# Study of $b_1(1235)$ meson decay via the $\omega\pi^0$ channel at GlueX

CAP CONGRESS 2025

Harsimran Singh[1], Justin Stevens[2], Karthik Suresh[2], Kevin Scheuer[2], Zisis Papandreou[1]

on behalf of the GlueX Collaboration

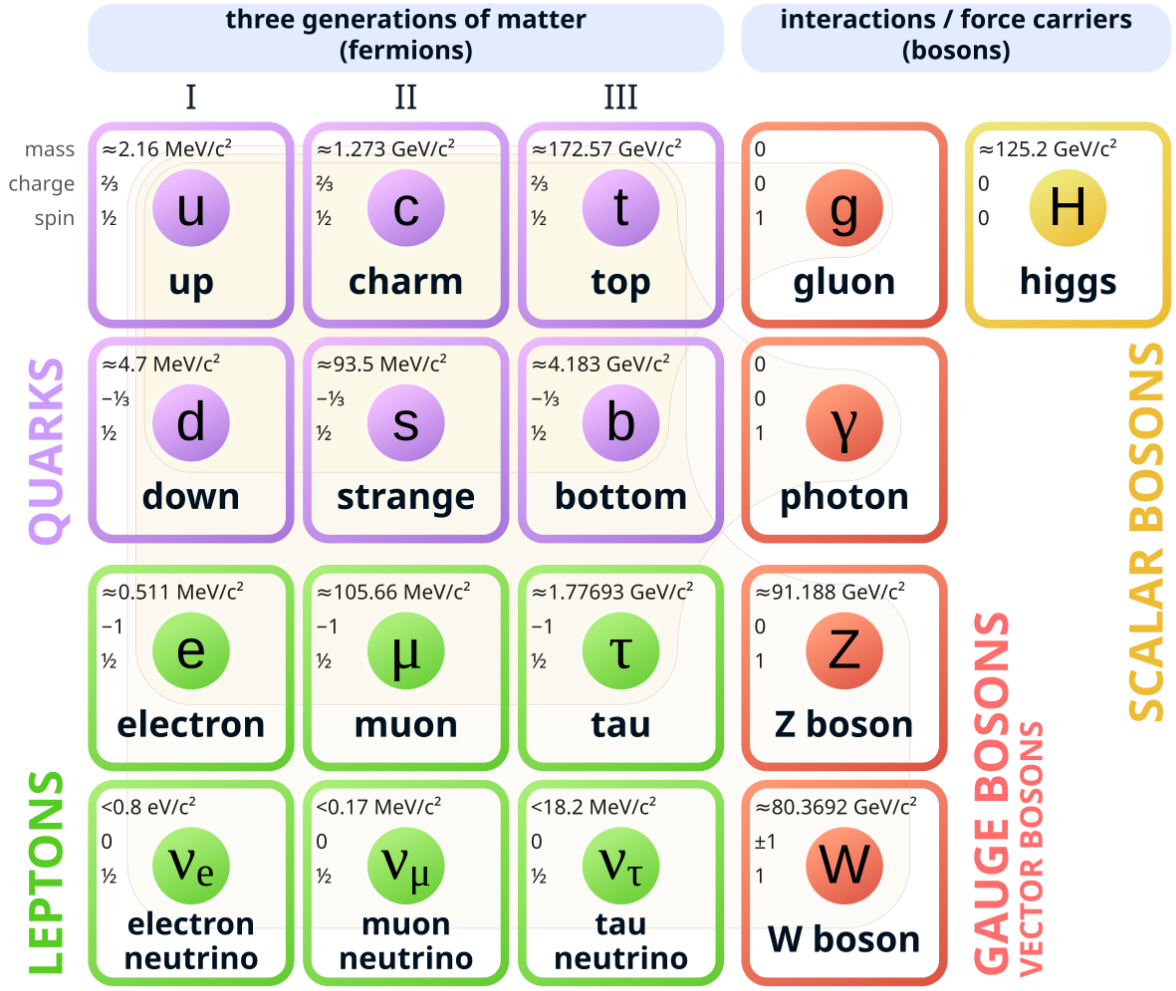
[1]Department of Physics, University of Regina, Saskatchewan, Canada
[2]Department of Physics, William & Mary, Virginia, USA

# Introduction

## The ‘current’ Standard Model of Particle Physics

It describes:

- Strong Interactions
- Weak Interactions
- Electromagnetic Interactions



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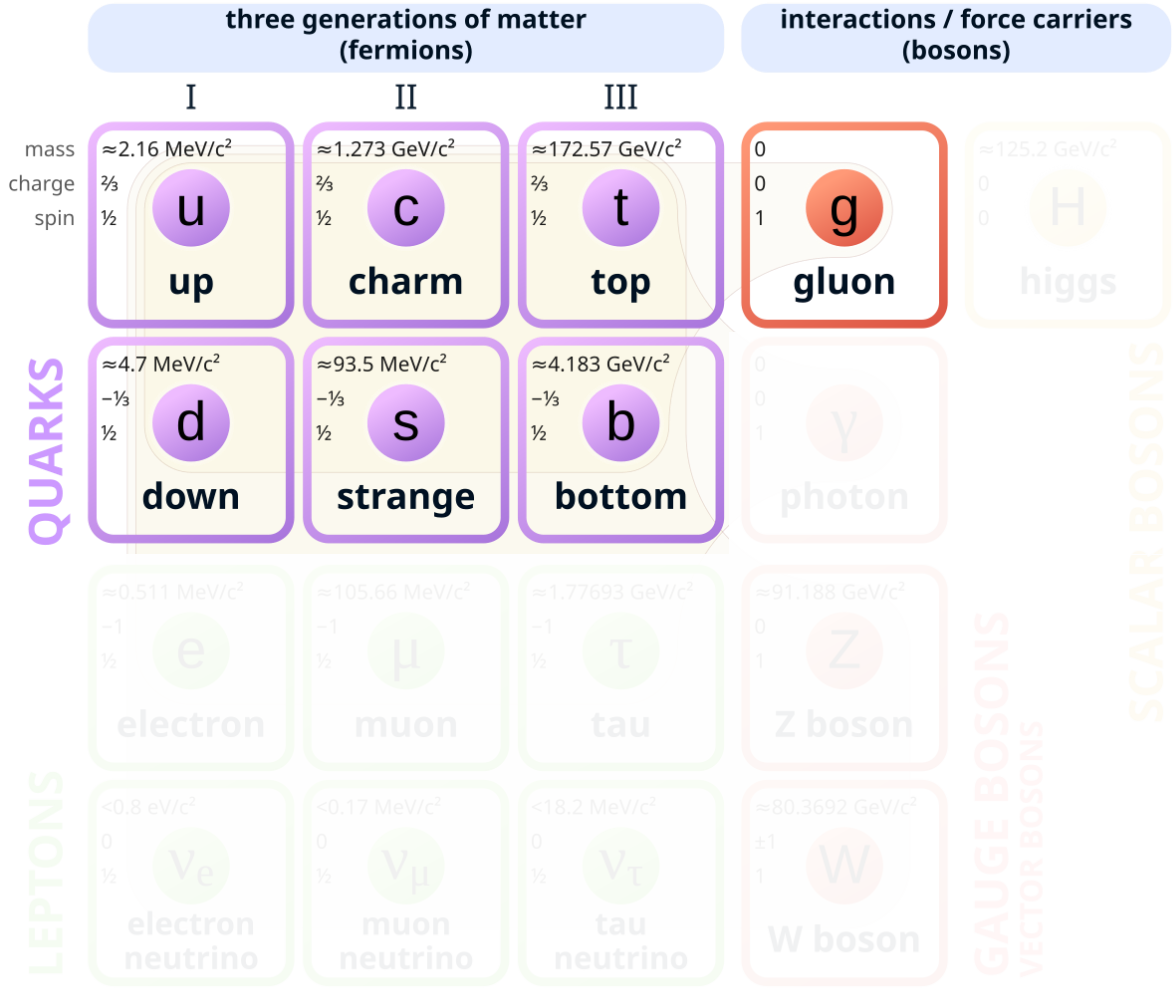

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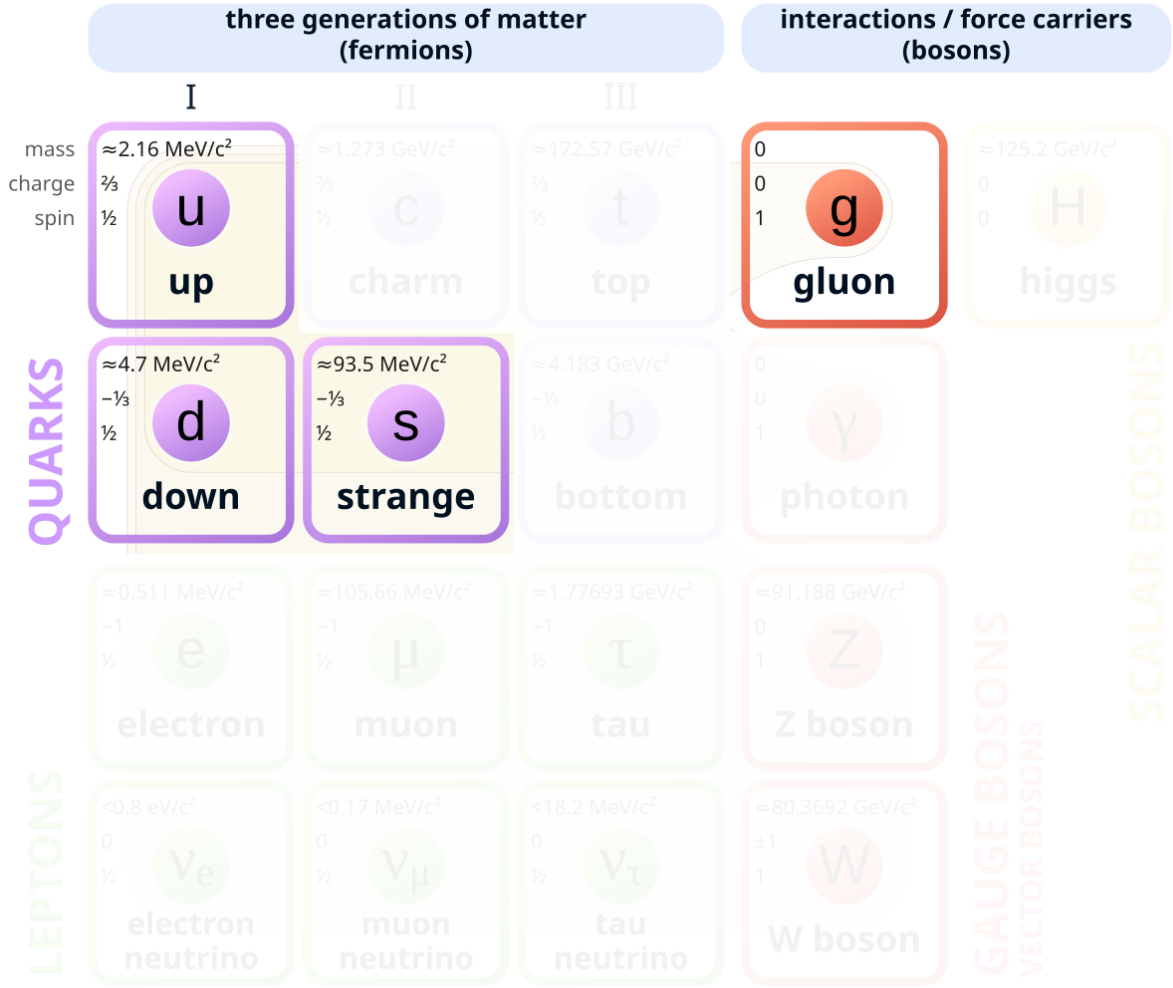
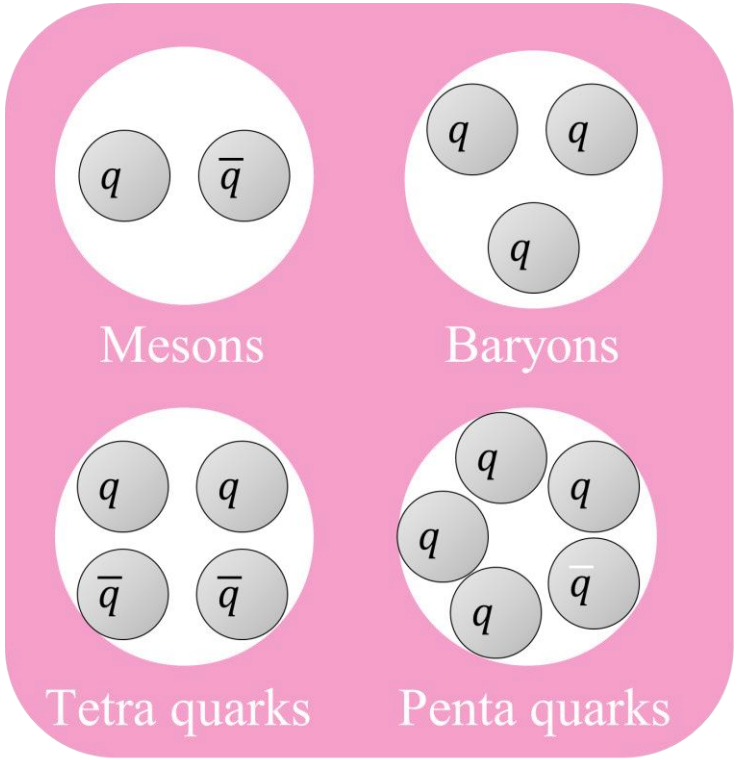
This talk will focus on Light Hadron Spectroscopy.



# Theoretical Background

## Quark Model: The first theory of Strong Interactions



# Theoretical Background

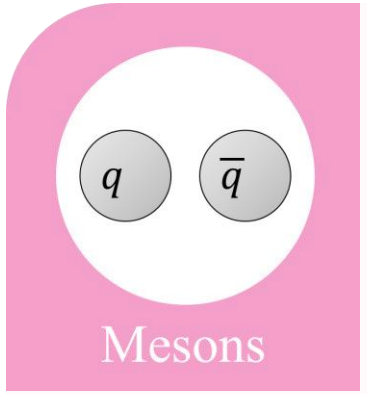
## Quark Model: The first theory of Strong Interactions

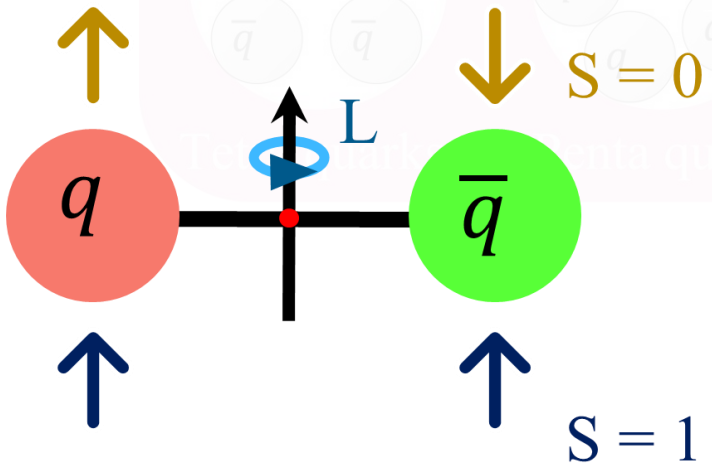
Mesons can be categorized by $J^{PC}$ ($I^{G}$).

