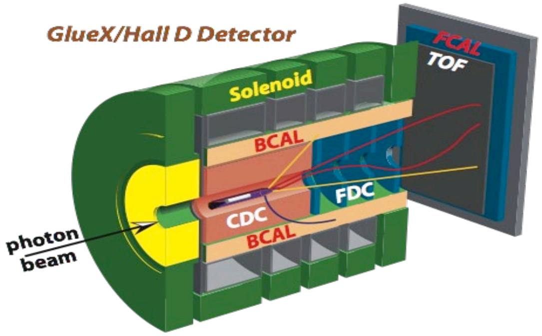


Jefferson Lab

Photoproduction of vector mesons off nuclei

A. Somov (JLab)

A. Gasparyan (NC A&T), L. Gan (UNCW), S. Gevorkyan (JINR), I. Larin (UMas, ITEP)

and GlueX Collaboration

- Physics motivation
- Theoretical predictions
- Reconstruction of vector mesons
- Projected errors
- Run conditions and beam request

PAC45 Response

PR12-17-010

Scientific Rating: N/A

Recommendation: deferred

Title: Photoproduction of vector mesons on nuclei with GlueX

Spokespersons: Liping Gan, Ashot Gasparian, Ilya Larin, Alexander Somov (Contact), Sergey Gevorkyan

Motivation: The proposed measurements aim to study the photoproduction of light vector mesons on nuclear targets with photon beam energies between 6 and 12 GeV using the GlueX detector. The primary focus is on the first extraction of the cross-section of longitudinally polarized ω on nucleons $\sigma_L(\omega N)$ from incoherent photoproduction off nuclear targets (C, Si, Sn and Pb). Two methods to access the $\sigma_L(\omega N)$ are proposed: the measurement of nuclear transparency $A_{eff}=\sigma_A/A\sigma_N$ and the spin density matrix element ρ_{00}. The measurements of the nuclear absorption in different nuclei are useful for extracting meson-nucleon cross sections while the use of different beam energies will shed light on the disagreement between earlier experimental results and existing theory predictions and provide additional information on color transparency. The proposed measurements provide a unique opportunity to access $\sigma_L(\omega N)$ and when combined with the already known cross section for transverse polarization $\sigma_T(\omega N)$ would give important information on the dependence of the vector meson – nucleon interaction on the polarization.

Measurement and Feasibility: The proposed experiment would utilize the standard GlueX detector package. The collaboration's extensive experience in reconstructing multi-particle π^0 and photon final states should make reconstruction of the vector mesons straightforward. However, the proposal lacks critical details about the methods that will be used to measure the nuclear transparency and to extract the meson-nucleon cross section. As a result it is not possible to verify the stated systematic errors and confirm the beam time estimates.

Issues: While a first measurement of $\sigma_L(\omega N)$ is compelling, the connection to theoretical models needs to be strengthened. It is not clear from the proposal how the measurement of $\sigma_L(\omega N)$ will aid in the "interpretation of color transparency effects in the electroproduction of vector mesons".

Summary: The PAC considers the proposed measurements and in particular the extraction of $\sigma_L(\omega N)$ interesting and encourages the collaboration to better spell out the experimental technique to be used.

The experimental similarities with the proposal PR12-17-007 must be studied in detail to hopefully overcome their differences and settle on a common beam time request.

Physics Goal

Measure photoproduction cross sections of vector mesons ω, ρ, and ϕ on C, Si, Sn and Pb targets in the energy range of 6-9 GeV with the GlueX detector

- Extract nuclear transparency at different energies
- Extract spin density matrix elements
- Extract cross section σ_L (ω N) with two methods

  - nuclear transparency A_{eff}

  - spin density matrix element ρ^A_{00}

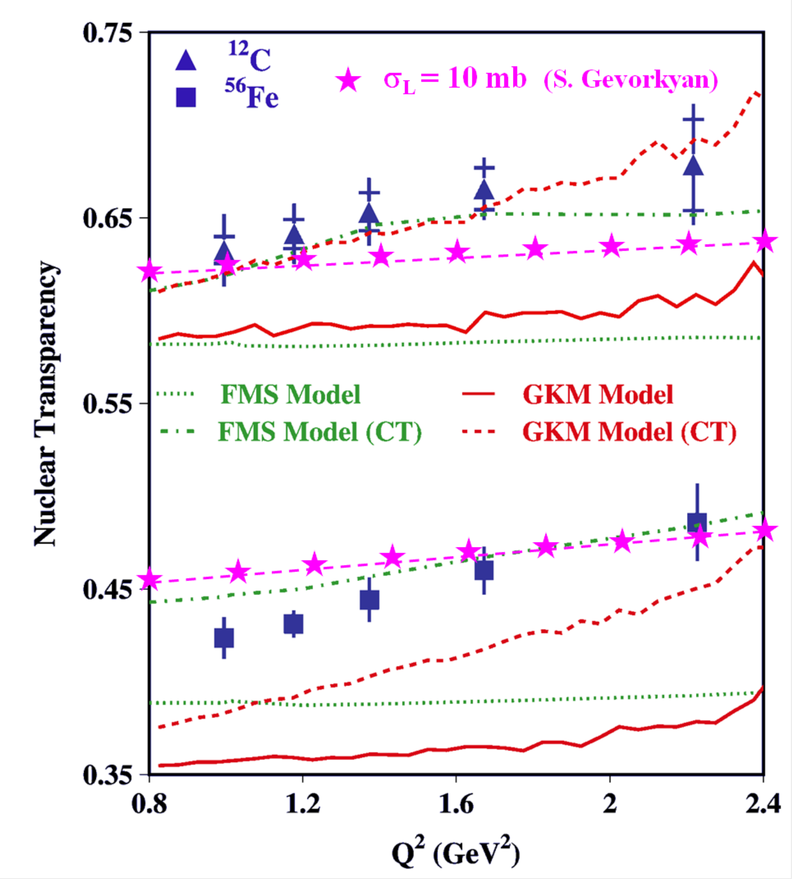
Why is it Important ?

- There are experimental indications that σ_L (VN) $< \sigma_T$ (VN), but there have been no direct measurements of σ_L (VN) so far. Measurements of σ_L are important for the interpretation of the color transparency in vector meson electroproduction and comparison between different theoretical approaches

- Disagreement between existing experimental data and theoretical predictions for nuclear transparency

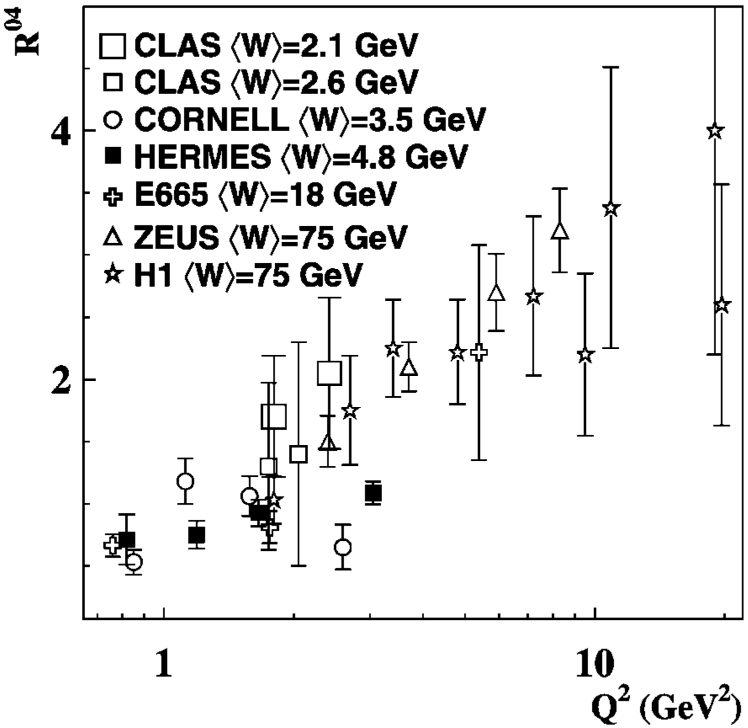
Effect of σ_L (VN) on Color Transparency

CT measurements at CLAS



Nuclei become more transparent at large Q^2
(color transparency effect)

Q^2 dependence of the longitudinal-to-transverse cross section ratio for ρ mesons

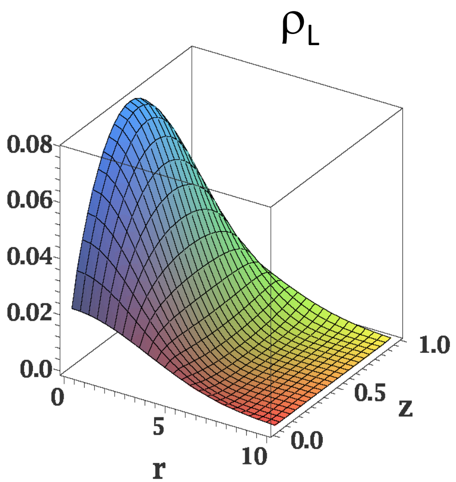


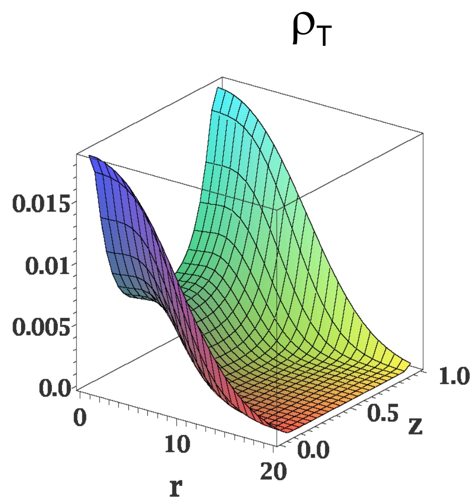
- Larger fraction of longitudinally polarized mesons produced at larger Q^2

screen CT if σ_T (VN) >> σ_L (VN)

