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

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Overview of Baryon Spectroscopy

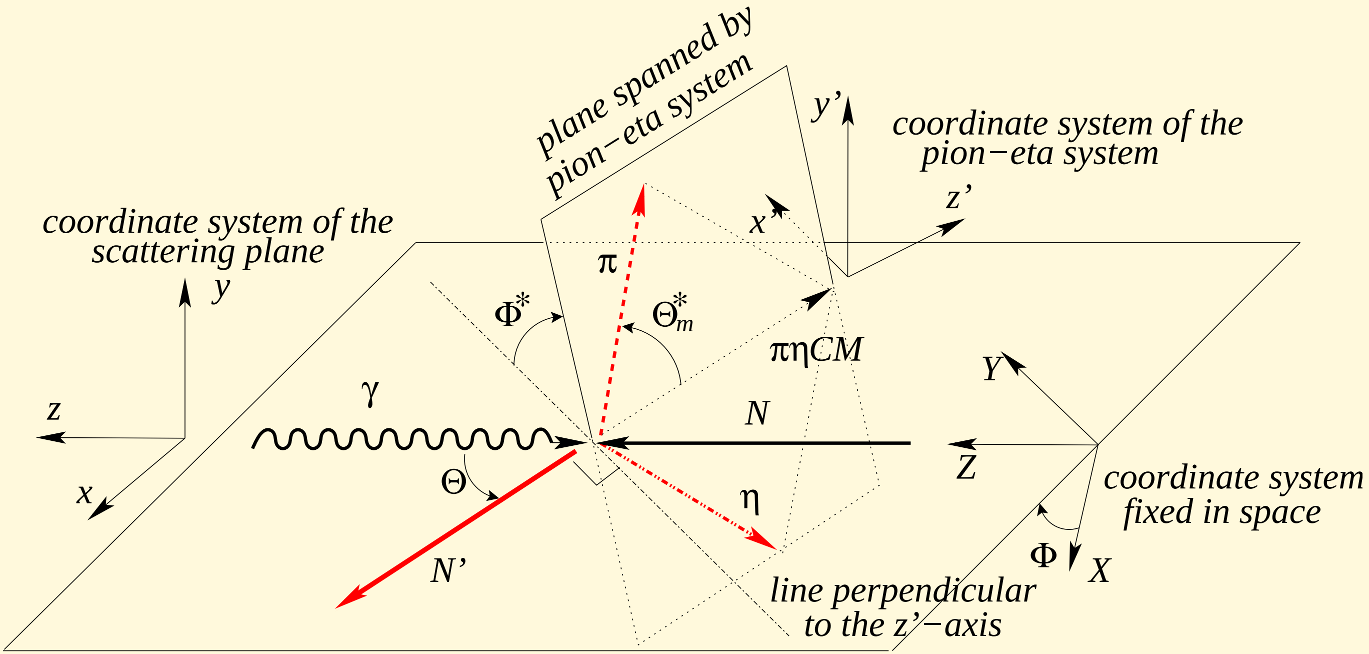
Understanding **baryon spectrum** is **crucial** in our efforts to study the **phenomenological interaction** between **quarks**.

$\Longrightarrow$ **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.

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



plane spanned by pion−eta system

coordinate system of the pion−eta system

coordinate system of the scattering plane

coordinate system fixed in space

line perpendicular to the z'−axis

plane spanned by initial and final states
photon and nucleon collide in CM−frame

Motivation

Why are the reactions important?

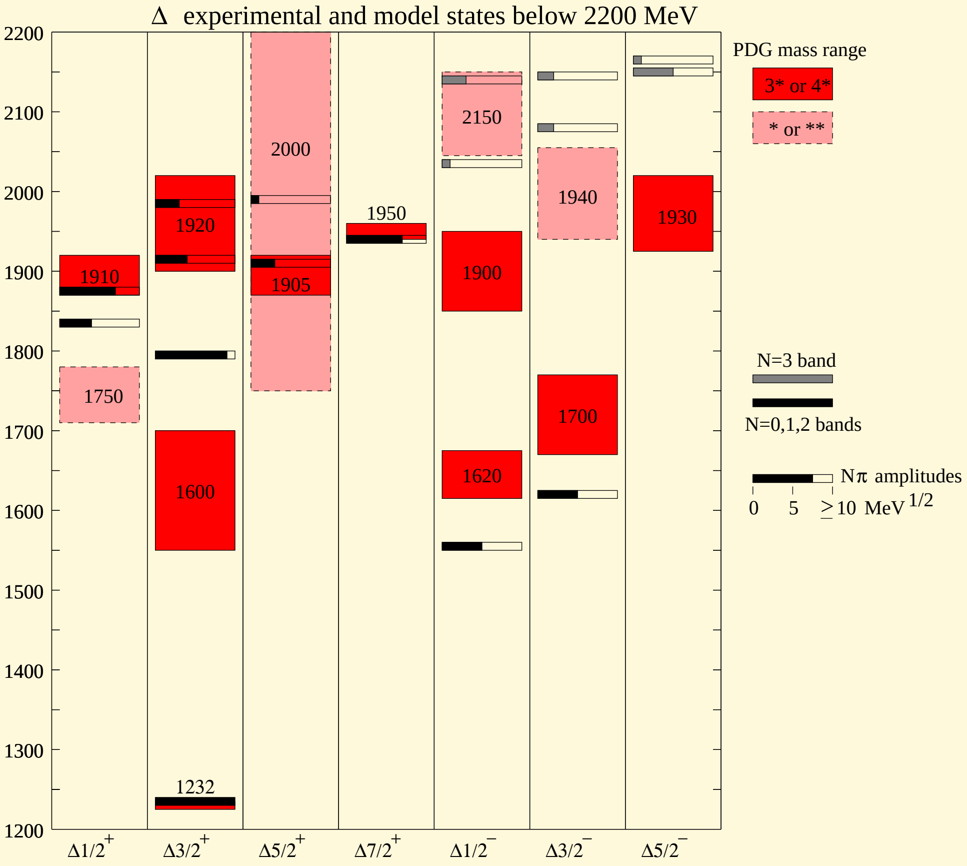
- **Most** of our understanding of **baryon resonance properties** comes from $\pi N \to \pi N$ **reaction**.

  $\Longrightarrow$ 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.

