

Searching for Exotic Hadrons at

From light quarks to charm

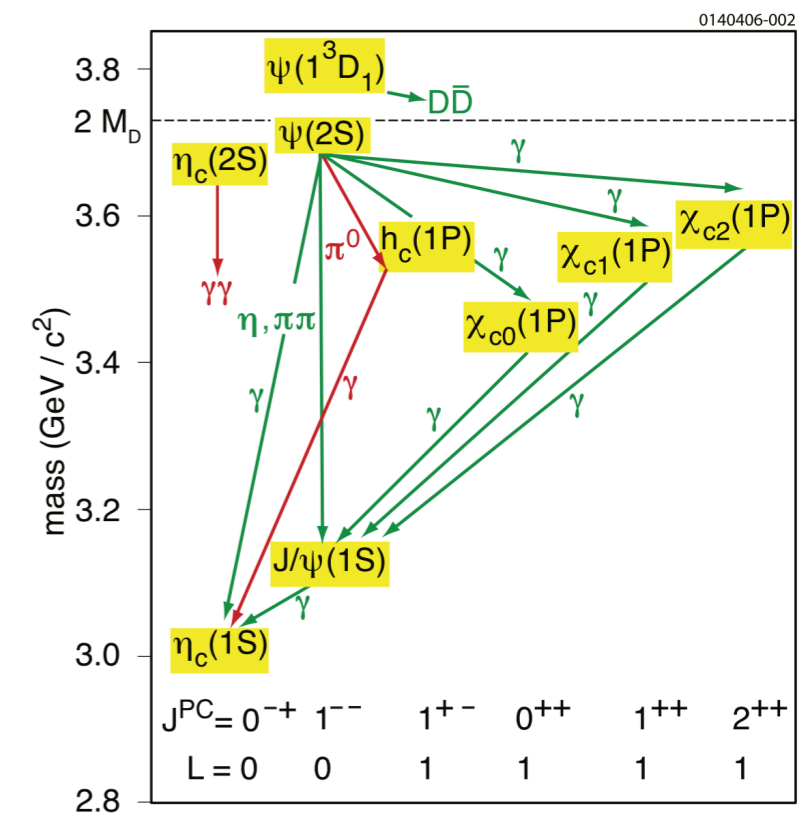
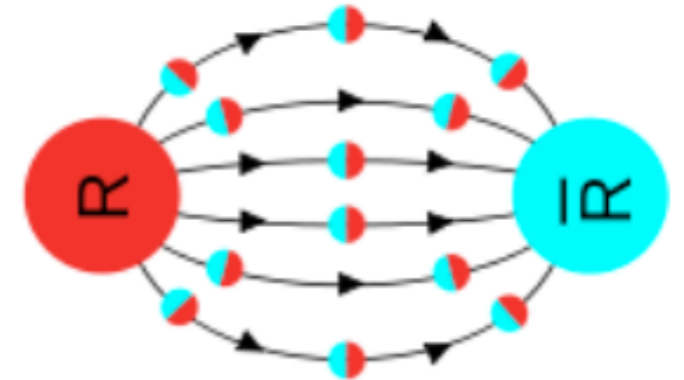
Sean Dobbs
Florida State U.

GSI, Darmstadt, Germany
February 13, 2019



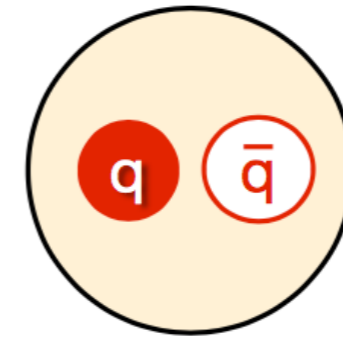
Introduction

- Quantum Chromodynamics (**QCD**)
 - Degrees of freedom: **quarks** and **gluons**
 - Rich spectrum of bound states predicted
 - Outstanding questions remain e.g., What is the role of gluonic degrees of freedom?
- New understanding gained by studying spectrum of bound QCD states
 - Recent progress in understanding hadron spectrum driven by large, high-quality data sets
 - New theoretical tools essential for accurately interpreting this data

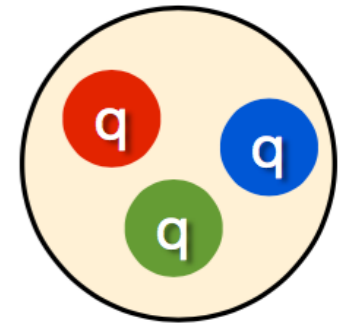


QCD and Hadron Spectroscopy

- Idea: study QCD through spectrum of bound states
 - Static properties of known hadrons well described by first-principles calculations
 - Modern experiments provide unprecedented data sets to push boundaries of our knowledge
- Open questions:
 - What is the origin of confinement?
 - Which color-singlet states exist in nature?



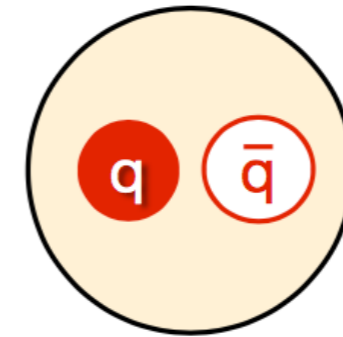
mesons



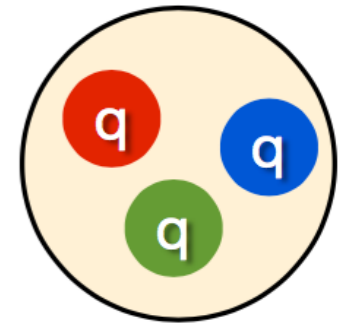
baryons

QCD and Hadron Spectroscopy

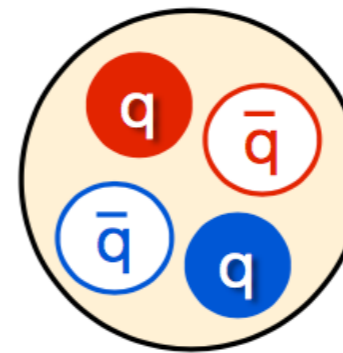
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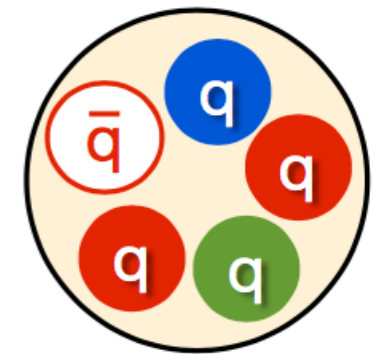
mesons



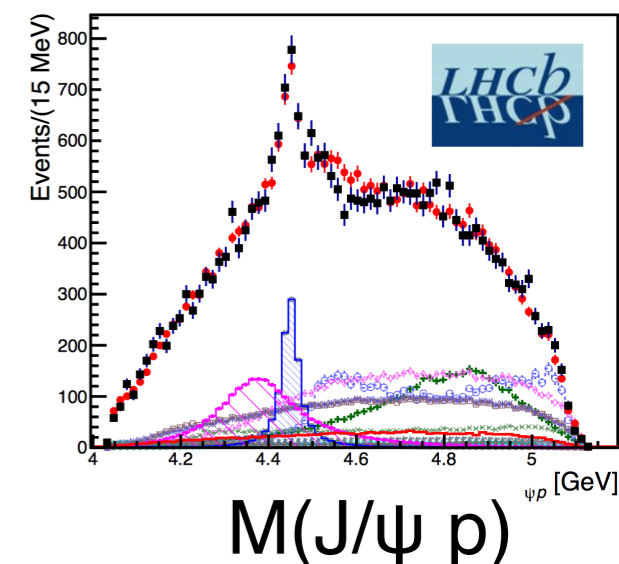
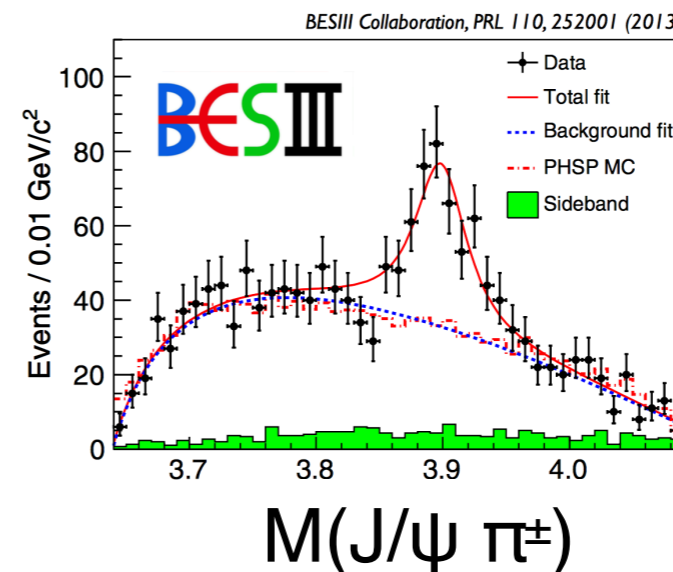
baryons



tetraquark

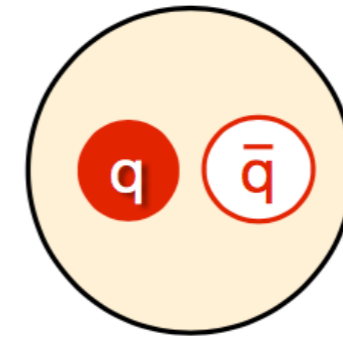


pentaquark

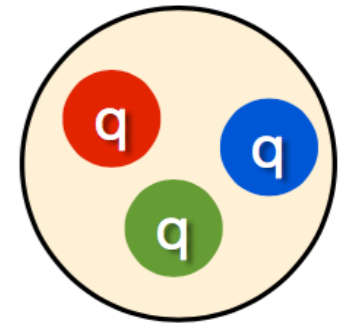


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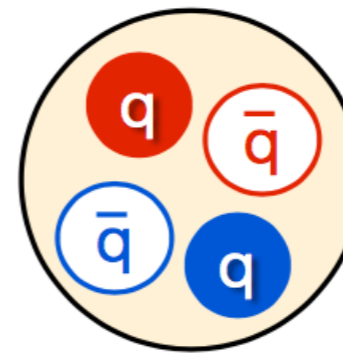
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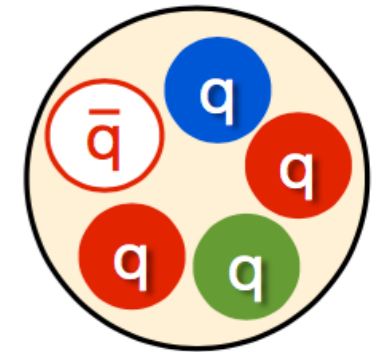
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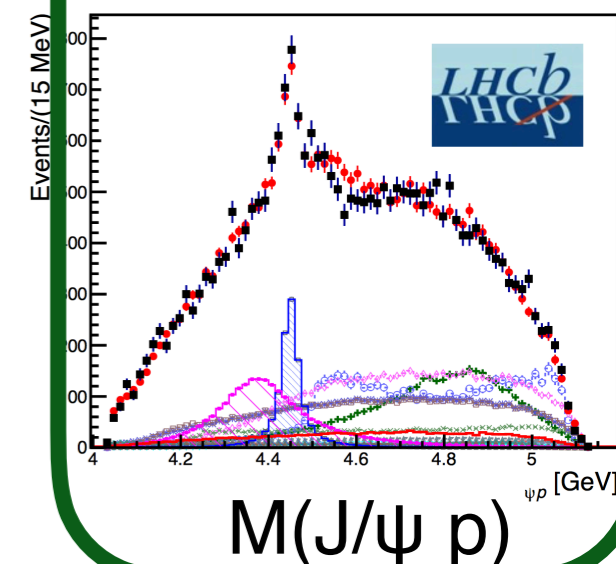
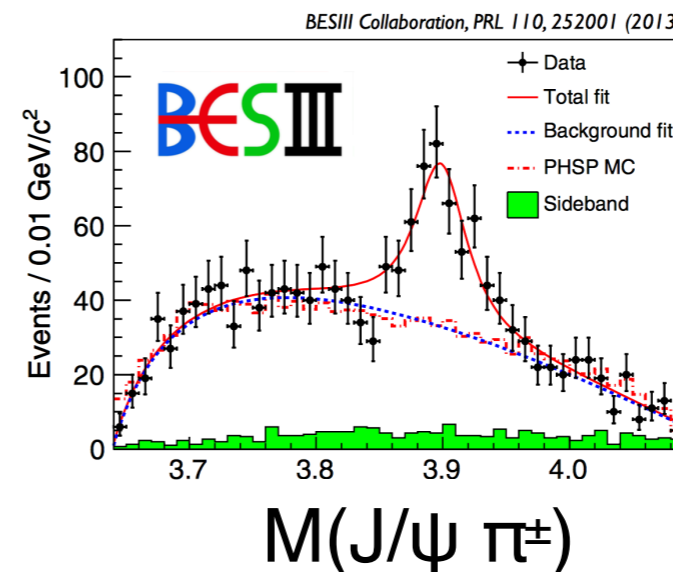
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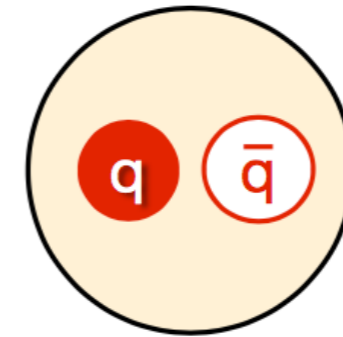


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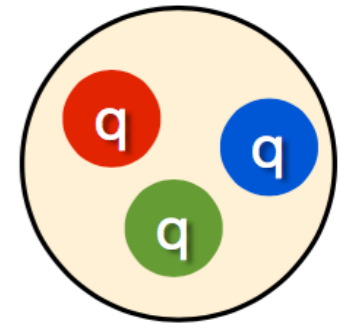


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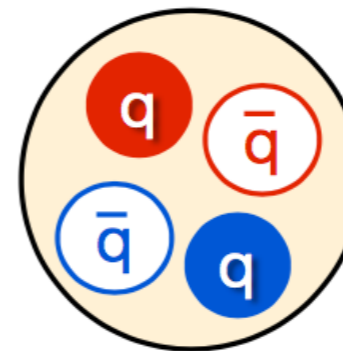
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 - **Do gluonic degrees of freedom manifest themselves in the bound states that we observe?**



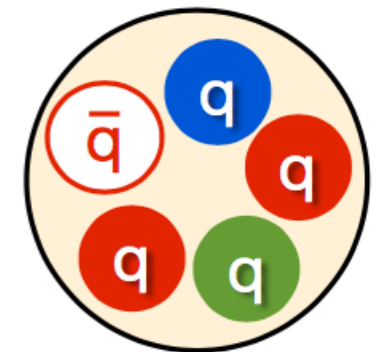
mesons



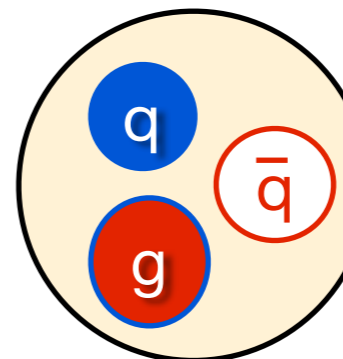
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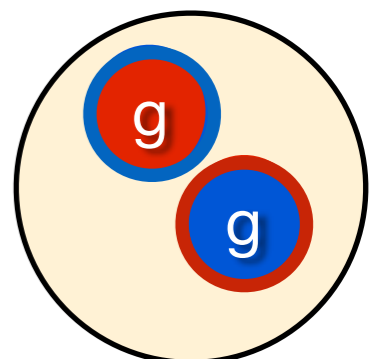
tetraquark



pentaquark



hybrid meson



glueball

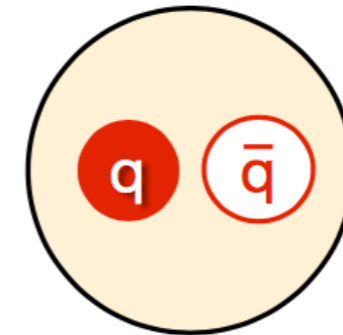
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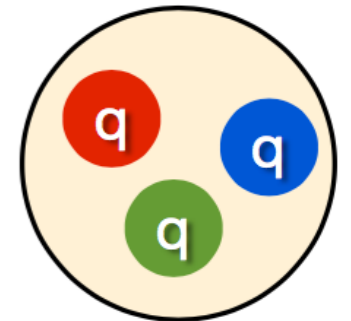
- Open questions:

- What is the origin of exotic hadrons?
- Which color-singlet configurations are possible?

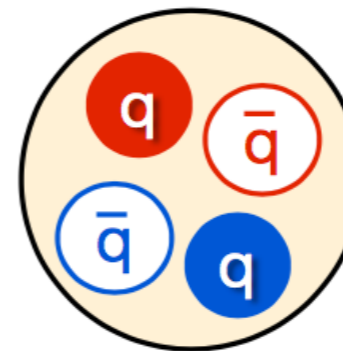
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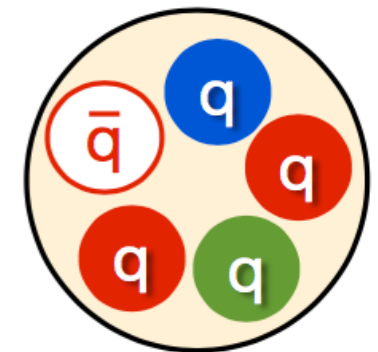
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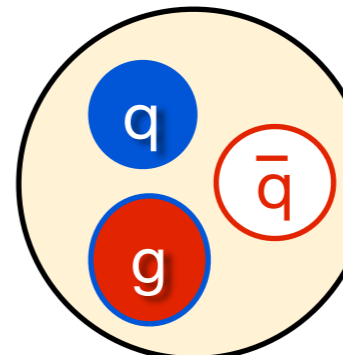
baryons



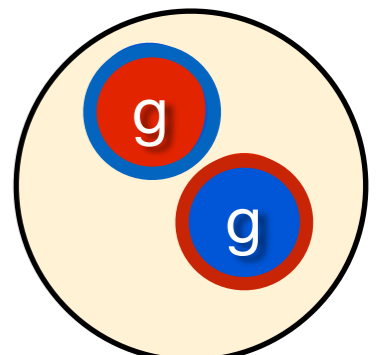
tetraquark



pentaquark



hybrid meson



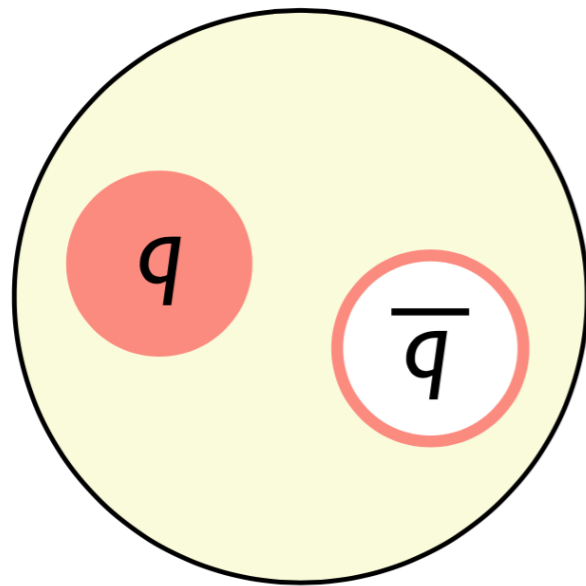
glueball

Meson Quantum Numbers

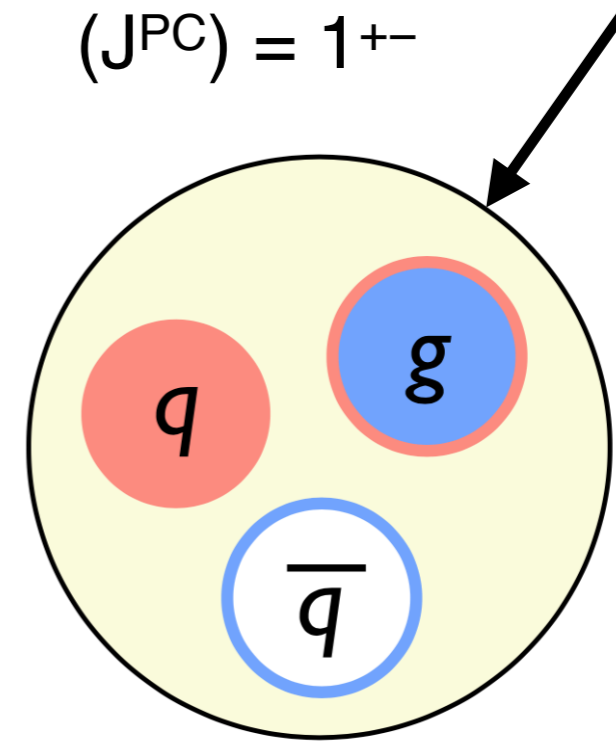
Mesons are arranged in groups of 9 (“nonets”) with same J^{PC}

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

gluonic field excitation → “constituent gluon”
 $(J^{PC}) = 1^{+-}$



“Normal” Meson



“Hybrid” Meson

Allowed J^{PC} : $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, 2^{-+}, \dots$

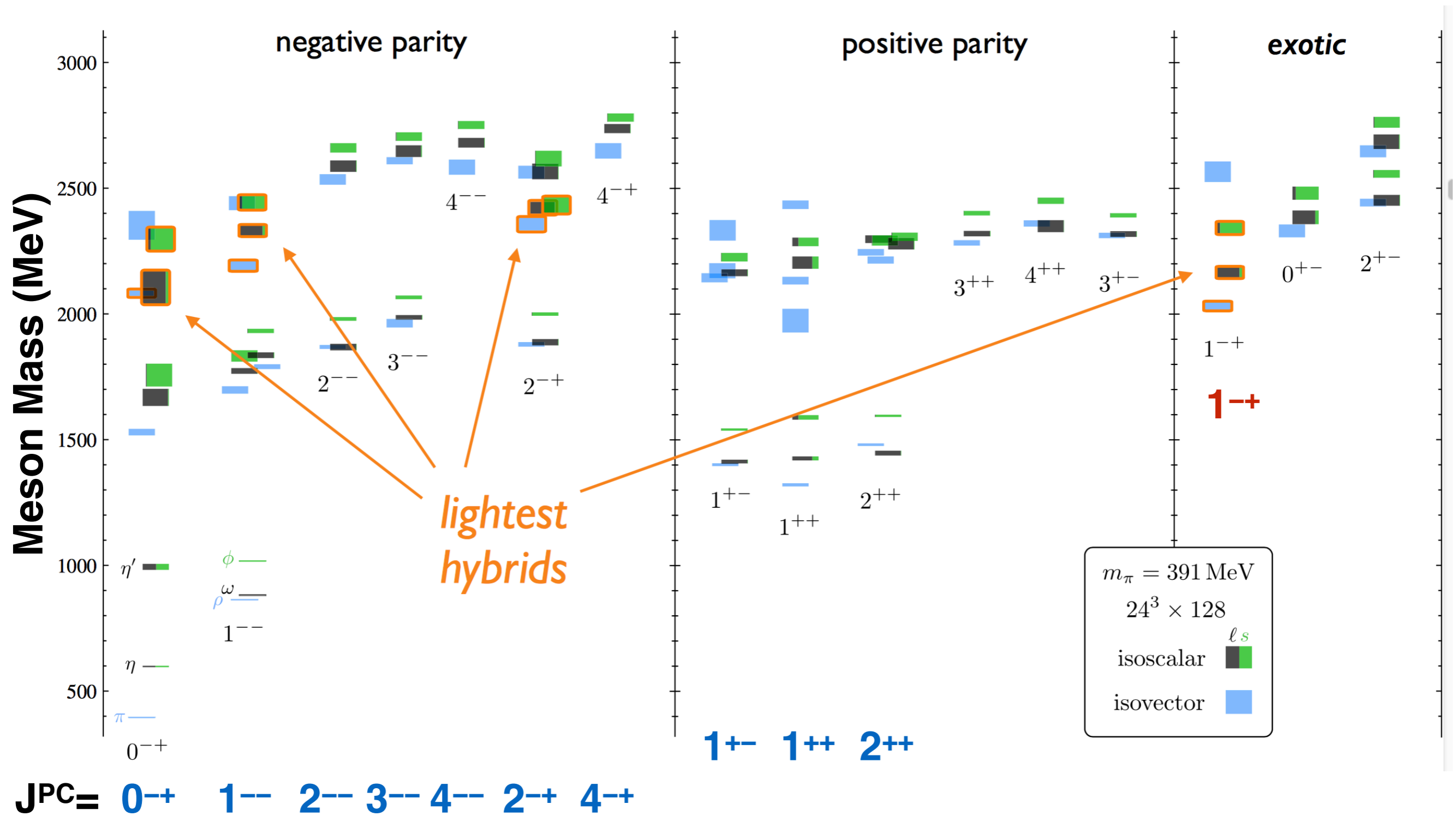
Forbidden J^{PC} : $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \dots$

Hybrid J^{PC} : $0^{-+}, 0^{+-}, 1^{--}, 1^{-+},$

$2^{-+}, 2^{+-}, \dots$

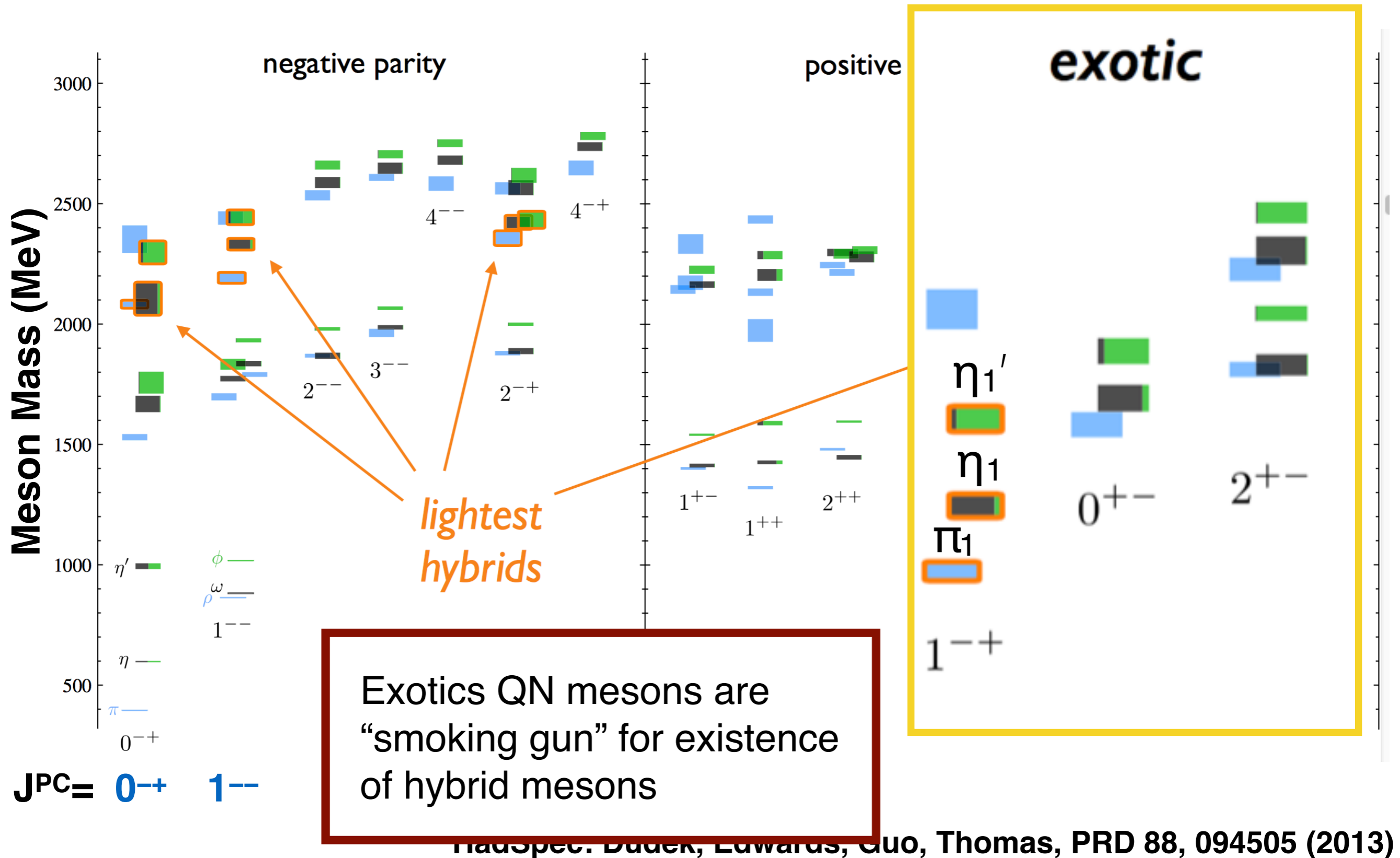
Hybrid–Meson mass splitting $\sim 1.0 - 1.5$ GeV

Light Meson Spectrum from Lattice QCD

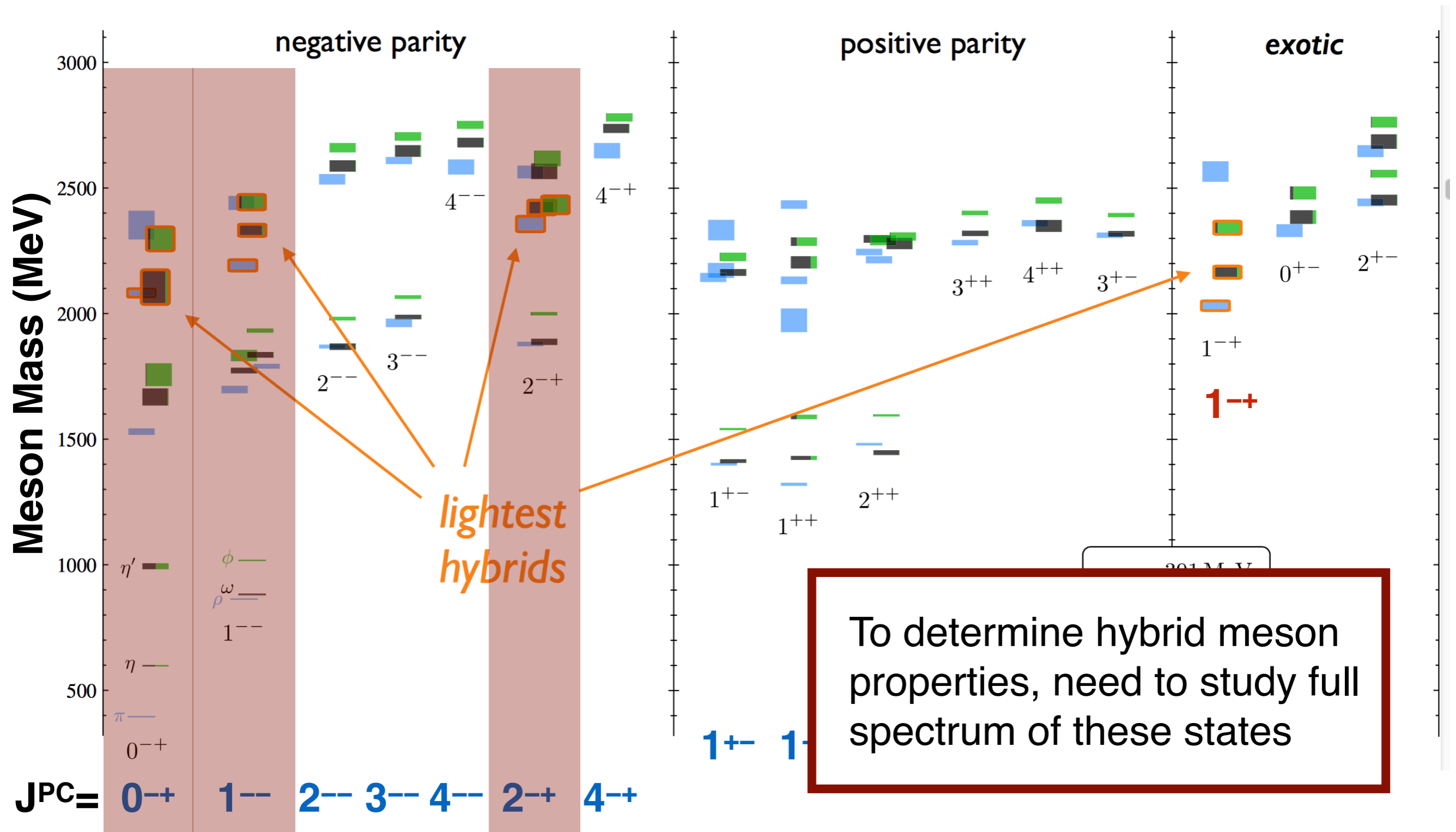


HadSpec: Dudek, Edwards, Guo, Thomas, PRD 88, 094505 (2013)

Light Meson Spectrum from Lattice QCD



Light Meson Spectrum from Lattice QCD



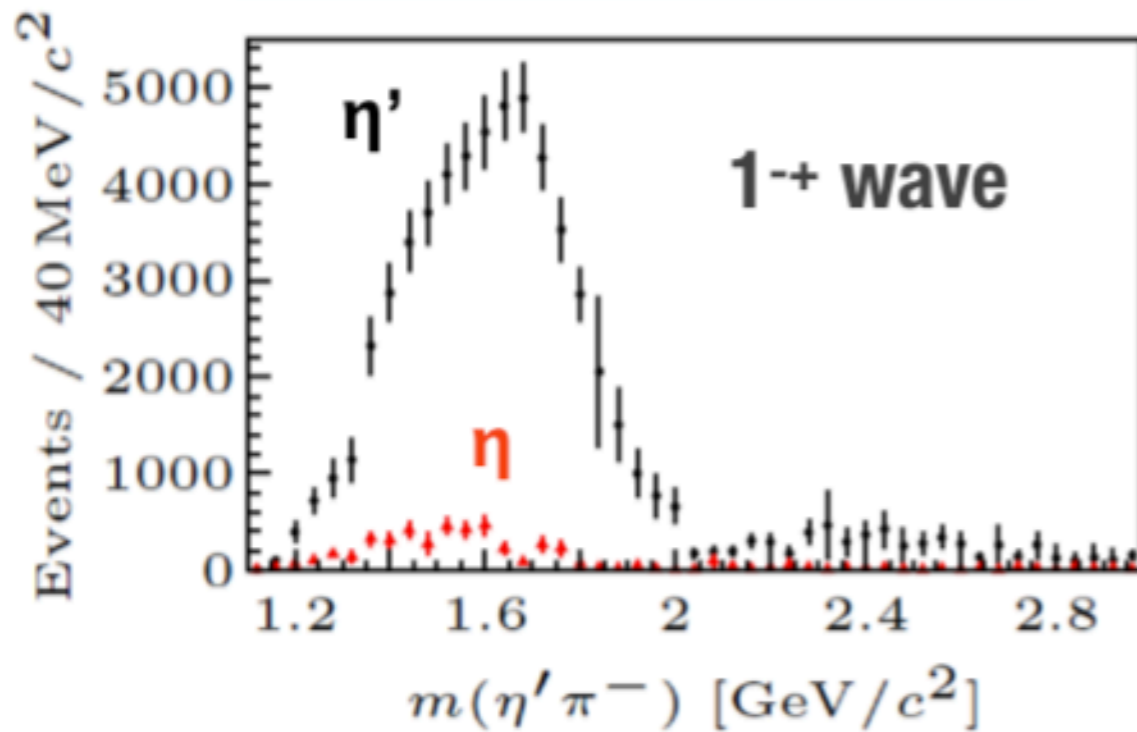
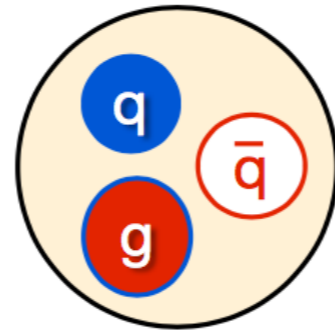
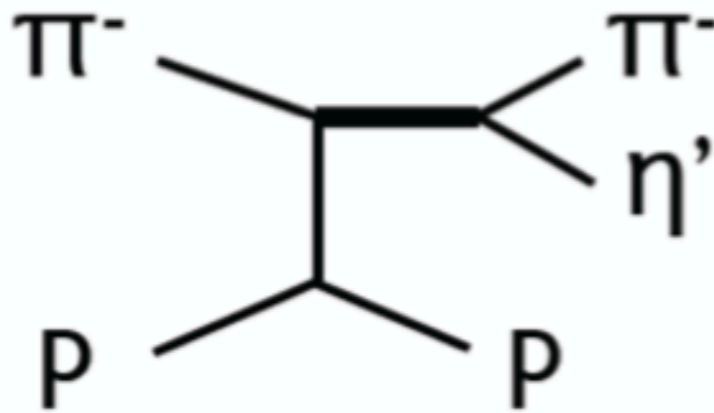
To determine hybrid meson properties, need to study full spectrum of these states

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

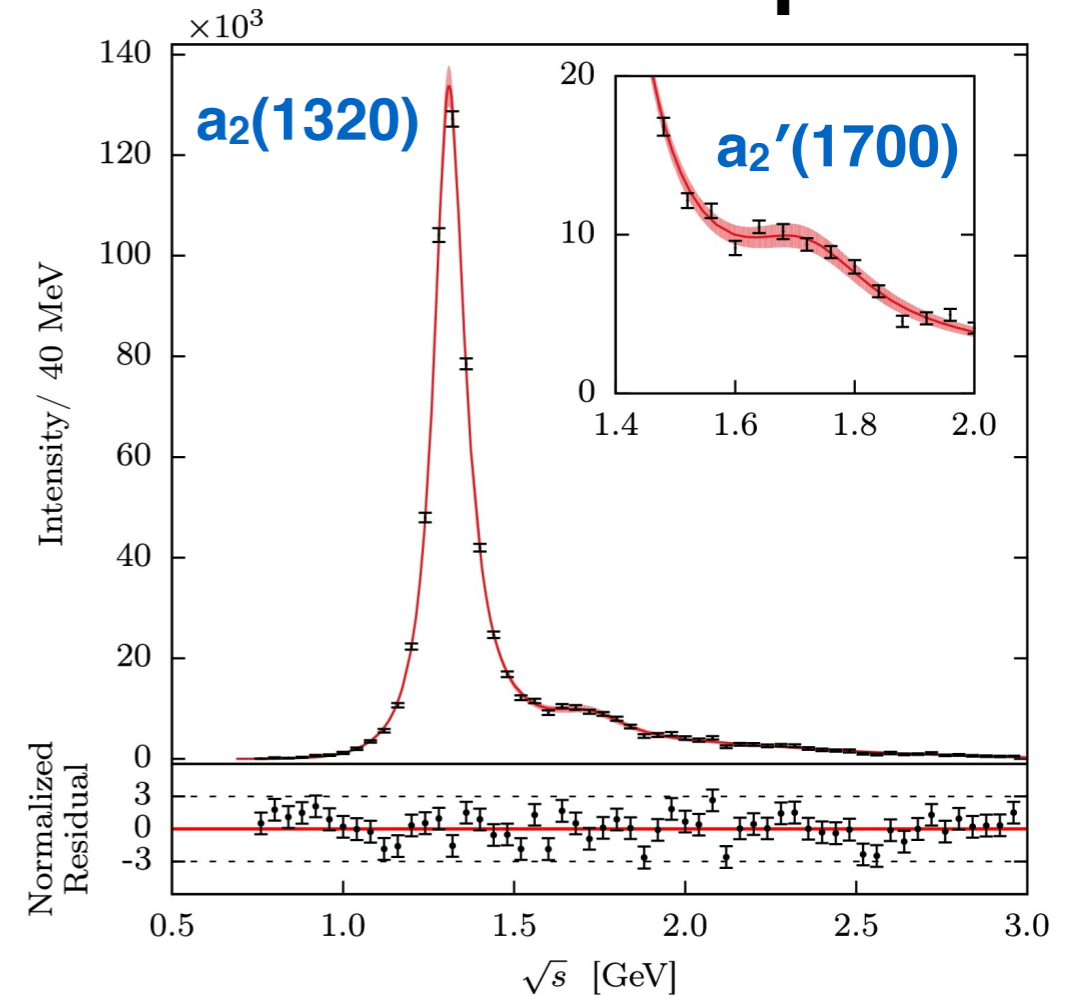
Evidence for exotic light-quark mesons

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

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



D-wave in $\eta'\pi$



Extract resonance parameters with unitary reaction model

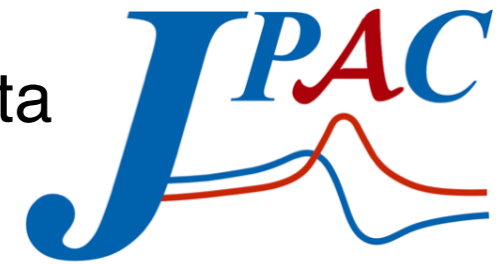
COMPASS: PLB 740, 303 (2015)



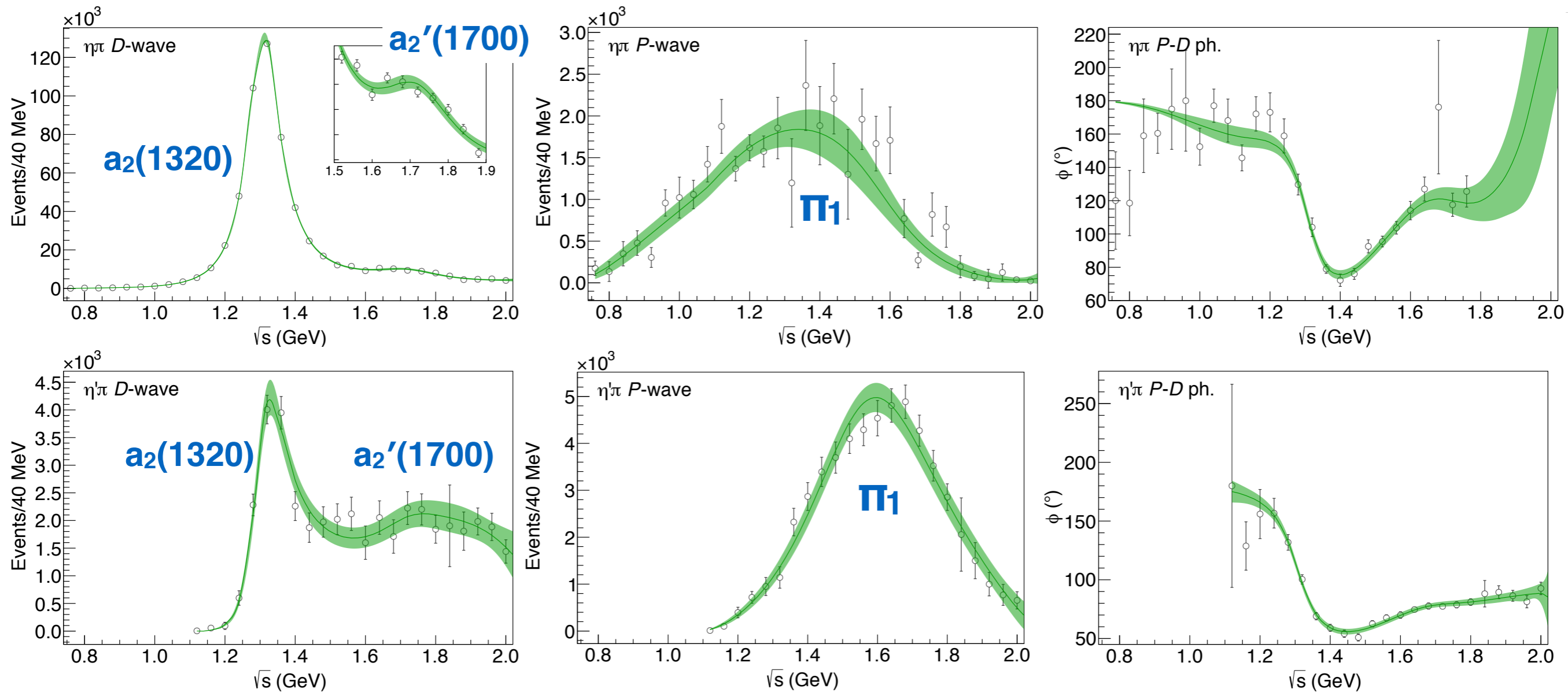
A. Jackura et al. [JPAC and COMPASS Collaborations], PLB 779, 464 (2018)

Evidence for exotic light-quark mesons

- Coupled channel analysis in progress for P-waves and D-waves
- High precision data & theoretical advances required to describe data

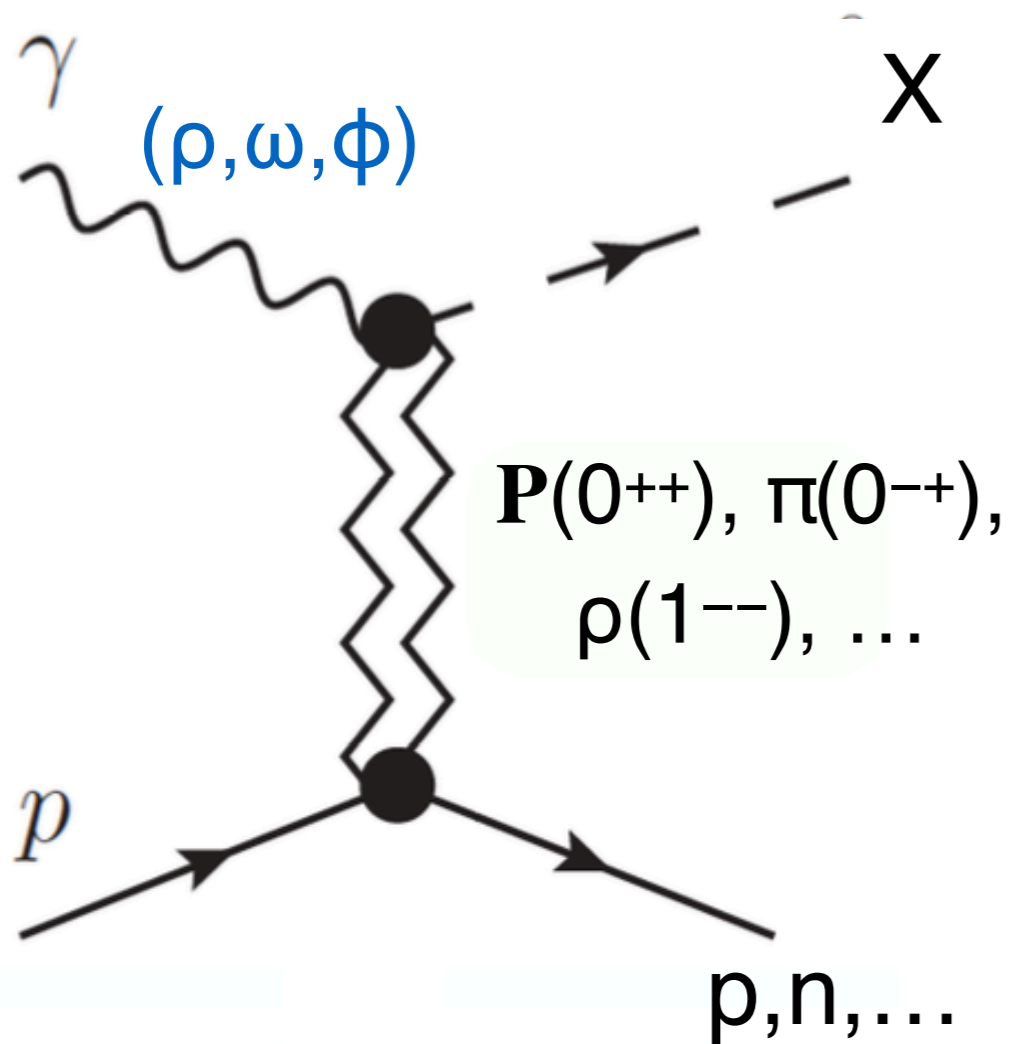


P/D-wave in $\eta\pi / \eta'\pi$

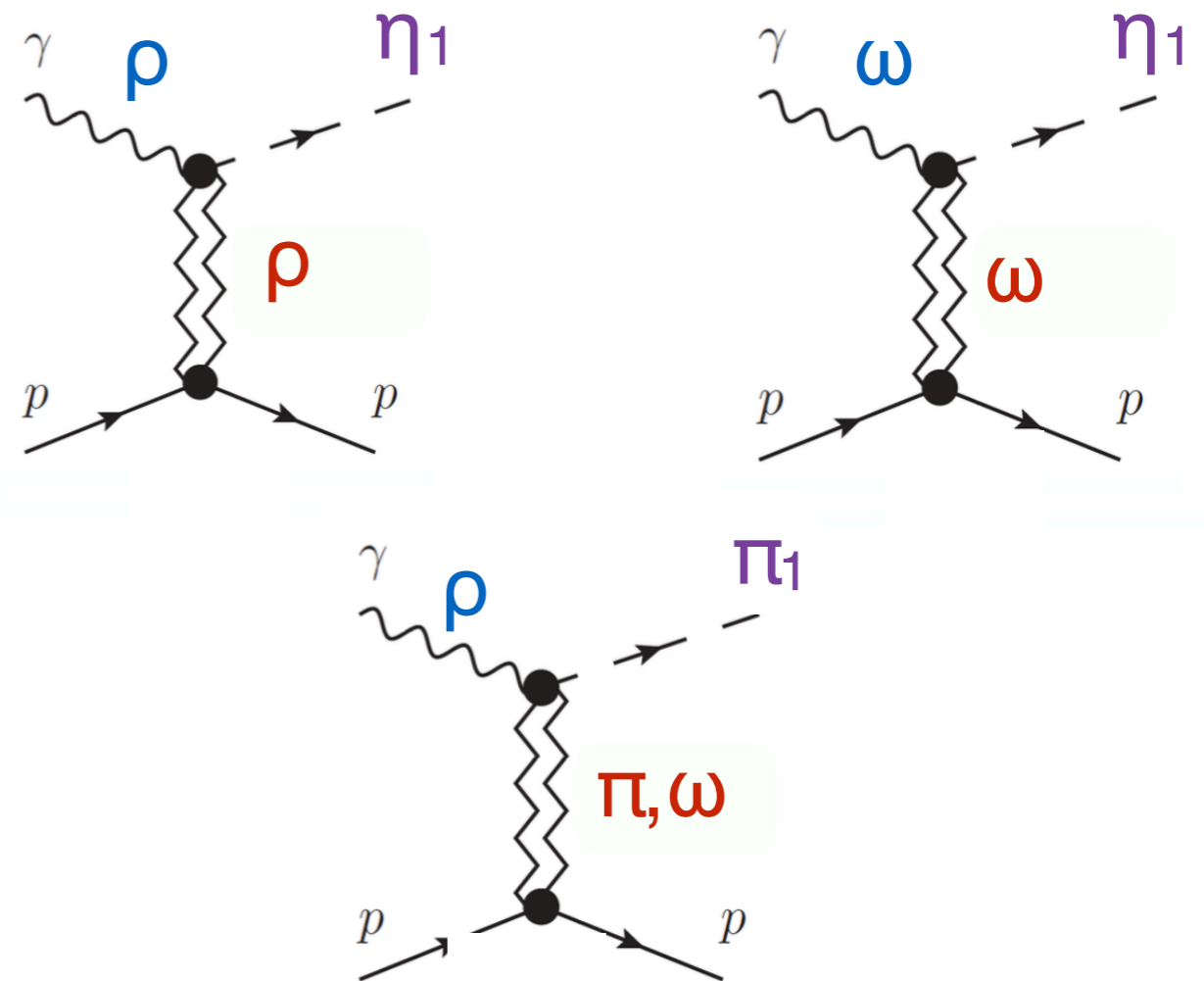


A. Rodas et al. (JPAC) [Phys. Rev. Lett. 122, 042002 (2019)]

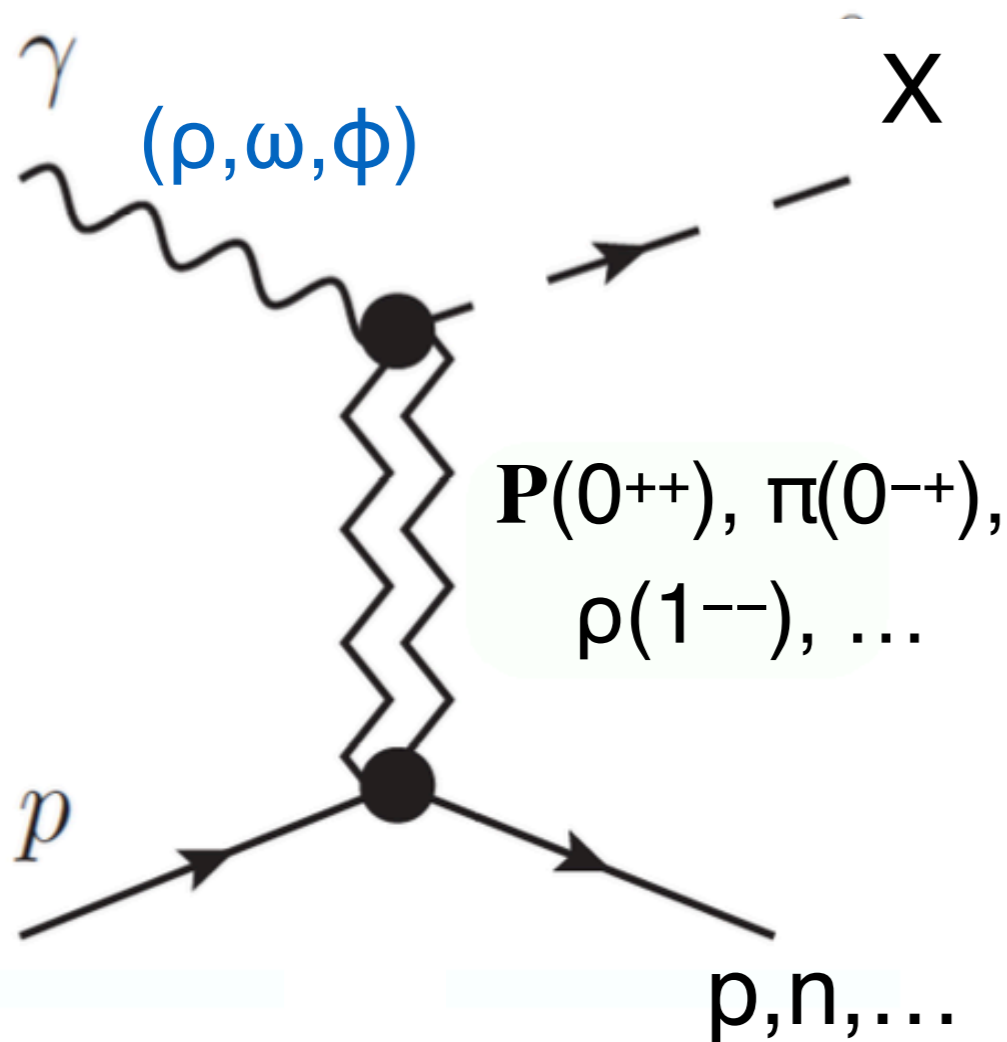
Meson Photoproduction



- Photon couples to exchanged QN via VMD, generates mesons with wide variety of J^{PC}
- All expected hybrids can be produced!

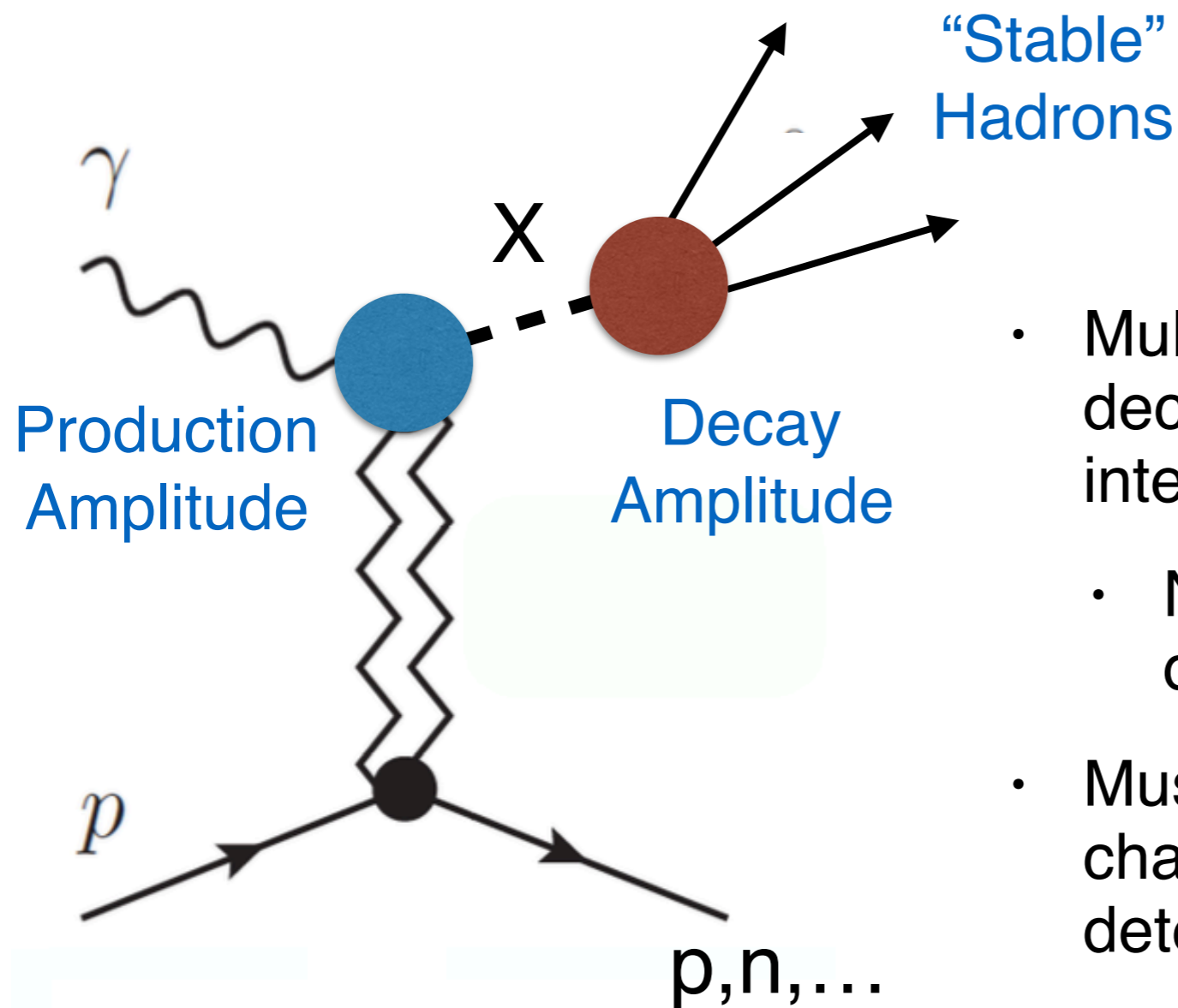


Meson Photoproduction



- Photon couples to exchanged QN via VMD, generates mesons with wide variety of J^{PC}
- All expected hybrids can be produced
- Variety of hybrid decays expected:
 - $\pi_1 \rightarrow \rho\pi, \pi b_1, \pi f_1$
 - $\eta_1 \rightarrow \eta f_2, \pi a_2, \eta f_1$
- Little existing photoproduction data. Neutral final states at these energies are mostly unexplored
- Photon polarization provides constraints on production processes

Meson Photoproduction & Amplitude Analysis



- Multiple states are produced which decay to the same set of particles and interfere
 - Need to study production and decay mechanisms
- Must understand photon beam characteristics and have detailed detector model
- Improved theoretical models for amplitudes also needed, work closely with JPAC and others

The GlueX Experiment in Hall D @ JLab

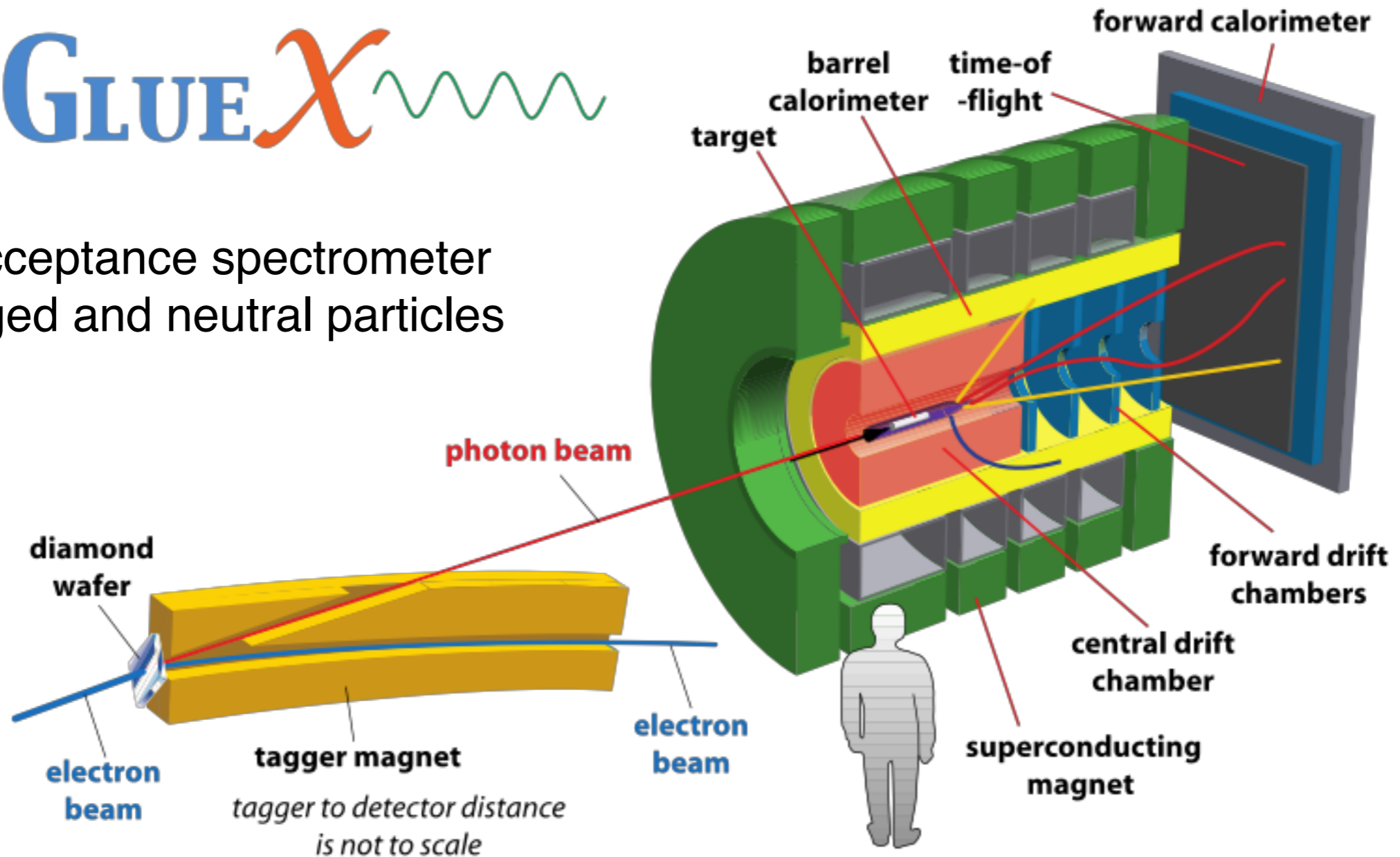
- The GlueX experiment is located in Hall D, newly constructed as part of the Jefferson Lab 12 GeV upgrade.
- Large acceptance solenoidal spectrometer
- Linearly polarized photon beam peaking at 9 GeV
- Detects all decay products from full hadronic photoproduction rate
- 100+ Collaborators from 26 institutions



The GlueX Experiment

GLUEX 

Large acceptance spectrometer
for charged and neutral particles



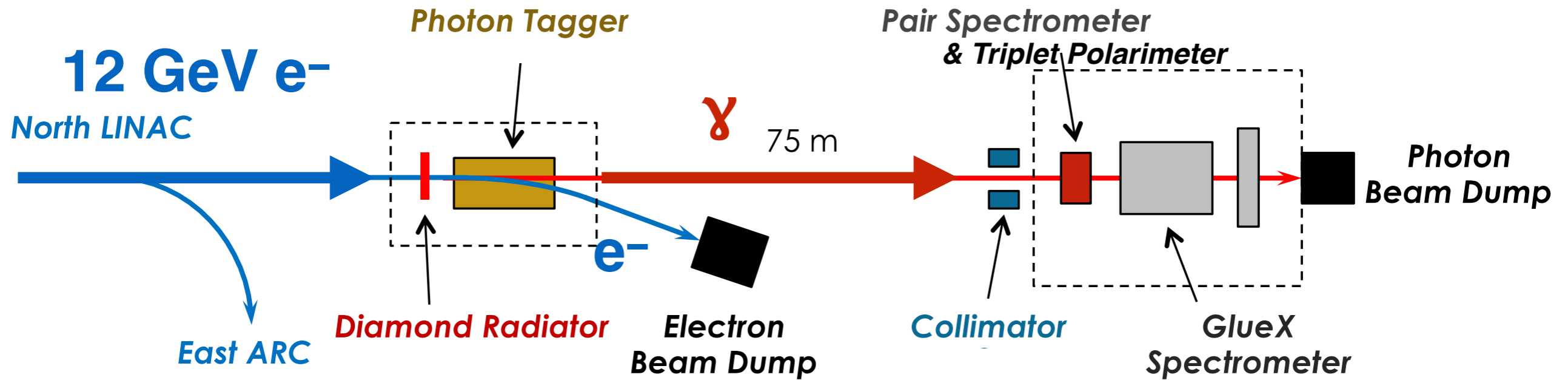
- **2016: 10 pb⁻¹**
- **2017: 45 pb⁻¹**
- **2018: ~150 pb⁻¹**

(~80 hours of physics-quality commissioning data)

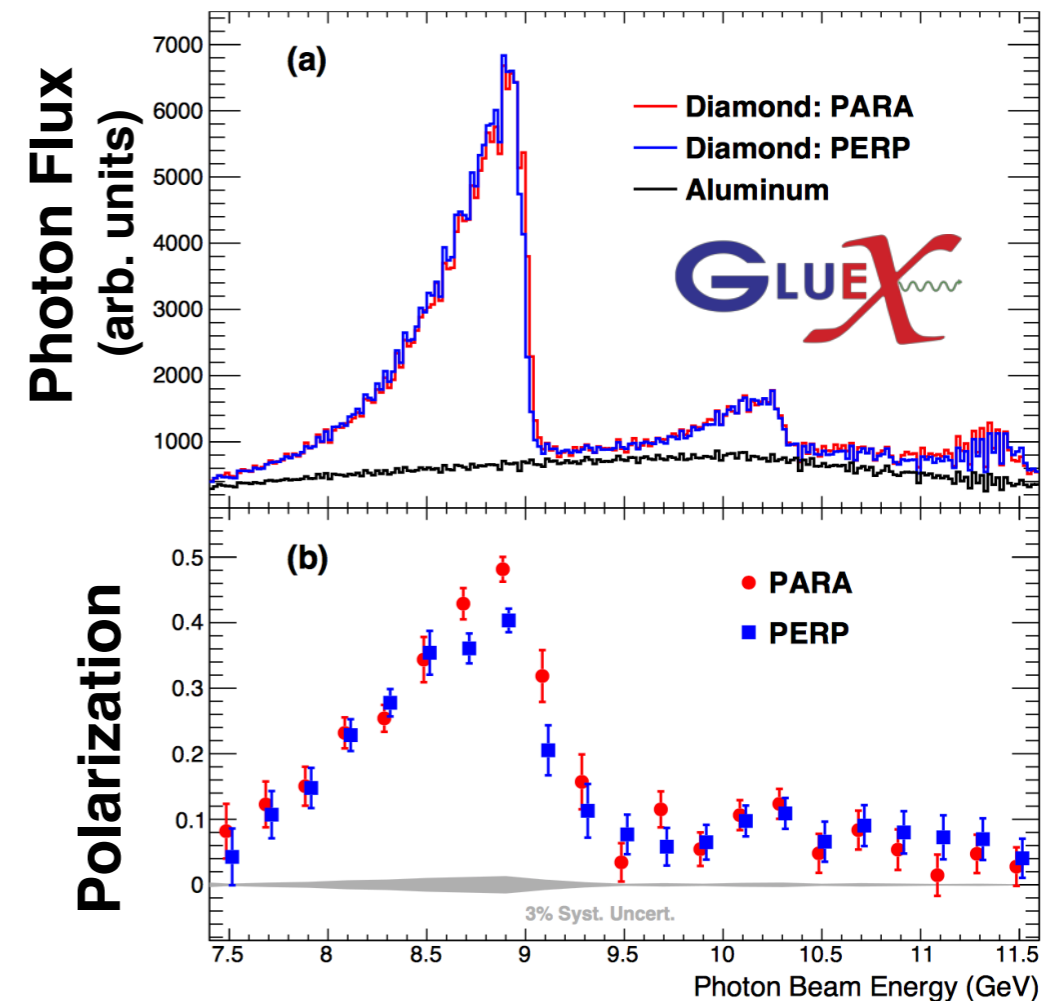
(used for most results shown here)

GlueX Phase-I **complete!**

The GlueX Experiment: Photon Beam



- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
 - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Intensity of $\sim 1-5 \times 10^7$ 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

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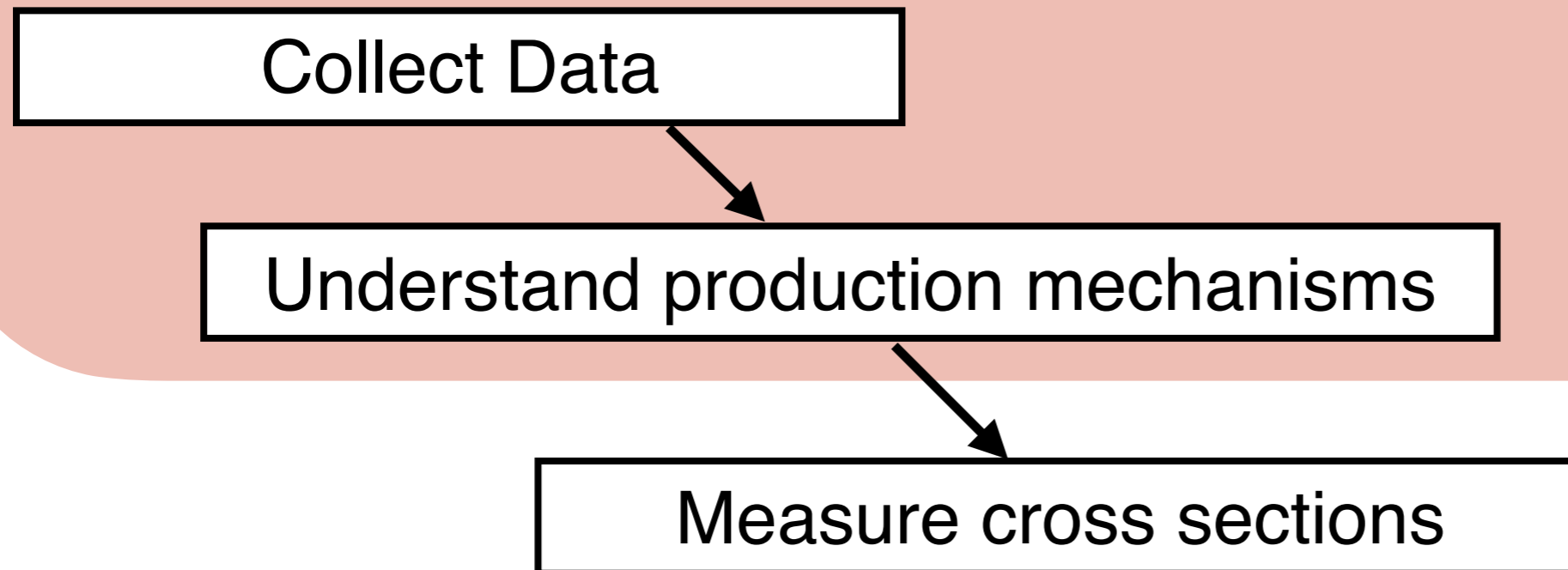
Collect Data

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graph TD; A[Collect Data] --> B[Understand production mechanisms]
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Understand production mechanisms

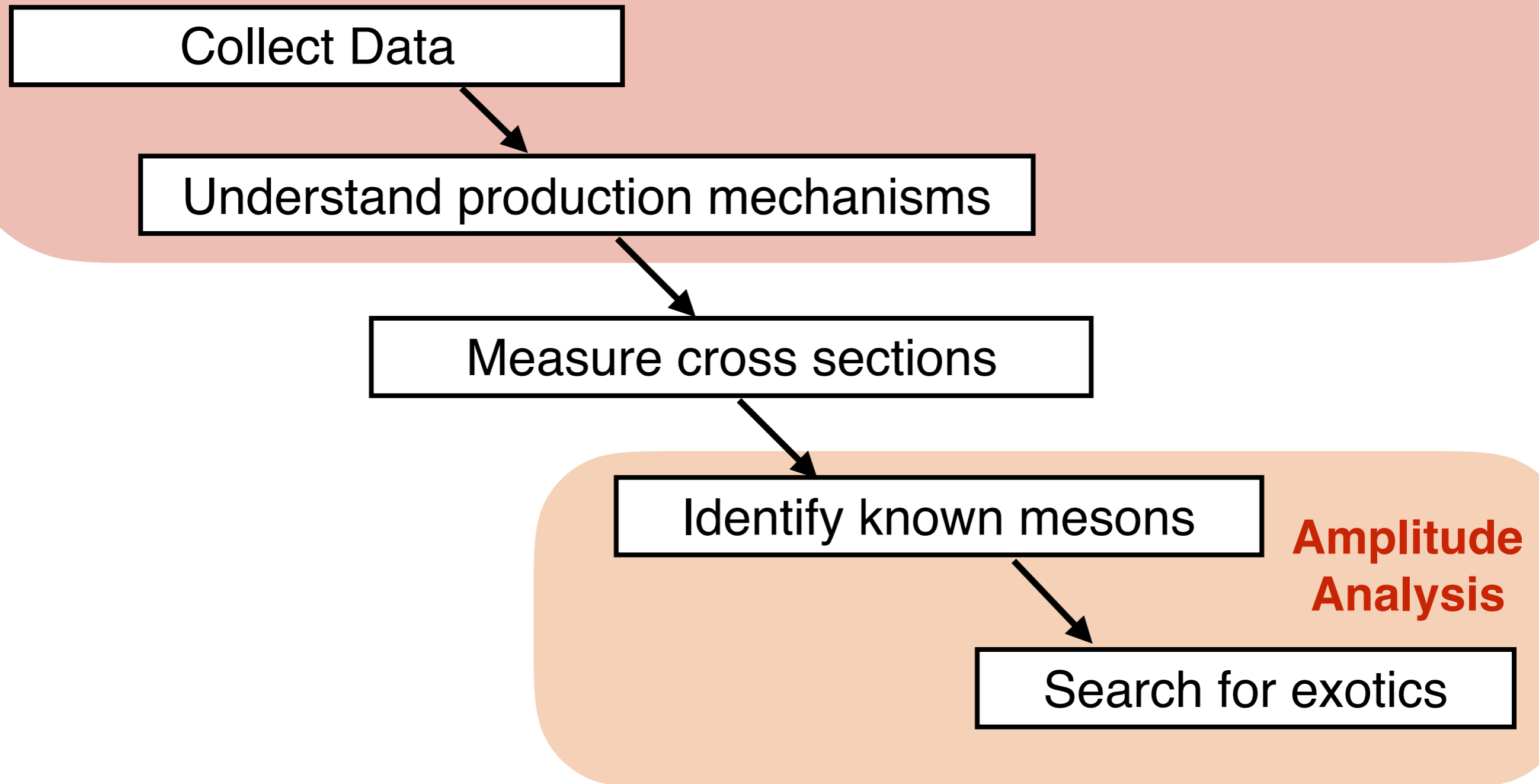
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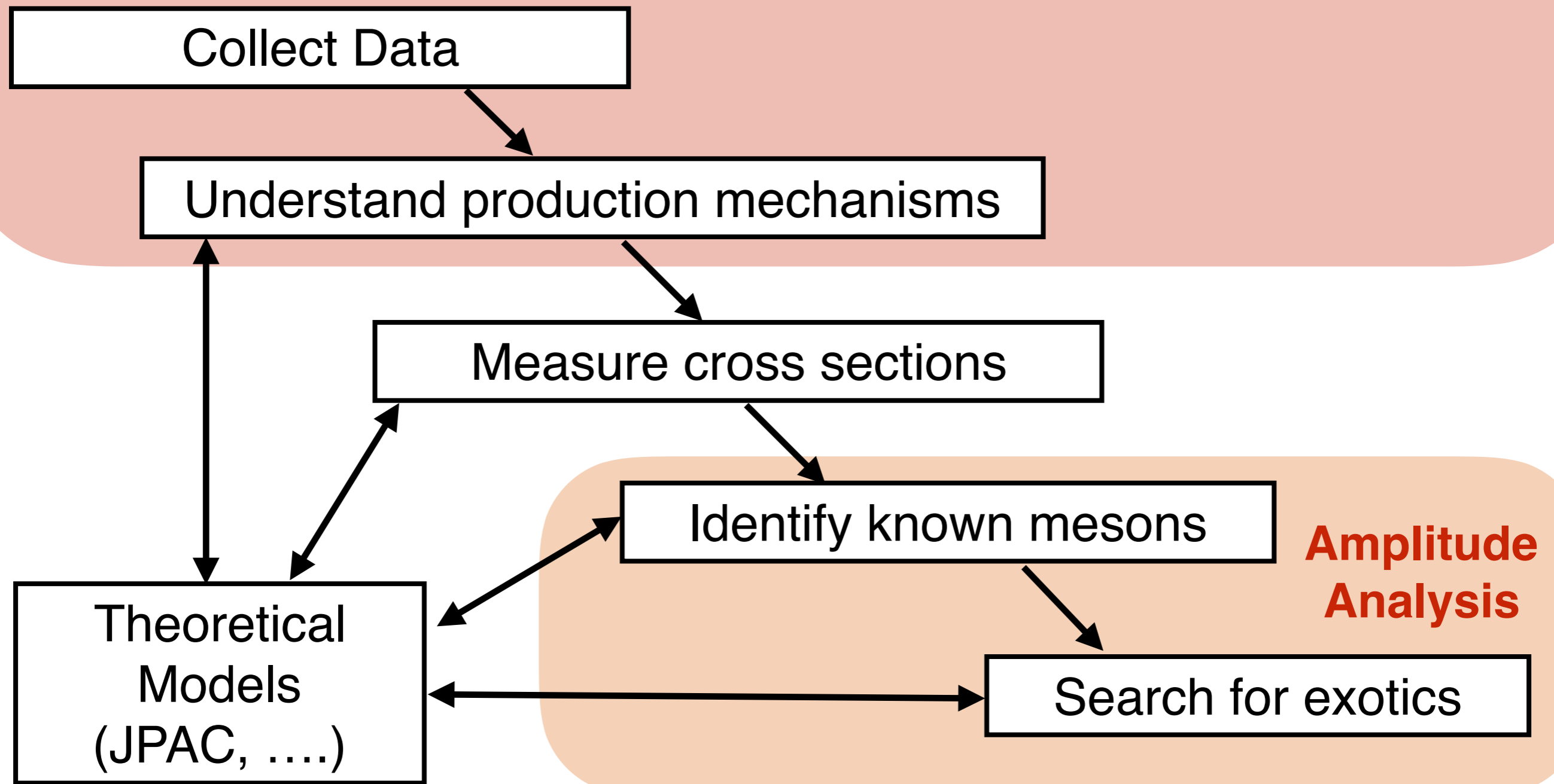
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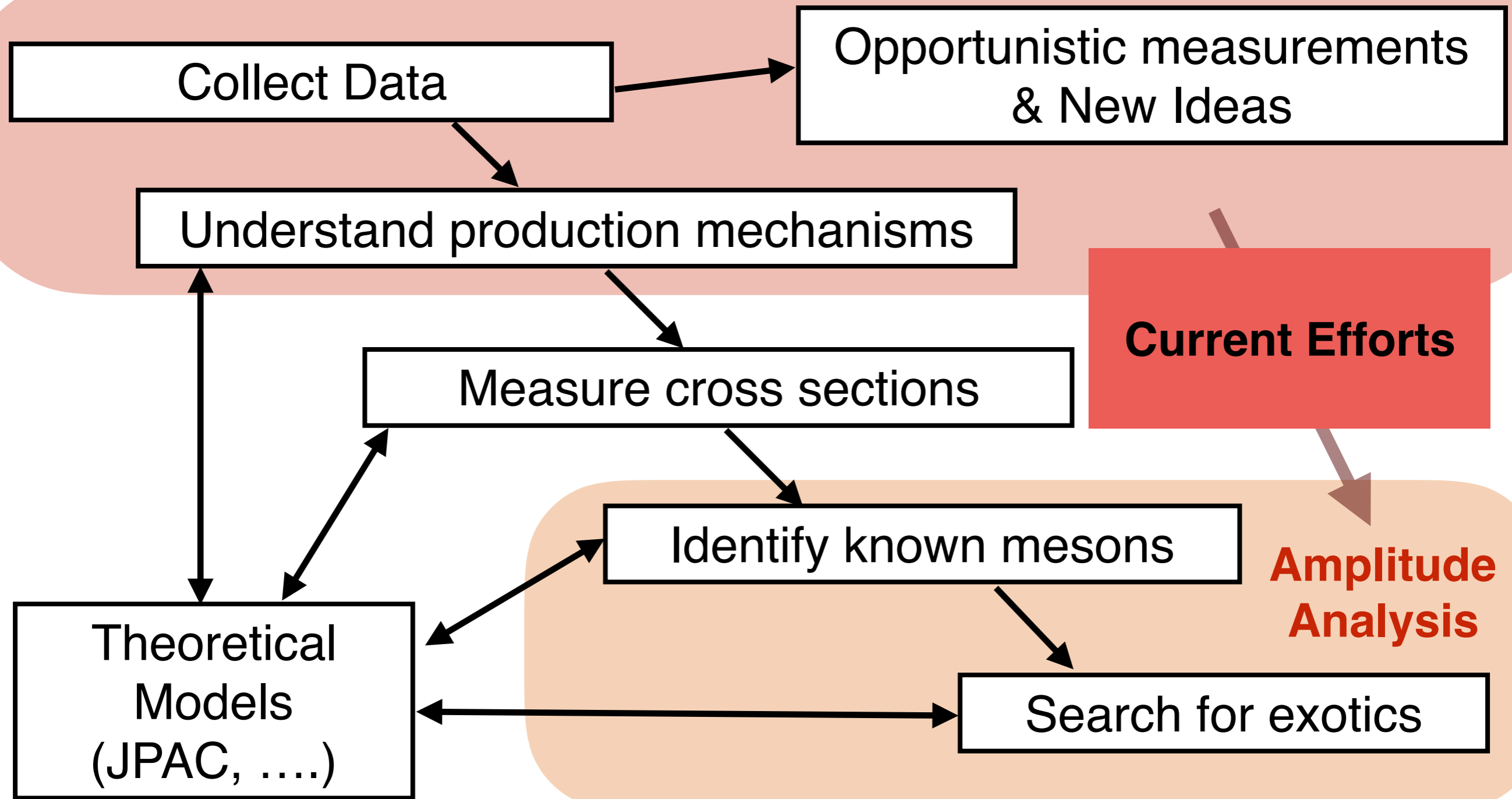
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Searching for Exotics in Photoproduction

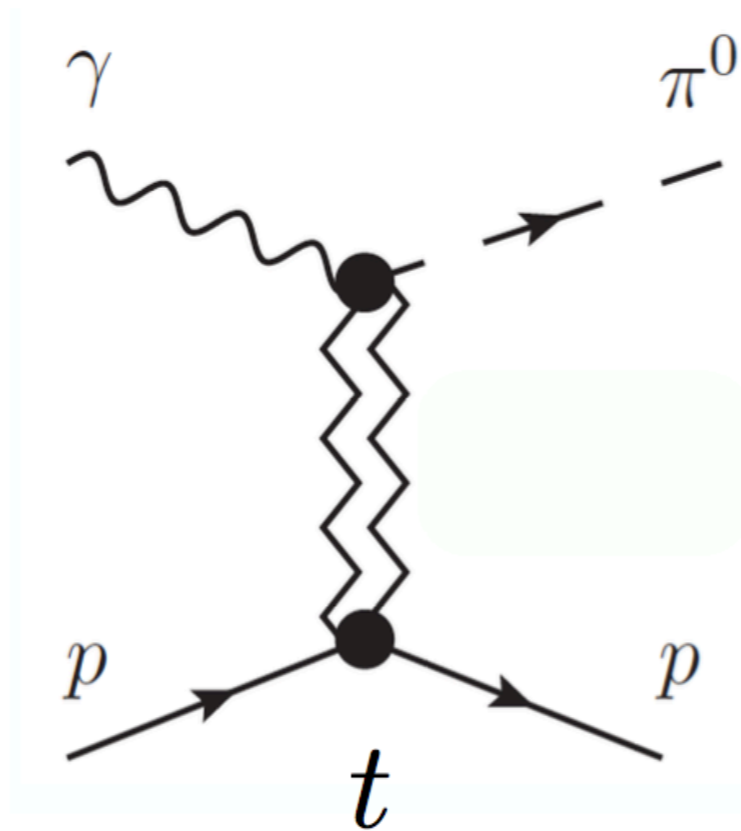
- Detailed understanding of light-quark meson spectrum requires amplitude analysis.



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

- Understanding production mechanisms necessary to determine J^{PC} of mesons in amplitude analyses, look at simplest reactions first
- Beam asymmetry Σ yields information on production mechanisms
- Combining data taken with different beam polarization cancels most acceptance effects

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



Exchange J^{PC}

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

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

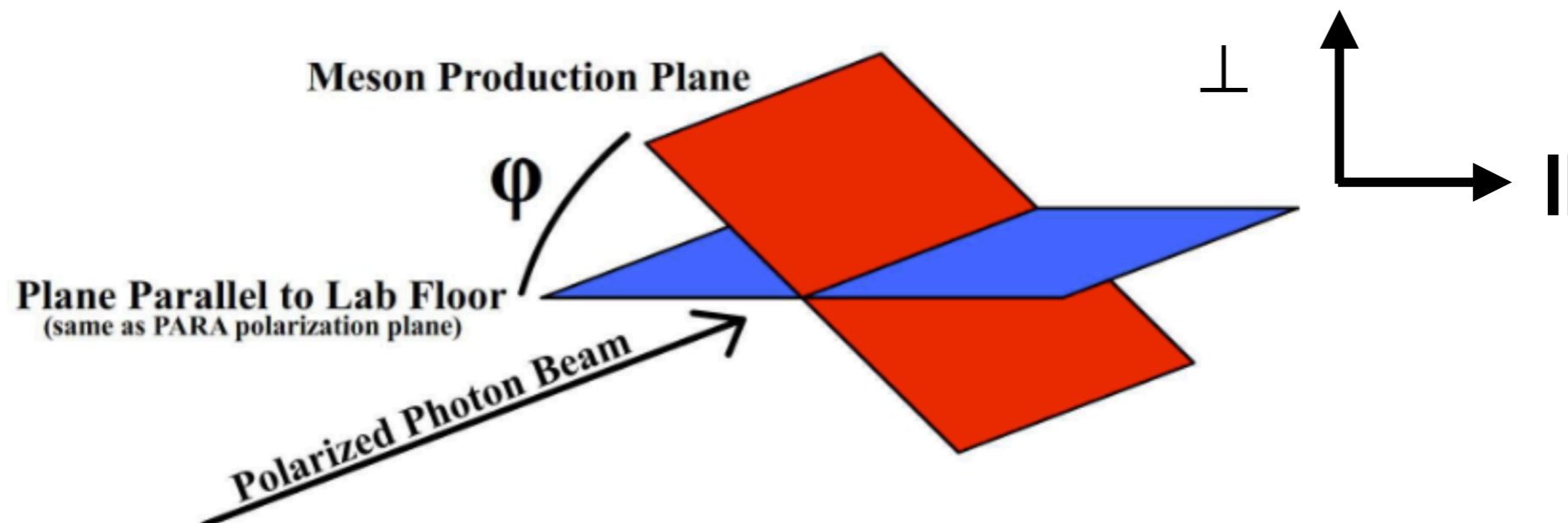
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$$\sigma = \sigma_0 [1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_{\text{lin}})]$$

Production plane

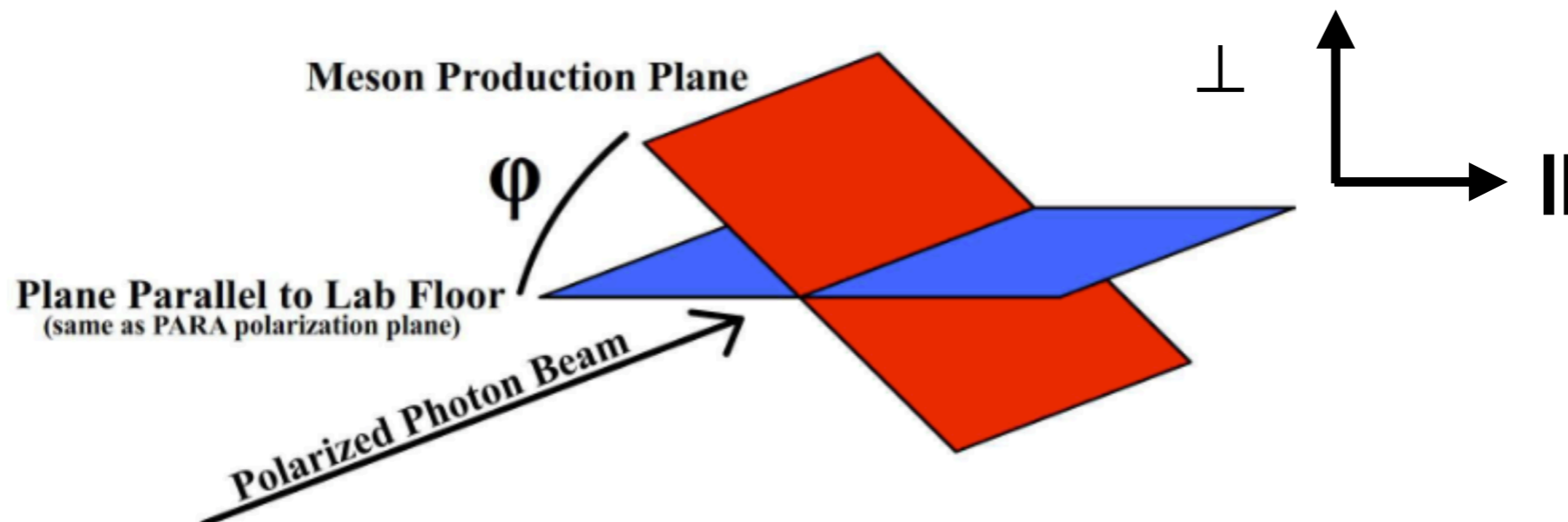
Polarization plane



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



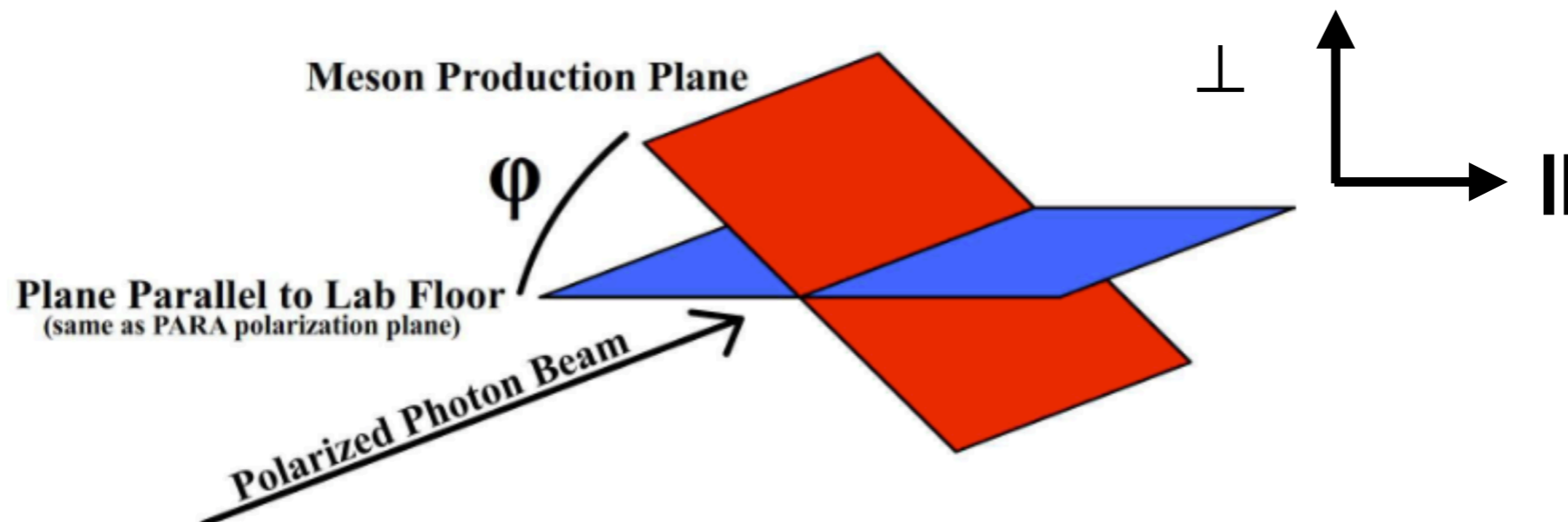
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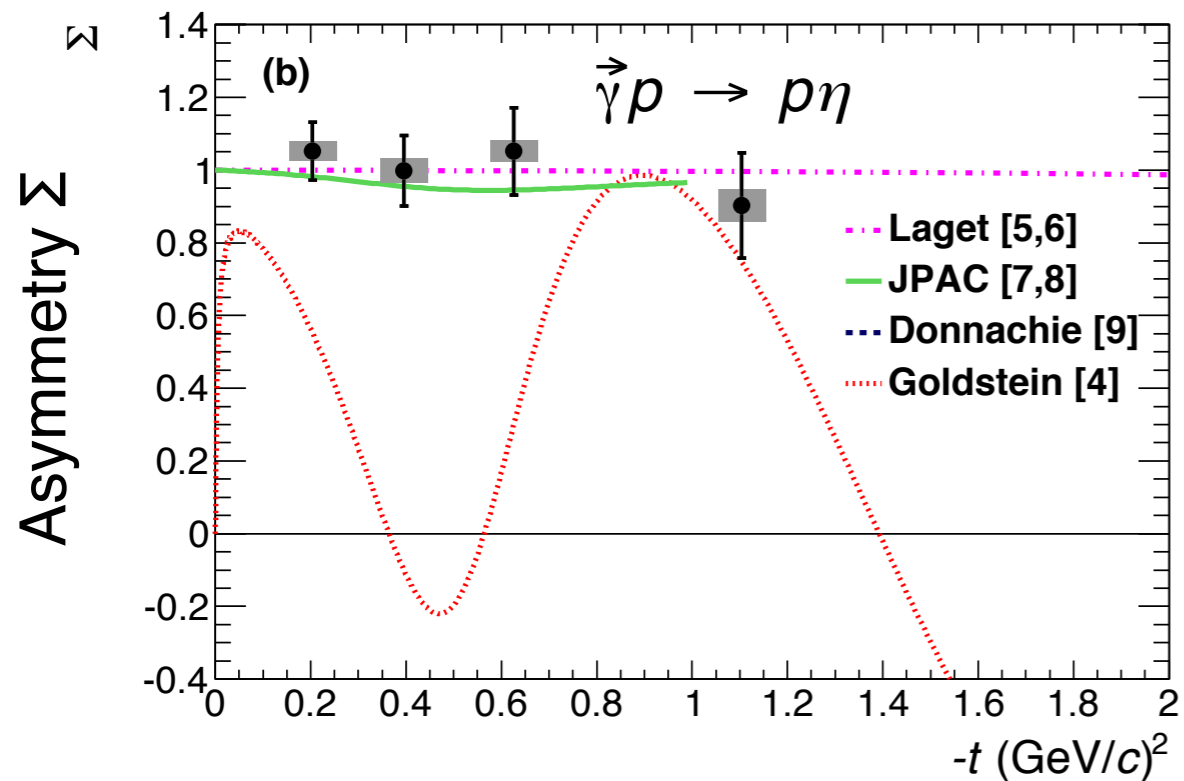
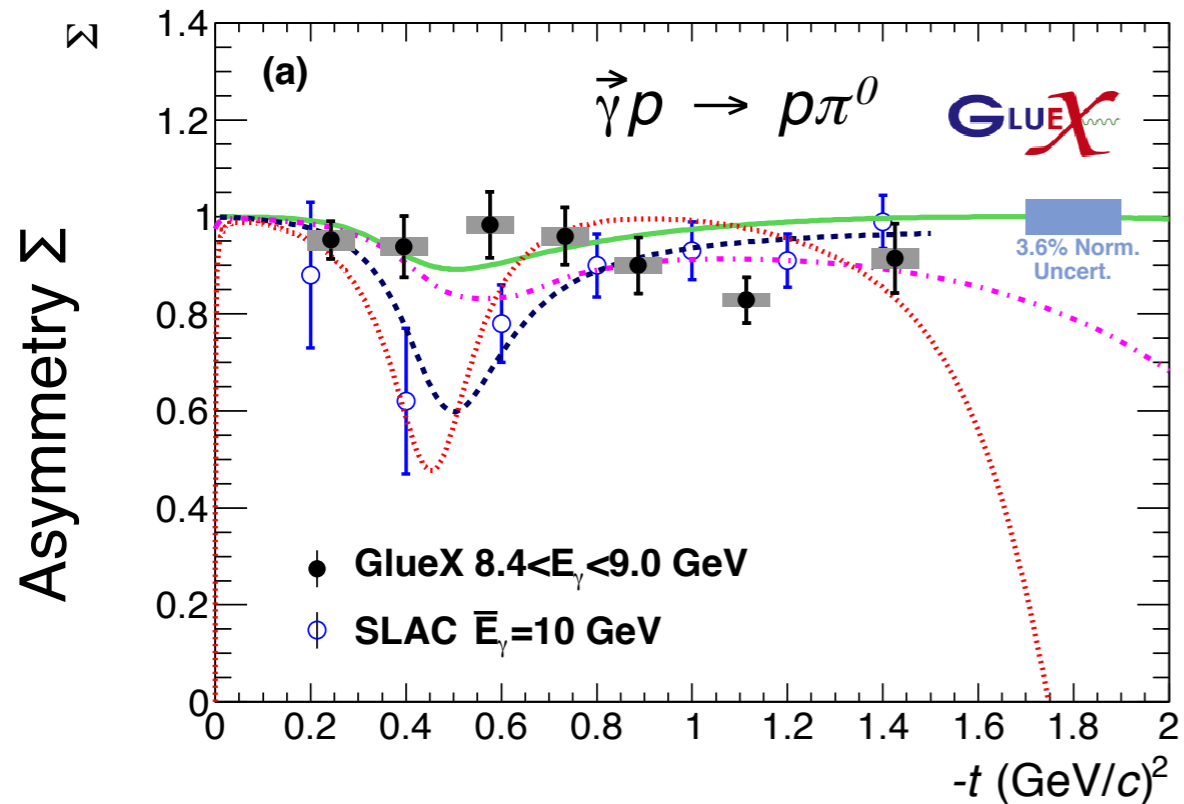
Measure with $\gamma e^- \rightarrow e^- e^+ e^-$

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

Isolate Σ



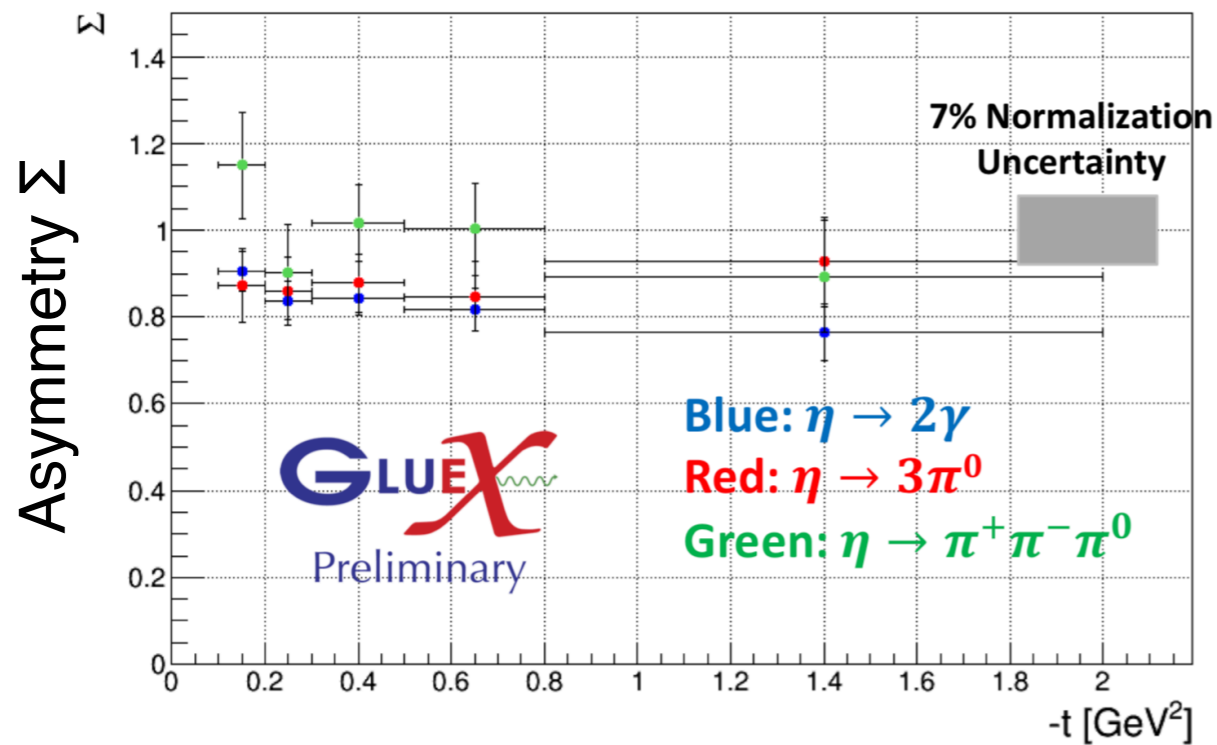
Beam Asymmetries: $\vec{\gamma} p \rightarrow p + \pi^0 / \eta$



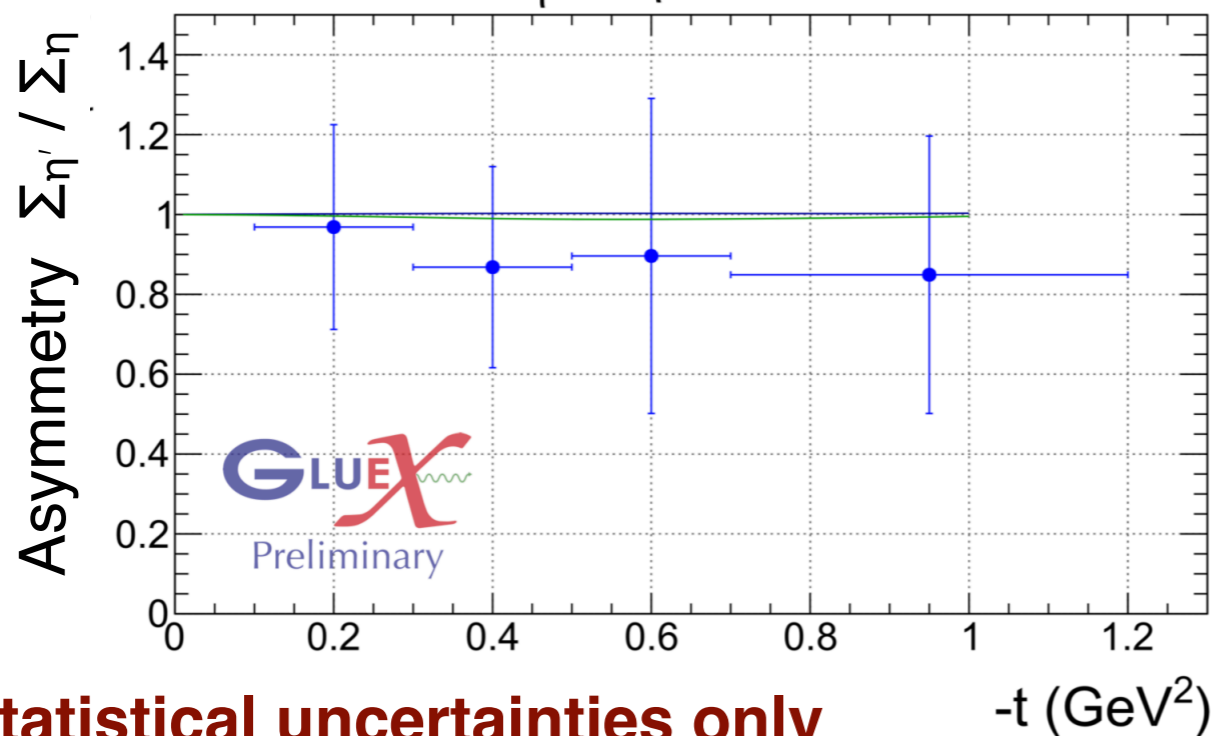
- First step towards study of photoproduction amplitudes made using 2016 data
- $\Sigma \approx 1$ indicates vector exchange dominates at this energy
- First η measurement at this energy
- Constrains background to baryon resonance production at lower energies [e.g. [arXiv:1708.07779](https://arxiv.org/abs/1708.07779)]

**First JLab 12 GeV publication:
Phys.Rev.C 95, 042201 (2017)**

Beam Asymmetries: $\gamma p \rightarrow p + \eta / \eta'$



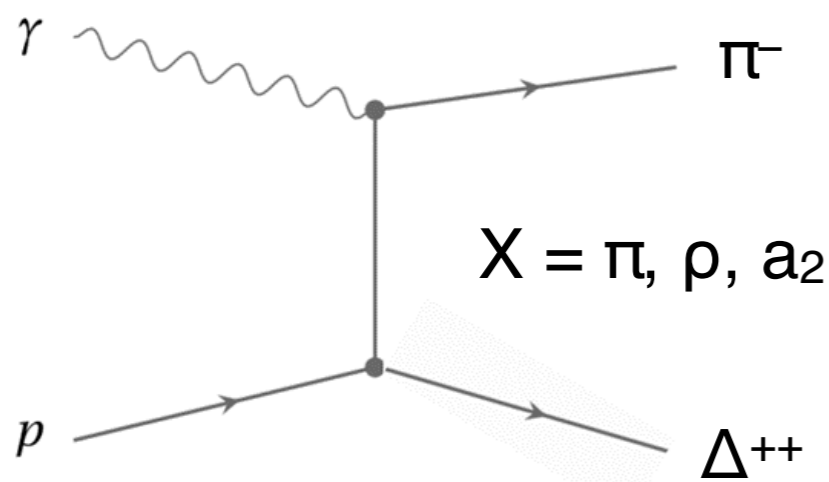
$\Sigma_{\eta'}/\Sigma_{\eta}$ vs $-t$



Statistical uncertainties only

- Initial studies of η and η' beam asymmetries using 2017 data and additional decay modes
- Expect similar mechanism for exotics
- Production is consistent with vector exchange dominance
- Full GlueX-I data will provide a factor 5 more events
- Program of production amplitude studies is well underway

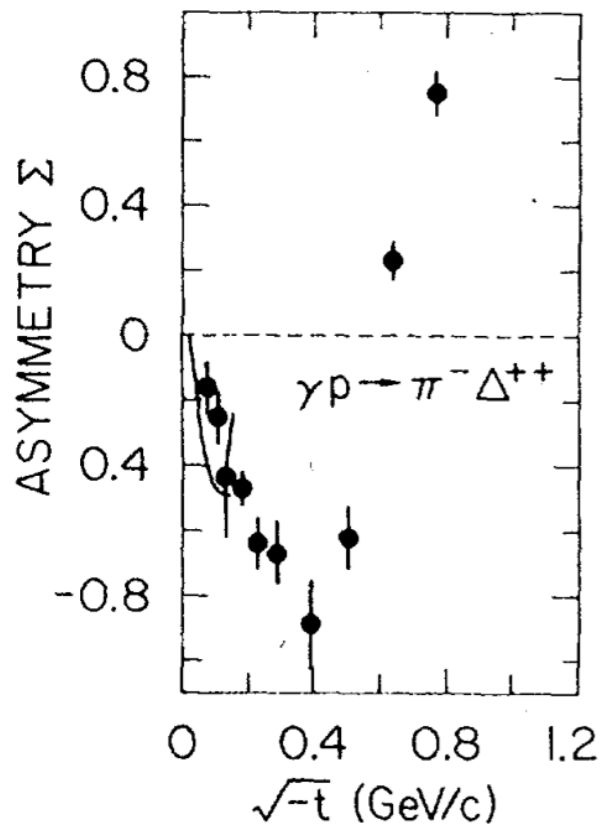
Beam Asymmetries: $\gamma p \rightarrow \pi^- \Delta^{++}$



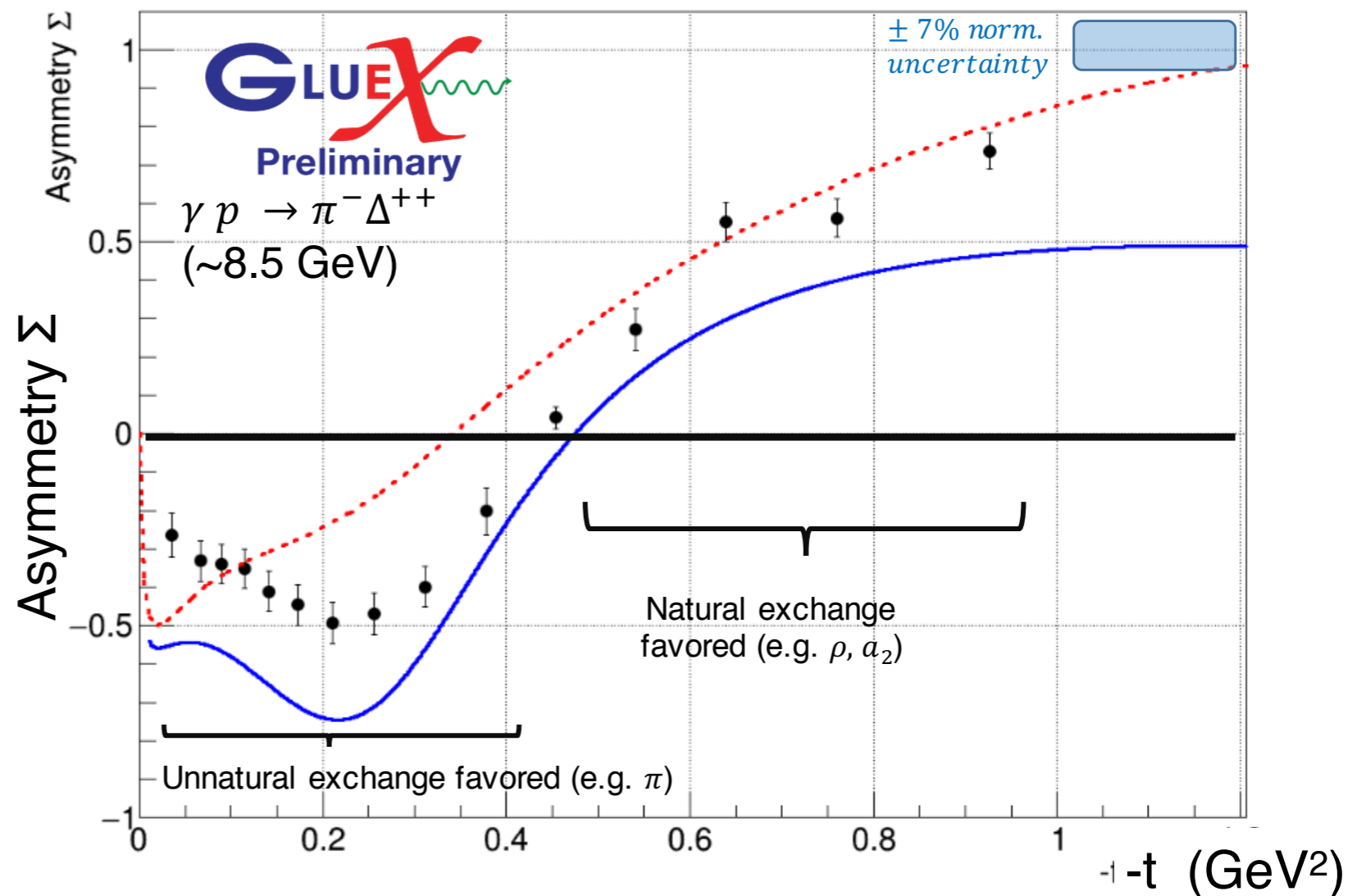
- Charged pseudoscalar beam asymmetry has more complicated t-dependance
- Preliminary results use order of magnitude more data than previous measurements

- - - B.G Yu (Korea Aerospace U.), arxiv:1611.09629v5 (16 GeV)
— J. Nys (JPAC), arxiv: 1710.09394v1 (8.5 GeV)

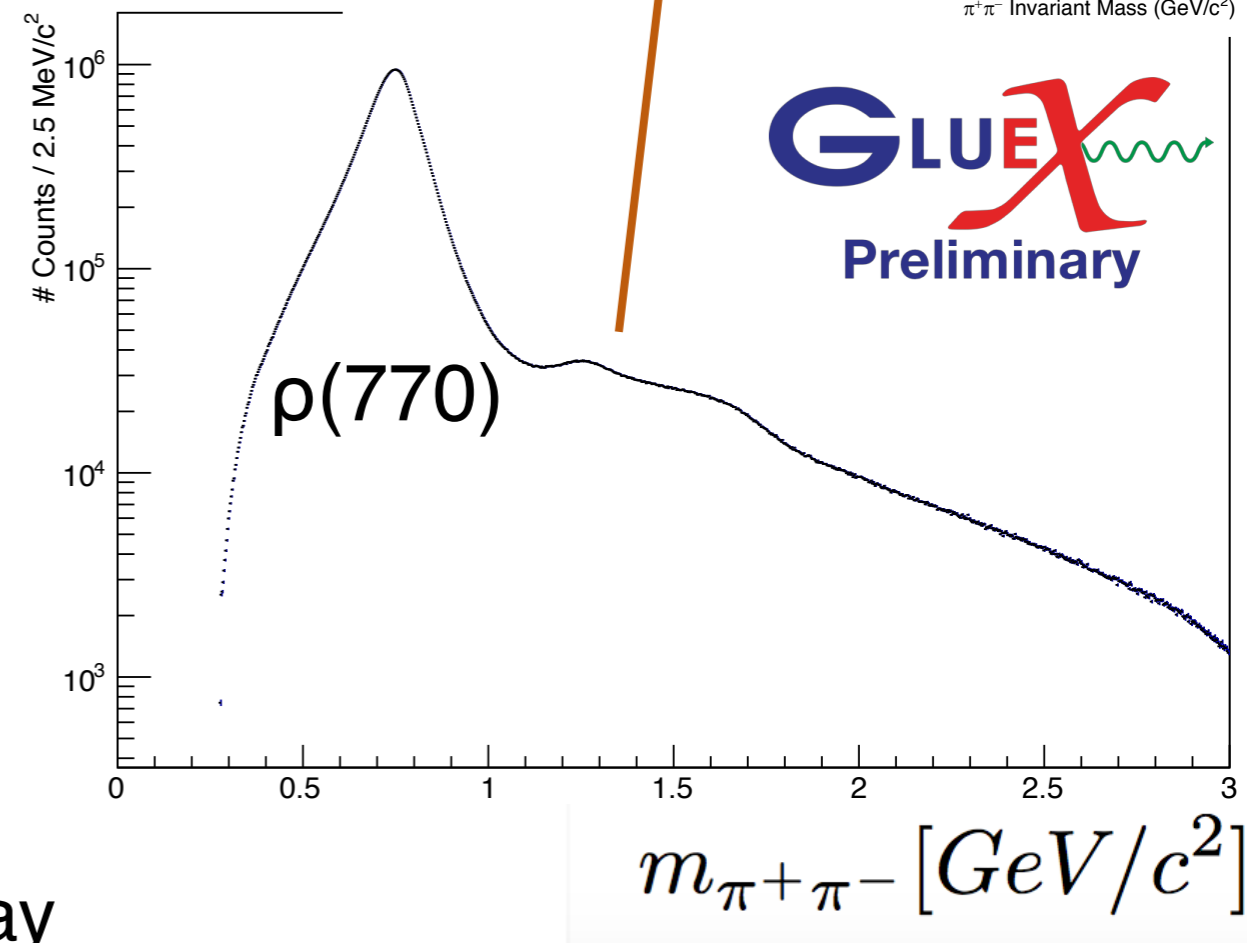
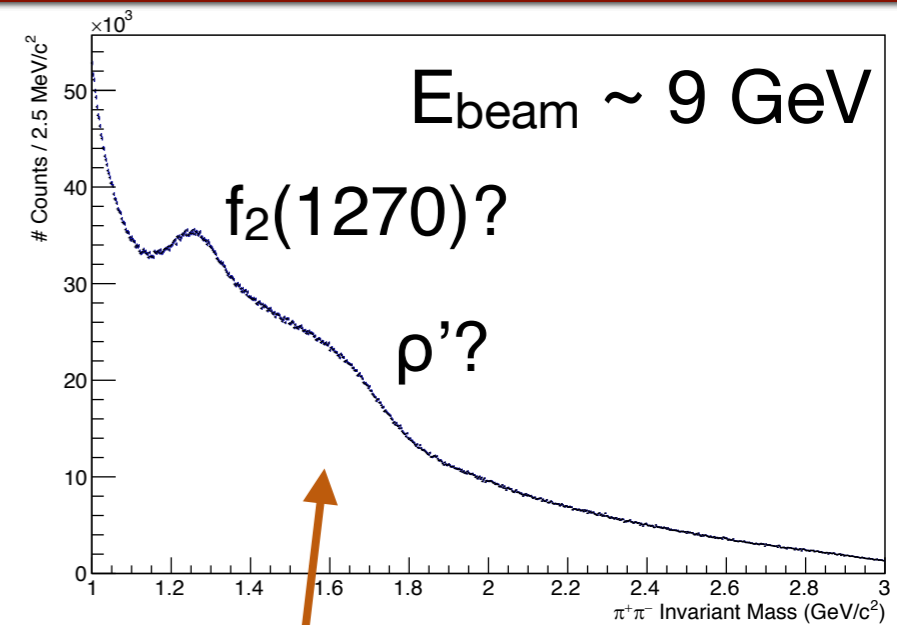
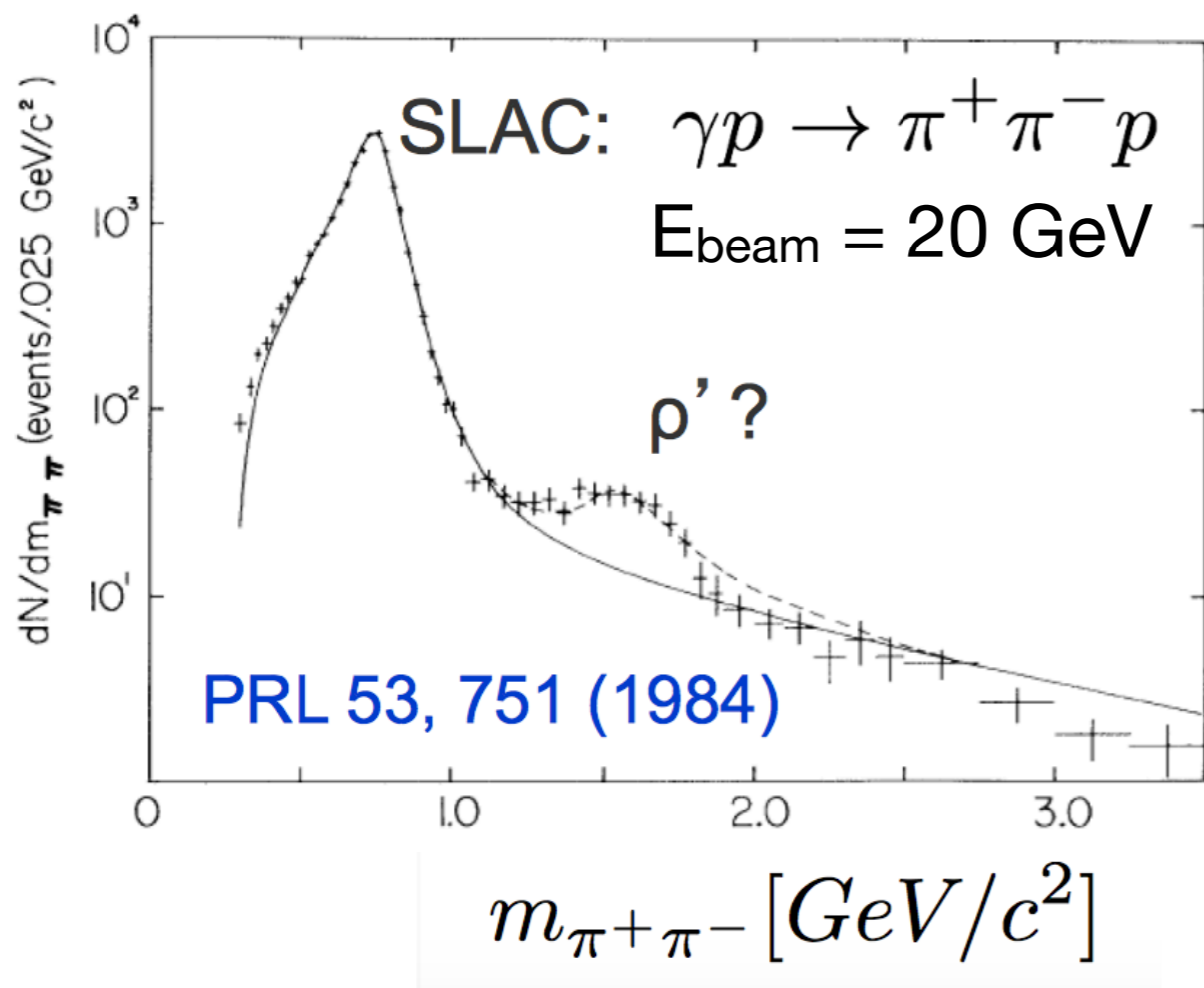
SLAC (16 GeV)



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



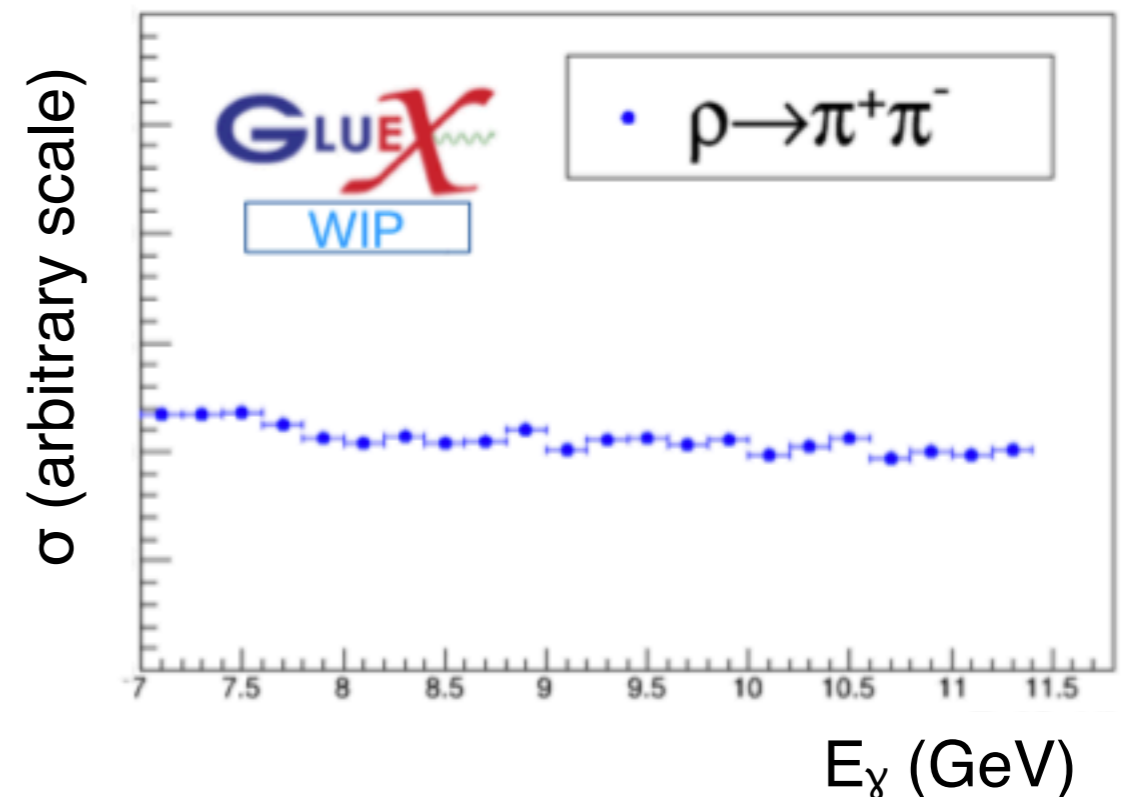
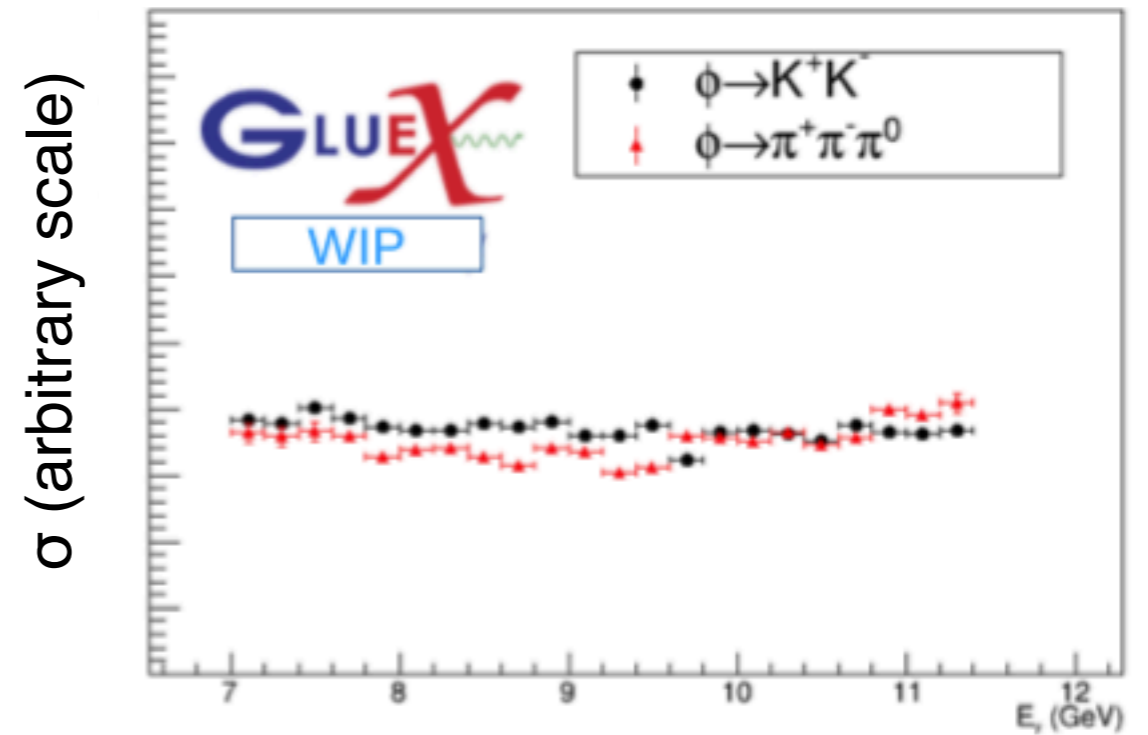
Spectroscopy Prospects: $\gamma p \rightarrow p + \pi^+ \pi^-$



- Take fresh look at $\pi^+ \pi^-$ photoproduction
 - Using two-orders of magnitude more data than SLAC
 - Enhancements seen with $M > 1 \text{ GeV}$
 - Moment / amplitude analysis underway
- $K^+ K^-$ photoproduction also being studied

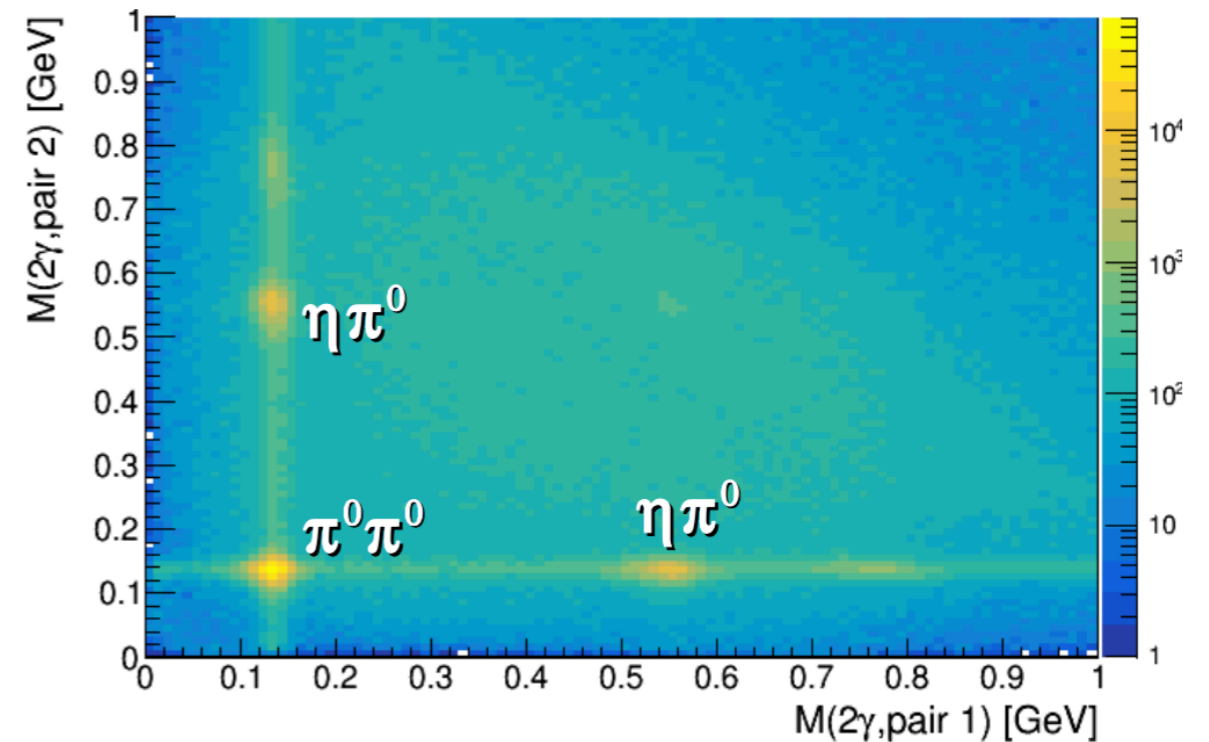
Work Towards Vector Meson Production Cross Sections

- Vector meson production cross sections provide important benchmarks
 - Comparison with previous measurements
 - Additional insight into production mechanisms
- Very preliminary “Work In Progress” shows similar beam energy dependence to previous measurements
- Recent data at lower beam energies taken for better comparison with CLAS results

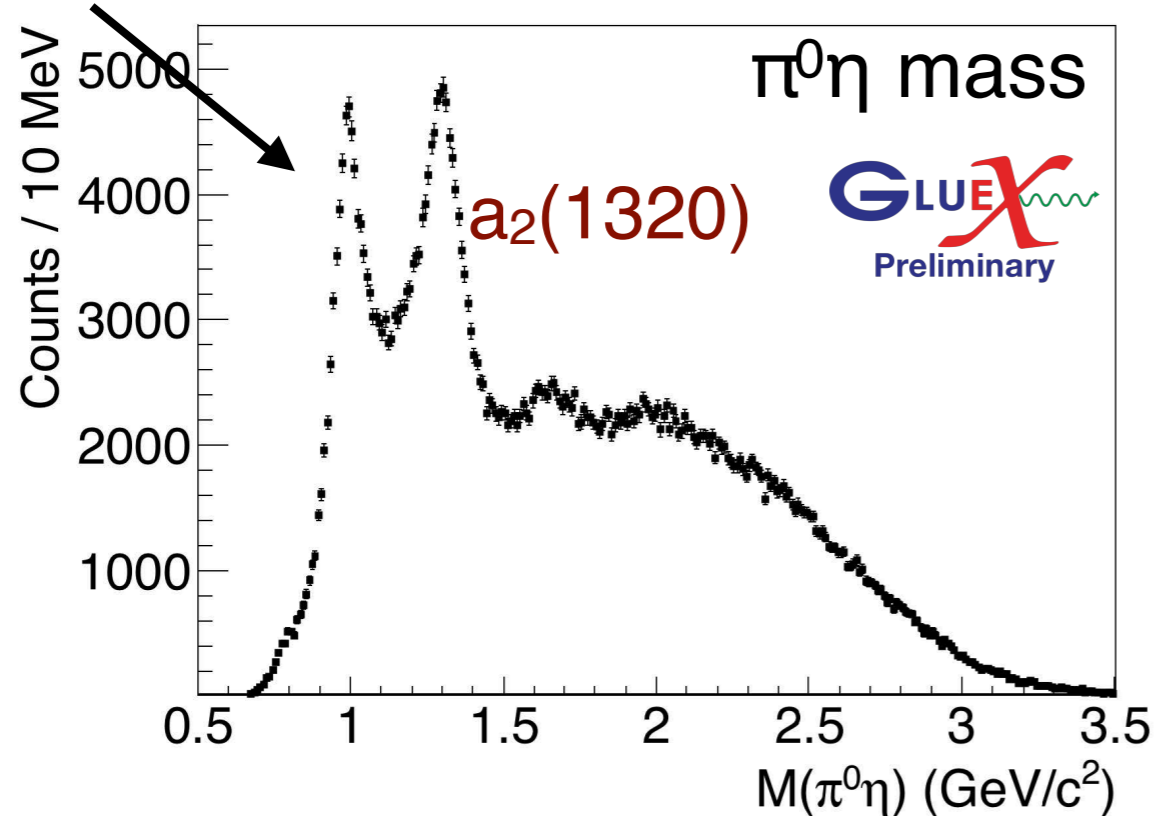


Spectroscopy Prospects: $\gamma p \rightarrow p + \pi\eta$

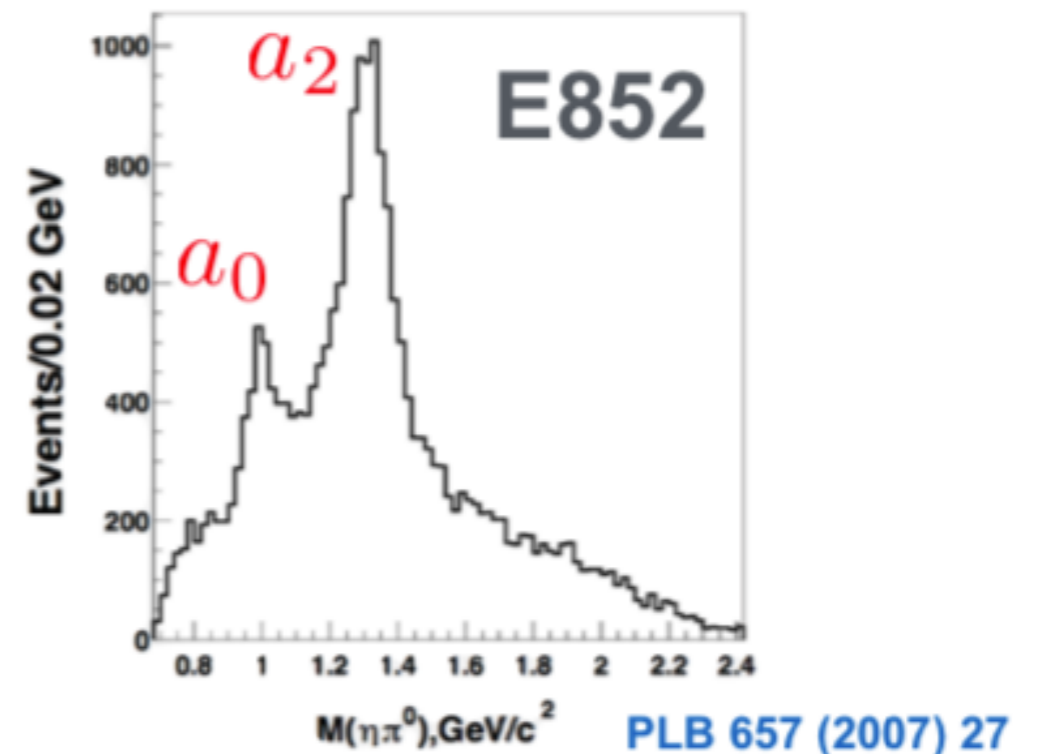
- $\pi\eta$ / $\pi\eta'$ promising channels for early hybrid searches
- With 20% of GlueX-I data, we see several well-known mesons
- Statistics are competitive with previous experiments



$a_0(980)$ $\gamma p \rightarrow p + \pi^0 \eta, \eta \rightarrow \gamma\gamma$



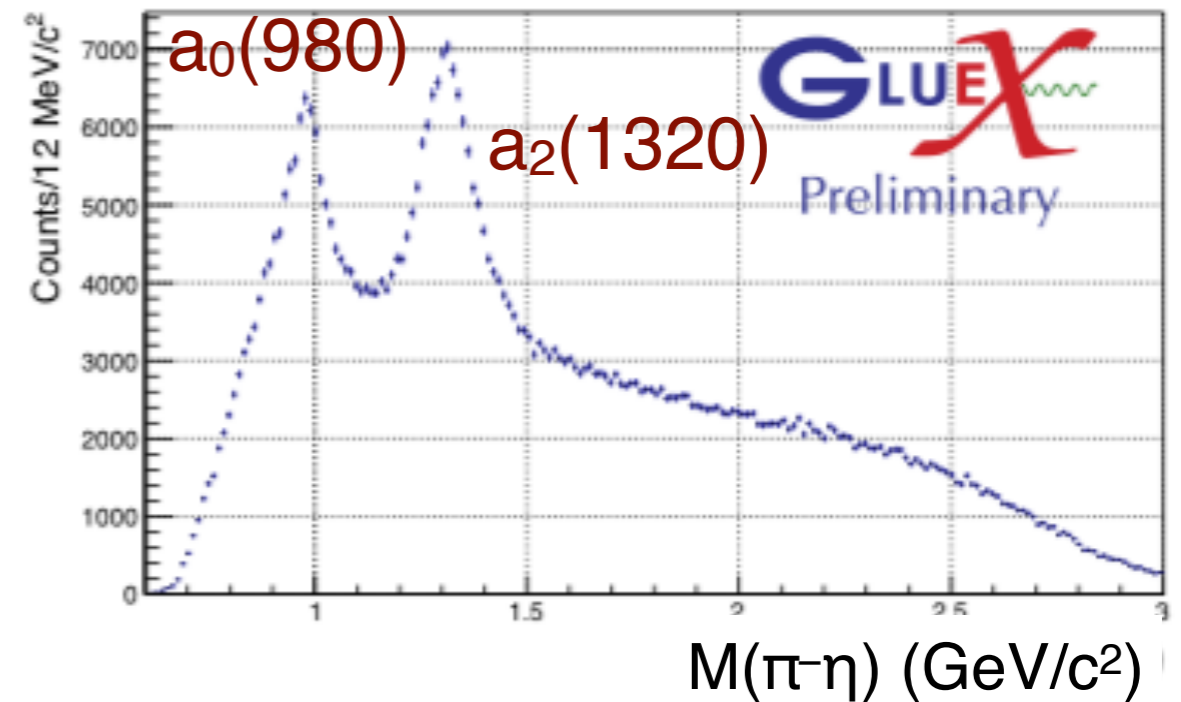
$\pi^- p \rightarrow \eta\pi^0 n$



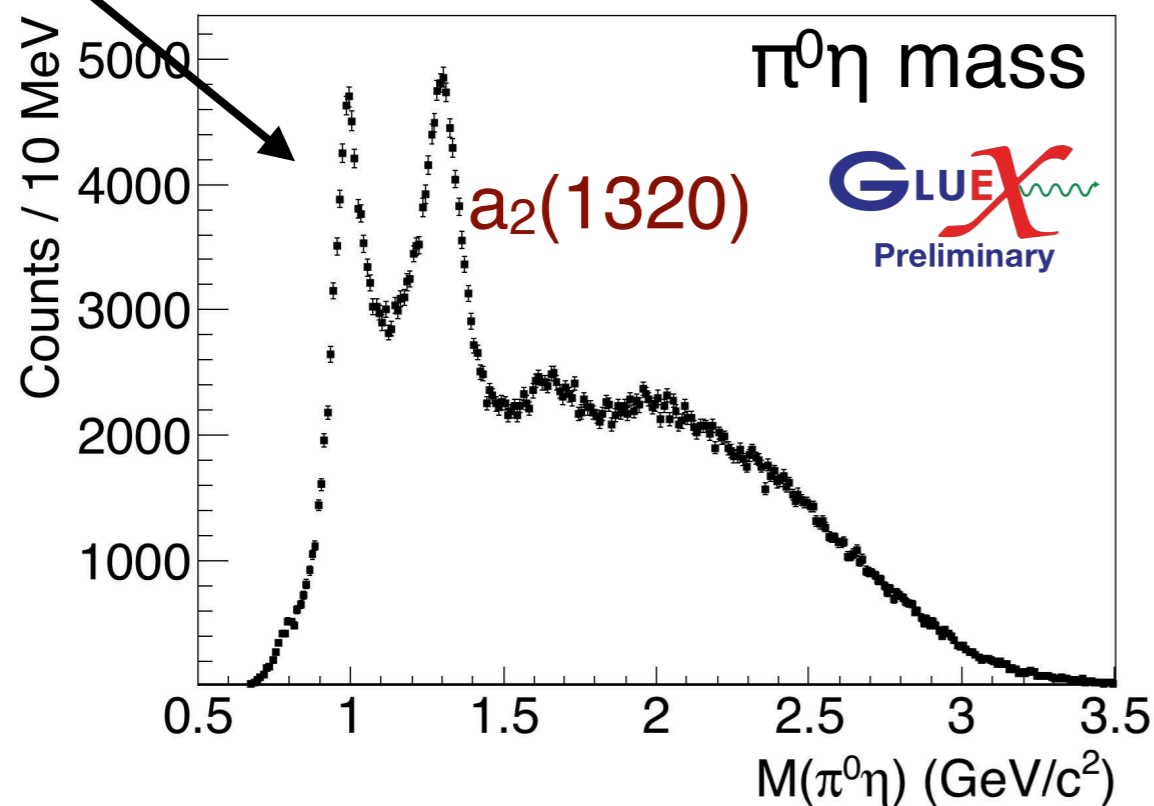
Spectroscopy Prospects: $\gamma p \rightarrow p + \pi \eta$

- $\pi \eta$ / $\pi \eta'$ promising channels for early hybrid searches
- With 20% of GlueX-I data, we see several well-known mesons
- Statistics are competitive with previous experiments

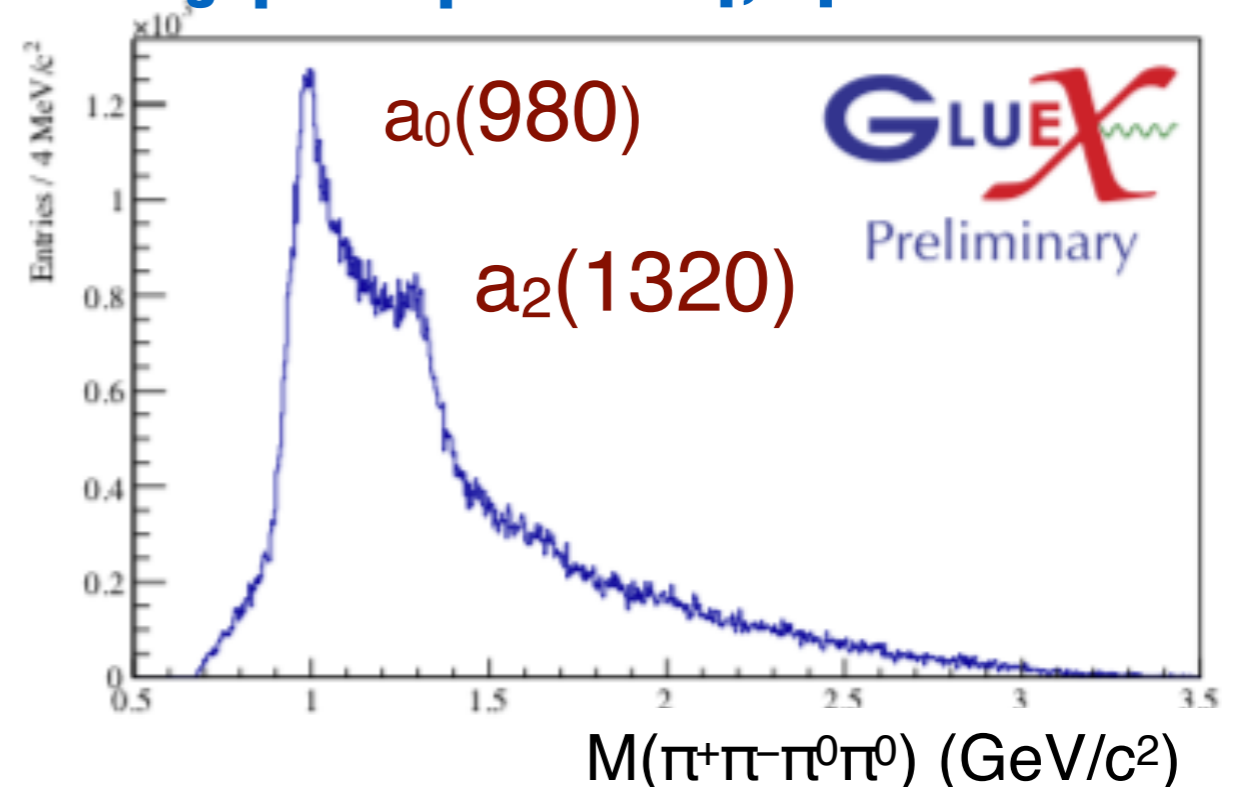
$$\gamma p \rightarrow \Delta^{++} + \pi^- \eta, \eta \rightarrow \gamma \gamma$$



$$a_0(980) \quad \gamma p \rightarrow p + \pi^0 \eta, \eta \rightarrow \gamma \gamma$$



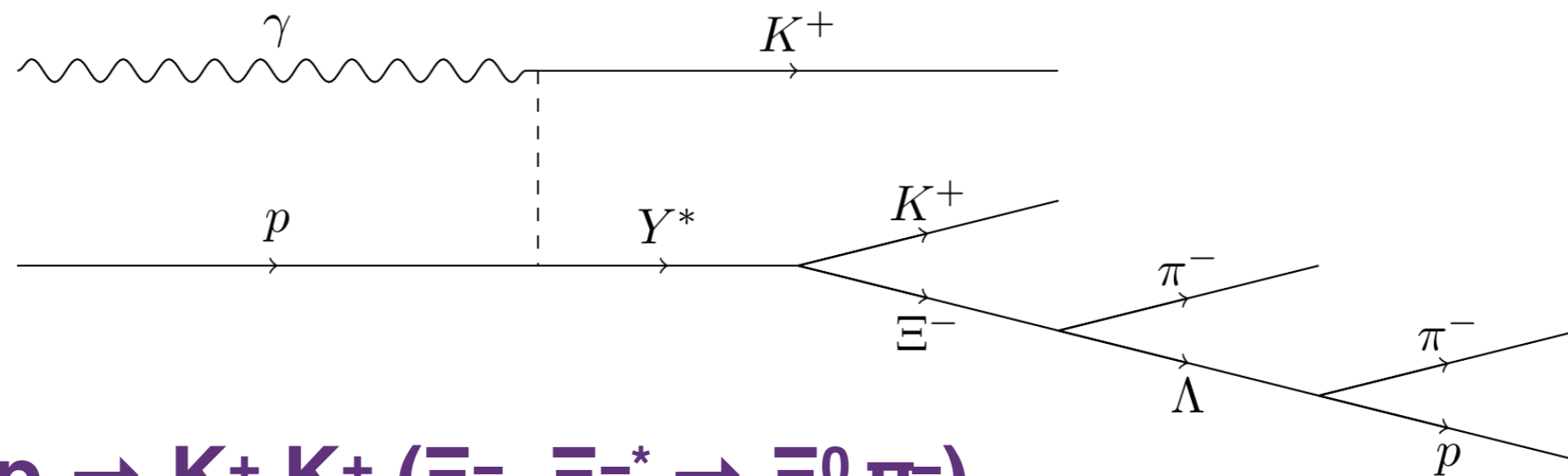
$$\gamma p \rightarrow p + \pi^0 \eta, \eta \rightarrow \pi^0 \pi^+ \pi^-$$



Prospects for Cascade Spectroscopy

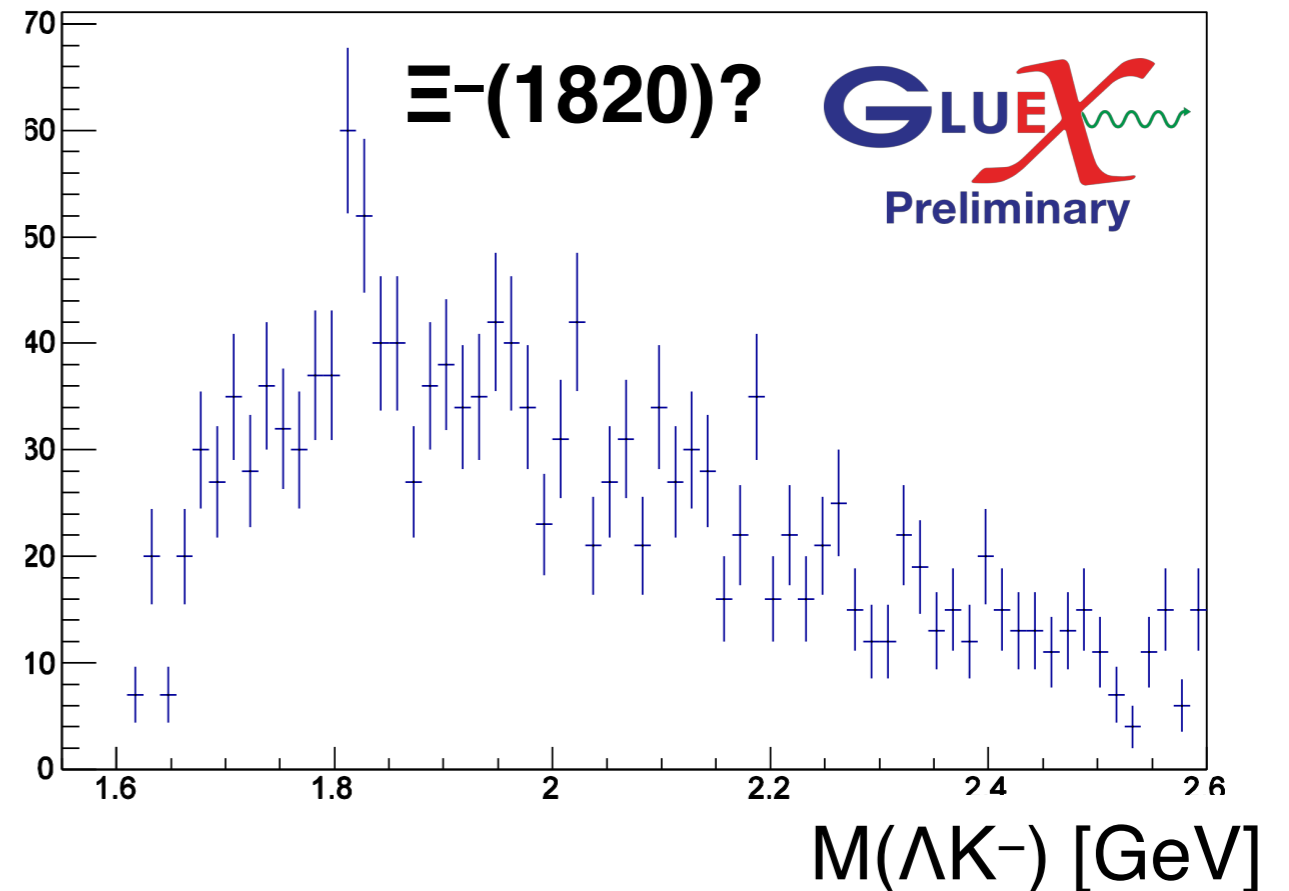
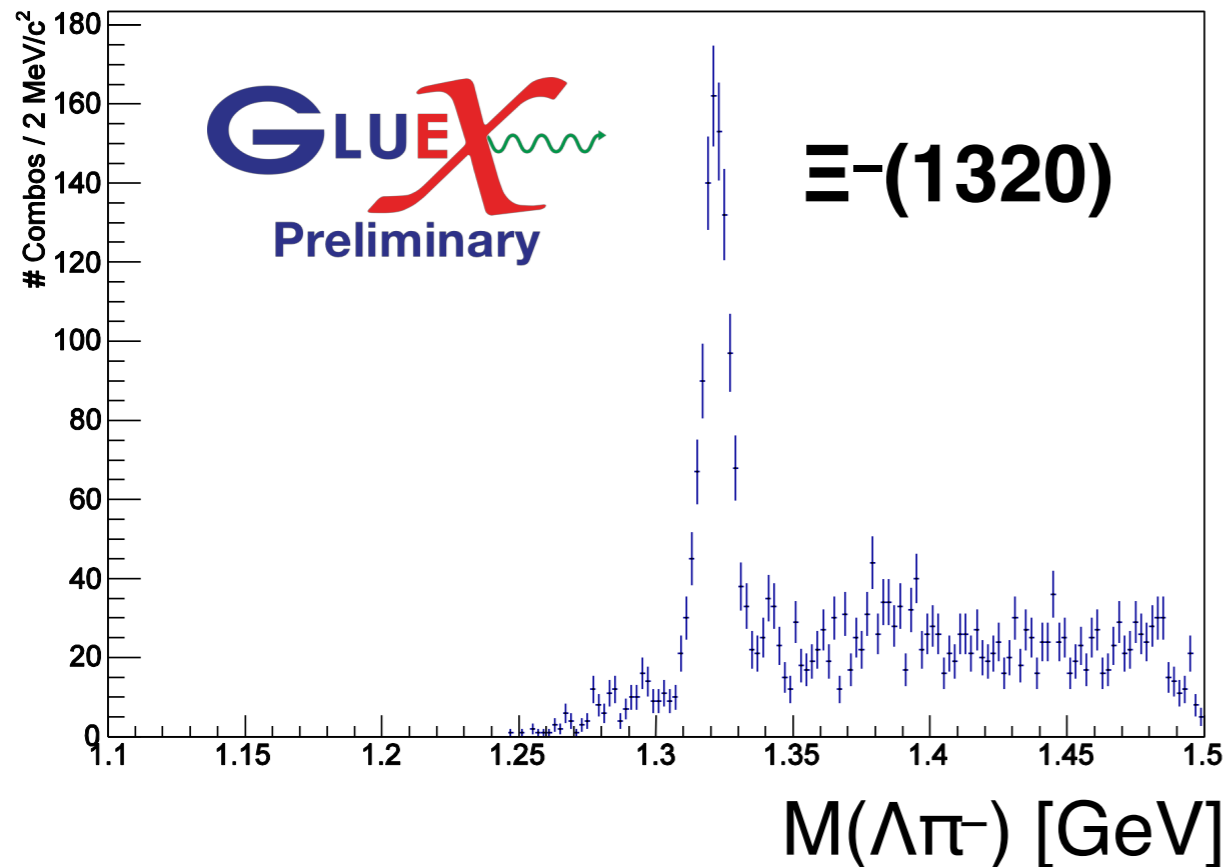
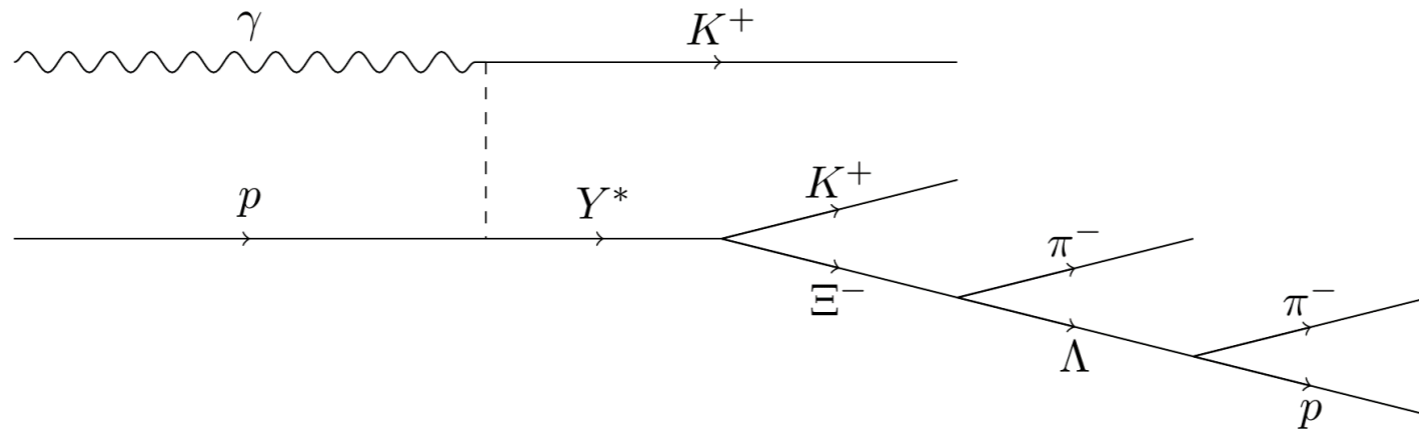
- The Cascade (ssd , ssu) spectrum is poorly known — nothing new since 1988!
 - LQCD predicts rich spectrum, many narrow states
- CLAS observed photoproduction of ground states
 - Production of excited cascades via a forward-going kaon?

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



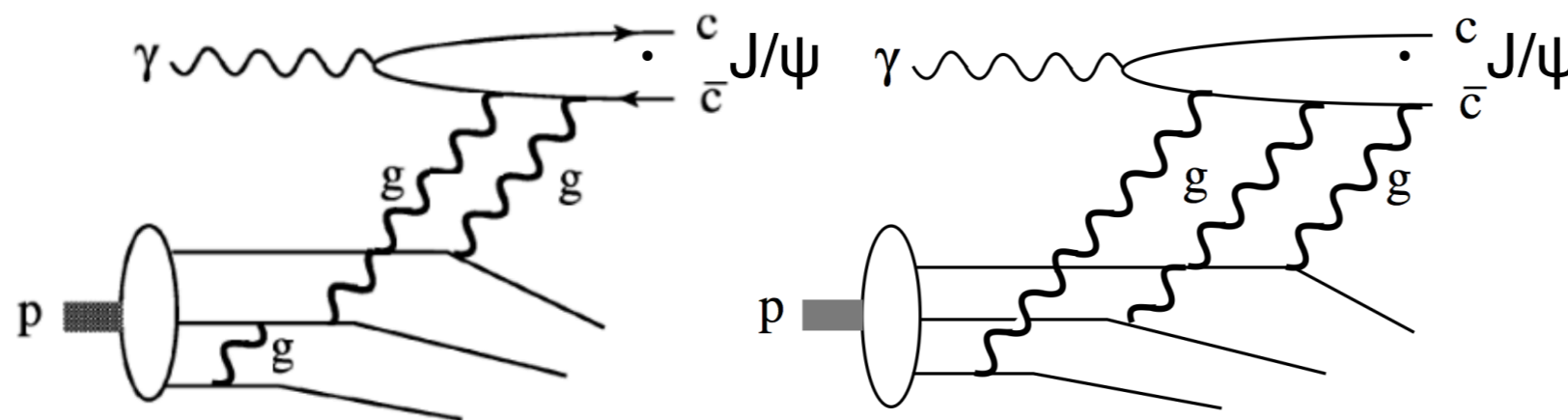
Hunting for Excited Cascades

- GlueX can reconstruct these multi-step reactions in 2017 data
- Full GlueX-I data opens door for more detailed studies



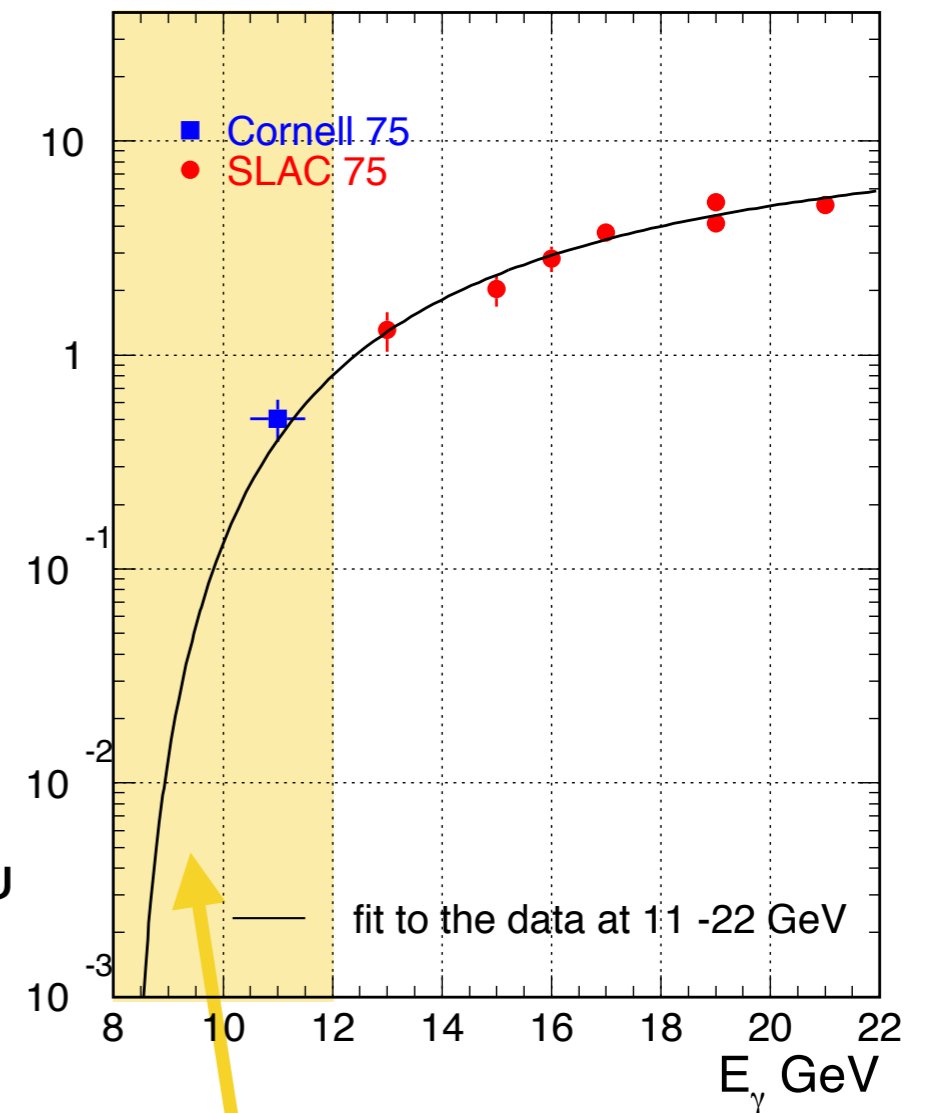
J/ψ Photoproduction Near Threshold

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



leading-twist

higher-twist

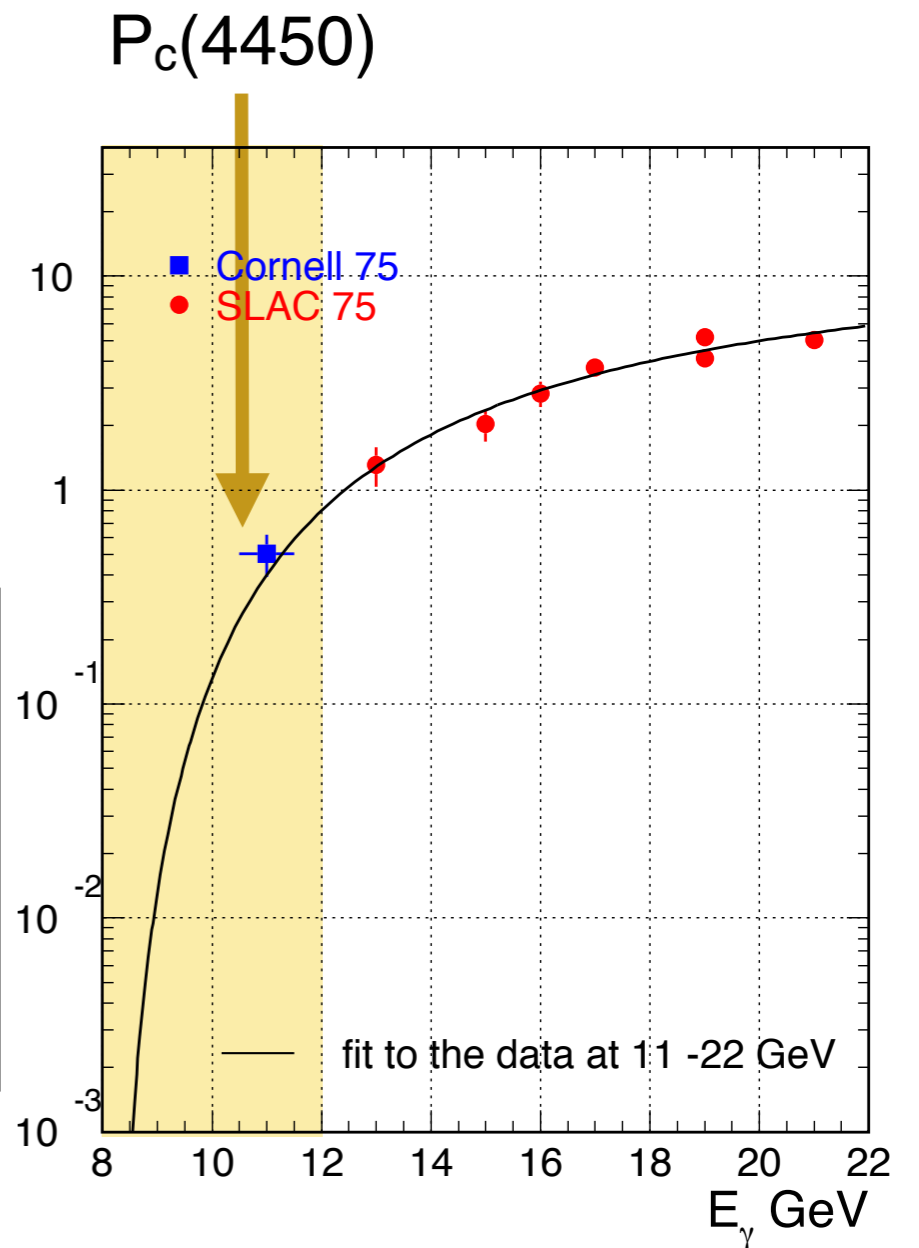
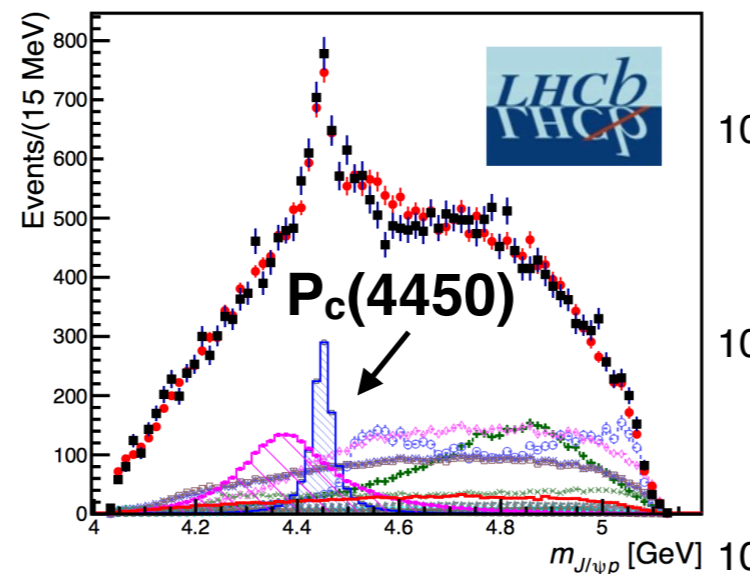
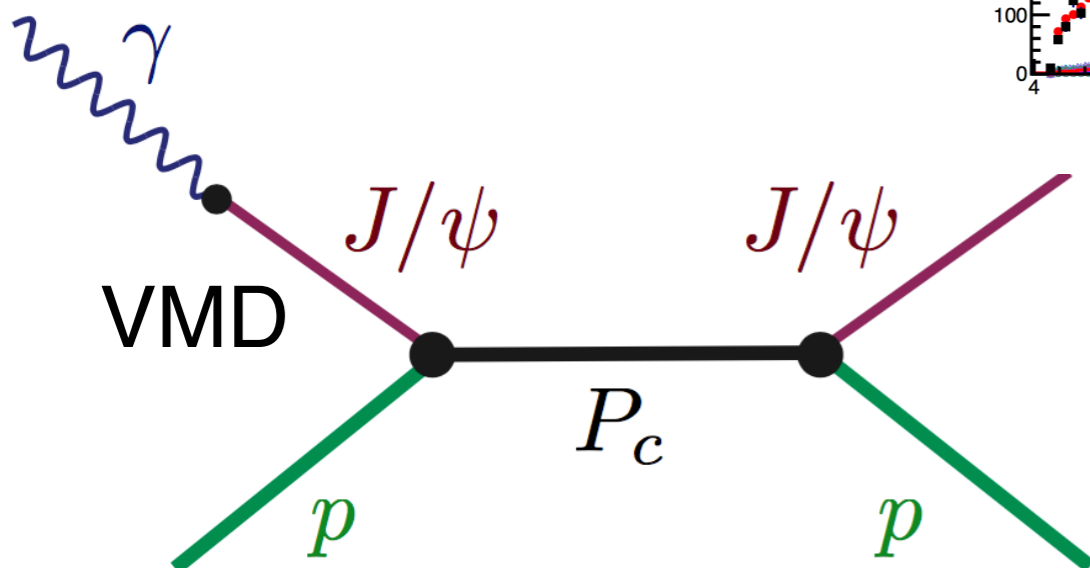


GlueX energy range

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
- P_c(4450) produced at **E(γ) ~ 10.3 GeV**

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

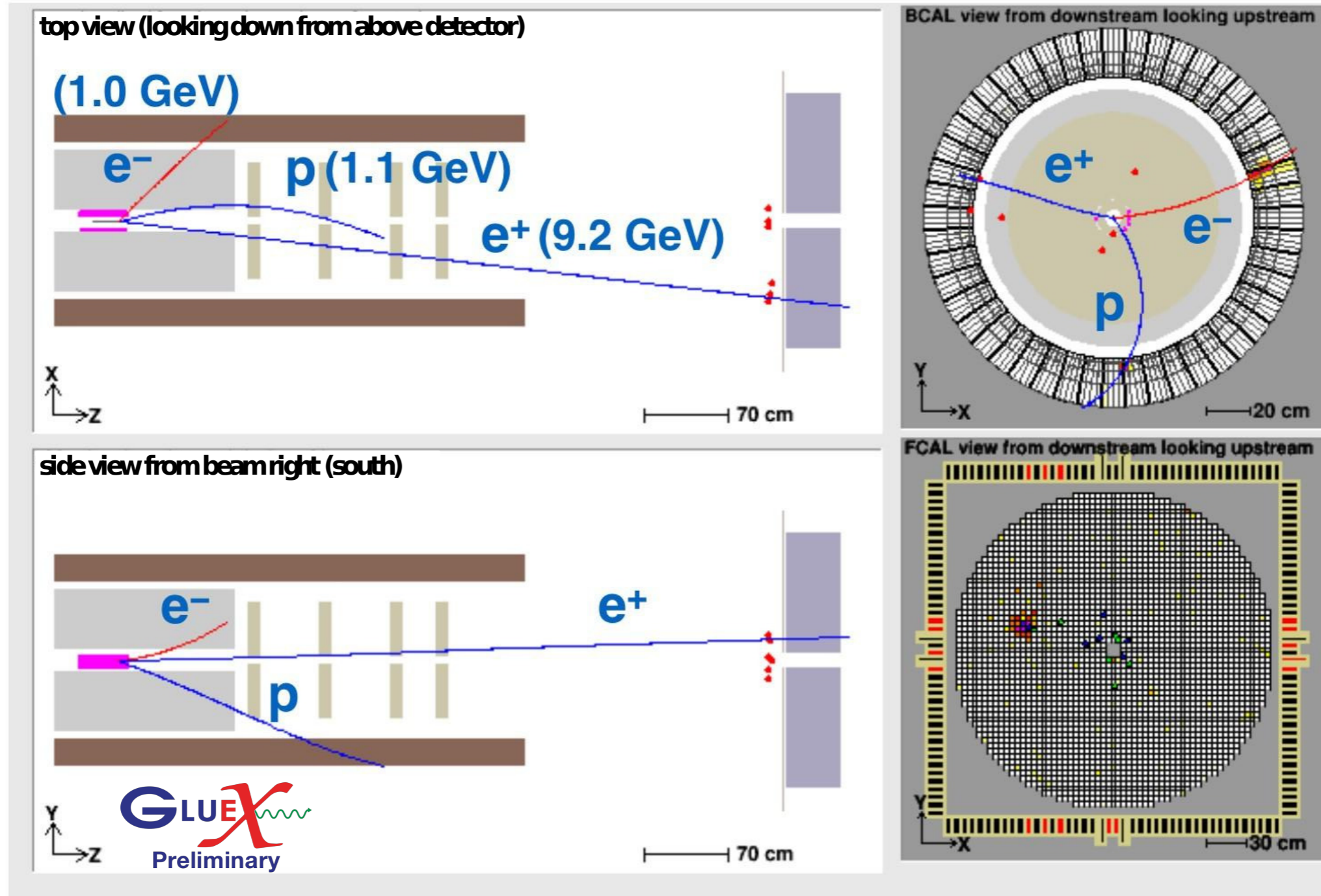


Theory papers:

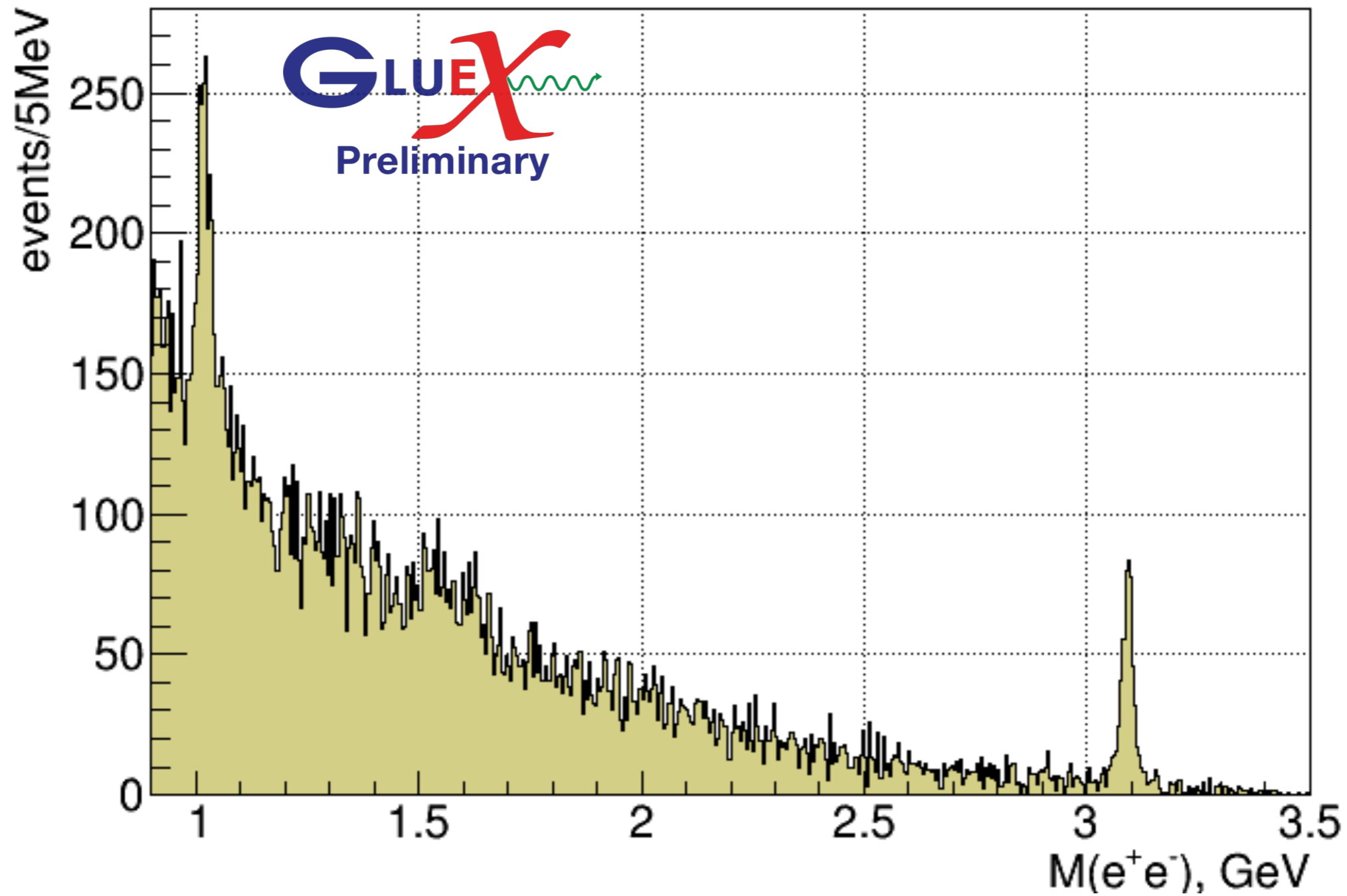
Wang, Liu, and Zhao, PRD 92, 034022 (2015).
 Kubarovsky and Voloshin, PRD 92, 031502 (2015).
 Karliner and Rosner, PLB 752, 329 (2016).
 Hiller Blin et al. (**JPAC**), PRD 94, 034002 (2016).
 and many more...

J/ψ Photoproduction at GlueX

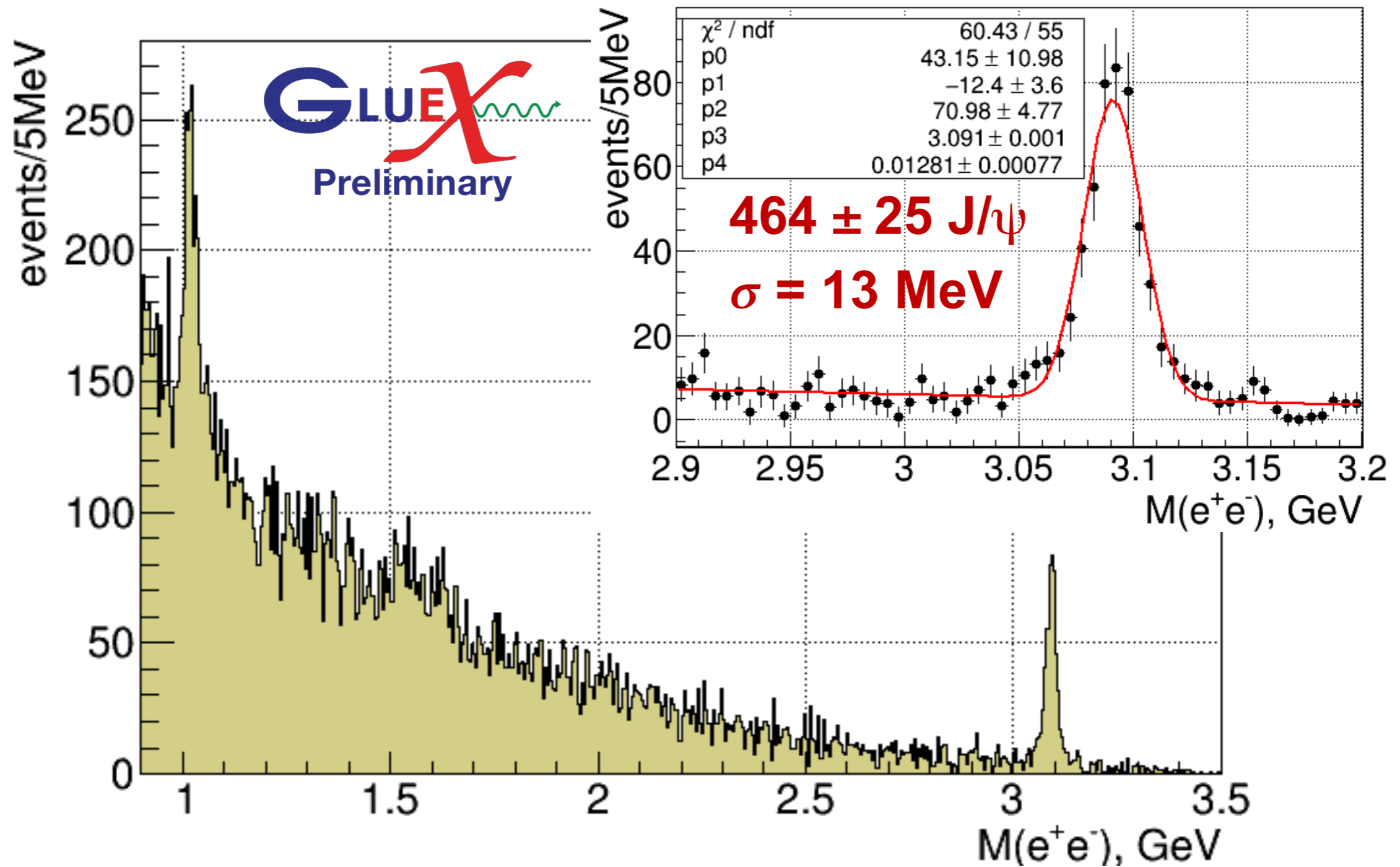
- Reconstruct $p \gamma \rightarrow p + J/\psi, J/\psi \rightarrow e^+e^-$
- Kinematically fit fully reconstructed events



J/ψ Photoproduction at GlueX: Mass Spectrum

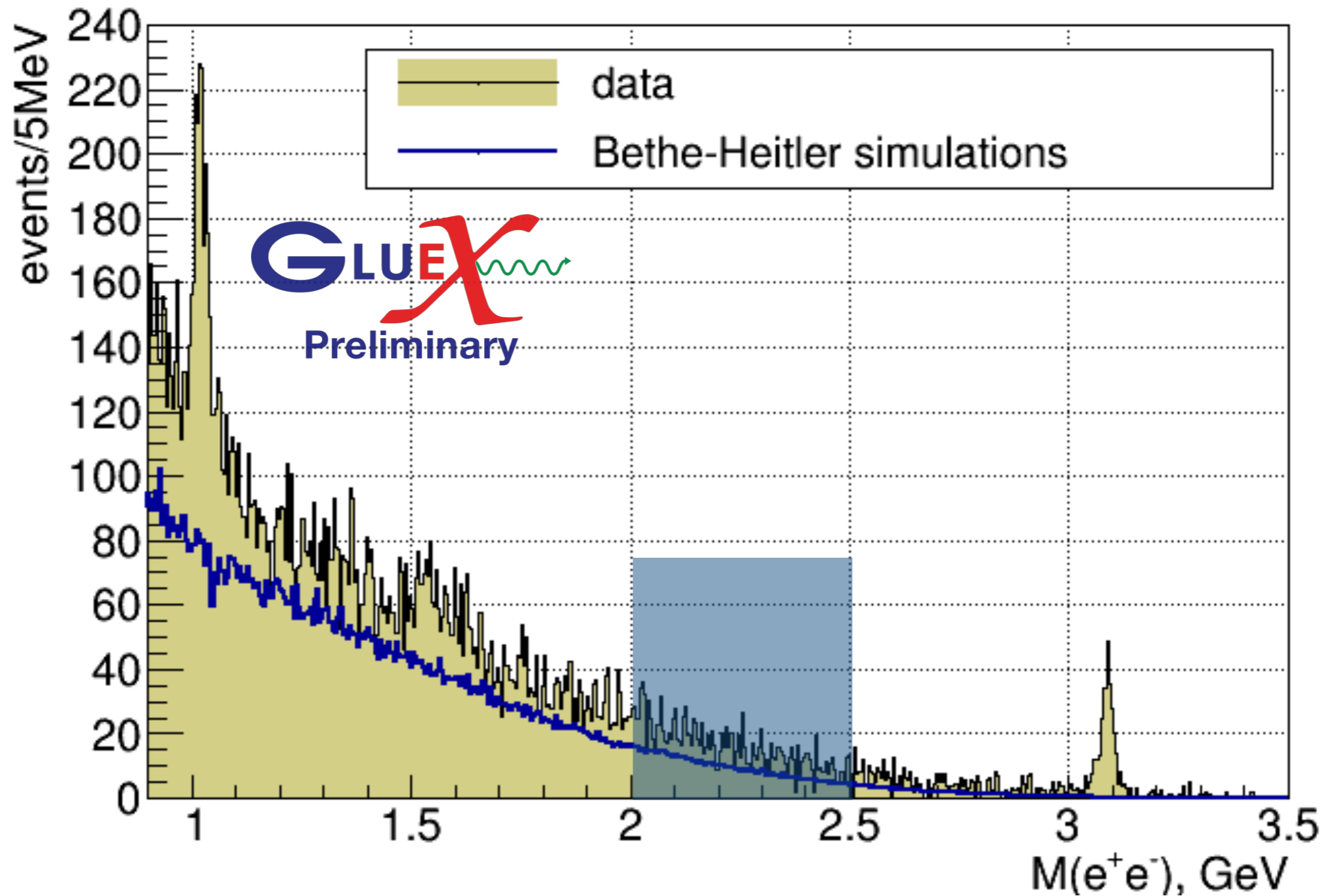


J/ψ Photoproduction at GlueX: Mass Spectrum



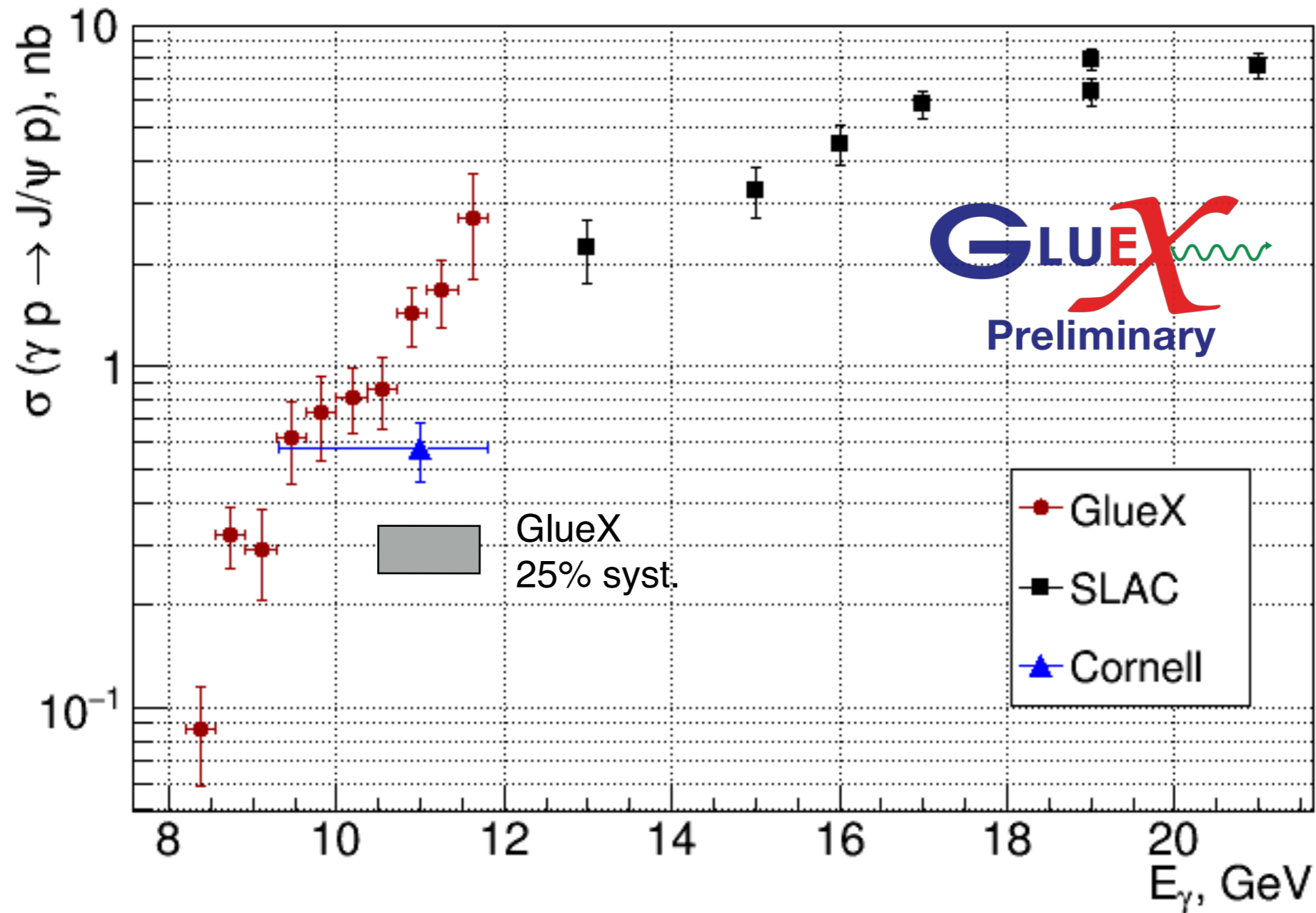
- Reconstruct $p \gamma \rightarrow p + J/\psi$, $J/\psi \rightarrow e^+e^-$

J/ ψ Photoproduction at GlueX: Mass Spectrum



- Calculate J/ψ cross sections normalized by non-resonant e^+e^-
- Absolute acceptances and efficiencies currently under study

J/ψ @ GlueX: Cross sections vs. theory



SLAC:

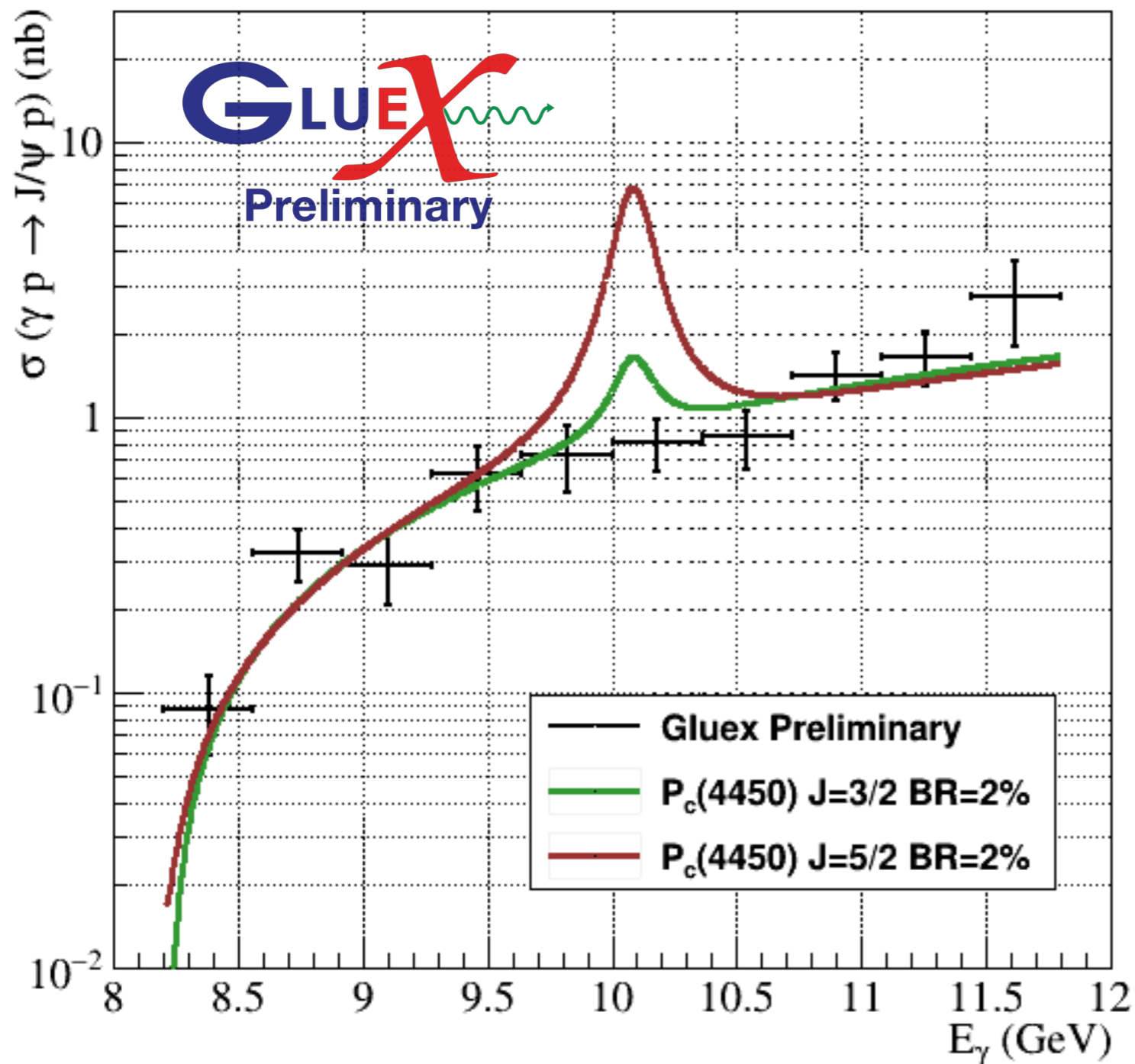
U. Camerini et al.
PRL 35, 1975

Cornell:

B. Gittelman et al.
PRL 35, 1975

- SLAC points calculated from measured $d\sigma/dt$ and dipole t -dependence
- Cornell horizontal error bars illustrate acceptance

J/ψ @ GlueX: Comparison with Pentaquark Predictions

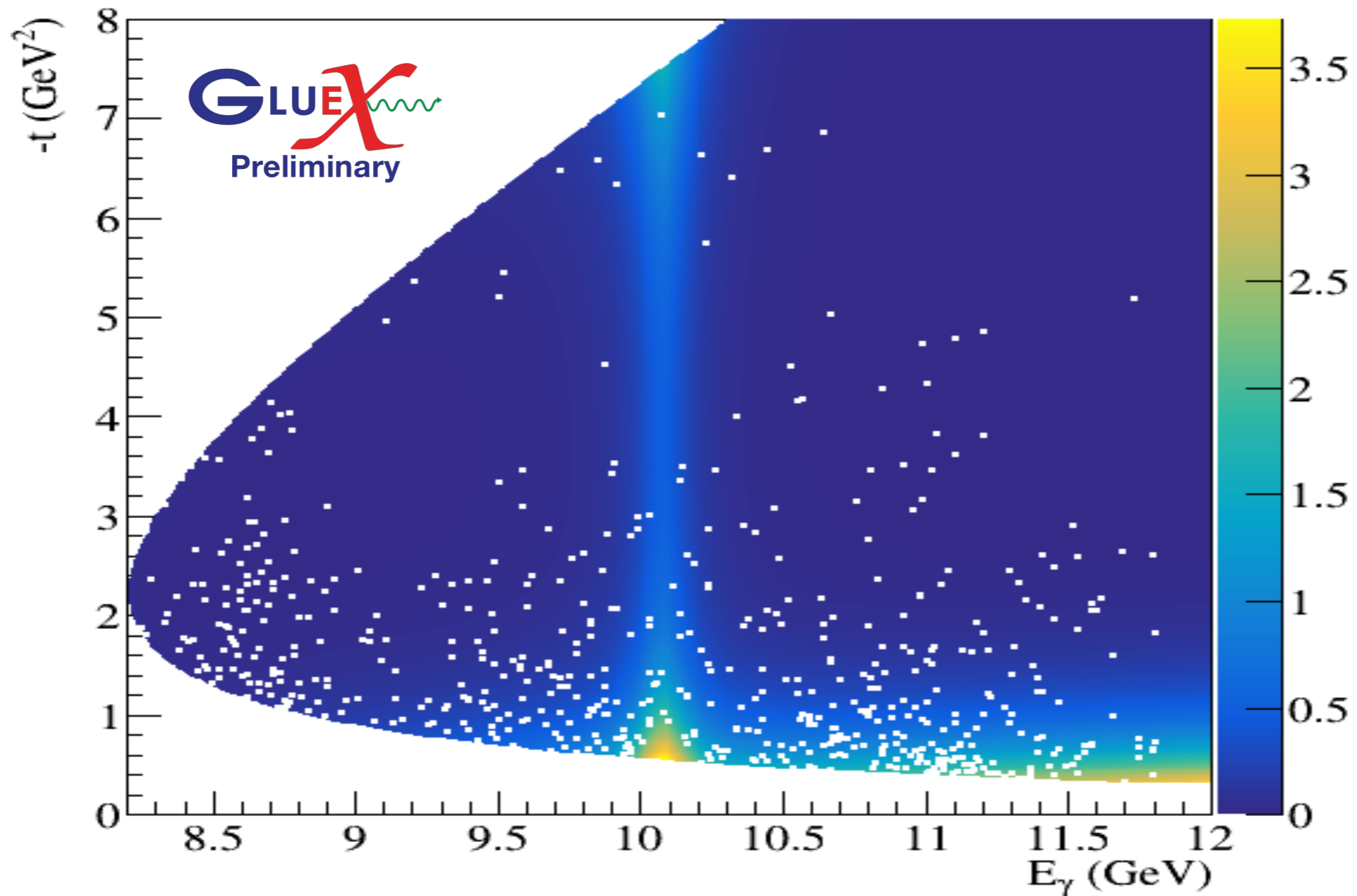


- JPAC model includes non-resonant production and pentaquark B-W via VMD
 - Sensitive to $\text{Br}(P_c \rightarrow J/\psi p)$
- Simple analysis indicates we can set limits (3σ separation) for $P_c(4450)$ production of **2% for $J^P = 3/2^-$ and less for $J^P = 5/2^+$**
- Final UL systematics will include:
 - Description of t-channel
 - Interference between s- and t-channels



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

J/ ψ @ GlueX: Unbinned $E(\gamma)$ vs. t



Not corrected
for beam
spectrum or
acceptance

No evidence
for s-channel
production

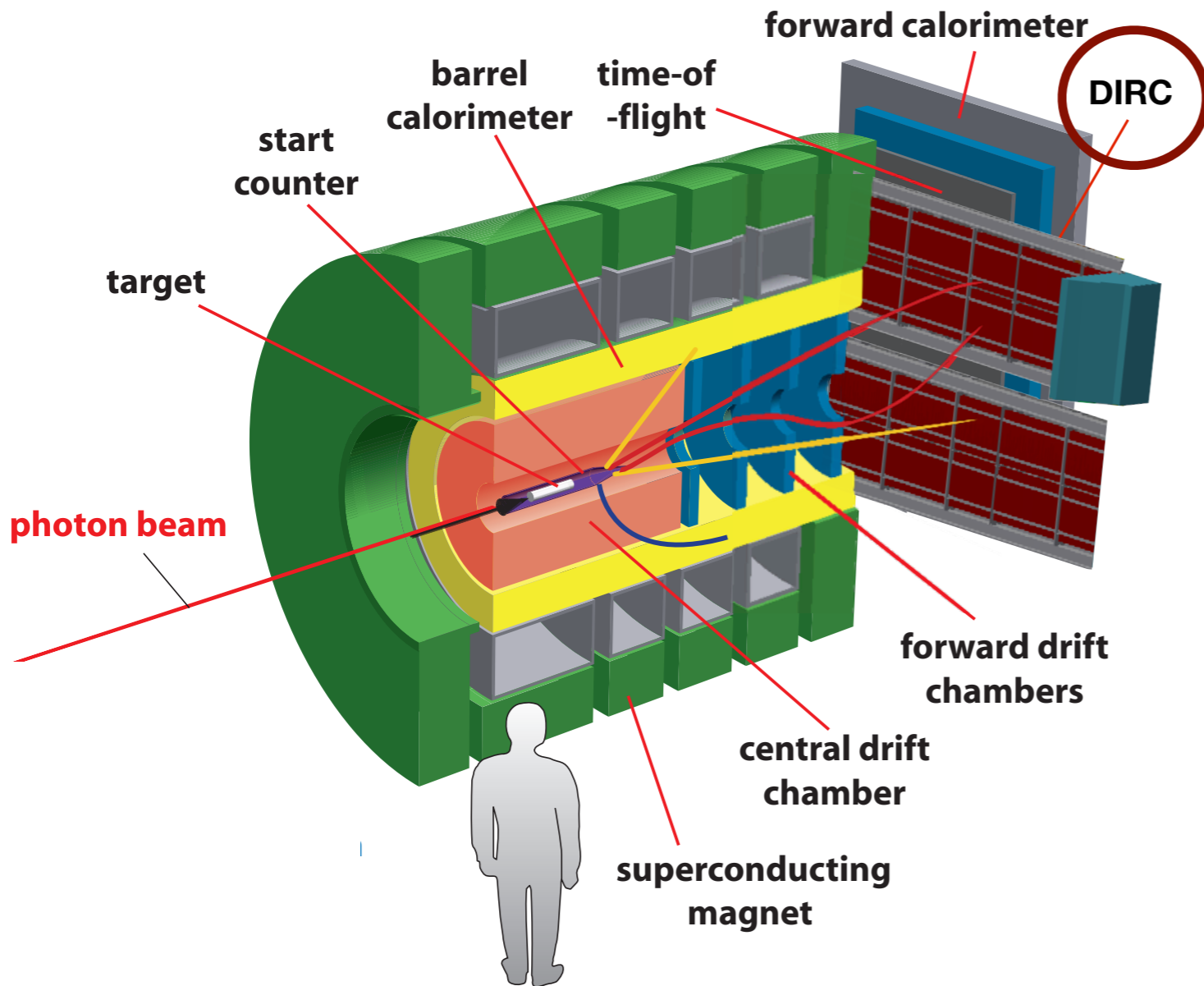
- JPAC model: 2% $P_c(4450)$, $J^P = 5/2^-$
- Points: GlueX data in J/ψ mass region

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

GlueX-II: Enter the DIRC



SLAC NATIONAL ACCELERATOR LABORATORY

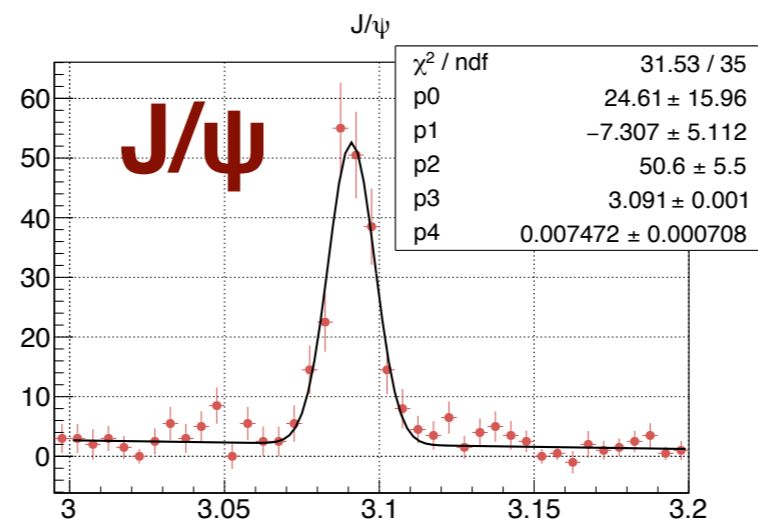
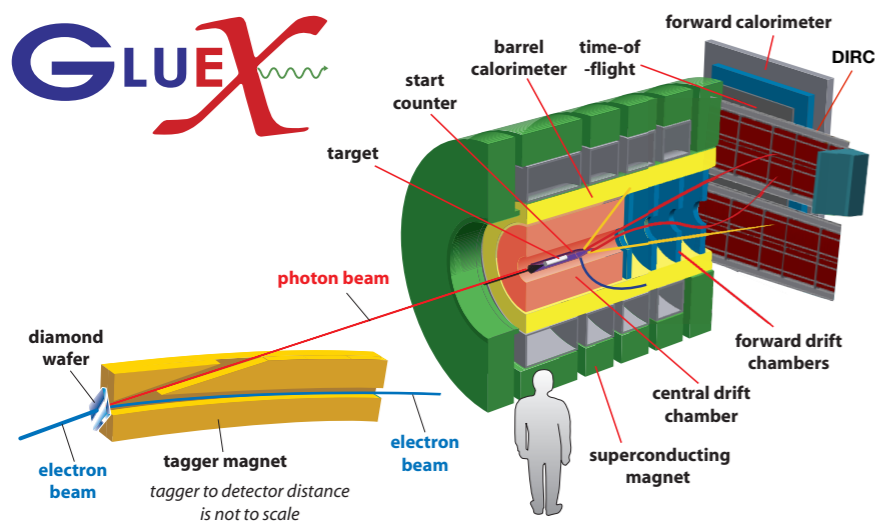


Jefferson Lab

- 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

Summary

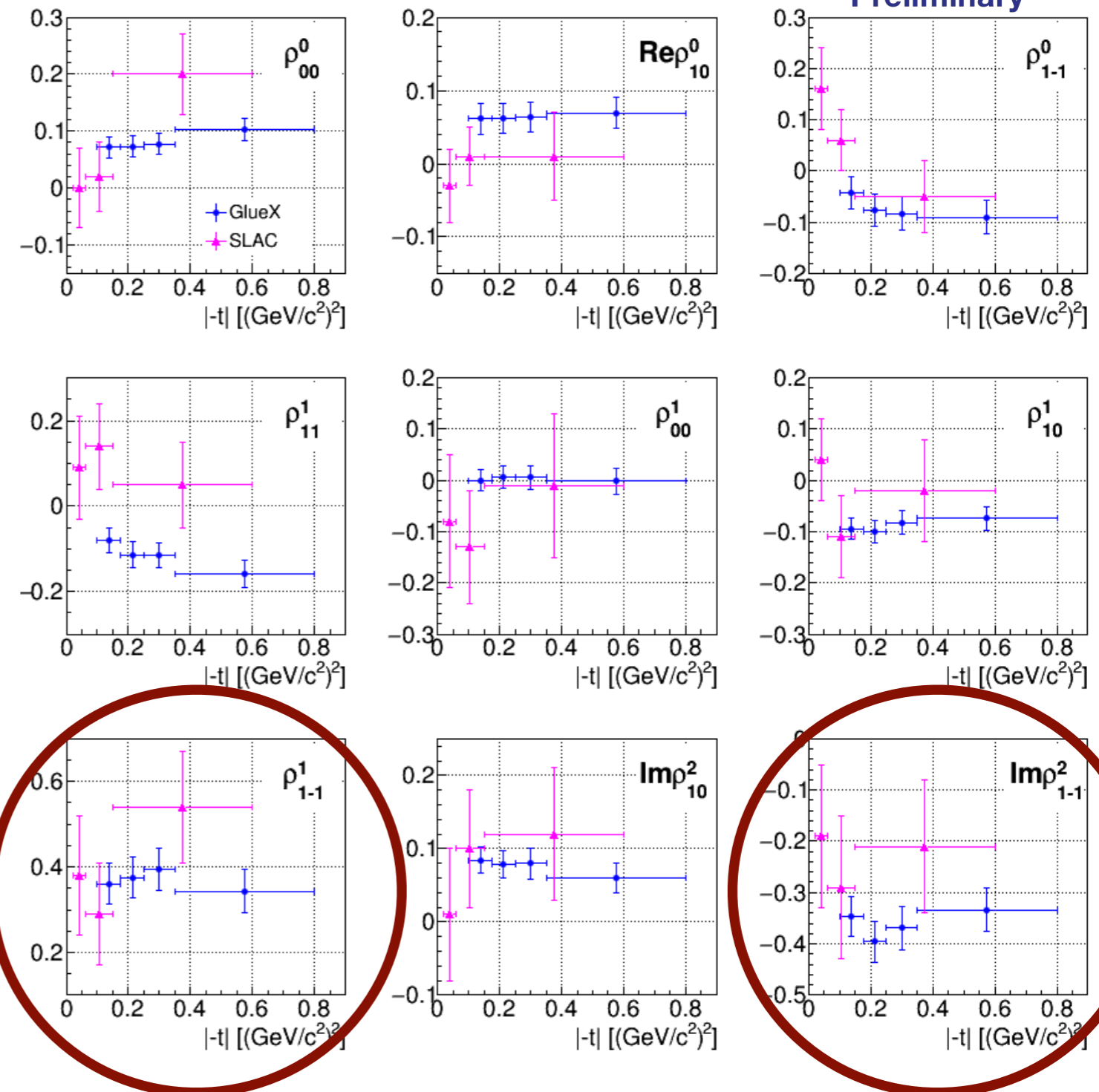
- GlueX has started mapping the **normal** meson spectrum!
First step towards establishing the **hybrid** meson spectrum.
- **Phase I** run completed, program of production & cross section measurements well underway
- Initial running will focus on spectroscopy of up/down quark states, initial studies of J/ψ and other rare processes
- High-luminosity running will begin this year, extend reach to strange-quark states.
- A rich physics program is underway!



Backup Slides

Spin Density Matrix Elements (SDMEs): $\gamma p \rightarrow p + \omega$

- SDMEs measure the transfer of polarization from the photon to the vector meson
- Two matrix elements are particularly 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 full GlueX-I data
- $\gamma p \rightarrow p + \phi$ and $p + \rho$ also under analysis



Spectroscopy Prospects: $\gamma p \rightarrow p + \eta \pi^+ \pi^-$

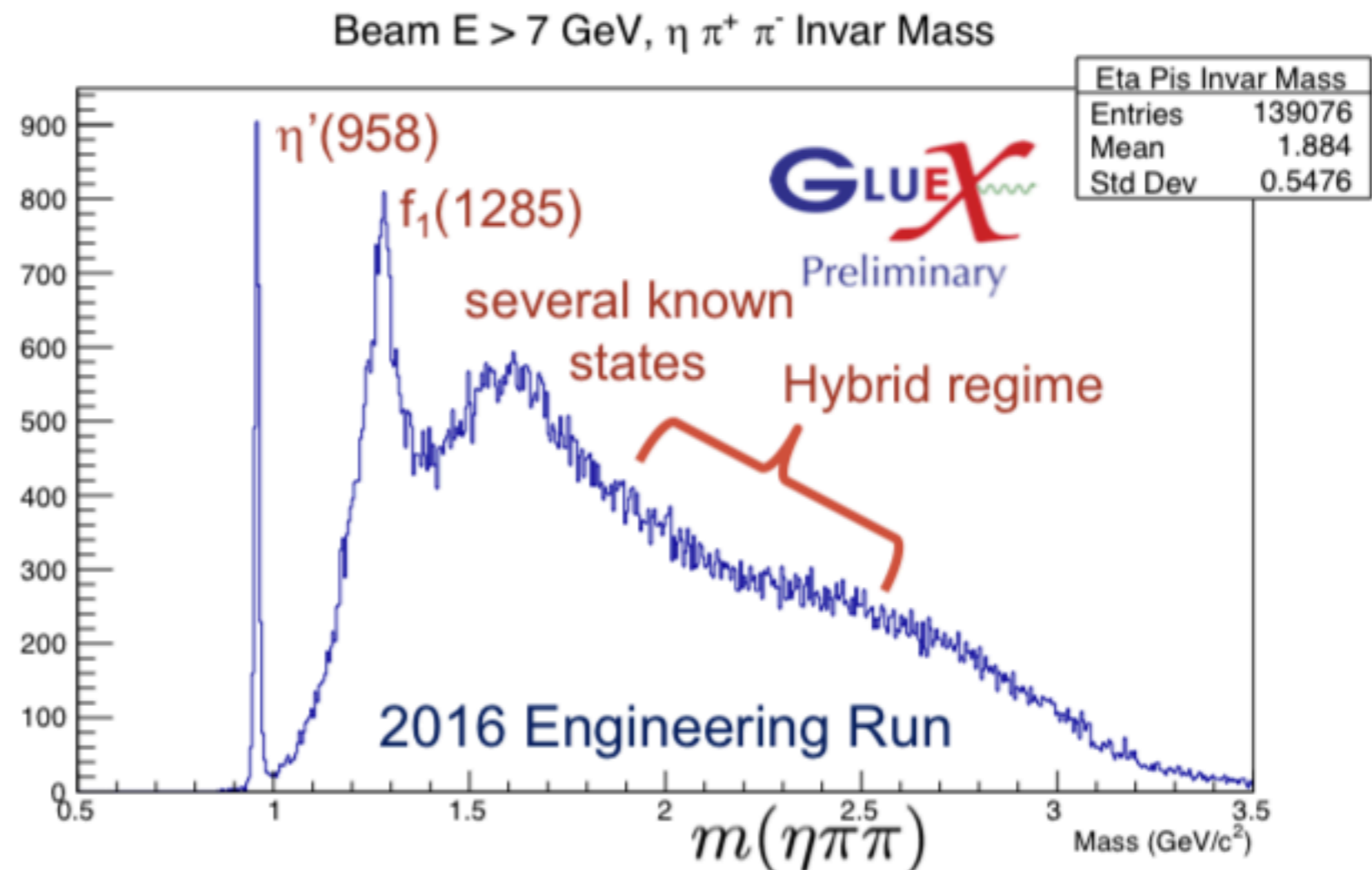
- Large sample of multiparticle decays collected as well
 - Example: $\eta \pi^+ \pi^-$ can have contributions from η_1 and b_1 hybrids
- Will analyze with models built from experience with 3-body reactions

Contributions from:

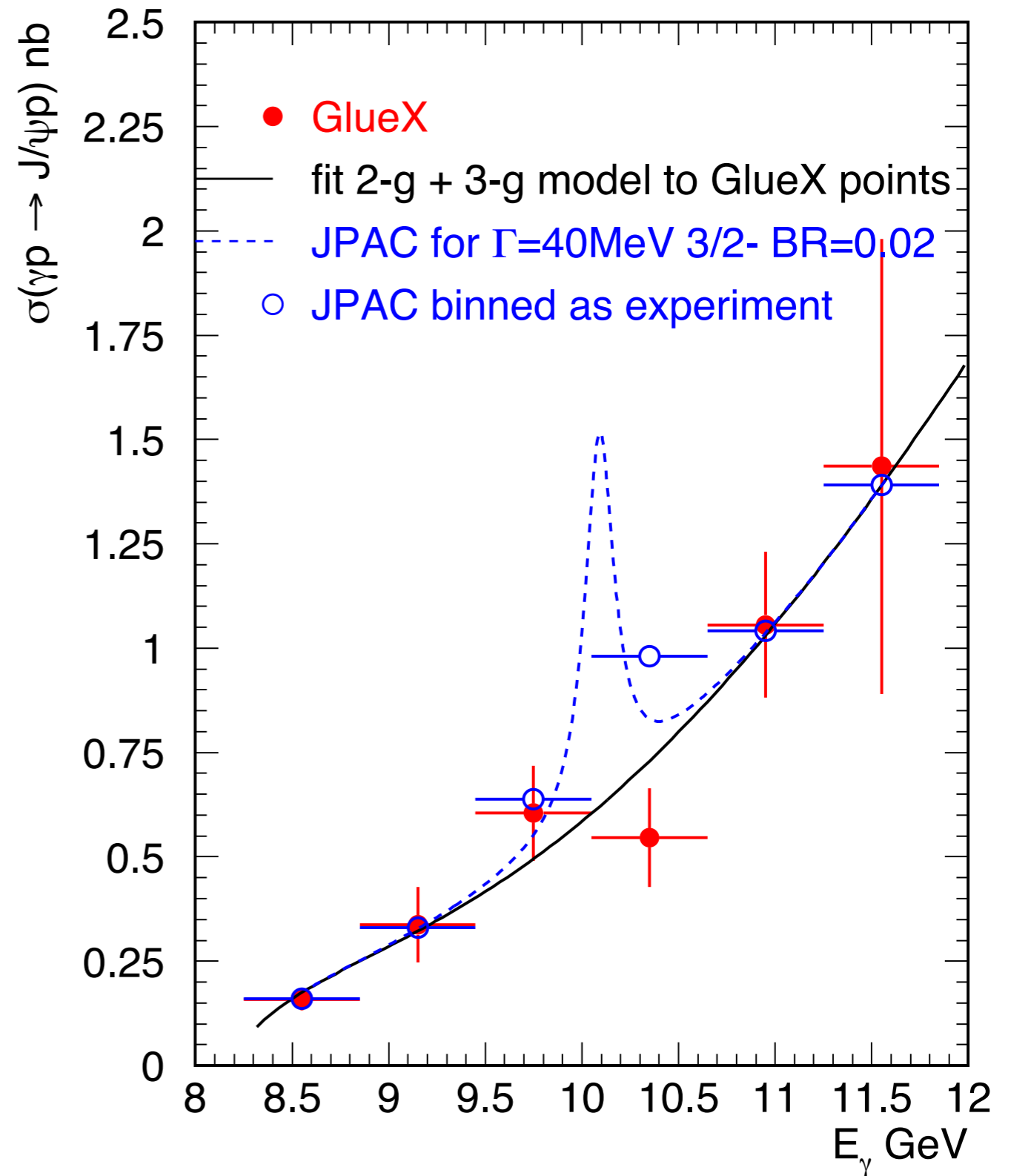
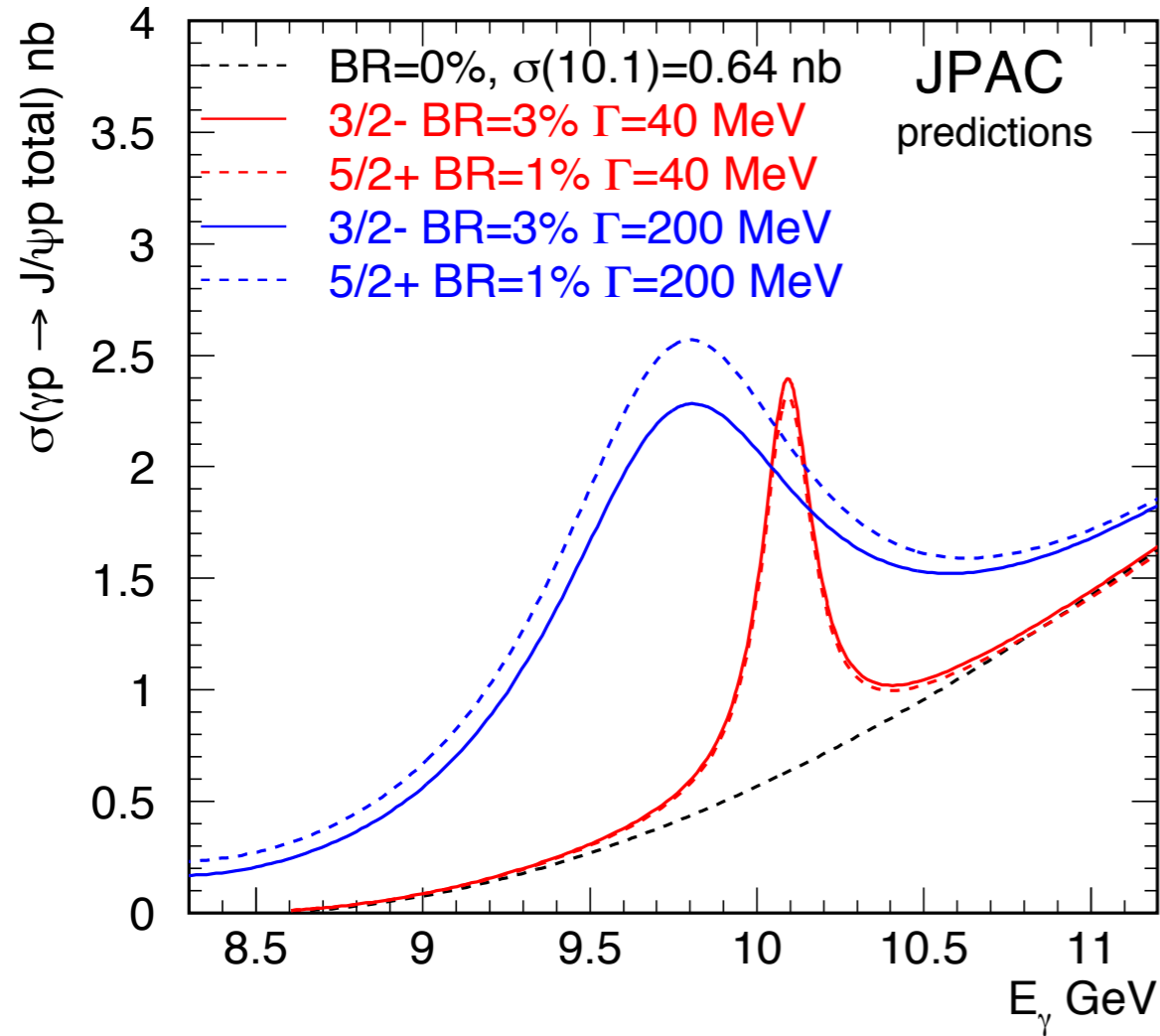
$$\gamma p \rightarrow p a_2^\pm \pi^\mp$$

$$\gamma p \rightarrow p f_2 \eta$$

$$\gamma p \rightarrow p \rho \eta$$

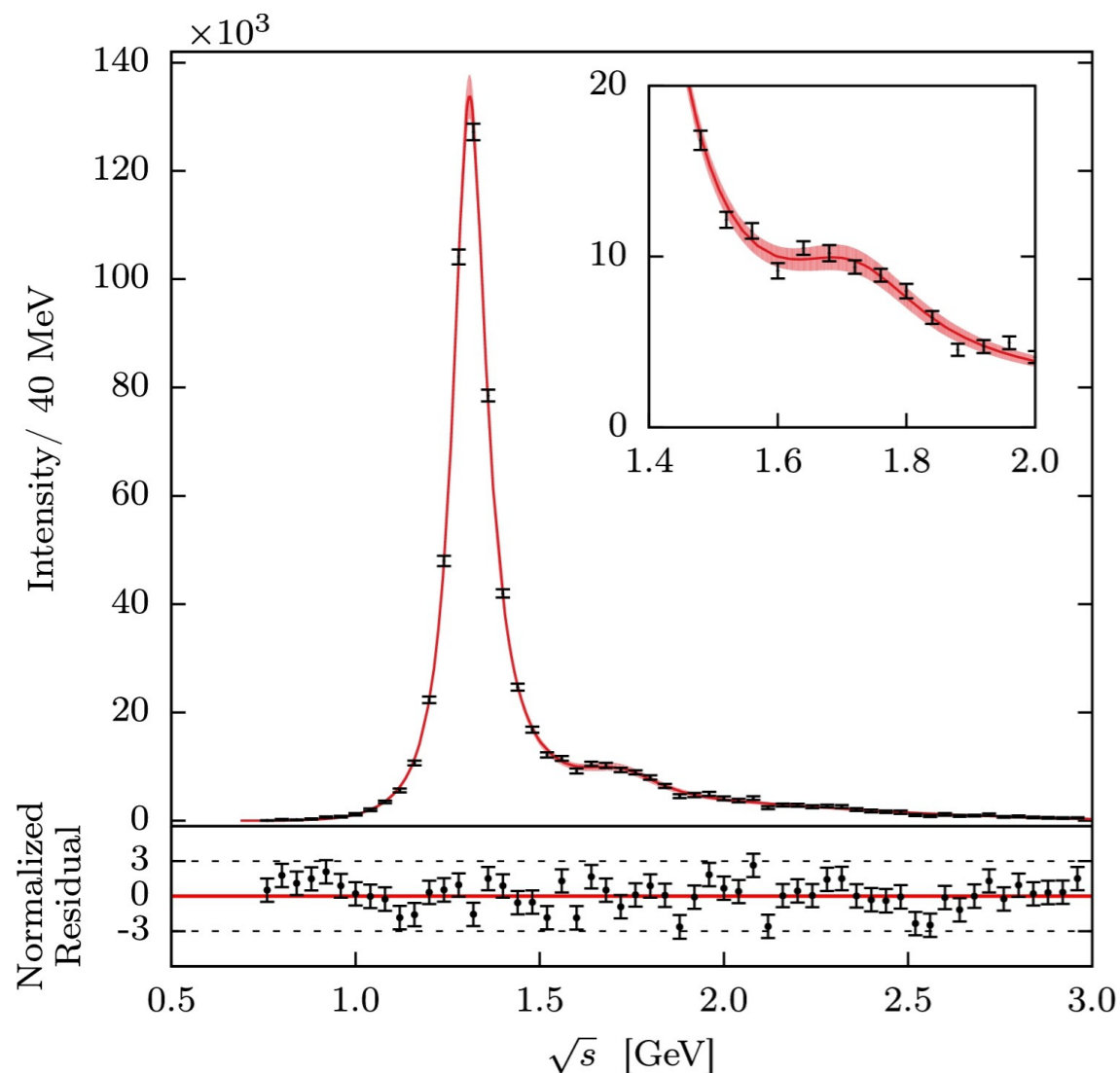


J/ψ Photoproduction at GlueX — Pentaquark Production



Sidebar: Experiment and Theory Working Hand-in-Hand

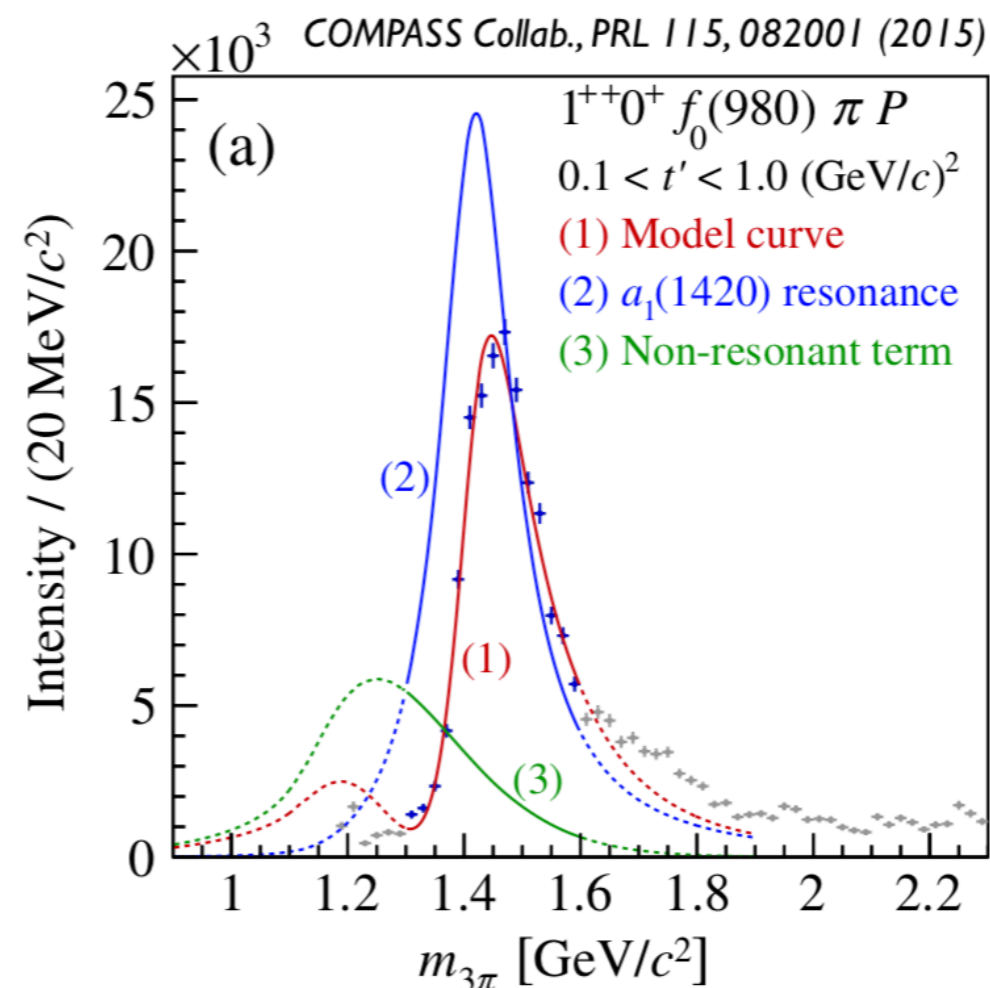
D-wave in $\pi p \rightarrow p \eta \pi^-$



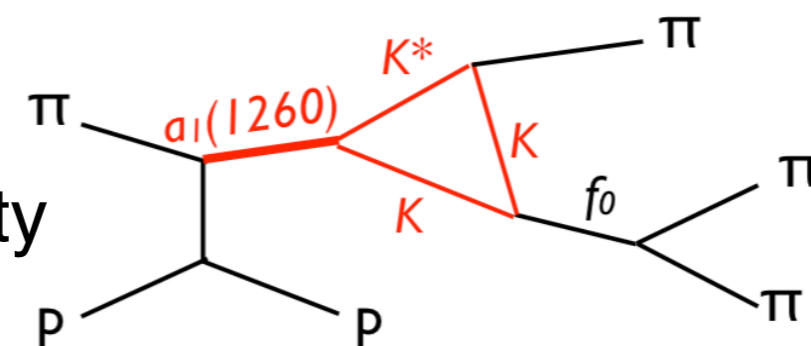
Extract resonance parameters with unitary reaction model

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

$a_1(1420) \rightarrow f_0(980) \pi$



Describe non-qq candidate as triangle singularity



M. Mikhasenko et al. [JPAC and COMPASS Collaborations], in preparation

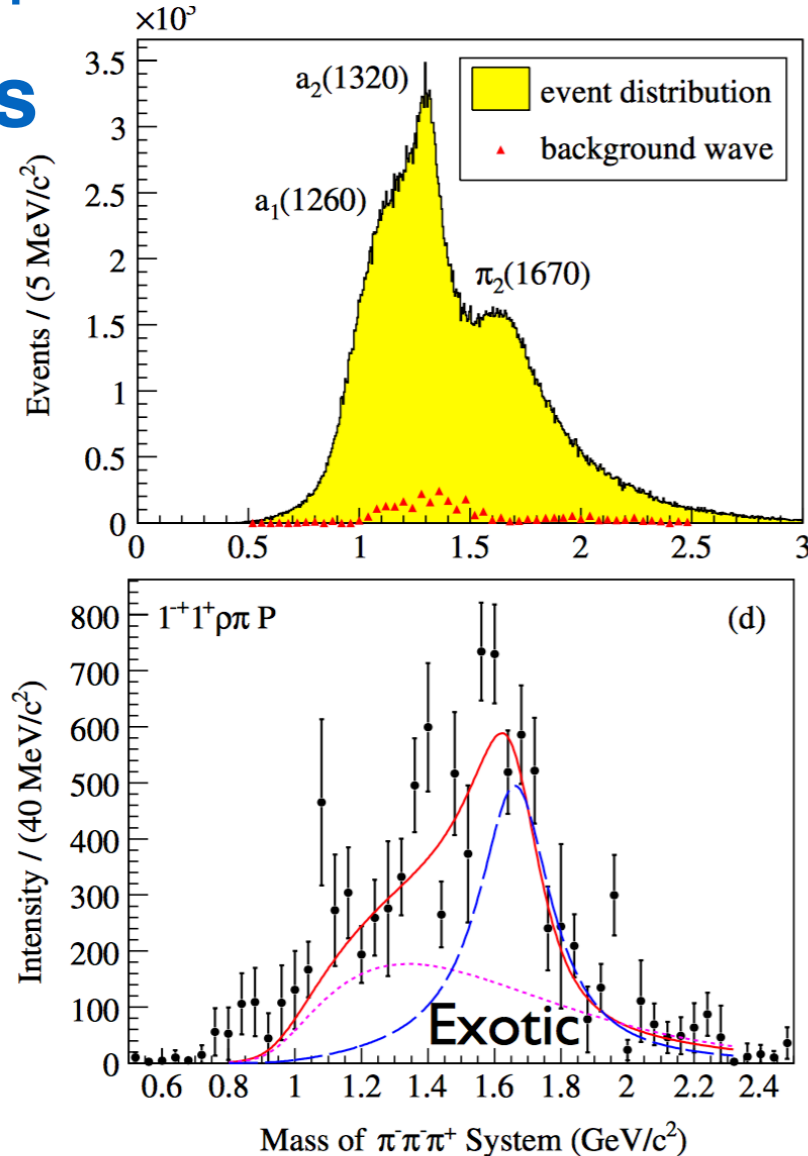
Evidence for exotic light-quark mesons

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

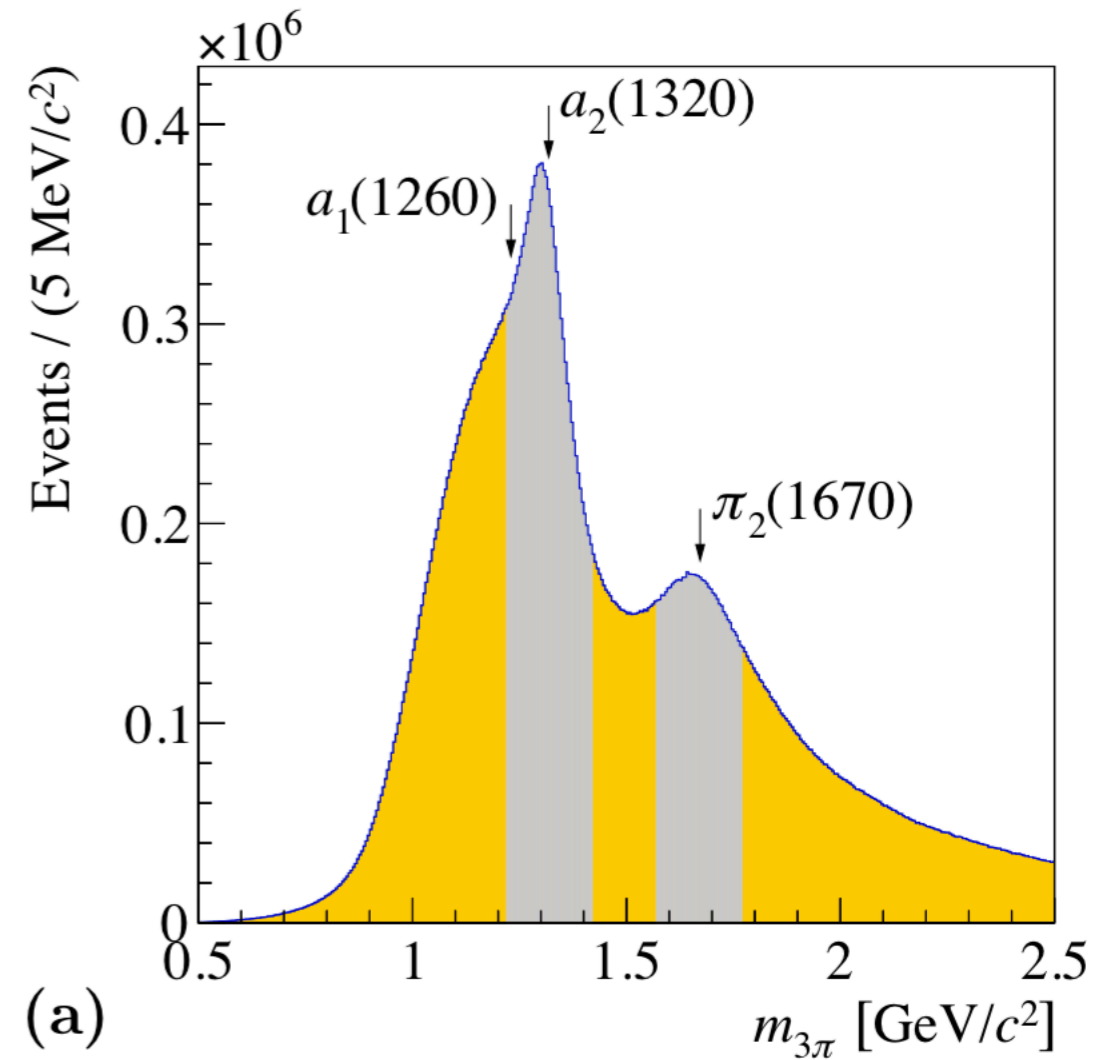
420k
 $\pi^-\pi^-\pi^+$
events

$$\pi_1 \rightarrow \rho\pi$$

COMPASS: 190 GeV π on Pb



50M $\pi^-\pi^-\pi^+$ events

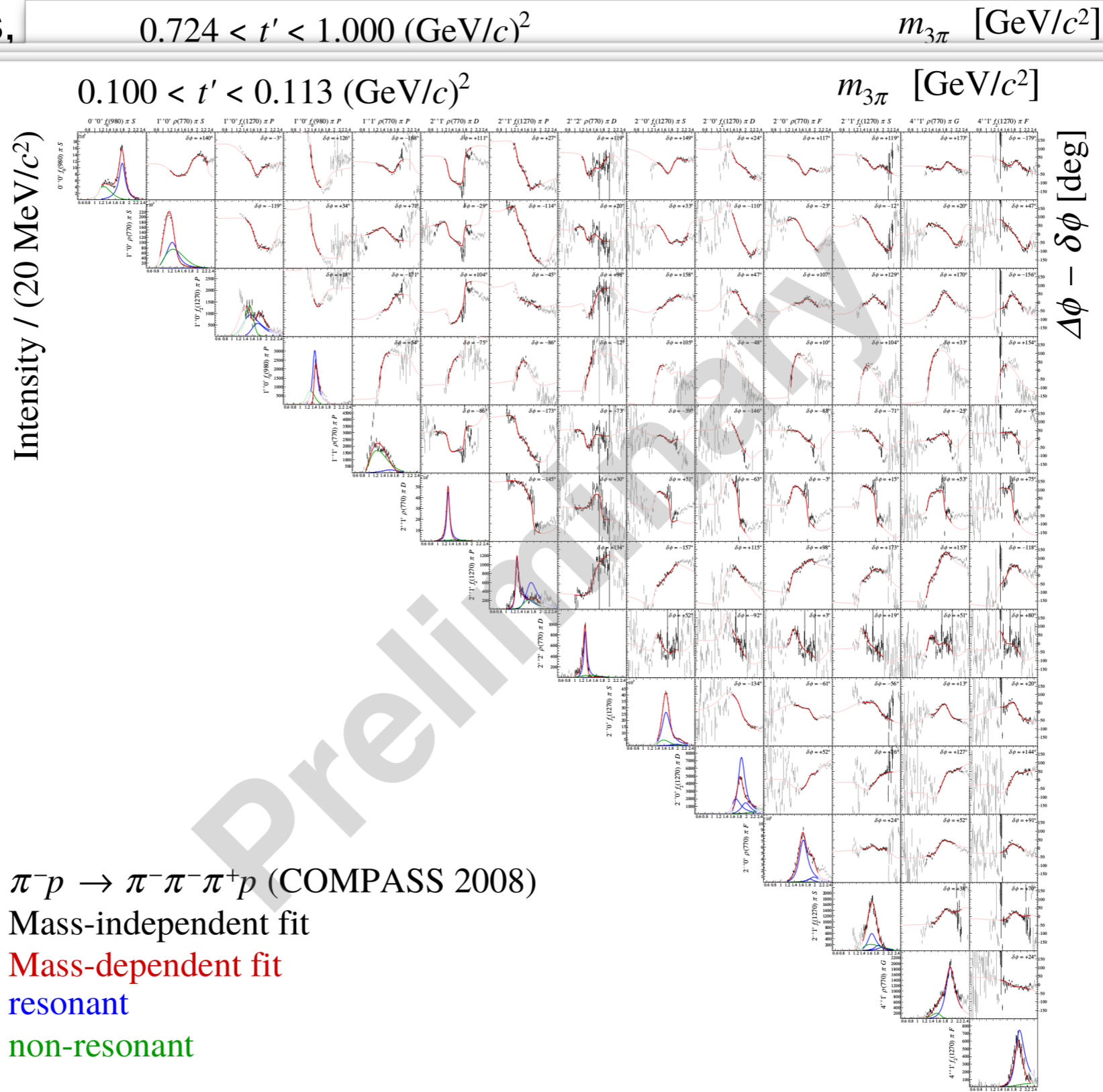
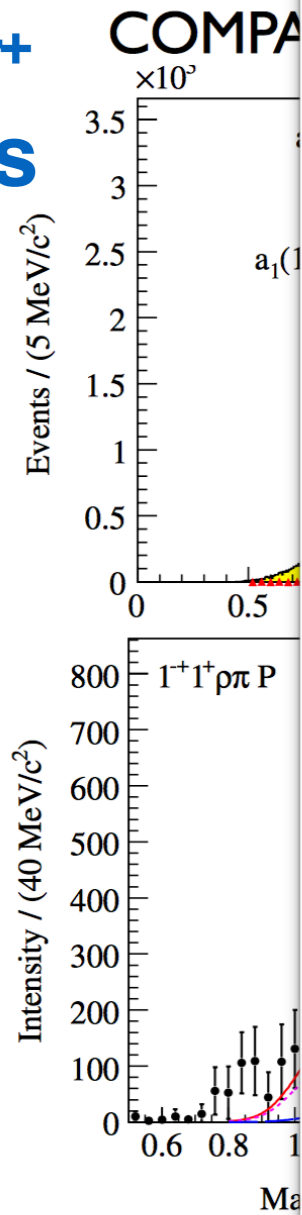


