Recent Studies of the Leptonic Decays of Photoproduced Vector and Pseudoscalar Mesons off of ^{1}H at Jefferson Lab

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For the CLAS Collaboration

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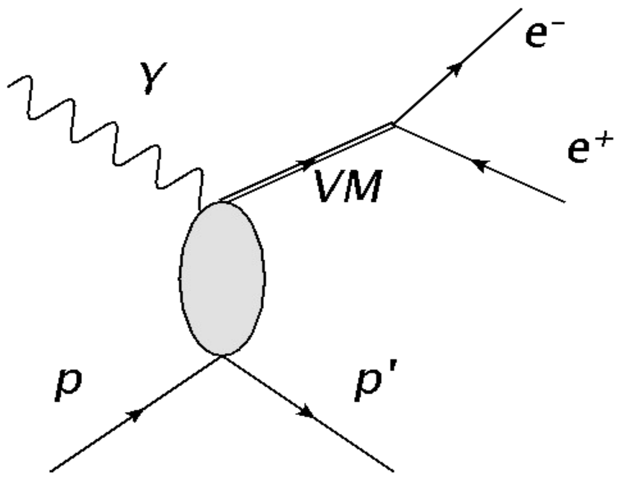
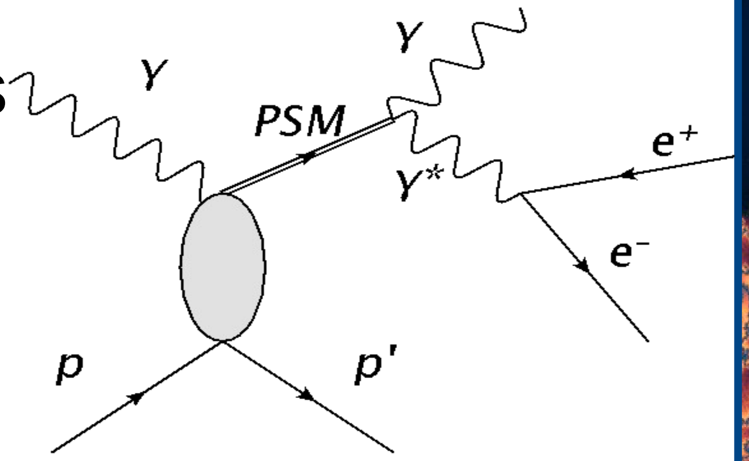
Photoproduction of light neutral mesons

- $\gamma p \rightarrow e^+ e^- (p)$ Vector Mesons
  - No Final State Interactions (FSI) in medium modification studies
  - Interference between the ρ and the ω

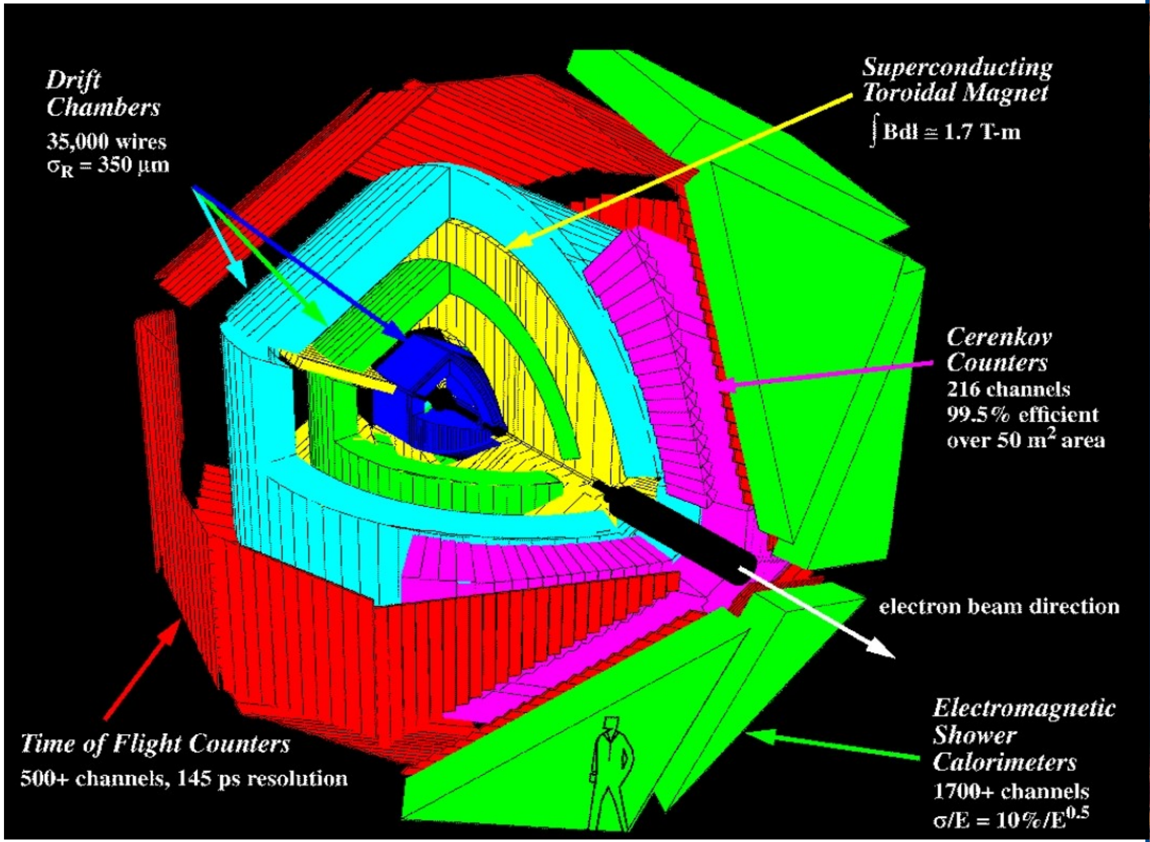


- $\gamma p \rightarrow p\, e^+ e^- \gamma$ Pseudoscalar Mesons
  - Access to transition charge form factors
  - Limited world statistics on Dalitz decays of photoproduced η and upper limits to the η' cross section.



Jefferson Lab Experiment g12

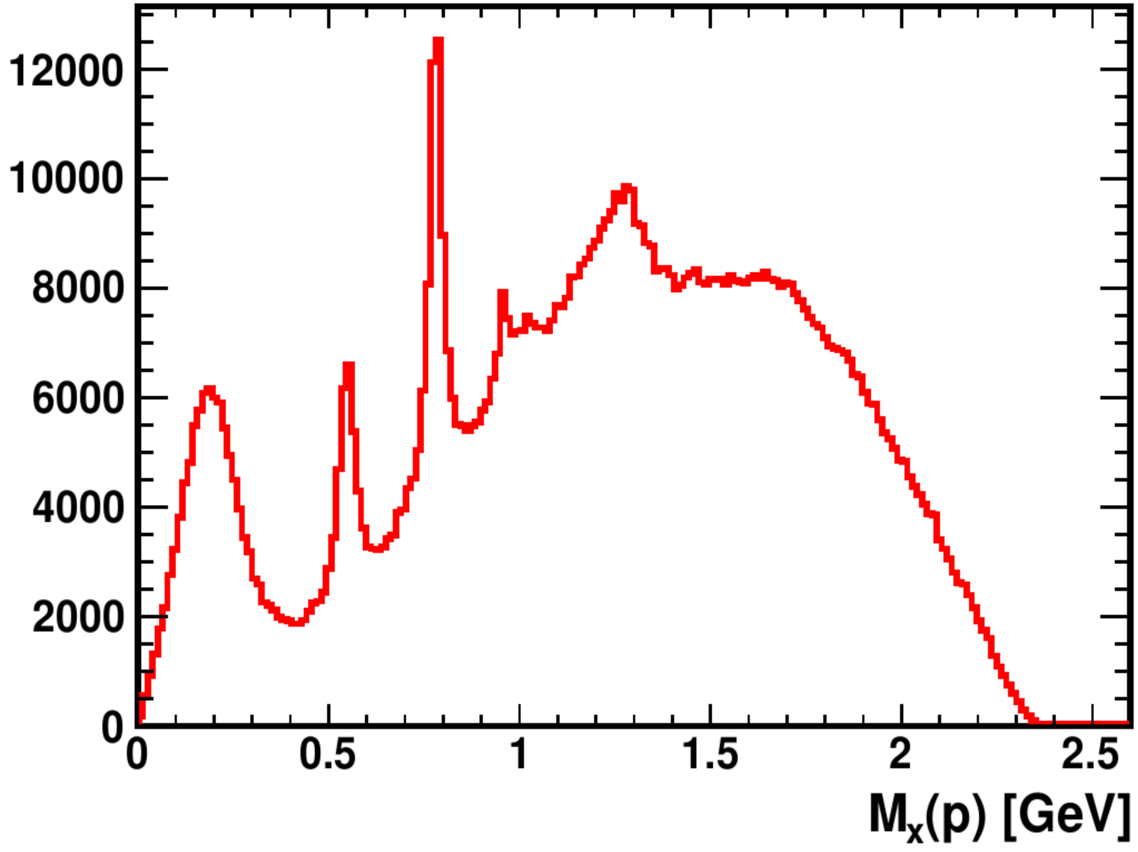
- Jefferson Lab is a 6 GeV continuous electron beam accelerator, capable of delivering beam to 3 independent experimental halls.
- Hall-B houses the CLAS detector, ideal for photoproduction and lepton identification.
- g12 in CLAS
  - Up to a 5.5 GeV photon beam incident on a LH_2 target
  - Raw sensitivity of ~ 68 pb^{-1}
  - 26.2 $\times 10^9$ production triggers (3 x 10^6 di-lepton triggers)



- **EC** and **CC** combine to provide an e/π rejection factor of 10^{-6} for di-lepton pairs.

Selecting VM or PSM

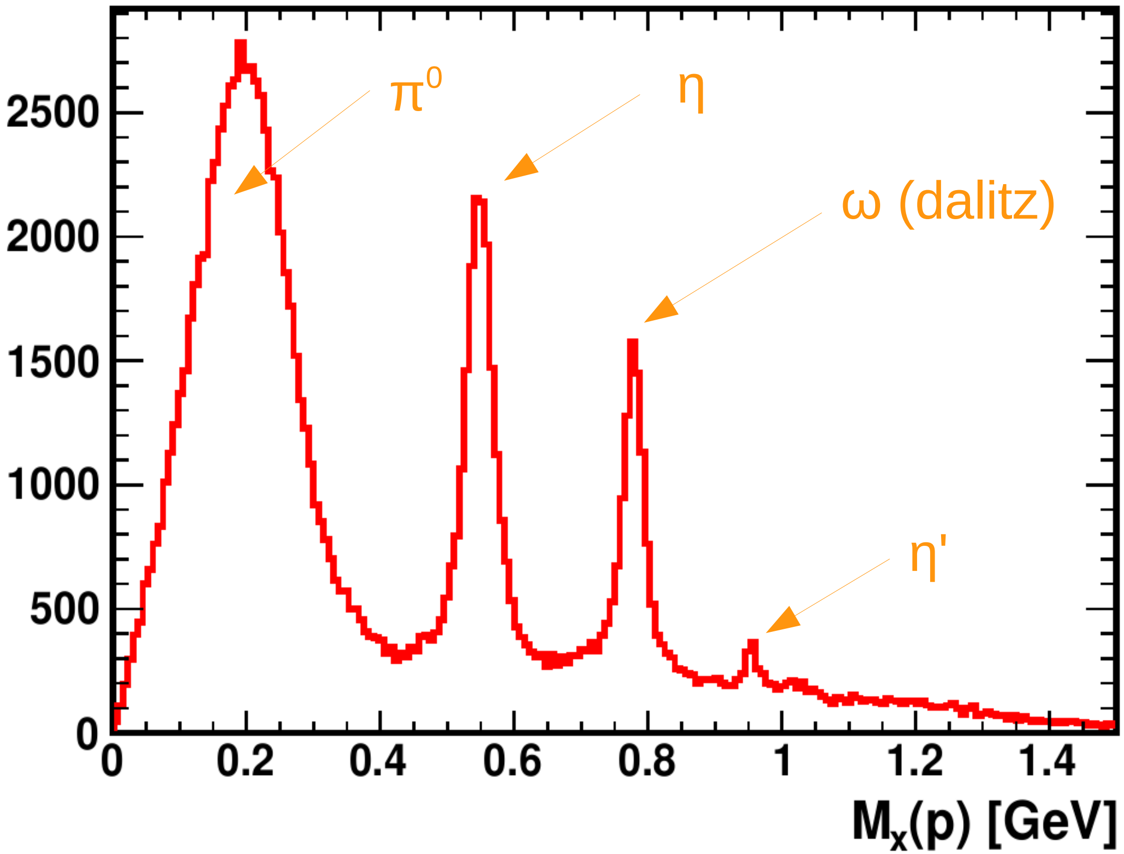
- By knowing:
  - Tagged photon energy.
  - Target mass
  - Scattered proton and dilepton four-vectors.
- Cuts can isolate VM from PSM:
  - Missing Energy
  - Dilepton Opening Angle



Selecting VM or PSM

- By knowing:
  - Tagged photon energy.
  - Target mass
  - Scattered proton and dilepton four-vectors.
- Cuts can isolate VM from PSM:
  - Missing energy greater than zero: additional particle:
    - ME > 0.0
  - Small dilepton opening angle: virtual photon $\rightarrow$ dilepton
    - $\theta_{ee} < 0.5$ rad

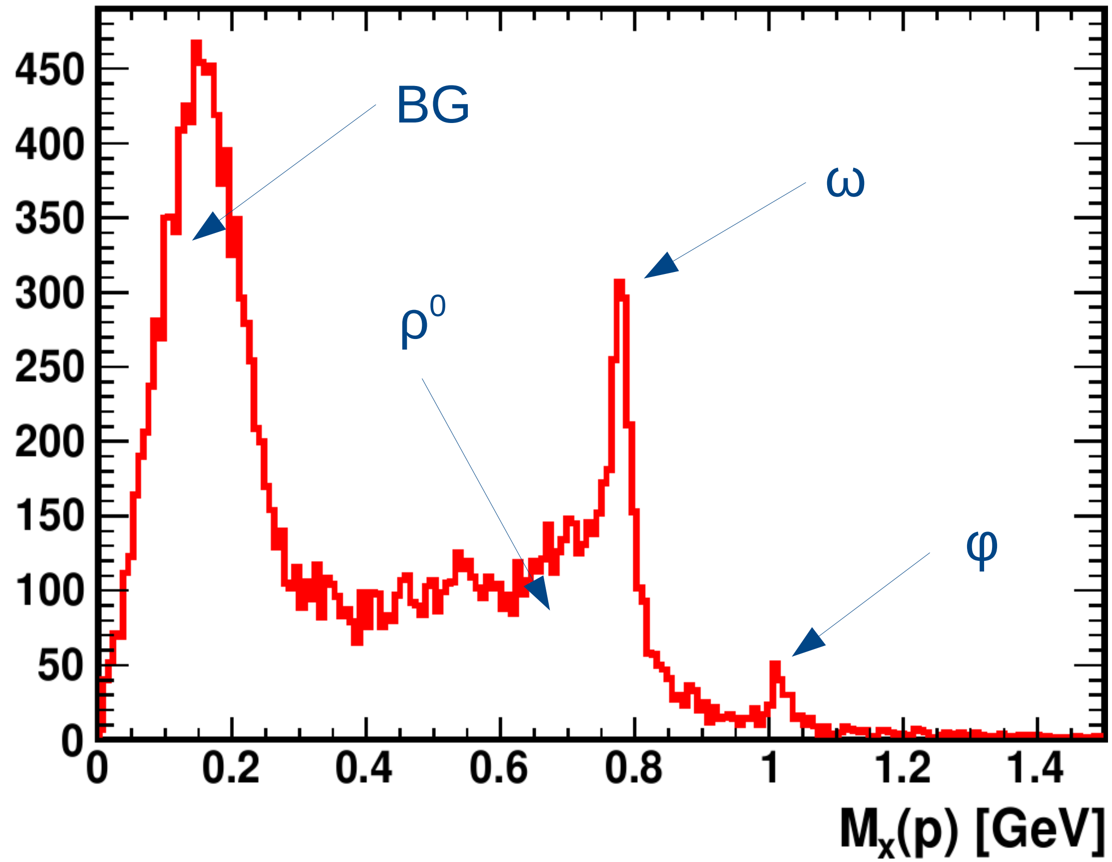
$$\gamma p \rightarrow e^+ e^- p(X)$$



Selecting VM or PSM

- By knowing:
  - Tagged photon energy.
  - Target mass
  - Scattered proton and dilepton four-vectors.
- Cuts can isolate VM from PSM:
  - Missing energy equal to zero: no additional photon
    - ME = 0
  - Large dilepton opening angle: VM $\rightarrow$ dilepton
    - θ_{ee} > 0.5 rad

$$\gamma p \longrightarrow e^{+}e^{-}p \quad \text{(exclusive)}$$



Part I: Vector Mesons and ρ-ω Interference

- Understanding the interference with electromagnetic production and decay is useful in interpretation of recent Medium Modification studies (Chaden Djalali's earlier talk).

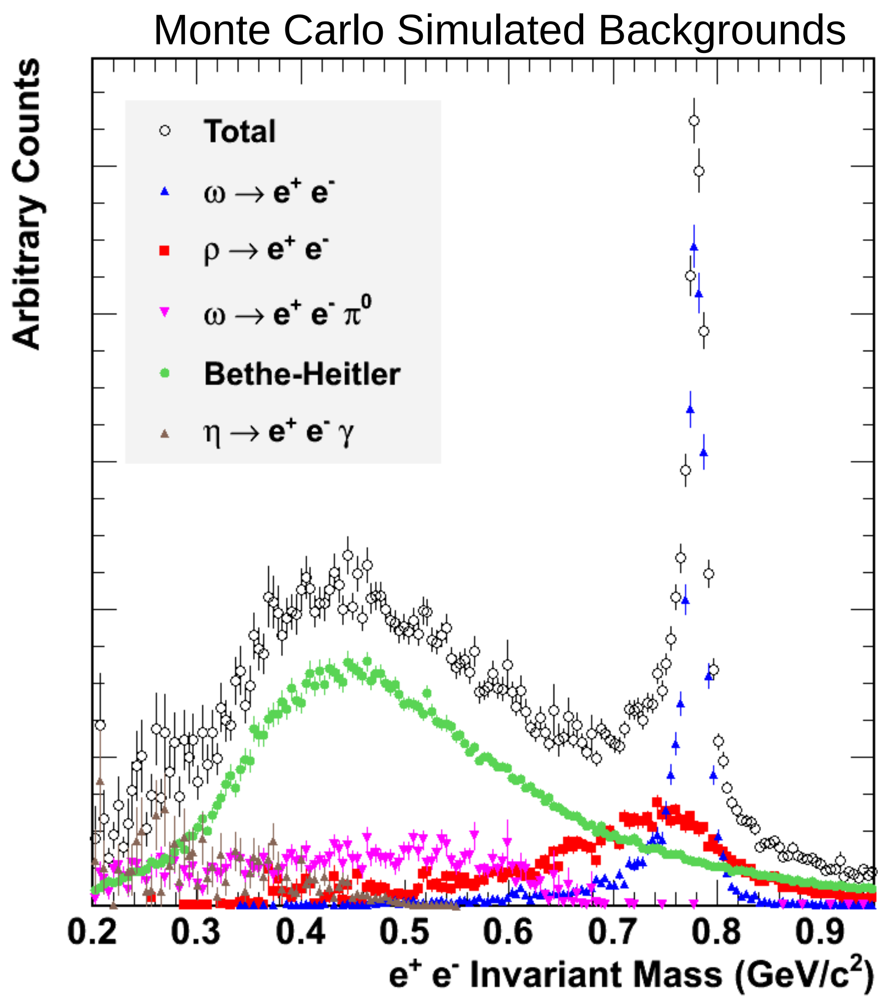
- Previous publications on the interference are from nuclear targets:

Target	K_{max} (GeV)	Range m_{e+e-} (MeV/c^2)	Phase ϕ (in deg)	Reference
Be	7.0, 5.1	700-870	41 ± 20	PRL25 (1970) 1373 NPB25 (1971) 333
C	4.1	675-850	100^{+38}_{-30}	PRL24 (1970) 1197
C	4.1	590-830	118^{+13}_{-22}	PRL27 (1971) 1157

- Theoretical predictions from Lutz and Soyeur (NPA750 2005) predict significant constructive interference on the proton, destructive on the neutron.