Distribution of Quarks in Vector Meson

Different distributions of quarks in the transversely and longitudinally polarized mesons





- In AdS/QCD (Brodsky & G.Teramond) light-cone wave functions depend on meson polarization
- Light-cone wave functions for ρ mesons: J.Forshaw and R.Sandapen Phys.Rev. Lett. 109,081601,2012
- Color dipole model of strong interaction

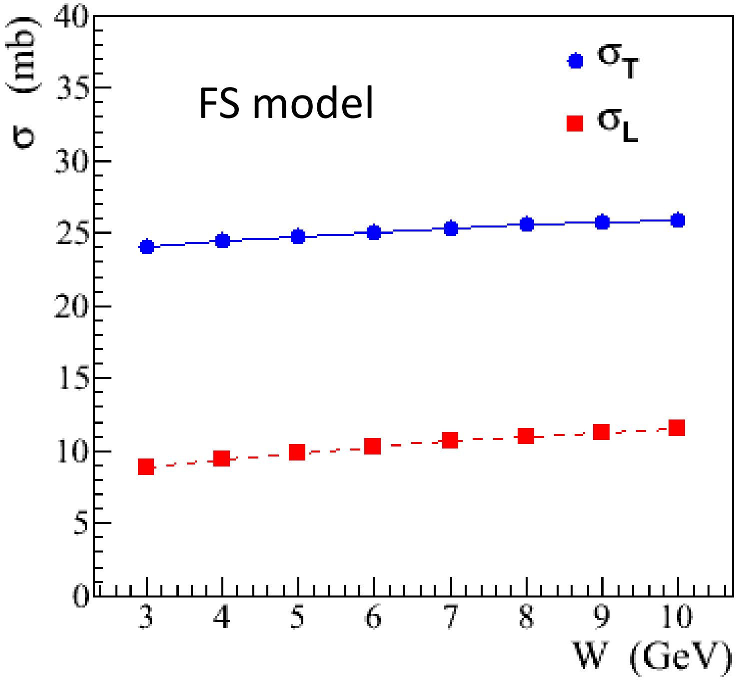
different cross sections for interactions of transversely and longitudinally polarized mesons

Recent Theoretical Calculations

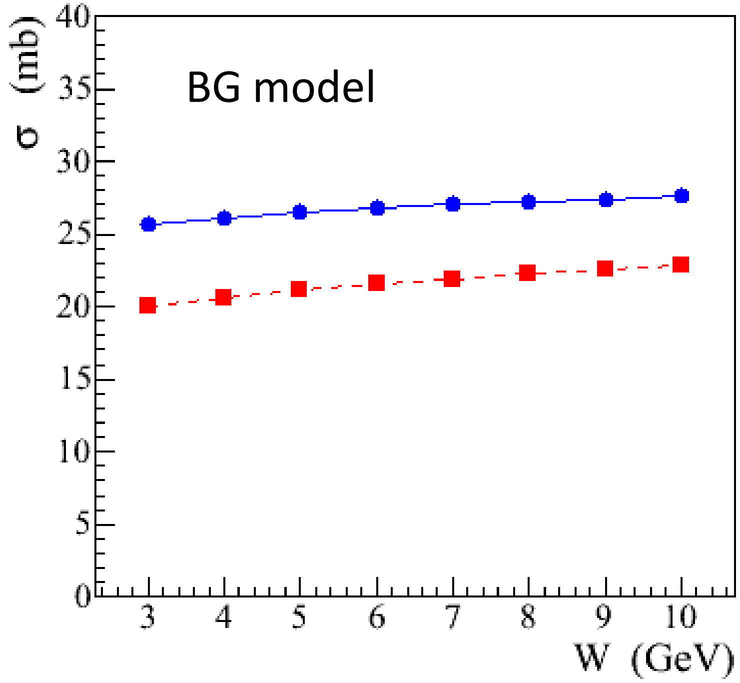
S. Gevorkyan, paper in preparation

$\sigma_{L,T}$ (ρ N) cross sections predicted in a color dipole model using different parameterizations of wave functions:

-AdS / QCD holographic wave function (FS)
J.Forshaw and R. Sandopen, Phys.Rev.Let. 109, 2012



Boosted Gaussian (BG) wave function
B.Kopeliovich et al., Phys.Rev. C65, 2002



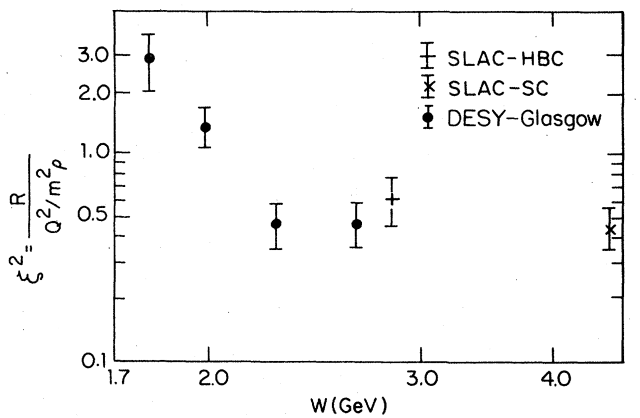
Polarization-Dependent Interactions: Experimental Observations

- Hints from the electroproduction of vector mesons:

$$R = \frac{\sigma(\gamma_L p \to V_L p)}{\sigma(\gamma_T p \to V_T p)} = \xi^2 \frac{Q^2}{m_\rho^2} \qquad \text{where} \qquad \xi = \frac{\sigma_L(Vp)}{\sigma_T(Vp)}$$

ρ mesons: $\xi \sim 0.7$ Nucl. Phys. B113, 53 (1976)

ϕ mesons: $\xi^2 \sim 0.33$ Phys. Rev. Let. 39, 516 (1977)



- Similar observations of the polarization-dependent interactions of deuterons with Carbon targer
  - measured in Dubna and Juelich

Phys. Part. Nucl. Lett. 7, 27, 2010
Phys. Rev. Lett. 104, 2010

- Measurements in the charge exchange process at Argonne: Nucl. Phys. B67, 333 (1973)

$$\pi^+ + Ne \to \rho + Ne'$$

Propose to measure σ_L (VN) using photoproduction on nuclei

Photoproduction of ω Mesons

- In the coherent $\gamma + A \to \omega + A$ production at JLab energies the essential contribution of pion exchange cancels out. From the absorption of ω's one can extract σ_T (ω N)

  - it has been measured by several experiments (σ_T ~ 26 mb)

- In the incoherent process $\gamma + A \to \omega + A'$ the cross section can be written as

$$\frac{d\sigma_A(q)}{dt} = \frac{d\sigma_N(q)}{dt}(\rho_{00} \cdot N(0,\sigma_L) + (1-\rho_{00}) \cdot N(E,\sigma_T)) \qquad \frac{\sigma_A}{\sigma_N} = A_{eff}$$

- *N (0, σ_L)* and *N (E, σ_T)* are absorptions of the longitudinally and transversely polarized mesons predicted by theoretical models
- ρ_{00} is the spin density matrix element measured in $\gamma\, p \to \omega\, p$ reaction

Why ω measons ?

- Some fraction of ω mesons is longitudinally polarized at GlueX energies, ρ_{00} measured by SLAC is 0.2 ± 0.07

How to Extract σ_L (ωN) ?

σ_L (ωN) can be extracted from the measurements of:

Method 1: Nuclear transparency (A_{eff})

Method 2: Spin density matrix element (ρ^A_{00})

Method 1

Calculations by S. Gevorkyan for GlueX Phys. Rev. C 93, 015203 (2016)

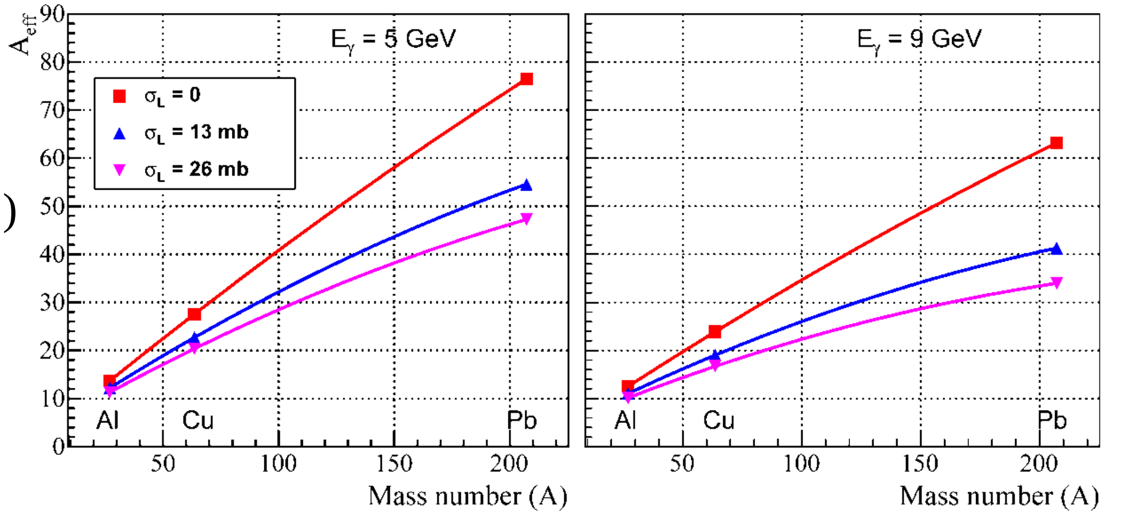
- Measure A_{eff} for each target
- A_{eff} depends on σ_L (see plot)

$$A_{eff} = \rho_{00} \cdot N(0, \sigma_L) + (1 - \rho_{00}) \cdot N(E, \sigma_T)$$

N (0, σ_L) and *N (E, σ_T)* are predicted by theoretical models.

