Light mesons from GlueX

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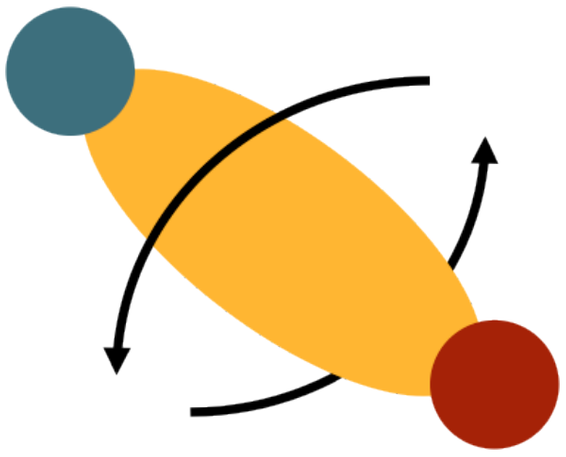
IWHSS 2016

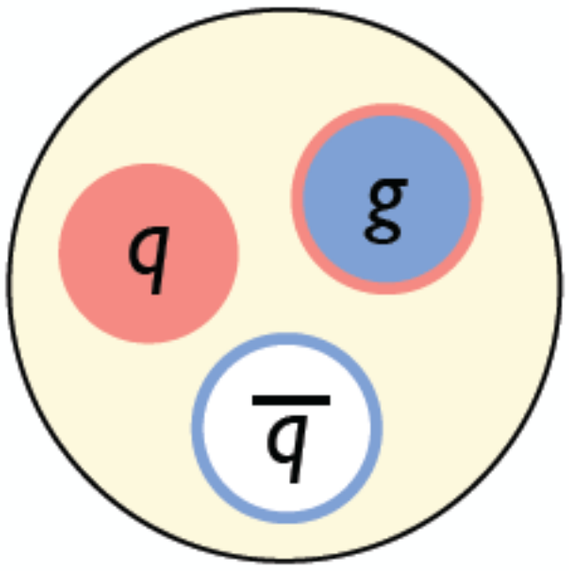
William & Mary
CHARTERED 1693

Hybrid mesons and gluonic excitations

- Excited gluonic field coupled to $q\bar{q}$ pair
- Rich spectrum of hybrid mesons predicted by Lattice QCD
- Gluonic field with $J^{PC} = 1^{+-}$ and mass = 1-1.5 GeV
- "Exotic" J^{PC} : not simple $q\bar{q}$ from the non-rel. quark model

$$J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} ...$$



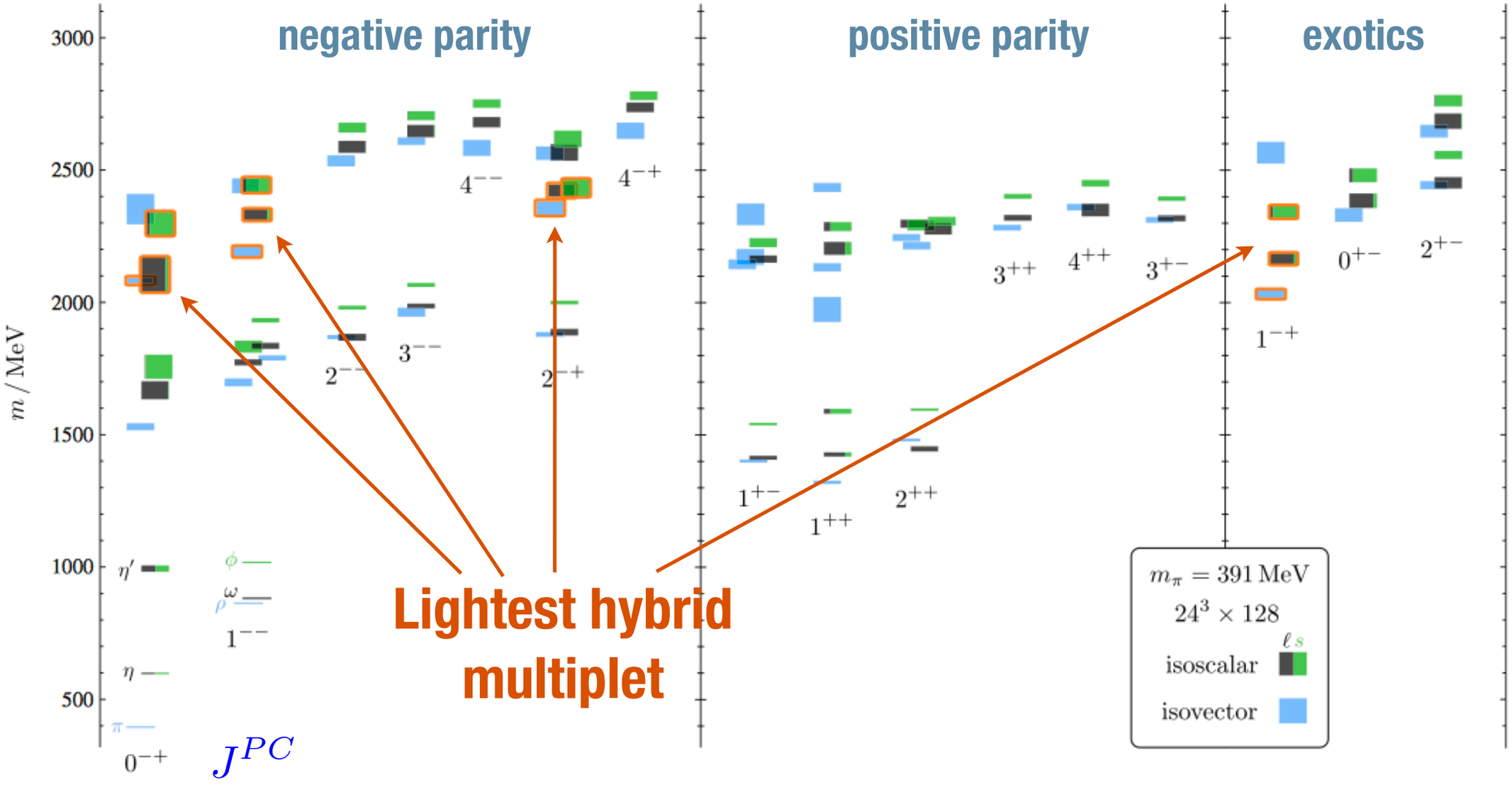


Hybrid Meson

$$\vec{J} = \vec{L} + \vec{S}$$
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

Lattice QCD predictions

Dudek et al. PRD 88 (2013) 094505



Lightest hybrid multiplet

Lattice QCD predictions

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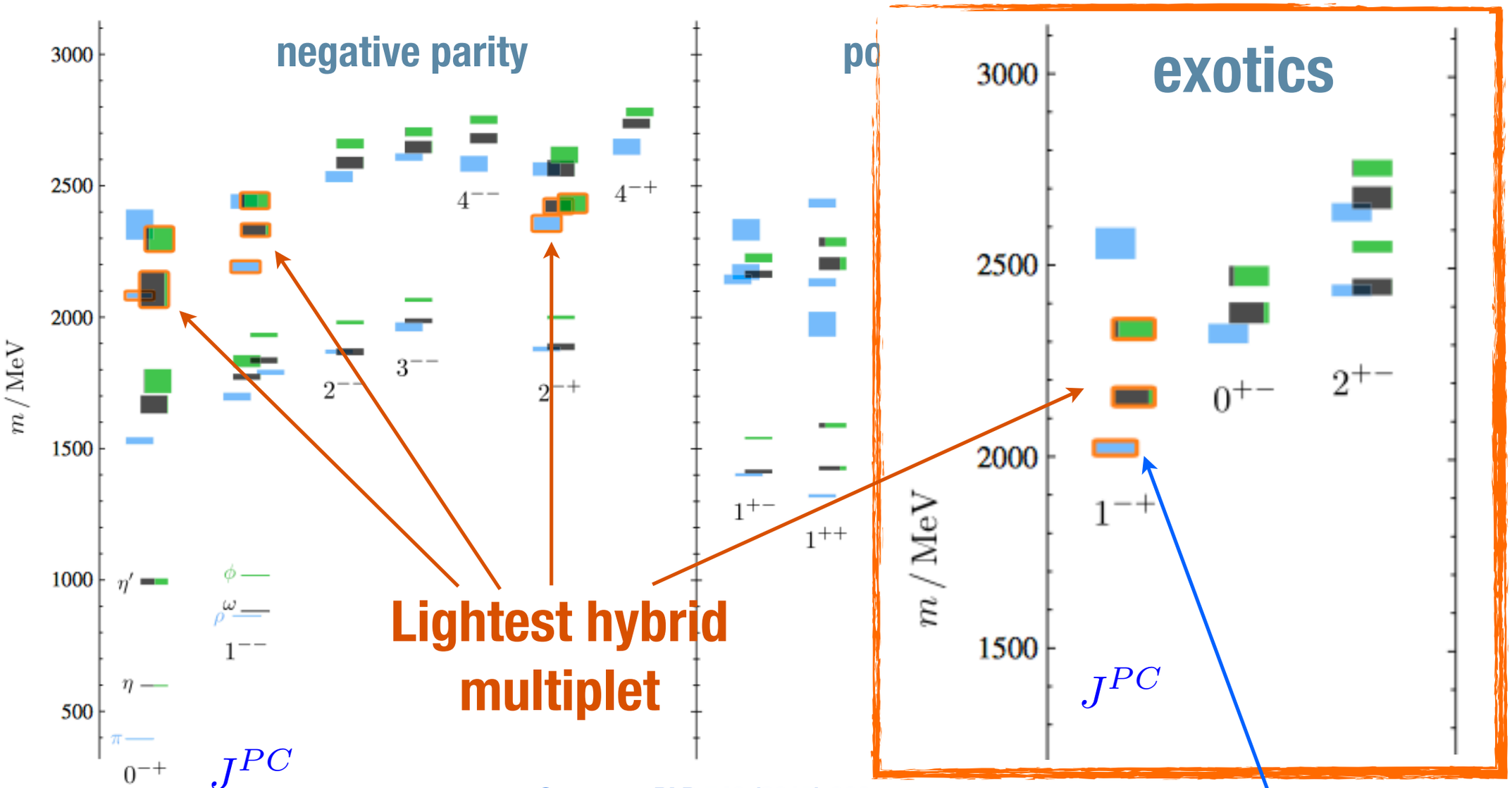
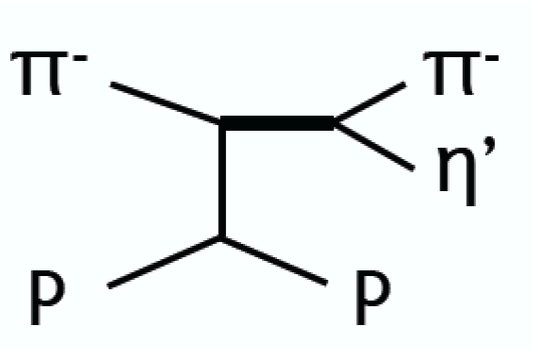
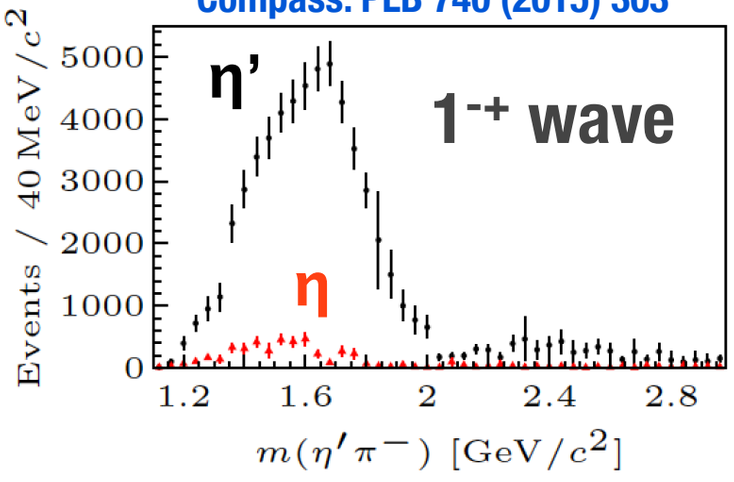


Lightest hybrid multiplet



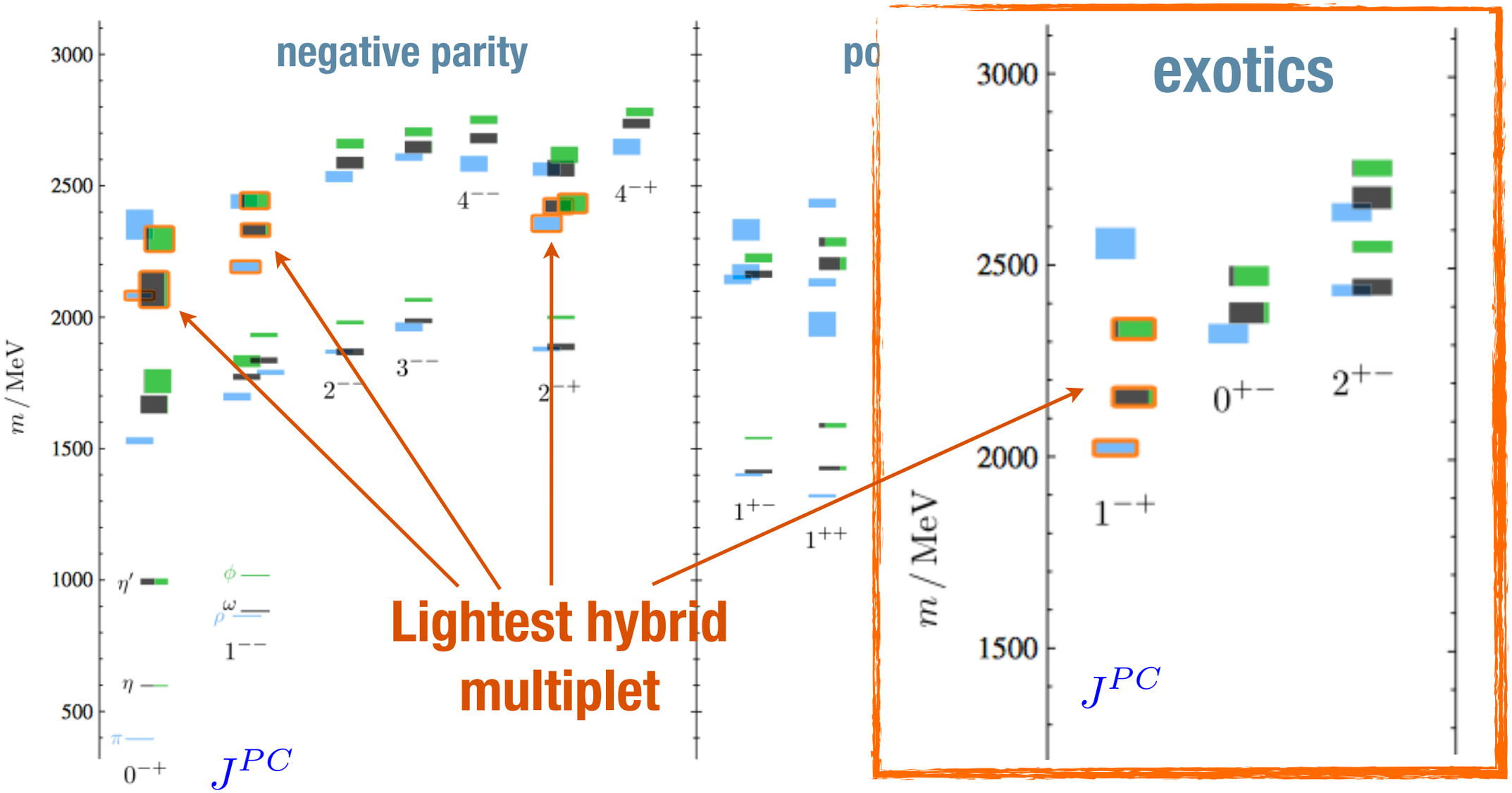
Compass: PLB 740 (2015) 303



Most experimental searches for hybrids limited to the **π_1 state**

Lattice QCD predictions

Dudek et al. PRD 88 (2013) 094505



- Ideally look for a pattern of hybrid states in multiple decay modes
- Primary goal of the GlueX experiment is to search for and ultimately map out the spectrum of light quark hybrid mesons

Exotic J^{PC} in photoproduction

	Approximate Mass (MeV)	J^{PC}
π_1	1900	1^{-+}
η_1	2100	1^{-+}
η_1'	2300	1^{-+}
b_0	2400	0^{+-}
h_0	2400	0^{+-}
h_0'	2500	0^{+-}
b_2	2500	2^{+-}
h_2	2500	2^{+-}
h_2'	2600	2^{+-}

$\rho\pi, \rho\omega \rightarrow \pi_1$

$\omega\omega, \rho\rho \rightarrow \eta_1$

$\omega\omega, \rho\rho, \phi\omega \rightarrow \eta'_1$

$\rho P \rightarrow b_0$

$\omega P \rightarrow h_0$

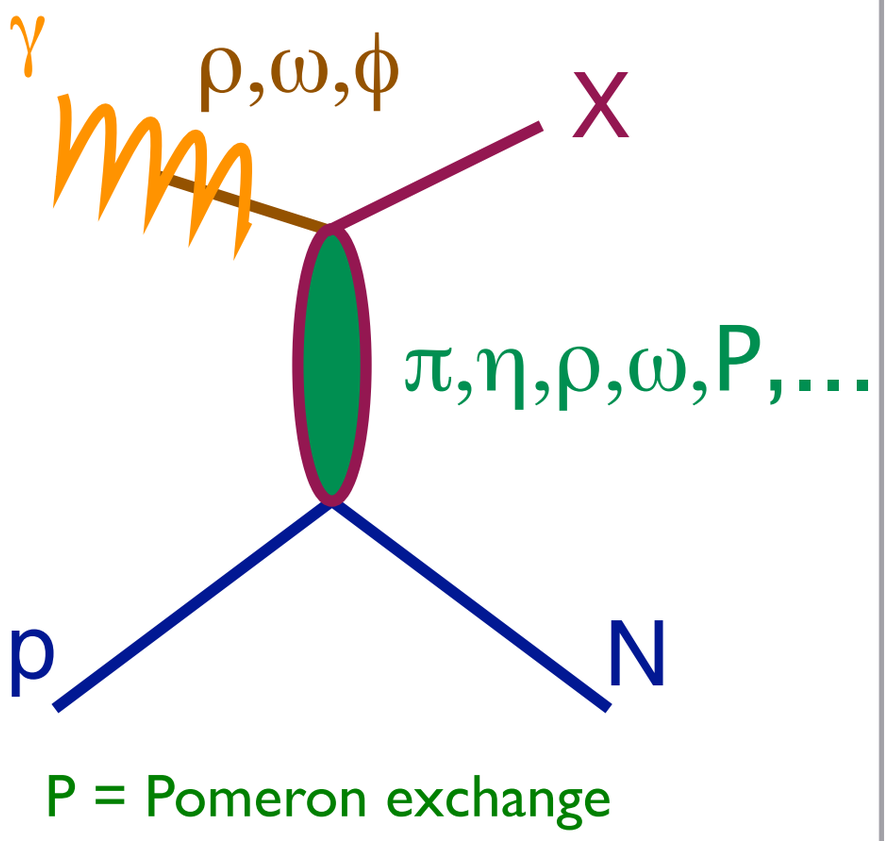
$\omega P, \phi P \rightarrow h'_0$

$\omega\pi, \rho\eta, \rho P \rightarrow b_2$

$\rho\pi, \omega\eta, \omega P \rightarrow h_2$

$\rho\pi, \omega\eta, \phi P \rightarrow h'_2$

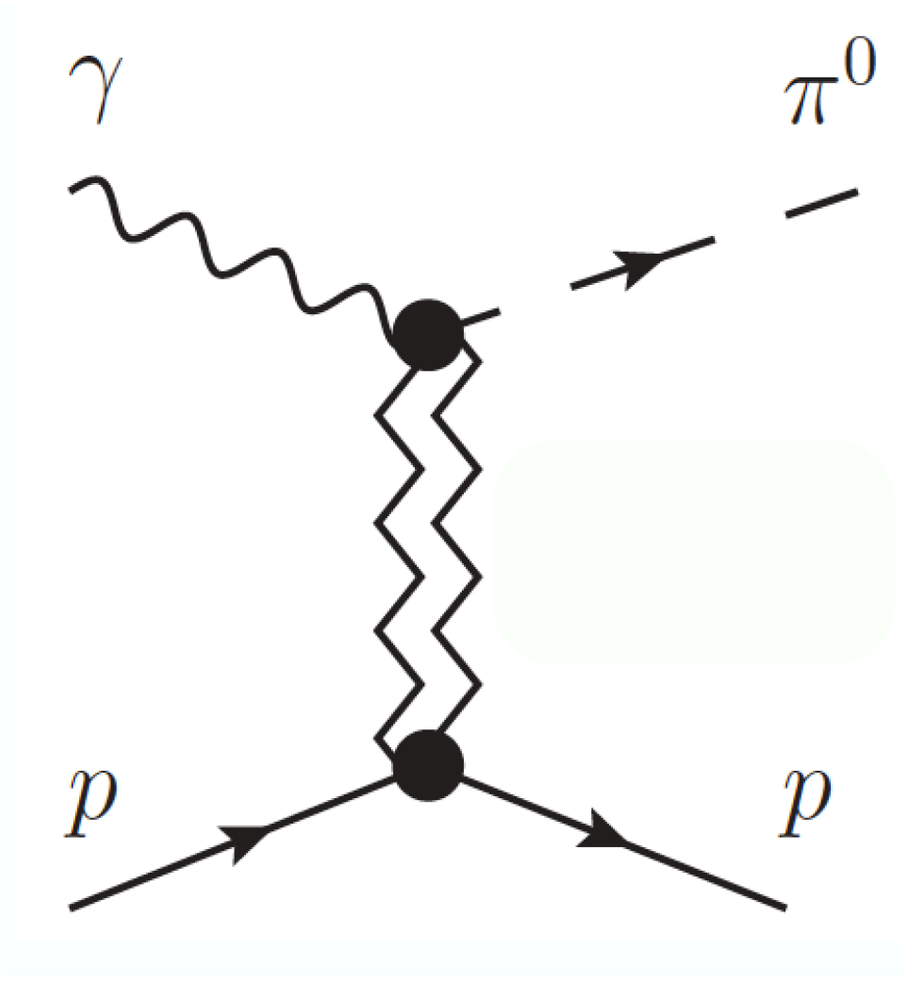
Possible quantum numbers from Vector Meson Dominance and t-channel exchange: $(I^G)J^{PC}$



P = Pomeron exchange

- Can couple to all states in the lightest hybrid multiplet through t-channel exchange and photoproduction (via Vector Meson Dominance)
- Photon beam polarization filters the “naturality” of the exchange particle

Non-exotic J^{PC} in photoproduction



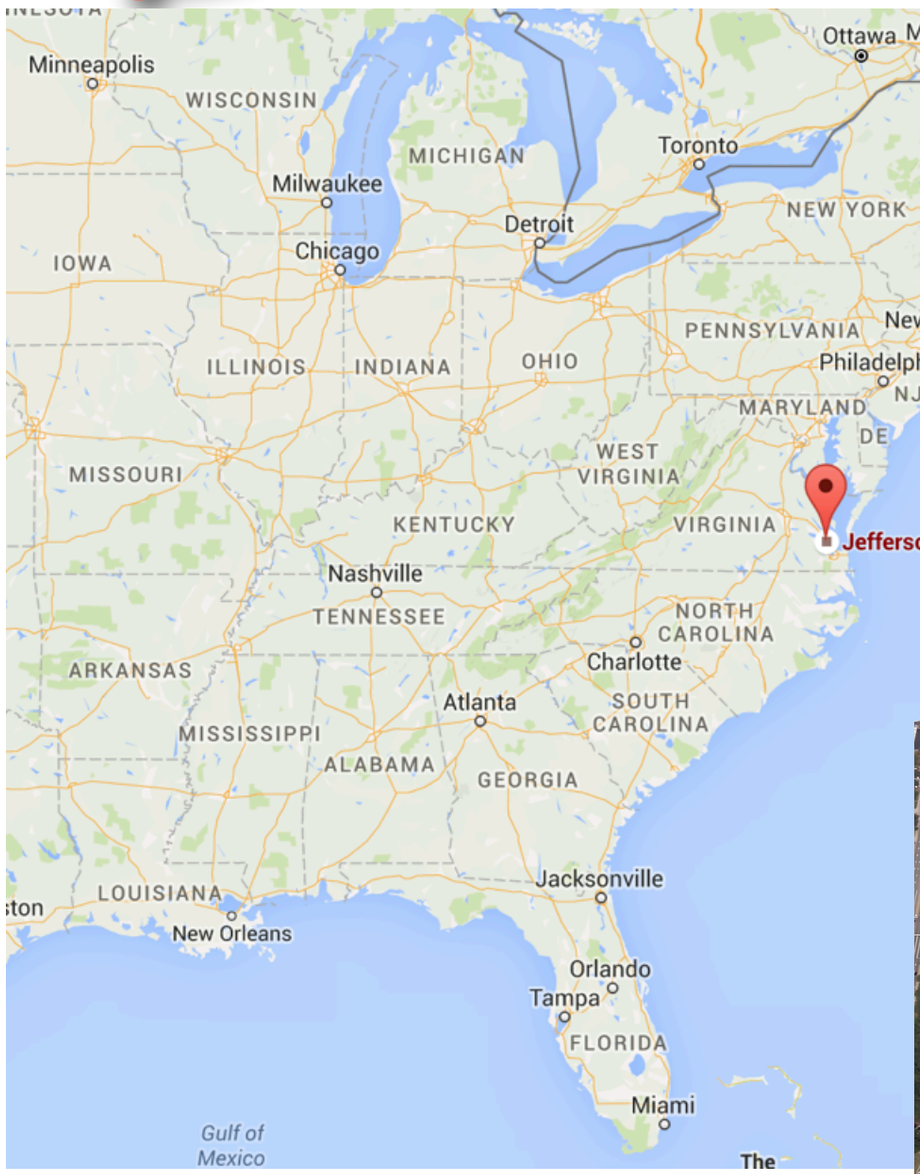
Exchange J^{PC}

$$1^{--} : \omega, \rho$$

$$1^{+-} : b, h$$

- Can couple to all states in the lightest hybrid multiplet through t-channel exchange and photoproduction (via Vector Meson Dominance)
- Photon beam polarization filters the “naturality” of the exchange particle

Jefferson Lab

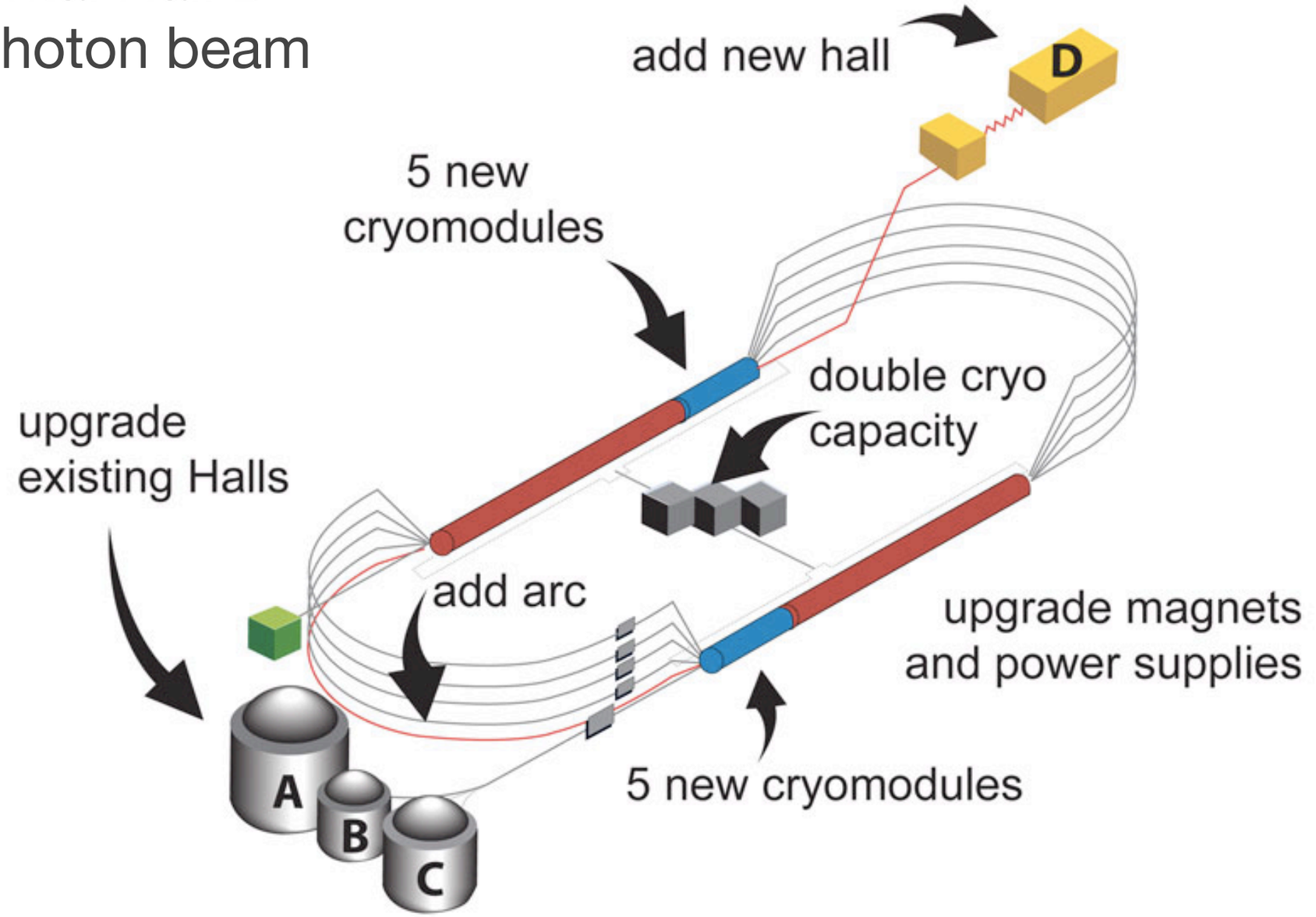


- Newport News, Virginia
- Home to the Continuous Electron Beam Accelerator Facility (CEBAF)

- Active theory community:
  - Lattice QCD (R. Briceno's talk)
  - JPAC (A. Pilloni's talk)