Signal and Background

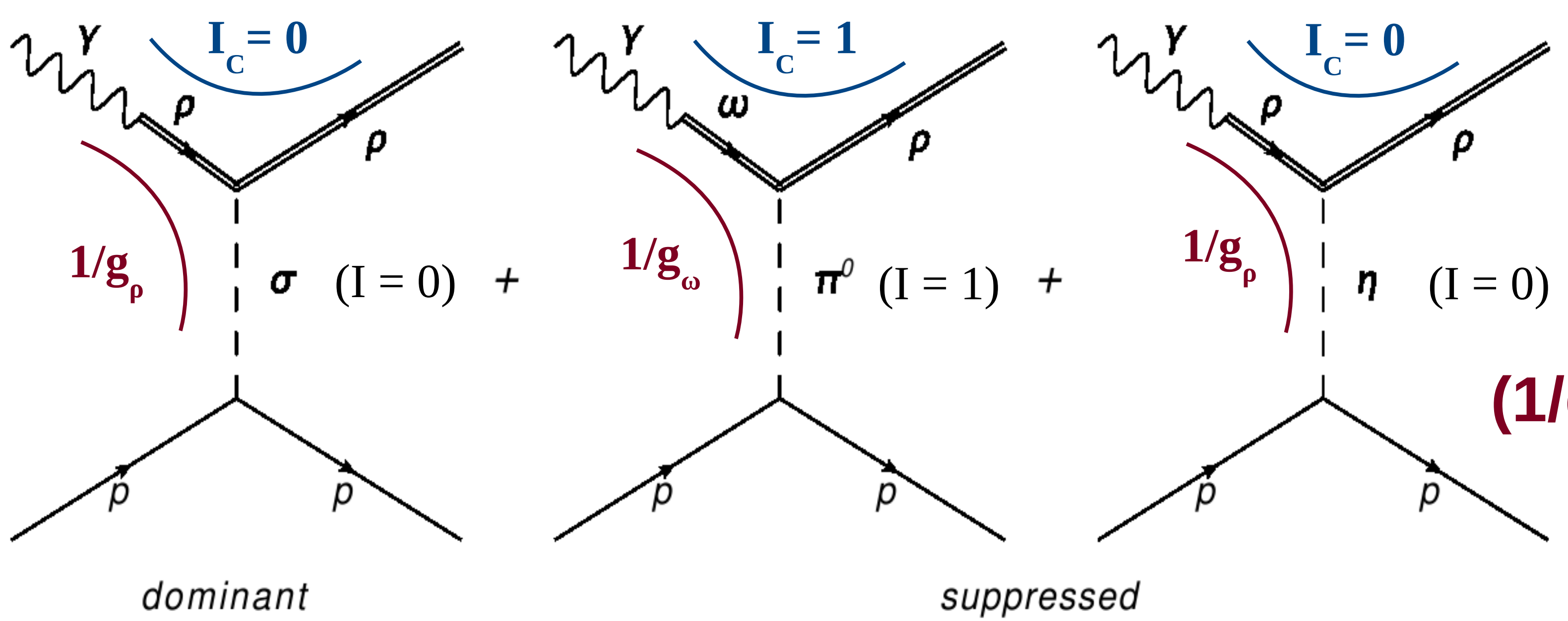
- Looking for $\rho \rightarrow e^+ e^-$ and $\omega \rightarrow e^+ e^-$
- Known Backgrounds:
  - $\omega \rightarrow e^+ e^- \pi^0$: Background reduced with tight missing mass cut on the proton.
  - Due to an upstream ^1H target, the Bethe-Heitler is significant and must be accounted for.
  - Uncorrelated lepton pairs are also eliminated by tight missing mass cuts on the proton.



VMD and t-channel VM production

- The Vector Meson Dominance (VMD) model assumes the photon interacts with hadrons as a virtual vector meson.
- Photoproduction of the ρ and ω off of a proton, leaving a proton in the final state can be described an exchange between scalar / pseudoscalar mesons. Vector mesons are prohibited by charge conjugation invariance. The Feynman diagrams can be drawn:

ρ-production:



$$\frac{\Gamma_{\rho\to\pi\gamma}}{\Gamma_{\rho\to\eta\gamma}} \approx 2.0$$

$$\mathbf{(1/g_\rho)^2 = 11.4(1/g_\omega)^2}$$

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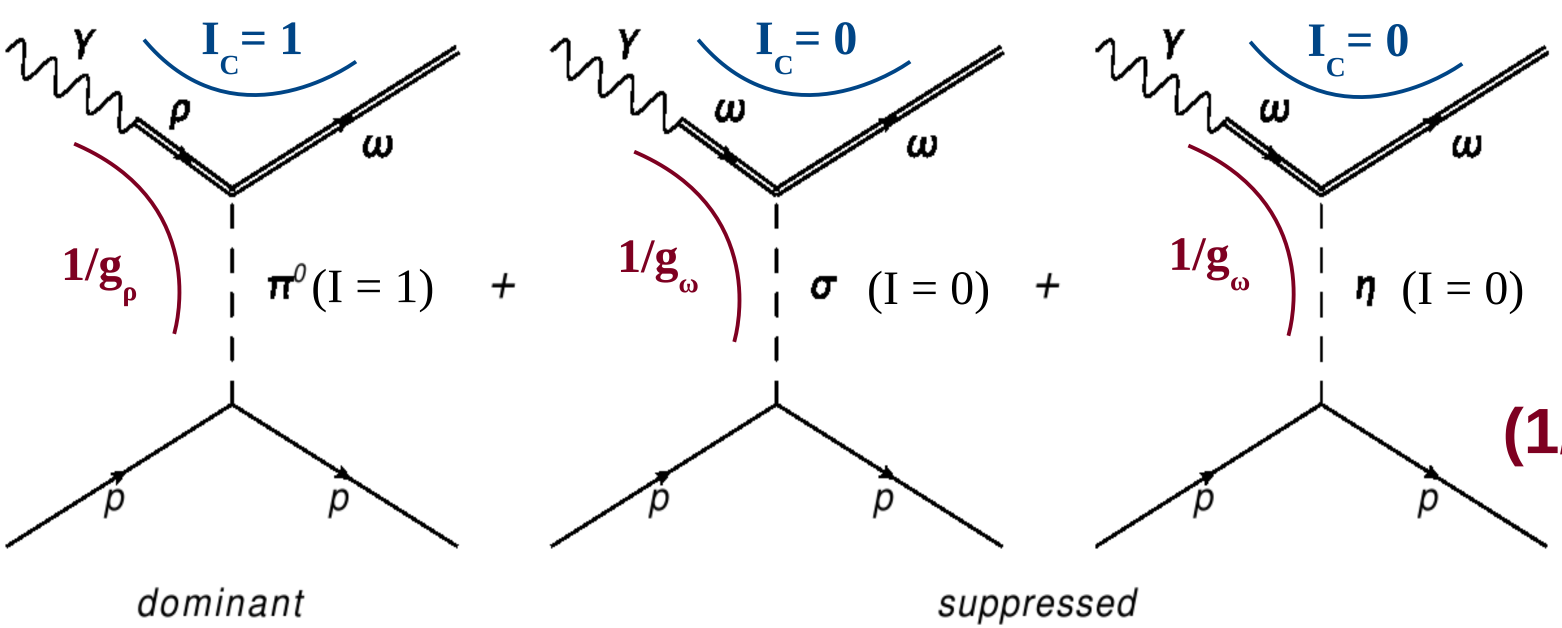
- Photoproduction of the ρ and ω off of a proton, leaving a proton in the final state can be described an exchange between scalar / pseudoscalar mesons. Vector mesons are prohibited by charge conjugation invariance. The Feynman diagrams can be drawn:

ω-production:

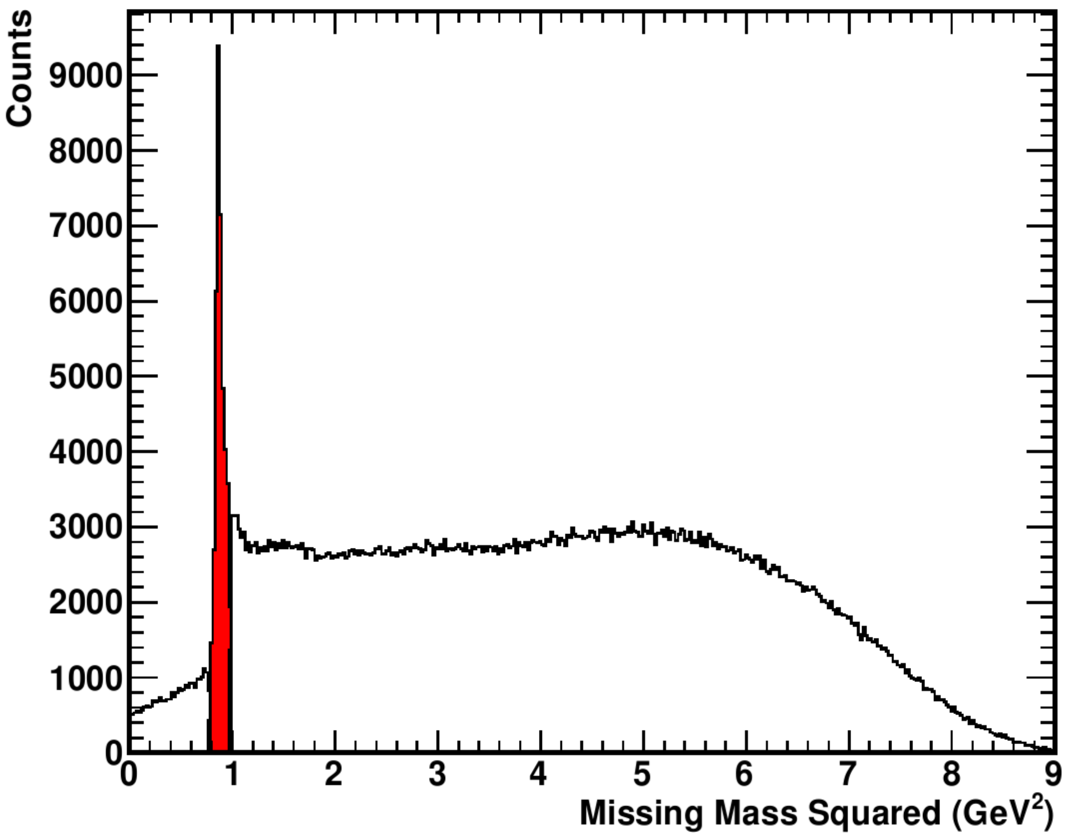


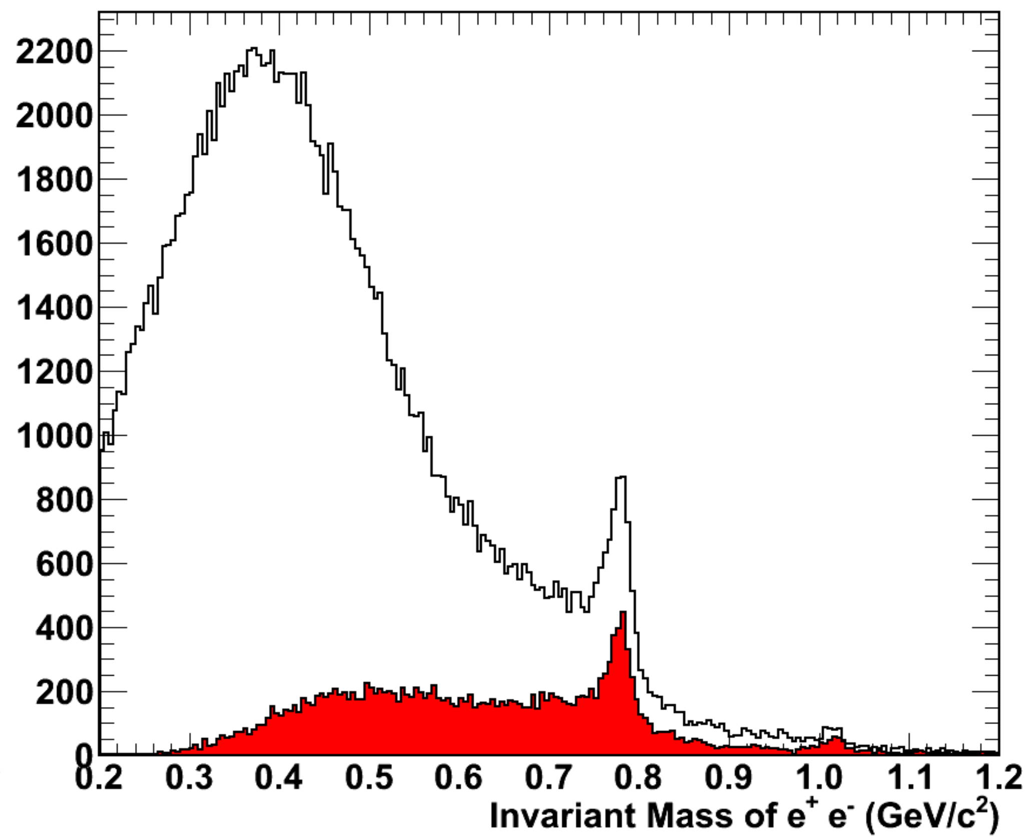
$$\frac{\Gamma_{\omega\to\pi\gamma}}{\Gamma_{\omega\to\eta\gamma}} \approx 100.0$$

$$(1/g_\rho)^2 = 11.4(1/g_\omega)^2$$

Selecting an Outgoing Proton

- Initial cuts must be made on the missing mass to isolate a proton in the final state and reduce background contamination.

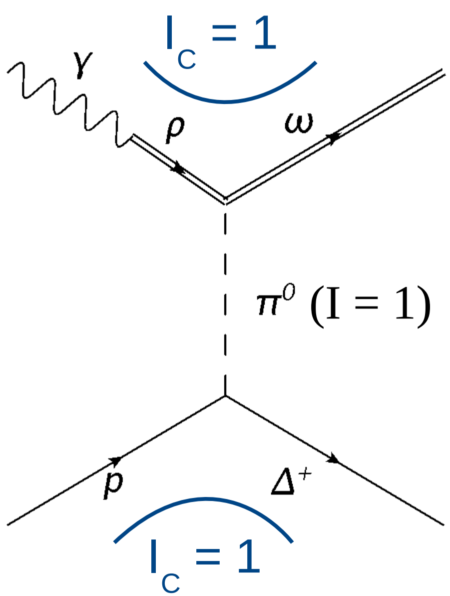




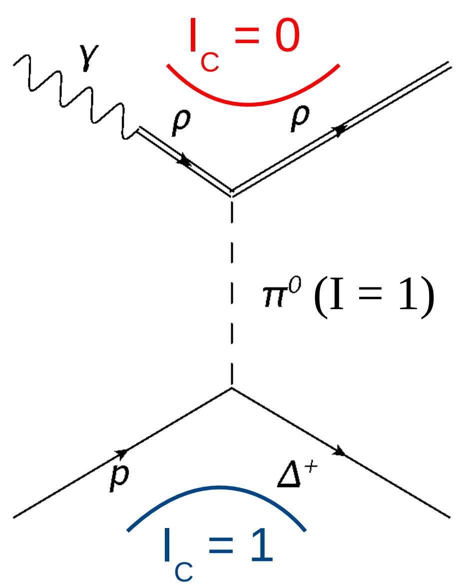
Selecting the Delta

- If a secondary cut is made on a (n π^+) mass to be (1232 +/- 100 MeV), the Δ^+ baryon resonance can be selected.

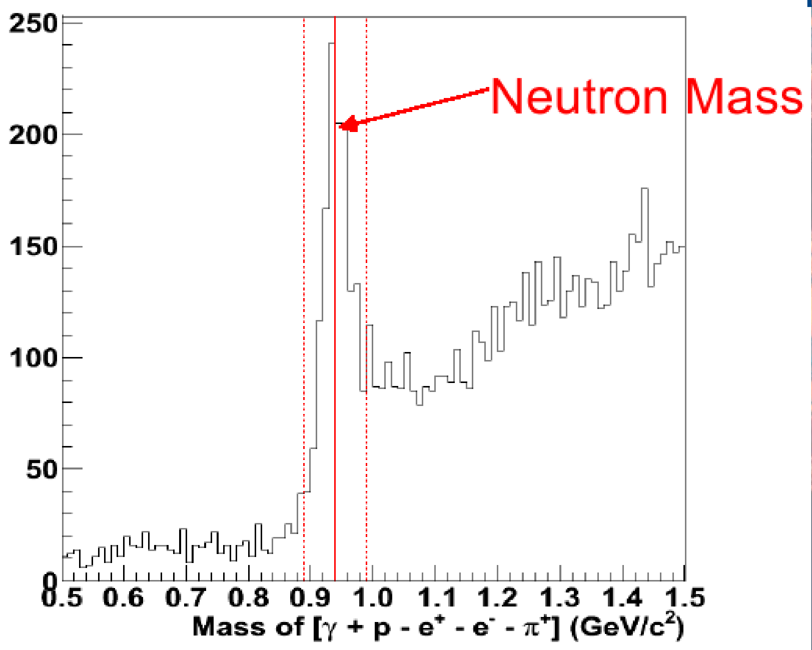
- This channel prefers ω production:

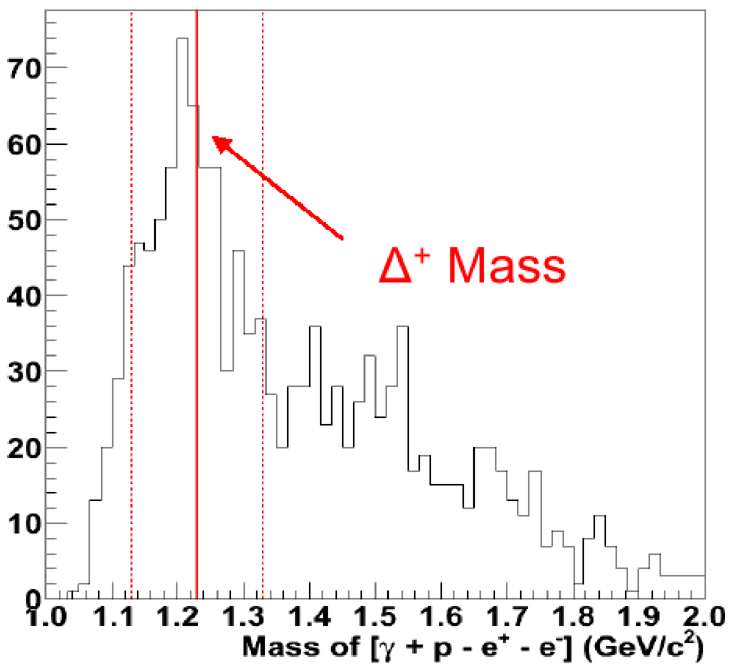


Allowed



Isospin Restricted





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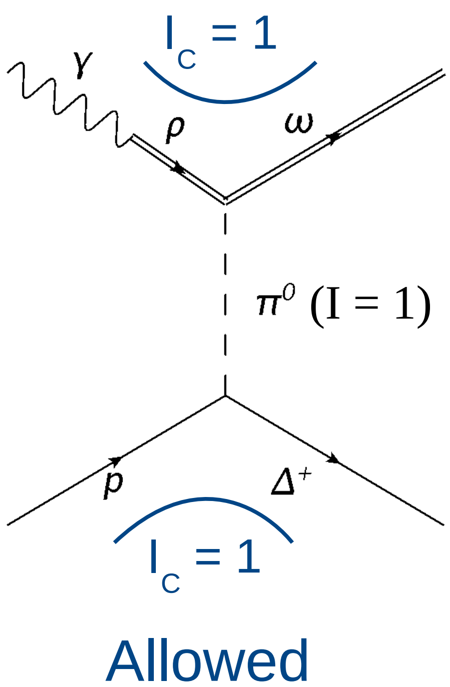
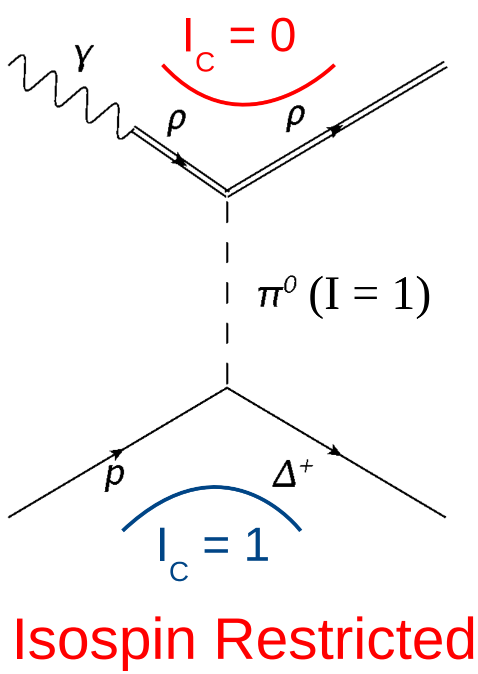
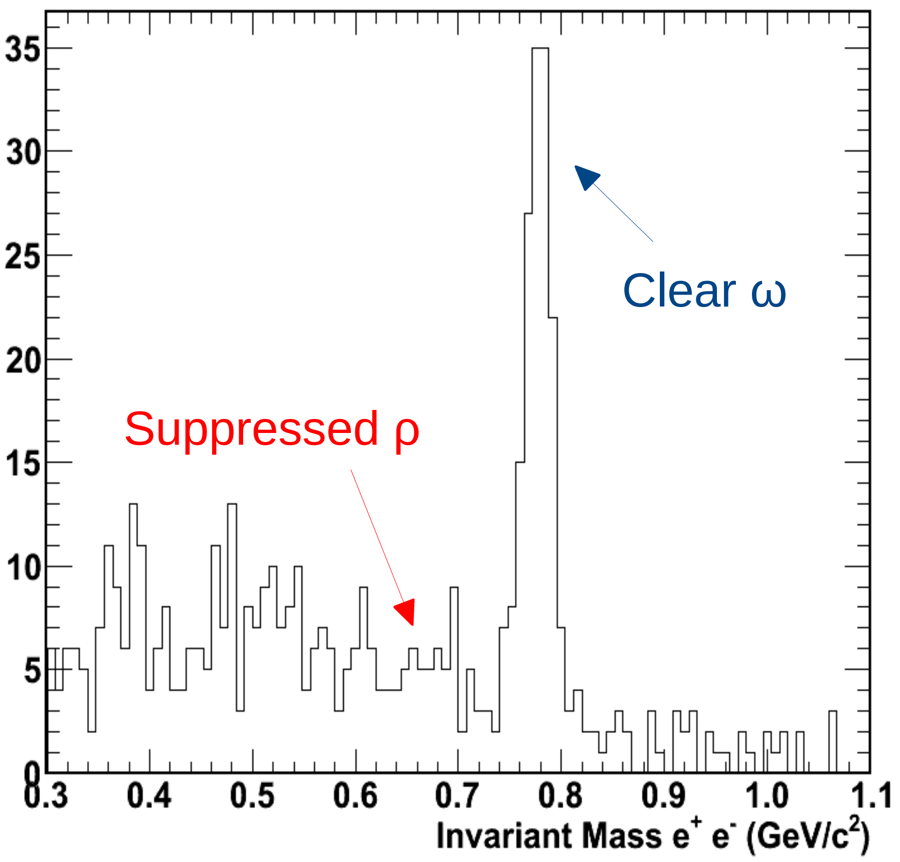






