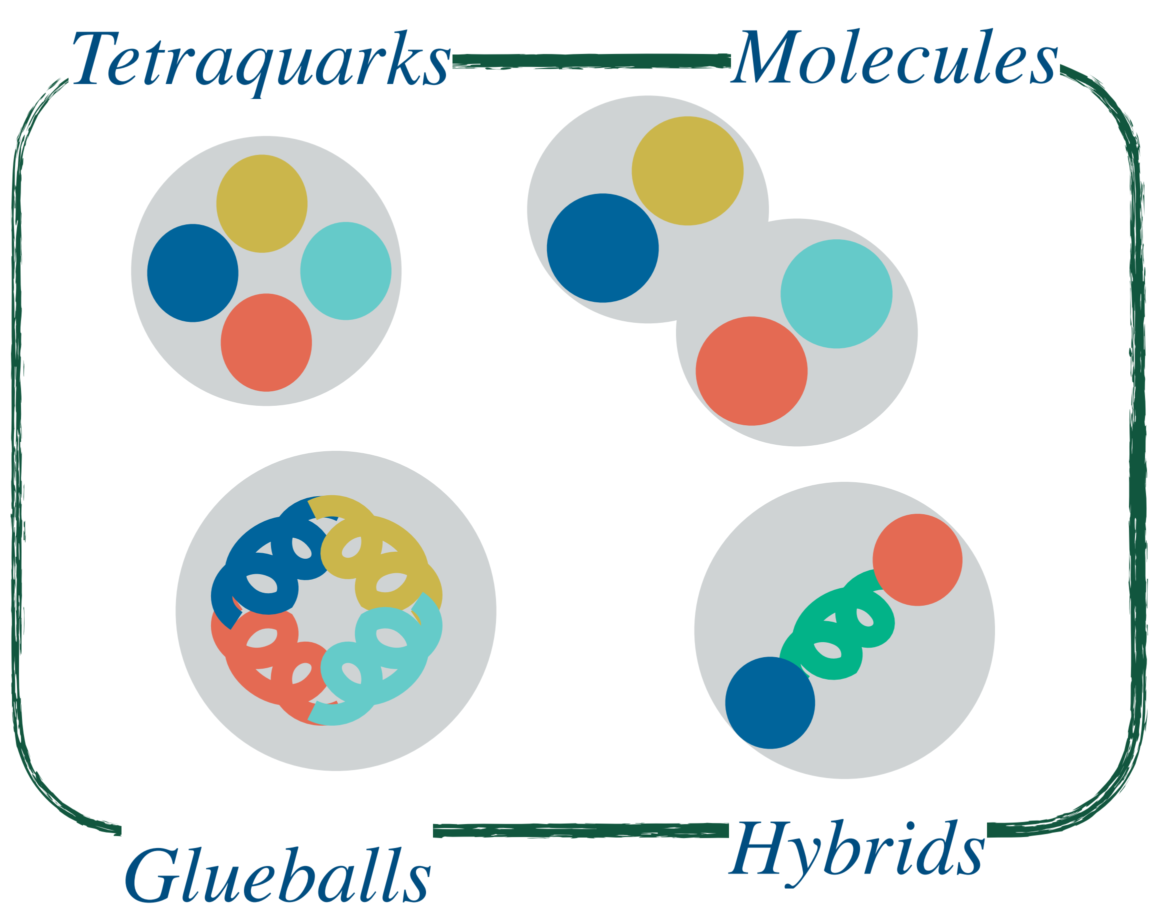
Amplitude analyses at ExoHad

Jefferson Lab
Thomas Jefferson National Accelerator Facility

OLD DOMINION UNIVERSITY

EXOHAD
EXOTIC HADRONS TOPICAL COLLABORATION

Amplitude analyses at ExoHad

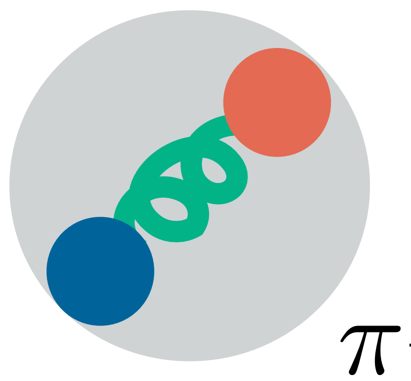


1- Ensure the success of JLab experimental efforts on the search for exotic hybrid candidates

Provide experimental groups with required theoretical inputs

Combine experimental, Lattice QCD, and model predictions needed to establish the existence of the hybrids

Develop reaction amplitudes to describe production and decays of hybrids



$\pi_1(1600)$

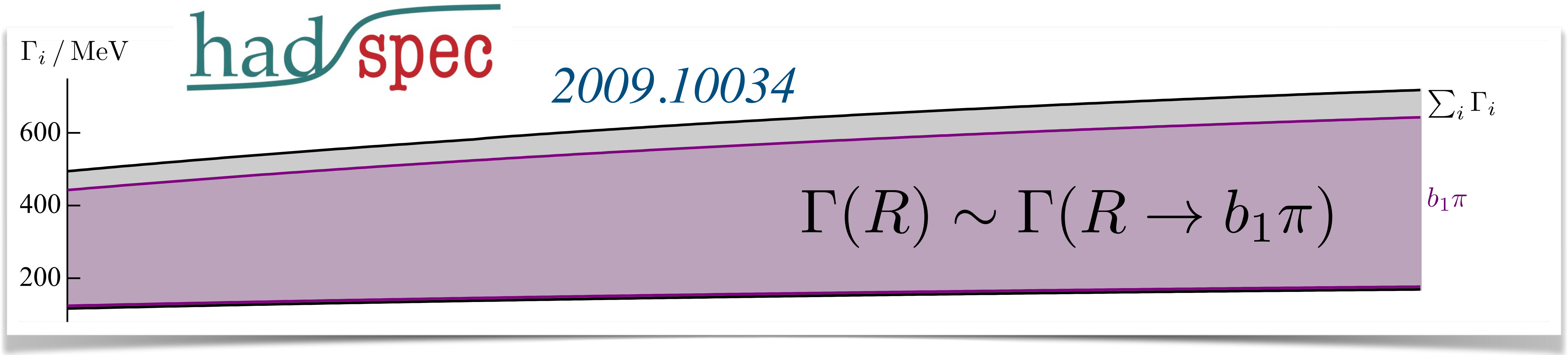
2- Develop a spectroscopy program for exotics, at future facilities (EIC/JLab 22)

Based on recent ExoHad work, establish optimal experimental configurations (final states, cross-sections, etc…)

Capitalize on this exciting opportunity to build a spectroscopy community

1- Hybrid exotic candidates

- Out of 8 possible decay modes, Lattice QCD predicts a dominant one



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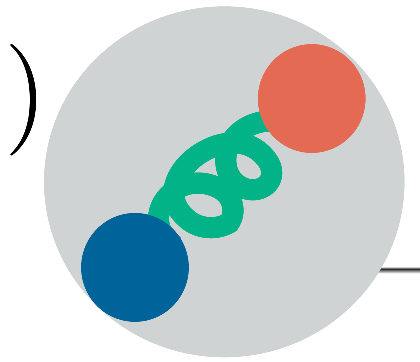

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$\eta\pi$	688	$0 \to 43$	$0 \to 1$
$\rho\pi$	910	$0 \to 203$	$0 \to 20$
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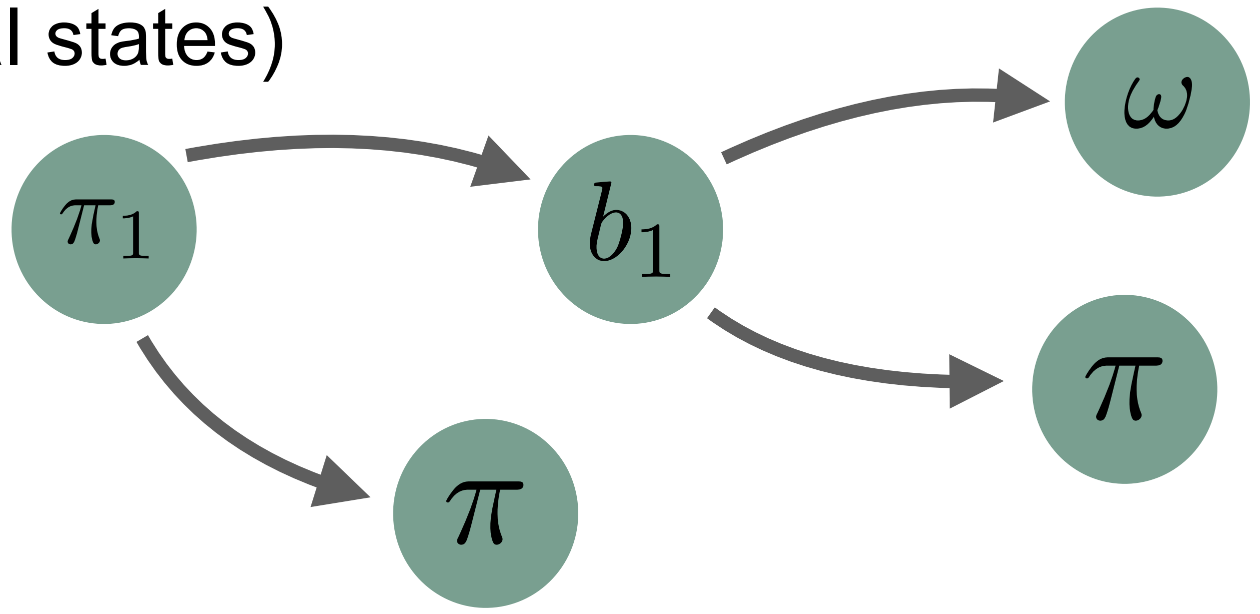
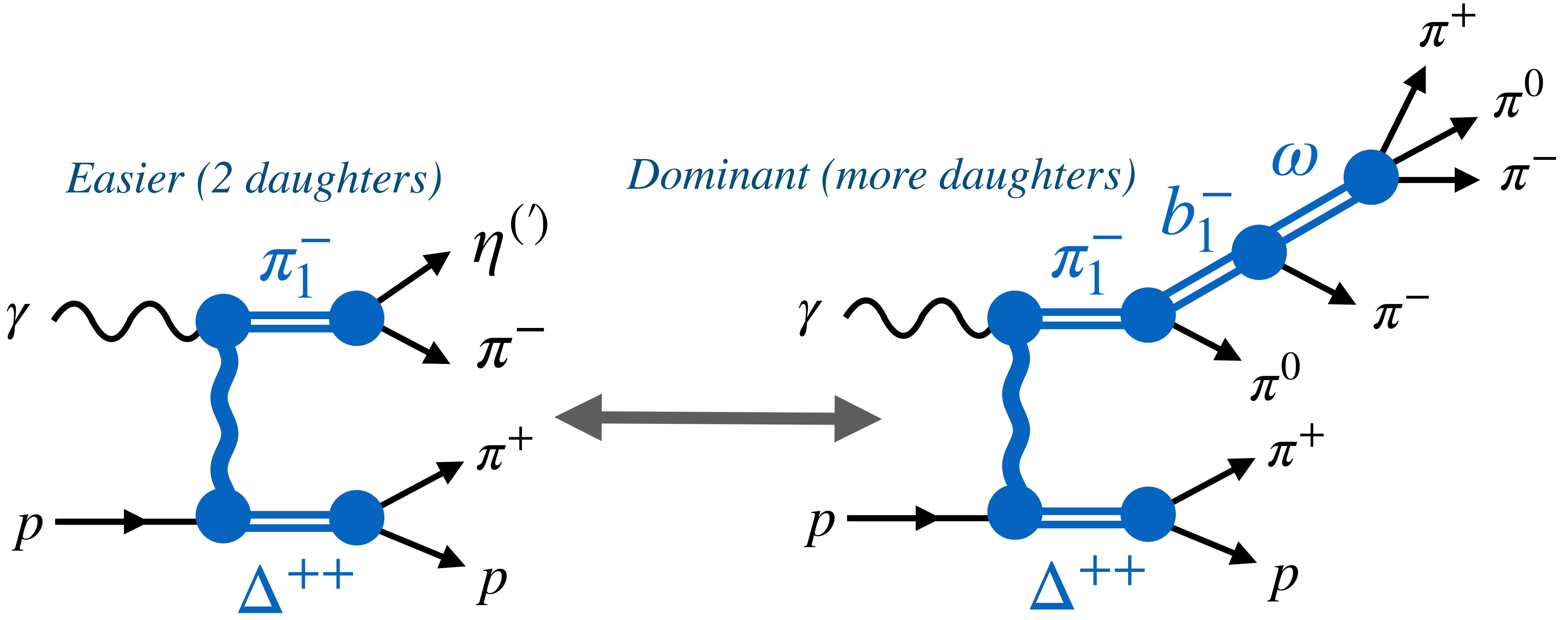
		$\Gamma = \sum_i \Gamma_i = 139 \to 590$	

We "know" decay products (final states)



JLab experiments are based on photoproduction (initial states)



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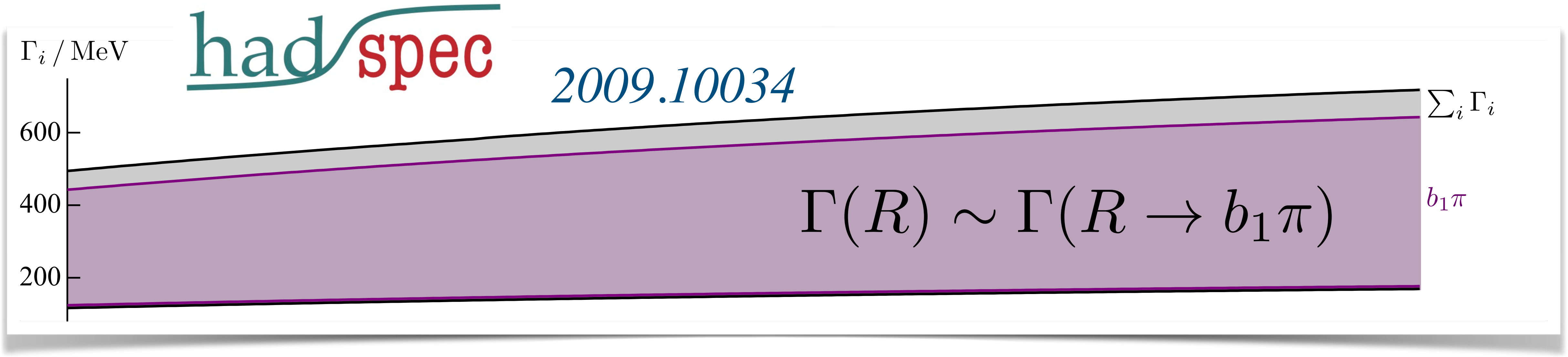

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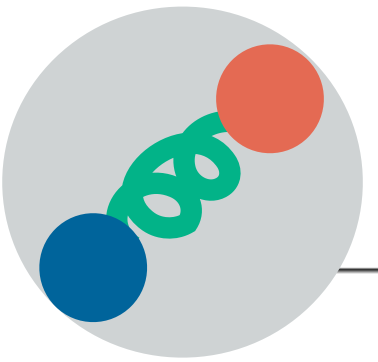

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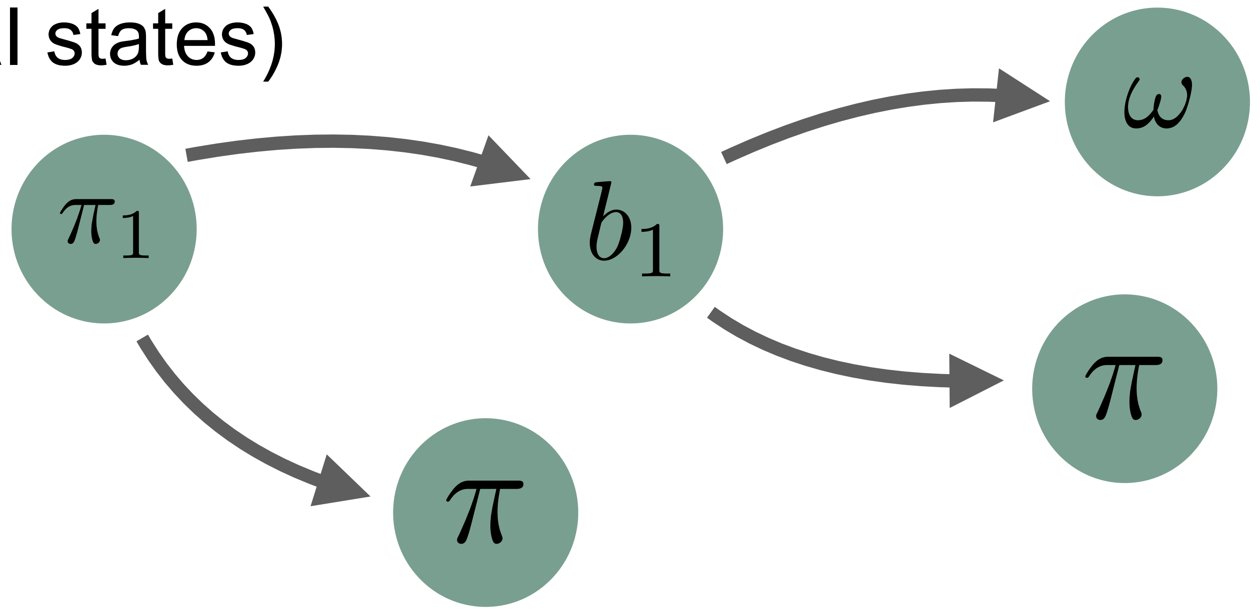
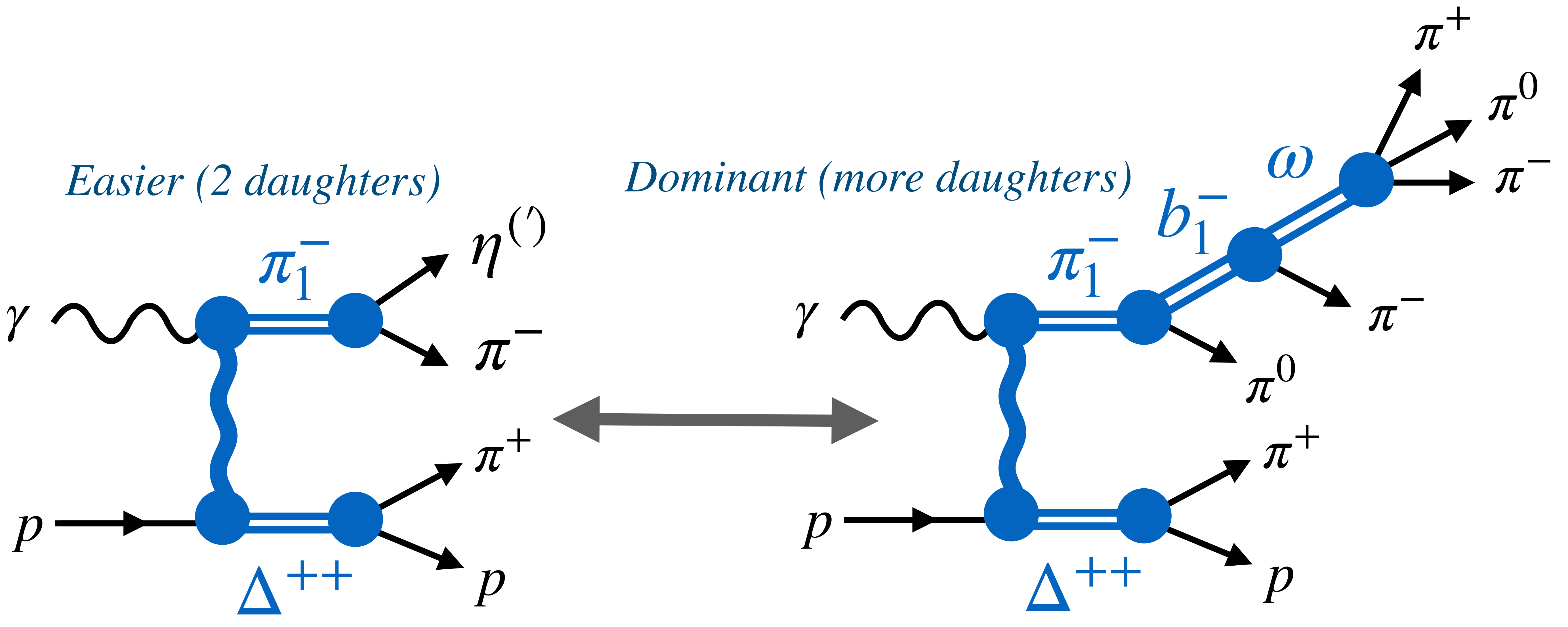


