Searches for Exotic Hadrons at GlueX

Sean Dobbs
Florida State U.
[For the GlueX Collaboration]

The 15th International Conference on Meson-Nucleon Physics
and the Structure of the Nucleon (MENU 2019)
Pittsburgh, PA June 3, 2019

Jefferson Lab

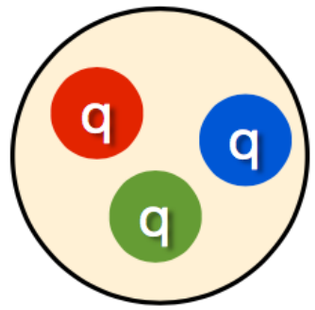
GlueX

Florida State University 1851

QCD and Hadron Spectroscopy

- Quantum Chromodynamics (**QCD**)
  - Degrees of freedom:
    quarks and gluons
- Recent progress in studying QCD through spectrum of bound states
  - New high-intensity experiments
  - More rigorous theoretical tools
- Open questions:
  - What is the origin of confinement?

mesons



baryons

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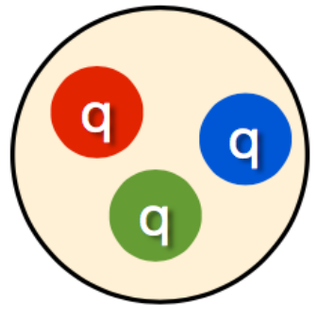
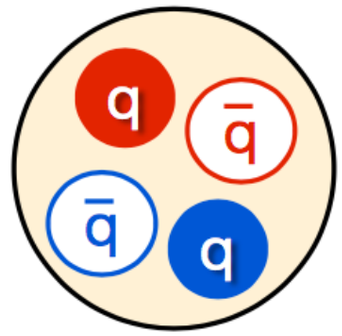
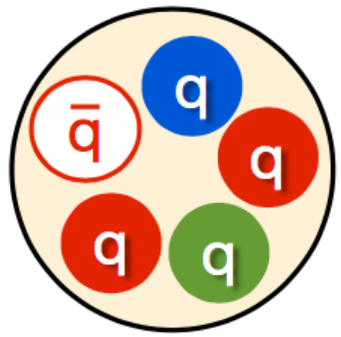


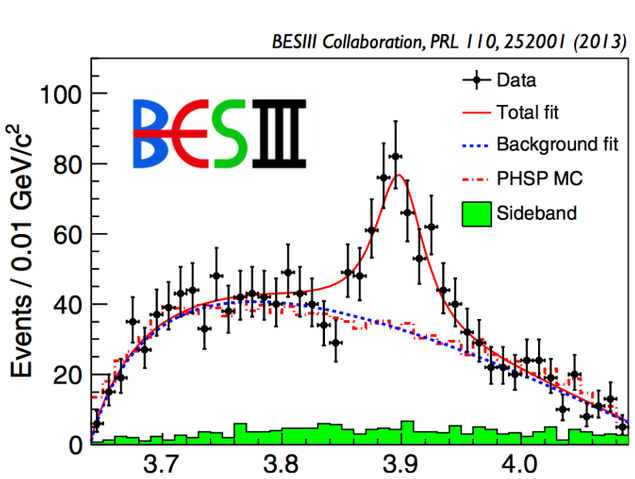
baryons



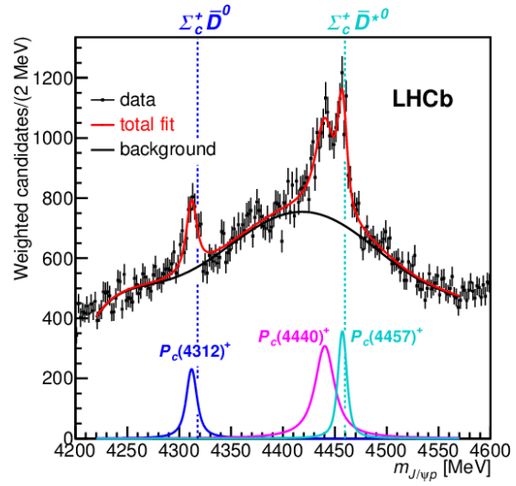
tetraquark



pentaquark



M(J/ψ π±)



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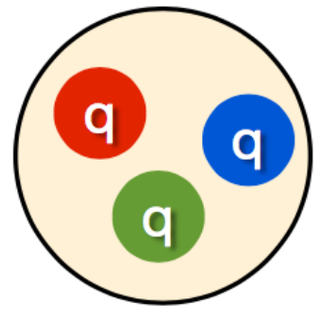
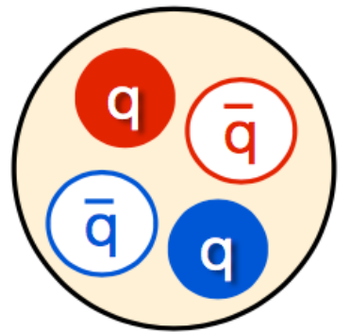


baryons



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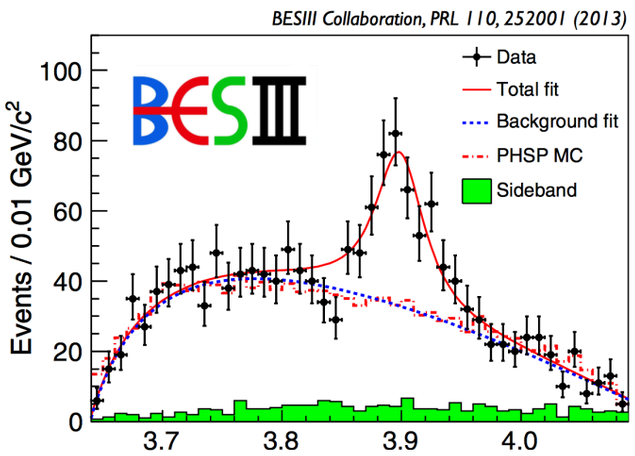

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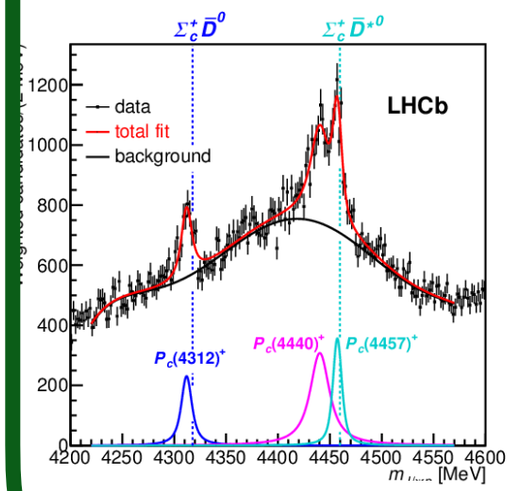

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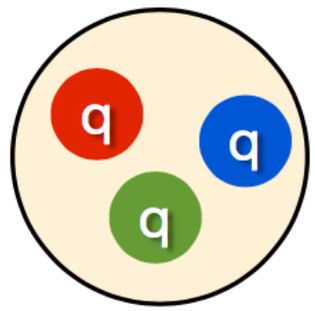
  - **Do gluonic degrees of freedom manifest themselves in the bound states that we observe?**

mesons



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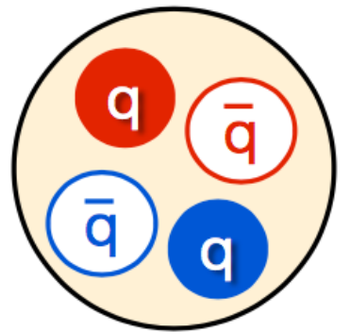

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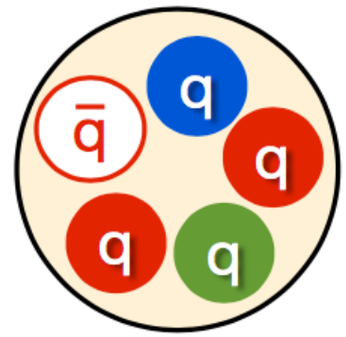

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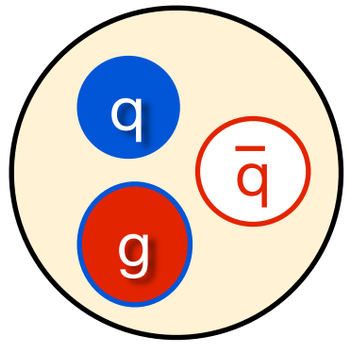
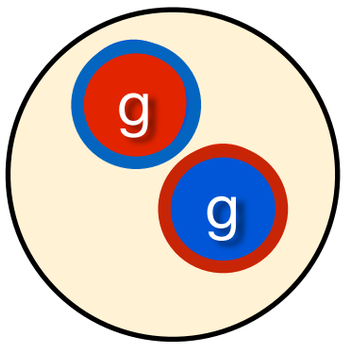


hybrid meson



glueball

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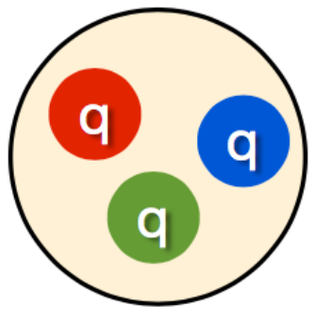

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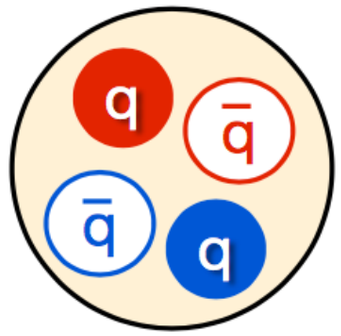
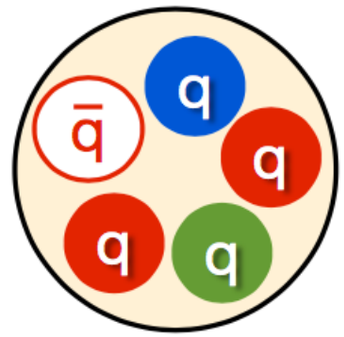


tetraquark



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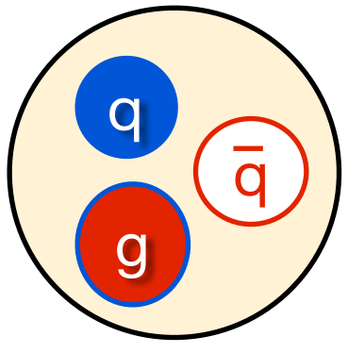

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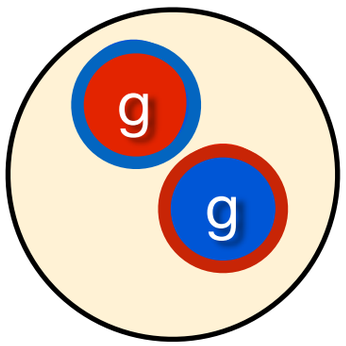
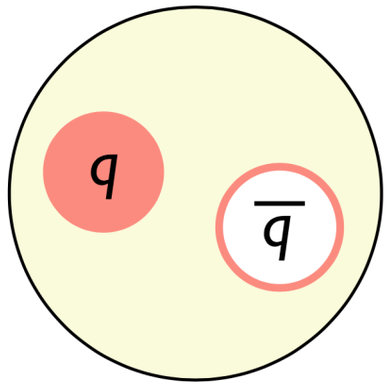


glueball

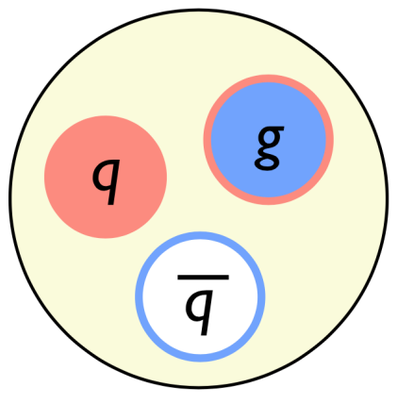
Searching For Hybrid Mesons

- Mesons grouped into nonets of similar J^{PC}
  - Must establish quantum numbers and pole parameters through amplitude analysis
- Meson QNs
  - Allowed: **0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{-+},…**
  - Forbidden: **0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, …**
- Hybrid Meson QNs
  - **0^{-+}, 0^{+-}, 1^{--}, 1^{-+}, 2^{-+}, 2^{+-},** …
- Hybrid mesons can be found with **normal** and **exotic** quantum numbers

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



"Normal" Meson

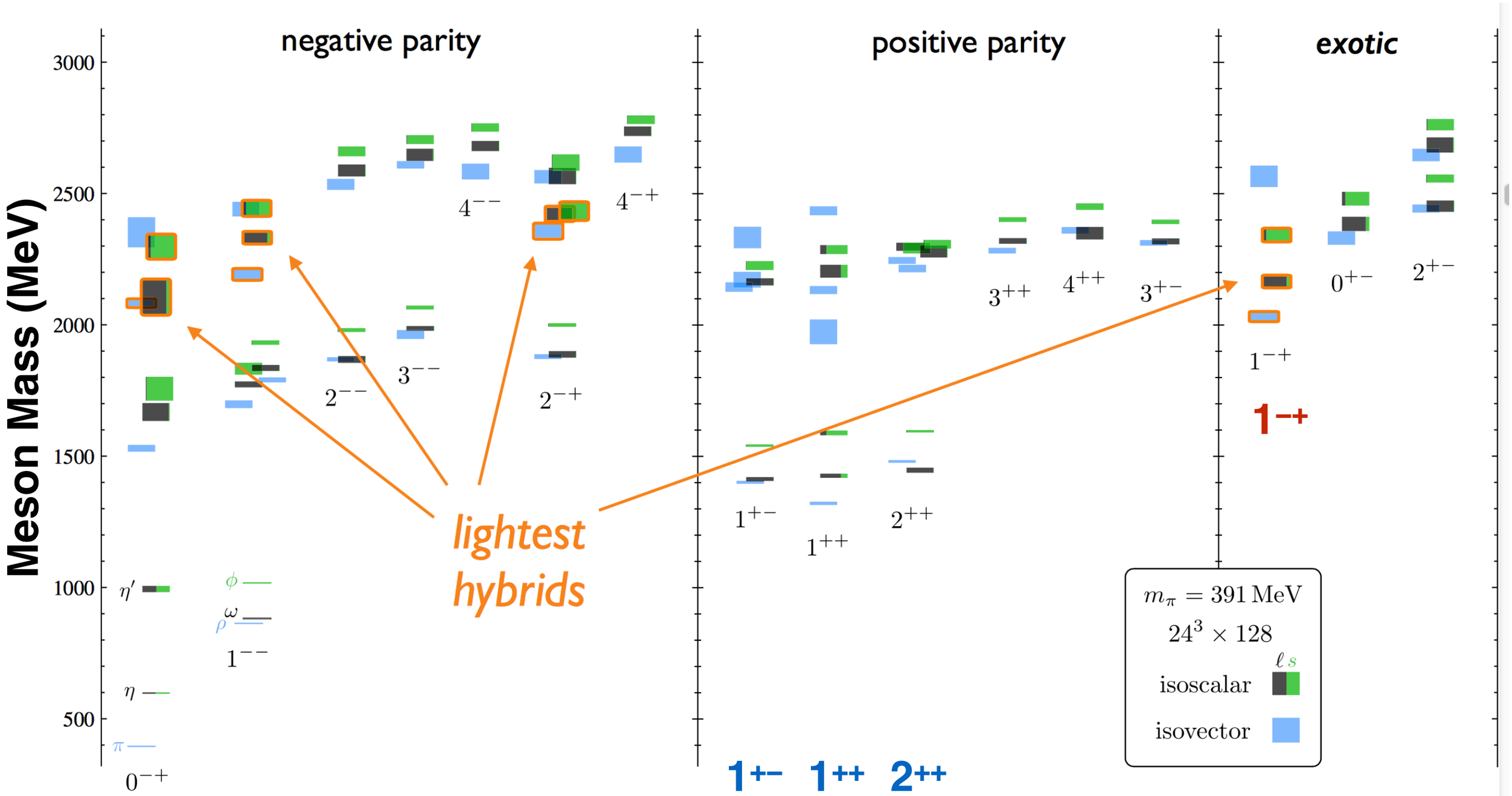


$(J^{PC})_g = 1^{+-}$

"Hybrid" Meson

Hybrid–Meson mass splitting ~ 1.0 – 1.5 GeV

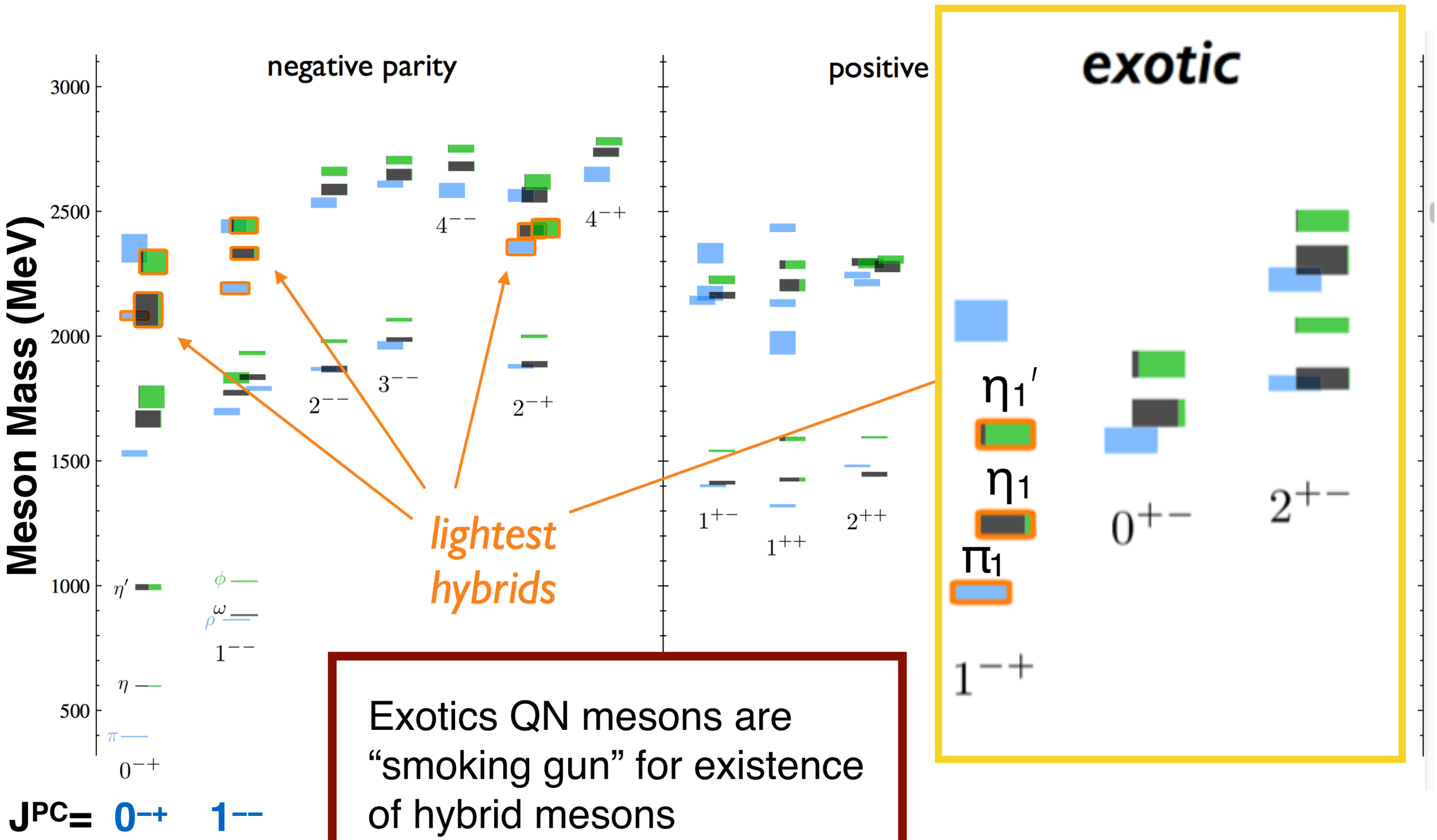
Light Meson Spectrum from Lattice QCD



J^{PC}= 0-+ 1-- 2-- 3-- 4-- 2-+ 4-+

HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

Light Meson Spectrum from Lattice QCD



Exotics QN mesons are "smoking gun" for existence of hybrid mesons

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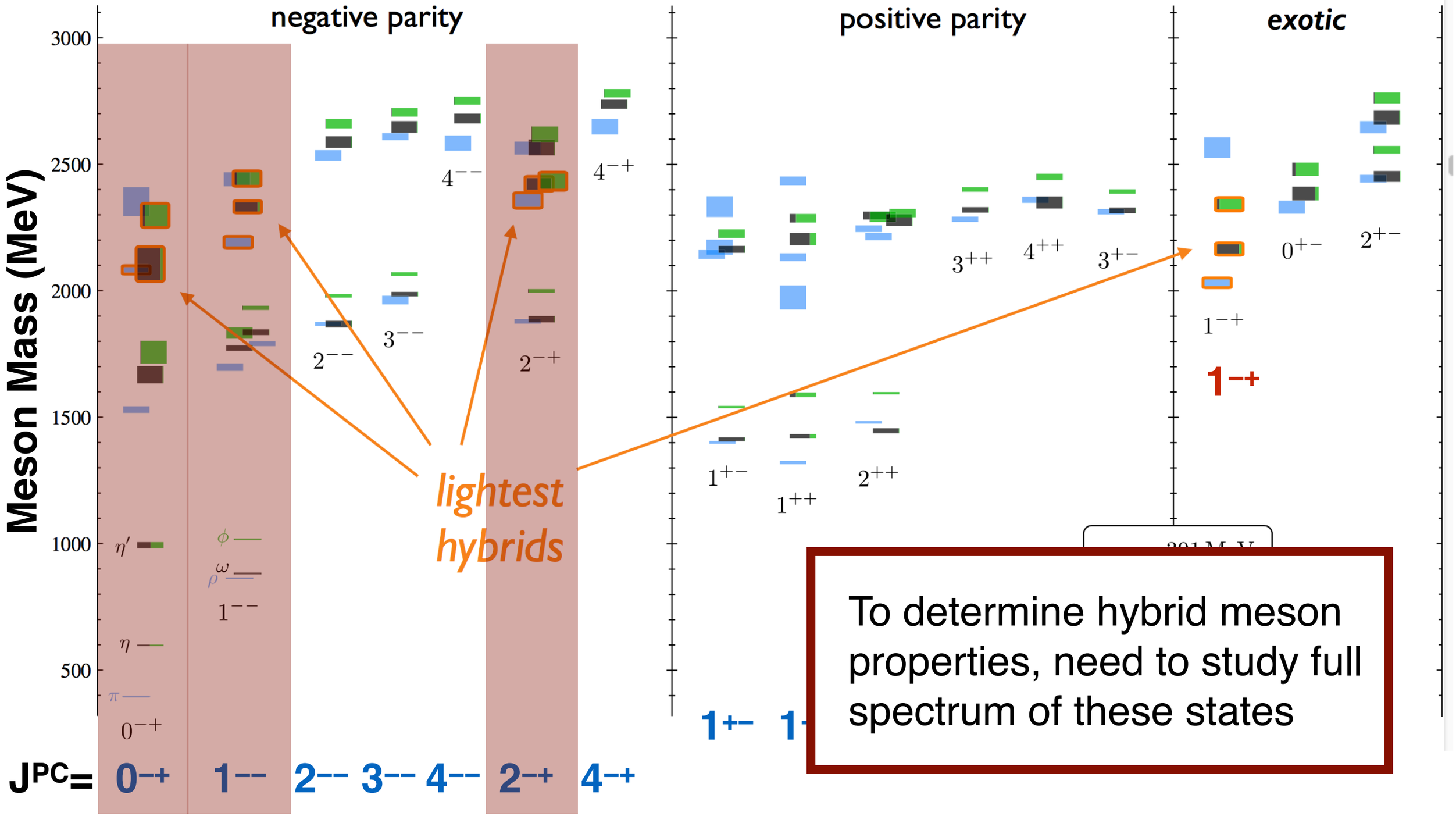
Light Meson Spectrum from Lattice QCD