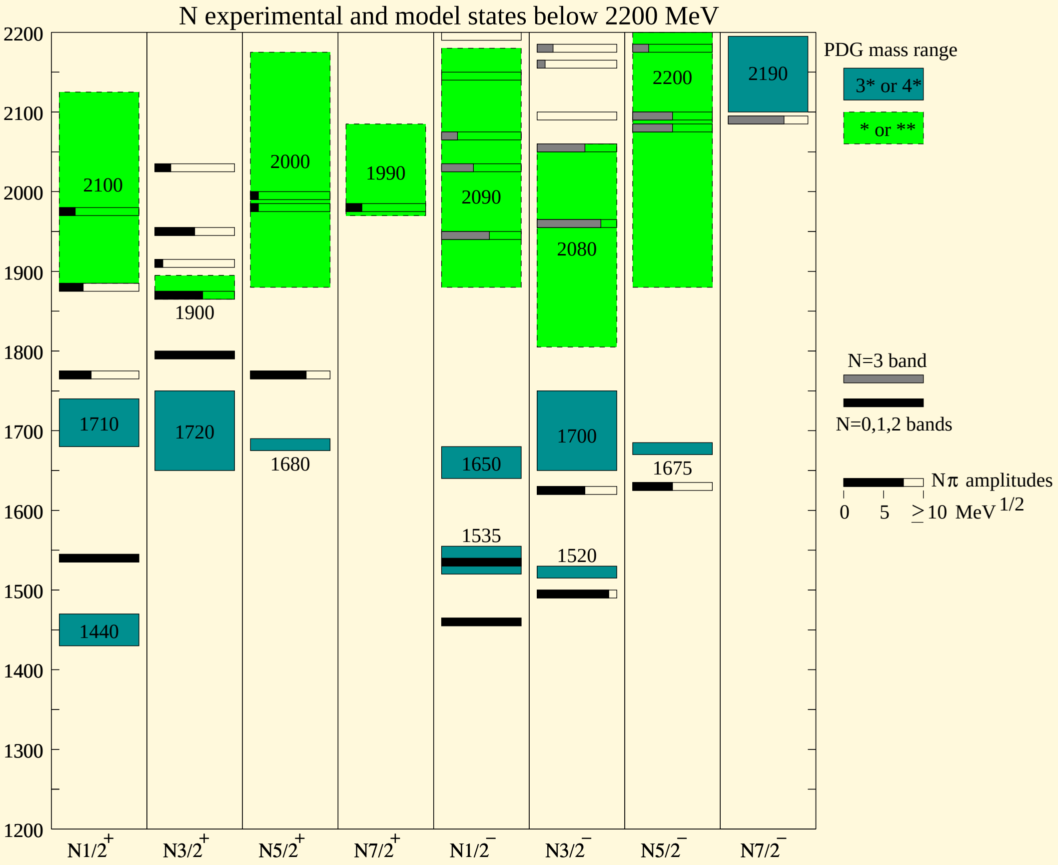
  $\Longrightarrow$ $\gamma N \to \pi\eta N$ is an ideal reaction to study these **supposedly existing** resonances.

△ states below 2200 MeV



Taken from Capstick and Roberts (Phys. Rev. D Vol. 57, Number 7, (1998))

N states below 2200 MeV



Experimental effort is underway

- **Crystal Barrel at ELSA** (CB-ELSA) is equipped with **neutral** particle detectors.
- They are **now** running the experiment on $\pi\eta$ photoproduction.
  $\Longrightarrow \gamma p \rightarrow p\pi^0\eta$
  - The reaction chain $\gamma p \rightarrow \Delta^* \rightarrow \Delta\eta \rightarrow p\pi^0\eta$ is an **isospin filter** for $I = 3/2$ Δ-states.
  - Reactions **above** $E_{CM} = 1700$ MeV mainly produce **more than one meson** in the final state.
- Analysis from **Volker Credé** shows the presence of $\Delta(1232)\eta$ **decay**.
  $\Longrightarrow$ Previously, **no higher resonance** is known to give this decay channel (PDG).
- Expected time-frame for data publication is about **one or two years from now**.

This effort requires matching effort from the theoretical side

- **Theoretical** input is needed to guide the ongoing experimental effort.
- Once the experiment is **done**, high-quality **data produced** need to be **interpreted** using a model of the reactions involved:
  - **Quark models** provide us with:
    - baryon masses
    - widths to various baryon-meson final states.
  - **Not directly comparable** to the experimental data.
- Reaction model **allows** a comparison.

For $\pi\eta$ photoproduction, such a model does not yet exist

EBAC (Excited Baryon Analysis Center) at JLab

- Uses **dynamical coupled-channel approach** to extract N^* properties in its effort to study the **quark-gluon** substructure of N^*.
- EBAC amplitudes, especially for ηN channel, can be used to further **enhance** the accuracy of a $\pi\eta$ photoproduction model.
- When a fit to data in $\pi\eta$ indicates new resonances, we will put the resonances into EBAC's analysis to see if their presence is **consistent** within the overall analysis.
  $\Longrightarrow$ **Important** when looking for signs of new resonances.

EBAC provides a consistent framework in which checking new findings in baryon spectroscopy becomes more reliable.

We need a model of $\pi\eta$ photoproduction during and after the experiment:

- **During**: Estimate scattering observables by using known parameters to help guide experimental efforts.
- **After**: When fitted to the experimental data it can produce parameters that can be compared to quark models.

A proposed model

Unitary and dynamical coupled-channel model for $\pi\eta$ photoproduction that includes rescattering

- **Unitarity** is important for conservation of **probability**.
- **Rescattering** needs 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.
  - The system we are studying is **strongly-interacting**.
    $\Longrightarrow$ **Higher-order** terms need to be taken into account.
  - Rescattering introduces **energy dependence** to the vertices.
    $\Longrightarrow$ Might **reduce** the need to use **form-factors**, although not eliminating their use completely.
- **Dynamical coupled-channel** $\Longrightarrow$ Rescattering is treated using the **correct** intermediate-state coupled-channel dynamics.

Previous research shows the importance of unitarity

- Studied **model-dependence** of baryon resonance parameters extracted using common models (Phys. Rev. C **69**, 025205 (2004)).
- They are **Carnegie-Mellon Berkeley(CMB)**, **K-matrix**, and **Breit-Wigner(BW)** models.
- Results of each model differs **significantly**, especially when two or more resonances mix.
- Important differences between the models are the **theoretical constraints** they satisfy:
  - **CMB** model satisfies **unitarity** and **analyticity**.
  - **K-matrix** model satisfies **unitarity** but **not analyticity**.
  - **BW model** does **not** satisfy either.