PRD 95, 032004 (2017)

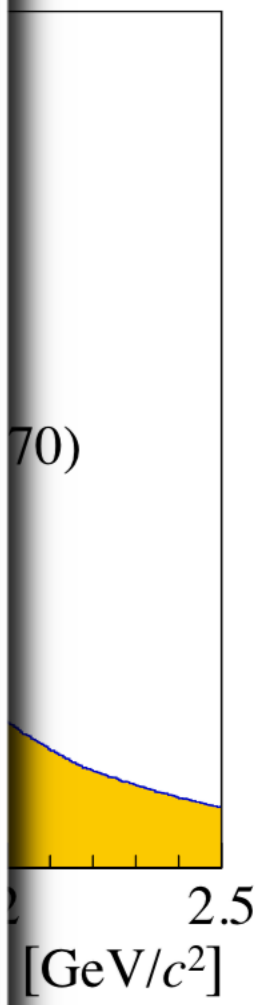
Evidence for exotic light-quark mesons

- Many searches,
- Resonance c

420k
 $\pi^-\pi^-\pi^+$
events



ents



COMPASS: PRL 1

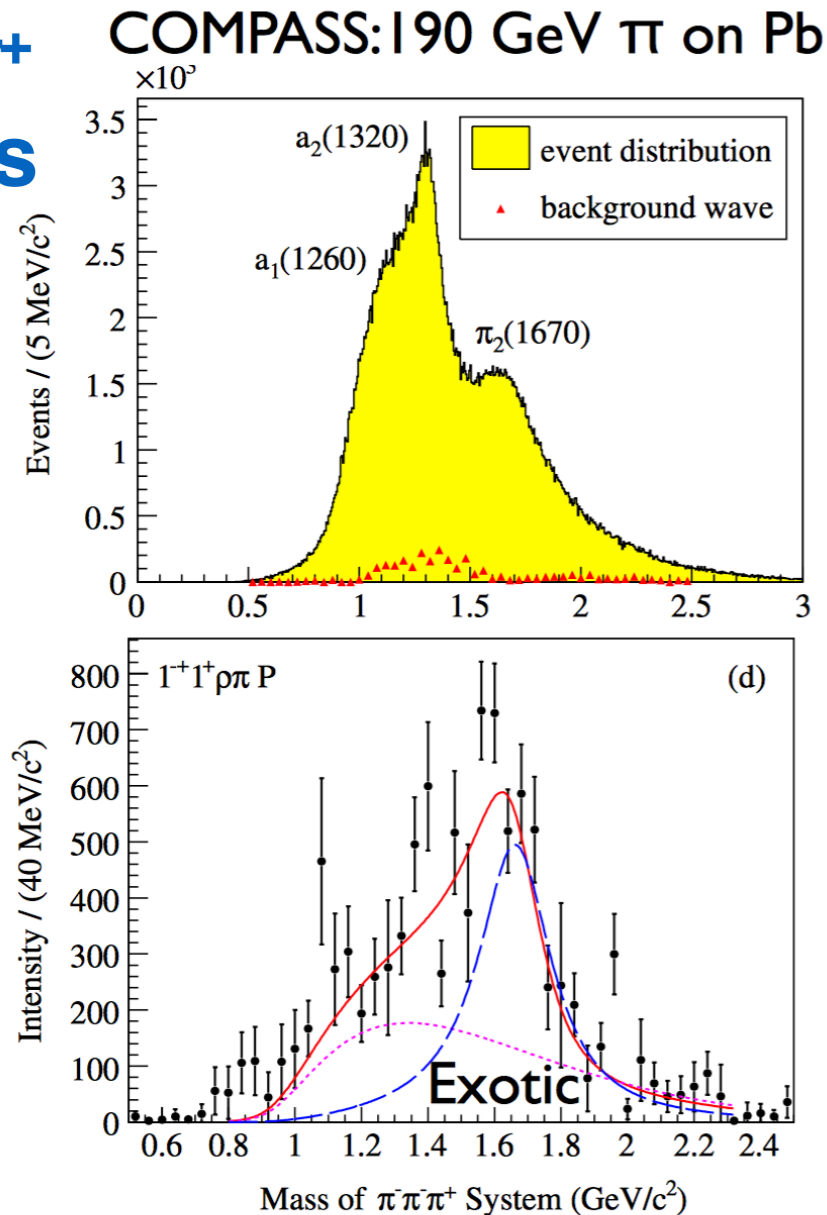
0+7' bin

Evidence for exotic light-quark mesons

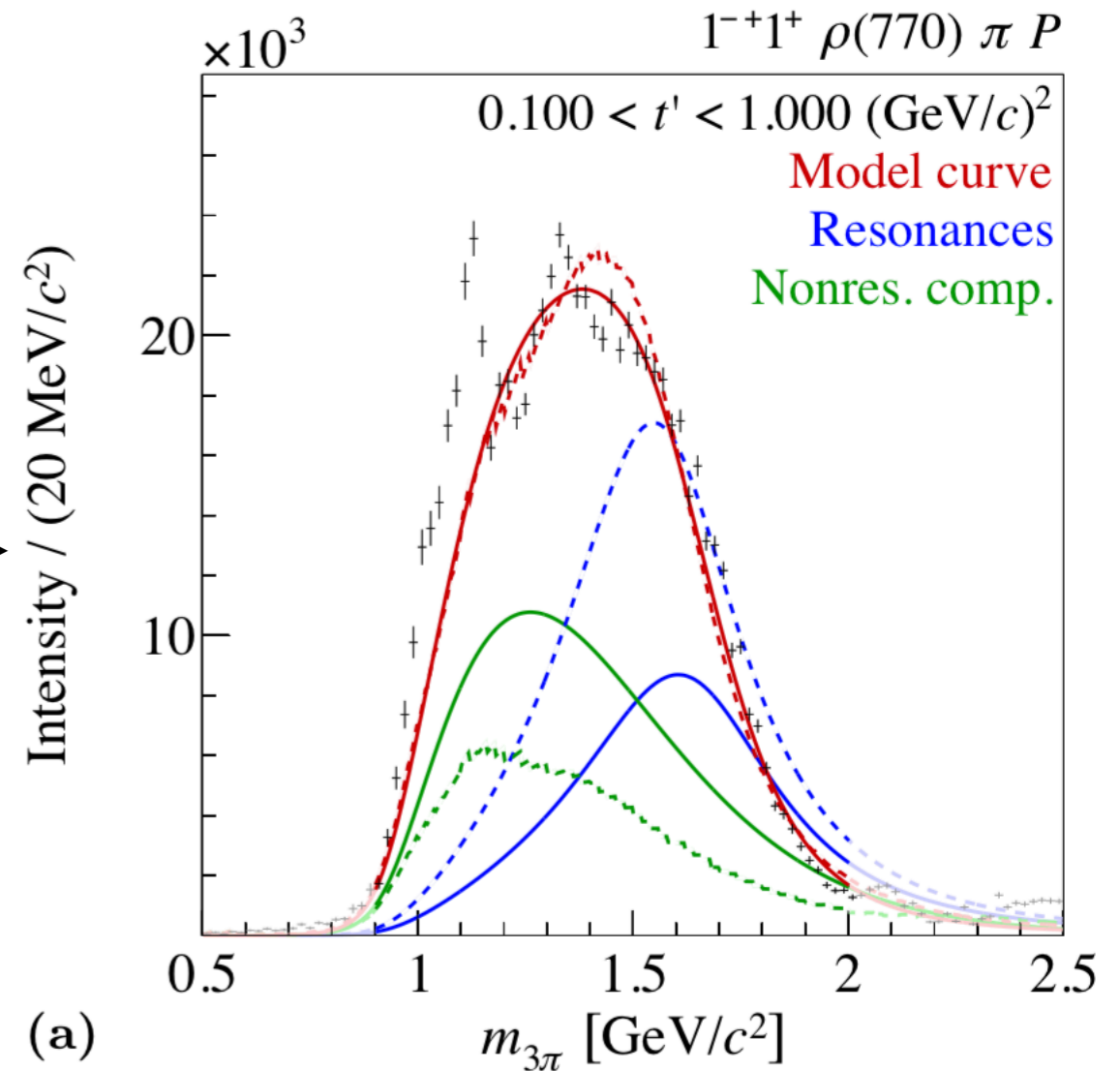
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420k
 $\pi^-\pi^-\pi^+$
events

$$\pi_1 \rightarrow \rho\pi$$



50M $\pi^-\pi^-\pi^+$ events



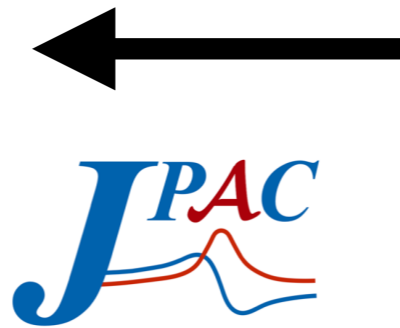
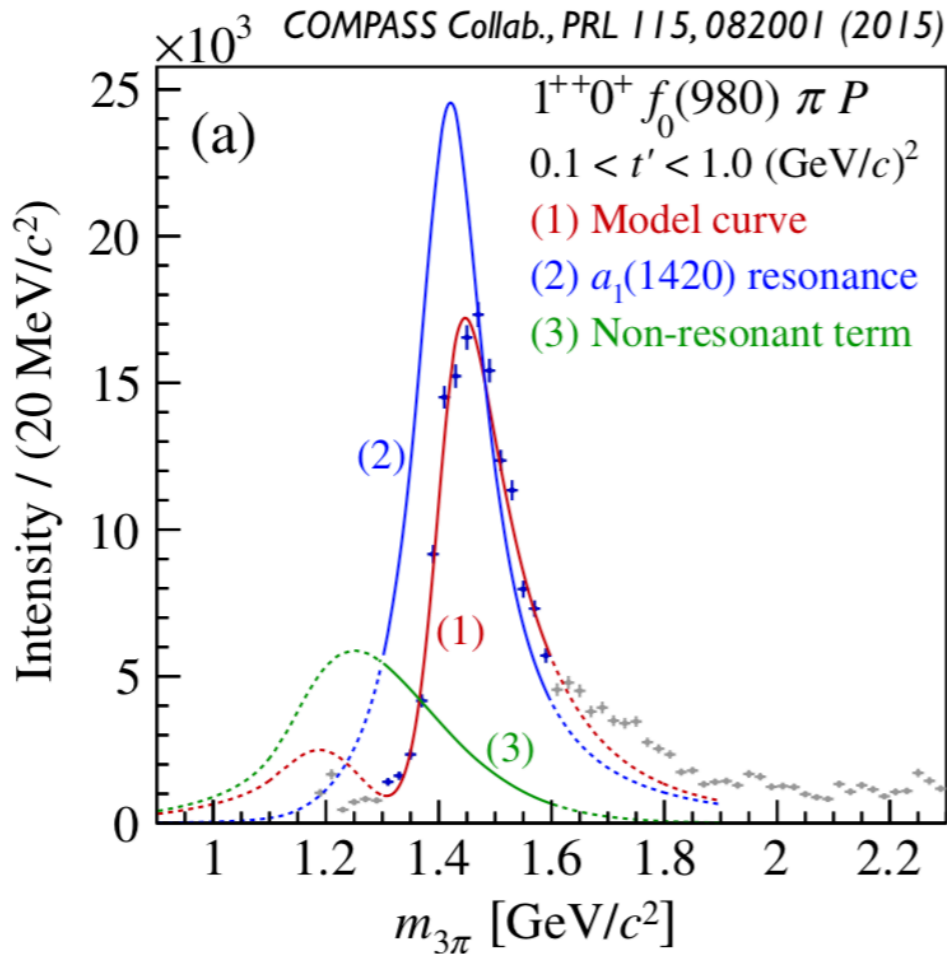
arXiv:1802.05913

COMPASS: PRL 104, 241803 (2010)

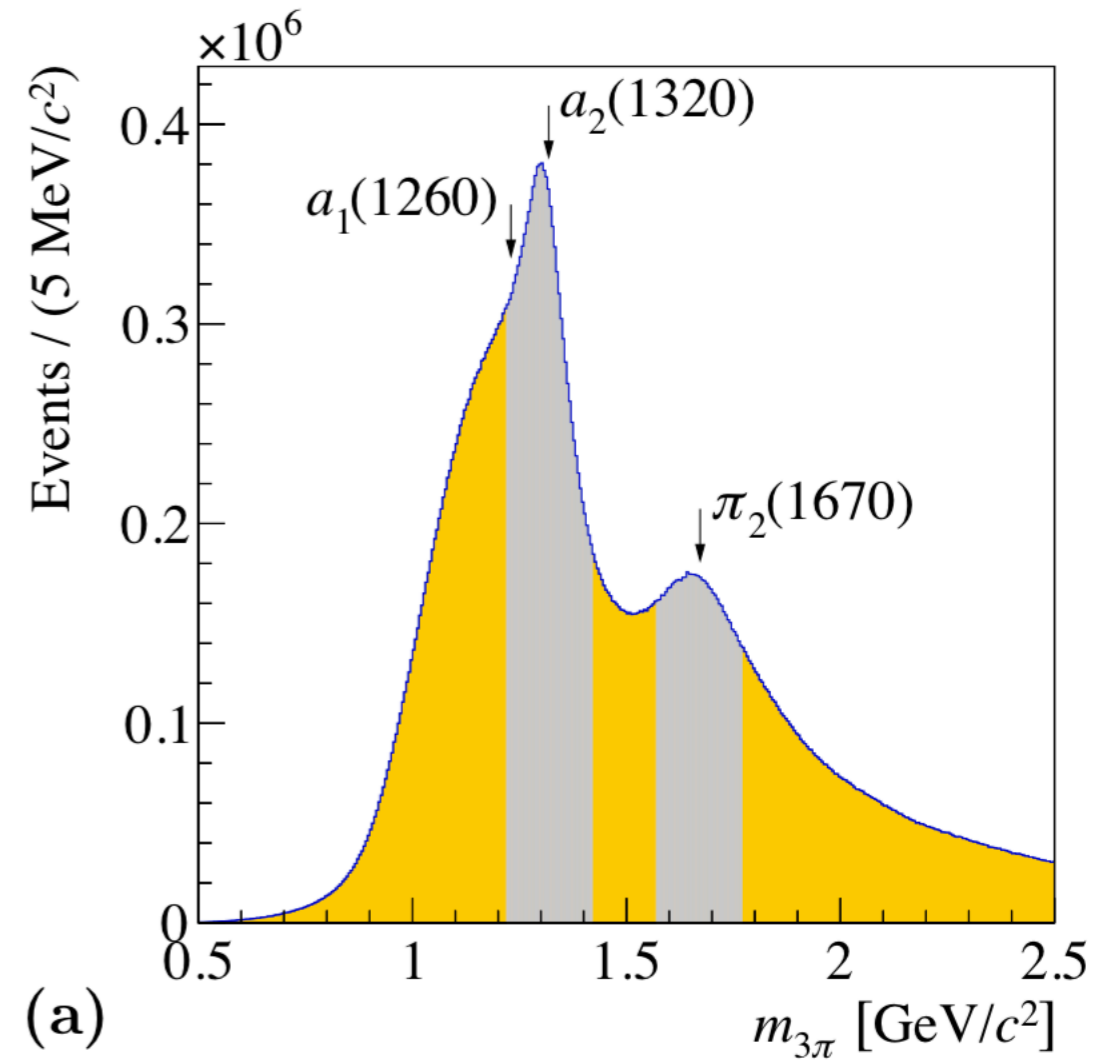
Evidence for exotic light-quark mesons

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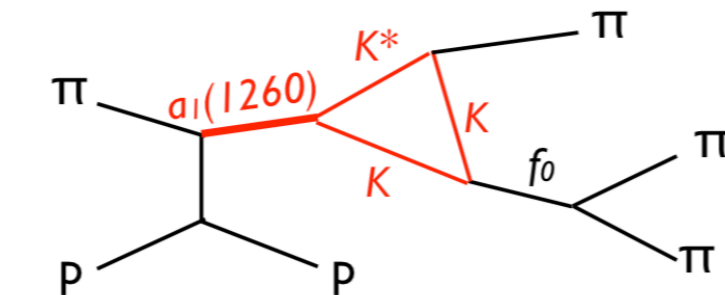
$a_1(1420) \rightarrow f_0(980) \pi$?



50M $\pi\pi\pi^+$ events



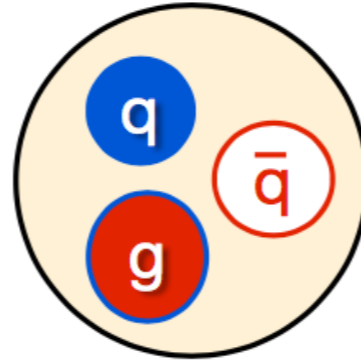
Describe non- $q\bar{q}$ candidate as triangle singularity



M. Mikhasenko, HADRON 2017

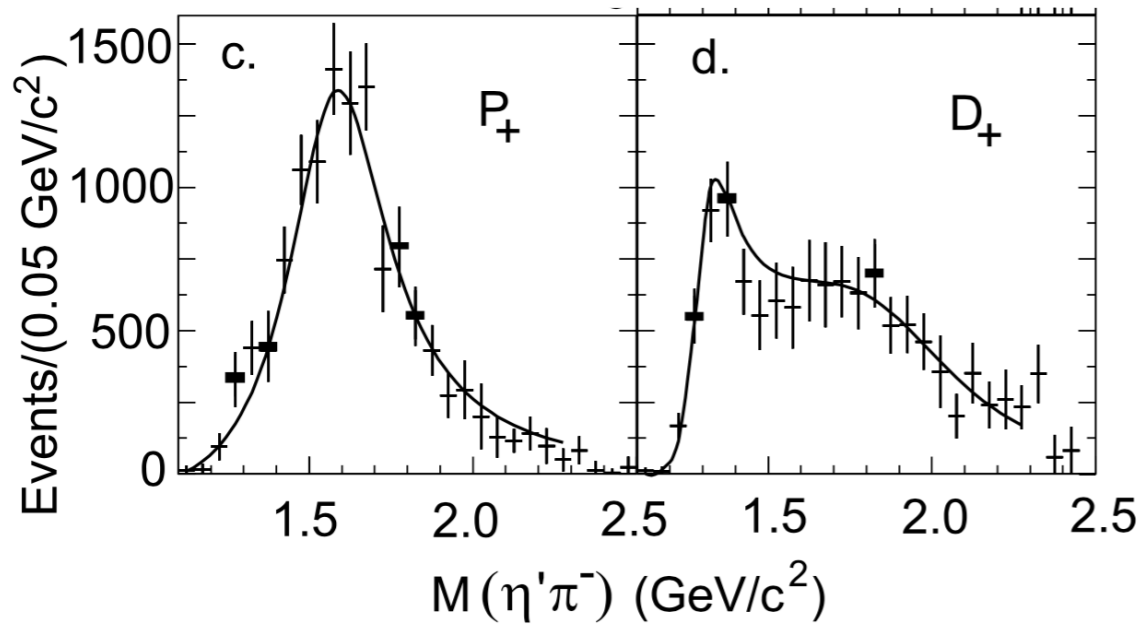
PRD 95, 032004 (2017)

Evidence for exotic light-quark mesons



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

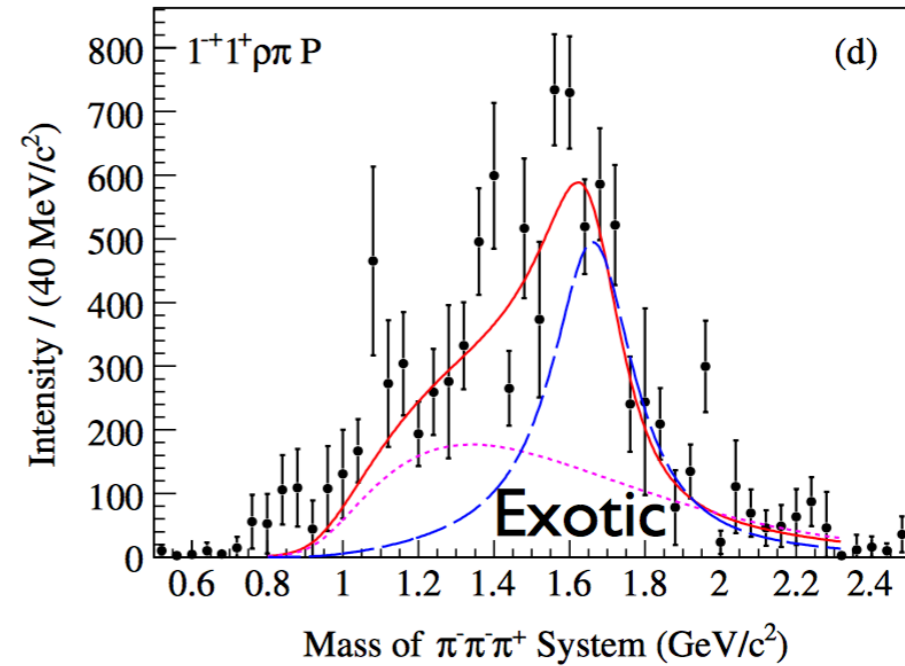
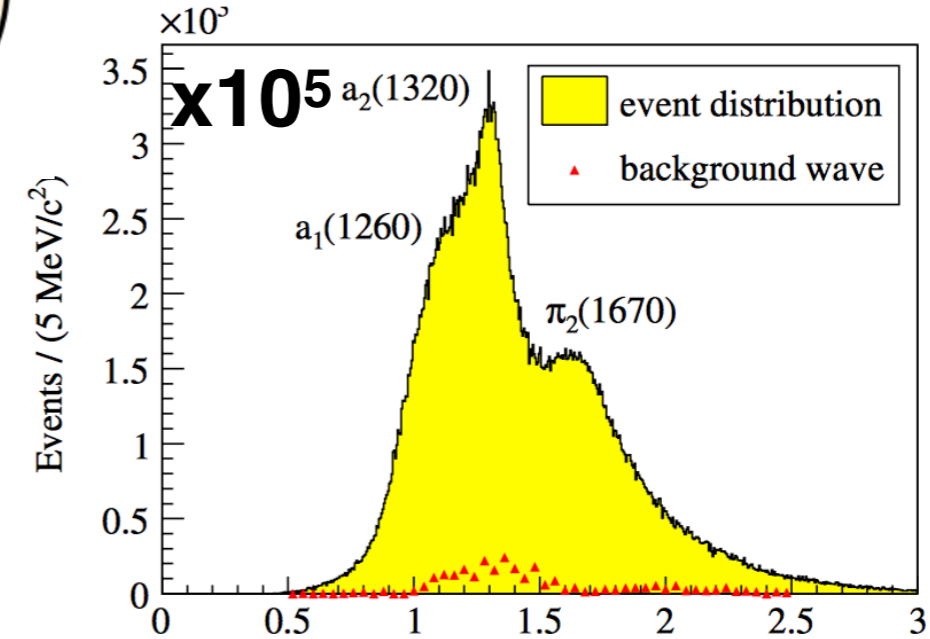
E852: 18 GeV π on p



PRL 86, 3977 (2001)

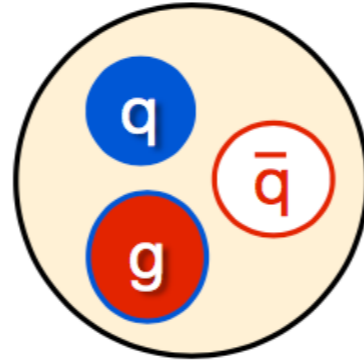
$$\pi_1 \rightarrow \rho \pi$$

COMPASS: 190 GeV π on Pb



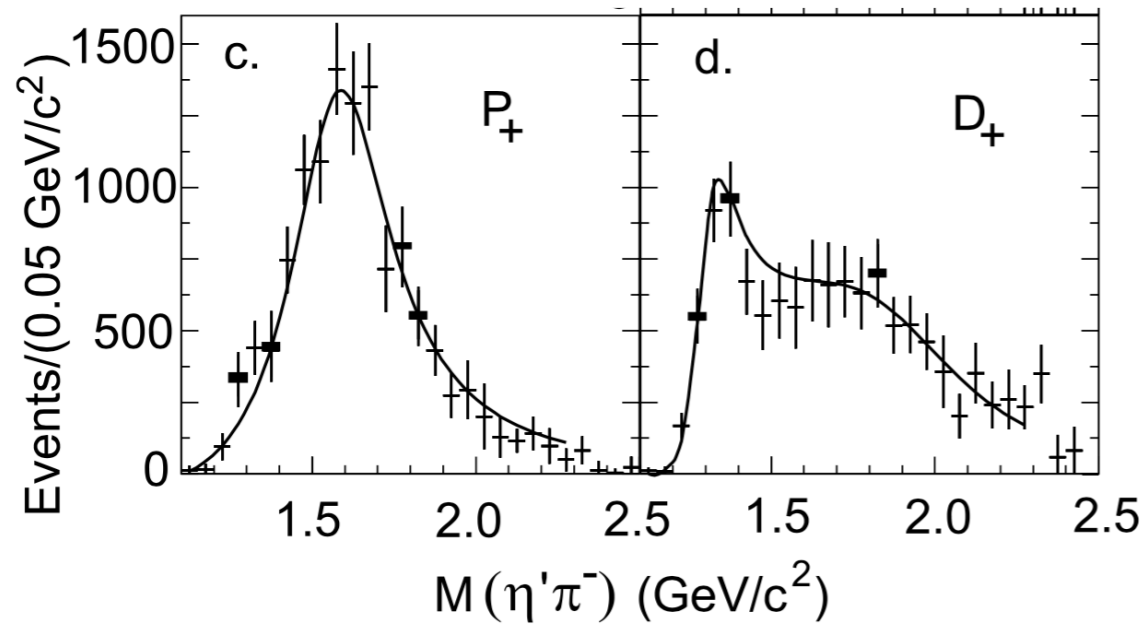
PRL 104, 241803 (2010)

Evidence for exotic light-quark mesons



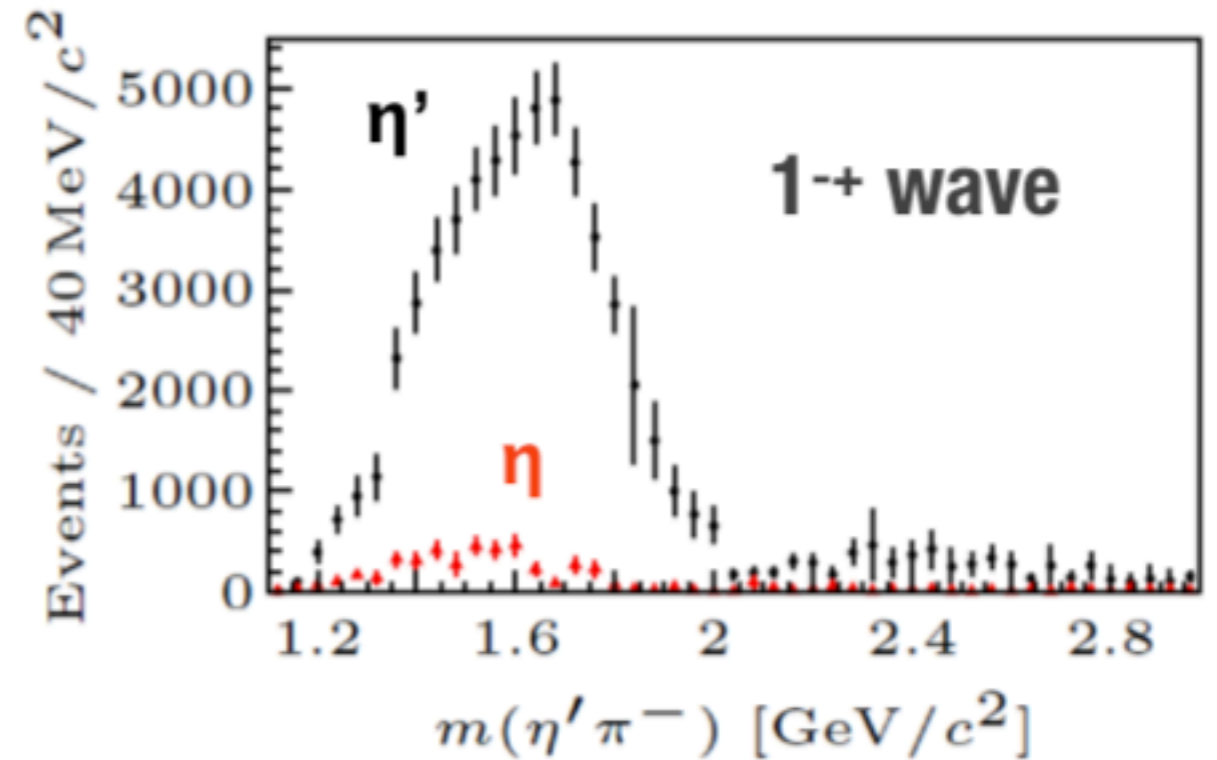
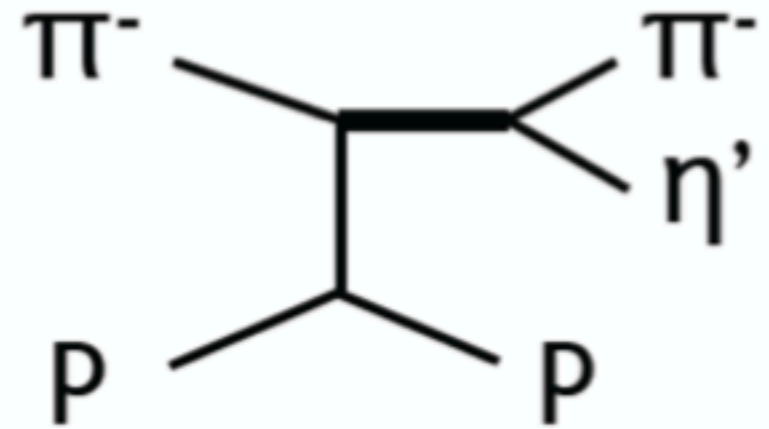
$$\pi_1 \rightarrow \eta' \pi$$

E852: 18 GeV π on p

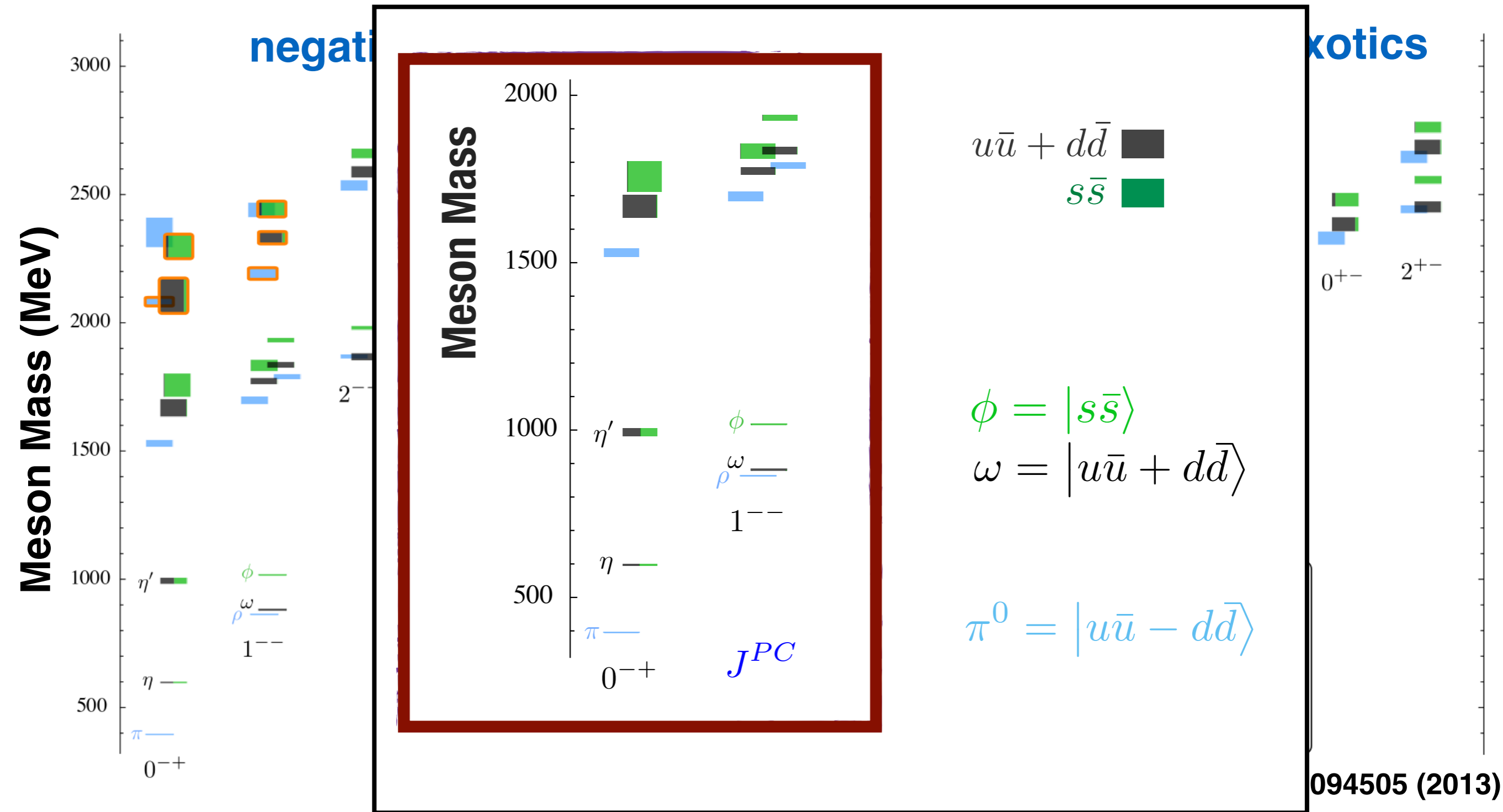


PRL 86, 3977 (2001)

Compass: PLB 740 (2015) 303

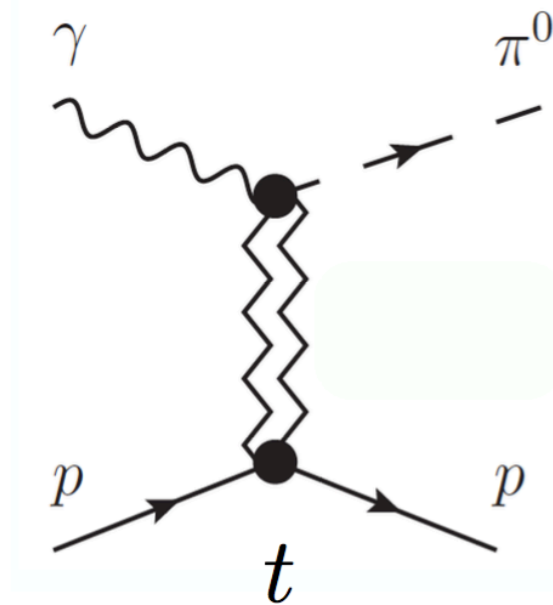


Light Meson Spectrum from Lattice QCD



- Many broad, overlapping states. Overpopulation of states?
- Progress requires multiple channels, amplitude analysis...

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



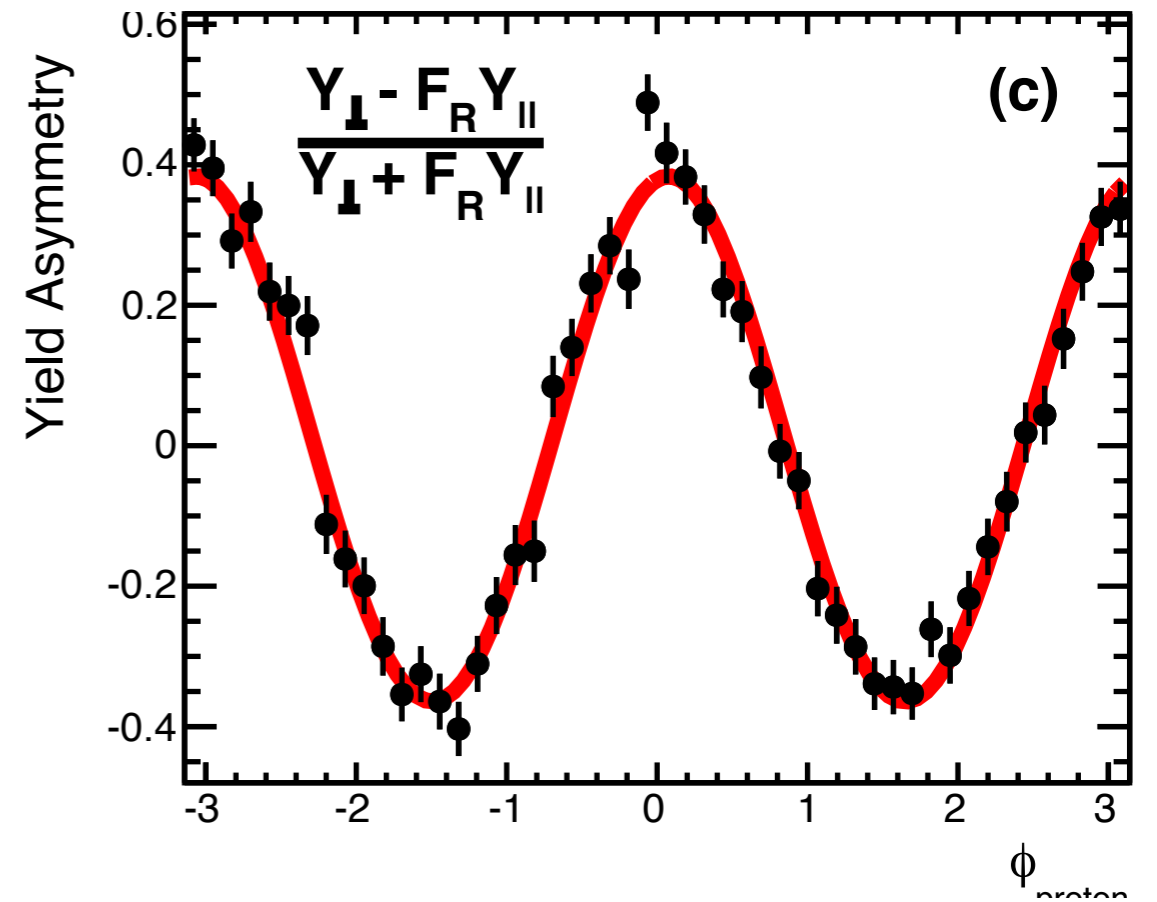
Exchange J^{PC}

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

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

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

JPAC: Mathieu et al., PRD 92, 074013

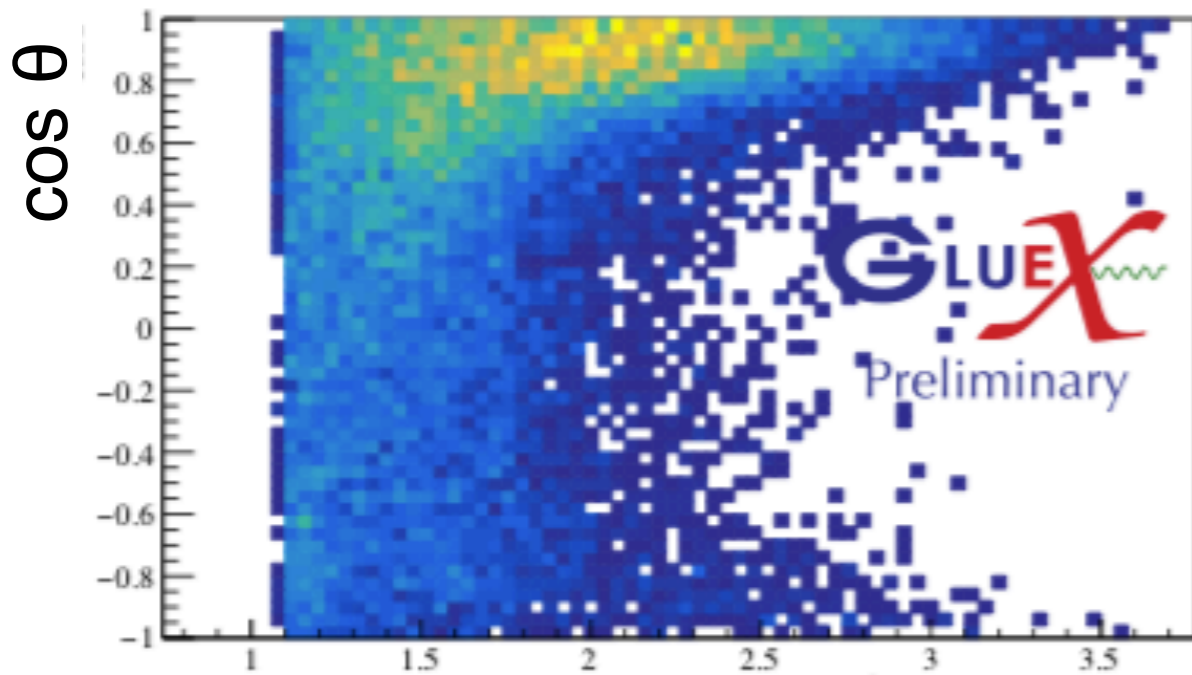


$$\frac{Y_{\perp} - F_R Y_{\parallel}}{Y_{\perp} + F_R Y_{\parallel}} = P_{\gamma} \Sigma \cos 2\phi_p$$

- Understanding production mechanisms necessary to determine J^{PC} of mesons in amplitude analyses
- Beam asymmetry Σ yields information on production mechanisms

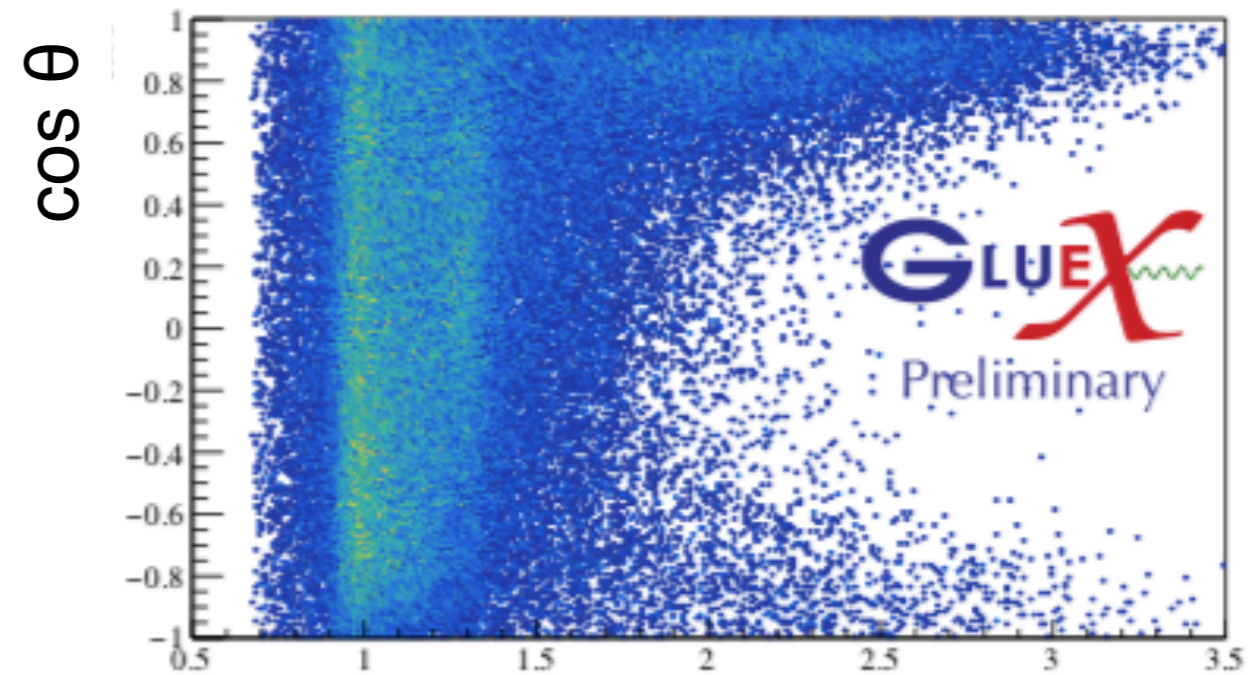
Angular Correlations in $\gamma p \rightarrow p + 4\gamma$

$\eta'\pi^0$



$\eta'\pi^0$ invariant mass (GeV)

$\eta\pi^0$



$\eta\pi^0$ invariant mass (GeV)

- Production near $\cos \theta \sim 1$ corresponds to meson production
- Stronger signal in $\eta'\pi^0$ than $\eta\pi^0$

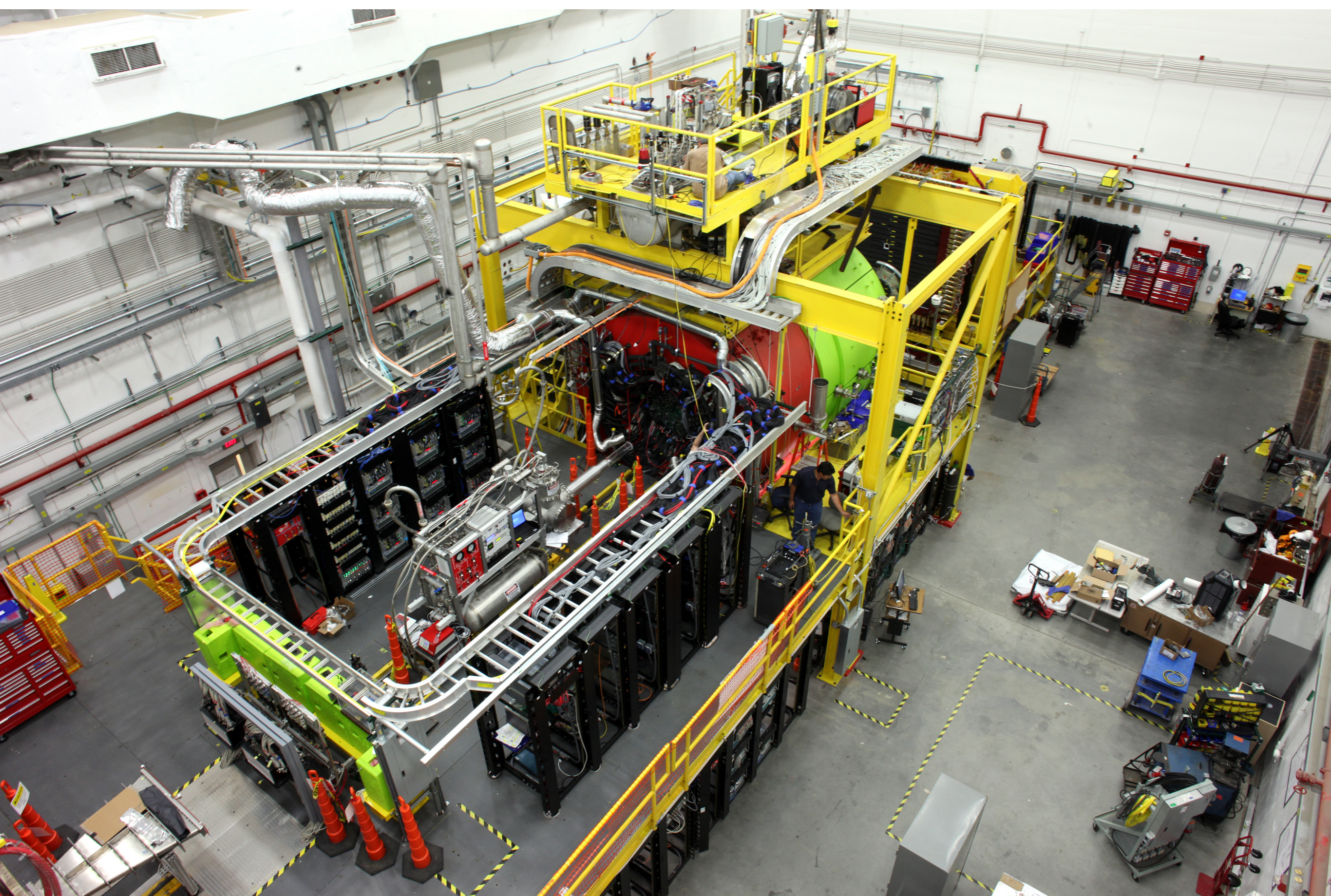


GlueX Detector, October 2014 (w/ Curtis Meyer, Spokesman)

The GlueX Experiment in Hall D @ JLab

- The GlueX experiment is located in Hall D, newly constructed as part of the Jefferson Lab 12 GeV upgrade.
- Large acceptance solenoidal spectrometer
- Linearly polarized photon beam peaking at 9 GeV
- Detects all decay products from full hadronic photoproduction rate
- 100+ Collaborators from 26 institutions



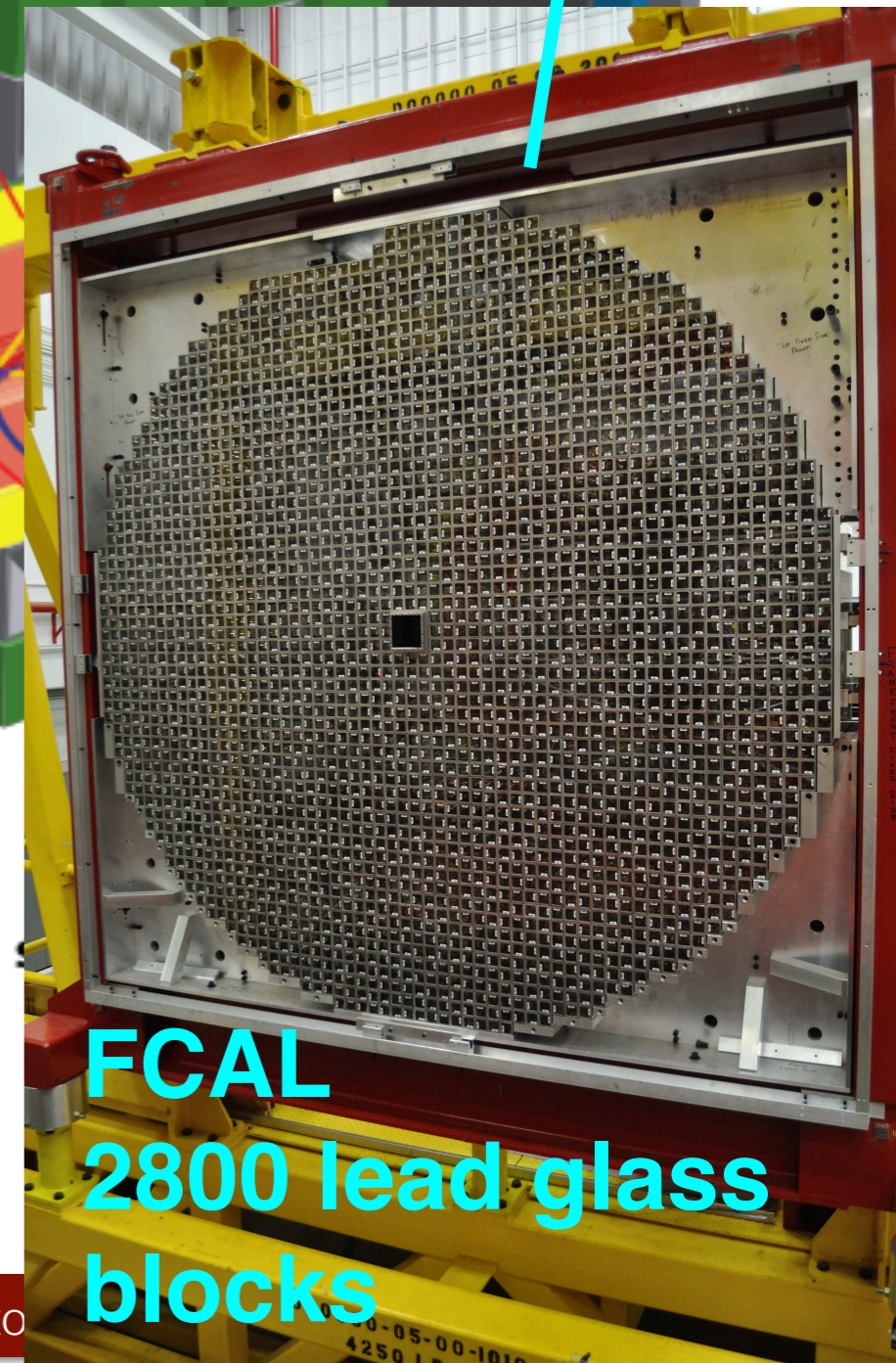
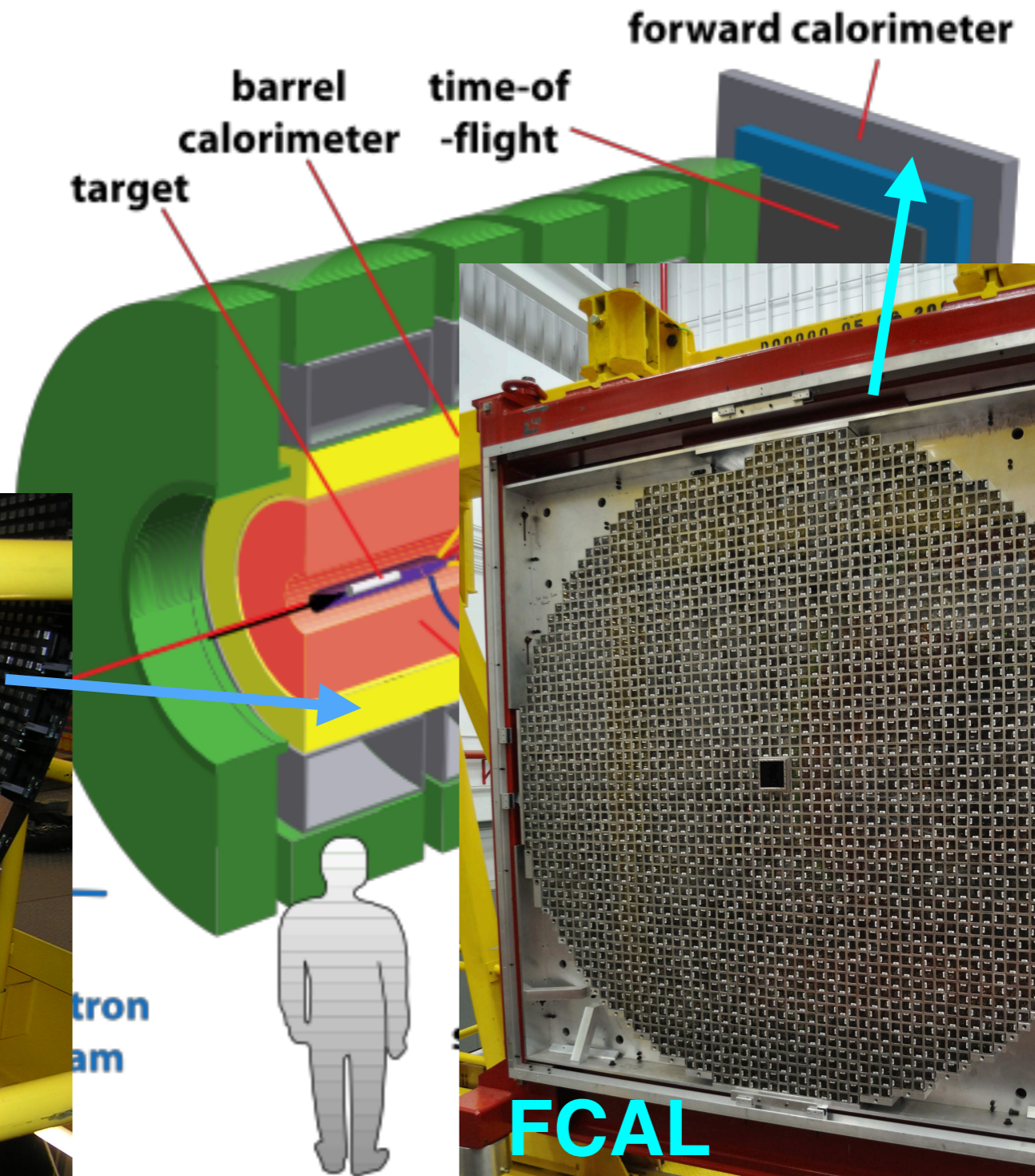
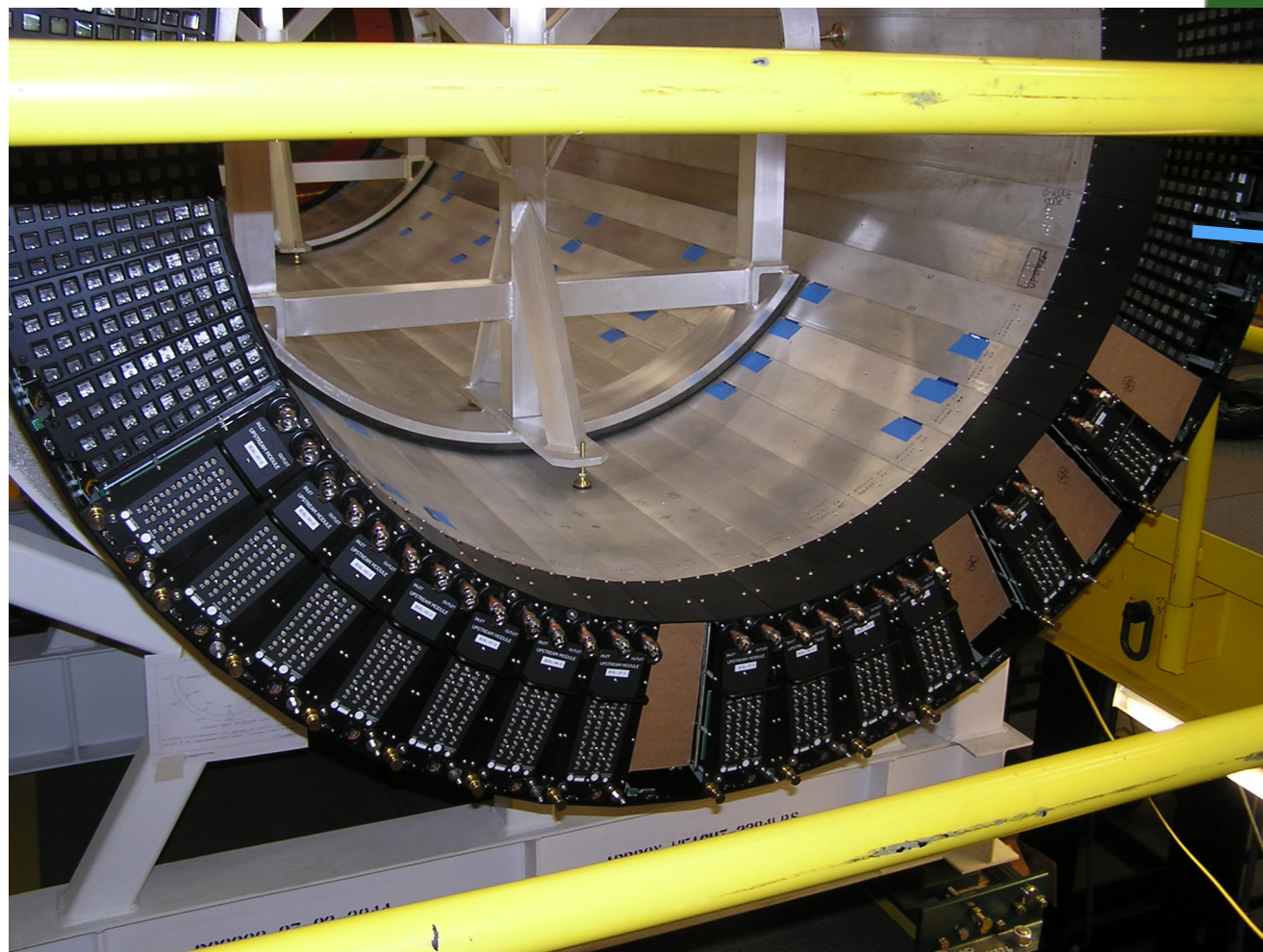


GlueX Detector, August 2014

The GlueX Experiment: Calorimetry

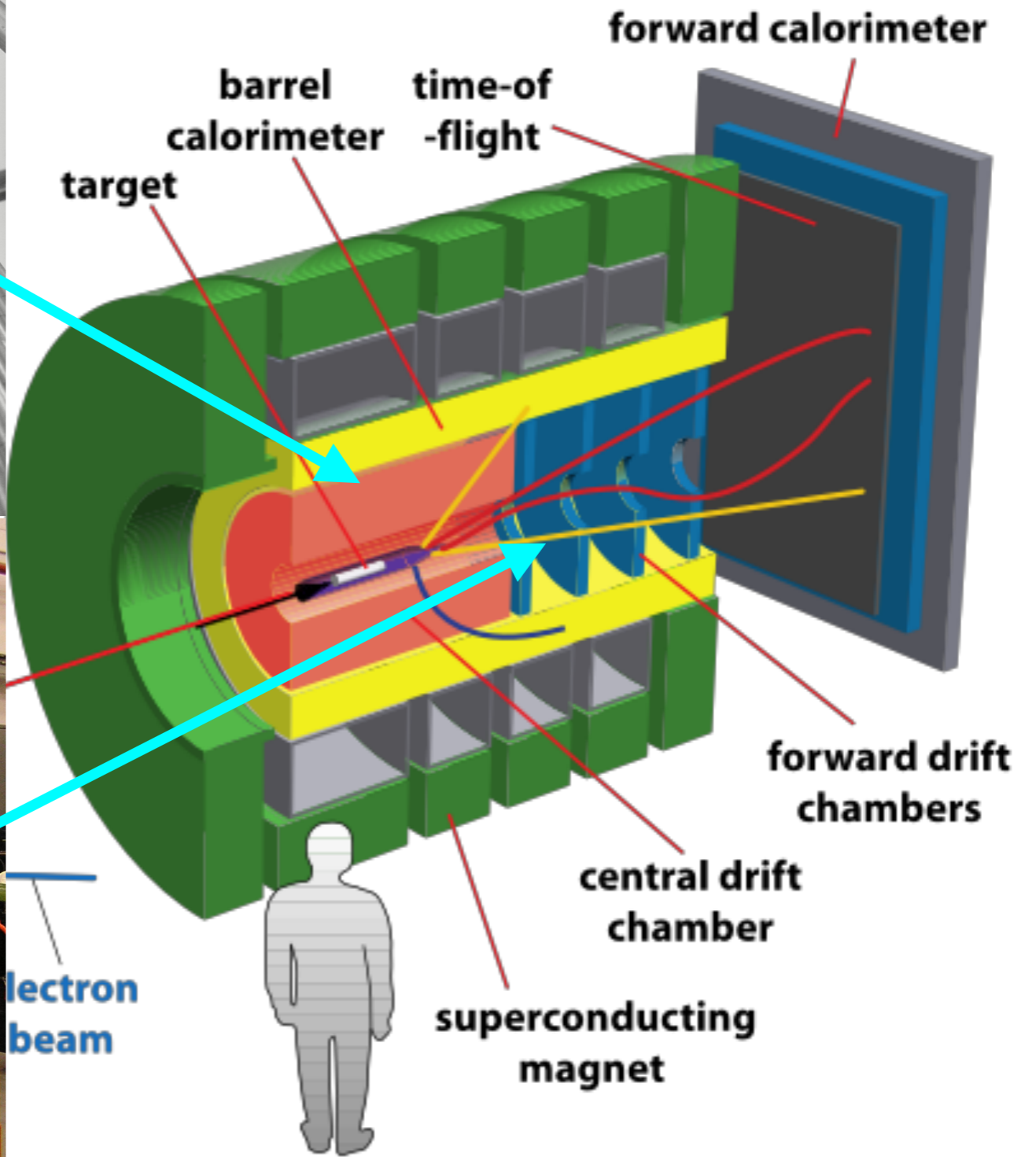
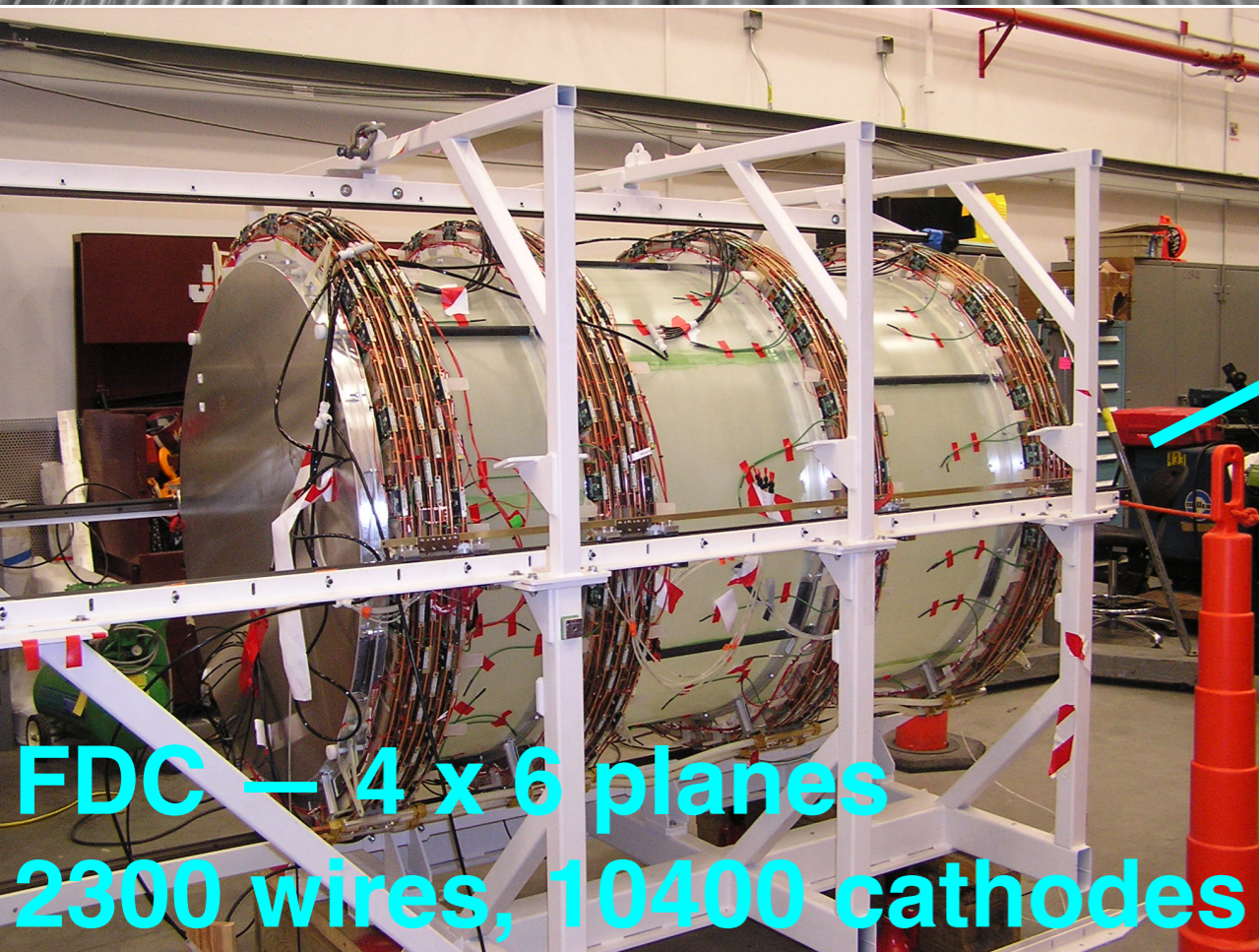
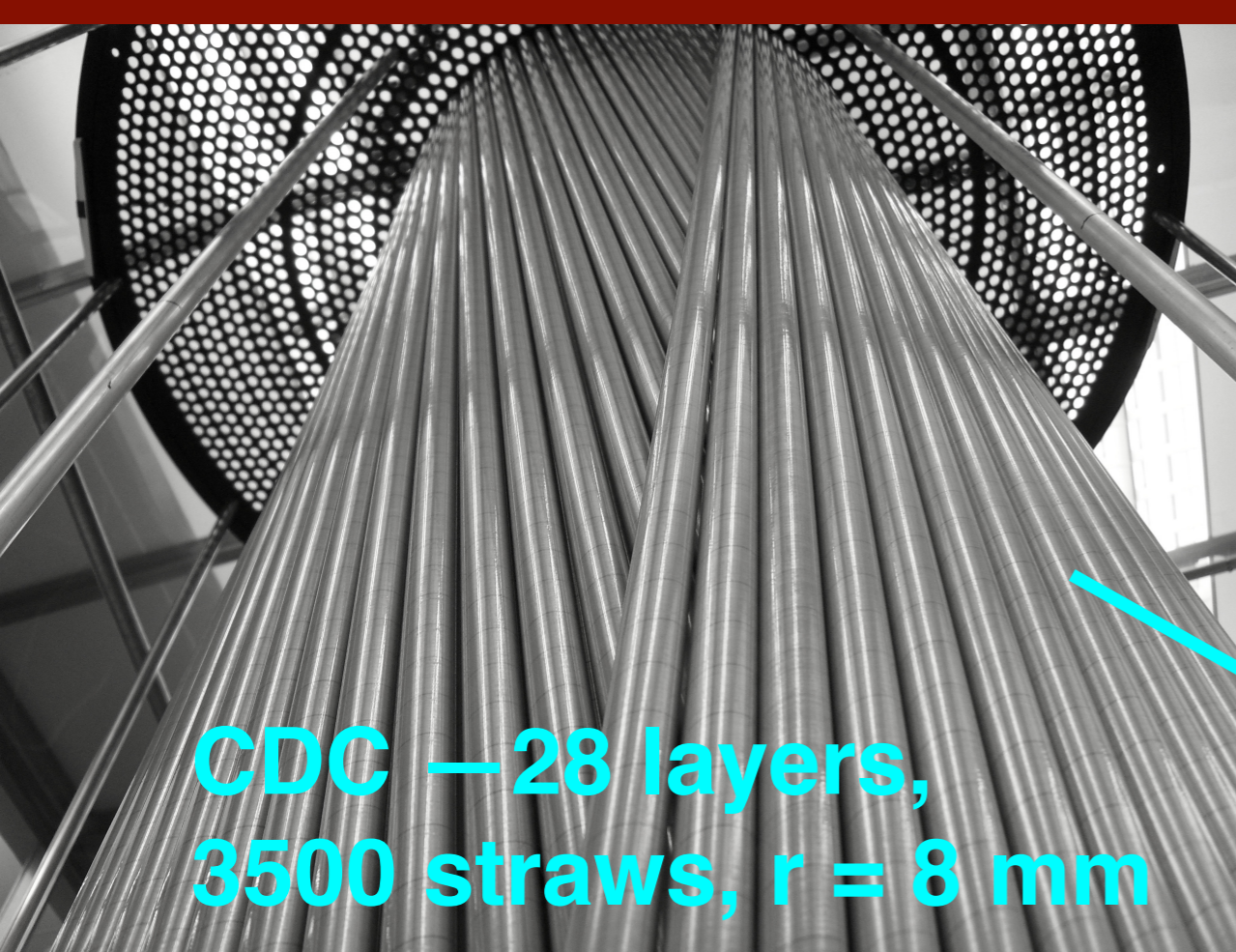
GLUE*X* 

**BCAL — lead/scin. fiber
3840 SiPM readout**



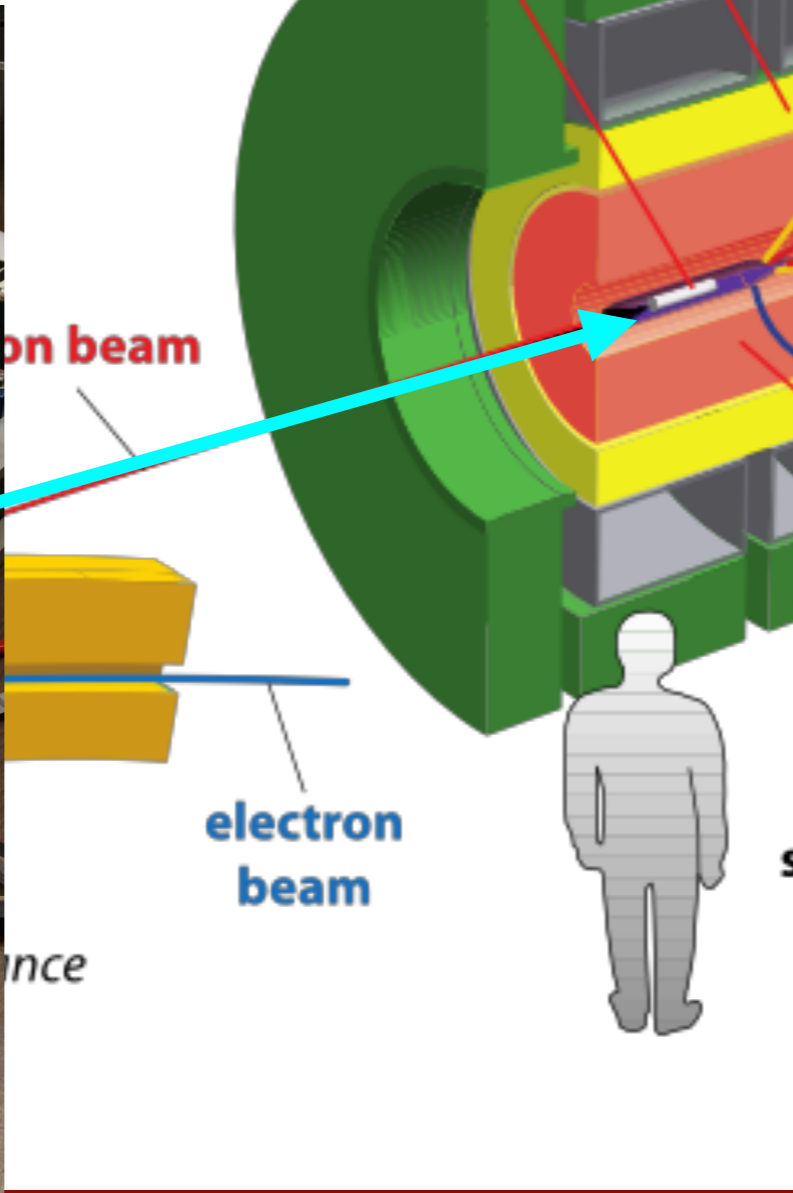
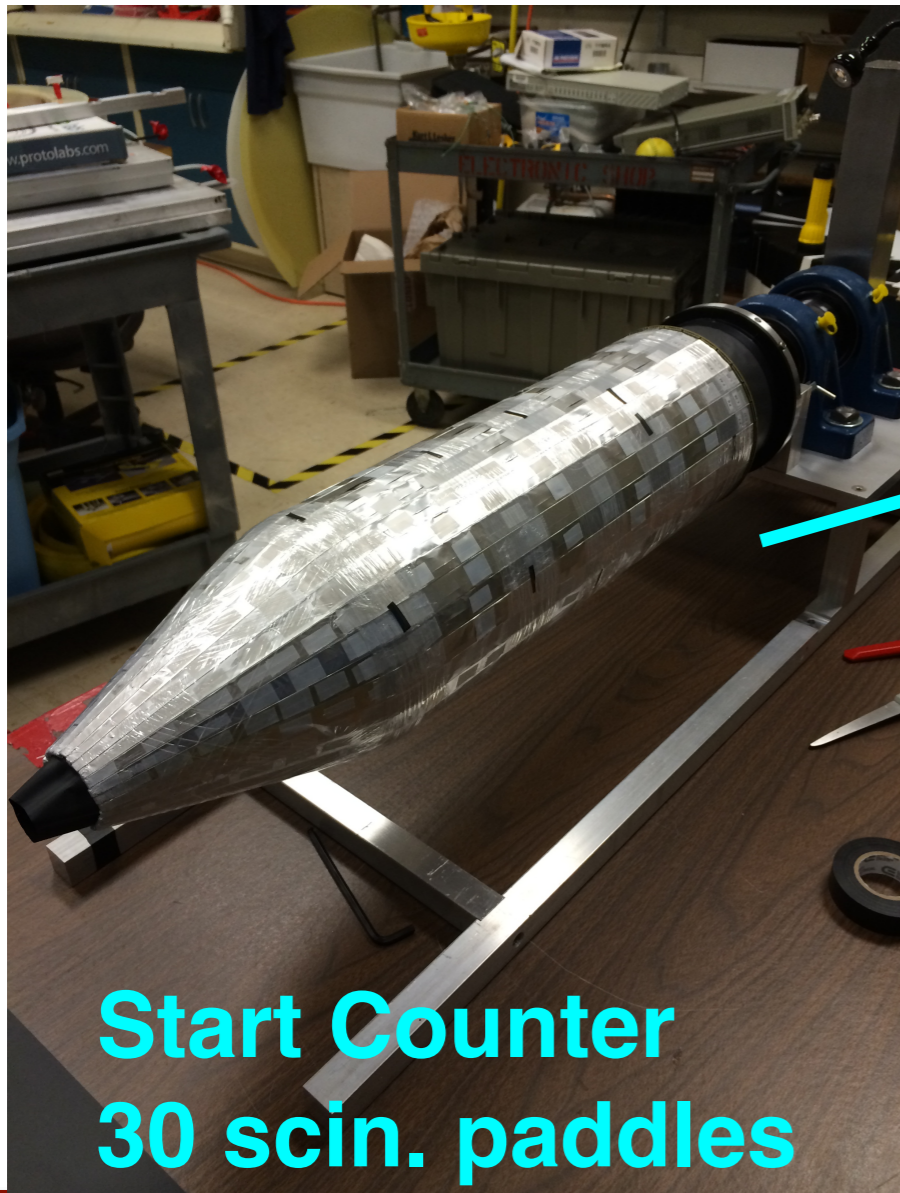
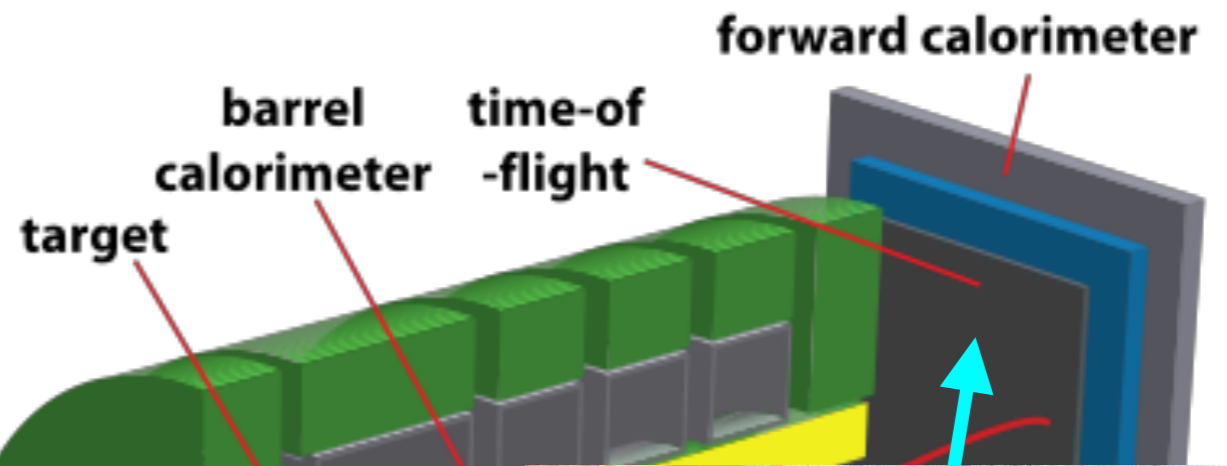
**FCAL
2800 lead glass
blocks**

Experiment: Tracking



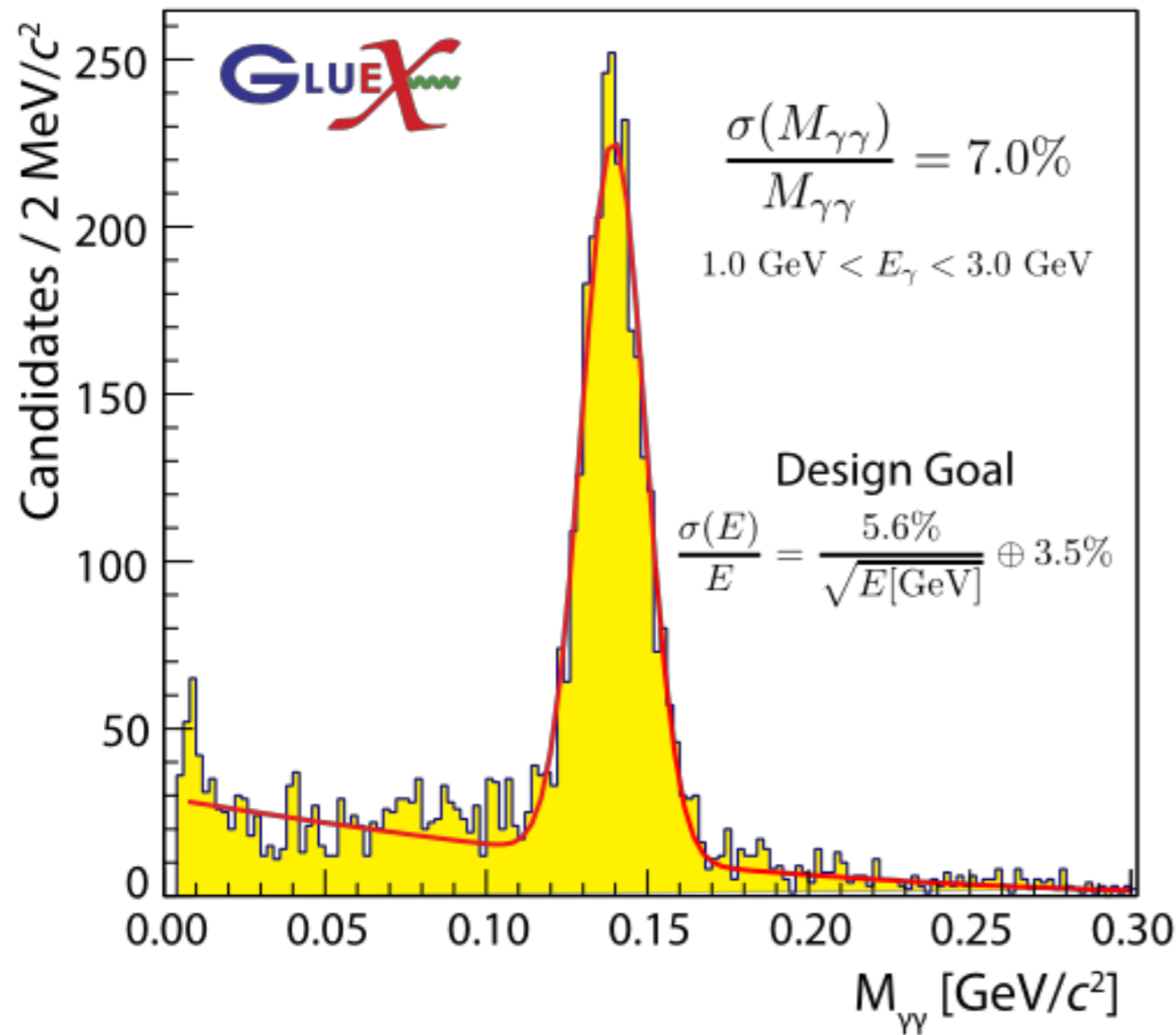
The GlueX Experiment: Particle ID

GLUEX 

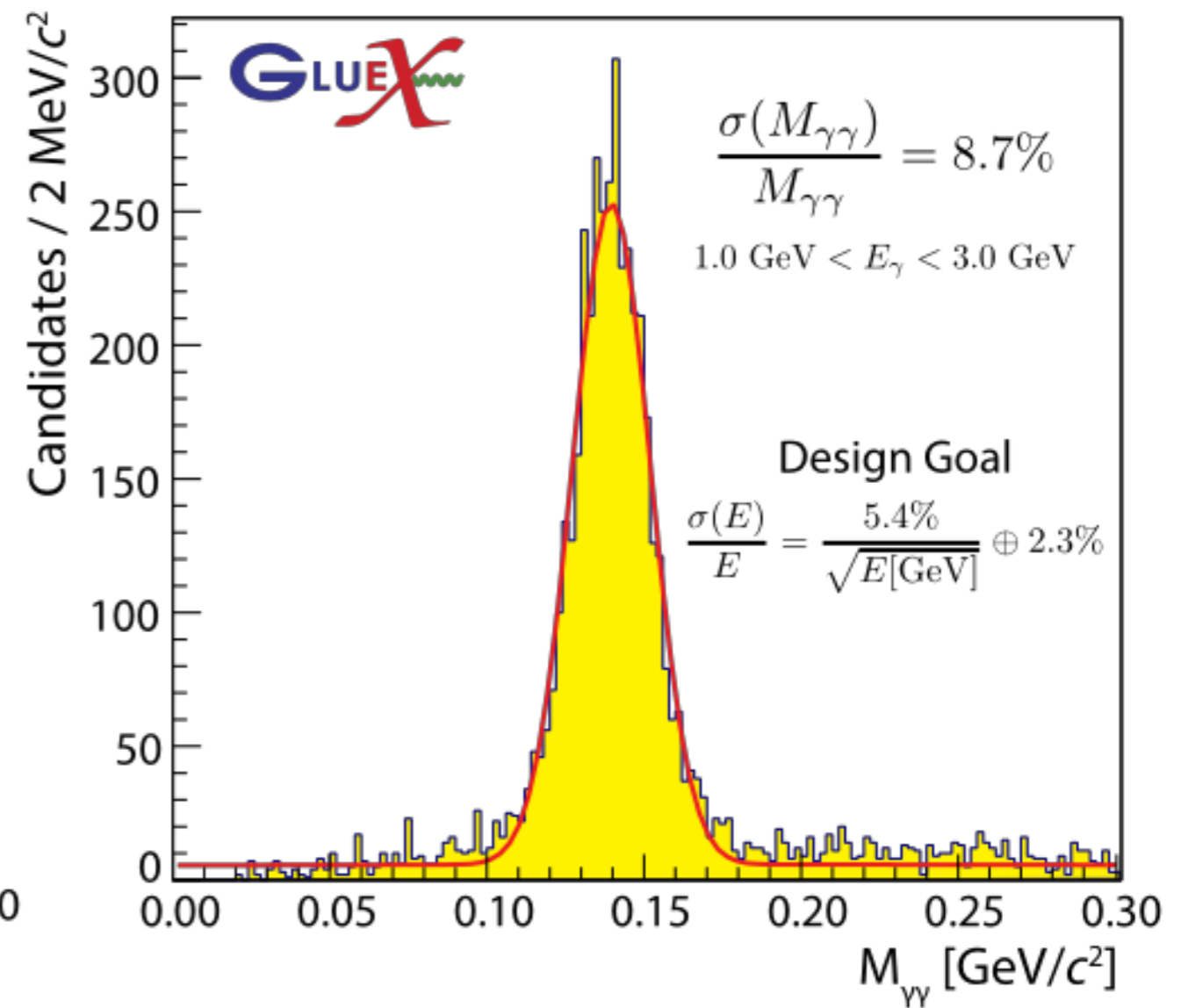


GlueX Calorimetry Performance

Forward Lead Glass Calorimeter

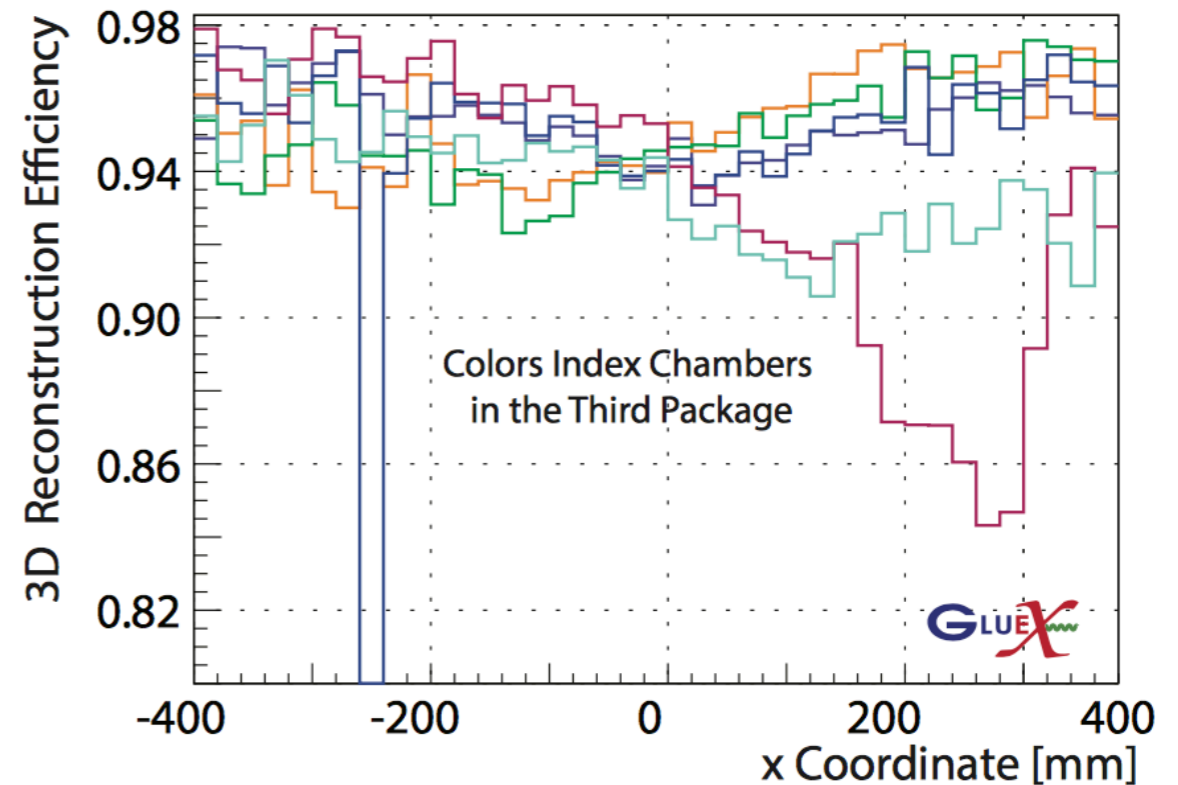
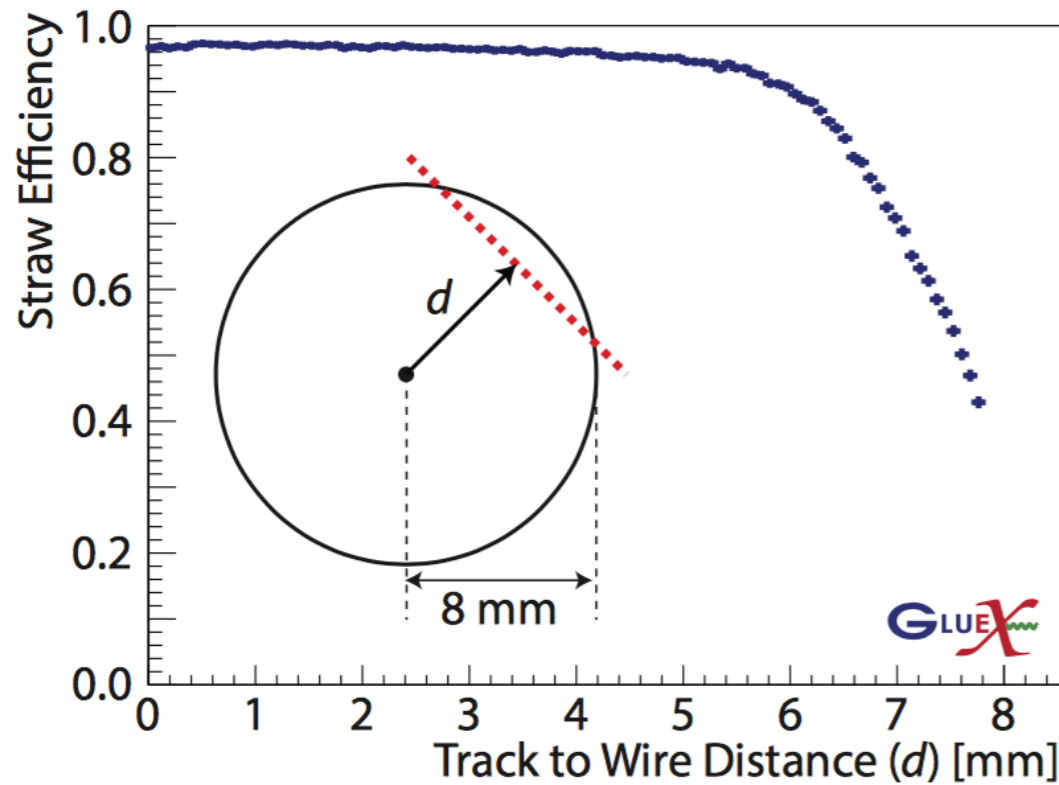
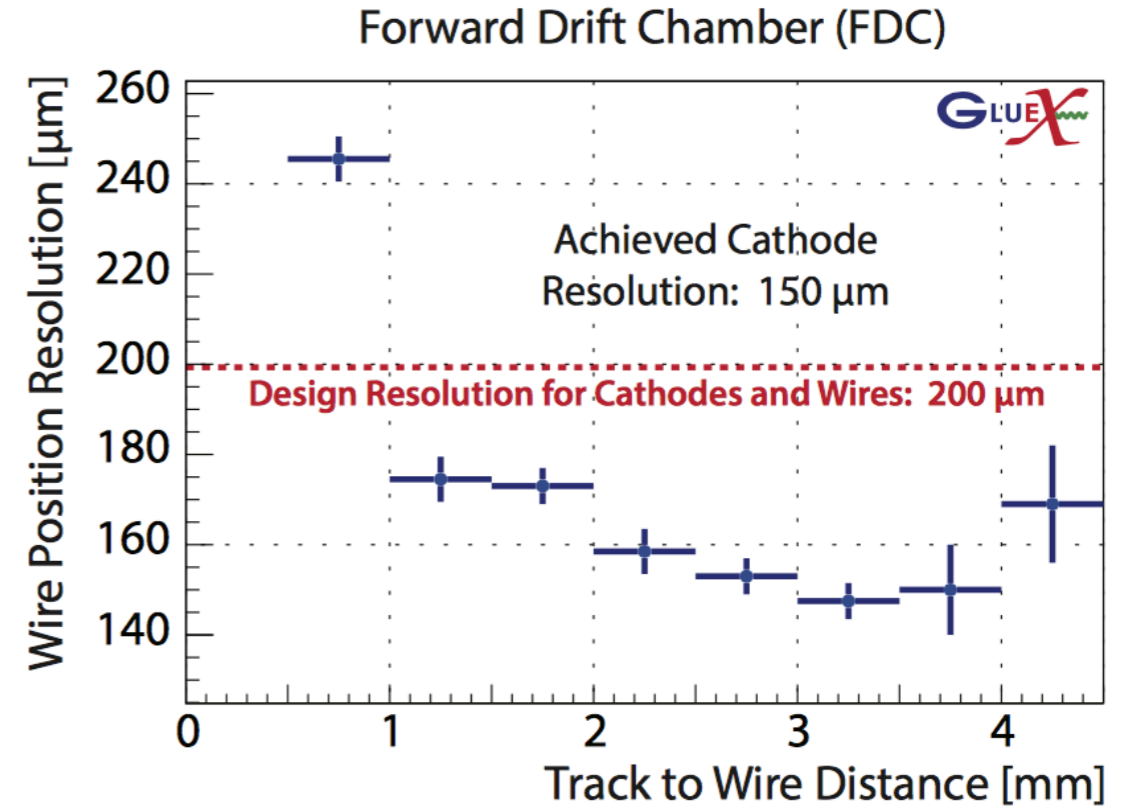
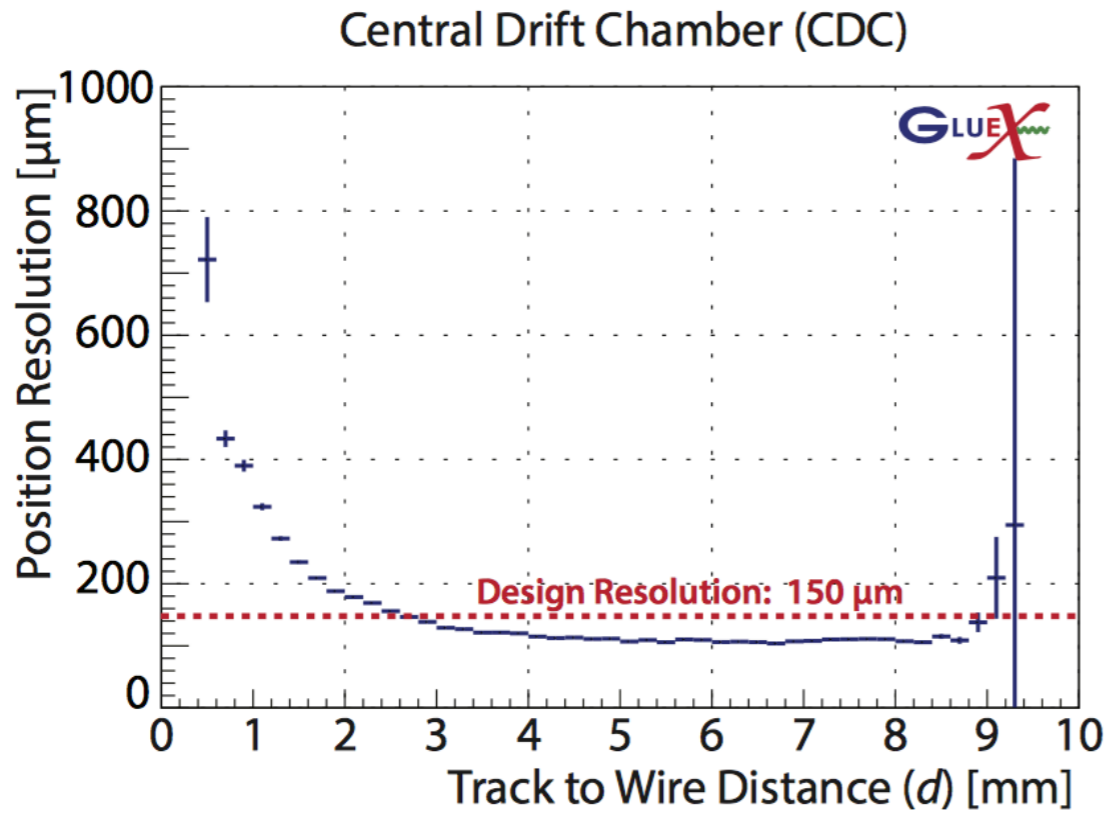