To determine hybrid meson properties, need to study full spectrum of these states

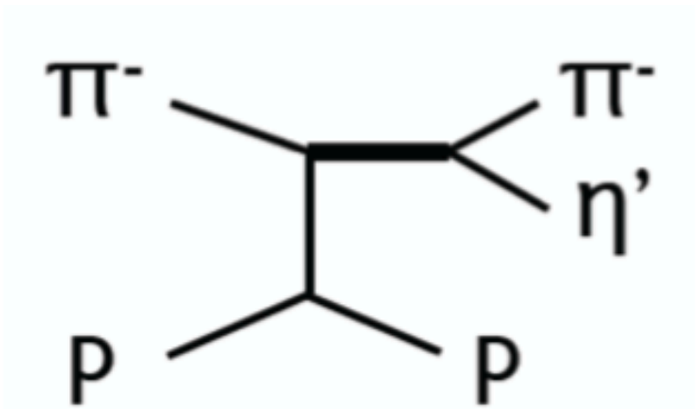
HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

Evidence for exotic light-quark mesons

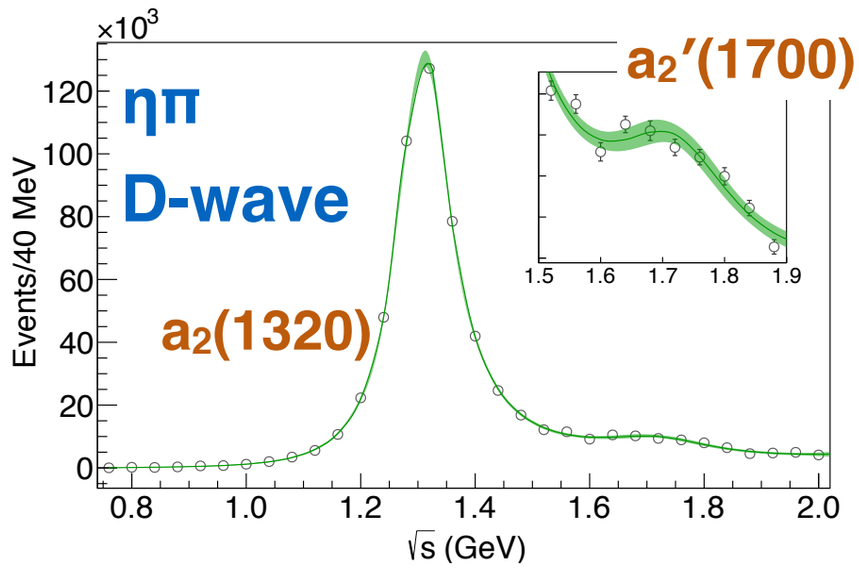
- Many searches, strongest evidence for π_1 in $\eta'\pi$ and $\rho\pi$ P-waves
- Coupled channel fit in unitary reaction model describes COMPASS data

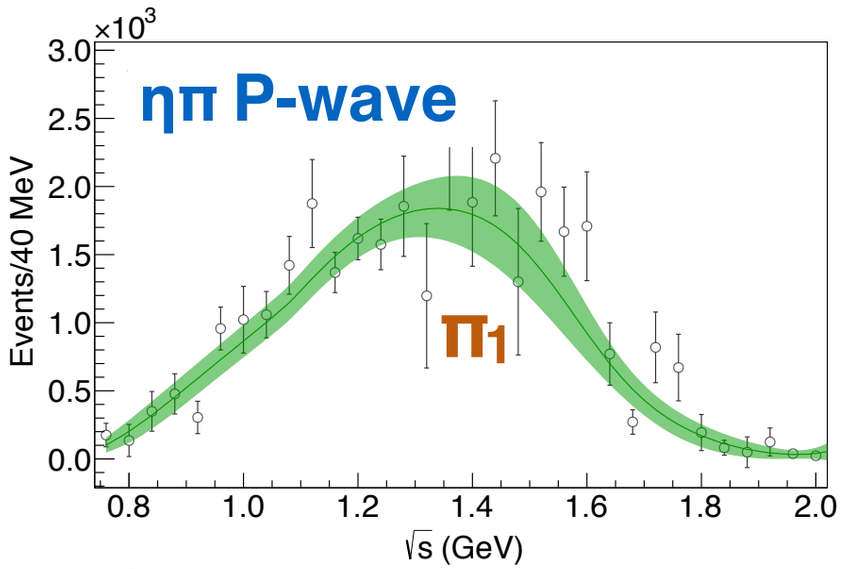
COMPASS

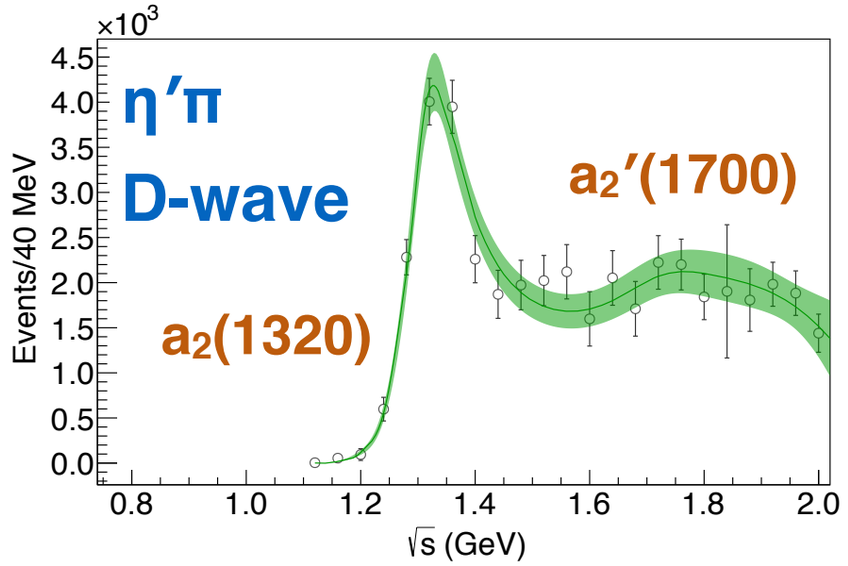
$\pi_1 \rightarrow \eta\pi$ / $\eta'\pi$

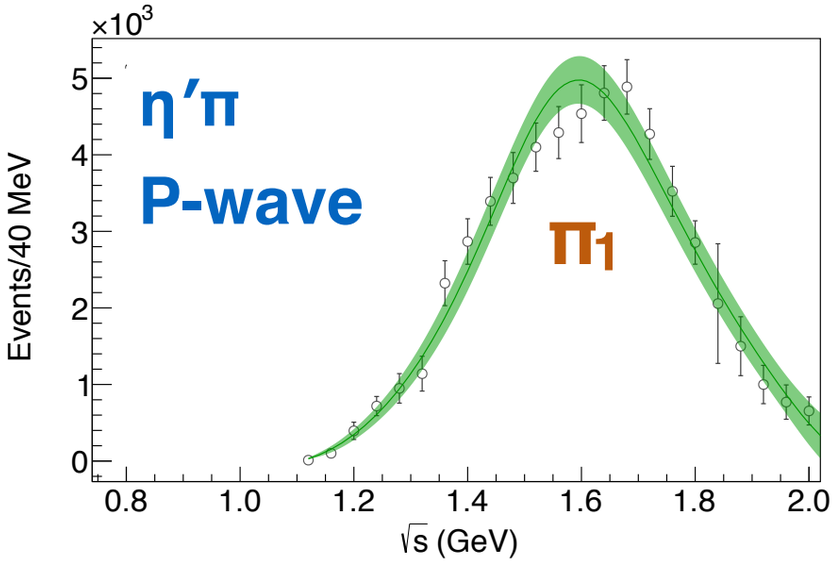


190 GeV π⁻ beam





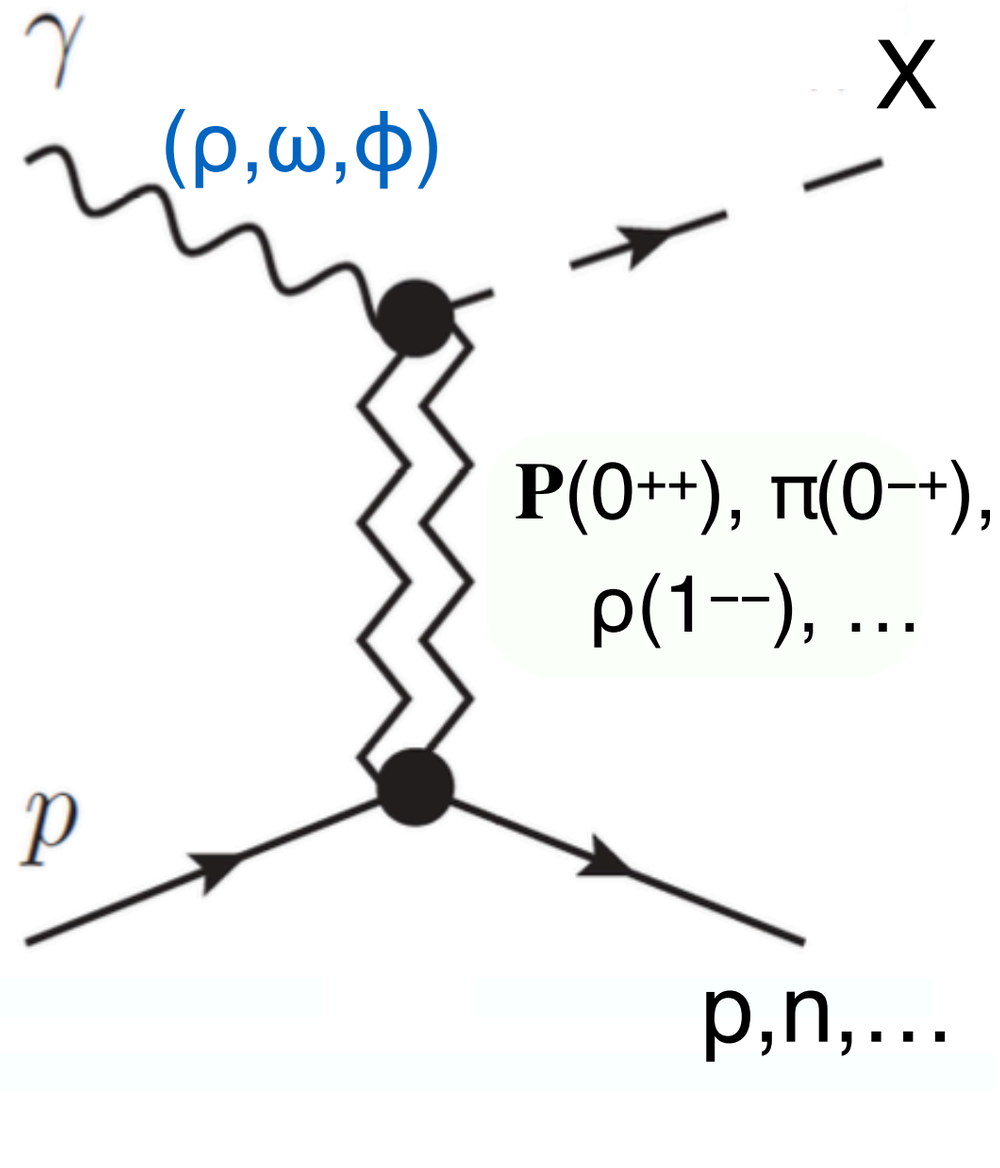




COMPASS
PLB 740, 303 (2015)

Rodas et al. (JPAC)
[PRL 122, 042002 (2019)]

Meson Photoproduction

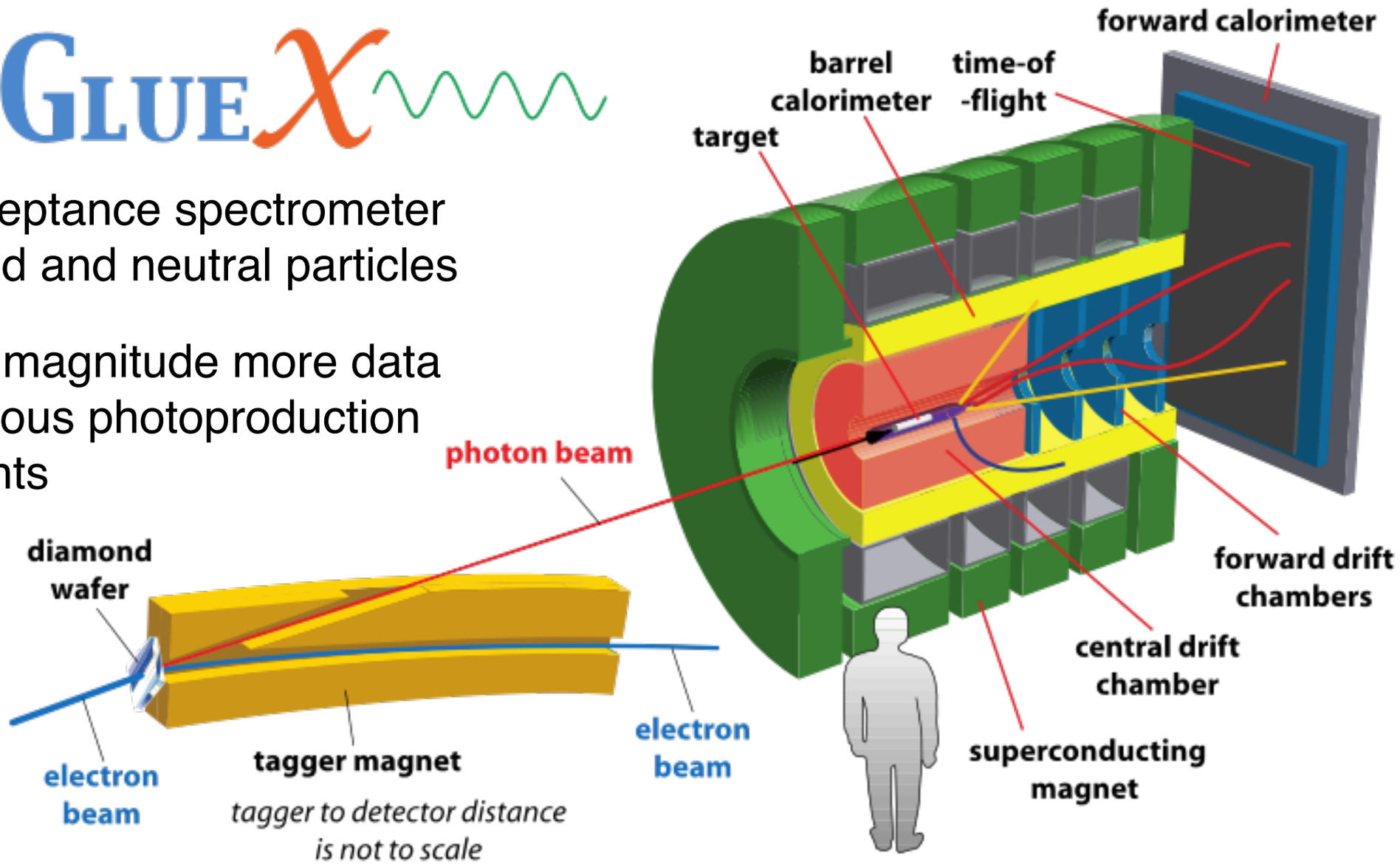


- Photon couples to exchanged QN via Vector Meson Dominance, generates mesons with wide variety of J^{PC}
  - **All** expected hybrids can be produced
- Little existing photoproduction data at $E_\gamma \approx 9$ GeV. Neutral final states at these energies are mostly **unexplored**
- Photon **polarization** provides constraints on production processes

The GlueX Experiment

Large acceptance spectrometer for charged and neutral particles

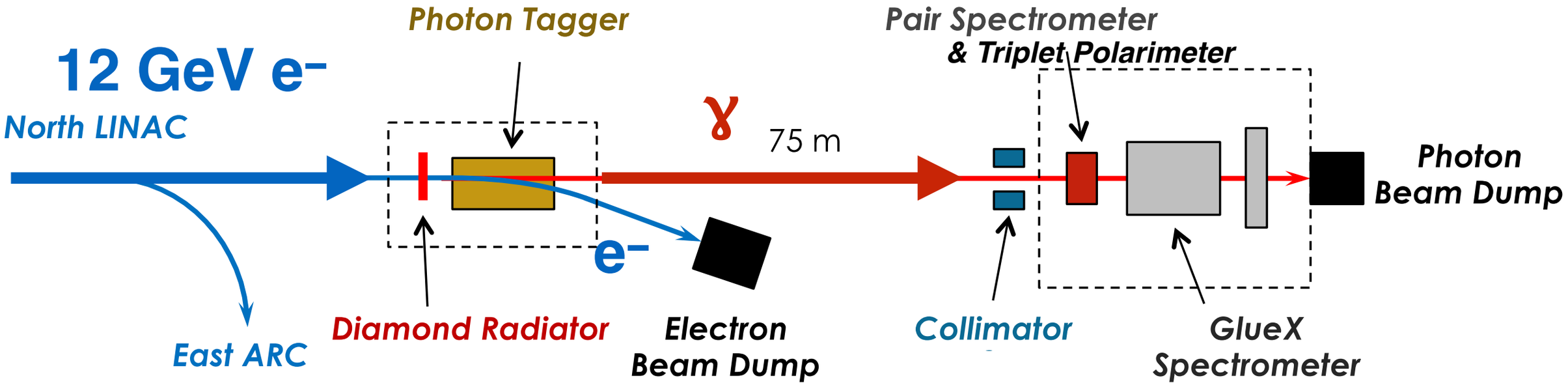
Orders of magnitude more data than previous photoproduction experiments



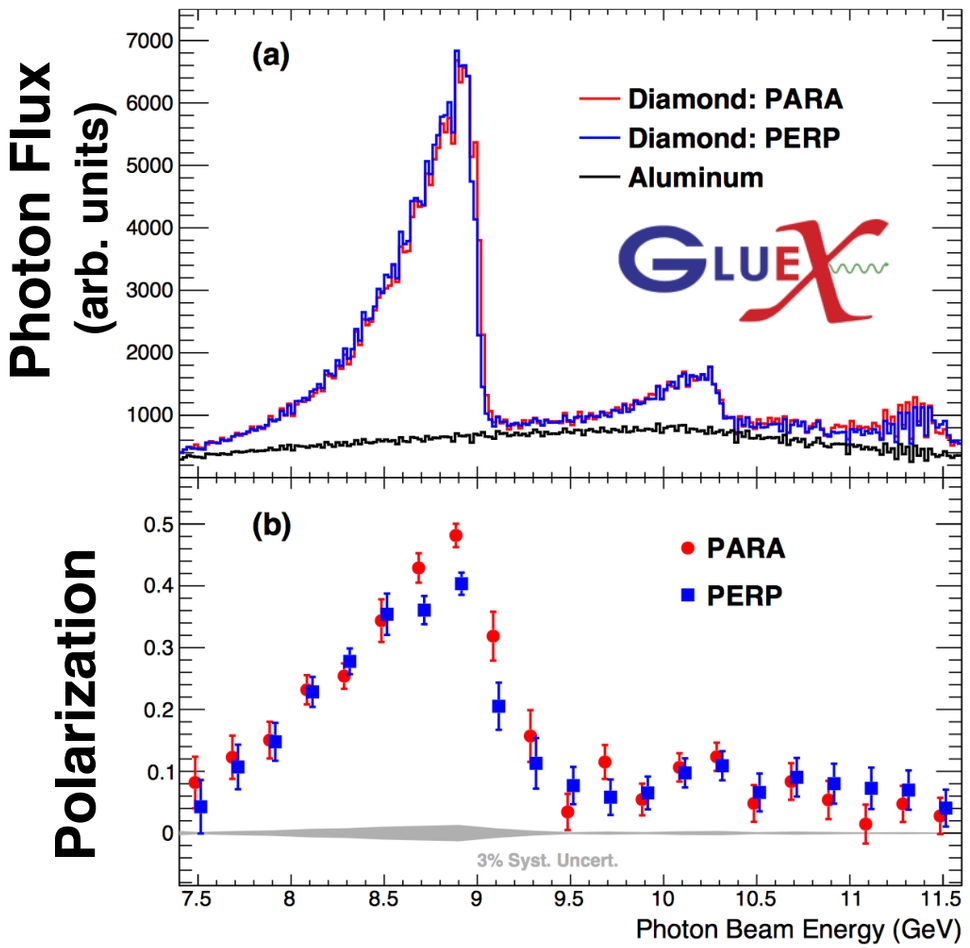
- **2016:** **2 pb^{-1}** ≈80 hours of physics-quality commissioning data
- **2017:** **21 pb^{-1}** used for most results shown here
- **2018:** **≈80 pb^{-1}** GlueX Phase-I **complete!**

over **300 B** events and **5 PB** of data!

