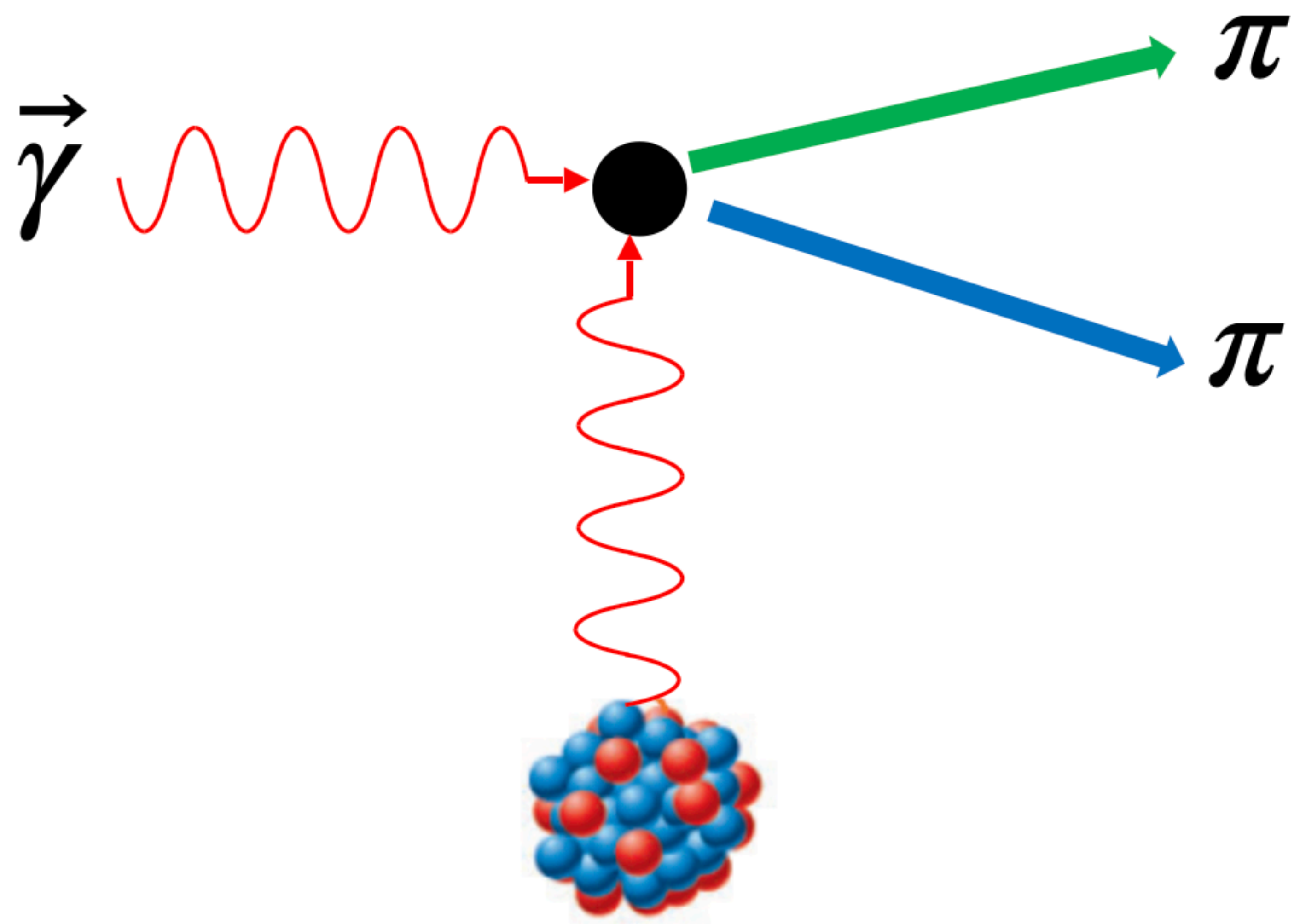
Measurements of Charged Pion Polarizability at Jefferson Lab

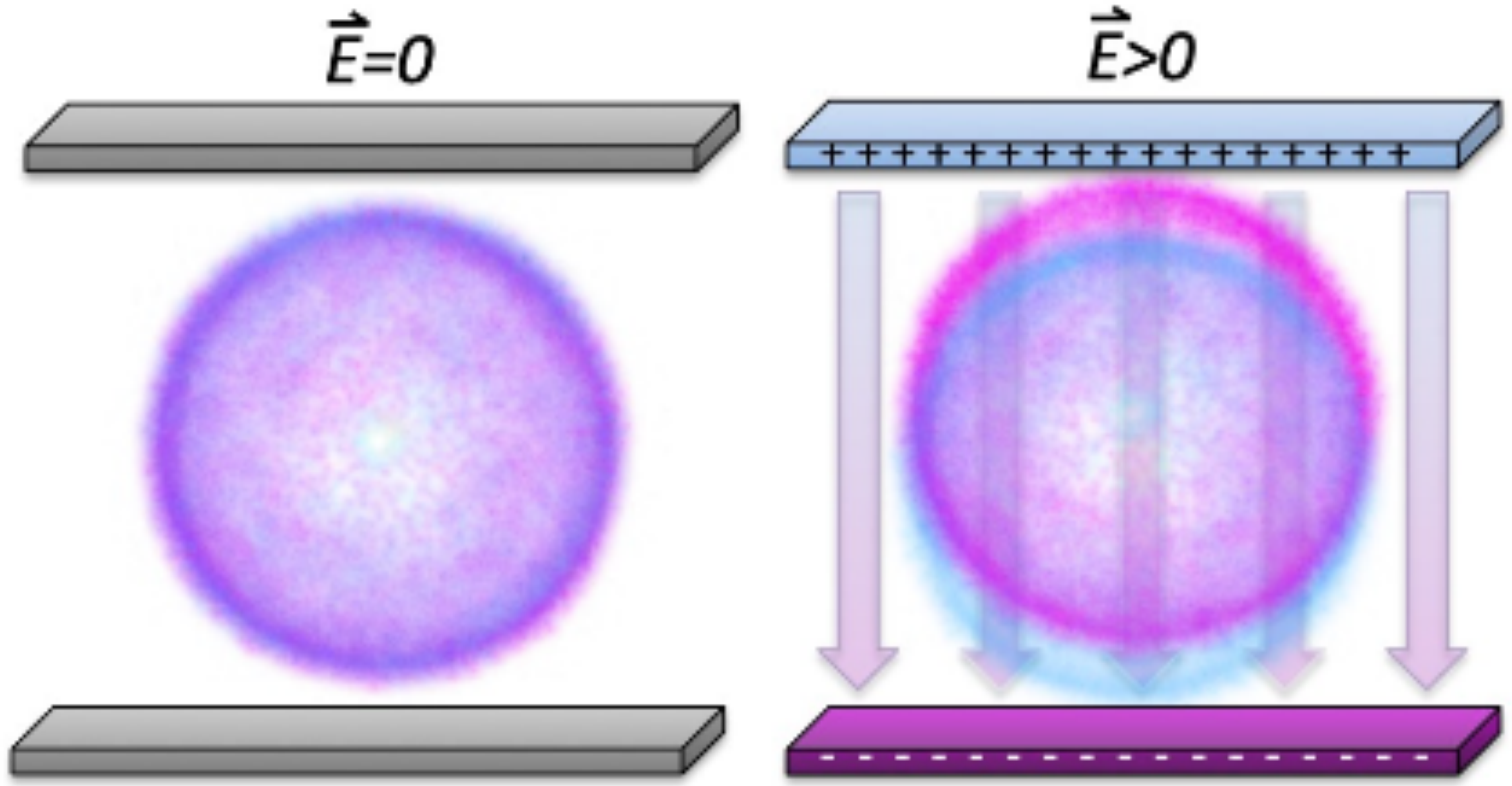


Albert Fabrizi
University of Massachusetts Amherst

Overview

- What is Pion Polarizability and how is it measured
- Past experimental results
- GlueX experiment at Jefferson Lab
- Status of Data Analysis for the Charged and Neutral Pion Polarizability Measurements

What is a Hadron Polarizability?



Hadron surrounded by Pion Cloud

Hadron surrounded by displaced Pion Cloud

Electric Polarizability $= \alpha \approx 10^{-4} \times$ **Volume** $\vec{p} = -\alpha\vec{E}$

Magnetic Polarizability $= \beta \approx 10^{-4} \times$ **Volume** $\vec{\mu} = \beta\vec{H}$

Measurements of Pion Polarizability provide a test of chiral symmetry

Chiral Perturbation Theory Prediction for Charged Pions:*

$$\alpha_\pi = -\beta_\pi = \frac{4\alpha}{m_\pi F_\pi^2}(L_9^r - L_{10}^r) = \boxed{2.8 \times 10^{-4}\text{fm}^3}$$

*Gasser et al. Annals Phys. 158, 142

Predictions* for the Neutral Pion Polarizability

NLO calculations:

- $\alpha_{\pi^0} + \beta_{\pi^0} = 0$
- $\alpha_{\pi^0} - \beta_{\pi^0} = -\dfrac{\alpha_{EM}}{48\pi^2 m_\pi F_\pi^2} \approx -1.1 \times 10^{-4} fm^3$

NNLO calculations:

- $\alpha_{\pi^0} + \beta_{\pi^0} = \quad 1.15 \pm 0.3 \times 10^{-4} fm^3$
- $\alpha_{\pi^0} - \beta_{\pi^0} = -1.90 \pm 0.2 \times 10^{-4} fm^3$

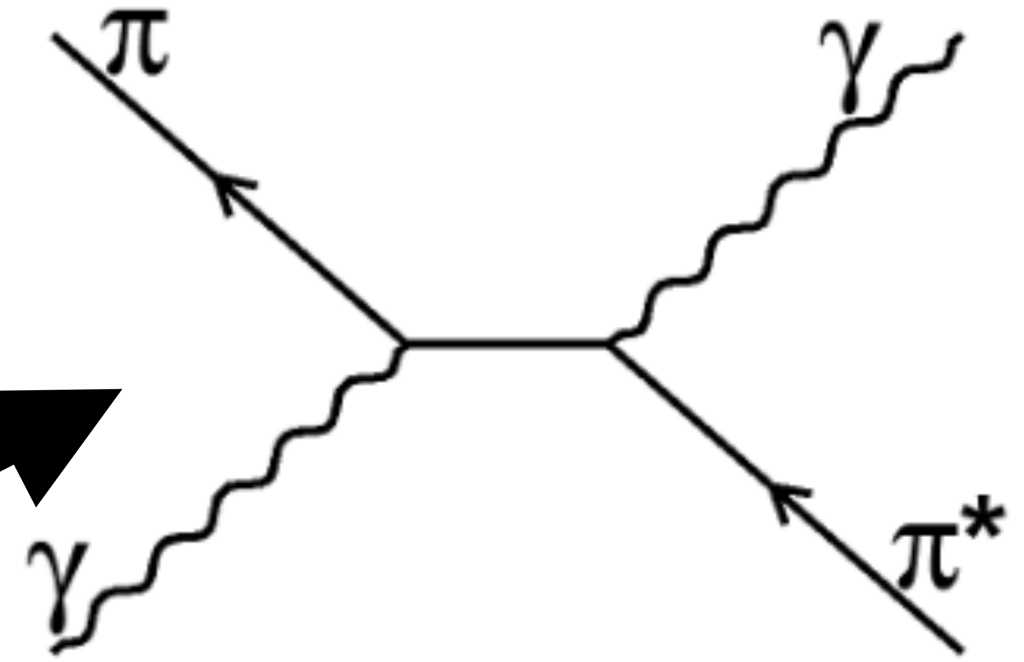
Neutral pion polarizability has never been reliably determined

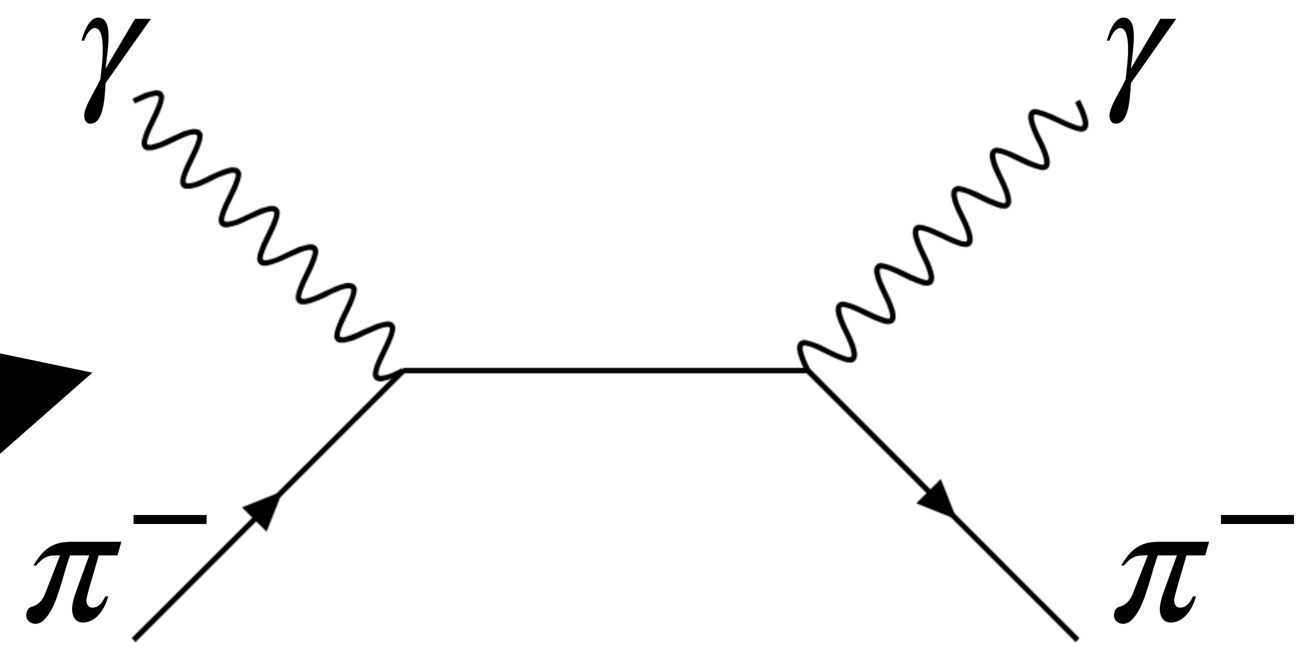
*S. Bellucci *In Chiral dynamics: Theory and experiment. Proceedings, Workshop, Cambridge, USA, July 25-29, 1994, pages 177–189, 1994. https://arxiv.org/pdf/hep-ph/9508282*

