Measuring the Polarizability of the Neutral Pion with GlueX

Proposal to run concurrently with
"Measuring the Charged Pion Polarizability (CPP)
in the $\gamma\gamma \to \pi^+ \pi^-$ Reaction"
E12-13-008

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Internal GlueX review

- Conclusion and summary from the *ad hoc* Review:
  - NPP is compatible with CPP
  - The proposed measurements were feasible in the beam time requested.

This experiment has been endorsed by the GlueX collaboration

Polarizability

- Polarizability: Ease with which an external field induces a dipole moment in a particle and is a property that reflects the internal structure of the particle
- The π^0 polarizability has NEVER been measured

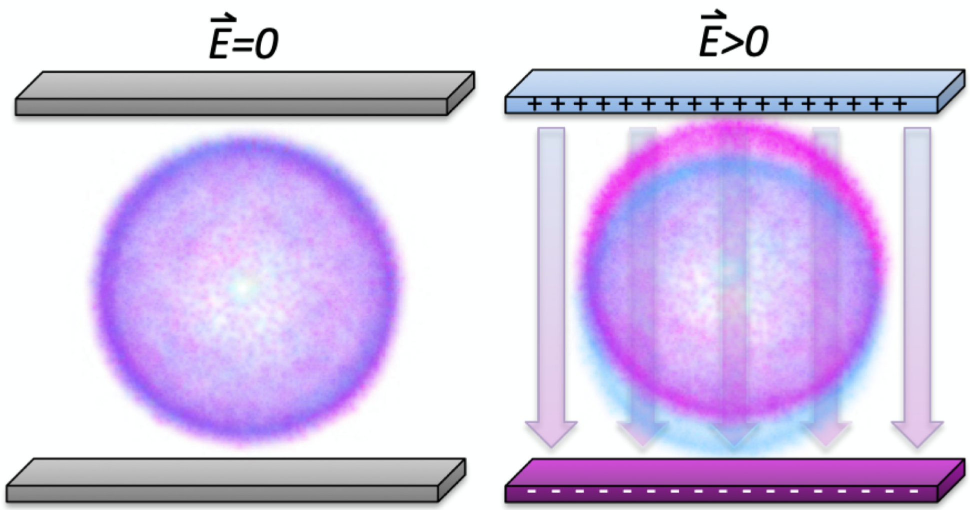
$$\alpha_{\pi^+} = 2.0 \pm 0.9 \times 10^{-4} \mathrm{fm}^3$$ (CPP)

COMPASS Phys. Rev. Lett., 114 (2015) 062002

$$\alpha = -\beta$$

Lowest order in χPT

Deviations are sensitive to two-loop calculations and meson cloud dynamics



α – electric polarizability
β - magnetic polarizability

$$\vec{p} = \alpha \vec{E}$$
$$\vec{\mu} = \beta \vec{H}$$

Experimental considerations

- Requirements are similar to Charged Pion Polarizability Ex (CPP)
  - High Z target -> signal is proportional to Z^2
  - Low beam energy -> 6 GeV gives better acceptance and higher polarization
  - Accurate normalization scheme -> measure absolute cross section
- Conclusion: Run concurrently with CPP

