

CLAS12 June/July Collaboration Meeting

Probing Proton GPDs through Exclusive $\omega(782)$ Electroproduction with RGA Data

Zhaozhong Shi

06/30/2026



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Organization

ω Meson Physics Program and Collaboration

15	Inclusive Double-Charged Pion (omega) ($e p \rightarrow e' p' \pi^+ \pi^+ (\pi^0)$) Channel	Resonance Region, All RG-A Data	Mace Mierisch	Zhaozhong Shi, Philip Cole / Chaden Djalali	Lamar University / Ohio University	2026	2029	TBD
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Nuclear Physics Group

Senior PI



Junior CoPI



Undergrad Student



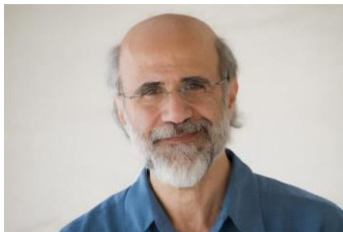
Hall B Leader



Staff Scientists



Senior PI



PhD Student: *Mace Mierisch*
 Thesis Title: *Exclusive ω (782) Vector Meson Electroproduction off the proton with CLAS12*



Existing Documents/Organization

- Official Analysis wikipage on the Hadron Spectroscopy Group Meeting
 - Regular analysis update in $\sim 1 - 2$ months
 - Receive feedback on the analysis
 - Will also get connected to RG-A and DPWG meeting regularly on ω meson analysis
- Existing note for the analysis:
 - Overleaf: [link](#)
 - Eventually converting them to CAAs
 - Become thesis topic for Mace
- Communication/Logistics
 - Email for formal discussions
 - Regular Zoom meeting
 - Slack channel for the ω analysis

Exclusive $\omega(782)$ Vector Meson Electroproduction with CLAS12 RGA Data

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³Ohio University

June 18, 2026

Abstract

The CLAS12 experiment is a state-of-the-art facility dedicated to hadronic and nuclear physics through electron scattering experiments at CEBAF at Jefferson Laboratory. Understanding how hadrons emerge from elementary quarks and gluons in QCD – via the dynamical emergence of the strong interaction described by quantum field theory – remains an unresolved puzzle and a central topic in modern nuclear physics. QCD factorization and perturbativity provide two key stepping stones toward addressing this question. Exclusive vector meson electroproduction in fixed-target proton experiments, $ep \rightarrow epV^0$ where $V^0 = \rho(770), \omega(782), \phi(1020), J/\psi$, and $\Upsilon(1S)$, offers a promising avenue for investigation.

In this CLAS Approved Analysis (CAA) proposal, we focus on exclusive isoscalar $\omega(782)$ ($\omega = u\bar{u} + d\bar{d}$ and $J^P = 1^-$) electroproduction in the decay channels $\omega \rightarrow \pi^+\pi^-\pi^0$ (Branching ratio: $\text{BR} \simeq 89\%$) and $\omega \rightarrow \pi^0\gamma$ ($\text{BR} \simeq 8.5\%$). The $\omega(782)$ has not previously been studied by CLAS12. This analysis is expected to have a high impact in hadronic physics. We will demonstrate the feasibility of fully reconstructing the ω meson through exclusive decays and report expected statistics using the full RGA Fall 2018 dataset.

Our research program follows two complementary directions:

1. Extraction of Generalized Parton Distribution Functions (GPDs):

We aim to extract GPDs through exclusive ω vector meson electroproduction using missing mass techniques and by analyzing beam spin asymmetry observables, $A_{LU}^{\text{sin}\phi}$ in the reaction plane. This analysis will cover a broad range in x_{Bj} , Q^2 , and t kinematics at large $W > 2$ GeV.

2. Excited Baryon Spectroscopy via $N^* \rightarrow \omega N$:

We will investigate the resonance region at low $1.7 < W < 2$ GeV, using the Jackson-Gorfield frame and perform partial wave analysis to extract amplitudes and phase shifts. This study will probe baryon resonance physics, including the meson-baryon cloud and three-quark structure. With the high-statistic $\omega(782)$ sample provided by CLAS12, we also plan to place more stringent constraints on the $N^* \rightarrow \omega N$ decay widths for different J^P states.

These two complementary directions will provide precision and differential measurements that constrain QCD phenomenology and deepen our understanding of hadron structure and reaction mechanisms. They also establish important connections to complementary programs at Japan Proton Accelerator Research Complex (J-PARC) through time-like channel studies of $\pi p \rightarrow N^* \rightarrow \omega N$, and to the future Electron-Ion Collider through $ep/A \rightarrow ep\omega$ measurements relevant for generalized parton distributions (GPDs) and transverse momentum dependent distributions (TMDs).

Physics Motivation

Major References for Exclusive $\omega(782)$ Electroproduction

Bill Li's Thesis

Exclusive Backward-Angle Omega Meson Electroproduction

A Thesis

Submitted to the Faculty of Graduate Studies and Research

In Partial Fulfilment of the Requirements

for the Degree of

Doctor of Philosophy

in Physics

University of Regina



By

Wenliang Li

Regina, Saskatchewan

October, 2017

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THE EUROPEAN
PHYSICAL JOURNAL A

Deeply virtual and exclusive electroproduction of ω -mesons

The CLAS Collaboration

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• Physics topics for ω meson are rich and meaningful, albeit at different phase spaces

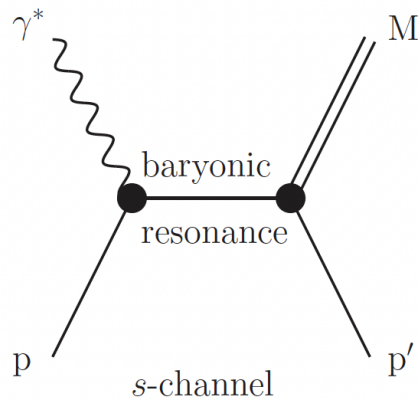
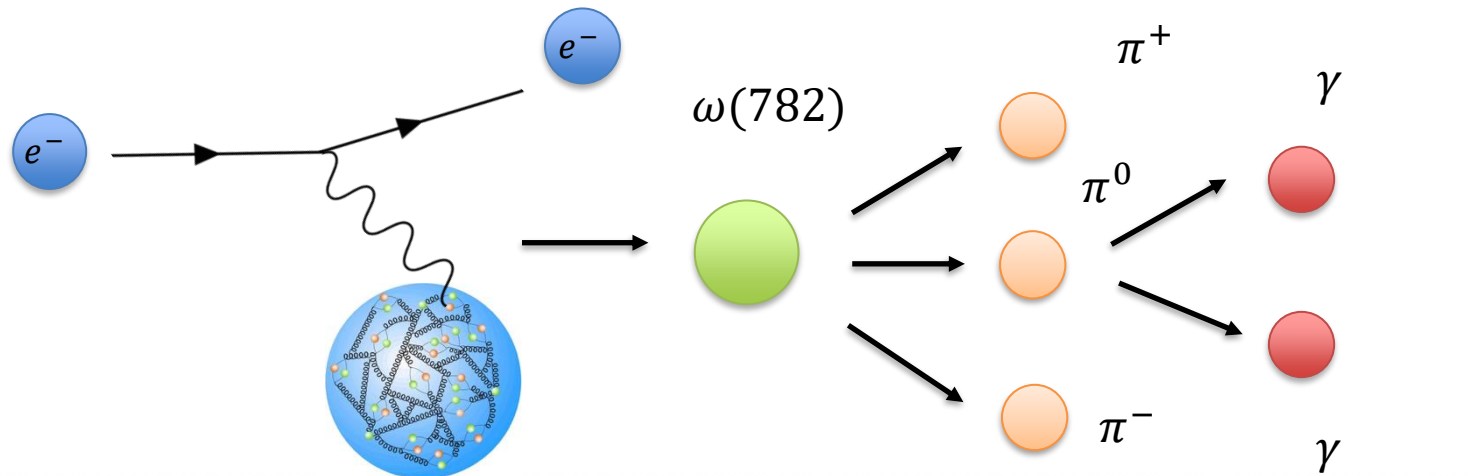
- Vector Meson Dominance
- Regge-Based Models
- GPD (TDA)-type of Physics
- Baryon Spectroscopy: $N^* \rightarrow \omega N$



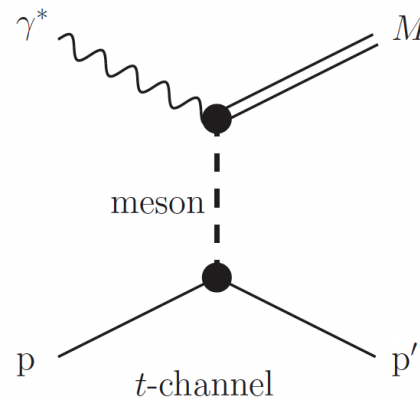
DPWG

arXiv:1712.03214v2 [nucl-ex] 11 Dec 2017

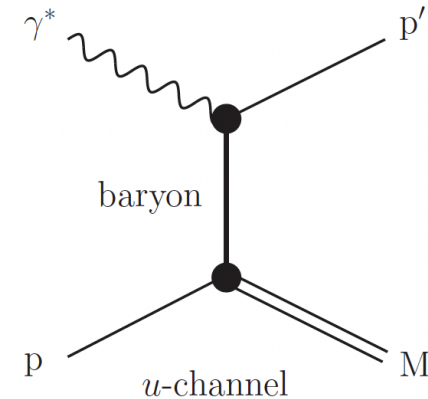
$\gamma^* p \rightarrow \omega p$ Meson Physics Program



N^* Spectroscopy



Deep Exclusive Physics



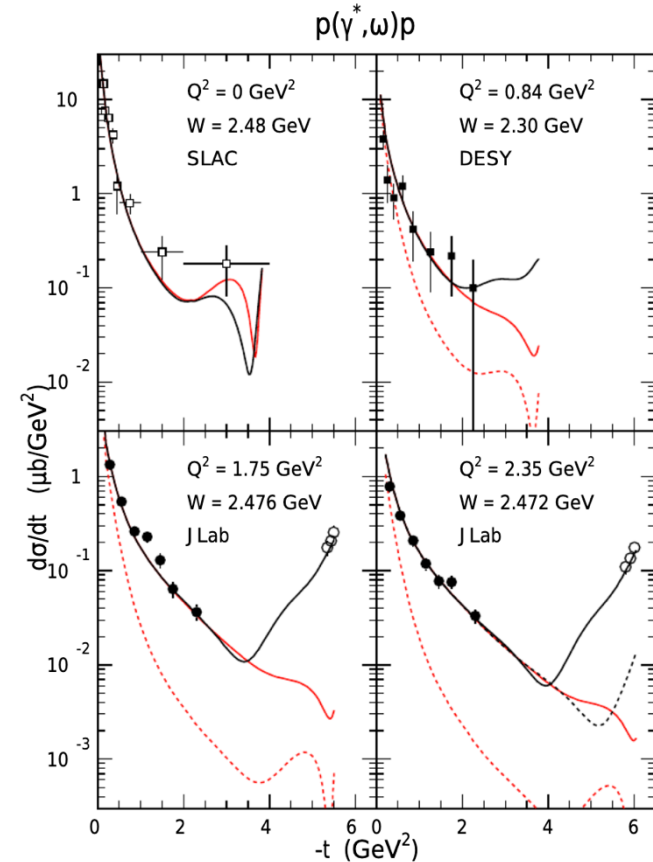
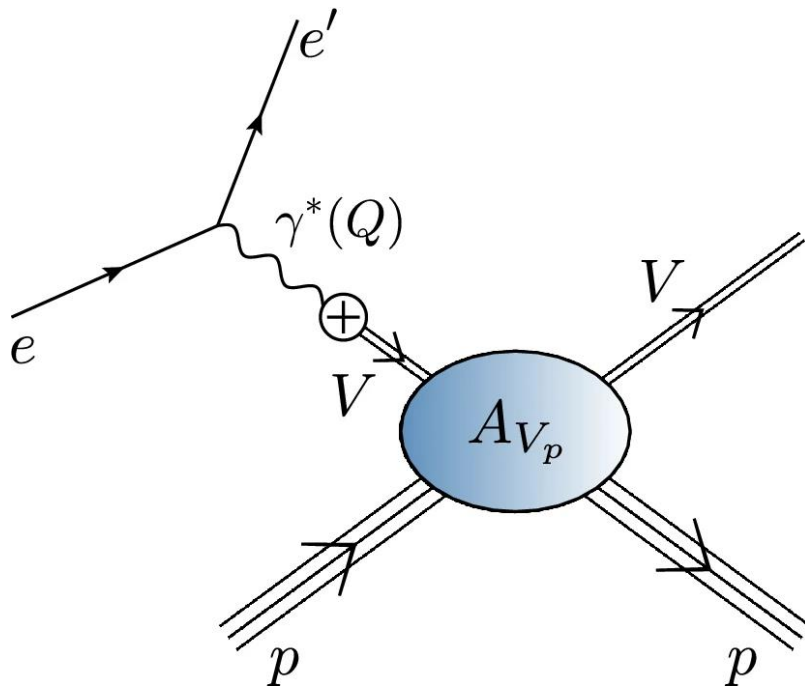
Hall C Efforts

Bill Li's PhD Thesis in 2017

- Exclusive $\omega(782)$ Mechanisms

- $\gamma^* \rightarrow q\bar{q} \rightarrow \omega$
- QCD (proton and quarks) interactions and produce ω
- Exclusivity is critical for CLAS12

