Investigation of the η_1 Exotic Meson at GlueX

WNPPC 2026

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on behalf of the GlueX Collaboration

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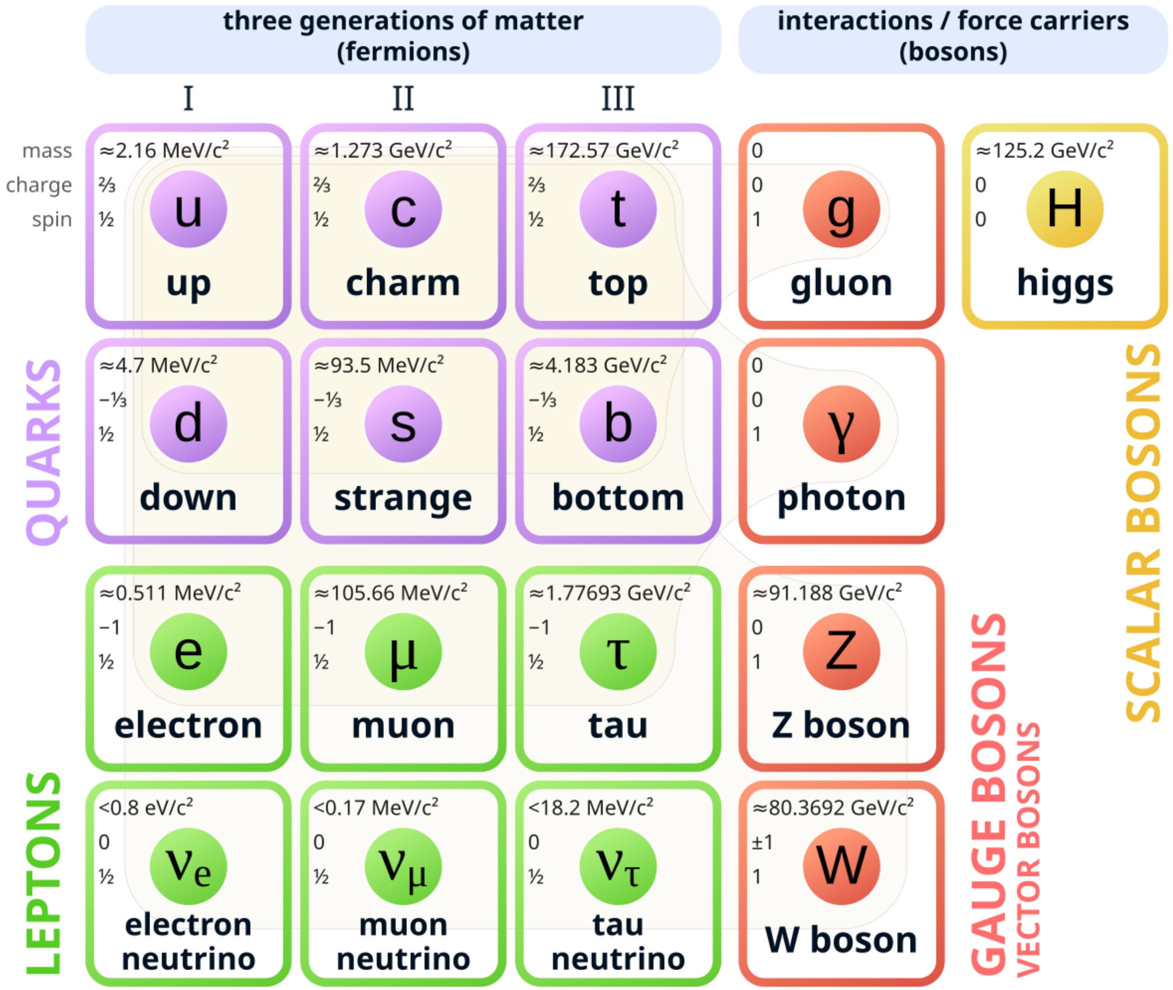
Introduction

The ‘current’ Standard Model of Particle Physics

It describes:

- Strong Interactions
- Weak Interactions
- Electromagnetic Interactions



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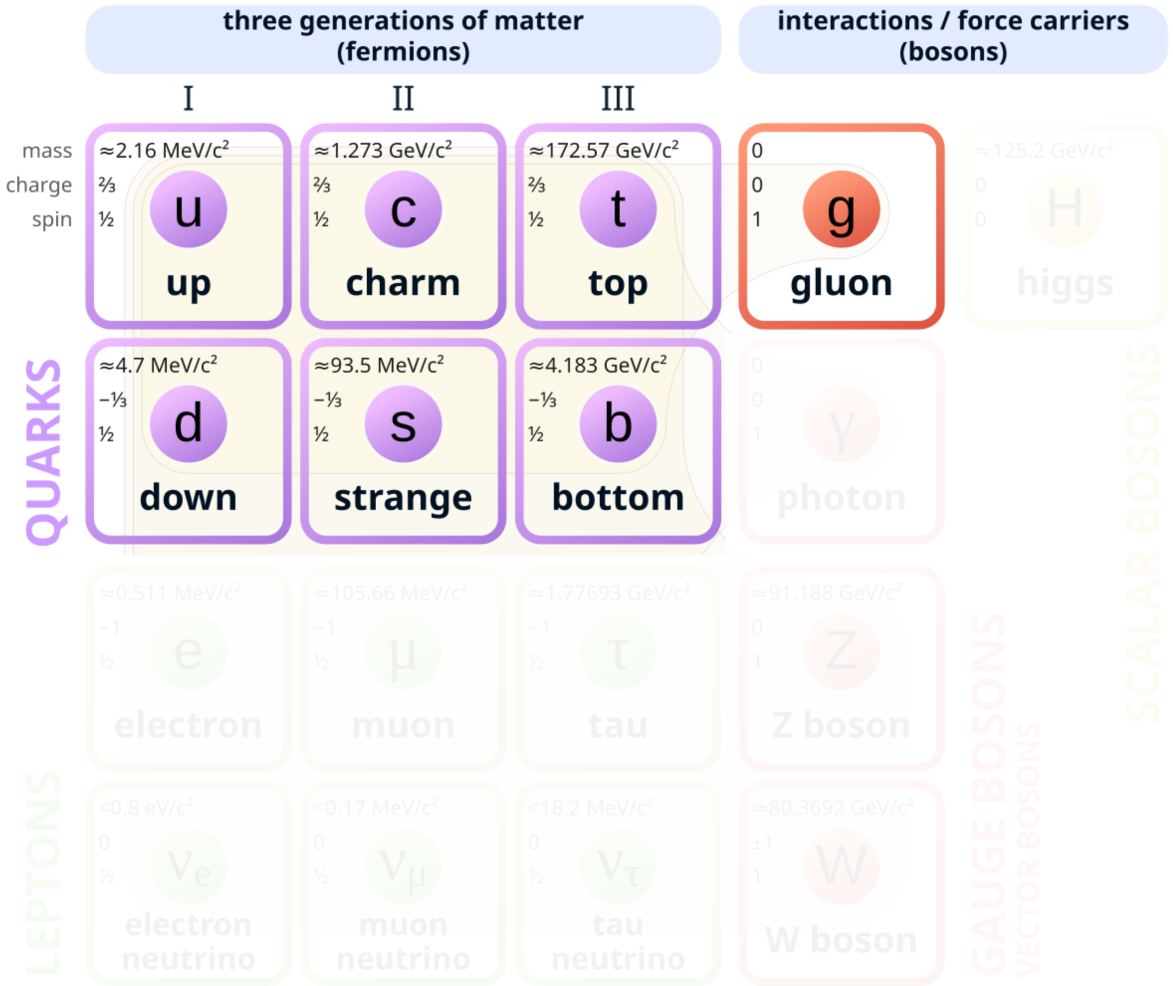
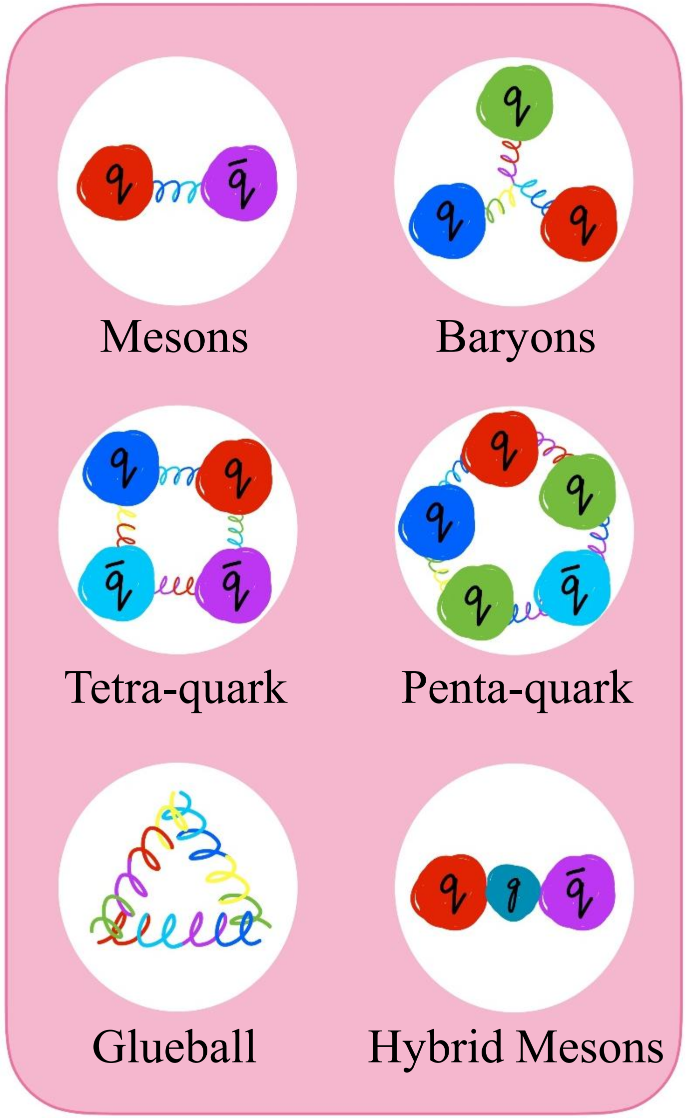


Introduction

Quantum Chromodynamics (QCD)

- Main Features:
  - Six flavors of Quarks (u,d,s,c,b,t) with various masses.
  - Quarks interact via exchange of Gluons.
  - Quarks and Gluons both carry color charge.
  - Quarks and Gluons combine to form Hadrons.
- Important outcomes:
  - Color Confinement
  - Asymptotic Freedom
  - Combinations with explicit gluonic degrees of freedom.



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Mesons can be categorized by J^{PC}.

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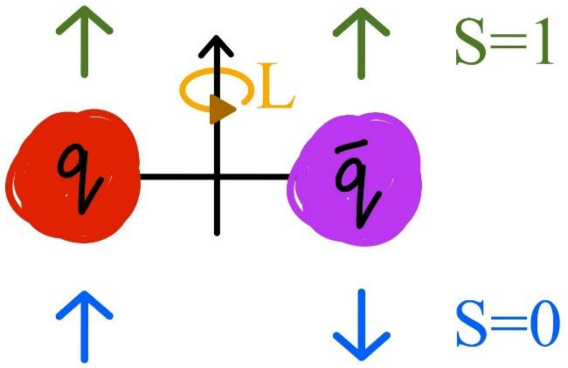

- Total Spin (J) ranges from $|L-S|$ to $|L+S|$
- Parity (P) = $(-1)^{(L+1)}$
- Charge Conjugation (C) = $(-1)^{(L+S)}$

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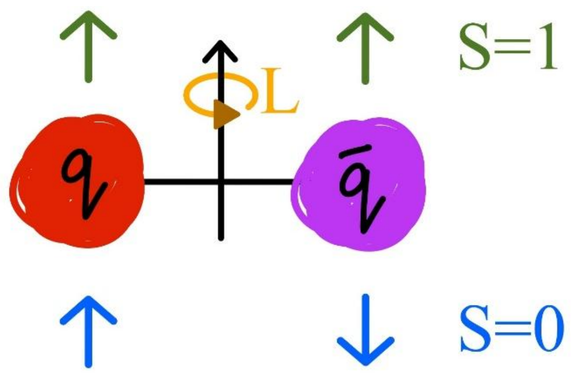

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Quark Model Forbidden J^{PC} Combinations: 0^{+-}, even^{+-}, odd^{-+}

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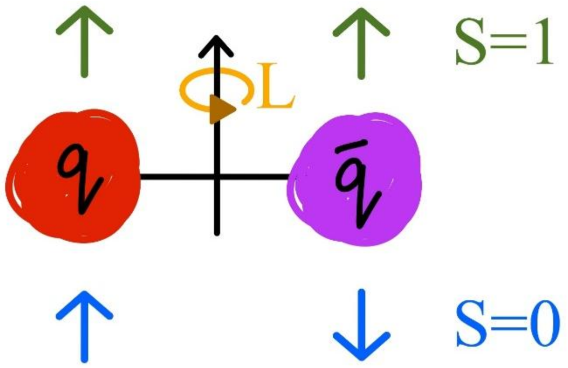

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Allowed by **QCD**
for Exotic States

Quark Model Forbidden J^{PC} Combinations: 0^{+-}, even^{+-}, odd^{-+}

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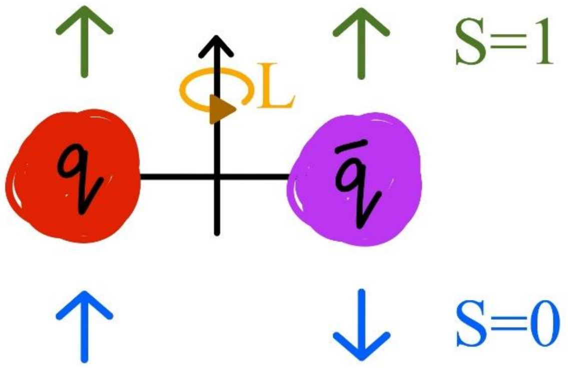

Study of Hybrid Mesons provides us with an opportunity to explore the role of Gluons in the formation of Hadrons.

