HADRONIC PHYSICS

WITH LEPTON AND HADRON BEAMS

GlueX results and overview of pentaquark searches

Justin Stevens

William & Mary
CHARTERED 1693

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+ PHOTON BEAMS!

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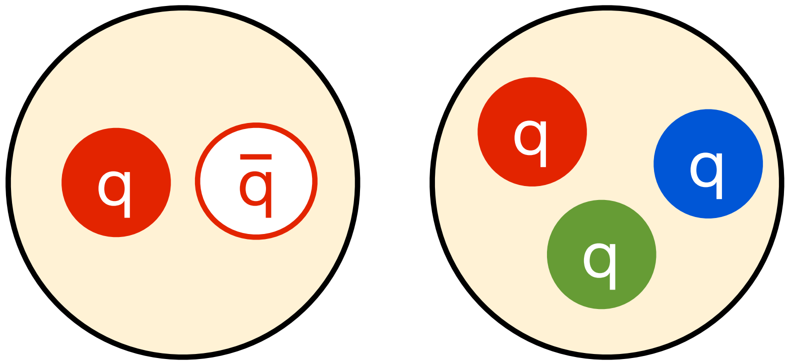
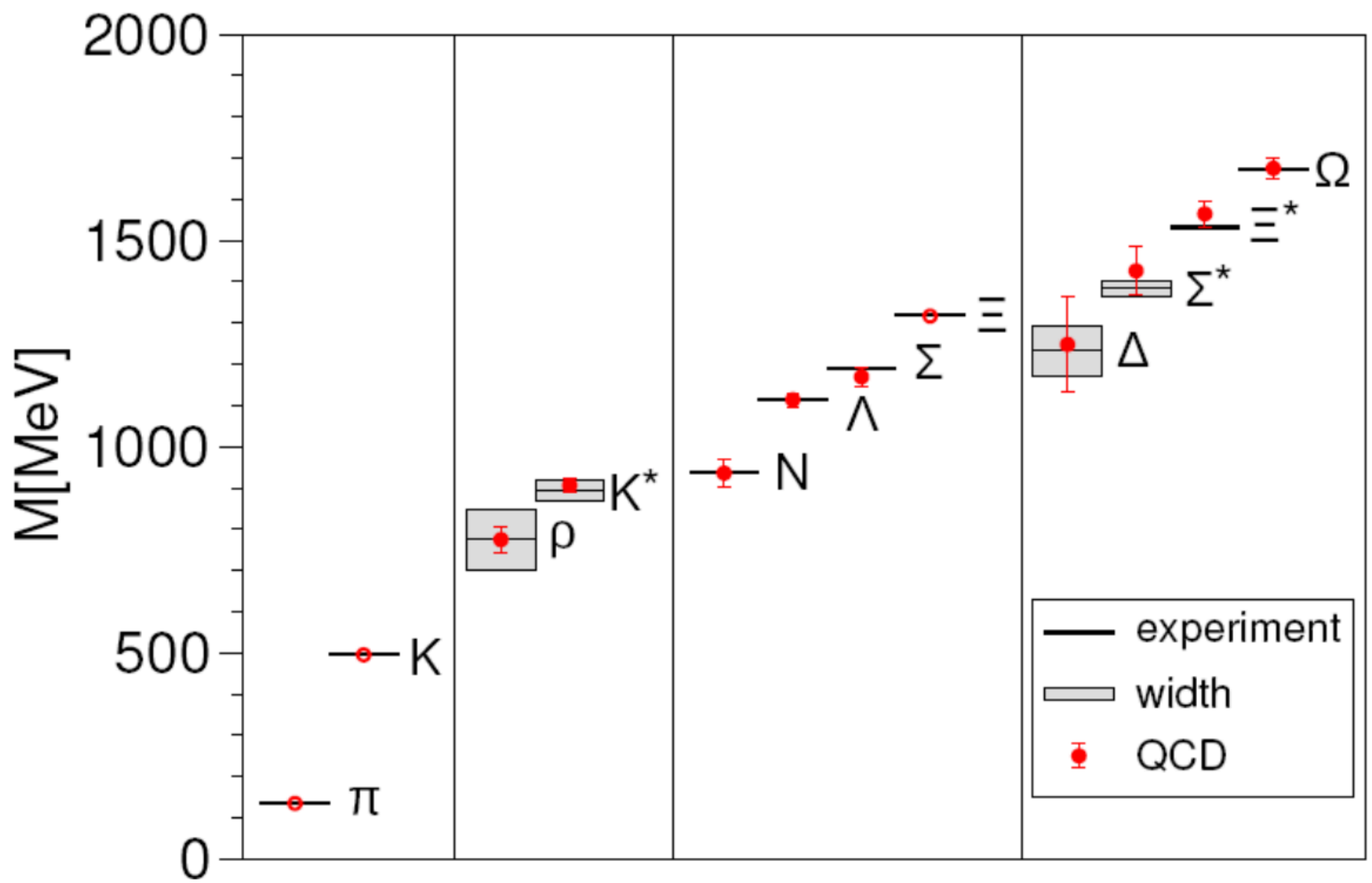
Confined states of quarks and gluons



mesons **baryons**

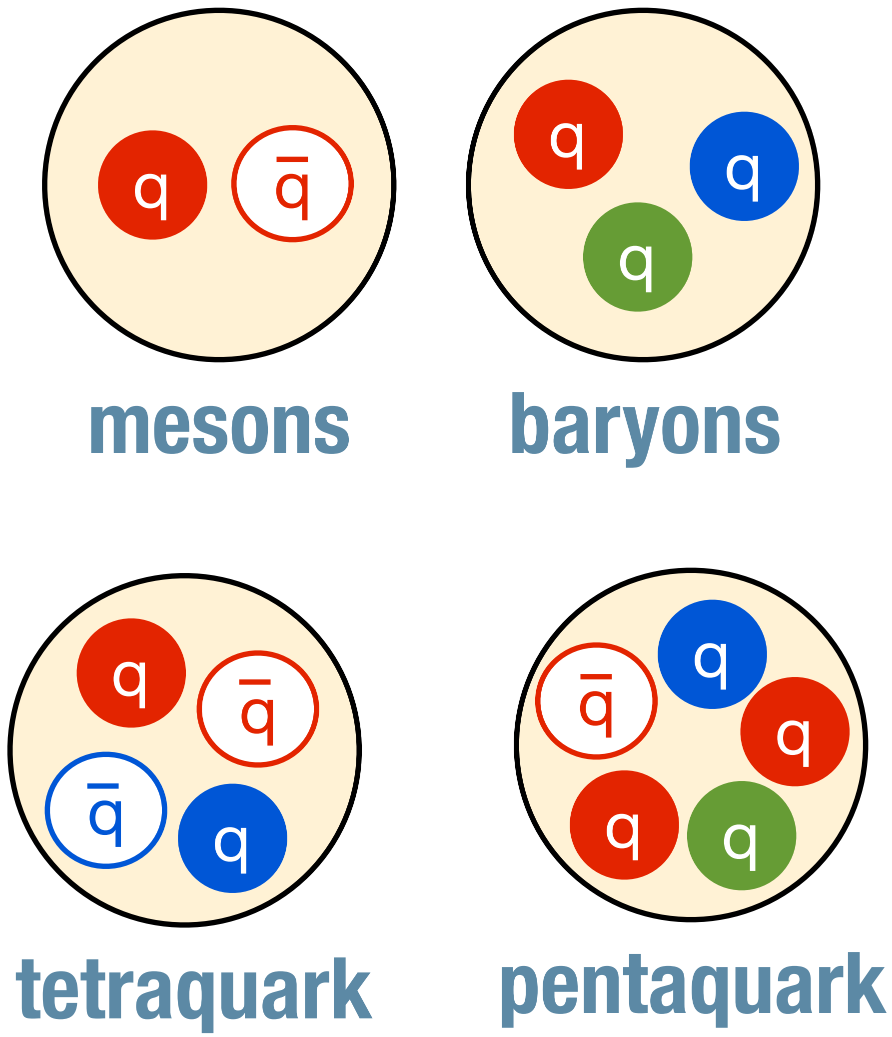
Observed mesons and baryons well described by 1st principles QCD

But these aren't the only states permitted by QCD



Science (2008)

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

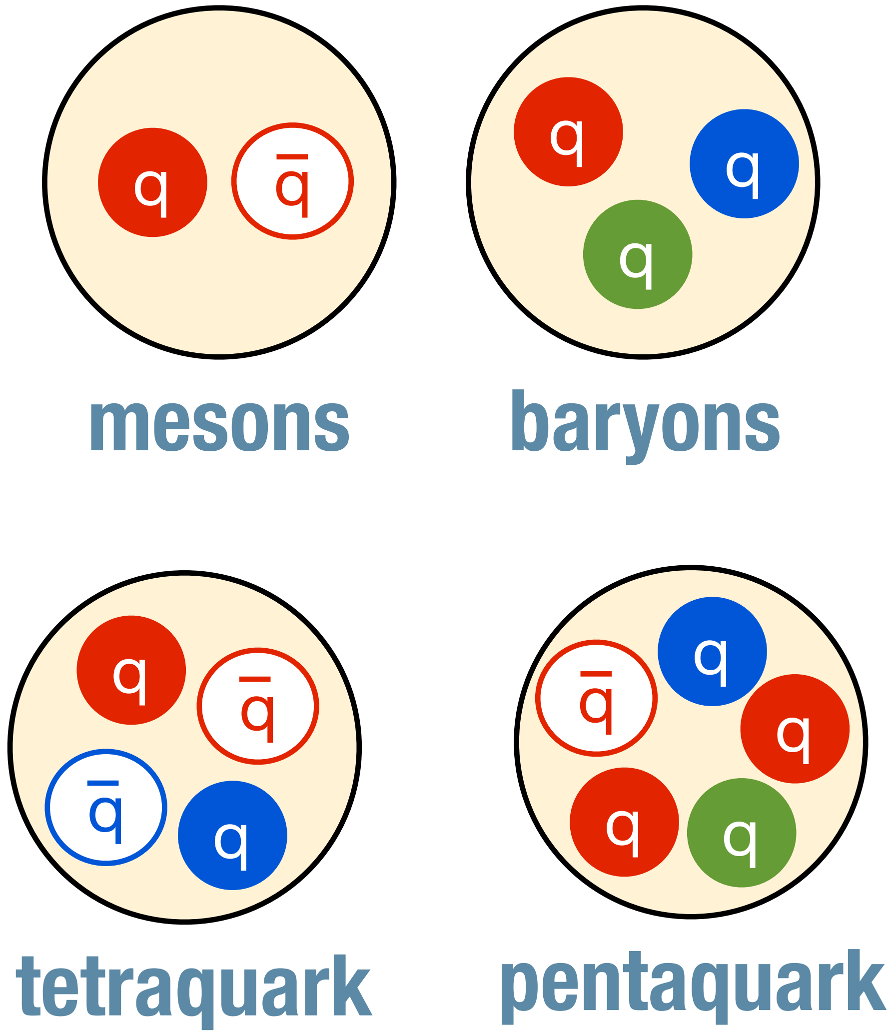
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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



Observed mesons and baryons well described by 1st principles QCD

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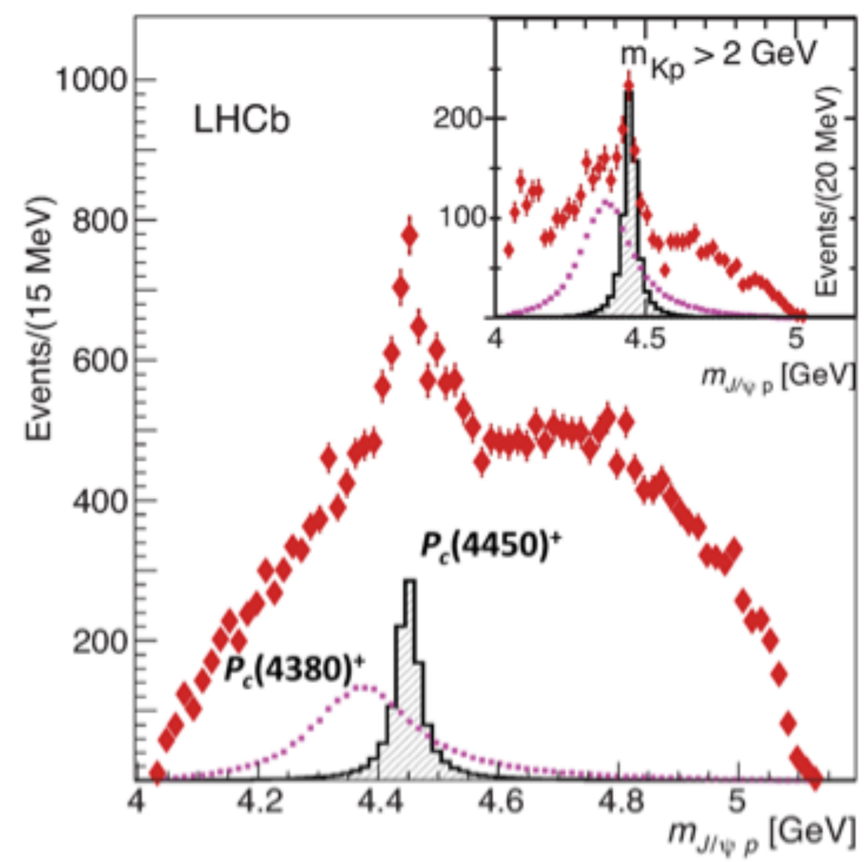
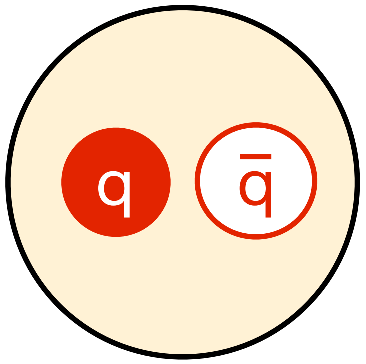
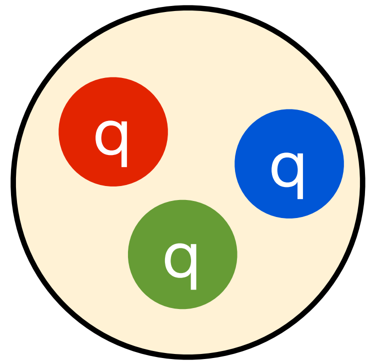
$$\Lambda_b \rightarrow J/\psi p K^-$$



Confined states of quarks and gluons



mesons



baryons

Observed mesons and baryons well described by 1st principles QCD

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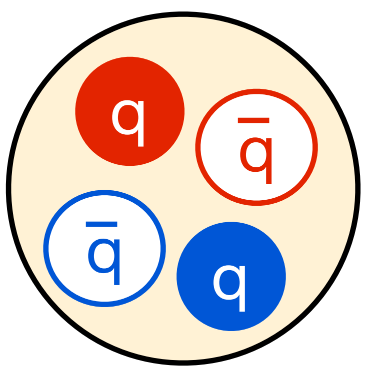
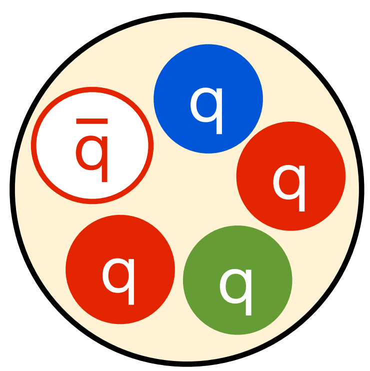
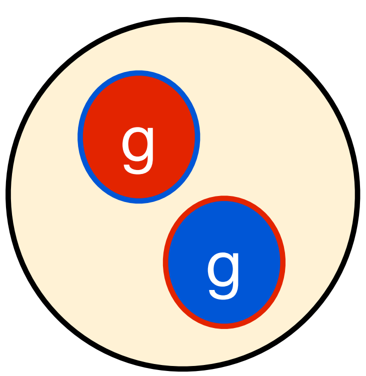


