Pion Polarizabilities

Update on a Recent Measurement with GlueX in Hall-D at Jefferson Lab

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61st International Winter Meeting on Nuclear Physics
Bormio, Italy
January 26, 2025

Mount Allison University

New Brunswick

Population: 840,000
Area: 72,908 km^2

English and French

Lobster, Lumber, and High Tides

Mount Allison University

- 2,250 students
- Undergrads only

~5600 km to Vancouver by car…

Outline

- Introduction/Motivation
- Status of Pion Polarizabilities
- JLab Measurement
- Outlook and Summary

Fundamental Question:

"Can the theory of quark and gluon confinement quantitatively describe the detailed properties of hadrons?"

Theory: QCD describes the strong force in terms of quarks and gluons.

Nobel Prize in 2004 for **Asymptotic Freedom** in the perturbative QCD regime. . .

However, in the non-perturbative region, QCD is still unsolved.

One of the top-10 challenges for all of physics!

How to test QCD in the non-perturbative regime?

High-precision measurements of polarization observables.

Hadron Polarizabilities:

- Fundamental structure constants
- Response of internal structure to external fields
- Fertile meeting ground between theory and experiment
- Best accessed via **Compton scattering**, both real and virtual

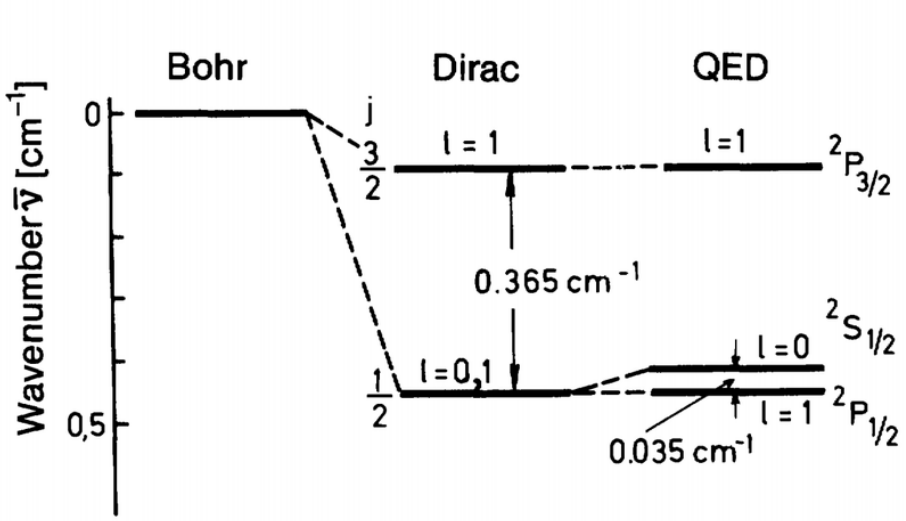
Theoretical Approaches:

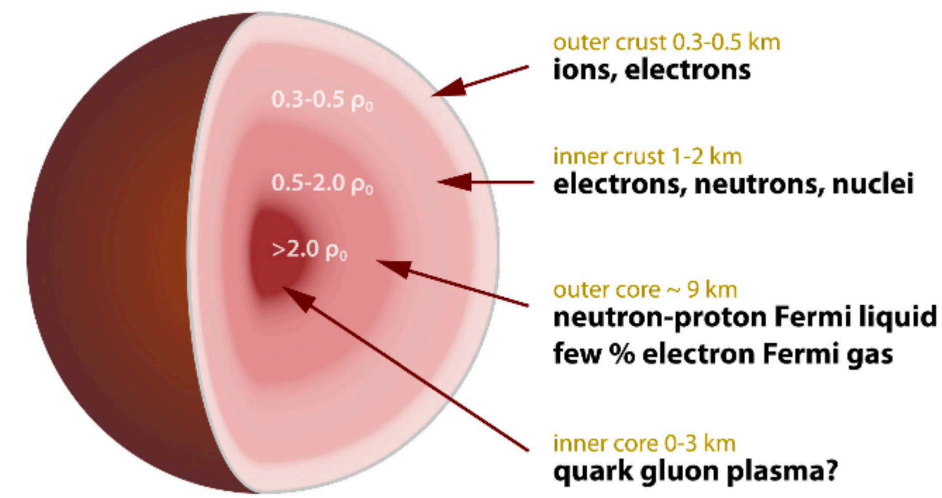
- Dispersion Relations
- **Chiral Perturbation Theory (ChPT)**
- Lattice QCD

In its domain of validity, **ChPT** represents predictions of QCD *subject to the errors imposed by uncertainties in the LECs and by neglect of higher order terms.*

Any discrepancy that is significantly larger than the combined experimental and theoretical errors **MUST** be taken seriously!

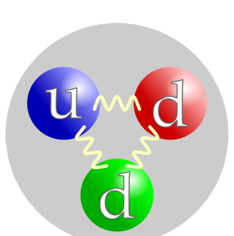
Why *else* do we care about polarizabilities?





Limit precision in other areas of physics:

- Lamb shift and hyperfine structure (proton radius).
- EM contribution to the $p - n$ mass difference.
- Neutron star Equation of State.



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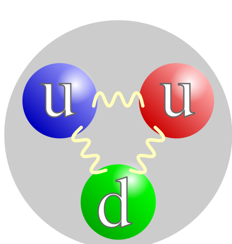
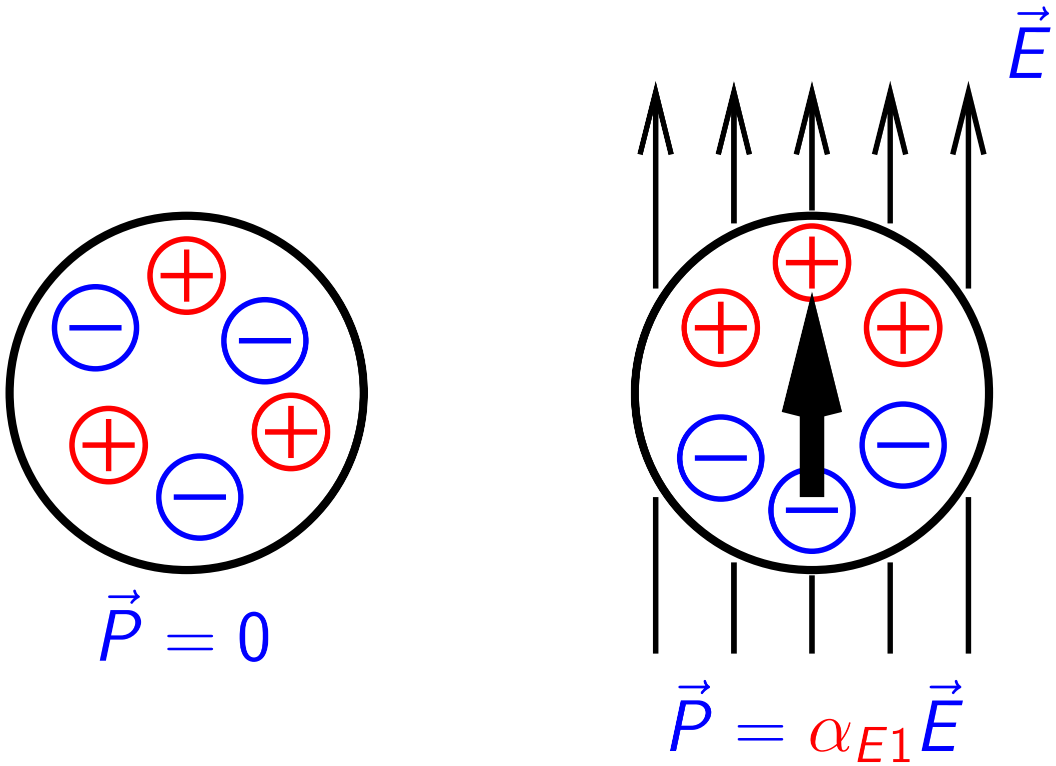


$= \Delta m_N$

Scalar Polarizabilities - Conceptual

Electric Dipole Polarizability

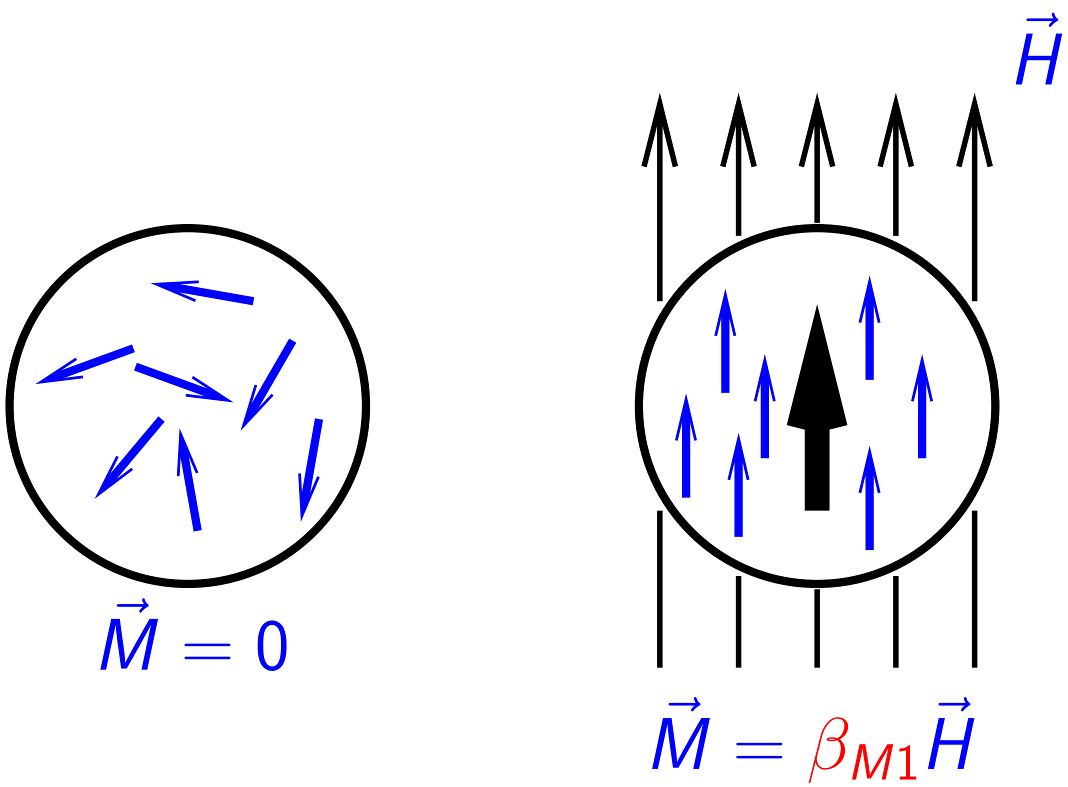


- Apply an electric field to a composite system
- Separation of Charge, or **"Stretchability"**
- Proportionality constant between electric dipole moment and electric field is the electric dipole polarizability, α_{E1}.

Provides information on force holding system together.

Scalar Polarizabilities - Conceptual

Magnetic Dipole Polarizability



- Apply a magnetic field to a composite system
- Alignment of dipoles or **"Alignability"**
- Proportionality constant between magnetic dipole moment and magnetic field is the magnetic dipole polarizability, β_{M1}.
- Two contributions, paramagnetic and diamagnetic, and they cancel partially, giving $\beta_{M1} < \alpha_{E1}$.

Provides information on force holding system together.

How about subatomic particles?

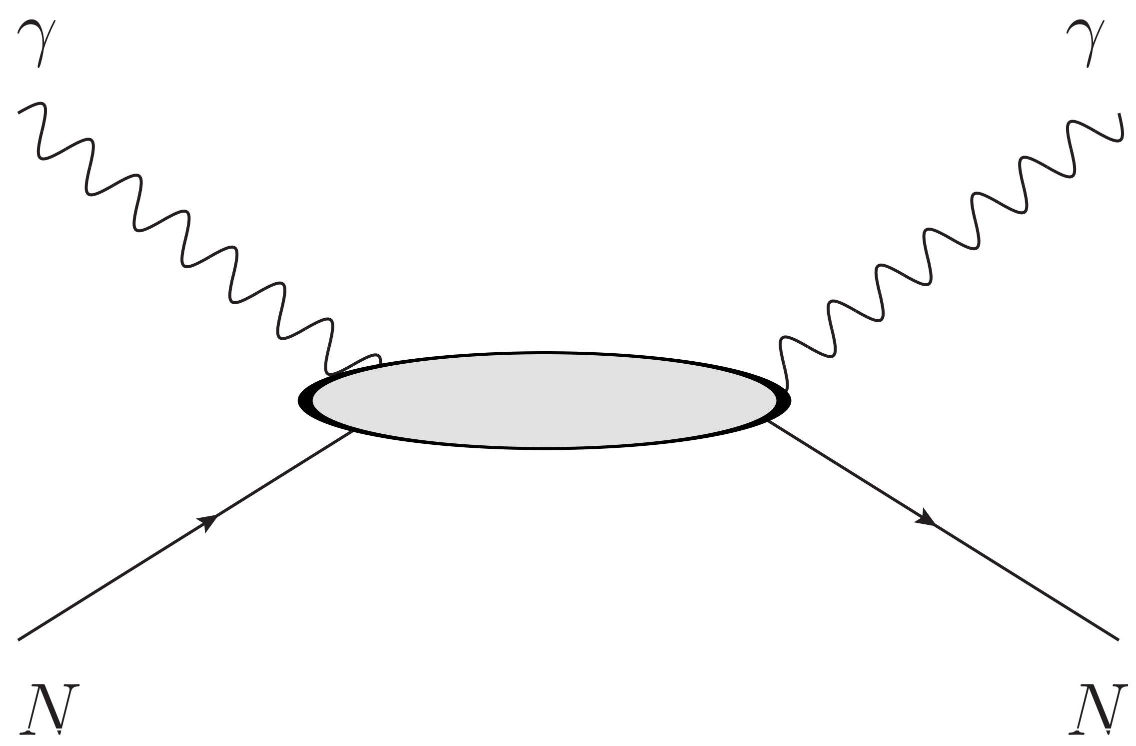
- Can’t just put a subatomic particle between the plates of a capacitor or the poles of a magnet and measure its deformation. What to do?
- The answer of course is Compton scattering.
- What kind of fields can we get from from a high-energy photon?
- Naively, for a 100-MeV photon:

$$E = \frac{V}{d} \simeq \frac{100 \text{ MV}}{10^{-15} \text{ m}} \simeq 10^{23} \text{ V/m}$$