The GlueX Experiment: Photon Beam



- Photon beam generated via **coherent bremsstrahlung** off thin diamond radiator
- Photon energies tagged by scattered electrons [precision **< 25 MeV**]
- Photon linear polarization **$P_\gamma \sim 40\%$** in peak
- Intensity of **~1–5 × 10^7 γ/s** in peak



Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data → Understand production mechanisms

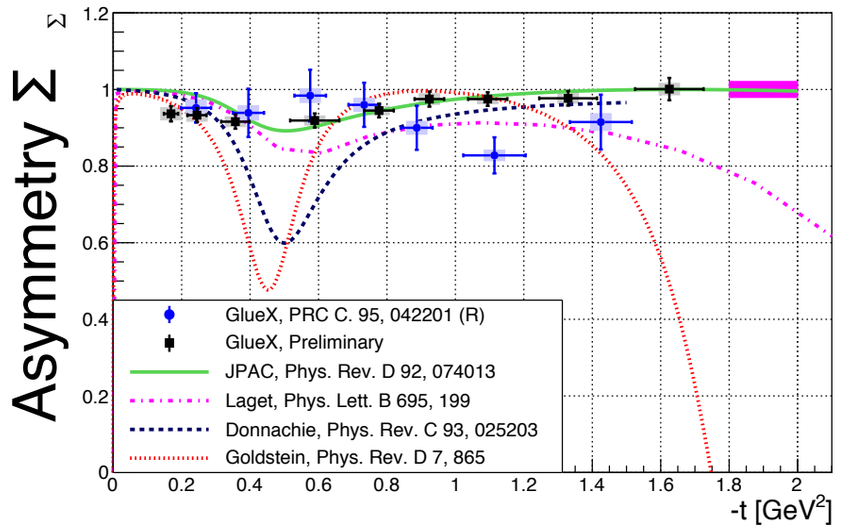
$\gamma p \to (\pi^0,\eta,\eta') p$

$\gamma p \to (\rho,\omega,\phi) p$

$\gamma p \to (\Lambda,\Sigma) K^+$

- A. Austregesilo — Monday @ 2:30 PM
- S. Fegan — Monday @ 5:00 PM
- W. McGinley — Thursday @ 3:00 PM
- N. Wickramaarachchi — Thursday @ 5:30 PM

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



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$\gamma p \to (\rho, \omega, \phi) p$

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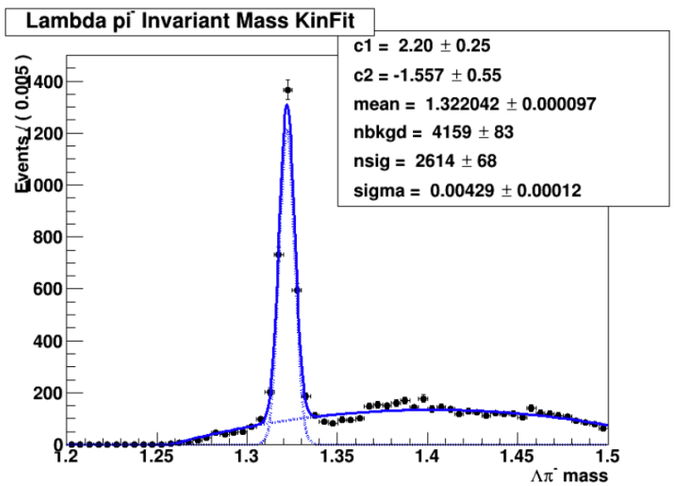
Understand production mechanisms

Measure cross sections

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



- A. Ernst — Friday @ 9:45 AM

Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

Collect Data

Understand production mechanisms

Measure cross sections

Identify known mesons

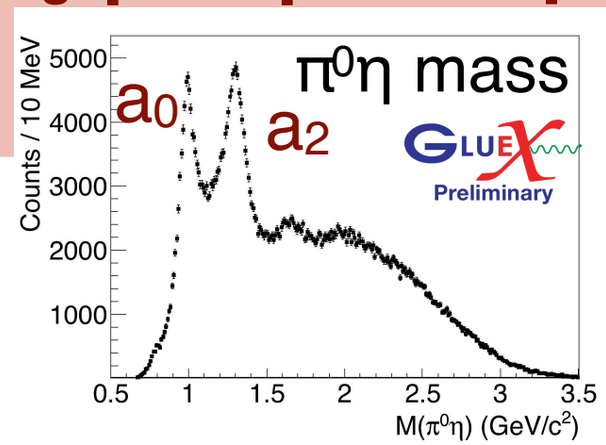
a, f, b, h, η, π, …

Search for exotics

π_1, η_1, η_1', $b_{0,2}$, $h_{0,2}$ …

Amplitude Analysis

$\gamma p \rightarrow p + \pi^0 \eta$



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Theoretical Models (JPAC, ….)

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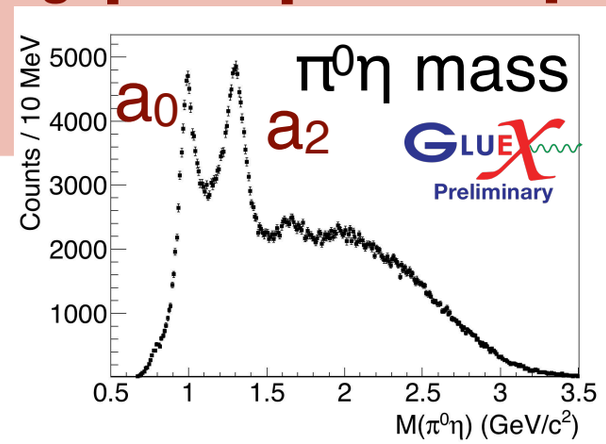
Amplitude Analysis

Collaboration Welcome!

$\gamma p \rightarrow p + \pi^0 \eta$



Searching for Exotics in Photoproduction

- Detailed understanding of light-quark meson spectrum requires amplitude analysis.

• H. Li — Friday @ 9:15 AM

Collect Data

Opportunistic measurements & New Ideas

Ξ*, ΛΛ̄, J/ψ, …

Understand production mechanisms

Measure cross sections

Theoretical Models (JPAC, ….)

Identify known mesons

a, f, b, h, η, π, …

Amplitude Analysis

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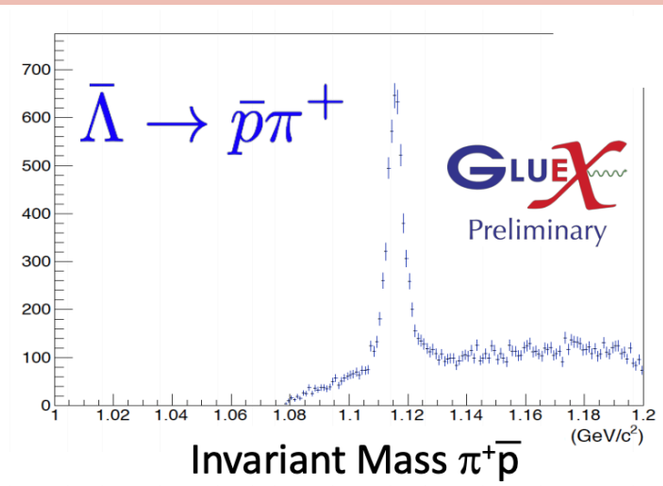
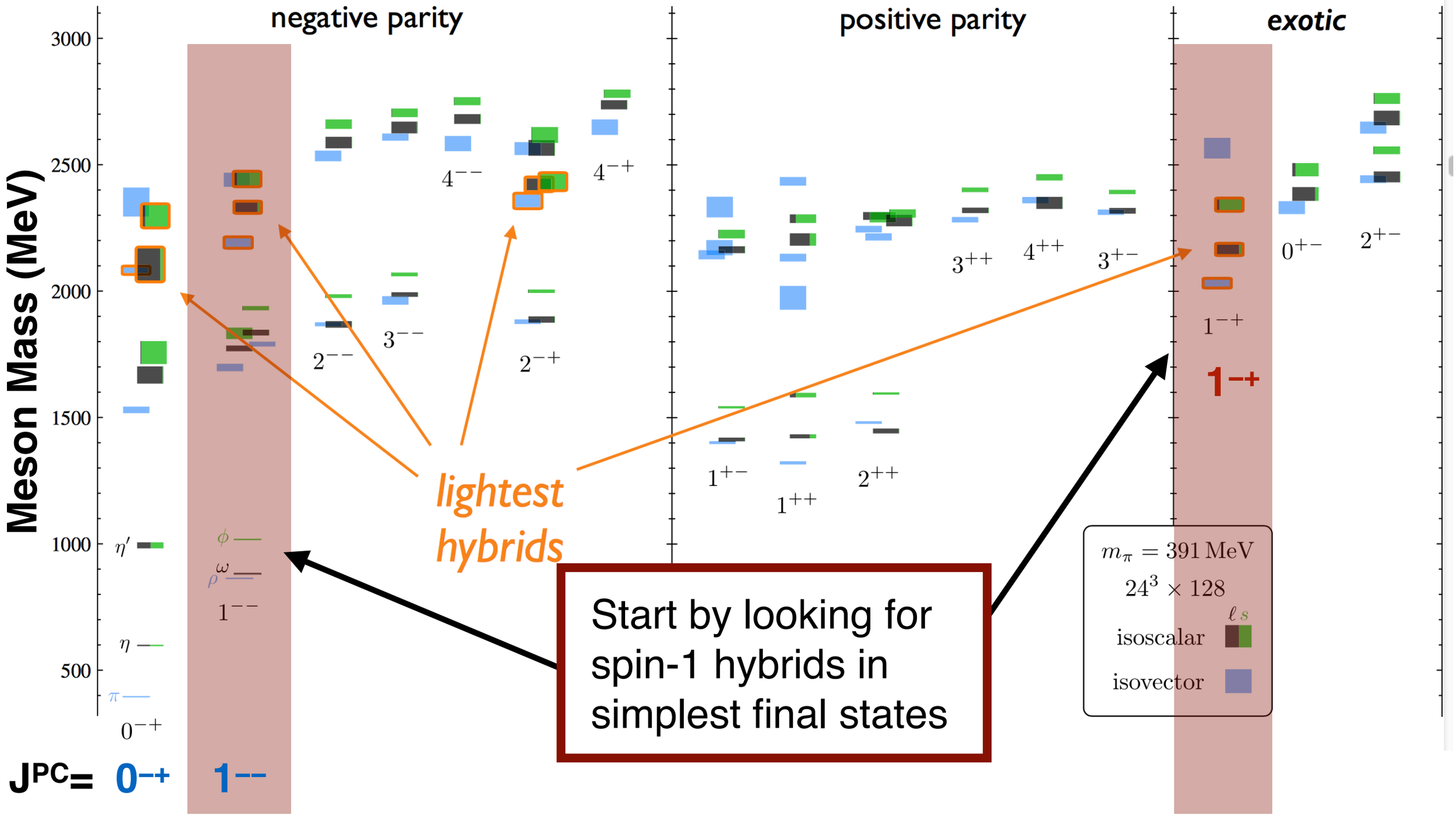
π_1, η_1, η_1', $b_{0,2}$, $h_{0,2}$ …

Collaboration Welcome!

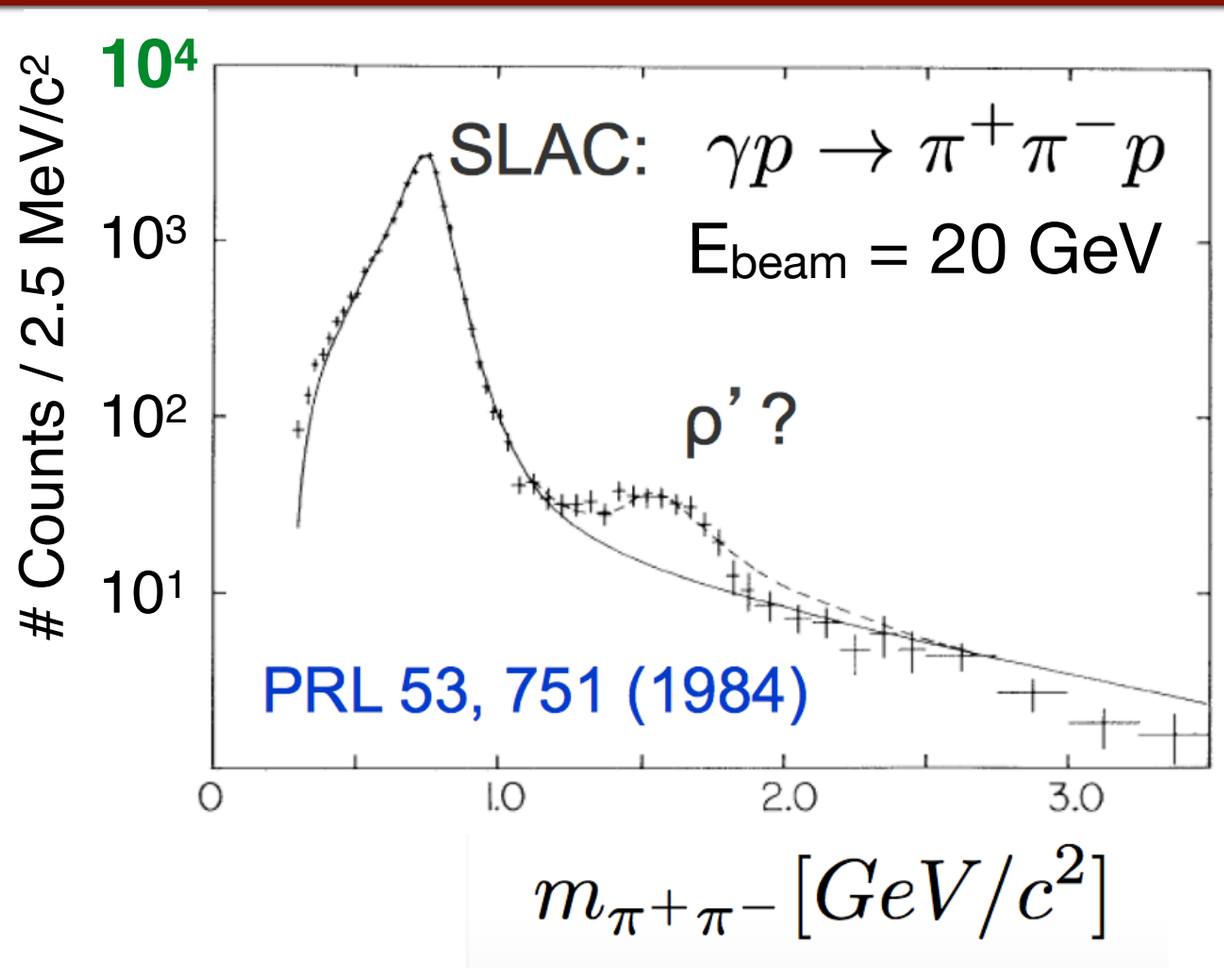


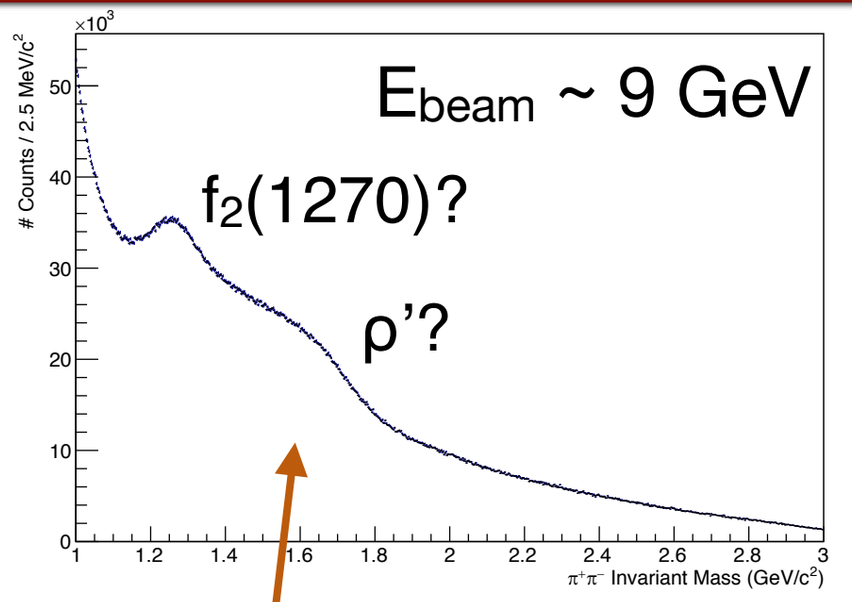
Light Meson Spectrum from Lattice QCD

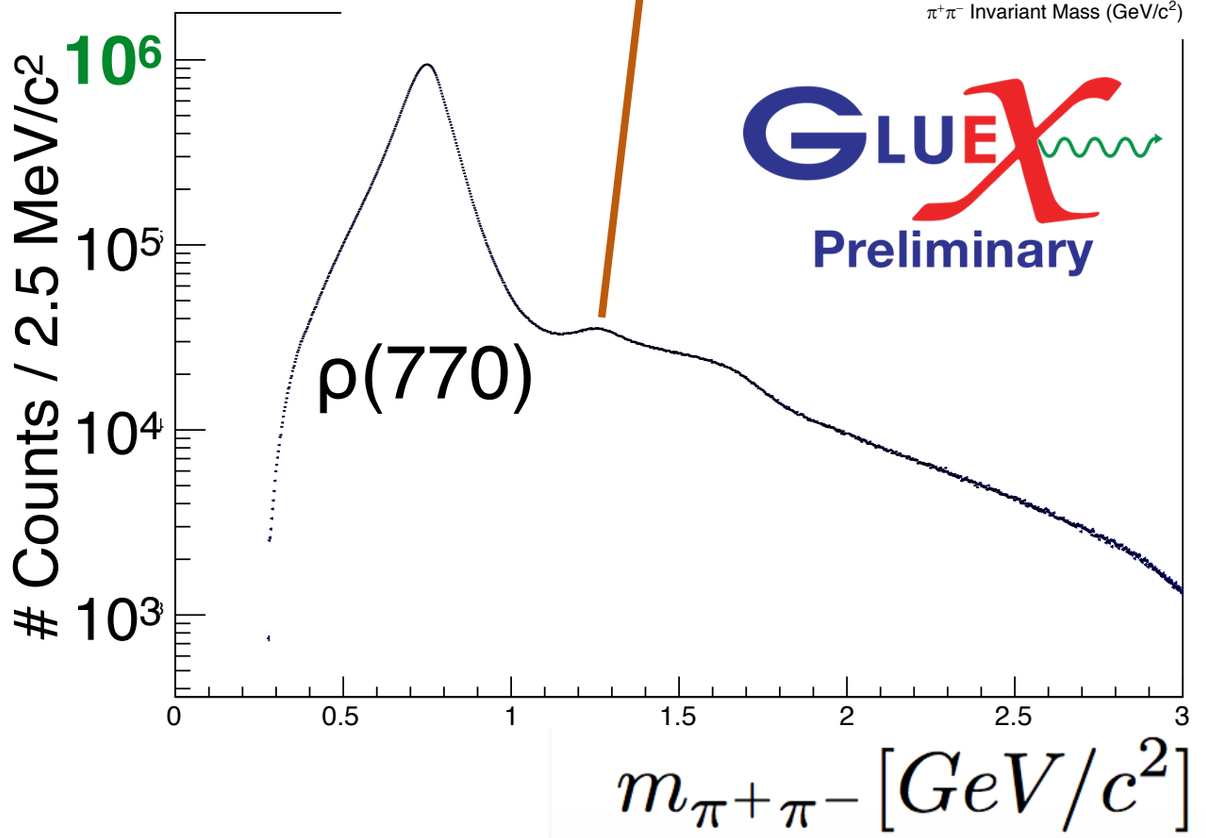


HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

Spectroscopy Prospects: γ p → p + π⁺ π⁻



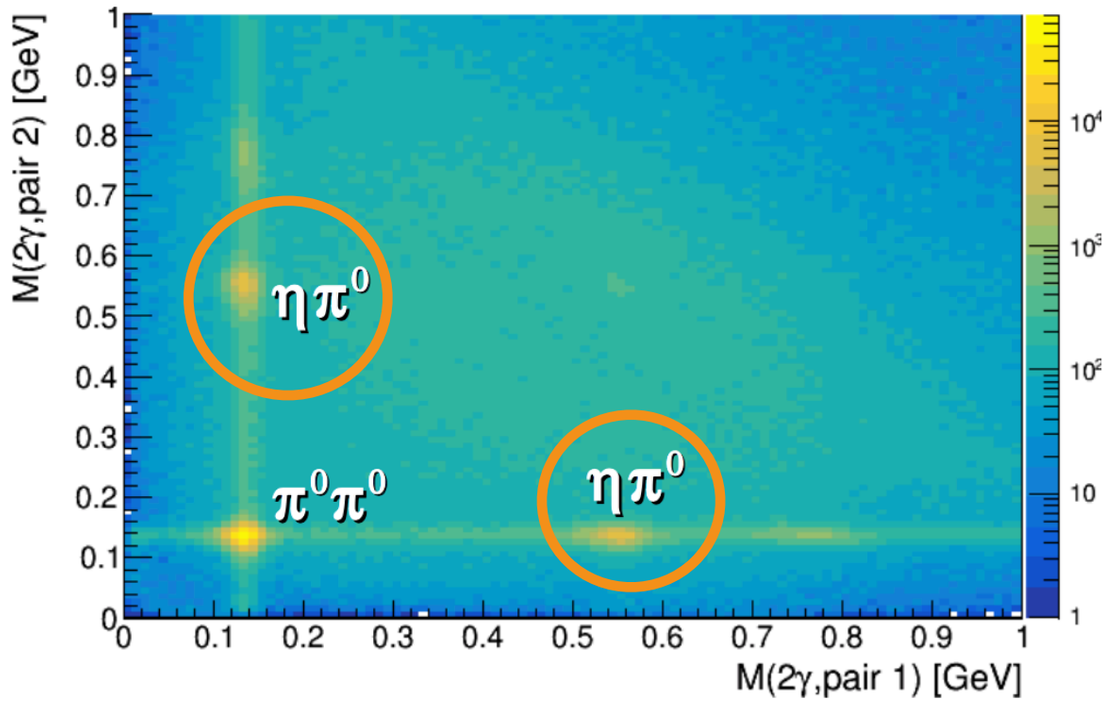




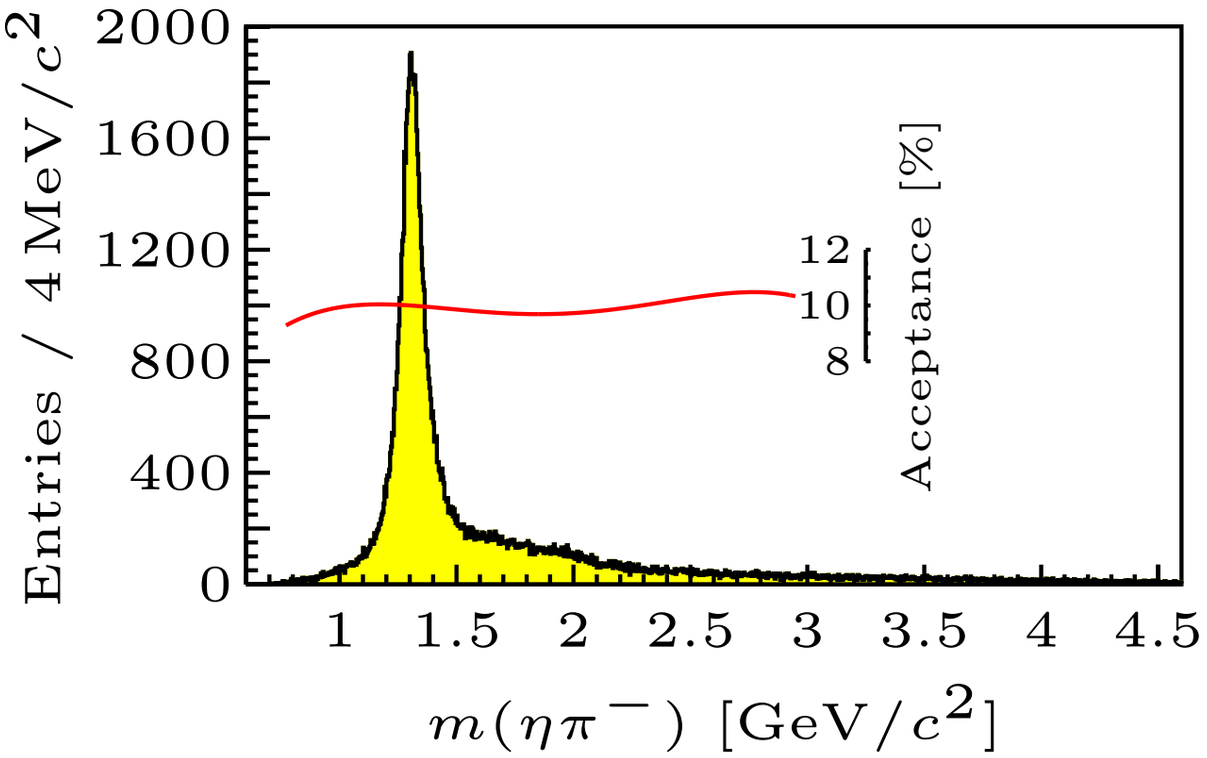
- Take fresh look at **π⁺ π⁻** photoproduction
  - Using two-orders of magnitude more data than SLAC
  - Enhancements seen with **M > 1 GeV**
  - Moment / amplitude analysis underway
- K⁺ K⁻ photoproduction also being studied

