Plans for a Measurement of Charged and Neutral Pion Polarizabilities with GlueX

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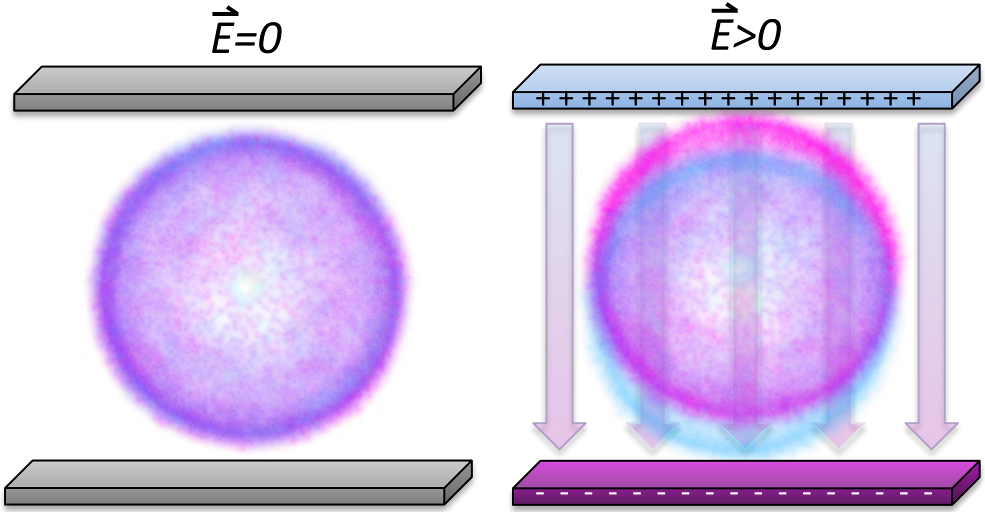
Outline

- Theory of Pion Polarizability
- Experimental Approach
- GlueX Experiment
- Charged Pion Analysis
- Charged Pion Sensitivity
- Neutral Pion Past Measurements
- GlueX and the Neutral Pion
- Neutral Pion Sensitivity
- Summary and Outlook

Classical View: Electromagnetic Polarizability

- Polarizability: Ease with which an external field may induce a dipole moment in a particle
- Property which reflects nature of internal structure of particle



$$\vec{p} = -\alpha\vec{E}$$

$$\vec{\mu} = \beta\vec{H}$$

Hadrons are Stiff

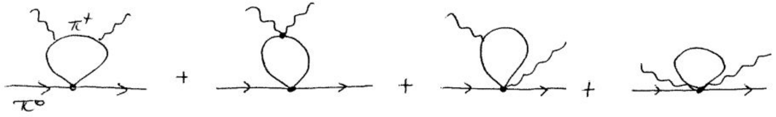
- Proton polarizability can be measured with Compton scattering: $\gamma p \longrightarrow \gamma p$
- $\alpha = 12 \text{x} 10^{-4}$ fm^3
- Atomic hydrogen, α = 4.5 atomic units
- Atomic unit of polarizability = $1.5 \text{x} 10^{14}$ fm^3

Theoretical Approach 1: Chiral Perturbation Theory

Pion polarizability is a fundamental prediction of Chiral Perturbation Theory

Neutral Pion

$$\alpha_{\pi^0} + \beta_{\pi^0} = 0$$
$$\alpha_{\pi^0} - \beta_{\pi^0} = -\frac{\alpha}{48\pi^2 M_\pi F_\pi^2} \simeq -1.1 \times 10^{-4}\ \mathrm{fm}^3$$



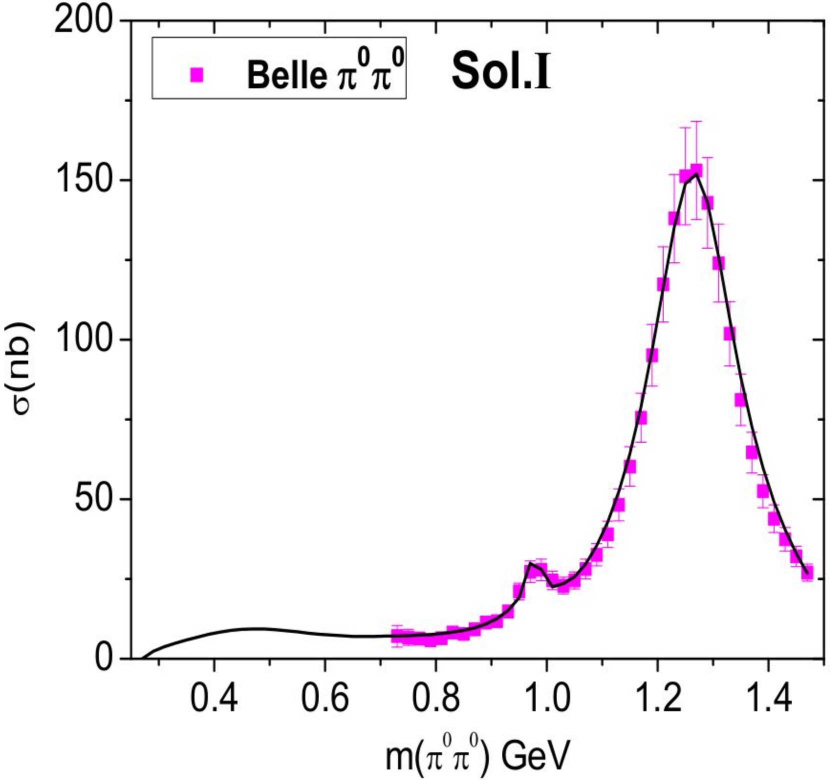
Charged Pion

$$\alpha_{\pi^+} = -\beta_{\pi^+} = (2.78 \pm 0.1) \times 10^{-4}\ \mathrm{fm}^3$$

- α = electric polarizability, β = magnetic polarizability
- Same physics for charged and neutral polarizabilities: pions are the Goldstone bosons of the spontaneous breaking of chiral symmetry
- Ideally: measure cross section for Compton scattering off the pion, γπ→γπ, in the limit of zero photon energy. Not practical.

Theoretical Approach 2: Dispersion Relations

- Not a prediction of cross sections, but a constraint on how cross section must evolve as a function of $W_{\pi\pi}$
- Theoretical interest in better measurements at all values of $W_{\pi\pi}$

