GlueX Experimental Efforts

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for the GlueX Collaboration

Workshop on Two-Meson Photoproduction

Jefferson Lab
September 18th, 2019

Outline

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1. Introduction
   - Motivation
   - GlueX Status
2. Early Results
   - Beam Asymmetries for Pseudoscalar Meson Production
   - Spin-Density Matrix Elements for Vector Mesons
   - J/ψ Cross Section and the Search for LHCb Pentaquarks
3. Ongoing Efforts
   - Search for Exotic Hybrids
   - The Future of GlueX

Introduction

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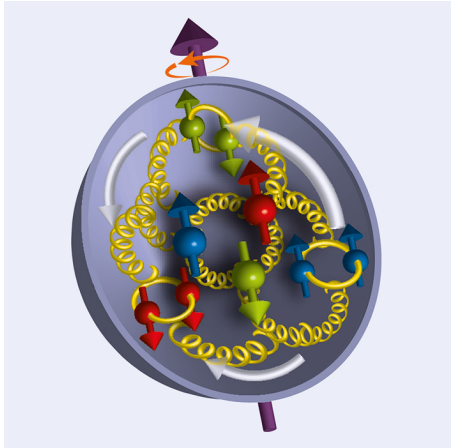
Gluons: the central theme of nuclear physics

- Gluons are an essential part of hadronic matter
- Major contributions to mass and spin of hadron
- Underlying degree of freedom in the hadronic spectrum?



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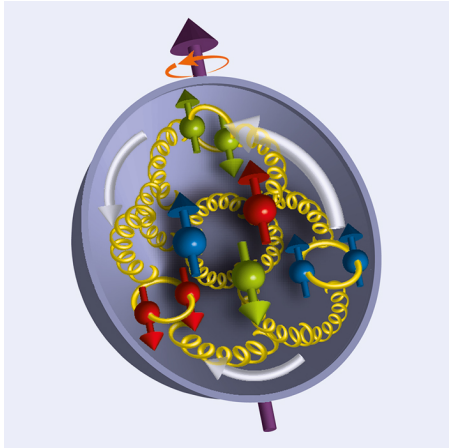
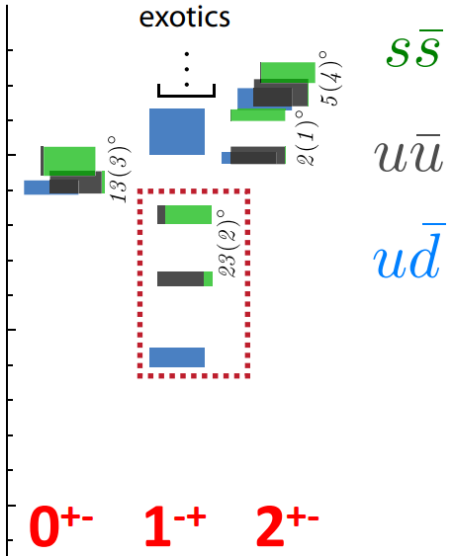


Meson Spectroscopy

- Constituent quark model describes conventional mesons
- Exotic states: quantum numbers forbidden by $q\bar{q}$
- Lattice QCD suggests several exotic nonets
- Sound experimental evidence for one single state: $\pi_1(1600)$
- Where are the other states?



PRD 88, 094505 (2013)

⇒ **Glu**on **Ex**citation Experiment part of global program

Photoproduction

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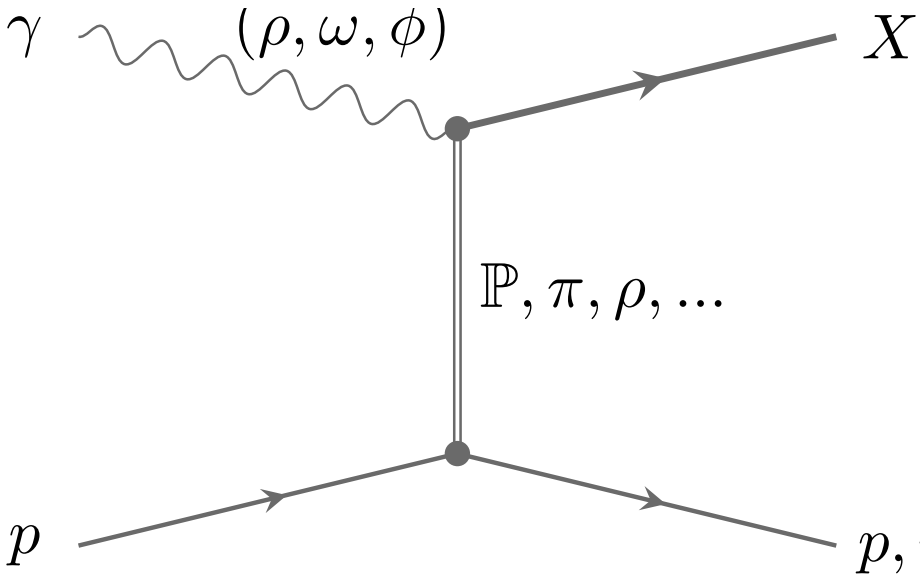

Exchange		Exotic Final States	
$\mathbb{P}$	0^{++}	b, h, h'	$2^{+-}, 0^{+-}$
π^0	0^{-+}	b_2, h_2, h_2'	2^{+-}
$\pi^{\pm}$	0^{-+}	$\pi_1^{\pm}$	1^{-+}
ω	1^{--}	π_1, η_1, η_1'	1^{-+}

Complementary Production Mechanism

- Photon coupling via **vector meson dominance**
- Wide variety of quantum numbers $I^G J^{PC}$ accessible
- Photon polarization provides **constraints** on produced systems
- Understanding of **production mechanism** is prerequisite for interpretation
- Very limited photoproduction data existing at these energies

