Measuring the Charged Pion Polarizability in the $\gamma\gamma \rightarrow \pi^+\pi^-$ Reaction

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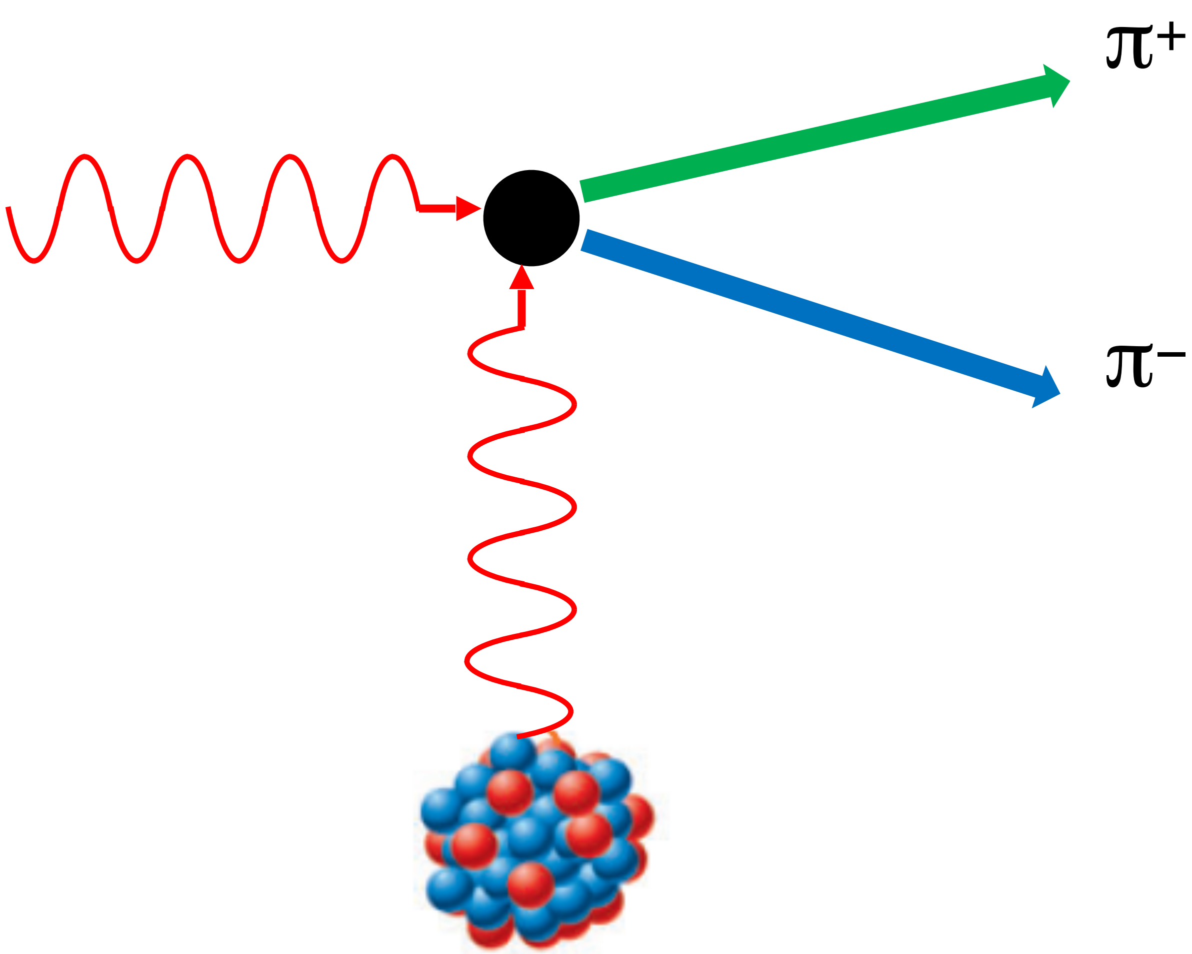
Endorsed and supported by the GlueX Collaboration

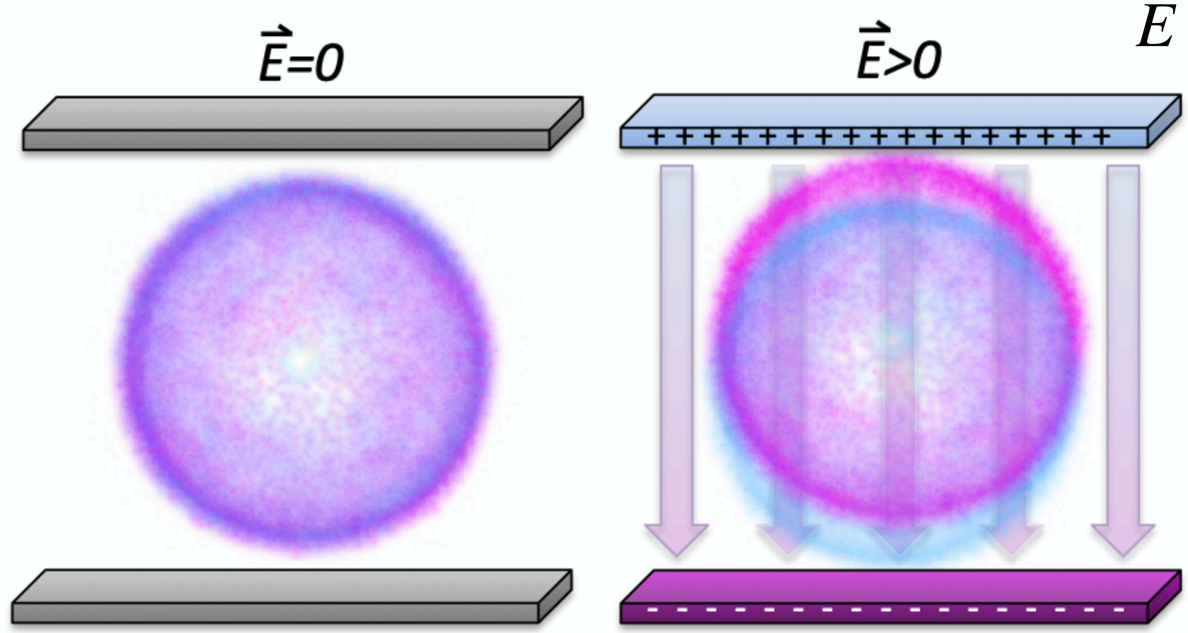


- Overview of experimental goals
- Update on theoretical calculations
- New results on CPP since PAC approval
- Preparations for the CPP experiment
  1. Design and construction of the muon detector system
  2. Engineering design for detector installation in Hall D
  3. Neural-net analysis for $e^{\pm}$, $\mu^{\pm}$, and $\pi^{\pm}$ identification
  4. Time-of-flight trigger for the experiment

- **"Thought experiment": place a pion in a parallel plate capacitor at very high electric field**

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

Pion surrounded by pion cloud



Pion surrounded by displaced pion cloud

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

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

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

Small numbers because hadrons are "stiff"!