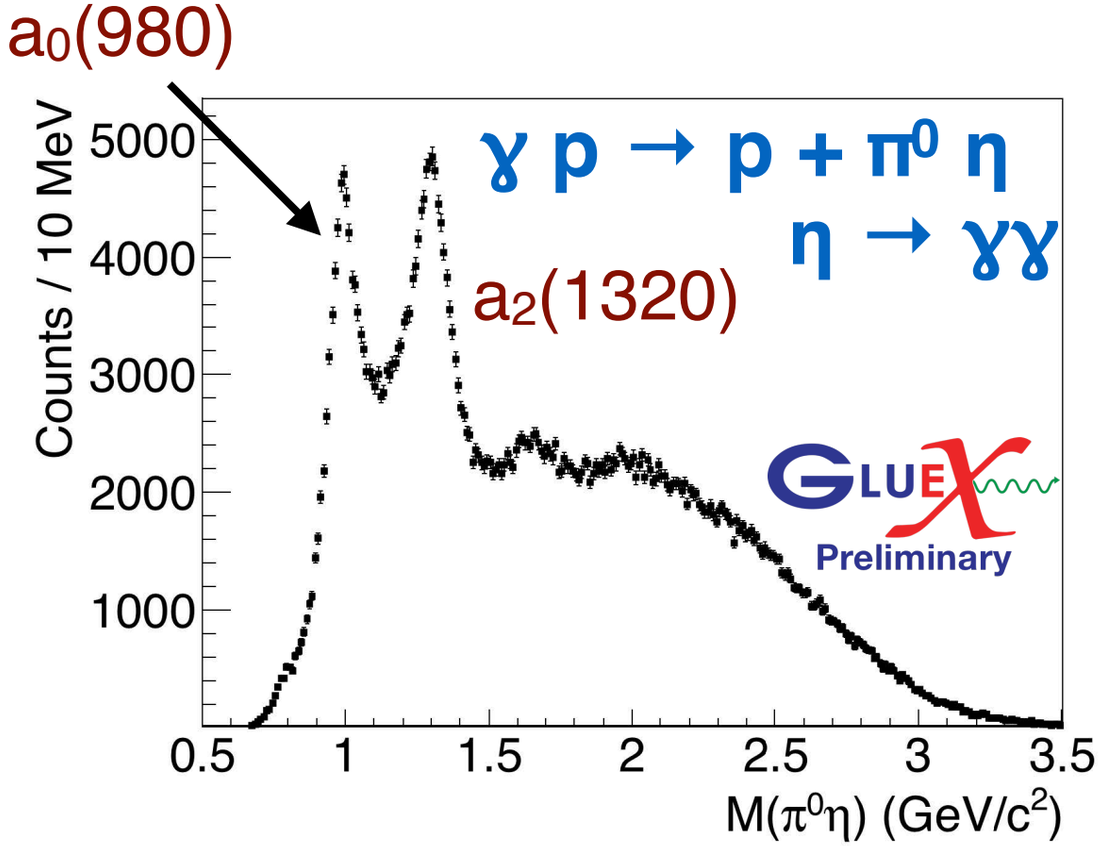
Spectroscopy Prospects: γ p → p + π η

- ηπ / η′π important channels for early hybrid searches
- With 20% of GlueX Phase-I data, we see several well-known mesons
- Expect twice COMPASS πη / πη′ events with full Phase-I data



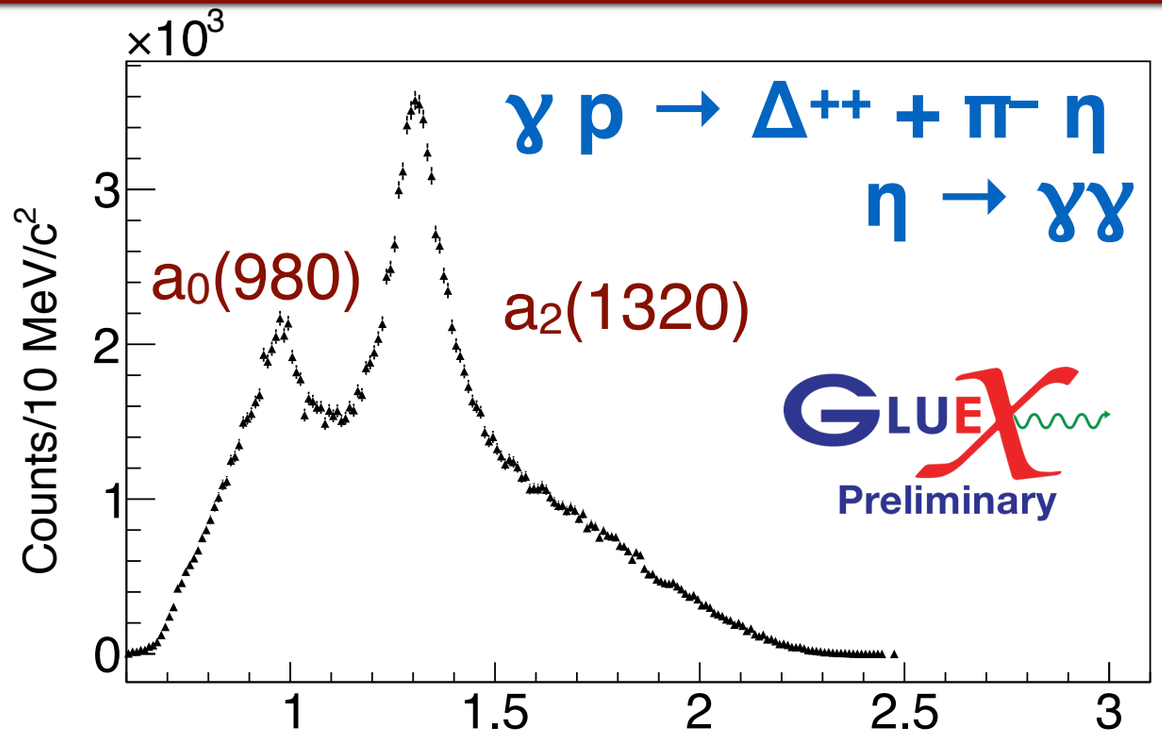
COMPASS: PLB 740, 303 (2015)

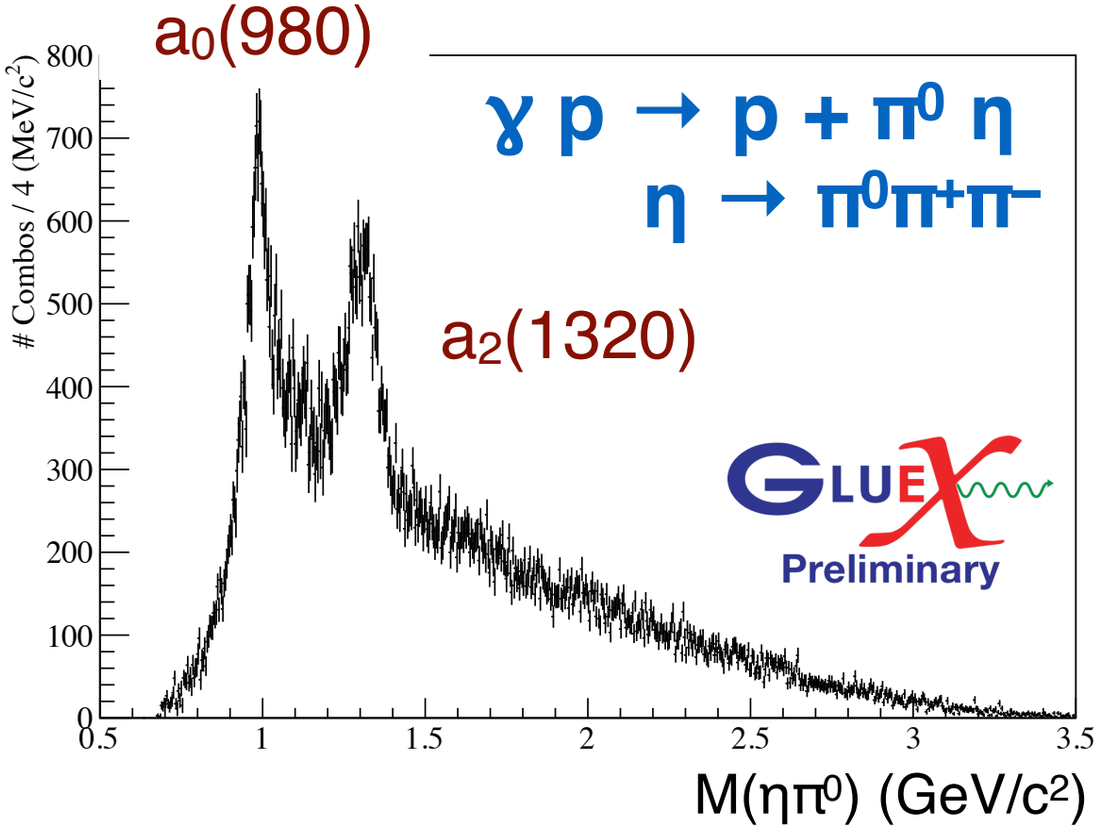


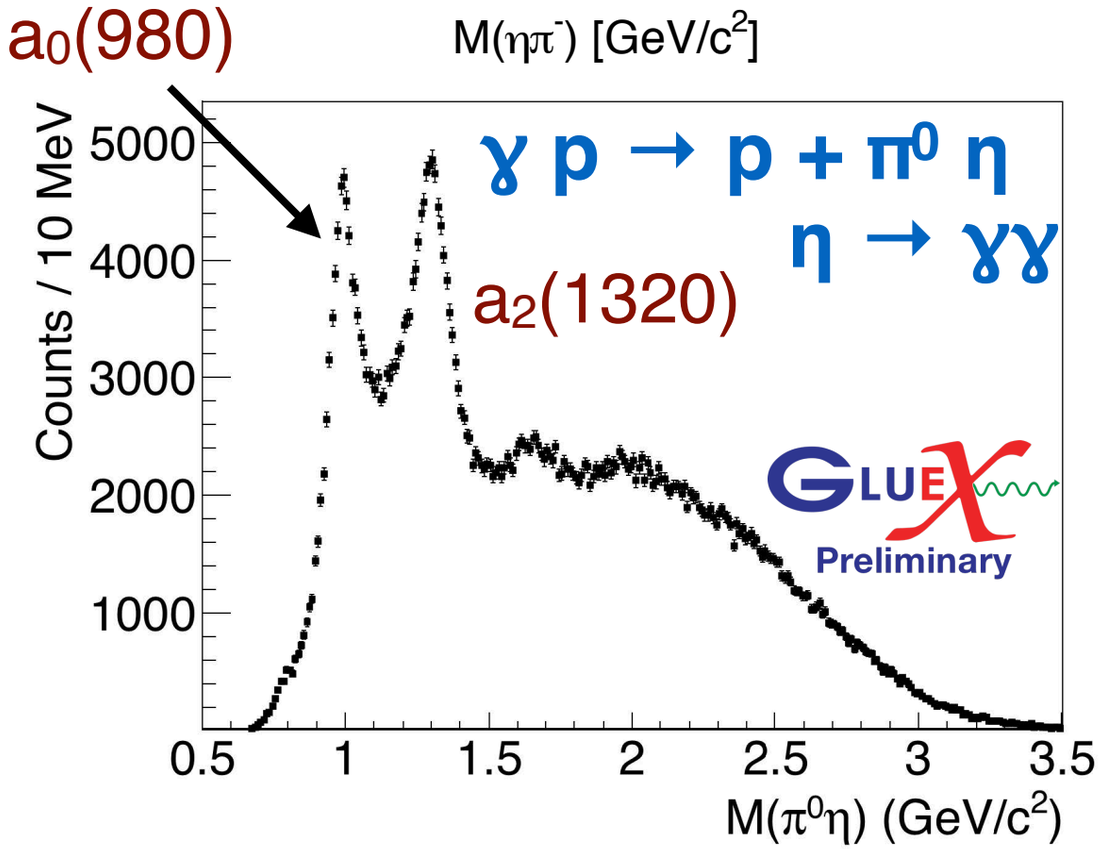


Spectroscopy Prospects: γ p → p + π η

- ηπ / η′π important channels for early hybrid searches
- With 20% of GlueX Phase-I data, we see several well-known mesons
- Expect twice COMPASS πη / πη′ events with full Phase-I data

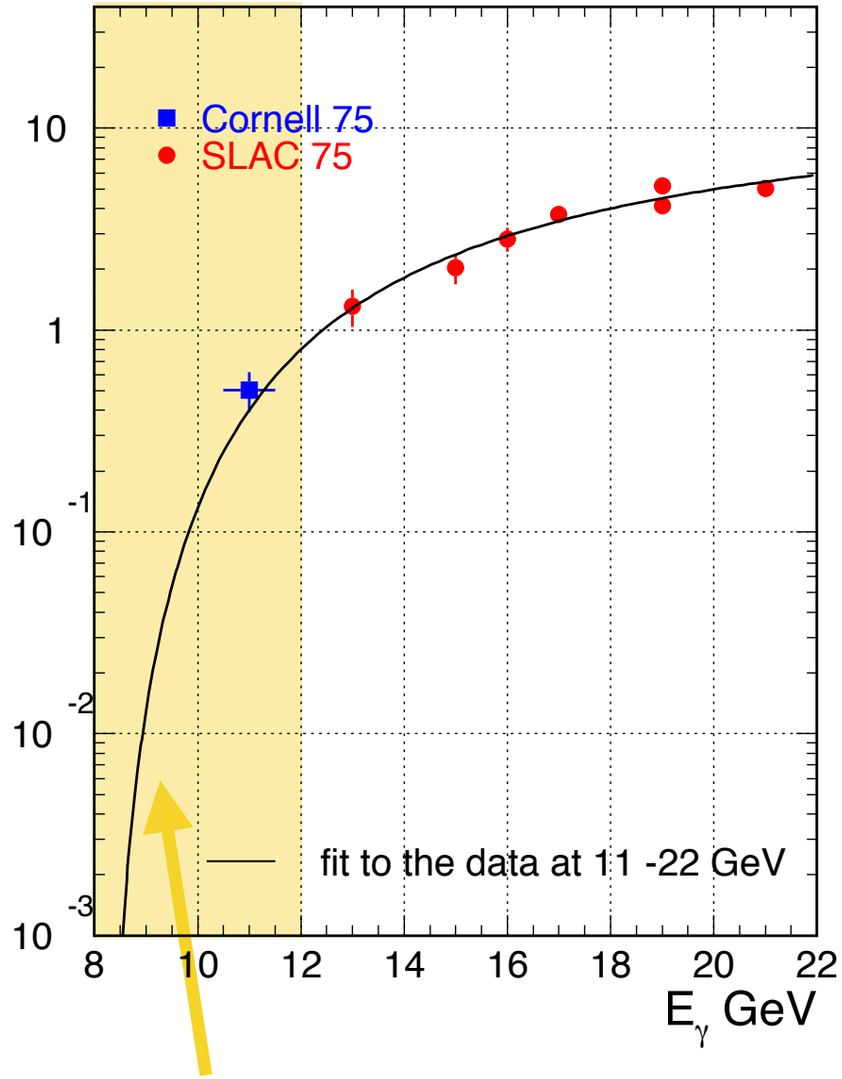




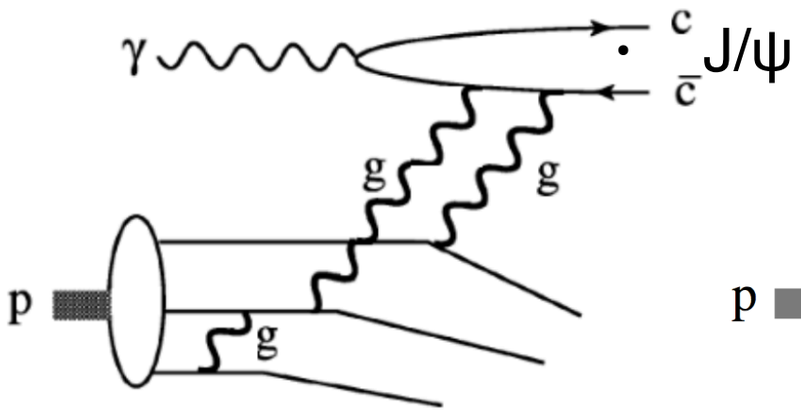


J/ψ Photoproduction Near Threshold

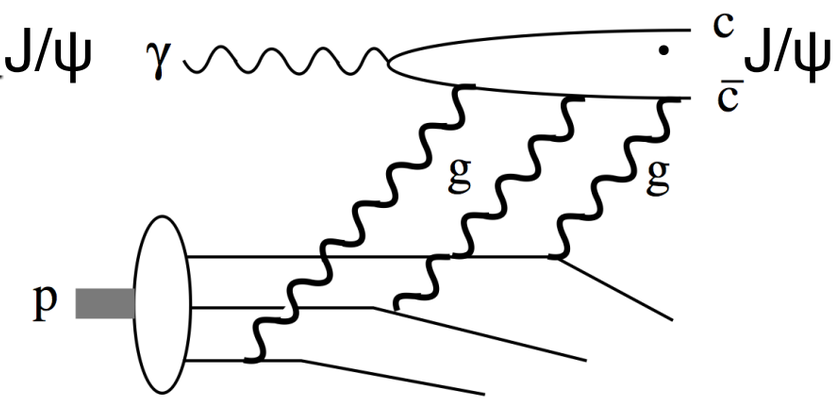
- Threshold production is experimentally clean, ideal for studying J/ψ+N interaction
  - Probes gluon distributions in proton [Kharzeev et al., NPA 661, 568 (1999)]
  - Also multiquark correlations, distributions at large-x [Brodsky et al., PLB 498, 23 (2001)]



GlueX energy range



leading-twist

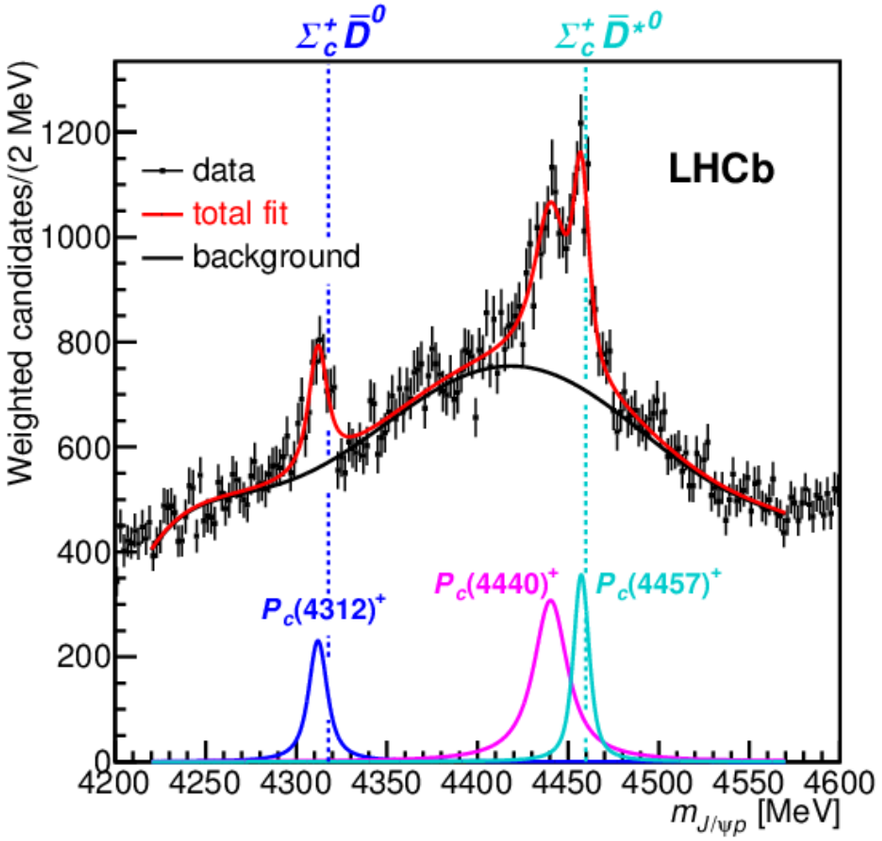


higher-twist

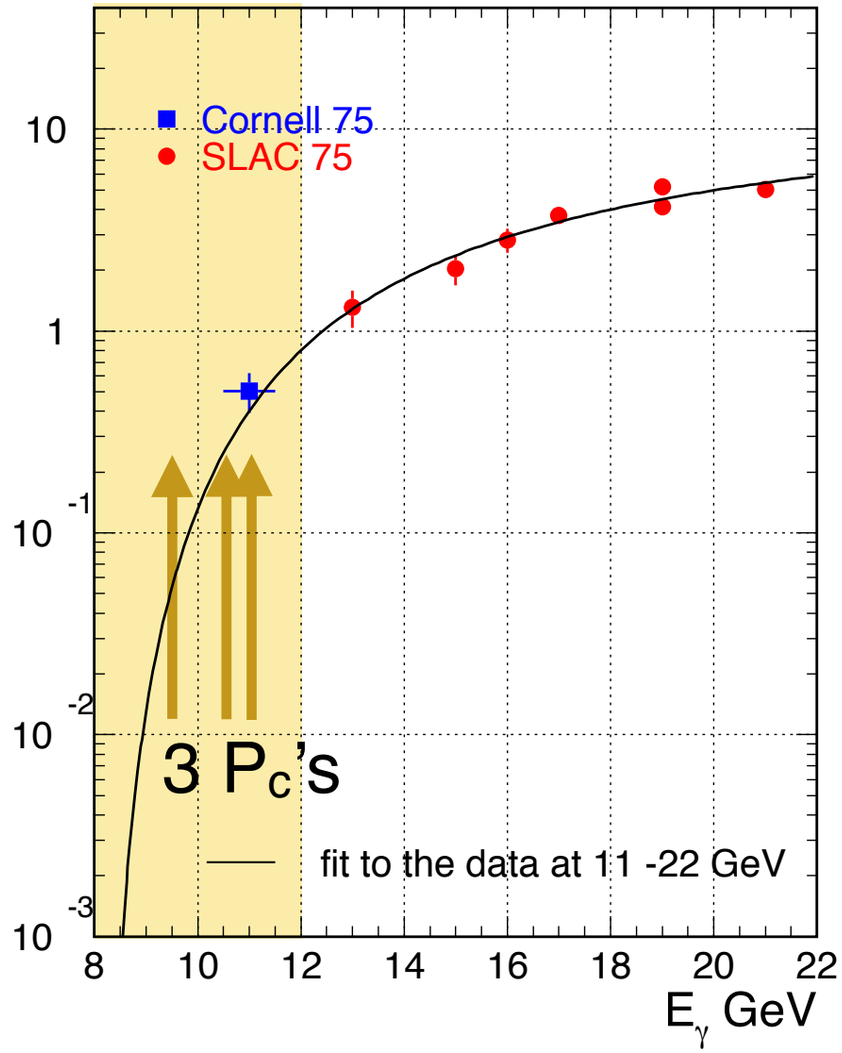
J/ψ Photoproduction Near Threshold

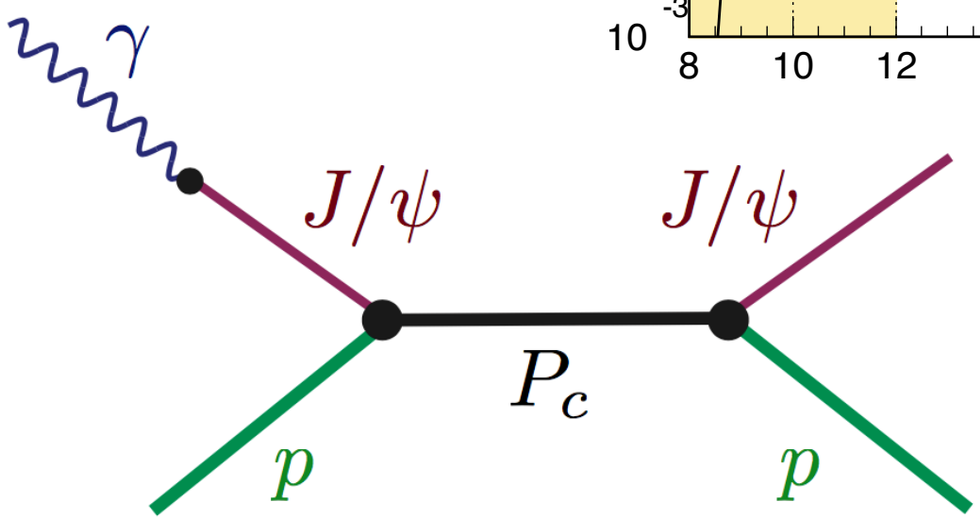
- Threshold production is experimentally clean, ideal for studying J/ψ+N interaction
  - Can also study coupling of resonant J/ψ+p states to photon