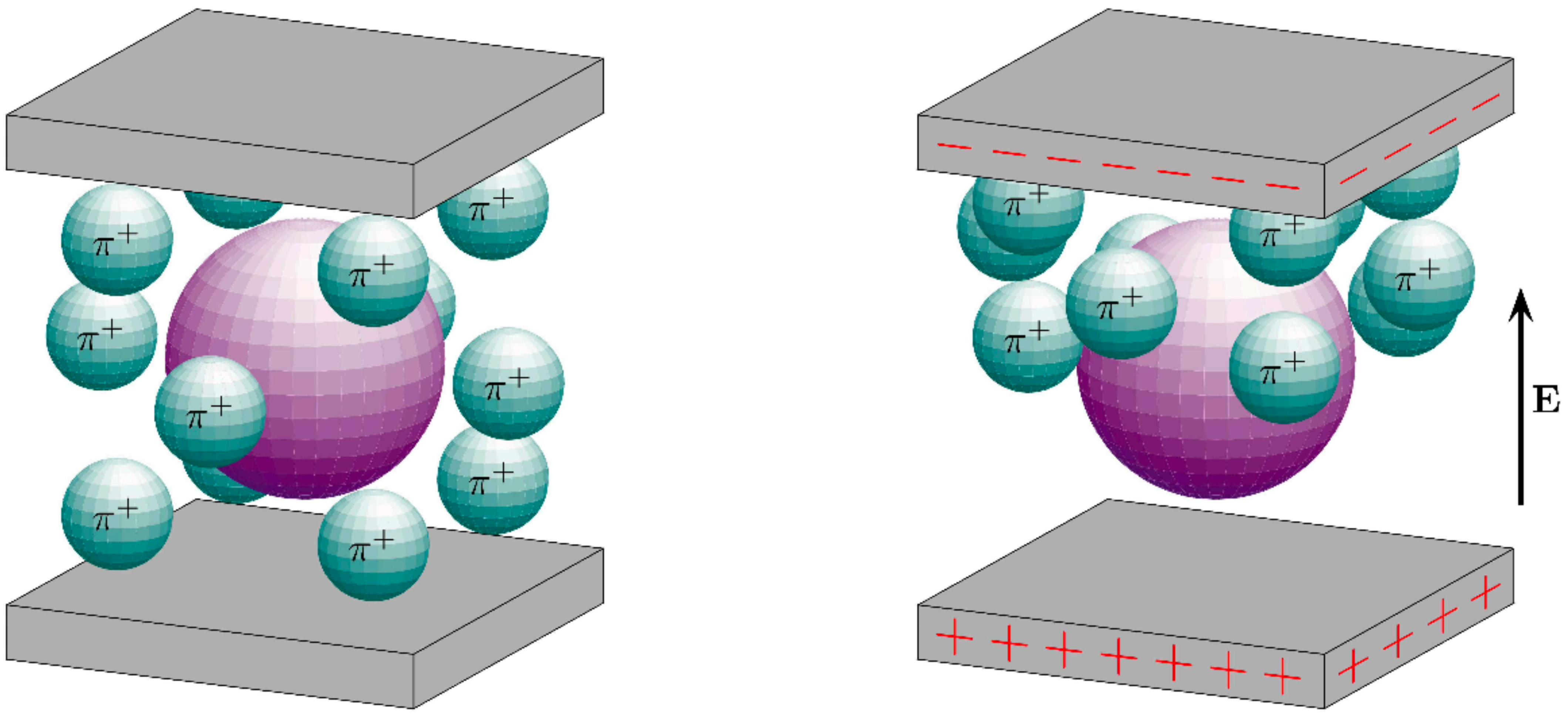
A HUGE field!

Real Compton Scattering

- The outgoing photon plays the role of the applied EM field.
- Internal Response.
- POLARIZABILITIES!
- Global response to the internal degrees of freedom.



Proton - Toy Model

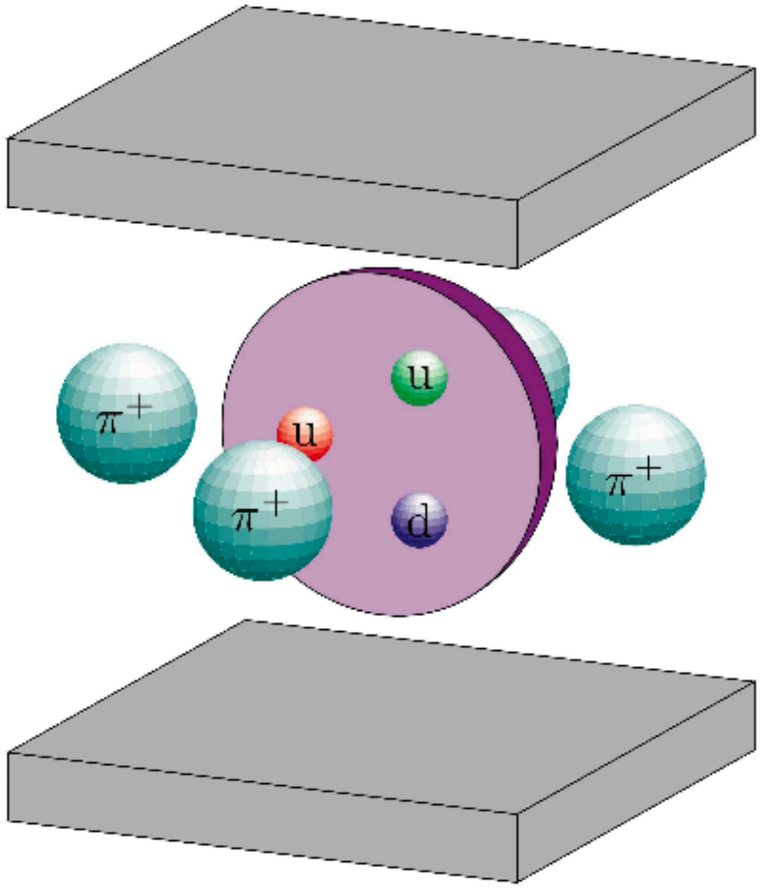


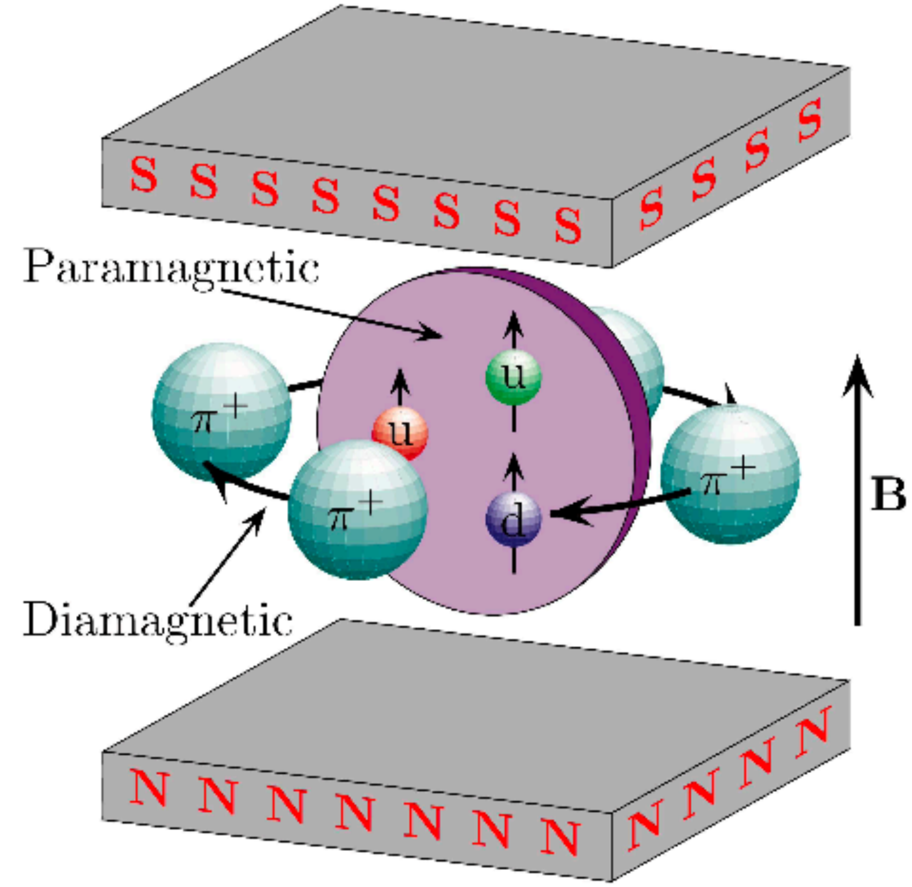
Electric Polarizability: proton between charged parallel plates.

$$\alpha_{E1} \approx 12 \times 10^{-4}\,\text{fm}^3 \approx 3 \times 10^{-4} V$$

Proton is VERY stiff! Not so easy to polarize.

Proton - Toy Model





Magnetic Polarizability: proton between poles of a magnet.

$$\beta_{M1} \approx 2 \times 10^{-4}\,\mathrm{fm}^3 \approx 10^{-4} V$$

Two contributions: paramagnetic and diamagnetic, and they partially cancel out.

Pion Polarizabilities

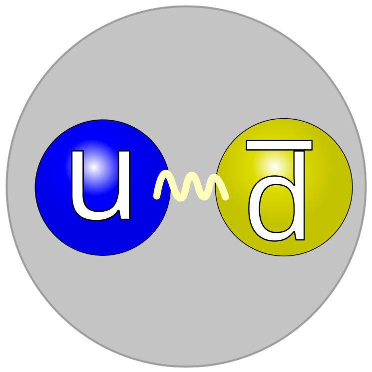
Mesons are "simpler" systems than baryons.

$\Rightarrow$ 2 quarks vs. 3

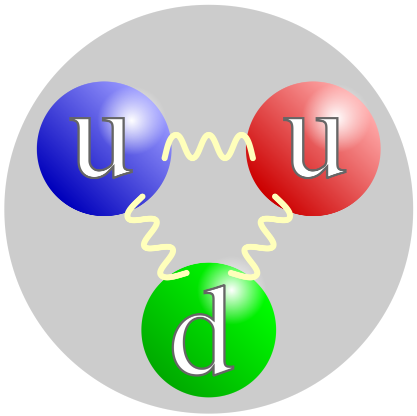
No pion target.

Very challenging to measure/extract from measurements.

Important tests of chiral dynamics.



π^+



p

Pion Polarizabilities

Provide a test for fundamental symmetries, specifically chiral symmetry and its realization in QCD.

Charged Pion Polarizability (CPP)

$\mathcal{O}(p^4)$ in ChPT:

$$\alpha_\pi = -\beta_\pi = \frac{4\alpha_{EM}}{m_\pi F_\pi^2}(L_9^r - L_{10}^r) \approx \frac{F_A}{F_V}$$

Where F_V and F_A are the weak FFs in $\pi^+ \to e^+ \nu \gamma$

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

$\mathcal{O}(p^6)$ ChPT:

$$\alpha_\pi - \beta_\pi = 5.7 \pm 0.1$$

$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1$$

$\mathcal{O}(p^6)$ corrections to the CPP are small.

Neutral Pion Polarizability (NPP)

LO ChPT:

$$\alpha_{\pi^0} + \beta_{\pi^0} = 0$$

$$\alpha_{\pi^0} - \beta_{\pi^0} = -\frac{\alpha_{EM}}{48\pi^2 m_\pi F_\pi^2} \approx -1.1$$

NLO ChPT:

$$\alpha_{\pi^0} + \beta_{\pi^0} = 1.15 \pm 0.30$$

$$\alpha_{\pi^0} - \beta_{\pi^0} = -1.90 \pm 0.20$$

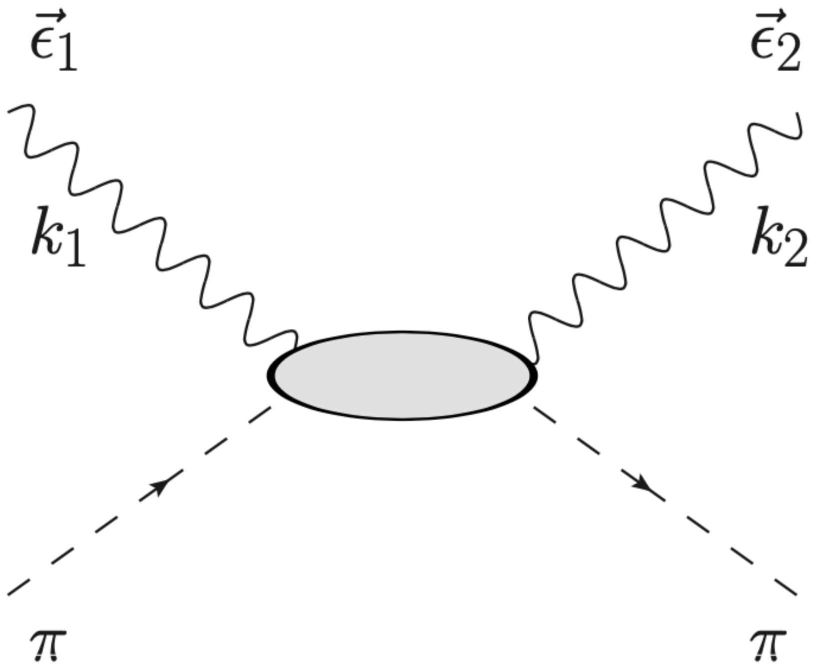
NPP has never been reliably determined.

Gasser, Ivanov and Sainio, Nucl. Phys. B **745**, 84 (2006)

Measuring Pion Polarizabilities

Lab-frame amplitude:

$$T = -\frac{e^2}{M_\pi} Q_\pi^2 \vec{\epsilon}_1 \cdot \vec{\epsilon}_2^{\,*} + 4\pi \left(\bar{\alpha}_\pi \omega_1 \omega_2 \vec{\epsilon}_1 \cdot \vec{\epsilon}_2^{\,*} + \bar{\beta}_\pi \vec{\epsilon}_1 \times \vec{k}_1 \cdot \vec{\epsilon}_2^{\,*} \times \vec{k}_2 \right) + \mathcal{O}(\omega^4)$$



Dispersion relation — Baldin-Lapidus sum rule:

$$\bar{\alpha}_\pi + \bar{\beta}_\pi = \frac{1}{2\pi^2} \int_{\omega_{thr}}^{\infty} d\omega \frac{\sigma(\gamma\pi \to X)}{\omega^2} \geq 0$$

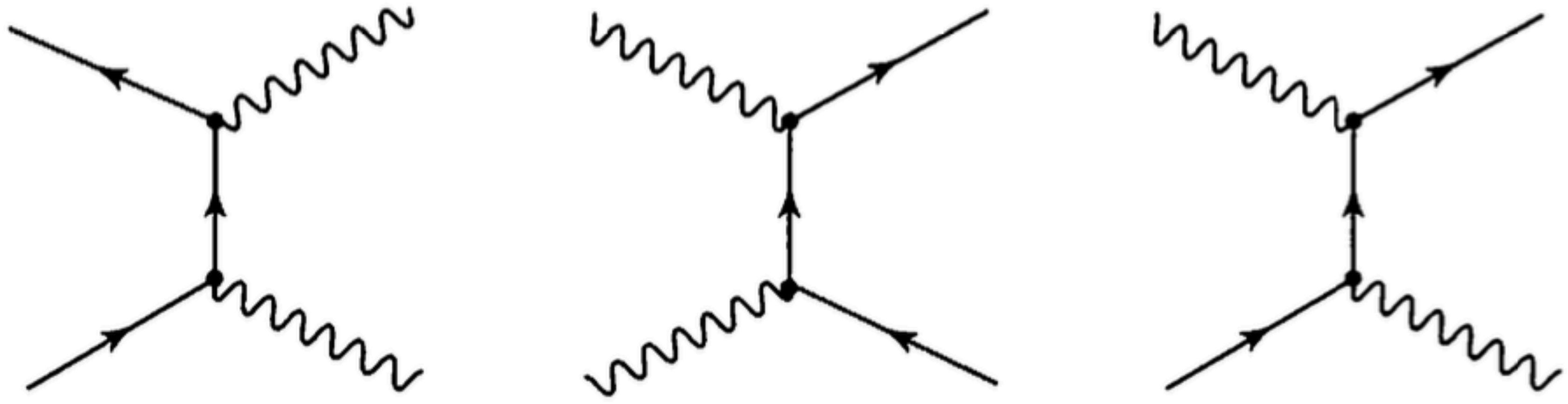
Gives a fundamental constraint.

	α_{E1}	β_{M1}
Proton (exp/EFT)	$12.7 \pm 0.8 \pm 0.1$	$2.4 \mp 0.6 \pm 0.1$
Pion (ChPT)	2.93 ± 0.1	-2.77 ± 0.1

$\left(10^{-4}\,\text{fm}^3\right)$

How to Compton scatter from a pion?!