Interference Formalism

- The ρ-ω interference can be described by constructing a complex and symmetric mass matrix:

$$M = \begin{bmatrix} M_\rho & -\delta \\ -\delta & M_\omega \end{bmatrix} \qquad M_a = (m^2 - m_a^2 + im\Gamma_a)/m\Gamma_a$$

- The propagator can then be constructed as:

$$P = |M|^{-1} = \frac{1}{M_\rho M_\omega - \delta^2} \begin{bmatrix} M_\omega & +\delta \\ +\delta & M_\rho \end{bmatrix} \approx \begin{bmatrix} 1/M_\rho & \delta/M_\rho M_\omega \\ \delta/M_\rho M_\omega & 1/M_\omega \end{bmatrix}$$

- And the amplitude then takes the form:

$$F(e^+e^-) = [T(\rho \to e^+e^-) \quad T(\omega \to e^+e^-)] P \begin{bmatrix} A(\gamma p \to \rho) \\ A(\gamma p \to \omega) \end{bmatrix}$$

- Combining to make:

$$F(e^+e^-) = \frac{T_\rho A_\rho}{M_\rho} + \frac{T_\omega A_\omega}{M_\omega} + \frac{\delta(T_\rho A_\omega + T_\omega A_\rho)}{M_\omega M_\rho}$$

Interference Formalism

- The a phase is then introduced, accounting for the cross amplitudes and mass term:

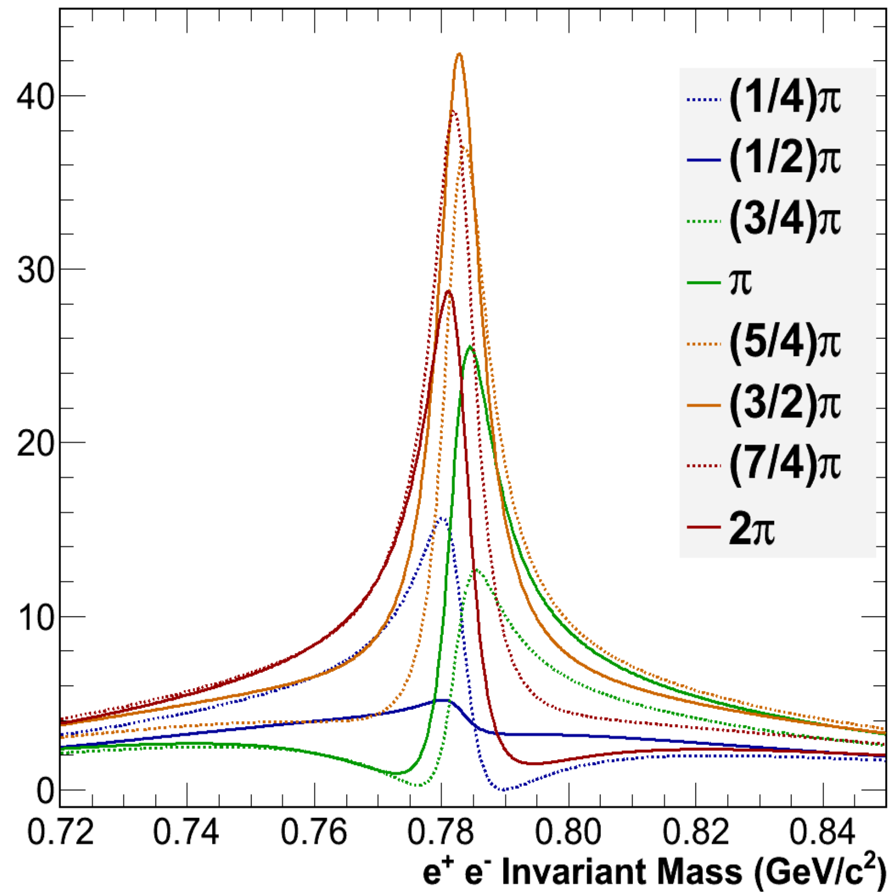
$$1 - ie^{i\phi_\rho} = -\frac{\delta}{M_\rho}\left(\frac{T_\rho A_\omega + T_\omega A_\rho}{T_\omega A_\omega}\right)$$

- The amplitude is then rewritten as a combination of the meson amplitudes with a complex phase term:

$$F = f_\rho + ie^{i\phi_\rho} f_\omega$$

- When squared, the amplitude takes the form:

$$F^2 = f_\rho^2 + f_\omega^2 - \frac{2a}{b^2 + c^2}(b\sin\phi_\rho + c\cos\phi_\rho)$$



Fitting Procedure

- The $e^+ e^-$ invariant mass spectrum is fit with:
  - Two Breit-Wigner functions
    - Relativistic
    - Mass dependent widths
    - Interference term
    - Gaussian convolution
  - Background function for Bethe-Heitler:

    1: Monte Carlo GiBUU form

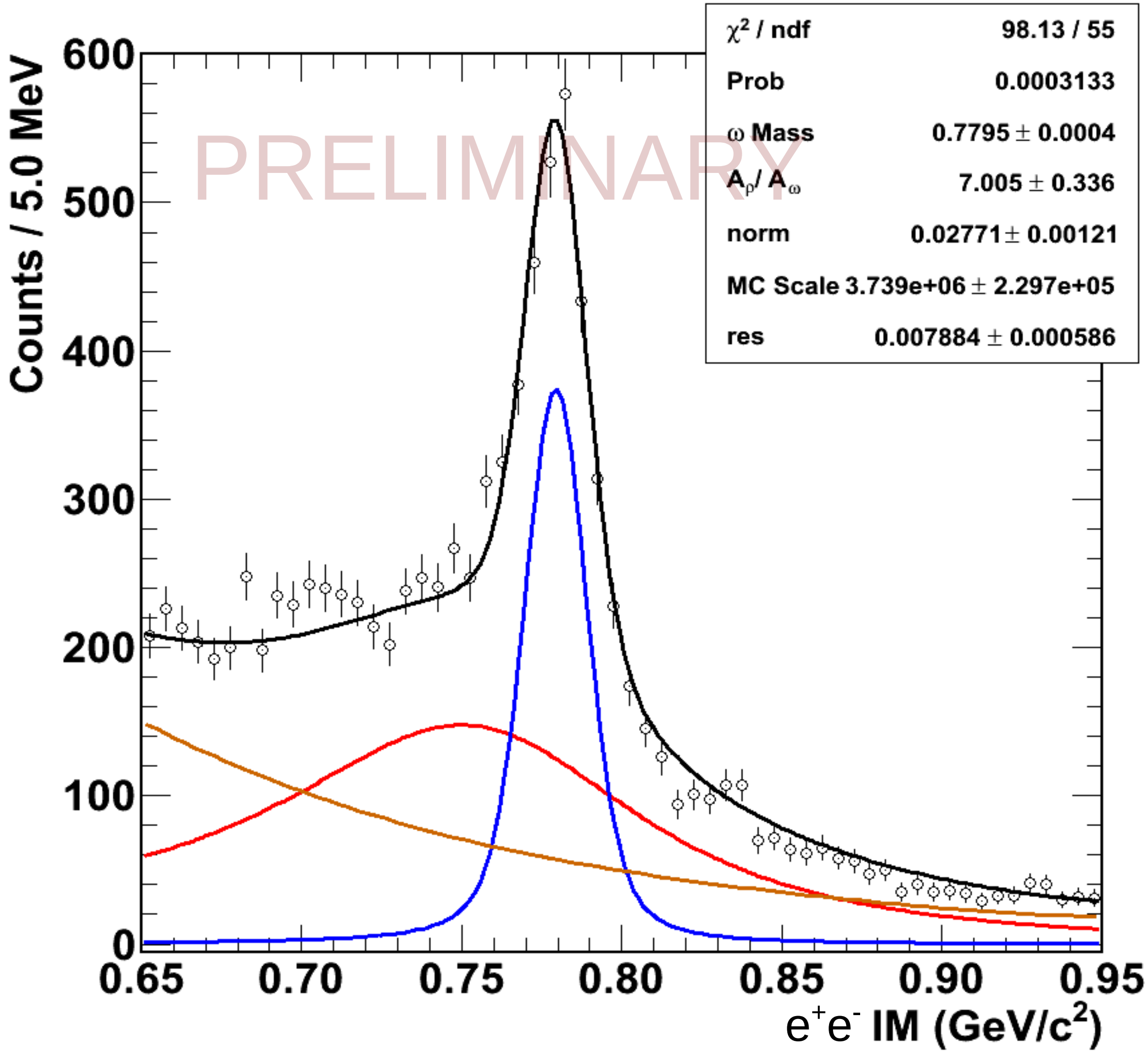
    2: Third-order Polynomial

Fits with a Selected Proton

Fit / non-interfering / MC background

- Proton MM cut.
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is taken from Monte Carlo and allowed to scale.

Total
ω
ρ
Bethe-Heitler



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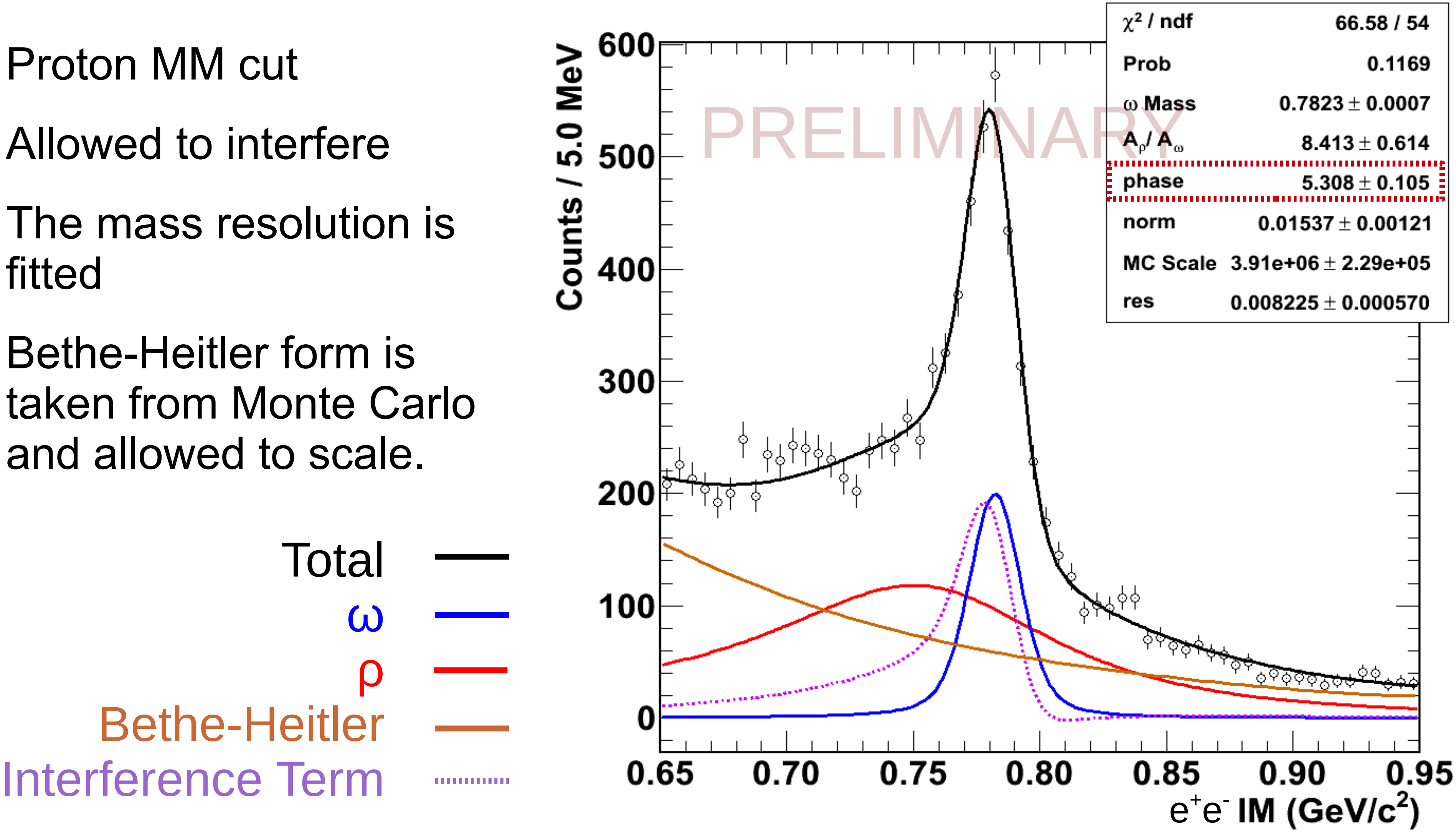
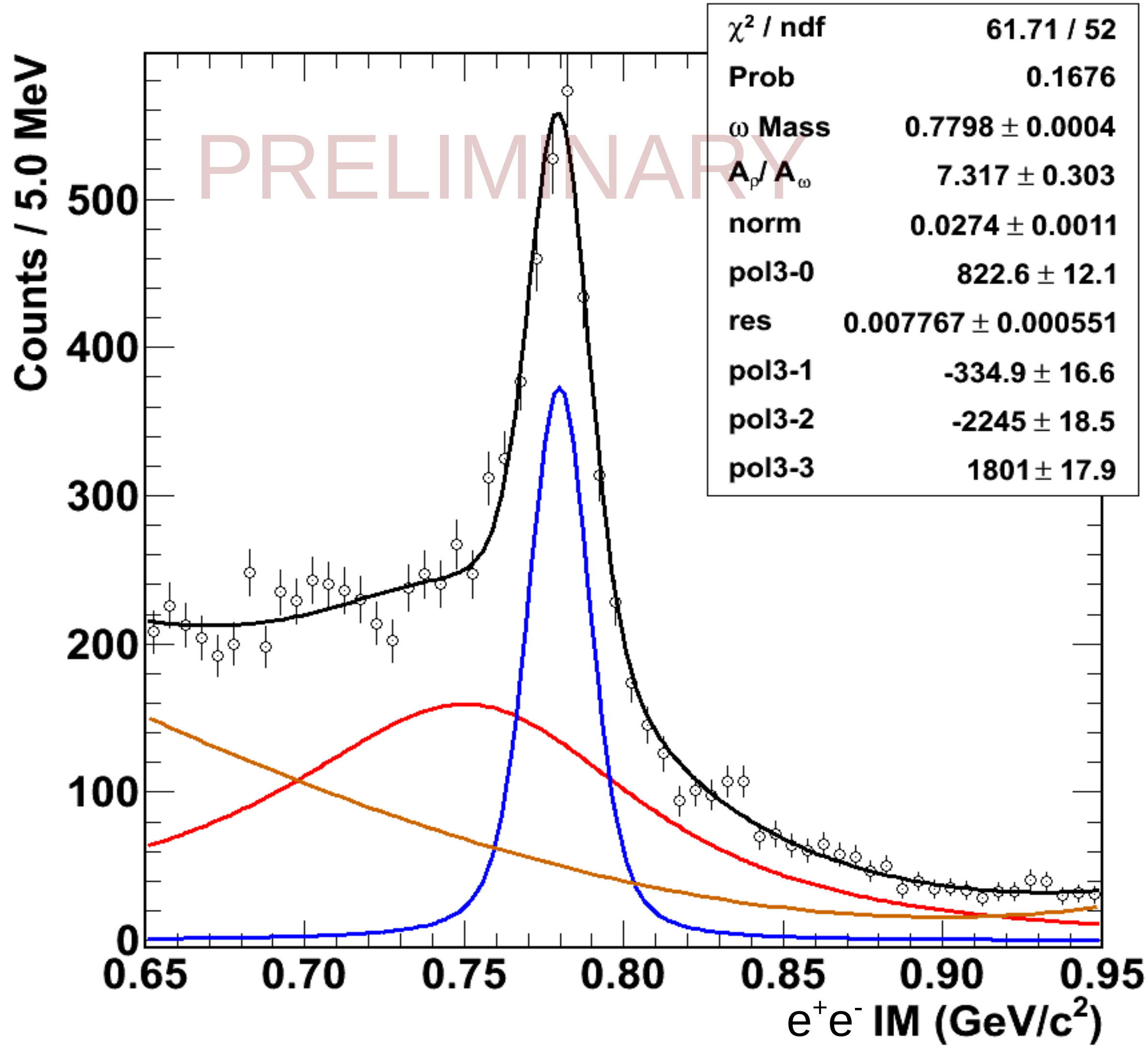


Fit / non-interfering / polynomial background

- Proton MM cut
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is a 3rd order polynomial, all parameters allowed to float.

Total
ω
ρ
Bethe-Heitler



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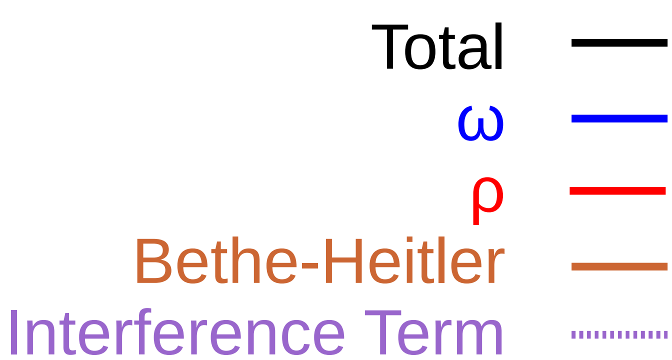
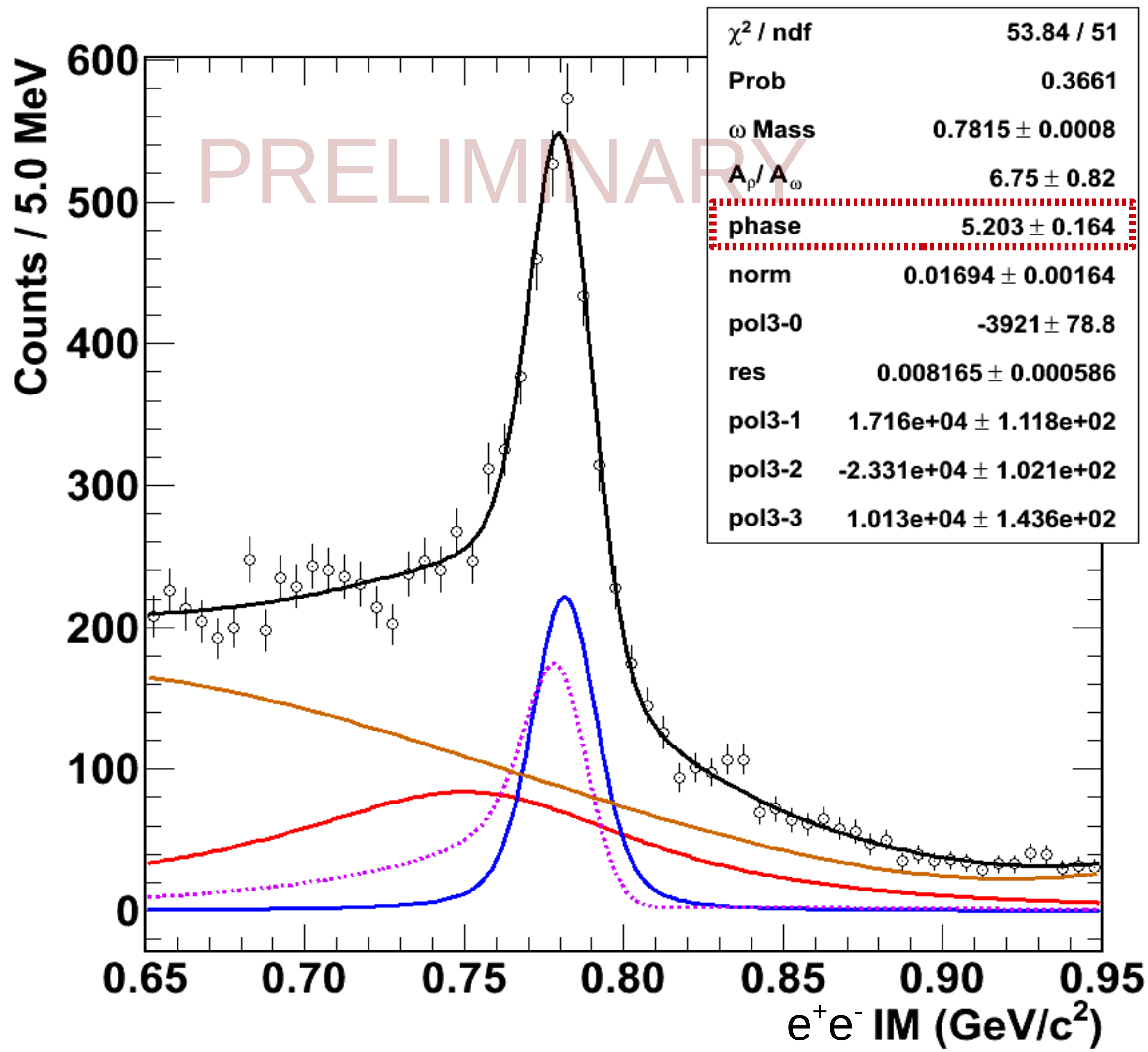
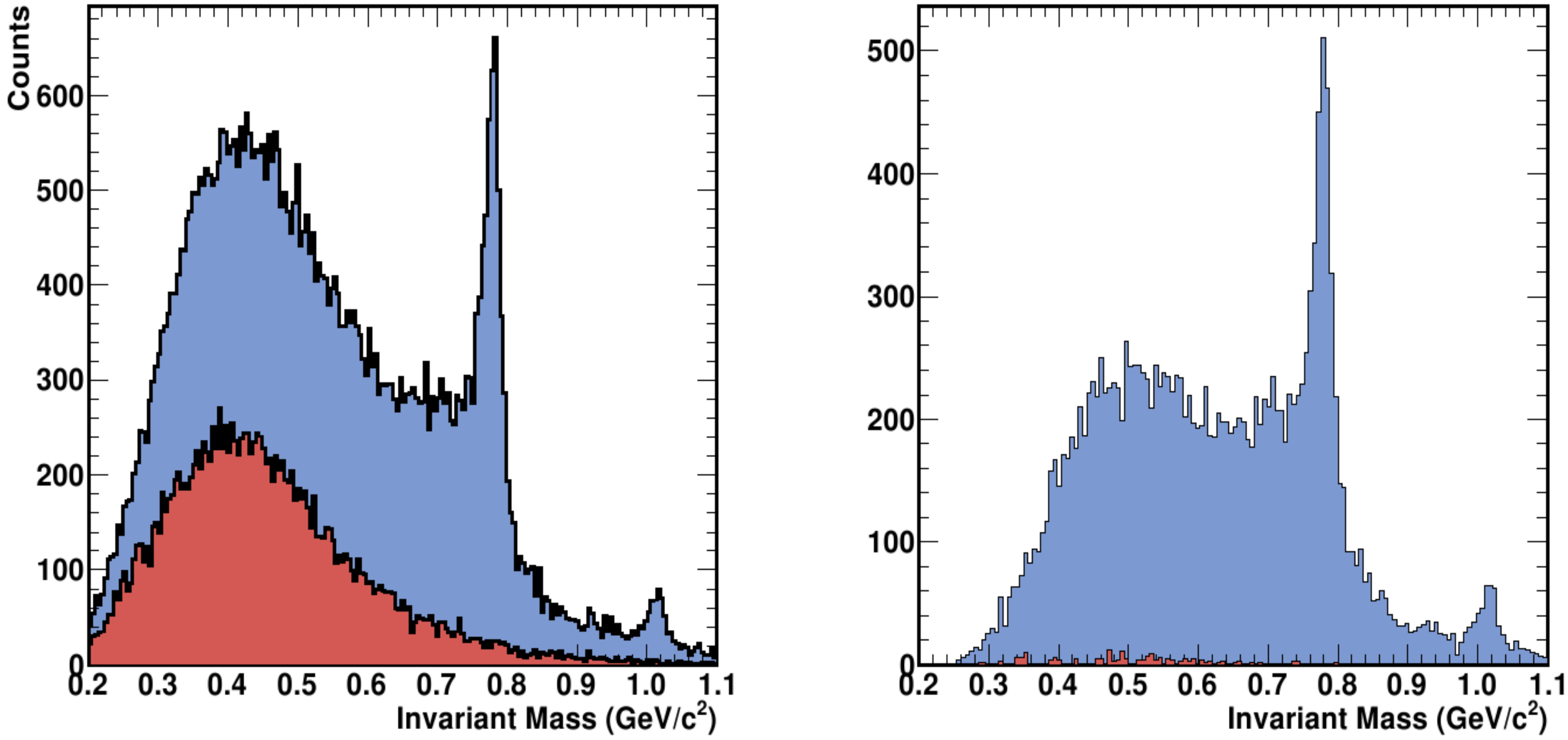




