NSTAR 2026 Conference

Jefferson Lab

NSF

Analysis of ω(782) Electroproduction at CLAS12

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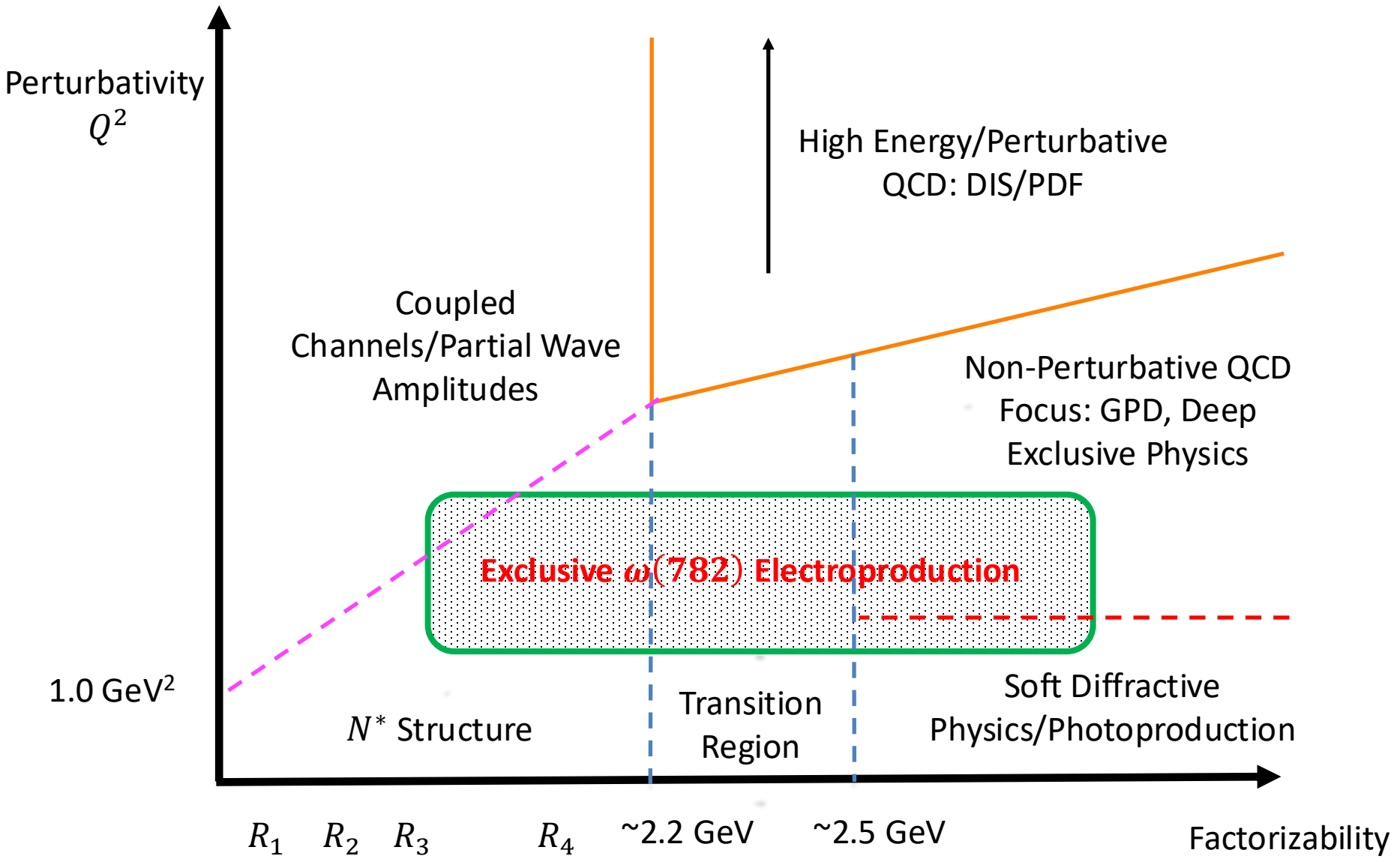
09/07/2026

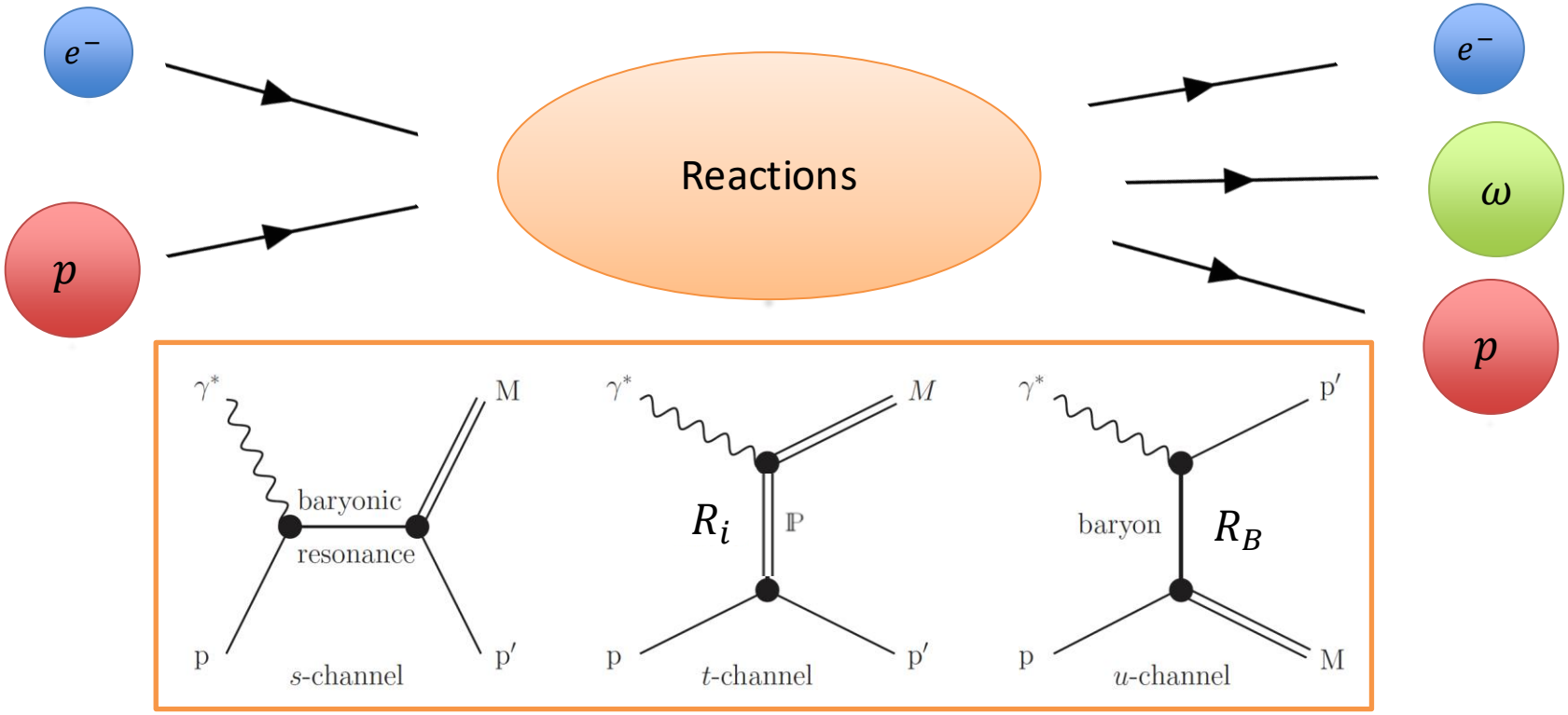
clas

Territory Map Electron-Proton Scattering



- Q^2 measure how close you approach the quarks
- Constructing the amplitude $A(W, Q^2)$