Whereas elastic form factors tell us about ground state properties of a hadron, polarizabilities encode information about the excited states

- **Among theoretical predictions for nucleon and meson polarizabilities, charged pion polarizability (CPP) ranks as the most constrained prediction:**

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

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

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

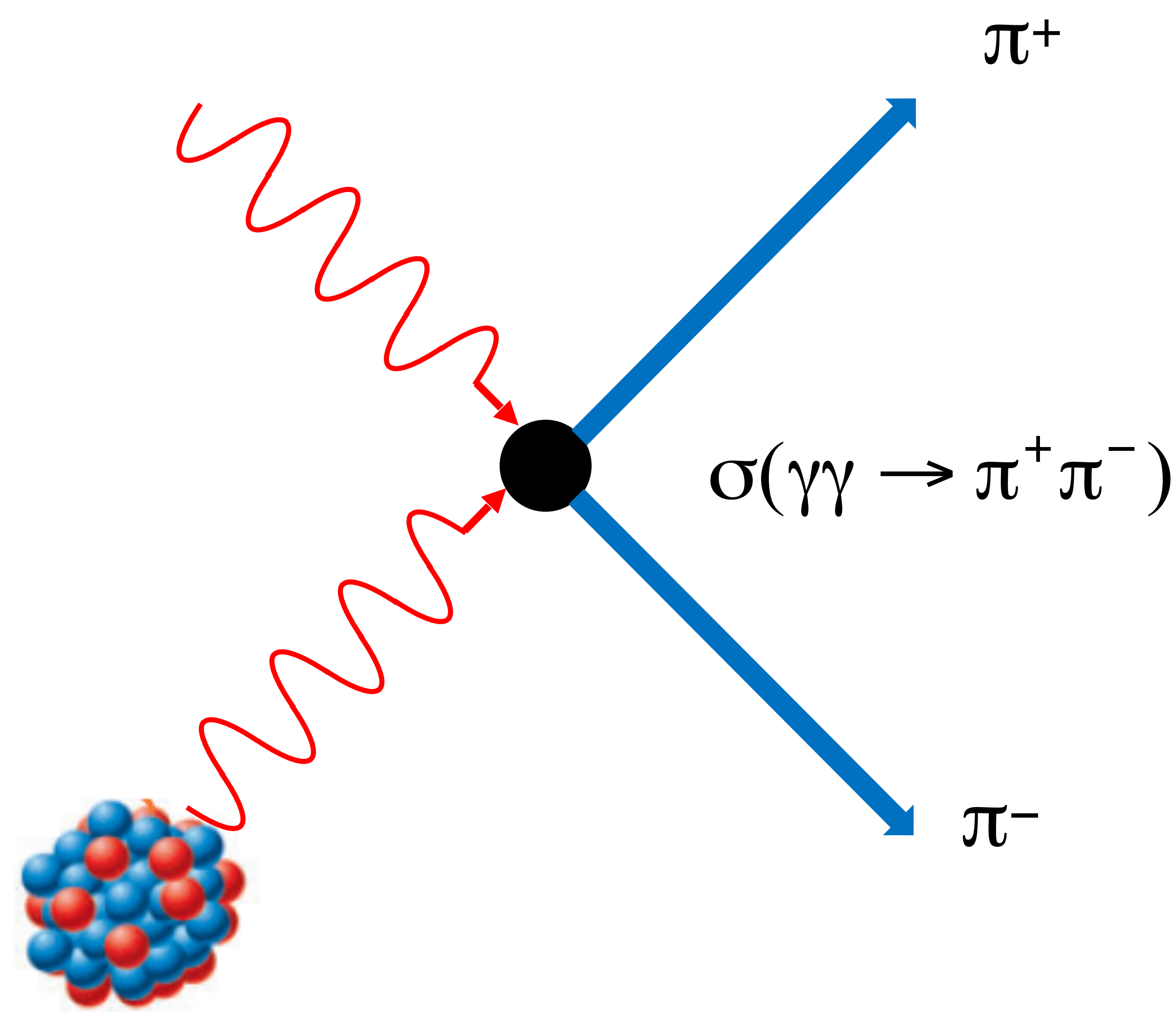
O(p^6) prediction: $$\alpha_\pi - \beta_\pi = 5.7 \pm 1.0 \times 10^{-4} e\, fm^3$$

$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \times 10^{-4} e\, fm^3$$

<u>O(p^6) corrections are predicted to be small</u>

If we had a pion target, then we would use Compton scattering to test this prediction ...

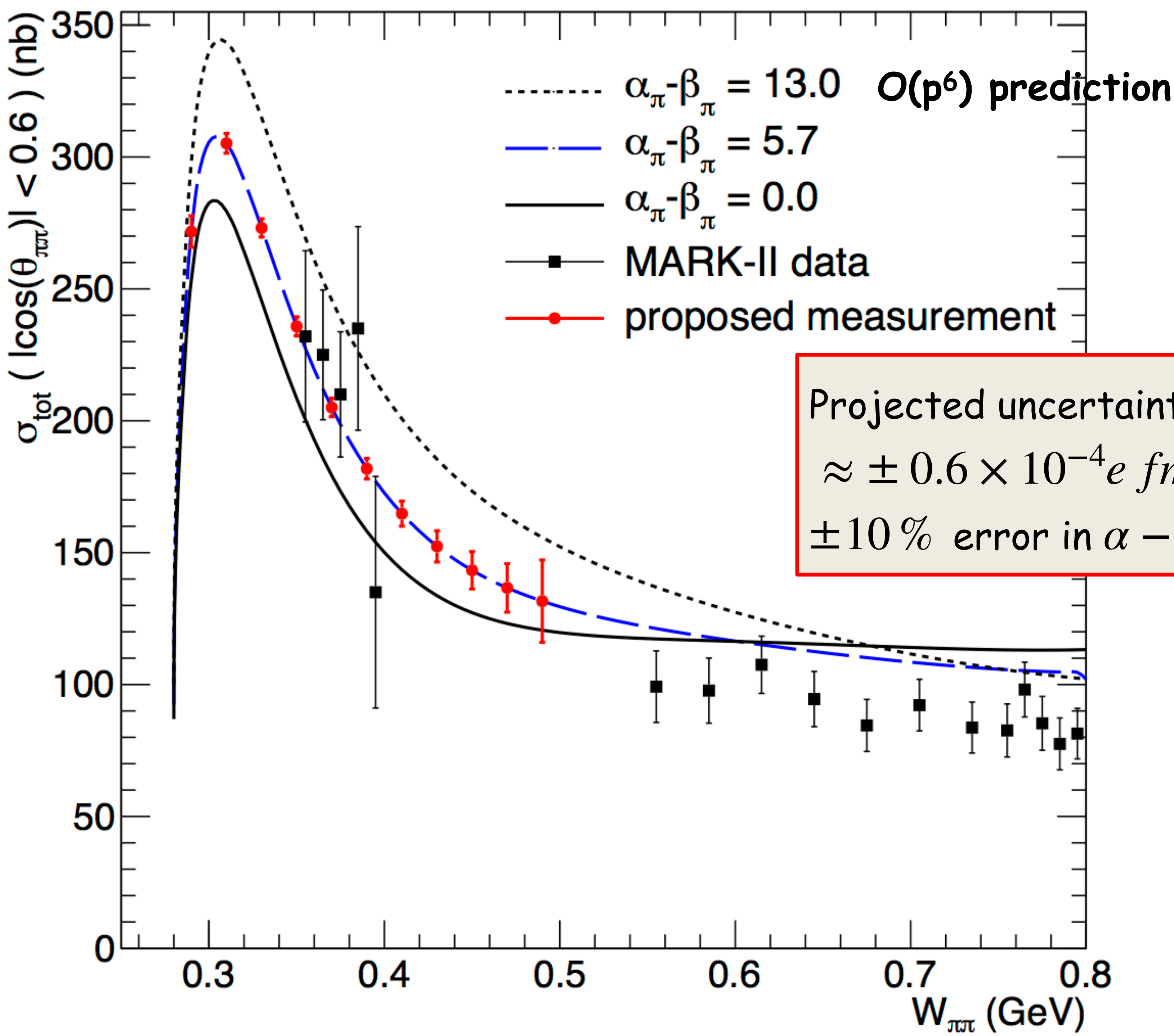
Use crossing symmetry (x $\leftrightarrow$ t) to relate $\sigma(\gamma\pi^+ \rightarrow \gamma\pi^+)$ to $\sigma(\gamma\gamma \rightarrow \pi^+\pi^-)$ and Primakoff reaction to measure $\sigma(\gamma\gamma \rightarrow \pi^+\pi^-)$



