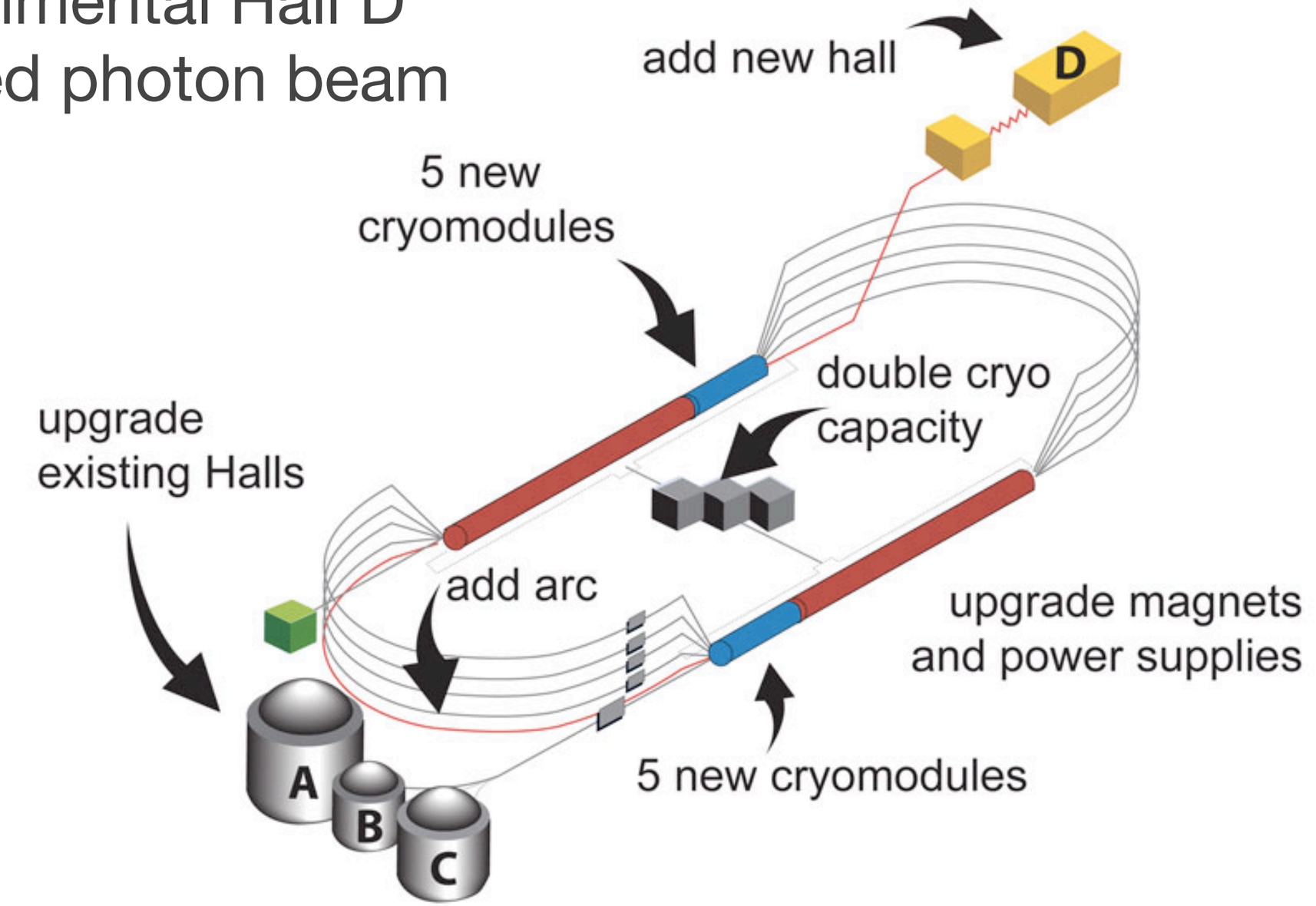
Hadron Spectroscopy at GlueX and Beyond (4)

Justin Stevens

WILLIAM & MARY
CHARTERED 1693

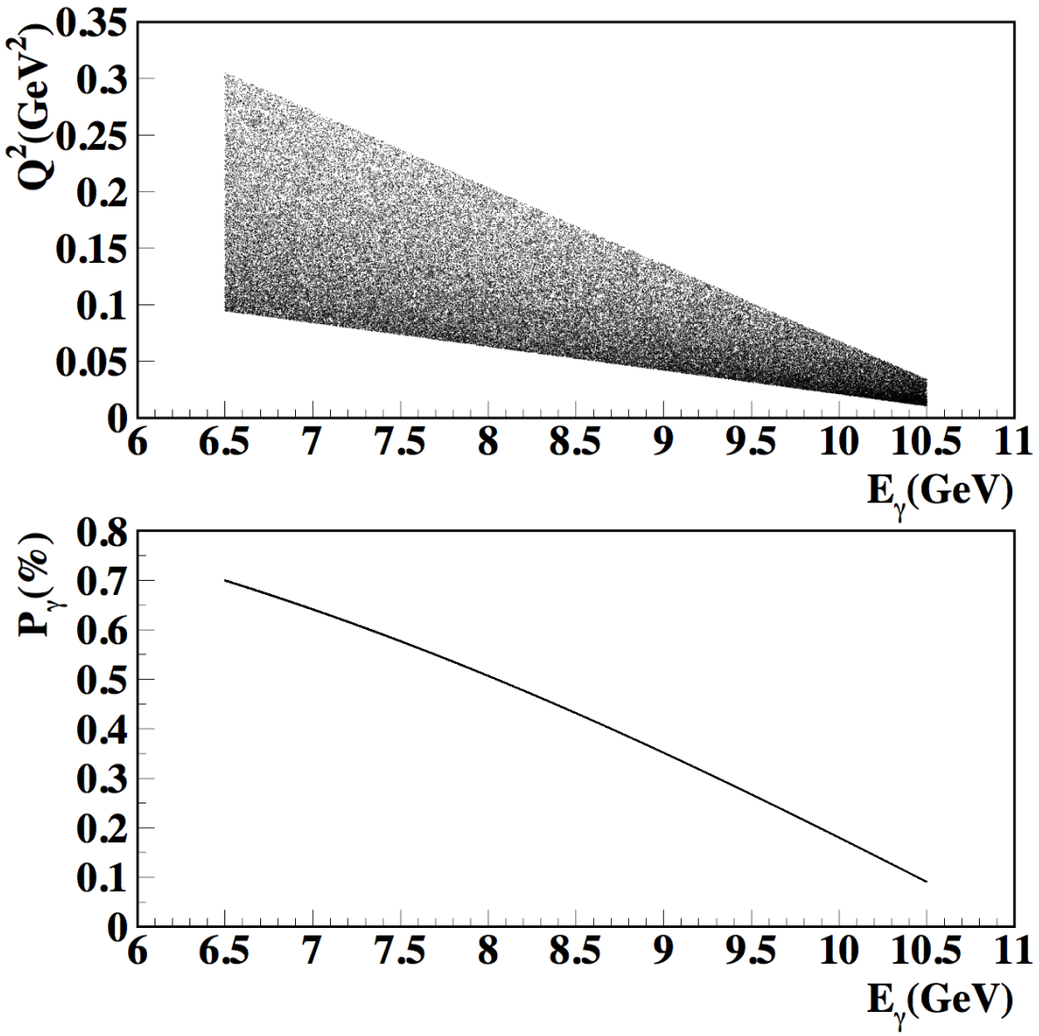
Jefferson Lab 12 GeV Upgrade

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

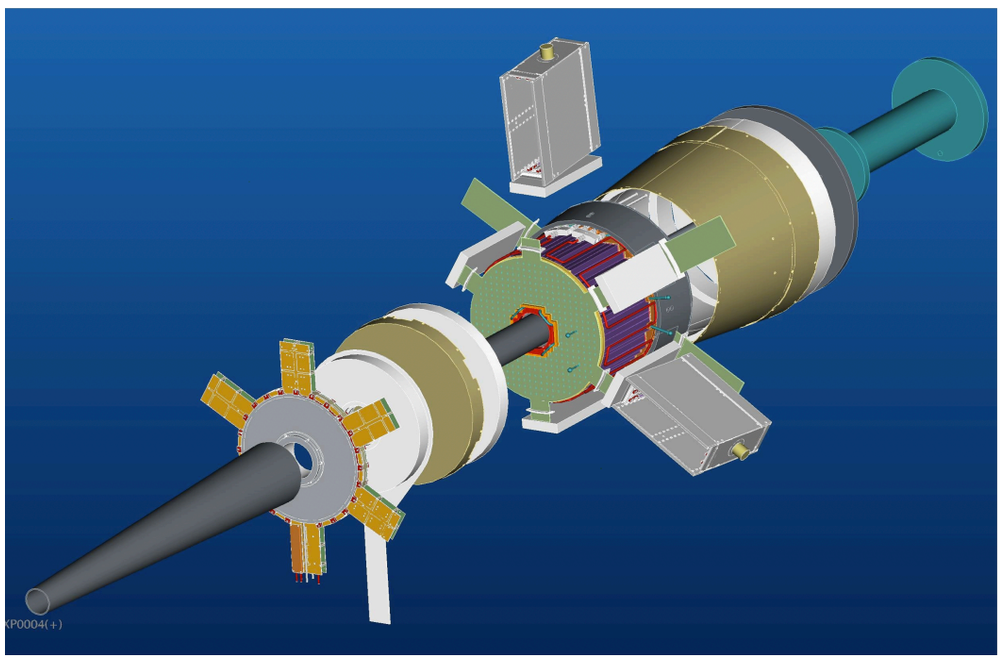


CLAS12 in Hall B

- CEBAF delivers 11 GeV electron beam to Hall B
  - Linearly polarized photons through quasi-real photoproduction
  - Electron scattering provides access to hybrid baryons



Forward Tagger (FT)



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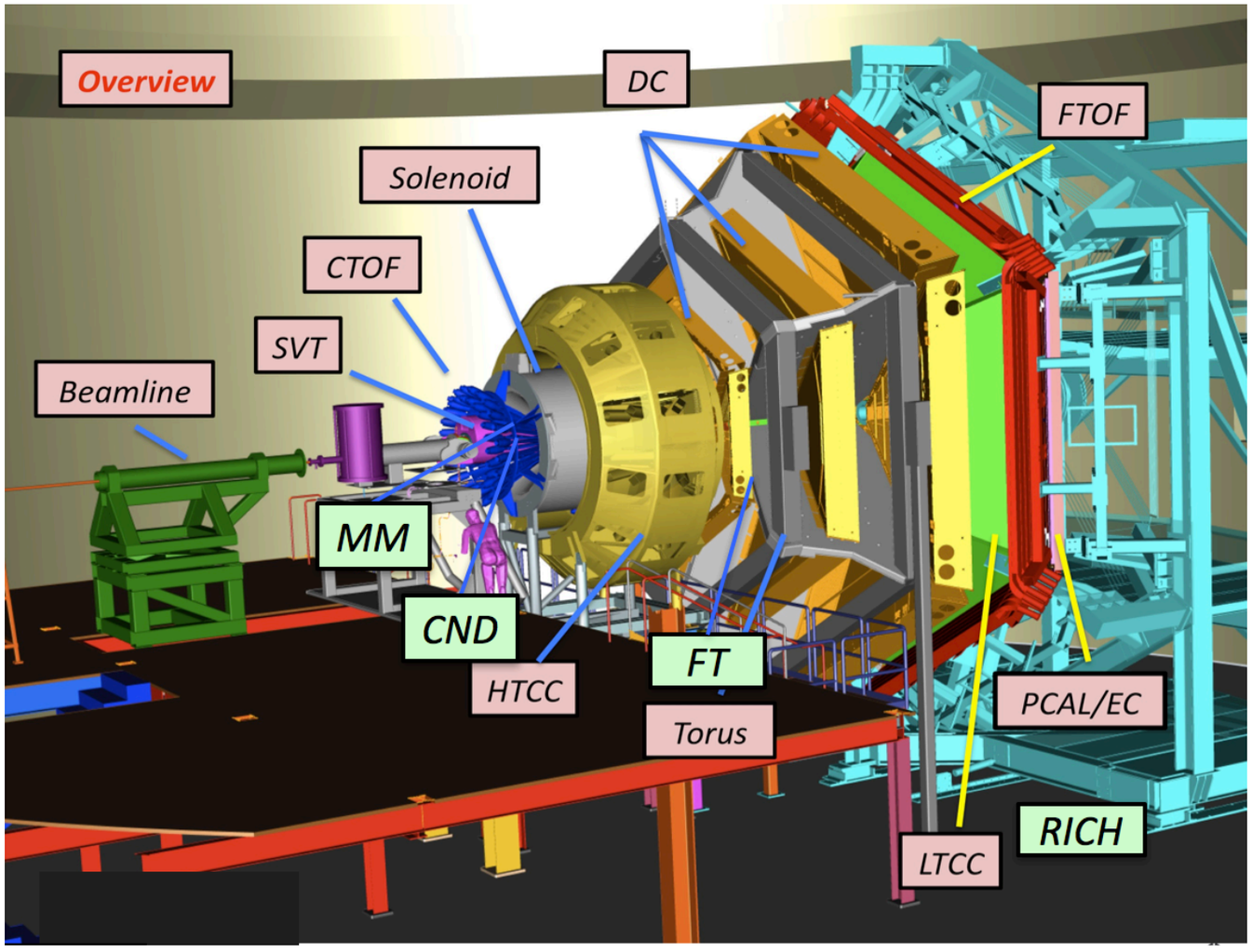

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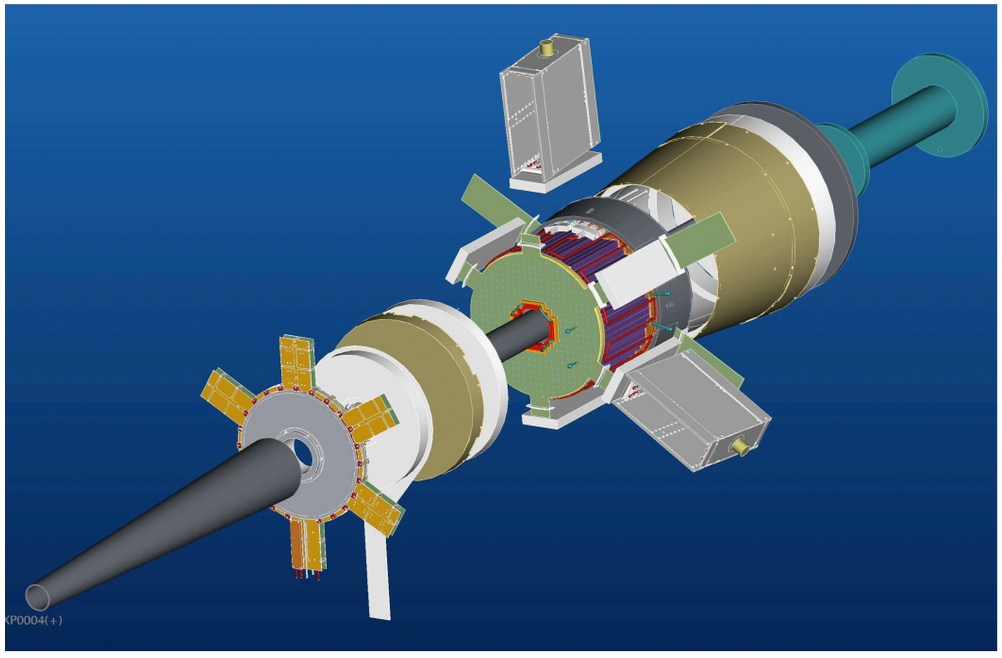
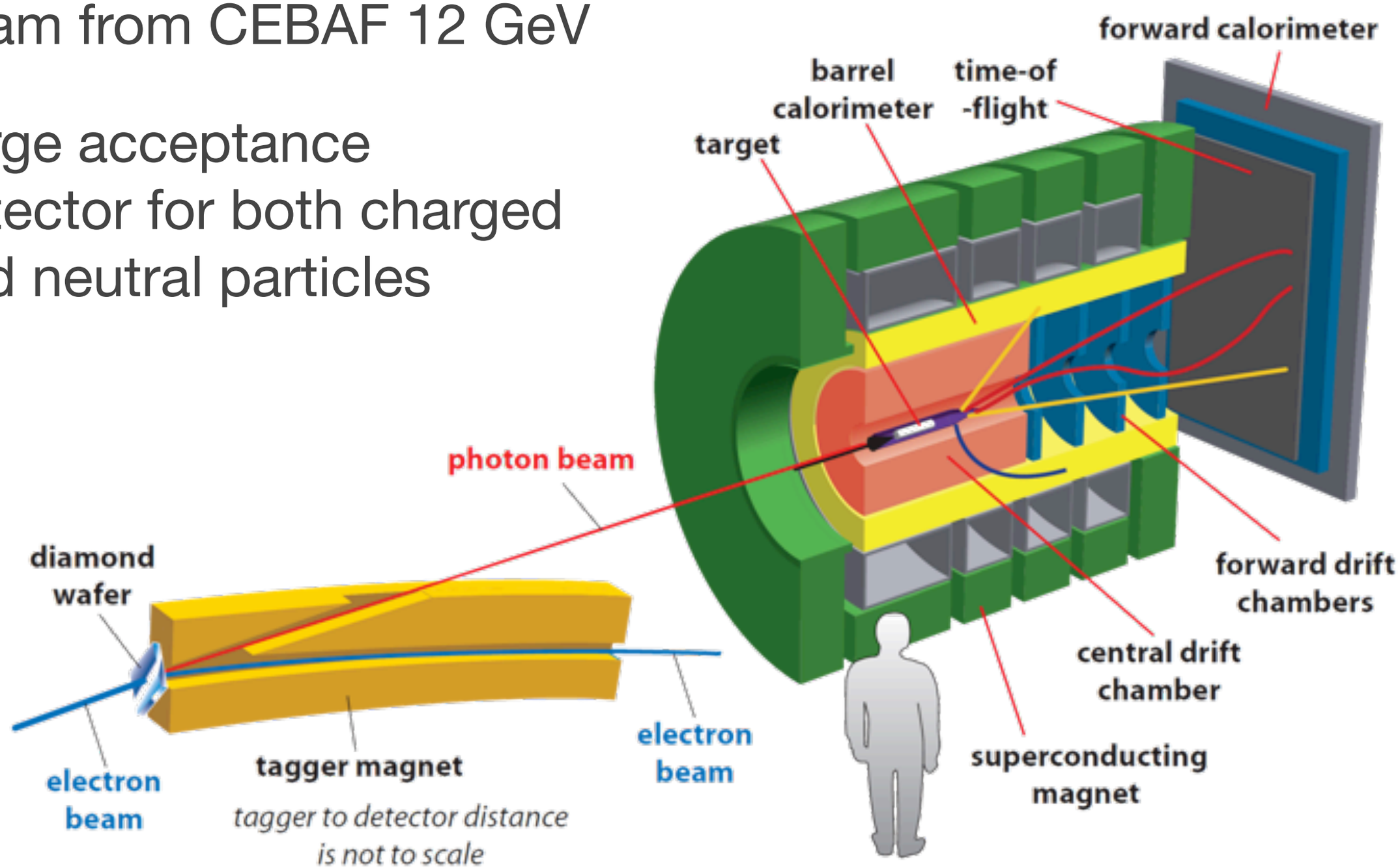
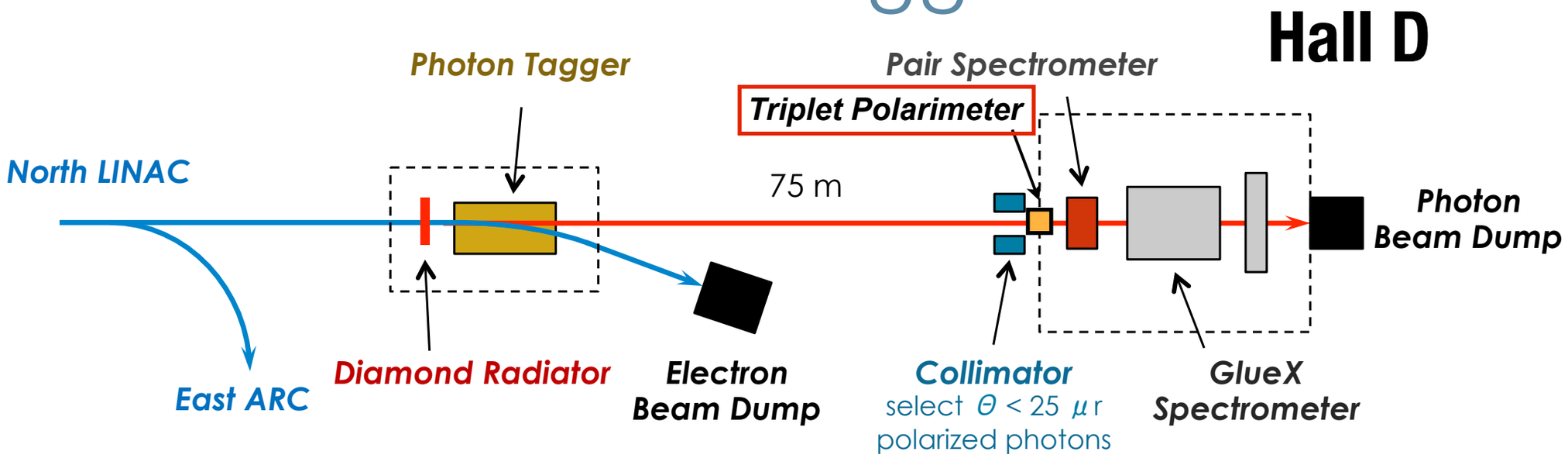


GlueX in Hall D

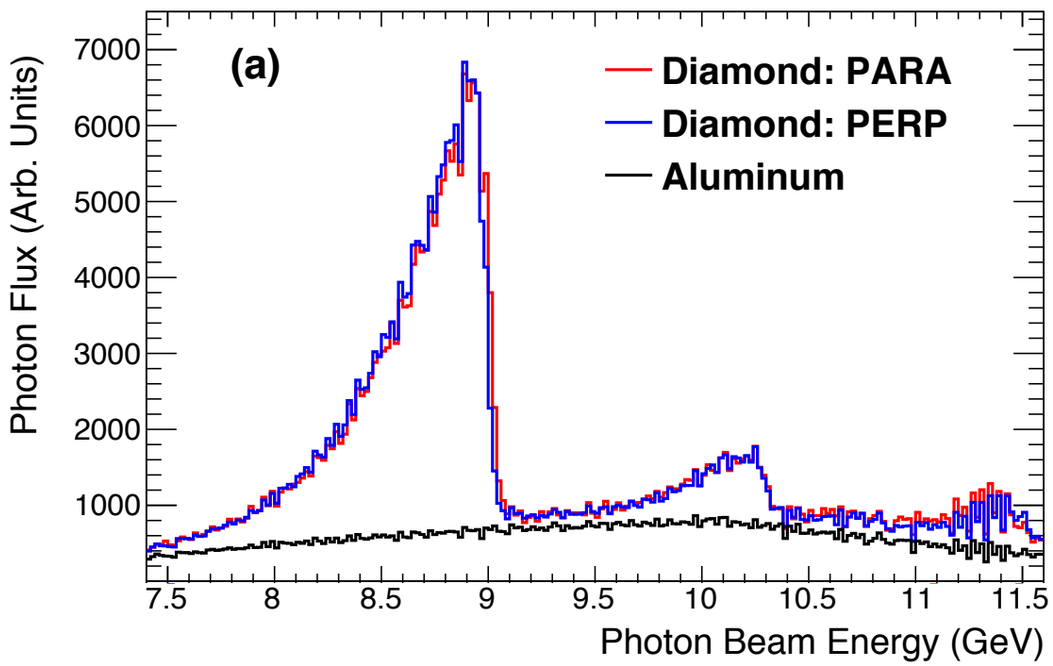
- Linearly polarized photon beam from CEBAF 12 GeV
- Large acceptance detector for both charged and neutral particles