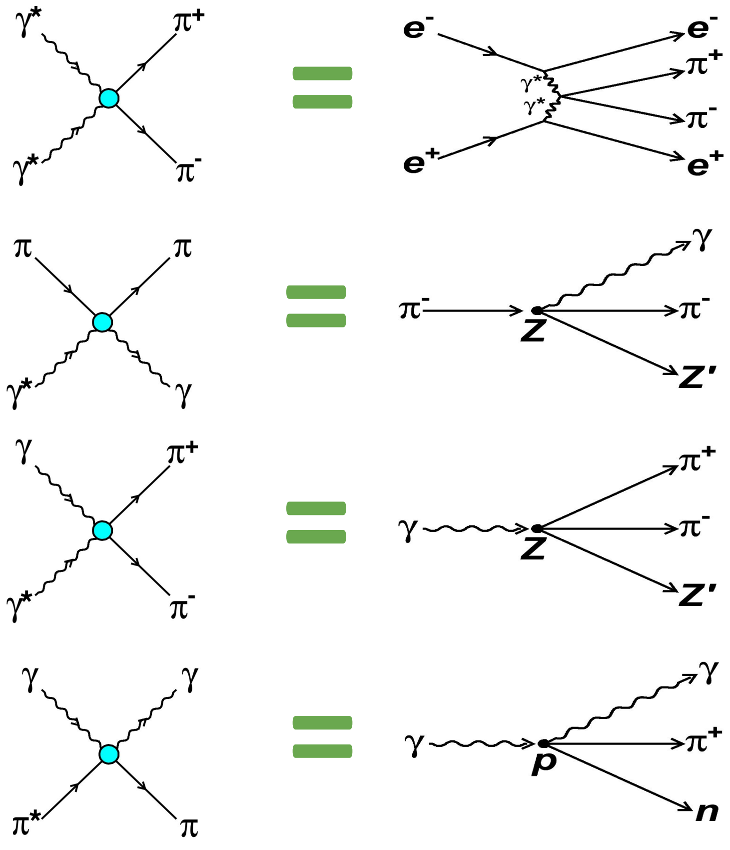


Interplay between two theoretical approaches

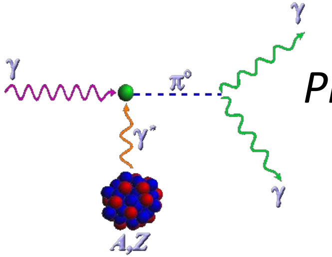
- CPT is perburbative: expansion in powers of momentum
- Convergence is challenged at higher $W_{\pi\pi}$
- Dispersion Relations provide bridge between low and high $W_{\pi\pi}$
- CPT provides connection between polarizability and spontaneous chiral symmetry breaking

Experimental Access

Light by light scattering
(by crossing symmetry)



PLUTO
DM1
DM2
MARK-II



Primakoff effect

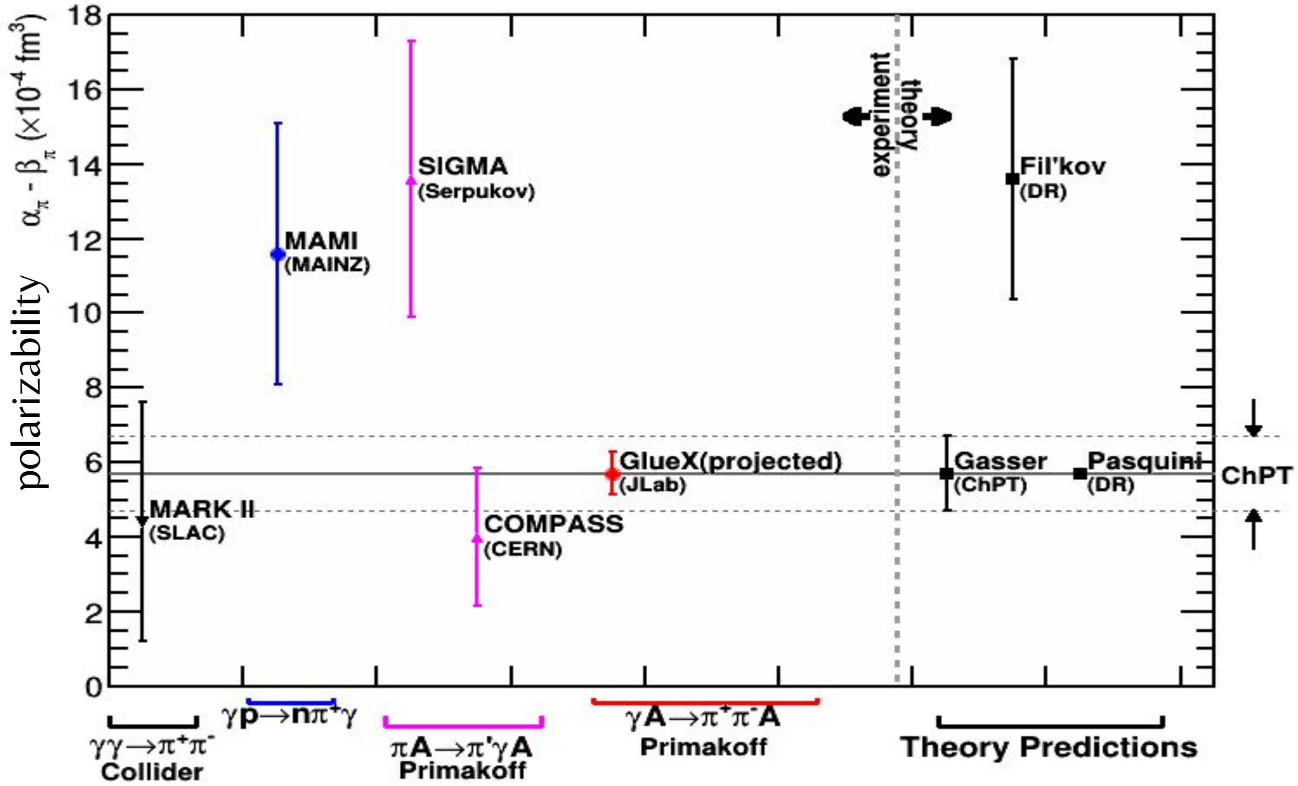
SIGMA
COMPASS

GlueX

Radiative pion photo-production

MAMI
PACHRA

EXPERIMENTAL/THEORETICAL LANDSCAPE, CHARGED PION



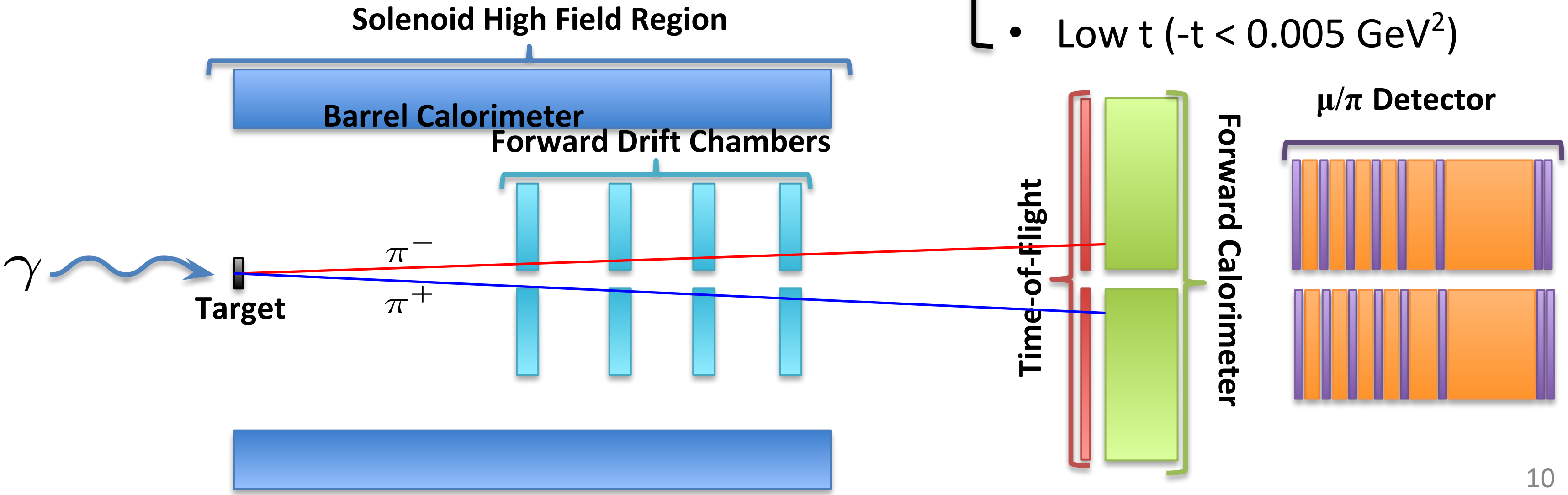
GlueX Experimental Setup

$$\gamma\gamma \xrightarrow[Z(\gamma,\pi^+\pi^-)Z]{} \pi^+\pi^-$$ Signal reaction