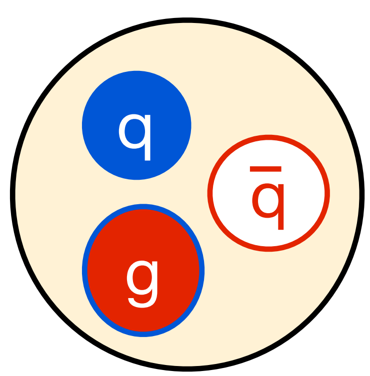
tetraquark



pentaquark



glueball

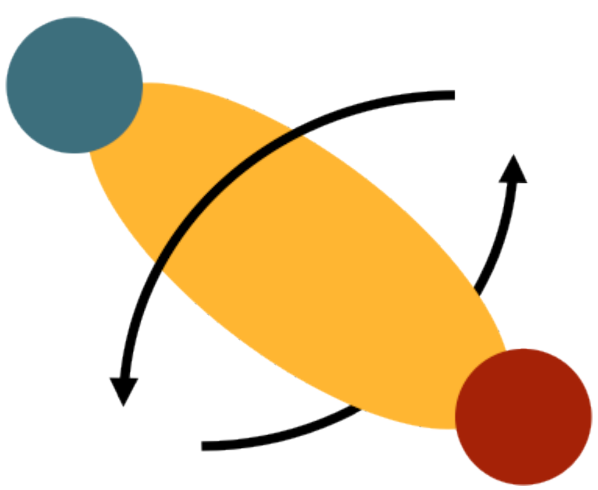


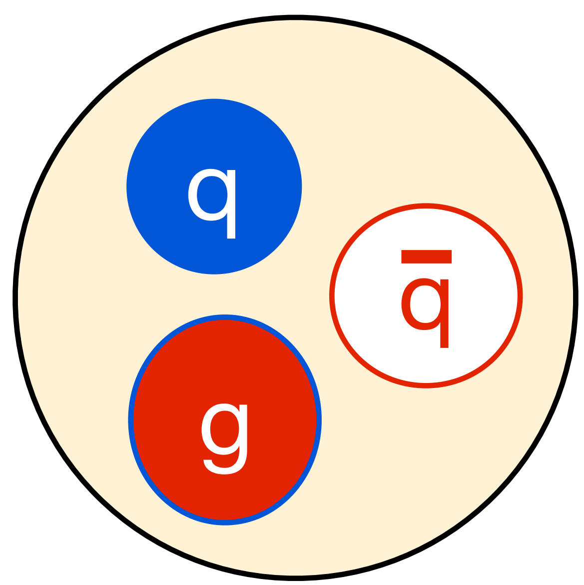
hybrid meson

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



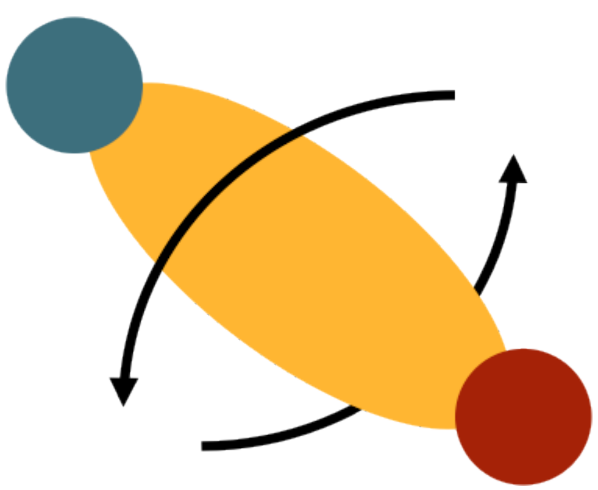


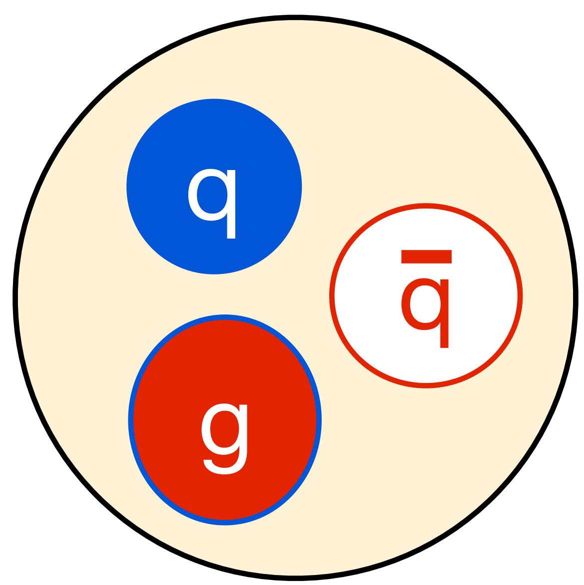
hybrid meson

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

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



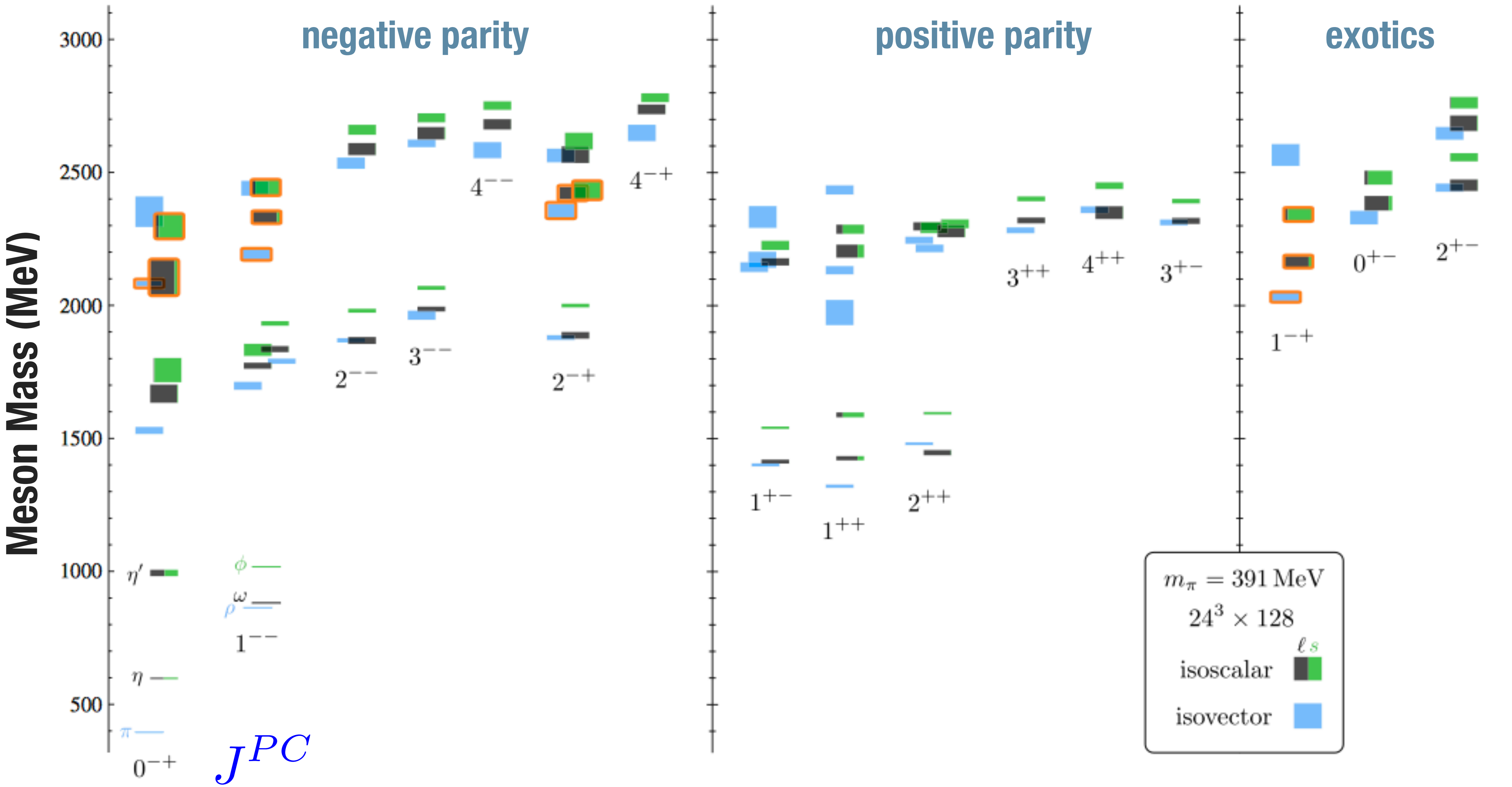


hybrid meson

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

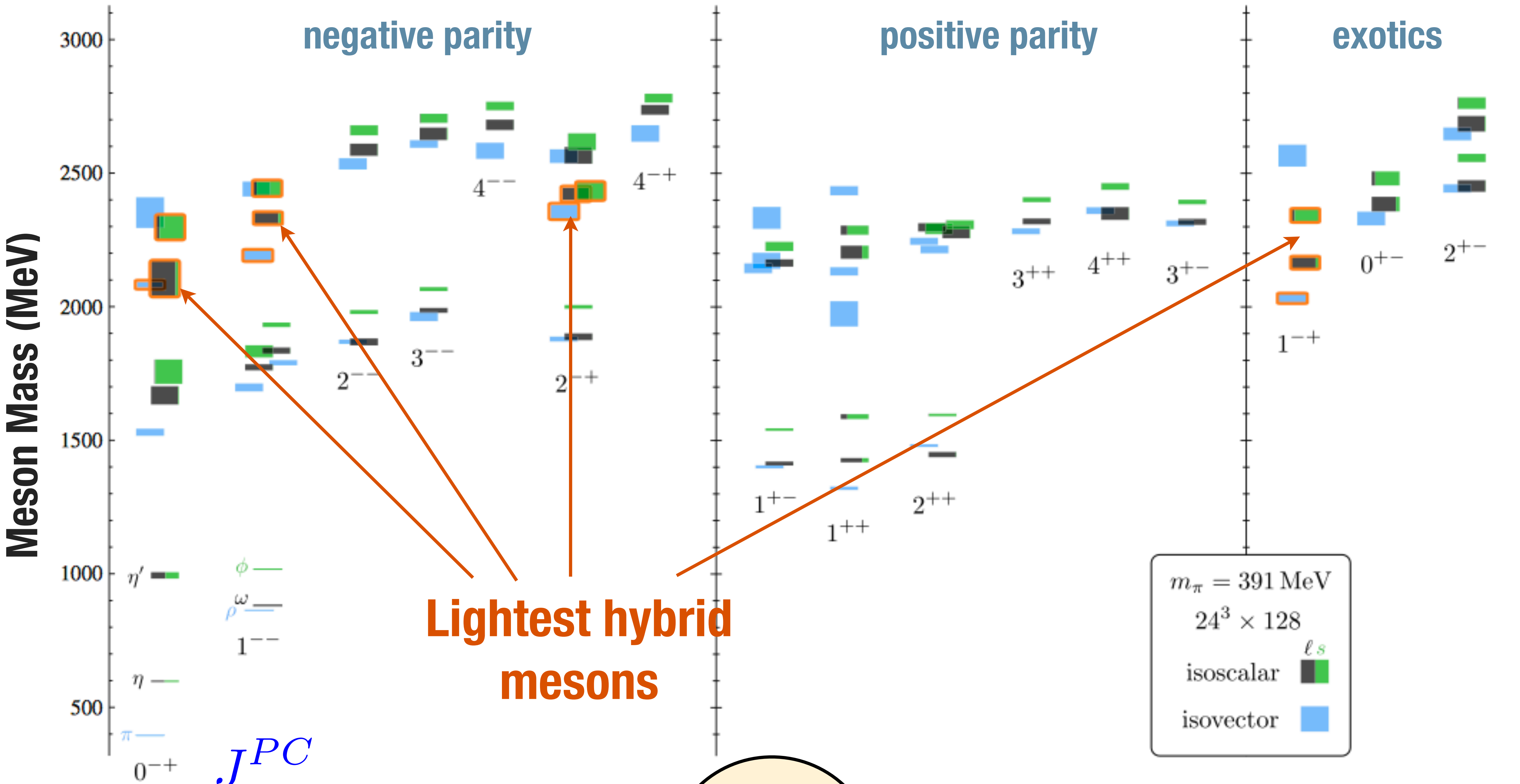
Lattice QCD: Mesons

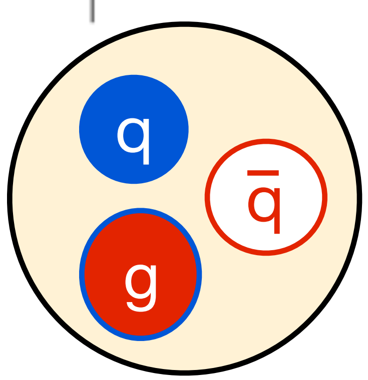
Dudek et al. PRD 88 (2013) 094505



Lattice QCD: Mesons

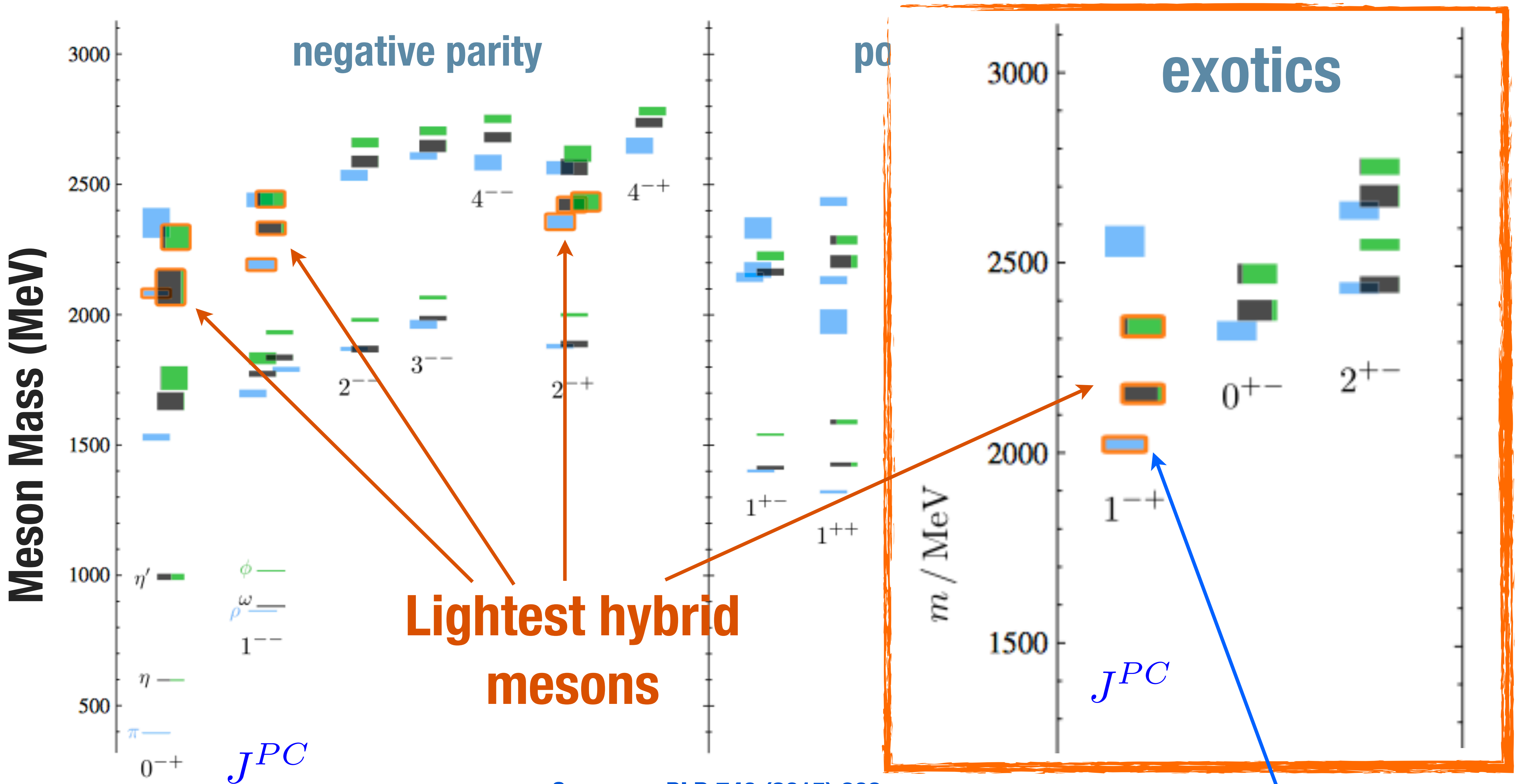
Dudek et al. PRD 88 (2013) 094505

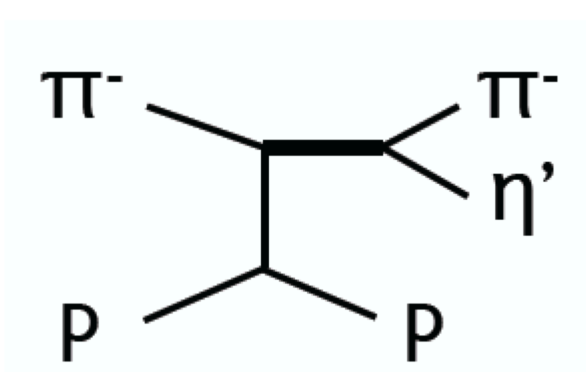




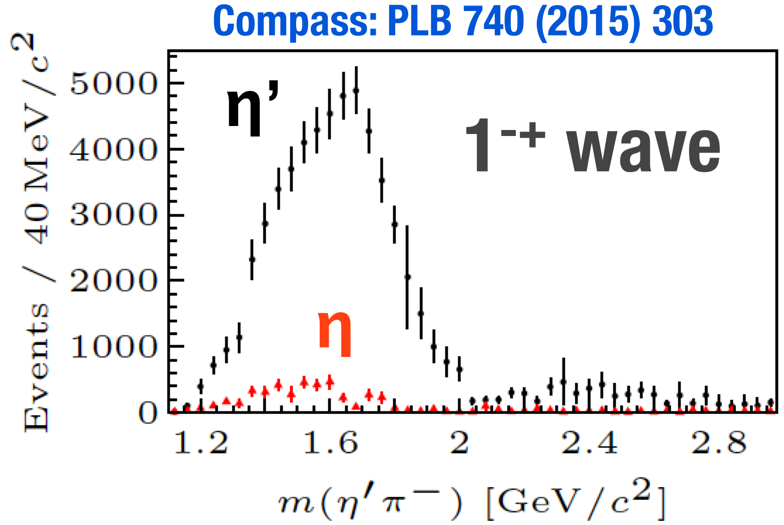
Lattice QCD: Mesons

Dudek et al. PRD 88 (2013) 094505





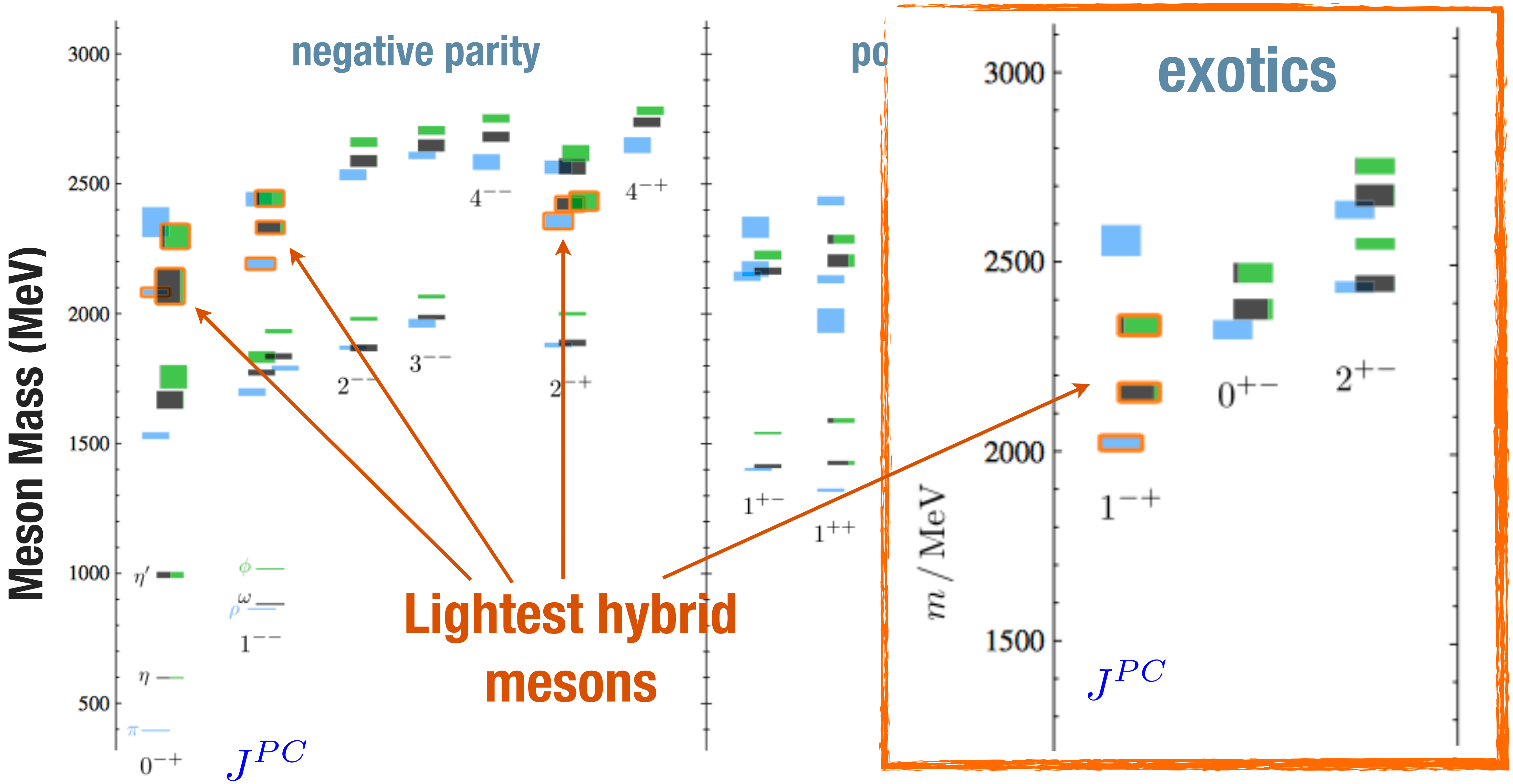
Compass: PLB 740 (2015) 303



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

Lattice QCD: Mesons

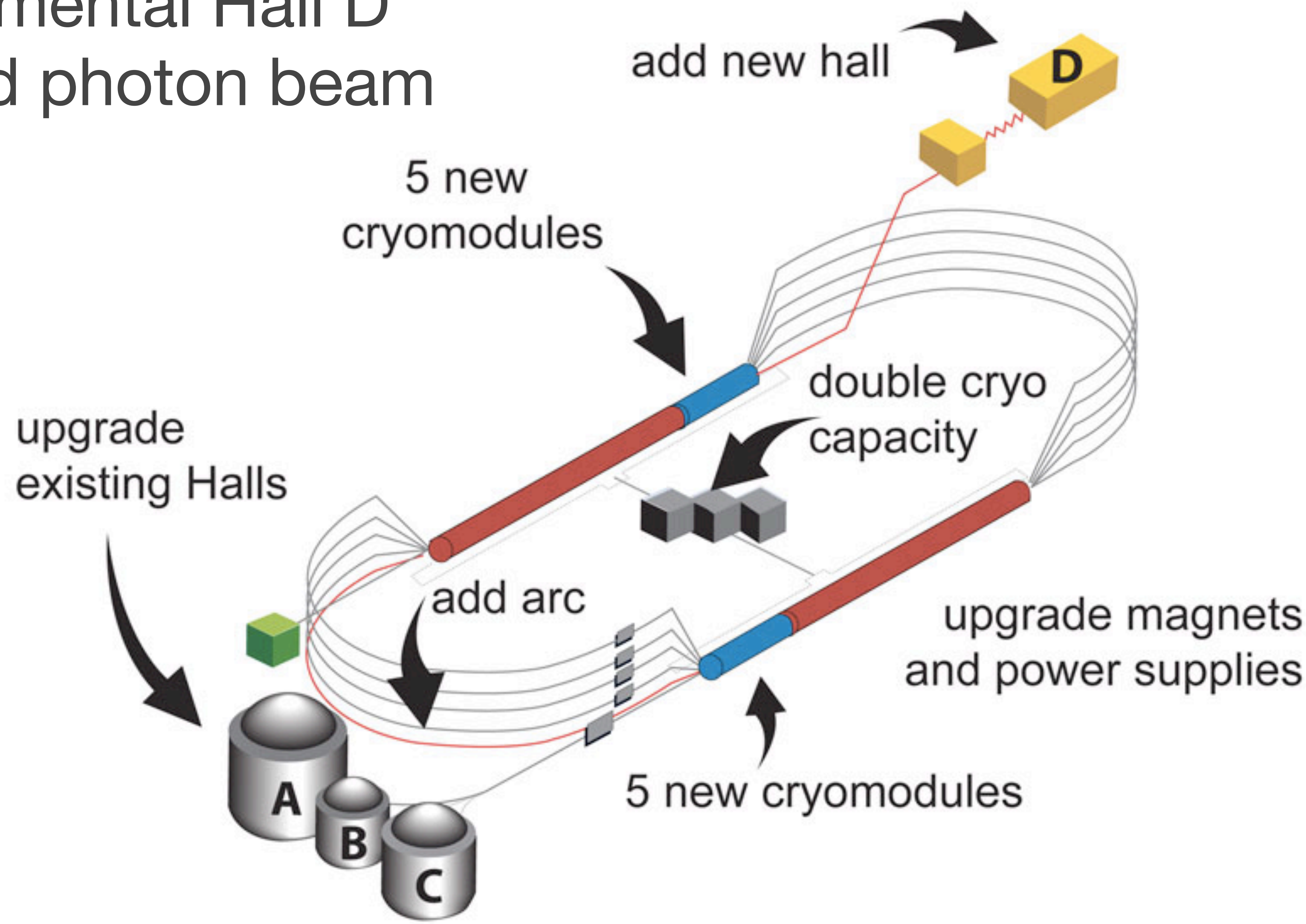
Dudek et al. PRD 88 (2013) 094505



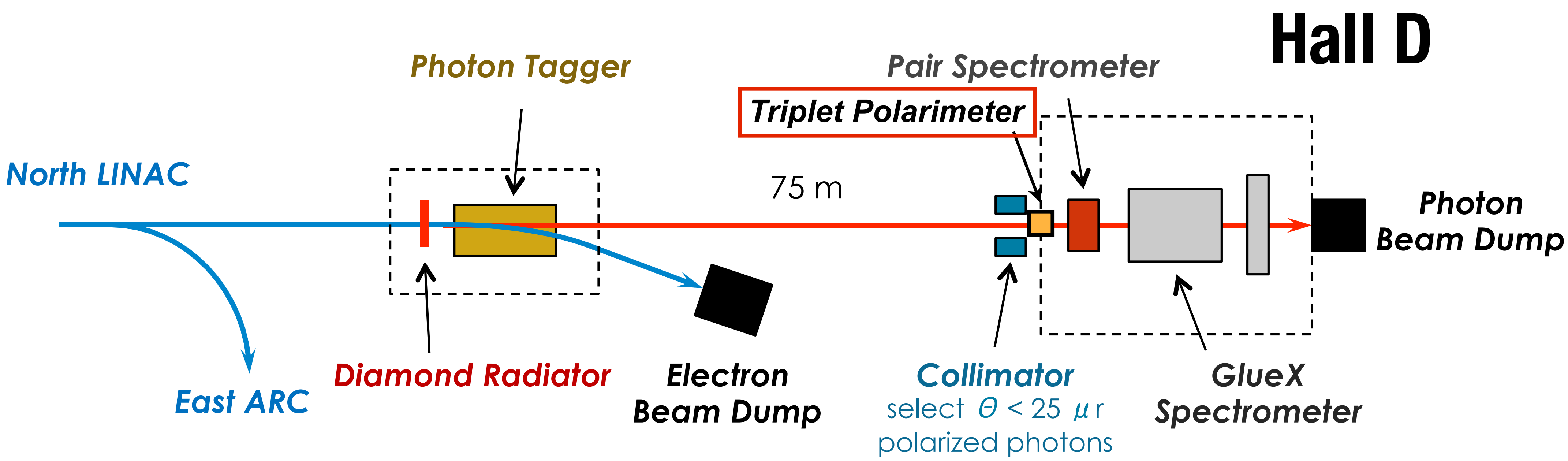
- Ideally look for a pattern of hybrid states in multiple decay modes
- Primary goal of the GlueX experiment is to search for and ultimately map out the spectrum of light quark hybrid mesons

Jefferson Lab 12 GeV Upgrade

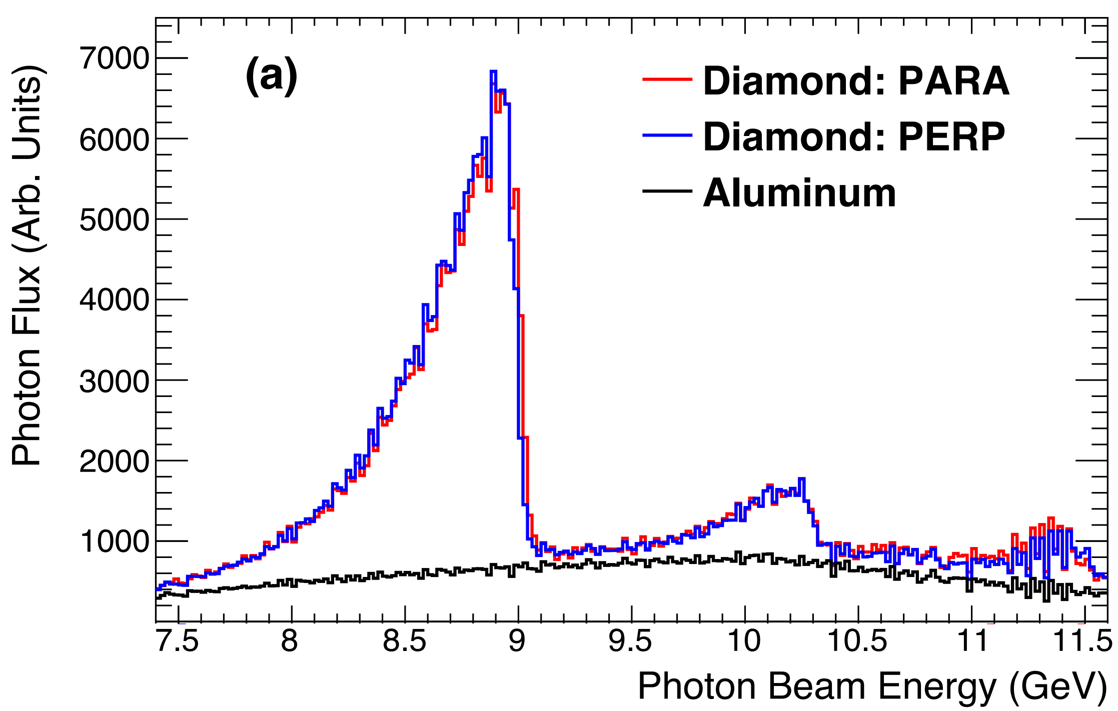
- Upgrade maximum electron beam energy from 6 to 12 GeV
- Add new experimental Hall D with a dedicated photon beam



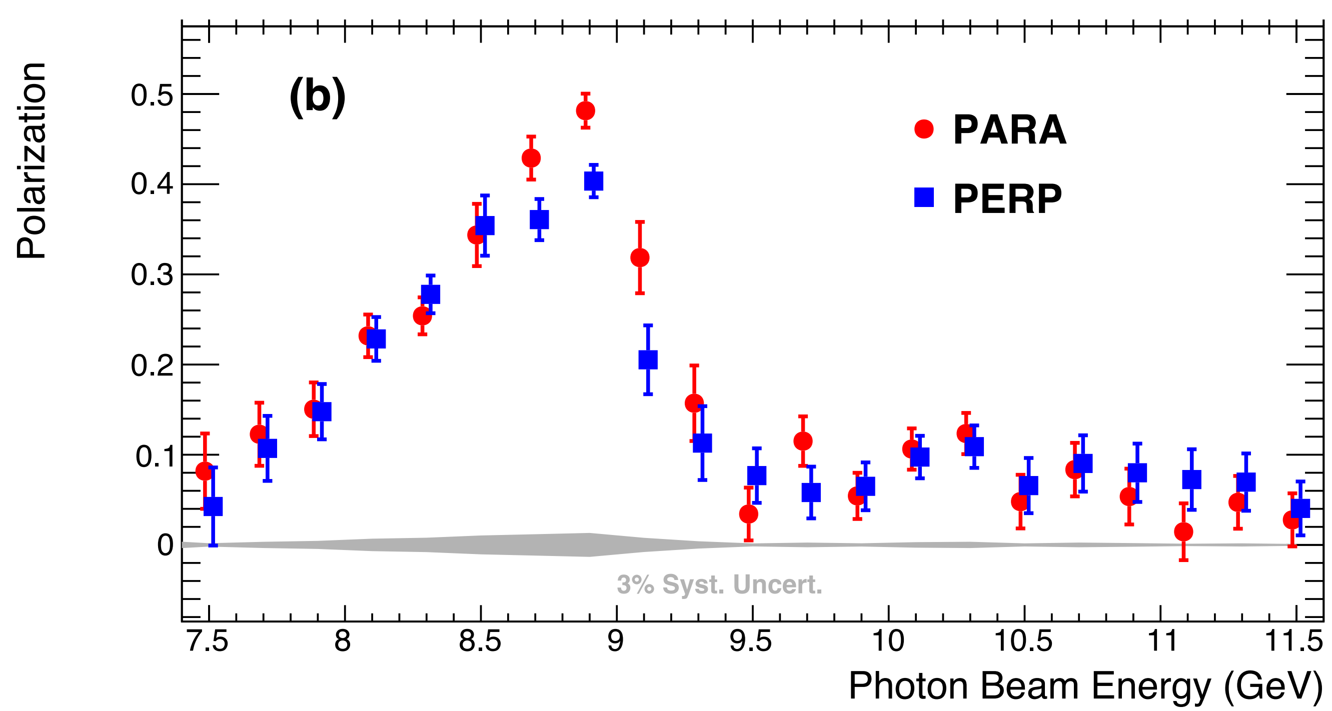
Photon Beam



Measured Flux

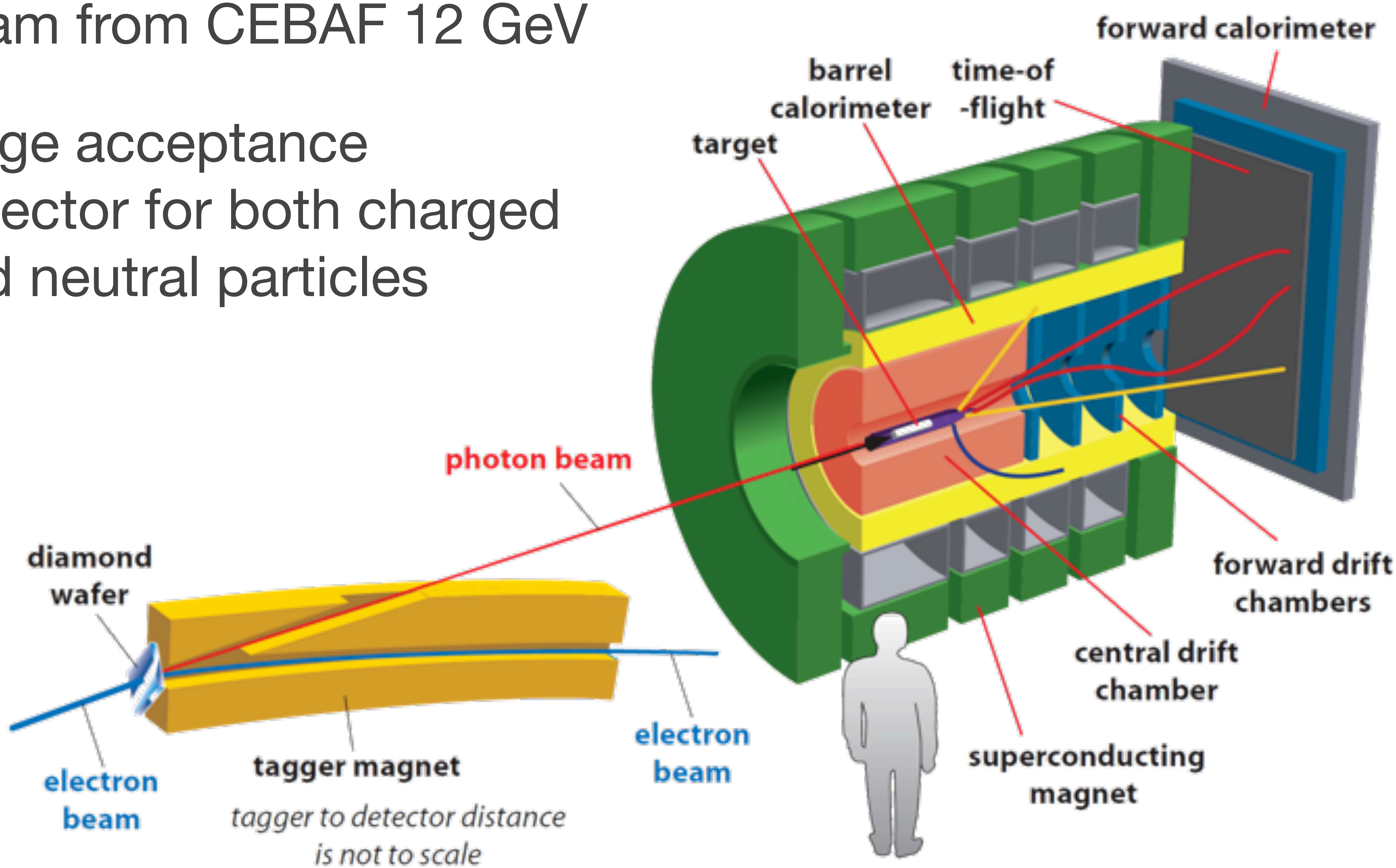


Measured Polarization



GlueX in Hall D

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

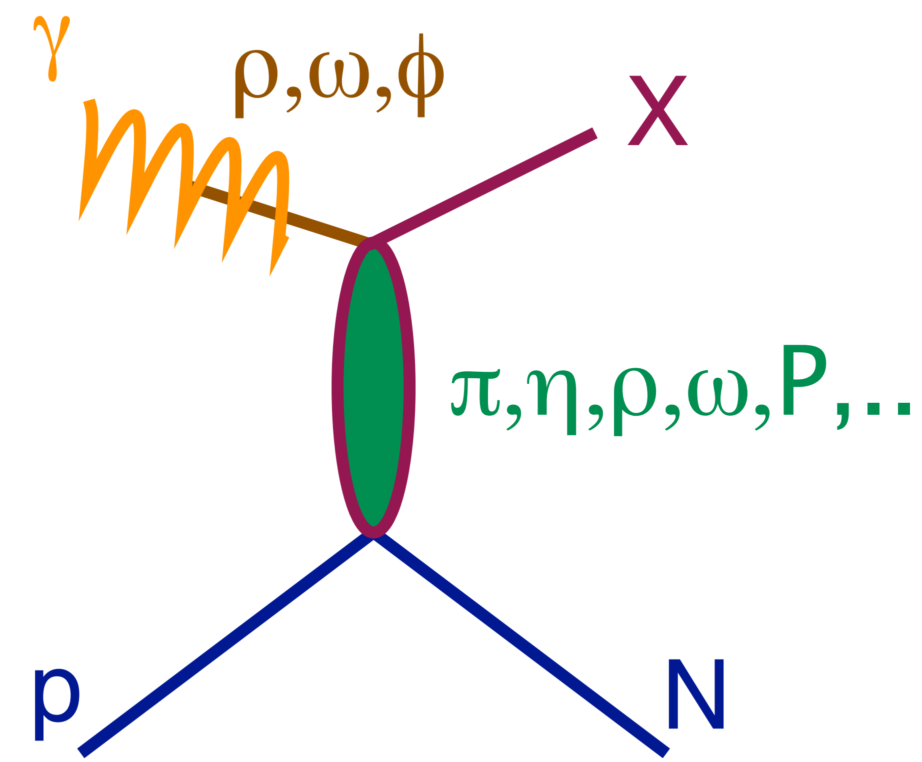


GlueX in Hall D

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^{+-}

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



P = Pomeron exchange

Exotic J^{PC} in photoproduction

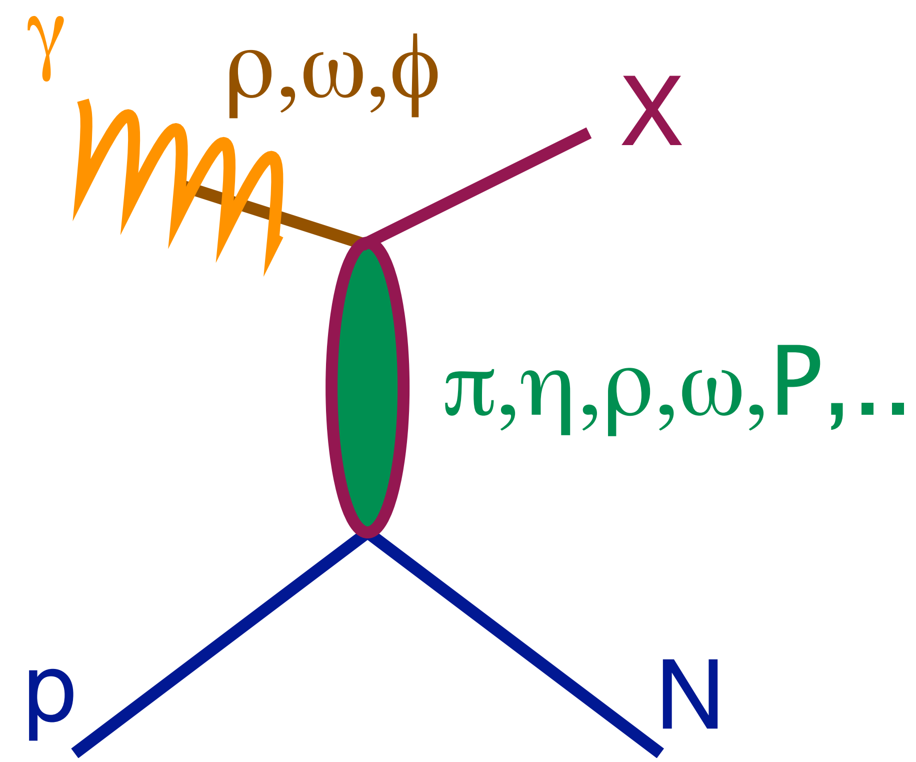
	Approximate Mass (MeV)	J^{PC}
π_1	1900	1^{-+}
η_1	2100	1^{-+}
η'_1	2300	1^{-+}
b_0	2400	0^{+-}
h_0	2400	0^{+-}
h'_0	2500	0^{+-}
b_2	2500	2^{+-}
h_2	2500	2^{+-}
h'_2	2600	2^{+-}

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

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

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

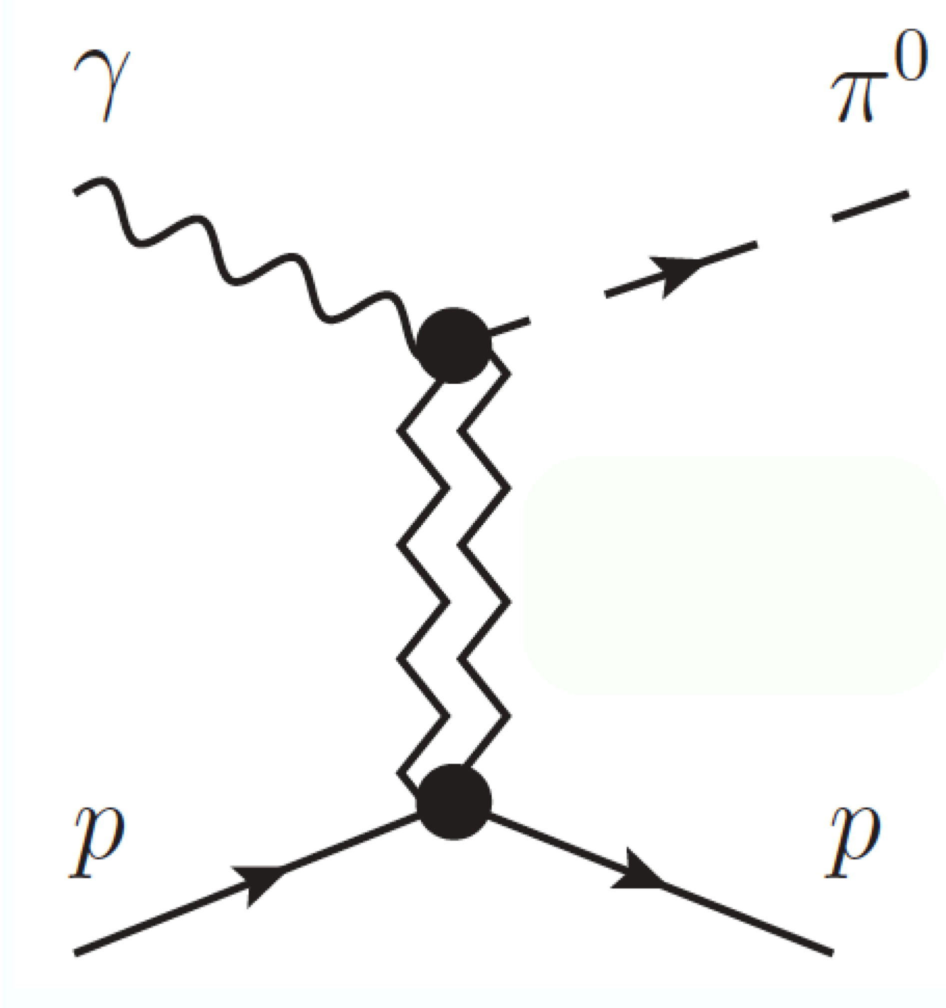
Possible quantum numbers from Vector Meson Dominance and t-channel exchange: $(I^G)J^{PC}$



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}

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

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

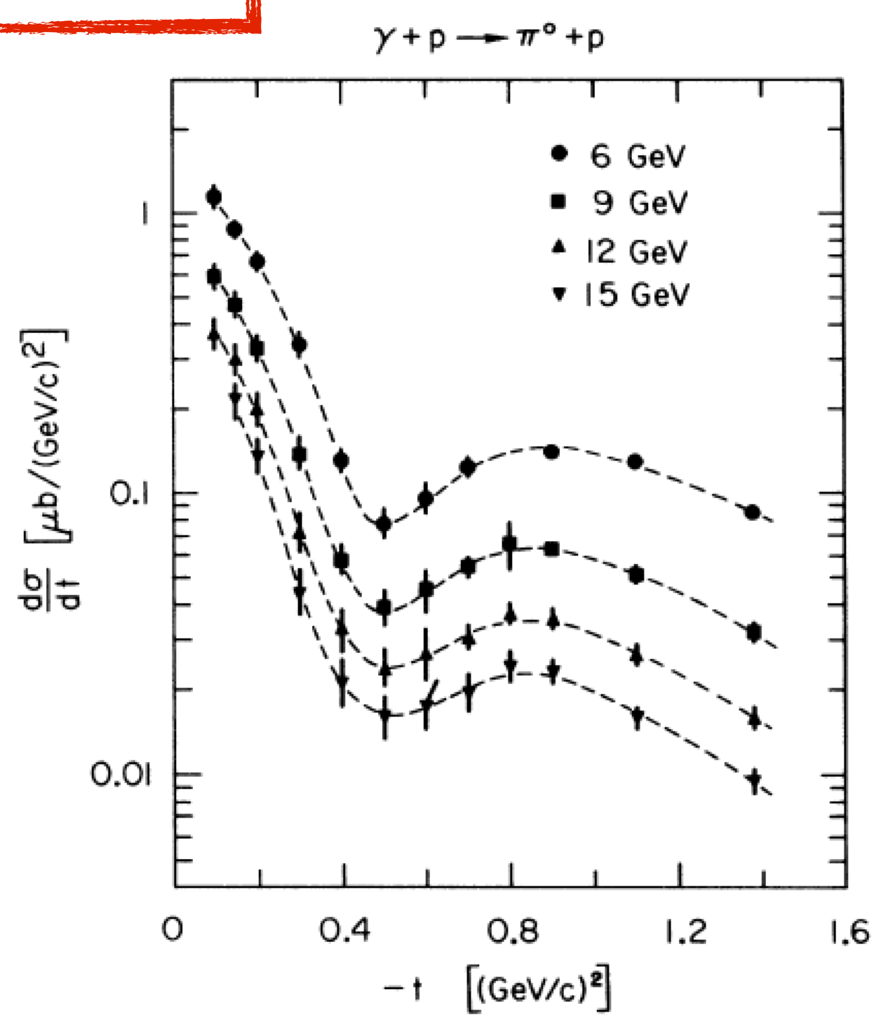
- Understand non-exotic production mechanism first
- Linear photon beam polarization critical to filter out "naturality" of the exchange particle

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

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



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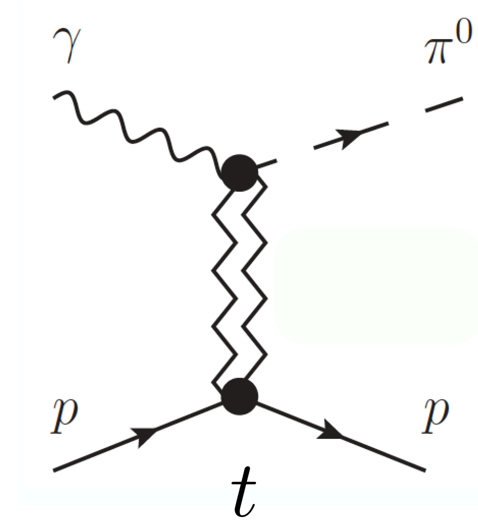
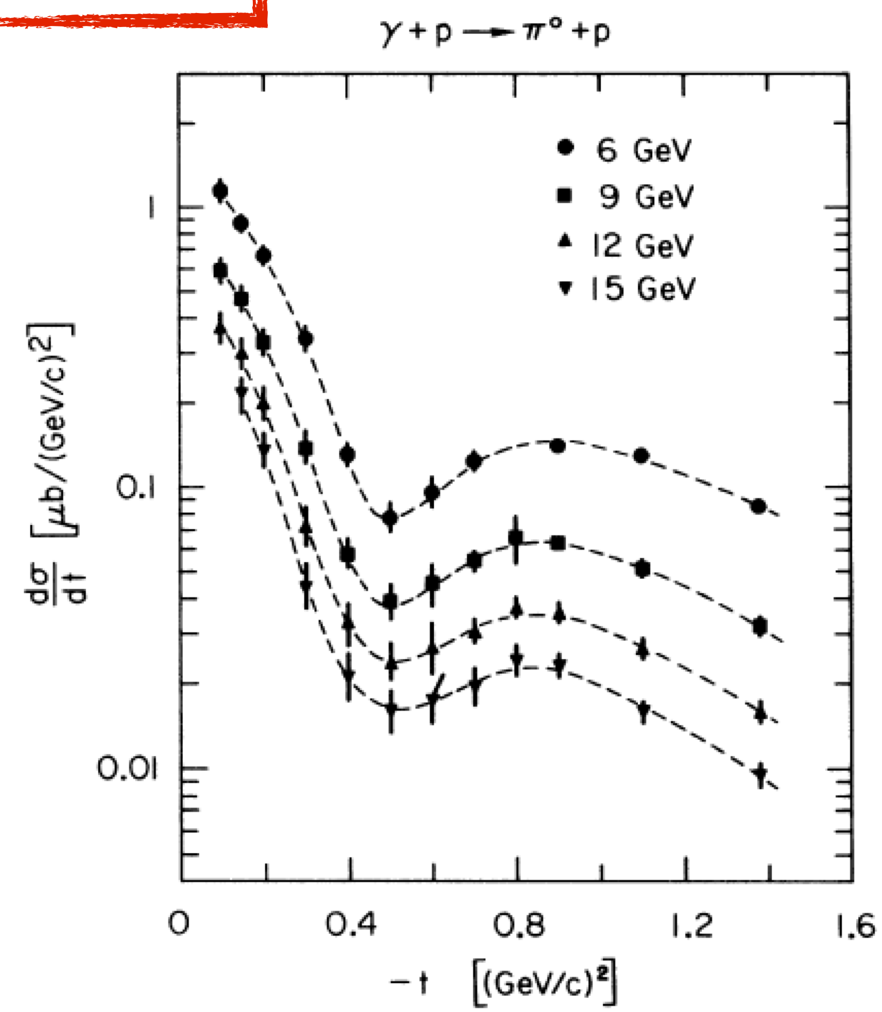


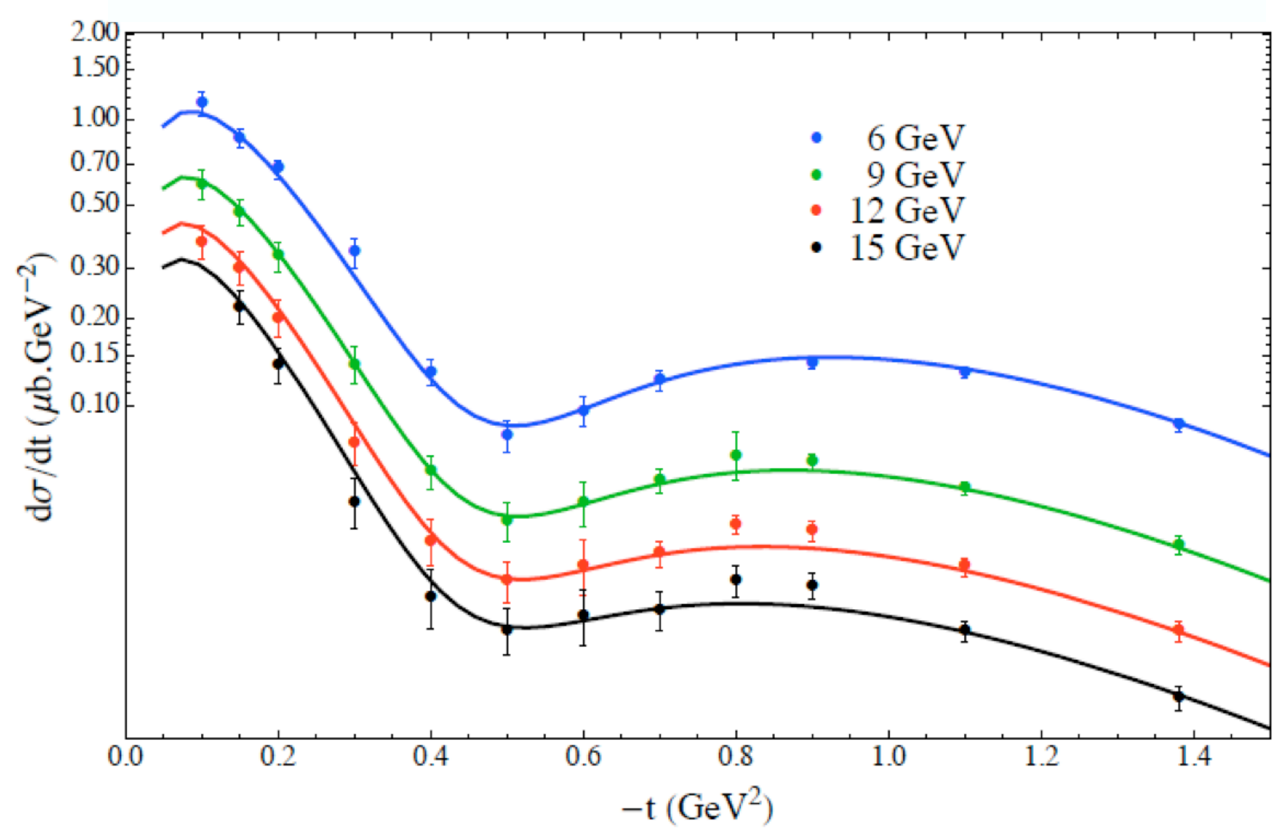
Exchange J^{PC}

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

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



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

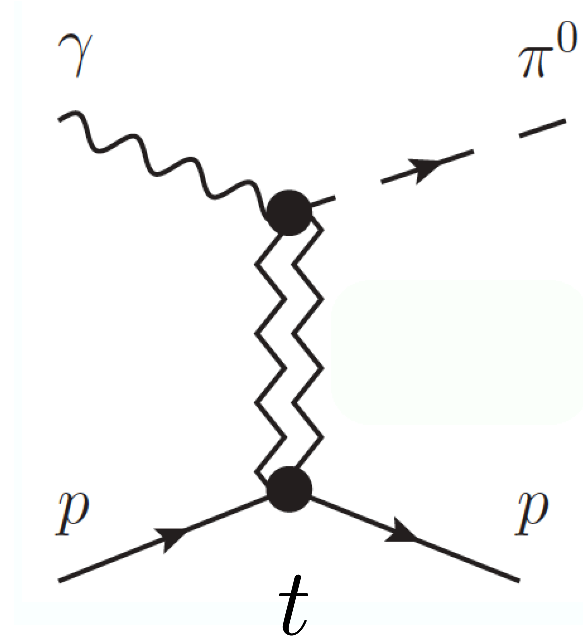


JPAC: Mathieu et al. PRD 92, 074013

$\gamma p \rightarrow \pi^0 p$ 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}