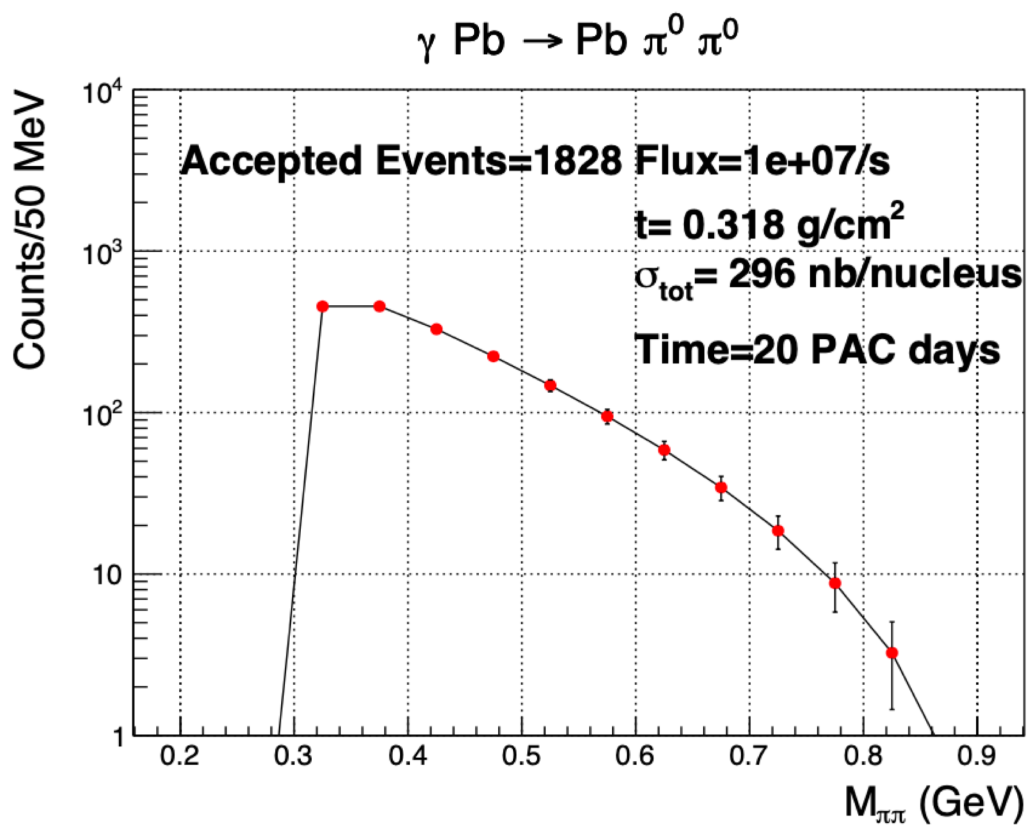
Configuration	Nominal GlueX I	Charged Pion Polarizability	Neutral Pion Polarizability
Coherent Peak Energy	8.4-9.0 GeV	5.5-6 GeV	5.5-6 GeV
Current	150 nA	20 nA	20 nA
Peak polarization	35%	72%	72%
Target Position	65 cm	1 cm	1 cm
Target	LH2, 30 cm	^{208}Pb, 0.028 cm	^{208}Pb, 0.028 cm
Muon Detector	None	Installed	Not needed
Trigger	FCAL/BCAL (40 kHz)	TOF (30 kHz)	FCAL/BCAL (10 kHz)

Note: Electron beam energy = 11.4 GeV

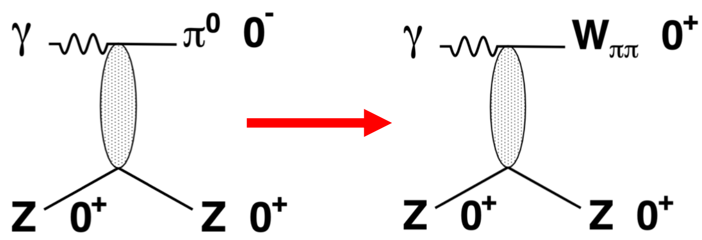
Expected signal for γ Pb –> Pb π^0 π^0

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

- Number of events estimated based on the Crystal Ball measurement
- Use CPP flux, target, running time, detector acceptance
- 20 PAC days
- Total signal events: 1800



Expected backgrounds



Integrated Fraction ($\theta < 1.5$ degrees)	$\gamma\, Pb \to \pi^0\, Pb$	$\gamma\, Pb \to \pi^0\pi^0\, Pb$ (This study)
Primakoff signal	1.0	1.0
Nuclear Coherent (NC)	0.39	0.35
Interference	0.12	0.17
$\gamma p \to \eta p$, BR($\eta \to 3\pi^0$)	–	0.37
Incoherent (IC)	0.02	0.06