$$\gamma\gamma \xrightarrow[Z(\gamma,\mu^+\mu^-)Z]{} \mu^+\mu^-$$ Normalization

$$\gamma\gamma \xrightarrow[Z(\gamma,\pi^\circ)Z]{} \pi^o$$ Polarization and Normalization

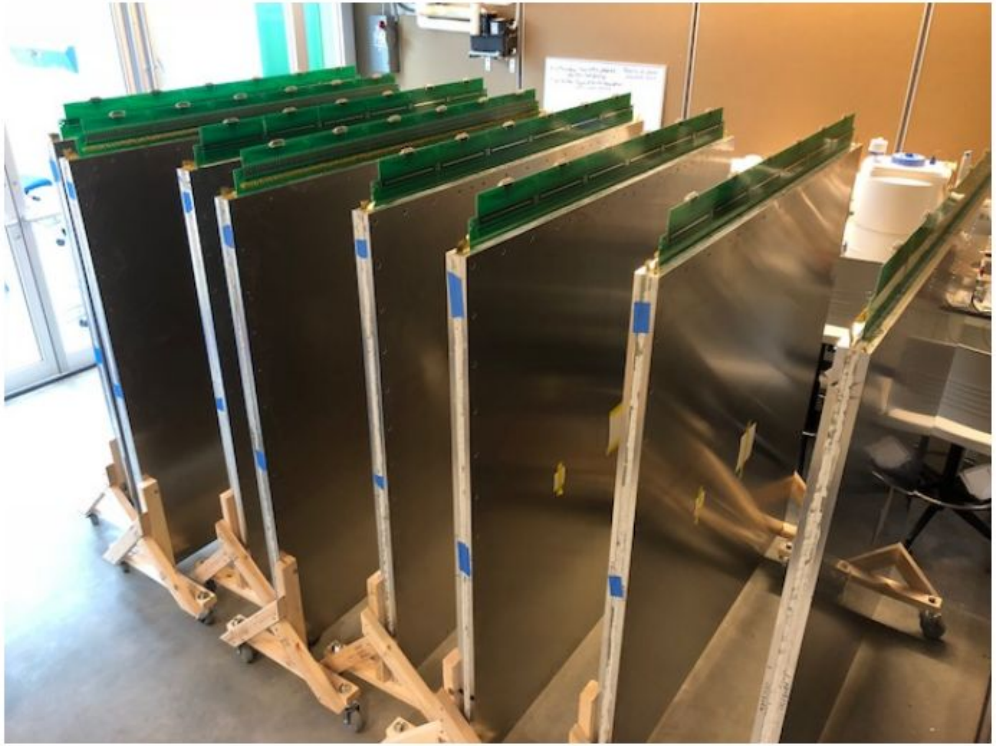
- All occur via the Primakoff effect (interaction with the Coulomb field of nucleus)
- All result in very forward going particles
- Low t ($-t < 0.005$ GeV^2)



Proposed Experimental Conditions

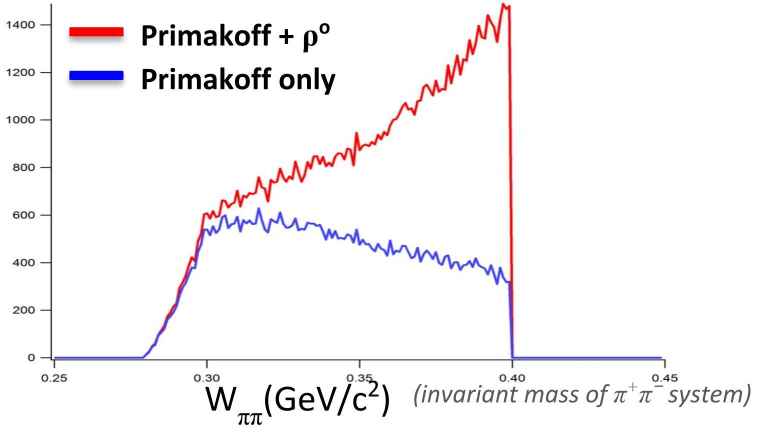
Configuration	**Nominal GlueX**	**Charged Pion Polarizability**
Coherent Peak Energy	8.4-9.0 GeV	5.5-6.0 GeV
Peak Polarization	44%	72%
Target Position	65 cm	1 cm
Target Material, Length	LH2, 30 cm	Pb-208, 0.028 cm
Muon Detector	none	present

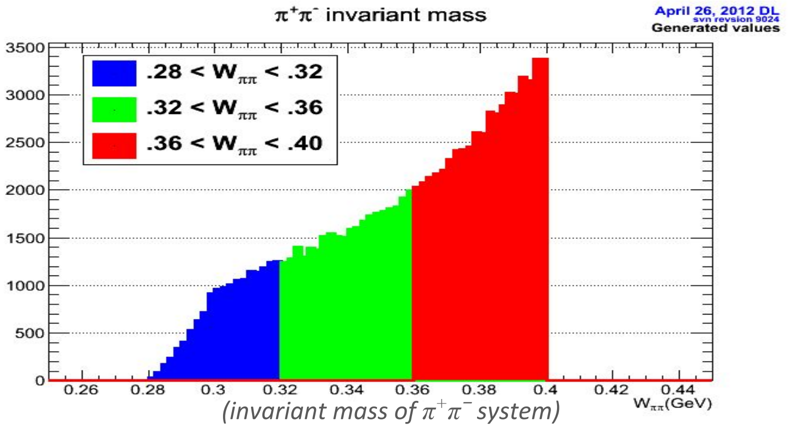
Charged pion polarizability at JLab GlueX