JLab experiments are based on photoproduction (initial states)

In position to understand these processes

Both charged (Δ^{++}) and neutral (p) modes under study

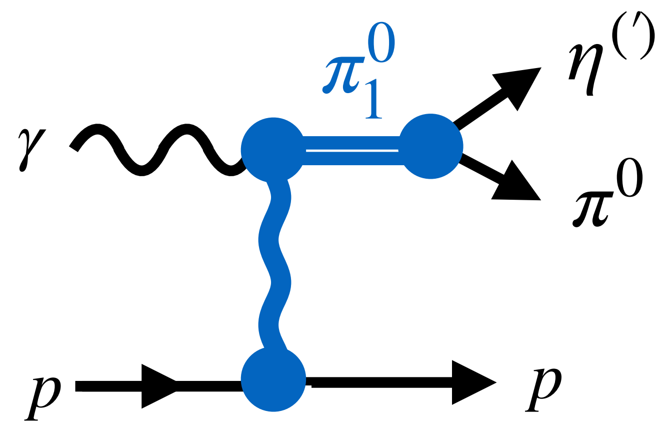


1- Hybrid exotic candidates: How (step-by-step + experiment)

Main goal: Understanding production and decay processes of hybrids

Can we obtain unambiguous results for simpler reactions?

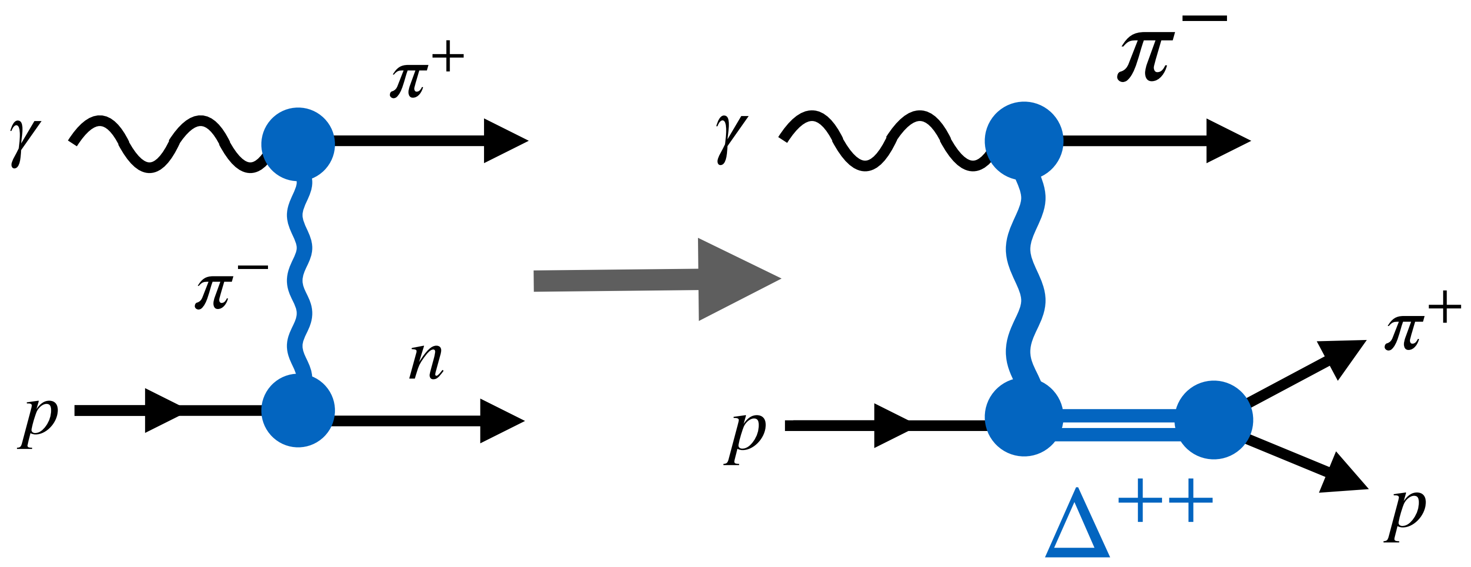
Milestone 1



Experiment: GlueX

Understand the production process, then recover bottom vertex

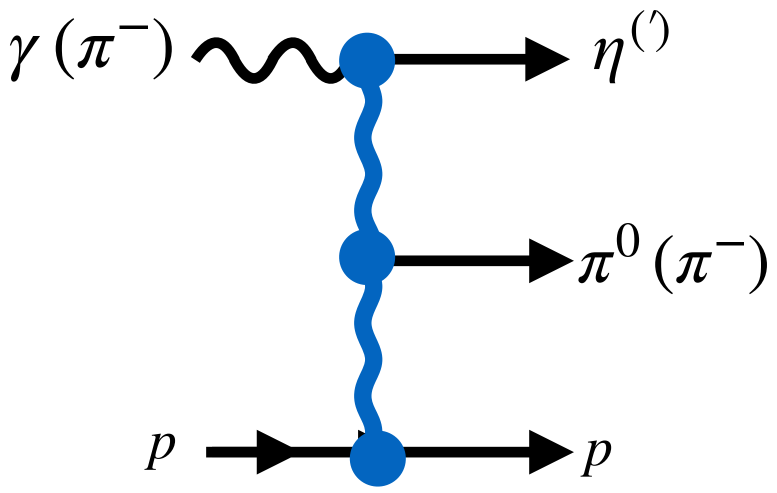
Milestone 2



Experiment: CLAS (CEBAF Large Acceptance Spectrometer) / GlueX

We also need to understand all processes that produce the same final state backgrounds

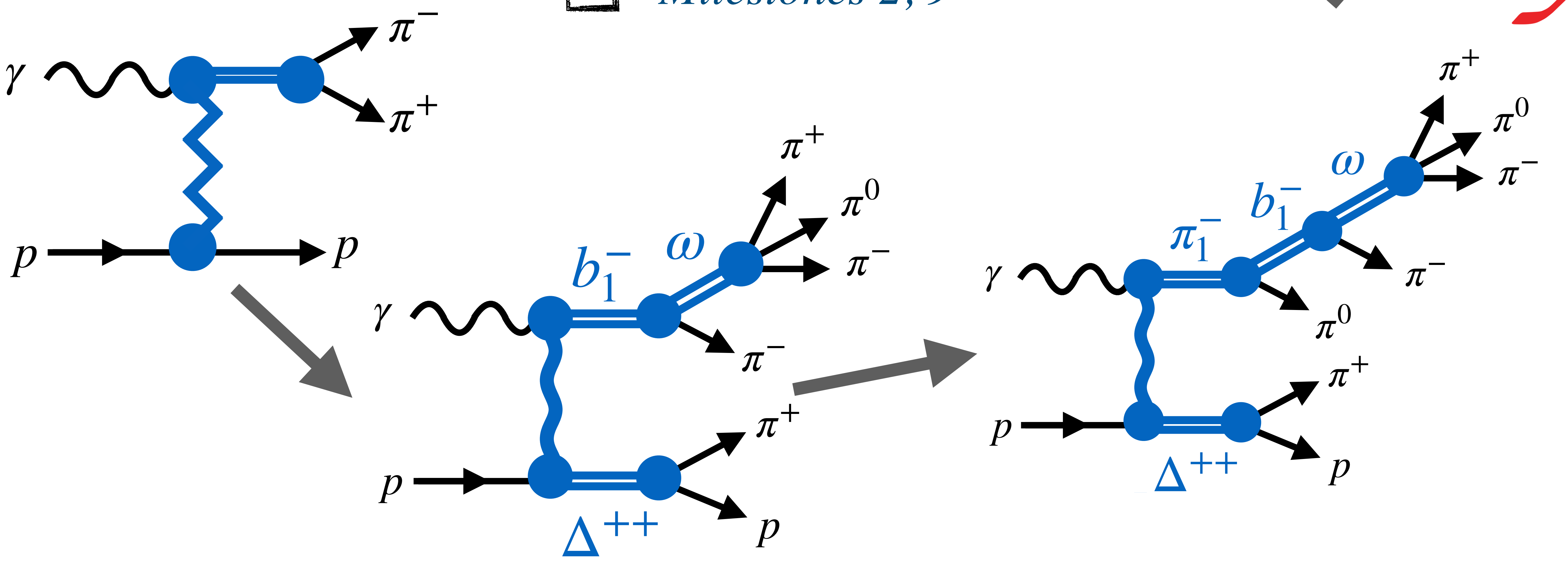
Milestones 10, 11



Experiment: GlueX / COMPASS

Understand top vertex, step-by-step

Milestones 2, 9



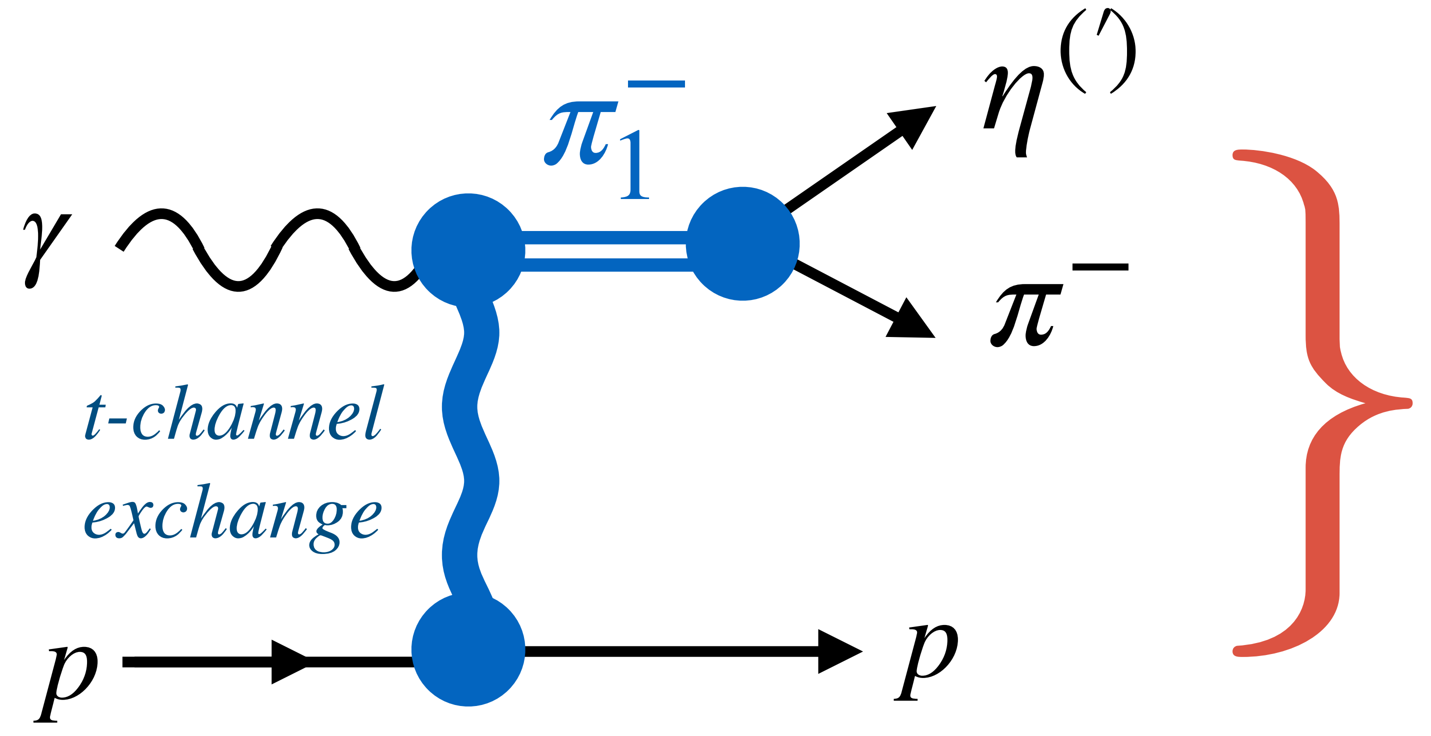
1- Ambiguities in $\pi\eta$ photoproduction (Milestone 1)

Reconstructing broad resonances from final states requires partial wave analyses

We need unambiguous extraction of information for known/simple reactions

Problem:

Production experiments can suffer from ambiguities in the partial wave extractions (more than one mathematical solution is possible). Only one is physical



$$f_m = \sum_{\ell=0}^{\ell_m} a_{\ell\, m}(s) Y_\ell^m(\theta, \phi)$$

The hybrid lives in ℓ=1

Novelty:

GlueX has a linearly polarized beam, which has not been studied extensively before

Result:

Discrete ambiguities in partial waves were *ruled out* for a linearly polarized photon beam! Including higher waves does not change this conclusion

GlueX can implement what we learned during this project, in other analyses

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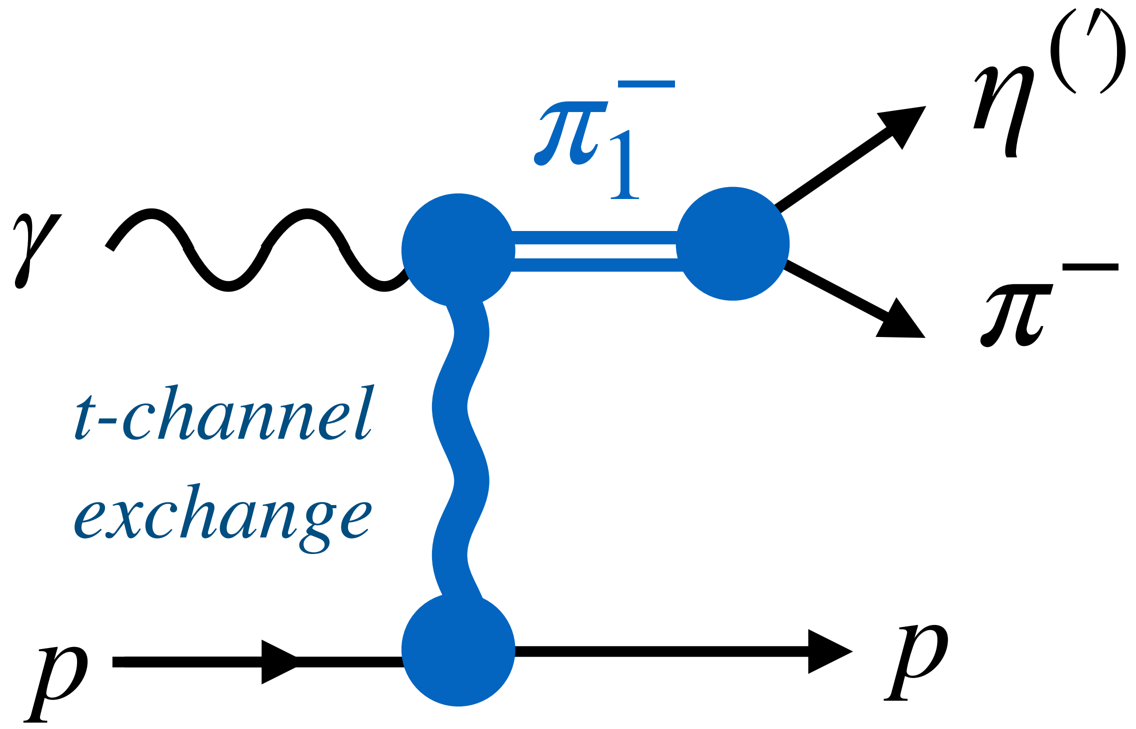