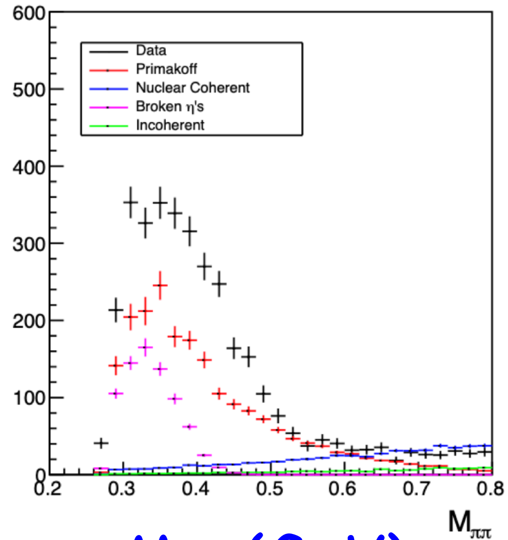
- Nuclear Coherent production (e.g. $f_0(500) \to \pi^0\pi^0$)
  - π^0's produced in the NC production are suppressed by Pauli blocking and absorption. Suppression is seen in PrimEx-π^0, expect stronger suppression in $\pi^0\pi^0$
  - Adjusted NC and Interference to approximately match PrimEx
- Misidentified backgrounds
  - Nuclear coherent η production: $\eta \to \pi^0\, \pi^0\, \pi^0 \to \gamma\gamma\gamma\gamma\, (\gamma\gamma)$
- Advantages: $\rho^0 \not\to \pi^0\pi^0$, no QED background, and no pion exchange due to CP conservation.

Fit to signal and background

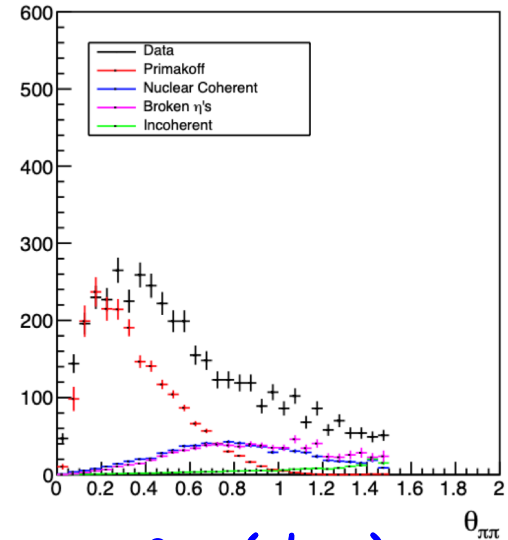
Full simulation with

- GEANT4
- Detector resolution
- Standard GlueX Reconstruction
- Kinematic fit
- Random hits
- Tagger accidentals

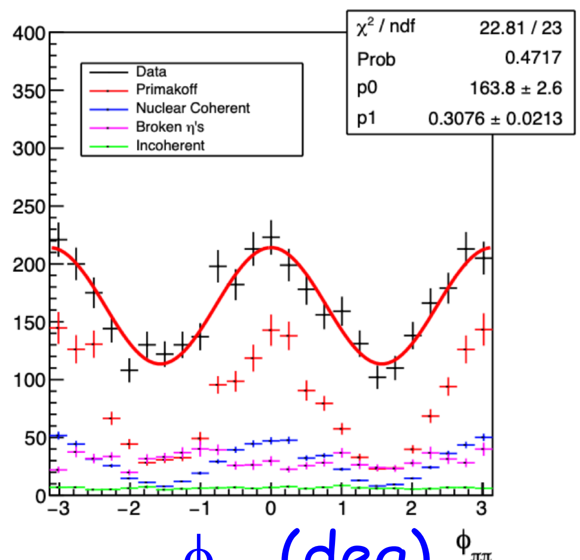
Results shown of Amplitude fit to all variables



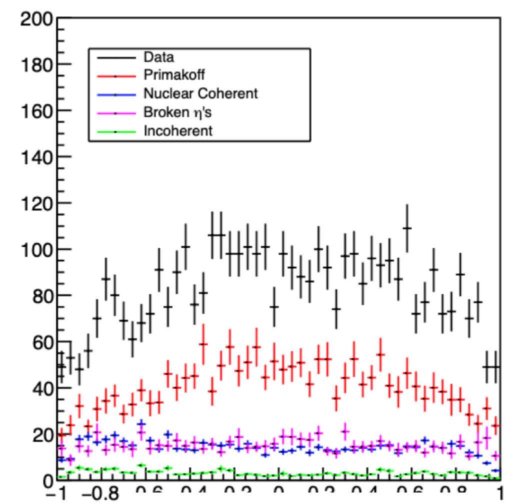
$M_{\pi\pi}$ (GeV)