Vector Meson Dominance (VMD) Physics



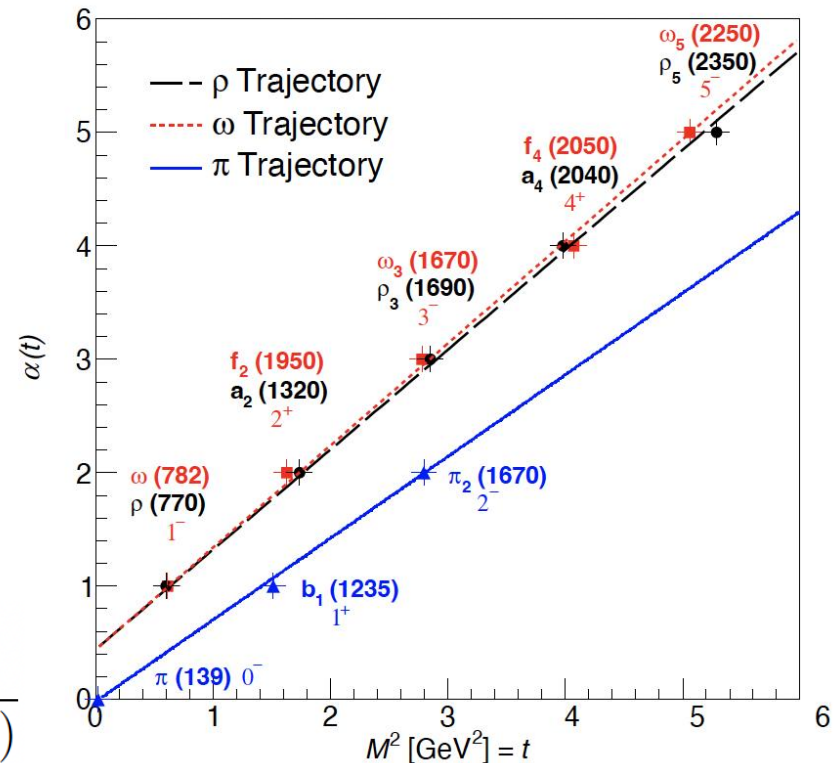
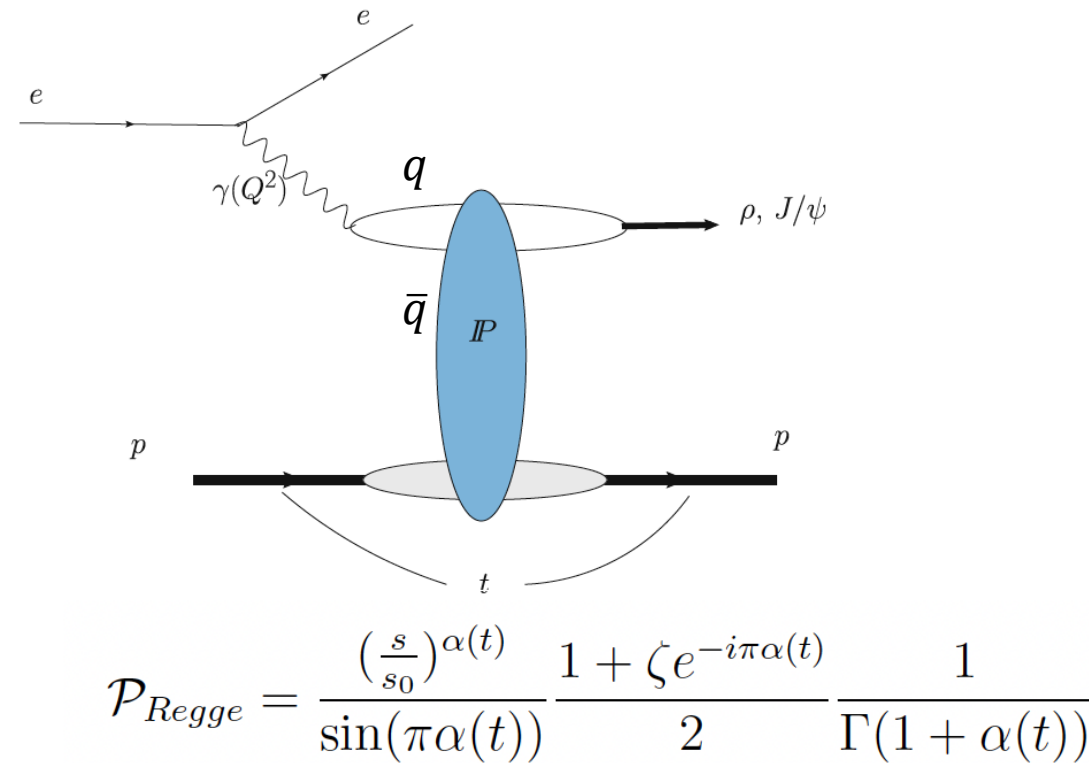
$$\mathcal{L} = g_{\rho\pi\pi}\epsilon_{abc}\rho_{\mu}^a\pi^b\partial^{\mu}\pi^c + g_{\omega\rho\pi}\delta_{ab}\epsilon^{\mu\nu\lambda\sigma}\partial_{\mu}\omega_{\nu}\partial_{\lambda}\rho_{\sigma}^a\pi^b$$

$$+ g_{3\pi}\epsilon_{abc}\epsilon^{\mu\nu\lambda\sigma}\omega_{\mu}\partial_{\nu}\pi^a\partial_{\lambda}\pi^b\partial_{\sigma}\pi^c + \frac{em_V^2}{g_V}V_{\mu}A^{\mu} + \dots$$

Conditions:

- Very small $|t|$ and Q^2
- Relatively small x_B or larger W
- Well established diffractive contribution

Pomeron/Regge Trajectory Physics



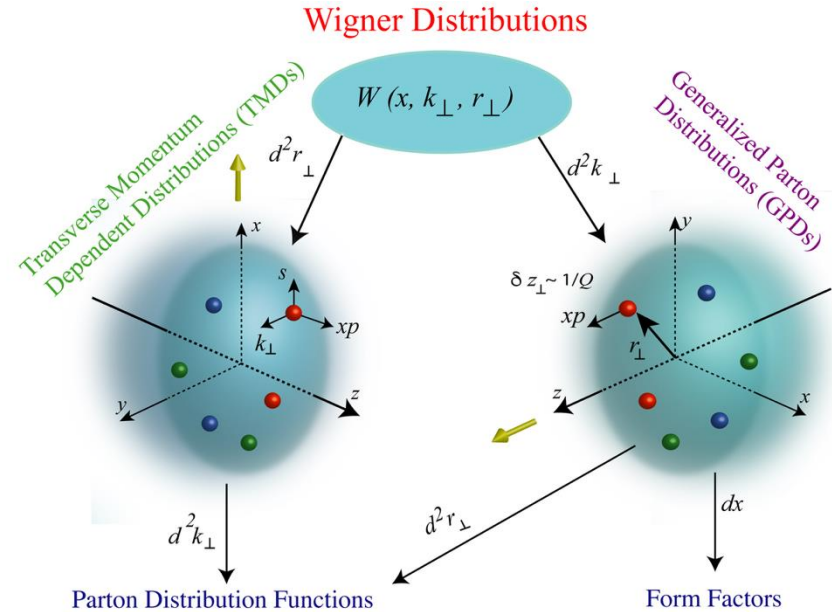
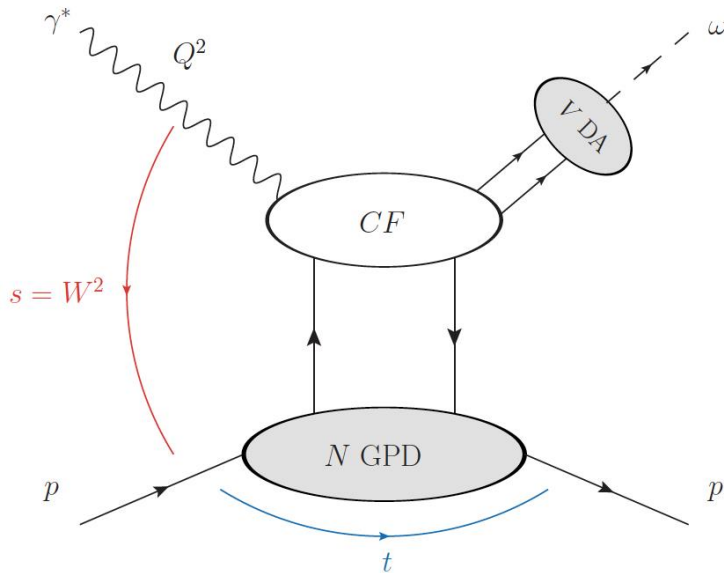
(a) Meson exchange trajectory

Conditions:

- Applicable to exclusive ω meson electroproduction at CLAS12
- Large W ($W > 2.5$ GeV)
- Interesting to also look at large t
 - Saturation: $t \rightarrow -\infty, \alpha(t) \rightarrow -1$
 - VGL and JML models

Produced vector meson	Exchanged Regge trajectories
ρ	$\sigma, f_2, P/2g$
ω	$\pi^0, f_2, P/2g$
ϕ	$P/2g$

Handbag Diagrams: GPD/TDA Type of Physics



$$\omega = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}} : I = 0 \text{ and } J^P = 1^-$$

Conditions

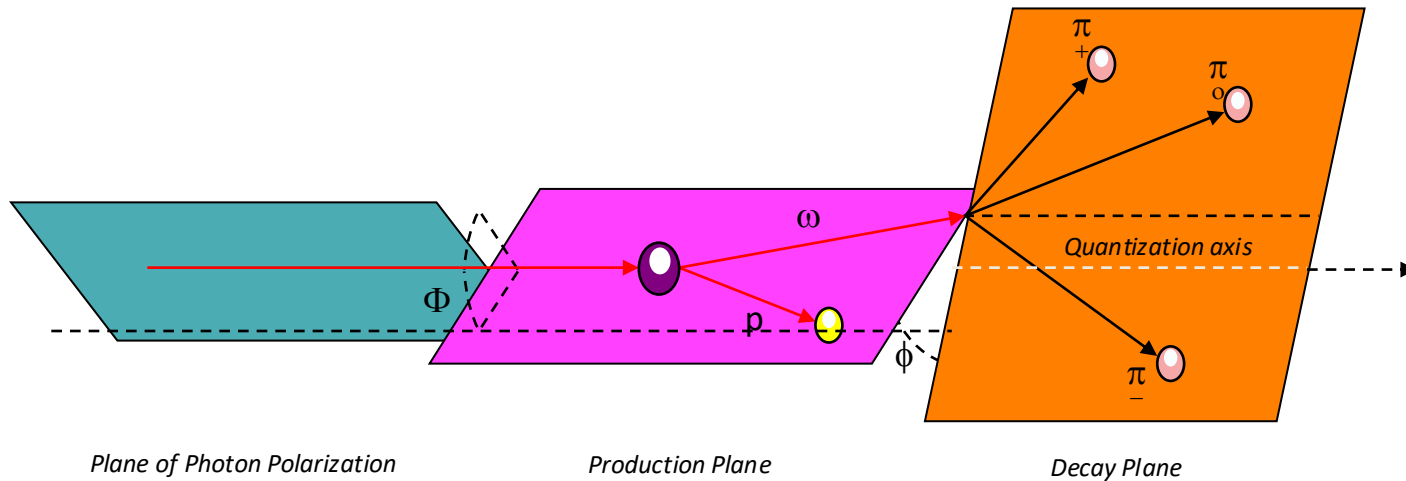
- GPD: a factorized approach particularly applied to exclusive reaction: $ep \rightarrow ep\omega$
- Sufficiently Large (Deep) $Q^2 \gg \Lambda_{QCD}^2$
- Large W ($W > 2.5$ GeV)
- Small t or $\frac{t}{Q^2}$
- Moderate x_B

Physics Impacts

- First ω meson measurement with CLAS12
- Sensitive to u - d quark flavor separated chiral-even GPDs (Complementary to ρ and π^0)
- Enable flavor-resolved imaging of the proton

Data Analysis

Kinematics Definition



Kinematics definitions for $ep \rightarrow e' p' \omega \rightarrow e' p' \pi^+ \pi^- \pi^0$

$$Q^2 = (p_{e'}^\mu - p_e^\mu)^2$$

$$t = (p_{p'}^\mu - p_p^\mu)^2$$

$$W = \left| \sum_{h_i}^N p_{h_i} \right| = |p_e + p_p - p_{e'}|$$

$$x_B = \frac{Q^2}{2m_p v} = \frac{Q^2}{2m_p (E_e - E_{e'})}$$

$$u = (p_e^\mu - p_{e'}^\mu - p_{p'}^\mu)^2$$

$$m_{\pi^0} = |p_{\gamma 1} + p_{\gamma 2}|$$

$$m_\omega = |p_{\pi^+} + p_{\pi^-} + p_{\pi^0}|$$

$$m_X^2 = (p_e^\mu + p_p^\mu - \sum_i^N p_i^\mu)^2$$

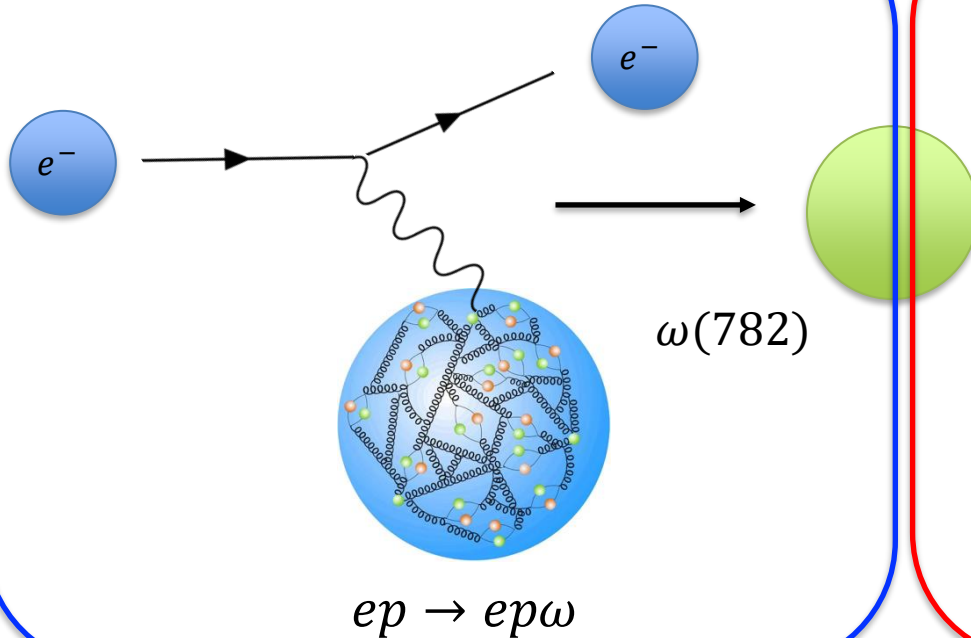
Missing Particle Summary

Channel	Reactions	Missing Mass Cut m_X^2 (GeV ²)	Availability
$\omega \rightarrow \pi^+ \pi^- \pi^0$	$ep \rightarrow e' p' \omega$	$ m_X^2 - m_p^2 < 0.1$	Both Torus + 1 and -1
	$ep \rightarrow e' (p') \omega$	$ m_X^2 - m_p^2 < 0.1$	Both Torus + 1 and -1
	$ep \rightarrow e' p' \omega$ $\rightarrow \pi^+ \pi^- (\pi^0)$	$ m_X^2 - m_{\pi^0}^2 < 0.01$	Torus + 1
	$ep \rightarrow e' p' \omega$ $\rightarrow \pi^+ (\pi^-) \pi^0$	$ m_X^2 - m_{\pi^-}^2 < 0.01$	Both Torus + 1 and -1
	$ep \rightarrow e' p' \omega$ $\rightarrow (\pi^+) \pi^- \pi^0$	$ m_X^2 - m_{\pi^+}^2 < 0.01$	Both Torus + 1 and -1
$\omega \rightarrow \pi^0 \gamma$	$ep \rightarrow e' p' \omega$	$ m_X^2 - m_p^2 < 0.1$	
	$ep \rightarrow e' (p') \omega$	$ m_X^2 - m_p^2 < 0.1$	
	$ep \rightarrow e' p' \omega \rightarrow (\pi^0) \gamma$	$ m_X^2 - m_{\pi^+}^2 < 0.01$	
	$ep \rightarrow e' p' \omega \rightarrow \pi^0 (\gamma)$	$ m_X^2 < 0.01$	