Measuring Pion Polarizabilities



Pair annihilation | Pair production | Compton scattering

The diagrams are related via *crossing symmetry*.

Information on one process gives you information on the other two!

Measuring Pion Polarizabilities

Pion targets do not exist for Compton scattering.

$\Rightarrow$ Alternate methods!

Charged Pion Polarizability (CPP):

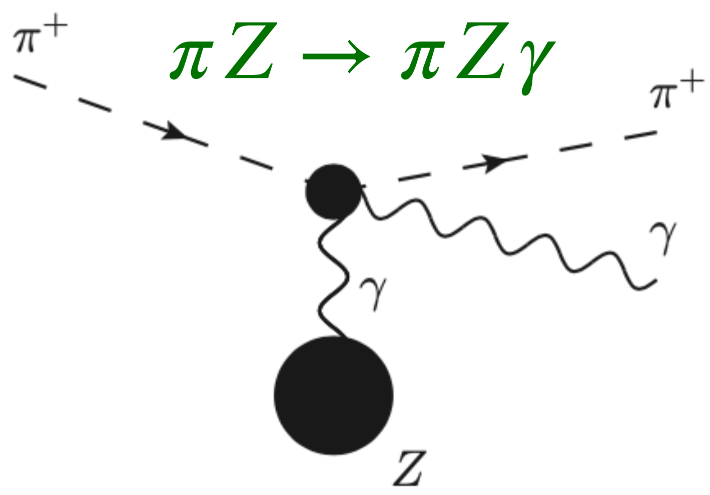
1. Radiative pion photo-production: $\gamma p \to \gamma' n \pi^+$ (Mainz A2)
2. Pion radiative scattering: $\pi^- A \to \gamma \pi^- A$ (COMPASS)
3. Production in two photon collisions: $\gamma\gamma \to \pi^+\pi^-$ (Mark II @ SLAC PEP)

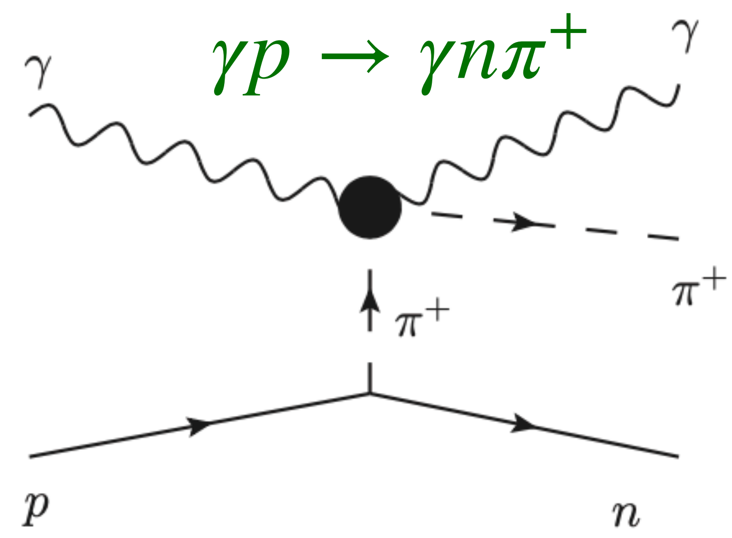
Neutral Pion Polarizability (NPP):

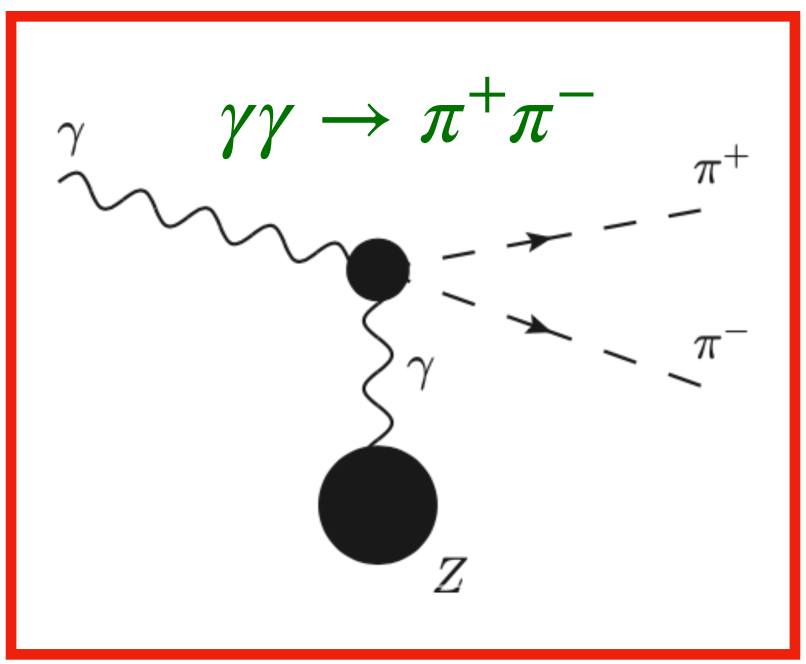
1. $\pi^0\pi^0$ production in two photon collisions: $\gamma\gamma \to \pi^0\pi^0$ (Crystal Ball @ DESY Doris II)

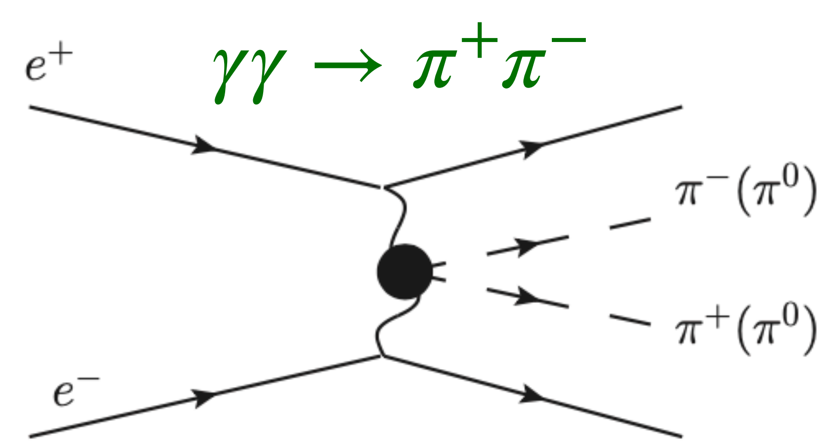
Measuring Pion Polarizabilities

Possible reactions





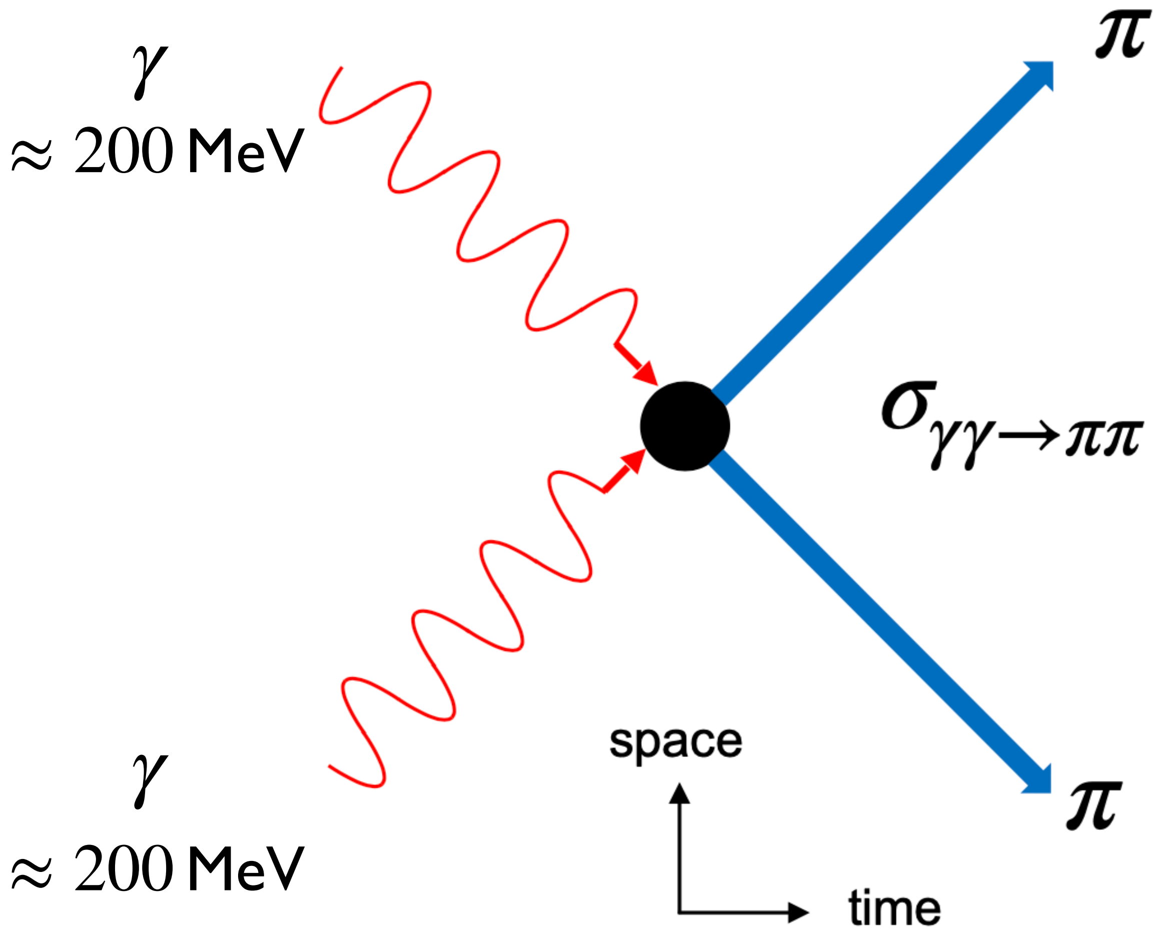




Each one contains the $\gamma\gamma \to \pi\pi$ vertex

Previous Measurements

Two-photon collisions $\gamma\gamma \to \pi\pi$



$\gamma\gamma \to \pi^+\pi^-$ at Mark-II
$\gamma\gamma \to \pi^0\pi^0$ at Crystal Ball

Theory

Donoghue and Holstein, Phys. Rev. D **48**, 137 (1993).
Gasser, Ivanov and Sainio, Nucl. Phys. B **745**, 84 (2006).
Pasquini, Drechsel, and Scherer, Phys. Rev. C **77**, 065211 (2008).
Dai and Pennington, Phys. Rev. D **90**, 036004 (2014), and Phys. Rev. D **94**, 116021 (2016).

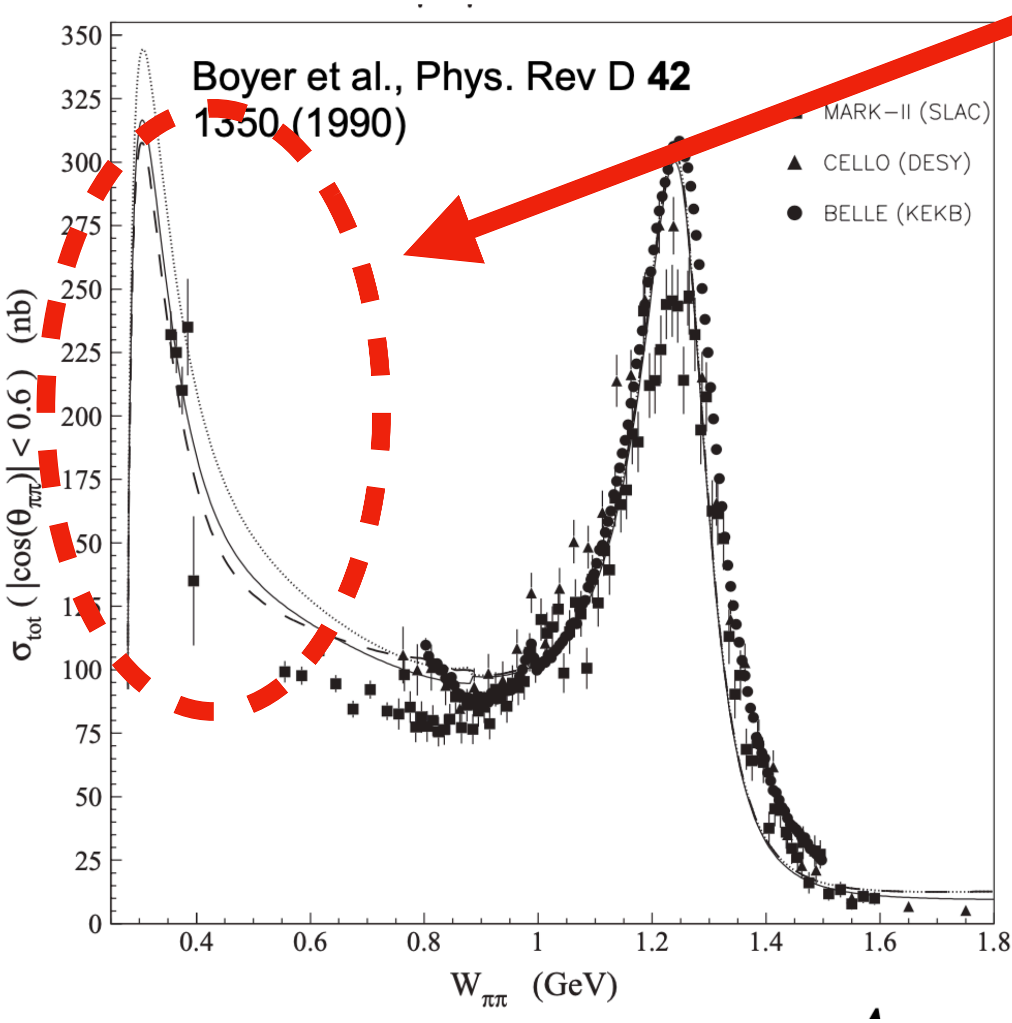
$$A_{\gamma\gamma\to\pi\pi} \xrightarrow{\text{dispersion theory}} A_{\text{Compton}} \to \alpha_\pi - \beta_\pi$$