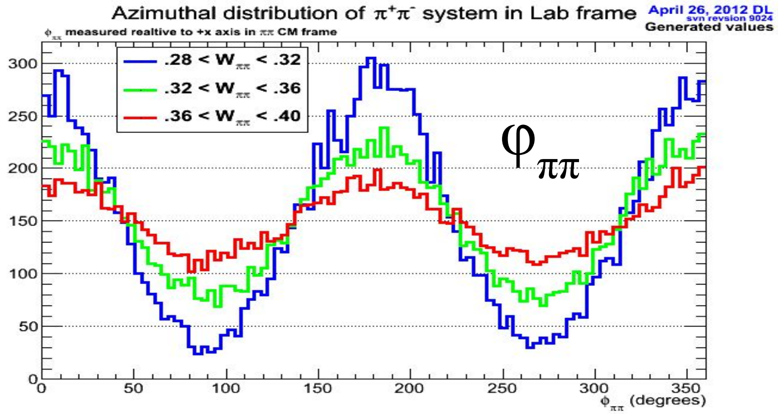


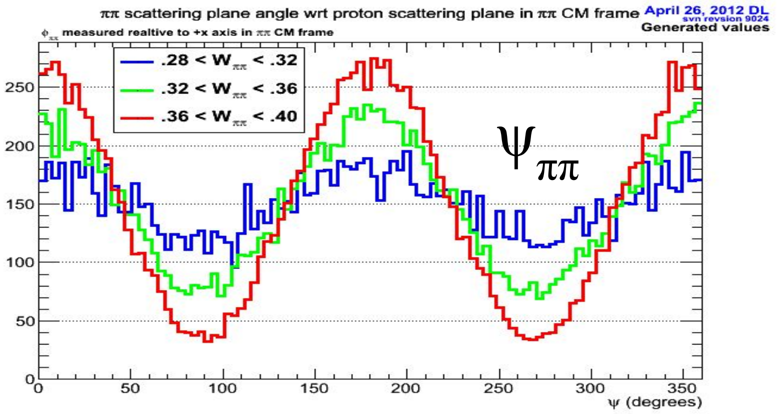
Construction of muon chambers at UMass

Linear Polarization of incident photon beam helps distinguish Charged Pion Primakoff from coherent ρ^o production





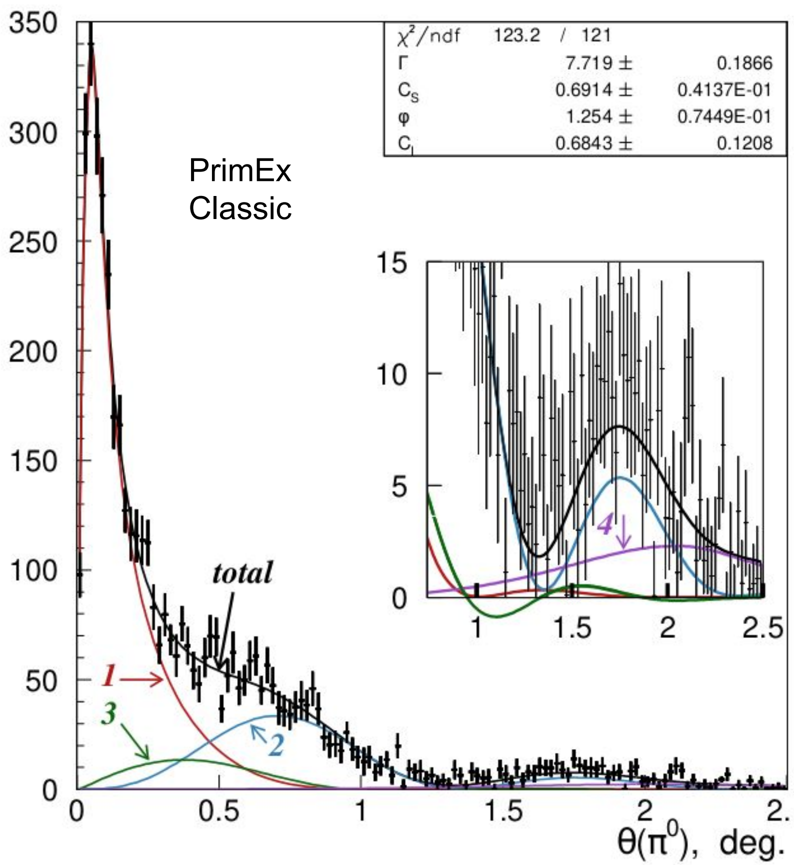




** all plots are of generated values*

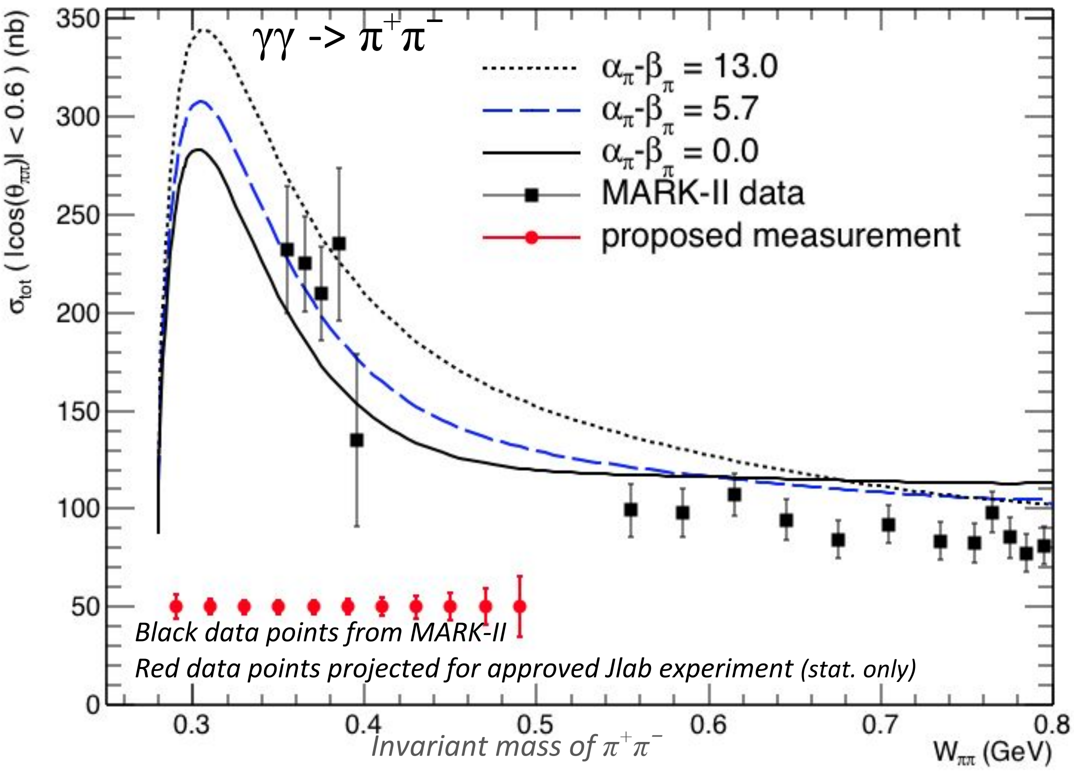
Beam Flux Determination

- 1. Pair spectrometer: standard GlueX method
- 2. Primakoff production of exclusive single neutral pion
  - Leverage PrimEx result from Hall B: 1.5% total error
  - For Hall D, different systematics: 3 to 4%
- 3. Muon pair production (Bethe-Heitler)
  - Main normalization channel for CPP
  - Additional systematics from using charged channel to normalize neutral channel