$\theta_{\pi\pi}$ (deg)



$\phi_{\pi\pi}$ (deg)



$\cos\theta_{\pi}$ (deg)

Error table

	Source	Uncertainty
1	Statistical uncertainty	2.3%
2	Signal extraction	3.0%
3	Detector acceptance and efficiency	3.5%
4	Total systematic error	4.6%
5	Total error on cross section	5.1%
6	Projected error in $\alpha - \beta$	39%

Taken from fit

Compare fits with/without misID η's and IC

Assess using uncertainty in measuring γ Pb -> π^0 Pb

Use estimate by Dai/Pennington

$$\Delta(\alpha_{\pi^0} - \beta_{\pi^0}) \sim 7.7\Delta(\sigma)$$

Compare COMPASS result

$$\alpha_{\pi^+} - \beta_{\pi^+} = 4 \pm 1.8 \times 10^{-4}\mathrm{fm}^3$$

Projected CPP rounded theory estimate for value

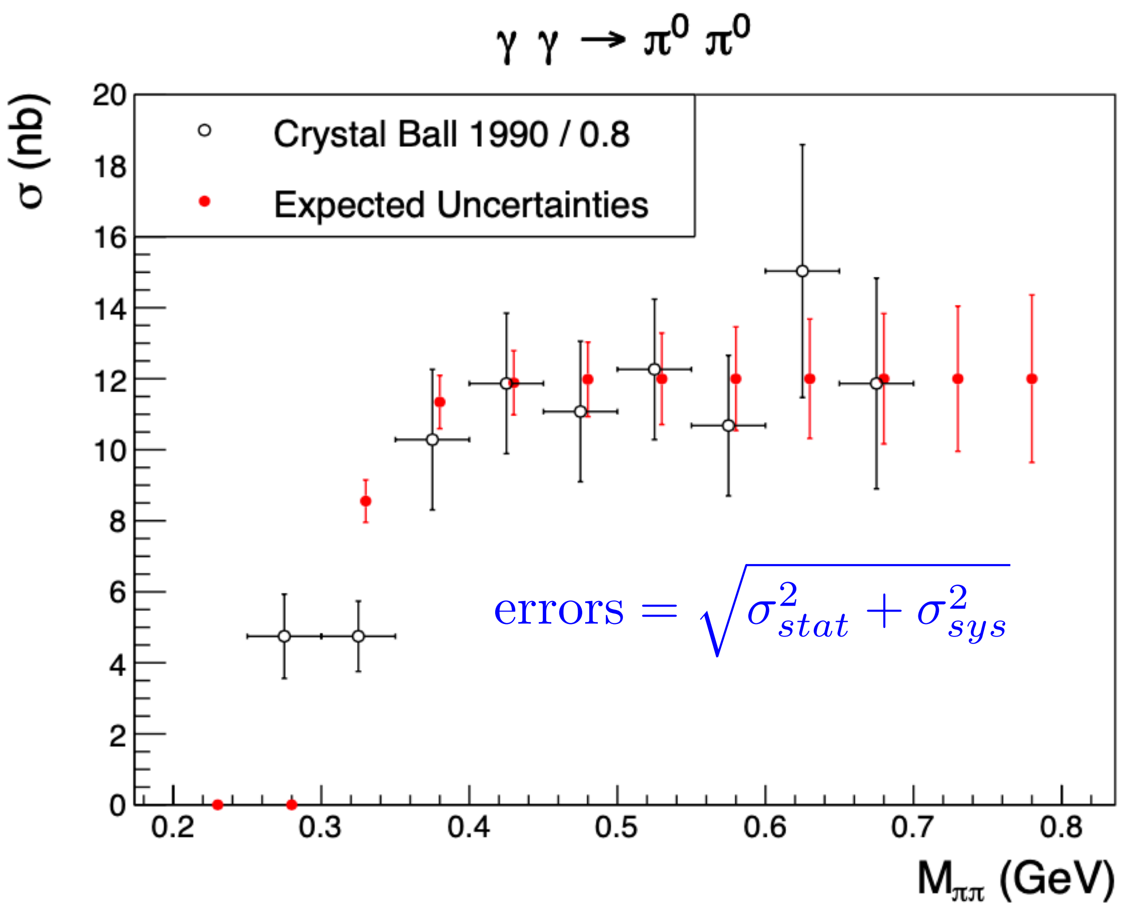
$$\alpha_{\pi^+} - \beta_{\pi^+} \sim 6 \pm 0.6 \times 10^{-4}\mathrm{fm}^3$$

