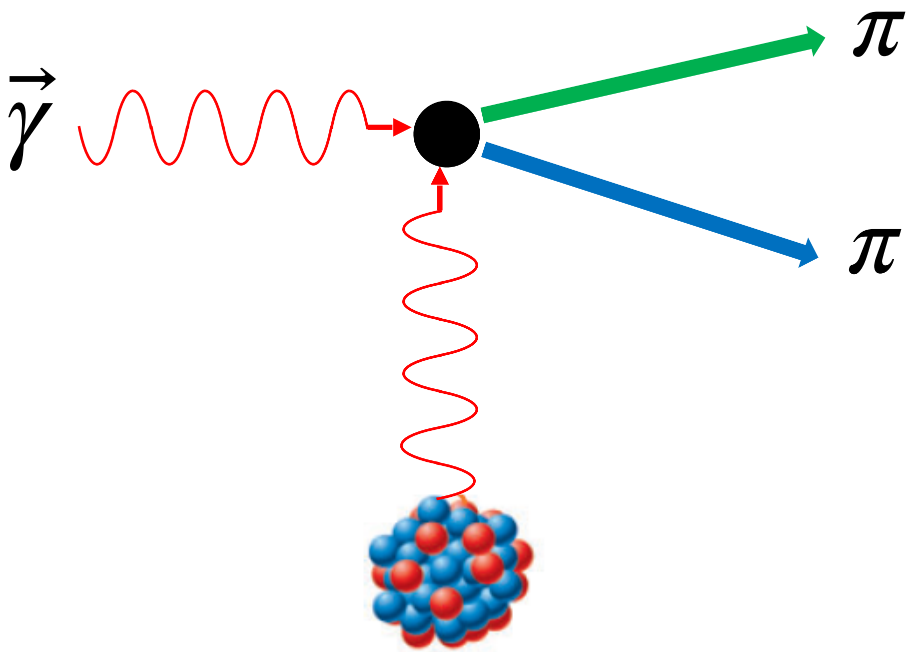
Measurements of charged pion and neutral pion polarizabilities at JLab GlueX

Rory Miskimen
University of Massachusetts, Amherst
and the GlueX Collaboration



i. Pion polarizability
ii. How to measure pion polarizability
iii. Update on the pion polarizability measurement at Jefferson Lab GlueX

I. Pion polarizability

Measurements provide a test for fundamental symmetries, specifically chiral symmetry and its realization in QCD

Charged pion polarizability (CPP)

O(p⁴) ChPT: $$\alpha_\pi = -\beta_\pi = \frac{4\alpha_{EM}}{m_\pi F_\pi^2}\left(L_9^r - L_{10}^r\right) \approx \frac{F_A}{F_V}$$

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

$$\alpha_\pi = -\beta_\pi = 2.78 \pm 0.1 \times 10^{-4} e\ fm^3$$

O(p⁶) ChPT: $$\alpha_\pi - \beta_\pi = 5.7 \pm 1.0$$

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

O(p⁶) corrections to the charged pion polarizability 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: $$\alpha_{\pi^0} + \beta_{\pi^0} = 1.15 \pm 0.30$$

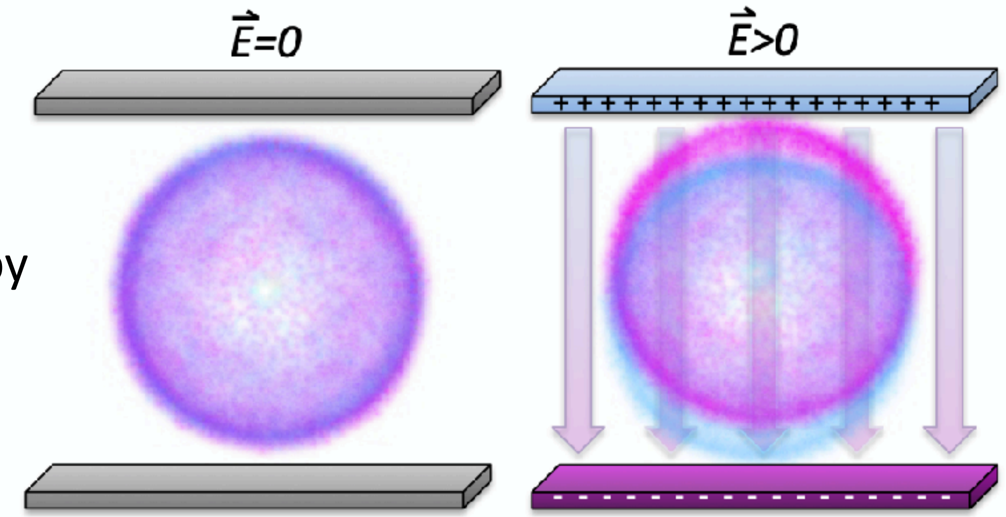
$$\alpha_{\pi^0} - \beta_{\pi^0} = -1.90 \pm 0.20$$

Neutral pion polarizability has never been reliably determined

"Thought experiment": place a pion in a capacitor at very high electric field

$$E \approx \frac{0.1GeV}{1\ fm} = 10^{23}\frac{volts}{m}$$

Pion surrounded by pion cloud



Displaced pion cloud gives E.M. polarizability

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

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

Small numbers because hadrons are "stiff"

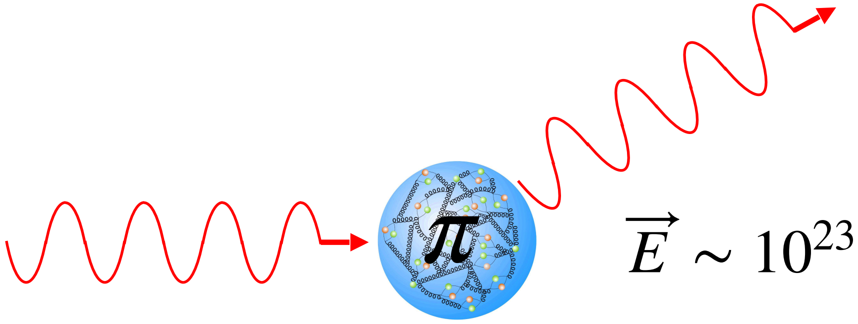
Polarizabilities encode information about the excited states of hadrons, and provide a test of effective field theories for low energy QCD

II. How to measure pion polarizability

Strong electric field is needed to polarize a hadron: $E \approx \frac{100MeV}{1fm} = 10^{23}\frac{V}{m}$

The best technique is Compton scattering on the pion

~100 MeV



$\vec{E} \sim 10^{23}\ V/m$

$$H = H_{Born} - 4\pi\left(\frac{1}{2}\alpha_E\vec{E}^2 + \frac{1}{2}\beta_M\vec{H}^2\right)$$

≈10%

Since a pion target doesn't exist, alternative methods must be utilized to determine pion polarizability

Charged pion polarizability:

i. Radiative pion photo-production: $\gamma p \rightarrow \gamma' \pi^+ n$ (Mainz A2)

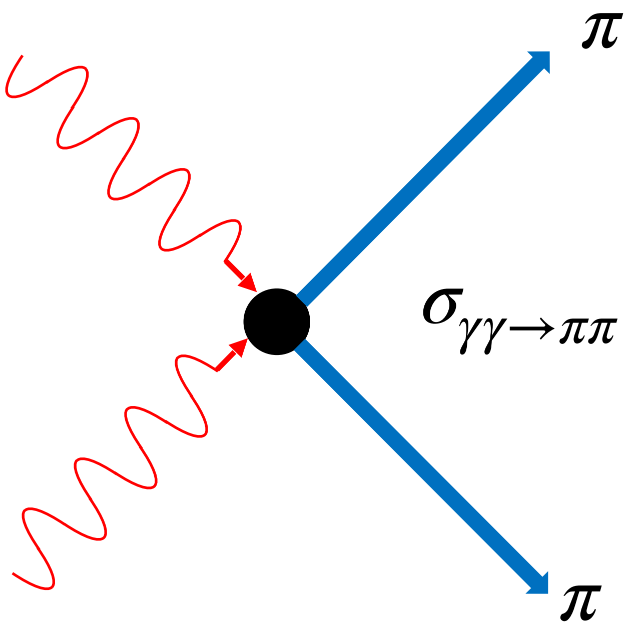
ii. Pion radiative scattering: $\pi^- A \rightarrow \gamma \pi^- A$ (Compass)

iii. $\pi^+ \pi^-$ production in two photon collisions: $\gamma\gamma \rightarrow \pi^+ \pi^-$ (Mark II)

Neutral pion polarizability:

iii. $\pi^0 \pi^0$ production in two photon collisions: $\gamma\gamma \rightarrow \pi^0 \pi^0$ (Crystal Ball)

iii. Two photon collisions $\gamma\gamma \to \pi\pi$



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

Theory

Donoghue and Holstein, Phys. Rev. D **48**, 137 (1993)

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

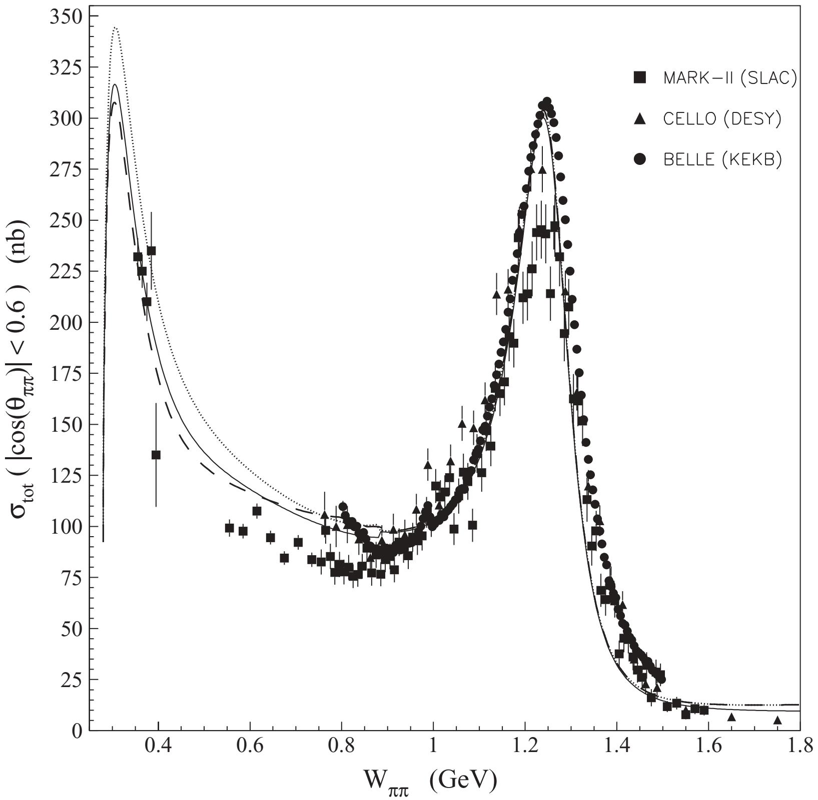
Pasquini, Drechsel, and Scherer, Phys. Rev. C **77**, 065211 (2008)

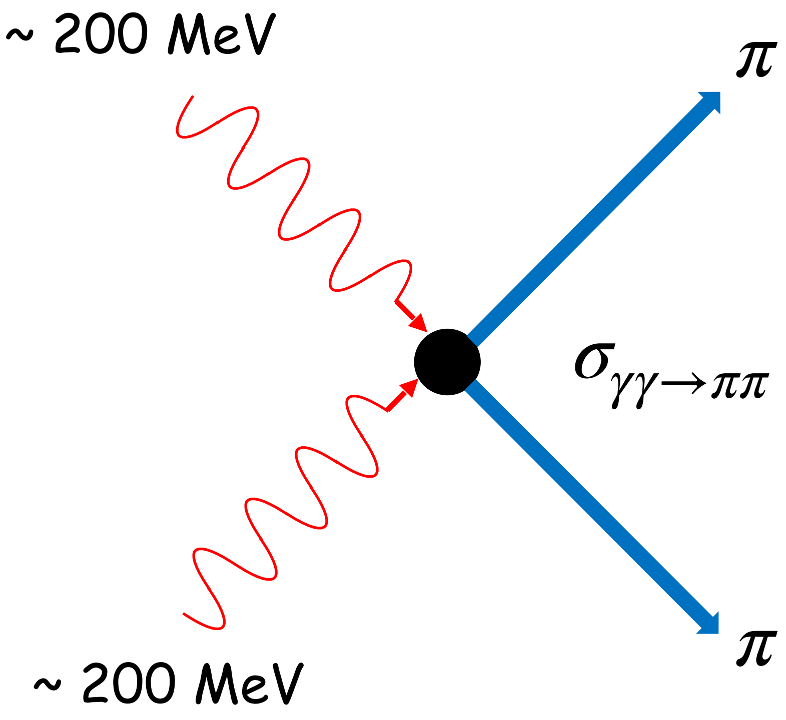
Dai and Pennington, Phys. Rev. D **90**, 036004 (2014), and Phys. Rev. D **94**, 116021 (2016)