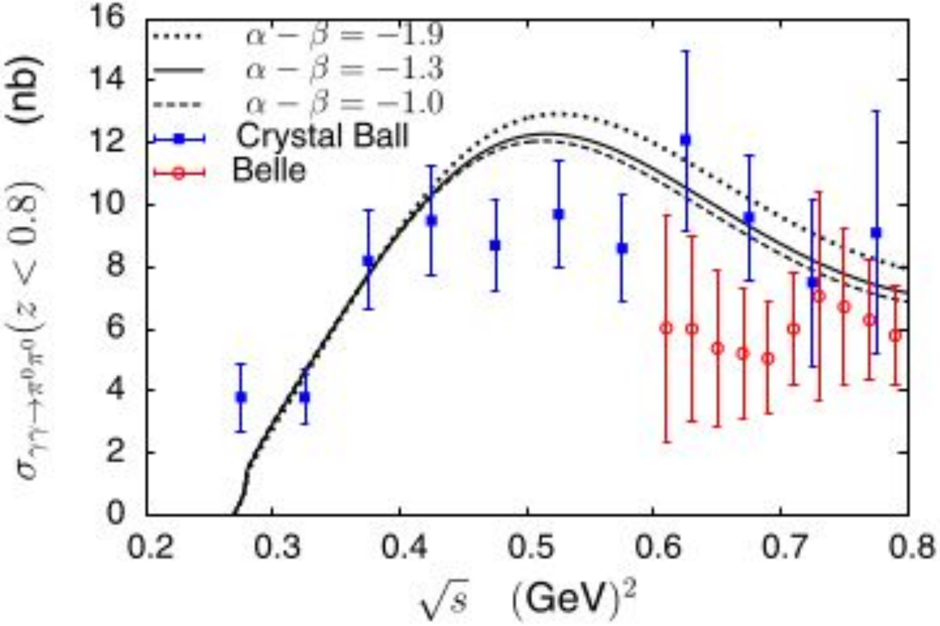
Sensitivity: 10% on α-β

Curves from figure 5. from Pasquini et al. Phys. Rev. C 77, 065211 (2008)



Neutral Pion Polarizability Past Measurements: $\gamma\gamma$ Collisions at e^+e^- Colliders

- Crystal Ball at DESY (DORIS II)
  - Early 1990's
  - Only data for $W_{\pi\pi}$ < 0.6 GeV
- BELLE at KEK (KEKB)
  - 2008-9
  - 0.6 < $W_{\pi\pi}$ < 4.0 GeV
- Cross section at low $W_{\pi\pi}$ not well known



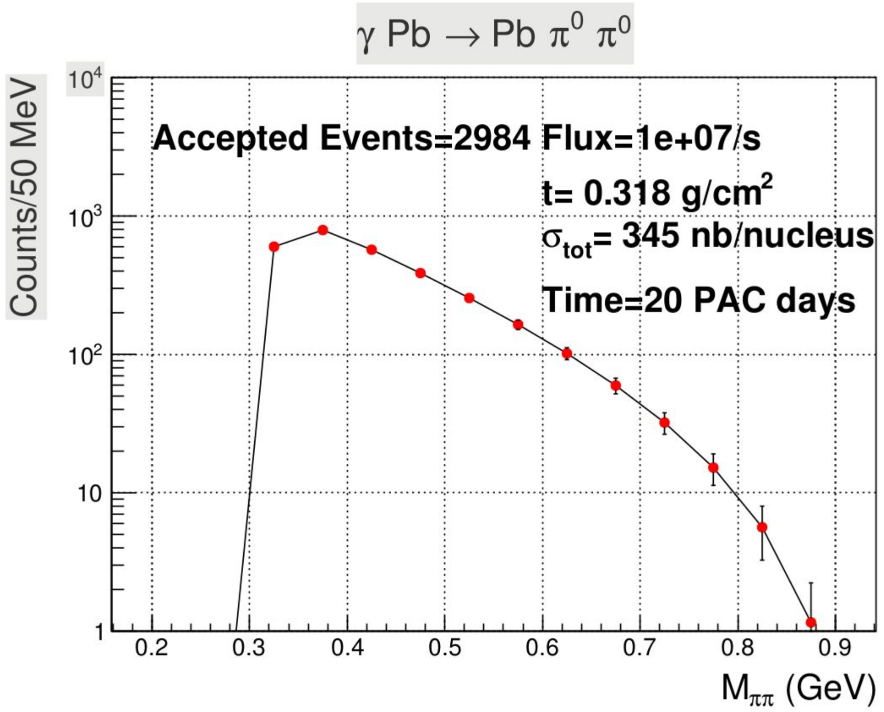
Neutral Pion Polarizability: Experimental Considerations

- Similar to Charged Pion Polarizability Experiment (CPP)
  - High Z target (lead) gives factor of 6,700 in cross section (Z^2 dependence)
    - Also production vertex constraint
  - Lower beam energy (6 GeV) gives better acceptance
    - At low $W_{\pi\pi}$ pions produced in forward direction
  - Need for an accurate normalization scheme
  - **Conclusion: run at the same time**
- Some contrasts
  - Charged mode has ρ^0 background ($\rho^0 \rightarrow \pi^+\pi^-$), no $\rho^0 \rightarrow \pi^0\pi^0$ background
  - Neutral mode has no $\mu^+\mu^-$ background
  - Neutral mode gets extra p_t boost from $\gamma\gamma$ decay
- Neutral pion polarizability has never been measured

Expected Signal

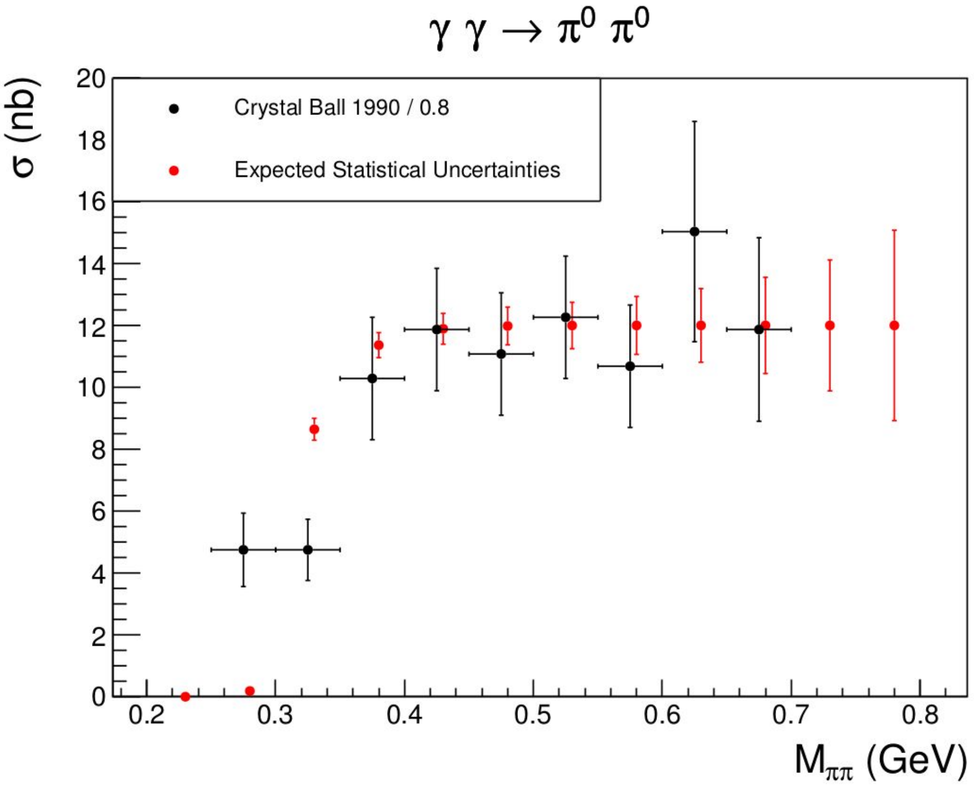
$$\frac{d^2\sigma}{d\Omega_{\pi\pi} dW_{\pi\pi}} = \frac{2\alpha Z^2}{\pi^2} \frac{E_\gamma^4 \beta^2}{W_{\pi\pi}} \frac{\sin^2\theta_{\pi\pi}}{Q^4} |F(Q^2)|^2 \sigma(\gamma\gamma \to \pi^0\pi^0)(1 + P_\gamma \cos 2\phi_{\pi\pi}).$$