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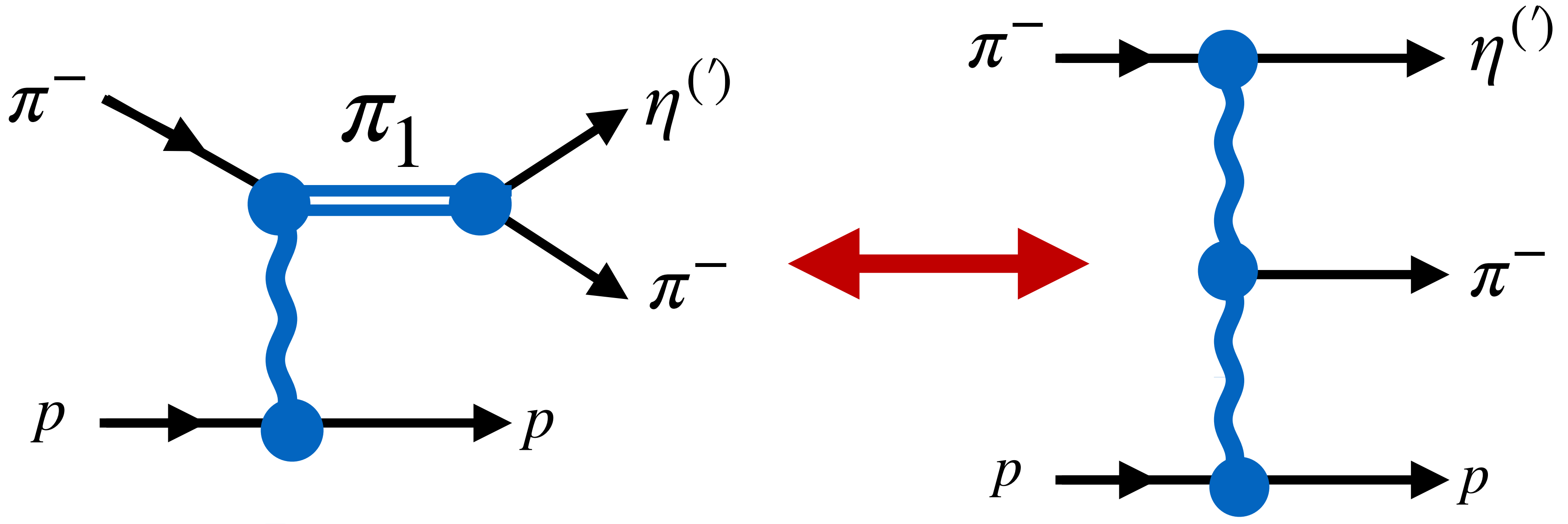
1- Double Regge contributions (Milestones 10, 11)

Other processes (right) produce the same final states as direct π_1 production (left)

We need a full understanding of all these backgrounds



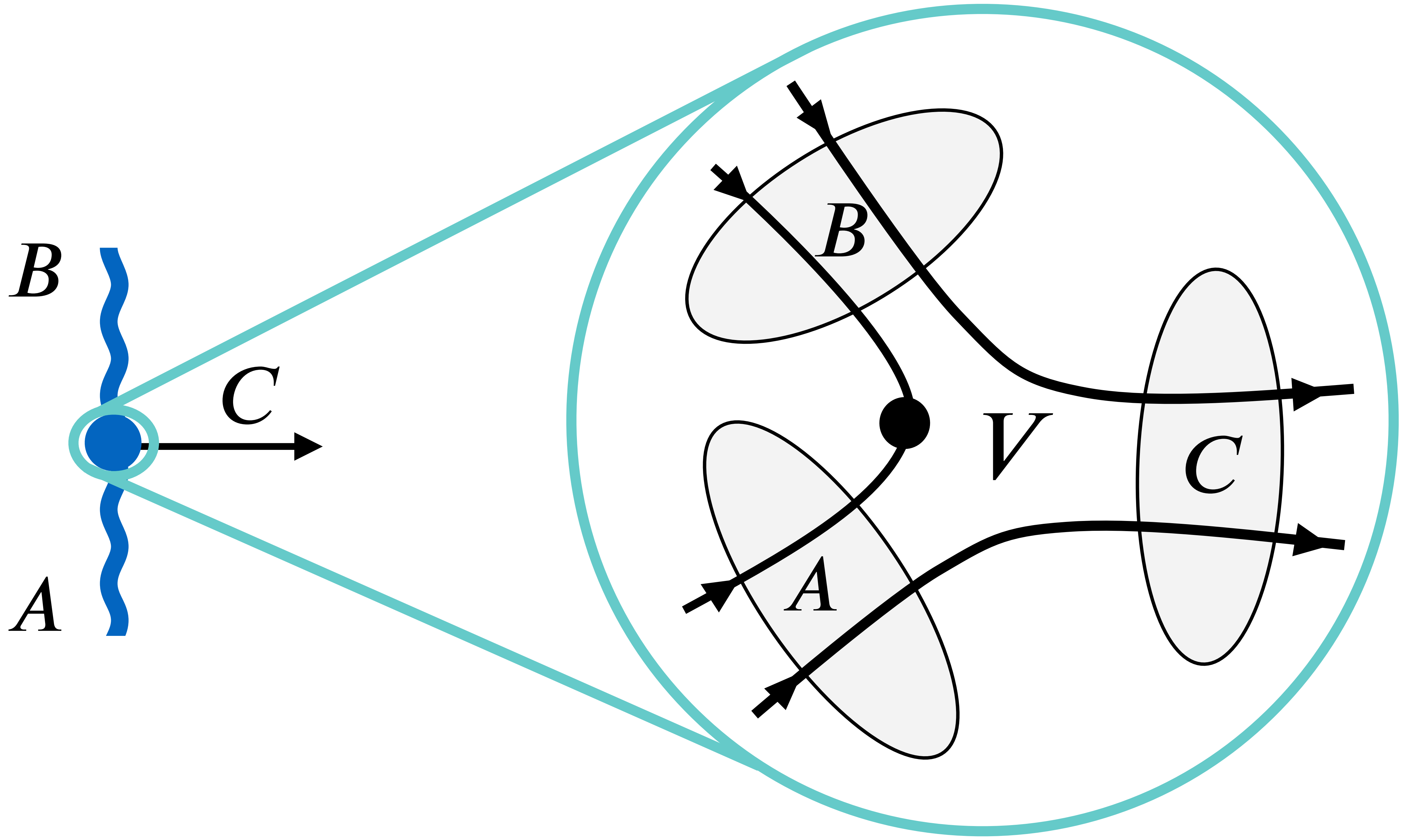
Issues:

The existing models suffer from pathologies (infinite narrow resonances)
No detailed comparison between these models and modern data exists

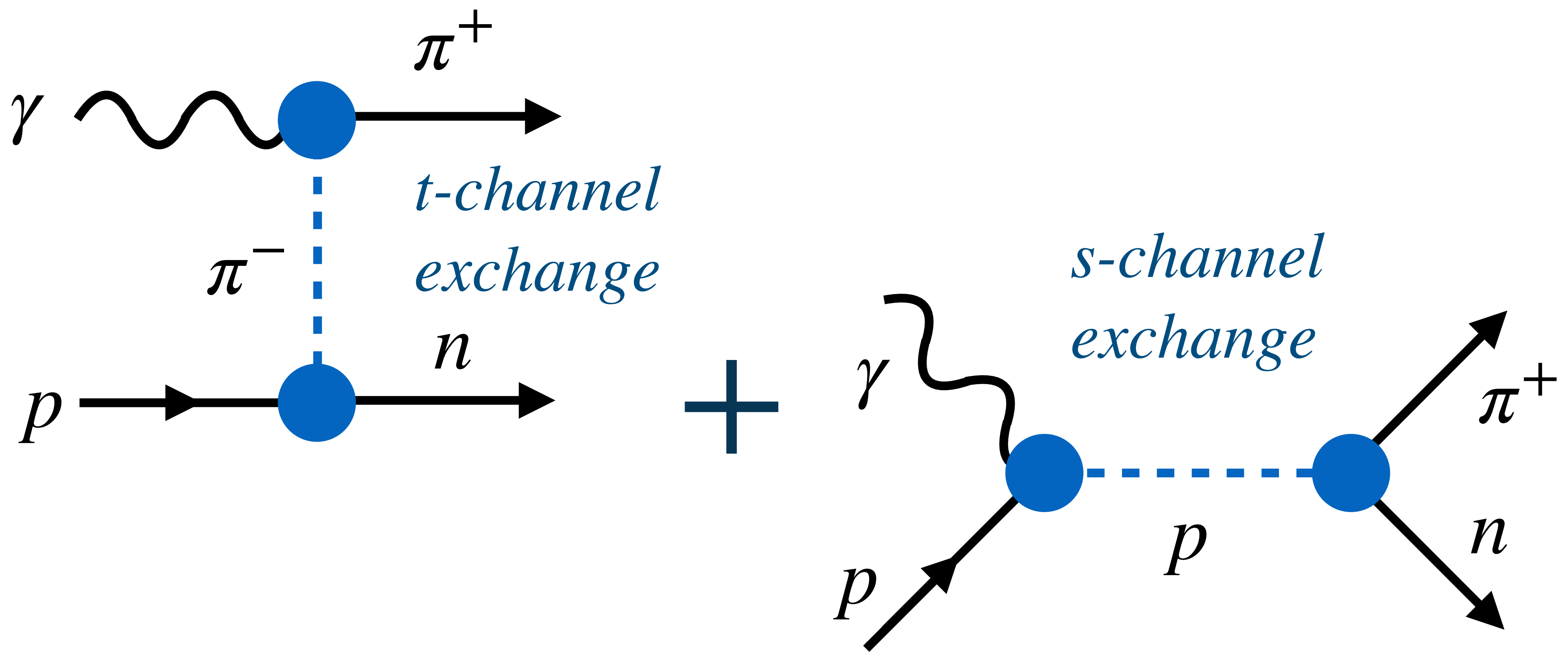
Solution:

1- Working together with COMPASS/GlueX and theory input to find the correct parametrization that describes multi-dimensional event distributions

2- Understanding these couplings from quark models/ lattice QCD



1- Pion exchange (Milestone 2)



Pion exchange is the most constrained by theory, but there are still issues

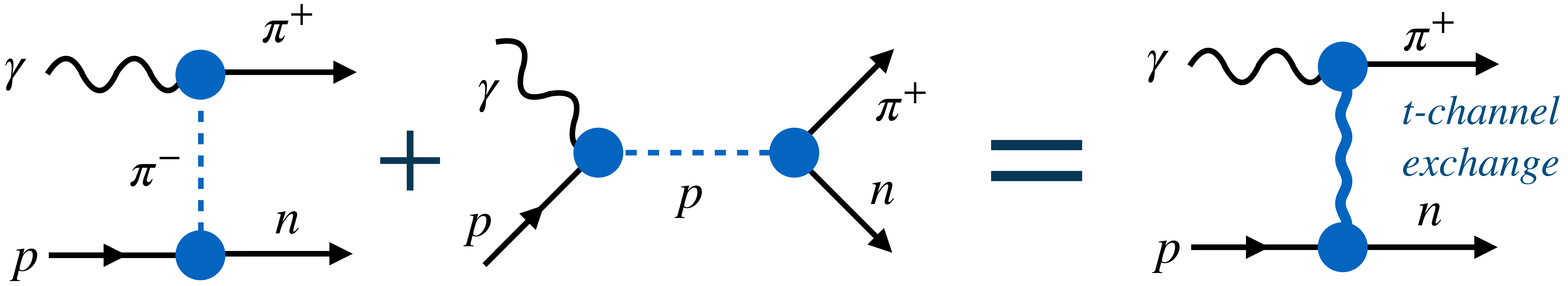
We need to understand this exchange to move forward

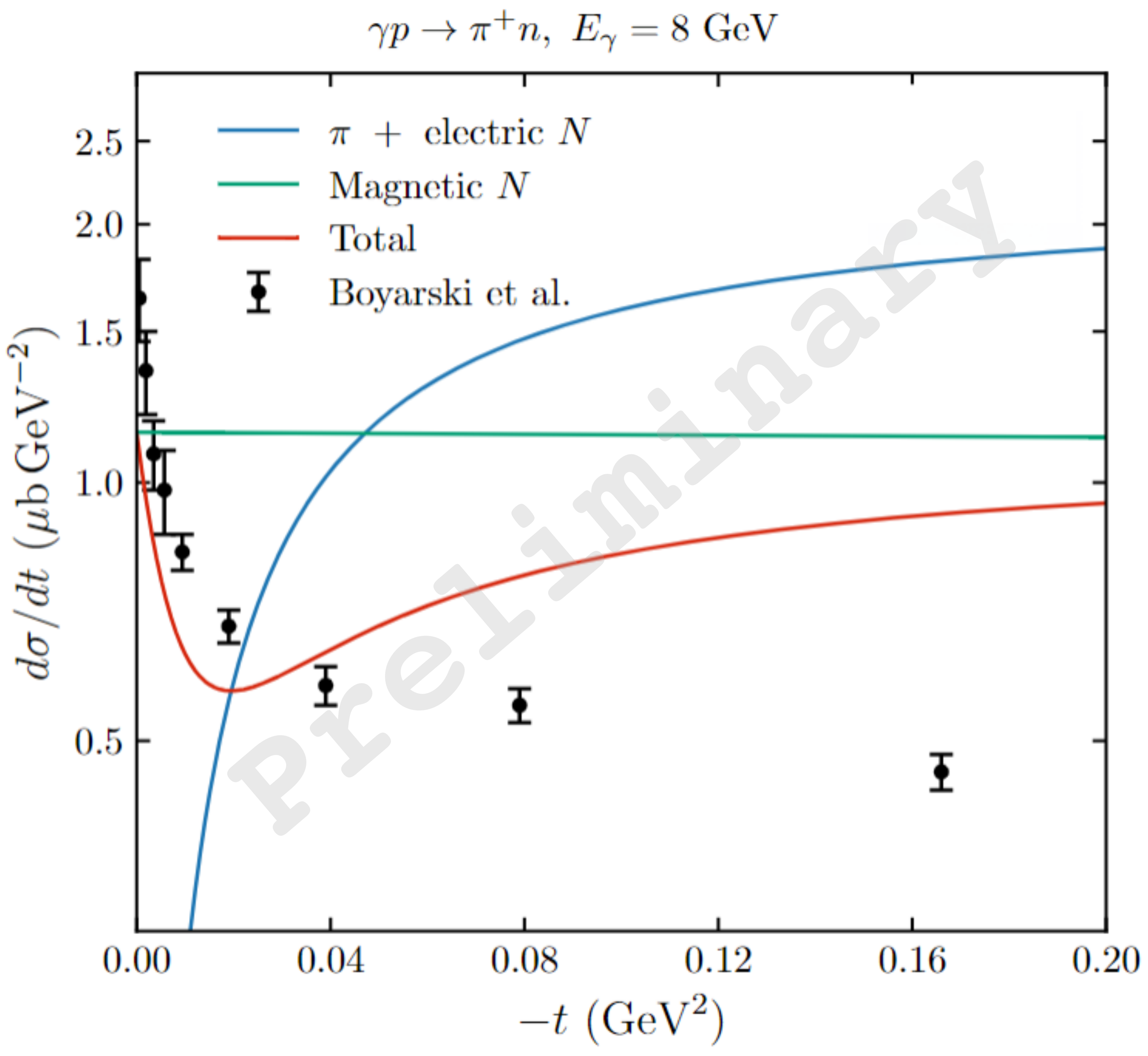
Issues:

- t-channel pion exchange is not gauge invariant
- Naively, this mixes t- and s-channel exchanges

Solution:

- Regge π exchange accounts for both t- and s-channel processes





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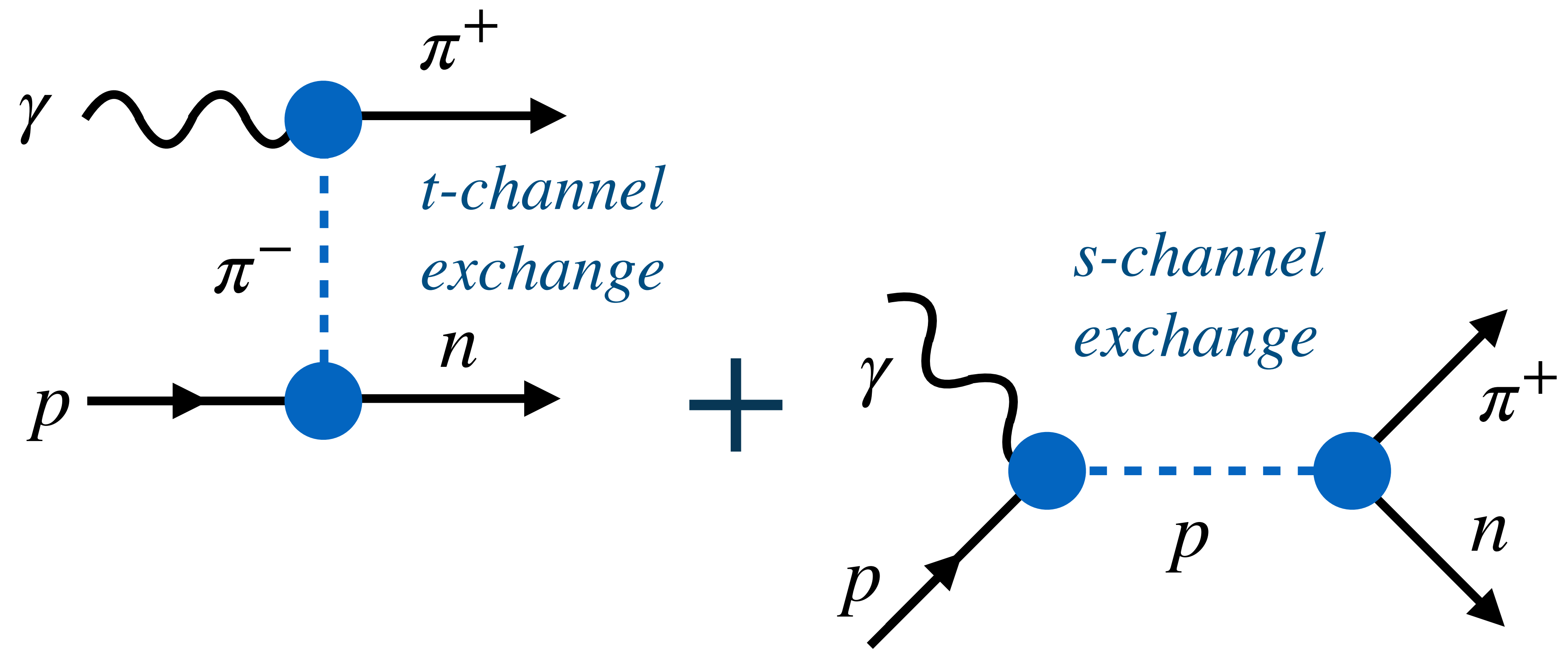