Projected NPP rounded theory estimate for value

$$\alpha_{\pi^0} - \beta_{\pi^0} \sim -2 \pm 0.8 \times 10^{-4}\mathrm{fm}^3$$

Sensitivity

- High sensitivity of experiment at low $W_{\pi\pi}$
- Dai and Pennington: 5.1% determination of $\sigma(\gamma\gamma\to\pi^0\pi^0)$ gives $\alpha_\pi - \beta_\pi$ to 39%
- Best analysis uses combination of χPT and dispersion relation analysis
- Cross section measurement as a function of $W_{\pi\pi}$ is of general theoretical interest



Summary and outlook

- NPP will measure the π^0 polarizability for the first time
- Pion polarizabilities are sensitive tests of their Goldstone Boson nature. There is keen theoretical interest and excellent support

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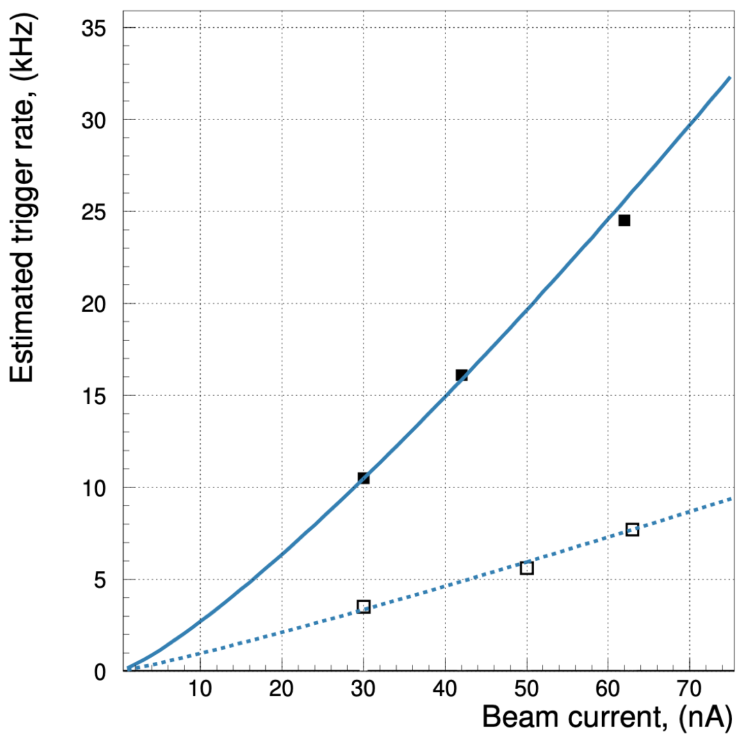
- We have simulated the primary backgrounds expected in the experiment
  - Nuclear coherent
  - Misidentified $\eta \rightarrow \pi^0 \pi^0 \pi^0$
  - Incoherent production
- We estimate we will measure the cross section $\sigma(\gamma\gamma \rightarrow \pi^0\pi^0)$ with an uncertainty of 5.1%, leading to an uncertainty on the neutral pion polarizability for $\alpha-\beta$ of 39%.
- The projected absolute uncertainty is similar to uncertainties for measurements of the polarizabities of charged pions and the proton.