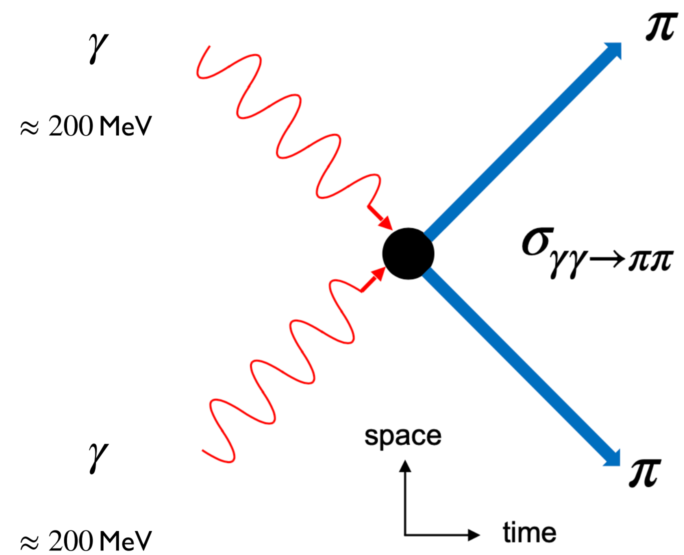
Previous Measurements

Two-photon collisions $\gamma\gamma \to \pi\pi$

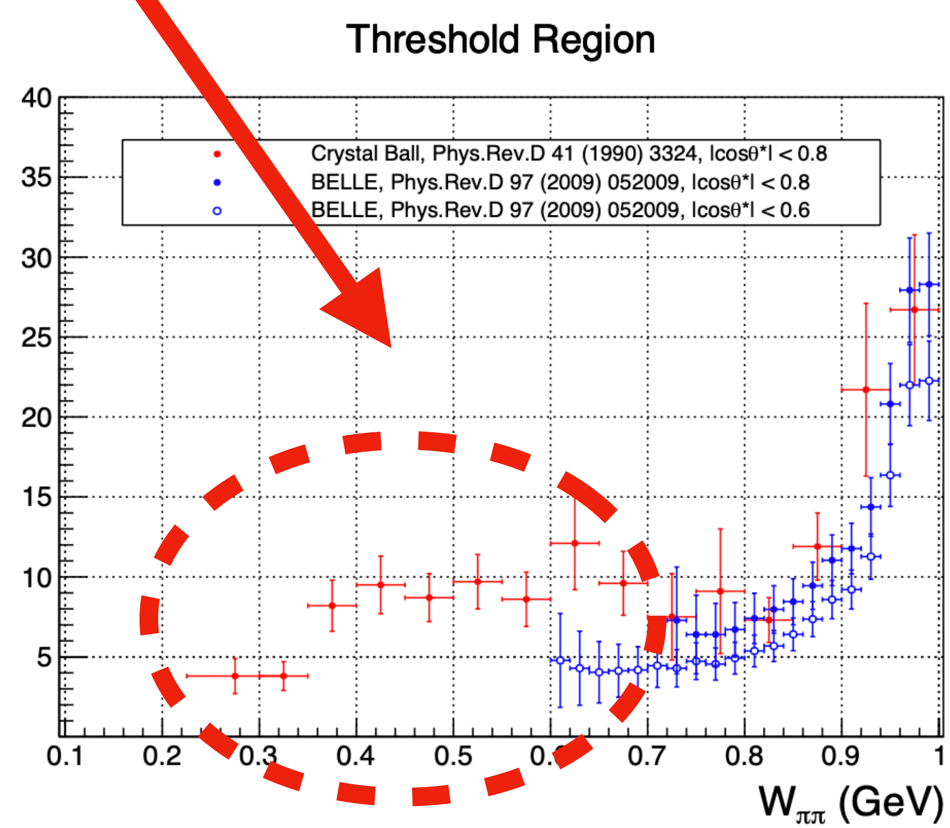
Poor statistics!

$\gamma\gamma \to \pi^+\pi^-$ at Mark-II





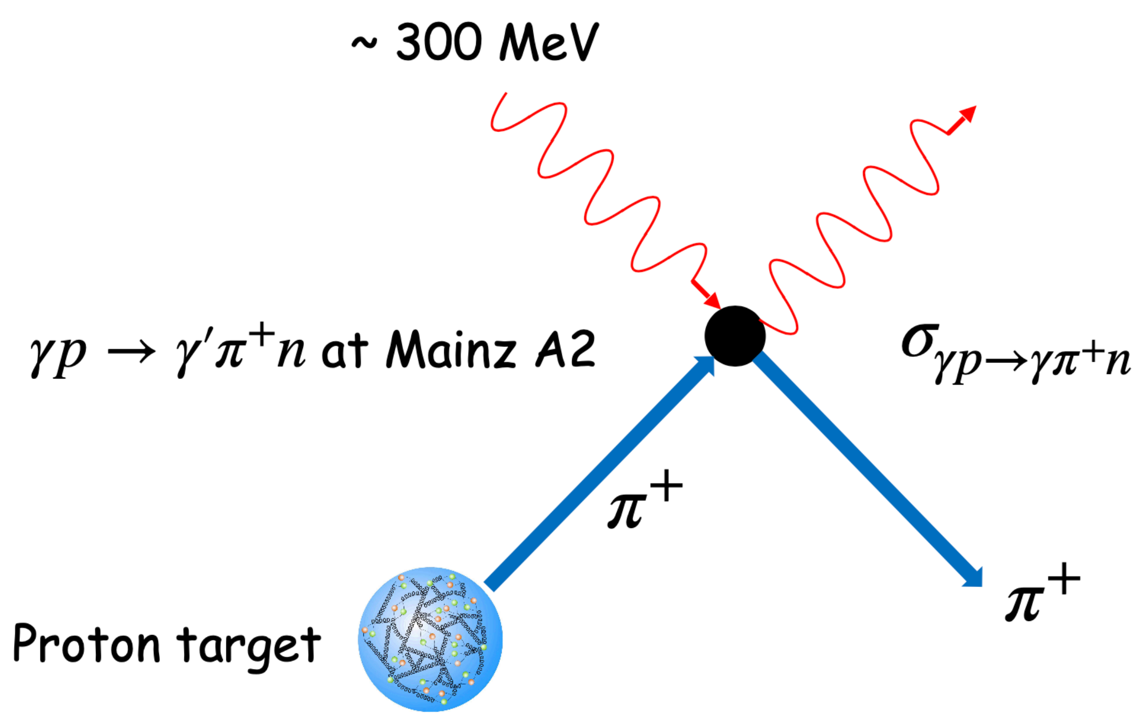
$\gamma\gamma \to \pi^0\pi^0$ at Crystal Ball



$$A_{\gamma\gamma\to\pi\pi} \xrightarrow{\text{dispersion theory}} A_{\text{Compton}} \to \alpha_\pi - \beta_\pi$$

Previous Measurements

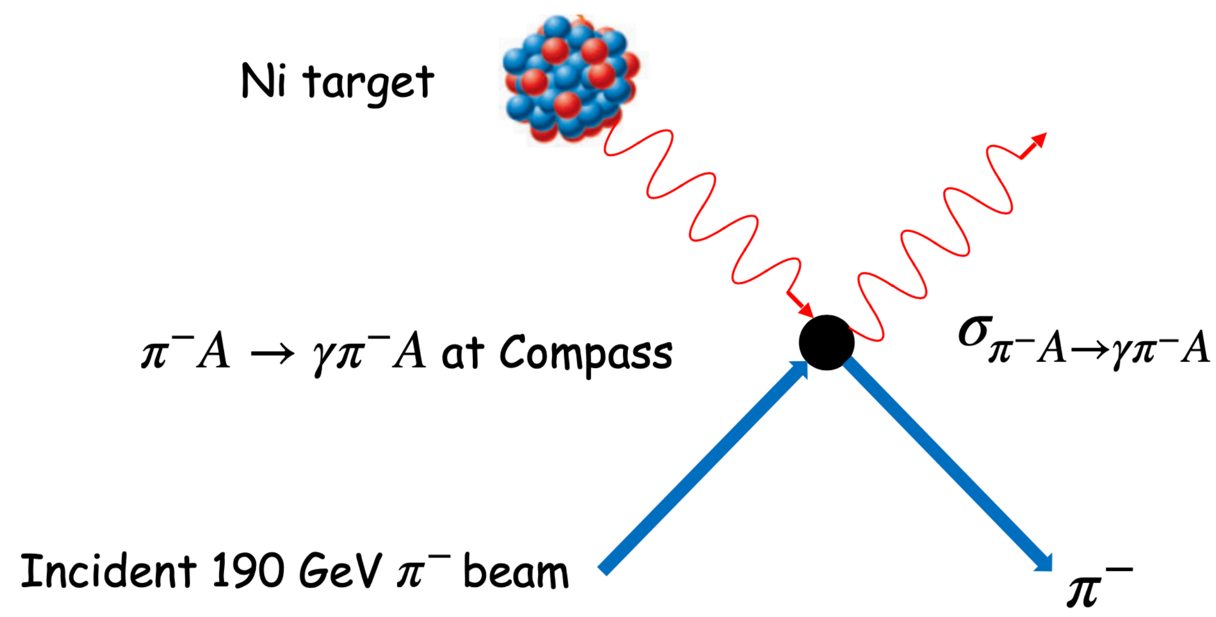
Radiative Pion



$$\sigma_{\gamma p \rightarrow \gamma \pi^+ n} \xrightarrow{hadronic\ models} \sigma^{Compton}_{\gamma \pi^+ \rightarrow \gamma \pi^+}$$

A2 Mainz

Pion Radiative

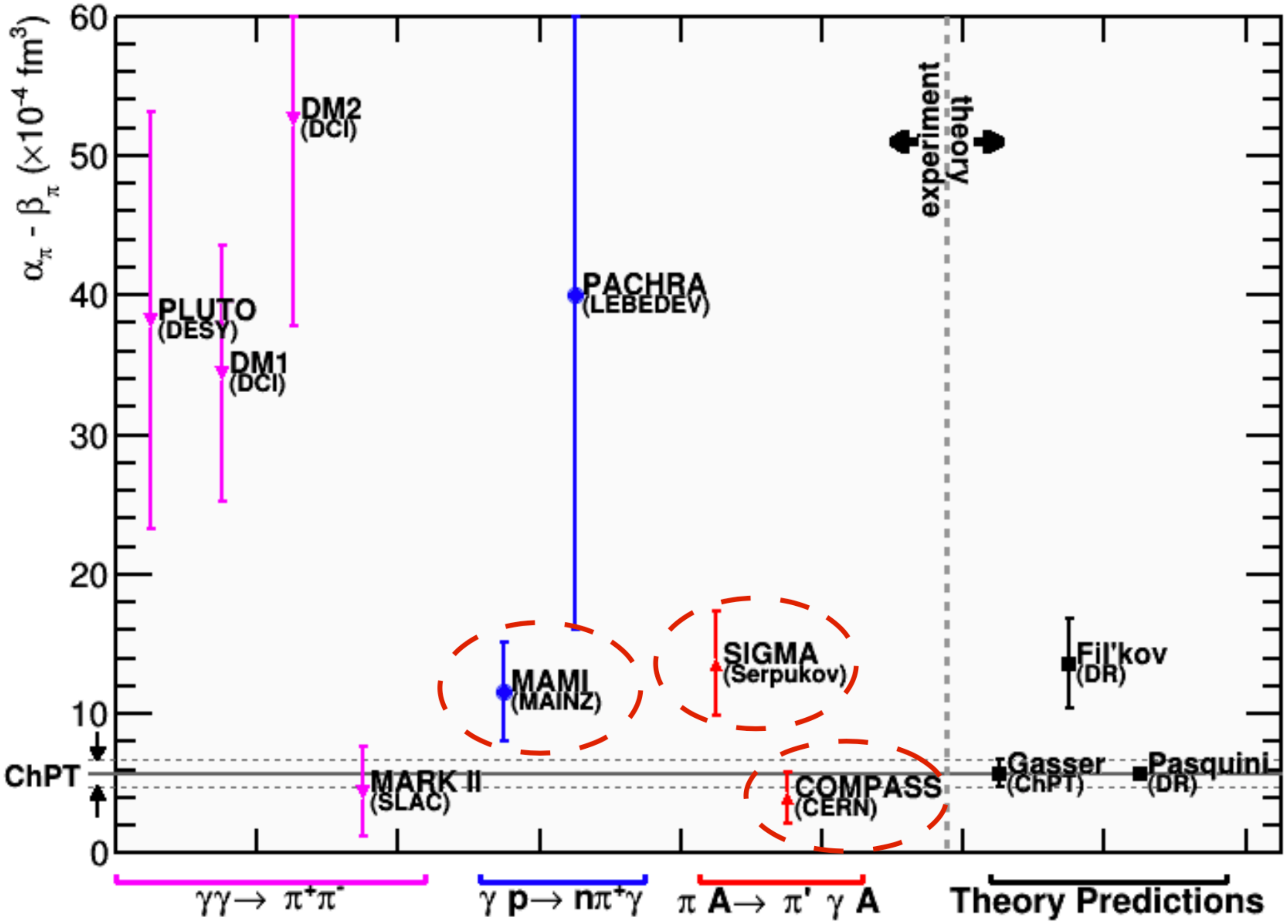


$$\sigma_{\pi^- A \rightarrow \gamma \pi^- A} \xrightarrow{LET} \sigma^{Compton}_{\gamma \pi^- \rightarrow \gamma \pi^-}$$

COMPASS

Pion Polarizabilities — Status

Published measurements & theory



Serpukov: Z. Phys. C **26,** 495 (1985).
$\pi^- A \to \pi^- A\gamma$ @ 40 GeV
$\alpha_\pi - \beta_\pi = (13.6 \pm 2.4) \times 10^{-4}\ \mathrm{fm}^3$

A2 Mainz: Eur. Phys. J. A **23,** 113 (2005).
$\gamma p \to \pi^- n\gamma$ @ 700 MeV
$\alpha_\pi - \beta_\pi = (11.6 \pm 1.5 \pm 3.0 \pm 0.5) \times 10^{-4}\ \mathrm{fm}^3$

COMPASS: PRL **114,** 062002 (2015).
$\pi^-\,\mathrm{Ni} \to \pi^-\,\gamma\,\mathrm{Ni}$ @ 160 GeV
$\alpha_\pi - \beta_\pi = (4.0 \pm 1.2 \pm 1.4) \times 10^{-4}\ \mathrm{fm}^3$

Tension in both the experiment and theory results.

Jefferson Lab Pion Polarizability Measurement

Modified GlueX Set-Up in Hall-D

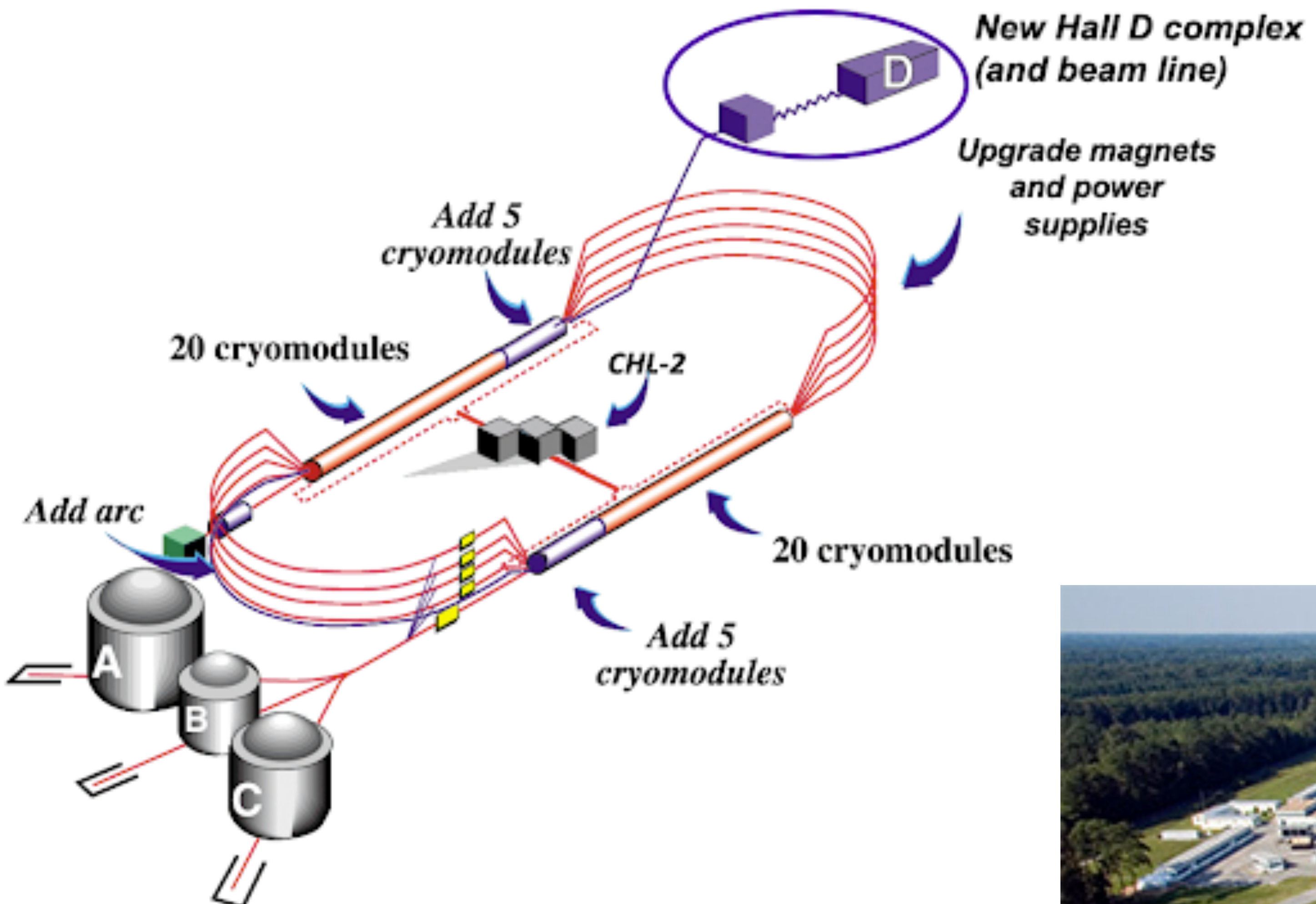
Goals for the JLab experiment:

1. Develop a new technique complementary to measurements at COMPASS and colliders.
2. Provide higher statistics for than existing collider data.
3. Provide a measurement of CPP with low statistical and systematic errors, and the first reliable measurement of NPP.

$$\frac{d^2\sigma_{Prim}}{d\Omega dM_{\pi\pi}} = \frac{2\alpha Z^2}{\pi^2}\frac{E_\gamma^2\beta^2}{M_{\pi\pi}}\frac{\sin^2\theta}{Q^4}\left|F_{EM}(Q^2)\right|^2\left(1 + P_\gamma \cos 2\phi_{\pi\pi}\right)\sigma_{\gamma\gamma\to\pi\pi}$$

Measuring Pion Polarizabilities at JLab

Newport News, Virginia, USA



Jefferson Lab

12-GeV CW electron machine

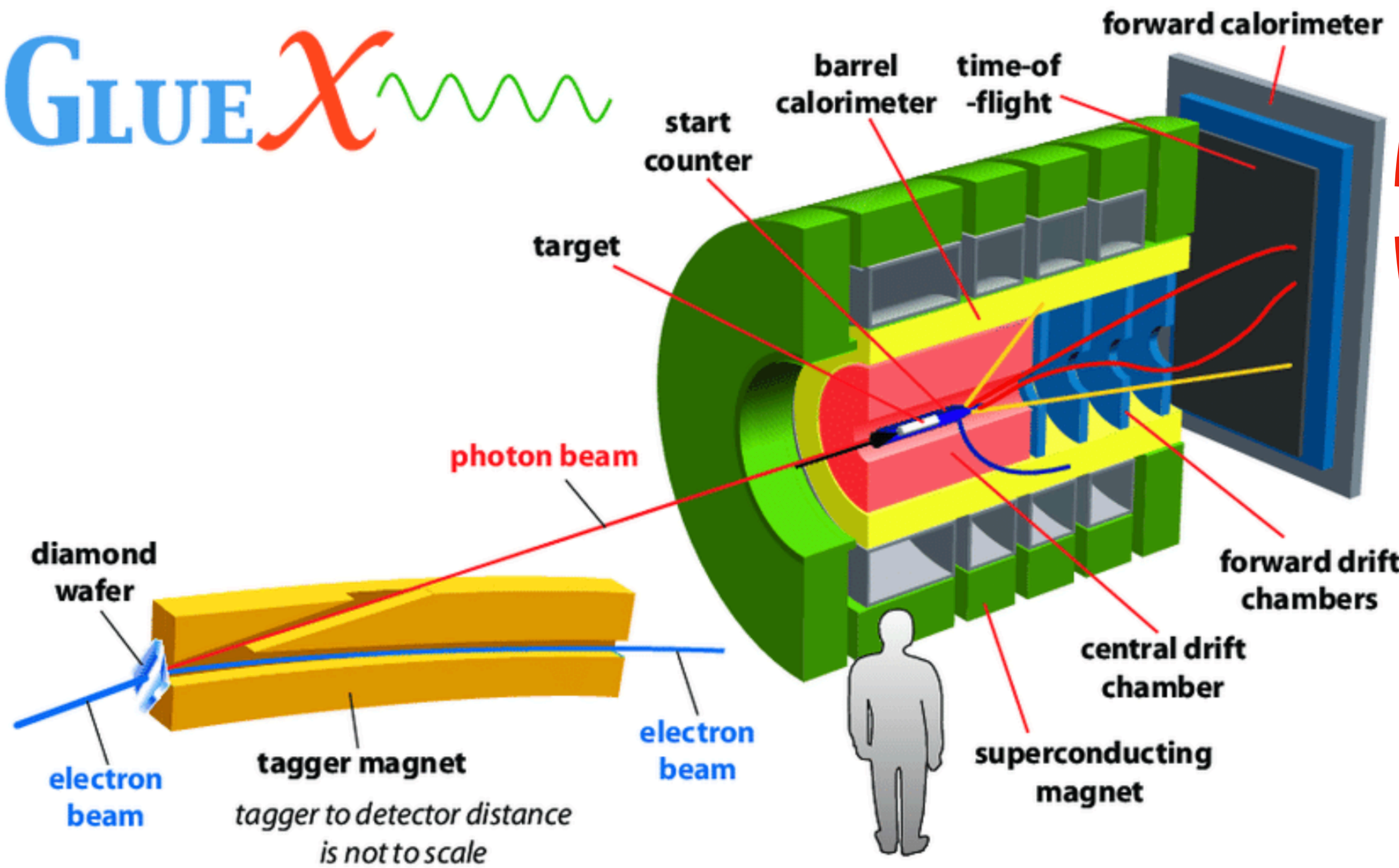
4 experimental halls

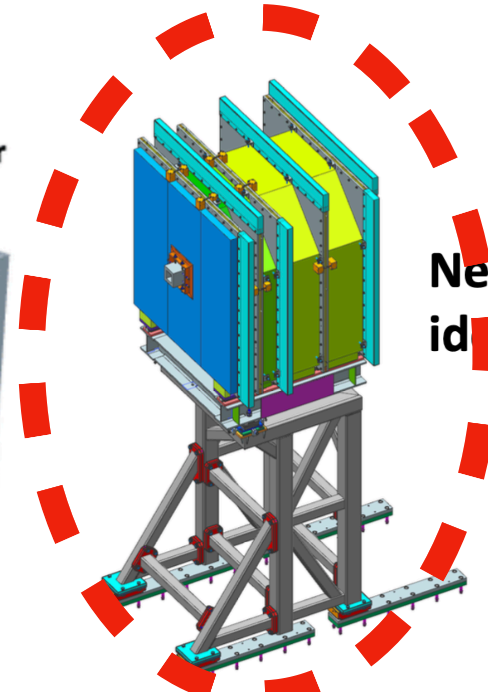
90 μA maximum current

90% Polarization

Measuring CPP/NPP at JLab

Modified GlueX Set-Up in Hall-D



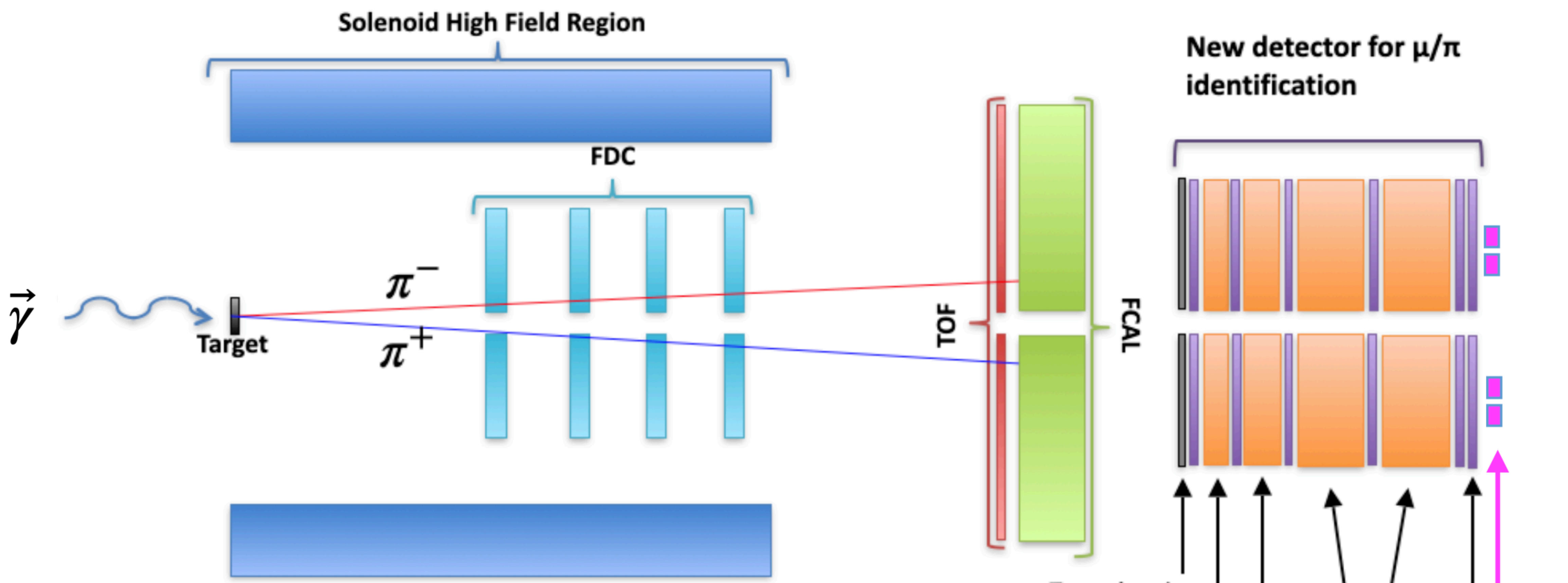


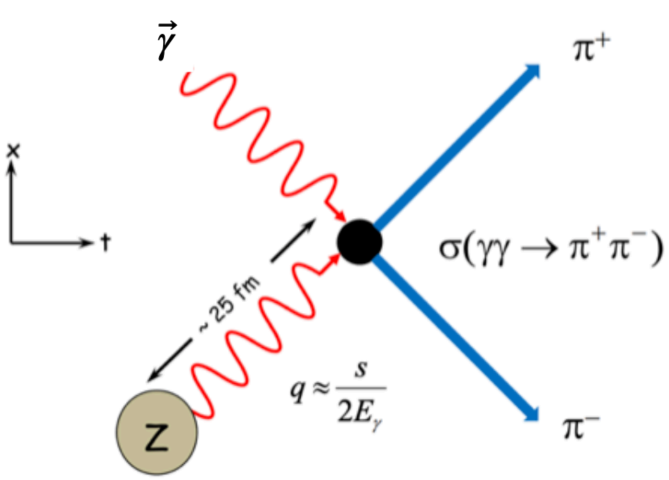
New detector for μ/π identification

Primary purpose is to study hybrid and exotic mesons.

Measuring CPP/NPP at JLab

Modified GlueX Set-Up in Hall-D





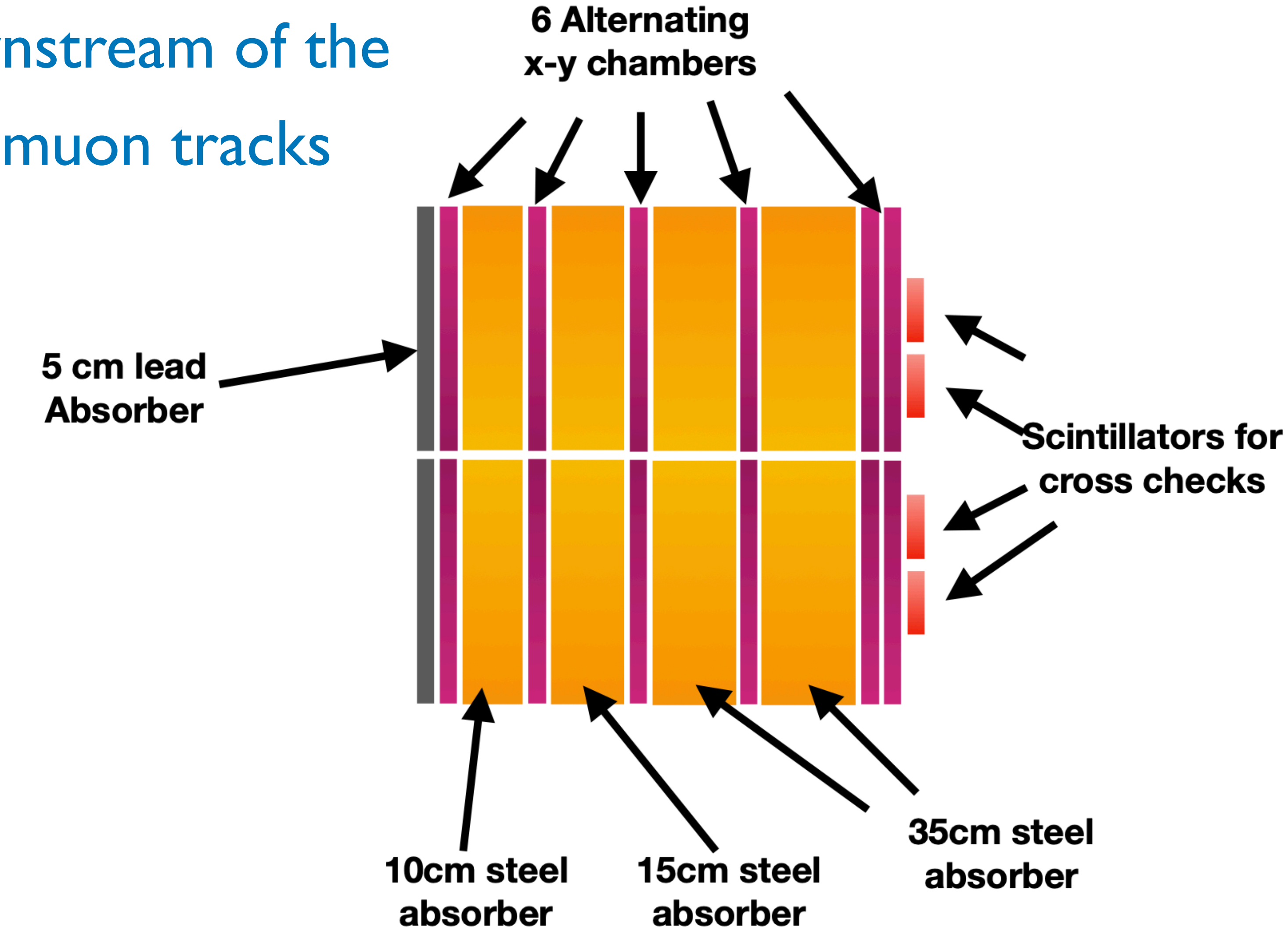
One of the main backgrounds is $\mu^+\mu^-$ production.

