The Pion Polarizability Experiments at Jefferson Lab

Presented by

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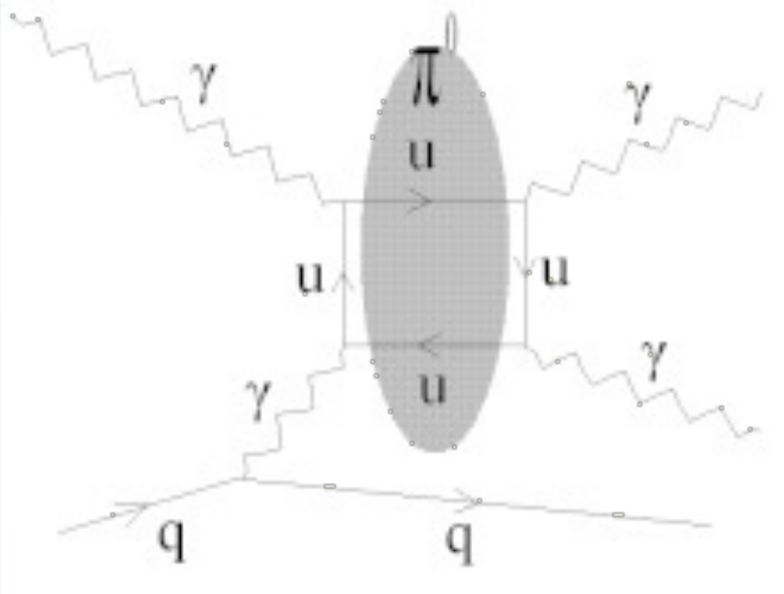
My Research Activity and the Motivation

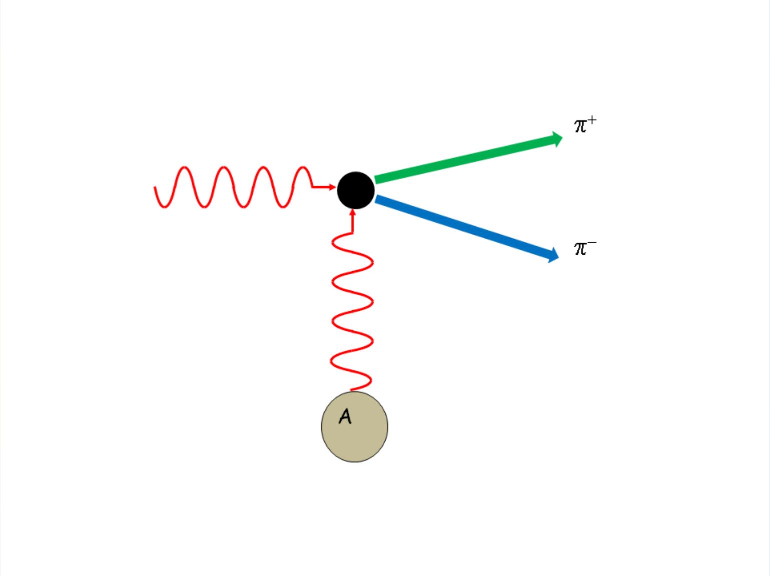
- Pion polarizability (GlueX at Jefferson Lab)
- From November 2016 under the supervision of Dr. David Lawrence.

- Hadron Physics (BESIII at IHEP)
- From October 2021 under the supervision of Pr. Ismail Ruhi Uman

Pion Polarizability

Strong interaction theory makes a precise prediction on the polarisability of pions – the degree to which their oppositely-charged constituents can be separated in an electromagnetic field. This has baffled scientists since the 1980s, when the first measurements were not in agreement with the strong interaction theory.





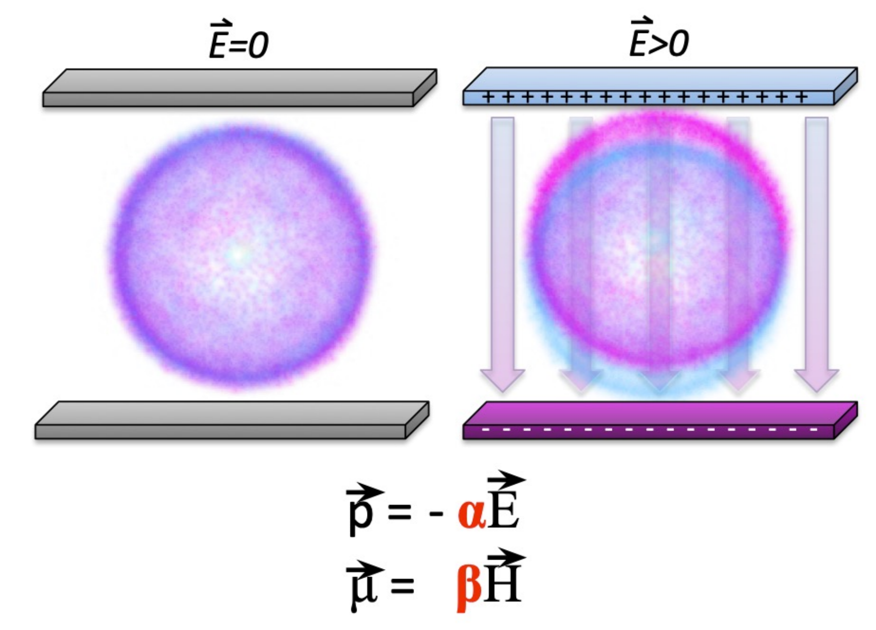
Our group is conducting an experiment at Jefferson Lab's Hall D to measure the electromagnetic polarizability of charged pions using the Primakoff reaction. The experiment involves two photons colliding to create charged pions, which are related to the pion Compton scattering amplitude using quantum mechanics' "crossing symmetry."

Overview

- Pion polarizability measurements
- CPP/NPP experiment setup
- Collected statistics
- Muon detector performance

Hadrons Polarizability

Hadron surrounded by pion cloud



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

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

Polarizability measurements provide an important test of Chiral Perturbaton Theory (ChPT), dispersion relation predictions, and QCD lattice calculations

Charged Pion Polarizability

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

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

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

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

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

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

Neutral Pion Polarizability

Has never been reliably determined

NLO calculation:

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

$$\alpha_{\pi^0} - \beta_{\pi^0} = -\frac{\alpha_{EM}}{48\pi^2 m_\pi F_\pi^2} \approx -1.1\times10^{-4} fm^3$$

NNLO calculation:

$$\alpha_{\pi^0} + \beta_{\pi^0} = 1.15 \pm 0.30\times10^{-4} fm^3$$

$$\alpha_{\pi^0} - \beta_{\pi^0} = -1.90 \pm 0.20\times10^{-4} fm^3$$

Methods to experimentally determine pion polarizability

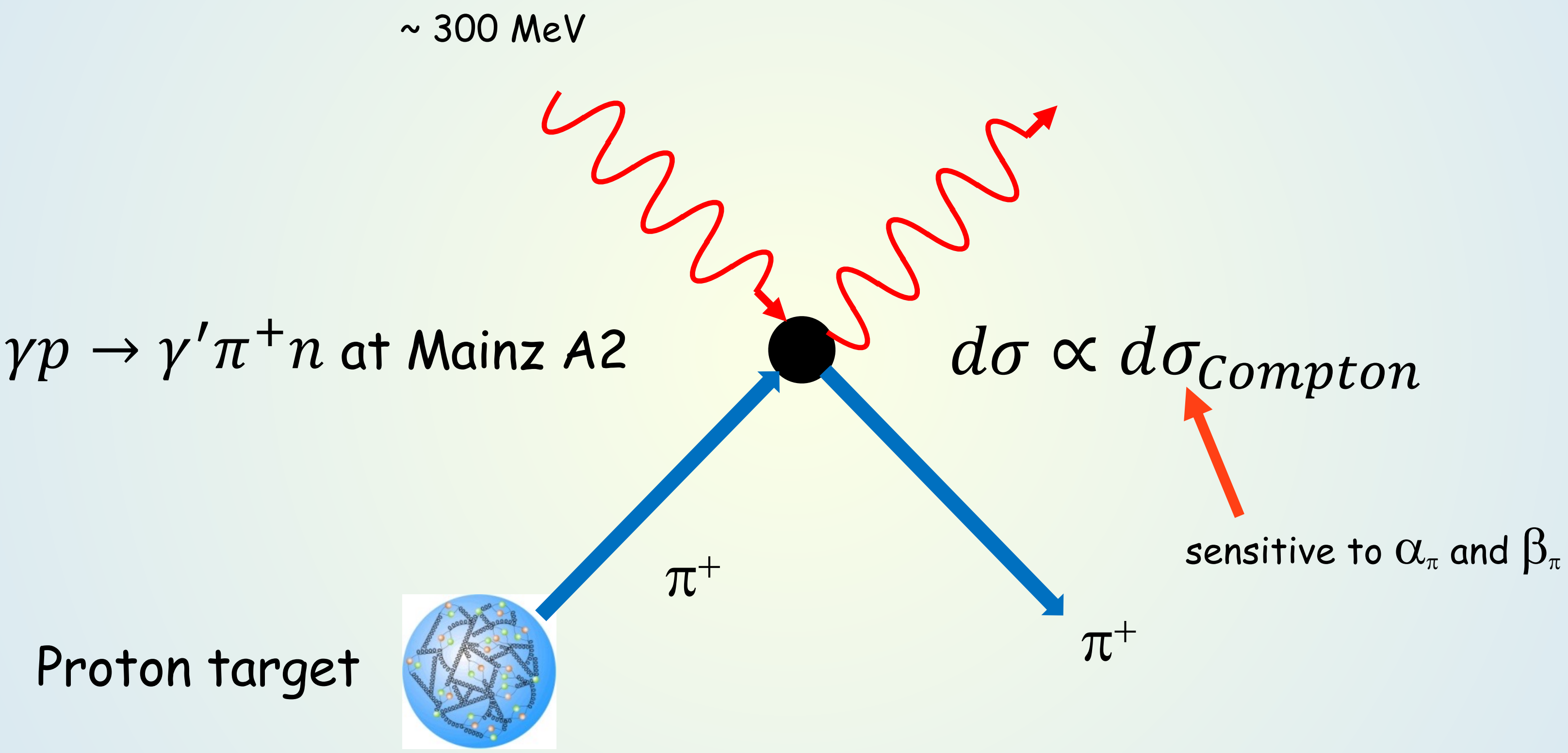
Charged pion:

1) Radiative pion photoproduction
2) Radiative pion scattering
3) Pion pair production in two photon collision

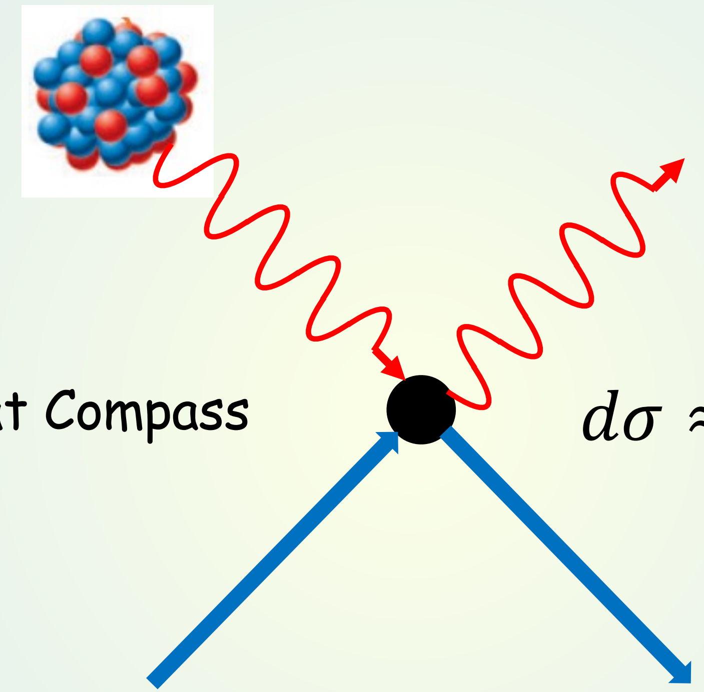
Neutral pion:

1) Pion pair production in two photon collision

Radiative pion photoproduction



Radiative pion scattering

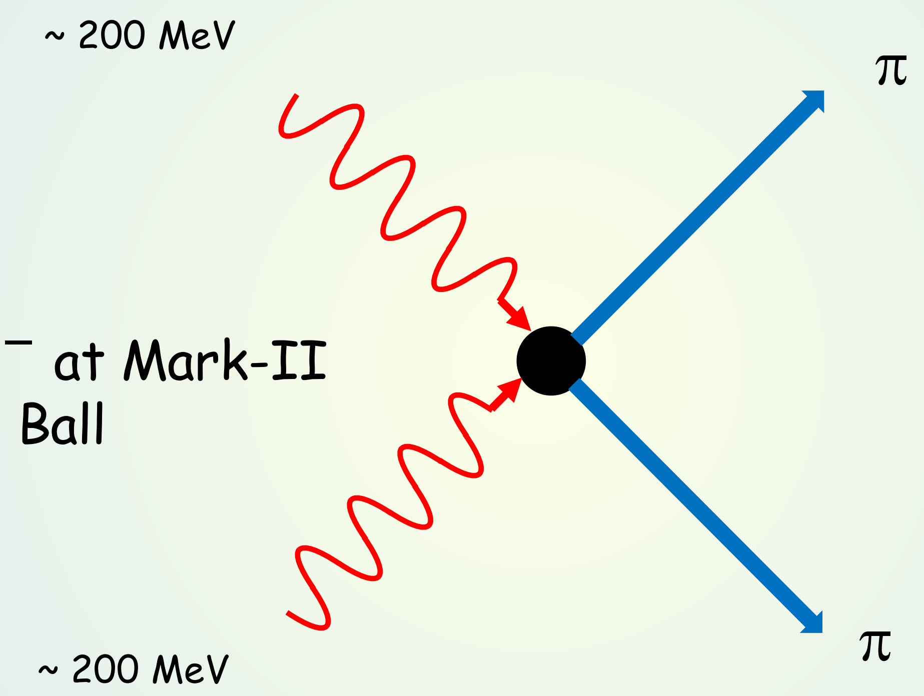


$\pi^- A \rightarrow \gamma \pi^- A$ at Compass

$d\sigma \approx d\sigma_{Compton}$

sensitive to α_π and β_π

Pion pair production in two photon collision

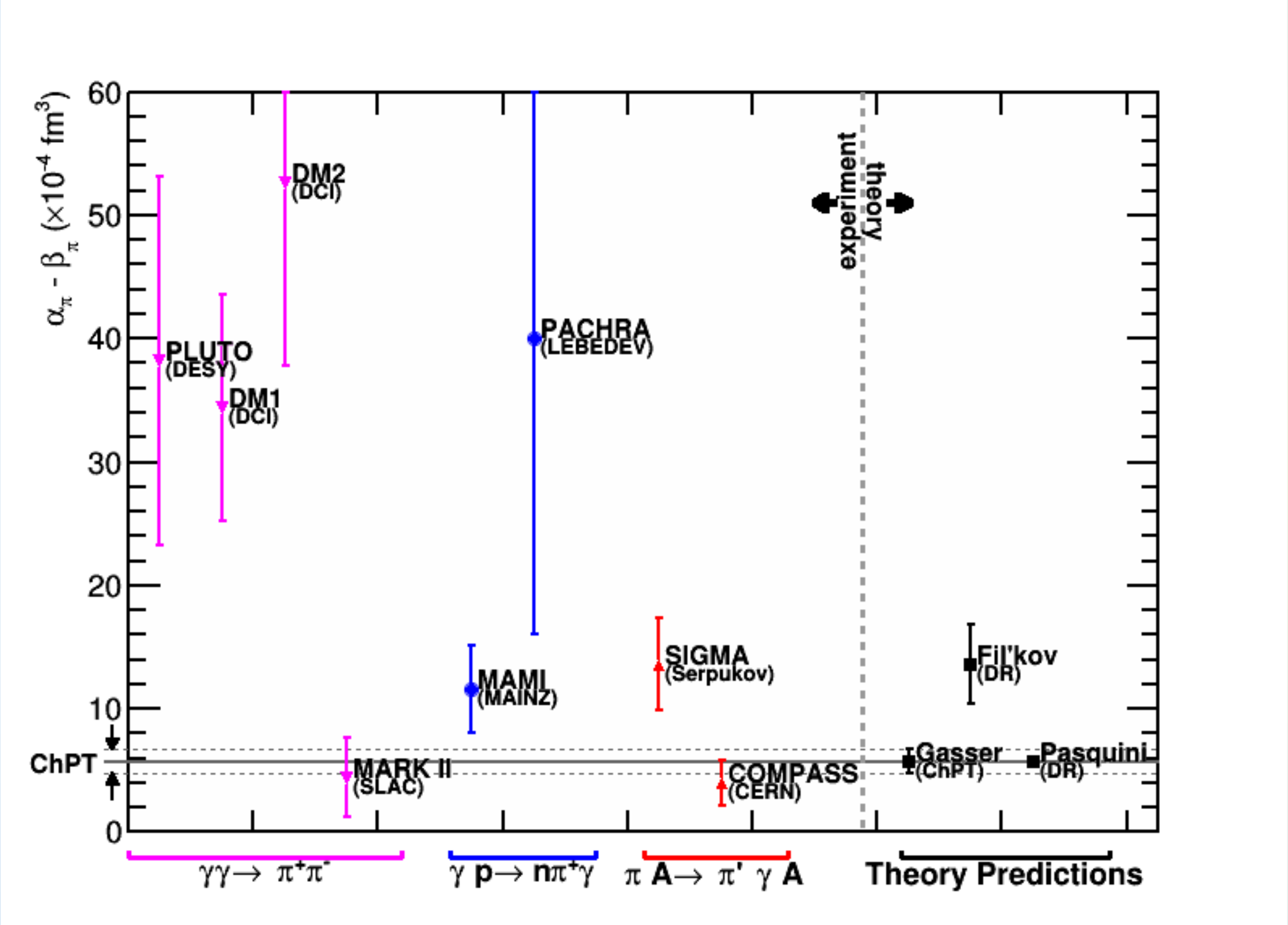


$\gamma\gamma \rightarrow \pi^+\pi^-$ at Mark-II and Crystal Ball

sensitive to α_π-β_π

$$A_{\gamma\gamma\rightarrow\pi\pi} \rightarrow dispersion theory \rightarrow A_{Compton}$$