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

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

Incomplete Theory!

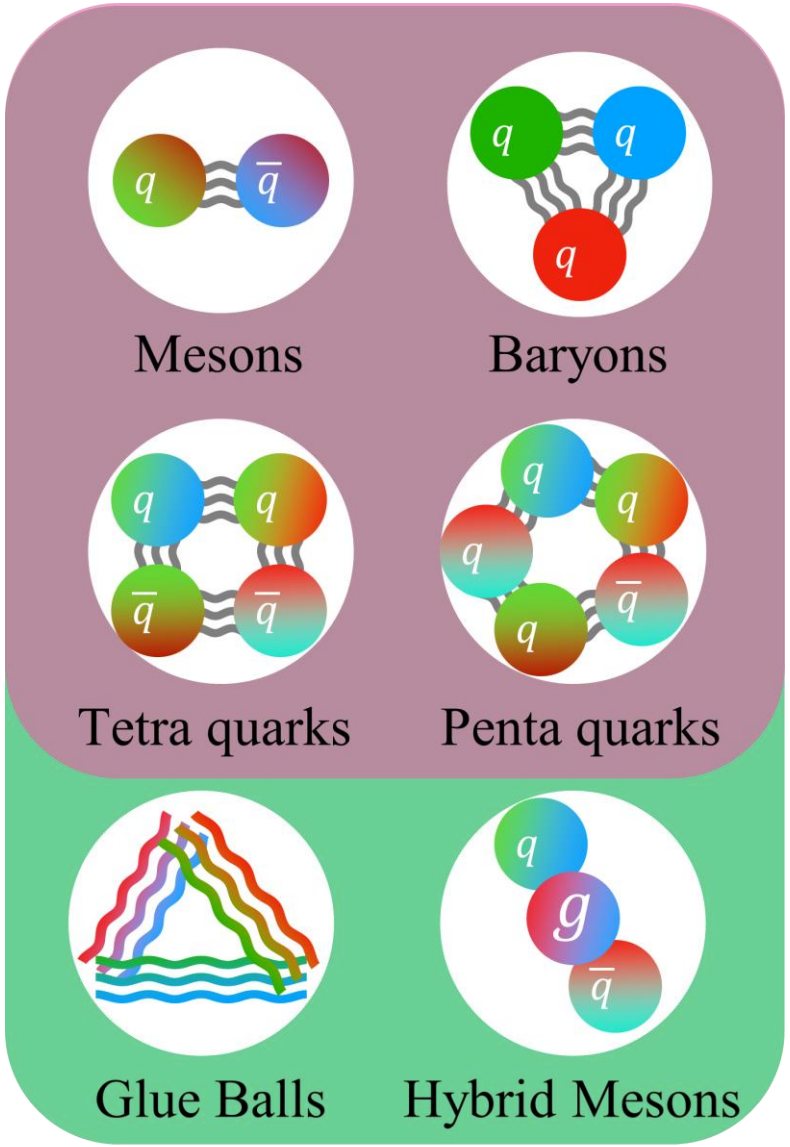


# Theoretical Background

## Quantum Chromodynamics (QCD)

- Quarks interact via exchange of gluons.
- Introduces a color charge degree of freedom in quarks.
- Predicts
  - Hybrid Mesons
  - Exotic States
- Important outcomes:
  - Color confinement i.e. “Free” quarks cannot be observed.
  - Non negligible $\alpha_s$ at low energy scale i.e. “Lattice QCD”



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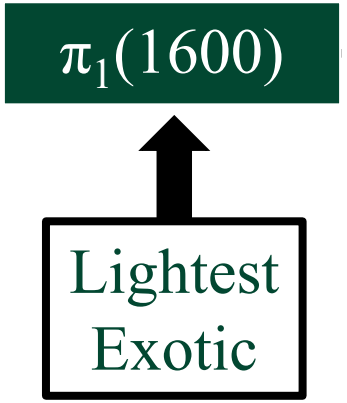
## Lattice QCD Predictions for Mesons



# Theoretical Background

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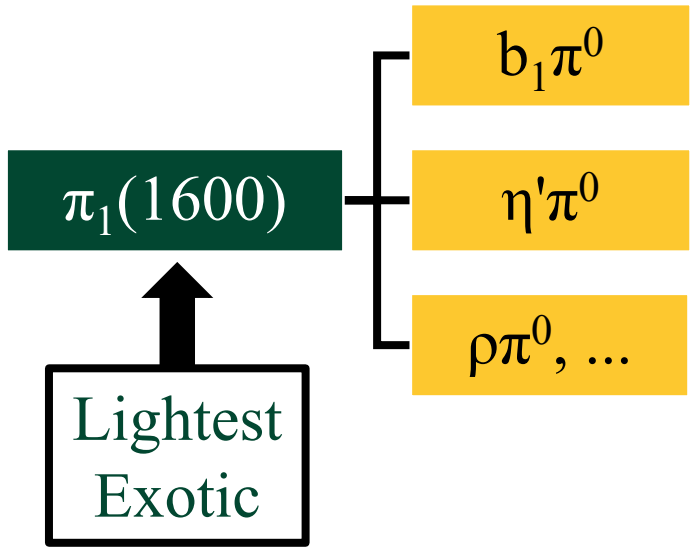

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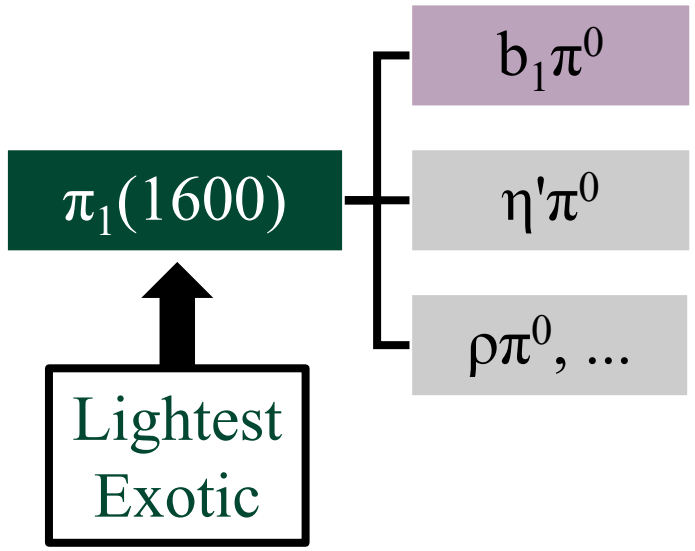
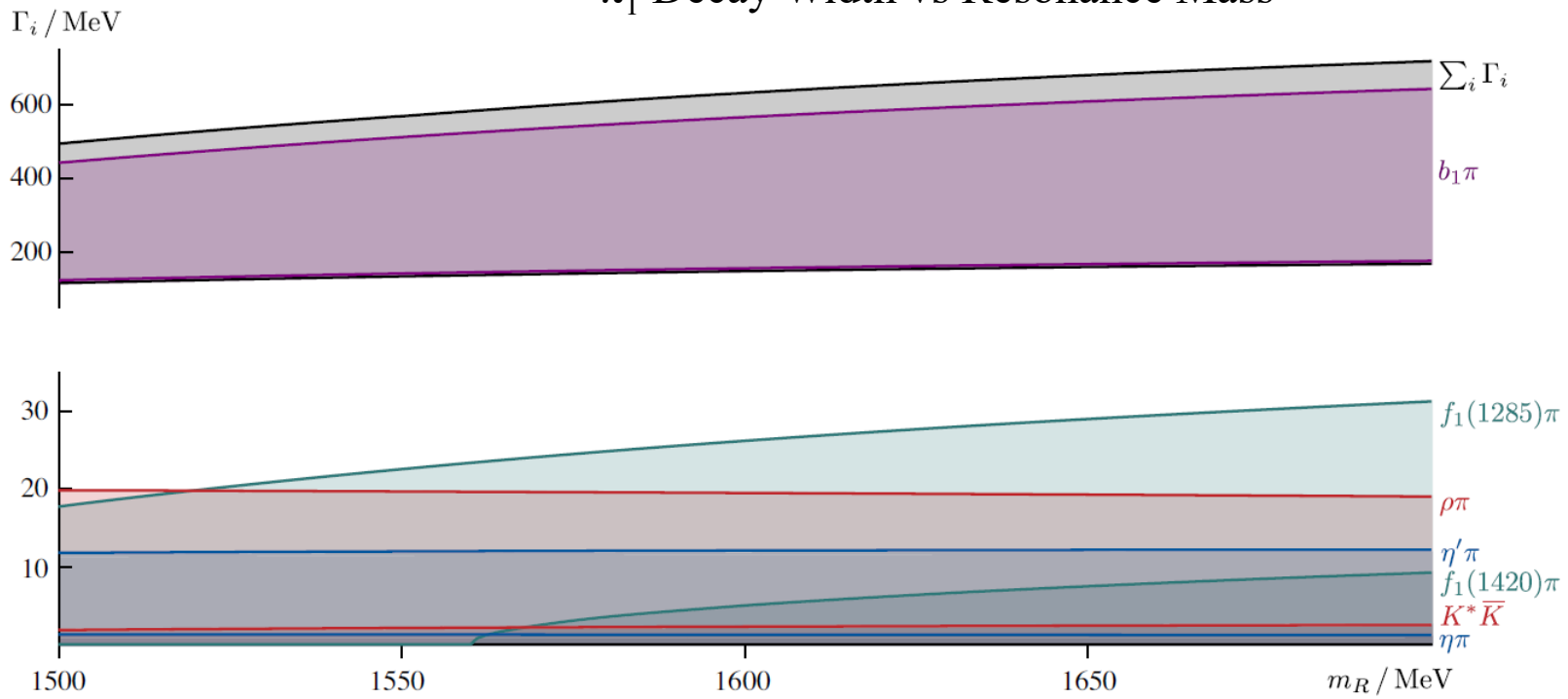



$\pi_1$ Decay Width vs Resonance Mass

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**Phys. Rev. D 103, 054502**

# Theoretical Background

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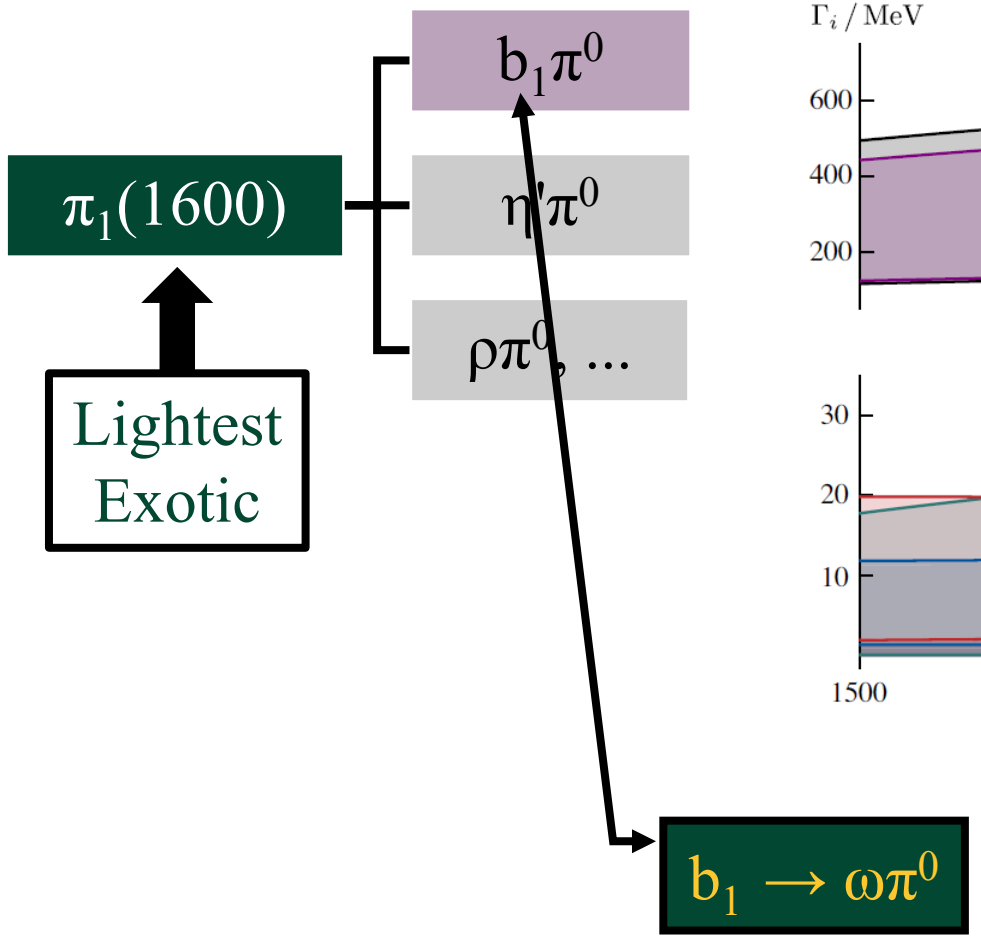


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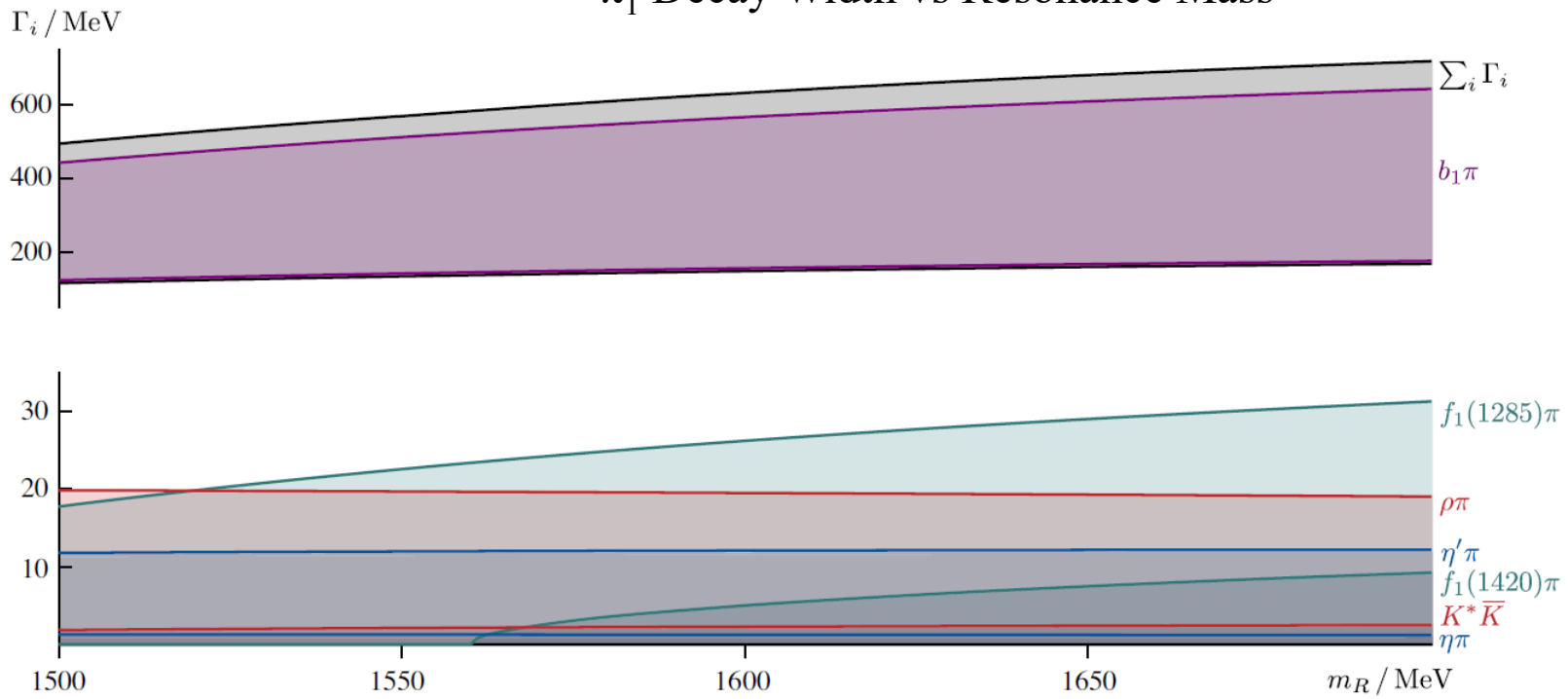


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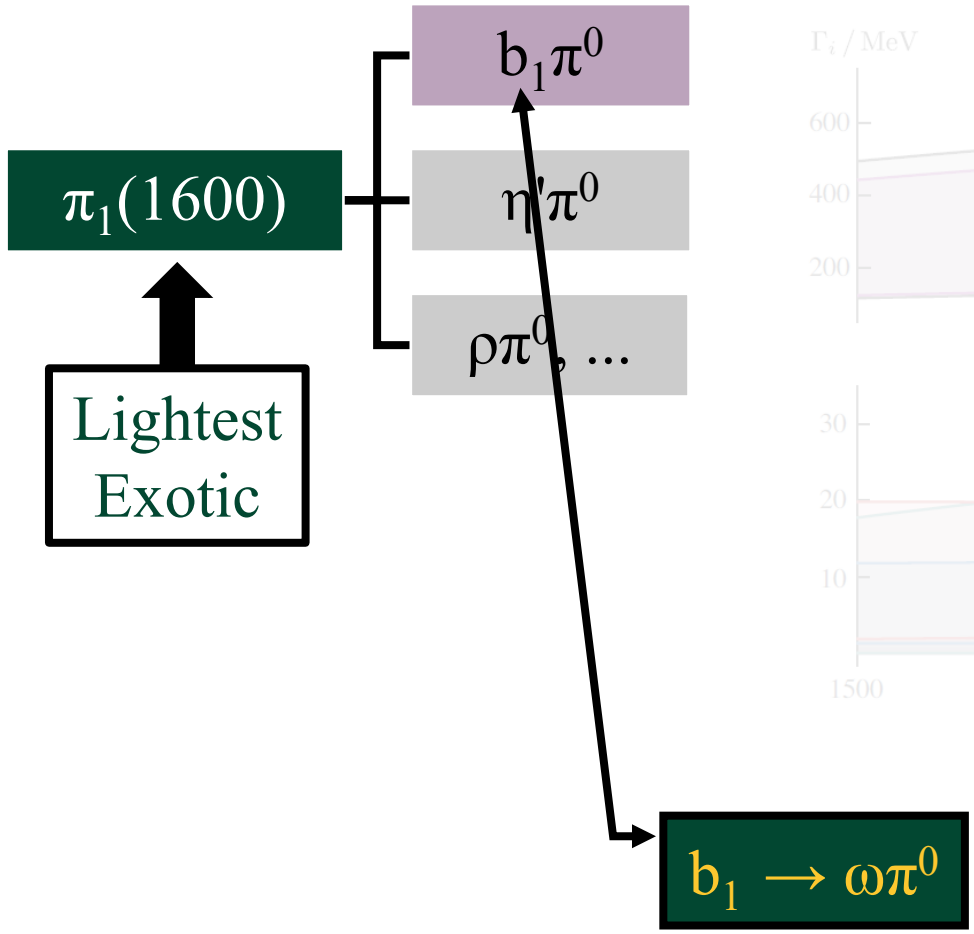
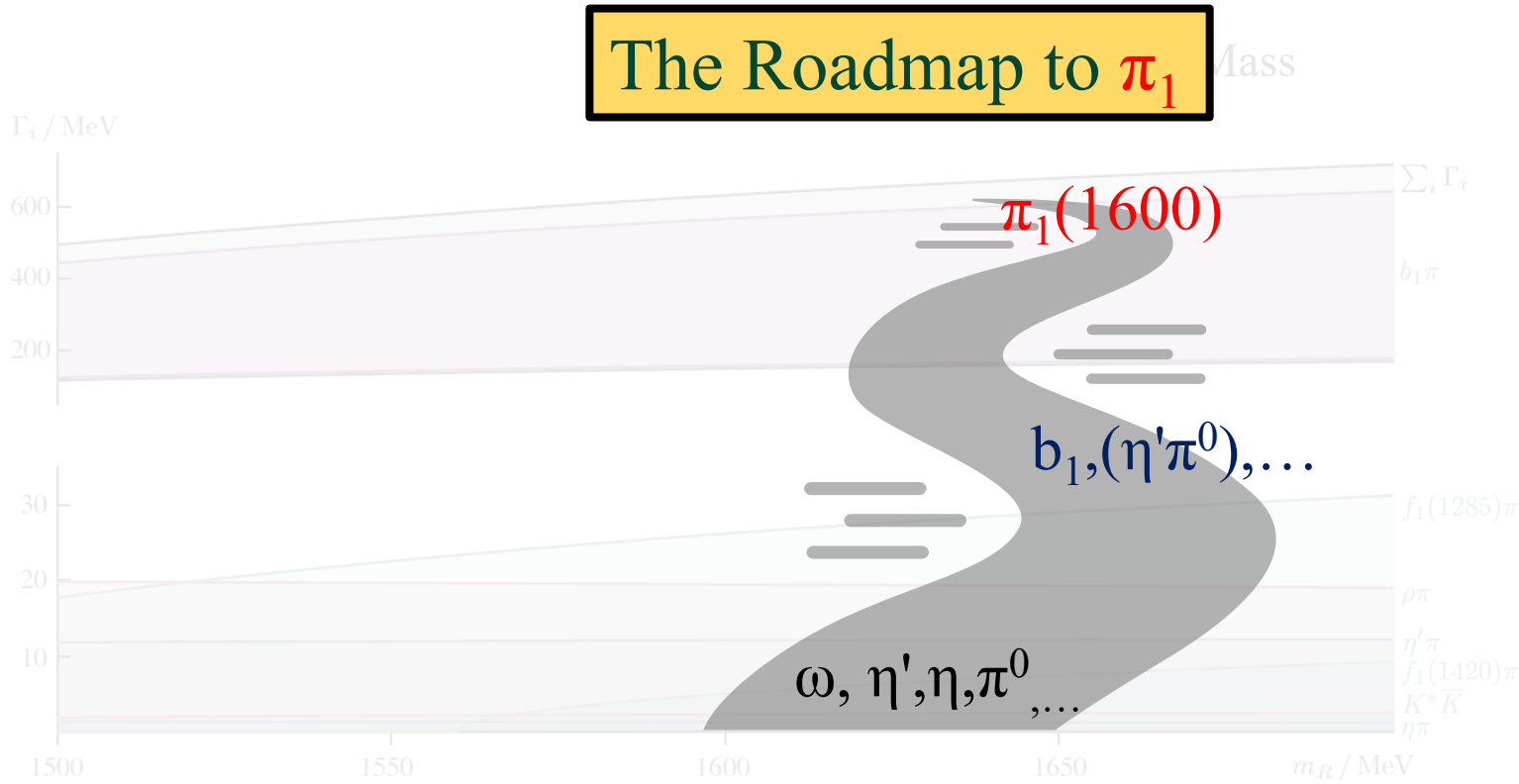
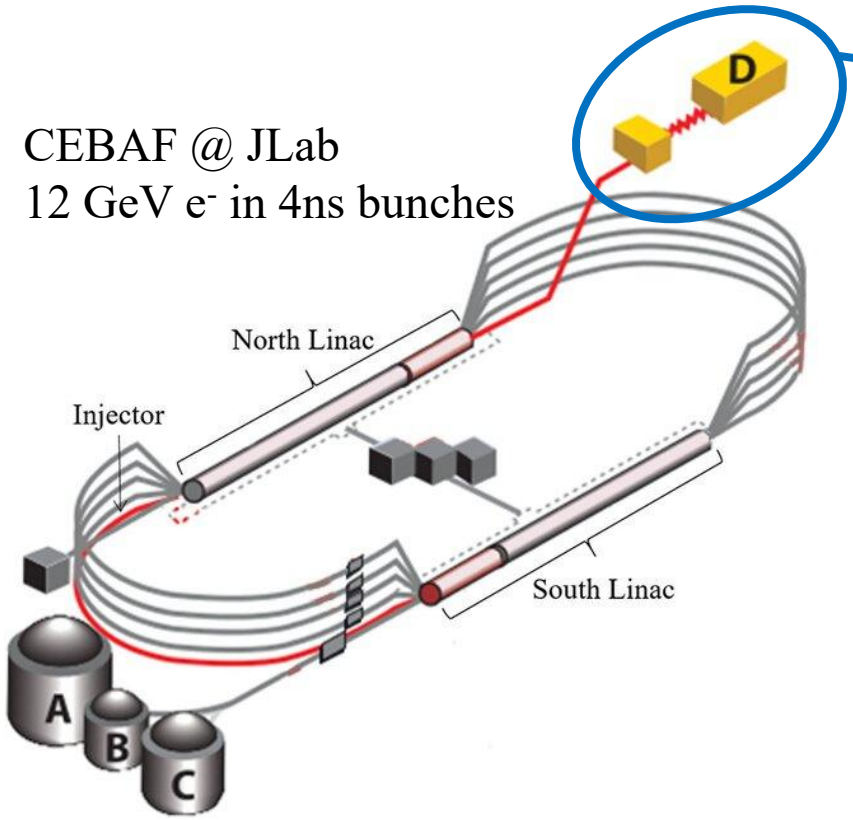


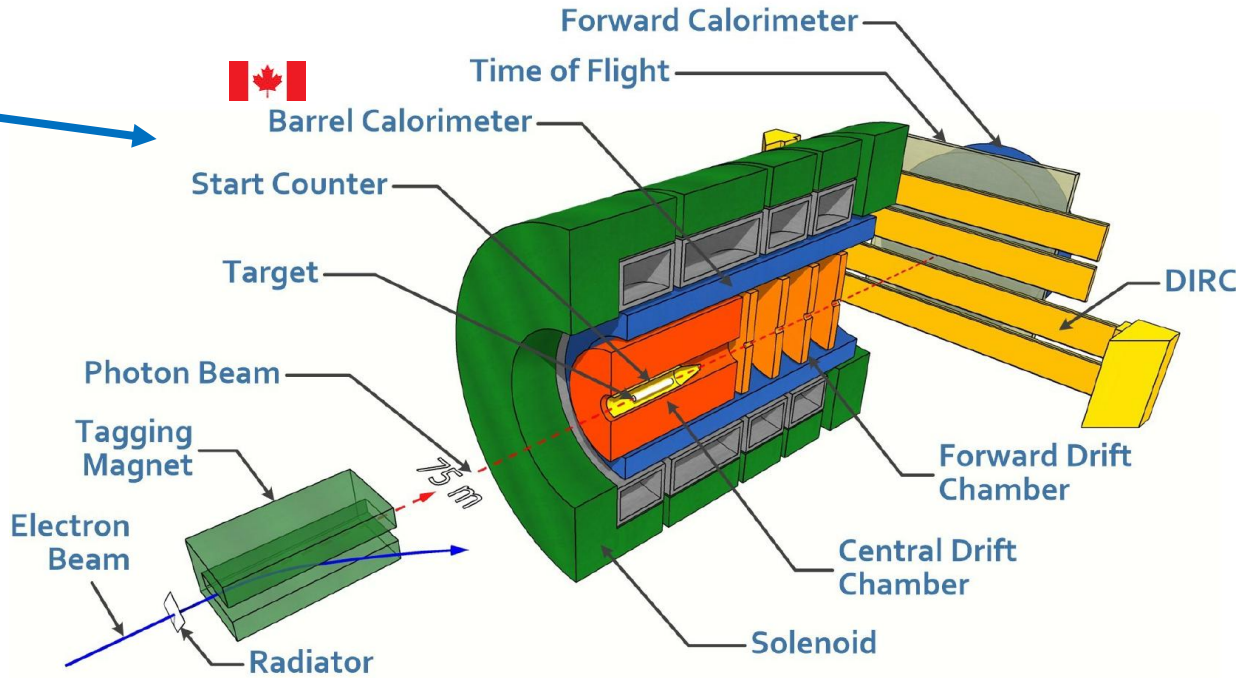



# The Experiment

A Photo-production Experiment @ Jefferson Lab Hall D

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



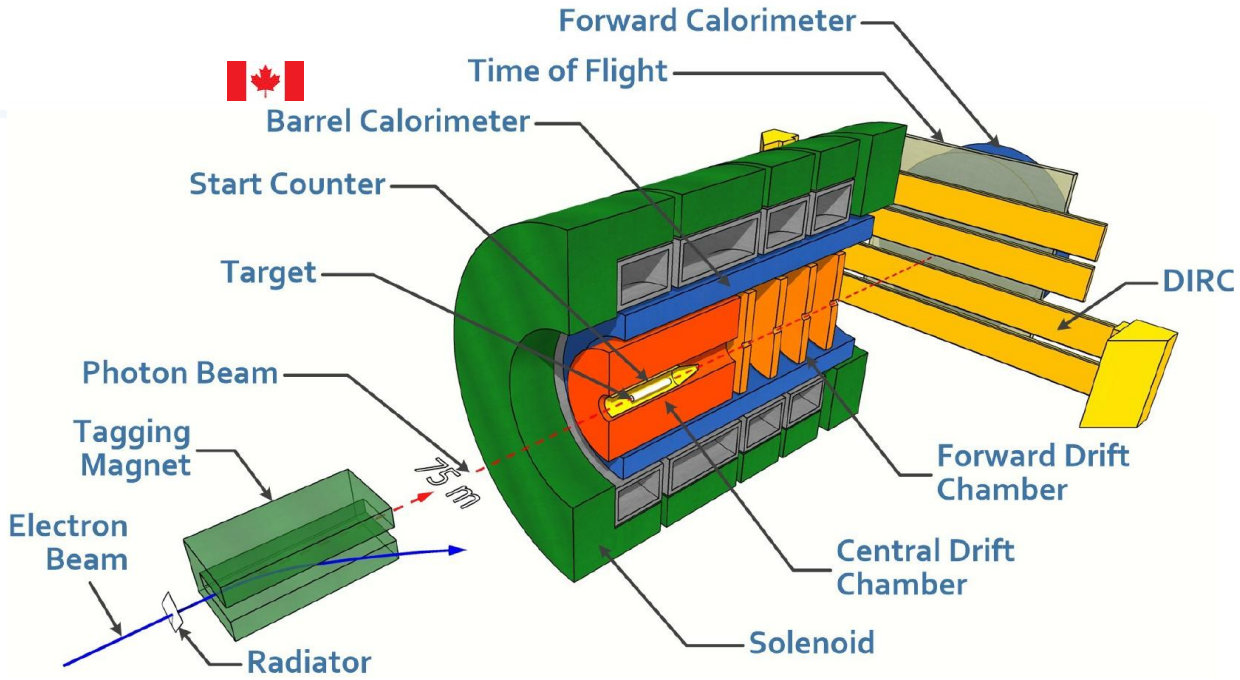



# The Experiment

A Photo-production Experiment @ Jefferson Lab Hall D

**Main Goals:**
- Map light meson spectrum
- Search for hybrid mesons

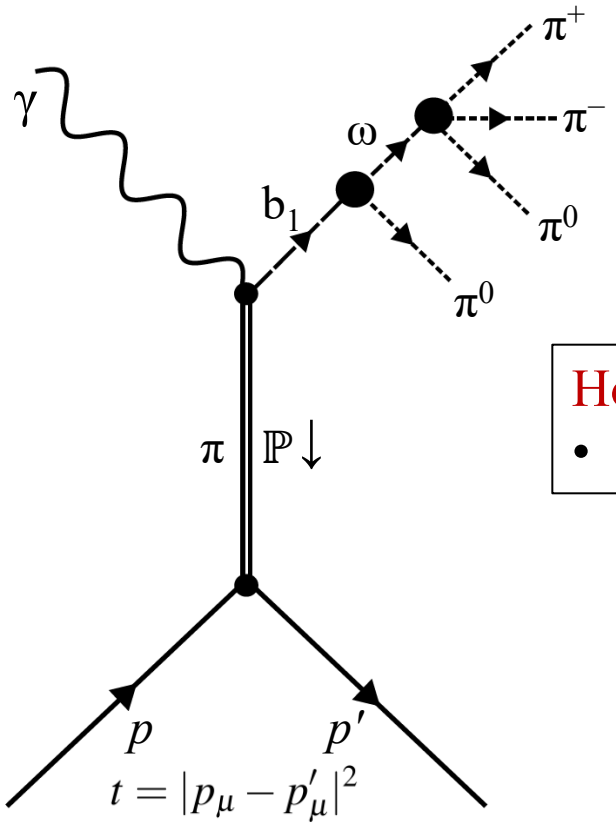
- 6-12 GeV γ beam energy
- Linearly polarized photons in 4 orientations (0,45,90,135)
- Peak Polarization ~35% @ 8.8 GeV
- $LH_2$ target



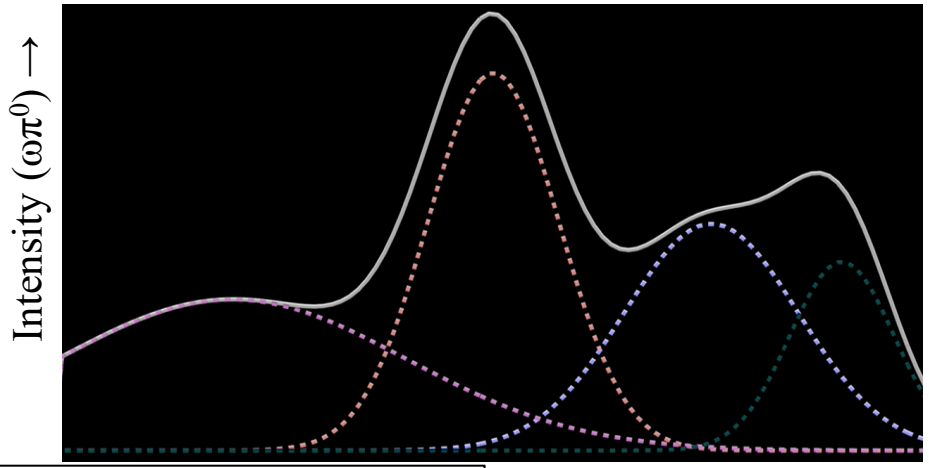

Detector system offers nearly 4π coverage!

# Partial Wave Analysis

$$\gamma p \to (b_1)p' \to (\omega\pi^0)p' \to ((\pi^+\pi^-\pi^0)\pi^0)p'$$




Mesons: $J^{PC}$




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

- Using "only" mass spectrum is incomplete.

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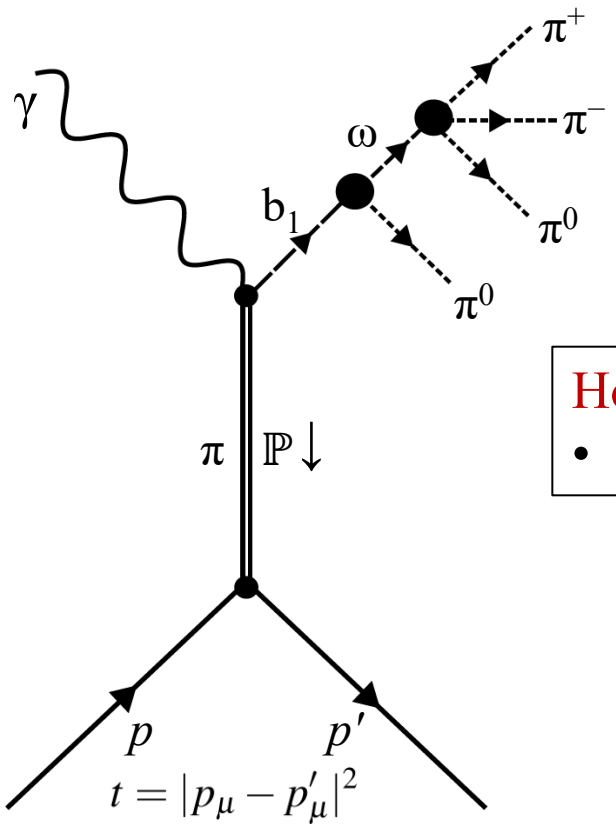


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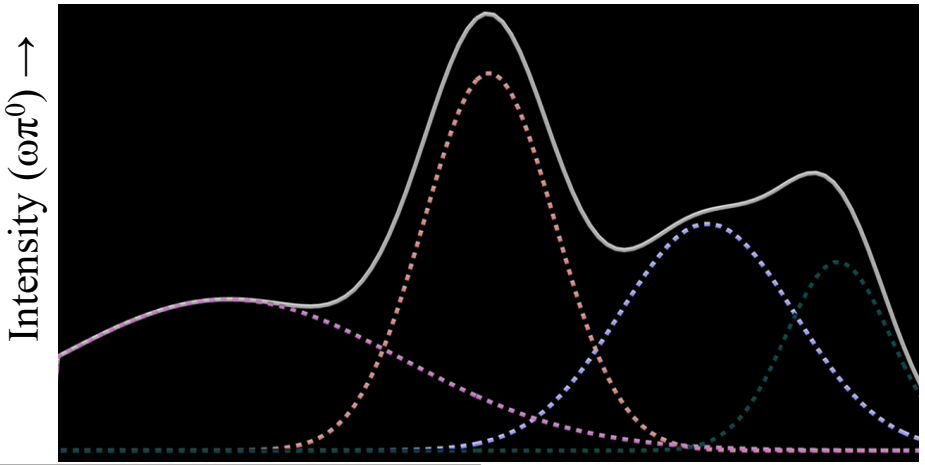


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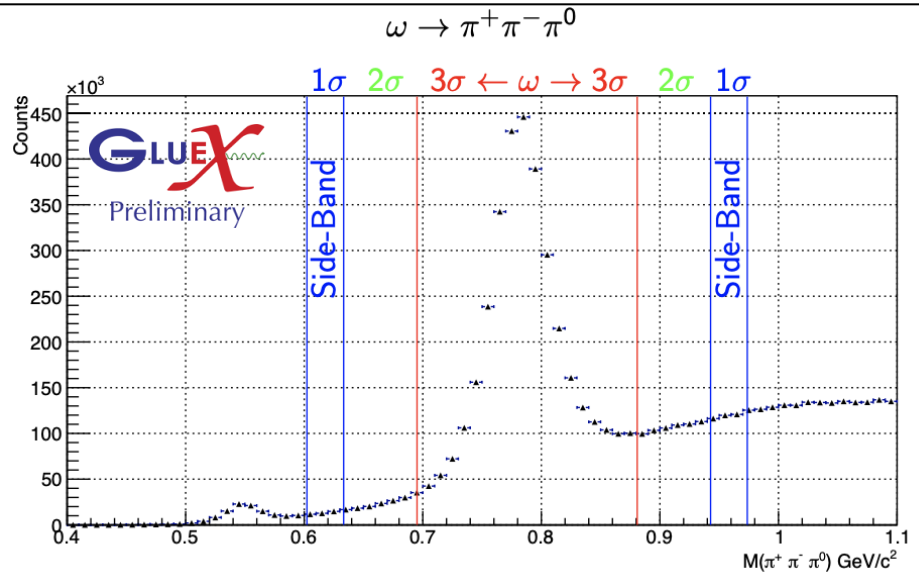


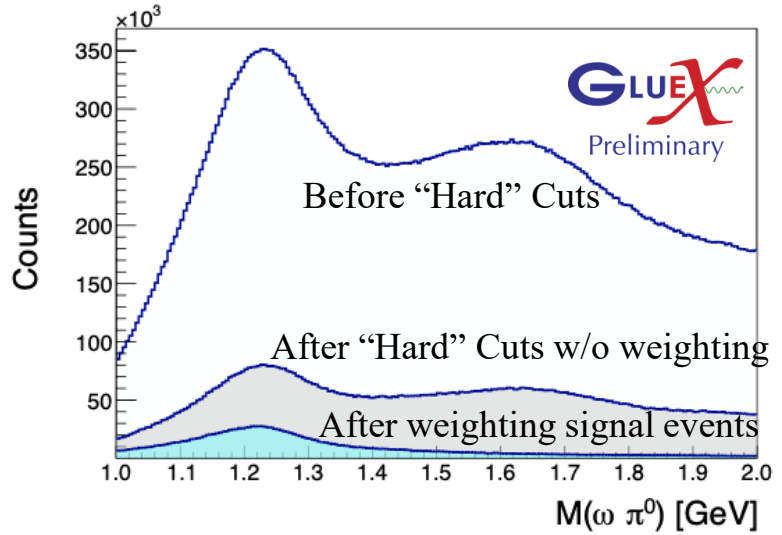

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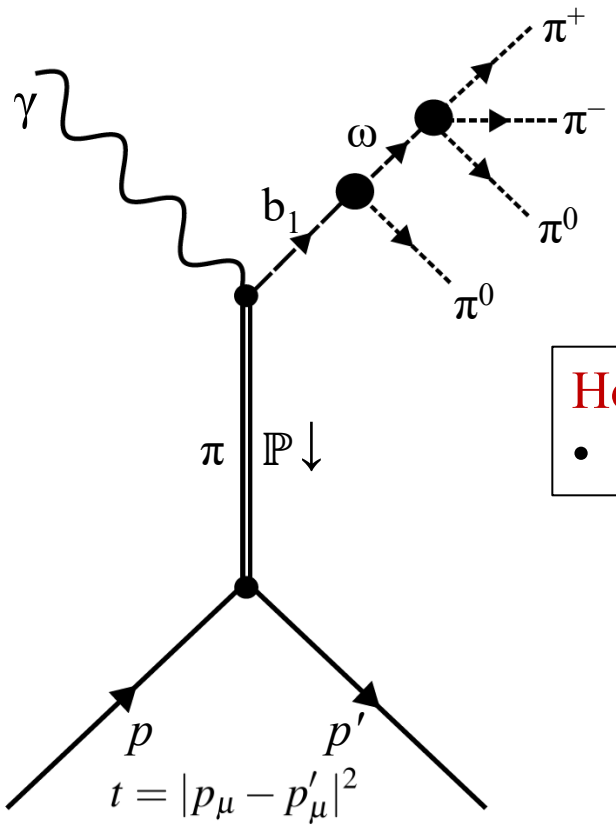


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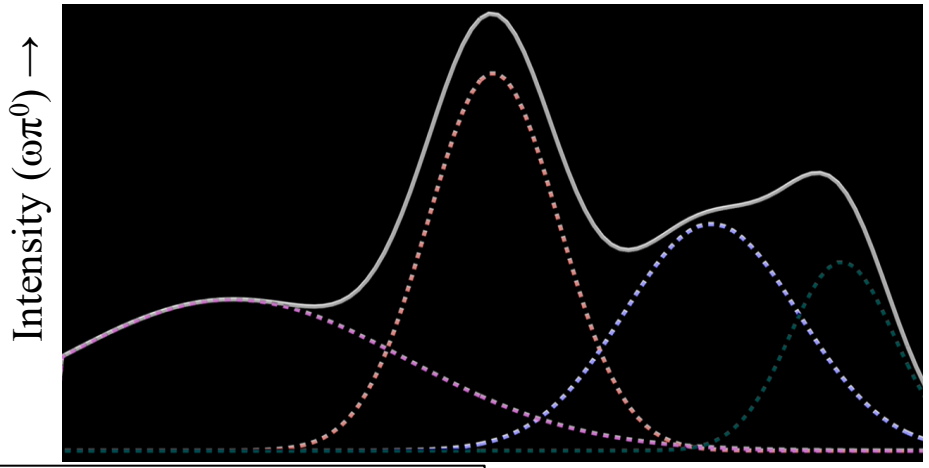


How to extract contributions from various $J^{PC}$ from this spectrum?

- 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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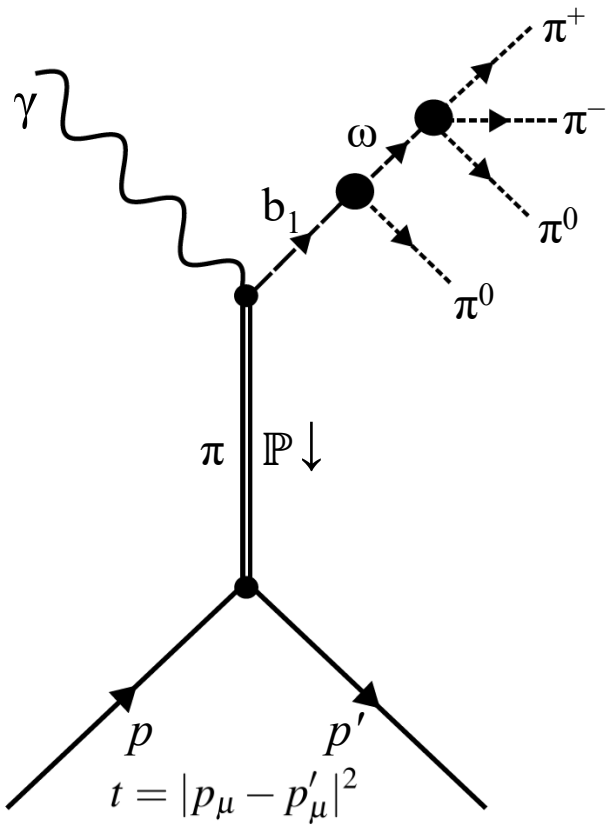


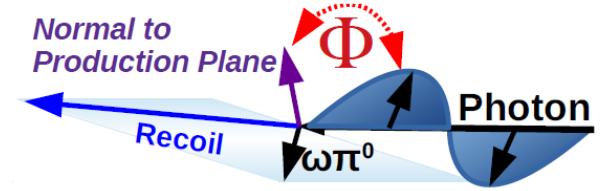





PWA - A tool that extracts contribution of $J^{PC}$ by studying intensity in multiple decay angles

Intensity, $I(\theta,\varphi,\theta_H,\varphi_H,\Phi_{prod})$

# Partial Wave Analysis

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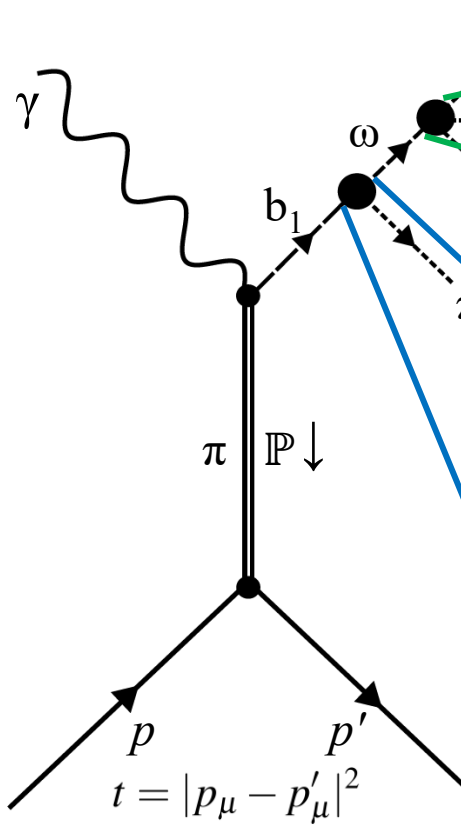
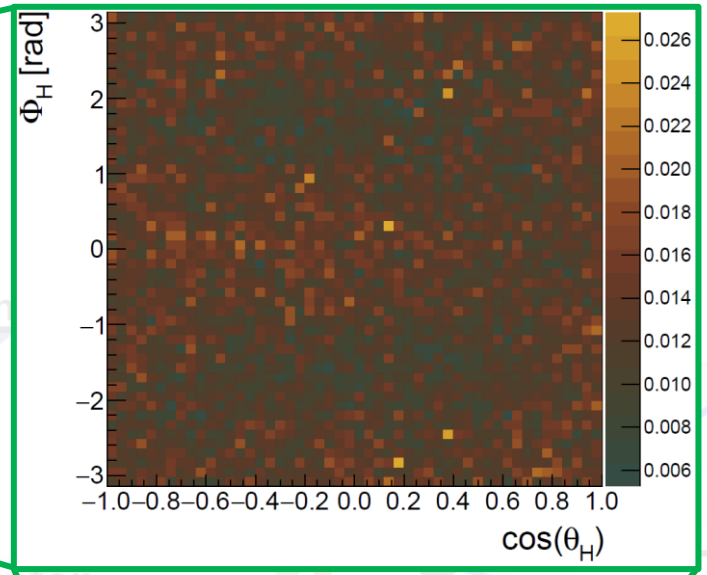
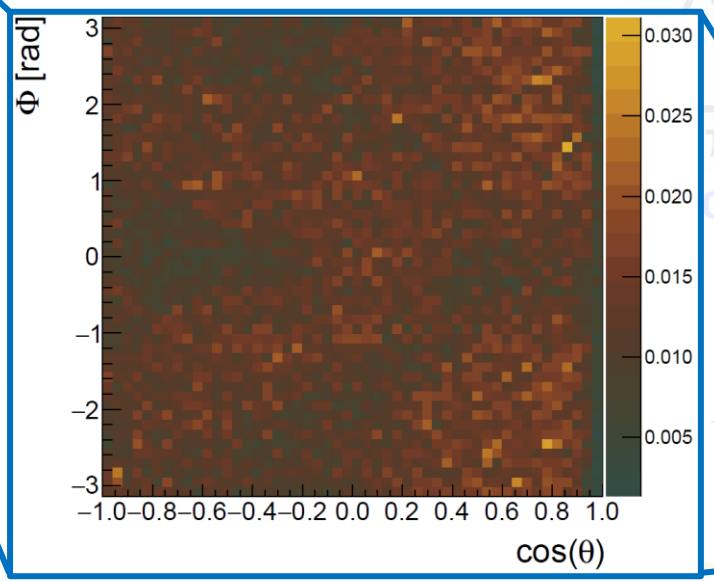



$\Omega_H(\theta_H,\varphi_H)$




$\Omega(\theta,\varphi)$




Intensity, $I(\theta,\varphi,\theta_H,\varphi_H,\Phi_{prod})$

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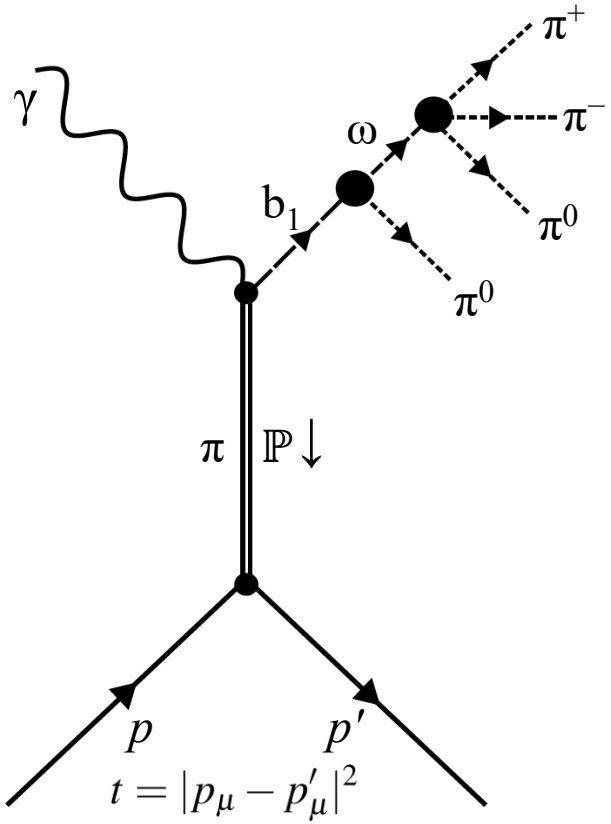



In "thin" M($\omega\pi^0$) and $|t|$ bin

$$I(\Omega,\Omega_H,\Phi) = \frac{\kappa}{4}(1-P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)+\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2 + \frac{\kappa}{4}(1+P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)-\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2$$

$$\tilde{A}_\pm = \sum_{J_i=1,2,\ldots}\sum_{m=-J_i,\ldots,J_i} T^i_{\pm,m} \sum_{\lambda_\omega=-1,0,1} e^{\mp i\Phi} D^{J_i*}_{m,\lambda_\omega}(\Omega) F^i_{\lambda_\omega} D^{1*}_{m,0}(\Omega_H) G_{\text{Dalitz}}\,\mathfrak{F}(p_0)$$

Contains D/S Ratio of Amplitudes

A decay parameter specified by theory.

# Fitting Machinery & I/O Tests

## Data Selection

Beam E cut

↓

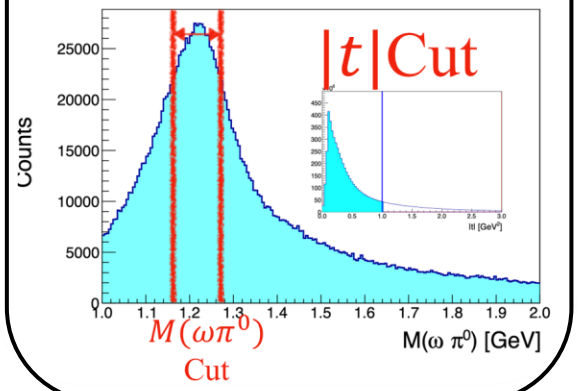
$|t|$ Cut

↓

$M(\omega\pi^0)$ Cut

↓

Make $p_4(\omega\pi^0)$ system




## AmpTools

- Unbinned Maximum Likelihood fitting

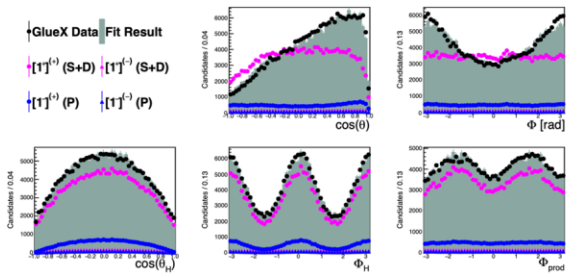
$$-2\ln\mathcal{L}(\theta) = -2\left(\sum_{i=1}^{N}\ln I(x;\theta) - \mu\right) + c_1$$

- Uses GPU computation with CUDA backend.
- Input Vectors + model params
- Eg. $[1^{+-}]^{(\pm)}, [1^{--}]^{\pm}$

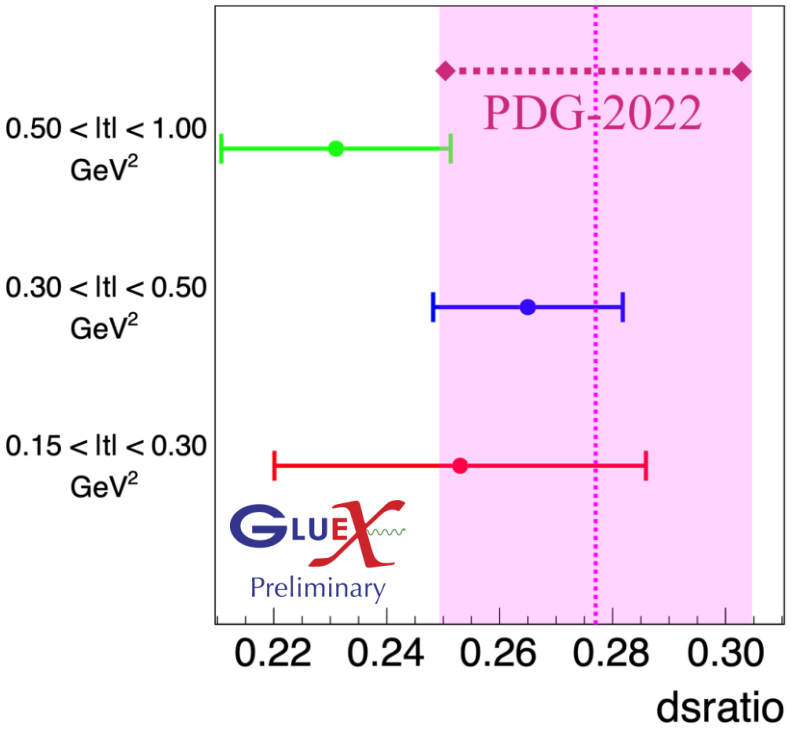
## Results

- Contribution of $J^{PC}$ state extracted by computing fit fractions from complex amplitudes

| Parameters | Input | Type | Fit Results |
|---|---|---|---|
| D/S ratio | 0.27 | float | 0.2697 ± 0.0062 |
| $[1^+]^{(+)}$ | 0 | Fit Fraction | 0.0100 ± 0.0005 |
| $[1^+]^{(-)}$ | 1 | Fit Fraction | 0.9871 ± 0.0065 |
| $[1^-]^{(+)}$ | 0 | Fit Fraction | 0.0020 ± 0.001 |
| $[1^-]^{(-)}$ | 0 | Fit Fraction | 0.0009 ± 0.0003 |



# Results




Agrees with previous experiments' measurements.