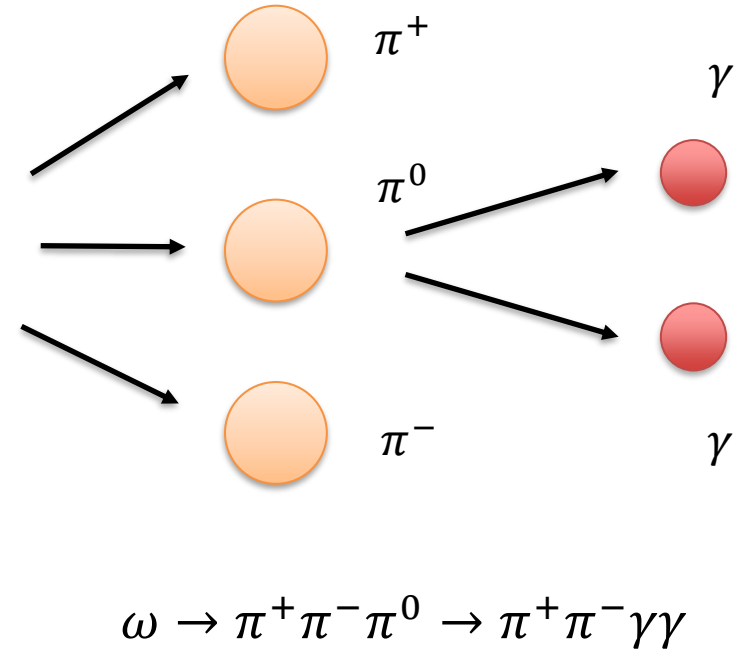
- RGA fall 2018 only data: both torus+1 (outbending) and torus -1 (inbending)
- Expect at least double of the statistics with Spring 2018 and Spring 2019 data

ω MC Simulations/Event Generator Plans

ω Meson Spectra



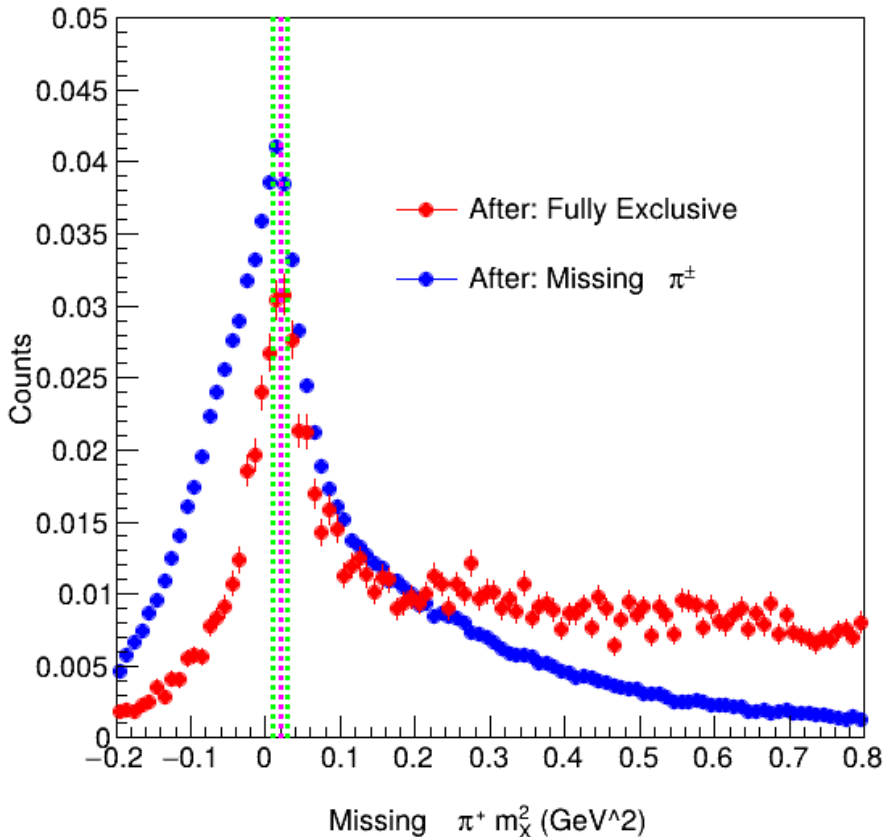
ω Meson Decayer



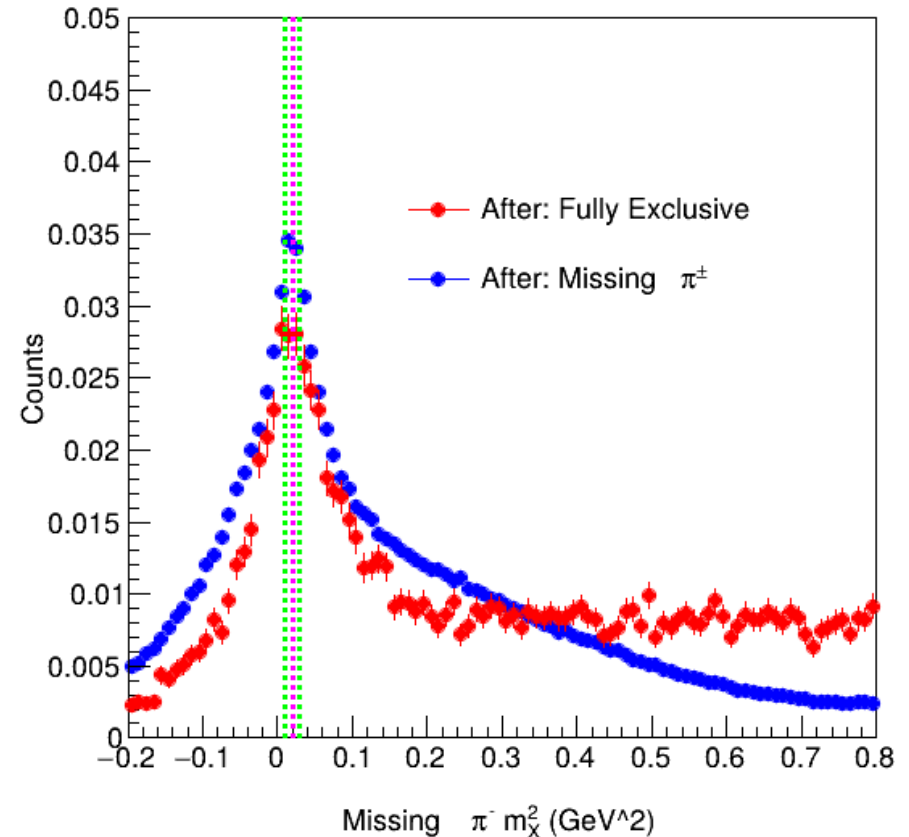
- Discuss with CLAS12 implementation
- Develop with experts on modeling general level (truth level) ω meson
 - Initial ω kinematics for the reaction: $ep \rightarrow e'p'\omega$ some models by Regge theory
 - MC Decayer for $\omega \rightarrow \pi^+\pi^-\pi^0$ with Wess–Zumino–Witten (WZW) implemented by *EvtGen* package (OmegaDalitz)?
 - Propagate the final state particles to CLAS12 GEANT detector model
- Renovate HPC at Lamar for extended event generation and MC simulations

π^\pm Missing Mass

Missing π^+ Invariant Mass Distribution with Cuts

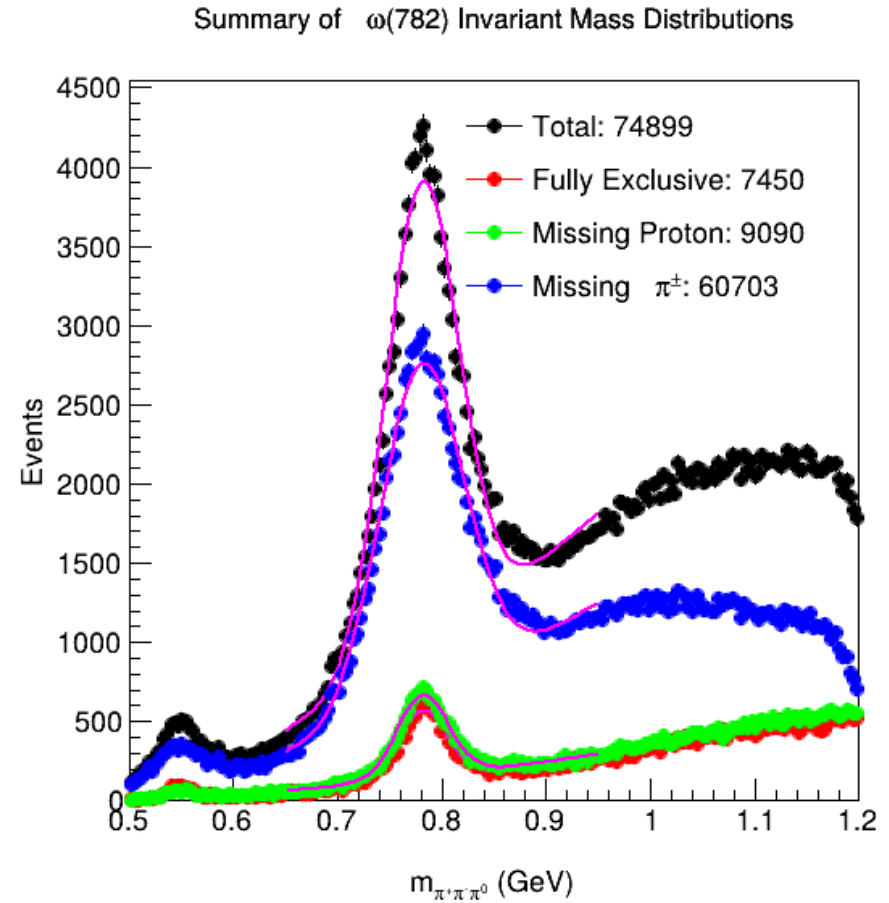
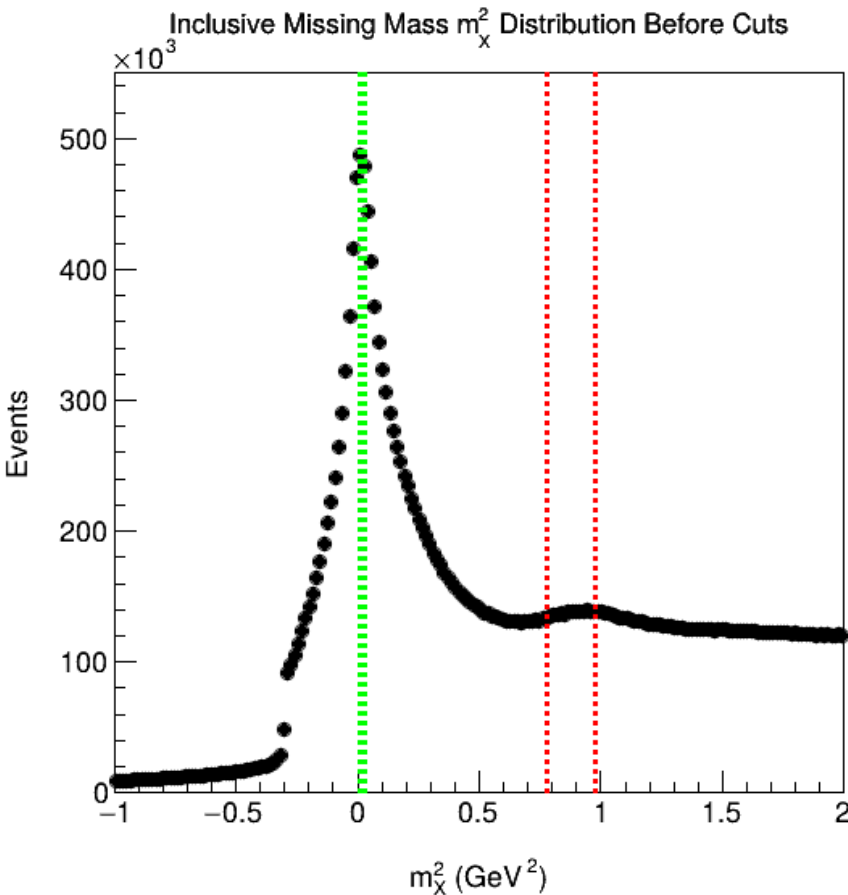