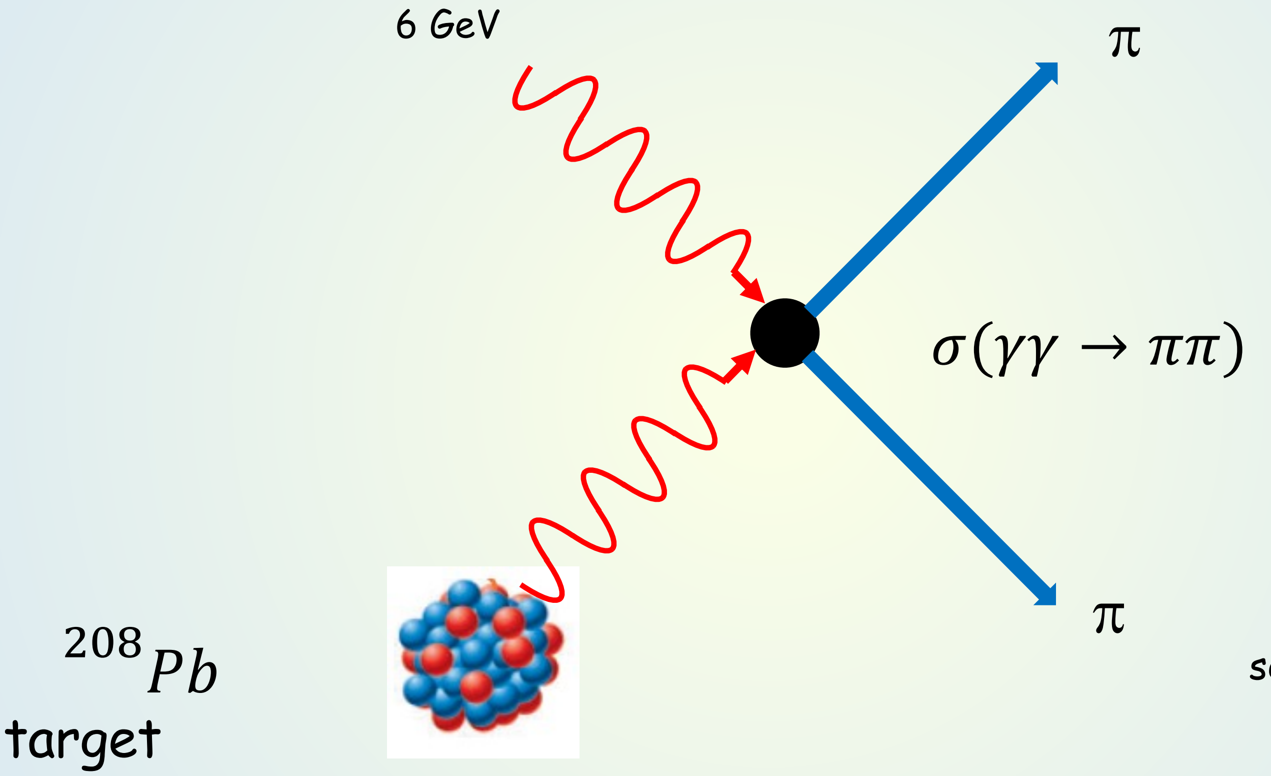
Published measurements of charged pion polarizability



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

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

The charged pion polarizability (CPP) and neutral pion polarizability experiments with the modified GlueX setup

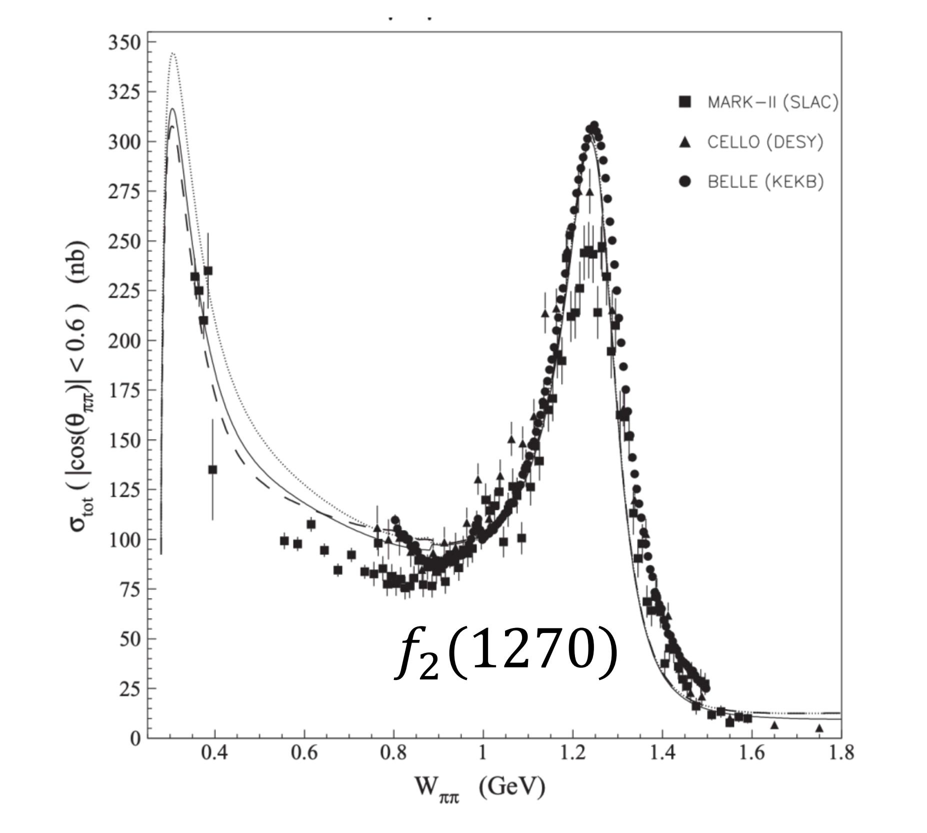


sensitive to α_π-β_π

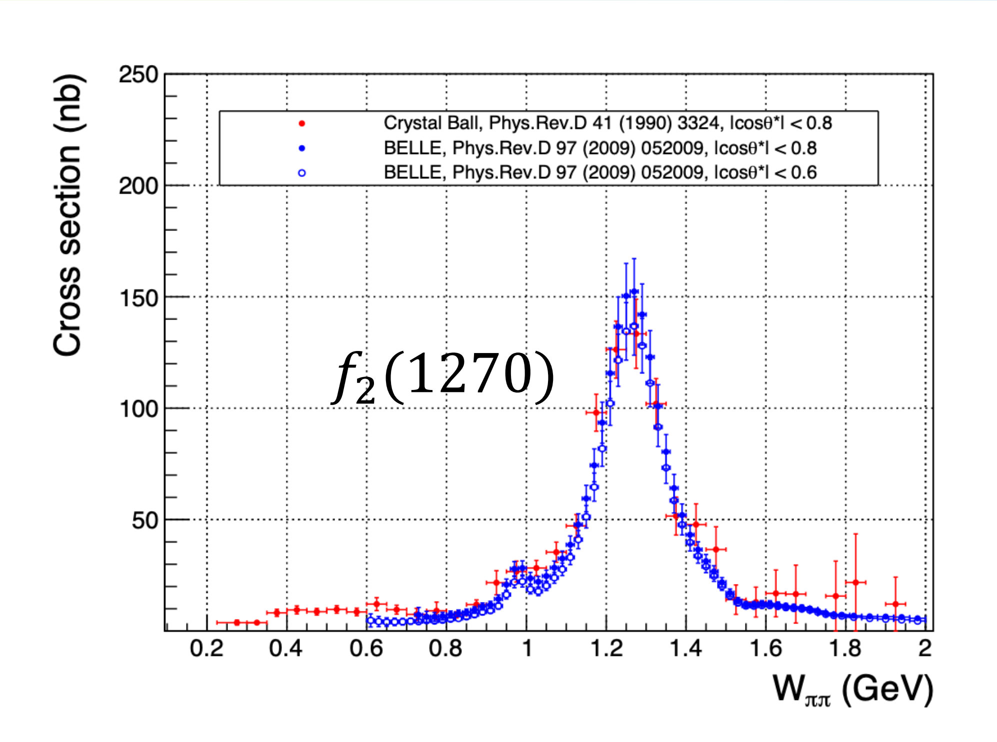
$$\frac{d^2\sigma_{Prim}}{d\Omega dM_{\pi\pi}} = \frac{2\alpha Z^2}{\pi^2}\frac{E_\gamma^2\beta^2}{M_{\pi\pi}}\frac{sin^2\theta}{Q^4}|F(Q^2)|^2\left(1 + P_\gamma cos2\phi_{\pi\pi}\right)\sigma(\gamma\gamma \to \pi\pi)$$