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



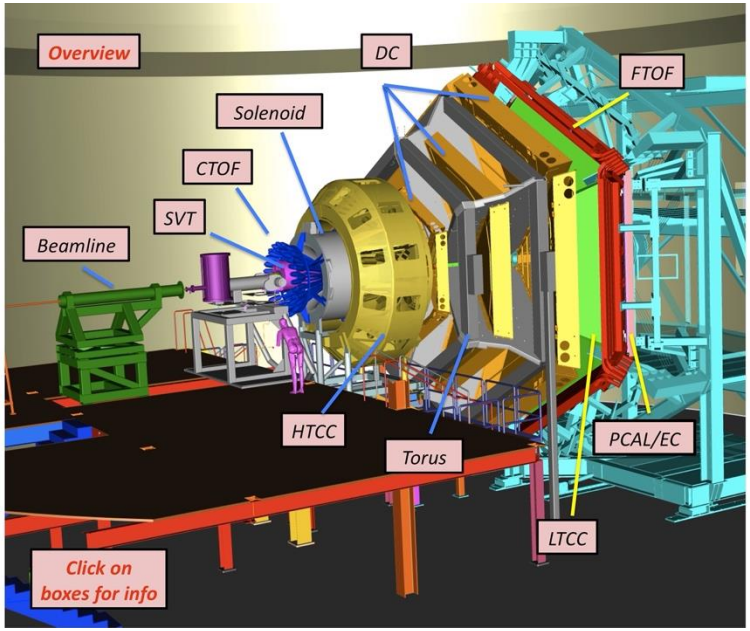
N^* Spectroscopy

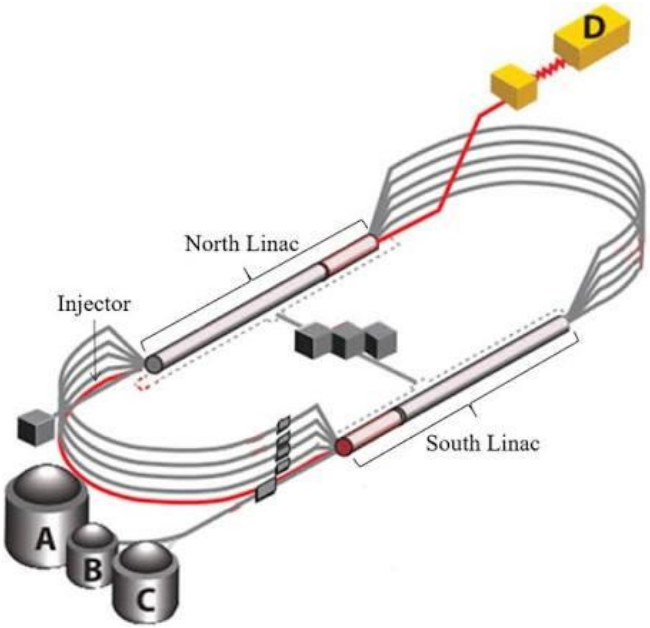
Forward Scattering Diffractive Physics

Backward Scattering Hall C Efforts

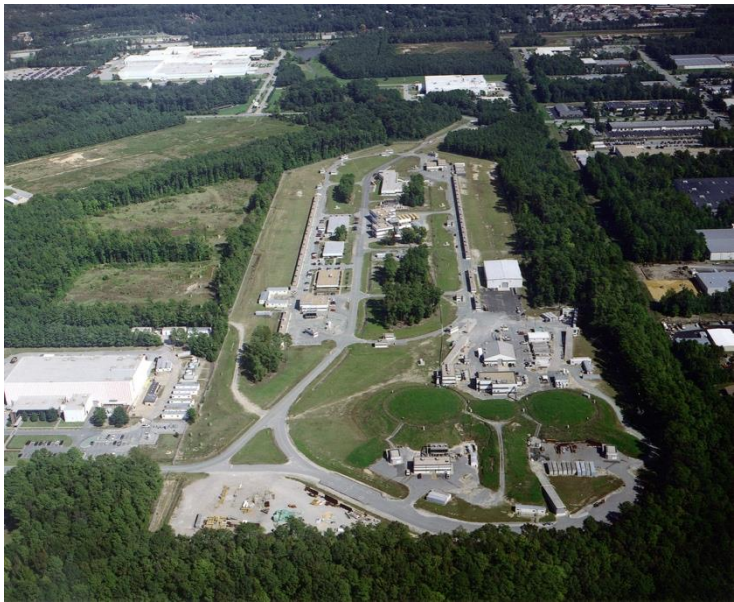
- Not many studies on $\omega(782)$ exist so far
  - Excellent exclusive measurement of CLAS12 in Hall B for s- and t-channel $\omega(782)$
  - Complementary to Hall C efforts on the u-channel studies
- $\omega(782)$ Studies: Bridge N^* and Deep Exclusive Physics
  - Fourth resonance region and extension to the non-resonance and transition regime → contribution to the amplitudes for DIS

CLAS12 in Hall B at CEBAF at Jefferson Laboratory



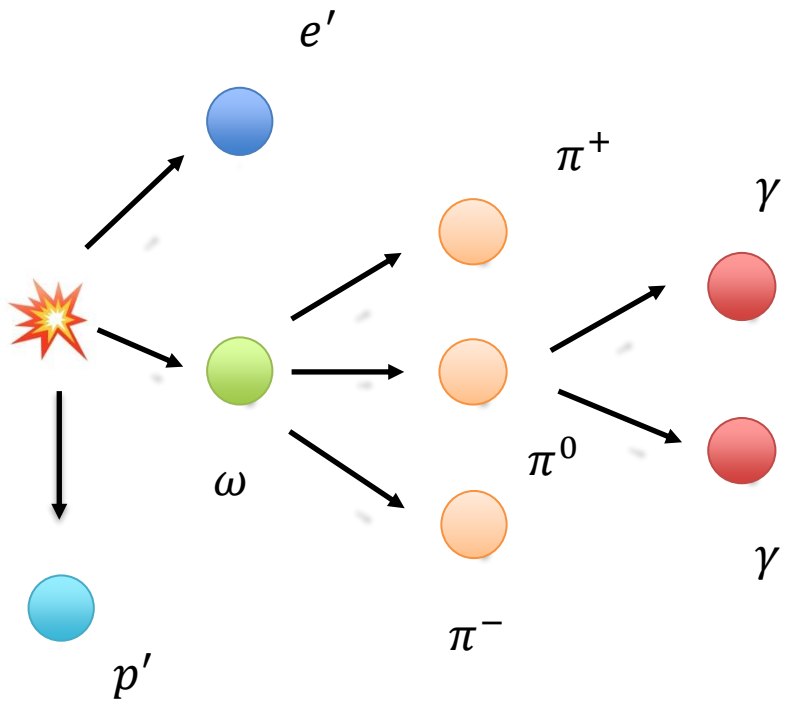


- CLAS12: State-of-the-art detector with CEBAF located in Hall B at Jefferson Laboratory
  - Large acceptance coverage
  - Fast DAQ/trigger rate and efficiency
  - Excellent tracking performance
  - Well calibrated forward ECAL
  - PID capability for π, K, p separation
- Excellent experiment for exclusive $\omega(872)$ electroproduction cross section measurement



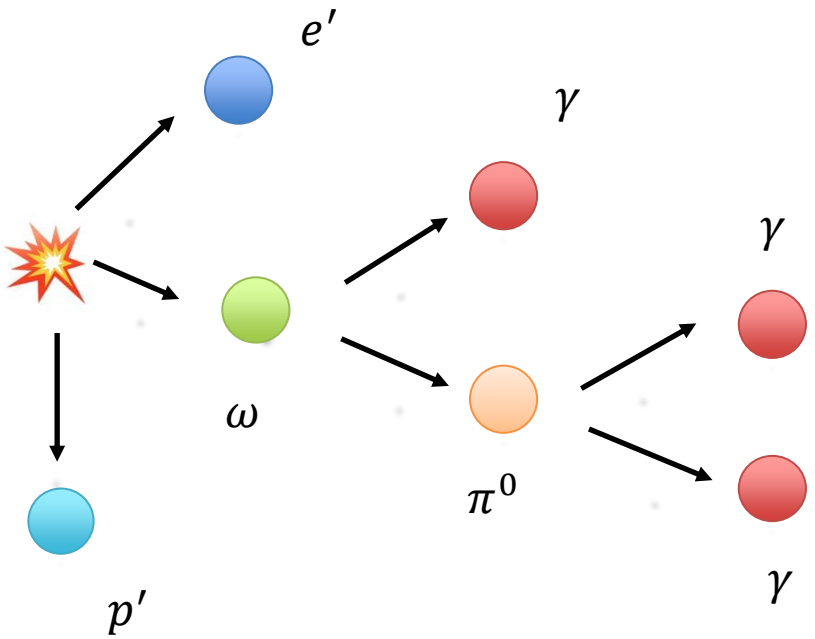
Decay Topology and Analysis Strategies

$ep \rightarrow e'p'\omega \rightarrow \pi^+\pi^-\pi^0 \rightarrow \pi^+\pi^-\gamma\gamma$



Channel 1 BR = 89.2%

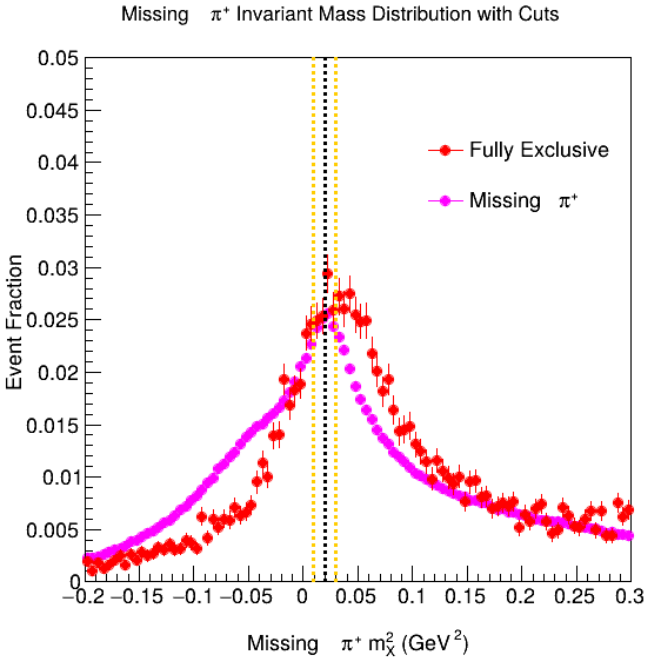
$ep \rightarrow e'p'\omega \rightarrow \gamma\pi^0 \rightarrow \gamma\gamma\gamma$

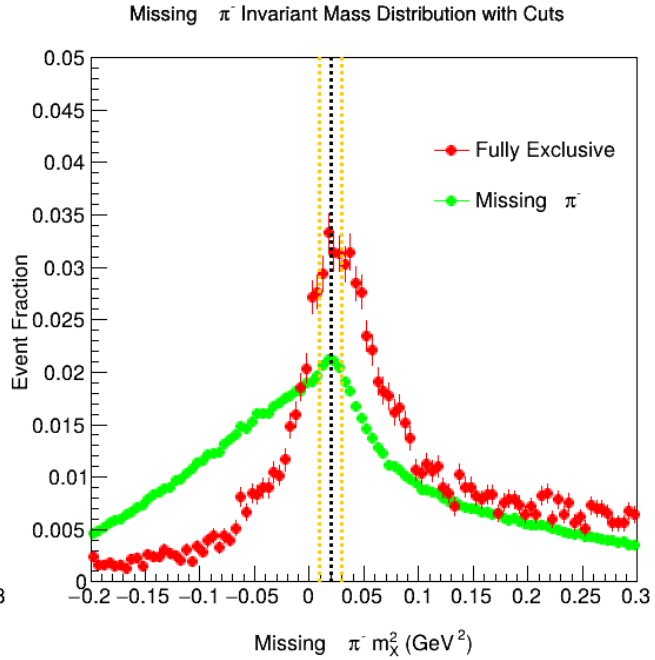


Channel 2 BR = 8.33%

- Full CLAS12 RG-A fall 2018 dataset
- Fully reconstructed $\omega(782)$ from decay daughters based on event information
- Exclusivity further classified according to missing mass selection

