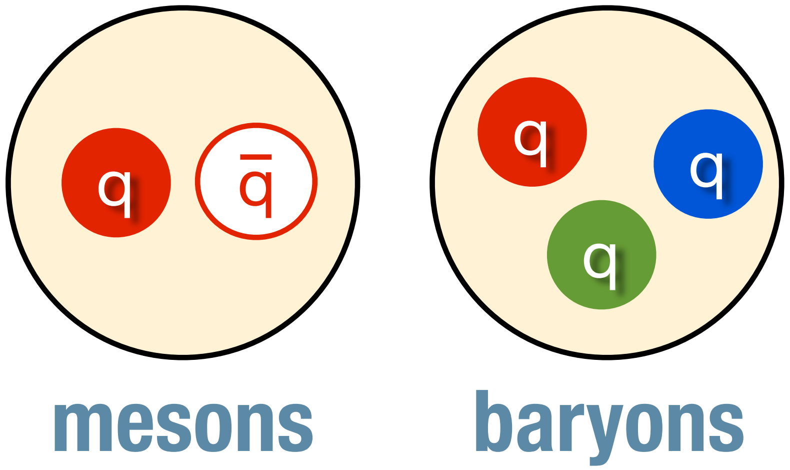
Recent results from GlueX

Justin Stevens

WILLIAM & MARY
CHARTERED 1693

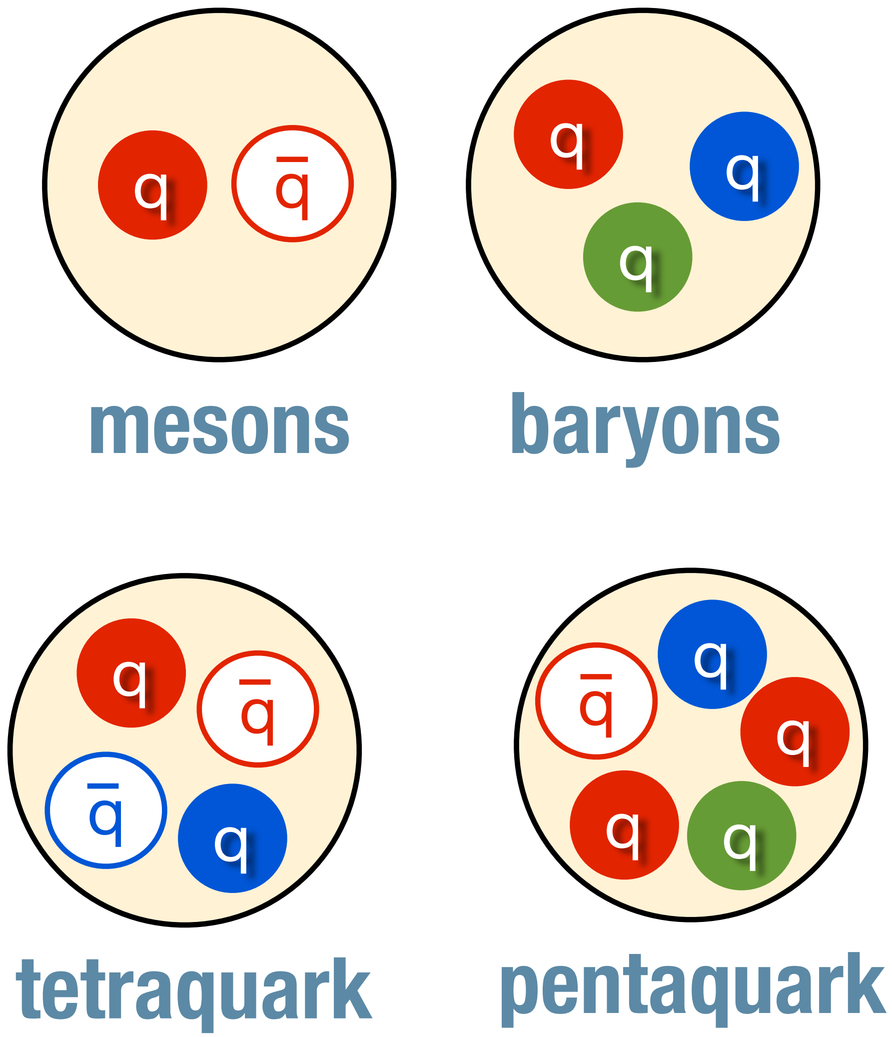
Confined states of quarks and gluons



Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

Confined states of quarks and gluons



Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

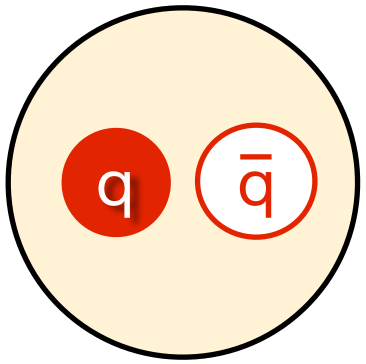
A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

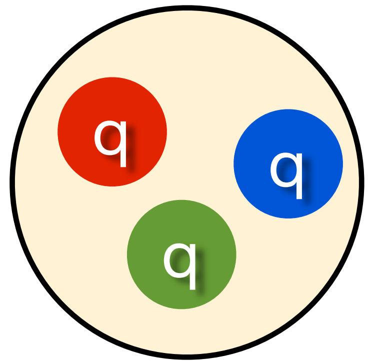
... Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. ...

Phys. Lett. 8 (1964) 214

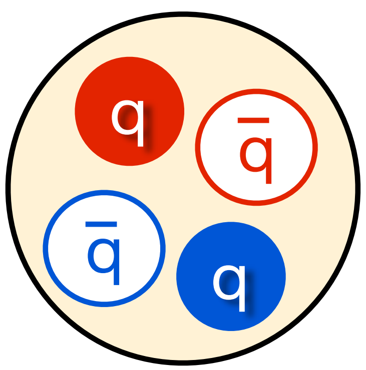
Confined states of quarks and gluons



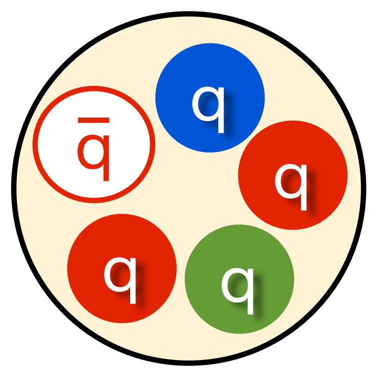
mesons



baryons



tetraquark

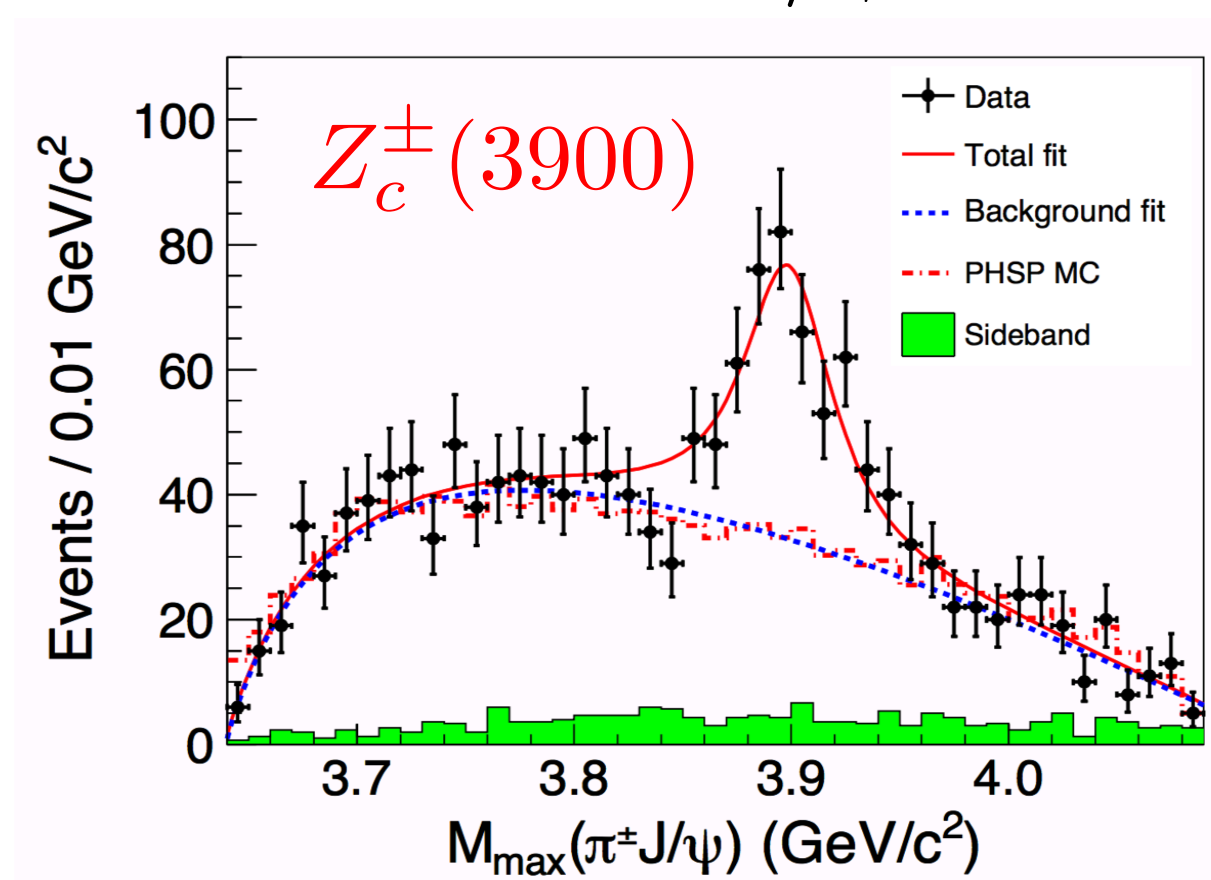


pentaquark

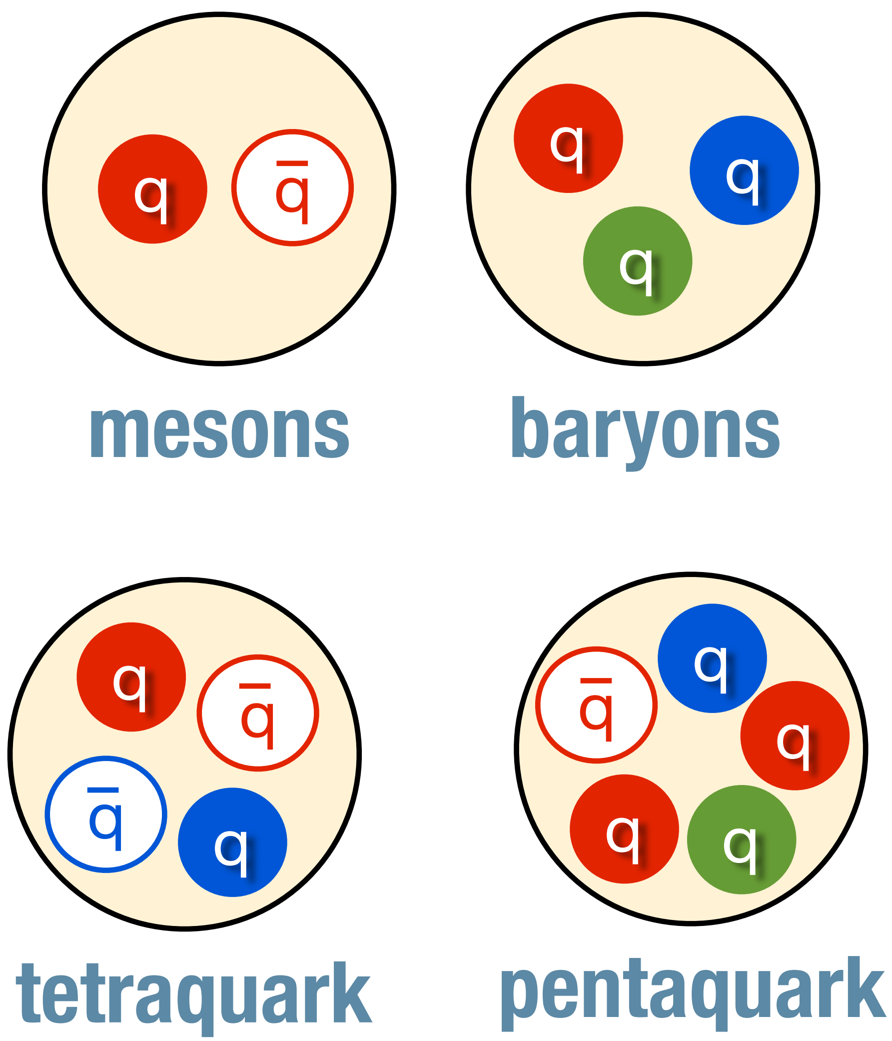
Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

$$e^+e^- \rightarrow J/\psi\pi^+\pi^-$$



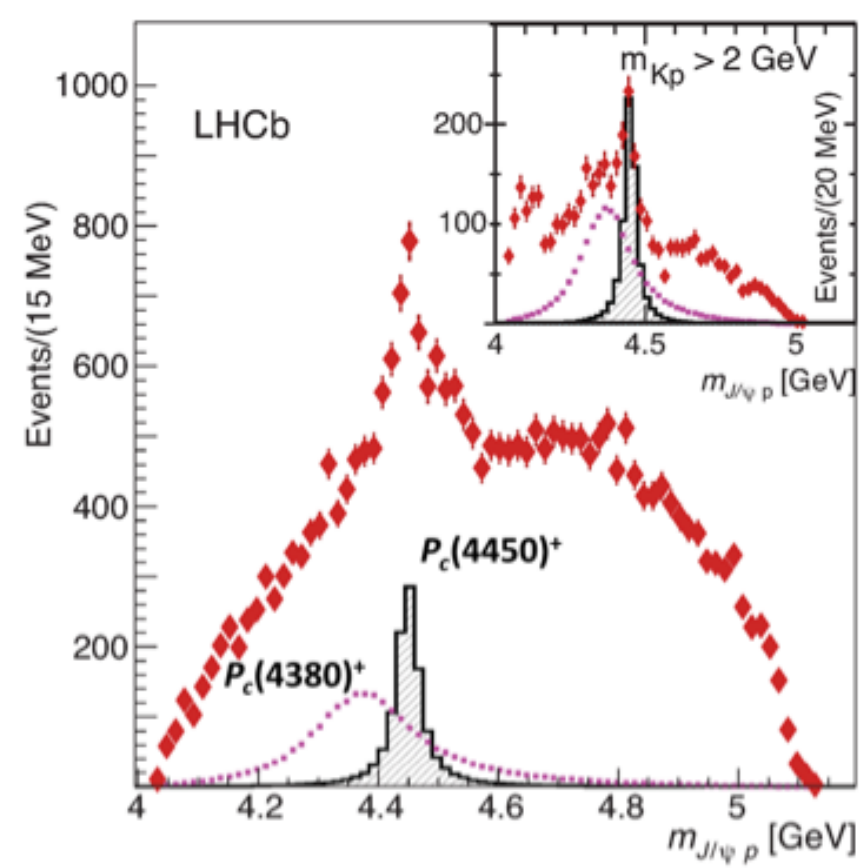
Confined states of quarks and gluons



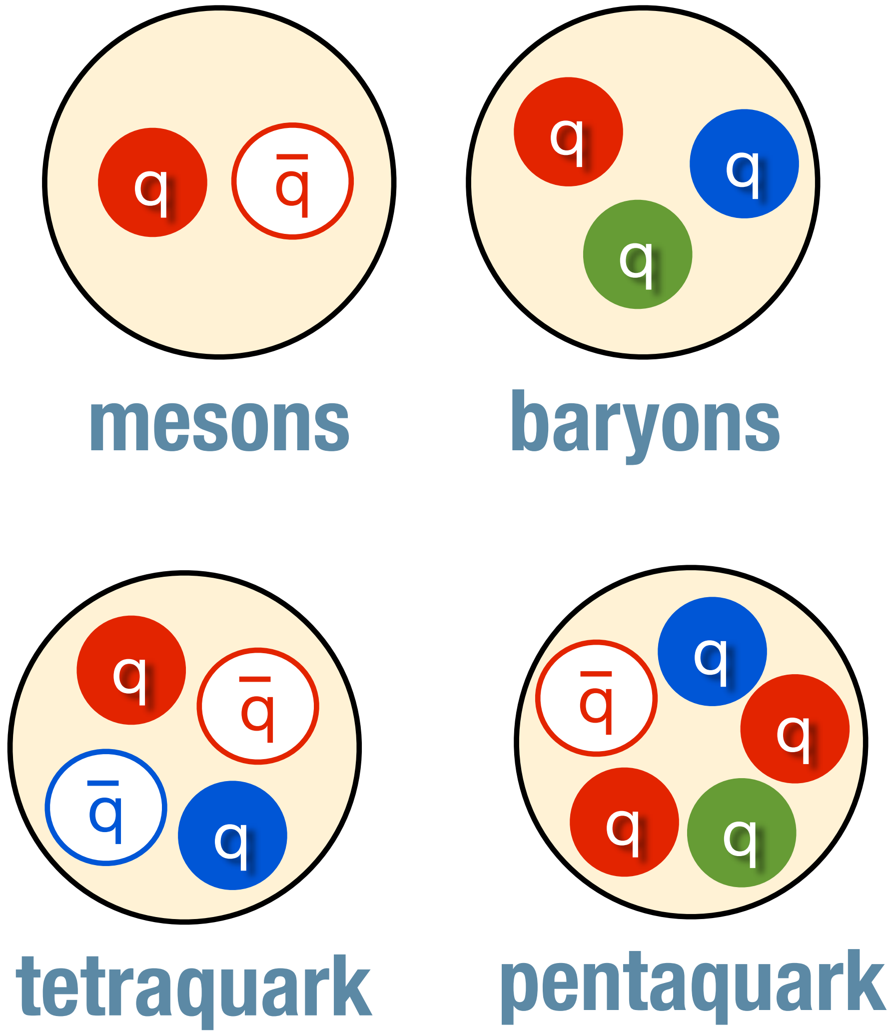
Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

$$\Lambda_b \to J/\psi p K^-$$



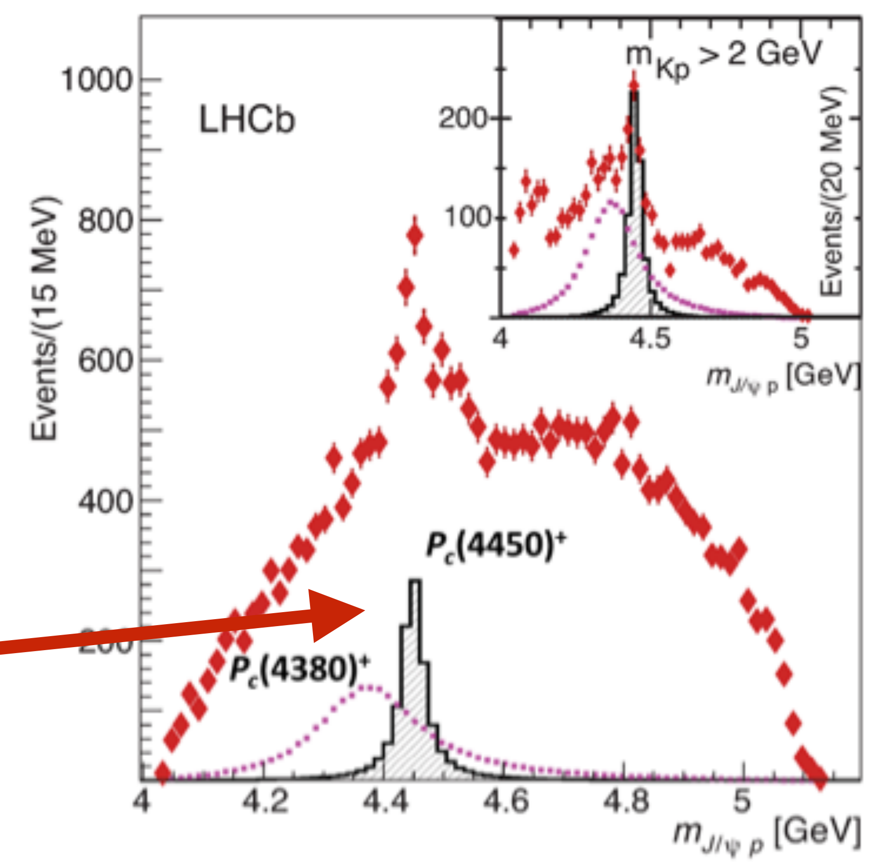
Confined states of quarks and gluons



Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD

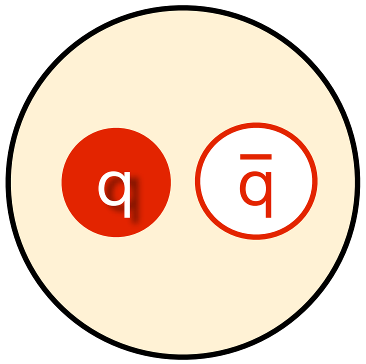
$$\Lambda_b \rightarrow J/\psi p K^-$$



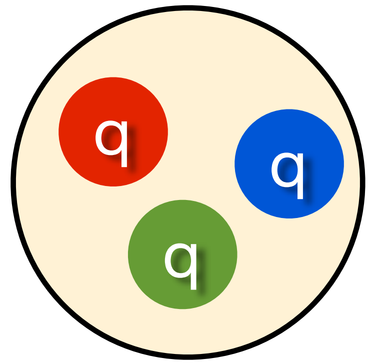
Accessible at

Jefferson Lab

Confined states of quarks and gluons



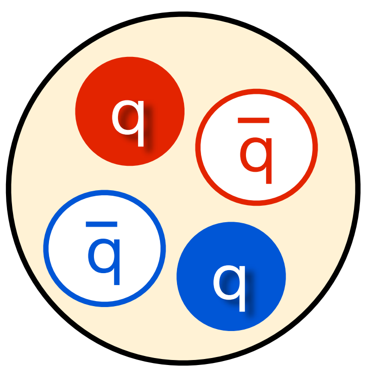
mesons



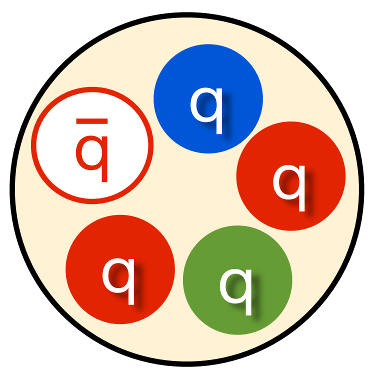
baryons

Observed mesons and baryons well described by 1st principles QCD

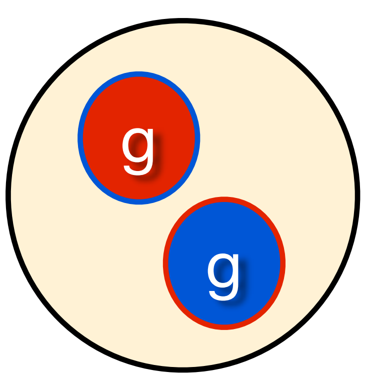
But these aren't the only states permitted by QCD



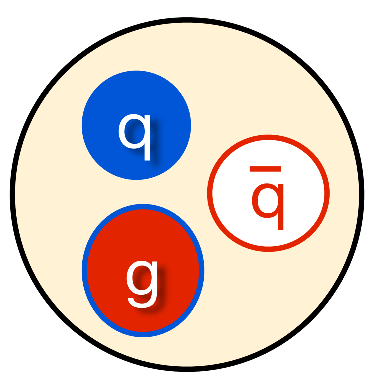
tetraquark



pentaquark



glueball

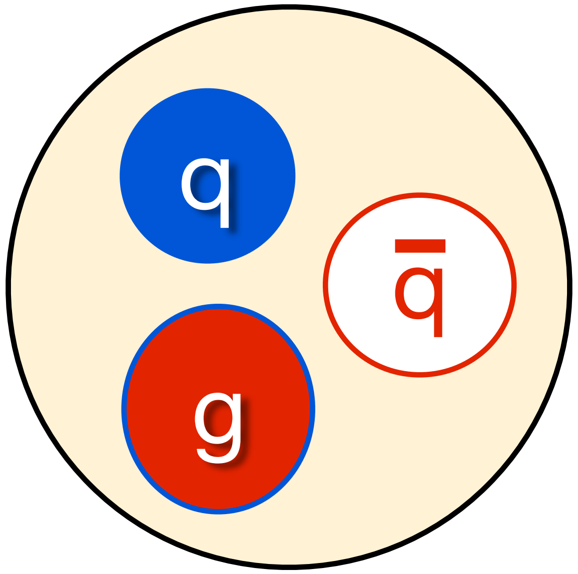


hybrid meson

Do gluonic degrees of freedom manifest themselves in the bound states we observe in nature?

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

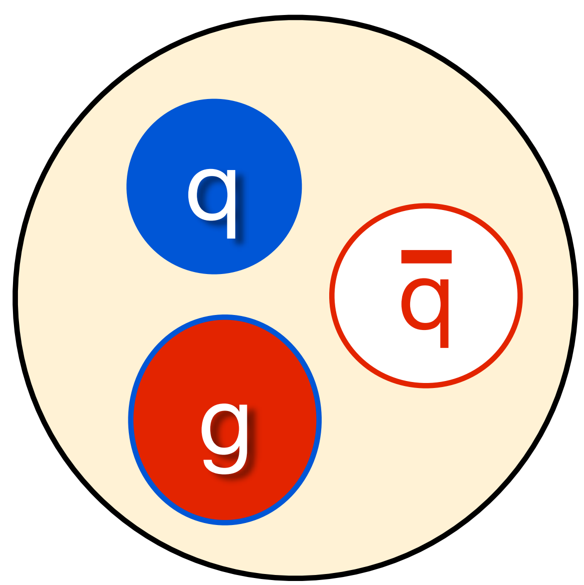


hybrid meson

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

$$\boxed{J^{PC} = 0^{+-}, 1^{-+}, 2^{+-} \ldots}$$

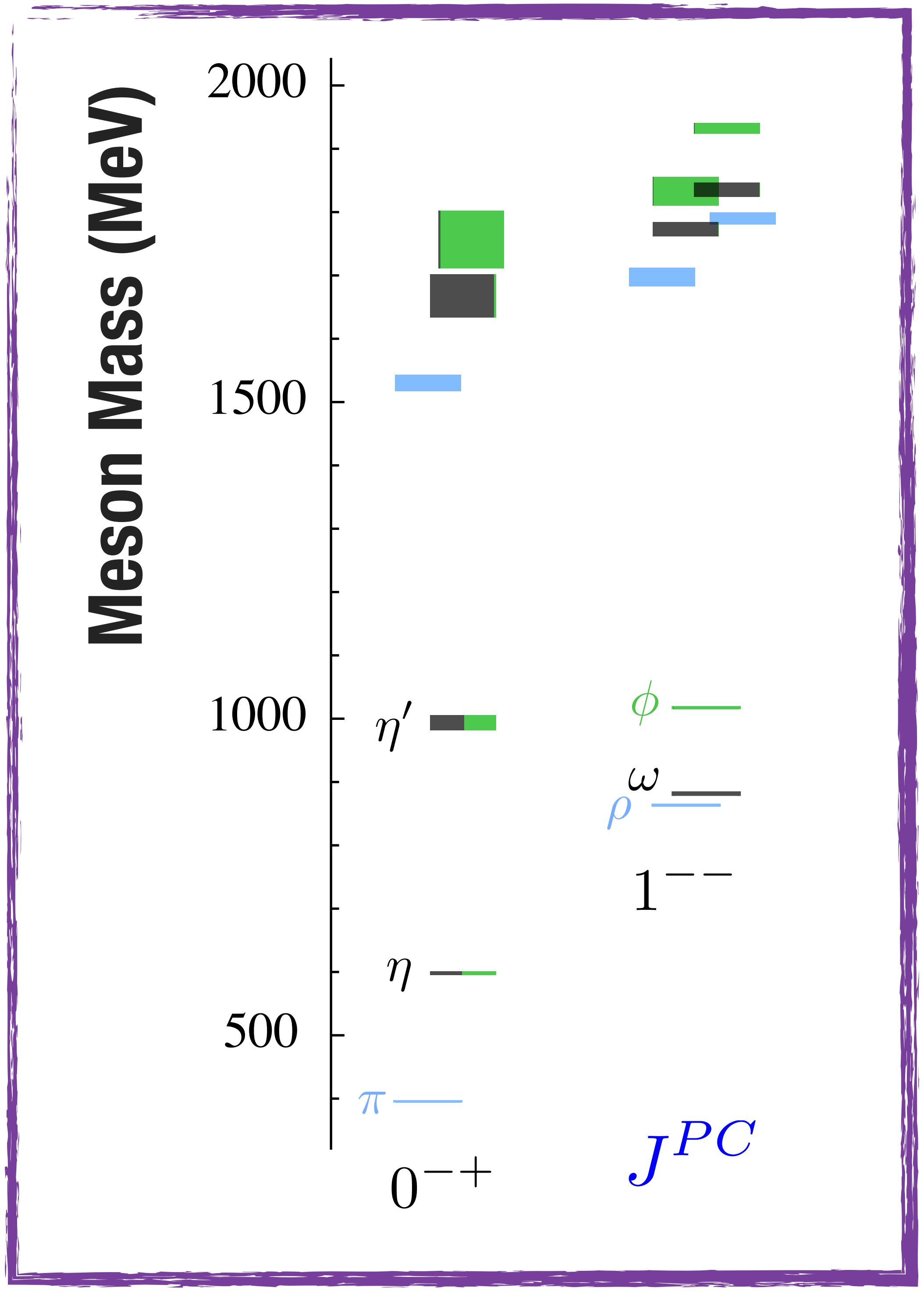


hybrid meson

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

Lattice QCD

Dudek et al. PRD 88 (2013) 094505



$u\bar{u} + d\bar{d}$

$s\bar{s}$

$$\phi = |s\bar{s}\rangle$$

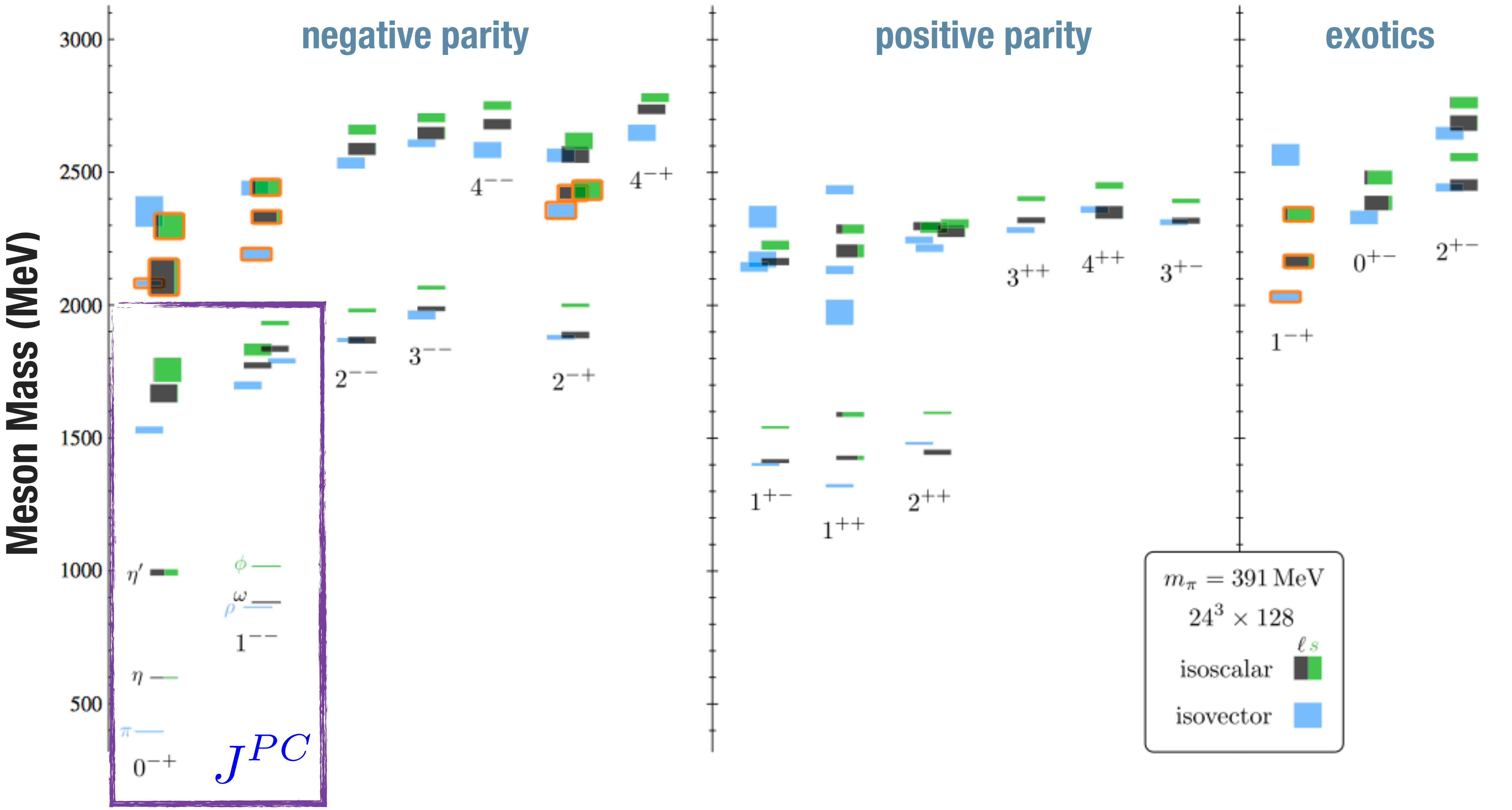
$$\omega = |u\bar{u} + d\bar{d}\rangle$$