- Normalize cross section to Crystal Ball data
- Use CPP flux, target, running time
- Gives yield with estimated acceptance, perfect resolution
- Total events produced: 2,984



Neutral Pion Polarizability Sensitivity

- Potential significant improvement in the data at low $W_{\pi\pi}$
  - Uncertainties in figure assume no background
- Dai and Pennington (PhysRevD94:116021 (2016)): 1.3% determination of σ ($\gamma\gamma \rightarrow \pi^0\pi^0$) gives $\alpha_\pi - \beta_\pi$ to 10%
- Goal: 4% on σ, 30% on $\alpha_\pi - \beta_\pi$
- Best analysis uses combination of CPT and dispersion relation analysis.
- Cross section measurement as function of $W_{\pi\pi}$ of general theoretical interest



Summary and Outlook

- Well-developed theoretical framework
  - Chance to measure low-energy constants in Chiral Perturbation Theory
  - Important input to dispersion-relation-based approaches
  - Excellent theoretical support
- Well-suited for CEBAF/Hall-D complex
  - Photon beam intensity, energy and polarization; tracking and calorimeters; trigger and data acquisition system
- Charged and Neutral Pion Polarization Measurement Complementarity
  - Similar physics
  - Significant differences in signal and background
  - Compatible experimental considerations; GlueX is general purpose!
- State-of-the-art measurements are anticipated

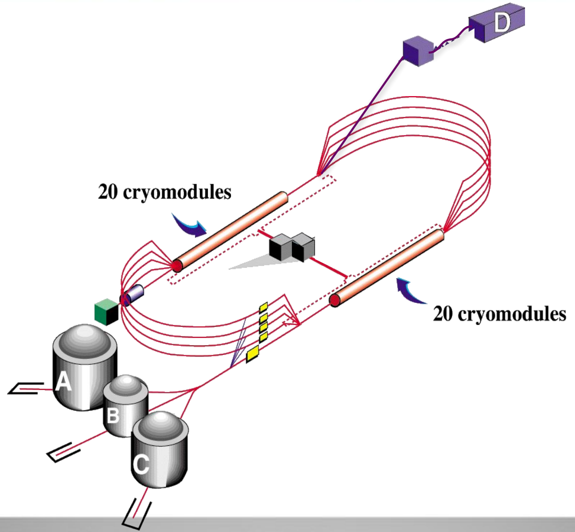
Backups

HALL-D AT JEFFERSON LAB

(HOME OF GLUEX)

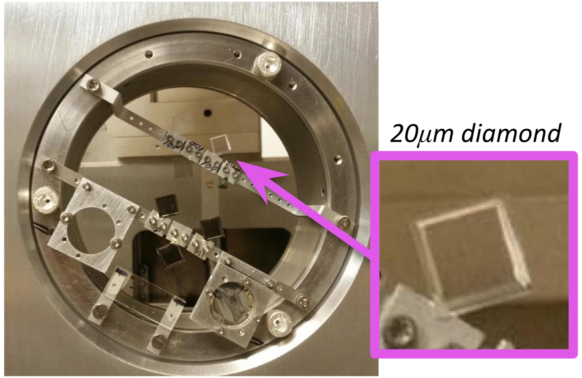
- 12GeV CW(250MHz) electron beam
- Only high energy photons enter Hall-D

Hall-D



Linearly polarized photon beam production

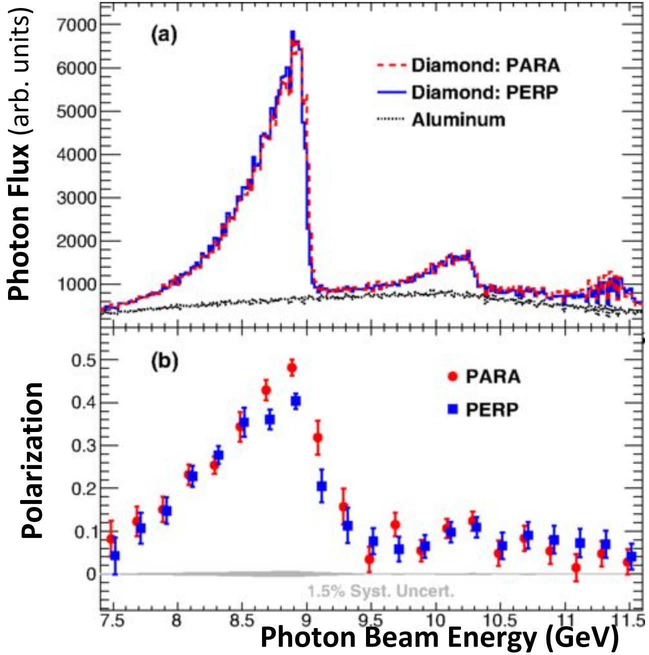
20μm diamond



Radiators on goniometer

	e^- beam	Coherent peak
GlueX	11.7 GeV	9 GeV
CPP	11.7 GeV	6 GeV

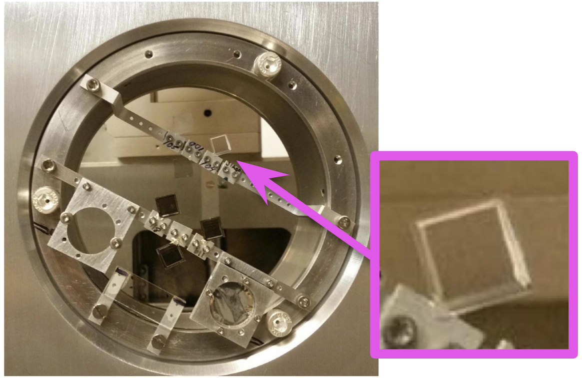
PHYSICAL REVIEW C **95**, 042201(R) (2017)



(a) Photon beam intensity versus energy as measured by the pair spectrometer (not corrected for instrumental acceptance)

(b) Photon beam polarization as a function of beam energy, as measured by the triplet polarimeter, with data points offset horizontally by ±0.015 GeV for clarity.