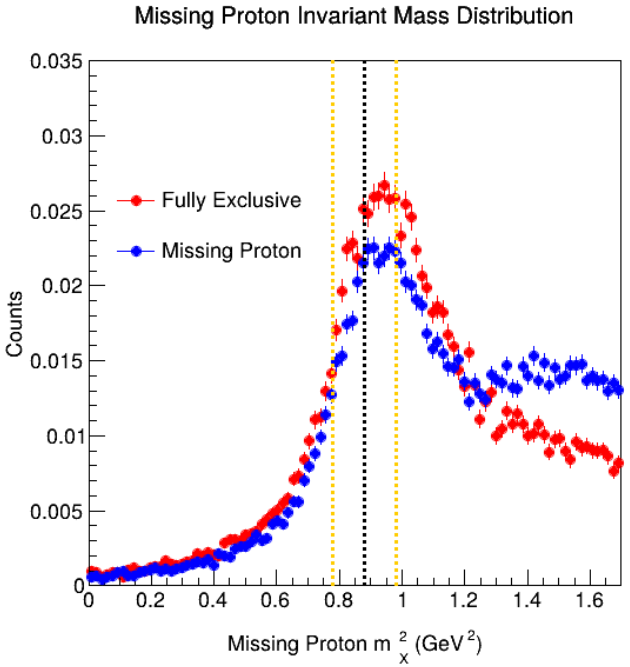
Missing Mass Distributions





Event Topology	Percent Statistics
Fully Exclusive	1.69%
Missing Proton	2.03%
Missing π^+	51.7%
Missing π^-	44.6%

- Reaction: $ep \rightarrow e'p'\omega \rightarrow e'p'\pi^+\pi^-\pi^0 \rightarrow e'p'\pi^+\pi^-\gamma\gamma$
- Require: $\left|m_{\pi^+\pi^-\pi^0} - m^{PDG}_{\omega(782)}\right| < 0.05$ GeV
- Black dashed line are PDG values
- Orange dashed lines are m_X^2 cut ranges near the PDG values
- Reconstruction sanity check: strong agreement between exclusive and missing π^+, π^-, p events



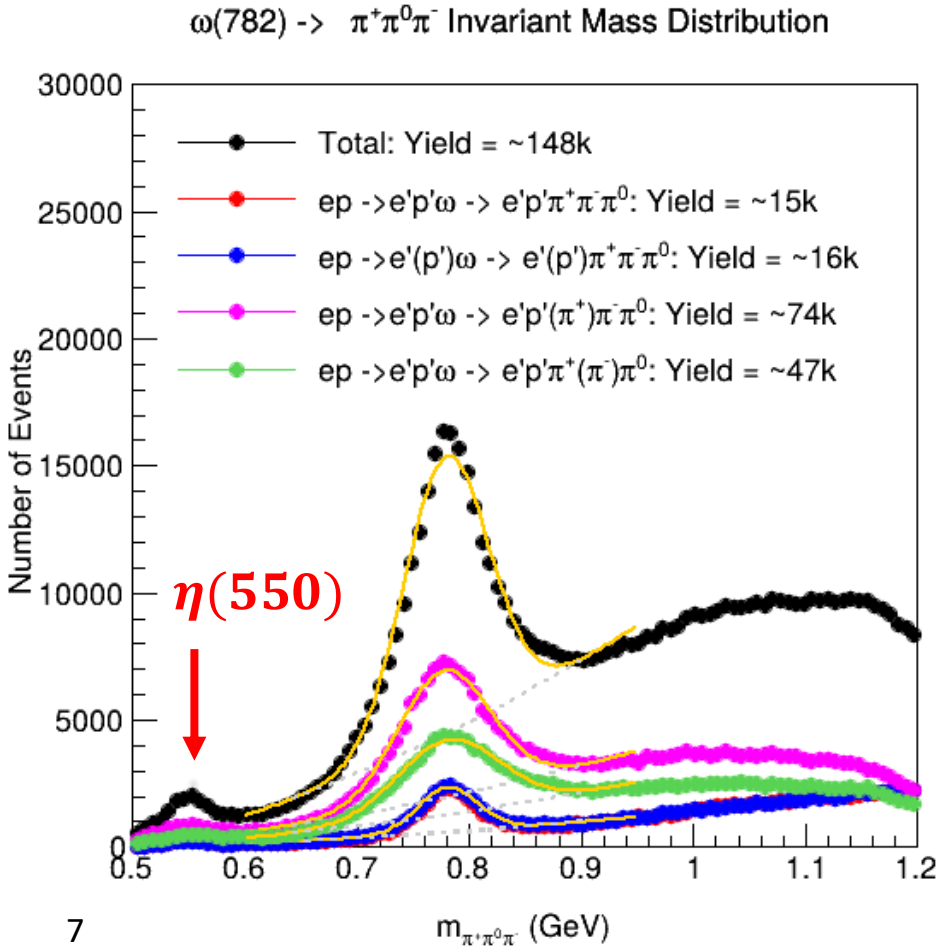
Channel 1: $\omega \rightarrow \pi^+\pi^-\pi^0$ Reconstruction

- Analysis Summary: $N_\gamma \geq 2$ and $\left|m_{\gamma\gamma} - m_{\pi^0}^{PDG}\right| < 0.025$ GeV
  - For fully exclusive: $|m_X^2| < 0.1$ GeV²
  - For $N_p = 0$: $|m_X^2 - m_p^{PDG\,2}| < 0.1$ GeV²
  - For $N_{\pi^\pm} = 0$: $|m_X^2 - m_{\pi^\pm}^{PDG\,2}| < 0.02$ GeV²

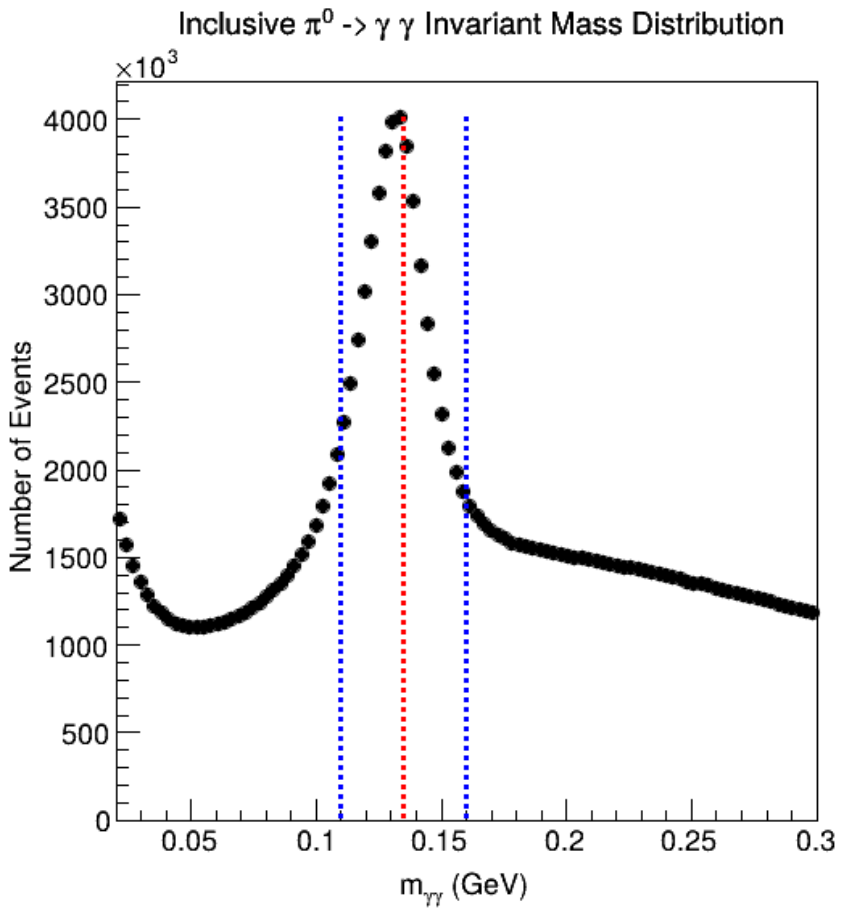
- Clear exclusive $\omega(782)$ with consistent peak, reasonable detector resolution, and high statistics observed after cuts

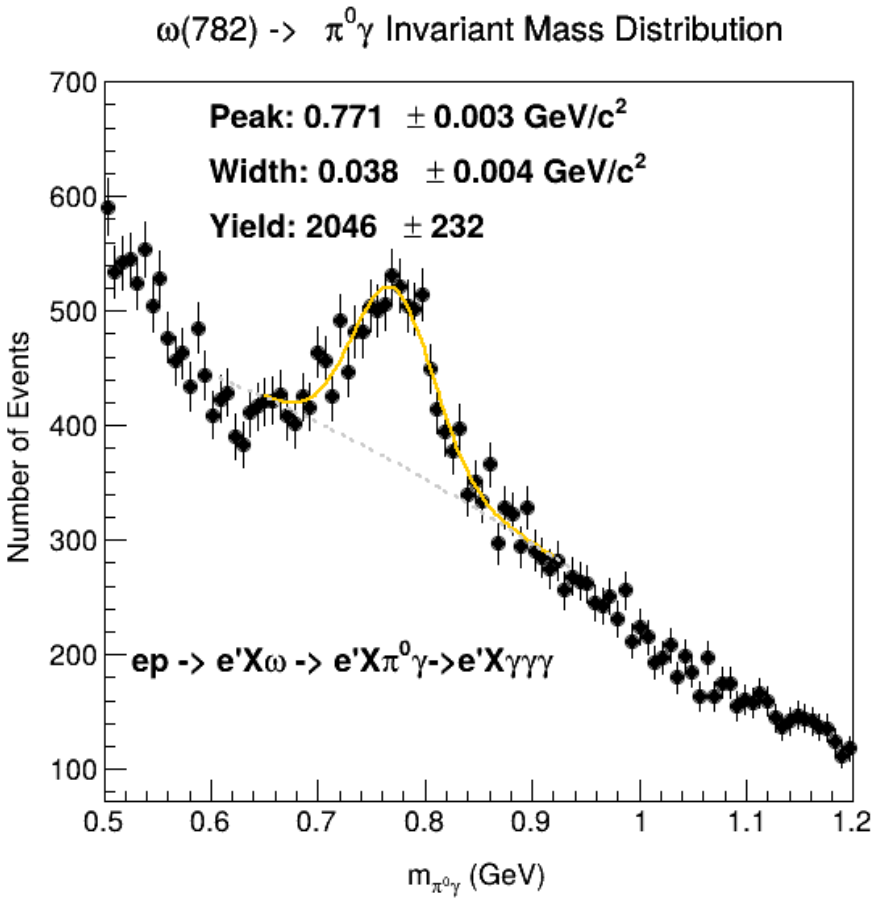
- Fits Model: Single Gaussian (signal region) + quadratic polynomial (background model)