Photon Beam Line

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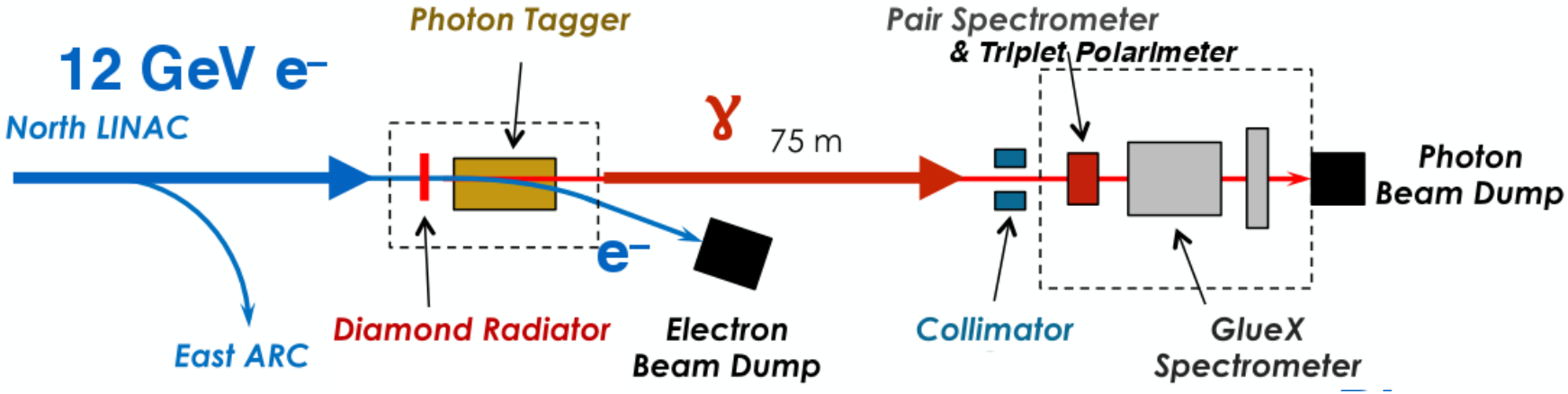

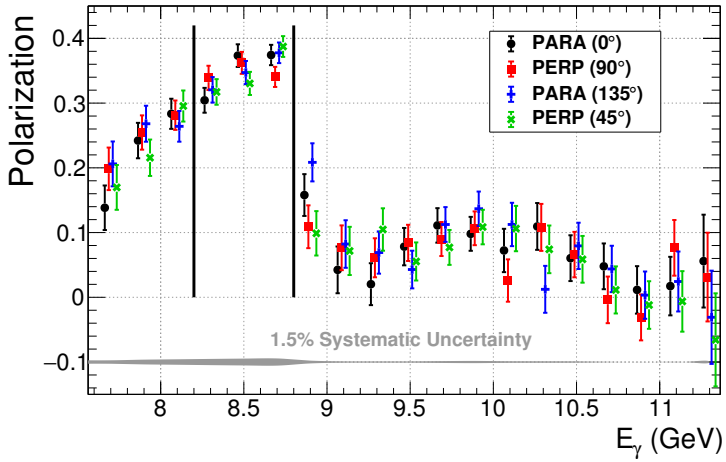

9 GeV Polarized Photon Beam

- Coherent Bremsstrahlung on thin diamond
- Energy tagged by scattered electrons
- Collimator to suppress incoherent part
- Linear polarization in peak $P_\gamma \sim 40\%$, measured by Triplet polarimeter: $\gamma e^- \rightarrow e^- e^+ e^-$
- Rotate polarization into 4 different orientations
- Beam intensity: $1 - 5 \cdot 10^7\ \gamma/\text{s}$ in peak

GlueX Detector

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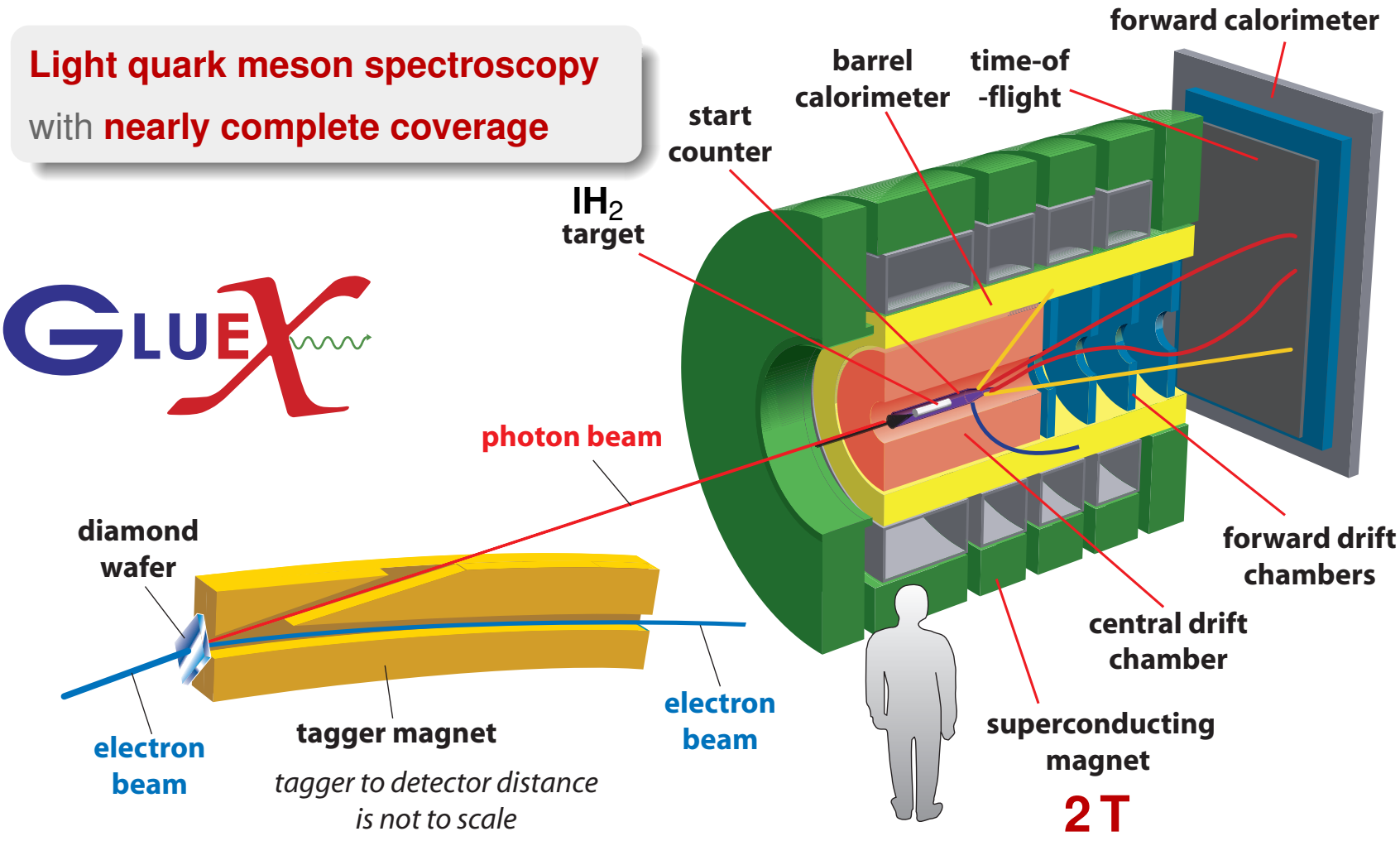
Light quark meson spectroscopy

with **nearly complete coverage**



GlueX Data Taking

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Spring 2016: GlueX Engineering Run

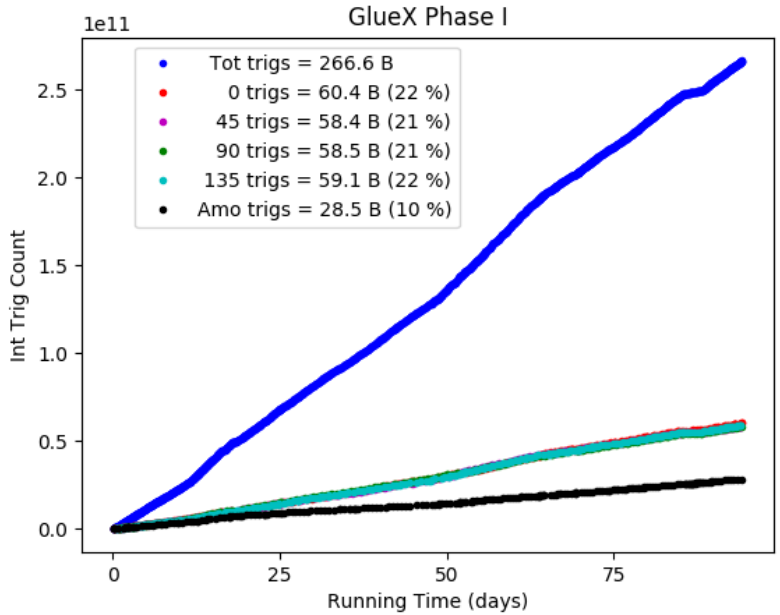
- Initial physics data ($\approx 80\,\text{h}$, $2\,\text{pb}^{-1}$)
- First publication

Spring 2017

- Luminosity: $21\,\text{pb}^{-1}$
- Most results presented here

Spring + Fall 2018

- Luminosity $\approx 90\,\text{pb}^{-1}$
- Completes first stage of GlueX
- Majority of data set processed, analysis started



More than **250 billion** events and over **5 PB** of data!

Pseudoscalar Beam Asymmetry

First GlueX Publication: PRC 95, 042201 (2017)

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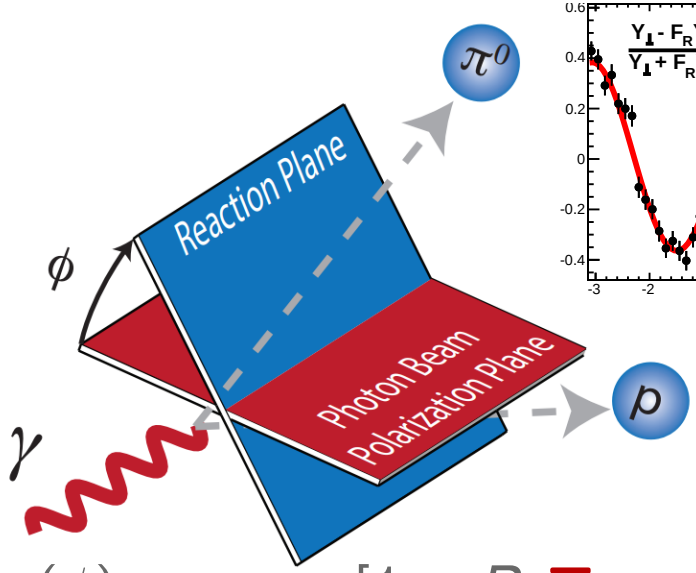
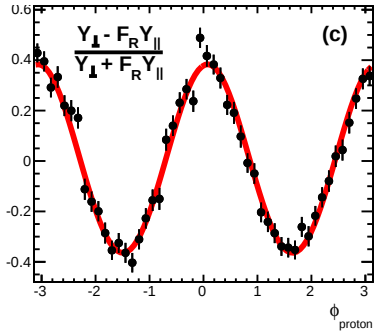
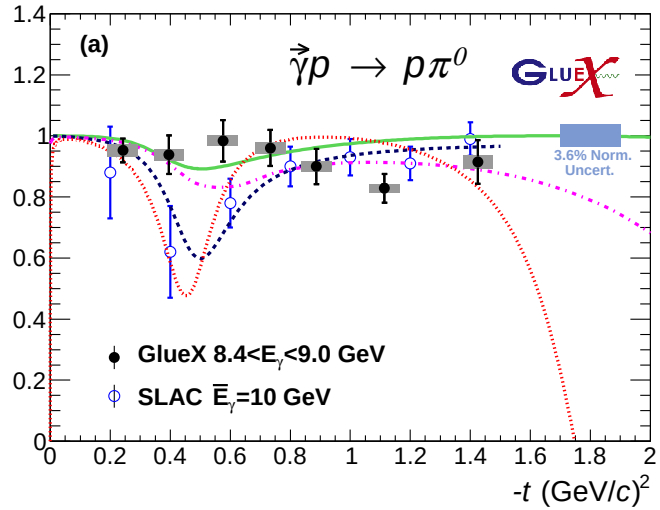
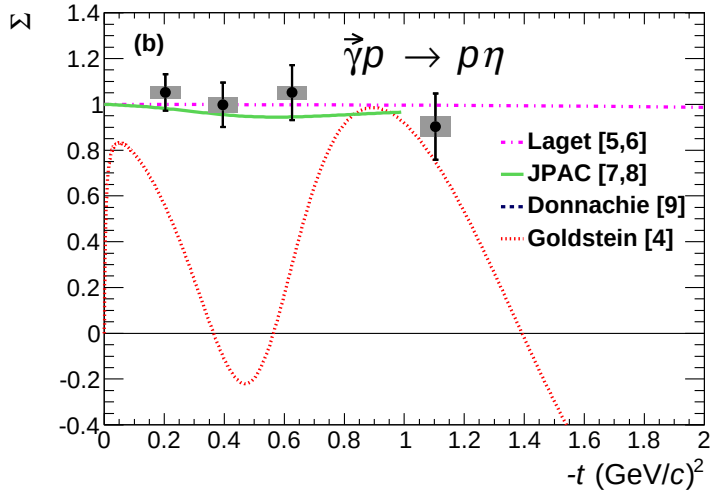






$$\sigma_{pol}(\phi) = \sigma_{unpol}\,[1 - P_\gamma \Sigma \cos 2\phi]$$



π^0 and η from 2016 Data

- Modeling production mechanism necessary for hybrid search
- Σ sensitive to exchanged J^{PC}
- Cancel systematic effects by rotating polarization plane by 90°
- First measurement for η in this energy

η and η' Beam Asymmetries

arXiv:1908.05563, submitted to PRC

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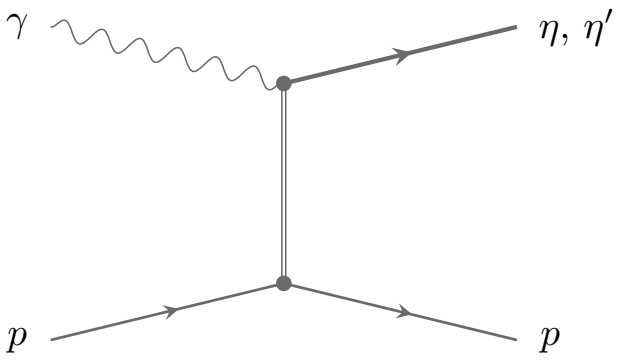
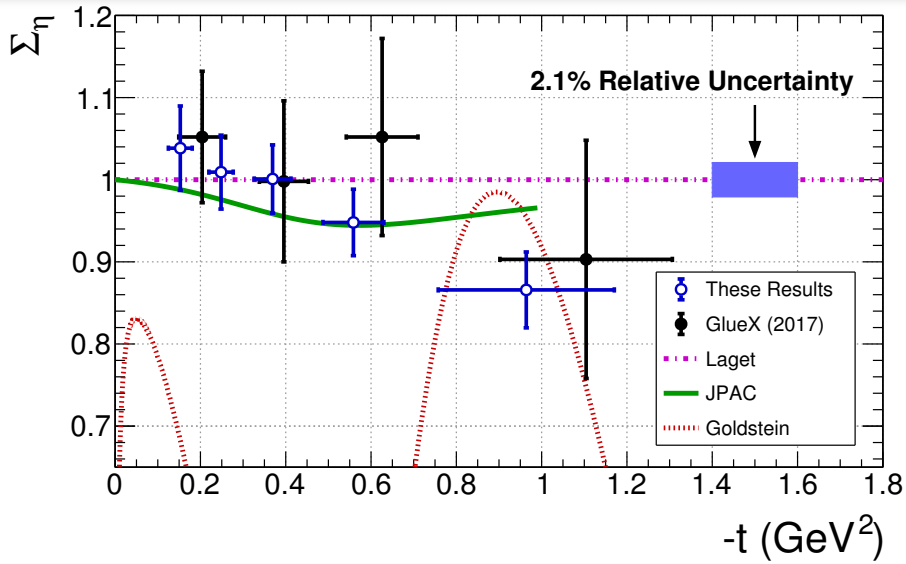
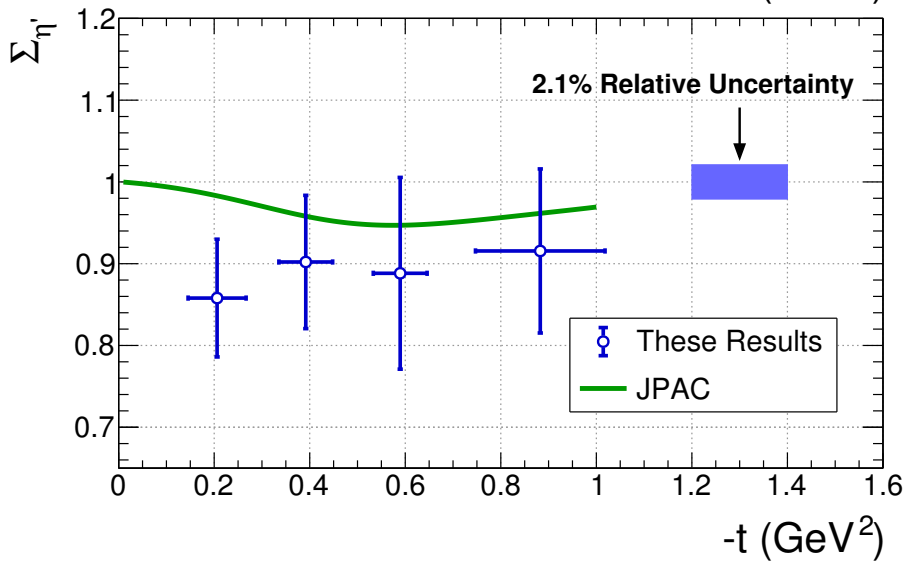


η and η' from 2017 Data

- Significantly higher precision for η
- First measurement for η' in this energy
- Dominated by natural-parity exchanges
- Weak dependence on $-t$
- Ratio sensitive to $s\bar{s}$ exchange





Charged Pseudoscalar Mesons

Publications in Preparation

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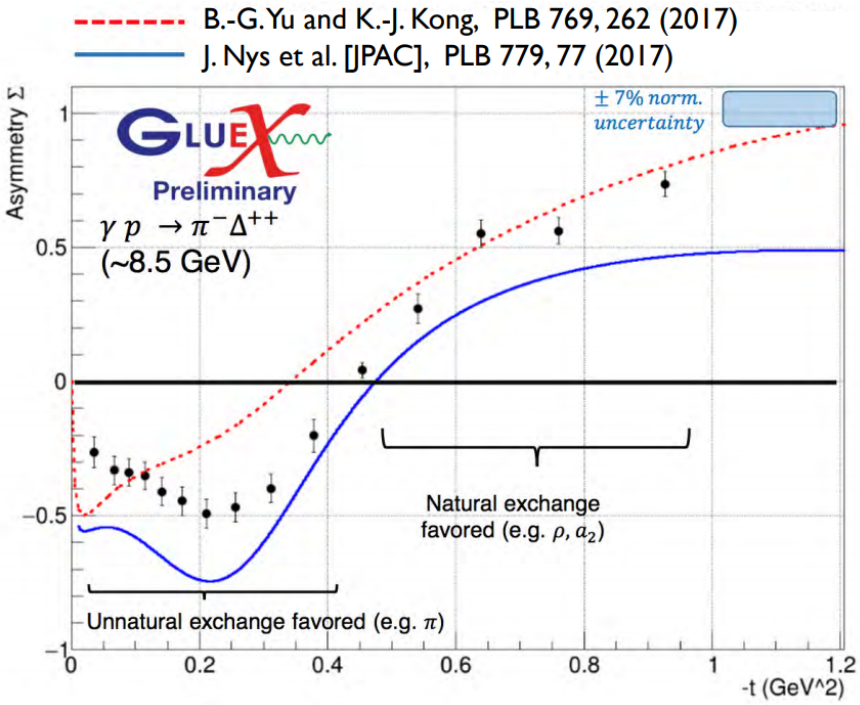
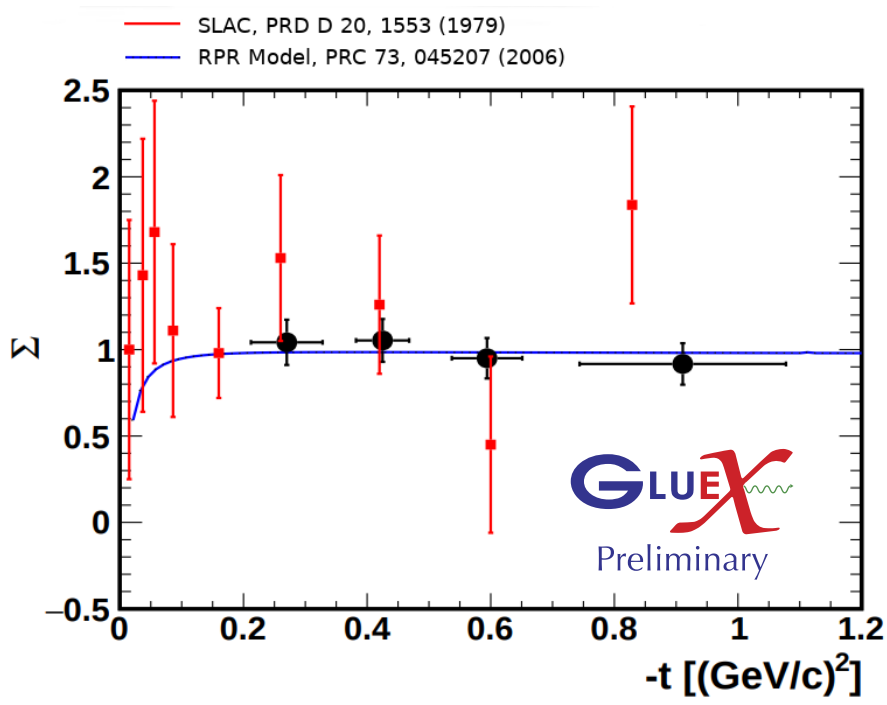
$\gamma p \to \pi^- \Delta^{++}$



$\gamma p \to K^+ \Sigma^0$



Charge Exchange Processes

- $\pi^- \Delta^{++}$ production: unnatural exchange favored for small $-t$
- No visible $-t$-dependence for $K^+ \Sigma^0$, but significant contribution from u-channel

Vector Meson Photoproduction

Spin-Density Matrix Elements

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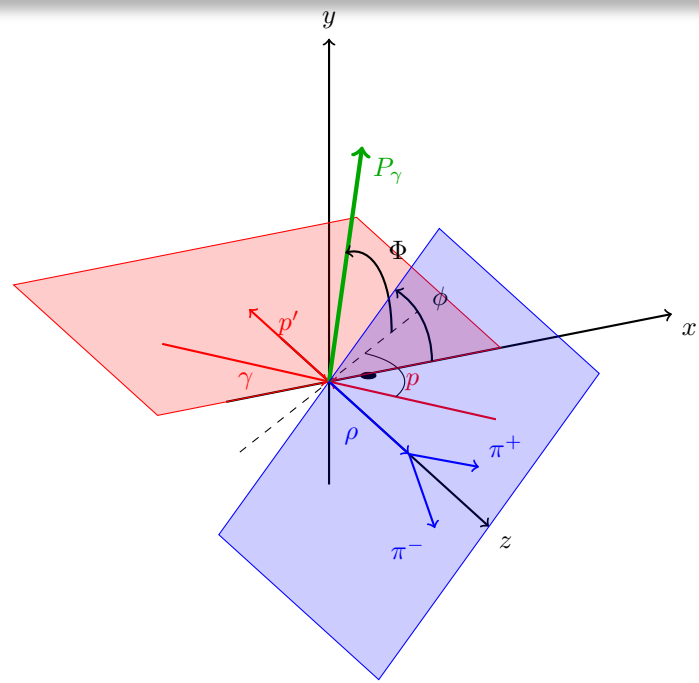
- Full angular distribution of vector meson production and decay is described by **spin-density matrix elements ρ^k_{ij}**
- Linear beam polarization provides access to **nine** linearly independent SDMEs
- Intensity ***W*** is expressed as function of angles **$\cos\vartheta, \varphi, \Phi$** and degree of polarization ***P_γ***



$$W(\cos\vartheta, \varphi, \Phi) = W^0(\cos\vartheta, \varphi) - P_\gamma \cos(2\Phi) W^1(\cos\vartheta, \varphi) - P_\gamma \sin(2\Phi) W^2(\cos\vartheta, \varphi)$$

$$W^0(\cos\vartheta, \varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^1(\cos\vartheta, \varphi) = \frac{3}{4\pi}\left(\rho^1_{11}\sin^2\vartheta + \rho^1_{00}\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^1_{10}\sin 2\vartheta\cos\varphi - \rho^1_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

$$W^2(\cos\vartheta, \varphi) = \frac{3}{4\pi}\left(\sqrt{2}\mathrm{Im}\rho^2_{10}\sin 2\vartheta\sin\varphi + \mathrm{Im}\rho^2_{1-1}\sin^2\vartheta\sin 2\varphi\right)$$

Schilling *et al.* [Nucl. Phy. B, 15 (1970) 397]

Extraction of SDMEs
with Amplitude Analysis Technique

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Extended Maximum-Likelihood Fit

$$\ln L = \underbrace{\sum_{i=1}^{N} \ln I(\Omega_i)}_{\text{Signal Events}} - \underbrace{\sum_{j=1}^{M} \ln I(\Omega_j)}_{\text{Background}} - \underbrace{\int d\Omega\, I(\Omega)\, \eta(\Omega)}_{\text{Normalization Integral}}$$

- Maximize by choosing SDMEs such that the intensity fits the observed N events
- Background can be subtracted in likelihood
- Normalization integral evaluated by a phase-space Monte Carlo sample with the acceptance $\eta(\Omega) = 0/1$

Analysis Strategy

- Improve theoretical description of photoproduction process
- Understand and evaluate detector acceptance
- Both prerequisites for amplitude analysis of possible exotic signals

Result in Bins of Momentum Transfer t

$\gamma p \to \rho(770) p$

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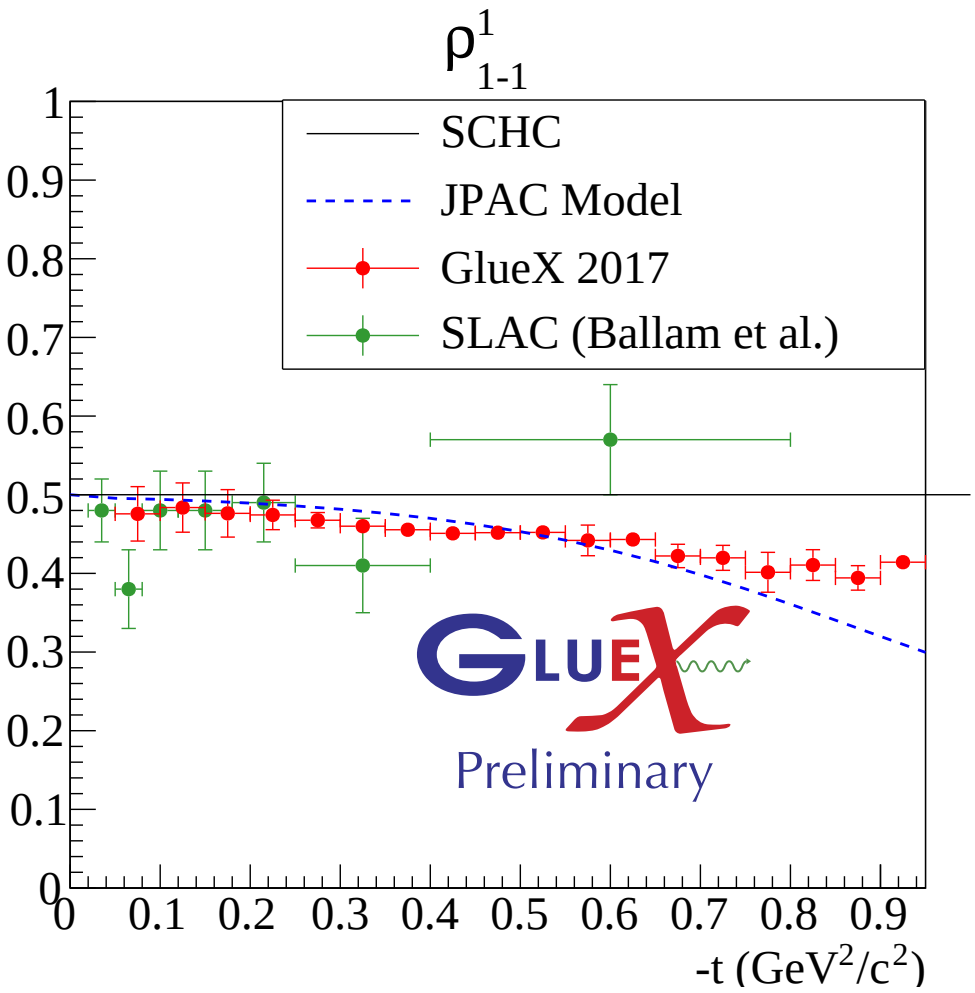

- Average of 4 orientations
- Errors dominated by systematics
- Agree with JPAC to $\sim 0.5\,\mathrm{GeV}^2/c^2$
  [PRD 97 094003 (2018)]

MENU2019 Proceedings [arXiv:1908.07275]

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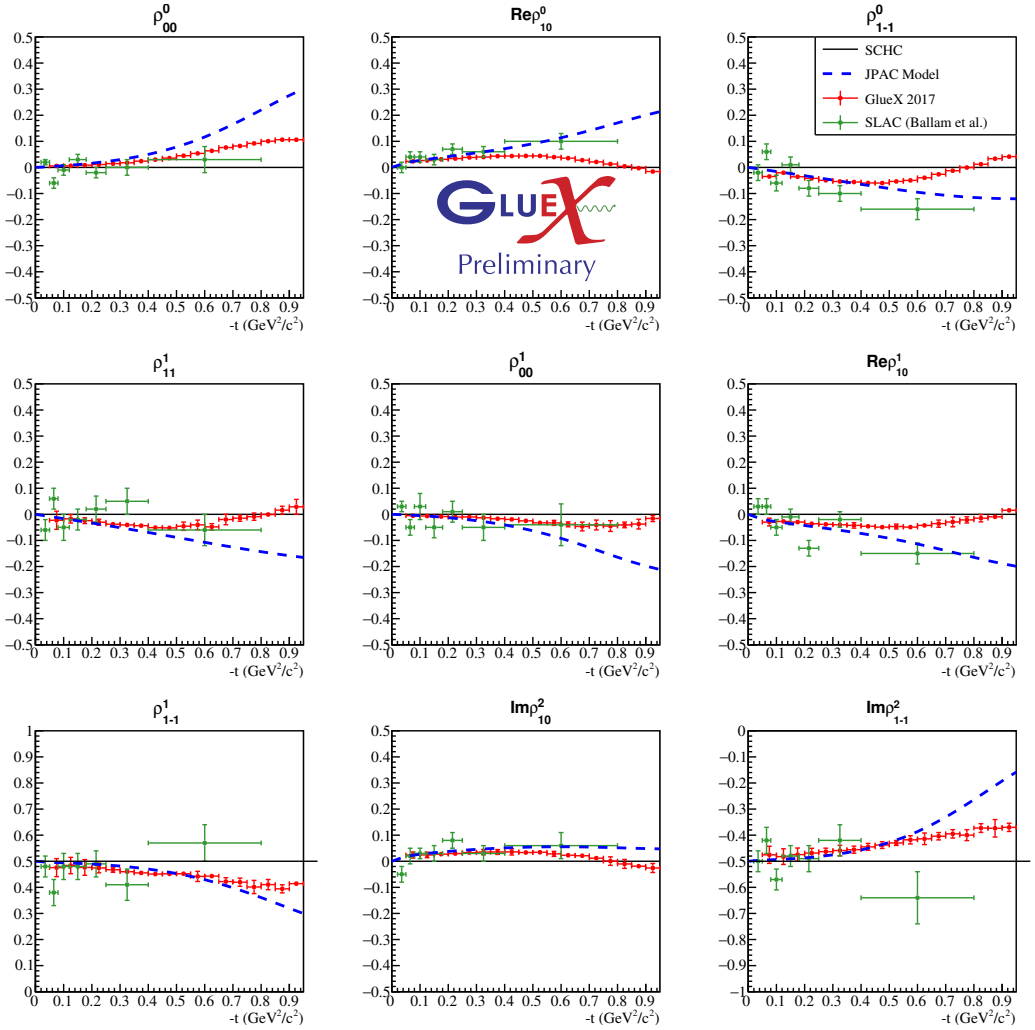