N (E, σ_T) will be independently measured for ρ mesons

Predictions for A_{eff}



A_{eff} will be normalized to Carbon data: some systematic uncertainties will cancel out ($\sigma_{N,}$ Br, some reconstruction efficiencies,)

How to Extract σ_L (ωN) ?

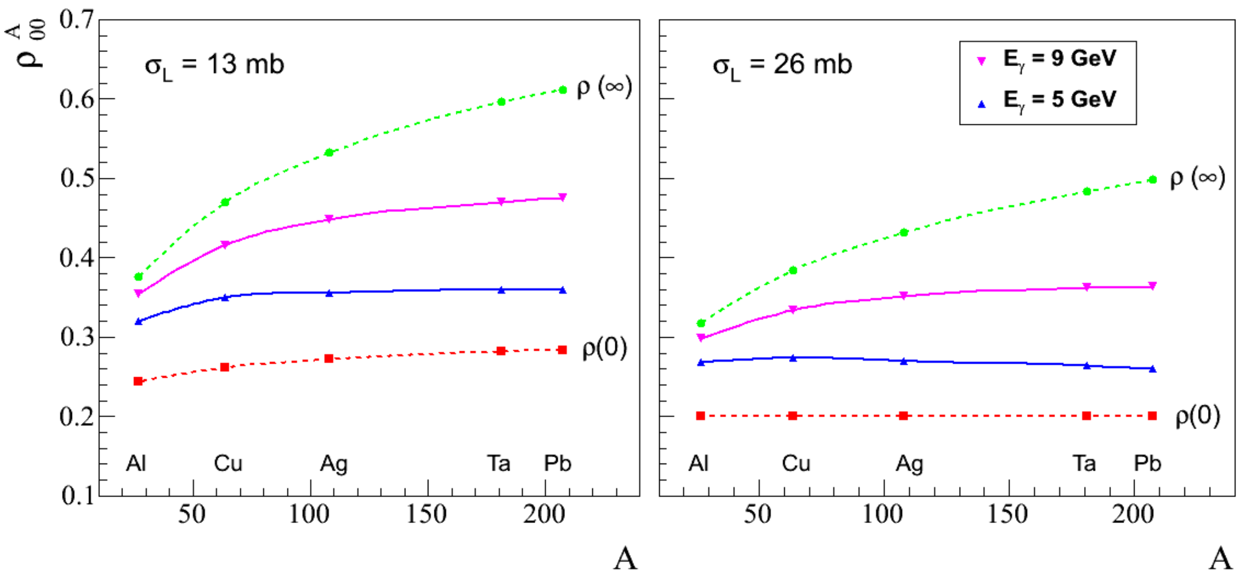
Method 2

- Measure ρ^A_{00} for each target from the fit to the ω decay angular distribution
- ρ^A_{00} depends on σ_L
  - extract σ_L

$$\rho^A_{00} = \frac{N(0,\sigma_L)}{\rho_{00} \cdot N(0,\sigma_L) + (1-\rho_{00}) \cdot N(k,\sigma_T)} \cdot \rho_{00}$$

ρ_{00} is measured in the γ p $\rightarrow$ ω p reaction

Predictions for ρ^A_{00} Phys. Rev. C 93, 015203 (2016)



A-dependence of the spin density matrix elements ρ^A_{00}

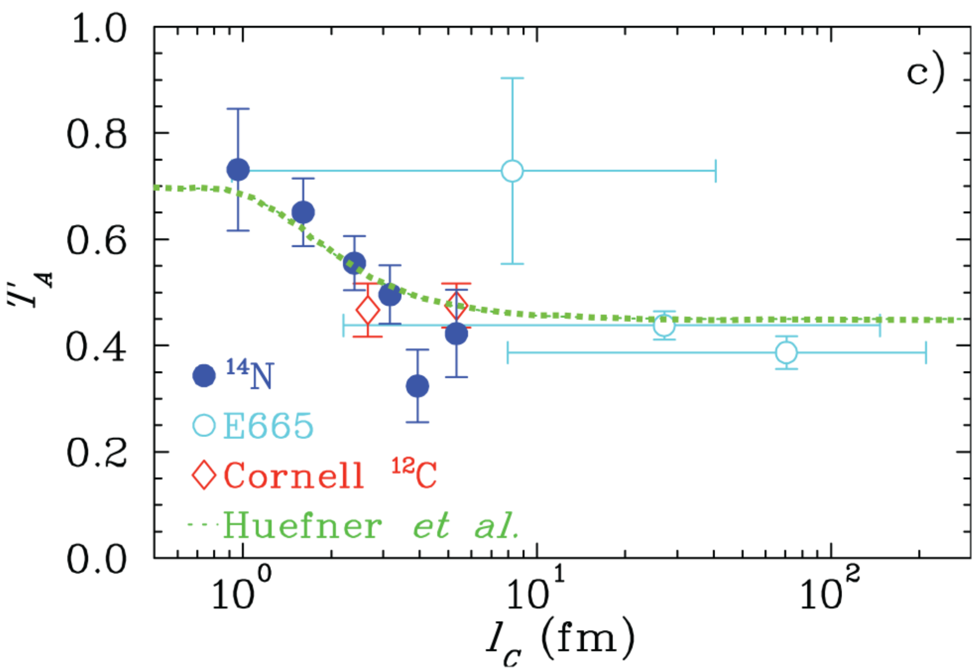
Energy Dependence of Nuclear Transparency

- Energy dependence of the nuclear transparency due to the interference of amplitudes in the production of mesons on nuclei
  - dependence of the incoherent cross section on energy ν via the coherence length