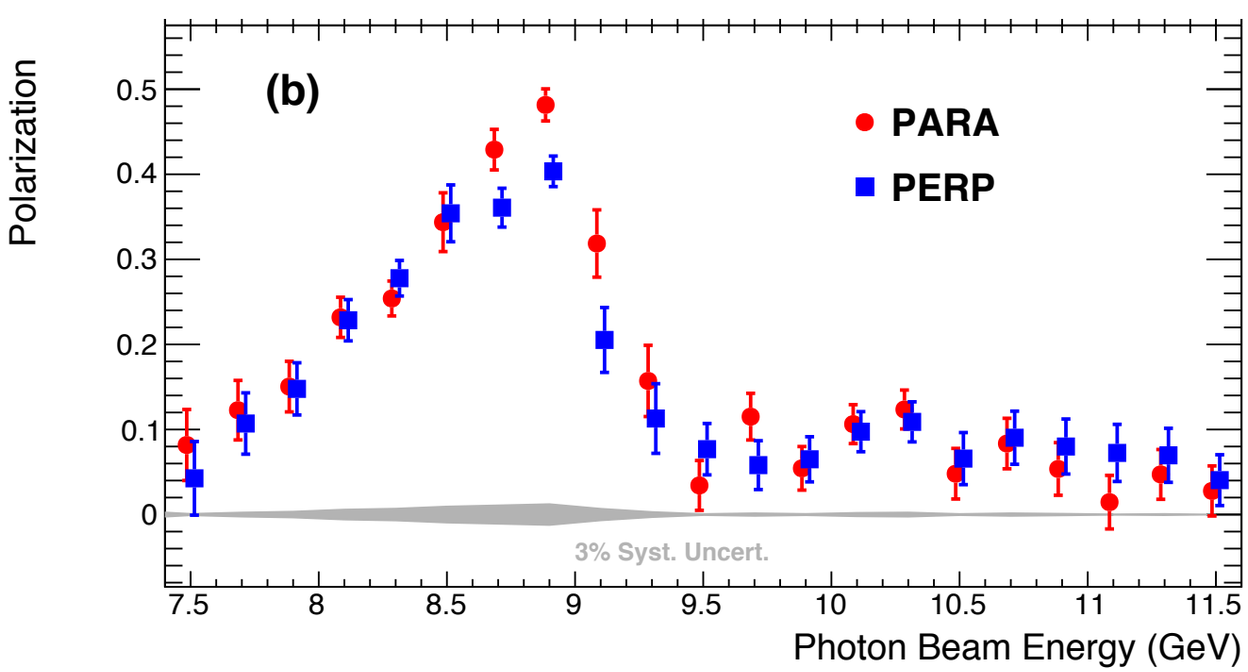
Photon Beam and Tagger



Measured Flux

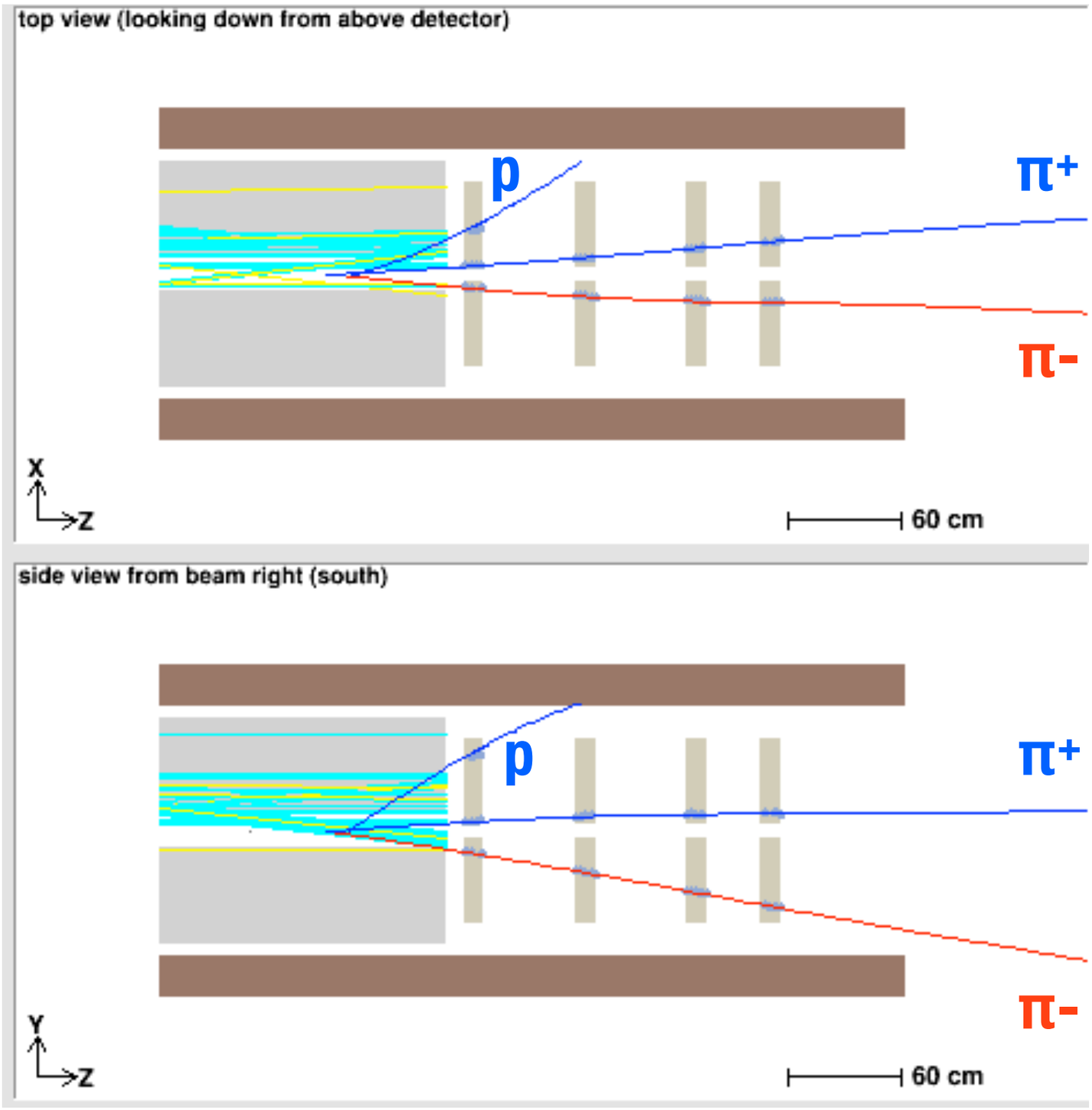


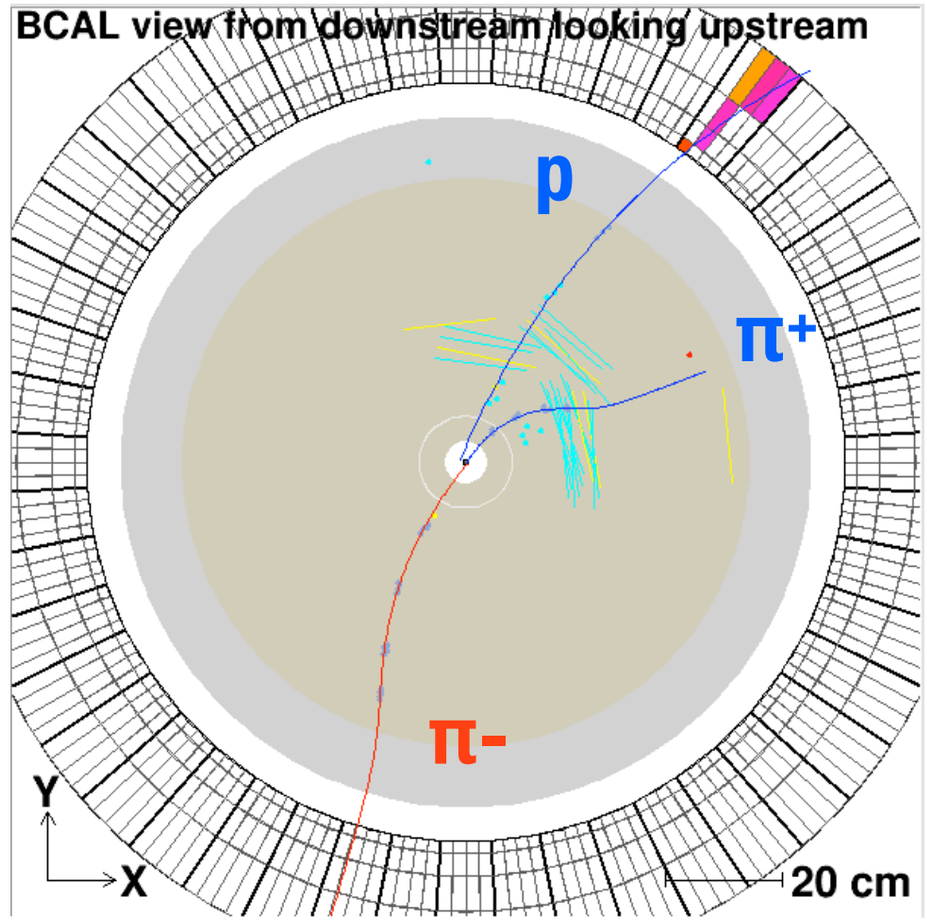
Measured Polarization



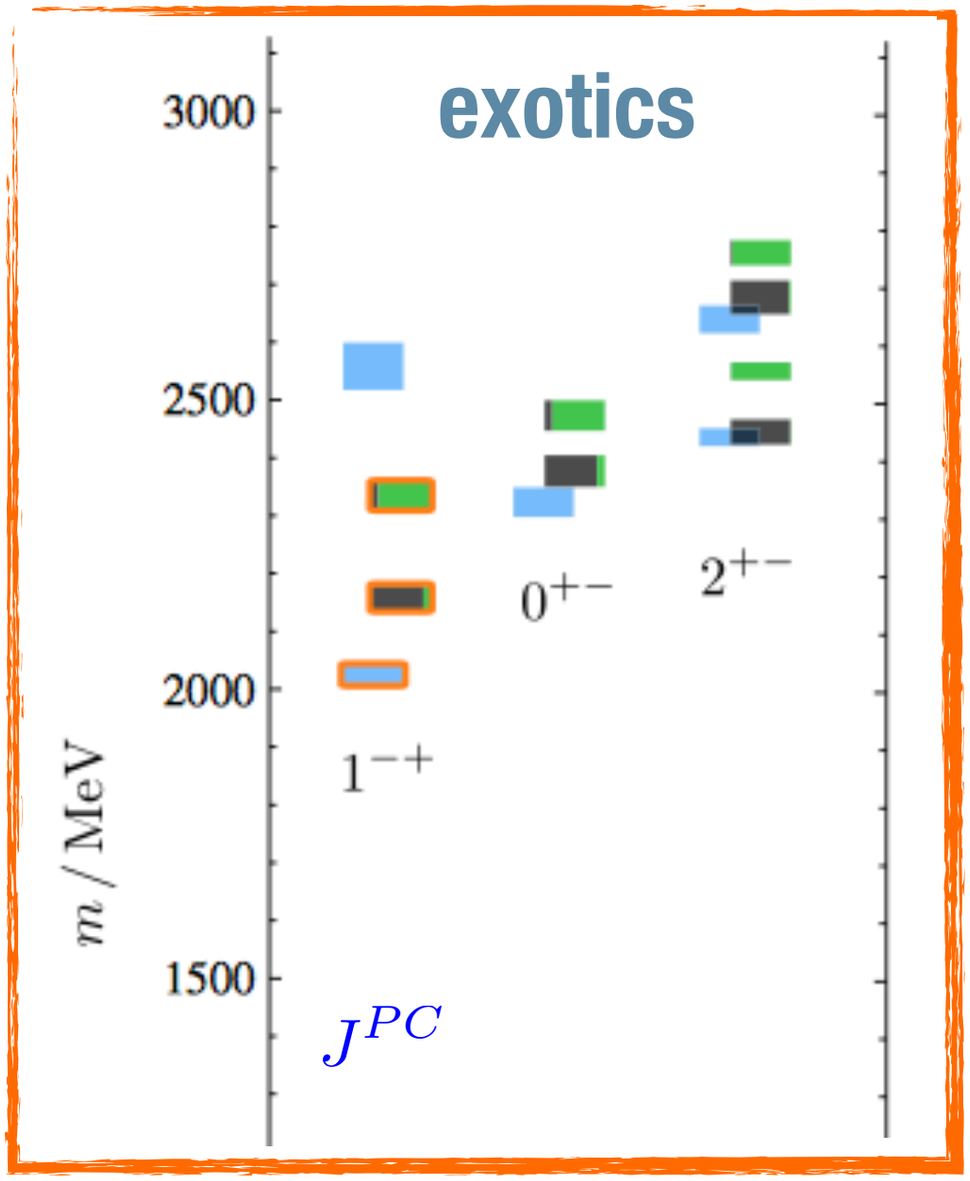
Construction (~5 years)

“Typical” γp→π⁺π⁻p event

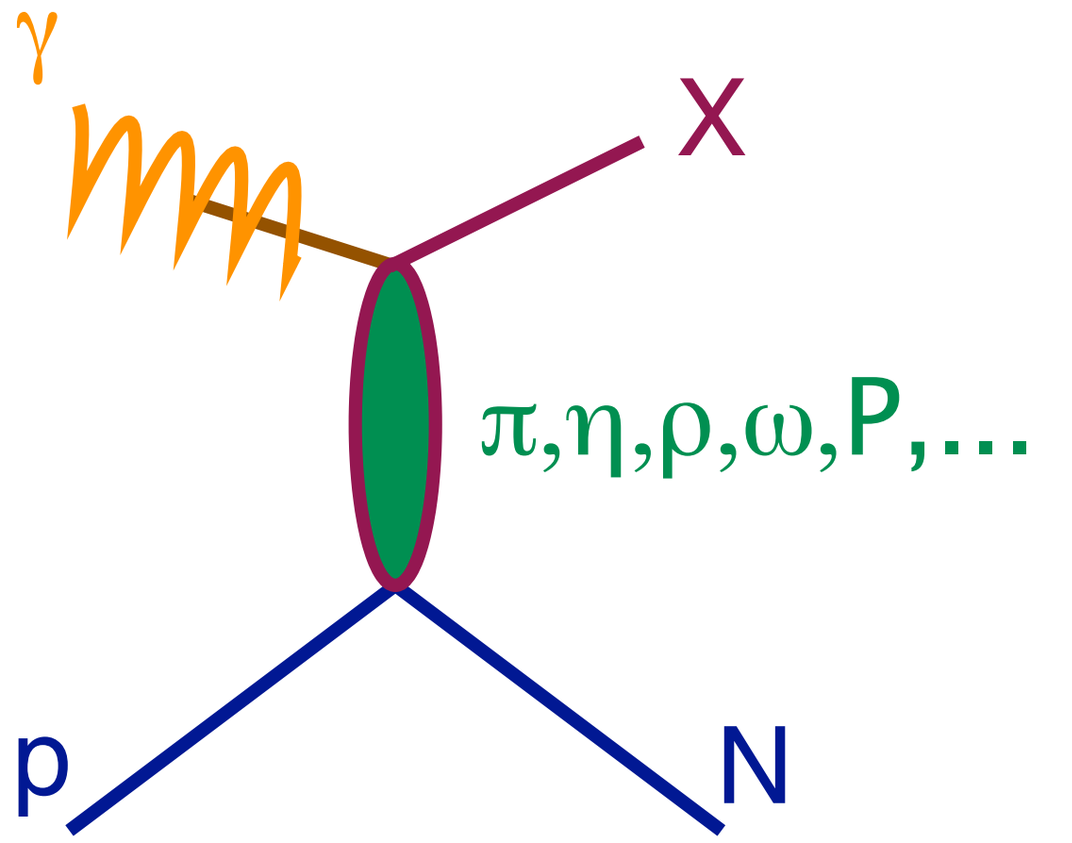




Exotic J^{PC} in photoproduction

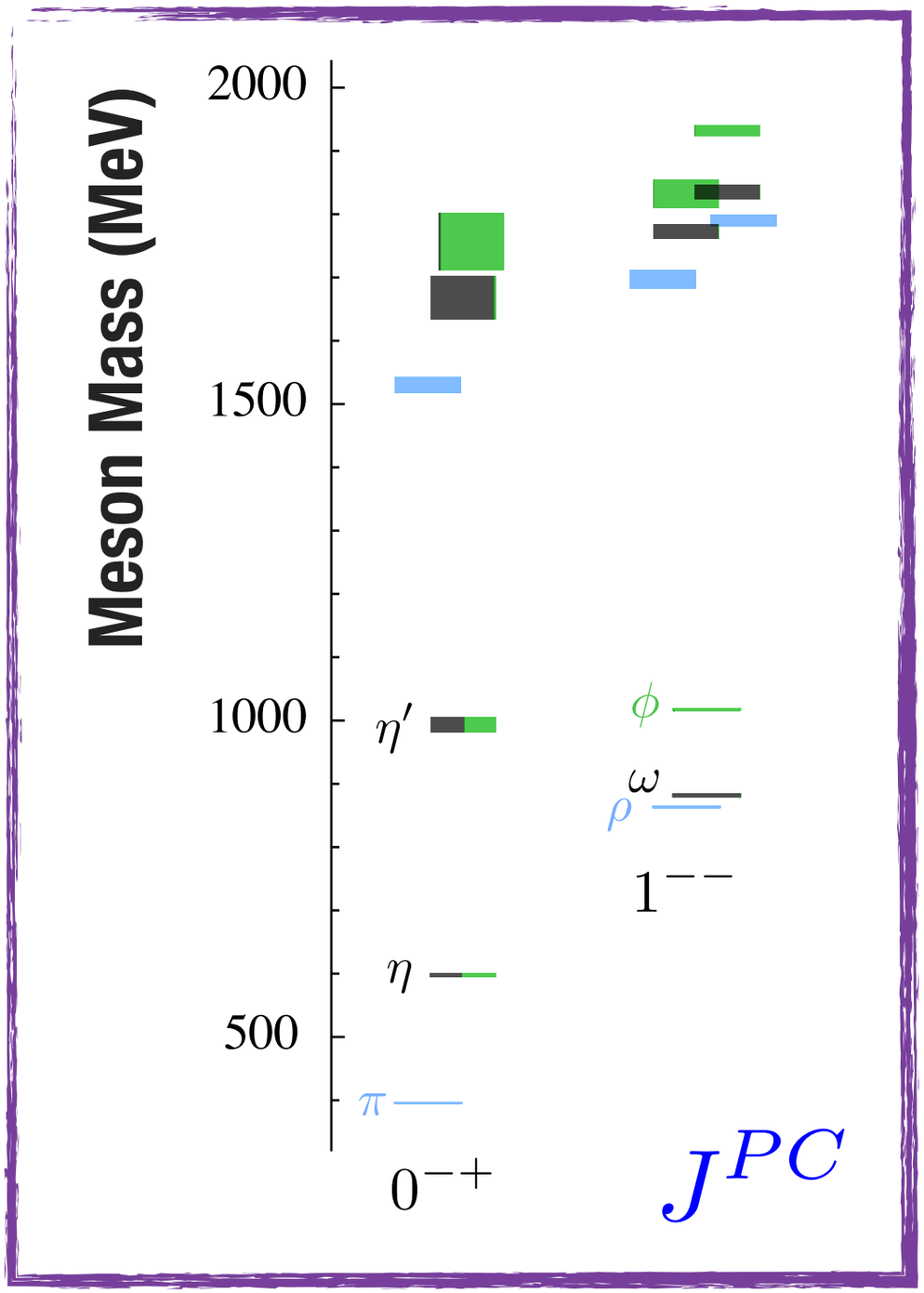


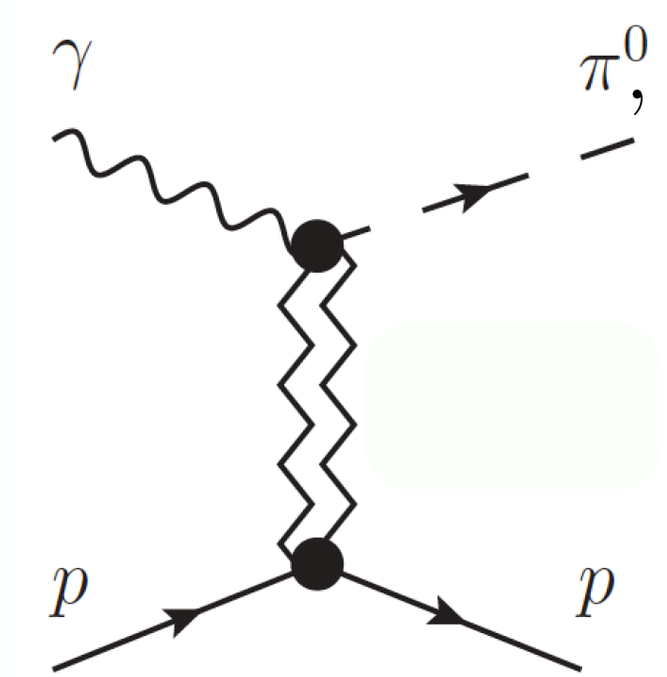
Meson X with particular J^{PC}



Production through t-channel "quasi-particle"exchange

Non-exotic J^{PC} in photoproduction





Exchange J^{PC}

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

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

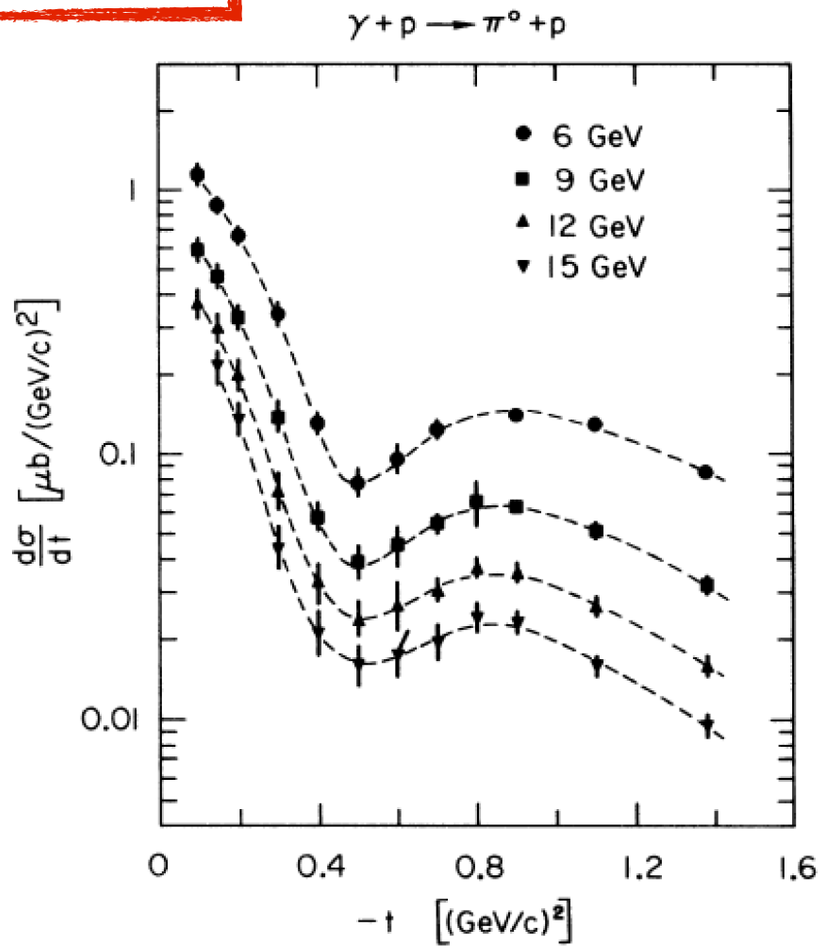
- Begin by understanding non-exotic production mechanism
- Linear photon beam polarization critical to filter out “naturality” of the exchange particle

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

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

R. L. Anderson, D. B. Gustavson, J. R. Johnson, I. D. Overman, D. M. Ritson, and B. H. Wiik
Stanford Linear Accelerator Center, Stanford, California 94305
and
D. Worcester†
Harvard University, Cambridge, Massachusetts 02138
(Received 25 June 1971)

1 OCTOBER 1971



How to describe old data and predictions for JLab?

Joint Physics Analysis Center (JPAC)!

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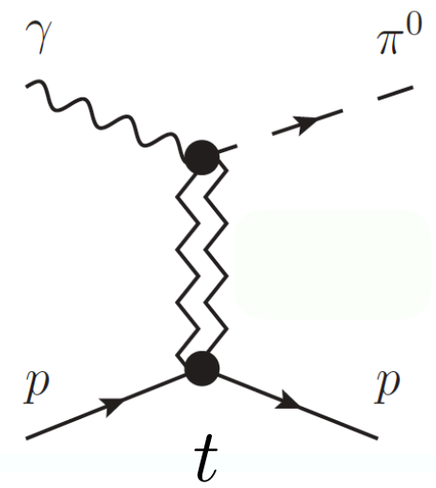

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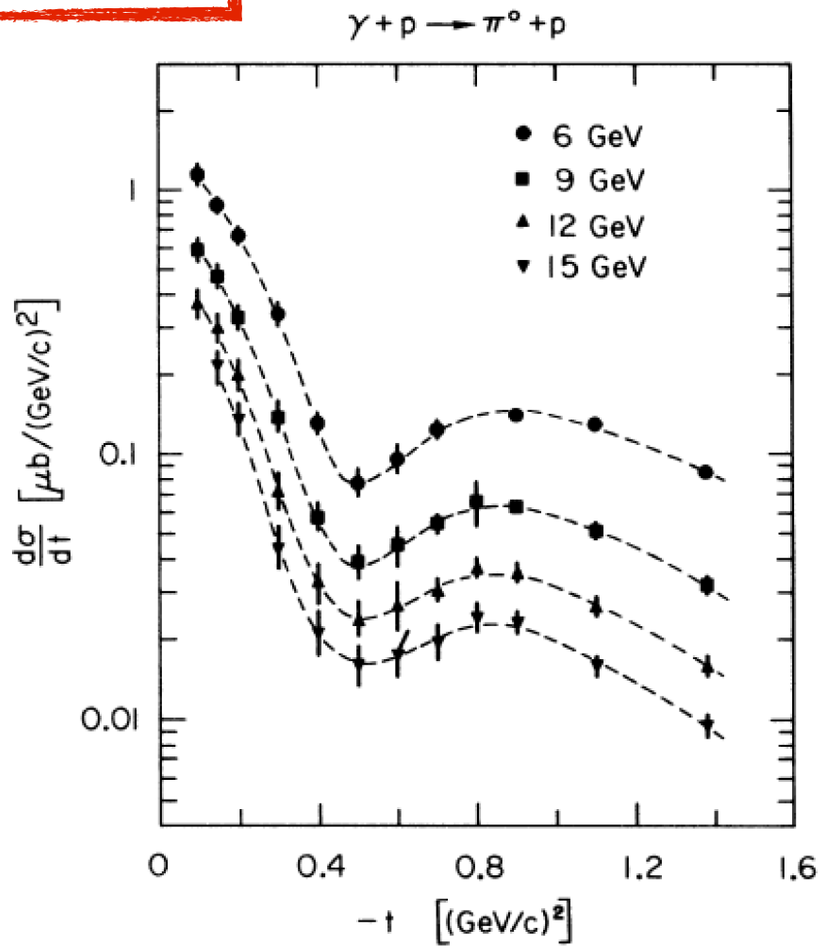
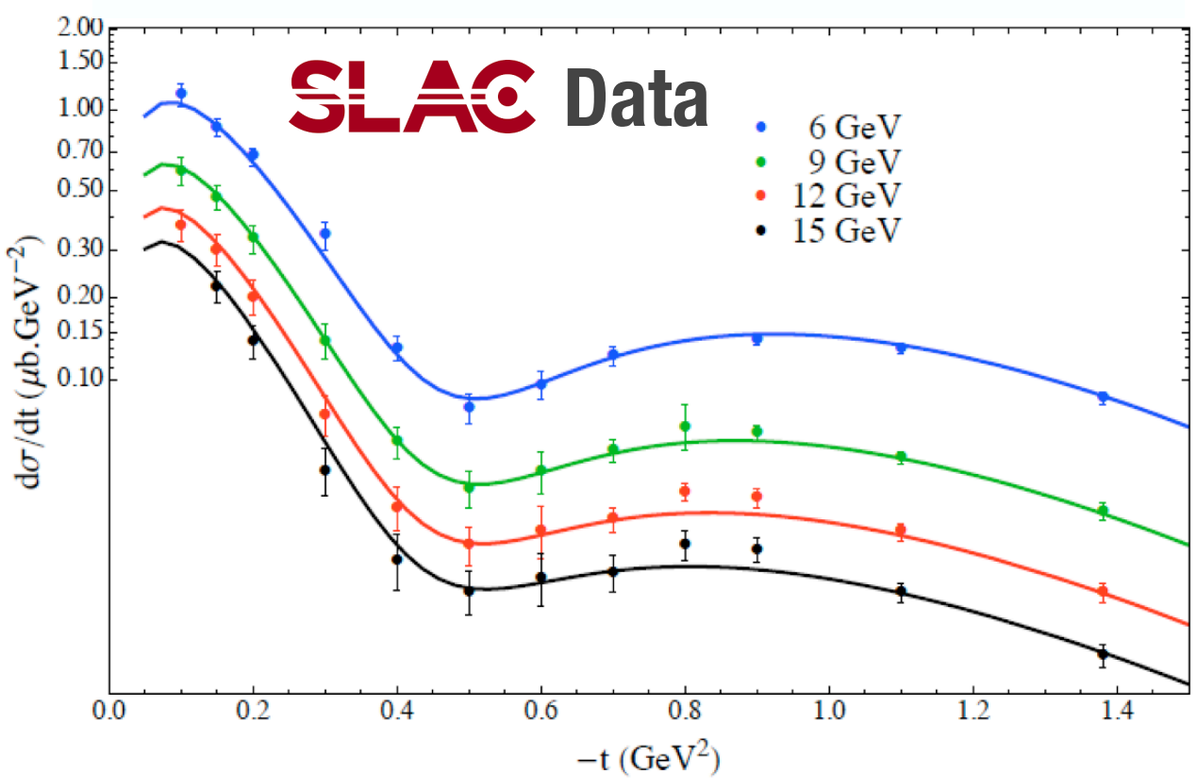


$$\frac{d\sigma}{dt} = \sigma_\perp + \sigma_\parallel = |\rho + \omega|^2 + |b + h|^2$$

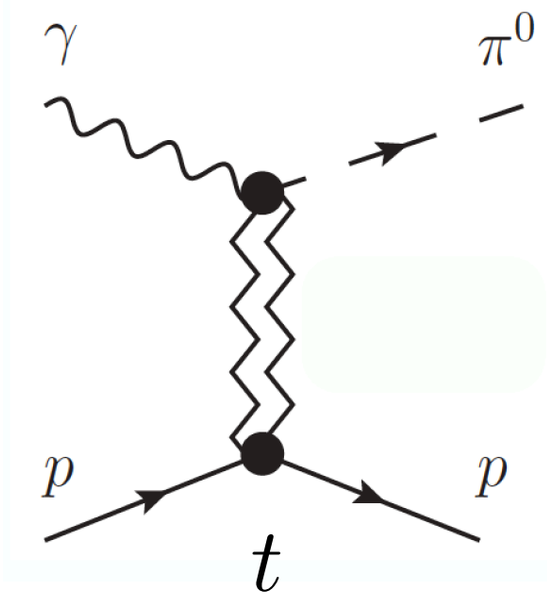


JPAC : Mathieu et al. PRD 92, 074013

γp→π⁰p beam asymmetry Σ

- Beam asymmetry Σ provides insight into dominant production mechanism

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



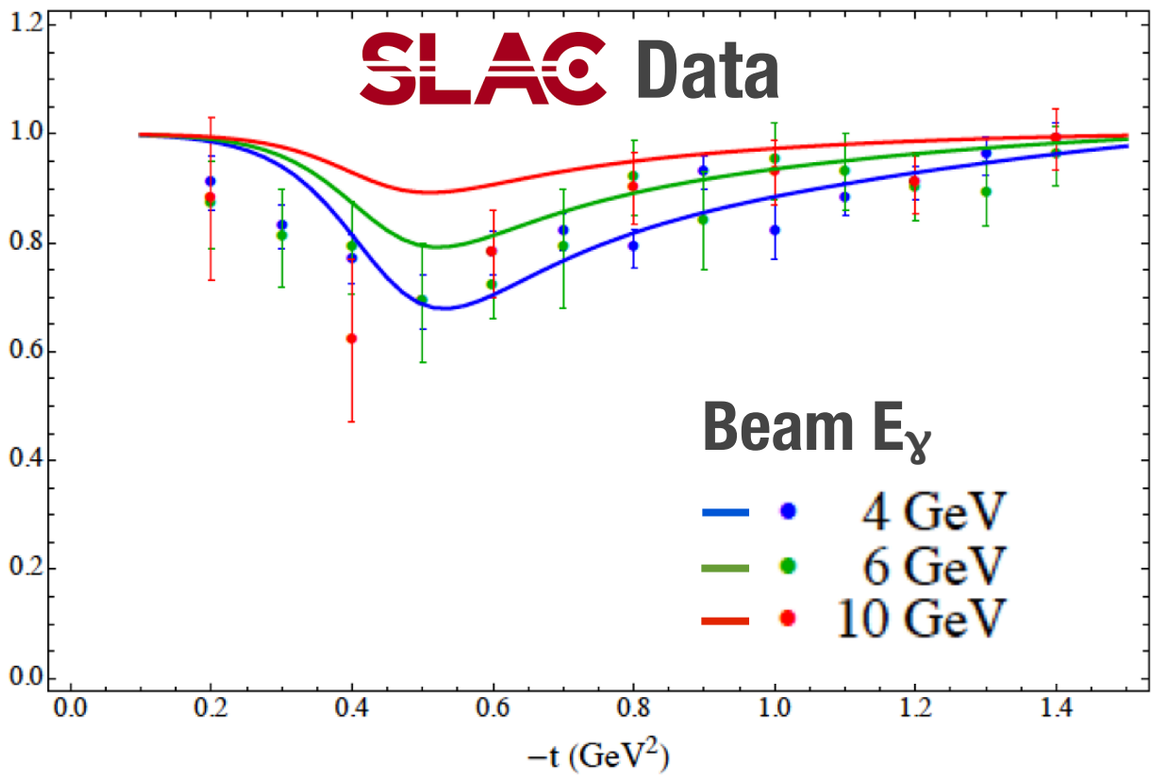
Exchange J^{PC}

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

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

- From experimental standpoint it's easily extended to γp→ηp
  - **No previous measurements!**

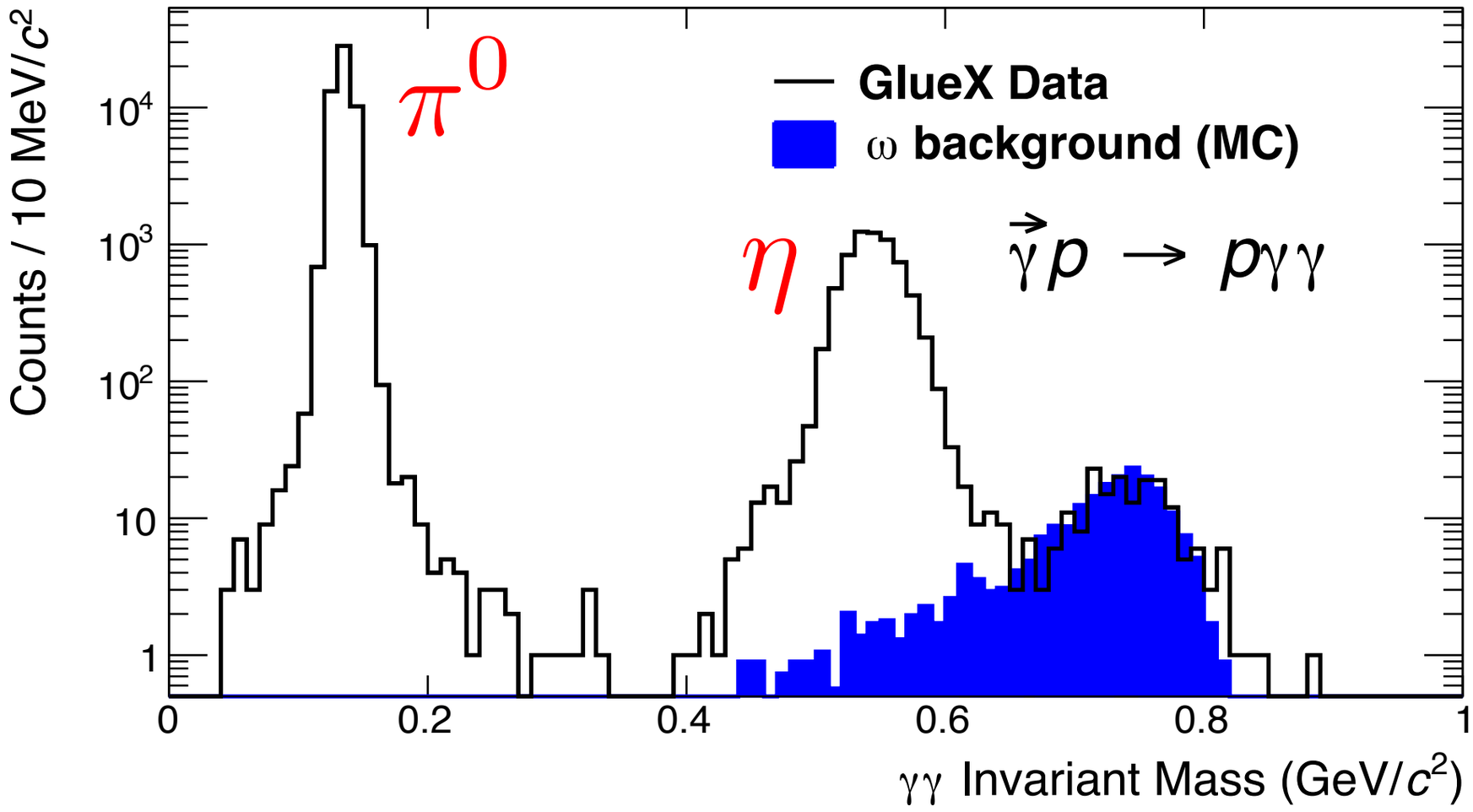
Σ_{π^0}



JPAC : Mathieu et al. PRD 92, 074013

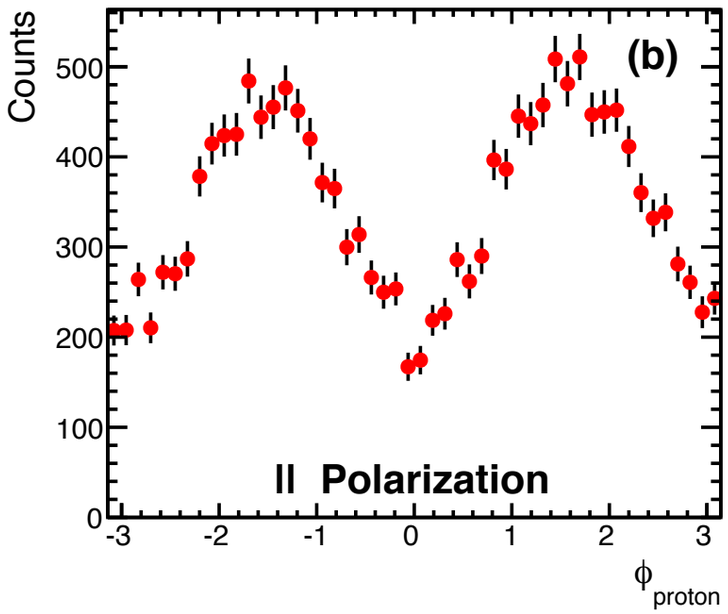
π^0 and η beam asymmetries

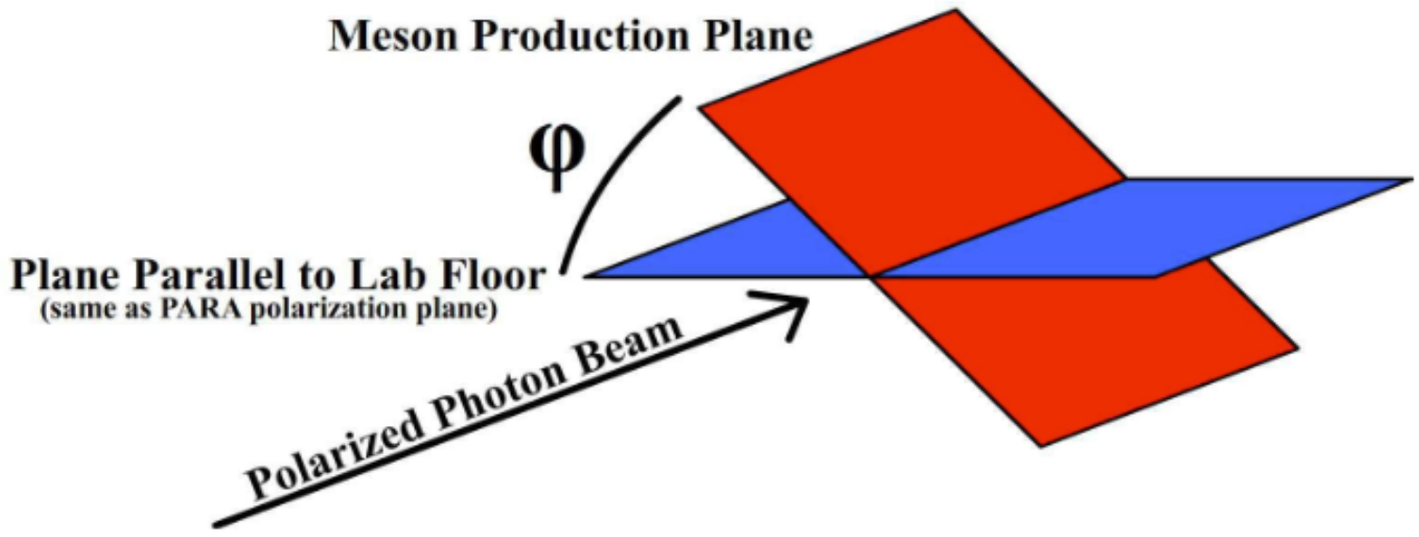
$$\gamma p \to p\gamma\gamma$$



Phys. Rev. C 95, 042201(R)

π^0 and η beam asymmetries

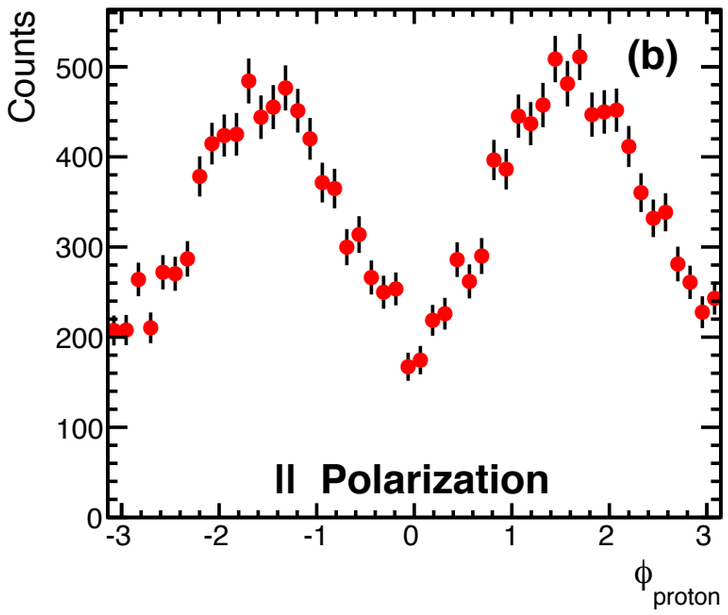


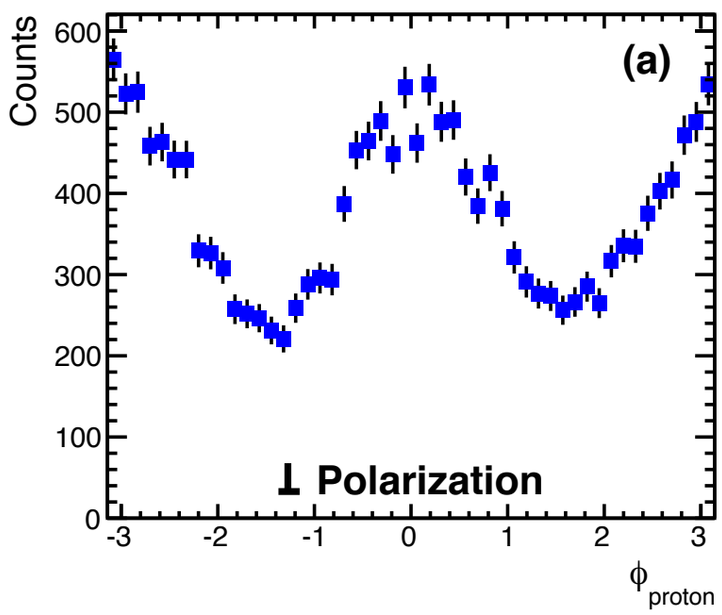


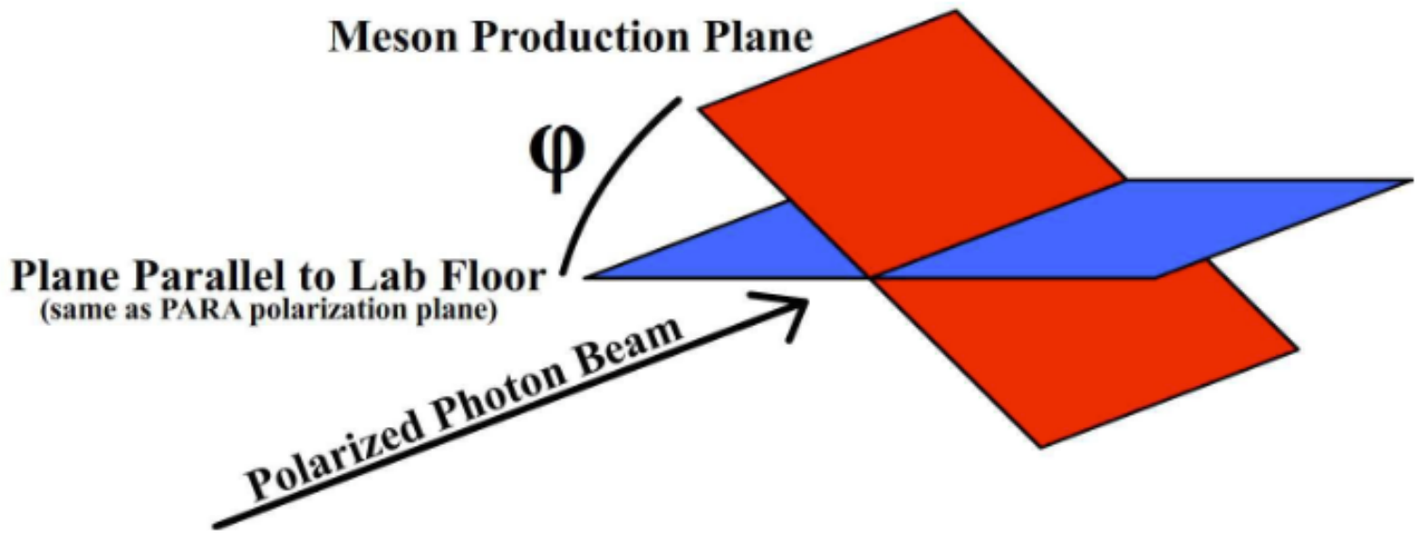
$$\sigma = \sigma_0 \left(1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_\gamma^{\text{lin}})\right)$$

Phys. Rev. C 95, 042201(R)

π^0 and η beam asymmetries







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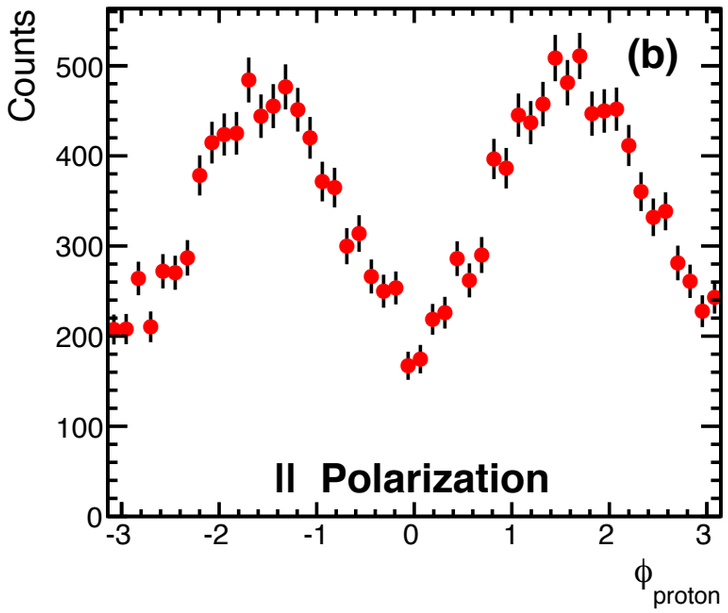
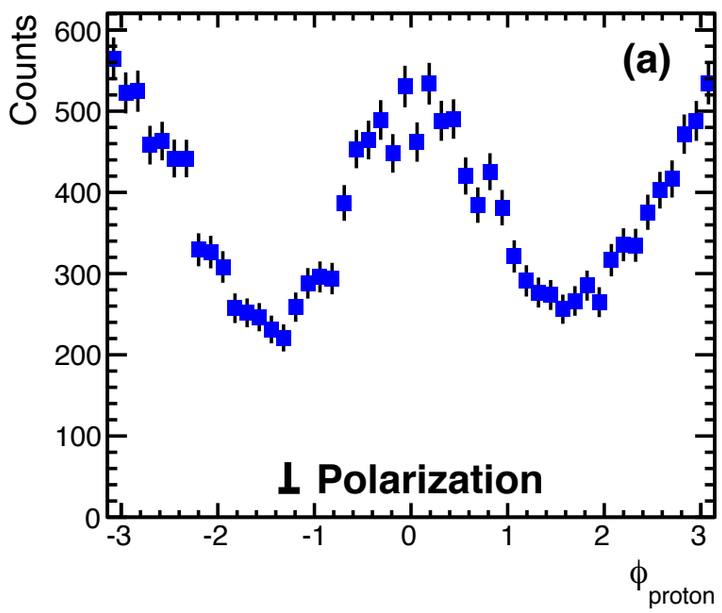
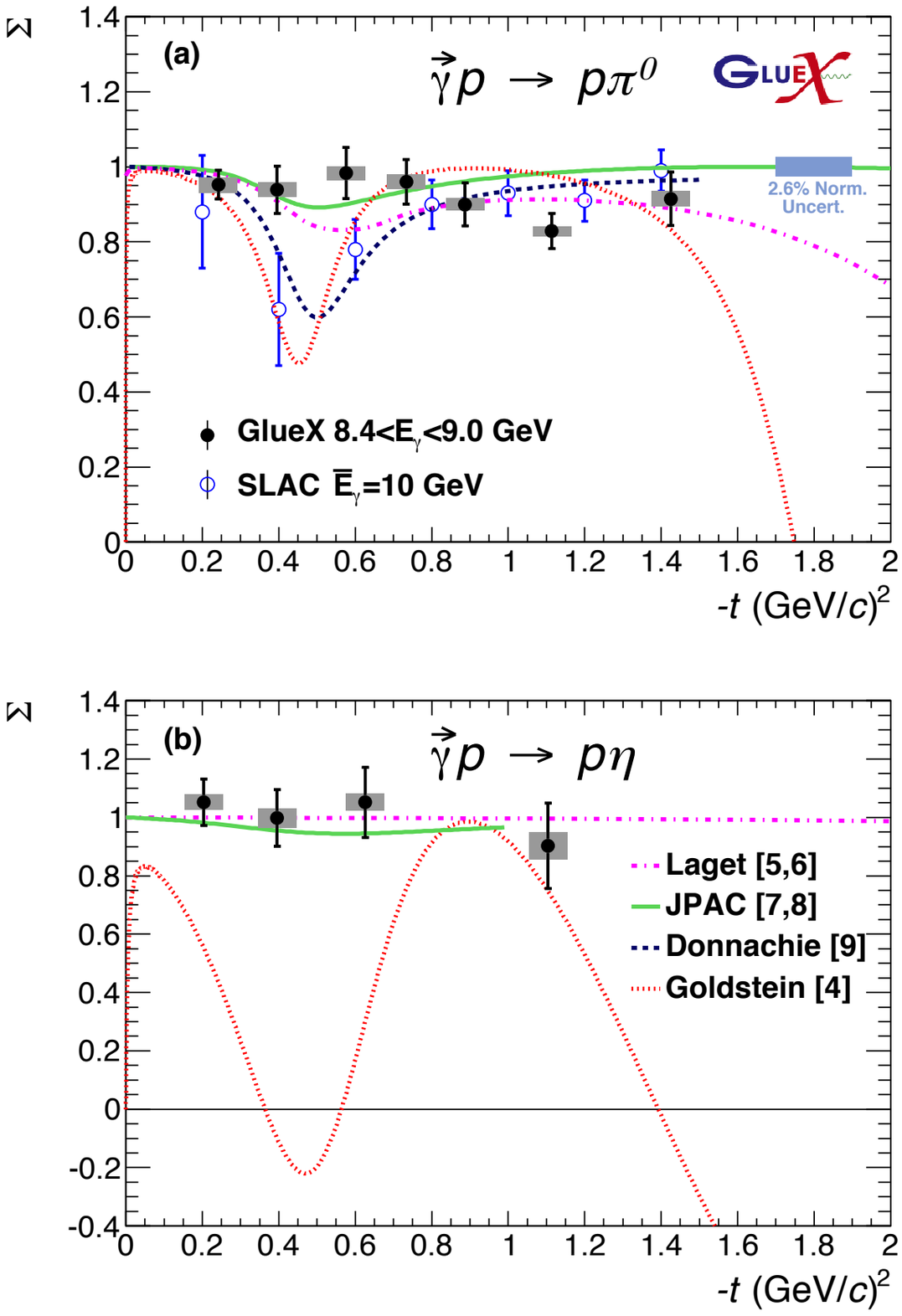




$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

Phys. Rev. C 95, 042201(R)

π^0 and η beam asymmetries

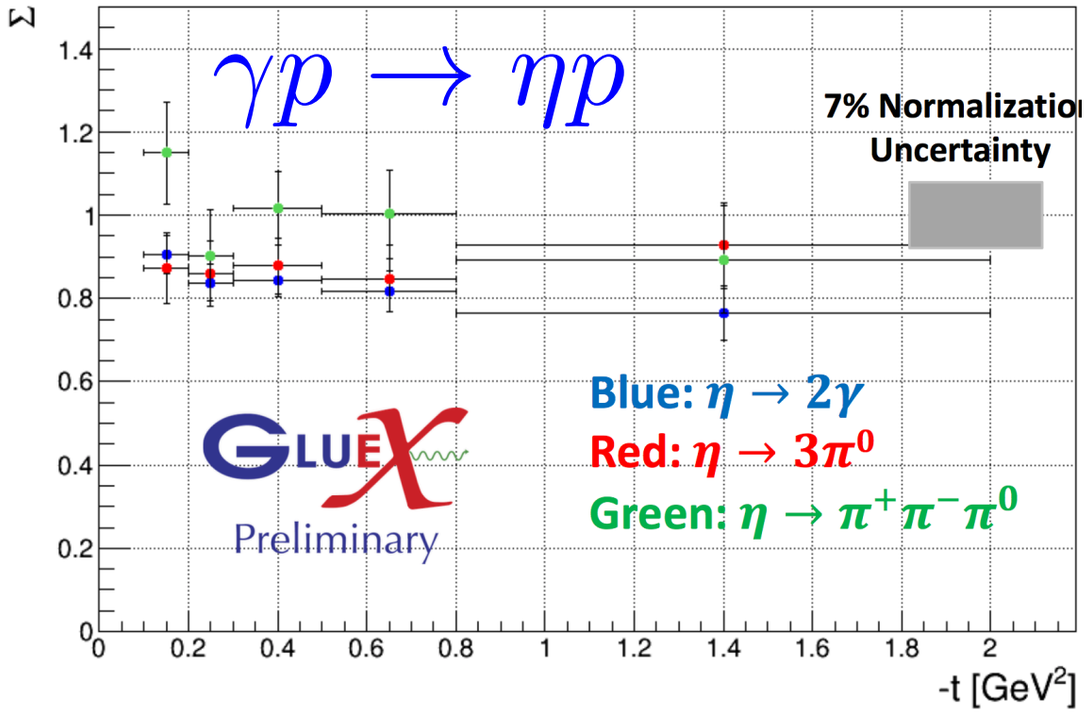


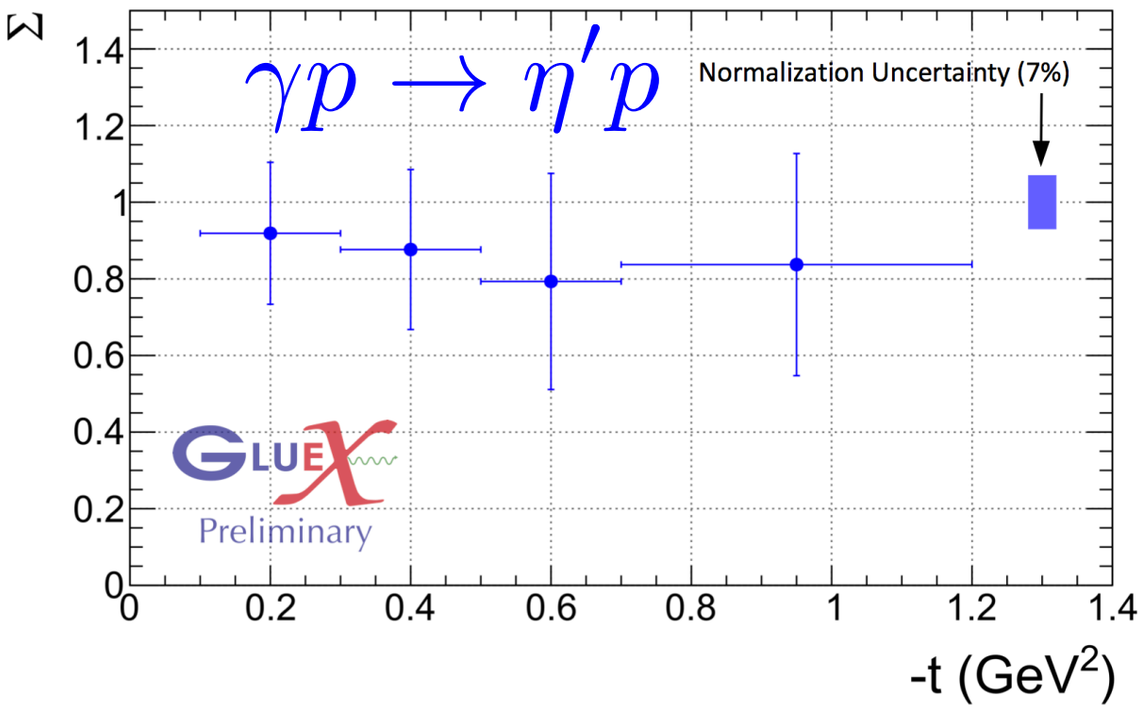
- Testing models for *t*-channel production at high energies
- No dip in *t*-dependence observed at 0.5 (GeV/c)^2
- Vector exchange mechanism dominant at these energies, expect similar mechanism for exotics

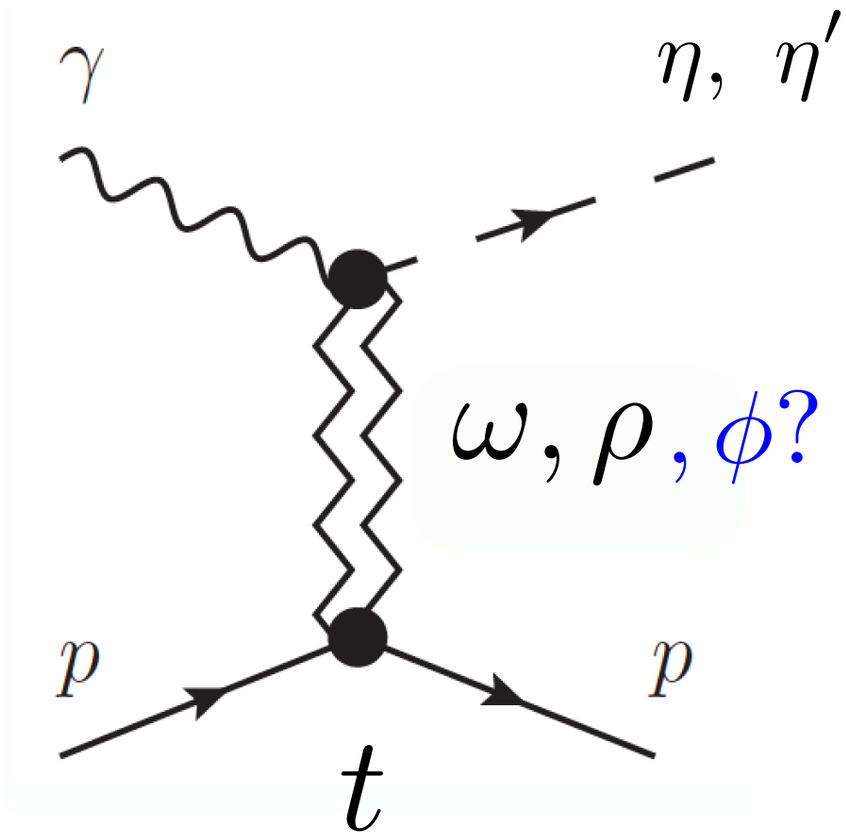
First JLab 12 GeV publication!

Phys. Rev. C 95, 042201(R)

Pseudoscalar beam asymmetries



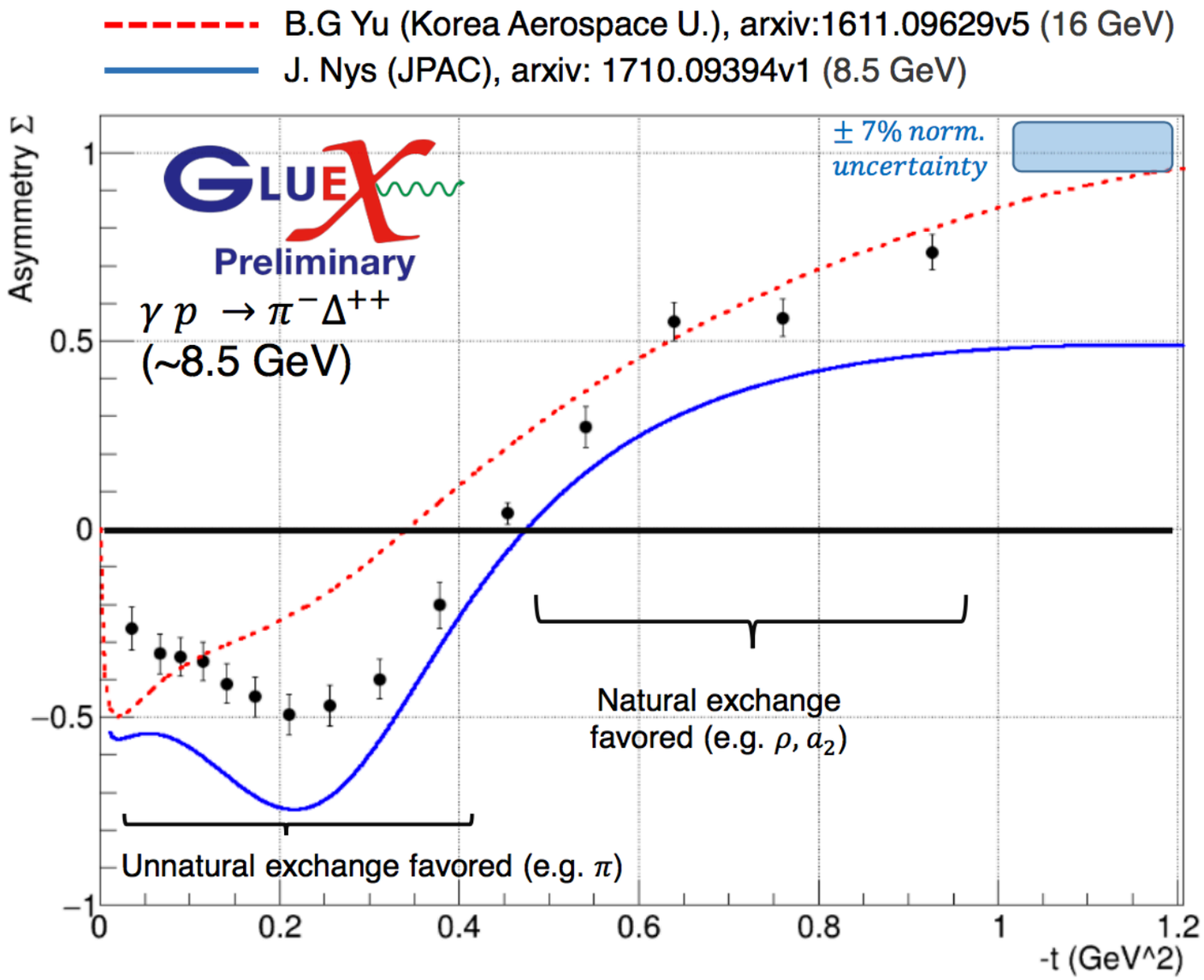


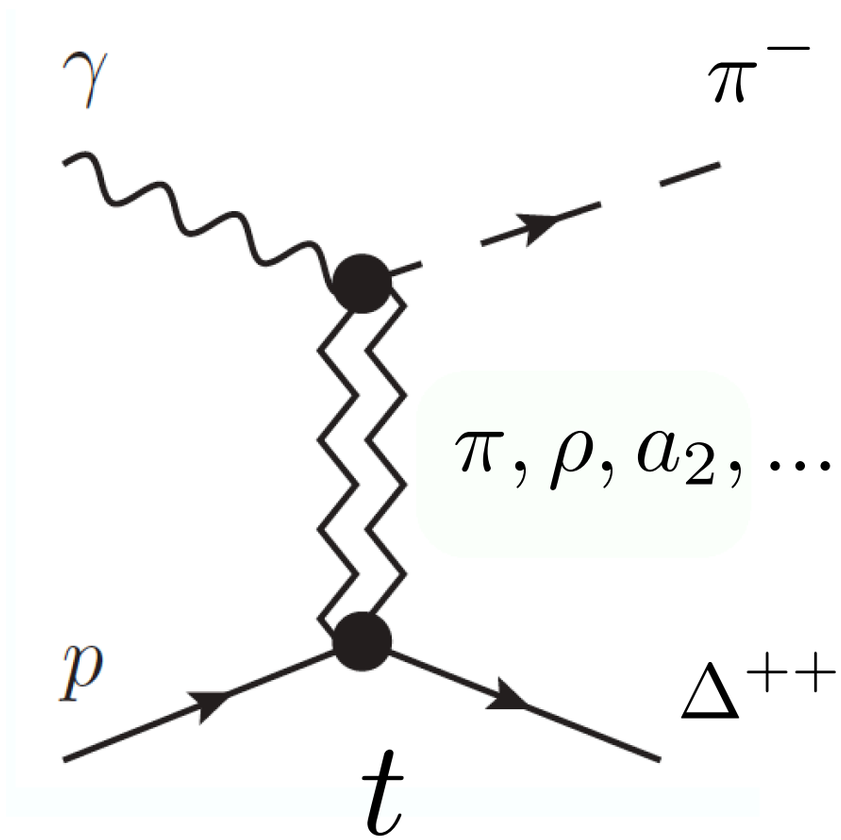


Consistent with prediction from JPAC: PLB 774 (2017) 362

Neutral pseudoscalars: Σ~1, dominated by vector exchange

Pseudoscalar beam asymmetries

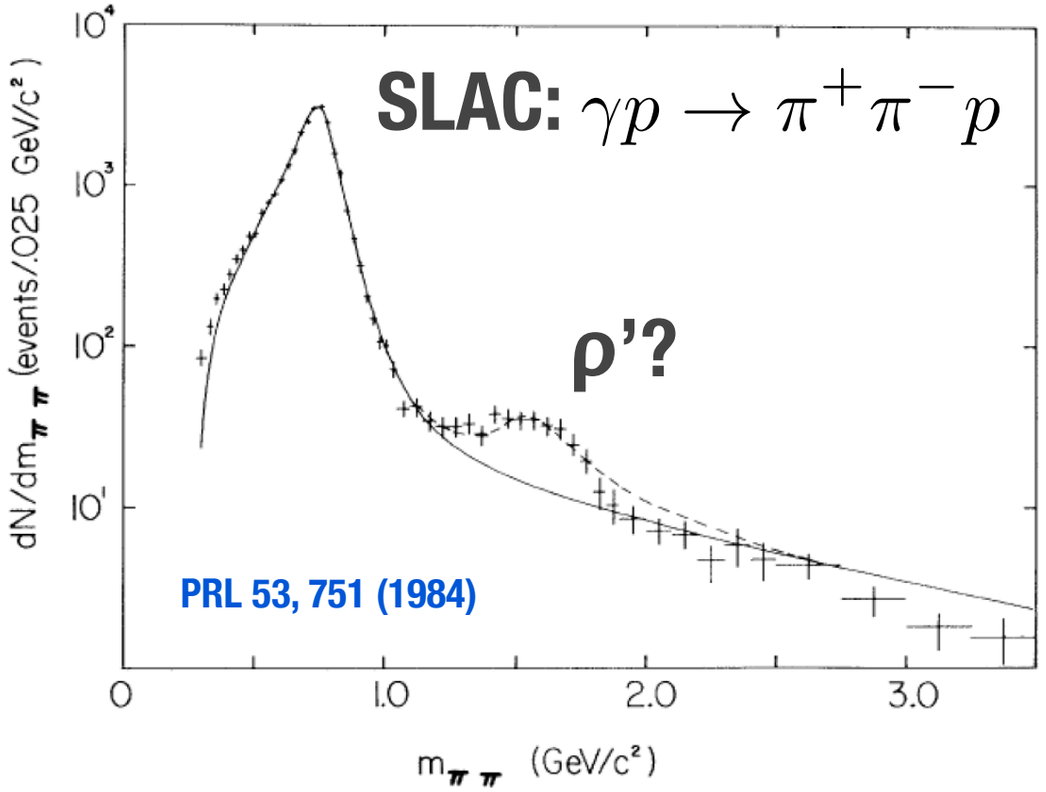


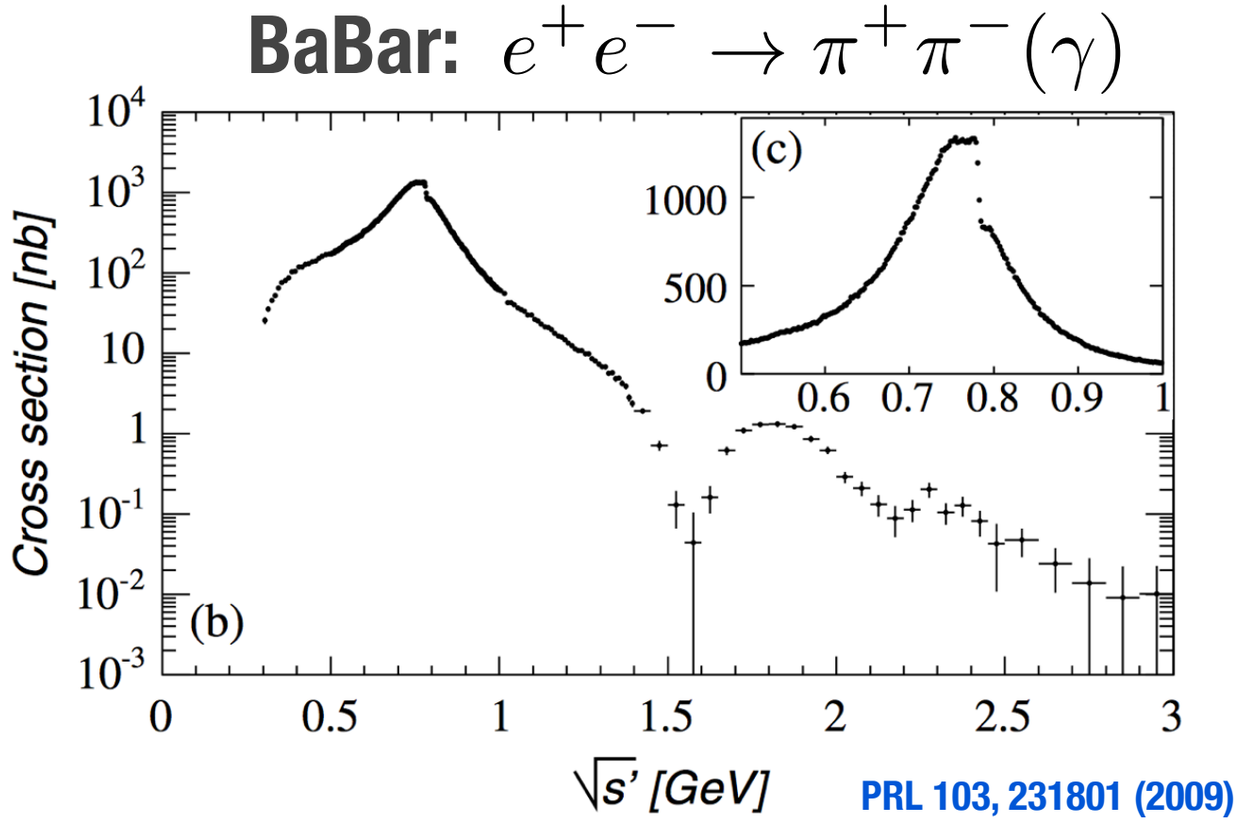


Charged pseudoscalars: more complicated *-t* dependence

Previous signals in photoproduction

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





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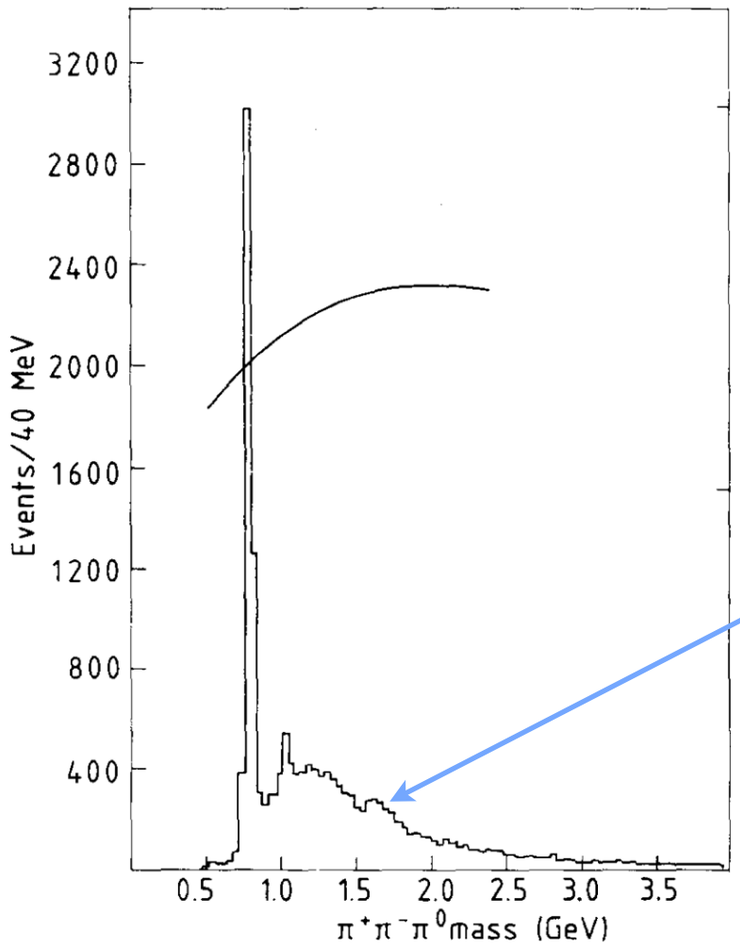
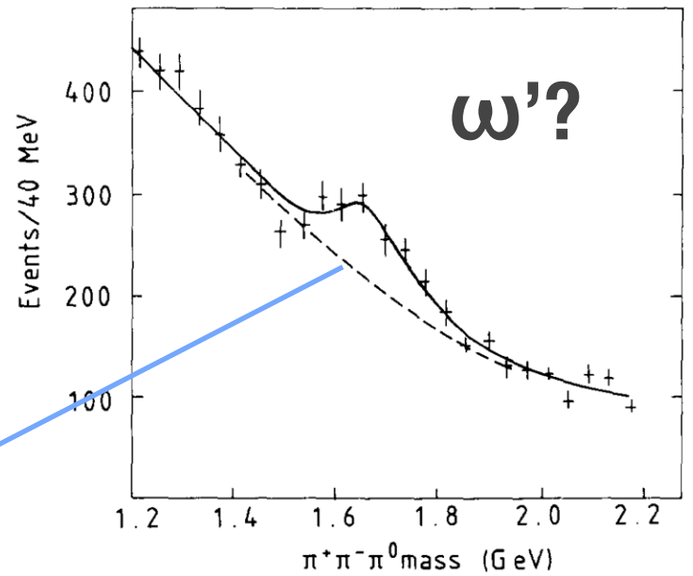




$$\gamma p \to \omega p \to \pi^+ \pi^- \pi^0 p$$

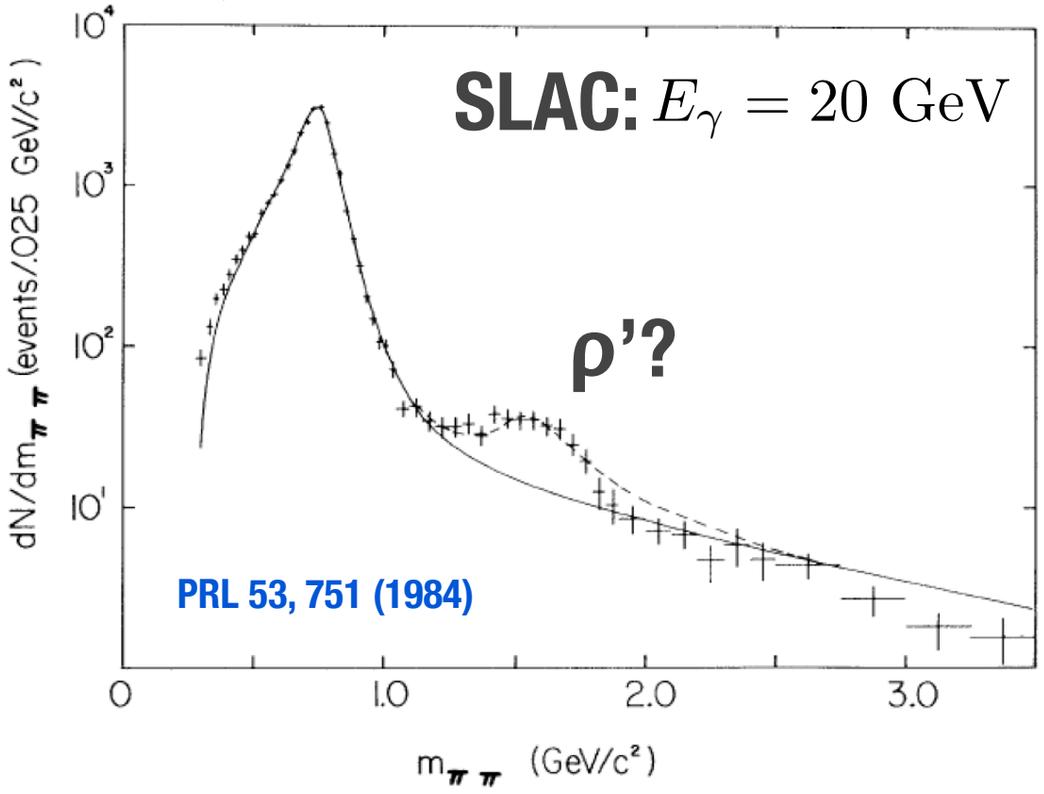
$$\gamma p \to \phi p \to \pi^+ \pi^- \pi^0 p$$