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

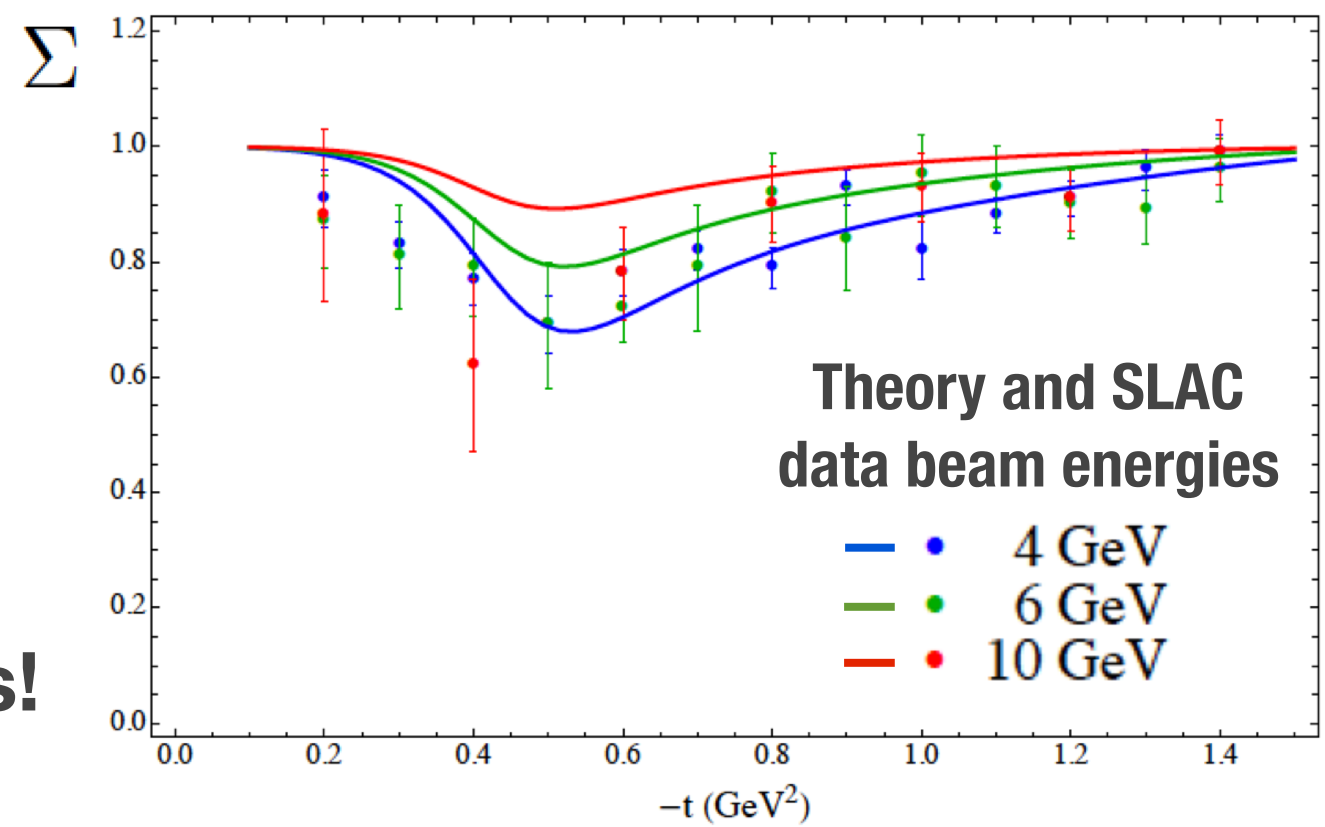
$1^{+-} : b, h$

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

- From experimental standpoint easily extended to $\gamma p \rightarrow \eta p$

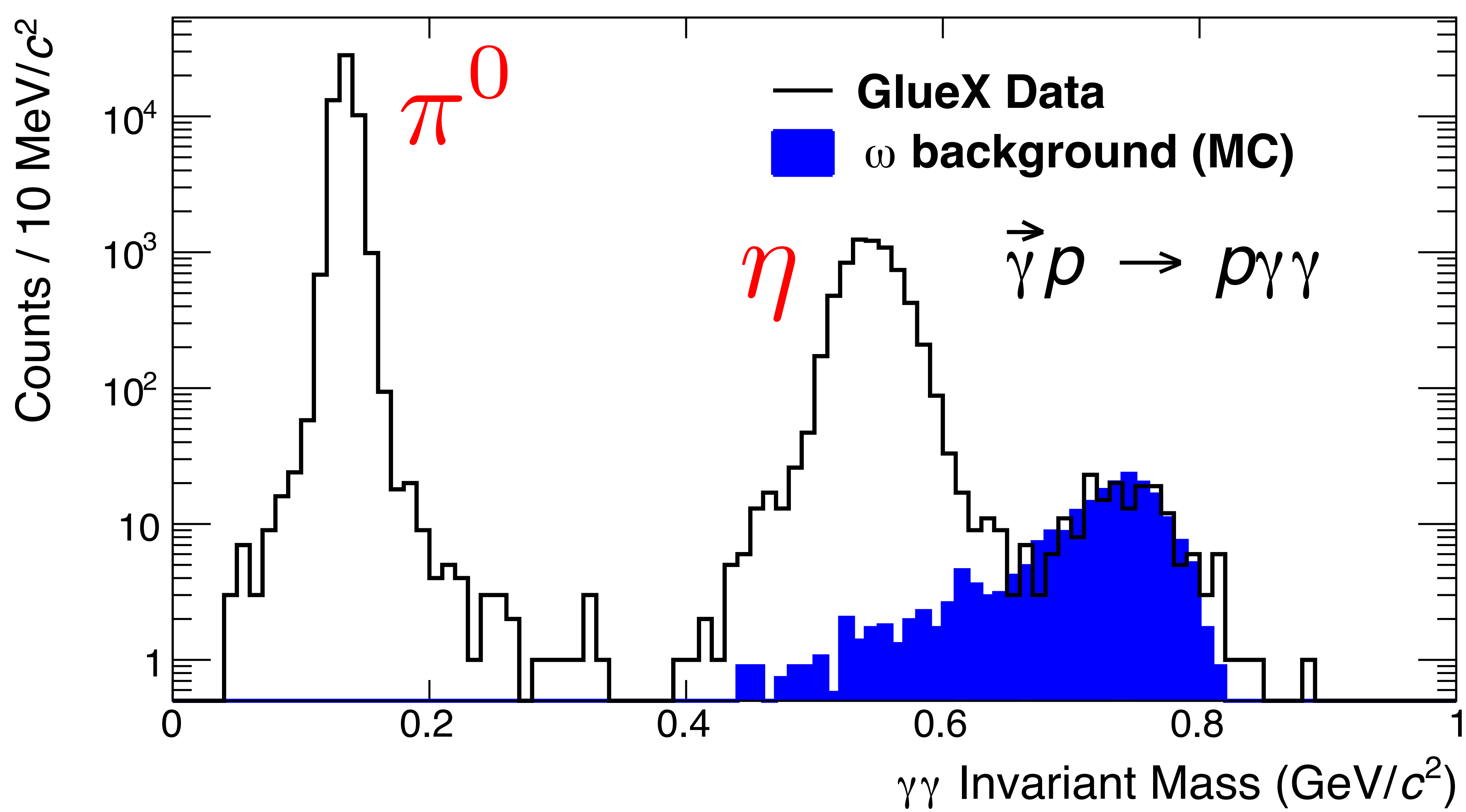
  - **No previous measurements!**

JPAC: Mathieu et al. PRD 92, 074013



π^0 and η beam asymmetries

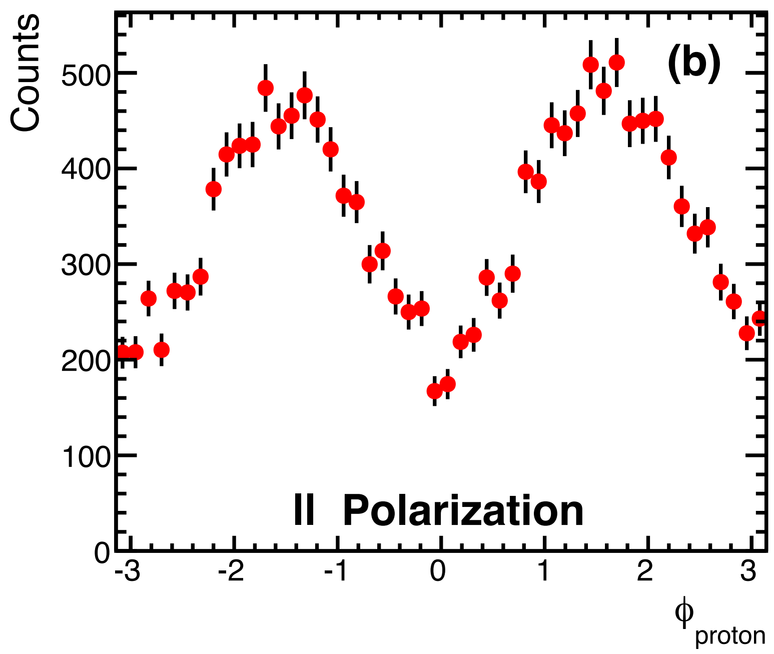
$$\gamma p \to p\gamma\gamma$$

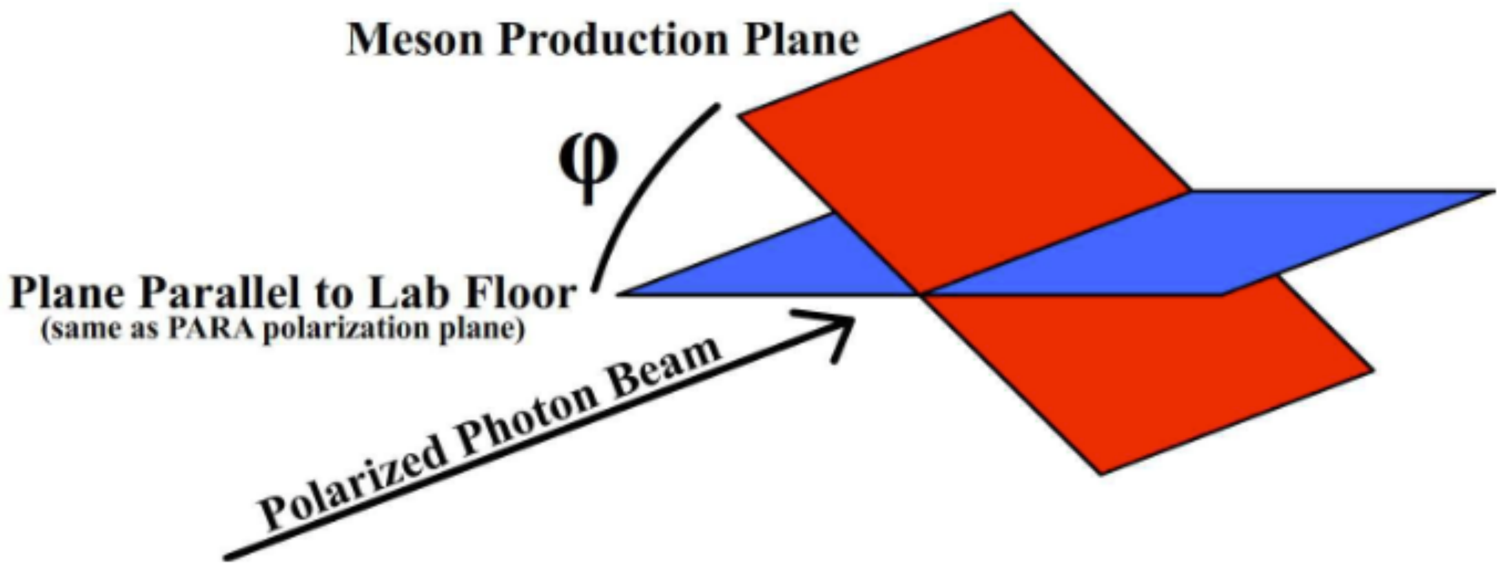


Phys. Rev. C 95, 042201(R)

First 12 GeV publication!

π^0 and η beam asymmetries

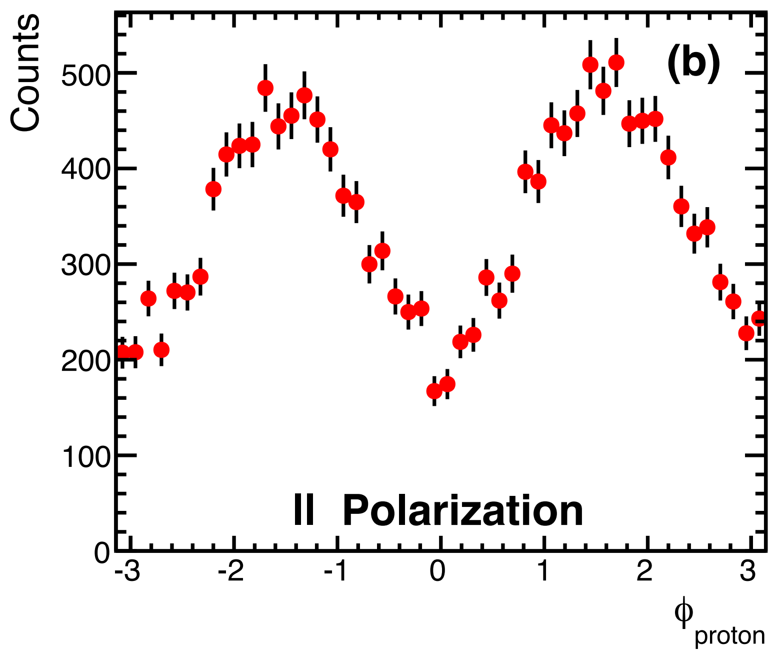


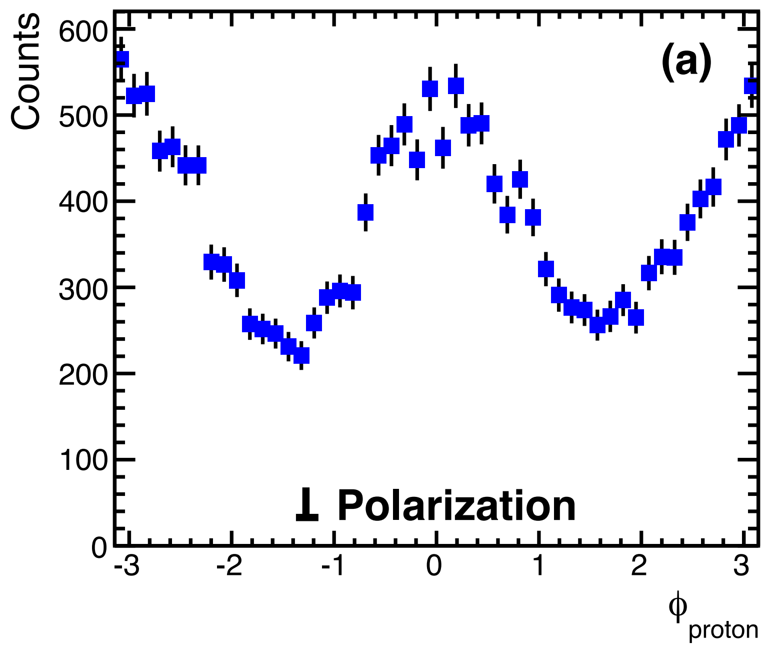


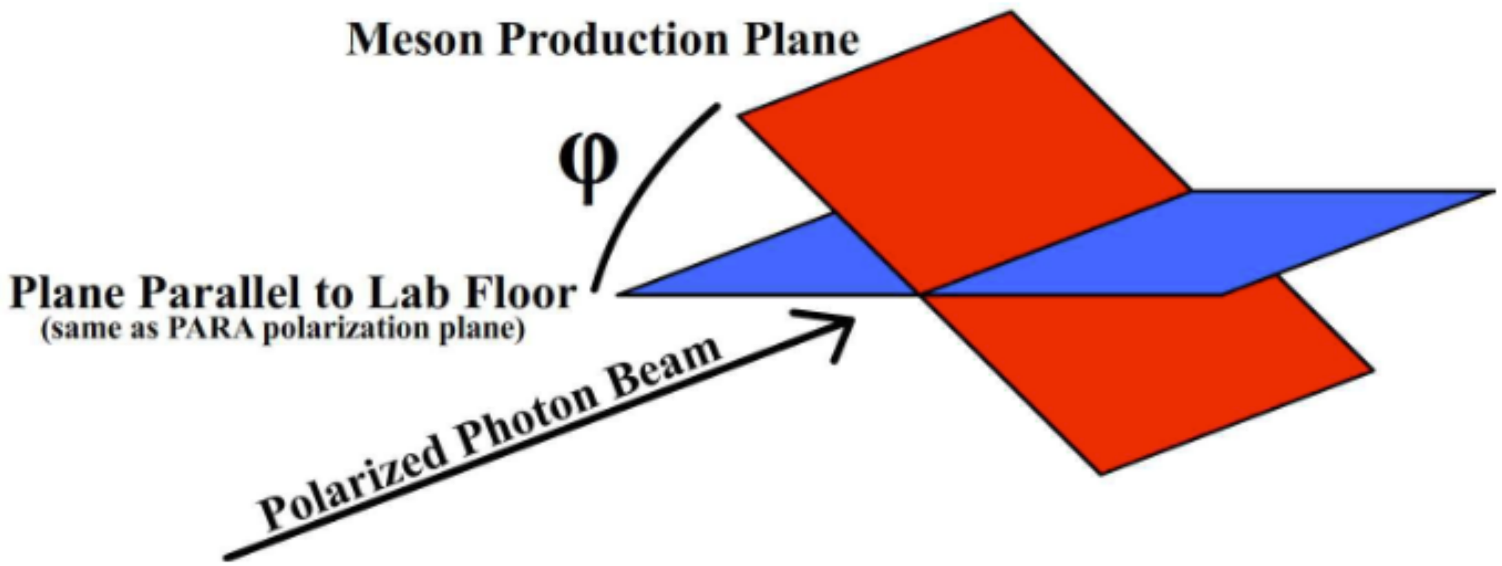
$$\sigma = \sigma_0 \left(1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_\gamma^{\text{lin}})\right)$$

Phys. Rev. C 95, 042201(R)

π^0 and η beam asymmetries







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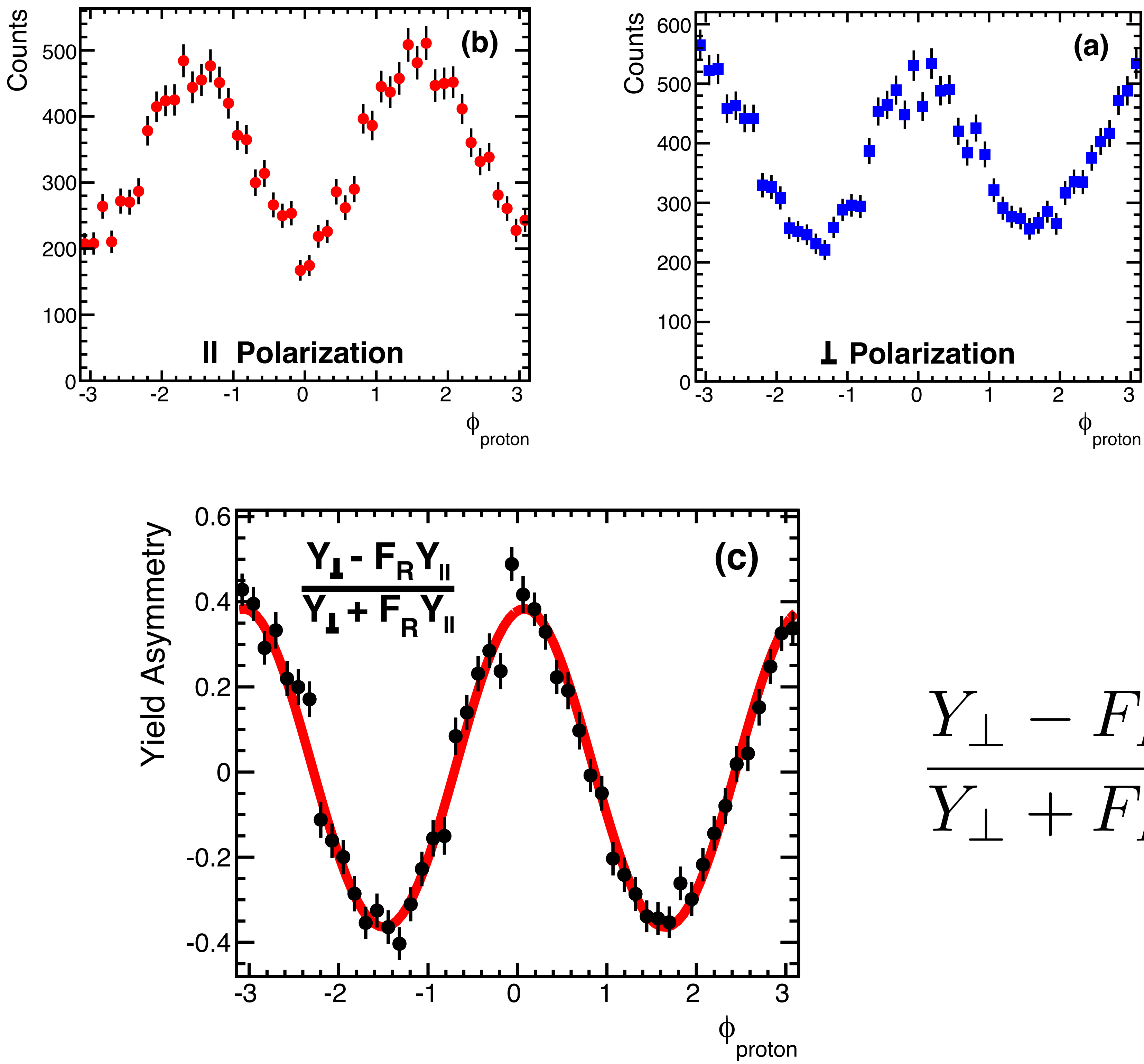
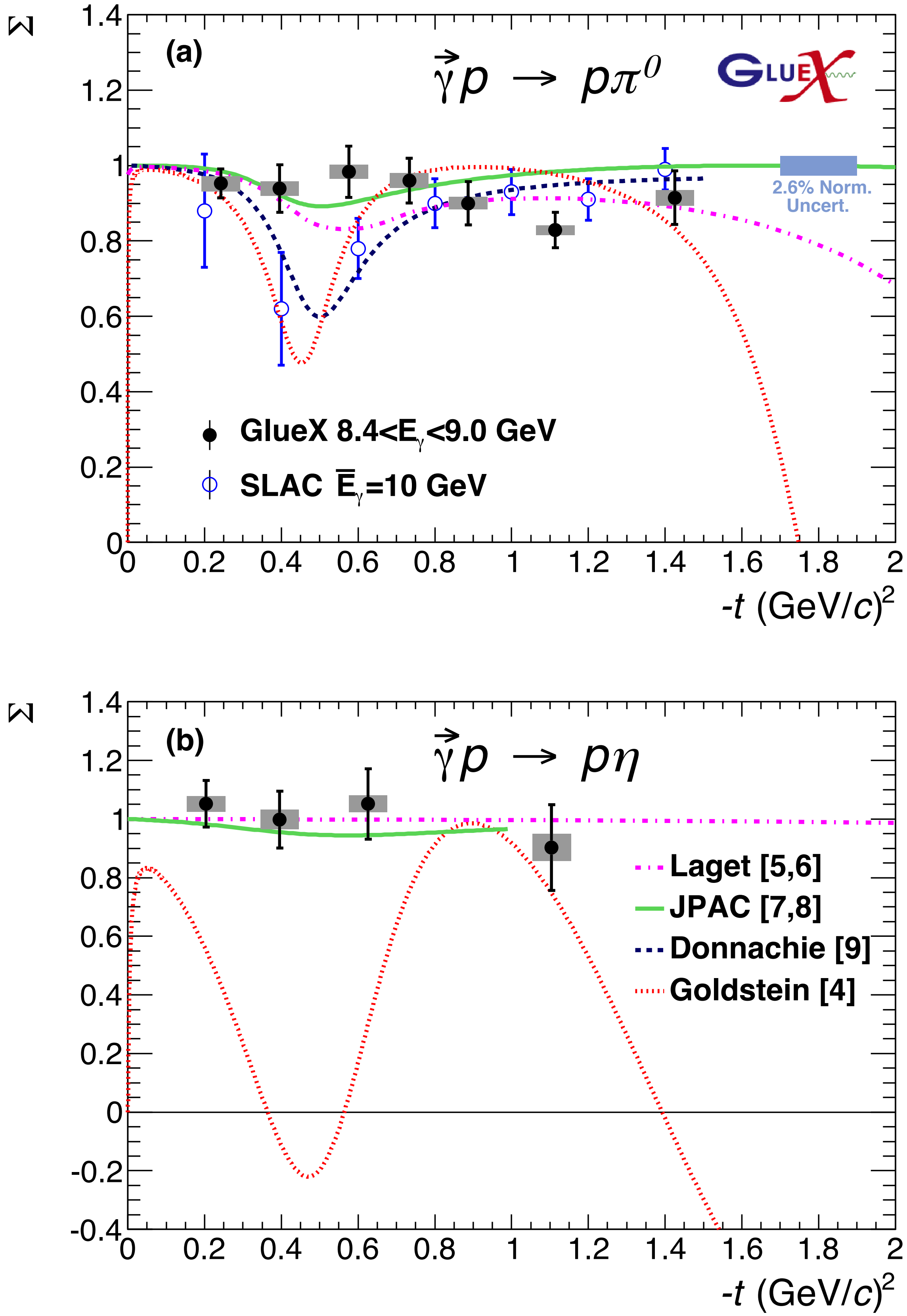
π^0 and η beam asymmetries



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

Phys. Rev. C 95, 042201(R)

π^0 and η beam asymmetries



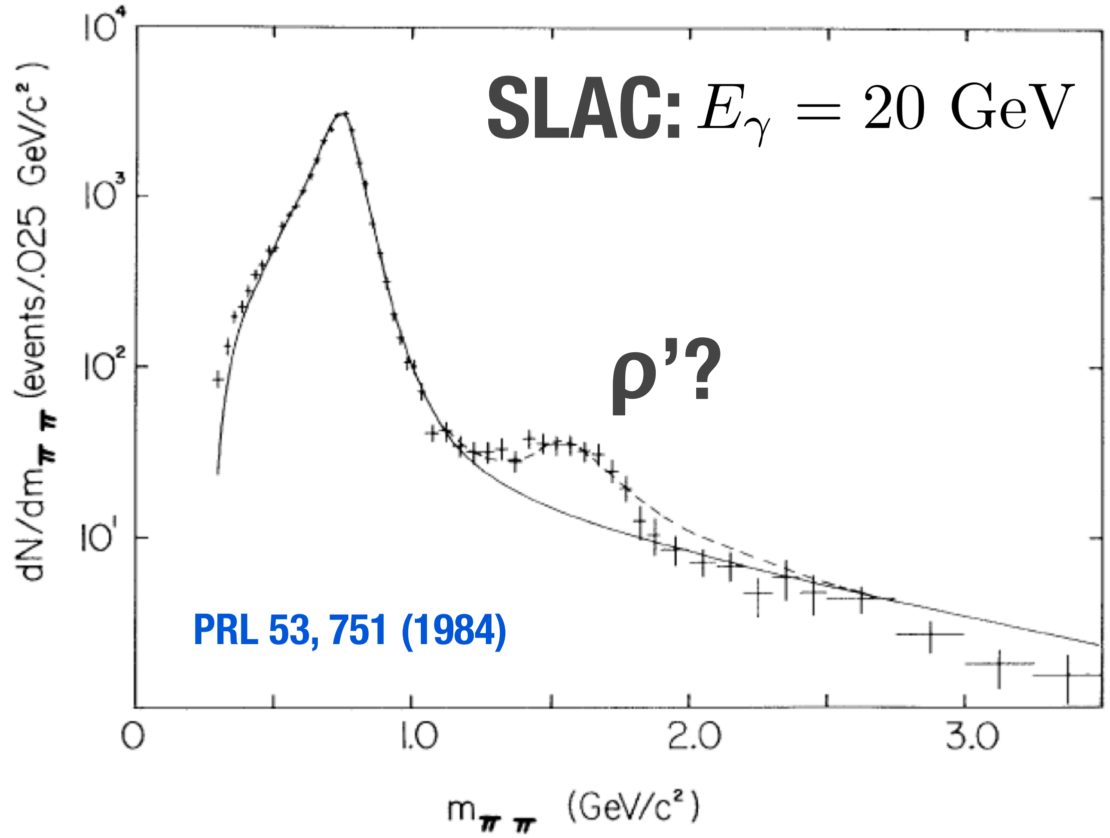
- Dip in multiple theory predictions not observed
- Indication of vector exchange dominance at this energy
- Additional asymmetry measurements ongoing with larger dataset

Phys. Rev. C 95, 042201(R)

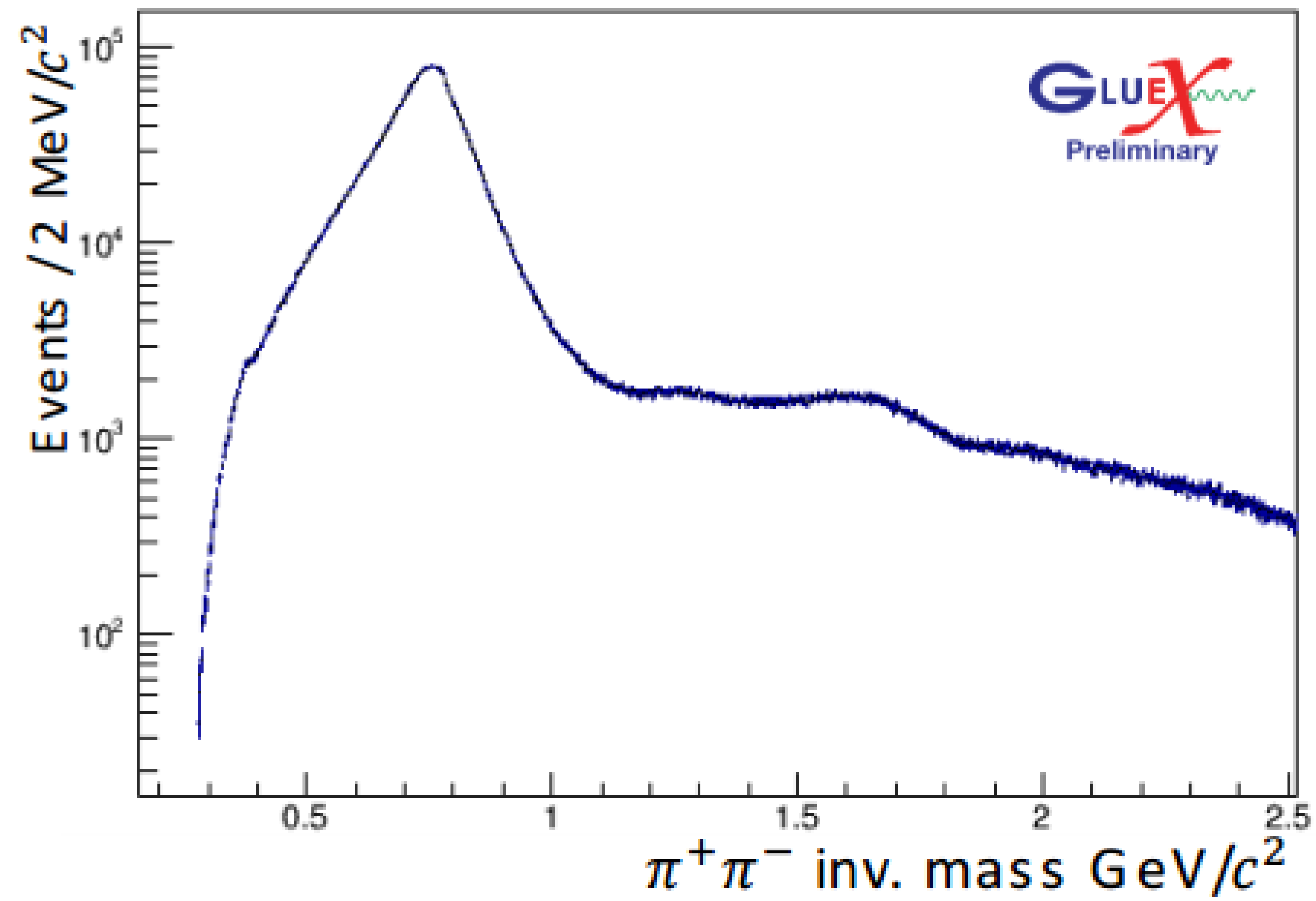
First 12 GeV publication!

Early spectroscopy opportunities

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



$8.4 < E_\gamma < 9.0$ GeV

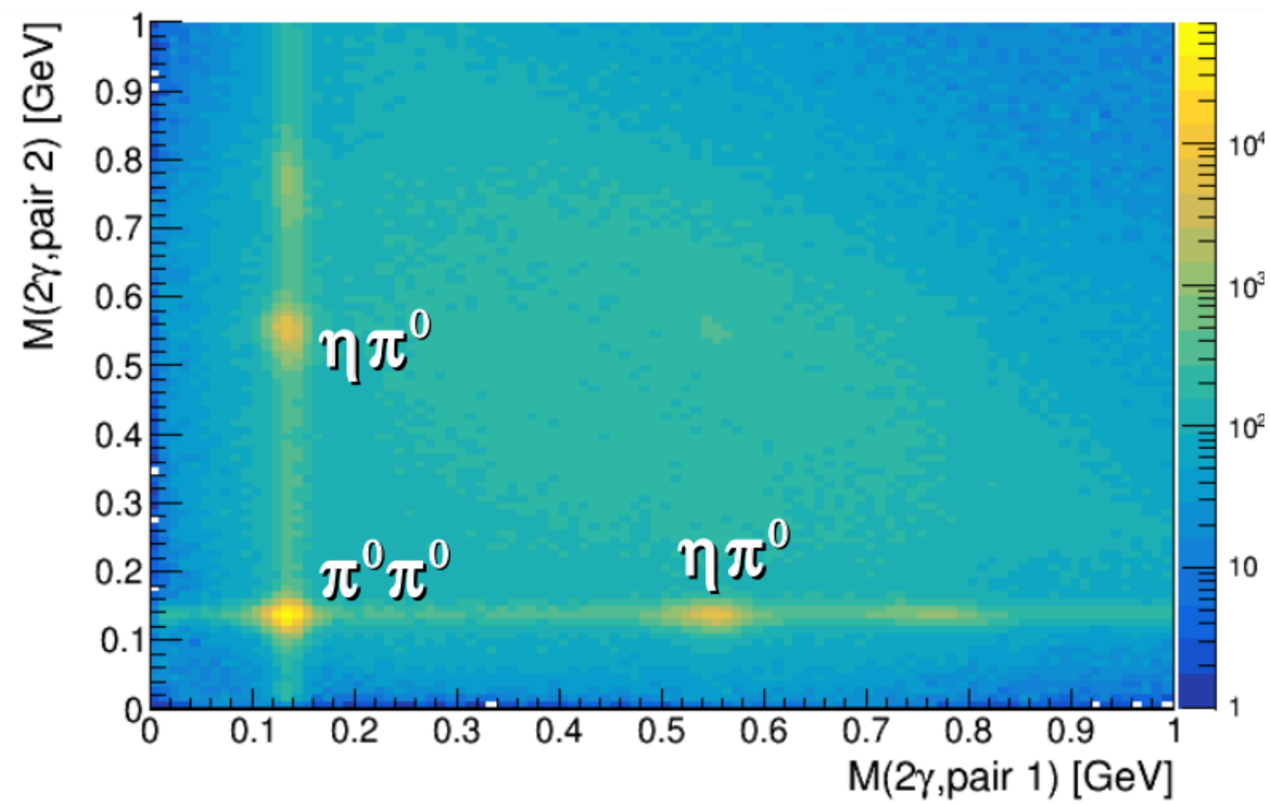


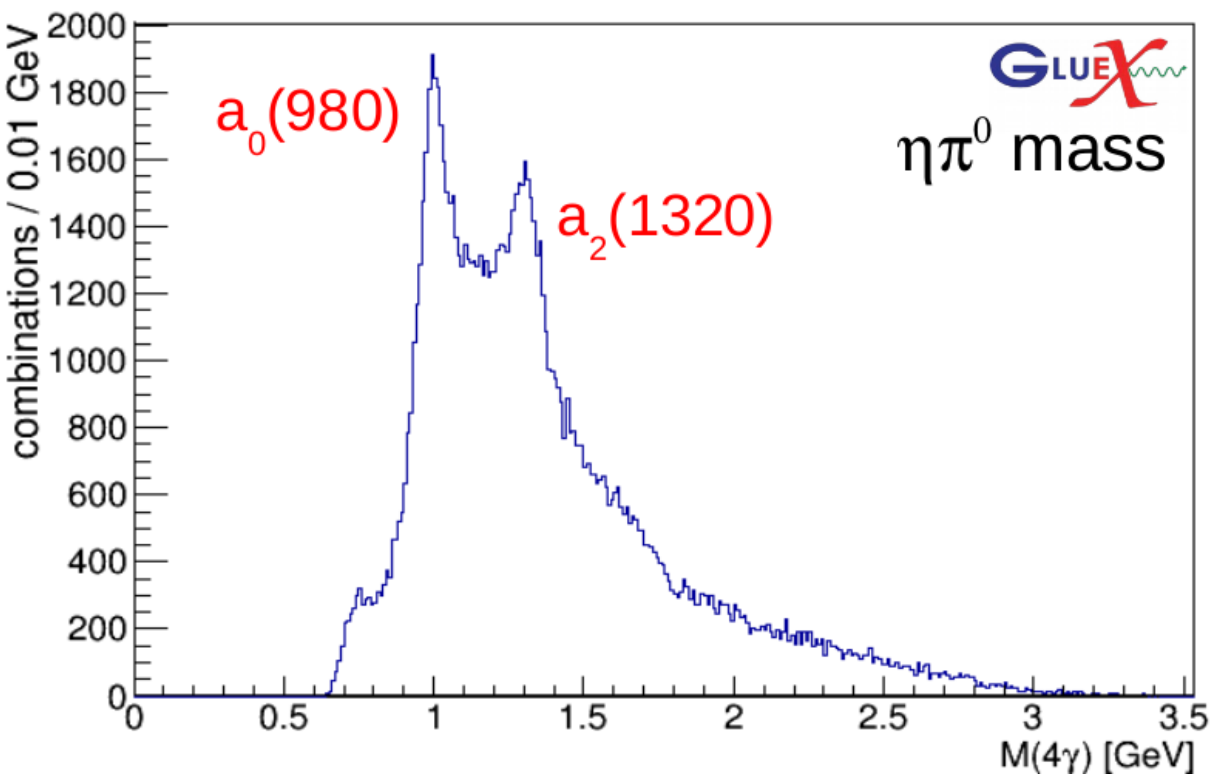
- Enhancement consistent with earlier SLAC measurement, but ~100x more statistics with early GlueX data
- Polarization observables will provide further insight into the nature of this enhancement