Existing data for pion pair production in two photon collision

charged pion pair

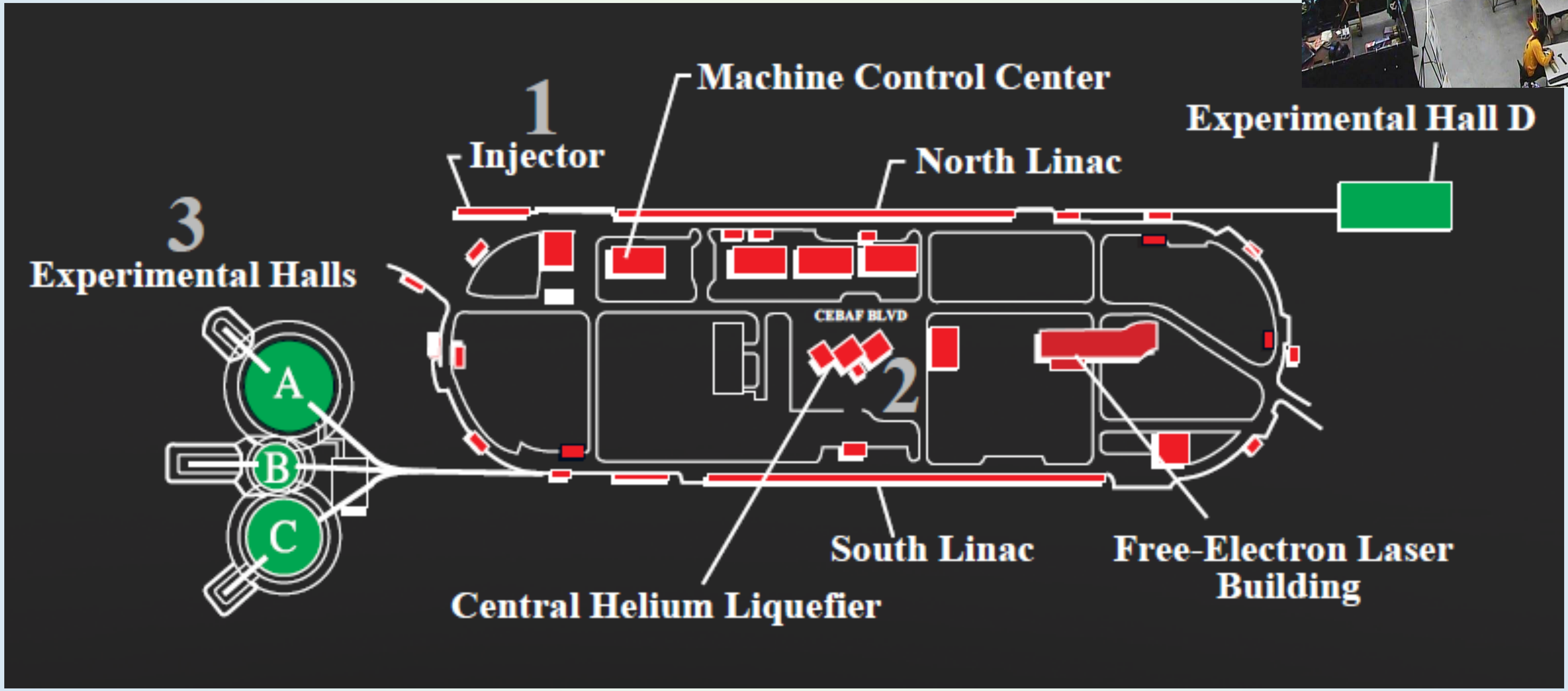


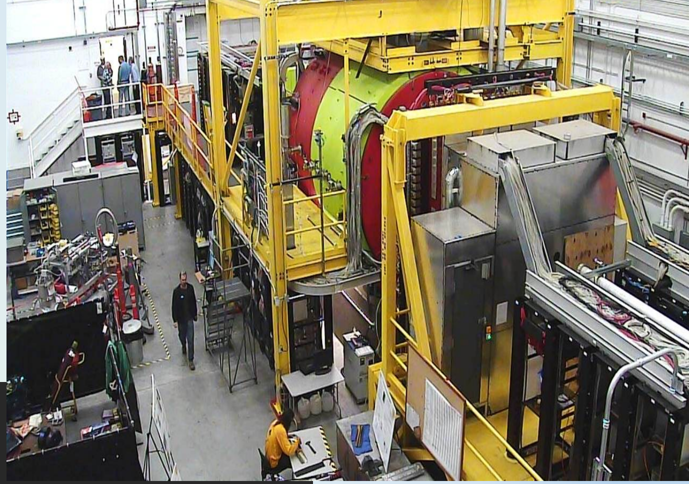
neutral pion pair

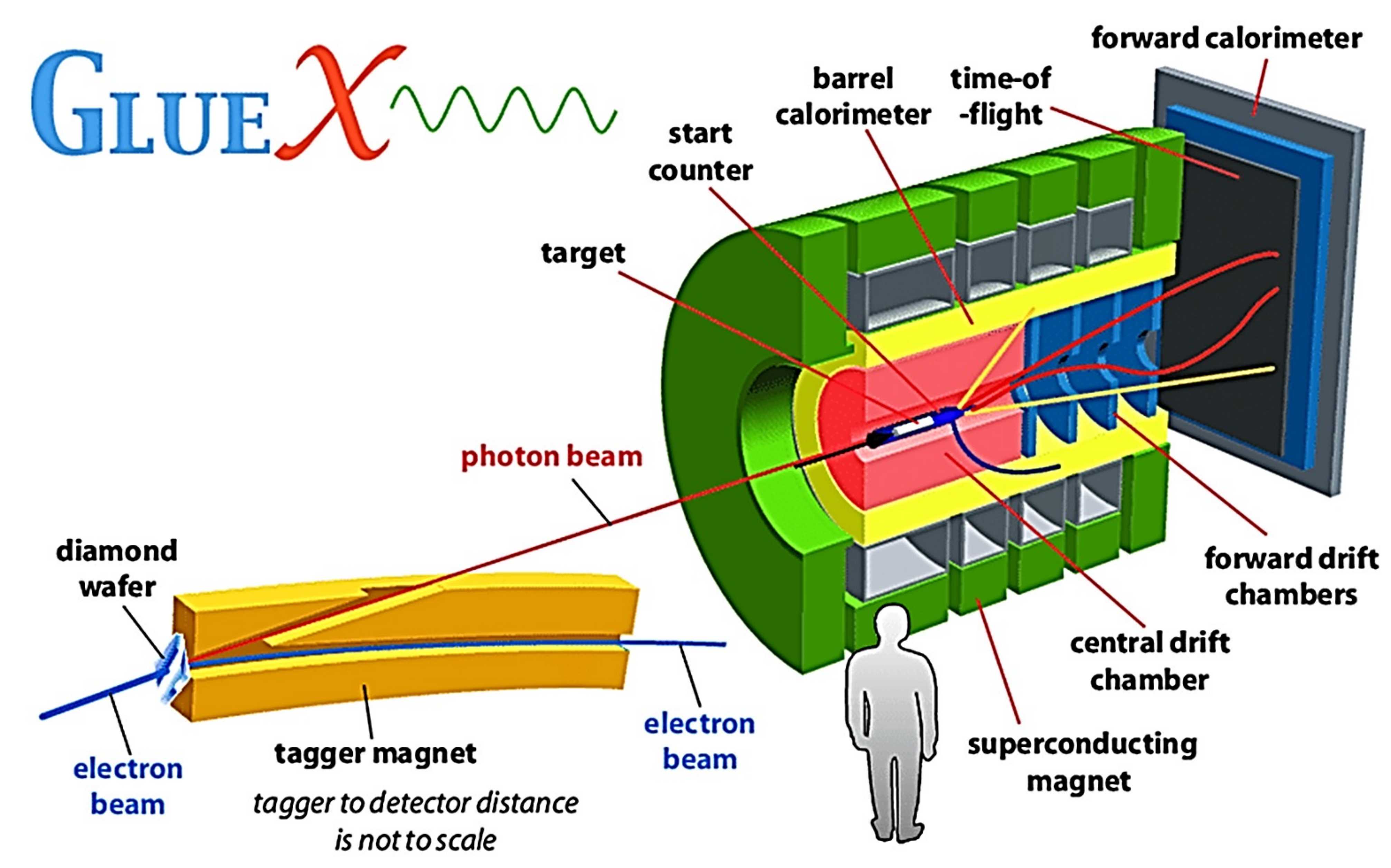


Accelerator Site

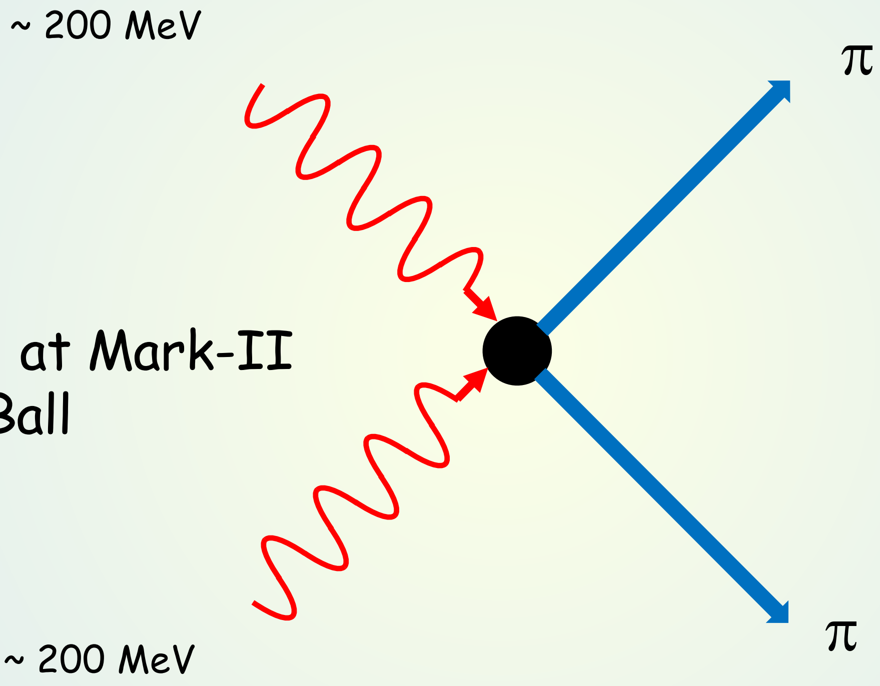
12 GeV






GLUEX
forward calorimeter
barrel calorimeter
time-of -flight
start counter
target
photon beam
diamond wafer
forward drift chambers
central drift chamber
superconducting magnet
electron beam
tagger magnet
electron beam
tagger to detector distance is not to scale

Pion pair production in two photon collision



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

sensitive to α_π-β_π

$$A_{\gamma\gamma\rightarrow\pi\pi} \rightarrow dispersiontheory \rightarrow A_{Compton}$$

Conguration of the charged pion polarizability experiment compared to nominal GlueX. Detectors not identied in the table are assumed to be operated under the same conditions as in the nominal conguration.

Configuration	Nominal GlueX	This Experiment