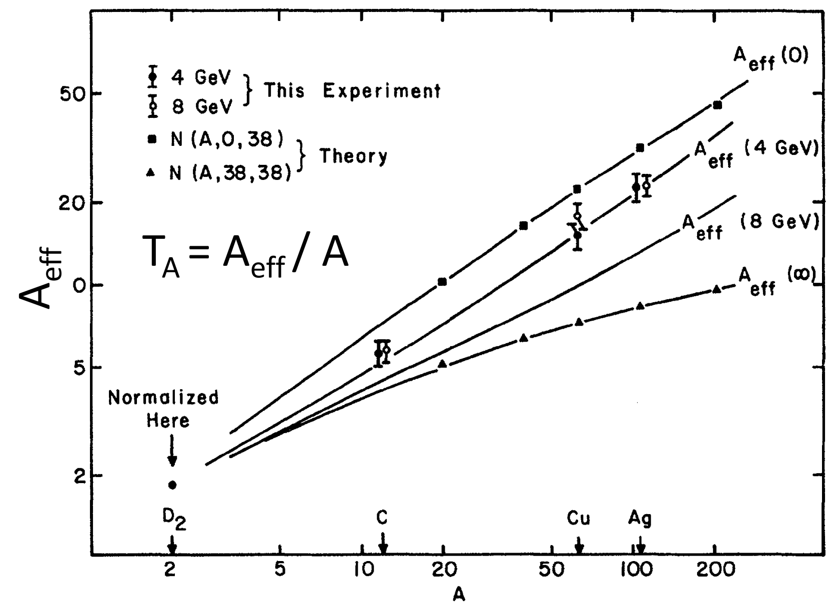
$$l_c = \frac{2\nu}{M^2 + Q^2}$$

- Predicted for both electroproduction and photoproduction

Measured in the electroptoduction



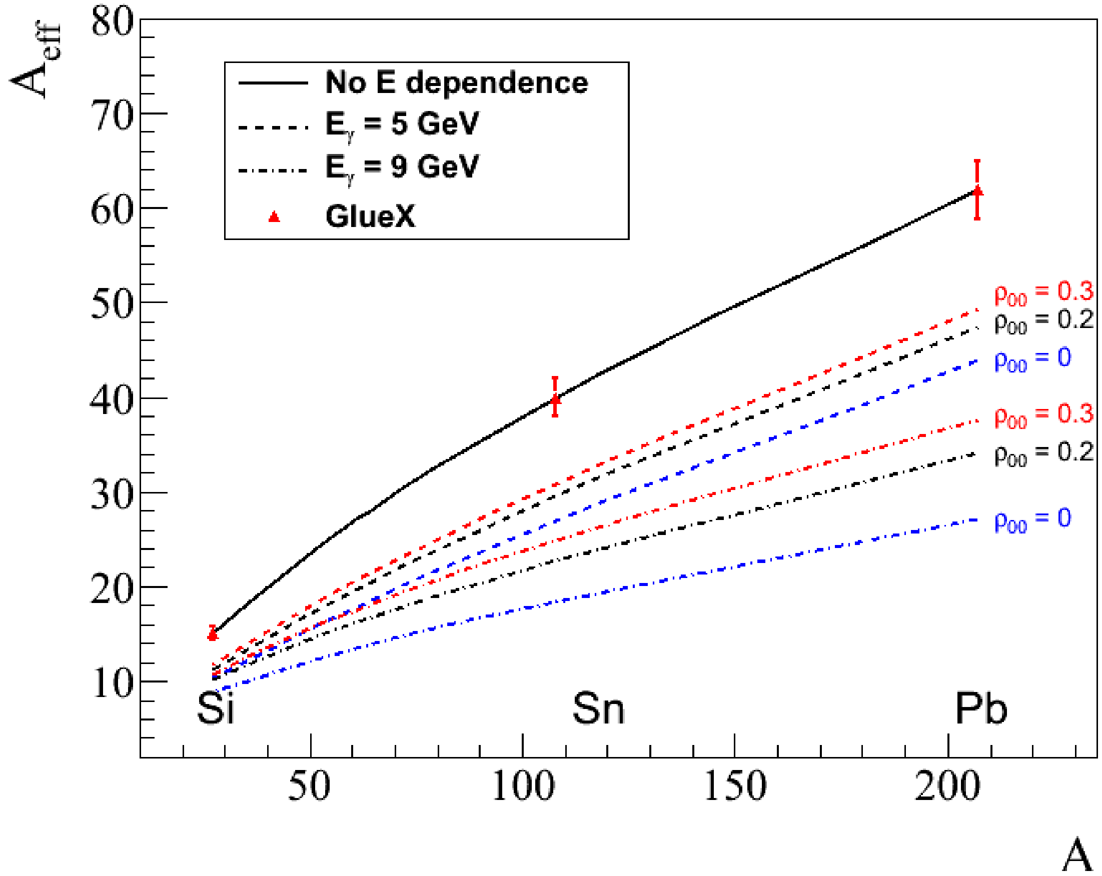
not observed in ρ photoproduction



G. McClellan, et al. Phys. Rev. Let. 23, 10, 1969

Energy Dependence Predicted for GlueX

• Predicted energy dependence of the nuclear transparency for ω mesons



similar dependence for ρ-mesons (ρ_{00} = 0)

Beamline Conditions

- Study meson production on the large energy range $E_\gamma > 6$ GeV
- Use amorphous radiator (incoherent bremsstrahlung)
- Decrease the flux of uncollimated photons by a factor of 12 compared with the GlueX flux at high lumi

  - rate of accidental hits in the tagging detectors is about 20 %

Conditions	GlueX	Proposed Exp
Collimator (mm)	3.4	5
R adiator thickness (X_0)	$2 \cdot 10^{-4}$	10^{-4}
	(Diamond)	(Aluminum)
Beam current (μA)	1.1	0.18
Photon beam energy range of interest (GeV)	8.4 - 9.1	6 - 11.7
Rate of uncollimated photons (Hz)	$1.2 \cdot 10^8$	$5.3 \cdot 10^7$
Photon rate on target (Hz)	$5 \cdot 10^7$	$1.5 \cdot 10^7$

Nuclear Targets

Use four nuclear targets: C, SI, Sn, Pb with the thickness of 7 % R.L.

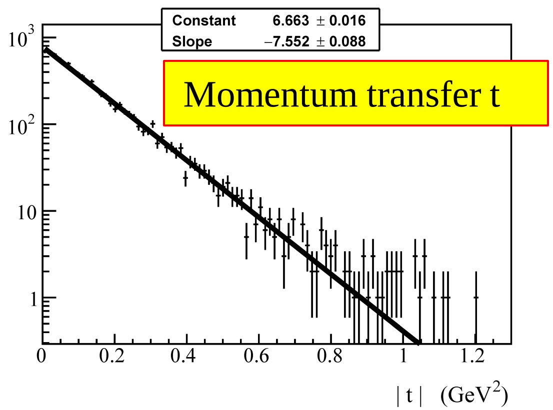
	LH_2 (GlueX)	C	Si	Sn	Pb
A	1	12	28	119	207
Target thickness (X_0)	3.4%	7 %			
Relative EM background	1	0.3			
Number of atoms (N/cm^2)	$1.28 \cdot 10^{24}$	$1.5 \cdot 10^{23}$	$3.3 \cdot 10^{22}$	$3.1 \cdot 10^{21}$	$1.3 \cdot 10^{21}$
$N^{Target} \cdot A/N^{LH_2}$	1	1.4	0.7	0.3	0.2

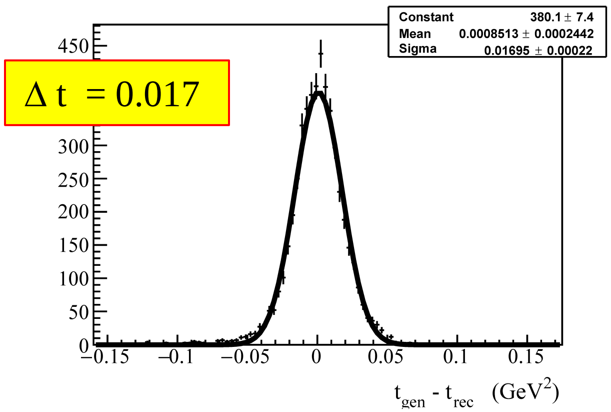
- small electromagnetic background compared with GlueX

- neutron background will not exceed the GlueX level
(JLAB-TN-11-005, 2011)

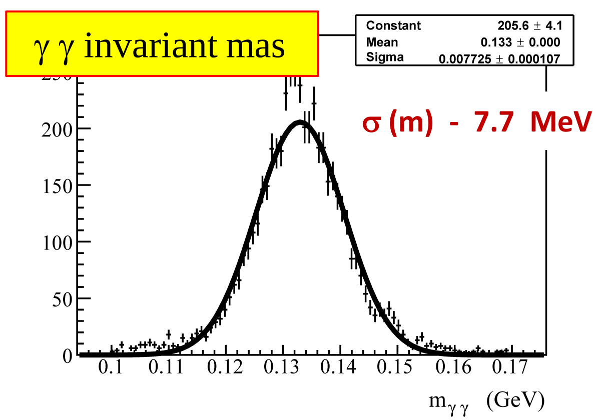
Monte Carlo Simulation

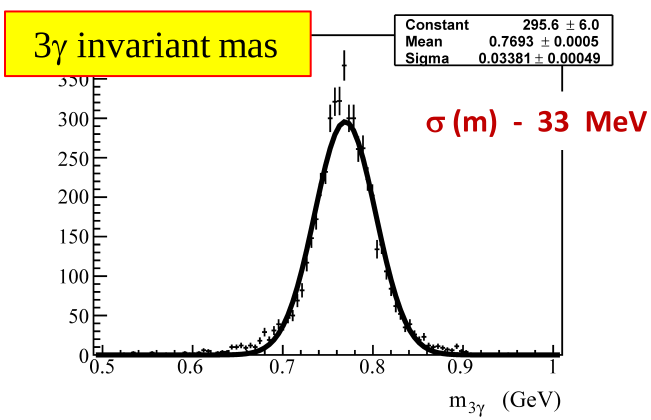
- We studied reconstruction capabilities for ρ, ω, and ϕ mesons using detailed GlueX detector simulation
- Signal events were generated by Pythia (with the Fermi motion taken into account) in the energy range between 6 GeV – 12 GeV





$\omega \rightarrow \pi^0 \gamma$



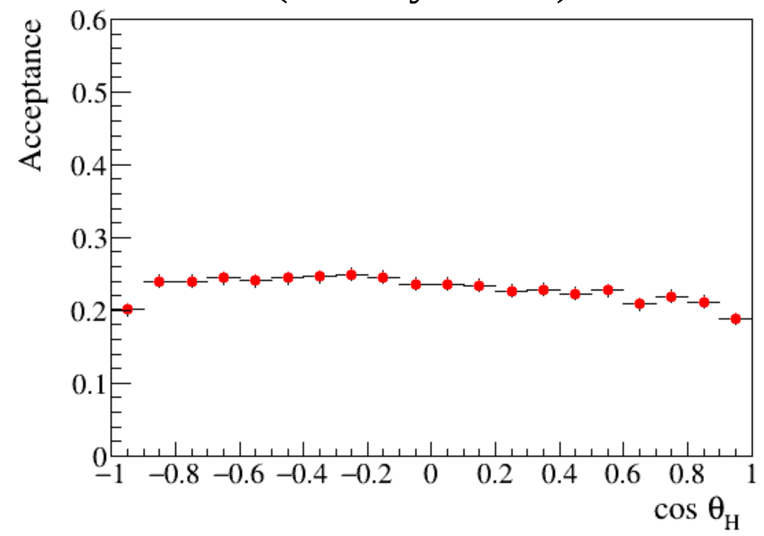


	$\pi^0 \gamma$	$\pi^+\pi^-\pi^0$
$M_{\gamma\gamma}$ (MeV)	7.7	7.8
M_{ω} (MeV)	33	30
Δt (GeV^2)	0.017	0.02