Fits Without Proton Selection

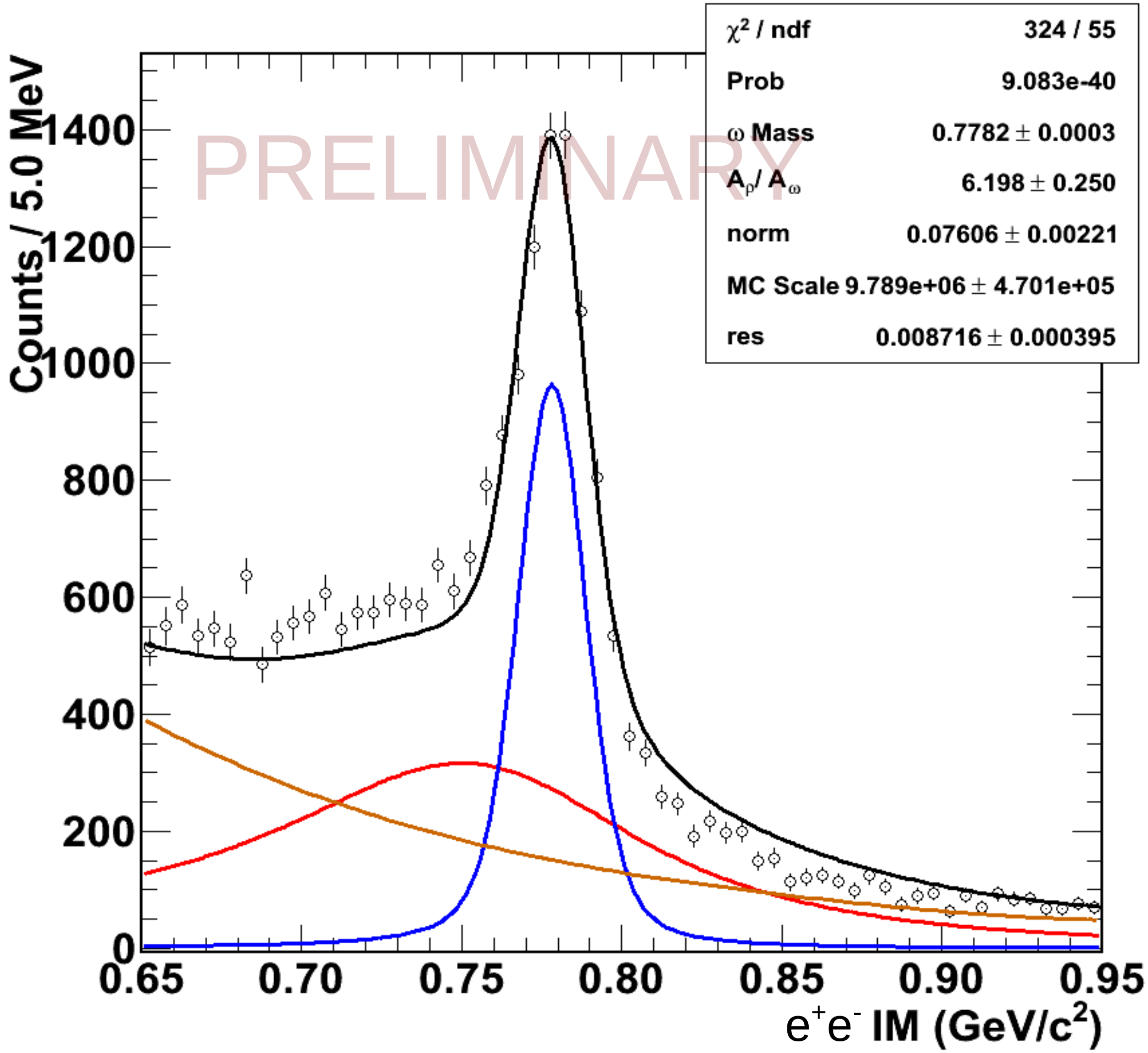
- Must subtract "uncorrelated" lepton pairs by looking at like-charge mass spectra: $N_{+-} = 2\sqrt{N_{++} + N_{--}}$



Fit / non-interfering / MC background

- No proton MM cut.
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is taken from Monte Carlo and allowed to scale.

Total
ω
ρ
Bethe-Heitler



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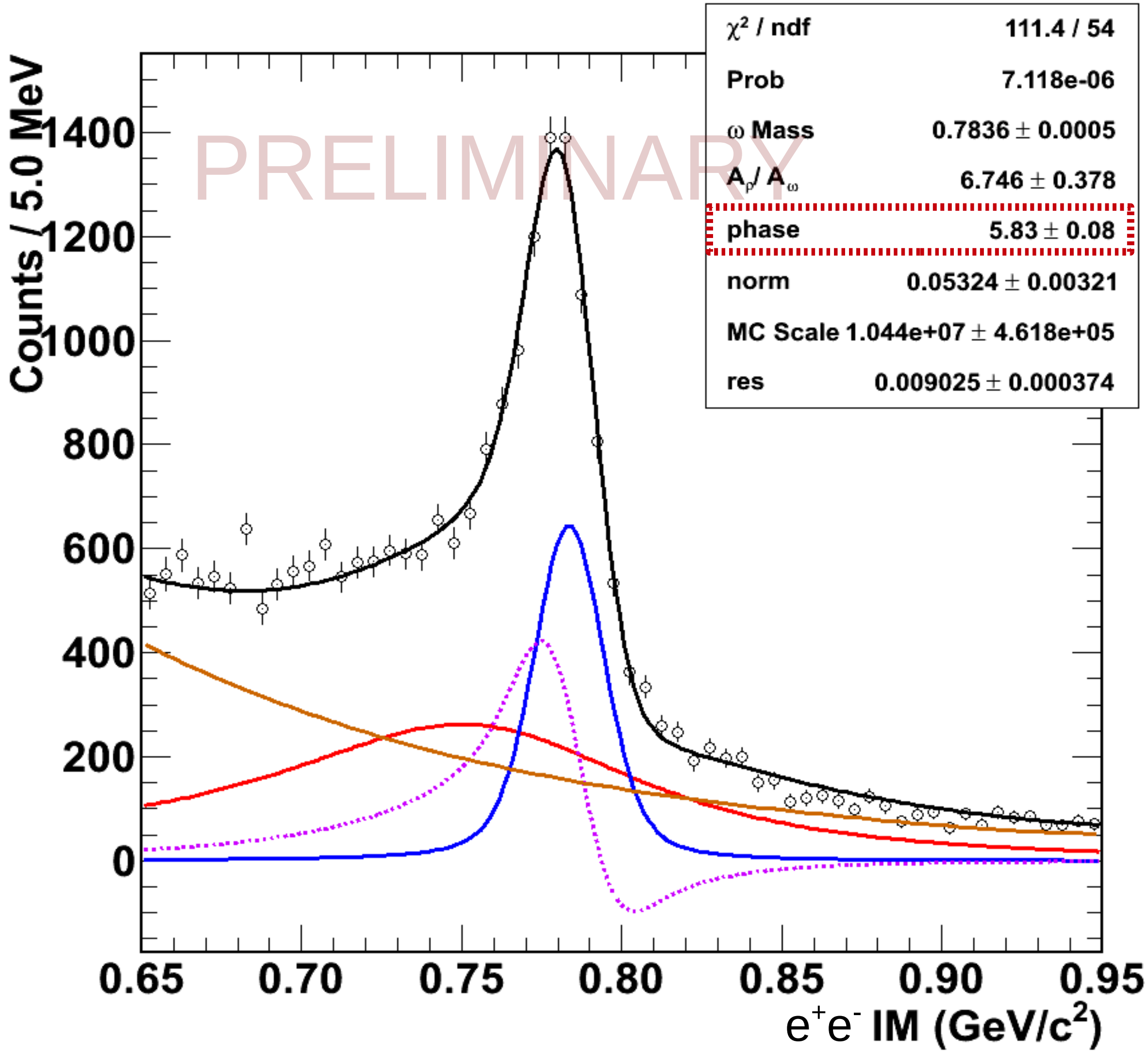
Total
ω
ρ
Bethe-Heitler
Interference Term



Fit / non-interfering / polynomial background

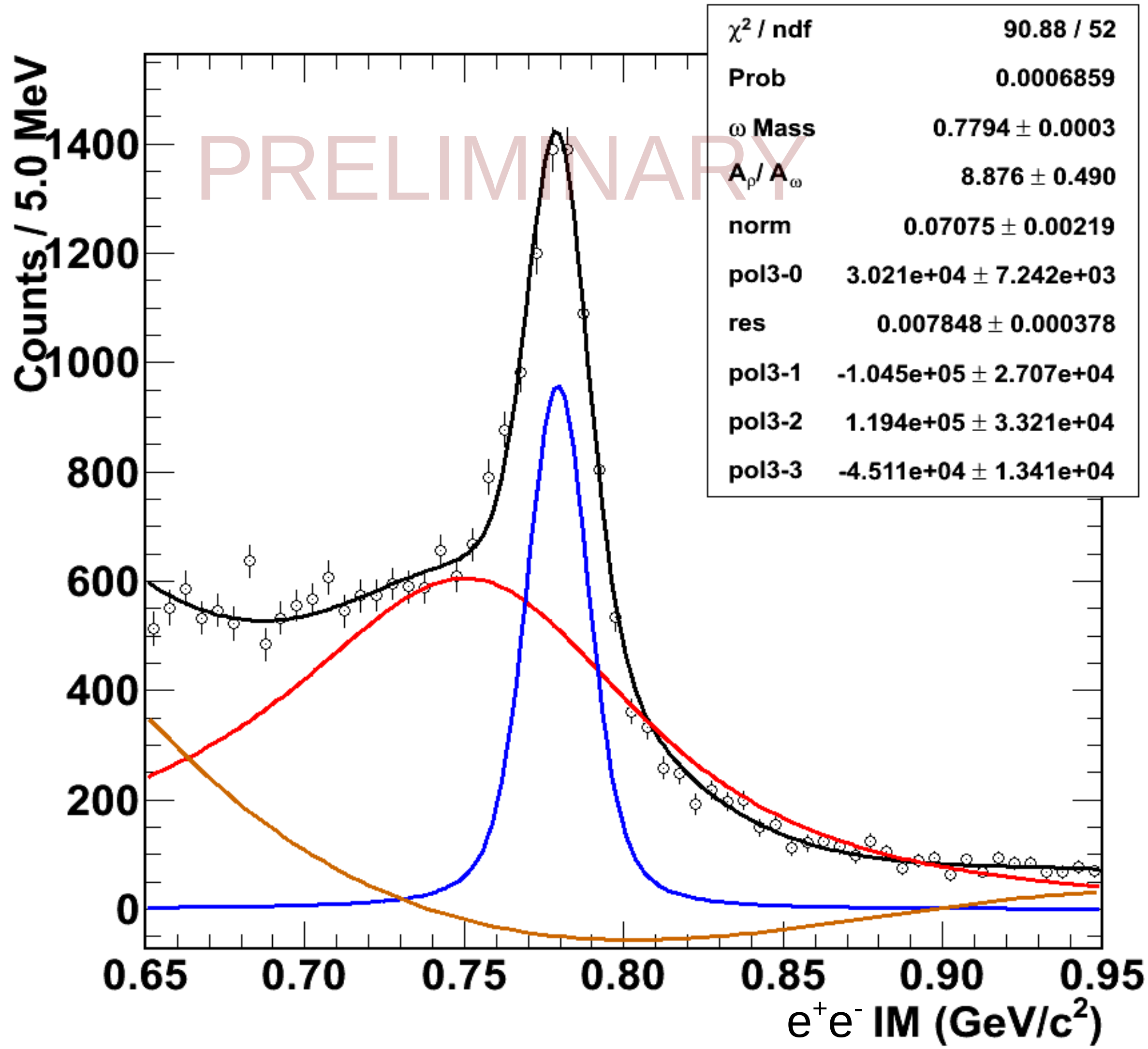
- No proton MM cut
- No interference term
- The mass resolution is fitted
- Bethe-Heitler form is a 3rd order polynomial, all parameters allowed to float.

Total

ω

ρ

Bethe-Heitler



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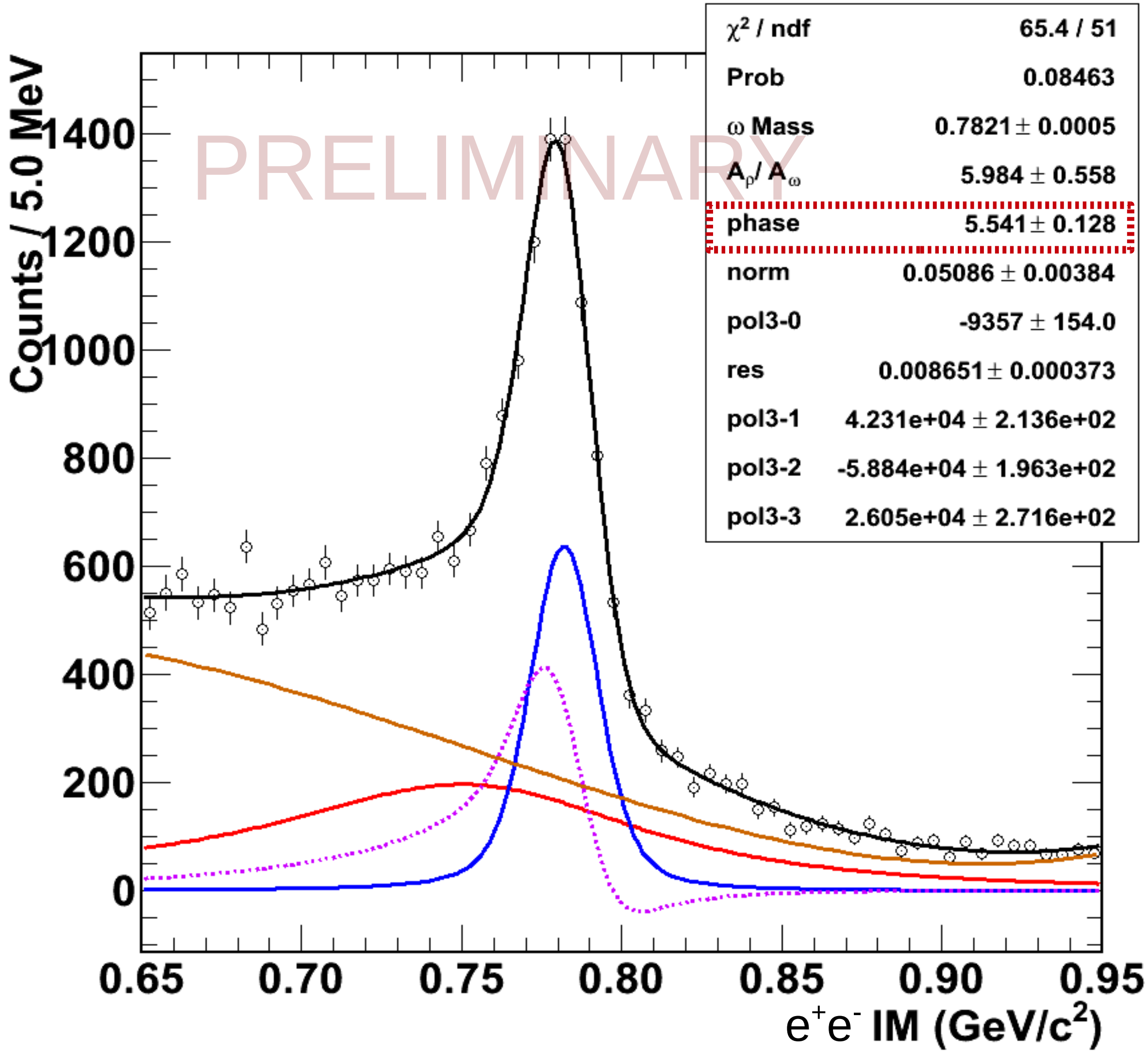
ω
ρ
Bethe-Heitler
Interference Term



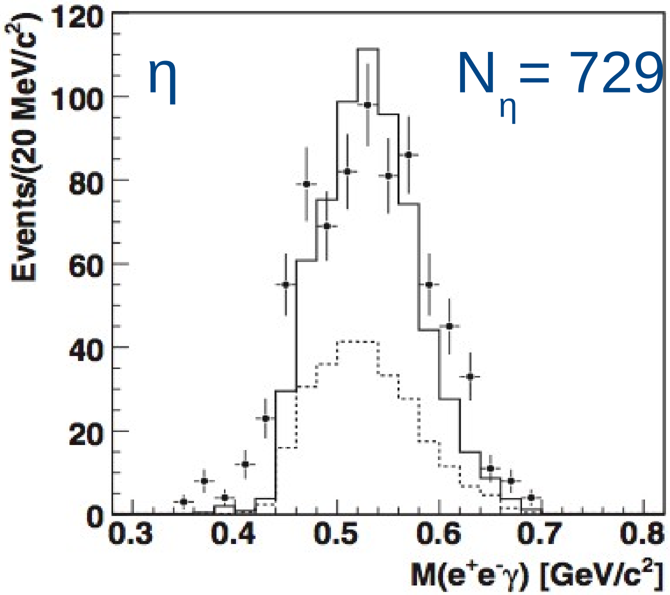
Interference Phase Preliminary Results

Fit Type	Interference Phase	X^2/ndf
MM cut / MC background	Not fit	1.784
MM cut / MC background	5.308 +/- 0.105	1.270
MM cut / 3^{rd} order pol.	Not fit	1.187
MM cut / 3^{rd} order pol.	5.203 +/- 0.164	1.056
No MM cut / MC background	Not fit	5.891
No MM cut / MC background	5.830 +/- 0.080	2.063
No MM cut / 3^{rd} order pol.	Not fit	1.748
No MM cut / 3^{rd} order pol.	5.541 +/- 0.128	1.263

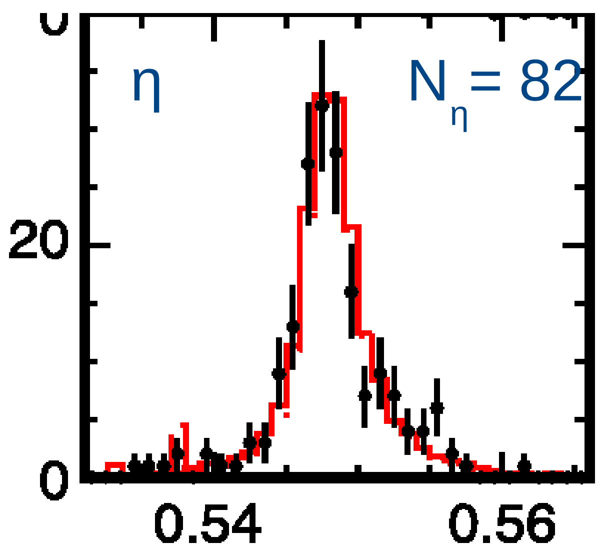
Part II: Pseudoscalar Mesons η and η'

Dissertation work from Michael C. Kunkel

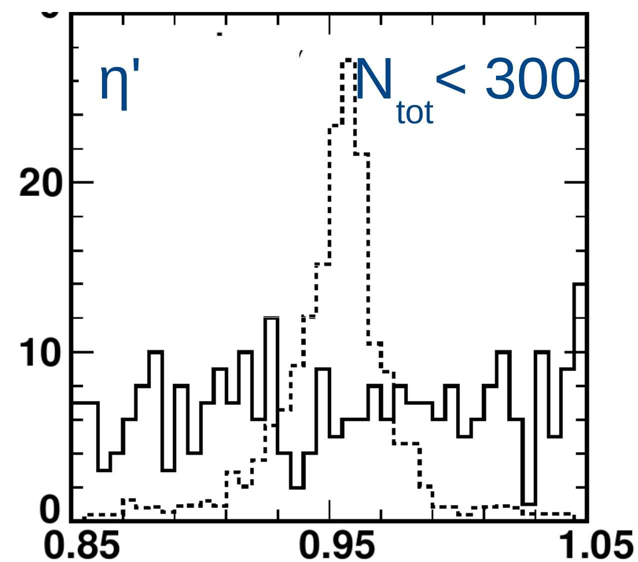
- Limited statistics on η and η' Dalitz decay studies.
- Currently only an upper limit on η' Dalitz cross section.