Sensitive to the polarizabilities

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

$\sigma(\gamma\gamma \rightarrow \pi^+\pi^-)$



Projected uncertainty in $\alpha - \beta$
$\approx \pm 0.6 \times 10^{-4} e\ fm^3$,
$\pm 10\,\%$ error in $\alpha - \beta$

- **Update on theoretical calculations**

✓ First "modern" dispersion theory calculation for the polarizability effect in $\gamma\gamma \to \pi^+\pi^-$, Pasquini et al., Phys. Rev. C 77, 065211 (2008).

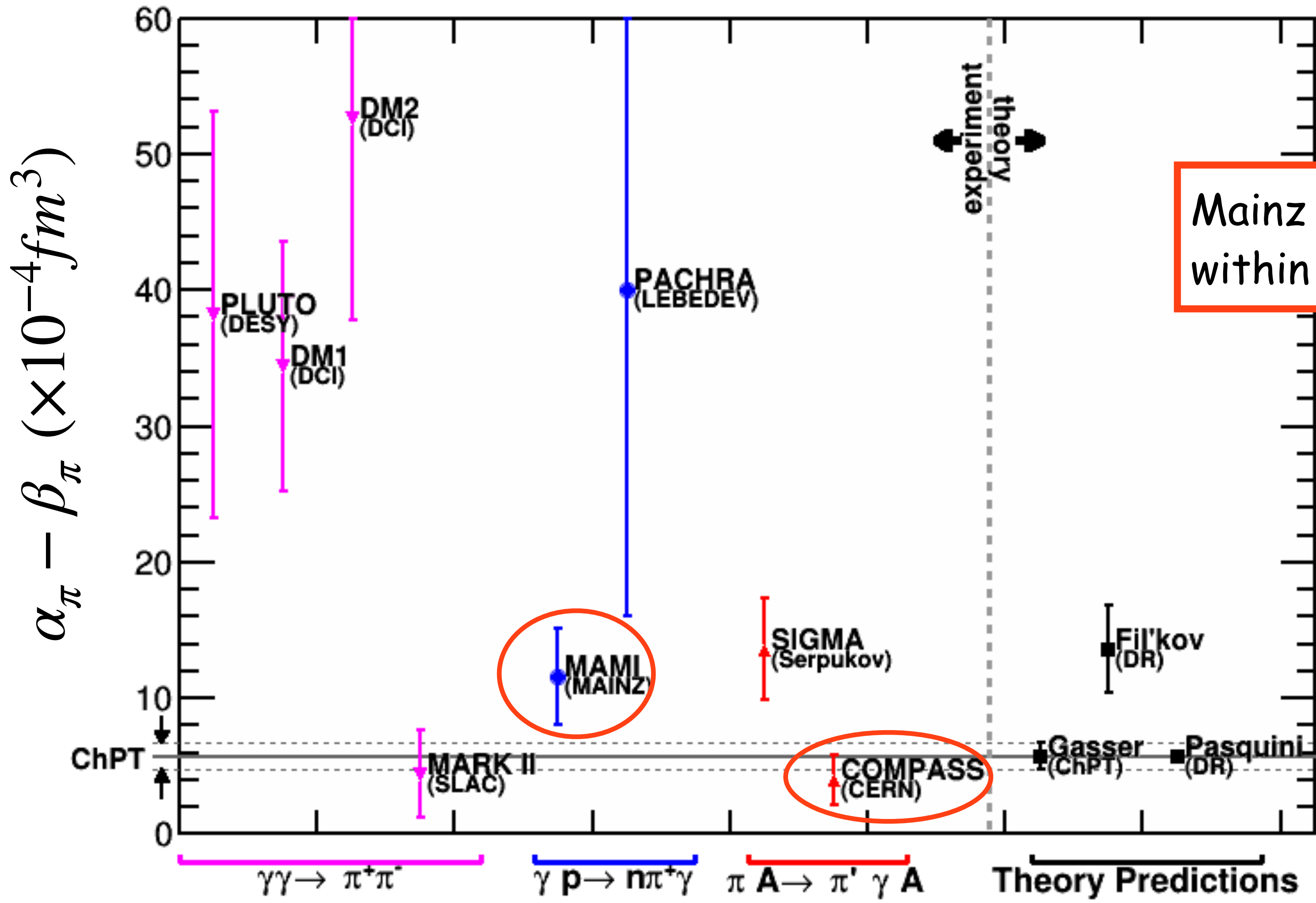
✓ Dai and Pennington publish a dispersion analysis for pion polarizabilities from $\gamma\gamma \to \pi\pi$ data based on their global analysis of $\gamma\gamma \to m\overline{m}$ data, Phys. Rev. D 94, 116021 (2016).

✓ Vanderhaeghen et al, hadronic light-by-light (HLbL) contributions to muon g-2. Largest contributions to HLbL are from:

1. $\gamma^*\gamma^* \to m$, with $m = \pi^0, \eta, \eta'$, and
2. $\gamma^*\gamma^* \to m\overline{m}$, with $m = \pi, k, \eta$

The uncertainties in HLbL from (1) and (2) are approximately equal.