Electron beam energy	12 GeV	12GeV
Electron current	220 nA	50 nA on 20 μm diamond
Coherent peak	8.4 – 9.0 GeV	5.5 – 6.0 GeV
Collimator aperture	3.5 mm	3.5 mm
Peak polarization	44%	76%
Coherent/Incoherent ratio	0.068	0.32
Tagging ratio	0.56	0.69
Target position	65 cm	1 cm
Target, length	H, 30 cm	^{116}Sn, 0.060 cm
Start counter	nominal	removed
Muon identification	None	Behind FCAL

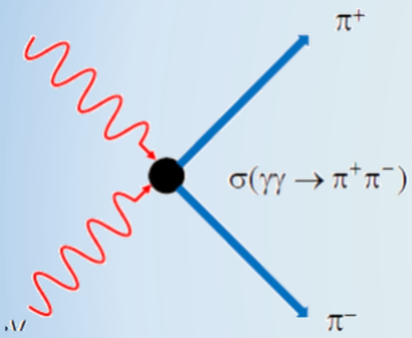
GlueX Detector

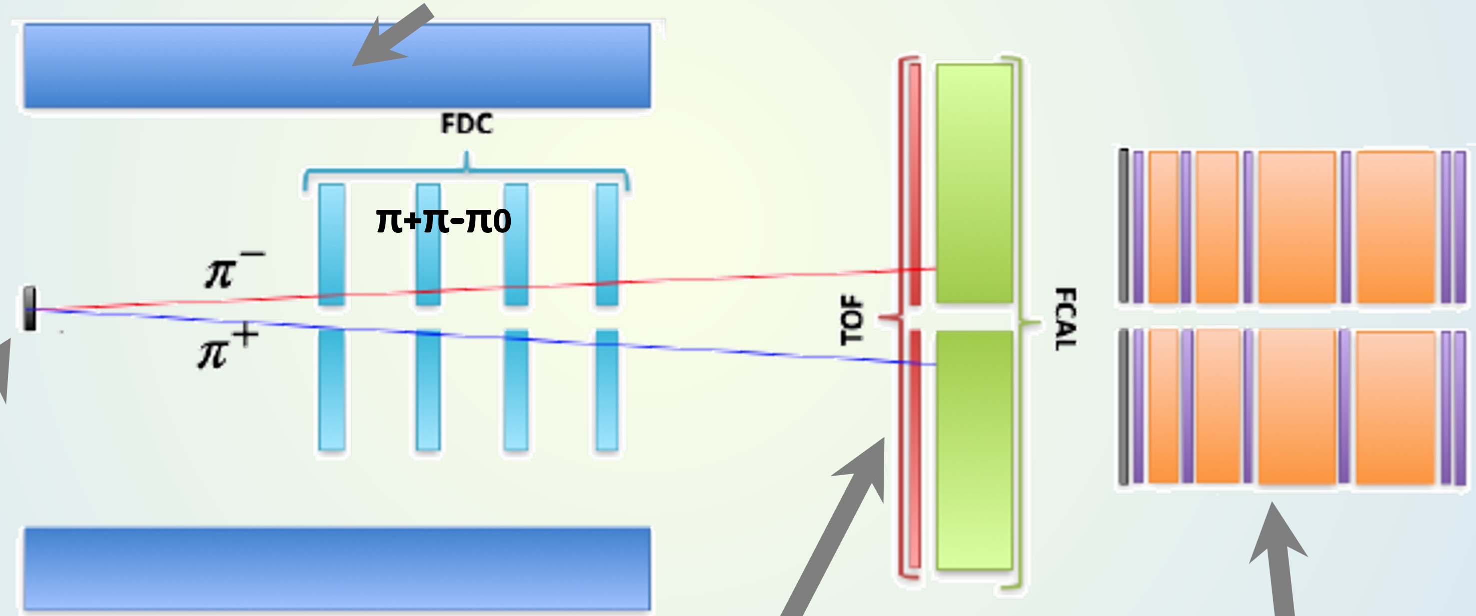
CPP/NPP experiment with the GlueX setup

The goal: Pion polarizability measurement via precision Primakoff pion pair production differential cross section measurement

¼ of CDC's fADCs have been sacrificed for the muon detector

Additional scintillators for MWPC efficiency control (CTOF detector and trigger)$\pi^+\pi^-\pi^0$





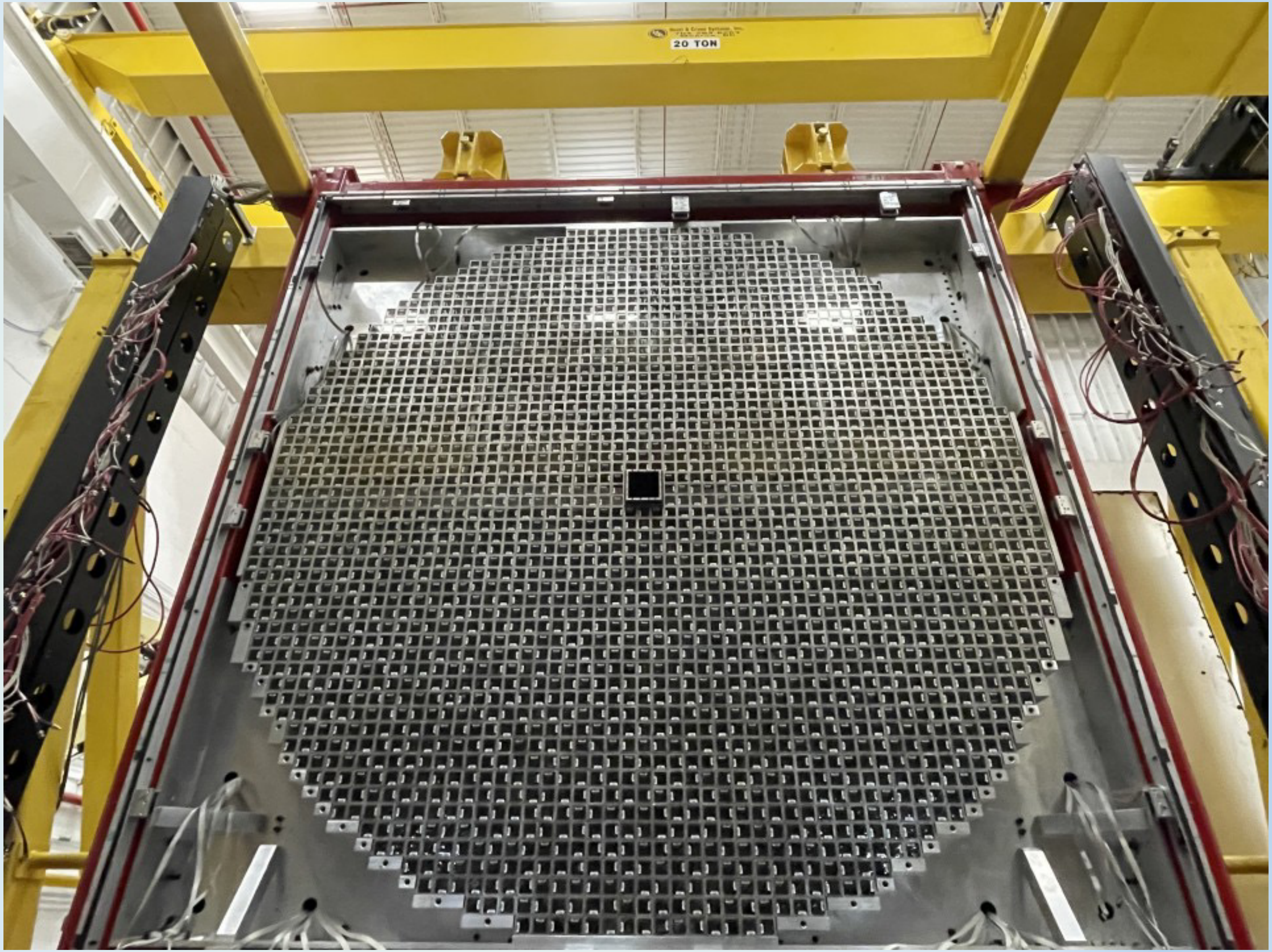
New 5% rad. len. lead-208 target.
64 cm upstream from the GlueX target to get better acceptance at low pion pair masses
Start counter removed