- **Constraints:**
  - **Unitarity** ensures **conservation of probability**.
  - **Analyticity** maintains the **correct relationship** between real and imaginary parts of scattering amplitudes.
- Extraction results from models with **stronger** theoretical constraints should be more **reliable**.
- Results of **CMB** and **K-matrix** approaches, both satisfying **unitarity**, are close to each other, while **BW** results are **distinctively** different.
- This shows that **unitarity** is a **strong, important** constraint.

model	CMB	K matrix	$\mathrm{BW}_{\mathrm{n.r.}}$	$\mathrm{BW}_{\mathrm{rel}}$	CMB all πN	CMB all πN, γN	PDG
$S_{11}(1535)$							
Mass (MeV)	1539±1	1533±1	1549±2	1558±1	1547±3	1539±5	1520–1555(1535)
Width (MeV)	135±4	115±3	142±9	143±4	131±19	122±20	100–200(150)
$B_{\pi N}$	29±1%	34±1%	67±5%	67±1%	34±4%	39±5%	35–55%
$S_{11}(1650)$							
Mass (MeV)	1682±1	1685±2	1648±5	1637±2	1690±12	1684±15	1640–1680(1650)
Width (MeV)	144±3	190±5	147±10	145±4	227±40	227±58	145–190(150)
$B_{\pi N}$	80±1%	77±1%	74±5%	79±1%	75±3%	75±3	55–90%
χ^2/N	3.8	3.7	1.5	1.9	3.6	5.6	

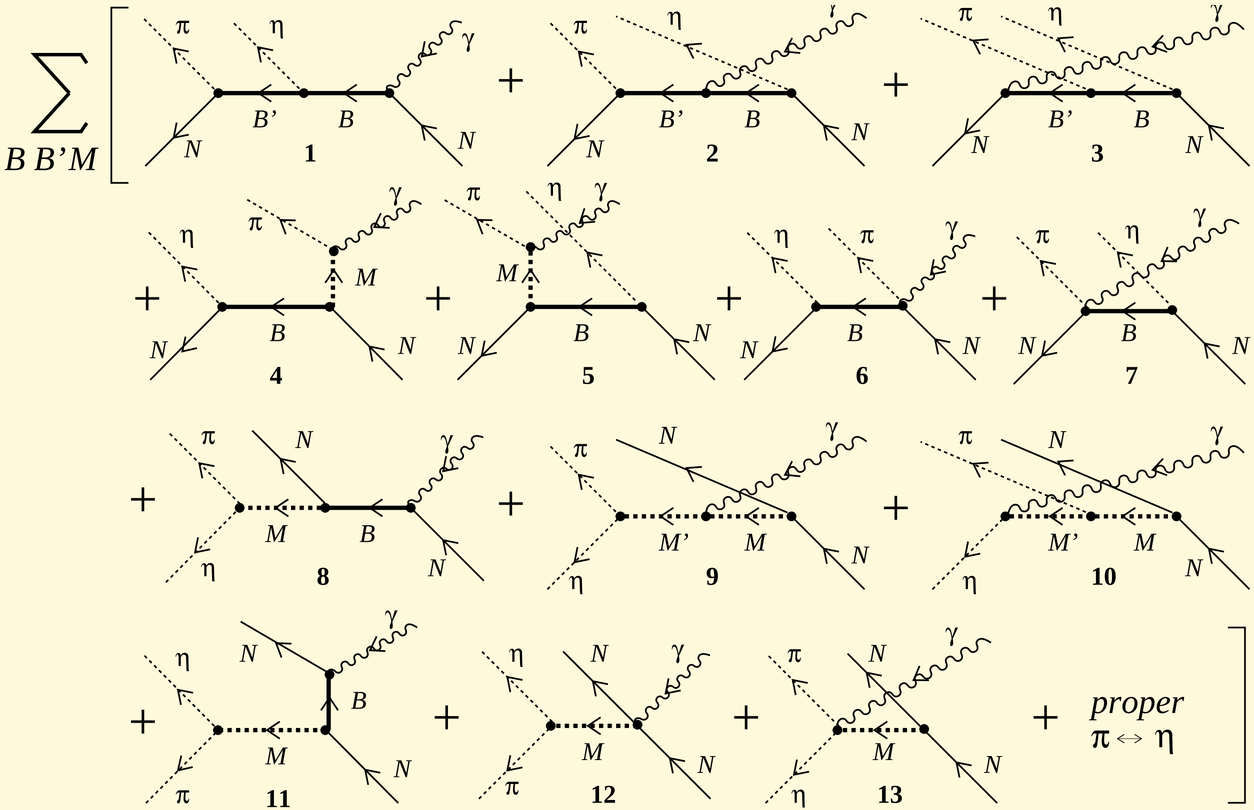
- We fit to the S_{11} **partial-wave** amplitudes with **two channels** πN and ηN using **two resonances** $S_{11}(1535)$ and $S_{11}(1650)$.
- "CMB" and "K matrix" are **very similar**, except for the width of $S_{11}(1650)$.
- But the two "BW" results, while very similar to each other, **deviate** strongly in their branching fraction to πN of $S_{11}(1535)$ and mass of $S_{11}(1650)$ compared to the "CMB" and "K matrix" results.

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**.

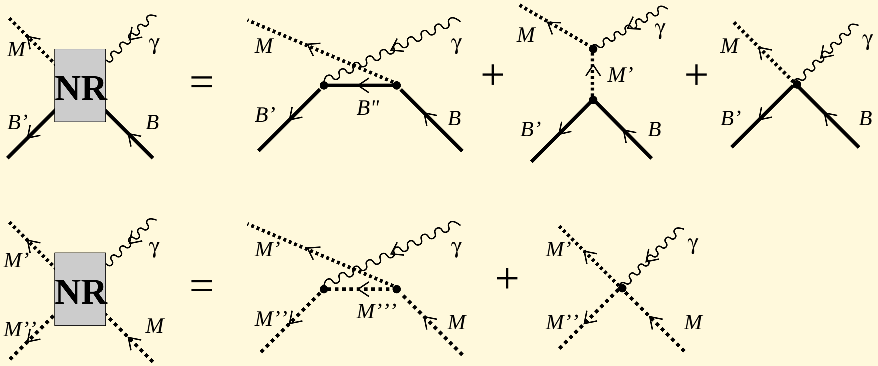
  $\Longrightarrow$ contains **free parameters** like **coupling constants** and **bare masses of baryon**.
- These **free parameters** can be fitted to the **experimental observables** to yield **baryon masses** and **widths** to various channels.
- **Winston Roberts** helps us in many details of the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

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

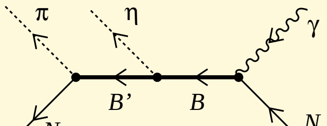


- For $\gamma N \longrightarrow \pi\pi N$ reaction, change η to π.
- Here, B and B' are **baryon** intermediate states, and M is **meson** intermediate state.