Measuring CPP/NPP at JLab

Muon Detector Specifically build for the CPP Measurement

8 MWPCs built at UMASS, 6 used in CPP.

- Each MWPC has 144 channels (sense wires)
- 90% Ar + 10% CO_2 gas mixture
- 4 scintillators were placed downstream of the final chamber for triggering on muon tracks



Measuring CPP/NPP at JLab

GlueX at Hall-D

Configuration	Nominal GlueX I	Charged Pion Polarizability	Neutral Pion Polarizability
Electron Beam Energy	11.6 GeV	11.6 GeV	11.6 GeV
Coherent Peak Energy	8.4-9.0 GeV	4.5-6 GeV	4.5-6 GeV
Current	150 nA	30 nA	30 nA
Radiator thickness	50 μm diamond	50 μm diamond	50 μm diamond
Collimator aperture	5 mm	3.4 mm	3.4 mm
Peak polarization	35%	73%	73%
Tagging ratio	0.6	0.56	0.56
Flux 5.5-6.0 GeV	-	11 MHz	11 MHz
Flux 8.4-9.0 GeV	20 MHz	-	-
Flux 0.3-11.3 GeV	367 MHz	56 MHz	56 MHz
Target Position	65 cm	1 cm	1 cm
Target, length	LH2, 30 cm	^{208}Pb, 0.03 cm	^{208}Pb, 0.03 cm
Start Counter and DIRC	Nominal	Removed	Removed
Tagger microscope	Nominal for Peak at 9 GeV	Moved for Peak at 6 GeV	Moved for Peak at 6 GeV
Muon Detector	None	Installed behind FCAL	Not needed
Trigger	FCAL/BCAL (40 kHz)	TOF (30 kHz)	FCAL/BCAL (10 kHz)

Measuring CPP/NPP at JLab

GlueX at Hall-D

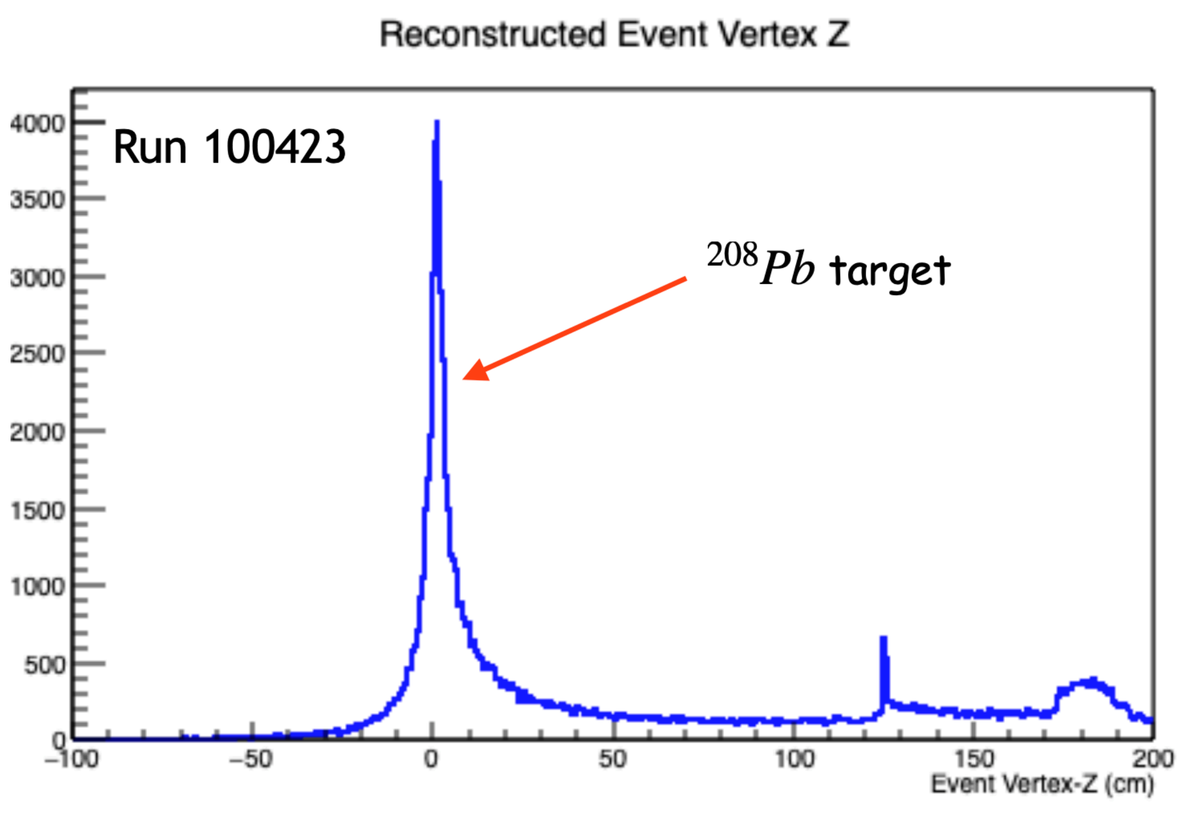
Modified Set-up:

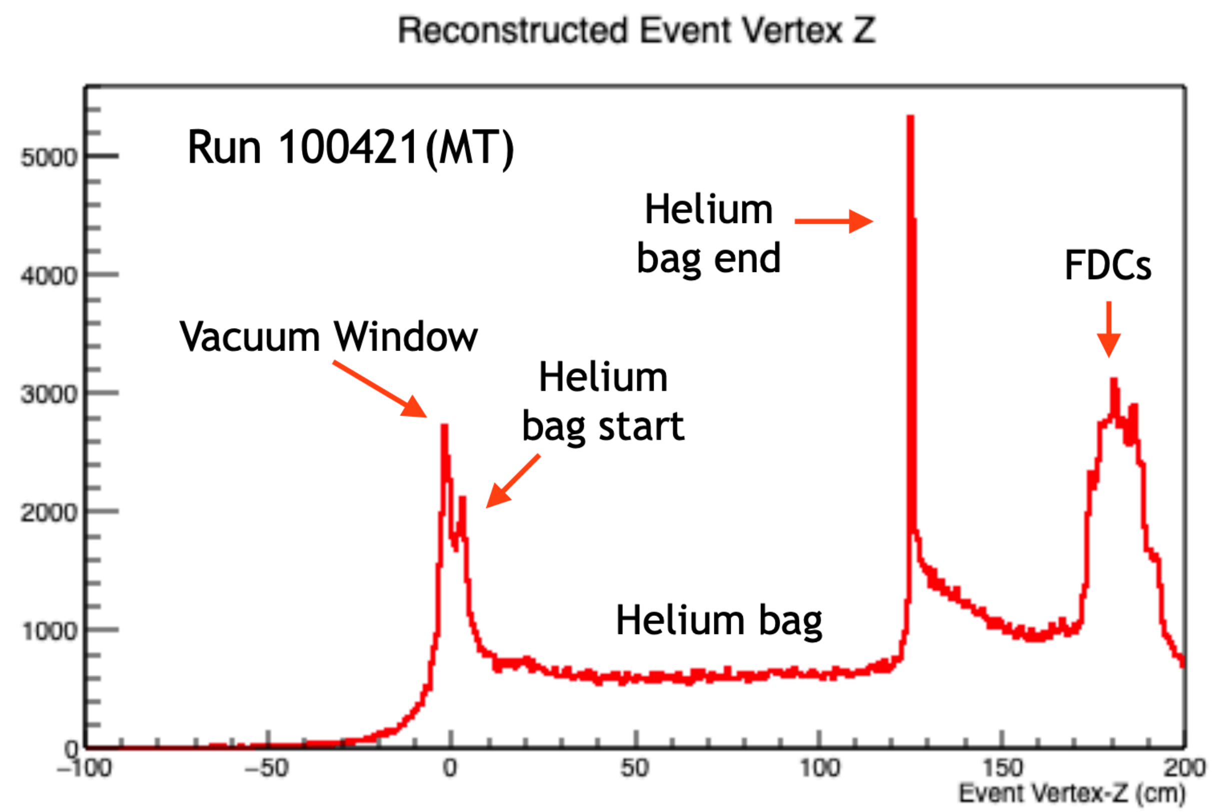
1. Installed and commissioned 6 MWPCs and 4 TOFs along with massive absorbers for $\mu^{\pm}$ detection.
2. Moved tagger microscope from 9 GeV to 6 GeV.
3. New diamond for coherent bremsstrahlung (polarized photon beam).
4. New trigger based on TOF and 2 charged particles.
5. New lead shielding.
6. New software to readout, monitor, and analyze data from the new detectors.

Took data in summer 2022 with **6 GeV linearly polarized photons** on Pb target, **~80% polarization**.