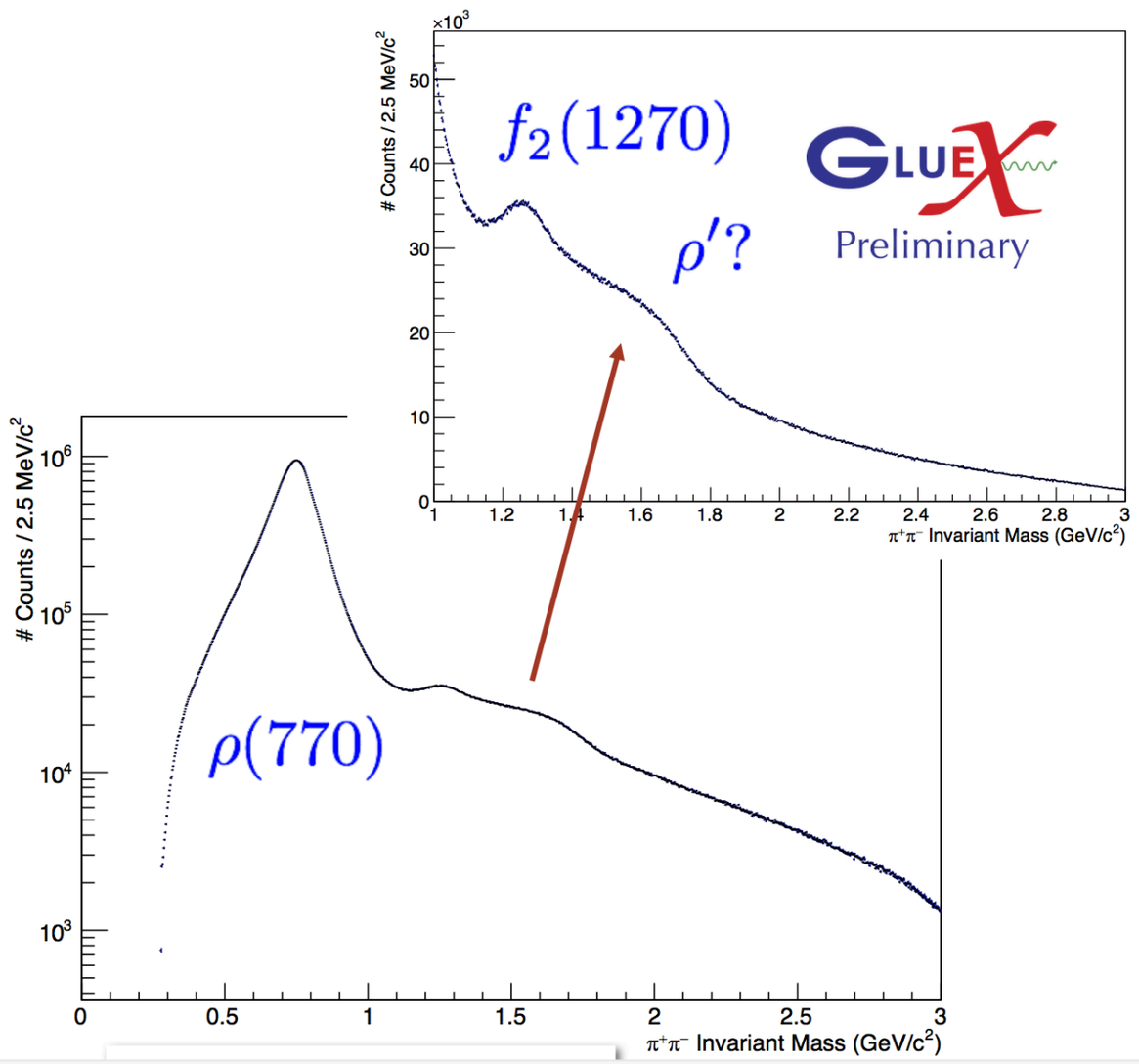
$$\gamma p \to \text{“}\omega'(1670)\text{”} p \to \pi^+ \pi^- \pi^0 p$$

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

Early spectroscopy opportunities

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



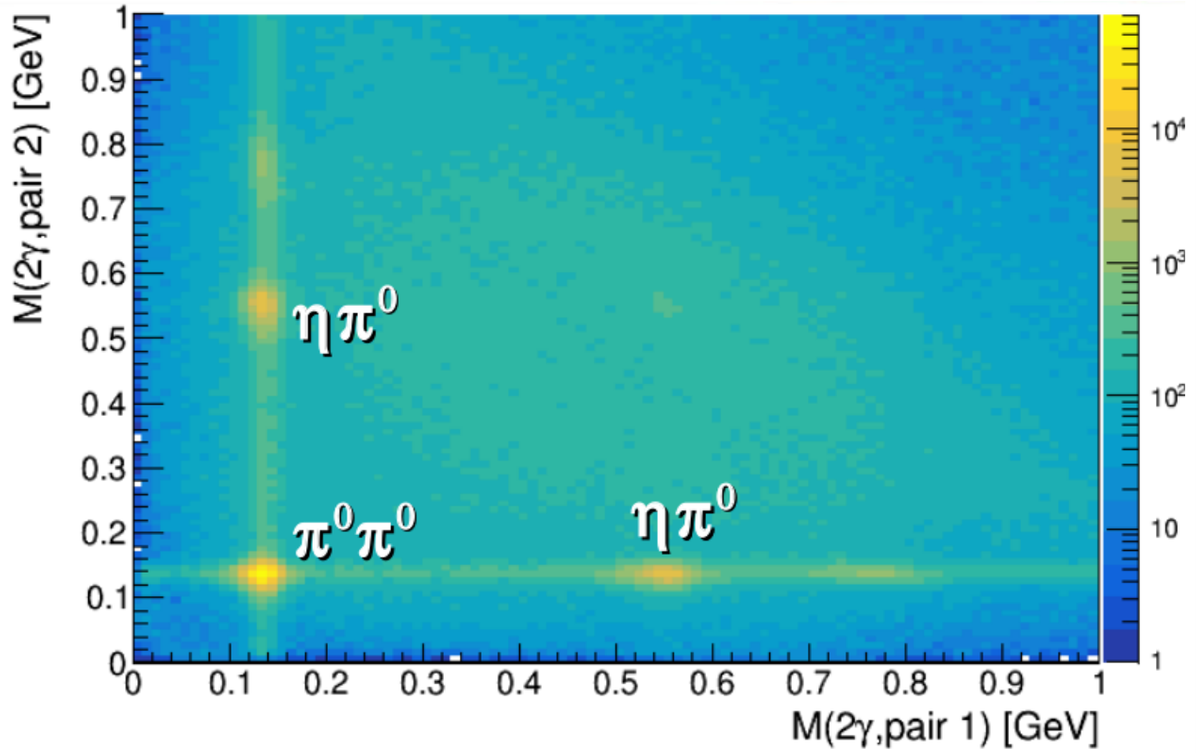


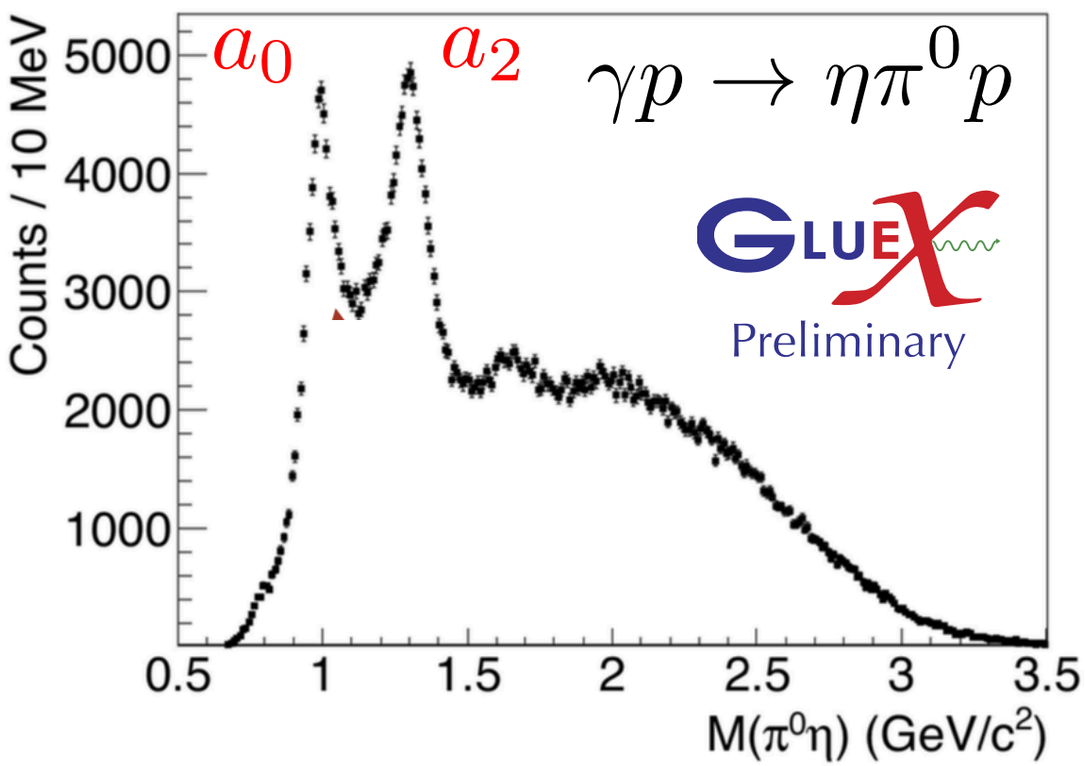
- Enhancement consistent with earlier SLAC measurement, but ~1000x more statistics with early GlueX data
- Polarization observables will provide further insight into the nature of this enhancement

Early spectroscopy opportunities

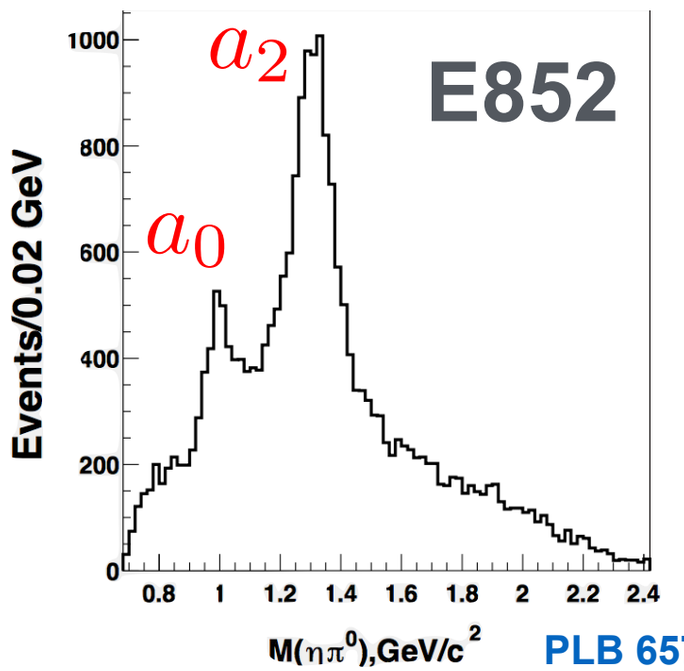
$$\gamma p \to 4\gamma p$$

- Previous photoproduction data very sparse for channels with multiple neutrals particles
- Early opportunity in ηπ/η'π since P-wave is exotic





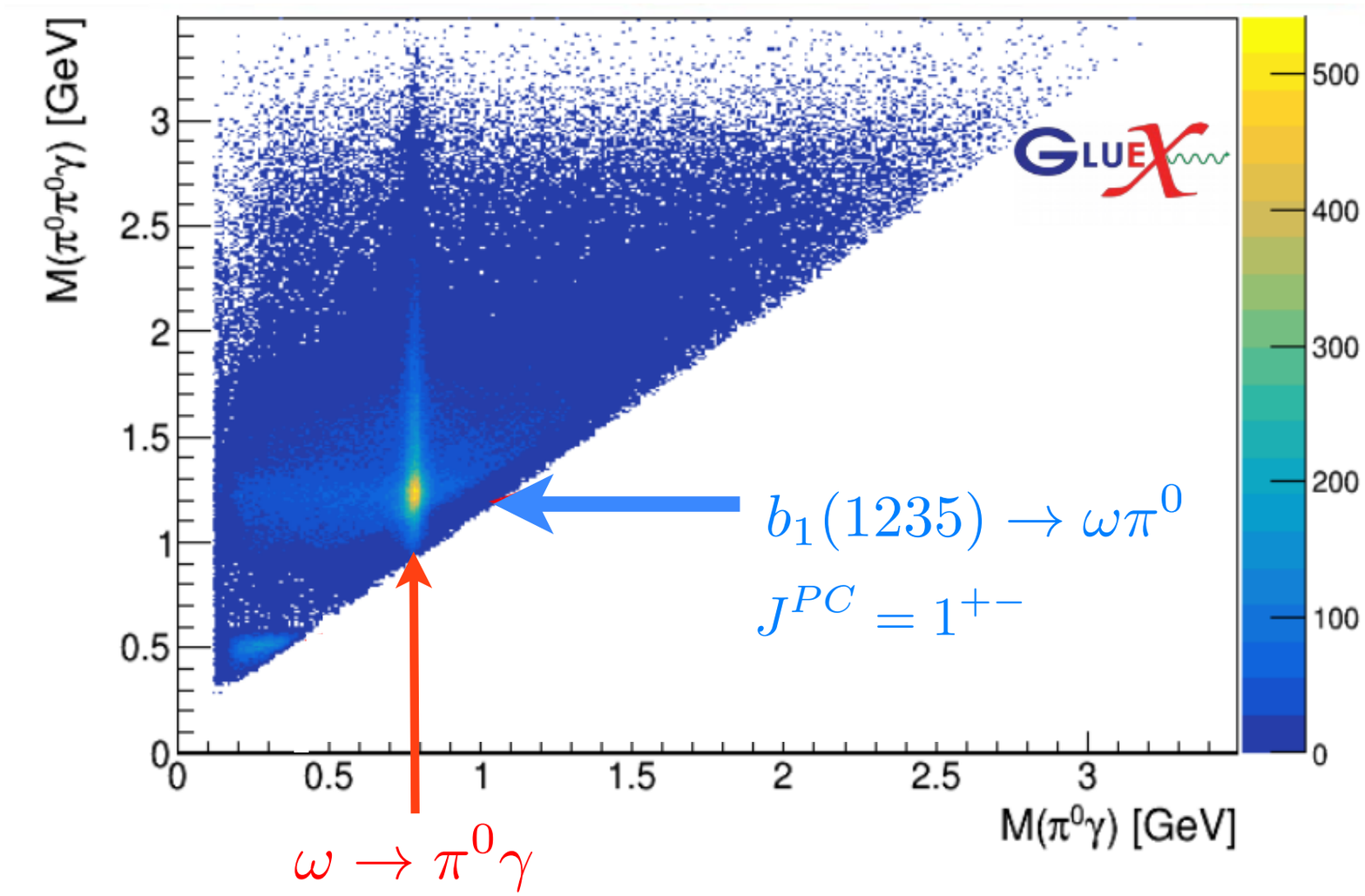
$$\pi^- p \to \eta\pi^0 n$$



PLB 657 (2007) 27

Early spectroscopy opportunities

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

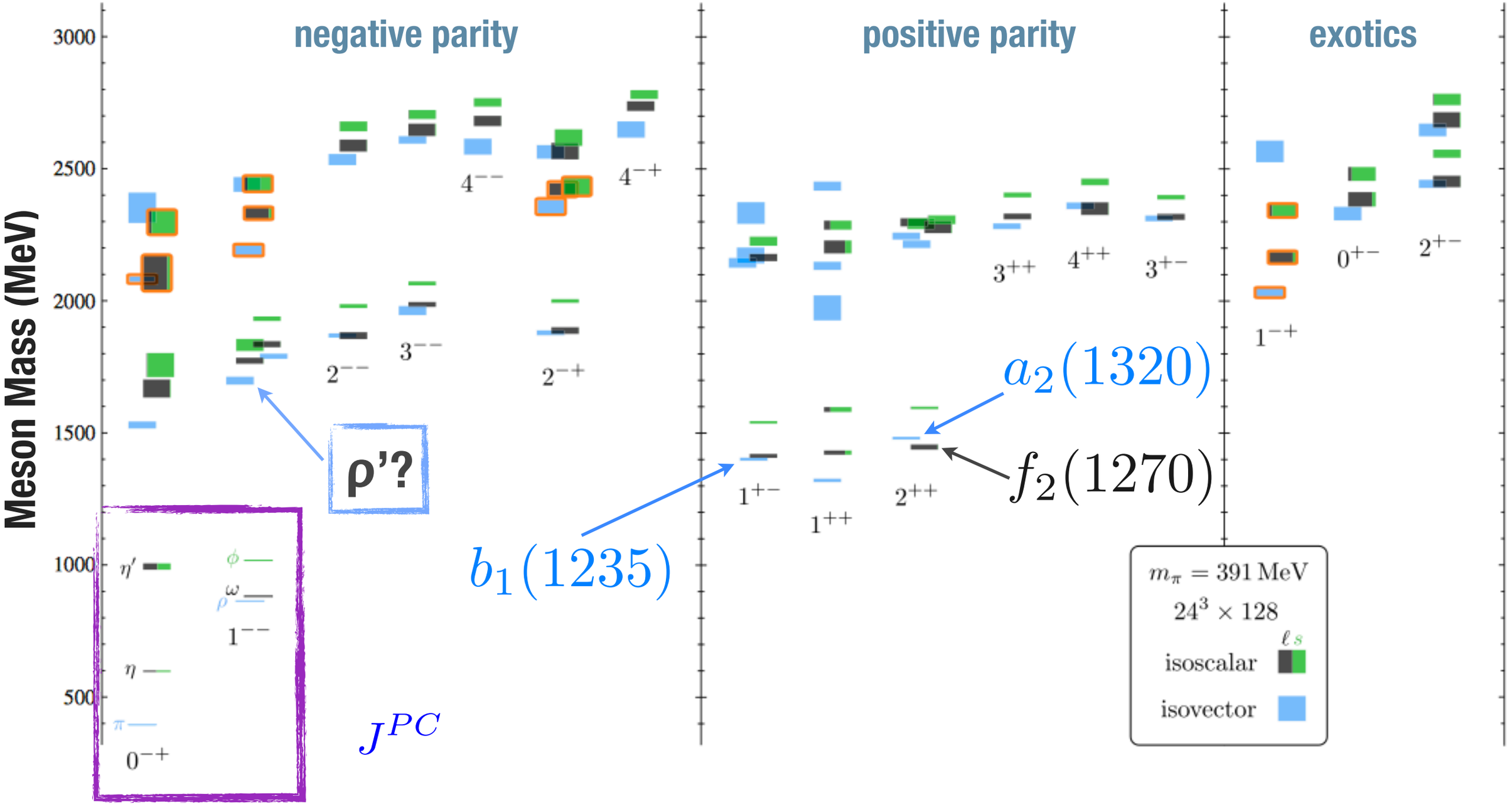


$$\gamma p \to b_1 p, b_1 \to \omega\pi^0, \omega \to \pi^0\gamma$$

- 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

Amplitude Analysis

$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\text{amps}}} V_\alpha A_\alpha(\vec{x}) \right|^2$$

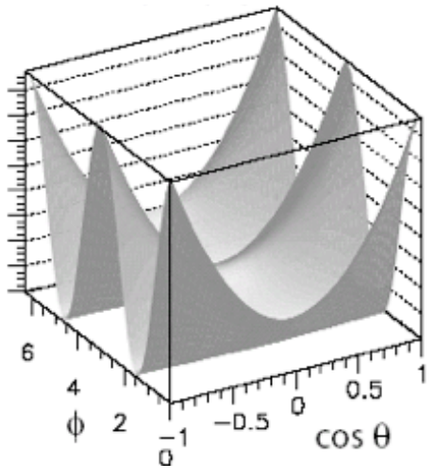
- Expand set of possible amplitudes over many X and I, and determine V_α via maximum likelihood fit
- Good angular acceptance critical for disentangling J^{PC}

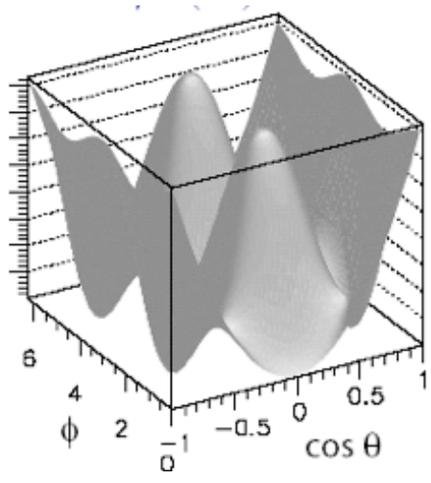
Example Intensities:

$X(1^{++})$
$\rightarrow \rho\pi^+$ (S wave)

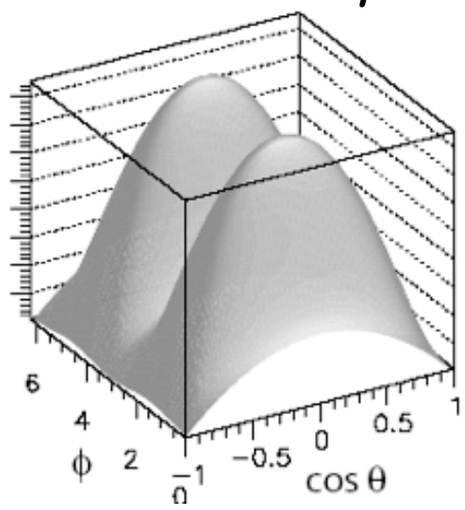
$X(2^{++})$
$\rightarrow \rho\pi^+$ (D wave)

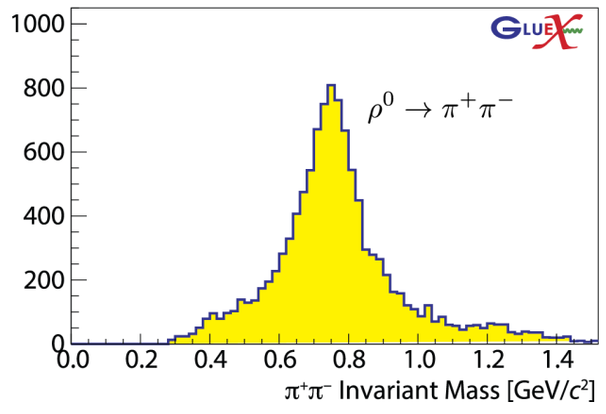
$X \rightarrow \rho\pi^+$

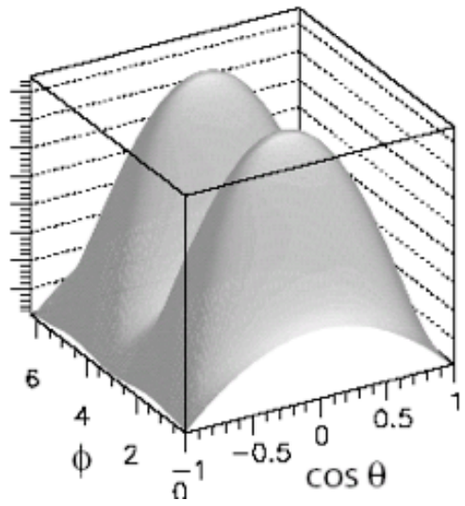


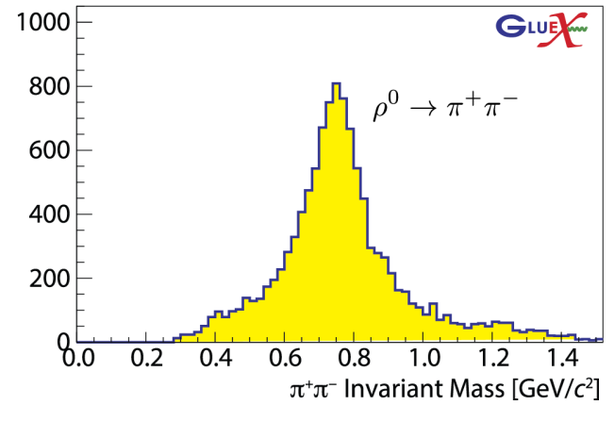


$\rho \rightarrow \pi^+\pi^-$

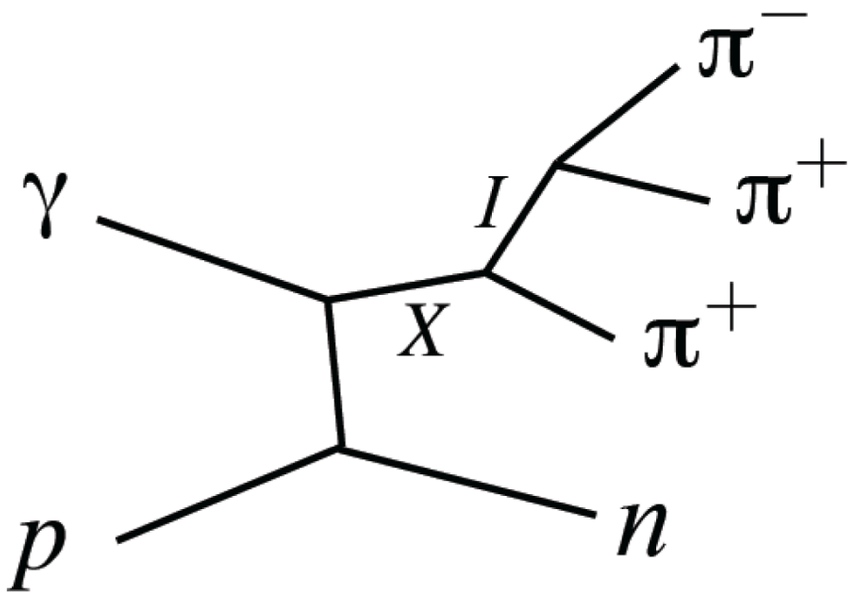






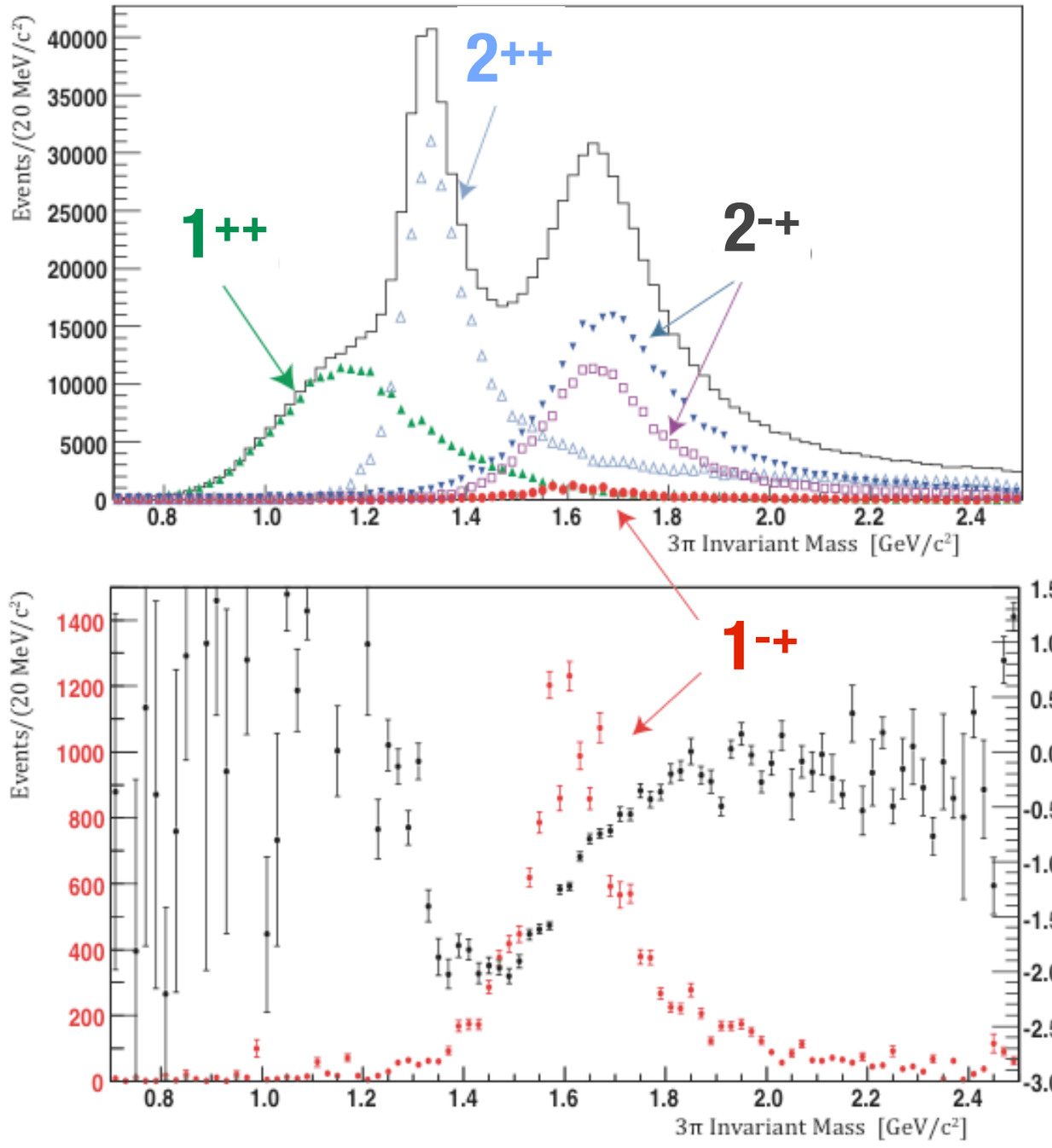


Amplitude Analysis



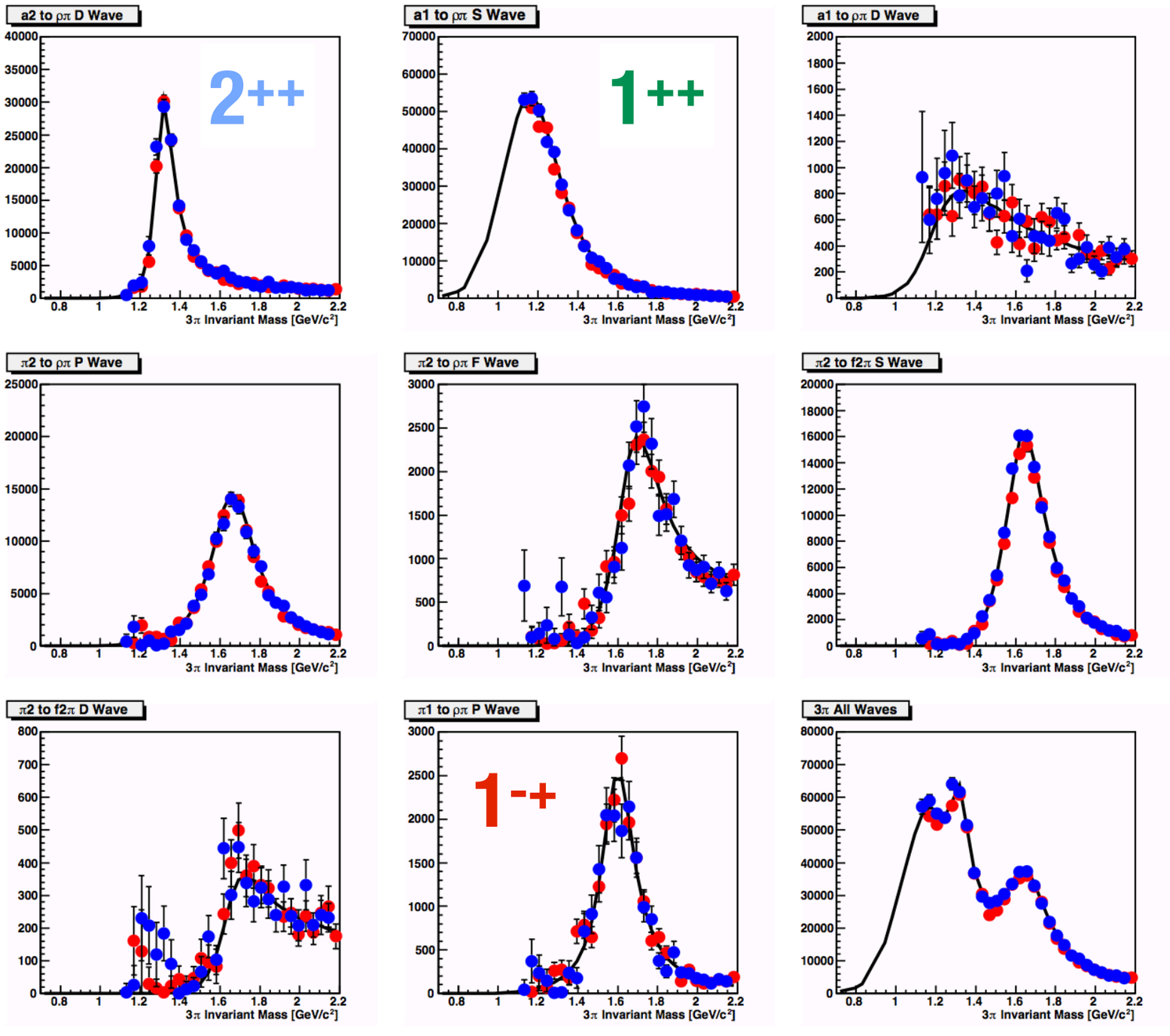
- **Simulate** production of known resonances and **exotic hybrid (1^{-+}) signal** with 1.6% relative strength
- Yields correspond to **~3.5 hours** of GlueX data taking (at full intensity)

GlueX Simulation



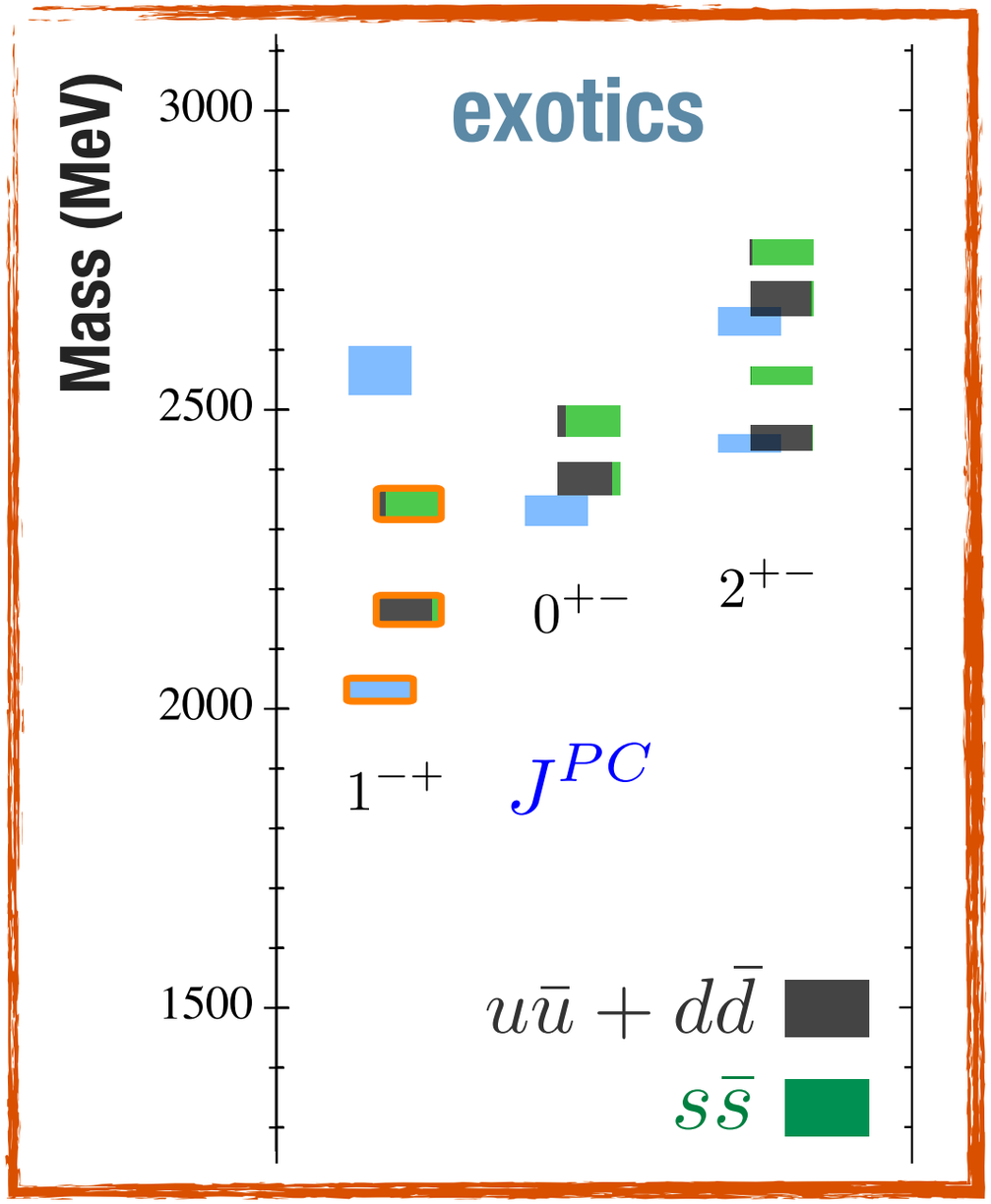
MesonEx Amplitude Analysis

CLAS12 Simulation



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



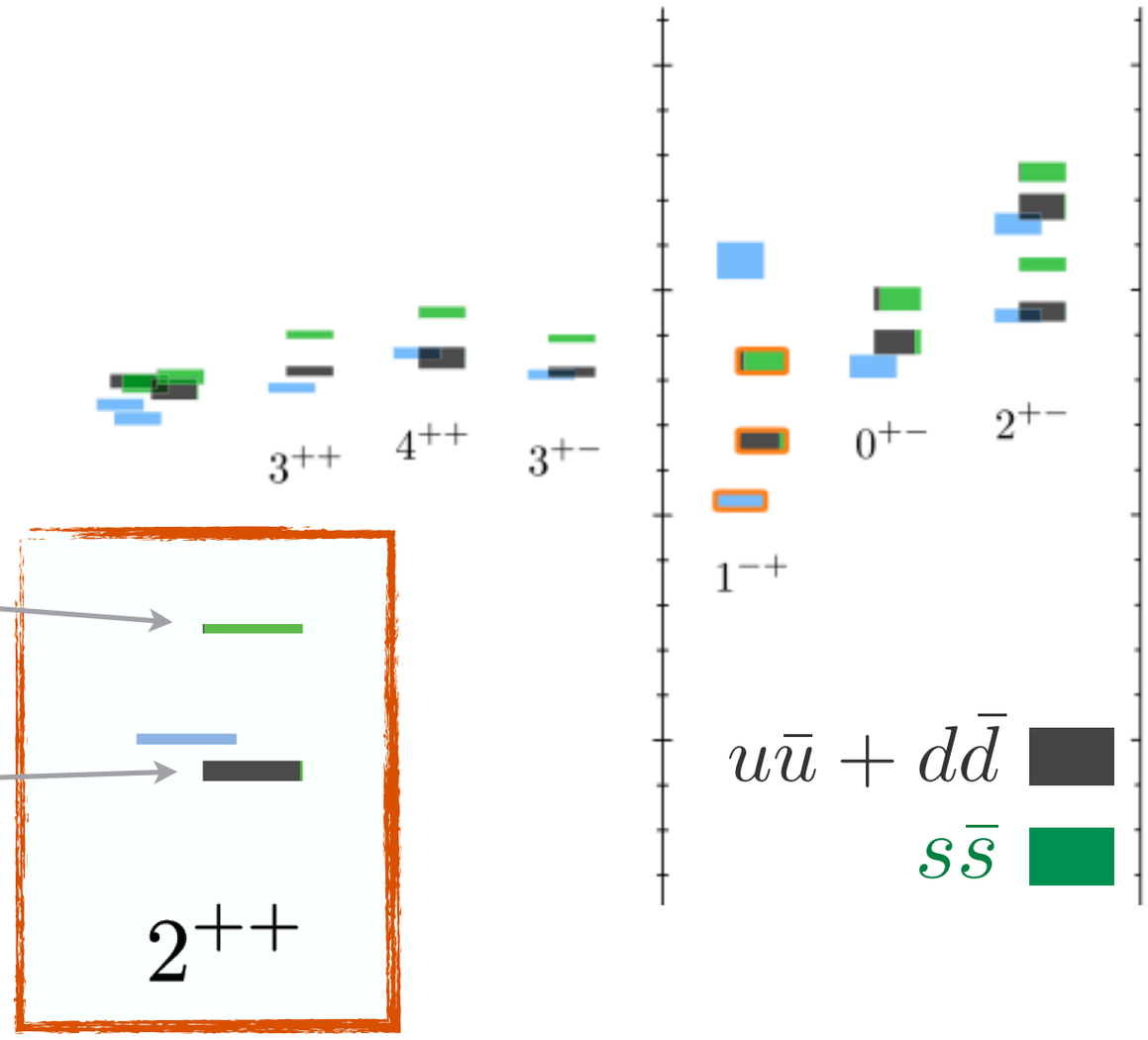
	Approximate Mass (MeV)	J^{PC}	Final States
π_1	1900	1^{-+}	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	2100	1^{-+}	4π, $\eta 4\pi$, $\eta\eta\pi\pi^\dagger$
η_1'	2300	1^{-+}	$KK\pi\pi^\dagger$, $KK\pi^\dagger$, $KK\omega^\dagger$

Strangeness program: decay patterns

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

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

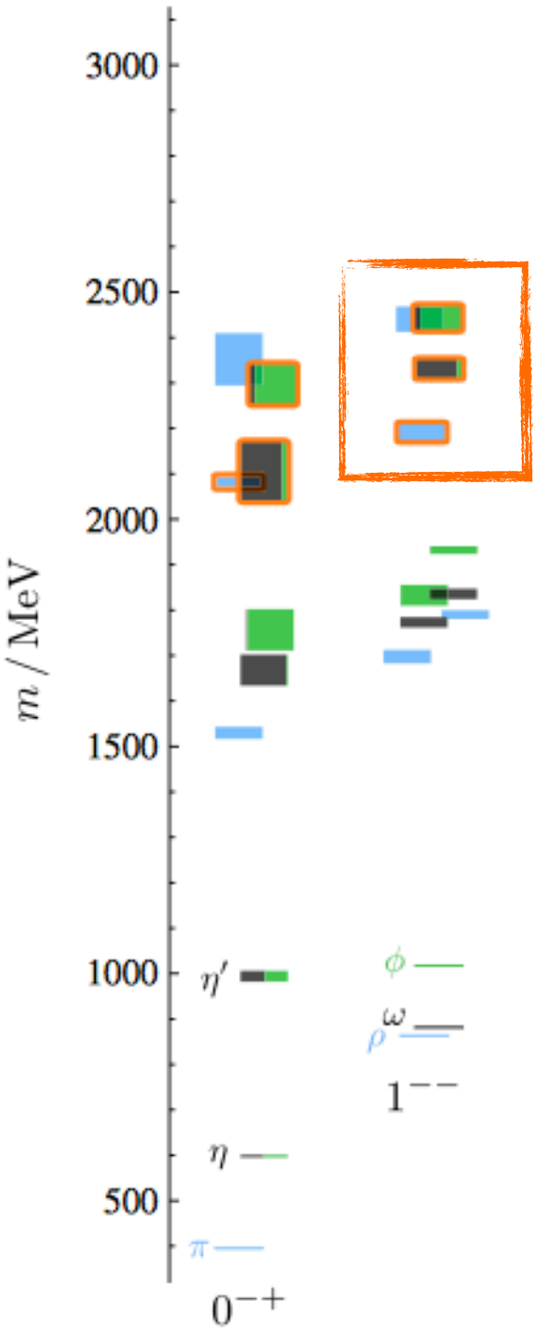
$$\frac{\mathcal{B}(f_2(1270) \to \pi\pi)}{\mathcal{B}(f_2(1270) \to KK)} \approx 20$$



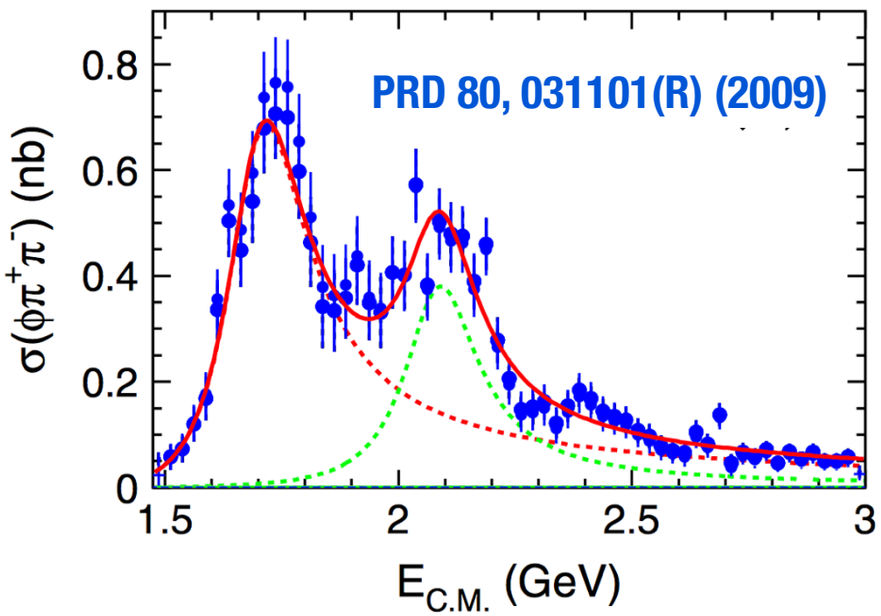
- Consistent with lattice QCD mixing angle for 2^{++}, and predictions for hybrids

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

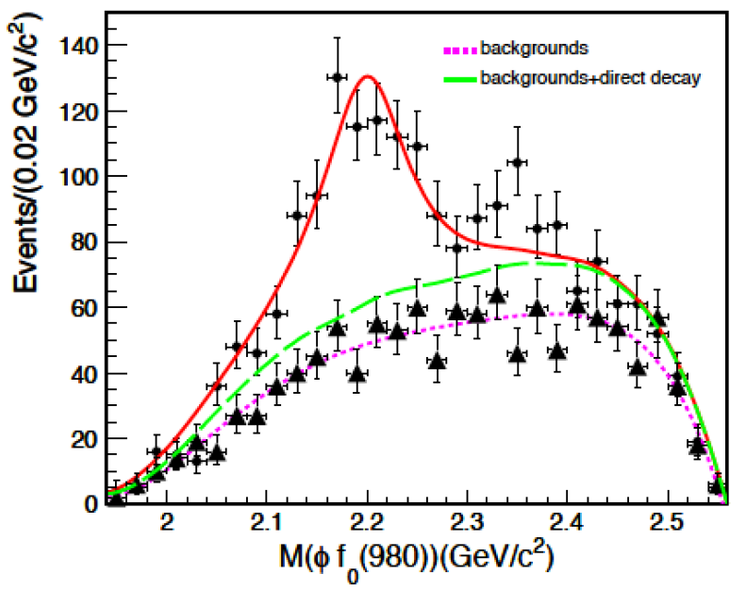
Strangeness program: Y(2175)



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

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

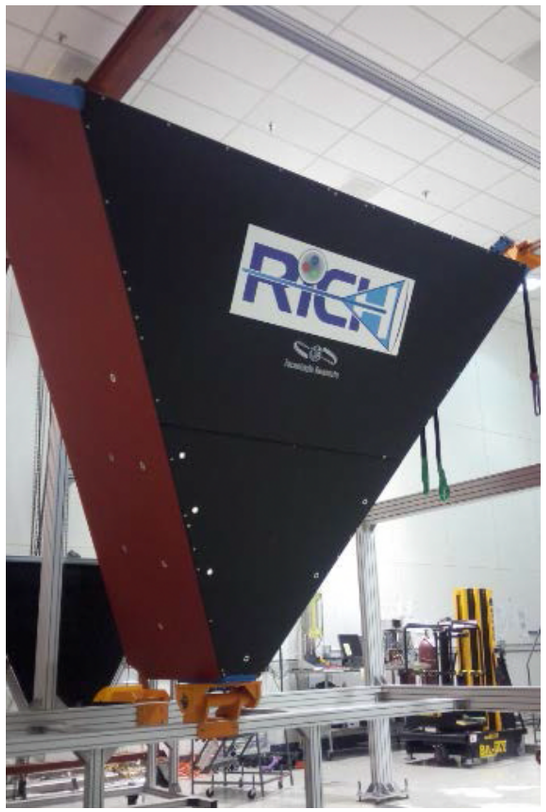
- Is it a supernumerary state in the strangeonium spectrum? Possibly a hybrid?

Strange hadron spectroscopy

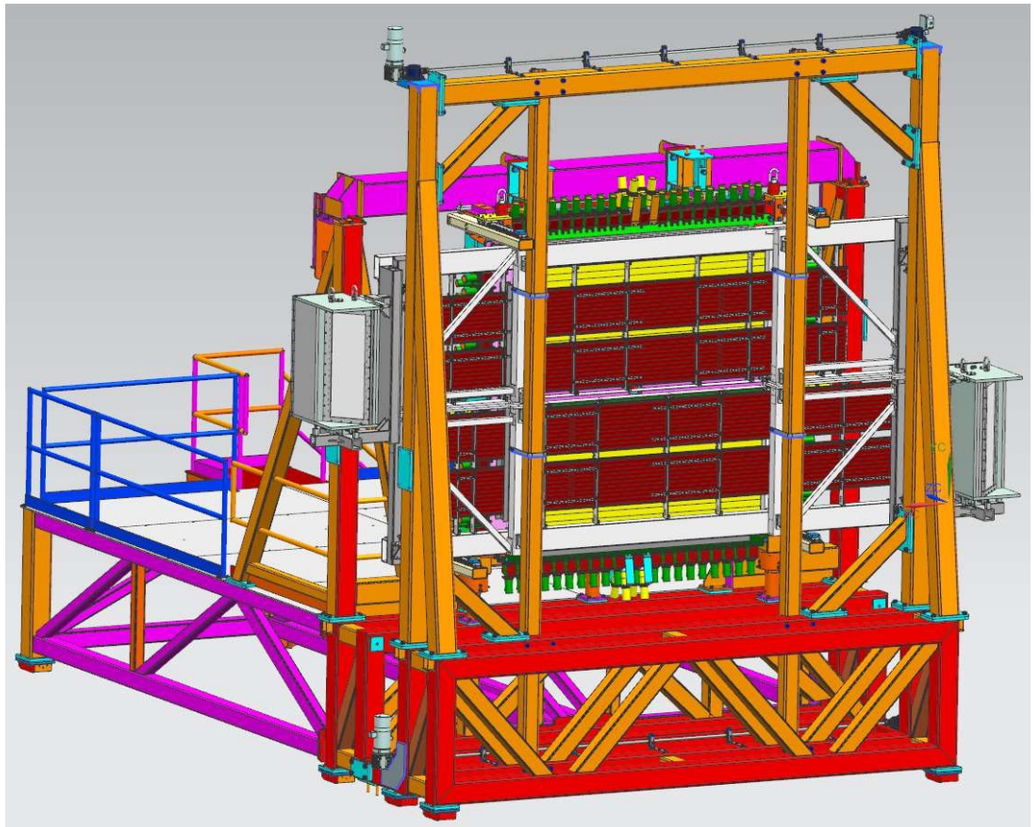
- **JLab strange quark program upgrades**