- Total Spin (J) ranges from |L−S| to |L+S|
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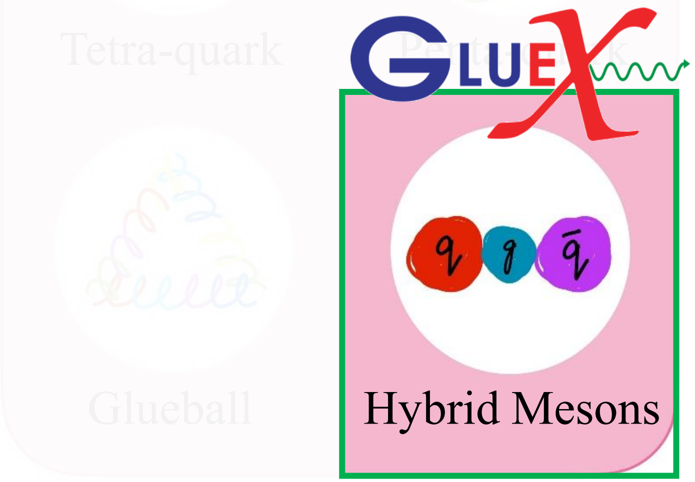
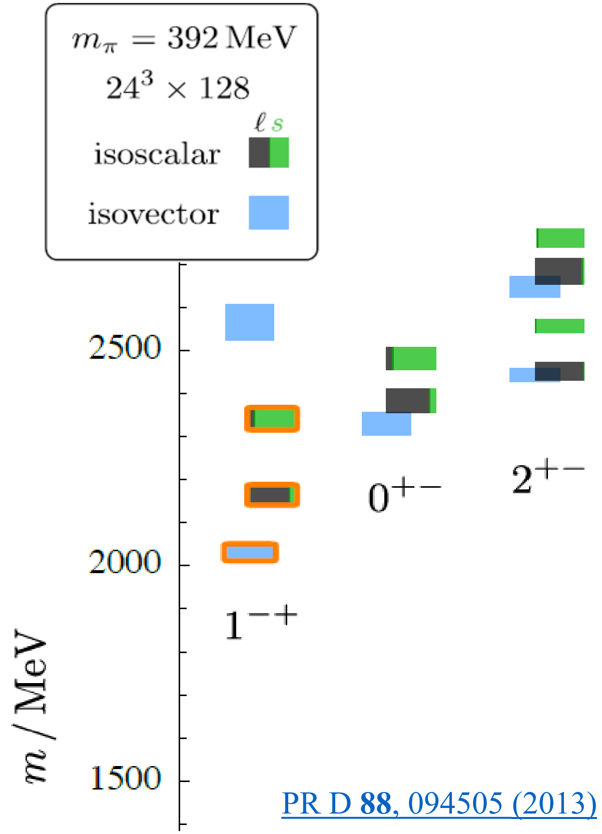
Quark Model Forbidden J^{PC} Combinations: 0^{+-}, even^{+-}, odd^{-+}



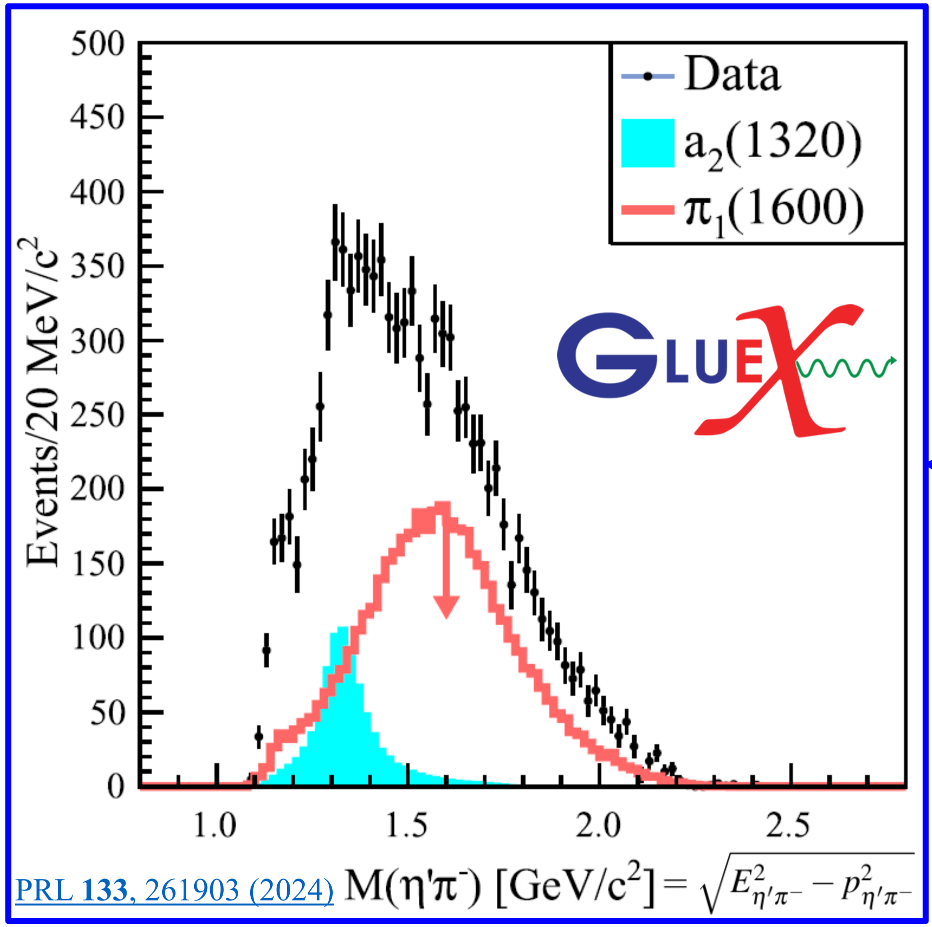
Predictions & Previous Work



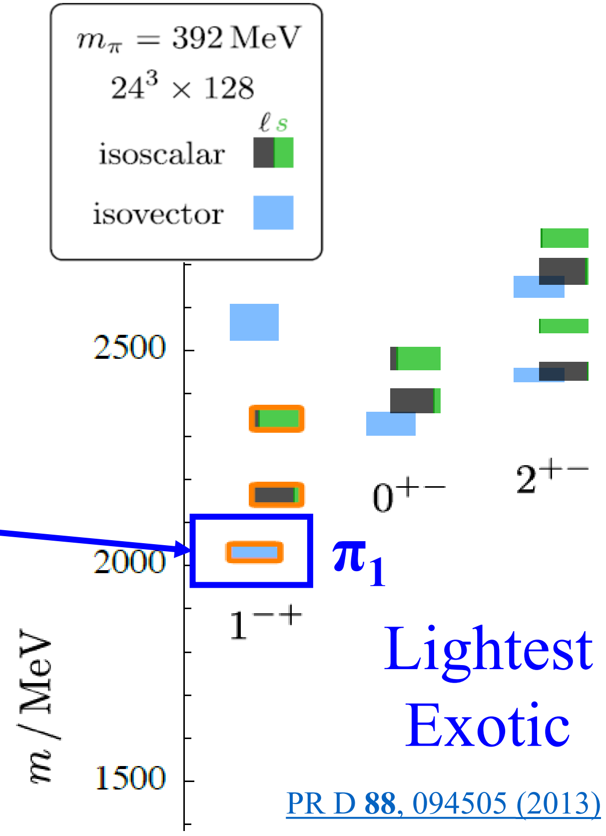
PR D **88**, 094505 (2013)

Lattice QCD
Exotic Meson
Predictions

Predictions & Previous Work



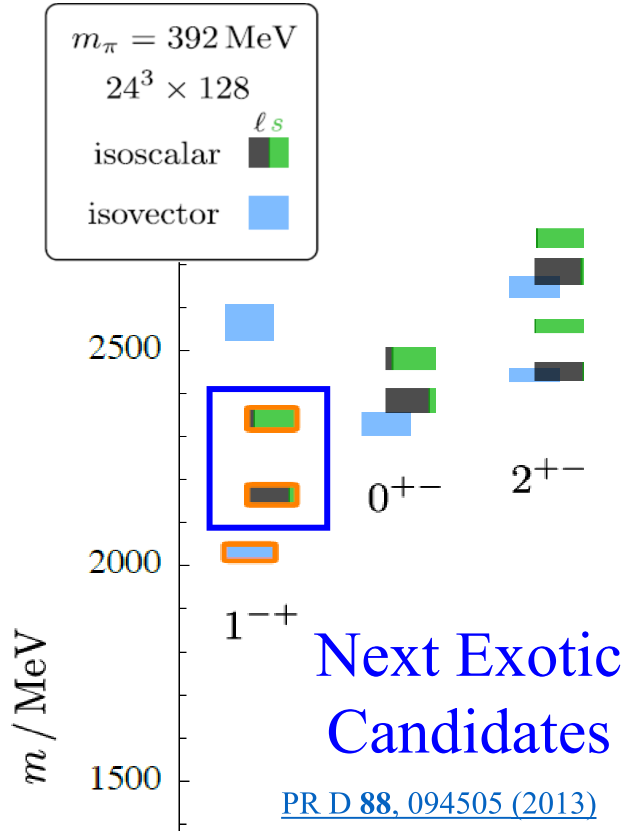
PRL **133**, 261903 (2024)



PR D **88**, 094505 (2013)

Lattice QCD Exotic Meson Predictions

Predictions & Previous Work

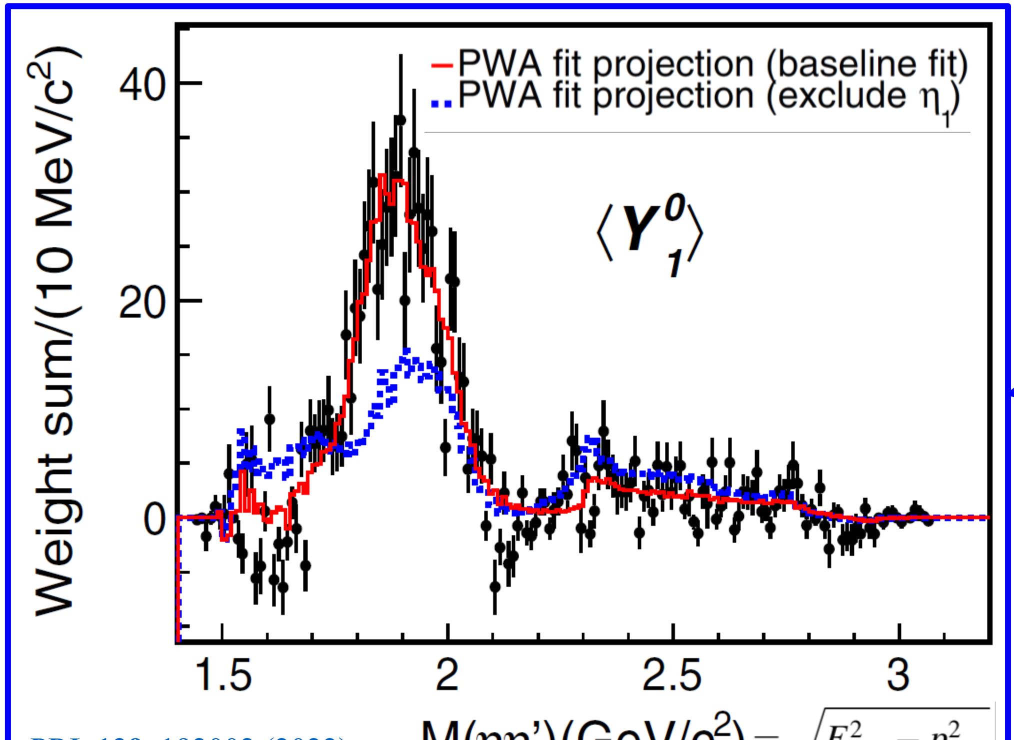


PR D **88**, 094505 (2013)

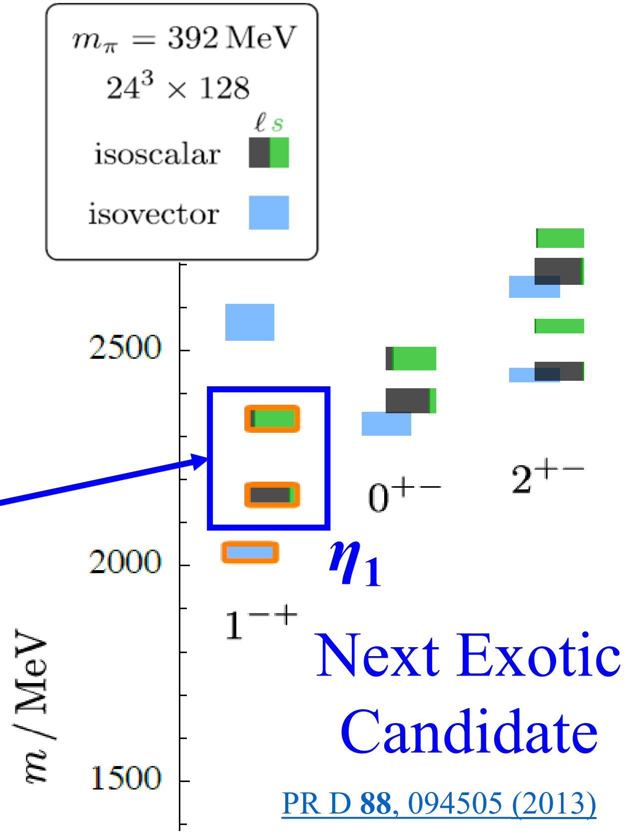
Lattice QCD Exotic Meson Predictions

BESIII Collaboration reported the signatures of an exotic $\eta_1(1855)$.

$$e^- e^+ \rightarrow J/\psi \rightarrow (\eta_1)\gamma \rightarrow (\eta\eta')\gamma$$



PRL **129**, 192002 (2022)



Next Exotic Candidate

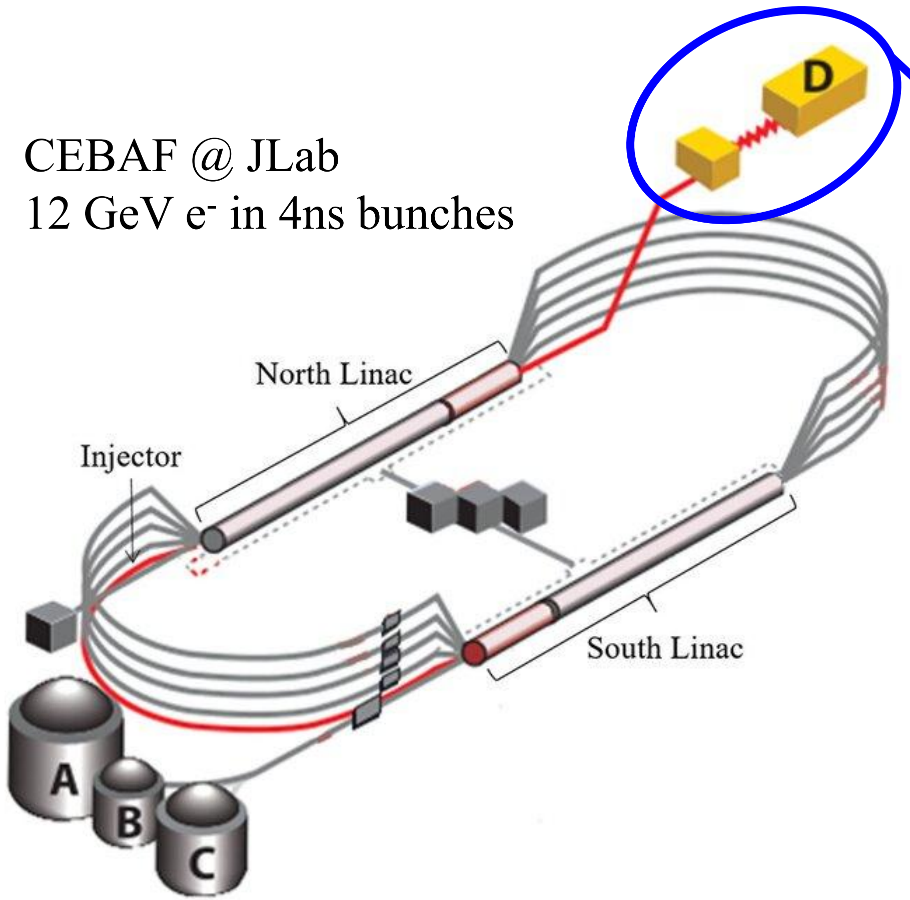
PR D **88**, 094505 (2013)