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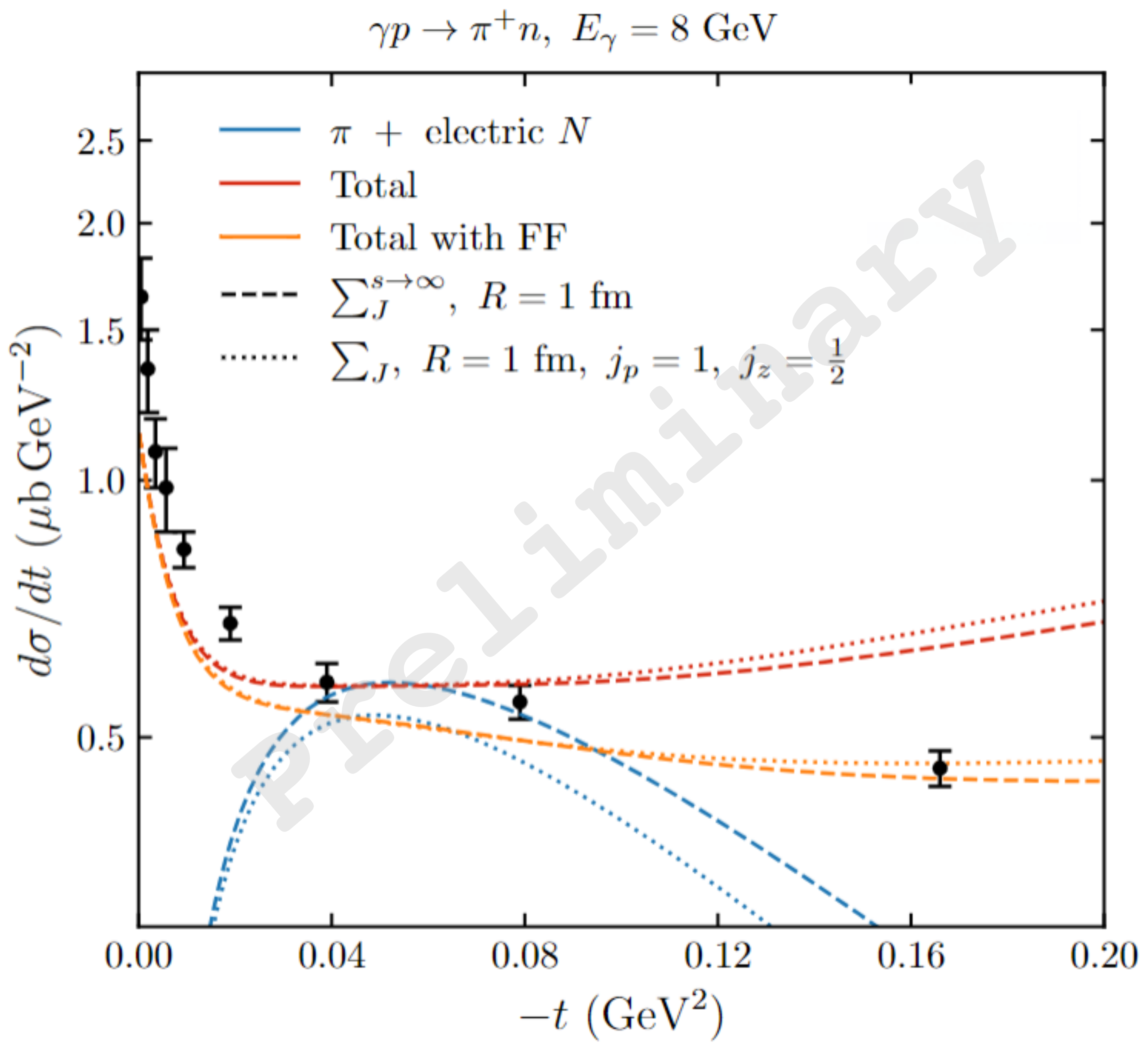
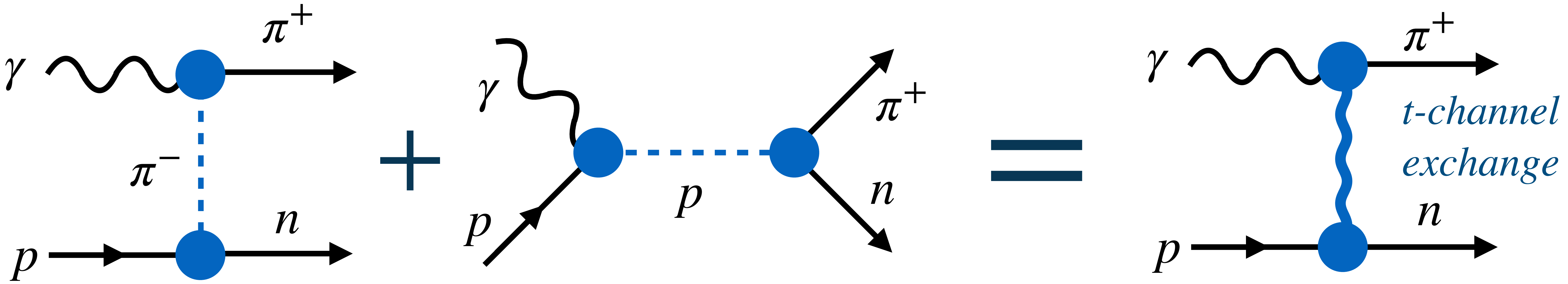
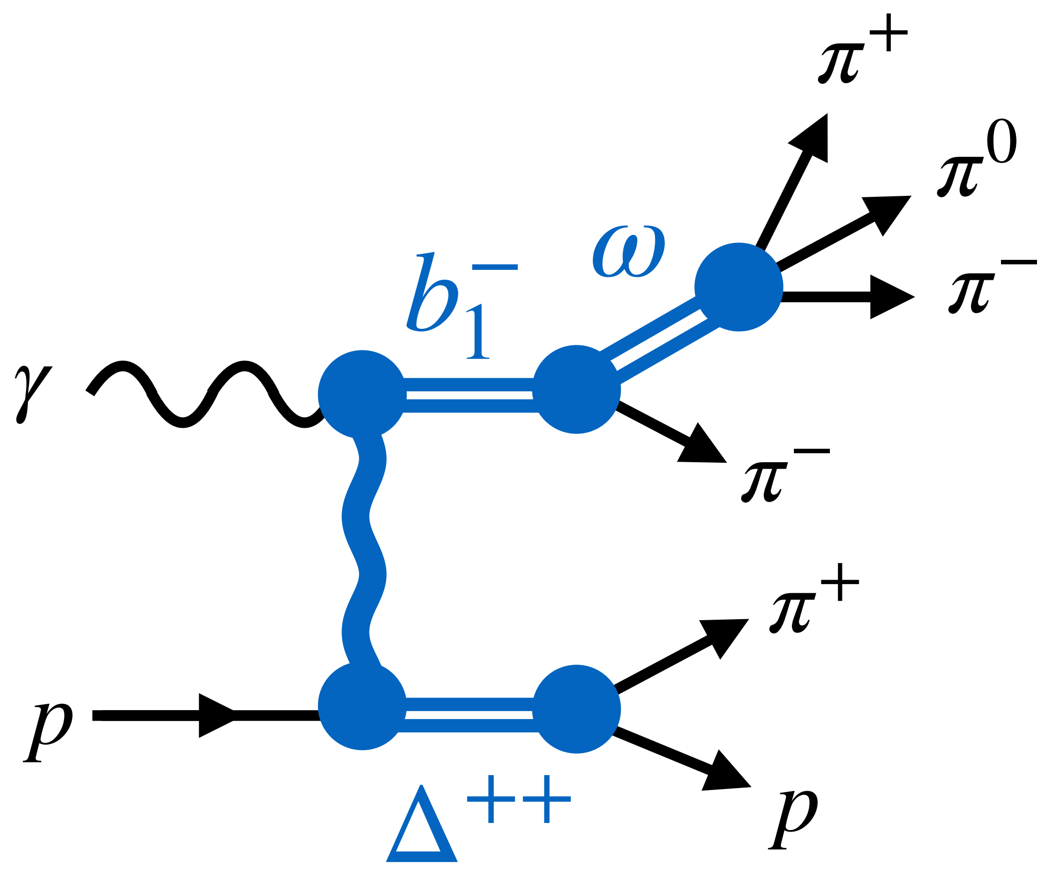




1- $b_1(1230)$ photoproduction

Main exotic decay is $\pi_1 \rightarrow b_1\pi$

Need first to understand b_1 photoproduction



$\gamma p \rightarrow b_1^- \Delta^{++}$

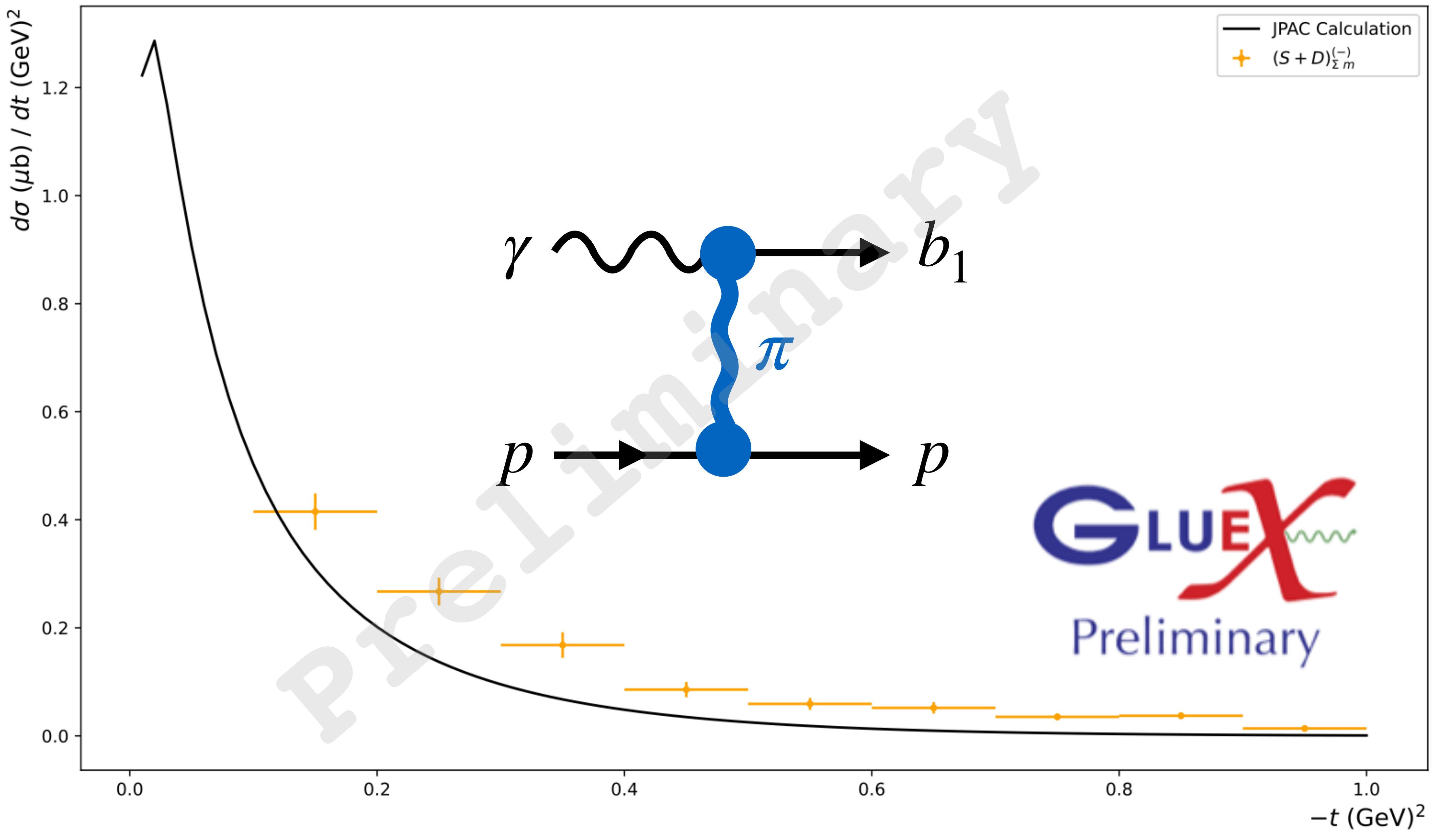
Also (right plot) $\gamma p \rightarrow b_1^0 p$

Model/Decay chain:

$$A_{\lambda_\gamma,\lambda_1,\lambda_2} = \sum_{\Lambda=-1}^{1} \sum_{\lambda_\Delta=-\frac{3}{2}}^{\frac{3}{2}} V_{\lambda_\gamma,\Lambda;\lambda_1,\lambda_\Delta}(s,t) \sum_{\lambda=-1}^{1} F_\lambda D^{J*}_{\Lambda,\lambda}(\Omega_\omega) Y^1_\lambda(\Omega_H) G \tilde{F}_{\lambda_2} D^{\frac{3}{2}*}_{\lambda_\Delta,\lambda_2}(\Omega_p)$$

Result1:

Pion exchange cross-section in agreement (prediction, not fit!) with preliminary data

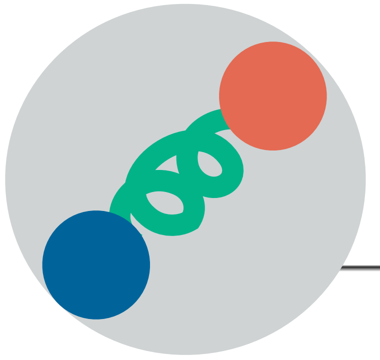


Result2:

Derivation of cross-section formula for AmpTools (GlueX) analysis software (Integration of theory input on AmpTools)