Missing π^- Invariant Mass Distribution with Cuts



- Position of the peaks agree in fully exclusive and missing π^+ and π^-
 - No explicitly bias \rightarrow systematics goes into the width
- We can impose a better mass range based on the missing mass of the golden events (fully exclusive: $e'p'\pi^+\pi^-\pi^0$)
 - Currently using the $m_\pi^{PDG^2}$ (magenta line) with a width of 0.01 GeV^2 (green lines)

Total Summary



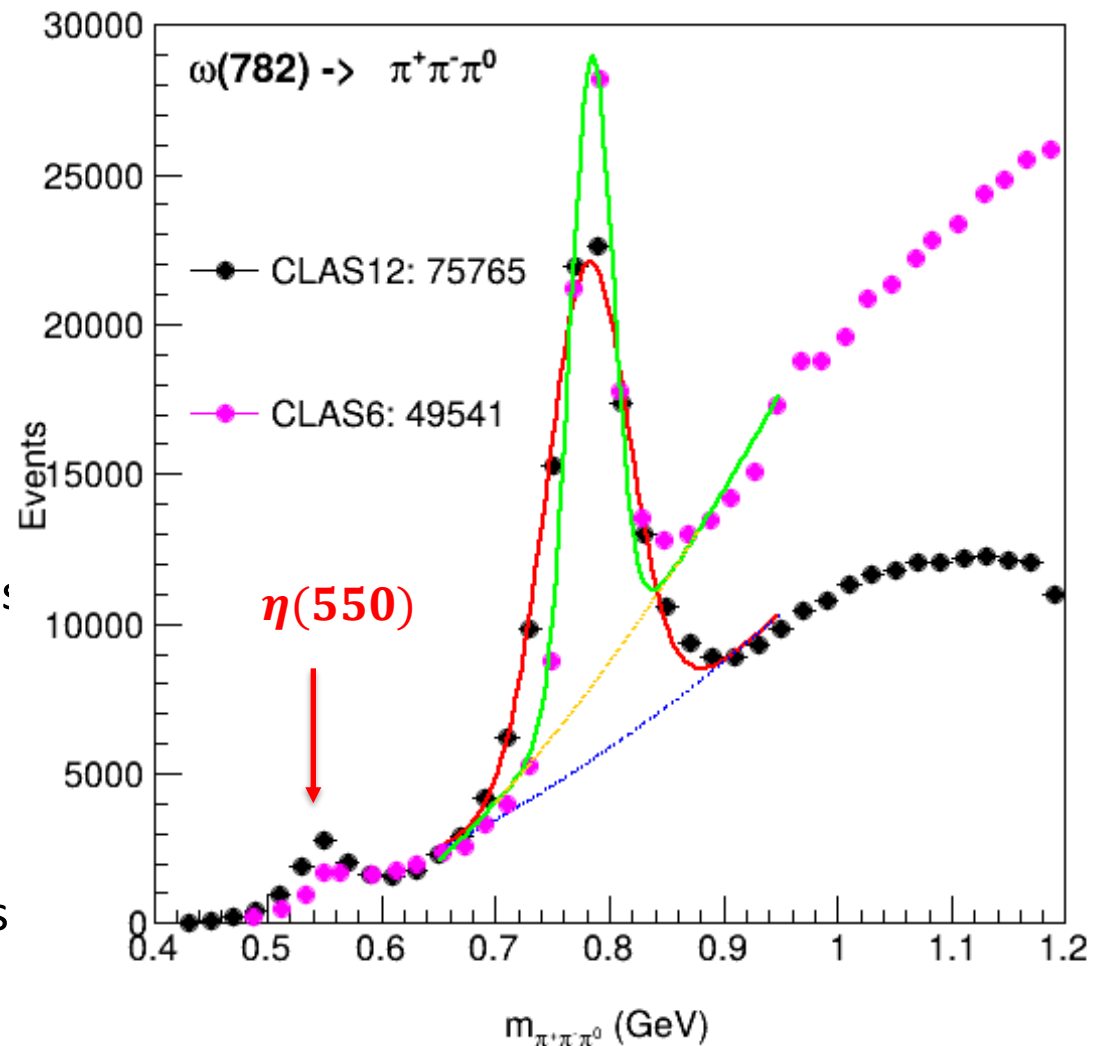
- Cutting on the missing mass from the left, we can get the right plot
- Nearly 75000 of ω mesons combining all $\omega \rightarrow \pi^+\pi^-\pi^0$ for fall 2018 RGA only data together
- Expect to have over >150000 (at least double) with spring 2018 and 2019 RGA data included

Results

Exclusive ω Statistics Comparison

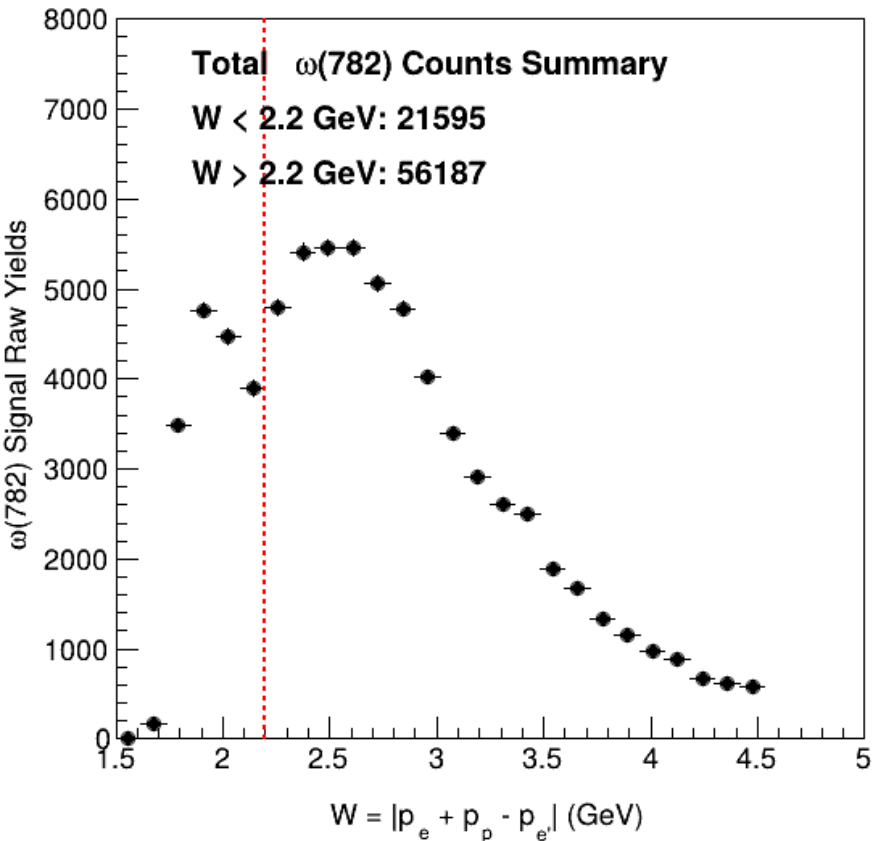
- We have more exclusive $\omega(782)$ statistics in CLAS12 signal yields than **CLAS6** with Fall 2018 RGA only data
 - Peaks of the $\eta(550)$ are both seen
 - The width is slightly wider with the **current CLAS12 data**
- This is done by a missing mass cut before any dedicated optimization of the cuts over the kinematics phase space
- Better physics measurements expected
- The more important question is phase space coverage

Summary of $\omega(782)$ Invariant Mass Distributions

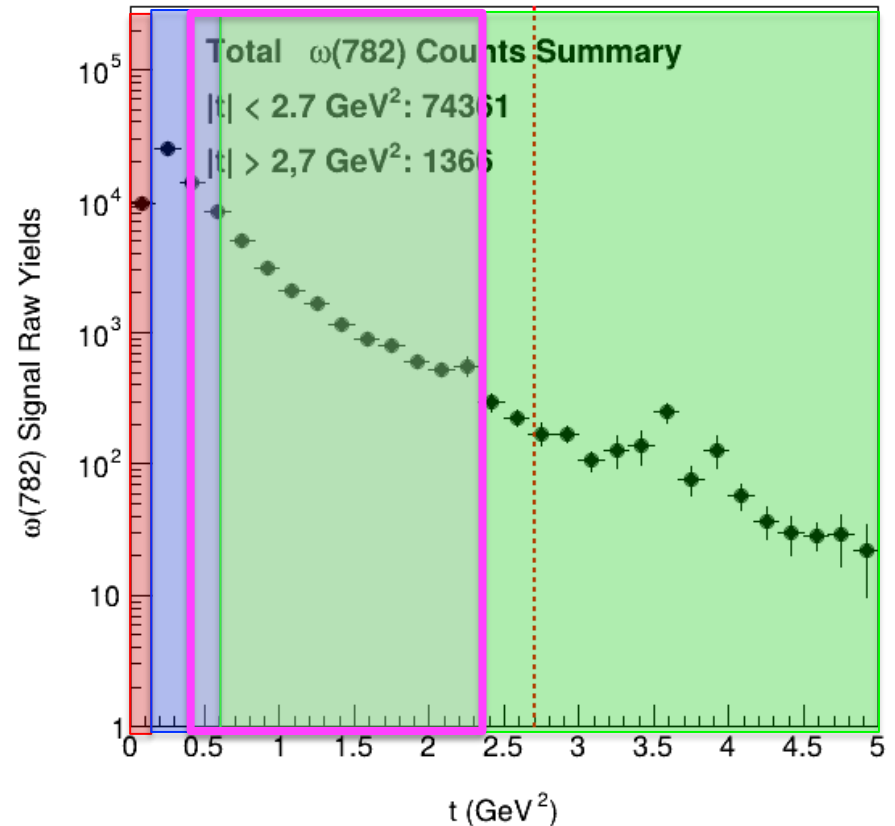


W and t Distribution

$W = |p_e + p_p - p_e'|$ (GeV) Signal Raw Yield Statistics Distribution



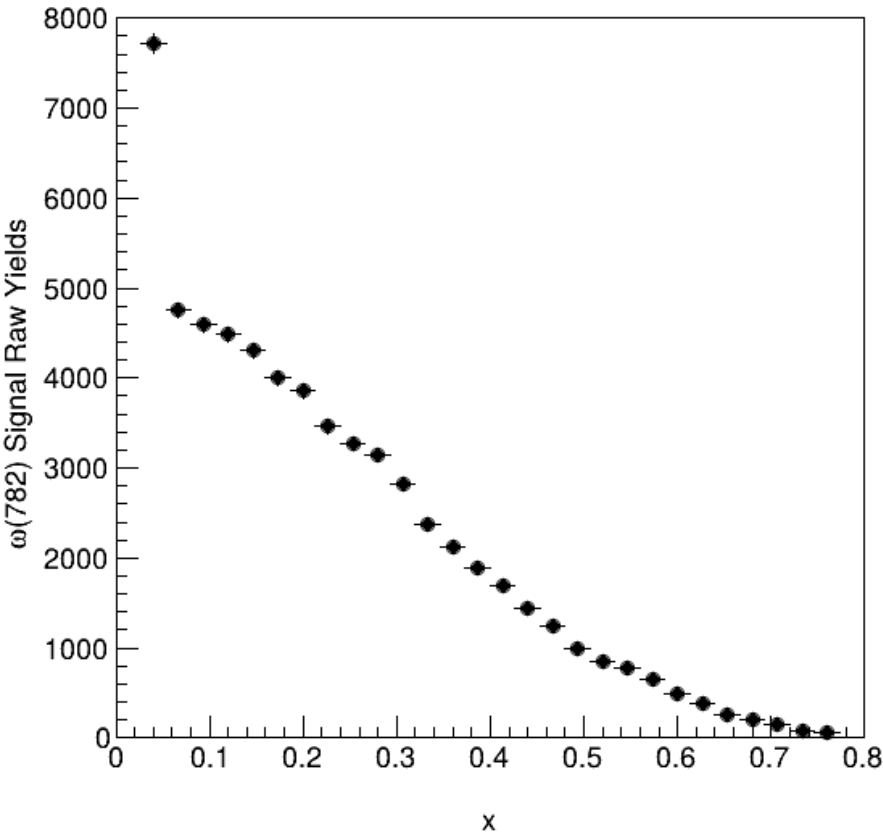
t (GeV^2) Signal Raw Yield Statistics Distribution