- **New result since PAC approval: COMPASS measurement**



Mainz and Compass agree within 2 standard deviations

$\pi^- Ni \to \pi^- \gamma\ Ni$ @ 160 GeV. Result is sensitive to dN/dE_γ at $E_\gamma \approx E_{beam}$

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

✓ The JLab and COMPASS experiments have different backgrounds and systematic errors: the measurements are complementary

- **Charged pion polarizability (CPP) will run concurrently with the PAC 48 approved neutral pion polarizability (NPP) experiment**

Goals for the pion polarizability program at JLab:

i. First ever measurement of the neutral pion polarizability

ii. Precision measurement of the charged pion polarizability, the most theoretically constrained of hadron polarizabilities

Measuring the Neutral Pion Polarizability

Proposal Submitted to PAC 48

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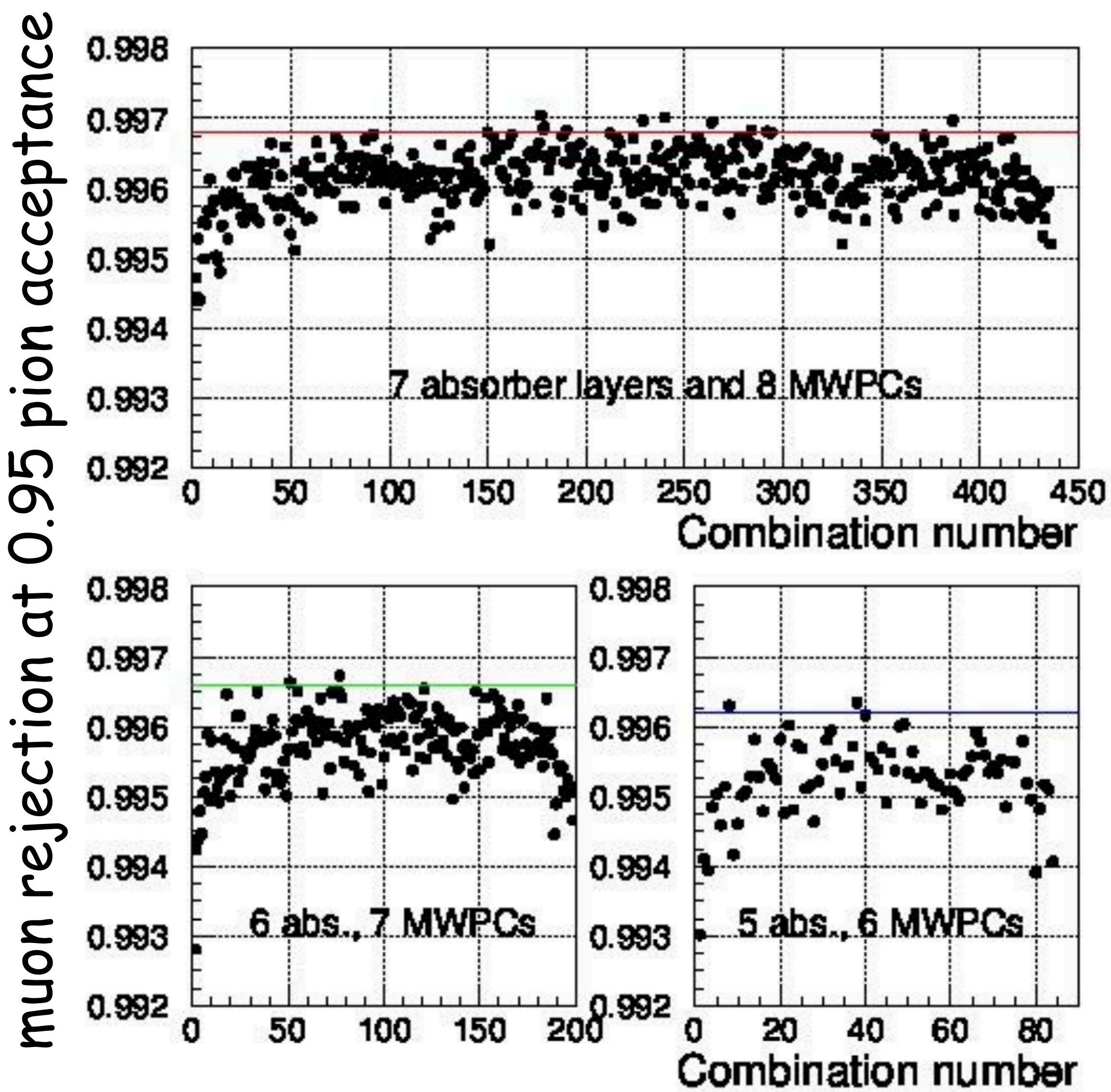
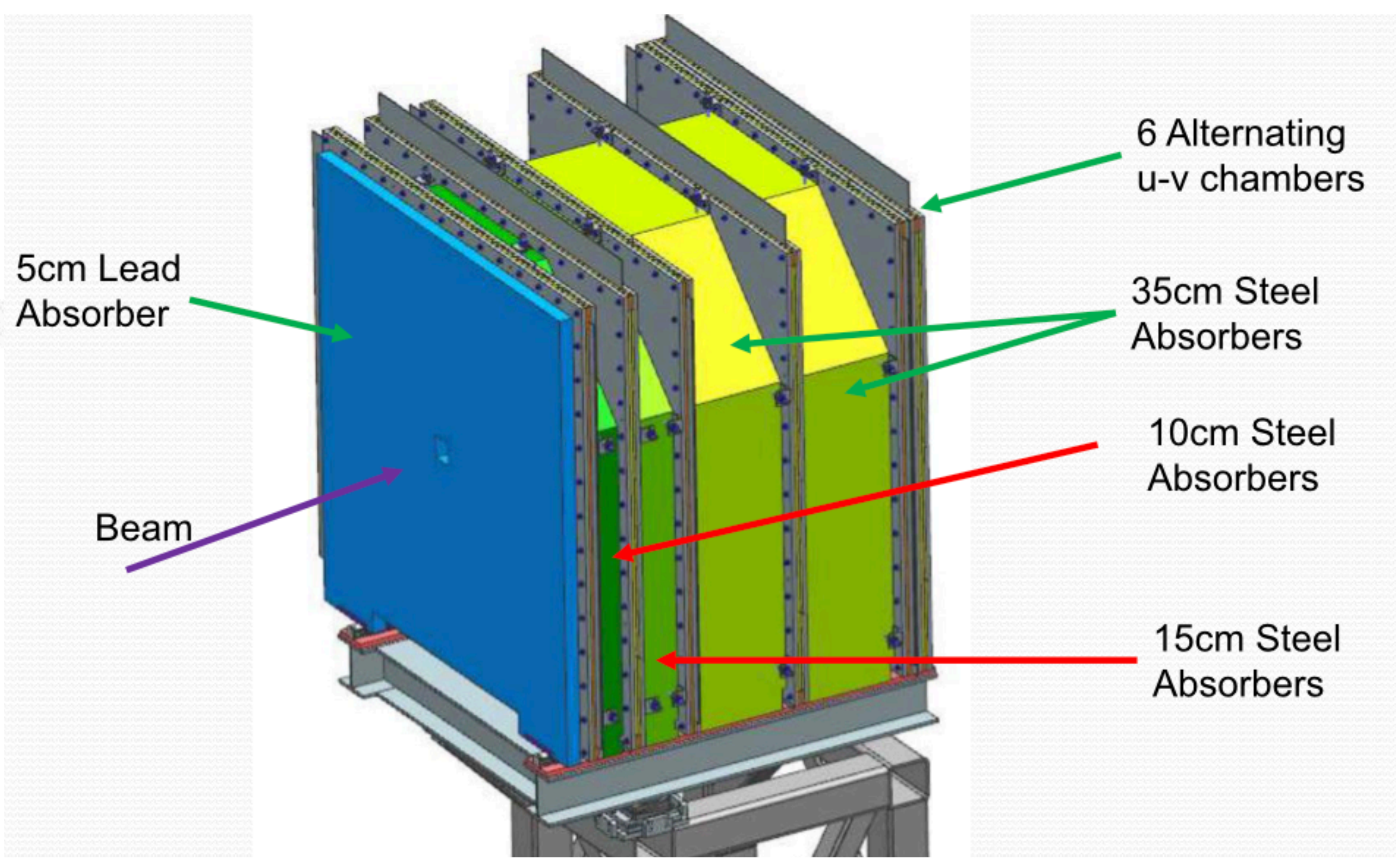
Preparations for running the CPP experiment

