From Light Hadrons to Charm: Early Results From GlueX

Sean Dobbs
Northwestern U.

GlueX Physics Symposium
Jefferson Lab
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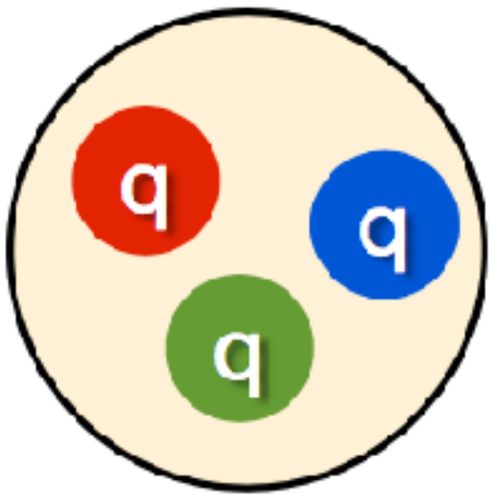
QCD and Hadron Spectroscopy

- Hadrons make up most of the visible mass of the universe.
  - Bound states of quarks that interact via gluons
- Quarks have “color charge” analogous to electric charge
  red, **green**, **blue**

Meson

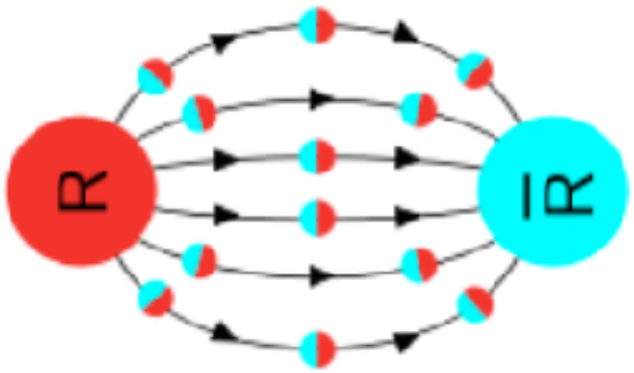
- Quarks confined into color neutral (“color-singlet”) combinations.
  Example: **qq̄** mesons
  qqq baryons

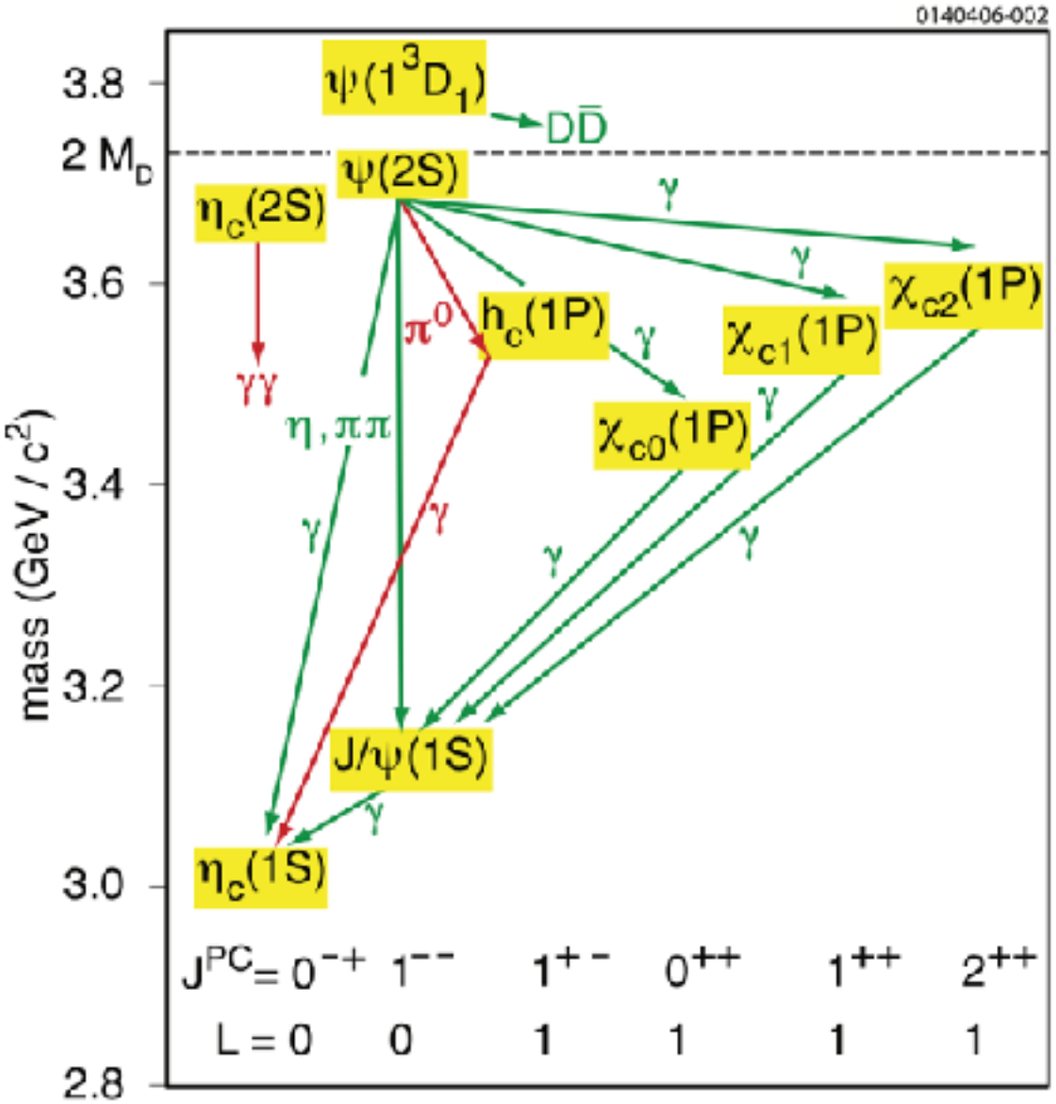


Baryon

QCD and Hadron Spectroscopy

- Quantum Chromodynamics (QCD) describes interaction of quarks and gluons.
  - Predicts spectrum of bound states.
  - Short-range “Coulombic” interaction.
  - Long-range gluonic confinement



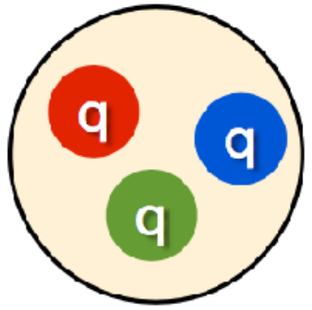


Charmonium
Bound Charm+Anticharm Quark States
“Hydrogen Atom” of QCD

Confined QCD States

What bound states of quarks and gluons do we know exist?

mesons



baryons

What bound states of quarks and gluons could exist in QCD?

Confined QCD States

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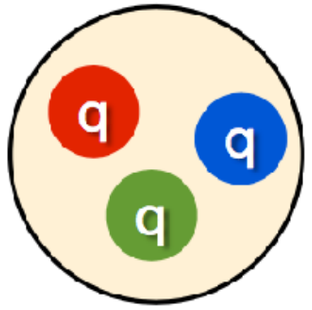


baryons

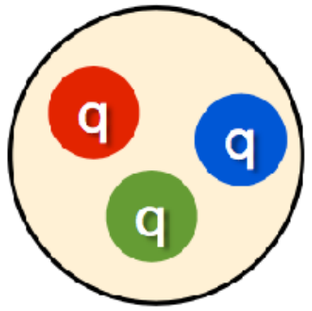
What bound states of quarks and gluons could exist in QCD?

Any color-singlet state!

Confined QCD States

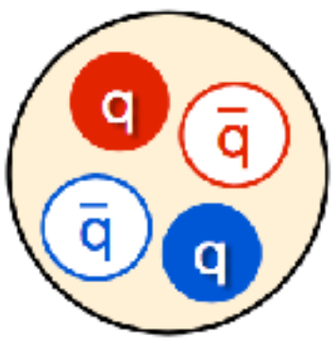
What bound states of quarks and gluons do we know exist?

mesons

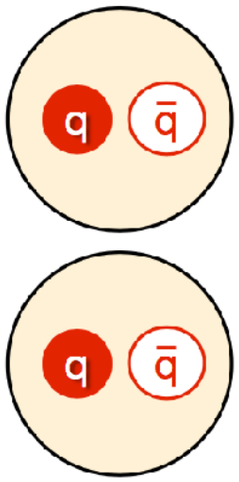


baryons

What bound states of quarks and gluons could exist in QCD?

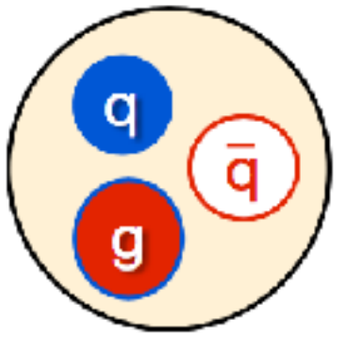


tetraquark



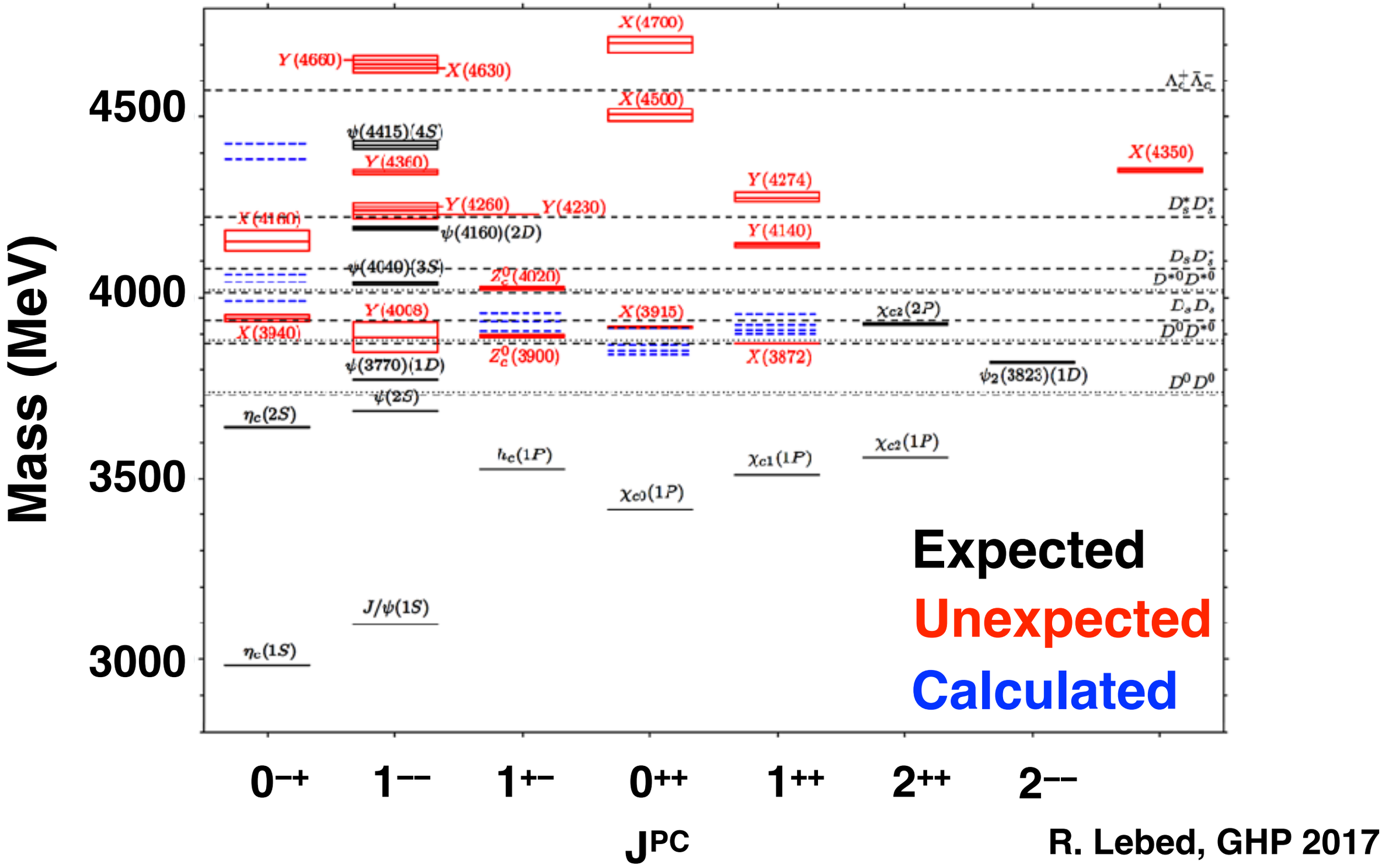
hadronic molecule

pentaquark



“hybrid” meson

Current State of Charmonium Spectrum



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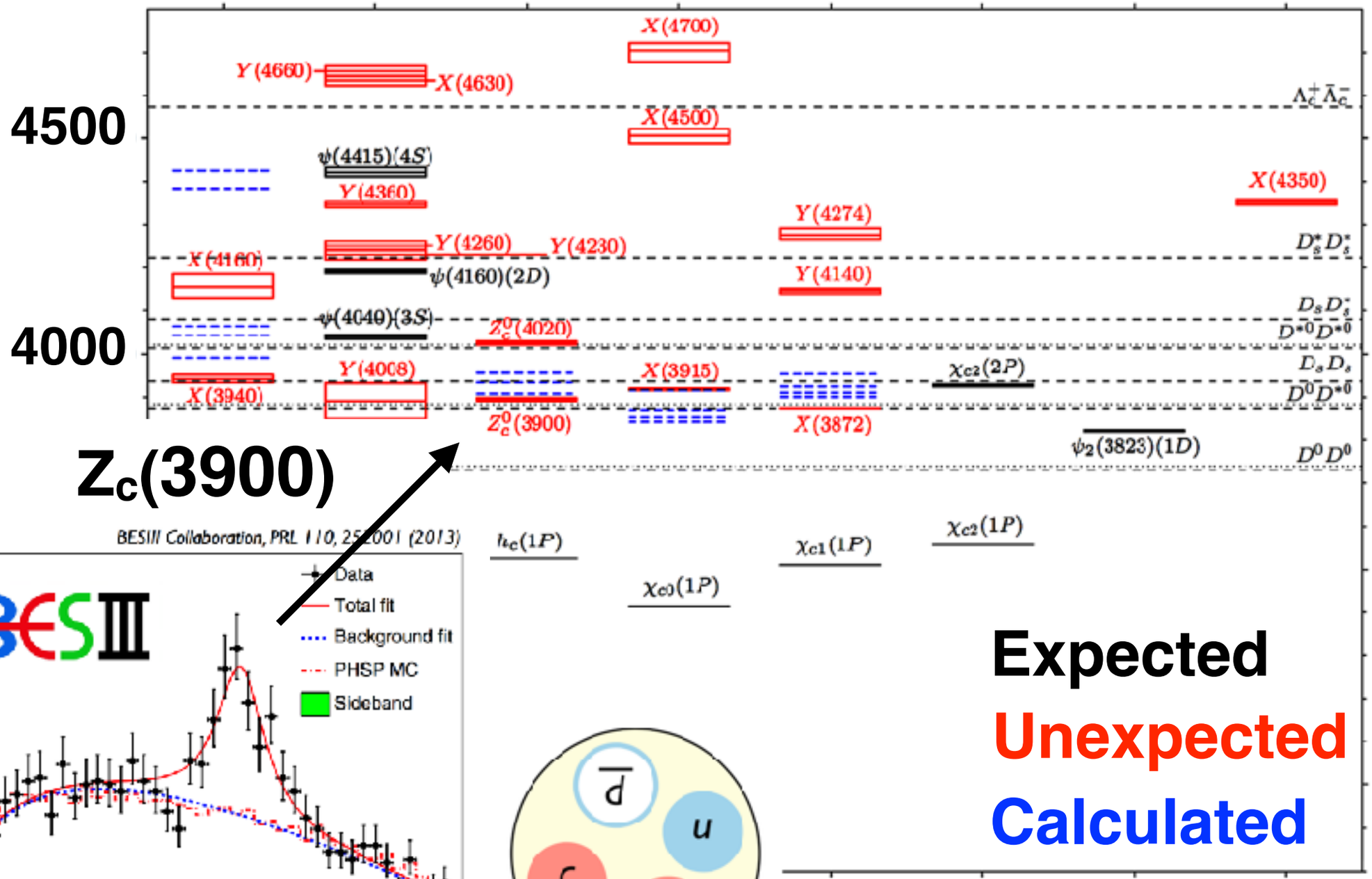
Current State of Charmonium Spectrum



Zc(3900)

Expected

Unexpected

Calculated

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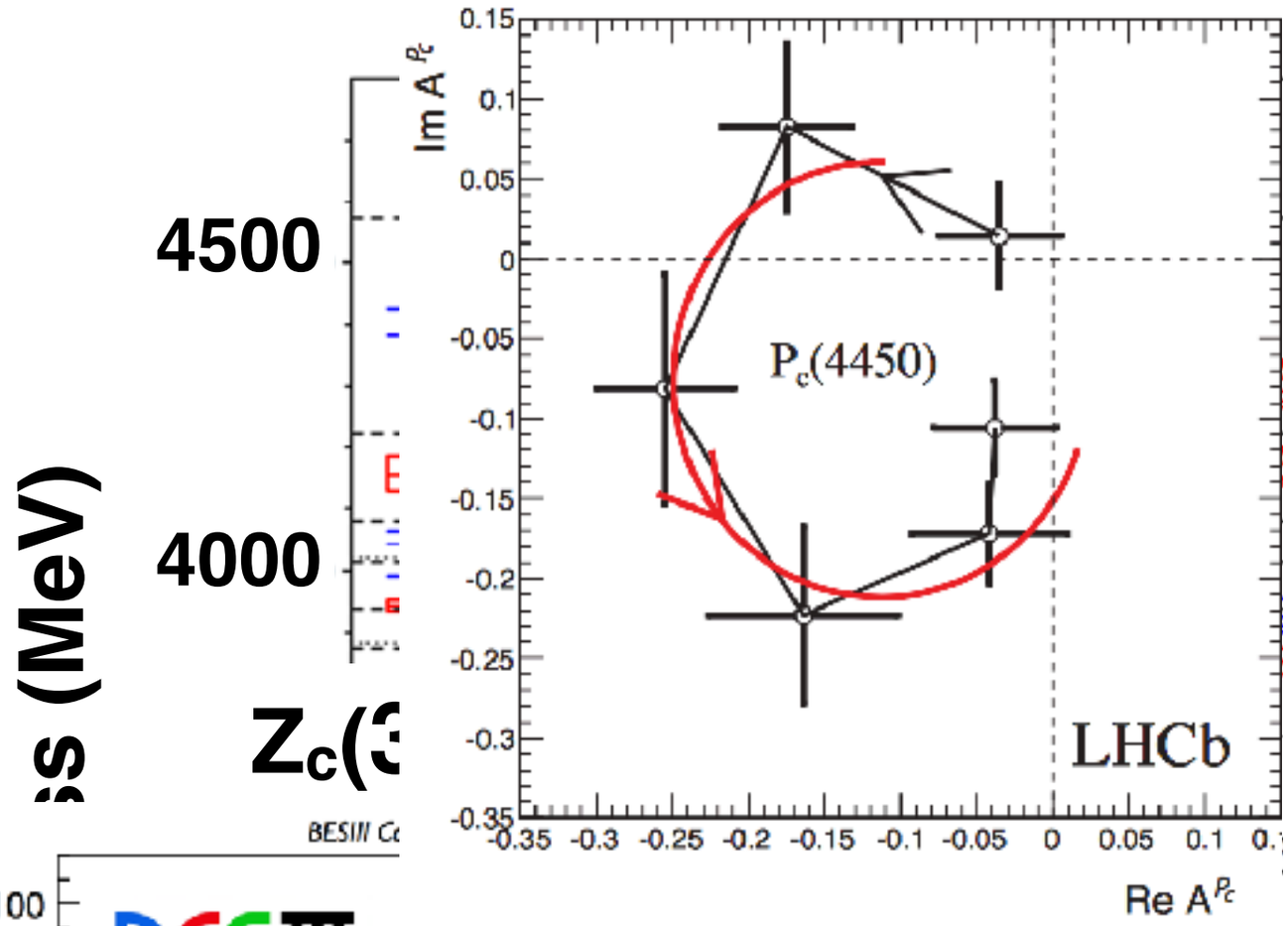

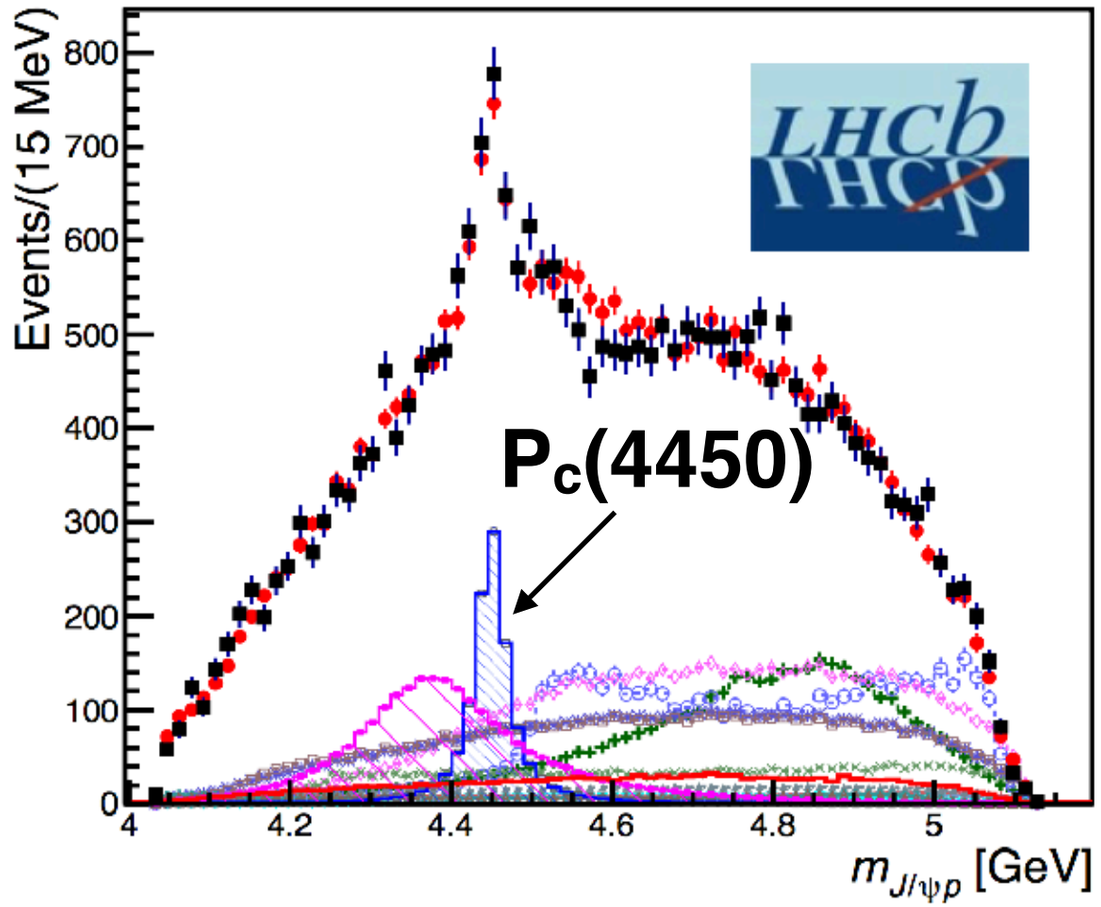

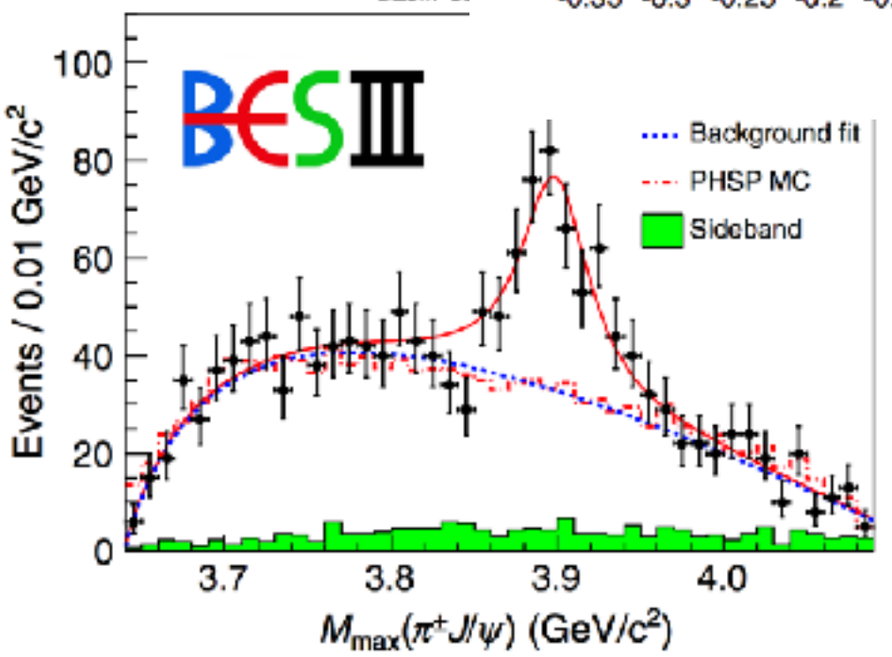

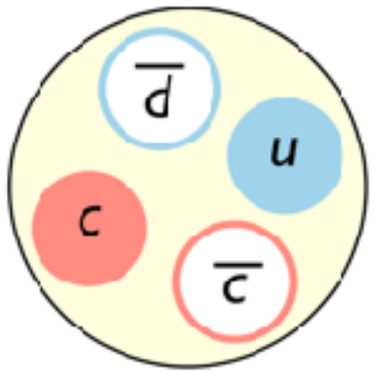

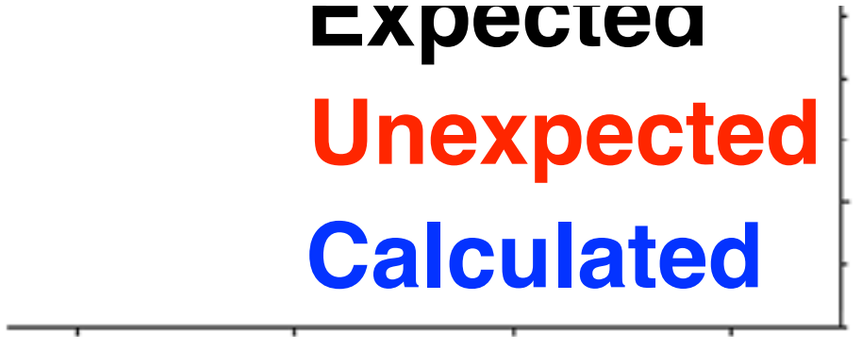

R. Lebed, GHP 2017

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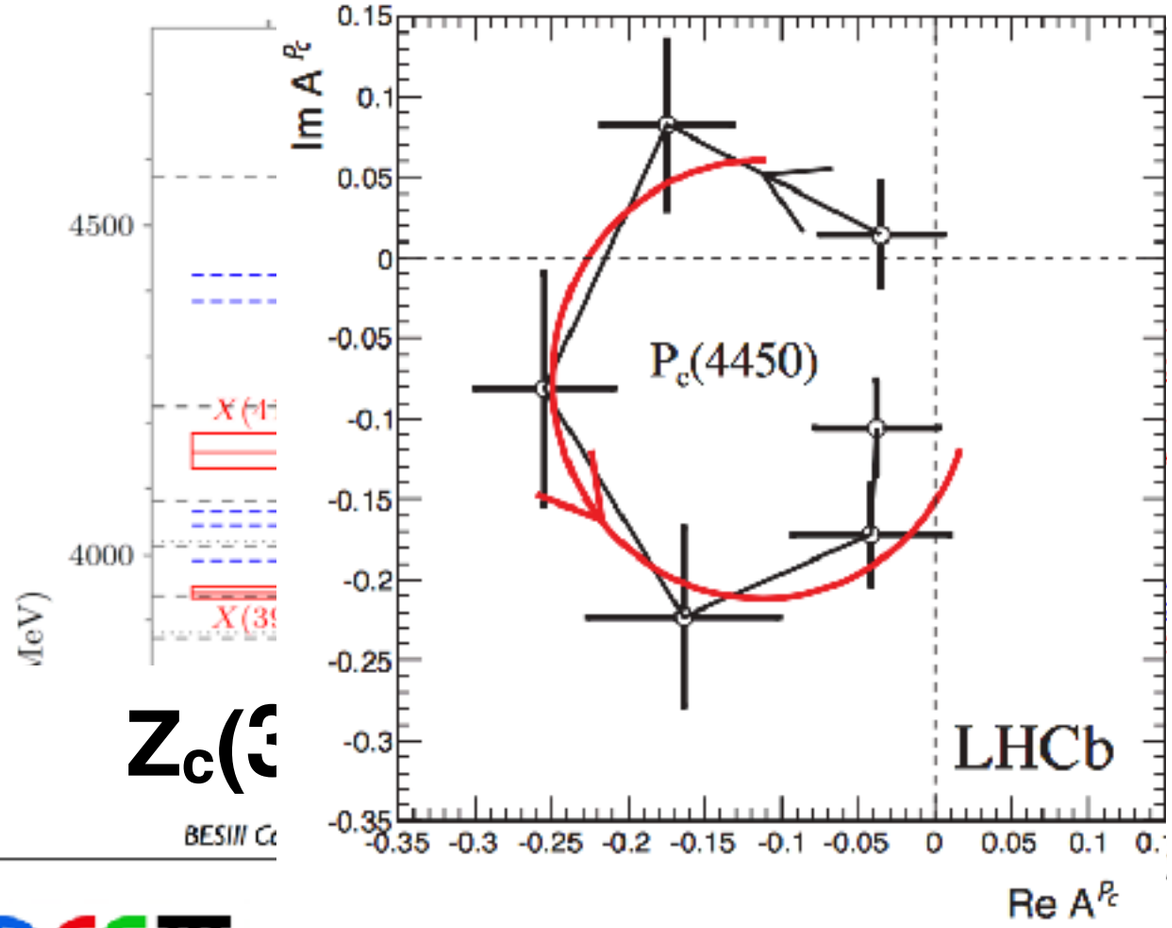
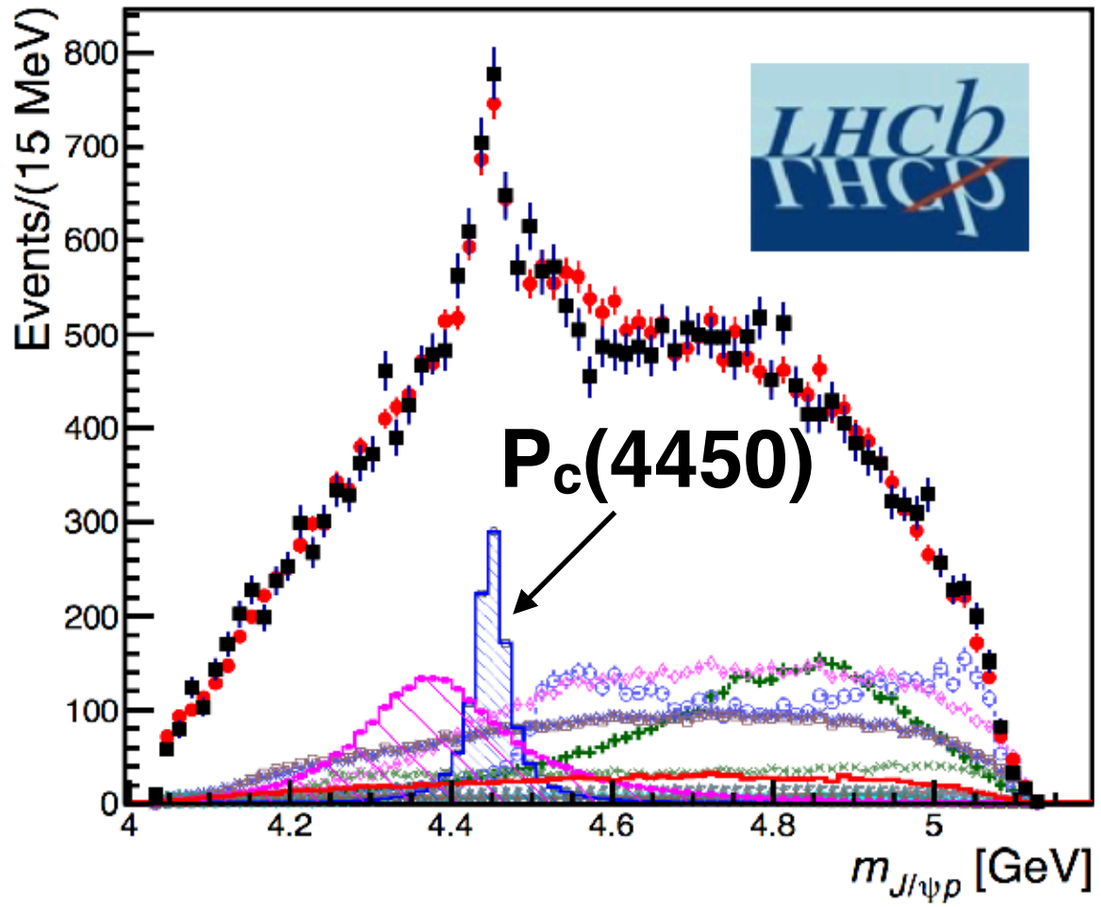
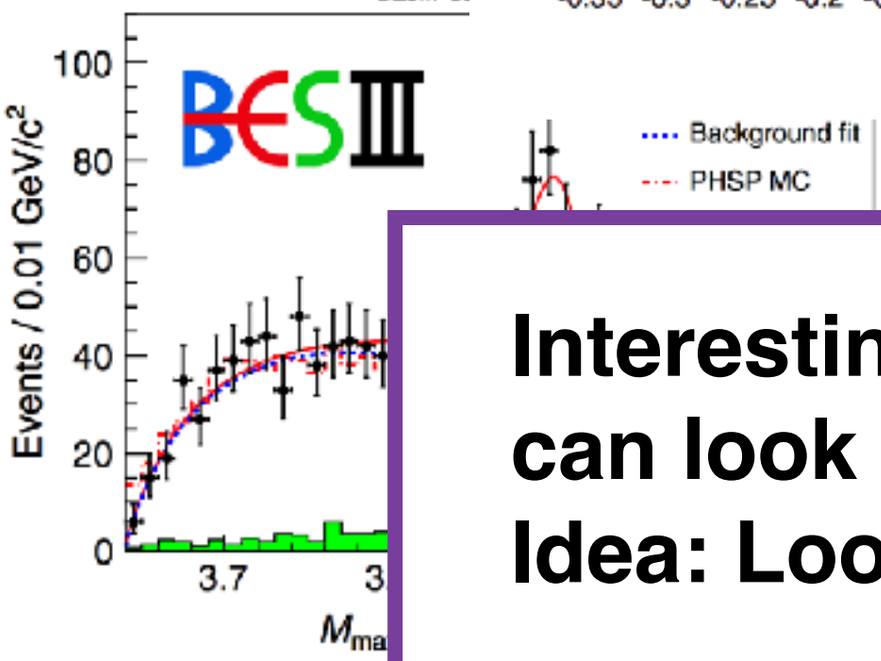




Z_c(3

BESIII Co



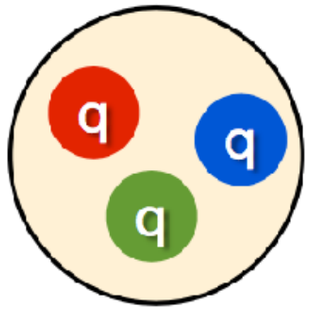
Expected

Interesting hints! For deeper understanding, can look to light-quark meson spectrum. Idea: Look for excitations of gluonic field

Confined QCD States

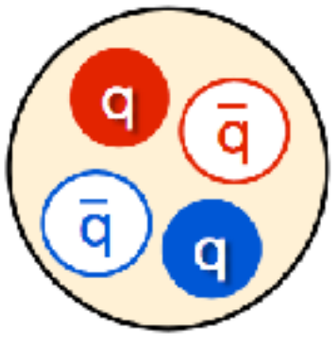
What bound states of quarks and gluons do we know exist?

mesons



baryon

What bound states of quarks and gluons co



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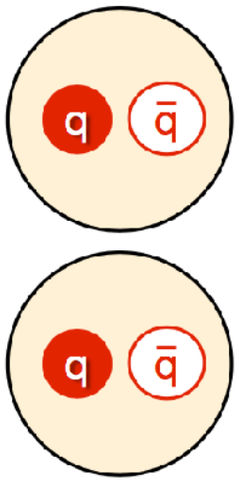

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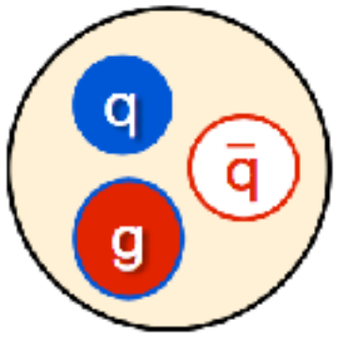
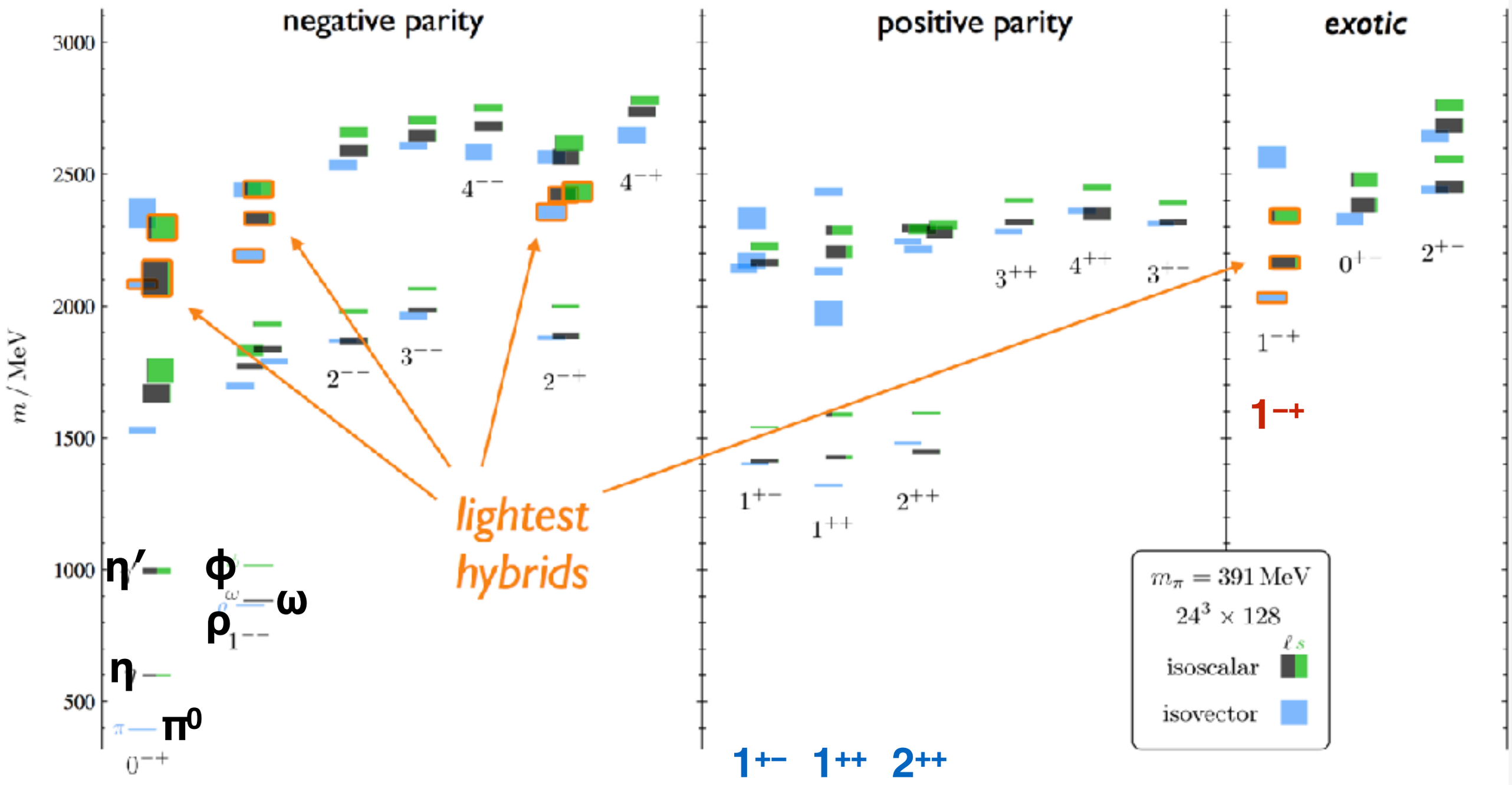


“hybrid” meson

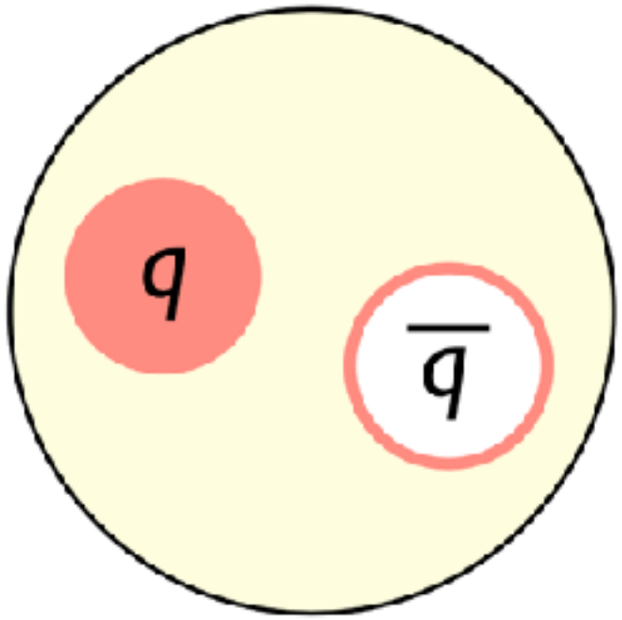
Light Meson Spectrum from Lattice QCD



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

Meson Quantum Numbers

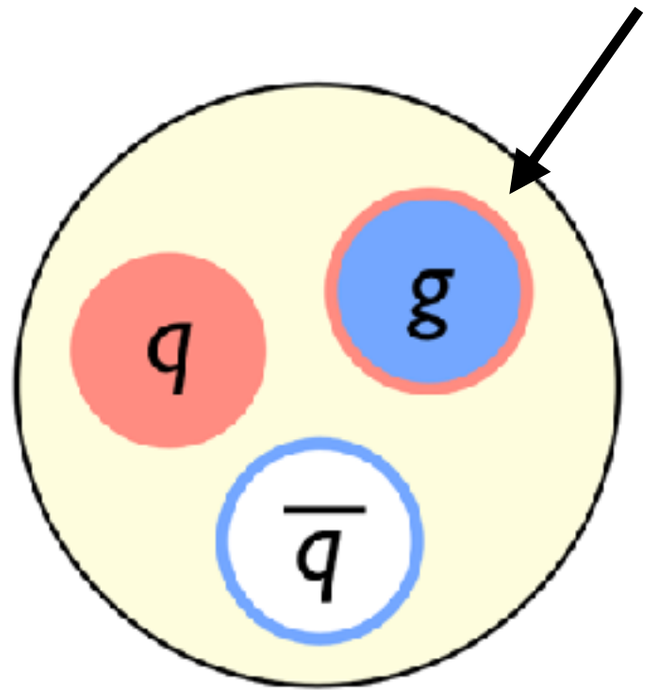
$J=L+S \quad P=(-1)^{L+1} \quad C=(-1)^{L+S}$



"Normal" Meson

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

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

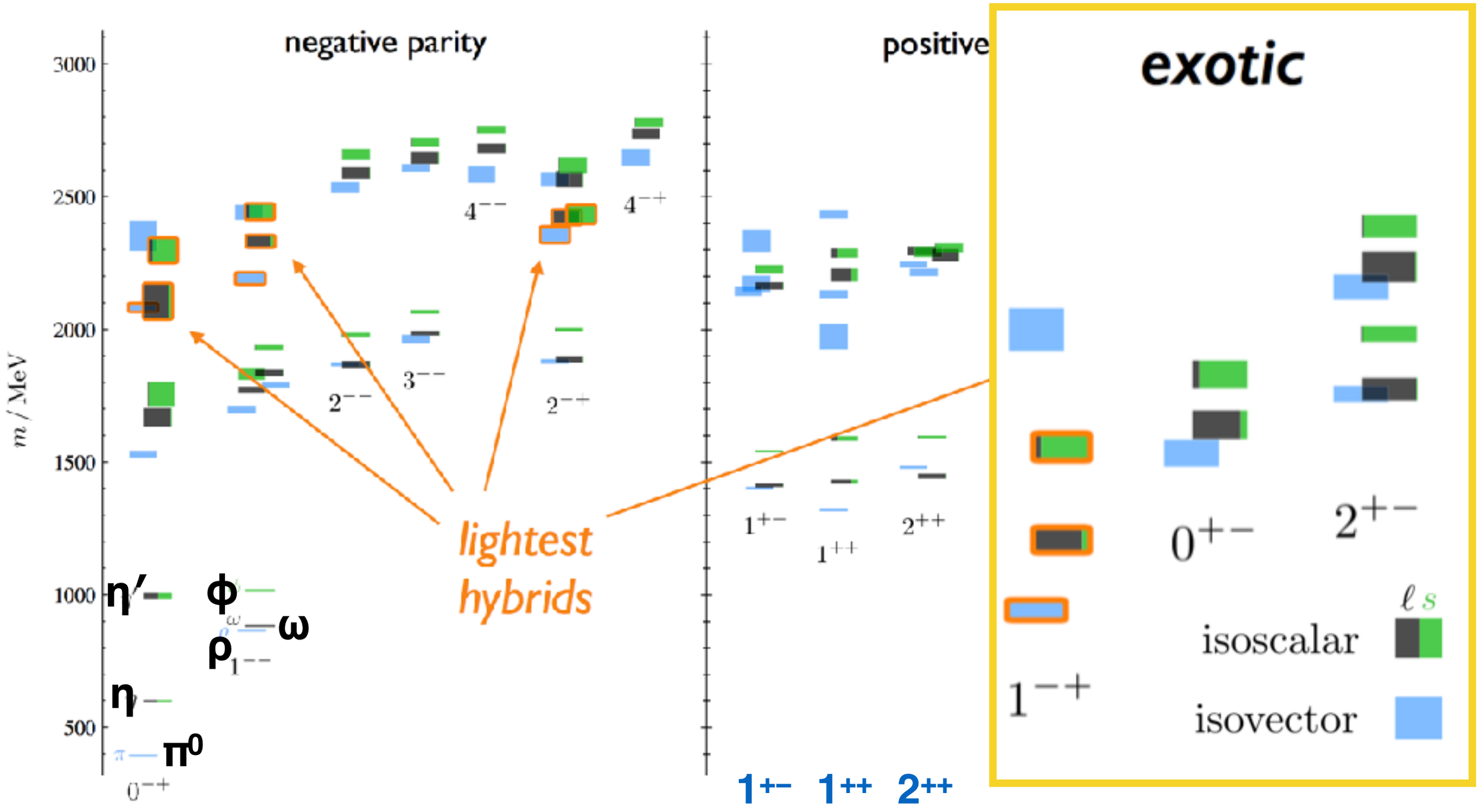


"Hybrid" Meson

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

Hybrid–Meson mass splitting ~ 1.0 – 1.5 GeV

Light Meson Spectrum from Lattice QCD



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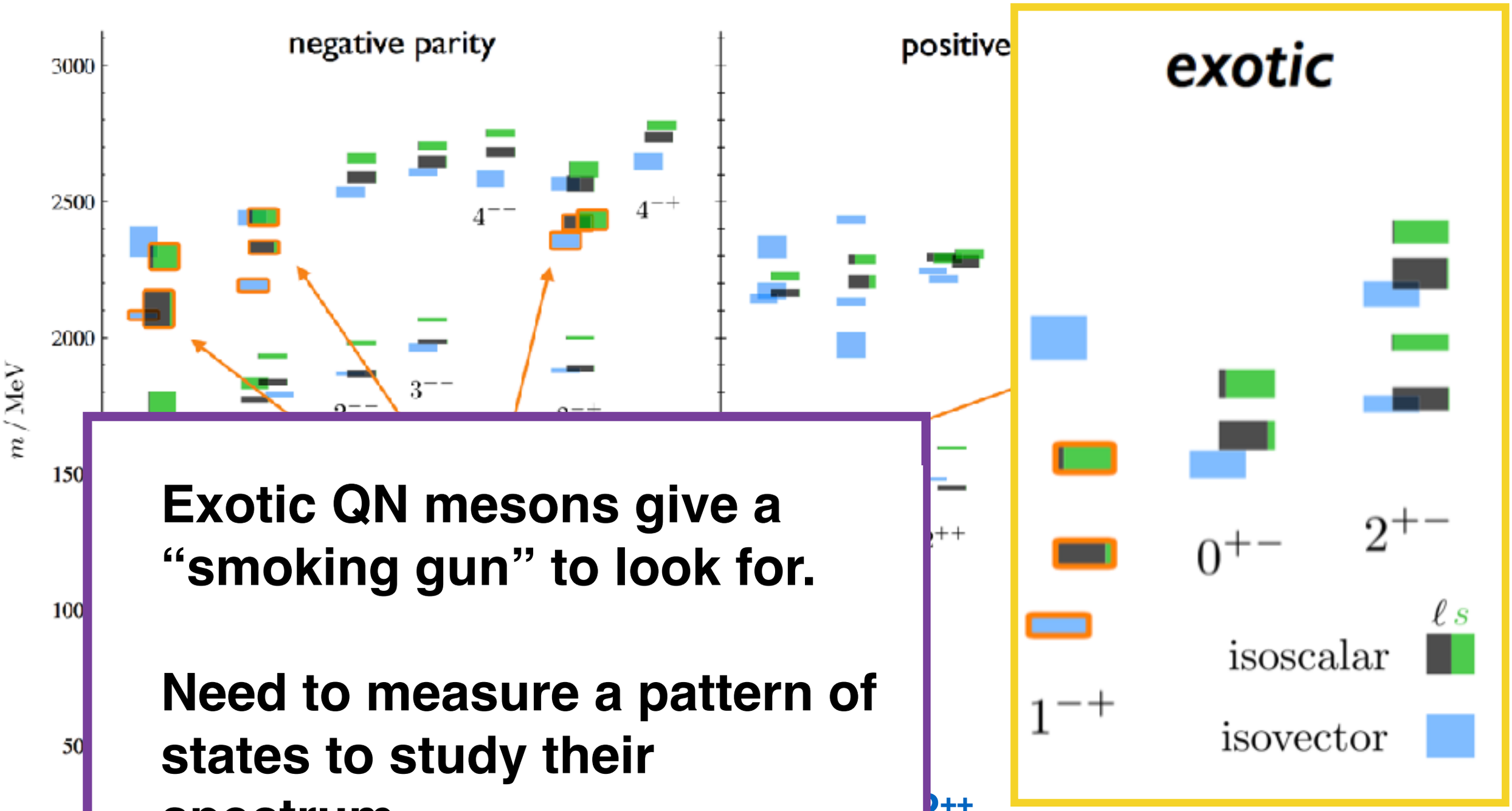
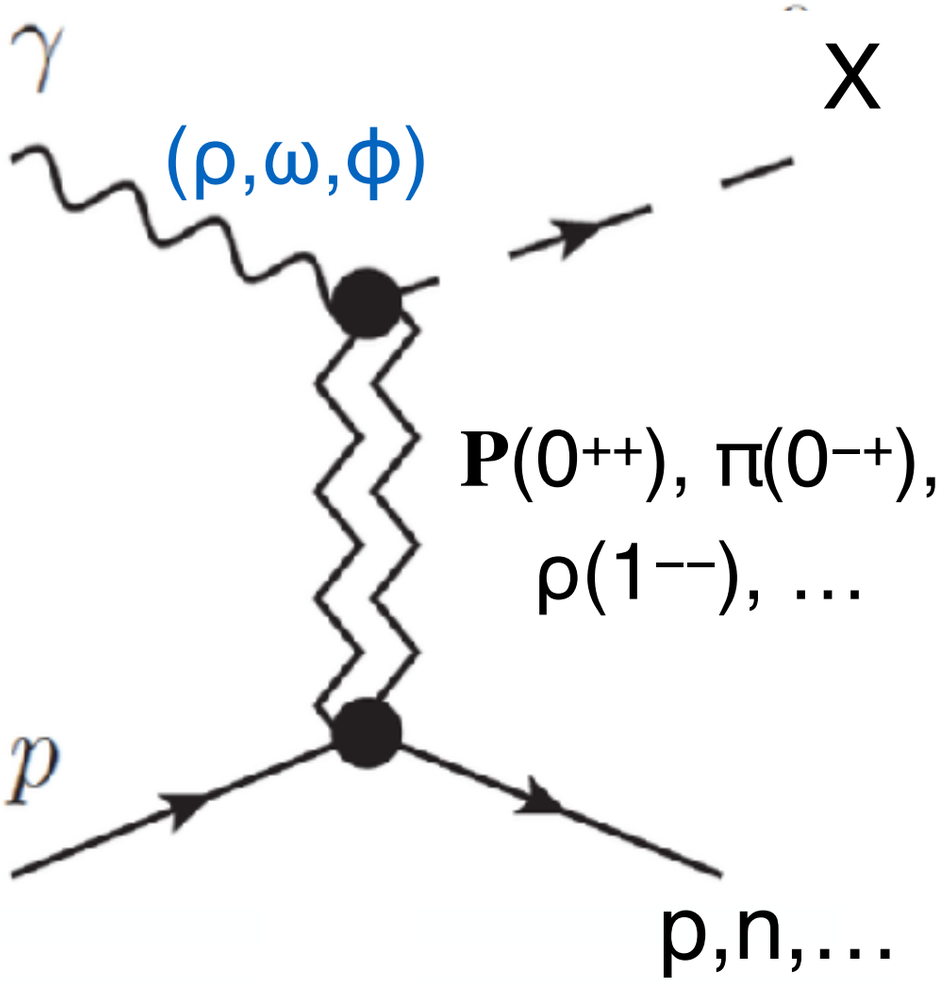


Exotic QN mesons give a "smoking gun" to look for.

Need to measure a pattern of states to study their spectrum.

Meson Photoproduction

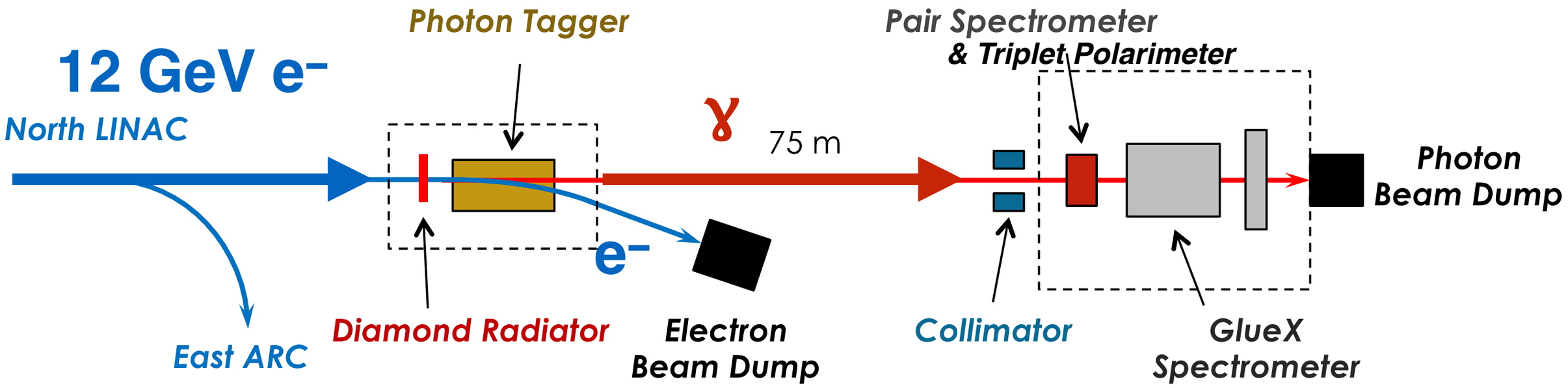


- Photon couples to exchanged QN via VMD, generates mesons with wide variety of J^{PC}
- Variety of hybrid decays expected, e.g.:
  - $\pi_1 \rightarrow \rho\pi, \pi b_1, \pi f_1$
  - $\eta_1 \rightarrow \eta f_2, \pi a_2, \eta f_1$
- Need to reconstruct charged and neutral particles
  - Neutral final states at these energies are mostly unexplored
- Photon polarization provides constraints on production processes

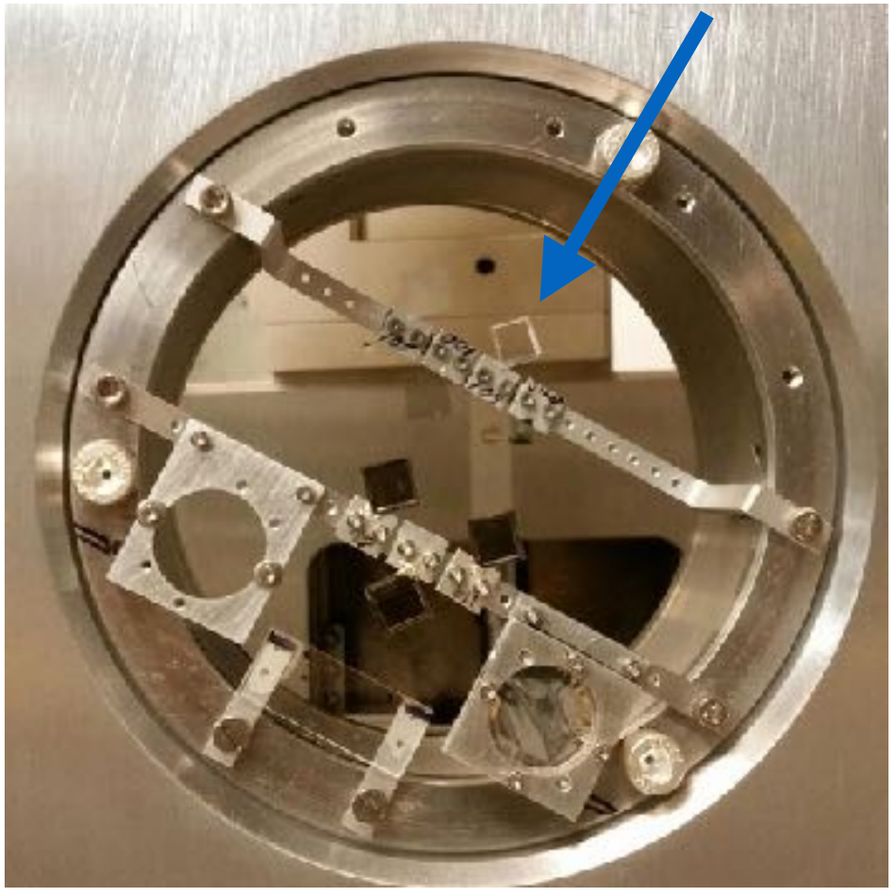
The GlueX Experiment in Hall D @ JLab

- 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

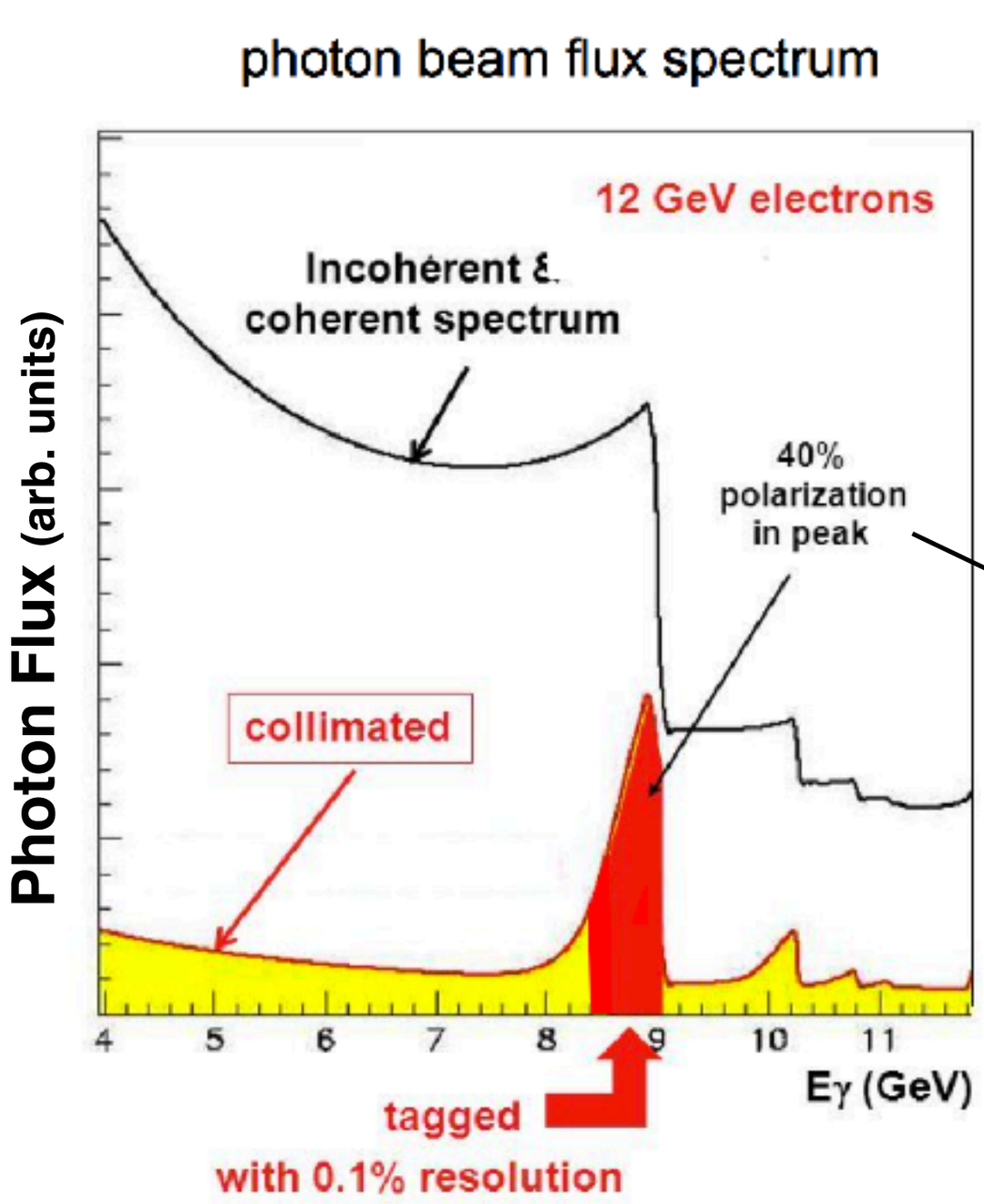
The GlueX Experiment: Photon Beamline

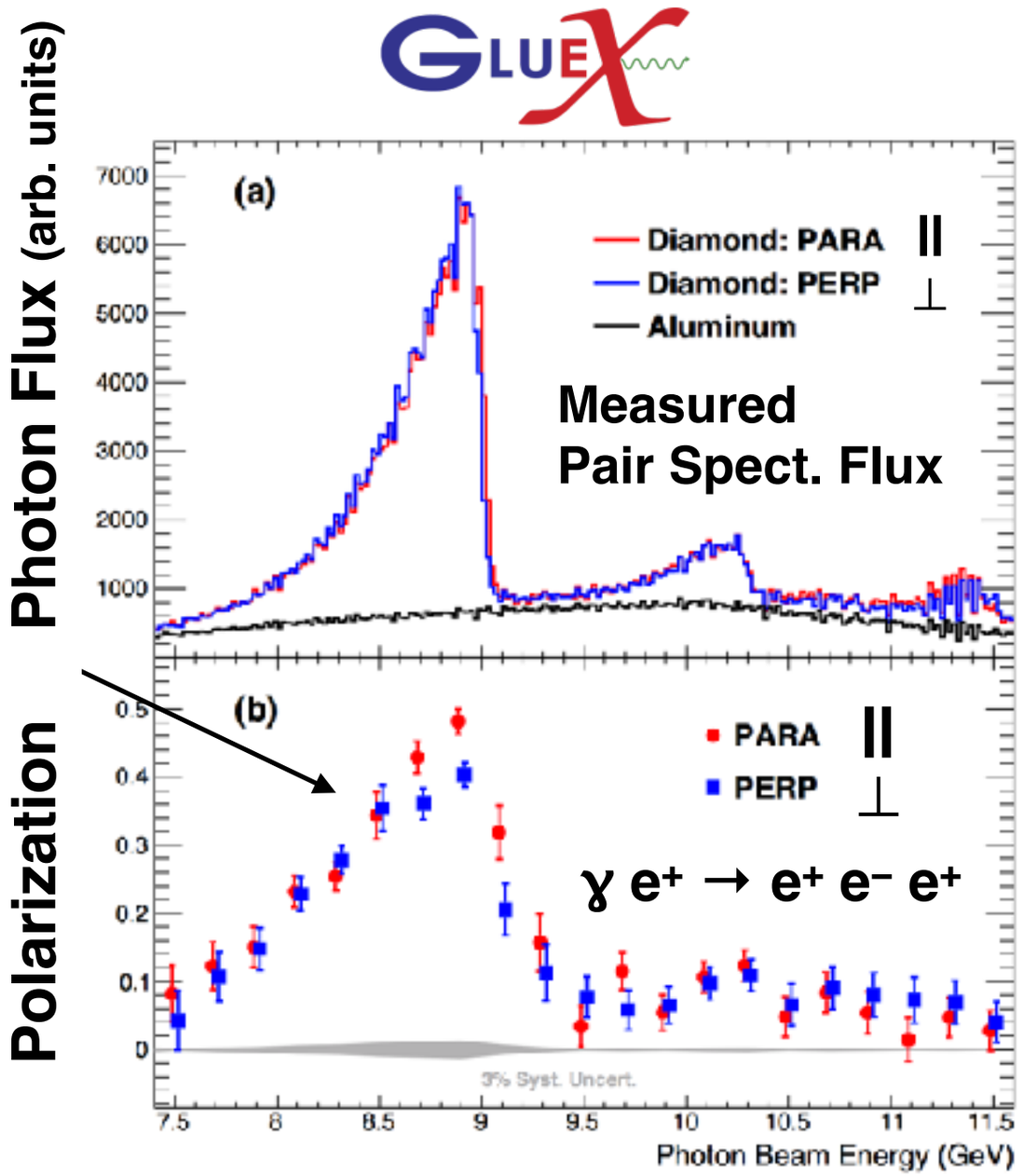


- Photon beam generated via coherent bremsstrahlung off thin diamond radiator
- Photon energies tagged by scattered electrons
  - Energy measurement precision < 25 MeV
- Photon linear polarization $P_\gamma \sim 40\%$ in peak
- Design intensity of 10^8 γ/s in peak



The GlueX Experiment: Photon Beam Spectrum





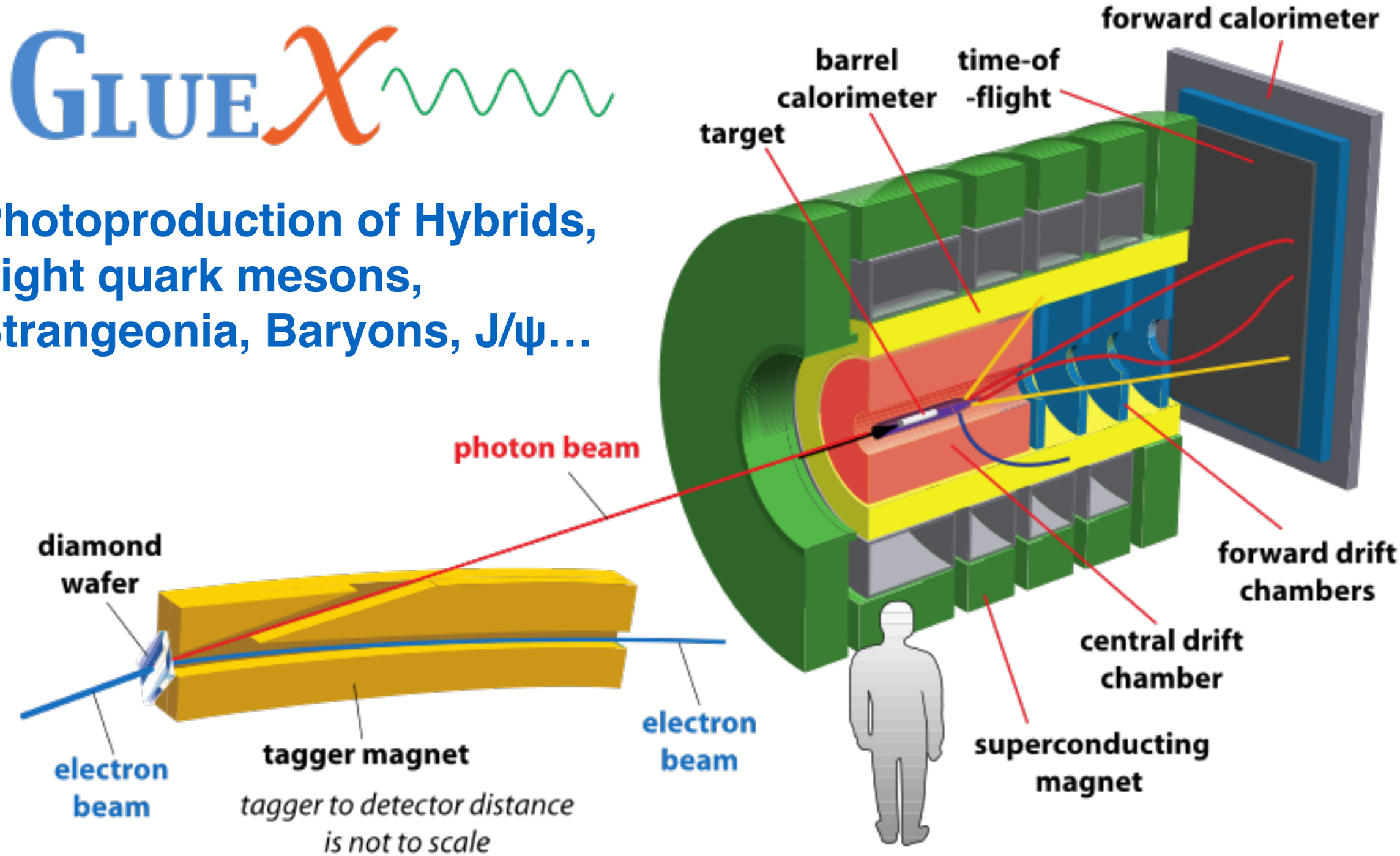
Calculated Spectrum

Measured Spectrum

The GlueX Experiment: Detector

GLUEX

Photoproduction of Hybrids,
Light quark mesons,
Strangeonia, Baryons, J/ψ…



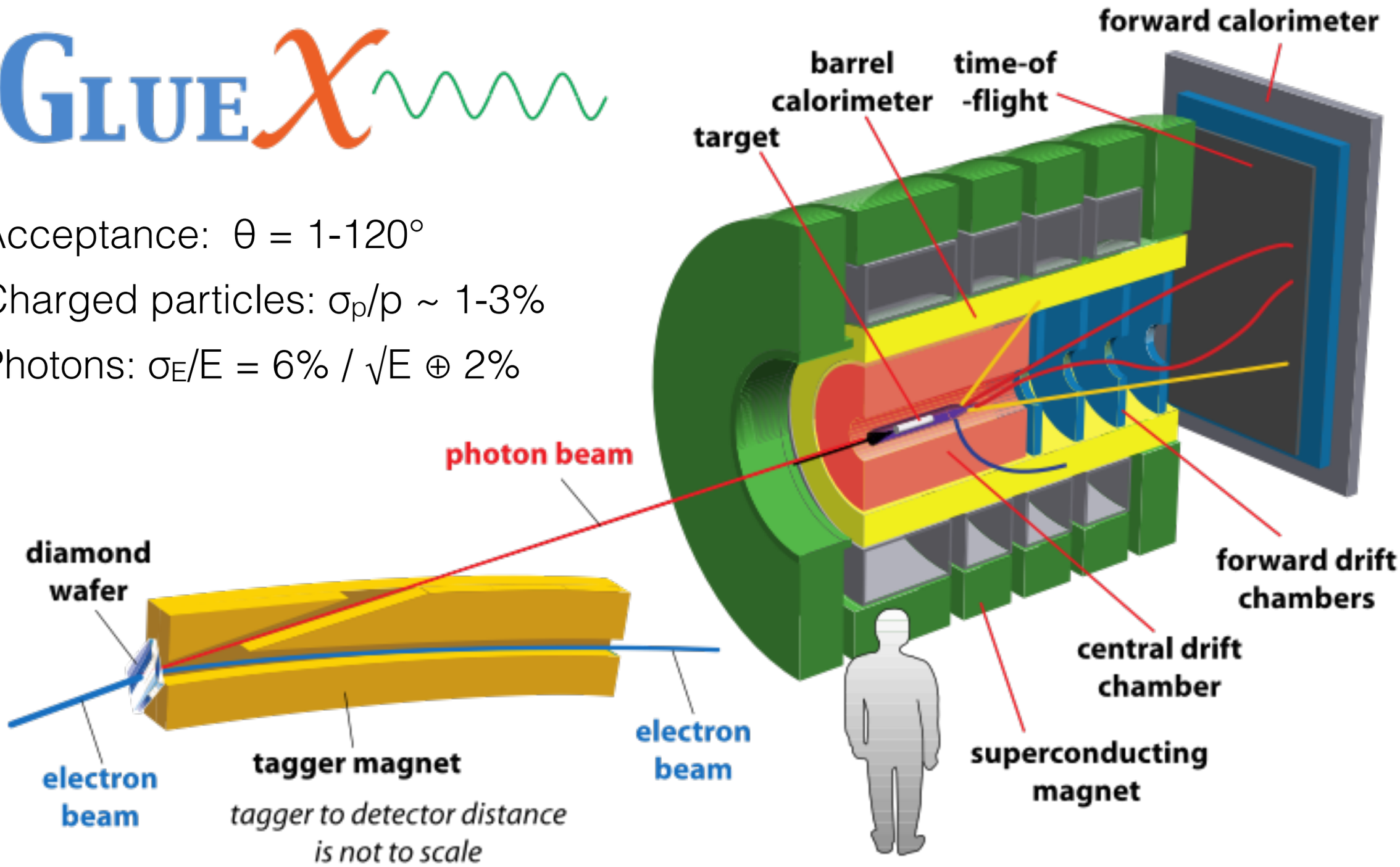
The GlueX Experiment: Detector

GLUEX

Acceptance: θ = 1-120°

Charged particles: $\sigma_p/p \sim 1\text{-}3\%$

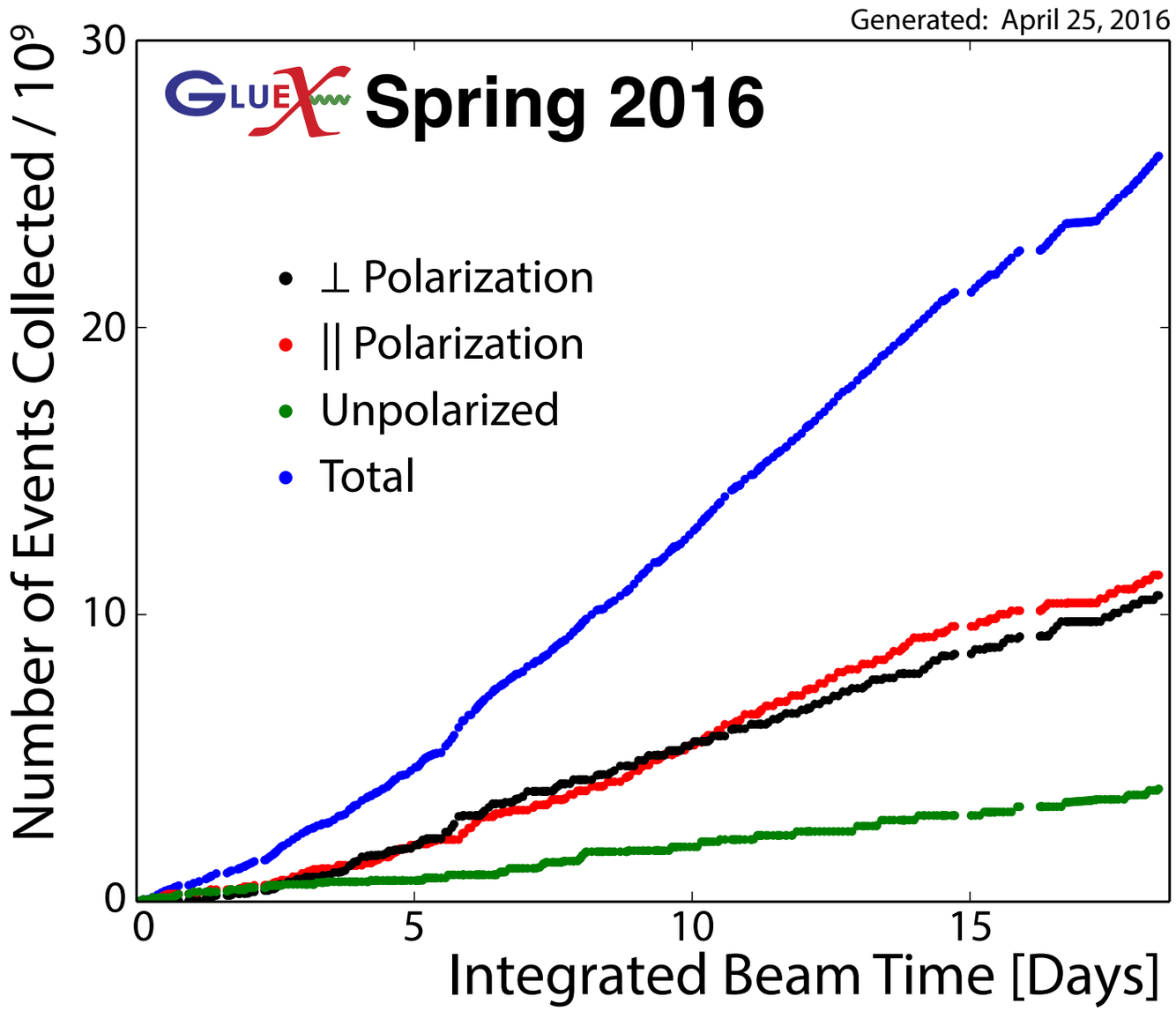
Photons: $\sigma_E/E = 6\% / \sqrt{E} \oplus 2\%$