$\Lambda_b^0 \to J/\psi\, p\, K^-$



LHCb, arXiv:1904.03947 (2019)

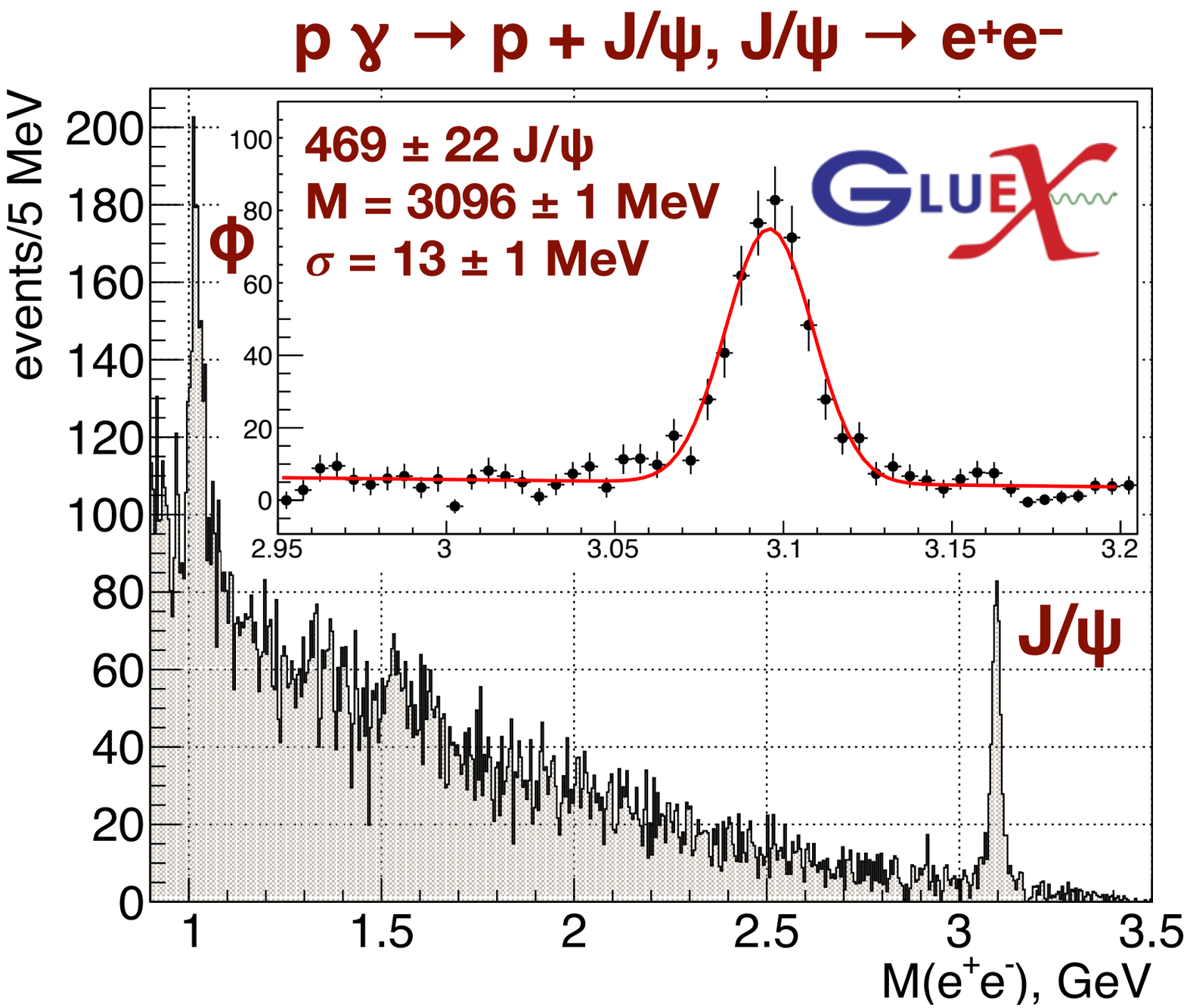




s-channel photoproduction probes nature of 5-quark interaction!

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

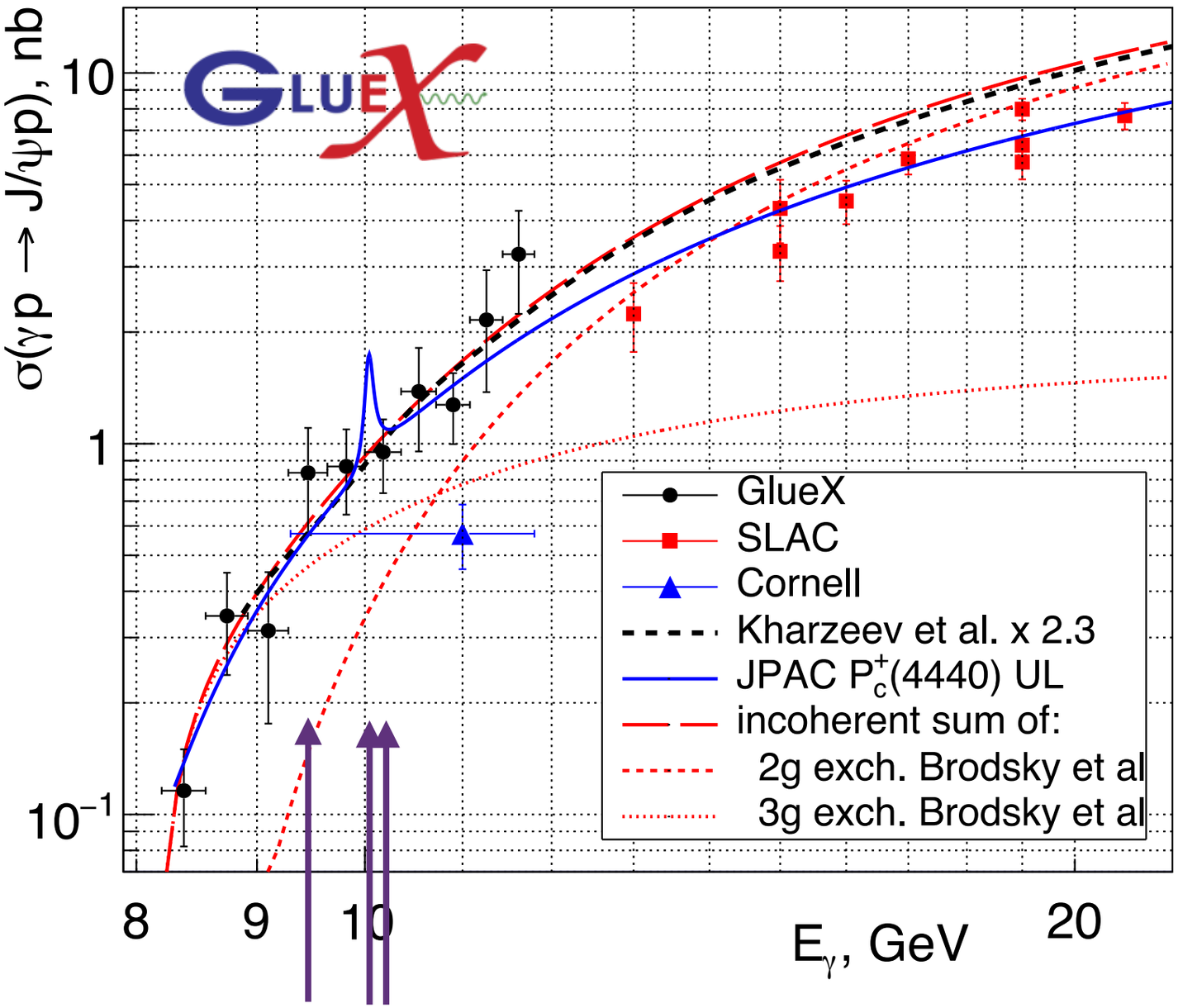
J/ψ Photoproduction at GlueX: Mass Spectrum



- Reconstruct exclusive reaction
- Calculate J/ψ cross sections normalized by non-resonant e^+e^-

J/ψ Photoproduction at GlueX: Cross Sections

arXiv:1905.10811: Submitted to PRL

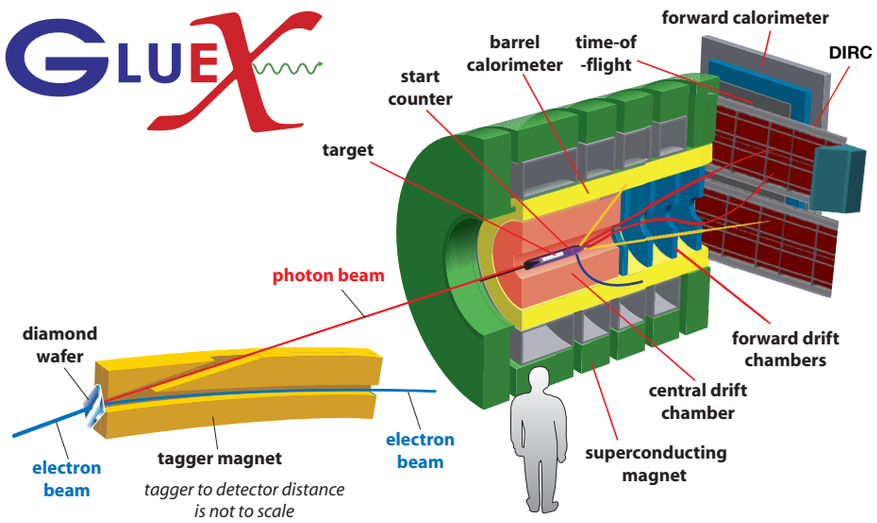


- First J/ψ cross section measurement at threshold
  - 27% normalization uncertainty
- Model-dependent upper limits at 90% CL:
  - Br($P_c(4312)$ → J/ψ p) **< 4.6%**
  - Br($P_c(4440)$ → J/ψ p) **< 2.3%**
  - Br($P_c(4457)$ → J/ψ p) **< 3.8%**
- Full Phase-I data is 3x larger, unbinned analyses planned

JPAC A.N. Hiller Blin, et al., PRD 94, 034002 (2016).

Summary

- GlueX has started mapping the **normal** meson spectrum!
  First step towards establishing the **hybrid** meson spectrum.
  - **Phase I** run is complete, program of production & cross section measurements well underway
    - Focus on spectroscopy of up/down quark states, initial studies of J/ψ and other rare processes
    - First limits on **Br($P_c \rightarrow J/\psi p$)** constrain nature of **LHCb P_c** states
- Phase-II High-luminosity running will begin this Fall, extend reach to **strange-quark** states — **see J. Stevens, Tuesday @ 1:30 PM**



Backup Slides

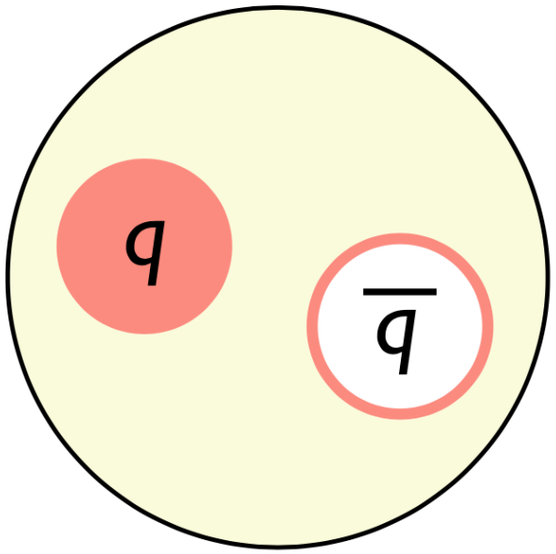
Meson Quantum Numbers

Mesons are arranged in groups of 9 (“nonets”) with same J^{PC}

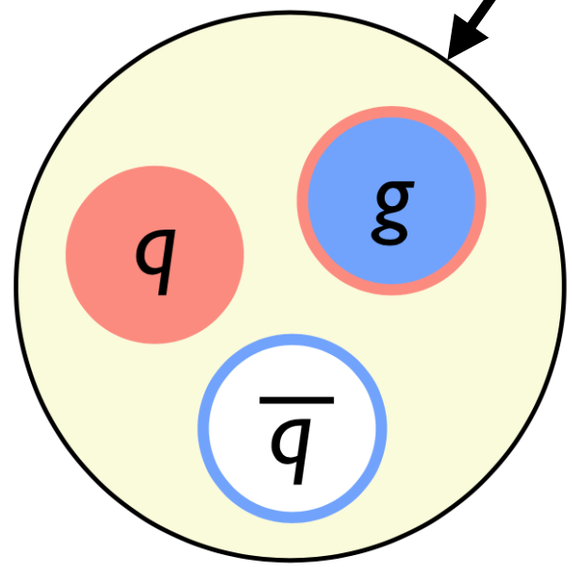
$J=L+S \quad P=(-1)^{L+1} \quad C=(-1)^{L+S}$

gluonic field excitation → “constituent gluon”

$(J^{PC}) = 1^{+-}$



“Normal” Meson



“Hybrid” Meson

Allowed J^{PC} : **0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{-+},…**

Forbidden J^{PC}: **0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, …**

Hybrid J^{PC} : **0^{-+}, 0^{+-}, 1^{--}, 1^{-+}, 2^{-+}, 2^{+-},** …

Hybrid–Meson mass splitting ~ 1.0 – 1.5 GeV

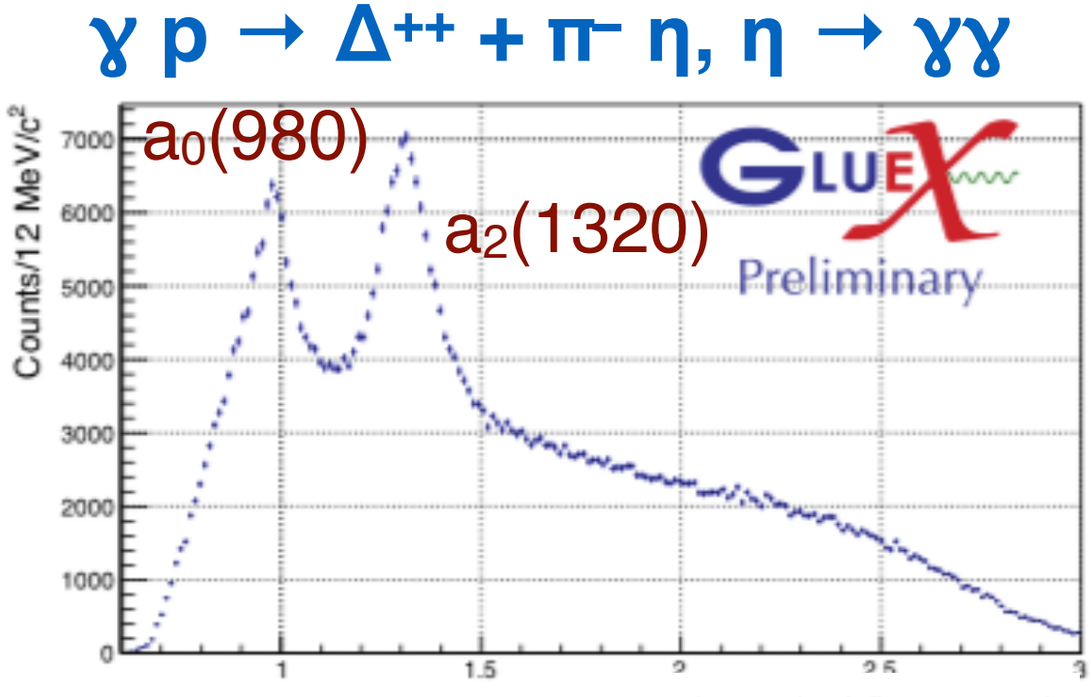
GlueX Experimental Program

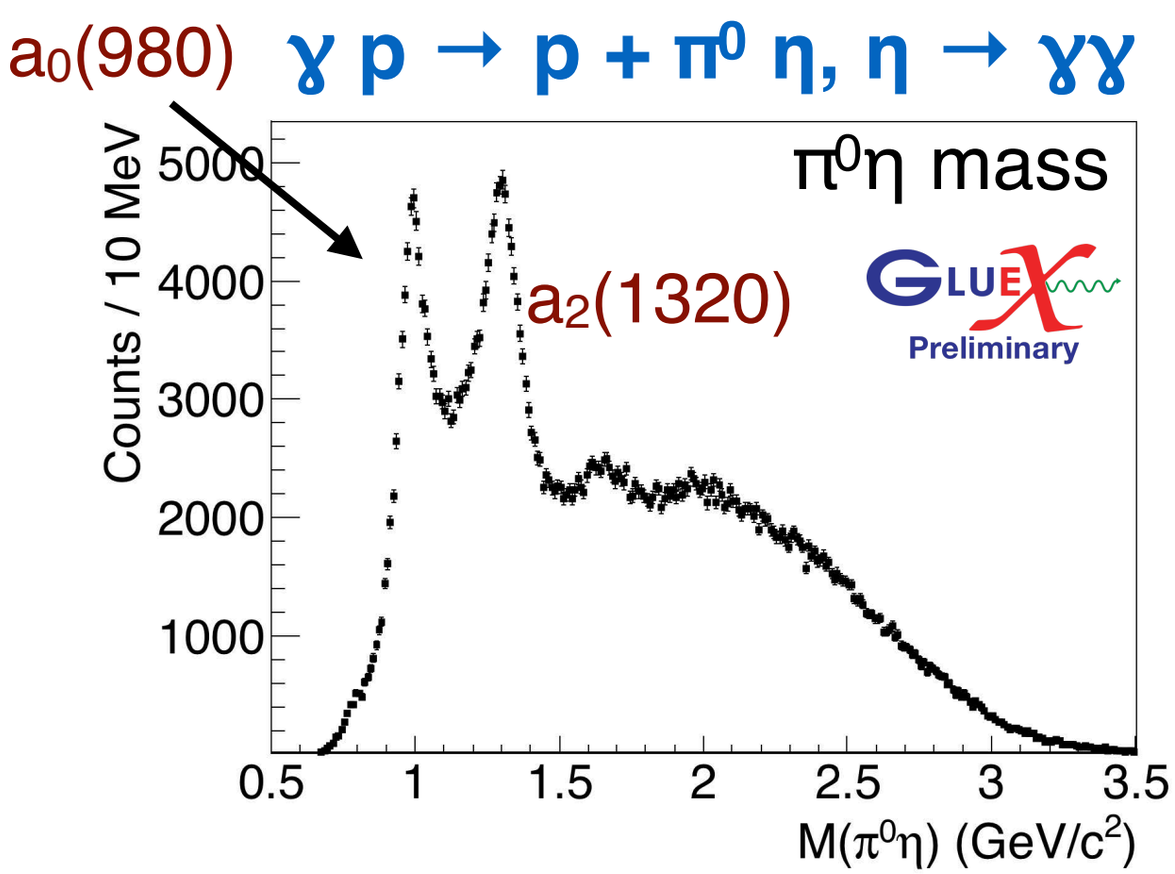
Experiment	Description	Beam Time (PAC days)
GlueX-I	Spectroscopy of light and hybrid mesons (low-intensity)	80
GlueX-II	Spectroscopy of hadrons with strange quark decays (high-intensity)	220+
PrimEx-eta	Eta radiative decay width	79
CPP	Charged pion polarizability	25
JEF	Rare eta decays	42

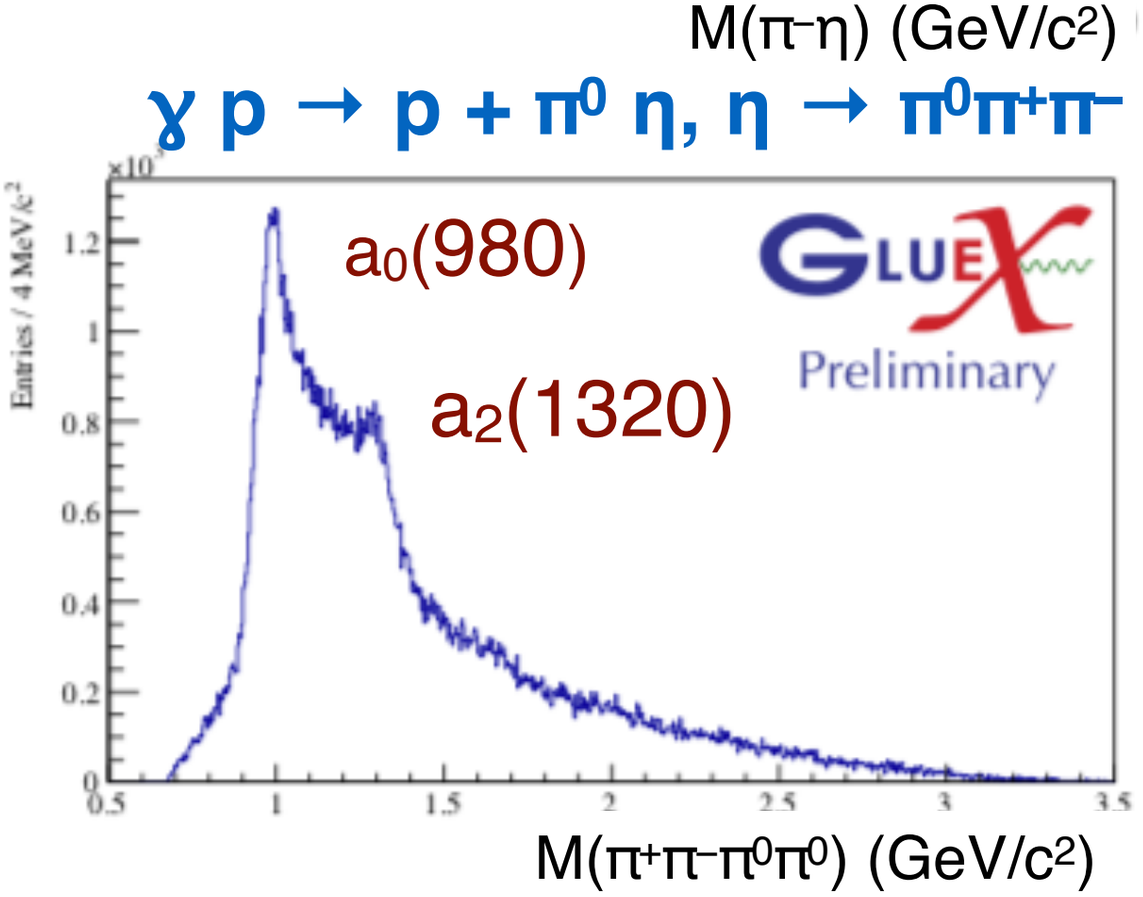
- Detector upgrades underway: DIRC for enhanced π/K separation being installed, CompCal for precision luminosity
- Rich menu of future ideas being developed: K_L beam, ω-photoproduction in nuclei, other ideas

Spectroscopy Prospects: γ p → p + π η

- In same decay modes as COMPASS, GlueX will have 280,000 πη and 52,000 πη′ events in the full data set (versus COMPASS with 116,000 & 39,000).

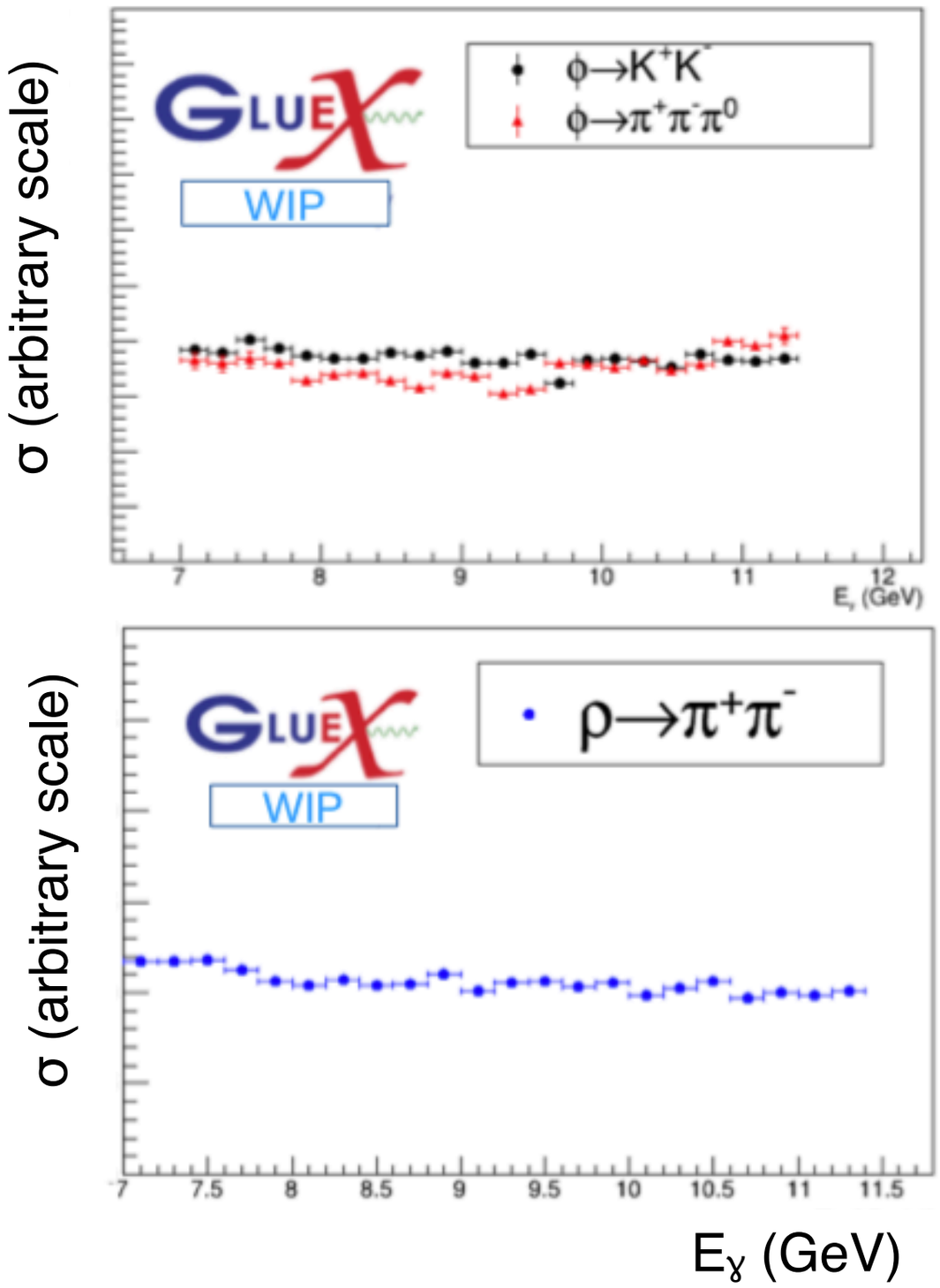






Work Towards Vector Meson Production Cross Sections

- Vector meson production cross sections provide important benchmarks
  - Require understanding of efficiencies and photon flux
  - Comparison with previous measurements
    - Photon energy and t dependence gives more insight into production mechanisms
- Very preliminary “Work In Progress” shows similar beam energy dependence to previous measurements



Spectroscopy Prospects: γ p → p + η π⁺ π⁻

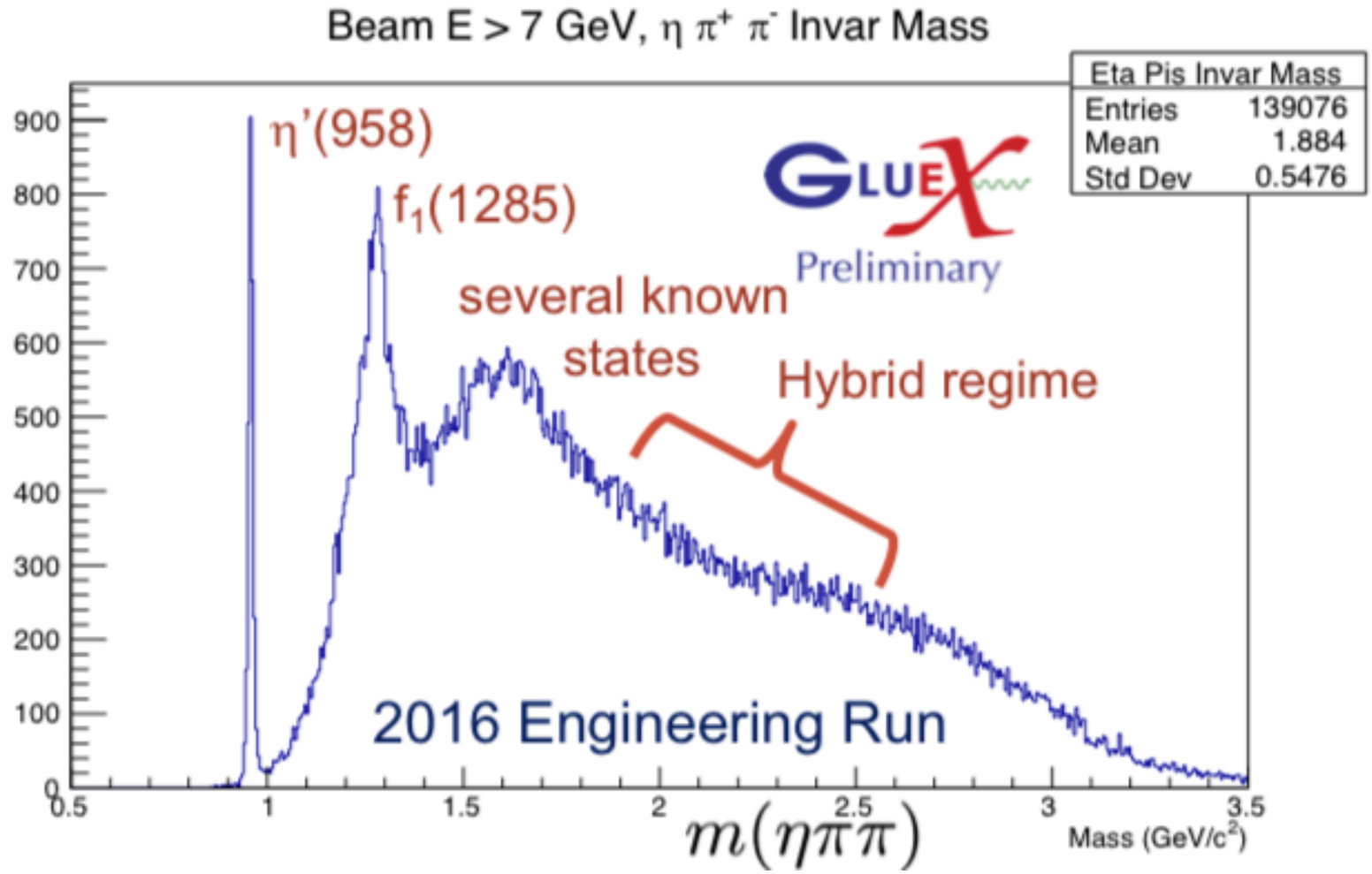
- Large sample of multiparticle decays collected as well
  - Example: η π⁺ π⁻ can have contributions from η_1 and b_1 hybrids
- Will analyze with models built from experience with 3-body reactions

Contributions from:

$\gamma p \to p\, a_2^{\pm} \pi^{\mp}$

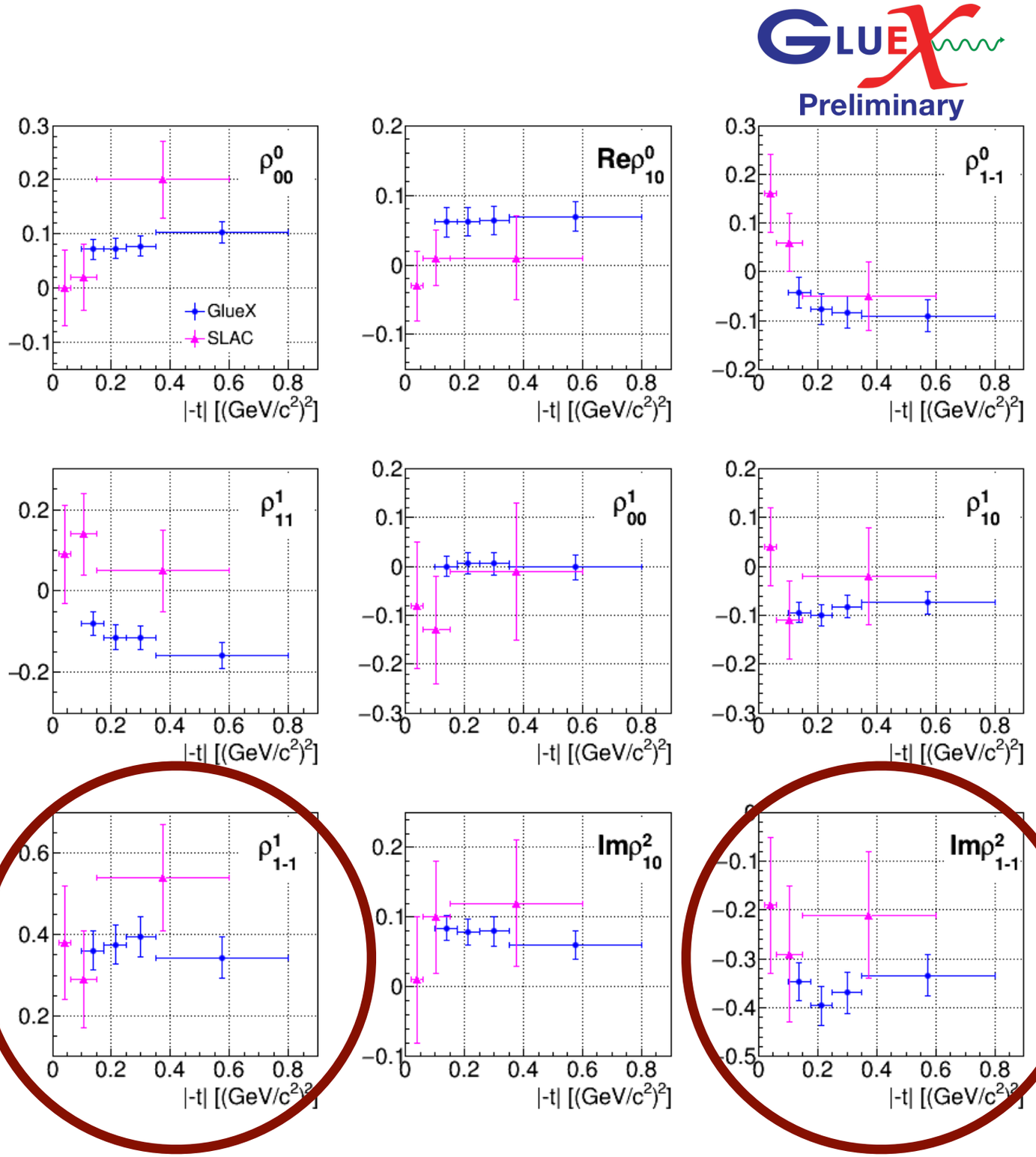
$\gamma p \to p\, f_2\, \eta$

$\gamma p \to p\, \rho\, \eta$



Spin Density Matrix Elements (SDMEs): γ p → p + ω

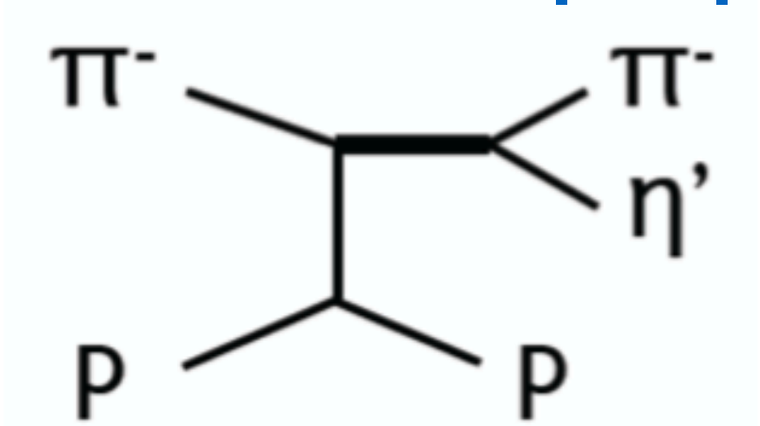
- SDMEs measure the transfer of polarization from the photon to the vector meson
  - Require understanding of detector acceptance
- Two matrix elements are particular sensitive to exchange particle in ω polarization transfer
  - Pomeron: **+1/2** and **–1/2**
  - Pion: **–1/2** and **+1/2**
- We observe around **+0.35** and **–0.35**
- Updating with more data
- **γ p → p + ϕ** and **p + ρ** also under analysis

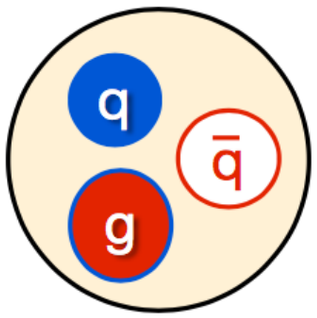


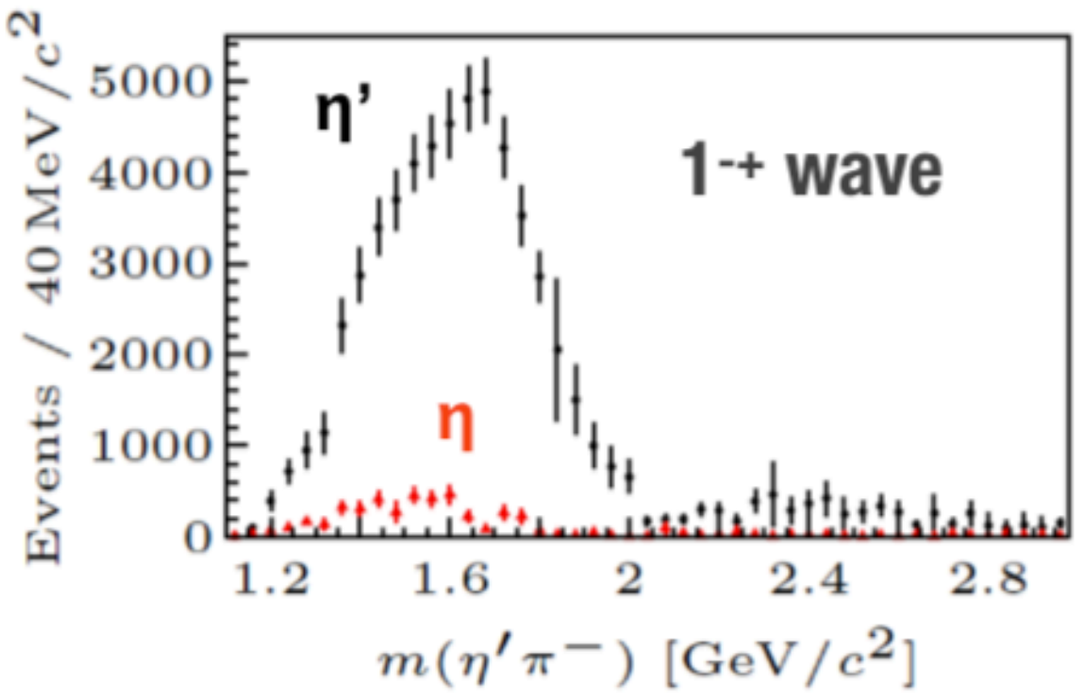
Evidence for exotic light-quark mesons

- Many searches, strongest evidence for π_1 in $\eta'\pi$ and $\rho\pi$ P-waves
- Resonance character not conclusively established

COMPASS: $\pi_1 \rightarrow \eta\pi$ / $\eta'\pi$

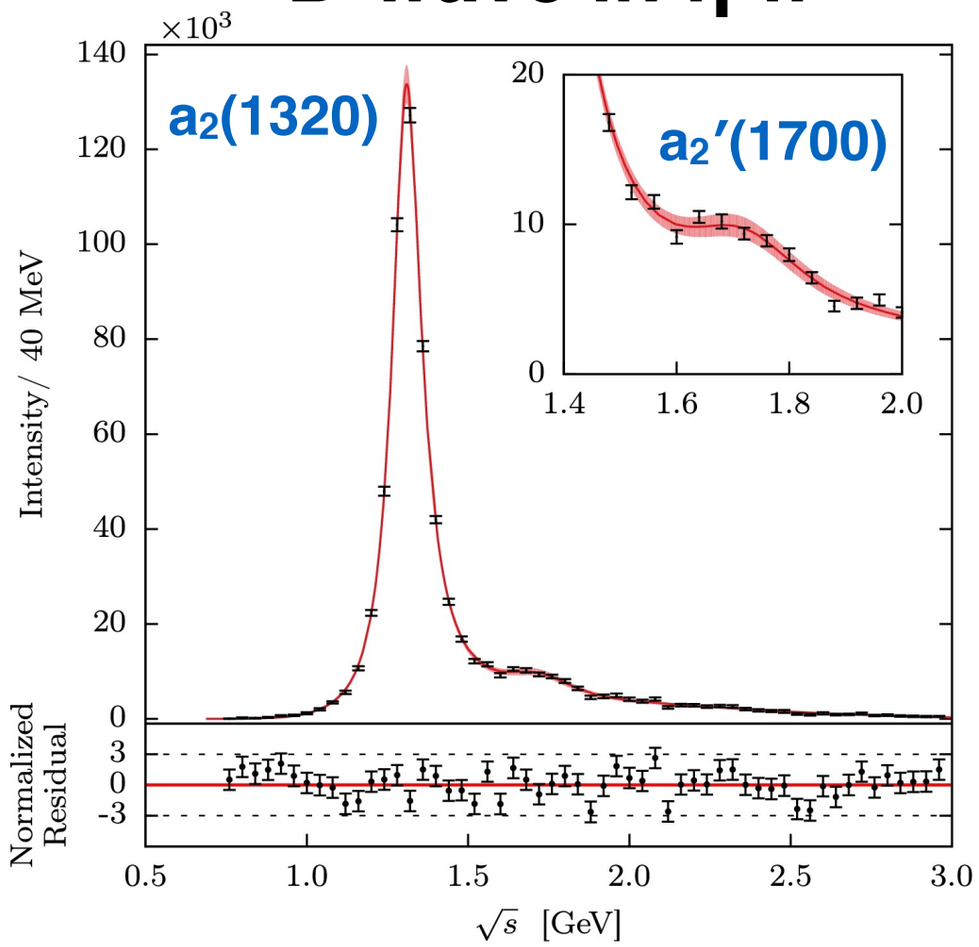






COMPASS: PLB 740, 303 (2015)

D-wave in η′π



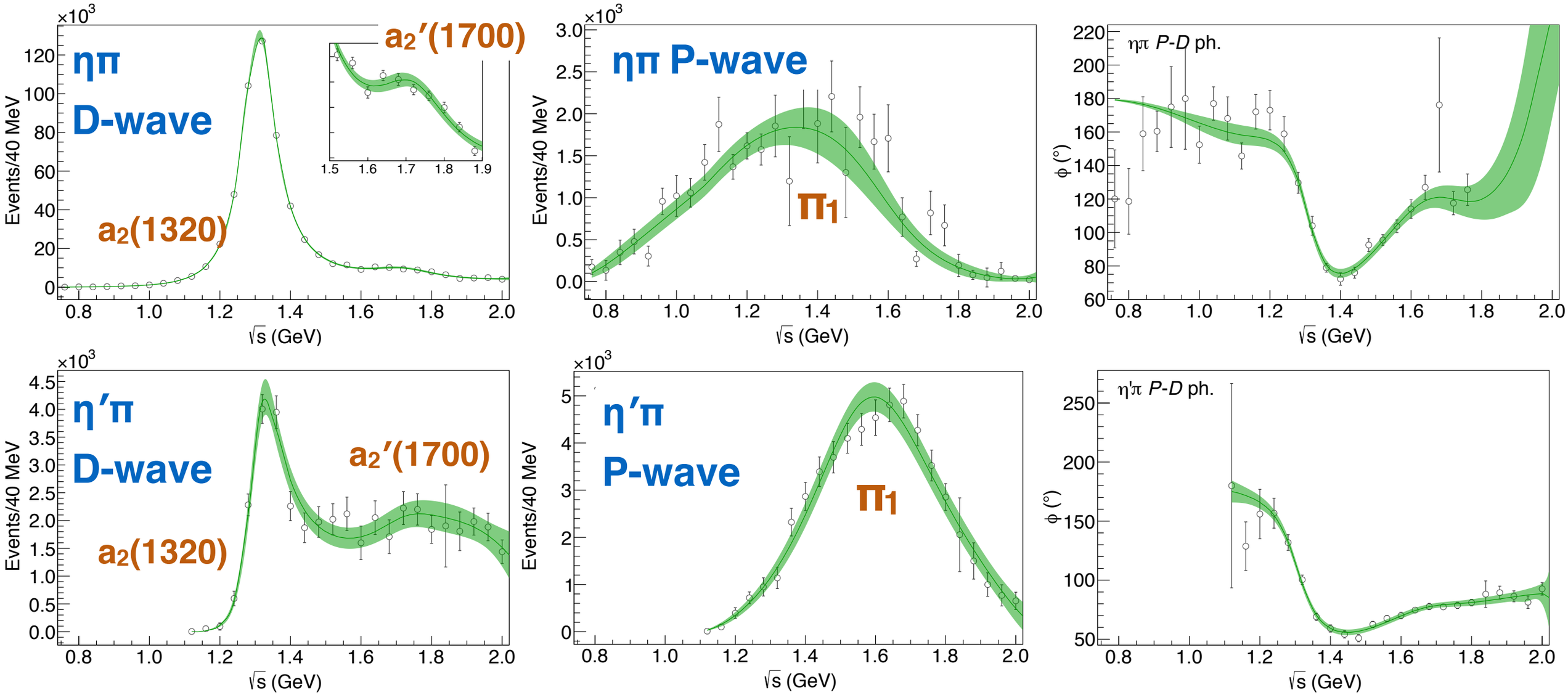
Extract resonance parameters with unitary reaction model

A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2018)

Evidence for exotic light-quark mesons

- Coupled channel analysis for P-waves and D-waves
- High precision data & theoretical advances required to extract pole parameters

P/D-wave in ηπ / η′π

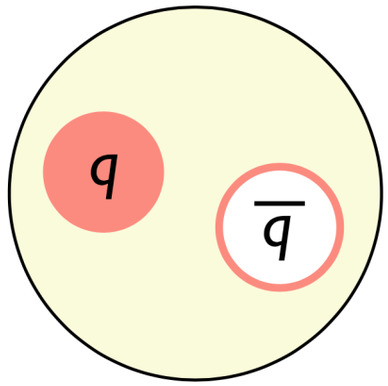


A. Rodas et al. (JPAC) [PRL 122, 042002 (2019)]

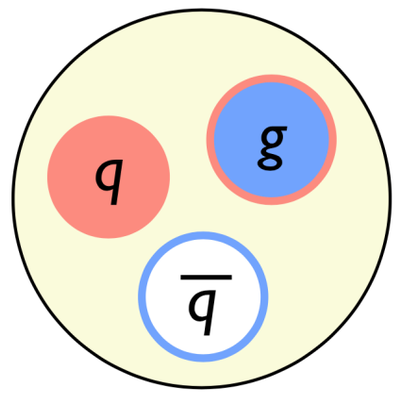
Searching For Hybrid Mesons

- **Wish:** Unambiguous narrow Breit-Wigner peaks in a mass spectrum
- **Reality:** Must establish resonance nature and determine pole parameters
  - Requires high-quality data in multiple channels and rigorous models: **experimentalists and theorists working closely**
- Meson QNs
  - Allowed: $\mathbf{0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{-+}, \ldots}$
  - Forbidden: $\mathbf{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots}$
- Hybrid Meson QNs
  - $\mathbf{0^{-+}, 0^{+-}, 1^{--}, 1^{-+}, 2^{-+}, 2^{+-}}$, …
- Hybrid mesons can be found with **normal** and **exotic** quantum numbers

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



"Normal" Meson



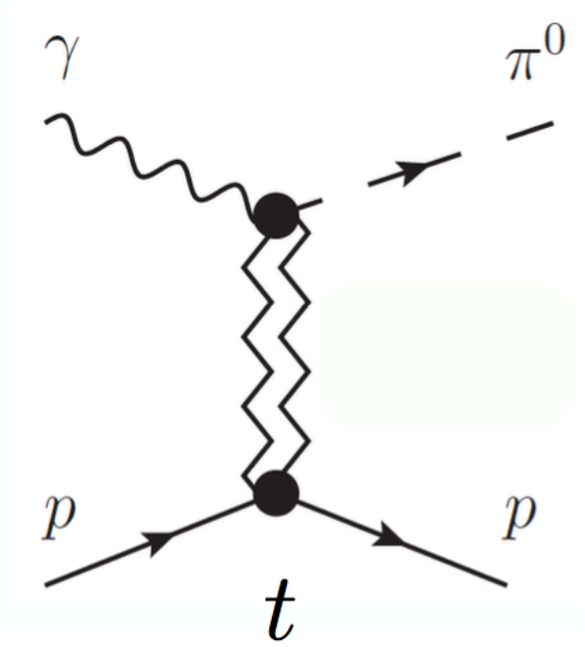
$(J^{PC})_g = 1^{+-}$

"Hybrid" Meson

Hybrid–Meson mass splitting ~ 1.0 – 1.5 GeV

Beam Asymmetries: γ p → p + π⁰ / η

- Need to understand hybrid meson photoproduction mechanisms
- Beam asymmetry Σ yields information on production mechanisms
- Combining data taken with different beam polarization cancels most acceptance effects

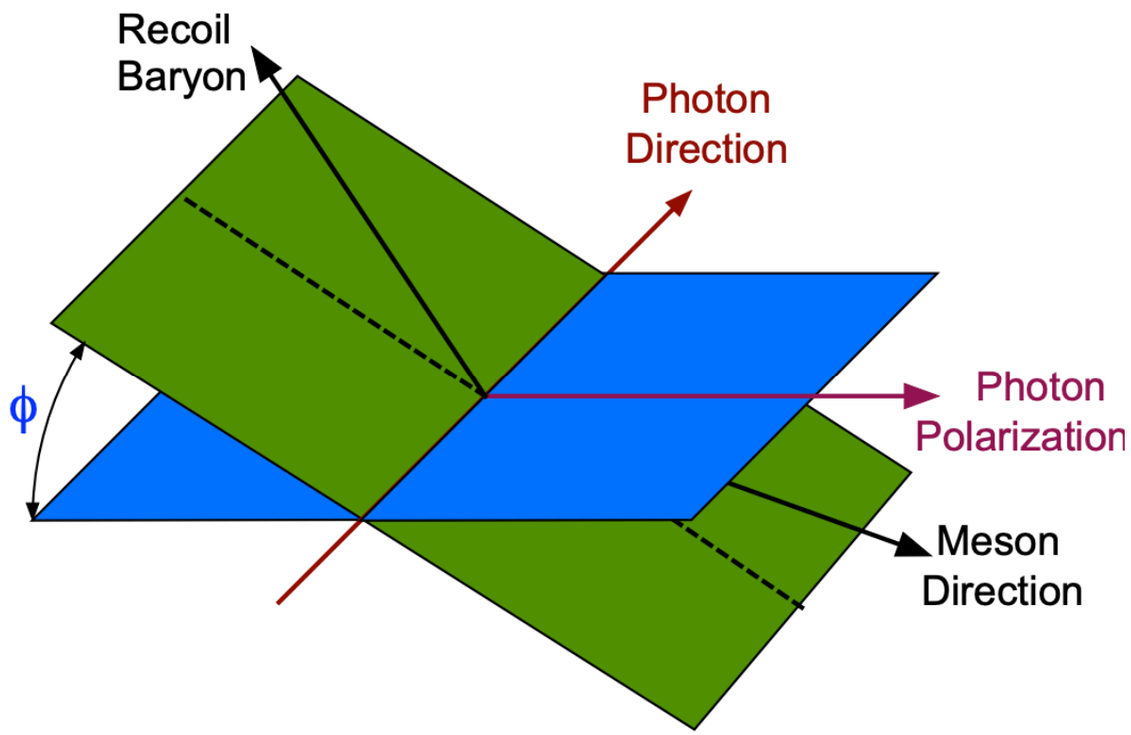


Exchange J^{PC}

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

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

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

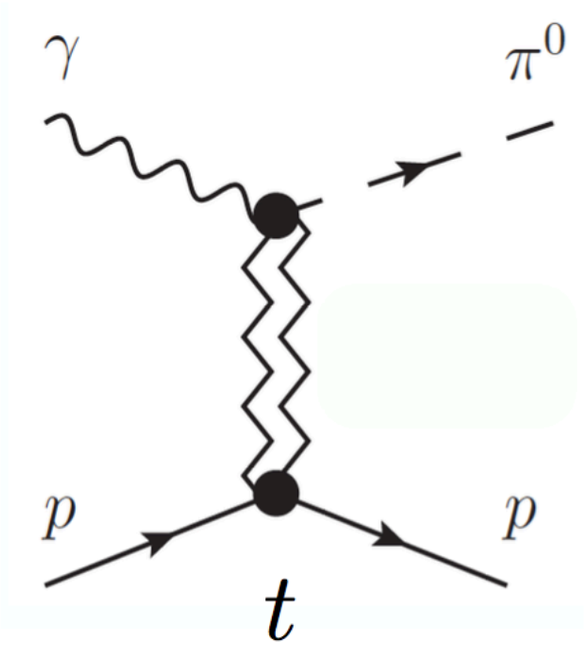


$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$

JPAC: PRD 92, 074013 (2015)

Beam Asymmetries: γ p → p + π⁰ / η

- Need to understand hybrid meson photoproduction mechanisms
- Beam asymmetry Σ yields information on production mechanisms
- Combining data taken with different beam polarization cancels most acceptance effects



Exchange J^{PC}

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

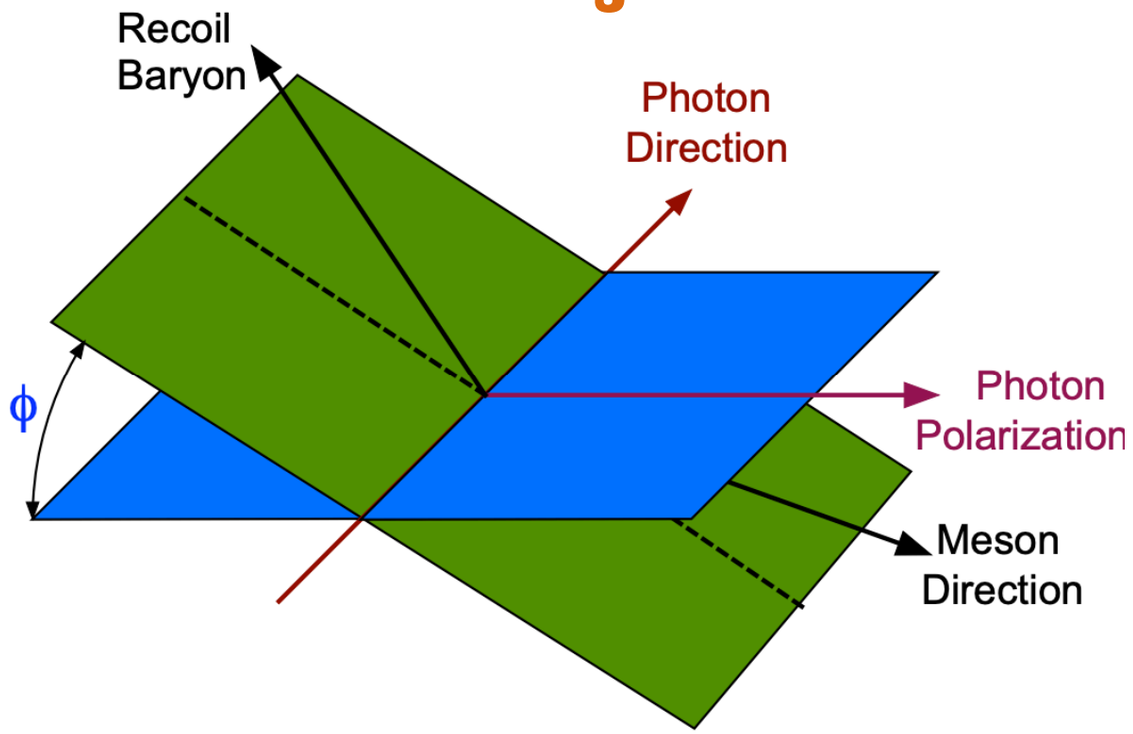
$$1^{+-} : b, h$$

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

Isolate Σ

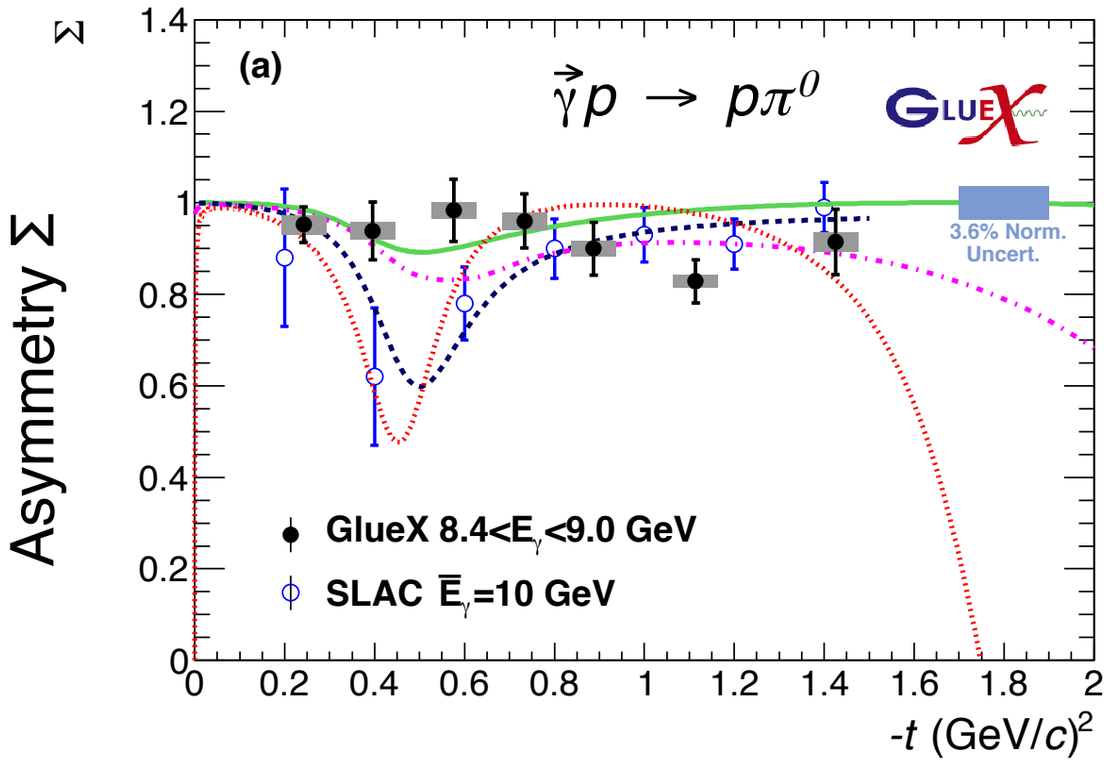
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

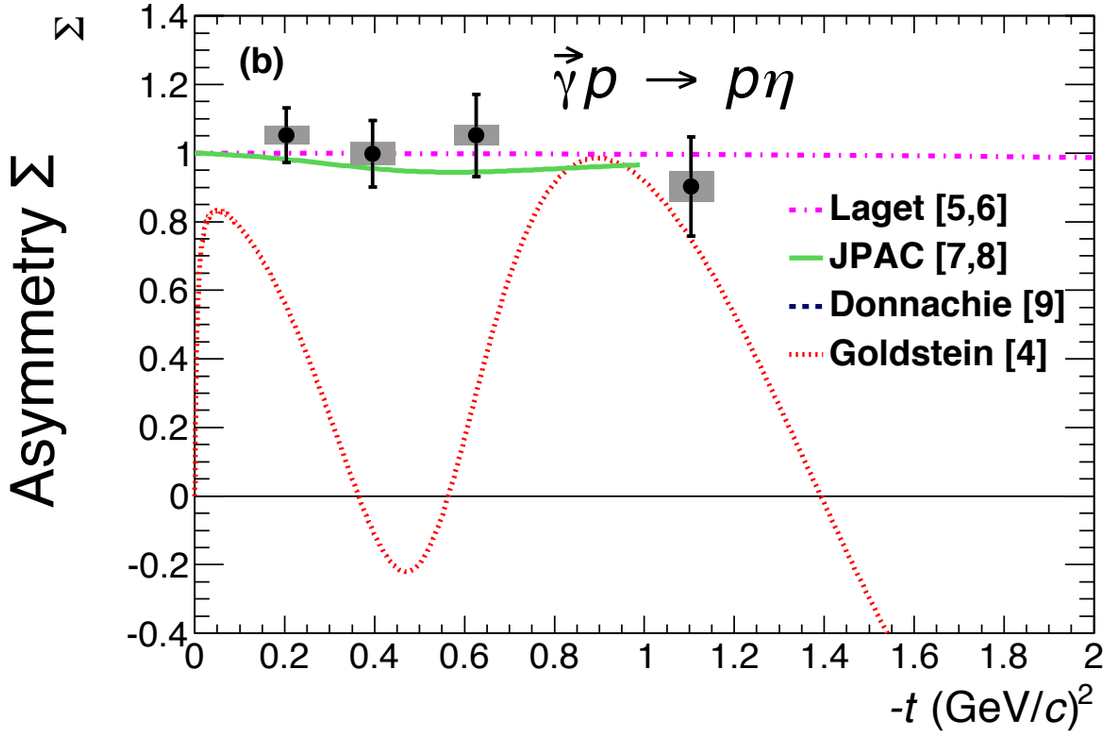
Measure with γ e⁻ → e⁻ e⁺ e⁻



JPAC: PRD 92, 074013 (2015)

Beam Asymmetries: $\gamma p \rightarrow p + \pi^0 / \eta$



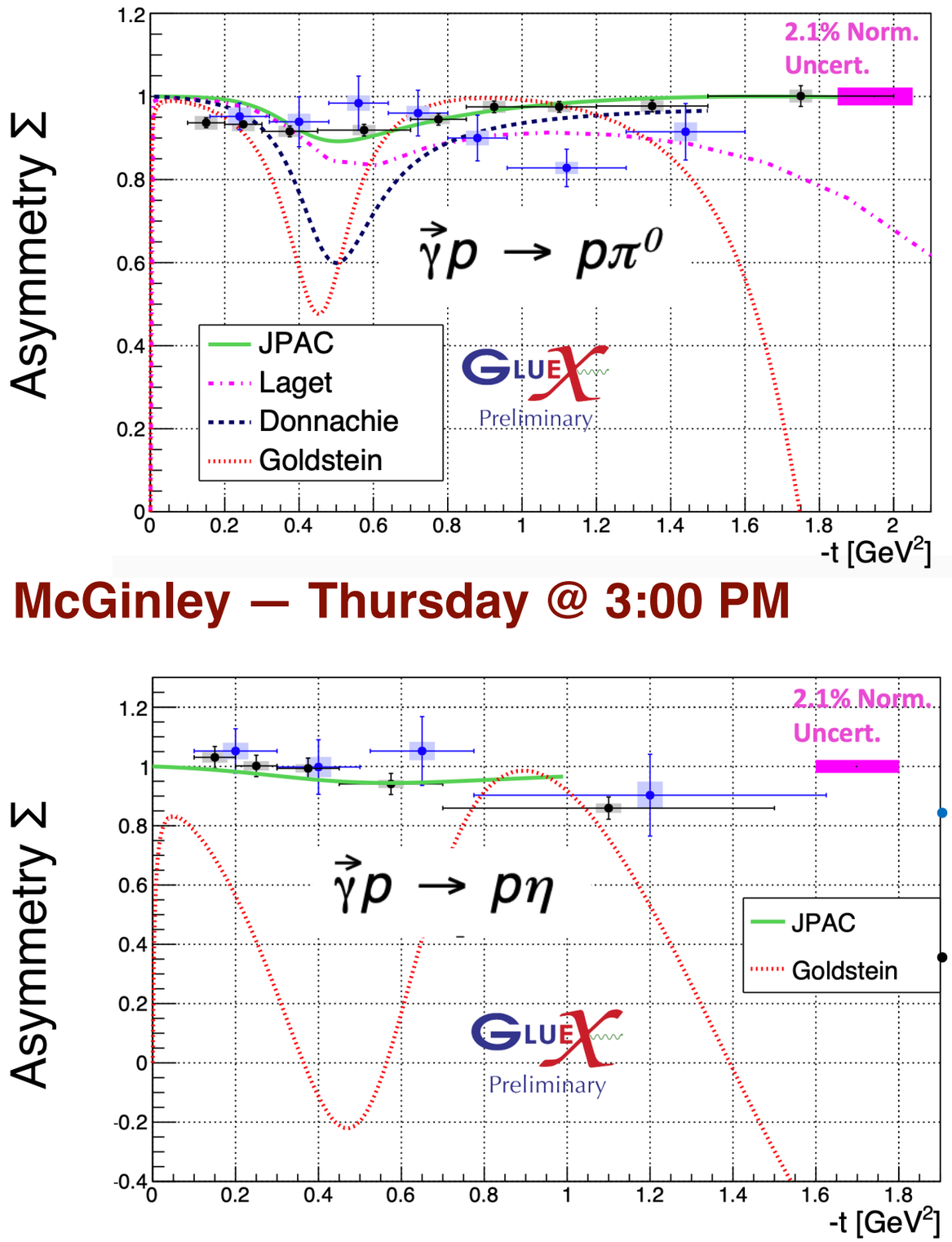


- First measurement of pseudoscalar beam asymmetry using GlueX commissioning data
  - **Σ ≈ 1** indicates vector exchange dominates at this energy
  - First **η** measurement at this energy
- GlueX energies dominated by t-channel processes
  - Constrains background to baryon resonance production at lower energies

First JLab 12 GeV publication:

Phys.Rev.C 95, 042201 (2017)

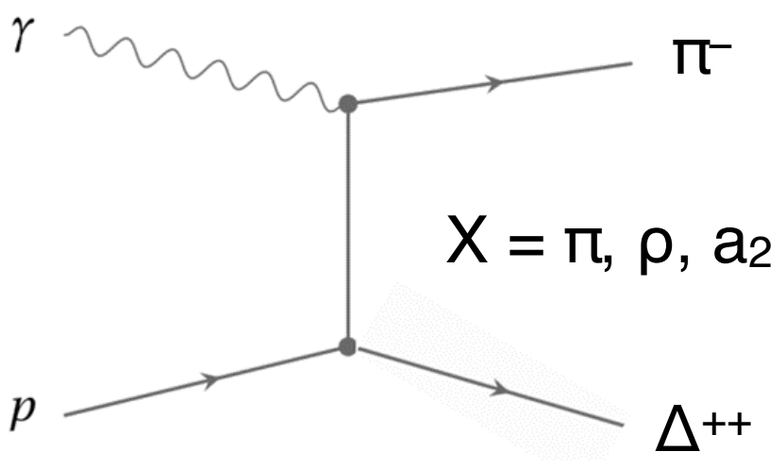
Beam Asymmetries: $\gamma p \rightarrow p + \pi^0 / \eta$



W. McGinley — Thursday @ 3:00 PM

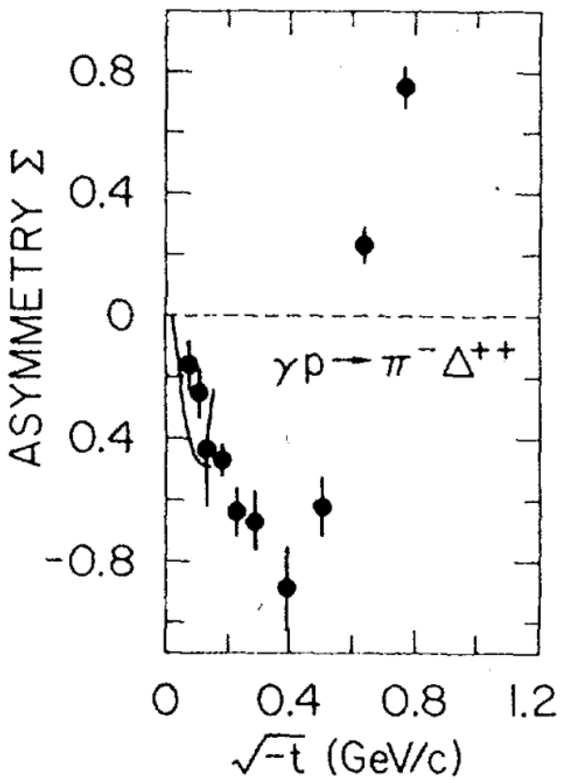
- Updated preliminary results using 20% of Phase-I data
- **Σ ≈ 1** indicates vector exchange dominates at this energy
- First **η** measurement at this energy
  - Stronger constraints on production models
- Many other processes under study
  - $\Sigma\eta \approx \Sigma\eta'$ implies negligible ϕ exchange