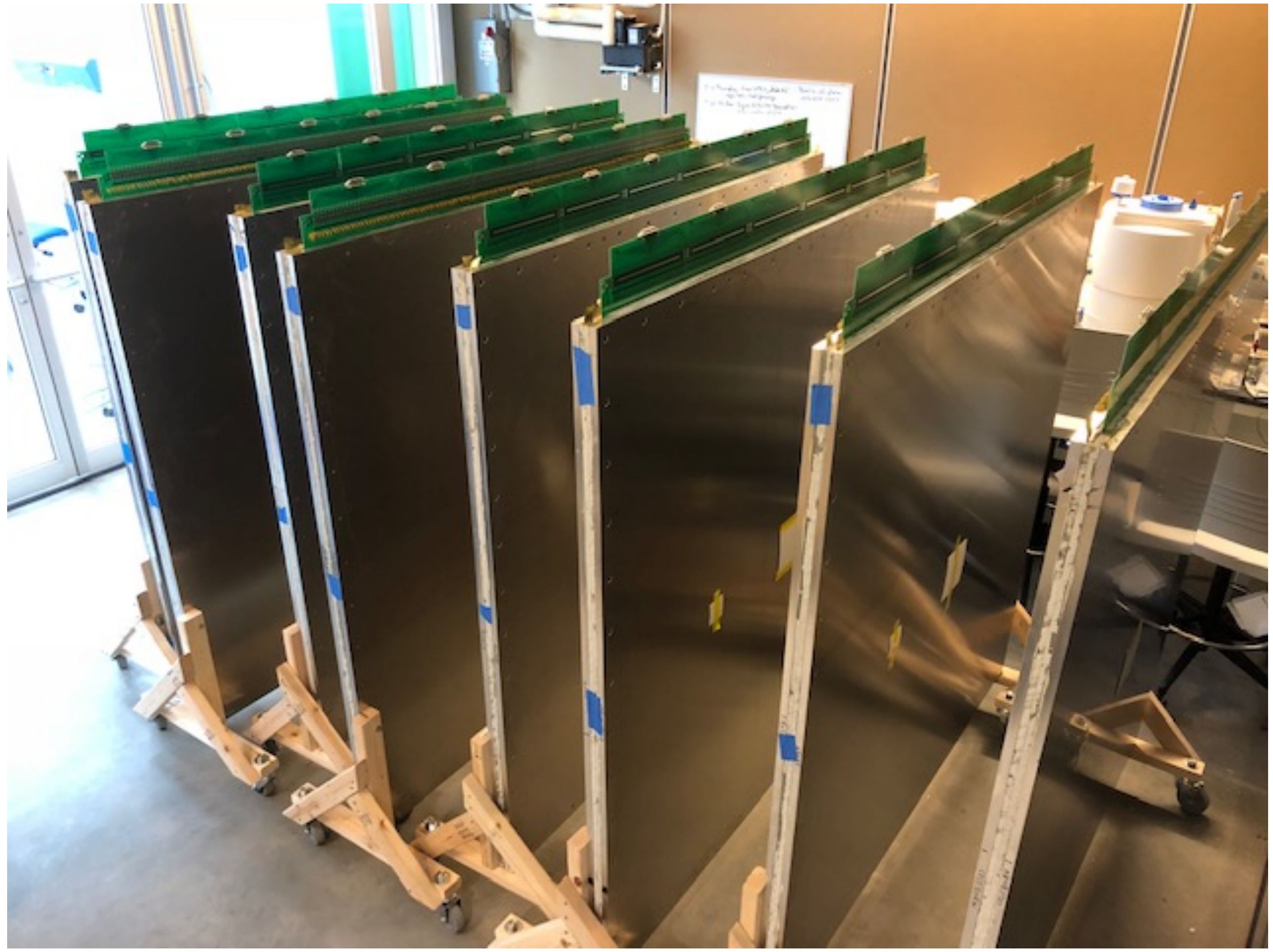
- **GEANT4 studies for the muon chambers and iron absorbers**

✓ Design studies indicate that acceptable π/μ separation can be obtained for 5 cm of lead + 95 cm of steel, and 6 muon chambers.





- **Muon chamber contruction and testing**



Sense wire pitch: 1 cm

Wire to cathode plane distance: 1 cm

Sensitive area: 60 x 60 in^2

Number of channels: 144

Deadened region: 10 x 10 cm^2

Operating voltage: +1800 V

Gas mixture: Ar:CO_2 90:10

Approximate operating gain: 10^5

✓ Early 2018 beam test in Hall D during GlueX running established that chambers can operate in this environment

UMass undergraduates that contributed to CPP muon chamber development and construction:

Albert Fabrizi, accepted to UMass PhD, nuclear exp.

Christian Haughwout, PhD MIT, aerospace science

Bobby Johnston, PhD MIT, nuclear exp.

Jordan Kornfeld, MS USC, aerospace eng.

Senrui Li, MS USC, aerospace eng.

Daniel Lis, PhD Colorado, nuclear exp.

Sean McGrath, travel software development

Nick Miller, PhD Northwestern, C.M. exp.