- Feasible for physics observable studies and exploration in different kinematics regions



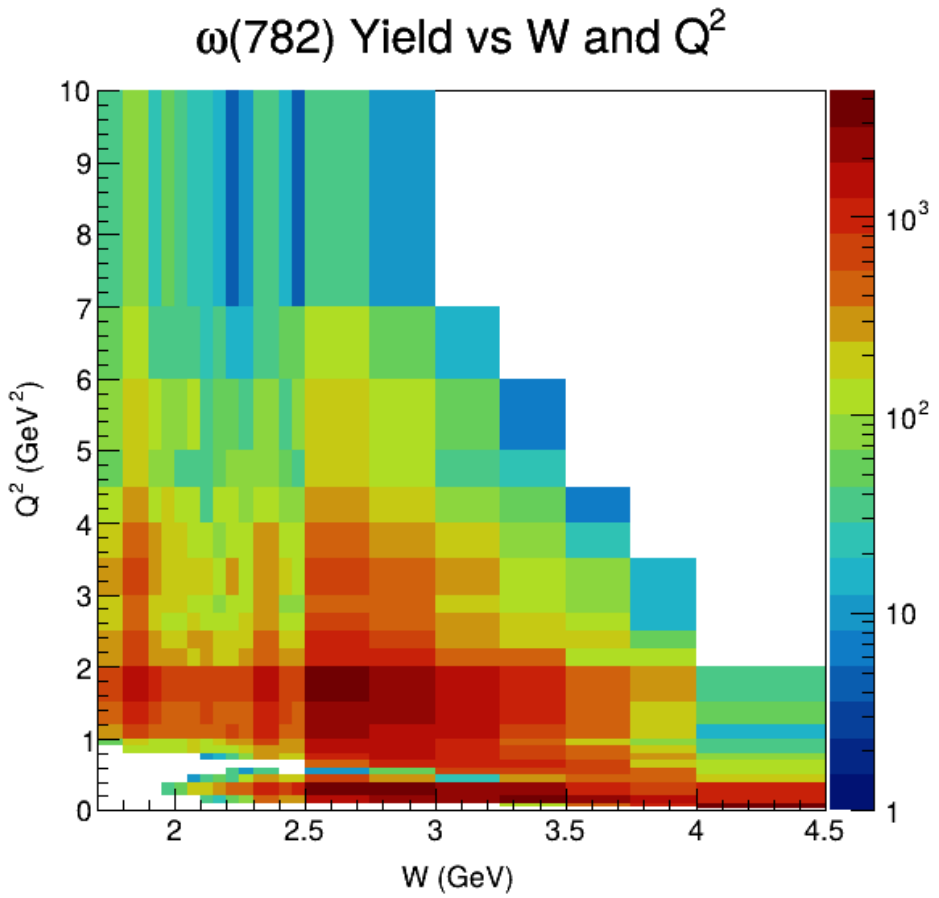
Channel 2: $\omega \rightarrow \pi^0\gamma$ Reconstruction

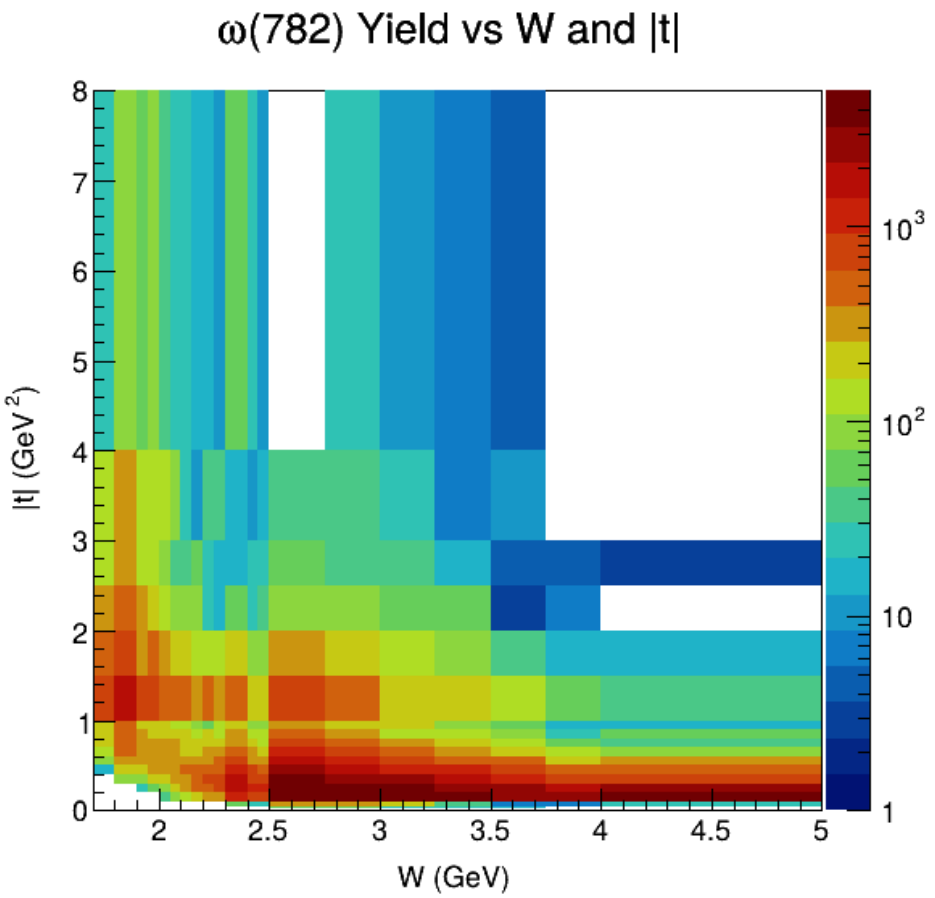




- Selection: $N_\gamma \geq 3$, $\left|m_{\gamma\gamma} - m_{\pi^0}^{PDG}\right| < 0.025$ GeV, $E_\gamma > 0.8$ GeV, $|m_X^2| < 0.01$ GeV^2
- Also, clear signal π^0 for $\omega(782)$ observed in the $\omega \rightarrow \pi^0\gamma \rightarrow \gamma\gamma\gamma$ channel
- Additional channel to constrain the ω spin density matrix elements (SDMEs)

$\omega(782)$ Signal Statistics Kinematics Distributions

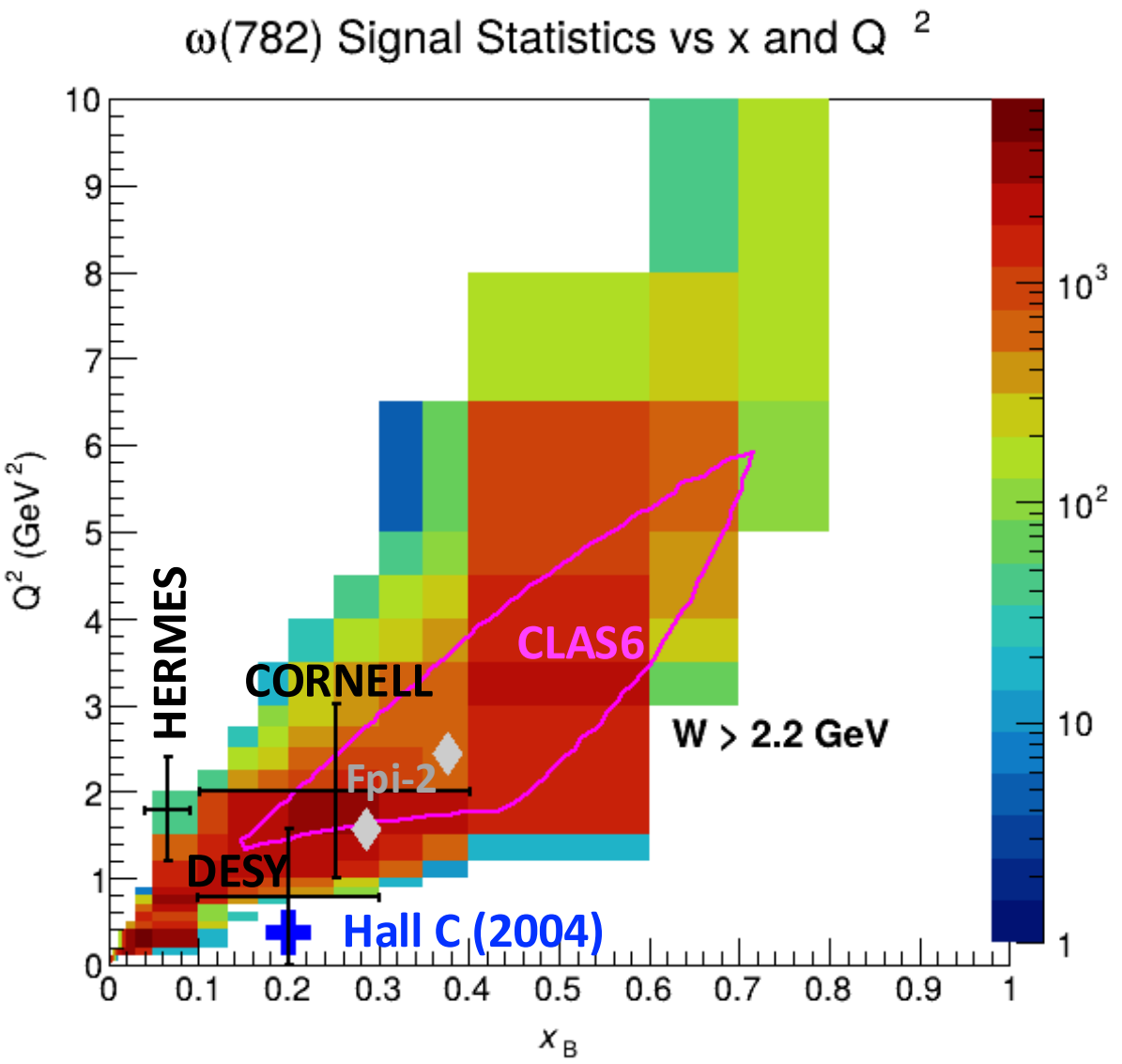




- Broad range of kinematics in the phase space coverage with excellent statistics
  - $1.8 < W < 4.5$ GeV, $Q^2 < 10$ GeV², $|t| < 4$ GeV²
  - Covering both N^* and deep exclusive physics regimes
- Both CLAS12 forward tagger (FT) and forward detector (FD) are included
  - Further trigger selections may be applied for different physics topics