$$\pi^0 = |u\bar{u} - d\bar{d}\rangle$$

Note: $m_\pi = 392\,\mathrm{MeV}$

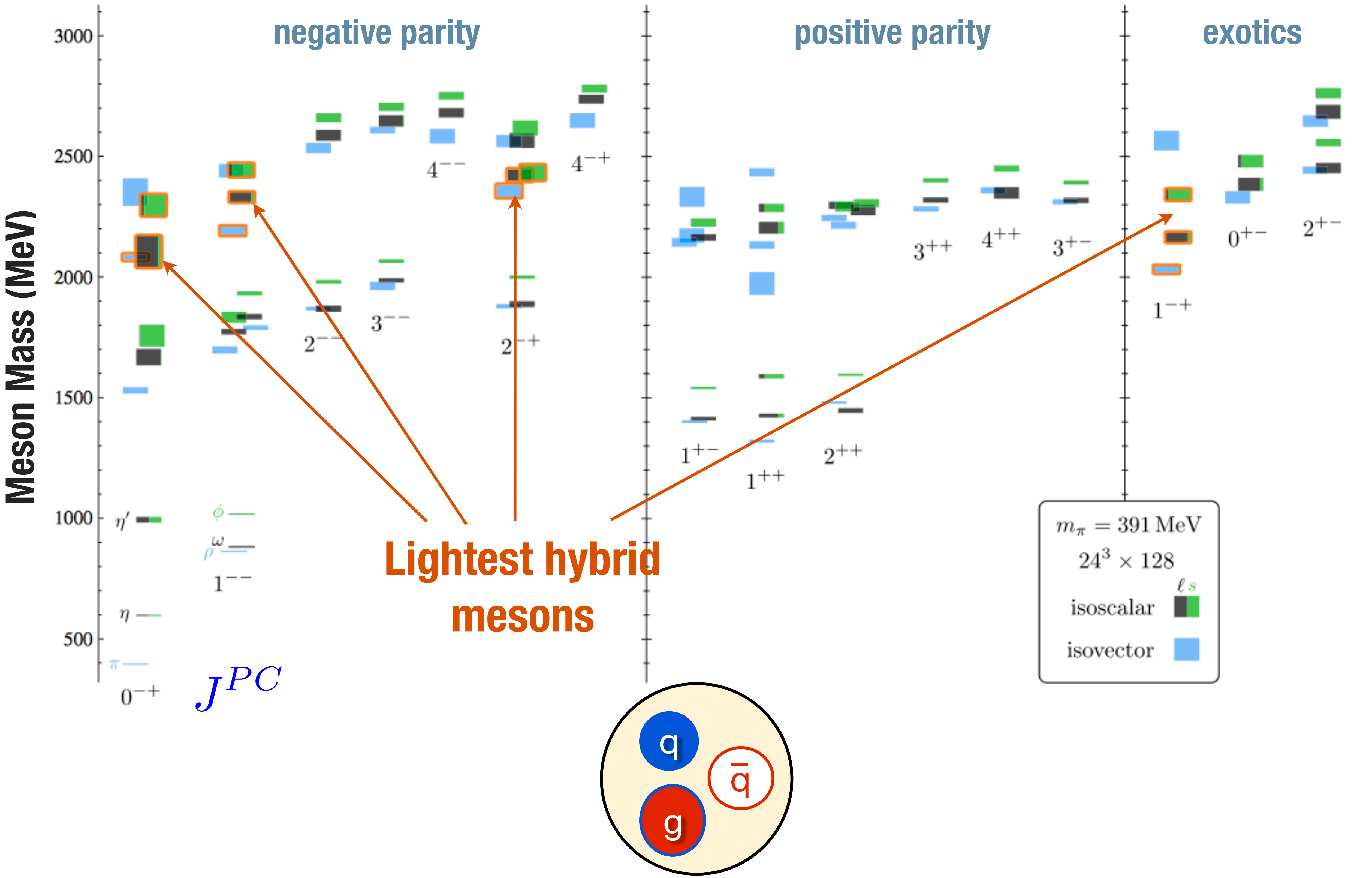
Lattice QCD

Dudek et al. PRD 88 (2013) 094505



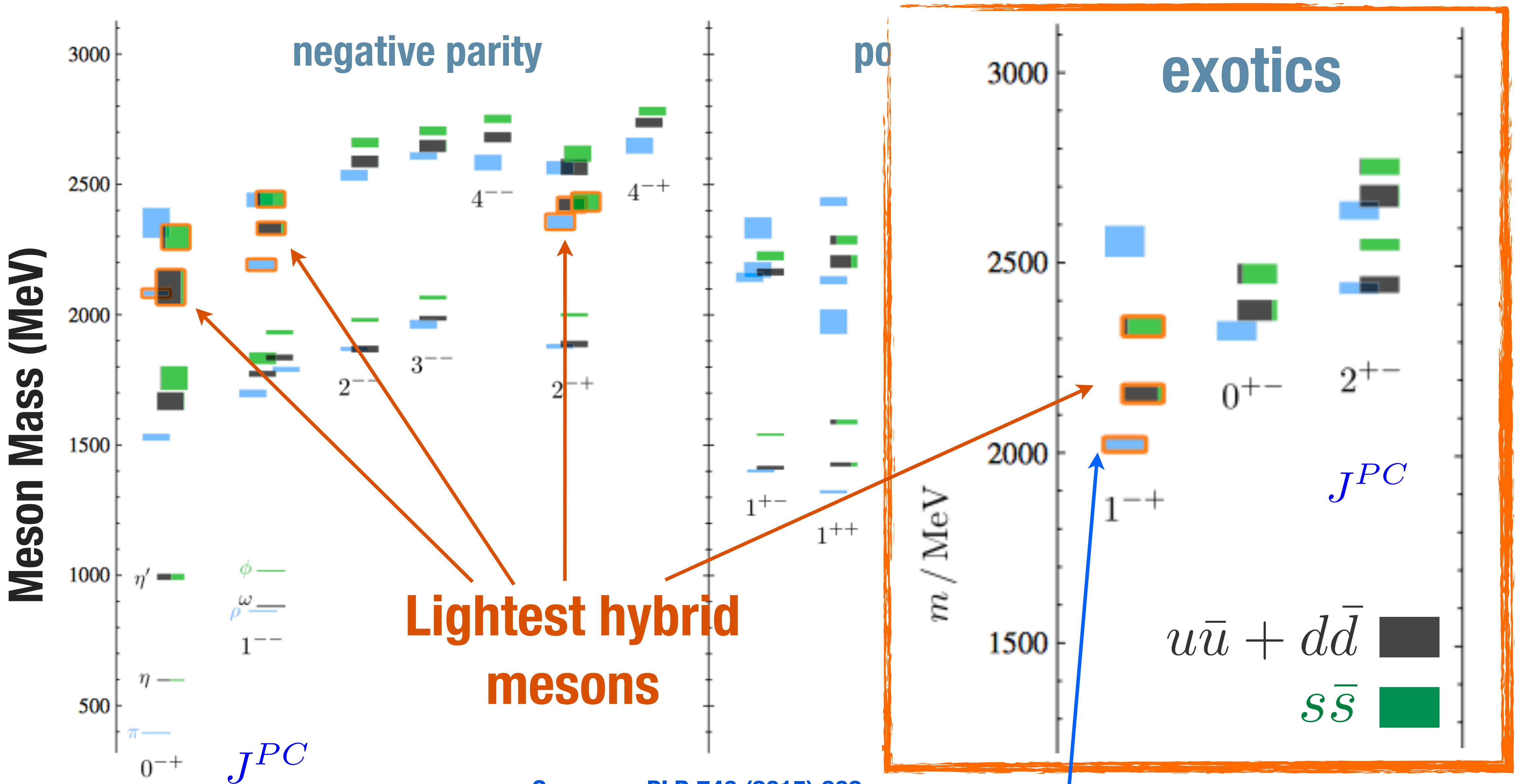
Lattice QCD

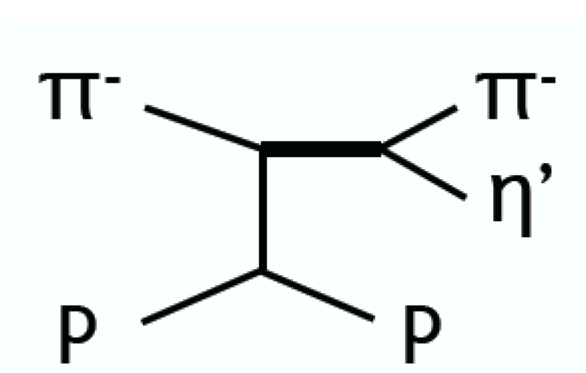
Dudek et al. PRD 88 (2013) 094505



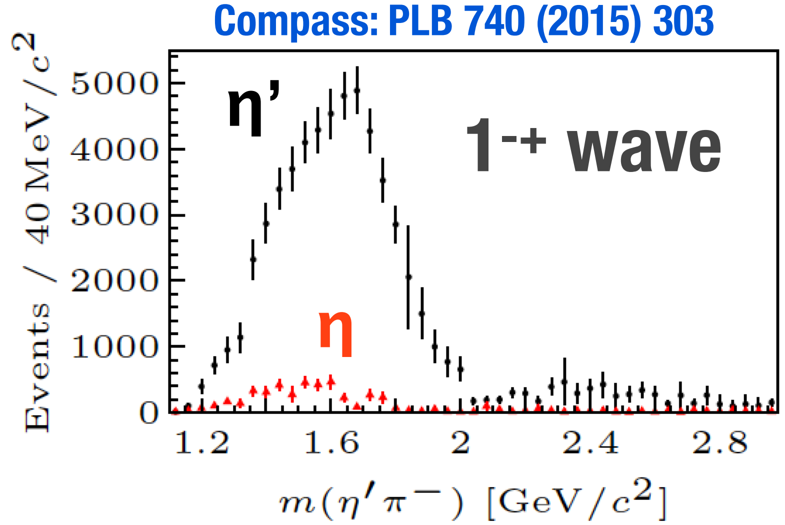
Lattice QCD

Dudek et al. PRD 88 (2013) 094505





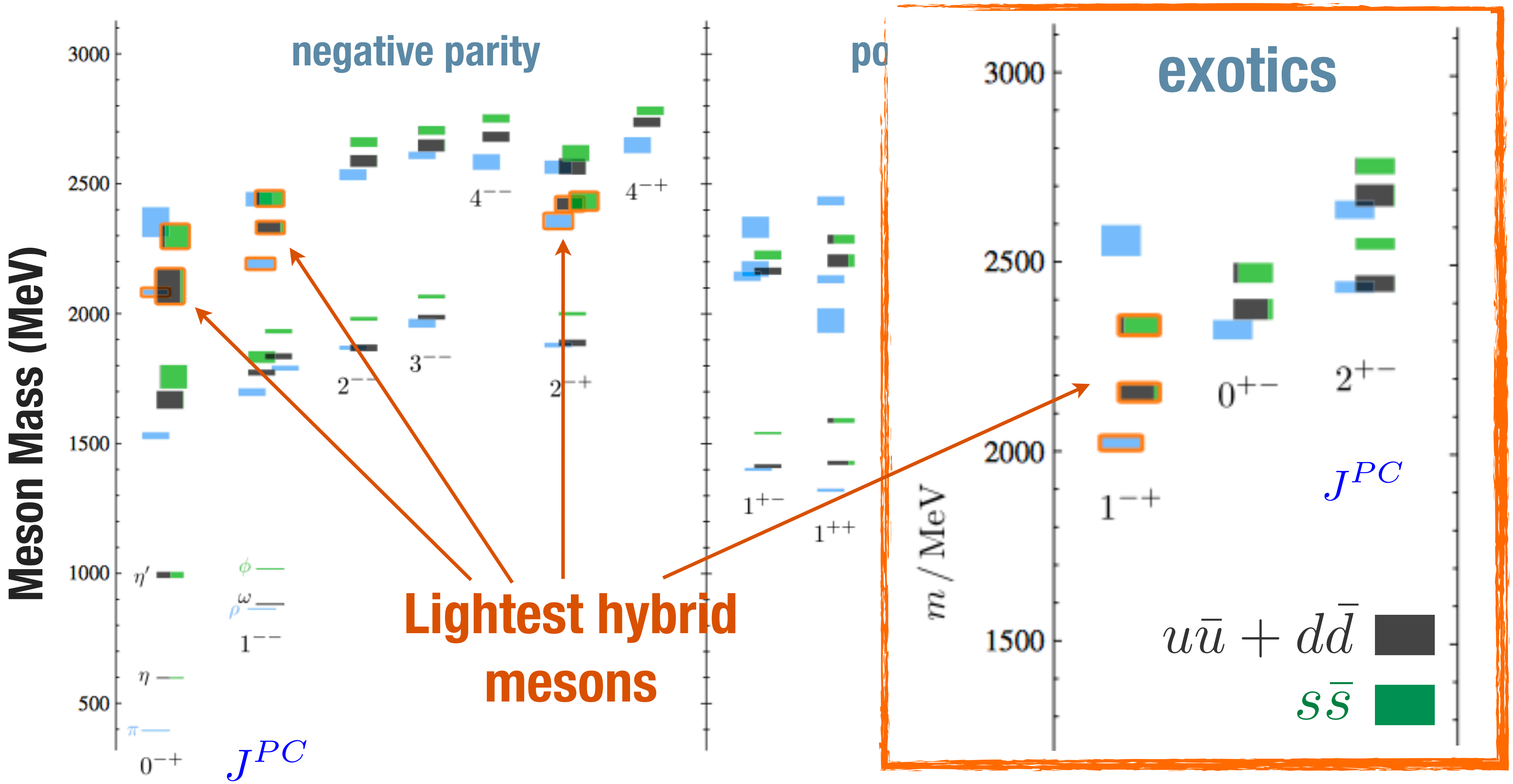
Compass: PLB 740 (2015) 303



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

Lattice QCD: Mesons

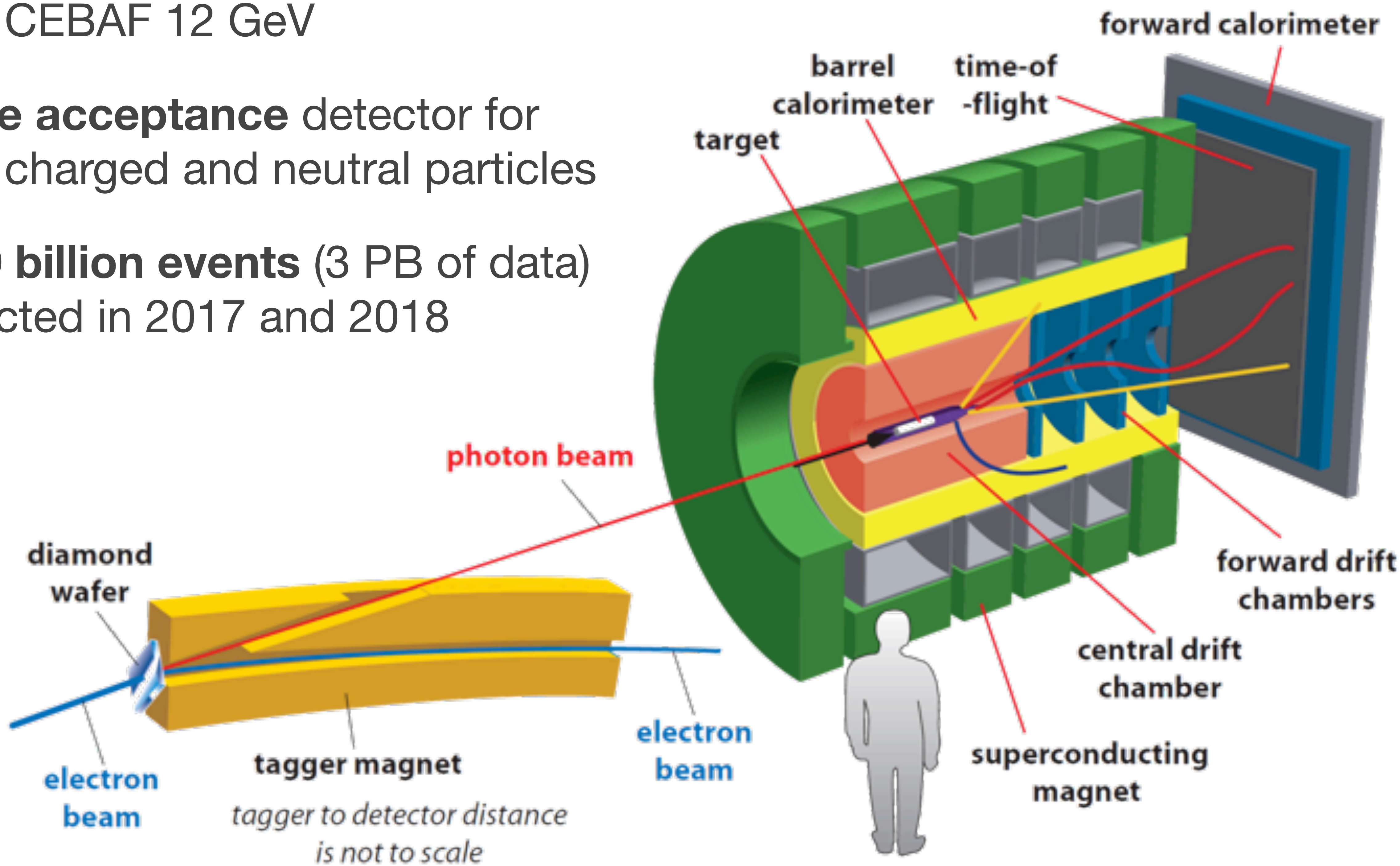
Dudek et al. PRD 88 (2013) 094505



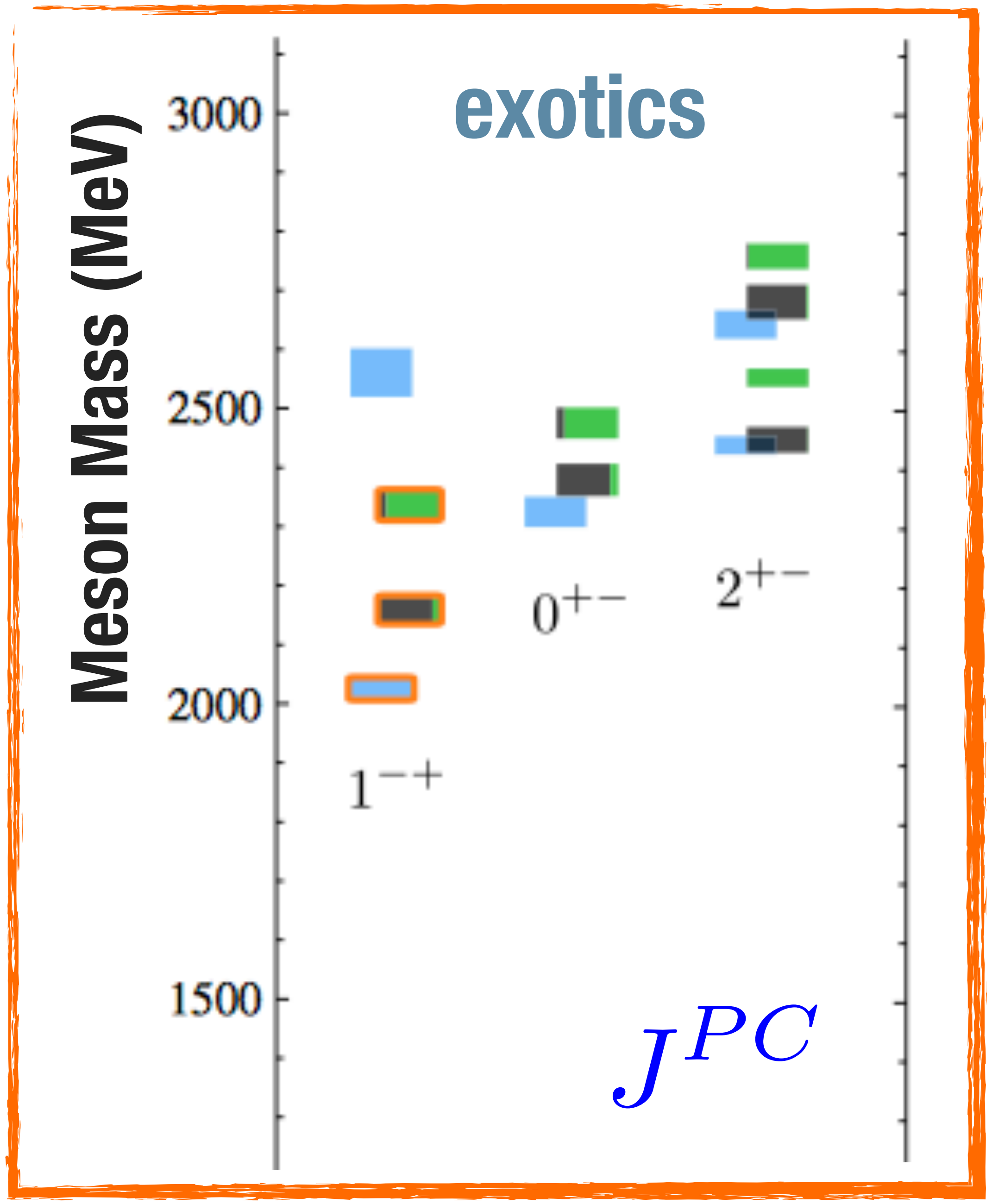
- Ideally look for a pattern of hybrid states in multiple decay modes
- Primary goal of the GlueX experiment is to search for and ultimately map out the spectrum of light quark hybrid mesons

GlueX in Hall D

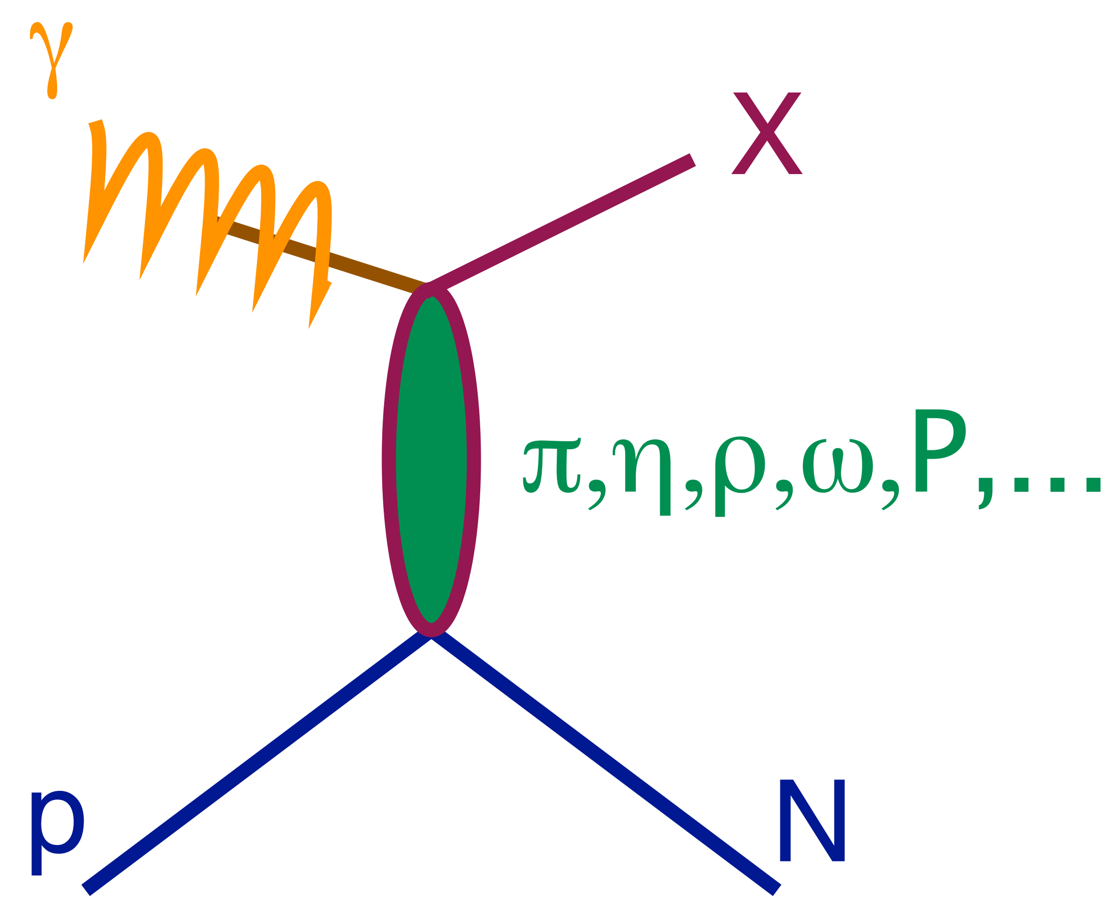
- **Linearly polarized photon beam** from CEBAF 12 GeV
- **Large acceptance** detector for both charged and neutral particles
- **~200 billion events** (3 PB of data) collected in 2017 and 2018



Exotic J^{PC} in photoproduction

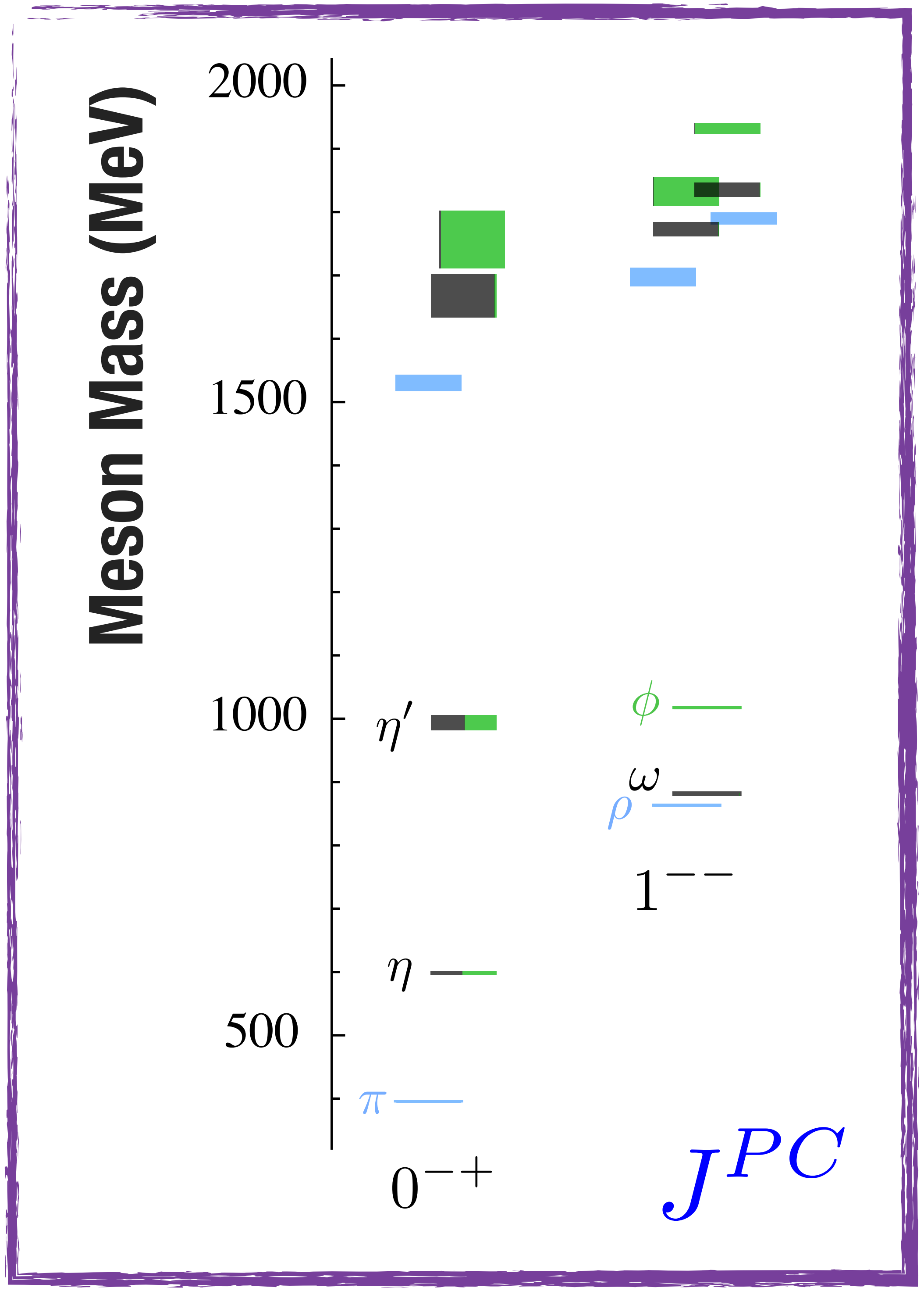


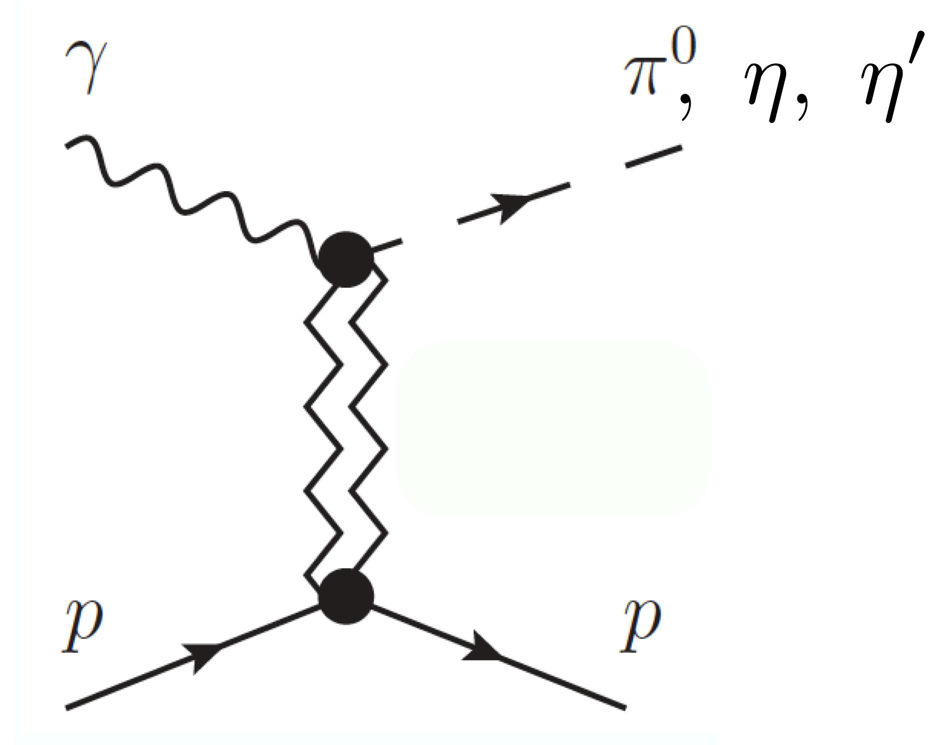
Meson X with particular J^{PC}



Production through t-channel "quasi-particle" exchange

Non-exotic J^{PC} in photoproduction





Exchange J^{PC}

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

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

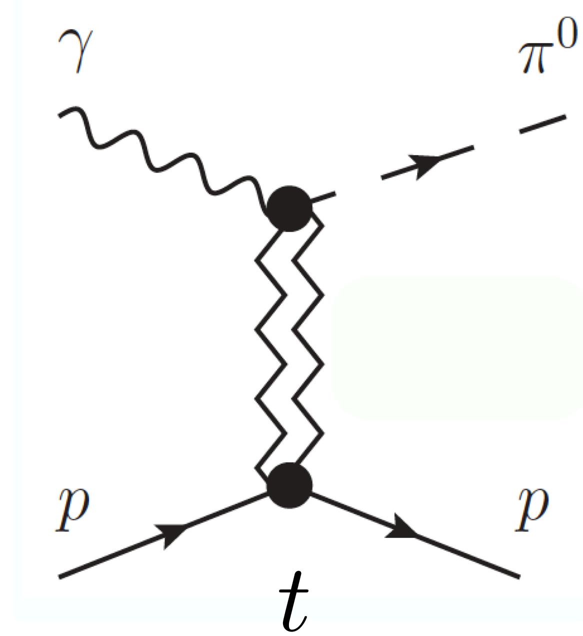
- Begin by understanding non-exotic production mechanism
- Linear photon beam polarization critical to filter out "naturality" of the exchange particle

ɣp→π⁰p beam asymmetry Σ

- Beam asymmetry Σ provides insight into dominant production mechanism

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

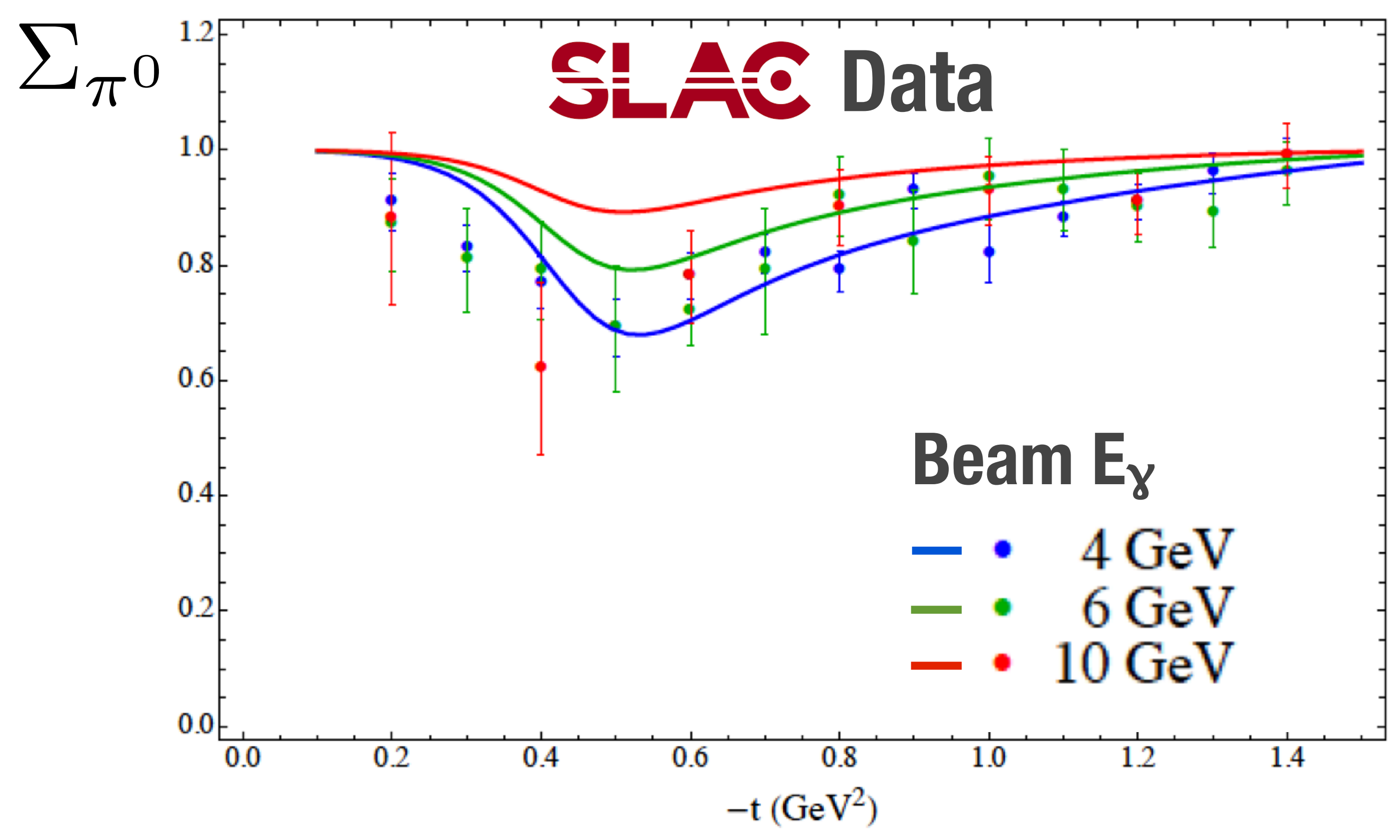
- From experimental standpoint it's easily extended to ɣp→ηp
  - **No previous measurements!**



Exchange J^{PC}

1^{--} : ω, ρ

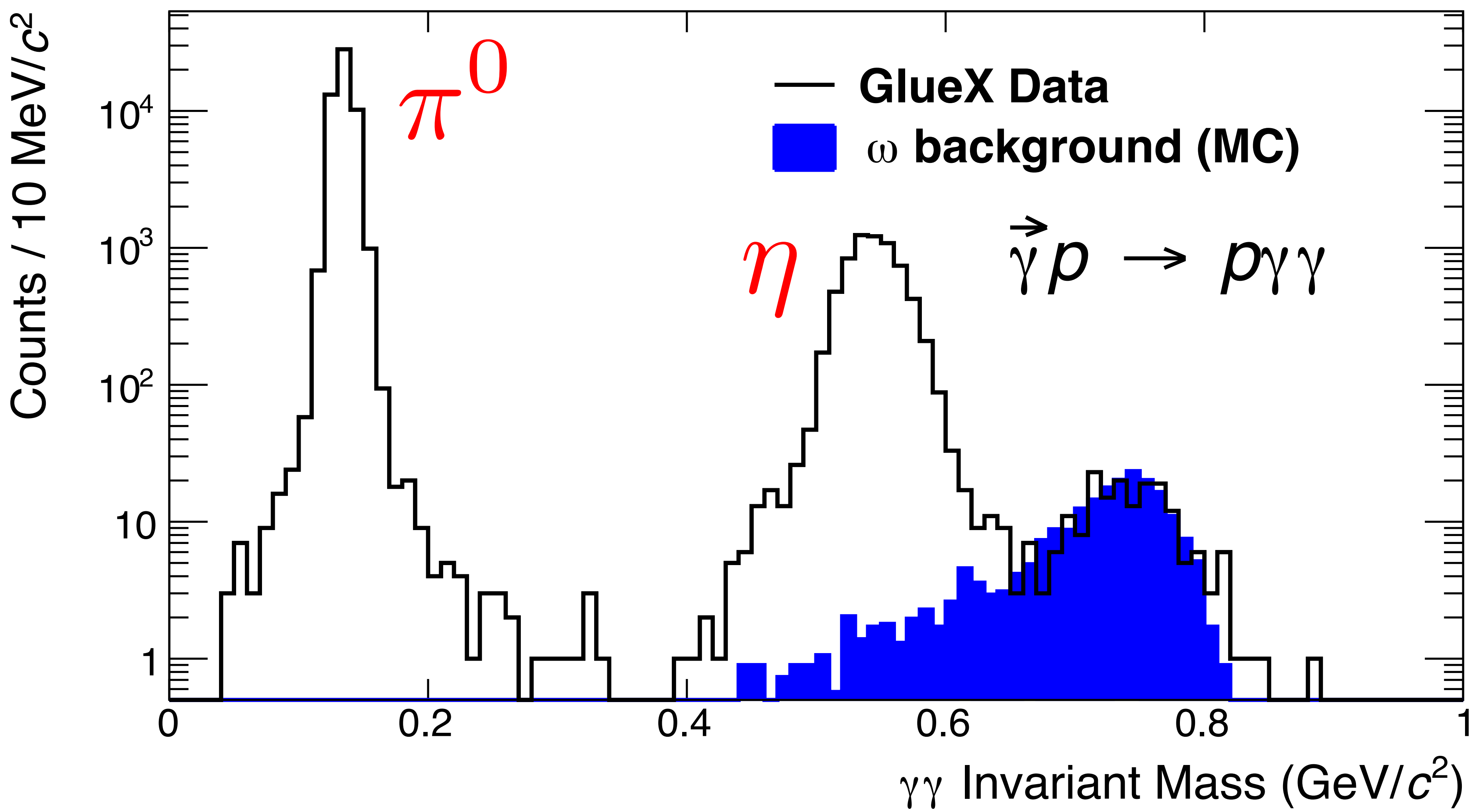
1^{+-} : b, h



JPAC : Mathieu et al. PRD 92, 074013

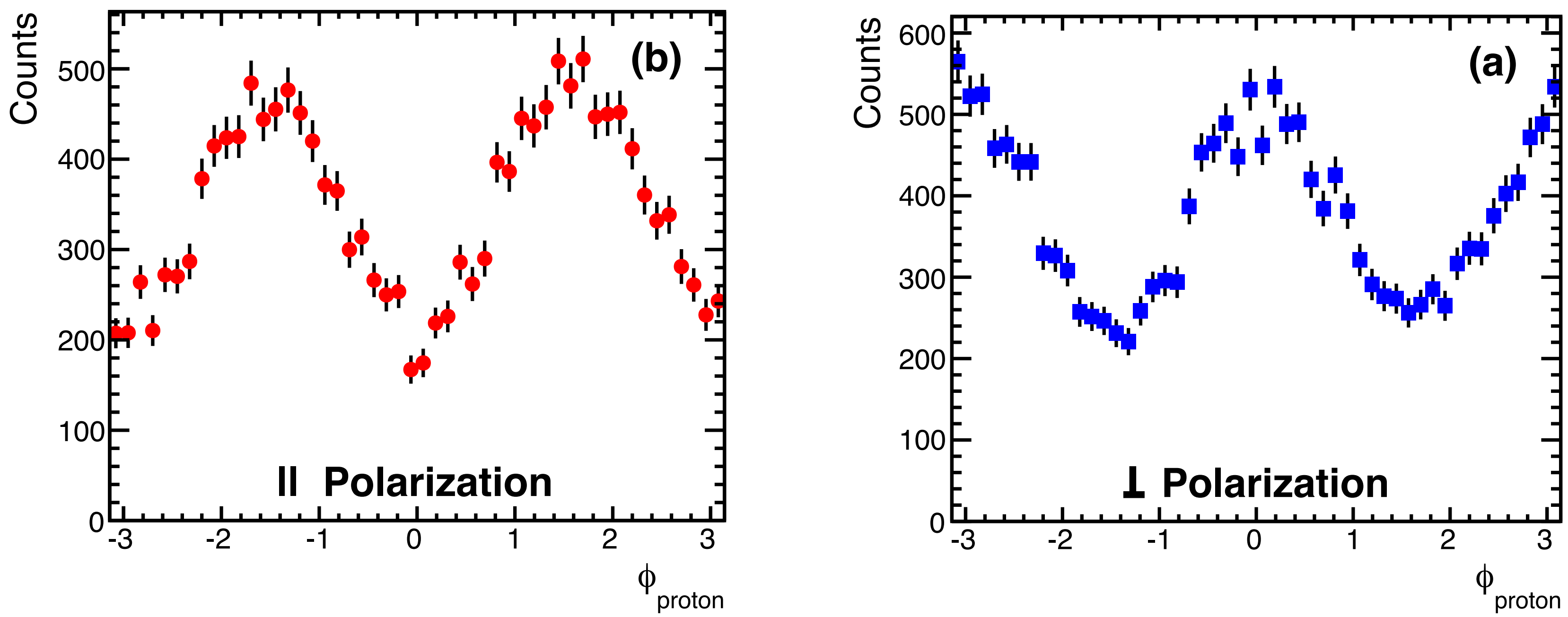
π^0 and η beam asymmetries

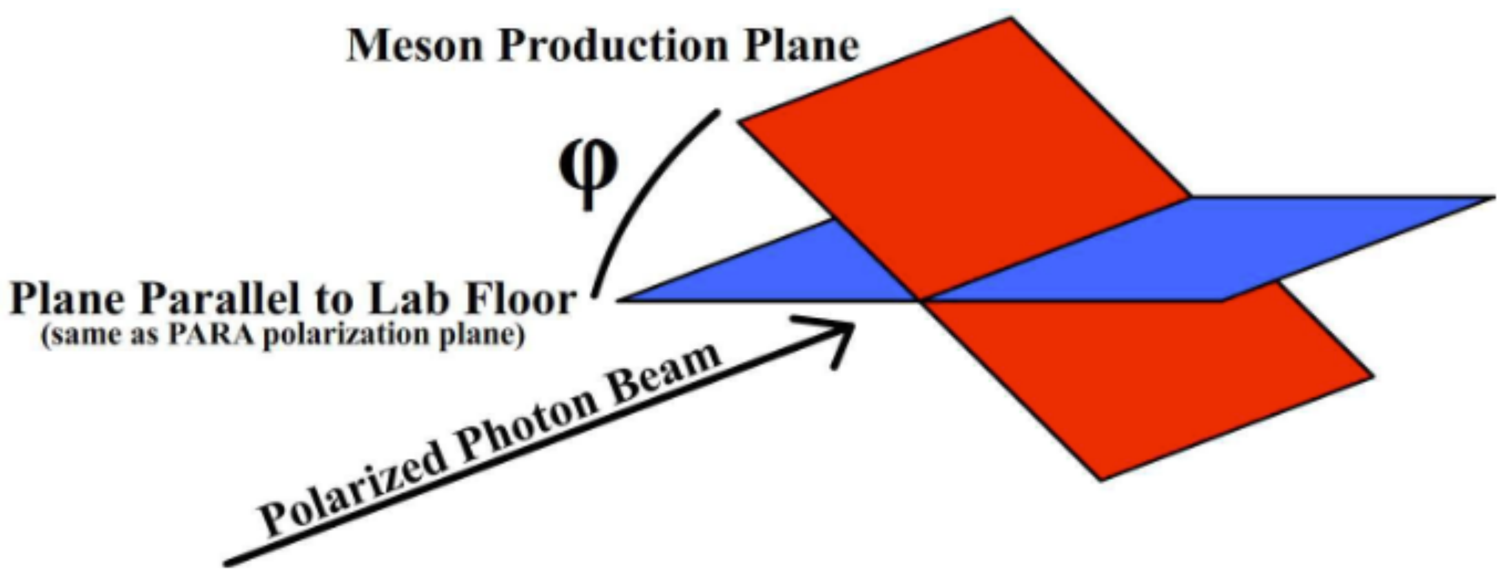
$$\gamma p \to p\gamma\gamma$$



Phys. Rev. C 95, 042201(R)

π^0 and η beam asymmetries

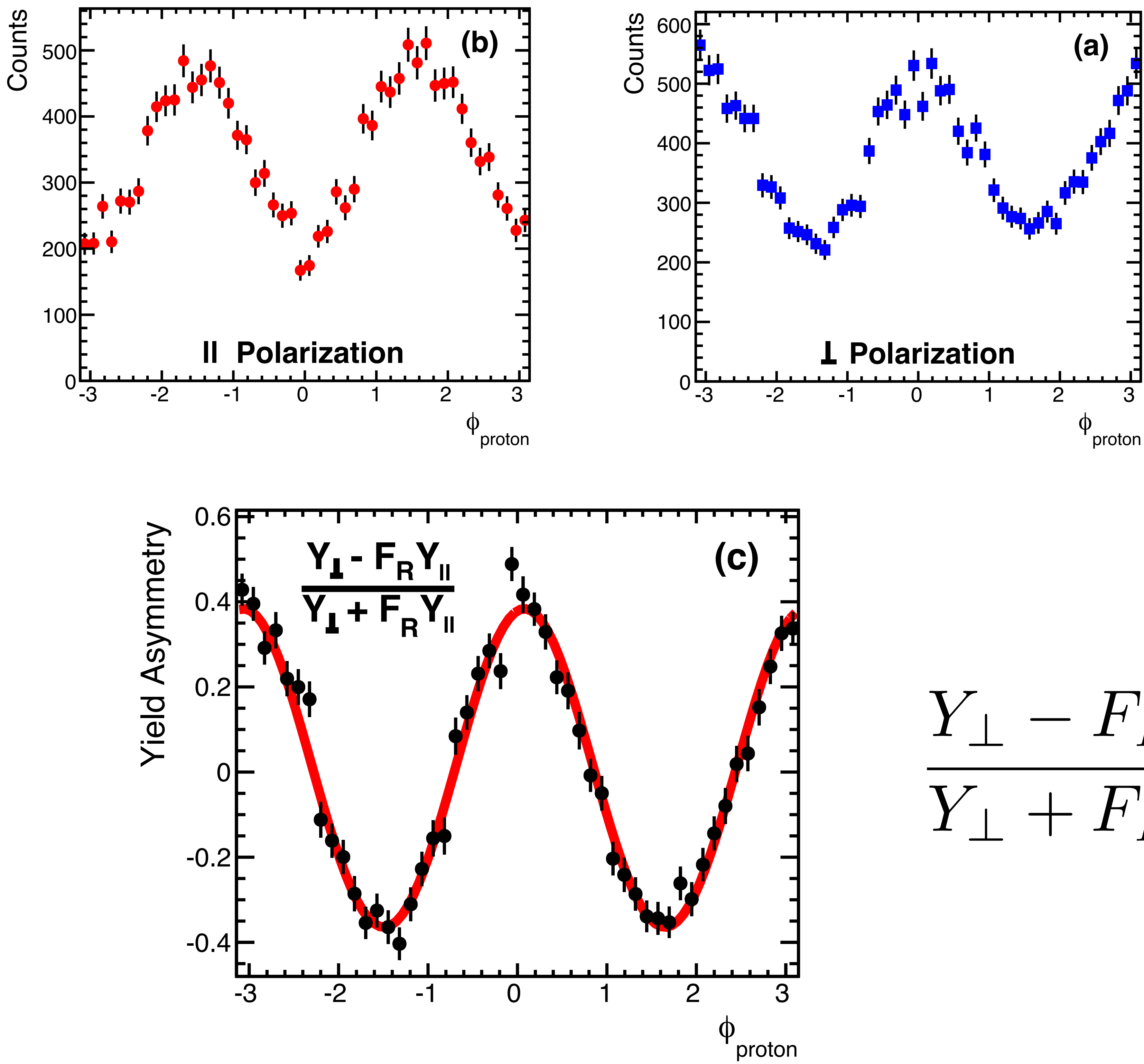




$$\sigma = \sigma_0 \left(1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_\gamma^{\mathrm{lin}})\right)$$

Phys. Rev. C 95, 042201(R)

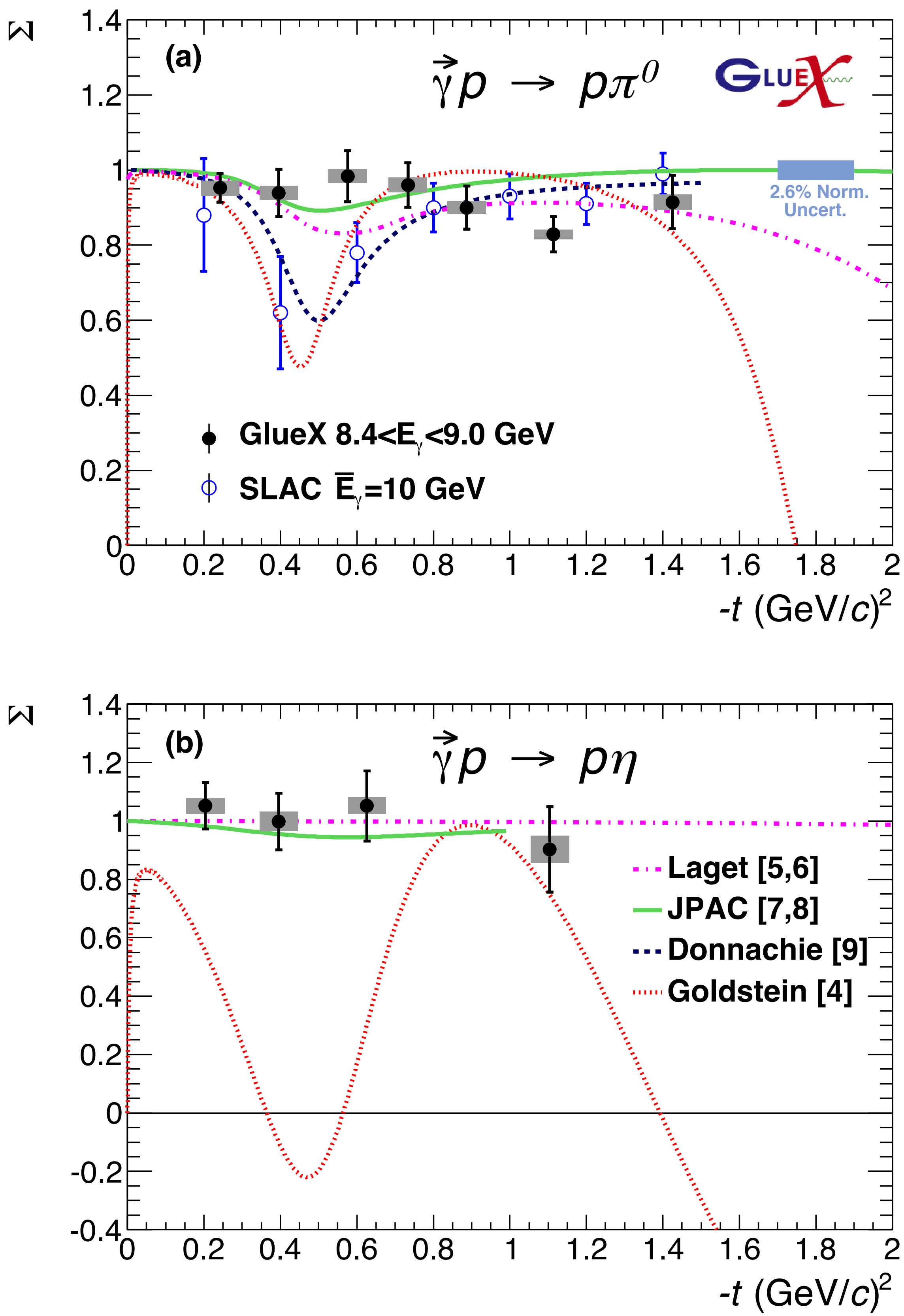
π^0 and η beam asymmetries



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

Phys. Rev. C 95, 042201(R)

π^0 and η beam asymmetries

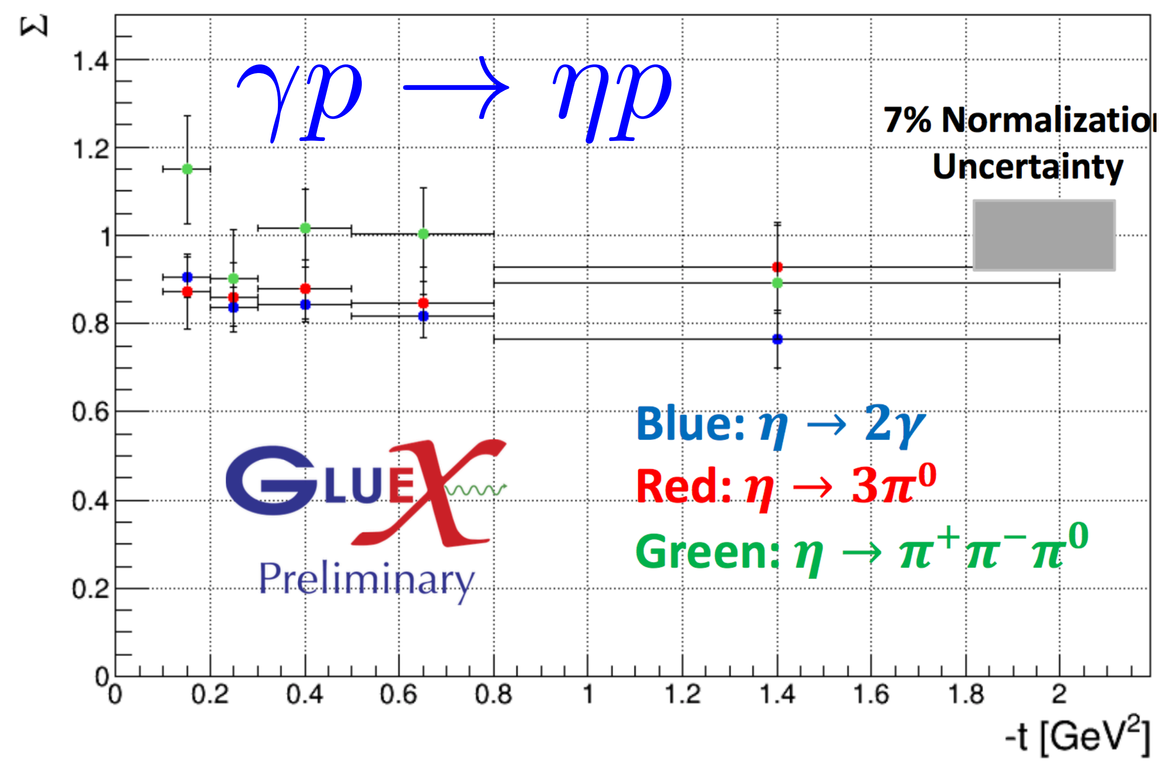


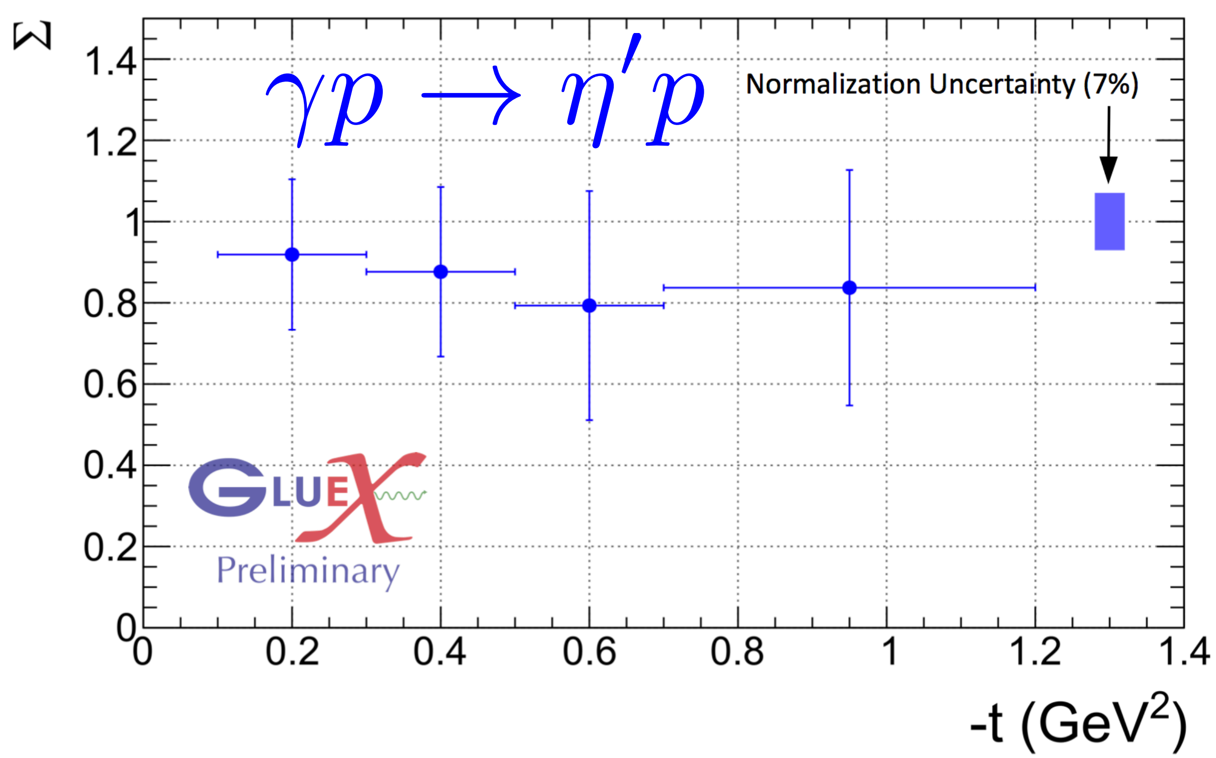
- Dip in multiple theory predictions not observed
- Indication of vector exchange dominance at this energy
- Additional asymmetry measurements ongoing with this dataset

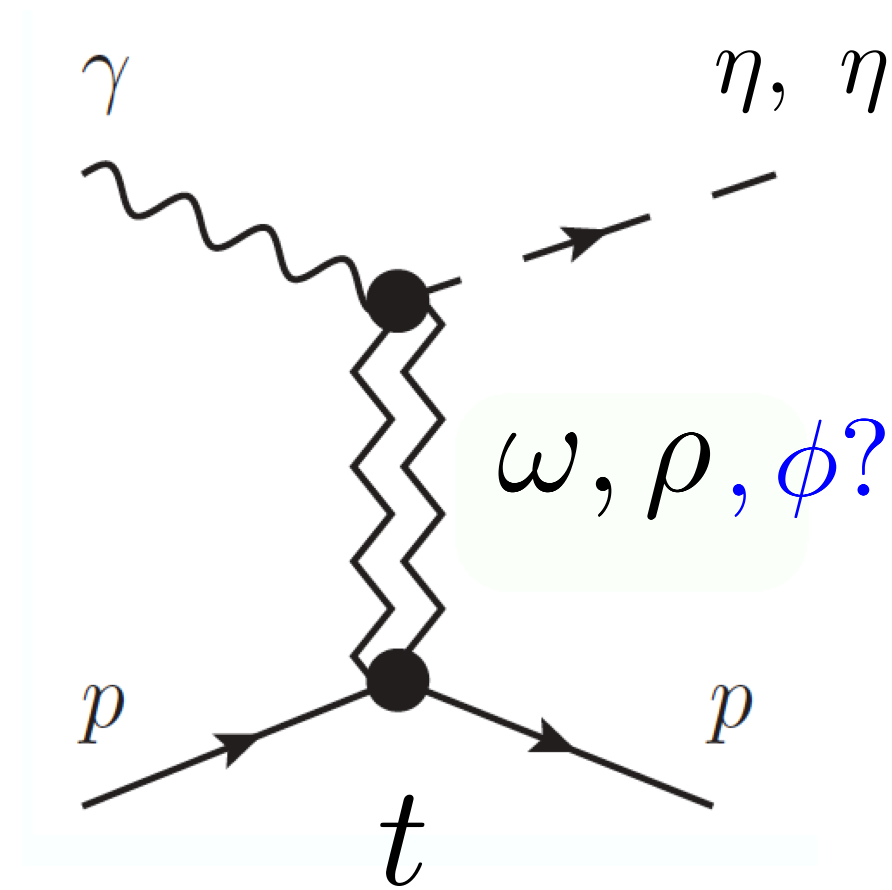
First 12 GeV publication!

Phys. Rev. C 95, 042201(R)