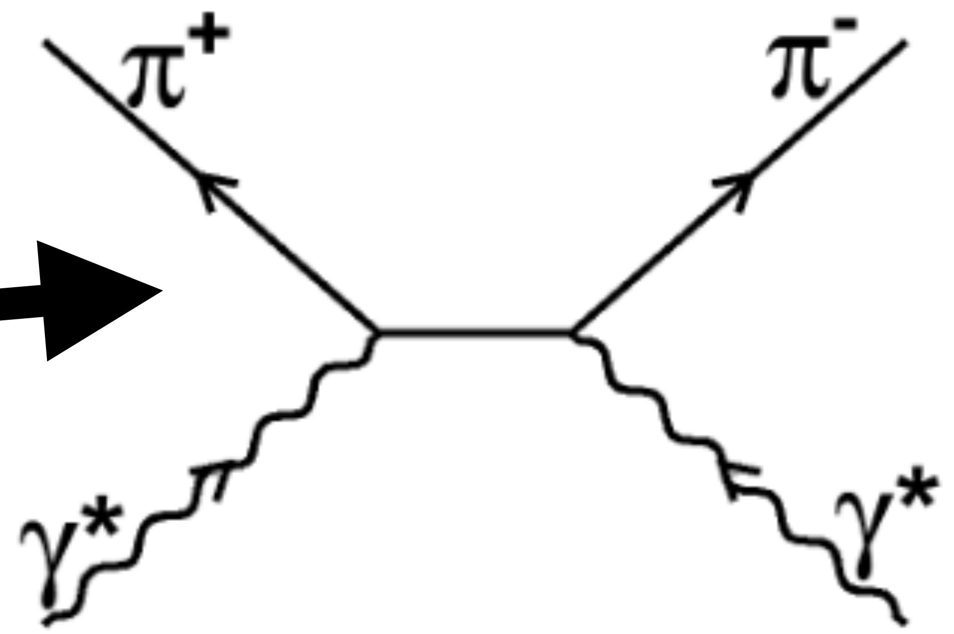
Past Experiments on Charged Pion Polarizability

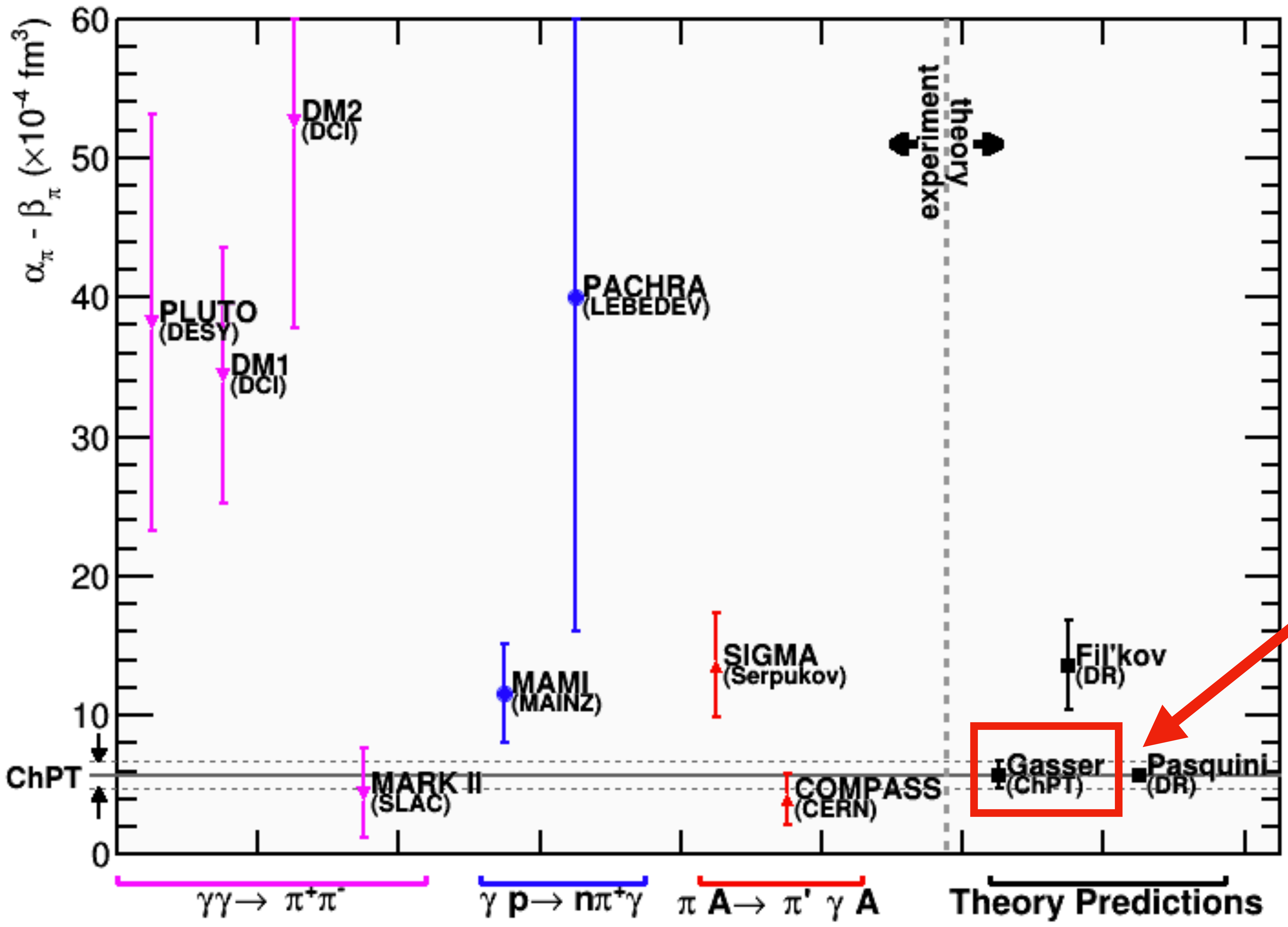
Since a Pion Target Can't Exist for Compton Scattering, other methods must be utilized

- Radiative Pion Photo-production: $\gamma p \to \gamma' \pi^+ n$ (Mainz)
- Radiative Pion Scattering: $\pi^- A \to \gamma \pi^- A$ (COMPASS)
- Pion Pair Production in 2 Photon Collision: $\gamma\gamma \to \pi^+\pi^-$ (Mark II)







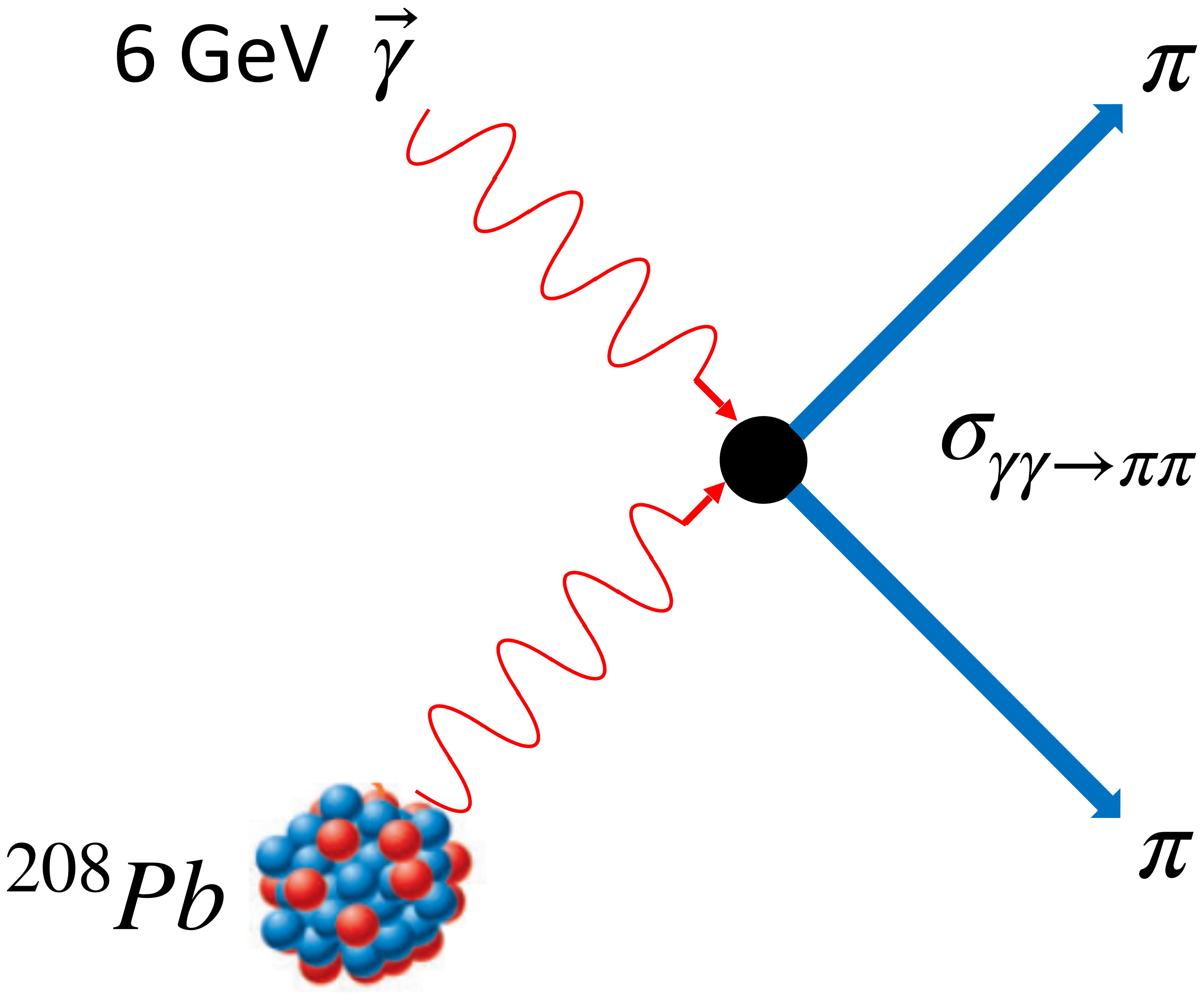


Theoretical Prediction from Gasser et al. Annals Phys. 158, 142

Pion Polarizability Measurement at Jefferson Lab

Goals for the JLab experiment

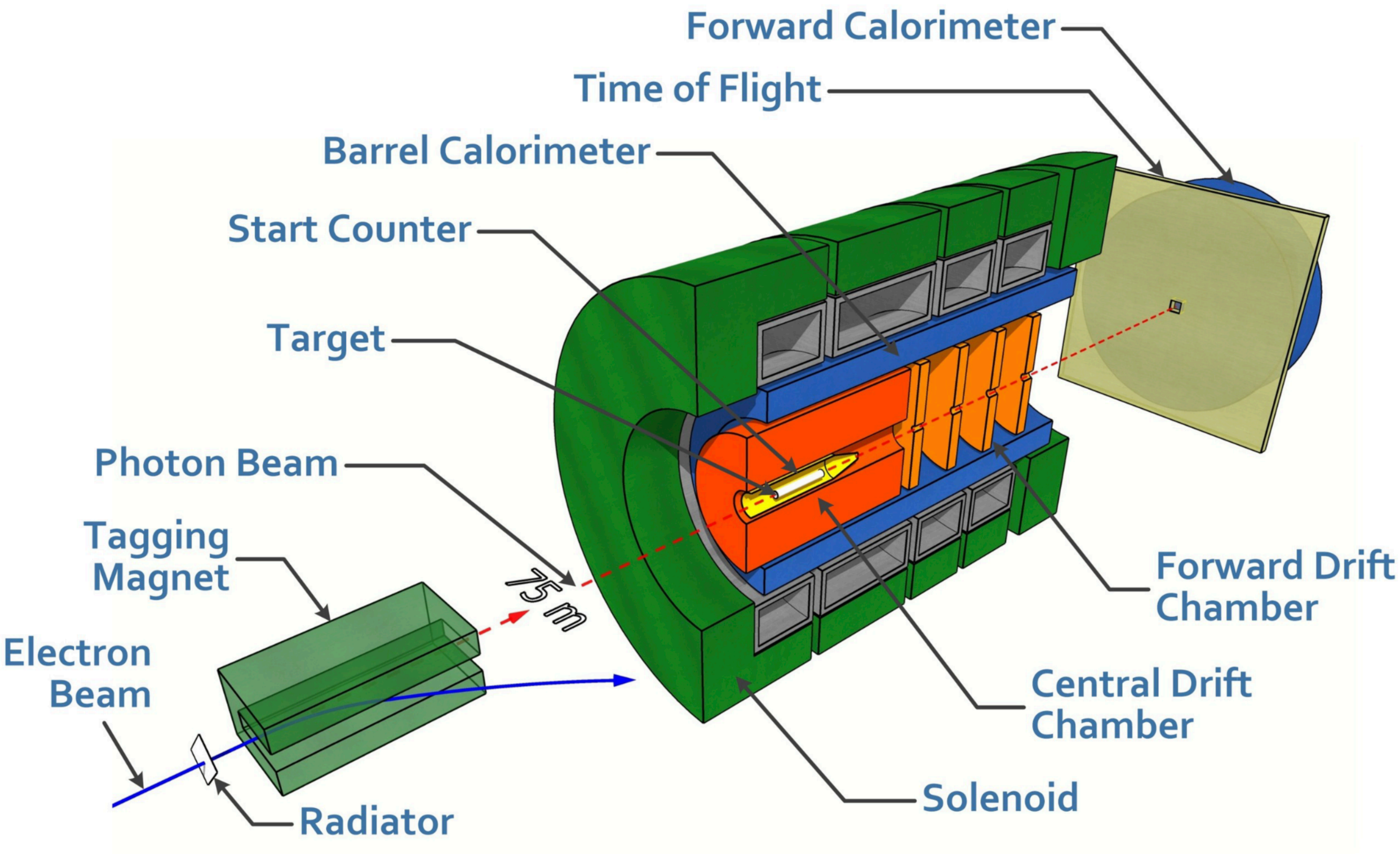
- Utilize a new technique complementary to measurements at COMPASS and e^+e^- colliders
- Provide higher statistics for $\sigma(\gamma\gamma \to \pi\pi)$ than existing collider data
- Provide a measurement of CPP with low statistical and systematic errors, and the first reliable measurement of NPP

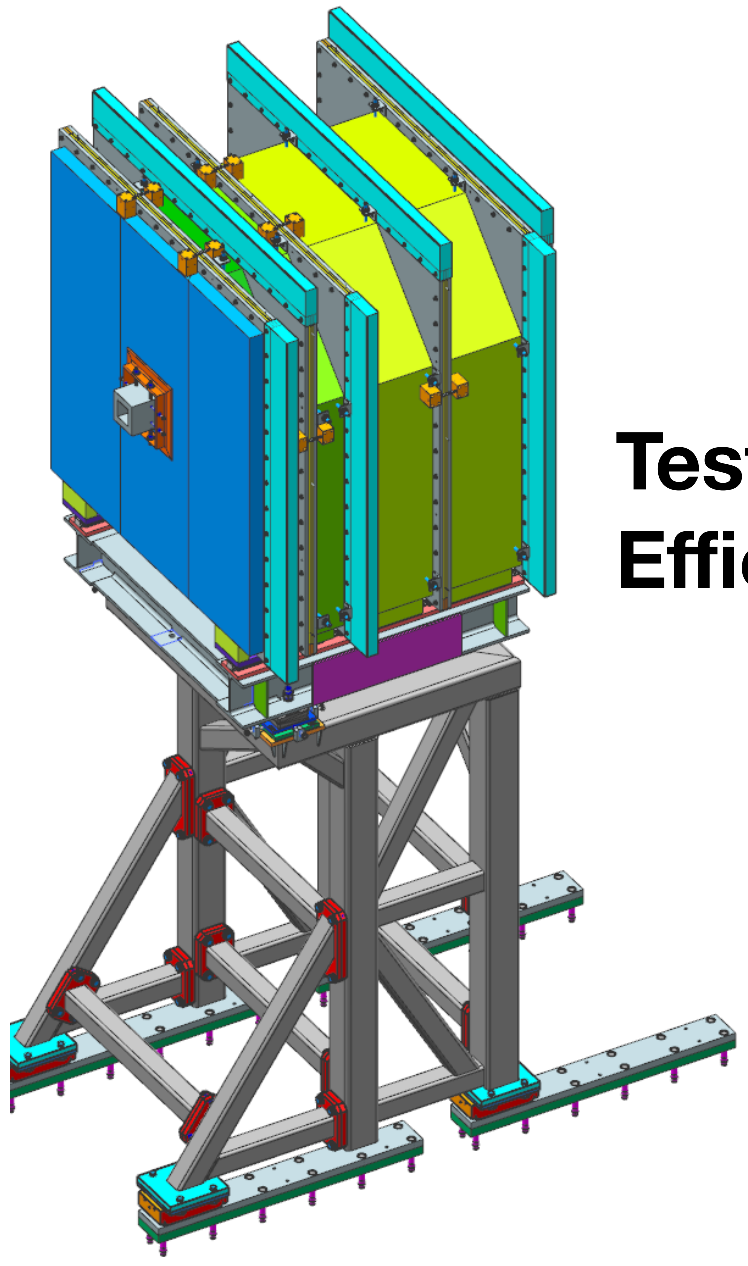


$$\frac{d^2\sigma_{Prim}}{d\Omega dM_{\pi\pi}} = \frac{2\alpha Z^2}{\pi^2}\frac{E_\gamma^2\beta^2}{M_{\pi\pi}}\frac{sin^2\theta}{Q^4}\left|F_{EM}(Q^2)\right|^2\left(1 + P_\gamma cos2\phi_{\pi\pi}\right)\sigma_{\gamma\gamma\to\pi\pi}$$