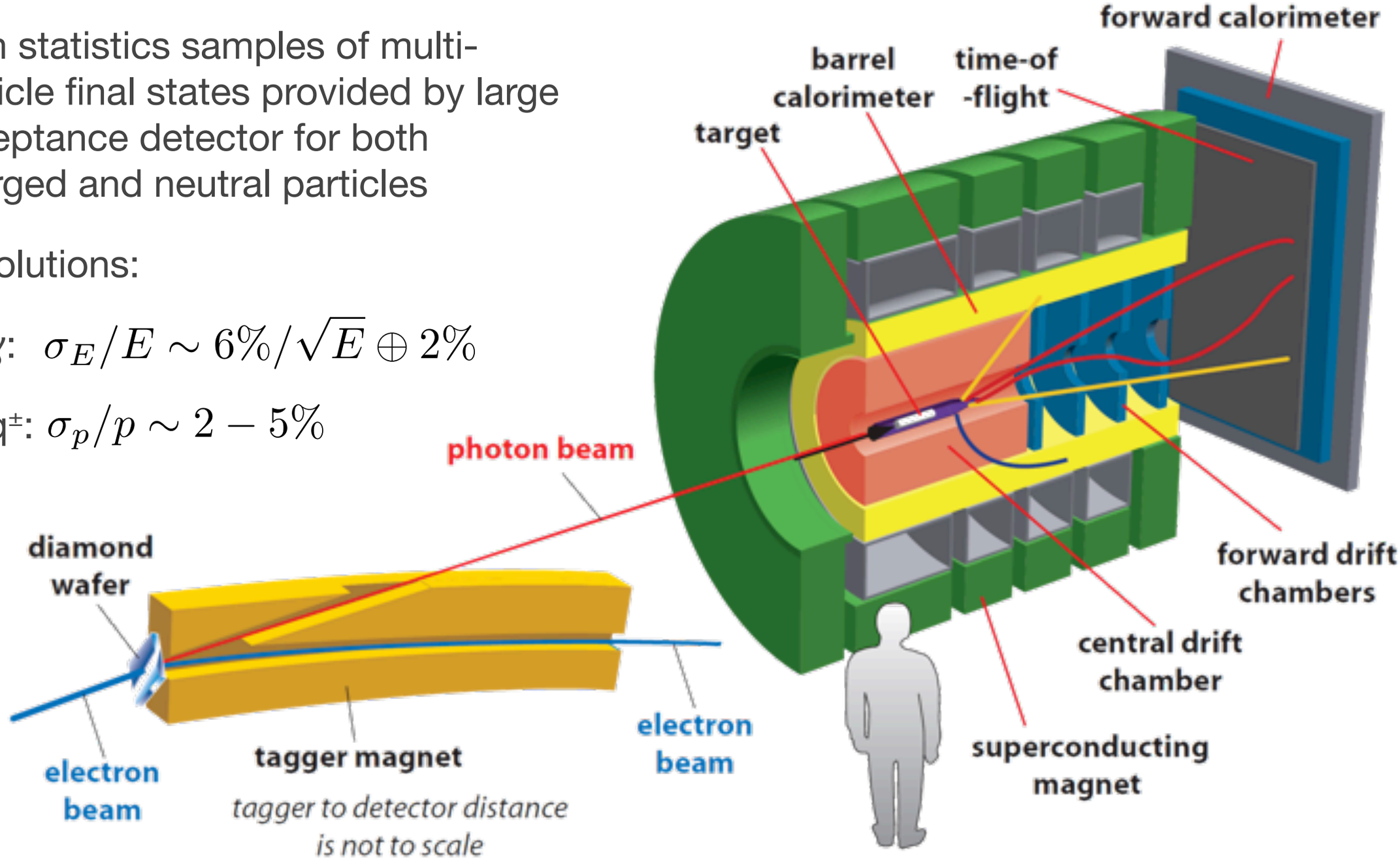
Jefferson Lab 12 GeV Upgrade

- Upgrade maximum electron beam energy from 6 to 12 GeV
- Add new experimental Hall D with a dedicated photon beam



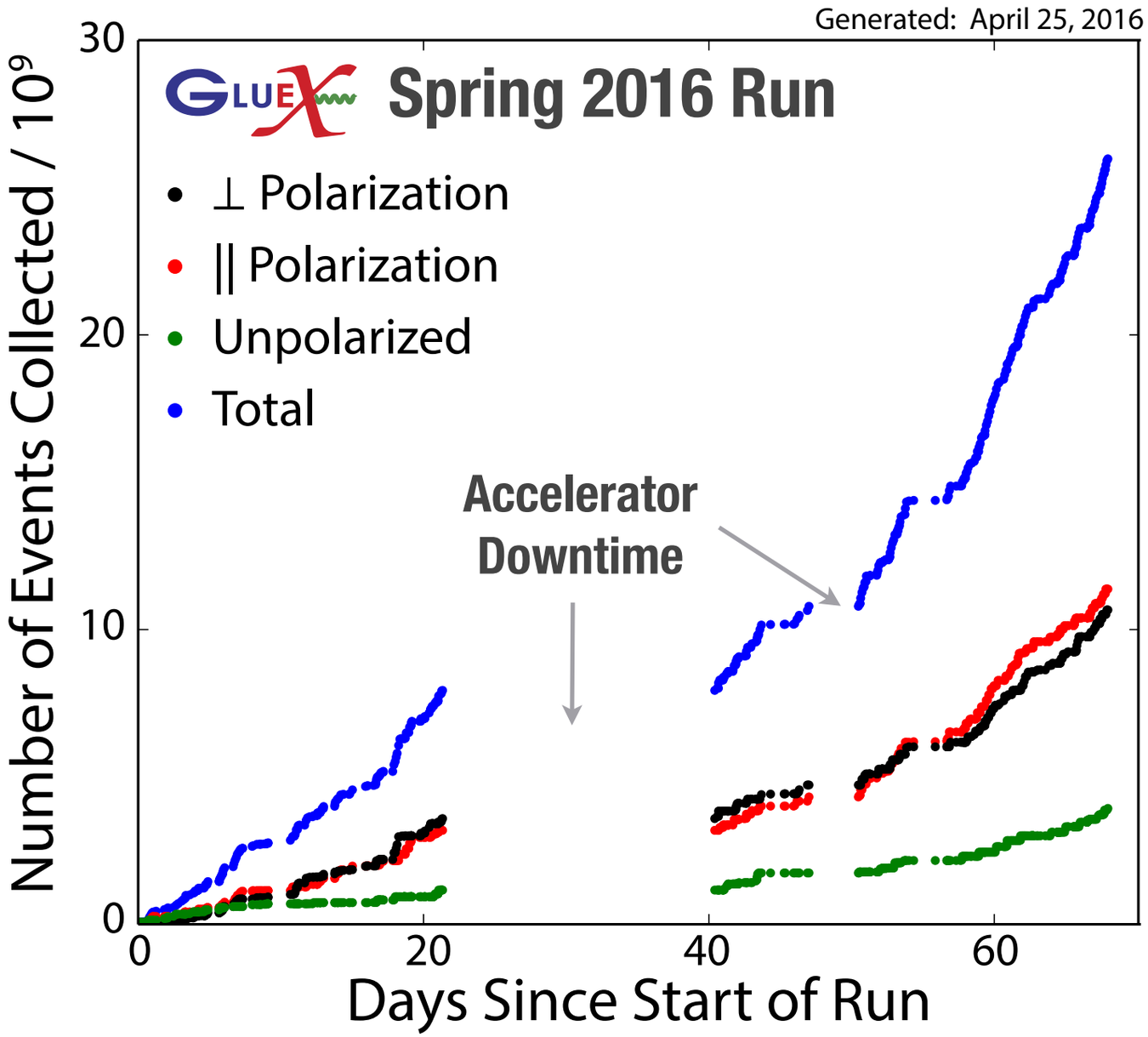
GlueX in Hall D

- Linearly polarized bremsstrahlung photon beam from CEBAF 12 GeV e^-
- High statistics samples of multi-particle final states provided by large acceptance detector for both charged and neutral particles
- Resolutions:
  - γ: $\sigma_E/E \sim 6\%/\sqrt{E} \oplus 2\%$
  - $q^{\pm}$: $\sigma_p/p \sim 2-5\%$

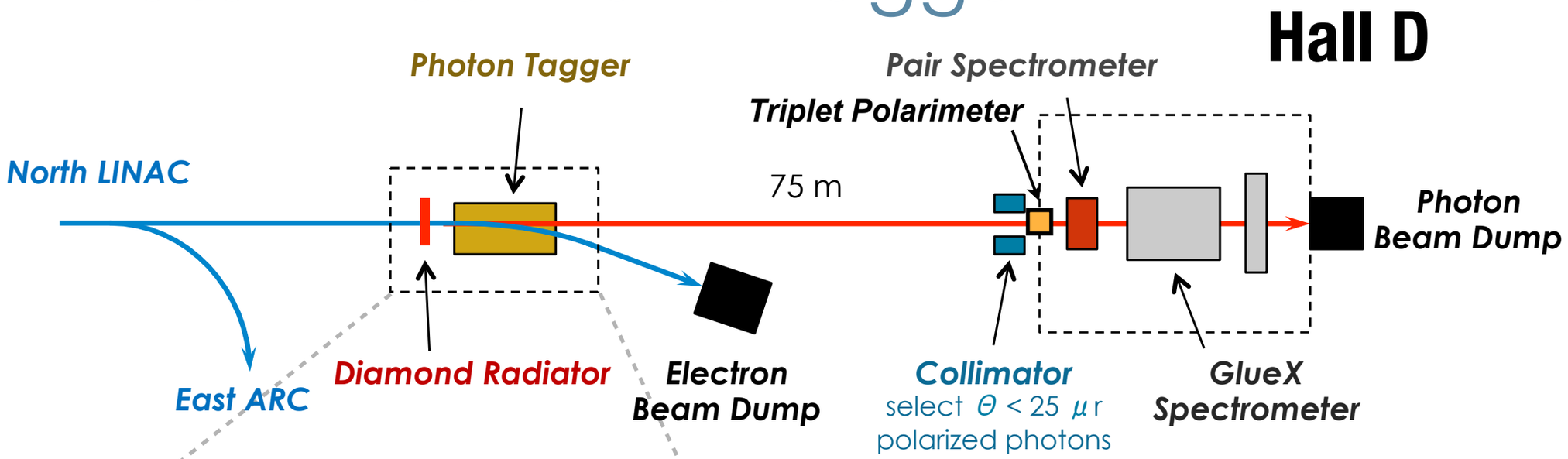


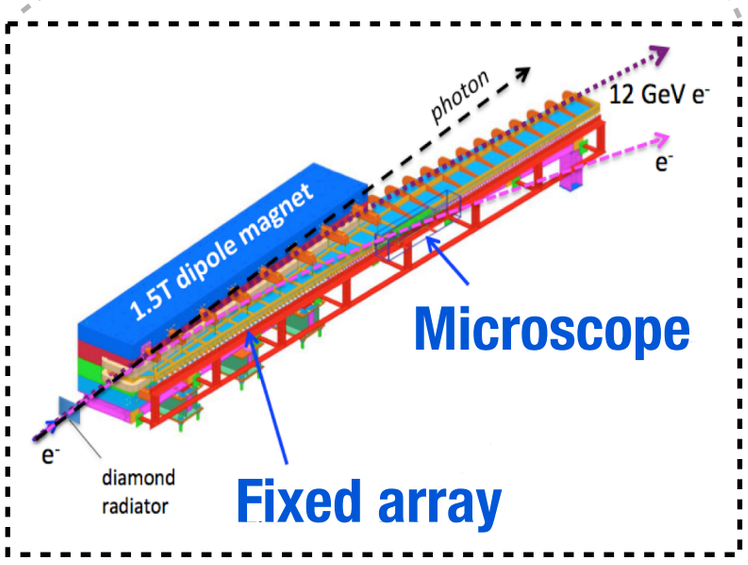
GlueX data taking

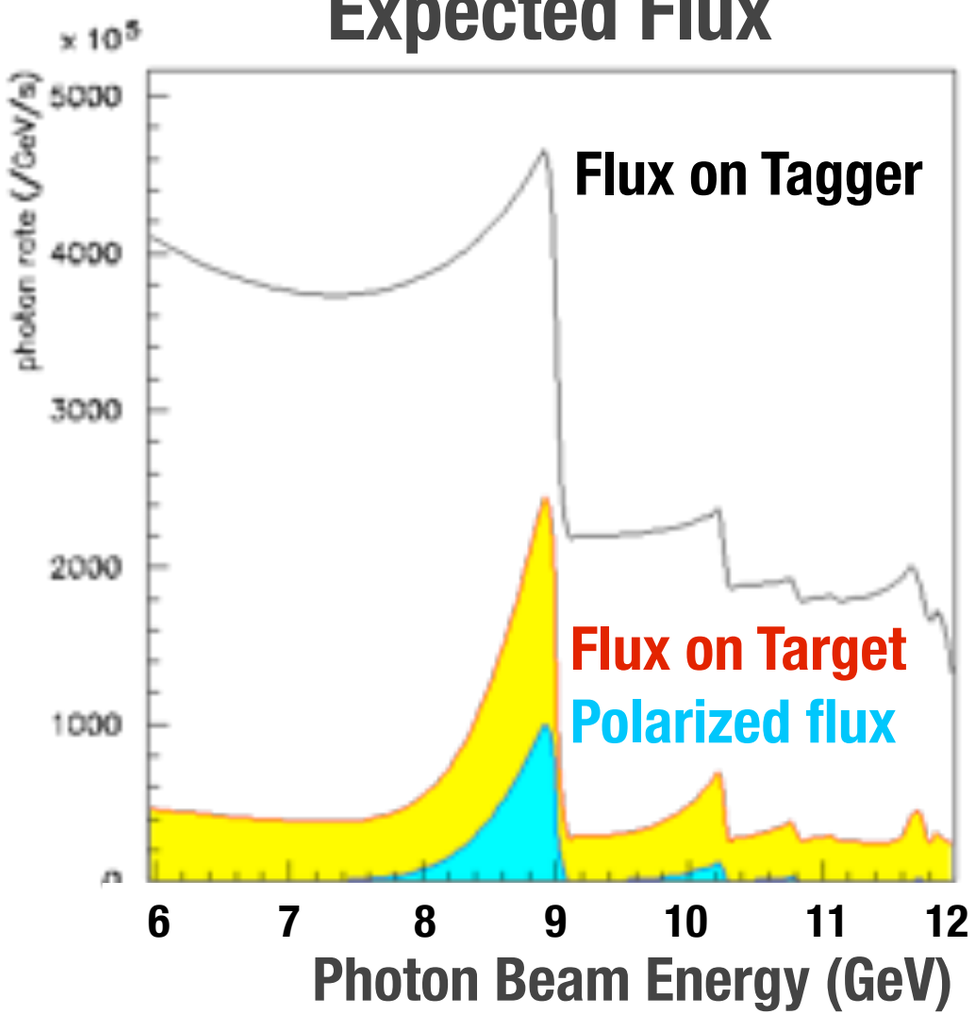
- **2014-2015:** Beam and detector commissioning
- **Fall 2015:** First 12 GeV electrons at JLab delivered to Hall D
- Detectors reaching design performance
- **Spring 2016:** First large dataset with possibility for physics publications



Photon Beam and Tagger

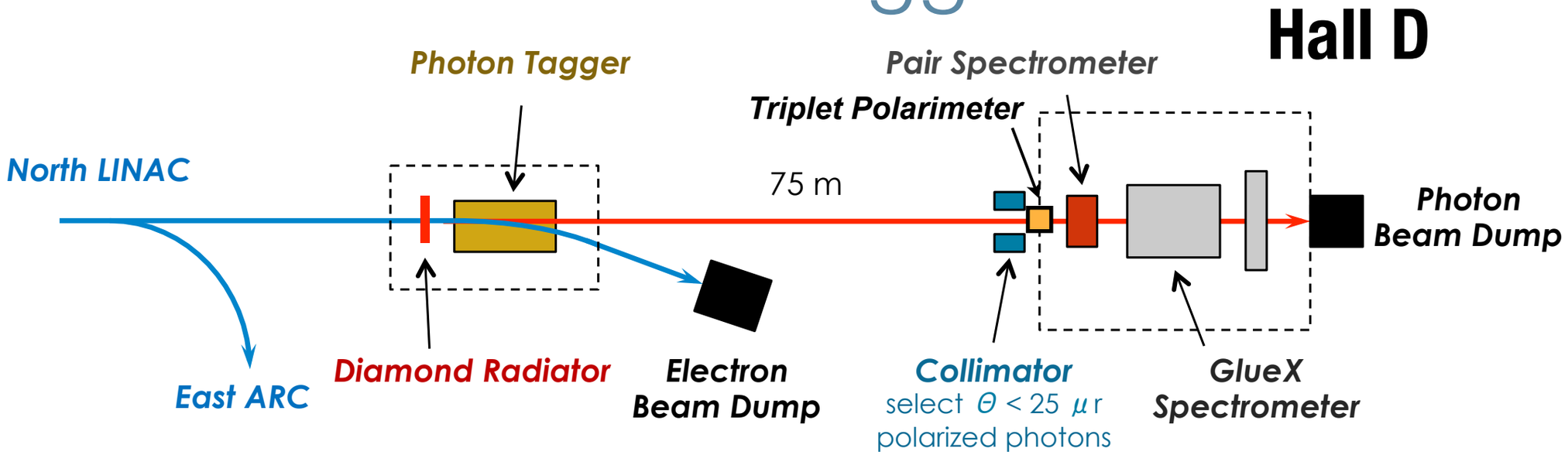


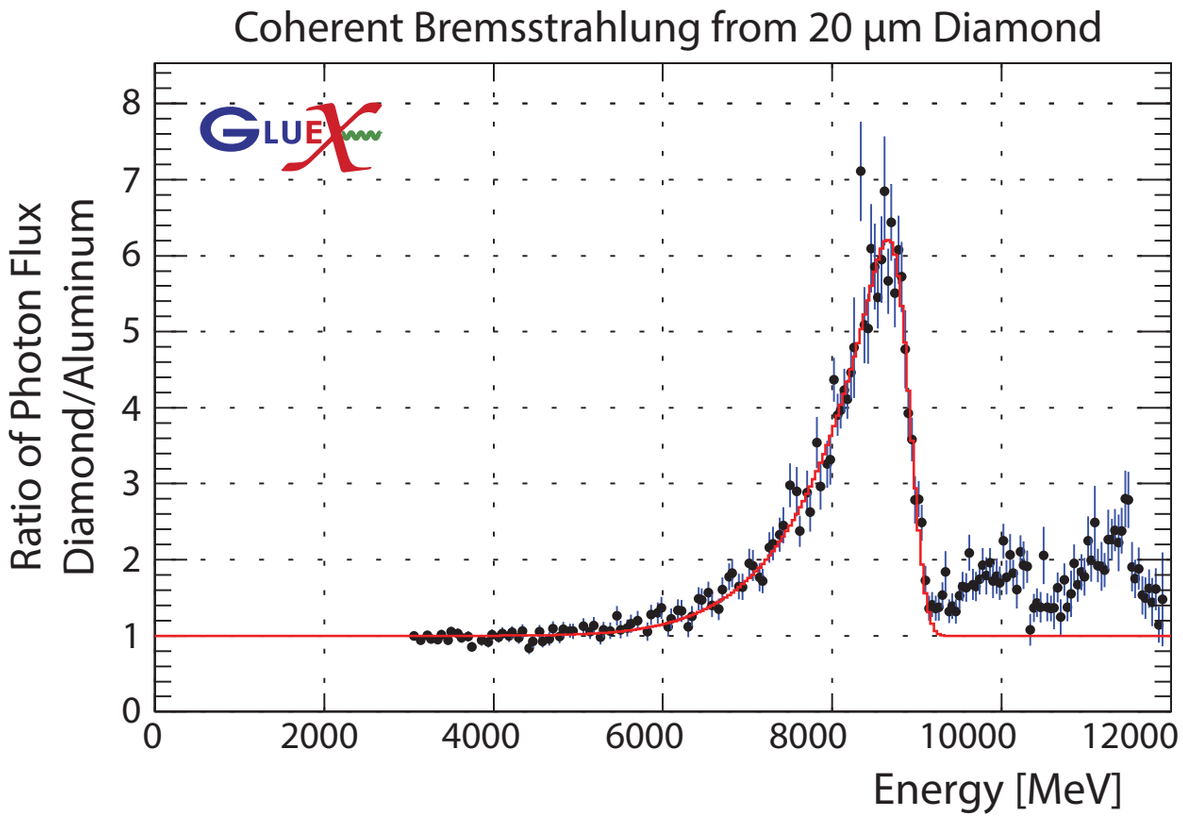


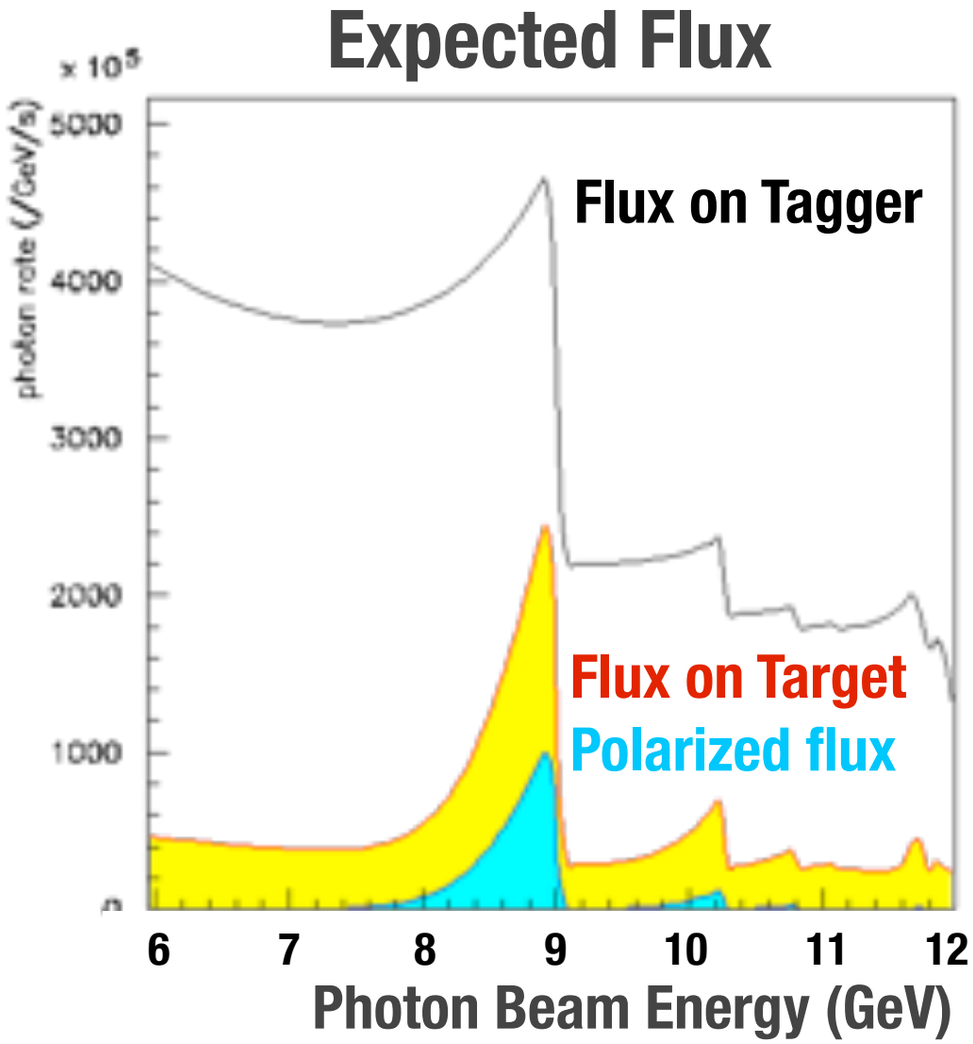


- Linearly polarized photons via coherent bremsstrahlung from diamond radiator
- Design intensity of 10^8 γ/s in coherent peak between E_γ = 8.4 and 9 GeV

Photon Beam and Tagger







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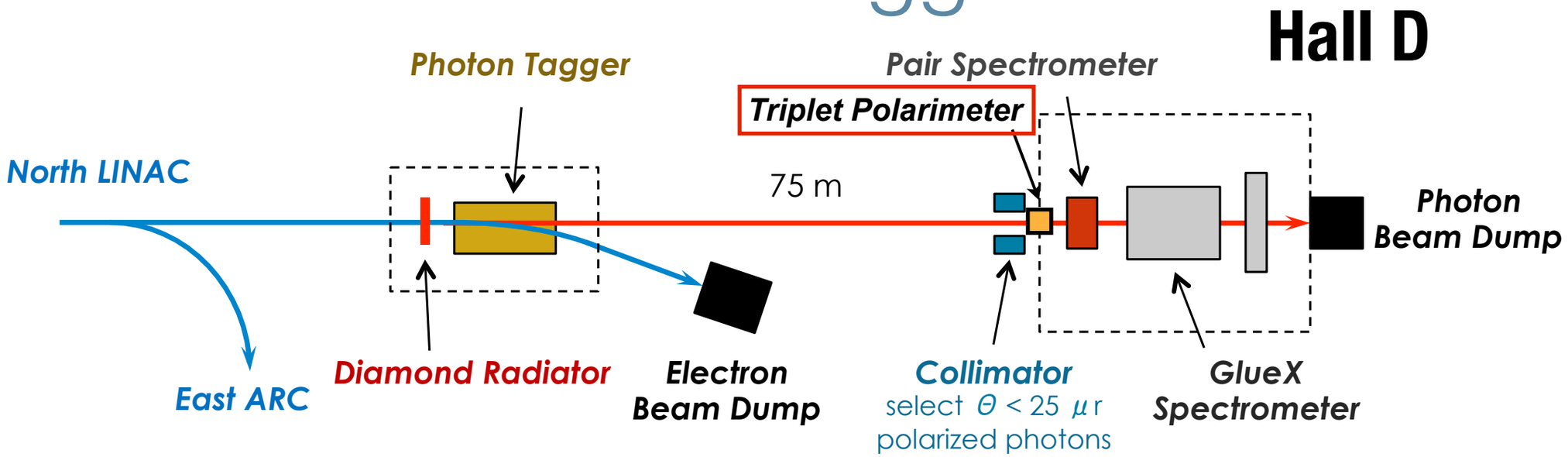


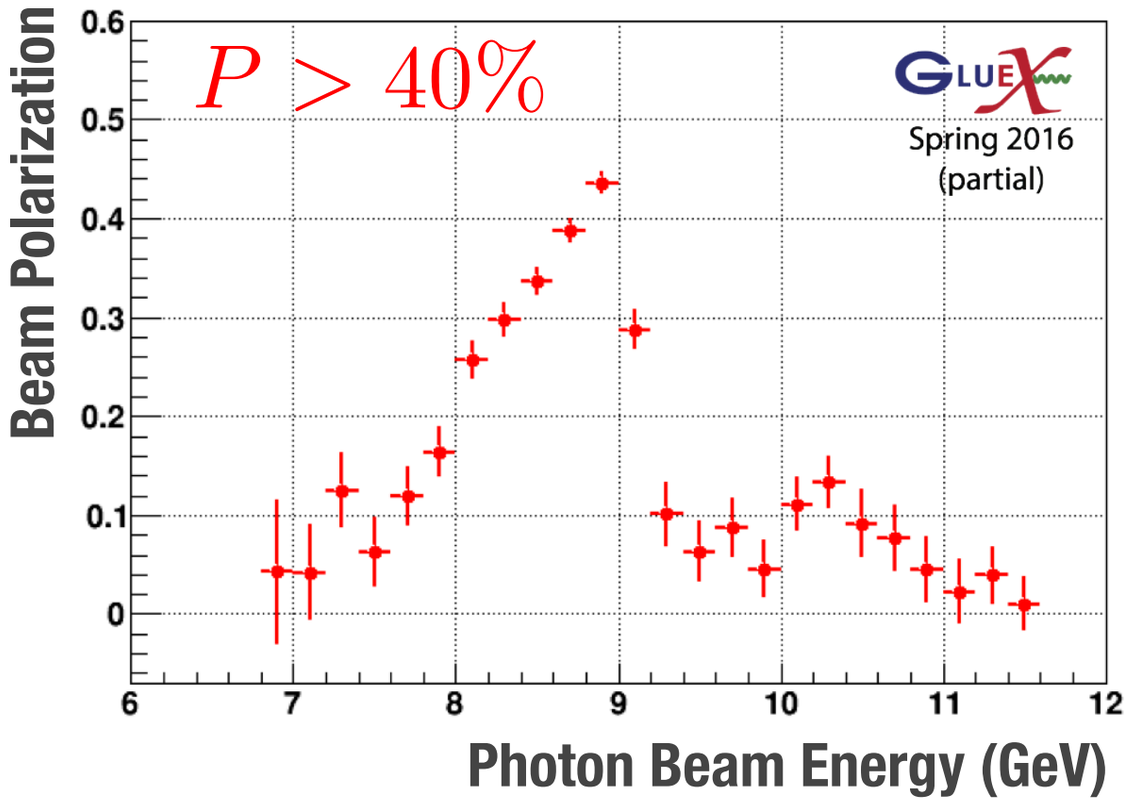
- **Triplet production for polarimetry**

$$\gamma e^- \rightarrow e^- e^+ e^-$$

  - Known analyzing power

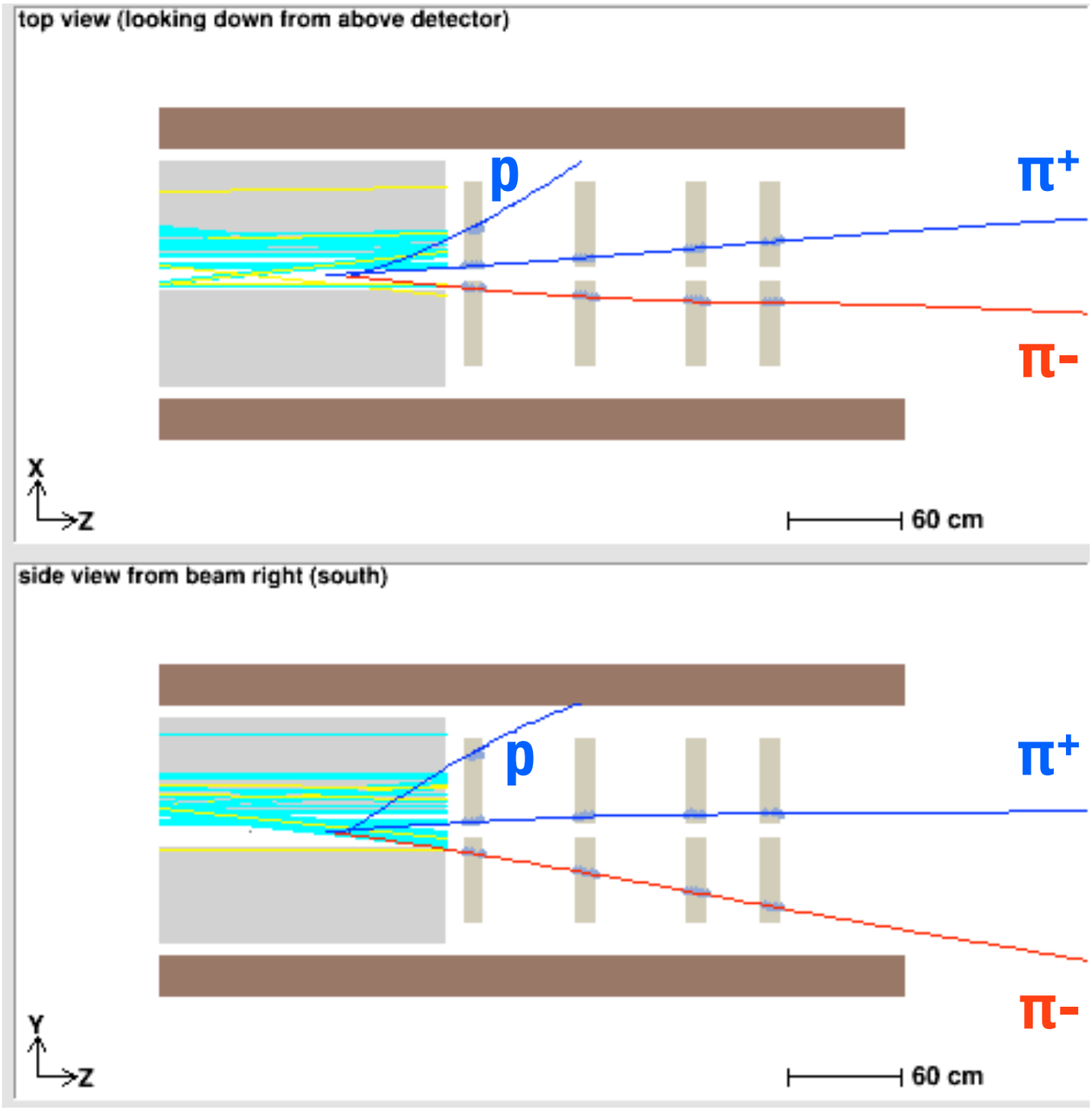
$$d\sigma \sim 1 \pm P\Sigma cos(2\phi_{e^-})$$

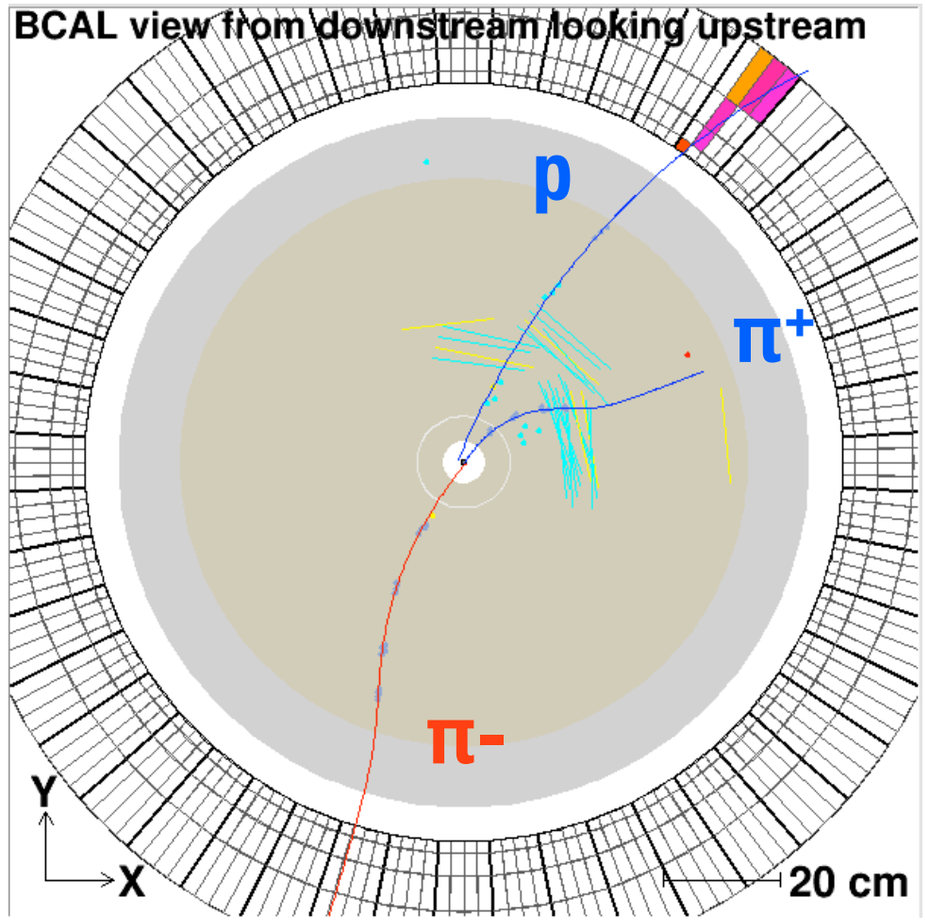
  - Determine beam polarization independent of GlueX spectrometer



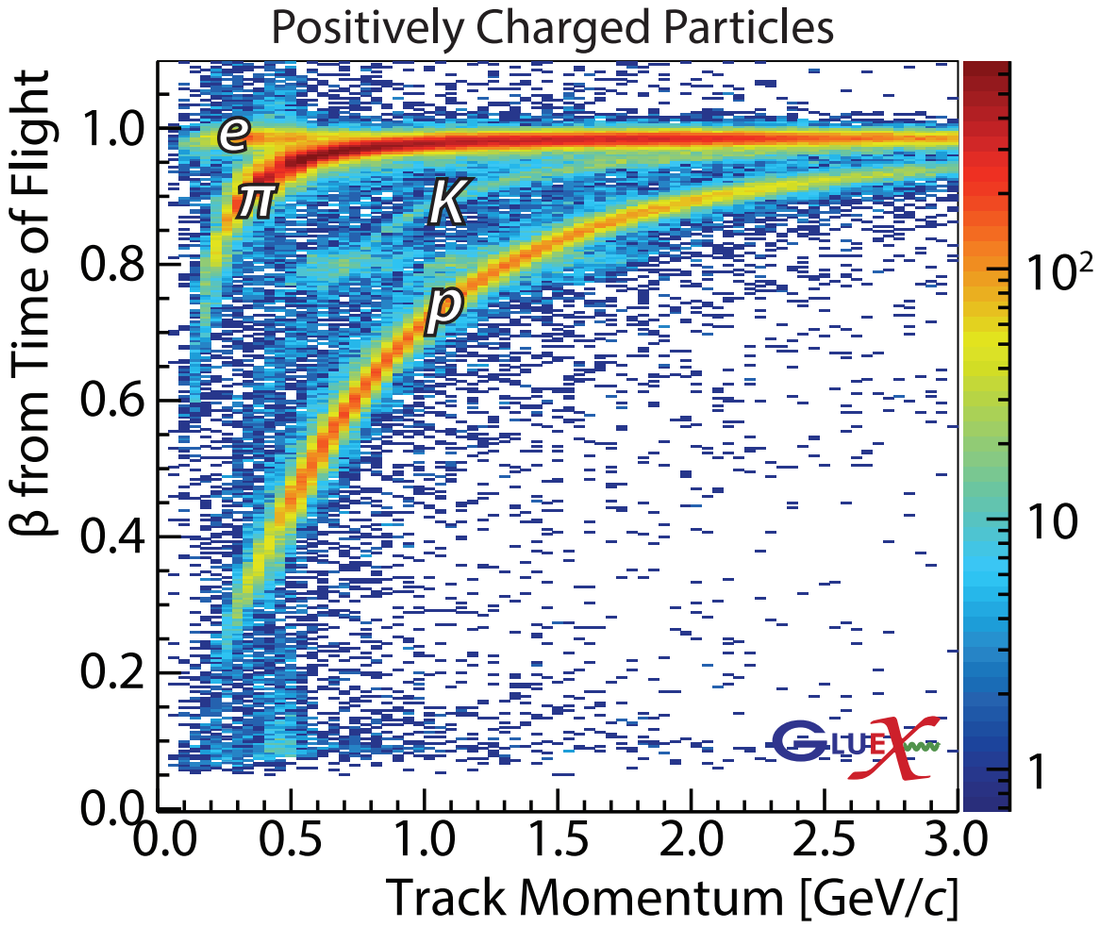
GlueX in Hall D

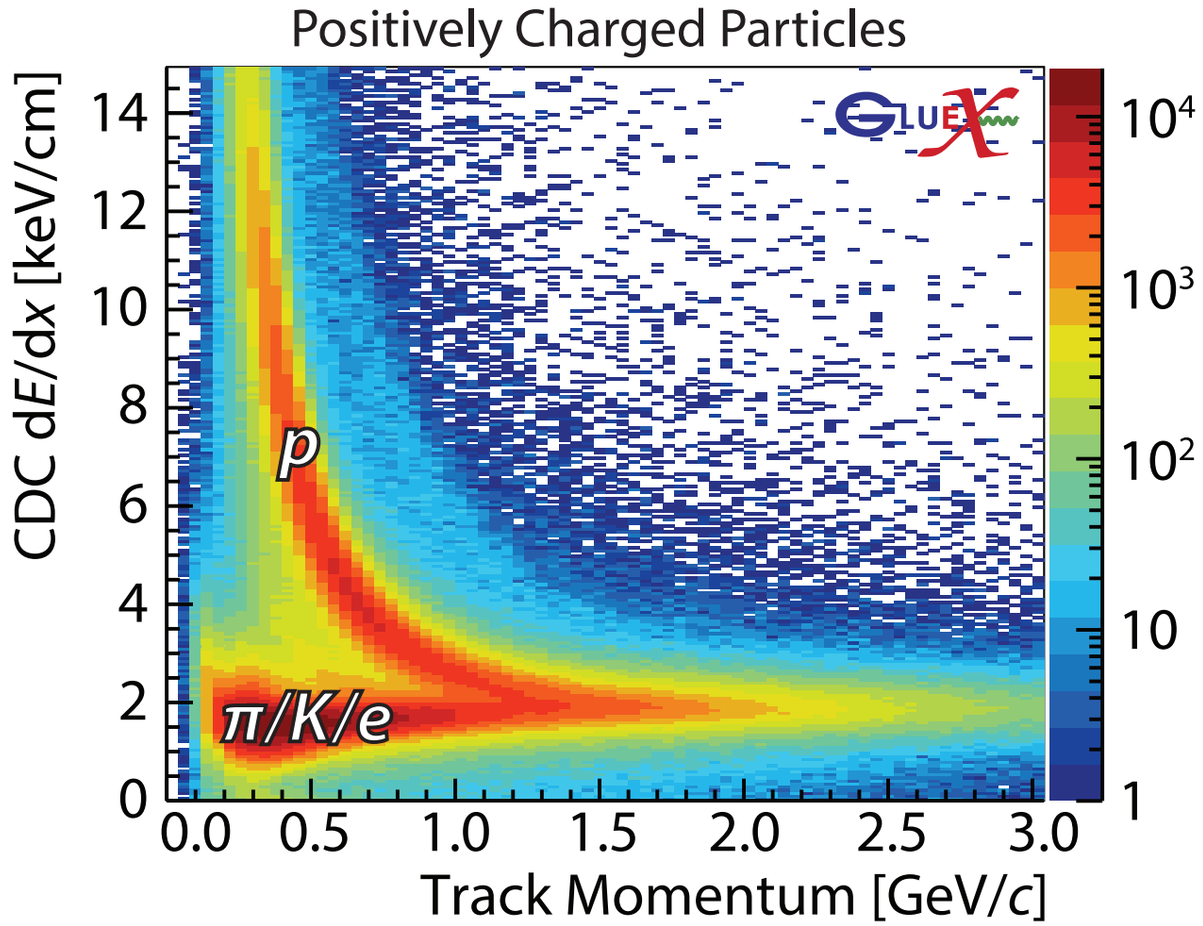
“Typical” γp→π⁺π⁻p event





Particle identification performance





Early GlueX physics: $\gamma p \to \rho^0 p$

PHYSICAL REVIEW D VOLUME 7, NUMBER 11 1 JUNE 1973

Vector-Meson Production by Polarized Photons at 2.8, 4.7, and 9.3 GeV*

J. Ballam, G. B. Chadwick, Y. Eisenberg,† E. Kogan,† K. C. Moffeit, P. Seyboth,‡
I. O. Skillicorn,§ H. Spitzer,‖ and G. Wolf**
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

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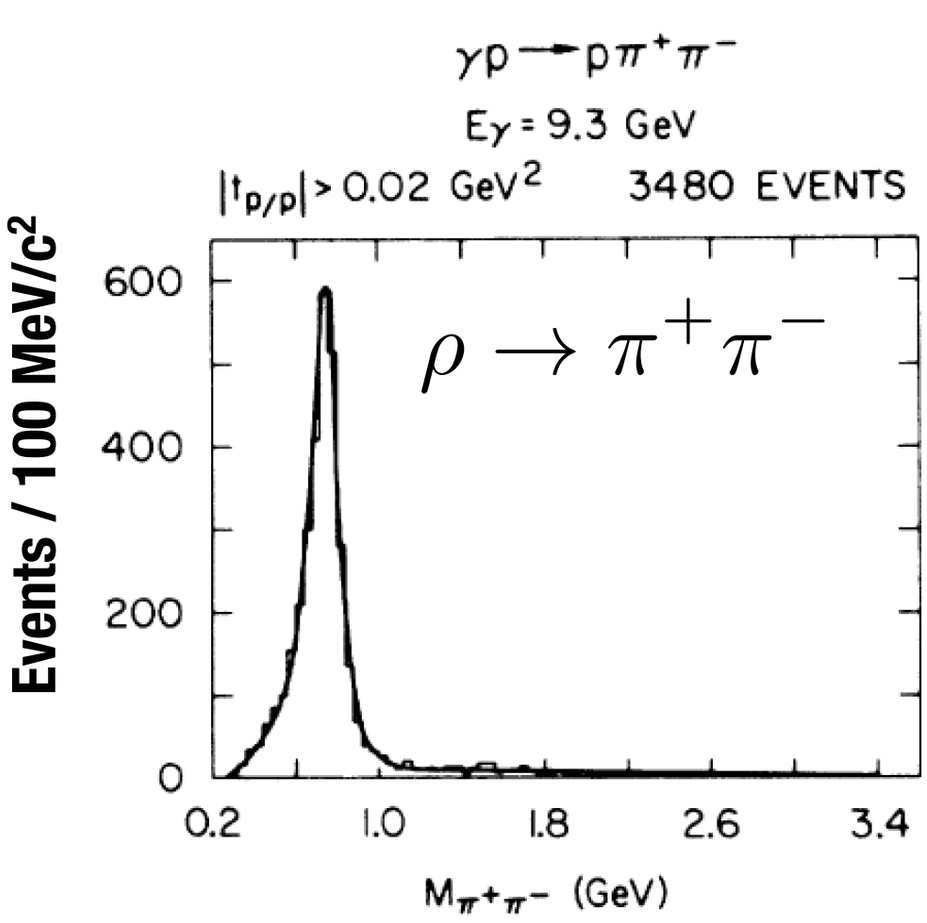
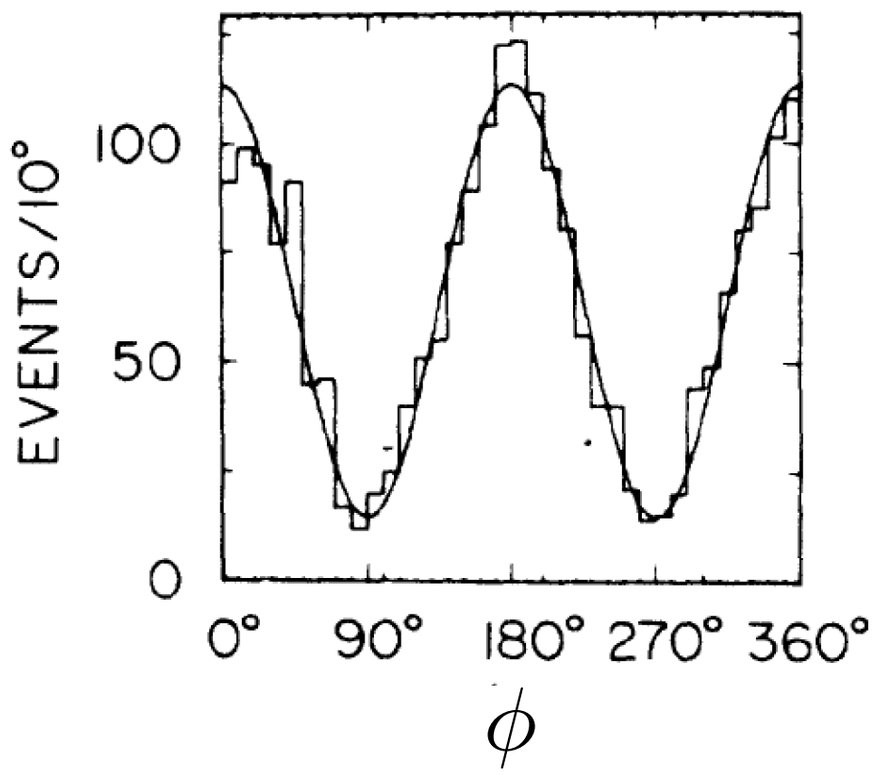
University of California and Lawrence Berkeley Laboratory, Berkeley, California 94720

(Received 13 November 1972)



$$d\sigma \sim 1 + P\Sigma \cdot cos2\phi$$



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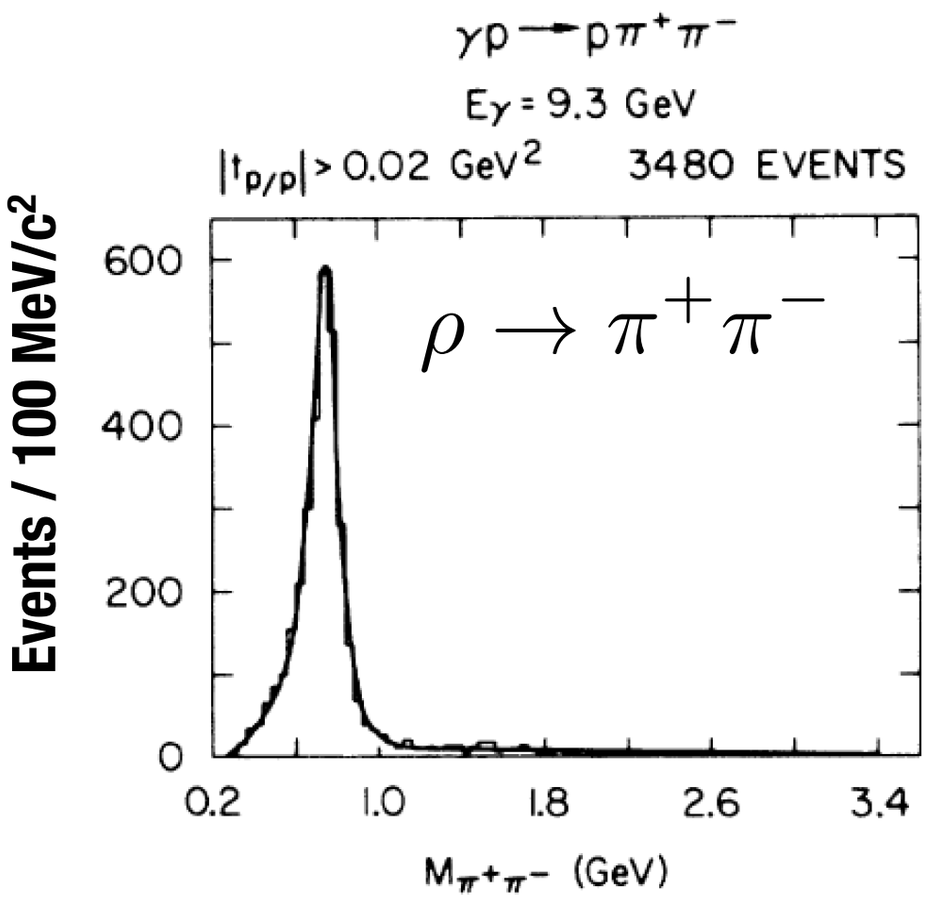
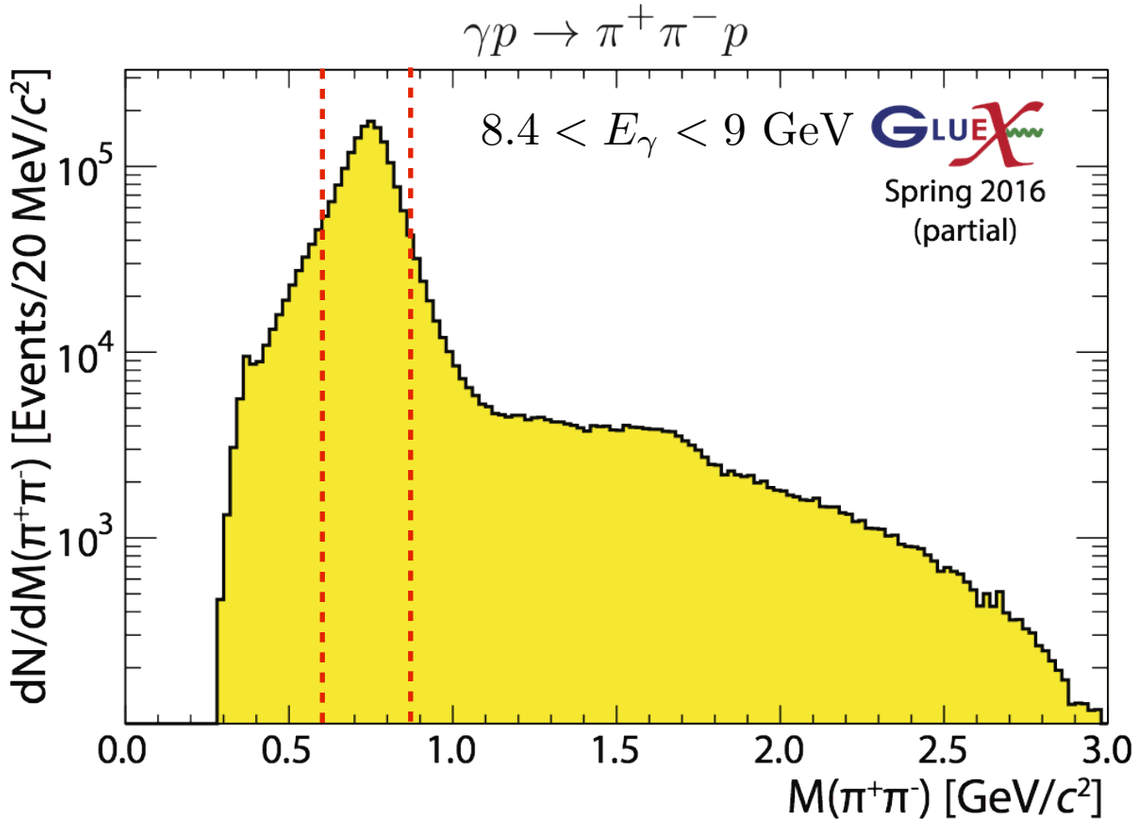
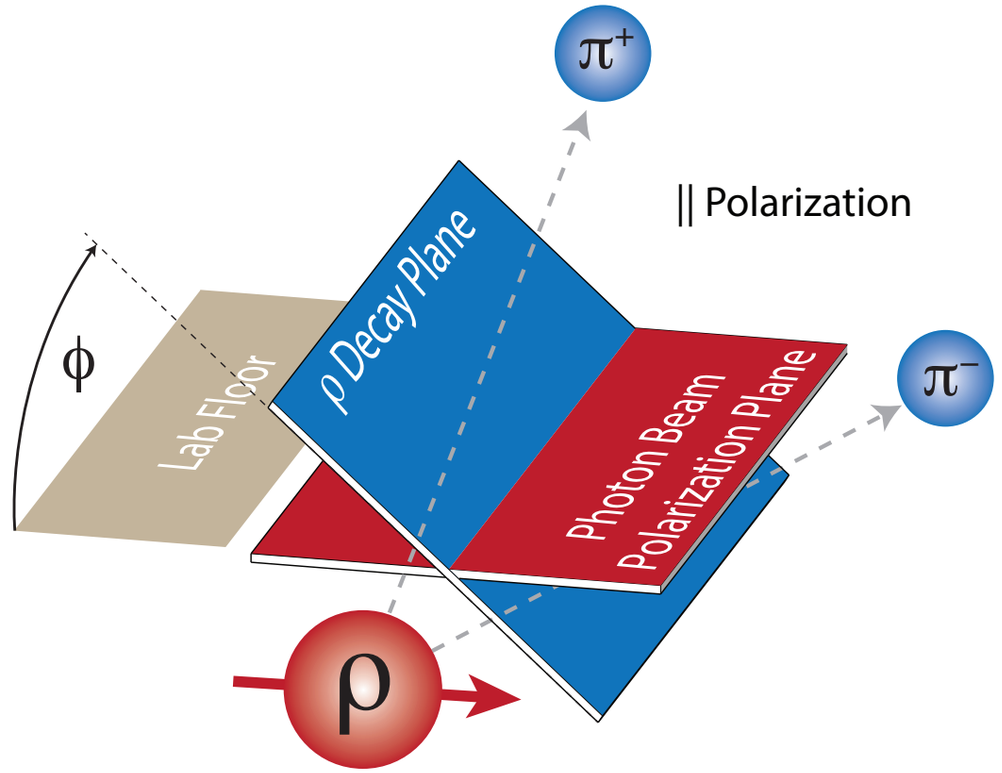


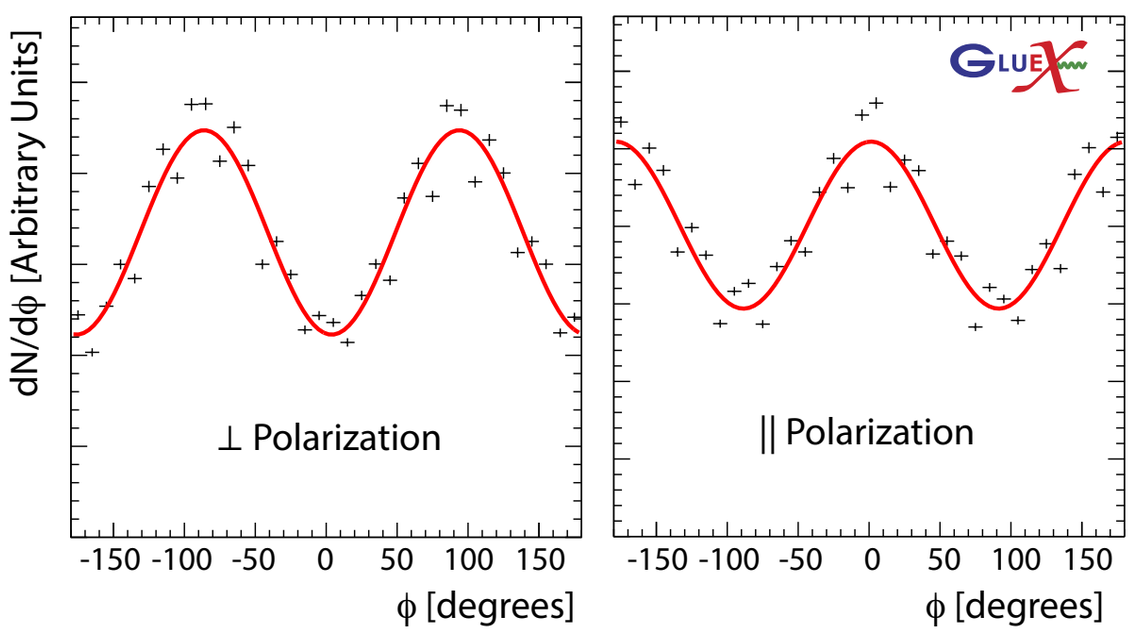


$\gamma p \rightarrow \rho^0 p$ asymmetry

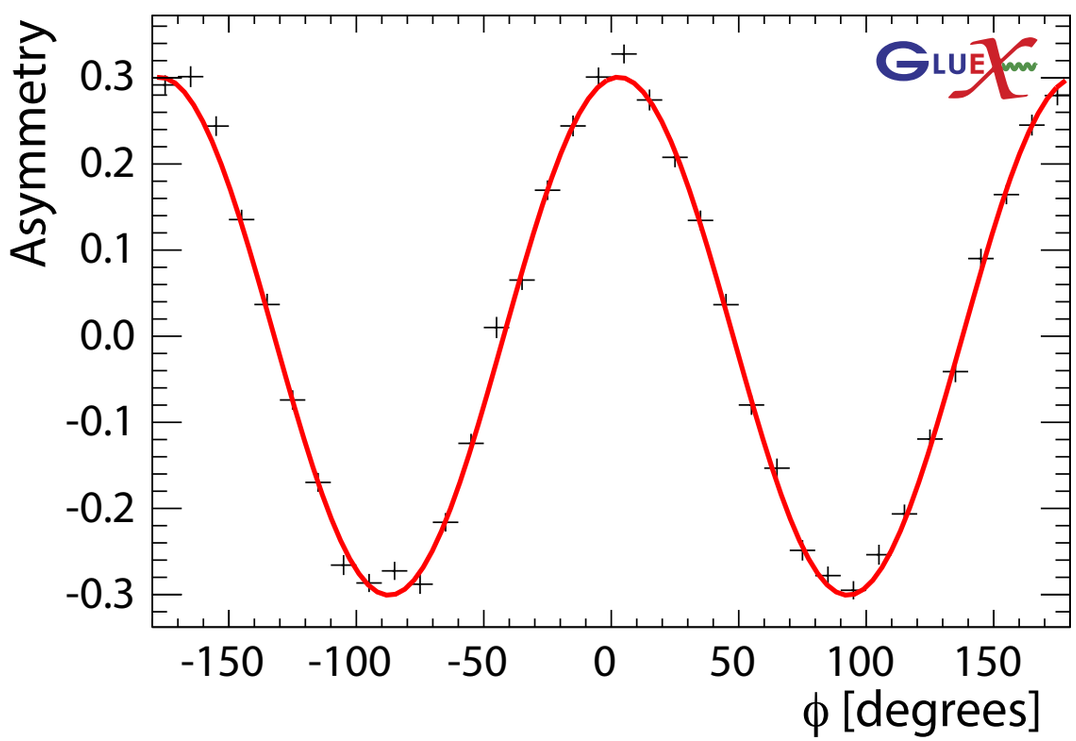
- Monitor for beam polarization
- Asymmetry between polarization orientations (|| and $\perp$) cancels detector acceptance
- More complete analysis of full angular distributions still required



Rotate polarization plane by 90°



$$\frac{N_{||} - N_{\perp}}{N_{||} + N_{\perp}} \sim P\Sigma cos(2\phi)$$



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High-Energy π^0 Photoproduction from Hydrogen with Unpolarized and Linearly Polarized Photons*

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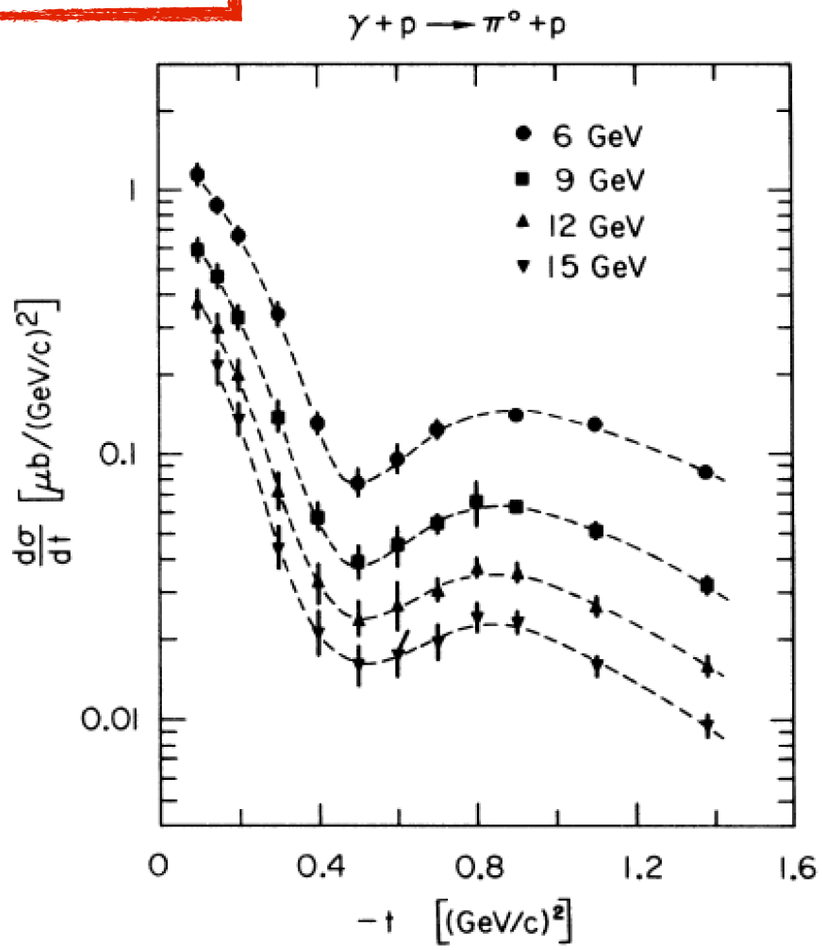
(Received 25 June 1971)

1 OCTOBER 1971



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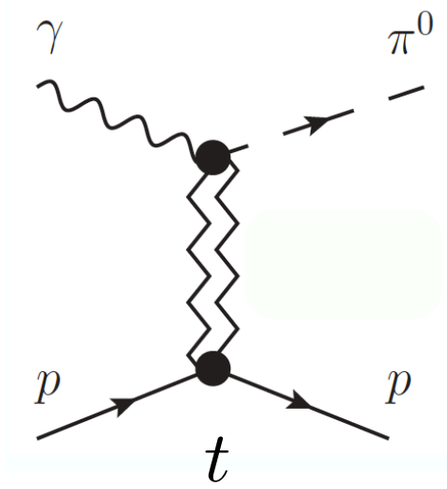
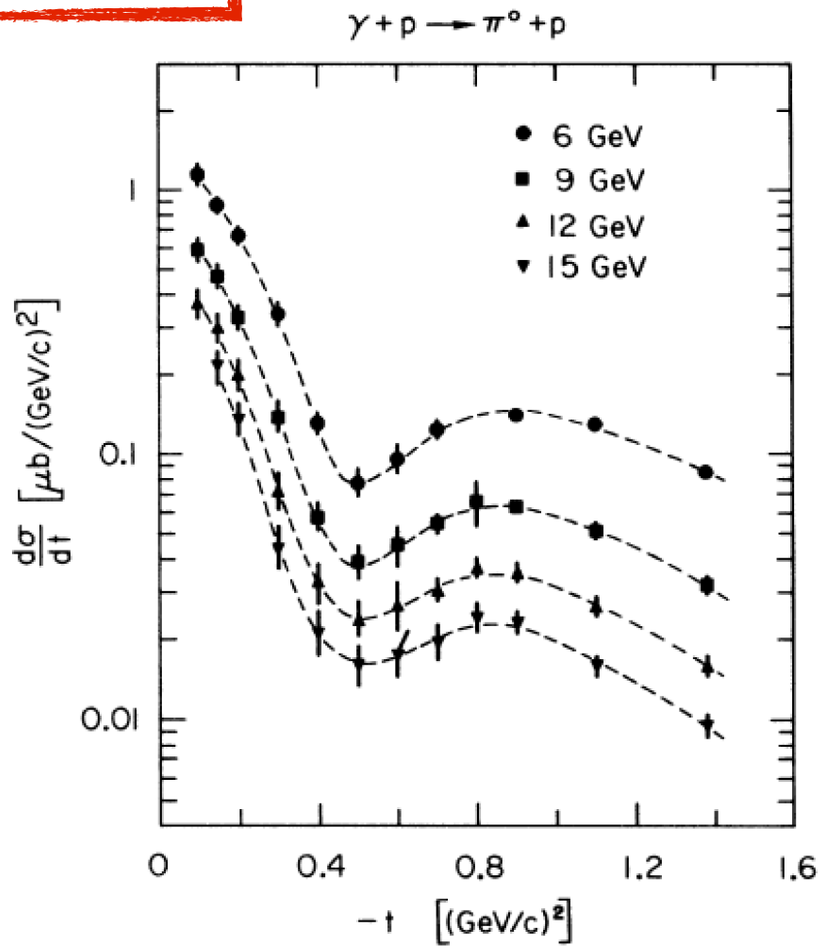


Exchange J^{PC}

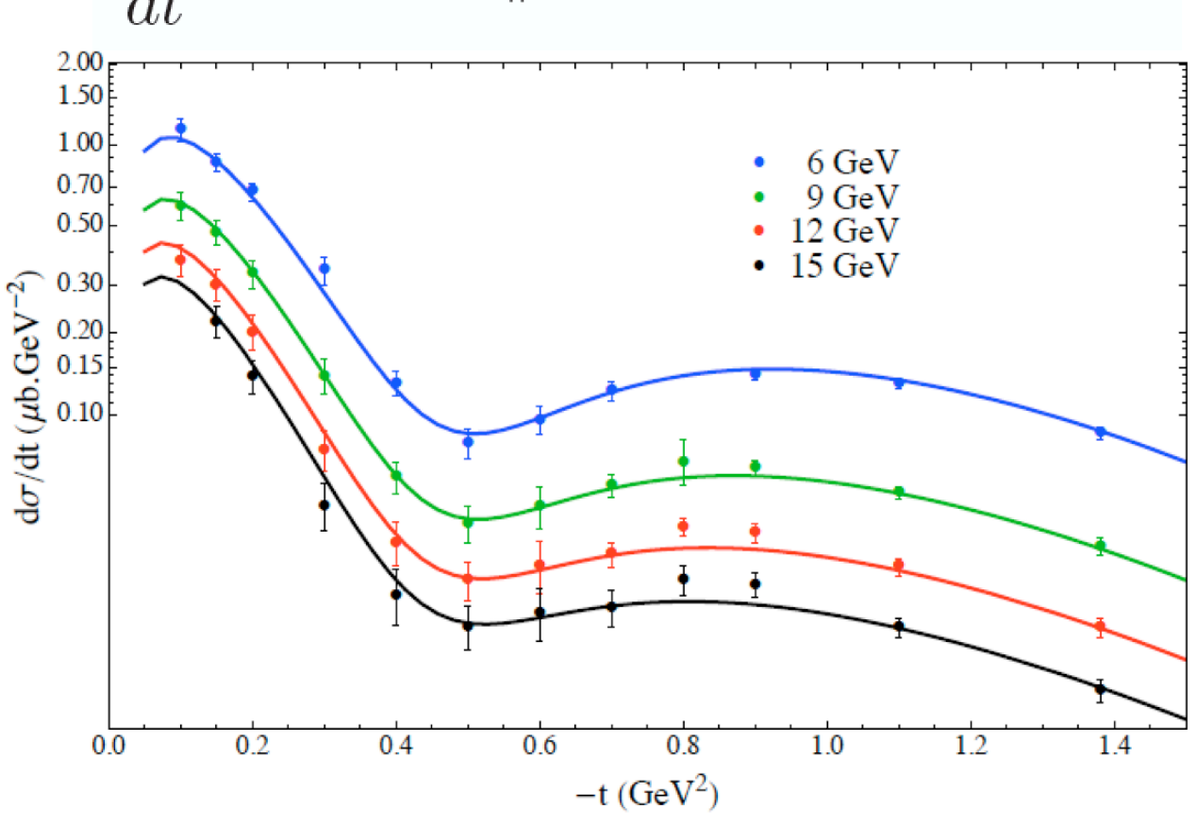
$1^{--} : \omega, \rho$

$1^{+-} : b, h$

1 OCTOBER 1971



$$\frac{d\sigma}{dt} = \sigma_\perp + \sigma_\parallel = |\rho + \omega|^2 + |b + h|^2$$

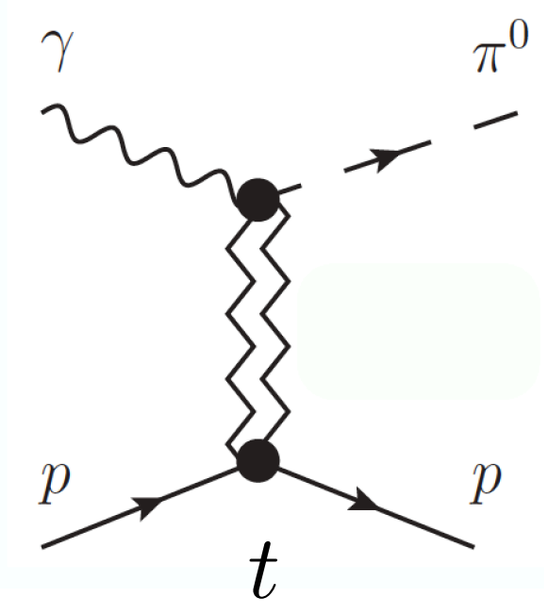


Mathieu et al. PRD 92, 074013

γp→π⁰p beam asymmetry Σ

- Beam asymmetry Σ provides insight into dominant production mechanism

$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$



Exchange J^{PC}

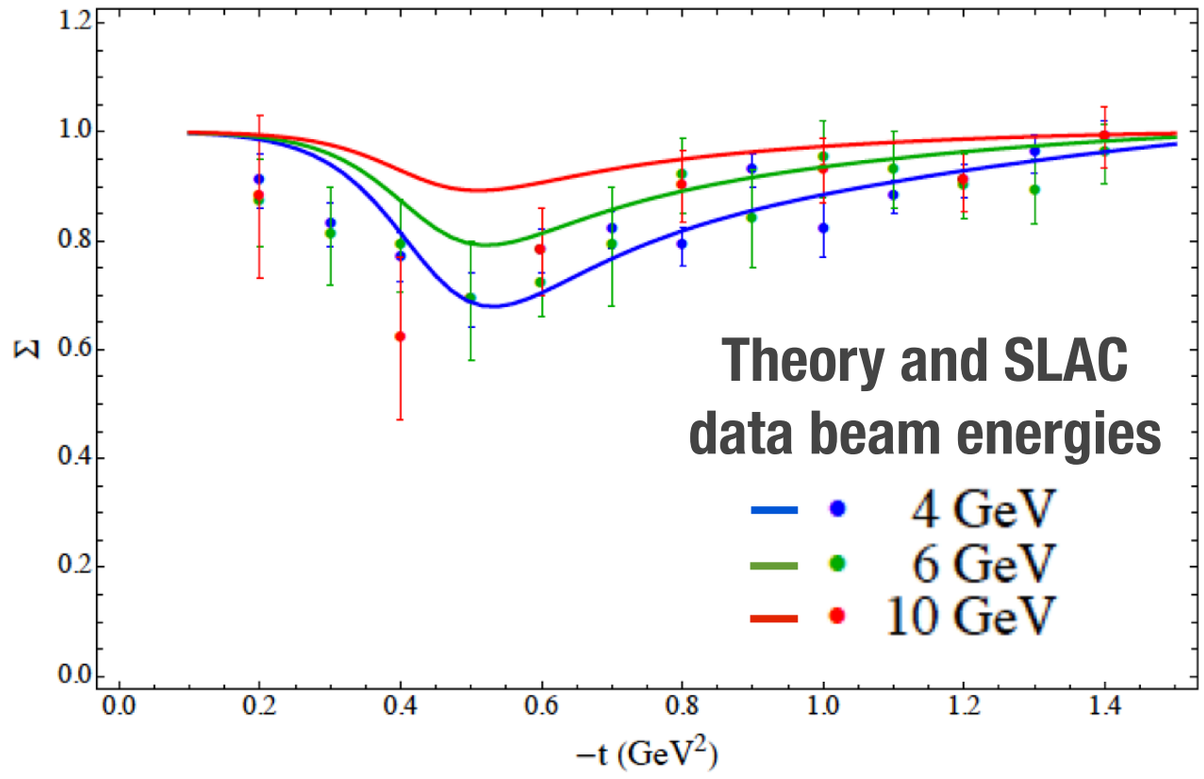
$1^{--} : \omega, \rho$

$1^{+-} : b, h$

- Understanding production mechanism critical to disentangling J^{PC} of observed states in exotic hybrid search

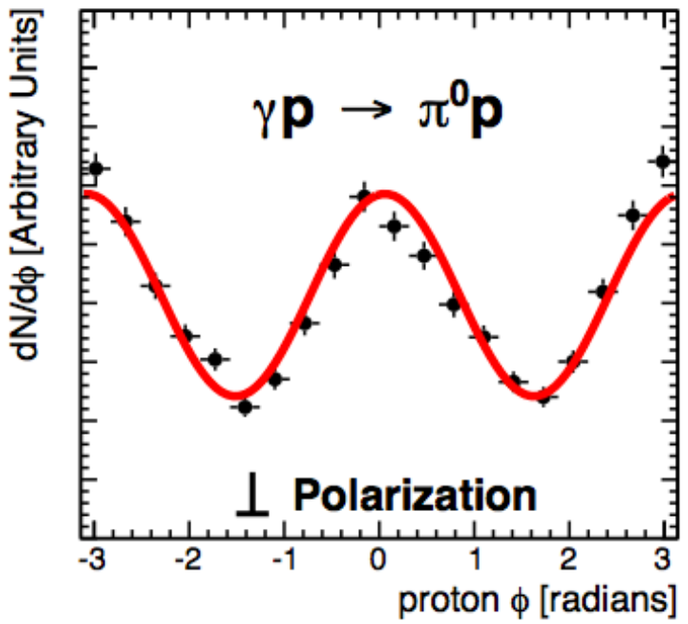
- From experimental standpoint easily extended to γp→ηp
  - No previous measurements!

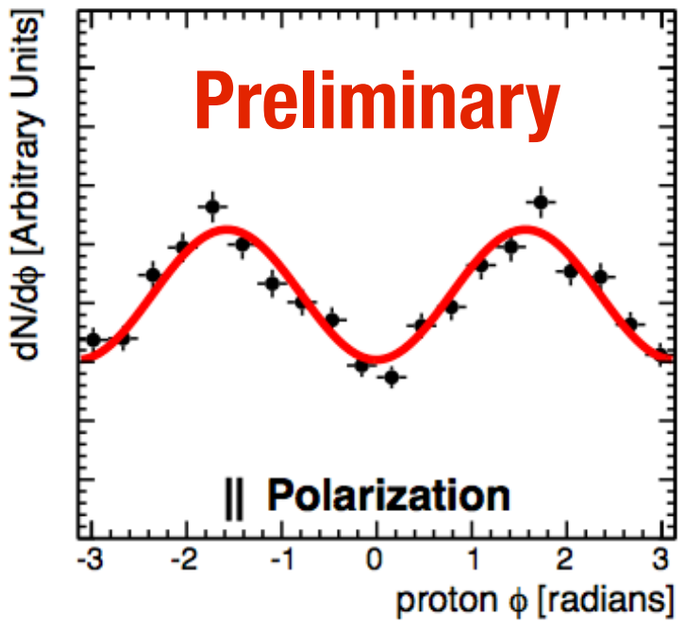
Mathieu et al. PRD 92, 074013

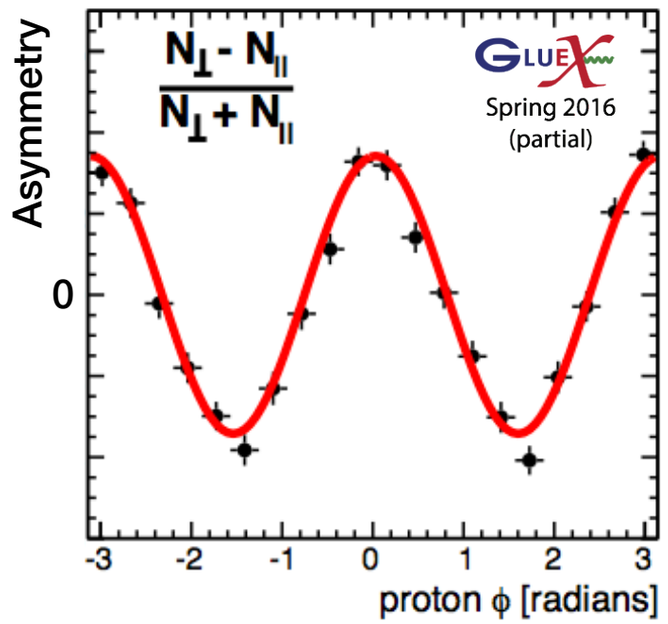


Pseudoscalar beam asymmetries Σ

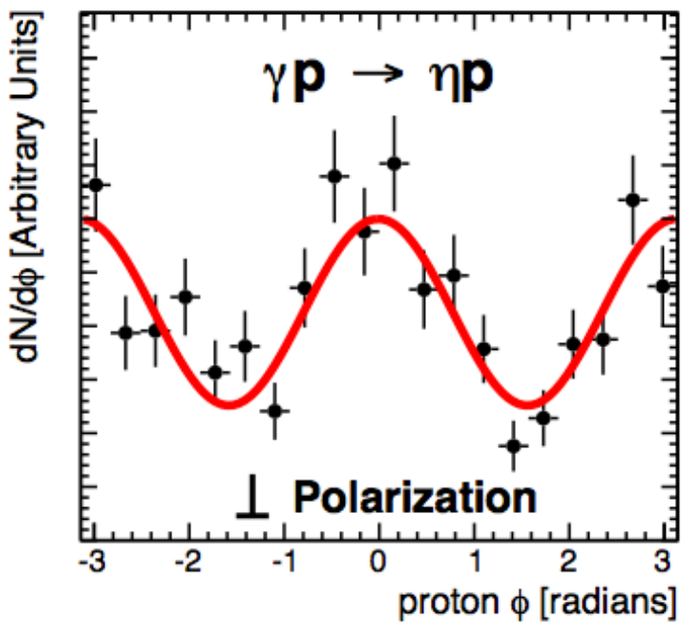
$$\gamma p \to \pi^0 p \qquad 8.4 < E_\gamma < 9 \text{ GeV}$$

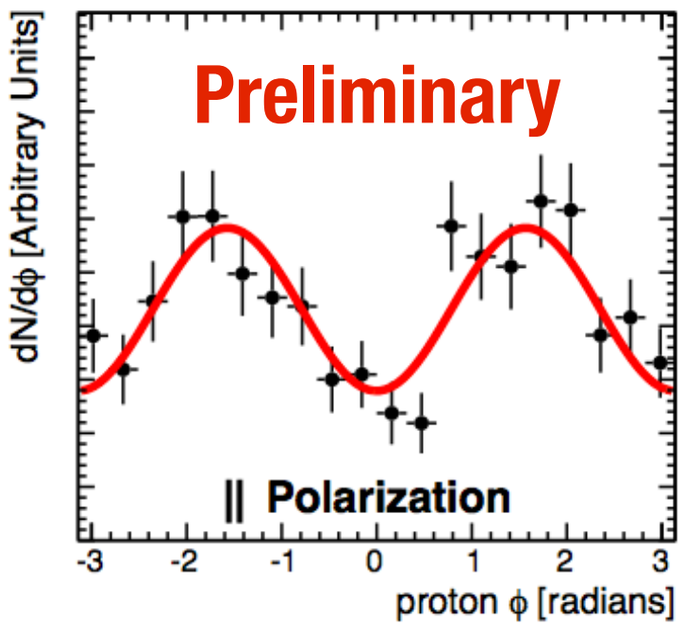


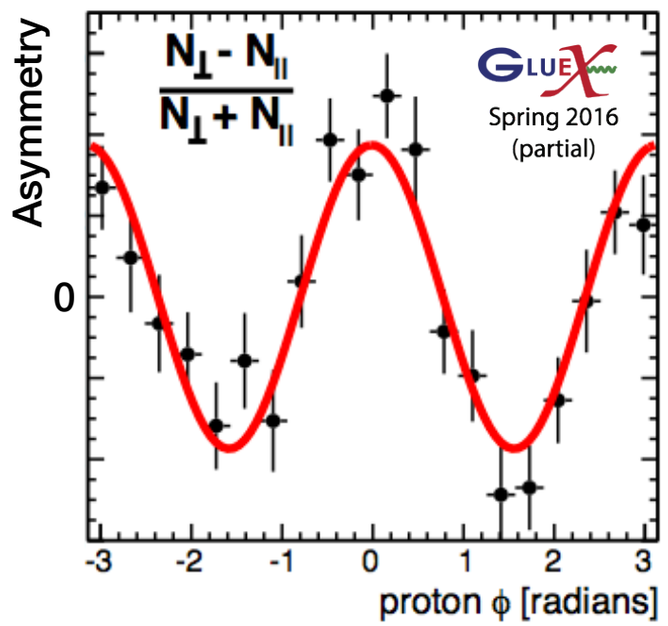




$$\gamma p \to \eta p \qquad \frac{N_\perp - N_\parallel}{N_\perp + N_\parallel} = P\Sigma cos(2\phi)$$

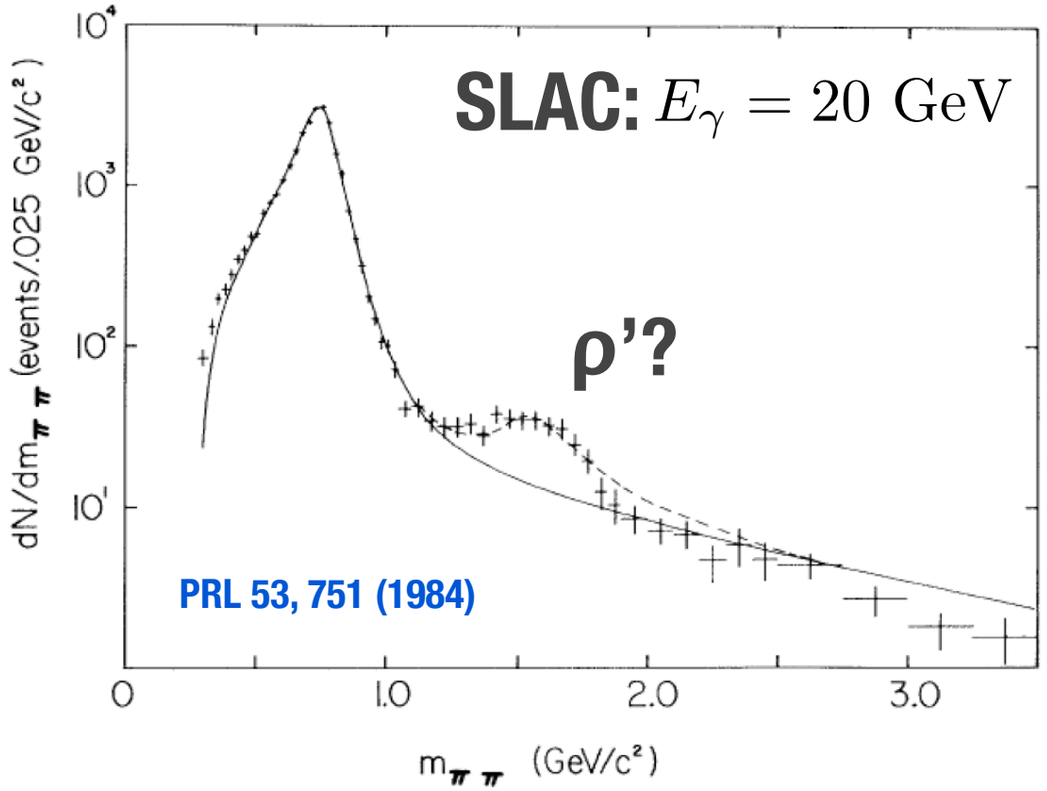


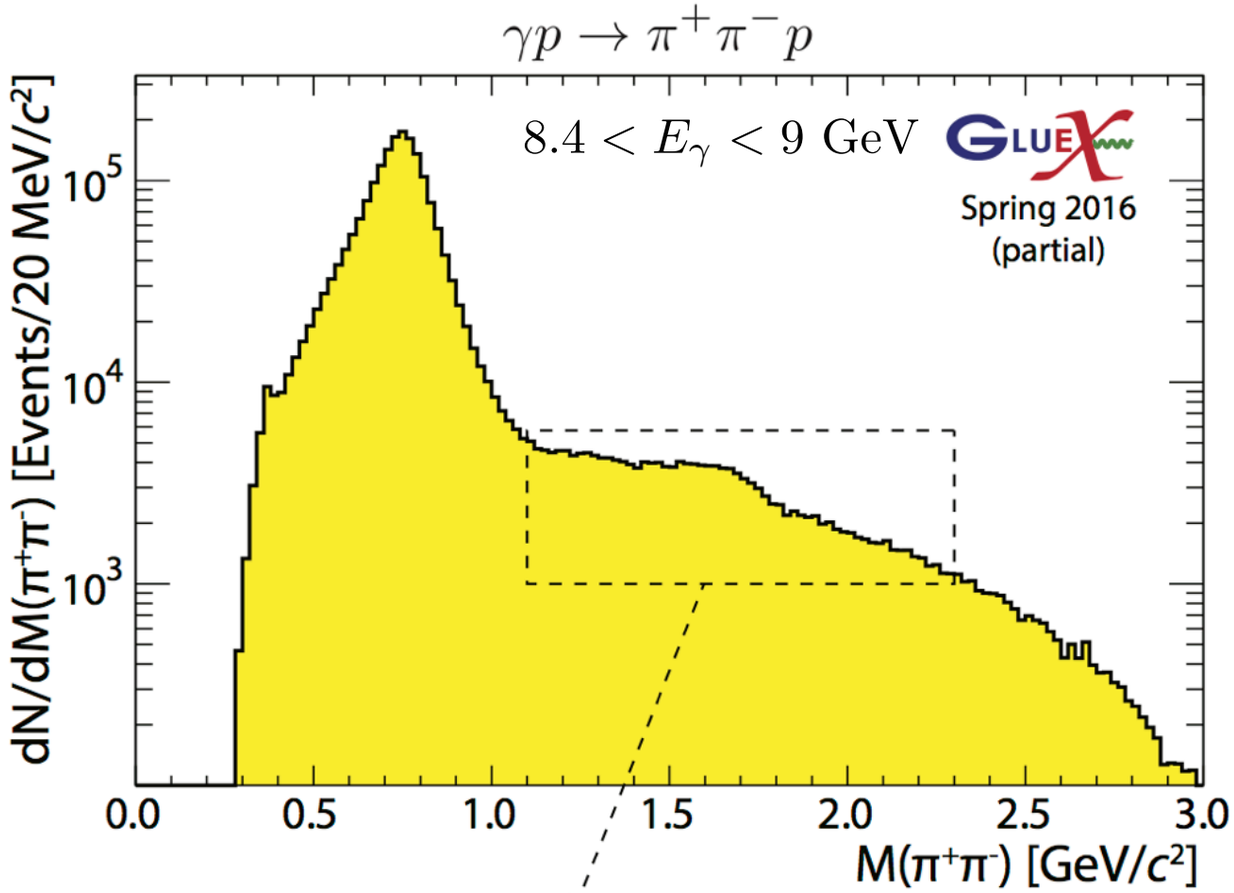


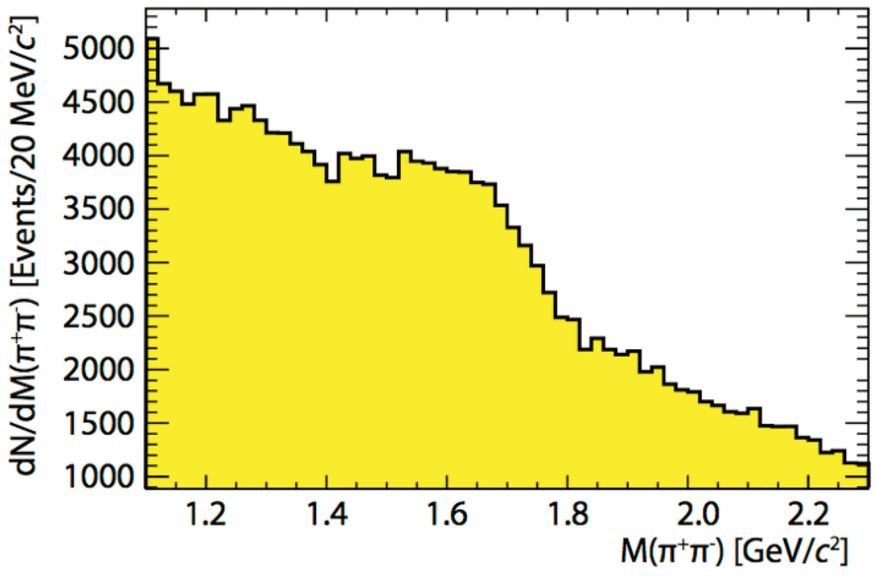


Early spectroscopy opportunities

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





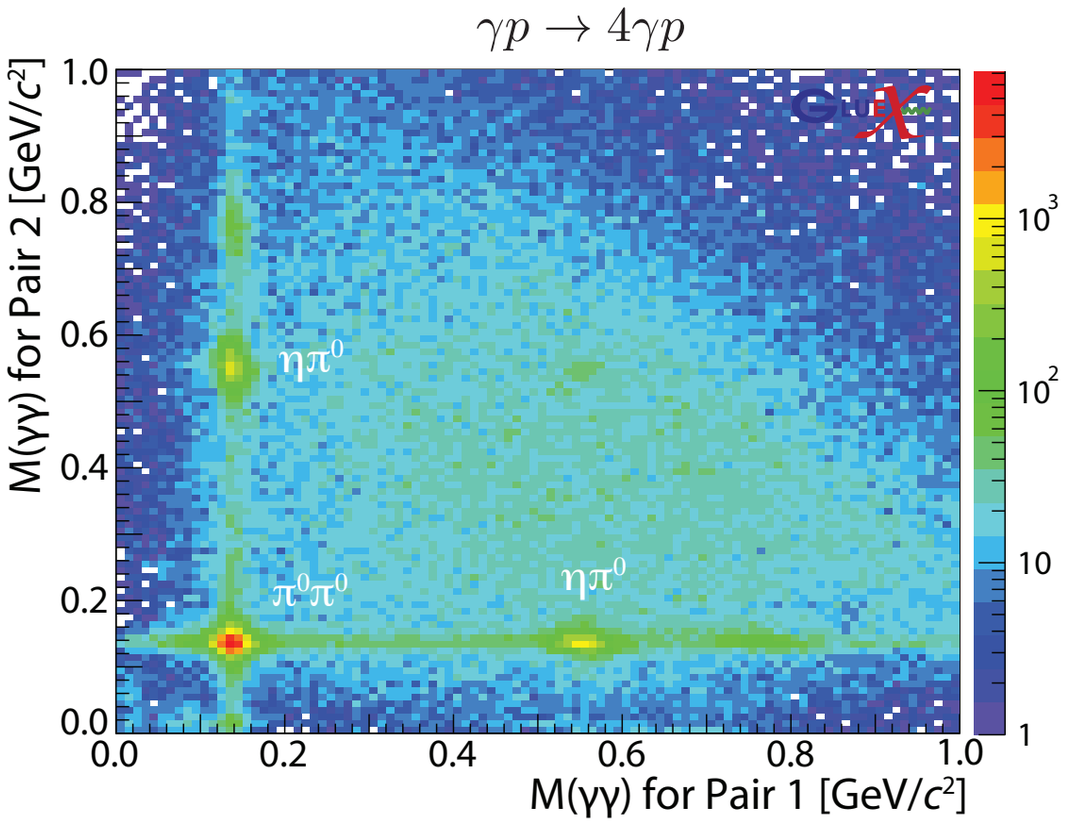


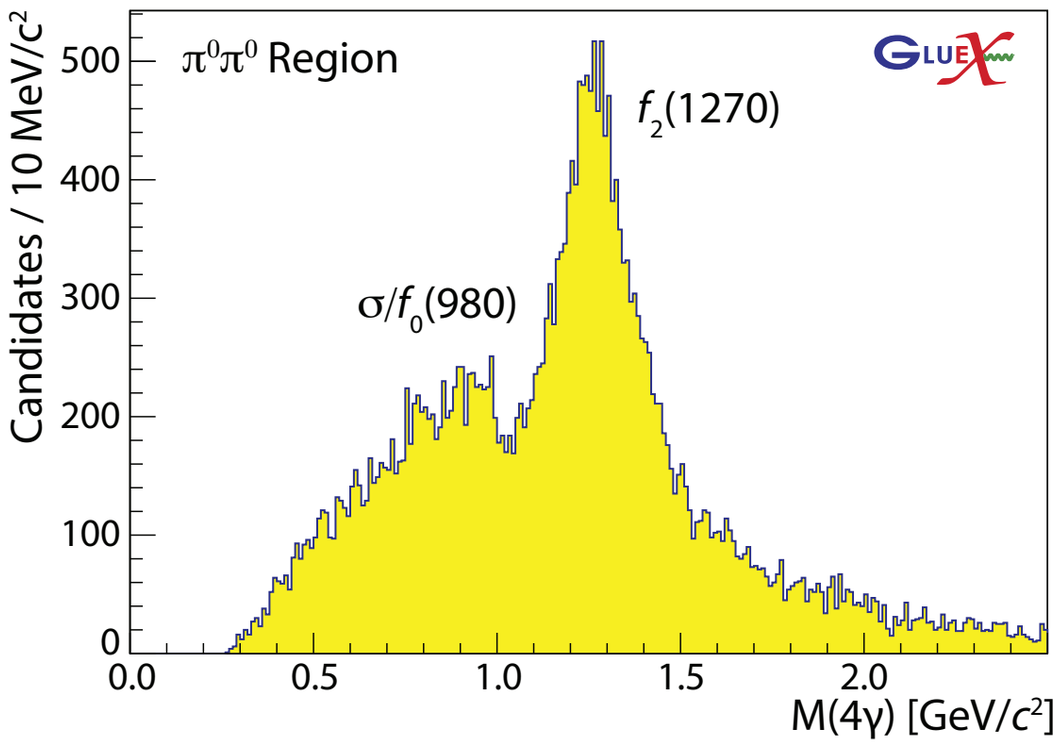
- Observe enhancement around 1.6 GeV with significantly larger statistics than previous SLAC measurements
- Polarization observables will provide further insight into the nature of this enhancement

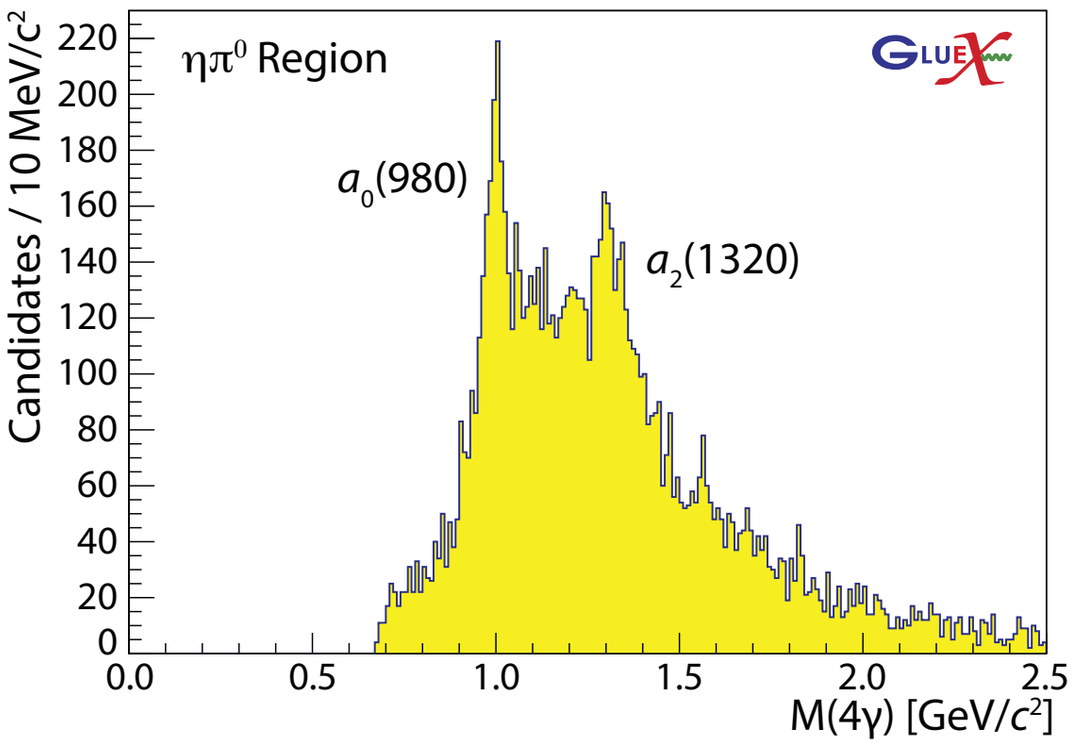
Early spectroscopy opportunities

$$\gamma p \to 4\gamma p$$

- Previous photoproduction data very sparse for channels with multiple neutrals particles
- Preliminary studies with a small fraction of the Spring 2016 data are already showing interesting features

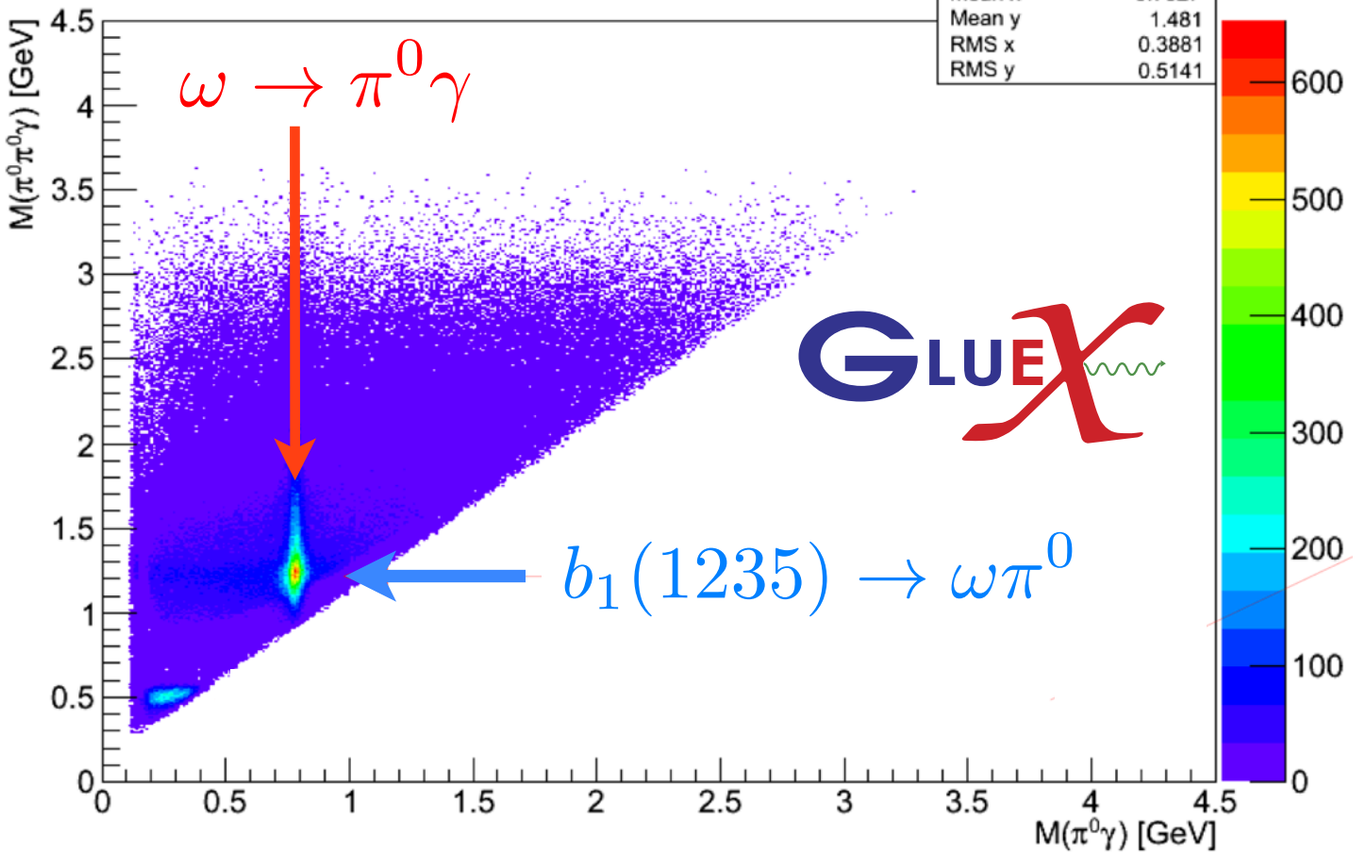


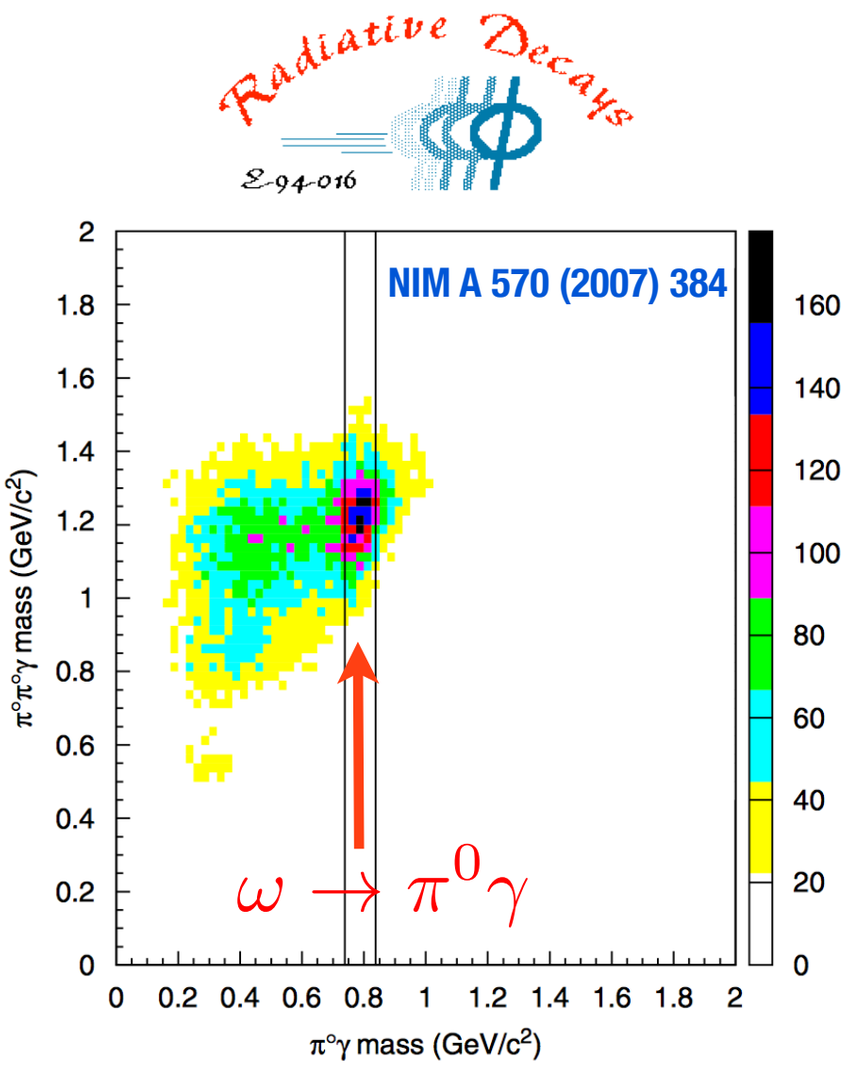




Early spectroscopy opportunities

$$\gamma p \to 5\gamma p$$



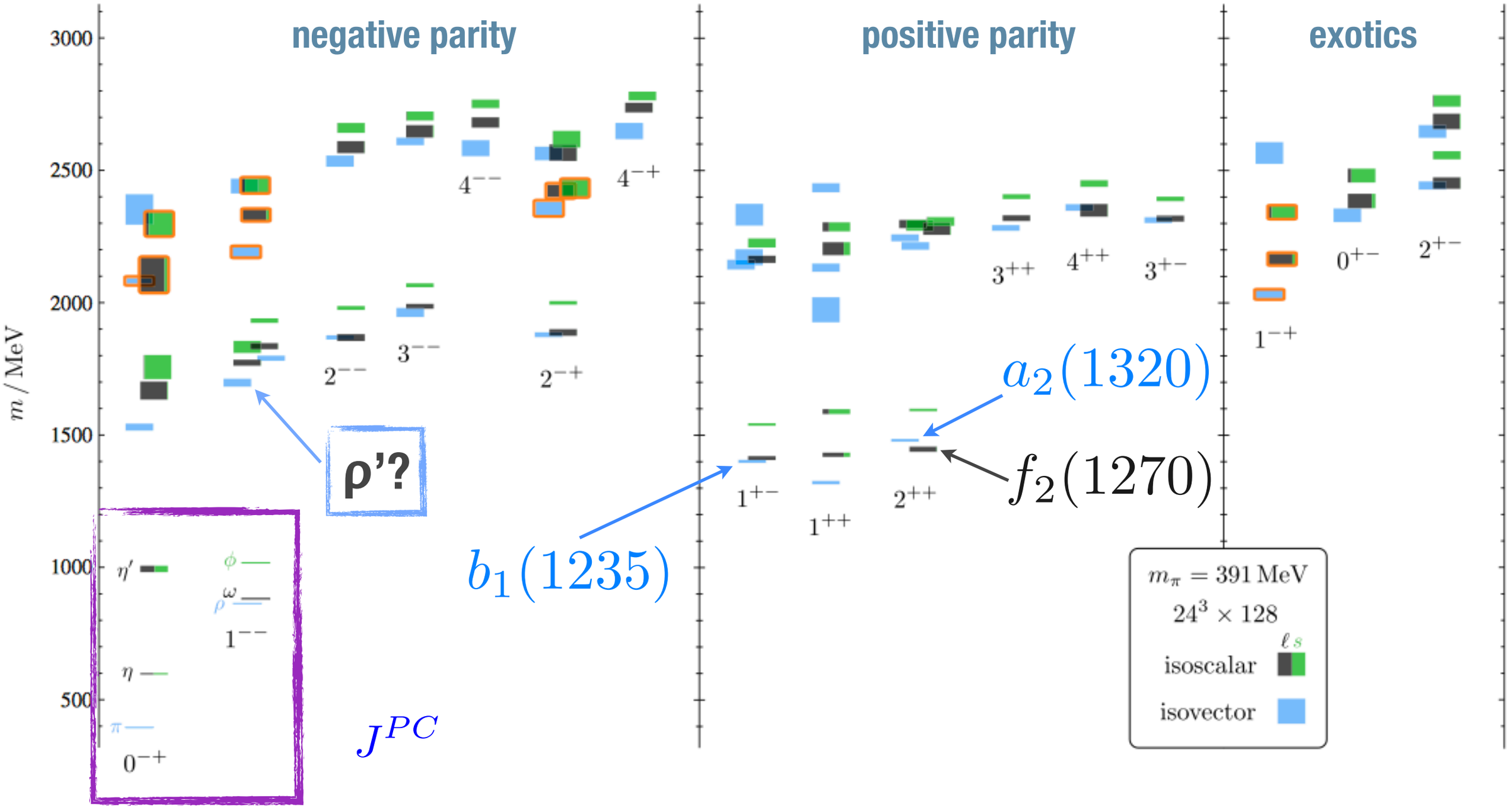


$$\gamma p \to b_1 p, b_1 \to \omega\pi^0, \omega \to \pi^0\gamma$$

- Successfully reconstructing 5γ final state and observe b_1 signal consistent with previous JLab photoproduction experiment (**RadPhi**)

Mapping the meson spectrum

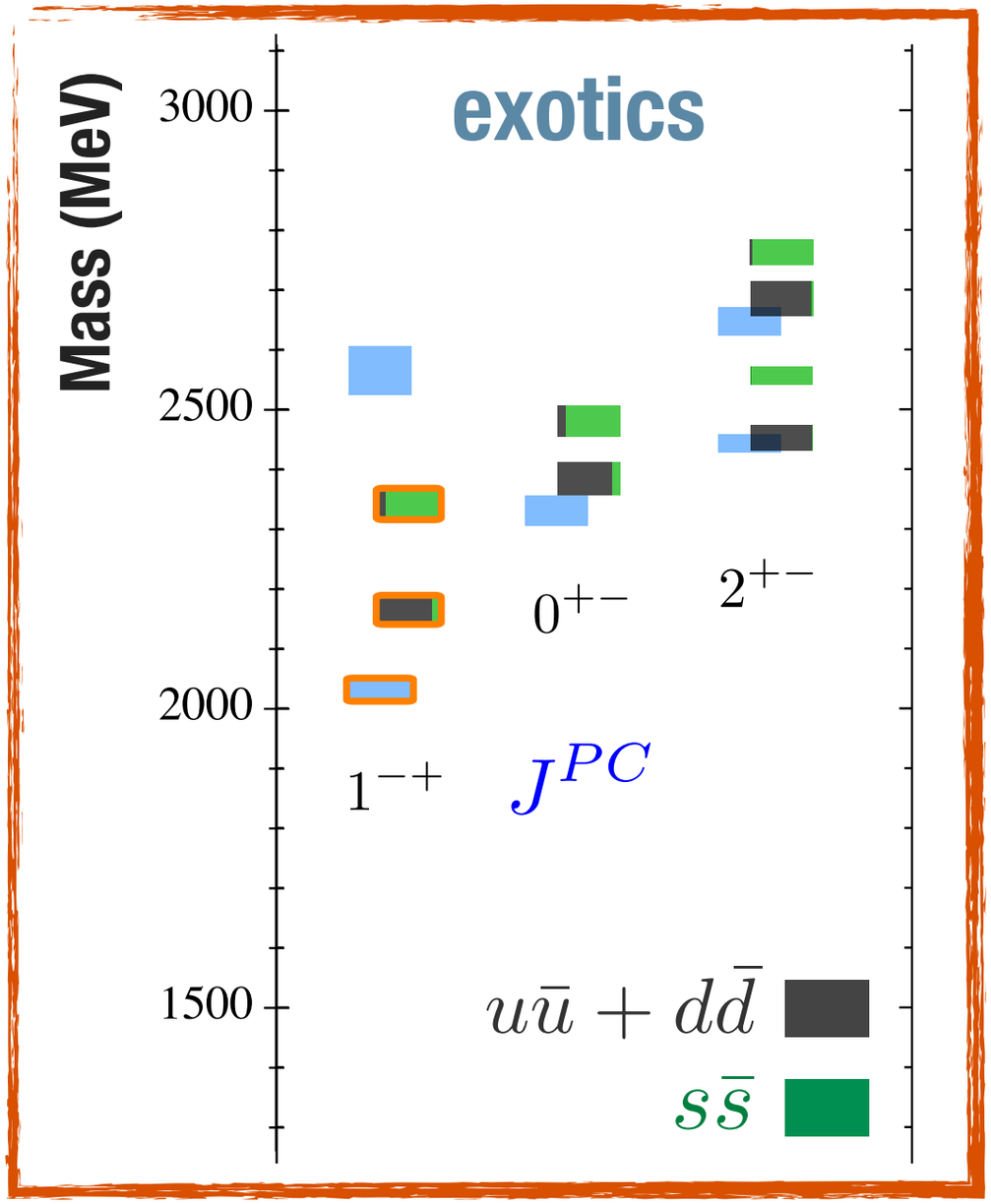
PRD 88 (2013) 094505



- Already studying polarization observables for **"simple" final states**
- Beginning to identify **known mesons** in multi-particle final states

GlueX future

- Lattice predicts **strange** and **light** quark content for mesons
- Search for a **pattern** of hybrid states in many final states
- Requires clean identification of charged pions and kaons



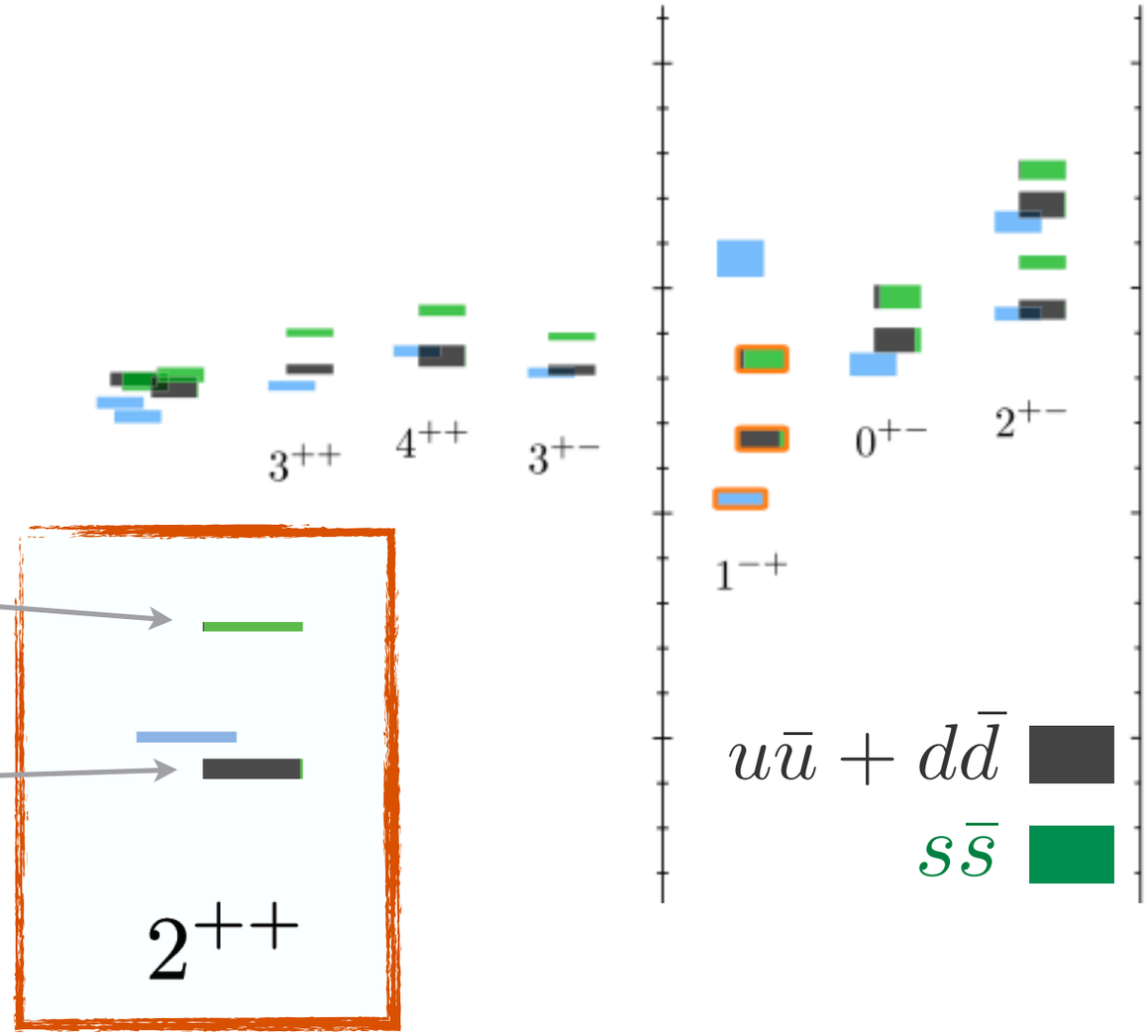
	Approximate Mass (MeV)	J^{PC}	Final States
π_1	1900	1^{-+}	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	2100	1^{-+}	4π, $\eta 4\pi$, $\eta\eta\pi\pi^\dagger$
η_1'	2300	1^{-+}	$KK\pi\pi^\dagger$, $KK\pi^\dagger$, $KK\omega^\dagger$

Strangeness program: decay patterns

- Experimentally infer quark flavor composition through branching ratios to strange and non-strange decays

$$\frac{\mathcal{B}(f_2'(1525) \to \pi\pi)}{\mathcal{B}(f_2'(1525) \to KK)} \approx 0.009$$

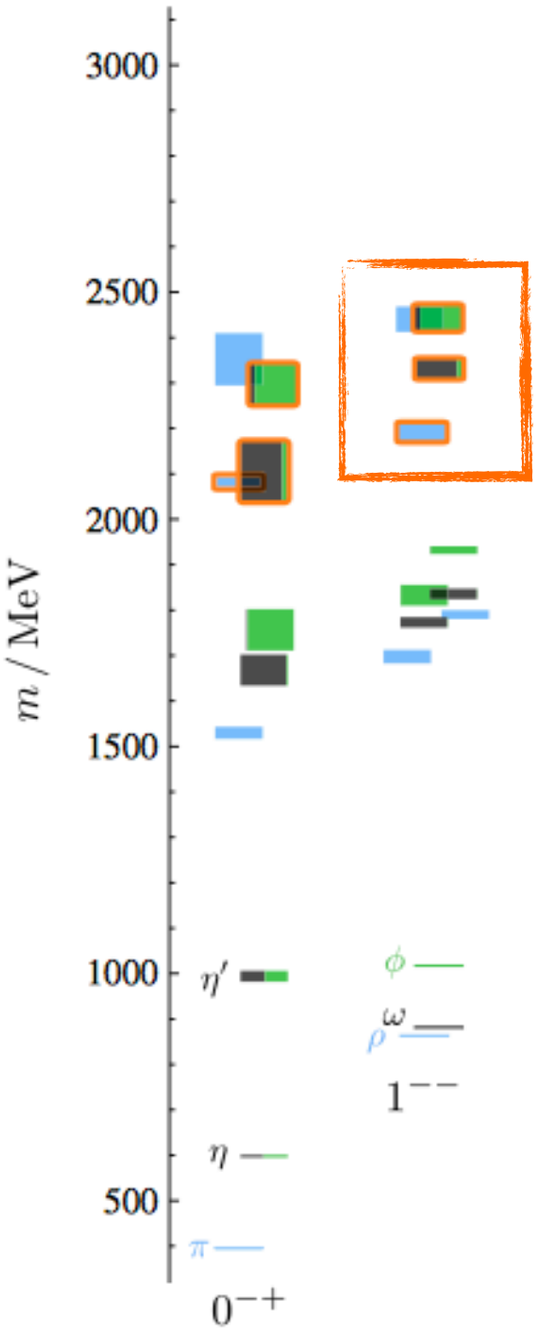
$$\frac{\mathcal{B}(f_2(1270) \to \pi\pi)}{\mathcal{B}(f_2(1270) \to KK)} \approx 20$$



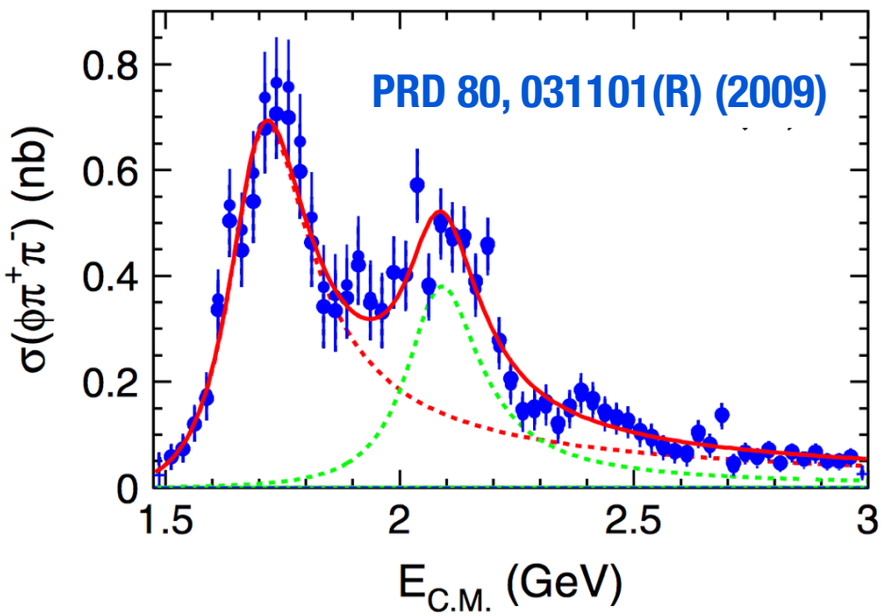
- Consistent with lattice QCD mixing angle for 2^{++}, and predictions for hybrids

- Need capability to detect strange and non-strange to infer hybrid flavor content

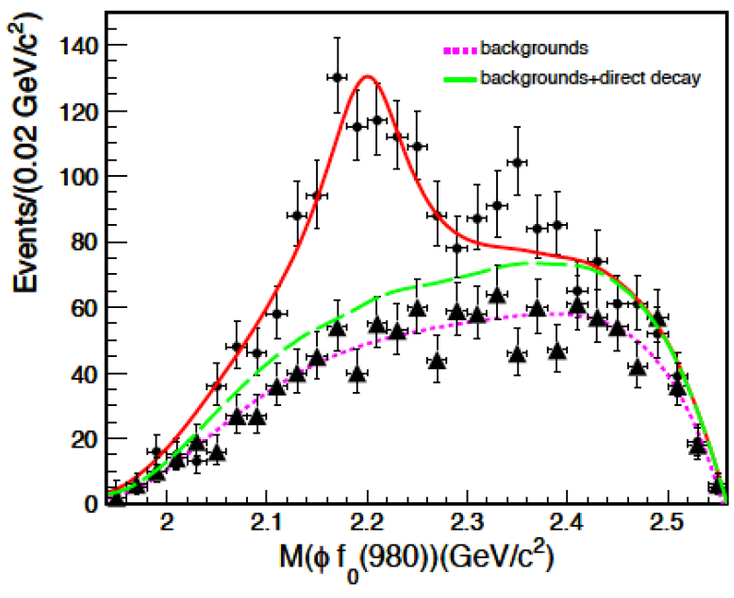
Strangeness program: Y(2175)



Belle: $e^+e^- \to \phi\pi^+\pi^-(\gamma)$



BES III: $J/\psi \to \eta\phi\pi^+\pi^-$



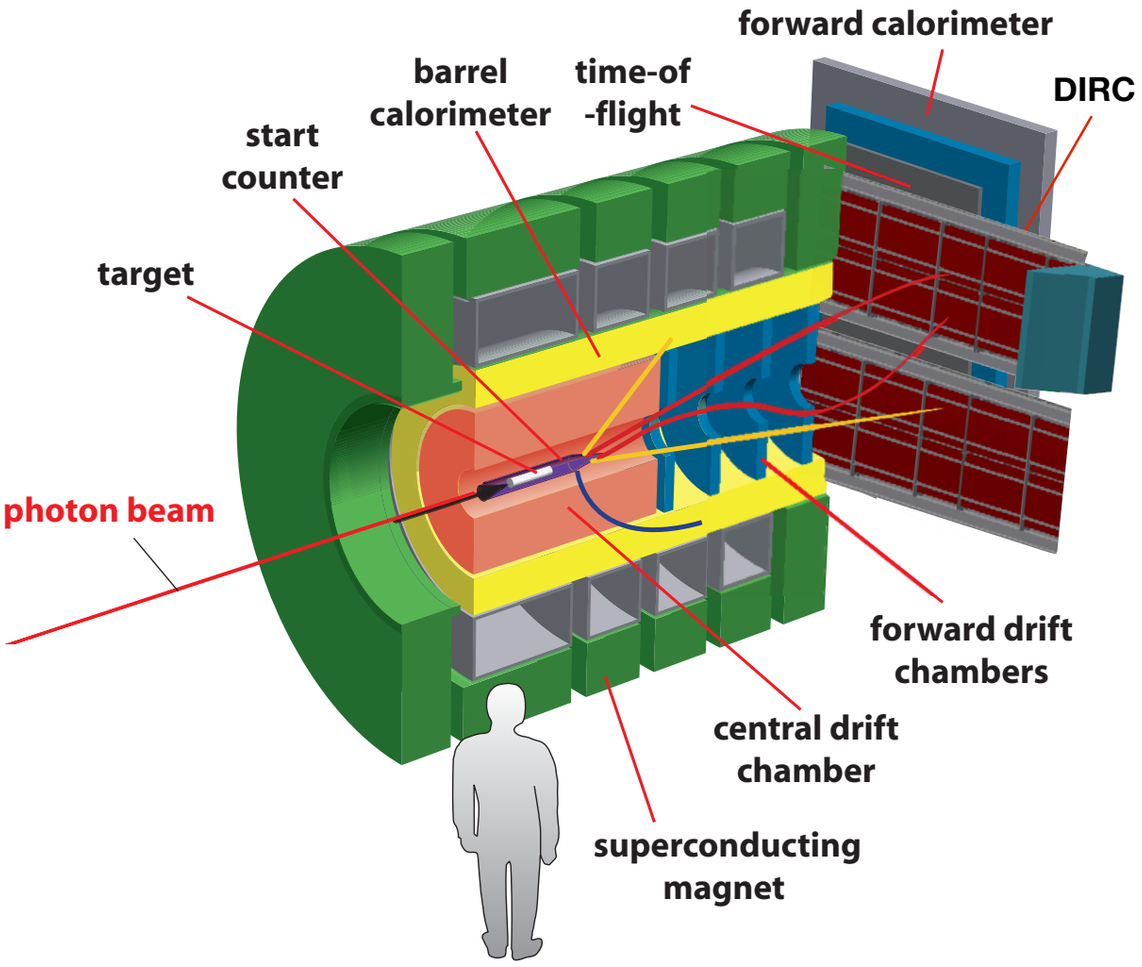
PRD 91, 052017 (2015)

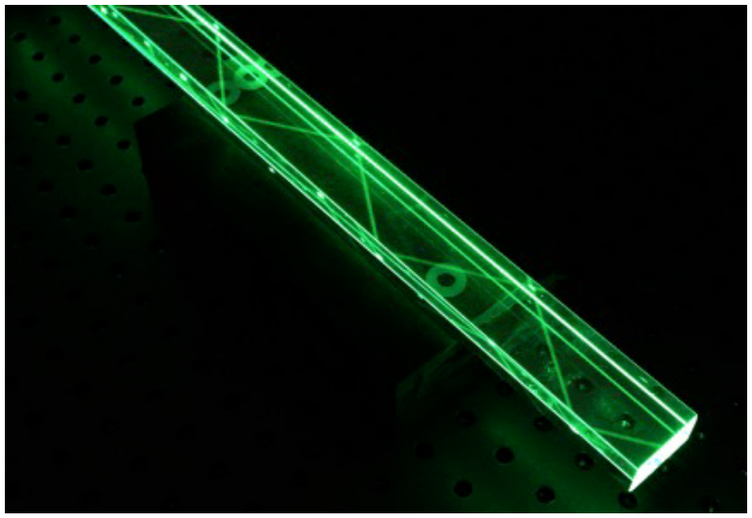
- Y(2175) $J^{PC}=1^{--}$ state observed by 3 experiments
- Decay pattern similar to Y(4260) in charmonium

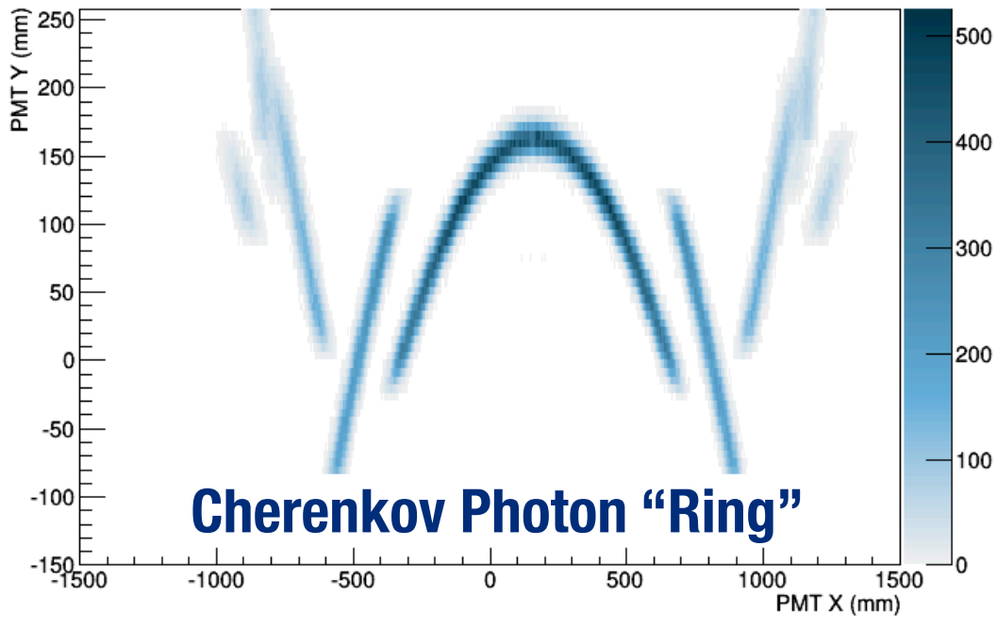
$$Y(2175) \to \phi\pi^+\pi^- \qquad Y(4260) \to J/\psi\pi^+\pi^-$$

- Is it a supernumerary state in the strangeonium spectrum? Possibly a hybrid?

DIRC upgrade

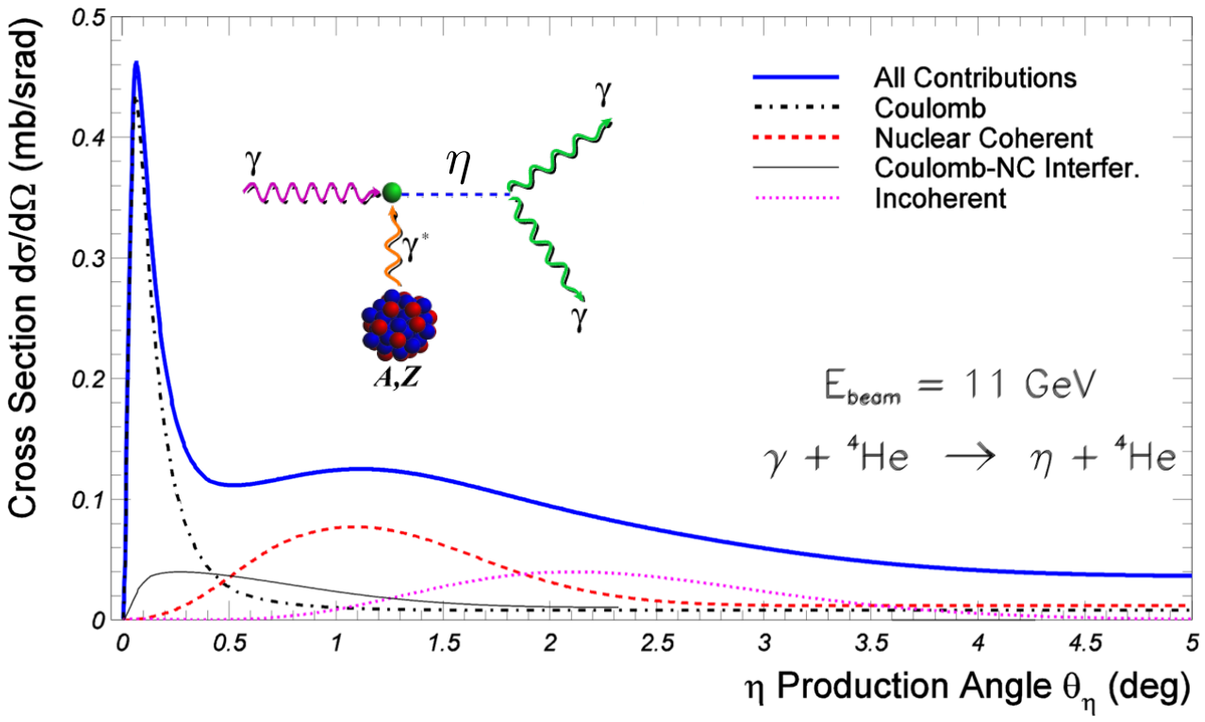






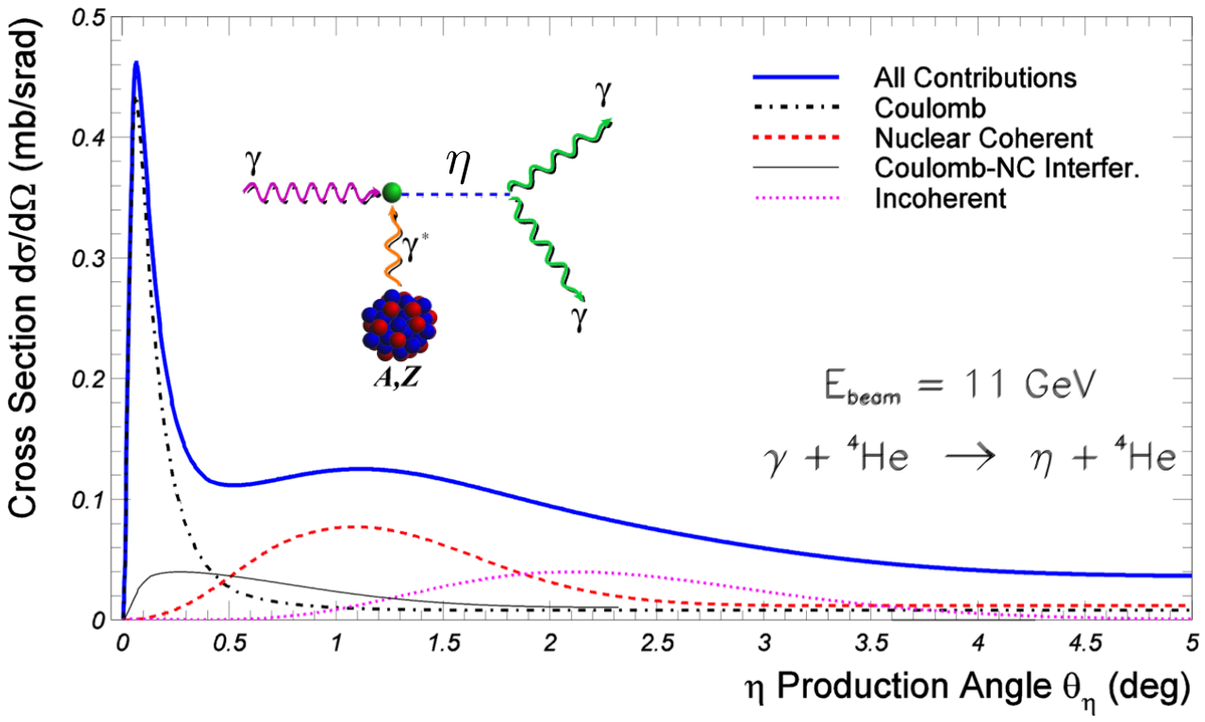
- The GlueX **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light) provides new K/π separation and will use components of the BaBar DIRC
- Installation and commissioning in **2018**

Primakoff program



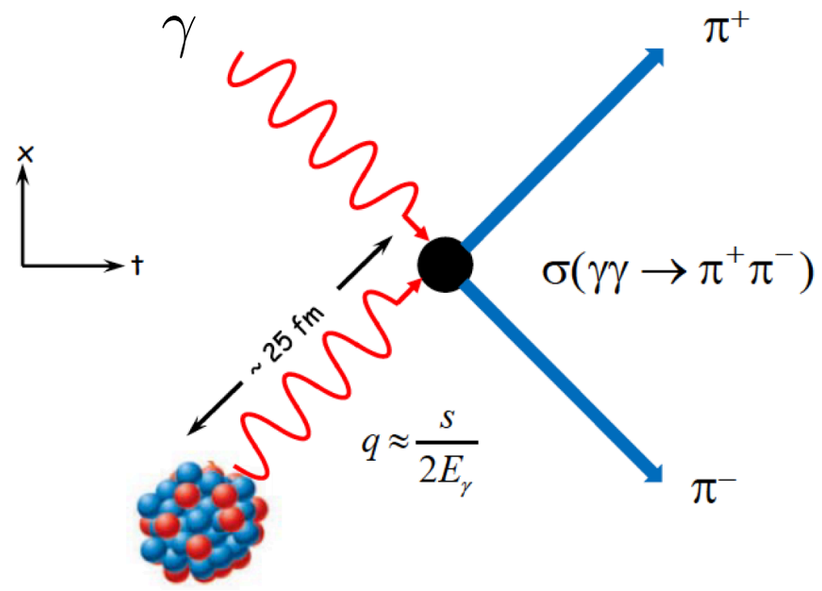
- η → γγ decay width through Primakoff production
- Test discrepancy between measurements at e^+e^- colliders and previous Primakoff results

Primakoff program



- η → γγ decay width through Primakoff production
- Test discrepancy between measurements at e^+e^- colliders and previous Primakoff results

- Extract charge pion polarizability from Primakoff production of pion pairs
- Comparison to other processes, eg. COMPASS's recent $\pi^- \gamma \to \pi^- \gamma$ and further test χPT predictions



GlueX outlook

- **Successful commissioning and first physics analyses ongoing**
- **Low-intensity GlueX: Begin Fall 2016 (complete in 2018)**
  - $\gamma p \to (\rho, \omega, \phi)p,\ \ \gamma p \to (\pi^0, \eta, \eta')p$, etc.
    - Cross sections, beam asymmetries and spin-density matrix elements to understand production mechanisms
    - Compare with previous measurements and models to confirm understanding of detector, normalization, etc.
  - Begin **spectroscopy analyses** towards identification of known resonances and hybrid candidates
- **Detector upgrade for improved K/π separation ~2018+**
- **Primakoff program for η decay width and $\pi^{\pm}$ polarizability**

Backup

Exotic J^{PC} decays

C. A. Meyer and E. S. Swanson,
Progress in Particle and Nuclear Physics B82, 21, (2015)

	Approximate Mass (MeV)	J^{PC}	Total Width MeV PSS	IKP	Allowed Decay Modes
π_1	1900	1^{-+}	81 – 168	117	$b_1\pi$, $\pi\rho$, πf_1, $\pi\eta$, $\pi\eta'$, ηa_1, $\pi\eta(1295)$
η_1	2100	1^{-+}	59 – 158	107	πa_1, πa_2, ηf_1, ηf_2, $\pi\pi(1300)$, $\eta\eta'$, KK_1^A, KK_1^B
η_1'	2300	1^{-+}	95 – 216	172	KK_1^B, KK_1^A, KK^*, $\eta\eta'$
b_0	2400	0^{+-}	247 – 429	665	$\pi\pi(1300)$, πh_1, ρf_1, ηb_1
h_0	2400	0^{+-}	59 – 262	94	πb_1, ηh_1, $KK(1460)$
h_0'	2500	0^{+-}	259 – 490	426	$KK(1460)$, KK_1^A, ηh_1
b_2	2500	2^{+-}	5 – 11	248	πa_1, πa_2, πh_1, $\eta\rho$, ηb_1, ρf_1
h_2	2500	2^{+-}	4 – 12	166	$\pi\rho$, πb_1, $\eta\omega$, ωb_1
h_2'	2600	2^{+-}	5 – 18	79	KK_1^B, KK_1^A, KK_2^*, ηh_1

- Predictions for the spectrum of hybrids from lattice, **but decay predictions are model dependent**

1^{-+} channels observed

$$\pi\rho \to \pi\pi\pi$$
$$\pi\eta' \to \eta\pi\pi\pi$$
$$\pi b_1 \to \omega\pi\pi$$

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$$\pi\eta' \to \eta\pi\pi\pi$$
$$\pi b_1 \to \omega\pi\pi$$

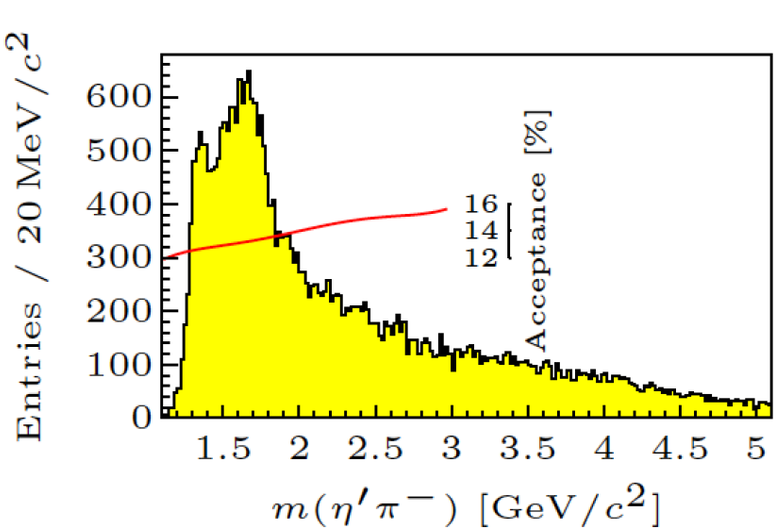
Some additional 1^{-+} channels

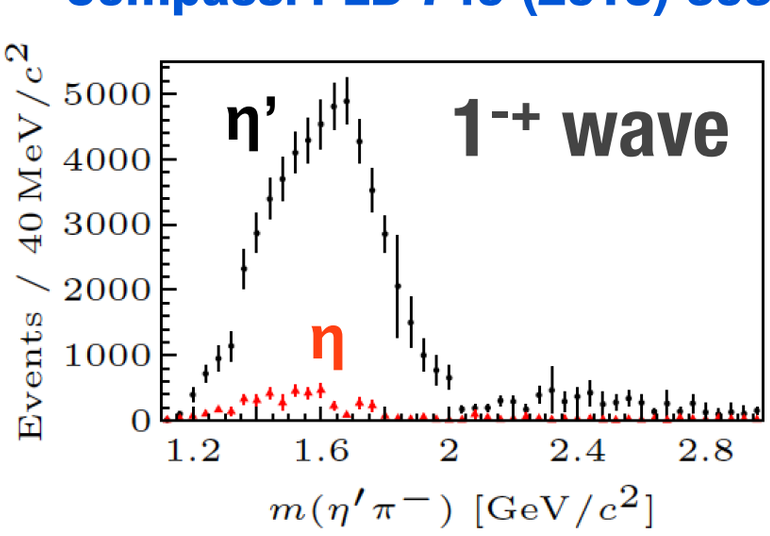
$$\pi a_2 \to \eta\pi\pi \qquad \eta f_1 \to \eta\eta\pi\pi$$
$$KK^* \to KK\pi$$
$$KK_1(1270) \to KK\pi\pi$$

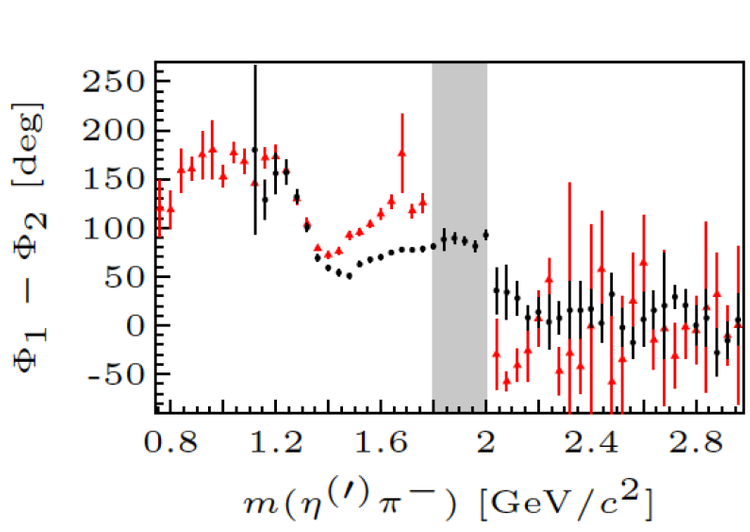
Evidence for 1^{-+} exotics

- **$\pi_1(1400) \rightarrow \eta\pi$**
  - Not likely a hybrid: dynamical origin or 4-quark state?
- **$\pi_1(1600) \rightarrow \pi\pi\pi$, $\eta'\pi$, $b_1\pi$, etc.**

Compass: PLB 740 (2015) 303







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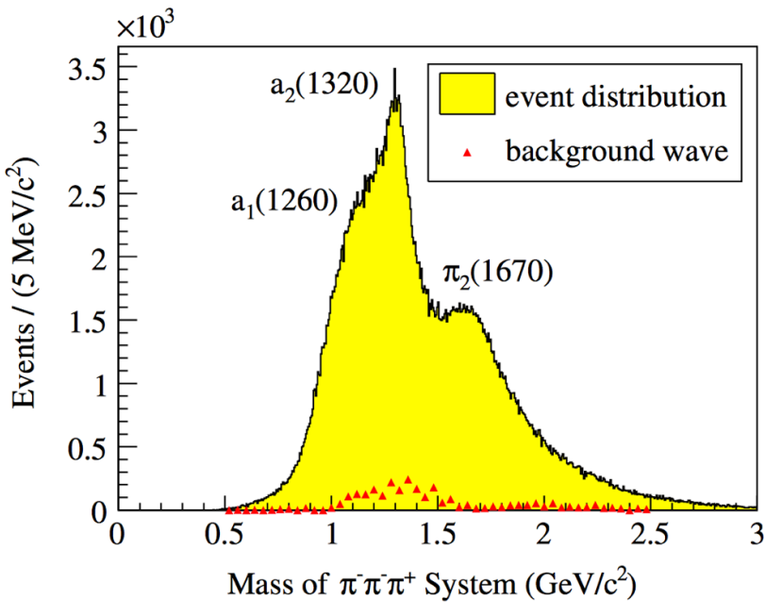
Compass: PRL 104, 241803 (2010)



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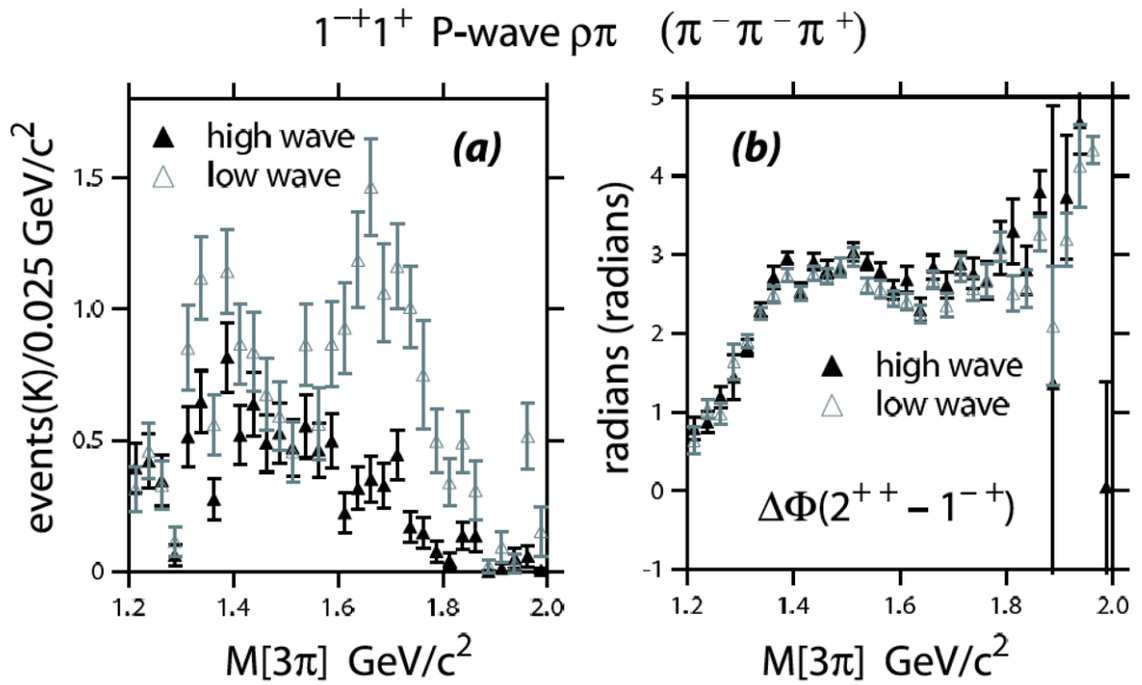
E852: PRD 73 (2006) 072001

Found no exotic when using a larger set of partial waves (ie. “high wave”) than previous analysis



- **Not** observed in $\gamma p \rightarrow n\,\pi^+\pi^-\pi^+$ at CLAS: charged vs neutral exchange?

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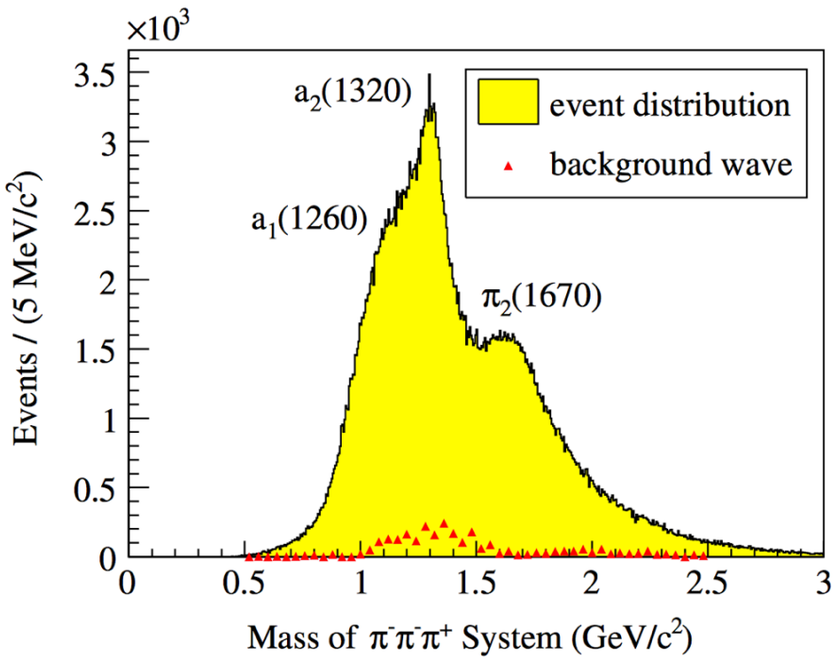
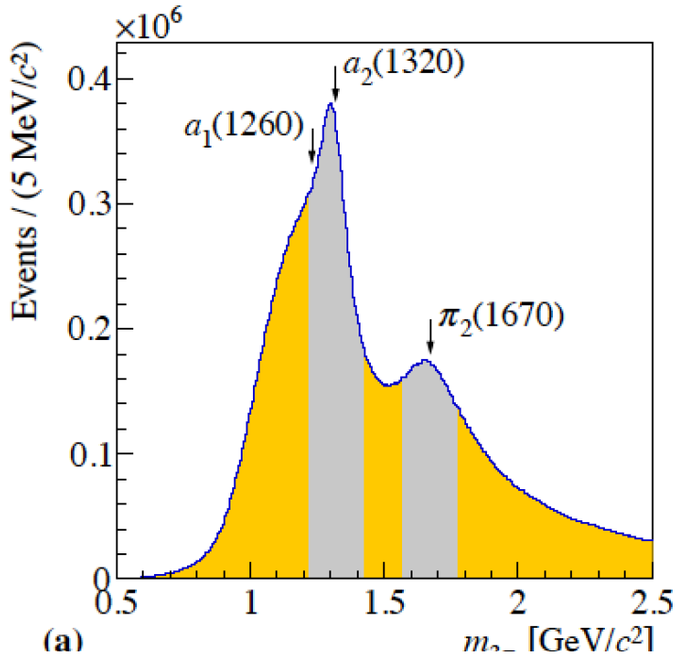


Unprecedented statistics

Compass: 1509.00992

Discuss non-exotic waves



- Clear evidence for $J^{PC}=1^{-+}$ partial waves, but interpretation not conclusive

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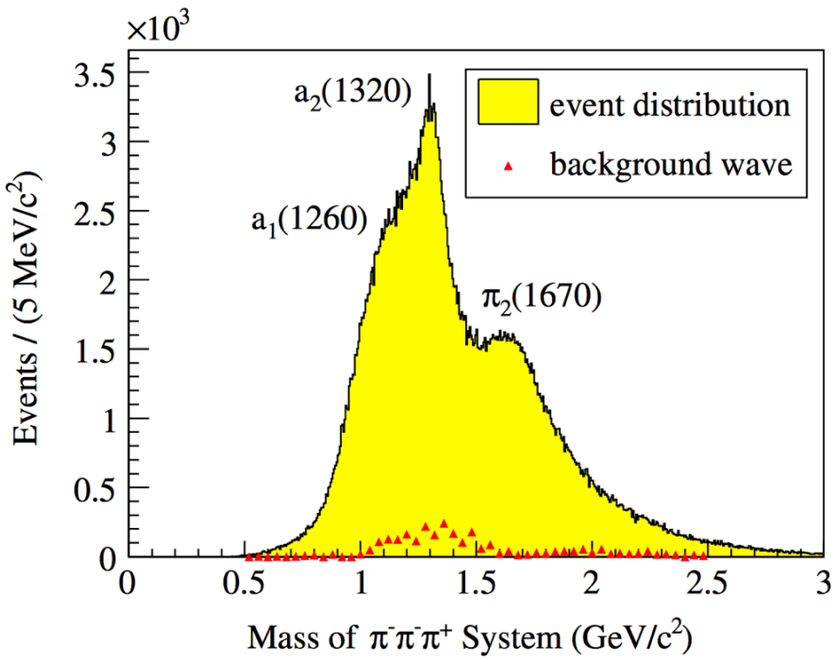

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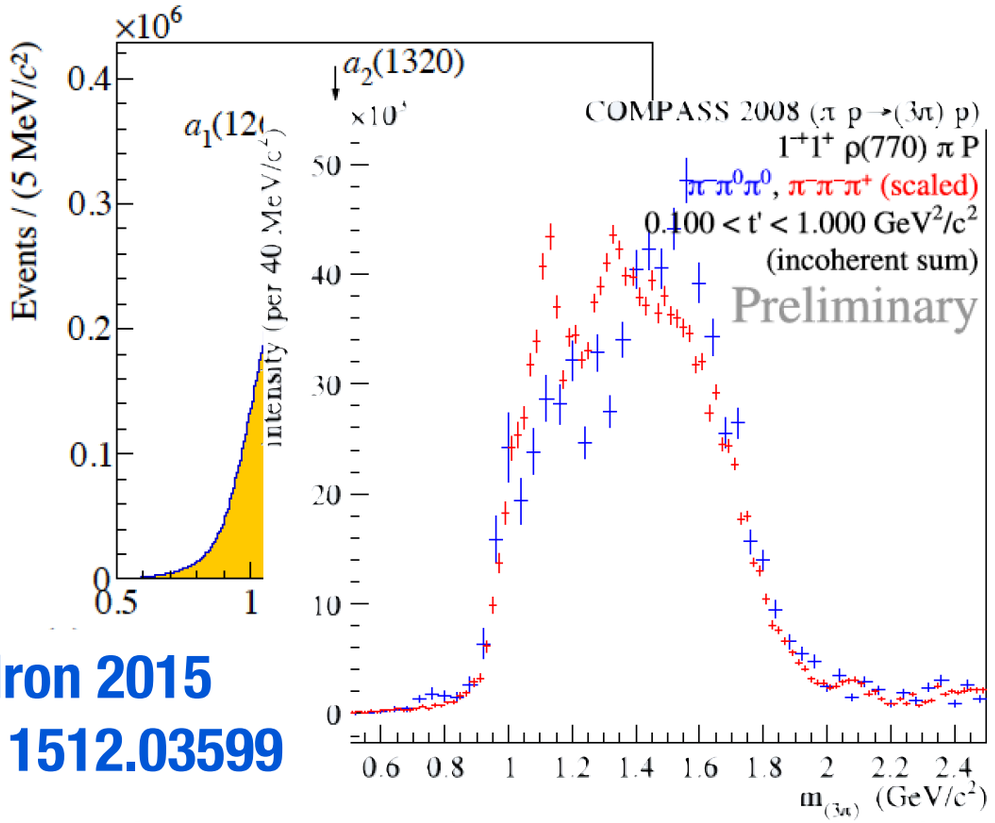
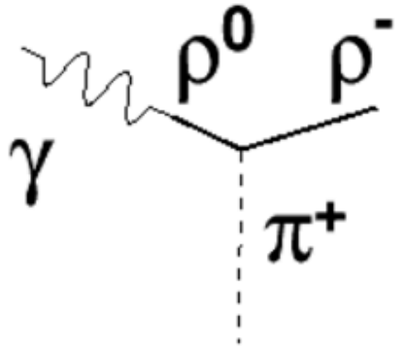


Hadron 2015
Grube: 1512.03599

- Clear evidence for $J^{PC}=1^{-+}$ partial waves, but interpretation not conclusive

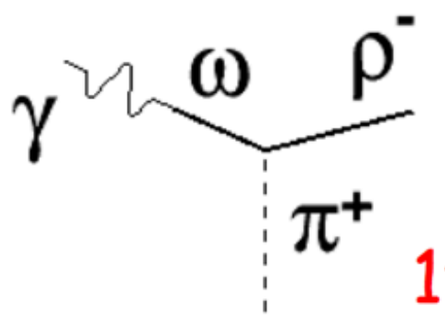
Quantum number counting

Assuming Vector Dominance



G = (+) → (-)(+)
Forbidden

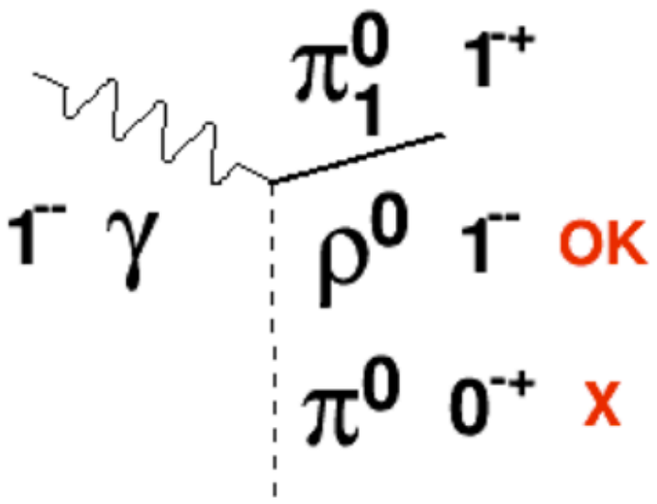
$0^-(1^{--})$ $1^+(1^{--})$ $I^G(J^{PC})$



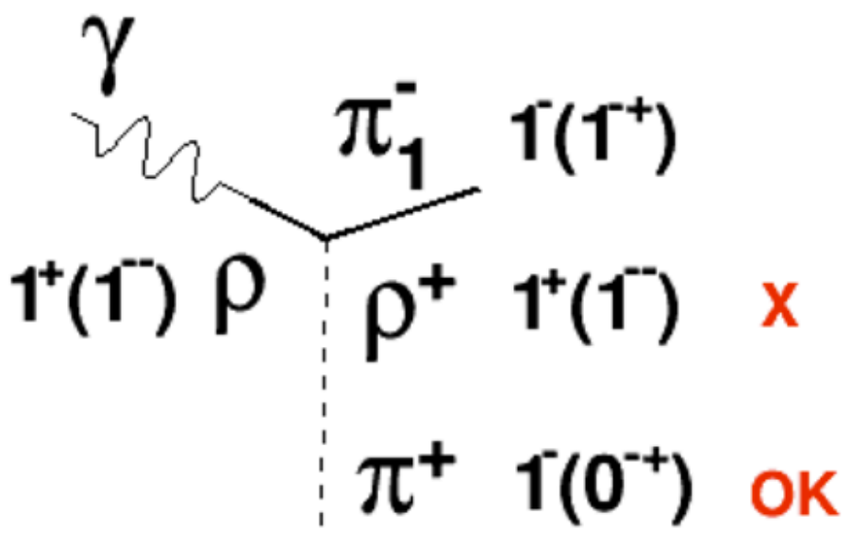
G = (-) → (-)(+)
Allowed

$1^-(0^{-+})$

-> Proceeds via ω coupling



C Conservation

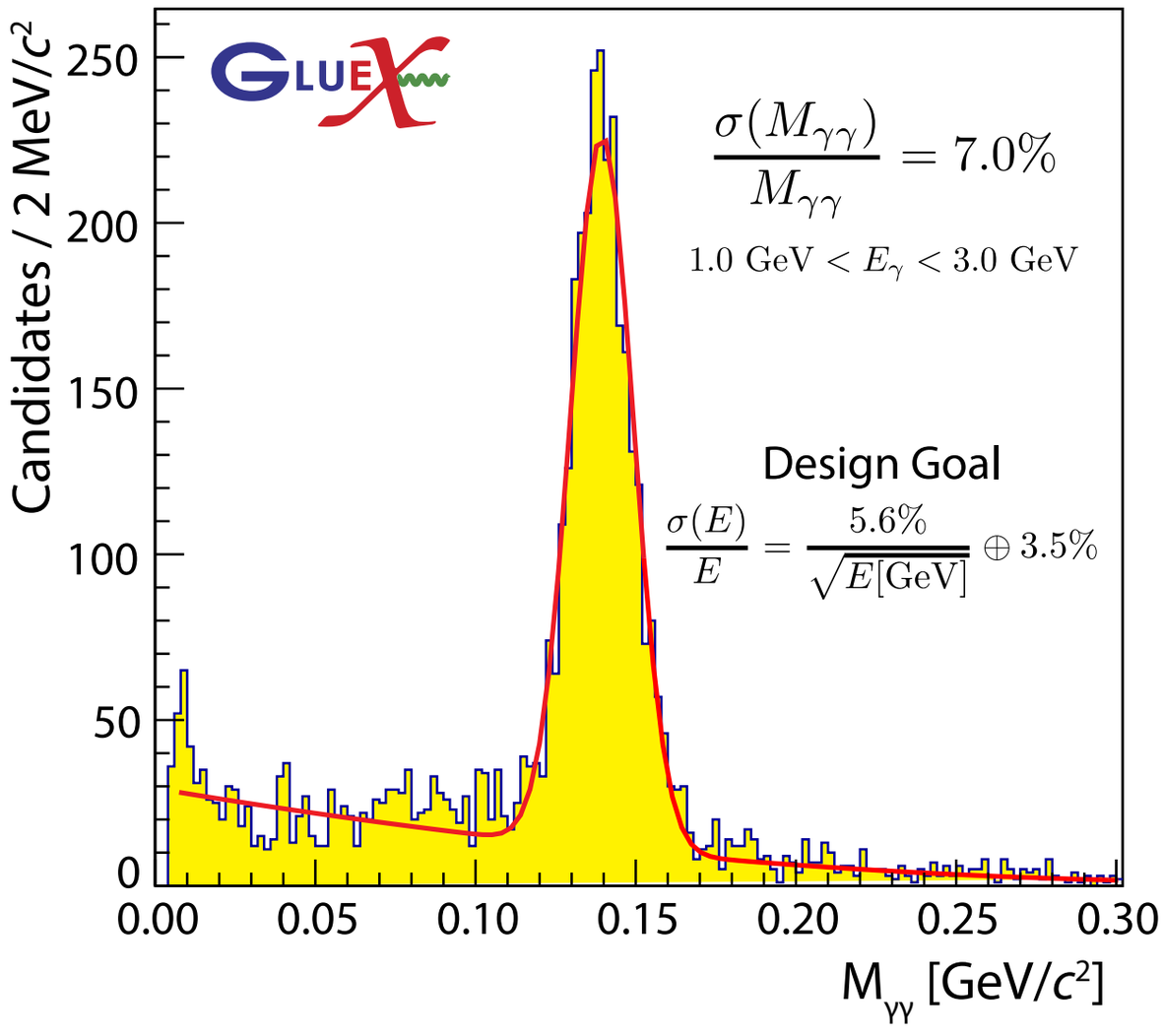


G-Parity Conservation

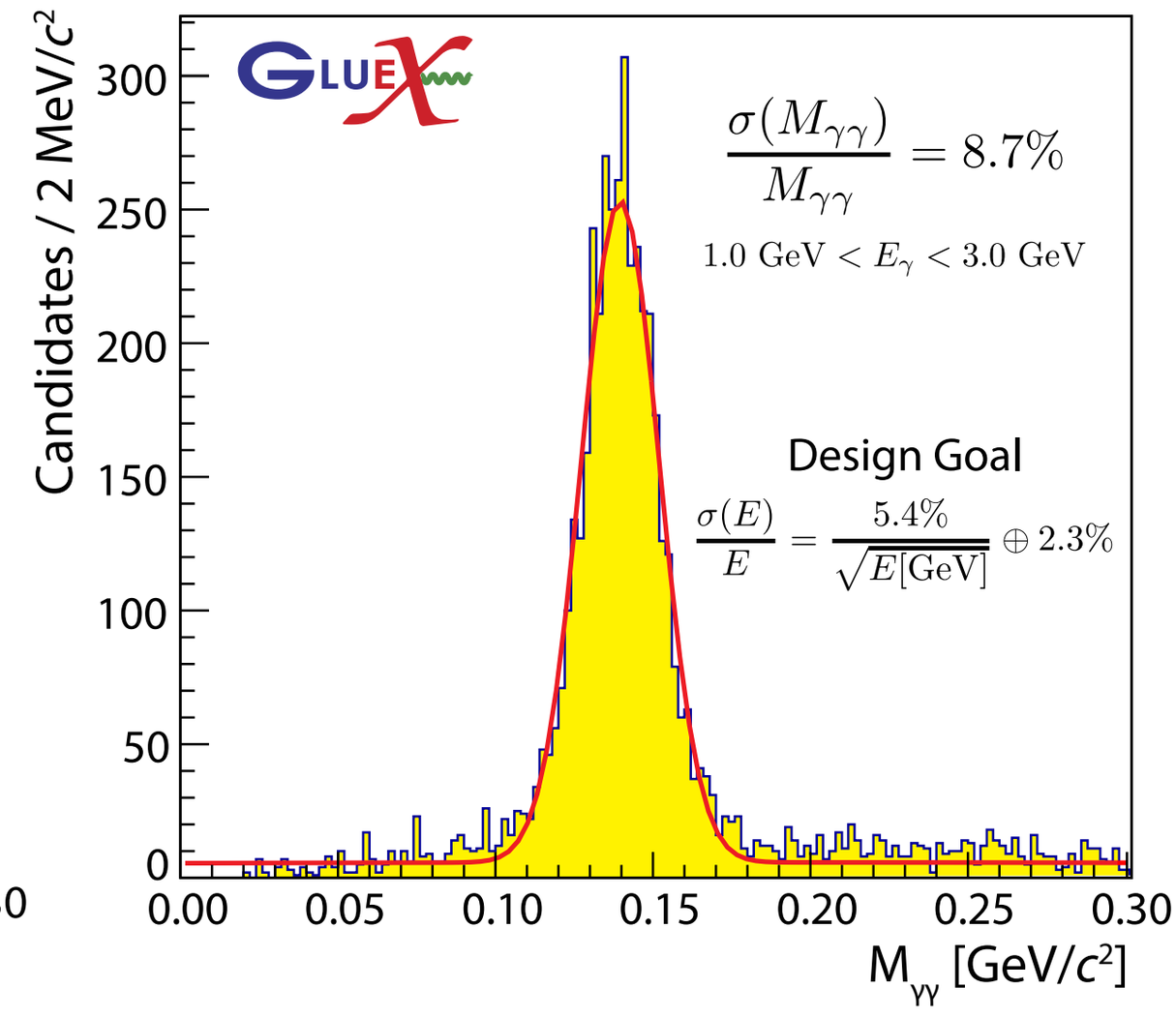
5

Calorimeter performance

Forward Lead Glass Calorimeter



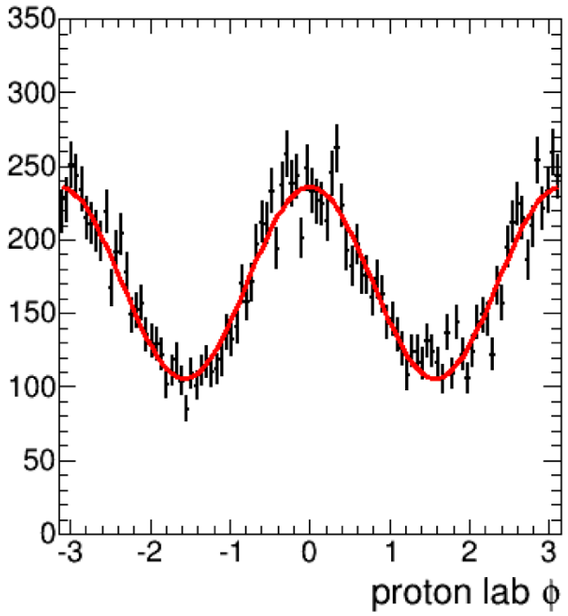
Barrel Lead-Scintillating Fiber Calorimeter



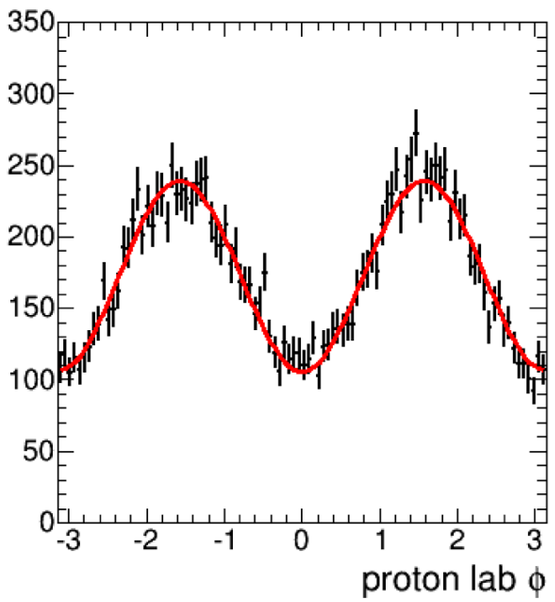
π^0 model: integration with JPAC

Simulation from JPAC Model

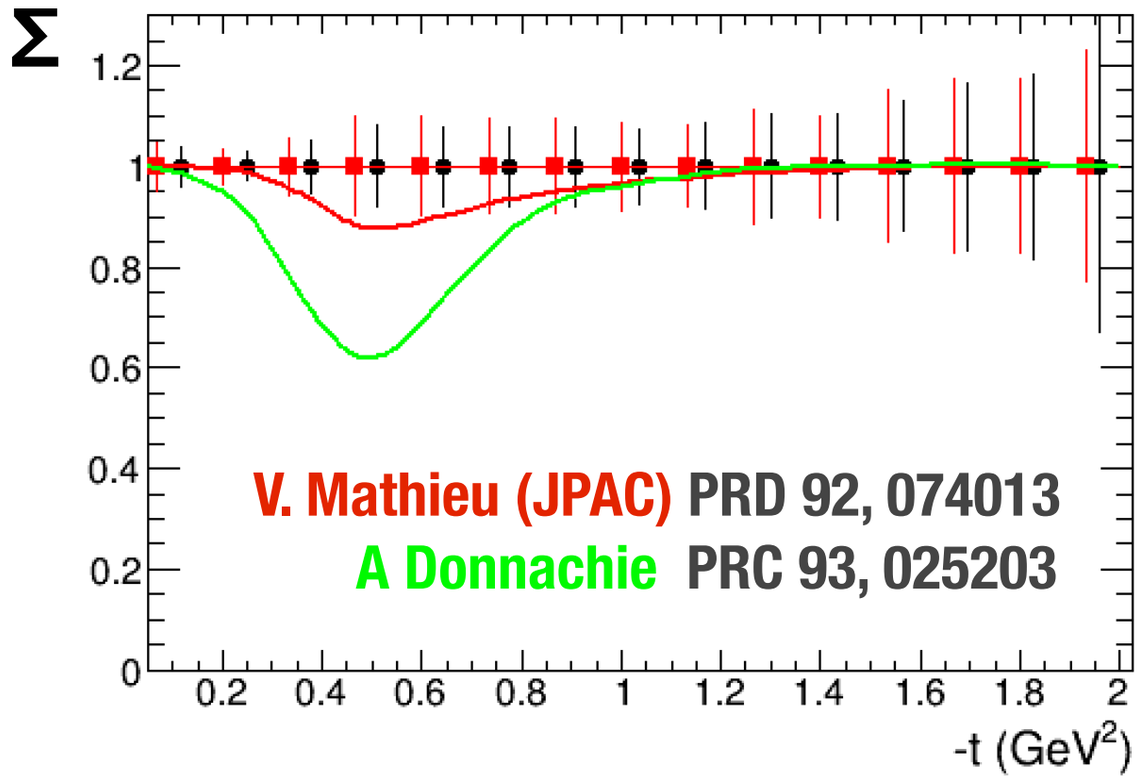
$$d\sigma_\perp \sim 1 + P_\perp \Sigma cos2\phi$$



$$d\sigma_\parallel \sim 1 - P_\parallel \Sigma cos2\phi$$



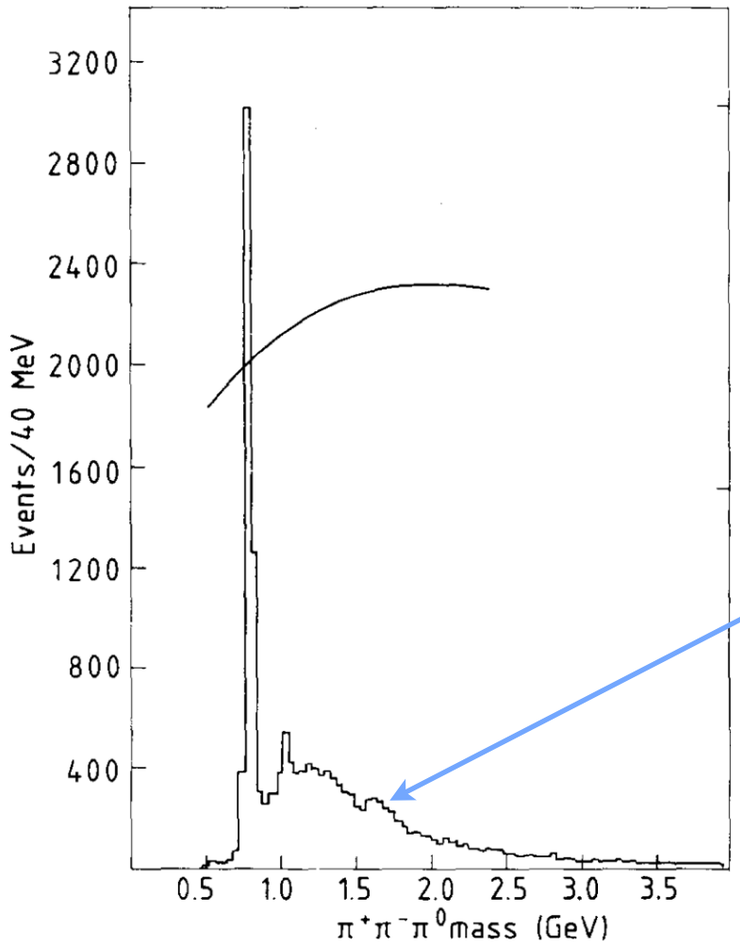
12 hours of beam: statistical errors only

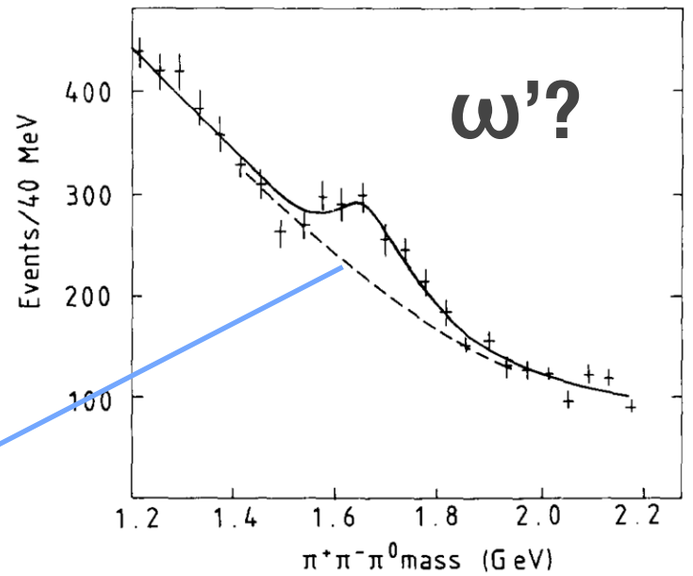


- Similar to ρ^0 model, simply calculate intensity based on JPAC provided function
- Generate $\gamma p \to \pi^0 p$ events and process through full detector simulation and reconstruction
- Before Spring 2016 run estimated yields for 12 hours of beam; evaluated statistical precision
  - Actually collected >10x more data!

Previous signals in photoproduction

- Some speculative ideas to look for “structure” observed in previous measurements
- eg. Excited vector mesons: ρ’, ω’, etc.





$$\gamma p \to \omega p \to \pi^+ \pi^- \pi^0 p$$

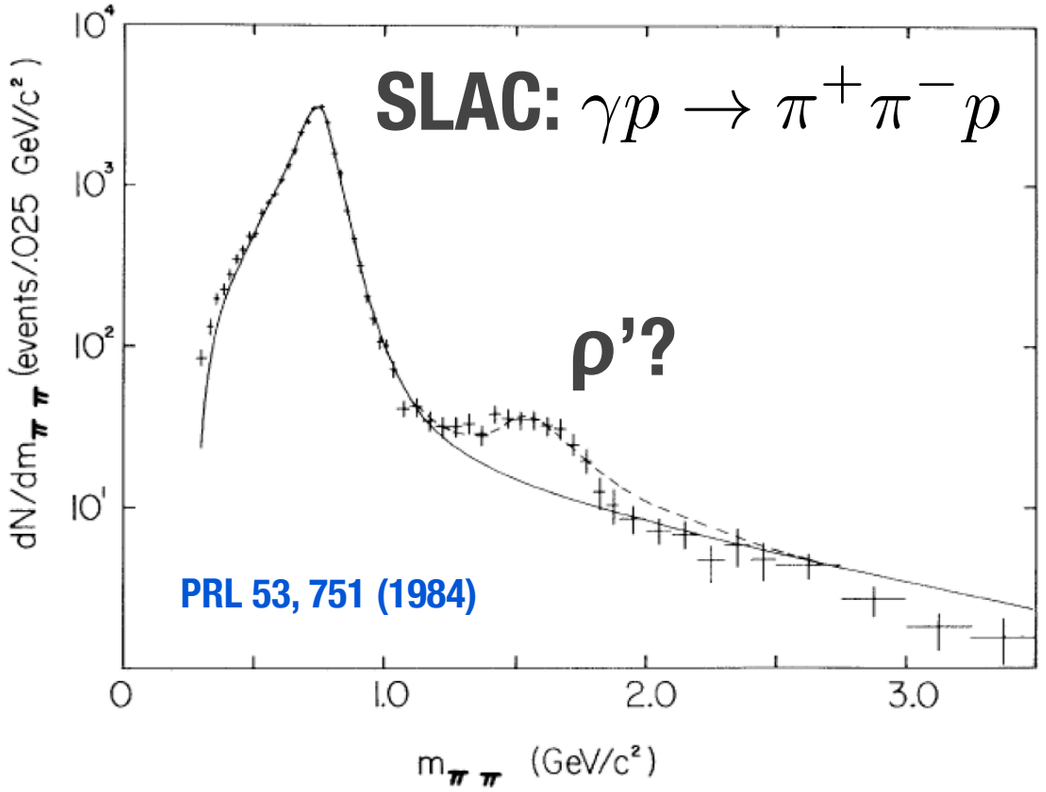
$$\gamma p \to \phi p \to \pi^+ \pi^- \pi^0 p$$

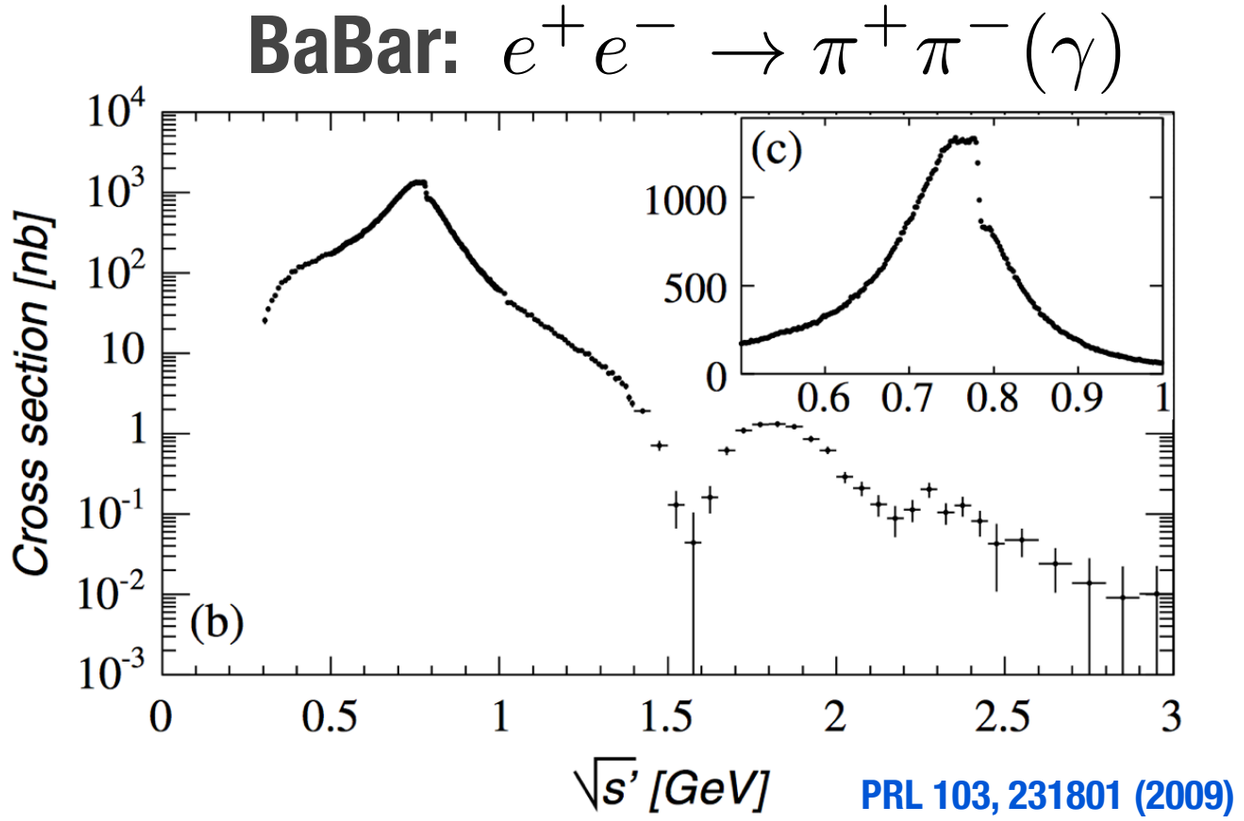
$$\gamma p \to \text{“}\omega'(1670)\text{”} p \to \pi^+ \pi^- \pi^0 p$$

Ω’ Spectrometer at the CERN SPS: Nucl. Phys. B231, 1 (1984)

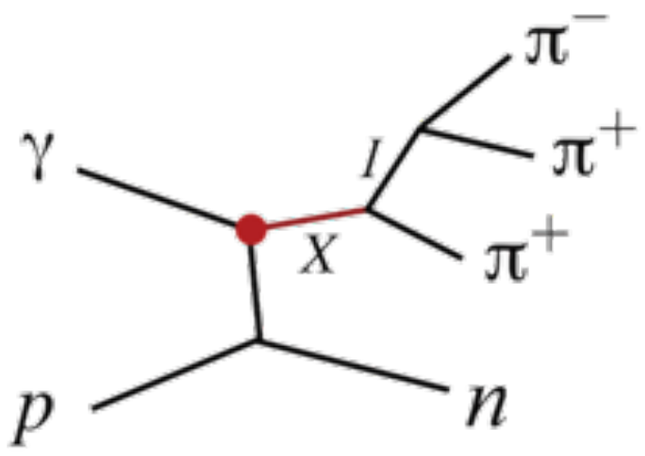
Previous signals in photoproduction

- Some speculative ideas to look for “structure” observed in previous measurements
- eg. Excited vector mesons: ρ’, ω’, etc.



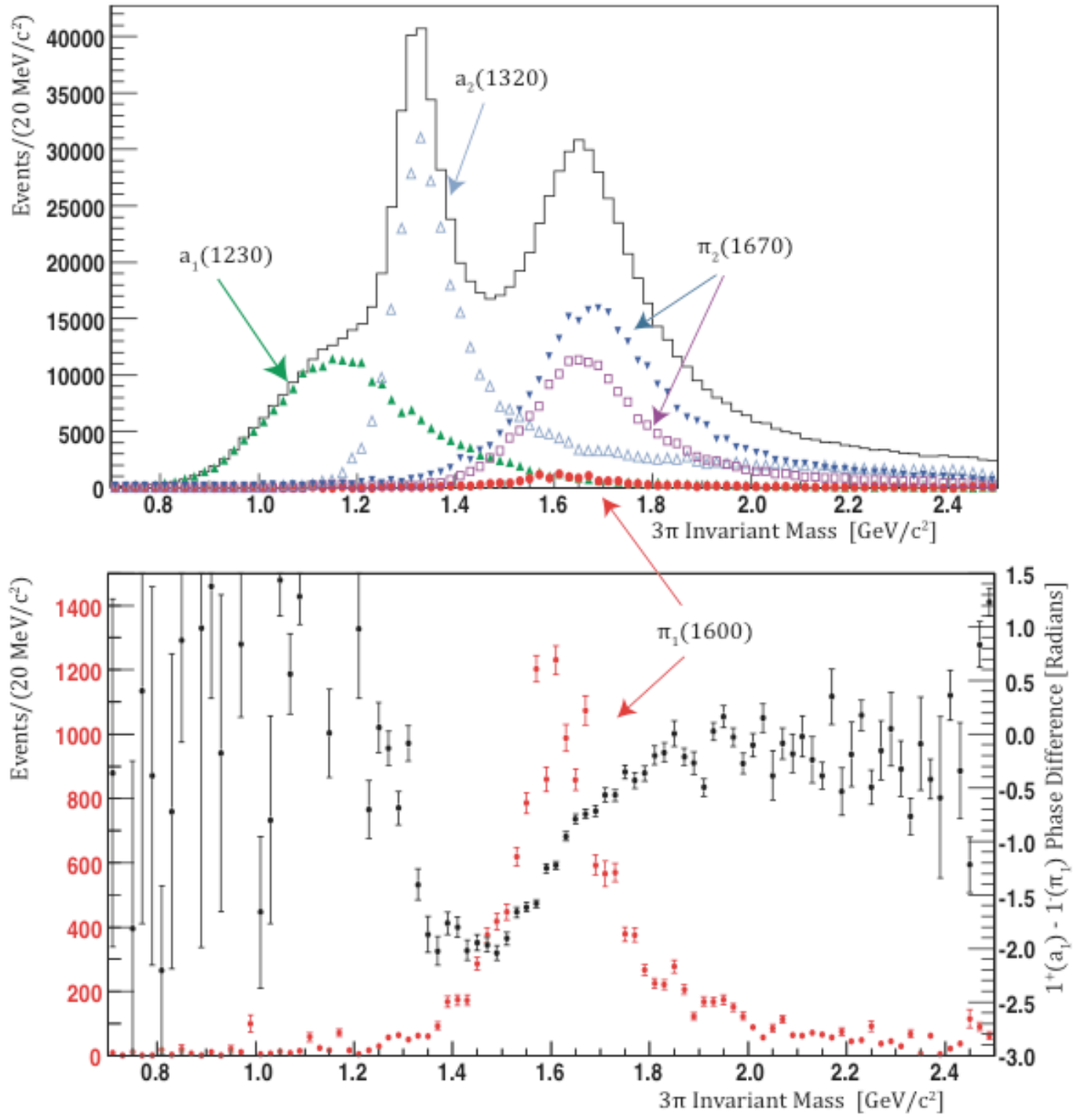


$\gamma p \to (n)\pi^+\pi^-\pi^+$: Partial Wave Analysis



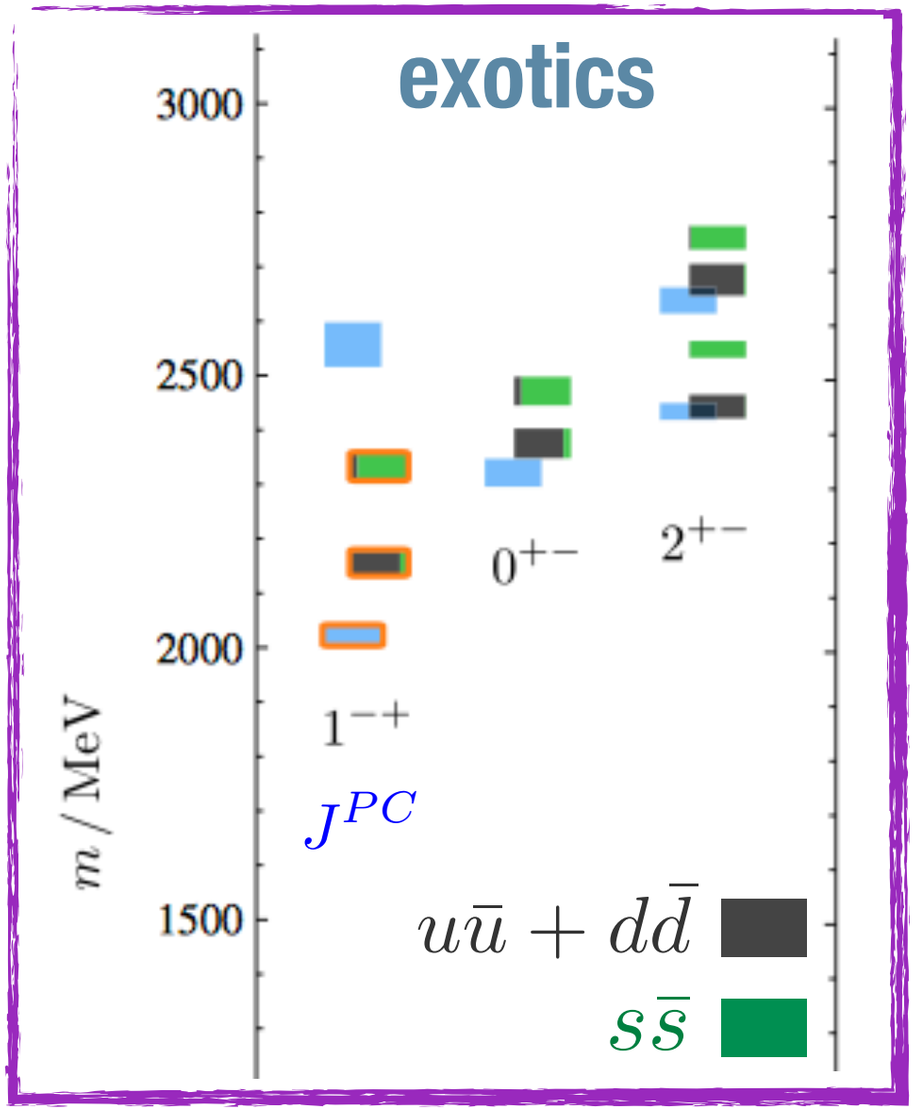
- Exclusive (n)$\pi^+\pi^-\pi^+$ is ~2% of the total hadronic cross section
- **Simulate** production of known resonances and **exotic hybrid (1^{-+}) signal** with 1.6% relative strength
- Yields correspond to **~3.5 hours** of GlueX data taking (at full intensity)
- Benchmark test of GlueX sensitivity to small amplitudes using detector full simulation and reconstruction, **but no background included**

GlueX Simulation



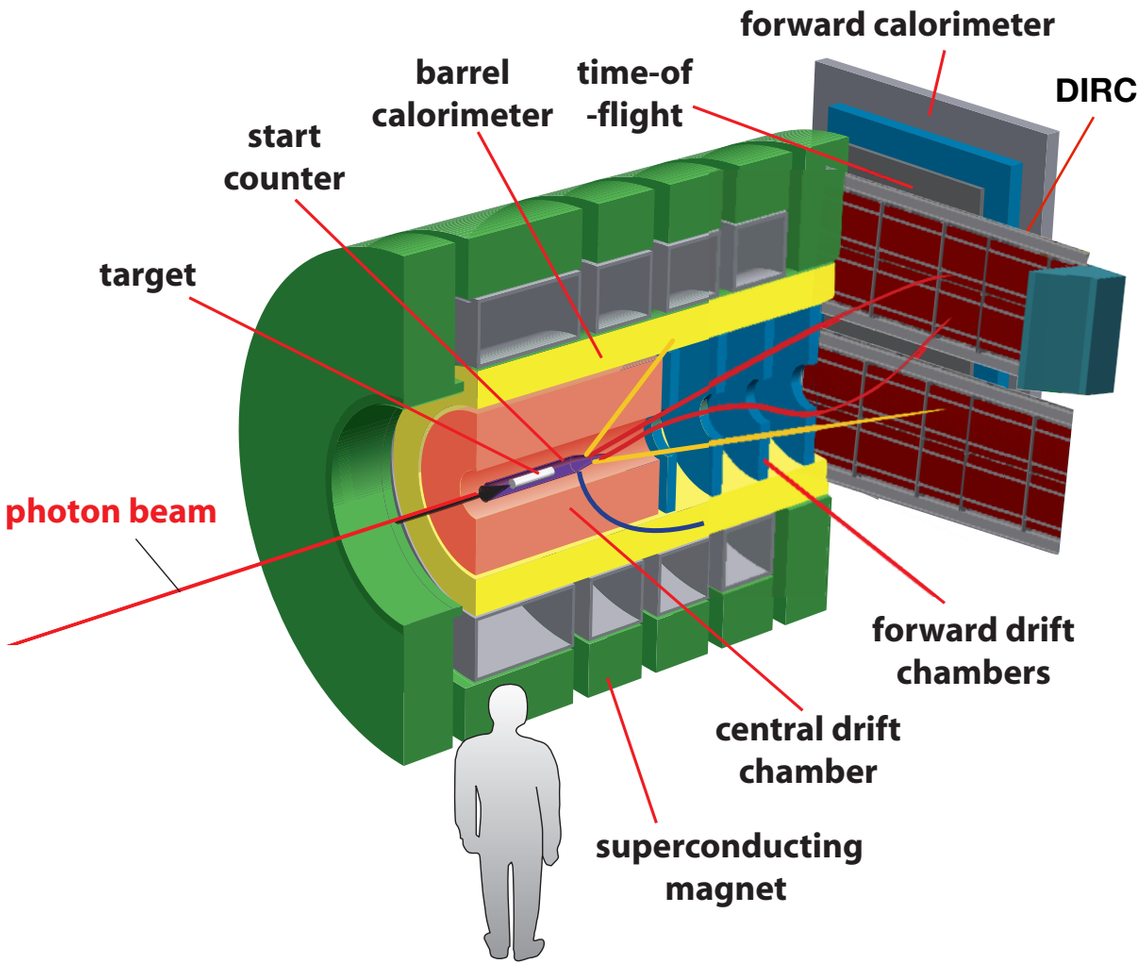
Strangeness program

	J^{PC}	Allowed Decay Modes
π_1	1^{-+}	$b_1\pi$, $\pi\rho$, πf_1, $\pi\eta$, $\pi\eta'$, ηa_1, $\pi\eta(1295)$
η_1	1^{-+}	πa_1, πa_2, ηf_1, ηf_2, $\pi\pi(1300)$, $\eta\eta'$, KK_1^A, KK_1^B
η_1'	1^{-+}	KK_1^B, KK_1^A, KK^*, $\eta\eta'$
b_0	0^{+-}	$\pi\pi(1300)$, πh_1, ρf_1, ηb_1
h_0	0^{+-}	πb_1, ηh_1, $KK(1460)$
h_0'	0^{+-}	$KK(1460)$, KK_1^A, ηh_1
b_2	2^{+-}	πa_1, πa_2, πh_1, $\eta\rho$, ηb_1, ρf_1
h_2	2^{+-}	$\pi\rho$, πb_1, $\eta\omega$, ωb_1
h_2'	2^{+-}	KK_1^B, KK_1^A, KK_2^*, ηh_1

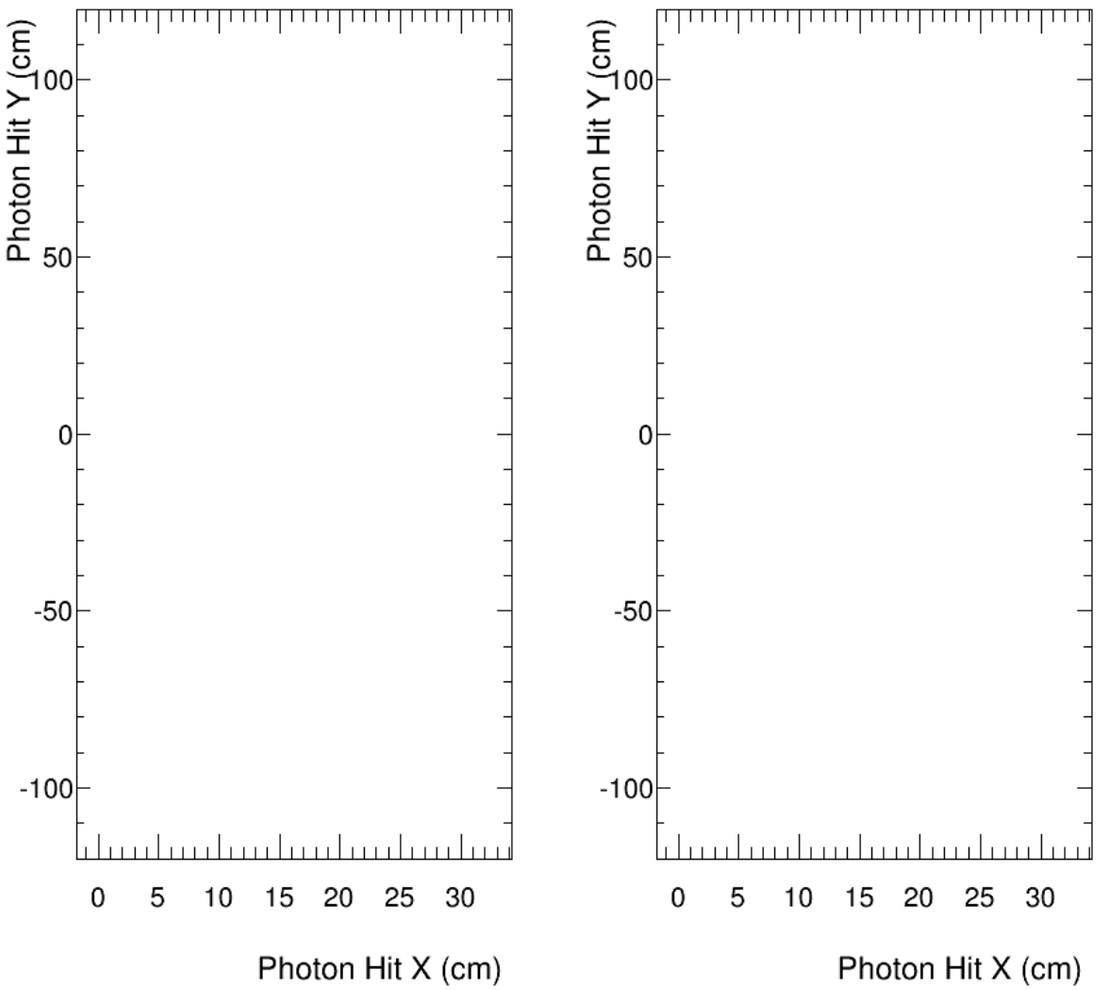


- Mapping the hybrid spectrum requires: large statistics samples of many particle final states in **strange** and **non-strange** decay modes
- Experimentally access to strangeness content of the state by comparing strange vs non-strange decay modes

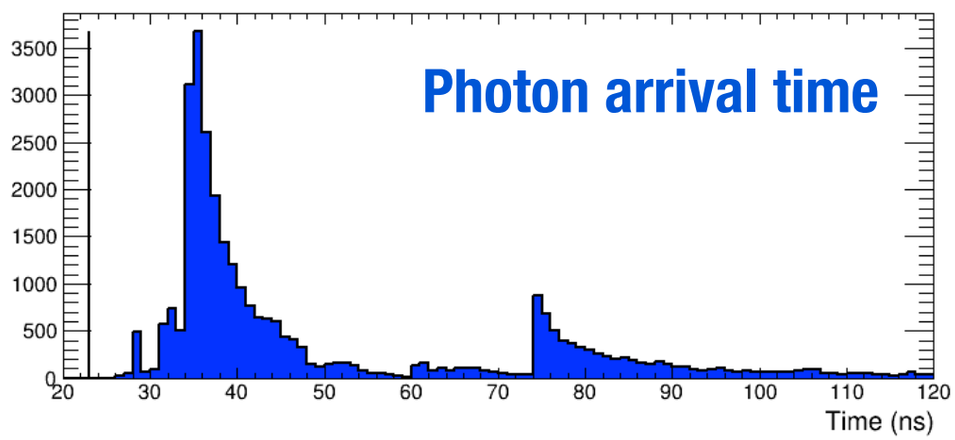
GlueX DIRC upgrade



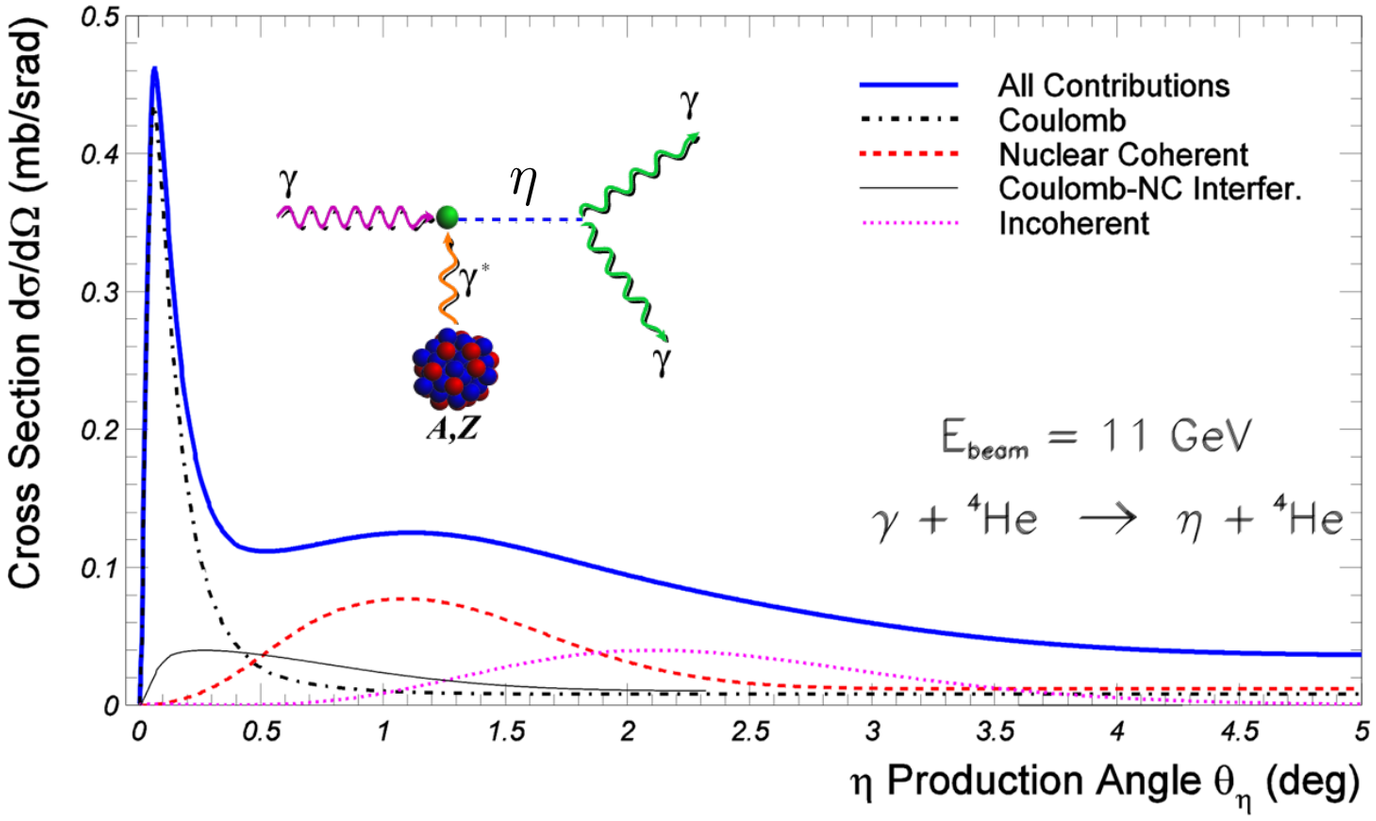
Cherenkov Photon "Ring"

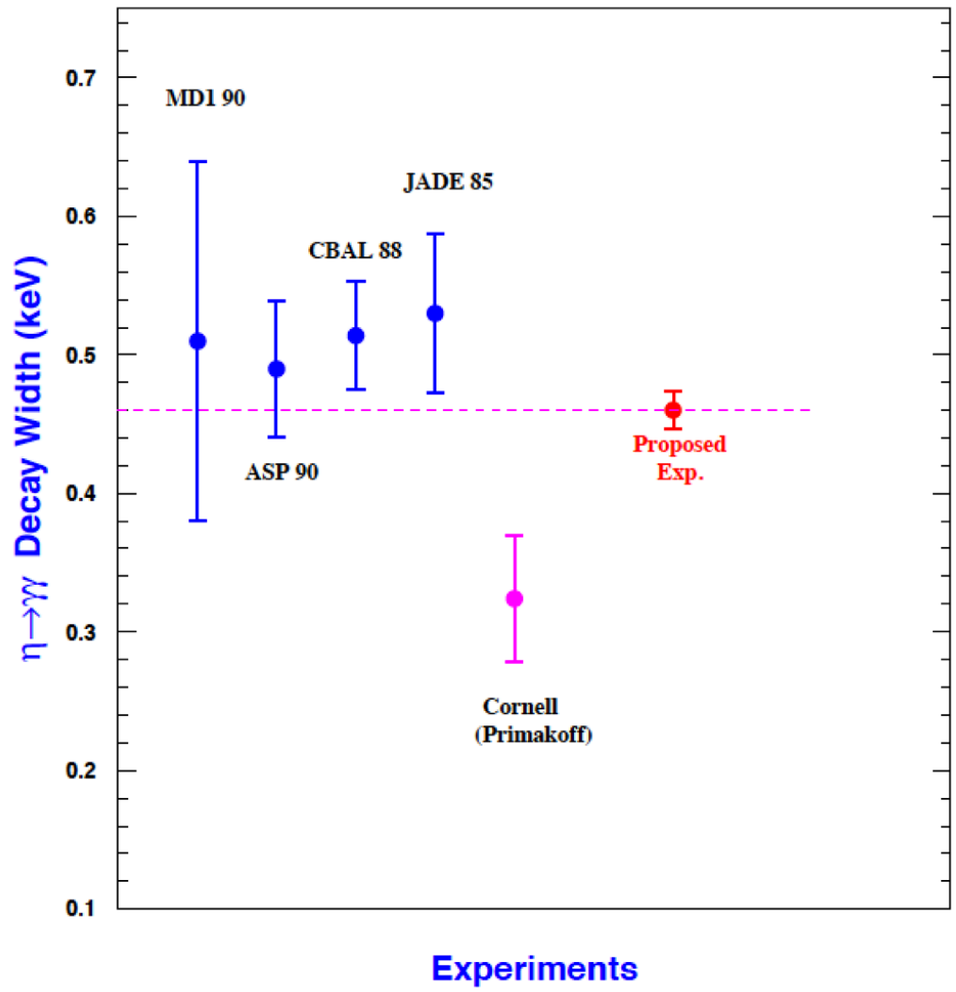


- The GlueX **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light) provides new K/π separation and will use components of the BaBar DIRC
- Installation and commissioning in **2018**



PIMEX η experiment

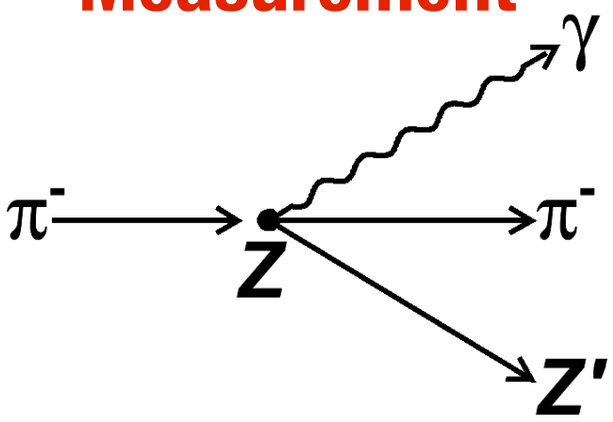




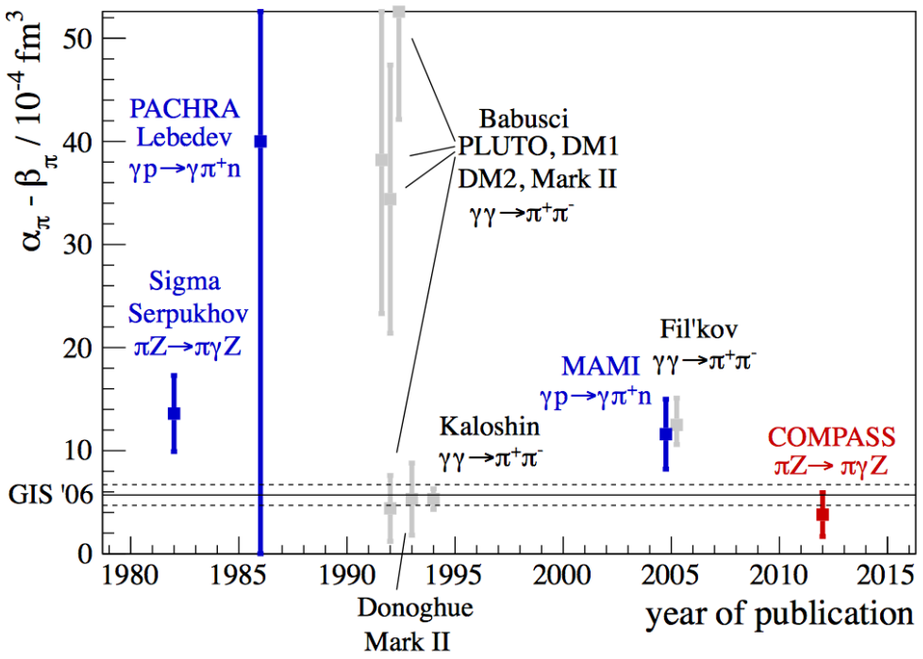
- η → γγ decay width via Primakoff production
- Follows successful determination of $\pi^0 \rightarrow \gamma\gamma$ decay width in previous JLab experiment
- Resolve discrepancy between e^+e^- collider and Primakoff results

Charged Pion Polarizability

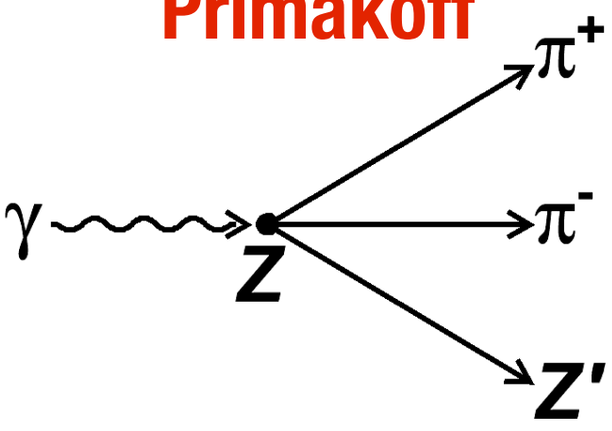
Recent Compass Measurement



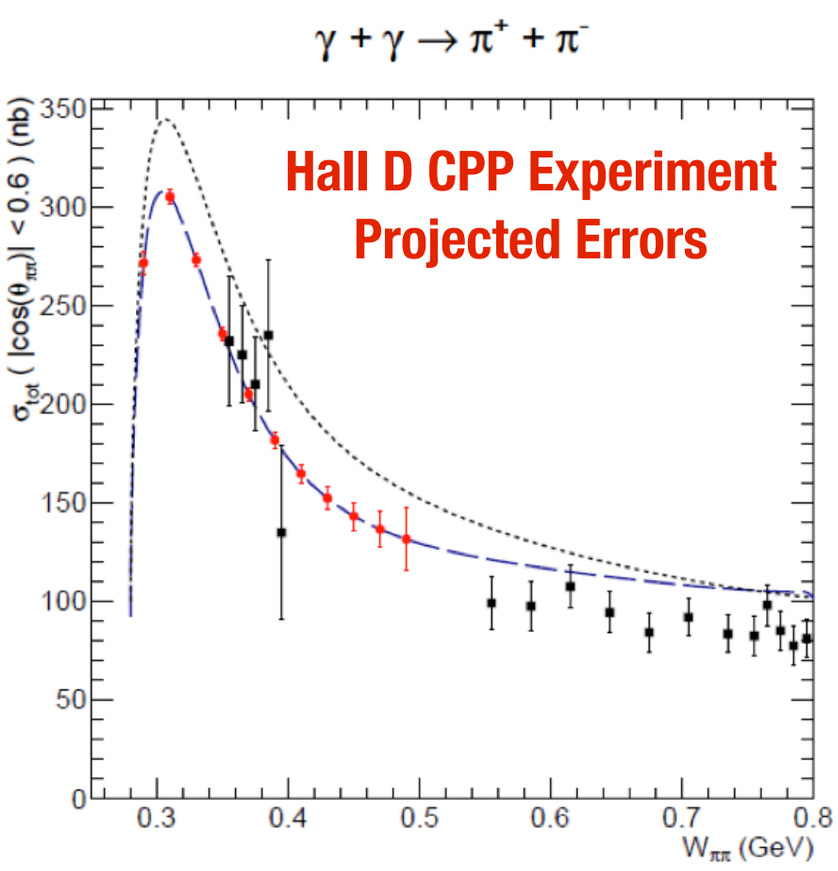
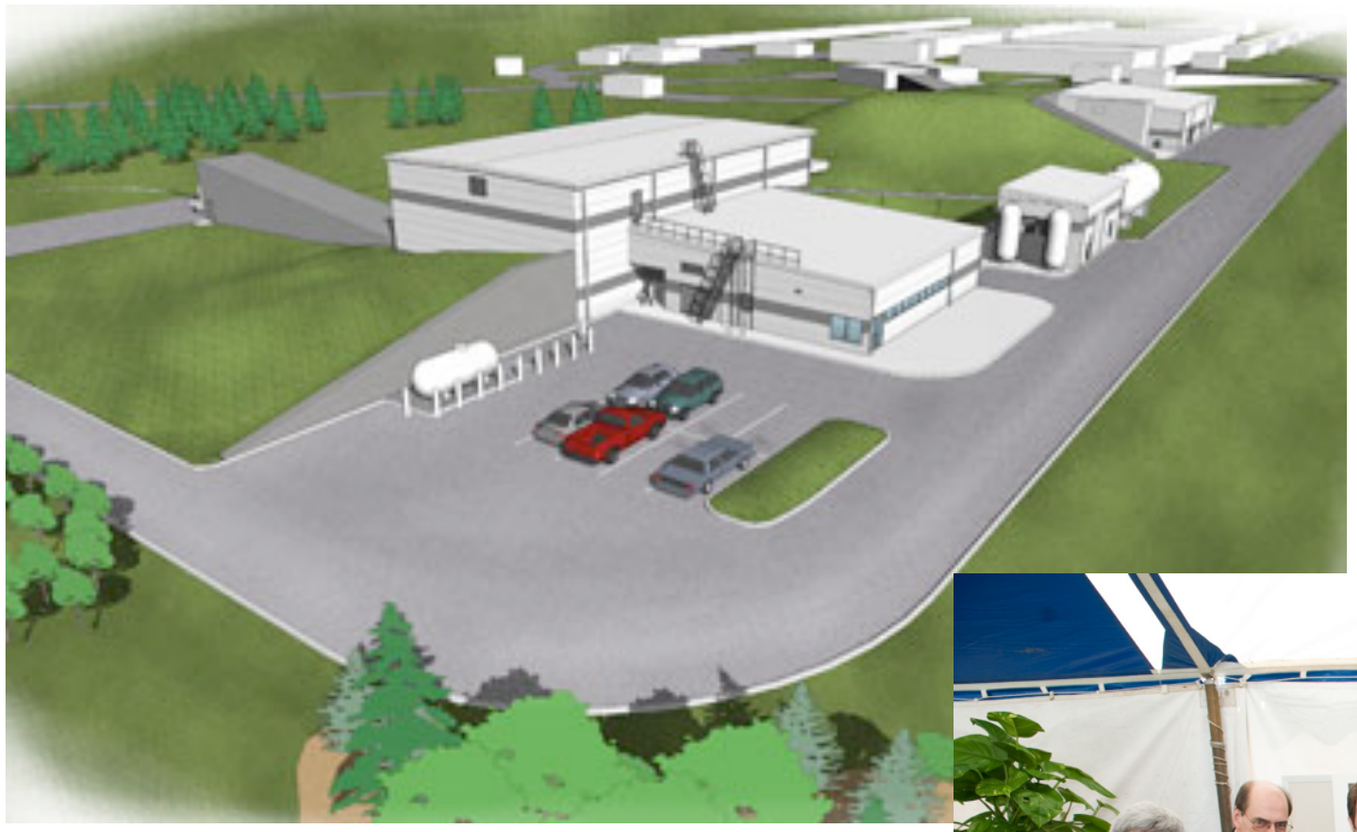
PRL 114, 062002 (2015)



Photoproduction Primakoff



- Primakoff production of pion pairs allows to extract pion polarizability which will test χPT predictions



GlueX circa 2009