$\sigma(M_{mis}) \sim 190$ MeV

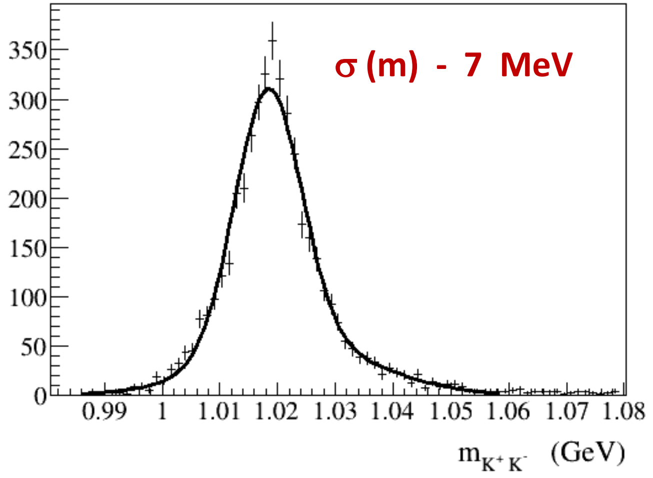
Monte Carlo Simulation

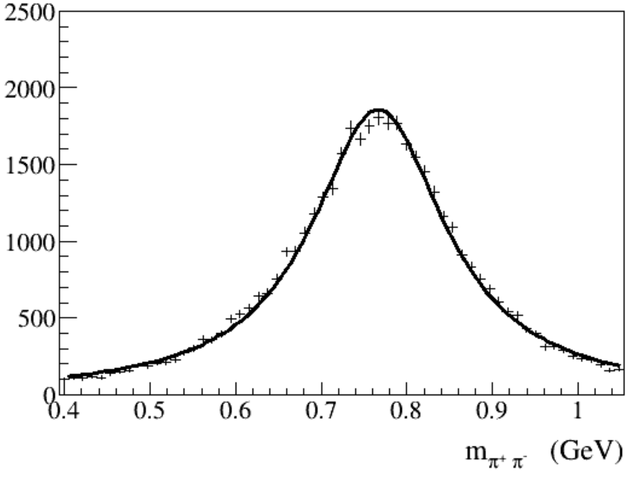
Angular acceptance for $\omega \to \pi^0 \gamma$ decays (helicity frame)



- Uniform angular acceptance
  - important for polarization measurements

- Reconstruction of $\rho \to \pi^+\pi^-$ and $\phi \to K^+ K^-$





σ (t) ~ 0.02 GeV^2

σ (M_{mis}) ~ 200 MeV

Reconstruction Efficiencies and Yields

	Final state			
	$\omega \to \pi^0\gamma$	$\omega \to \pi^+\pi^-\pi^0$	$\rho \to \pi^+\pi^-$	$\phi \to K^+K^-$
Branching Fraction (%)	8.28	89.2	1	48.9
Efficiency (%)	23.9	12.5	20.6	13.3
$\sigma(M_{\gamma\gamma})$ (MeV)	7.7	7.8		
$\sigma(M_\omega)$ (MeV)	33	30		
$\sigma(M_{K^+K^-})$ (MeV)				7.1
σ(t) (GeV^2)	0.017	0.02	0.02	0.02
$\sigma(M_{mis})$ (MeV)	180	195	200	200

Reconstruction properties of ω, ρ, and ϕ mesons

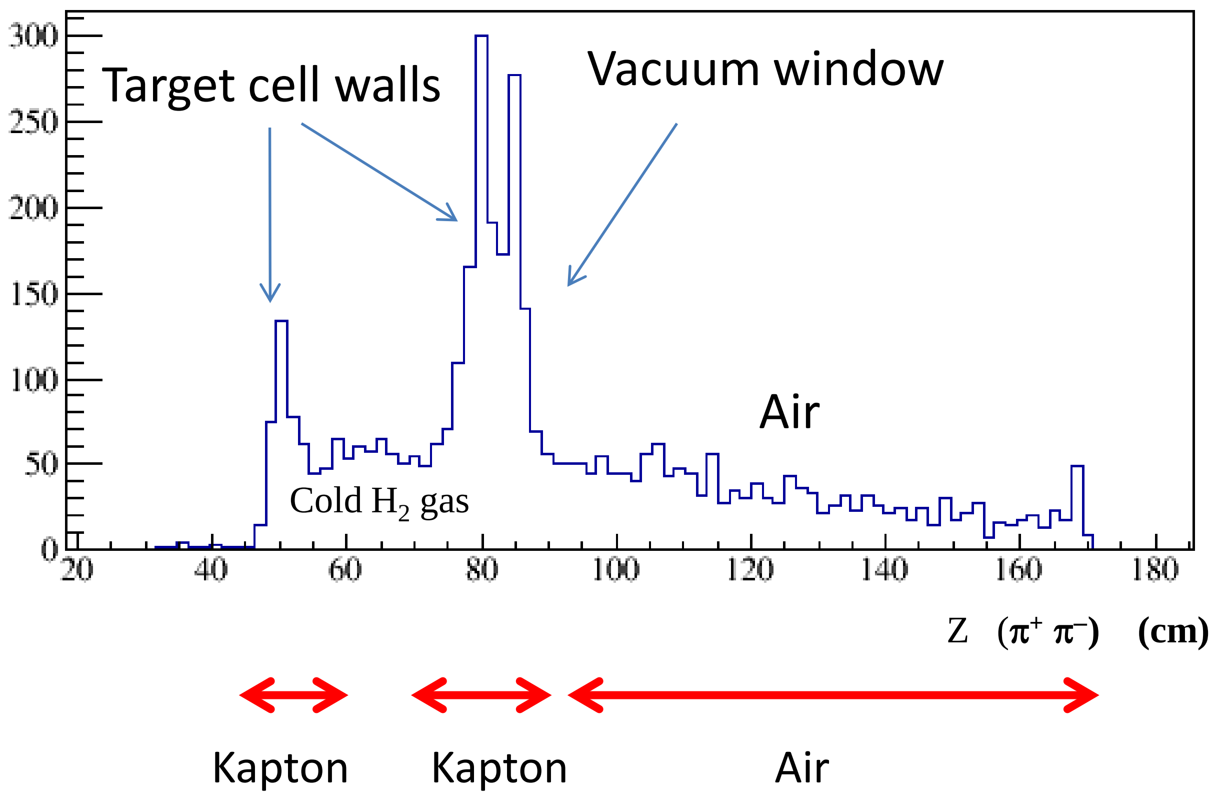
Expected number of reconstructed ω, ρ, and ϕ mesons

	$N_{\rm rec}$ $(\times 10^3)$							
	$\omega \to \pi^0\gamma$		$\omega \to \pi^+\pi^-\pi^0$		$\rho \to \pi^+\pi^-$		$\phi \to K^+K^-$	
Range (GeV)	6 - 9	9 - 12	6 - 9	9 - 12	6 - 9	9 - 12	6 - 9	9 - 12
C	52.7	40.2	338.7	235.5	3233	270.9	57.9	65.1
Si	28.4	18.8	165.6	110.8	152.4	120.0	31.6	34.4
Sn	9.6	5.4	57.0	33.6	496.8	317.4	12.6	12.6
Pb	10.0	6.0	60.0	33	523	301	14	13

S/B Estimates

- Estimate background using photoproduction on target walls and air (runs with empty target)