Measuring CPP/NPP at JLab

Vertex Resolution for Charged Tracks in GlueX





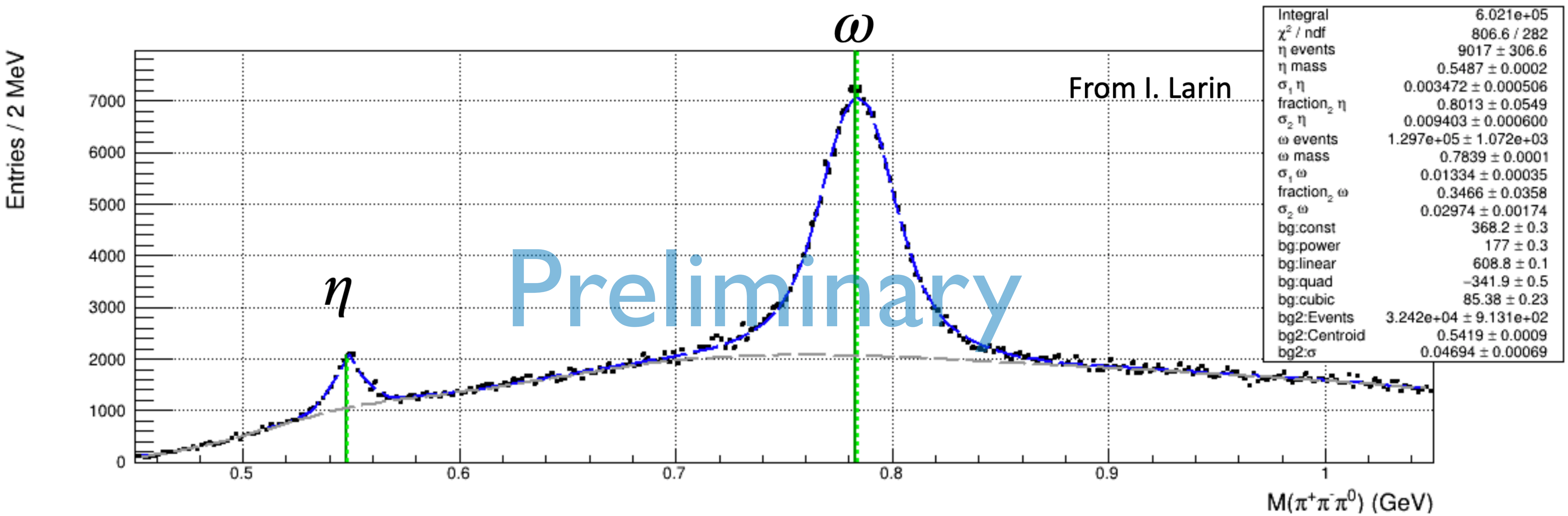
Pb target in

Pb target out

Measuring CPP/NPP at JLab

Very Preliminary Look at ω Production

$$\vec{\gamma}\, Pb \rightarrow \pi^+\pi^-\pi^0$$



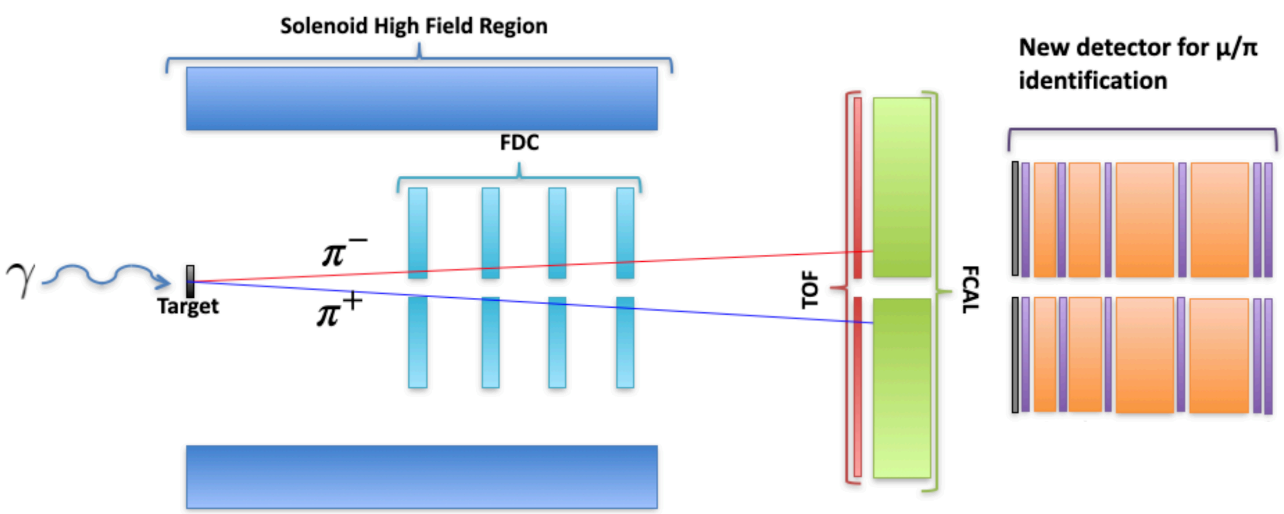
$\pi^+\pi^-\pi^0$ invariant mass

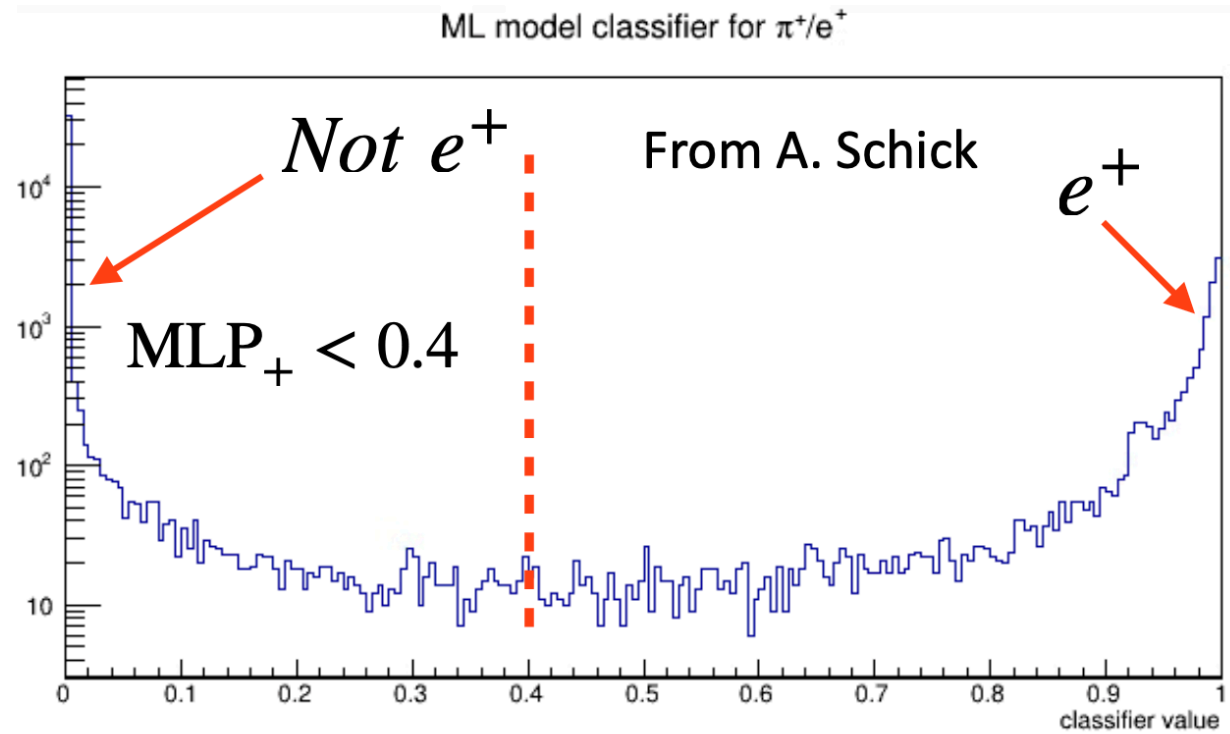
Measuring CPP/NPP at JLab

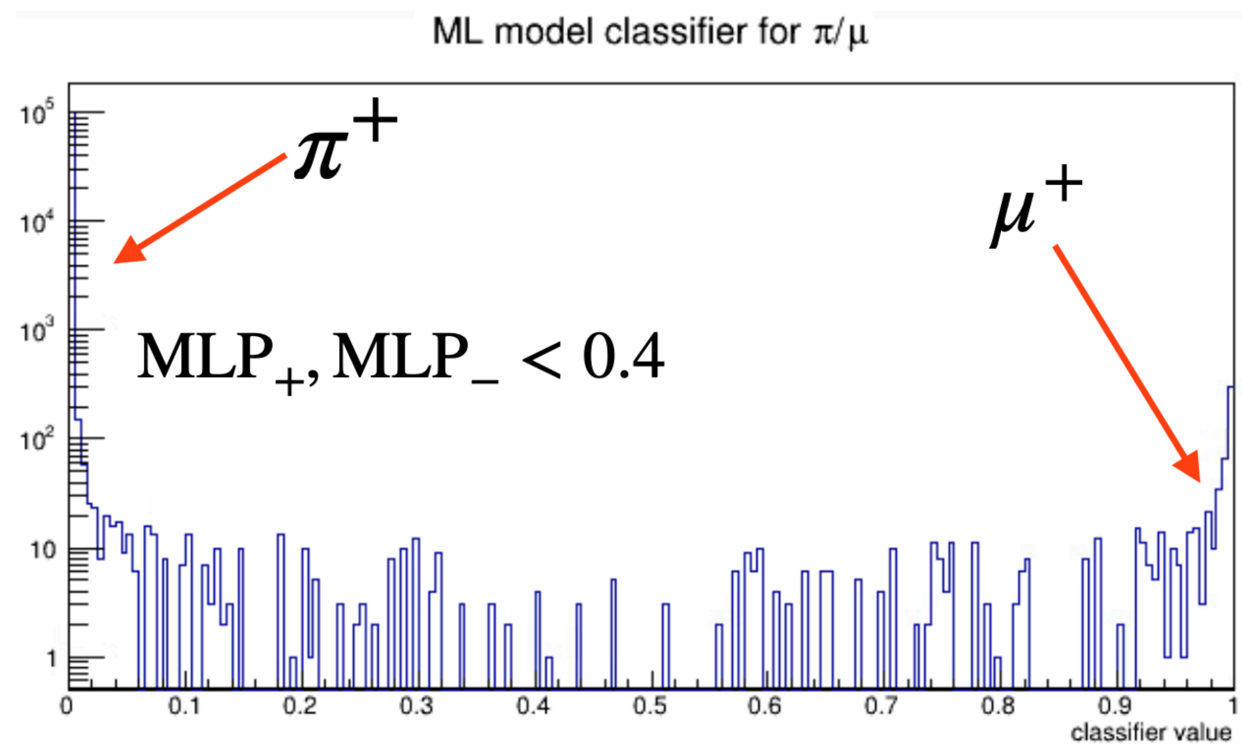
Particle ID: Neural Net Analysis (A. Schick)

MLP = "multilayer perceptron" neural net

MLP response is the "score" the neural net gives to an event as to it being signal or background based on the recorded detector responses





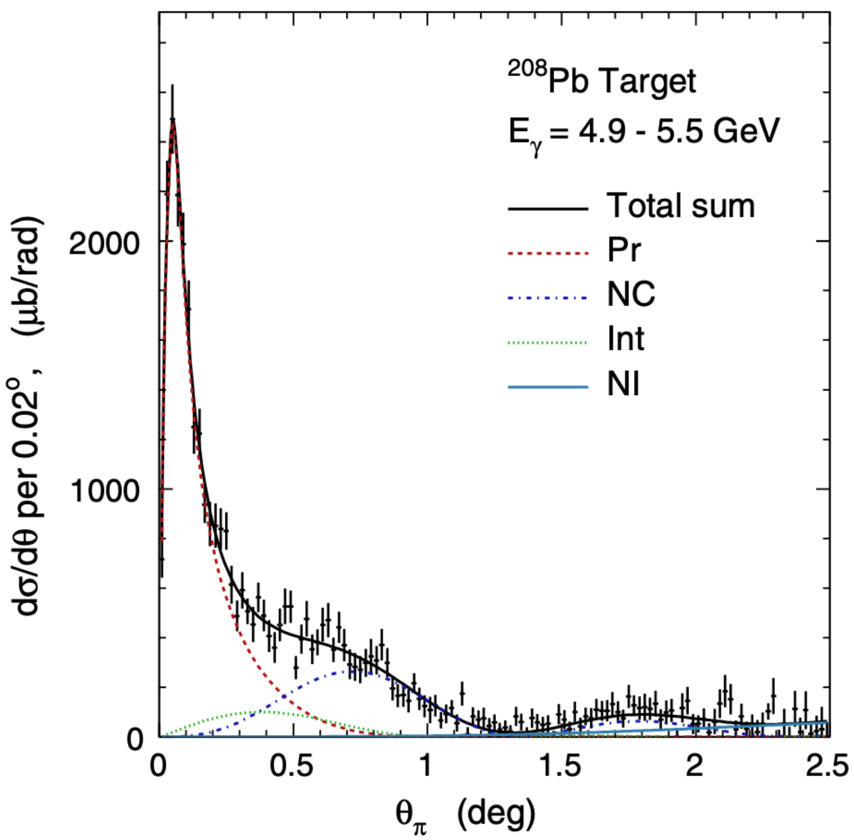


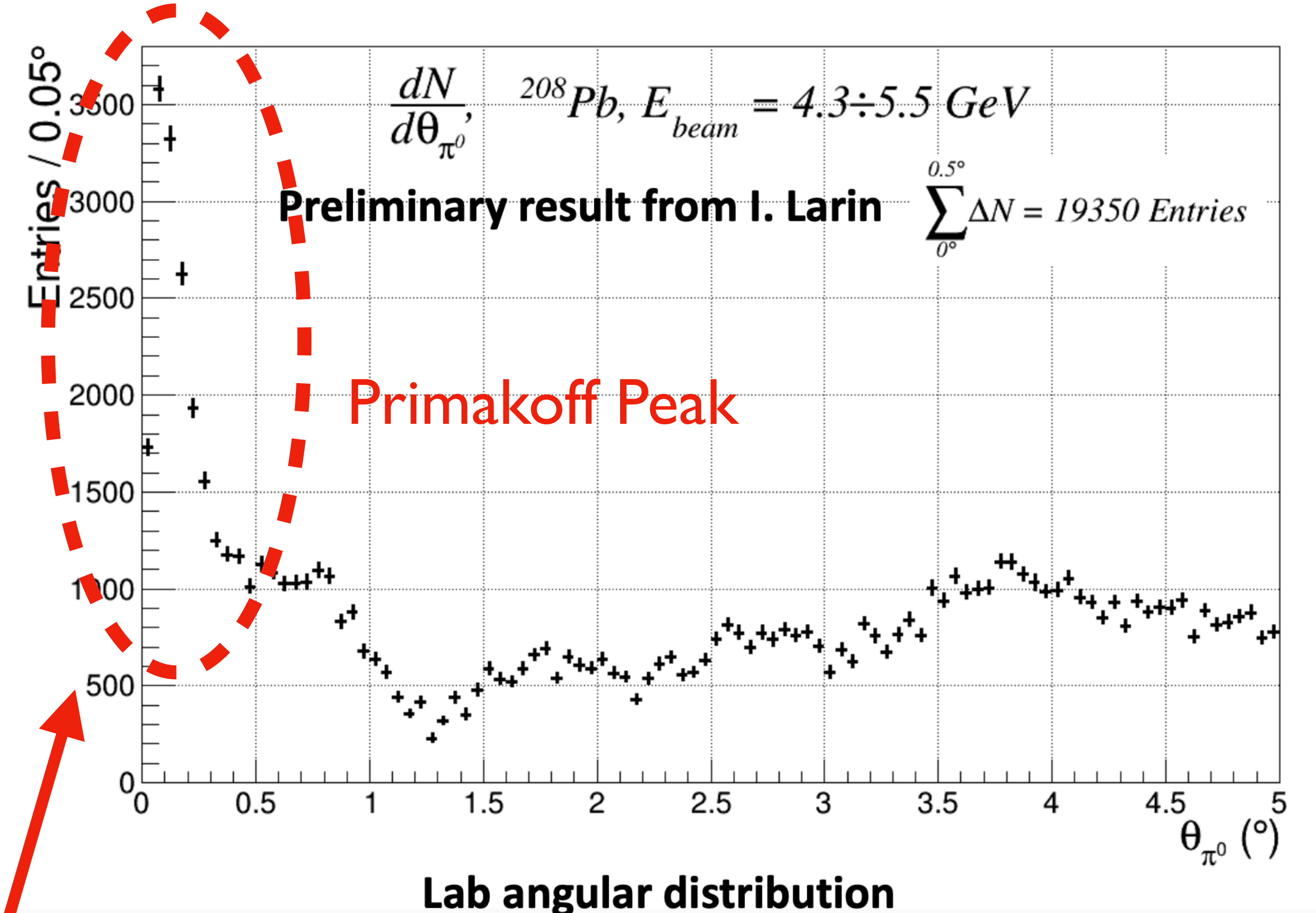
Status of Measurement / Data Analysis

Very preliminary look at exclusive π^0 photoproduction

$\vec{\gamma}\,\mathrm{Pb} \to \pi^0 \to \gamma\gamma$

PrimEx I: $\gamma\,\mathrm{Pb} \to \mathrm{Pb}\,\pi^0$





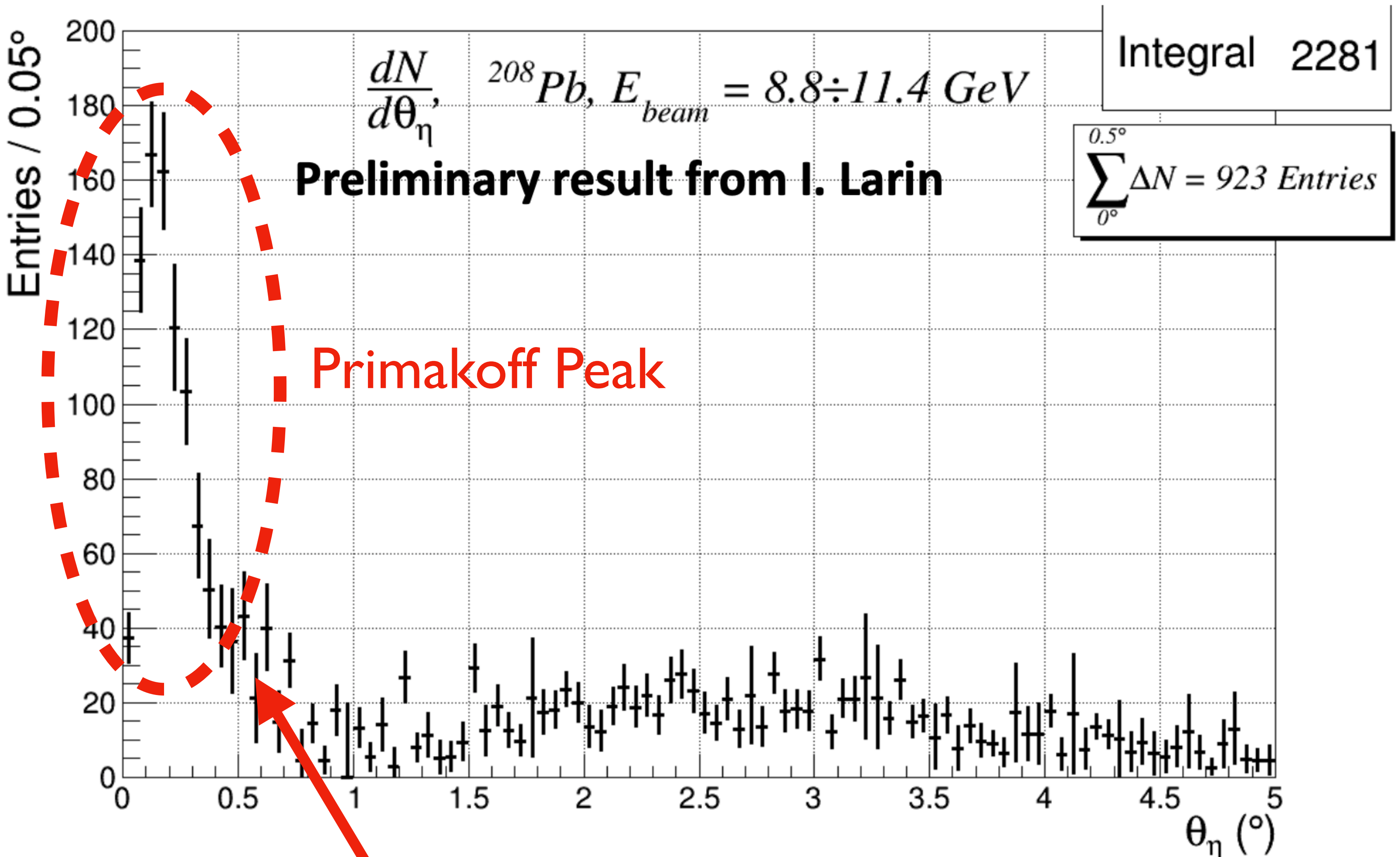
Larin et al., PRL **106**, 162303 (2011).

$$\frac{d\sigma_{Prim}}{d\Omega} = \Gamma(\pi^0 \to \gamma\gamma)\frac{8\alpha Z^2}{m_\pi^3}\frac{E_\gamma^4\beta^3}{Q^4}\left|F_{EM}(Q^2)\right|^2 \sin^2\theta_\pi$$