Photon polarization

CPP/NPP Experiment at JLab





New detector for μ/π identification

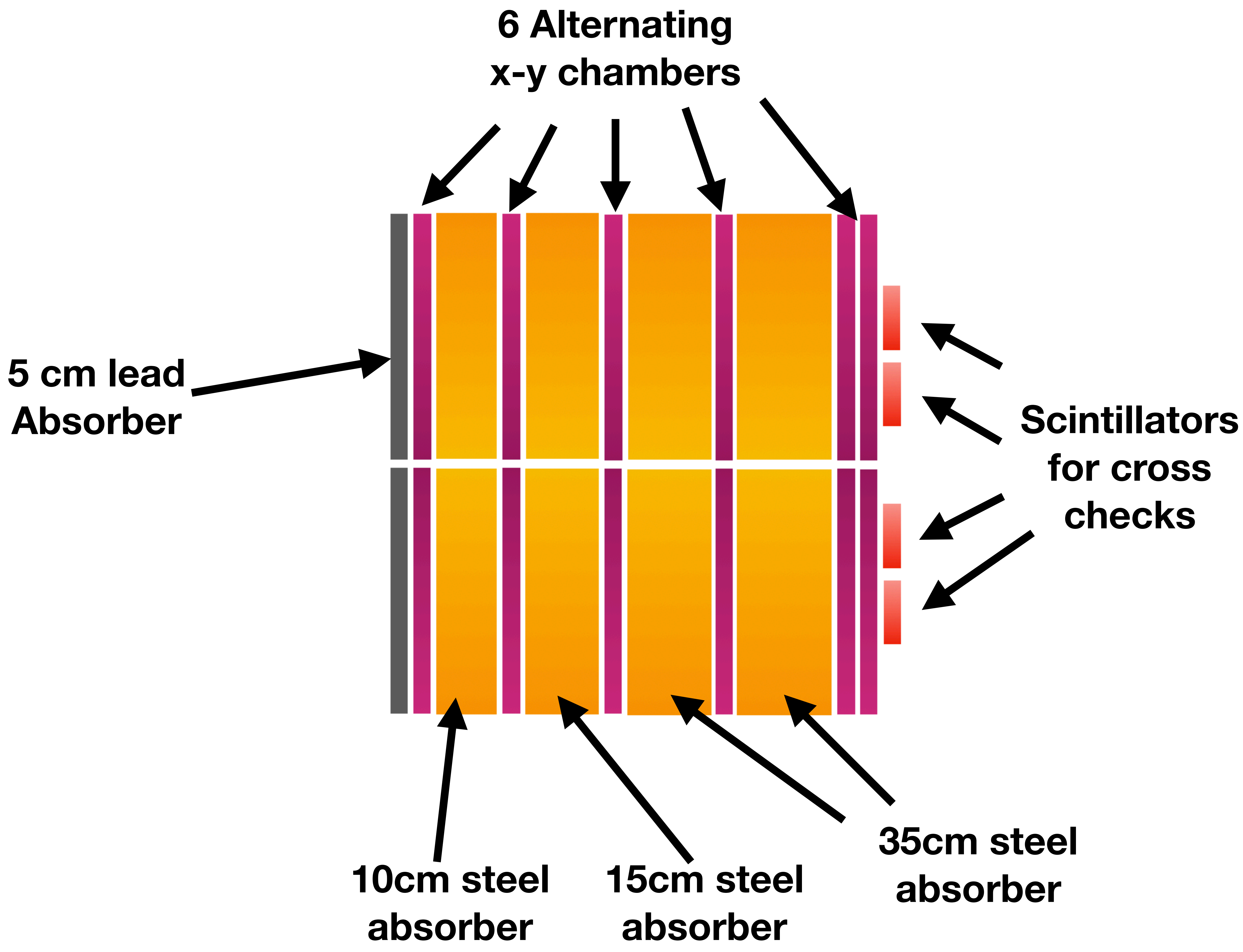
Test Efficiency: 99.7%
Efficiency During Experiment: 99.9%

Compare $\mu^+\mu^-$production with respect to $\pi^+\pi^-$ production

GlueX Detector

Muon Detector

- 8 Chambers built at UMASS, 6 used in CPP
- Each MWPC has 144 channels (sense wires)
- 90% Ar + 10% CO_2 gas mixture
- Ran at 1780V
- 4 Scintillators (CTOF) placed downstream of final chamber
- Total Pion Interaction Lengths in Lead and Iron Absorbers $= 4.9$

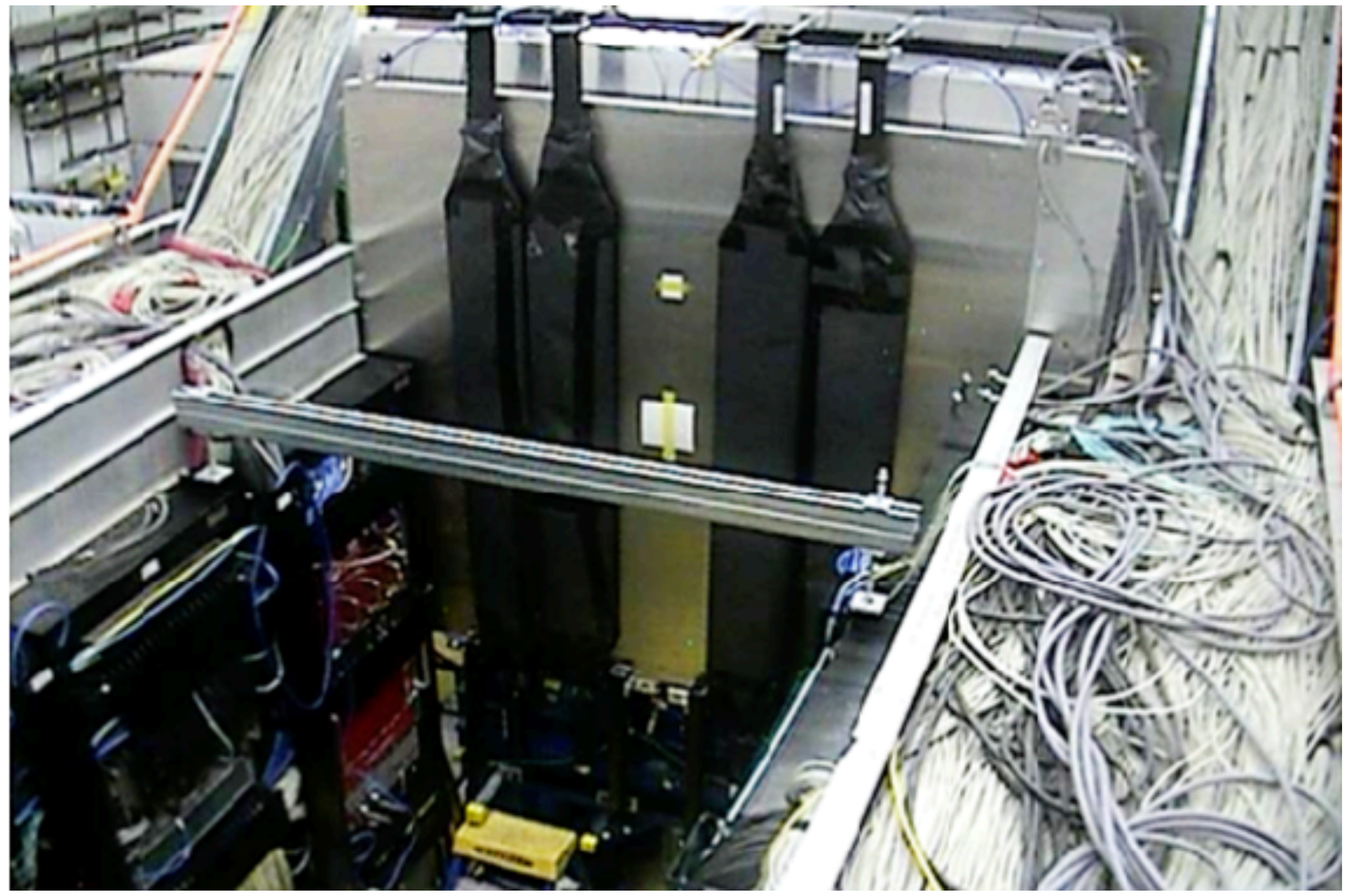


Muon Detector

Wire Chambers

Chambers installed with Iron Absorbers

CTOF Installed behind muon chambers



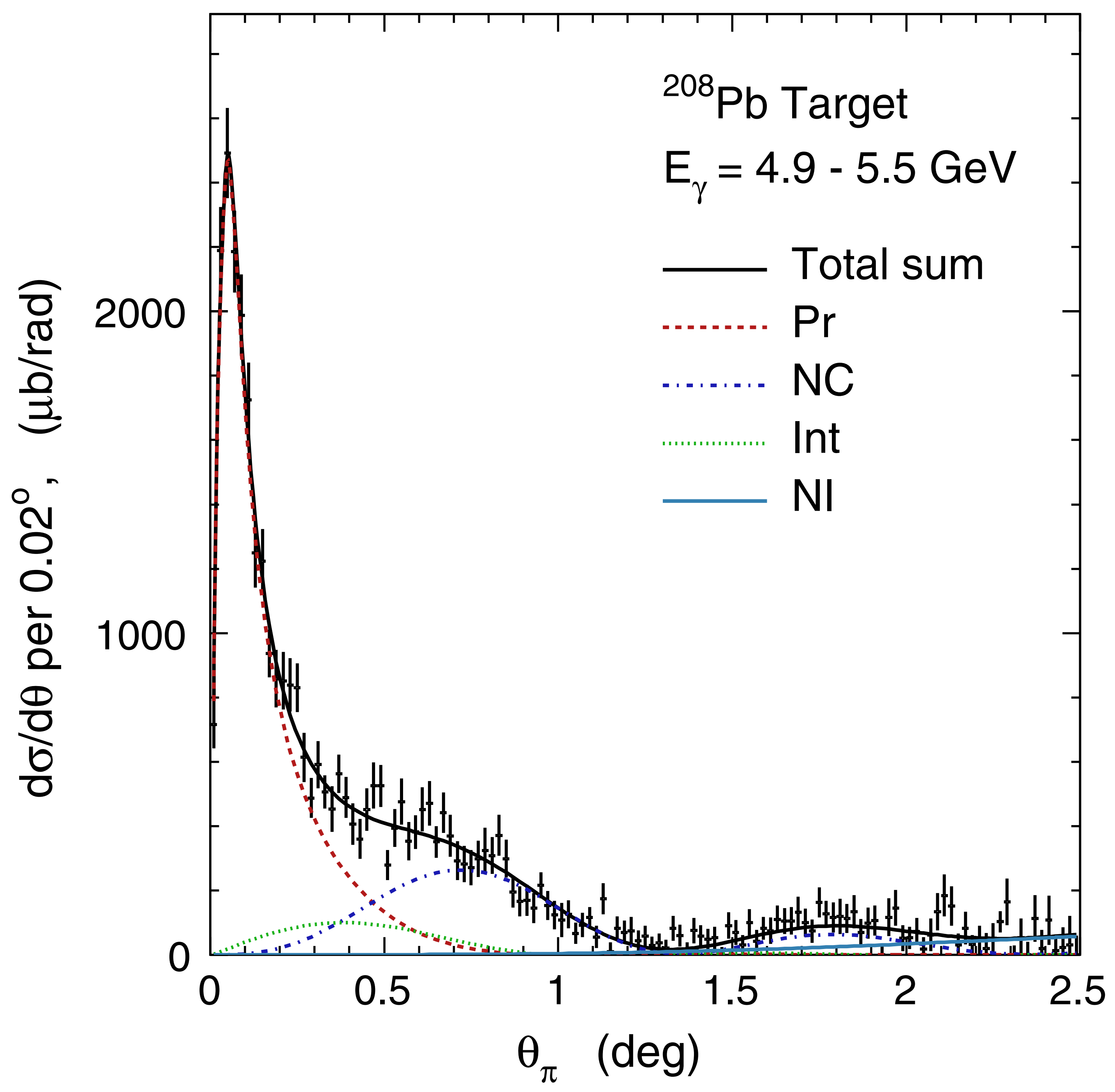
Status of the JLab GlueX CPP and NPP measurements

- Data was taken in summer 2022 with 6 GeV linearly polarized photons on ^{208}Pb target, ~ 80% polarization
- Calorimeter and charged particle tracking calibrations have been completed
- Data processing was concluded October 2024
- Currently working on Neural Nets for separation of $e^+e^-, \pi^+\pi^-, \mu^+\mu^-$Particle ID
- We expect to have preliminary physics distributions at end of summer.
- Neutral Pion Polarizability has Preliminary physics distributions