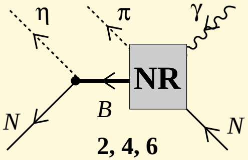
Collect all the **nonresonant** interactions:



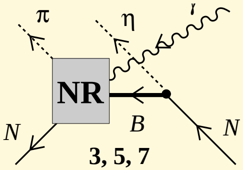
The diagrams can be written **compactly** as follows:



1



2, 4, 6



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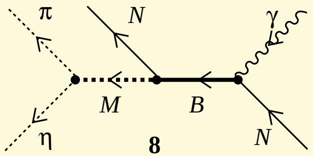

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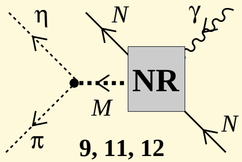
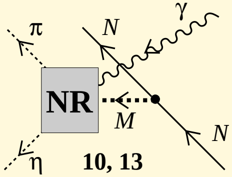


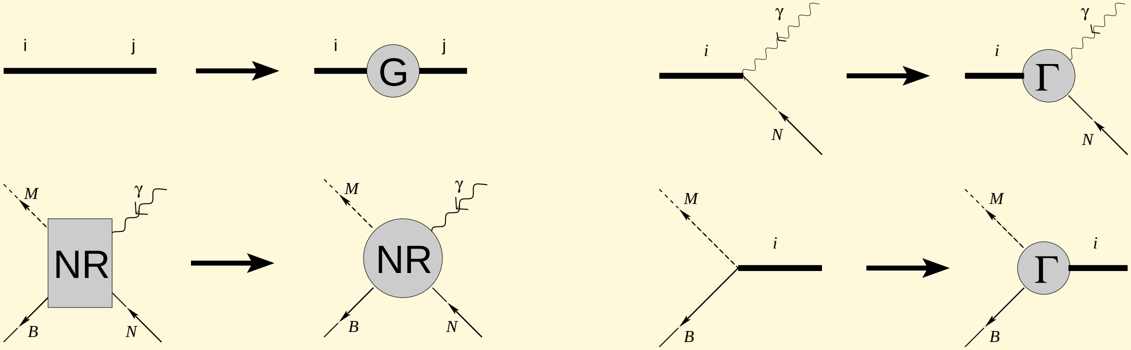
9, 11, 12



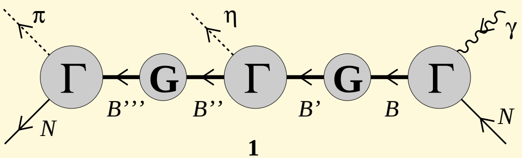
10, 13

Unitarization of the scattering amplitude

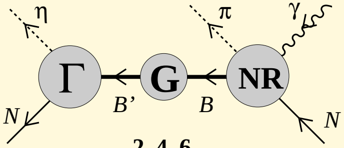
- **Unitarization** is done by including **rescattering**.
- **Diagrammatically**, it can be described as:



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



1



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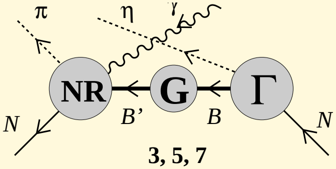

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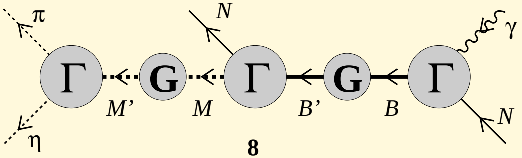

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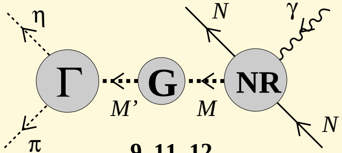

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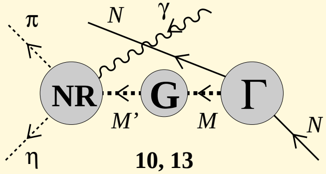

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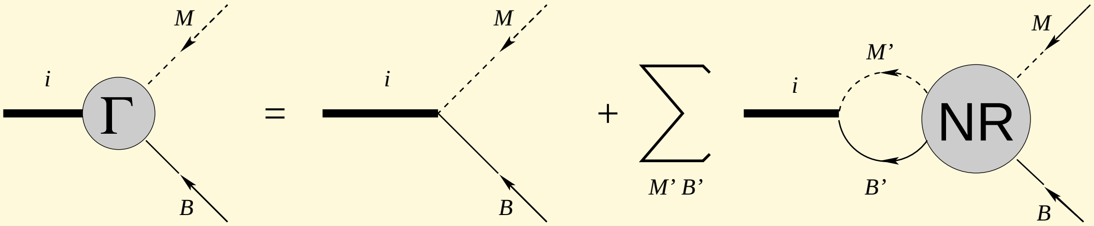
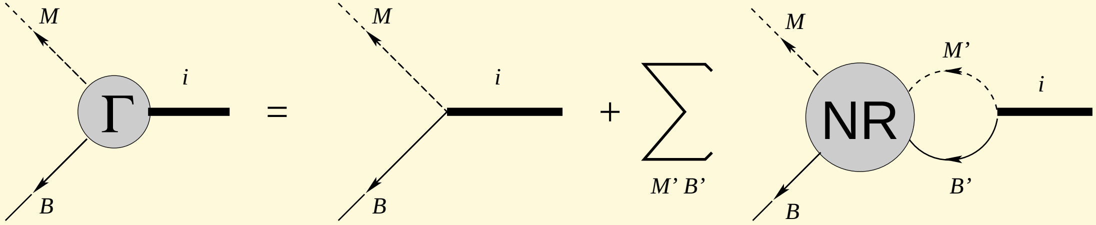
The **dressed vertices** and **propagators** are:

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

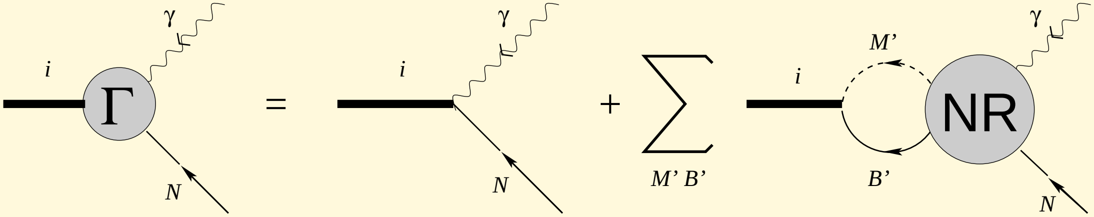


$$\Gamma_{N_i^*\leftarrow MB}(E) = \Gamma^0_{N_i^*\leftarrow MB}(E) + \sum_{M'B'} \Gamma^0_{N_i^*\leftarrow M'B'}(E) G_{M'B'}(E) t_{M'B'\leftarrow MB}(E)$$