Production vertex for $\omega \to \pi^+ \pi^- \pi^0$



Vacuum cell and window:
75 , 100 μm Kapton

Cold H_2 gas:
$\rho = 1.8 \cdot 10^{-3}$ g /cm^3

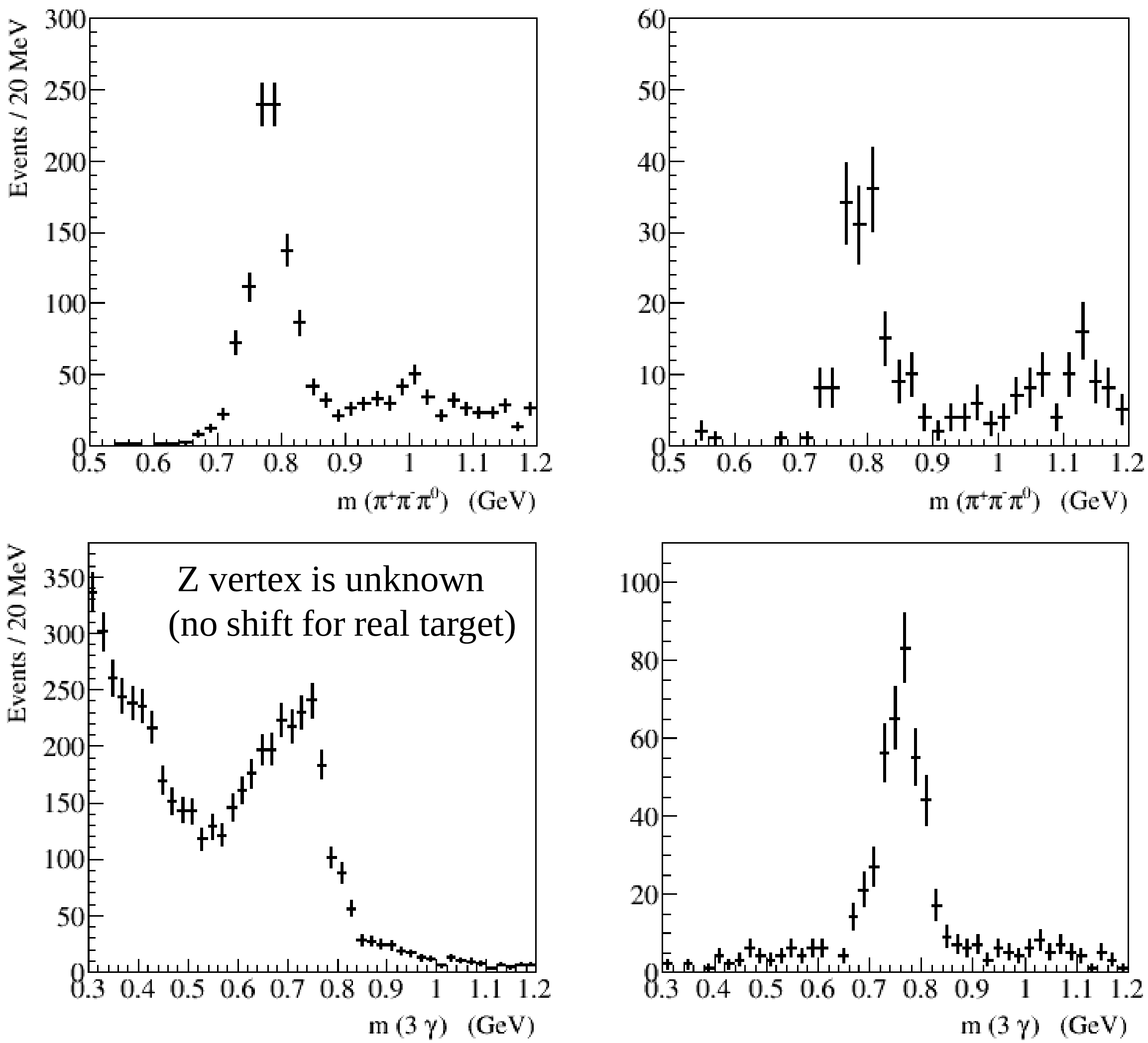
Air:
$\rho = 1.2 \cdot 10^{-3}$ g /cm^3

Runs with Empty Target

γ (p, A) $\rightarrow$ ω (X)

(require to reconstruct only ω)

γ (p, A) $\rightarrow$ p ω



$\omega \rightarrow \pi^+ \pi^- \pi^0$

$\omega \rightarrow \pi^0 \gamma$

Relatively small BG for both ω decay channels

Errors on Measurements of A_{eff} and Extraction of σ_L (ωN)

- Systematic uncertainties dominate

  - smallest data sample of $\omega \rightarrow \pi^0\gamma$ reconstructed decays (16 K per target)
  - conservatively assume that S/B = 1
  - measure the ratio of cross section σ_A / σ_N some uncertainties related to reconstruction efficiencies will be canceled out

- Statistical errors on A_{eff}

  $\delta(A_{eff}) / A_{eff}$ = 1.4 % (6 – 9 GeV)
  = 1.8 % (9 -12 GeV)

- σ_L is computed according to the predicted dependence of A_{eff} on σ_L

systematic uncertainties on A_{eff}

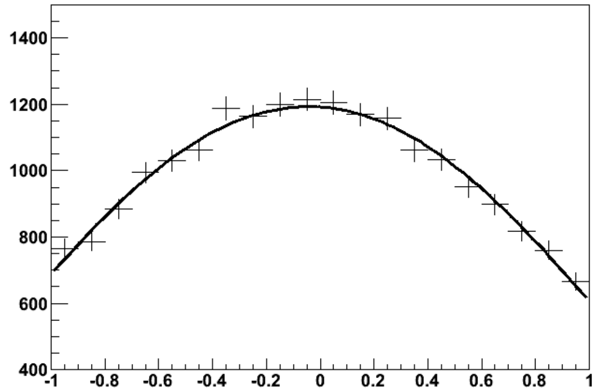
Target thickness	1.2 %
Photon flux determination	1.6 %
Signal yield (bg subtraction) and event selection	3.7 %
Total measured	**4.3 %**
Dependence on input value of ρ_{00}	1.2 %

Measued by SLAC ⇒

Polarization of ω mesons	**Error on σ_L (26 mb) (mb)**	
	6 – 9 GeV	**9 – 12 GeV**
$\rho_{00} = 0.2$	1.1 (stat) 3.5 (syst)	1.1(stat) 2.7 (syst)
$\rho_{00} = 0.1$	2.1 (stat) 6.6 (syst)	2.0 (stat) 5.0 (syst)

Errors on Measurements of ρ^A_{00} and Extraction of σ_L (ωN)

- Obtain ρ^A_{00} from the fit to the decay angular distribution in the helicity frame
- Statistical errors : $\sigma(\rho^A_{00})$ = 0.011 (6 – 9 GeV)
  (from the fit) = 0.014 (9 -12 GeV)



cos θ

$\omega \to \pi^+ \pi^- \pi^0$ (6 – 9 GeV)
Signal + BG, realistic acceptance
(input ρ_{00} = 0.2)

$$W(\cos\theta) \sim \frac{1}{2}\cdot(1-\rho_{00})\cdot\sin^2\theta + \rho_{00}\cdot\cos^2\theta$$

systematic uncertainties on ρ^A_{00}

Signal yield (bg subtraction)	2.6 %
Acceptance determination	3.9 %
Dependence on ρ_{00}	3.7 %
Total	**5.9 %**

- σ_L is computed according to the predicted dependence of ρ^A_{00} on σ_L

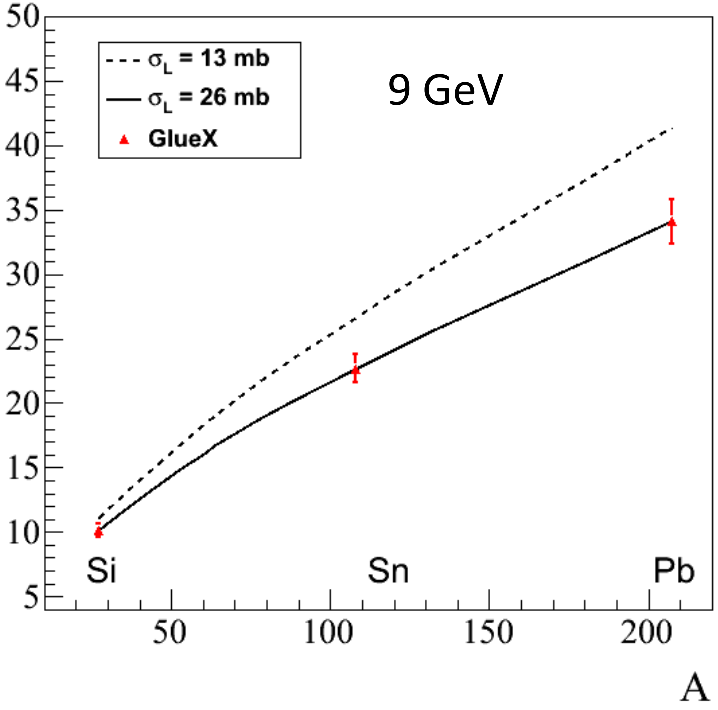
σ_L (26 mb) $\pm$1.4 (stat) $\pm$2.1 (syst) mb 6 – 9 GeV

σ_L (26 mb) $\pm$1.6 (stat) $\pm$2.3 (syst) mb 9 – 12 GeV

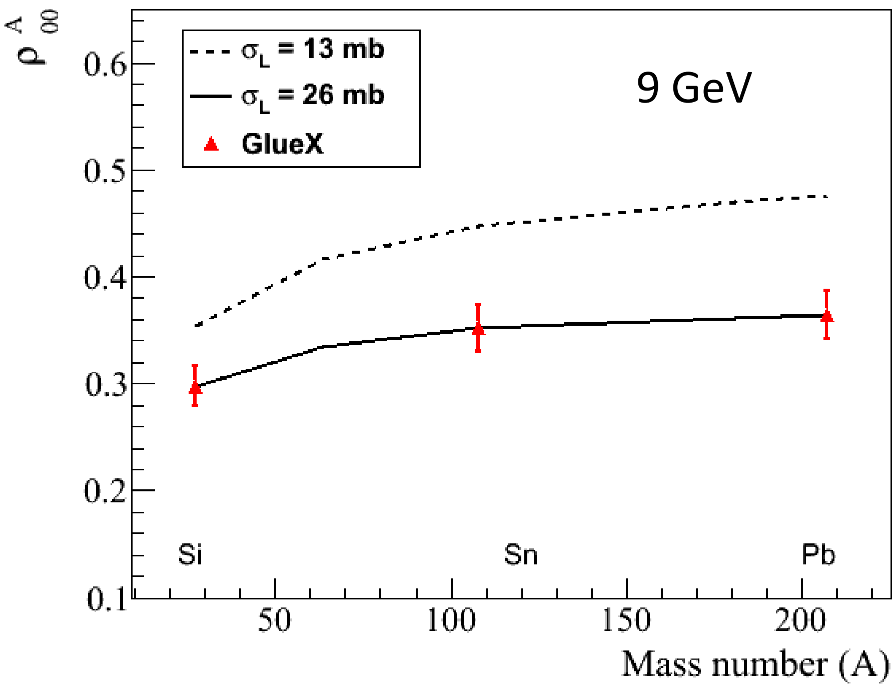
Projected Errors: A_{eff} and ρ^A_{00}

- Projected errors on measurements of A_{eff} and ρ^A_{00} for $\omega \rightarrow \pi^0 \gamma$ decays (input values: σ_T = 26 mb, ρ_{00} = 0.2)