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

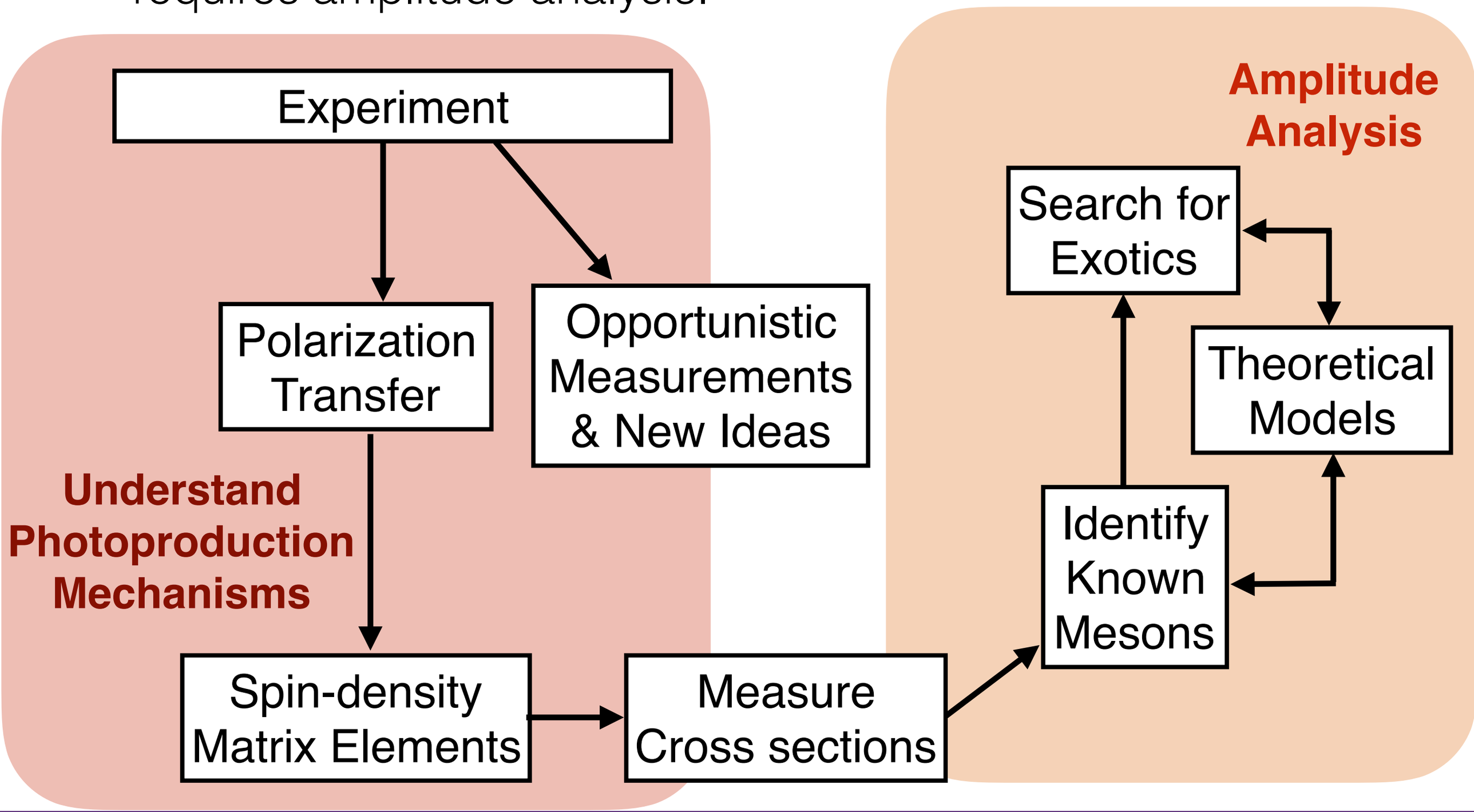
GlueX Running

- **Fall 2014—Spring 2015:**
  Detector + beamline commissioning
- **Spring 2016:**
  GlueX Engineering Run
  - Obtained initial physics data
  - Results shown today from ~80 hours of beam time
- **GlueX-I [low-intensity]: 2017-18**
  - Started last week,
    > half of 2016 data collected
  - 10x more data than 2016 planned
- **GlueX-II [high-intensity]: 2019+**
  - 100x current data with upgraded detector



Spectroscopy and Amplitude Analysis

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



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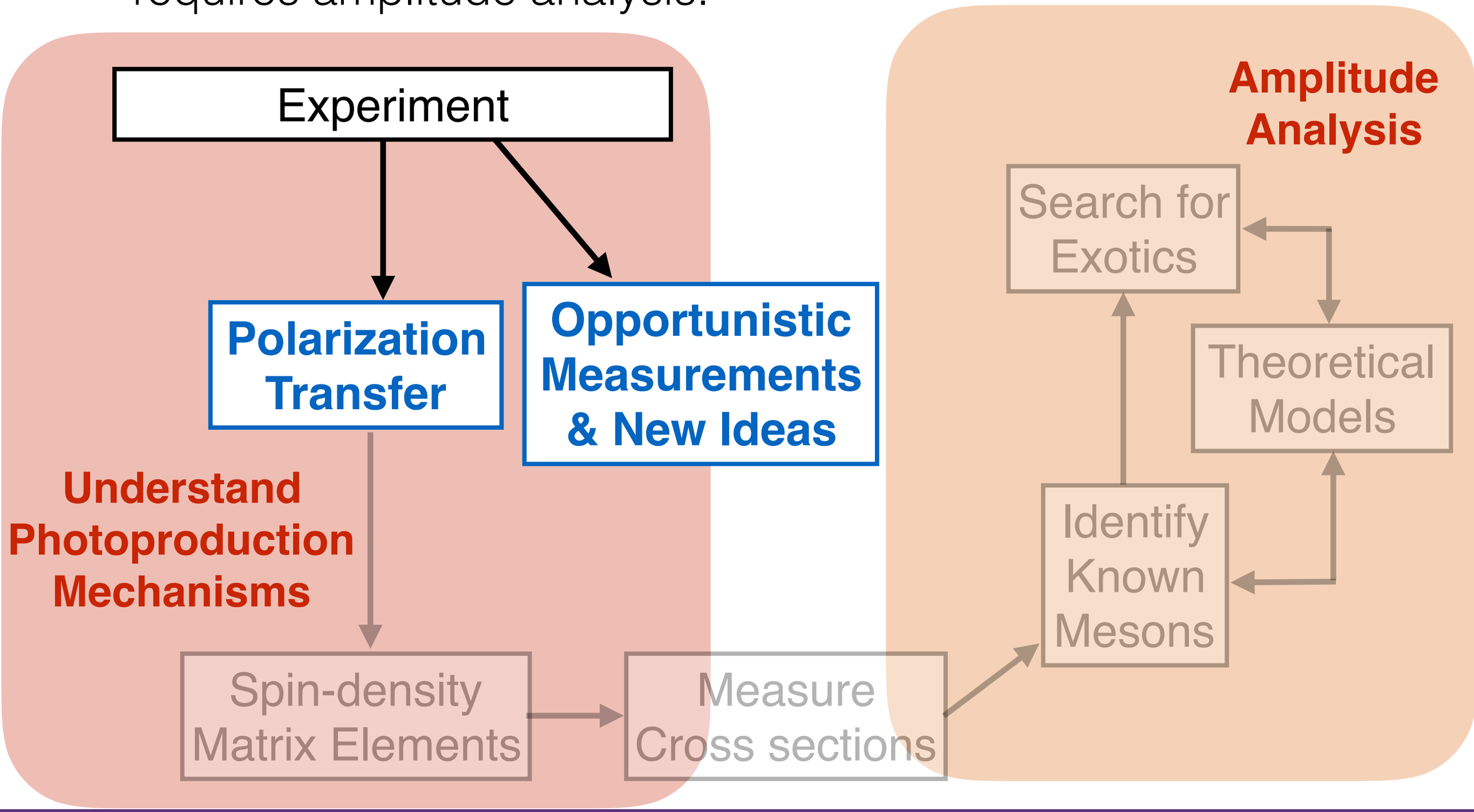
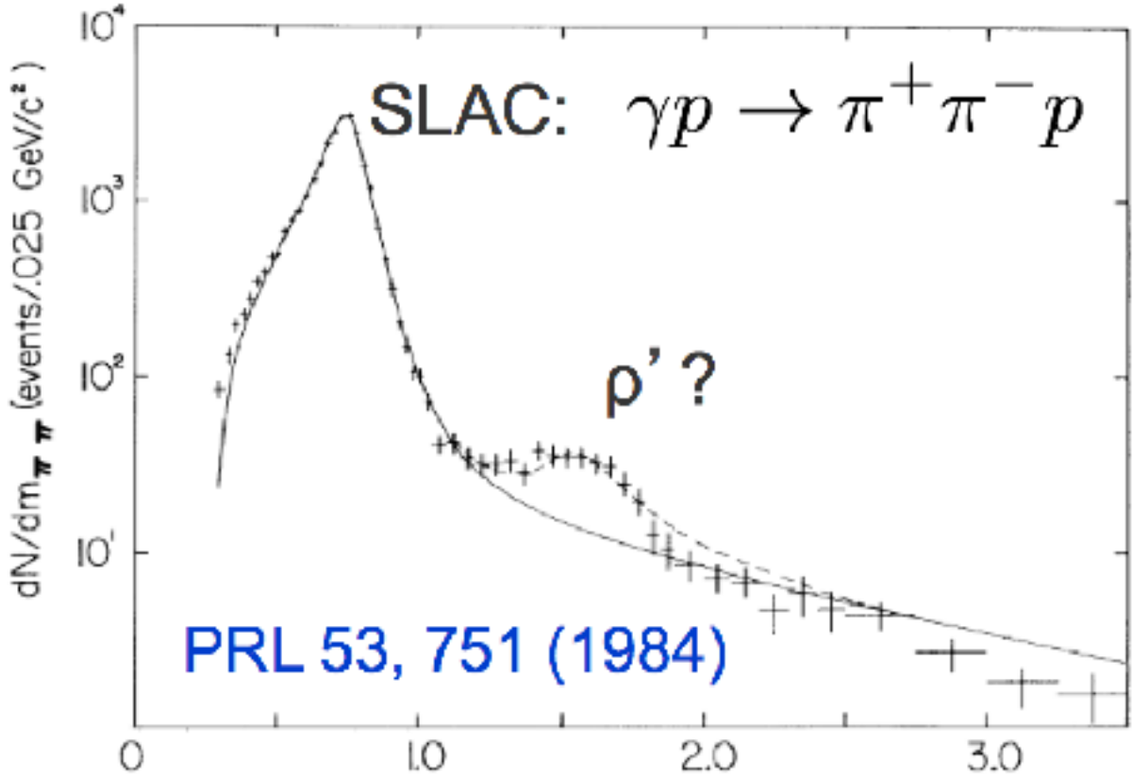
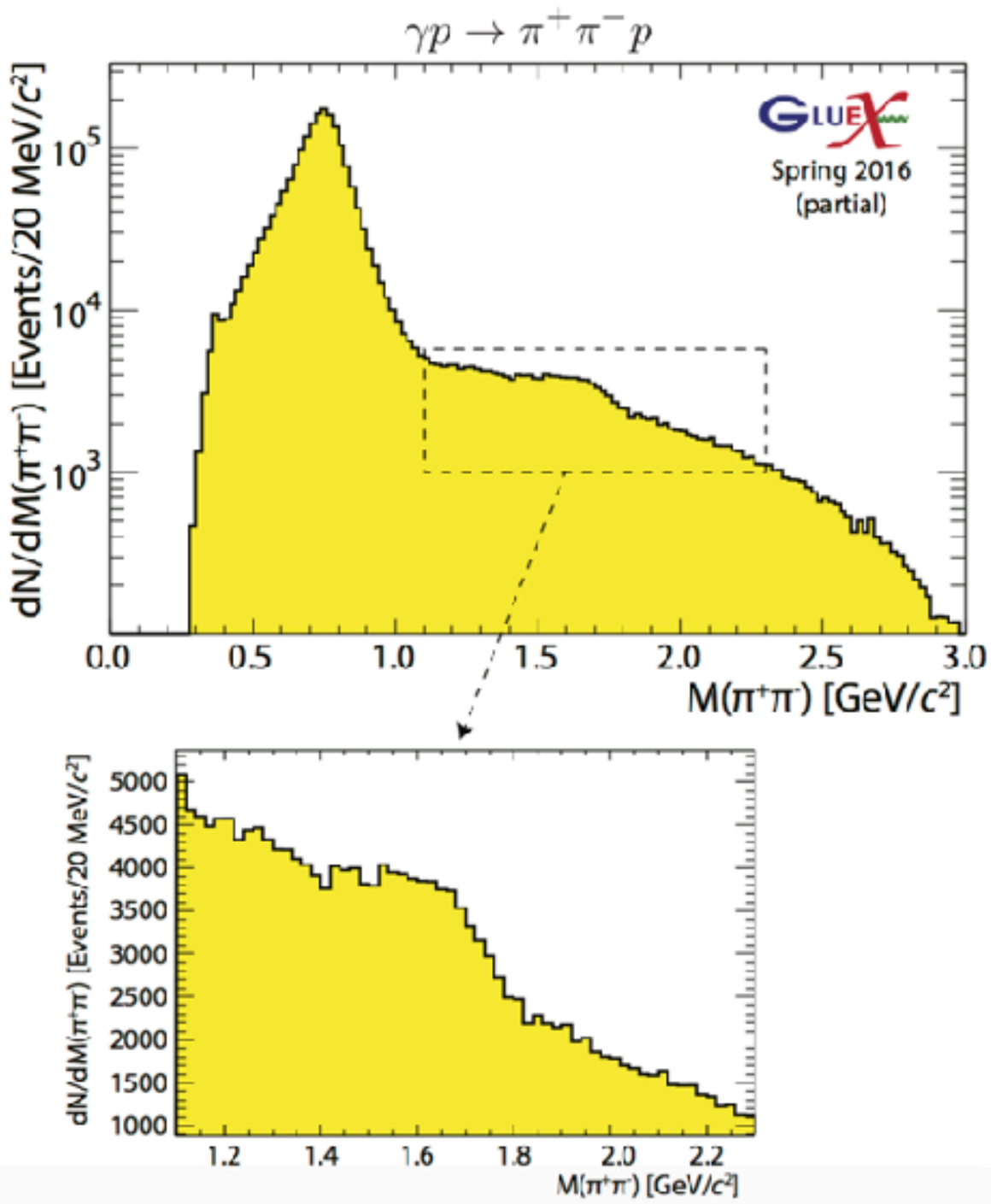


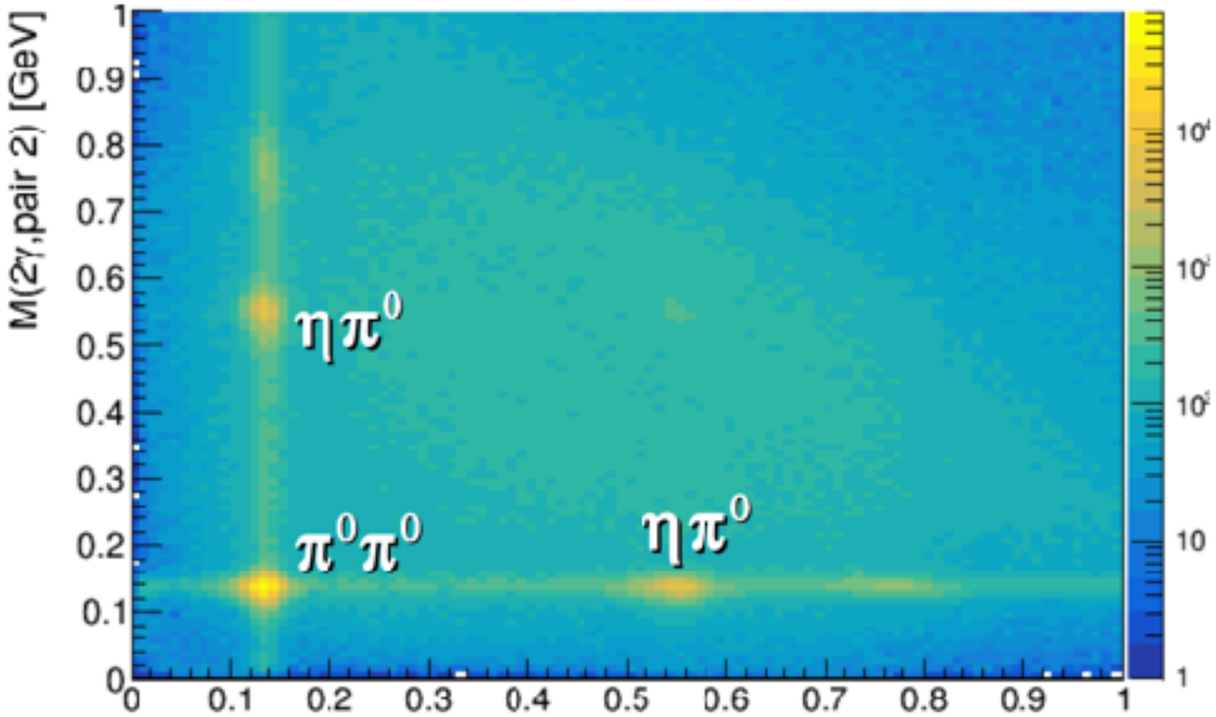
Final State Survey: $\gamma p \to p + \pi^+ \pi^-$

- Using data from initial running in Spring 2016, we see signals ~100 times larger than previous experiments.
- Evidence for ρ′ from SLAC, production studies underway

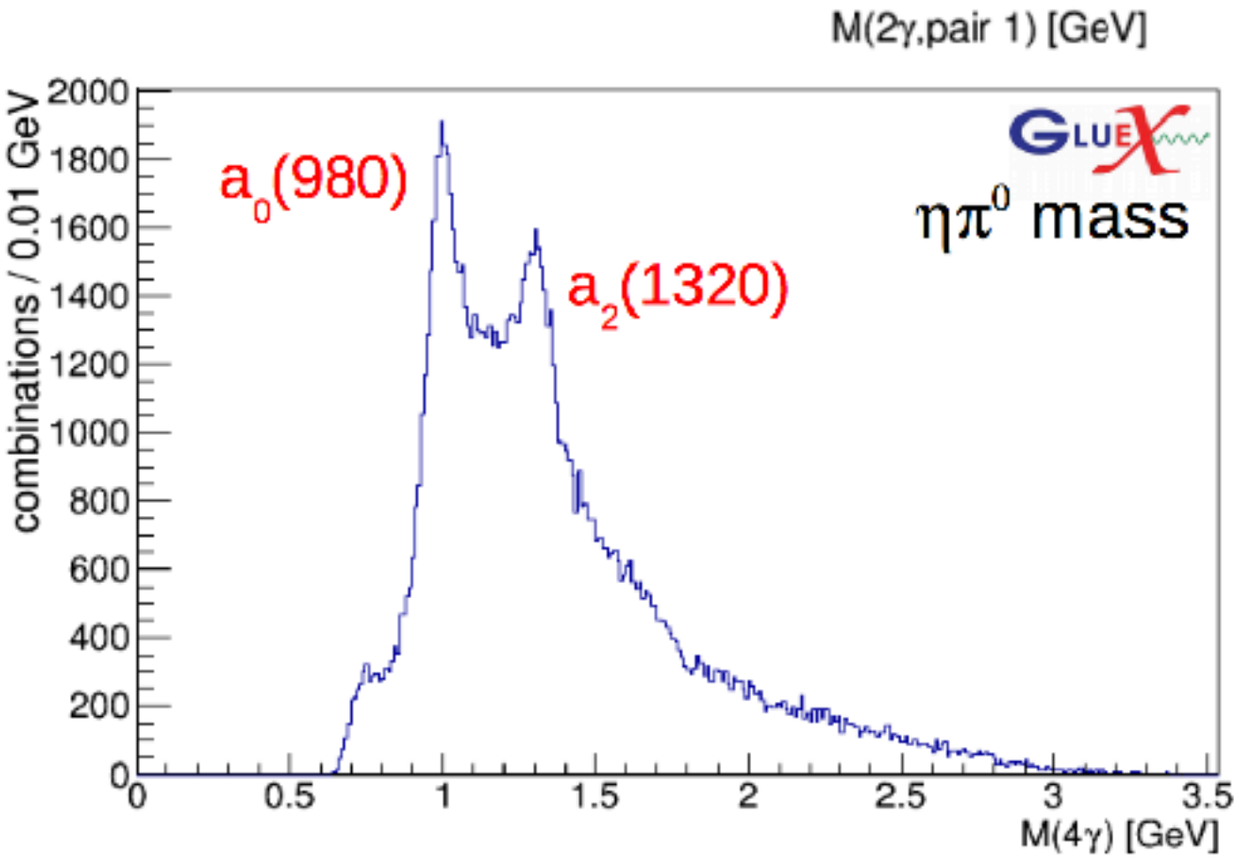


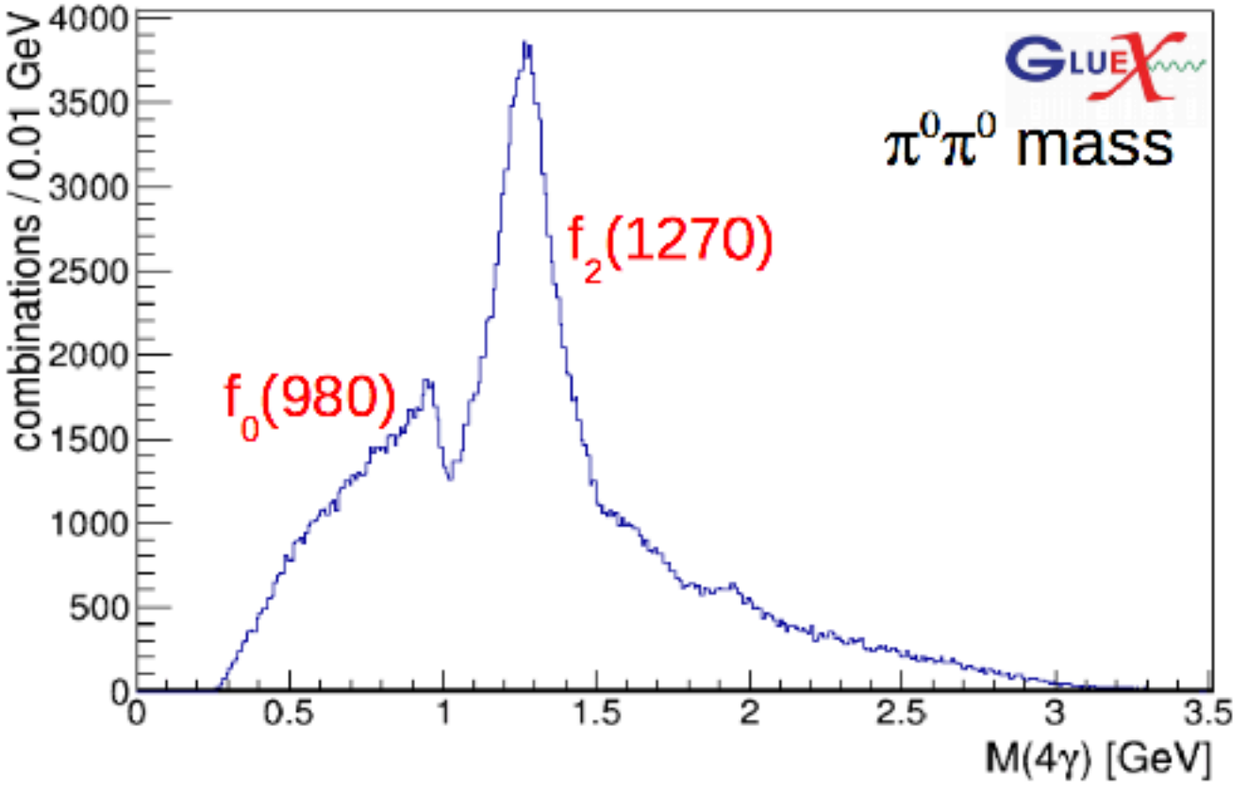


Final State Survey: γ p → p + 4γ

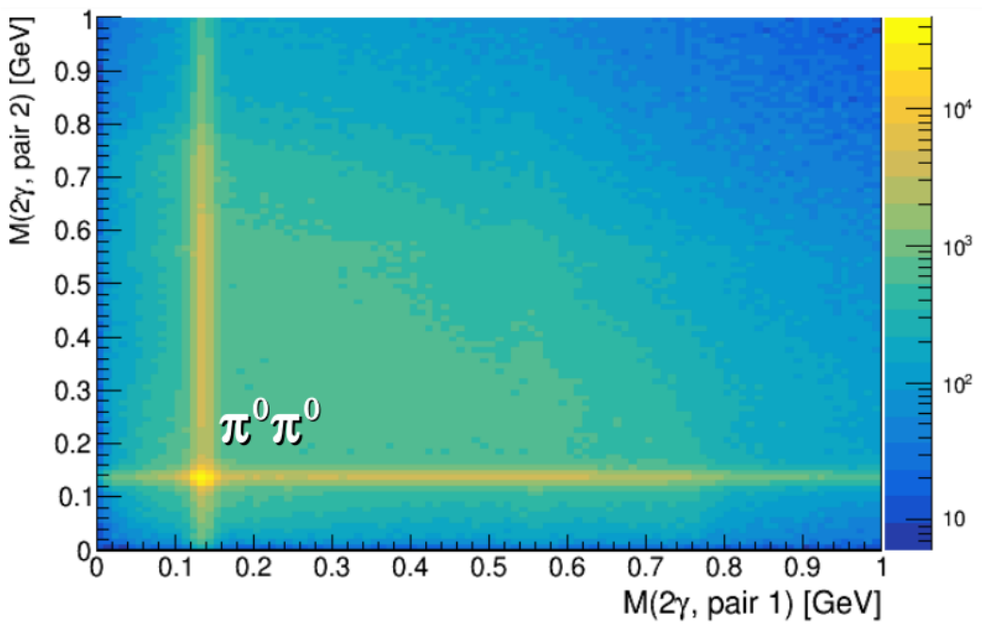


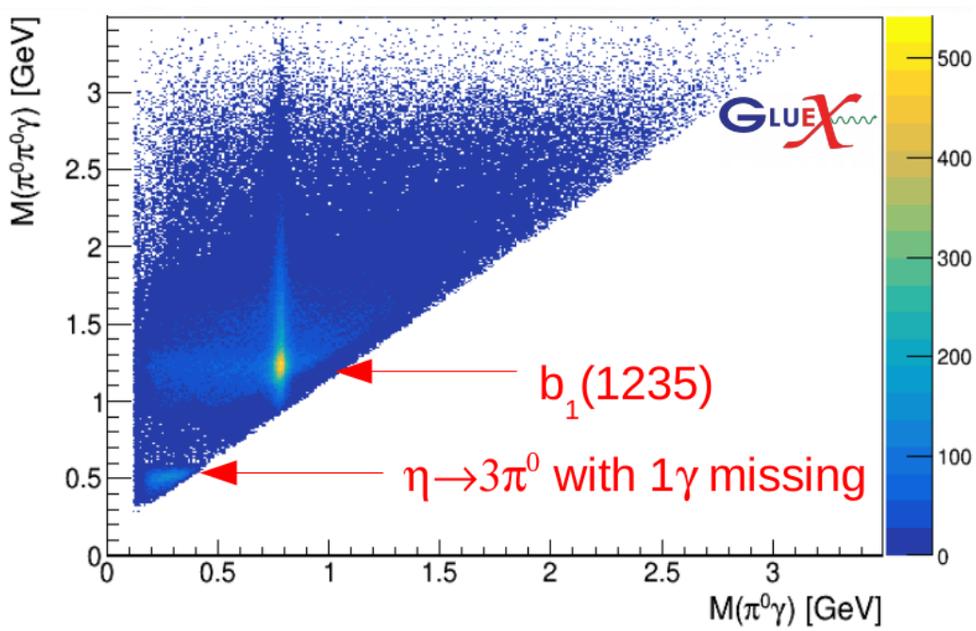
- Early data illustrates reconstruction of neutral final states
- Several scalar and tensor mesons are seen, good spectroscopy prospects.

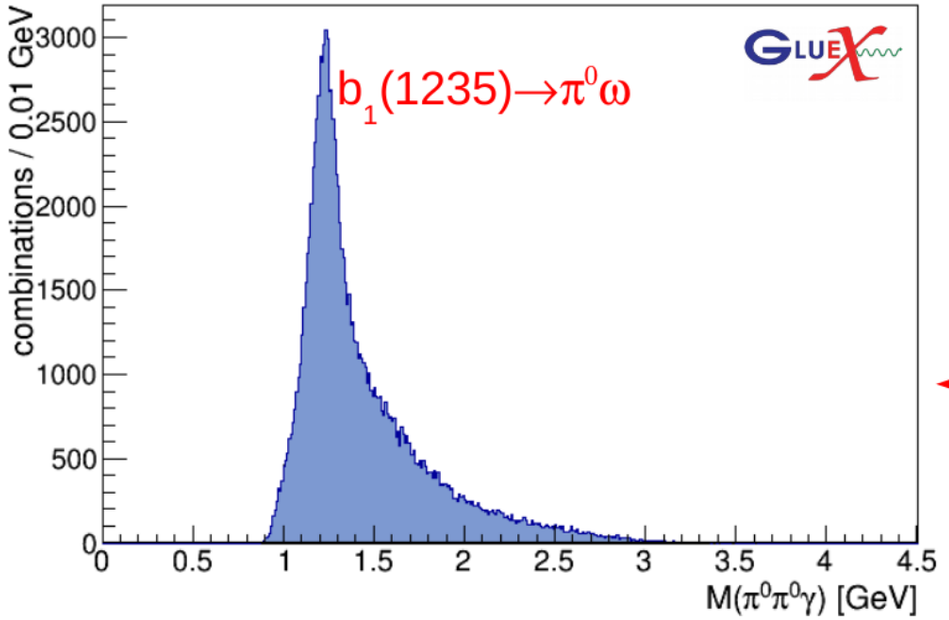


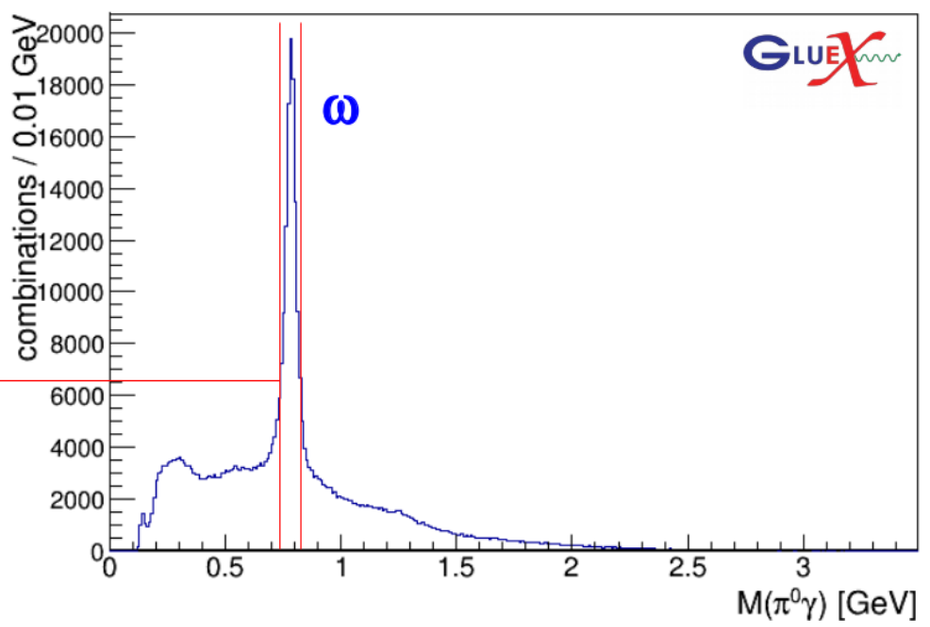


Final State Survey: γ p → p + 5γ









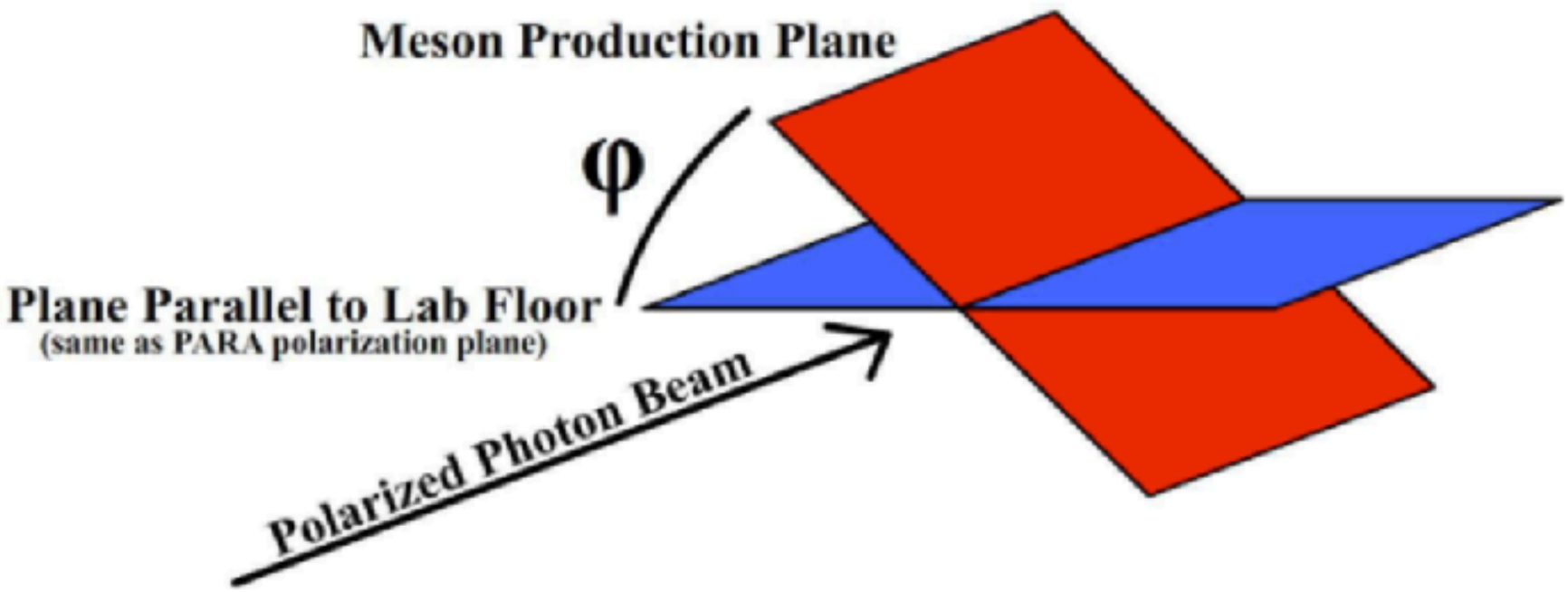
- Reconstruction of 5γ final states is also seen:

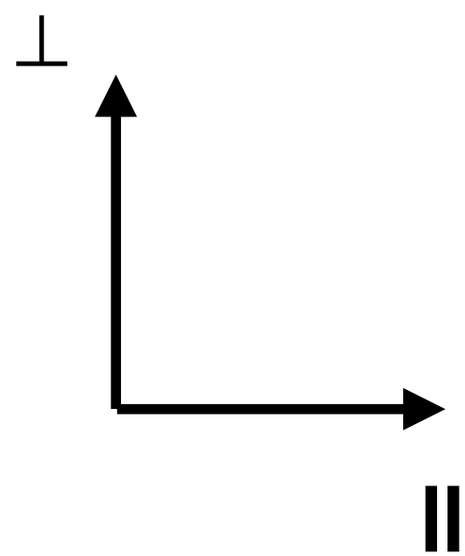
  γ p → p + b_1, b_1 → ω π^0, ω → π^0 γ

- $b_1\pi$ expected to be promising for exotic search.

S. Taylor (JLab)

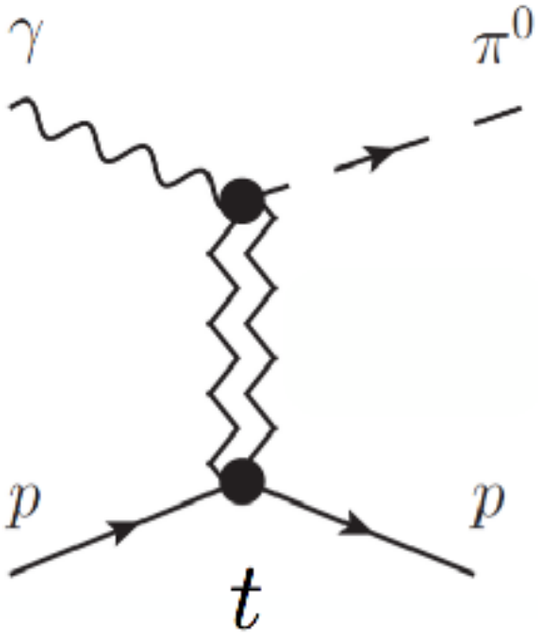
Beam Asymmetries





- Understanding production mechanisms necessary to determine J^{PC} of mesons in amplitude analyses
- Beam asymmetry Σ yields information on production mechanisms
  - Measure azimuthal dependence with orthogonally polarized beams
  - Early measurements made with pseudoscalar [**π^0,η**] and vector mesons [**ρ,ω**]

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

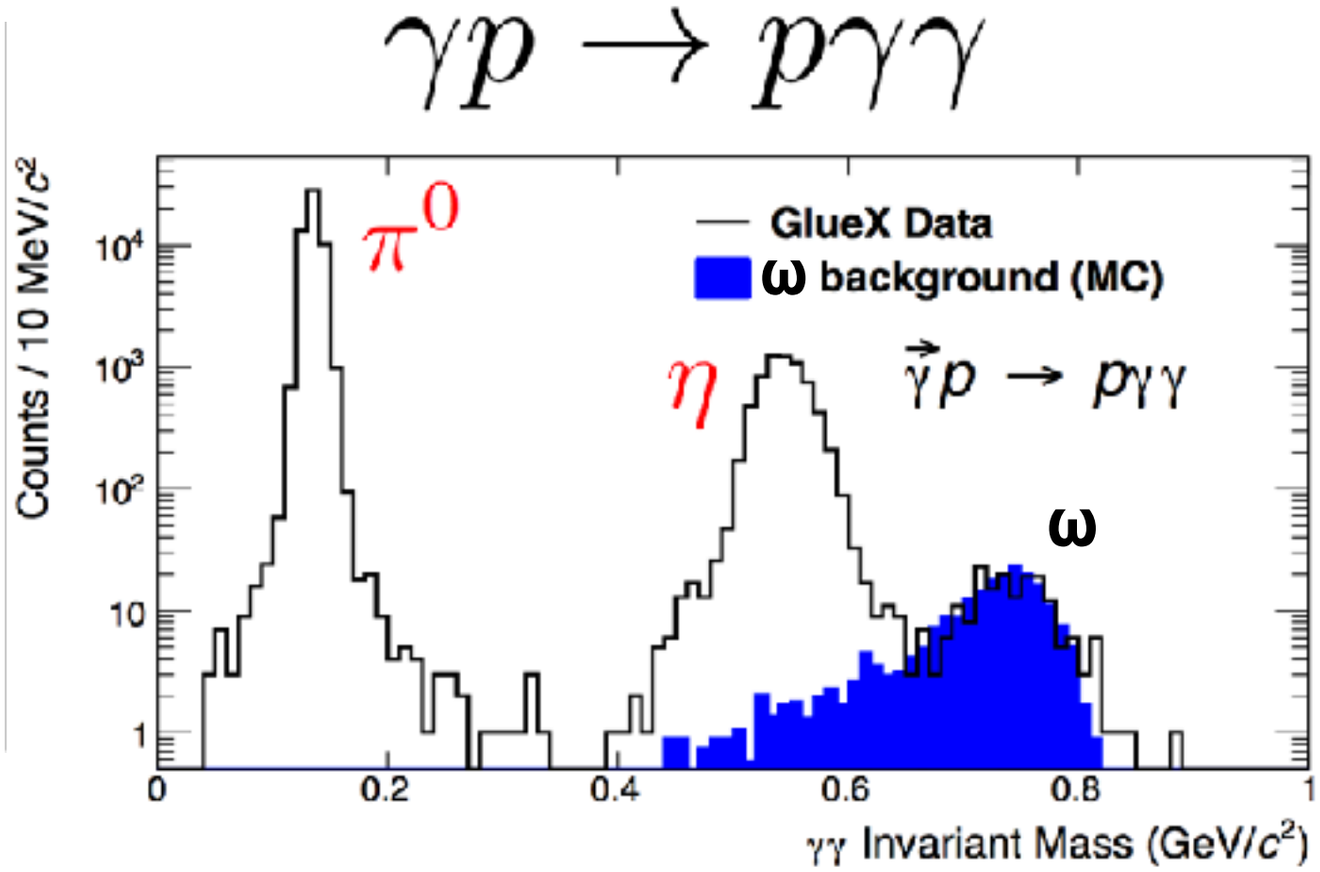


Exchange J^{PC}

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

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

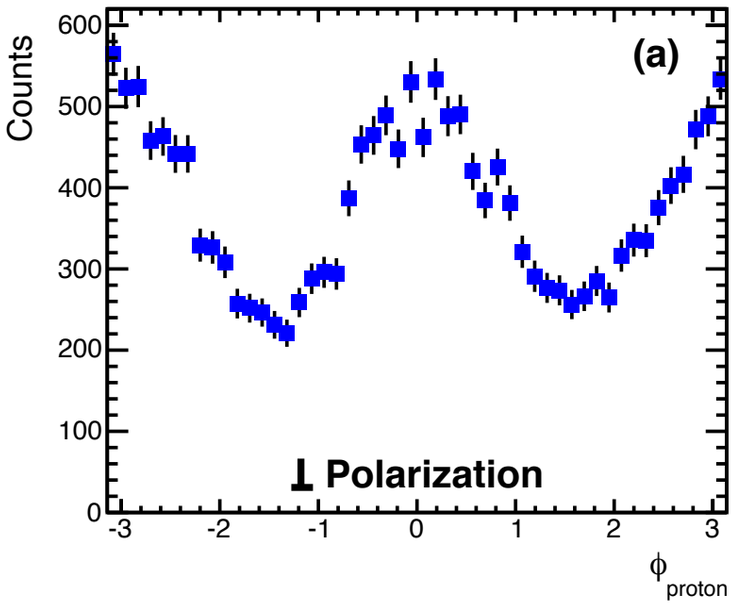
$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$

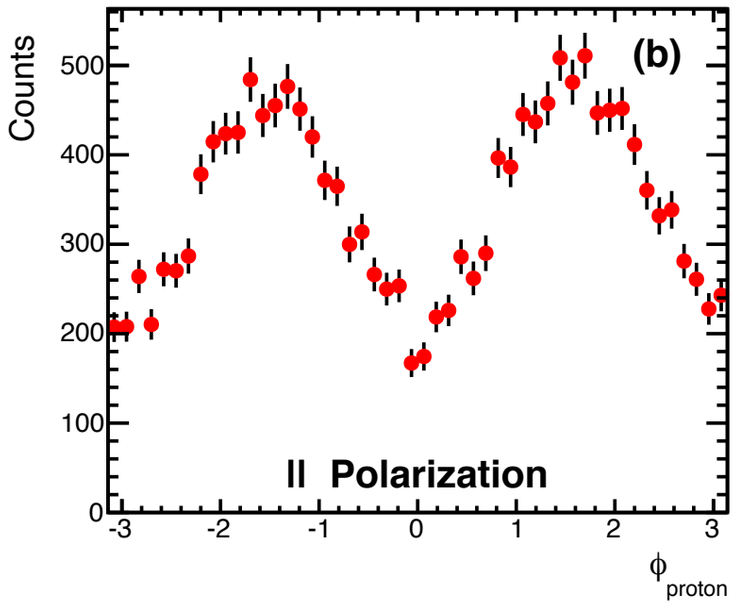


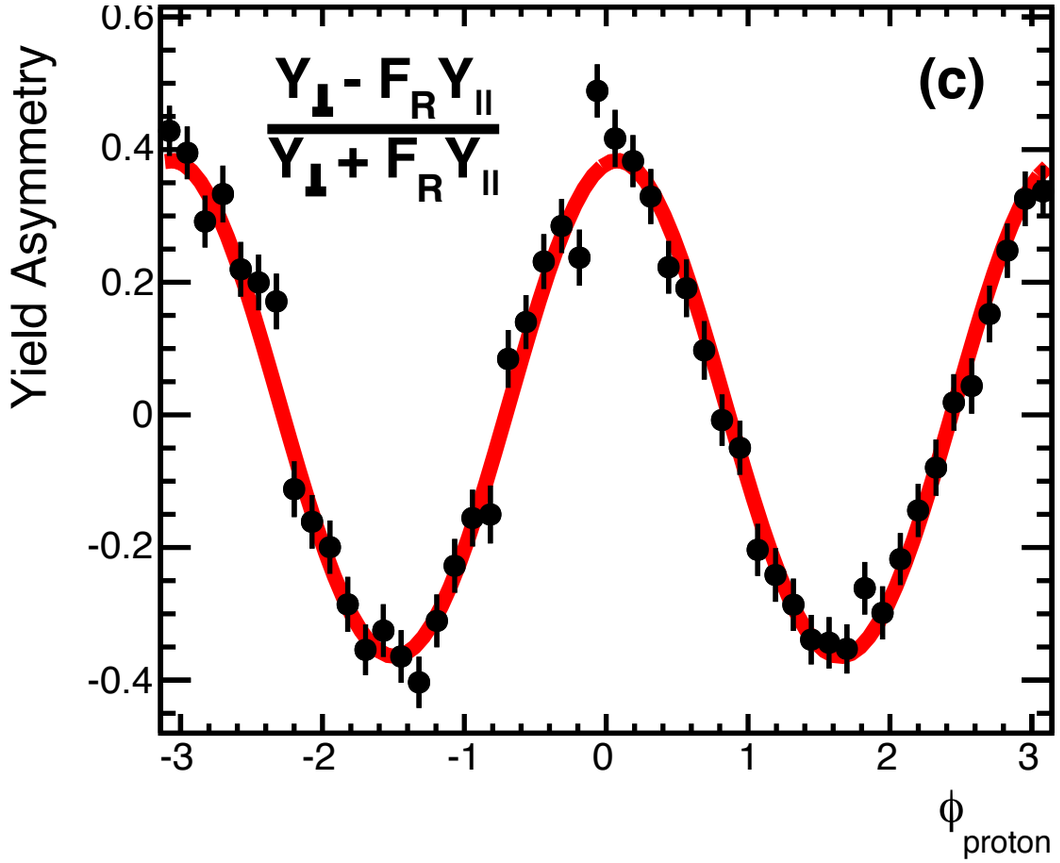
Mathieu et al., PRD 92, 074013

J. Stevens (W&M), D. Mack, S. Taylor (JLab), I. Strakovsky (GWU), Z. Zhang (Wuhan)

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

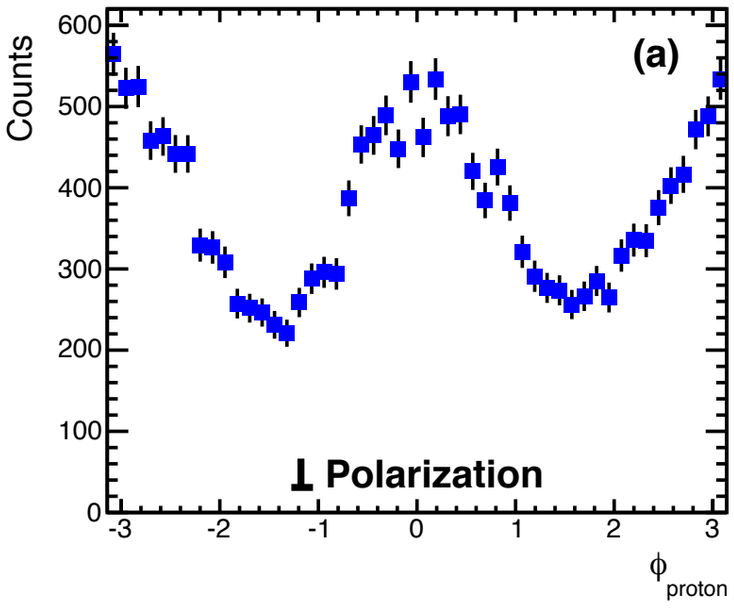


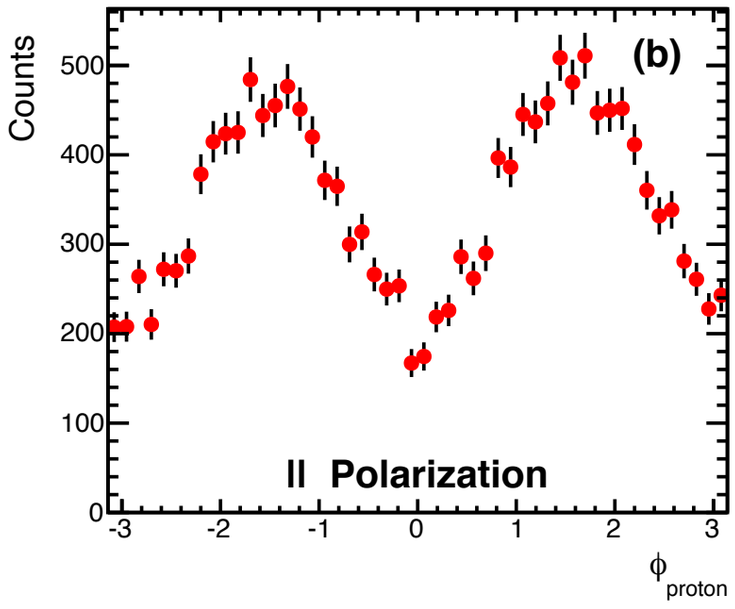


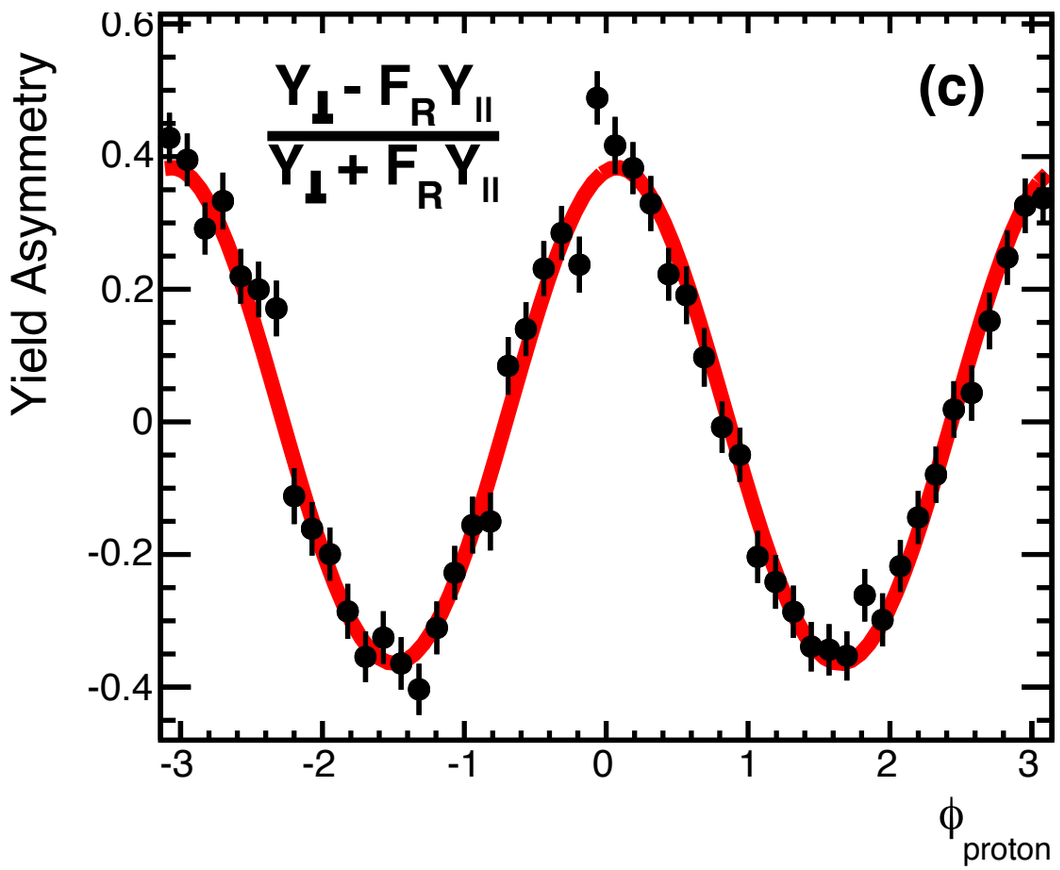


$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

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

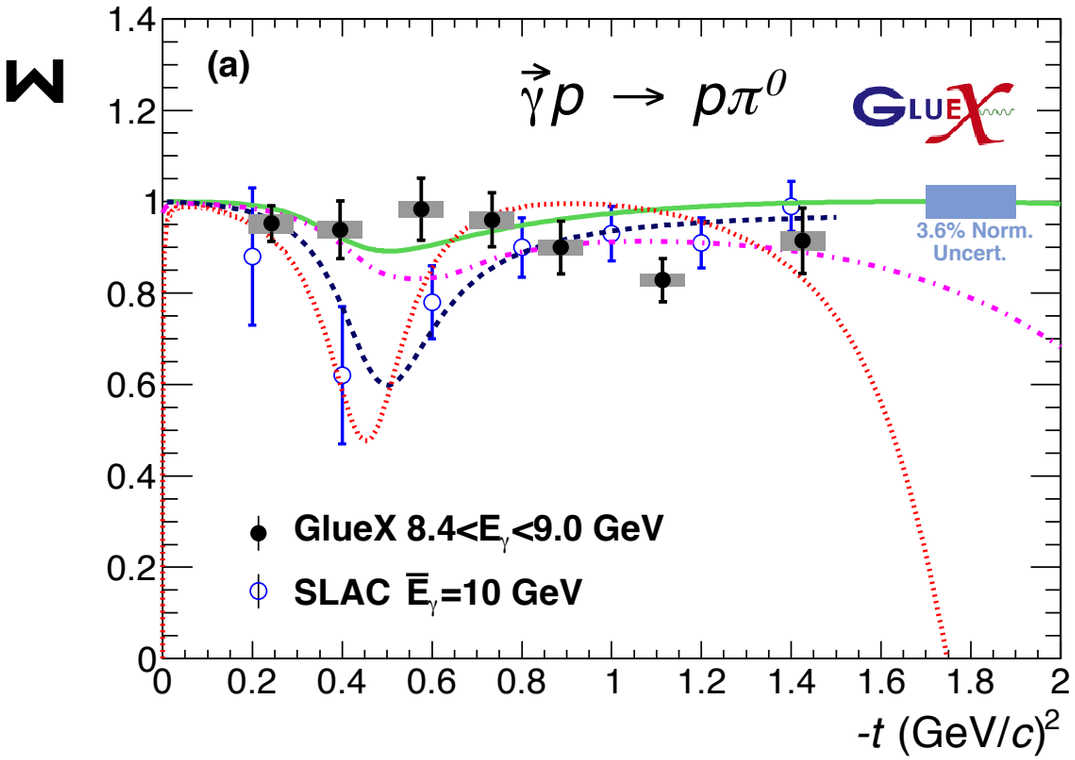


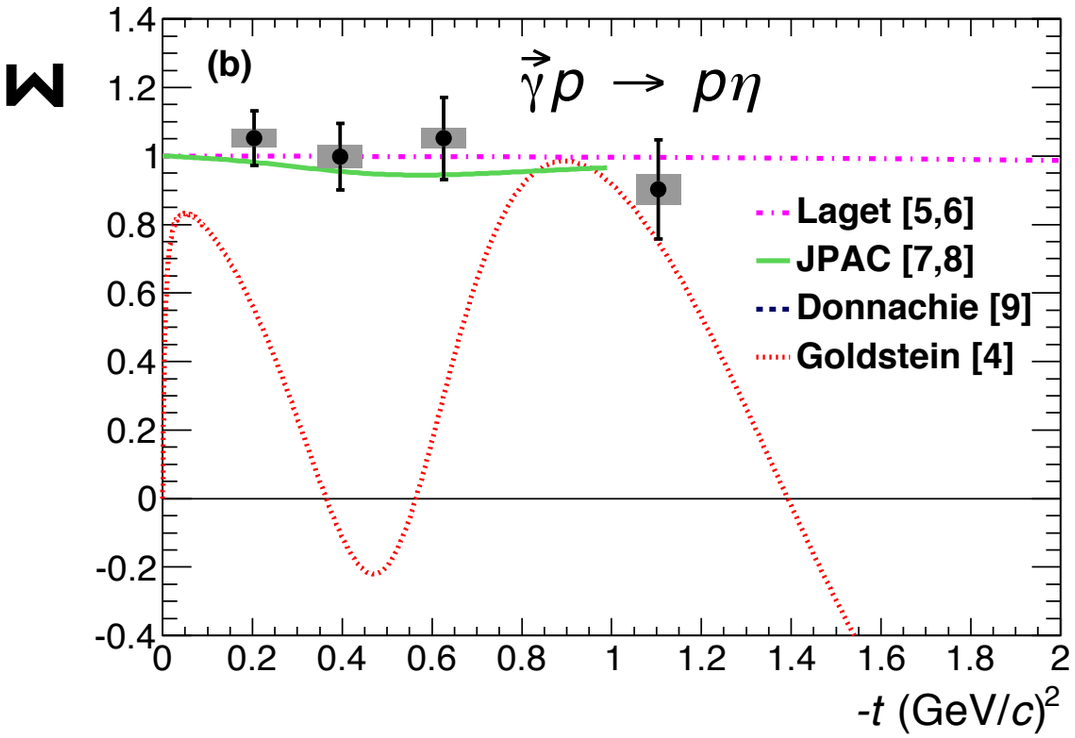




$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = P_\gamma \Sigma \cos 2\phi_p$$

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

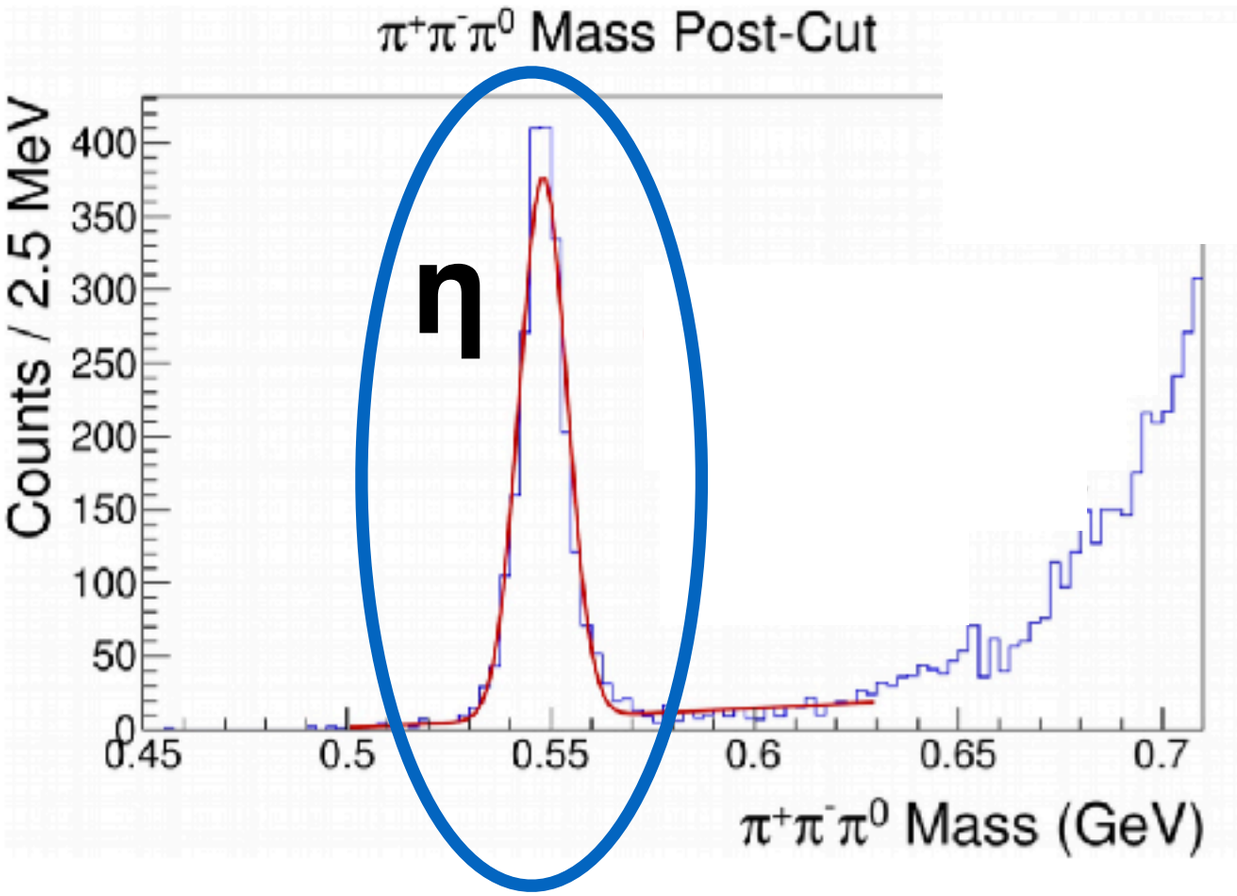




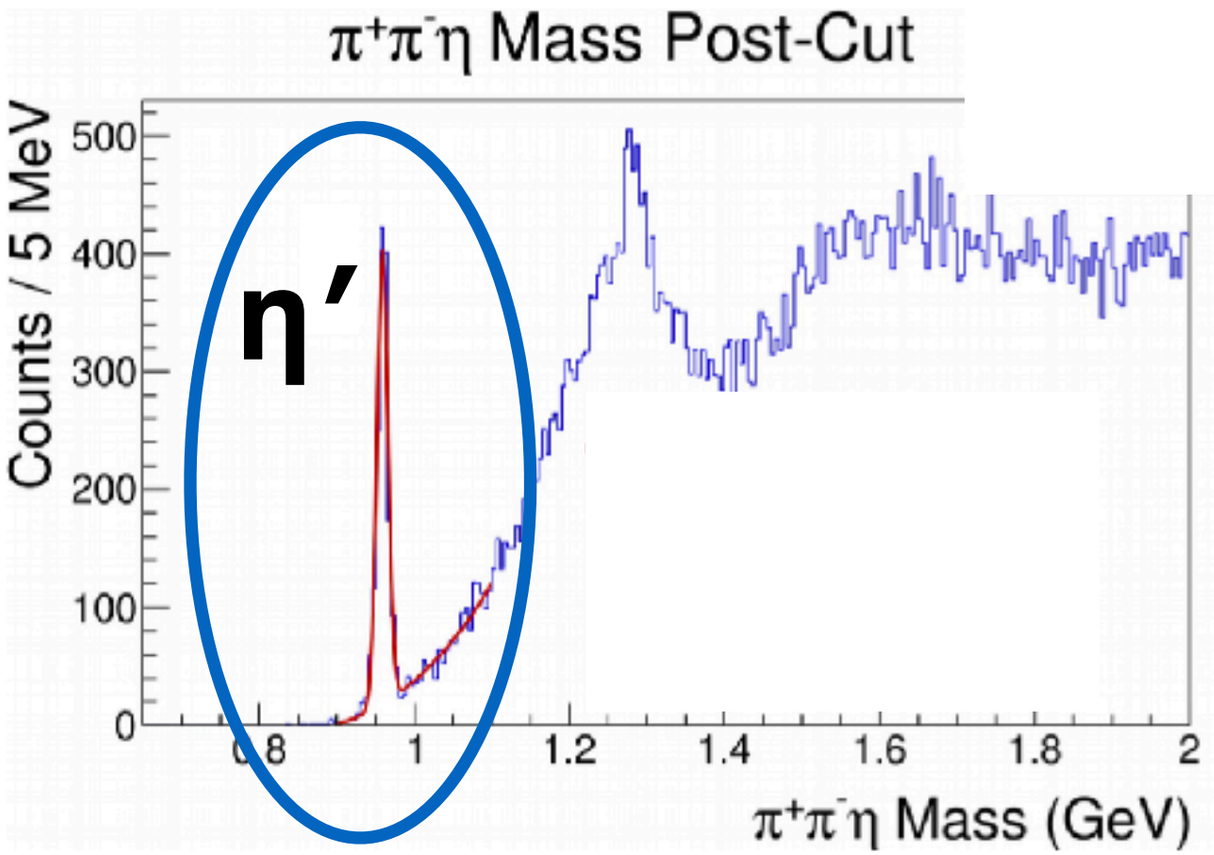
- **Results submitted to PRL [arXiv:1701.08123]**
  First GlueX paper!
- First η measurement at this energy
- Data compared to several theory calculations
- Dip at -t = 0.5 (GeV/c)^2 not observed
  - Indicates vector exchange dominates at this energy
- Constrains background to baryon resonance production

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

$\eta \rightarrow \pi^+ \pi^- \pi^0$



$\eta' \rightarrow \eta \pi^+ \pi^-$

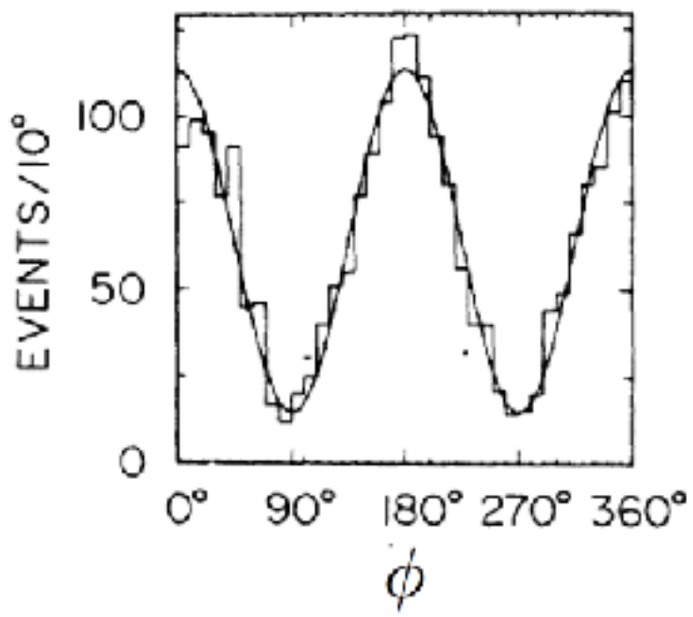


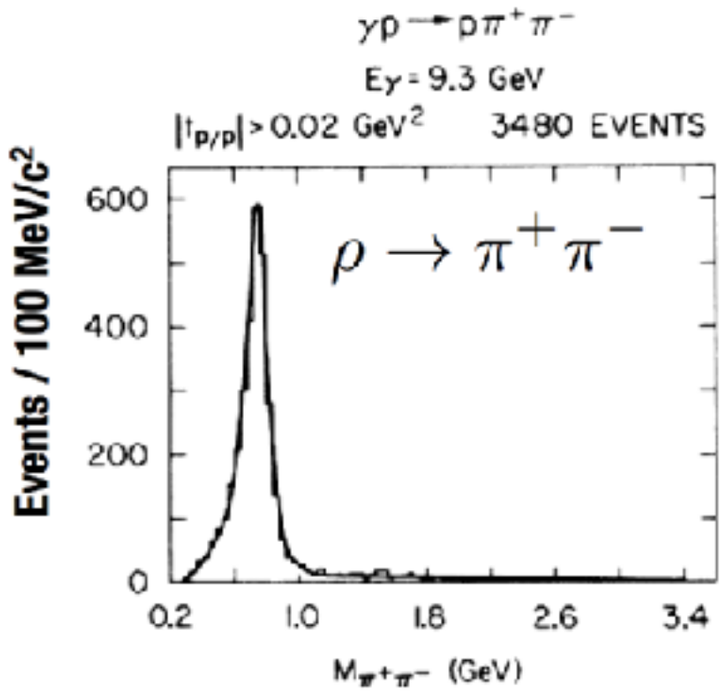
Good prospects with the full data set.

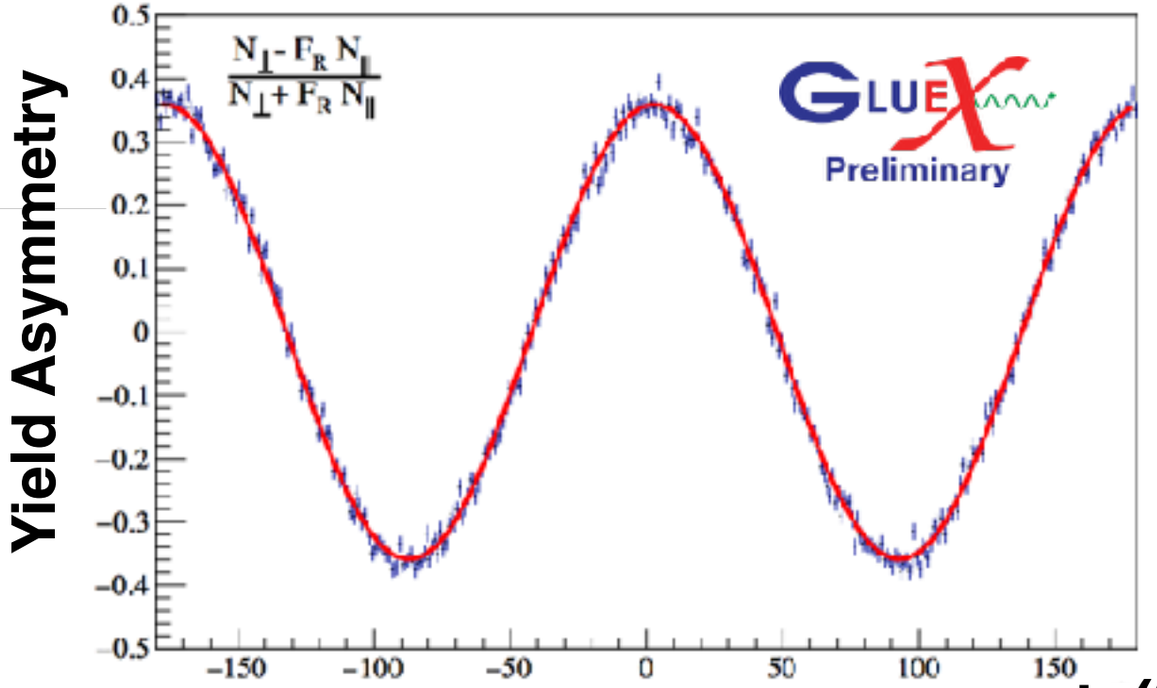
T. Beattie (Regina)

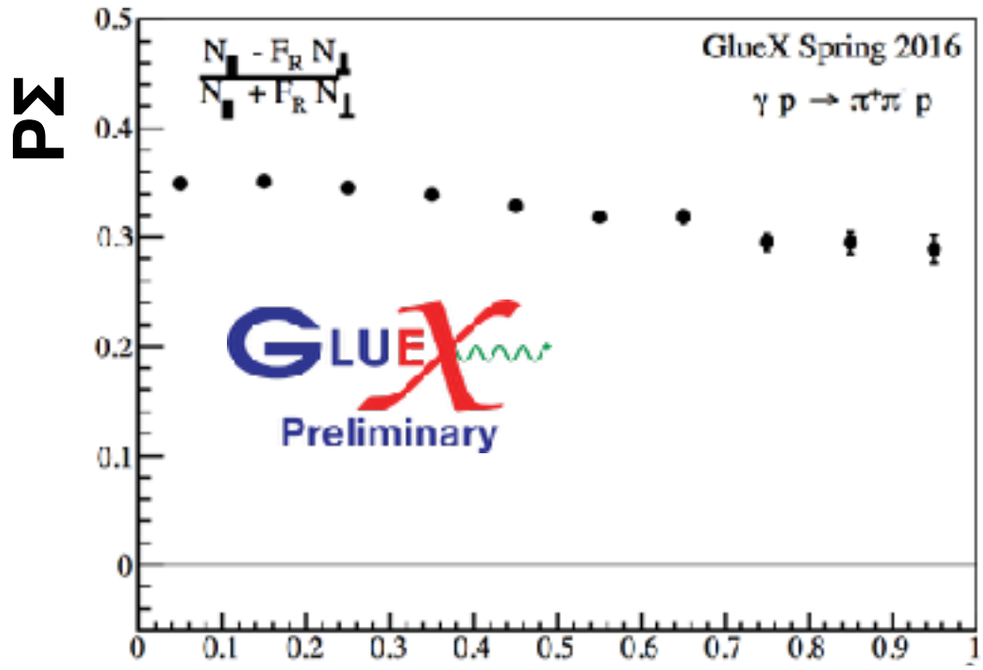
Beam Asymmetries: γ p → p + π⁺ π⁻

J. Ballam et al., PRD 7, 3150 (1973)









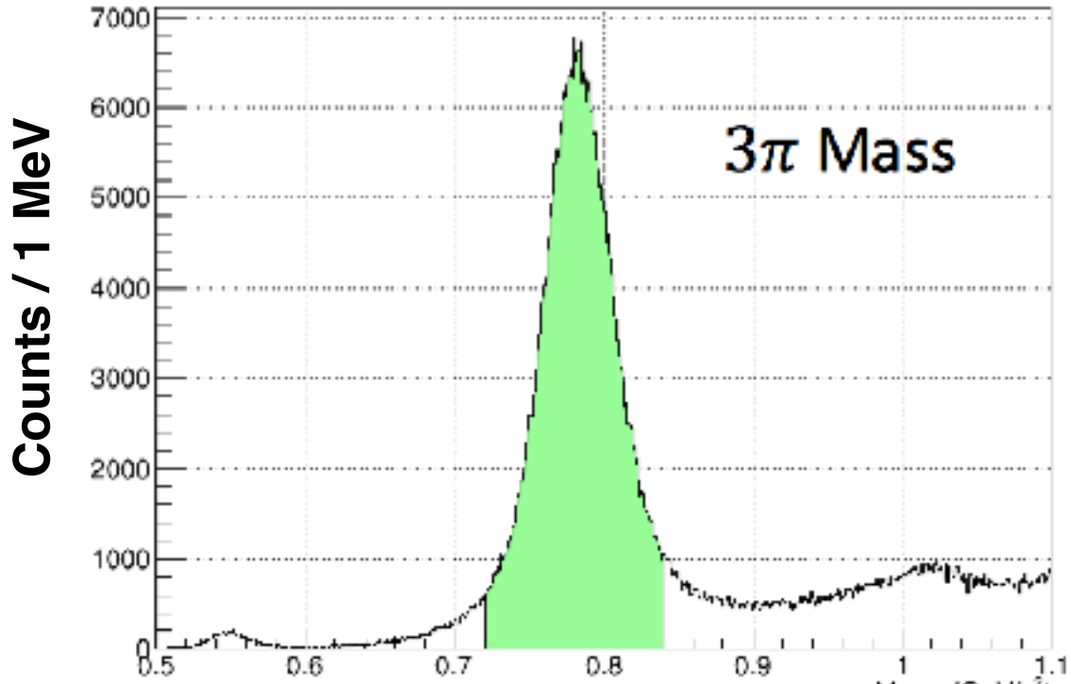
- Full analysis of angular distributions under way.

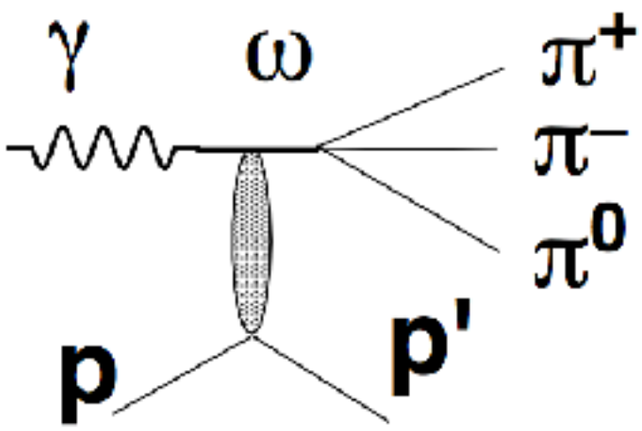
A. Austregesilo (JLab)

Beam Asymmetries: γ p → p + ω

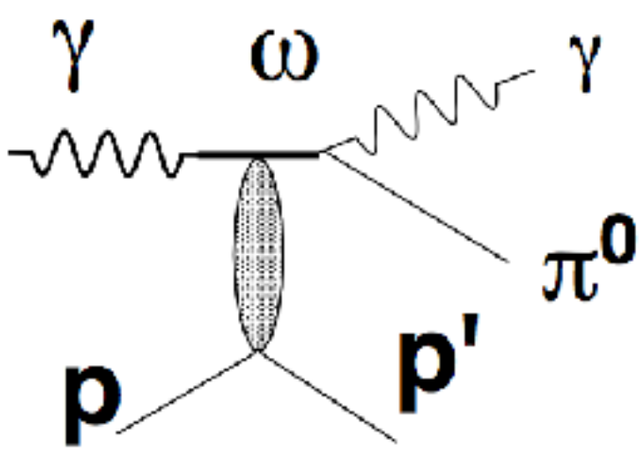
- Probe production mechanism with two different decays
- Assuming Vector Meson Dominance (VMD):

$$\Sigma(\pi^+ \pi^- \pi^0) / \Sigma(\pi^0 \gamma) = -2$$

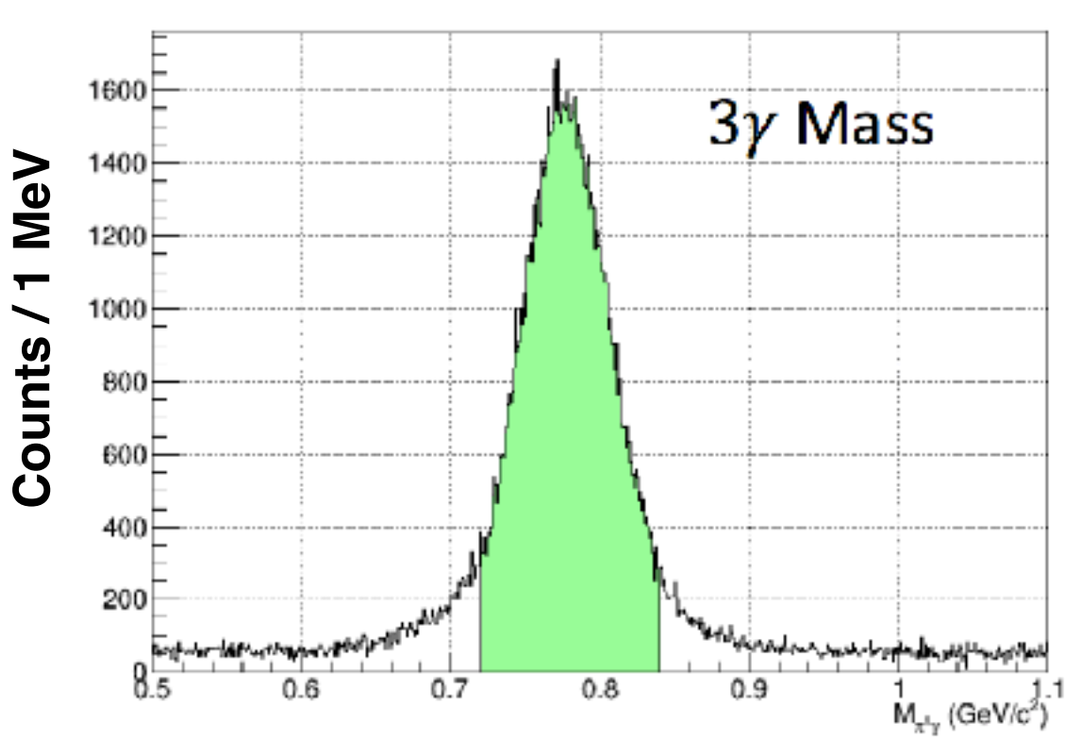




Hadronic ω



Radiative ω



M. Staib (CMU)

Beam Asymmetries: γ p → p + ω

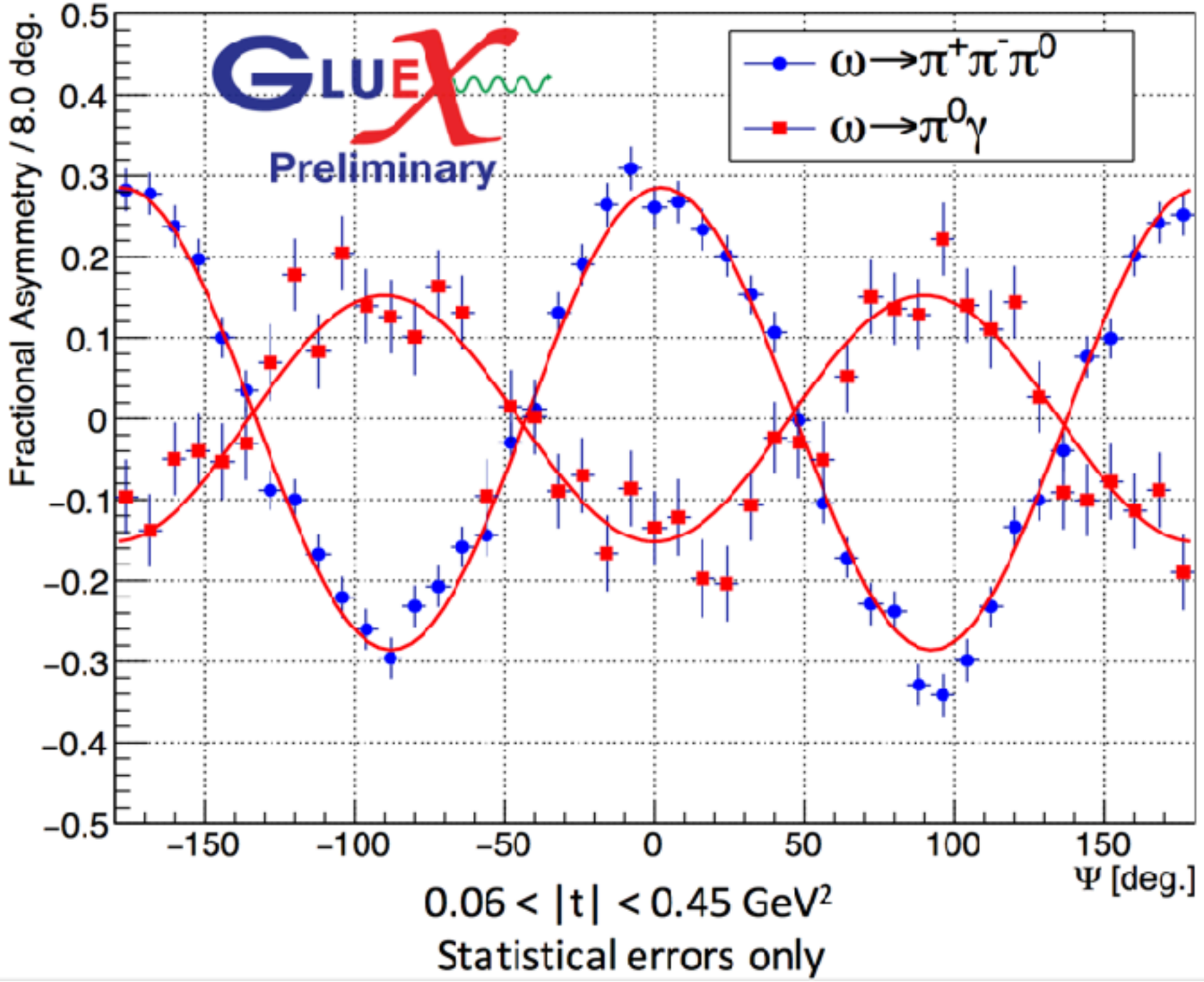
Expected:

$\Sigma(\pi^+ \pi^- \pi^0) / \Sigma(\pi^0 \gamma) = -2$

Measured:

$\Sigma(\pi^+ \pi^- \pi^0) / \Sigma(\pi^0 \gamma) = -1.88 \pm 0.13$

Consistent with VMD expectations.



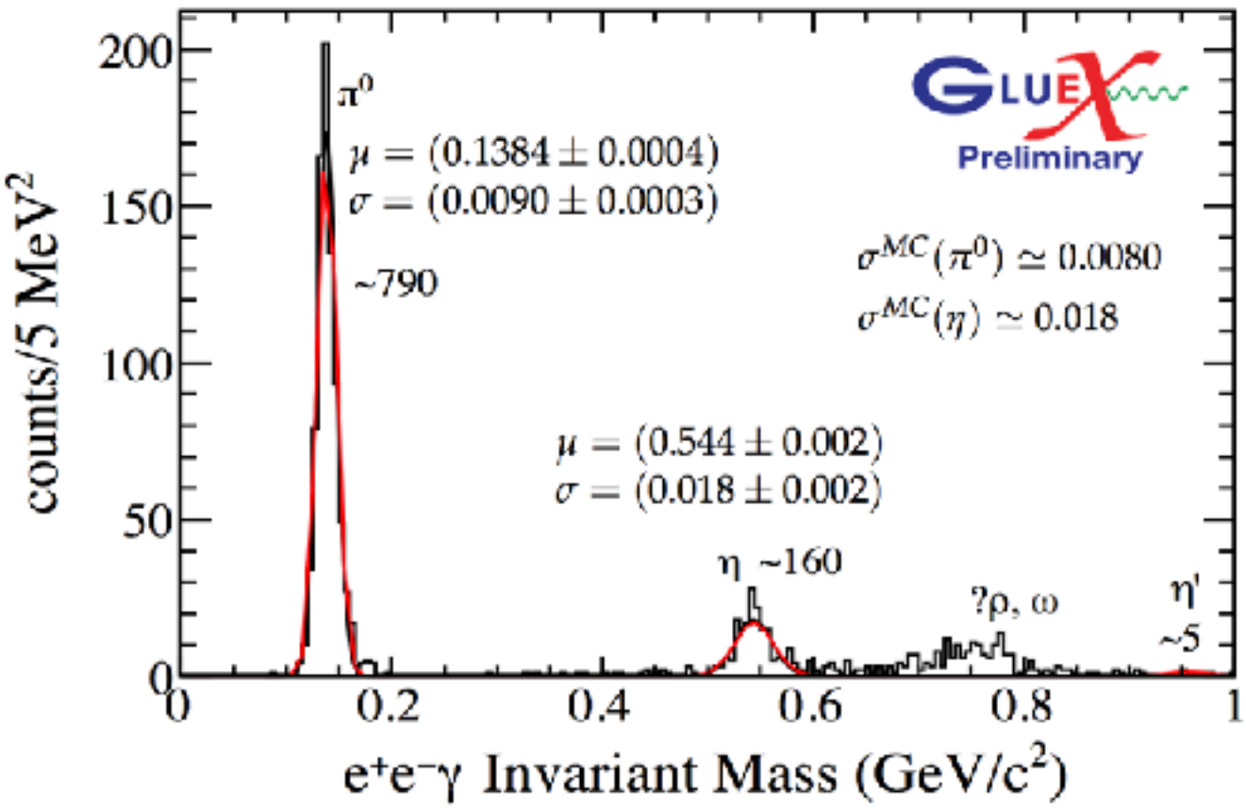
- Eventual goal: determine Spin Density Matrix Elements (SDMEs).

Transition Form Factors (TFF): $\eta^{(\prime)} \to e^+e^-\gamma$

- EM decays of pseudoscalar mesons, $P \to e^+e^-\gamma$, probe internal structure of hadrons.
- Estimated rates for total approved GlueX running competitive with world data sets:
  - **$\gamma p \to p\,\eta$, $\eta \to e^+e^-\gamma$: 15 k**
    [compare to ~20k at MAMI]
  - **$\gamma p \to p\,\eta'$, $\eta' \to e^+e^-\gamma$: 1 k**
    [compare to <1k at BES-III]
  - Other reactions may increase yield.
- Signals for **$\gamma p \to p\,e^+e^-\gamma$** seen in current data, bgkd. from photon conversions under study.

$$\frac{d\Gamma(\eta' \to \gamma l^+ l^-)}{dq^2 \Gamma(\eta' \to \gamma\gamma)} = [\mathrm{QED}(q^2)] \times |F(q^2)|^2$$

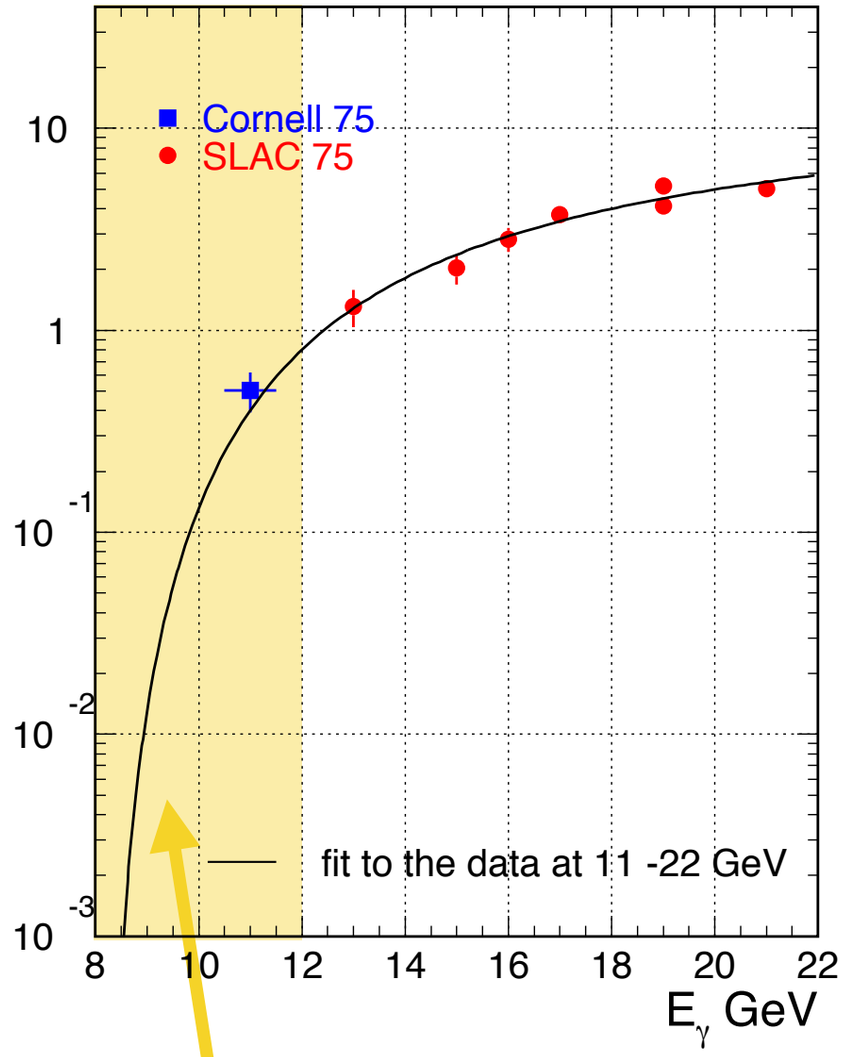
Point-like **TFF**



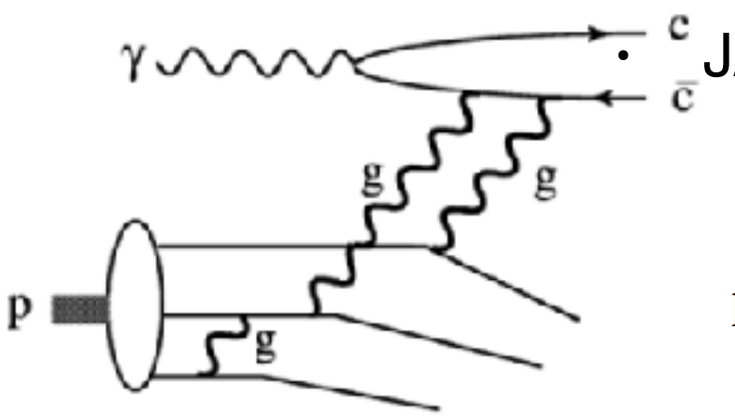
C. Fanelli (MIT)

J/ψ Photoproduction Near Threshold

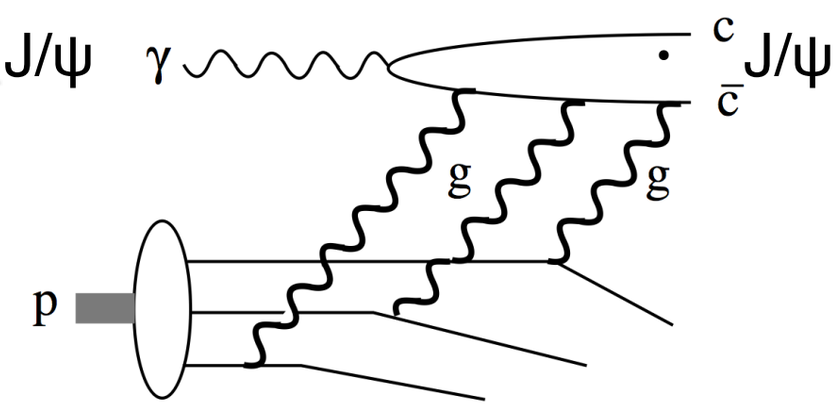
- Threshold production is experimentally clean, ideal for studying J/ψ+N interaction
  - Probes gluon distributions in proton
    [Kharzeev et al., NPA 661, 568 (1999)]
  - Also multiquark correlations
    [Brodsky et al., PLB 498, 23 (2001)]



GlueX energy range



leading-twist

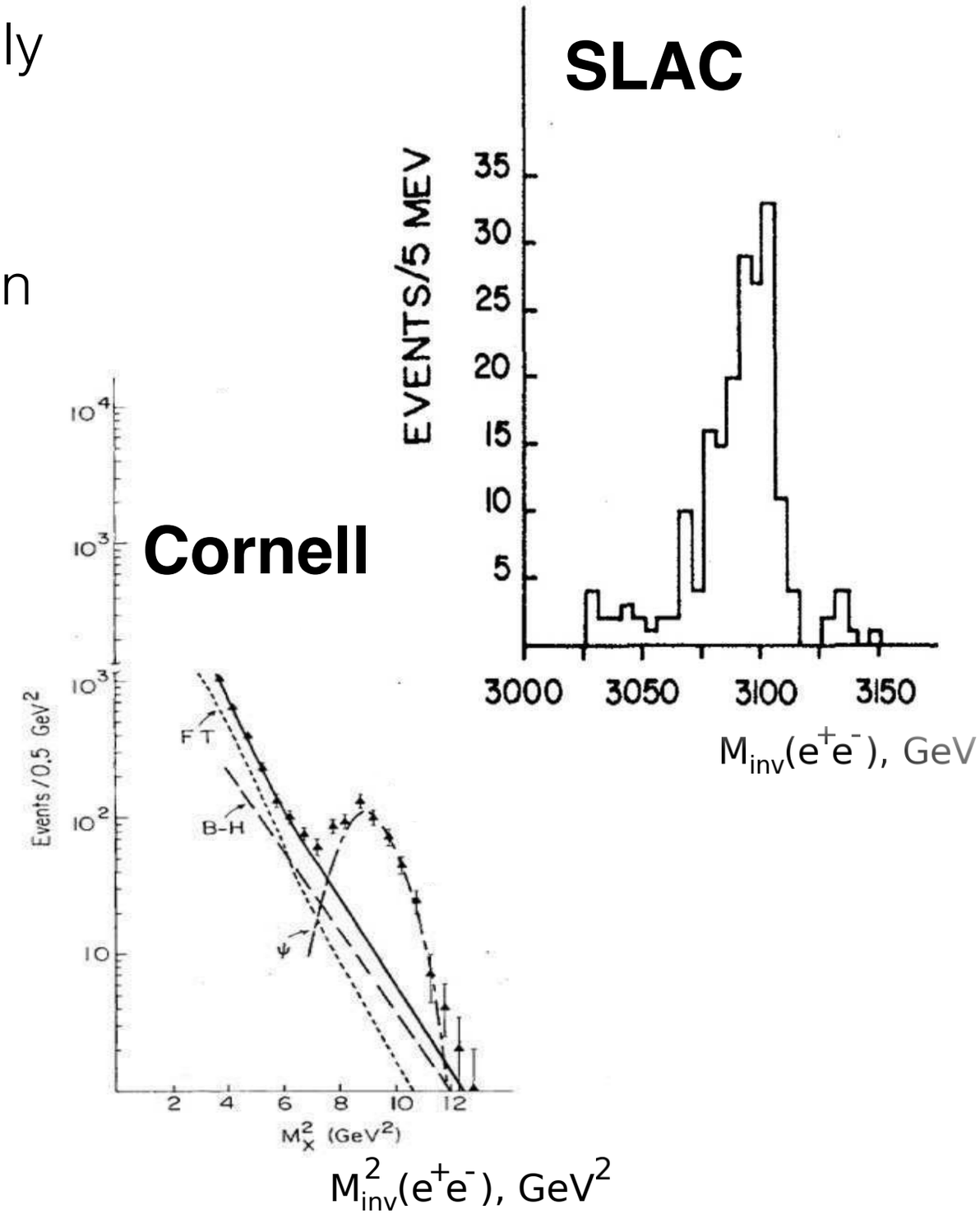


higher-twist

J/ψ Photoproduction Near Threshold

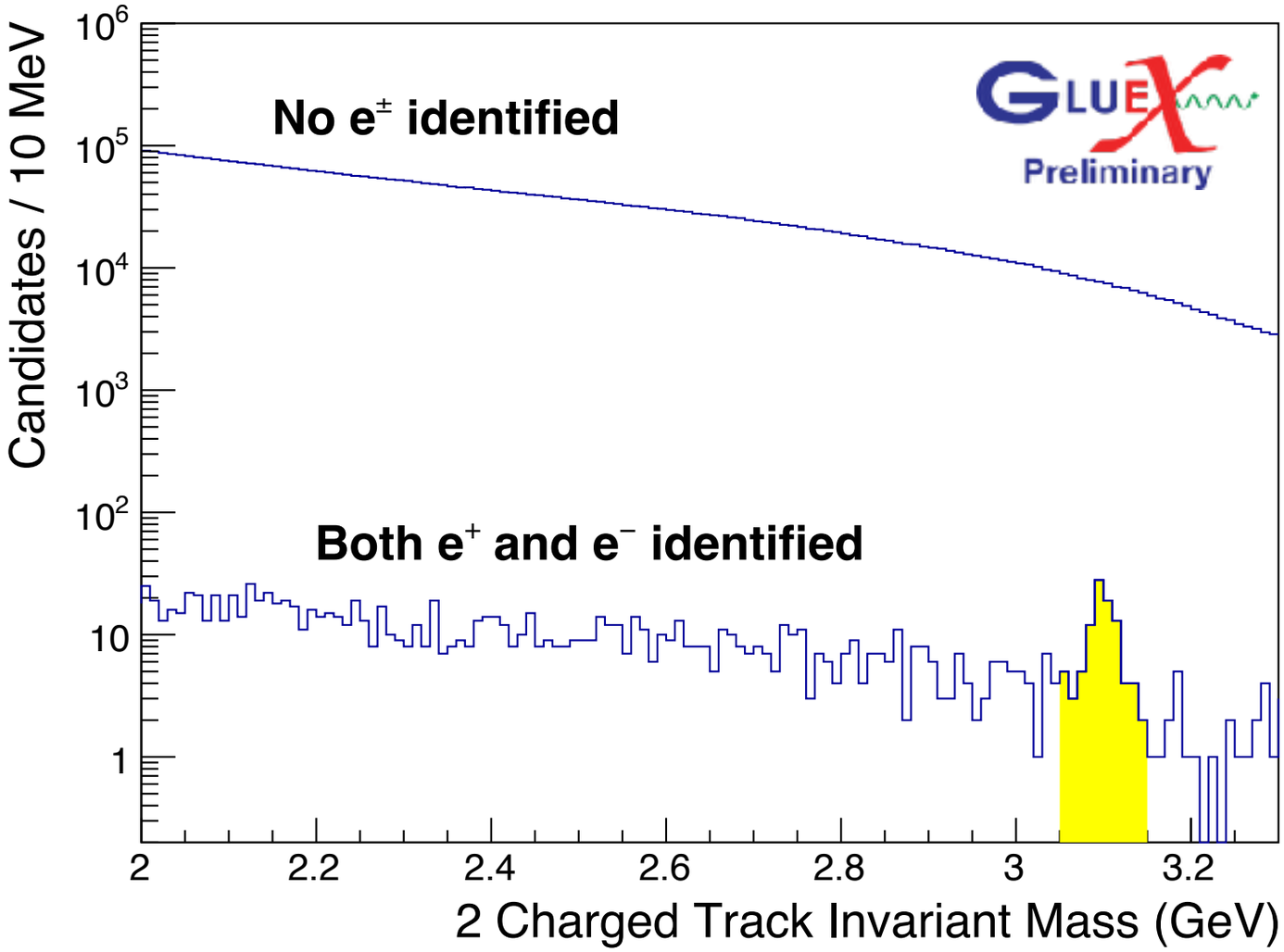
- Threshold production is experimentally clean, ideal for studying J/ψ+N interaction
  - Probes gluon distributions in proton
    [Kharzeev et al., NPA 661, 568 (1999)]
  - Also multiquark correlations
    [Brodsky et al., PLB 498, 23 (2001)]

- Few existing measurements:
  - **Cornell: E(γ) = 9 – 11.8 GeV**
    γ + Be → Be + e^+e^-
    [Gittelman et al., PRL 35, 1616 (**1975**)]
  - **SLAC: E(γ) = 13 – 20 GeV**
    γ + LH_2 → p + (e^+e^-, $\mu^+\mu^-$)
    [Camirini et al., PRL 35, 389 (**1975**)]



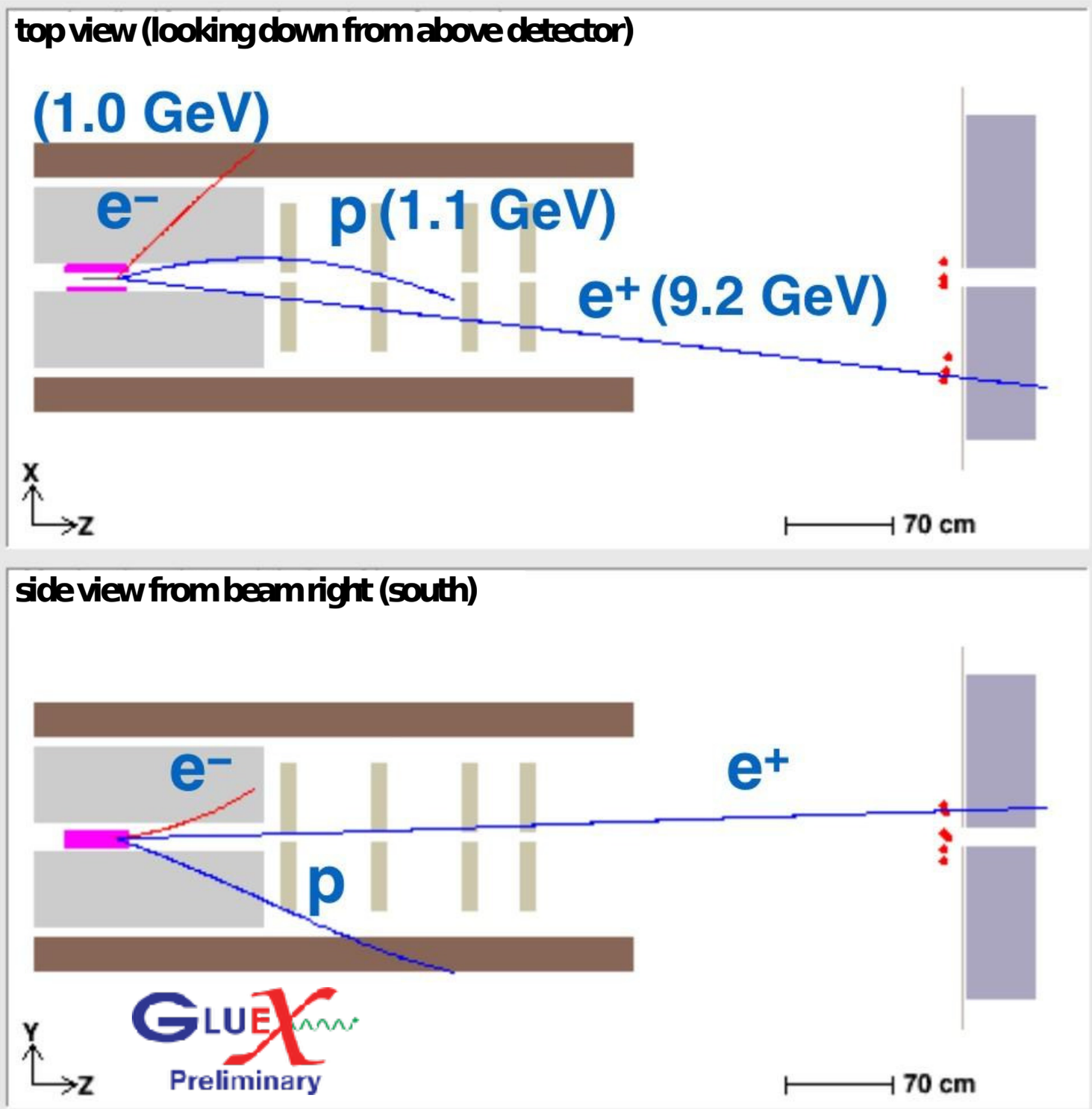
Identifying J/ψ in Photoproduction

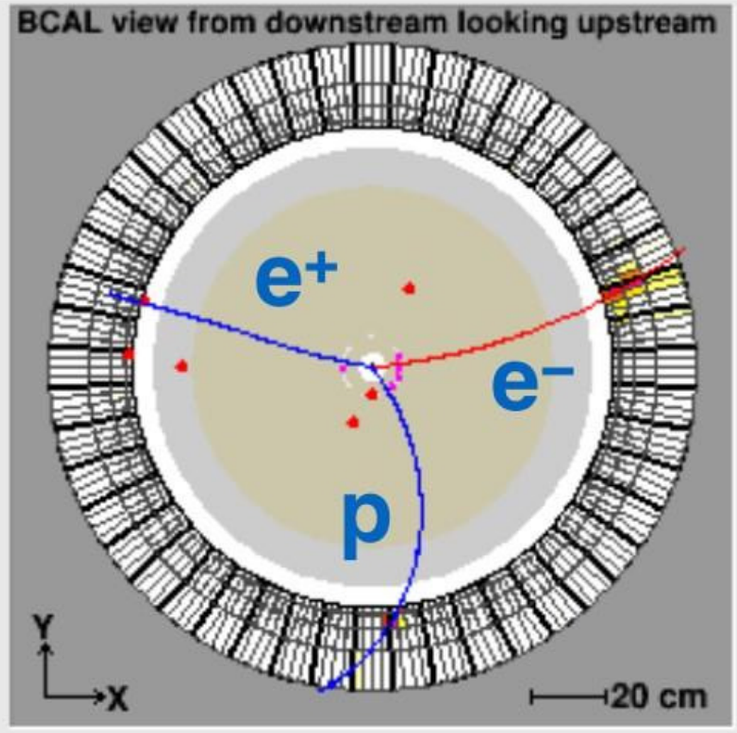
- We select fully reconstructed, kinematically fitted **$\gamma + p \rightarrow p + J/\psi$, $J/\psi \rightarrow e^+e^-$** events using the taken in Spring 2016 with:
  - At least 3 tracks in the event; matched to tagged beam photon, $E_\gamma > 8$ GeV
  - Electron ID using calorimeter information: reduces background by ~10^4

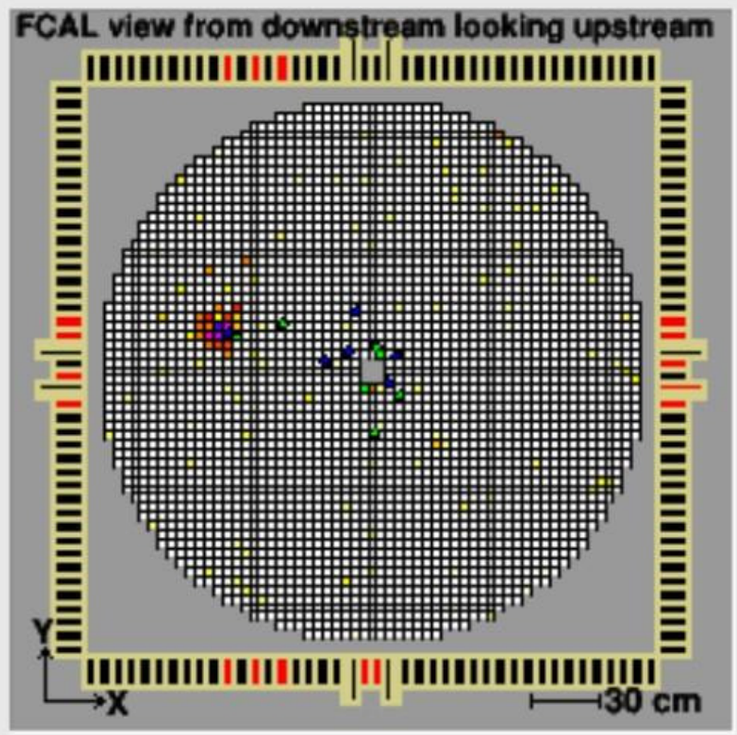


SD, L. Robison, T. Xiao, K. Seth (NU), L. Pentchev (JLab)

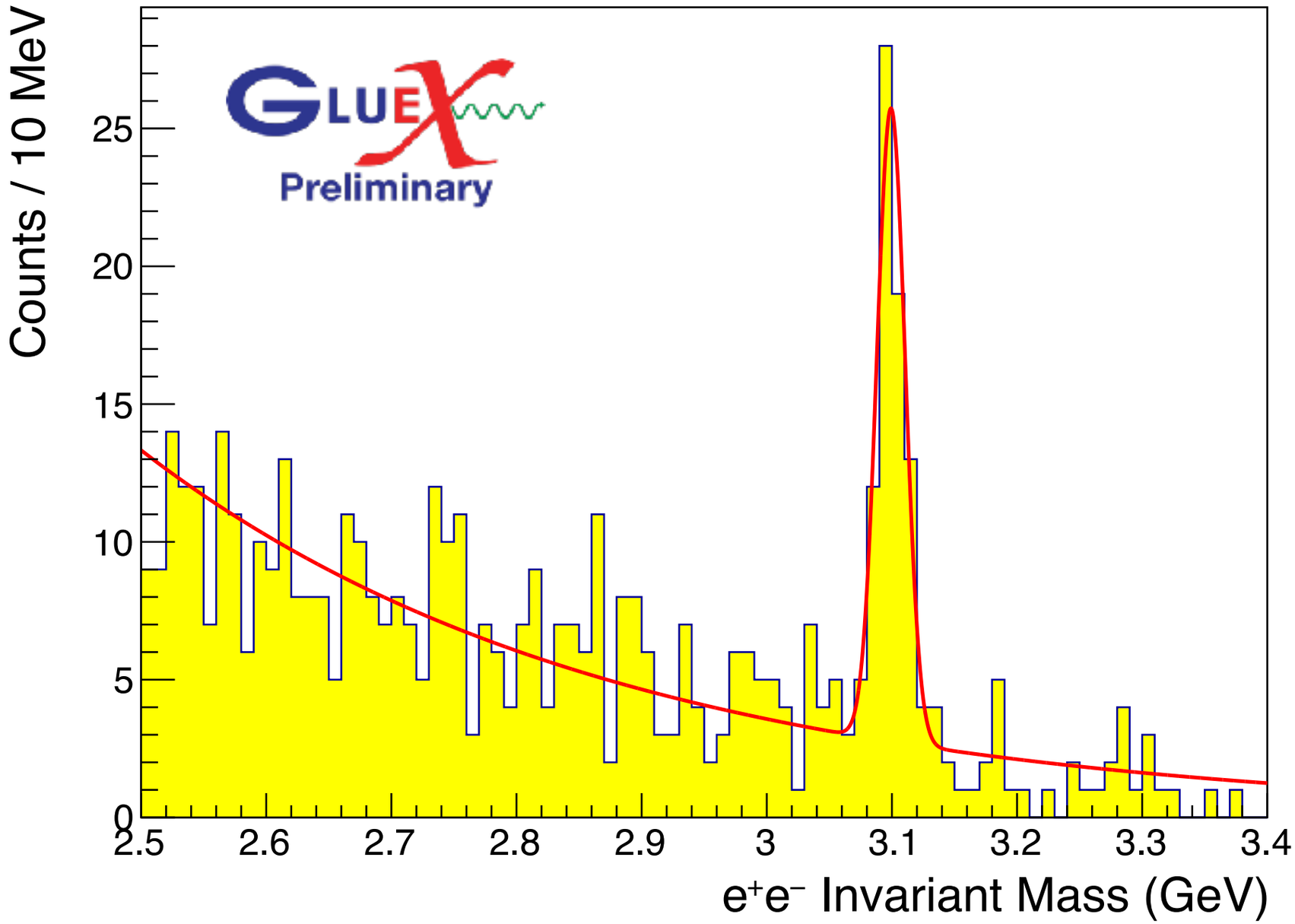
Example J/ψ Candidate Event







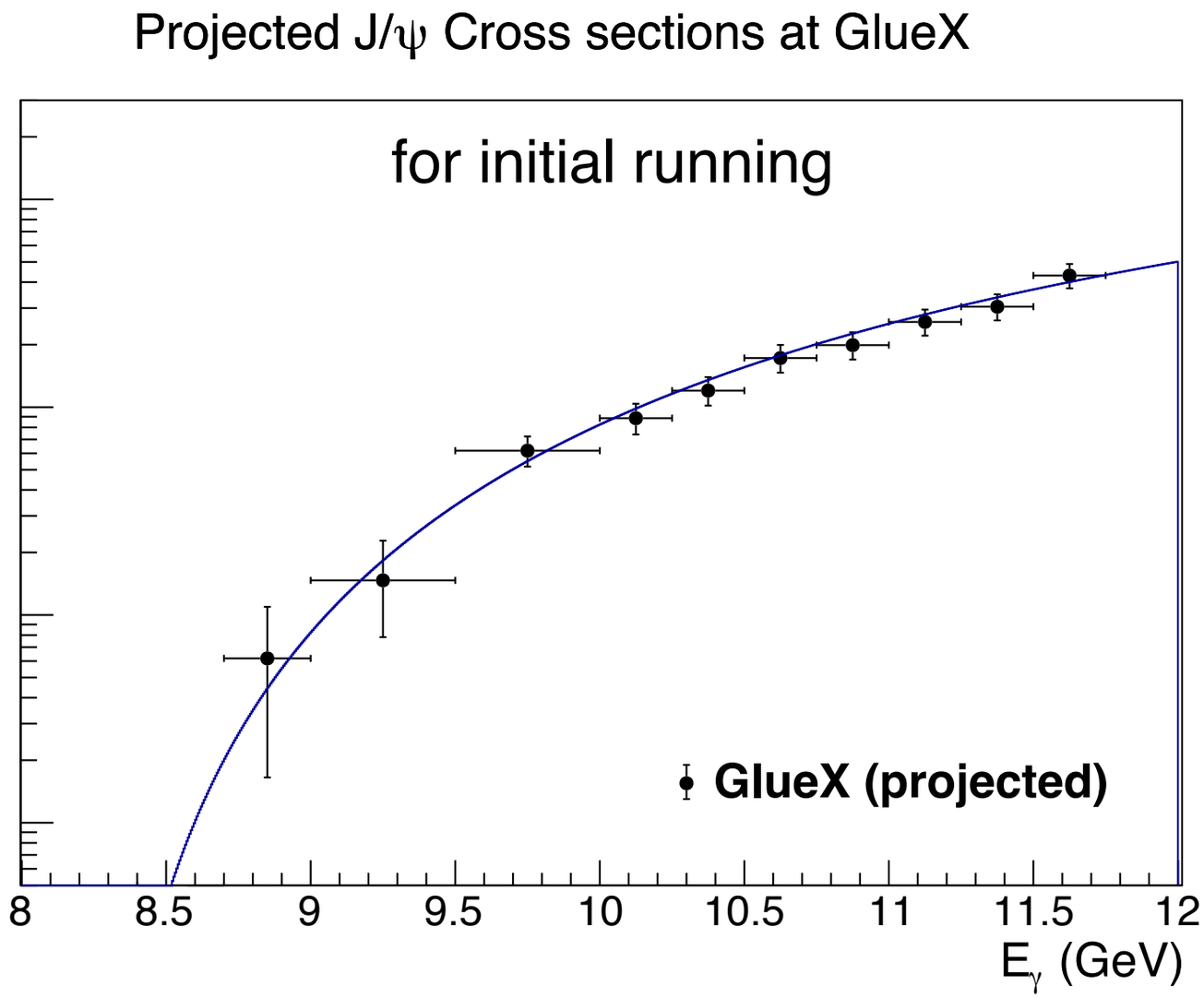
J/ψ Invariant Mass at GlueX



$N(J/\psi) = 66 \pm 9$ $M(J/\psi) = 3099.3 \pm 1.8$ MeV $\sigma = 11.2 \pm 1.6$ MeV

J/ψ Prospects at GlueX

- For initial GlueX running, expect 10x current data, ~700 J/ψ.
  - Allows first detailed look at cross sections near threshold
    [L. Robison Ph.D. project]
  - First searches for resonant states in this region.

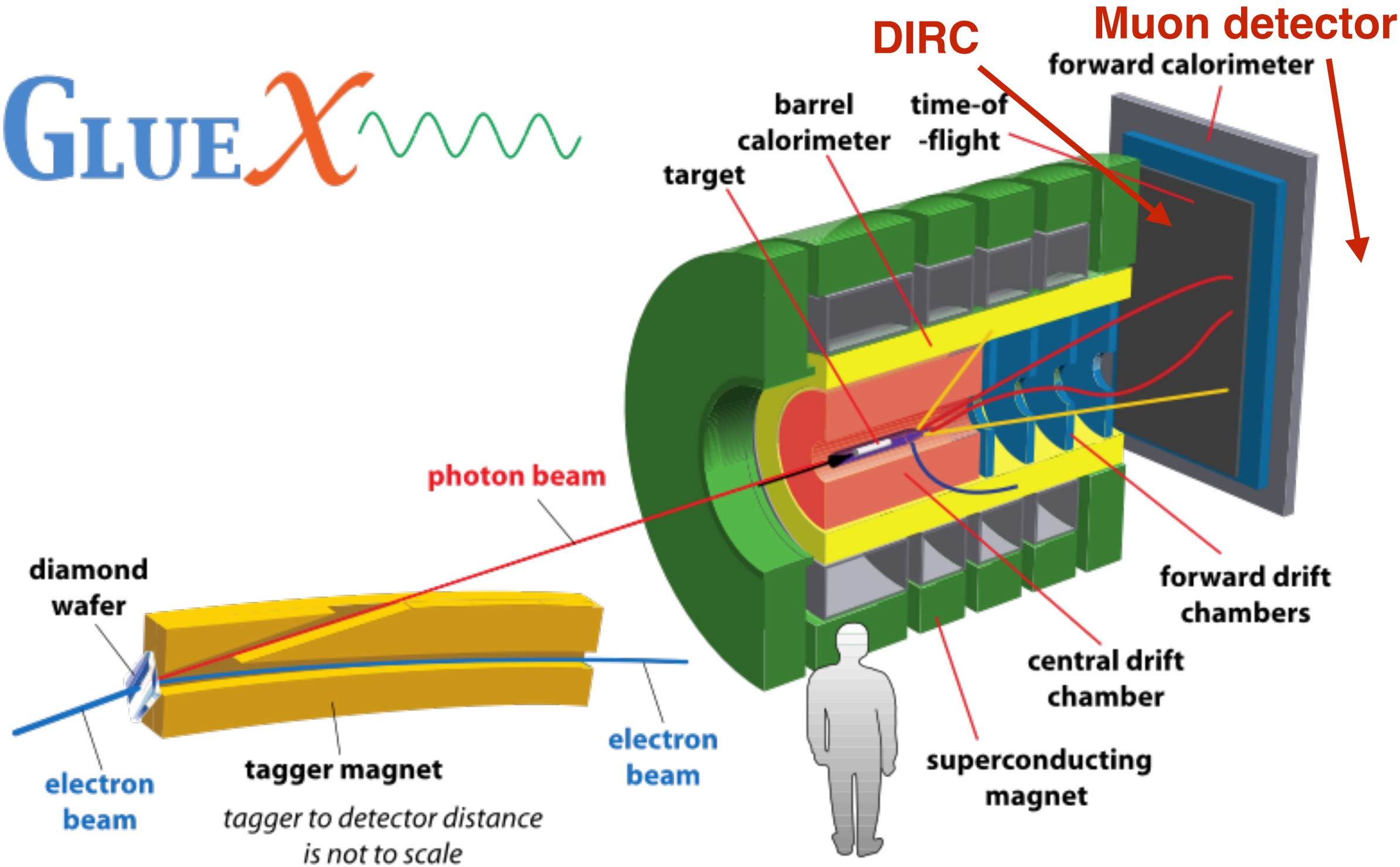


GlueX Experimental Program

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 (conditional)

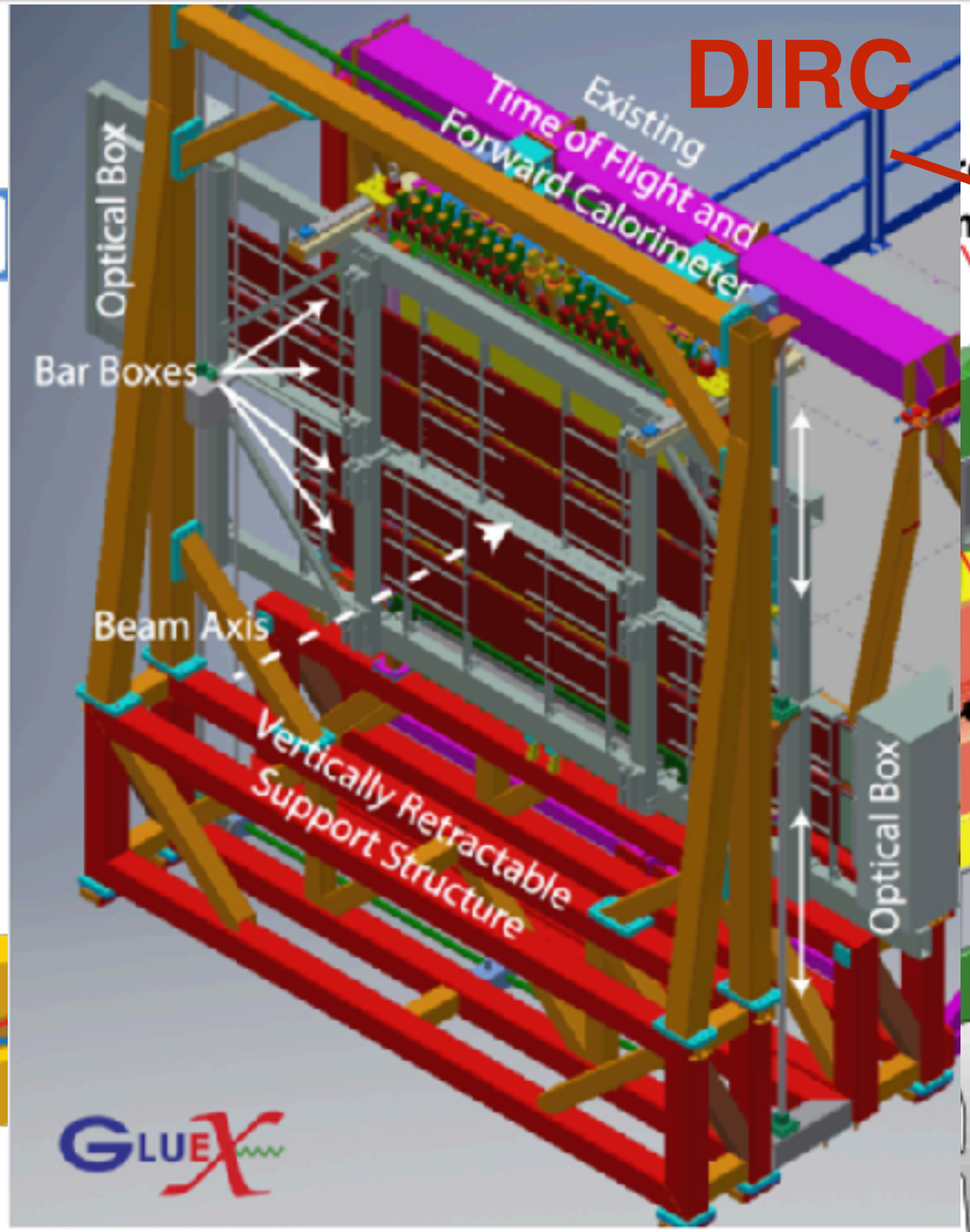
- Detector upgrades underway: DIRC for enhanced π/K separation to be installed starting this summer.
  - Software trigger to be added for high-intensity running
- Workshops: K_L beam, ω-photoproduction in nuclei

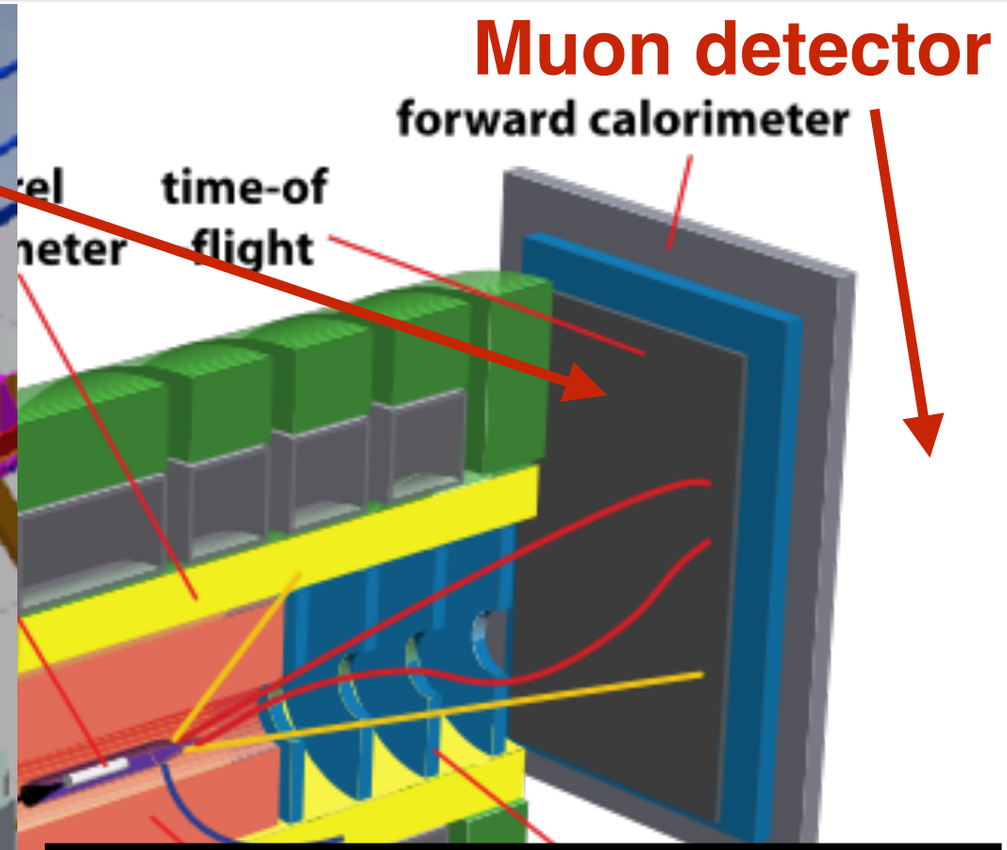
The GlueX Experiment: Future Detector Upgrades

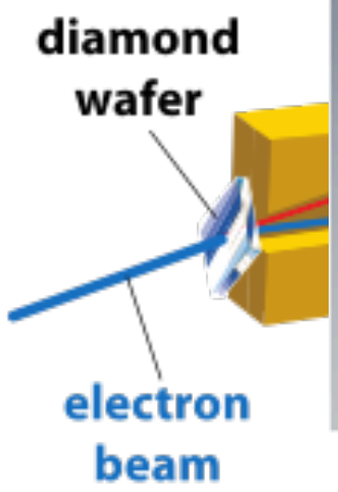


Not shown: Software Trigger Farm

The GlueX Experiment: Future Detector Upgrades







tagger to detector distance is not to scale

DIRC Detector
Improves π/K separation
Installation: 2017-2018
Available: 2018+

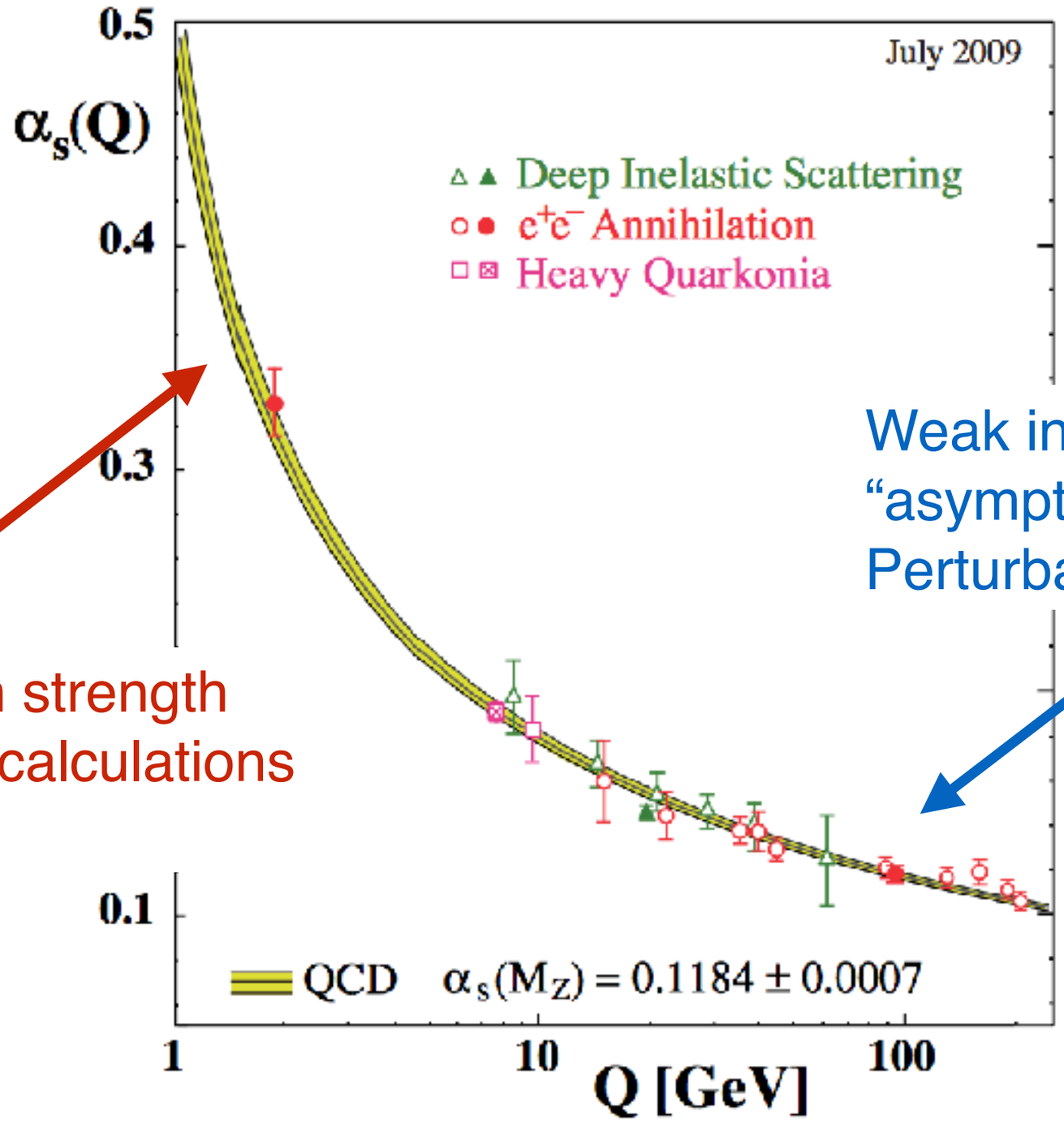
Enables detailed studies of strange-quark hadrons

Summary

- A rich spectrum of hadronic states is seen in nature.
  Studying them will yield fresh insight into the nature of quark confinement.
- Photoproduction allows for the production of a wide variety of hadrons, normal and “exotic”.
- The GlueX experiment has just started its first physics run!
  - Commissioning data show rich prospects for spectroscopy and other physics measurements
  - Initial running will focus on spectroscopy of up/down quark states and provide enough data for initial studies of J/ψ and other rare processes
  - High-luminosity running will focus on strange-quark states.
  - A rich physics program is underway!

Backup Slides

α_S — Strong Force Coupling Constant



Weak interaction strength
"asymptotic freedom"
Perturbative calculations OK

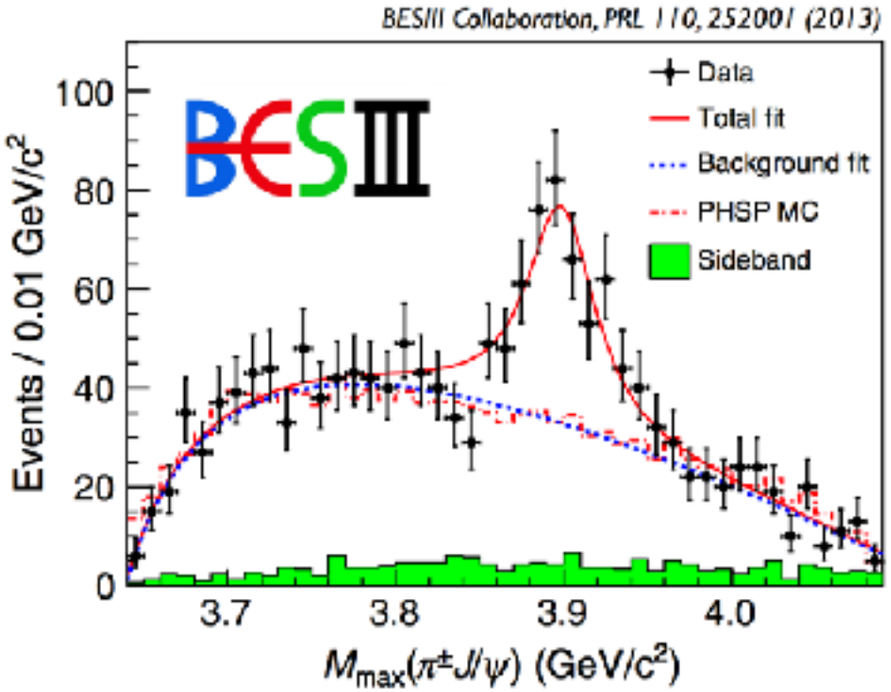
Strong interaction strength
Numerical lattice calculations
Bound states

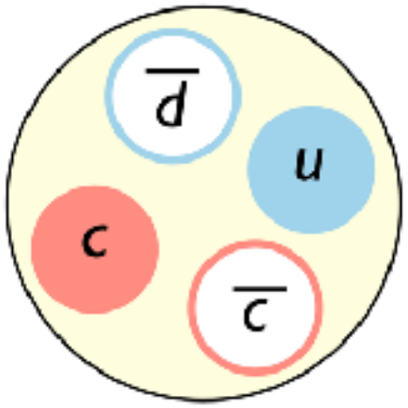
“Charmed” Tetraquark Candidates

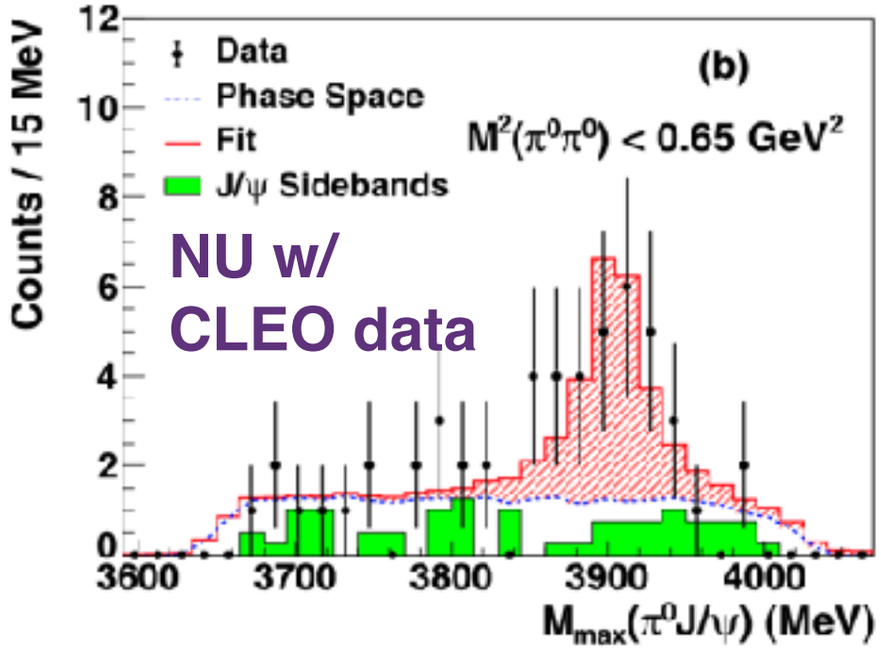
$$e^+e^- \to \pi^\mp Z_c^\pm$$

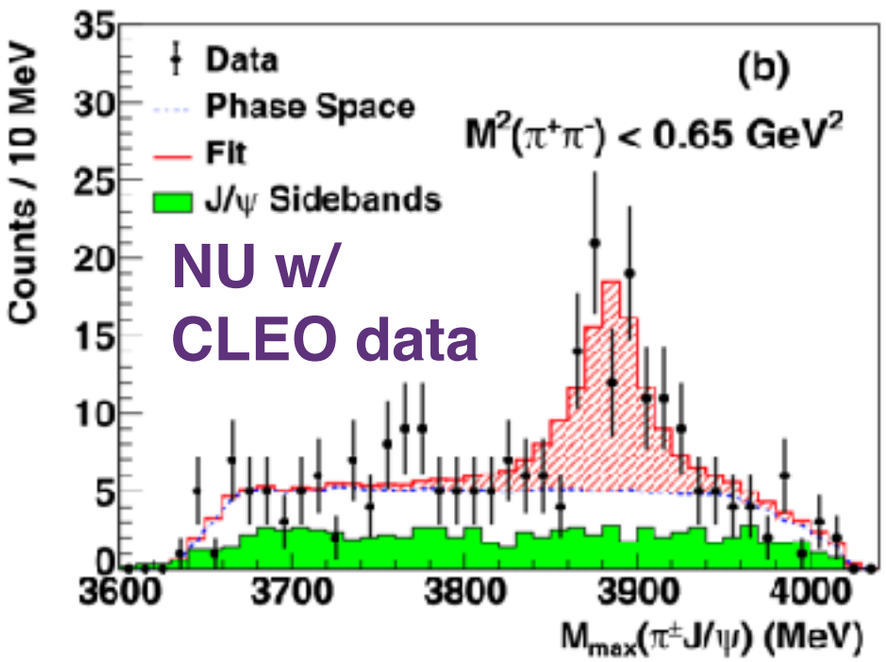
$Z_c(3900)$

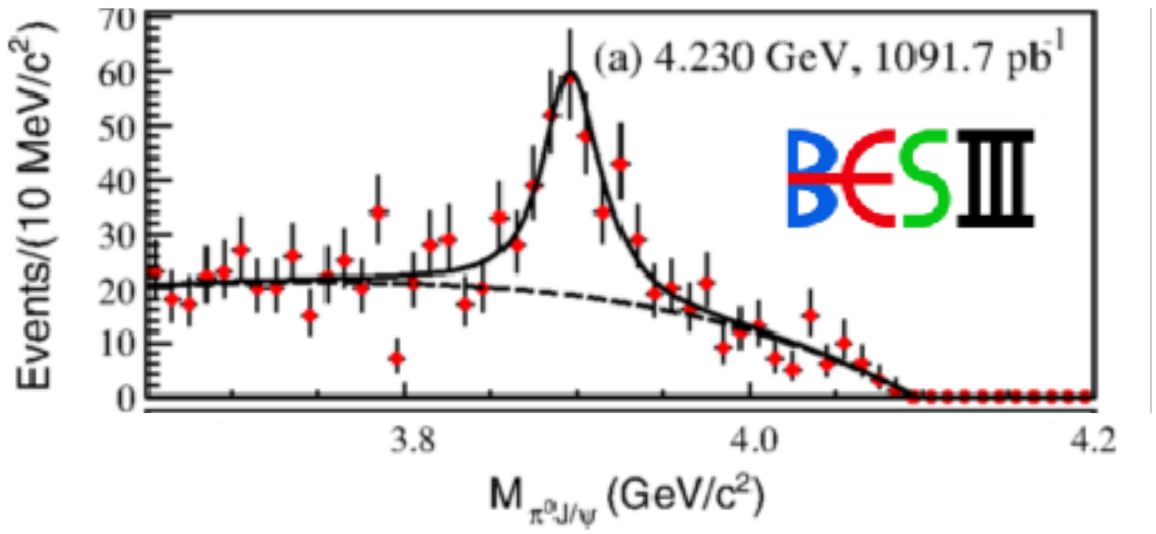
$$e^+e^- \to \pi^0 Z_c^0$$











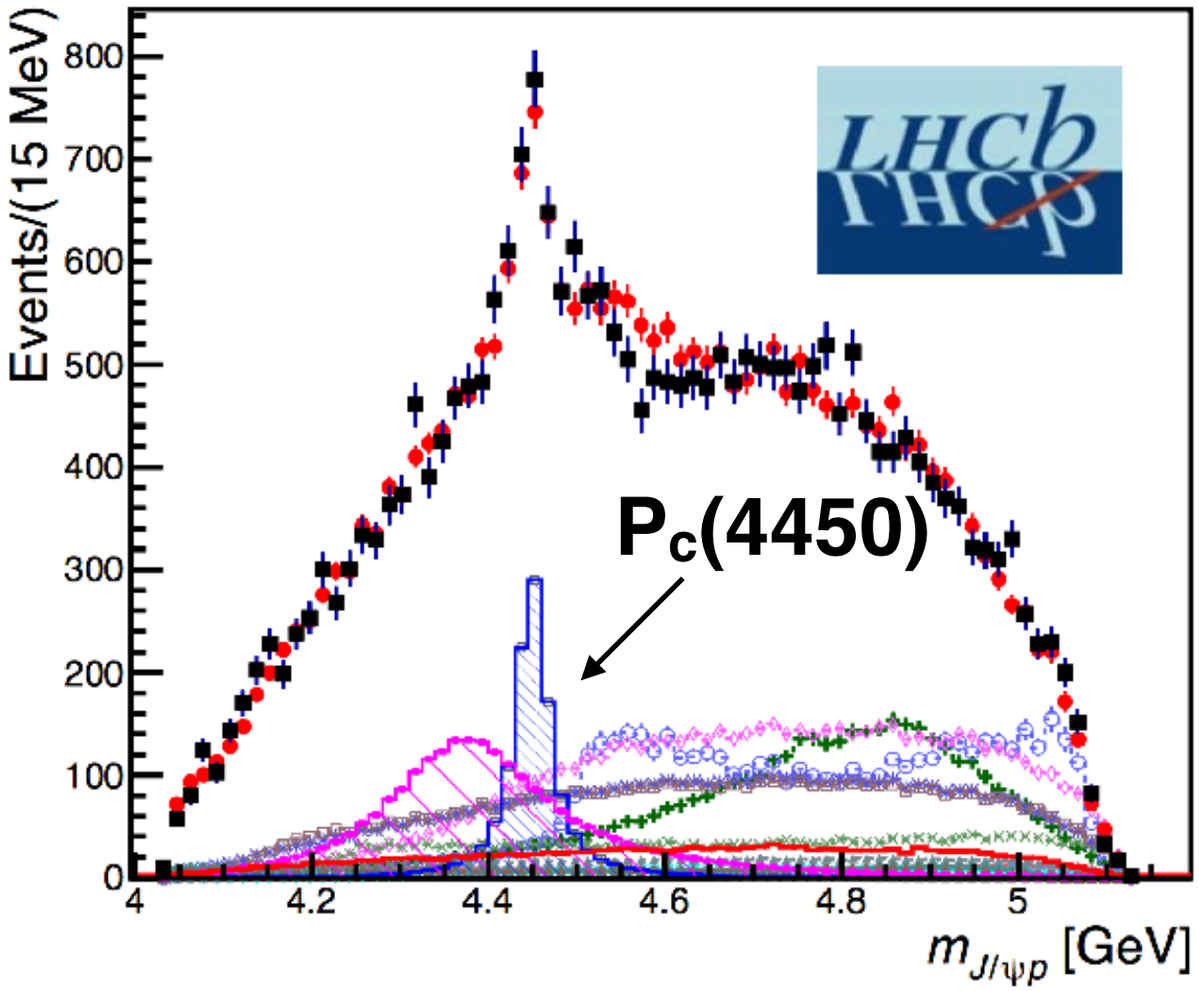
Identification of neutral partner confirms isospin-1 nature

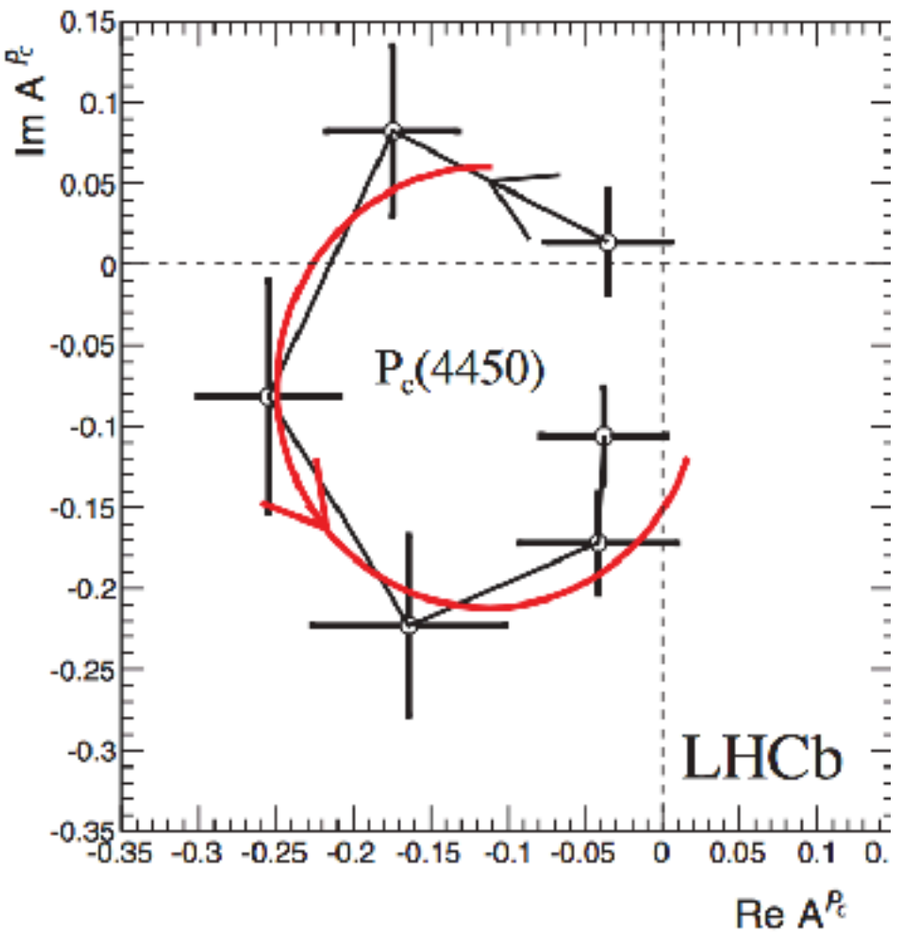
“Charmed” Pentaquark Candidate from LHCb

$P_c(4450)$

$$B \to pKJ/\psi$$

LHCb Collaboration, PRL 115, 072001 (2015)

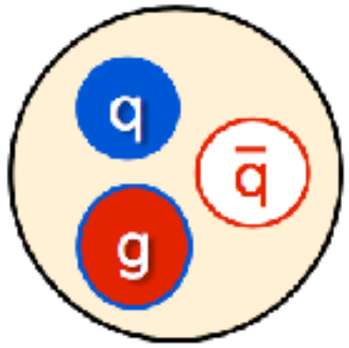




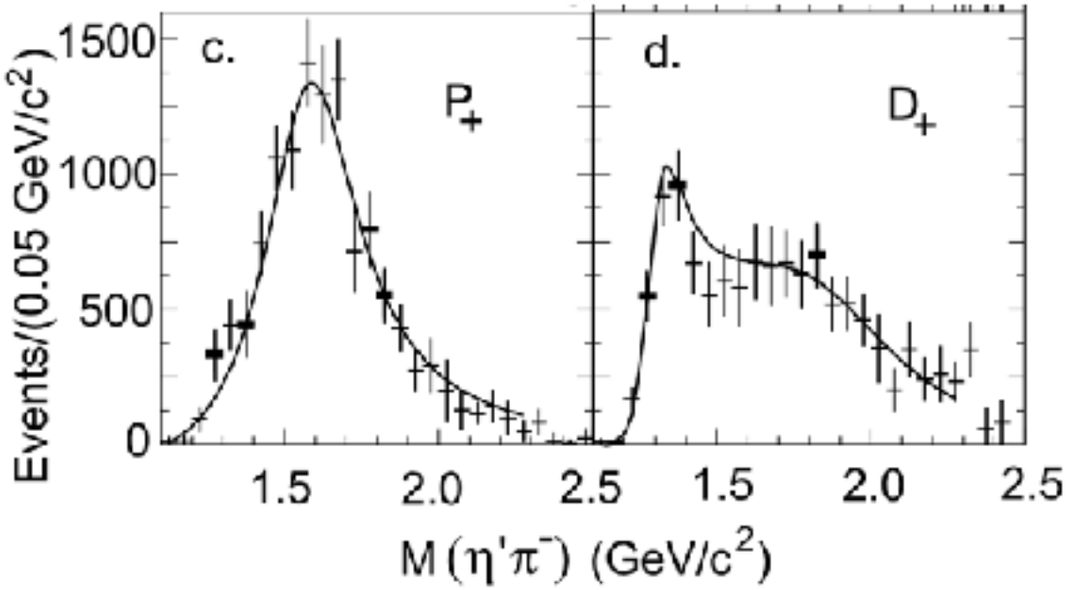
p+J/ψ decay implies 5-quark structure

Evidence for exotic light-quark mesons

$\pi_1 \to \eta' \pi$



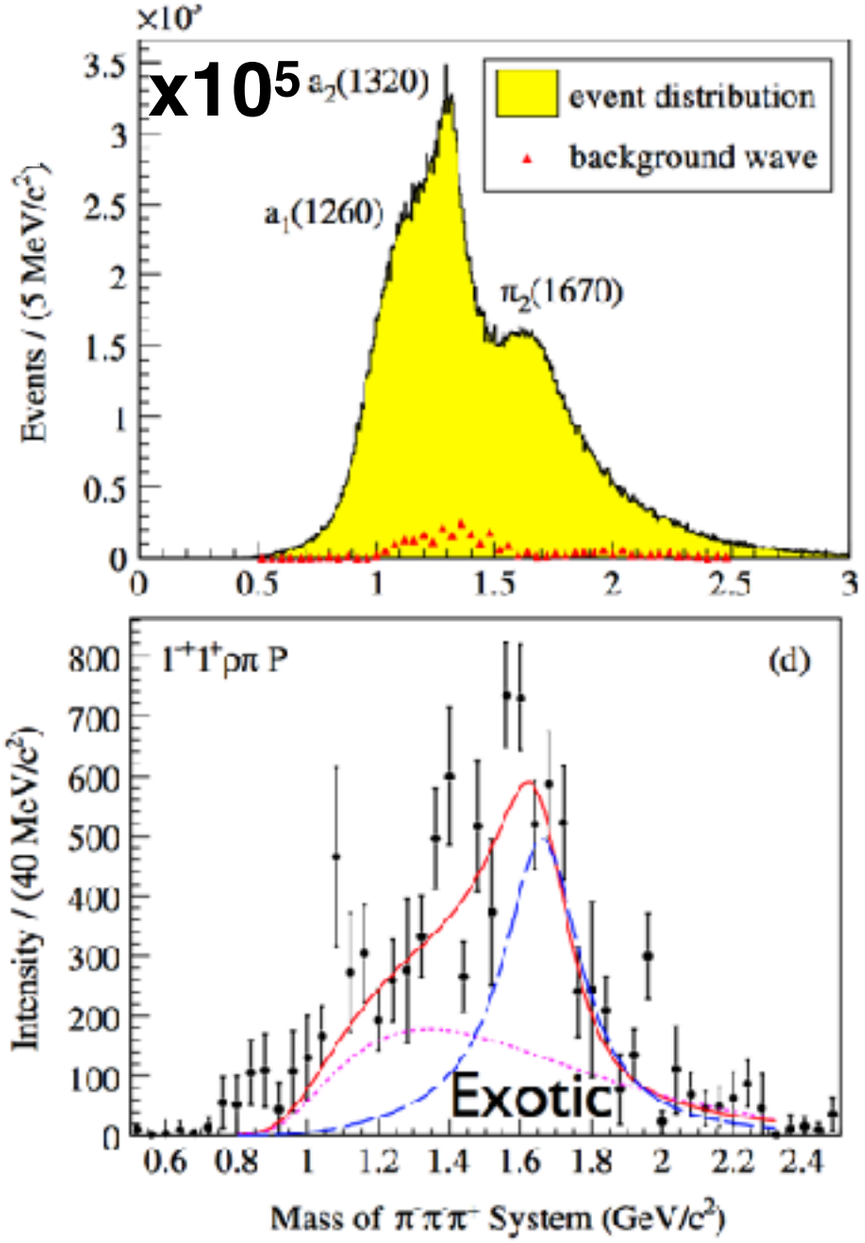
E852: 18 GeV π on p



PRL 86, 3977 (2001)

$\pi_1 \to \rho\pi$

COMPASS: 190 GeV π on Pb

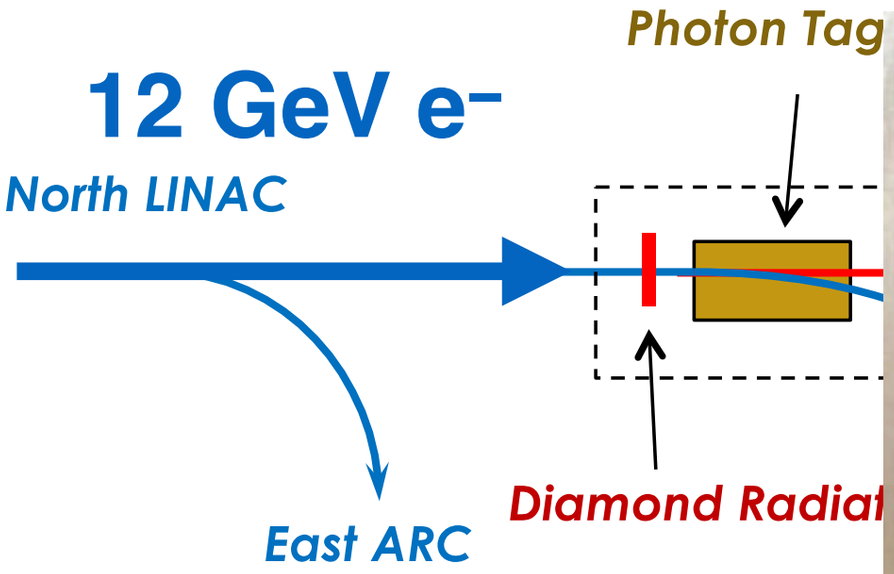


PRL 104, 241803 (2010)

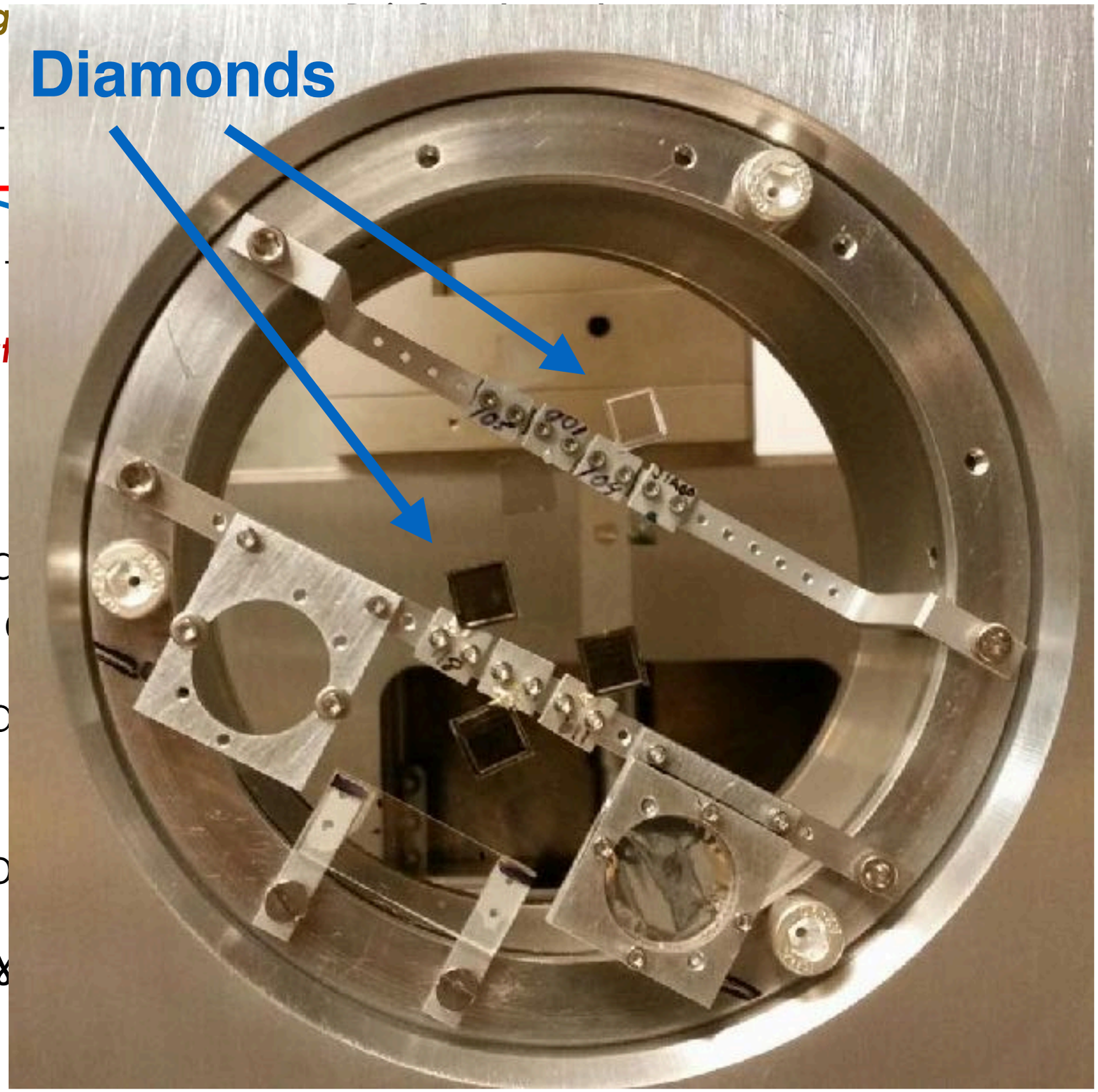
GlueX DNP 2016 Presentations

- Light Meson Spectroscopy: First Results from GlueX — Matthew Shepherd
- Single Meson Photoproduction at JLab Energies — Vincent Mathieu
- Photoproduction of the $\rho^0(770)$ meson at GlueX — Alexander Austregesilo
- Beam asymmetry Σ for π^0 and η photoproduction on the proton at GlueX — Zhenyu Zhang
- Photoproduction of $\pi\pi$ Resonances at GlueX — Jonathan Zarling
- Analysis of the $\eta(548) \to \pi^+ \pi^- \pi^0$ and $\eta'(958) \to \pi^+ \pi^- \eta$ channels using a 8–9 GeV tagged photon beam for the GlueX Experiment — Tegan Beattie
- Photoproduction of J/Psi at GlueX — Kam Seth
- K-Long Facility for JLab and its Scientific Potential — Igor Strakovsky
- Antikaon-nucleon scattering and the hyperon spectrum — Cesar Fernandez-Ramirez
- Performance of the GlueX Polarized Photon Source — Richard Jones
- A survey of multi-photon final states using the GlueX detector — Simon Taylor
- Exclusive $\omega(782)$ photoproduction at GlueX — Michael Staib
- $\eta'\pi$ production and search for exotic mesons at COMPASS and JLab12 — Vladyslav Pauk
- Study of the $\eta^{(\prime)} \to \pi^+ \pi^- \gamma$ decay at GlueX and Transition Form Factors — Cristiano Fanelli
- Partial wave analysis of 3π with pion and photon beams — Andrew Jackura
- Leptophobic Boson Searches — John Hardin
- 3π resonance poles from COMPASS data — Mikhail Mikhasenko