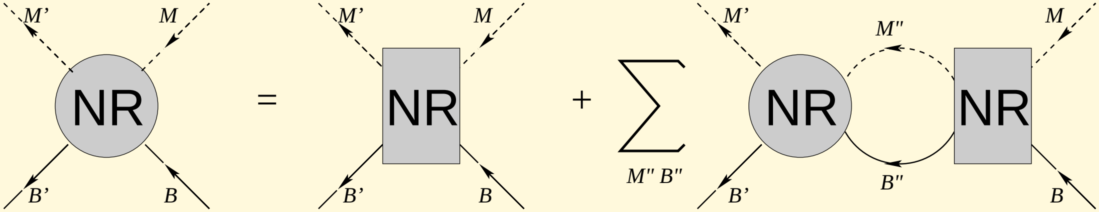
$$\Gamma_{MB\leftarrow N_i^*}(E) = \Gamma^0_{MB\leftarrow N_i^*}(E) + \sum_{M'B'} t_{MB\leftarrow M'B'} G_{M'B'}(E) \Gamma^0_{M'B'\leftarrow N_i^*}(E)$$

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

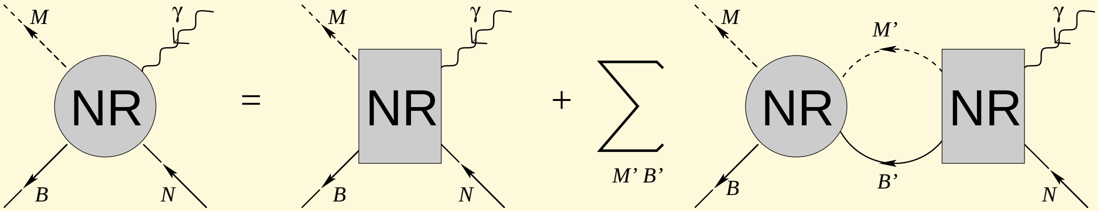


$$\Gamma_{N_i^*\leftarrow\gamma N}(E) = \Gamma^0_{N_i^*\leftarrow\gamma N}(E) + \sum_{M'B'} \Gamma^0_{N_i^*\leftarrow M'B'}(E) G_{M'B'}(E) t_{M'B'\leftarrow\gamma N}$$

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



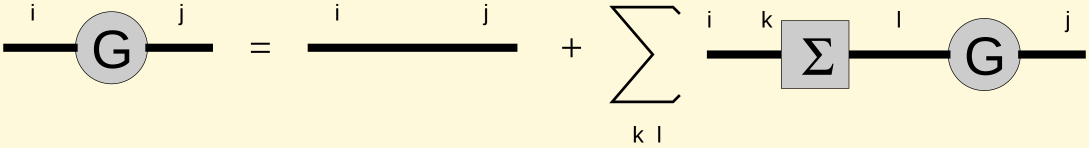
$$t_{M'B'\leftarrow MB}(E) = V_{M'B'\leftarrow MB}(E) + \sum_{M''B''} t_{M'B'\leftarrow M''B''}(E) G_{M''B''} V_{M''B''\leftarrow MB}(E)$$



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

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

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

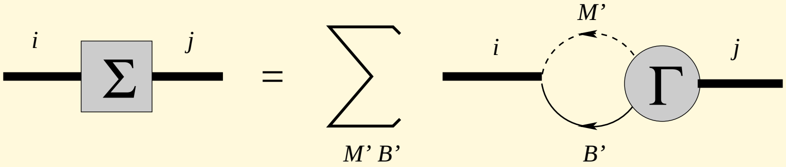


$$G_{ij}(E) = G^0_{ij}(E) + \sum_{kl} G^0_{ik}(E)\Sigma_{kl}(E)G_{lj}(E),$$

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

- This reaction 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** on the reaction is more readily **available**
- **Many approaches** using different models have some **success** in fitting the data.
- **Comparing** our results to other's results of $\pi\pi$ photoproduction can be useful to check our model.
- Particularly **hard** to obtain a good fit to data in **all charge states** simultaneously.
- This reaction 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**)

In our preliminary study:

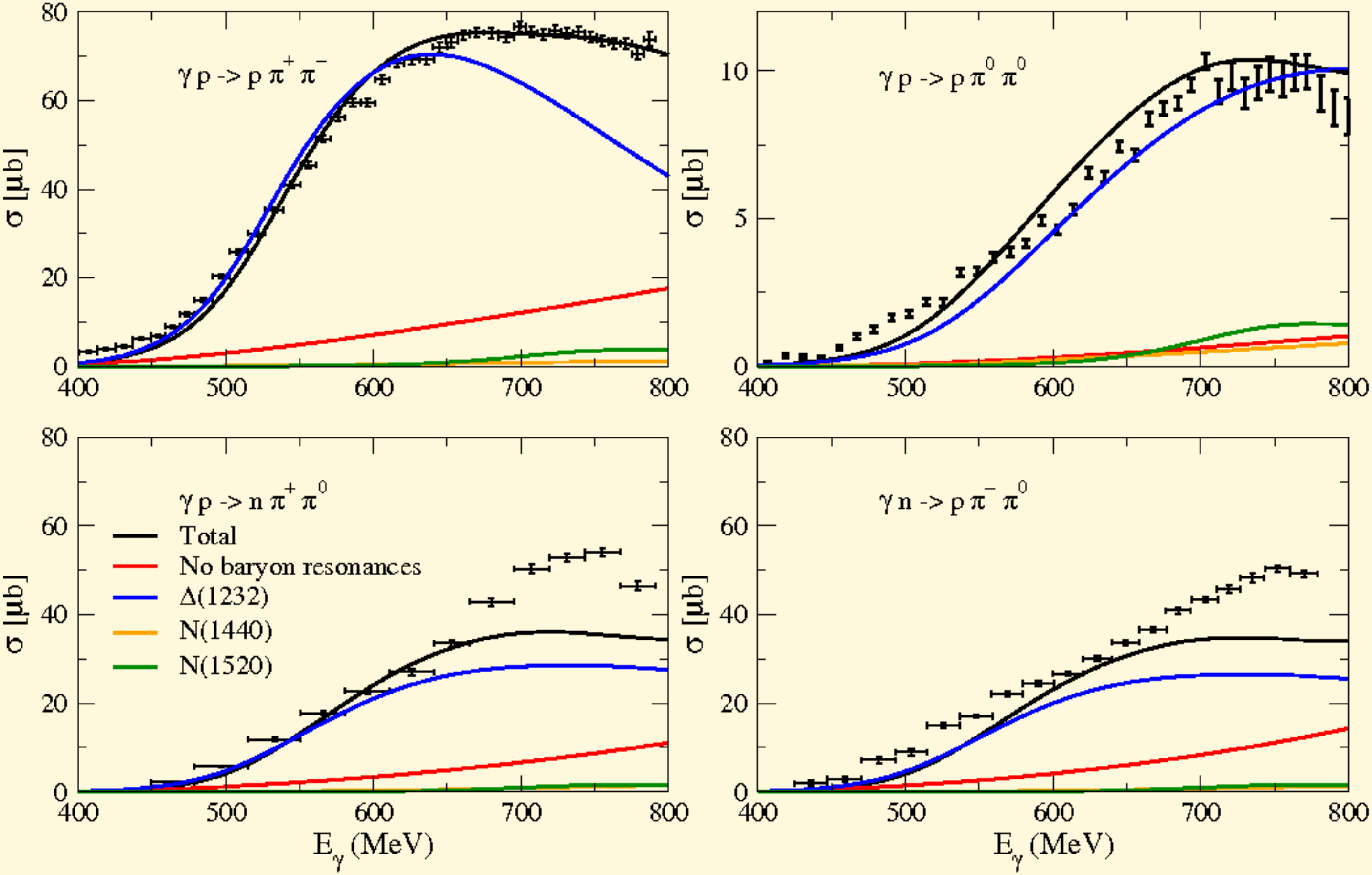
- **Rescattering** is implemented only in the **propagator** of the **excited** baryon states (to develop resonance **widths**).
  $\Longrightarrow$ **Not** a thoroughly **unitary** model.