1- Hybrid: other decays

$\pi_1(1600)$



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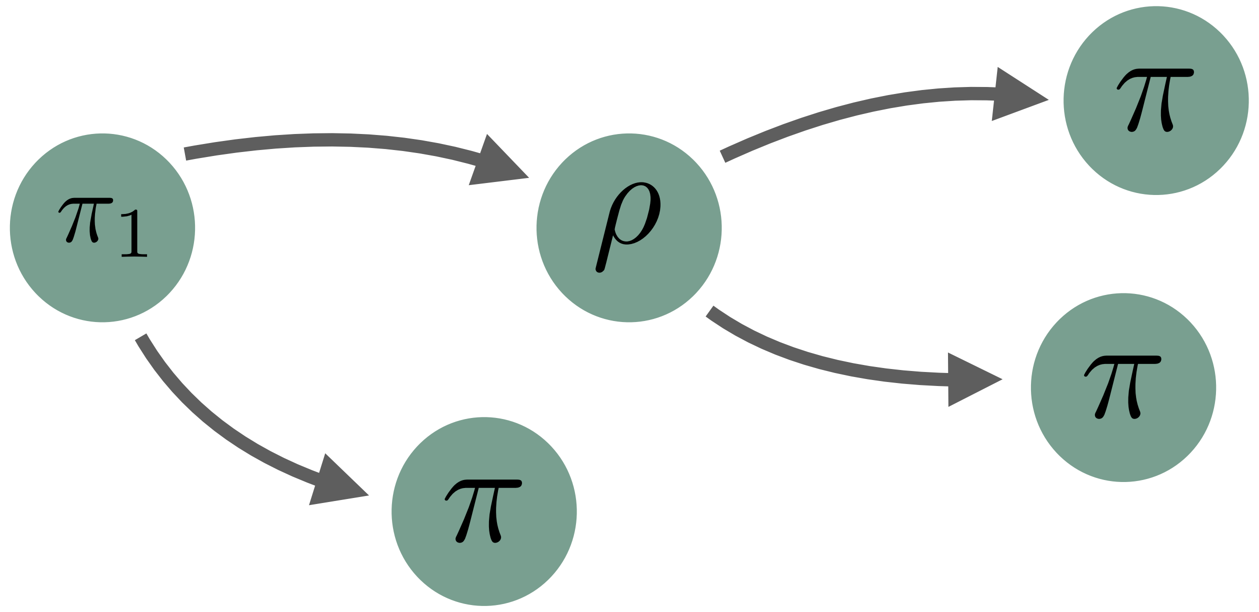
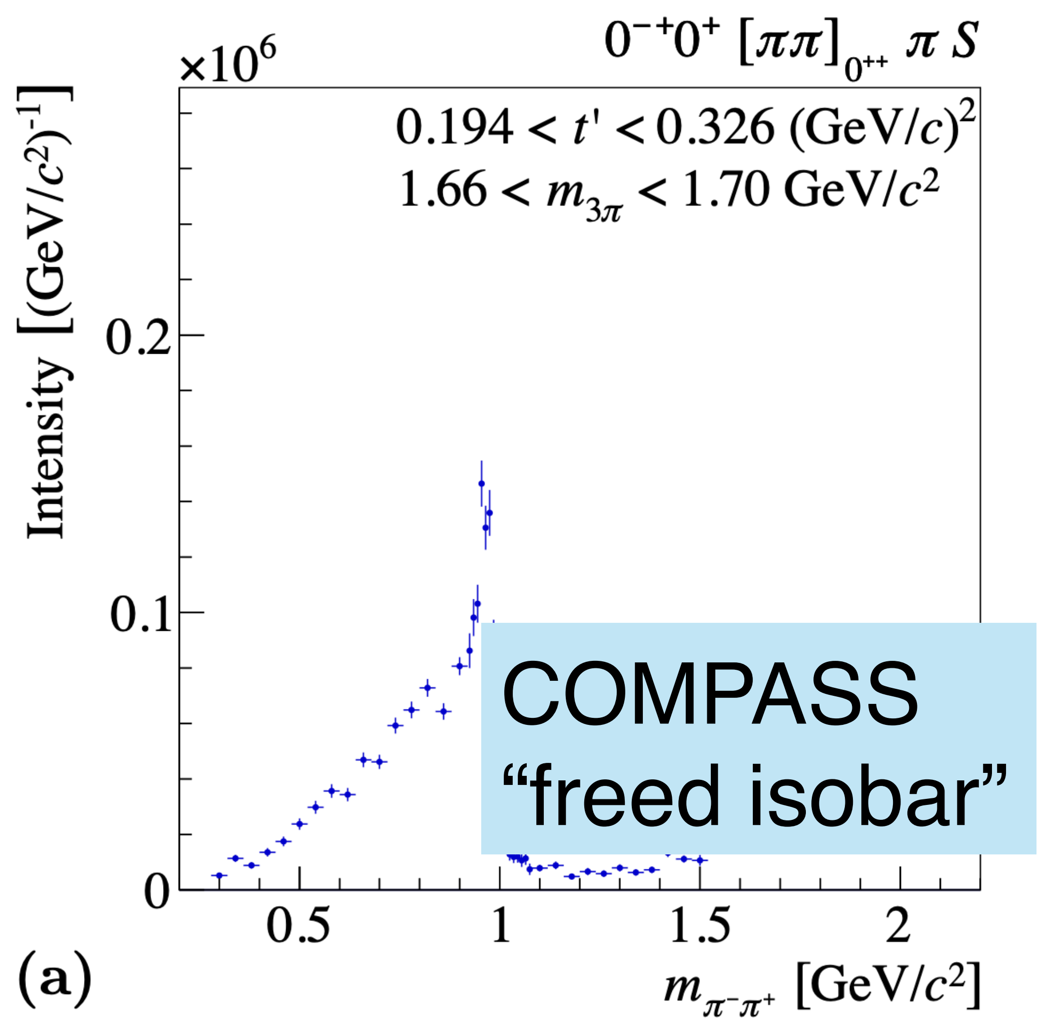
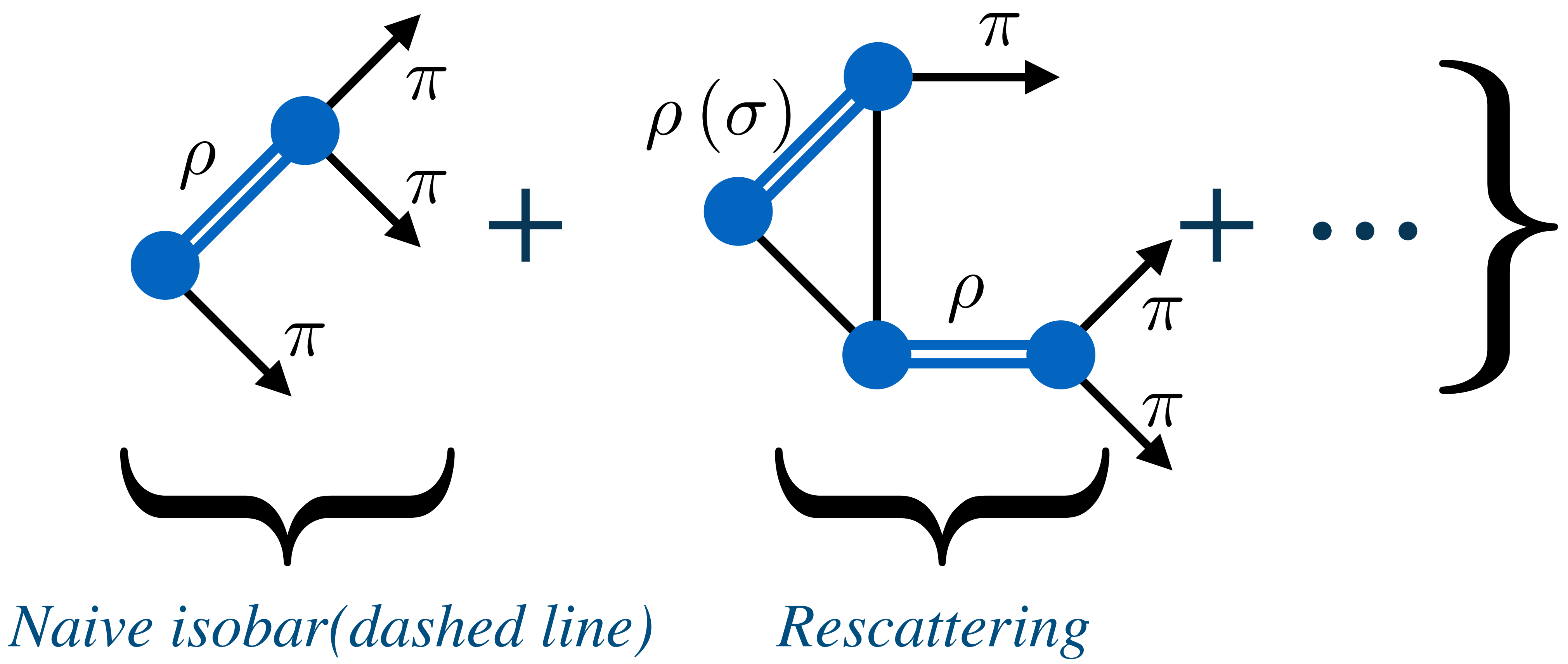


1- Rescattering effects in 3b decays (Milestone 26)

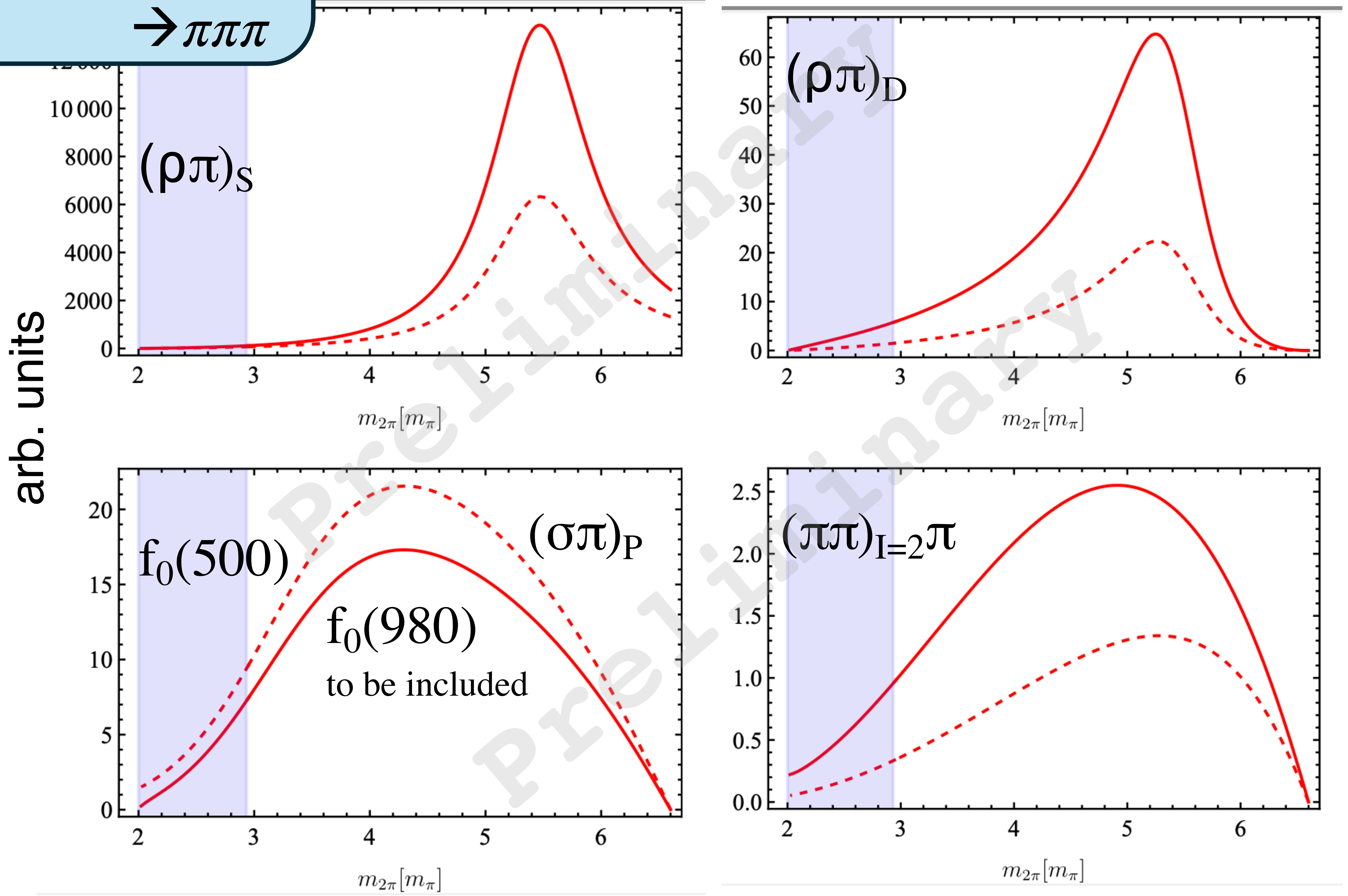
Determination of resonances with 3-body decays depends on “lineshape” of two-body subsystems

In experiments, intermediate resonance estates are simplified as “freed isobars”, simple phenomenological descriptions fitted to data





$I^G(J^{PC}) = 1^-(1^{++})$
→ $(\rho\pi)_S$, $(\rho\pi)_D$, $(\sigma\pi)_P$, $(\pi\pi)_{I=2}\pi$,…
→ $\pi\pi\pi$



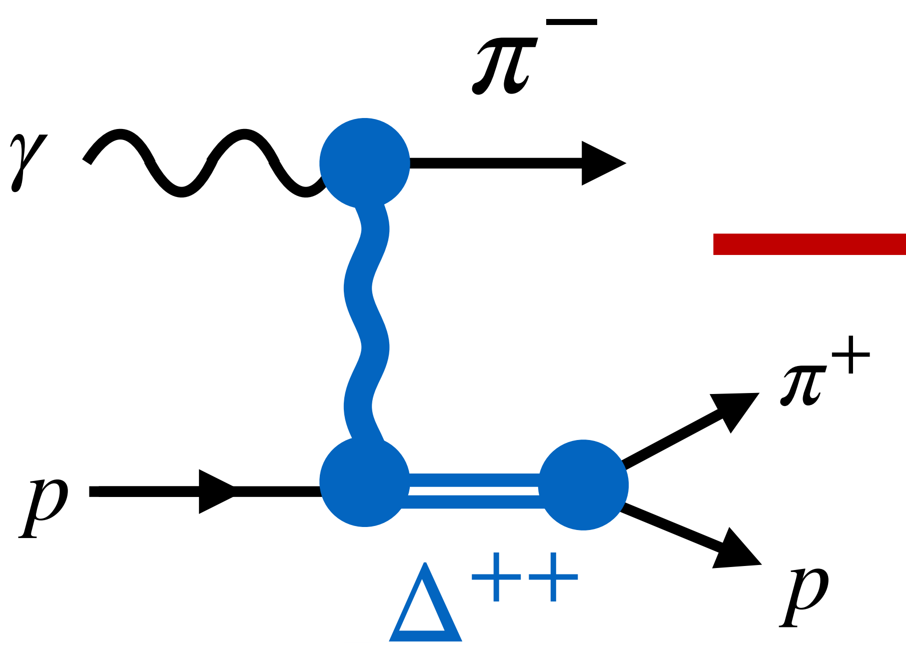
Unitarity provides constraints on coupled-channel 3-body rescattering that add to full “isobars”, modifying the lineshapes beyond a constant multiplicative factor

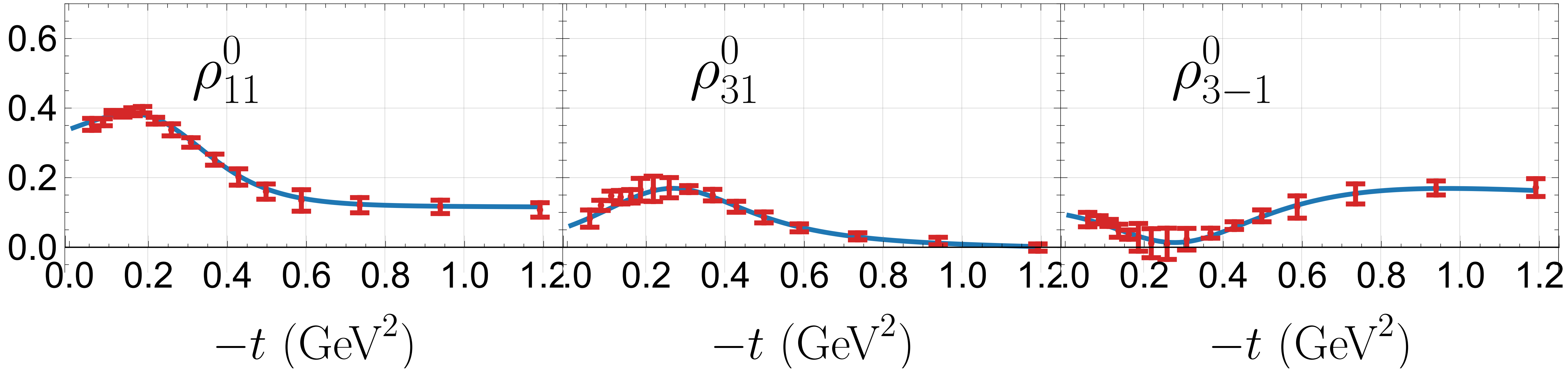
Final goal:

- How does coupled-channel rescattering compare to “freed isobars”

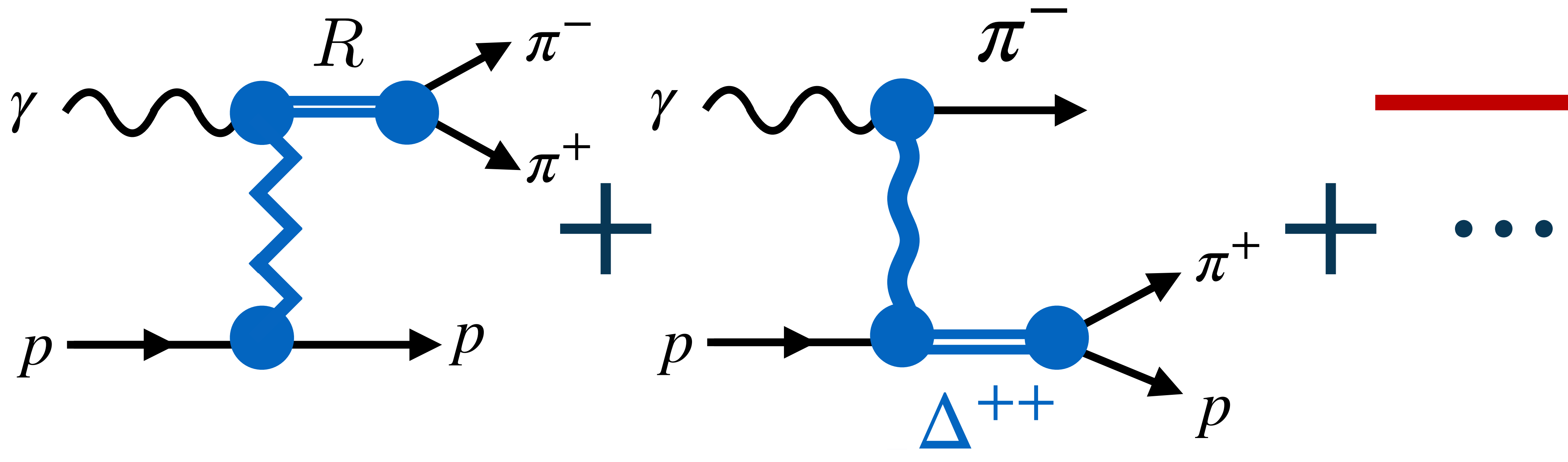
1- Towards complete understanding of photoproduction reactions

Understanding Δ^{++} production is underway (Milestone 2)





Two-pion photo production project almost completed (impressive data agreement)