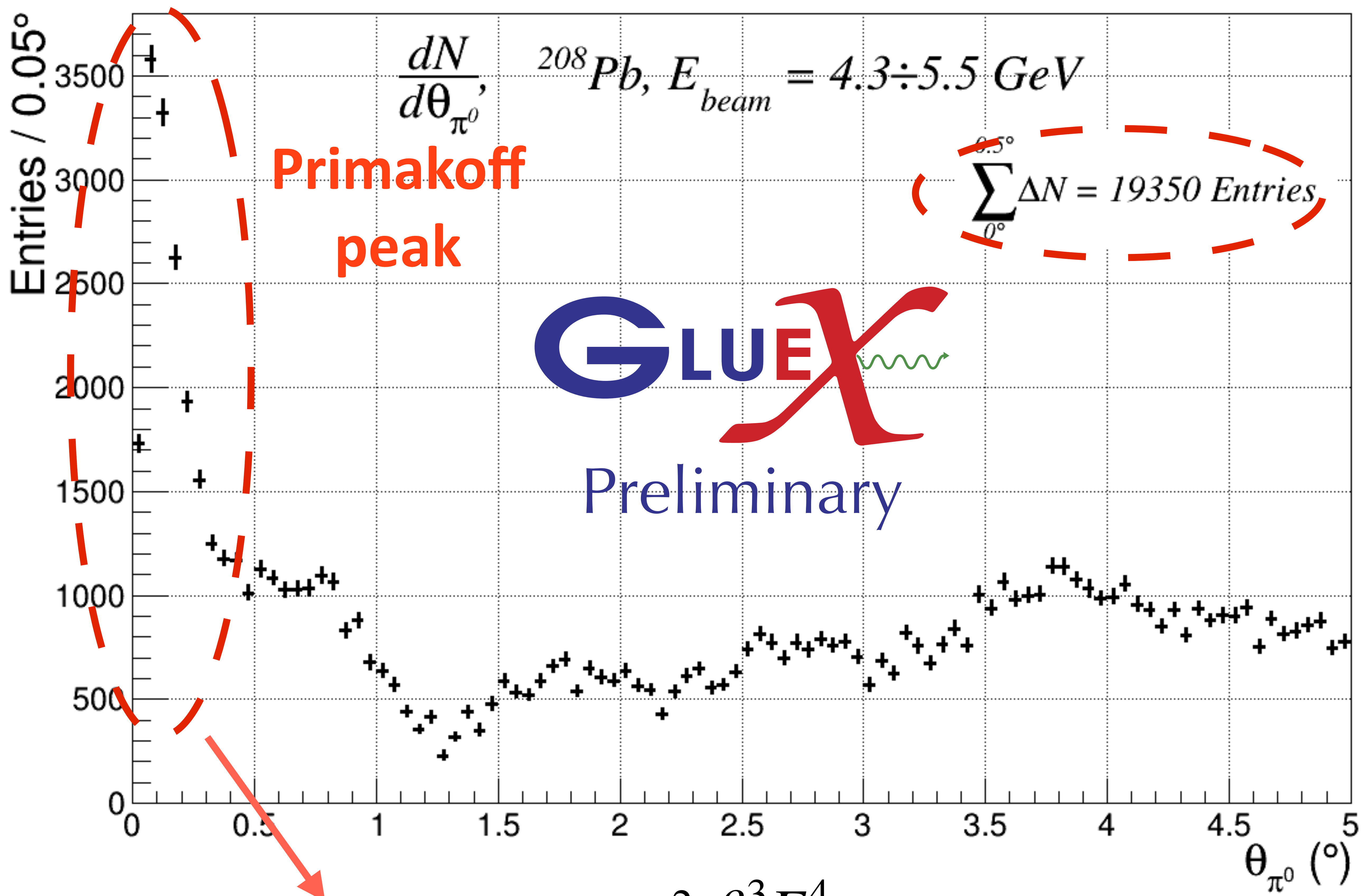
Very preliminary look at exclusive π^0 photoproduction

$$\vec{\gamma}\ Pb \rightarrow \pi^0 \rightarrow \gamma\gamma$$

PrimEx I $\gamma\ Pb \rightarrow \pi^0\ Pb$



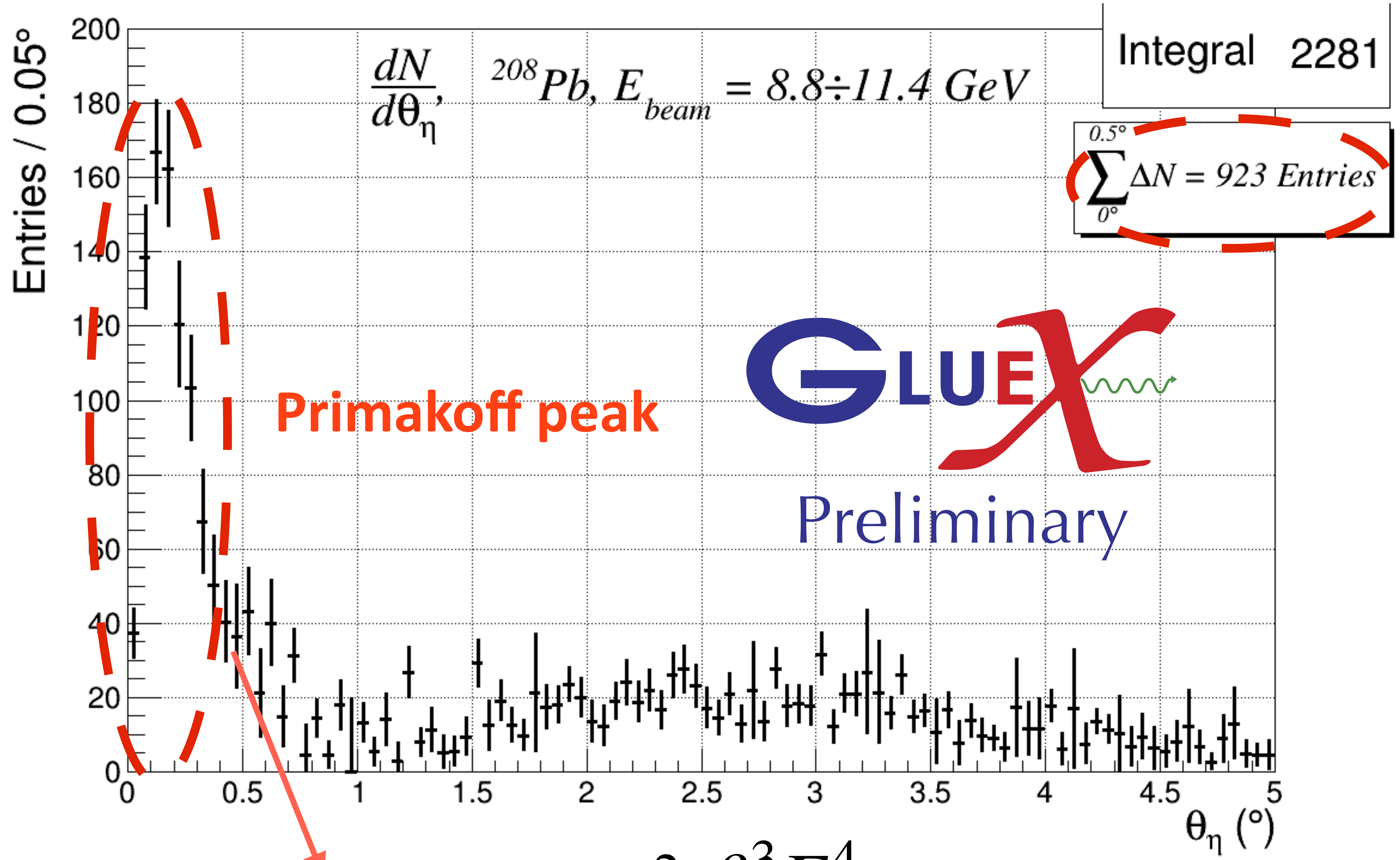
Larin et al., PRL 106, 162303 (2011)



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

Very preliminary look at exclusive η photoproduction

$$\vec{\gamma}\, Pb \rightarrow \eta \rightarrow \gamma\gamma$$



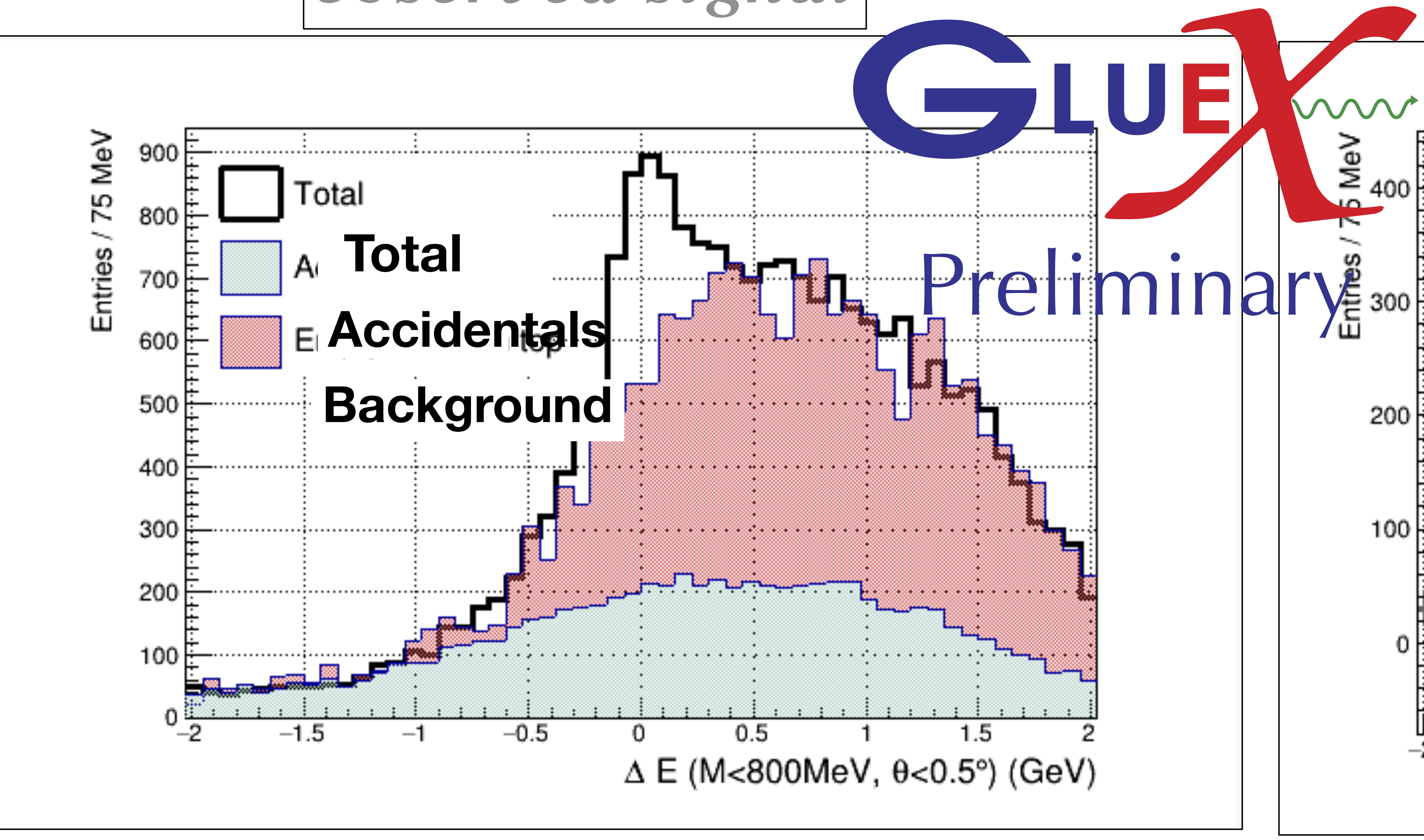
$$\frac{d\sigma_{Prim}}{d\Omega} = \Gamma(\eta \rightarrow \gamma\gamma)\frac{8\alpha Z^2}{m_\eta^3}\frac{\beta^3 E_\gamma^4}{Q^4}\left|F_{EM}(Q^2)\right|^2 sin^2\theta_\eta$$

Observed and Expected $\pi^0\pi^0$ Signal

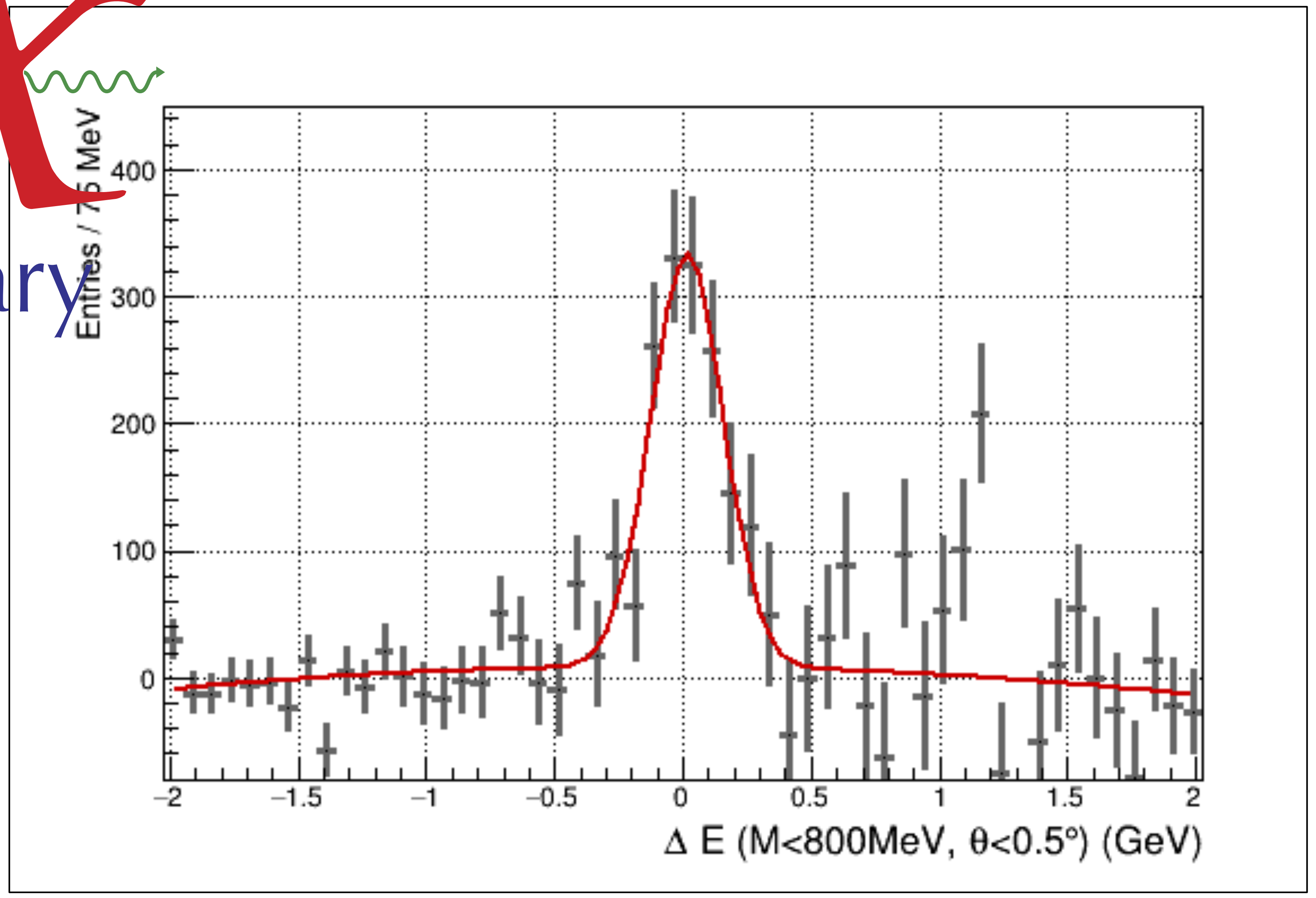
- The experimental background conditions are favorable for the angular range below 0.5°
- For 4.5÷5.9 GeV photon beam energy, $M_{\pi\pi} < 800 MeV$ and $\theta_{\pi\pi} < 0.5°$:
  - –Observed yield: 1.6K ± 8% (very preliminary)
  - –Expected Primakoff yield based on Crystal Ball $\sigma(\gamma\gamma \rightarrow \pi^0\pi^0)$ data: 1.7K ± 16%