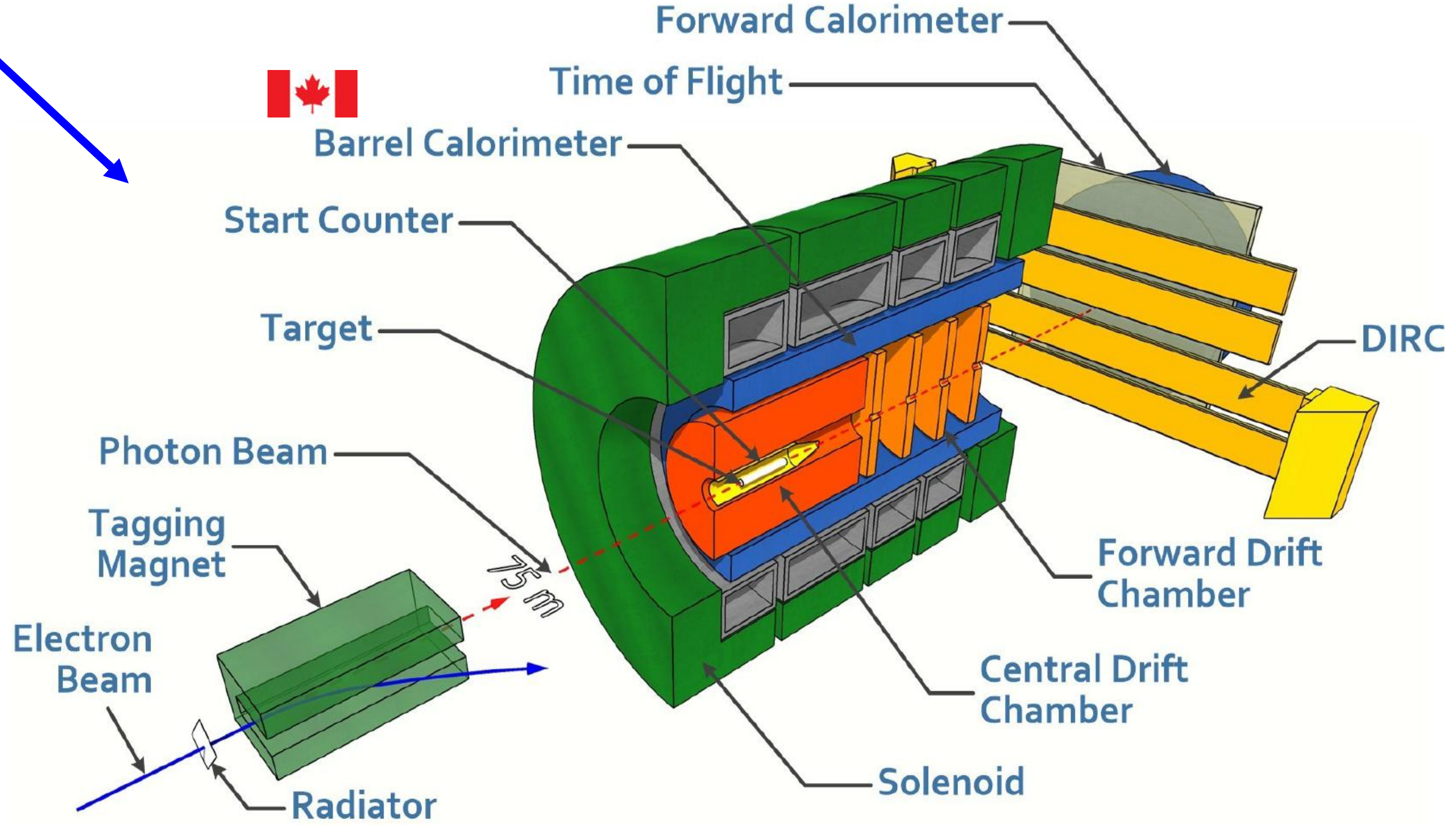
Lattice QCD Exotic Meson Predictions

The Experiment

A Photo-production Experiment @ Jefferson Lab Hall D

CEBAF @ JLab
12 GeV e^- in 4ns bunches

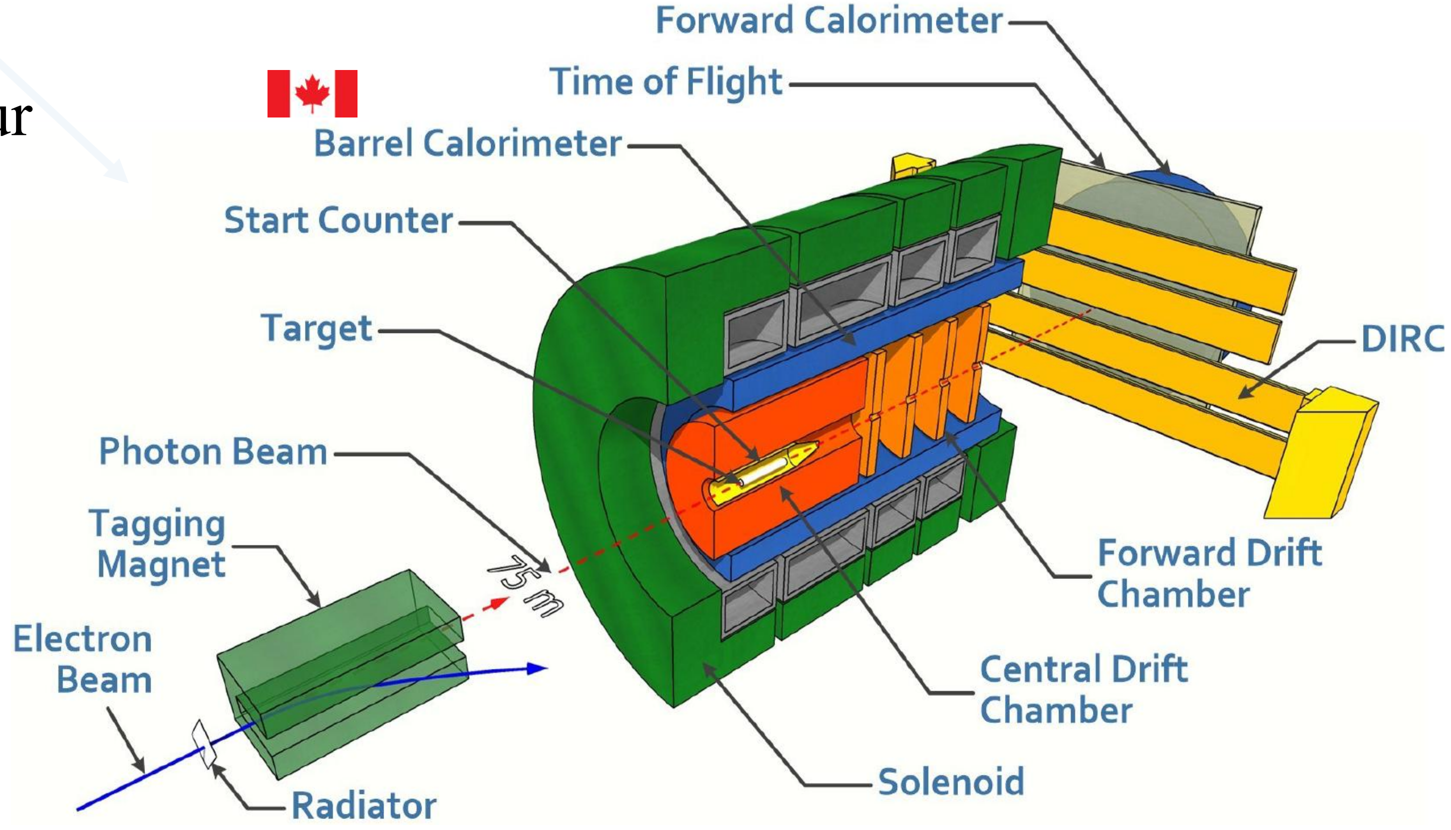




The Experiment

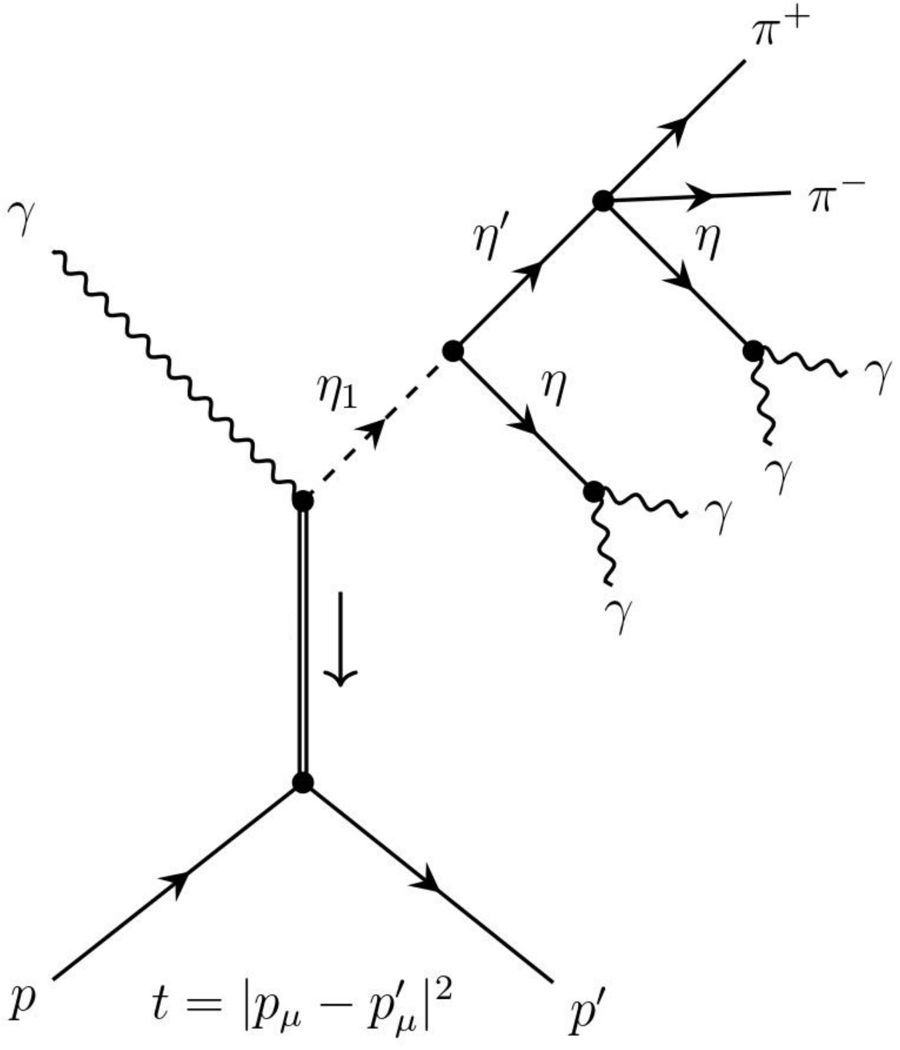
A Photo-production Experiment @ Jefferson Lab Hall D

- Key Features:
  - 6-12 GeV γ beam energy
  - Linearly polarized photons in four orientations
  - LH_2 target
  - Detector system offers nearly 4π coverage



Reaction Channel

$$\gamma p \rightarrow (\eta_1)p' \rightarrow (\eta\,\eta')p' \rightarrow (\eta(\eta\pi^+\pi^-))p' \rightarrow (\gamma\gamma(\gamma\gamma\pi^+\pi^-))p'$$



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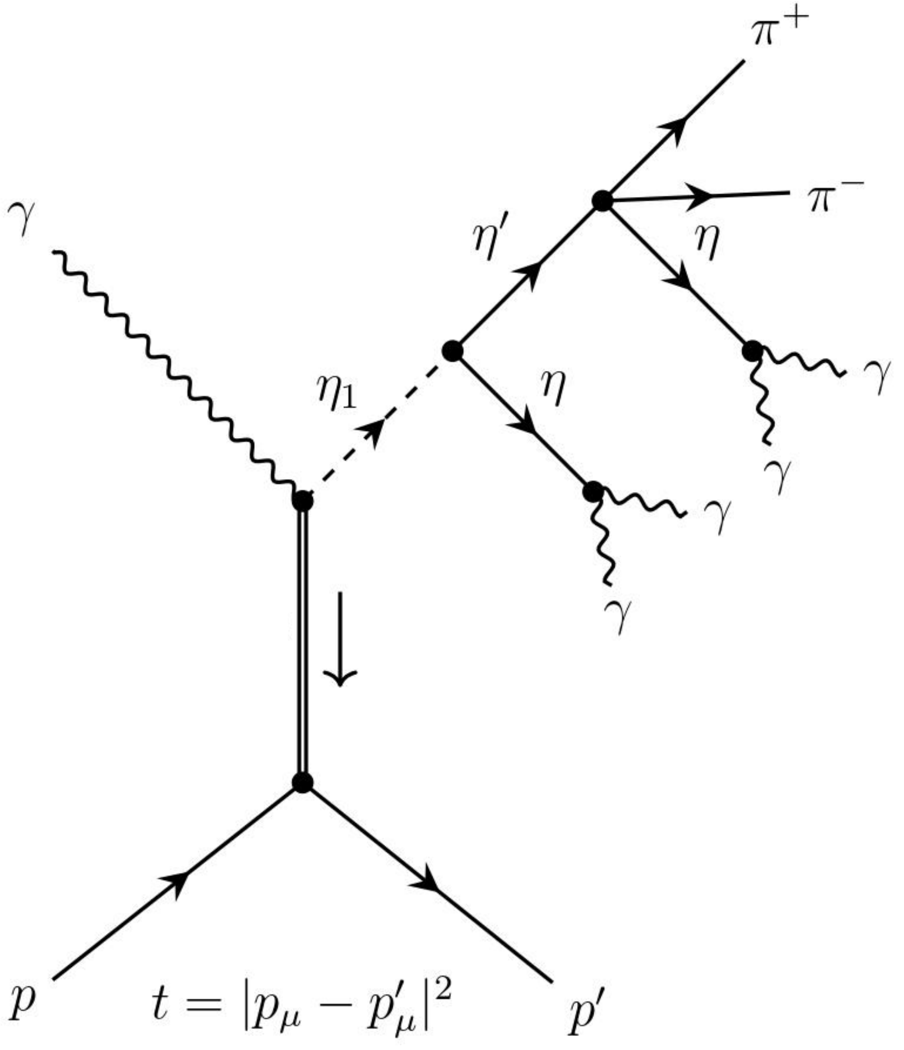
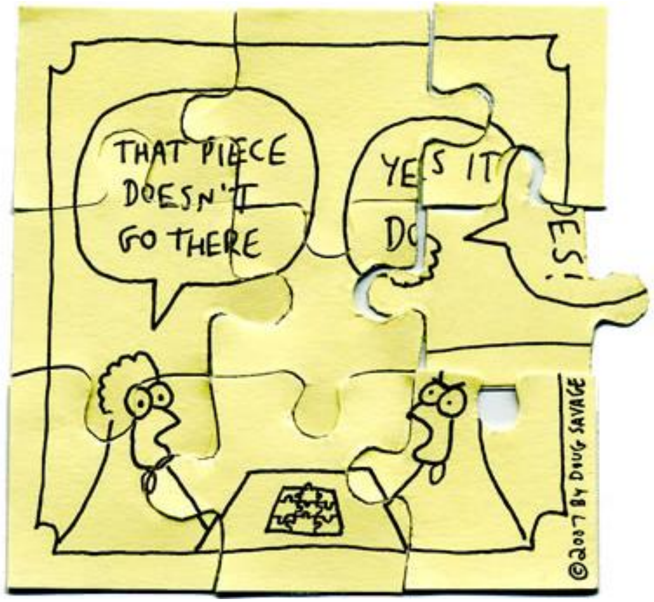


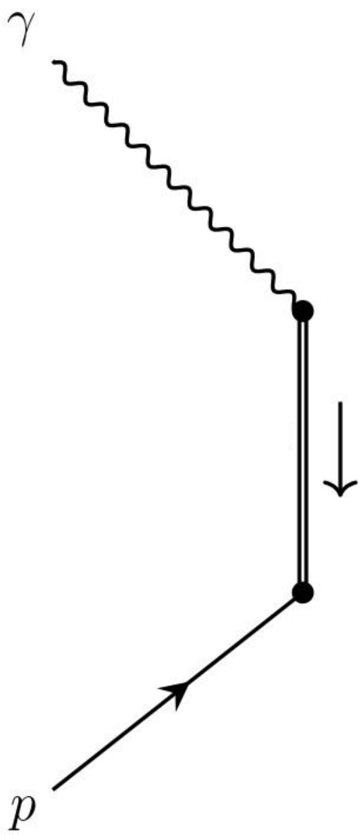
- Detector only gives us the final states which is: $\gamma\gamma\gamma\gamma\pi^+\pi^- p$
- Reconstruction is putting the pieces of a puzzle together.