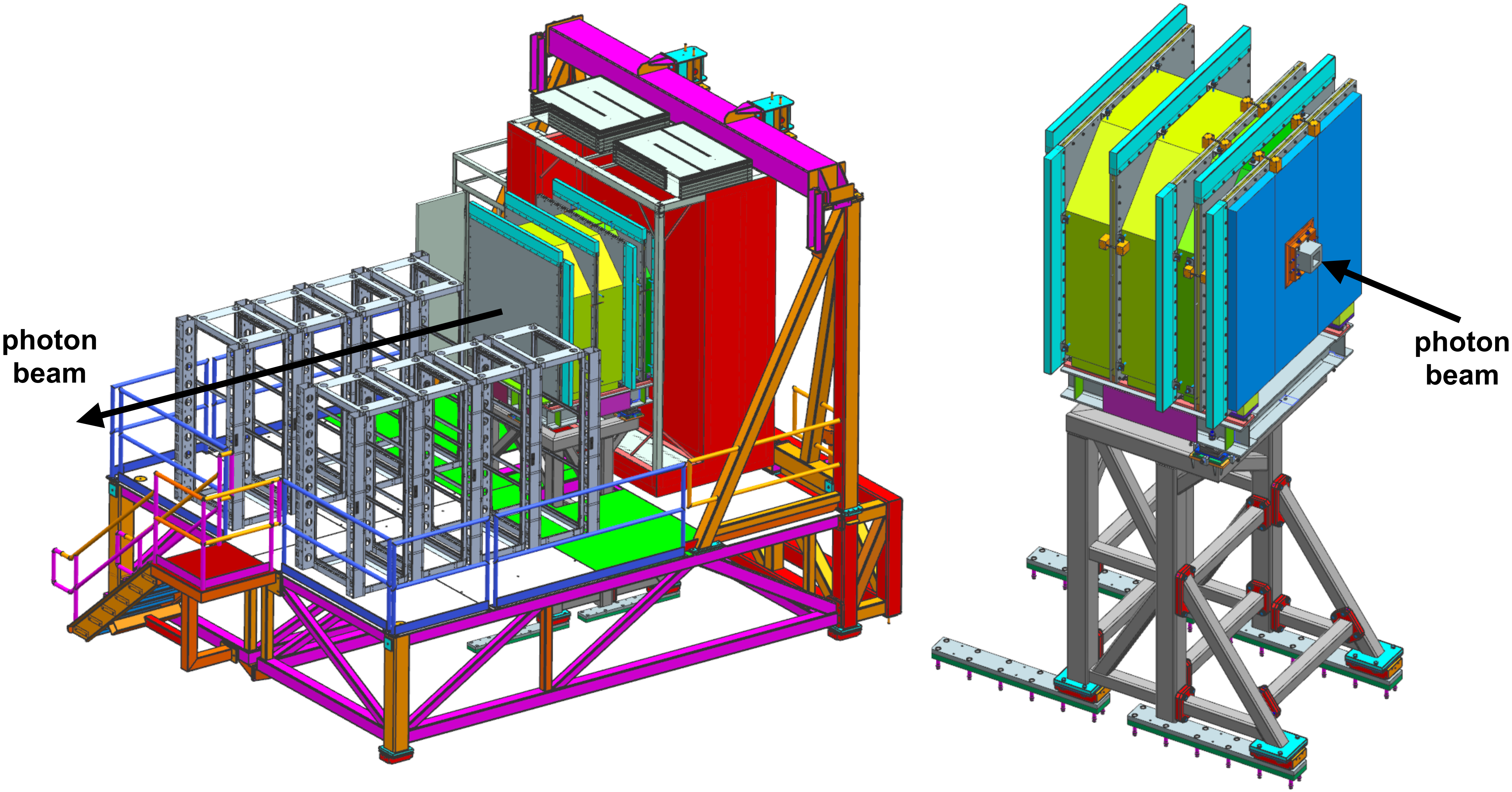
Jack Moody, undergraduate, Army ROTC

Alexander Moschella, defense electronics

Andrew Schick, PhD UMass, nuclear exp.

Jacob Stanley-Grey, undergraduate

- **Engineering design for detector installation in Hall D**



Procurement of parts and materials for installation has started

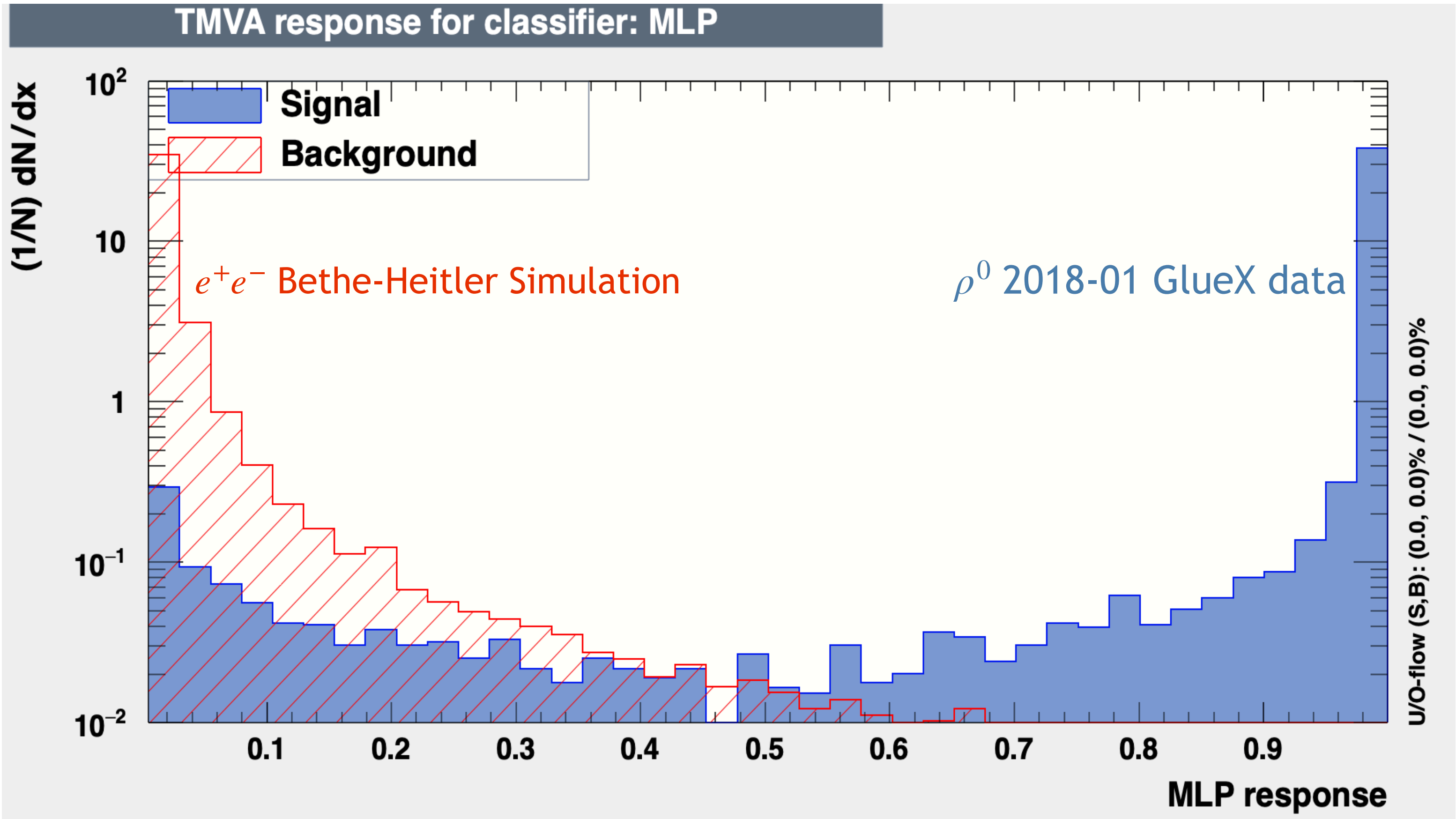
- **Neural-net analysis for $e^{\pm}$, $\mu^{\pm}$, and $\pi^{\pm}$ identification**

$e^{\pm}/\pi^{\pm}$ identification is based on three FCAL measurements:

i. $E_{FCAL}/P_{kinematic-fit}$
ii. FCAL DOCA (distance between the shower and track projection)
iii. FCAL E9/E25 shower ratio ("E9" and "E25" are the summed energies in a 3x3 and 5x5 array of Pb-glass centered on the shower)

✓ $e^{\pm}$ neural-net response trained on Bethe-Heitler $\gamma p \to e^+e^-$ simulation

✓ $\pi^{\pm}$ neural-net response trained on GlueX $\gamma p \to \rho^0 \to \pi^+\pi^-$ data