Direct Comparison with Other Experiments

- CLAS12 vs CLAS6: more statistics, broader kinematics phase space coverage, and better event reconstruction
- Broader x and Q^2 distribution due to the higher electron beam energy → Feasibility to investigate twist-2 GPDs σ_L
- Q^2 can go up to 10 GeV²
  - Opportunities for better understand N^* structure
  - More information on the N^* resonances at higher $|t|$



Eur. Phys. J. A 24 (2005) 445-458
Phys. Rev. Lett. 123 (2019) 182501

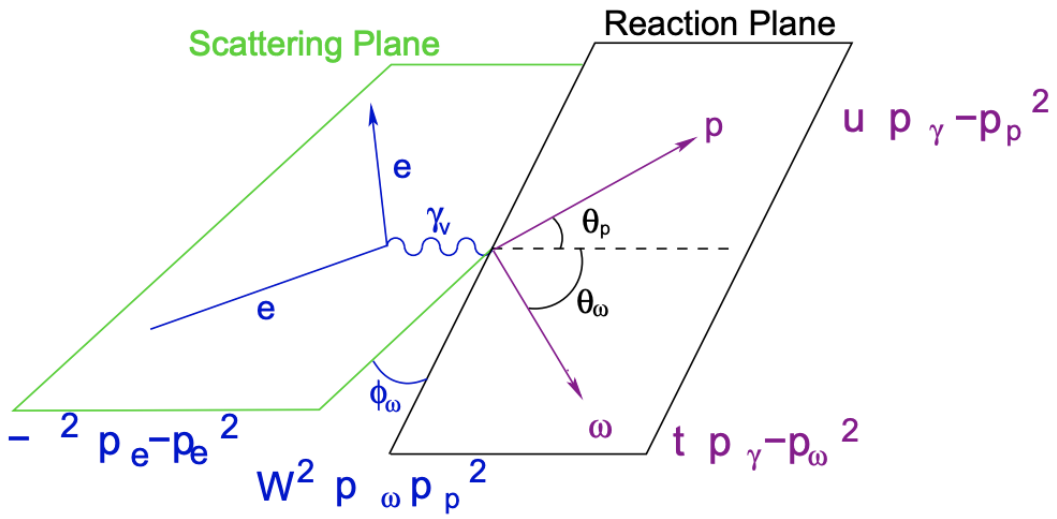
$\omega(782)$ Physical Observable Outlook

Measurements of Experimental Observables

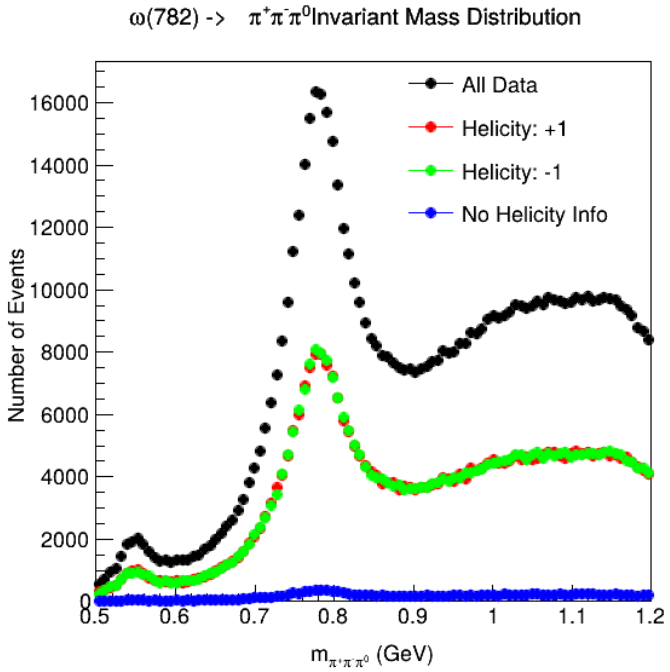
- Polarization dependent exclusive ω cross section
- Beam Spin Asymmetry $A_{LU}^{sin\phi}$
- Potential SDMEs and coupled channel partial wave amplitude analysis

$$\frac{d\sigma}{d\phi} = \frac{1}{2\pi}(\sigma + \varepsilon cos2\phi)\sigma_{TT} + \sqrt{2\varepsilon(1+\varepsilon)}cos\phi\sigma_{TL}$$

Trento ϕ Convention



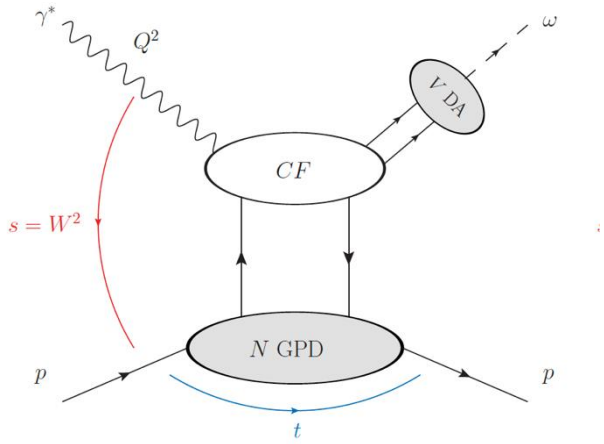
Excellent statistics of longitudinally polarized electron beam with ±1 helicity



Almost all $\omega(782)$ events contain helicity information and are statistically equal for +1 and - 1

Bridging Forward with N^* Physics

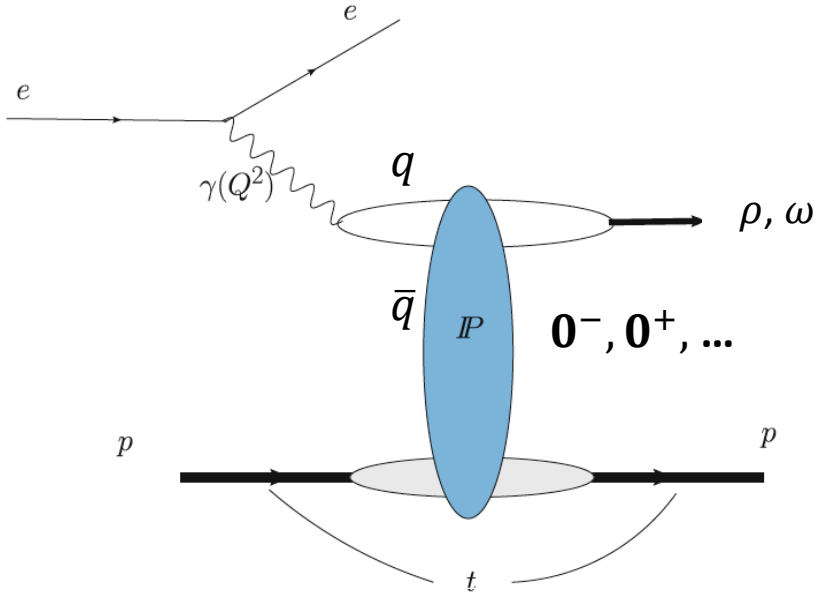
$u-d$ Flavor Decomposed GPDs



- 4 chiral-even GPDs: H, E, $\tilde{H}$, $\tilde{E}$
- 4 chiral-odd GPDs: H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$

	Meson	GPD flavor composition
$\tilde{H}$, $\tilde{E}$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
H_T, $\bar{E}_T$	η	$2\Delta u - \Delta d$
H, E	ρ^0	$2u + d$
	ρ^+	$u - d$
H_T, $\bar{E}_T$	ω	$2u - d$

Regge Phenomenology



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

Bridging N^* and Deep Exclusive Physics

- Fourth resonance + non-resonance effect studies
- Explore the QCD factorization transition regime and hard cut off range

Summary

- $\omega(782)$ electroproduction at CLAS12 provides access to previously unexplored kinematic regions, offering new opportunities to study the strong interaction in electron scattering

- Complementary $\omega(782)$ Measurements with CEBAF at Jefferson Laboratory
  - **Hall B/CLAS12:** large kinematic coverage with excellent exclusivity
  - **Hall C:** precision focused cross section measurement through missing mass techniques

- **Clear exclusive $\boldsymbol{\omega(782)}$ signal** observed for both channels $\boldsymbol{\omega \to \pi^+\pi^-\pi^0}$ **and** $\boldsymbol{\omega \to \pi^0\gamma}$
  - Analysis development currently focusing on: $\omega \to \pi^+\pi^-\pi^0$
  - Further improvement for $\omega \to \pi^0\gamma$ with potential **ML/AI applications**

- **CLAS12 RG-A Data: Improved $\boldsymbol{\omega(782)}$ studies compared with CLAS6**
  - Current results: Fall 2018 RG-A data only from CLAS12
  - Inclusion of RG-A spring 2018 and 2019 expect **factor of >2 statistics**