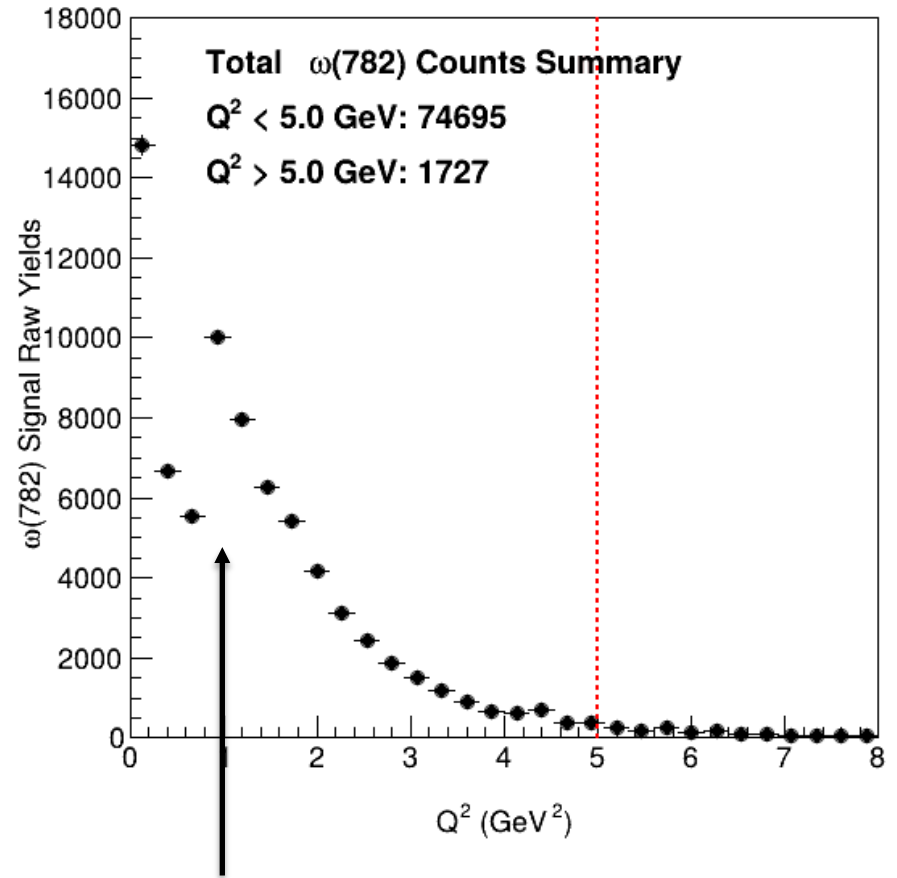
- Small t : red region is VDM type physics
- Intermediate t : blue region can be Regge Trajectory/GPD depending on the combinations of
- Green region of large t can be N^* physics
- CLAS6 coverage: magenta frame

x and Q^2 Range

x Signal Raw Yield Statistics Distribution



Q^2 (GeV²) Signal Raw Yield Statistics Distribution

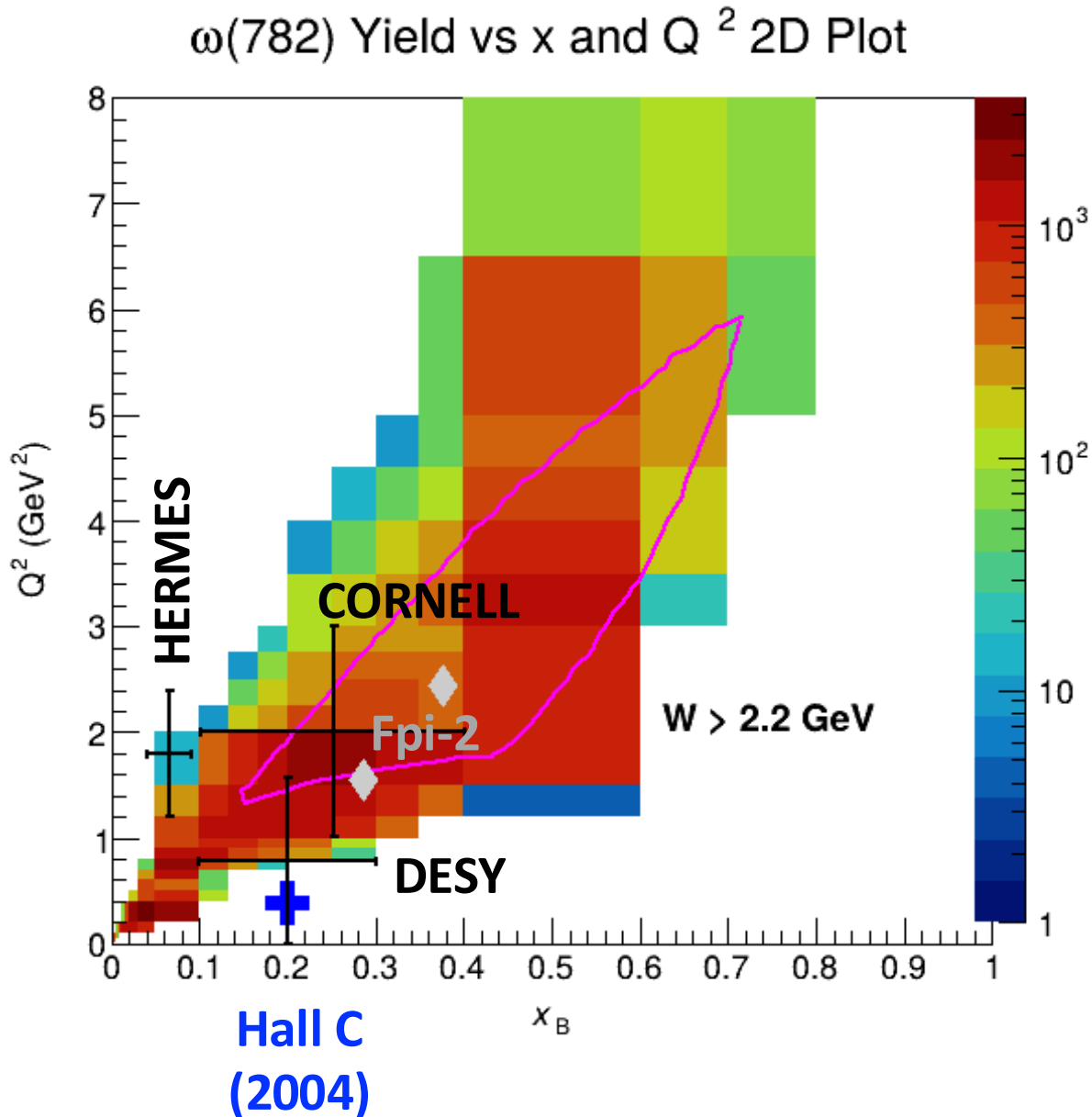


Forward Tagger/Forward Detector Effect

- $Q^2 > 5$ GeV² has great statistics for our studies, good for deep exclusive physics

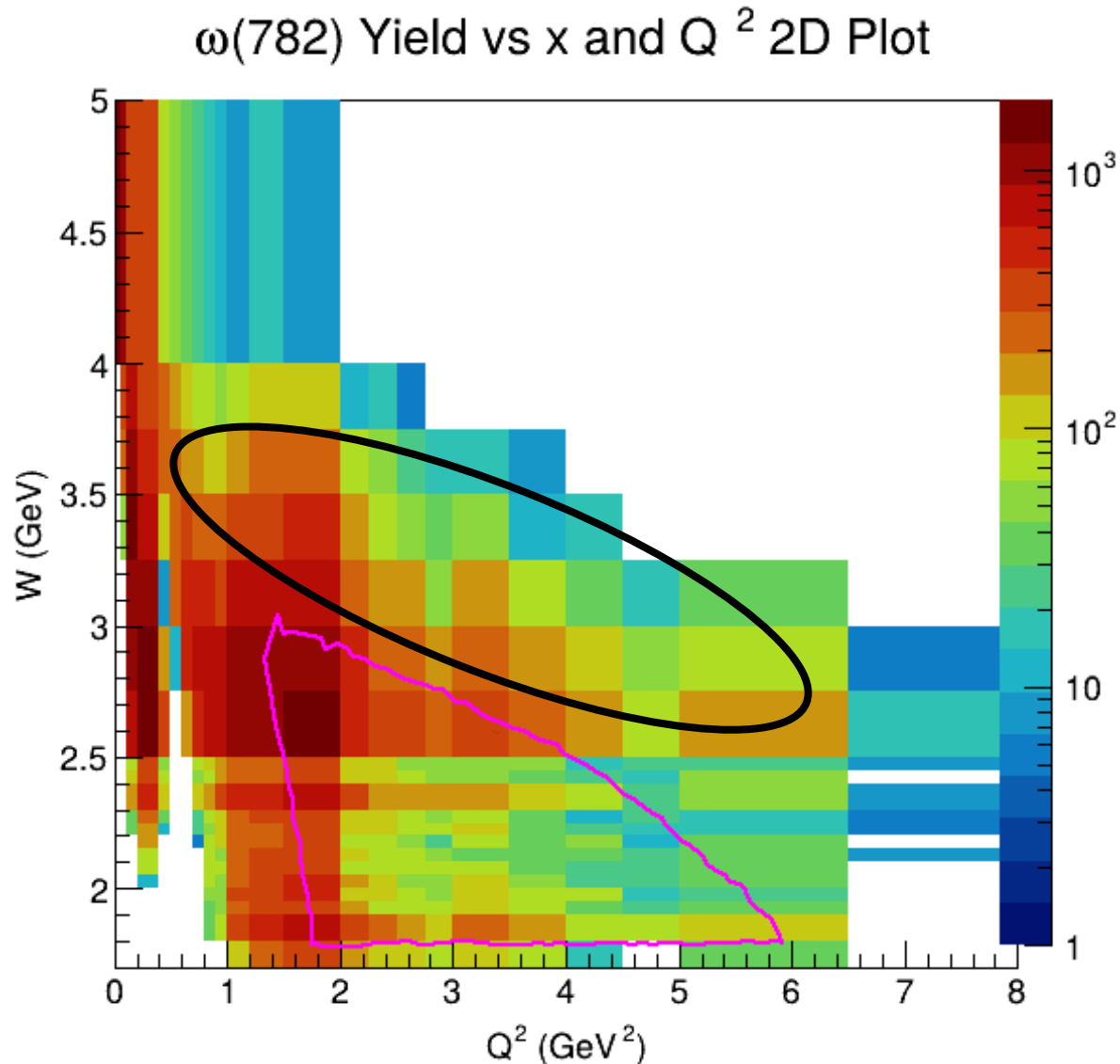
Overlay: x and Q^2 2D Plots

- We can safely say that our ω statistics with CLAS12 RGA datasets not only have a larger statistics with more area coverage but also completely contains the (x, Q^2) of the CLAS6 paper
- Area outside the region can be good candidate for deep physics?
 - Low x high Q^2 region we have a lot of statistics
 - What are the important physics here?



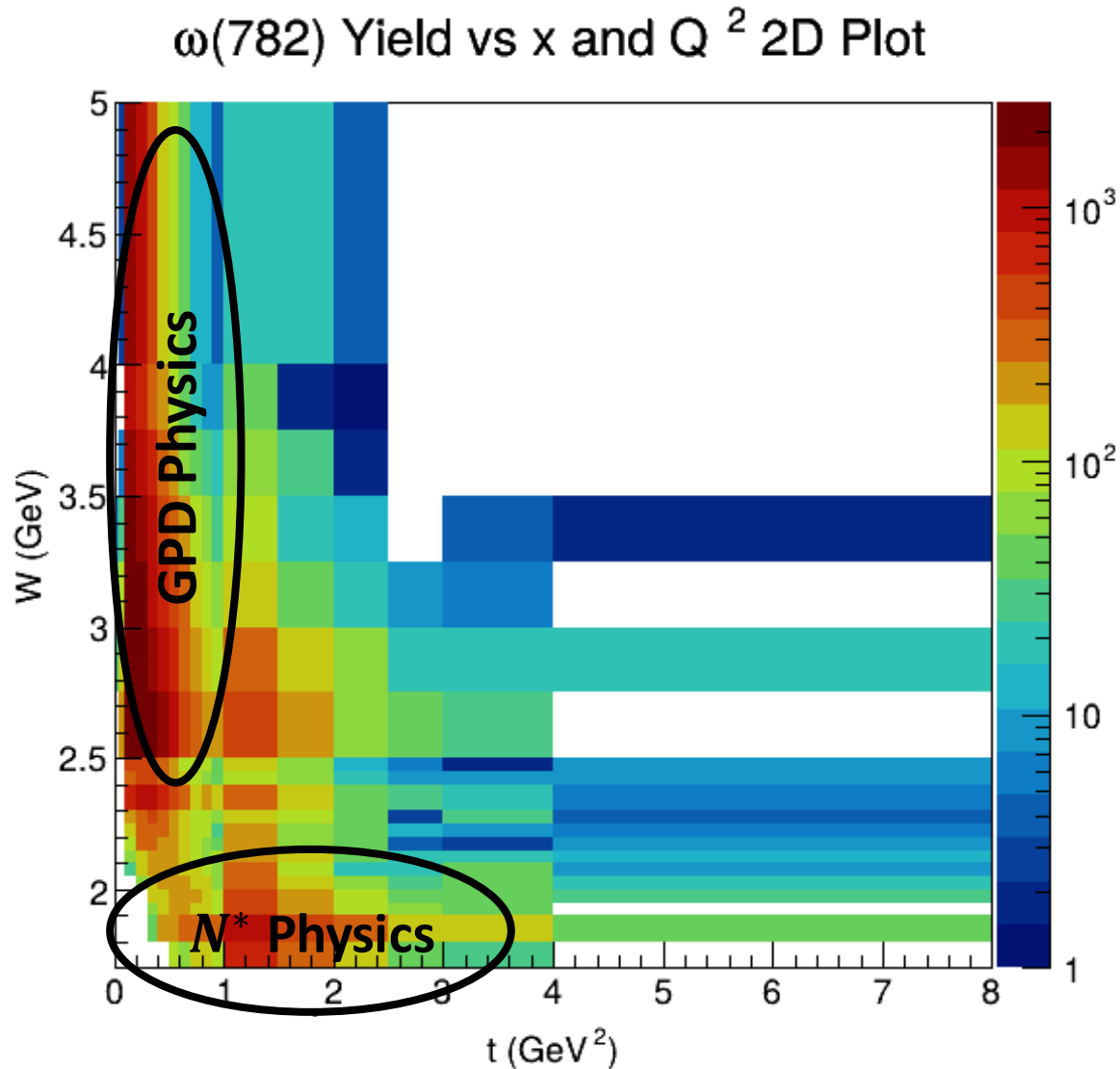
Overlay: W and Q^2 2D Plots

- We can safely say that our ω statistics with CLAS12 RGA datasets not only have a larger statistics with more area coverage but also completely contains the (Q^2, W) of the CLAS6 paper
- Area outside the region (black circle) can be good candidates for deep exclusive physics?
 - High W and high Q^2 region we have a lot of statistics
 - What is important here? Probably GPD type of deep physics



Overlay: t and W Coverage

- GPD Physics at Large W and small t
- Potential high t and Small W for N^* spectroscopy physics?
- Any suggestions for the interesting physics?
- Proposed to discuss with theoreticians, for instance, Christian Weiss, to get suggestions



Bigger Picture: Multi-Hall Efforts for ω Channel Physics

Efforts	Hall B (CLAS12)	Hall C
Reactions	Exclusive $ep \rightarrow e'p'\omega$ in the forward/central region	ω in the backward region
Exclusivity	Fully reconstructed ω via $\omega \rightarrow \pi^+\pi^-\pi^0$ and $\omega \rightarrow \pi^0\gamma$	ω via the missing-mass techniques
Kinematics Phase Space Coverage	Broad t -channel coverage	Backward scattering u -channel physics
Statistics	Excellent	Great
Physics Goals	GPD-Type and Potentially N^* Spectroscopy	TDA Physics
Advantages	Physics over a broad kinematics phase space	Focused precision cross section measurements
Timeline	24 – 36 months	18 – 24 months

- Put together Hall B + C exclusive $\omega(782)$ meson kinematics phase space coverage: x_B , Q^2 , t , u , and W together will be very interesting!