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

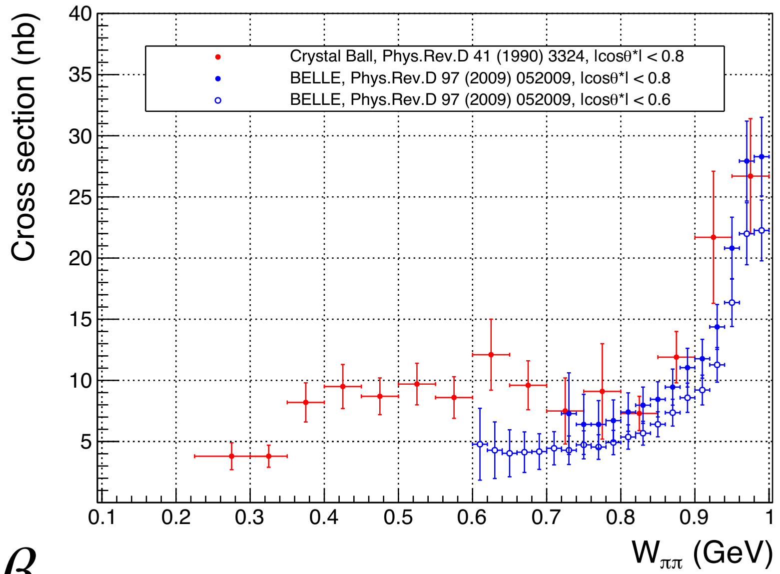
Charged and neutral pion polarizabilties measured in two photon collisions

$\sigma(\gamma\gamma \to \pi^+\pi^-)$ at Mark-II





$\sigma(\gamma\gamma \to \pi^0\pi^0)$ at Crystal Ball



$$\sigma_{\gamma\gamma\to\pi\pi} \xrightarrow{\textit{dispersion theory}} \alpha_\pi - \beta_\pi$$

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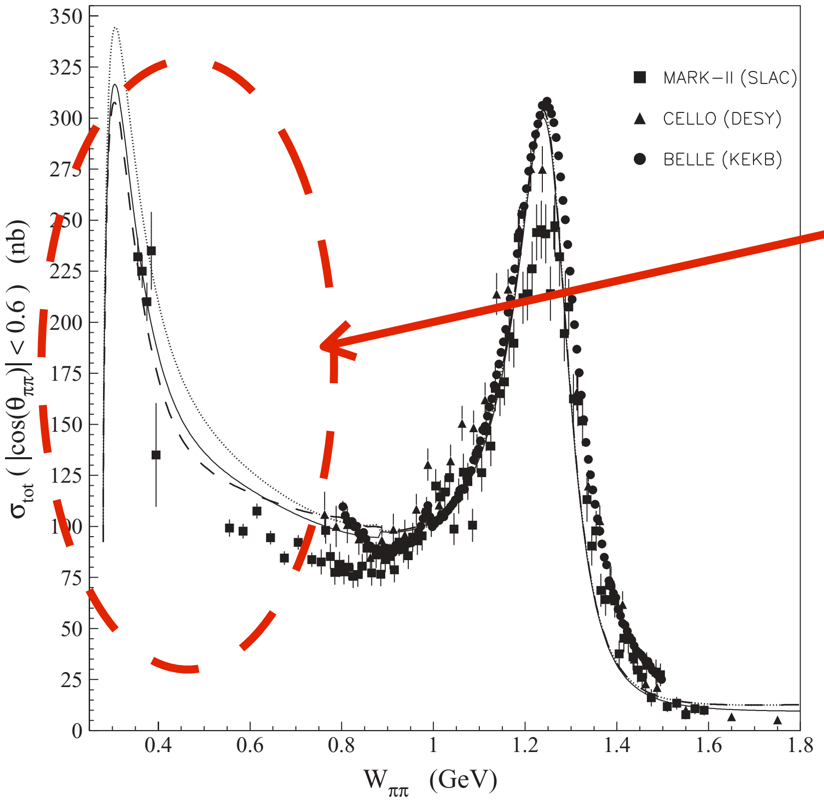
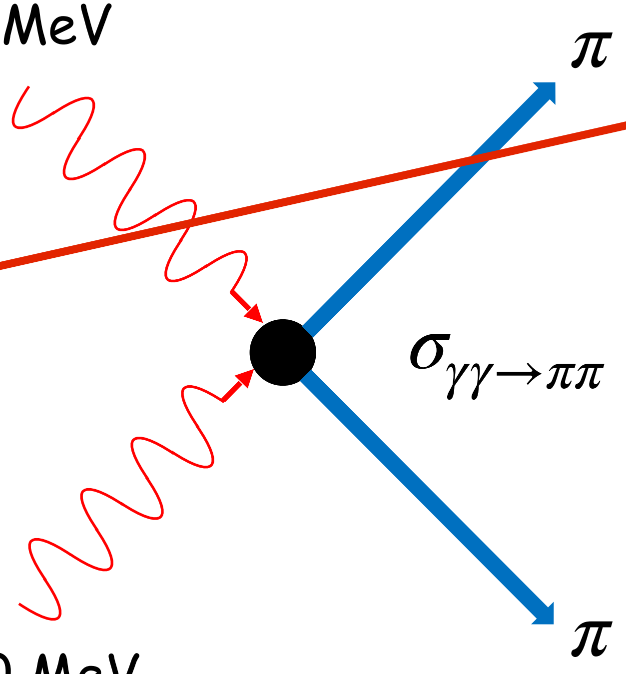
$\sigma(\gamma\gamma \to \pi^+\pi^-)$ at Mark-II



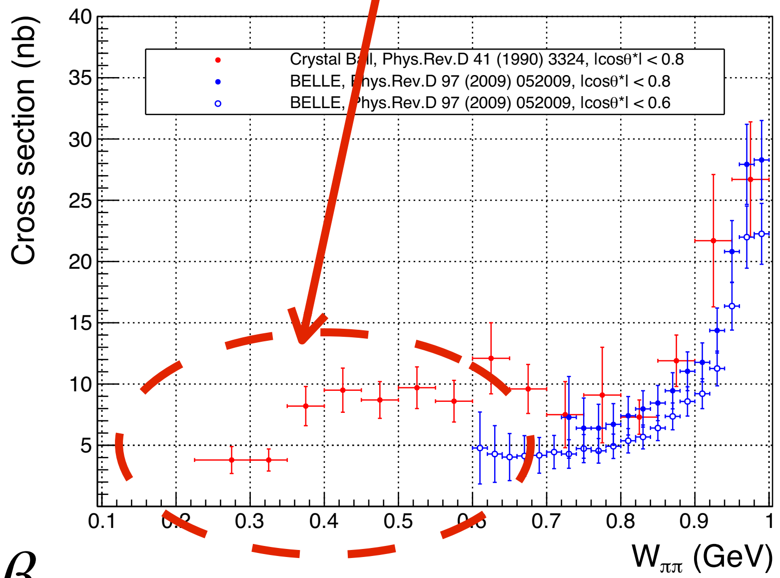
~ 200 MeV



~ 200 MeV

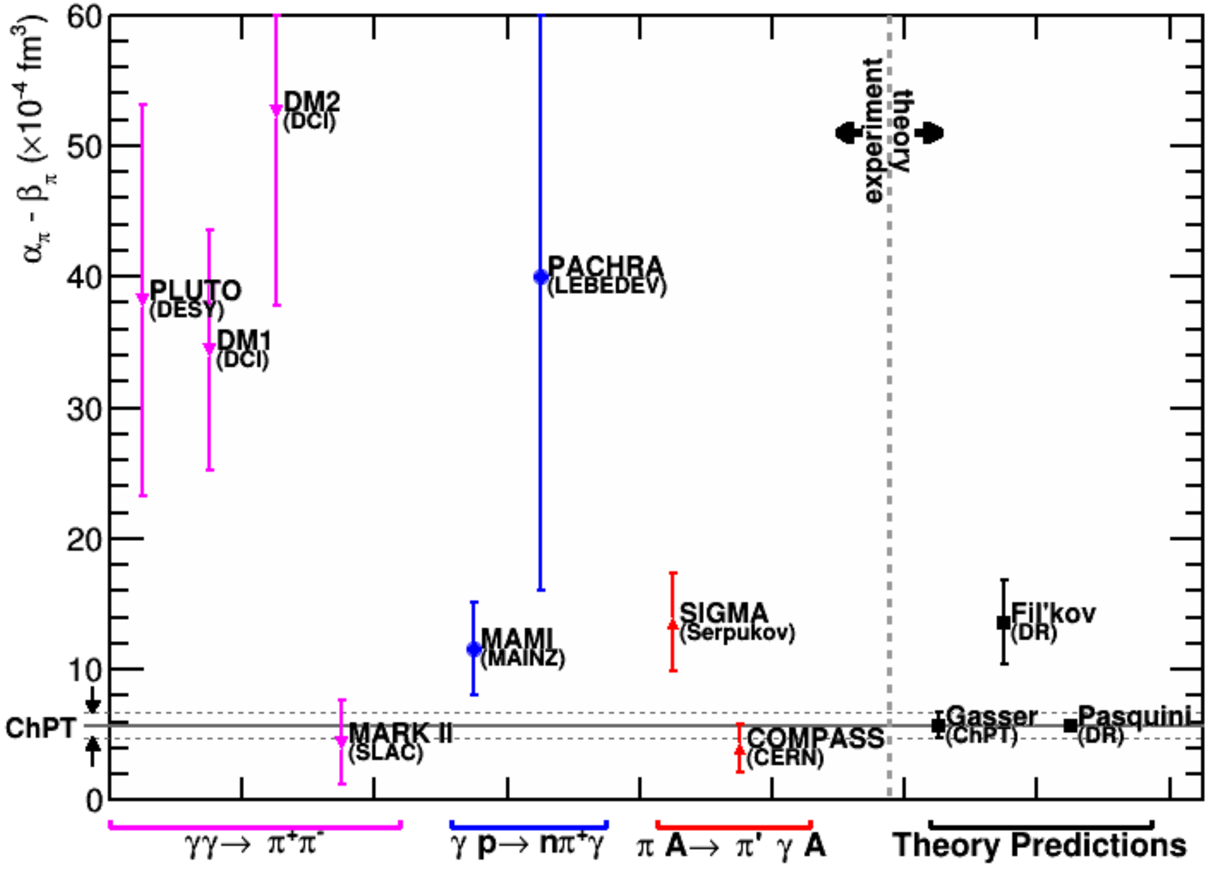
sparse statistics !