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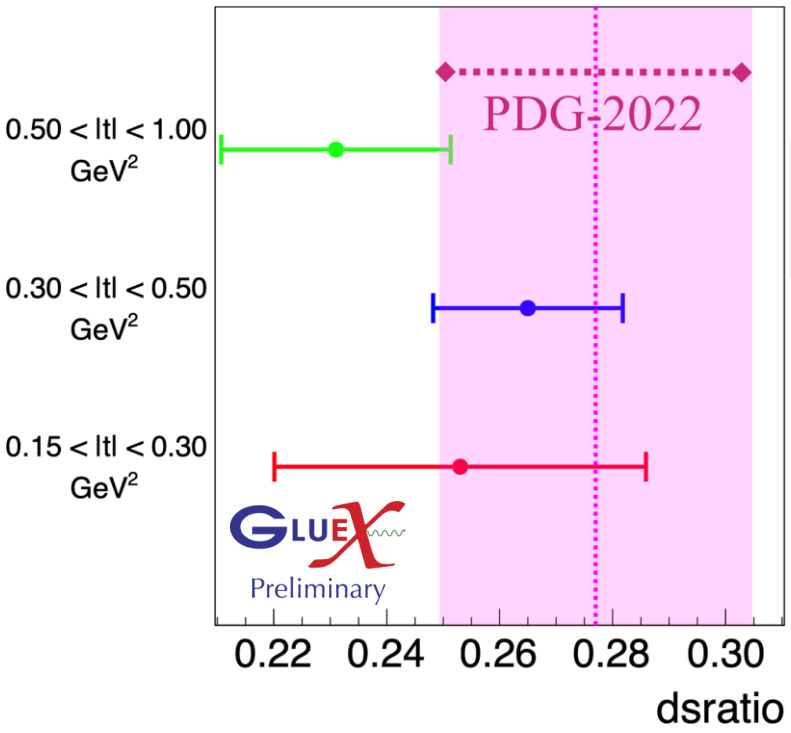
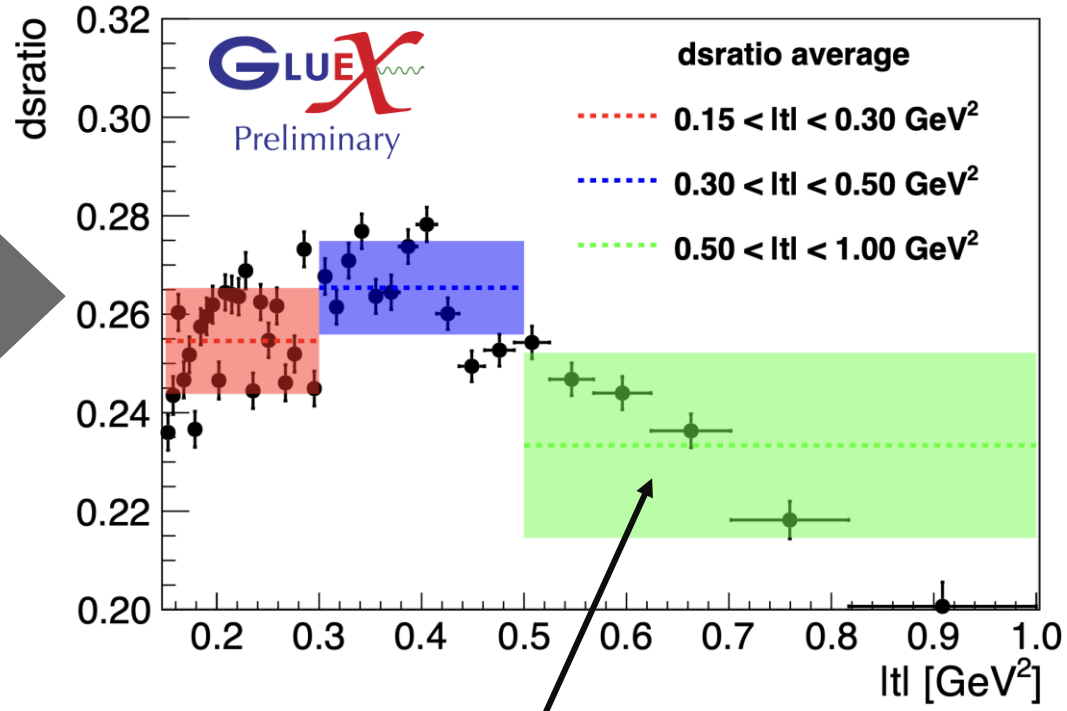



Looking in finer $|t|$ bins




Agrees with previous experiments' measurements.

Strong monotonic decrease at high $|t|$

D/S ratio: A decay parameter so expected to be independent of $|t|$

# Summary

- PWA effectively extracts $J^{PC}$ contributions
- This work:
  - D/S Ratio consistent with PDG & theoretical prediction
  - A strong correlation found in D/S Ratio as a function of $|t|$
  - Unprecedented statistical precision; systematics dominate
- Future Work:
  - Compare to charged $b_1$ ($\gamma p \rightarrow b_1 \Delta^+$)
  - Extract cross-sections → input to theory
  - Access to excited vectors in higher mass range

Thank You!

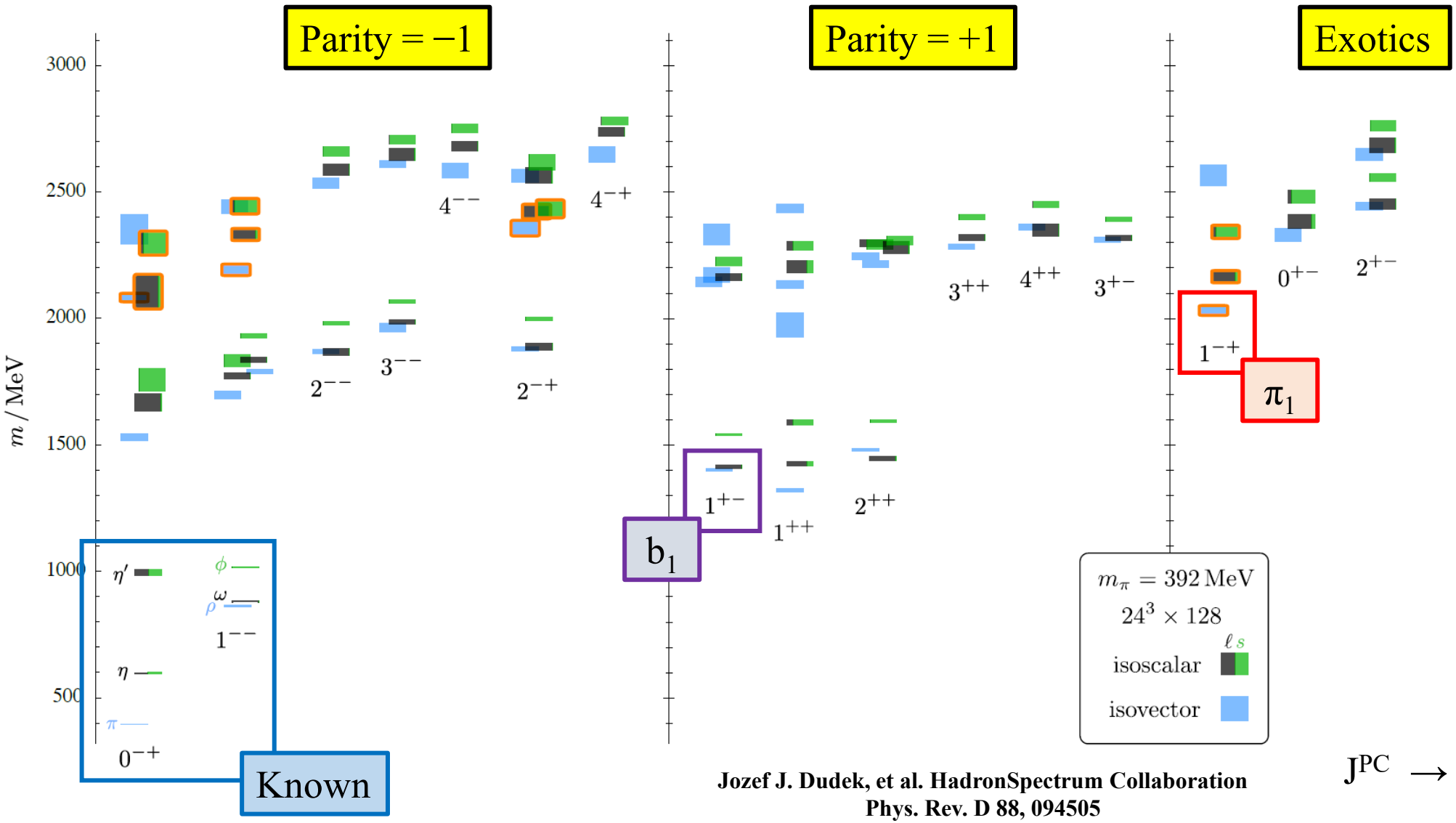
GlueXperiment
gluexexperiment
Glue_X

www.gluex.org/thanks

NSERC CRSNG

# Backups

# Lattice QCD Predictions

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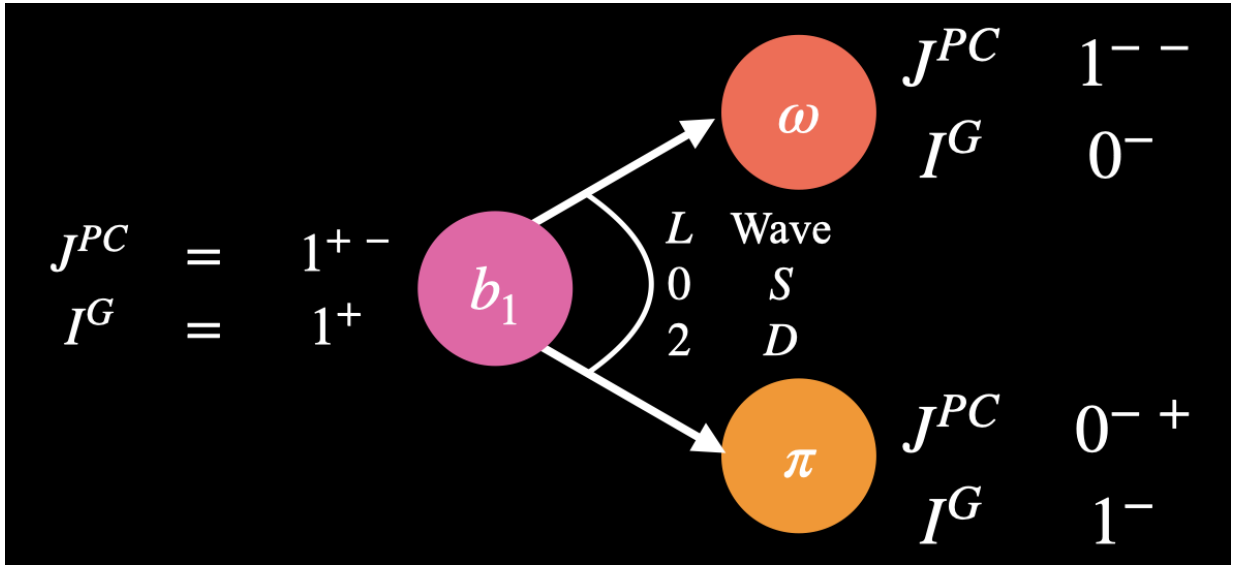
# $\equiv b_1 \rightarrow \omega\pi^0$ Quantum Numbers



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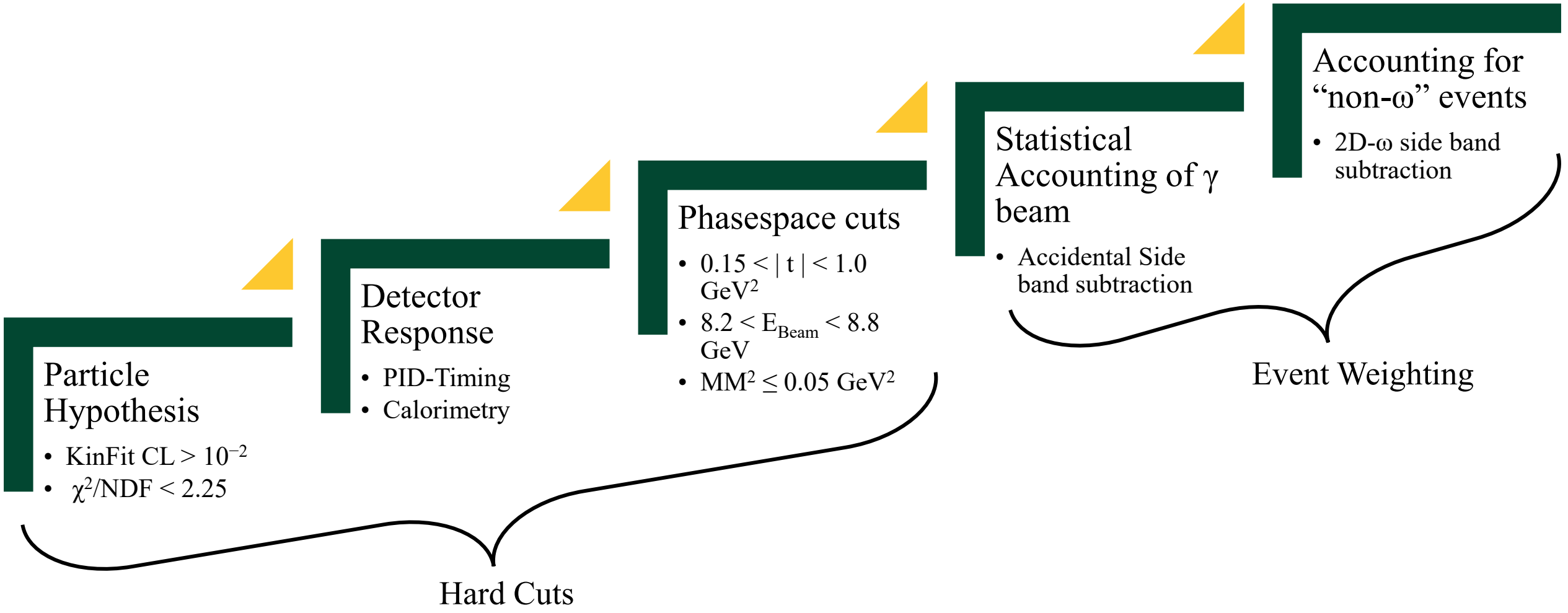