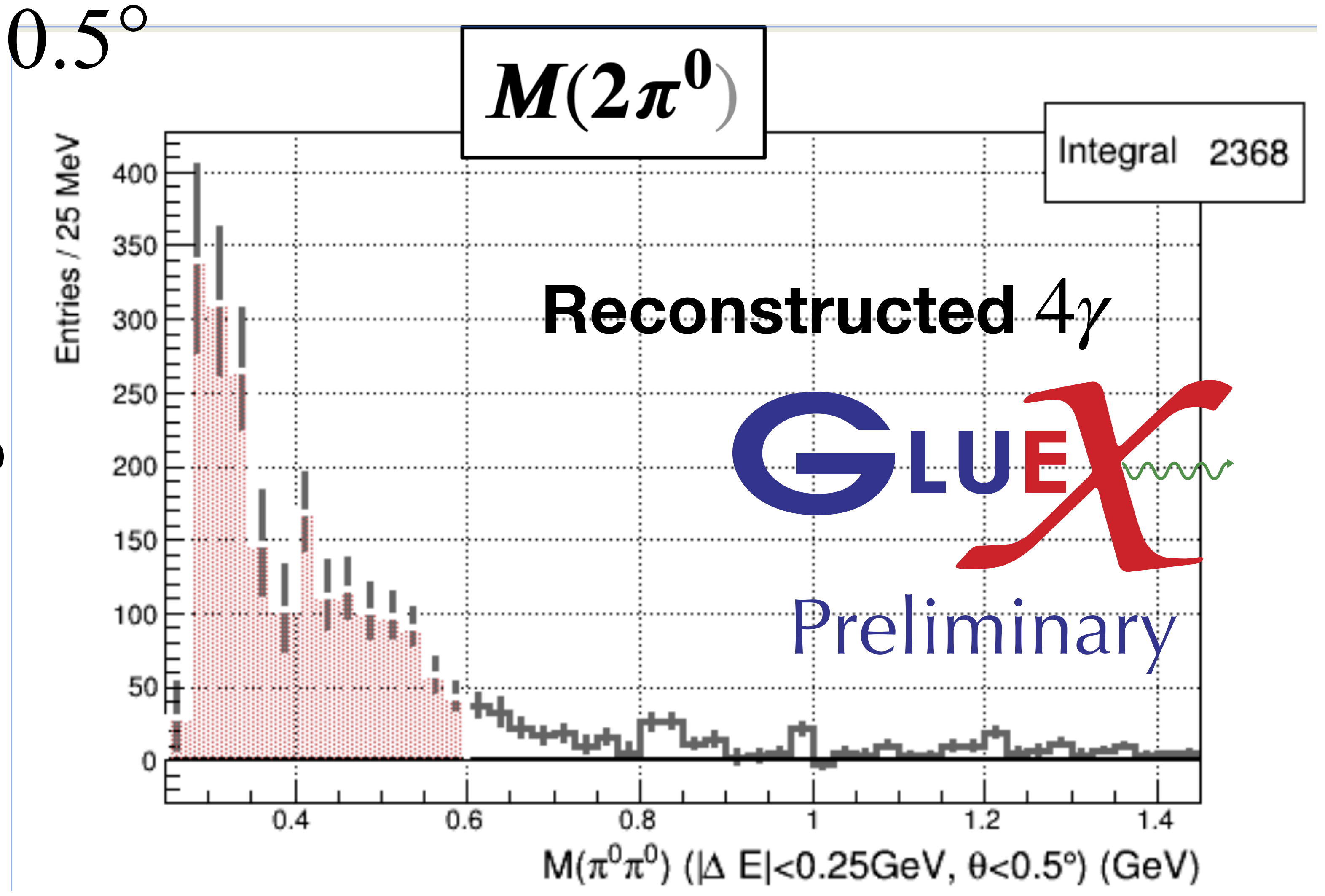
We are close to our expectations

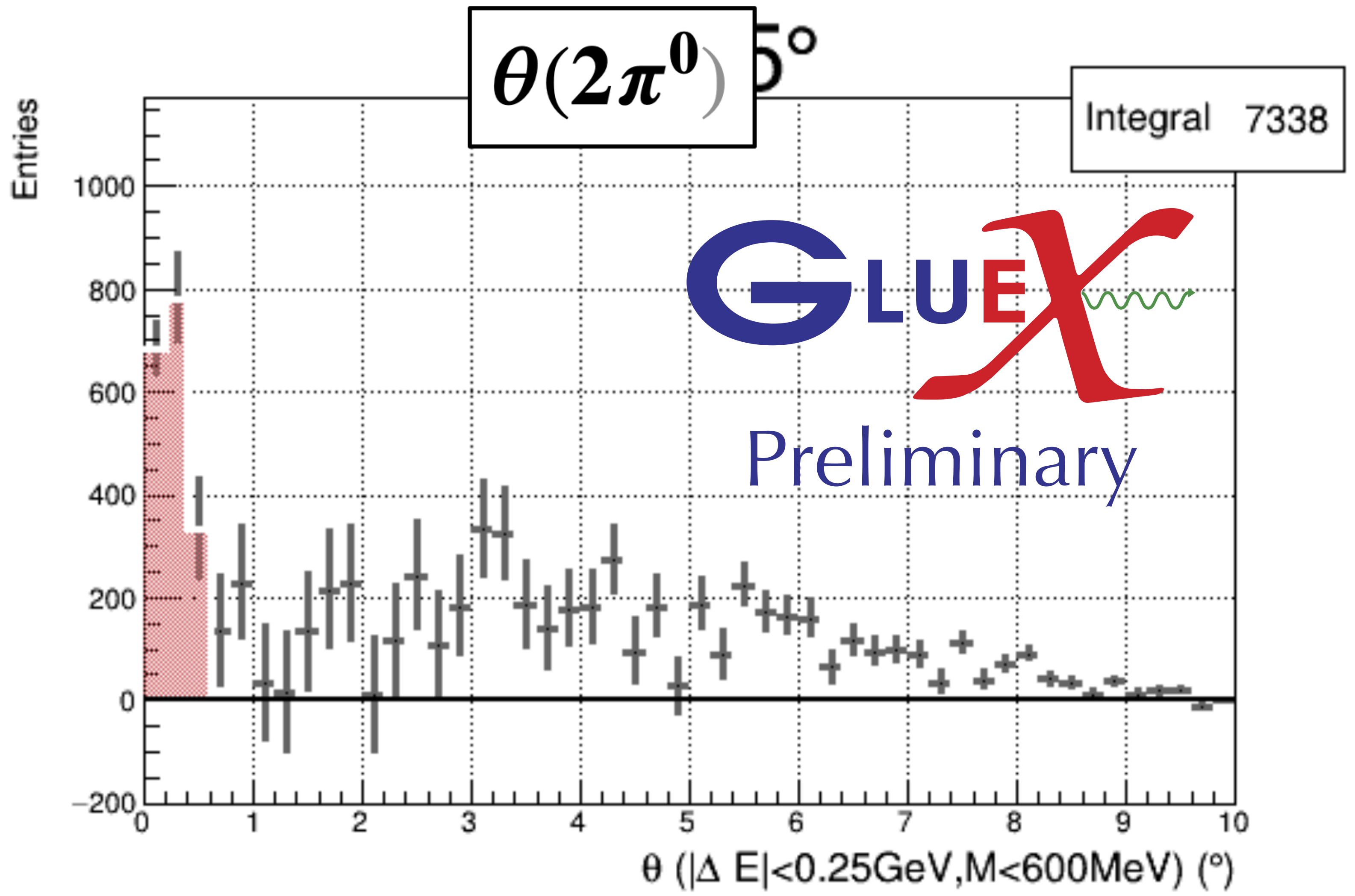
observed signal



backgound subtracted







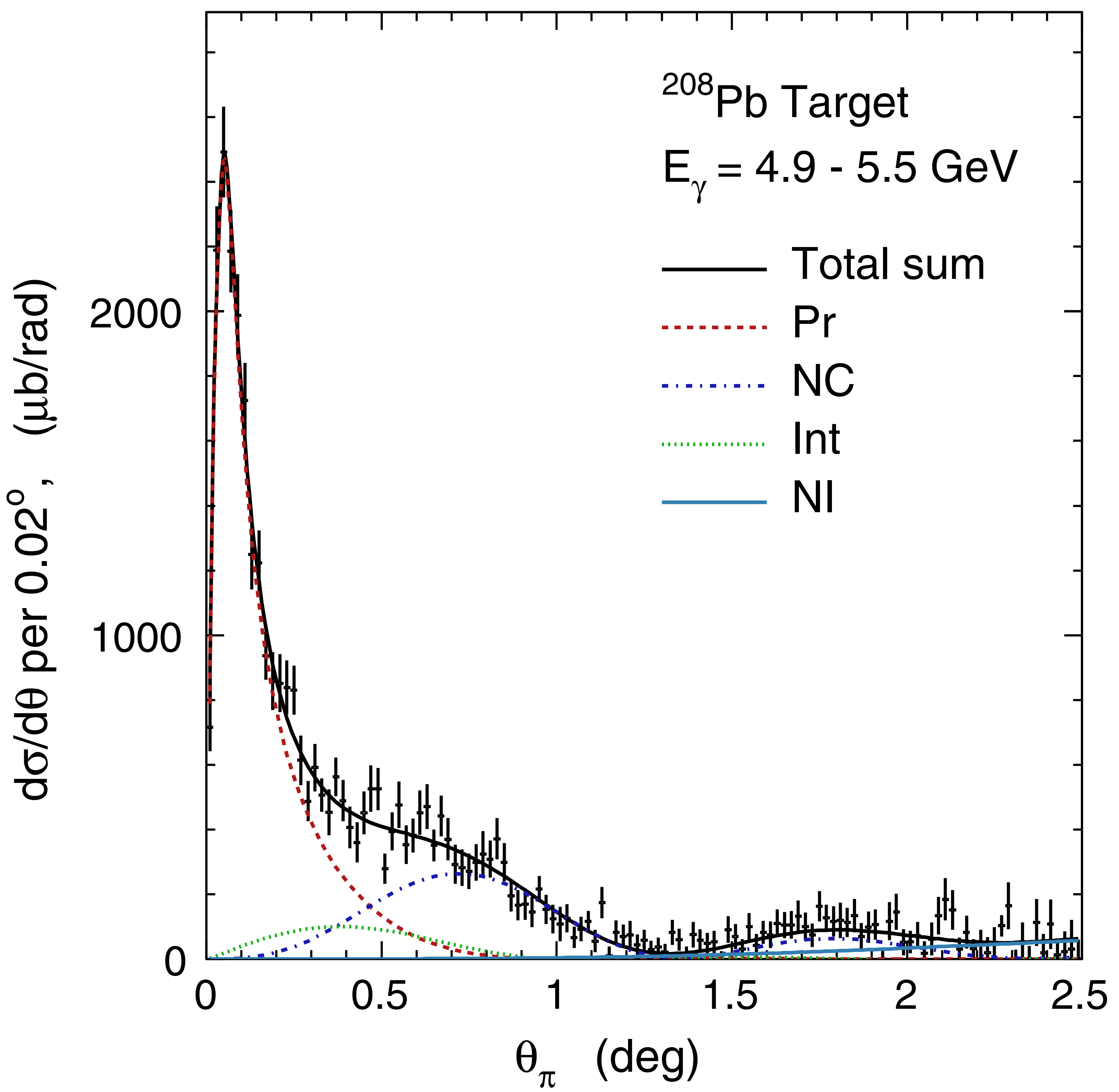
Upcoming analysis for Charged and Neutral Polarizability

$\theta^{lab}_{(\pi\pi)}$ distributions for CPP/NPP are qualitatively similar to θ^{lab}_{π} distribution for single pion photo-production, <u>with some important differences:</u>

- Nuclear coherent photo-production dominated by coherent $f_0(500)$ photo-production
- Significant background from ρ^0 in CPP, completely absent for NPP
- Primakoff peak is broadened and shifted to higher angles

Use incident photon linear polarization to help disentangle the $\gamma\gamma \rightarrow \pi\pi$ cross section from background reactions

PrimEx I $\gamma\, Pb \rightarrow \pi^0\, Pb$



Summary

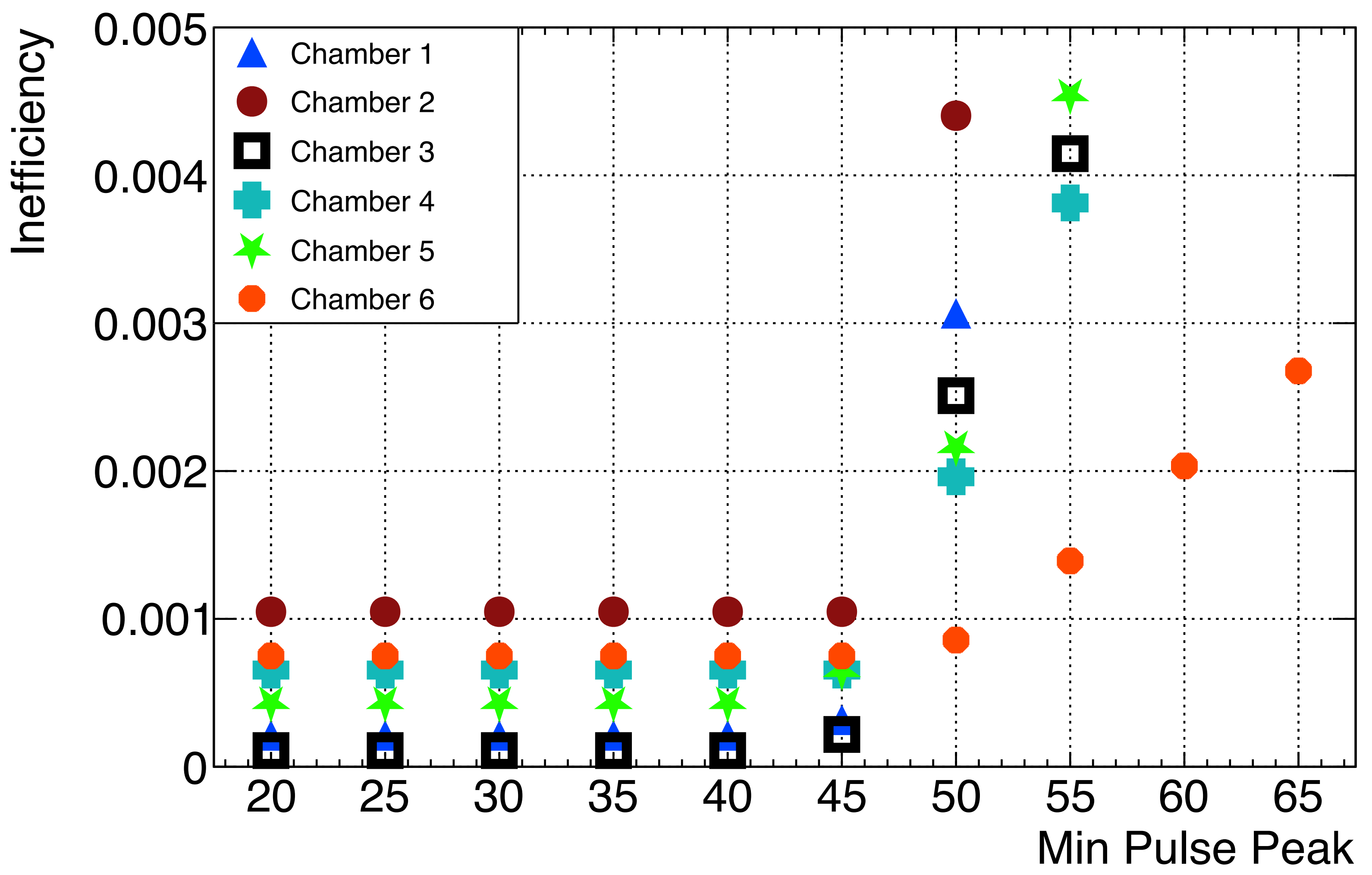
- Pion polarizability gives insight into fundamental symmetries in ChPT and low energy QCD
- Differing from past experiments, CPP/NPP at JLab utilize Primakoff Photo-Production of $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs
- Data taking and processing has been completed
- Neutral Pion Polarizability Analysis shows promising results
- Charged Pion Polarizability Analysis is still in the works and we are looking forward to presenting cross section and polarizabilities in the near future