A_{eff}



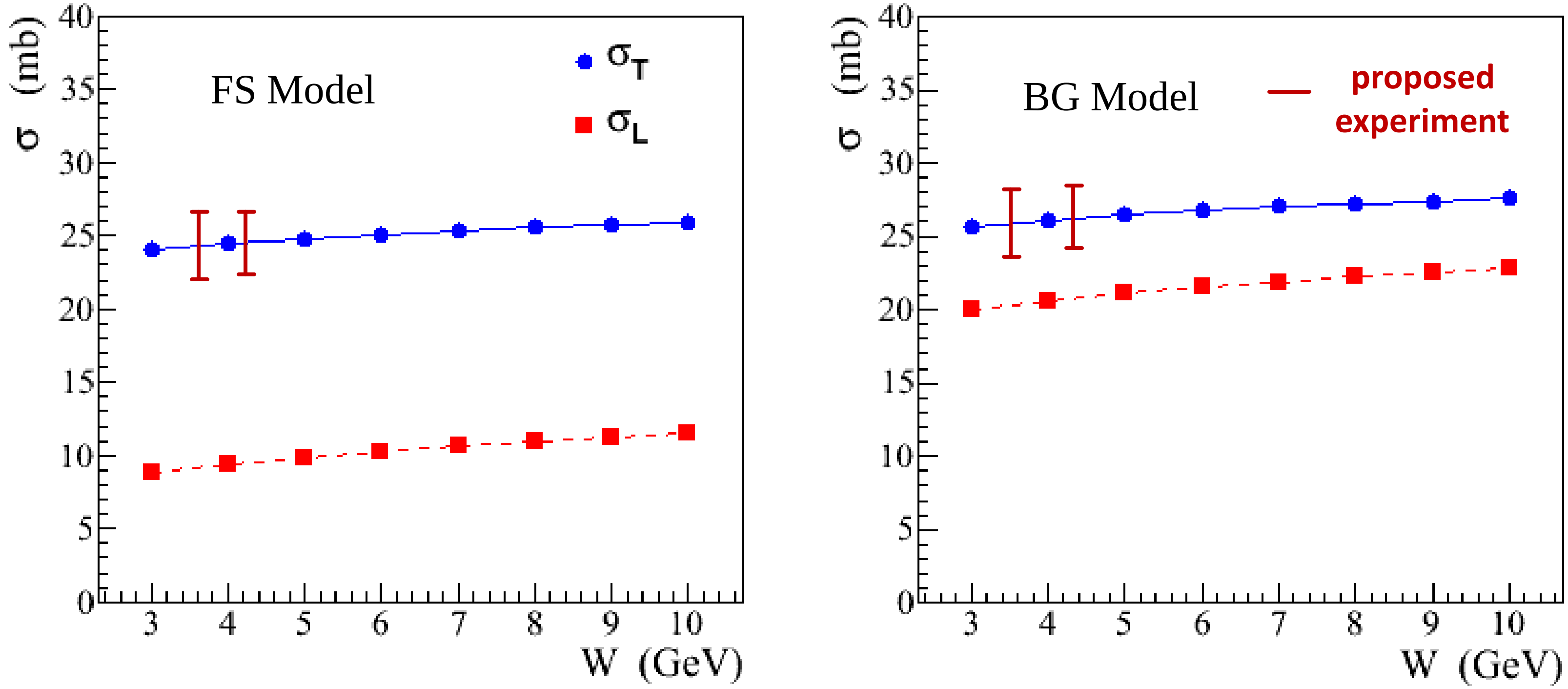
ρ^A_{00}



Projected errors on σ_L (ωN)

- σ_L will be extracted for ω mesons using two measurements: A_{eff} and ρ^A_{00}
- Expected errors on σ_L for $\omega \rightarrow \pi^0\gamma$ decays obtained from measurements on a Pb target:

$\sigma(\sigma_L)$ =	3.7 mb (6 – 9 GeV) ;	2.9 mb (9 – 12 GeV)	extracted from	A_{eff}
$\sigma(\sigma_L)$ =	2.6 mb (6 – 9 GeV) ;	2.8 mb (9 – 12 GeV)	extracted from	ρ^A_{00}
Combined:	2.3 mb	2.0 mb		



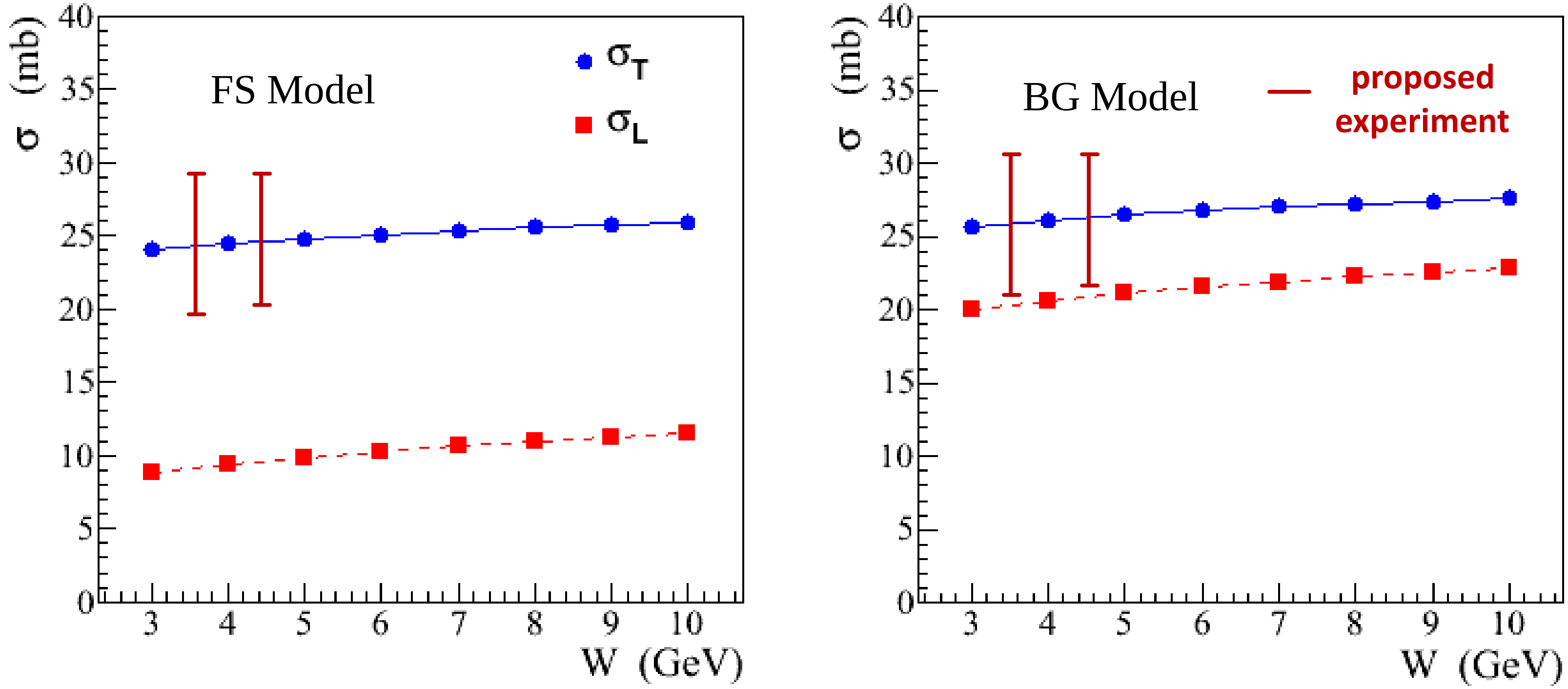
- σ_L will be independently measured using $\omega \rightarrow \pi^+\pi^-\pi^0$ decays

Projected errors on σ_L (ωN)

- σ_L will be extracted for ω mesons using two measurements: A_{eff} and ρ^A_{00}
- Expected errors on σ_L for $\omega \rightarrow \pi^0\gamma$ decays obtained from measurements on a Pb target:

(Input values of ρ_{00} = 0.14)

$\sigma(\sigma_L)$ = 5.0 mb (6 – 9 GeV) ; 4.6 mb (9 – 12 GeV)



- σ_L will be independently measured using $\omega \rightarrow \pi^+\pi^-\pi^0$ decays

Beam Time Request

Activity	Time (days)
C production	3
Si production	4
Sn production	6
Pb production	10
Empty target	3
Calibration	2
Total	28

- Propose to take data for 28 days (one run)
- No modifications of the GlueX detector except for the target installation

Compatibility with the PR12-17-007 Experiment (CT and SRC)

PR12-17-007: large lumi, small energy range, light targets (^{40}Ca the heaviest)

This proposal: smaller lumi, large energy range, 16 days on heavy targets (Sn, Pb)
(accidental hits in tagger) we can use ^{40}Ca instead of Si

Take data at high and low lumi sequentially for C and Ca targets:
- minimize overhead for target installation and calibration runs
- simplify offline detector calibration and data analyses

Both experiments will benifit from additional data sets acquired on light heavy targets

Summary

- We propose to use the GlueX detector to study photoproduction of light mesons on nuclear targets: C, Si, Sn, and Pb in the large beam energy range between 6 GeV and 12 GeV. The primary goal is:

  Measure nuclear transparency and the SDME for omega mesons in incoherent photoproduction and extract the total cross section of the longitudinally polarized ω mesons with nucleon. Measurements are important in interpreting color transparency effects.