M. Berlowski, *et. al.*, Phys. Rev. D77
WASA / CELCIUS, 2008

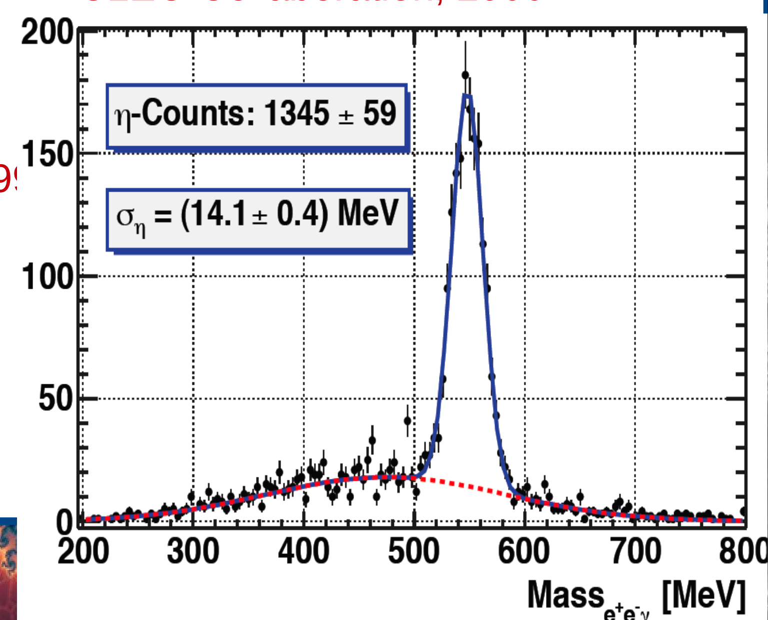


A. Lopez, *et. al.*, Phys. Rev. Lett. 9
CLEO Collaboration, 2007



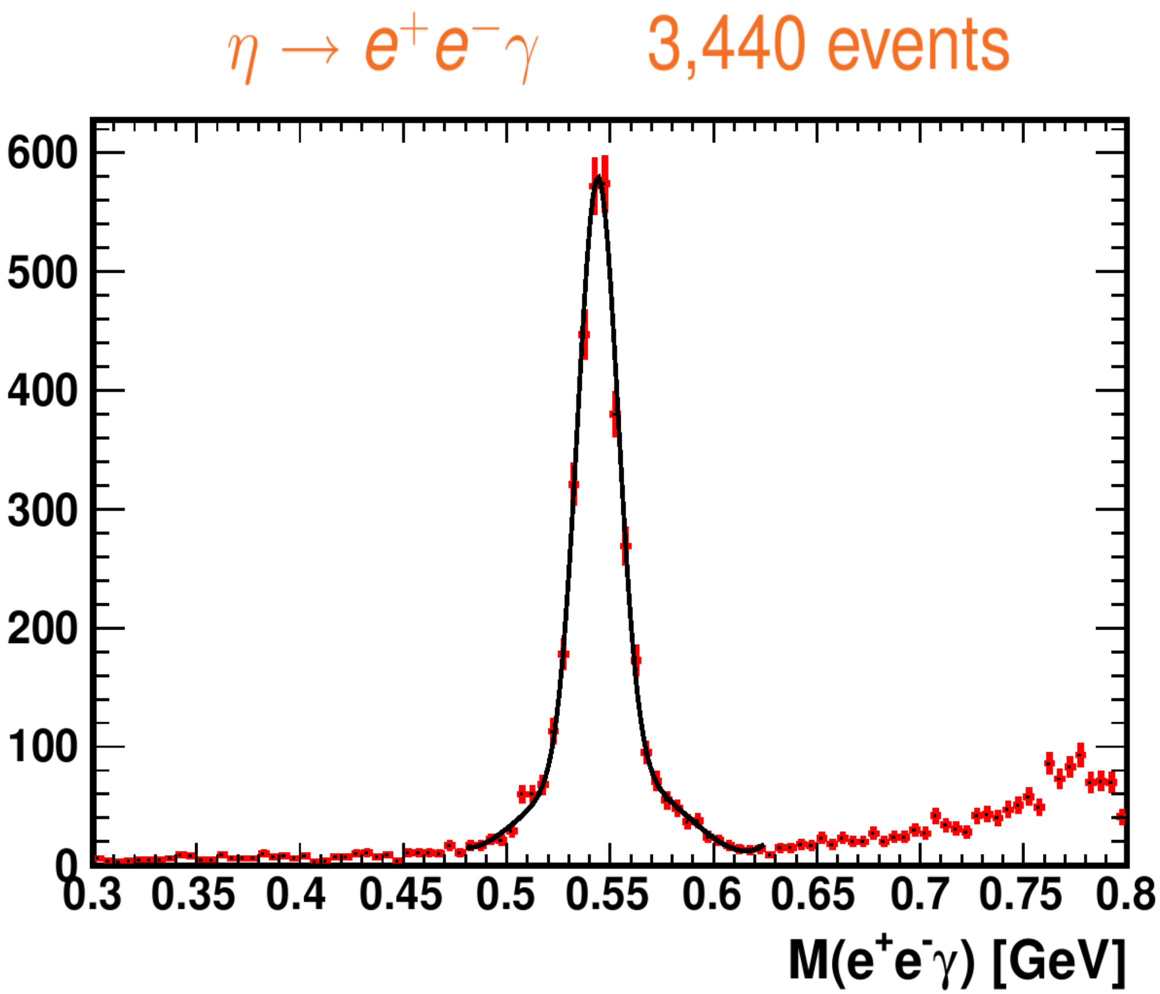
R. A. Briere, *et. al.*, Phys. Rev. Lett. 84
CLEO Collaboration, 2000

- Soon to be published data from CB / TAPS@MAMI:



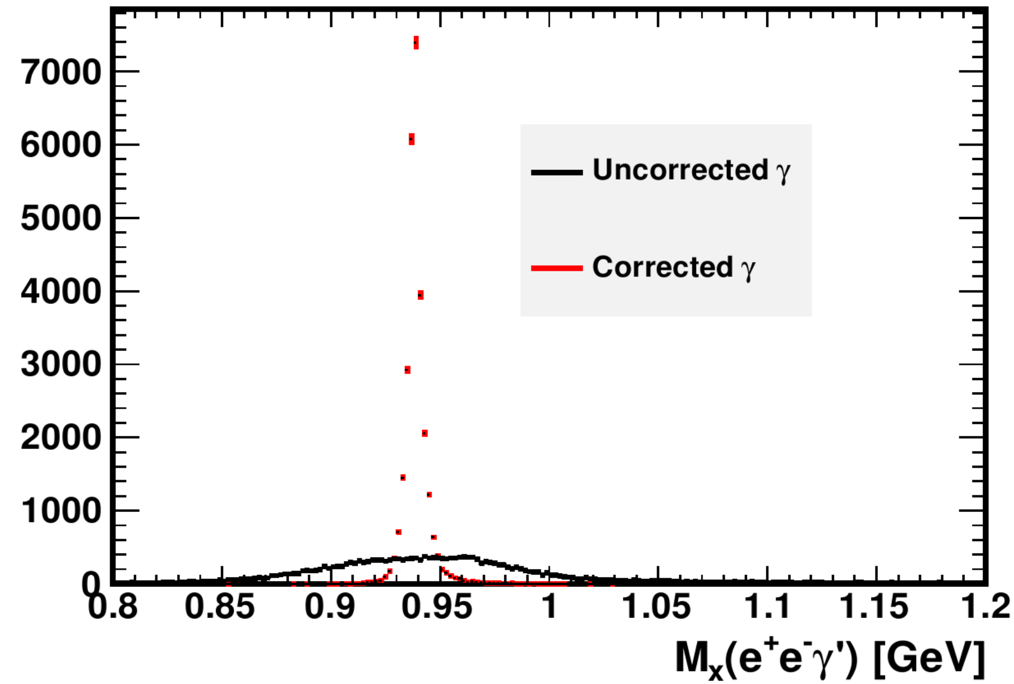
η Statistics from g12

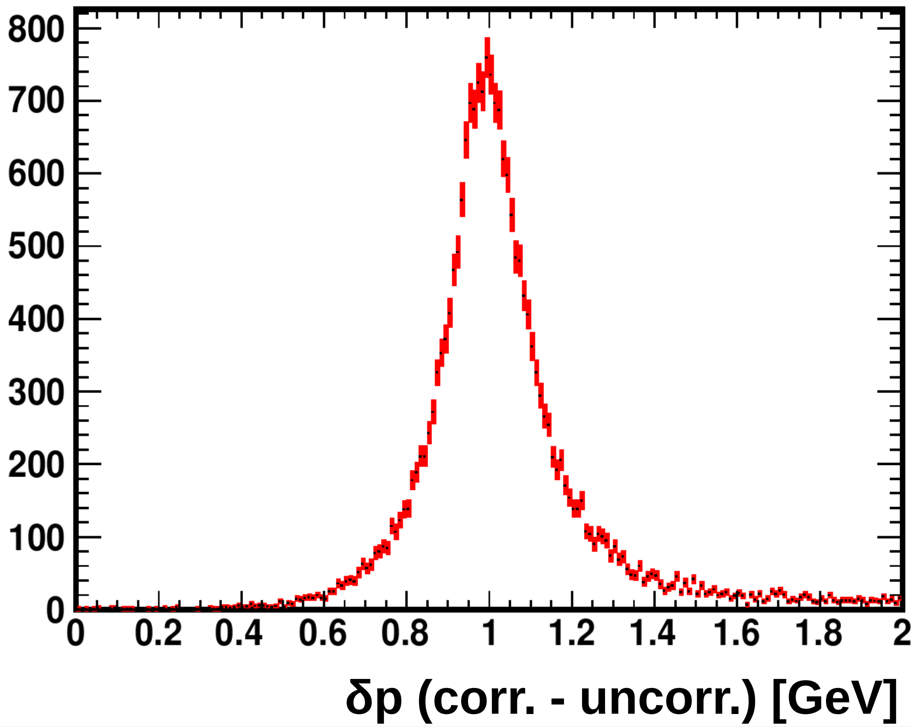
- g12 experiment has largest world statistics for η reconstructed from Dalitz decays
- Data has not yet been corrected for η → γγ, where one of the photons pair creates in the target medium.

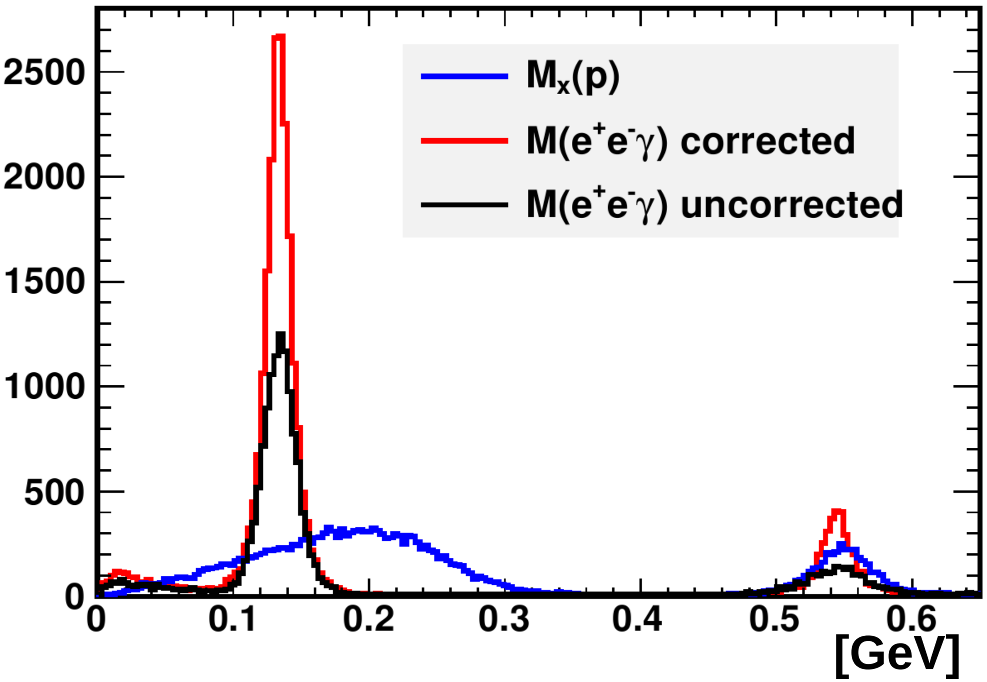


Selecting Dalitz Decays

- Beyond Exclusivity Cuts:
  - Correcting for the detected photon momentum significantly increases statistics within exclusivity cuts.

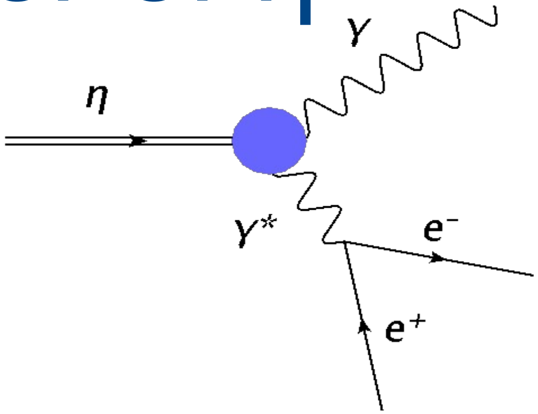






The Charge Form Factor of η

- For $\eta \to e^+ e^- \gamma$:



$$\frac{d\Gamma}{dq^2} = \left(\frac{d\Gamma}{dq^2}\right)_{pointlike} \cdot \left|F(q^2)\right|^2$$

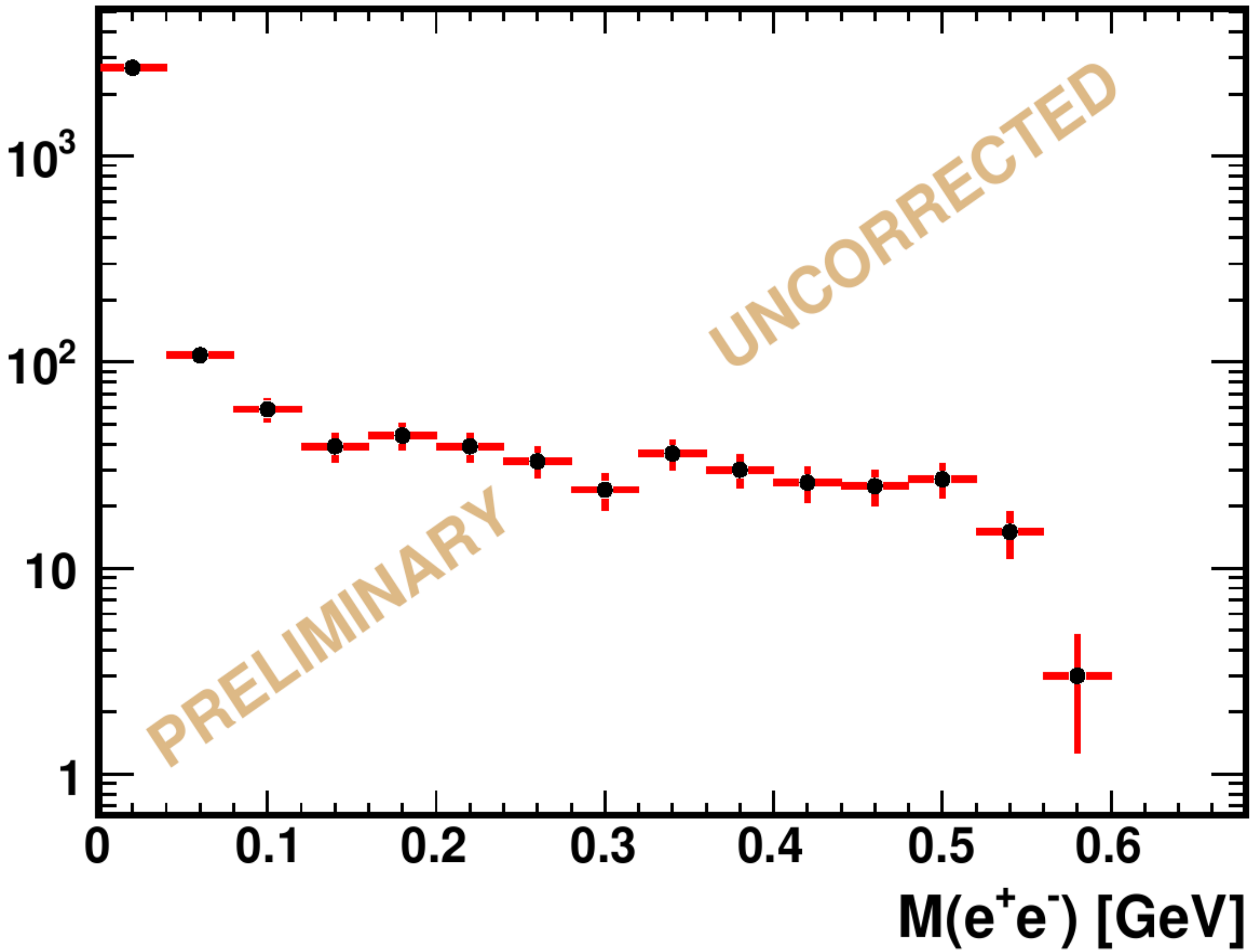
$$\frac{d\Gamma\left(P \to e^+e^-\gamma\right)}{dm\,\Gamma\left(P \to \gamma\gamma\right)} = \frac{4\alpha}{3\pi m}\sqrt{1-\frac{4m_e^2}{m^2}}\left(1+\frac{2m_e^2}{m^2}\right)\left[1-\frac{m^2}{m_P^2}\right]^3\left|F\left(q^2\right)\right|^2$$

$$F(q^2) = \frac{1}{1-\frac{q^2}{\Lambda^2}}$$

m is the dilepton mass
m_e is the electron mass
m_P is the parent meson mass
Λ is the monopole FF parameter

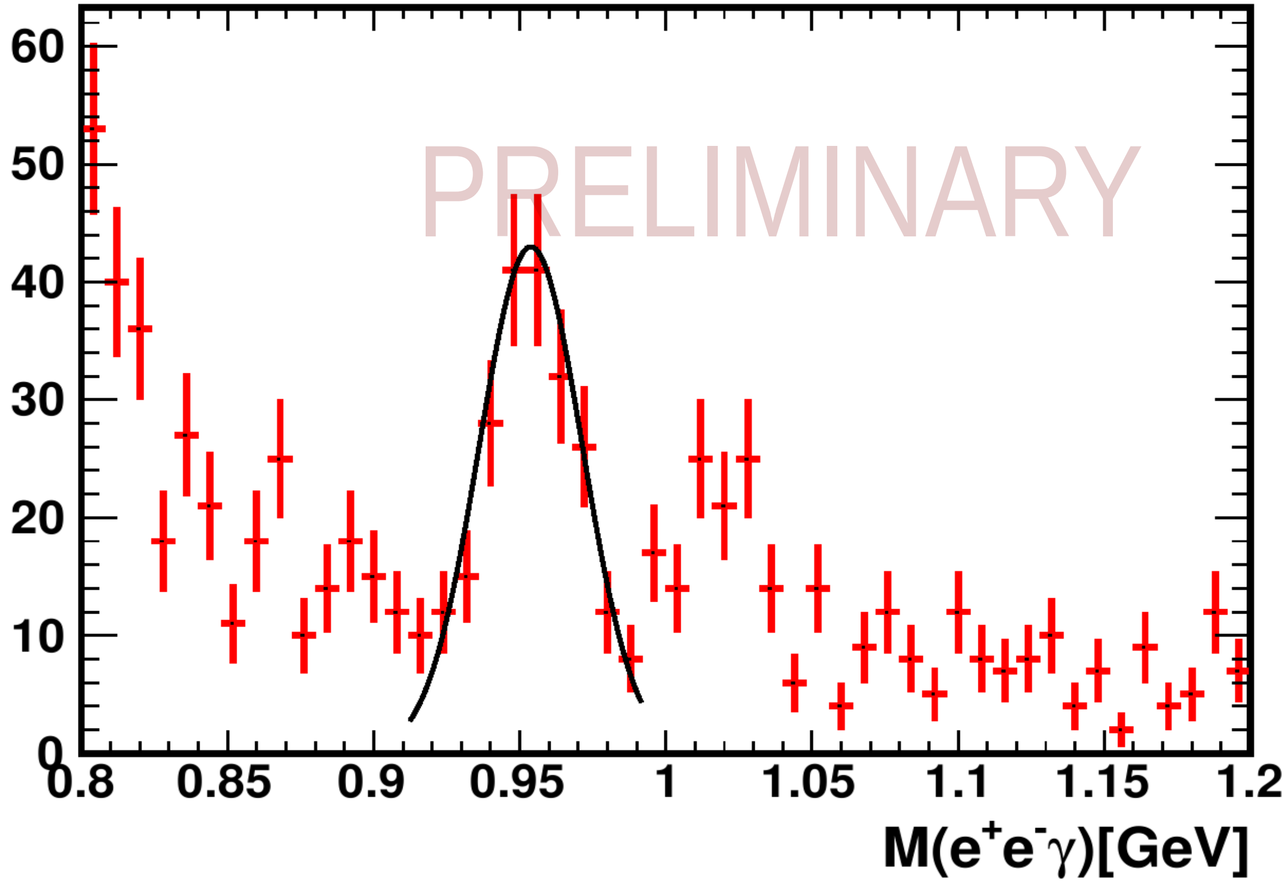
The η dilepton mass spectrum

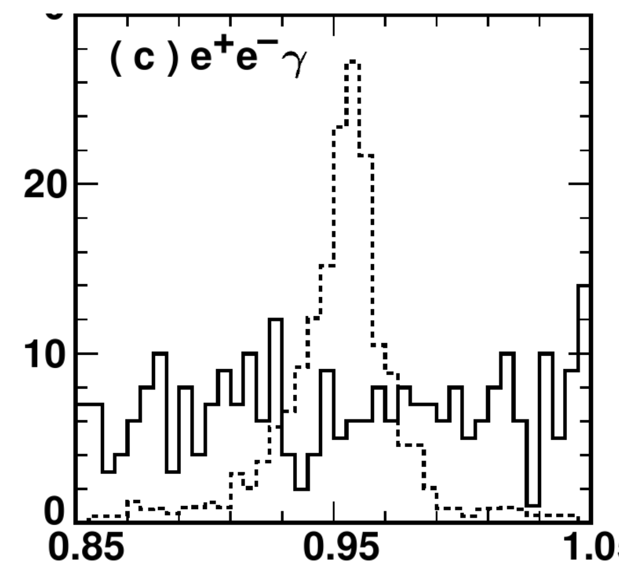
- The lowest mass bin has more events than are expected. This is likely from two sources:
  - Acceptance in the low mass region drops significantly.
  - The decay $\eta \rightarrow \gamma\gamma$, where one of the photons pair produce in the target or target walls. Currently, simulation is being run on this process.