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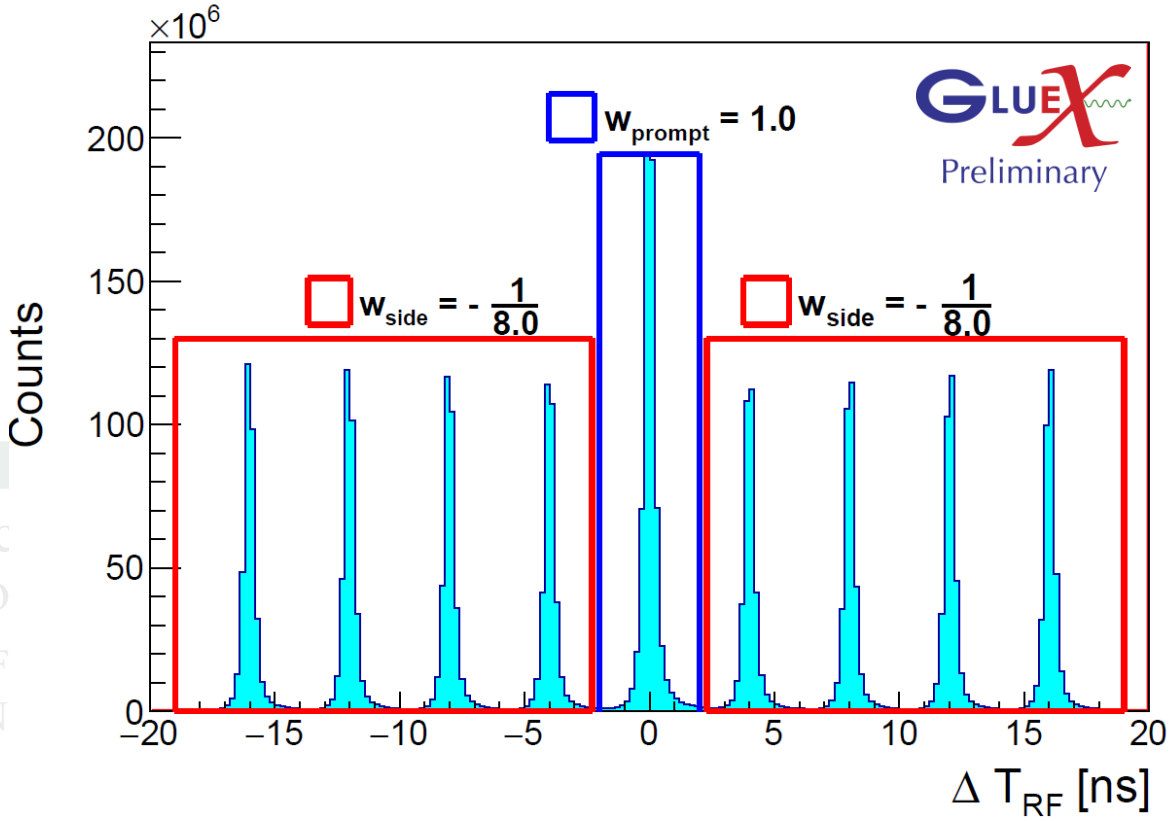


## Statistical Accounting of γ beam

- Accidental Side band subtraction

Accounting for "non-ω" events

- 2D-ω side band subtraction

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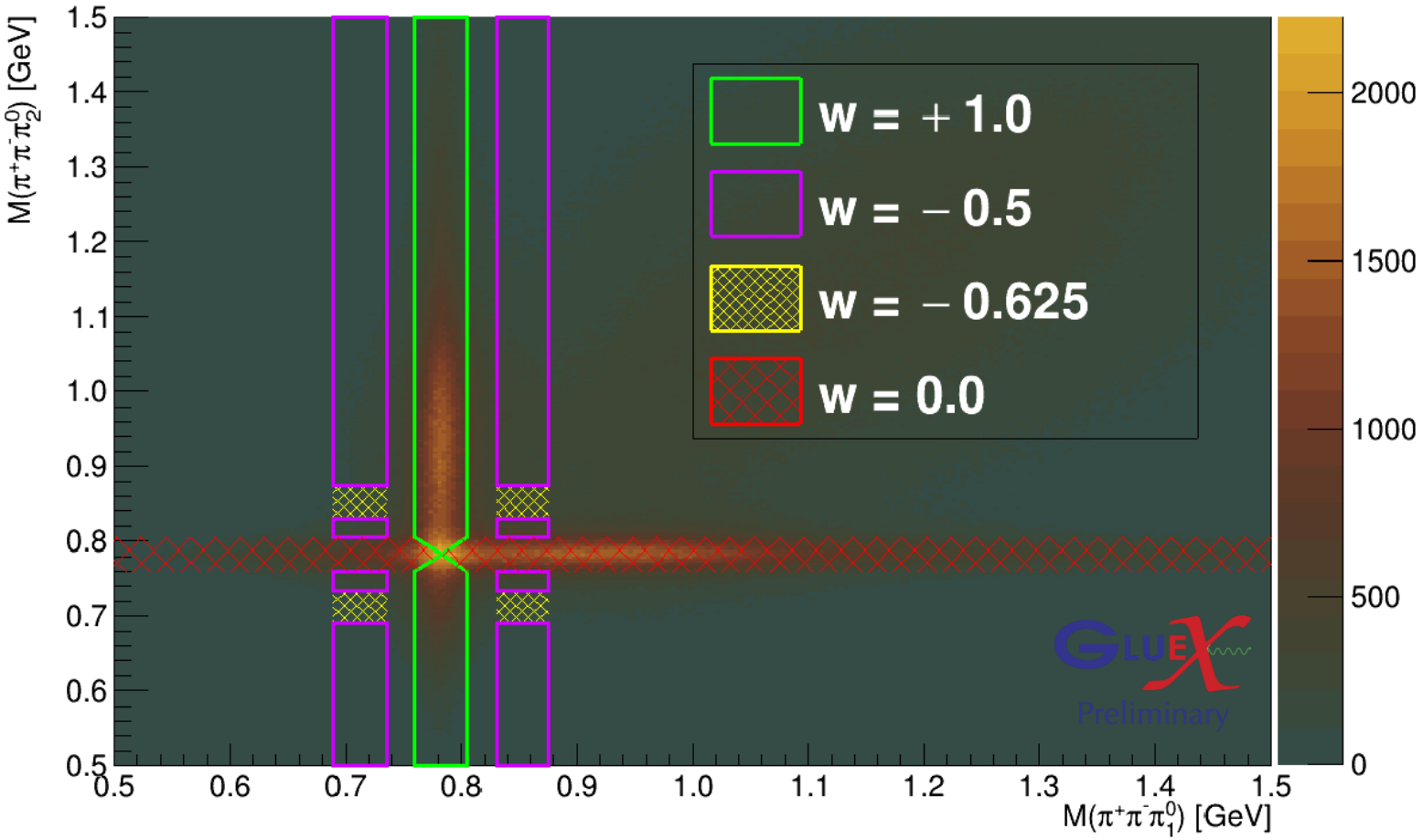
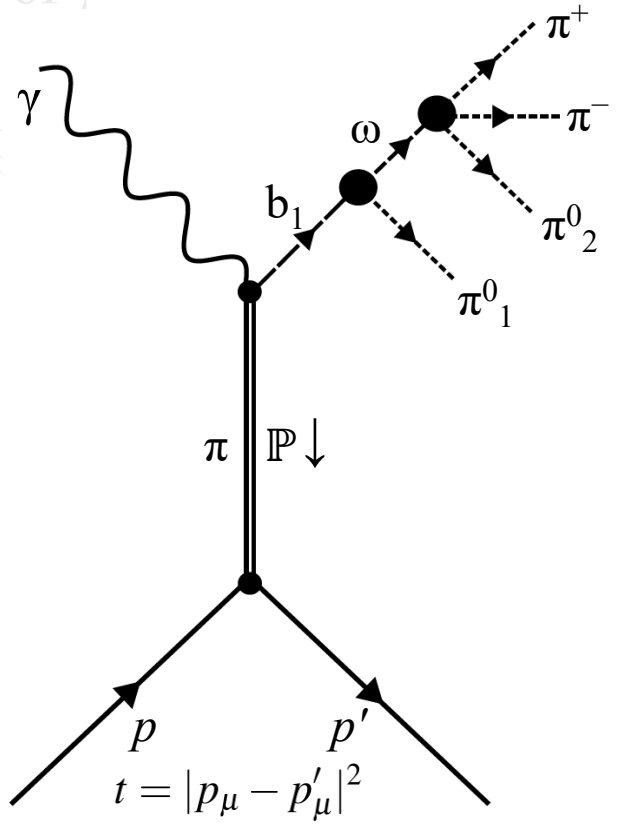
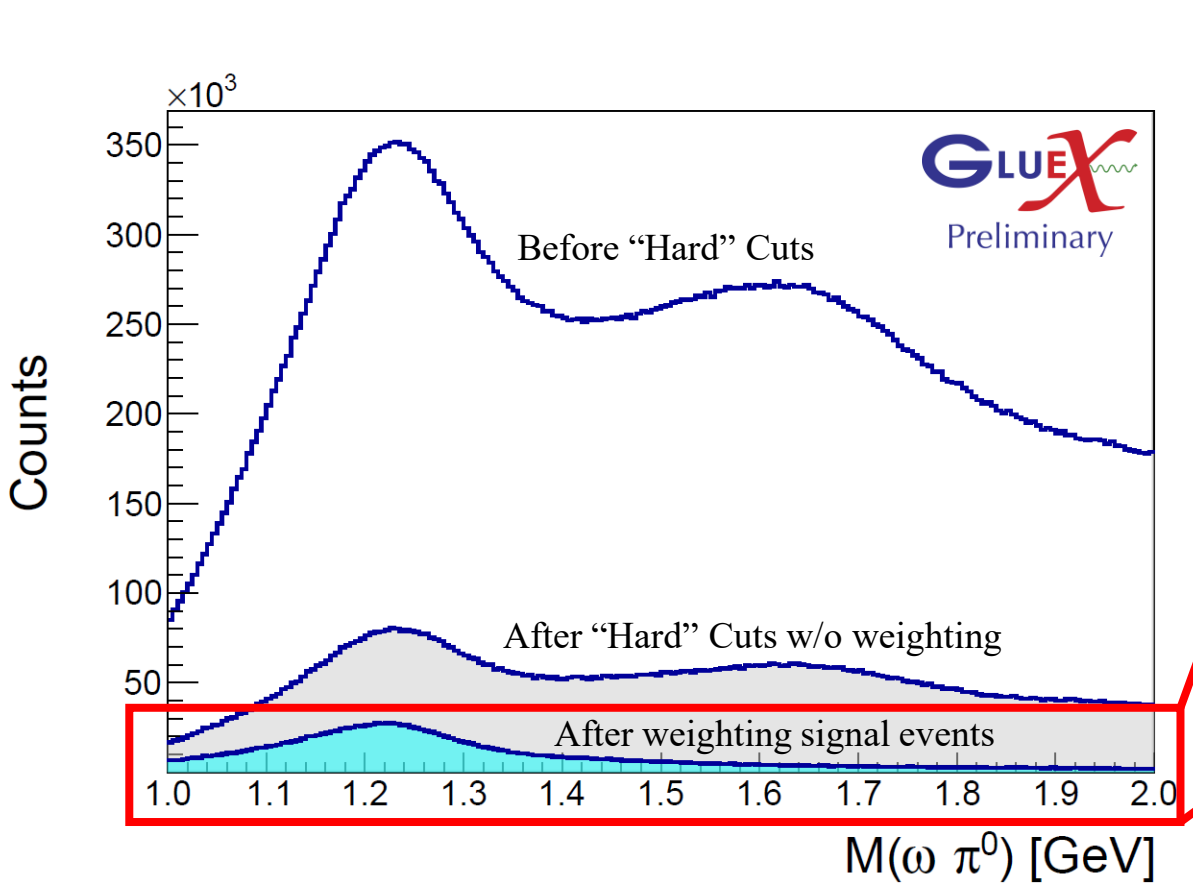


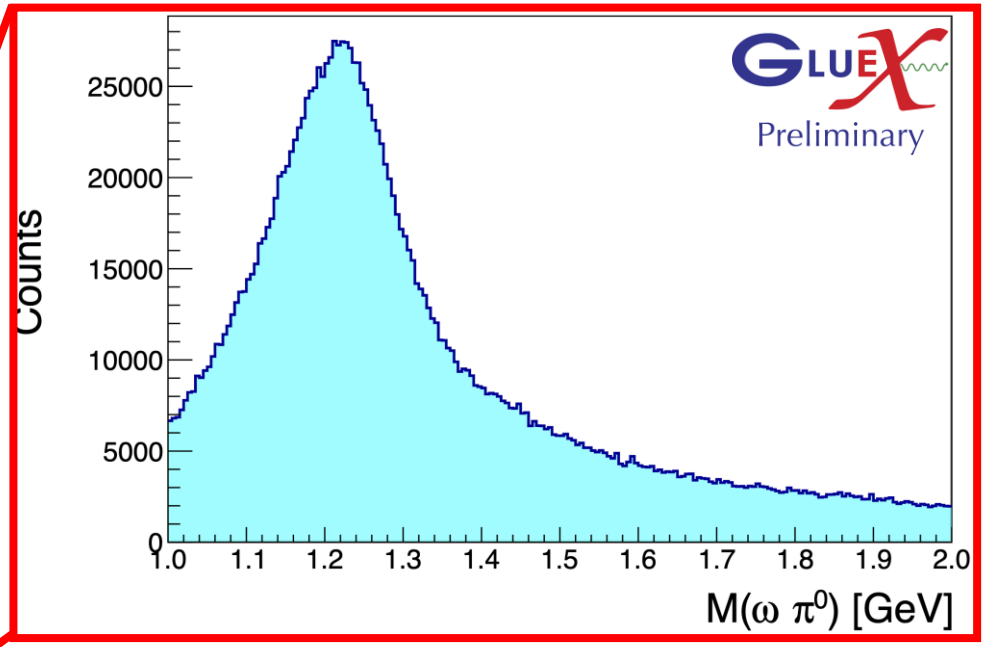

## Accounting for "non-ω" events

- 2D-ω side band subtraction



# Data Selection

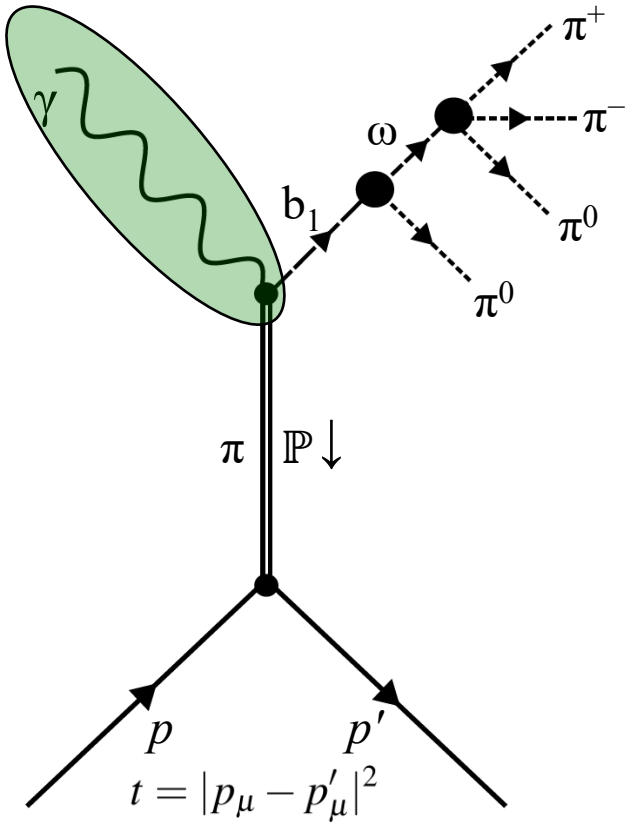



High purity events of $\omega\pi^0$ selected.