  Measure nuclear transparency of light mesons such as ρ, ω, φ. Study the dependency of the nuclear transparency on the beam energy, predicted by theoretical models.

  Data sample acquired on nuclear target will allow to study other physics topics, like production of mesons at larger t, etc.

- The expected length of the experiment is 28 days of taking data. The detector will be operated at small luminosity. No modifications of the GlueX detector is required

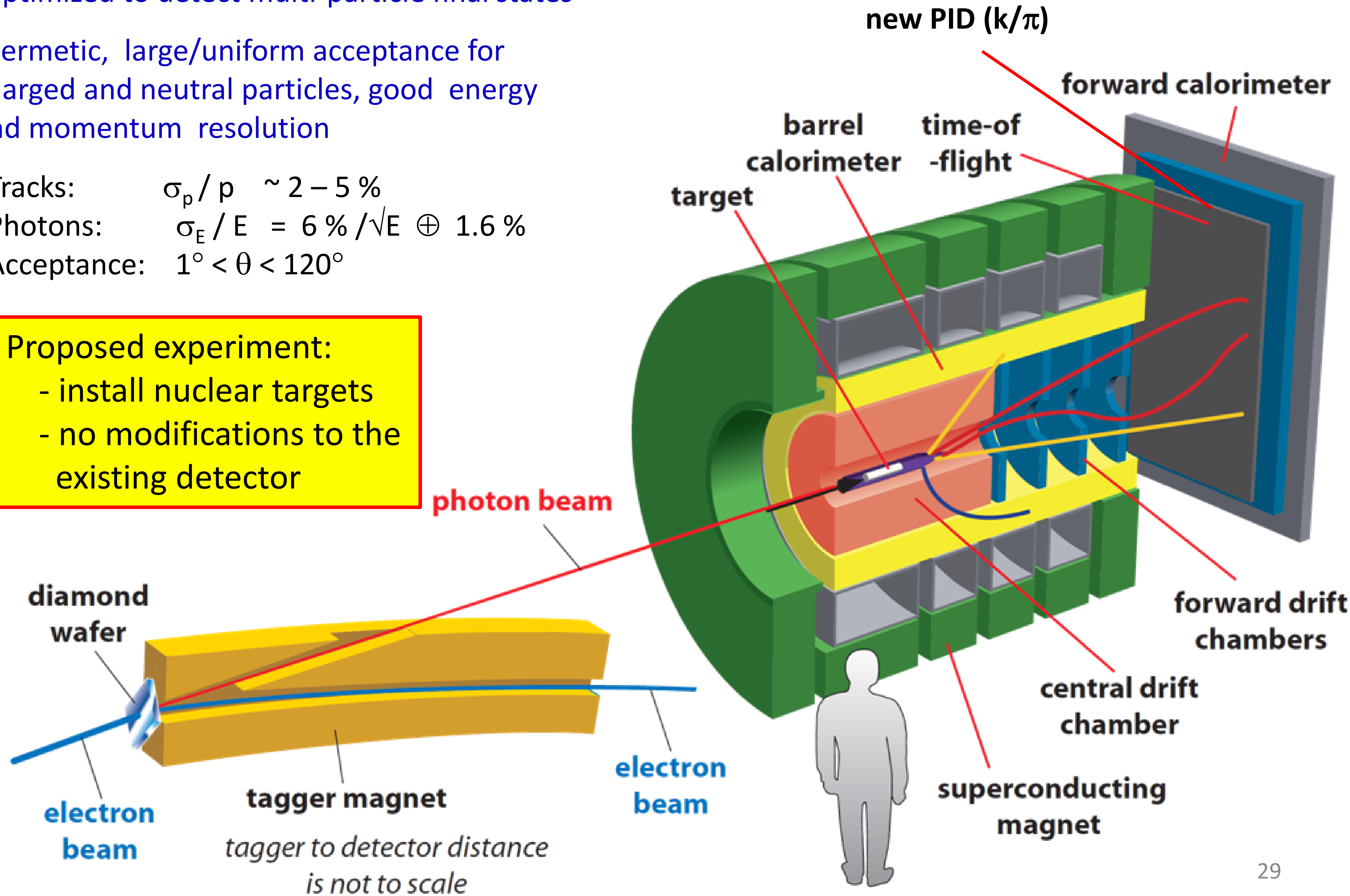
Backup Slides

GlueX Spectrometer

- Optimized to detect multi-particle final states
- Hermetic, large/uniform acceptance for charged and neutral particles, good energy and momentum resolution

Tracks: $\sigma_p / p \sim 2 - 5\,\%$
Photons: $\sigma_E / E = 6\,\% / \sqrt{E} \oplus 1.6\,\%$
Acceptance: $1^\circ < \theta < 120^\circ$

Proposed experiment:
- install nuclear targets
- no modifications to the existing detector



Timeline

- Nuclear Photoproduction with GlueX Workshop, Jefferson Lab, April 28 - 29, 2016
  https://www.jlab.org/conferences/photoproduction16/

  - interesting discussions, motivated further theoretical studies

- Photoprodiction of ω mesons of nuclei and impact of polarization on the meson-nucleon interactions, Phys. Rev. C93, 1, 015203, 2016

- Topic presented at several conferences / workshops

Measurement of ρ_{00}

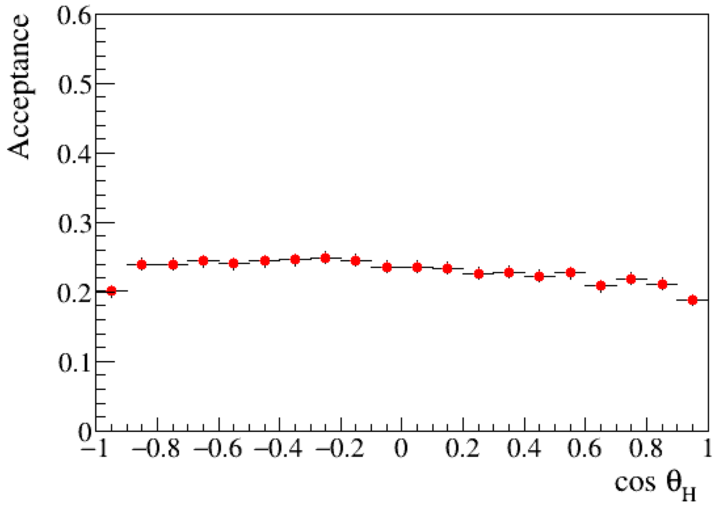
- Originally measured by SLAC in the $\gamma\, p \to \omega\, p$ reaction: bubble chamber experiment, small statistics $\rho_{00} = 0.2 \pm 0.07$ *at 9.3 GeV* [J.Ballam et. al. Phys.Rev. D7, 3150, 1973]

- ρ_{00} will be independently measured by the GlueX experiment in the $\gamma\, p \to \omega\, p$ reaction using a very large data sample of reconstructed ω mesons. ρ_{00} will be extracted from the fit to the ω decay angular distribution in the helicity frame (see page 11, Eq. 2) using existing GlueX data

- Based on the quality of the GlueX experimental data for $\omega \to \pi^0 \gamma$ decays, we expect the dominant systematic error on the ρ_{00} determination to be on the level of 4%

  - the GlueX detector has a uniform angular acceptance for $\omega \to \pi^0 \gamma$ and $\omega \to \pi^+ \pi^- \pi^0$ decays

tructed ω mesons



- angular acceptance for $\omega \to \pi^0 \gamma$ decays (helicity frame)

Sensitivity of A_{eff} and ρ^A_{00} to ρ_{00}

I)

$$A_{eff} = \rho_{00} \cdot N(0,\sigma_L) + (1-\rho_{00}) \cdot N(E,\sigma_T)$$

uncertainties of ρ_{00} of $\pm$ 4 % affect A_{eff} by $\pm$ 1.2 %

total systematic error on A_{eff} = 4.7 %

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$$\rho^A_{00} = \frac{N(0,\sigma_L)}{\rho_{00} \cdot N(0,\sigma_L) + (1-\rho_{00}) \cdot N(k,\sigma_T)} \cdot \rho_{00}$$

uncertainties of ρ_{00} of $\pm$ 4 % affect A_{eff} by $\pm$ 3.7 %

total systematic error on A_{eff} = 5.6 %

Extract from A_{eff}	Extract from ρ^A_{00}
σ_L (26 mb) $\pm$1.1 (stat) $\pm$3.5 (syst) mb	σ_L (26 mb) $\pm$1.4 (stat) $\pm$2.1 (syst) mb