Pseudoscalar beam asymmetries



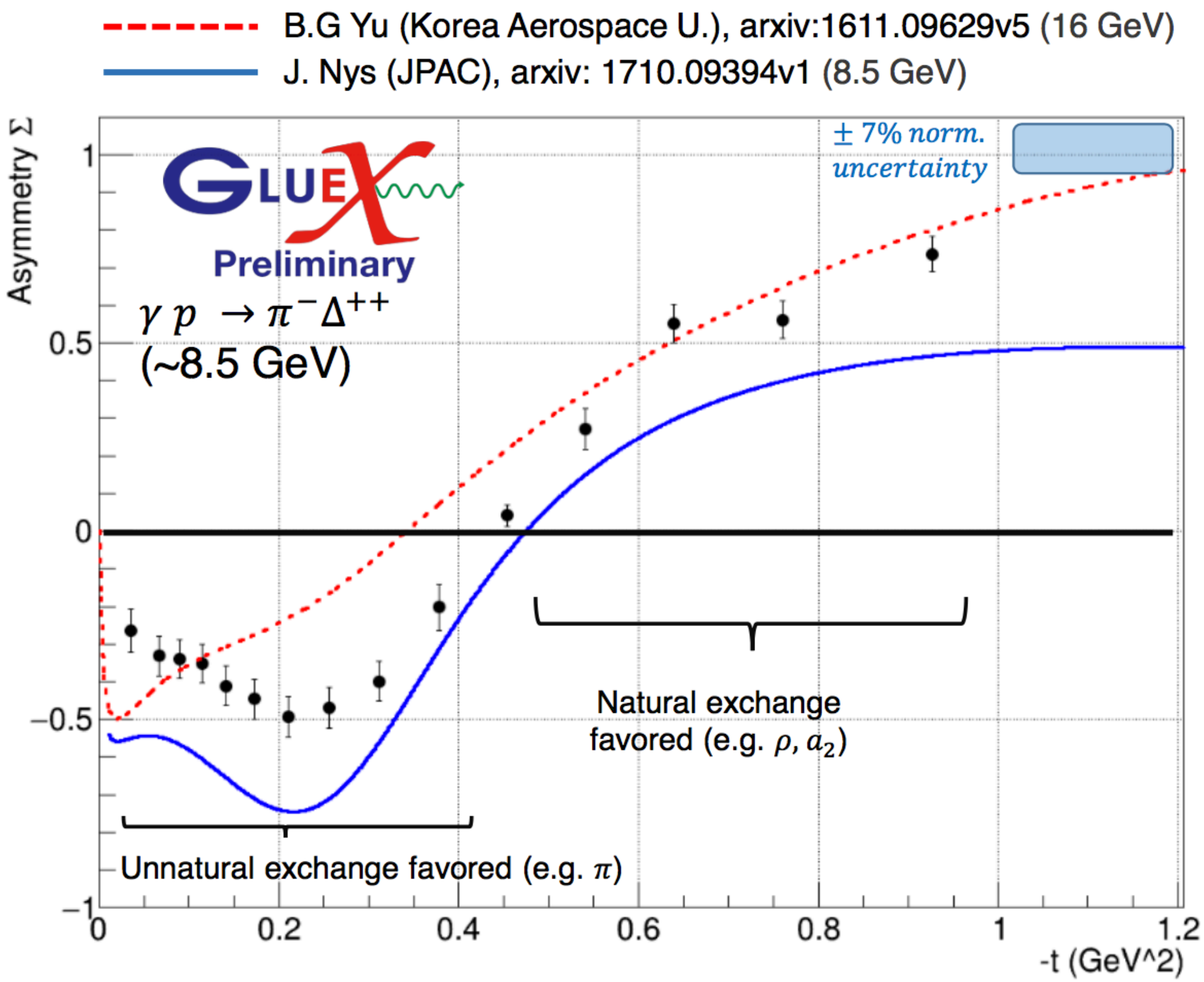


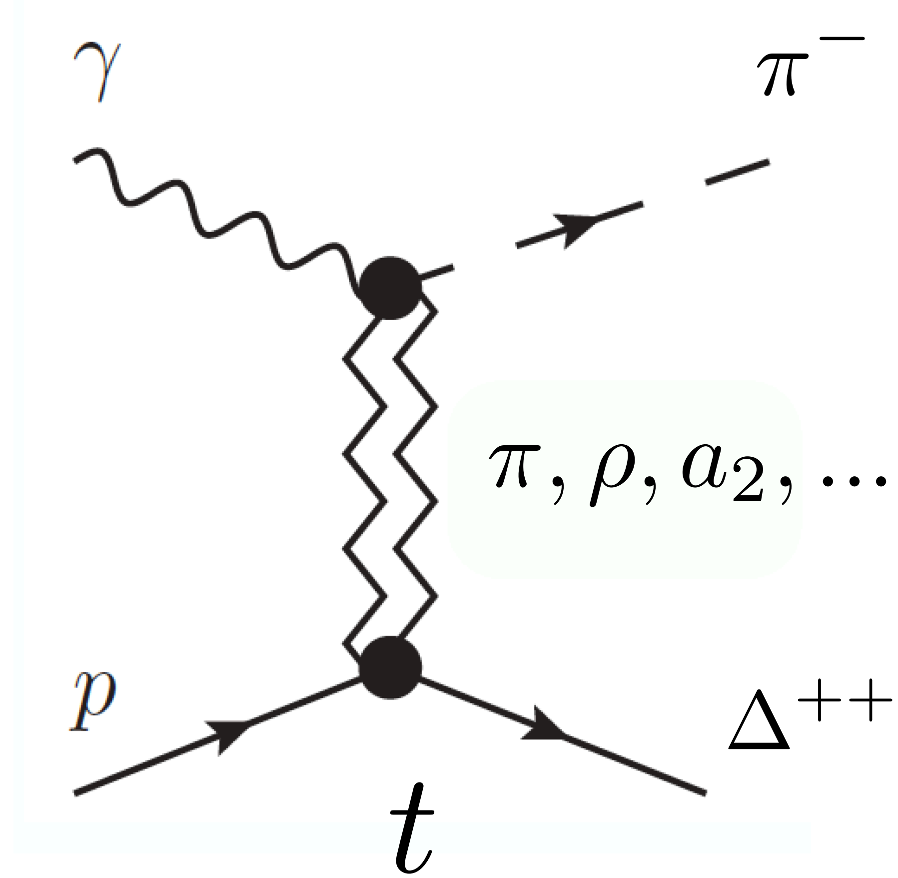


Consistent with prediction from JPAC: PLB 774 (2017) 362

Neutral pseudoscalars: Σ~1, dominated by vector exchange

Pseudoscalar beam asymmetries

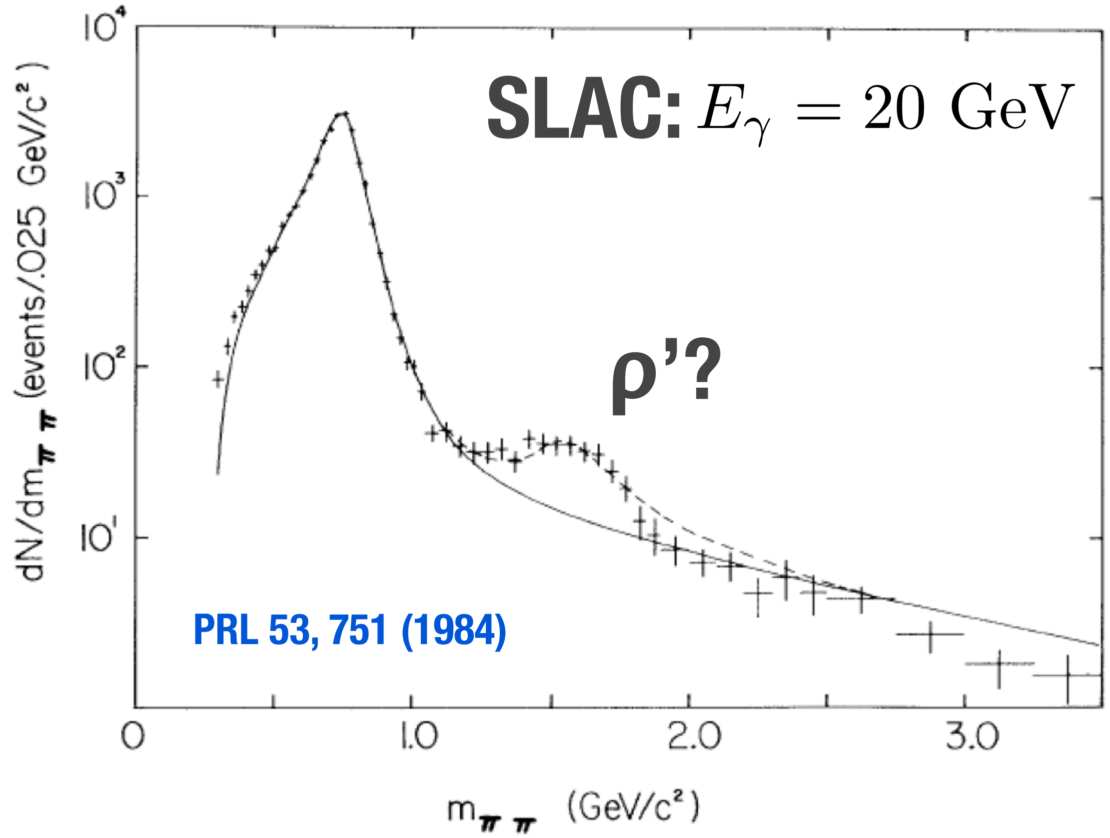


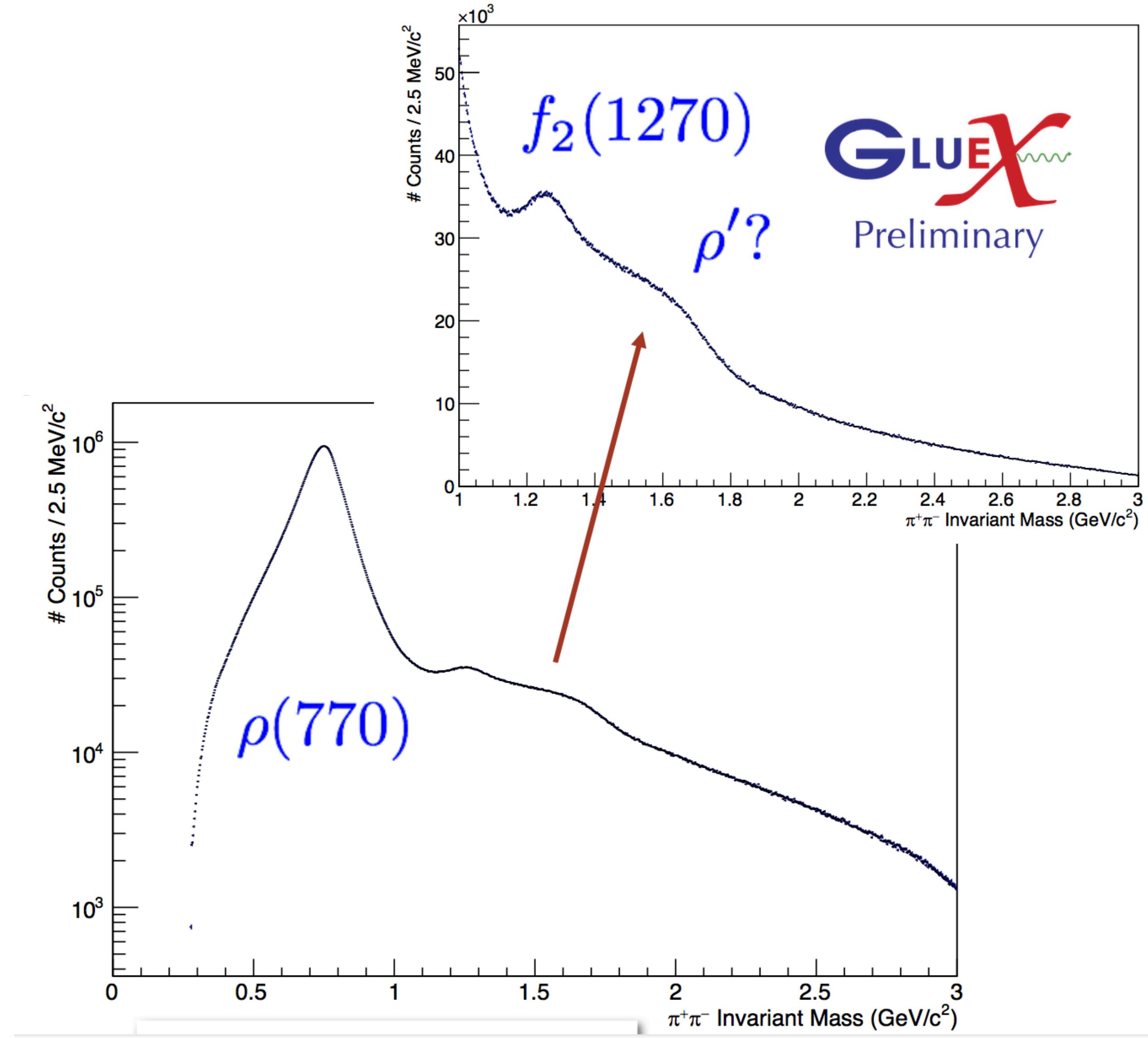


Charged pseudoscalars: more complicated $-t$ dependence

Early spectroscopy opportunities

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



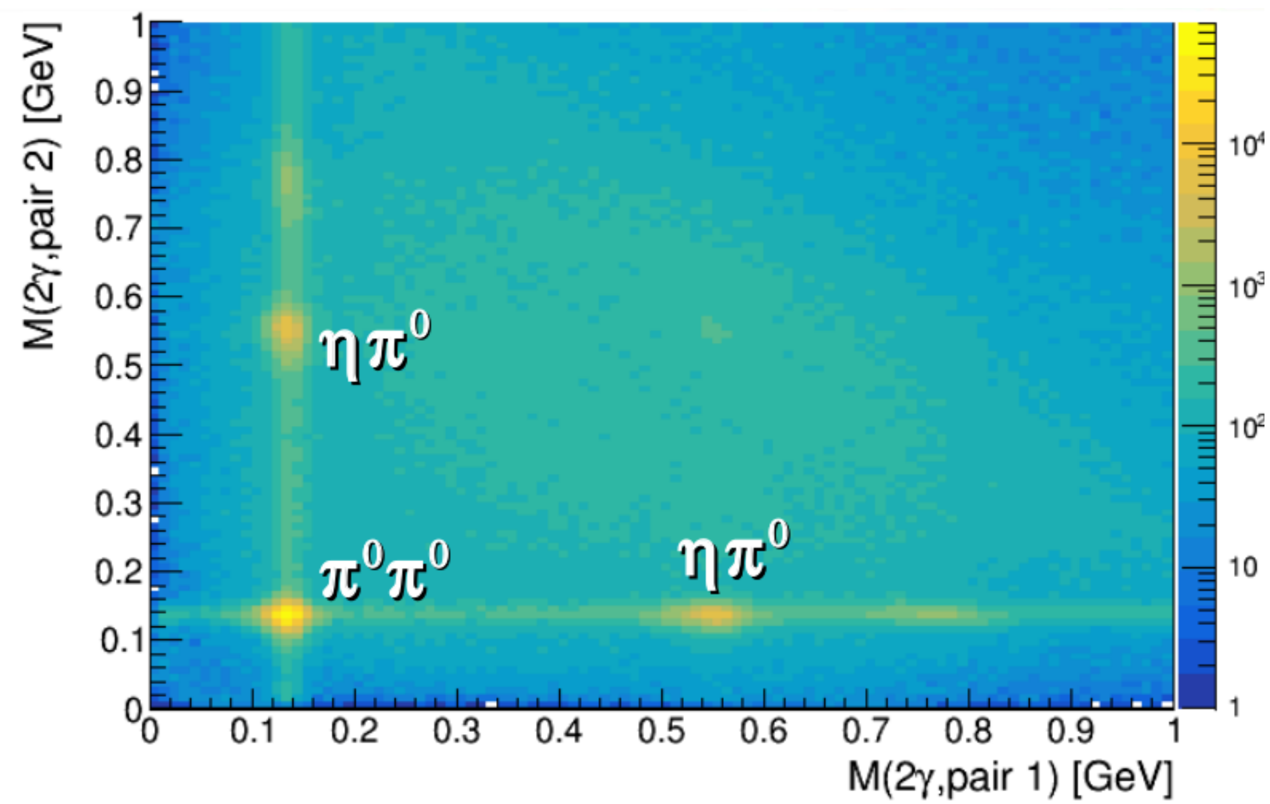


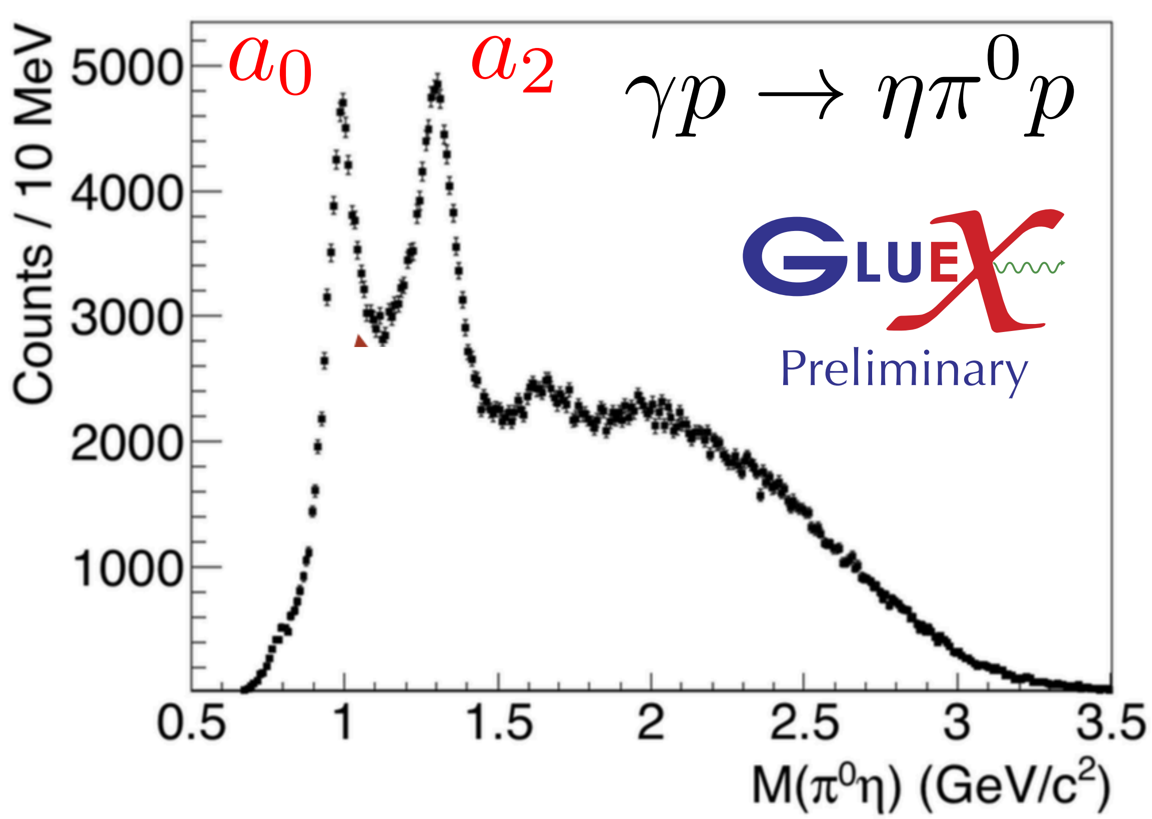
- Enhancement consistent with earlier SLAC measurement, but ~1000x more statistics with early GlueX data
- Polarization observables will provide further insight into the nature of this enhancement

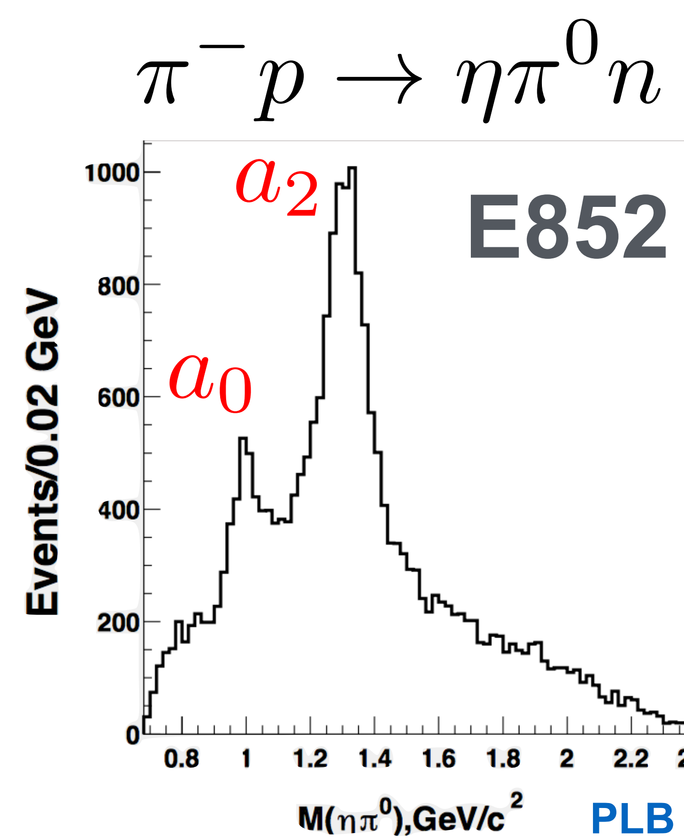
Early spectroscopy opportunities

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

- Previous photoproduction data very sparse for channels with multiple neutrals particles
- Early opportunity for exotic search since P-wave is exotic



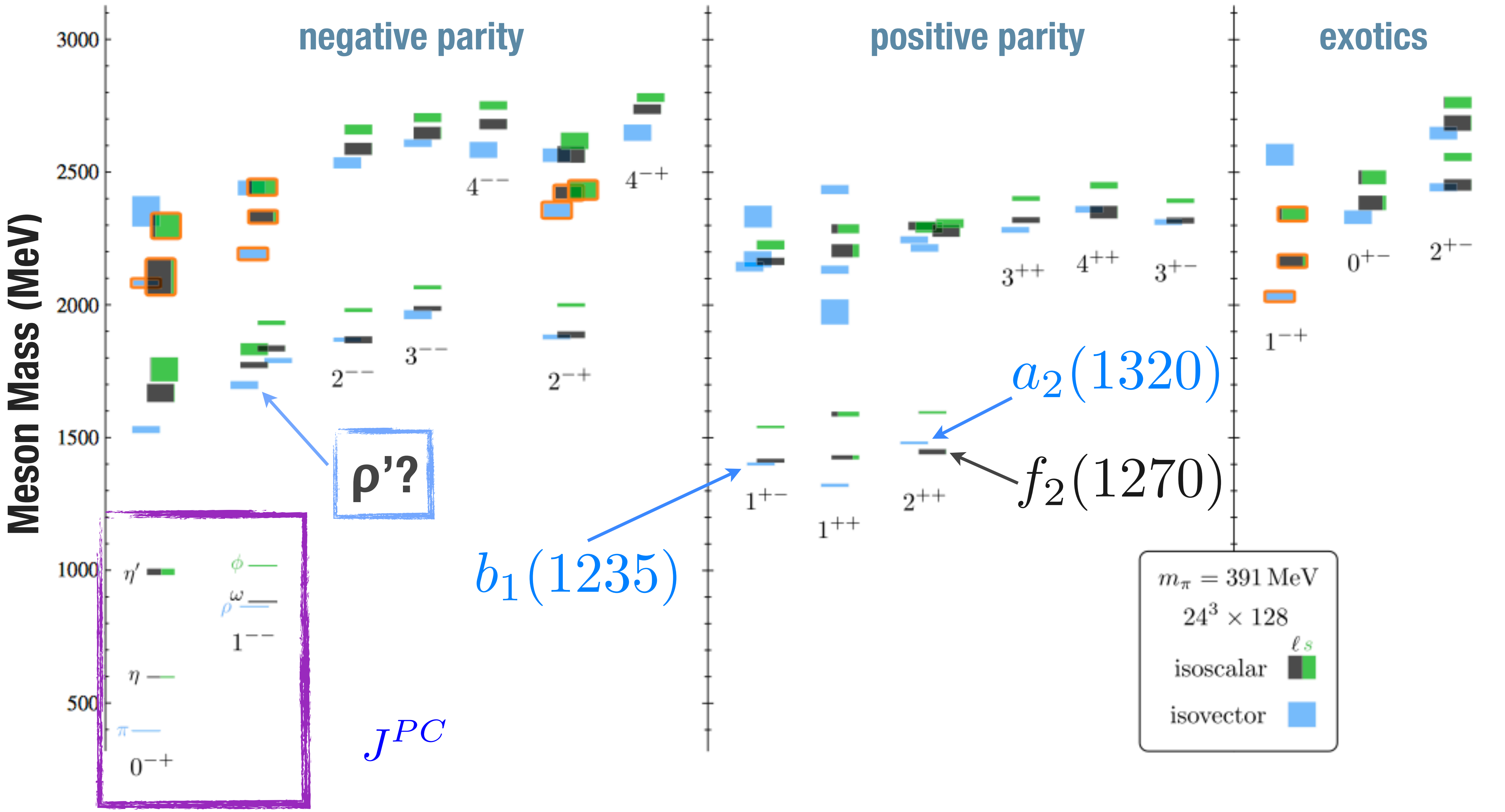




PLB 657 (2007) 27

Mapping the meson spectrum

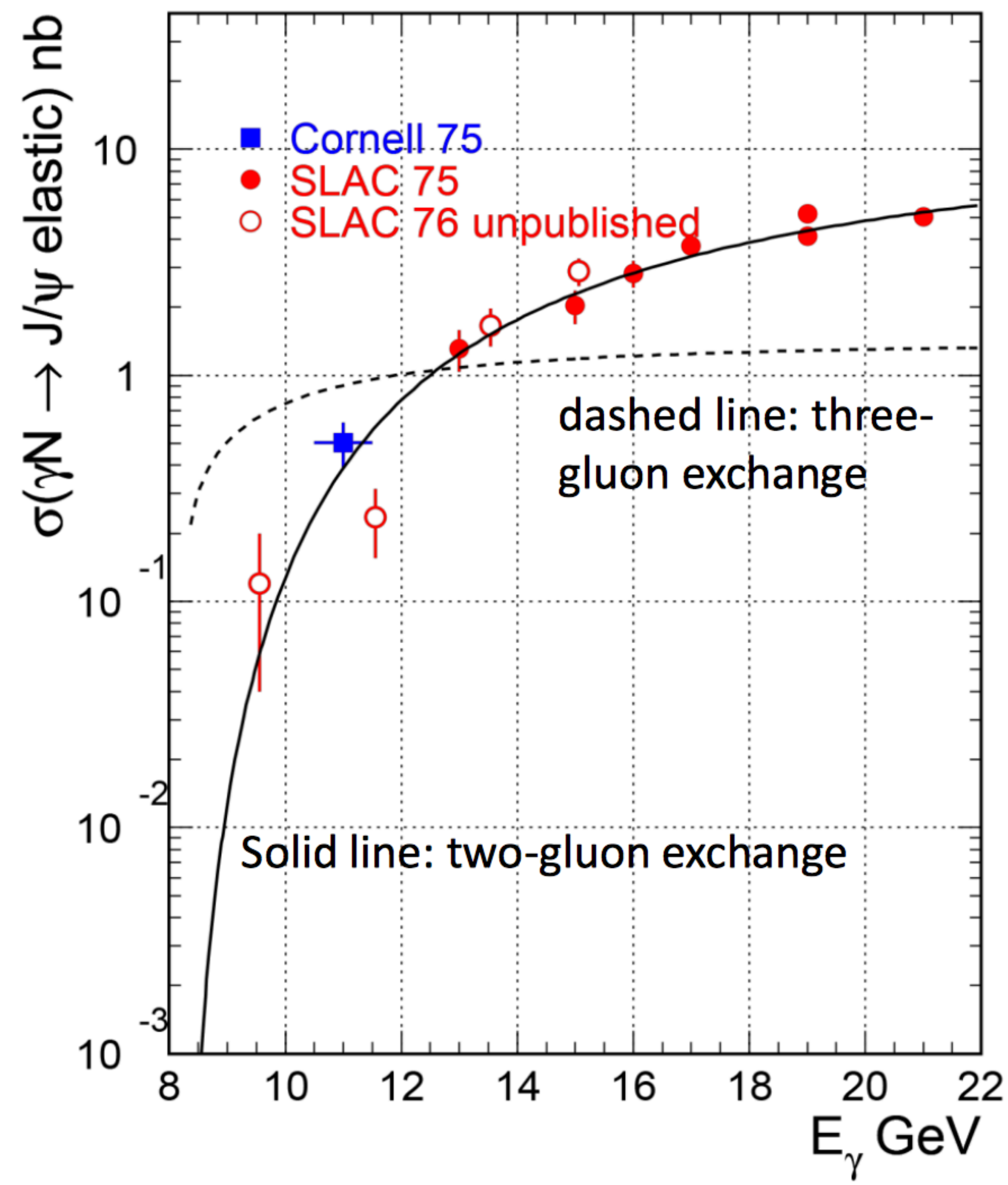
PRD 88 (2013) 094505

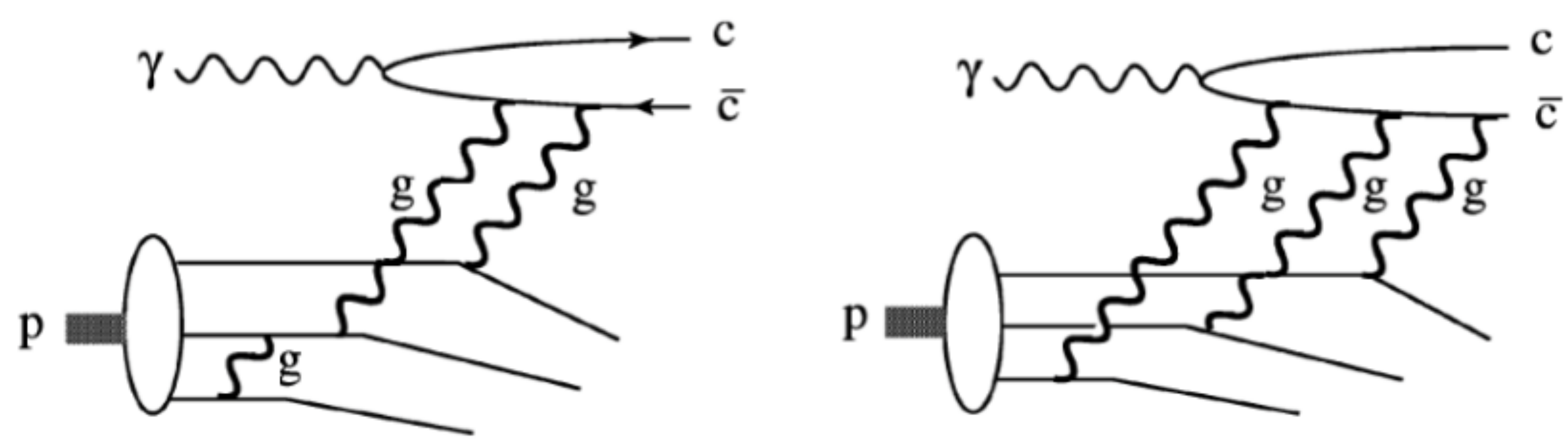


- Already studying polarization observables for **"simple" final states**
- Beginning to identify **known mesons** in multi-particle final states

J/ψ photoproduction at JLab

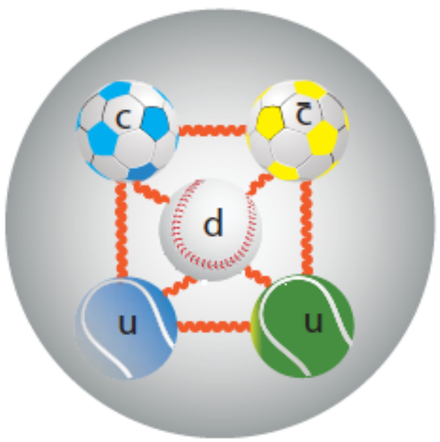
- Threshold J/ψ provides information on the gluon distributions in the nucleon
- Planned measurements in Hall A, B and C
- First data from Hall D already under analysis



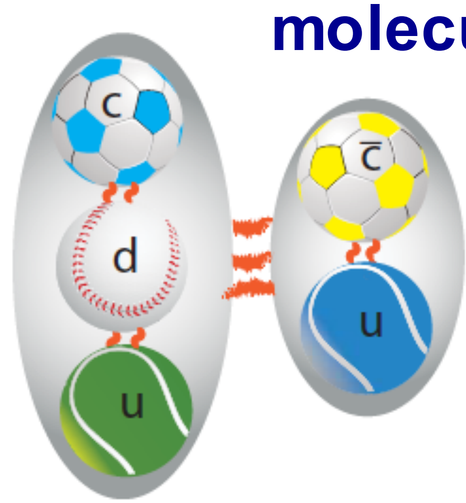


Charm Quarks at JLab

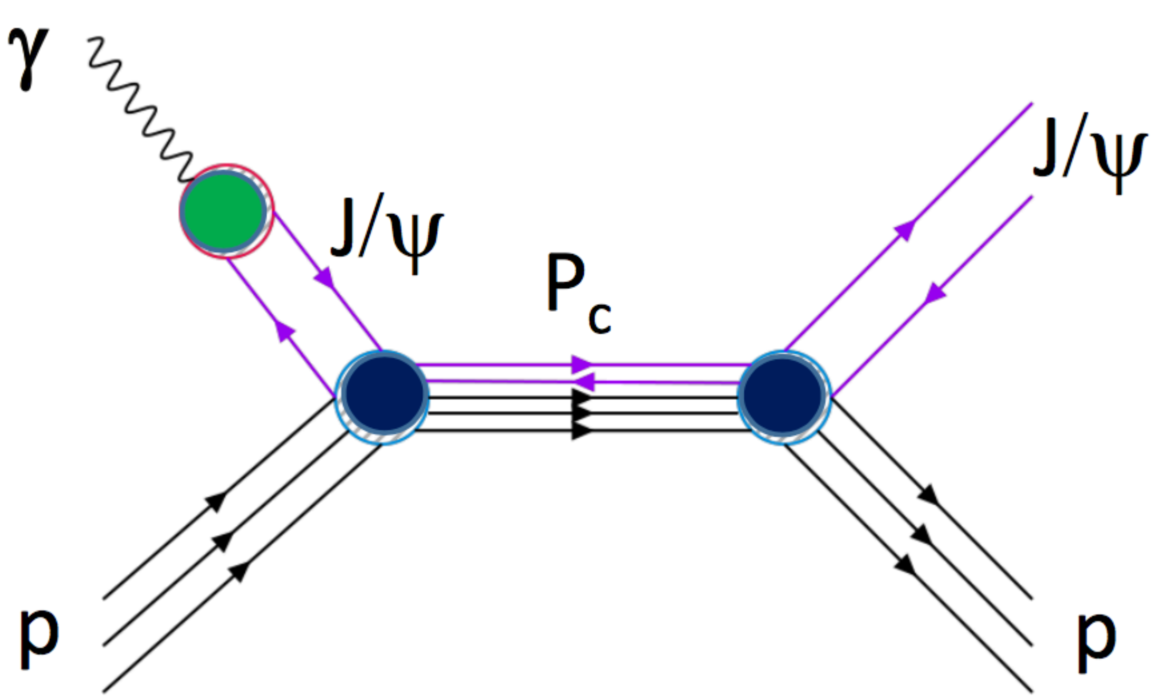
5-quark bound state

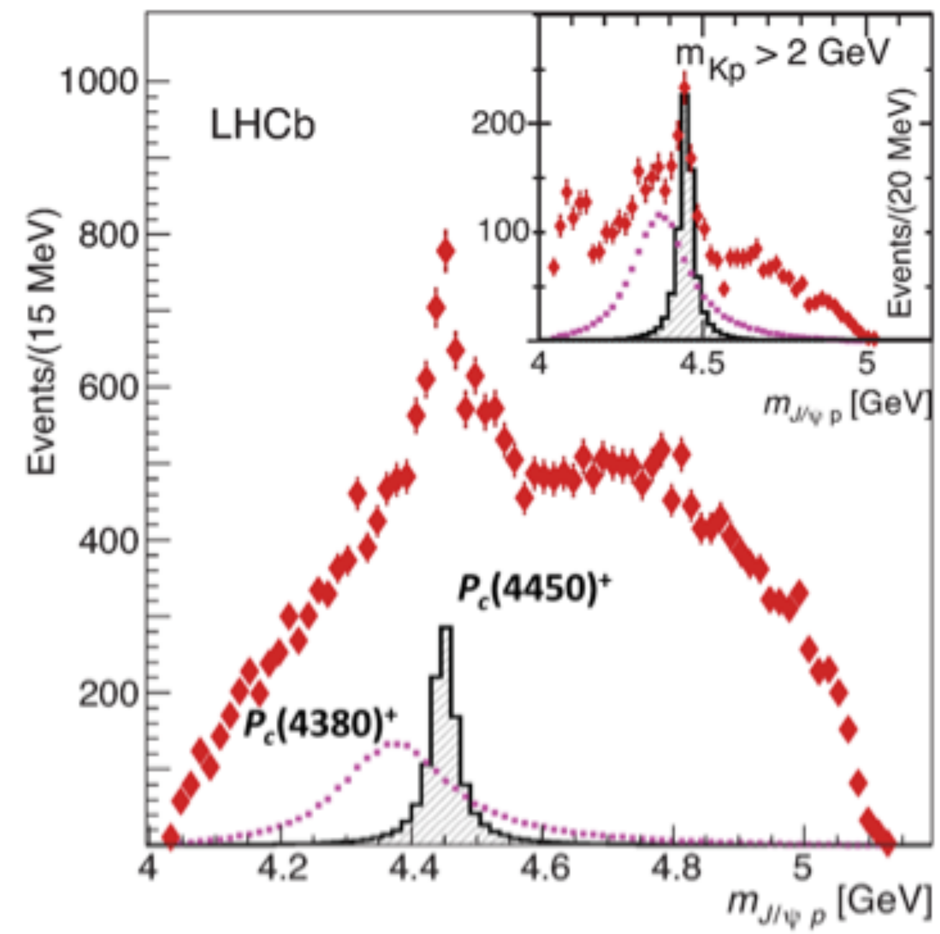


Hadronic molecule



$$\Lambda_b \to J/\psi p K^-$$

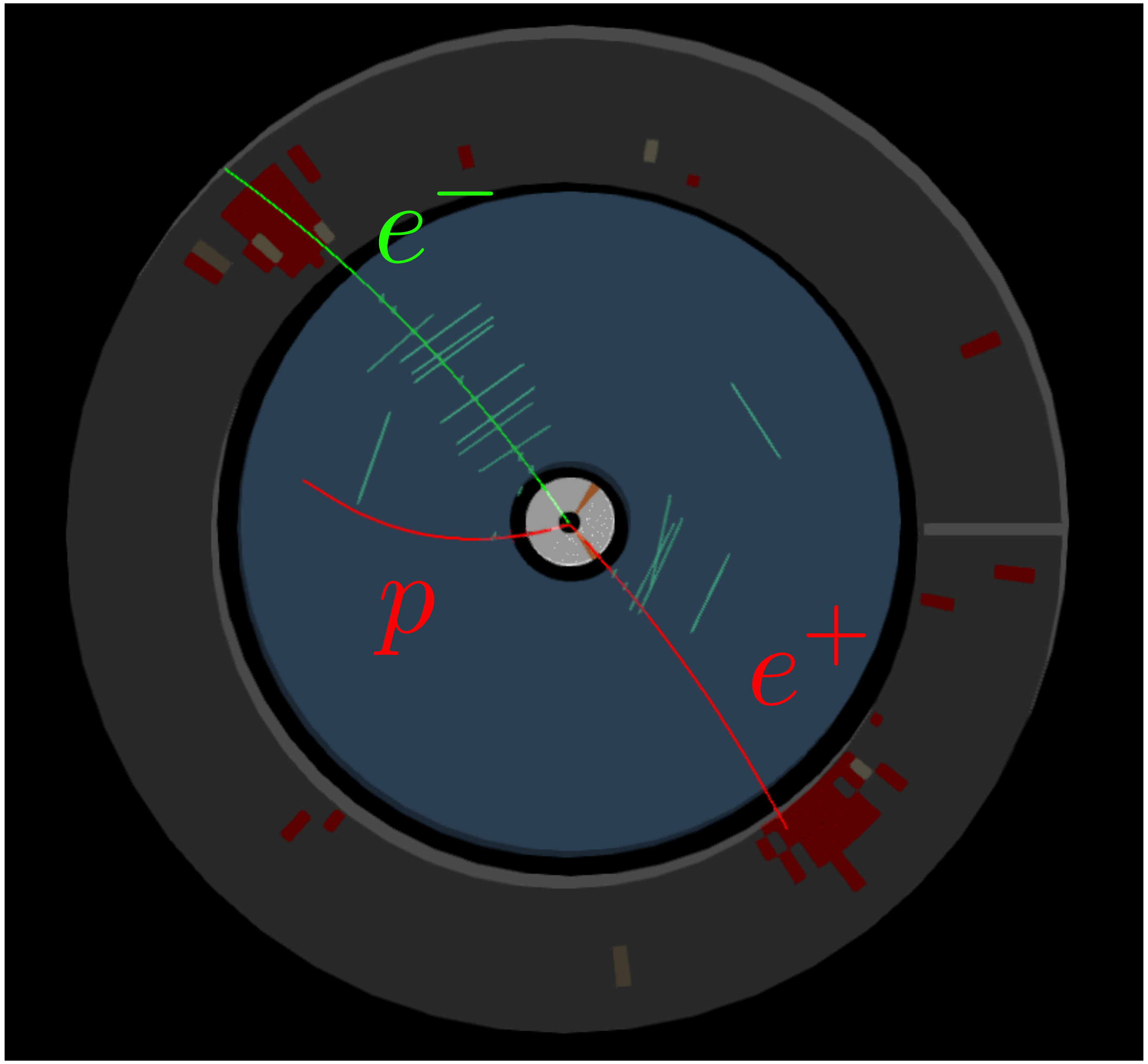




LHCb 2015

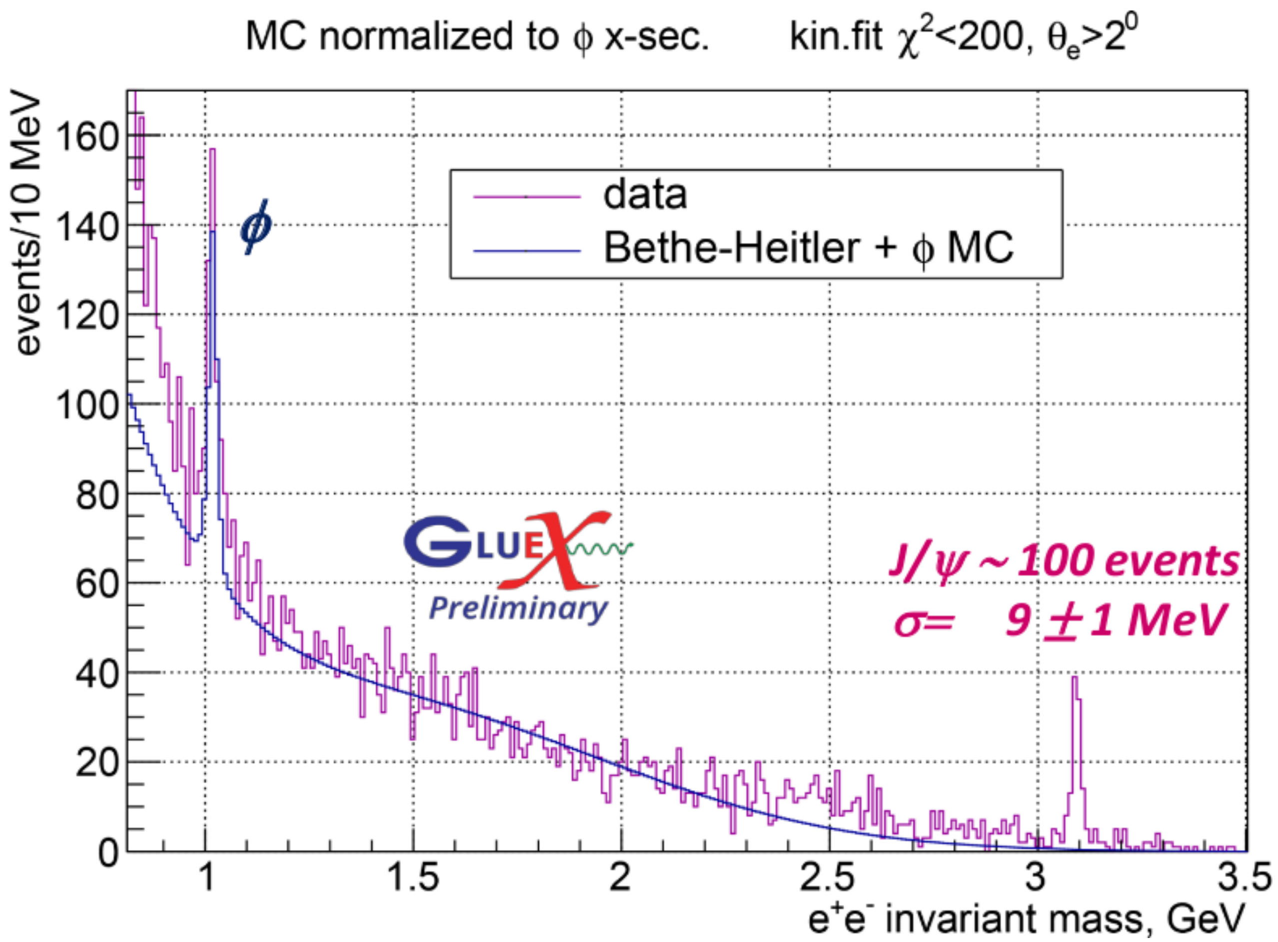
Observation of charm at GlueX

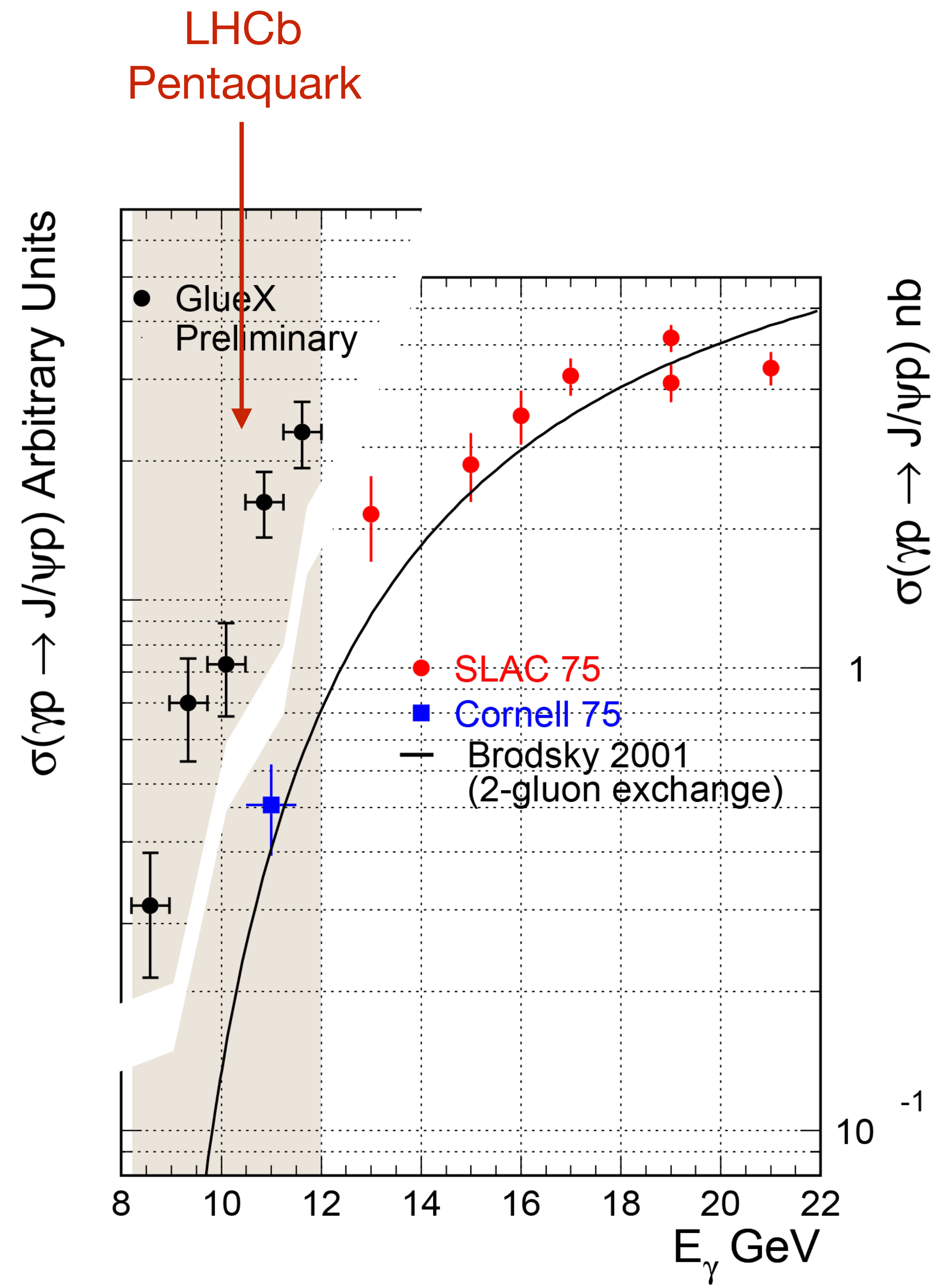
$$\gamma p \to p e^+ e^-$$

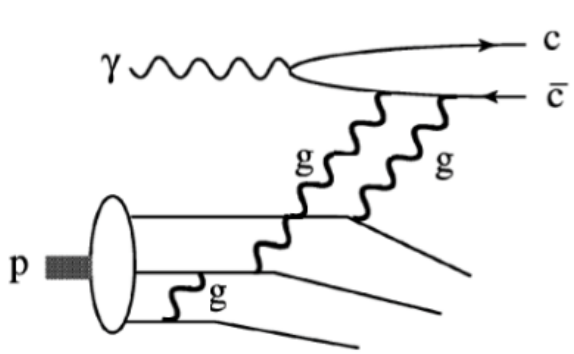


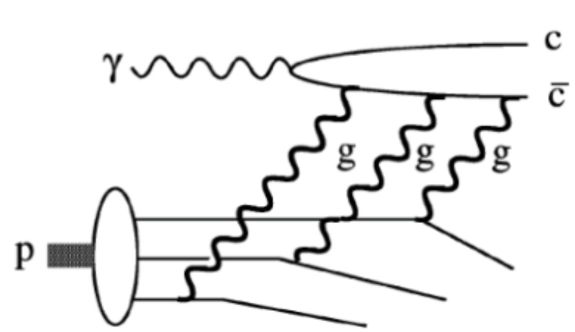
J/ψ photoproduction at GlueX

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



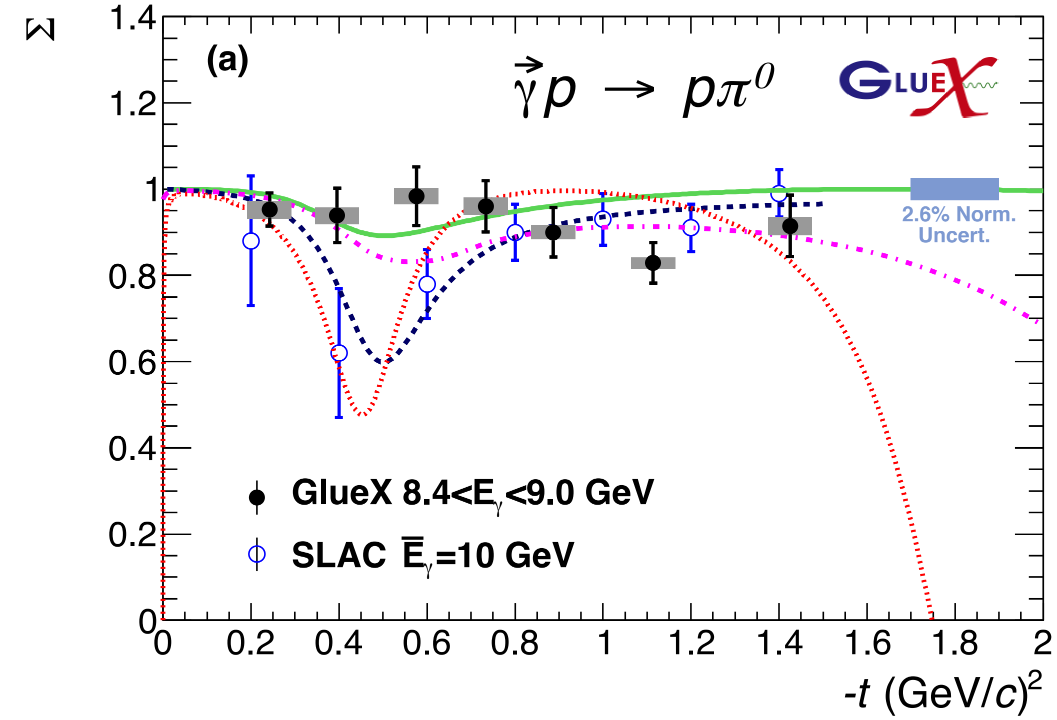


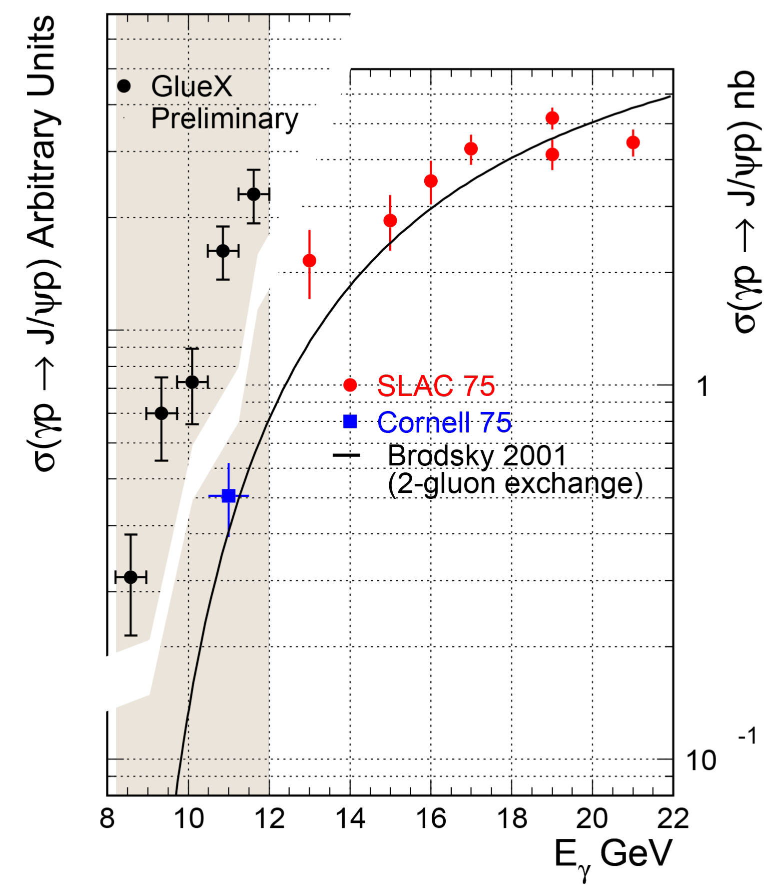




Summary

- 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
- First observation of charm at JLab, potential limits on pentaquark production





Supported by DE-SC0018224

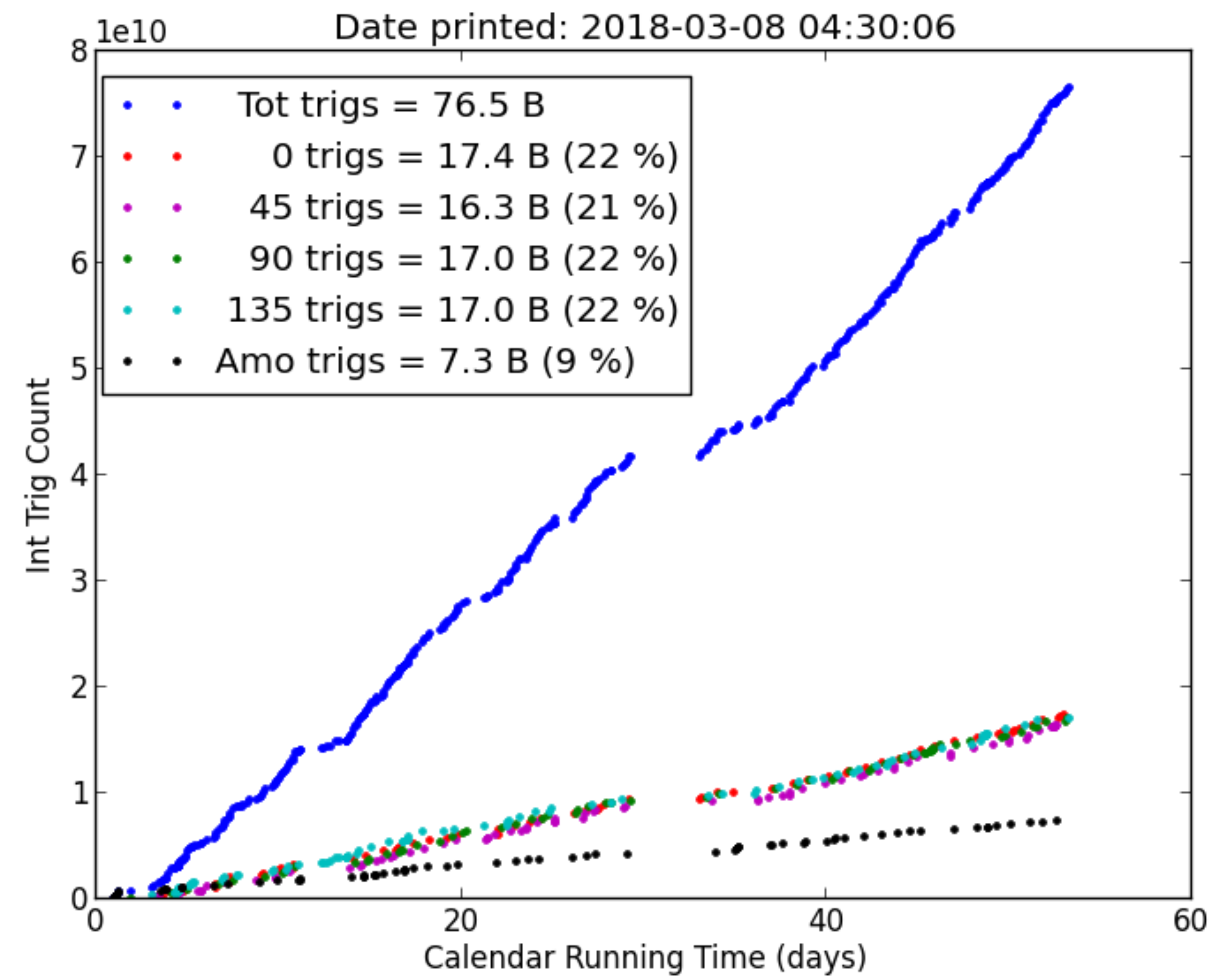
U.S. DEPARTMENT OF ENERGY | Office of Science

Backup

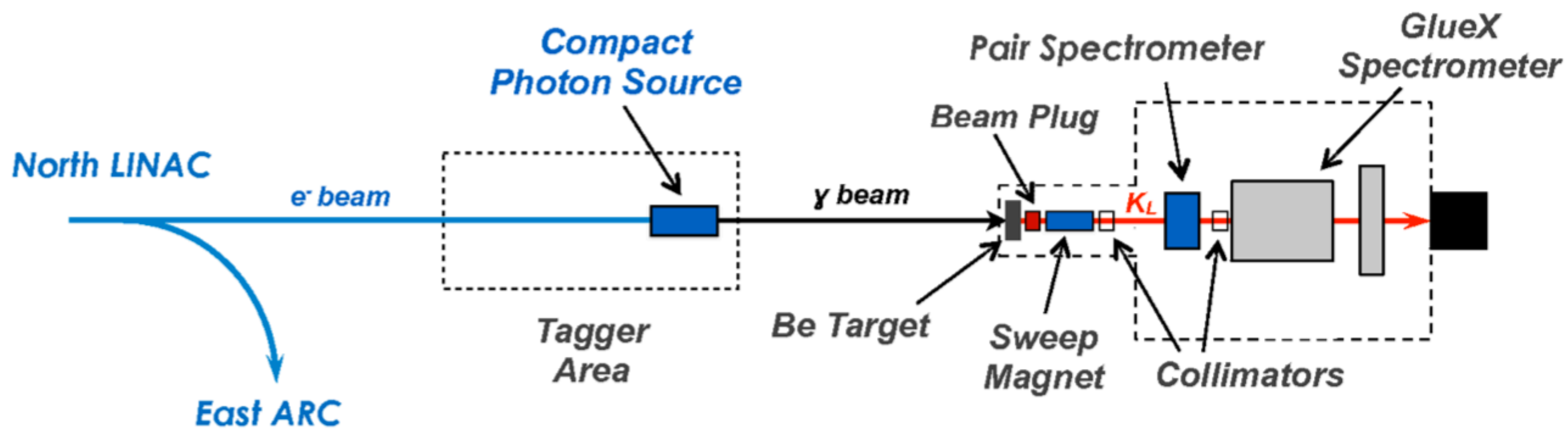
GlueX Timeline

* GlueX “Low intensity” program expected to be completed in 2018
* High intensity program including DIRC will collect 10x more data
* Primakoff and other experiments interleaved

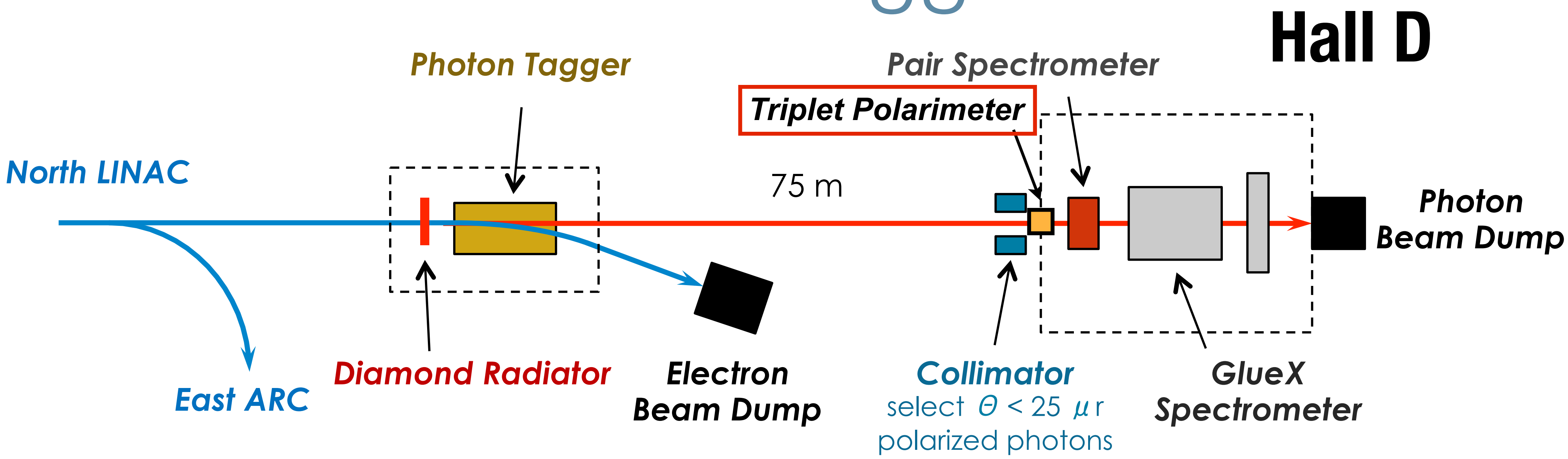
2018: ~75B events, ~1 PB of data



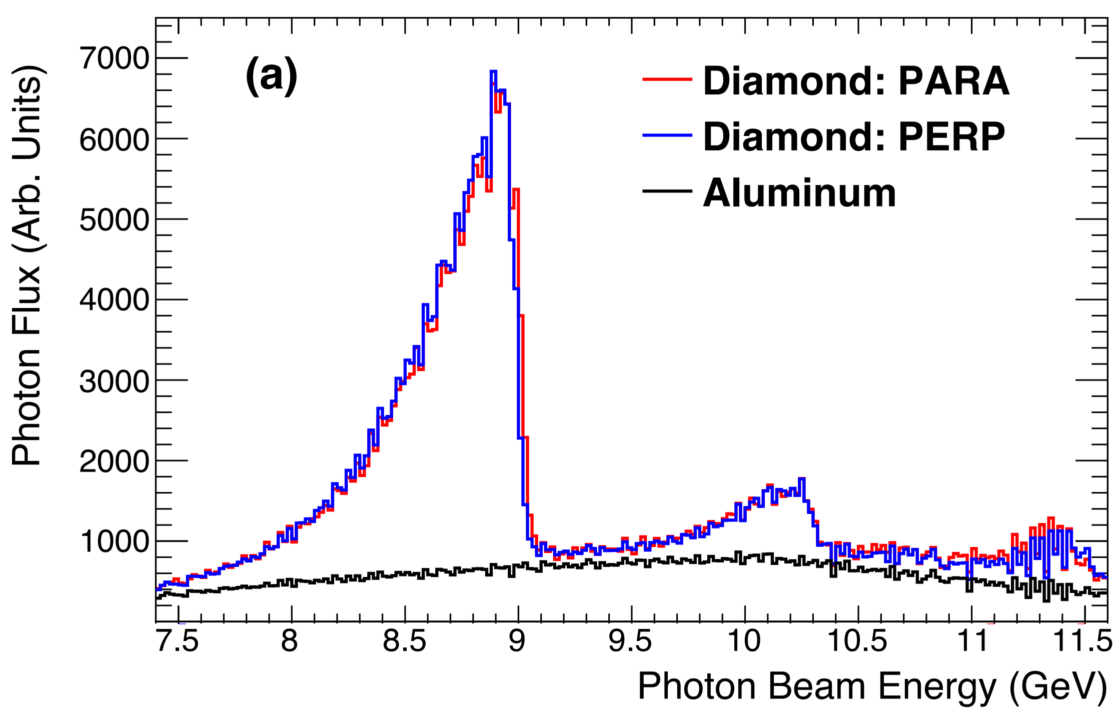
* **Longer term:** proposed K_L beam facility (PAC proposal)



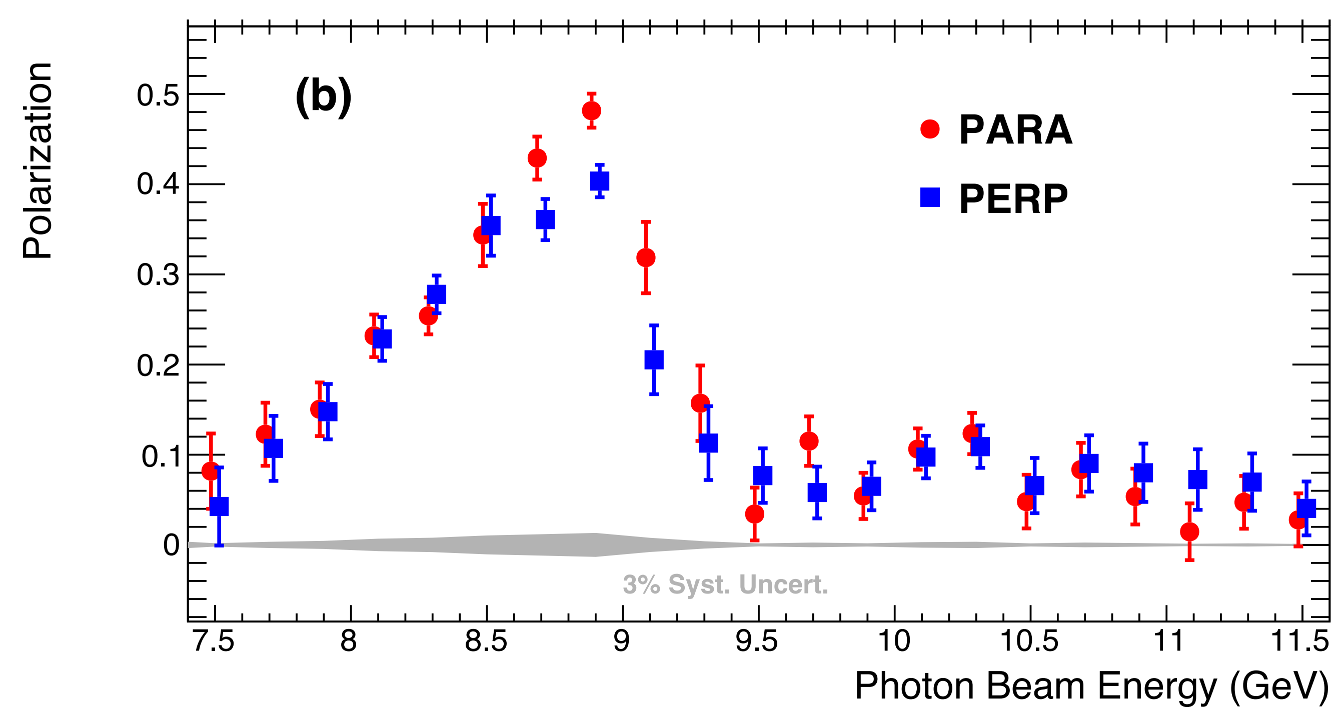
Photon Beam and Tagger



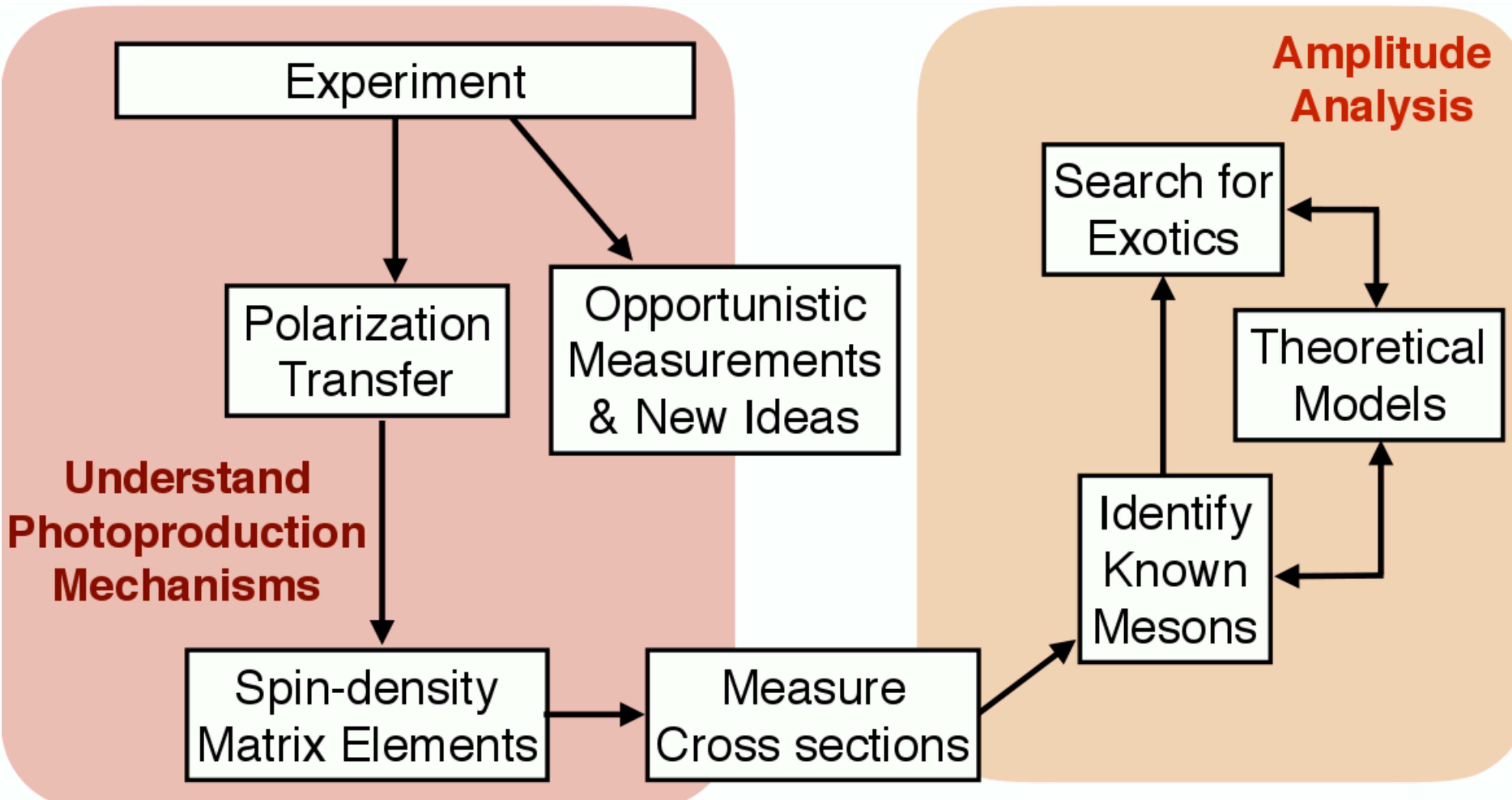
Measured Flux



Measured Polarization



GlueX Physics Program



Exotic J^{PC} in photoproduction

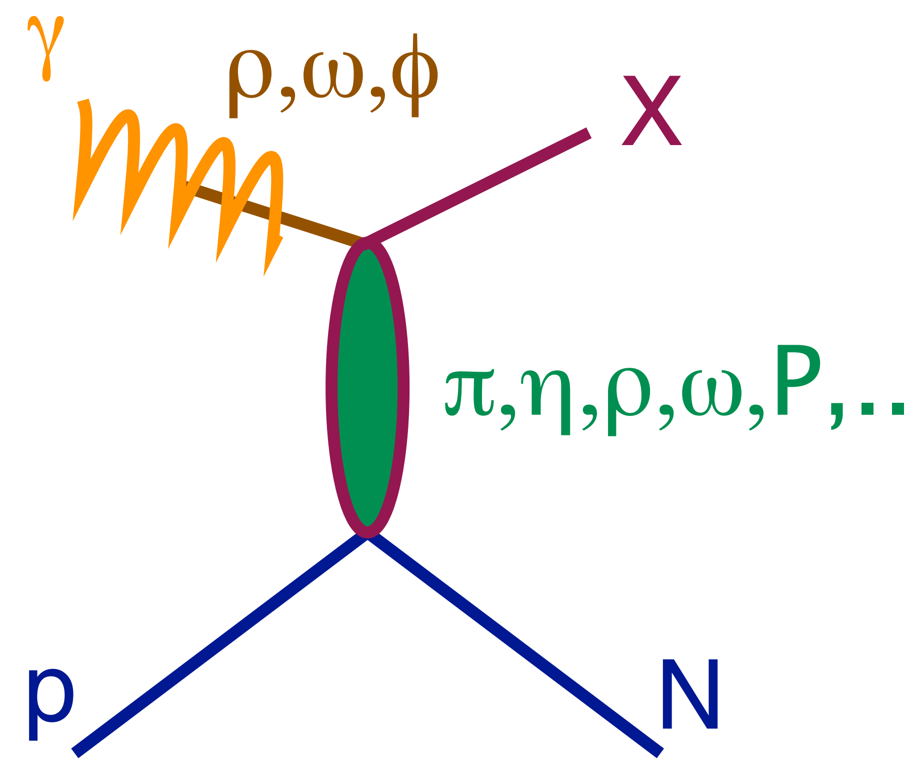
	Approximate Mass (MeV)	J^{PC}
π_1	1900	1^{-+}
η_1	2100	1^{-+}
η_1'	2300	1^{-+}
b_0	2400	0^{+-}
h_0	2400	0^{+-}
h_0'	2500	0^{+-}
b_2	2500	2^{+-}
h_2	2500	2^{+-}
h_2'	2600	2^{+-}

$\rho\pi, \rho\omega \rightarrow \pi_1$
$\omega\omega, \rho\rho \rightarrow \eta_1$
$\omega\omega, \rho\rho, \phi\omega \rightarrow \eta'_1$

$\rho P \rightarrow b_0$
$\omega P \rightarrow h_0$
$\omega P, \phi P \rightarrow h'_0$

$\omega\pi, \rho\eta, \rho P \rightarrow b_2$
$\rho\pi, \omega\eta, \omega P \rightarrow h_2$
$\rho\pi, \omega\eta, \phi P \rightarrow h'_2$

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

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	$b_1\pi,\ \pi\rho,\ \pi f_1,\ \pi\eta,\ \pi\eta',\ \eta a_1,\ \pi\eta(1295)$
η_1	2100	1^{-+}	$59-158$	107	$\pi a_1,\ \boxed{\pi a_2,\ \eta f_1}\ \eta f_2,\ \pi\pi(1300),\ \eta\eta',\ KK_1^A,\ KK_1^B$
η_1'	2300	1^{-+}	$95-216$	172	$KK_1^B,\ \boxed{KK_1^A,\ KK^*}\ \eta\eta'$
b_0	2400	0^{+-}	$247-429$	665	$\pi\pi(1300),\ \pi h_1,\ \rho f_1,\ \eta b_1$
h_0	2400	0^{+-}	$59-262$	94	$\pi b_1,\ \eta h_1,\ KK(1460)$
h_0'	2500	0^{+-}	$259-490$	426	$KK(1460),\ KK_1^A,\ \eta h_1$
b_2	2500	2^{+-}	$5-11$	248	$\pi a_1,\ \pi a_2,\ \pi h_1,\ \eta\rho,\ \eta b_1,\ \rho f_1$
h_2	2500	2^{+-}	$4-12$	166	$\pi\rho,\ \pi b_1,\ \eta\omega,\ \omega b_1$
h_2'	2600	2^{+-}	$5-18$	79	$KK_1^B,\ KK_1^A,\ KK_2^*,\ \eta h_1$

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

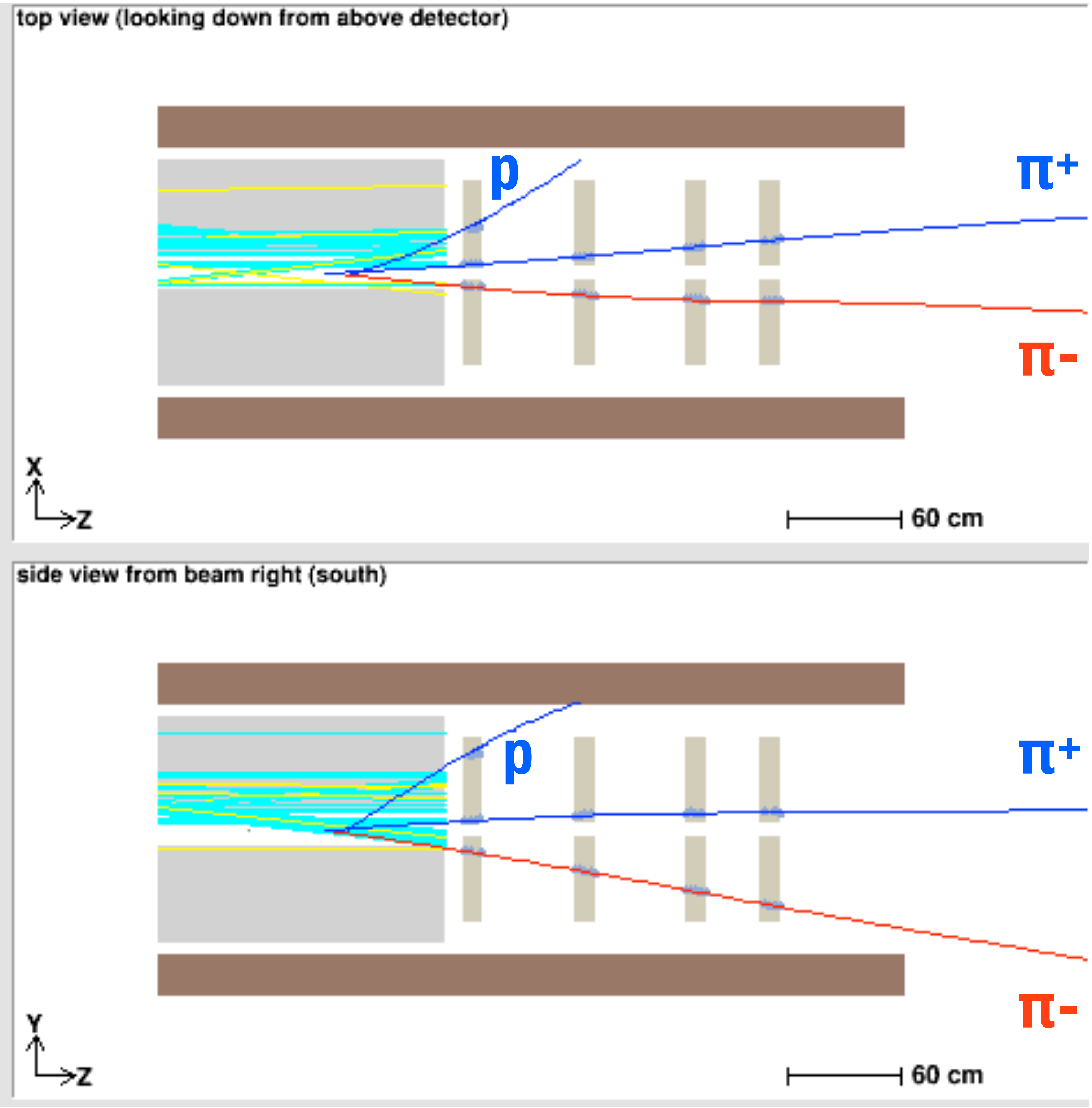
1^{-+} channels observed

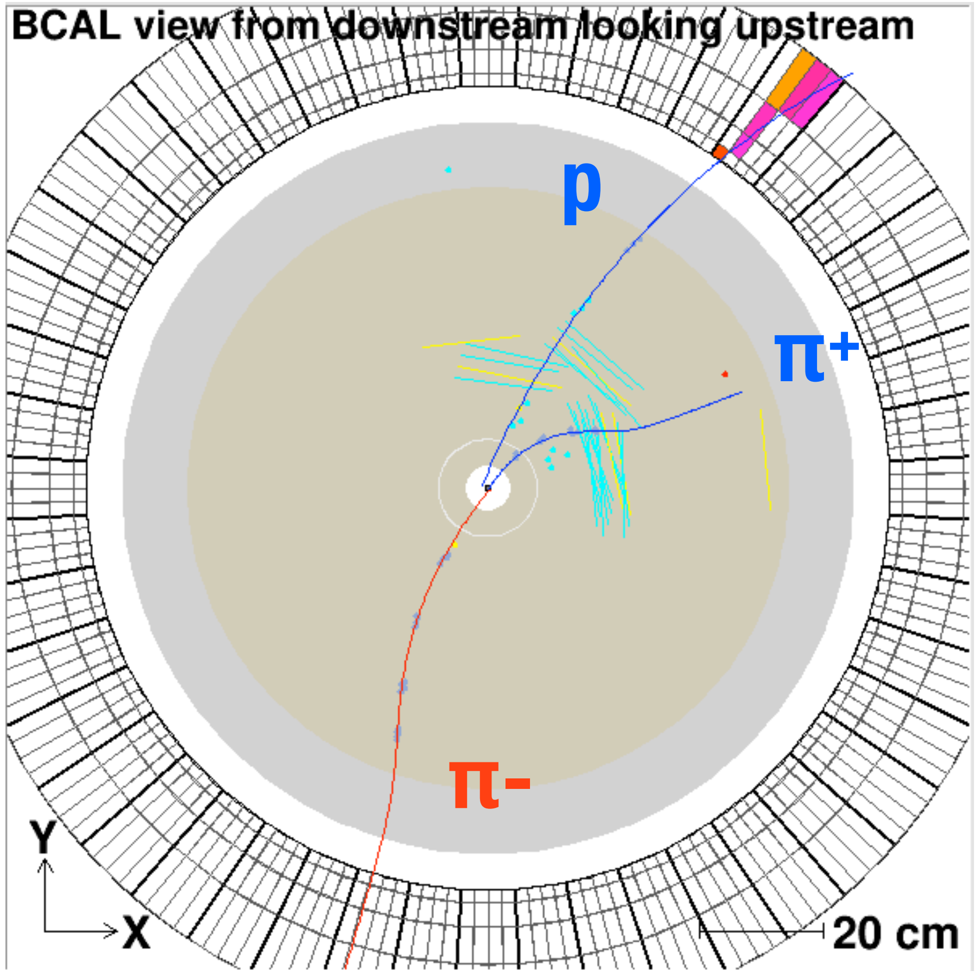
$$\pi\rho \to \pi\pi\pi$$
$$\pi\eta' \to \eta\pi\pi\pi$$
$$\pi b_1 \to \omega\pi\pi$$

Some additional 1^{-+} channels

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

“Typical” $\gamma p \to \pi^+\pi^- p$ event



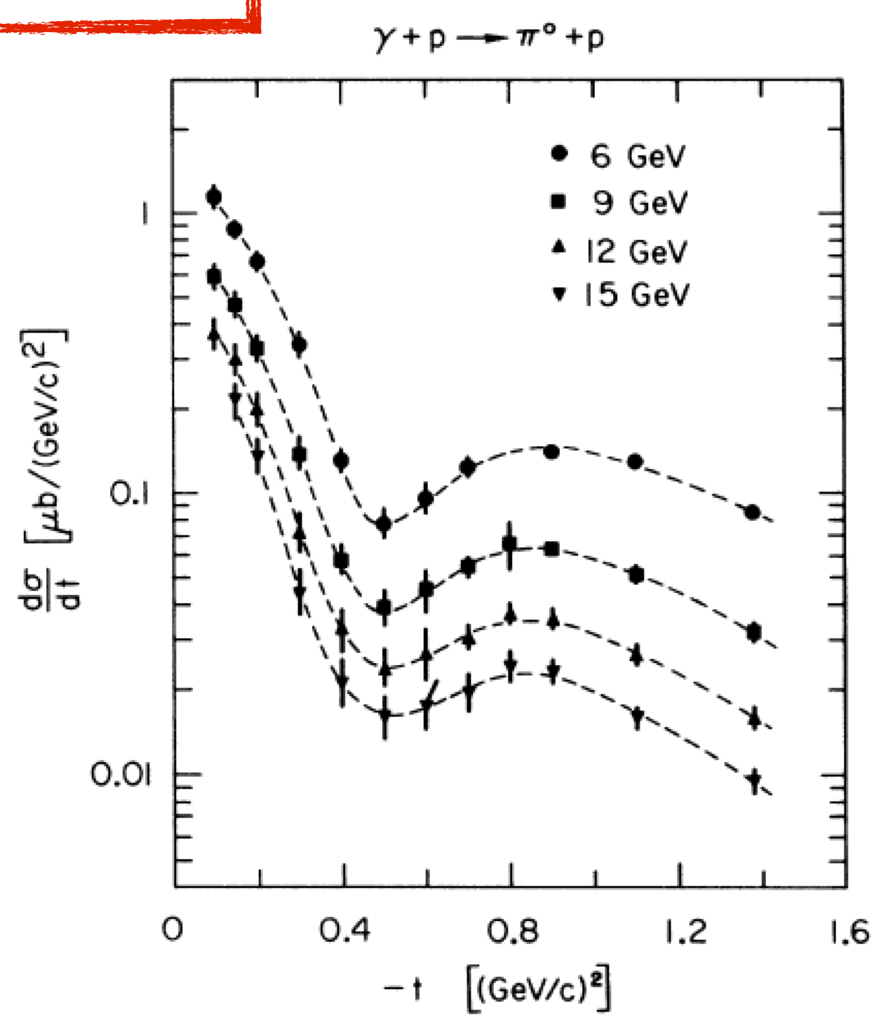


Early GlueX physics: $\gamma p \to \pi^0 p$

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)

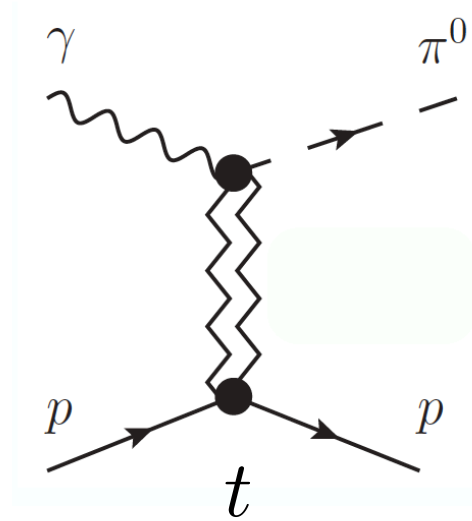
1 October 1971



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)

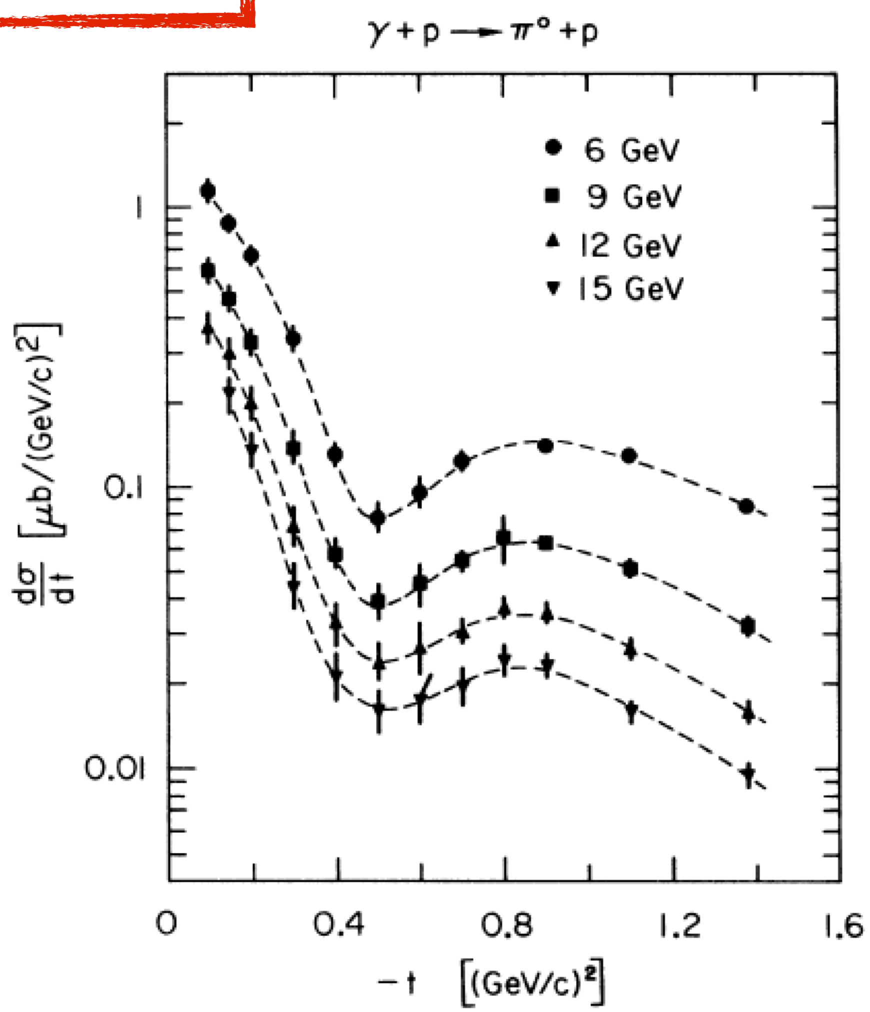


Exchange J^{PC}

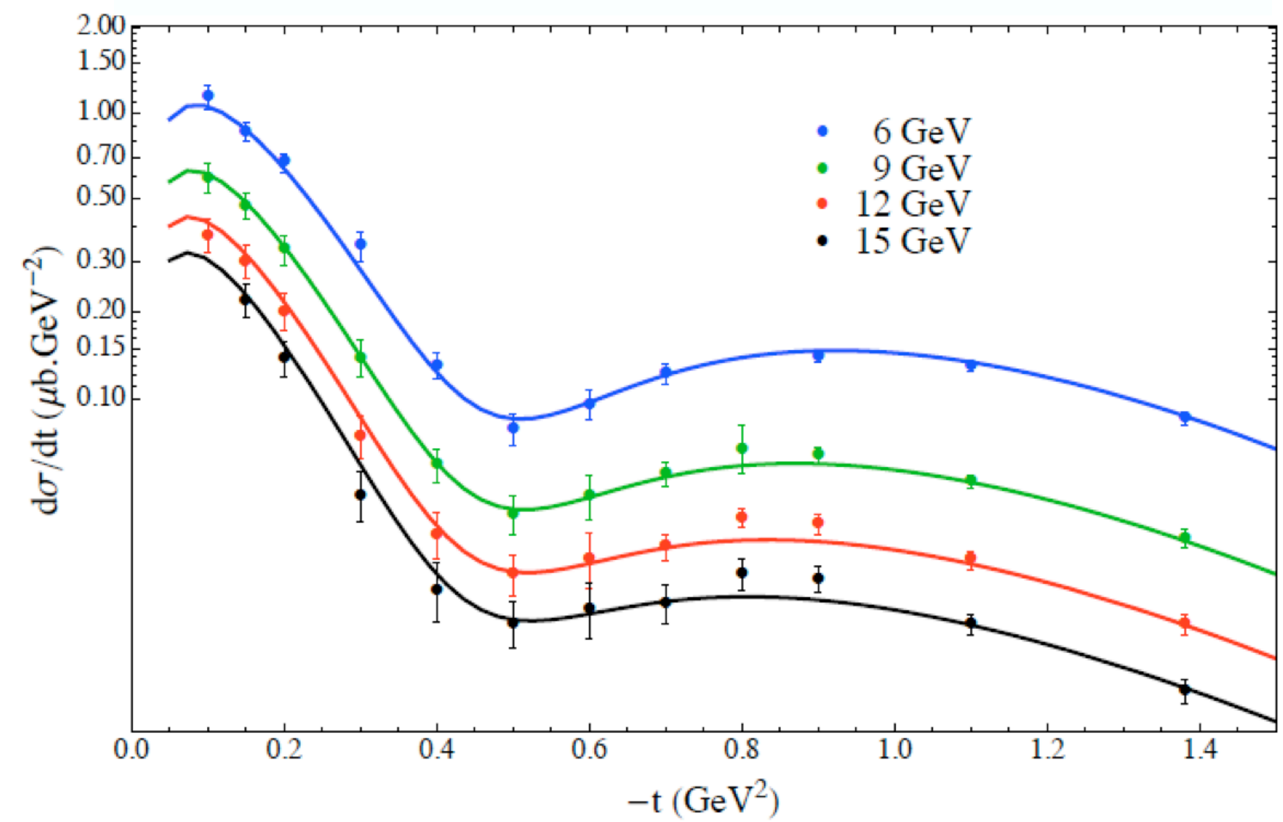
1^{--} : ω, ρ

1^{+-} : b, h

1 October 1971



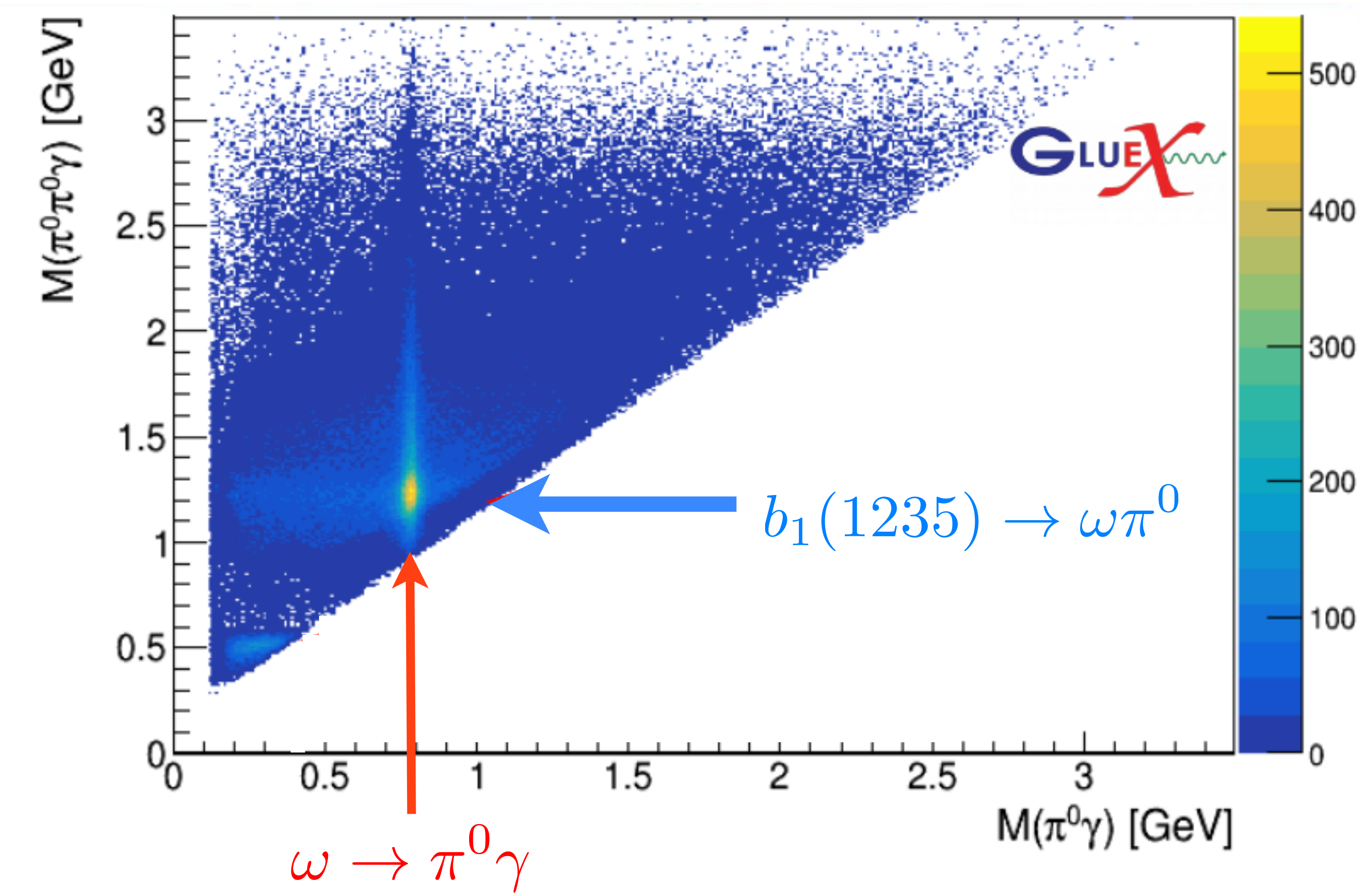
$$\frac{d\sigma}{dt} = \sigma_\perp + \sigma_\parallel = |\rho + \omega|^2 + |b + h|^2$$



JPAC: Mathieu et al. PRD 92, 074013

Early spectroscopy opportunities

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

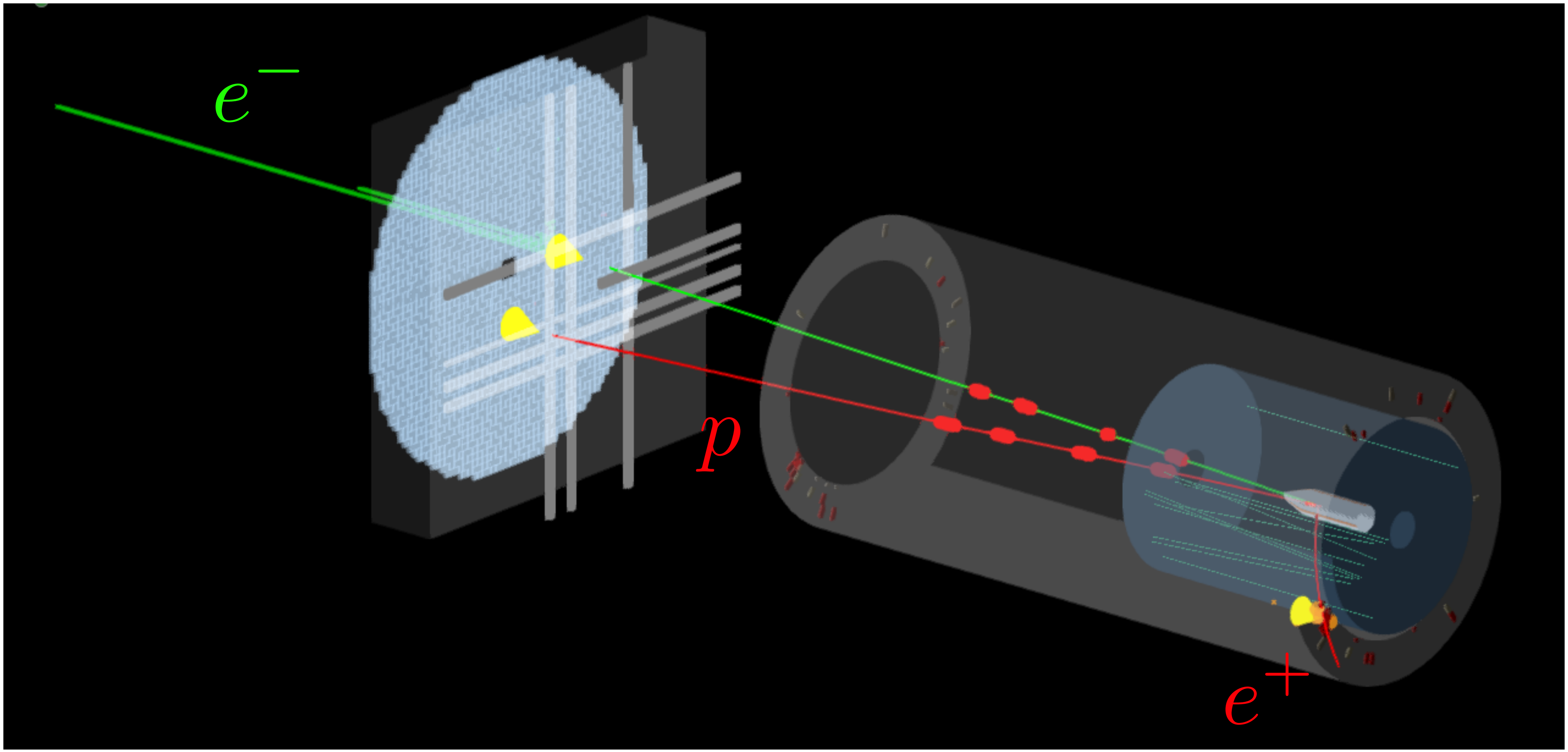


$$\gamma p \to b_1 p, b_1 \to \omega\pi^0, \omega \to \pi^0\gamma$$

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

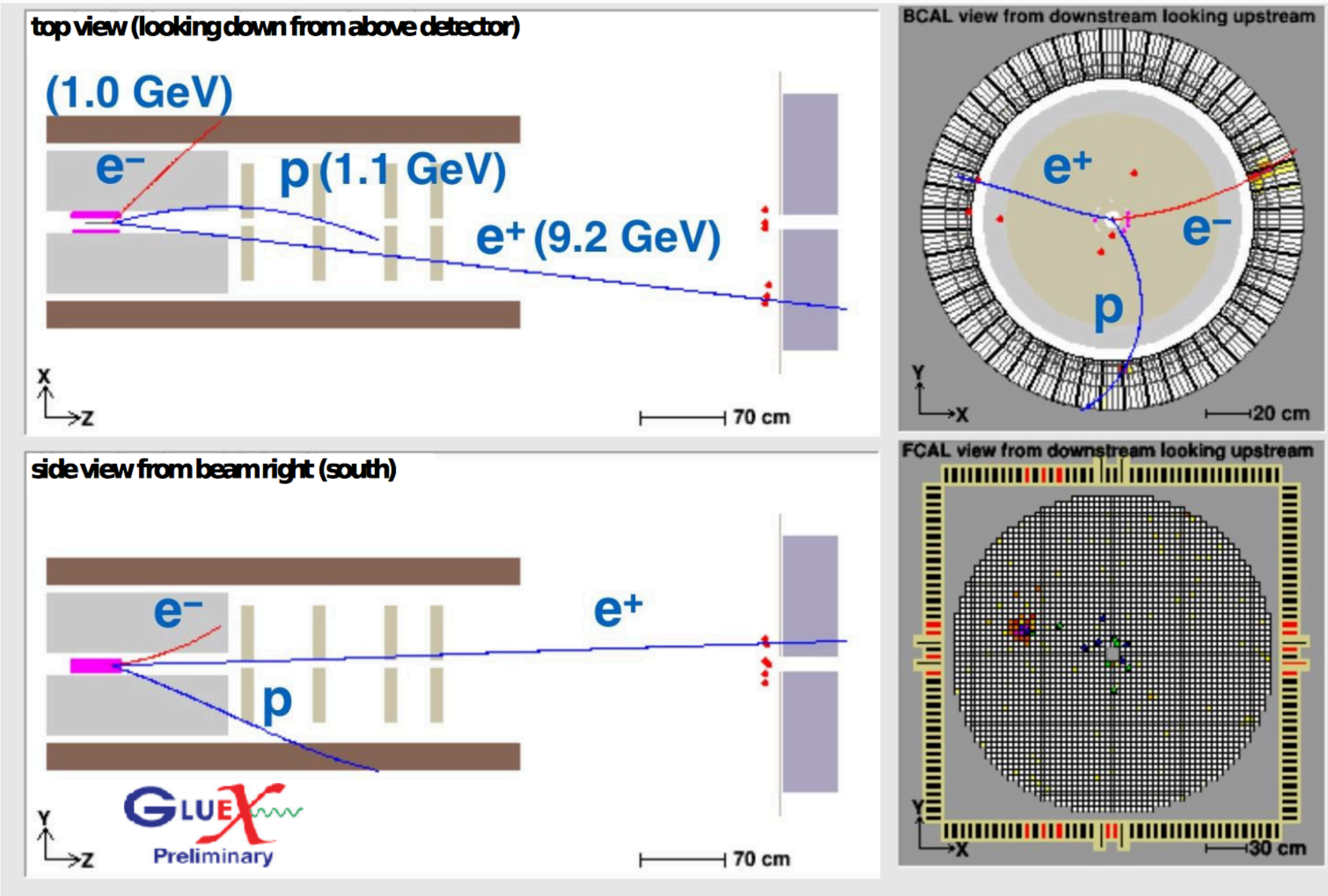
Observation of charm at GlueX

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

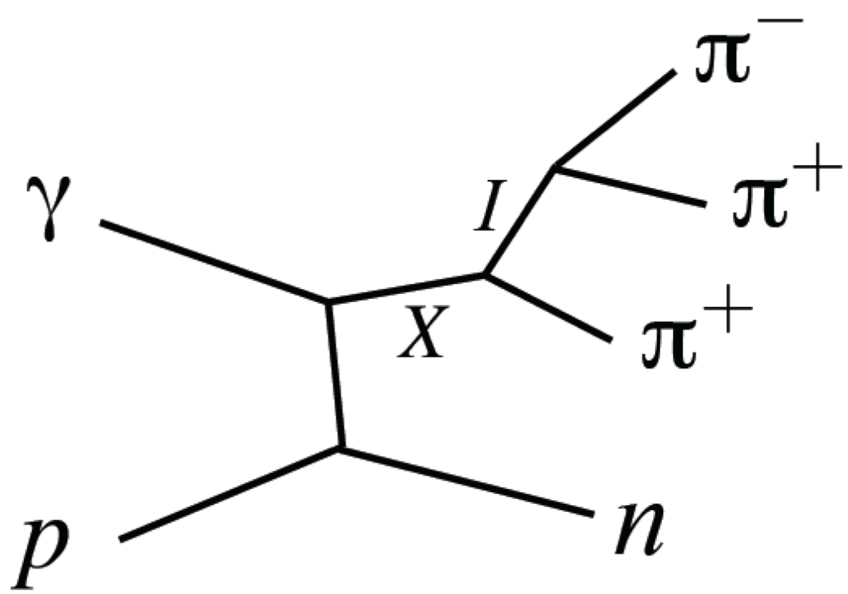


Observation of charm at GlueX

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



Amplitude Analysis



- **Goal:** Identify J^PC of $X \to \pi^+\pi^-\pi^+$
- Model the intensity of events at the level of QM amplitudes (allow for interference)

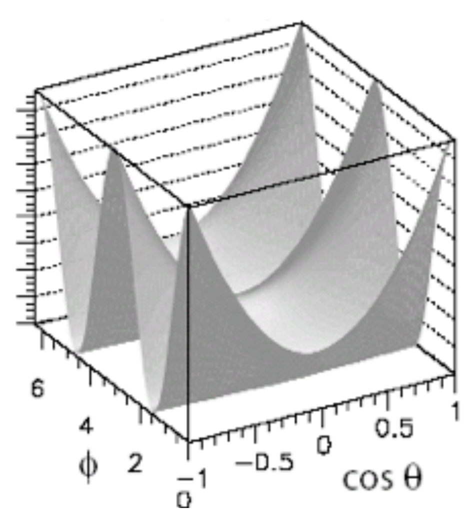
$$I(\vec{x}) = \frac{dN}{d\vec{x}} = \left| \sum_{\alpha}^{N_{\rm amps}} V_\alpha A_\alpha(\vec{x}) \right|^2$$

- 5-dimensional problem: two new angles at each decay step (X and I)

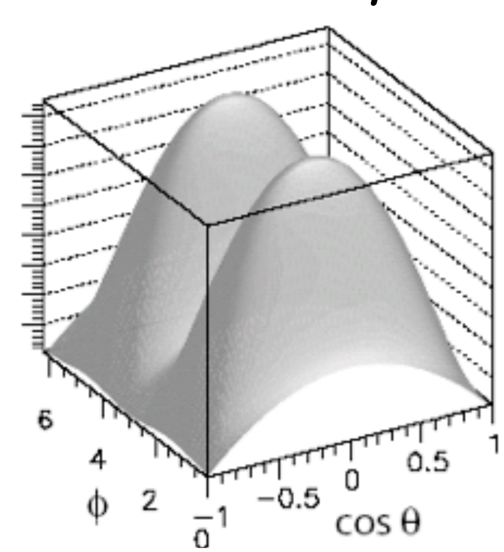
Example Intensity:

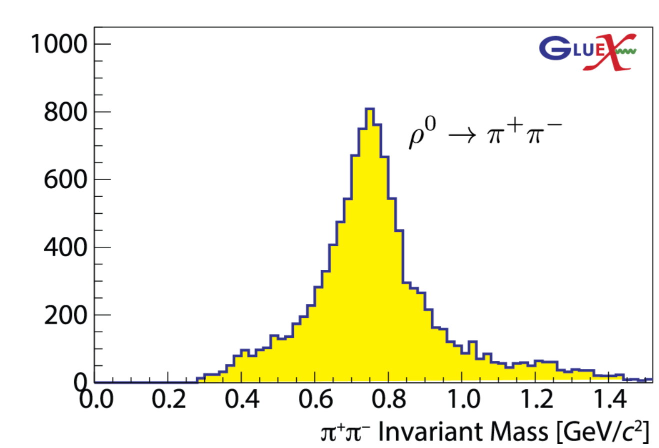
$$X(1^{++}) \to \rho\pi^+ \text{ (S wave)}$$

$X \to \rho\pi^+$



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





Amplitude Analysis

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

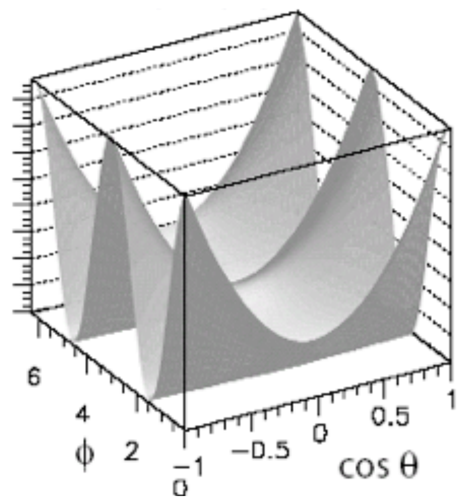
- Expand set of possible amplitudes over many $\boldsymbol{X}$ and $\boldsymbol{I}$, and determine $\boldsymbol{V_\alpha}$ via maximum likelihood fit
- Good angular acceptance critical for disentangling J^{PC}

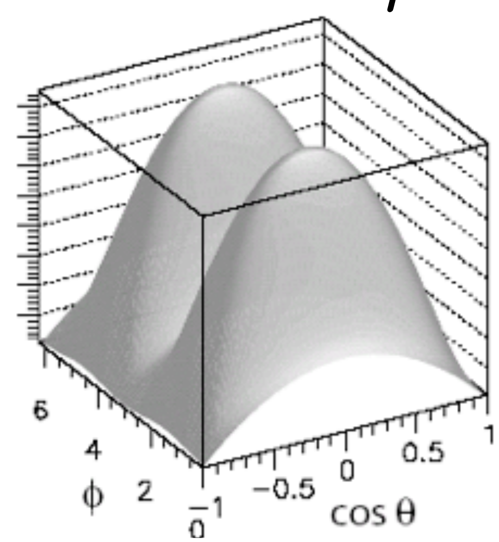
$X \to \rho\pi^+$

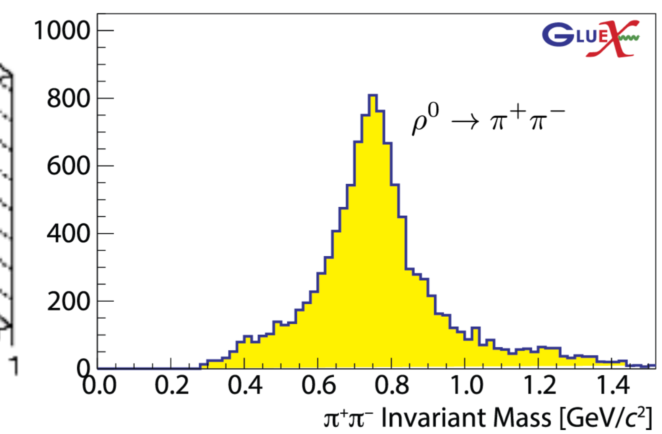
$\rho \to \pi^+\pi^-$

Example Intensities:

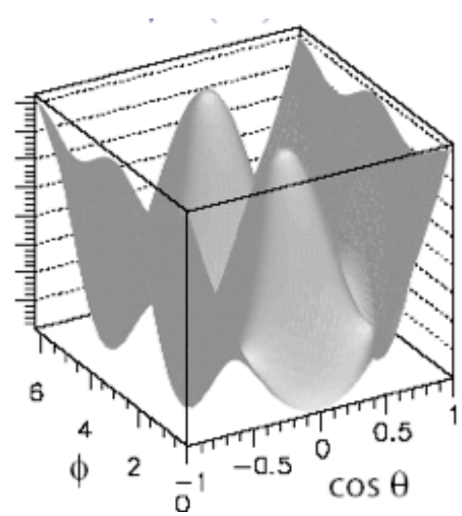
$X(1^{++}) \to \rho\pi^+$ (S wave)

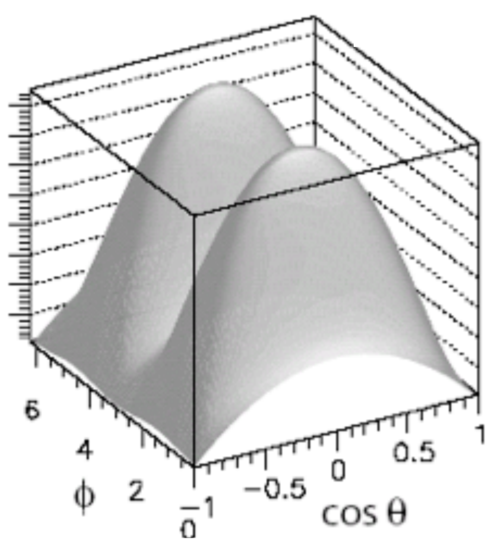


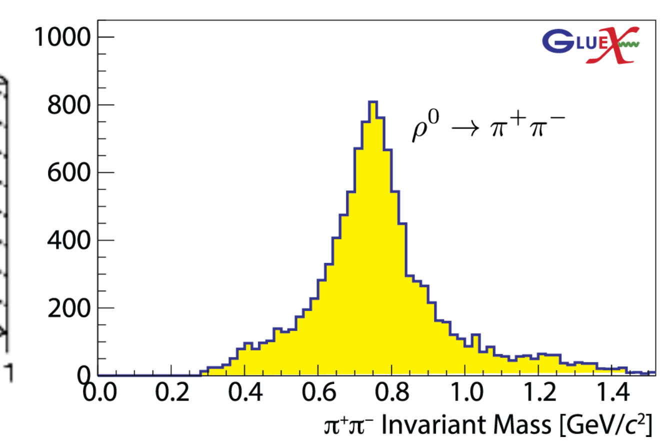




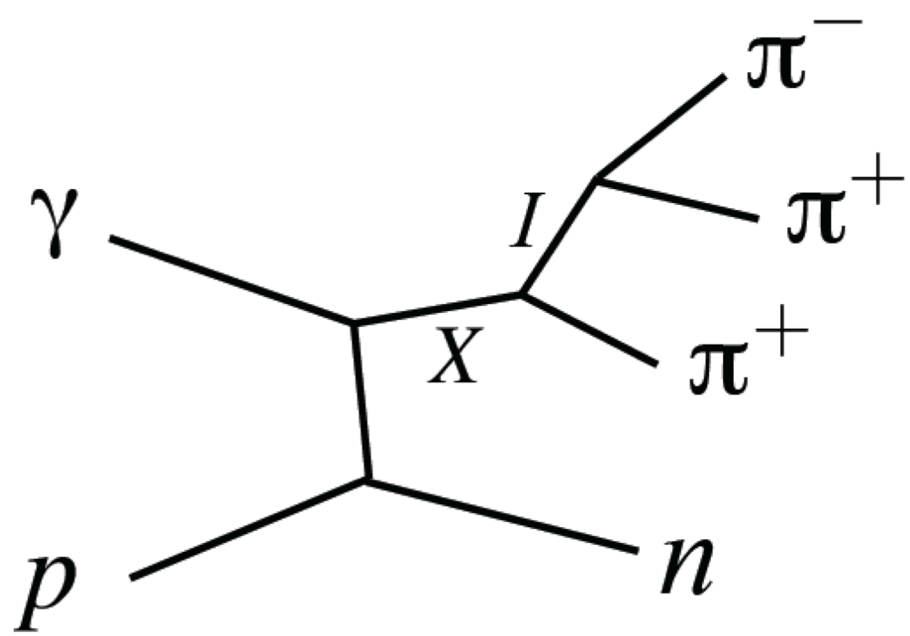
$X(2^{++}) \to \rho\pi^+$ (D wave)

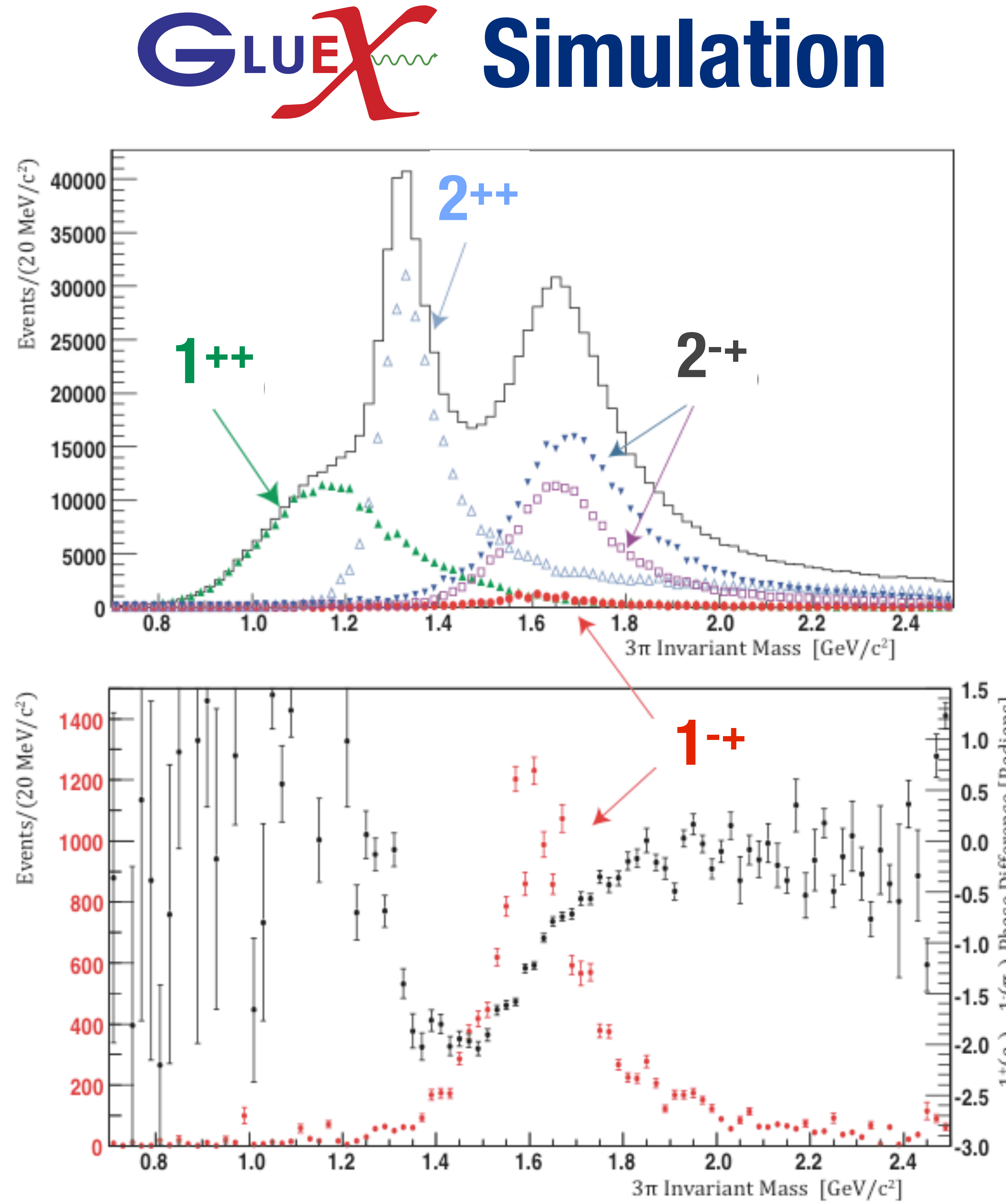






Amplitude Analysis

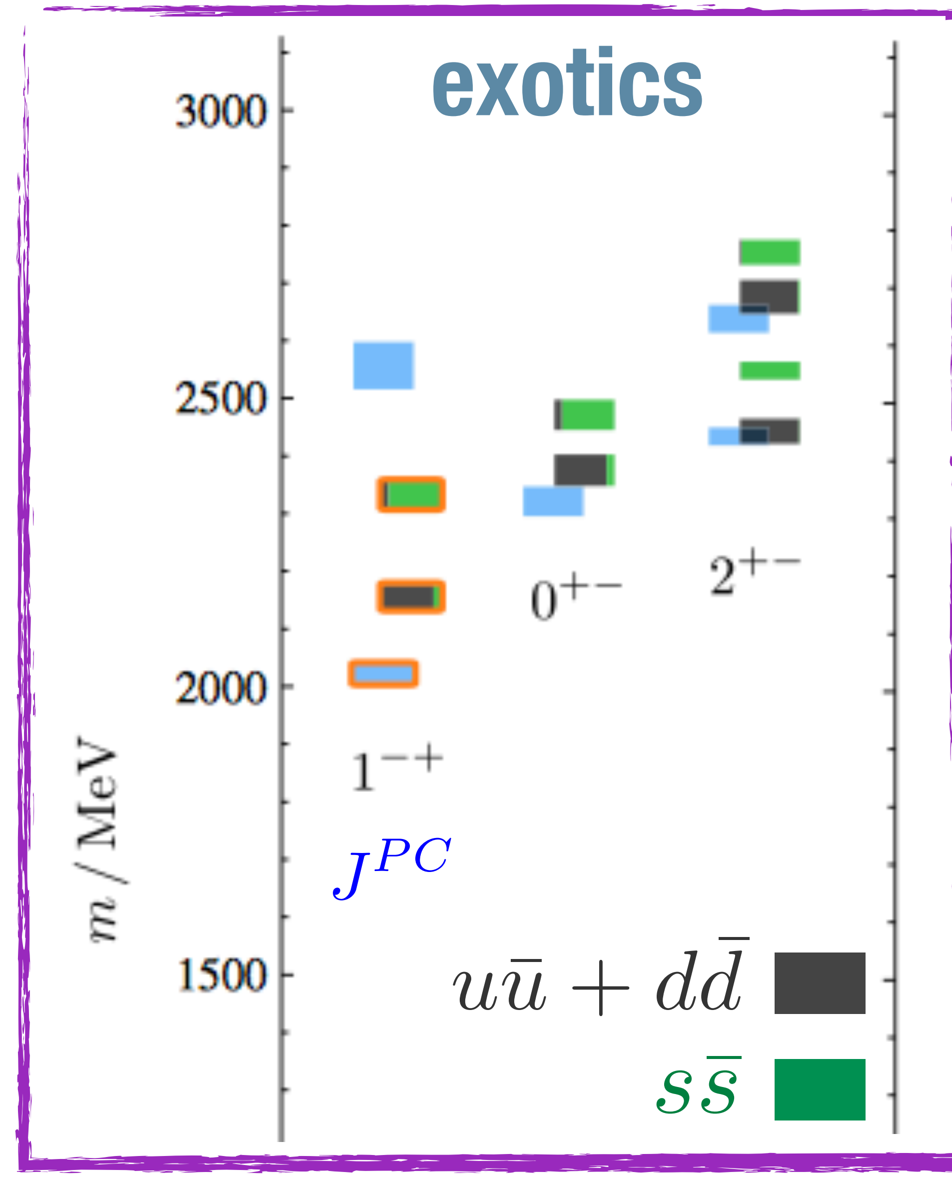




- **Simulate** production of known resonances and **exotic hybrid (1-+) signal** with 1.6% relative strength
- Yields correspond to **~3.5 hours** of GlueX data taking (at full intensity)

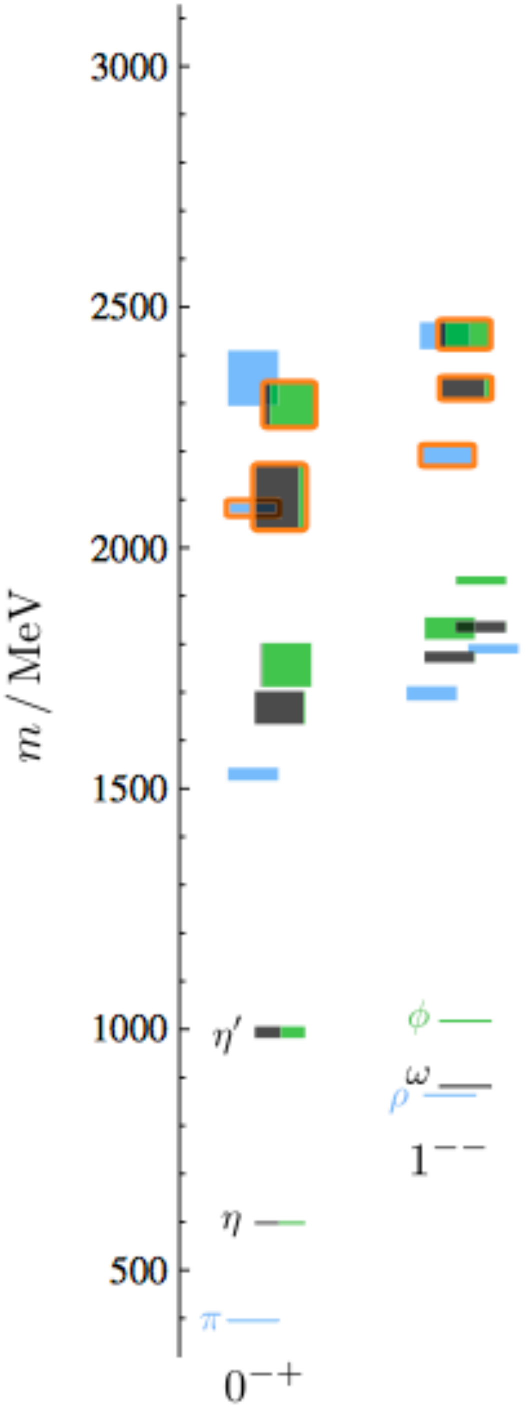
Strangeness program

	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^{-+}	$\boxed{\pi a_1, \pi a_2, \eta f_1, \eta f_2}$ $\pi\pi(1300)$, $\eta\eta'$, KK_1^A, KK_1^B
η'_1	1^{-+}	$\boxed{KK_1^B, KK_1^A, KK^*}$ $\eta\eta'$
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

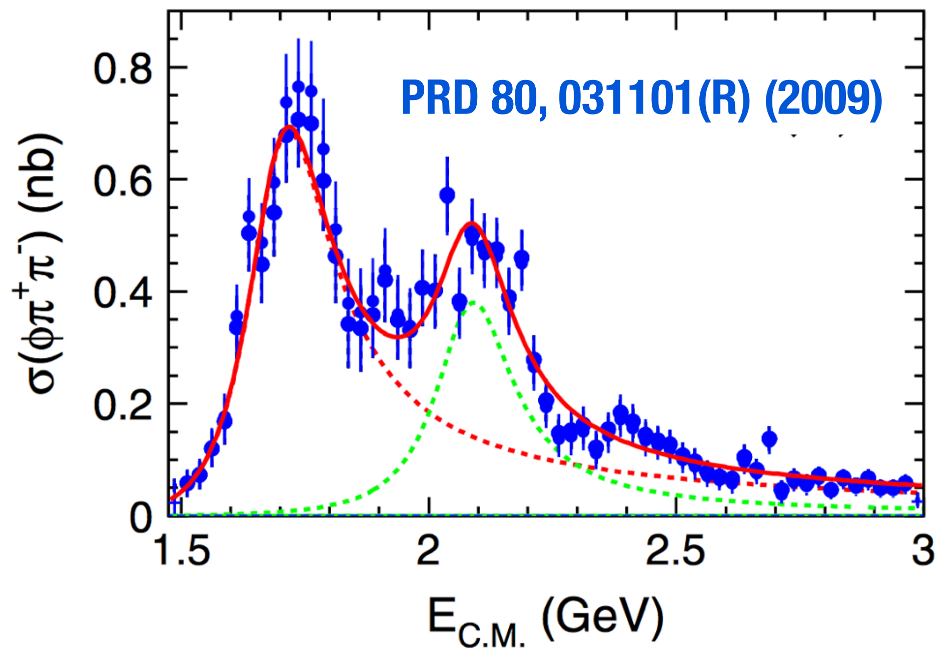


- Mapping the hybrid spectrum requires: large statistics samples of many particle final states in **strange** and **non-strange** decay modes
- Experimentally access to strangeness content of the state by comparing strange vs non-strange decay modes

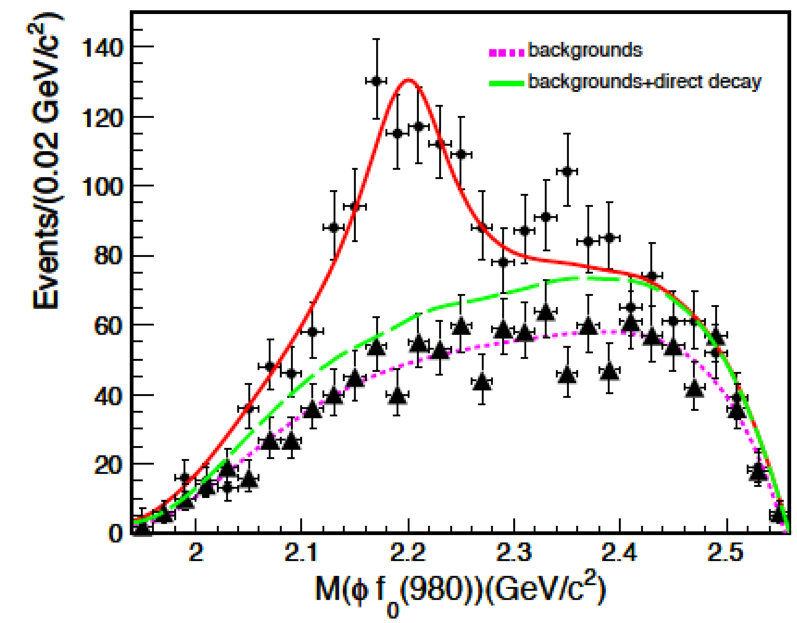
Strangeness program: Y(2175)



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



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



PRD 91, 052017 (2015)

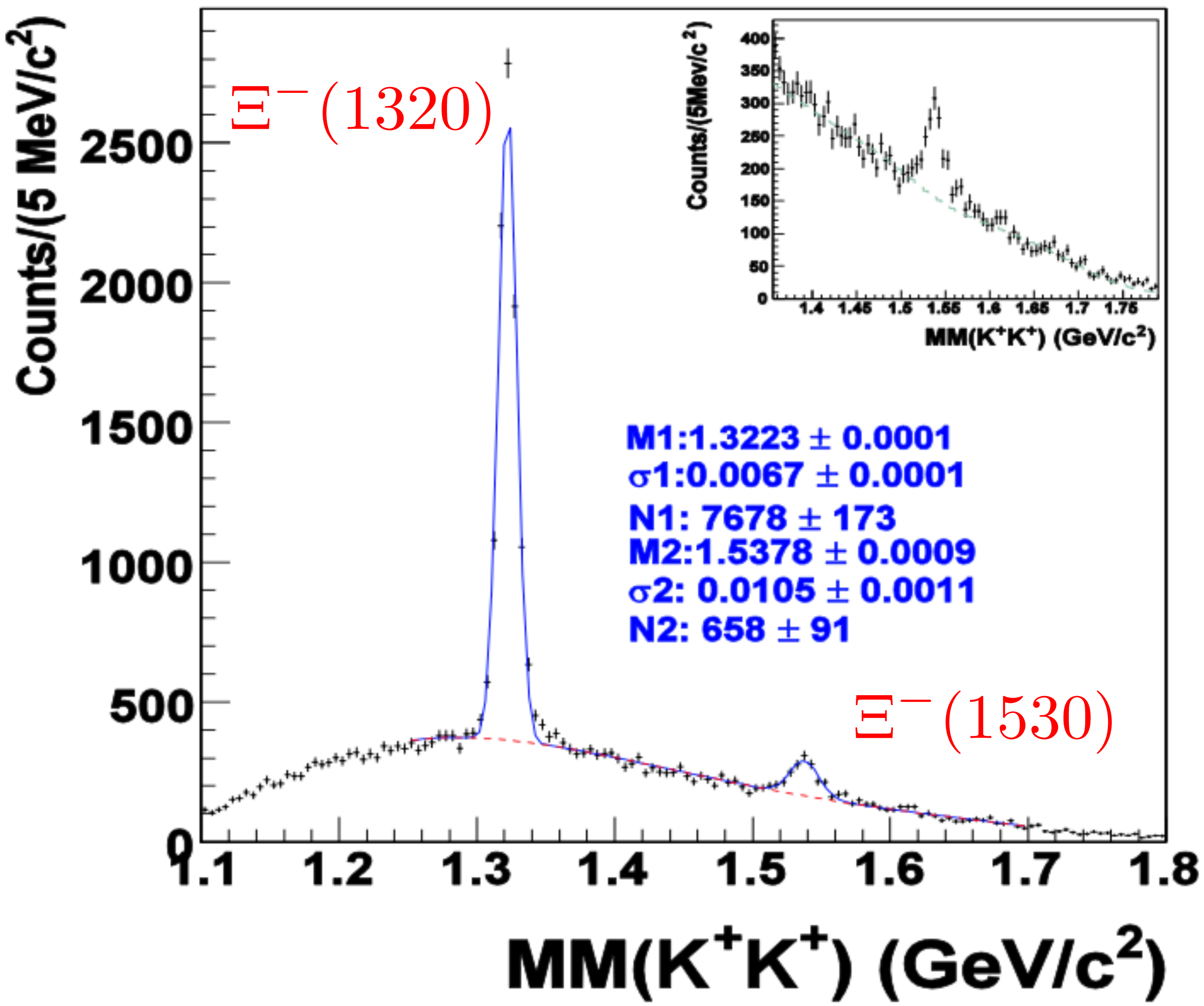
- Y(2175) $J^{PC}=1^{--}$ state observed by 3 experiments
- Decay pattern similar to Y(4260) in charmonium

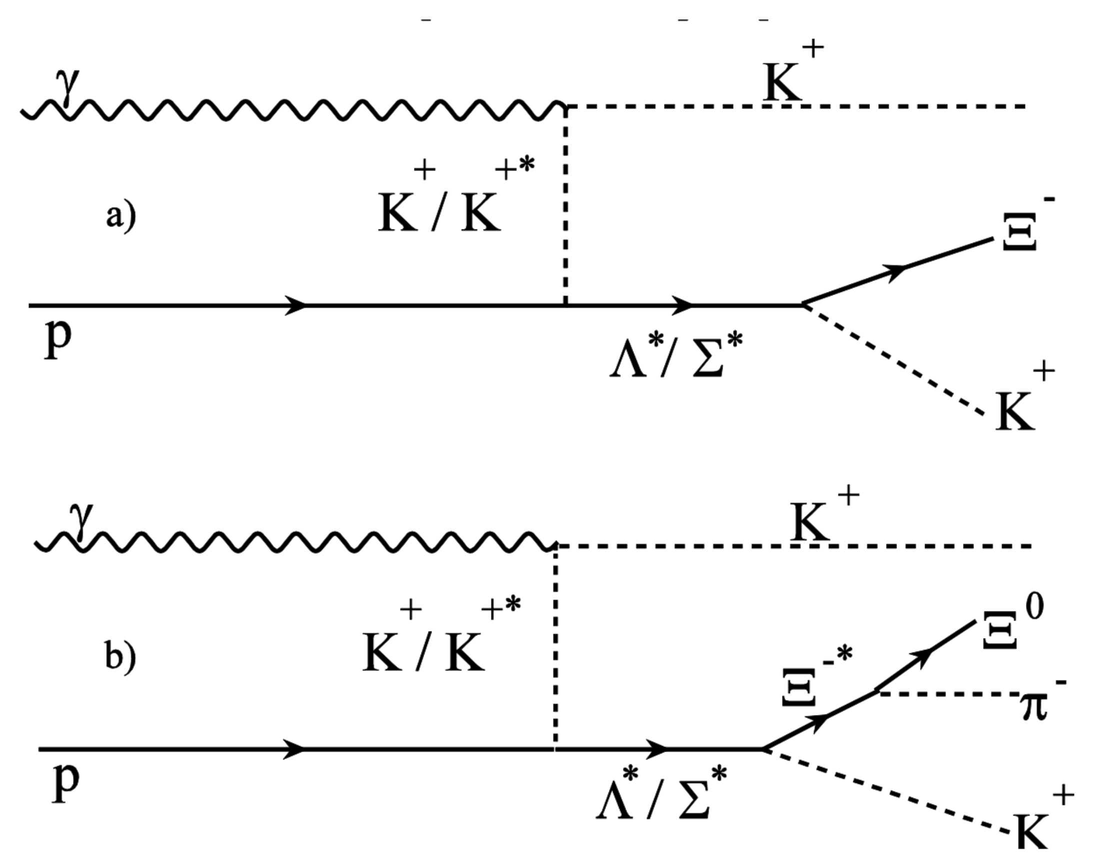
$$Y(2175) \to \phi\pi^+\pi^- \qquad Y(4260) \to J/\psi\pi^+\pi^-$$

- Is there evidence for such strangeonium states in photoproduction?

Hyperon Spectroscopy: $\Xi^-(dss)$

6 GeV

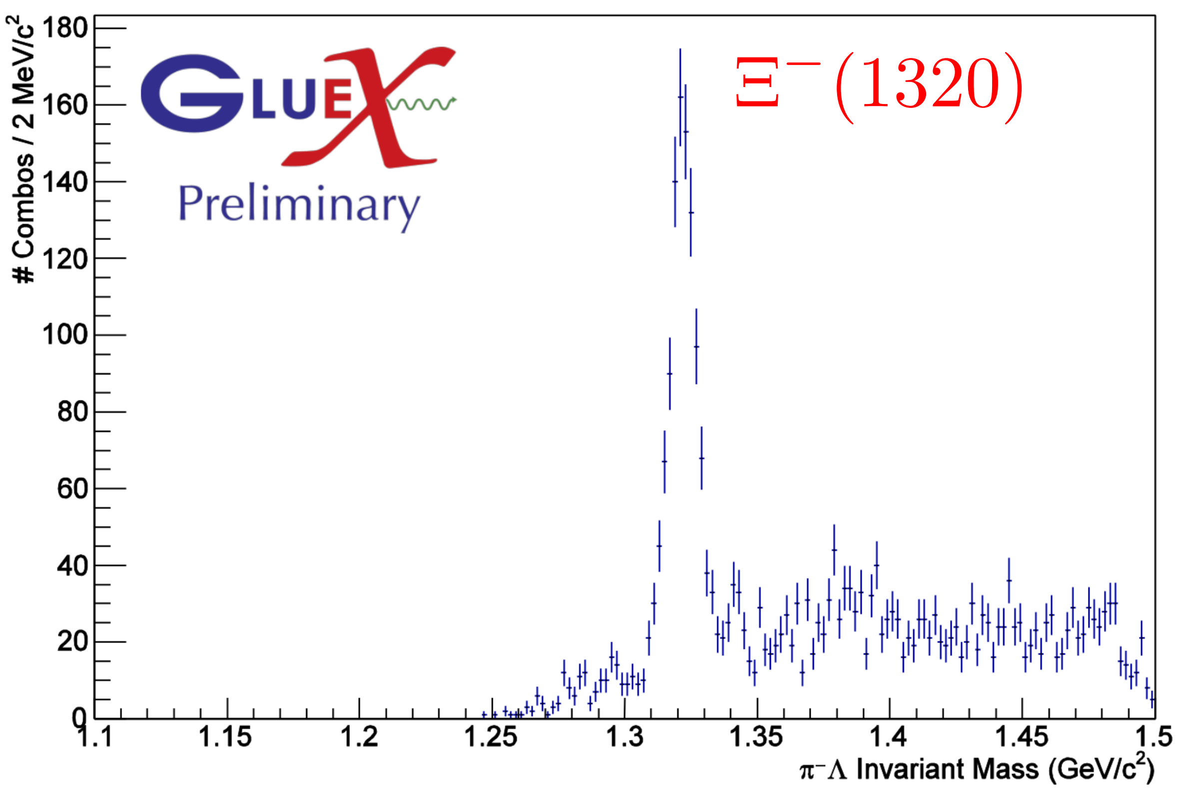




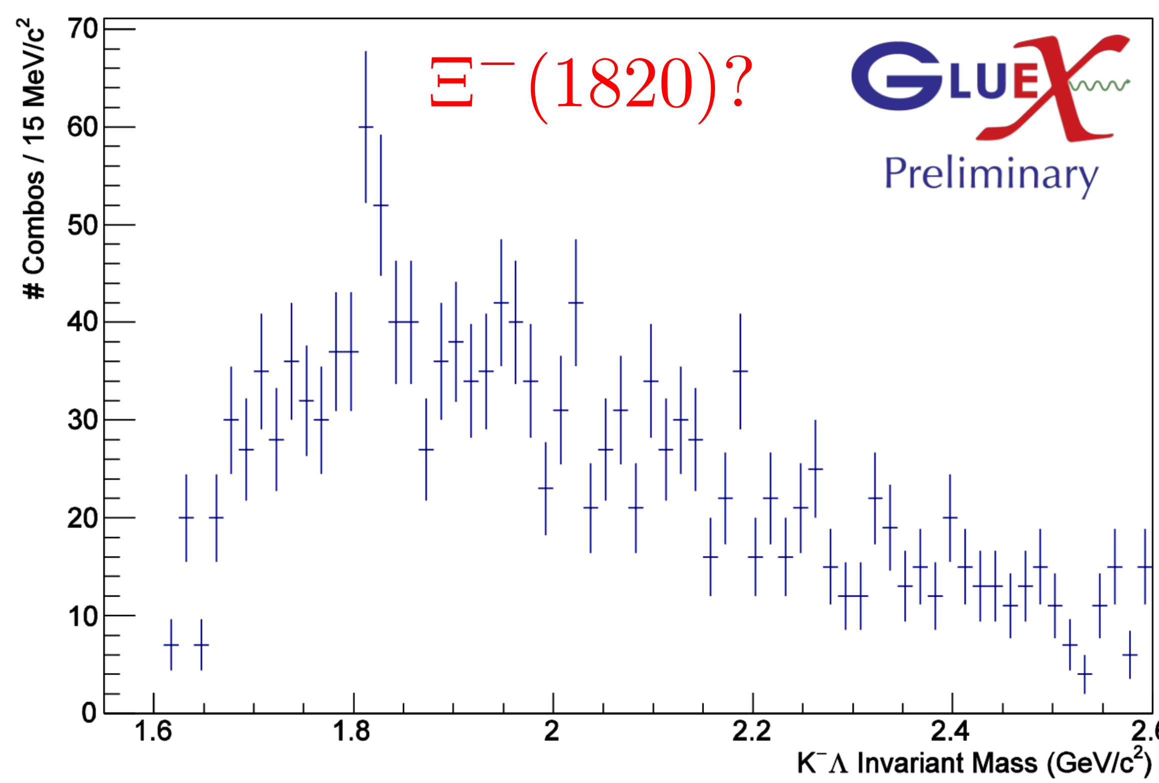
Hyperon Spectroscopy: $\Xi^-(dss)$

NEW!

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



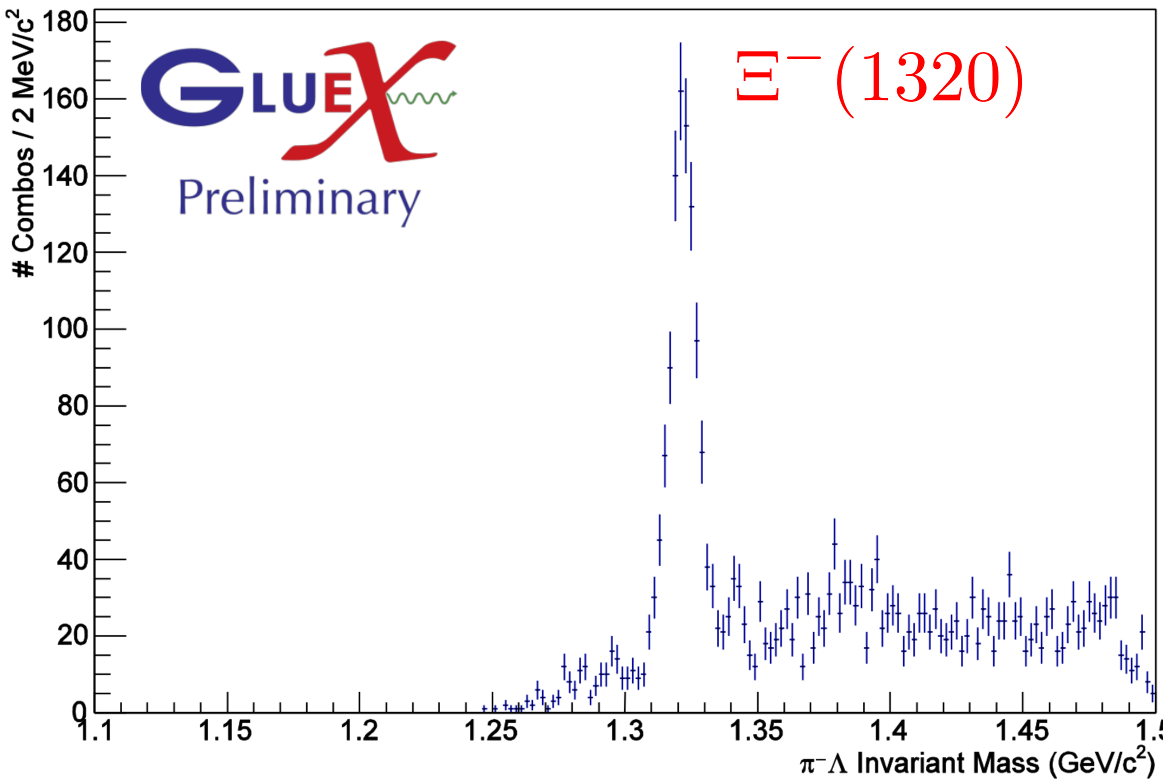
$\gamma p \to K^+K^+\Lambda K^-$



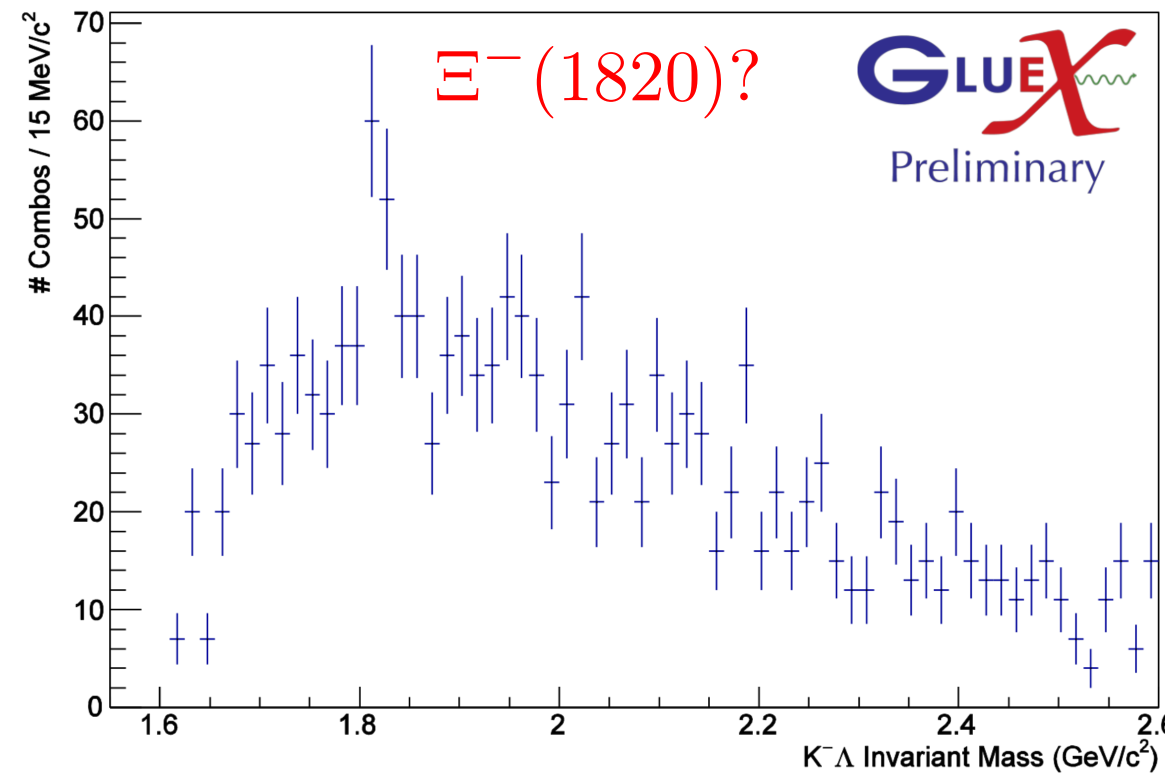
Hyperon Spectroscopy: $\Xi^-(dss)$

NEW!

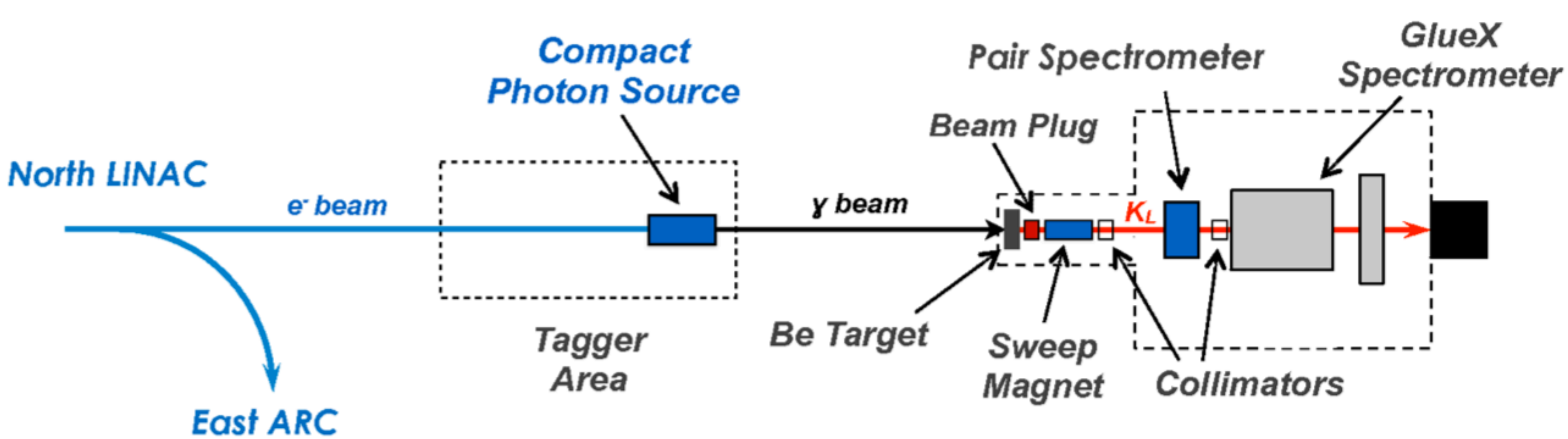
$\gamma p \to K^+ K^+ \Lambda \pi^-$



$\gamma p \to K^+ K^+ \Lambda K^-$

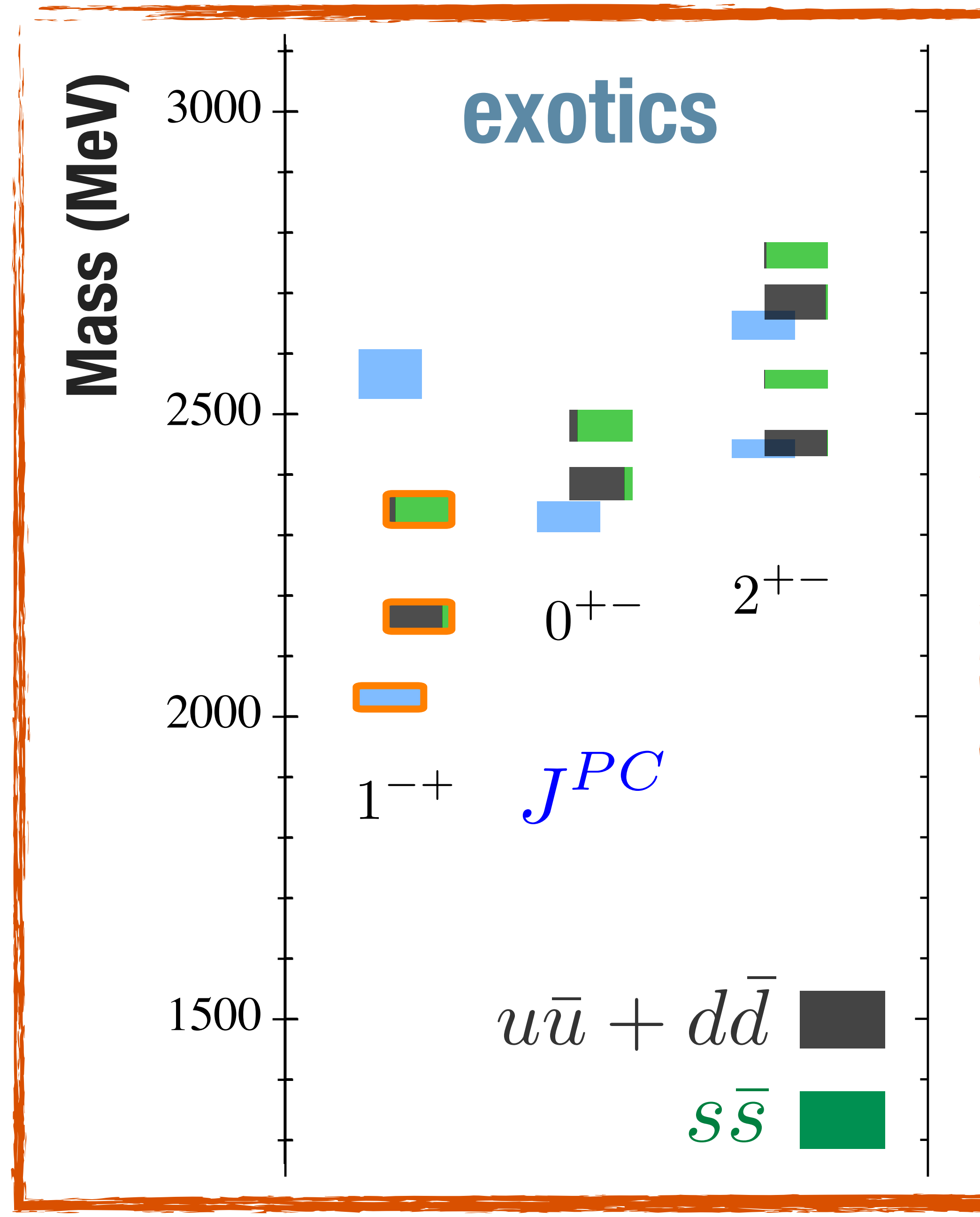


- **Longer term:** K_L beam facility (PAC proposal)



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



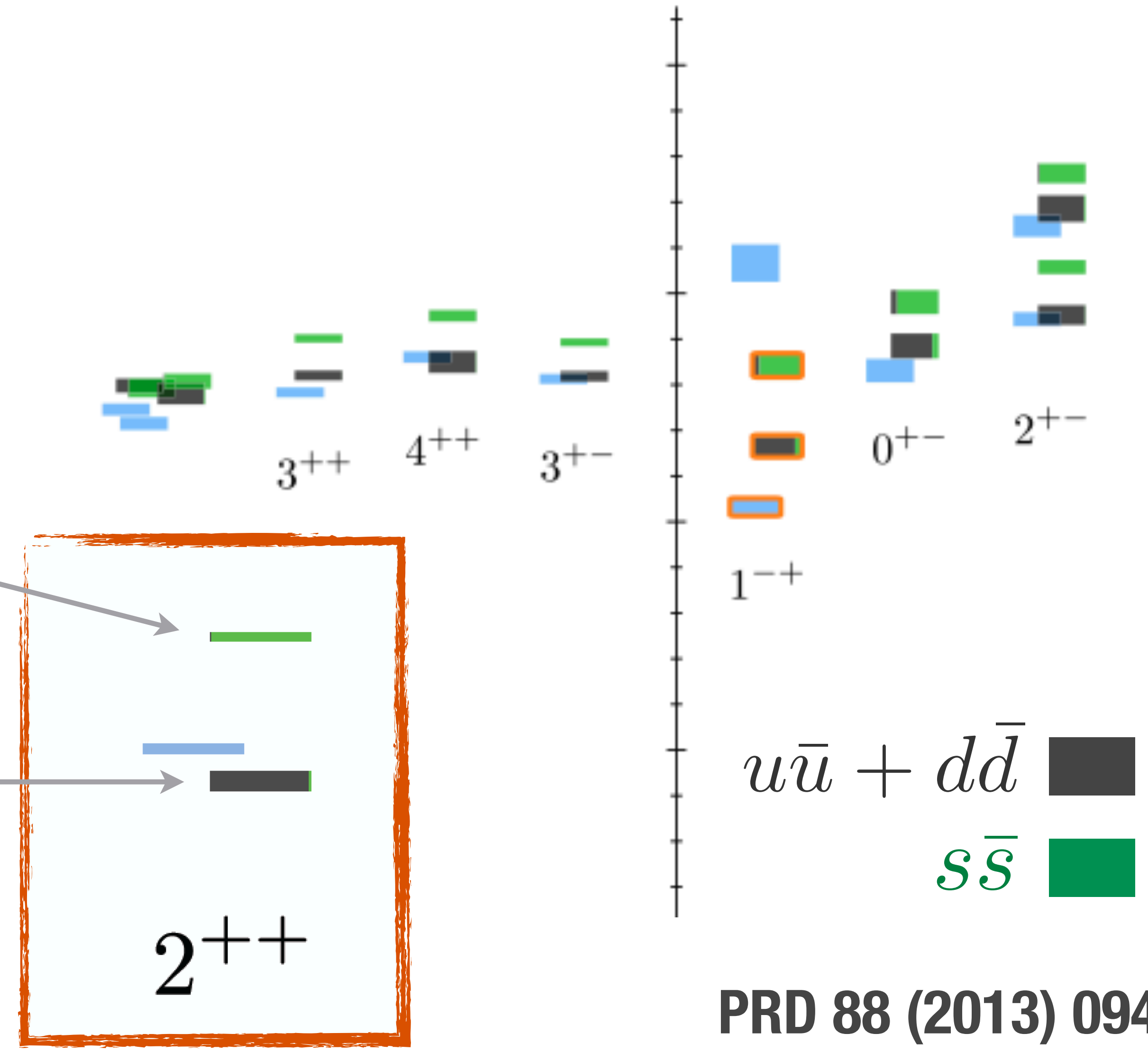
	Approximate Mass (MeV)	J^{PC}	Final States
π_1	1900	1^{-+}	$\omega\pi\pi^{\dagger}$, $3\pi^{\dagger}$, 5π, $\eta 3\pi^{\dagger}$, $\eta'\pi^{\dagger}$
η_1	2100	1^{-+}	4π, $\eta 4\pi$, $\eta\eta\pi\pi^{\dagger}$
η'_1	2300	1^{-+}	$KK\pi\pi^{\dagger}$, $KK\pi^{\dagger}$, $KK\omega^{\dagger}$

Strangeness program: decay patterns

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

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

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

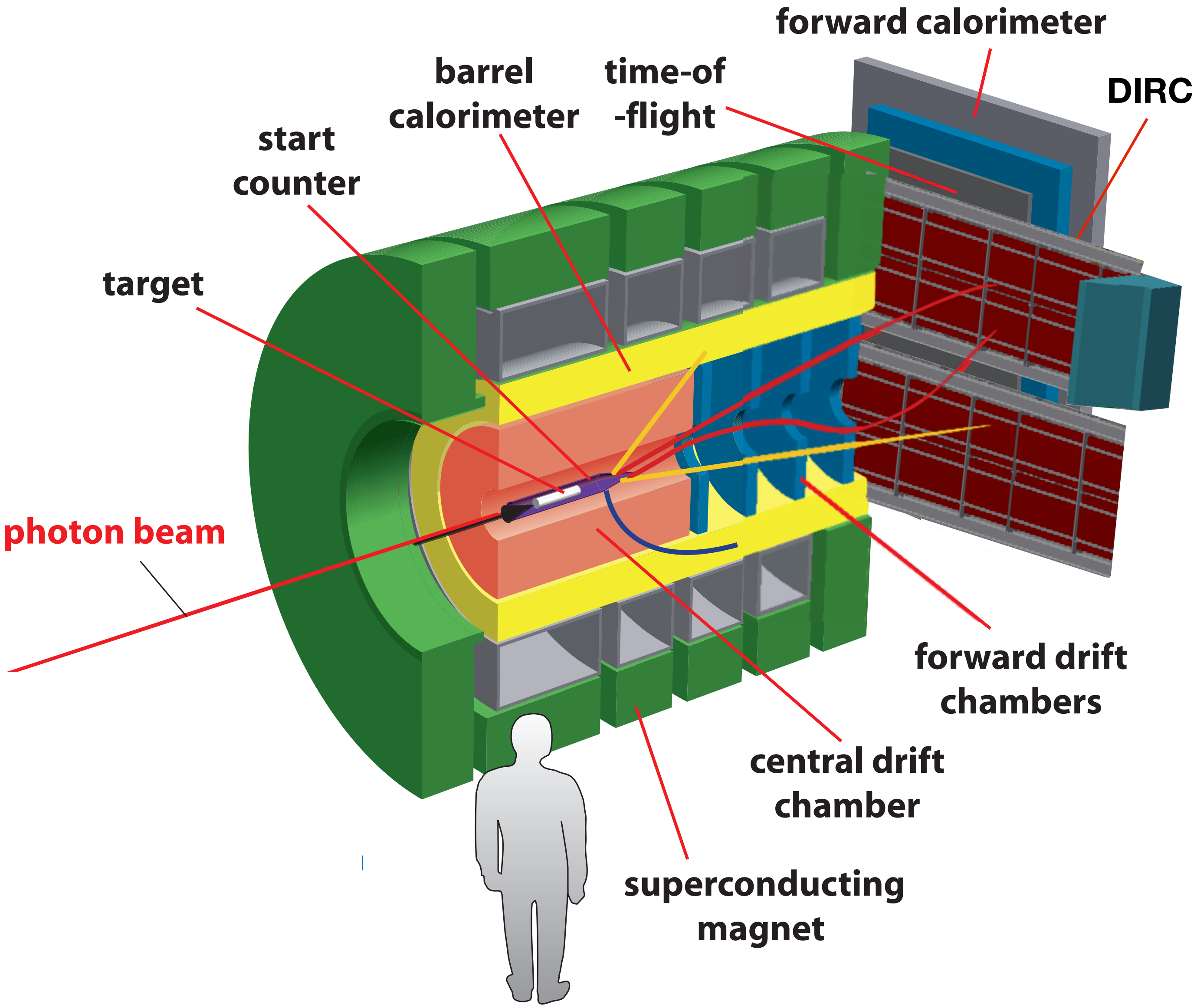


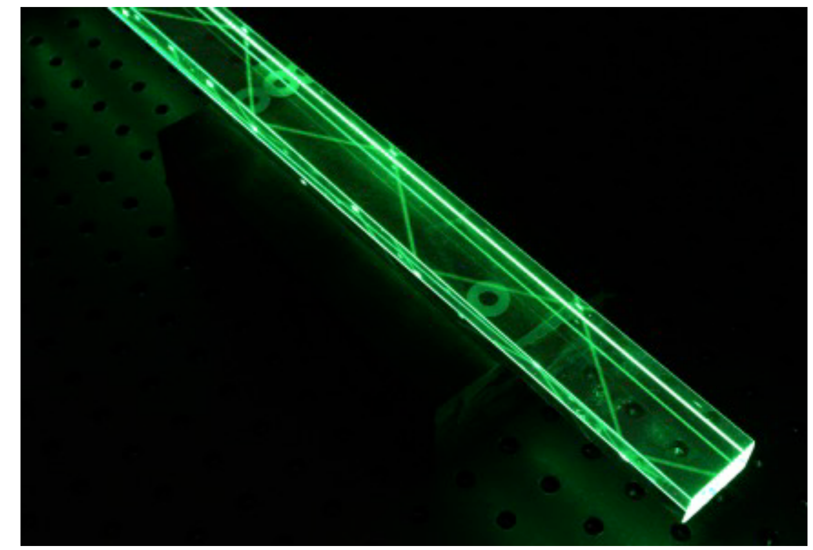
PRD 88 (2013) 094505

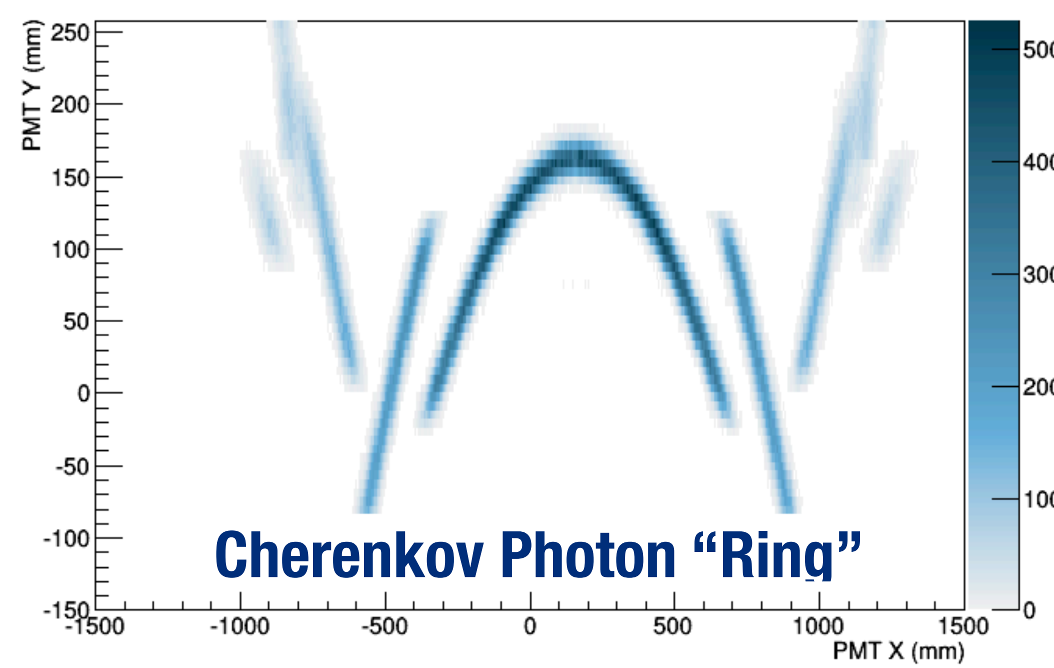
- Consistent with lattice QCD mixing angle for 2^{++}, and predictions for hybrids

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

DIRC upgrade

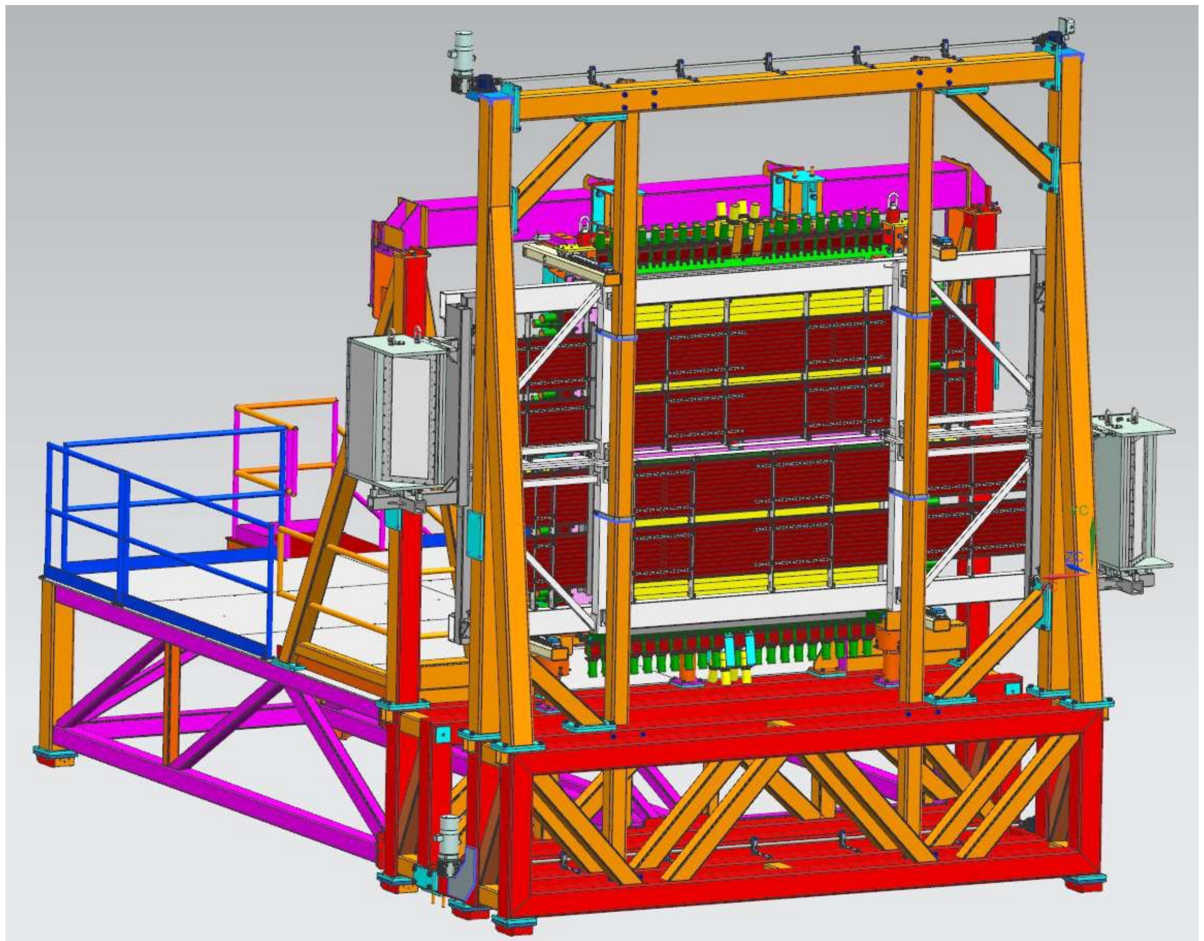


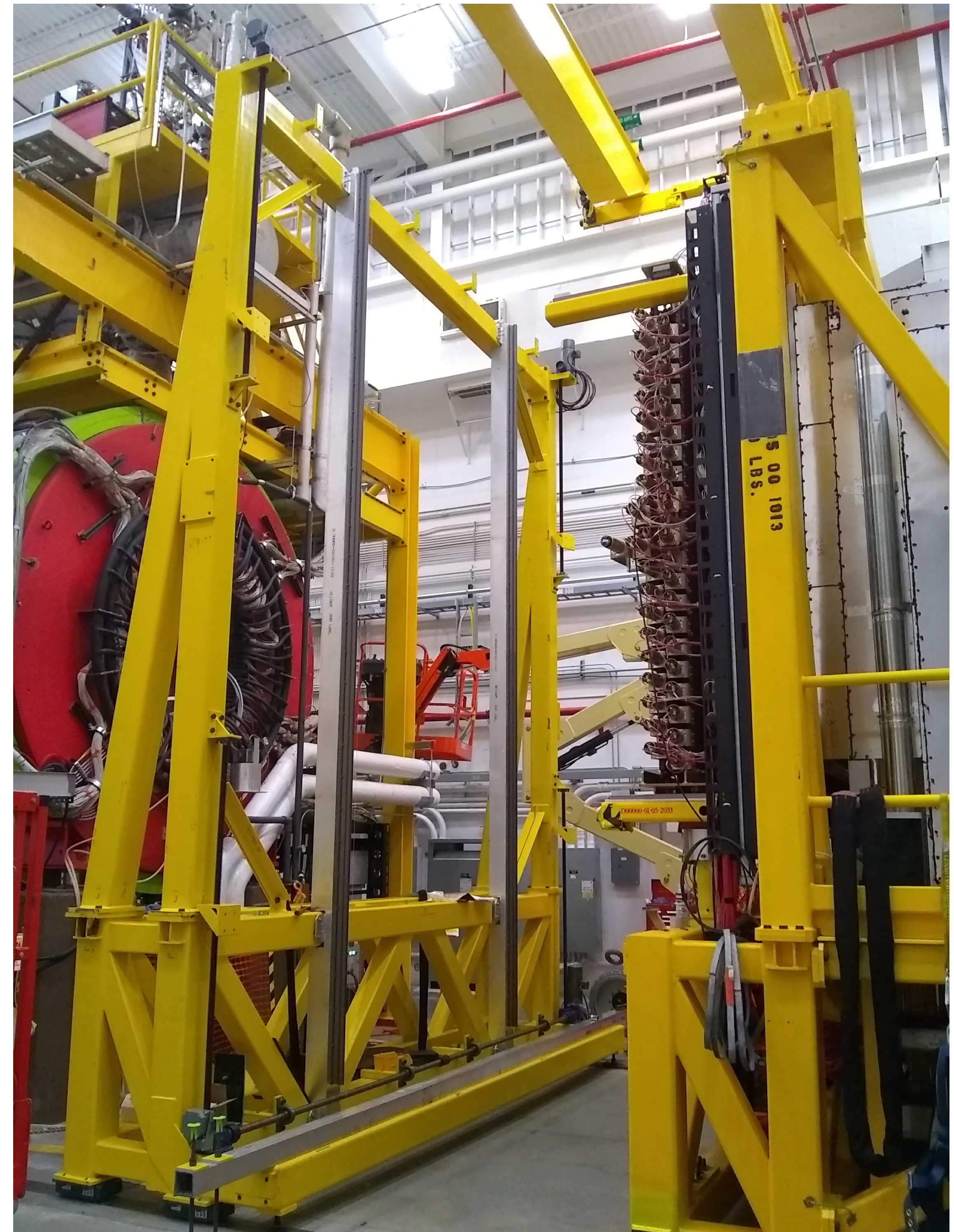




- The GlueX **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light) provides new K/π separation and will use components of the BaBar DIRC
- Partial installation and commissioning in **2018**

GlueX DIRC upgrade





Support structure in place and alignment underway

GlueX DIRC upgrade

Loading of 1st BaBar bar box at SLAC

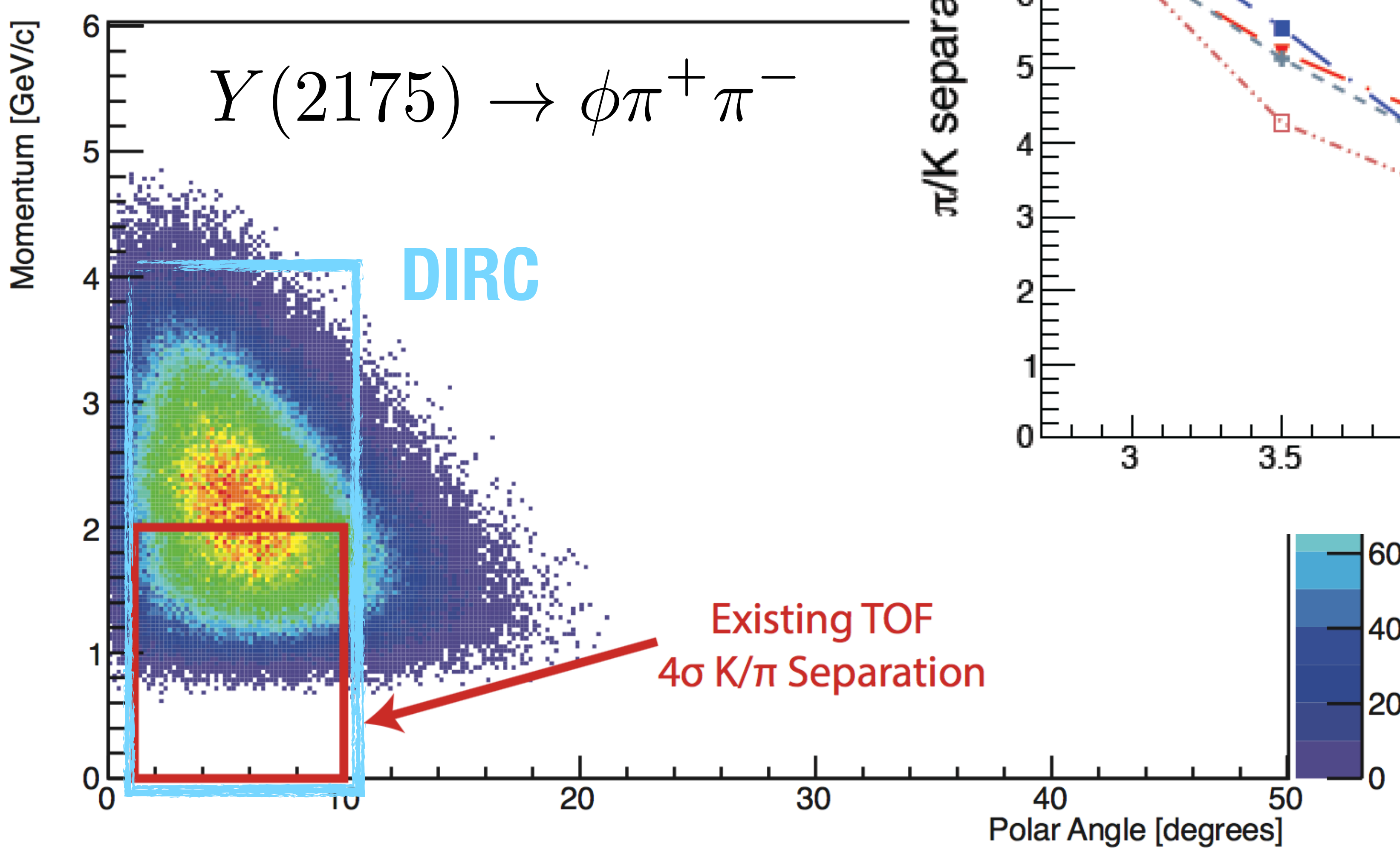
Delivered safely to JLab in November 2017

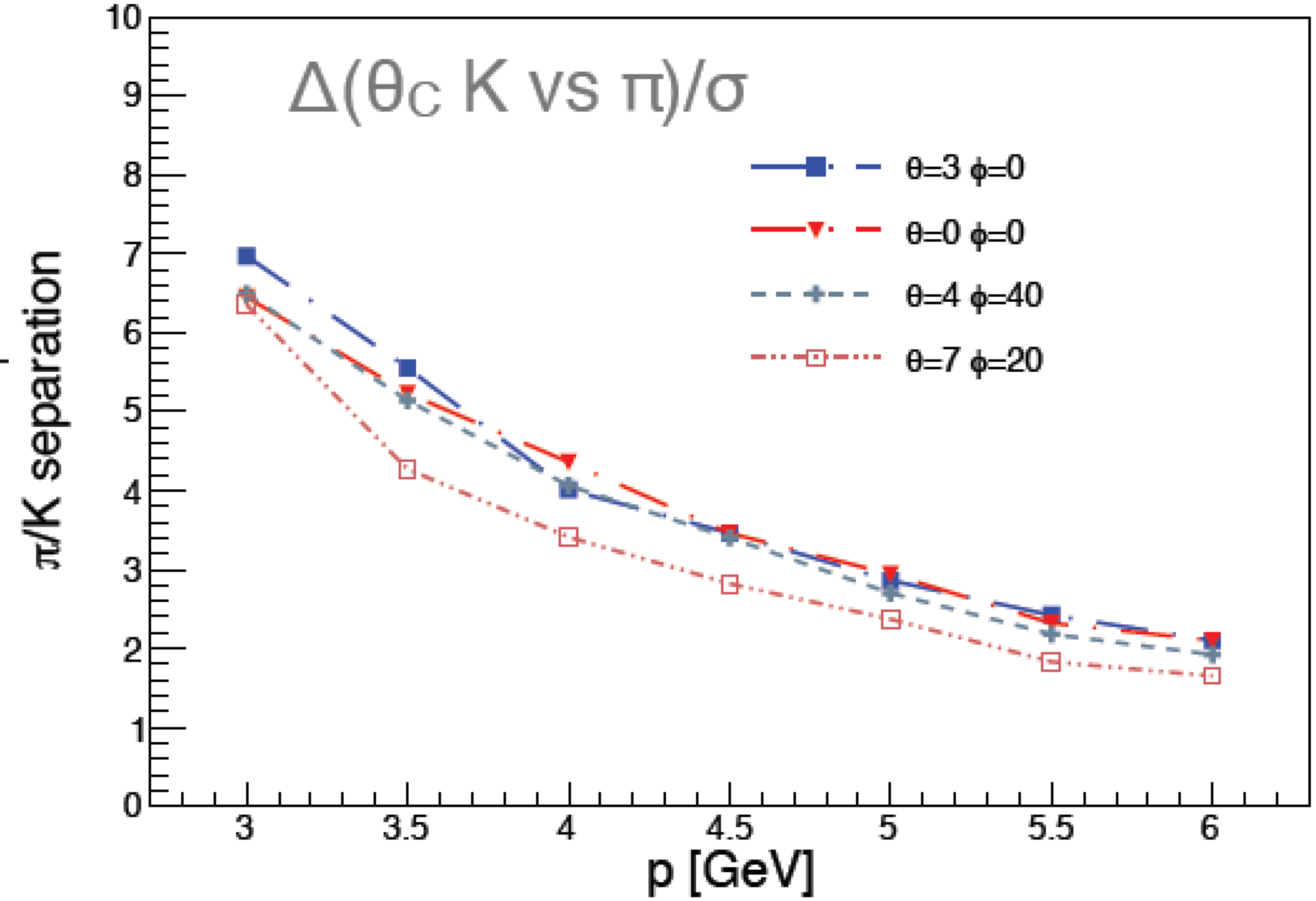
Follow our next trip in June with the final 3 boxes:

twitter @GlueX_DIRC

Expected DIRC performance

Simulation





- Significantly extends reach in search for exotic hadrons (hybrid, multi-quark, etc.) containing strange quarks