New TOF trigger was commissioned and added to the data stream

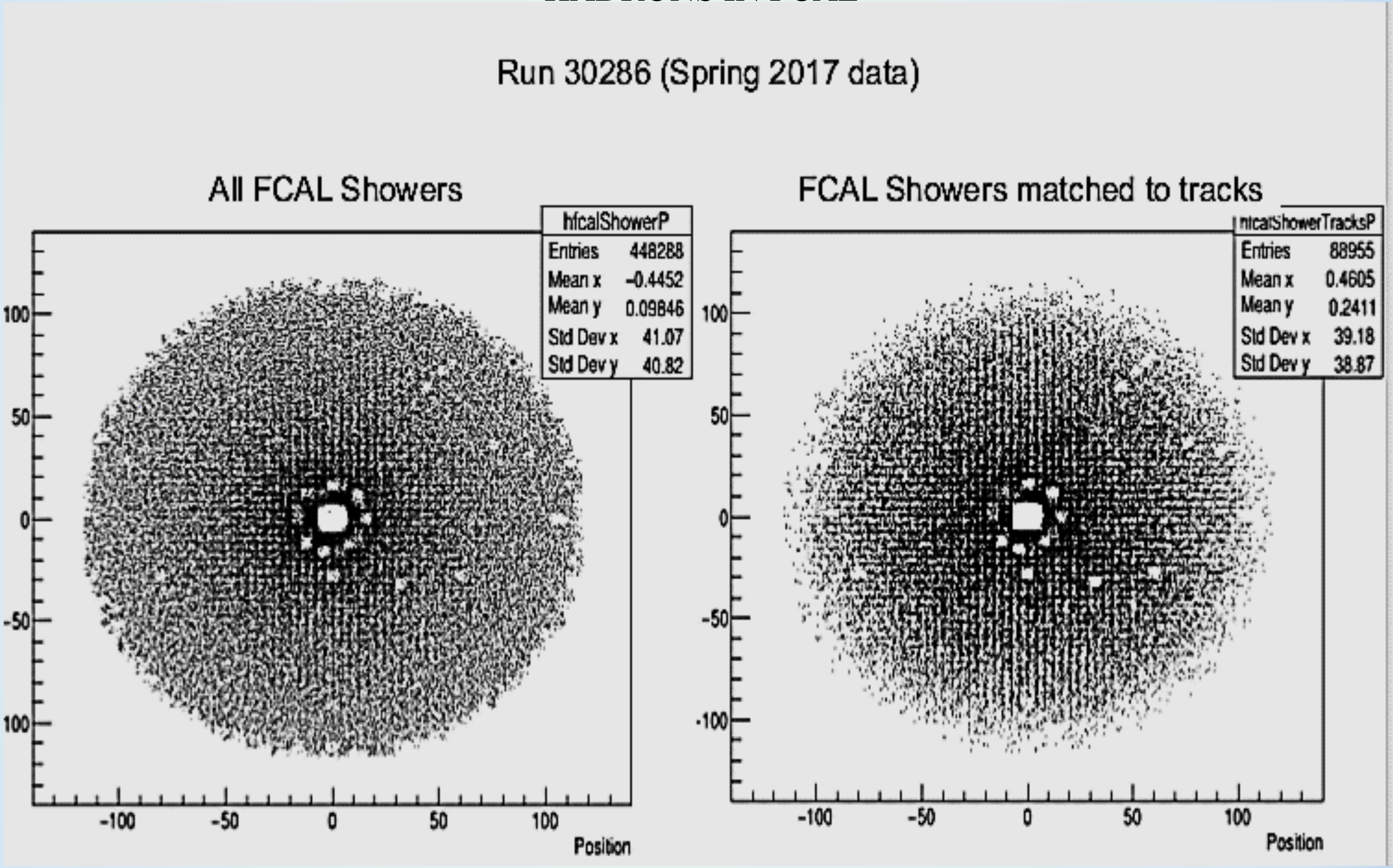
Muon detector (6 MWPC planes spaced with iron walls) has been commissioned and installed for π/μ separation.
Required support, gas system, and fADCs