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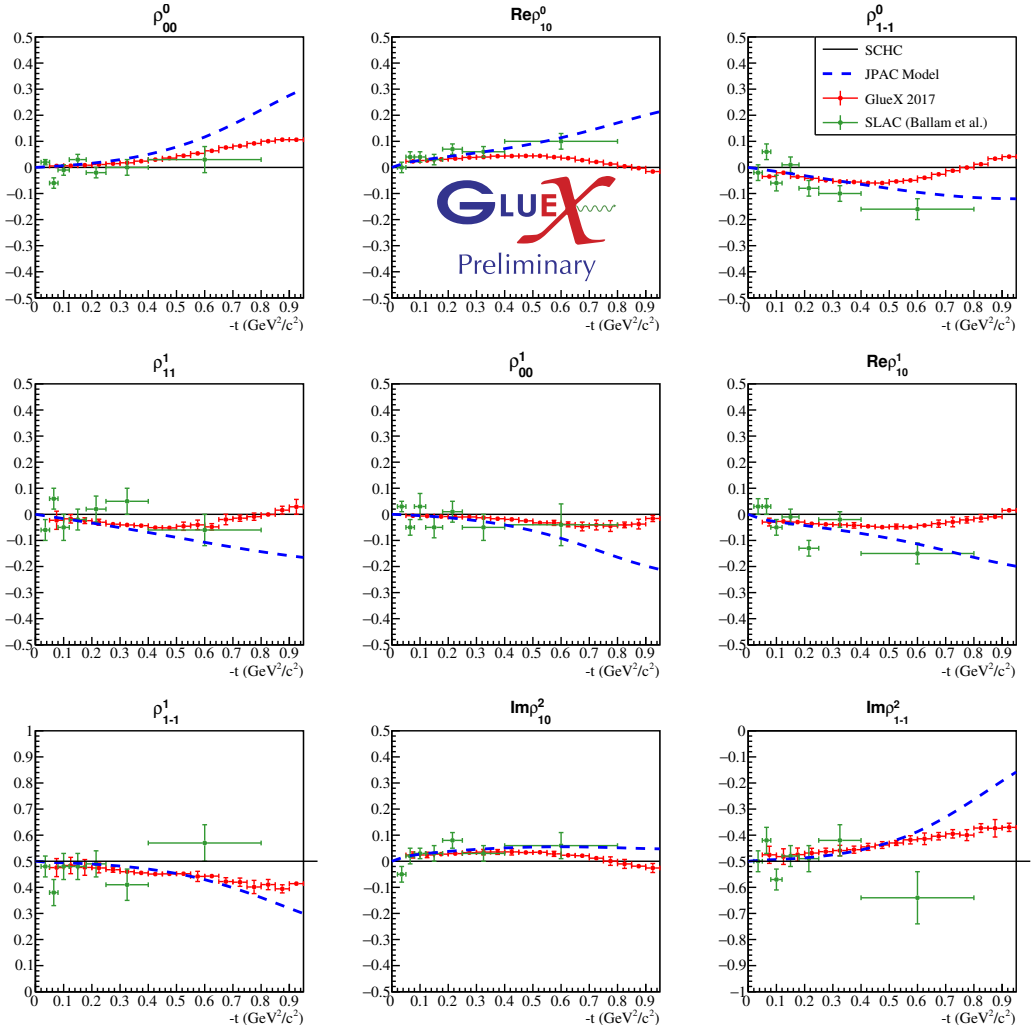

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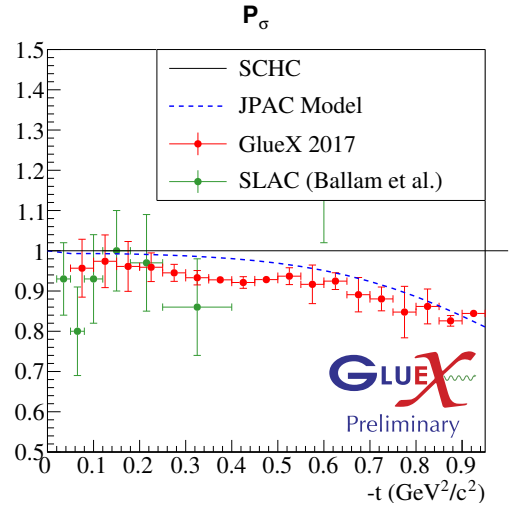

$$P_\sigma = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U} = 2\rho^1_{1-1} - \rho^1_{00}$$