CLAS12

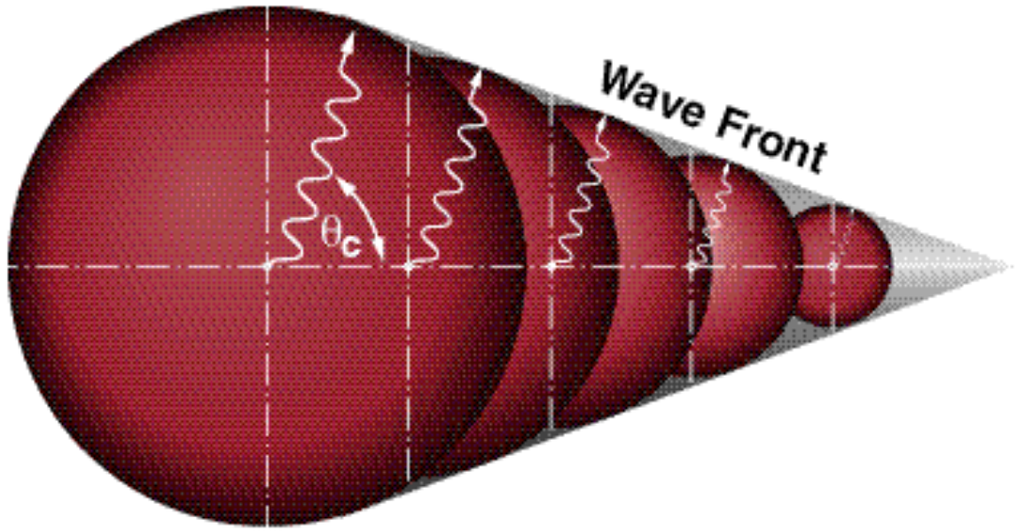
RICH



GlueX

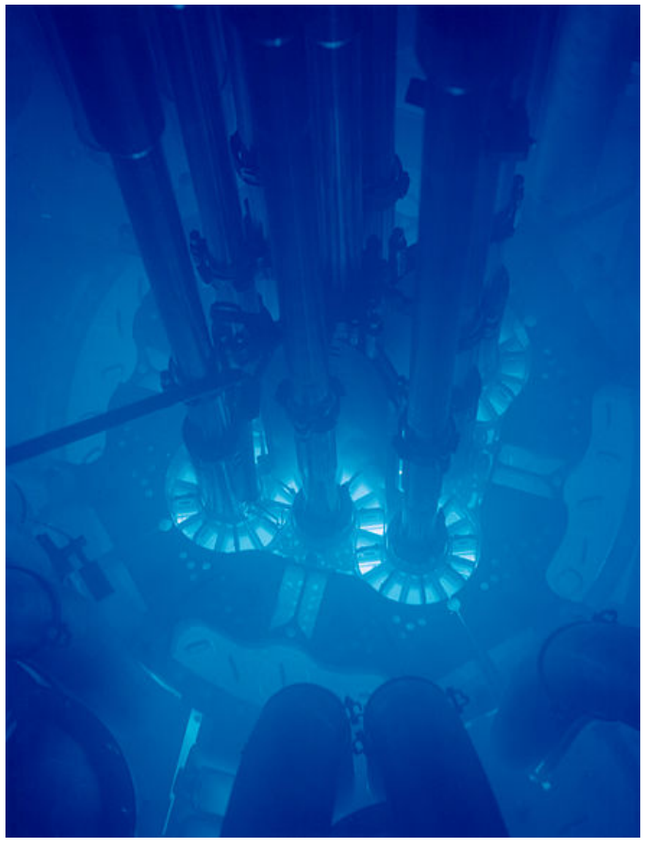


Charged particle identification



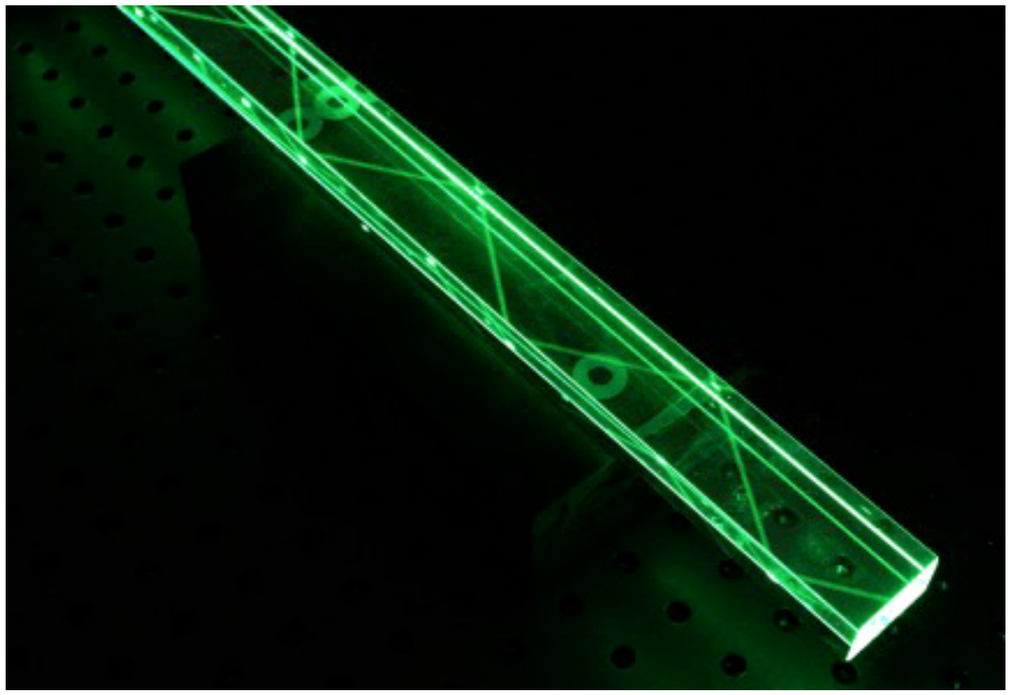
- Charged particles traveling faster than the speed of light in a medium emit Cherenkov light
  - Wavelength dependence: $$N_\gamma \sim \frac{1}{\lambda^2}$$
  - Cherenkov angle: $$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$
  - Determine β = v/*c*, separate kaons from pions by difference in mass

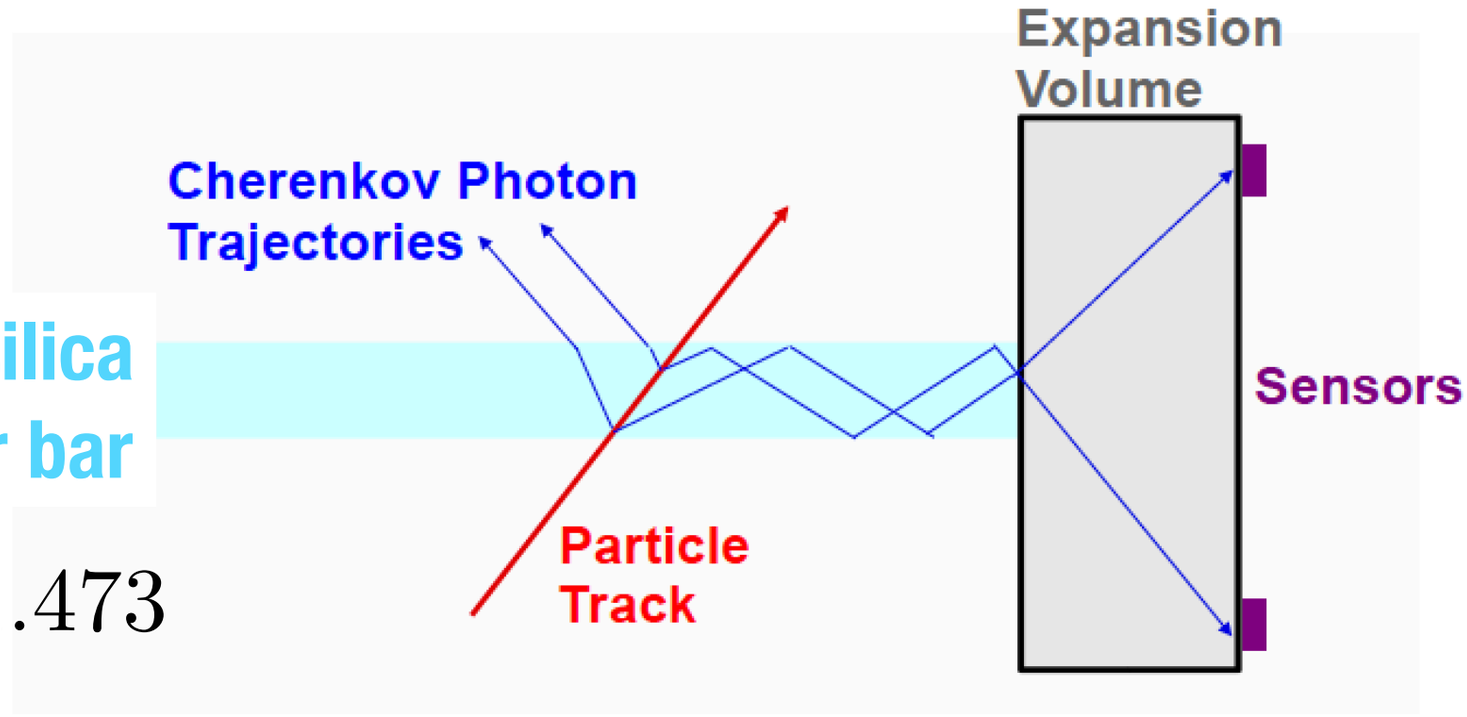
Nuclear Reactor



Particle Identification: DIRC

- **DIRC**: Detection of Internally Reflected Cherenkov Light
- Pioneered for BaBar detector at SLAC PEP-II
- Image photons to measure Cherenkov angle





$$\langle n \rangle = 1.473$$

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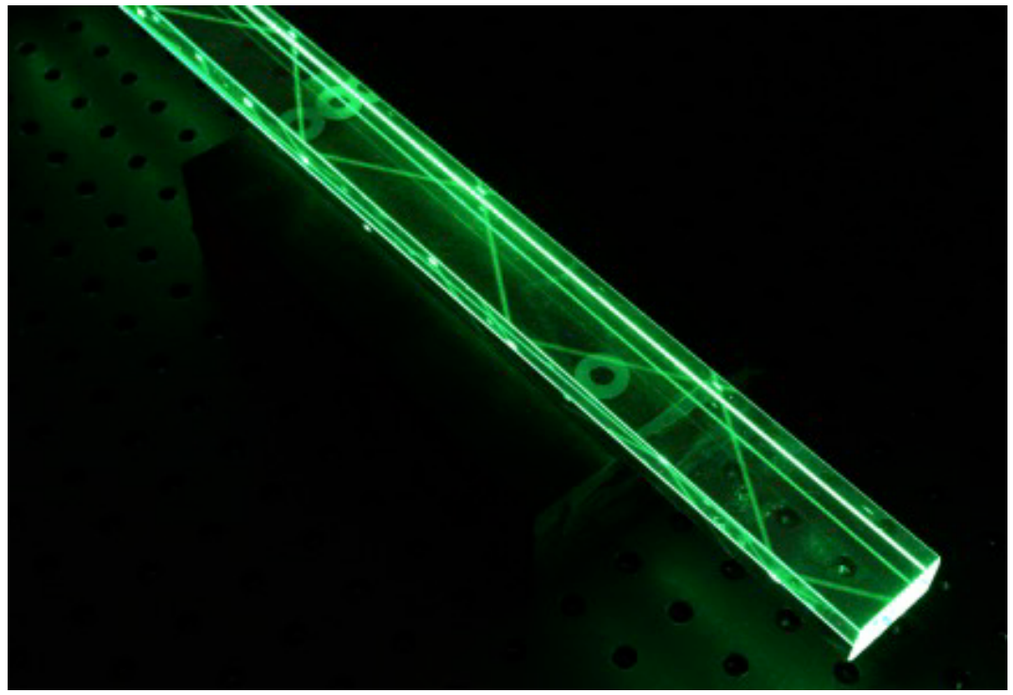
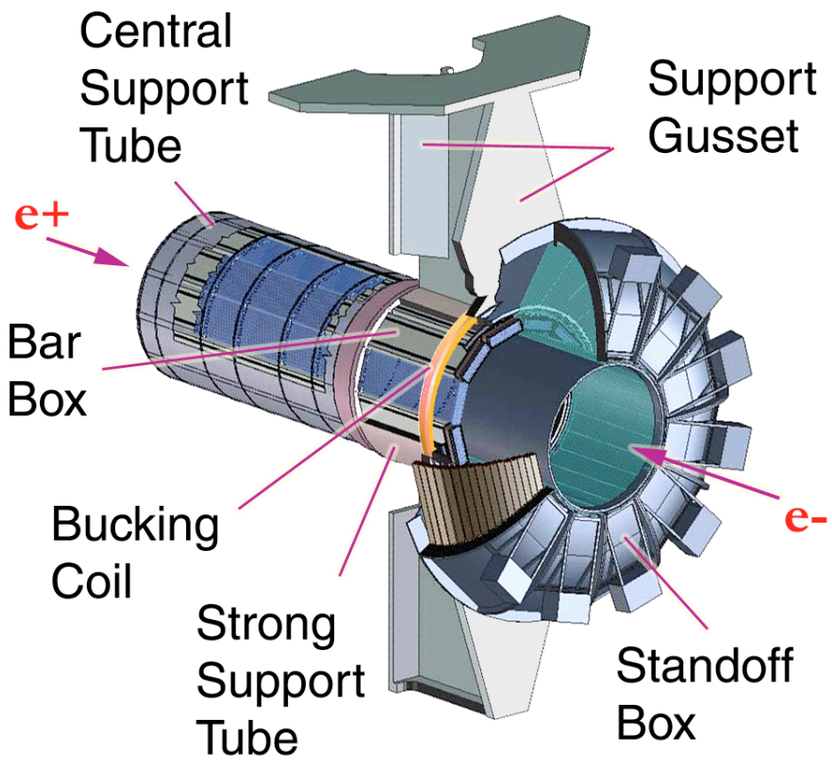
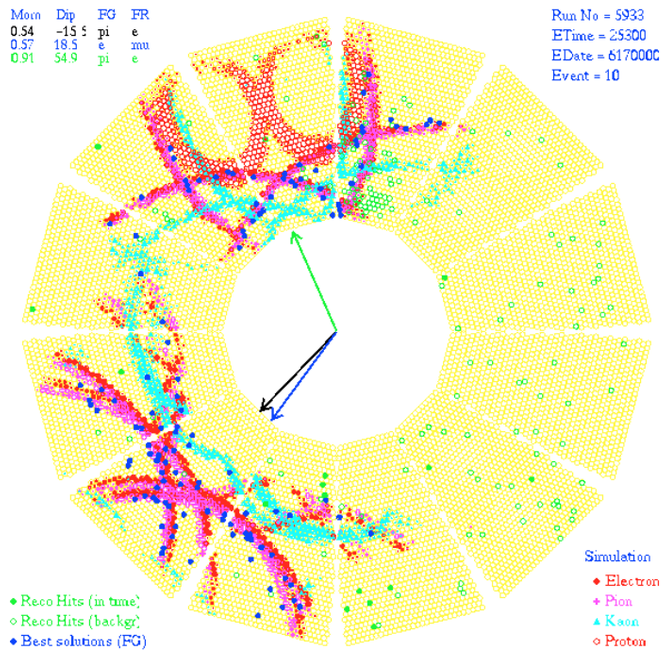
- Image photons to measure Cherenkov angle





BaBar DIRC Event Display



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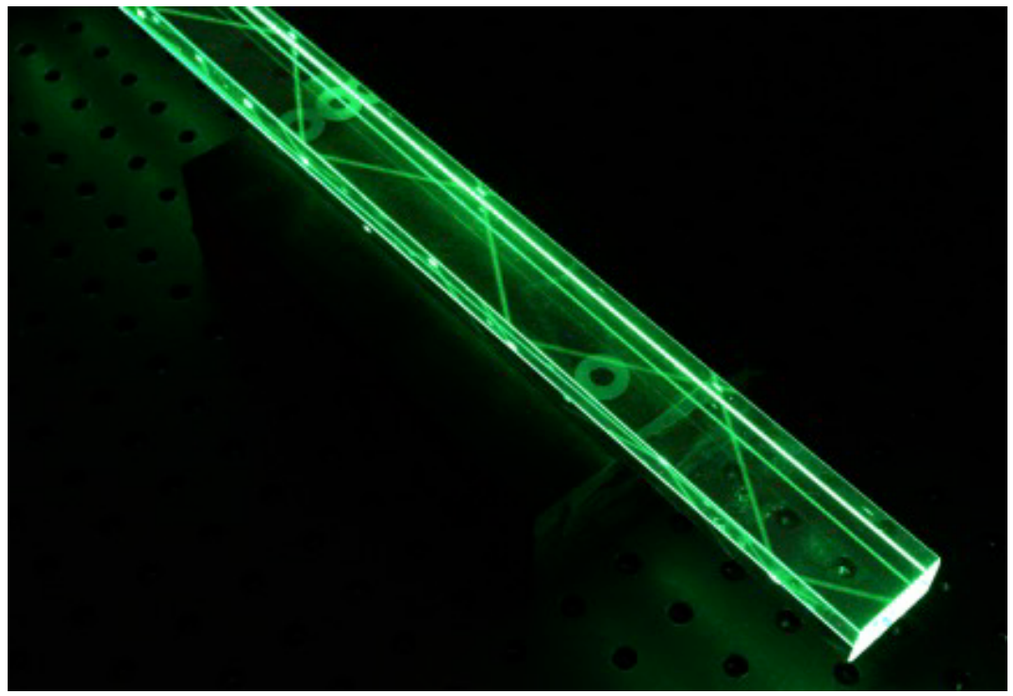
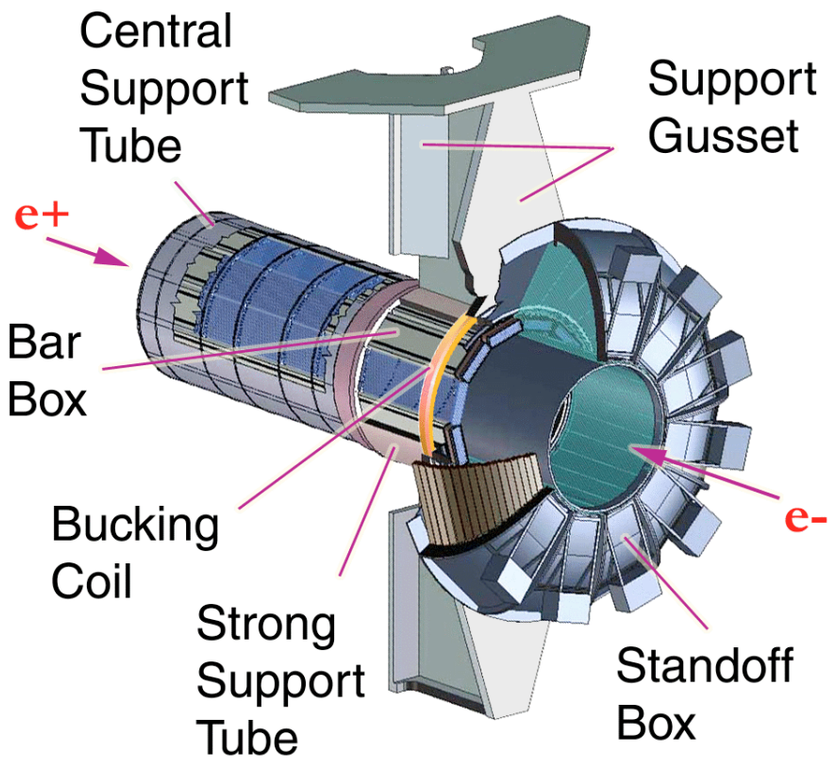
- Image photons to measure Cherenkov angle



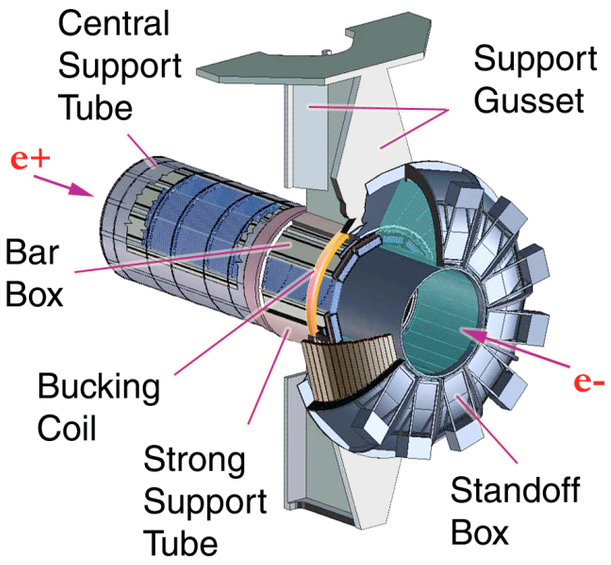


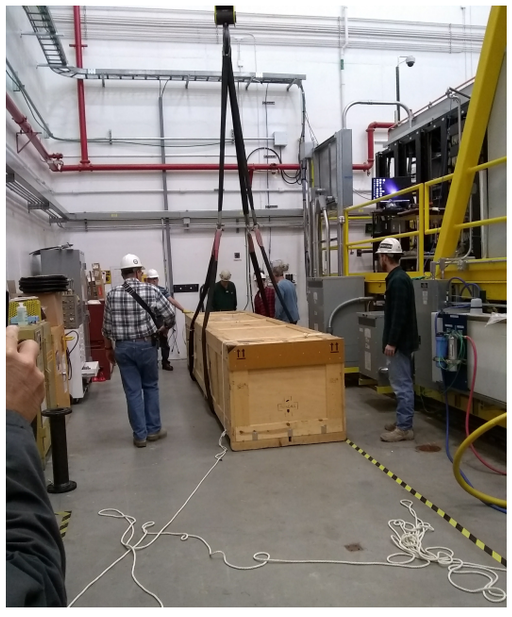
BaBar finished data taking in 2008

GlueX DIRC

Final shipment from SLAC to JLab this today!

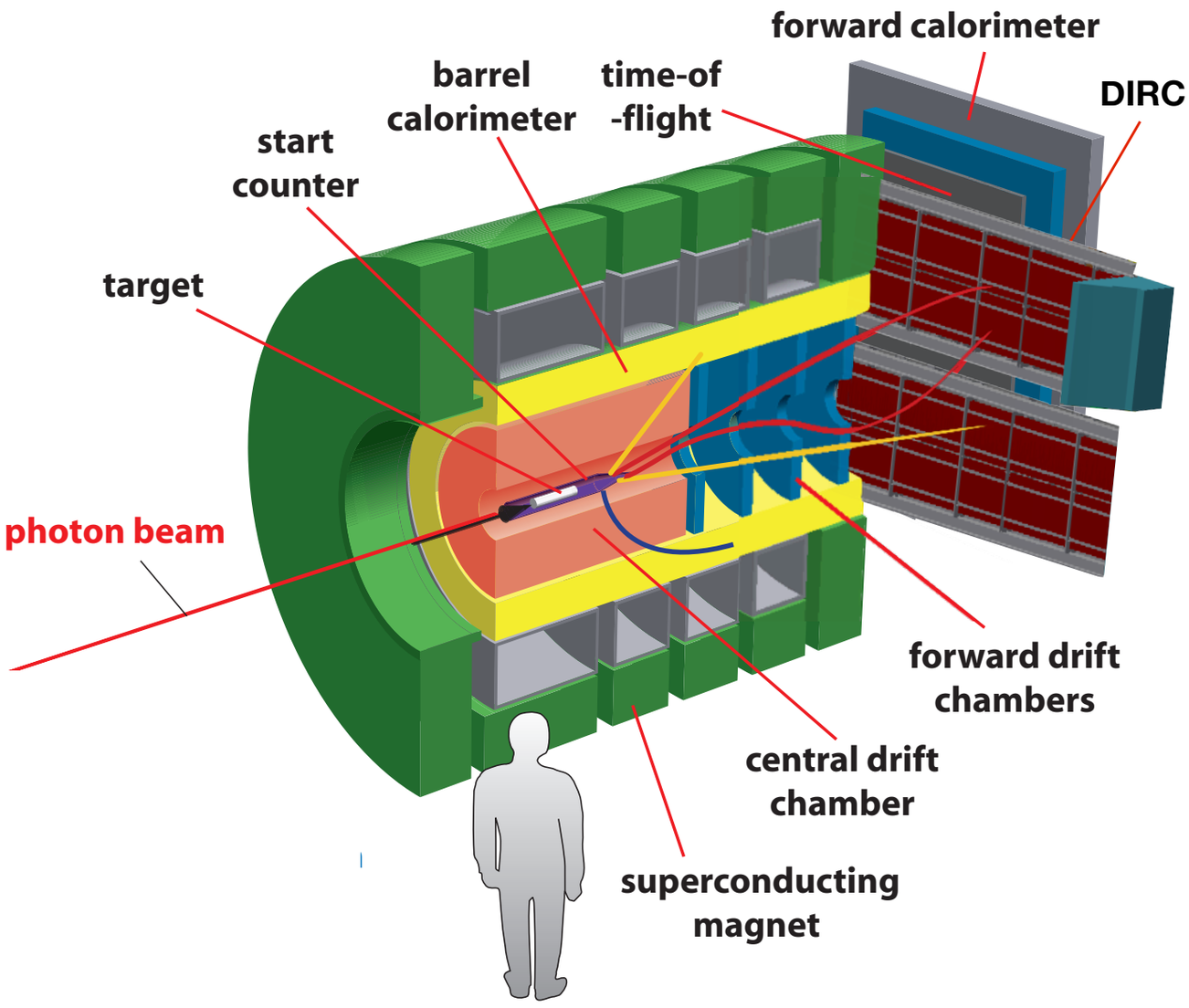
RECYCLE



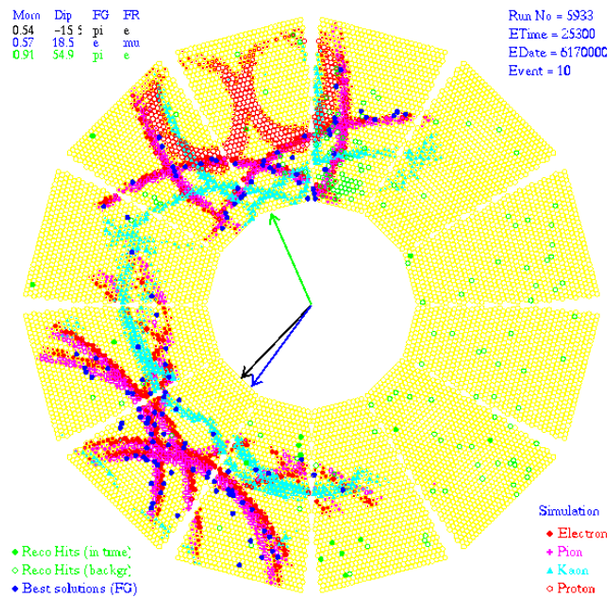


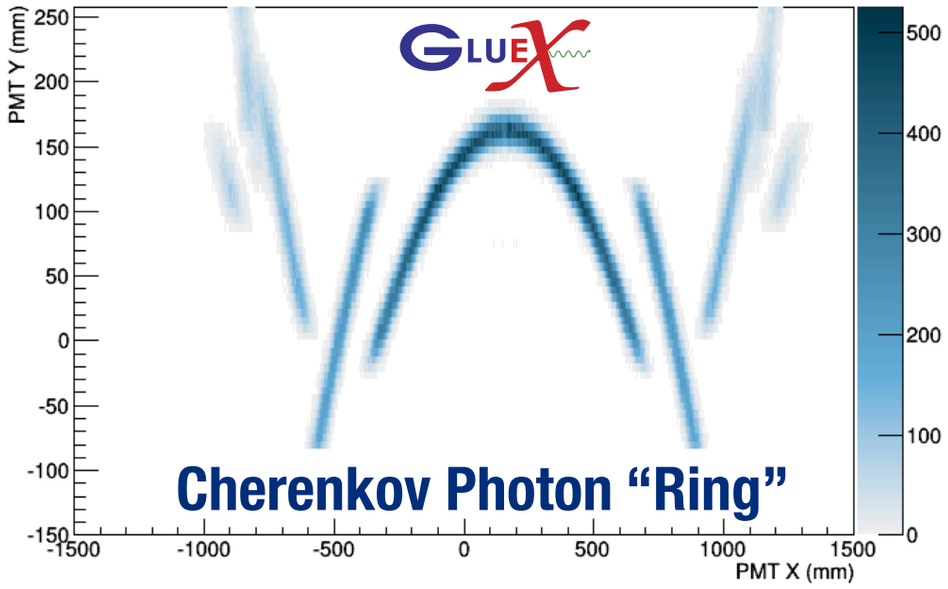
Follow the trip: twitter **@GlueX_DIRC**