The GlueX Experiment: Photon Beamline



- Photon beam generated
  bremsstrahlung off thin
- Photon energies tagge
  electrons
- Photon linear polarizatio
- Design intensity of 10^8 γ

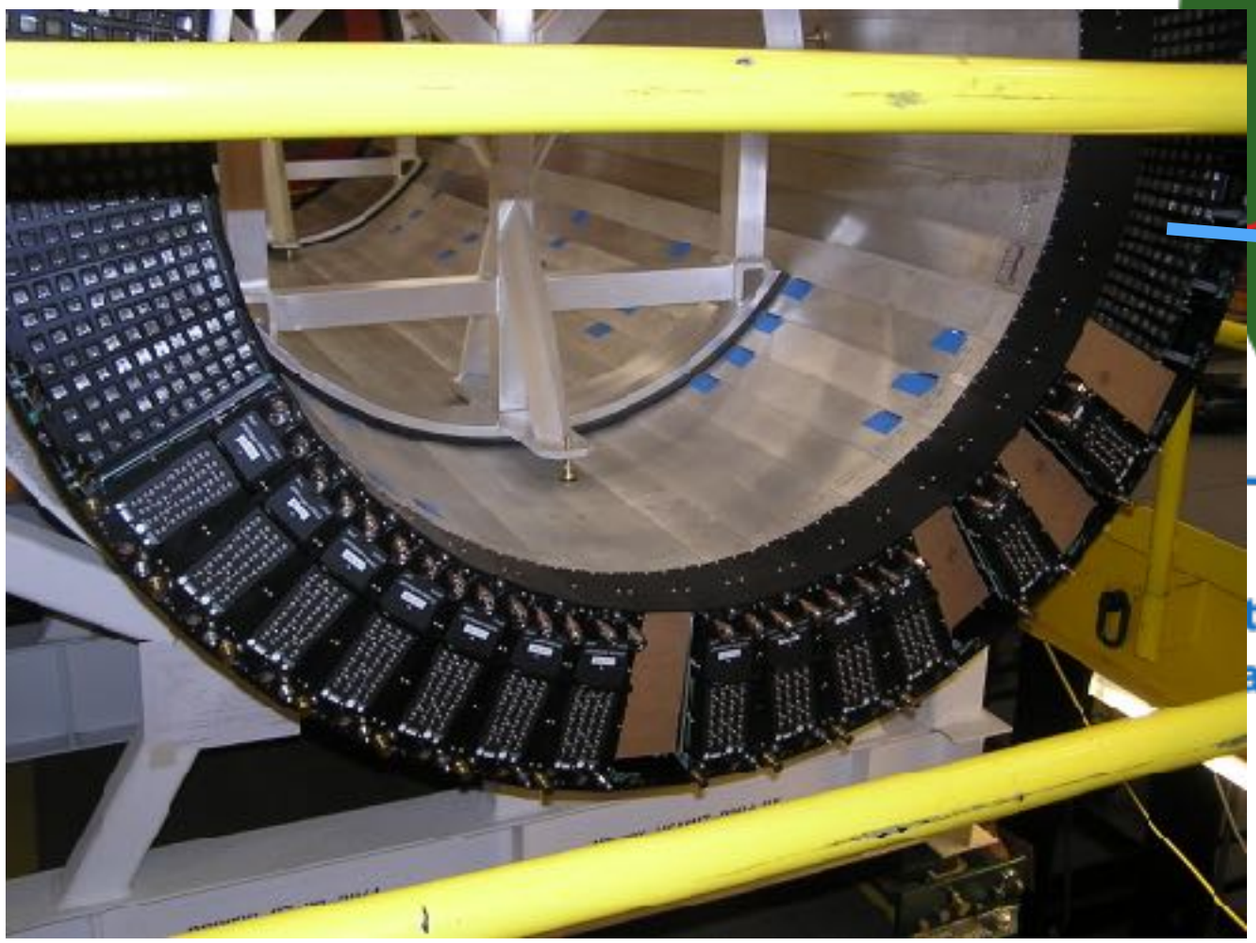


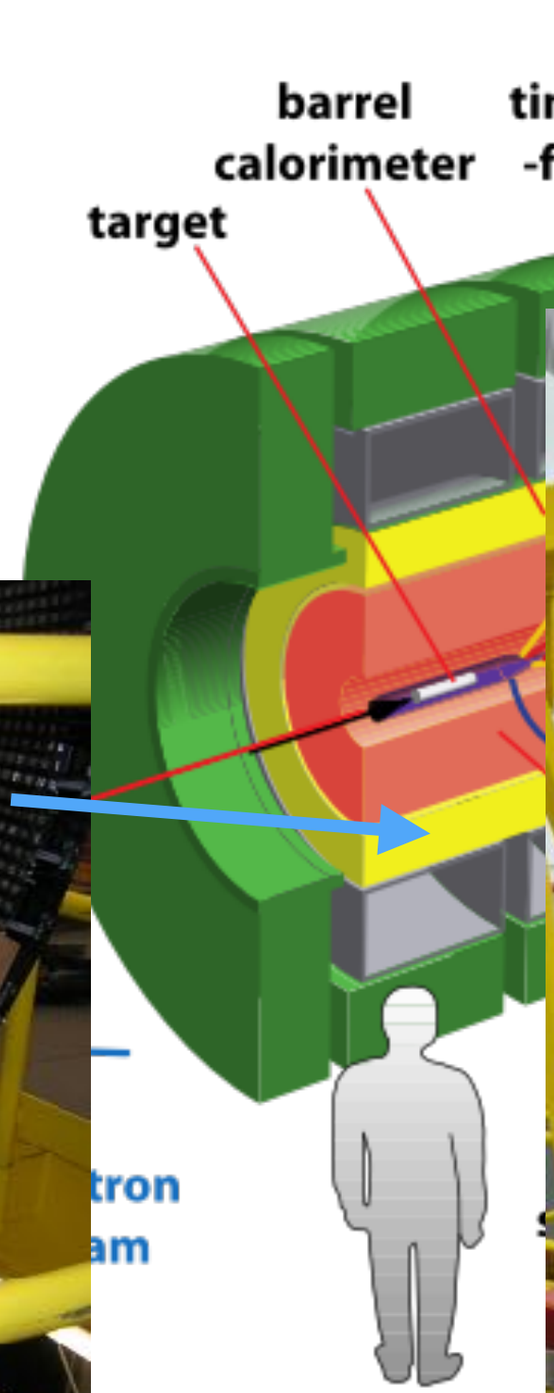
GlueX Detector, August 2014

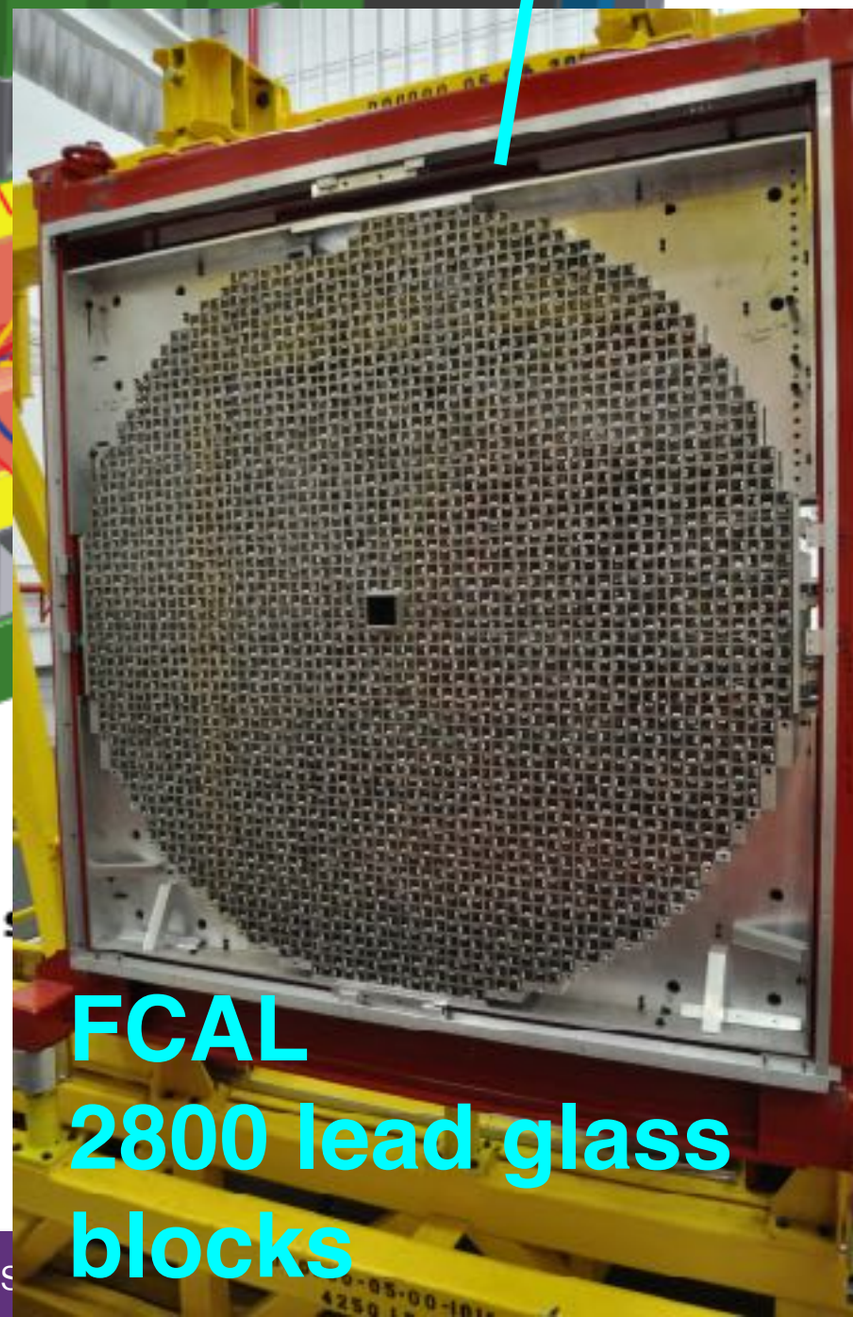
The GlueX Experiment: Calorimetery

GLUEX

BCAL — lead/scin. fiber
3840 SiPM readout

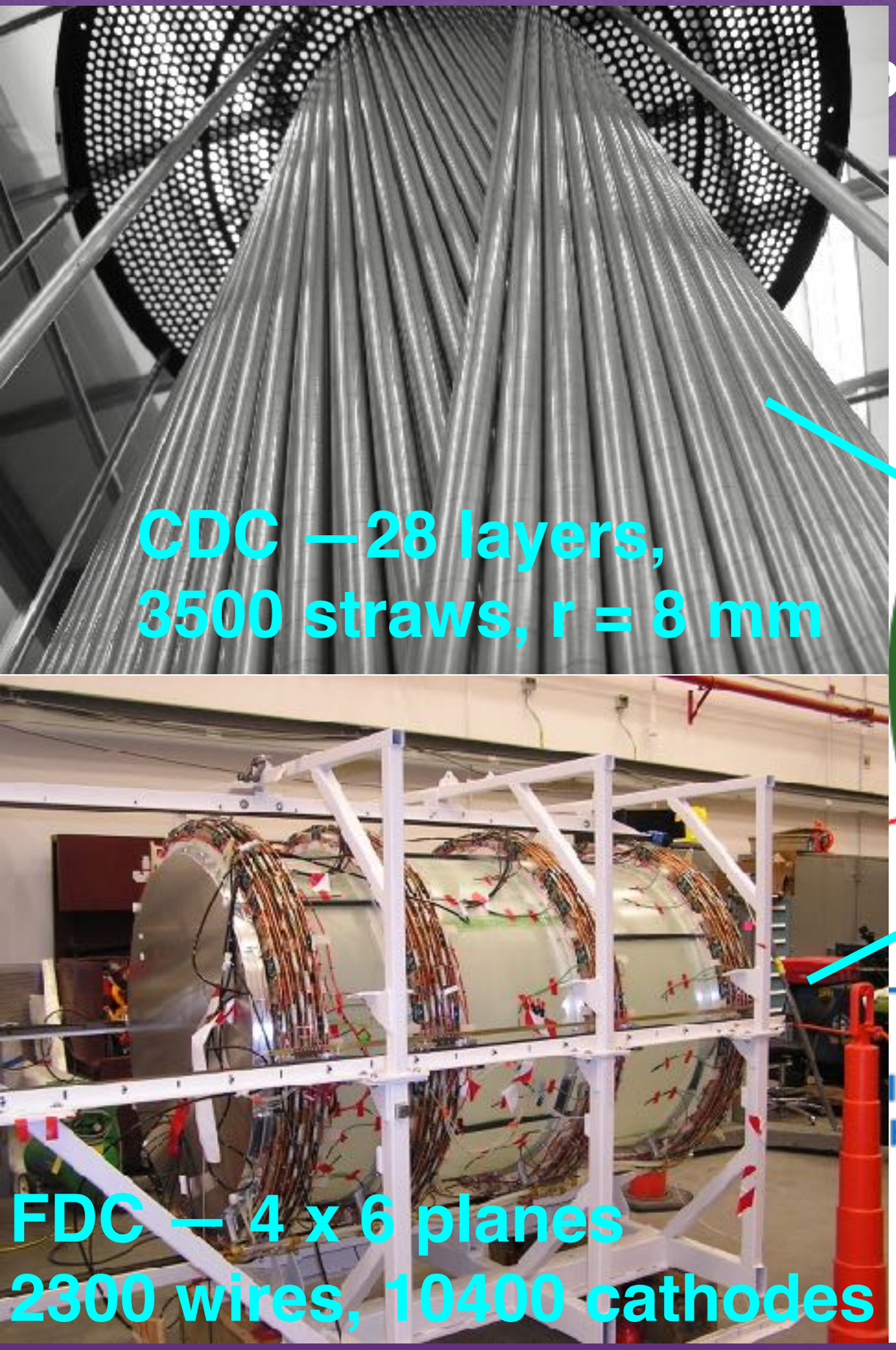


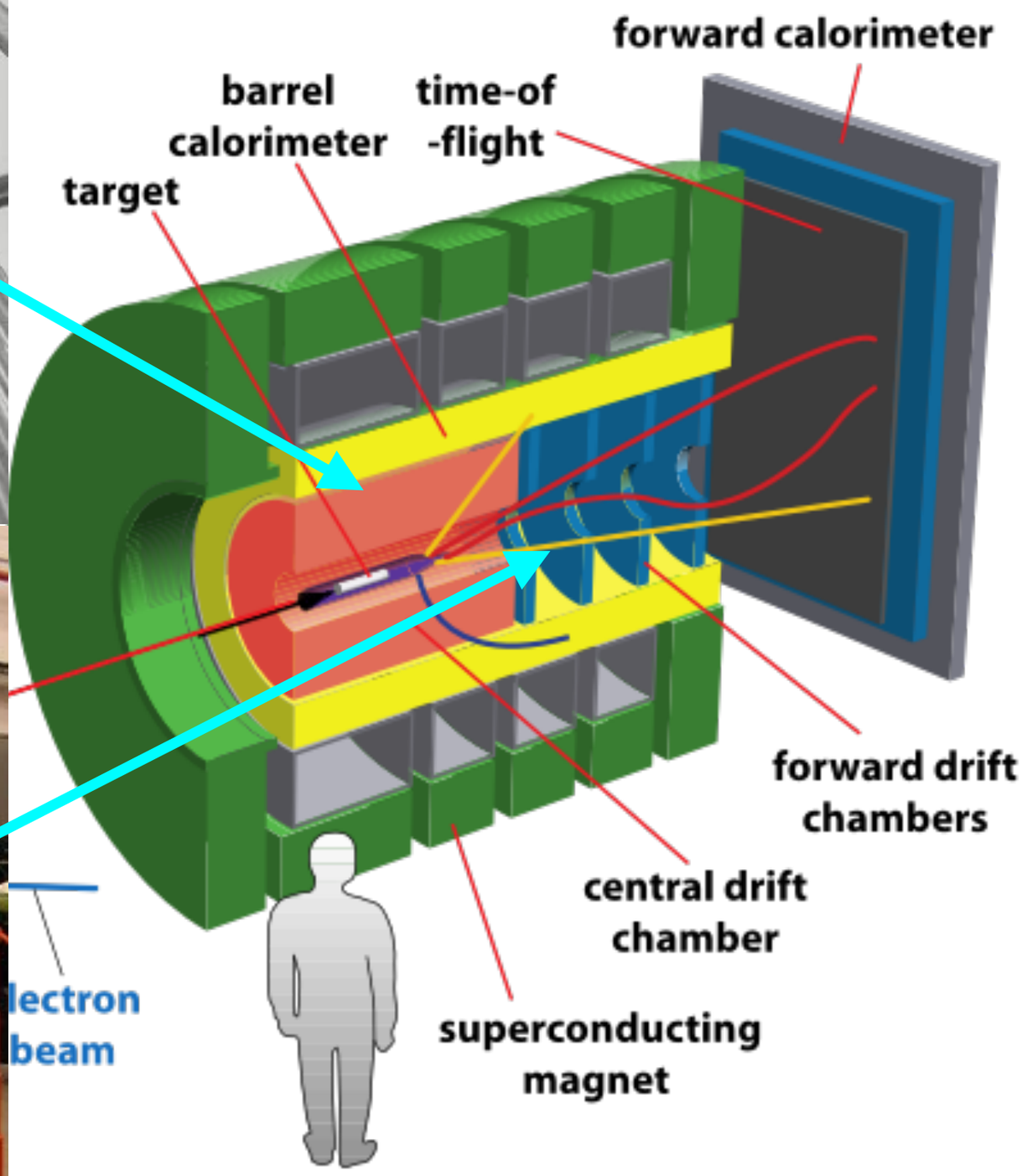




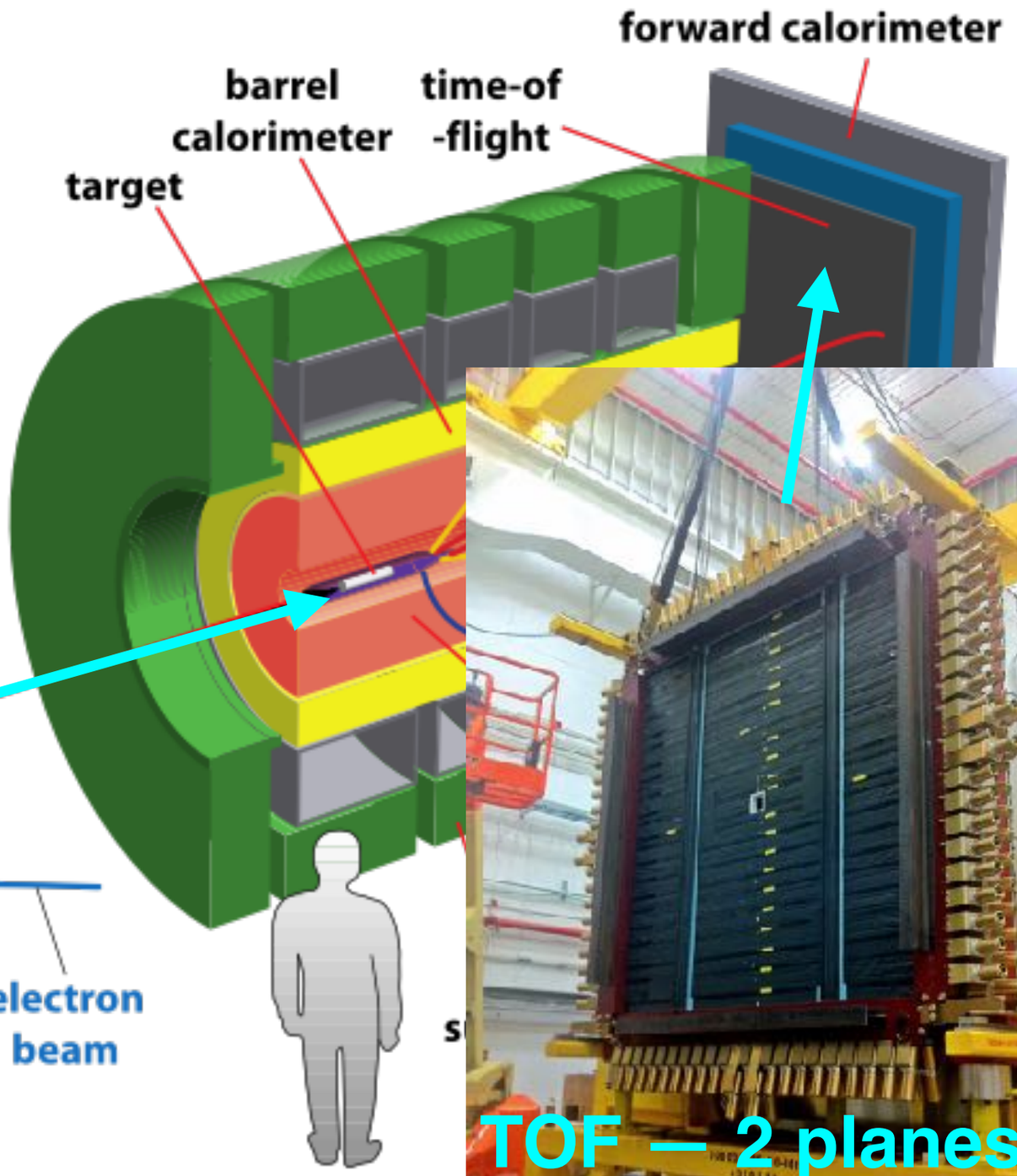
FCAL
2800 lead glass blocks

eriment: Tracking



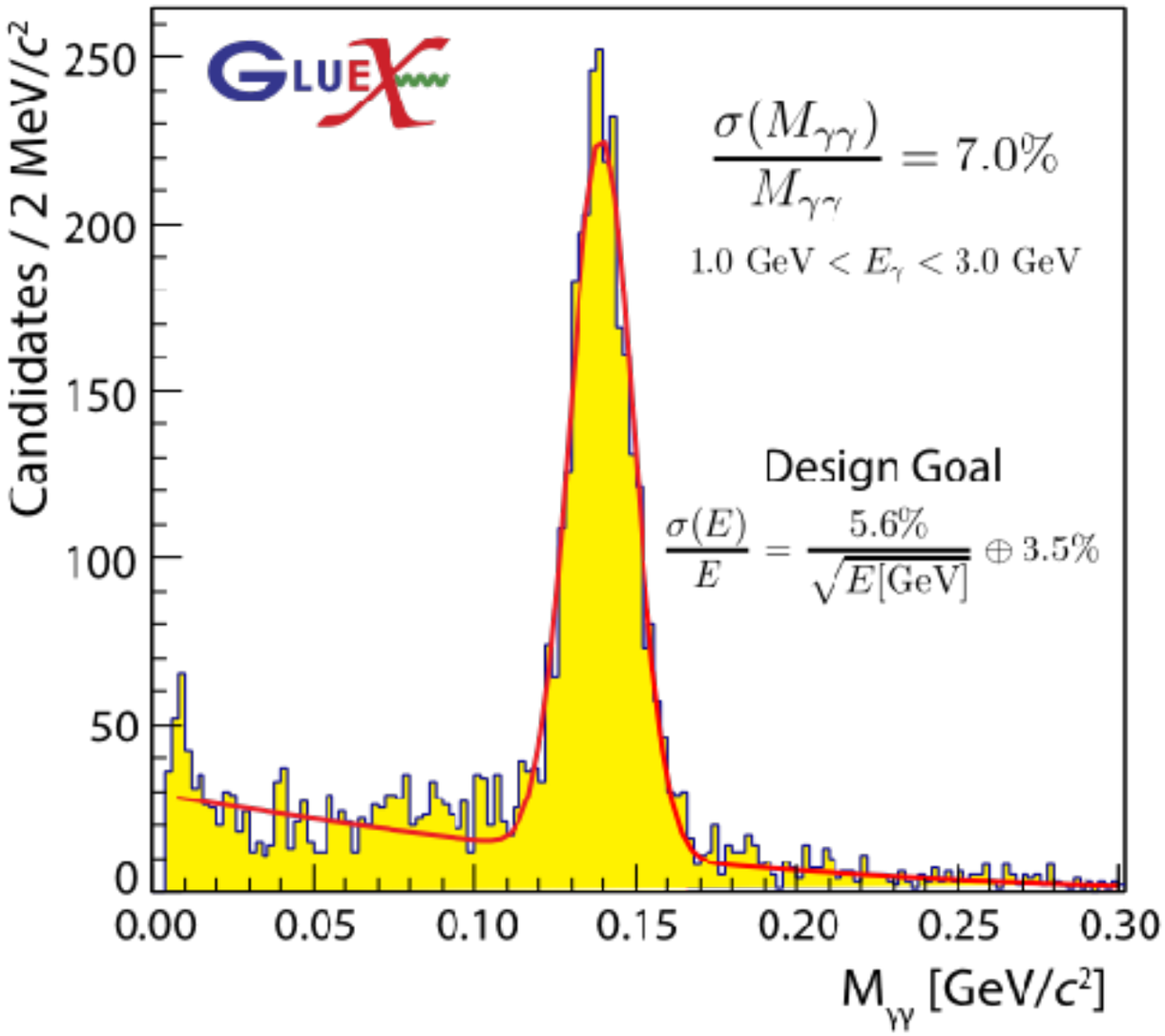


The GlueX Experiment: Particle ID

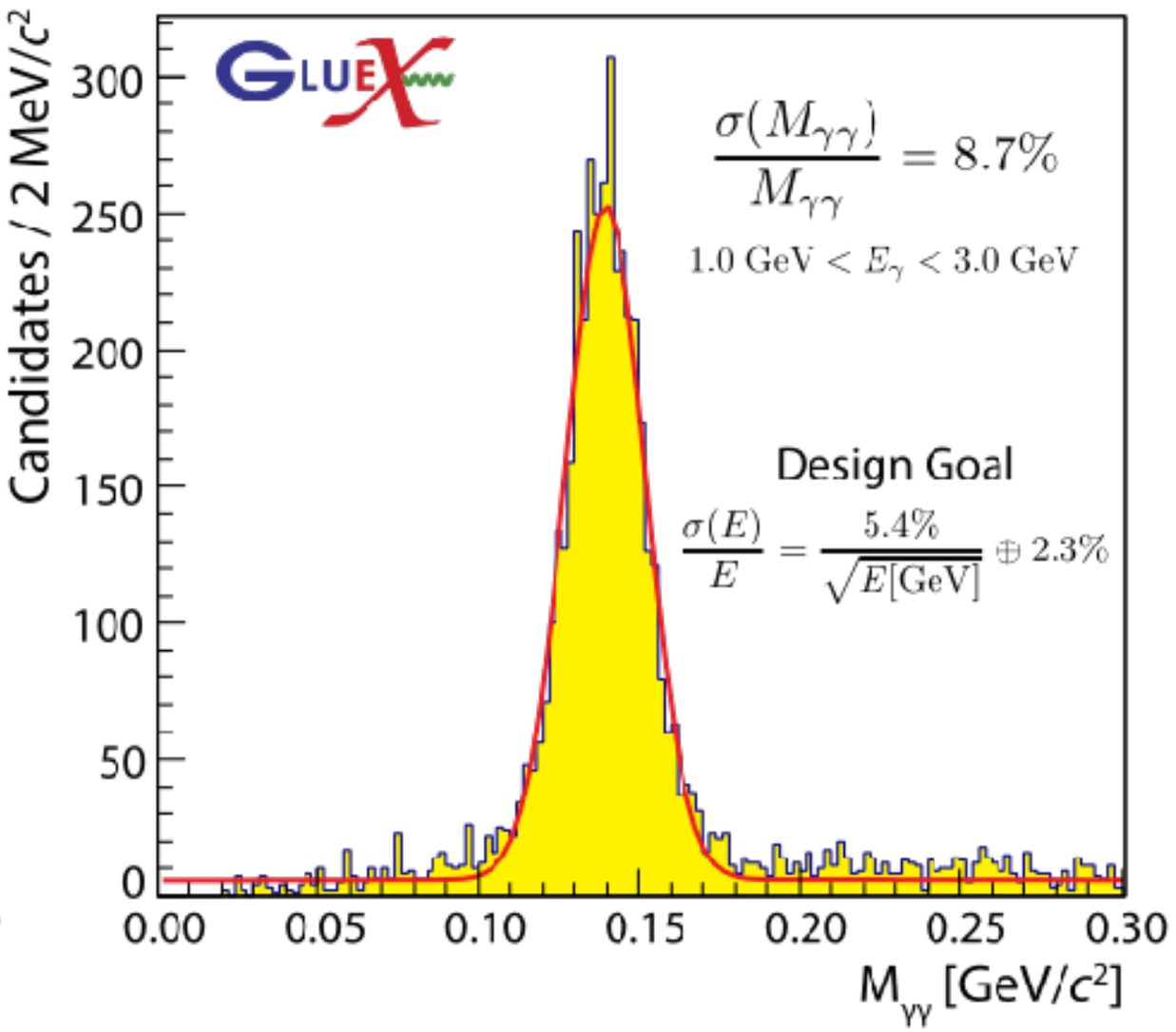


GlueX Calorimetry Performance

Forward Lead Glass Calorimeter

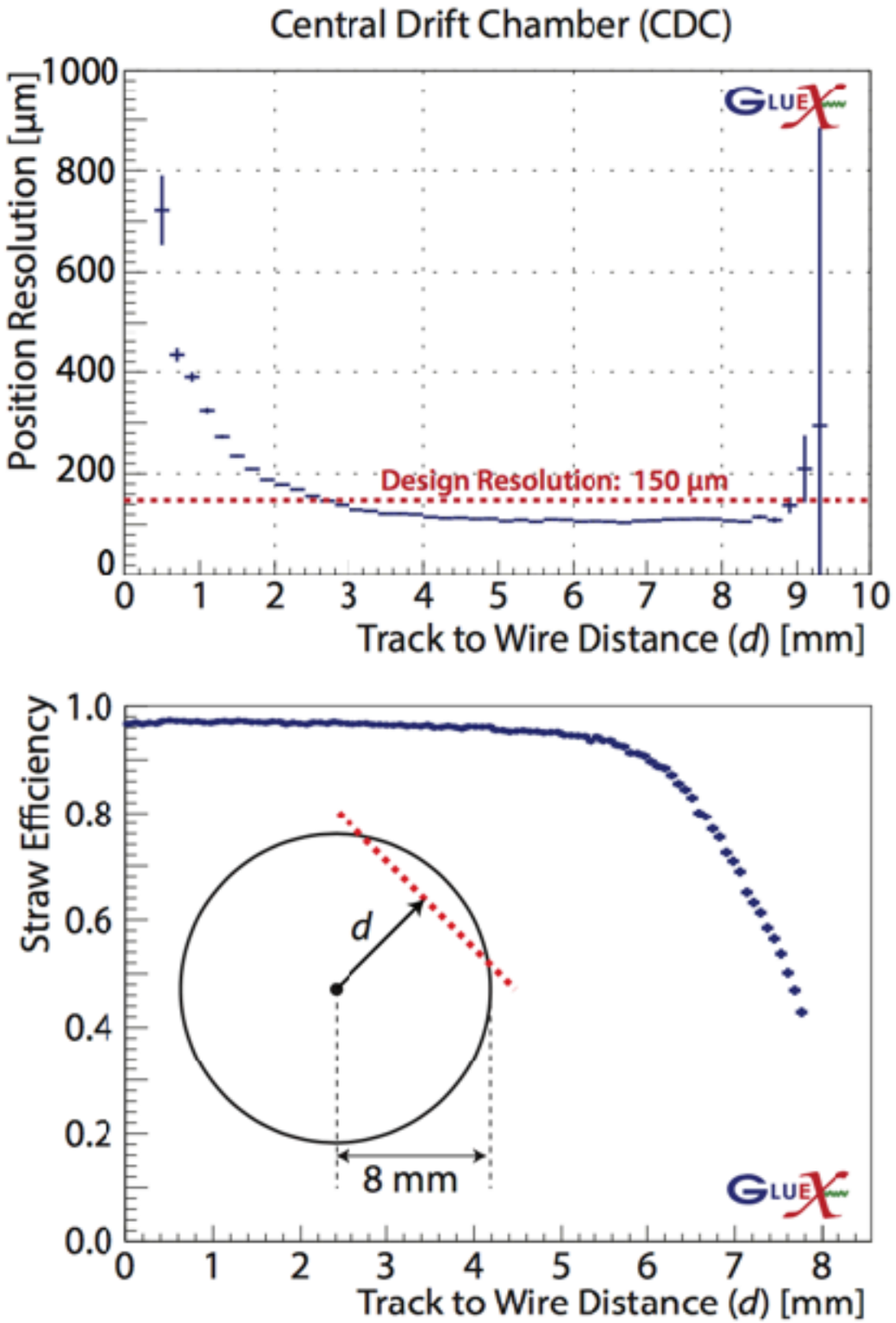


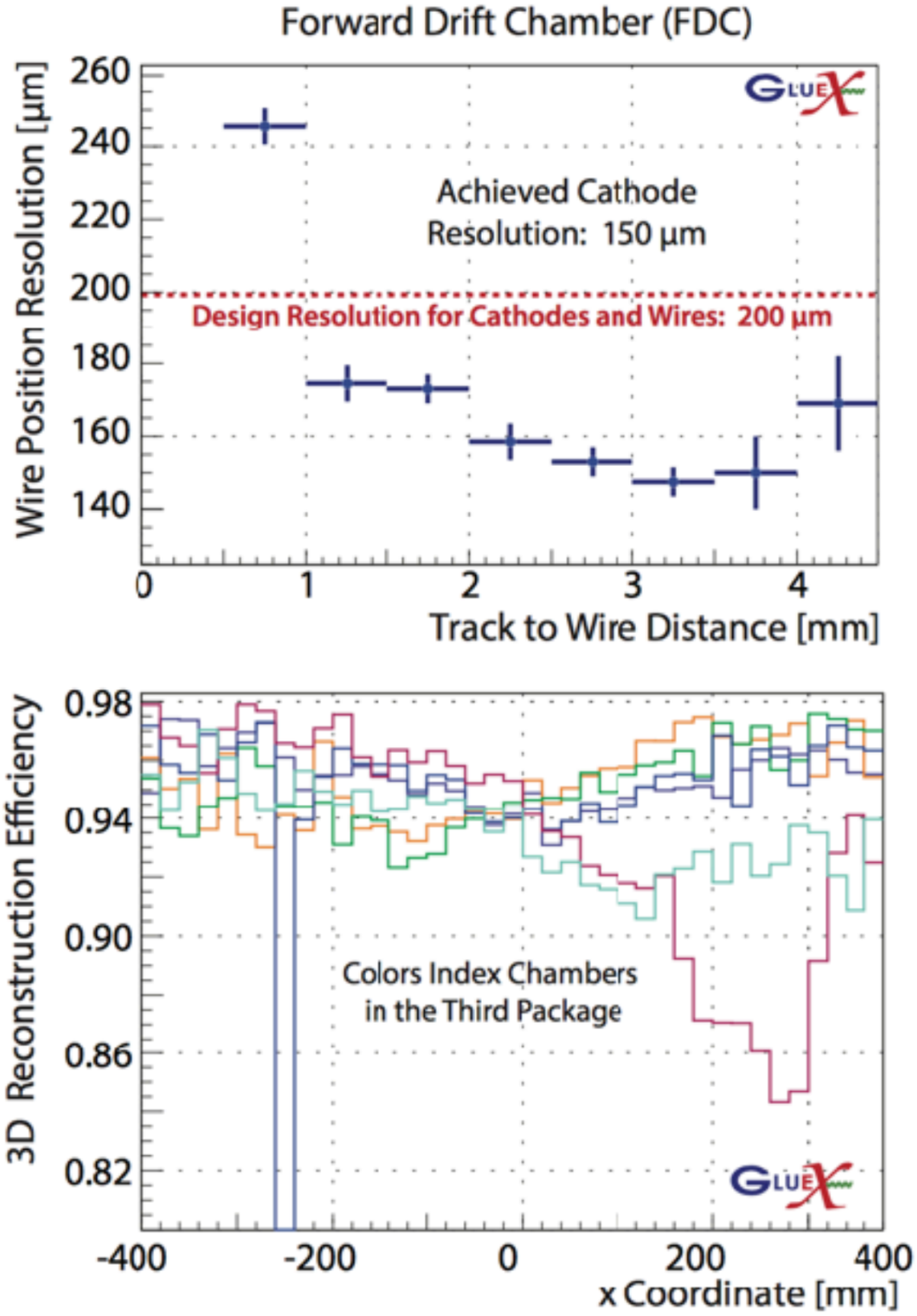
Barrel Lead-Scintillating Fiber Calorimeter



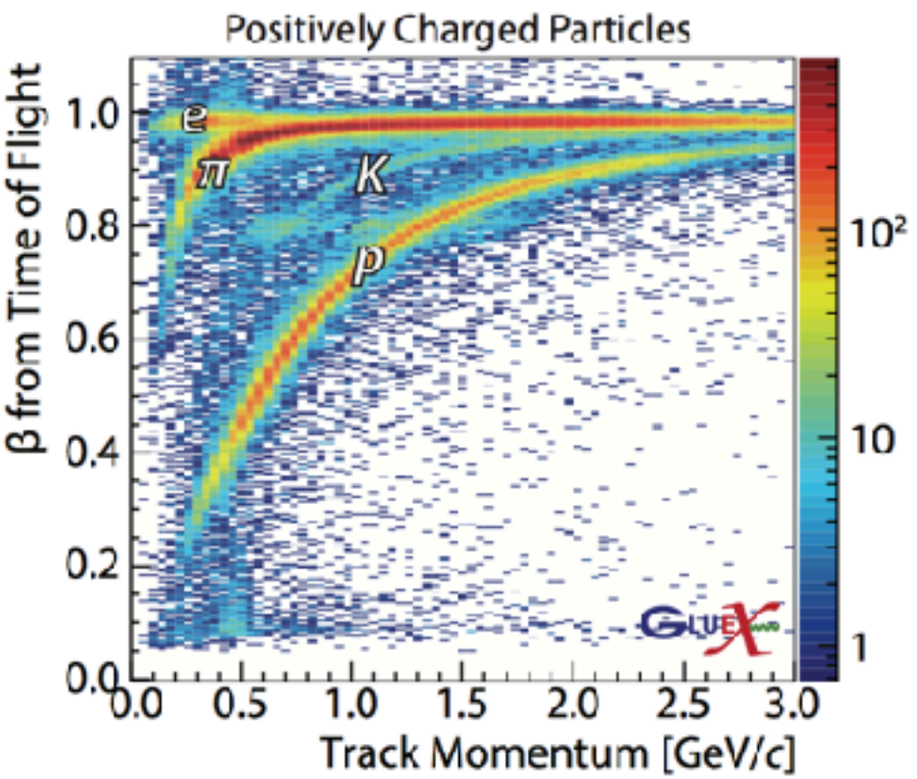
Measured using $\gamma p \rightarrow p \gamma\gamma\gamma\gamma$ events

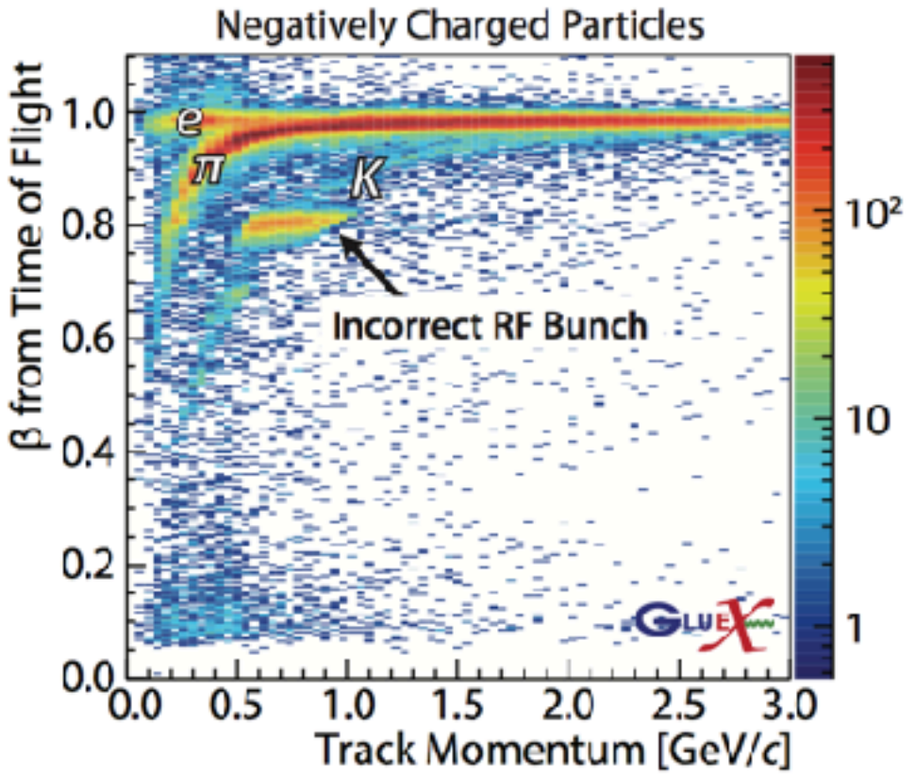
GlueX Tracking Performance

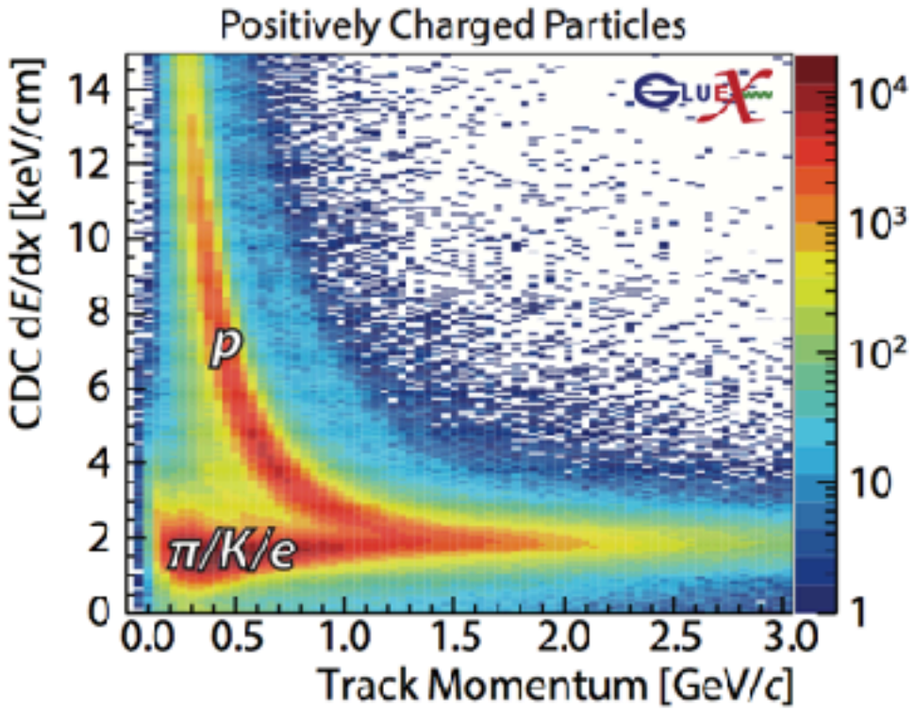


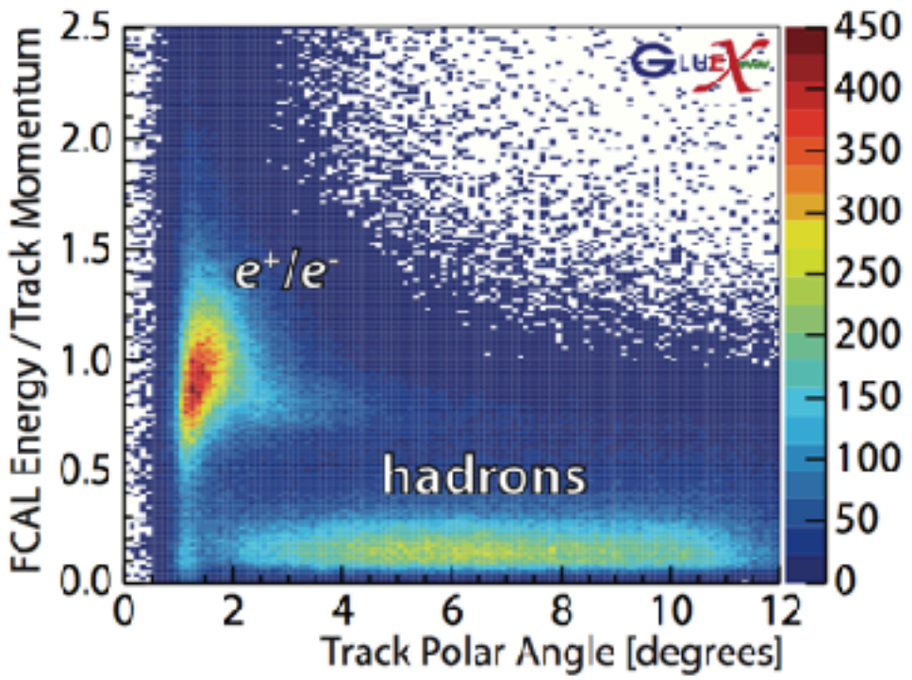


GlueX Particle ID Performance

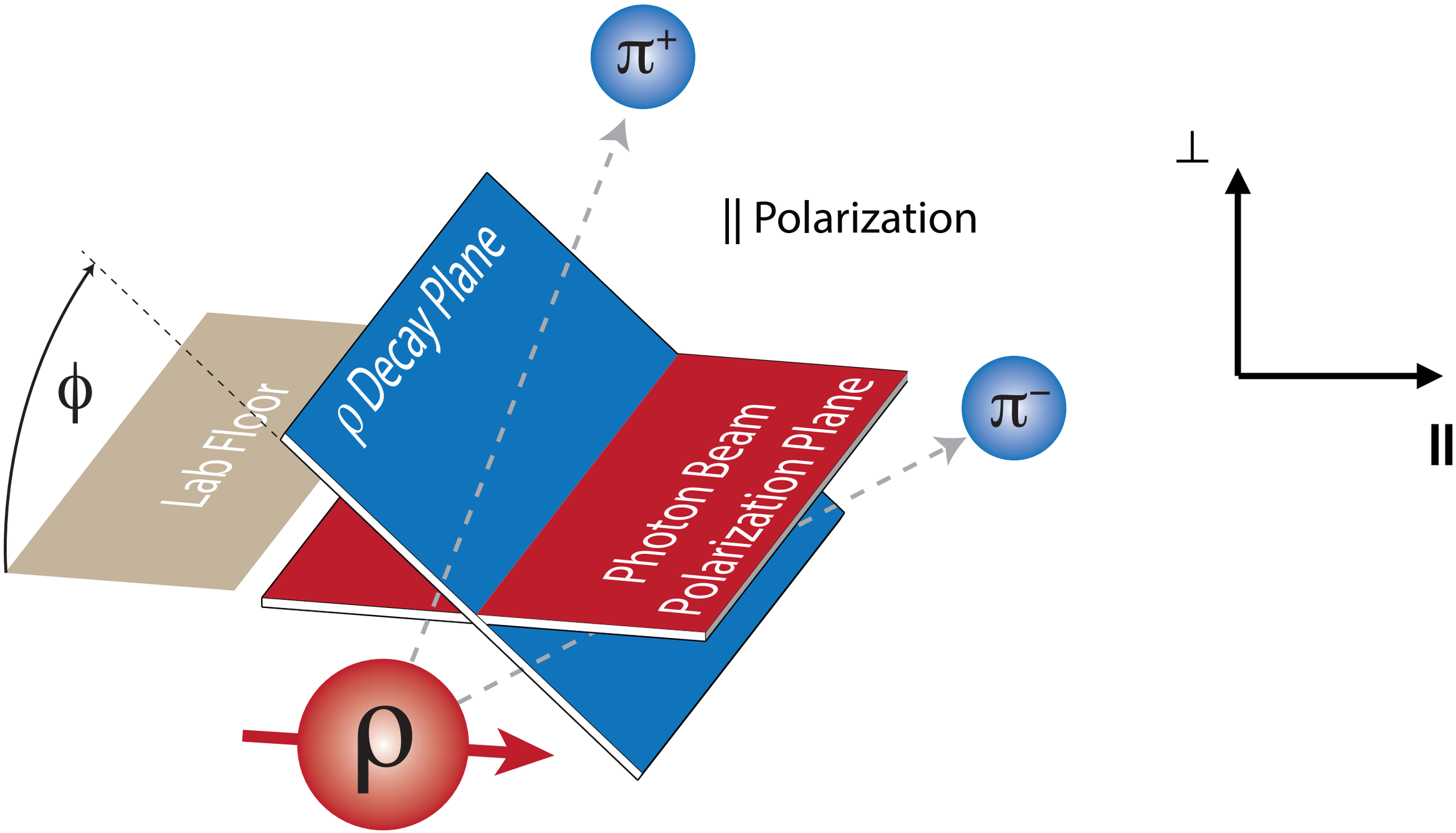






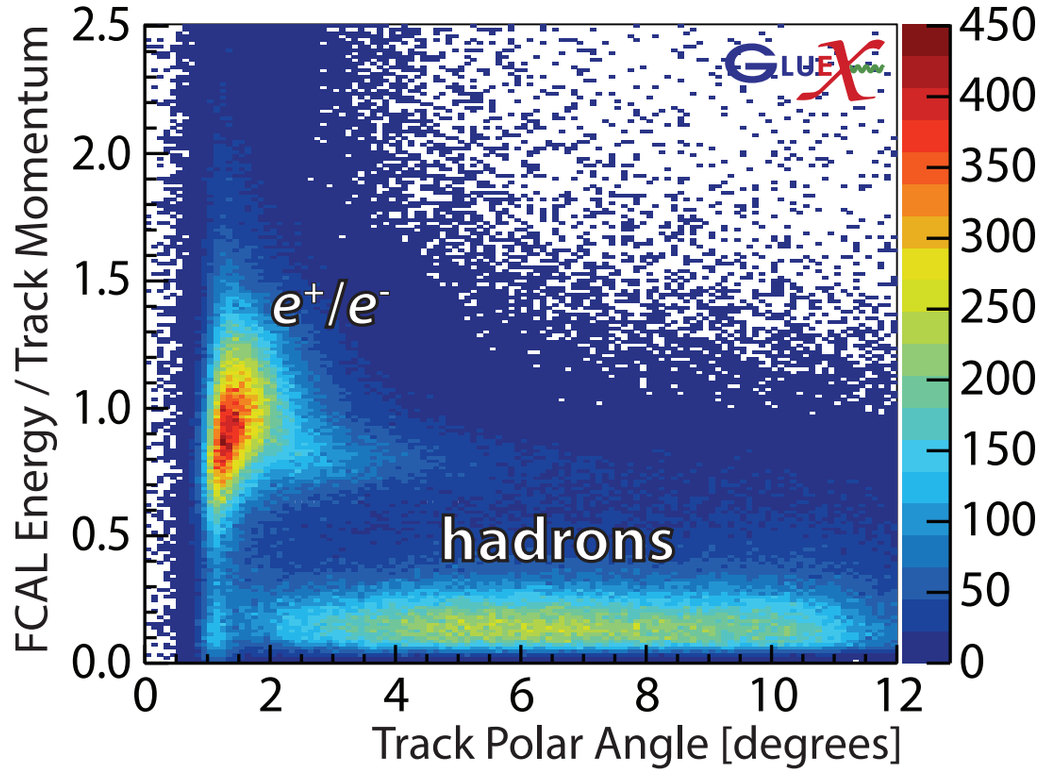


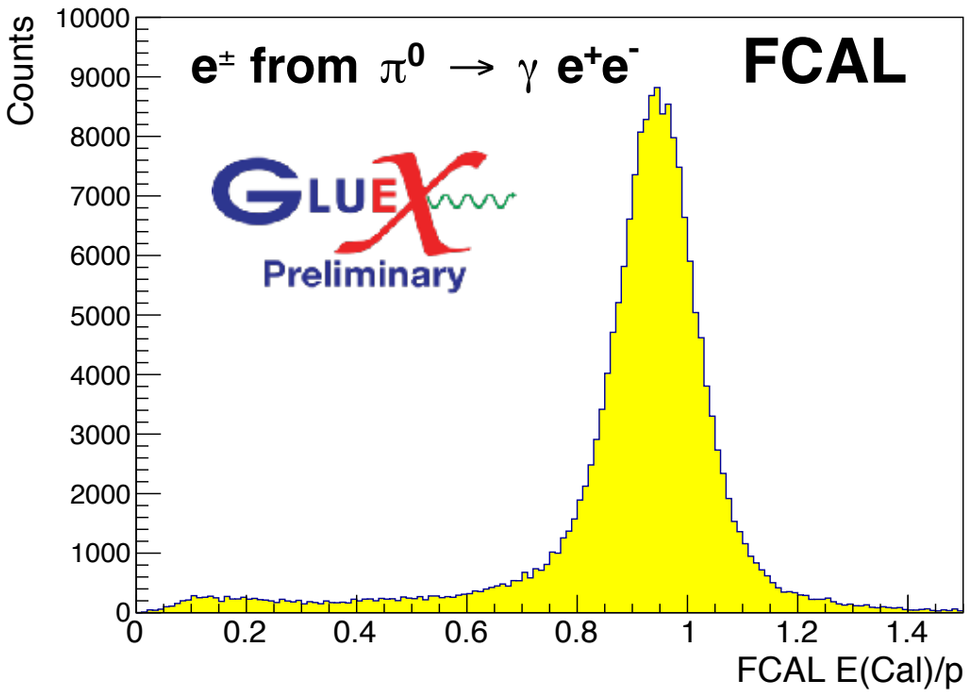
Beam Asymmetries



Electron Identification

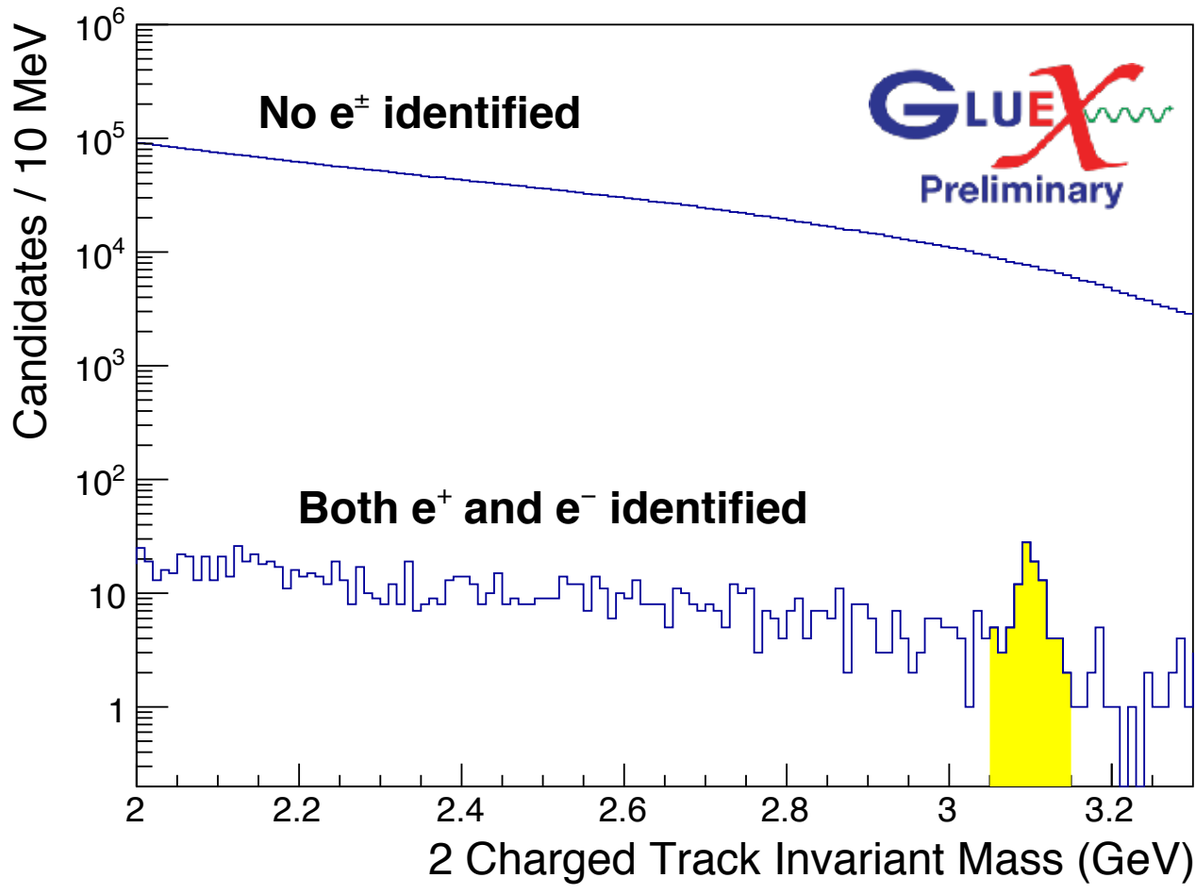
- Electrons identified by energy deposition in calorimeter
- FCAL: 2800 lead-glass blocks
  - Electrons have E(cal)/p(track) ~ 1
- BCAL: lead/scintillating fiber matrix
  - 192 ϕ-segments
    4 radial layers
  - Electrons have E(cal)/p(track) ~ 1
  - Can also use shower shape information [under study]





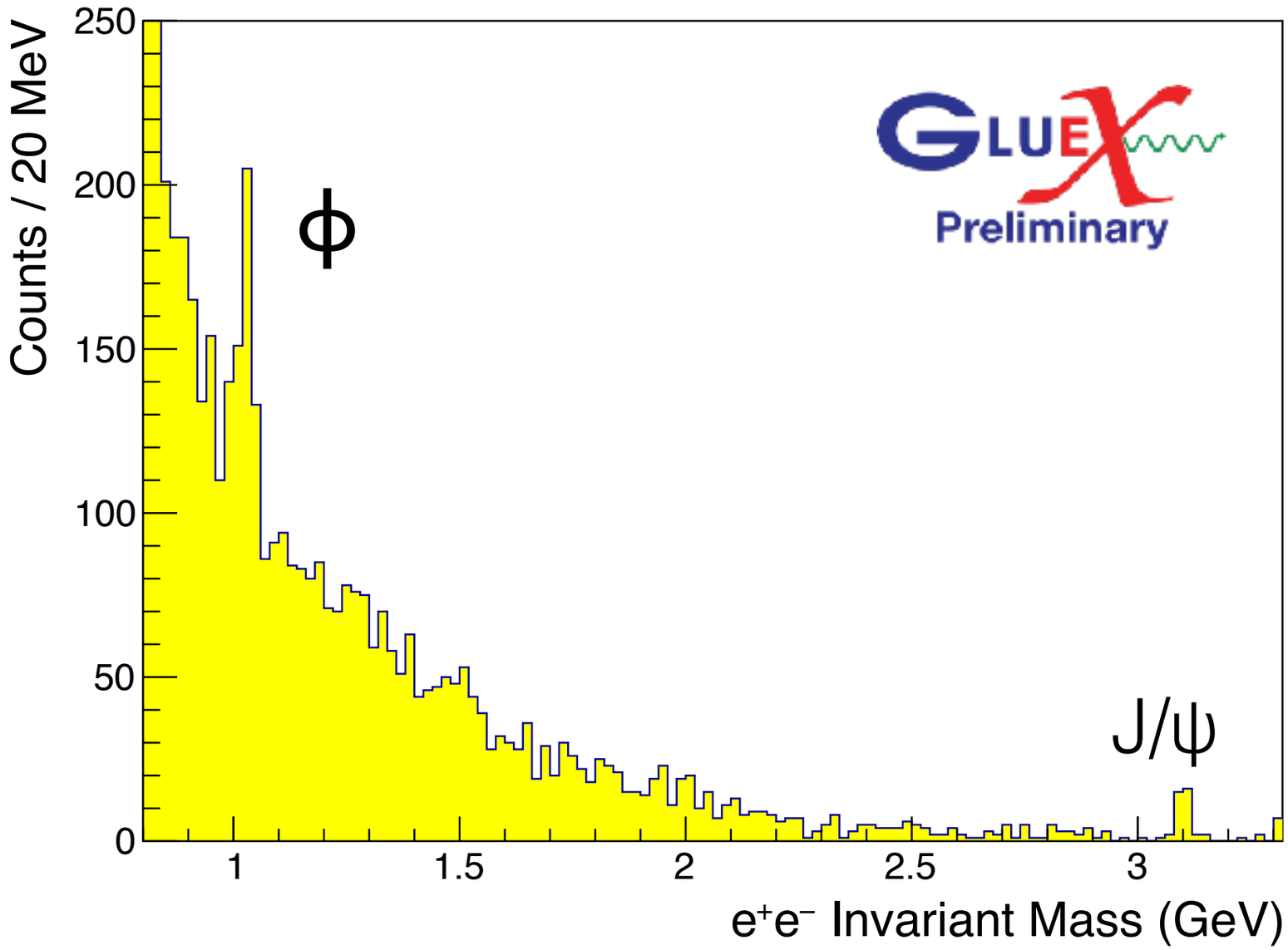
J/ψ Production: Event Selections

- We fully reconstruct $\gamma + p \rightarrow p + J/\psi$, $J/\psi \rightarrow e^+e^-$ events using the ~5 pb-1 of data taken in Spring 2016 with the following criteria:
  - At least 3 tracks in the event;
    event matched to tagged beam photon, $E_\gamma > 8$ GeV
  - Standard loose timing cuts
    on electrons and proton
  - Electron ID: E(cal) / p(track) > 0.8
    - Identifying e^+ and e^- reduces background by ~10^4
  - $|\text{Missing mass of p } e^+e^-|^2 < 0.05$ GeV^2
  - Energy/momentum conservation kinematic fit is performed



S. Dobbs, L. Robison, T. Xiao, K. Seth (NU), L. Pentchev (JLab)

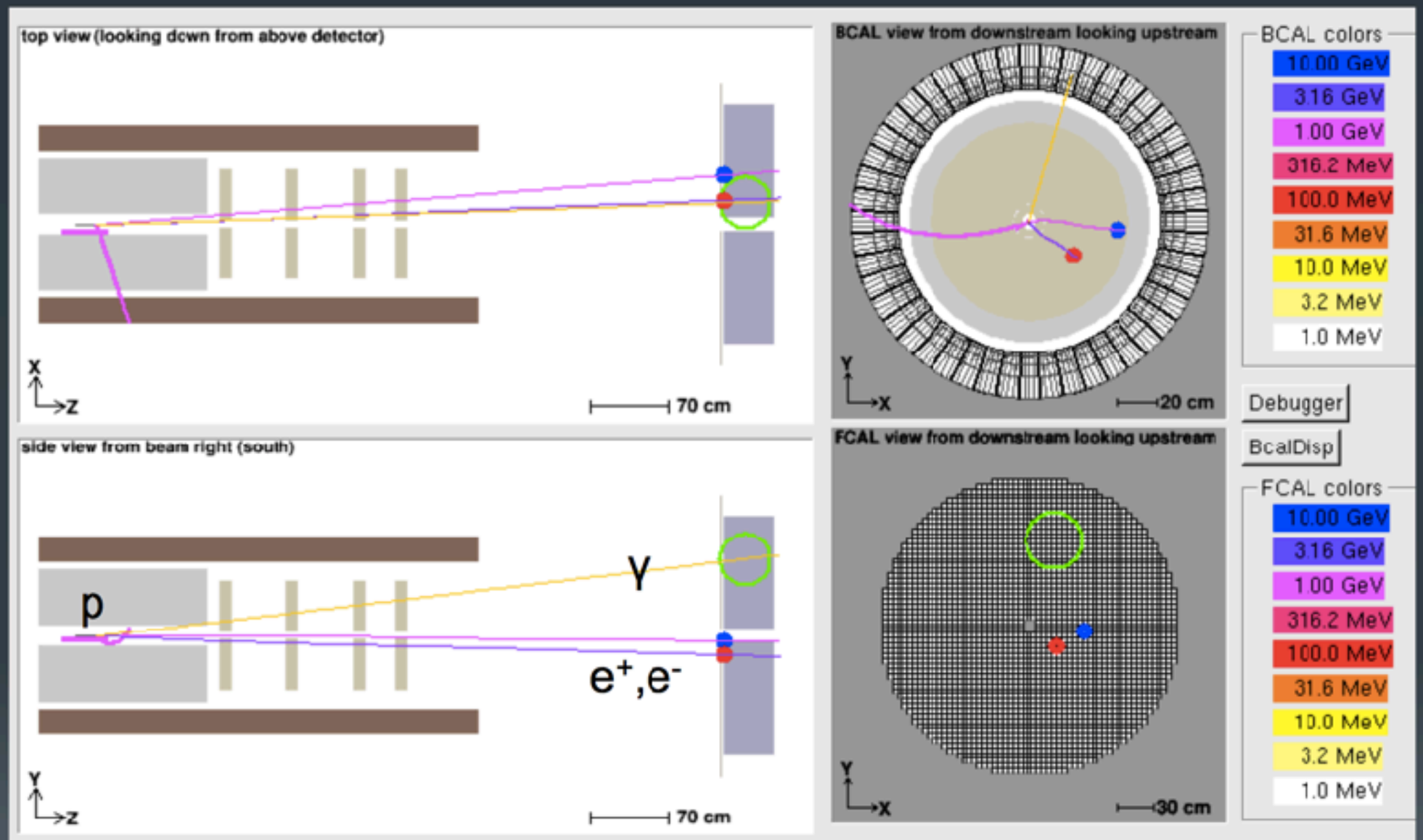
Di-electron Invariant Mass at GlueX: Full Range



- Using tighter electron identification reveals $\phi \rightarrow e^+e^-$ peak
- Electron ID is being optimized for this lower mass region
- Opens possibility of doing dilepton physics at lower masses (vector meson production, TCS, etc.)

Event Topology of γp->pη (η->e^+e^-γ)

MC



Track Info

Thrown

trk:	type:	p:	theta:	phi:	z:
1	Photon	2.045	7.154	1.298	68.94
2	Positron	3.778	4.554	0.1192	68.94
3	Electron	2.571	2.895	5.294	68.94
4	Proton	0.495	71.91	3.517	68.94

Reconstructed

trk:	type:	p:	theta:	phi:	z:	chisq/Ndof:	Ndof:	FOM:
1	gamma	2.05	7.095	73.86	68.96	--------	--------	--------
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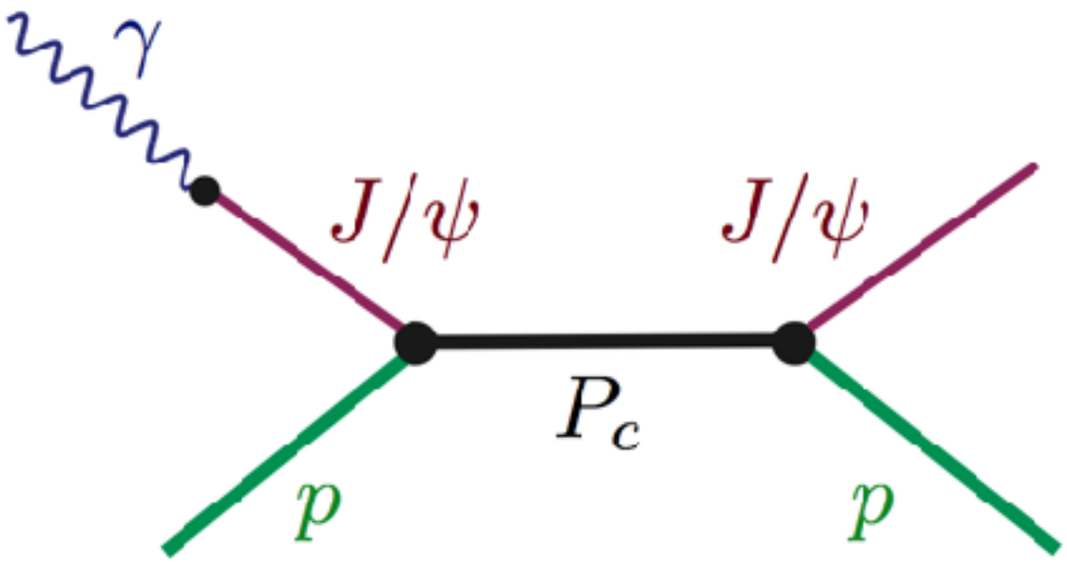
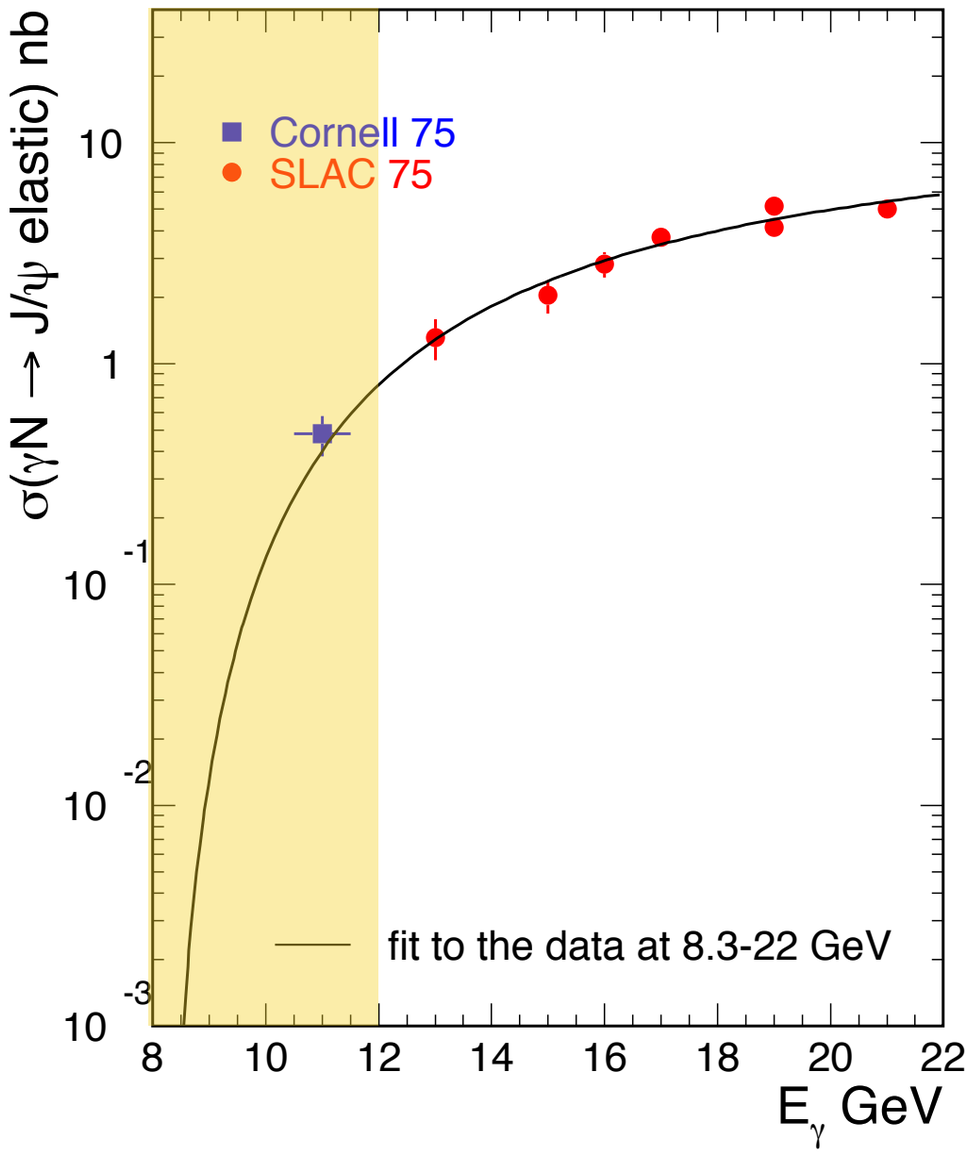
J/ψ Photoproduction Near Threshold

- 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**
  - Several existing studies:
    Example: KR finds σ_{peak} ~ 12 nb
    assuming Br($P_c \rightarrow p\ J/\psi$) =10%.
    Large theoretical uncertainties exist.



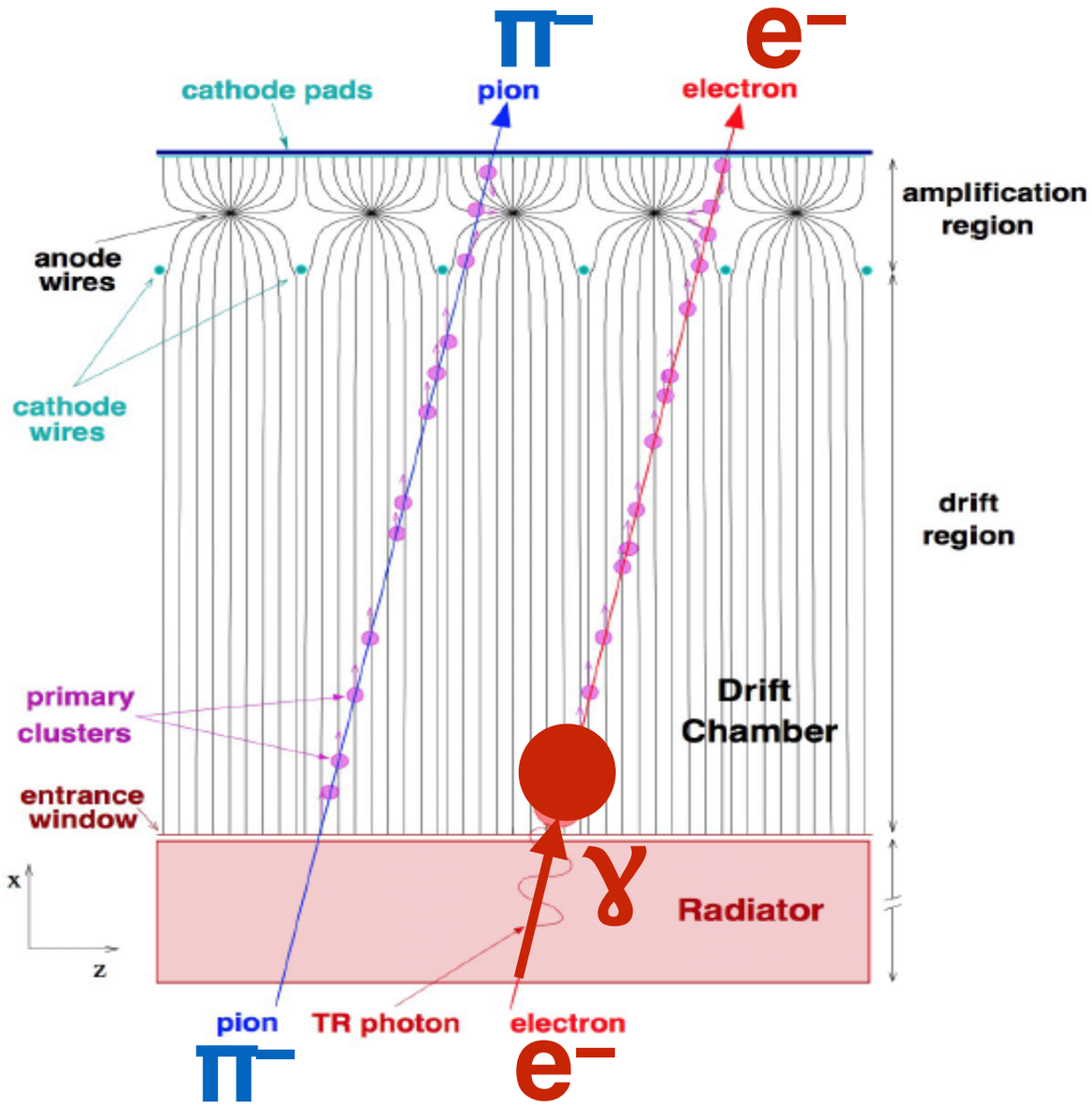
Pentaquark Photoproduction

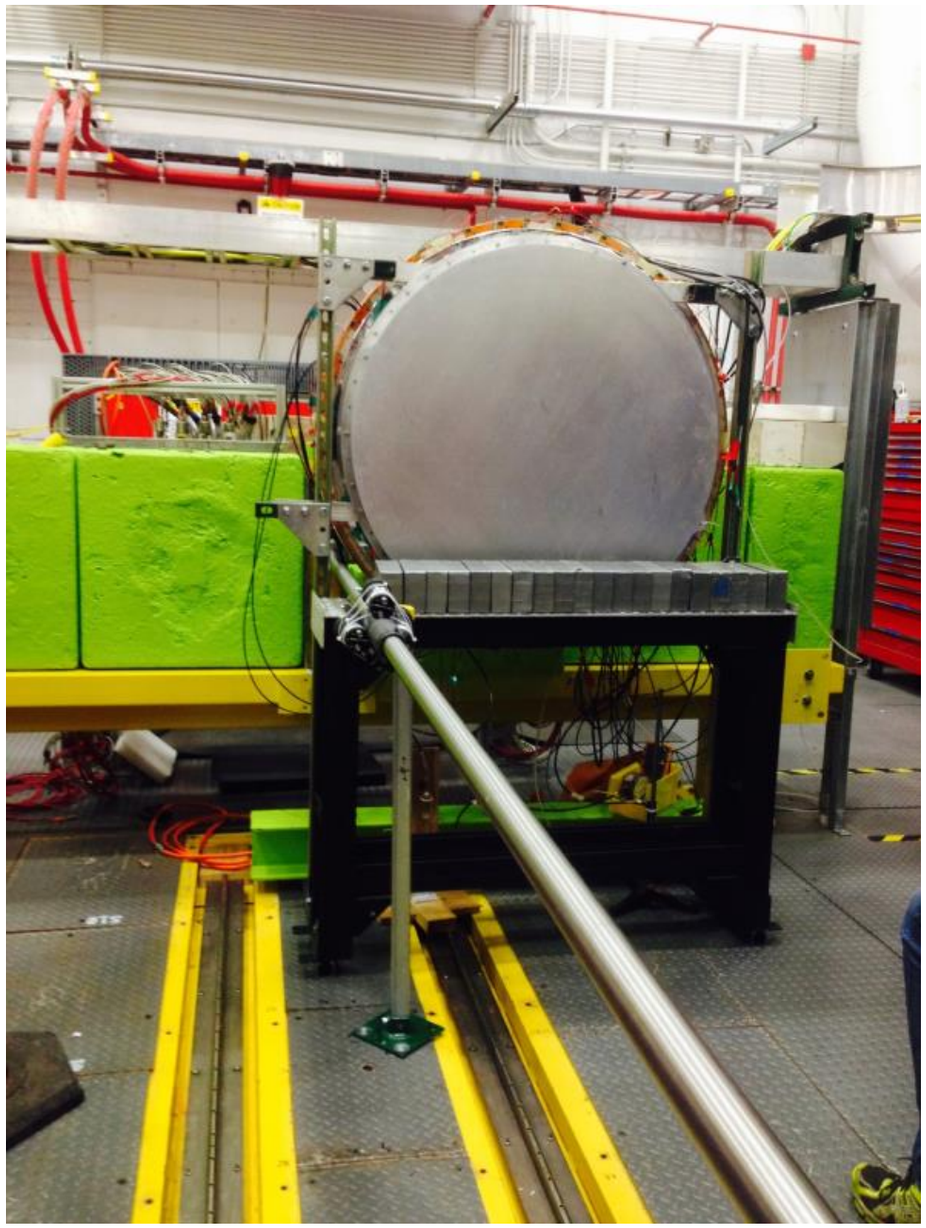


Theory papers:
Wang, Liu, and Zhao, PRD 92, 034022 (2015).
Kubarovsky and Voloshin, PRD 92, 031502 (2015).
Karliner and Rosner, PLB 752, 329 (2016).
Hiller Blin et al., PRD 94, 034002 (2016).

Transition Radiation Detector

- e/π separation: for p>1.5 GeV, π suppression factor 100-1000 depending on # of chambers
- Prototype tests done with Ar and Xe gas mixtures, using electrons with/without radiator
- Chamber design similar to ALICE TRD:





TRD Prototype