- The $\omega(782)$ channel analysis is currently **in continual progress**
  - Proposed polarized cross section, beam spin asymmetry, and potential SDMEs
  - Shedding light on higher resonance regions and hybrid baryon structure
  - Monte Carlo acceptance and efficiency simulations are being developed
  - Radiative correction and final state interaction will also be included

- **Stay tuned for our preliminary physics results with full CLAS12 statistics in the Future!**

Thank You

This work is supported by:

- NSF Grant PHY-2310034
- JLab-University Bridge Program under the direction of the DOE

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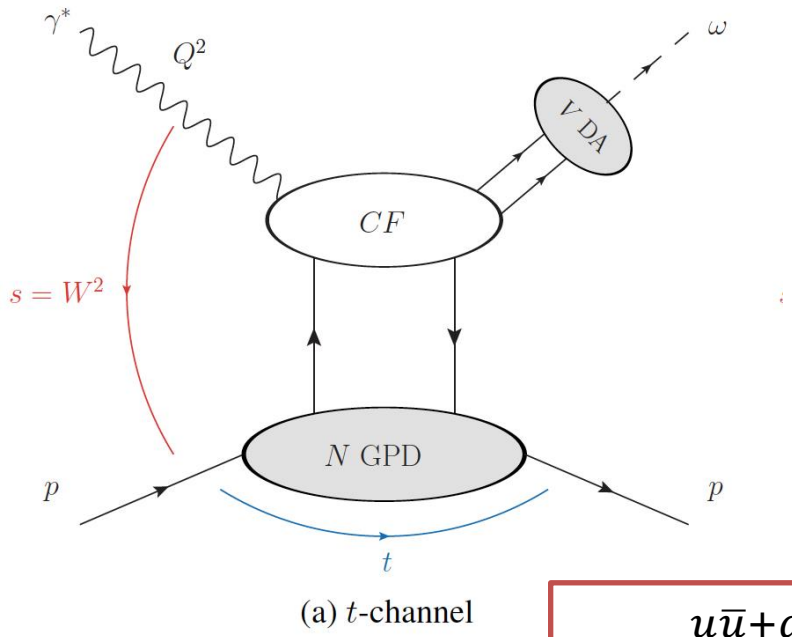
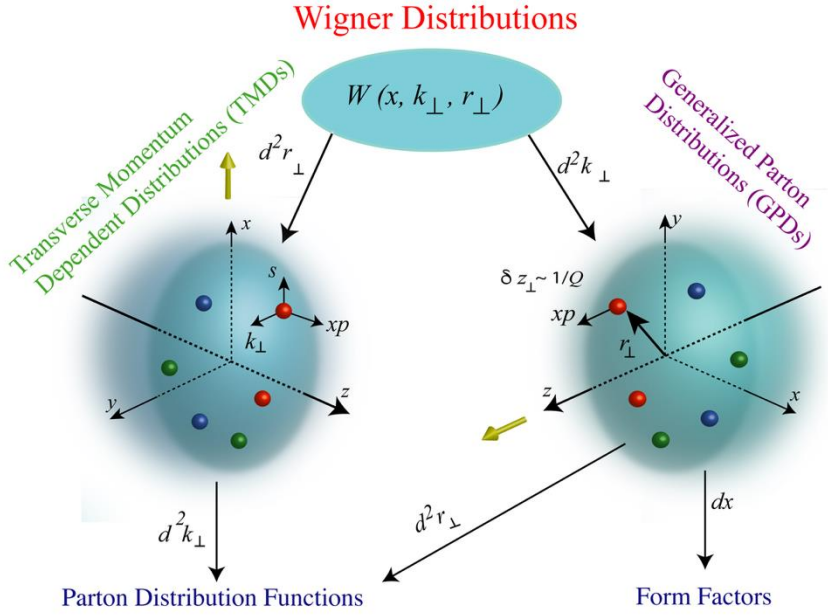
U.S. DEPARTMENT of ENERGY

Back Up

Handbag Diagrams: GPD/TDA Type of Physics



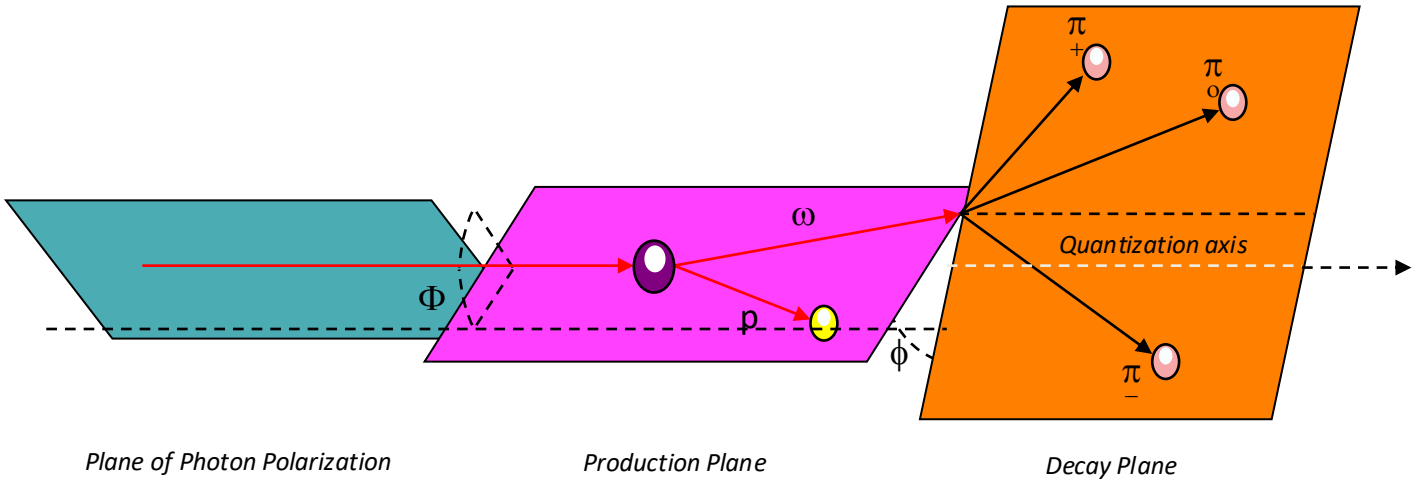
(a) t-channel



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

- Conditions
  - GPD: a factorized approach particularly applied to exclusive reaction: $ep \to ep\omega$
  - Sufficiently Large (Deep) $Q^2 \gg \Lambda^2_{QCD}$
  - 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

Kinematics Definition



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

$$Q^2 = (p^\mu_{e'} - p^\mu_e)^2$$

$$t = (p^\mu_{p'} - p^\mu_p)^2$$

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

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

$$u = \left(p^\mu_e - p^\mu_{e'} - p^\mu_{p'}\right)^2$$

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

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

$$m_X^2 = (p^\mu_e + p^\mu_p - \sum_i^N p^\mu_i)^2$$

$\omega(782)$ Reconstruction with Missing $\pi^{\pm}$

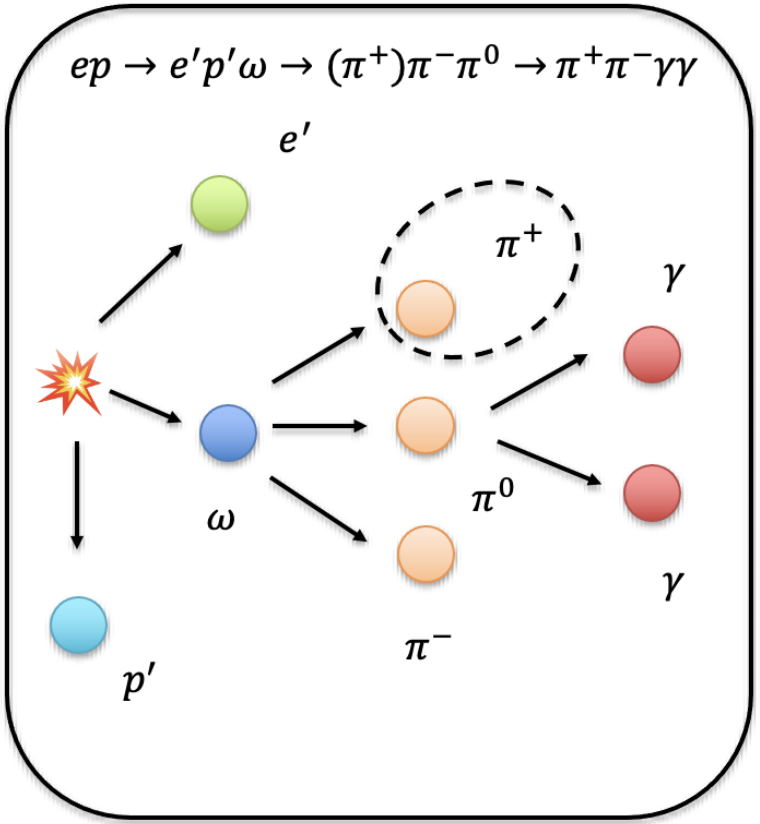
Algorithms

- Select events with exactly 1 proton, 1 electron, 1 π^+ or π^-, and at least 2 photons
- Calculate the missing 4 vector