Beam Asymmetries: γ p → π⁻ Δ⁺⁺

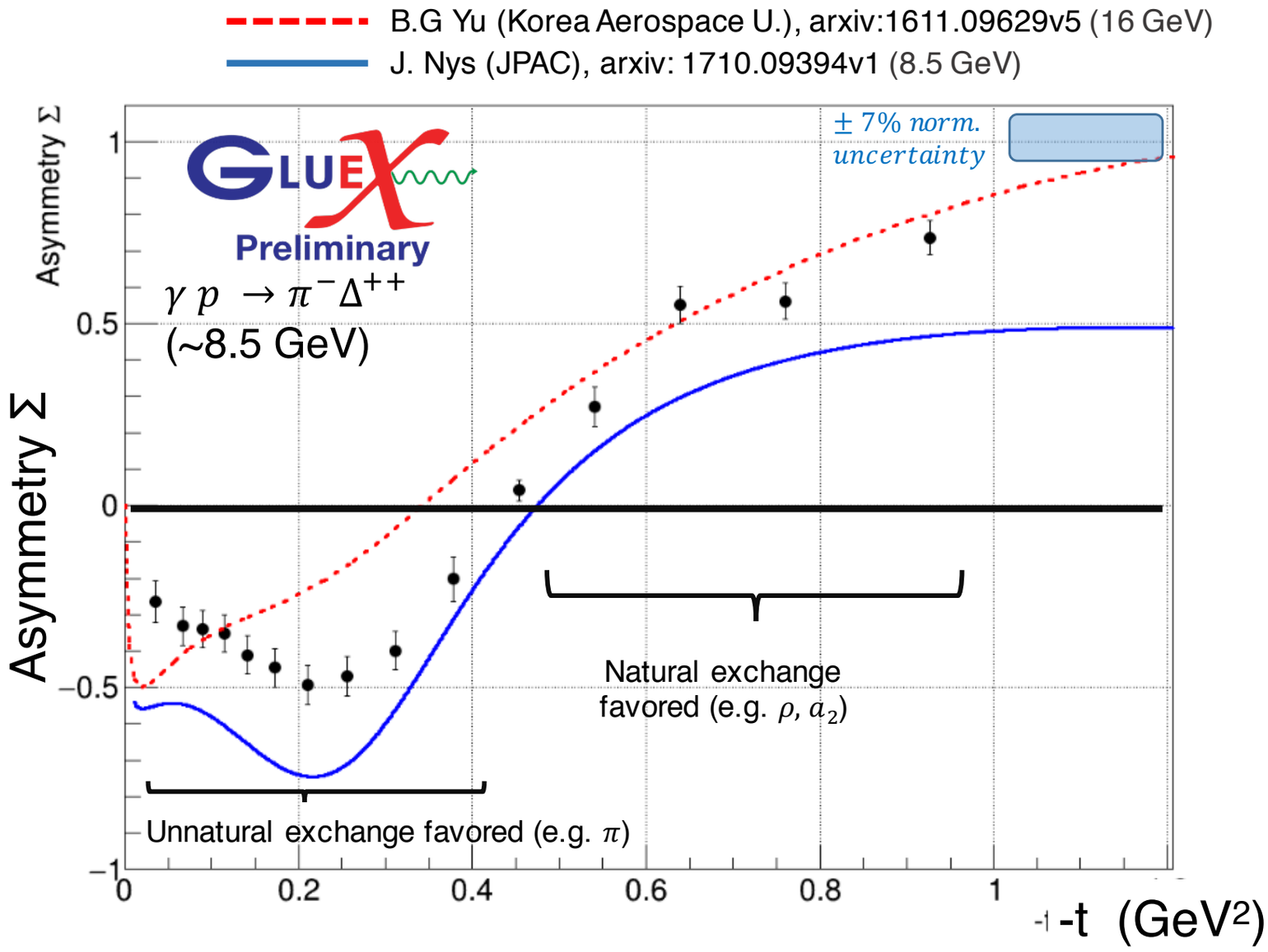


- Charged pseudoscalar beam asymmetry has more complicated t-dependance
- Preliminary results use order of magnitude more data than previous measurements

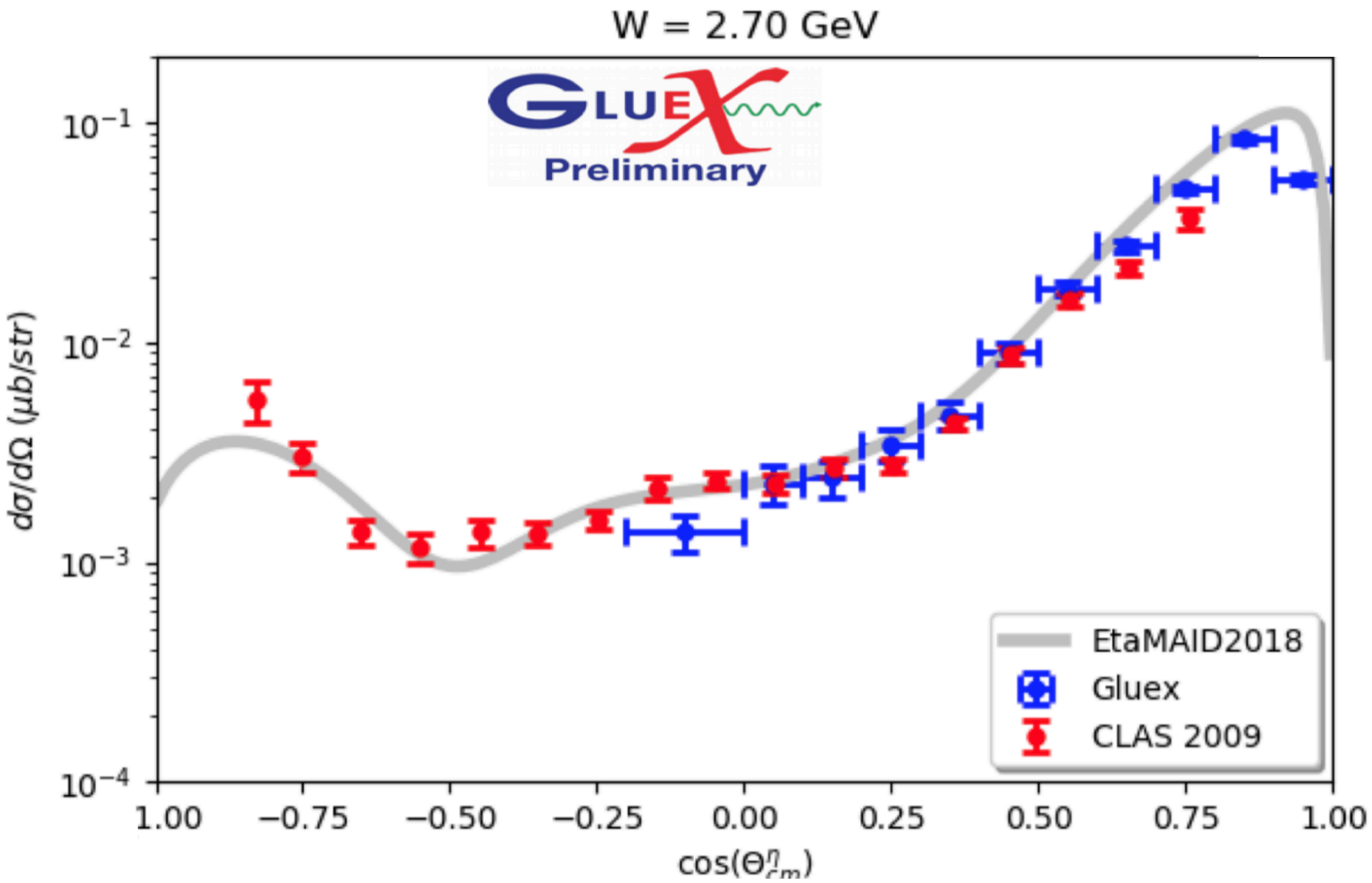
SLAC (16 GeV)



Phys. Rev. D **20**, 1553 (1979)



Cross Section Measurements: γ p → η p



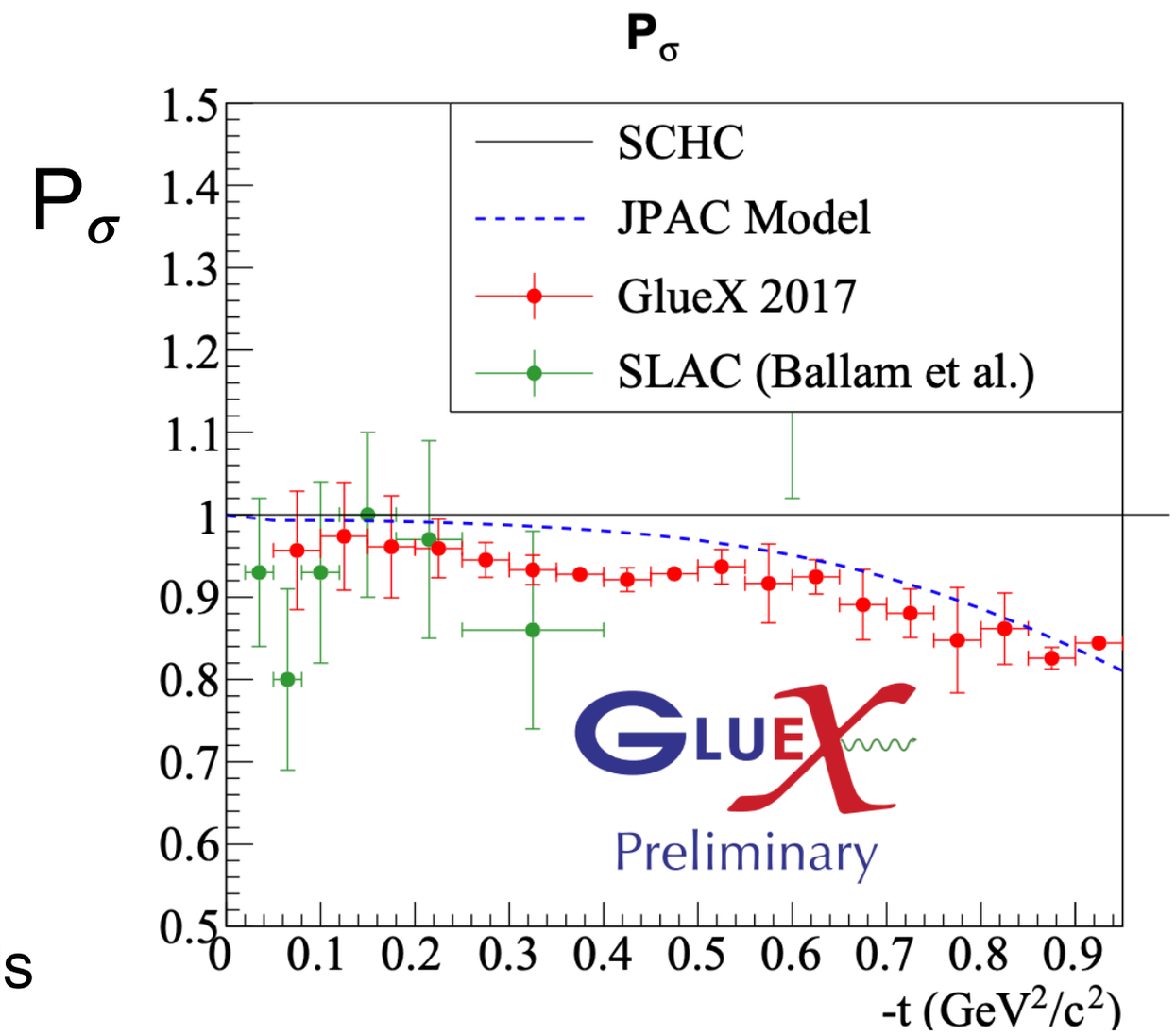
Statistical Uncertainties Only

- Cross section measurements provide complementary constraints on production process
  - Requires understanding of absolute efficiency and photon flux
- GlueX plans to measure differential cross sections over large energy range
  - Dedicated run to compare with existing CLAS measurements

Spin Density Matrix Elements: $\gamma p \to \rho^0 p$

- Vector meson polarization described by spin density matrix
  - 9 elements from linear polarization
- Matrix elements extracted through fits to angular distributions
  - Understanding of detector acceptance required
- Dominated by natural parity exchange
  - Well described by Regge models at low-t

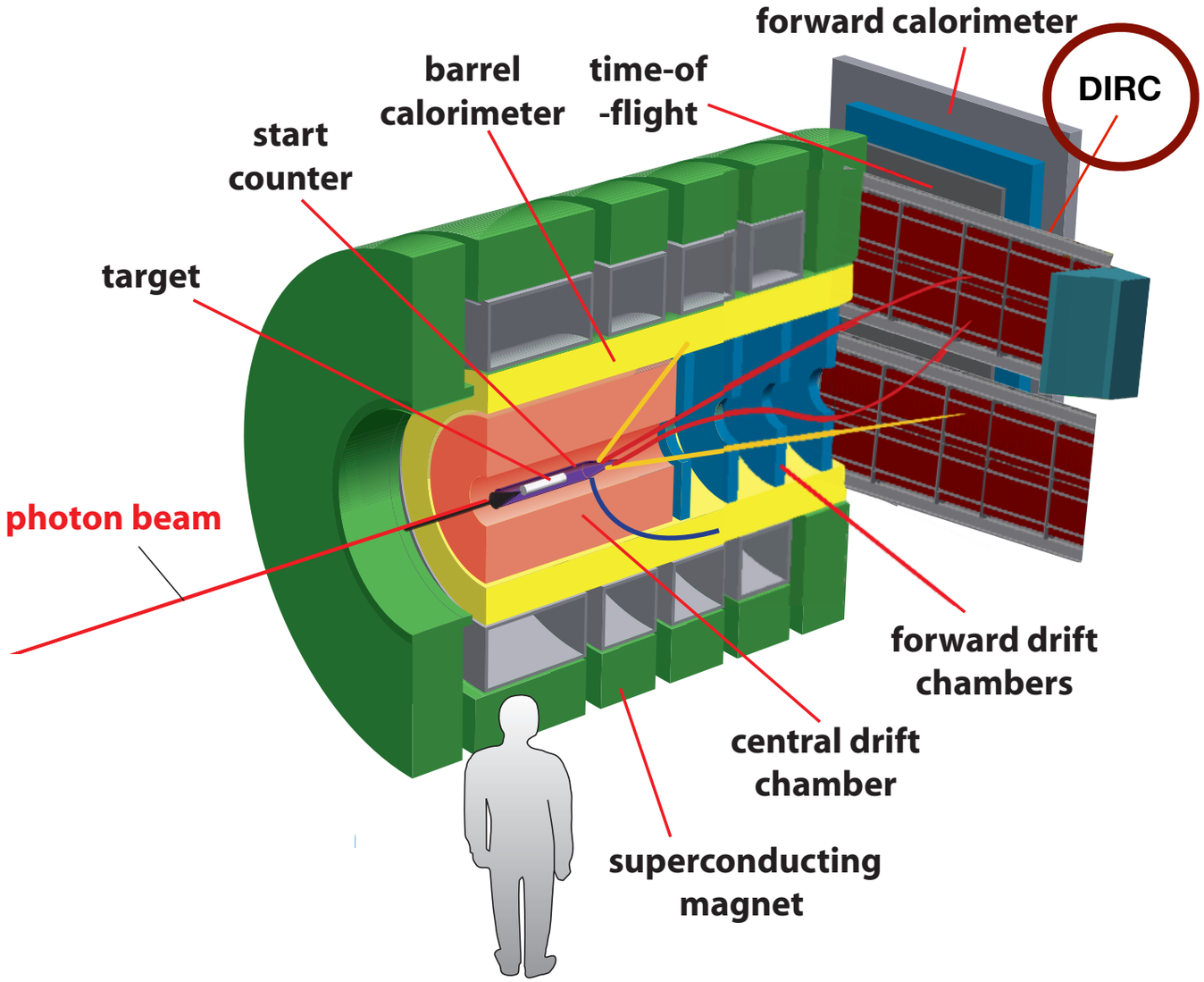
A. Austregesilo — Monday @ 2:30 PM



$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U} = 2\rho^1_{1-1} - \rho^1_{00}$$

JPAC: PRD 97 094003 (2018)

GlueX-II: Enter the DIRC



SLAC NATIONAL ACCELERATOR LABORATORY

Jefferson Lab

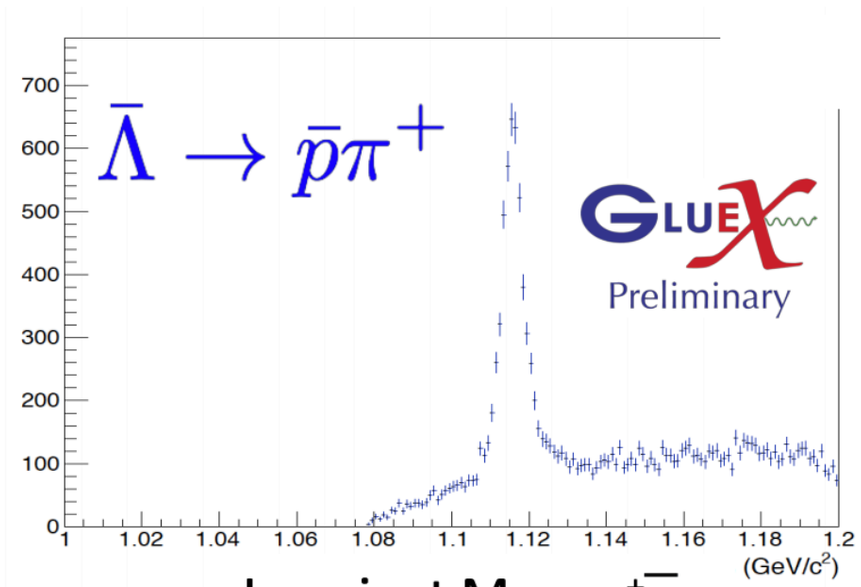
J. Stevens — Tuesday @ 1:30 PM

- To study hybrids containing **strange quarks**, need clean identification of charged pions and kaons
- New addition: **DIRC** (**D**etection of **I**nternally **R**eflected **C**herenkov light)
- Installation & commissioning currently underway

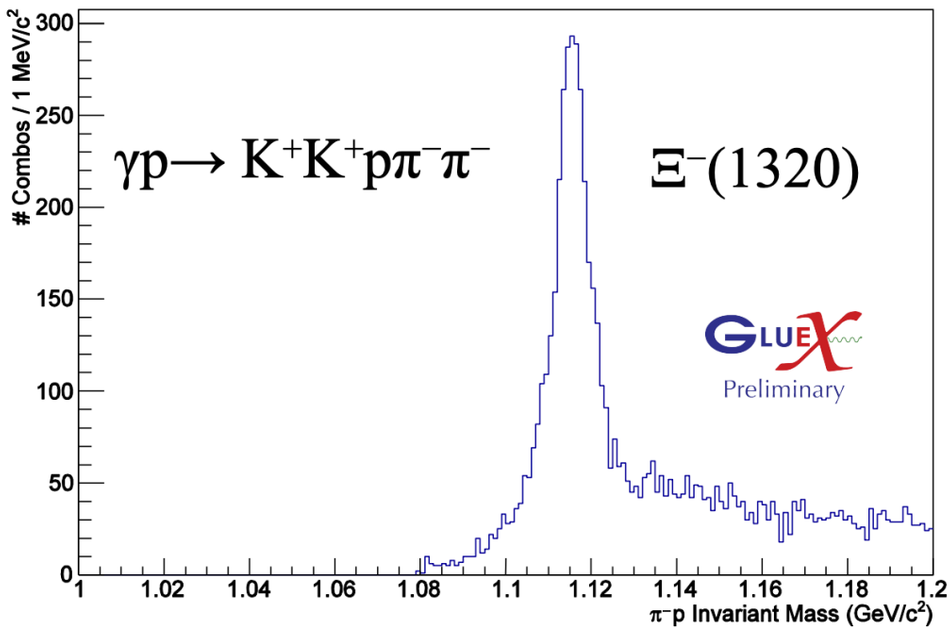
Prospects for Hyperon Measurements

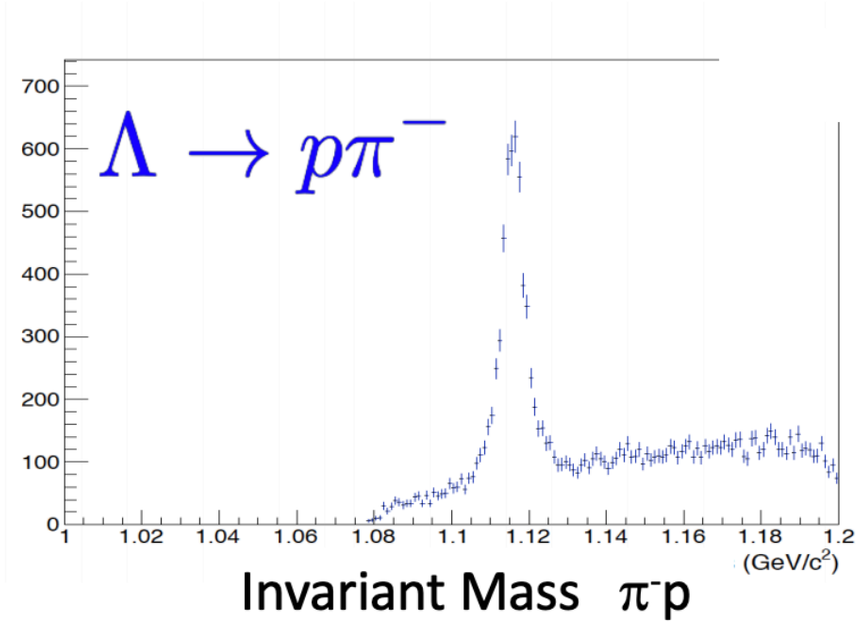
- Rich GlueX data enables wide range of measurements
- The Cascade (ssd, ssu) spectrum is poorly known — exclusive measurements allow determination of quantum numbers
- Detailed studies of baryon—antibaryon production, first observation of $\Lambda\,\bar{\Lambda}$ production

$\gamma\, p \rightarrow \Lambda\, \bar{\Lambda}\, p$



State	Quality
$\Xi(1320)$	$(1/2)^+$ ****
$\Xi(1530)$	$(3/2)^+$ ****
$\Xi(1690)$	***
$\Xi(1820)$	$(3/2)^-$ ***
$\Xi(1950)$	***
$\Xi(2030)$	***





A. Ernst — Friday @ 9:45 AM

H. Li — Friday @ 9:15 AM