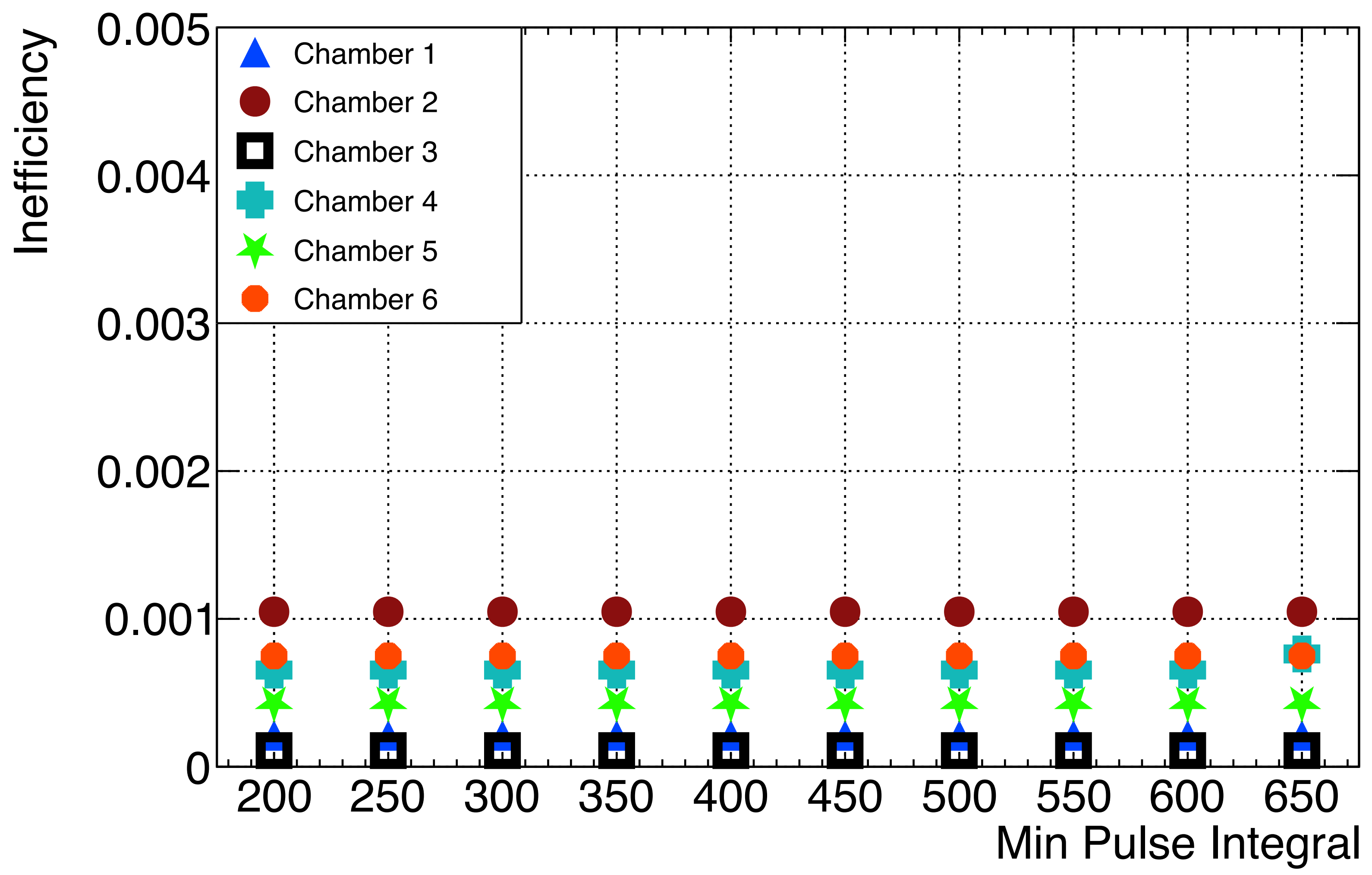
Thank you to the Organizers for the opportunity to speak at this meeting and thank you for your attention!

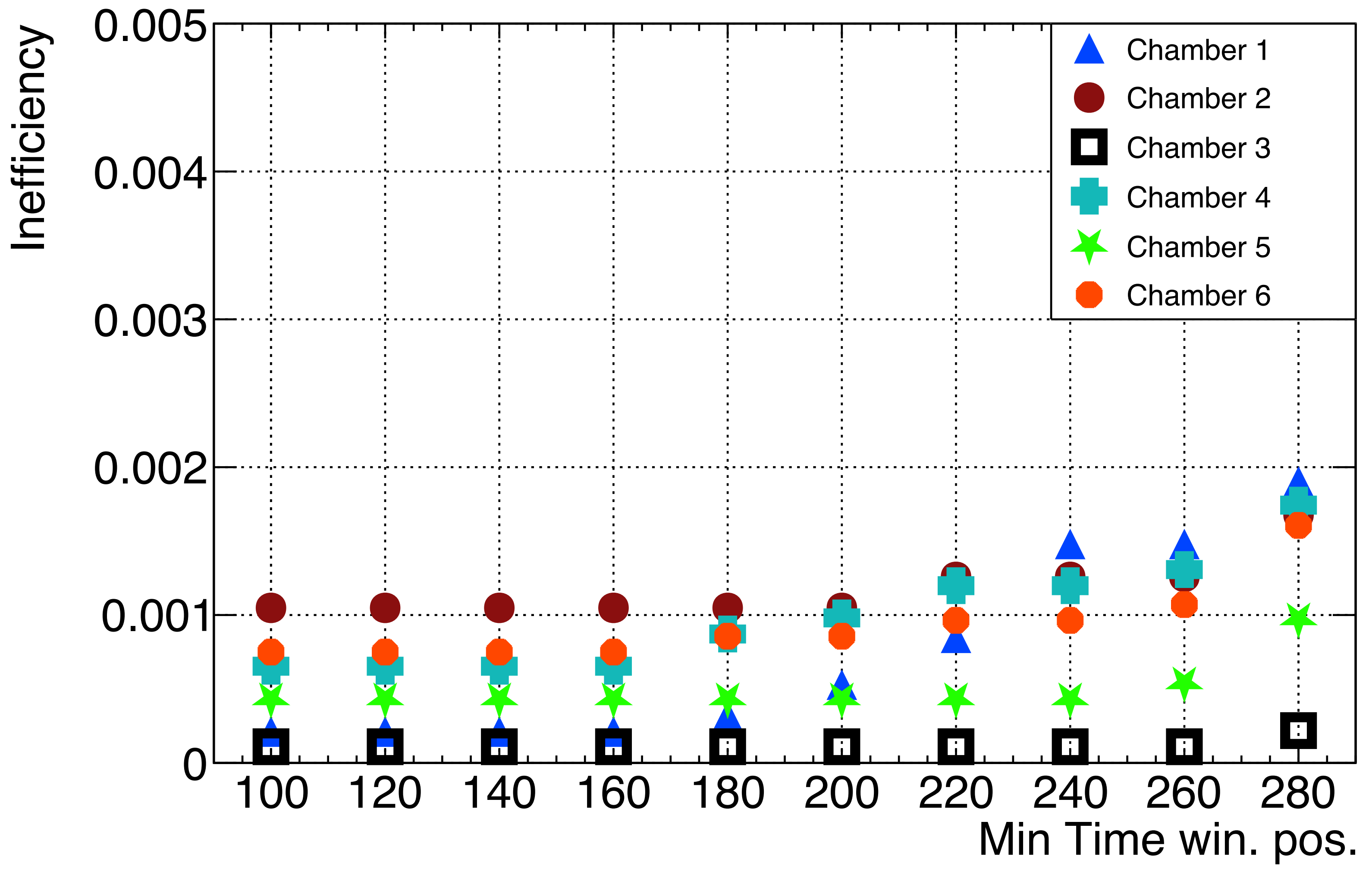
GlueX acknowledges the support of several funding agencies and computing facilities: gluex.org/thanks