Status of Measurement / Data Analysis

Very preliminary look at exclusive η photoproduction

$$\vec{\gamma}\,\mathrm{Pb} \to \eta \to \gamma\gamma$$



Lab angular distribution

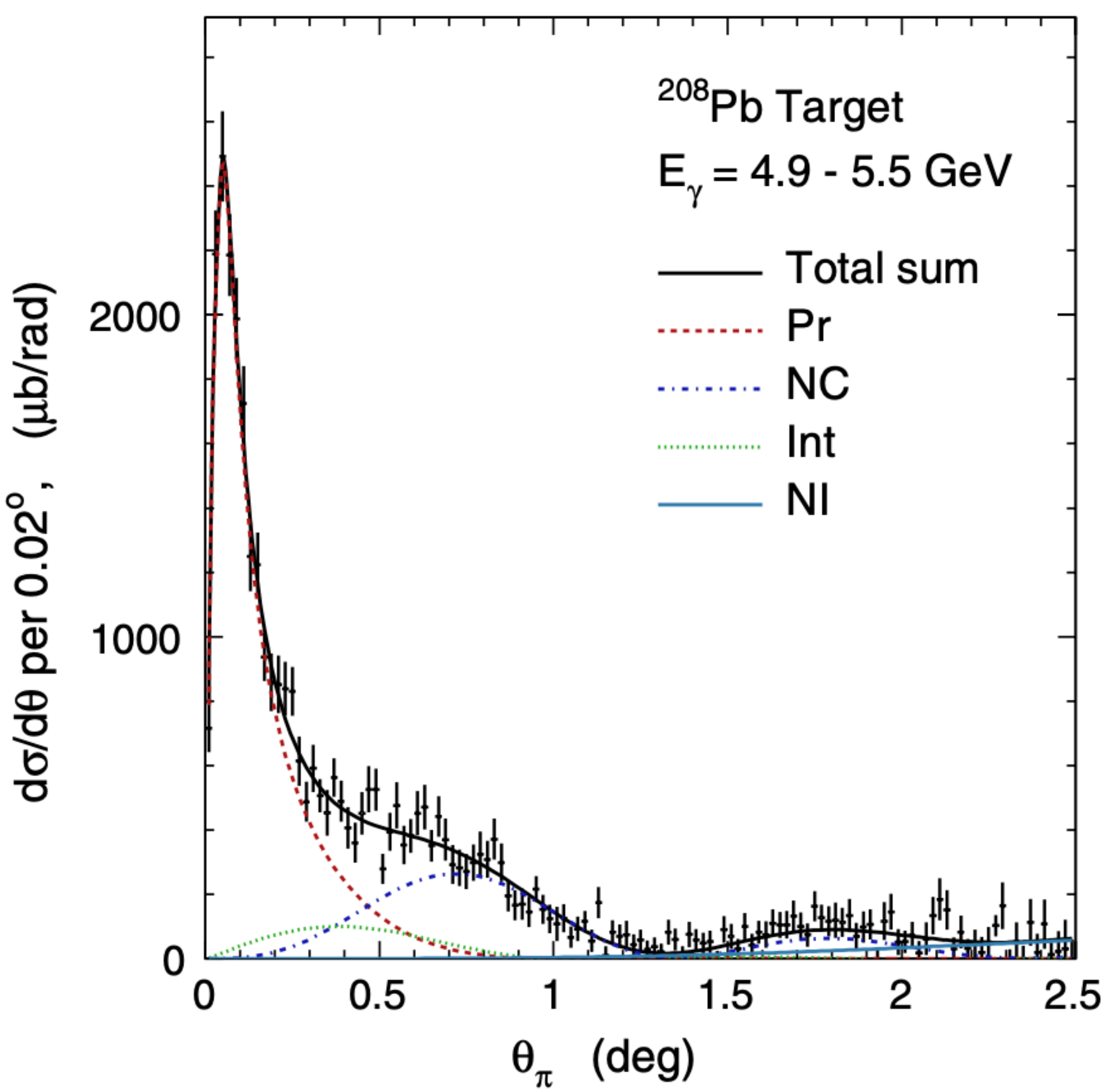
$$\frac{d\sigma_{Prim}}{d\Omega} = \Gamma(\eta \to \gamma\gamma)\frac{8\alpha Z^2}{m_\eta^3}\frac{E_\gamma^4 \beta^3}{Q^4}\left|F_{EM}(Q^2)\right|^2 \sin^2\theta_\eta$$

Upcoming Analysis for CPP/NPP

$\theta_{\pi\pi}^{\text{lab}}$ distributions for CPP/NPP are qualitatively similar to $\theta_{\pi}^{\text{lab}}$ distribution for π photoproduction, with some important differences:

1. Nuclear coherent photoproduction dominated by coherent $f_0(500)$ photoproduction.
2. Significant background from ρ^0 in CPP, completely absent for NPP.
3. Primakoff peak is broadened and shifted to higher angles.
4. Use incident photon linear polarization to help disentangle the $\gamma\gamma \to \pi\pi$ cross section from background reactions.

PrimEx I: γ Pb $\to$ Pb π^0

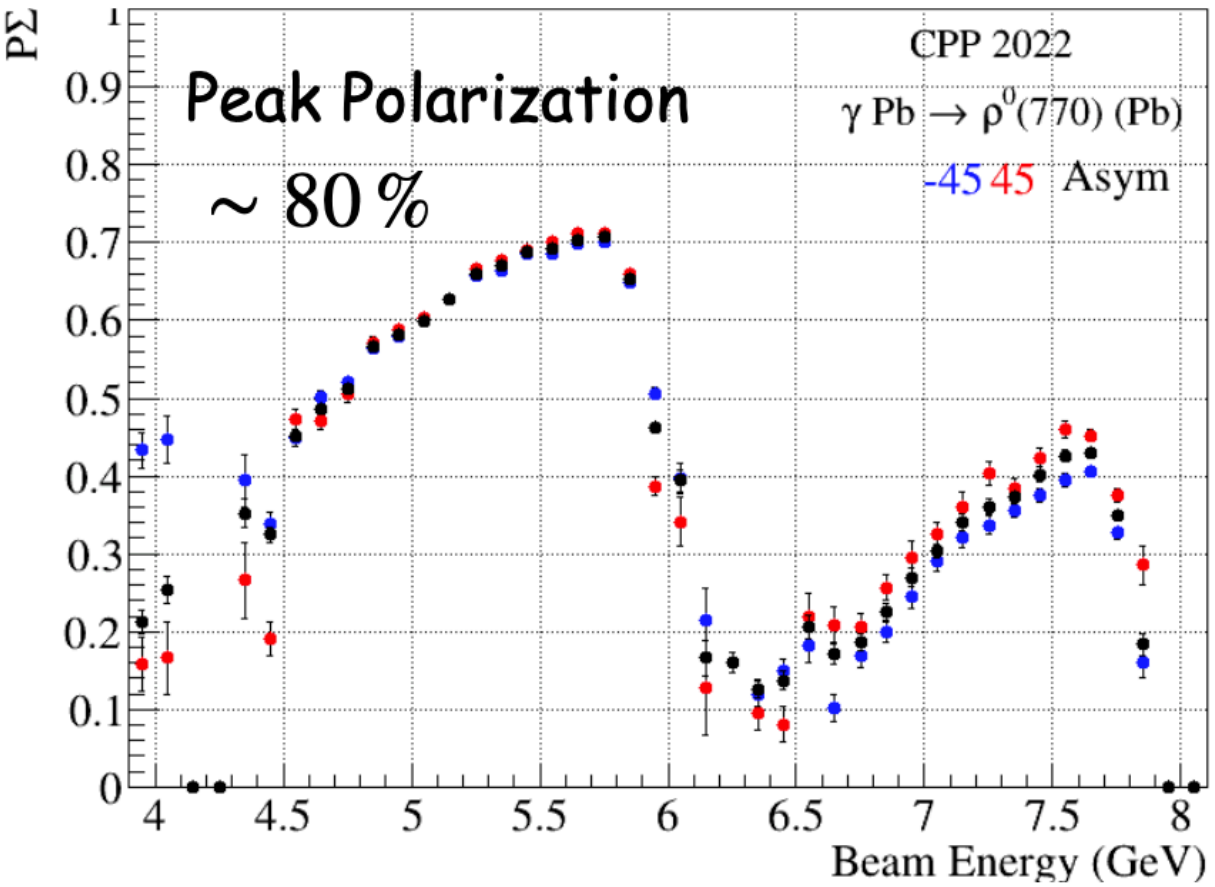


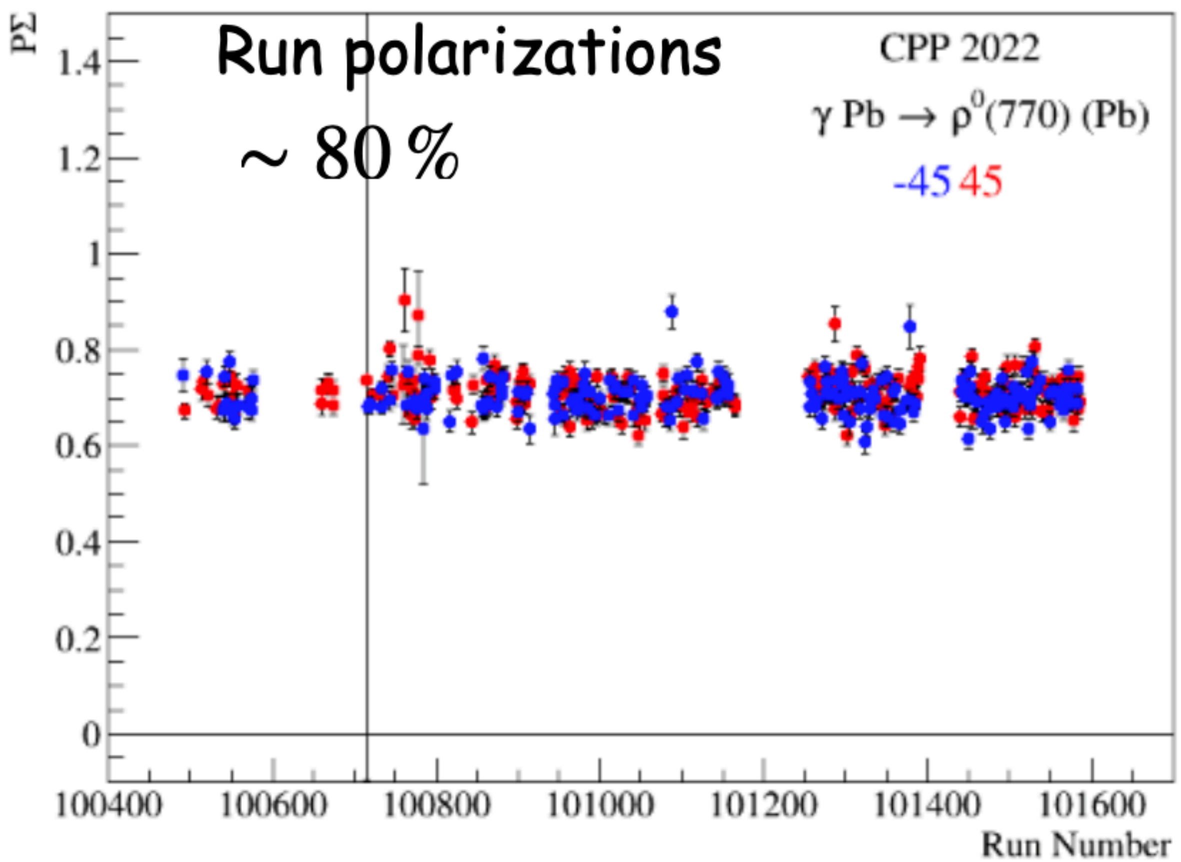
Larin et al., PRL **106**, 162303 (2011).

Beam Polarization — Coherent Bremsstrahlung

Very important to know have high linear photon beam polarization, and to know the absolute value of the polarization.

$\vec{\gamma}$ Pb $\rightarrow \rho^0$ Pb from A. Austregesilo





Benefits of polarized photons:

- Improves S/B and tagging efficiency.
- F.O.M. increases by 18.

Novel Polarimetry Technique

A. Schick, UMass.

Developed for CPP: $\vec{\gamma}\, Pb \to e^+e^-\, Pb$ where both e^+ and e^- are detected.

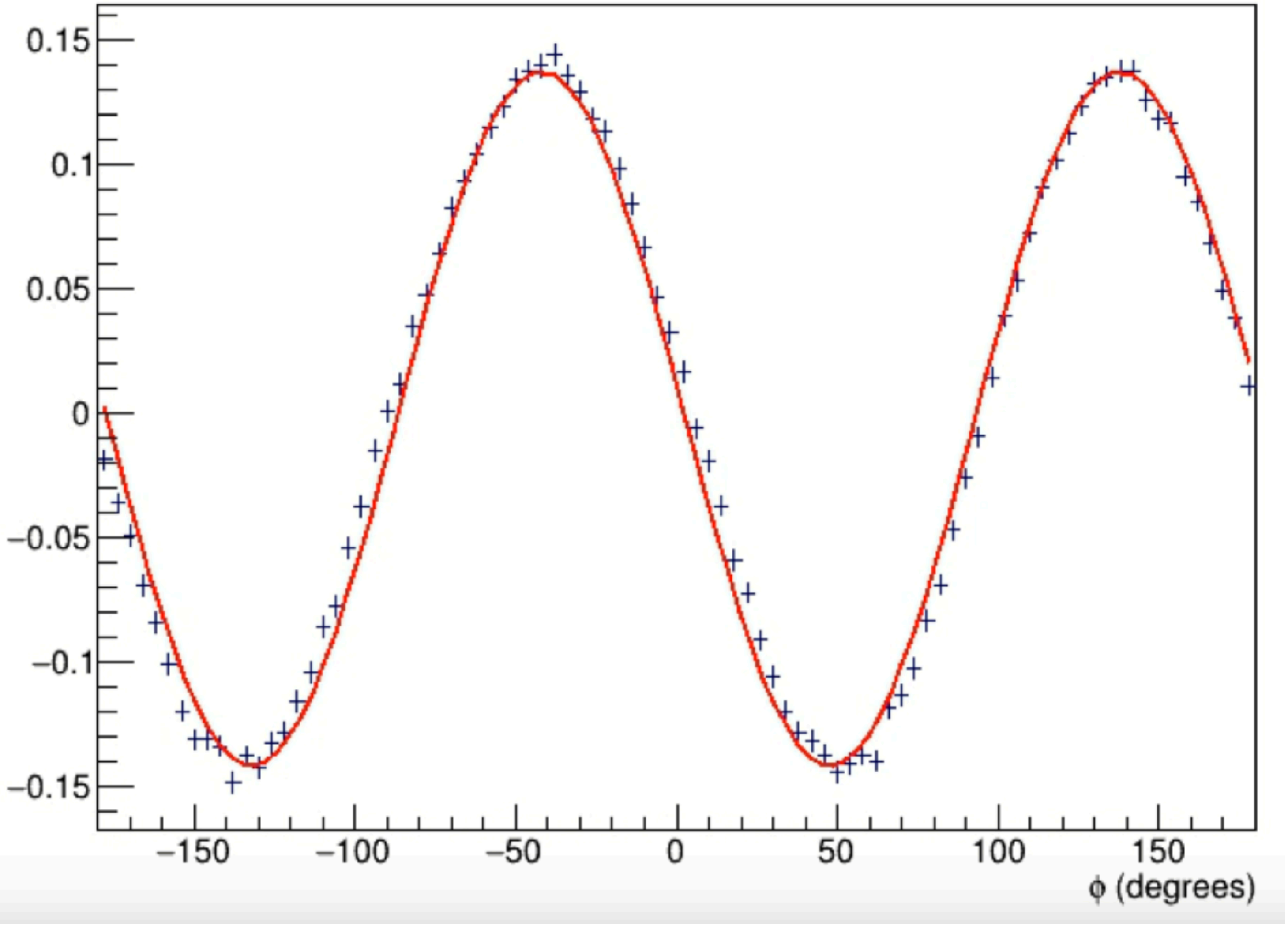
$$\frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}} = \Sigma P_{\gamma} \cos(2\phi_J)$$

Σ is known

Fit $\cos(2\phi_J)$ and extract P_{γ}

$$\Rightarrow \quad P_{\gamma} \approx 80\,\%$$

ϕ_J yield asymmetry



Measuring CPP/NPP at JLab — Summary

Pion polarizability → tests fundamental symmetries → chiral symmetry and its realization in QCD.

- The JLab GlueX CPP/NPP experiments utilize a new technique for measuring $\pi^{\pm}$ and π^{0} polarizabilities: Primakoff production of and pairs on a nuclear target.
- Data taking for the CPP and NPP experiments has been completed. Calibrations are finished.
- The data are of high quality, and we don't see any "show stoppers" so far. We look forward to presenting results for cross sections and pion polarizabilities in the near future.

GlueX acknowledges the support of several funding agencies and computing facilities: