feynman diagrams**.

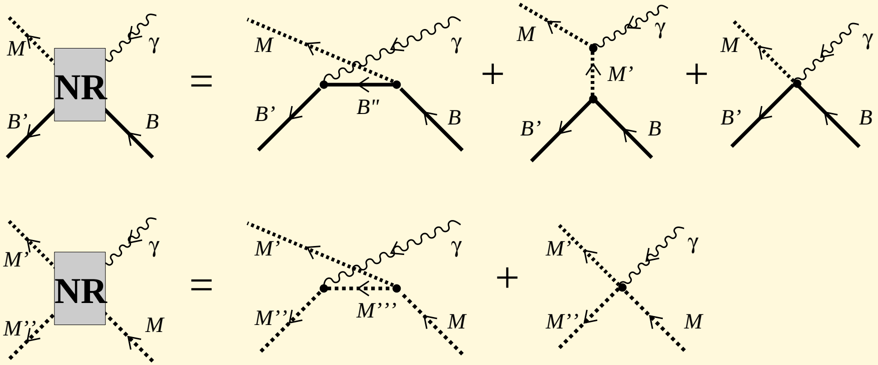
  $\Longrightarrow$ contains **free parameters** like **coupling constants** and **bare masses of baryon**.
- These **free parameters** can be fitted to the **experimental observables** to yield **baryon masses** and **widths** to various channels.
- **Winston Roberts** helps us in many details of the calculation.

The tree-level diagrams of the amplitude are ...

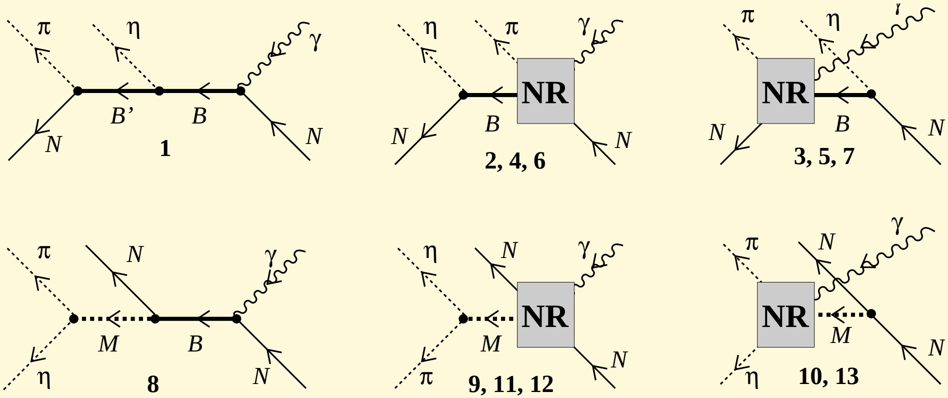


- For $\gamma N \to \pi\pi N$ reaction, change η to π.
- Here, B and B' are **baryon** intermediate states, and M is **meson** intermediate state.

Collect all the **nonresonant** interactions:

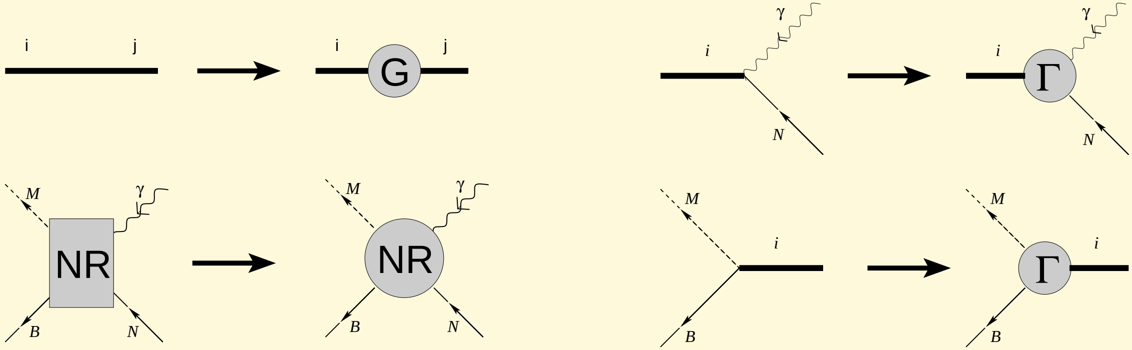


The diagrams can be written **compactly** as follows:

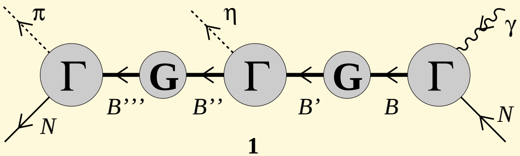


Unitarization of the scattering amplitude

- **Unitarization** is done by including **rescattering**.
- **Diagrammatically**, it can be described as:



- Therefore, the **tree-level** diagrams become, after **dressing**:



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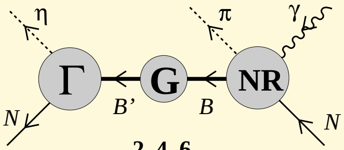
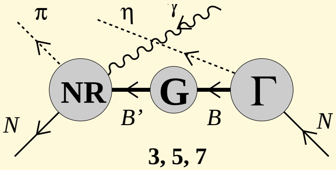
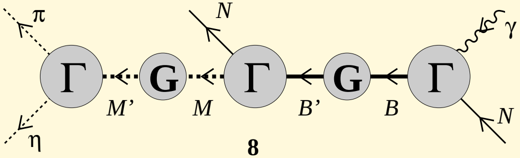


2, 4, 6



3, 5, 7



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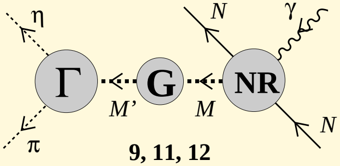
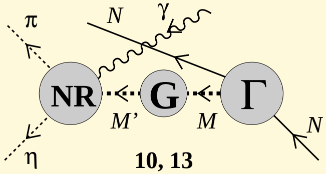


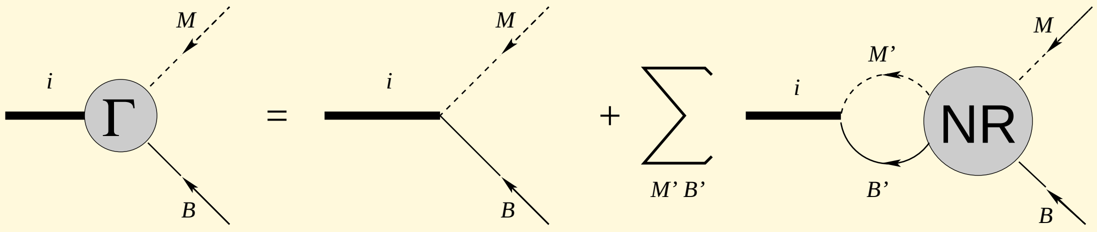
9, 11, 12



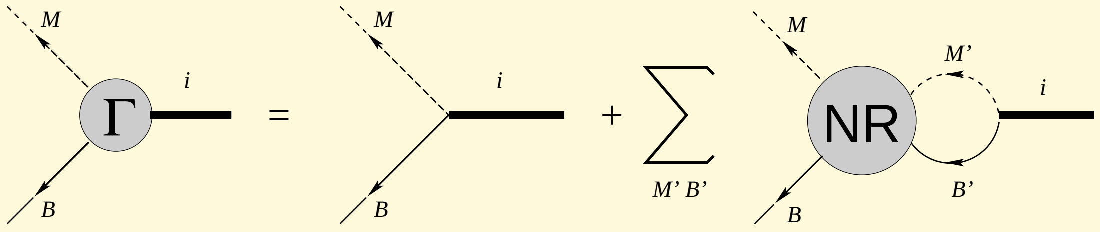
10, 13

The **dressed vertices** and **propagators** are:

- **Hadronic dressed vertices** $\Gamma_{N_i^*\leftarrow MB}(E)$ **and** $\Gamma_{MB\leftarrow N_i^*}(E)$

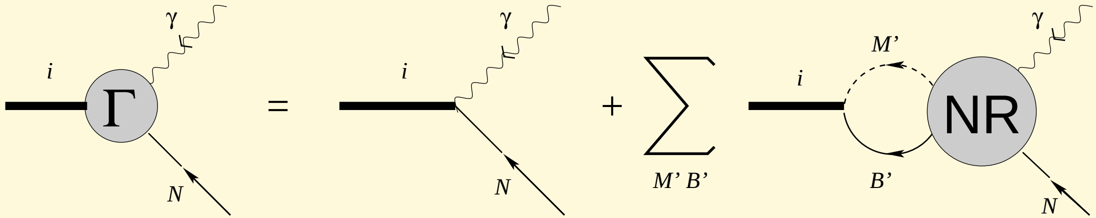


$$\Gamma_{N_i^*\leftarrow MB}(E) = \Gamma^0_{N_i^*\leftarrow MB}(E)+\sum_{M'B'}\Gamma^0_{N_i^*\leftarrow M'B'}(E)G_{M'B'}(E)t_{M'B'\leftarrow MB}(E)$$



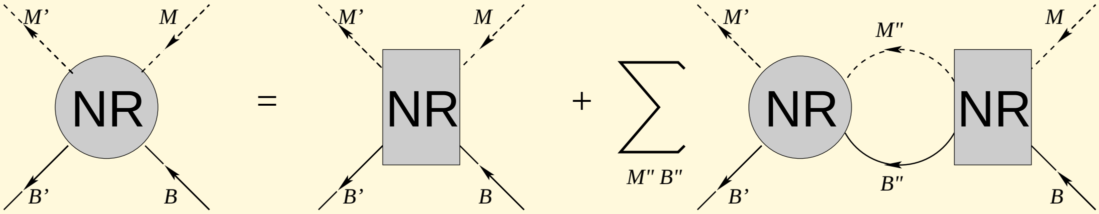
$$\Gamma_{MB\leftarrow N_i^*}(E) = \Gamma^0_{MB\leftarrow N_i^*}(E) + \sum_{M'B'} t_{MB\leftarrow M'B'}G_{M'B'}(E)\Gamma^0_{M'B'\leftarrow N_i^*}(E)$$

- **Electromagnetic dressed vertices** $\Gamma_{N_i^*\leftarrow\gamma N}(E)$

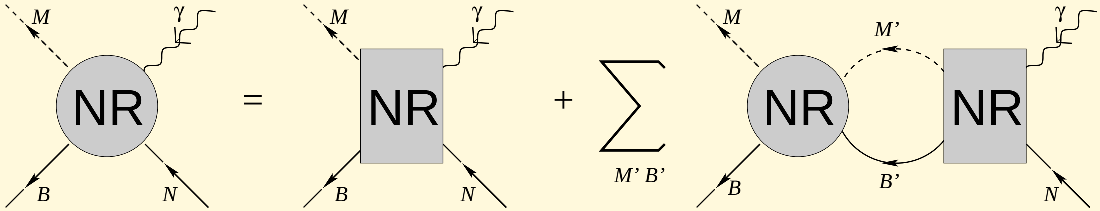


$$\Gamma_{N_i^*\leftarrow\gamma N}(E) = \Gamma^0_{N_i^*\leftarrow\gamma N}(E) + \sum_{M'B'} \Gamma^0_{N_i^*\leftarrow M'B'}(E)G_{M'B'}(E)t_{M'B'\leftarrow\gamma N}$$

Here $t_{M'B'\leftarrow MB}$ and $t_{MB\leftarrow\gamma N}$ are **iterated** to **all orders**:



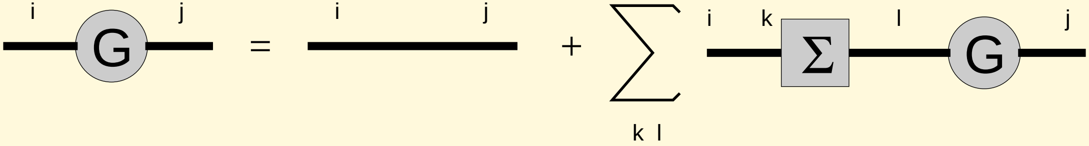
$$t_{M'B'\leftarrow MB}(E) = V_{M'B'\leftarrow MB}(E) + \sum_{M''B''} t_{M'B'\leftarrow M''B''}(E)G_{M''B''}V_{M''B''\leftarrow MB}(E)$$



$$t_{MB\leftarrow\gamma N}(E) = V_{MB\leftarrow\gamma N}(E) + \sum_{M'B'} t_{MB\leftarrow M'B'}(E)G_{M'B'}V_{M'B'\leftarrow\gamma N}(E)$$

in which $V_{MB\leftarrow MB}(E)$ and $V_{MB\leftarrow\gamma N}(E)$ are **sums** of **all nonresonant** diagrams.