$\sigma(\gamma\gamma \to \pi^0\pi^0)$ at Crystal Ball



$$\sigma_{\gamma\gamma\to\pi\pi} \xrightarrow{\textit{dispersion theory}} \alpha_\pi - \beta_\pi$$

Published measurements of charged pion polarizability



COMPASS: $\pi^- Ni \rightarrow \pi^- \gamma\ Ni$ @ 160 GeV

$$\alpha_\pi - \beta_\pi = 4.0 \pm 1.2(stat) \pm 1.4(sys) \times 10^{-4} fm^3$$

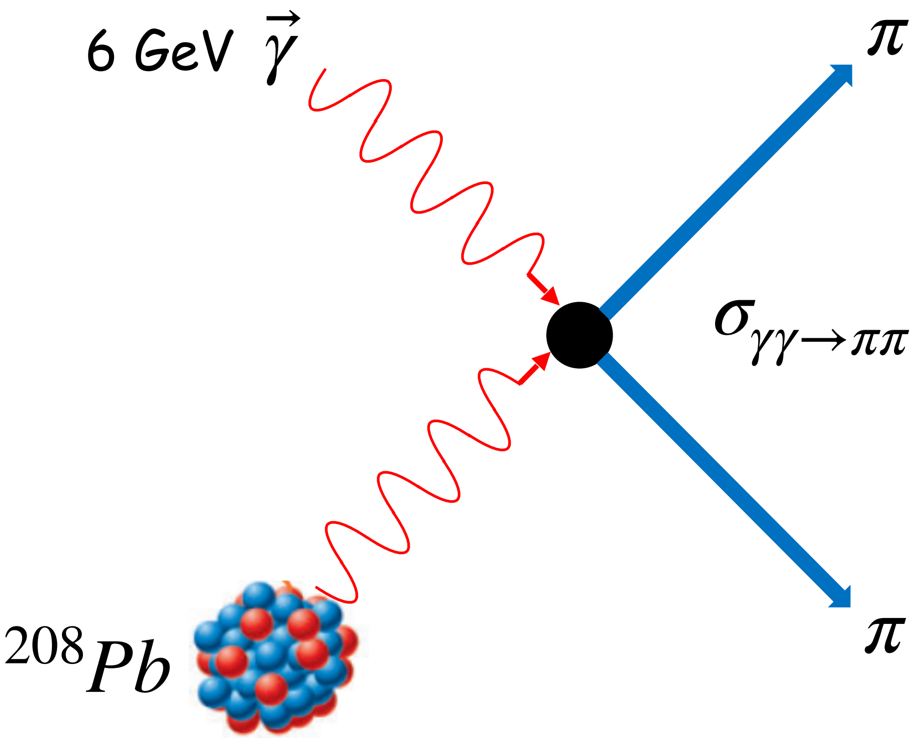
III. Update on the pion polarizability measurement at Jefferson Lab GlueX

Goals for the JLab experiment

i. Develop a new technique that's complementary to measurements at COMPASS and e^+e^- colliders

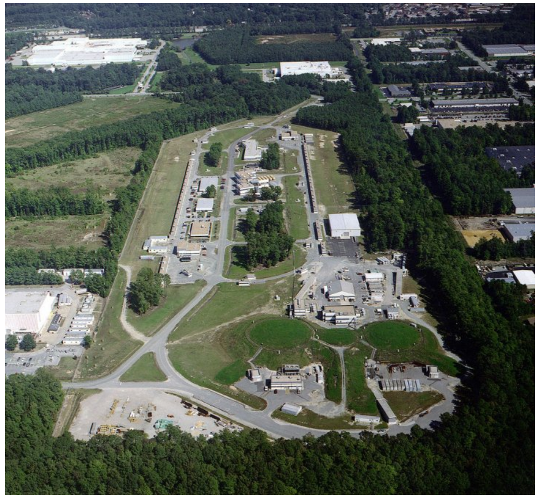
ii. Provide higher statistics for $\sigma(\gamma\gamma \rightarrow \pi\pi)$ than existing collider data

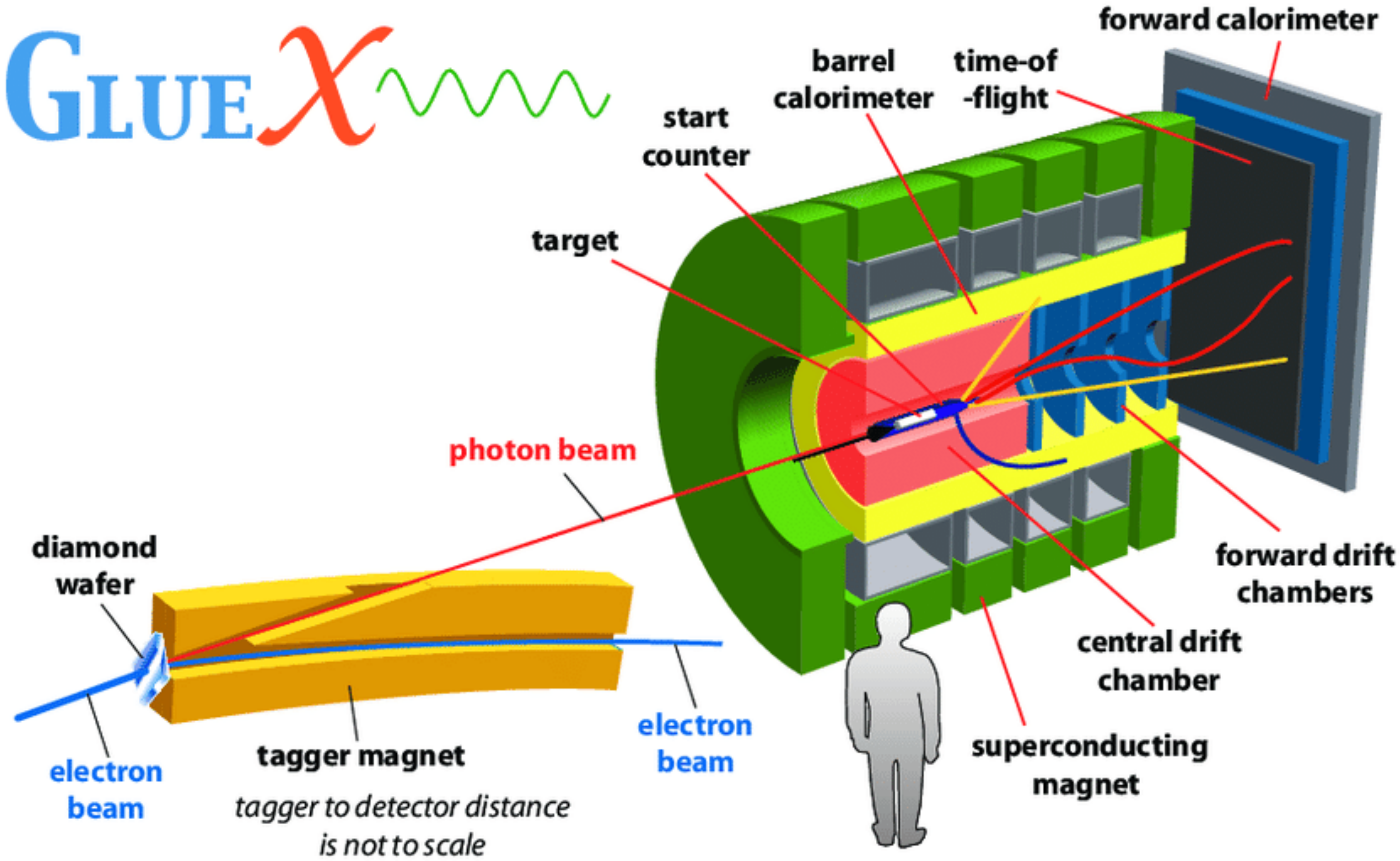
iii. Provide a measurement of CPP with low statistical and systematic errors, and the first reliable measurement of NPP



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

CPP and NPP experiment at JLab GlueX

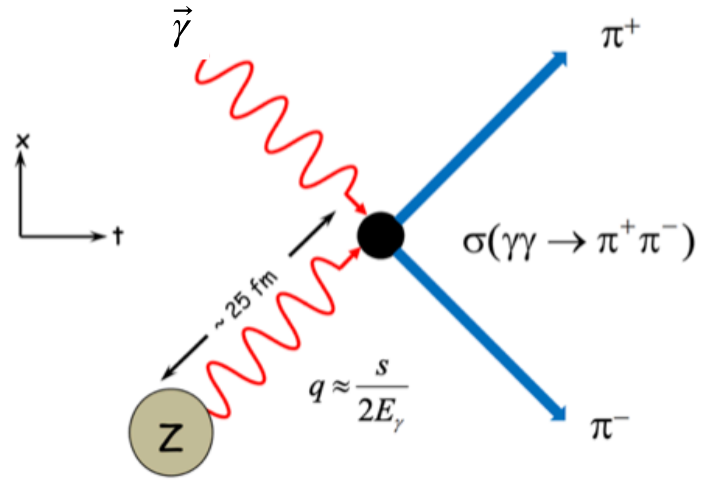


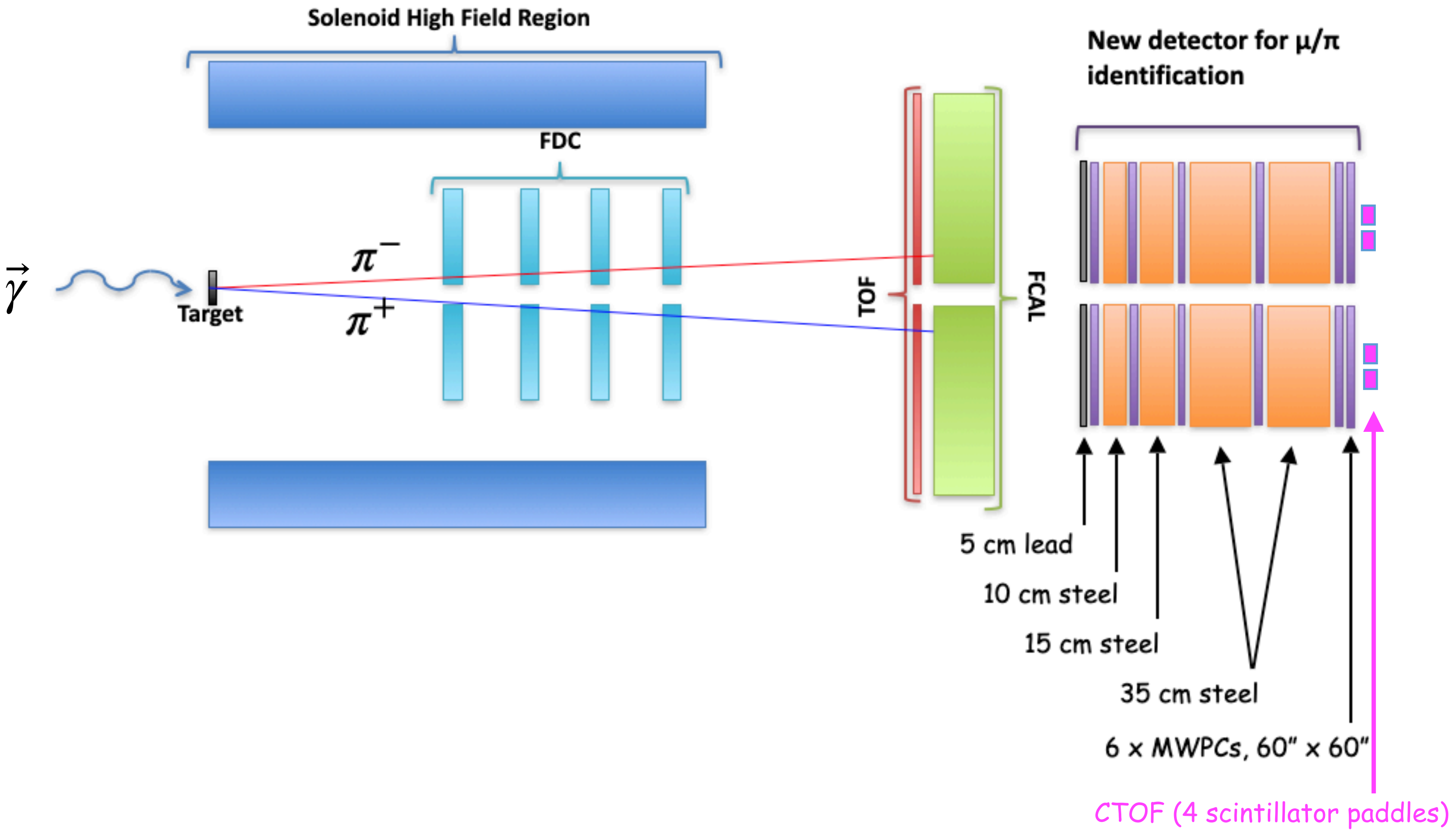


CPP and NPP experiment at JLab GlueX

Primakoff process:

very low-t photoproduction $\gamma A \to \pi$



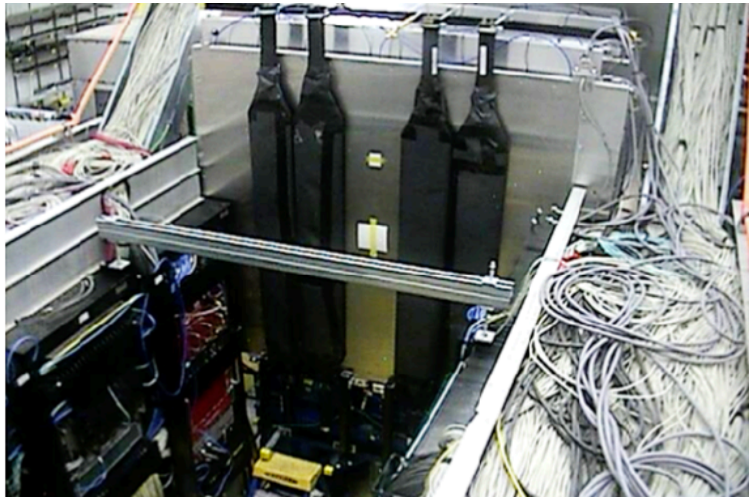


Muon detector

Assembled muon chambers at UMass

Chambers installed with iron absorbers

Trigger scintillators installed behind muon chambers

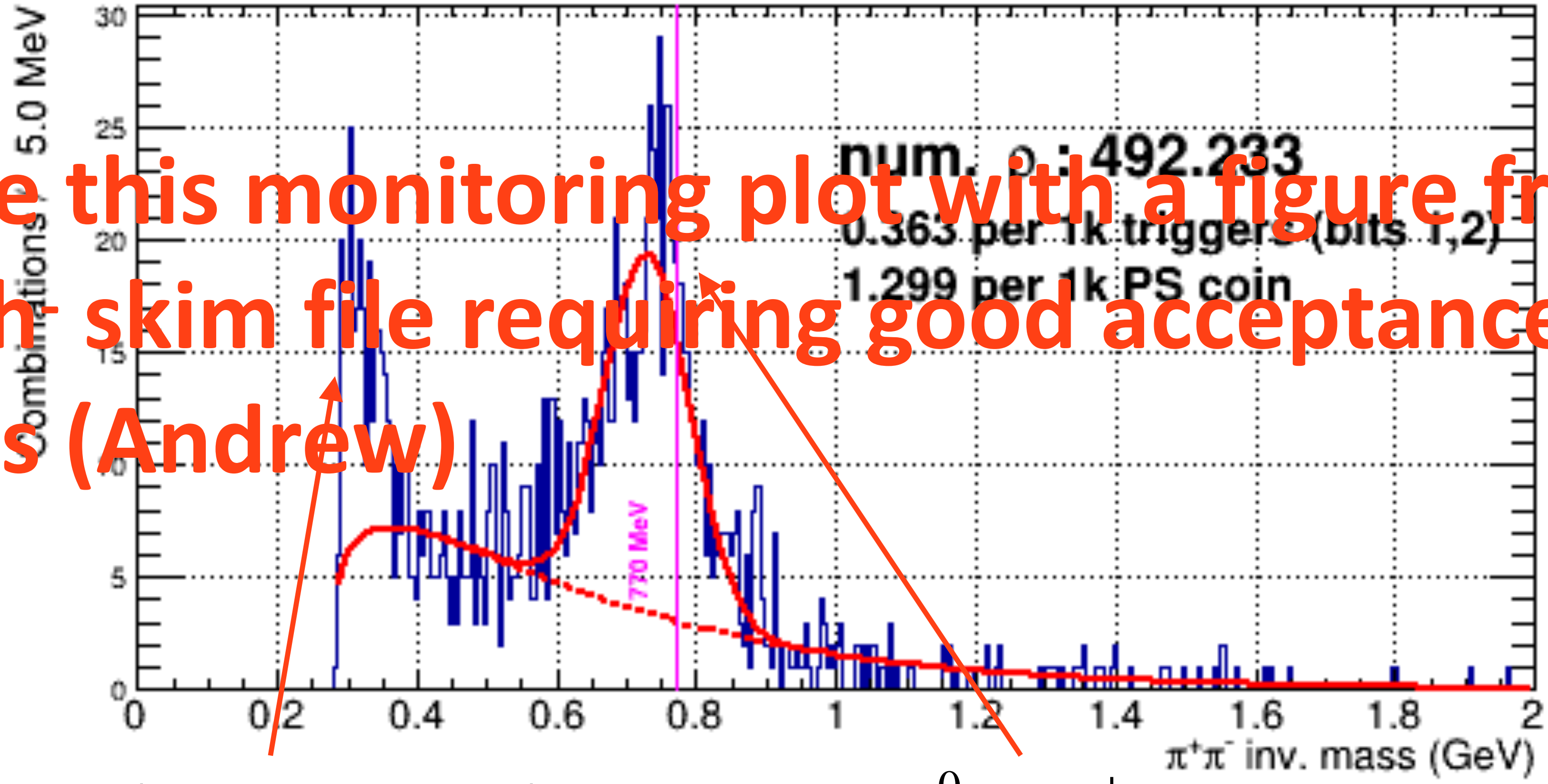


Status of the JLab GlueX CPP and NPP measurements

- Took data in summer 2022 with 6 GeV linearly polarized photons on ^{208}Pb target, taking the full allotment of beam-days awarded by the JLab PAC. Ran with a modified beam-line to obtain higher beam polarizations, $\sim 80\,\%$
- All known calorimeter and charged particle tracking calibrations have been completed
- The data are currently being “cooked”, where the raw data are converted into a form that can be more quickly analyzed. Data cooking will conclude in a couple of months.
- We expect to have preliminary physics distributions later this year.
- Here I’ll show some preliminary results to indicate the quality of the data

"Online" look at invariant mass of h^+h^- pairs where

$h^\pm = e^\pm$, $\mu^\pm$ or $\pi^\pm$ (i.e. no particle ID requirement)



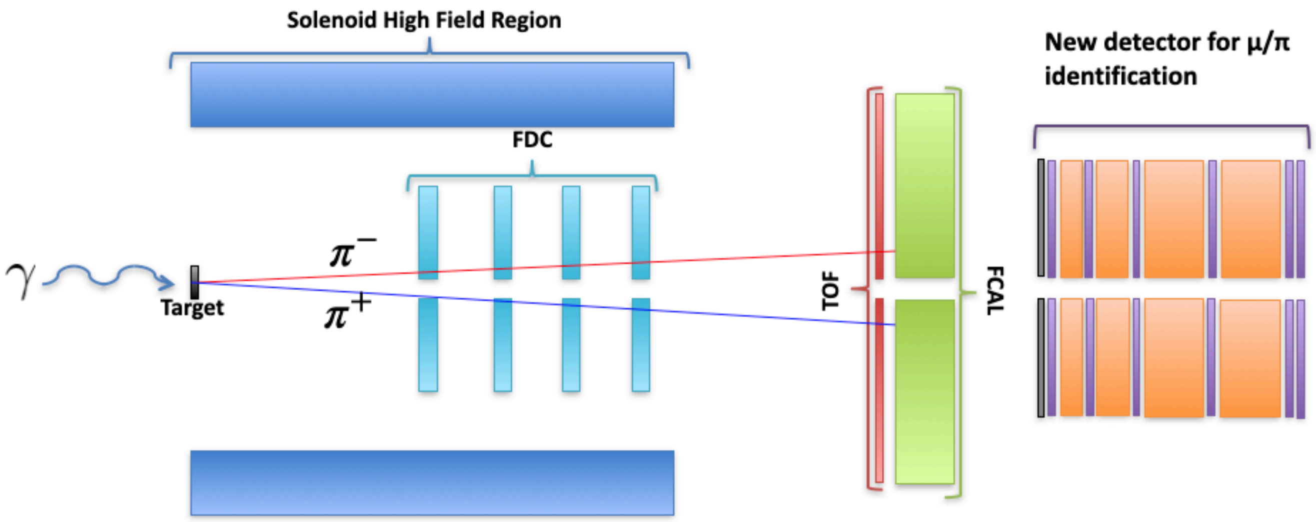
Replace this monitoring plot with a figure from the CPP h+h- skim file requiring good acceptance for all 6 MWPCs (Andrew)

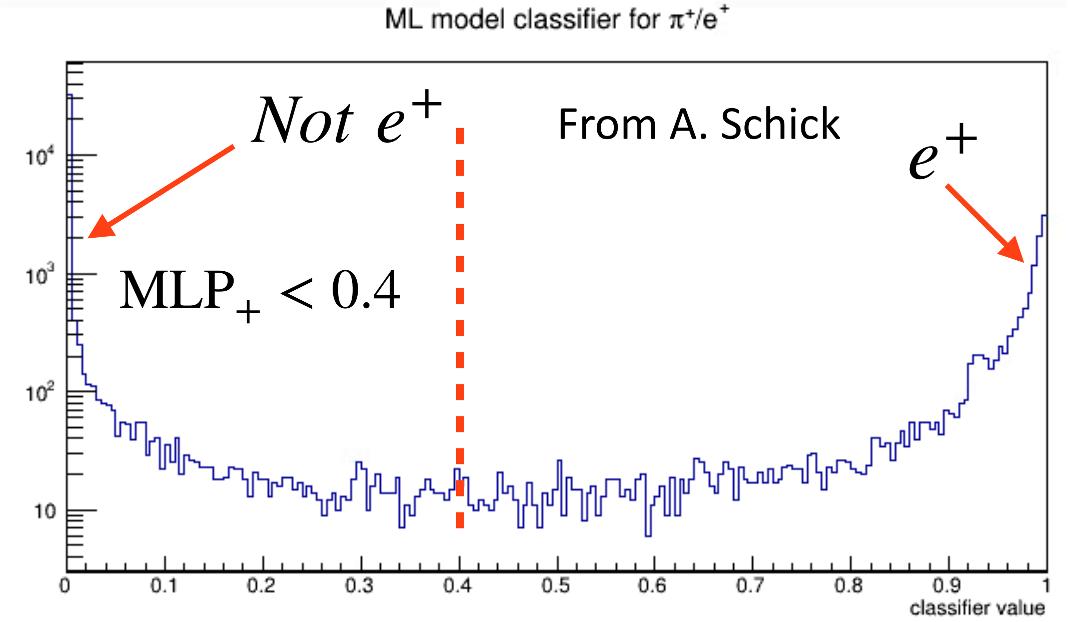
$\gamma A \to e^+e^-$ and $\gamma A \to \mu^+\mu^-$ $\rho^0 \to \pi^+\pi^-$

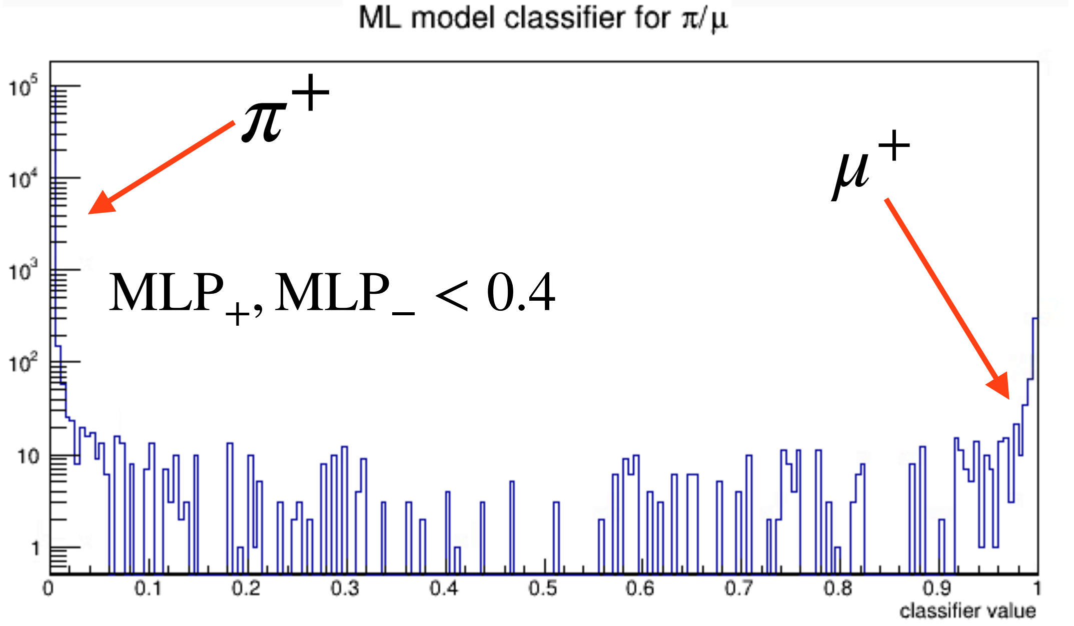
Particle identification: neural net analysis