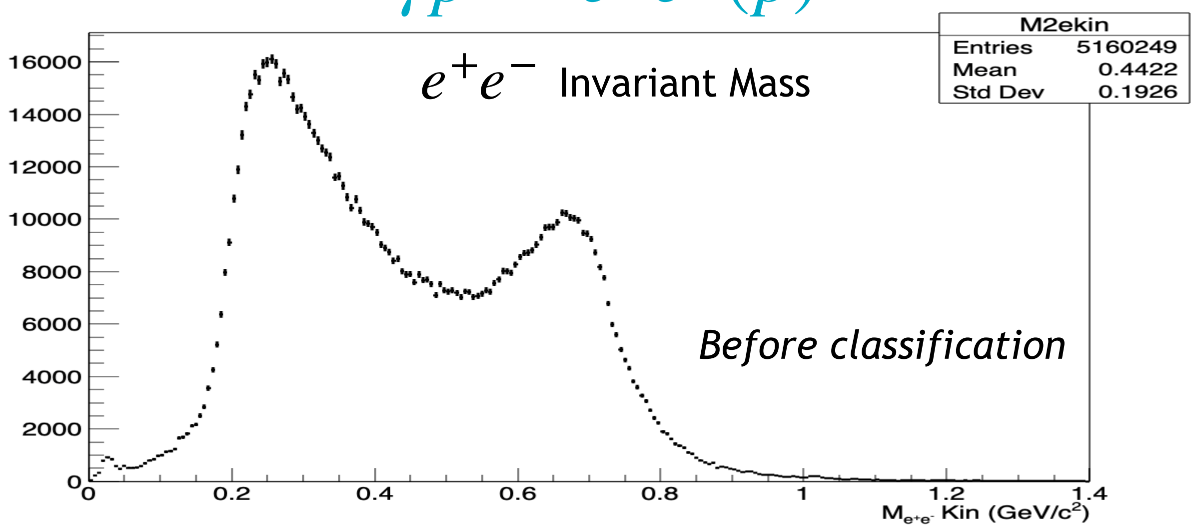


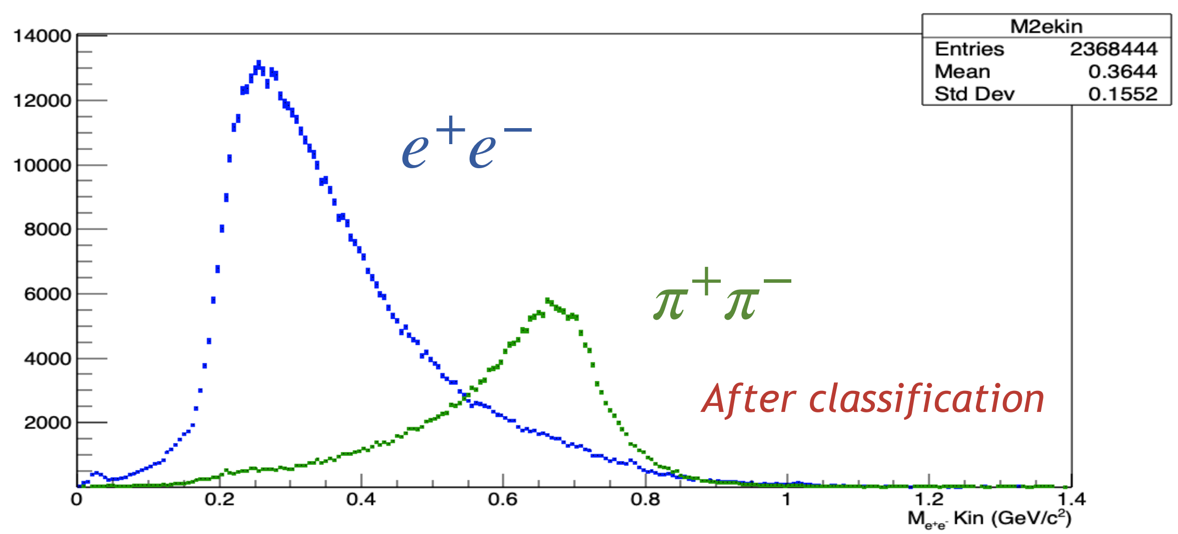
Benchmark studies in $e^{\pm}/\pi^{\pm}$ identification using GlueX data

LEFT: 2018 GlueX data containing BH pairs and ρ^0. Use NN to classify and separate.

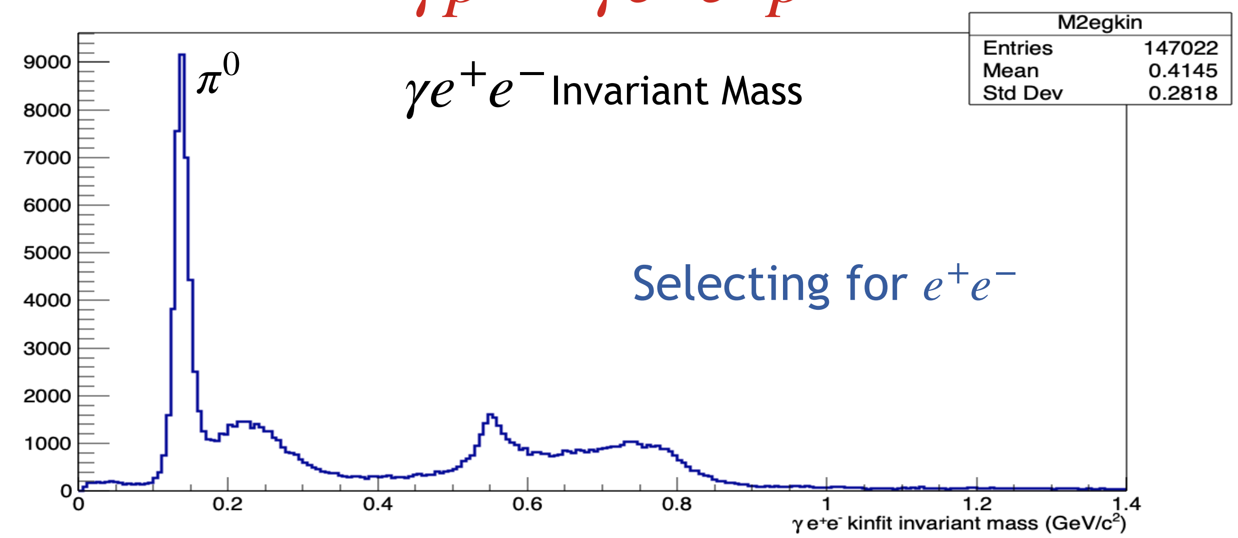
RIGHT: 2018 GlueX data containing π^0 Dalitz decay. Select for pions and see how many e+e- pairs from π^0 get through.