Compatibility with CPP

- Target for CPP and NPP will be ^{208}Pb
  - This decision was made for CPP after PAC approval
- Rate for neutral trigger is < 10 kHz (E_{FCAL} > 1 GeV), which will allow running concurrently with CPP

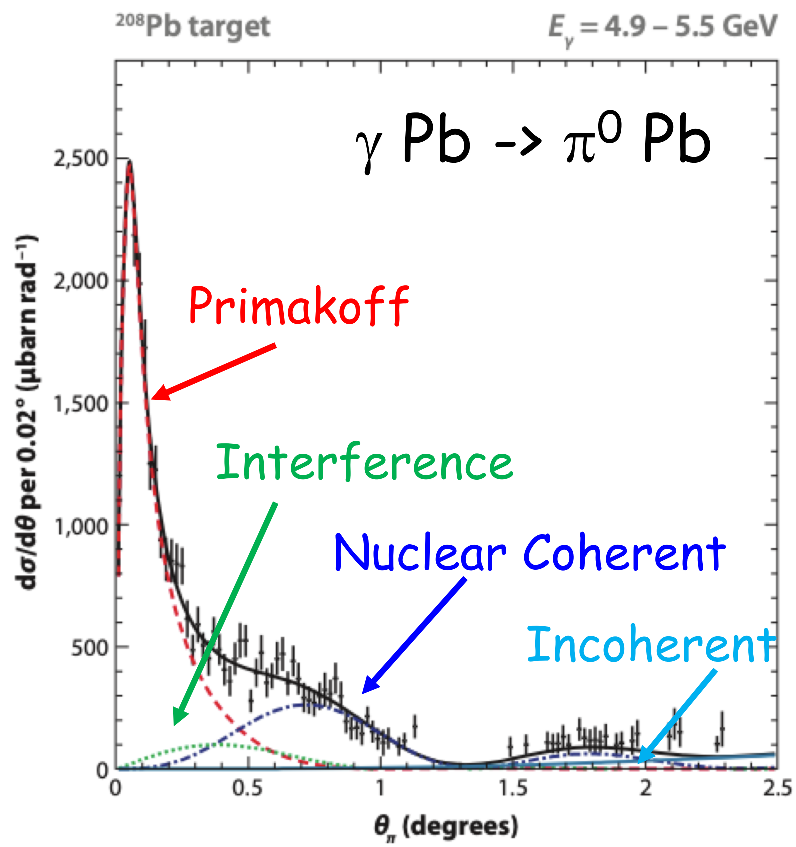


- Scale measured rates during test to CPP conditions:
  - Current = 20 nA
  - Target = 5% Rad. Length
  - Trigger rate < 10 kHz

Review: single p0 production (PrimEx)

- Primakoff production (photon-exchange mechanism). Peaks at 0.02⁰
- Nuclear Coherent production (vector-meson exchange mechanism). Peaks at ~ 0.75⁰.
- Interference between Primakoff and Nuclear Coherent.
- Incoherent production $\gamma N \rightarrow N \pi^0\pi^0$. Peaks at large angle and high $W_{\pi\pi}$