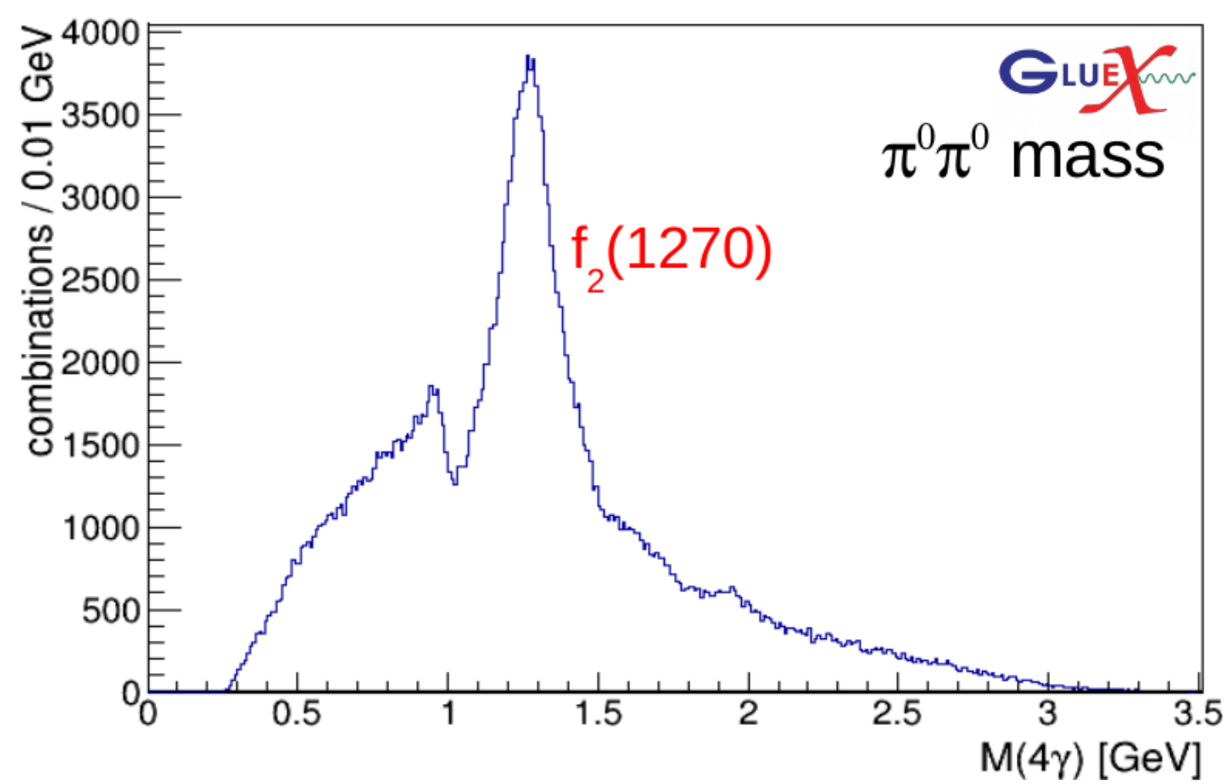
Early spectroscopy opportunities

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

- Previous photoproduction data very sparse for channels with multiple neutrals particles
- Preliminary studies are already showing interesting features

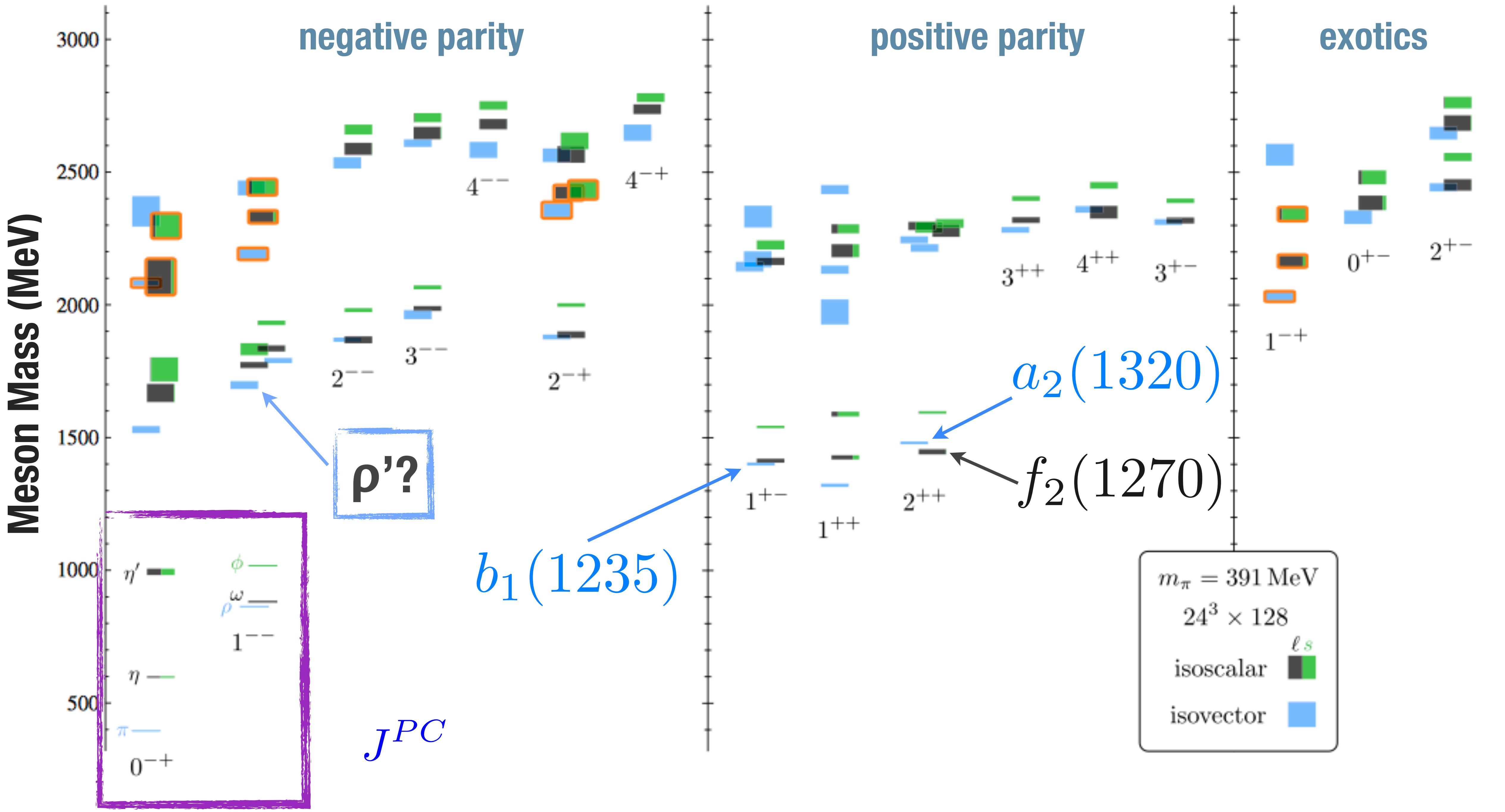






Mapping the meson spectrum

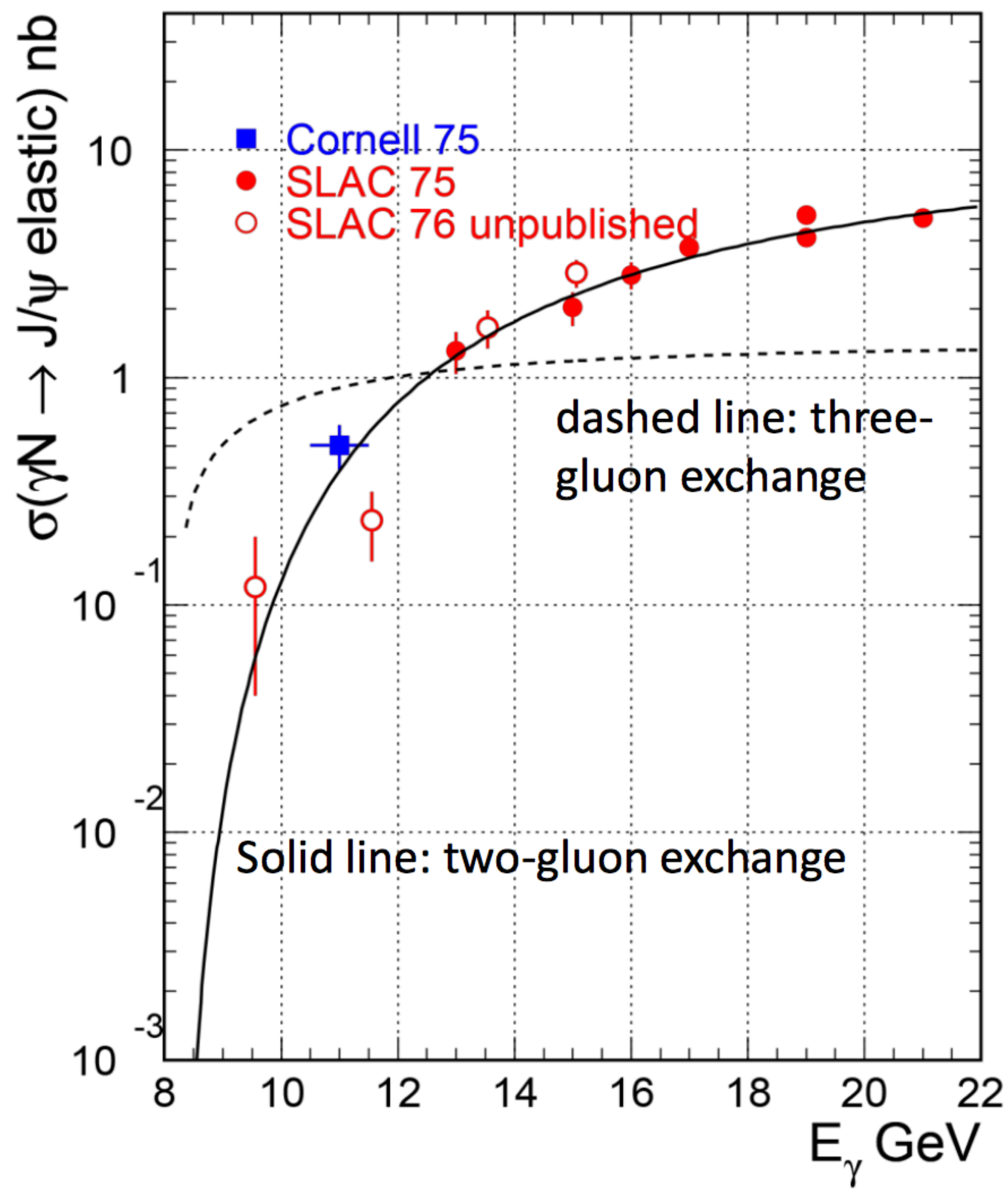
PRD 88 (2013) 094505

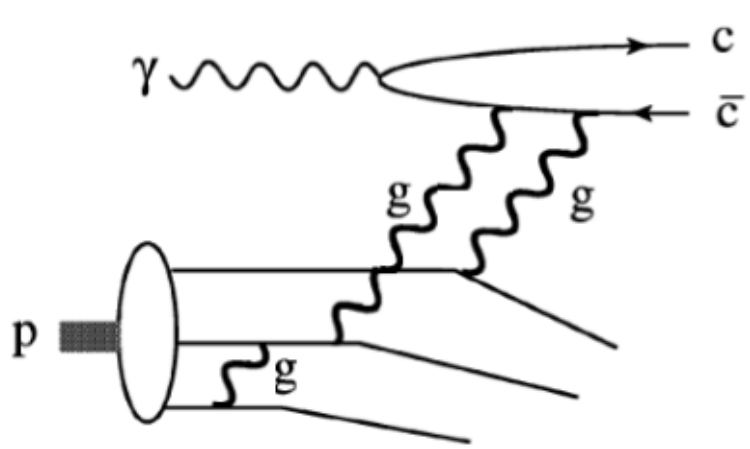


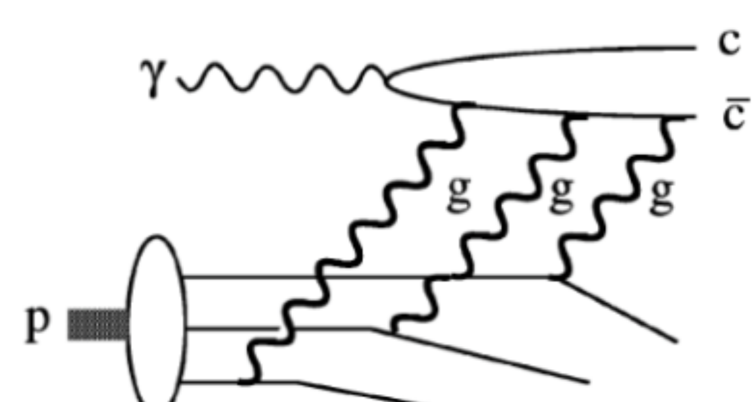
- Already studying polarization observables for **"simple" final states**
- Beginning to identify **known mesons** in multi-particle final states

J/ψ photoproduction at JLab

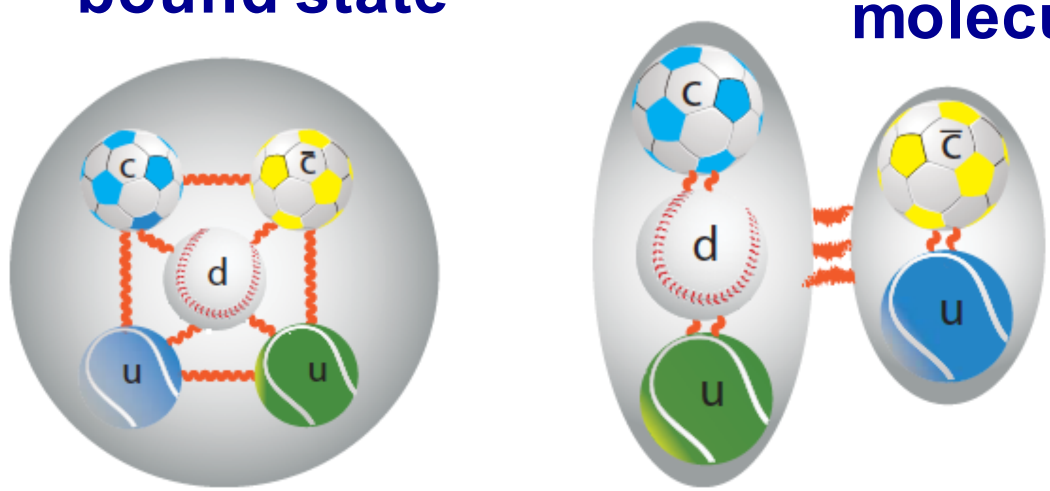
- Threshold J/ψ provides information on the gluon distributions in the nucleon
- Planned measurements in Hall A, B and C
- First data from Hall D already under analysis



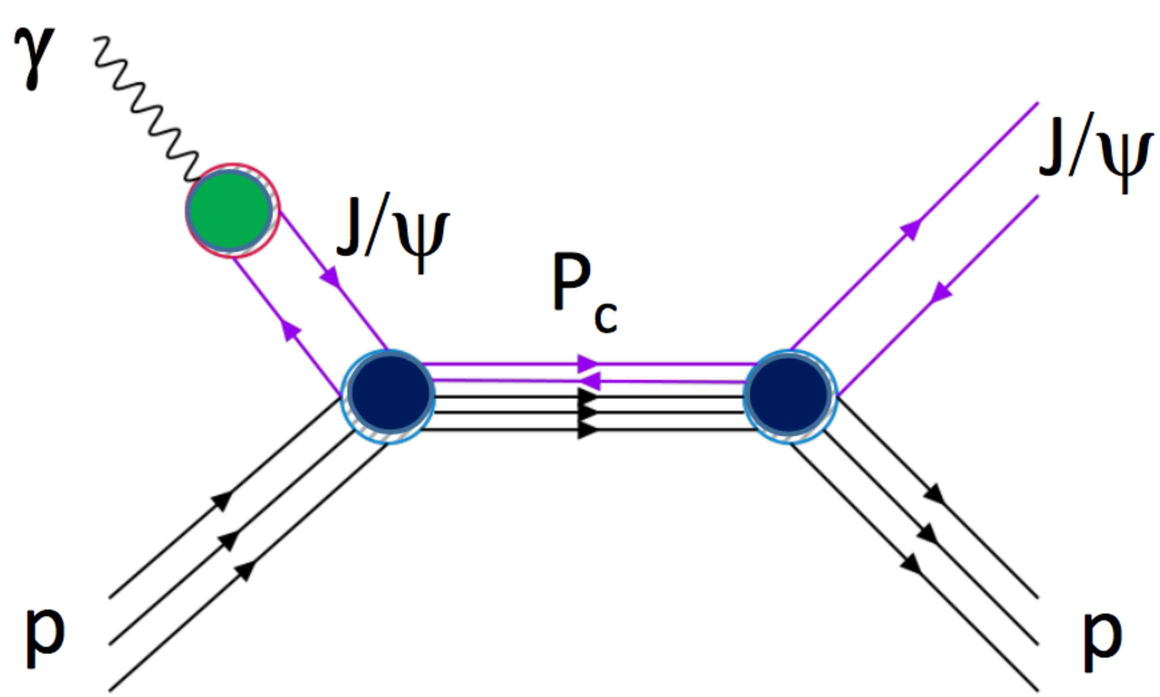




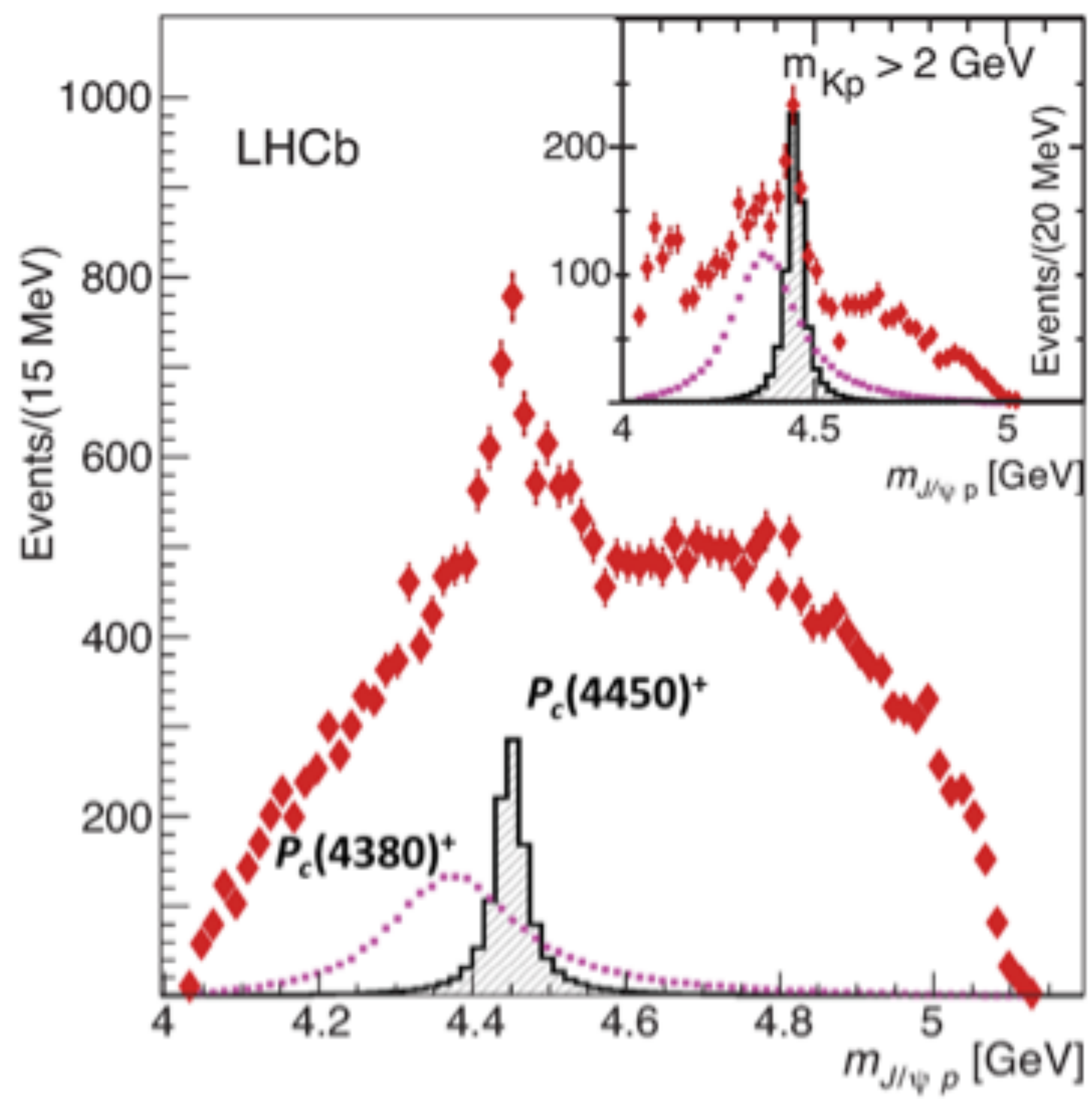
Pentaquark searches at JLab



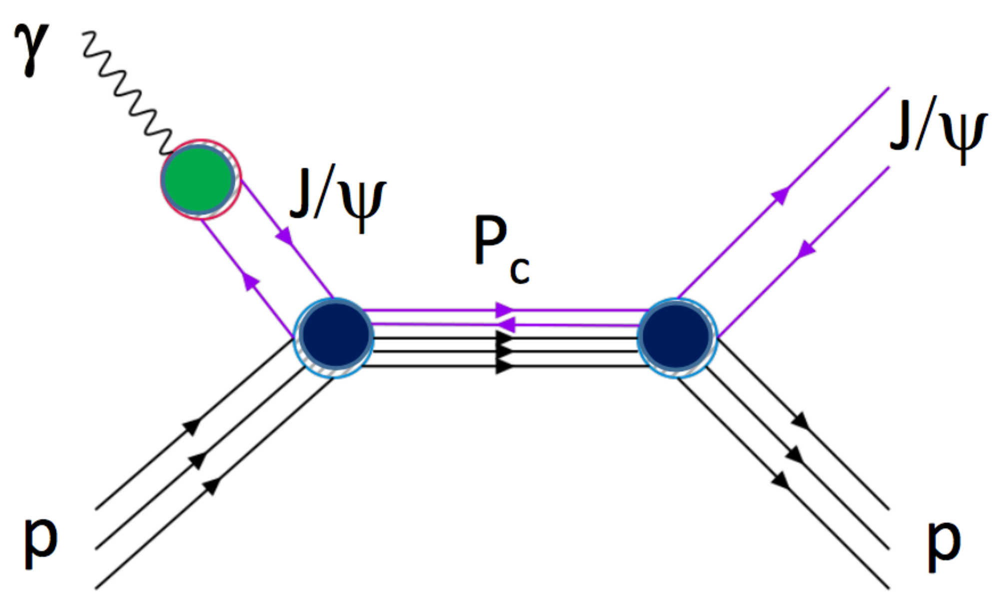
or cusp, triangle singularity, etc…



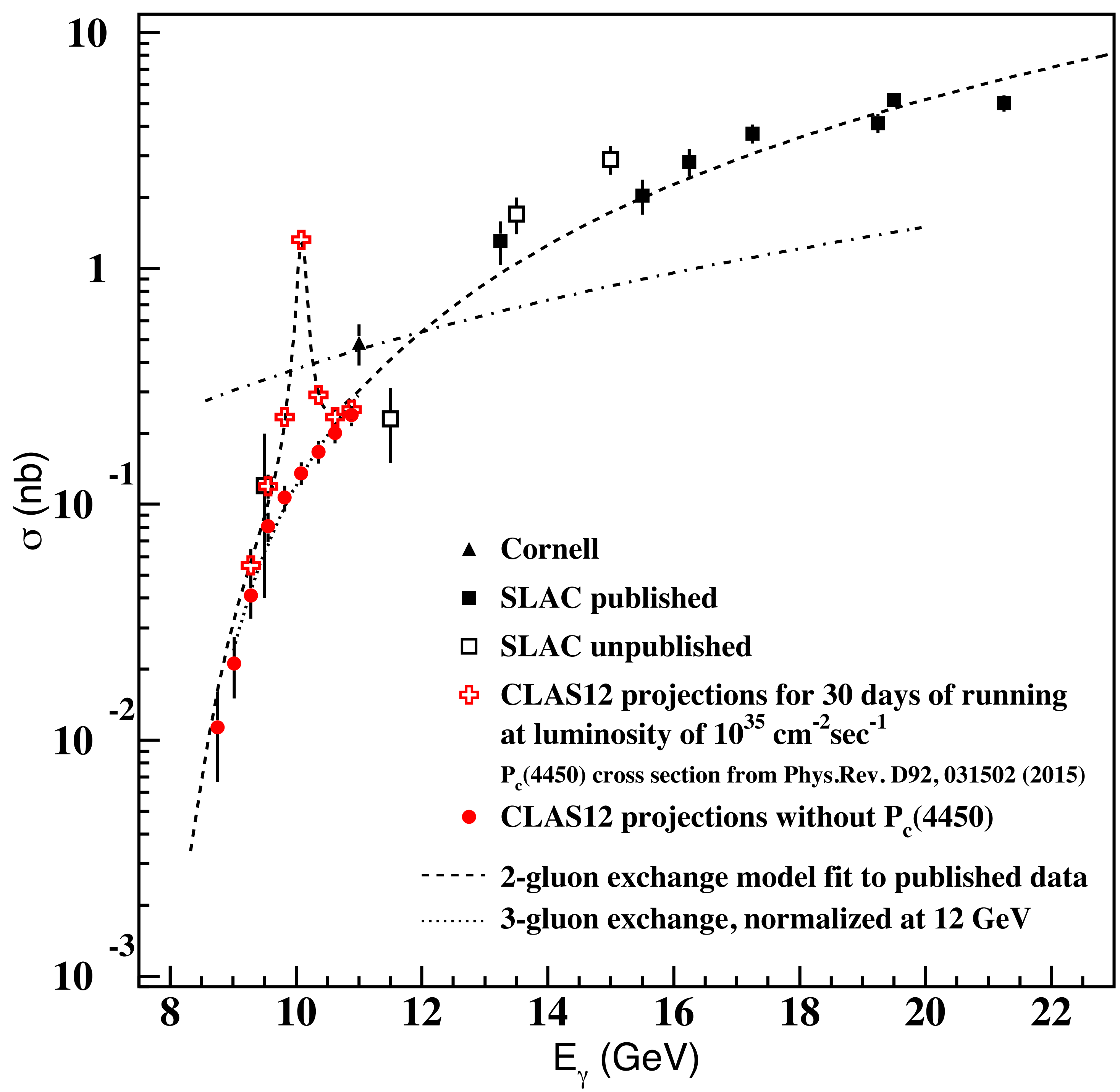
$$\Lambda_b \to J/\psi p K^-$$



Pentaquark search at CLAS12



- Projection for 30 days at full luminosity
- Uses CLAS12 standard equipment, first data in 2018

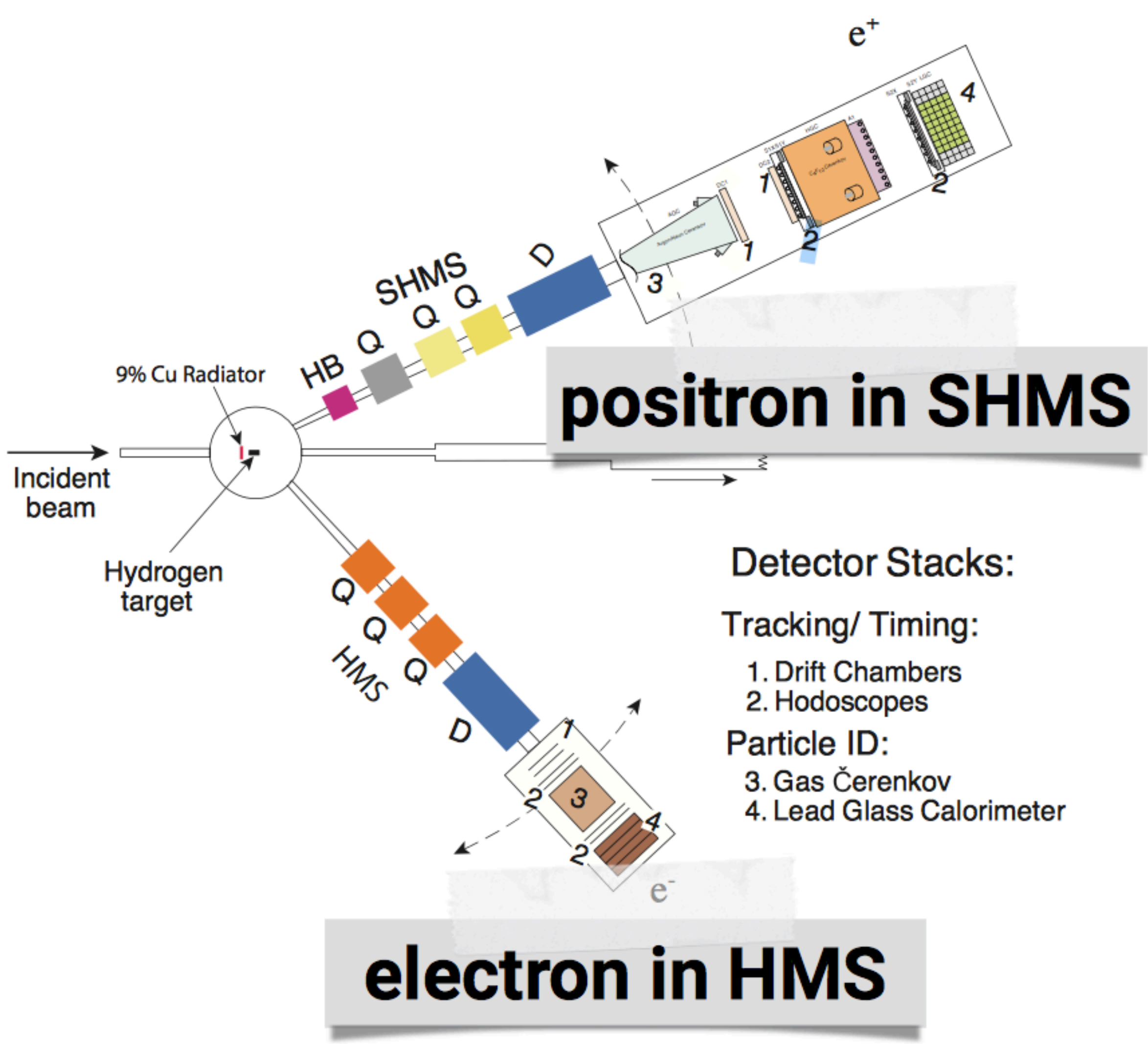


Run Group: E12-12-001A

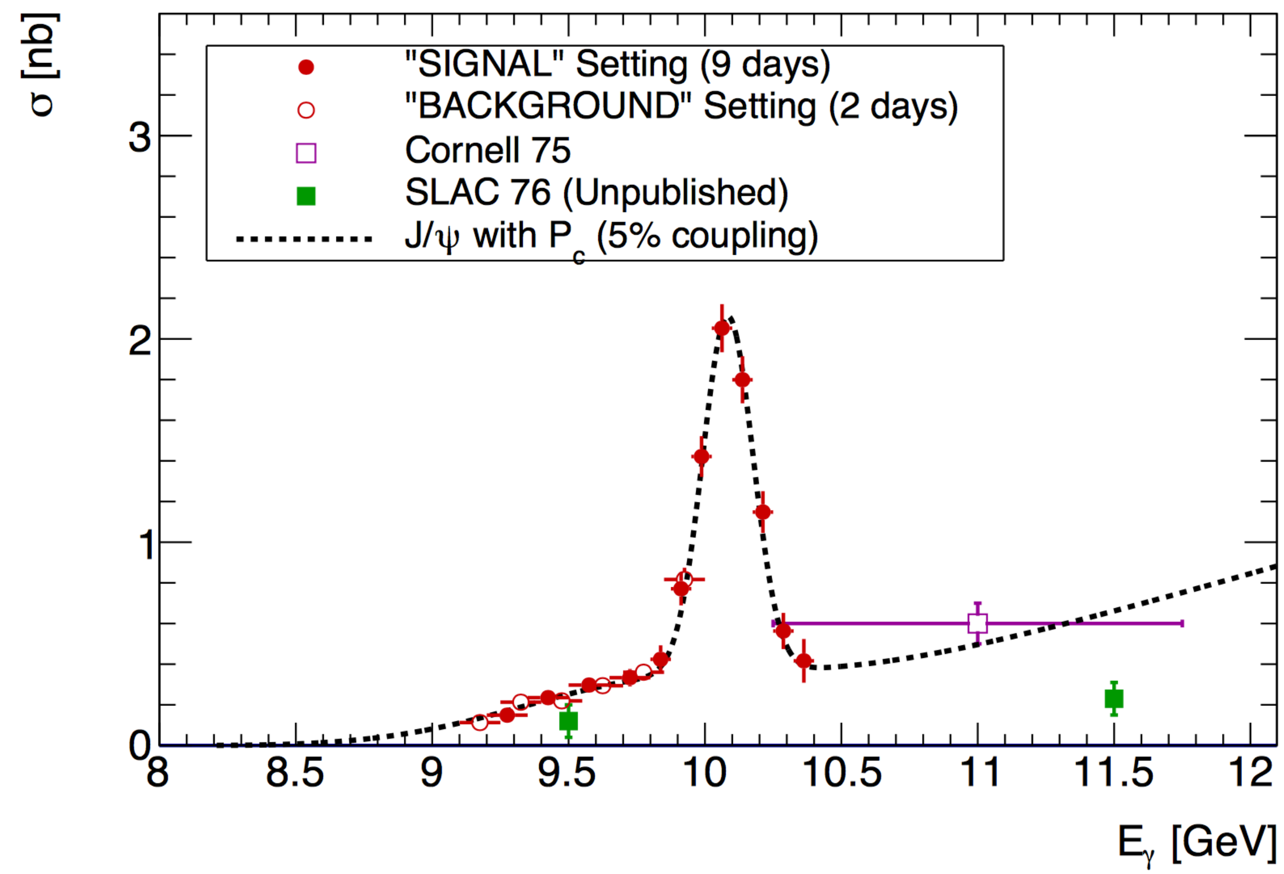
Pentaquark Search in Hall C

$$\gamma p \to J/\psi p$$

$$J/\psi \to e^+ e^-$$

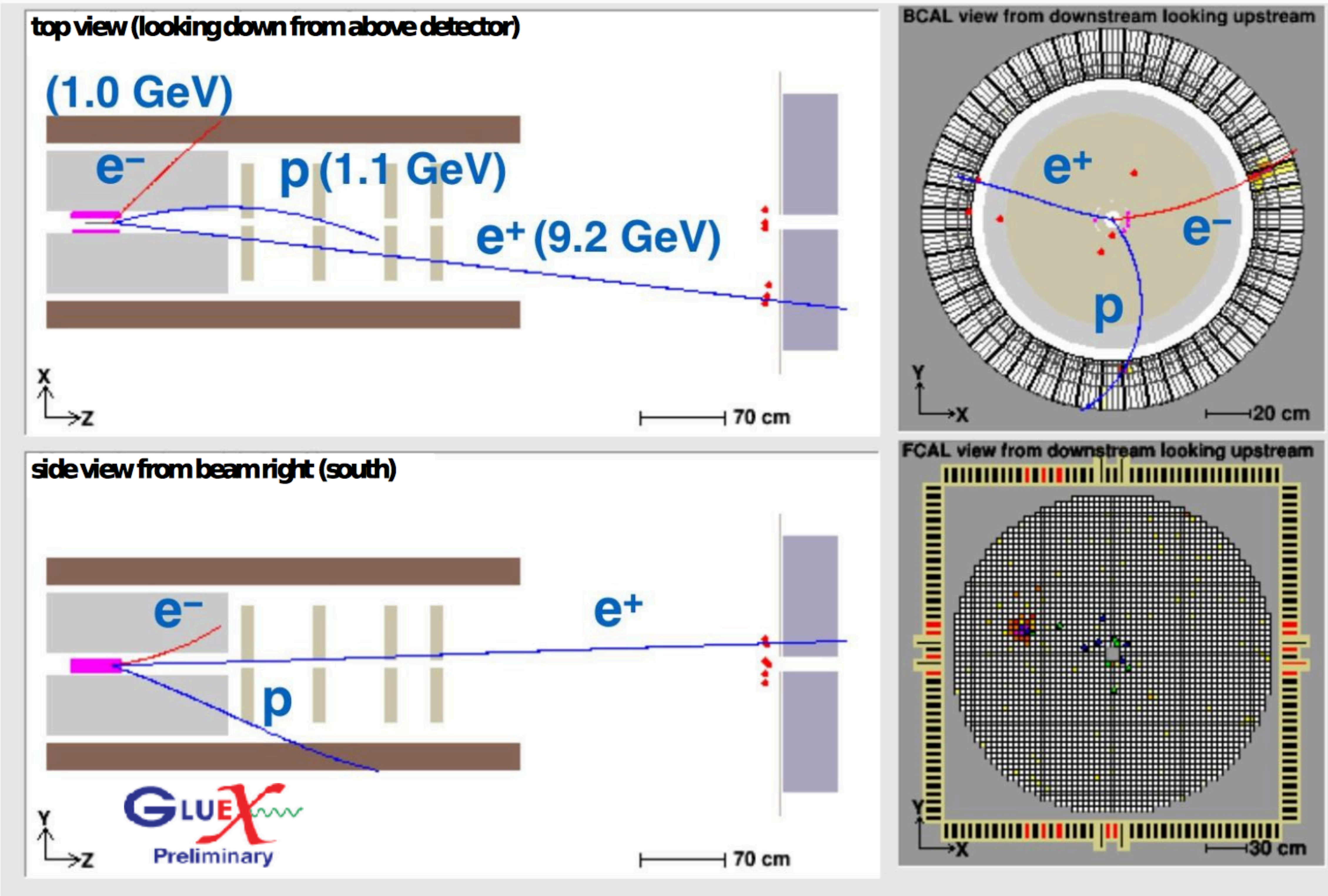


E12-16-007

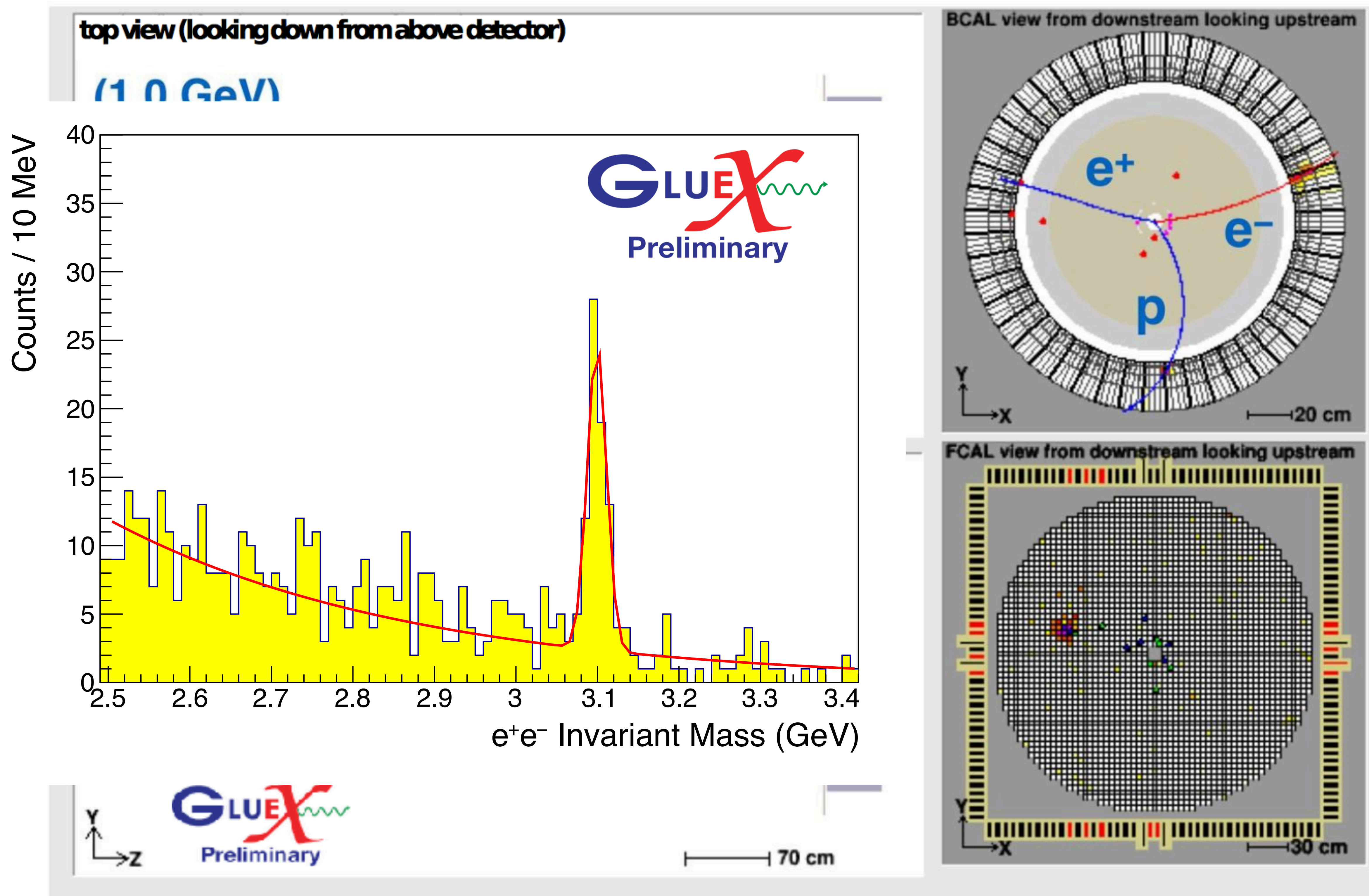


- Elastic J/ψ production using Hall C standard equipment
- Short experiment (11 days) with high impact

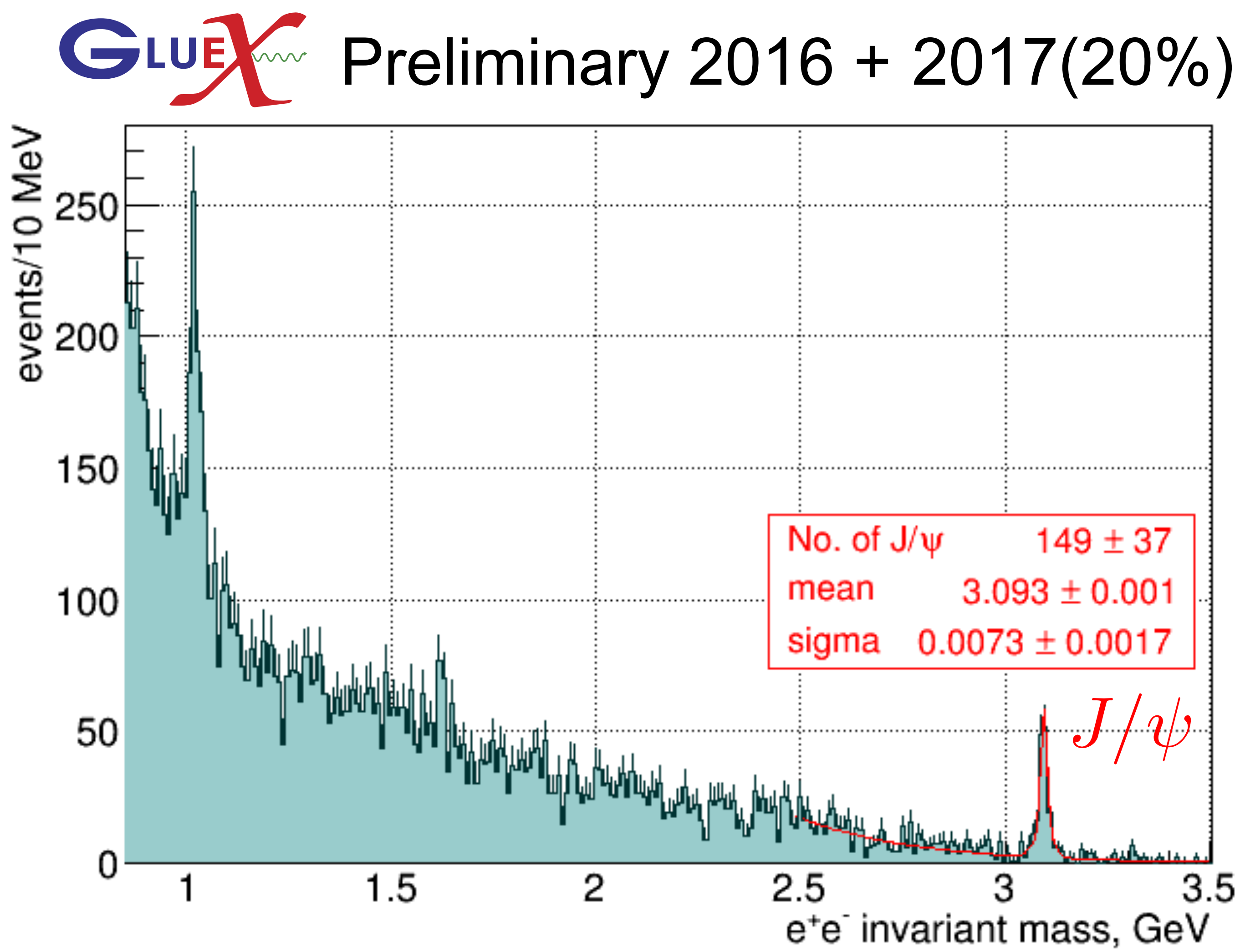
Observation of charm at GlueX

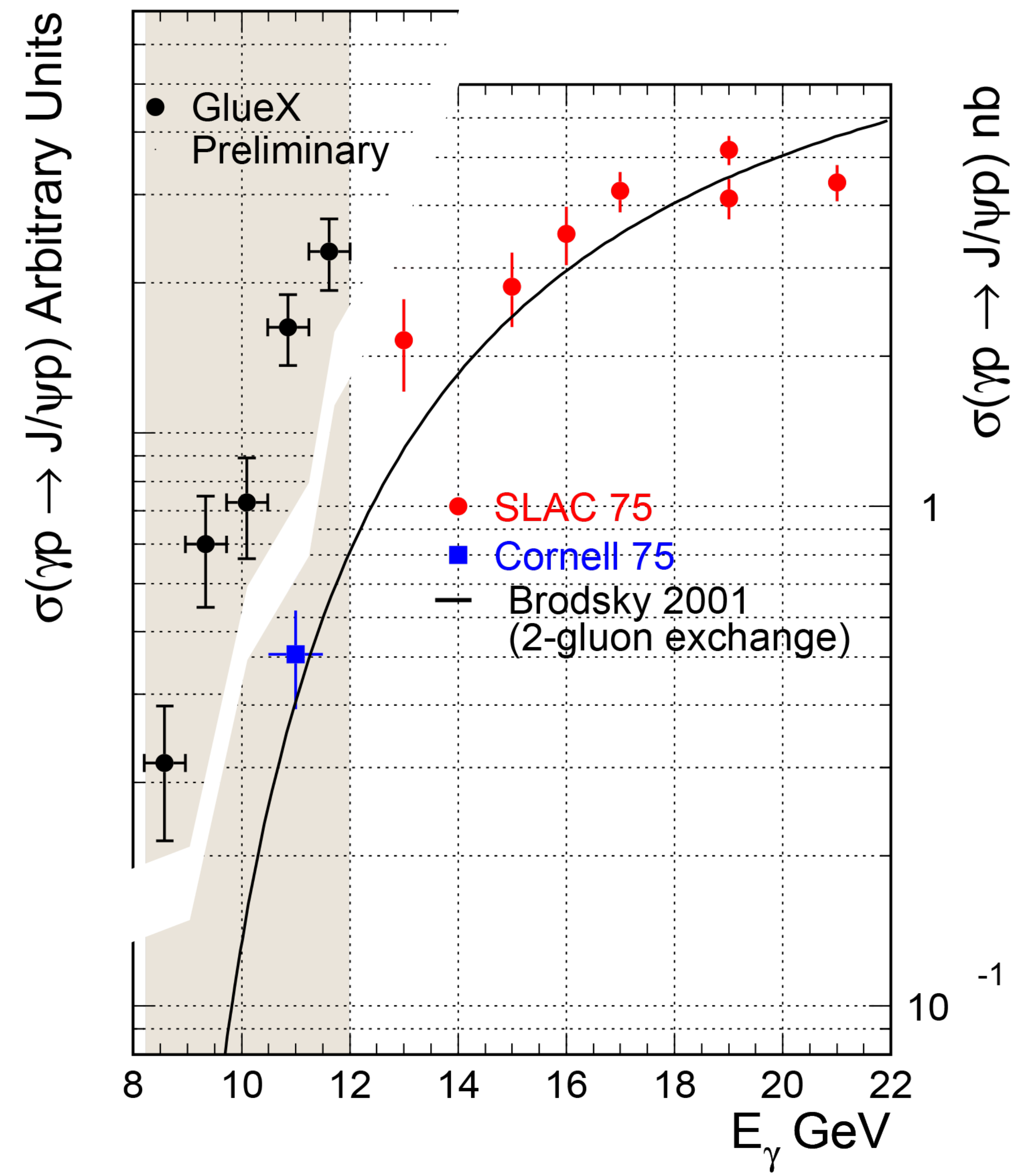


Observation of charm at GlueX



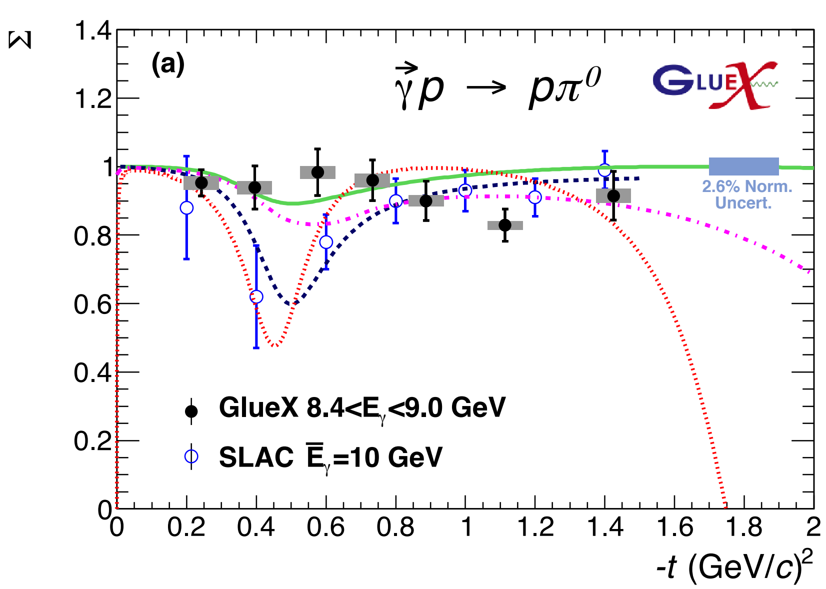
J/ψ photoproduction at GlueX

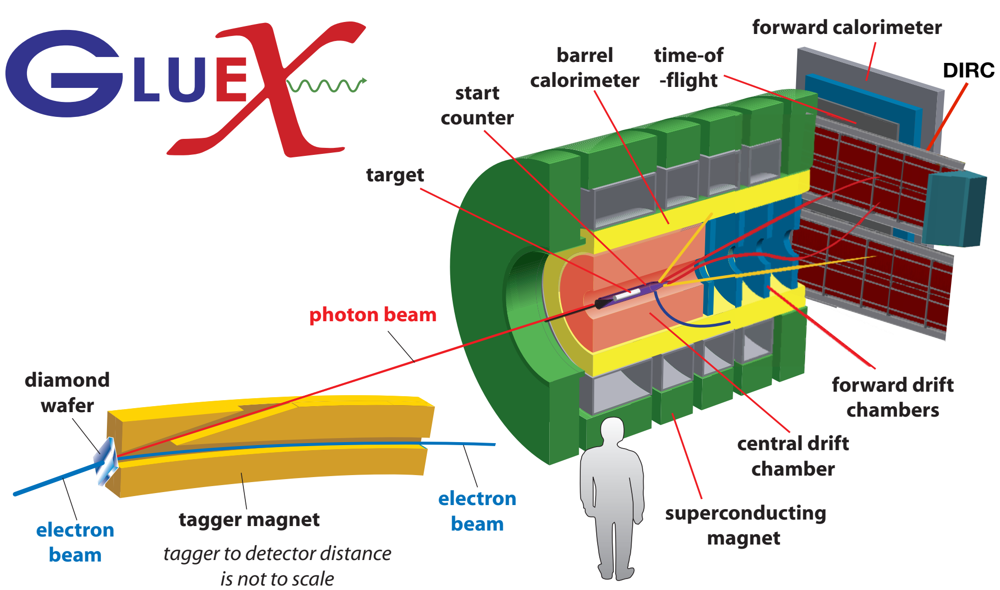


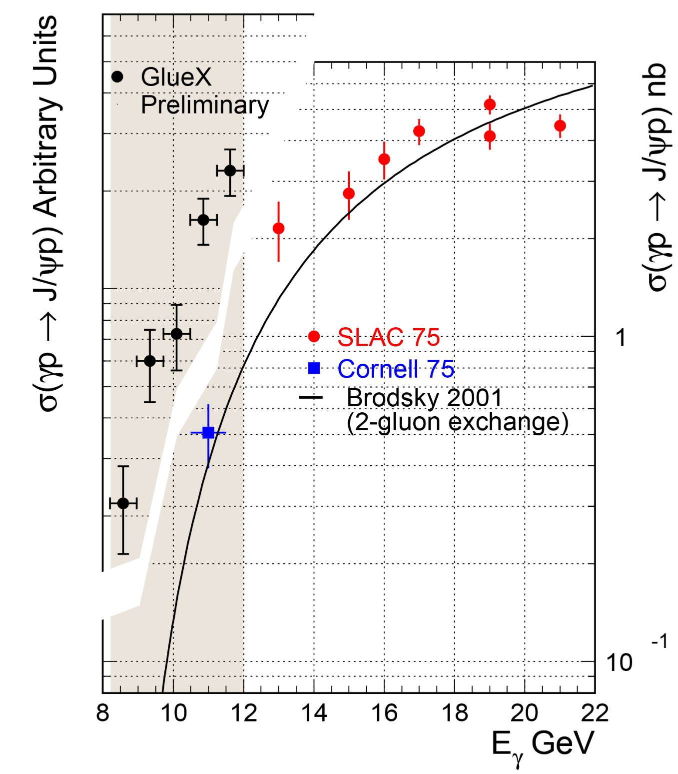


Summary

- The GlueX detector has completed commissioning and the initial physics program has begun
- First 12 GeV publication from the Spring 2016 data has implications for the meson production mechanism
- Program of threshold J/ψ measurements in all four halls to search for LHCb pentaquark

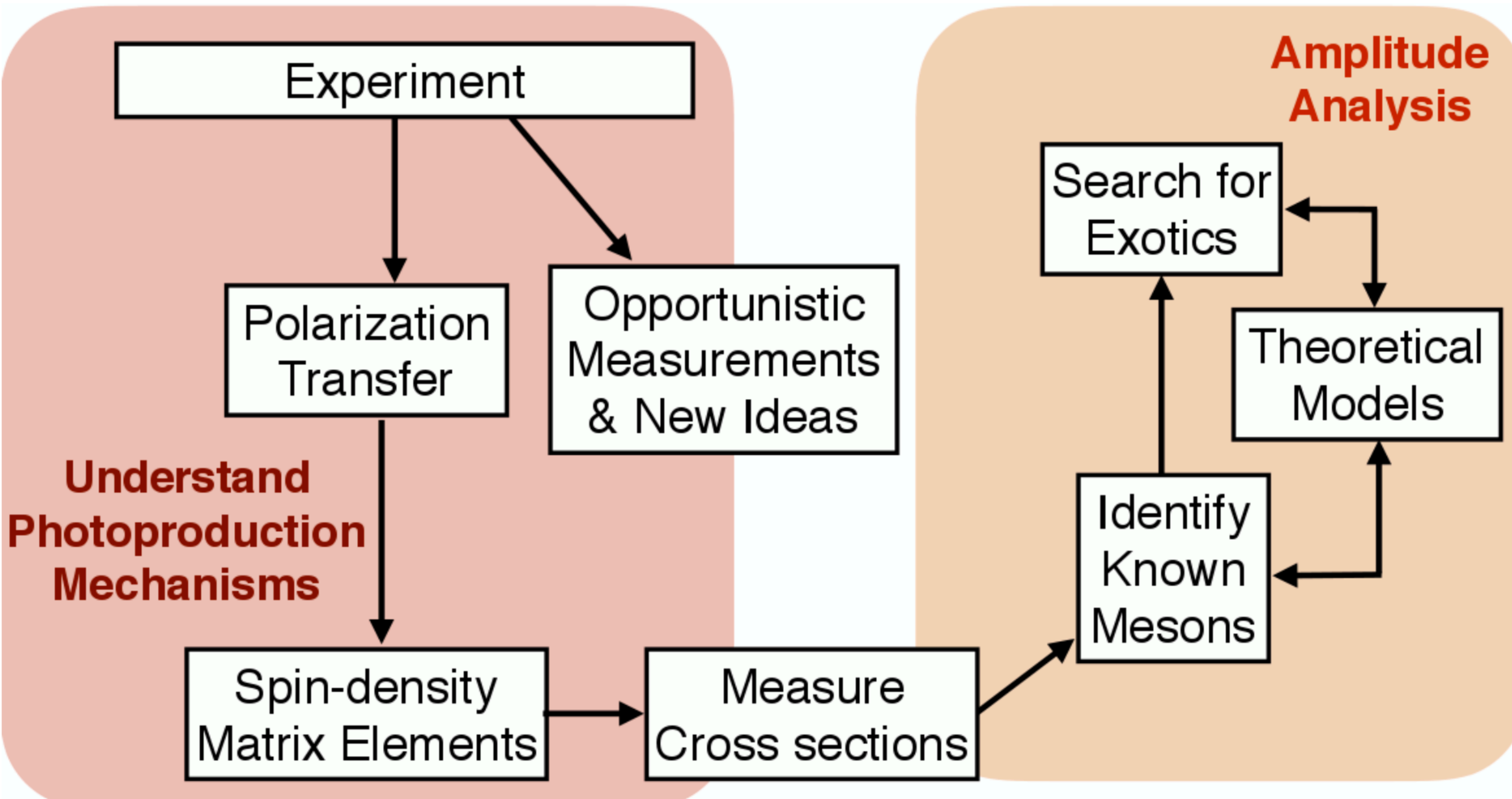






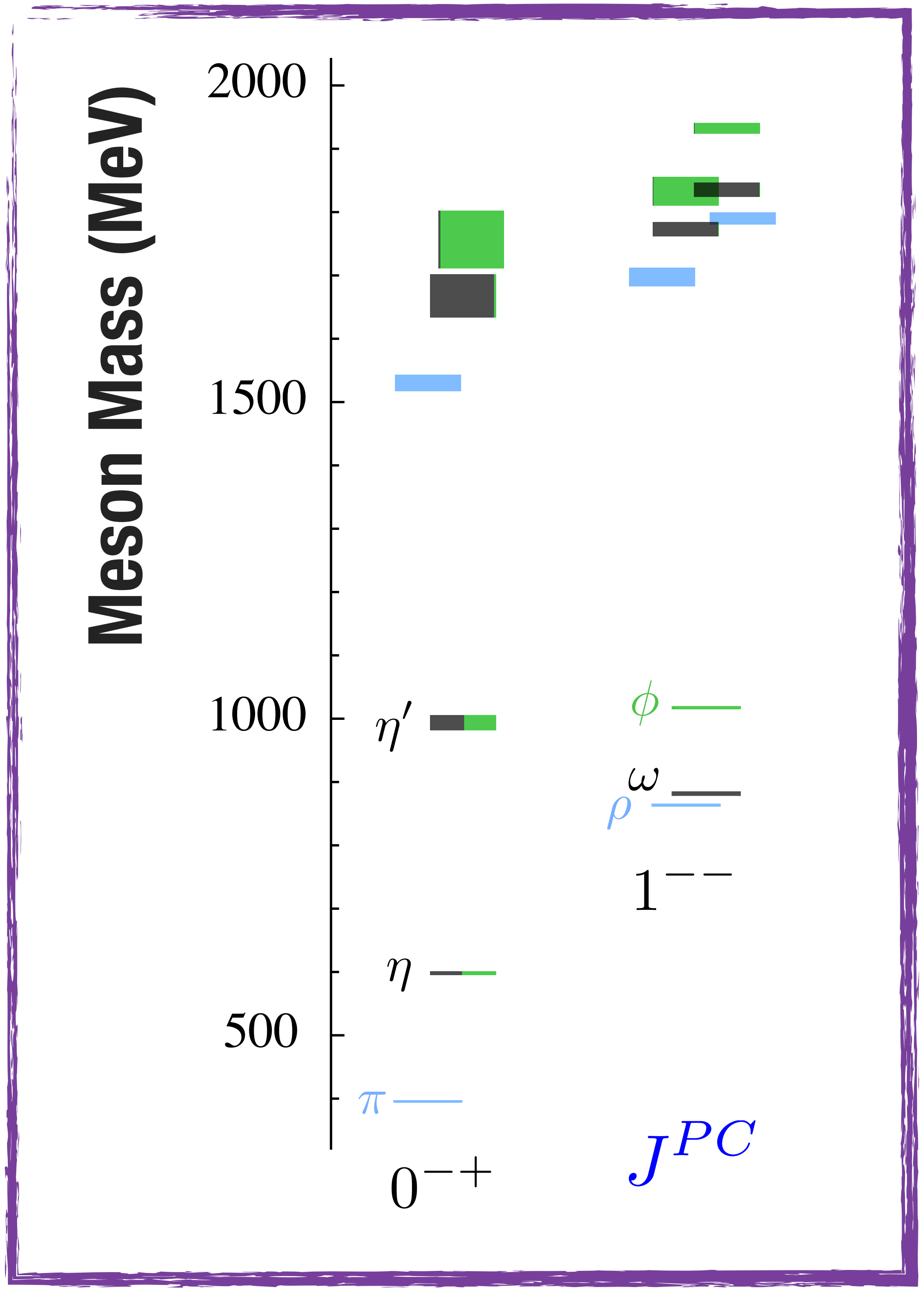
Backup

GlueX Physics Program



Lattice QCD: Mesons

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: Mesons

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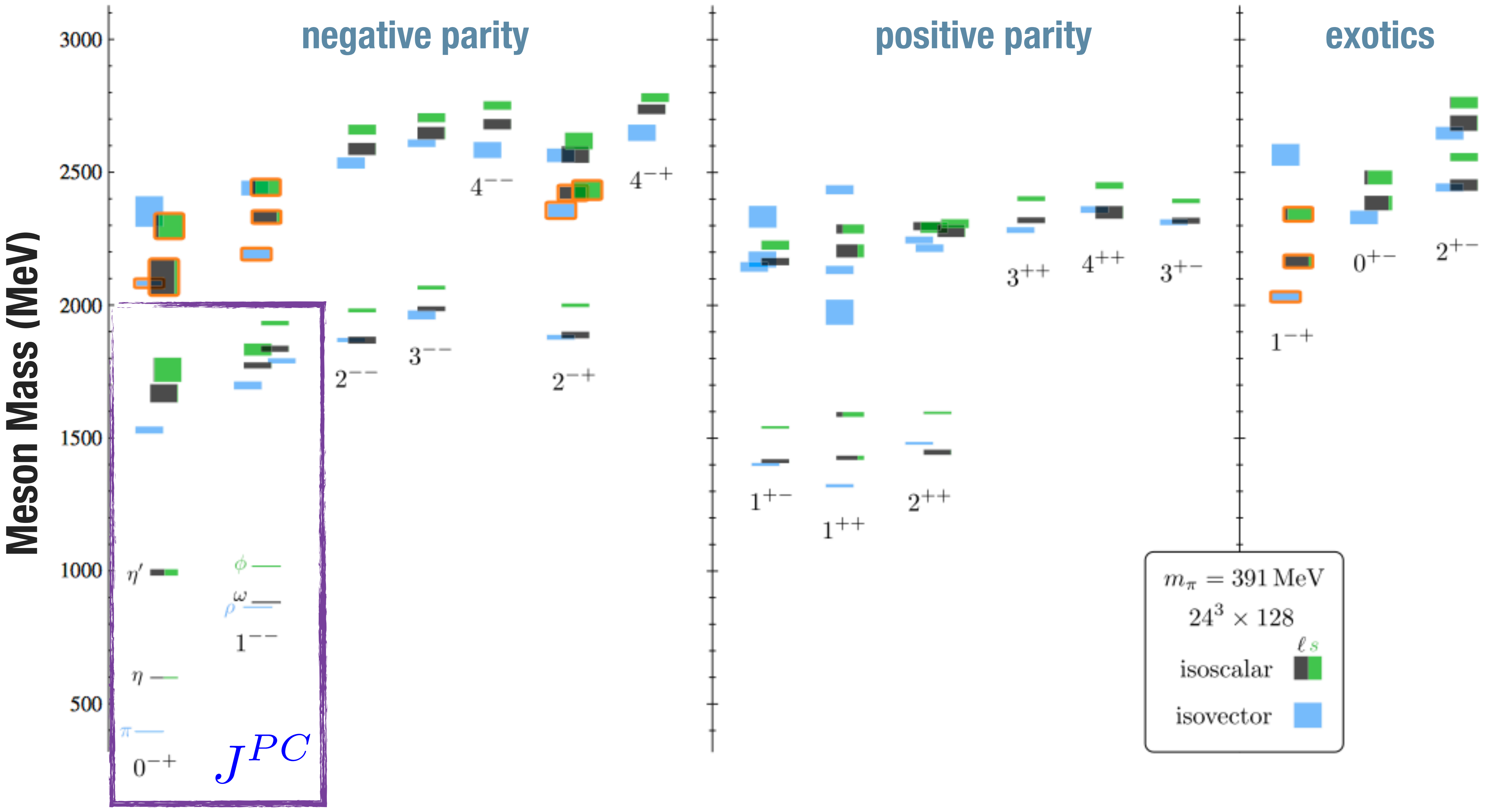

Exotic J^{PC} decays

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

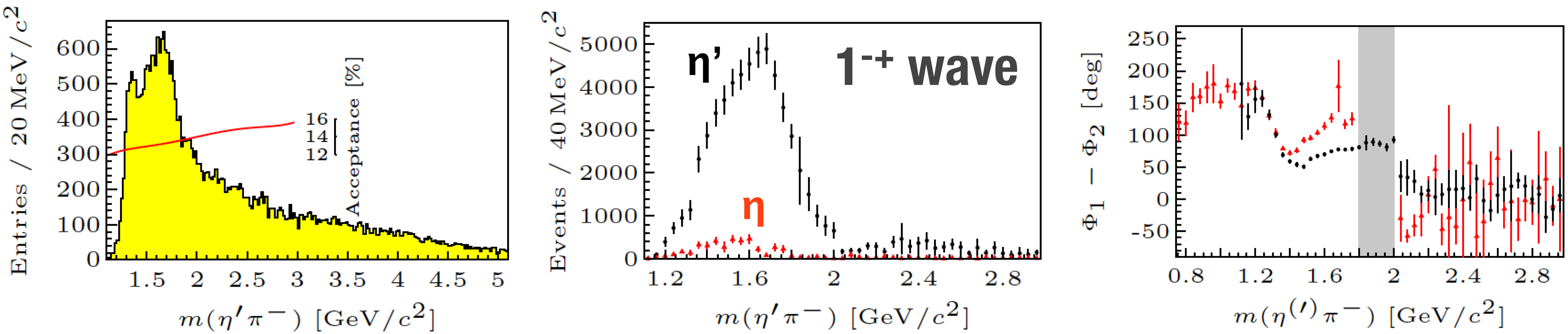
Some additional 1^{-+} channels

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

Evidence for 1^{-+} exotics

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

Compass: PLB 740 (2015) 303



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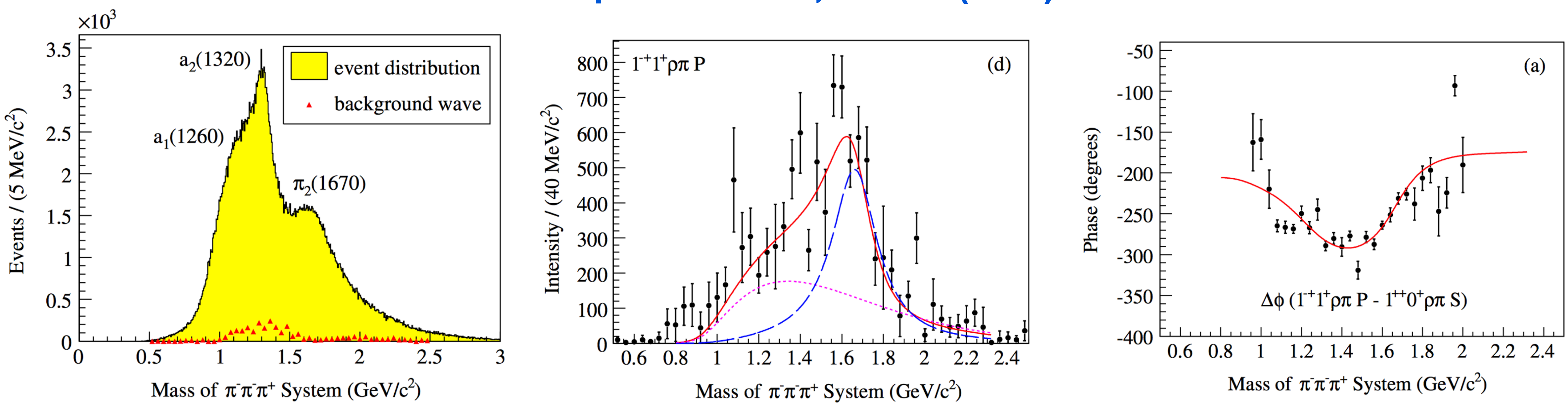
Compass: PRL 104, 241803 (2010)



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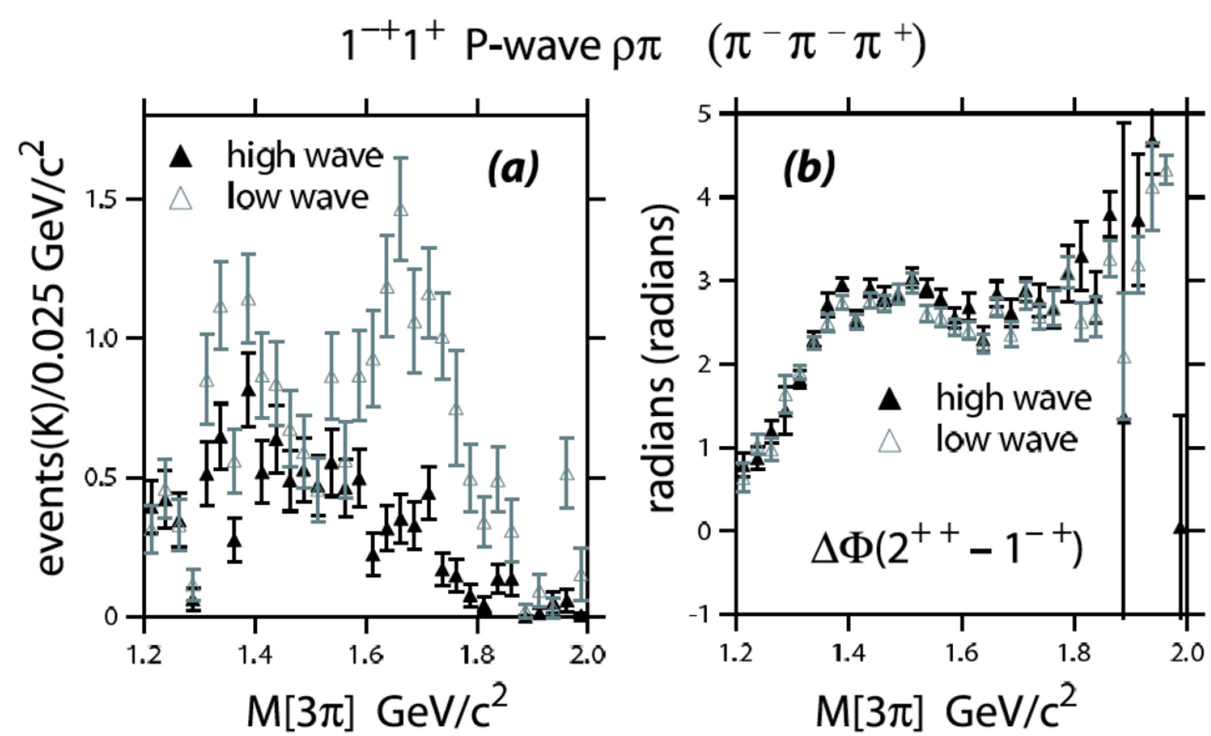
E852: PRD 73 (2006) 072001

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



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

Evidence for 1^{-+} exotics

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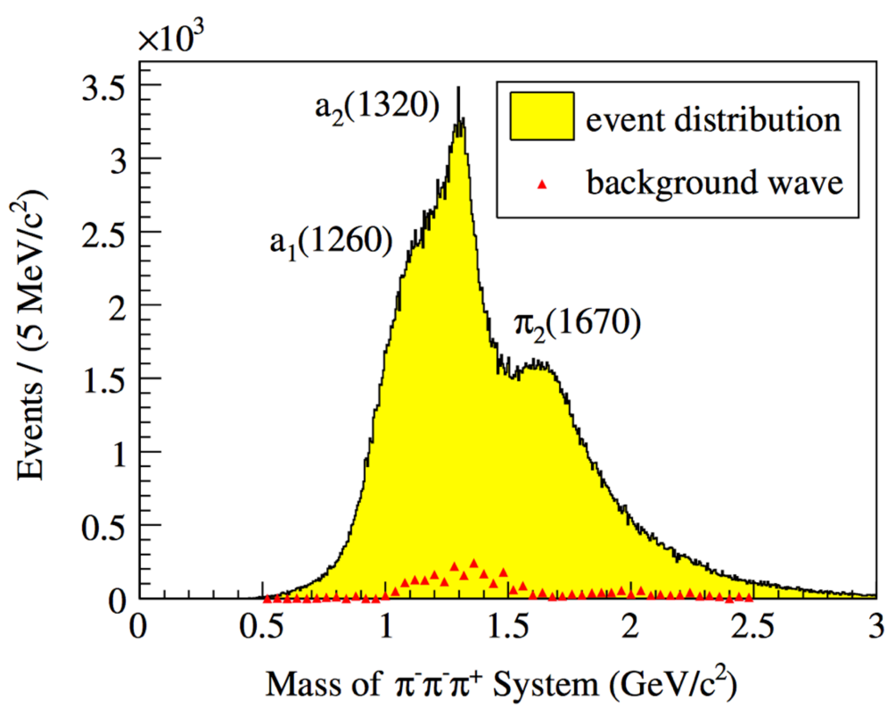
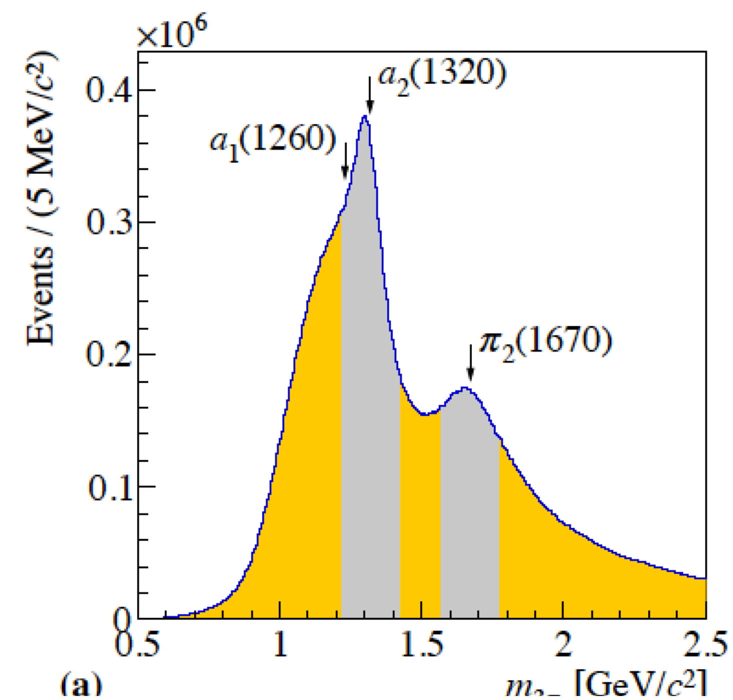


Unprecedented statistics

Compass: 1509.00992
Discuss non-exotic waves



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

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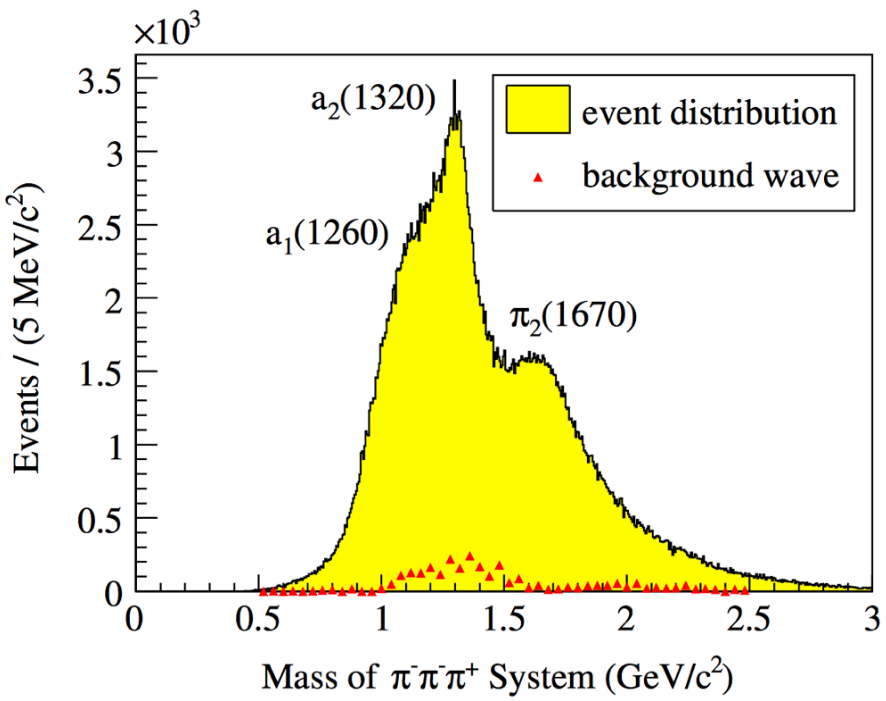

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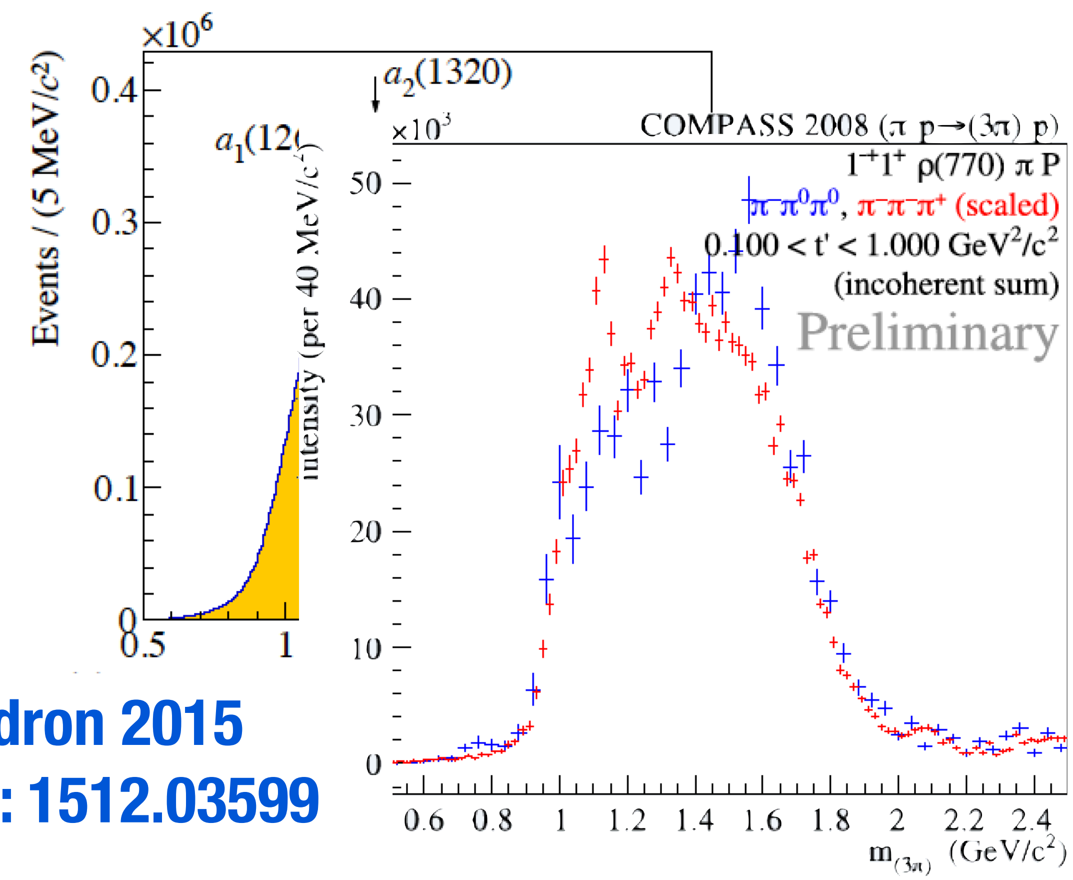
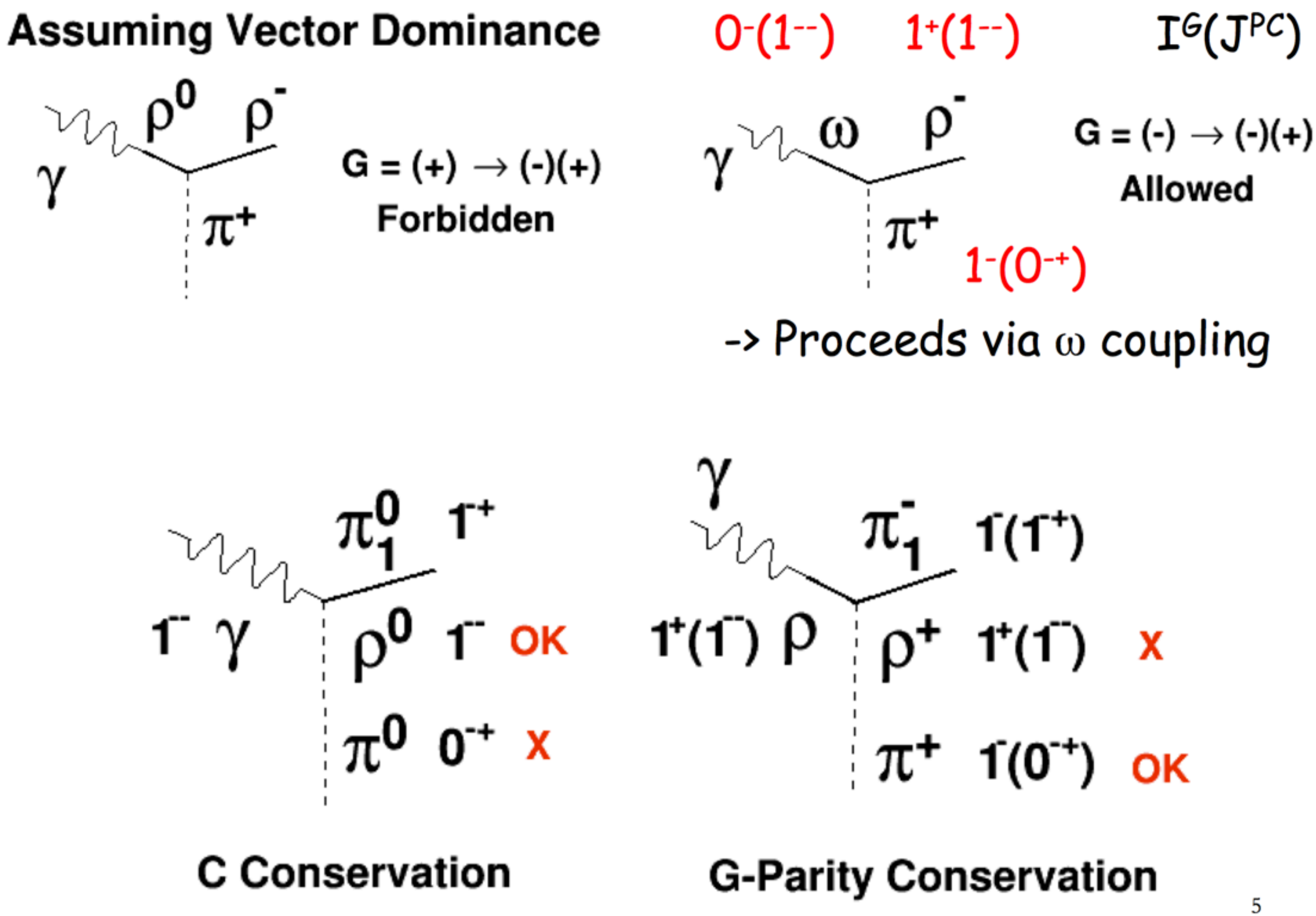


Hadron 2015

Grube: 1512.03599

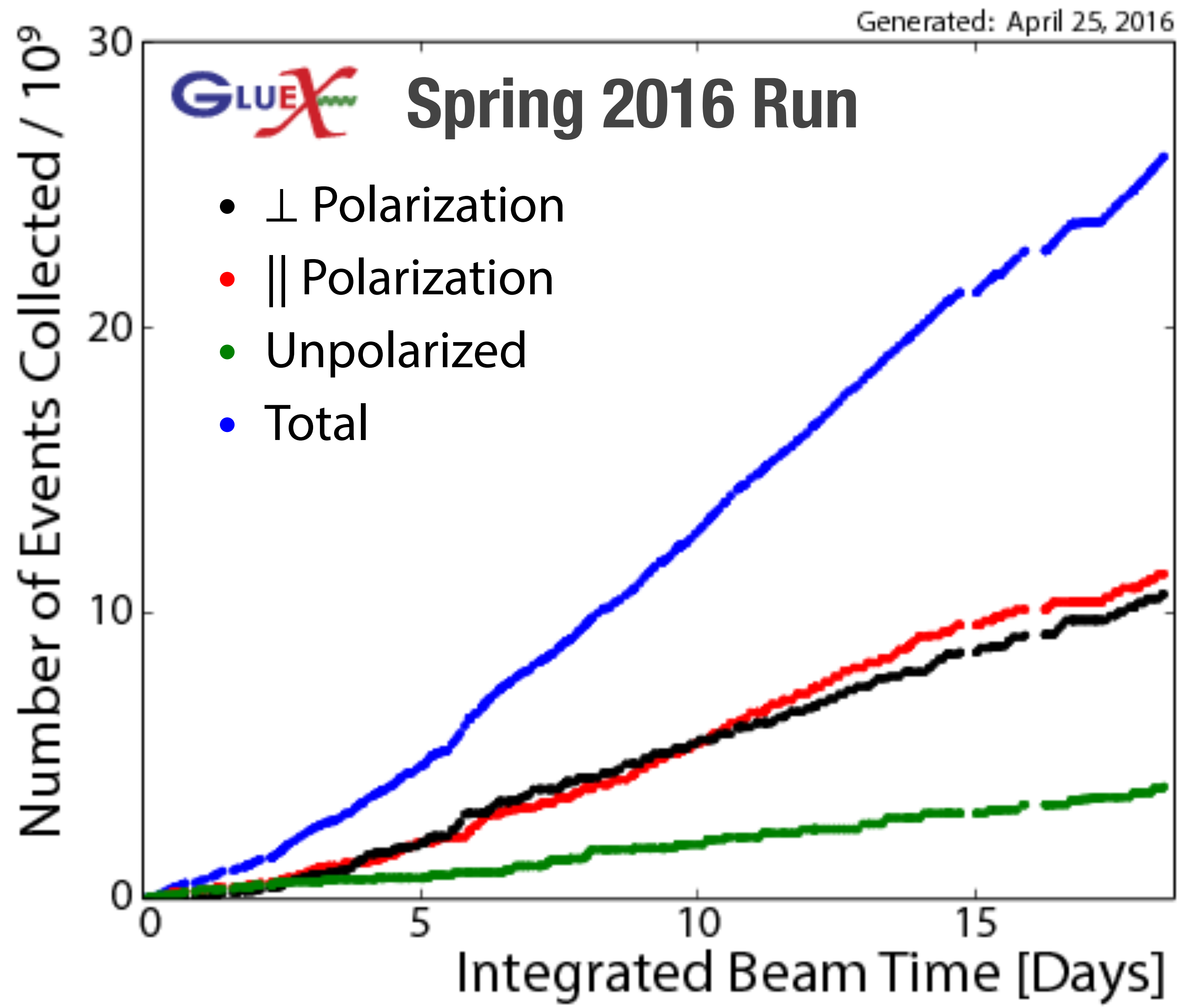
- Clear evidence for $J^{PC}=1^{-+}$ partial waves, but interpretation not conclusive

Quantum number counting

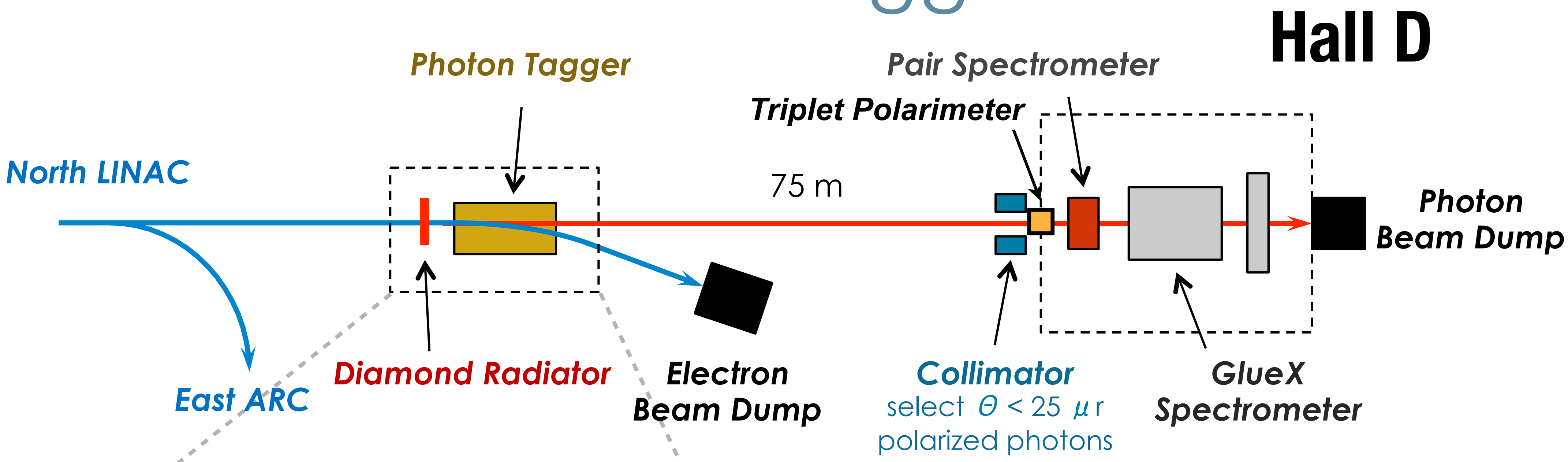


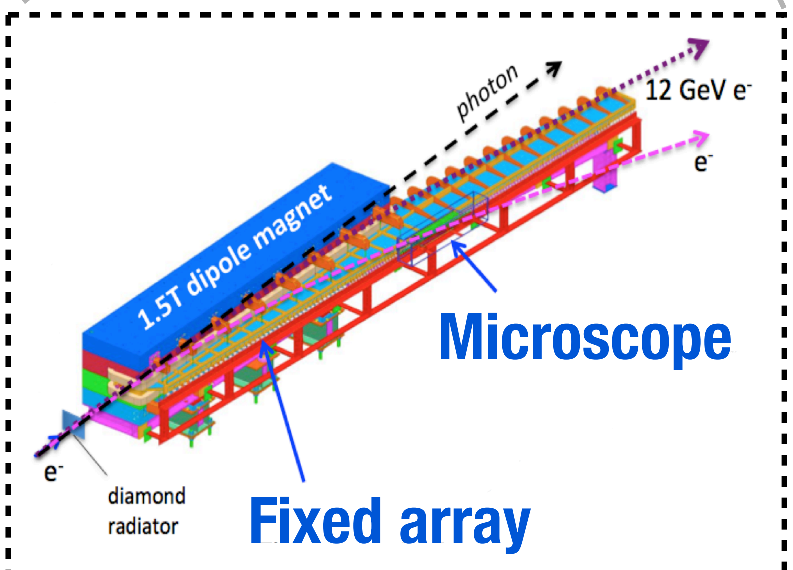
GlueX data taking

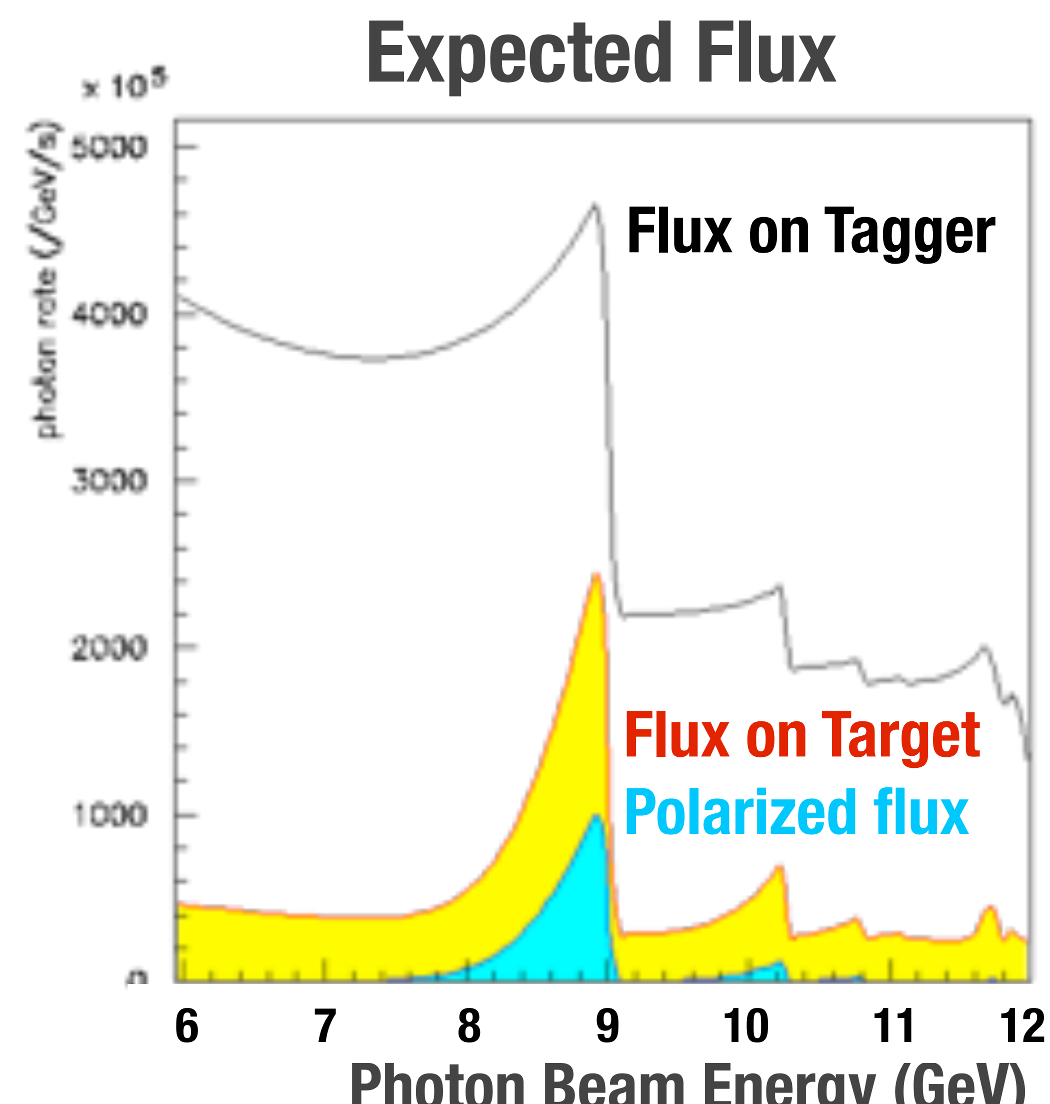
- **2014-2015:** Beam and detector commissioning
- **Spring 2016:** Detector commissioning and first physics results
  - ~10^7 ɣ/s in coherent peak 8.4 < Eɣ < 9 GeV
  - Results shown today from ~80 hours of beam time
- **Initial program:**
  - 100 days at ~10^7 (10x stats)
- **High intensity running**
  - 200 days at ~5×10^7 (100x stats)



Photon Beam and Tagger

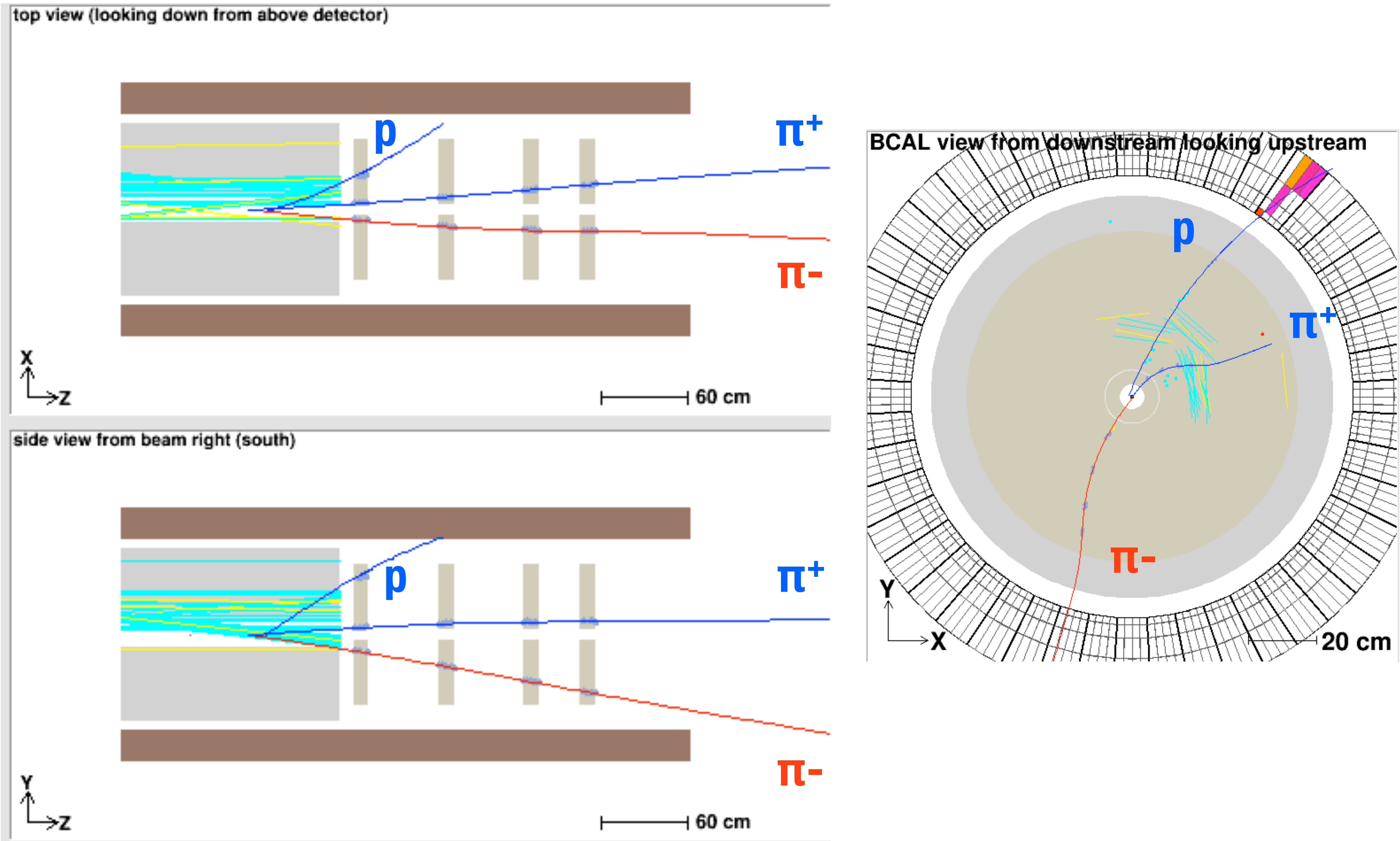




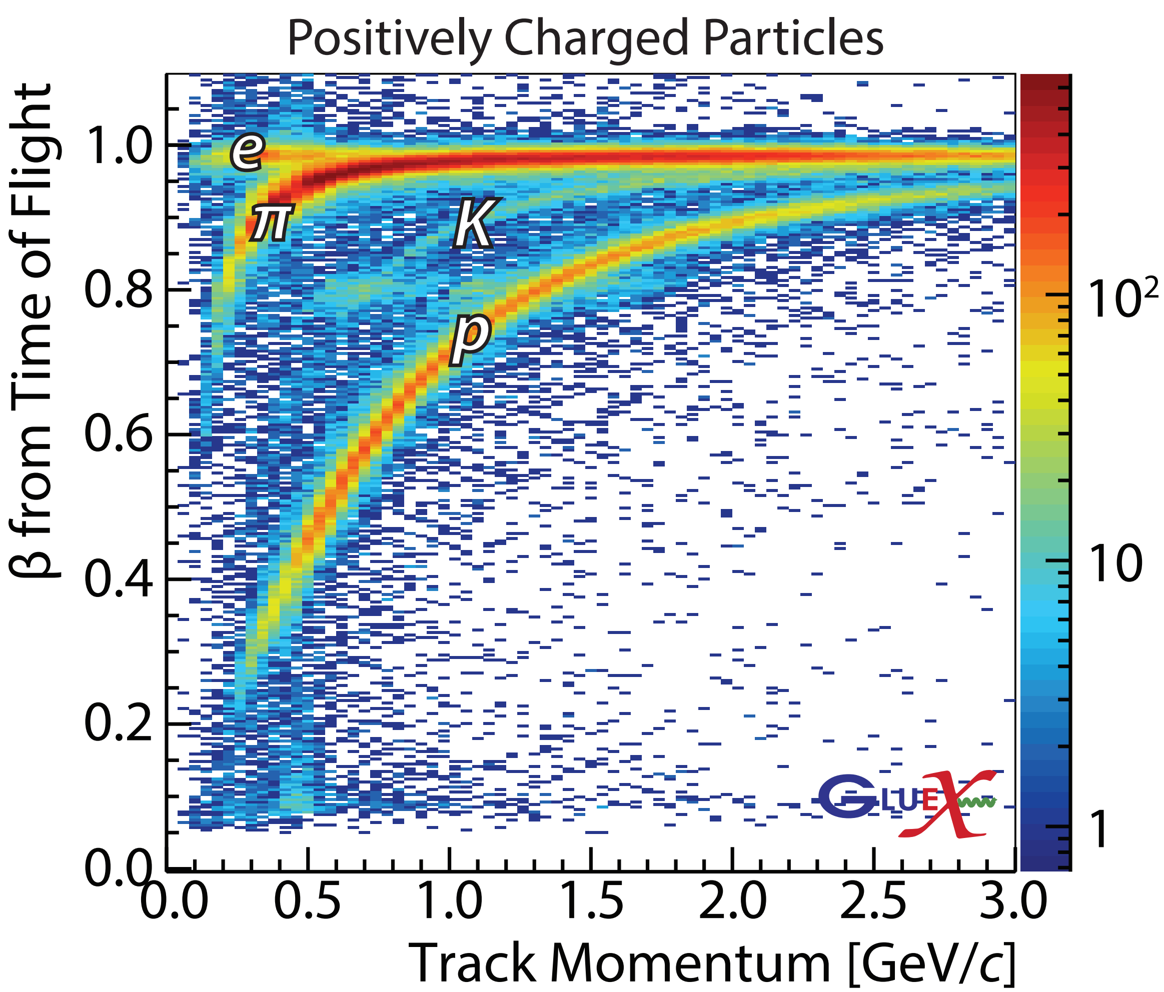


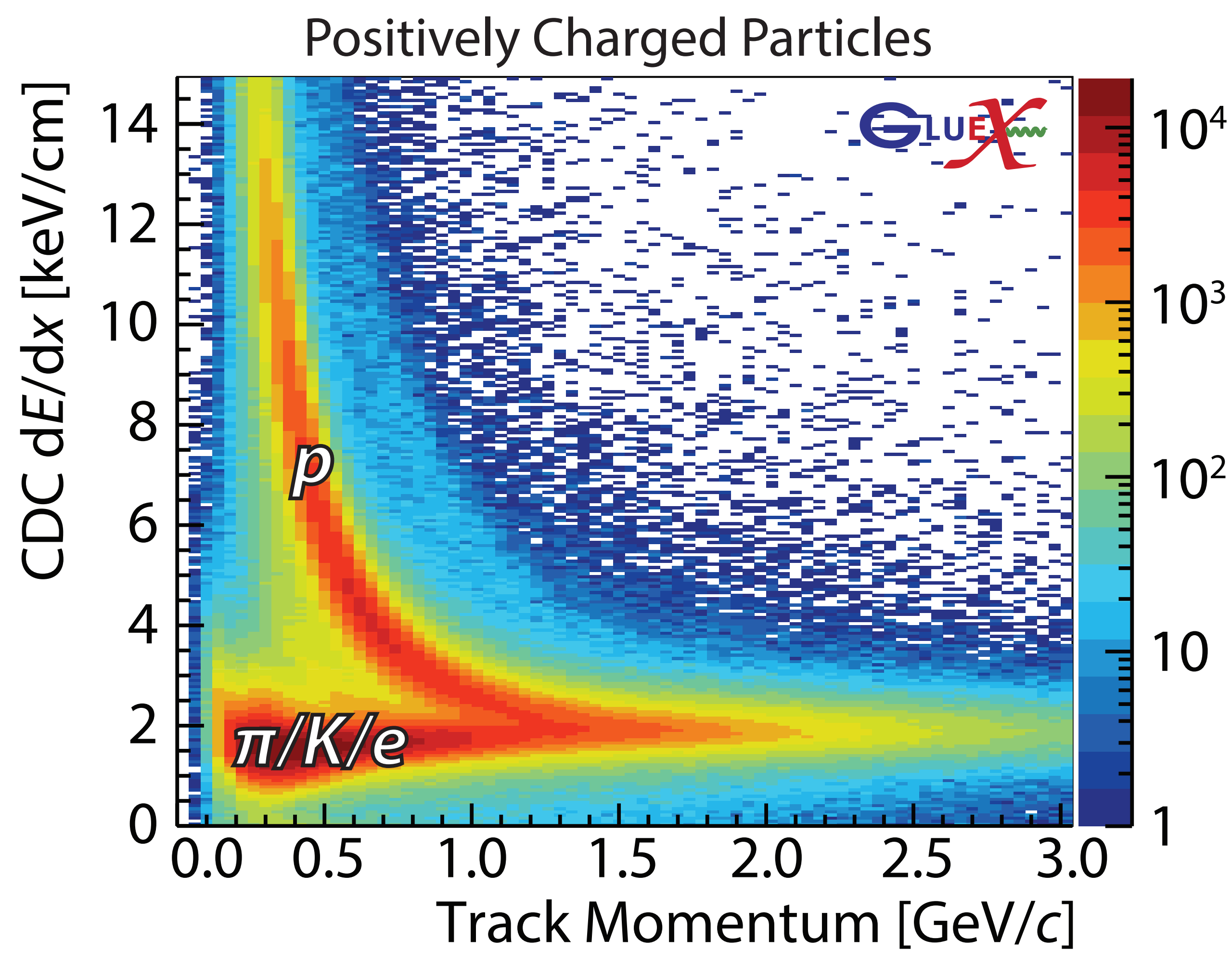
- Linearly polarized photons via coherent bremsstrahlung from diamond radiator
- Design intensity of 10^8 γ/s in coherent peak between E_γ = 8.4 and 9 GeV

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



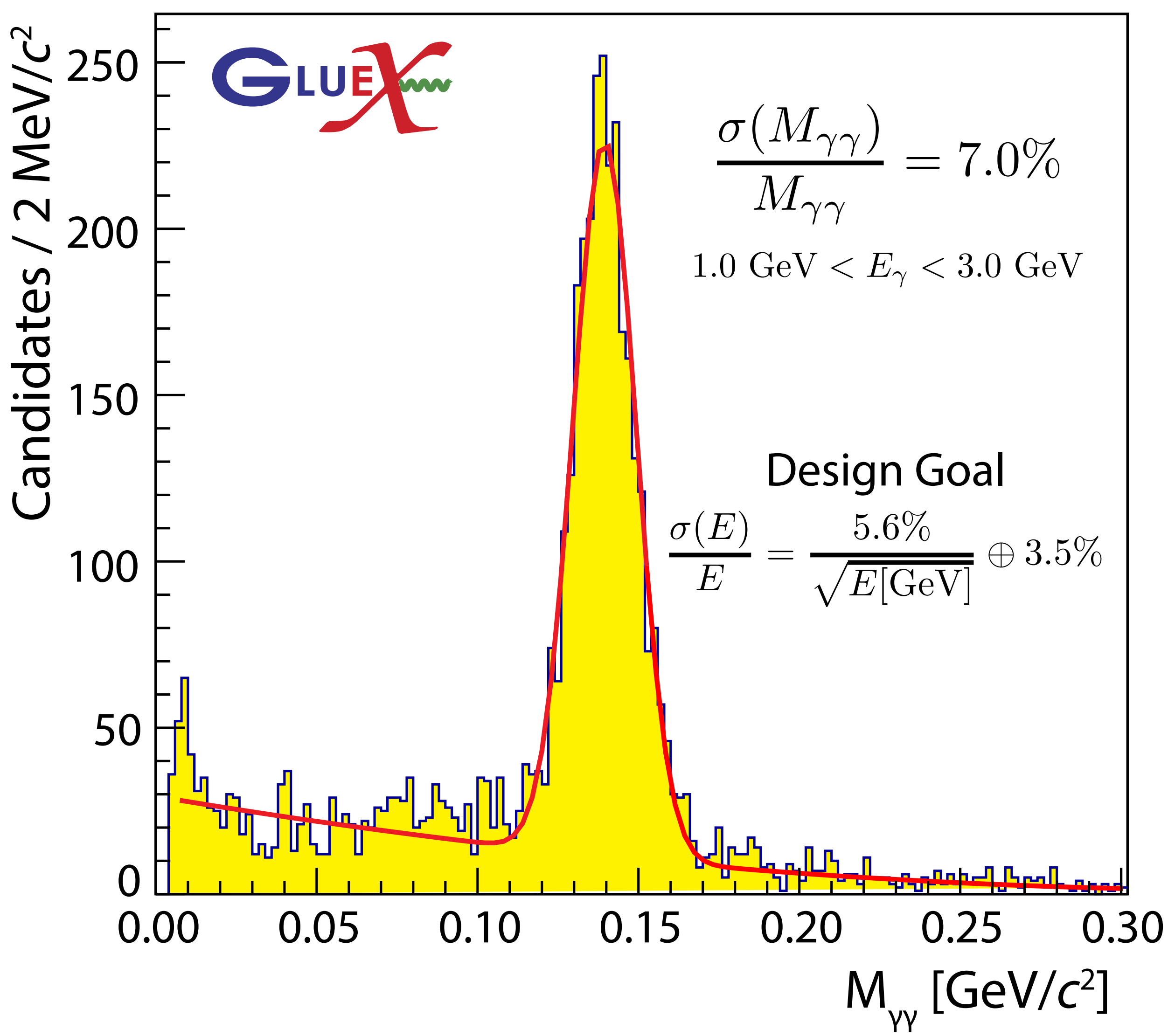
Particle identification performance



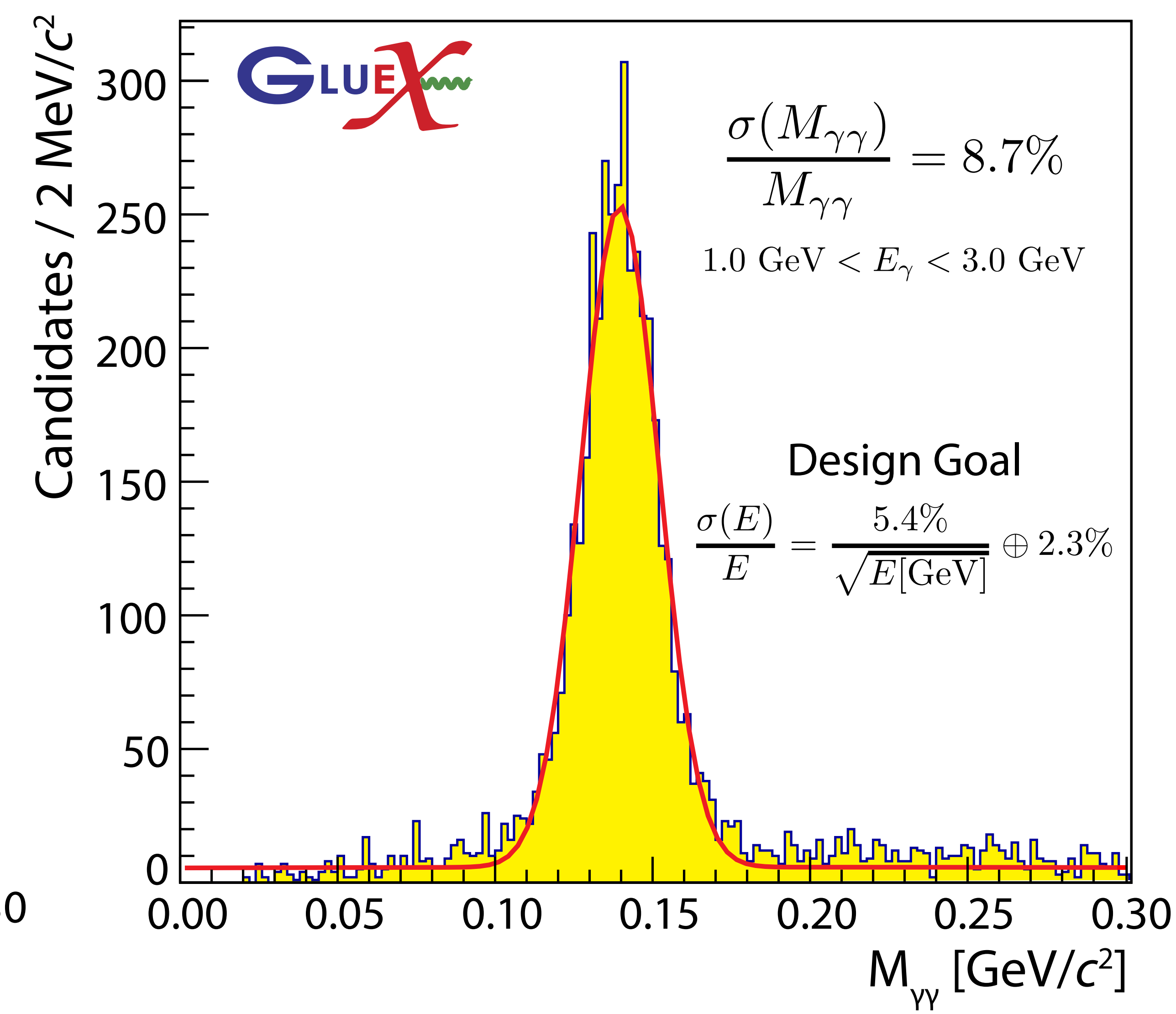


Calorimeter performance

Forward Lead Glass Calorimeter



Barrel Lead-Scintillating Fiber Calorimeter



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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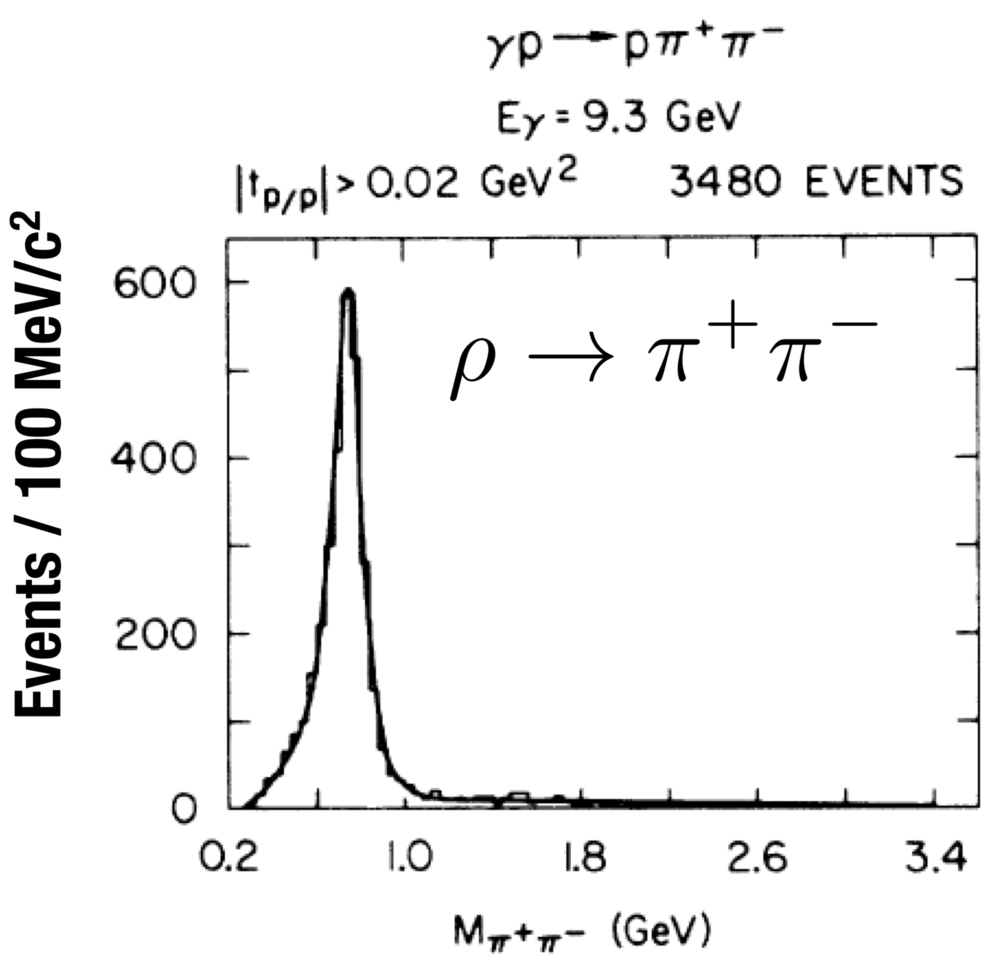
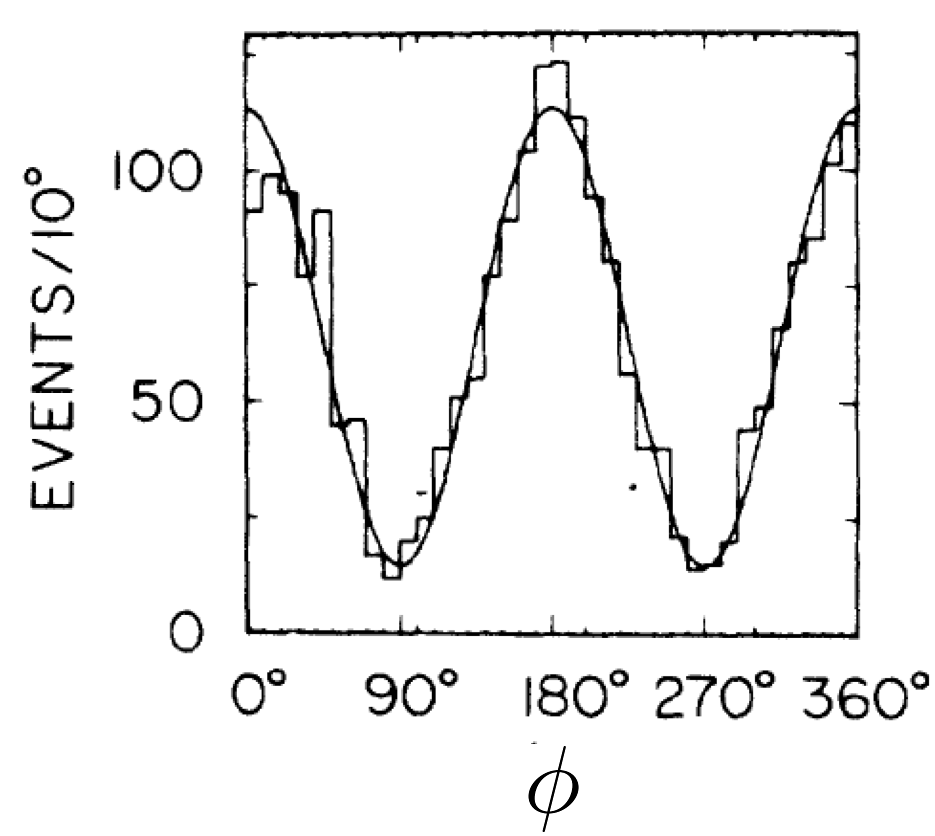
University of California and Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 13 November 1972)



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



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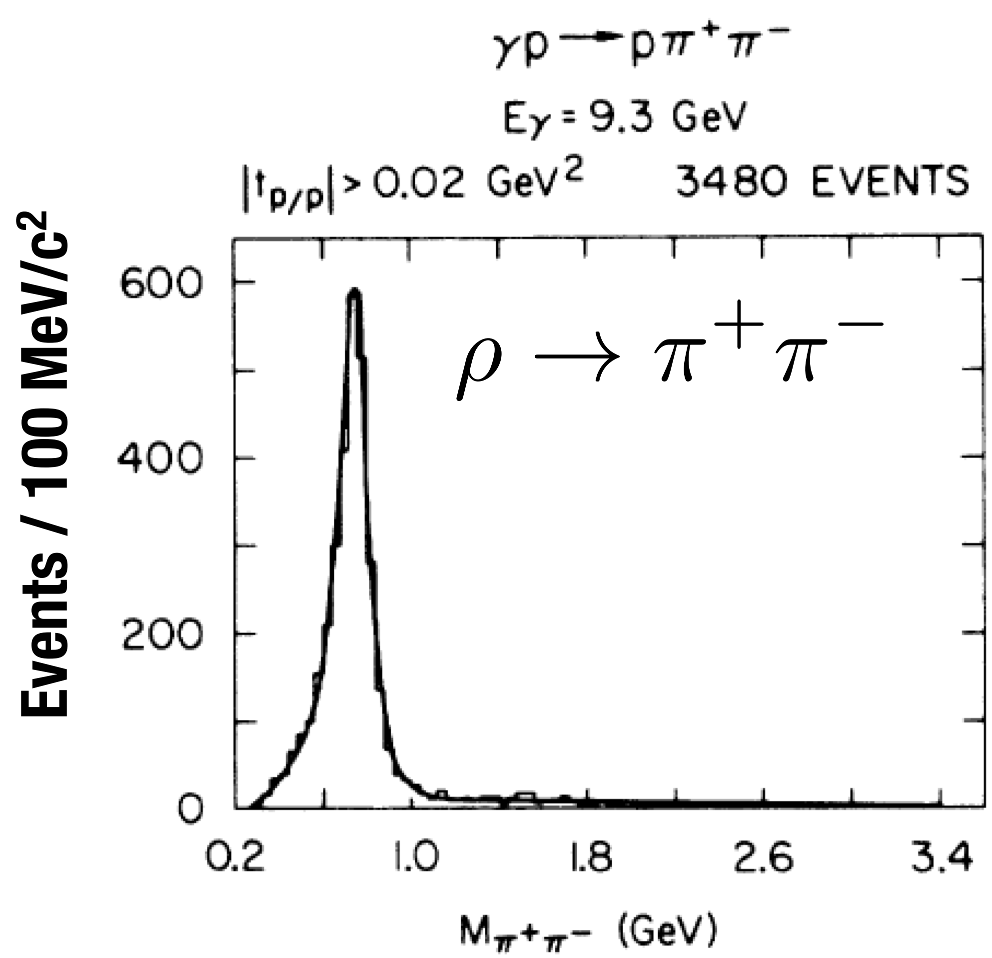
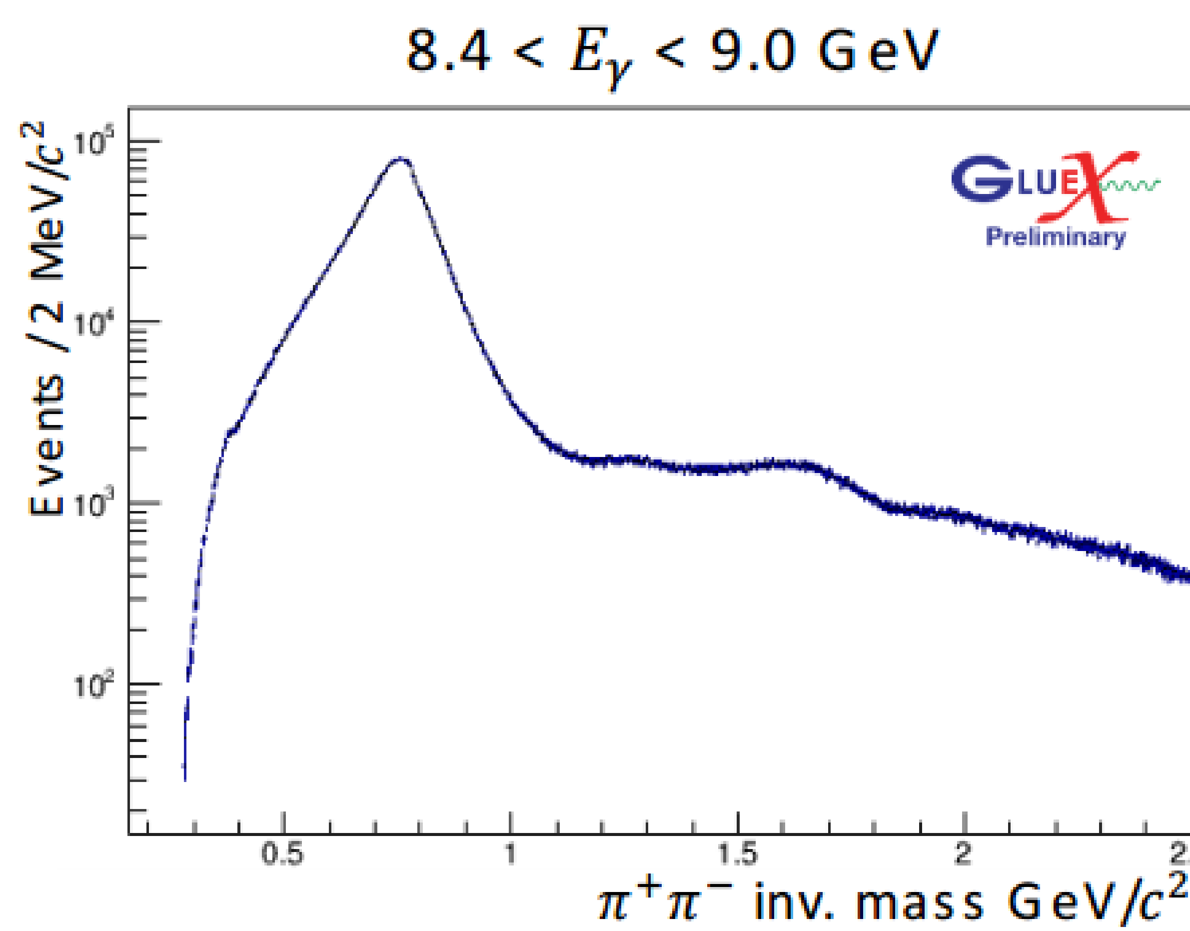
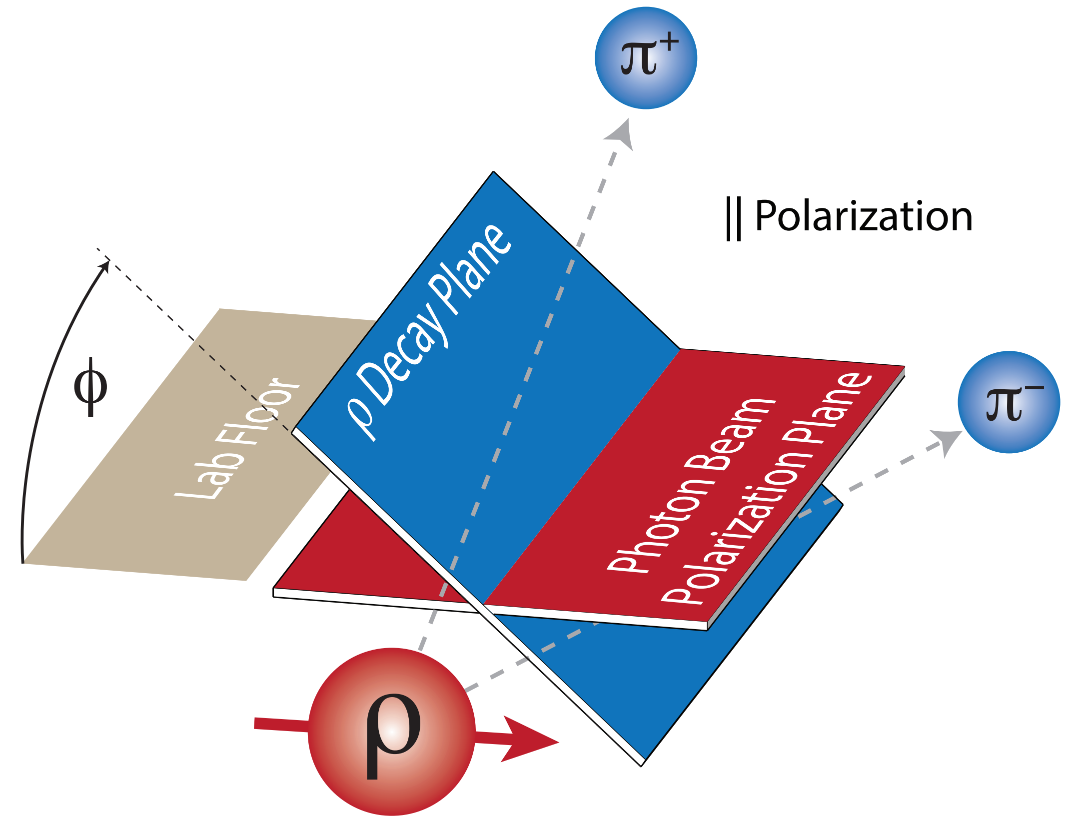
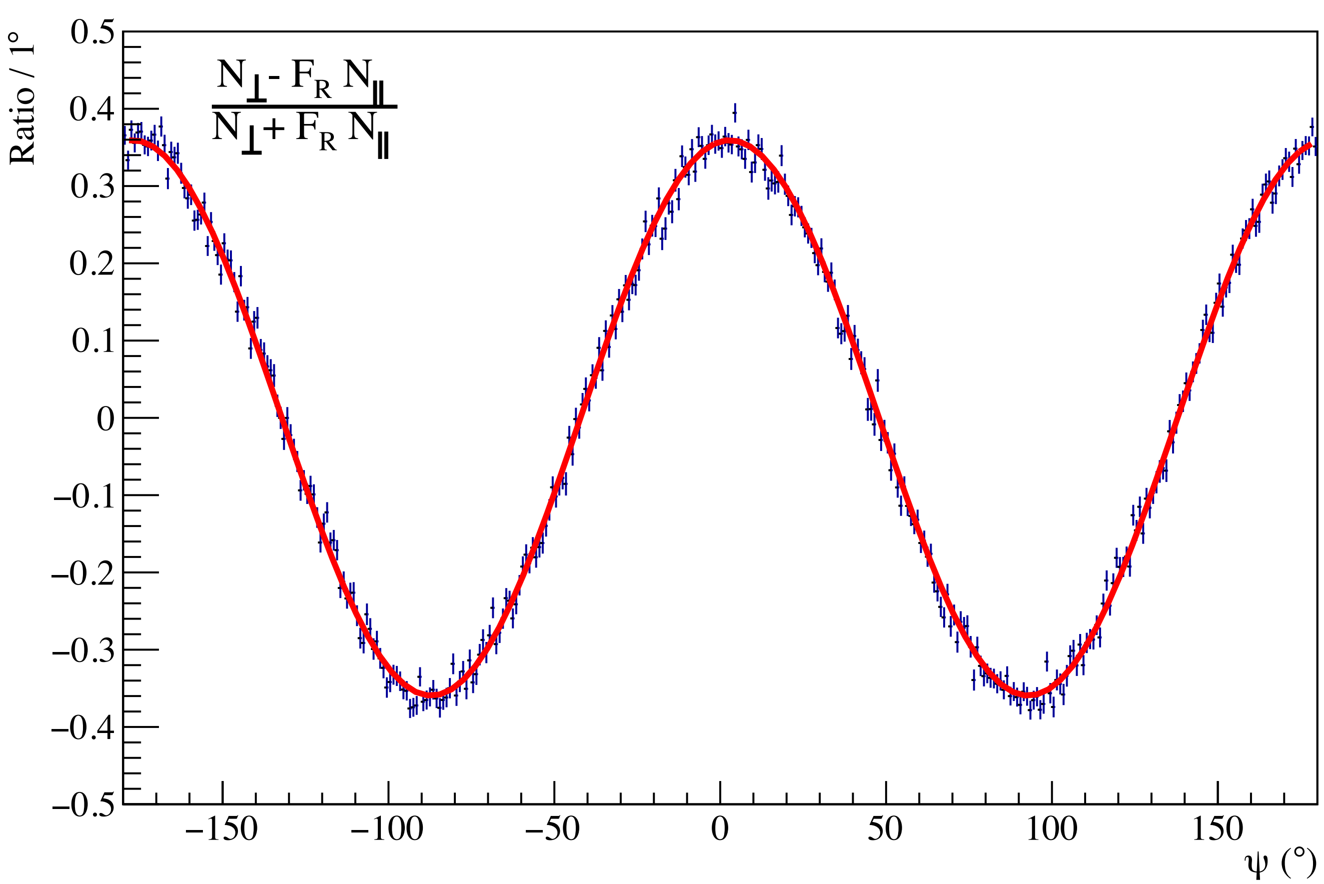


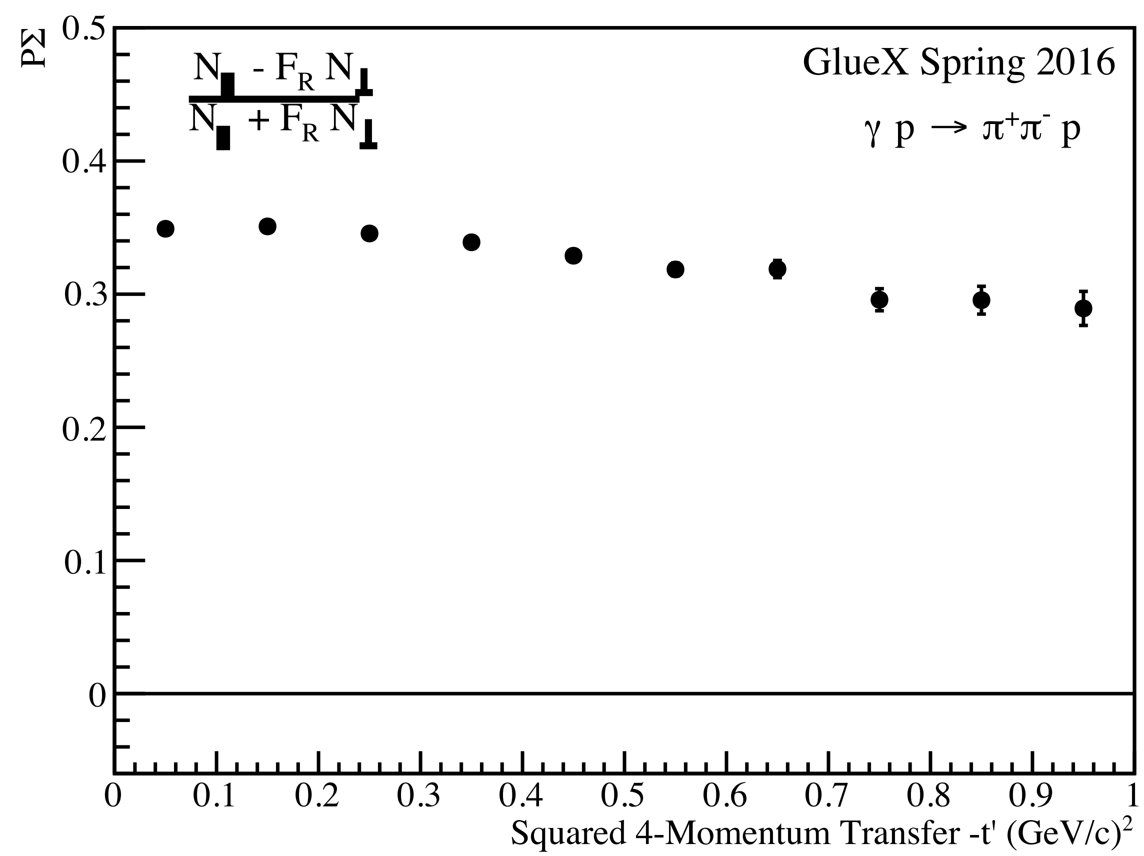


$\gamma p \rightarrow \rho^0 p$ asymmetry

- Asymmetry between polarization orientations (|| and ⊥) cancels detector acceptance
- More complete analysis of full angular distributions still required

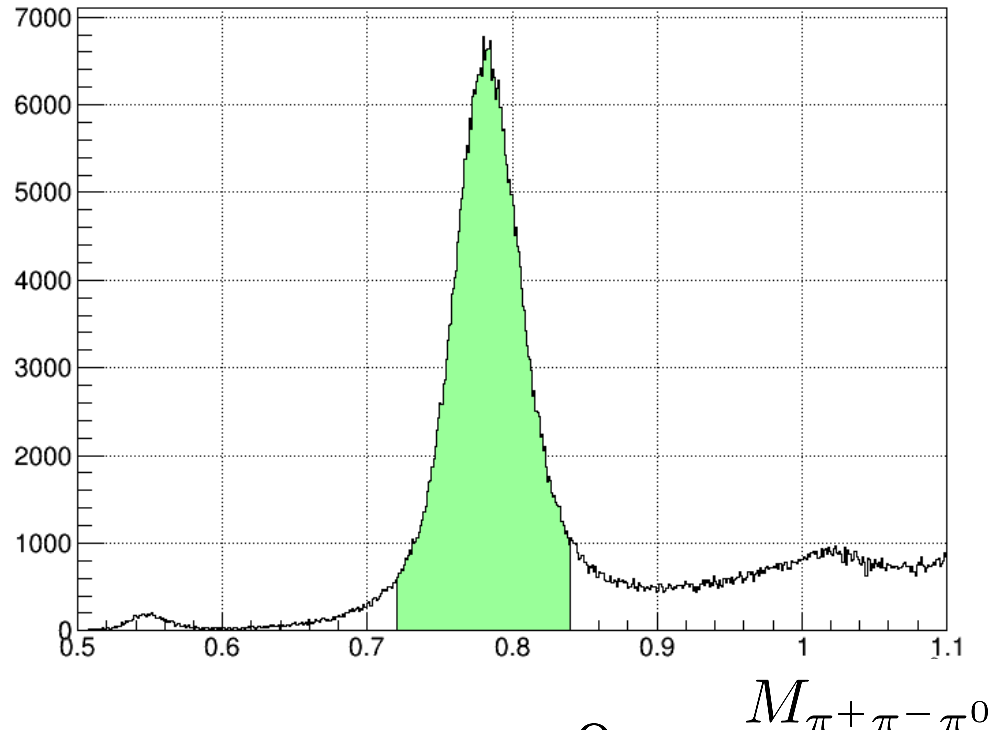




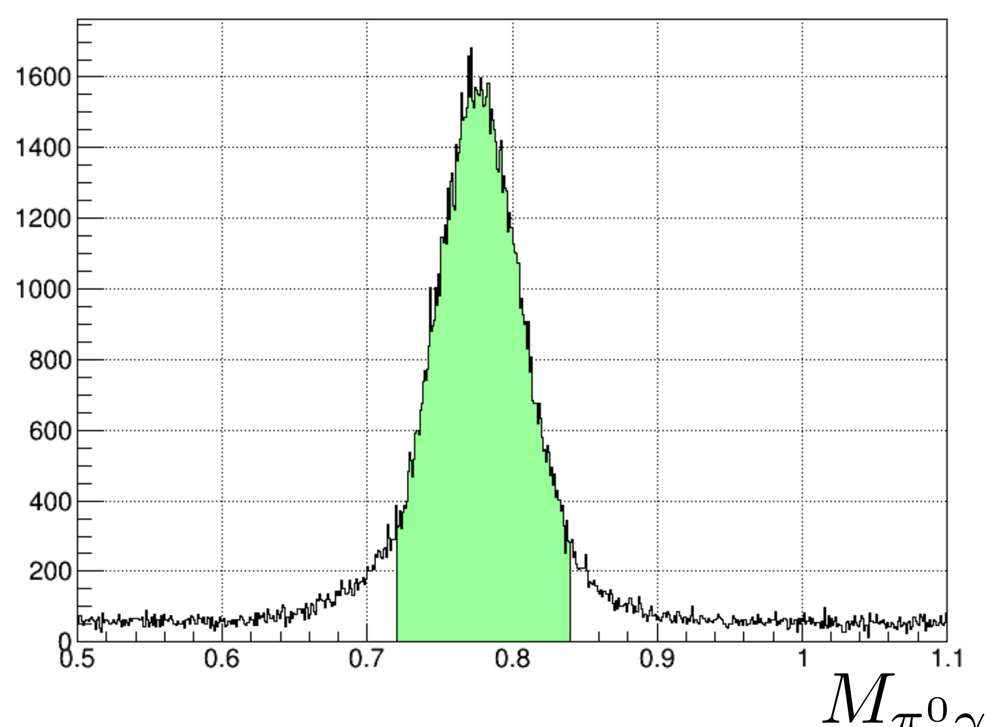


γp→ωp asymmetry

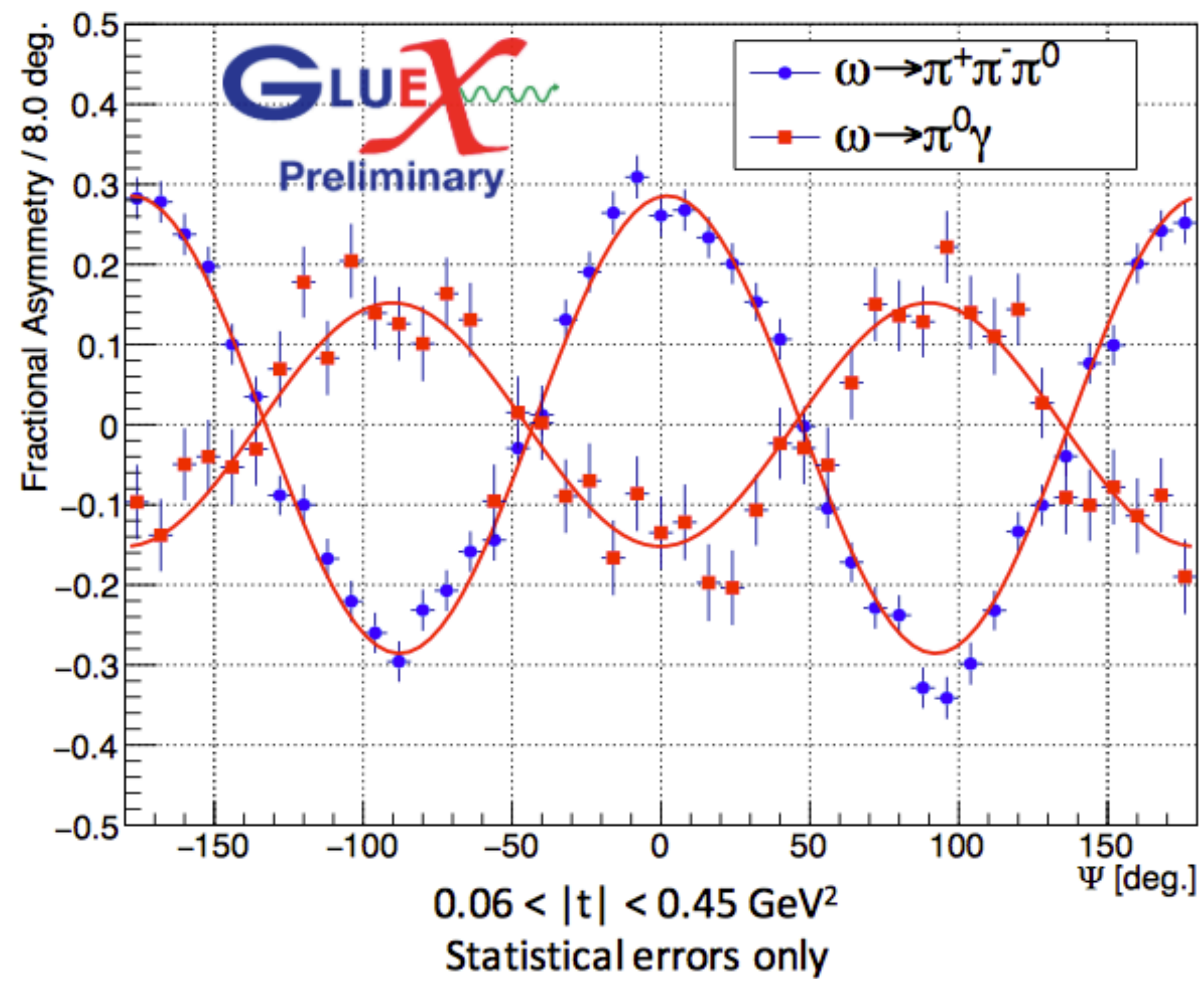
$$\gamma p \to \pi^+\pi^-\pi^0 p$$



$$\gamma p \to \pi^0 \gamma p$$

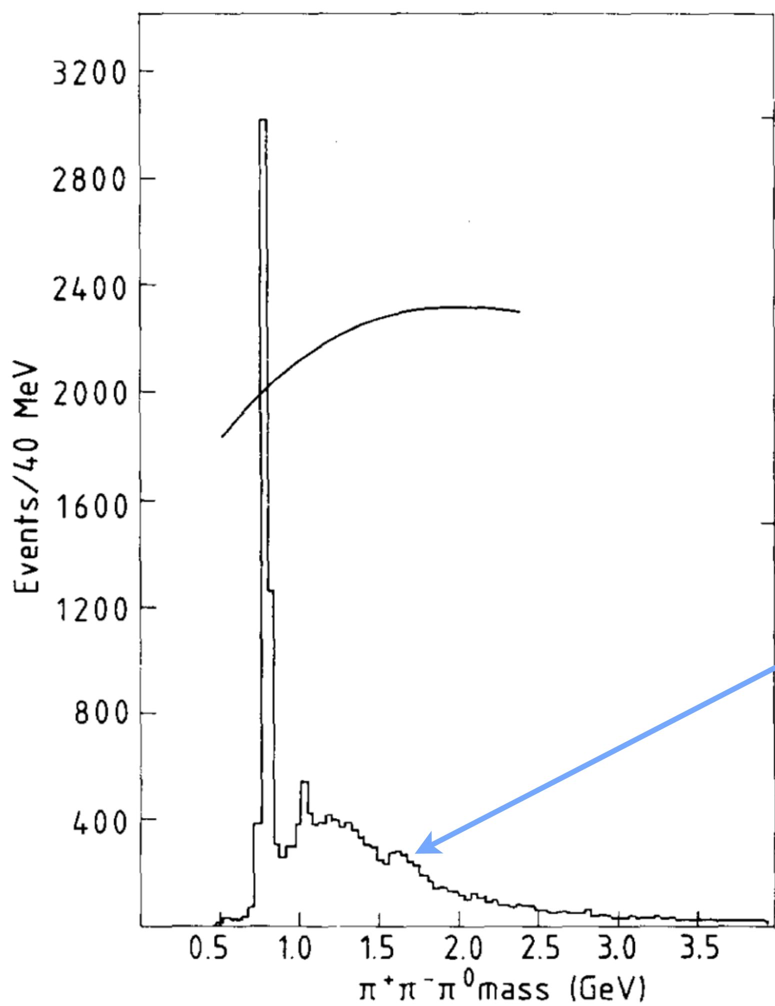


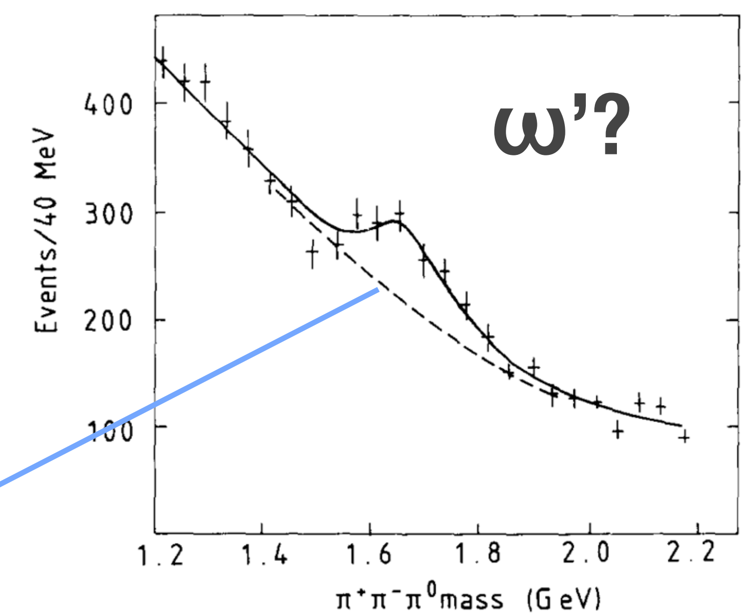
- Probe production mechanism through multiple decay modes
- Observe expected phase shift and amplitude ratio for 2 decay modes