Conclusions

Summary and To Do List

- Exclusive $\omega(782)$ Electroproduction of the Proton with CLAS12 RGA Datasets
 - More statistics with broader phase space than the CLAS6 publication
 - ω meson physics is promising
 - Get ready for CAA in the next Collaboration Meeting
- Future Directions/Next Steps
 - Decide the physics topics that is interesting, impactful, and complementary to Hall C efforts
 - Work closely with DPWG to understand the priorities
 - Suggestions or feedback are highly appreciated
 - Construct the experimental observables for measurement
 - Convenient to obtain
 - Systematics canceling
 - Direct comparison with CLAS6 published data and theory curves
 - Examples: *differential cross section* or *beam spin asymmetry*
 - Complete analysis sample processing
 - RG-A: Spring 2018 and Spring 2019 datasets
 - Event generator R&D and MC generation with OSG/Lamar HPC
 - Refine measurement (improve signal yield and reduce systematics)
 - Obtain first preliminary results

Thank You

$\omega(782)$ Reconstruction with Missing π^\pm

Algorithms

- Select events with exactly 1 proton, 1 electron, 1 π^+ or π^- , and at least 2 photons

- Calculate the missing 4 vector

$$p_{\pi^\mp}^\mu = p_e^\mu + p_p^\mu - p_{e'}^\mu - p_{p'}^\mu - p_{\pi^\pm}^\mu - p_{\pi^0}^\mu$$

$$p_\omega^\mu = p_{\pi^\mp}^\mu + p_{\pi^\pm}^\mu + p_{\pi^0}^\mu$$

- Mass definitions:

- $m_{\pi^0} = \sqrt{p_{\pi^0}^\mu p_{\pi^0}^\mu}$
- $m_{\pi^\pm} = \sqrt{p_{\pi^\pm}^\mu p_{\pi^\pm}^\mu}$

- Mass forcing

- If $|m_{\pi^0} - m_{\pi^0}^{PDG}| < 0.025$ GeV, we force the m_{π^0} to be $m_{\pi^0}^{PDG}$ for p_ω^μ calculations

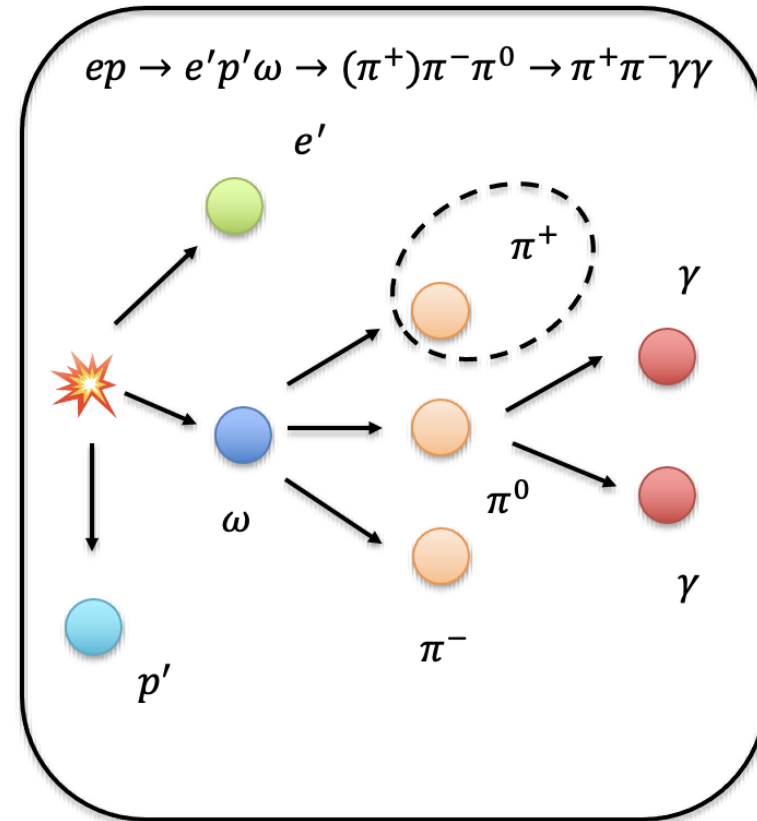
PID Cuts Options

- No Cuts

- $|m_{\pi^0} - m_{\pi^0}^{PDG}| < 0.025$ GeV

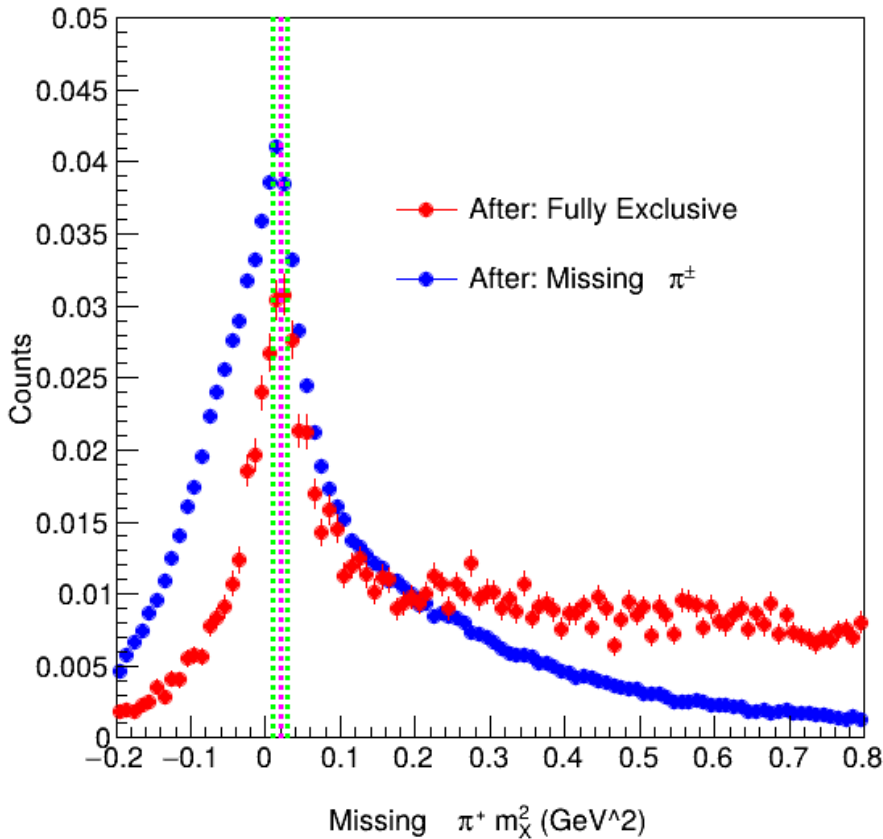
- $|m_{\pi^0} - m_{\pi^0}^{PDG}| < 0.025$ GeV AND $|m_{\pi^\pm}^2 - (m_{\pi^\pm}^{PDG})^2| < 0.005$ GeV

- Exclusion: $|m_{\pi^0} - m_{\pi^0}^{PDG}| < 0.025$ GeV AND $|m_{\pi^\pm}^2 - (m_{\pi^\pm}^{PDG})^2| > 0.1$ GeV

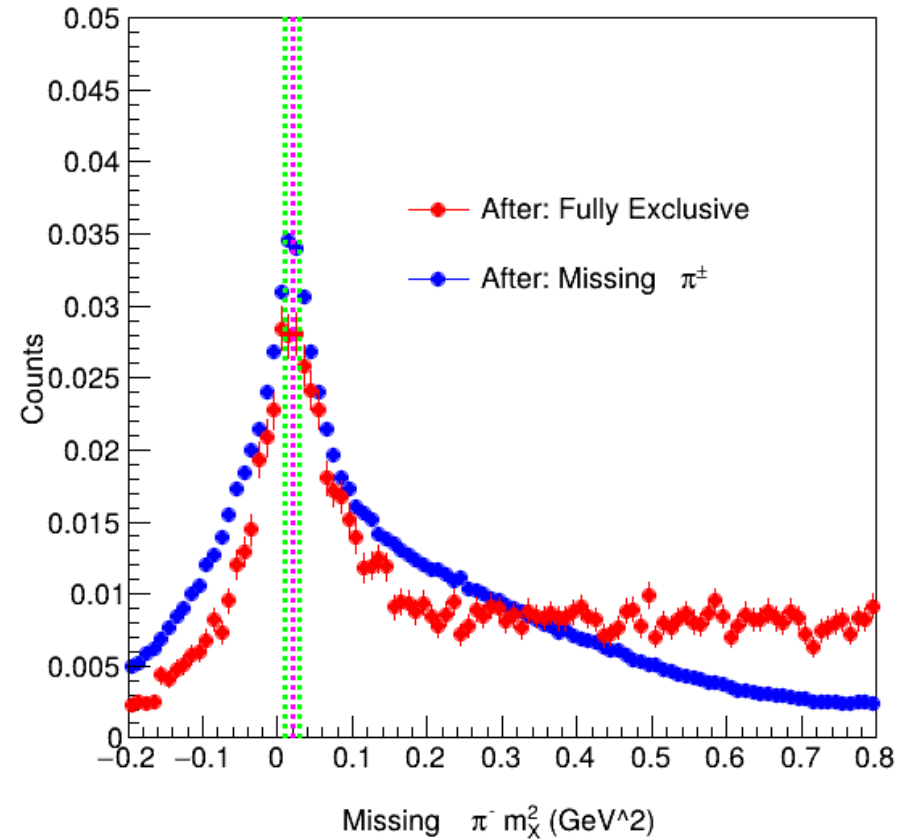


π^\pm Missing Mass

Missing π^+ Invariant Mass Distribution with Cuts

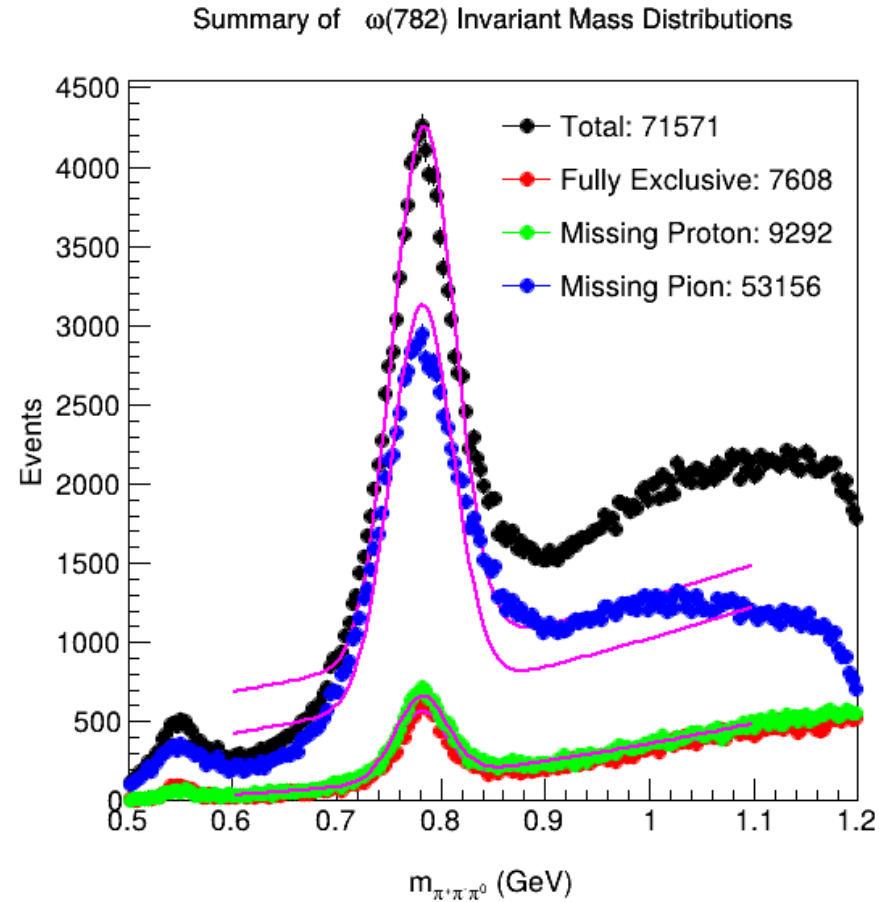
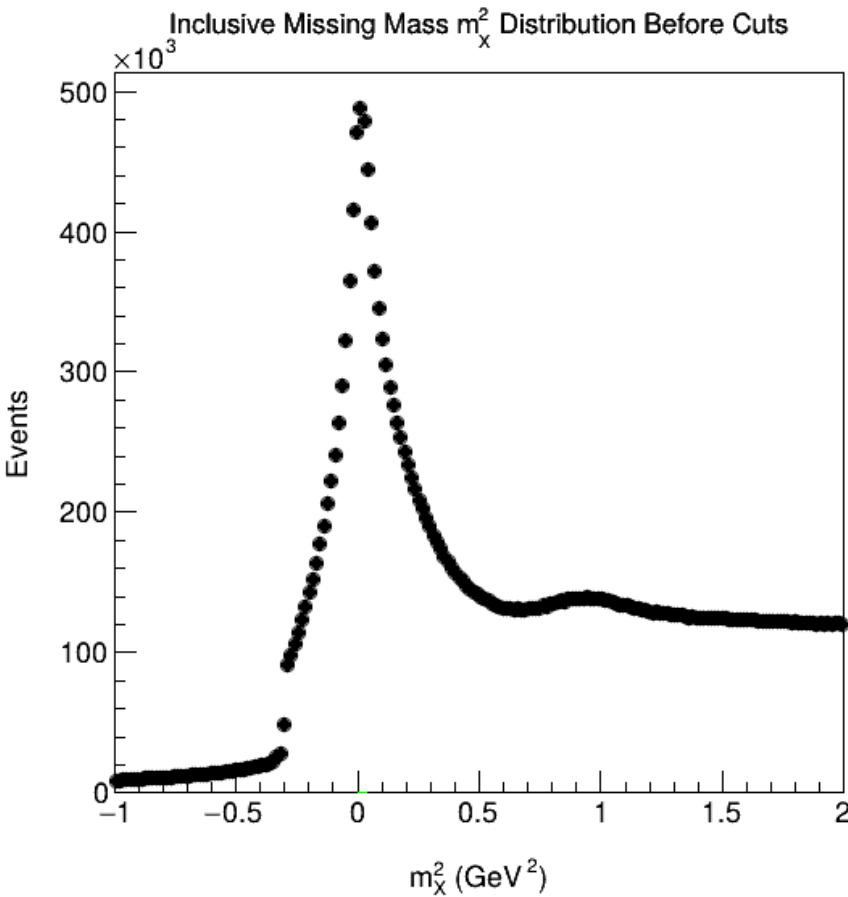