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

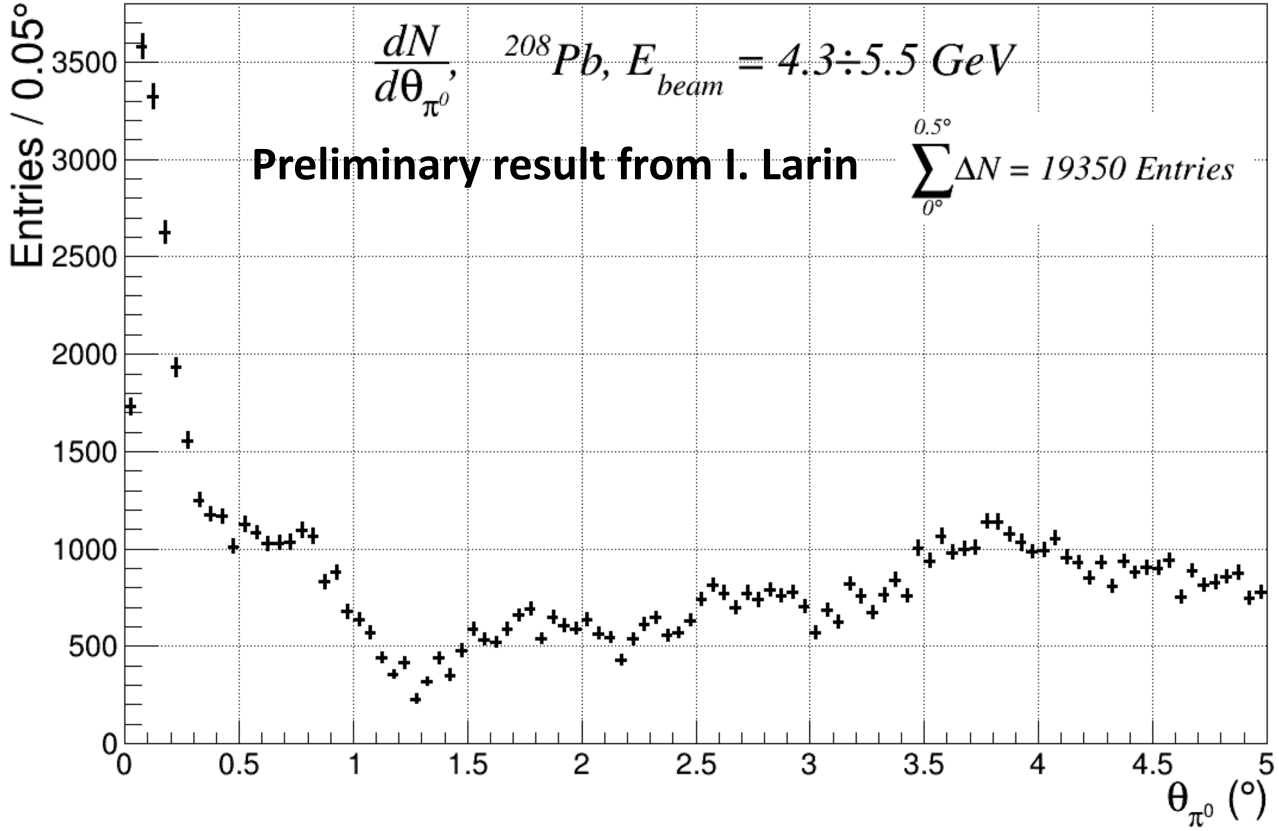






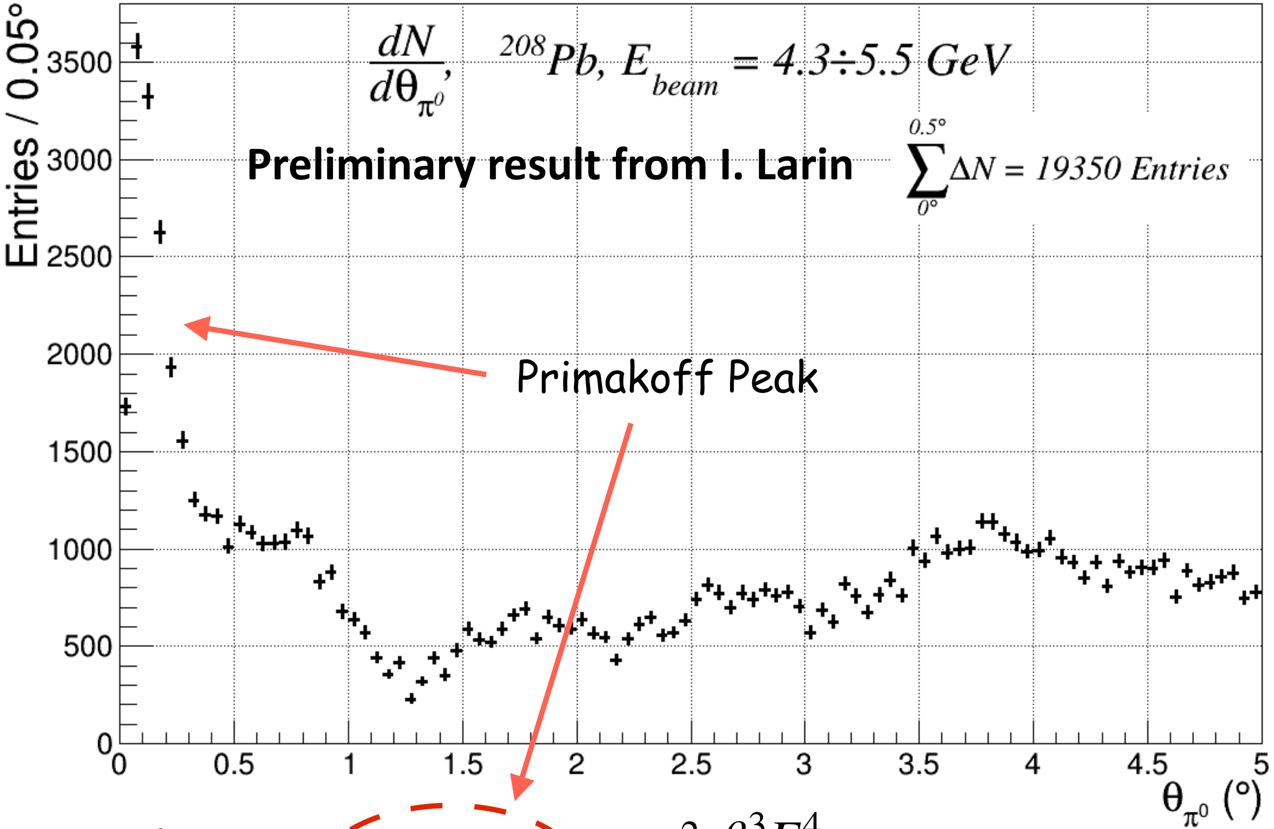
Very preliminary look at exclusive π^0 photoproduction

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



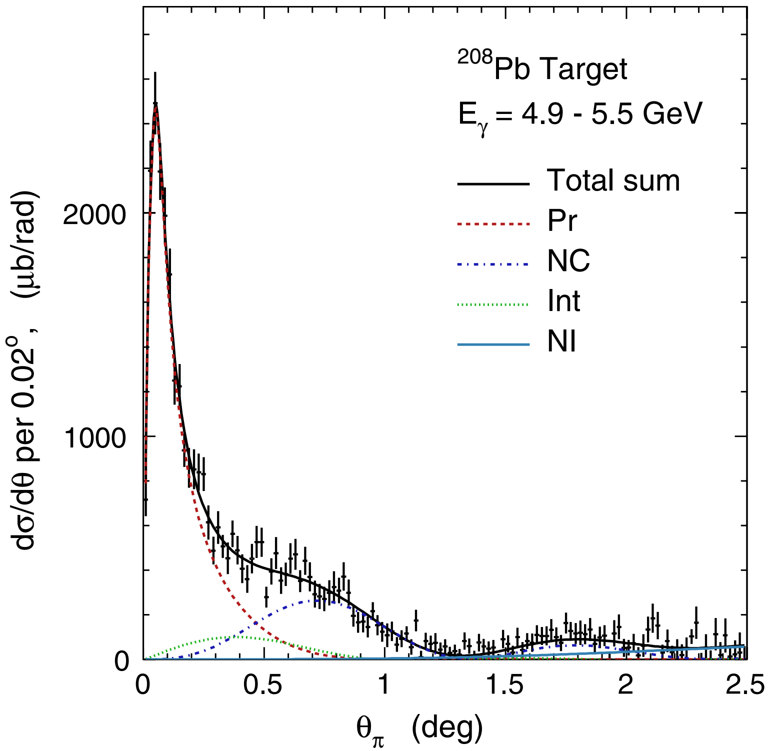
Very preliminary look at exclusive π^0 photoproduction

$$\gamma\ Pb \to \pi^0 \to \gamma\gamma$$



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

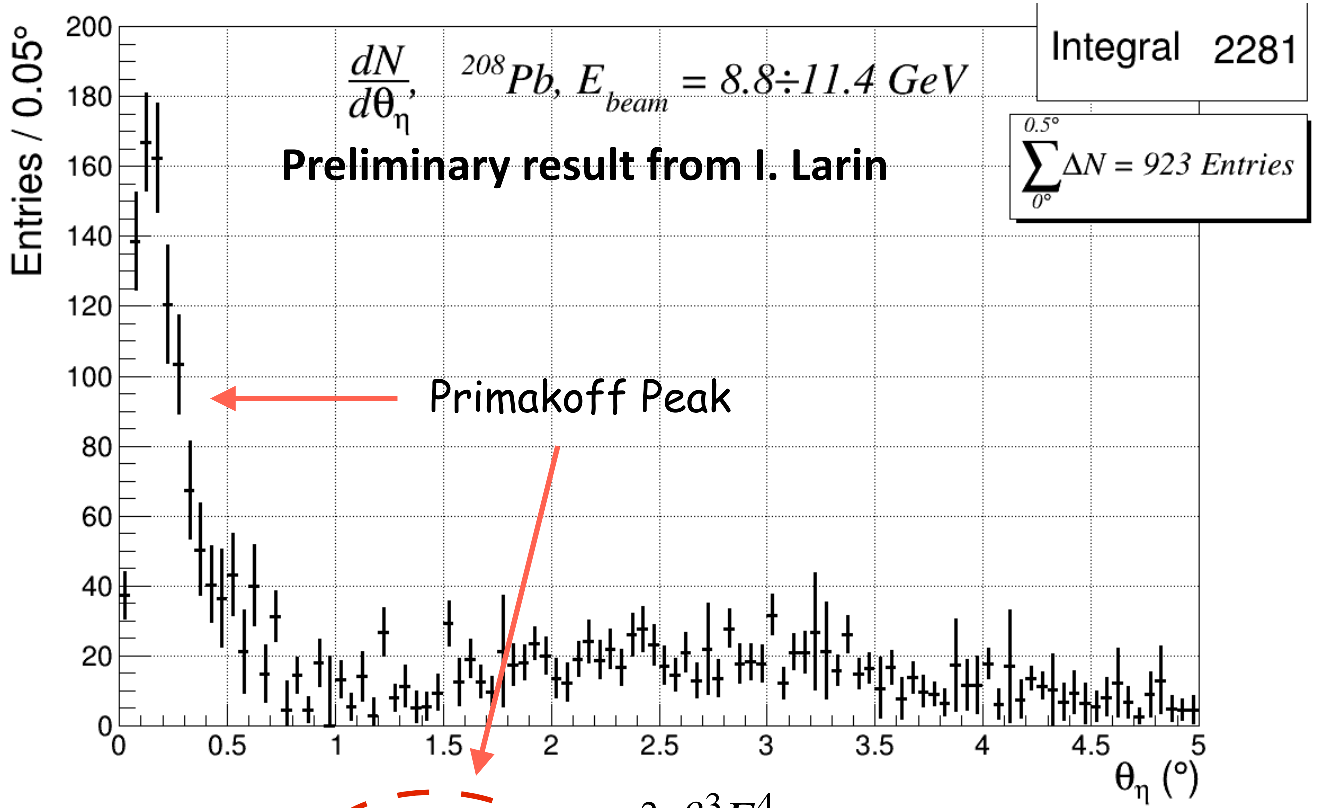
PrimEx I $\sigma(\gamma\ Pb \to \pi^0\ Pb)$



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

Very preliminary look at exclusive η photoproduction

$$\gamma\, Pb \to \eta \to \gamma\gamma$$



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

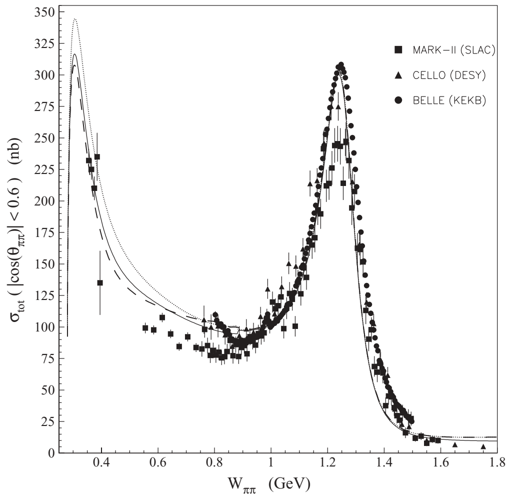
Upcoming analysis for CPP/NPP

For each bin in $\pi\pi$ invariant mass $M_{\pi\pi}$ the $\theta^{lab}_{(\pi\pi)}$ distribution is qualitatively similar to the θ^{lab}_{π} distribution for PrimEx I, with some important differences:

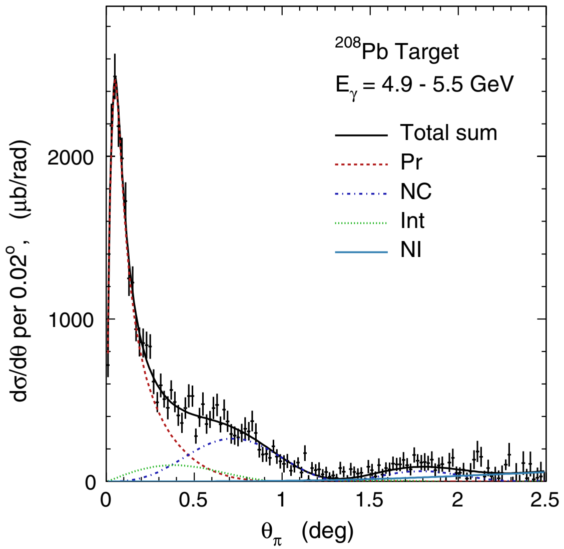
- Nuclear coherent photo-production in the low $M_{\pi\pi}$ region is dominated by coherent $f_0(500)$ photo-production
- For CPP in the low $M_{\pi\pi}$ region there is significant background from ρ^0, completely absent for NPP
- Because $2m_\pi \lesssim M_{\pi\pi} \lesssim 5m_\pi$, the Primakoff peak is broadened and shifted to higher angles relative to the PrimEx I result

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

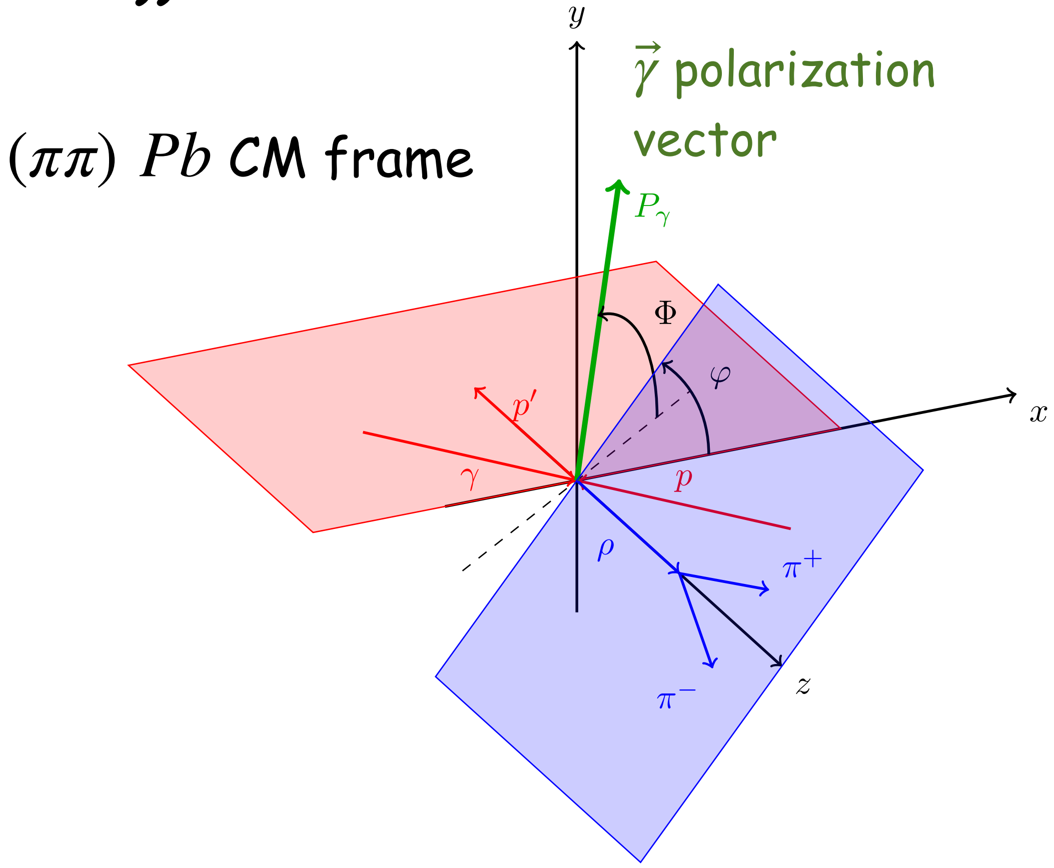
Mark II $\sigma(\gamma\gamma \to \pi^+\pi^-)$

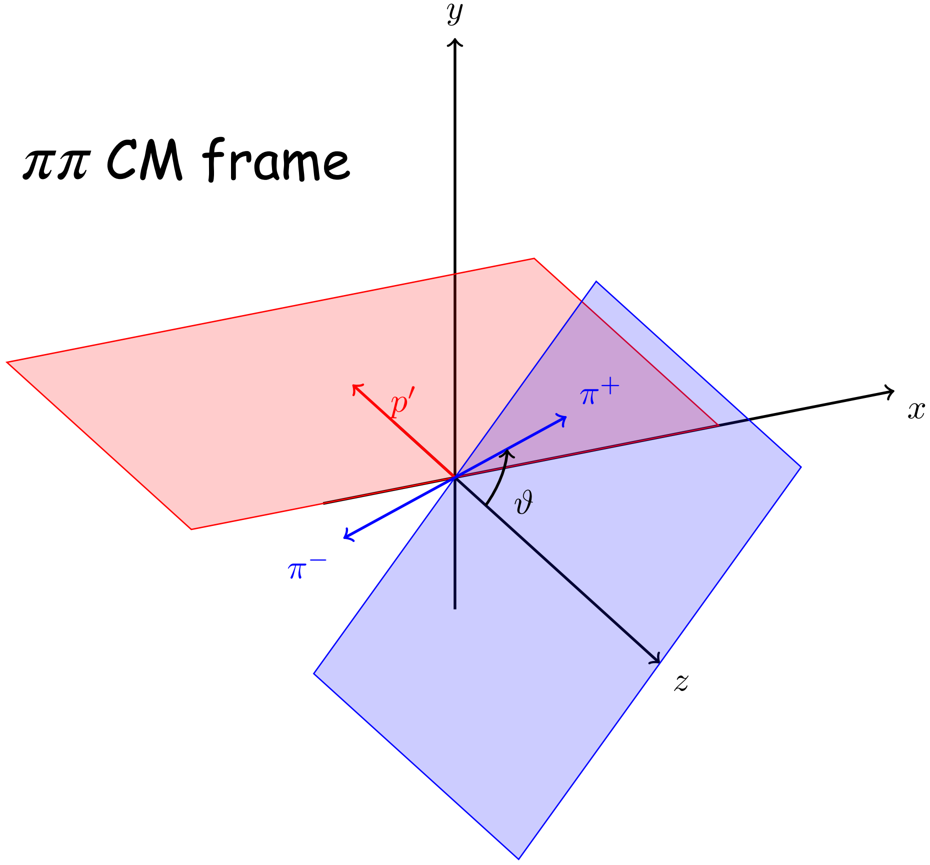


PrimEx I $\sigma(\gamma\, Pb \to \pi^0\, Pb)$

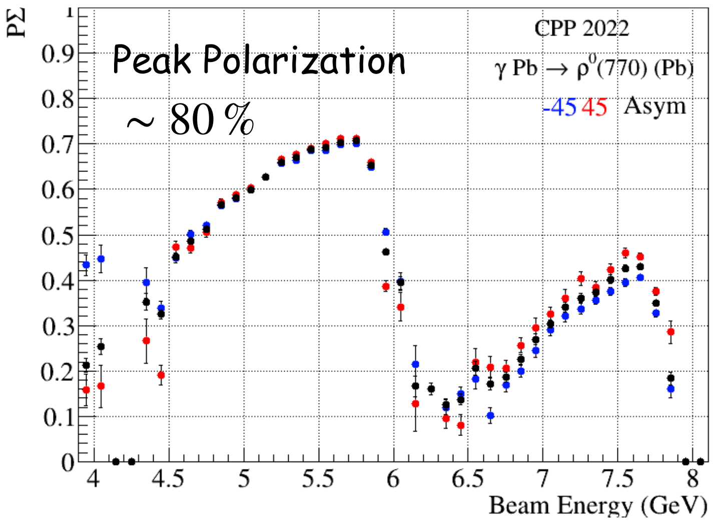


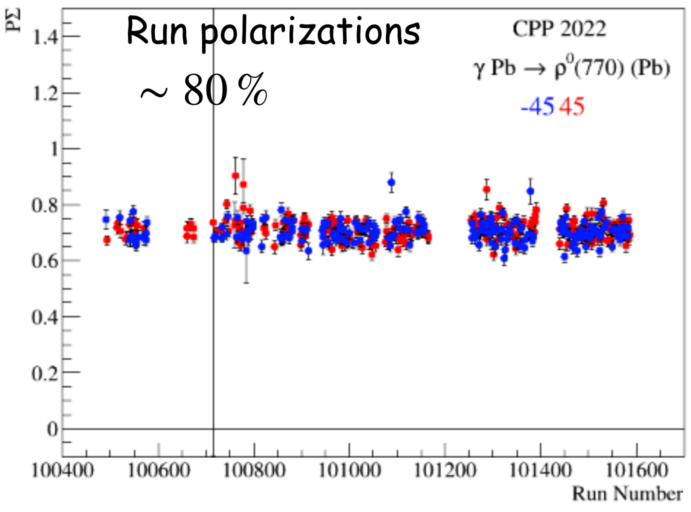
Amplitude analysis: use analysis tools developed for the GlueX $\vec{\gamma} p \to \rho^0 p$ measurement to analyze $\vec{\gamma}\ Pb \to \pi\pi\ Pb$ (see Phys. Rev. C 108, 055204 (2023))





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

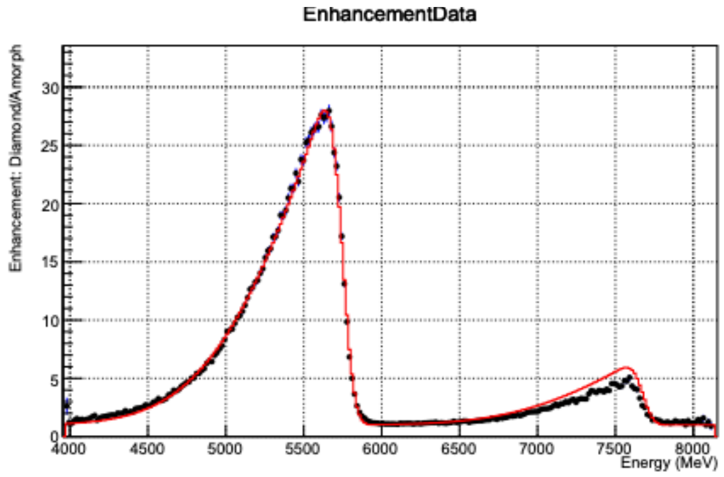


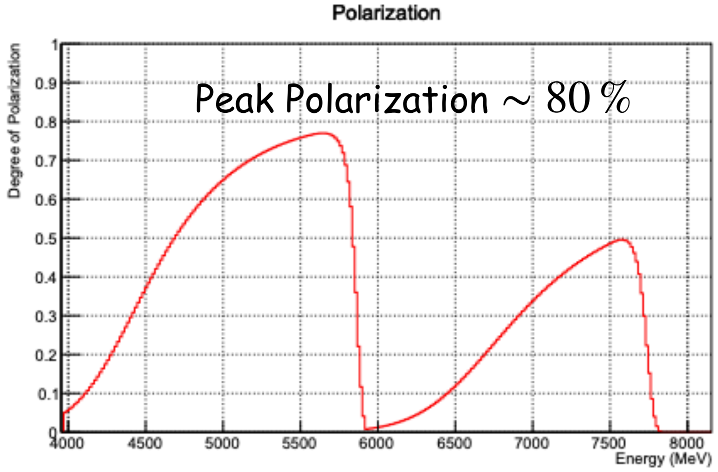


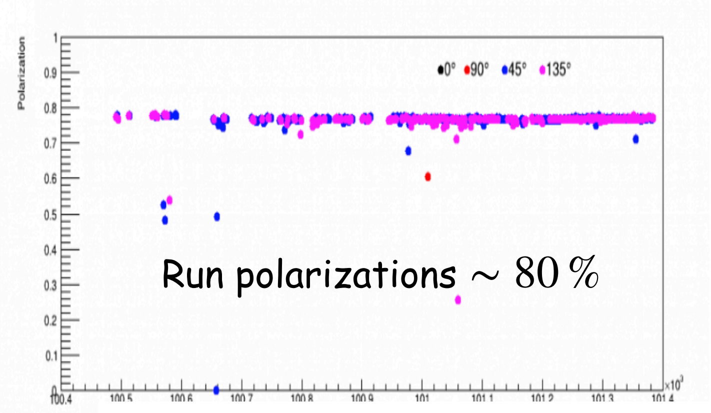
Polarization vs run number

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

ii. Enhancement of radiation from diamond relative to amorphous radiator (from J. Stevens)







Polarization vs run number

iii. $\vec{\gamma}\ Pb \rightarrow e^+e^-\ Pb$ (from A. Schick)

Need $\vec{\gamma}\ Pb \rightarrow e^+e^-\ Pb$ asymmetry plot (Andrew)

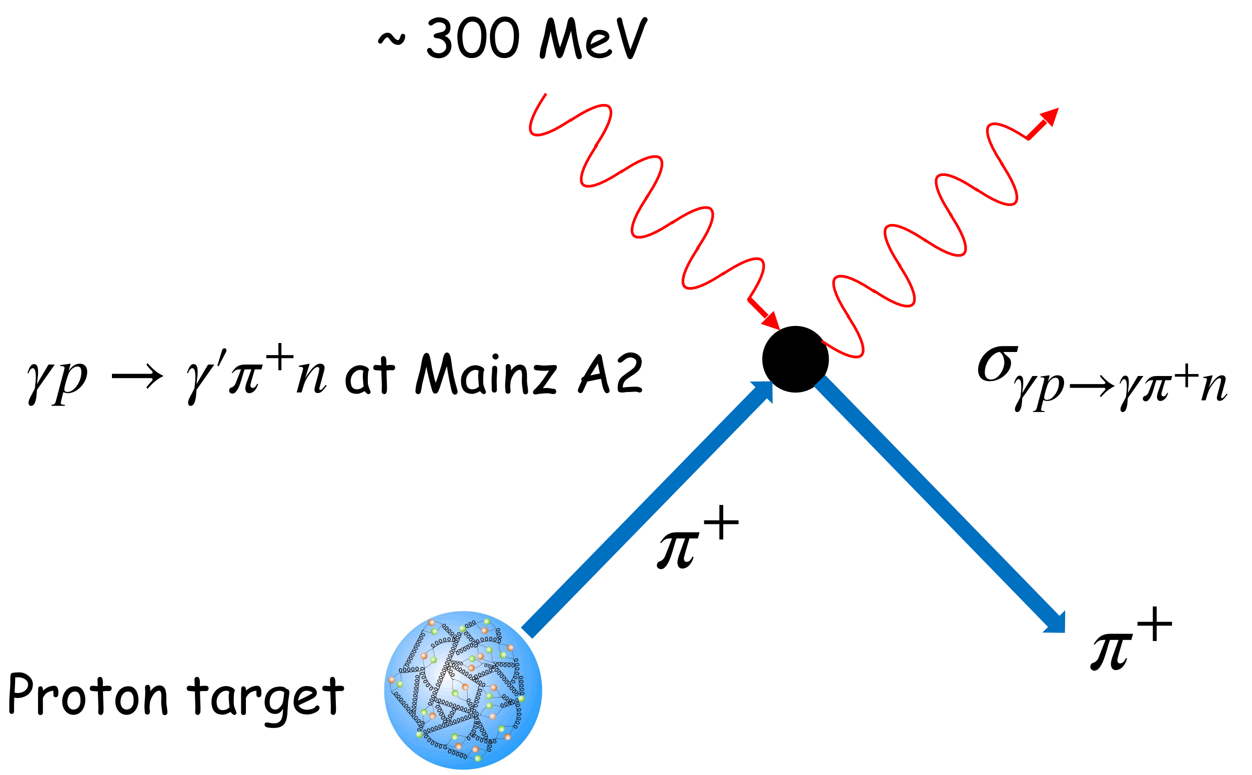
Summary

- Pion polarizability has special importance because it tests fundamental symmetries, specifically chiral symmetry and its realization in QCD
- The JLab GlueX CPP and NPP experiments utilize a new technique for measuring pion polarizability: Primakoff production of $\pi^+\pi^-$and $\pi^0\pi^0$ pairs on a nuclear target
- Data taking for the CPP and NPP experiments has been completed. The data are of high quality, and we don't see any "show stoppers" so far. We look forward to presenting results for $\gamma\gamma \rightarrow \pi\pi$ cross sections and pion polarizabilities in the near future

Thanks for your attention, and thanks to the Organizers for the opportunity to speak at this meeting !

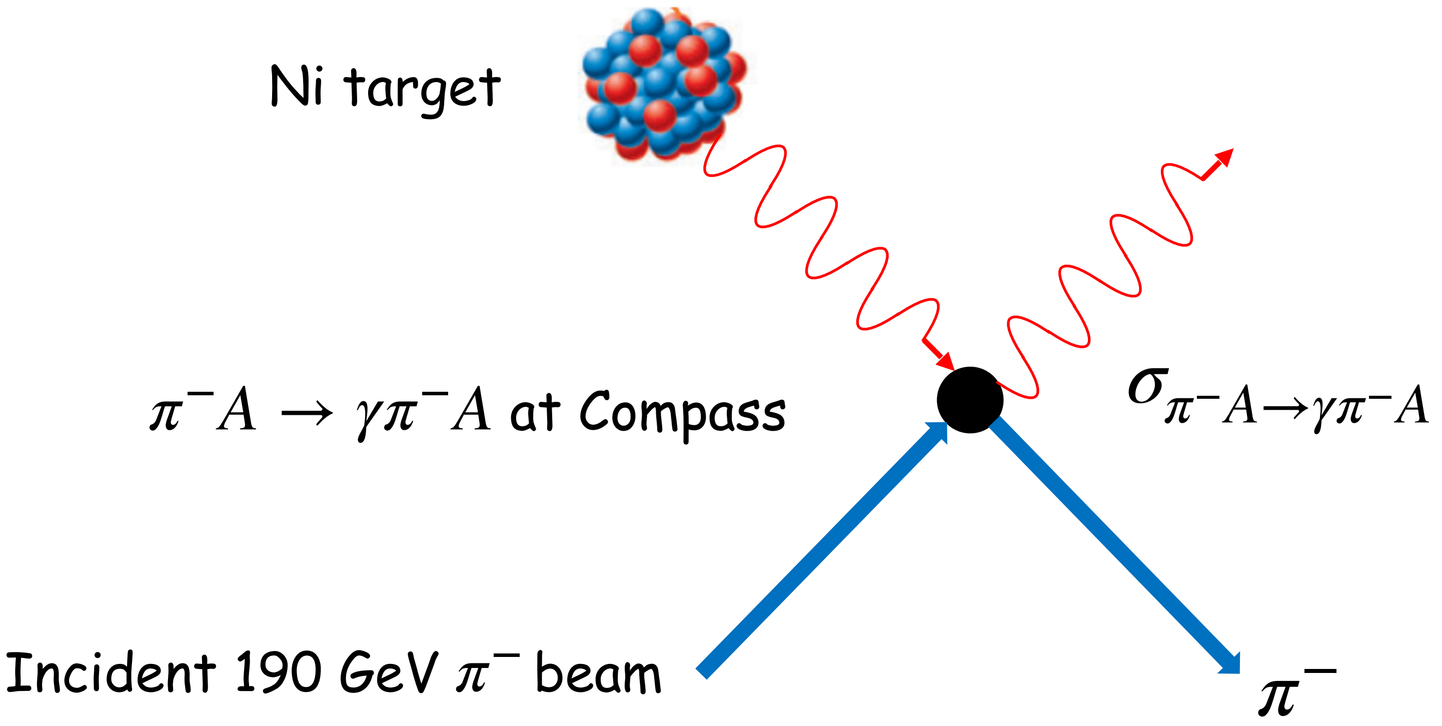
Extra Slides

i. Radiative pion photoproduction



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

ii. Pion radiative scattering



$$\sigma_{\pi^- A \rightarrow \gamma\pi^- A} \xrightarrow{\textit{Primakoff analysis}} \sigma^{Compton}_{\gamma\pi^- \rightarrow \gamma\pi^-}$$

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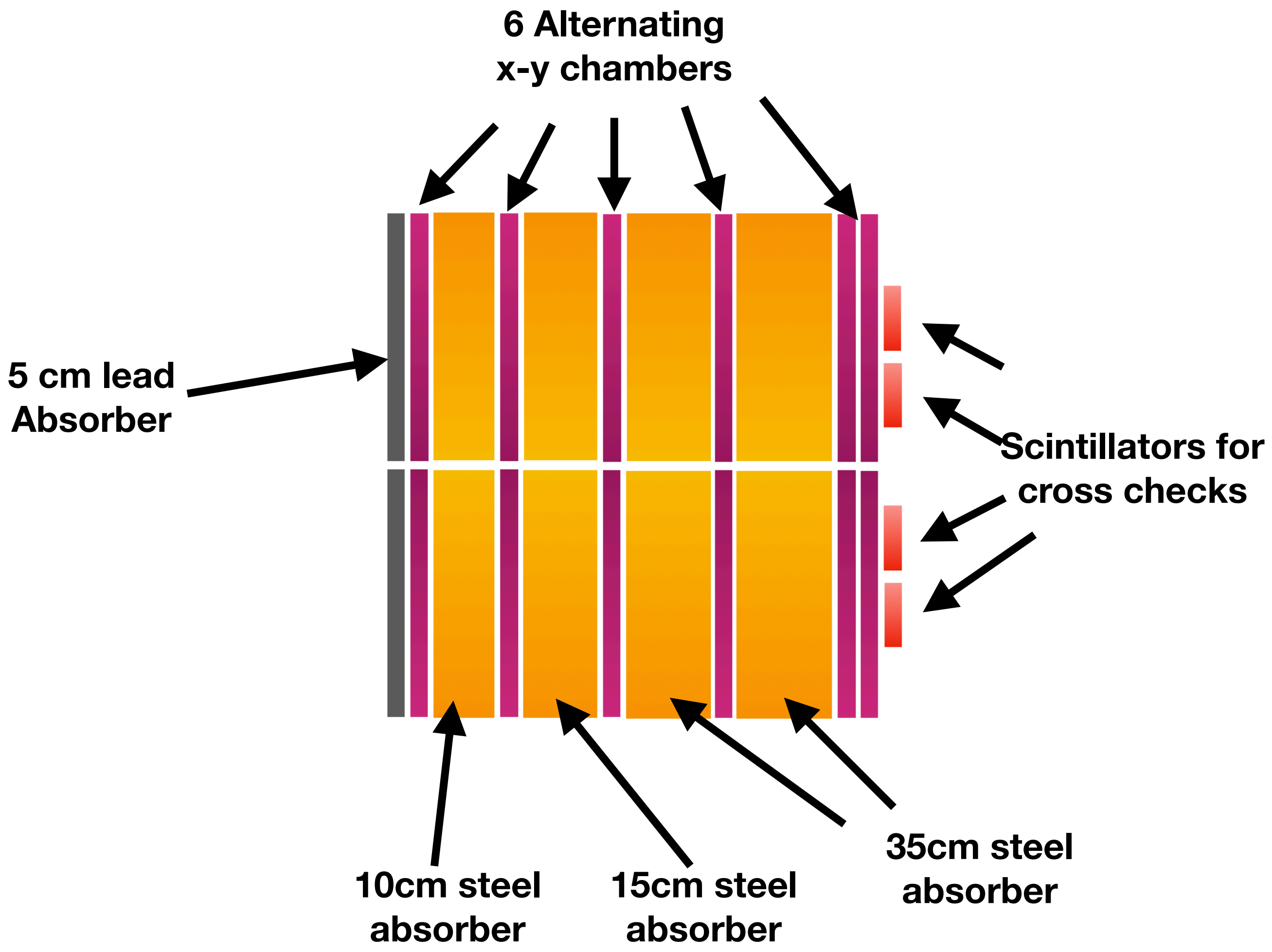
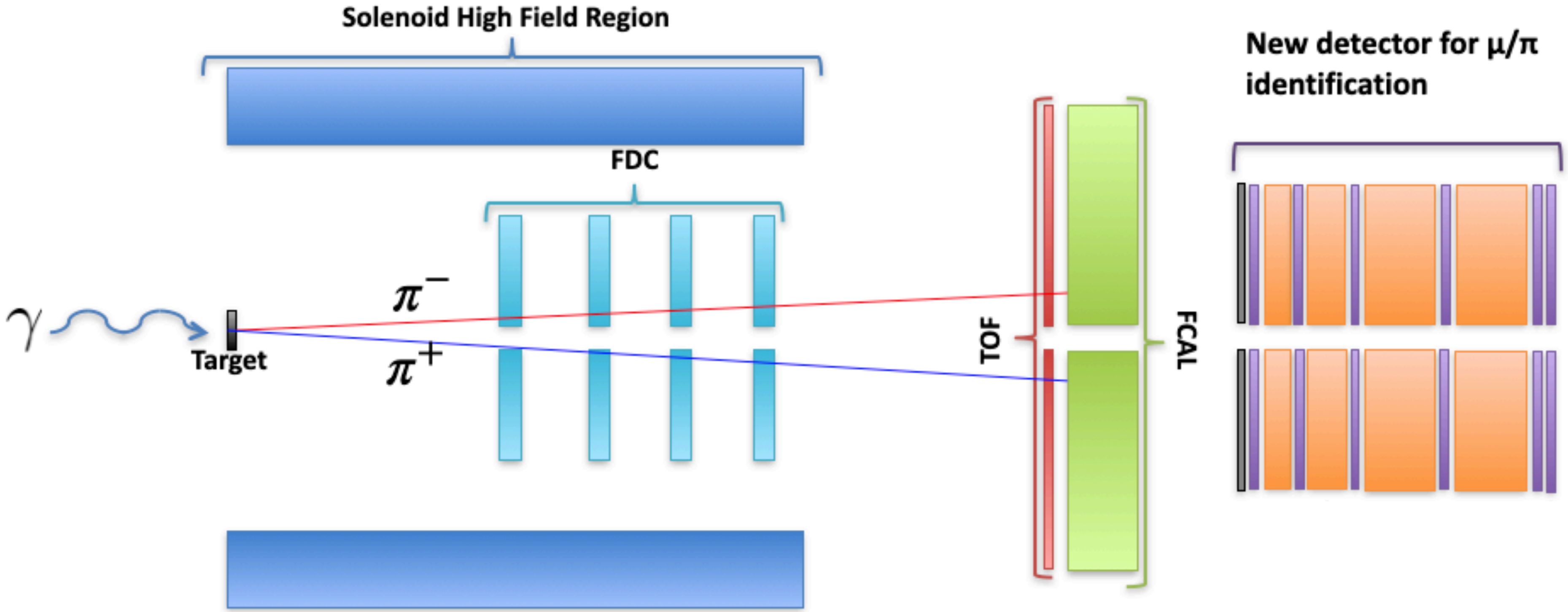
Muon detector built for the CPP measurement