Source: savagechickens.com

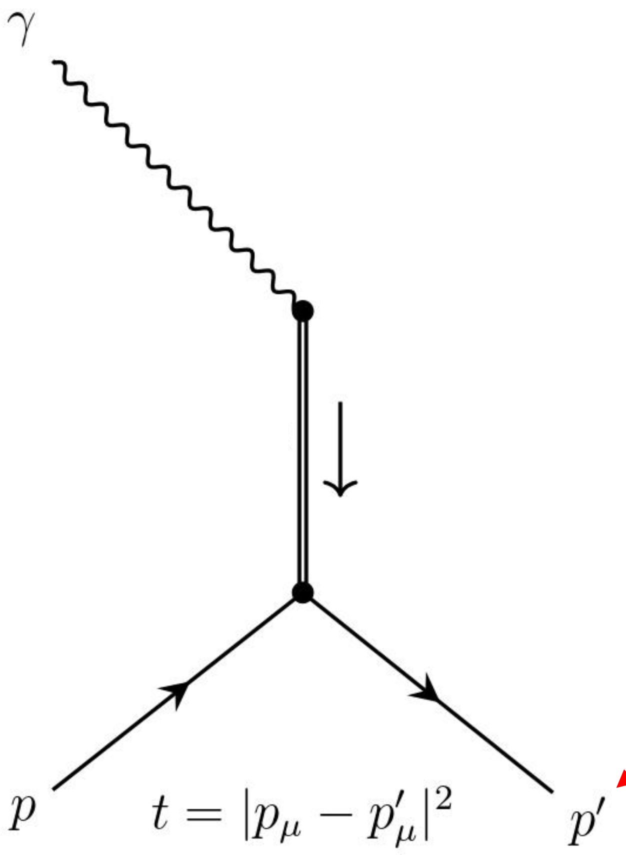
Reconstruction

$$\gamma\gamma\gamma\gamma\pi^{+}\pi^{-}p'$$



Reconstruction

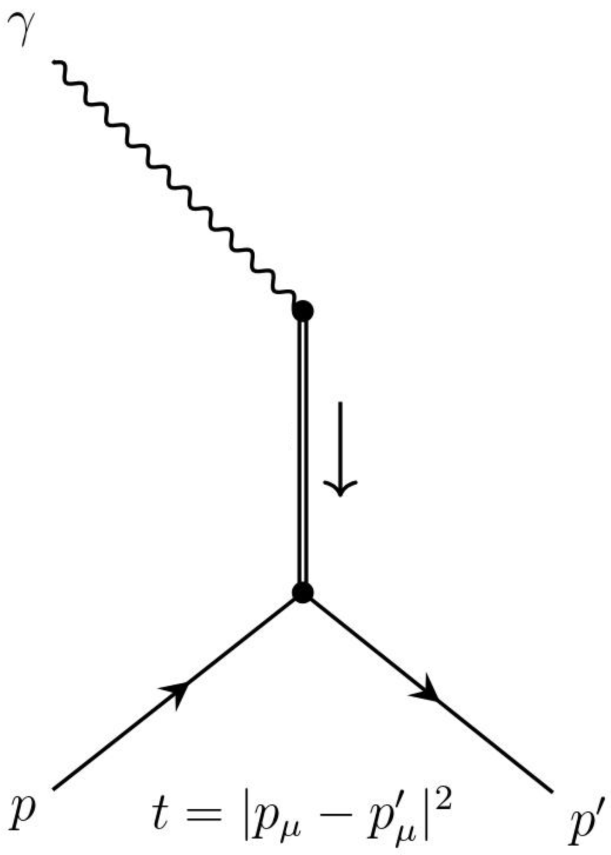
$\gamma\gamma\gamma\gamma\pi^+\pi^-\boxed{p'}$



Proton is in lower vertex (t-channel).

Reconstruction

$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$

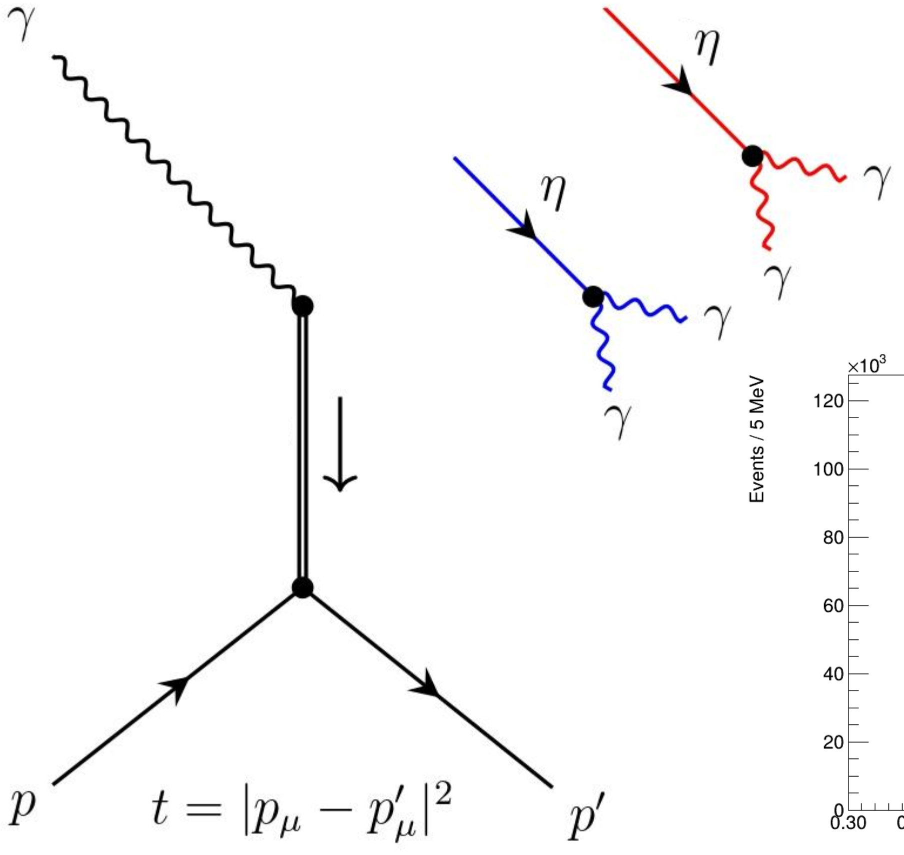


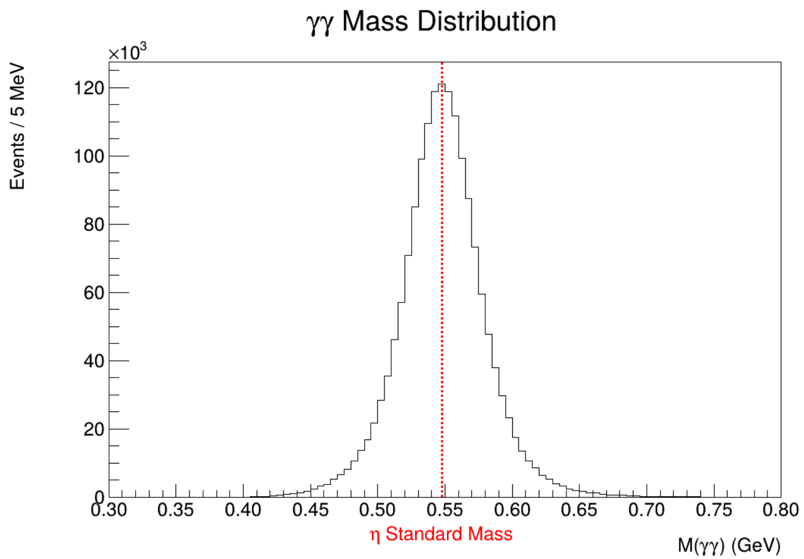
$\boxed{\eta \rightarrow \gamma\gamma}$

Combinatorics to decide how 4 γ should be combined to form 2 η

Reconstruction

$$\gamma\gamma\gamma\gamma\pi^+\pi^-p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^-p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^-p'$$





$$\boxed{\eta \to \gamma\gamma}$$

Combinatorics to decide how 4 γ should be combined to form 2 η

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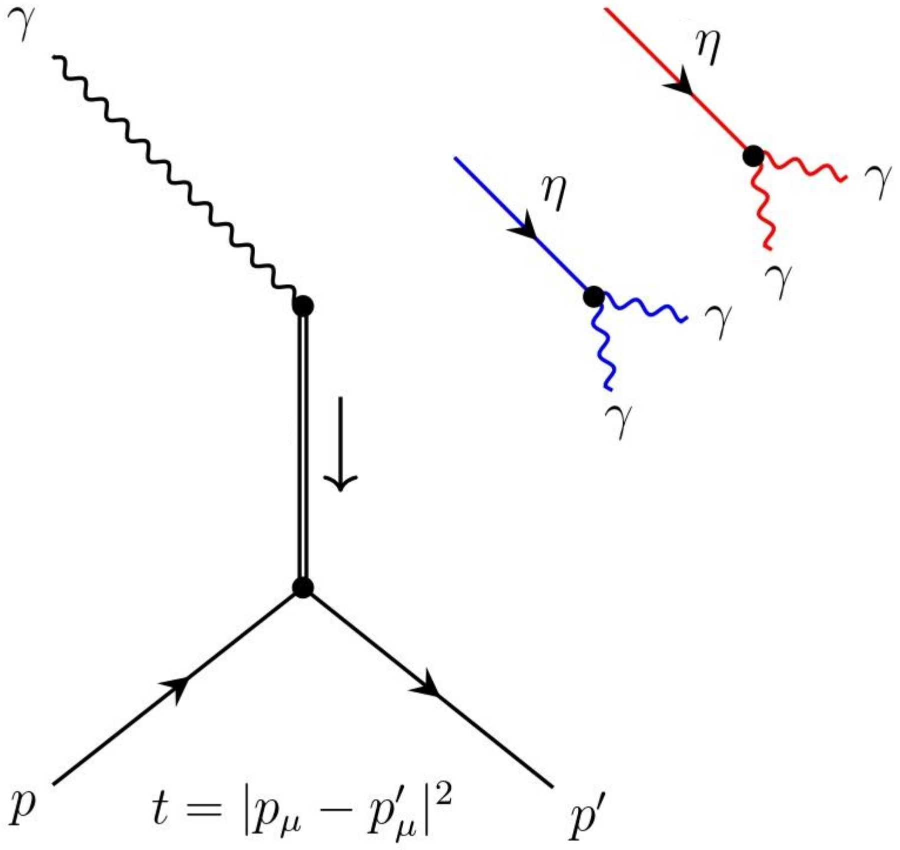
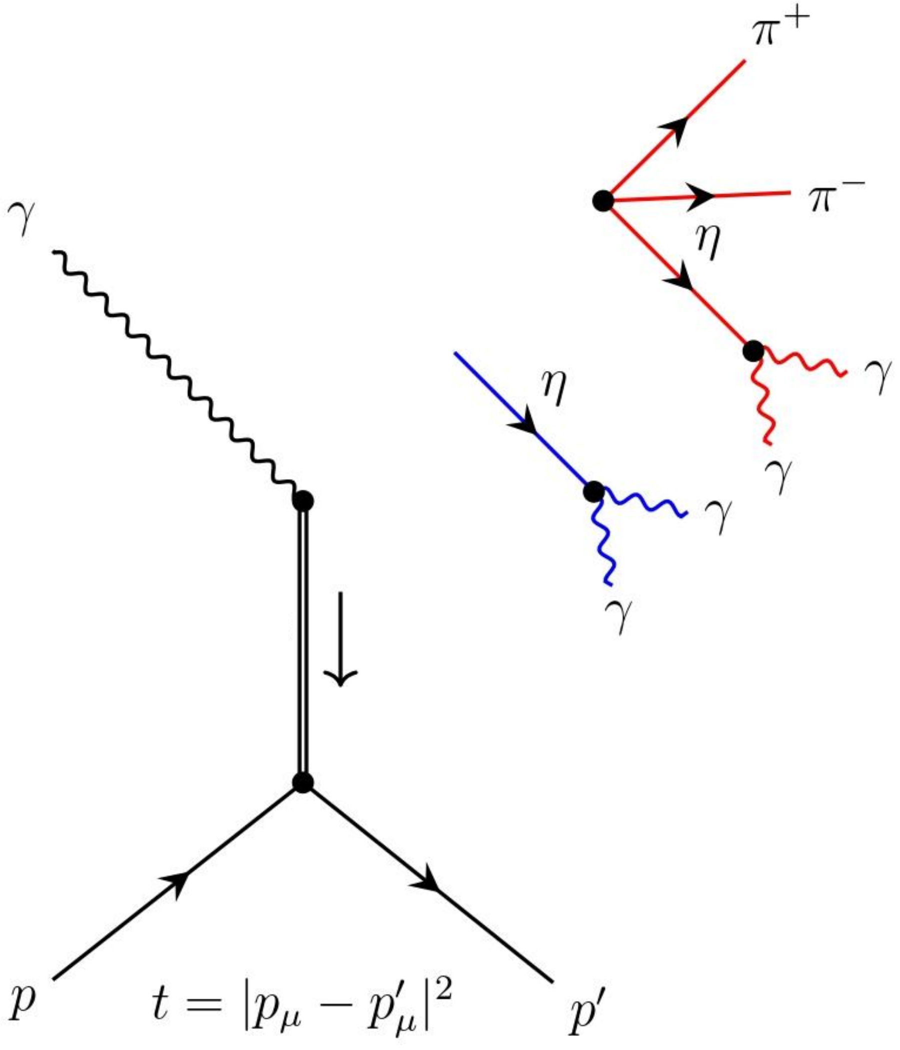


$$\gamma\gamma\gamma\gamma\pi^+\pi^-p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^-p'$$
$$\downarrow$$
$$\eta\eta\pi^+\pi^-p'$$

$$\boxed{\eta' \to \eta\pi^+\pi^-}$$

Combinatorics to decide which η has decayed from η'