- **Dressed propagator** $G_{ij}(E)$

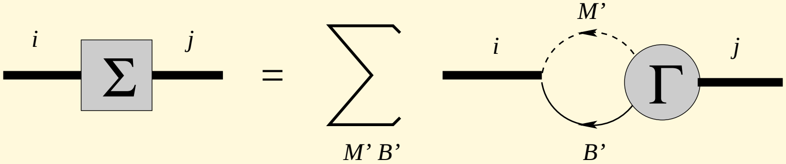


$$G_{ij}(E) = G^0_{ij}(E) + \sum_{kl} G^0_{ik}(E)\Sigma_{kl}(E)G_{lj}(E),$$

which can be **solved** to give:

$$G(E)_{ij} = \frac{1}{(E - M^0_{N_i^*})\delta_{ij} - \Sigma_{ij}(E)}$$

with **self-energy term** $\Sigma_{ij}(E)$:



$$\Sigma_{ij}(E) = \sum_{M'B'} \Gamma^0_{N_j^* \leftarrow M'B'}(E) G_{M'B'}(E) \Gamma_{M'B' \leftarrow N_i^*}(E).$$

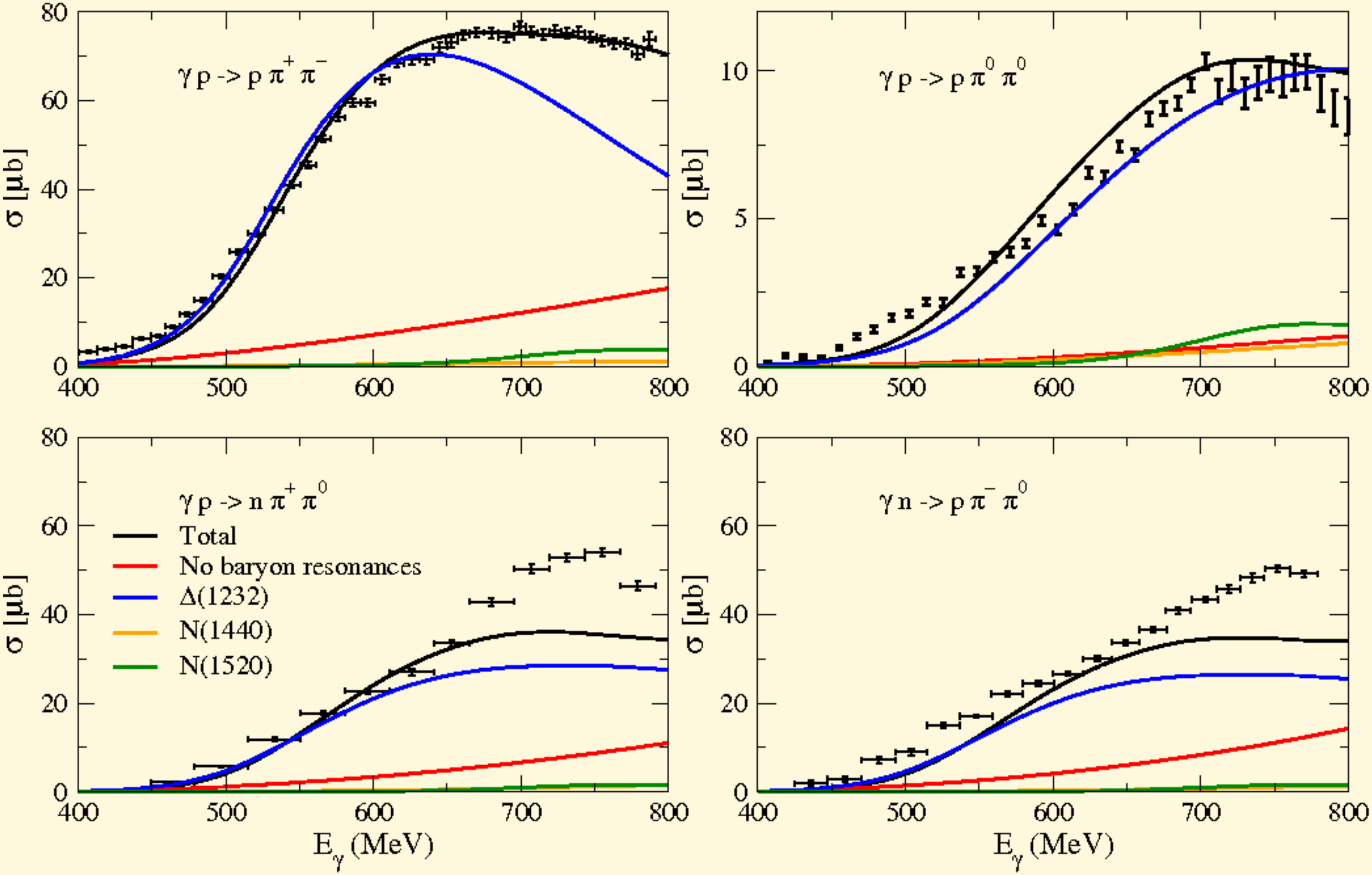
- The correction prescribed here is enough to implement **two-body unitarity**.
- Here, **two-body** is meant to designate any two bodies appear in a decay channel, for example $N\pi$, $N\eta$, $\Delta(1232)\eta$, $N(1535)\pi$, $N\rho(770)$, etc.