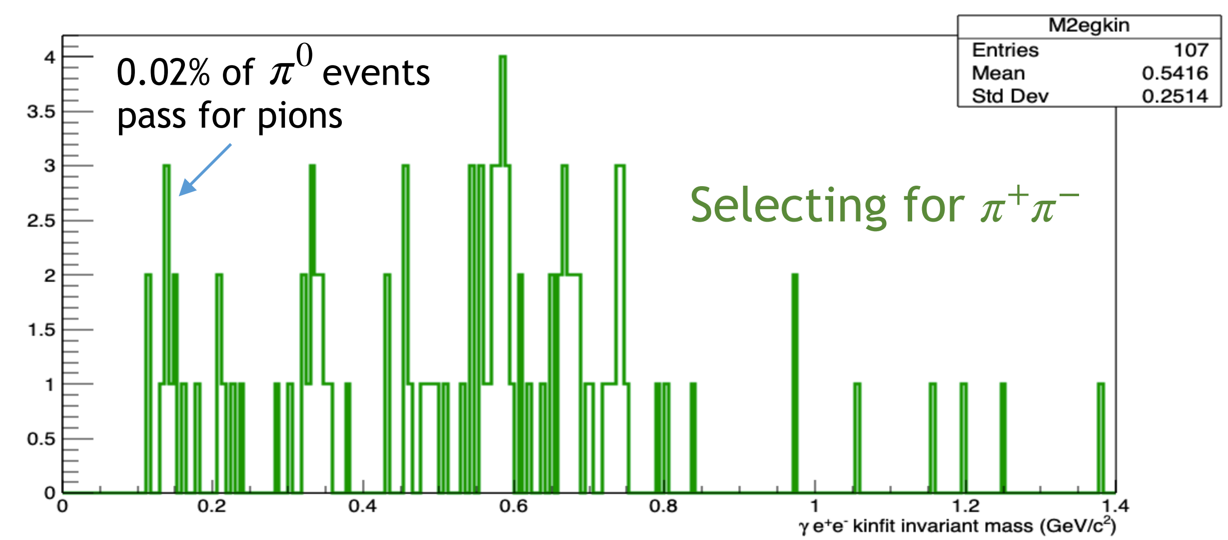
$\gamma p \to e^+e^-(p)$





$\gamma p \to \gamma e^+e^- p$





Same neural net and cut on NN response used in both studies

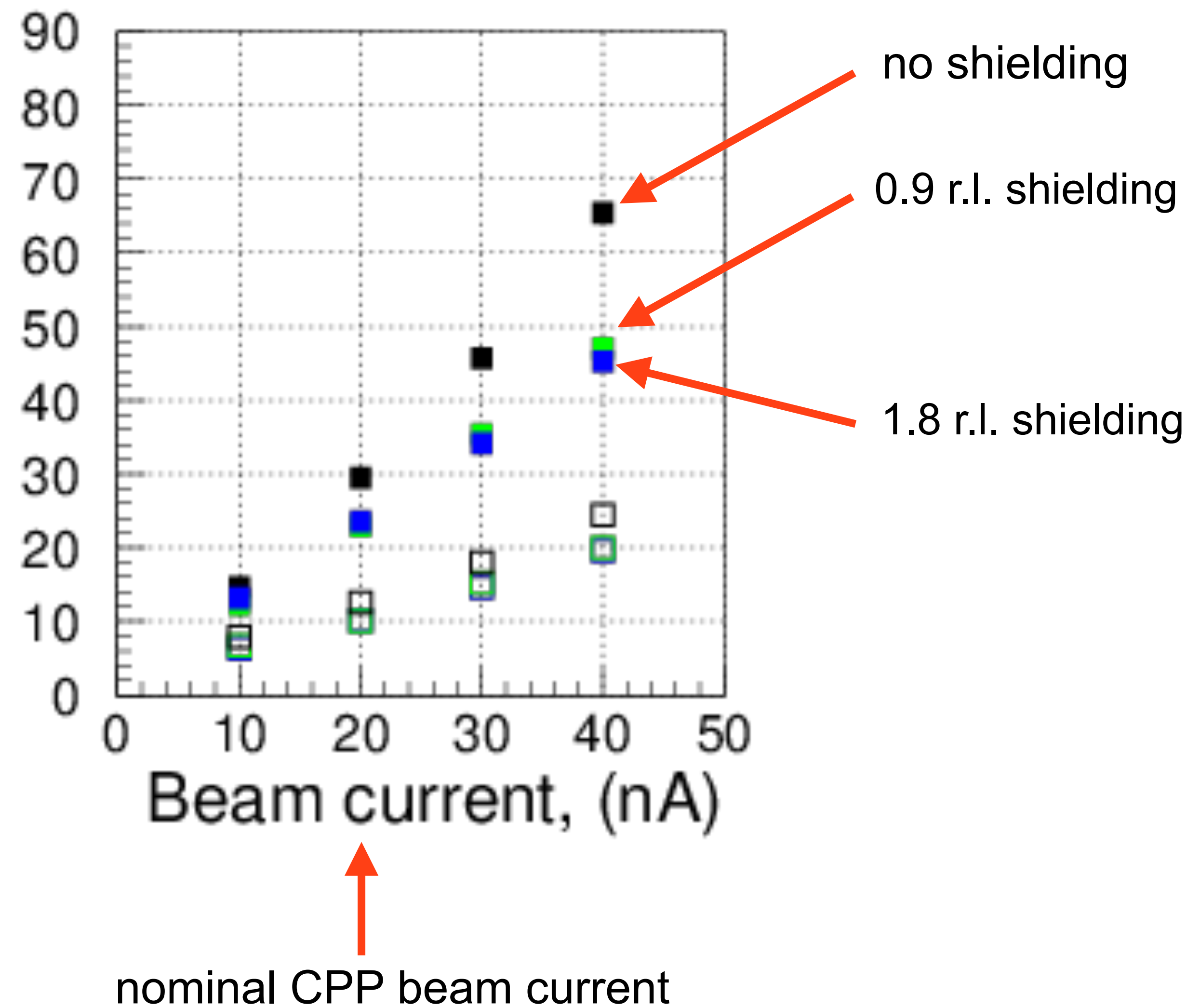
• Time-of-flight trigger studies for CPP

CPP uses non-standard GlueX trigger based on two charged tracks going forward into the time-of-flight system

✓ Preliminary results from CPP trigger test in late August

TOF trigger rate vs beam current

At least 4 TOF hits, at least **two** TOF hit per plane



- **Time-of-flight trigger studies for CPP**

Questions we've answered so far:

✓The 30 kHz TOF trigger rate at the nominal 20 nA CPP current is within the operational range of the GlueX DAQ system.

✓ Lead absorbers from 1 to 2 r.l. thick in front of the central region of the TOF system are not needed, the shielding giving only a modest $\approx 20\,\%$ reduction in trigger rate.

✓ It may be possible to run CPP at a higher beam current than 20 nA.

- **Summary of experimental goals**
  - ✓ Precision measurement of charged pion polarizabity
  - ✓ Test of low-energy QCD
  - ✓ Develop technique complementary to $\pi^- A \to \pi^- \gamma A$ (Compass), and $\gamma p \to \pi^+ \gamma n$ (Mainz), and allowing for measurement of neutral pion polarizability
  - ✓ $\gamma\gamma \to \pi^+\pi^-$ cross sections can constrain and test calculations of HLbL corrections for muon g-2

- **Summary of preparations for CPP running**
  - ✓ Design of muon system is finalized
  - ✓ Muon chambers are nearing completion at UMass
  - ✓ Engineering design for detector installation is far along and procurement has started
  - ✓ Design of neural-net analysis for $e^\pm/\pi^\pm$ identification nearly finalized
  - ✓ Beam tests indicate that a time-of-flight trigger for CPP is workable