Reconstruction

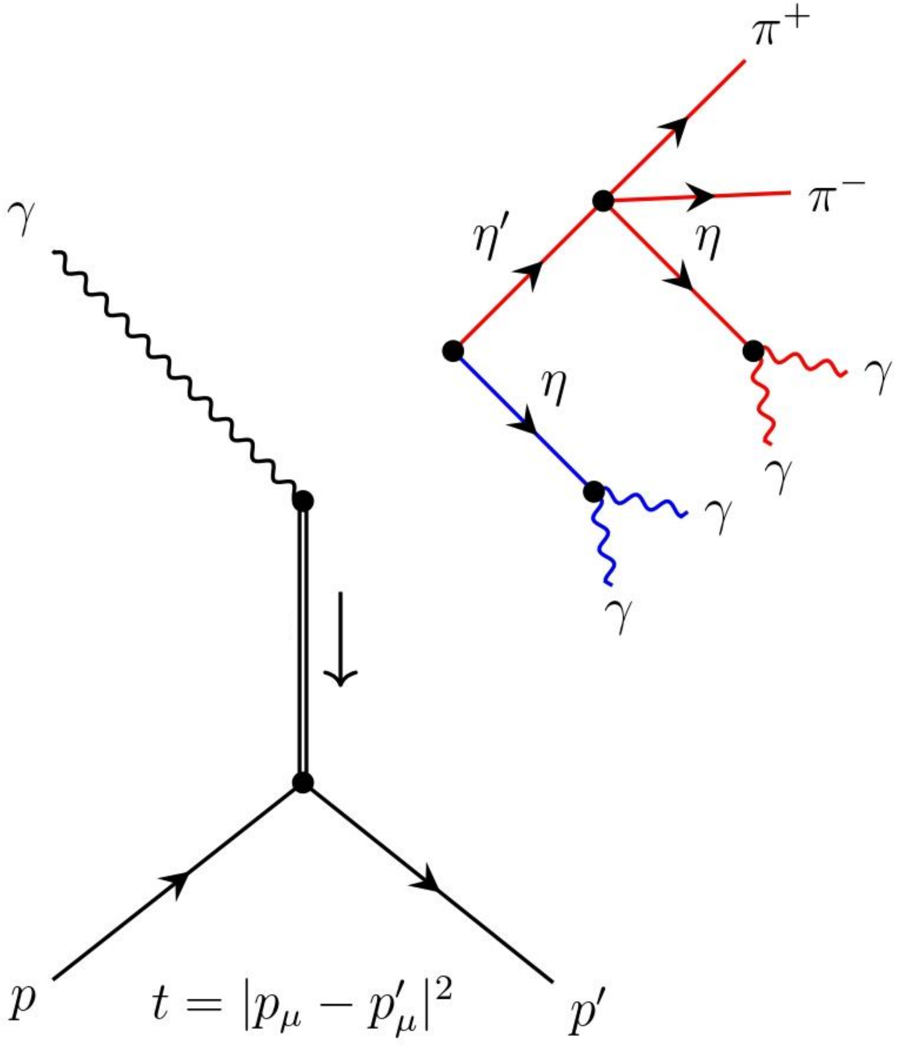


$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\eta\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta(\eta\pi^+\pi^-)p'$$

$$\boxed{\eta' \to \eta\pi^+\pi^-}$$

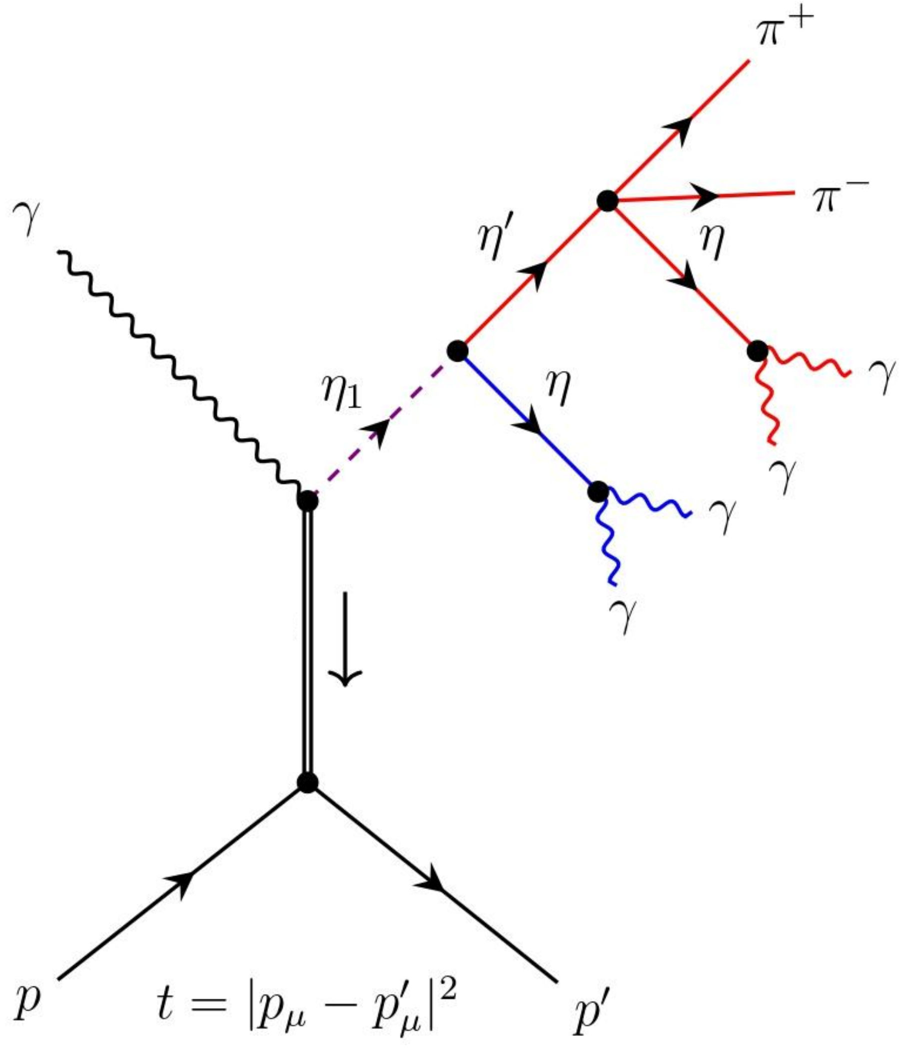
Combinatorics to decide which η has decayed from η'

Reconstruction



$$\gamma\gamma\gamma\gamma\pi^+\pi^-p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^-p'$$
$$\downarrow$$
$$\eta\,\eta\,\pi^+\pi^-p'$$
$$\downarrow$$
$$\eta(\eta\pi^+\pi^-)p'$$
$$\downarrow$$
$$\eta\,\eta'p'$$

Reconstruction

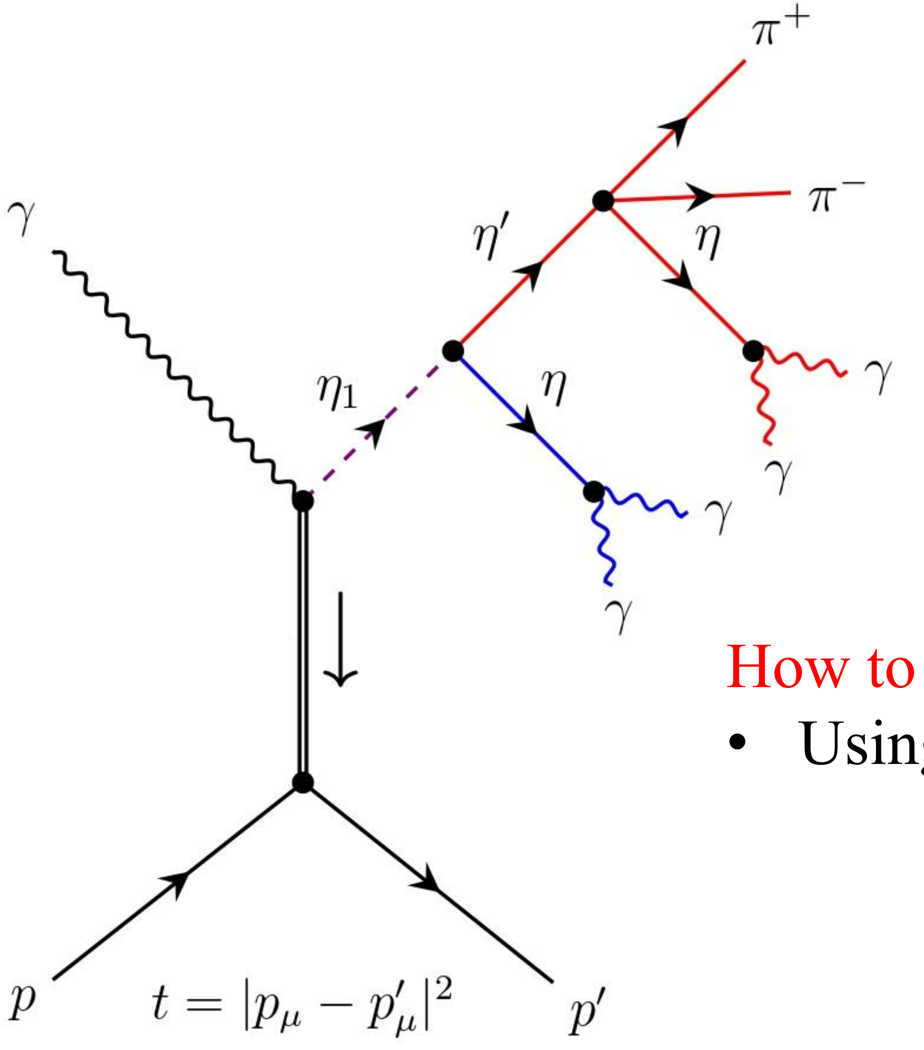


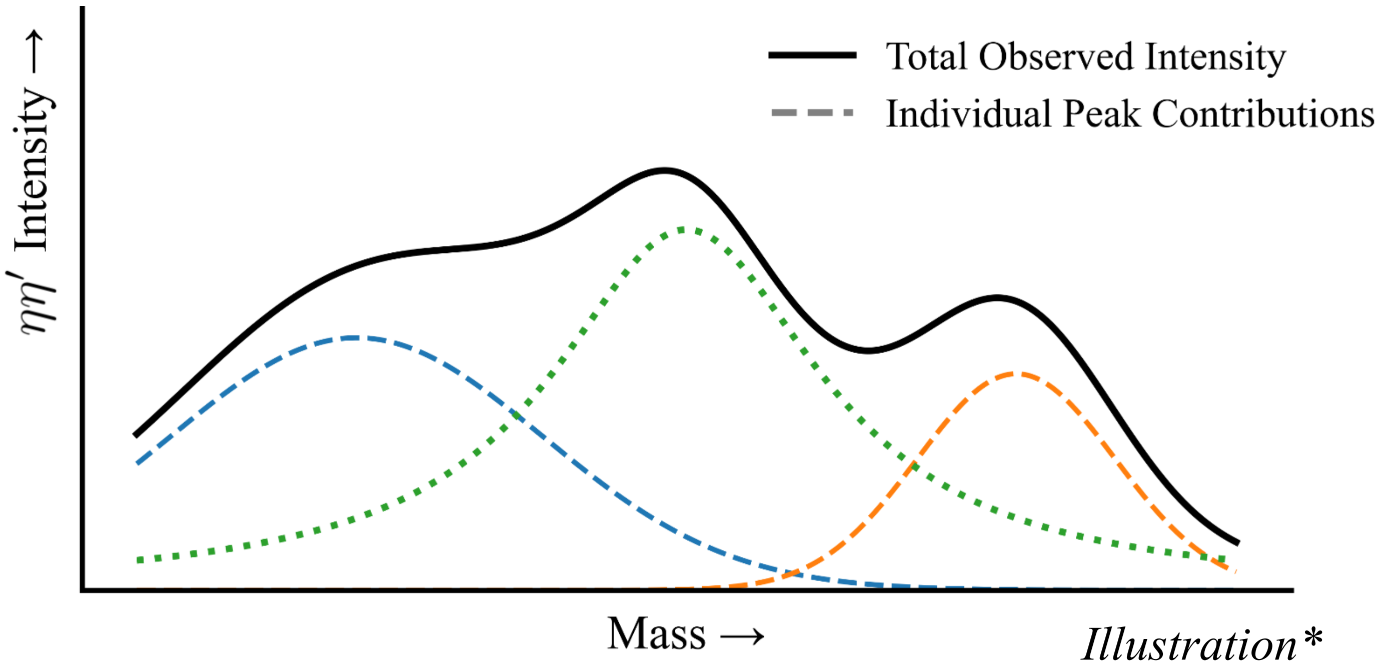
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\gamma\gamma\gamma\gamma\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta\eta\pi^+\pi^- p'$$
$$\downarrow$$
$$\eta(\eta\pi^+\pi^-)p'$$
$$\downarrow$$
$$\eta\eta' p'$$
$$\downarrow$$

Analyse the spectrum

Partial Wave Analysis

$$\gamma p \to (\eta_1)p' \to (\eta\eta')p' \to (\eta(\eta\pi^+\pi^-))p' \to (\gamma\gamma(\gamma\gamma\pi^+\pi^-))p'$$





*Illustration**

How to extract contributions from various J^{PC} from this spectrum?

- Using only mass spectrum is incomplete.