Missing π^- Invariant Mass Distribution with Cuts



- Position of the peaks agree in fully exclusive and missing pions between for both π^+ and π^-
 - No explicit bias \rightarrow systematics goes into the width
- We can impose a better mass range based on the missing mass of the golden events (fully exclusive: $e'p'\pi^+\pi^-\pi^0$)
 - Currently using the $m_\pi^{PDG^2}$ (magenta line) with a width of 0.01 GeV² (green lines)

Total Summary



- Cutting on the missing mass from the left we can get the right plot
- Over 70000 statistics of ω mesons combing all $\omega \rightarrow \pi^+\pi^-\pi^0$ data together

$\omega(782)$ Reconstruction with Missing π^0

Algorithms

- Select events with exactly 1 proton, 1 electron, 1 π^+ and π^- , and 0 photons

- Calculate the missing 4 vector

$$p_{\pi^0}^\mu = p_e^\mu + p_p^\mu - p_{e'}^\mu - p_{p'}^\mu - p_{\pi^+}^\mu - p_{\pi^-}^\mu$$

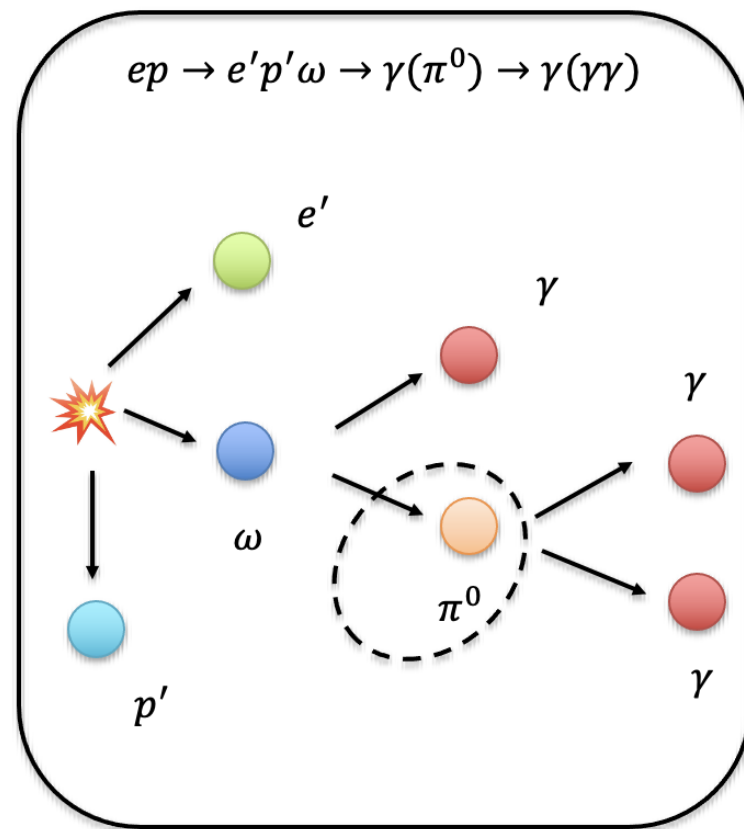
$$p_\omega^\mu = p_{\pi^+}^\mu + p_{\pi^-}^\mu + p_{\pi^0}^\mu$$

- Mass definitions:

- $m_{\pi^0} = \sqrt{p_{\pi^0}^\mu p_{\pi^0}^\mu}$

- Mass forcing

- If $|m_{\pi^0} - m_{\pi^0}^{PDG}| < 0.025 \text{ GeV}$, we force the m_{π^0} to be $m_{\pi^0}^{PDG}$ for p_ω^μ calculations

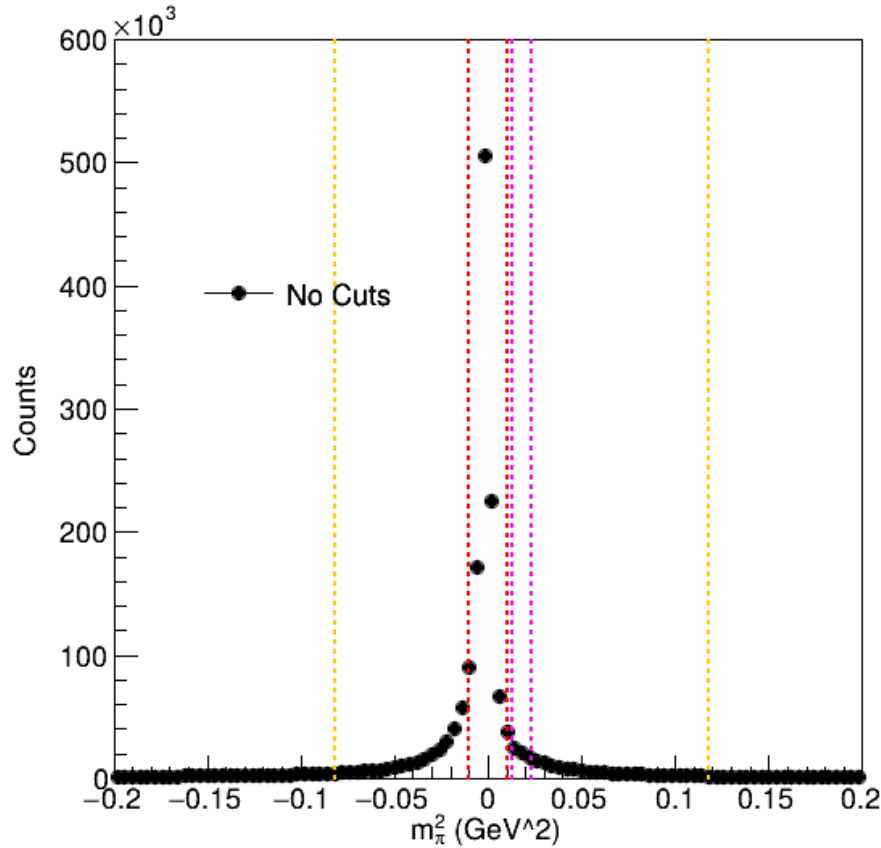


PID Cuts Options

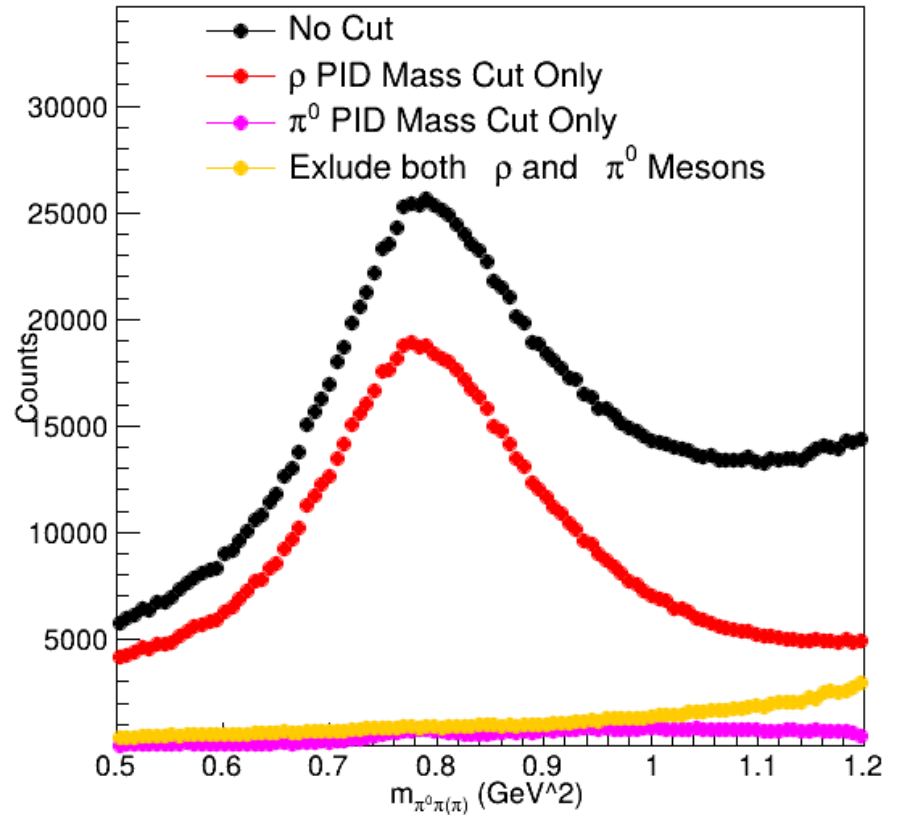
- No Cuts
- $\rho \rightarrow \pi^+\pi^-$ contamination check: $|m_{\pi^0}^2| < 0.01 \text{ GeV}$
- $|m_{\pi^0}^2 - (m_{\pi^0}^{PDG})^2| < 0.025 \text{ GeV}$
- Exclusion: $|m_{\pi^0}^2 - (m_{\pi^0}^{PDG})^2| > 0.1 \text{ GeV}$

Cut UnZoom and Background Check (Torus - 1)

Missing π Mass with ω Resonance



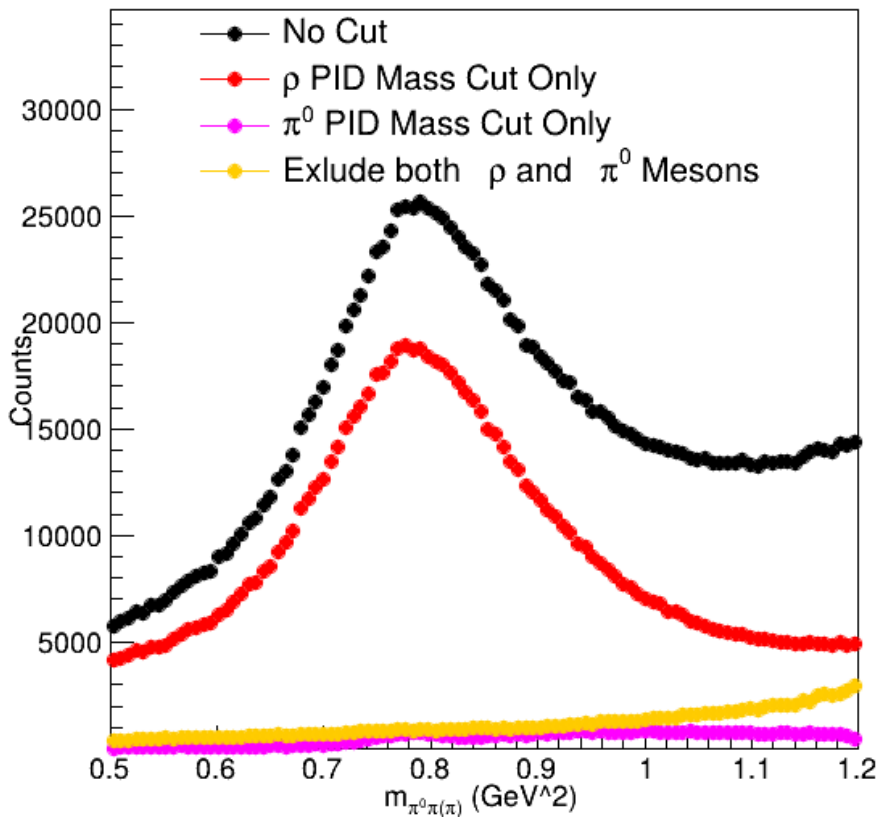
Reconstructed ω from Missing Pion



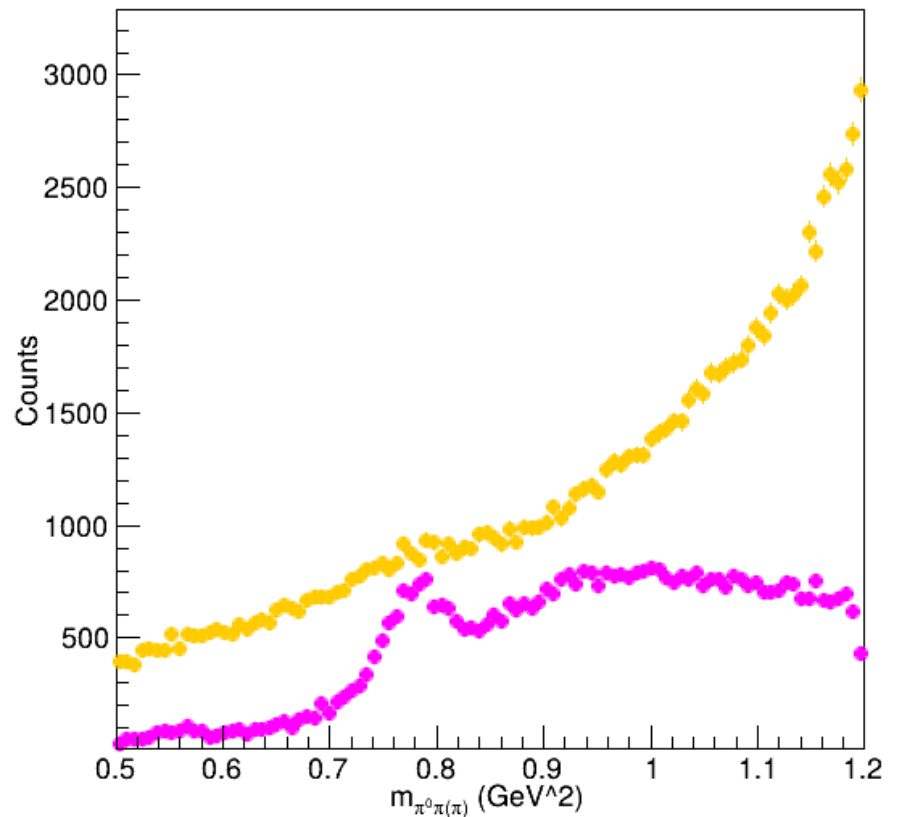
- Peaking shape for m_{X}^2 near 0: π^+ and π^- no γ
 - Either not accepting the $\gamma\gamma$ from π^0 by the ECAL
 - Or it is simply $\rho \rightarrow \pi^+\pi^-$ which fundamentally does not have γ
 - Break into 3 cases: Enforcing π^0 , Enforcing ρ , and excluding everything