# Partial Wave Analysis

$$\gamma p \to (b_1)p' \to (\omega\pi^0)p' \to ((\pi^+\pi^-\pi^0)\pi^0)p'$$



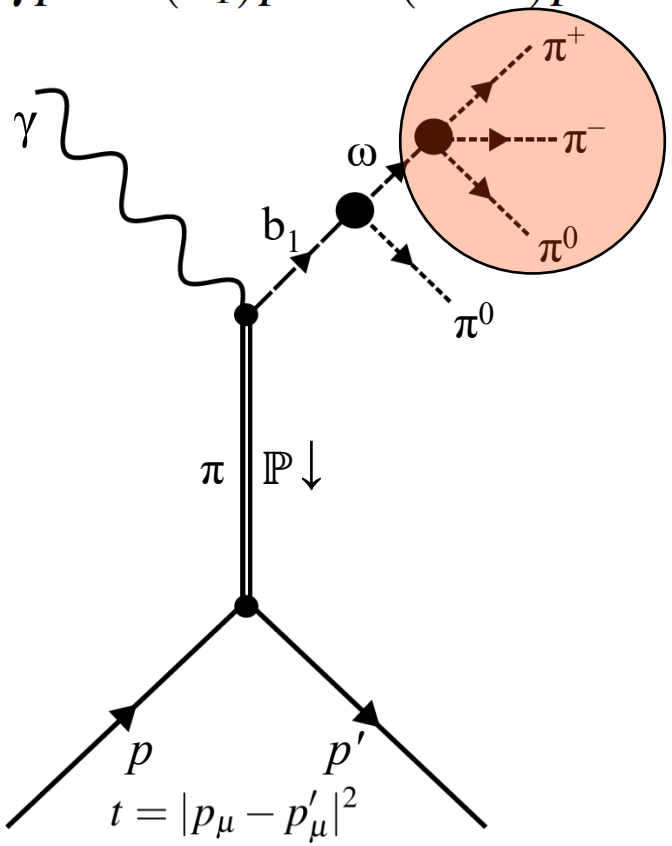

**Beam Photon γ**
$P_\gamma$ - Polarization Fraction
$\Phi$ - Production angle

$$I(\Omega, \Omega_H, \Phi) = \frac{\kappa}{4}(1 - P_\gamma)\left|\tilde{A}_+(\Omega, \Omega_H, \Phi) + \tilde{A}_-(\Omega, \Omega_H, \Phi)\right|^2 + \frac{\kappa}{4}(1 + P_\gamma)\left|\tilde{A}_+(\Omega, \Omega_H, \Phi) - \tilde{A}_-(\Omega, \Omega_H, \Phi)\right|^2$$

$$\tilde{A}_\pm = \sum_{J_i=1,2,\ldots} \sum_{m=-J_i,\ldots,J_i} T^i_{\pm,m} \sum_{\lambda_\omega=-1,0,1} e^{\mp i\Phi} D^{J_i *}_{m,\lambda_\omega}(\Omega) F^i_{\lambda_\omega} D^{1*}_{m,0}(\Omega_H) G_{\text{Dalitz}}\, \mathfrak{F}(p_0)$$

# Partial Wave Analysis

$$\gamma p \to (b_1)p' \to (\omega\pi^0)p' \to ((\pi^+\pi^-\pi^0)\pi^0)p'$$




**ω Decay Dynamics**

$\lambda_\omega$ - ω helicity (J=1)

$\Omega_H$ - Decay angles in the ω decay plane

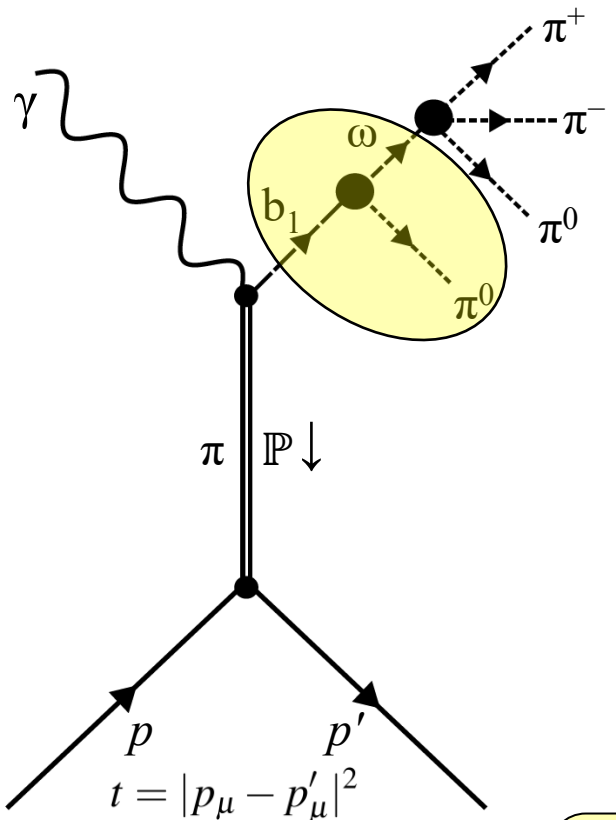
$G_{Dalitz}$ - Distribution of pions in ω decay plane

$$I(\Omega,\Omega_H,\Phi) = \frac{\kappa}{4}(1-P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)+\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2 + \frac{\kappa}{4}(1+P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)-\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2$$

$$\tilde{A}_\pm = \sum_{J_i=1,2,\ldots}\sum_{m=-J_i,\ldots,J_i} T^i_{\pm,m} \sum_{\lambda_\omega=-1,0,1} e^{\mp i\Phi} D^{J_i*}_{m,\lambda_\omega}(\Omega) F^i_{\lambda_\omega} D^{1*}_{m,0}(\Omega_H) G_{\text{Dalitz}} \mathfrak{F}(p_0)$$

# Partial Wave Analysis

$$\gamma p \to (b_1)p' \to (\omega\pi^0)p' \to ((\pi^+\pi^-\pi^0)\pi^0)p'$$




**$\omega\pi^0$ Decay Dynamics**

$T^i_{\pm,m}$ - decay amplitude. Depends $\omega\pi^0$ relative spin, naturality of exchange

$\Omega$ - Decay angles in the $\omega\pi^0$ decay plane

$\mathfrak{F}(p_0)$ - Biatt-Weisskopf angular momentum barrier factor. Suppress high $l$ waves in low $\omega\pi^0$ mass

$$I(\Omega,\Omega_H,\Phi) = \frac{\kappa}{4}(1-P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)+\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2 + \frac{\kappa}{4}(1+P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)-\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2$$

$$\tilde{A}_\pm = \sum_{J_i=1,2,\ldots}\sum_{m=-J_i,\ldots,J_i} T^i_{\pm,m} \sum_{\lambda_\omega=-1,0,1} e^{\mp i\Phi} D^{J_i*}_{m,\lambda_\omega}(\Omega) F^i_{\lambda_\omega} D^{1*}_{m,0}(\Omega_H) G_{\text{Dalitz}} \mathfrak{F}(p_0)$$

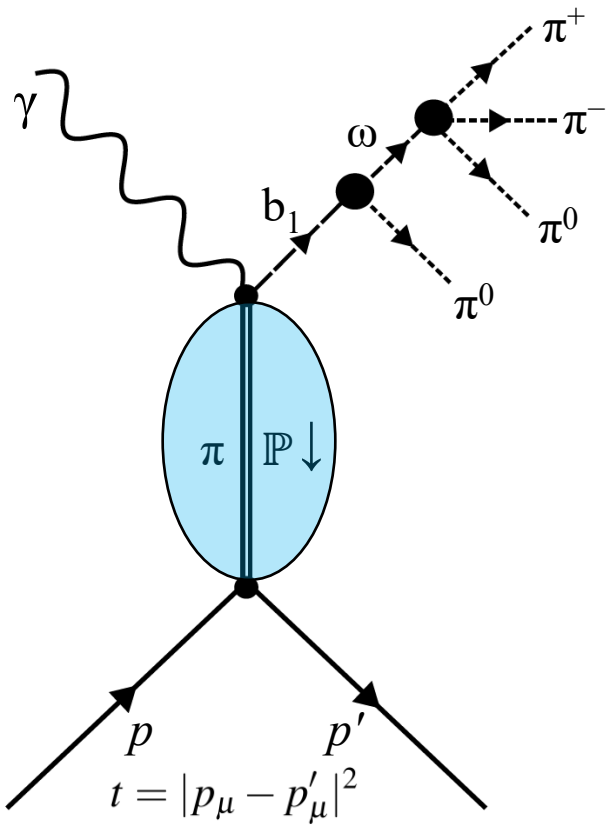
$F^i_{\lambda\omega}$ - $\omega$ helicity amplitude

For $b_1$; $F^i_{\lambda\omega} = \langle 1\lambda_\omega | 00,1\lambda_\omega\rangle C_0 + \langle 1\lambda_\omega | 20,1\lambda_\omega\rangle C_2$

Defined DS Ratio = $C_2/C_0$

# Partial Wave Analysis

$$\gamma p \to (b_1)p' \to (\omega\pi^0)p' \to ((\pi^+\pi^-\pi^0)\pi^0)p'$$




**The Exchange Mechanism**

$A_\pm \leftrightarrow T^i_{\pm,m}$ : All amplitudes $A_\pm$ can be expressed in linear combinations of "reflectivity" basis.

Can easily infer naturality of exchange.

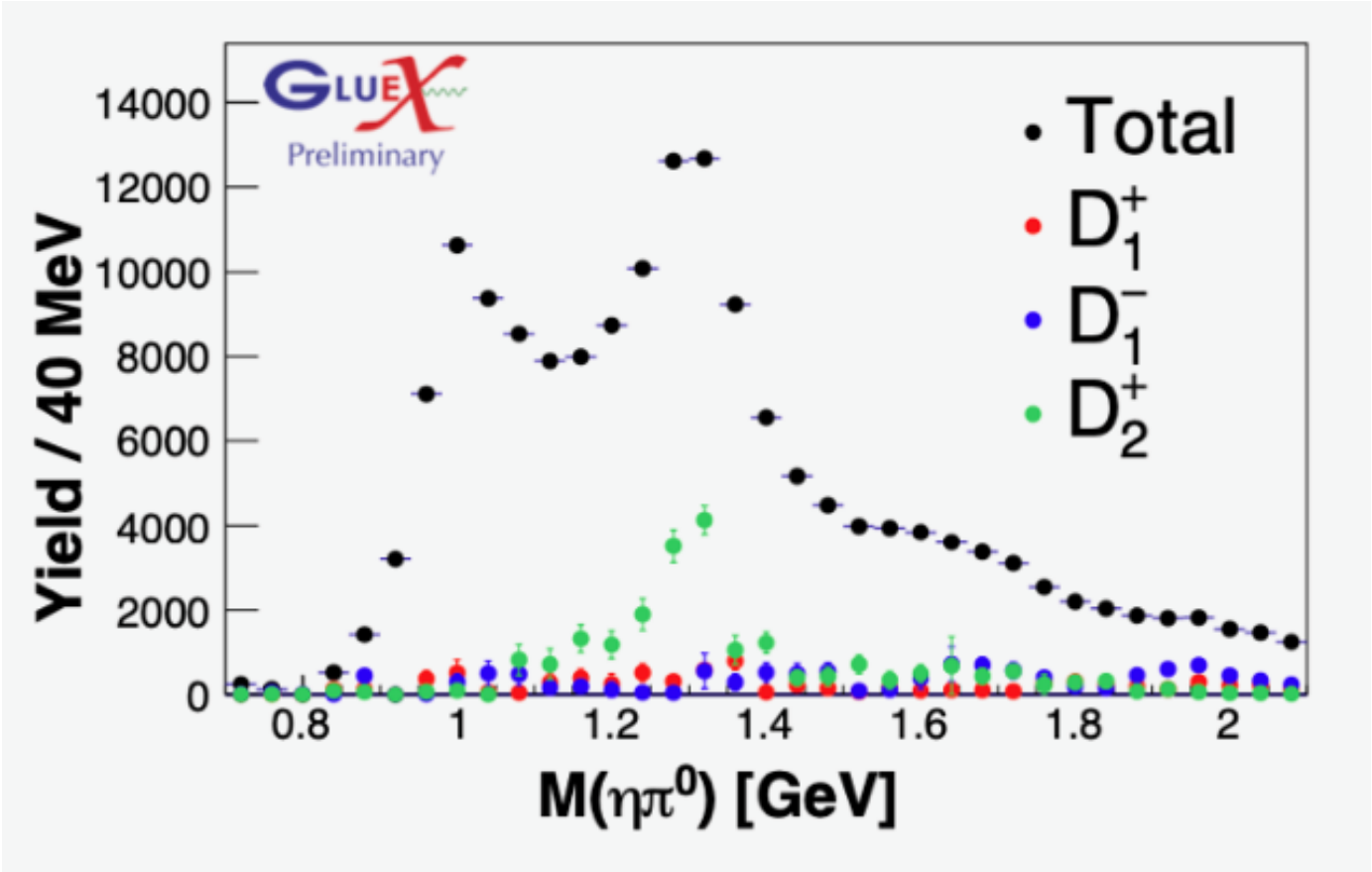
$\varepsilon$("refl") = $\tau_i$ ("meson")× $\tau_e$ ("exchange")

Amplitudes will be defined as $\varepsilon = \pm$ reflectivities $[J^{PC}]^\varepsilon$

$$I(\Omega,\Omega_H,\Phi) = \frac{\kappa}{4}(1-P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)+\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2 + \frac{\kappa}{4}(1+P_\gamma)\left|\tilde{A}_+(\Omega,\Omega_H,\Phi)-\tilde{A}_-(\Omega,\Omega_H,\Phi)\right|^2$$

$$\tilde{A}_\pm = \sum_{J_i=1,2,\ldots}\sum_{m=-J_i,\ldots,J_i} T^i_{\pm,m} \sum_{\lambda_\omega=-1,0,1} e^{\mp i\Phi} D^{J_i*}_{m,\lambda_\omega}(\Omega) F^i_{\lambda_\omega} D^{1*}_{m,0}(\Omega_H) G_{\text{Dalitz}}\,\mathfrak{F}(p_0)$$

# $\eta\pi^0$ PWA


GLUEX
Preliminary
Total
$D_1^+$
$D_1^-$
$D_2^+$
Yield / 40 MeV
14000
12000
10000
8000
6000
4000
2000
0
0.8
1
1.2
1.4
1.6
1.8
2
$M(\eta\pi^0)$ [GeV]