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

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

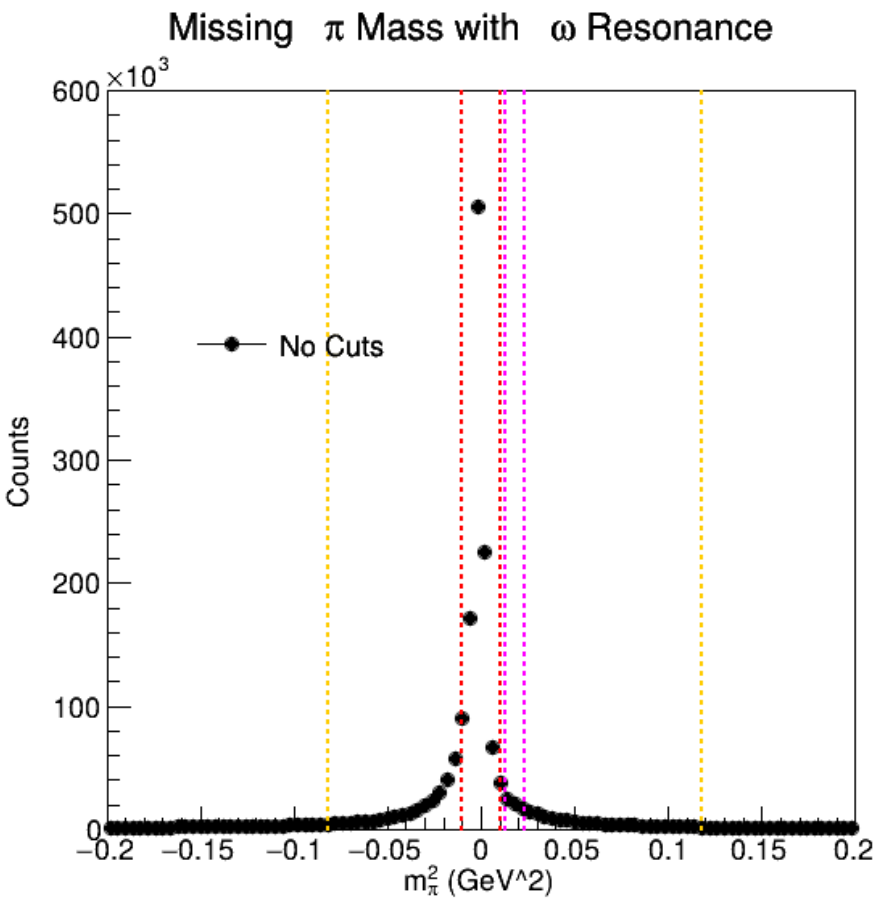
- Mass definitions:
  - $m_{\pi^0} = \sqrt{p^{\mu}_{\pi^0} p^{\pi^0}_{\mu}}$
  - $m_{\pi^{\pm}} = \sqrt{p^{\mu}_{\pi^{\pm}} p^{\pi^{\pm}}_{\mu}}$
- Mass forcing
  - If $\left|m_{\pi^0} - m^{PDG}_{\pi^0}\right| < 0.025$ GeV, we force the m_{π^0} to be $m^{PDG}_{\pi^0}$ for p^{μ}_{ω} calculations

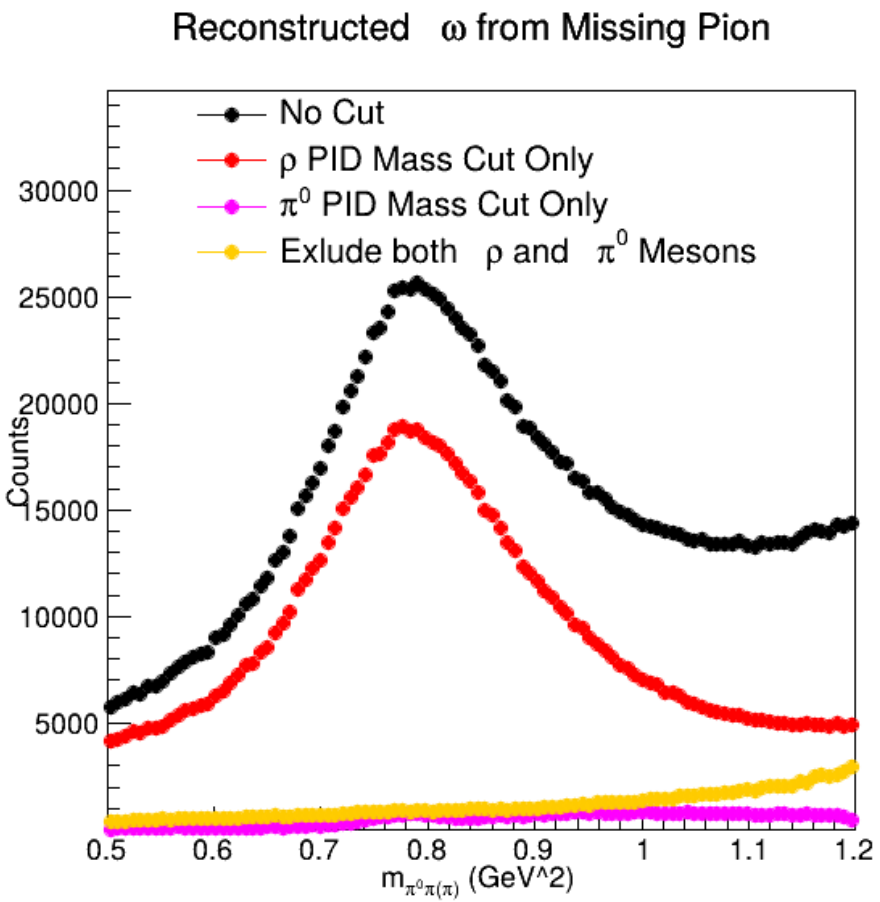


PID Cuts Options

- No Cuts
- $\left|m_{\pi^0} - m^{PDG}_{\pi^0}\right| < 0.025$ GeV
- $\left|m_{\pi^0} - m^{PDG}_{\pi^0}\right| < 0.025$ GeV AND $\left|m^2_{\pi^{\pm}} - \left(m^{PDG}_{\pi^{\pm}}\right)^2\right| < 0.005$ GeV
- Exclusion: $\left|m_{\pi^0} - m^{PDG}_{\pi^0}\right| < 0.025$ GeV AND $\left|m^2_{\pi^{\pm}} - \left(m^{PDG}_{\pi^{\pm}}\right)^2\right| > 0.1$ GeV

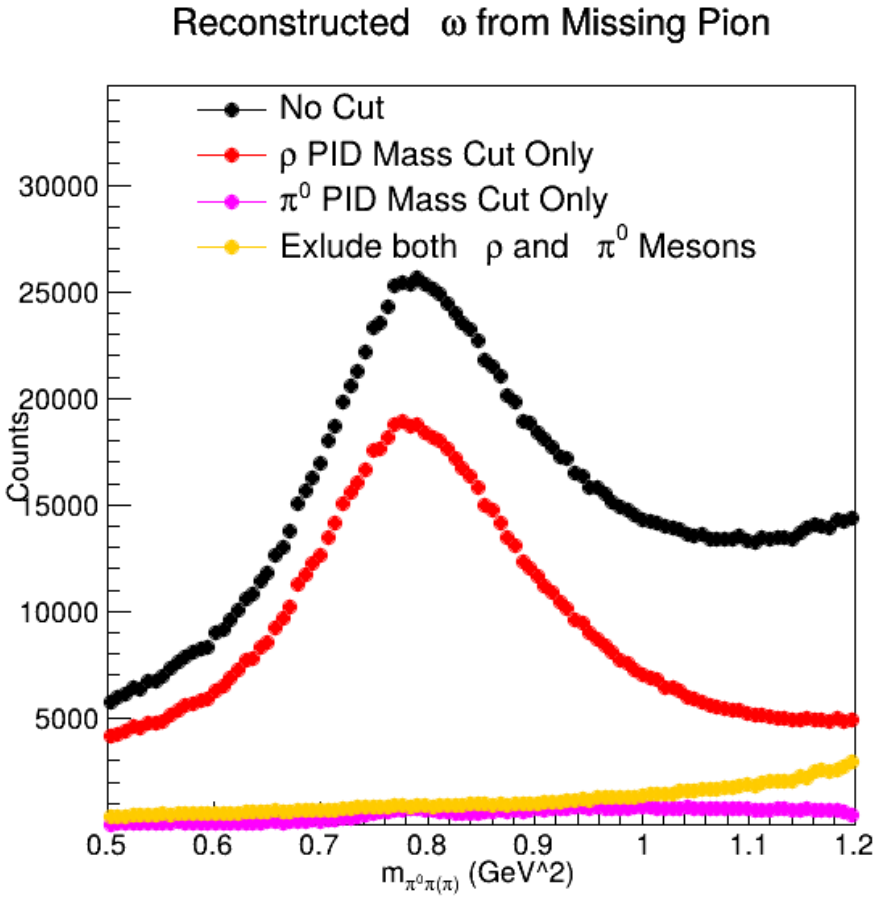
Cut UnZoom and Background Check (Torus - 1)

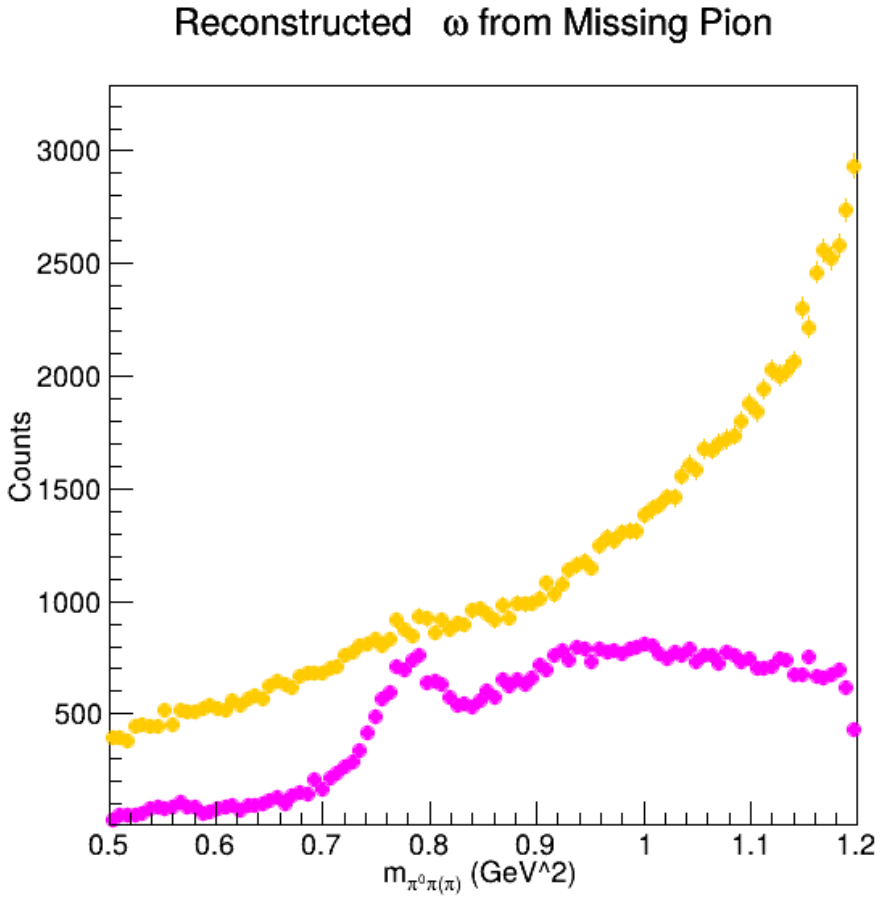




- Peaking shape for m_X^2 near 0: π^+ and π^- no γ
  - Either not accepting the $\gamma\gamma$ from π^0 by the ECAL
  - Or it is simply $\rho \rightarrow \pi^+\pi^-$ which fundamentally does not have γ
  - Break into 3 cases: Enforcing π^0, Enforcing ρ, and excluding everything