η' Dalitz

- G12 data shows a clear enhancement at the η' mass (958 MeV): $\eta' \rightarrow e^+e^-\gamma$ 213 events





R. A. Briere, *et. al.*, Phys. Rev. Lett. 84
CLEO Collaboration, 2000

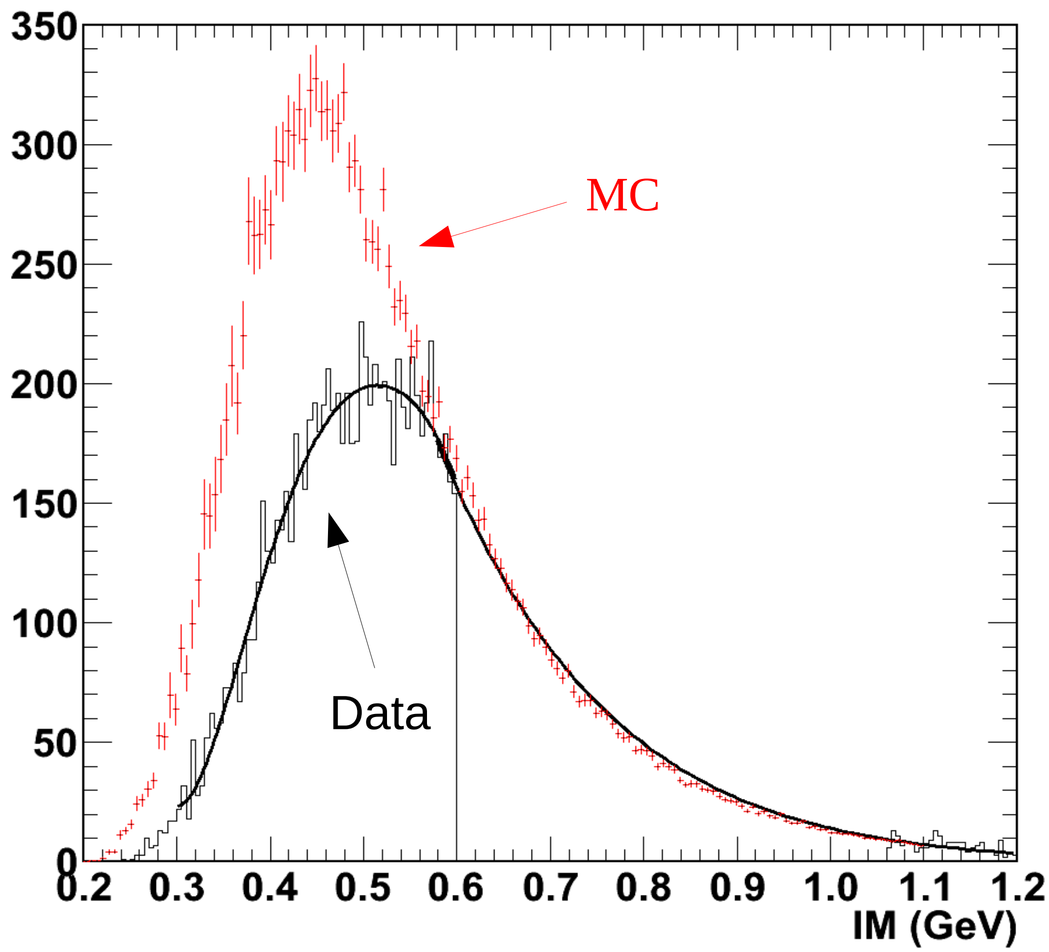
Conclusion

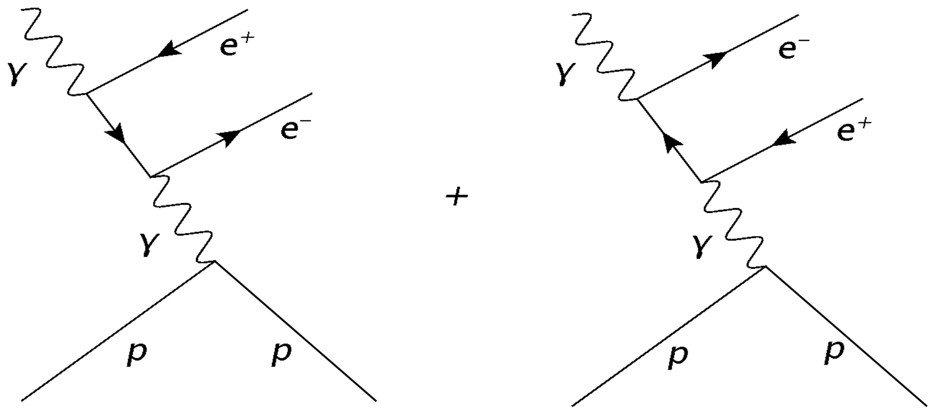
- Understanding the ρ-ω interference in the elementary process will help with the of interpretation of in-medium studies.
- The interference phase itself from fits with different background shapes all agree within statistical error: preliminary phase: φ = 5.25 +/- 0.20.
- The transition charge FF for the η (and π^0) are being studied
- The first ever η' dalitz decay is being measured in experiment g12, with cross sections and branching ratios upcoming.

Extra Slides:

Bethe-Heitler

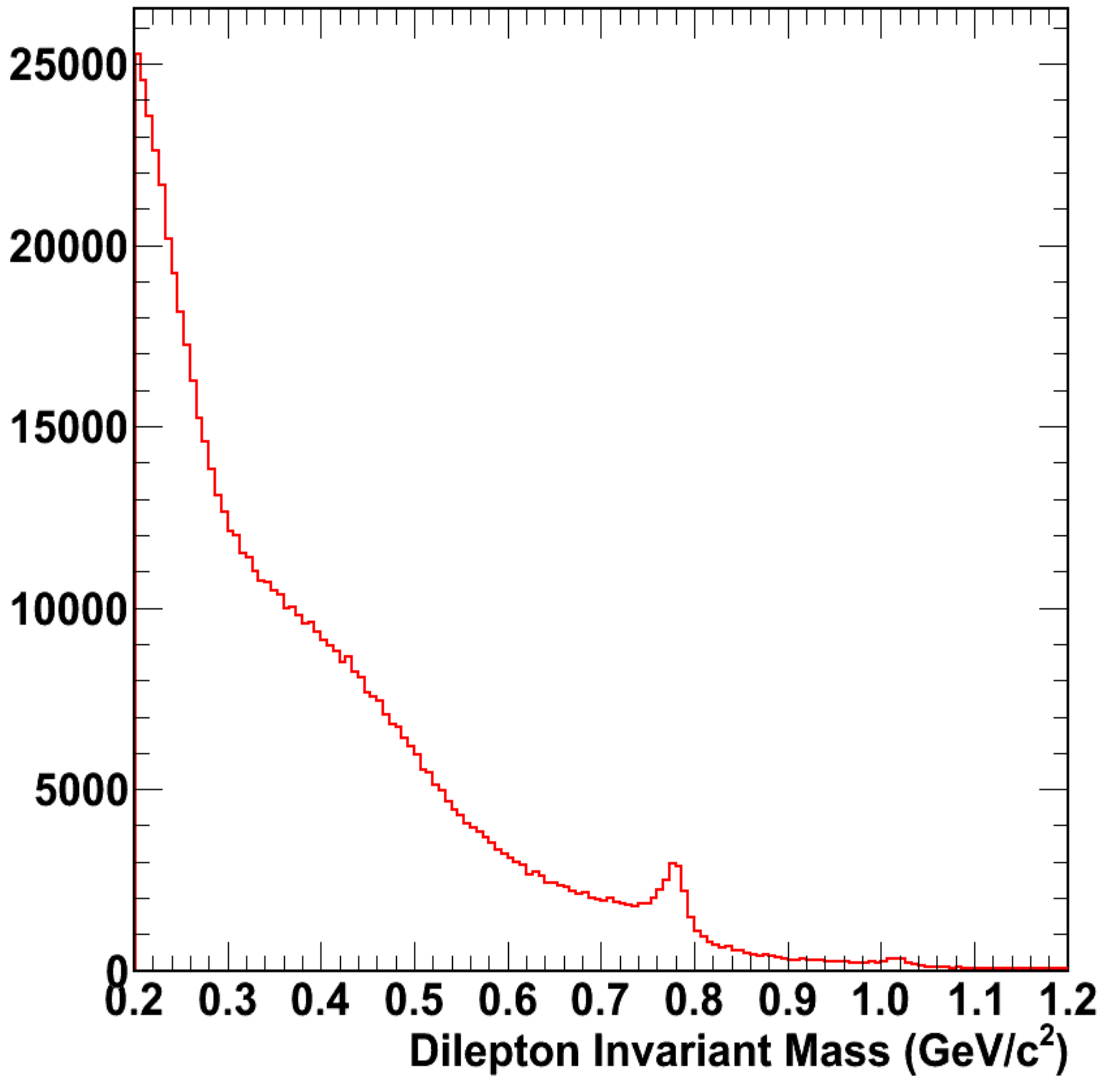
- Problems:
  - Bethe-Heitler MC and data do not agree well.
  - Possible Bethe-Heitler / VM interference.
    - Shows up in detected asymmetries. CLAS is asymmetric in electron / positron acceptance.





Background and Cuts

- Cut 1: Two leptons are skimmed from the total g12 data set.
- Cut 2: Both leptons must be in different sectors of CLAS.
- Cut 3: Vertex cut on event to be inside target walls.
- Cut 4: Coincidence timing cut between the leptons and the tagged photon.
- Cut 5: Additional EC cut to remove pions.
- Cut 6: Opening angle cut between leptons.



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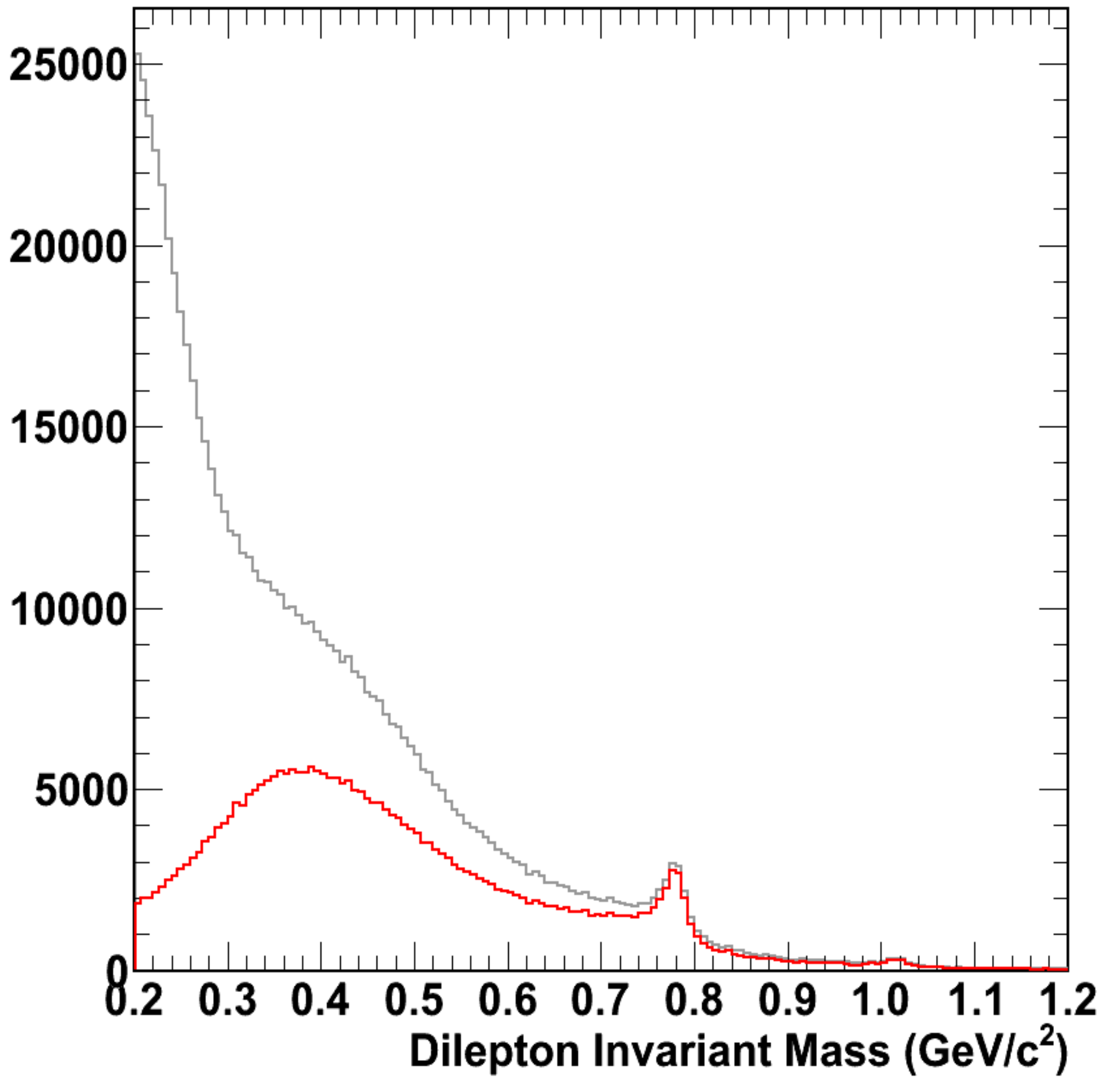

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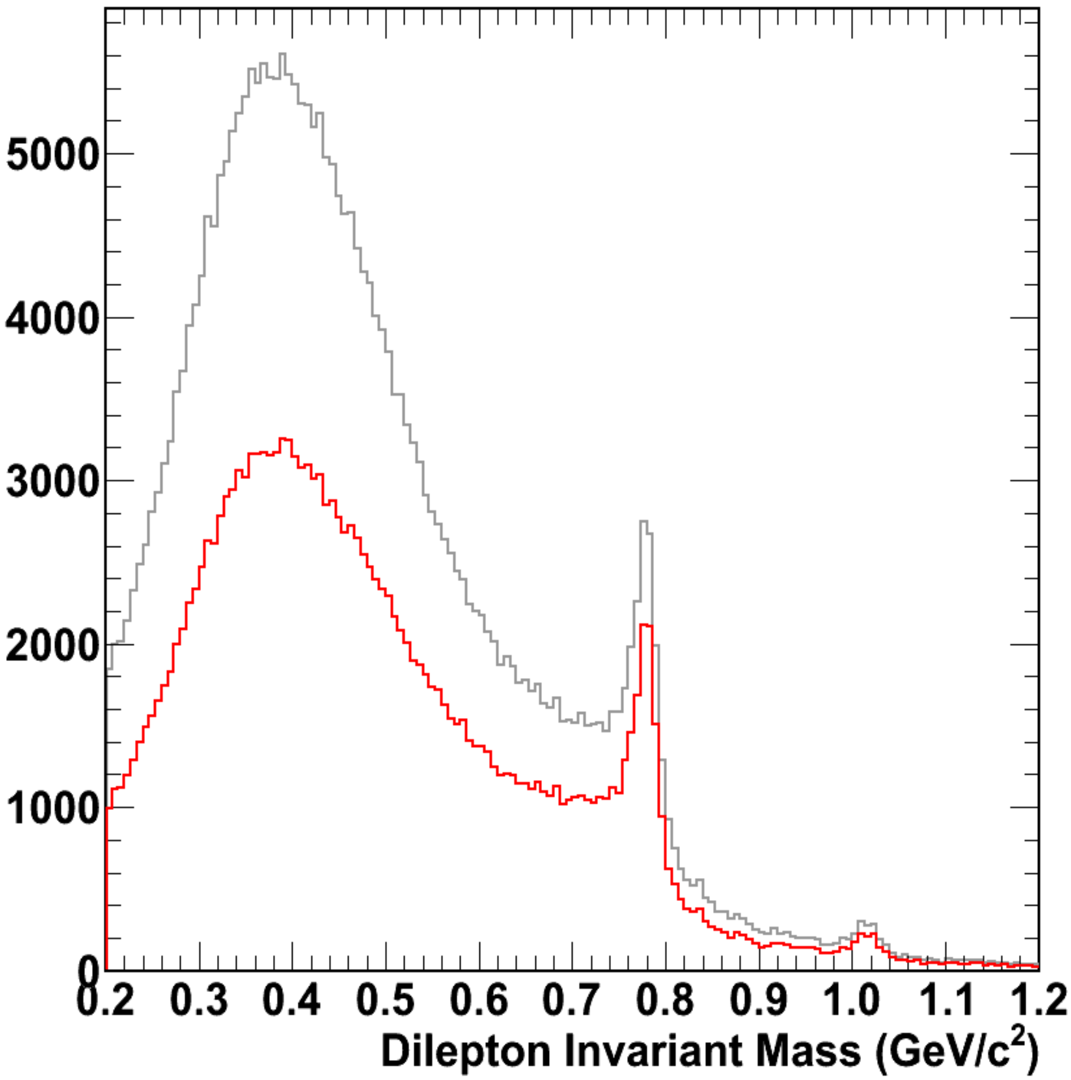

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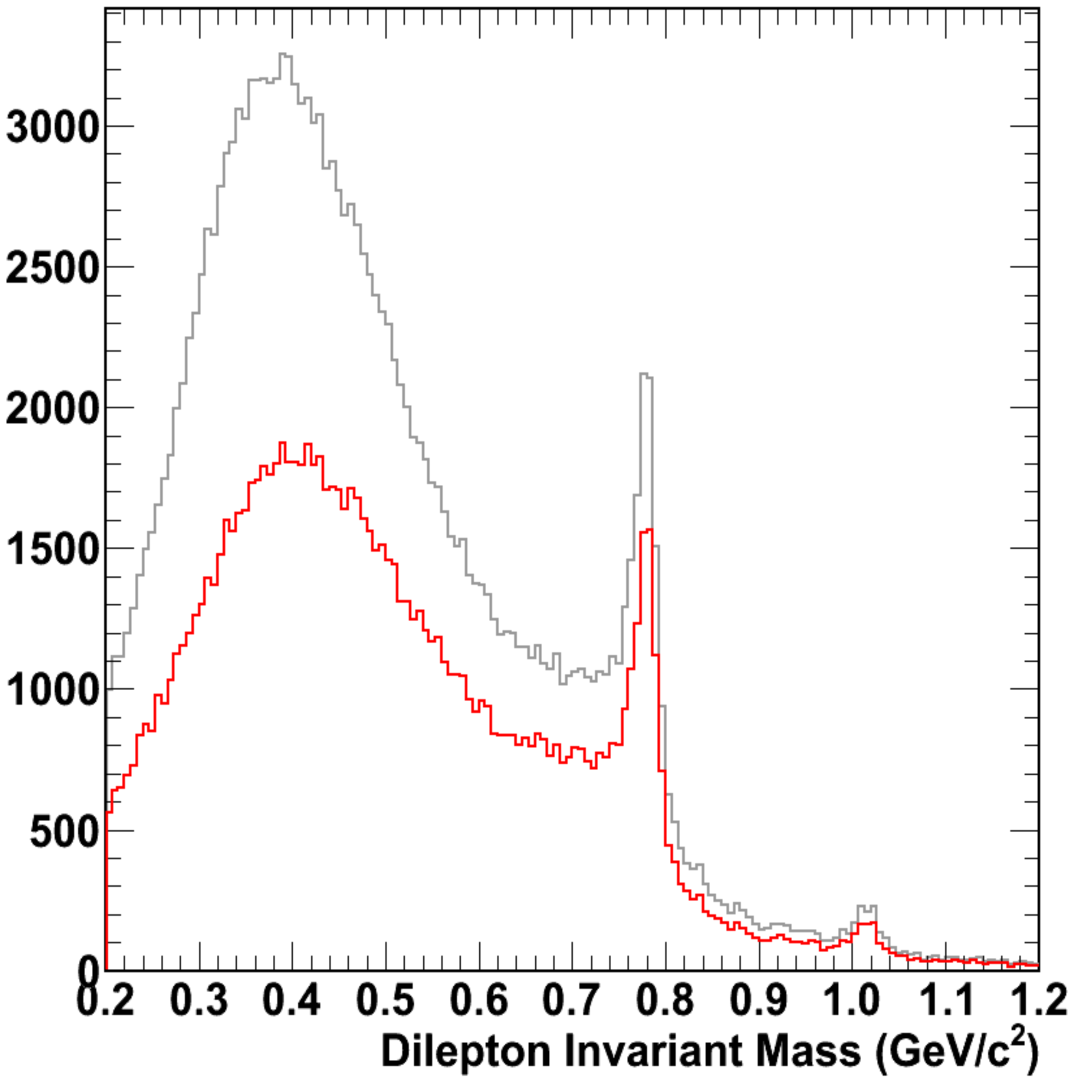