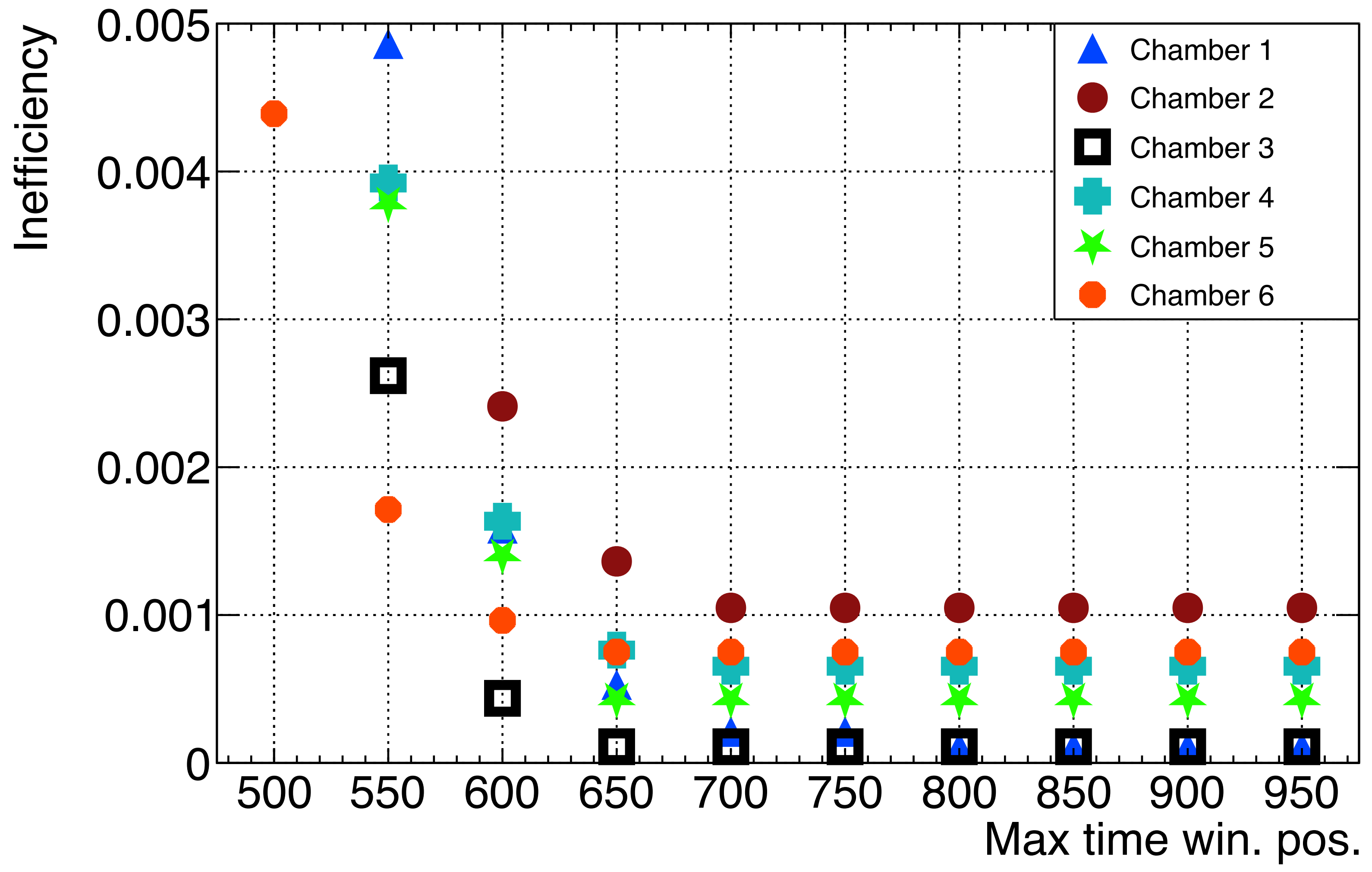
Back Ups

MWPC Inefficiencies



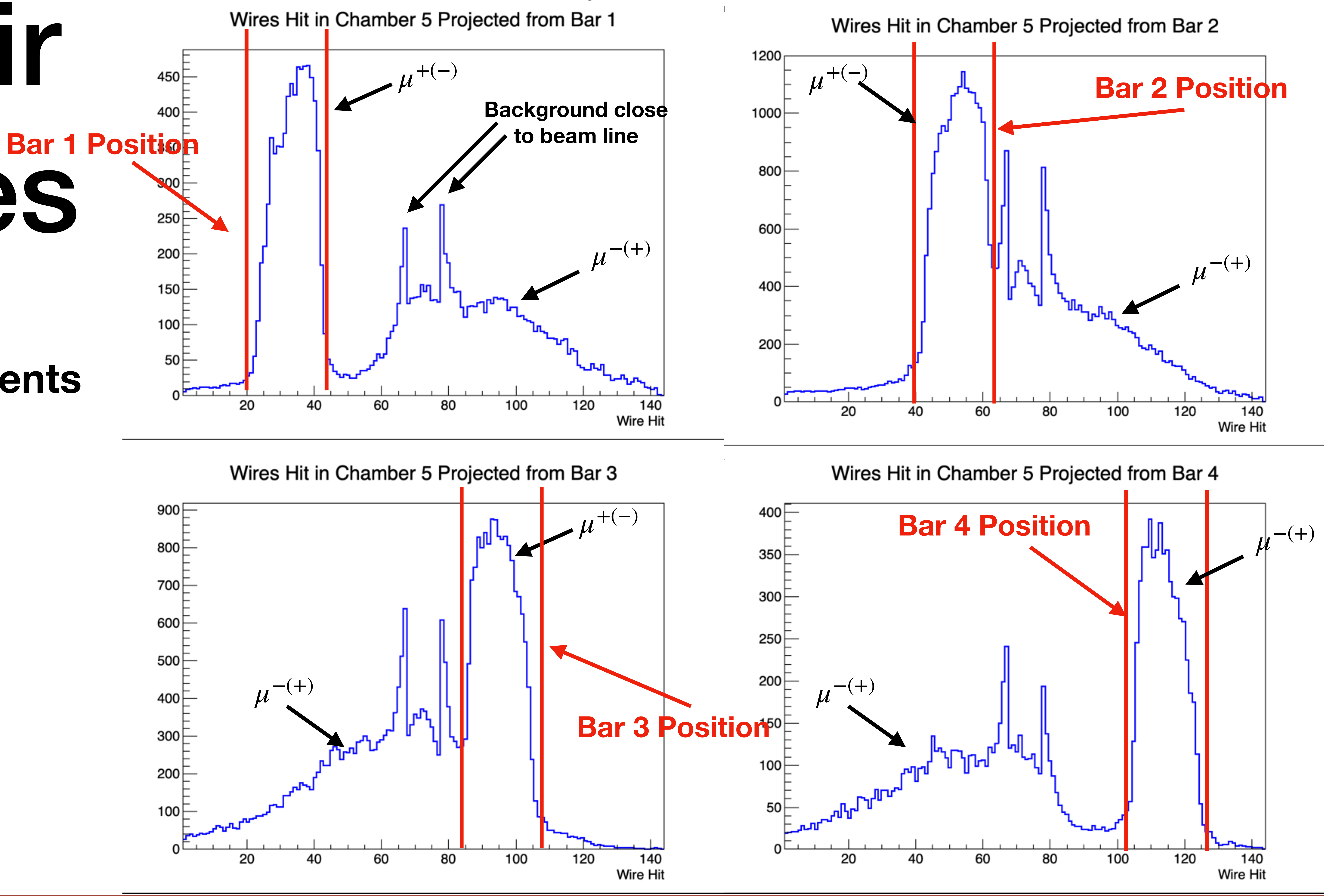






$\mu^+\mu^-$ Pair Candidates

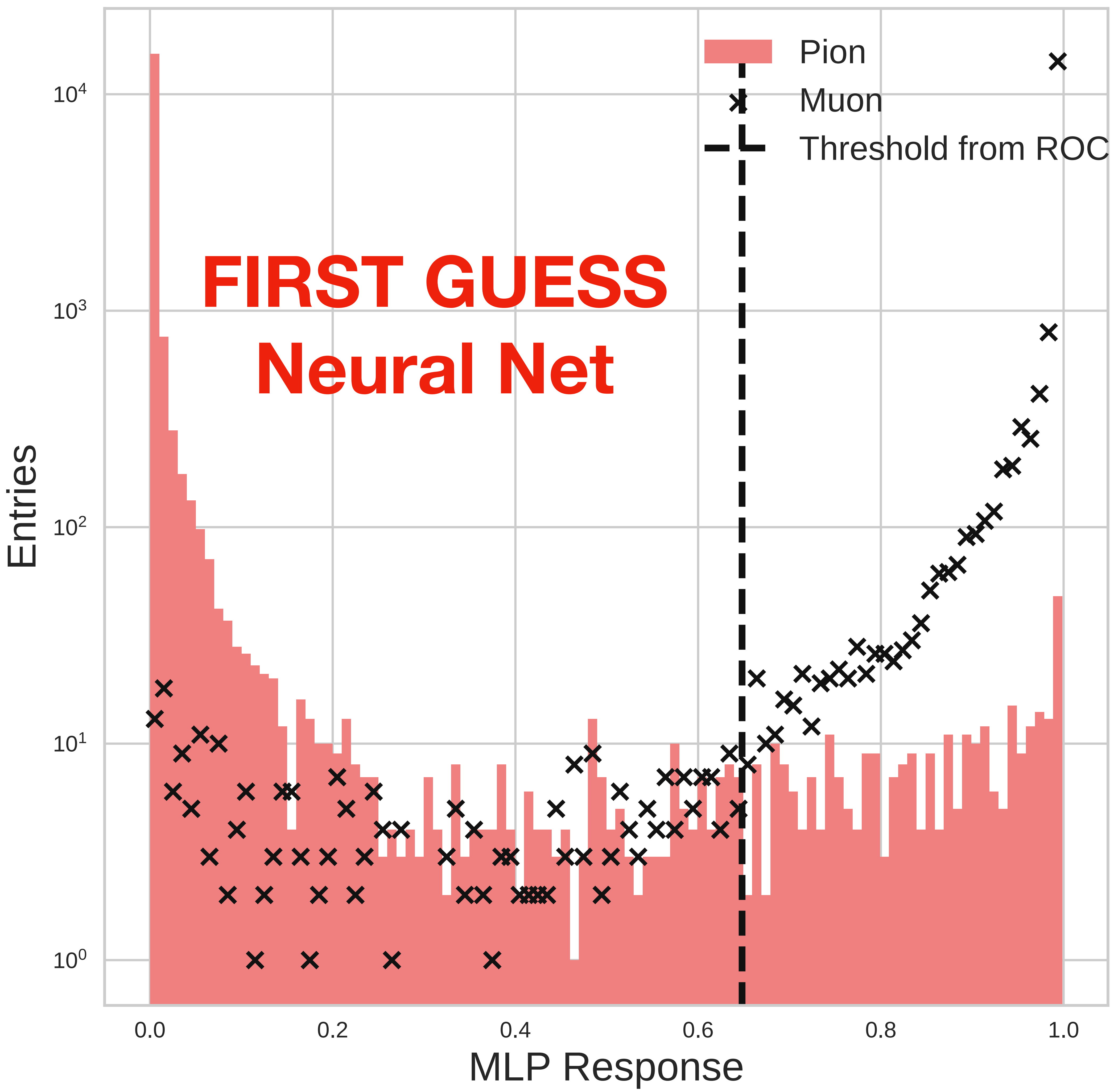
Chamber 5 Hits



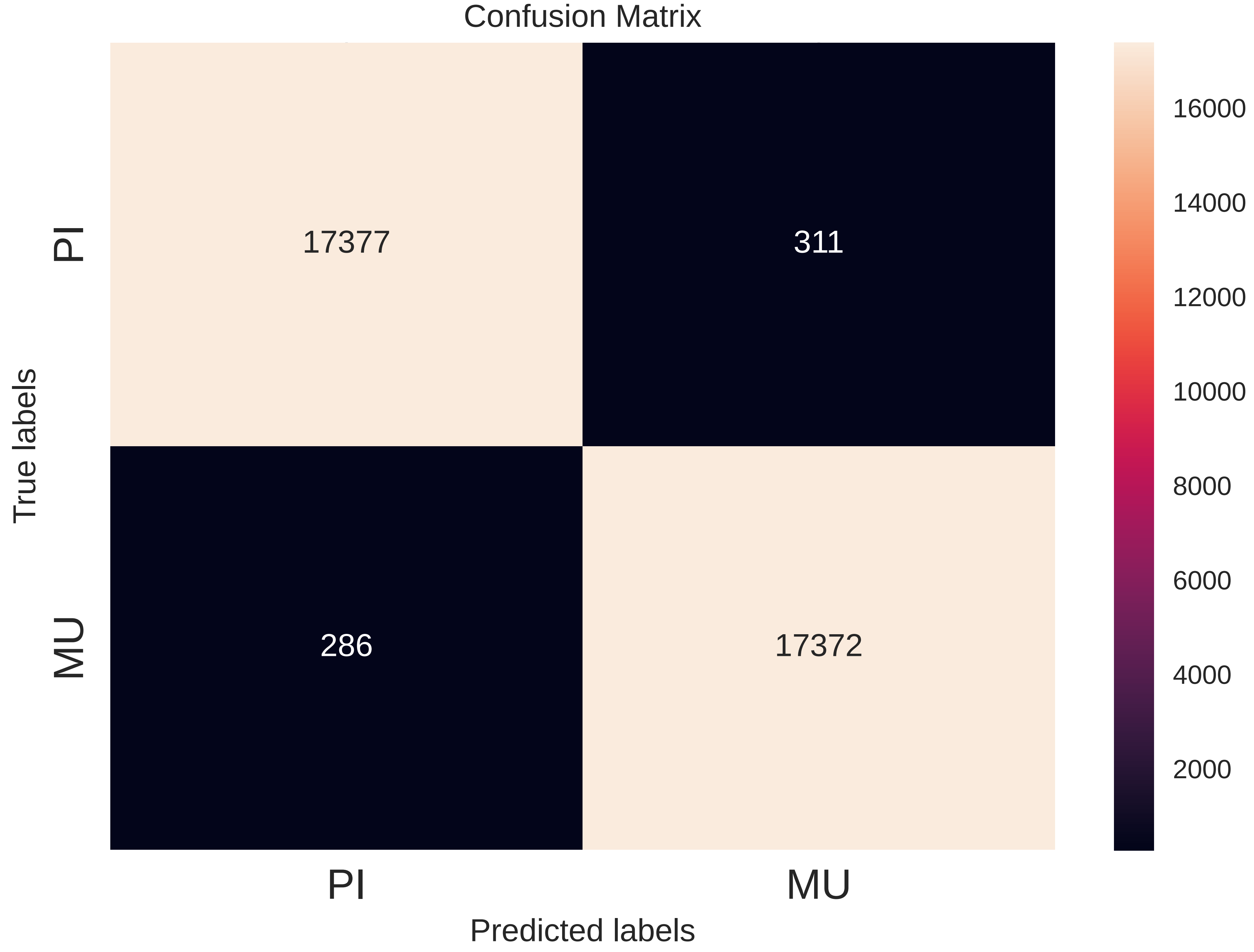
Charged Track Requirements

- Muon Detection in scintillators

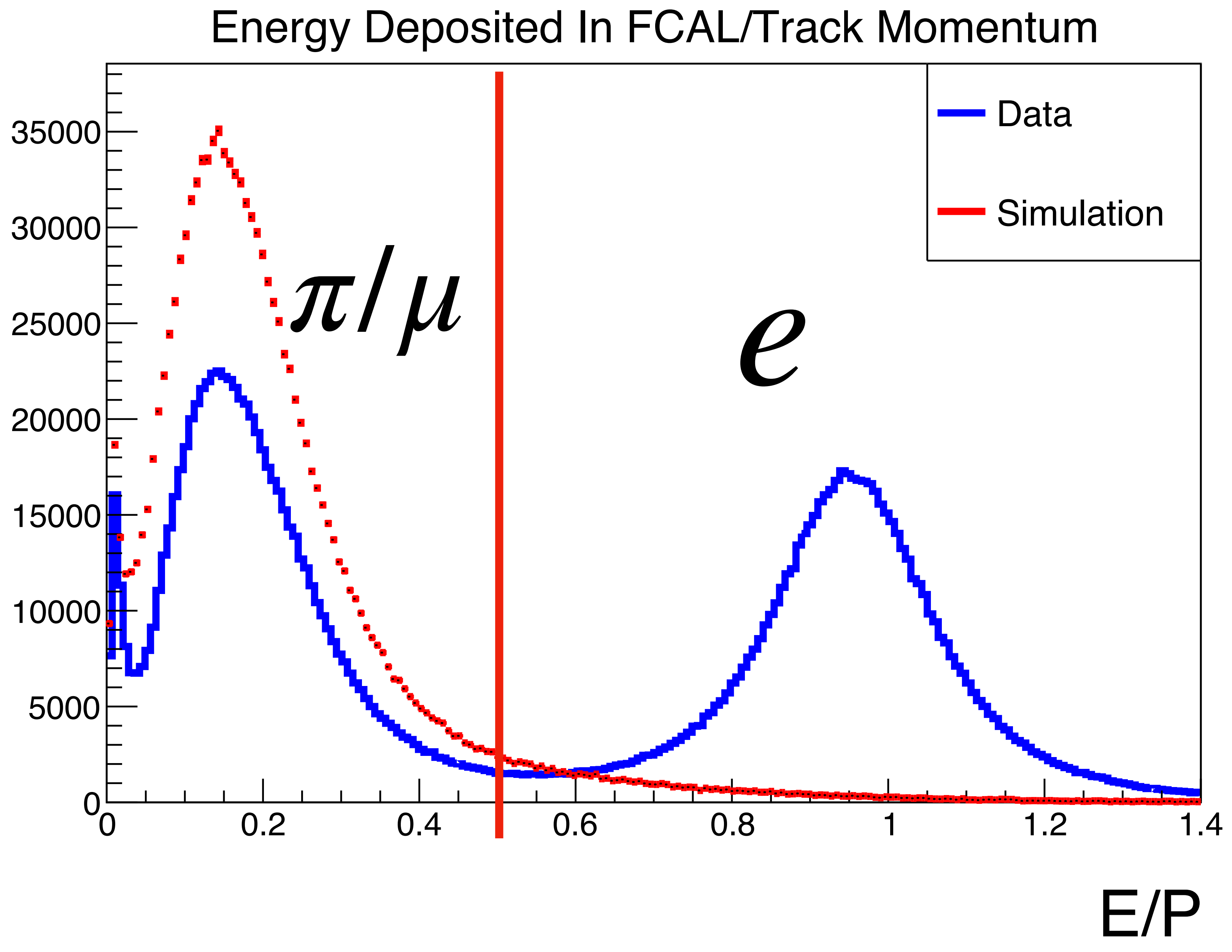
Neural Net Response

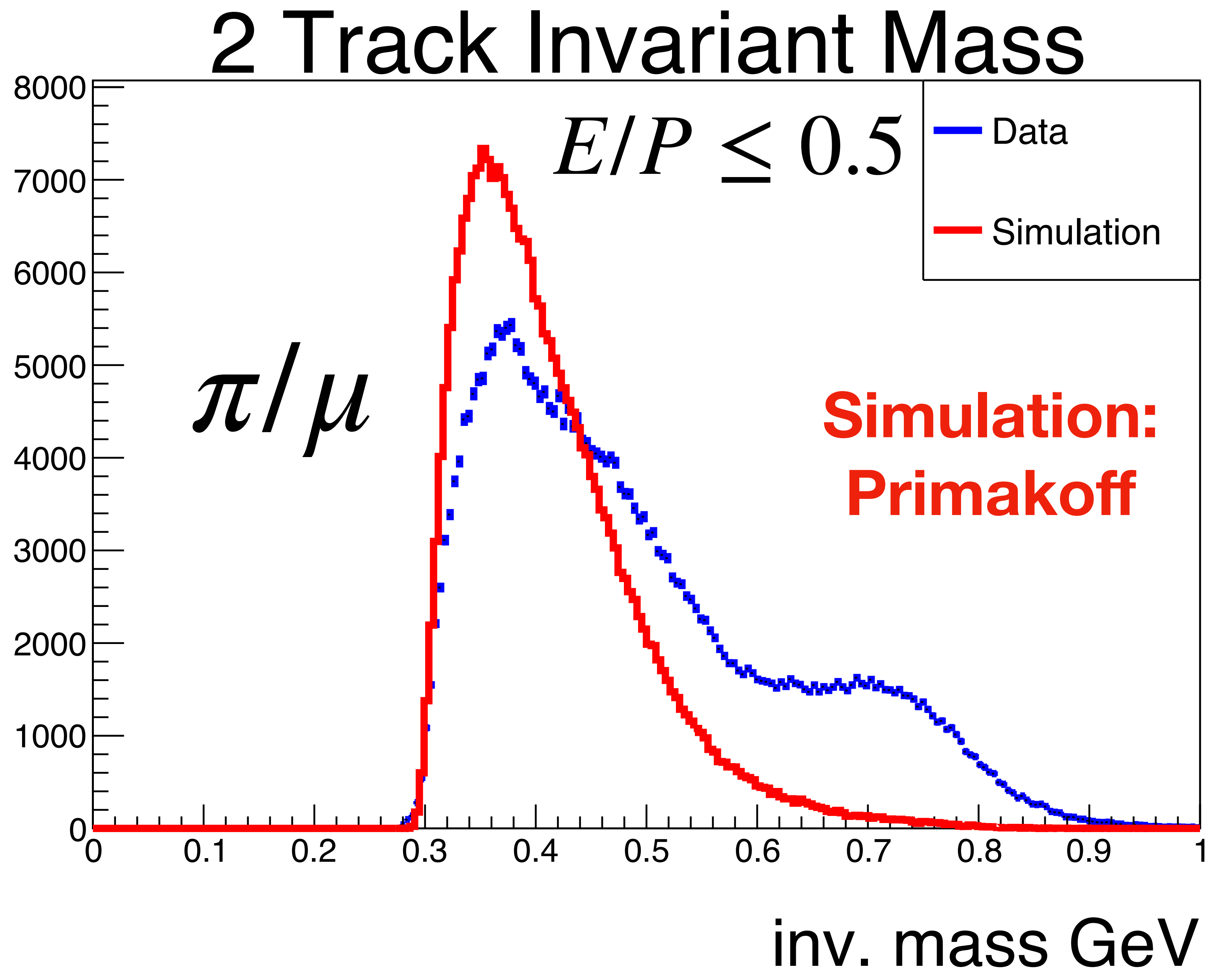


- Train a Neural Net with simulation for Primakoff $\pi^+\pi^-$ and Bethe-Heitler $\mu^+\mu^-$
- Use Calorimeter and Wire Chamber response as features for training.

