Measurements of charged pion and neutral pion polarizabilities at JLab GlueX

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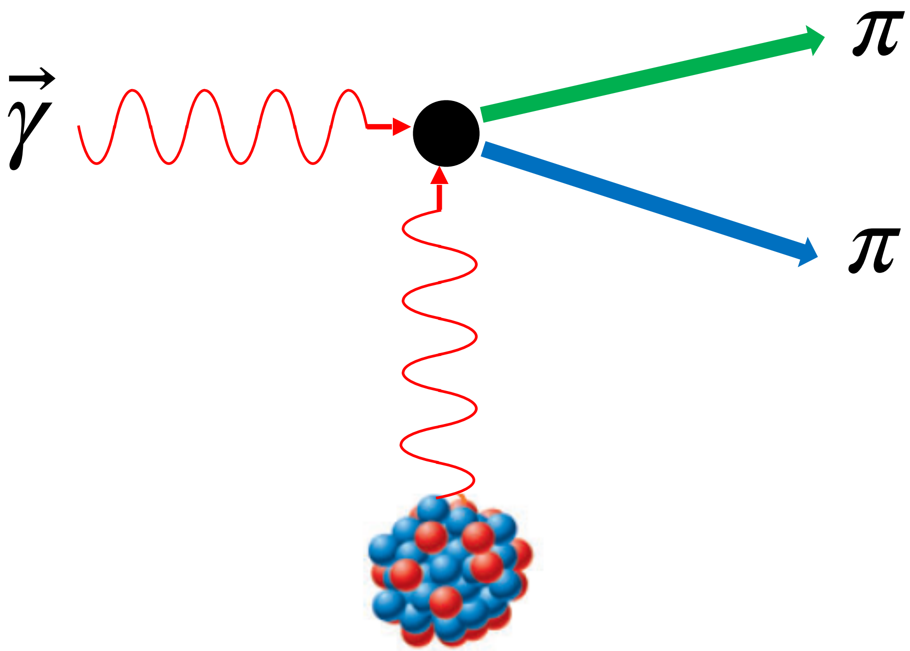
and the GlueX Collaboration



i. Pion polarizability and how it's measured

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

I. Pion polarizability and how it's measured

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 $\pi^+ \rightarrow e^+ \nu \gamma$

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

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

Since a pion target doesn't exist for use in Compton scattering, alternative methods must be utilized

Charged pion polarizability:

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

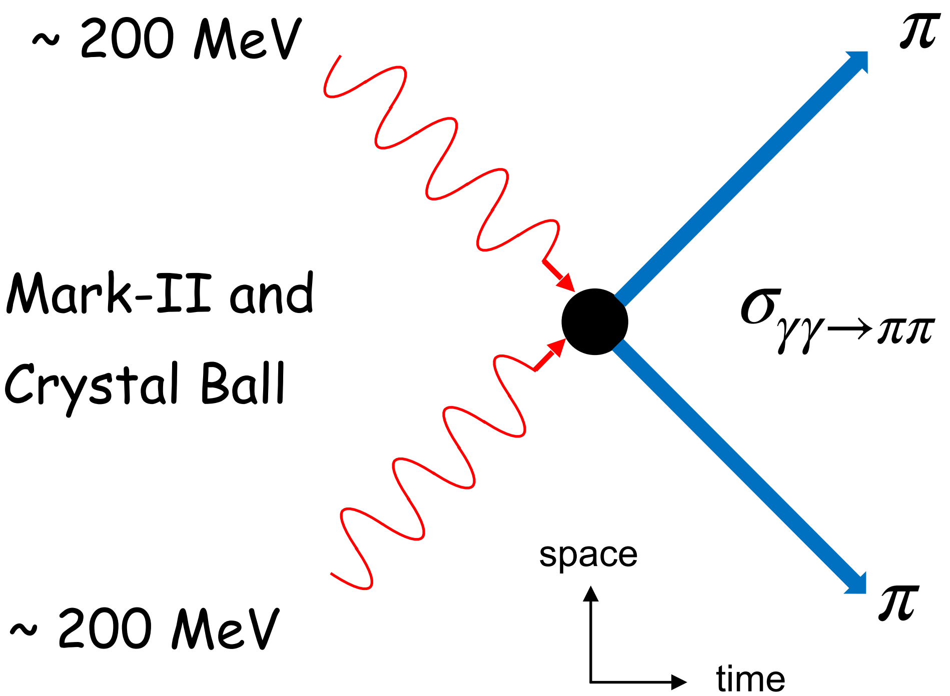
ii. Pion radiative scattering: $\pi^- A \rightarrow \gamma \pi^- A$ (Compass)

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

Neutral pion polarizability:

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

Two photon collisions $\gamma\gamma \rightarrow \pi\pi$



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

Theory

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

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

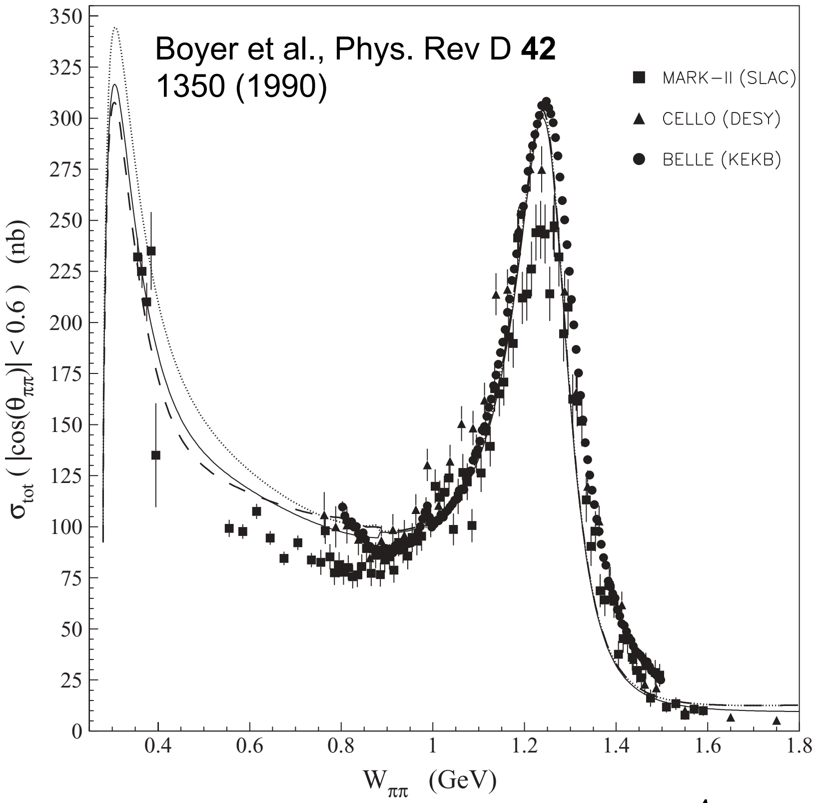
Pasquini, Drechsel, and Scherer, Phys. Rev. C **77**, 065211 (2008)

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

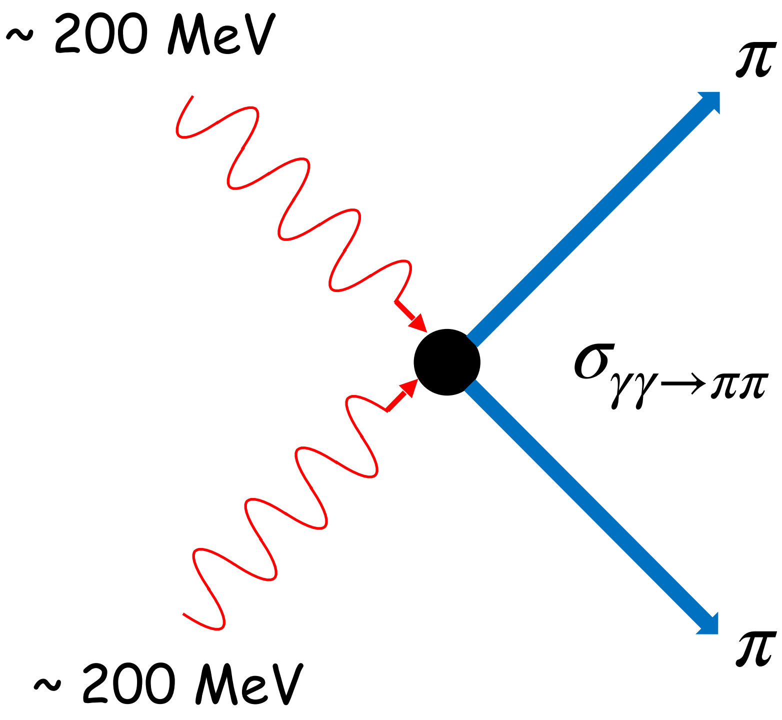
$$A_{\gamma\gamma\rightarrow\pi\pi} \xrightarrow{dispersion\ theory} A_{Compton} \rightarrow \alpha_\pi - \beta_\pi$$

Charged and neutral pion polarizabilties measured in two photon collisions

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



Boyer et al., Phys. Rev D **42** 1350 (1990)



~ 200 MeV

π

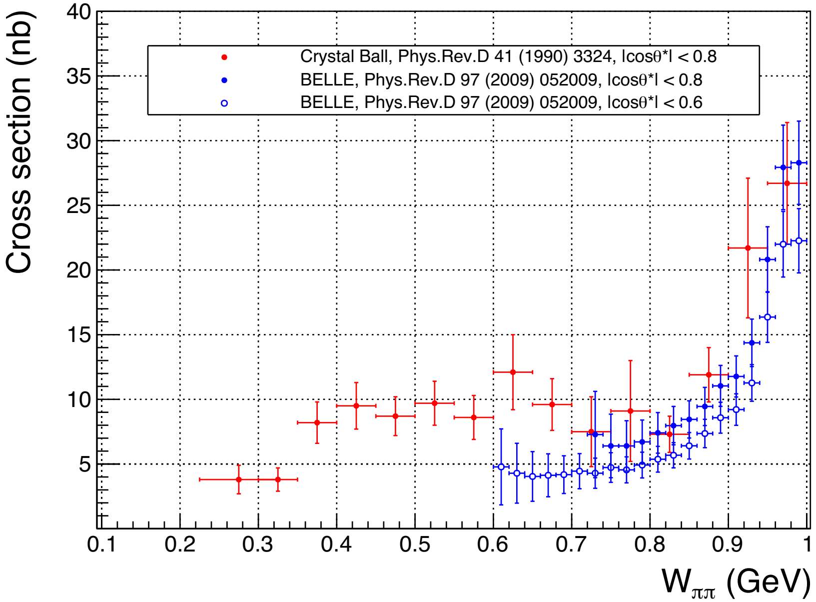
$\sigma_{\gamma\gamma\to\pi\pi}$

π

~ 200 MeV

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

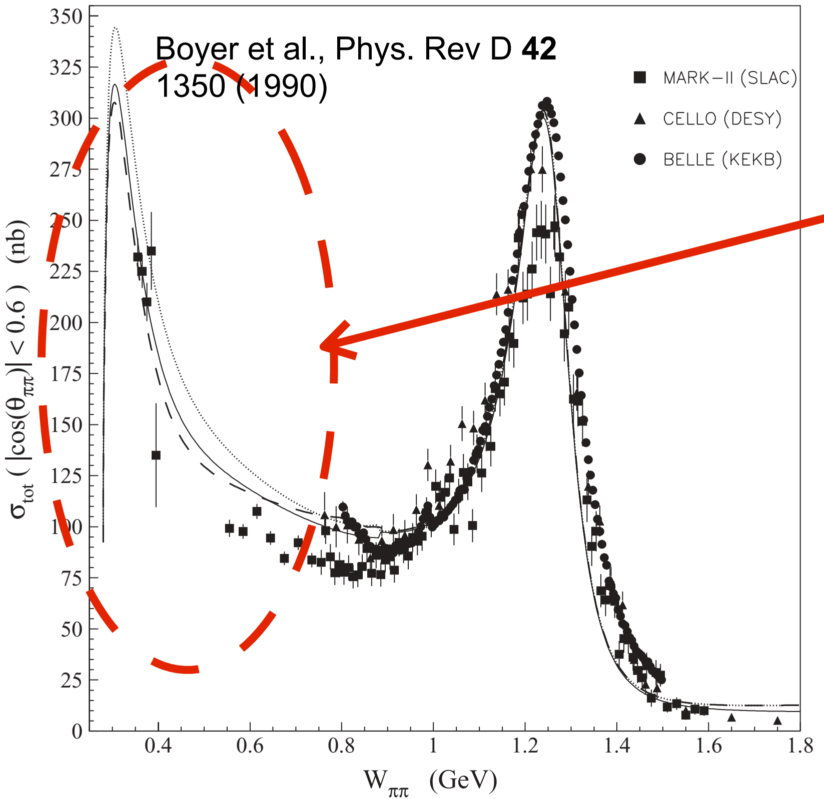
Threshold Region



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

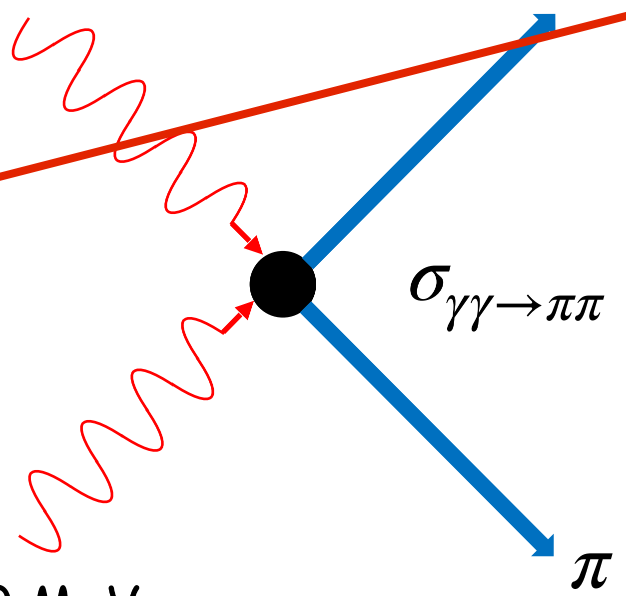
Charged and neutral pion polarizabilties measured in two photon collisions

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



Boyer et al., Phys. Rev D **42** 1350 (1990)

~ 200 MeV



π

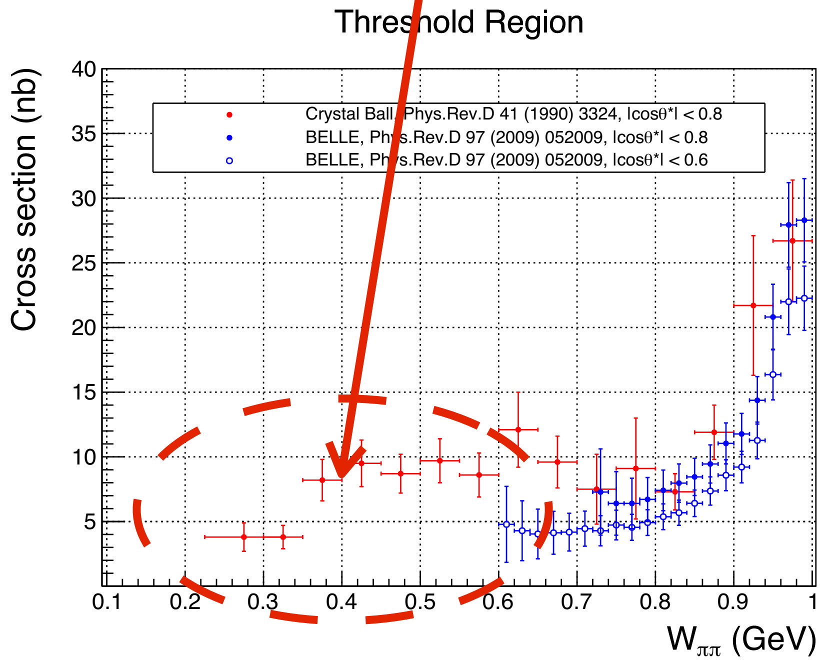
$\sigma_{\gamma\gamma\to\pi\pi}$

π

~ 200 MeV

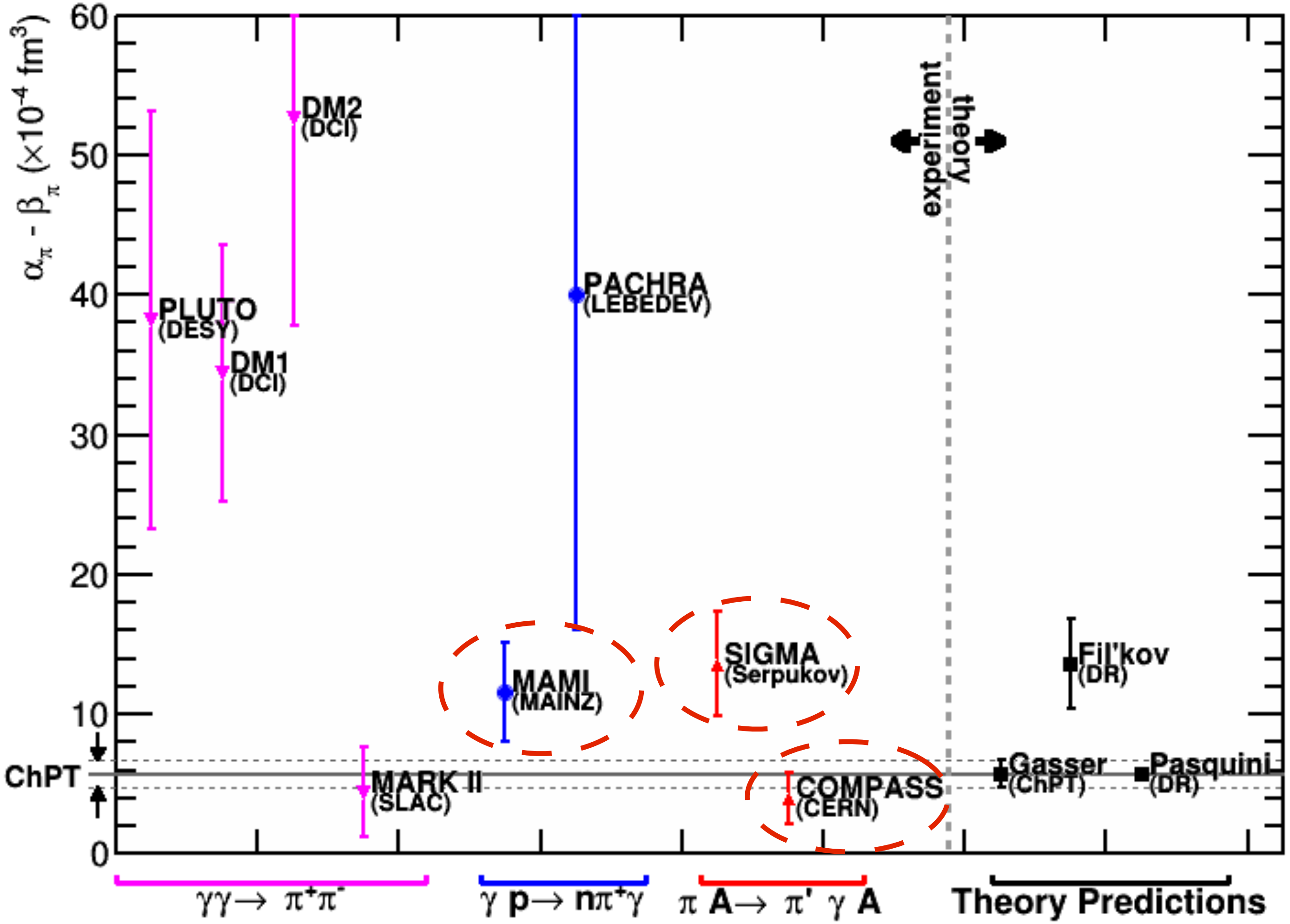
sparse statistics !

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



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

Published measurements of charged pion polarizability



Serpukov: *Z. Phys. C,* ***26*** *495 (1985)*

$\pi^- A \to \pi^- \gamma\ A$ *@ 40 GeV*

$\alpha_\pi - \beta_\pi = 13.6 \pm 2.4 \times 10^{-4} fm^3$

Mainz A2: *Eur. Phys. J. A* ***23*** *113 (2005)*

$\gamma p \to \gamma \pi^+ n$ *@ ~ 700 MeV*

$\alpha_\pi - \beta_\pi = 11.6 \pm 1.5(stat) \pm 3.0(sys) \pm 0.5(mod)$

COMPASS: *PRL* ***114*** *062002 (2015)*

$\pi^- Ni \to \pi^- \gamma\ Ni$ *@ 160 GeV*

$\alpha_\pi - \beta_\pi = 4.0 \pm 1.2(stat) \pm 1.4(sys)$

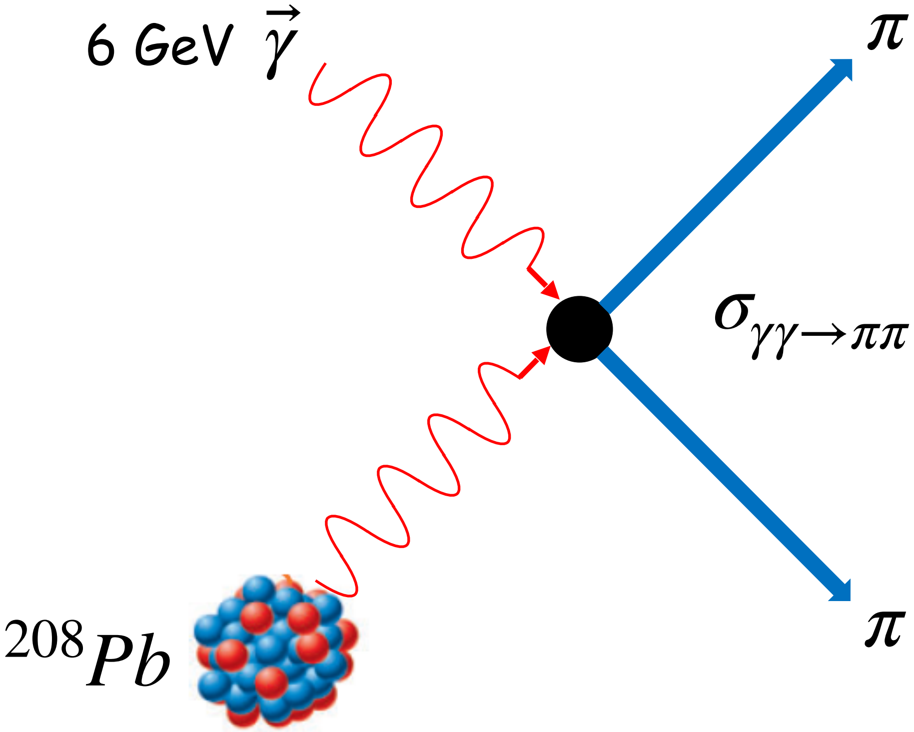
II. Update on the pion polarizability measurement at Jefferson Lab GlueX

Goals for the JLab experiment

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

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

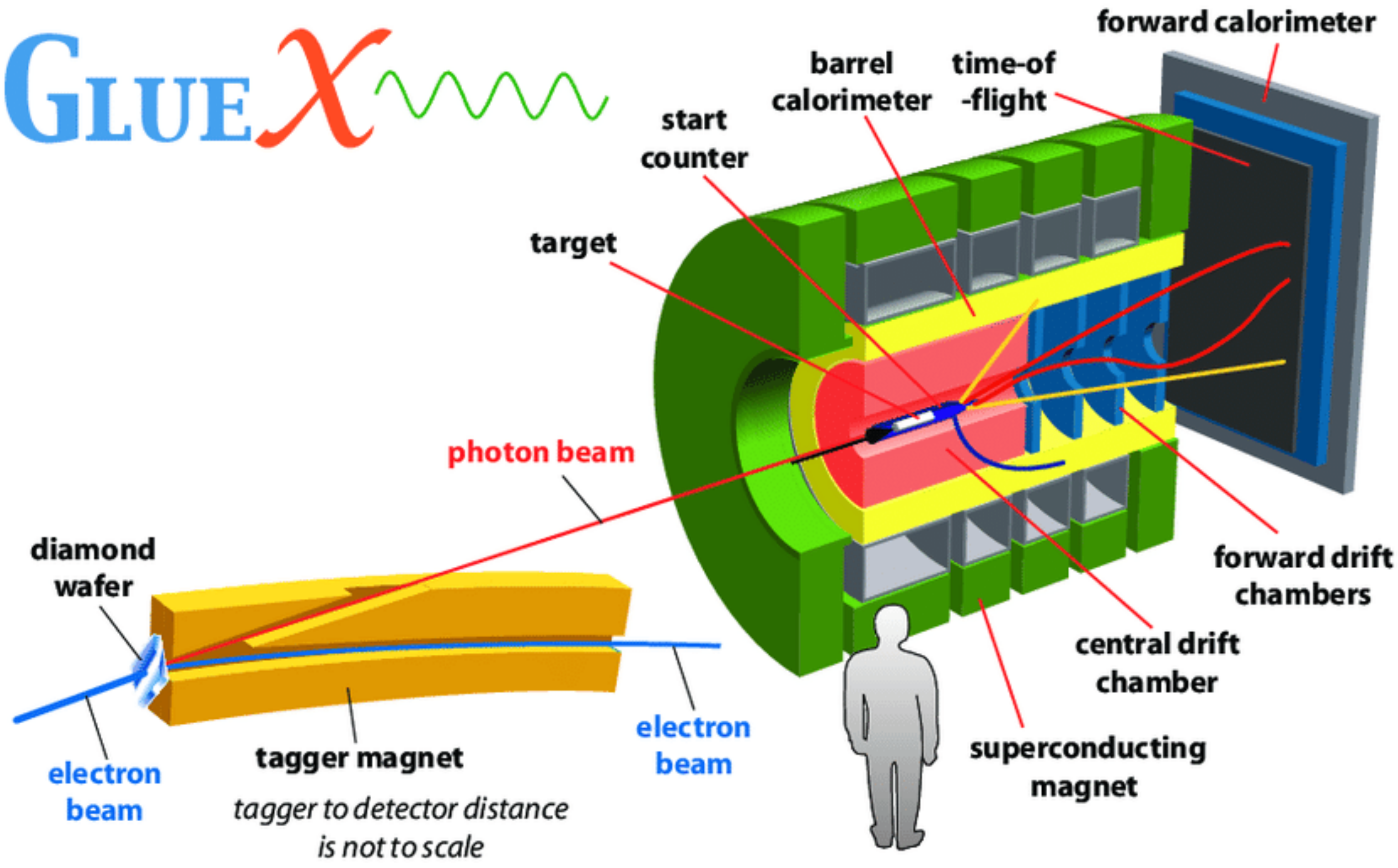
iii. Provide a measurement of CPP with low statistical and systematic errors, and the first reliable measurement of NPP

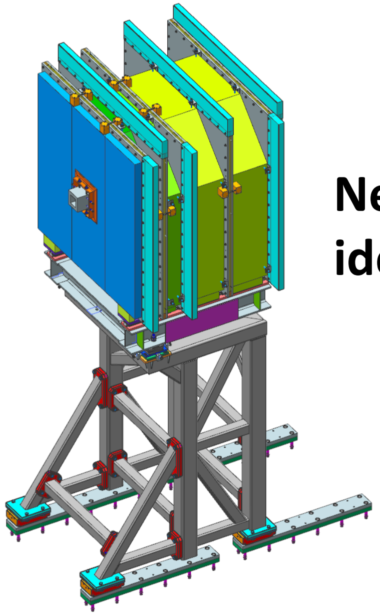


$$\frac{d^2\sigma_{Prim}}{d\Omega dM_{\pi\pi}} = \frac{2\alpha Z^2}{\pi^2}\frac{E_\gamma^2\beta^2}{M_{\pi\pi}}\frac{sin^2\theta}{Q^4}\left|F_{EM}(Q^2)\right|^2\left(1+P_\gamma cos2\phi_{\pi\pi}\right)\sigma_{\gamma\gamma\to\pi\pi}$$

Photon polarization

CPP and NPP experiment at JLab GlueX





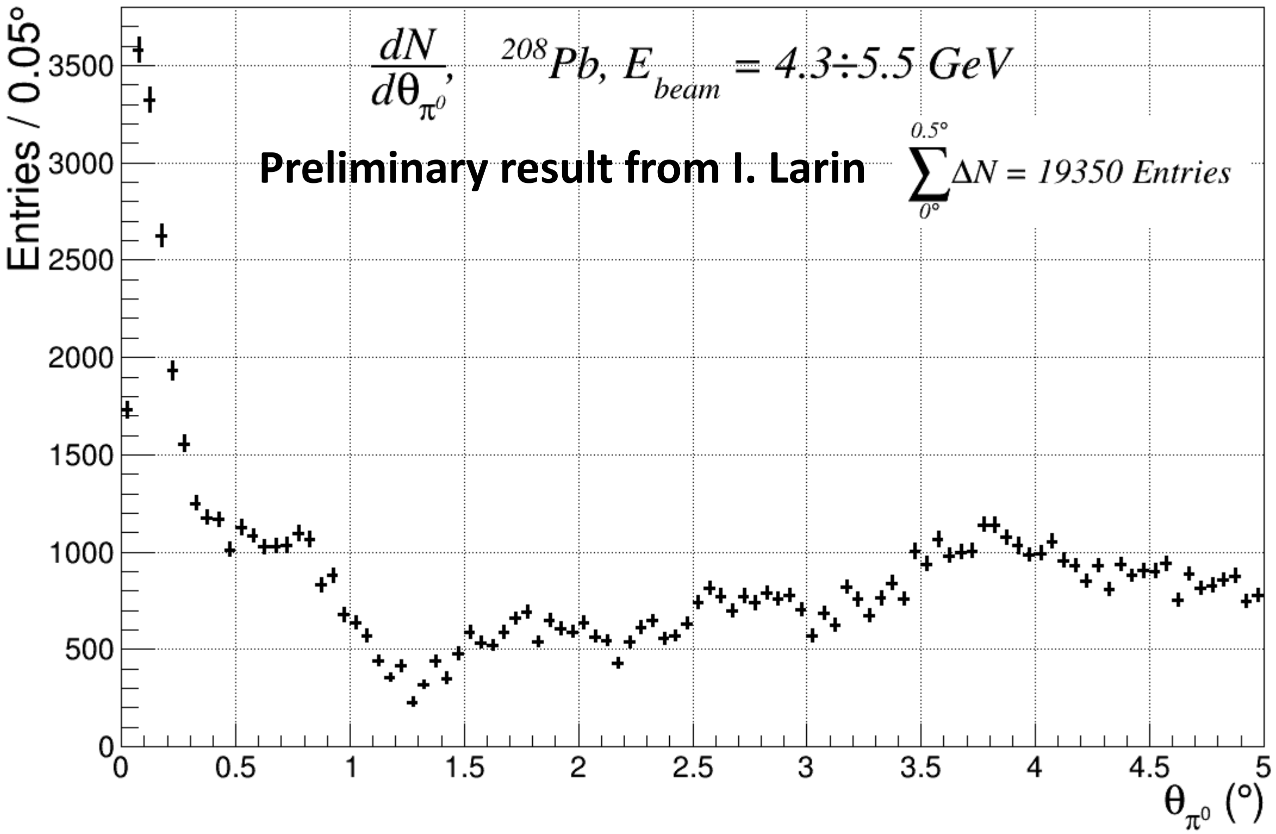
New detector for μ/π identification

Status of the JLab GlueX CPP and NPP measurements

- Took data 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 will conclude October 2024
- We expect to have preliminary physics distributions later this year; here I'll show results to indicate the quality of the data

Very preliminary look at exclusive π^0 photoproduction

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



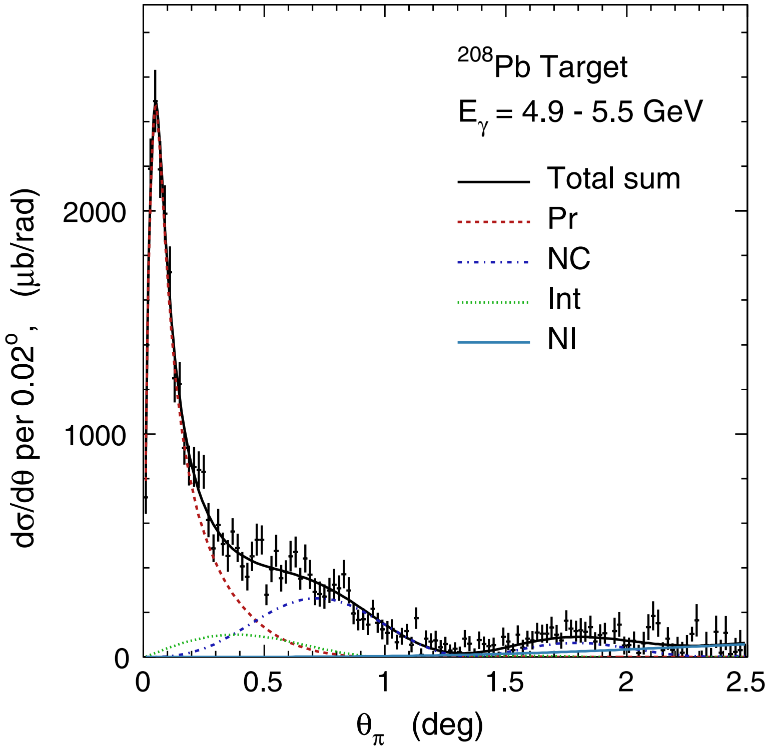
Preliminary result from I. Larin

Lab angular distribution

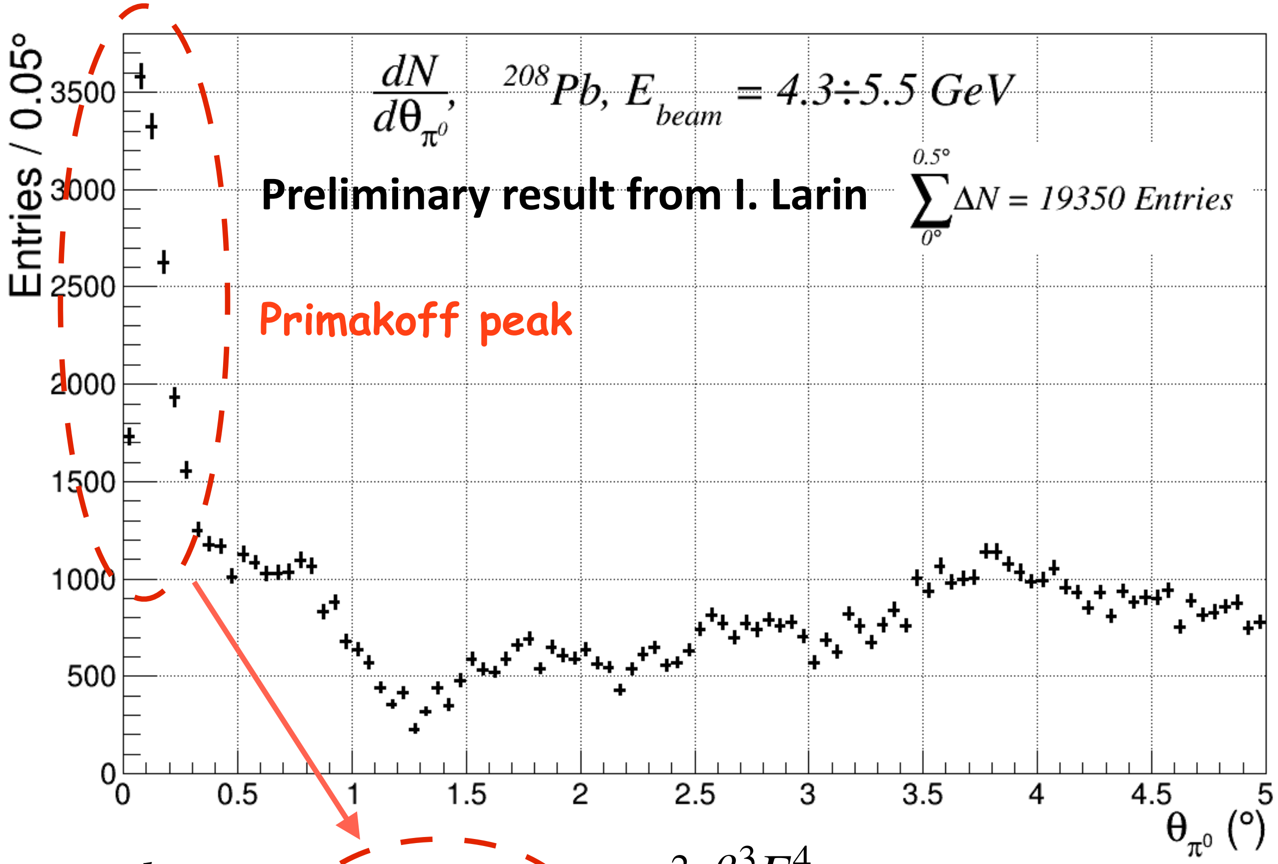
Very preliminary look at exclusive π^0 photoproduction

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

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



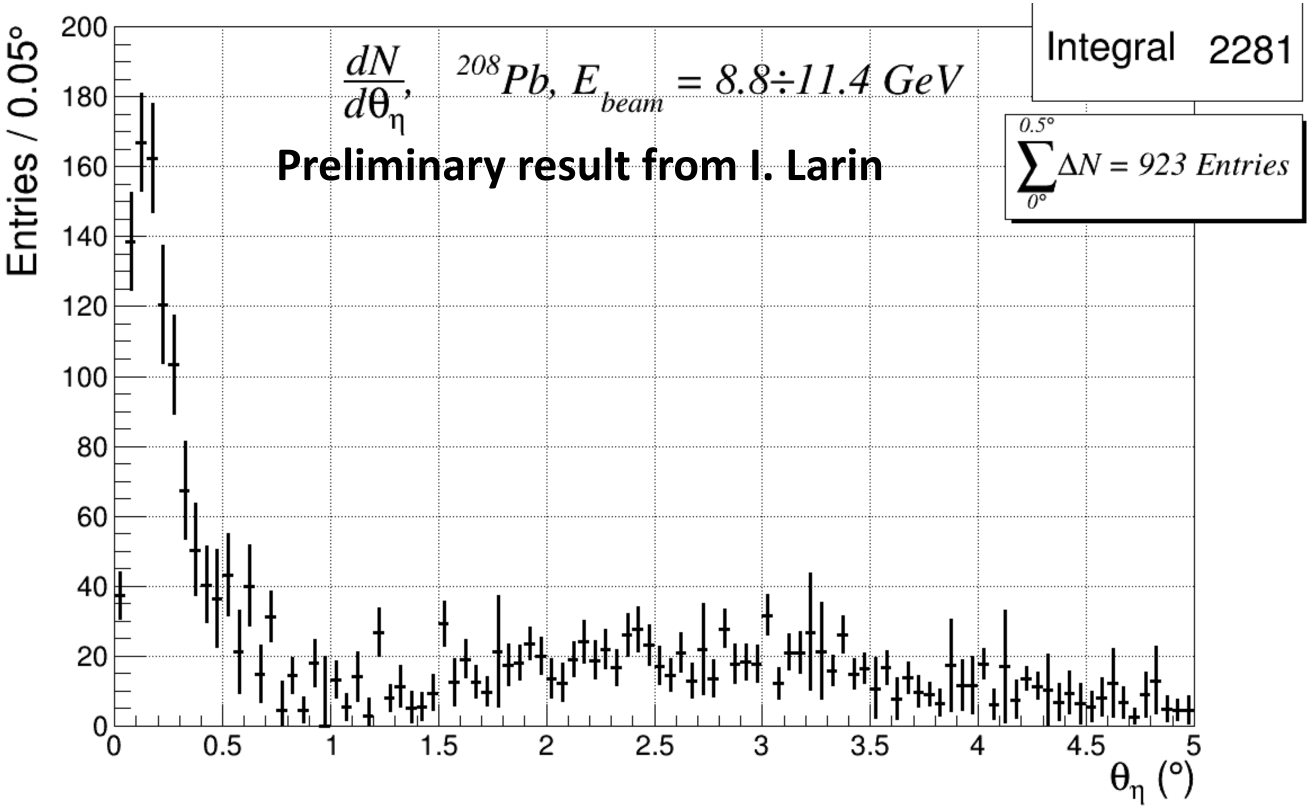
Larin et al., PRL 106, 162303 (2011)



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

Very preliminary look at exclusive η photoproduction

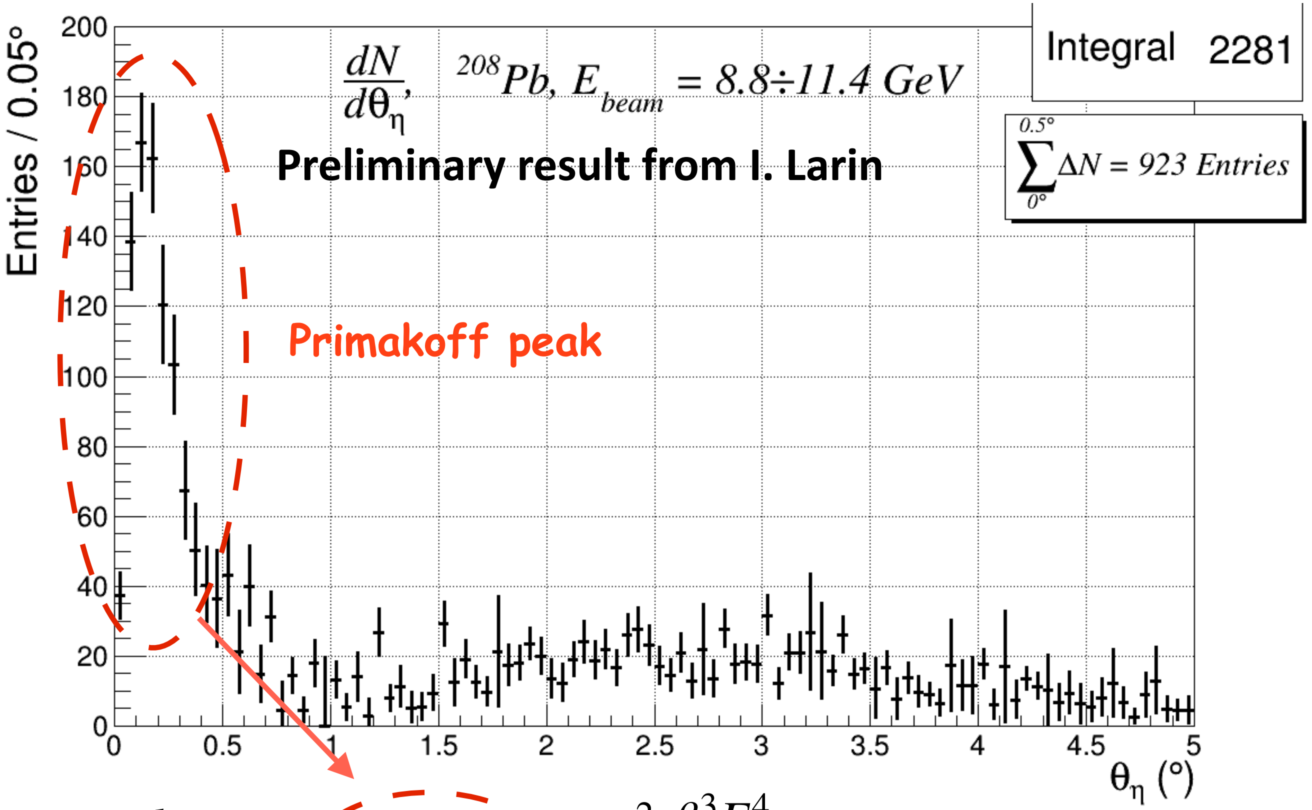
$$\vec{\gamma}\, Pb \rightarrow \eta \rightarrow \gamma\gamma$$



Lab angular distribution

Very preliminary look at exclusive η photoproduction

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



Preliminary result from I. Larin

Primakoff peak

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

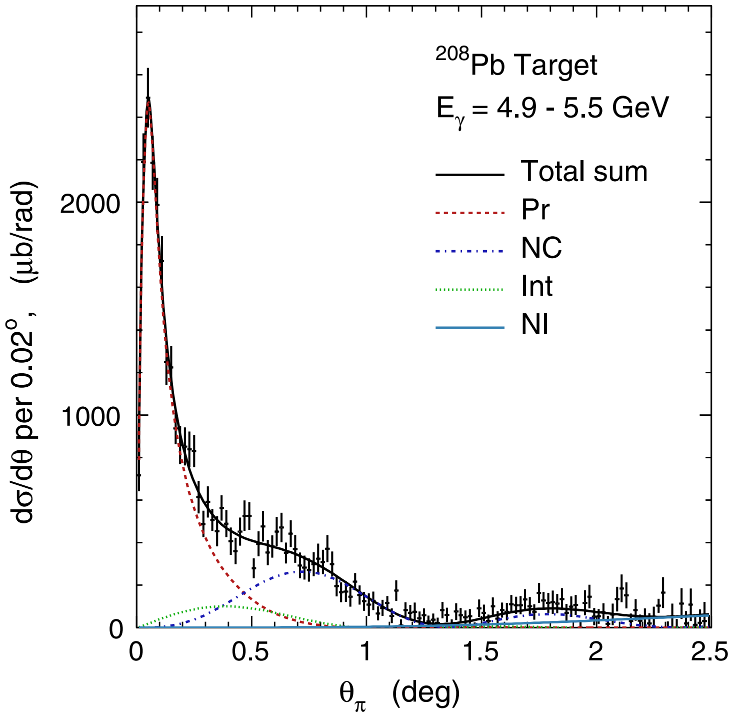
Upcoming analysis for CPP/NPP

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

- 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 $\gamma\gamma \to \pi\pi$ cross section from background reactions

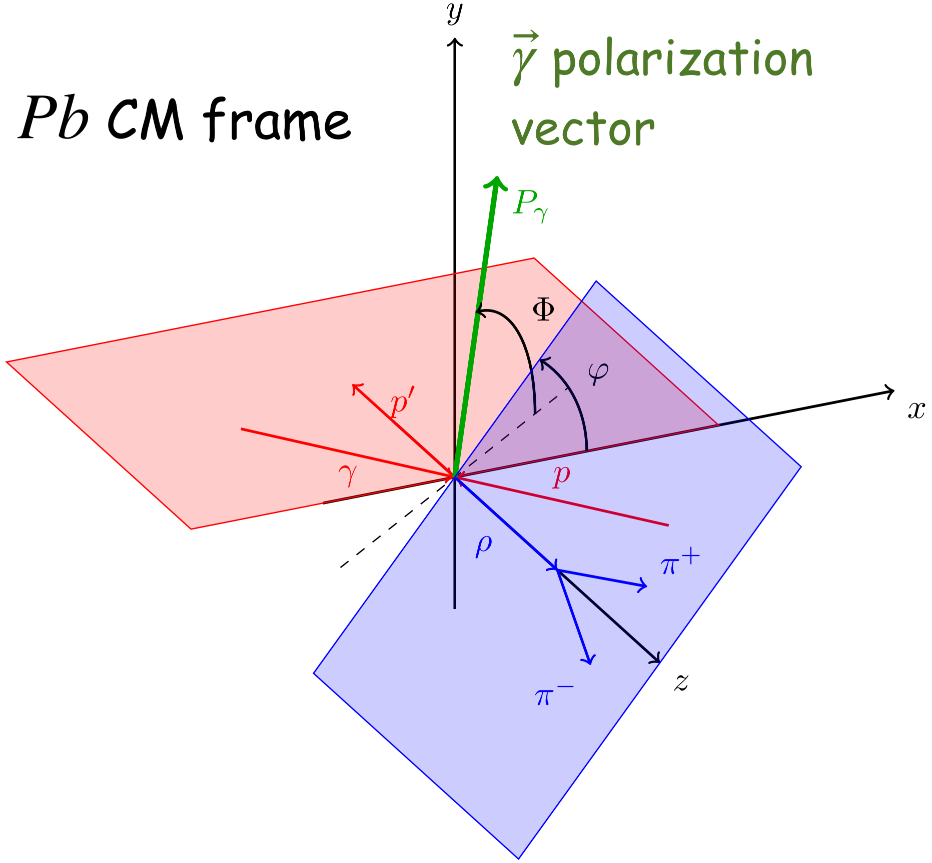
PrimEx I $\gamma\ Pb \to \pi^0\ Pb$



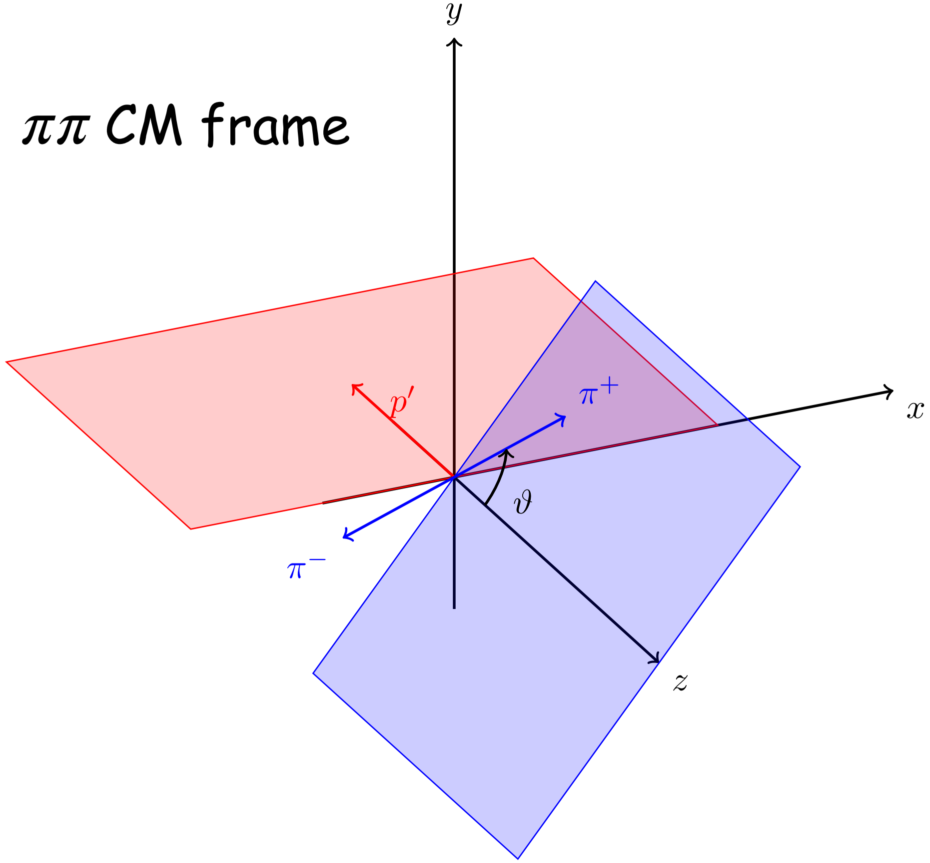
Utilize amplitude analysis tools developed for the GlueX $\vec{\gamma}p \rightarrow \rho^0 p$ measurement for analysis of $\vec{\gamma}\ Pb \rightarrow \pi\pi\ Pb$ data (see Phys. Rev. C **108**, 055204 (2023))

$(\pi\pi)\ Pb$ CM frame

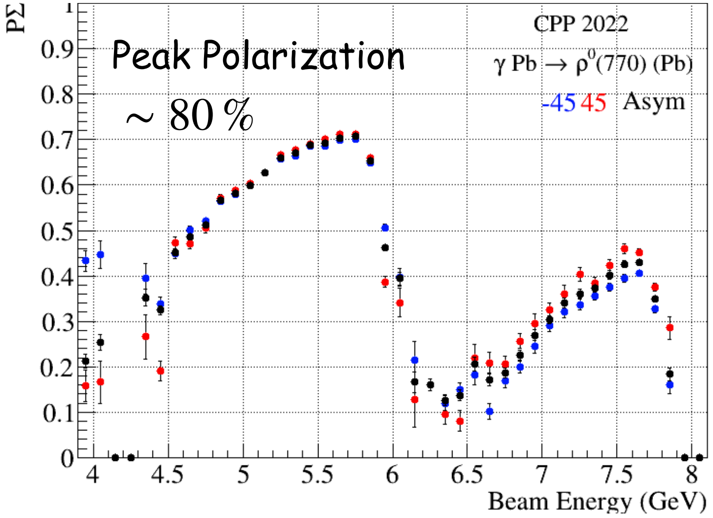
$\vec{\gamma}$ polarization vector



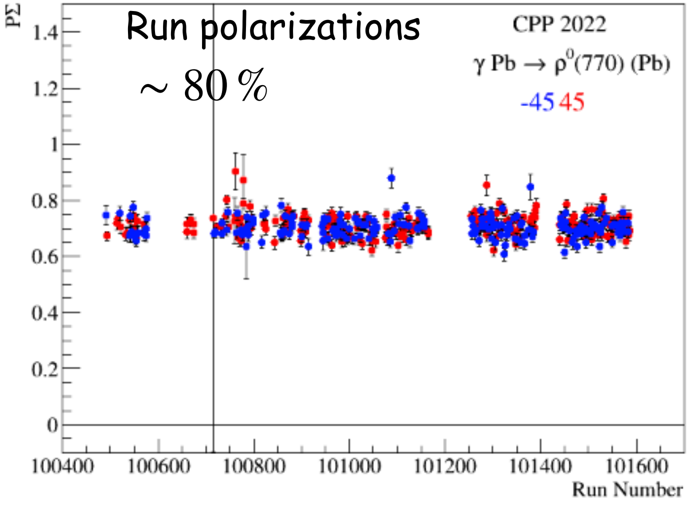
$\pi\pi$ CM frame



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


Peak Polarization

$\sim 80\,\%$

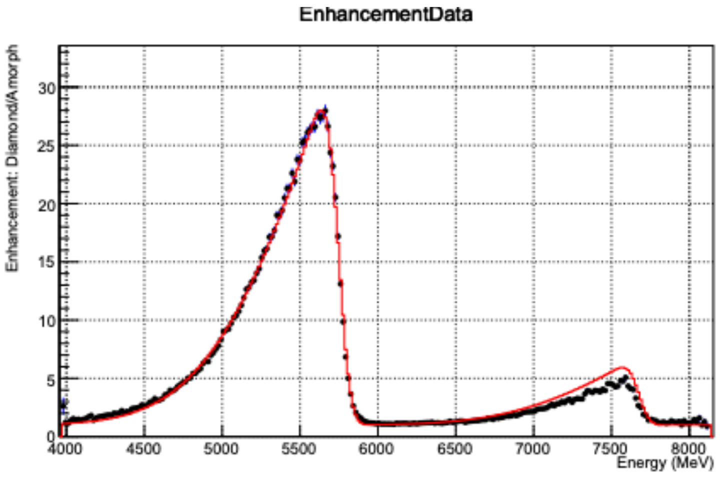

Run polarizations

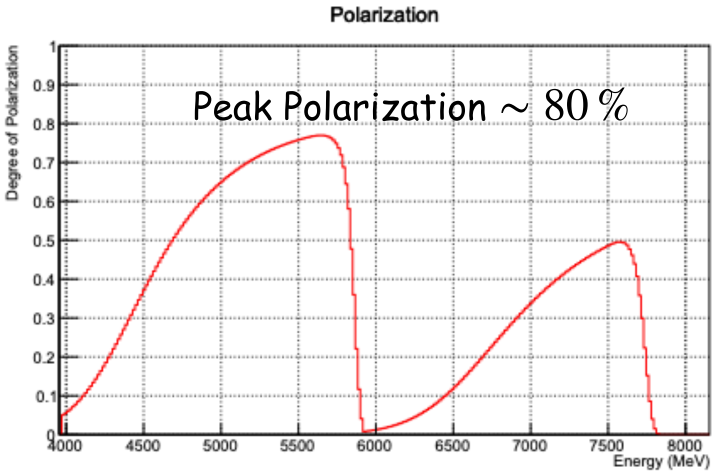
$\sim 80\,\%$

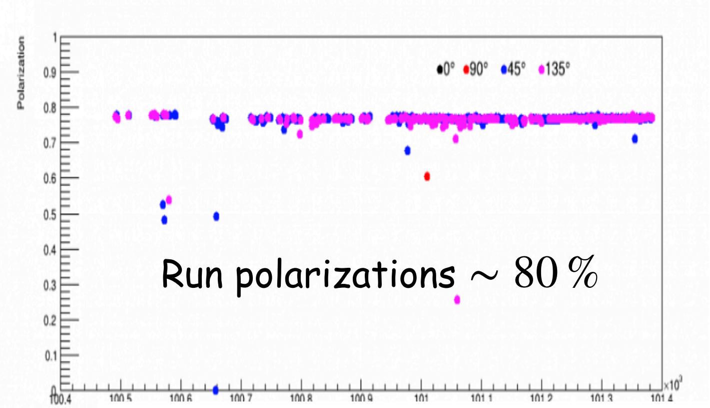
Polarization vs run number

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)




Peak Polarization $\sim 80\,\%$

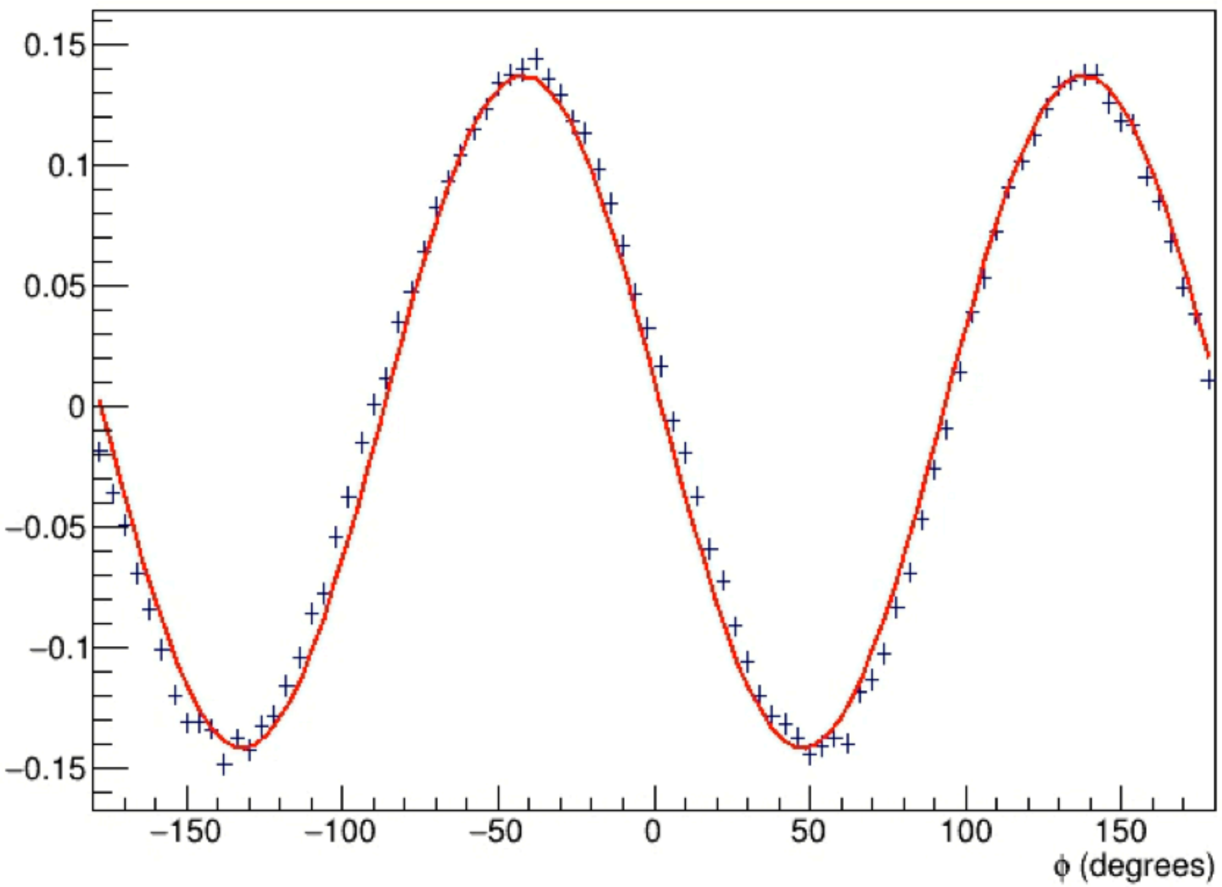

Run polarizations $\sim 80\,\%$

Polarization vs run number

iii. New polarimetry technique developed for CPP: $\vec{\gamma}\ Pb \rightarrow e^{+}e^{-}\ Pb$ where both e^{+} and e^{-} are detected (from A. Schick)

Beam Polarization $\sim 80\,\%$

ϕ_J Yield Asymmetry



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

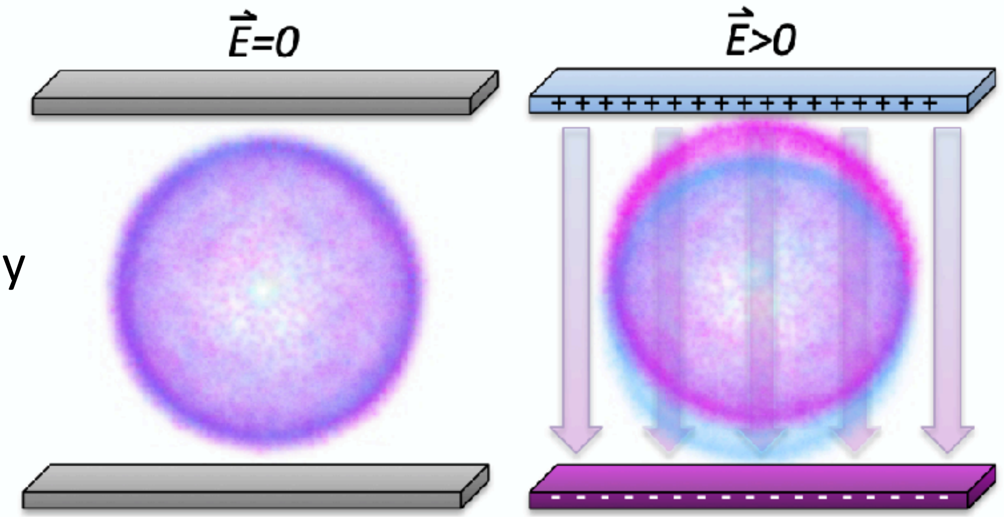
Thanks for your attention, and thanks to the Organizers for the opportunity to speak at this meeting !

Extra Slides

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

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

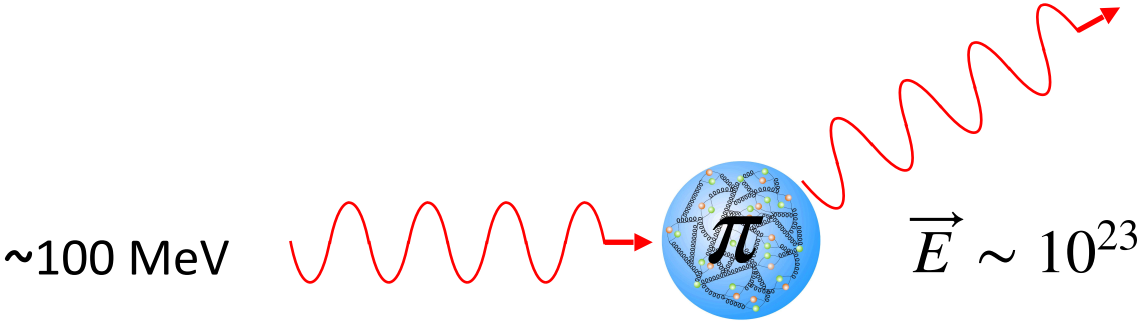
Small numbers because hadrons are “stiff”

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: $E \approx \frac{100MeV}{1fm} = 10^{23}\frac{V}{m}$

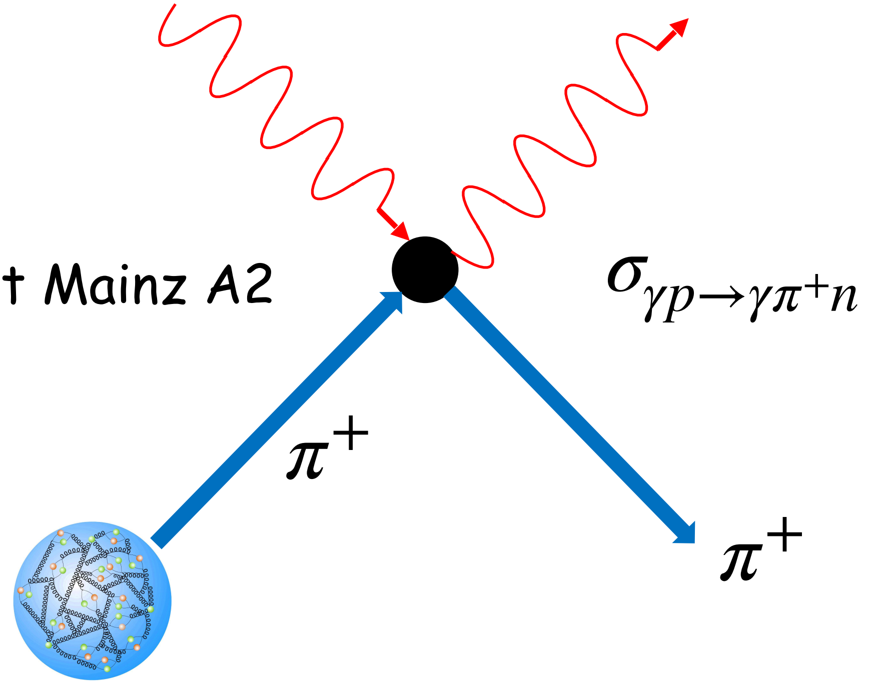
The best technique is Compton scattering on the pion



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

$$H = H_{Born} - 4\pi \underbrace{\left(\frac{1}{2}\alpha_E \vec{E}^2 + \frac{1}{2}\beta_M \vec{H}^2\right)}_{\approx 10\%}$$

i. Radiative pion photoproduction



~ 300 MeV

$\gamma p \to \gamma' \pi^+ n$ at Mainz A2

$\sigma_{\gamma p \to \gamma \pi^+ n}$

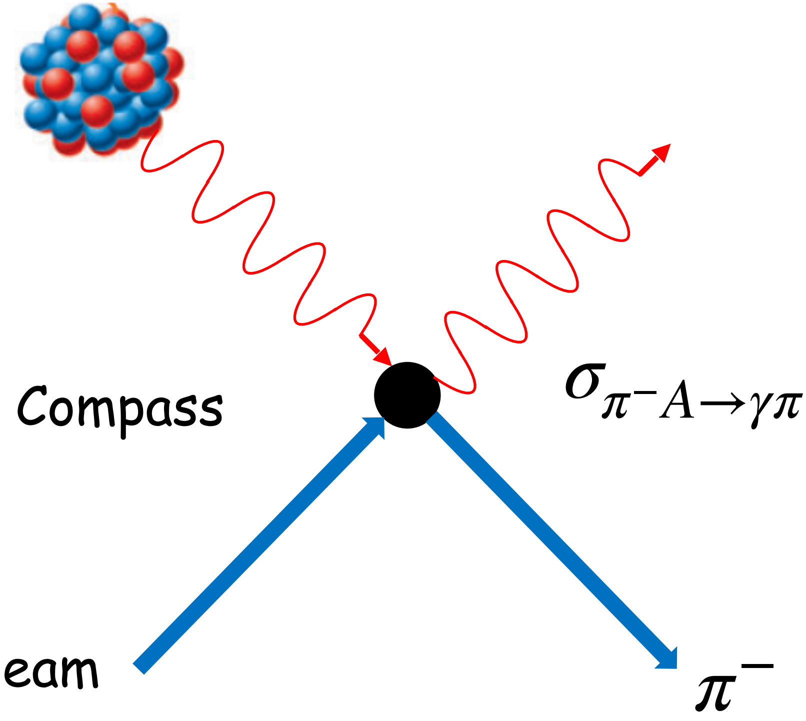
π^+

π^+

Proton target

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

ii. Pion radiative scattering

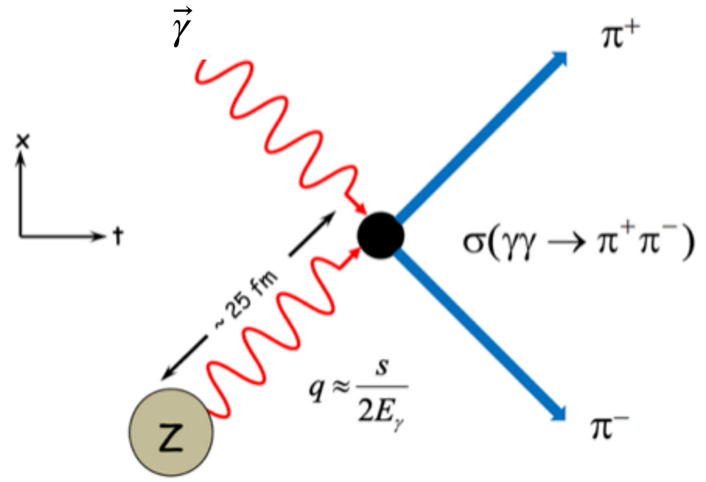


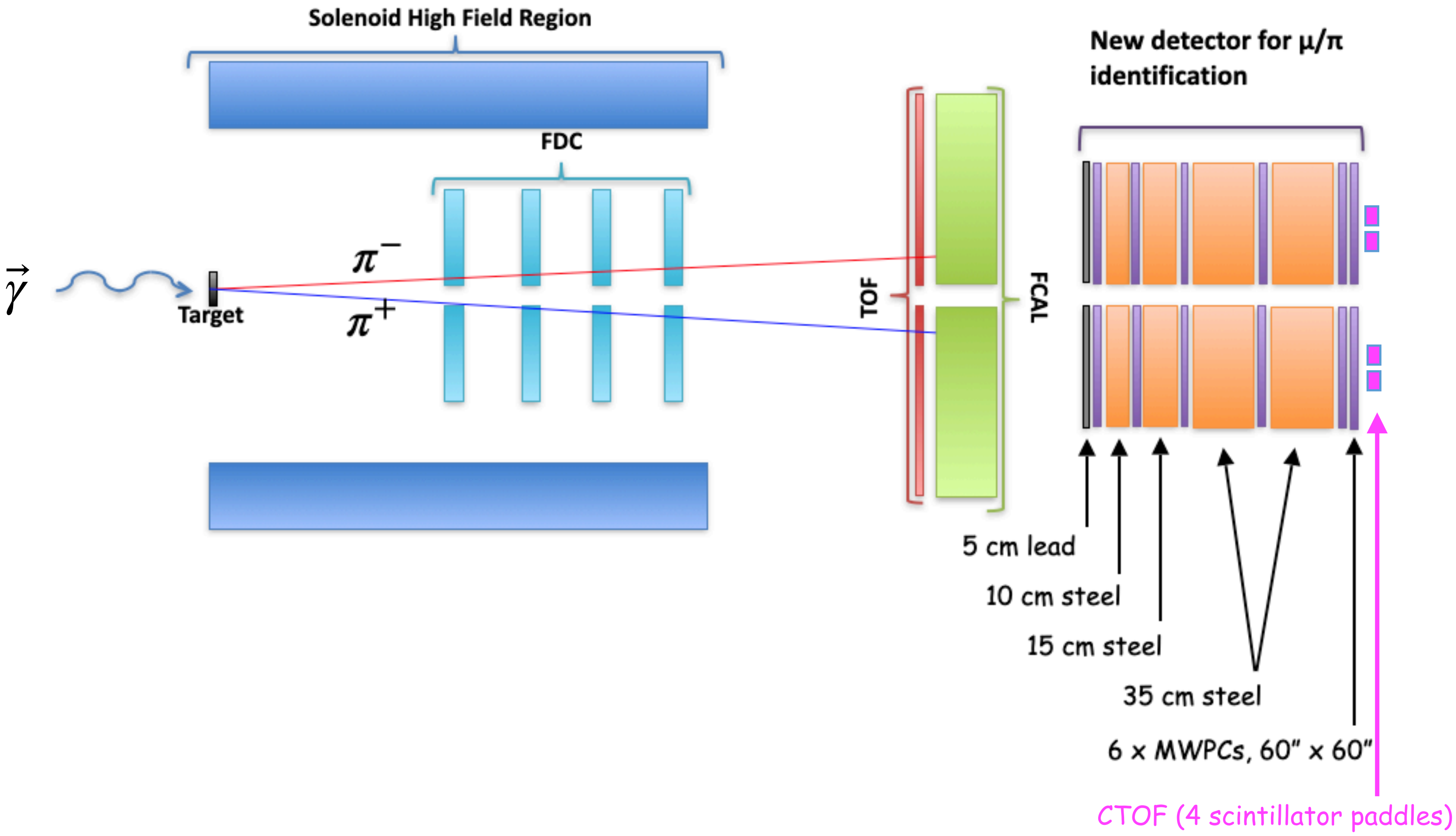
$$\sigma_{\pi^- A\to\gamma\pi^- A} \xrightarrow{LET} \sigma^{Compton}_{\gamma\pi^-\to\gamma\pi^-}$$

CPP and NPP experiment at JLab GlueX

Primakoff process:

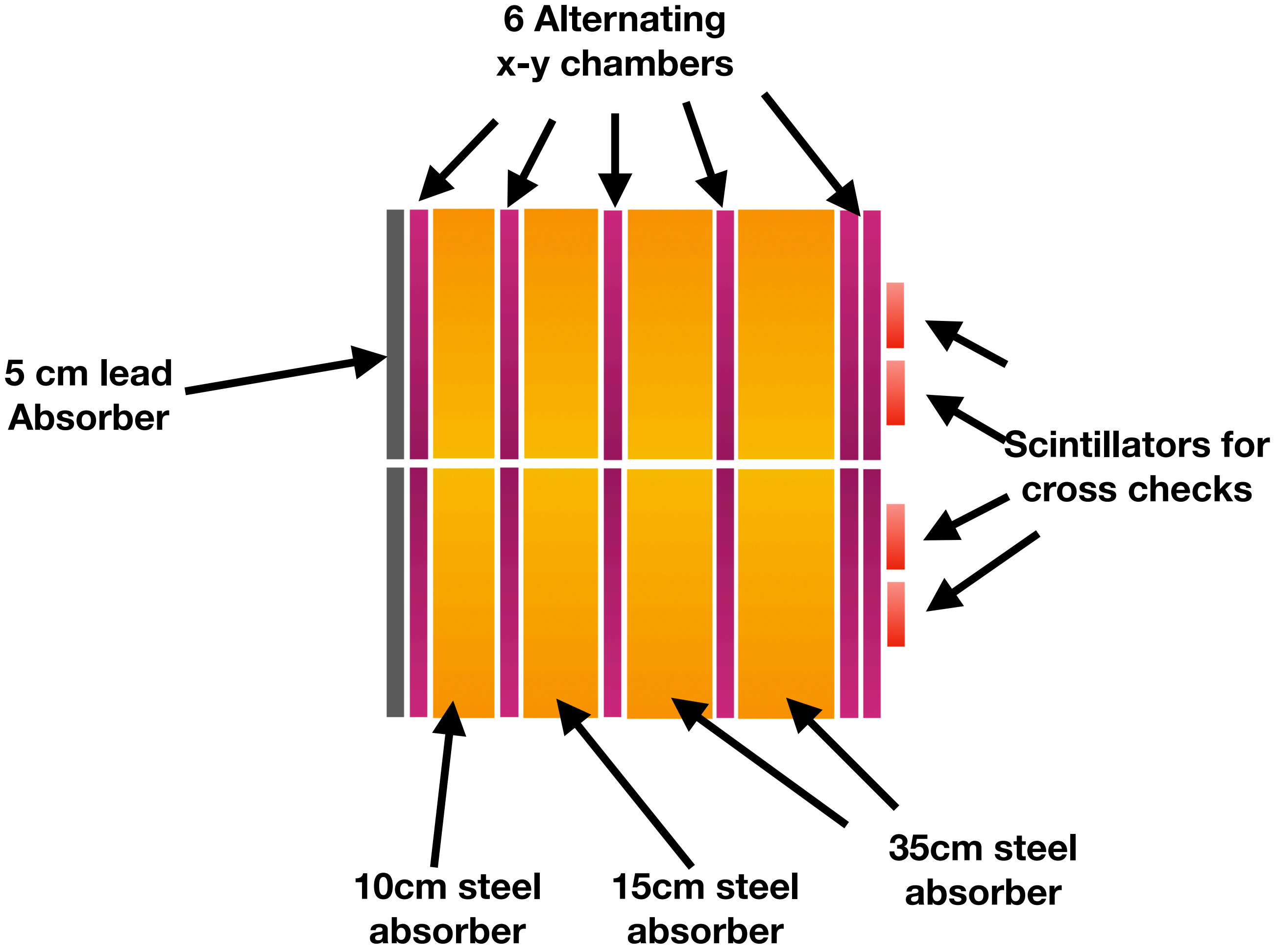
very low-t photoproduction $\gamma A \rightarrow \pi$





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

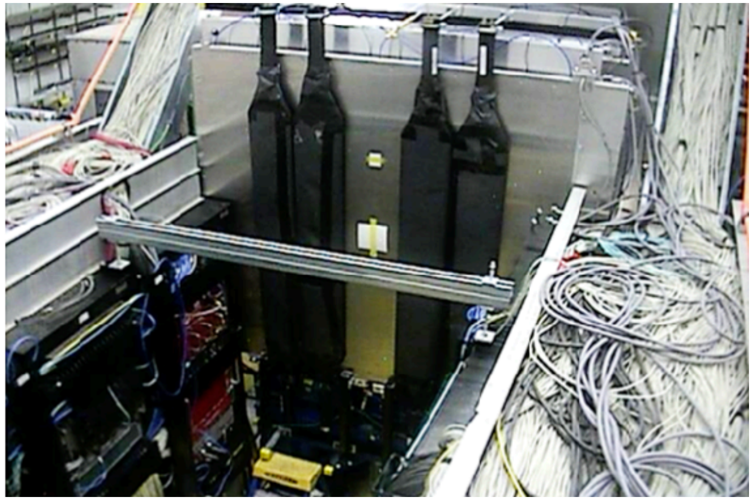


Muon detector

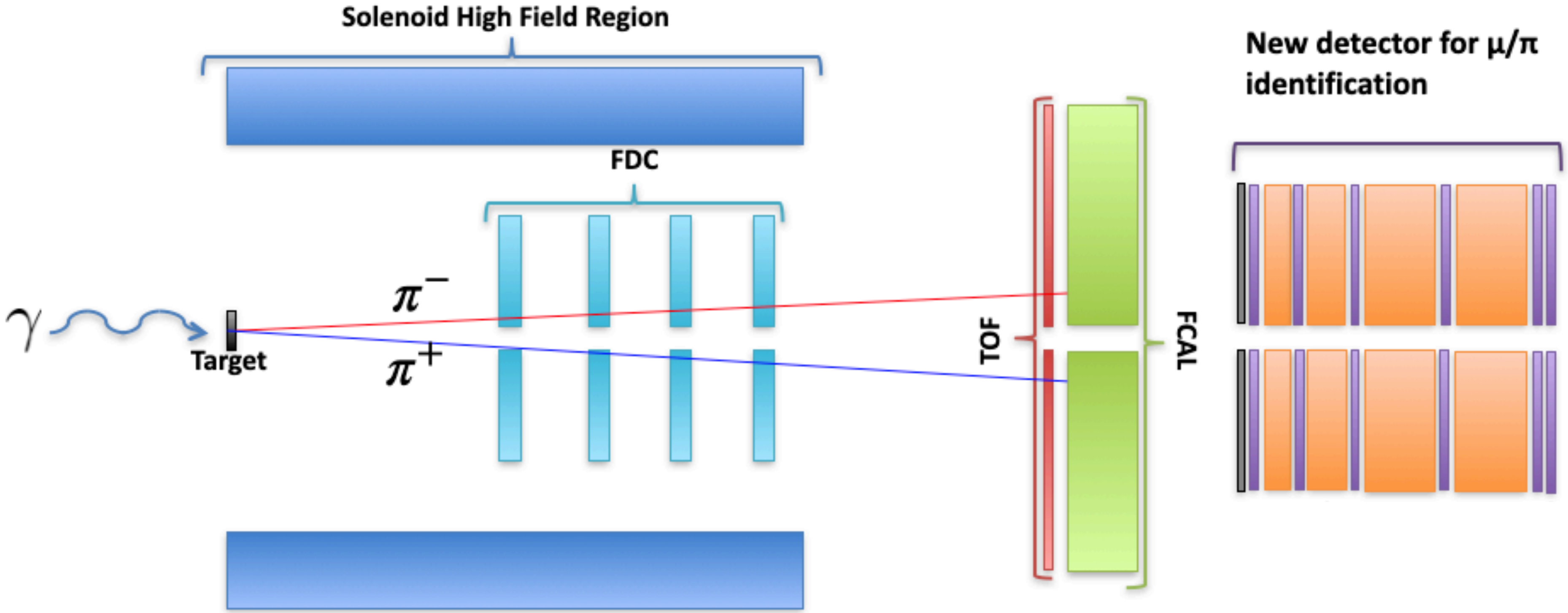
Assembled muon chambers at UMass

Chambers installed with iron absorbers

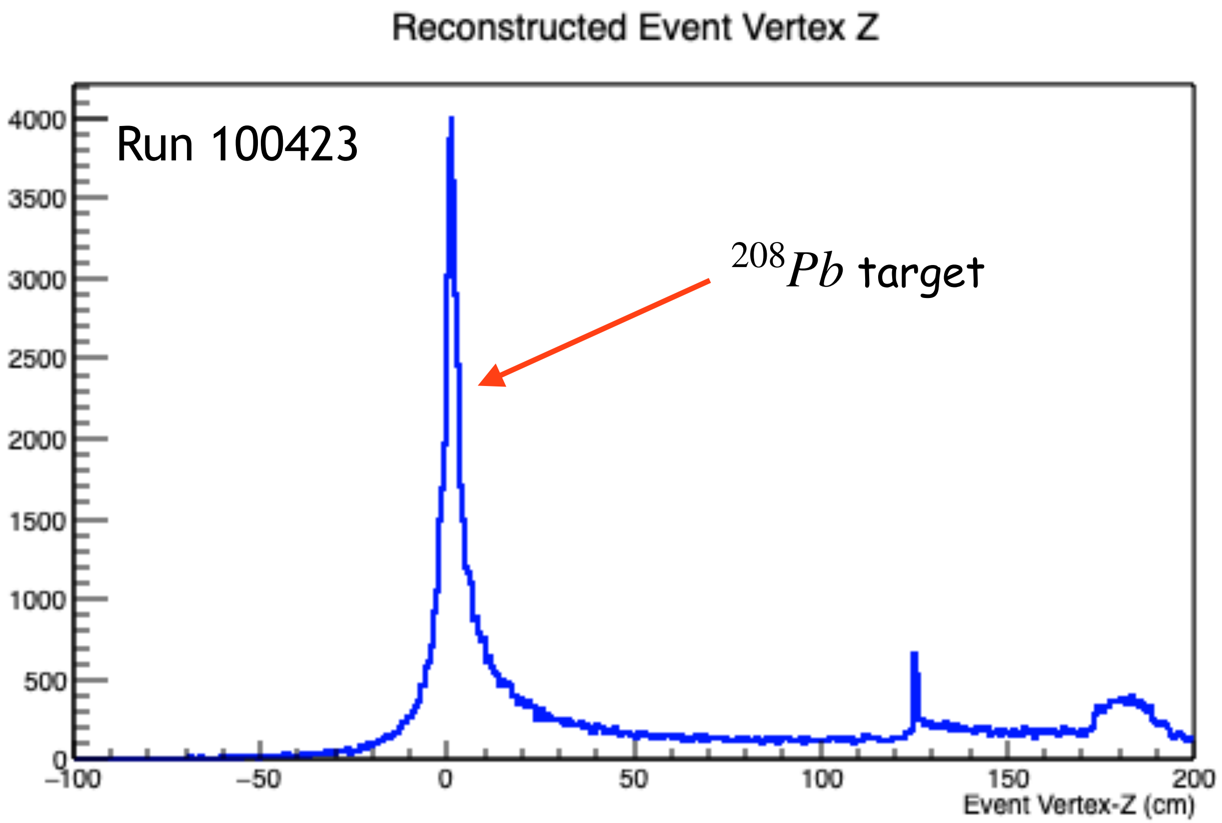
Trigger scintillators installed behind muon chambers



Vertex resolution for charged tracks in GlueX



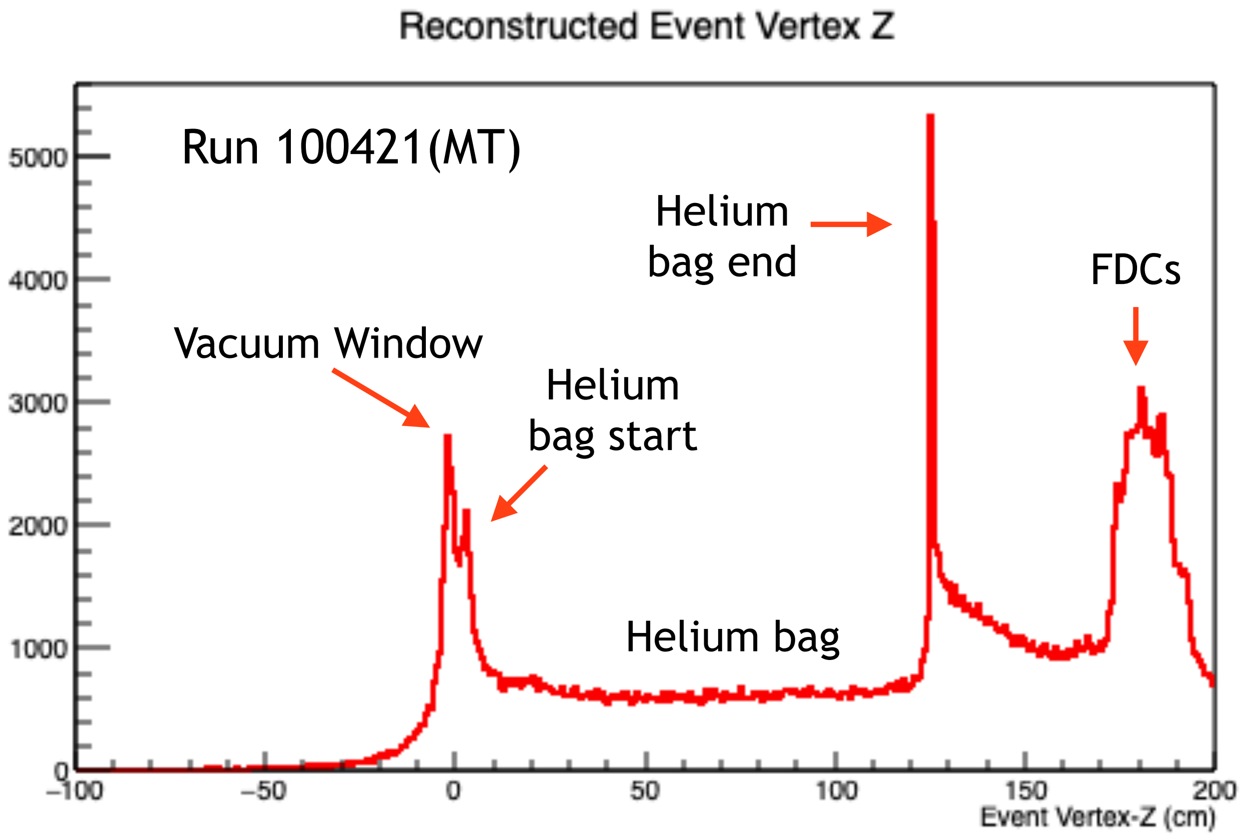
Vertex resolution for charged tracks in GlueX



Run 100423

^{208}Pb target

Run with ^{208}Pb target in



Run 100421(MT)

Helium bag end

FDCs

Vacuum Window

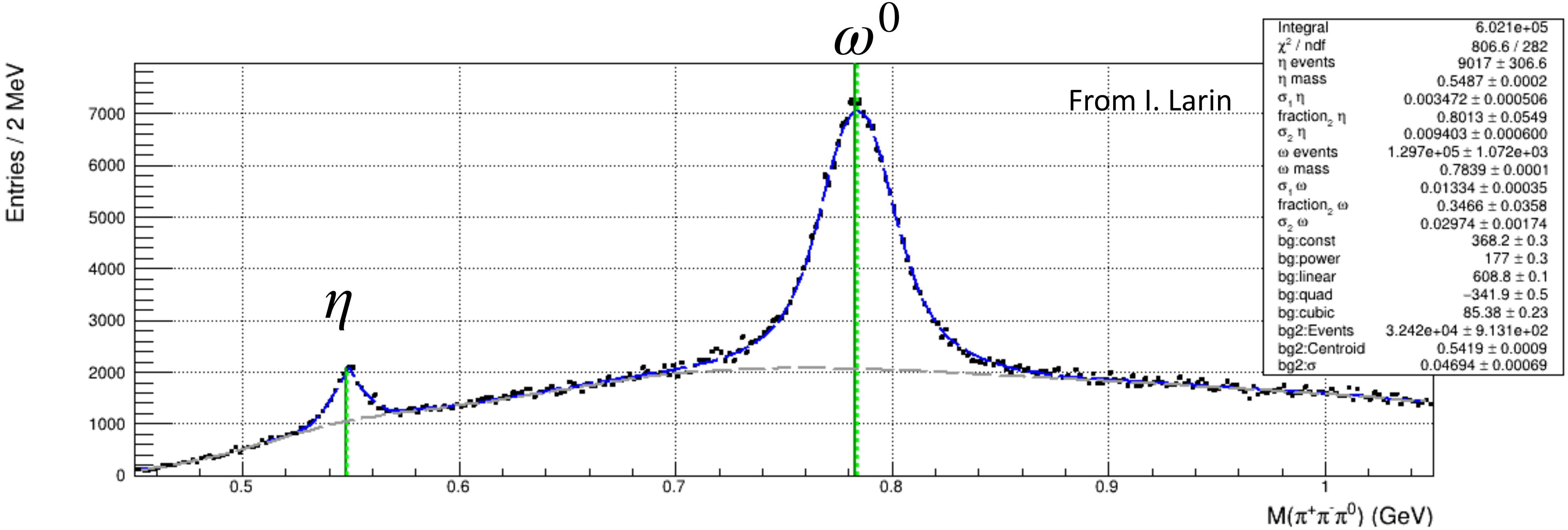
Helium bag start

Helium bag

Run with ^{208}Pb target out

Very preliminary look at ω^0 photoproduction

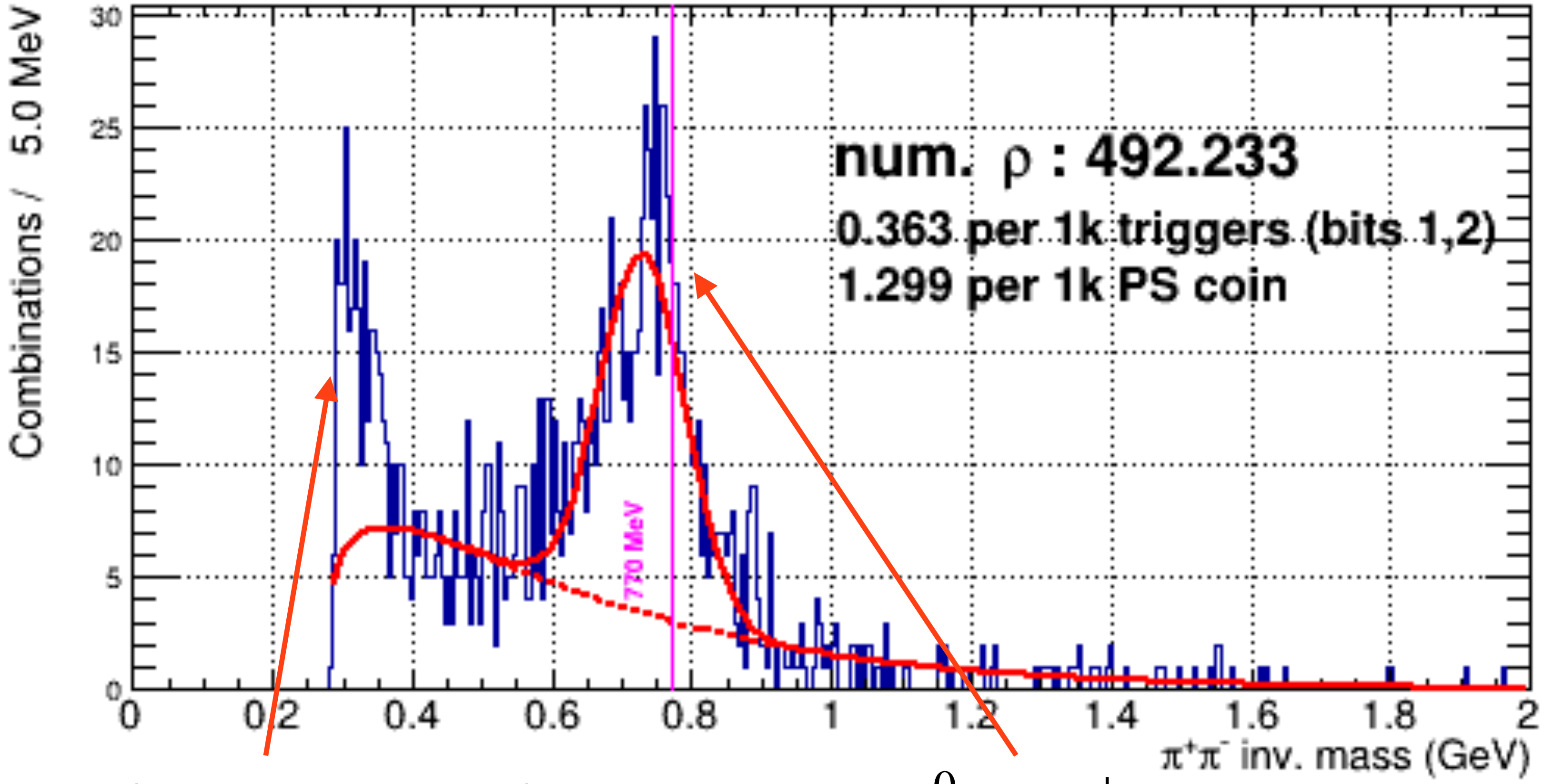
$$\gamma\ Pb \to \pi^+\pi^-\pi^0$$



Integral	6.021e+05
χ^2 / ndf	806.6 / 282
η events	9017 ± 306.6
η mass	0.5487 ± 0.0002
σ_1 η	0.003472 ± 0.000506
fraction$_2$ η	0.8013 ± 0.0549
σ_2 η	0.009403 ± 0.000600
ω events	1.297e+05 ± 1.072e+03
ω mass	0.7839 ± 0.0001
σ_1 ω	0.01334 ± 0.00035
fraction$_2$ ω	0.3466 ± 0.0358
σ_2 ω	0.02974 ± 0.00174
bg:const	368.2 ± 0.3
bg:power	177 ± 0.3
bg:linear	608.8 ± 0.1
bg:quad	−341.9 ± 0.5
bg:cubic	85.38 ± 0.23
bg2:Events	3.242e+04 ± 9.131e+02
bg2:Centroid	0.5419 ± 0.0009
bg2:σ	0.04694 ± 0.00069

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

"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)



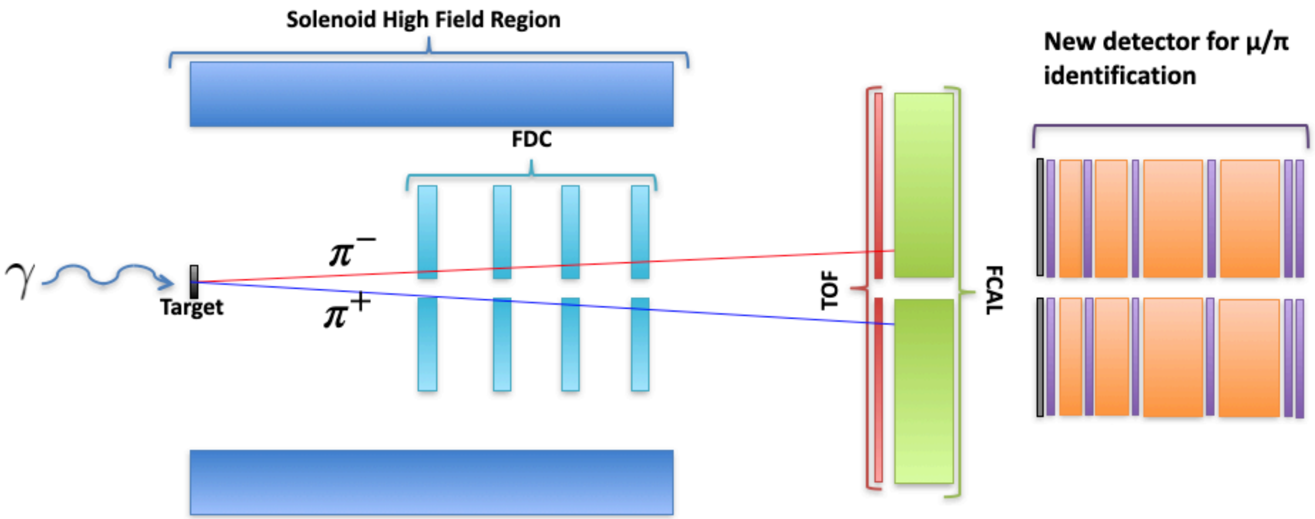
$\gamma A \to e^+e^-$ and $\gamma A \to \mu^+\mu^-$

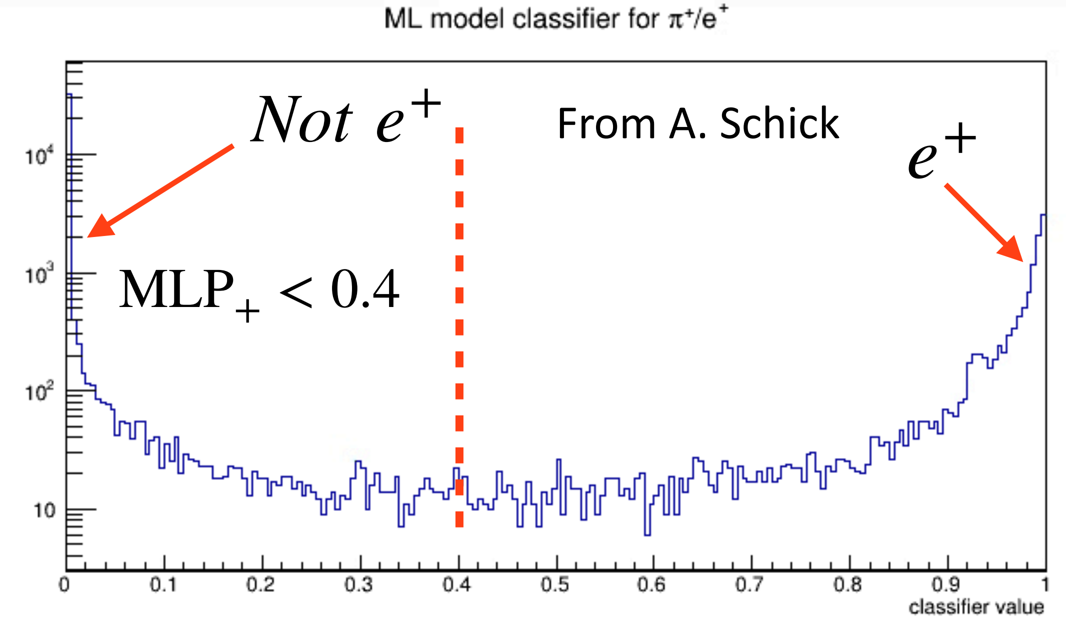
$\rho^0 \to \pi^+\pi^-$

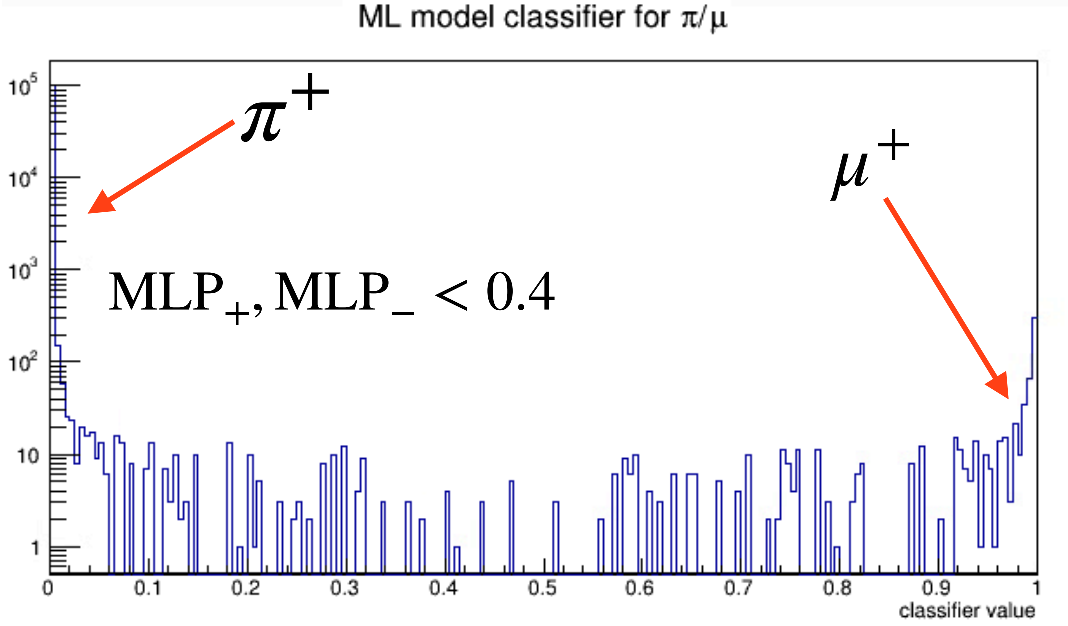
Particle identification: neural net analysis

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




ML model classifier for π^+/e^+


ML model classifier for π/μ