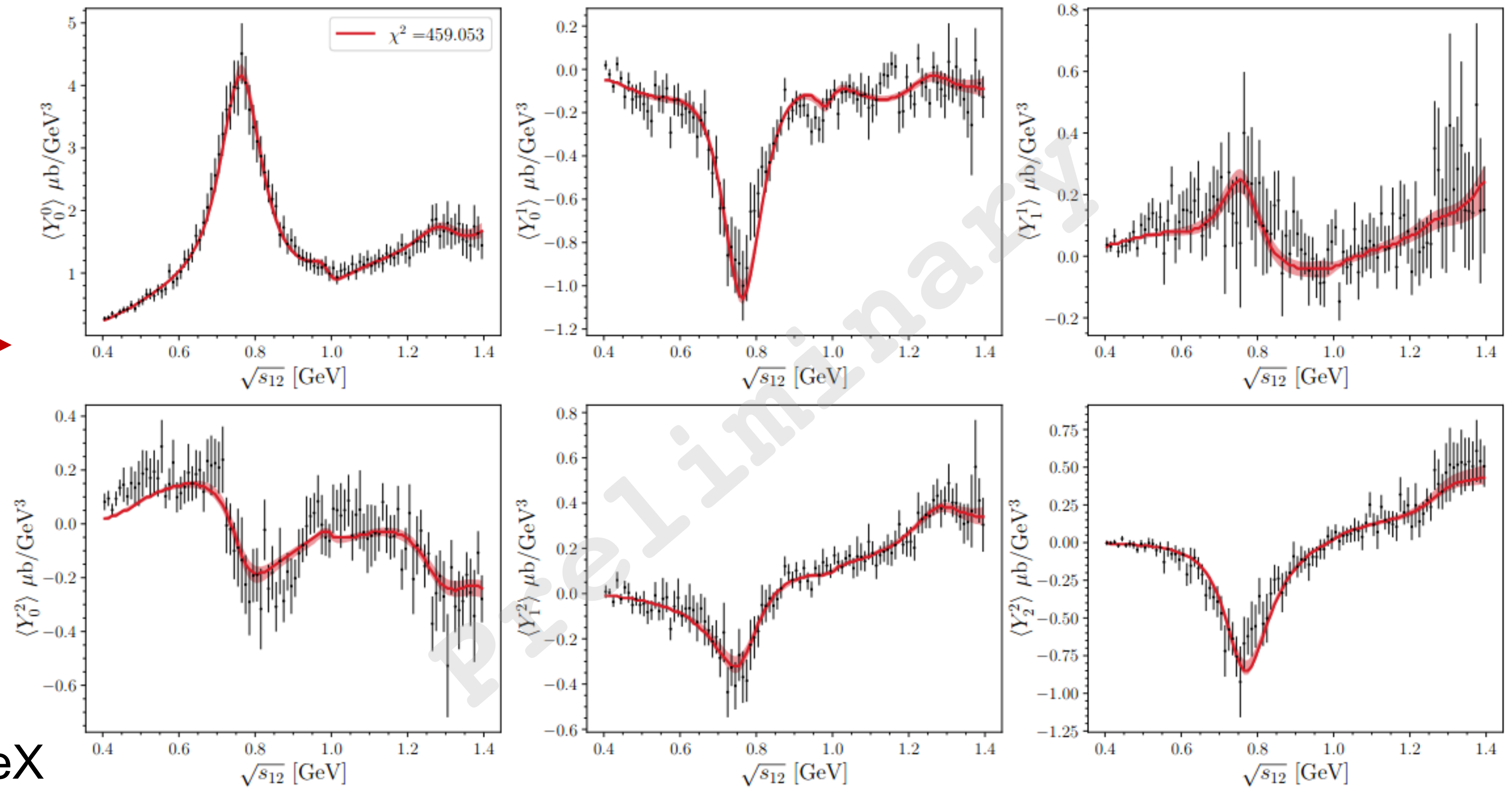
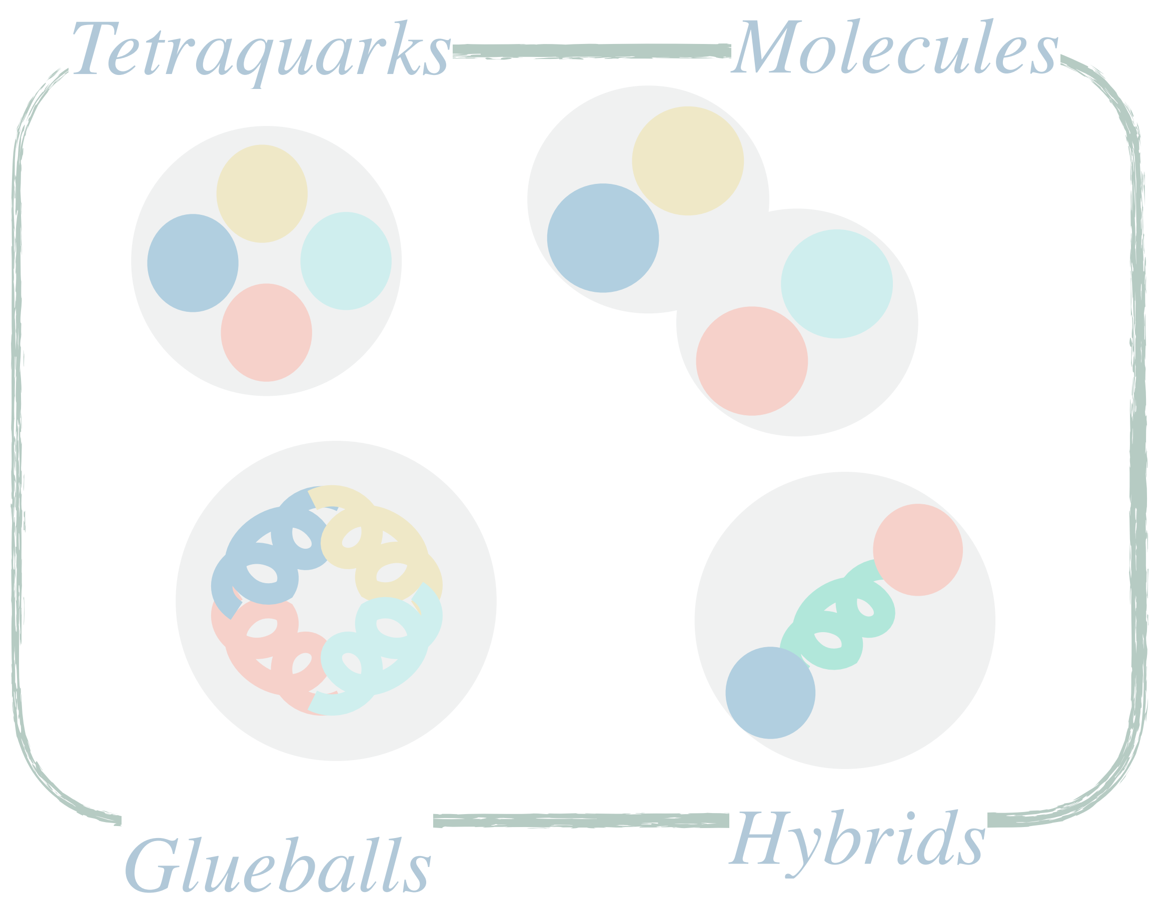


FIG. 6. Fitted angular moments $\langle Y_L^M \rangle$ for $L = 0, 1, 2$ and $M = 0, \ldots L$ for $E_\gamma = 3.7$ GeV and $t = -0.95$ GeV^2.

High quality data from CLAS, more expected from CLAS12 and GlueX

Amplitude analyses at ExoHad

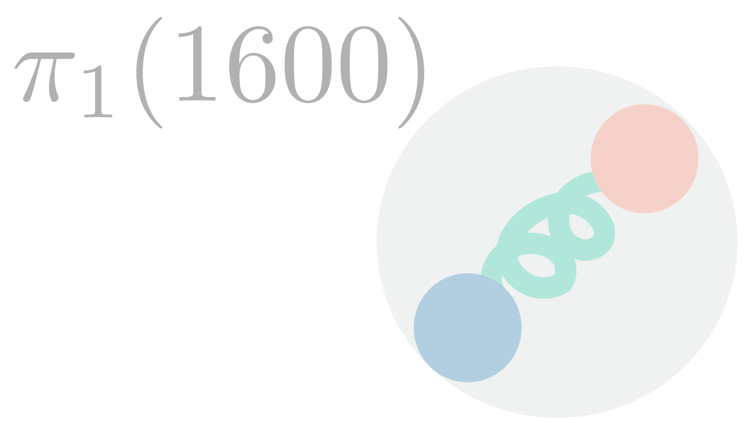


1- Ensure the success of JLab experimental efforts on the search for exotic hybrid candidates

Provide experimental groups with required theoretical inputs

Combine experimental, Lattice QCD, and model predictions needed to establish the existence of the hybrids

Develop reaction amplitudes to describe production and decays of hybrids



2- Develop a spectroscopy program for exotics, at future facilities (EIC/JLab 22)

Based on recent ExoHad work, establish optimal experimental configurations (final states, cross-sections, etc…)

Capitalize on this exciting opportunity to build an spectroscopy community

2- Exotics at future facilities: J/ψ photoproduction at GlueX (Milestone 8)

Need to assess the impact of existing models in this sector

Main goal:

Determine if data is described by smooth (non-resonant) models or by the existence of intermediate states → pentaquarks

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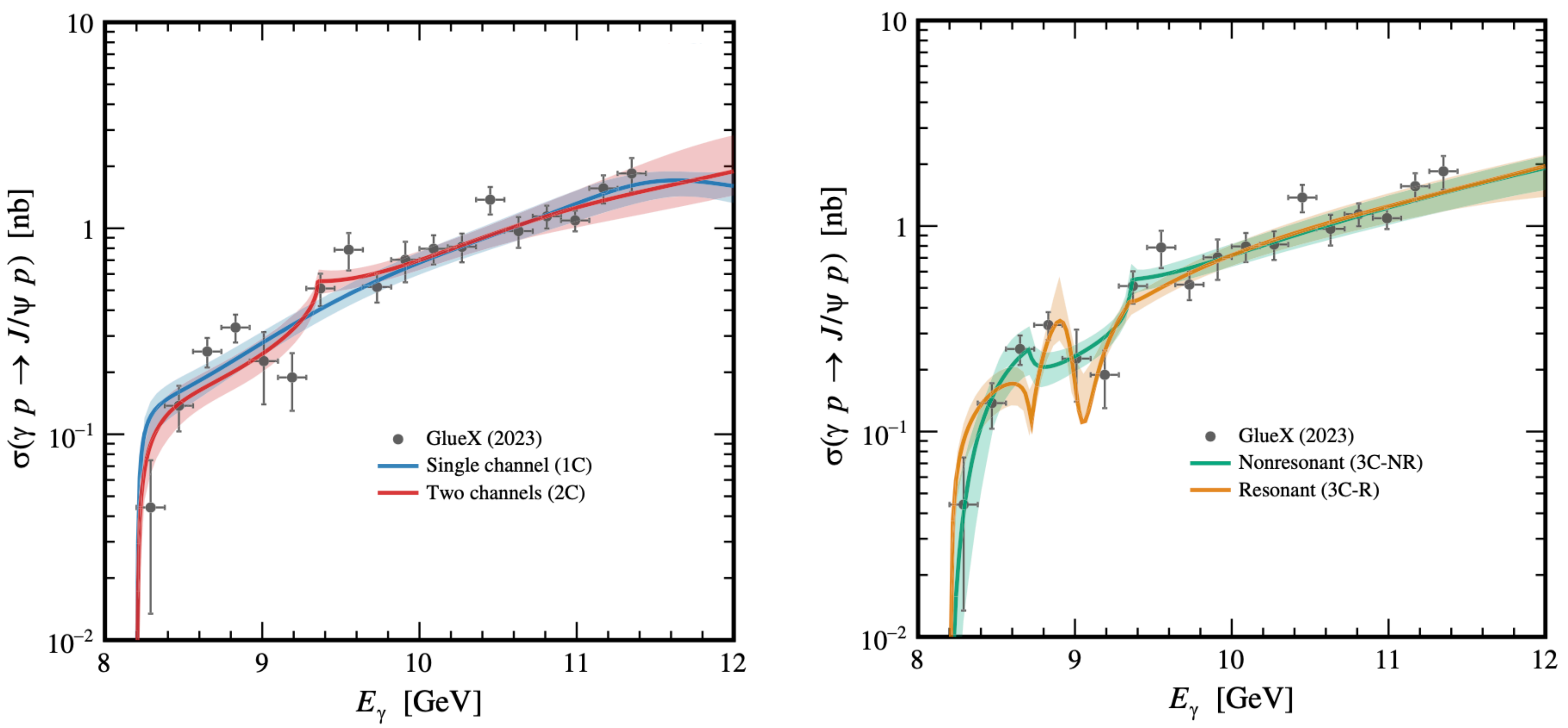
Current results are not conclusive

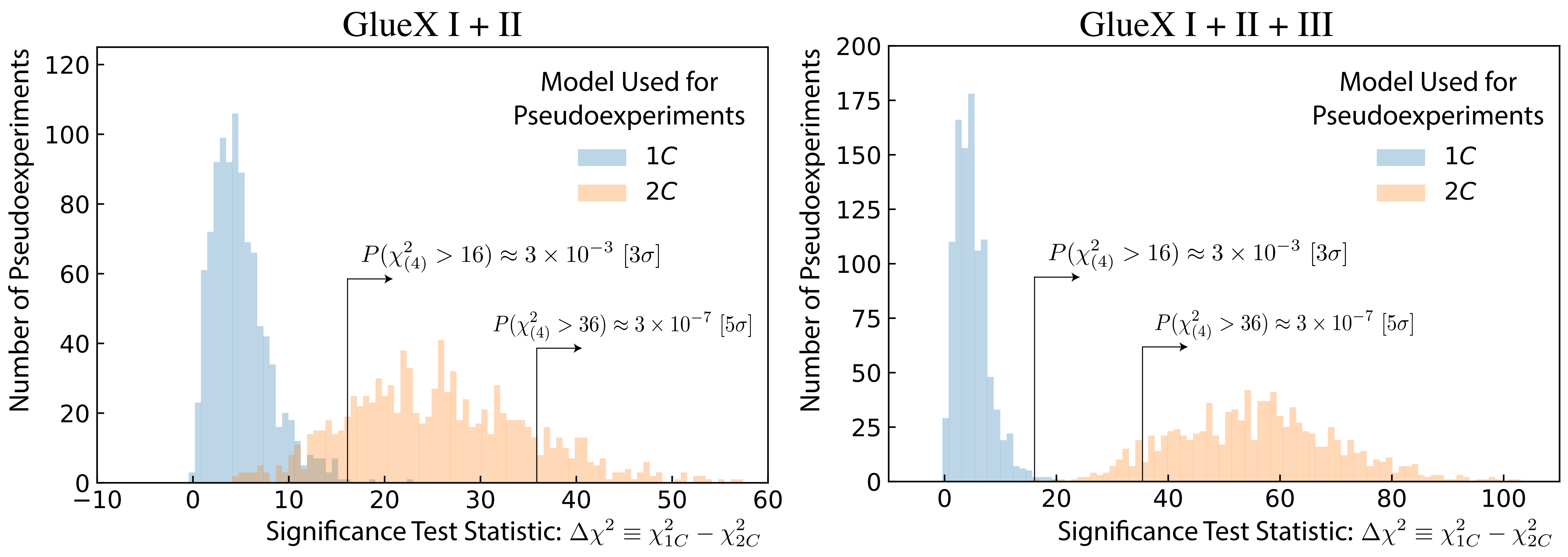
Future work:

GlueX II+III runs would produce conclusive results (GlueX III proposal for PAC2024, right plot)

Combined analysis of J/ψ-007 and GlueX I



GlueX I+II vs. GlueX I+II+III discrimination power



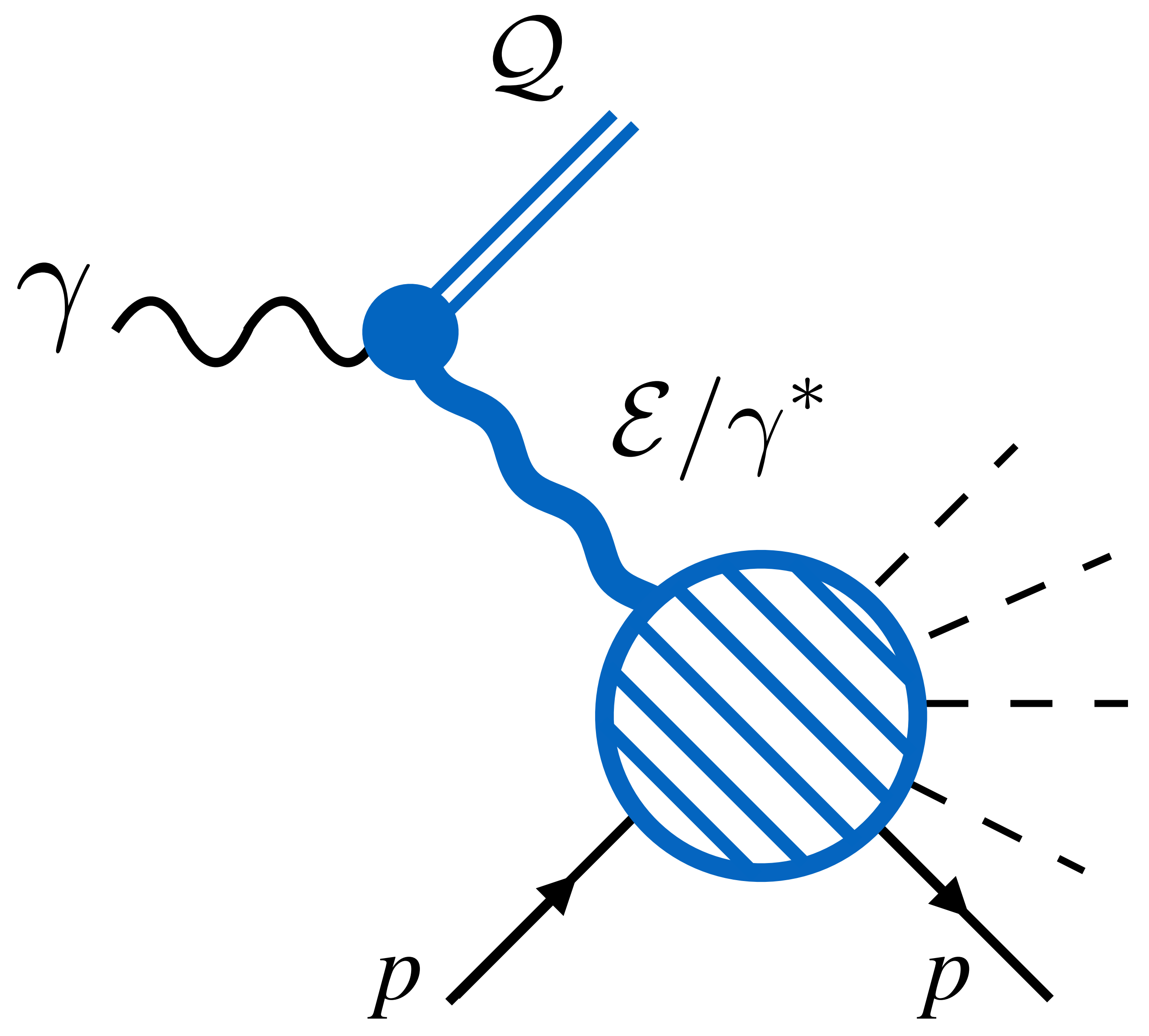
2-XYZ searches in future facilities: Photoproduction