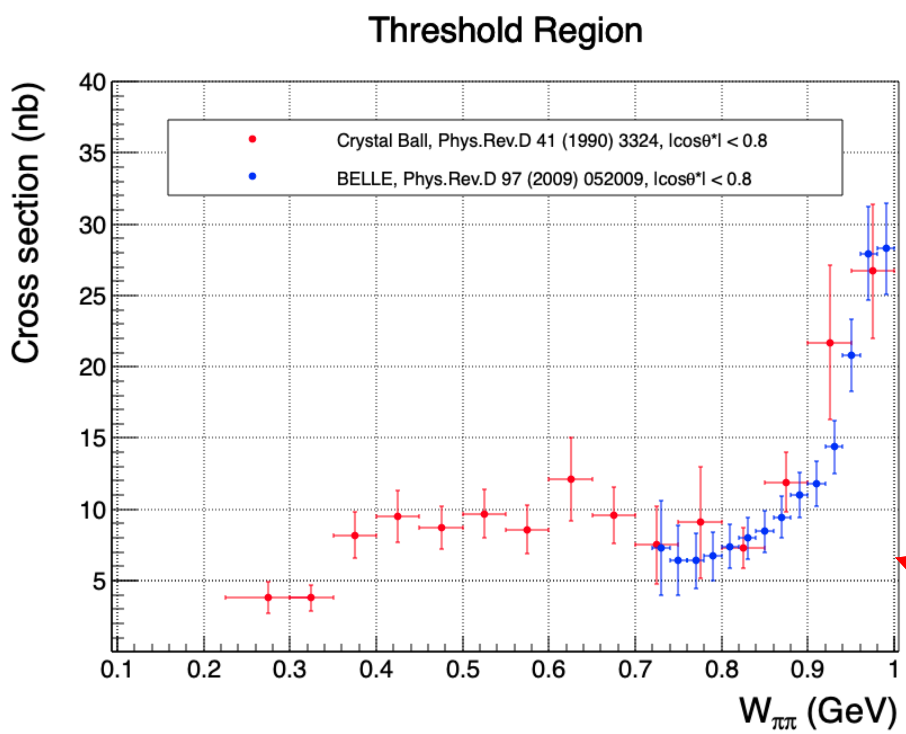
Ann Rev Nucl Part Sci 61 (2011) 1

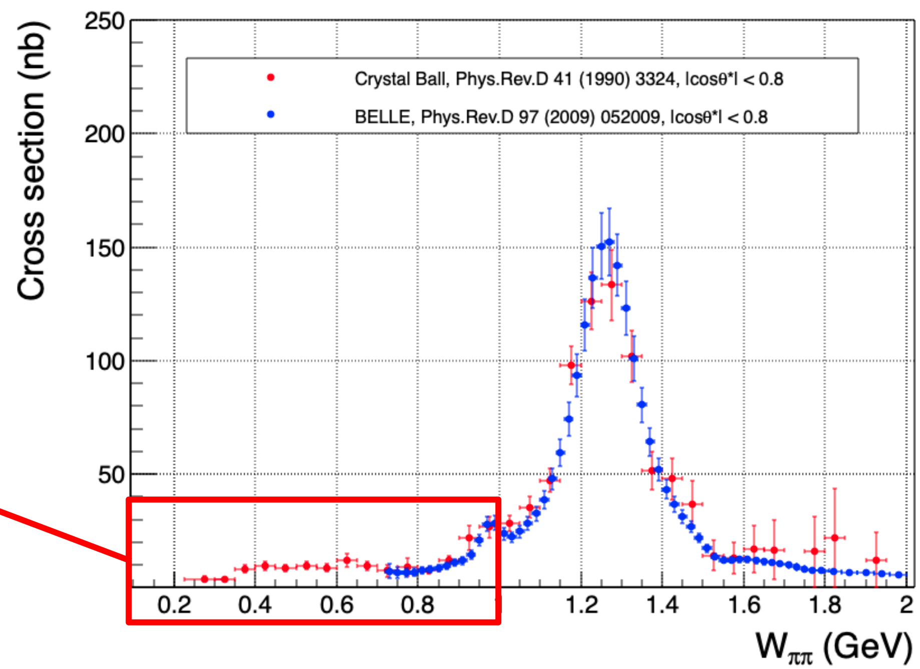


Past measurements (e+e-)

$$\gamma\gamma \rightarrow \pi^+\pi^-$$

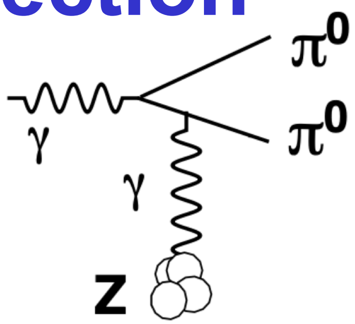
- Crystal Ball at DESY (DORIS II), 1990 [$W_{\pi\pi}$ < 0.6 GeV]
- BELLE at KEK (KEKB), 2009 [0.7 < $W_{\pi\pi}$ < 4.0 GeV]
- Cross section at low $W_{\pi\pi}$ is poorly known





Polarizabilities -> χPT -> dispersion relations -> cross section

$$\gamma\, Pb \rightarrow (Pb)\, \pi^0 \pi^0$$



- The polarizabilities are defined in terms of the forward Compton Amplitudes ($\gamma\pi^0 \to \gamma\pi^0$).
- Extrapolation is needed to relate these amplitudes to the measured ($\gamma\gamma \to \pi^0\pi^0$) cross section
- χPT provides the connection between the polarizability and spontaneous chiral symmetry breaking, but χPT is perturbative and diverges at high momentum.
- Dispersion Relations provide bridge between low and high $W_{\pi\pi}$
- Extraction of polarizabilities from the experimental cross section requires Dispersion theory matched with chiral perturbation theory.