Present results

Study of $\pi\pi$ photoproduction (preliminary)

- **Rescattering** is implemented only in the **propagator** of the excited baryon states (to develop resonance **widths**).
  $\Longrightarrow$ **Not** a thoroughly **unitary** model.
- The diagrams are treated **relativistically** in the **phenomenological Lagrangian** approach.
  $\Longrightarrow$ Contain γ, N, $\pi(139)$, $\rho(770)$, and $\omega(782)$.
  $\Longrightarrow$ **Baryon resonances** include $\Delta(1232)$, $N(1440)$, and $N(1520)$.
- **Coupling constants** are adjusted to the **decays** of various resonances to various channels.
  $\Longrightarrow$ But allow a little freedom when fitting data.
- Also try to fit **signs** between coupling constants.

Our preliminary results



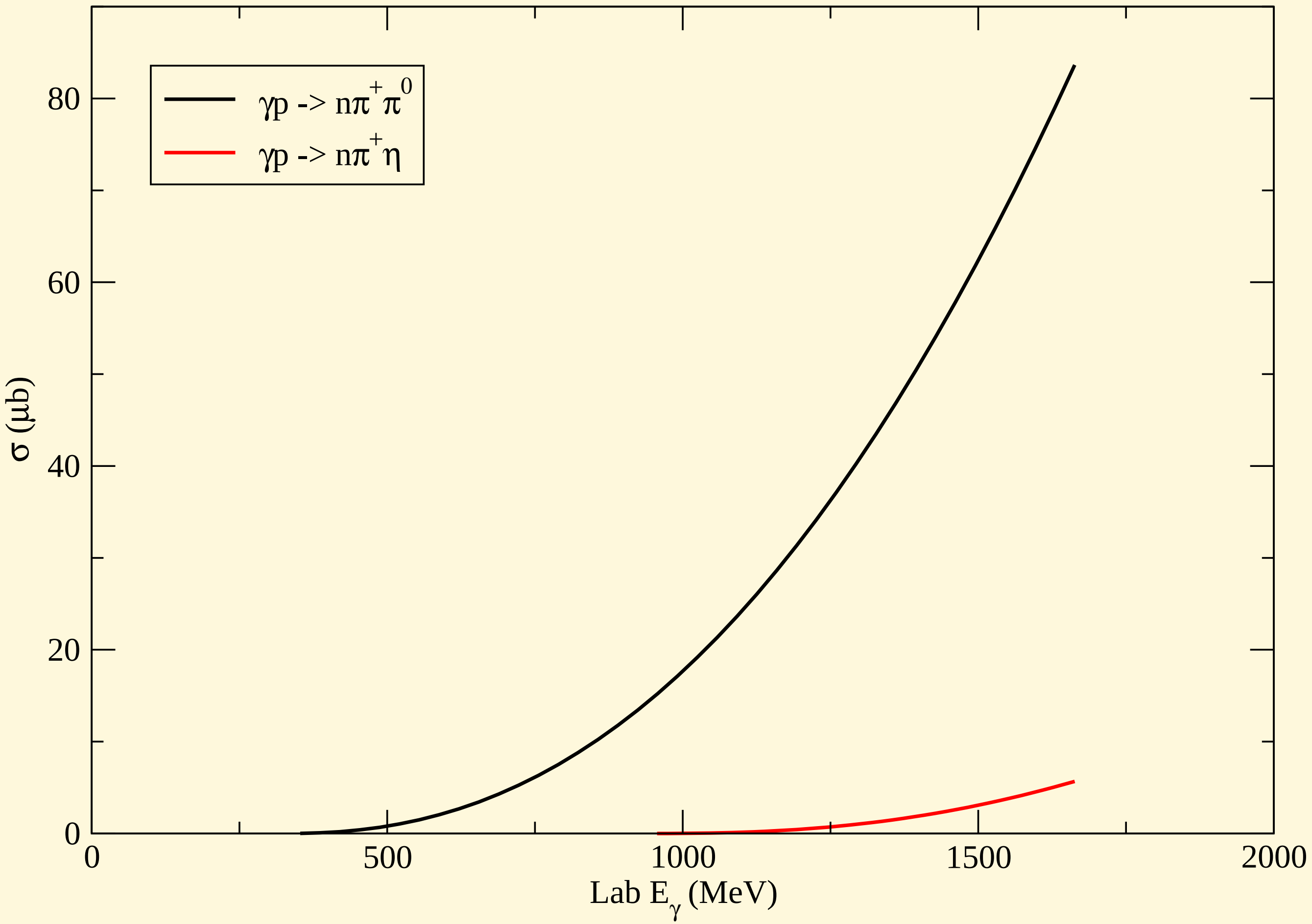
- Reactions $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\pi^0\pi^0$ seem to be described **quite well**. But, $\gamma p \to n\pi^+\pi^0$ and $\gamma n \to p\pi^-\pi^0$ reactions do **not** seem to be well-described by the model.
- **Other** works done in **similar** fashion (using phenomenological Lagrangian and fitting coupling constants to decay widths) also suffer the **same problem**, i.e. **Tejedor and Oset** (Nucl. Phys. A600: 413-435, 1996).
- **Adding** $N(1535)$ does **not** cause a **significant** change in the **cross sections**.
- This points out the necessity to include:
  - **vertex correction** from **rescattering**
  - **final state interaction** of the **two pions** (in some cases known to give a **significant** contribution)
  - more **baryon resonances** with higher energy and spin.

Preliminary study of $\pi\eta$ photoproduction