Barrel Lead-Scintillating Fiber Calorimeter

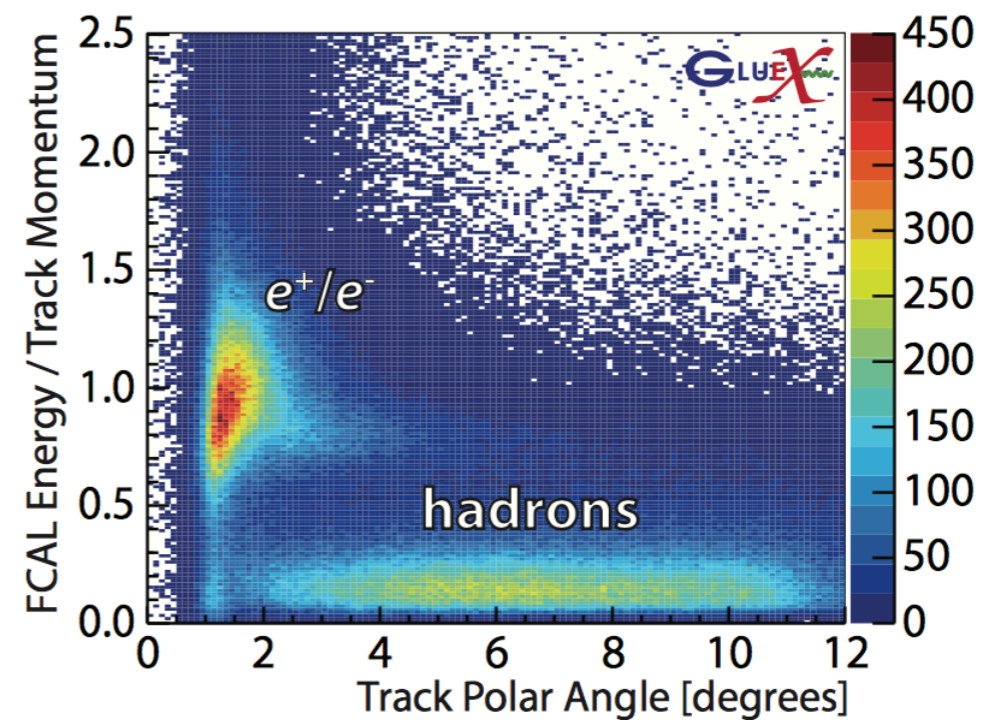
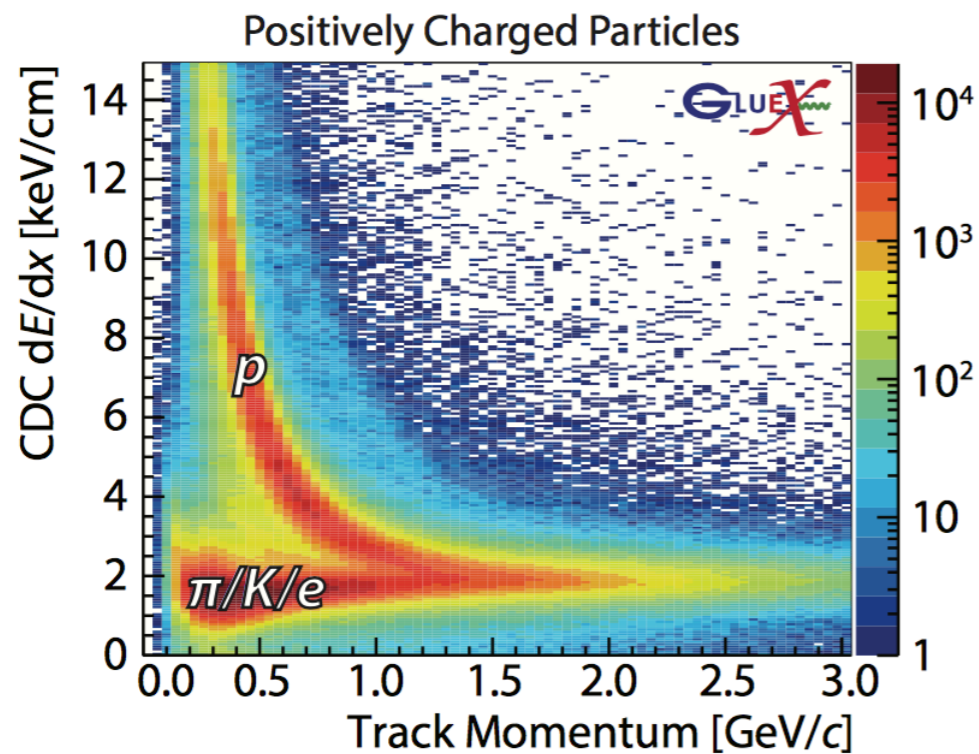
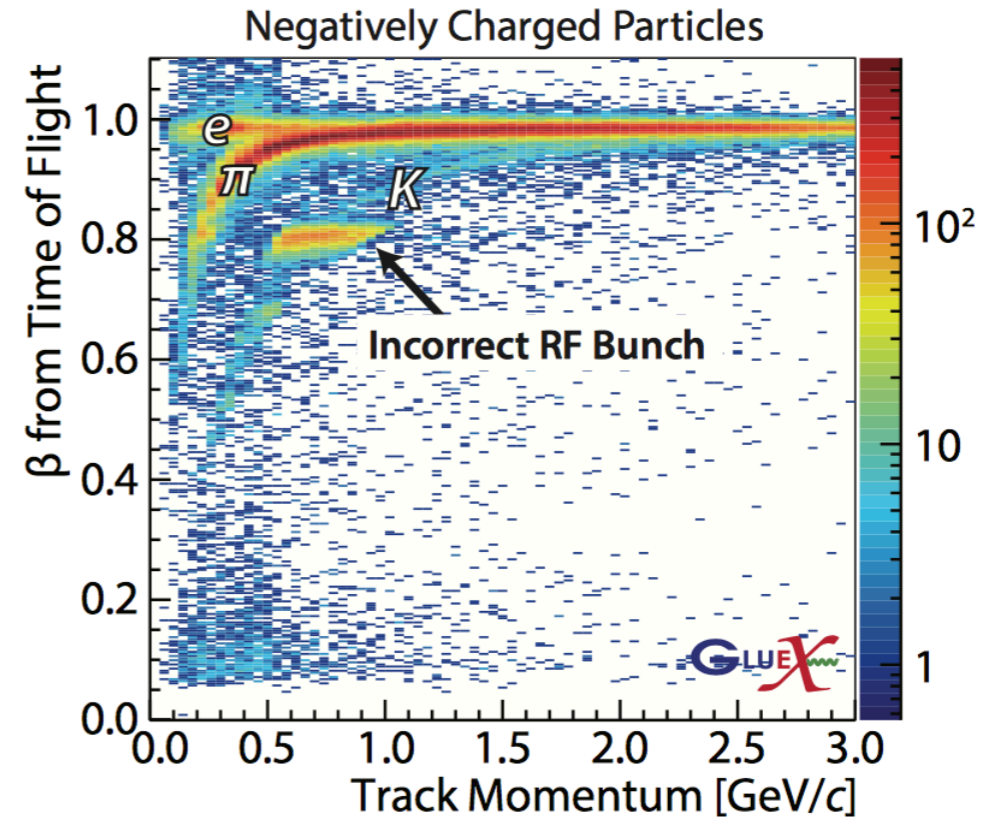
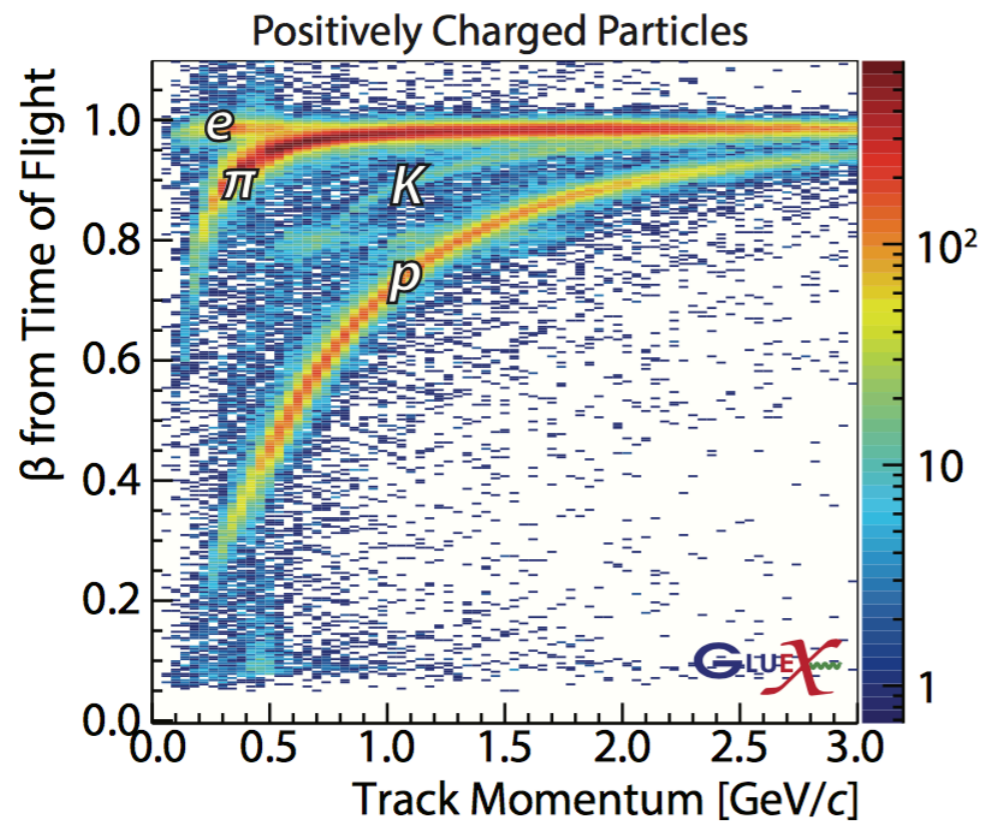


Measured using $\gamma p \rightarrow p \gamma \gamma \gamma \gamma$ events

GlueX Tracking Performance

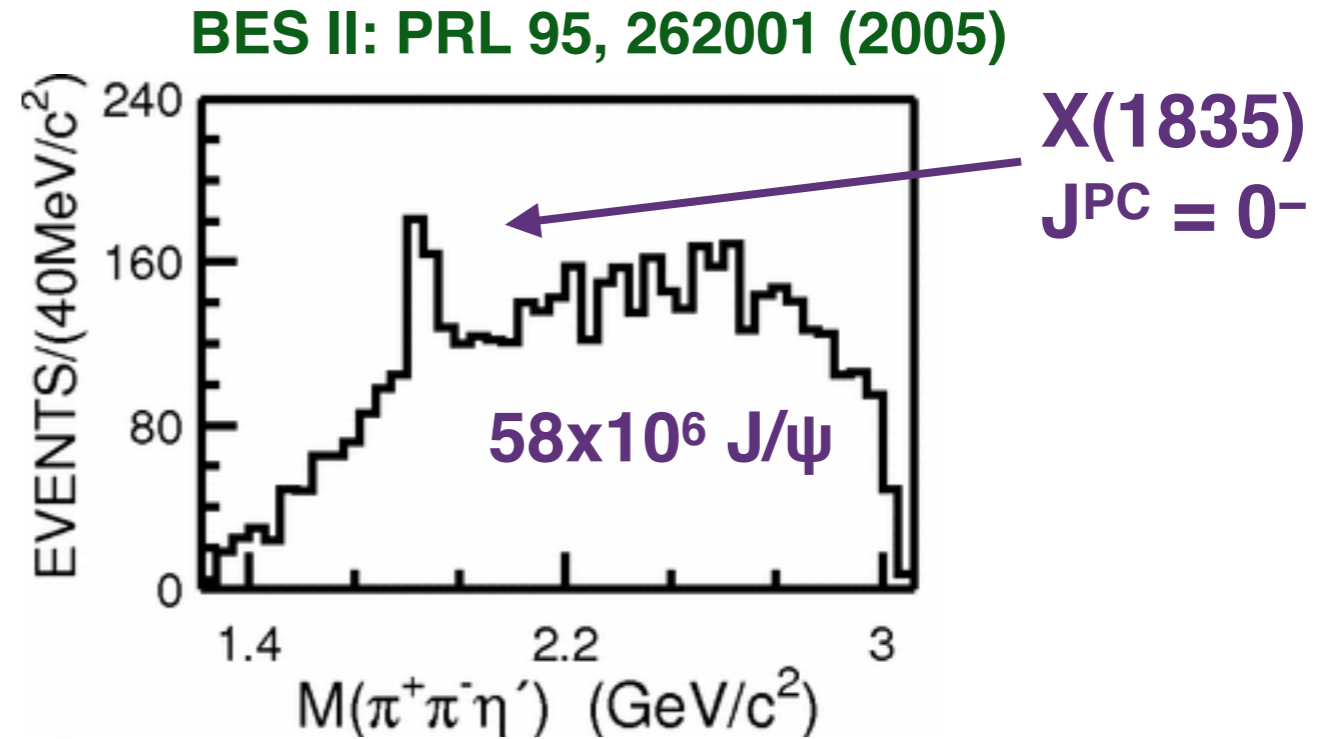


GlueX Particle ID Performance



Precision and Spectroscopy: BES III & $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

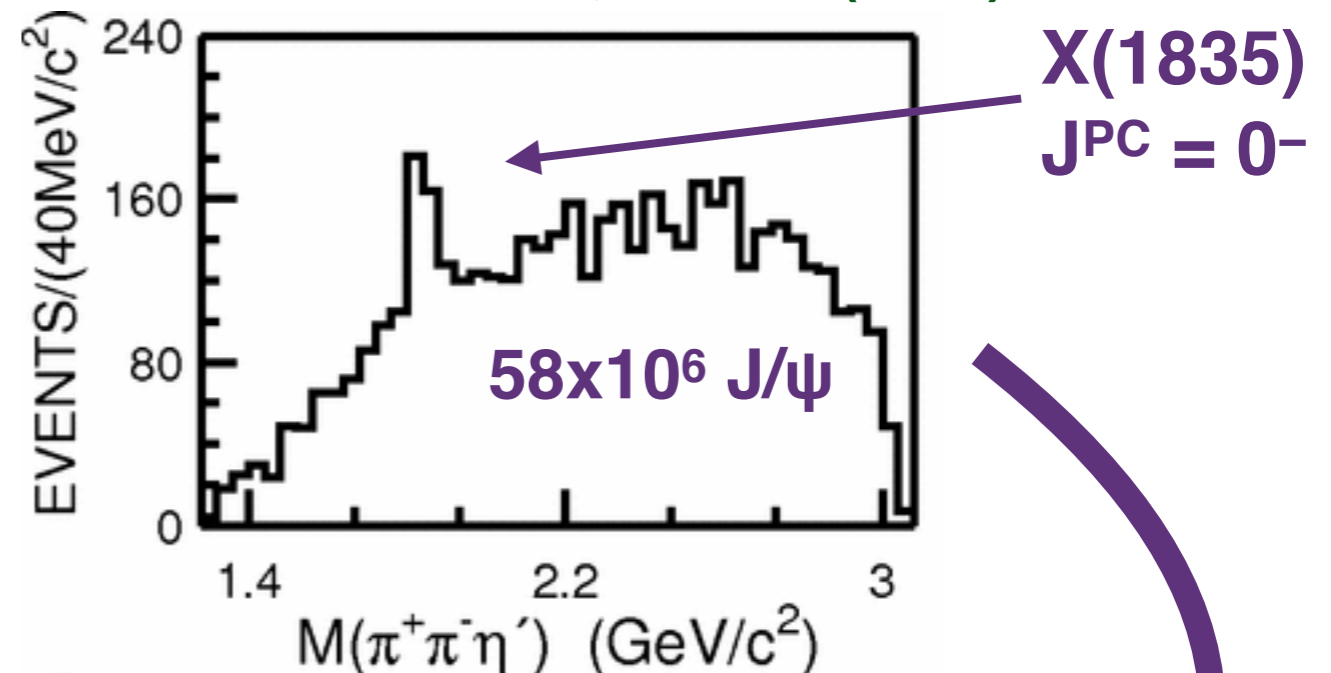
- Search by BES for resonances in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ in e^+e^- annihilation
 - Structure seen near $2M(p)$
 - Understanding evolves as more data collected



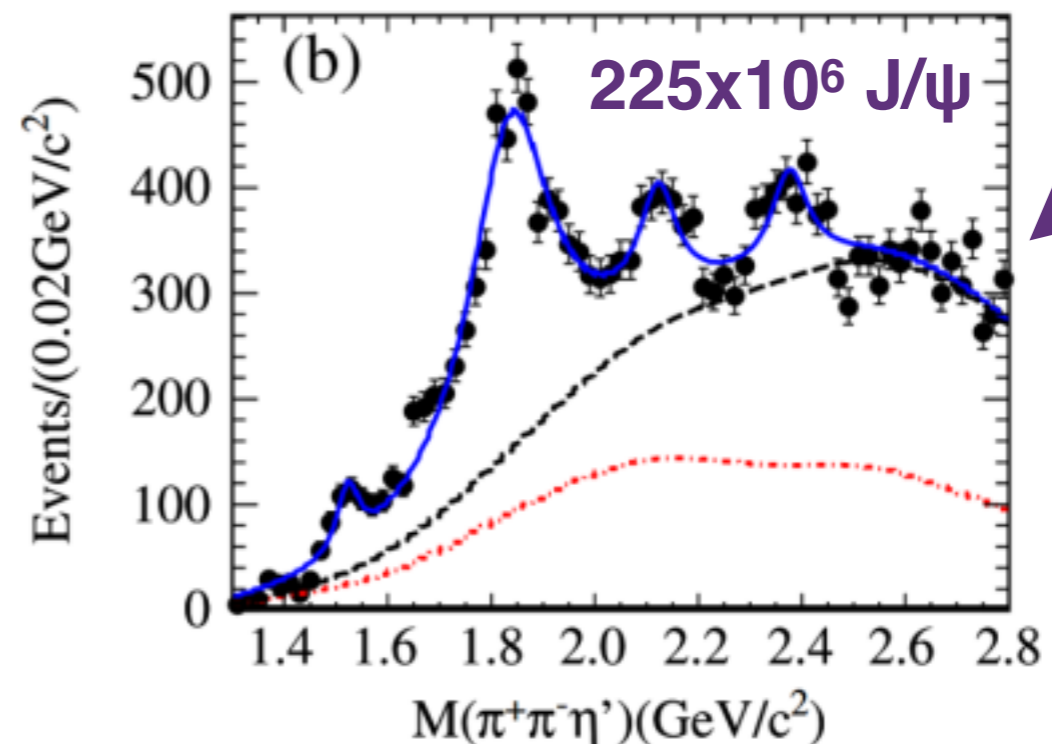
Precision and Spectroscopy: BES III & $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- Search by BES for resonances in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ in e^+e^- annihilation
- Structure seen near $2M(p)$
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BES II: PRL 95, 262001 (2005)



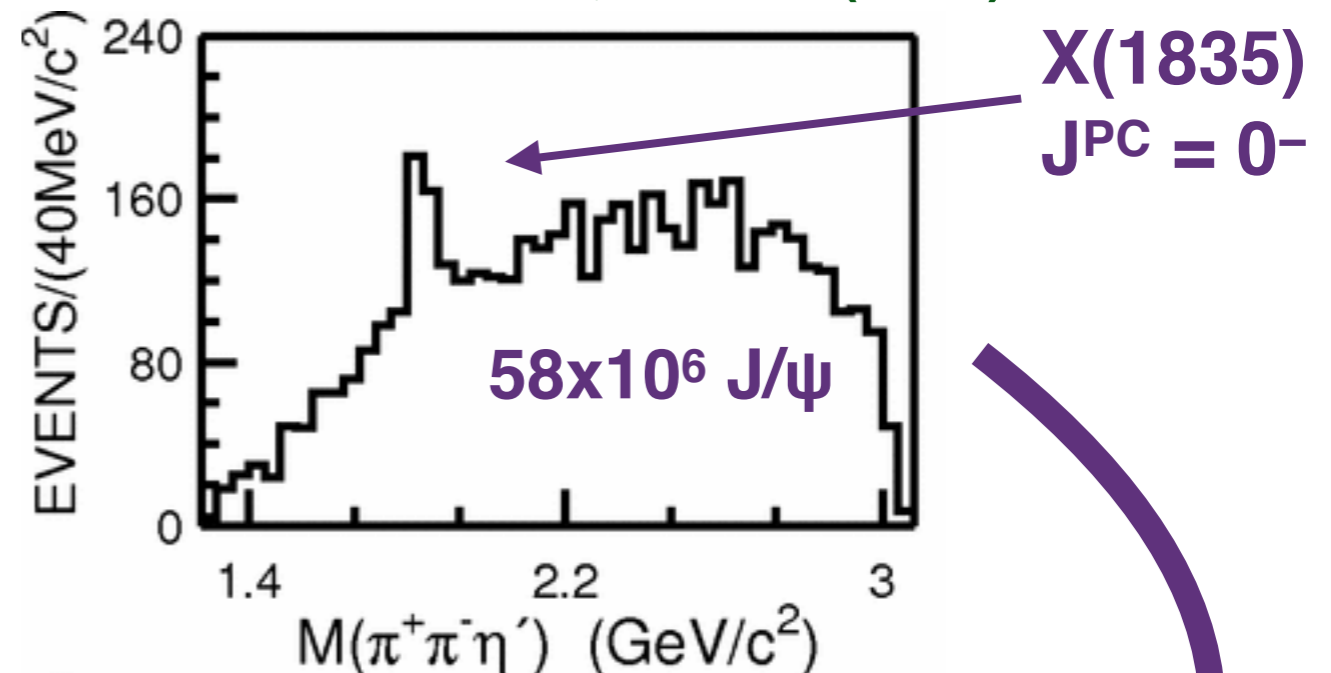
BESIII: PRL 106, 072002 (2011)



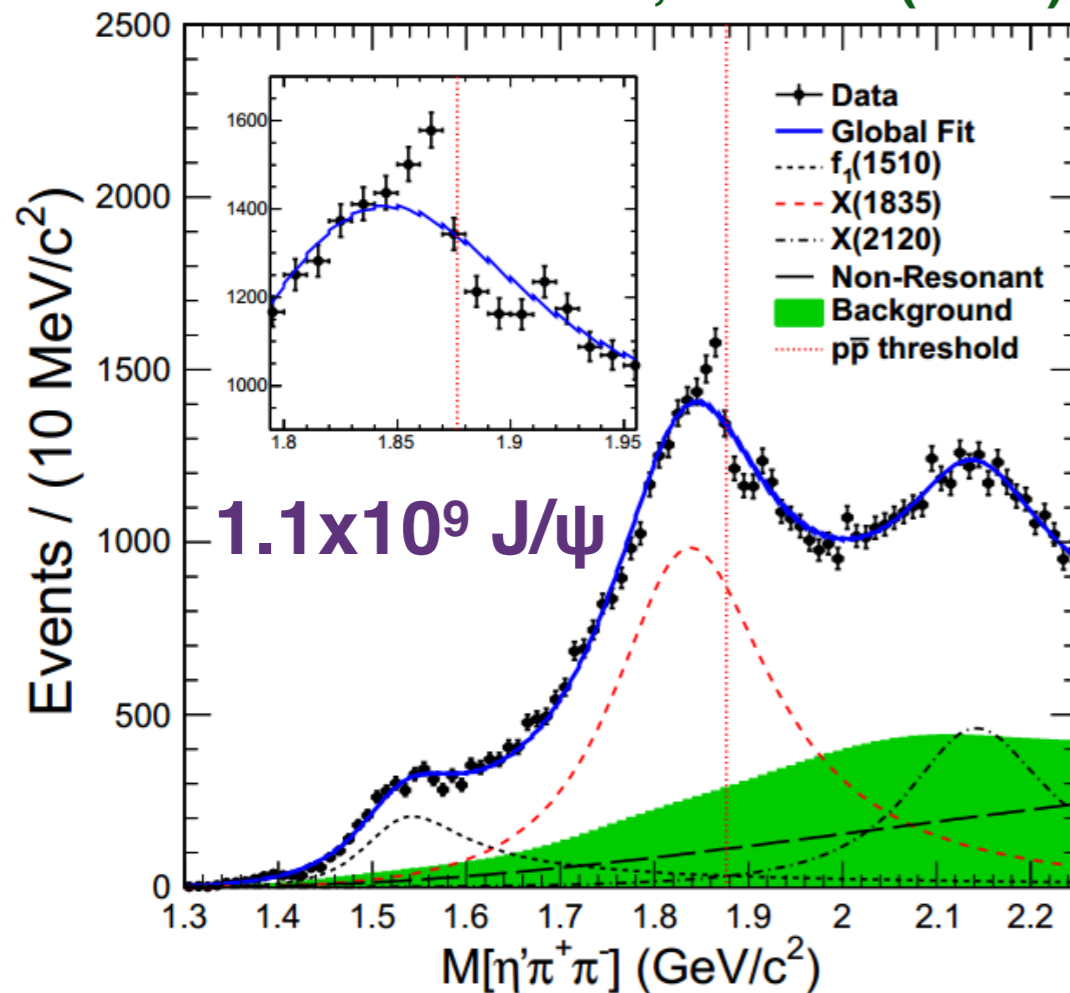
Precision and Spectroscopy: BES III & $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- Search by BES for resonances in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ in e^+e^- annihilation
 - Structure seen near $2M(p)$
 - More data reveals more complexity, more sophisticated analysis required

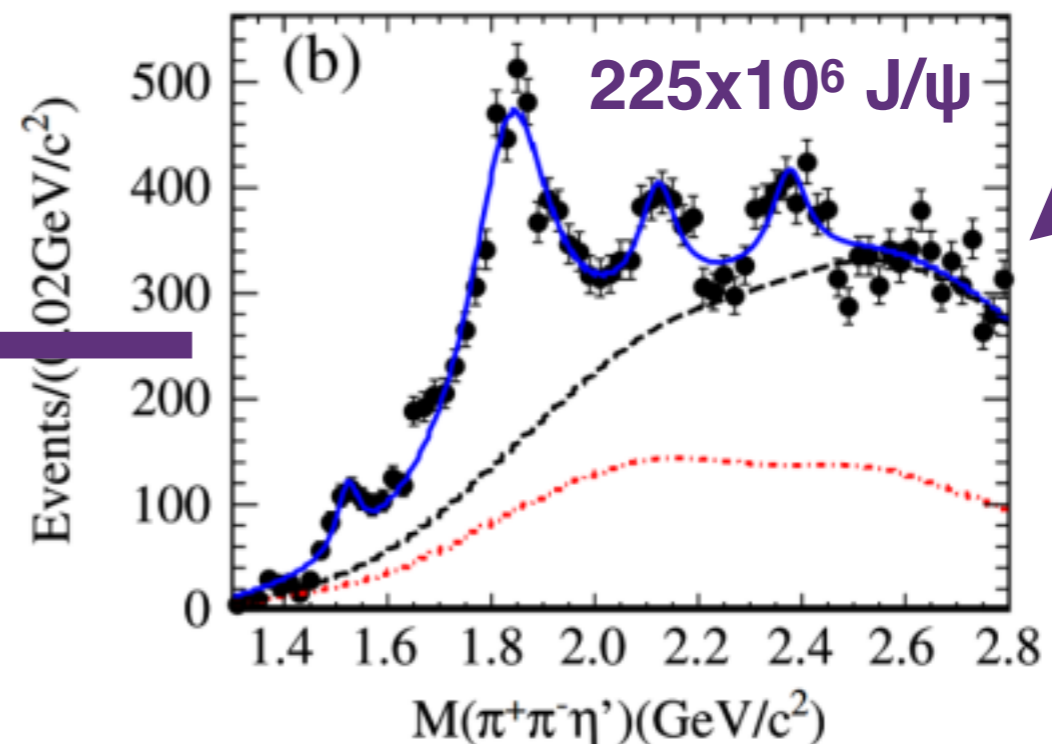
BES II: PRL 95, 262001 (2005)



BESIII: PRL 117, 042002 (2016)



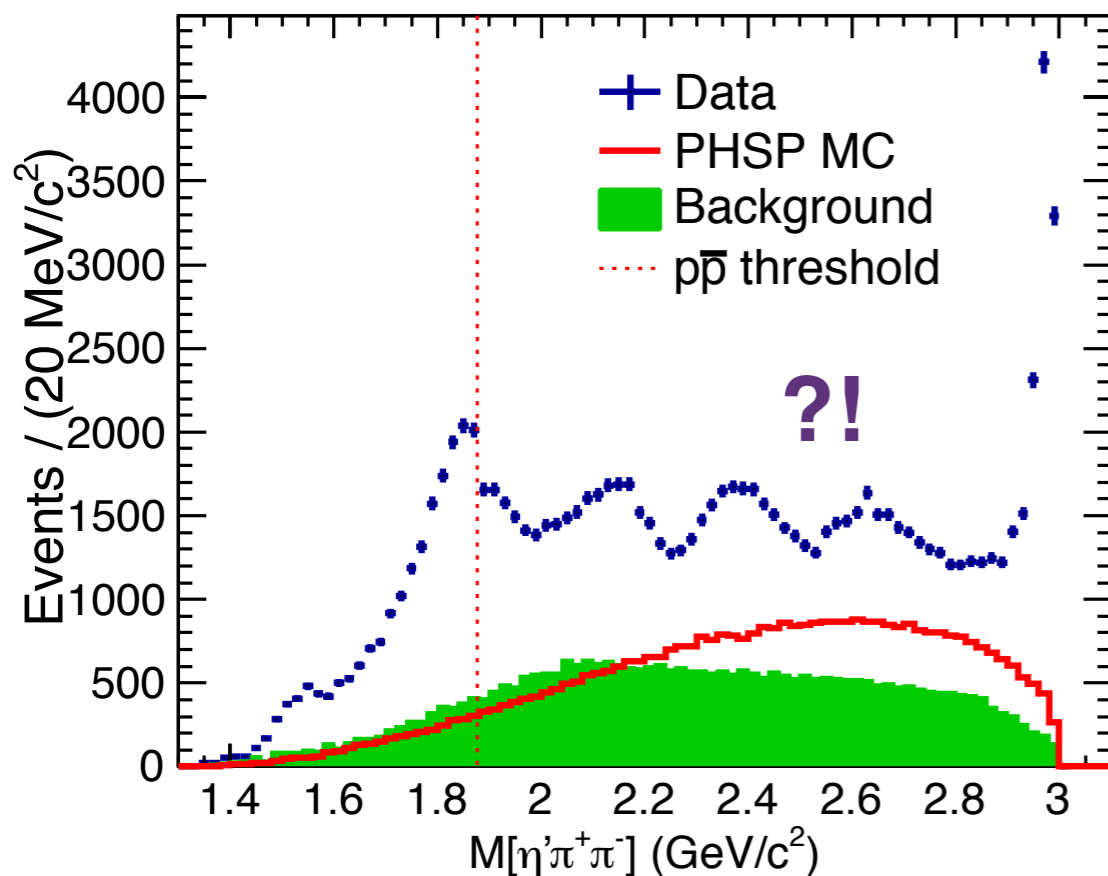
BESIII: PRL 106, 072002 (2011)



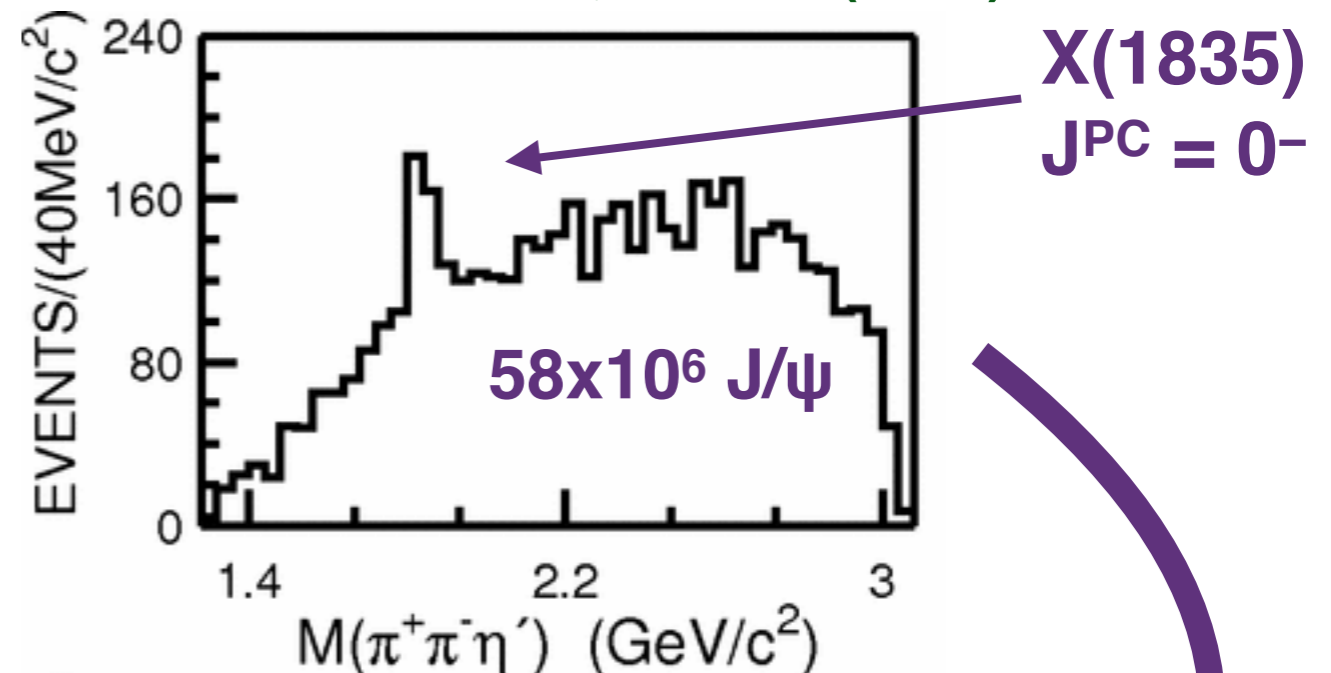
Precision and Spectroscopy: BES III & $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$

- Search by BES for resonances in $J/\psi \rightarrow \gamma \eta' \pi^+ \pi^-$ in e^+e^- annihilation
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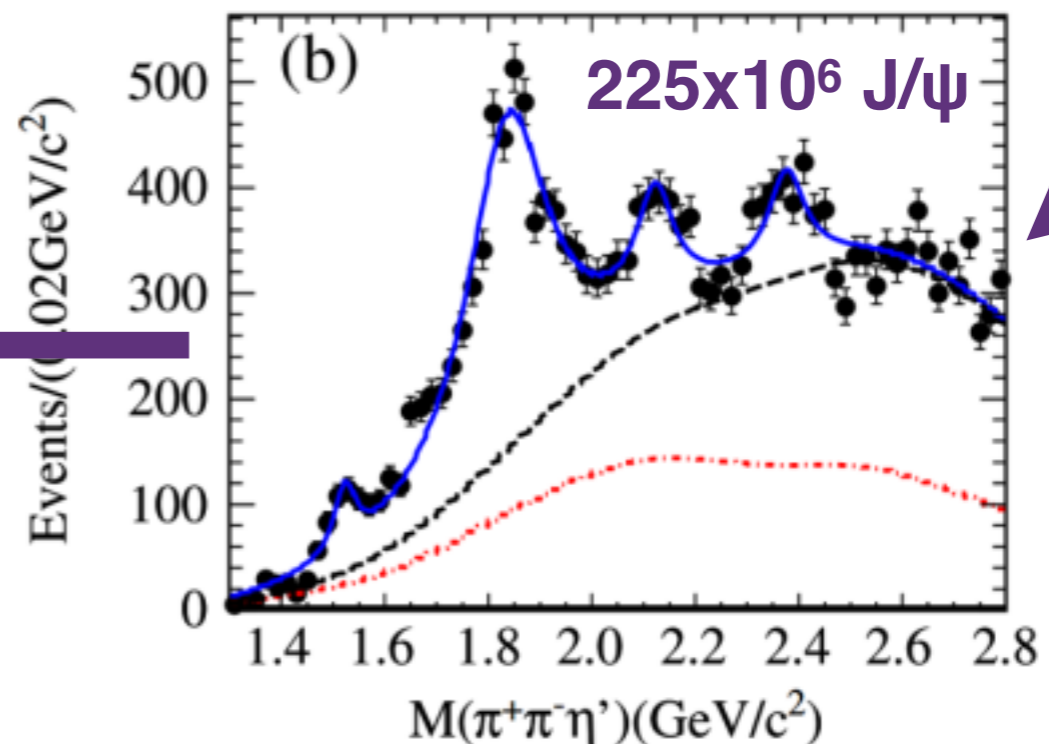
BESIII: PRL 117, 042002 (2016)



BES II: PRL 95, 262001 (2005)

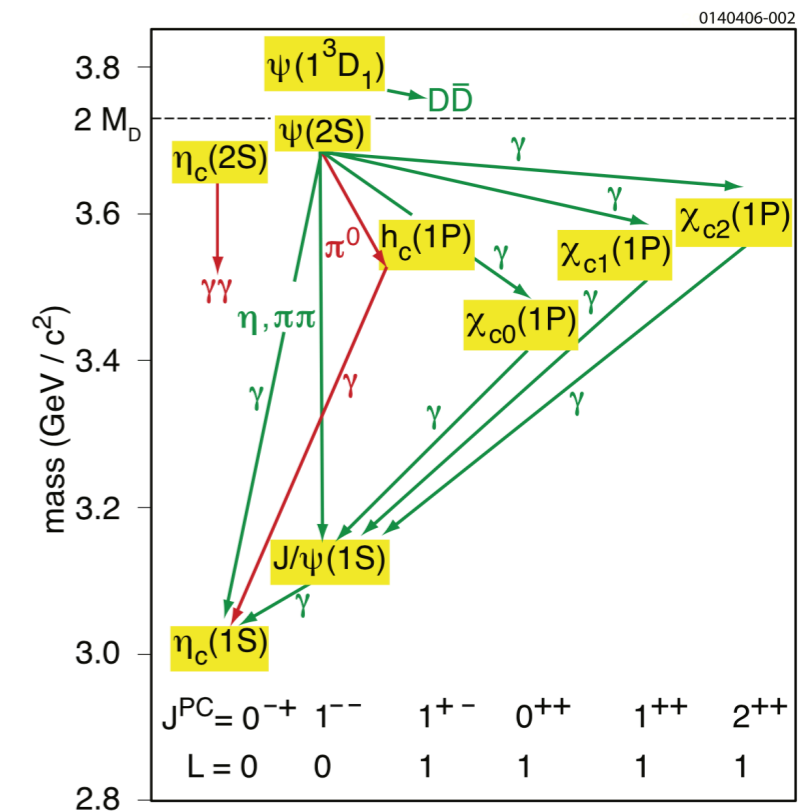
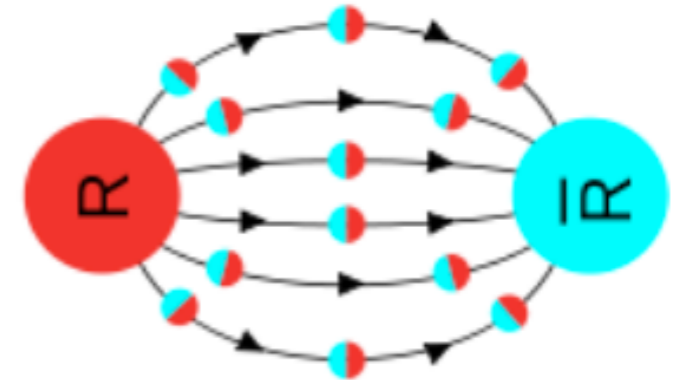


BESIII: PRL 106, 072002 (2011)



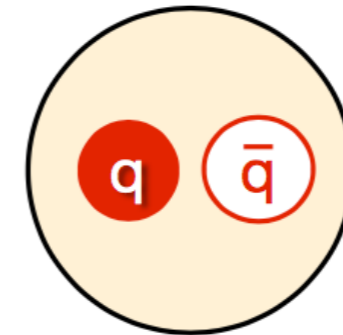
Introduction

- Quantum Chromodynamics (**QCD**)
 - Degrees of freedom: **quarks** and **gluons**
 - Rich spectrum of bound states predicted
 - Outstanding questions remain
e.g., What is the nature of confinement?
- New understanding gained by studying spectrum of bound QCD states
 - Recent progress in understanding hadron spectrum driven by large, high-quality data sets
 - New theoretical tools essential for accurately interpreting this data

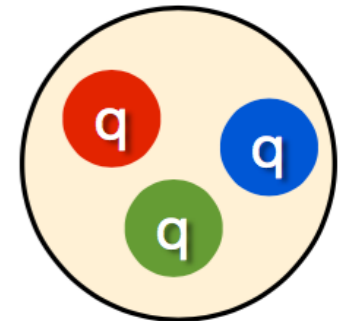


QCD and Hadron Spectroscopy

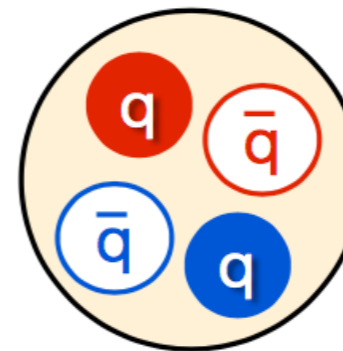
- Idea: study QCD through spectrum of bound states
 - Static properties of known hadrons well described by first-principles calculations
 - Modern experiments provide unprecedented data sets to push boundaries of our knowledge
- Open questions:
 - What is the origin of confinement?
 - Which color-singlet states exist in nature?
 - **Do gluonic degrees of freedom manifest themselves in the bound states that we observe?**



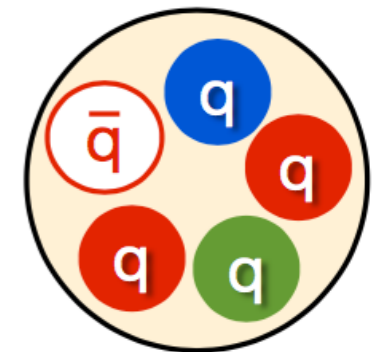
mesons



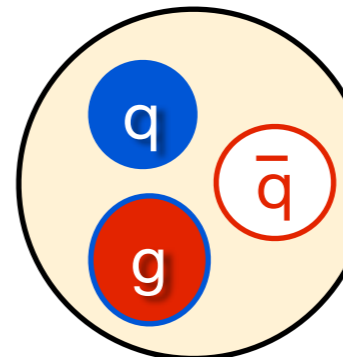
baryons



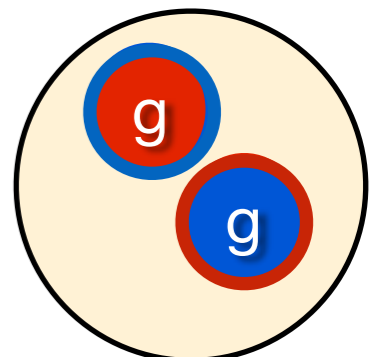
tetraquark



pentaquark



hybrid meson



glueball