Theory support

- Significant theoretical interest in a ~40% measurement of the neutral pion polarizability (-> 5% uncertainty of cross section)
- Theory involves the use of dispersion relations supplemented with chiral perturbation theory, which together permits an extrapolation of the Compton amplitudes from the $\gamma\,\gamma \to \pi^0\,\pi^0$ to the $\gamma\,\pi^0 \to \gamma\,\pi^0$ channel.
- Two-loop corrections will be significant; methodology is available; work is in progress
- Complimentary expertise in the theory support group: Jose Goity (JLab) and Aleksandrs Aleksejevs + Svetlana Barkanova (Memorial University of Newfoundland, Canada), S. Gevorkyan (Joint Institute for Nuclear Research, Dubna, Russia), L.-Y. Dai (Hunan University, China)

Detector resolution

$\sigma_{M\pi\pi} = 12$ MeV

$\sigma_\theta = 0.1$ deg

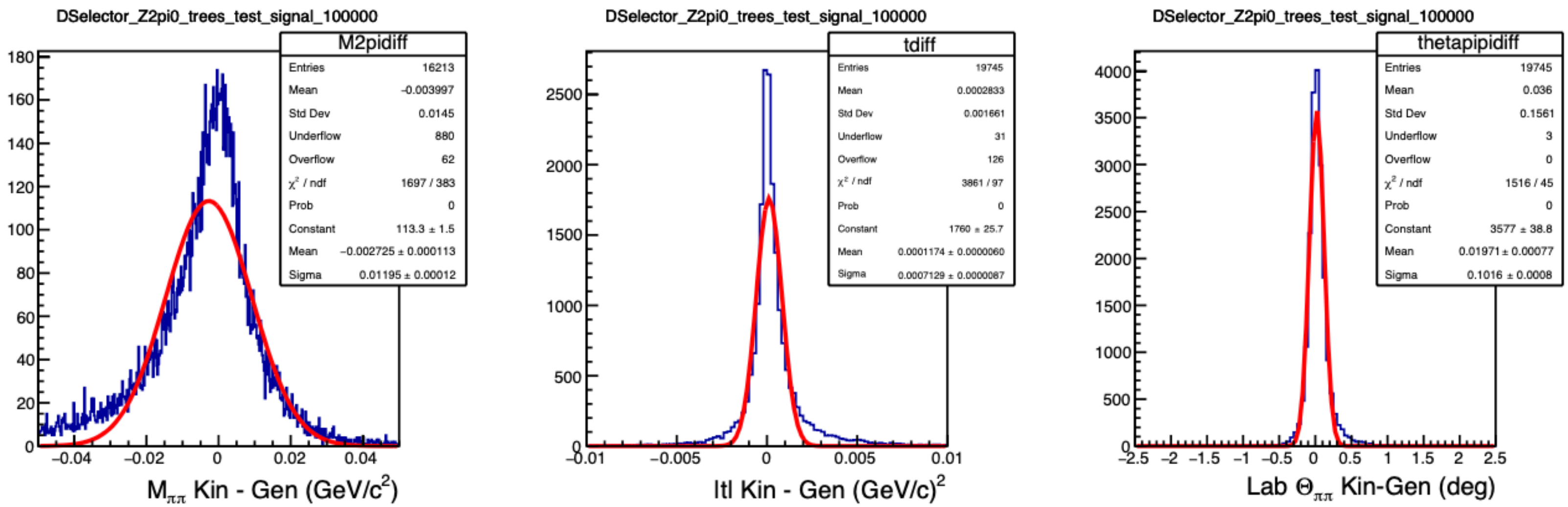


Figure 11: Left: Difference between kinematically fit and generated 2π mass. The central 2π-mass σ is about 12 MeV. Center: Difference between kinematically fit and generated -t. Right: Difference between kinematically fit and generated 2π polar angle. The resolution σ of the reconstructed angle is 0.1 degrees.