Forward calorimater

2048 crystal blocks
each 4cm x 4cm base and
45 cm length



EXPERIMENTATION AND ANALYSE: RESPONSE OF HADRONS IN FCAL



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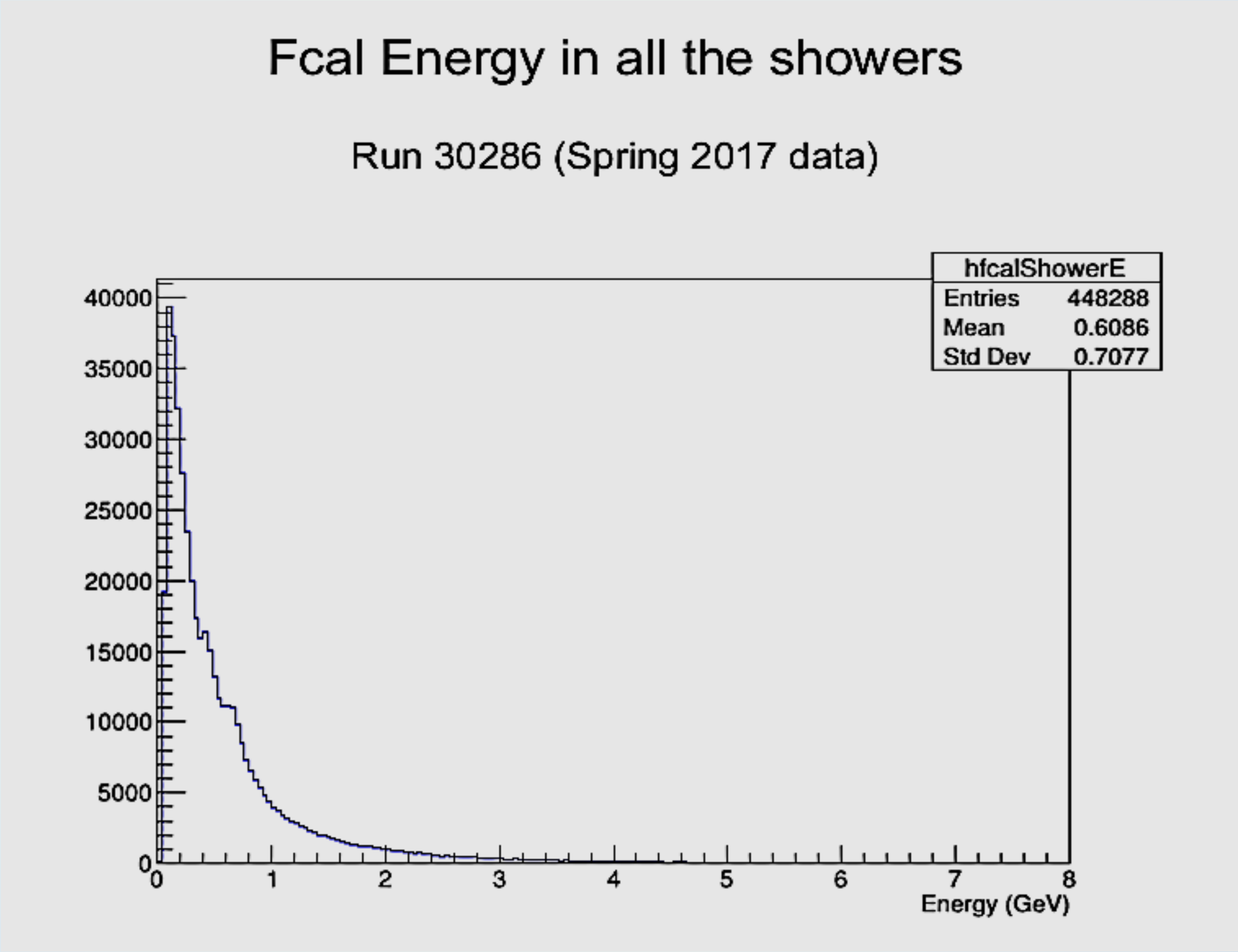
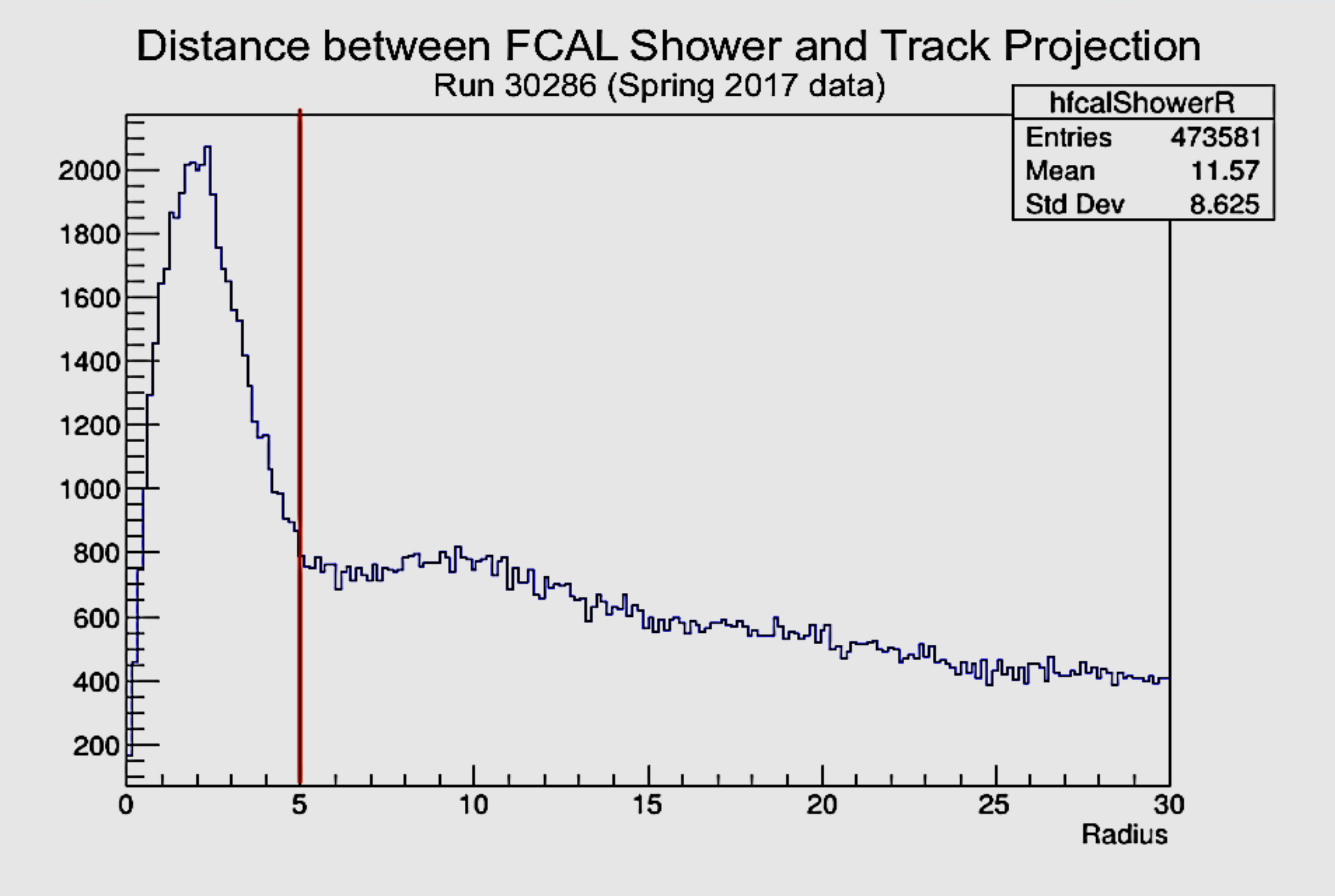
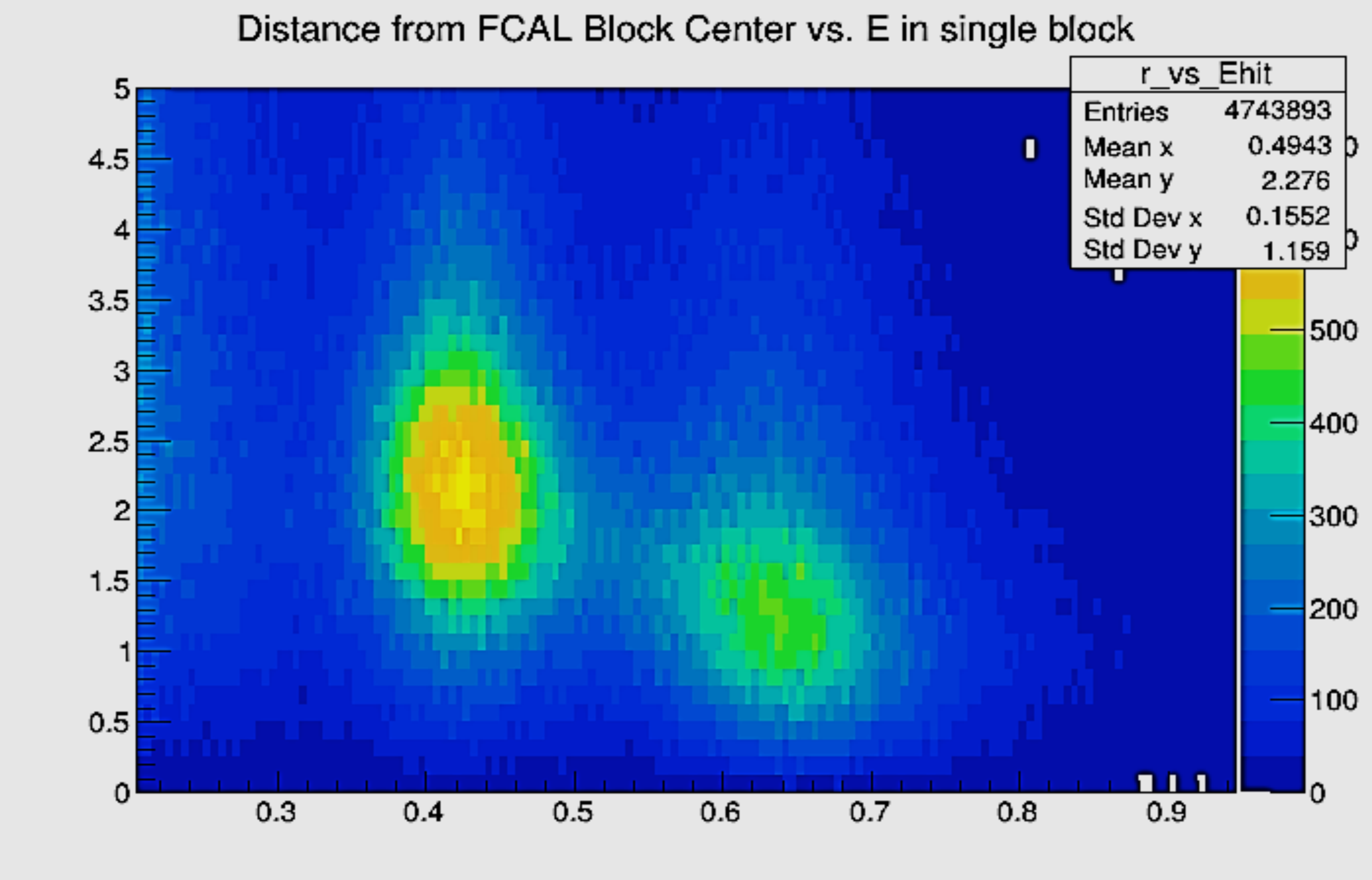