$\rho^0 \rightarrow \pi^+ \pi^-$ Background Rejection

Reconstructed ω from Missing Pion



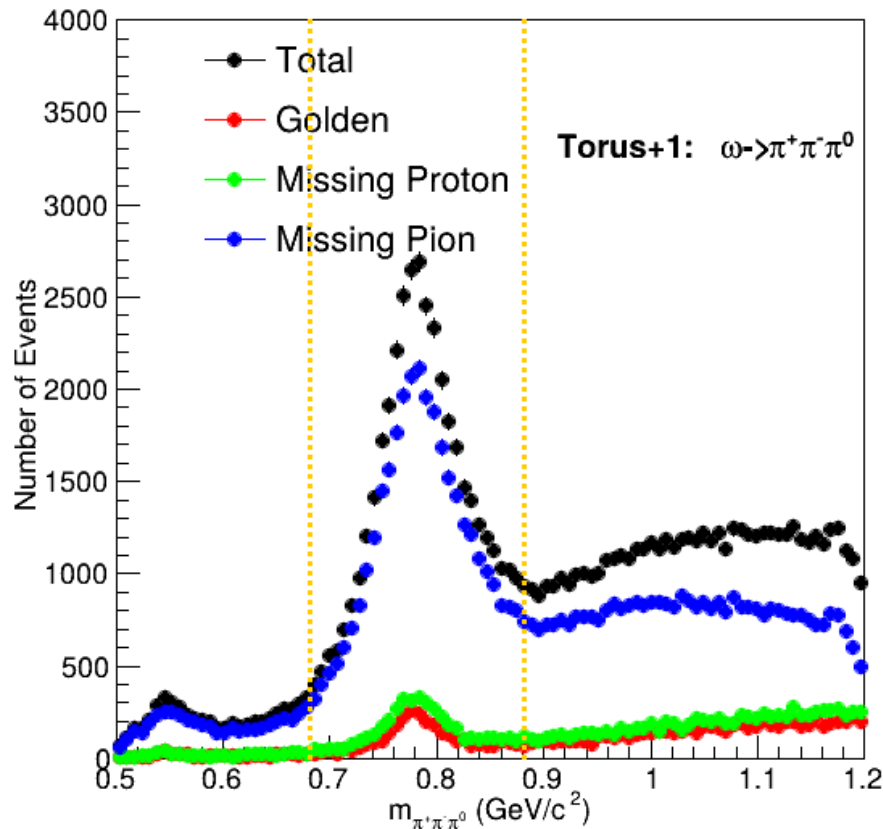
Reconstructed ω from Missing Pion



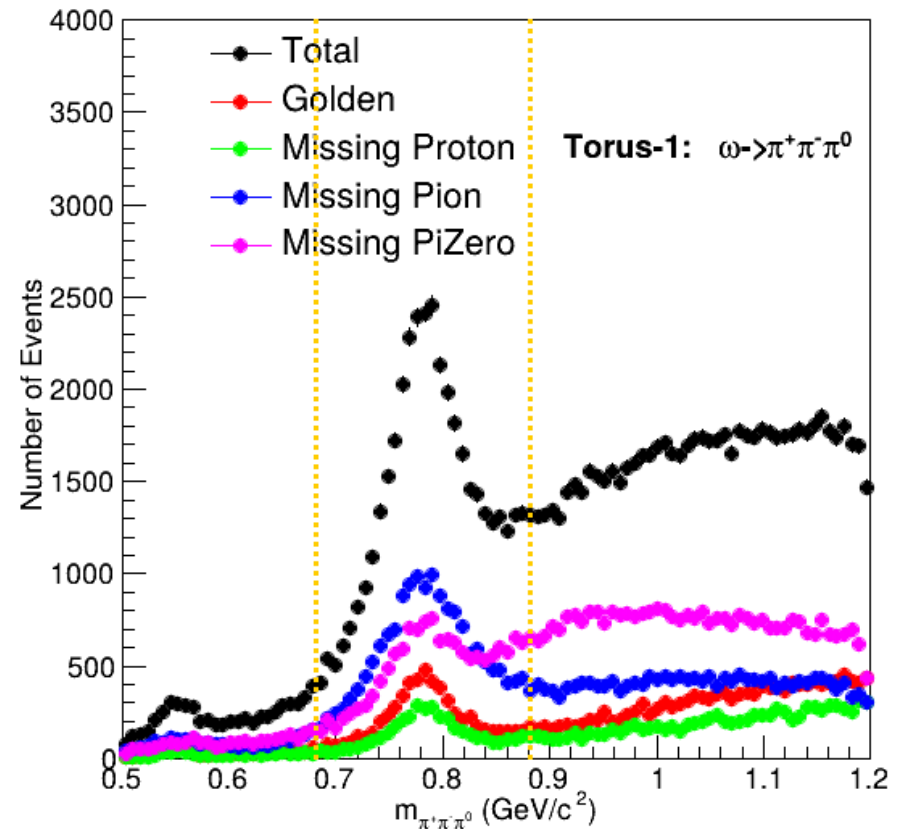
- Indeed, the ρ meson cases dominates if there is no $|m_X^2| < 0.1 \text{ GeV}^2$ cuts
 - Need to trace deeper into missing photon studies to extract additional ω from the ρ meson decay background
- If we enforce $|m_{\pi^0}^2 - (m_{\pi^0}^{PDG})^2| < 0.025 \text{ GeV}$, we are able to see the clear $\omega(782)$

$\omega(782)$ Summary for Torus + 1 and Torus-1

Summary of $\omega(782)$ Invariant Mass Distributions



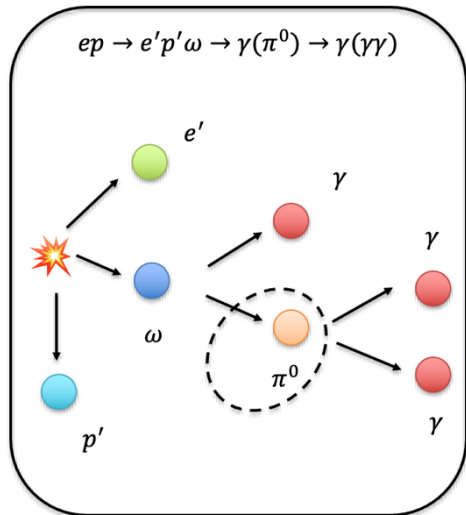
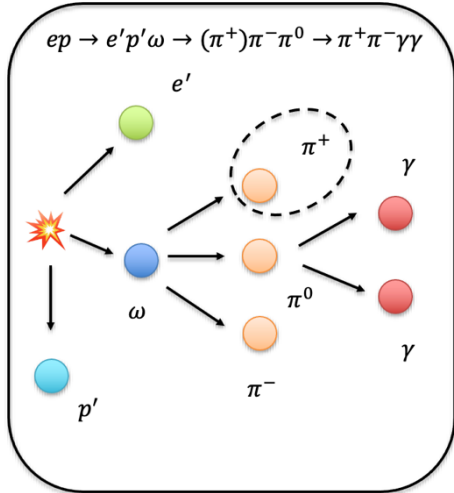
Summary of $\omega(782)$ Invariant Mass Distributions



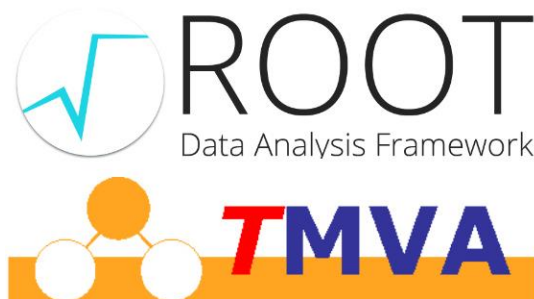
- Not worth doing the missing π^0 channel for now because the gain in statistics is not that much compared to the effort of dealing with the systematics

ω Analysis To Do List

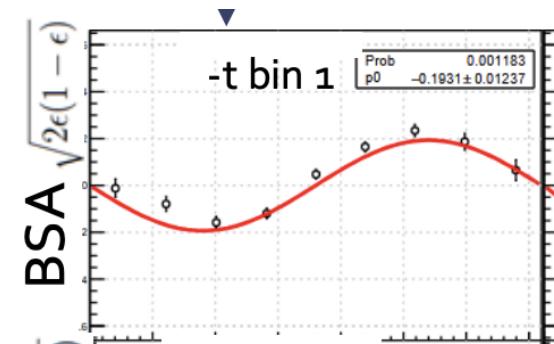
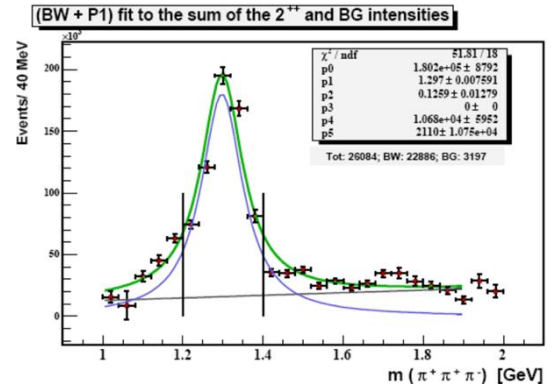
Include Missing Pions to Enhance the ω Yield



MC Generation and ω Yield Optimization



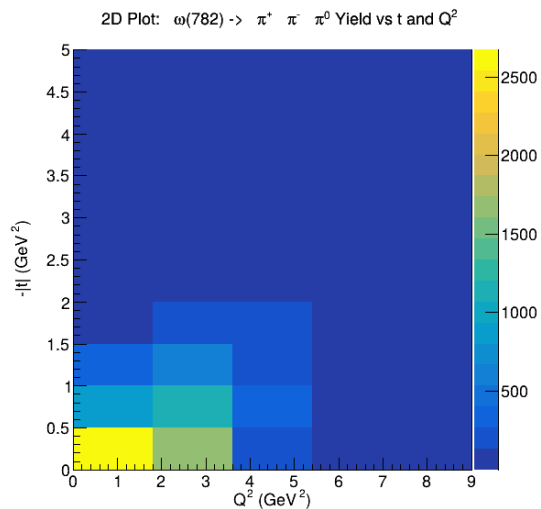
Efficiency Correction and Physics Measurements



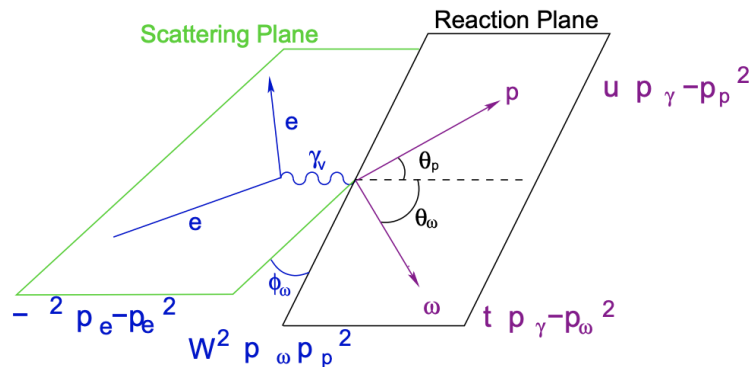
$$\sigma_{LT'}^{\sin\Phi} \sim [\bar{E}_T H + H_T E]$$

Next Steps in Analysis

ω Phase Space



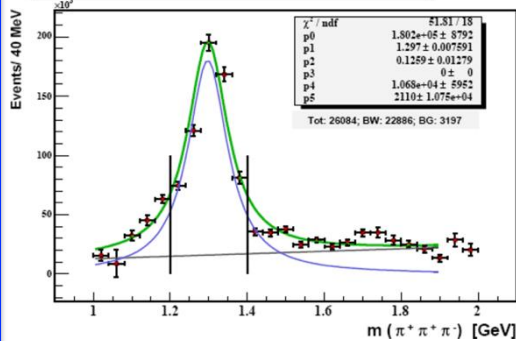
Moving into ω CM frame



Credit: Wenliang Li's PhD Thesis

$1.7 < W < 2.2$ GeV

(BW + P1) fit to the sum of the 2^{++} and BG intensities



N^*	J^P	Γ (MeV/c ²)	Γ_i/Γ
N(1700)	0^{-+}	100 - 200	10-34%
N(1710)	1^{-+}	80 - 200	1-5%
N(1720)	1^{++}	150 - 400	12-40%
N(1875)	1^{-+}	120 - 250	15-25%
N(1880)	2^{-+}	200 - 400	12-28%
N(1895)	1^{-+}	80 - 200	16-40%
N(1900)	1^{-+}	100 - 320	2-13%
N(2060)	1^{-+}	300 - 450	1-7%
N(2100)	1^{-+}	200 - 320	10-25%
N(2120)	1^{-+}	260 - 360	4-20%
N(2190)	1^{-+}	300 - 500	8-20%

$N^* \rightarrow \omega N$

$W > 2.2$ GeV

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\Phi} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}^{\cos 2\Phi} \cos 2\Phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}^{\cos\Phi} \cos\Phi + P_b\sqrt{2\epsilon(1-\epsilon)}\sigma_{LT'}^{\sin\Phi} \sin\Phi$$

$$BSA = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim A_{LU}^{\sin\Phi} \sin\Phi$$

$$A_{LU}^{\sin\Phi} = \sqrt{2\epsilon(1-\epsilon)} \frac{\sigma_{LT'}^{\sin\Phi}}{\sigma_0}$$

$$\sigma_{LT'}^{\sin\Phi} \sim [\bar{E}_T H + H_T E]$$

Credit: Nicholas Troтта

GPД - DVMP