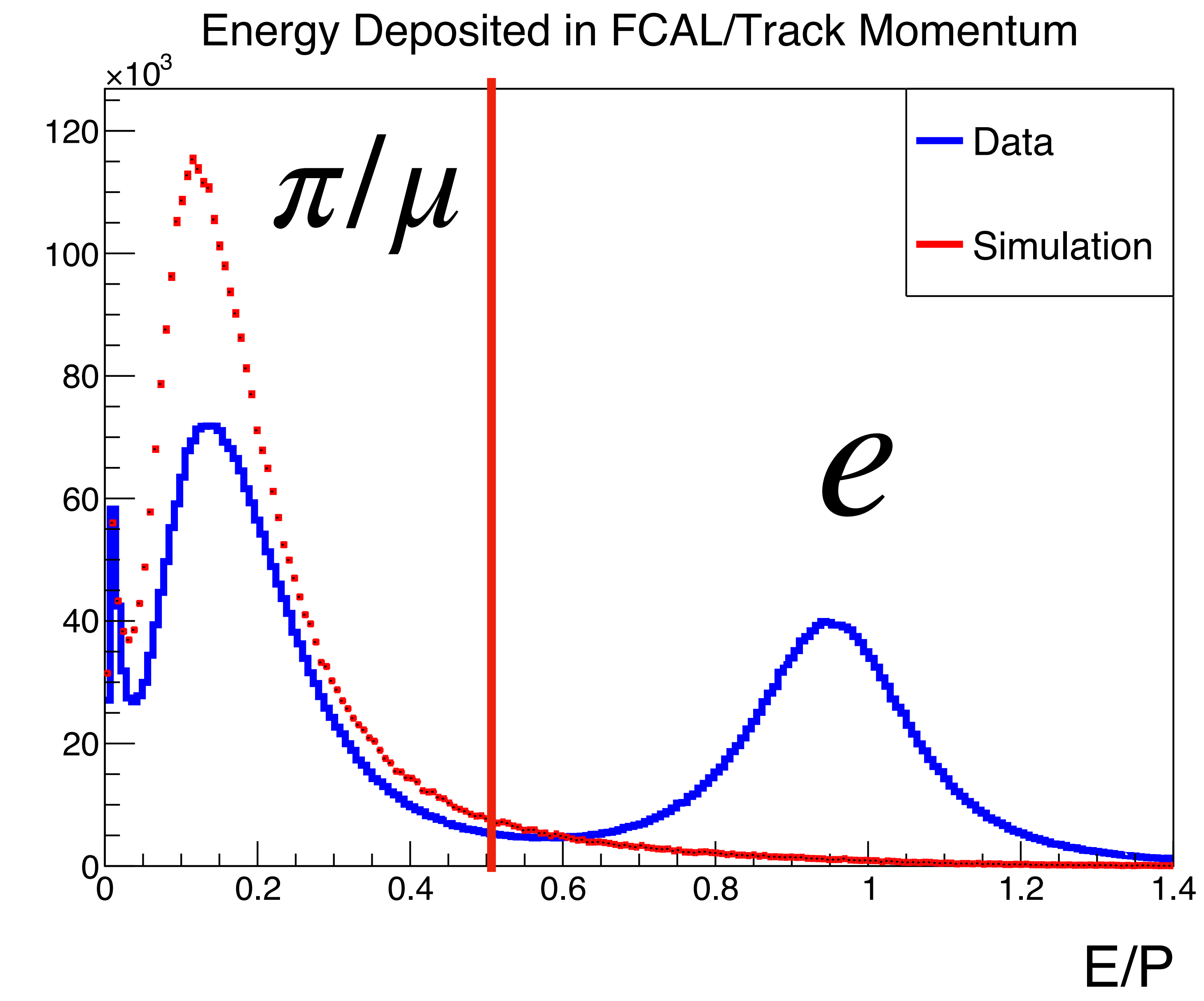


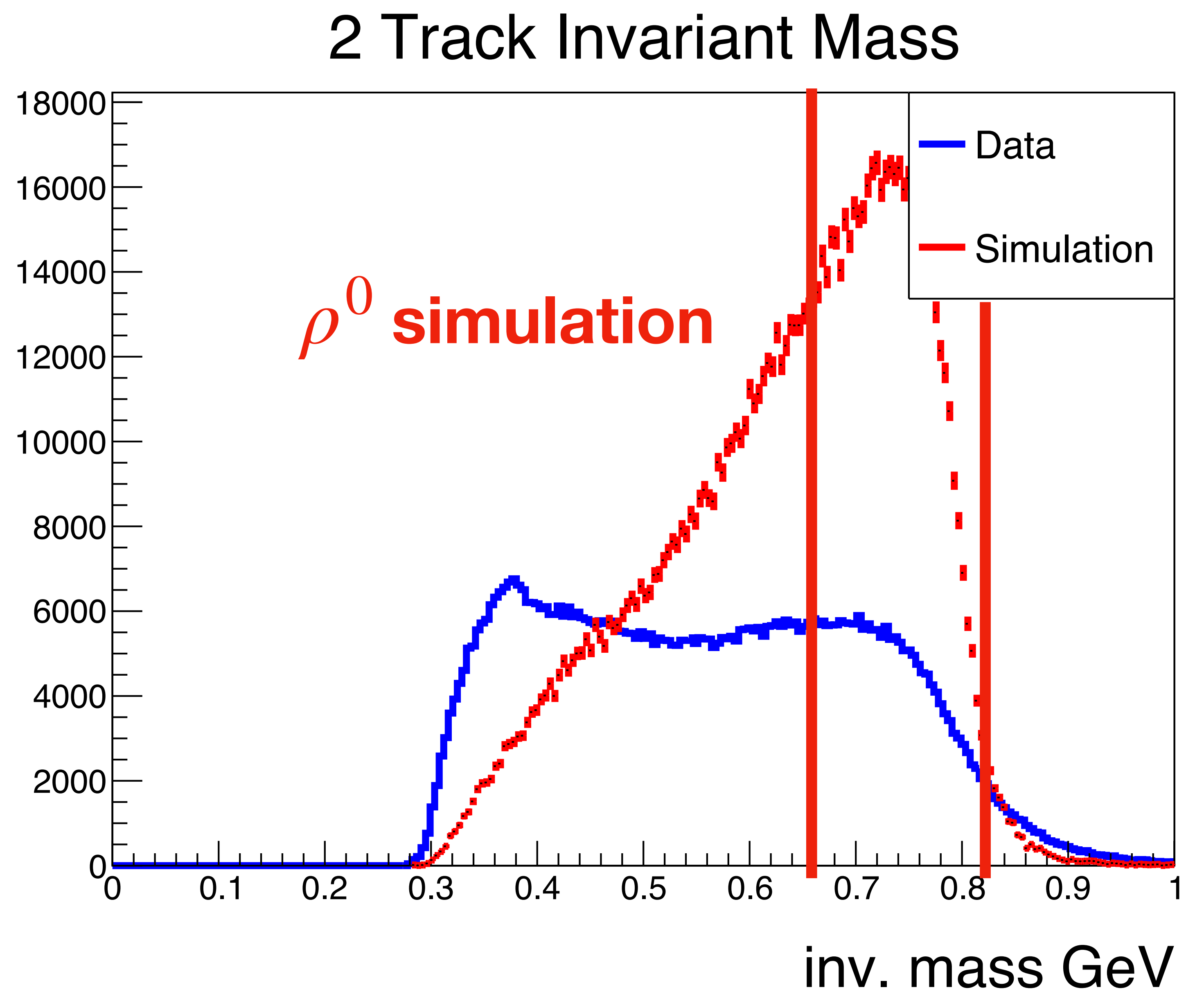
Selecting $\pi^+\pi^-$ in CPP





- Use Calorimeter, drift chambers, and wire chambers to identify two track events
- Muon Contamination is Prevalent in Primakoff peak





Pion Candidate Selection

- In order to look at clean $\pi^+\pi^-$ events can explore $\gamma\mathrm{Pb208} \rightarrow \rho^0\mathrm{Pb208}$
- Main decay mode: $\rho^0 \rightarrow \pi^+\pi^-$ where the final state has similar kinematics to Primakoff

Chiral Perturbation Theory (χPT)

Chirality

Left/Right Projection Operators

$$\Gamma_{L,R} = \frac{1 \pm \gamma_5}{2}$$

- Chirality is defined by Left/Right Projection Operators

- $\psi_L = \Gamma_L \, \psi, \; \psi_R = \Gamma_R \, \psi$ where $\psi = \psi_L + \psi_R$

- We first observe the limit wherein $m \rightarrow 0$

Recall: massive fermions break Chiral Symmetry explicitly!

$$\mathscr{L}_{mass} = -m\bar{\psi}\psi$$

$m \rightarrow 0$ **Chirality = Helicity**

Right-handed: *Left-handed:*

$$\mathscr{L}_{QCD} = \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{q}_R i\gamma^\mu D_\mu q_R$$

Chiral Symmetry

Rotations

$q_L \to e^{i\theta_L} q_L,\ q_R \to q_R$
$q_L \to q_L,\ q_R \to e^{i\theta_R} q_R$

- Our Lagrangian now in this $m \to 0$ limit is invariant under global left or right hand rotations (Chiral Symmetry!).

$$\mathscr{L}_{QCD} = \bar{q}_L i\gamma^\mu D_\mu q_L + \bar{q}_R i\gamma^\mu D_\mu q_R$$

- This invariance is called: $SU(3)_L \otimes SU(3)_R$

- In this limit the world is chiral symmetric: This would lead to 16 conserved Noether Currents (meaning 16 continuous symmetries from this theory!), 8 describing left handed fields, 8 describing right handed fields

- However in nature quarks are not massless!

Chiral Lagrangian

- These symmetries are broken which leads to Goldstone's theorem. (Broken explicitly from mass term AND spontaneously from vacuum state)

- From this Goldstone's theorem states there are 8 scalar particles (one for each generator of symmetry) that are very light that describe these interactions

- When working with low energy scale (< 1 GeV) we can define an effective Lagrangian for pseudoscalar mesons

$$\mathscr{L}_2 = \frac{F_\pi^2}{4} Tr(\partial_\mu U \partial^\mu U^\dagger) + \frac{m_\pi^2}{4} F_\pi^2 \, Tr(U + U^\dagger)$$

Field

$$U(x) = \exp\left(i\phi(x)/F_\pi\right)$$

$$F_\pi = 93 MeV$$

Higher than Tree Level

$$D_\mu U = \partial_\mu U + \{A_\mu, U\} + [V_\mu, U]$$

$$F^{L,R}_{\mu\nu} = \partial_\mu F^{L,R}_\nu - \partial_\nu F^{L,R}_\mu - i[F^{L,R}_\mu, F^{L,R}_\nu],\ F^{L,R}_\mu = V_\mu \pm A_u$$

Gasser-Leutwyler

- Going above tree level (one loop and beyond) brings about divergences.
- Weinberg posited that these divergences can be absorbed in to phenomenological constants, much like QED.

$$\begin{aligned}
\mathcal{L}_4 &= \sum_{i=1}^{10} L_i \mathcal{O}_i = L_1 \left[\mathrm{tr}(D_\mu U D^\mu U^\dagger)\right]^2 + L_2 \mathrm{tr}(D_\mu U D_\nu U^\dagger)\cdot \mathrm{tr}(D^\mu U D^\nu U^\dagger) \\
&+ L_3 \mathrm{tr}(D_\mu U D^\mu U^\dagger D_\nu U D^\nu U^\dagger) + L_4 \mathrm{tr}(D_\mu U D^\mu U^\dagger)\mathrm{tr}(\chi U^\dagger + U\chi^\dagger) \\
&+ L_5 \mathrm{tr}\left(D_\mu U D^\mu U^\dagger \left(\chi U^\dagger + U \chi^\dagger\right)\right) + L_6 \left[\mathrm{tr}\left(\chi U^\dagger + U\chi^\dagger\right)\right]^2 \\
&+ L_7 \left[\mathrm{tr}\left(\chi^\dagger U - U\chi^\dagger\right)\right]^2 + L_8 \mathrm{tr}\left(\chi U^\dagger \chi U^\dagger + U\chi^\dagger U \chi^\dagger\right) \\
&+ i L_9 \mathrm{tr}\left(F^L_{\mu\nu} D^\mu U D^\nu U^\dagger + F^R_{\mu\nu} D^\mu U^\dagger D^\nu U\right) + L_{10} \mathrm{tr}\left(F^L_{\mu\nu} U F^{R\mu\nu} U^\dagger\right)
\end{aligned}$$

This Lagrangian, written by Gasser and Leutwyler incorporates 4th order derivative interactions. The L_i terms absorb the Divergences

$$L_i^r = \underset{\uparrow}{L_i} - \frac{\gamma_i}{32\pi^2}\left[-\frac{2}{\epsilon} - \ln(4\pi) + \gamma - 1\right]$$

Bare value

Coefficient	Value	Origin
L_1^r	0.65 ± 0.28	$\pi\pi$ scattering
L_2^r	1.89 ± 0.26	and
L_3^r	-3.06 ± 0.92	$K_{\ell 4}$ decay
L_5^r	2.3 ± 0.2	F_K/F_π
L_9^r	7.1 ± 0.3	π charge radius
L_{10}^r	-5.6 ± 0.3	$\pi \to e\nu\gamma$

Pion Polarizability as a Predicted Quantity

- Gasser and Leutwyler performed one loop integration on the $\mathcal{O}(p^4)$ form

Charged Pion Polarizability

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

$$L_{QCD}(p^4) = L^{chiral\ even} + L^{chiral\ odd}$$

Reaction	Quantity	Theory	Experiment
$\pi^+ \to e^+\nu_e\gamma$	$h_V(m_\pi^{-1})$	0.027	0.029 ± 0.017[11]
$\pi^+ \to e^+\nu_e e^+ e^-$	r_V/h_V	2.6	2.3 ± 0.6[11]
$\gamma\pi^+ \to \gamma\pi^+$	$(\alpha_E + \beta_M)\,(10^{-4}\,\mathrm{fm}^3)$	0	1.4 ± 3.1[12]
	$\alpha_E\,(10^{-4}\,\mathrm{fm}^3)$	2.8	6.8 ± 1.4[13]
			12 ± 20[14]
			2.1 ± 1.1[15]

Pion Polarizability Prediction, with 3 experimental results. One in disagreement