Partial Wave Analysis

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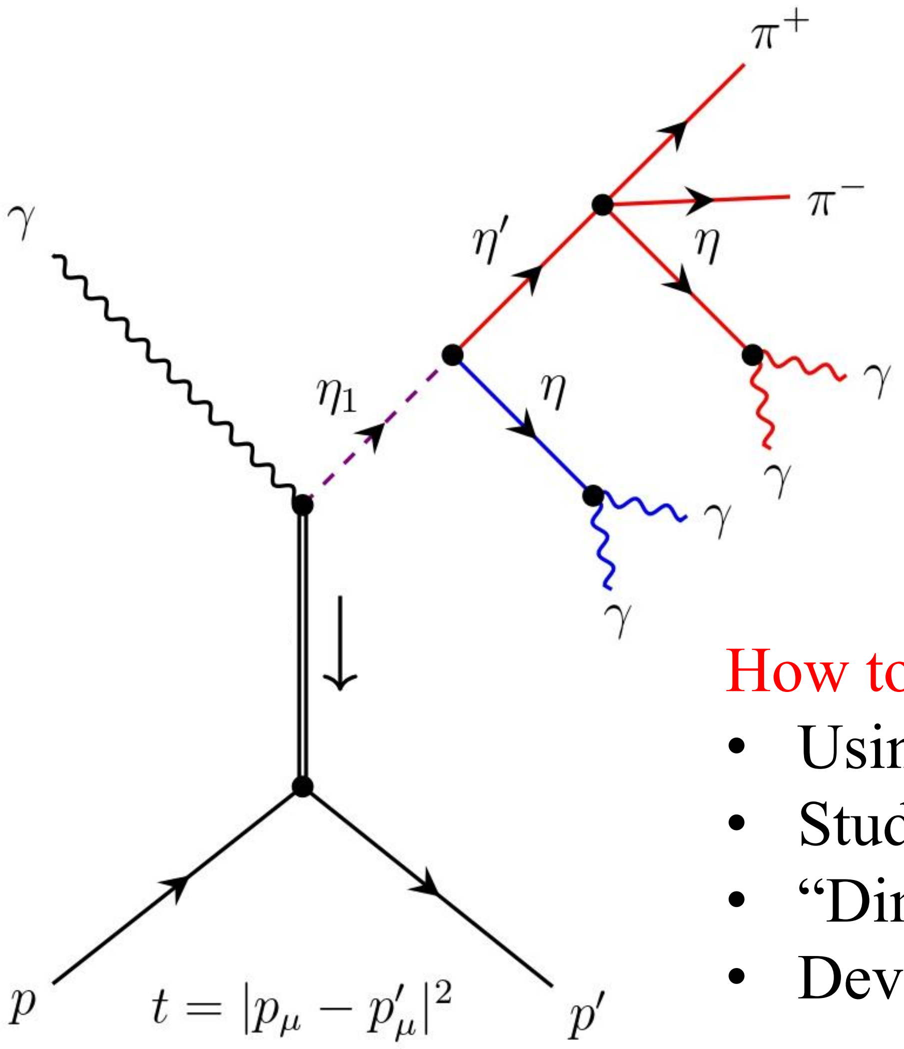

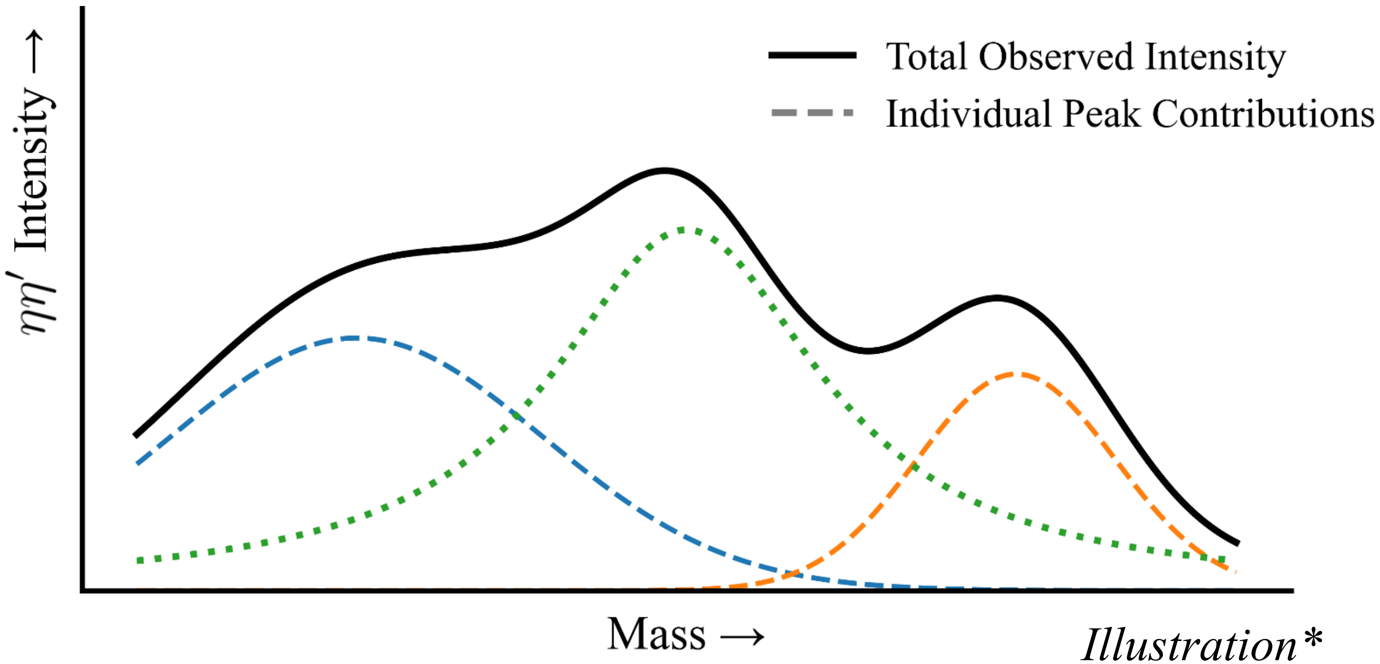

*Illustration**

How to extract contributions from various J^{PC} from this spectrum?

- Using only mass spectrum is incomplete.
- Study and analyze intensity in more “dimensions”!
- “Dimensions” - Decay angles of the constituent particles.
- Develop model from scattering theory.

Partial Wave Analysis

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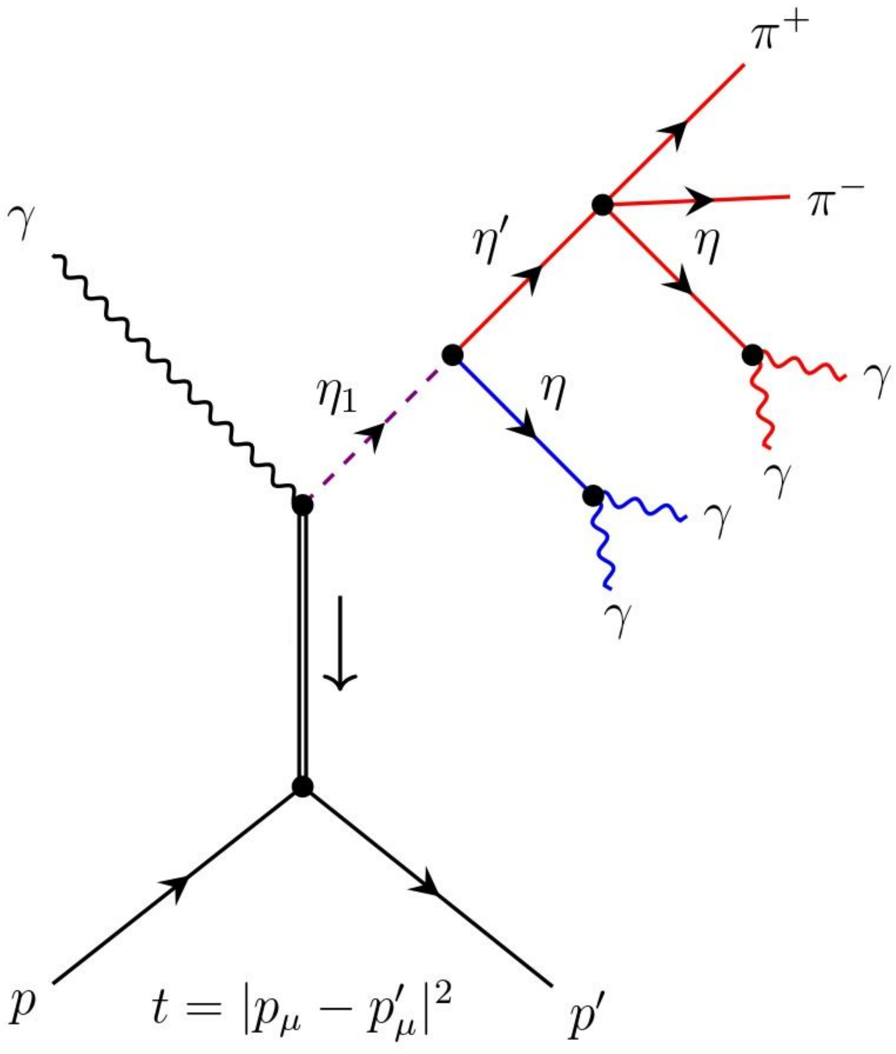


Partial Wave Analysis (PWA):

Intensity distribution under amplitude analysis framework can be written as:

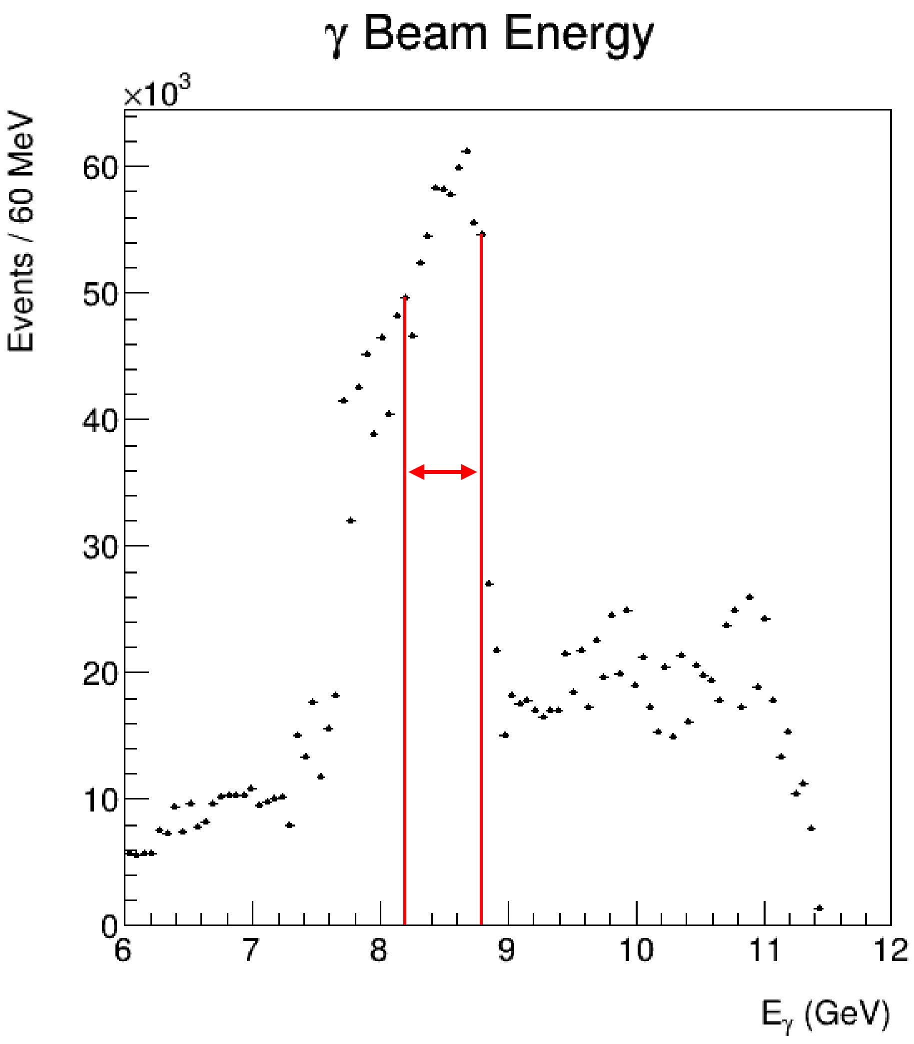
$$I(\Omega, \Phi) \equiv \frac{d\sigma}{dt\,dm_{\eta\eta'}\,d\Omega\,d\Phi}$$

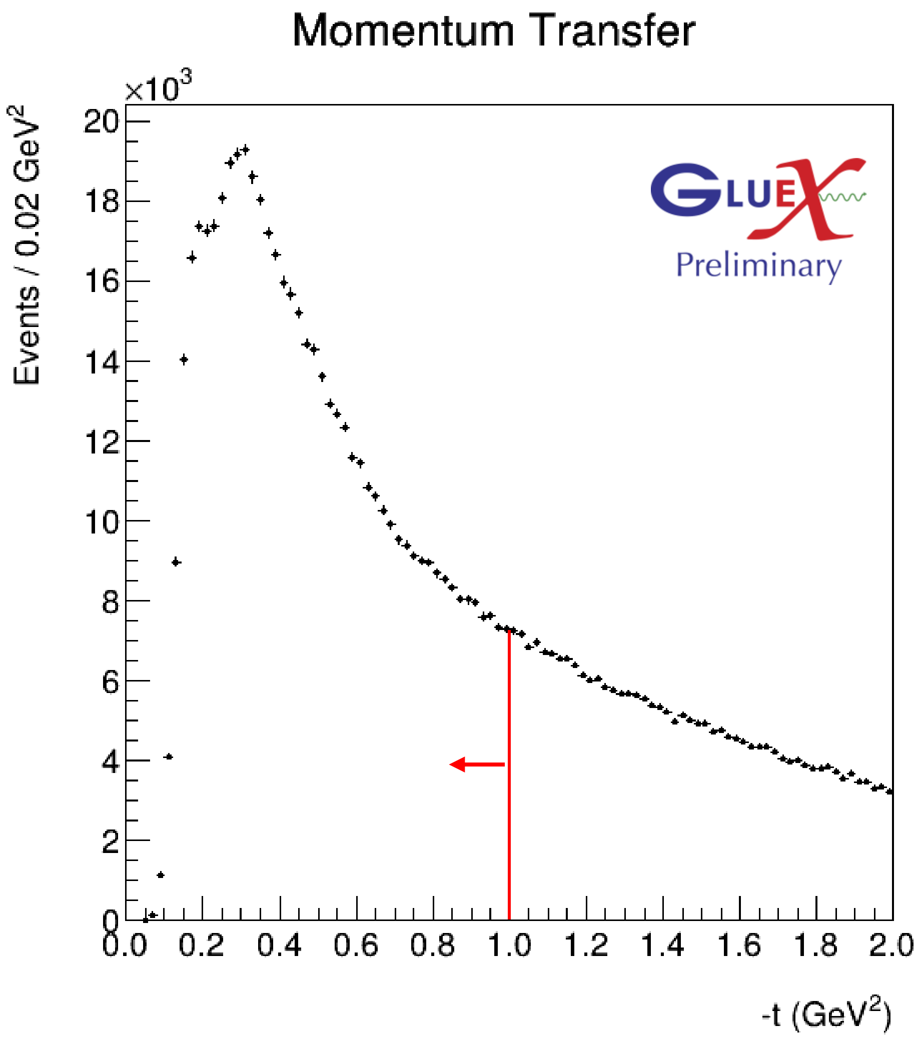
which can be solved to give:

$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma)\left|\sum_{l,m} [l]^{(-)}_{m;k} \Re[Z^m_l(\Omega,\Phi)]\right|^2 + (1-P_\gamma)\left|\sum_{l,m} [l]^{(+)}_{m;k} \Im[Z^m_l(\Omega,\Phi)]\right|^2 + (1+P_\gamma)\left|\sum_{l,m} [l]^{(+)}_{m;k} \Re[Z^m_l(\Omega,\Phi)]\right|^2 + (1+P_\gamma)\left|\sum_{l,m} [l]^{(-)}_{m;k} \Im[Z^m_l(\Omega,\Phi)]\right|^2 \Bigg\}$$

PWA - A framework that extracts contribution of J^{PC} by studying intensity in multiple decay angles

Preliminary Data Filtering Plots





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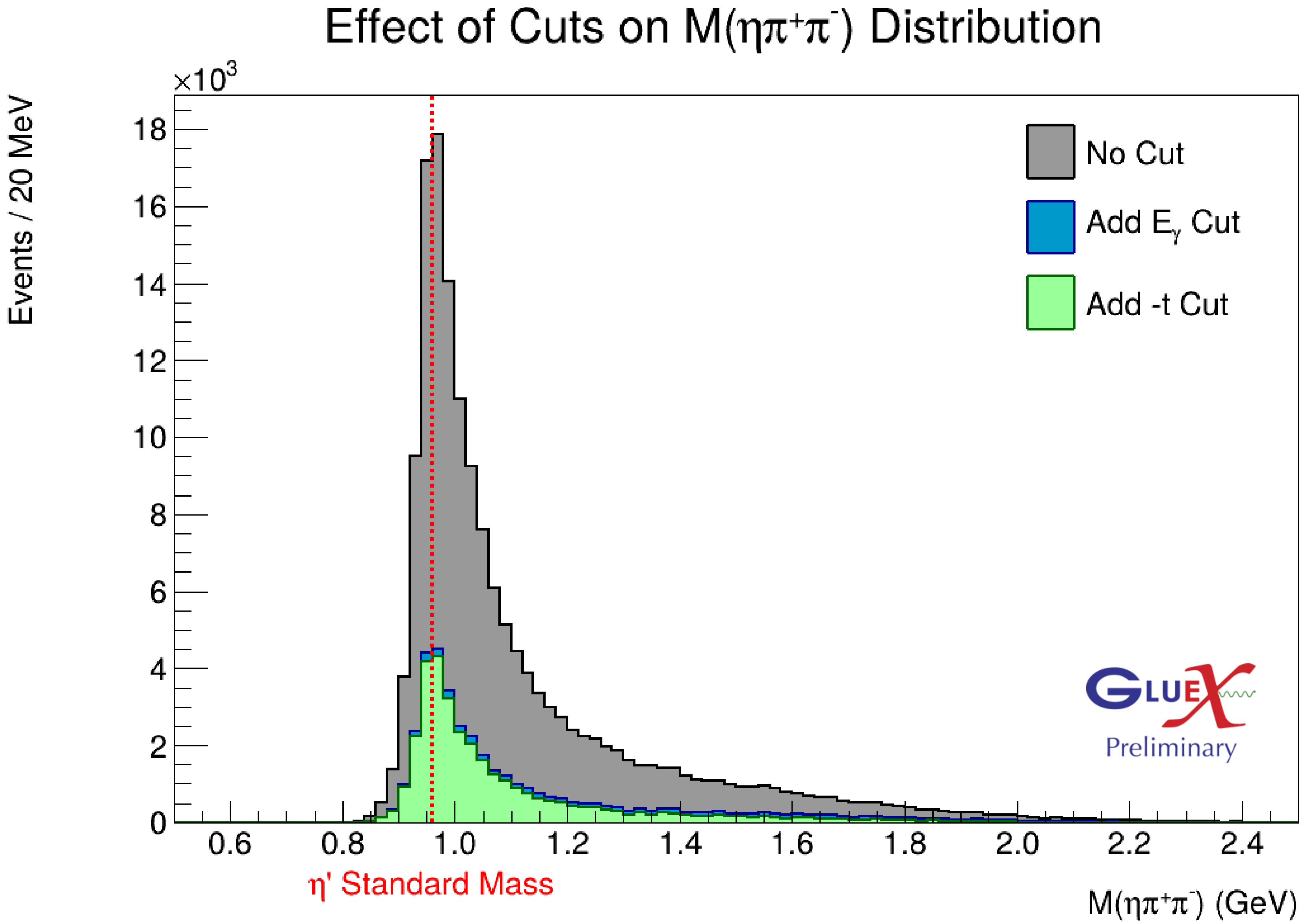


Summary

- PWA will help extract individual J^{PC} contributions.
- $\eta\eta'$ state, decayed from exotic η_1, is accessible in GlueX spectrometer.
- Study of Hybrid Mesons help us explore role of Gluons in internal dynamics of Hadrons.
- Next Steps:
  - Create signal and background Monte Carlo data.
  - Extract a clean $\eta\eta'$ signal from data.
  - Fit that data with PWA to find signatures of η_1.
  - Get observable like moments & cross-section.

Thank You!

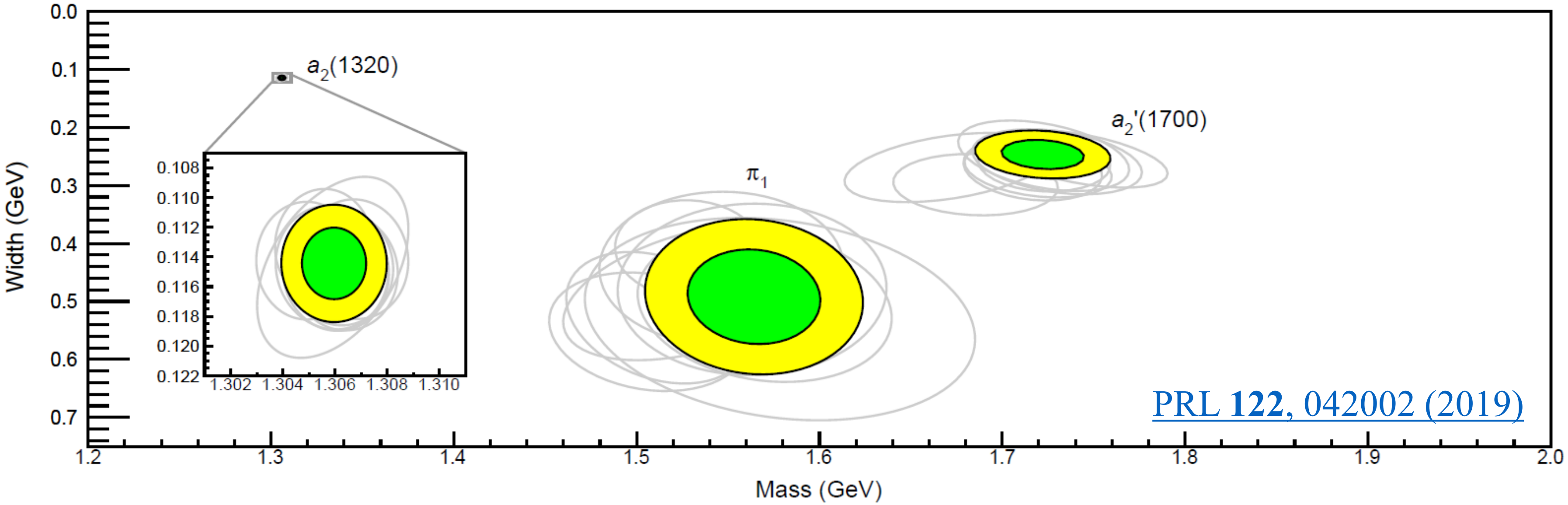
GlueXperiment
gluexexperiment
Glue_X

www.gluex.org/thanks

Backups

Phenomenological Calculations

JPAC Collaboration calculations about conventional $a_2^{(\prime)}$ mesons & exotic π_1 in $\eta^{(\prime)}\pi$ channels.

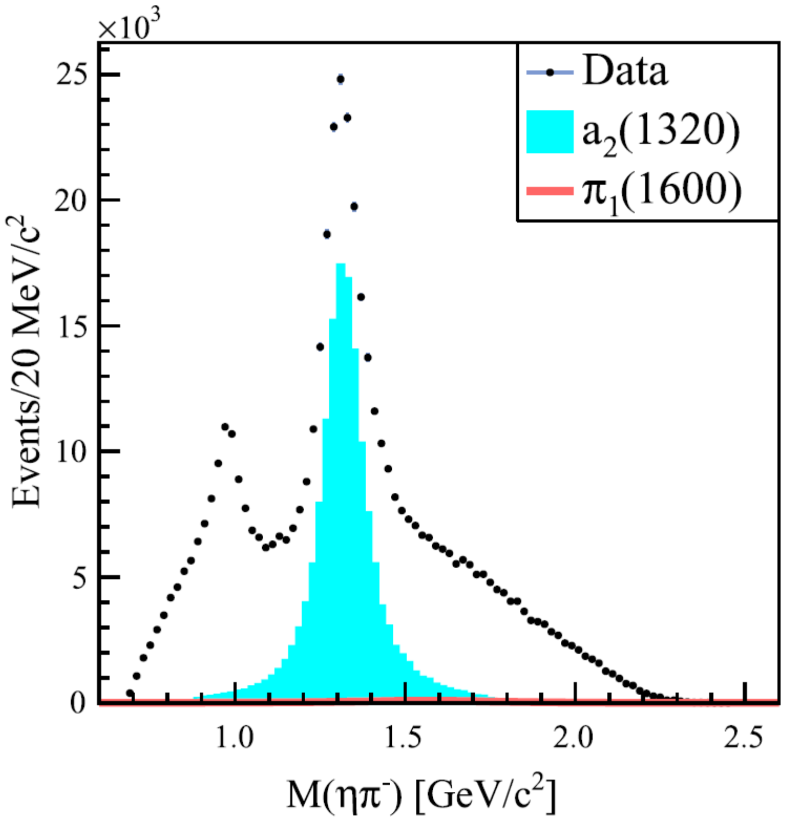


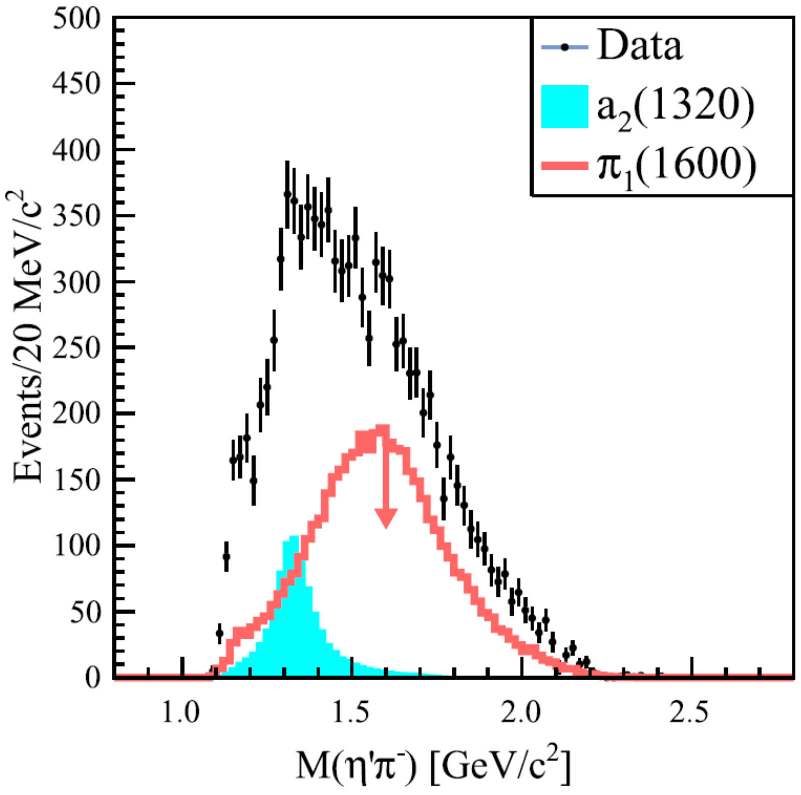
PRL **122**, 042002 (2019)

Meson Spectroscopy at GlueX

GlueX published papers on:

- Upper limit on the photoproduction cross-section of the spin-exotic $\pi_1(1600)$ PRL **133**, 261903 (2024)
- First measurement of a_2^0 (1320) polarized photoproduction cross section PR C **112**, 015204 (2025)





PRL **133**, 261903 (2024)

BESIII Moment Formulae

The moment for the kth bin of M($\eta\eta'$) is:

$$\langle Y_l^0 \rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(\cos\theta_\eta^i)$$

N_k is the number of observed events in the kth bin of M($\eta\eta'$), and
W_i is a weight used to implement background subtraction.
m=0 means no ϕ dependence

$$\sqrt{4\pi}\langle Y_1^0 \rangle = 2SP\cos\phi_P + 4PD\cos(\phi_P - \phi_D)$$

S, P, D are spin-0, spin-1, and spin-2 amplitudes respectively, and ϕ_P and ϕ_D are the phases of the P wave and D wave relative to the S wave respectively.

PRL **129**, 192002 (2022)

PWA Formula Description

Intensity distribution under amplitude analysis framework can be written as:

$$I(\Omega, \Phi) \equiv \frac{d\sigma}{dt\,dm_{\eta\eta'}\,d\Omega\,d\Phi}$$

σ is the total cross-section,

Ω is the direction of η' in the helicity frame,

Φ is the angle of beam photon polarization with respect to production plane,

$t = (p_\mu - p'_\mu)^2$ is the four-momentum transfer to proton, and

$m_{\eta\eta'}$ is the invariant mass of $\eta\eta'$ system.

PWA Formula Description

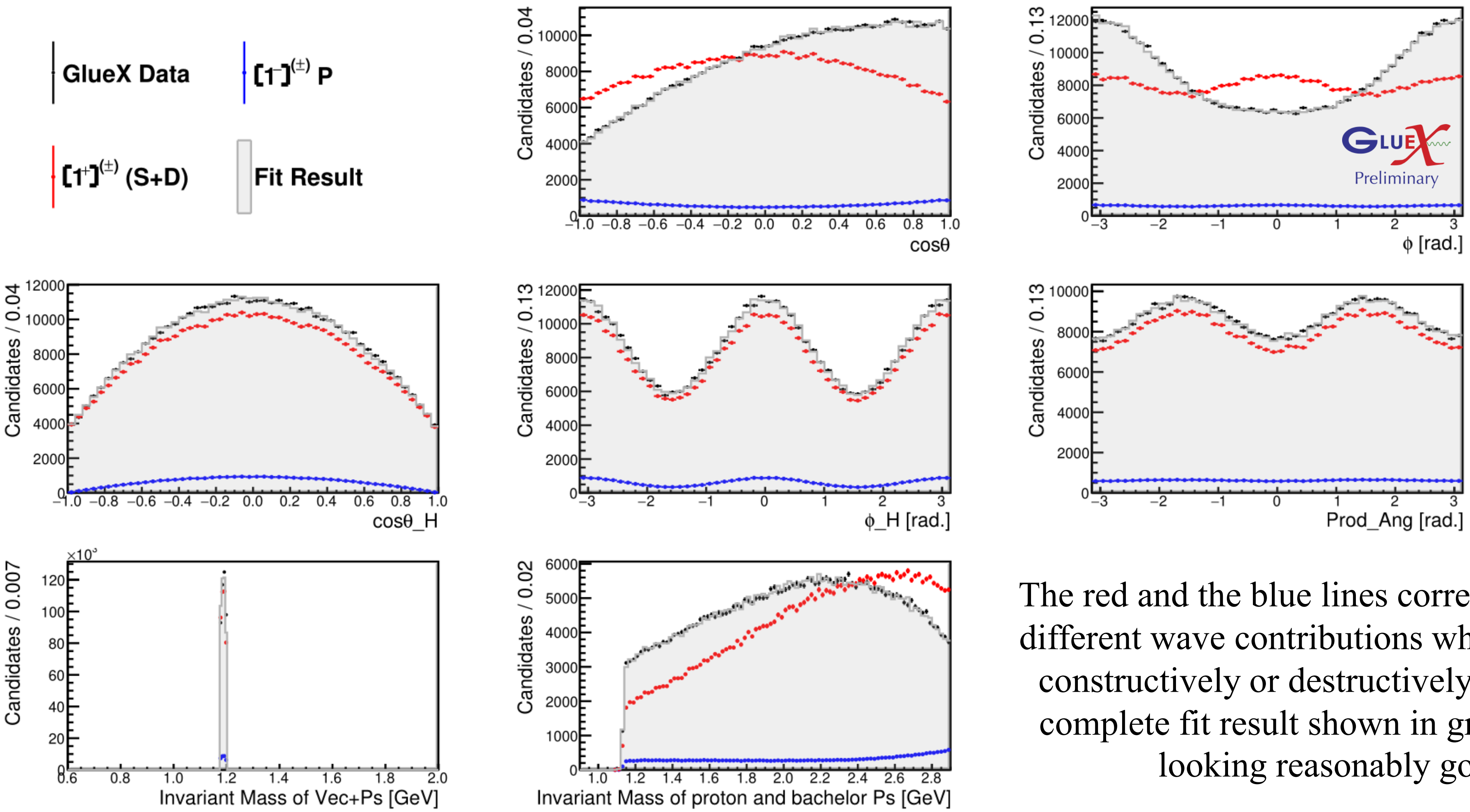
which can be solved to give:

$$I(\Omega,\Phi) = 2\kappa \sum_k \Bigg\{ (1-P_\gamma) \left| \sum_{l,m} [l]^{(-)}_{m;k} \Re[Z^m_l(\Omega,\Phi)] \right|^2 + (1-P_\gamma) \left| \sum_{l,m} [l]^{(+)}_{m;k} \Im[Z^m_l(\Omega,\Phi)] \right|^2$$
$$+ \ (1+P_\gamma) \left| \sum_{l,m} [l]^{(+)}_{m;k} \Re[Z^m_l(\Omega,\Phi)] \right|^2 + (1+P_\gamma) \left| \sum_{l,m} [l]^{(-)}_{m;k} \Im[Z^m_l(\Omega,\Phi)] \right|^2 \Bigg\}$$

Here,
each term is a coherent sum for each configuration of nucleon spin in reflectivity basis,
κ is the phase space factor,
k is the spin-flip (1) or spin non-flip (0) at nucleon vertex,
$P_\gamma \in [0,1]$ is the fraction of linear polarization of the beam,
l is the total angular momentum of the $\eta\eta'$ system,
$m = -l, \ldots, +l$ is the projection of l along z-axis, and
$Z^m_l(\Omega,\Phi) \equiv Y^m_l(\Omega)e^{-i\Phi}$ are the complex phase-rotated spherical harmonics, and
$[l]^{(\epsilon)}_{m;k}$ are the partial wave amplitudes, where $\epsilon = \pm 1$ is a reflectivity operator used in the framework of PWA to incorporate the principle of parity conservation in strong interaction processes involving polarized particles.