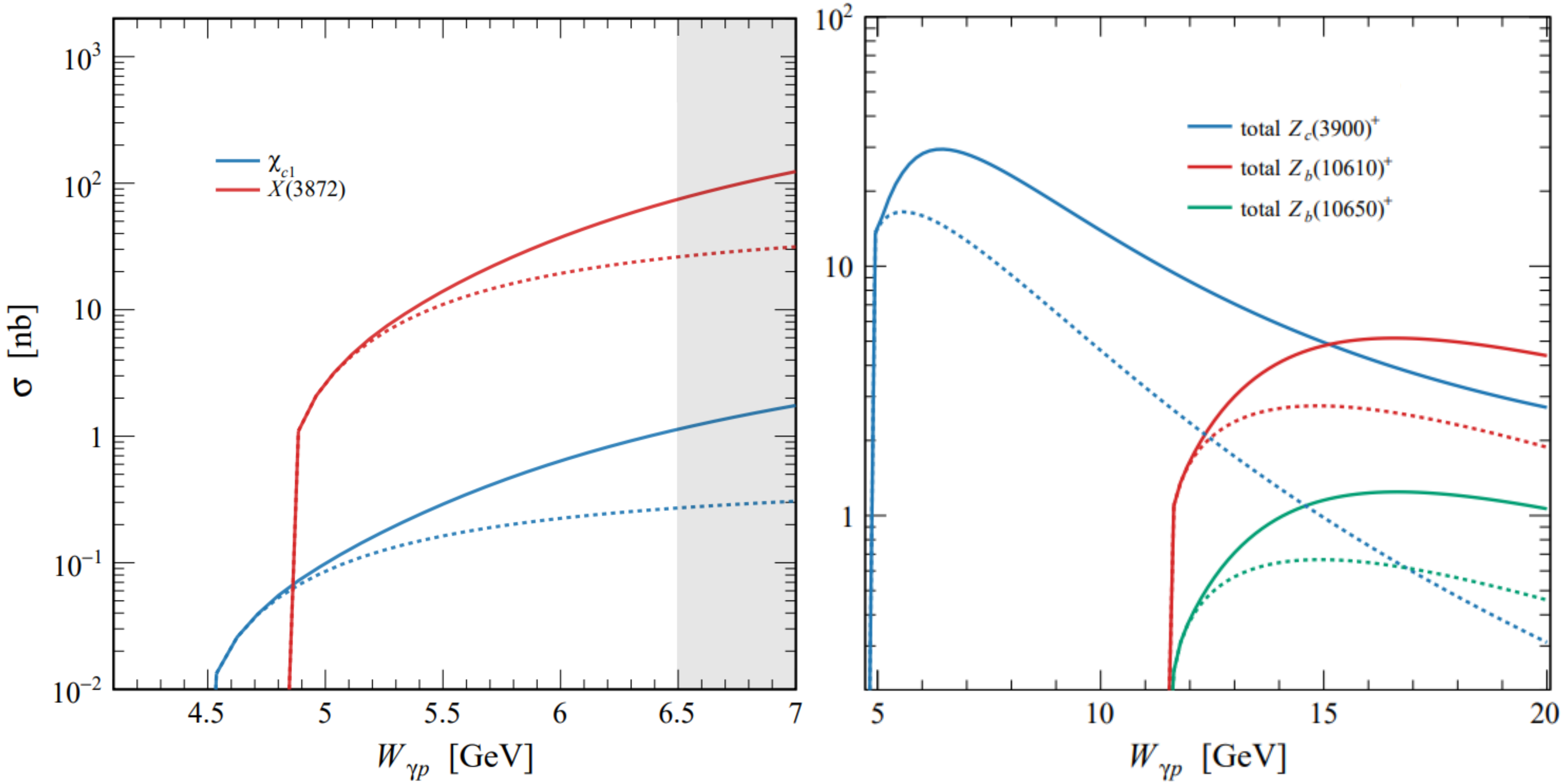
Semi-inclusive processes have more backgrounds than exclusive ones, but higher cross sections! Ideal for the first observation

Predictions are based on one-particle exchange mechanisms and are likely a conservative underestimation of total production rates

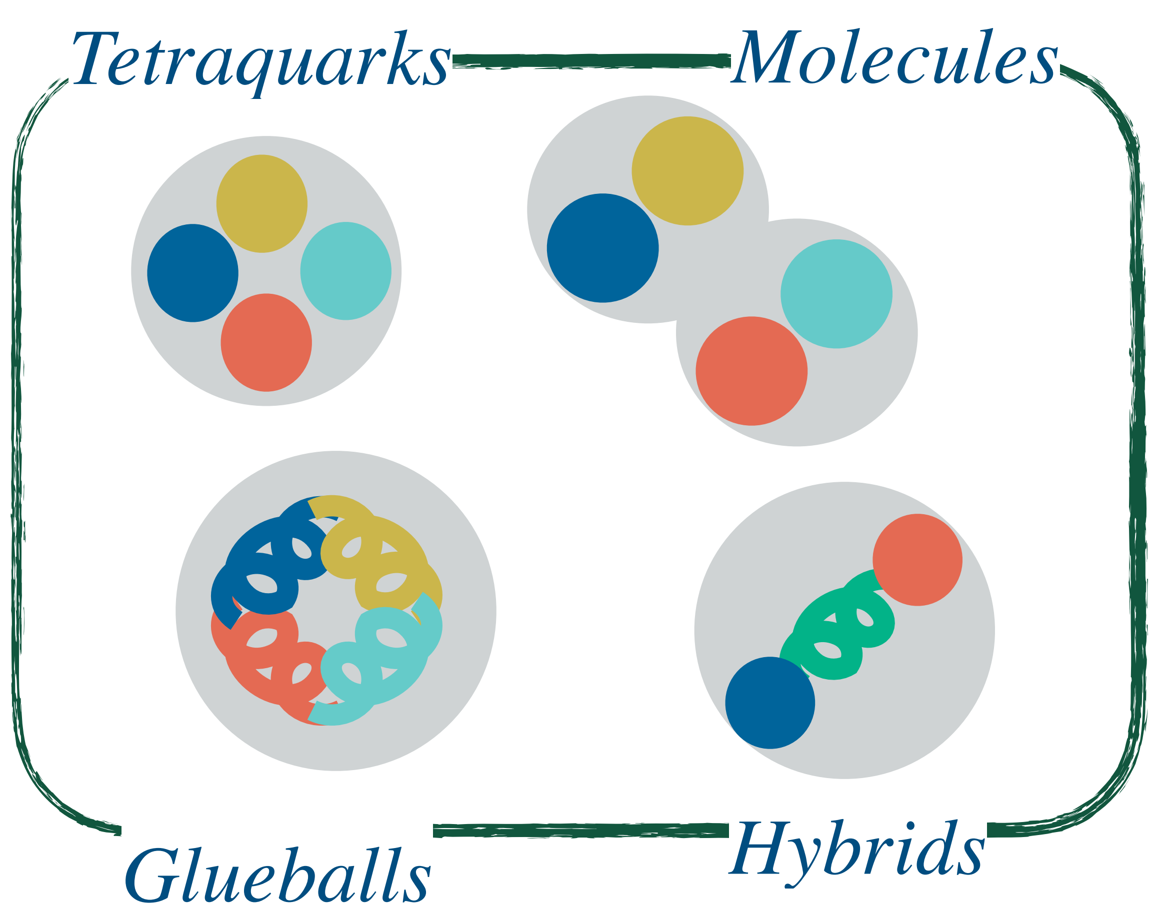
These predictions suggest that the extraction of exotics at JLab 22 is a possibility
(XZ searches might be better at JLab 22, Y searches better at EIC)

Phys. Rev. D 106 (2022) 09, 094009
arXiv:2404.05326





Amplitude analyses at ExoHad: Summary



1- Ensure the success of JLab experimental efforts on the search for exotic hybrid candidates

Partial wave extraction issues/ambiguities have been addressed

- [x] *Milestone 1: Phys.Rev.D 108 (2023) 076001*

Models for $\pi/\Delta^{++}/b_1/\pi\pi$ production are getting closer to completion

- [x] *Milestone 2*

Double Regge underway, COMPASS analysis moving in the right direction

- [x] *Milestones 10, 11*

Quasi-3b amplitudes for $\pi_1 \to b_1\pi$ have been developed. We provided them to GlueX and we are starting to analyze them further

- [ ] *Milestone 9 (evolved to better align with GlueX priorities)*

2- Develop a spectroscopy program for exotics, at future facilities (EIC/JLab 22)

J/psi photoproduction studies hint that older predictions for pentaquark searches need not be correct

- [x] *Milestone 8: Phys.Rev.D 108 (2023) 054018*

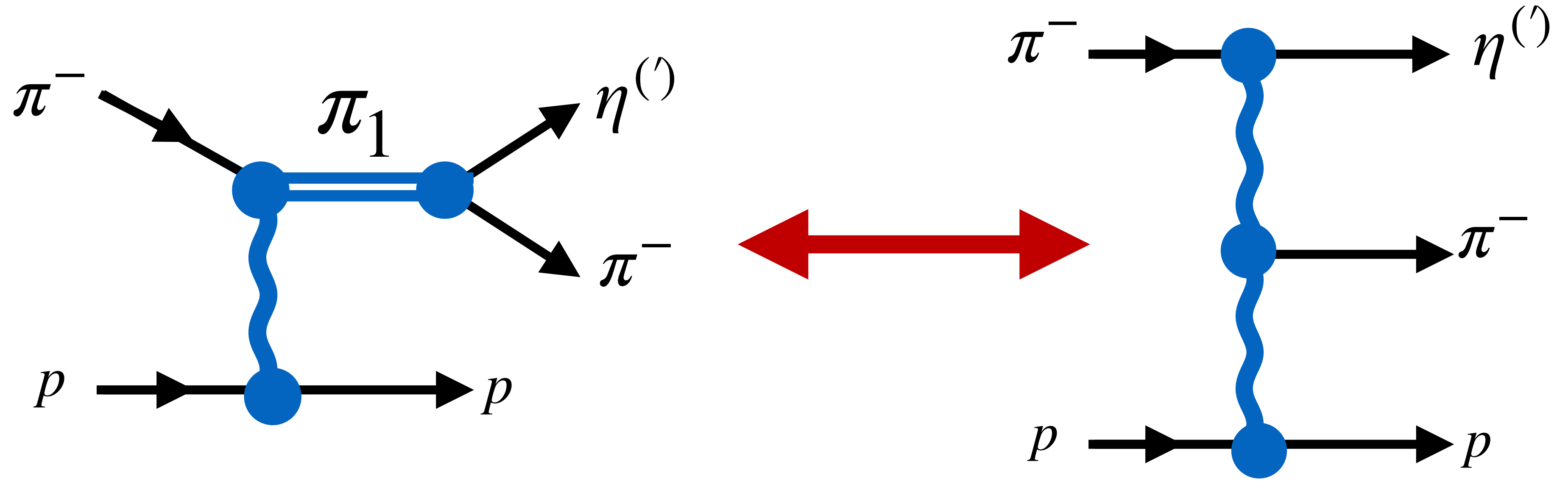
Studies of XYZ states at future facilities are feasible

- [x] *Milestone 8: arXiv:2404.05326*

Backup slides!!

1- Double Regge contributions (COMPASS) (Milestone 10)

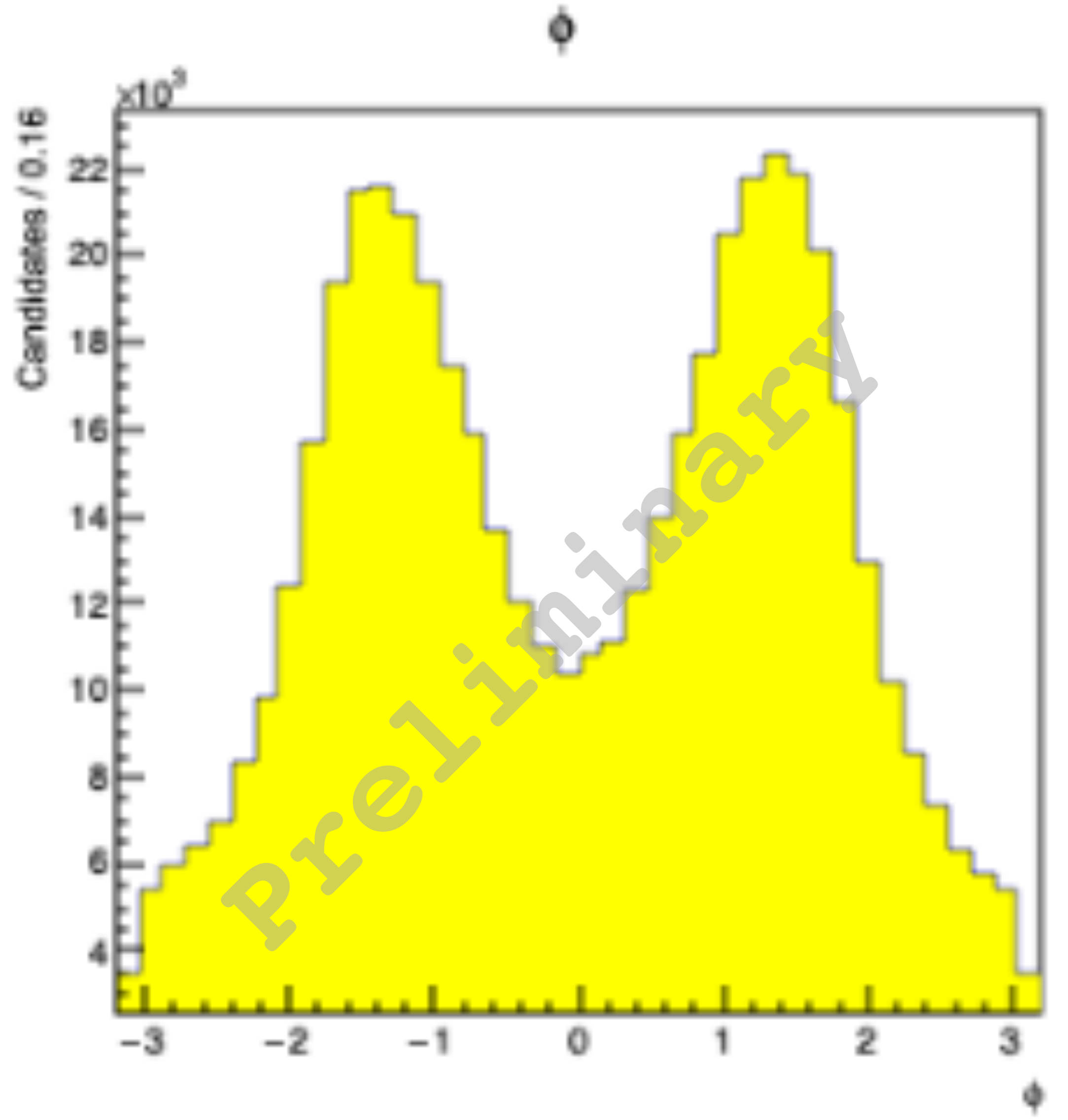
Reconstructing from final states in experiments is not easy. Other processes (right) produce the same final states as our direct π_1 production (left)



Original model described in

Shimada, Martin, Irving, NPB 142, 344 (1978)

JPAC, EPJC 81 (2021)



Issues:

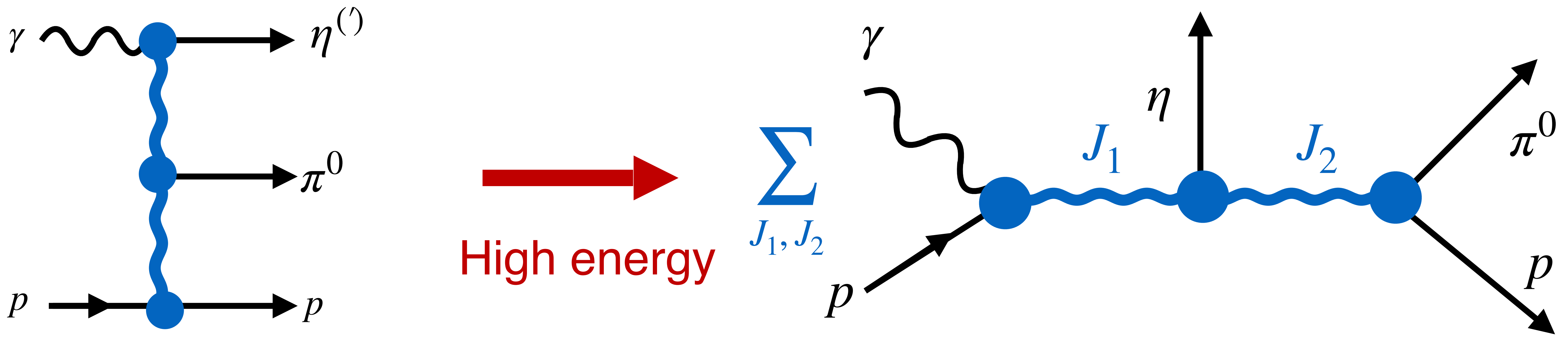
The original model (right) is too restrictive/rigid, not fully consistent with Regge physics (Talk about their pathologies)

Solution:

Working together with COMPASS and GlueX to find a Regge-inspired phenomenological parametrization that describes data at high energy in all kinematic variables

1- Double Regge contributions (Milestone 11)

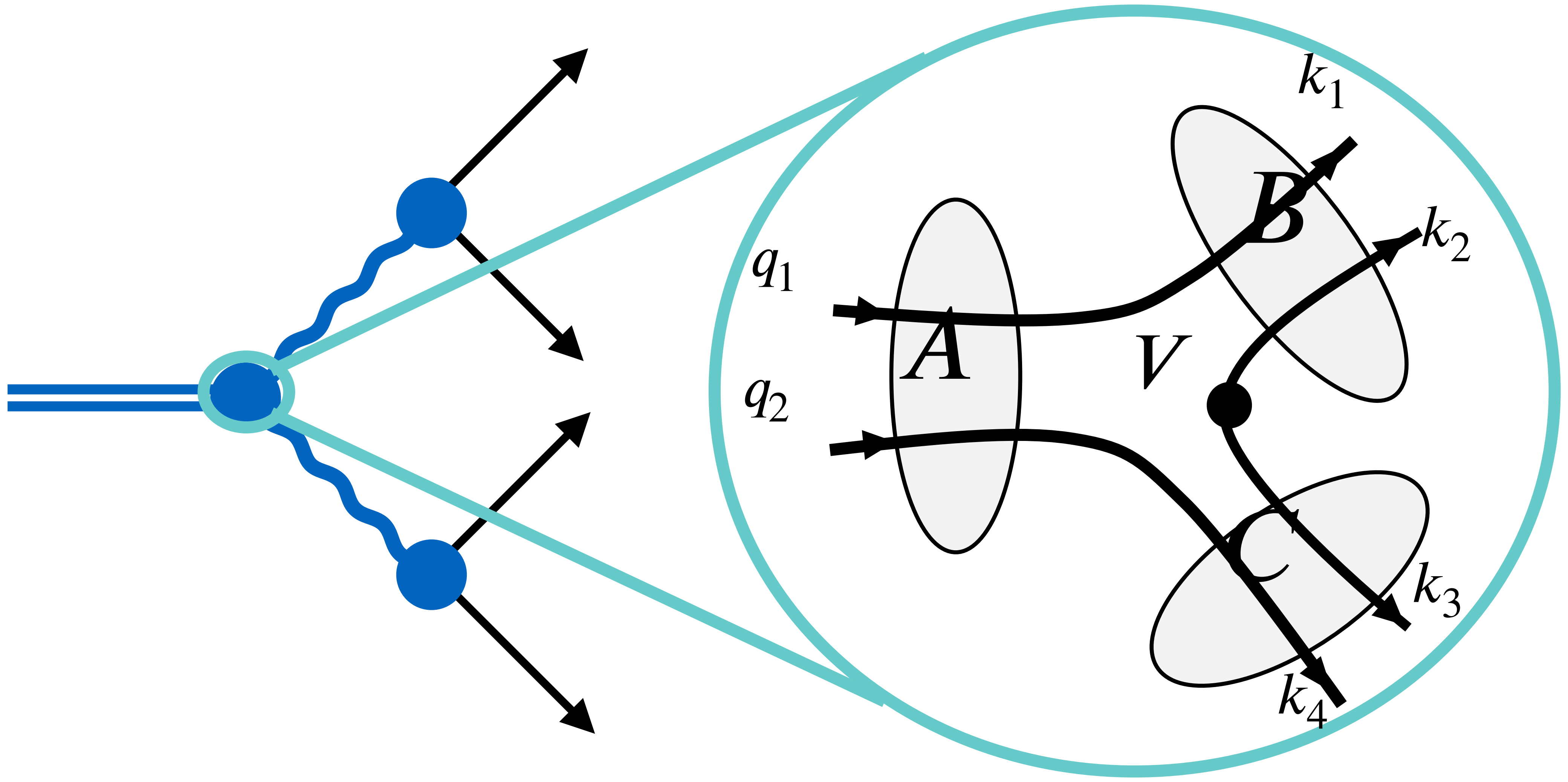
These double Regge exchanges can be described in different energy regimes. They all must be consistent with one another



$$\sim V_1(-s)^{\alpha_1}(-s_2)^{\alpha_2-\alpha_1} + V_2(-s)^{\alpha_2}(-s_1)^{\alpha_1-\alpha_2}$$

We understand these processes in the High energy limit (right). The problem is making the diagrams above consistent with one another.

Quark string-breaking models allow for analytic calculation of helicity dependence, giving us insight into these Regge couplings



$$\left\langle \psi_B, \psi_C \middle| V \middle| \psi_A \right\rangle = \int d^3k \; V \psi_A\left(\vec{k}\right)\psi_B^*\left(\vec{k} + \vec{P}_c\right)\psi_C^*(\vec{k} + \vec{P}_C)$$

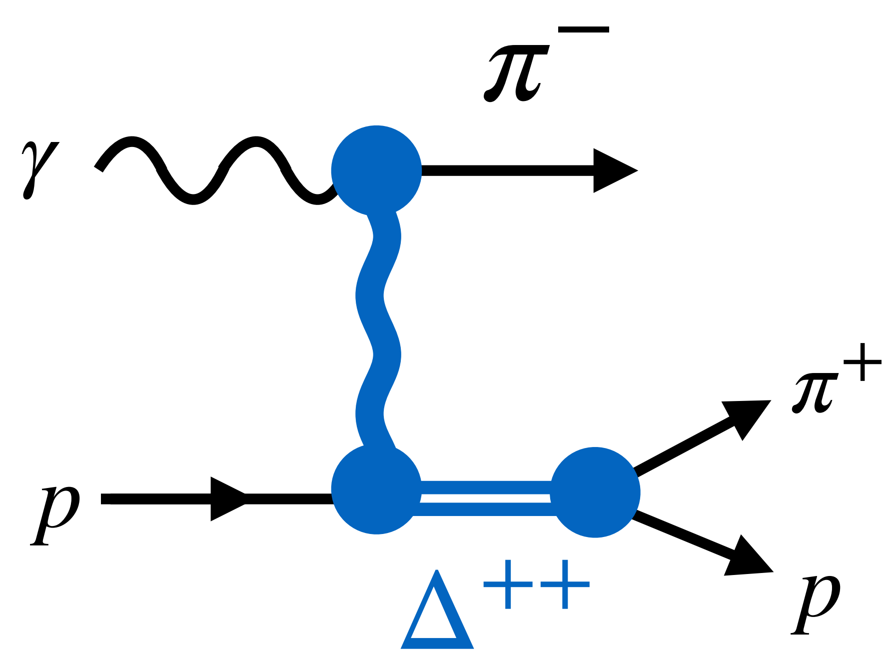
High energy

These couplings could also be extracted from lattice QCD (ExoHad)

Physical, explicitly helicity-dependent couplings valid in double Regge-region!

1- Delta production (Milestone 2)

First starting process:



Issues:

- Our previous base model reproduces the cross-section but not the spin density matrix elements SDMEs accurately

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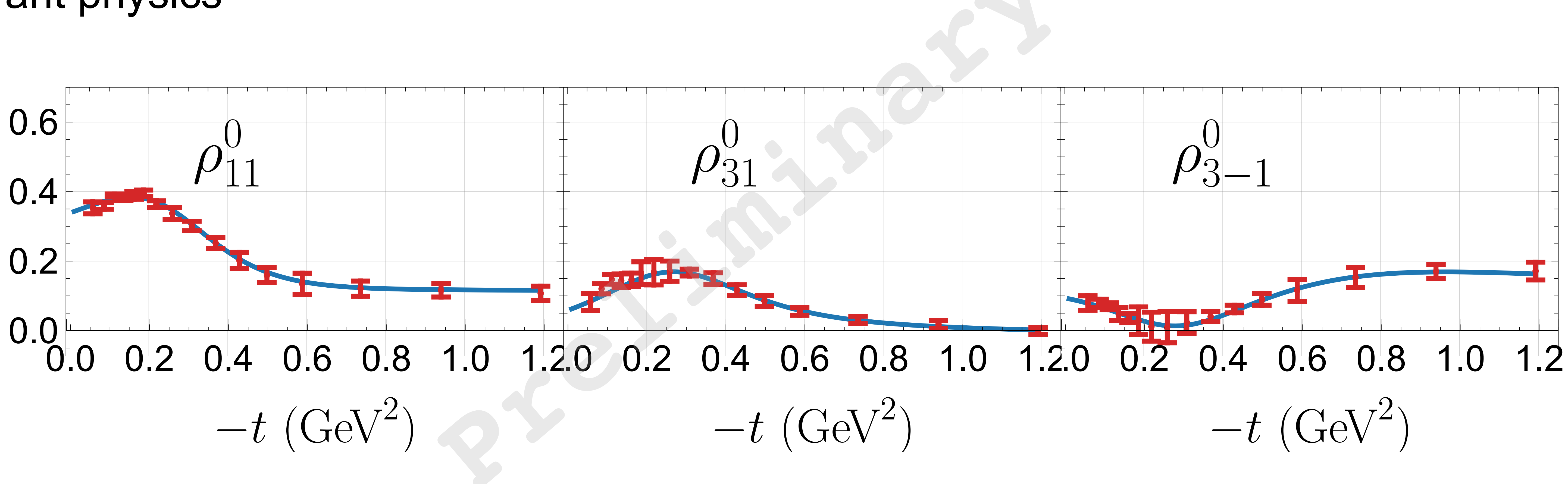
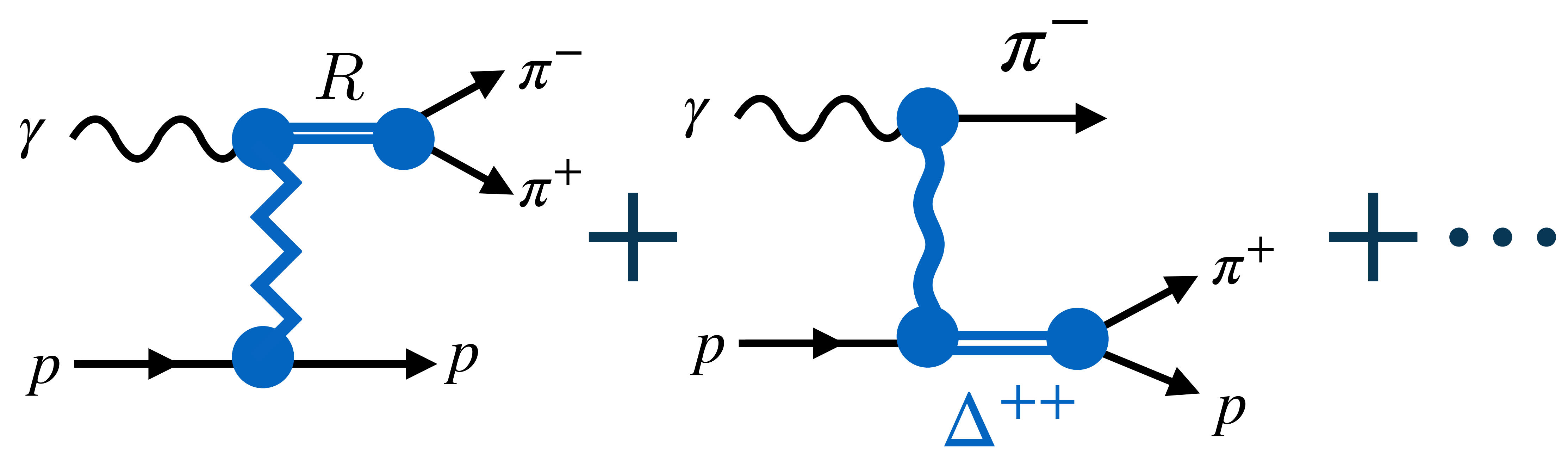
Solution:

- A richer structure is required by the data (fitted below), we are working on identifying the relevant physics



1- Two-pion photoproduction *To appear soon…*



High quality data from CLAS, more expected from CLAS12 and GlueX

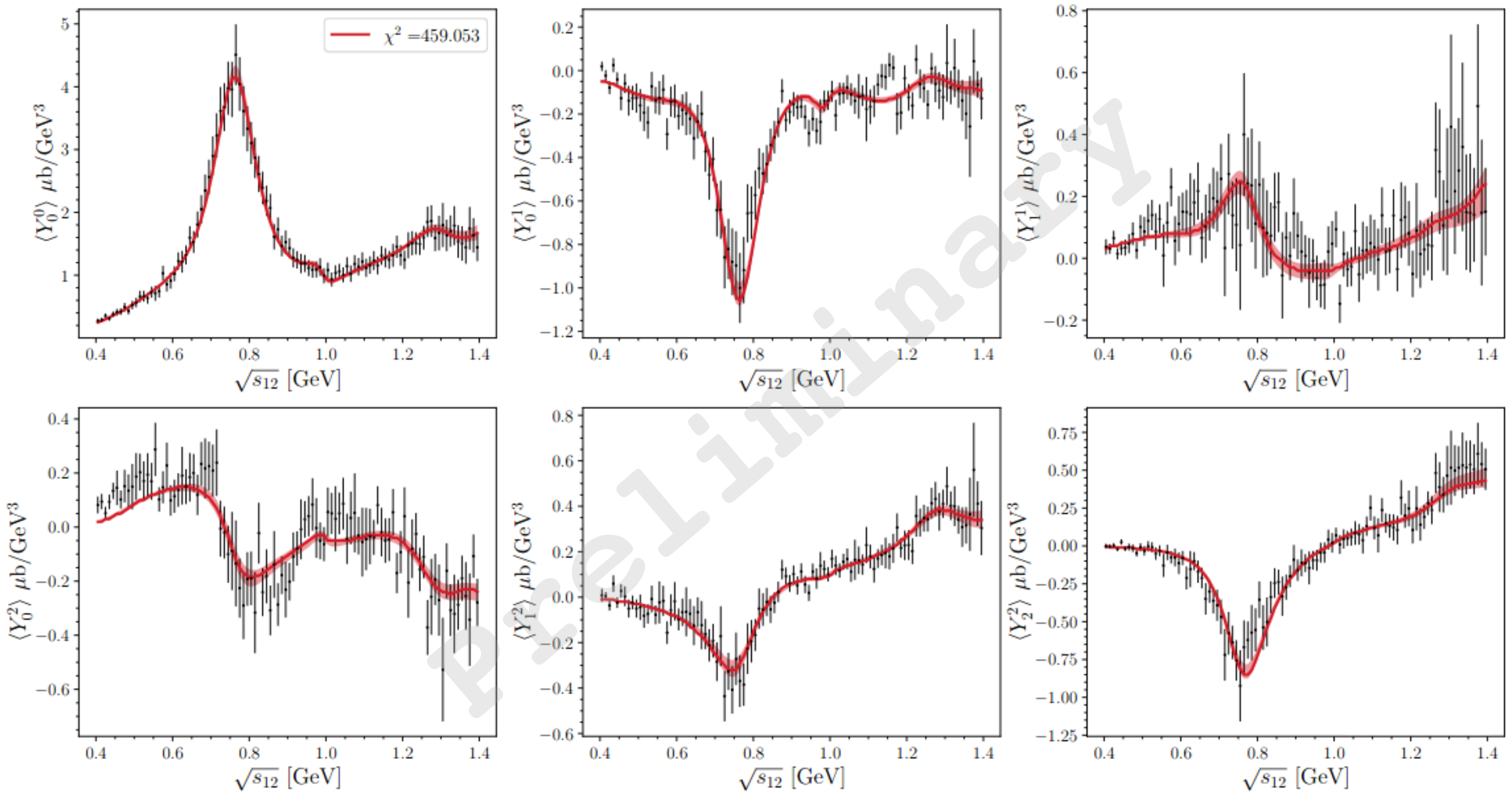
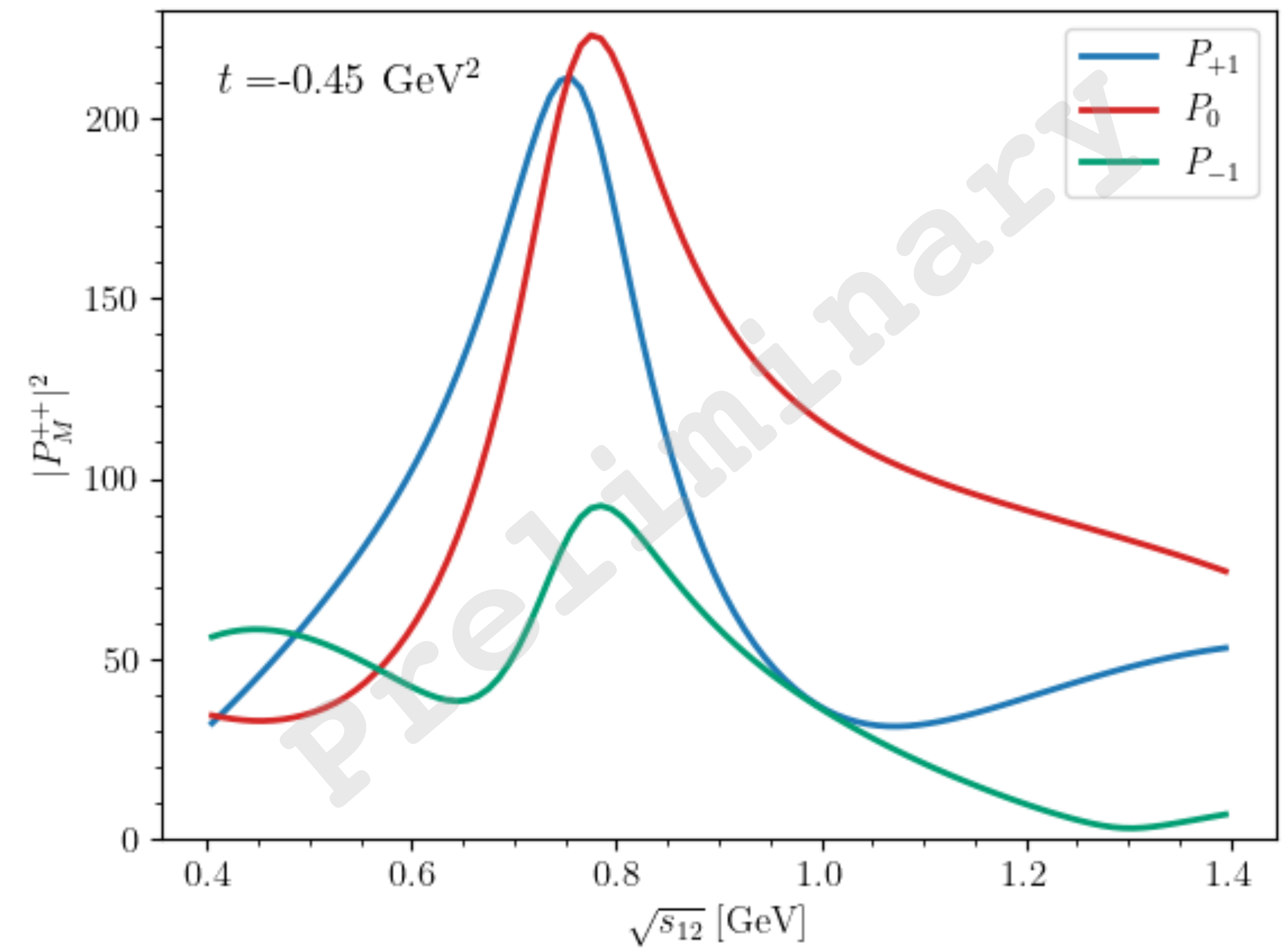


FIG. 6. Fitted angular moments $\langle Y_L^M \rangle$ for $L = 0, 1, 2$ and $M = 0, \ldots L$ for $E_\gamma = 3.7$ GeV and $t = -0.95$ GeV^2.

$$\langle Y_M^L \rangle = \sqrt{4\pi} \int d\Omega^{\mathrm{H}} \frac{d\sigma}{dt dm_{12} d\Omega^{\mathrm{H}}} \mathrm{Re}\{Y_M^L(\Omega^{\mathrm{H}})\},$$

Impressive agreement between fit and data!

At larger |t|, competing production mechanisms produce comparable P+ and P0 partial waves. **Qualitatively** different to small |t|!



Hierarchy of P-waves for various helicities:

Complicated dynamics give rise to other helicity structures for |t|≳0.45 GeV^2