- Study of this reaction will **benefit** much from our study of $\pi\pi$ **photoproduction**.
  $\Longrightarrow$ will be performed after solid results on $\pi\pi$ photoproduction are obtained.
- Of particular interest are decays to $\Delta(1232)\eta$ and $N(1535)\pi$ because of the strong coupling $\Delta \longrightarrow N\pi$ and $N(1535) \longrightarrow N\eta$.
  $\Longrightarrow$ These decays might actually come from the **unobserved** resonances.
- Moreover, **their threshold energies** are **close** to the energy where the **unobserved resonances** are predicted to be.
  $\Longrightarrow$ **Less nonresonant interference** to deal with.
- We can only provide the total cross-section **without baryon resonance contribution** at this point (shown **without** form-factors at the strong and EM vertices).

Total cross-section (no baryon resonances present)

Comparison between $\pi\eta$ and $\pi\pi$ photoproduction



Summary and Outlook

- $\pi\eta$ **photoproduction** is a **good place** to look for **new** resonances.
- **Poorly** understood resonances may also be studied **better** using this reaction.
- **Recent developments** in $\pi\eta$ **photoproduction experiments** are a further reason for a model of this reaction to be constructed **soon**.
  $\Longrightarrow$ This model can be useful in guiding the experimental effort.
- Later, when experimental data is **ready**, this model can also serve as a bridge to compare with **quark model results**.
- Our model under development includes **rescattering**.
  $\Longrightarrow$ **Direct comparison** with **quark models** results is **possible**.
- With this model in hand, **calculation** for any two-meson photoproduction will be relatively easy to develop.

Thank you!