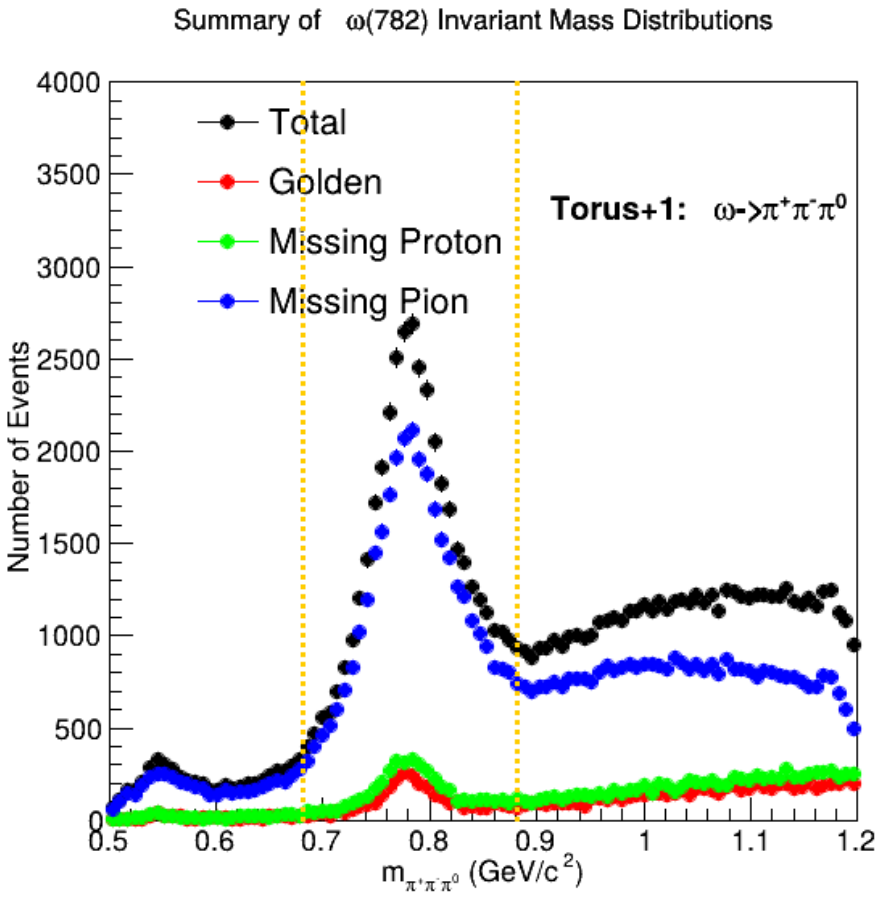
$\rho^0 \rightarrow \pi^+\pi^-$ Background Rejection

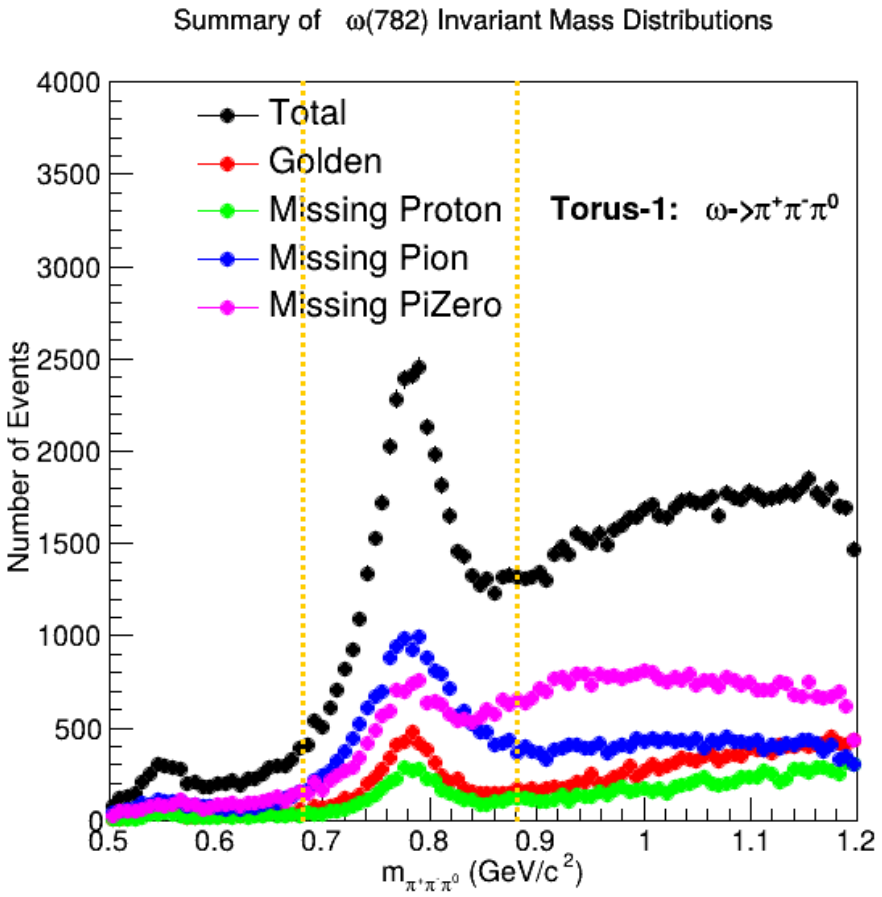




- Indeed, the ρ meson cases dominates if there is no $\left|m_X^2\right| < 0.1$ GeV^2 cuts
  - Need to trace deeper into missing photon studies to extract additional ω from the ρ meson decay background
- If we enforce $\left|m_{\pi^0}^2 - \left(m_{\pi^0}^{PDG}\right)^2\right| < 0.025$ GeV, we are able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

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

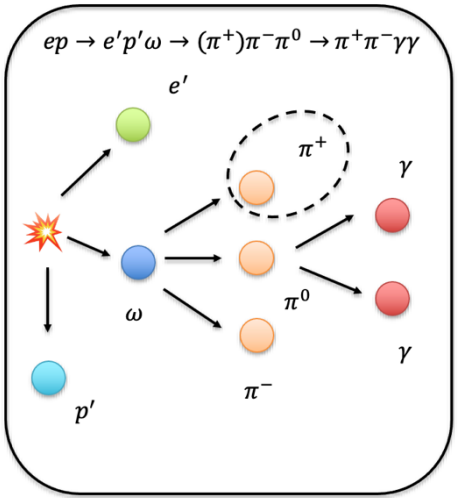


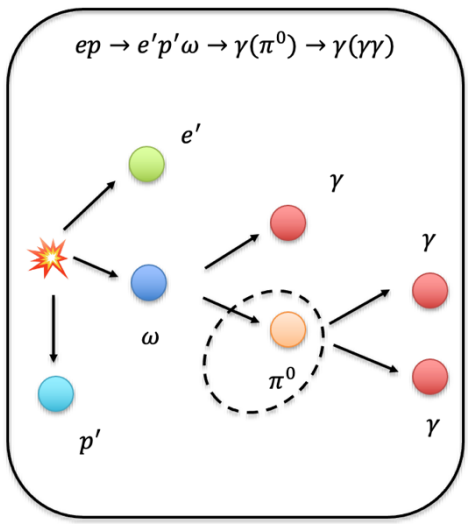


- Not worthing doing the missing π^0 channel for now because the gain in statistics is not that much compared to the effort of dealing with the systematics

ω Analysis To Do List

Include Missing Pions to Enhance the ω Yield





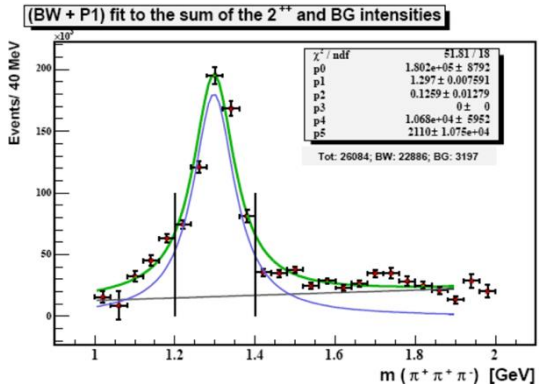
MC Generation and ω Yield Optimization

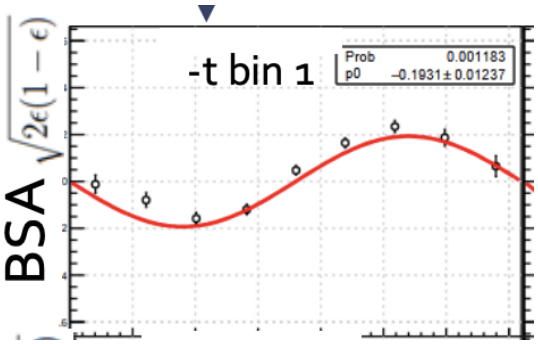
Open Science Grid

ROOT
Data Analysis Framework

TMVA

Efficiency Correction and Physics Measurements





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