GlueX DIRC



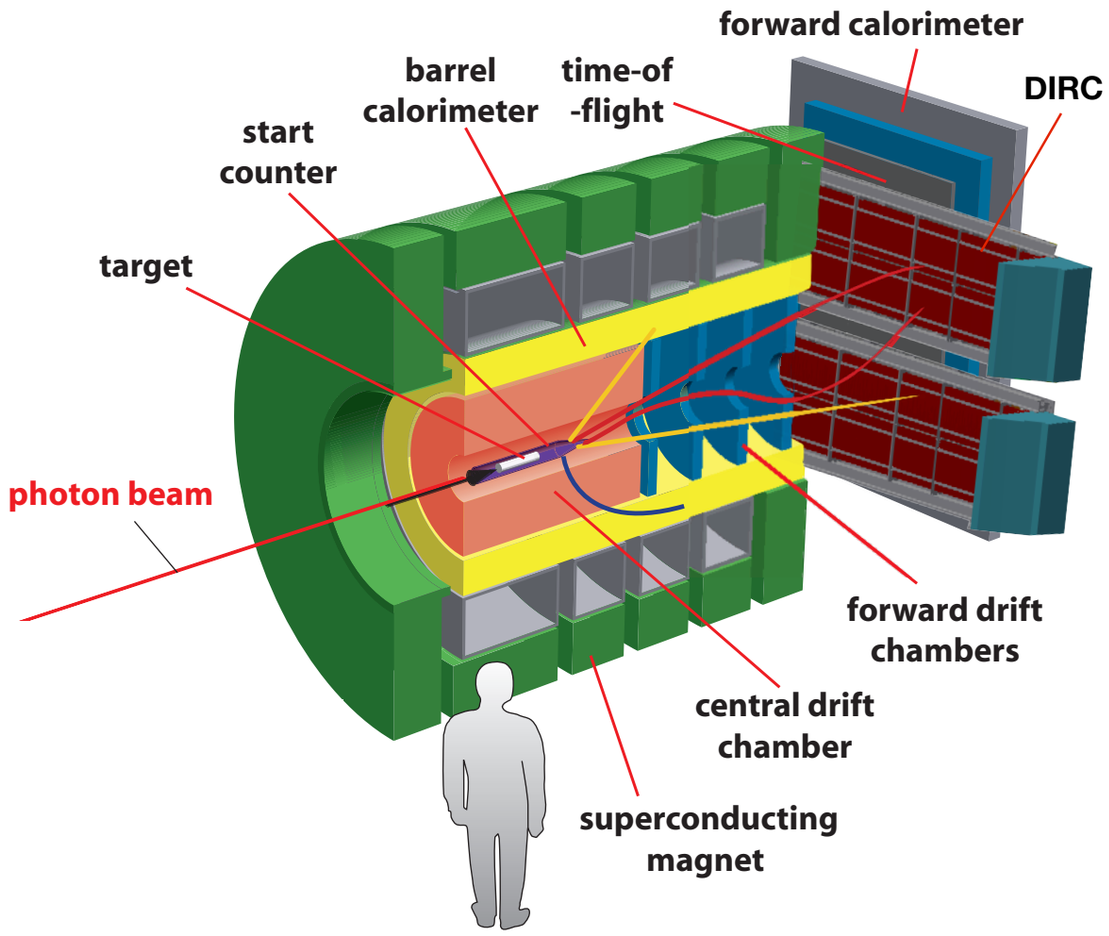
BaBar



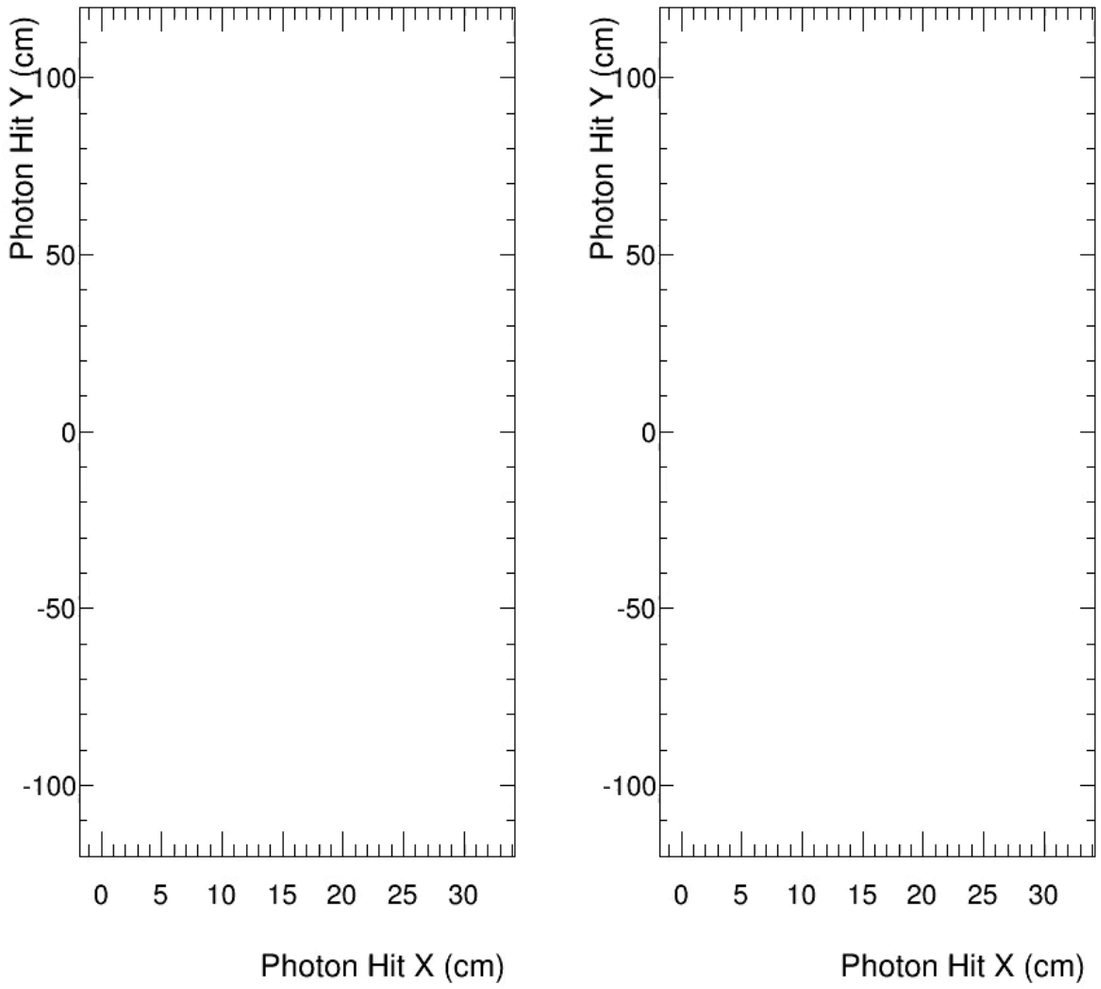


- The GlueX **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light) provides new K/π separation and will use components of the BaBar DIRC
- Partial installation and commissioning in **2018**

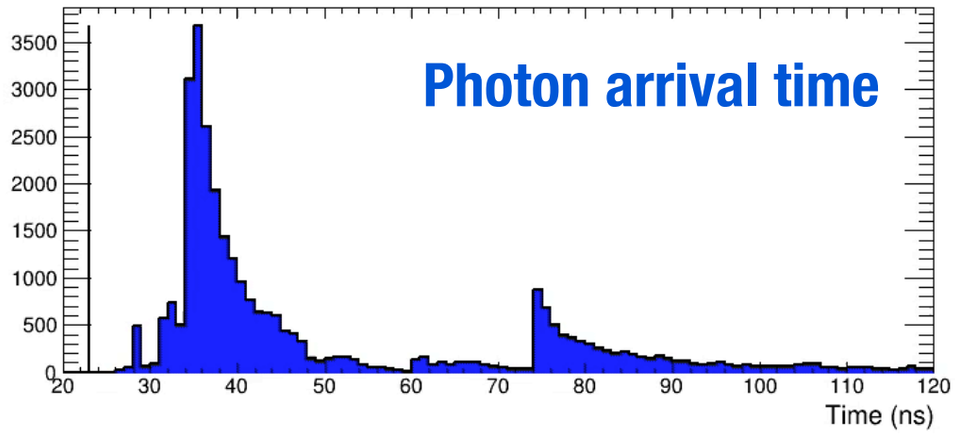
GlueX DIRC



Cherenkov Photon "Ring"

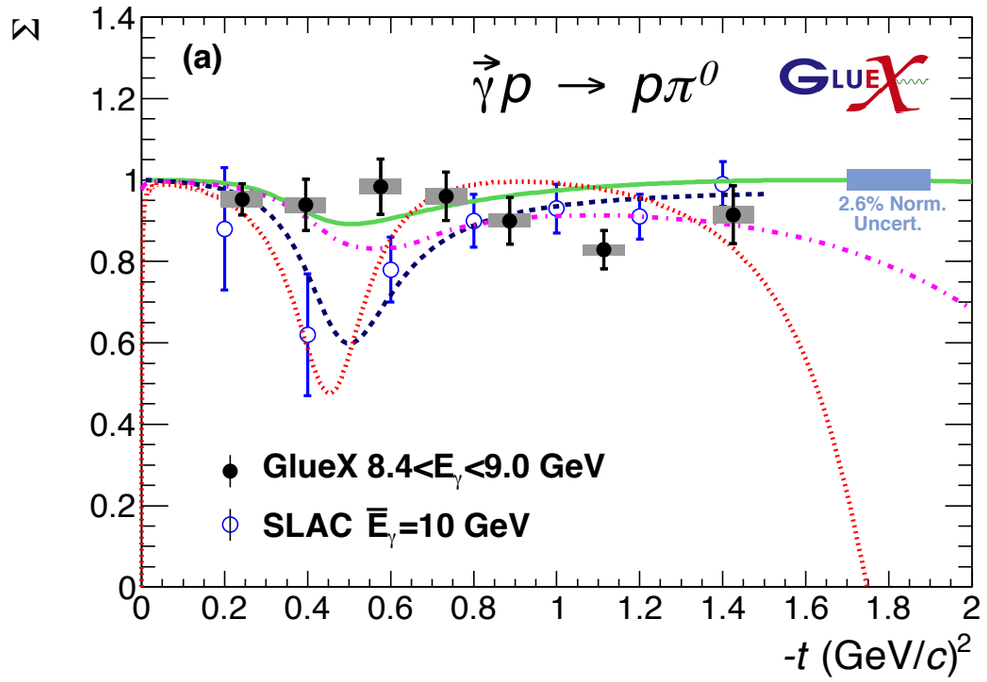


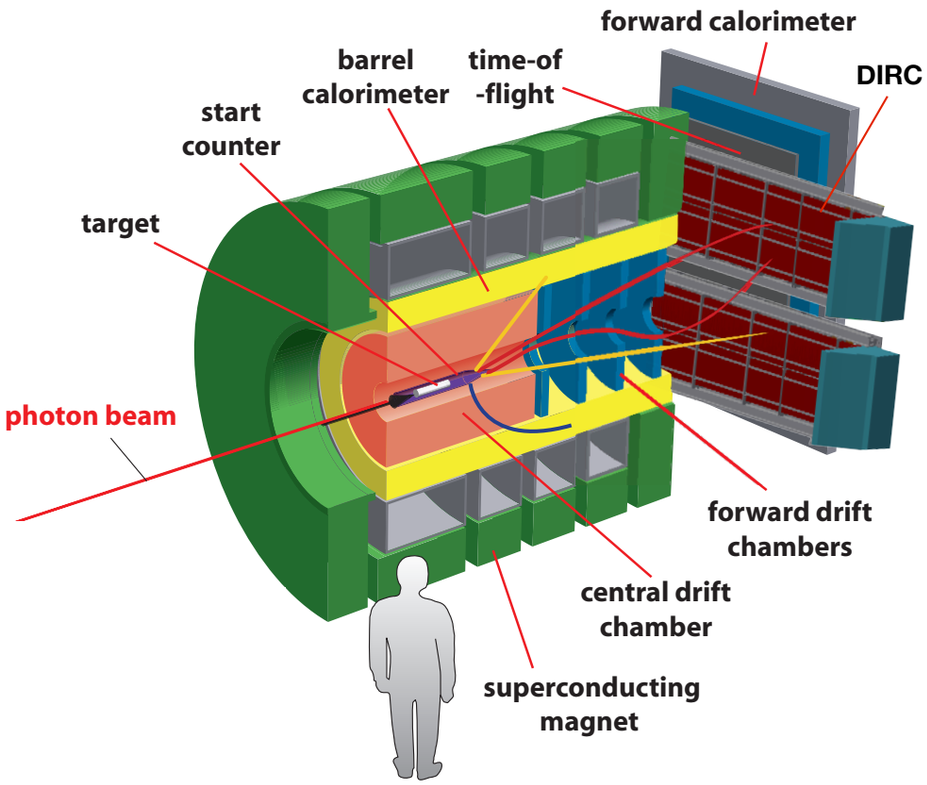
- Installation and commissioning begins this year!
- Installation complete by 2019



Summary

- The GlueX experiment is commissioned and the initial meson program is well underway
- Early measurements aimed at understanding the meson production mechanism through polarization observables
- Cherenkov detectors provided access to strange quark sector enhancing the discovery potential for hybrid mesons





Supported by DE-SC0018224

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Further Reading

- **Light isovector resonances in $\pi^- p \to \pi^- \pi^- \pi^+$**
  Compass Collaboration
  [arXiv:1802.05913]

- **Searching for the rules that govern hadron construction**
  Matt Shepherd, Jozef J. Dudek, and Ryan Mitchell
  Nature 534 (2016) 487

- **Hybrid mesons**
  Curtis A. Meyer and Eric S Swanson, Progress in Particle and Nuclear Physics 82, 21-58 (2015)

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

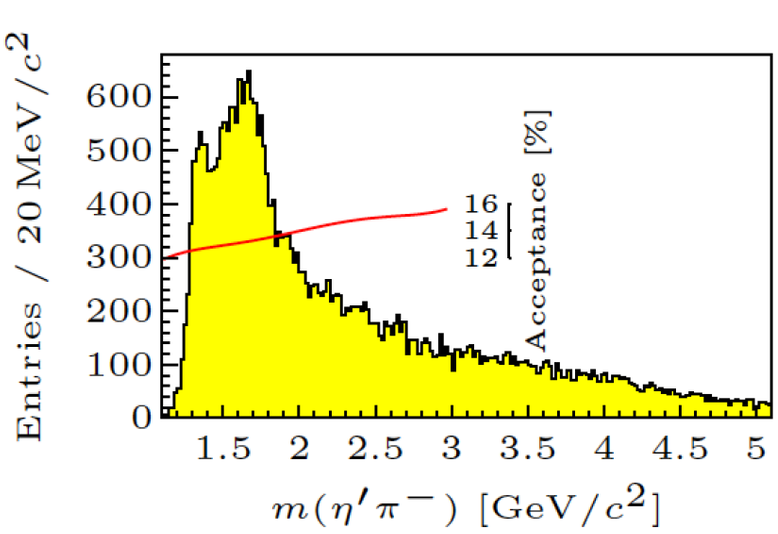
Some additional 1^{-+} channels

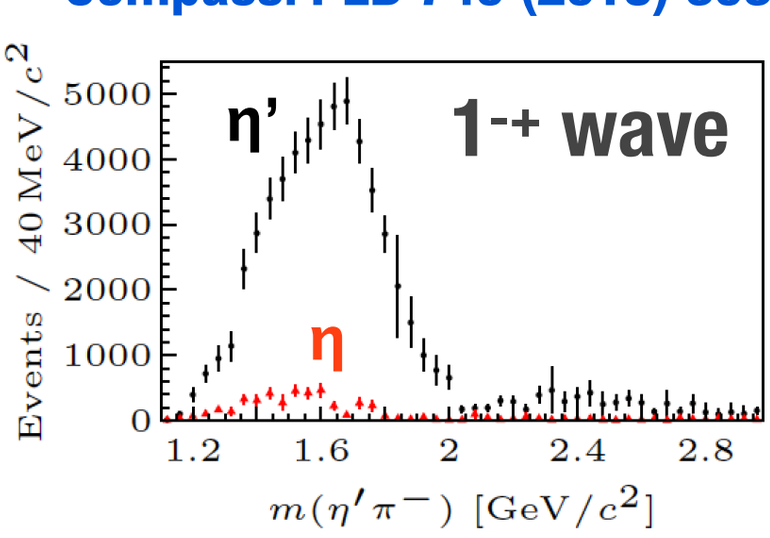
$$\pi a_2 \to \eta\pi\pi \qquad \eta f_1 \to \eta\eta\pi\pi$$
$$KK^* \to KK\pi$$
$$KK_1(1270) \to KK\pi\pi$$

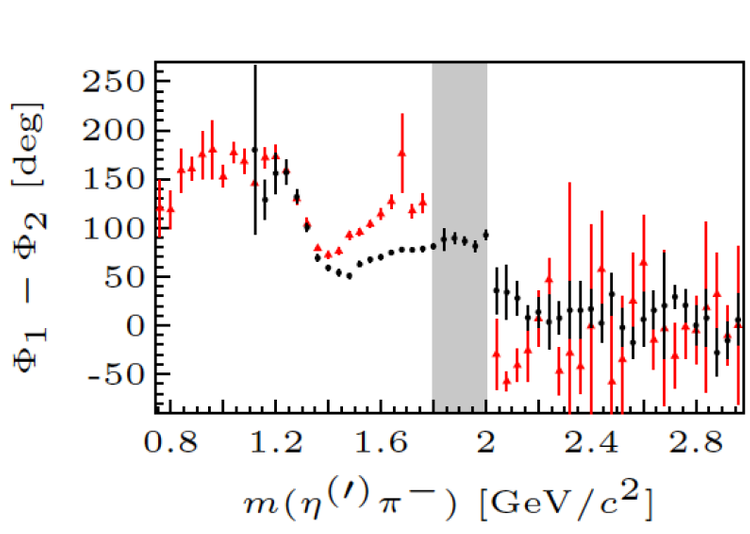
Evidence for 1^{-+} exotics

- **$\pi_1(1400) \rightarrow \eta\pi$**
  - 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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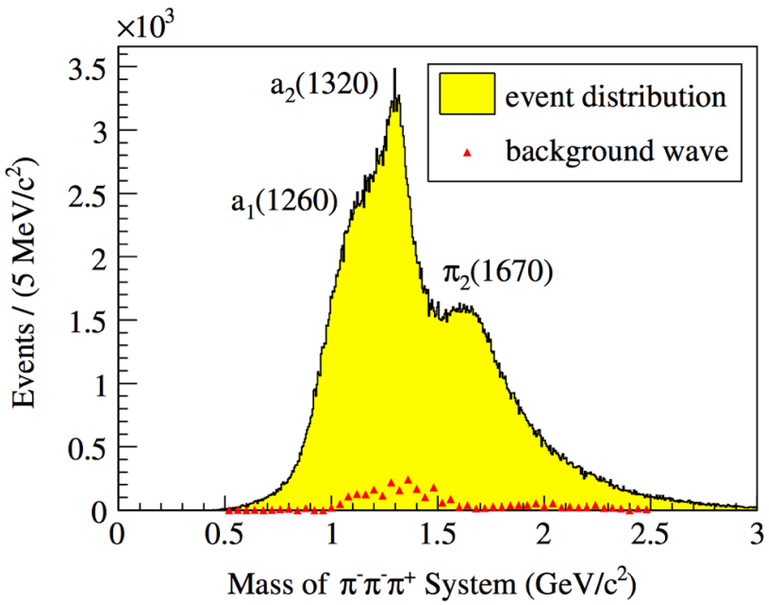
Compass: PRL 104, 241803 (2010)



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  - Not likely a hybrid: dynamical origin or 4-quark state?
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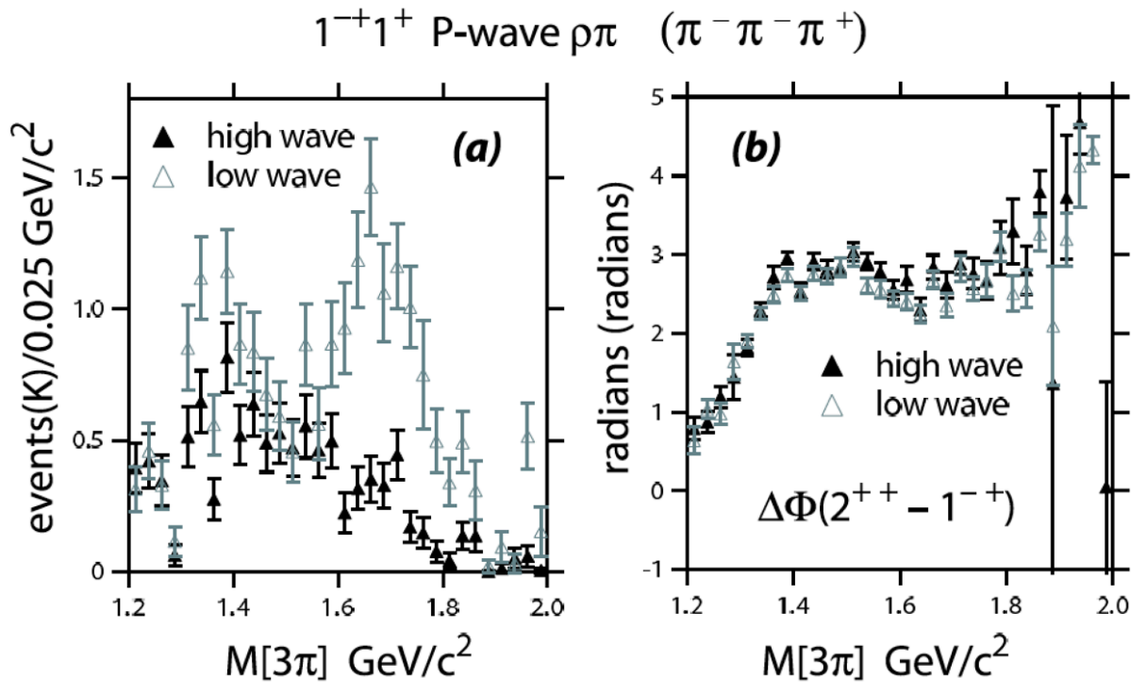
E852: PRD 73 (2006) 072001

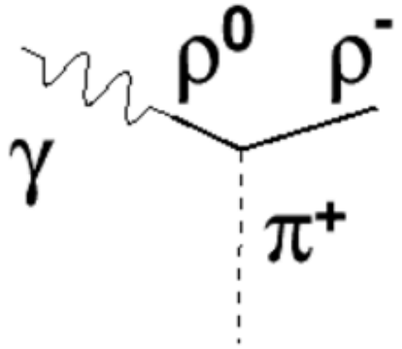
Found no exotic when using a larger set of partial waves (ie. “high wave”) than previous analysis



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

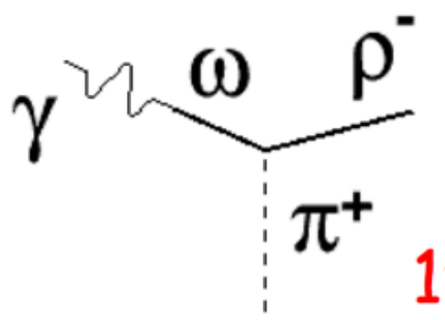
Quantum number counting

Assuming Vector Dominance



G = (+) → (-)(+)
Forbidden

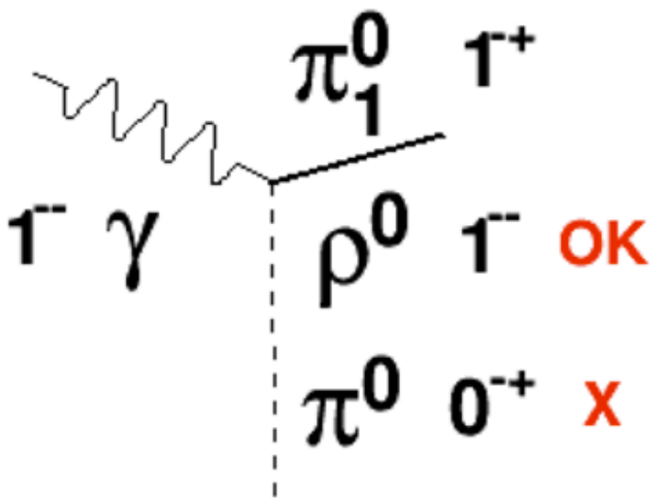
$0^-(1^{--})$ $1^+(1^{--})$ $I^G(J^{PC})$



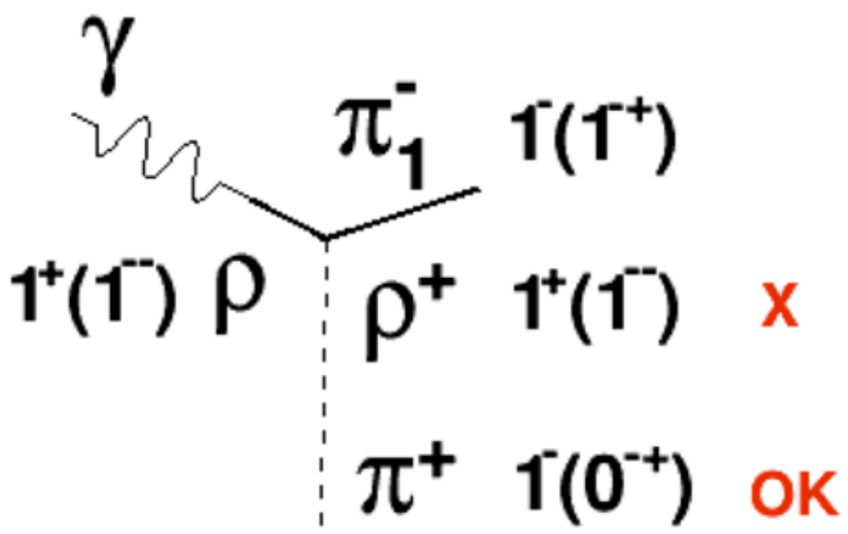
G = (-) → (-)(+)
Allowed

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

-> Proceeds via ω coupling



C Conservation



G-Parity Conservation

5