- The diagrams are treated **relativistically** in the **phenomenological Lagrangian** approach.
  $\Longrightarrow$ Contain γ, N, $\pi(139)$, $\rho(770)$, and $\omega(782)$.
  $\Longrightarrow$ **Baryon resonances** included are $\Delta(1232)$, $N(1440)$, and $N(1520)$.

- **Coupling constants** are adjusted to the **decays** of various resonances to various channels.
  $\Longrightarrow$ But allow some freedom when fitting data.

- Also try to fit **signs** between coupling constants.

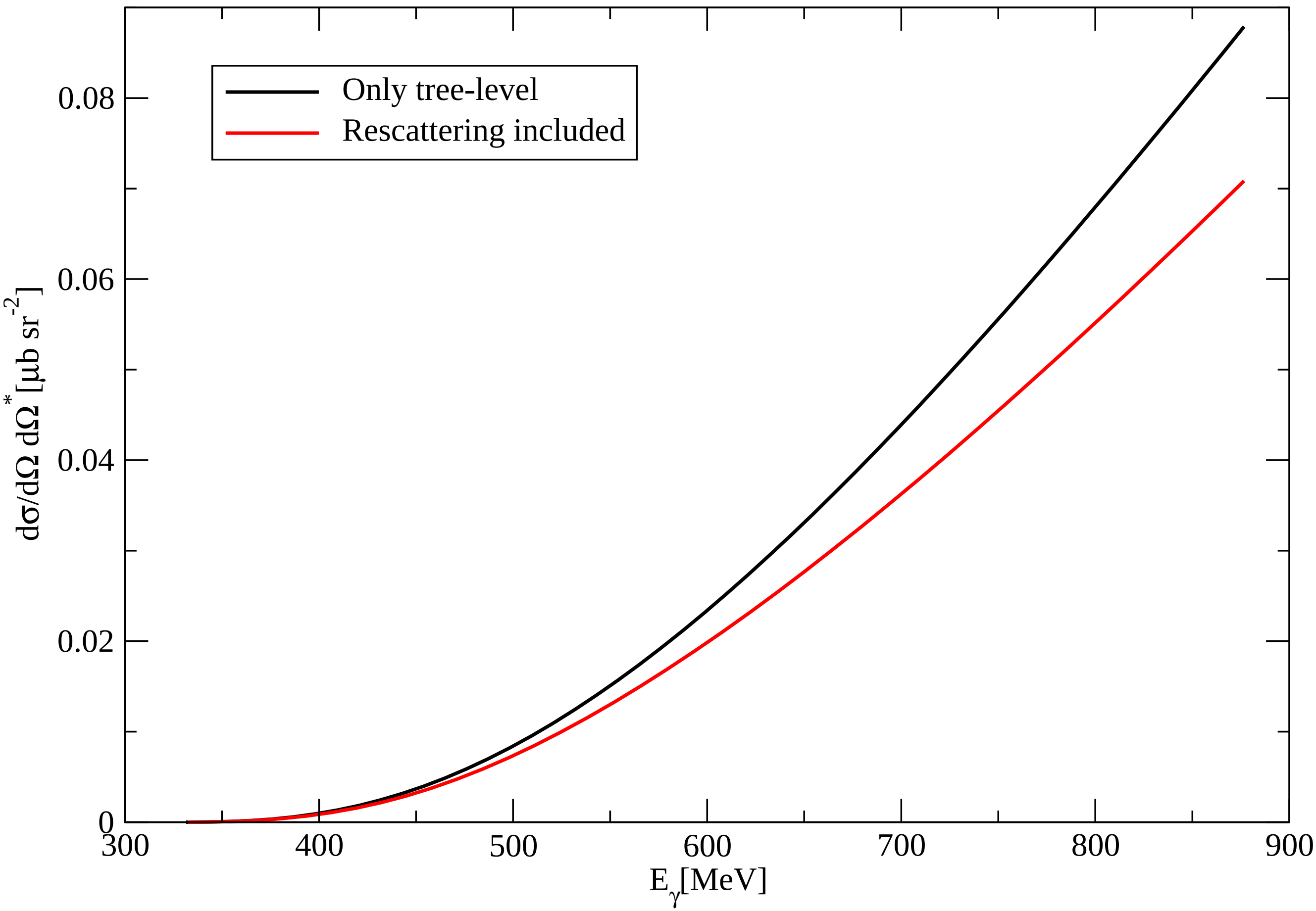
Our preliminary results



- 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.
- We are **ready** to implement the **rescattering effect** on this reaction.