LINEARLY POLARIZED PHOTON BEAM PRODUCTION



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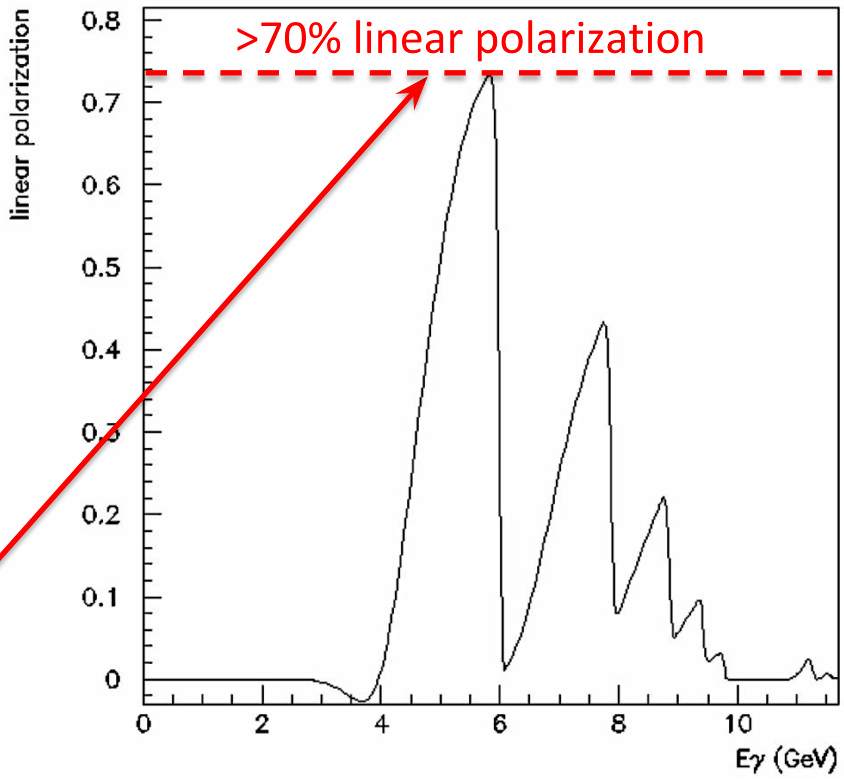


Detector Resolution I

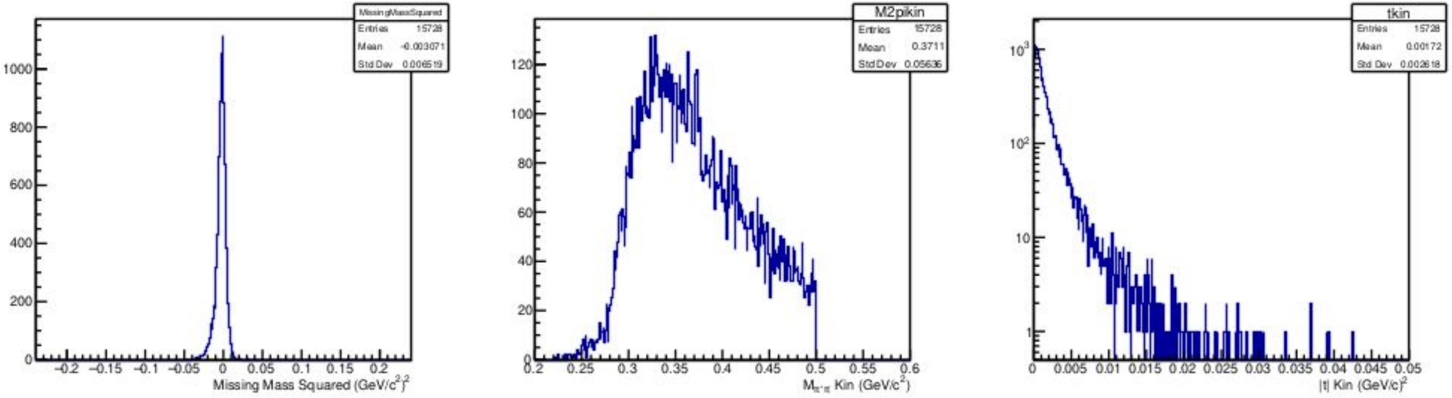


Figure 8: Left: Missing mass distribution minus the mass of the recoil nucleus. Center: Kinematically fit 2π mass distribution. Right: Kinematically fit -t distribution.

- Starting from produced distribution, full GEANT Monte Carlo simulation
- Standard smearing
- Full detector reconstruction
- Kinematic fitting

Detector Resolution II

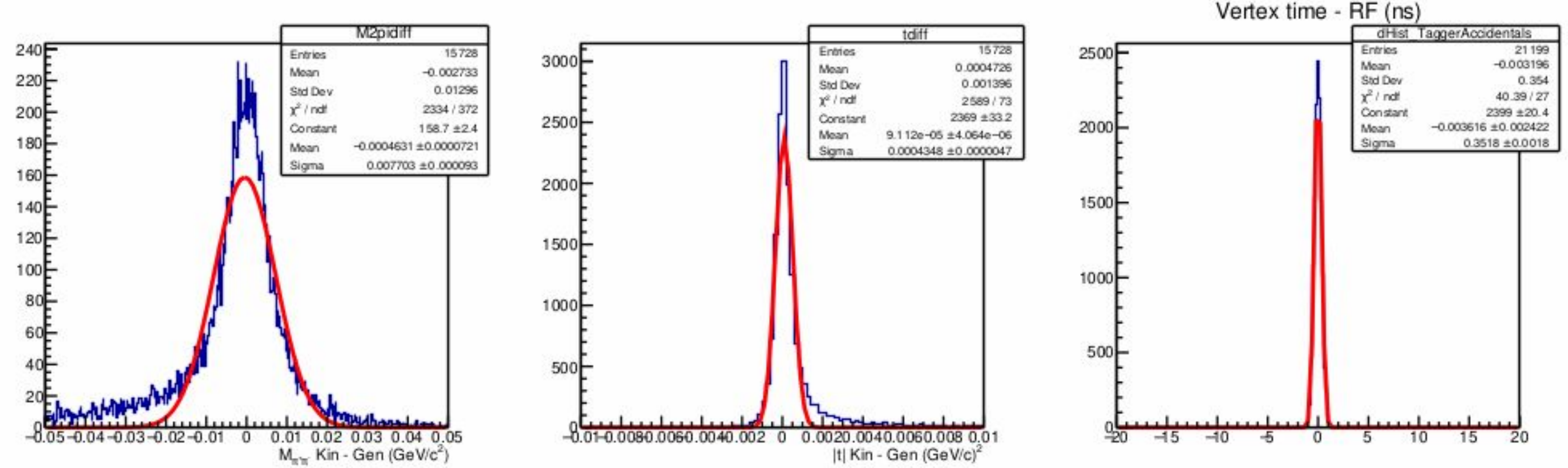
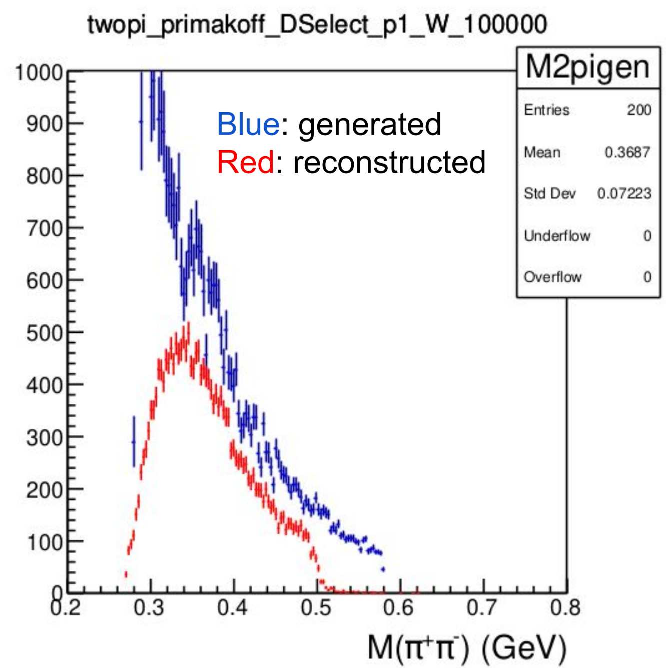
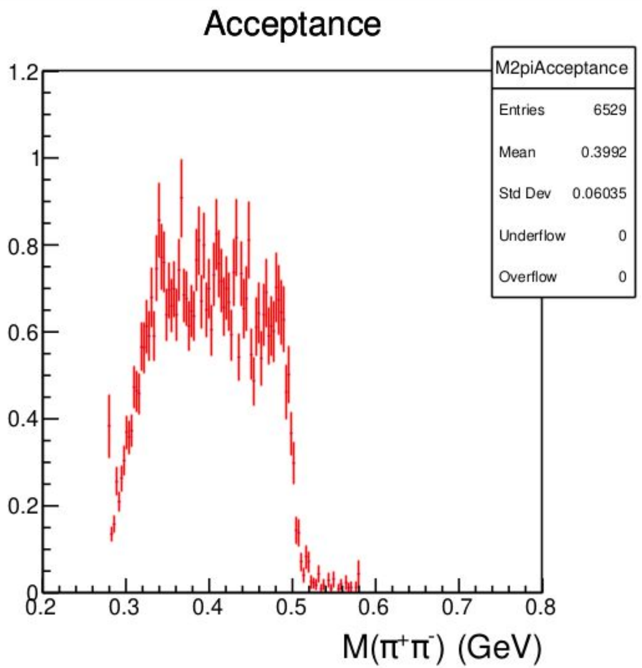