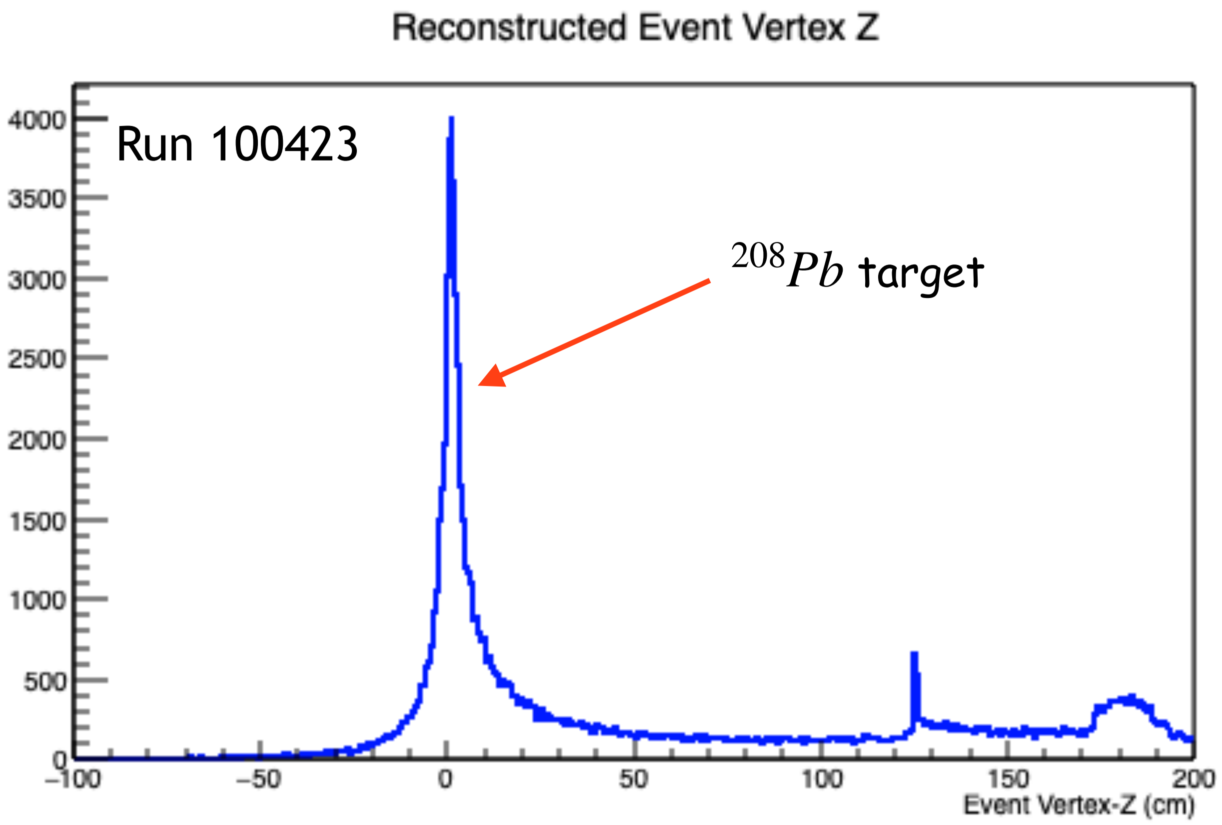
- 8 MWPCs built at UMASS, 6 used in CPP
- Each MWPC has 144 channels (sense wires)
- 90% Ar + 10% CO_2 gas mixture
- 4 scintillators were placed downstream of the final chamber for triggering on muon tracks



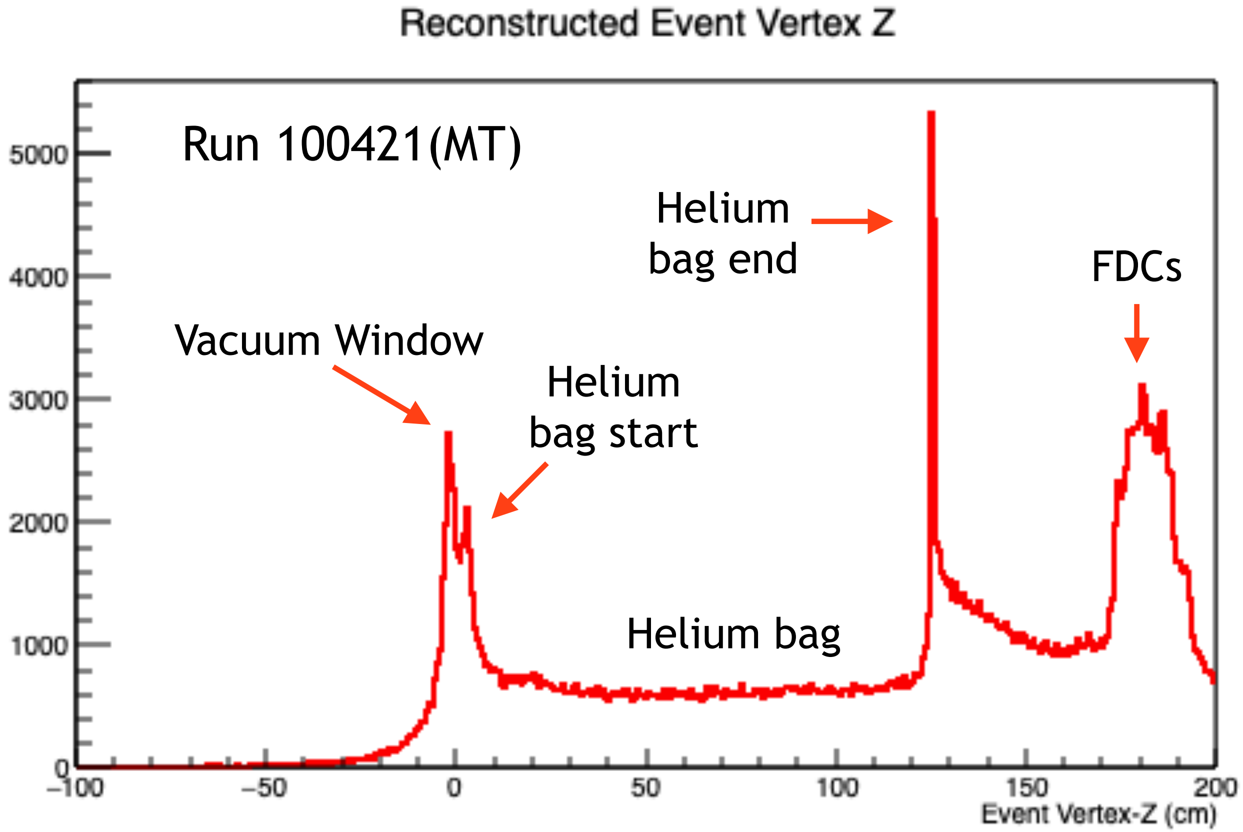
Vertex resolution for charged tracks in GlueX



Vertex resolution for charged tracks in GlueX



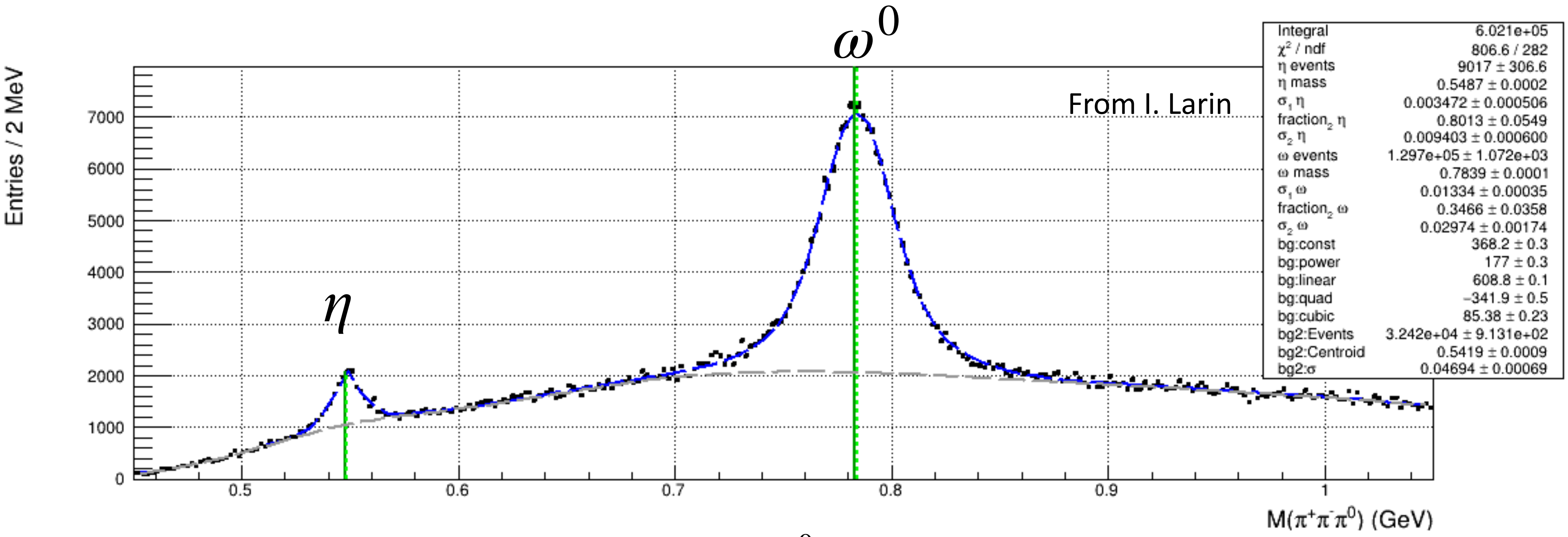
Run with ^{208}Pb target in



Run with ^{208}Pb target out

Very preliminary look at ω^0 photoproduction

$$\gamma\ Pb \rightarrow \pi^+\pi^-\pi^0$$



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