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)

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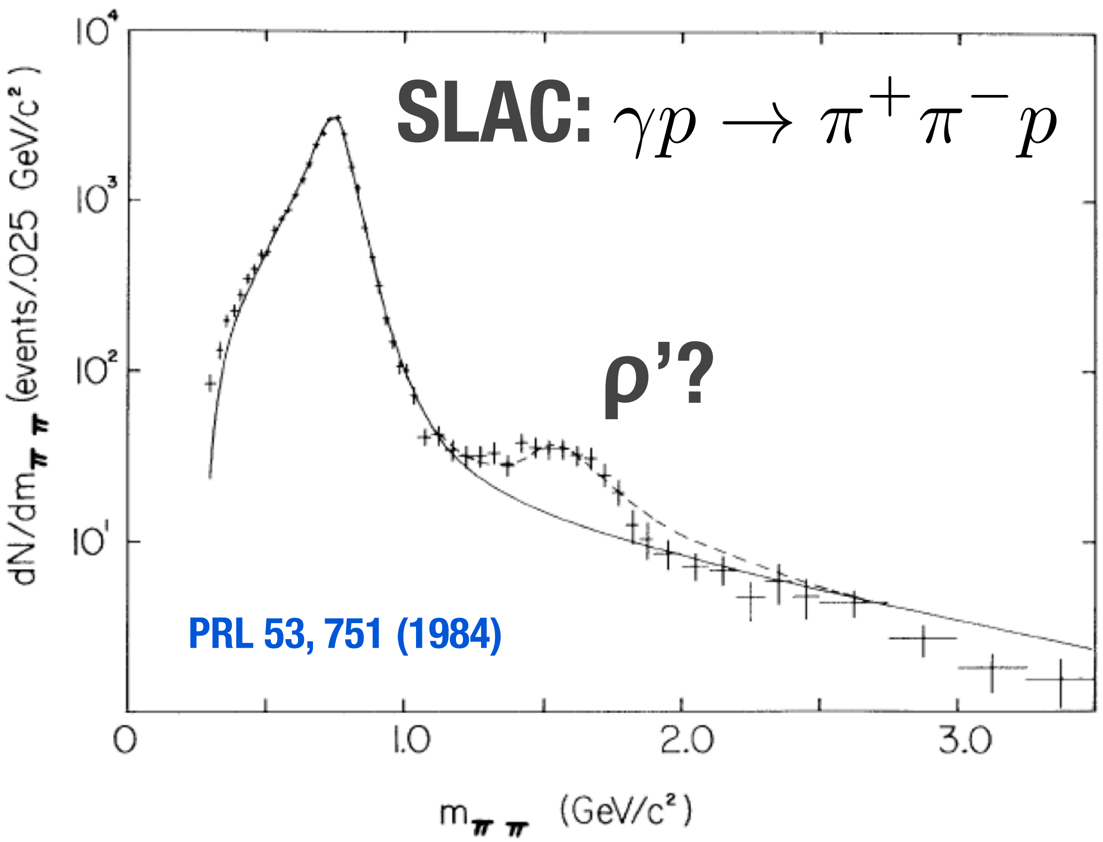
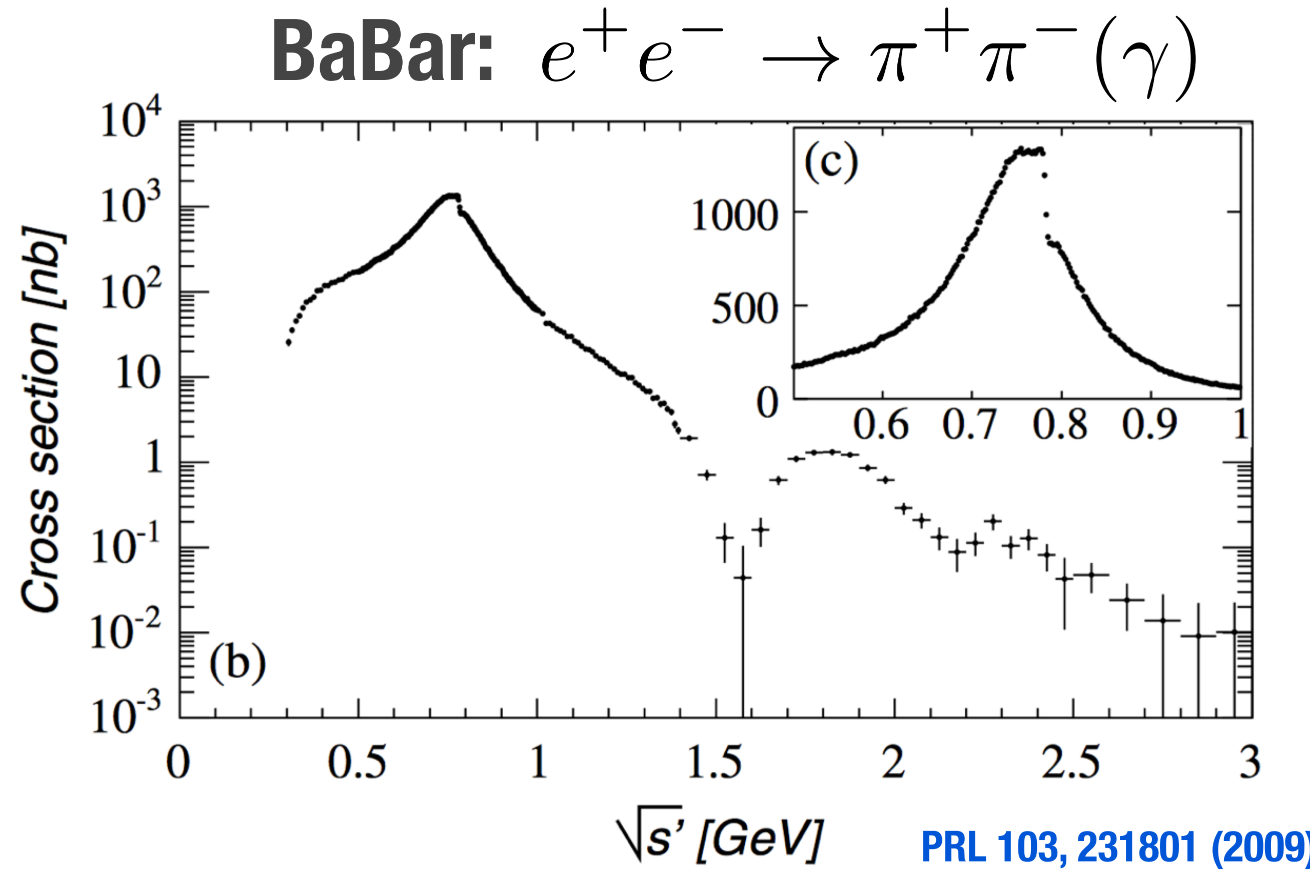
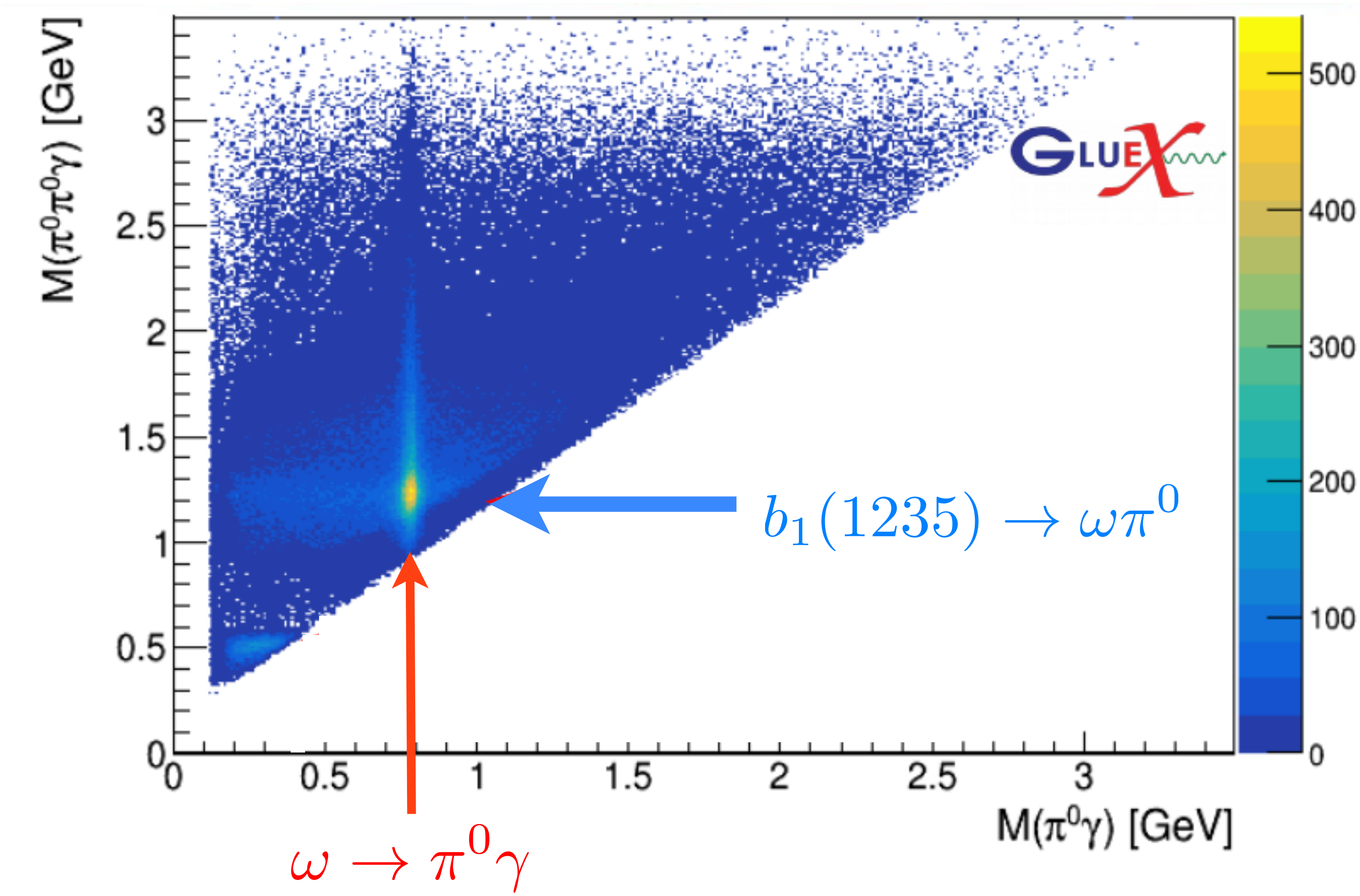
- Some speculative ideas to look for "structure" observed in previous measurements
- eg. Excited vector mesons: ρ', ω', etc.





Early spectroscopy opportunities

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

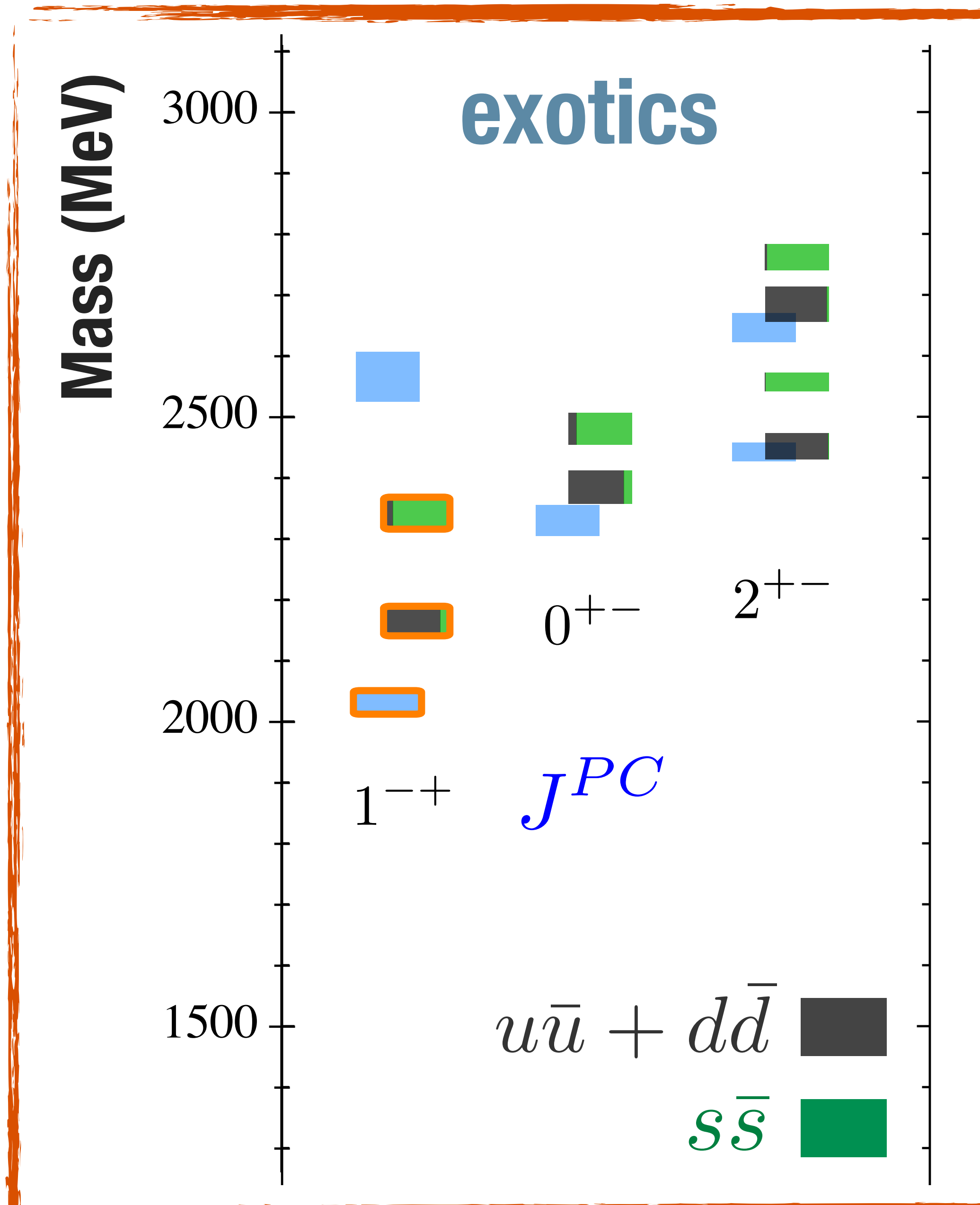


$$\gamma p \to b_1 p, b_1 \to \omega\pi^0, \omega \to \pi^0\gamma$$

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

GlueX future

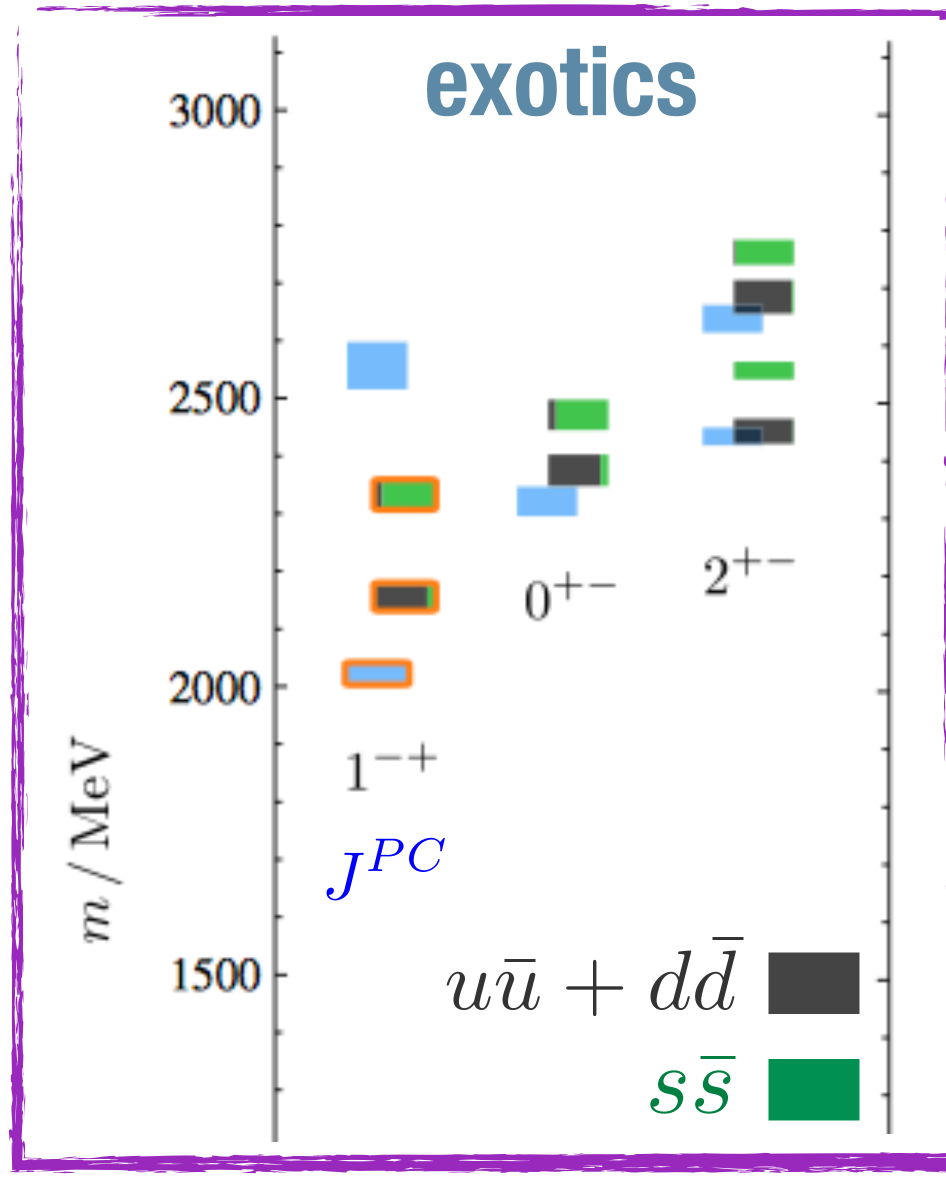
- Lattice predicts **strange** and **light** quark content for mesons
- Search for a **pattern** of hybrid states in many final states
- Requires clean identification of charged pions and kaons



	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

	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

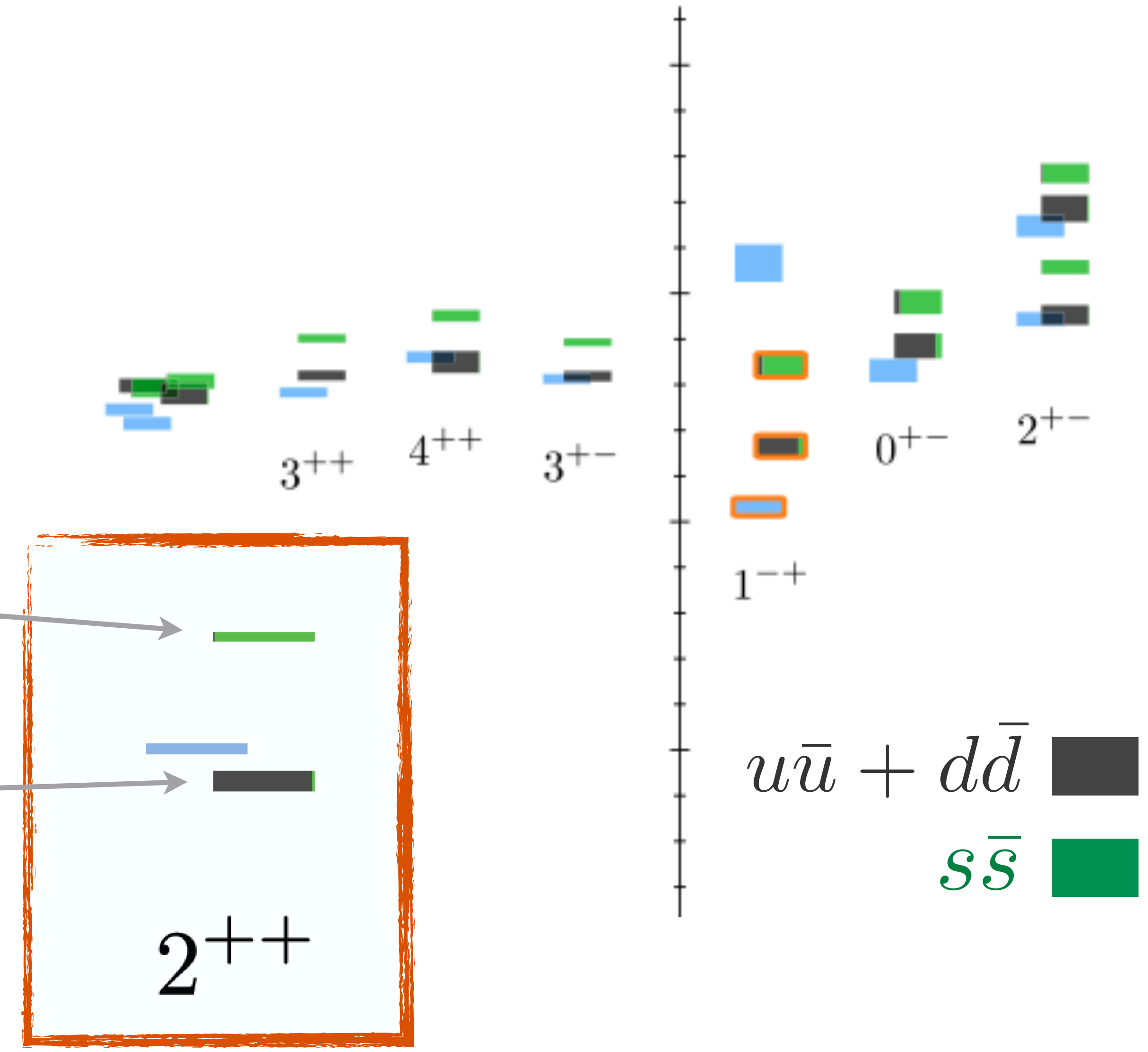
- Experimentally access to strangeness content of the state by comparing strange vs non-strange decay modes

Strangeness program: decay patterns

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

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

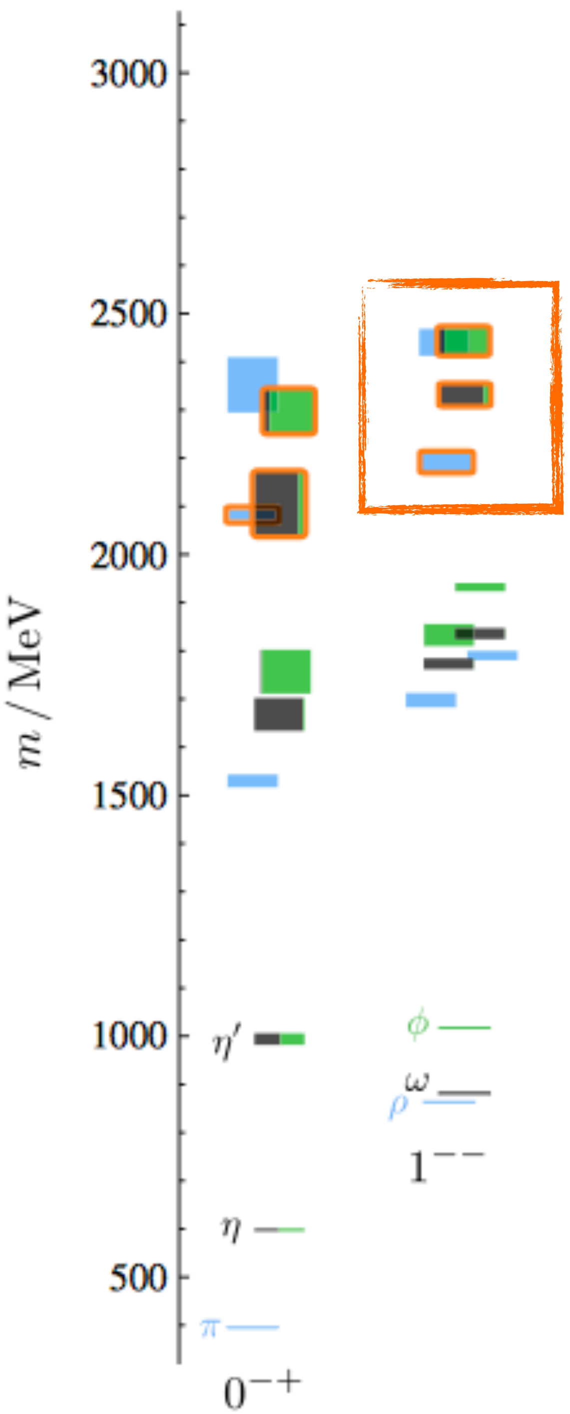
$$\frac{\mathcal{B}(f_2(1270) \to \pi\pi)}{\mathcal{B}(f_2(1270) \to KK)} \approx 20$$



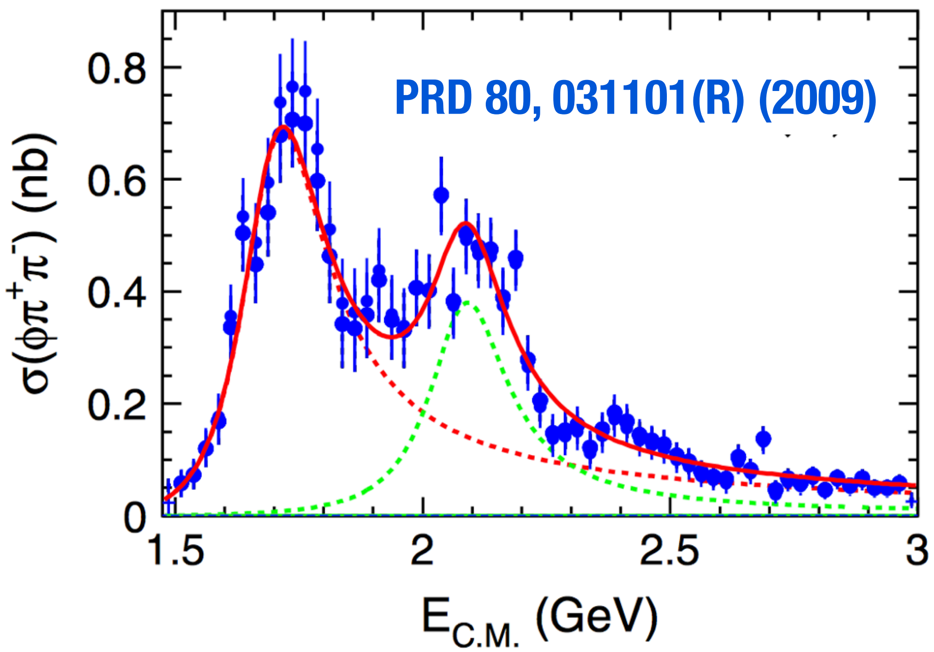
- Consistent with lattice QCD mixing angle for 2^{++}, and predictions for hybrids

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

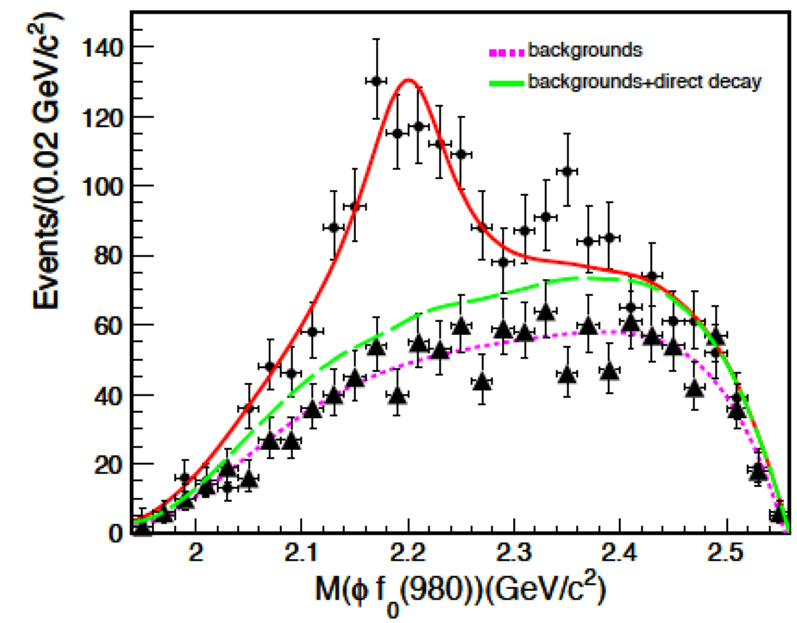
Strangeness program: Y(2175)



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



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



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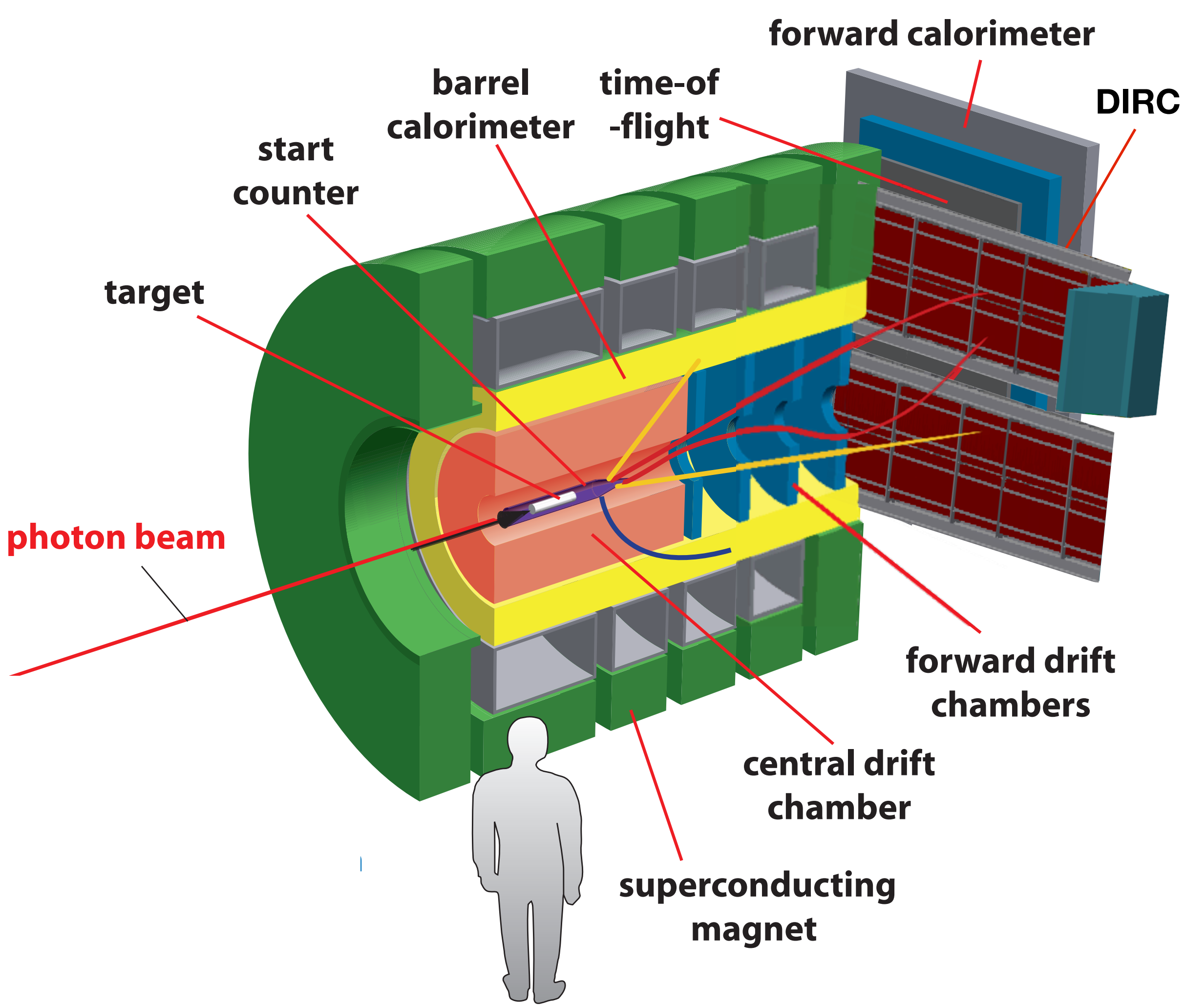
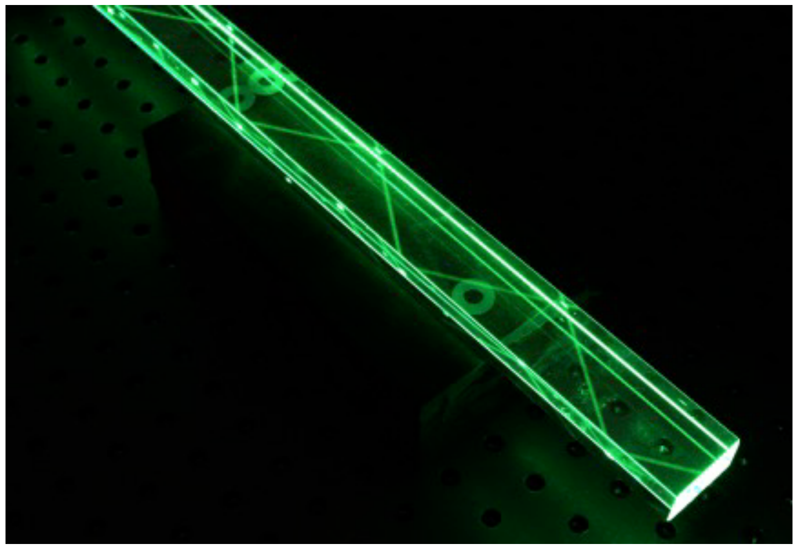
- Y(2175) $J^{PC}=1^{--}$ state observed by 3 experiments
- Decay pattern similar to Y(4260) in charmonium

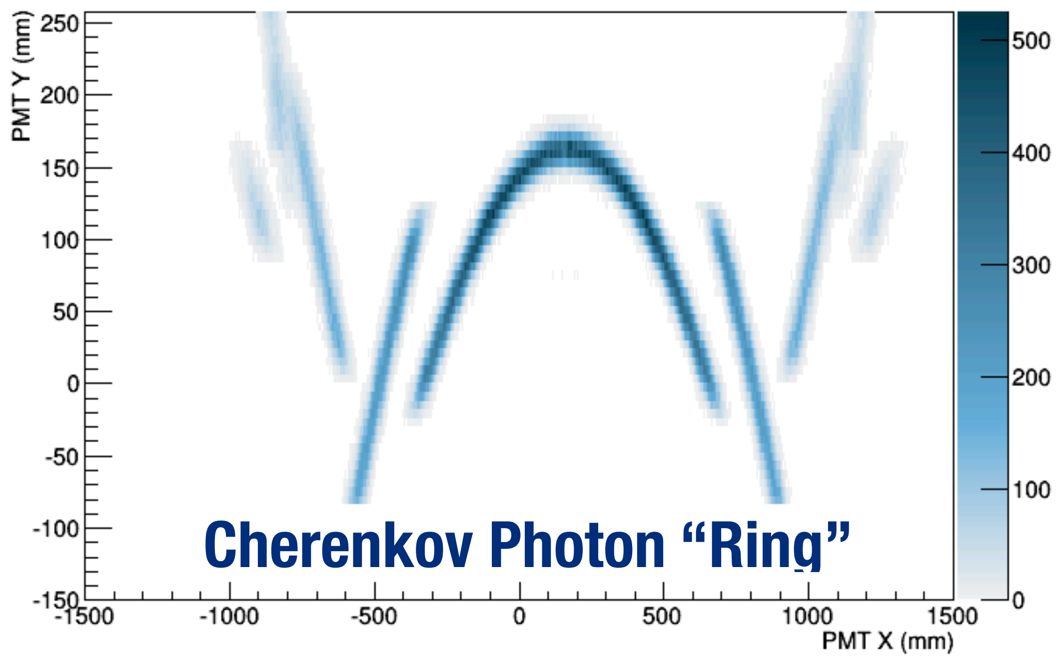
$$Y(2175) \to \phi\pi^+\pi^- \qquad Y(4260) \to J/\psi\pi^+\pi^-$$

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

GlueX DIRC upgrade







- The GlueX **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light) uses recycled components of the BaBar DIRC

- Extends K/π separation, allowing GlueX to study mesons and baryons containing strange quarks