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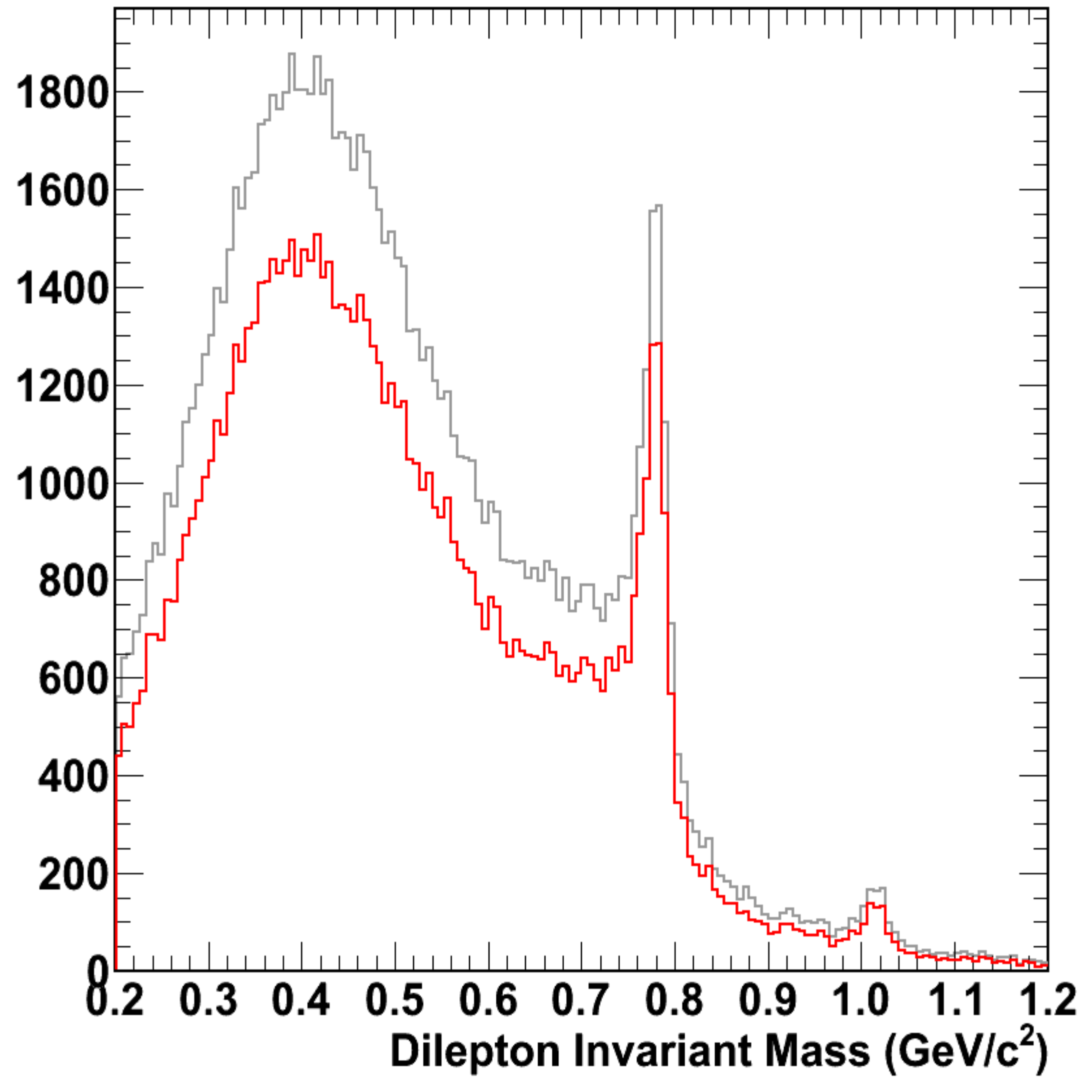

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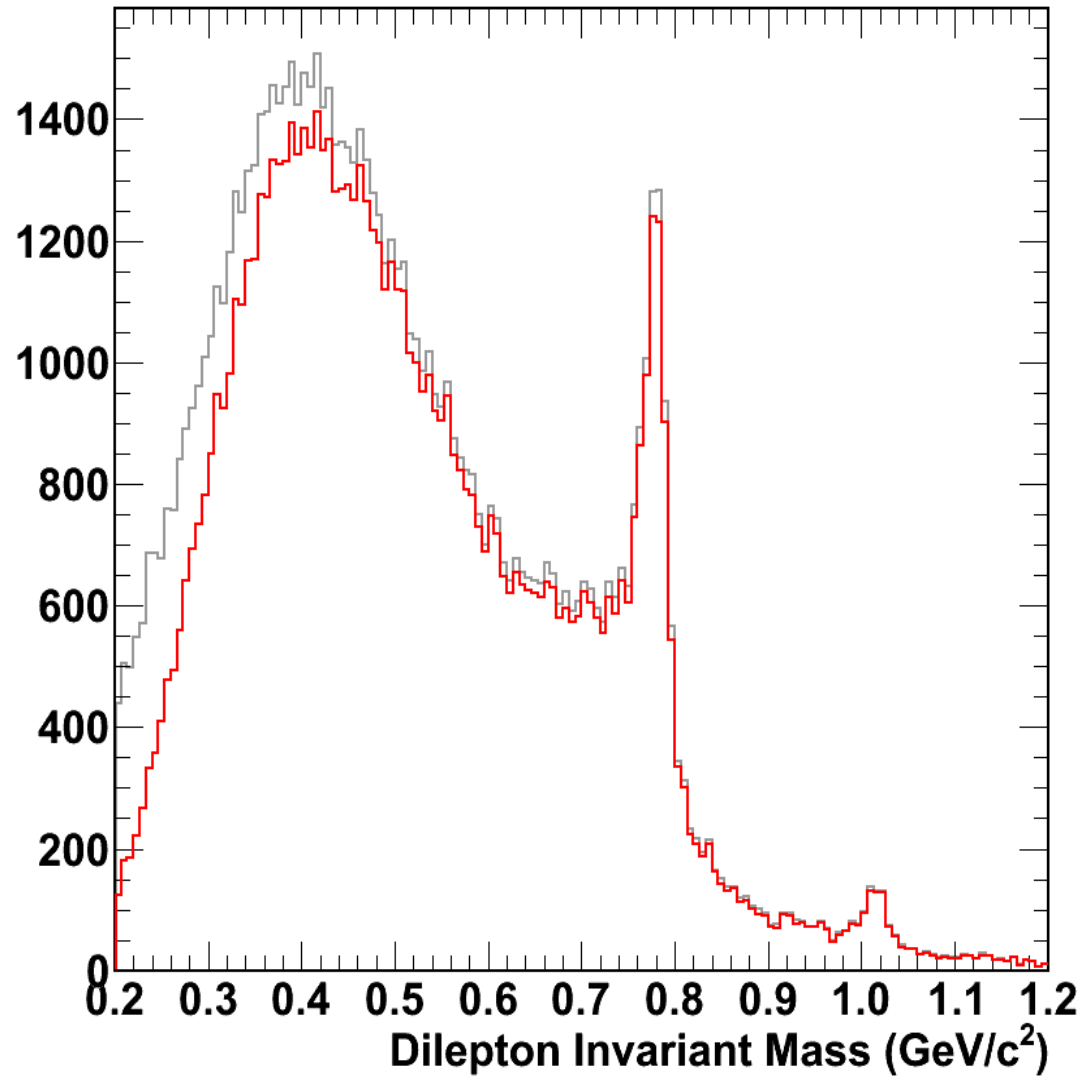
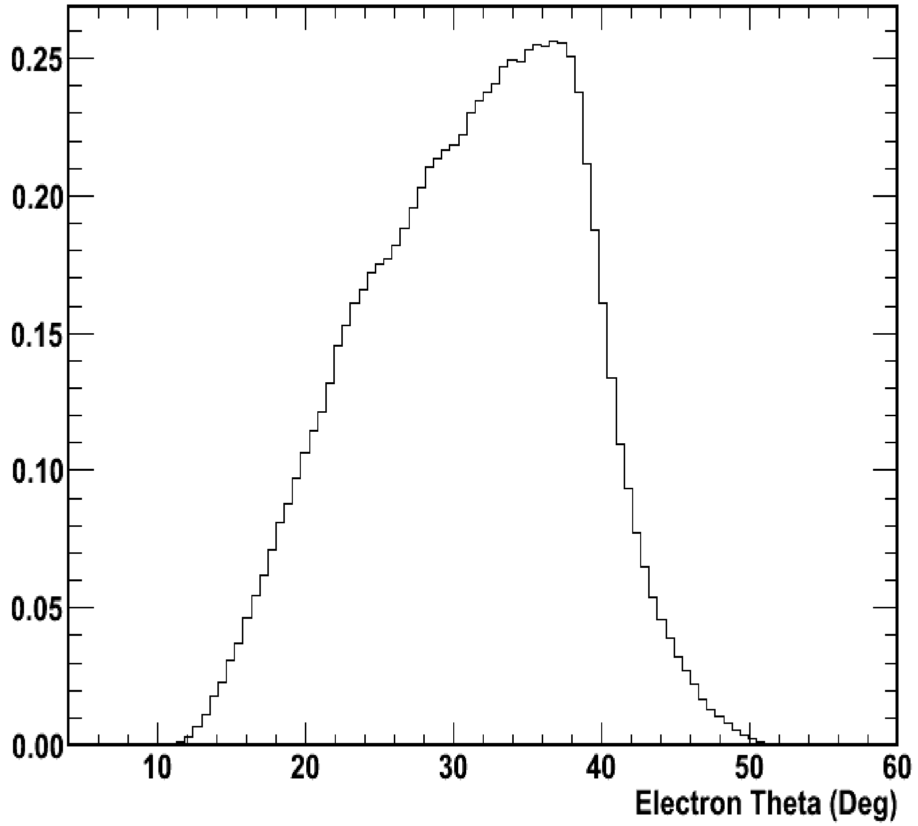
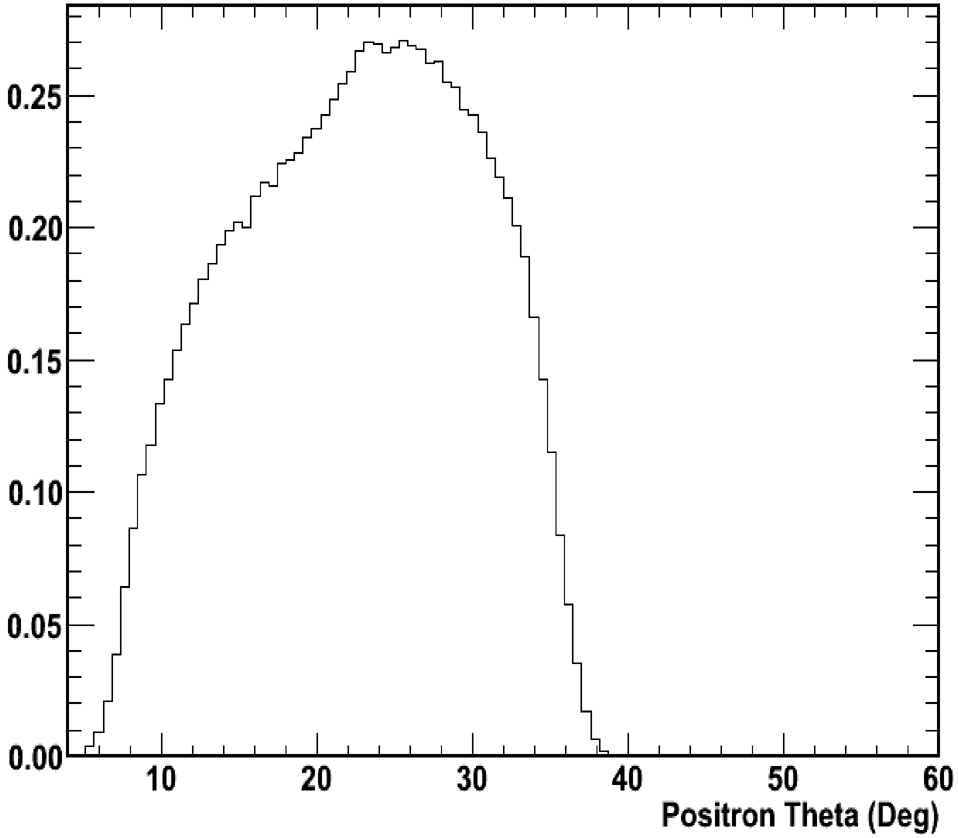


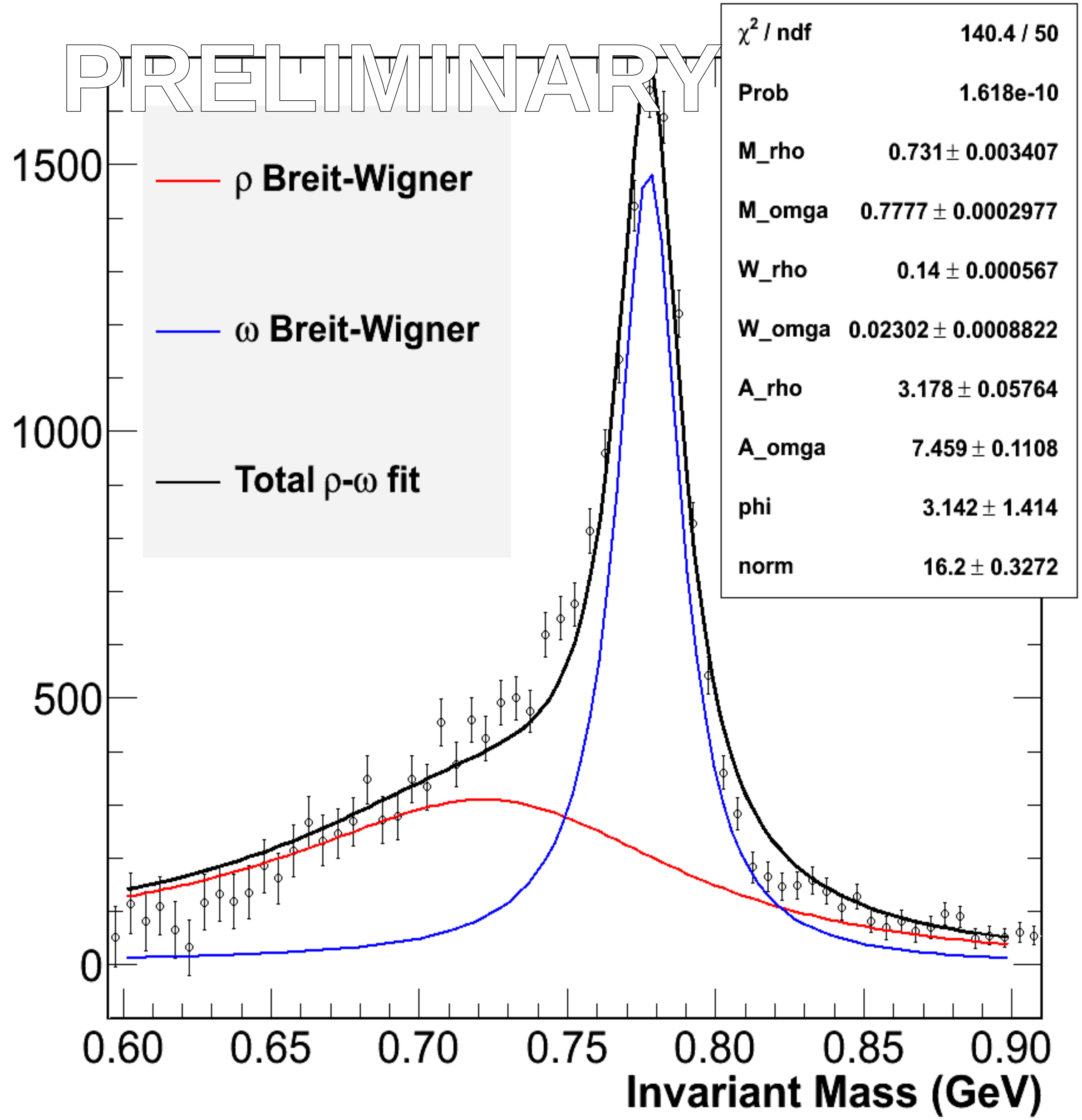
CLAS Positron / Electron Acceptance





Fit Results (Non-Interfering)

- Assuming two separate non-interfering Breit-Wigner forms, the fit does not describe the data very well:
  - χ^2/ndf ~ 2.8
  - ρ mass is 35 MeV low

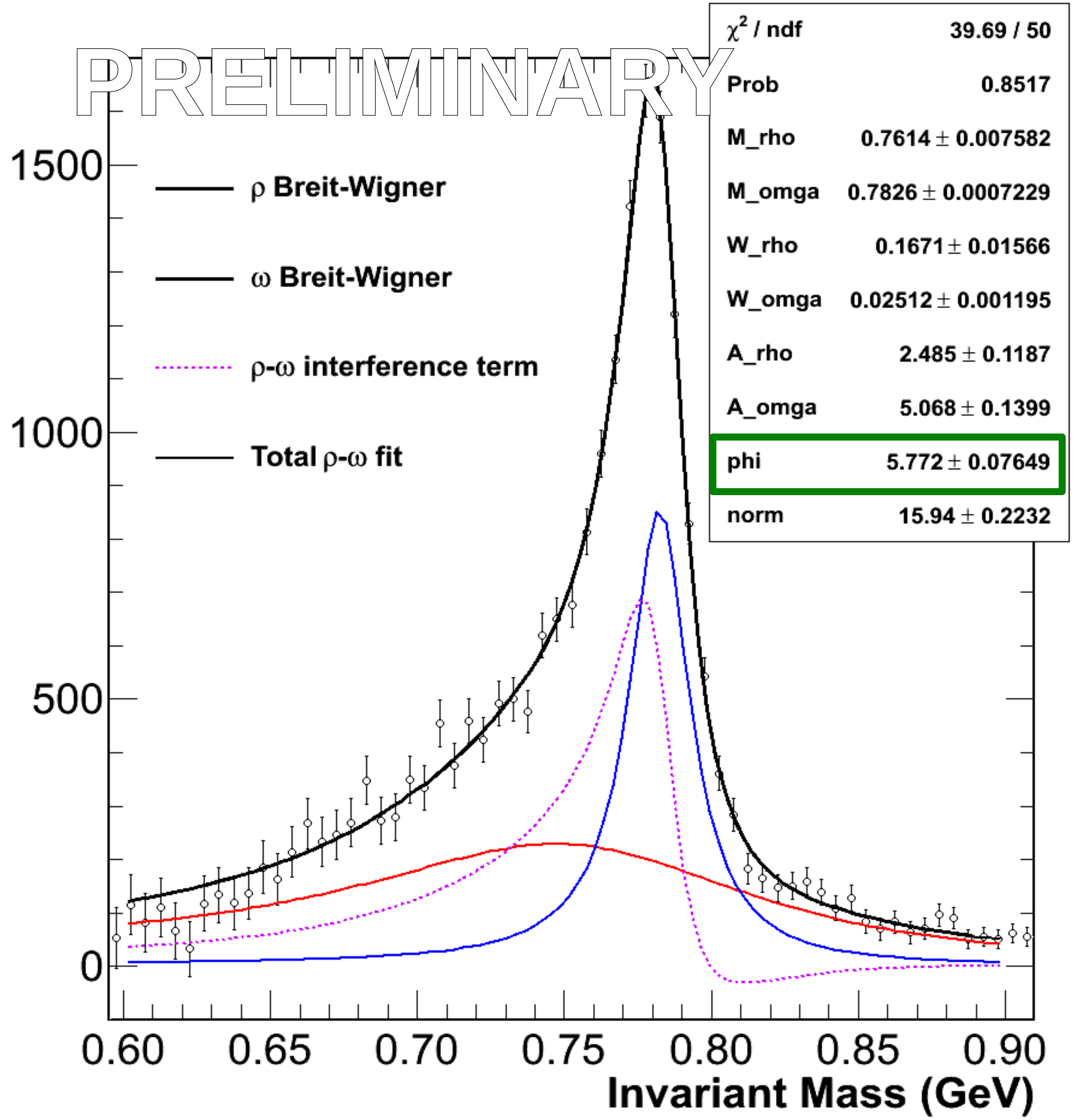


Fit Results (Interfering)