Figure 10: Left: Difference between kinematically fit and generated 2π mass. The central 2π-mass σ is about 8 MeV. Center: Difference between kinematically fit and generated -t. Right: Timing resolution relative to the accelerator RF signal is about 0.35 ns.

Trigger and Acceptance

- Trigger: energy in the FCAL, 4 photons with summed energy nearly the beam energy
- Acceptance: about 60%, uniform in $W_{\pi\pi}$





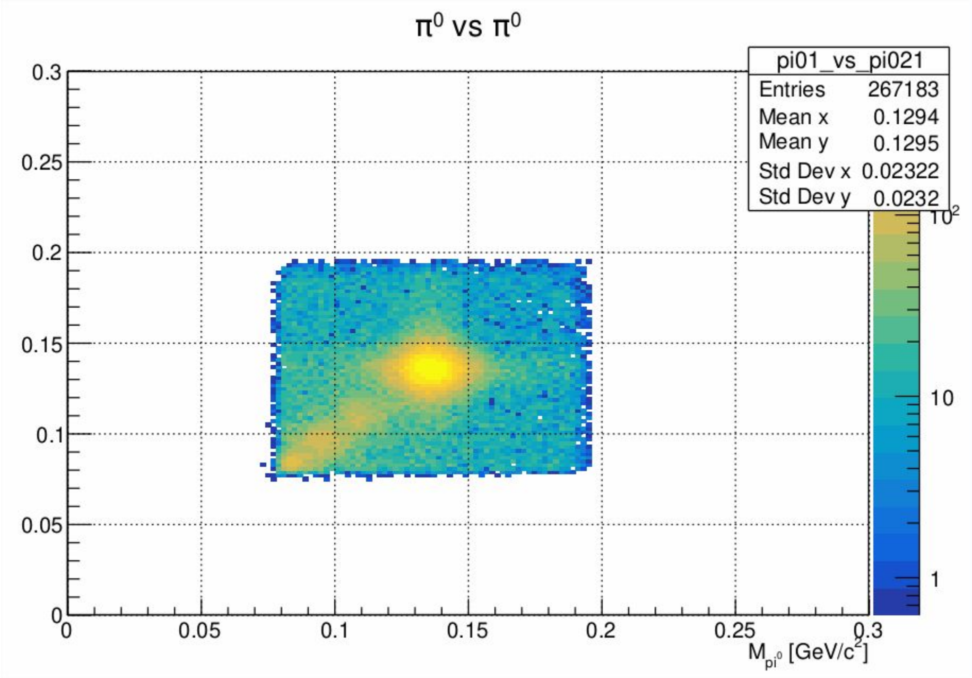
Physics Backgrounds I: Nuclear Coherent

- No $\rho^0 \rightarrow \pi^0\pi^0$ background
- $f_0(980) \rightarrow \pi^0\pi^0$: full width Γ = 10 - 100 MeV
  - Use $m_{\pi\pi}$ cut
  - Problem: eliminates Primakoff production of $f_0(980)$
- $f_0(500) \rightarrow \pi^0\pi^0$: full width Γ = 400 - 700 MeV
  - Use t cut, a la PrimEx-π^0
- All nuclear coherent processes: π^0's suppressed by absorption in heavy nuclear target
  - Seen in PrimEx-π^0, should be even better for 2 π^0's

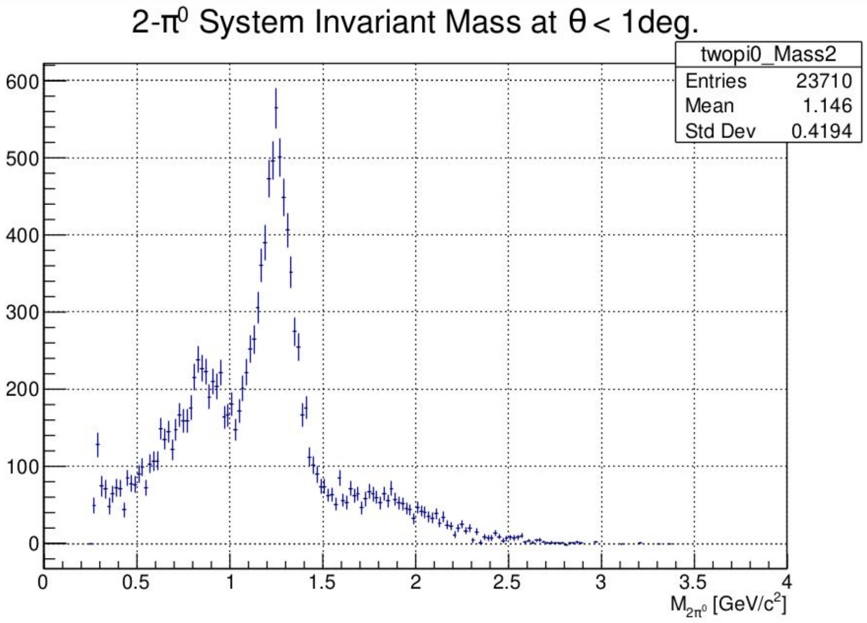
Physics Backgrounds II: Nuclear Incoherent, Inelastic

- Nuclear coherent η production: $\eta \rightarrow \pi^0\pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma(\gamma\gamma)$
  - Inelastic, veto on extra photons
- $\gamma N \rightarrow N\pi^0\pi^0$
  - Incoherent, should be small, peaks at high $m_{\pi\pi}$

Analysis of GlueX Data Already Taken



- 2017 data, hydrogen target (extended in z)
- Four photons, proton assumed missing



- $f_2(1270)$ visible
- Structure just below not understood
- Primakoff production suffers from Z = 1