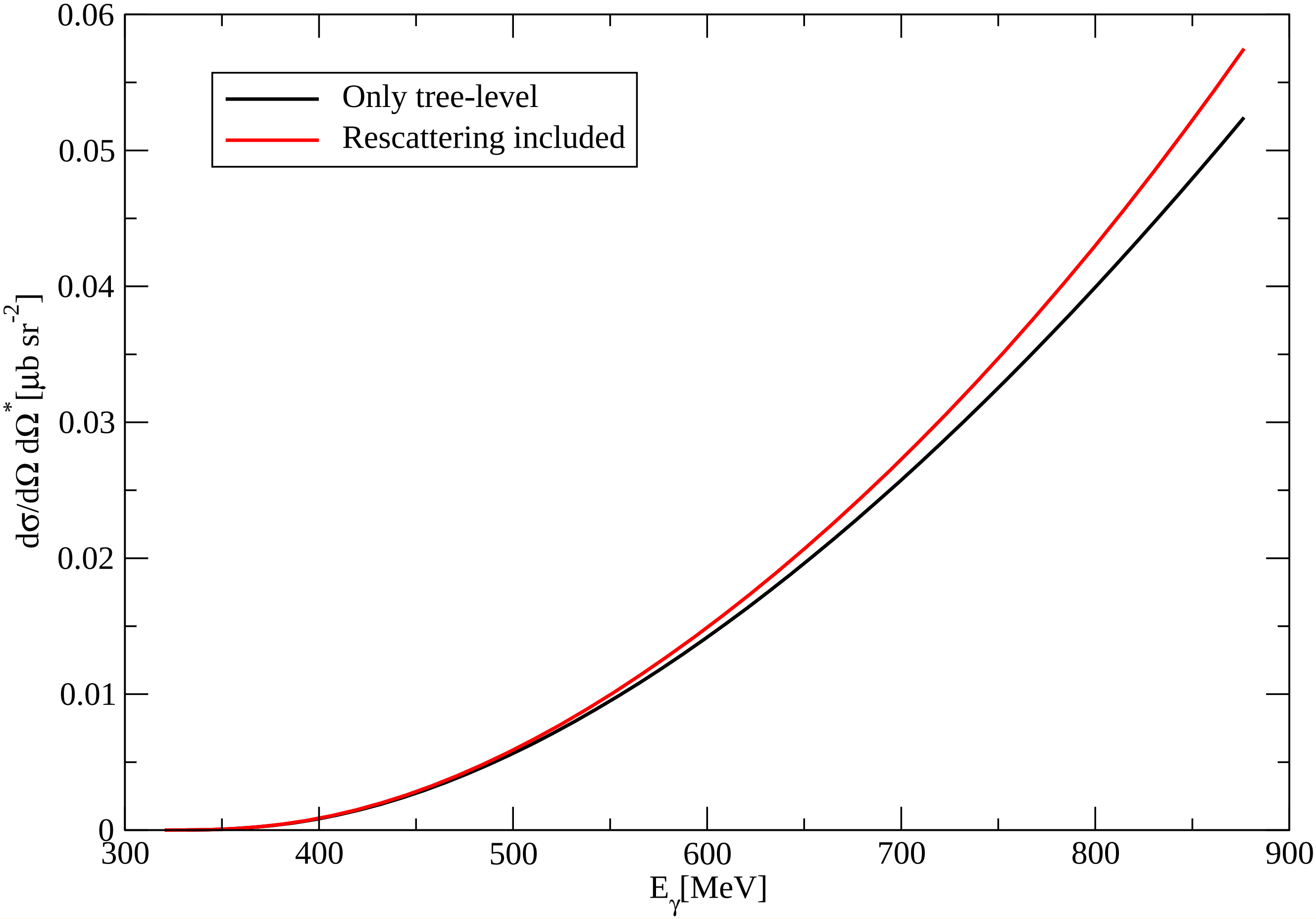
Cross Section to a specific helicities and directions configuration

Nucleons helicities are positive (+), photon negative (-), $\theta = 30^o$, $\phi = 90^o$, $\theta^* = 30^o$, $\phi^* = 120^o$



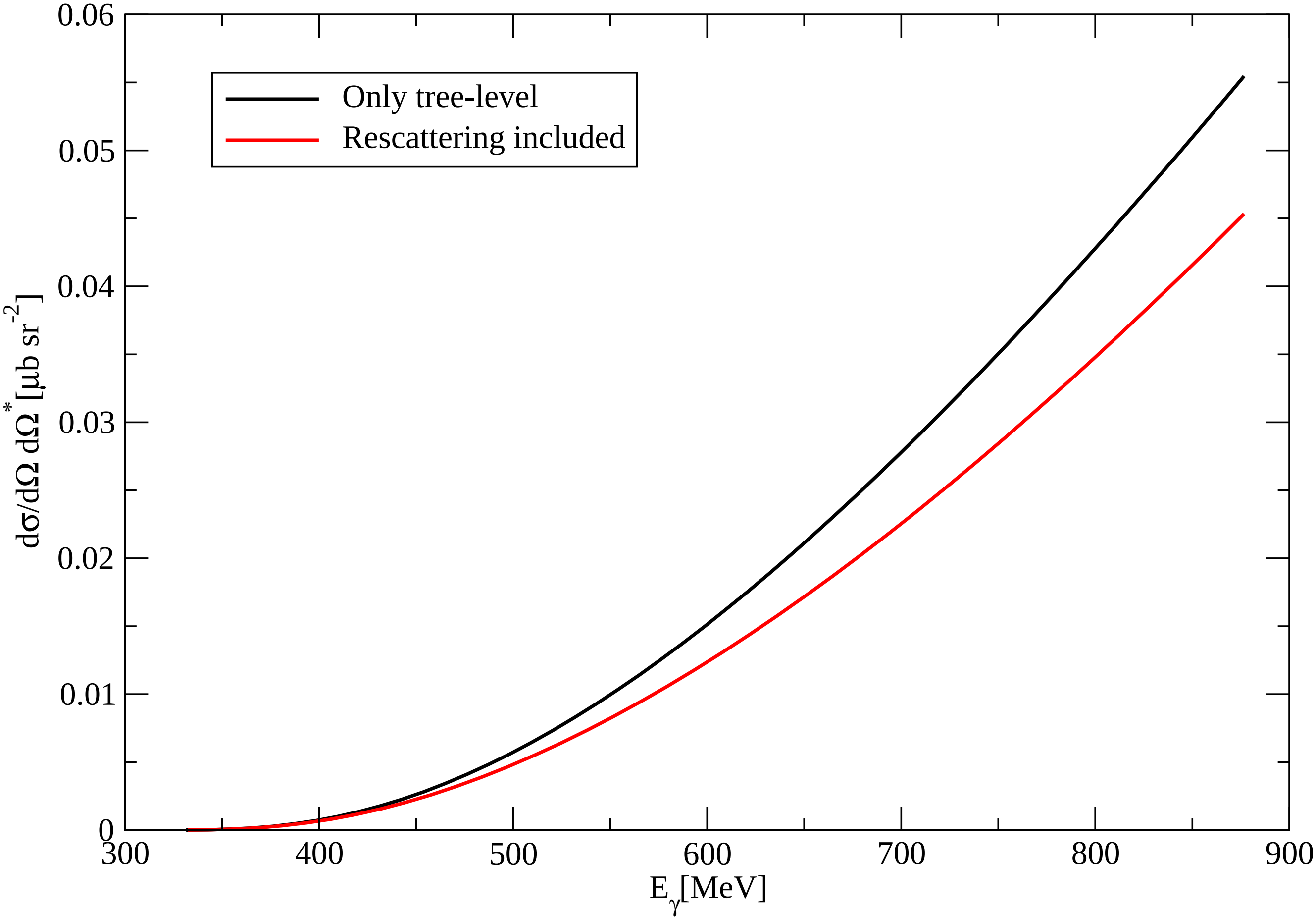
Cross Section to a specific helicities and directions configuration