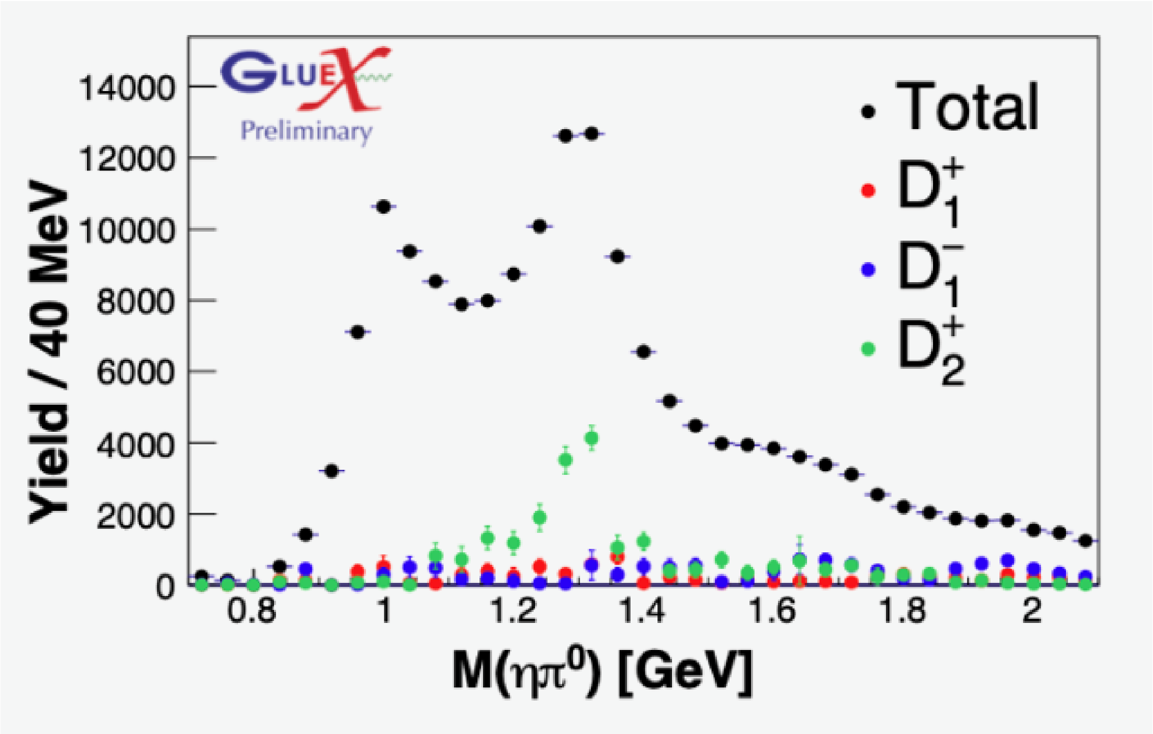
PWA in Action

$b_1 \to \omega\pi_0$



The red and the blue lines corresponds to the different wave contributions which interfere, constructively or destructively, to give the complete fit result shown in grey, and it is looking reasonably good.

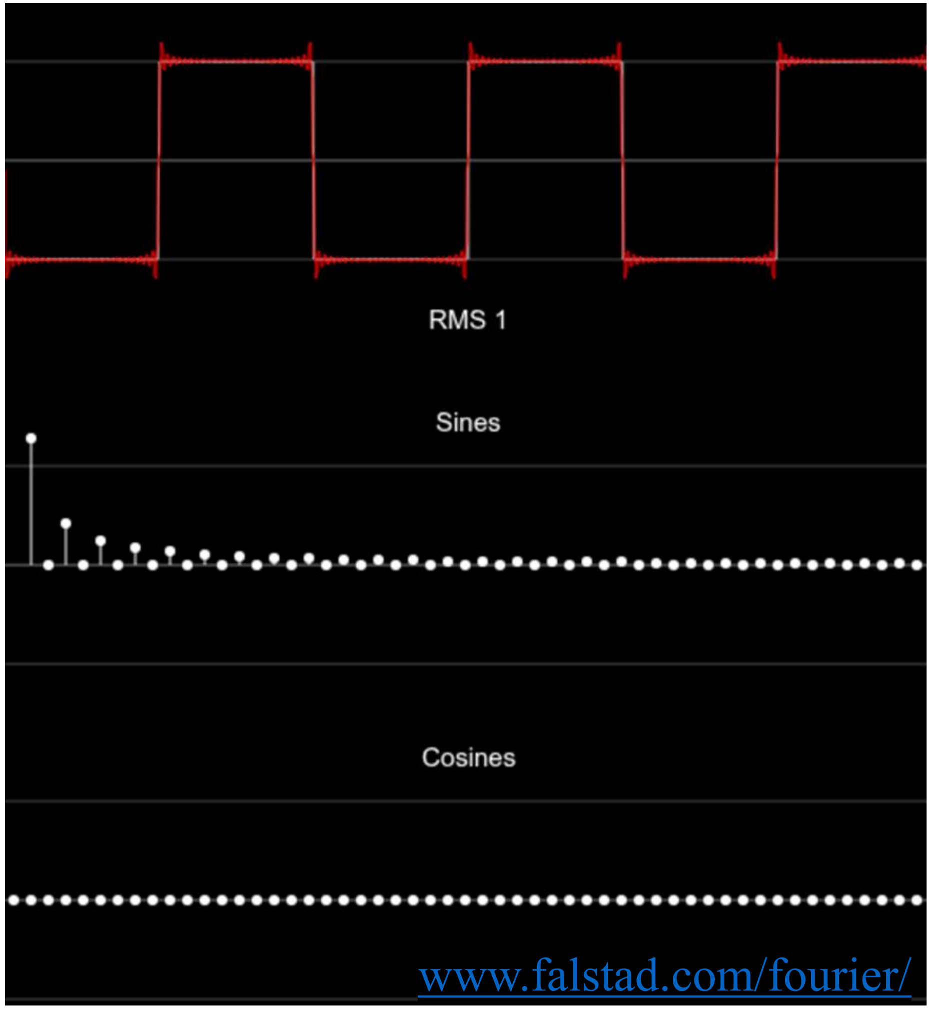
PWA in Action



Analogy of PWA with Fourier Analysis

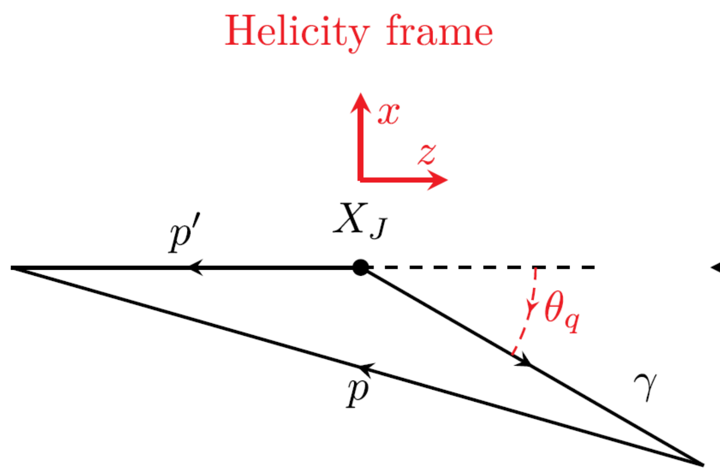
$$f(x) = \begin{cases} -1, & -\pi < x < 0, \\ +1, & 0 < x < \pi. \end{cases}$$

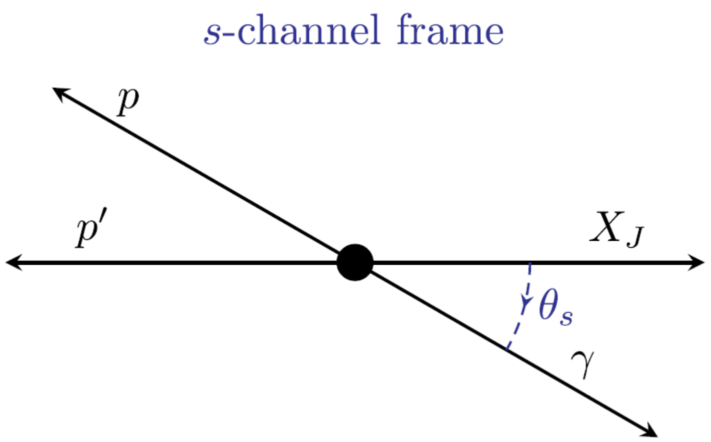
$$f(x) = \frac{4}{\pi}\left(\sin x + \tfrac{1}{3}\sin 3x + \tfrac{1}{5}\sin 5x + \cdots\right)$$



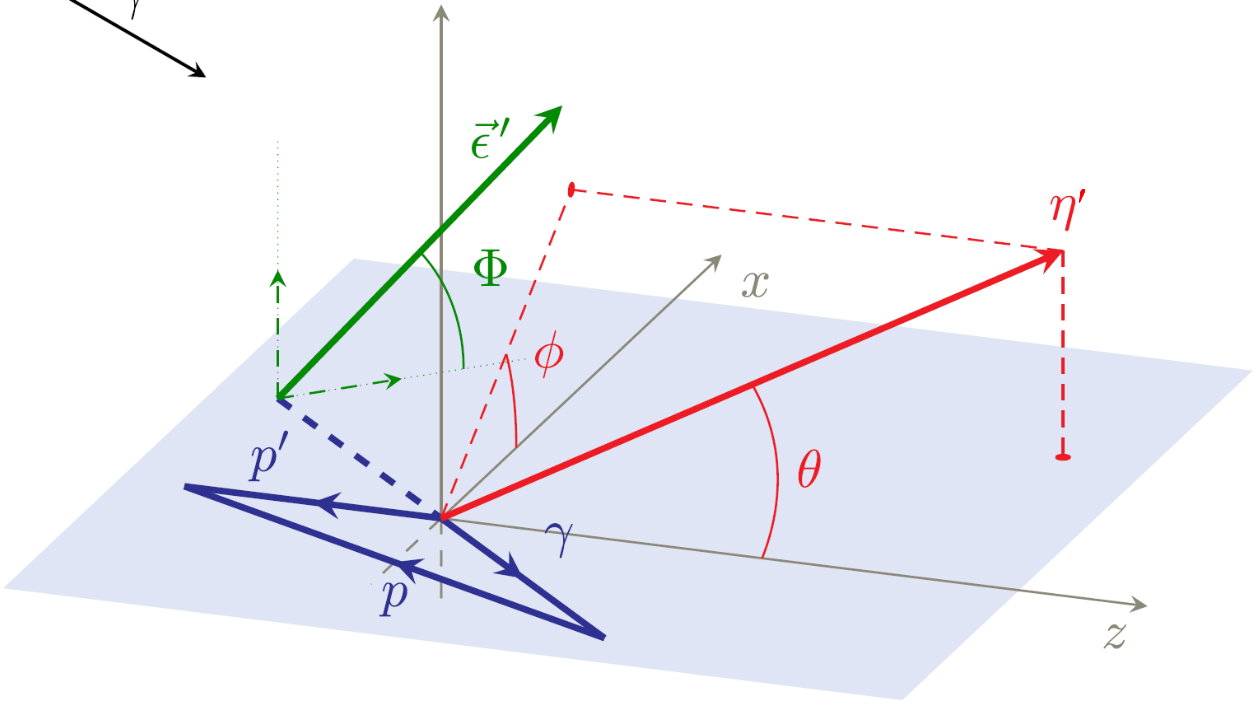
www.falstad.com/fourier/

Angles Description for PWA





p: initial proton
γ: photon beam
p: recoiling proton
X_J: resonance of Spin J
Φ: polarization angle wrt reaction plane
Ω = (θ,ϕ): polar and azimuthal angle of η'
in helicity frame



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η' & η Decay Modes

η' Decay	Branching Fraction
$\pi^+\pi^-\eta$	$(42.5 \pm 0.5)\%$
$\gamma\rho$	$(29.48 \pm 0.35)\%$
$\pi^0\pi^0\eta$	$(22.4 \pm 0.5)\%$
$\gamma\omega$	$(2.52 \pm 0.07)\%$
$\gamma\gamma$	$(2.307 \pm 0.033)\%$

η Decay	Branching Fraction
$\gamma\gamma$	$(39.36 \pm 0.18)\%$
$\pi^0\pi^0\pi^0$	$(32.56 \pm 0.21)\%$
$\pi^+\pi^-\pi^0$	$(23.02 \pm 0.25)\%$
$\gamma\pi^+\pi^-$	$(4.28 \pm 0.07)\%$

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Particles of Interest

Particle	J^P/J^{PC}	Mass (MeV/c^2)	Composition
γ	1^{--}	0	gauge boson
p	$\frac{1}{2}^+$	938.3	uud
π^+	0^-	139.6	$u\bar{d}$
π^-	0^-	139.6	$d\bar{u}$
η	0^{-+}	547.9	$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$
η'	0^{-+}	957.8	$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$
e^-	$\frac{1}{2}^+$	0.511	lepton
e^+	$\frac{1}{2}^-$	0.511	anti-lepton
J/ψ	1^{--}	3096.9	$c\bar{c}$
$\pi_1(1^{-+})$	1^{-+}	1350–1600	exotic (non-$q\bar{q}$)
$\eta_1(1855)$	1^{-+}	1855^{+11}_{-9}	exotic (non-$q\bar{q}$)

Table of particles of interest, their relevant quantum numbers, masses (rounded), and composition.

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