- Fit results much better with an interfering Breit-Wigner.
  - χ^2 /ndf ~ 0.8
  - ρ mass and width consistent with pdg values.
- Interference phase of

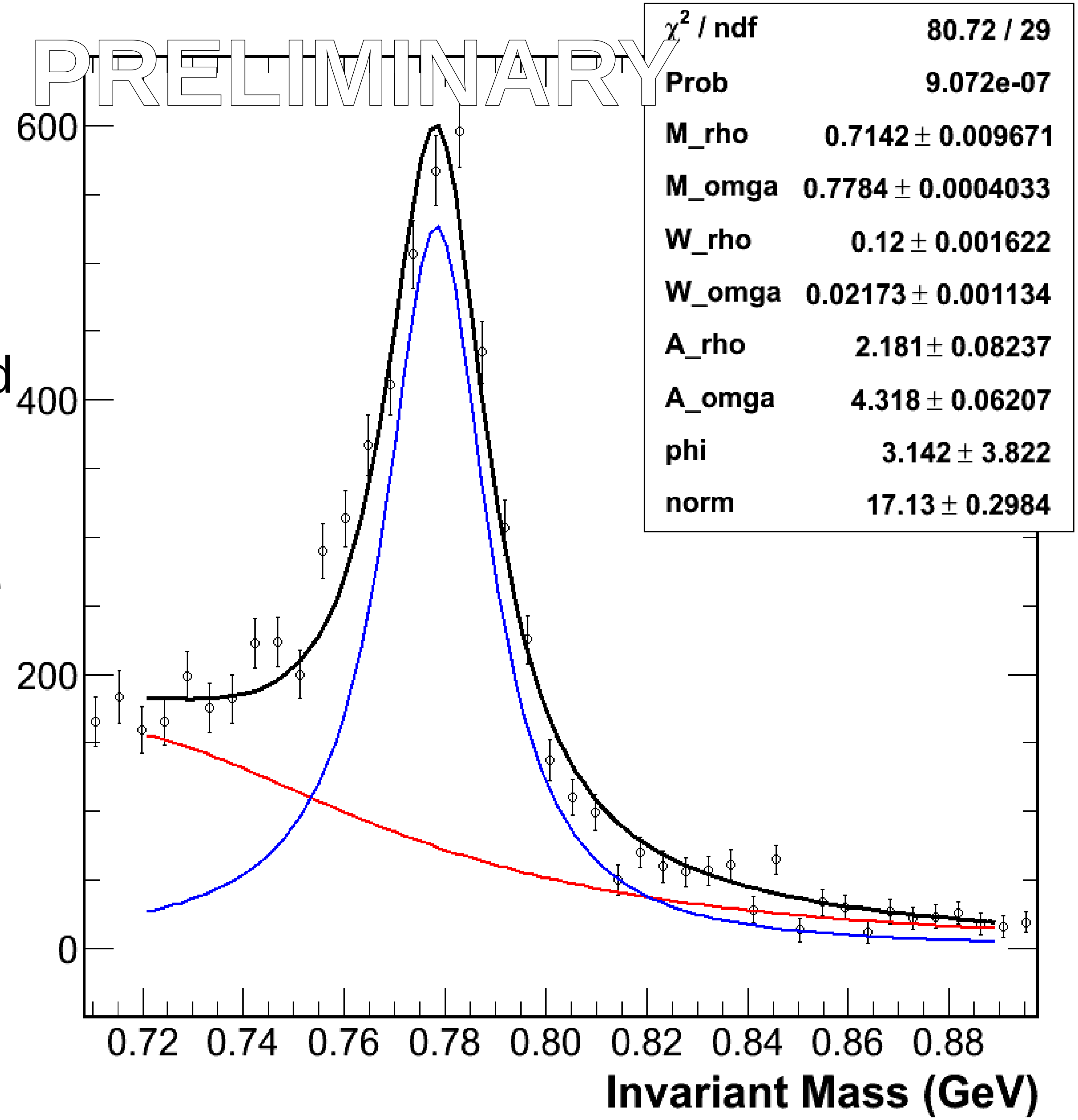
  5.772 +/- 0.076

  1.837π +/- 0.002π



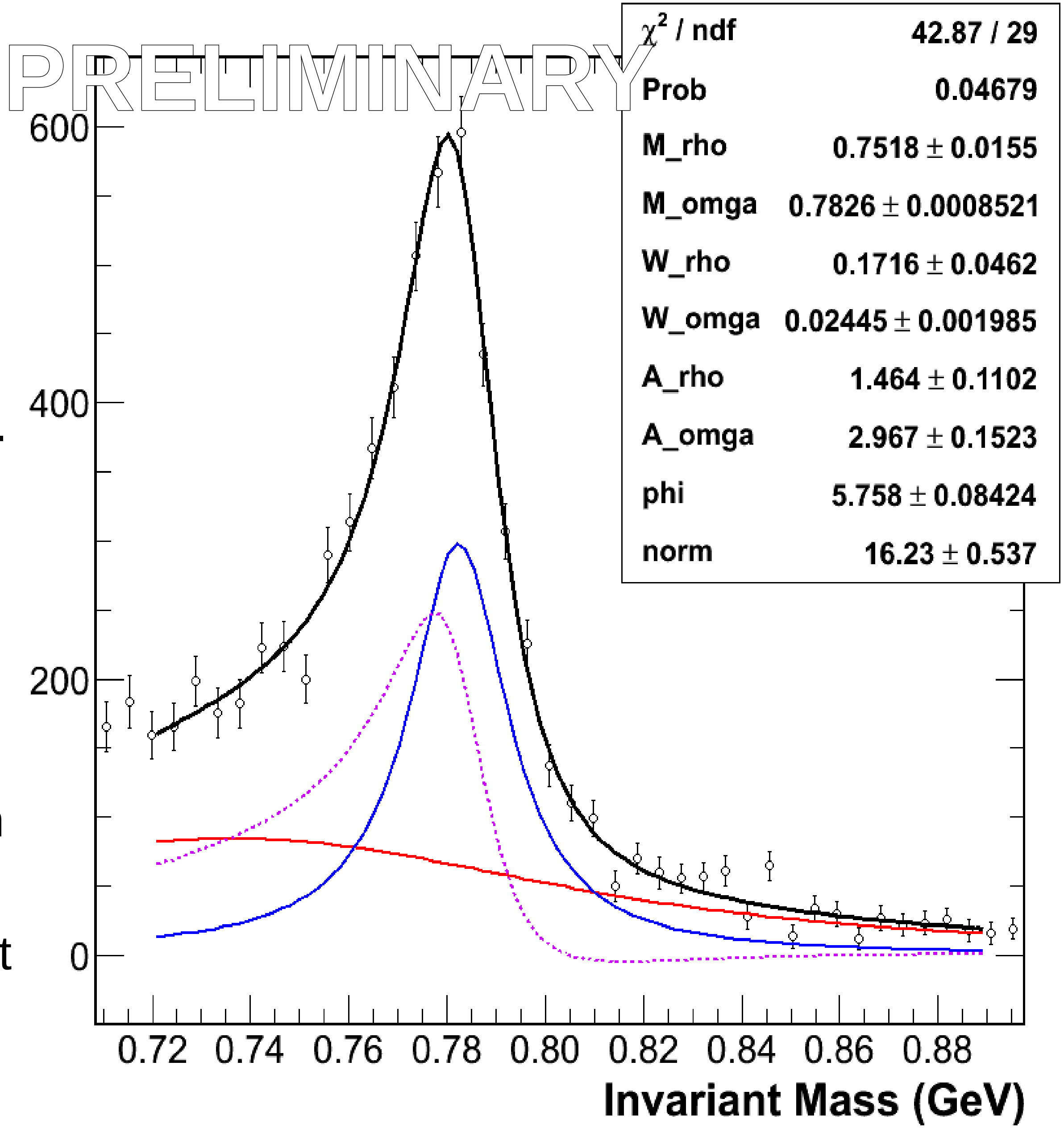
Alternate Subtraction / Fit (non-interfering)

- Subtraction of uncorrelated lepton pairs and MC background.
- Tighter fit range to exclude low mass backgrounds.
  - χ^2 /ndf ~ 2.8
  - ρ mass is 50 MeV low
  - ρ width is 30 MeV too small



Alternate Subtraction / Fit (Interfering)

- Subtraction of uncorrelated lepton pairs and MC background.
- Tighter fit range to exclude low mass backgrounds.
- Fit is better / reasonable
  - χ^2/ndf ~ 1.5
  - ρ mass is low, width is within errors.
  - Interference phase consistent with alternate method of background subtraction.

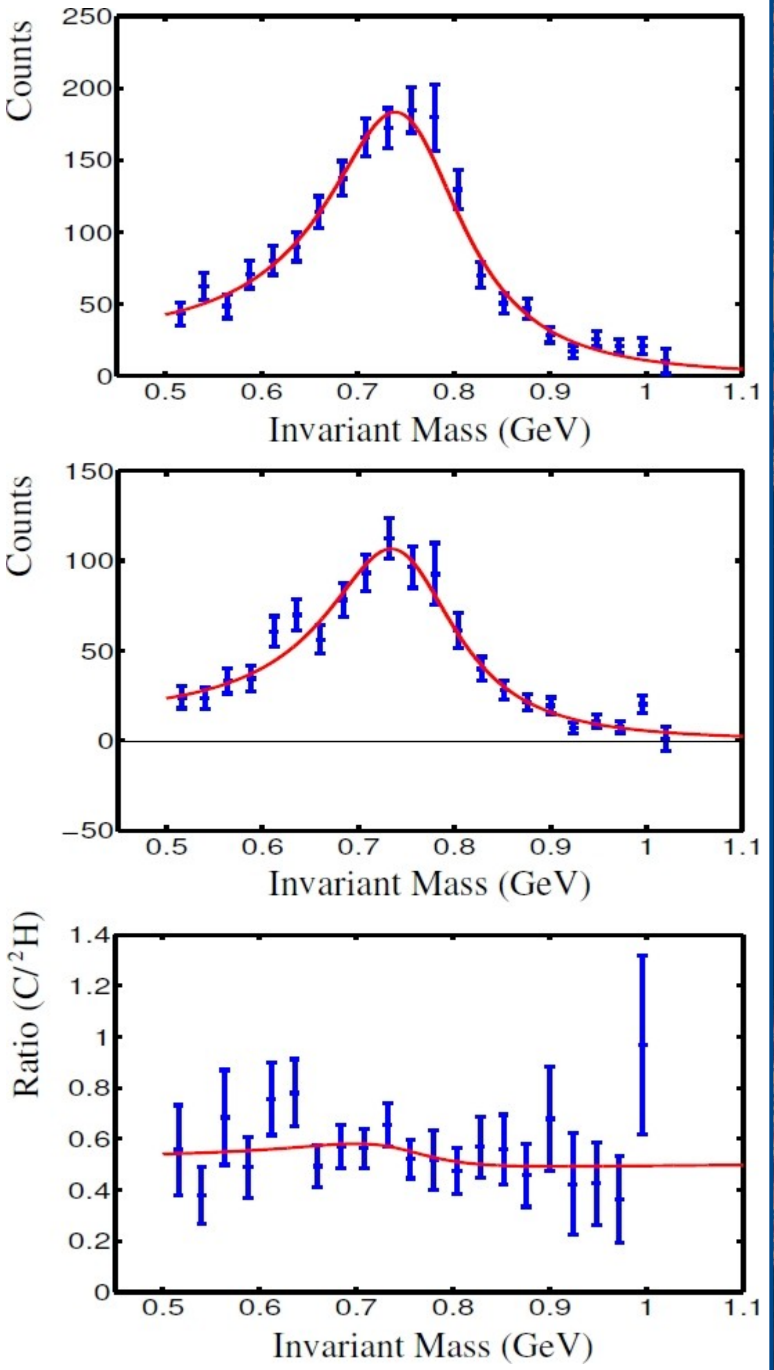


Conclusion

- ρ and ω in-medium publications have produced conflicting results.
- The ρ and ω have been studied in experiment g12 at JLab; photoproduced off of Hydrogen and reconstructed via the dileptonic decay channel to eliminate FSIs.
- When allowed to interfere, a good fit is obtained to the ρ-ω mass spectrum, giving a preliminary interference phase (Φ) of 5.772 +/- 0.076 (stat) radians.

- A number of studies have looked for medium modification effects in the ρ and ω, with somewhat conflicting results:

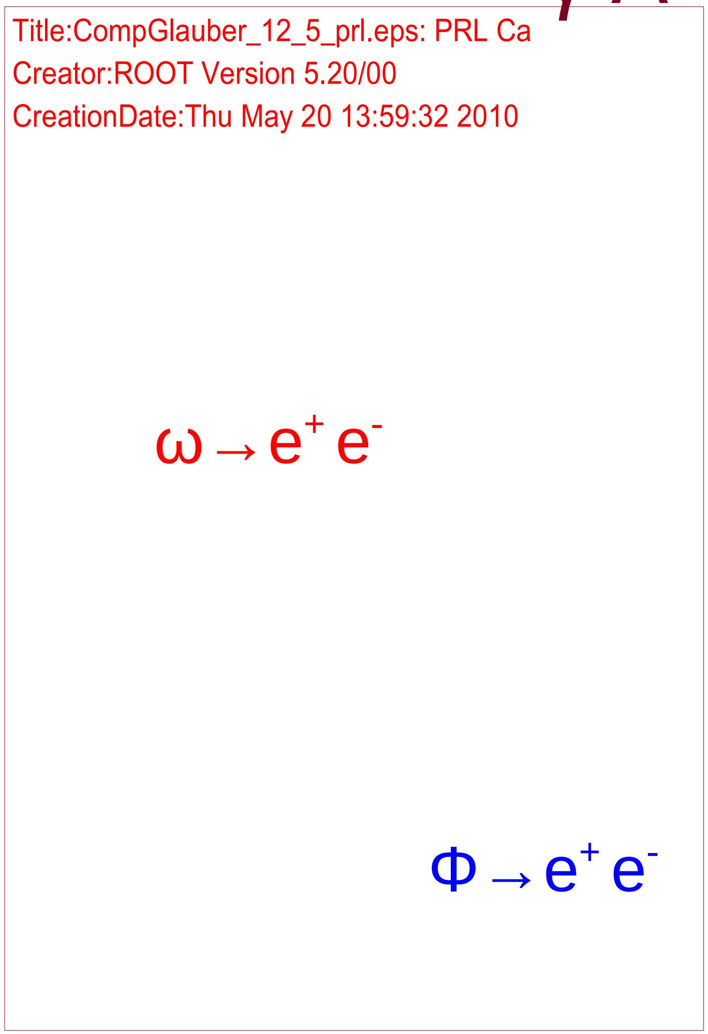
- ρ studies:
  - NA45 / CERES-CERN -- Width broadening
  - NA60 / CERN-SPS -- Width broadening
  - KEK-PS – Mass shift
  - JLAB / g7a – No change to mass or width
- ω studies:
  - KEK-PS -- Mass Shift
  - CBELSA / TAPS – Inconclusive.
  - JLAB / g7a – Large width broadening through absorption



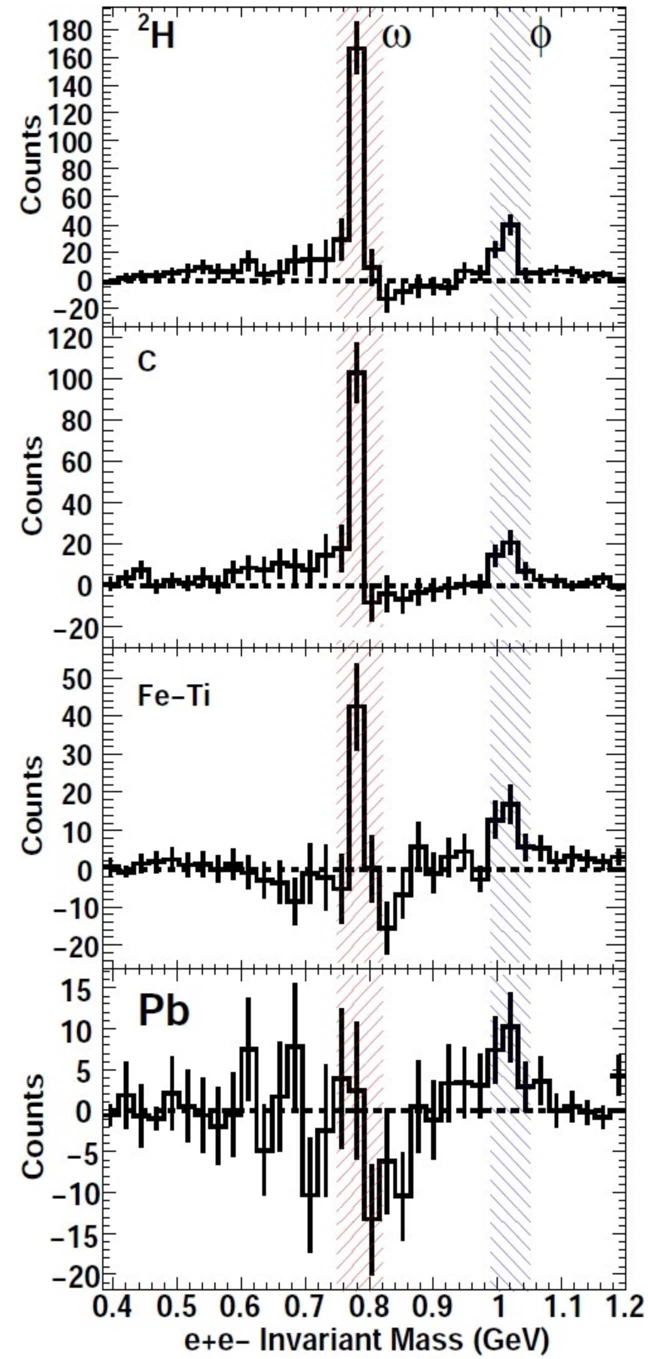
Nasseripour *et al*, Phys. Rev. Lett. **99** 2007

ω Absorption at Jefferson Lab (Experiment g7a)

$\gamma A \rightarrow e^+ e^- (X)$



- Mass “dip” after ω-peak and calculated transparency significantly less than predicted or previously measured.
    - Can ρ-ω interference account for this?
    - High statistics analysis needed on the elementary production channel.



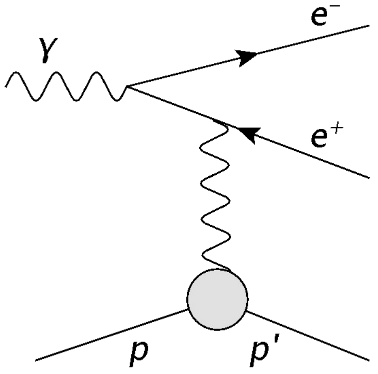
Wood *et al*, Phys. Rev. Lett. **105** 2010

2^{nd} Order Born Corrections

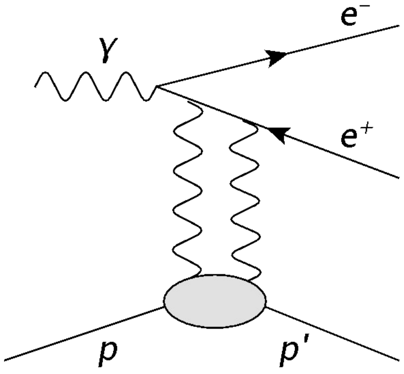
- In leptonic pair photoproduction, the 2^{nd} order Born contributions can be accessed through asymmetric detector acceptance between electrons and positrons.

- $N_+(\delta)$ {or $N_-(\delta)$ } is the rate of positrons {or electrons} with identical and opposite angle of the electron pair, but have an excess momentum of δ.

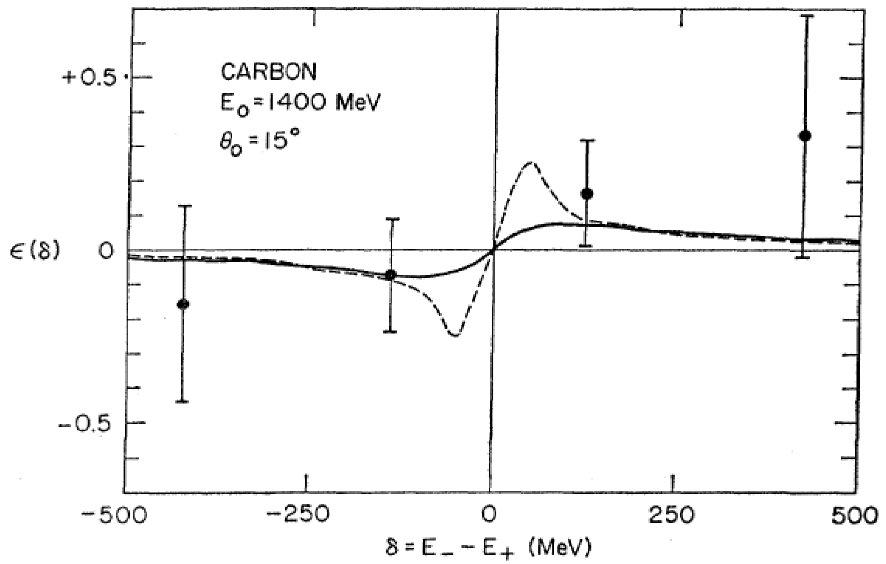
$$\epsilon(\delta) = \frac{N_+(\delta) - N_-(\delta)}{N_+(\delta) + N_-(\delta)}$$



First Order



Second Order



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