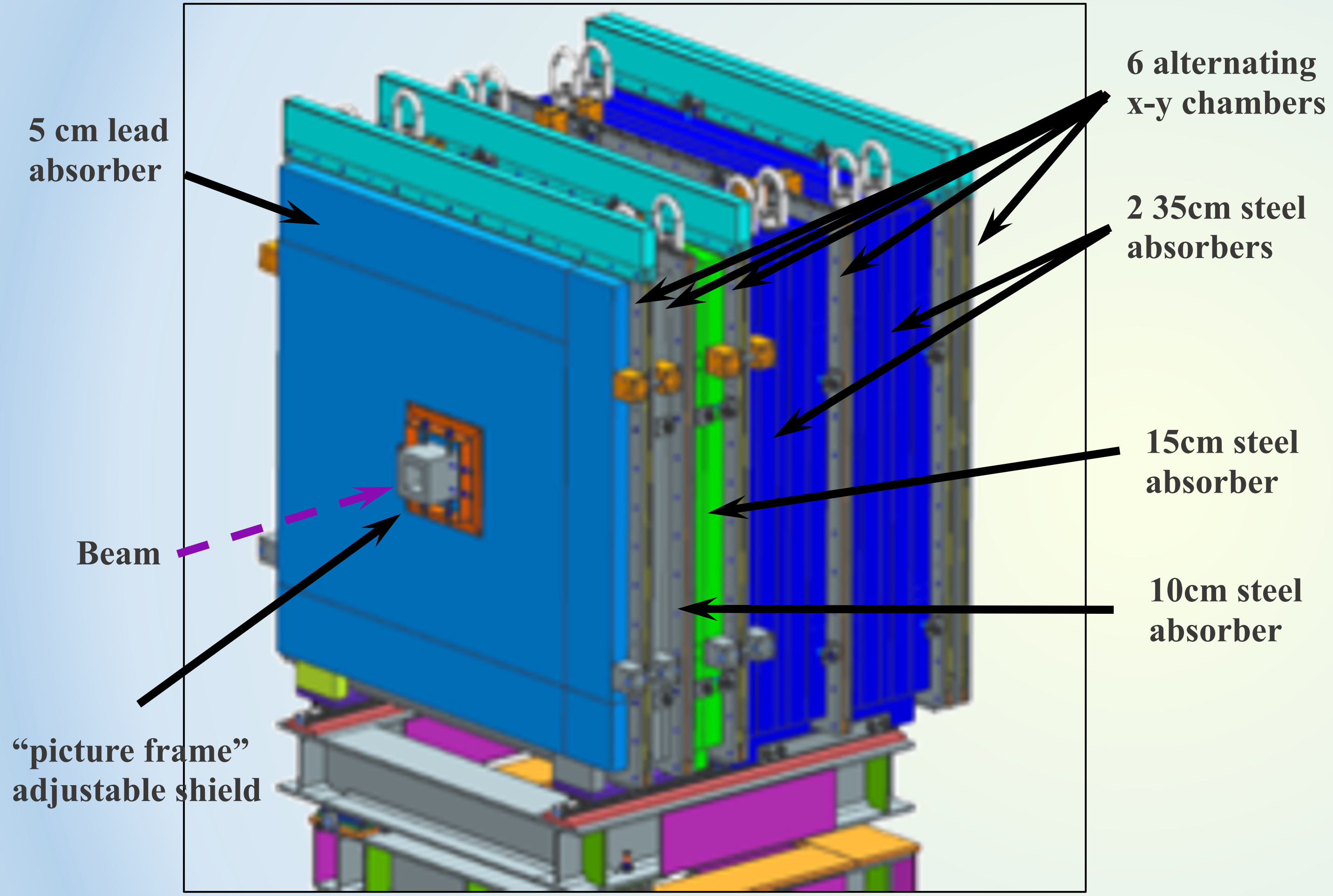
EXPERIMENTATION AND ANALYSE: RESPONSE OF HADRONS IN FCAL



EXPERIMENTATION AND ANALYSE: RESPONSE OF HADRONS IN FCAL



Muon detector



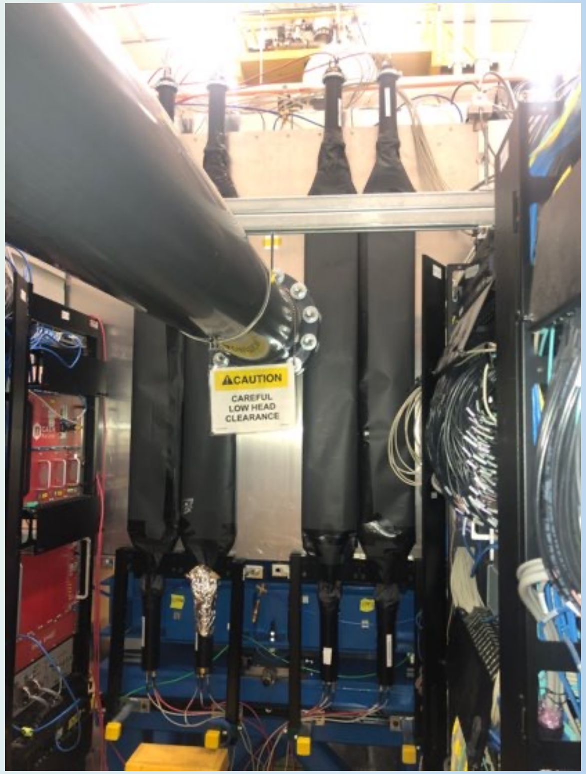
- Designed and assembled at UMASS, tested at JLAB and in beam
- Shielding thickness distribution has been optimized with AI
- First wall material has been changed to lead as we were tight in space for the deep e-m background tails after FCAL suppression
- 8 MWPC planes have been constructed, 6 of them were used during the run
- Each MWPC has 144 channels (i.e. sense wires, connected to fADC-125)
- Grounding has been improved in the Hall, suppressing high frequency noise
- 90% Ar + 10% CO_2 mixture has been chosen after beam tests for better timing
- Operated at ~1780V

Muon detector

8 chambers have been built at UMASS for CPP

chambers installed in between of iron walls in the Hall

Additional scintillators were installed behind the muon detector for cross-checks



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Review

Precision studies of QCD in the low energy domain of the EIC

V.D. Burkert [1,*], L. Elouadrhiri [1], A. Afanasev [2], J. Arrington [3], M. Contalbrigo [4], W. Cosyn [5,6], A. Deshpande [7], D.I. Glazier [8], X. Ji [9,10], S. Liuti [11], Y. Oh [12,13], D. Richards [1], T. Satogata [1], A. Vossen [14,1], H. Abdolmaleki [15], A. Albataineh [16], C.A. Aidala [17], C. Alexandrou [18,19], H. Avagyan [1], A. Bacchetta [20], M. Baker [1], F. Benmokhtar [21], J.C. Bernauer [7,22], C. Bissolotti [20], W. Briscoe [2], D. Byers [14], Xu Cao [23], C.E. Carlson [24], K. Cichy [25], I.C. Cloet [26], C. Cocuzza [27], P.L. Cole [28], M. Constantinou [27], A. Courtoy [29], H. Dahiyah [30], K. Dehmelt [7], S. Diehl [31,32], C. Dilks [14], C. Djalali [33], R. Dupré [34], S.C. Dusa [1], B. El-Bennich [35], L. El Fassi [36], T. Frederico [37], A. Freese [38], B.R. Gamage [1], L. Gamberg [39], R.R. Ghoshal [1], F.X. Girod [1], V.P. Goncalves [40,23,41], Y. Gotra [1], F.K. Guo [42,43], X. Guo [9], M. Hattawy [44], Y. Hatta [45], T. Hayward [31], O. Hen [46], G.M. Huber [47], C. Hyde [44], E.L. Isupov [48], B. Jacak [3], W. Jacobs [49], A. Jentsch [45], C.R. Ji [50], S. Joosten [26], N. Kalantarians [51], Z. Kang [52,53,54], A. Kim [31,1], S. Klein [3], B. Kriesten [10], S. Kumano [55], A. Kumar [56], K. Kumericki [57], M. Kuchera [58], W.K. Lai [59,60,52], Jin Li [61], Shujie Li [3], W. Li [62], X. Li [63], H.-W. Lin [64], K.F. Liu [65], Xiaohui Liu [66,67], P. Markowitz [5], V. Mathieu [68,69], M. McEneaney [14], A. Mekki [70], J.P.B.C. de Melo [71], Z.E. Meziani [26], R. Milner [46], H. Mkrtchyan [72], V. Mochalov [73,74], V. Mokeev [1], V. Morozov [75], H. Moutarde [76], M. Murray [77], S. Mtingwa [78], P. Nadel-Turonski [54], V.A. Okorokov [74], E. Onyie [1], L.L. Pappalardo [4,79], Z. Papandreou [80], C. Pecar [14], A. Pilloni [81,82], B. Pire [83], N. Polys [84], A. Prokudin [39,1], M. Przybycien [85], J.-W. Qiu [1], M. Radici [86], R. Reed [87], F. Ringer [1,44], B.J. Roy [88], N. Sato [1], A. Schäfer [89], B. Schmookler [90], G. Schnell [91], P. Schweitzer [31], R. Seidl [92,22], K.M. Semenov-Tian-Shansky [12,93,94], F. Serna [95,96], F. Shaban [97], M.H. Shabestari [98], K. Shiells [10], A. Signori [99,100], H. Spiesberger [101], I. Strakovsky [2], R.S. Sufian [24,1], A. Szczepaniak [102,1], L. Teodorescu [103], J. Terry [52,53], O. Teryaev [104], F. Tessarotto [105], C. Timmer [1], Abdel Nasser Tawfik [106], L. Valenzuela Cazares [107], A. Vladimirov [89,108], E. Voutier [34], D. Watts [109], D. Wilson [110], D. Winney [59,111], B. Xiao [112], Z. Ye [113], Zh. Ye [114], F. Yuan [3], N. Zachariou [109], I. Zahed [7], J.L. Zhang [61], Y. Zhang [1], J. Zhou [115]

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Summary

- Pion polarizability plays a special role in the Chiral symmetry test in QCD
- CPP / NPP experiments successfully collected statistics during summer 2022 run in Hall-D at Jefferson Lab, extracted Primakoff pion pairs, which will allow to measure the photoproduction cross section and of the pion polarizability.
- Detector calibration phase is currently in the final stage
- Beam conditions and detector performance look excellent
- Our next steps are the exclusive pion pair photoproduction yields extraction, Primakoff cross sections calculation, and systematics assessment.

Thank you !