Nucleons helicities are positive (+), photon negative (-), $\theta = 80^o$, $\phi = 170^o$, $\theta^* = 60^o$, $\phi^* = 150^o$



Cross Section to a specific helicities and directions configuration

Nucleons helicities are positive (+), photon negative (-), $\theta = 50^o$, $\phi = 70^o$, $\theta^* = 25^o$, $\phi^* = 125^o$



Rescattering effects cannot be undermined

- The **rescattering effects** are calculated for a set of diagram with only **nucleon**, **pion**, and **photon**.
  $\Longrightarrow$ Just to **demonstrate** how much effects of the rescattering can be.
- The $\gamma p \rightarrow p\pi^+\pi^-$ reaction is chosen on the above plots.
- Cross-section is chosen for a **certain configuration** of **helicities** and **momenta directions** of the nucleons and photon.
- The **rescattering effect** introduces **10-20%** change to the differential cross-section.
  $\Longrightarrow$ Certainly this effect is **quite significant** to change the overall results.
- More **complete** results including **Δ(1232)**, **N(1440)**, and **N(1520)** will be ready later.
  $\Longrightarrow$ Can be done relatively **quick** since the **rescattering code** has been finished.

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.

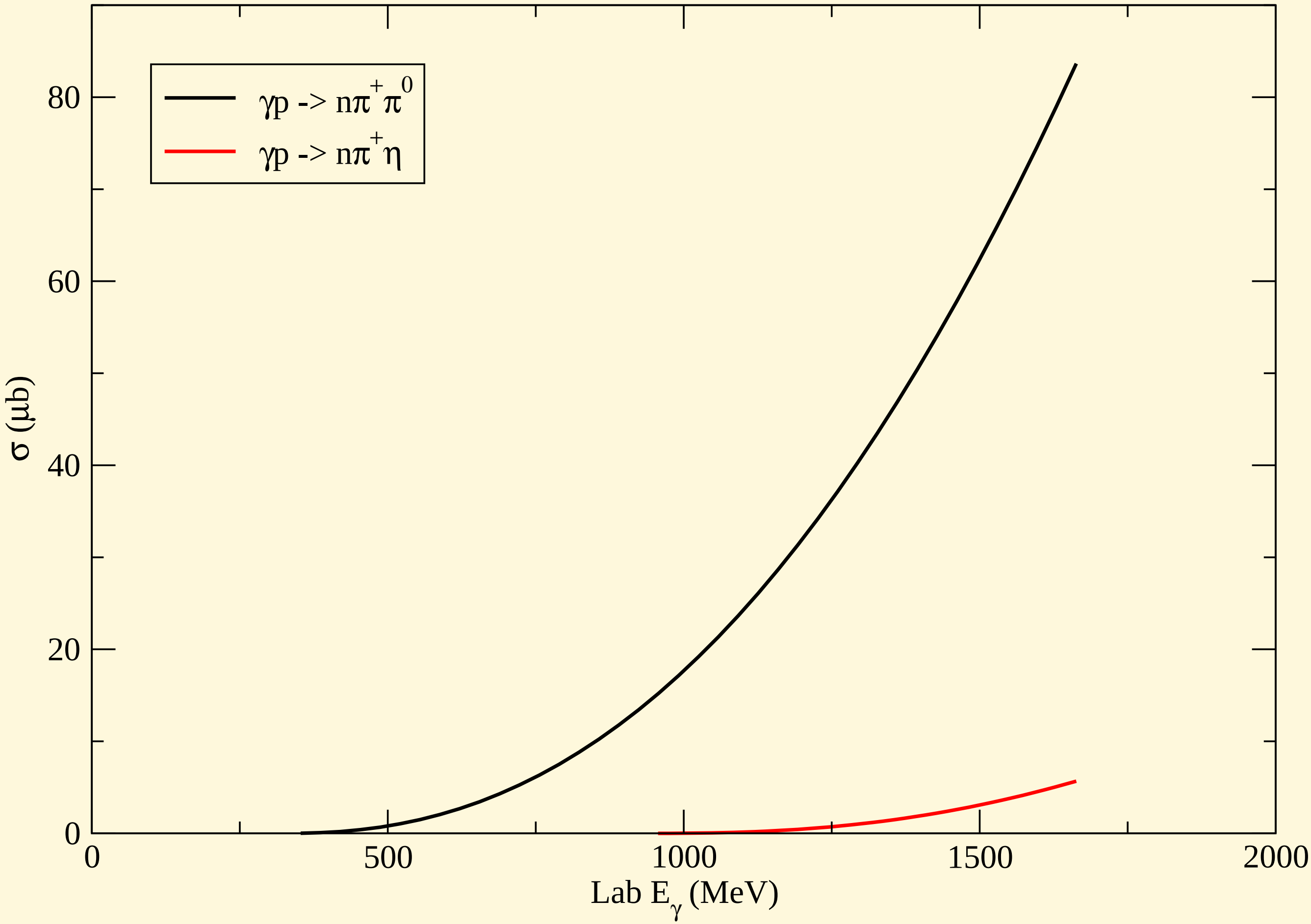
- Of particular interest are decays to $\Delta(1232)\eta$ and $N(1535)\pi$ because of the strong coupling $\Delta \rightarrow N\pi$ and $N(1535) \rightarrow N\eta$.
  $\Longrightarrow$ These decays might actually come from the **unobserved** resonances.

- 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 πη and ππ 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**.
- **Rescattering** is expected to contribute **significantly**.
- With this model in hand, **calculation** for any **two-meson photoproduction** will be relatively easy to develop.

Thank you!