Parity Asymmetry

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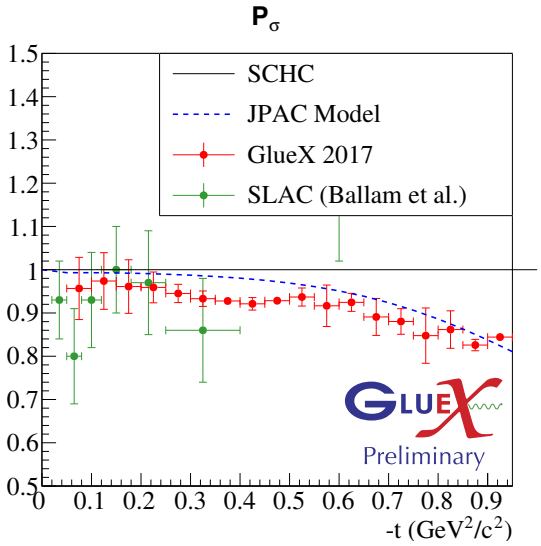
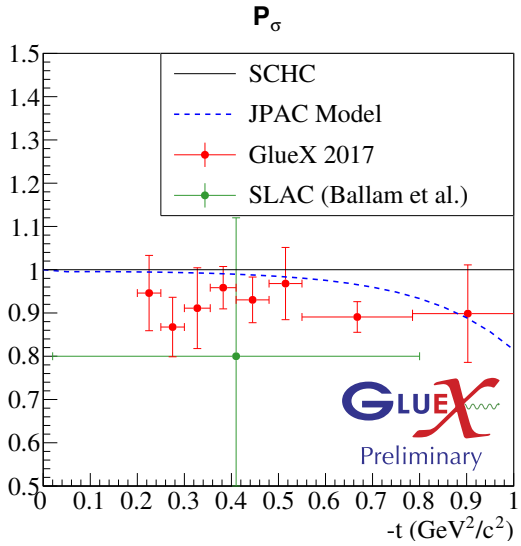
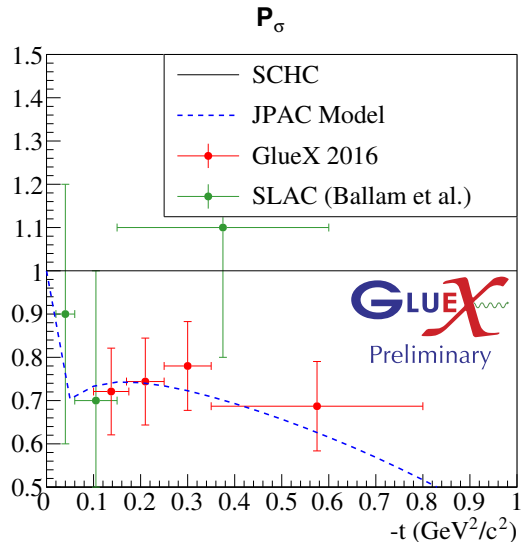
$\rho(770) \to \pi^+\pi^-$ | $\phi(1020) \to K^+K^-$ | $\omega(782) \to \pi^+\pi^-\pi^0$







- Analysis in various stages, but all results improve previous measurements
- Generally good agreement with model predictions
- Natural-parity exchange dominates for all channels

MENU2019 Proceedings [arXiv:1908.07275]

Event Selection

$\gamma p \to J/\psi p, \quad J/\psi \to e^+ e^-$

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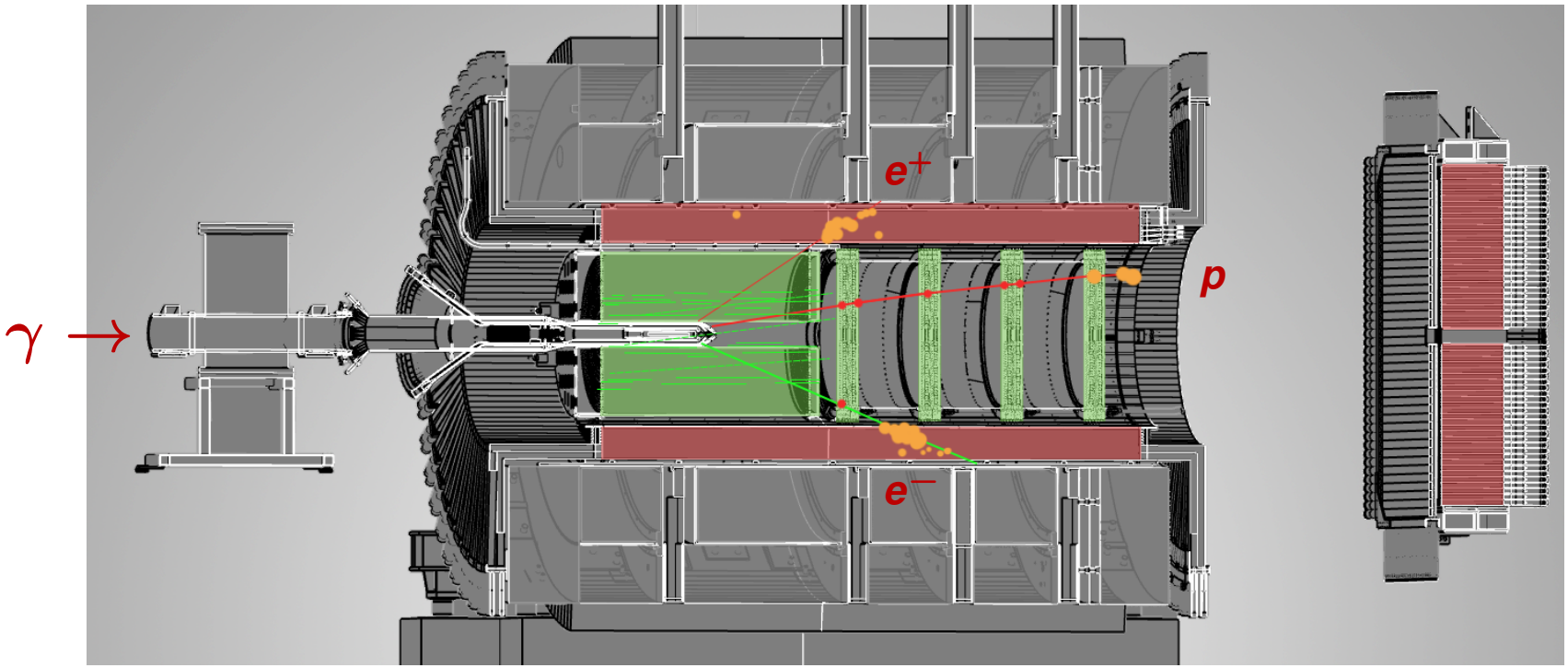
Threshold for J/ψ production: $E_\gamma = 8.22\,\text{GeV}$



- Electron identification: E/p in calorimeters, pion background suppression by 10^{-4}
- Kinematic Fit with 0.1% precision on photon beam energy

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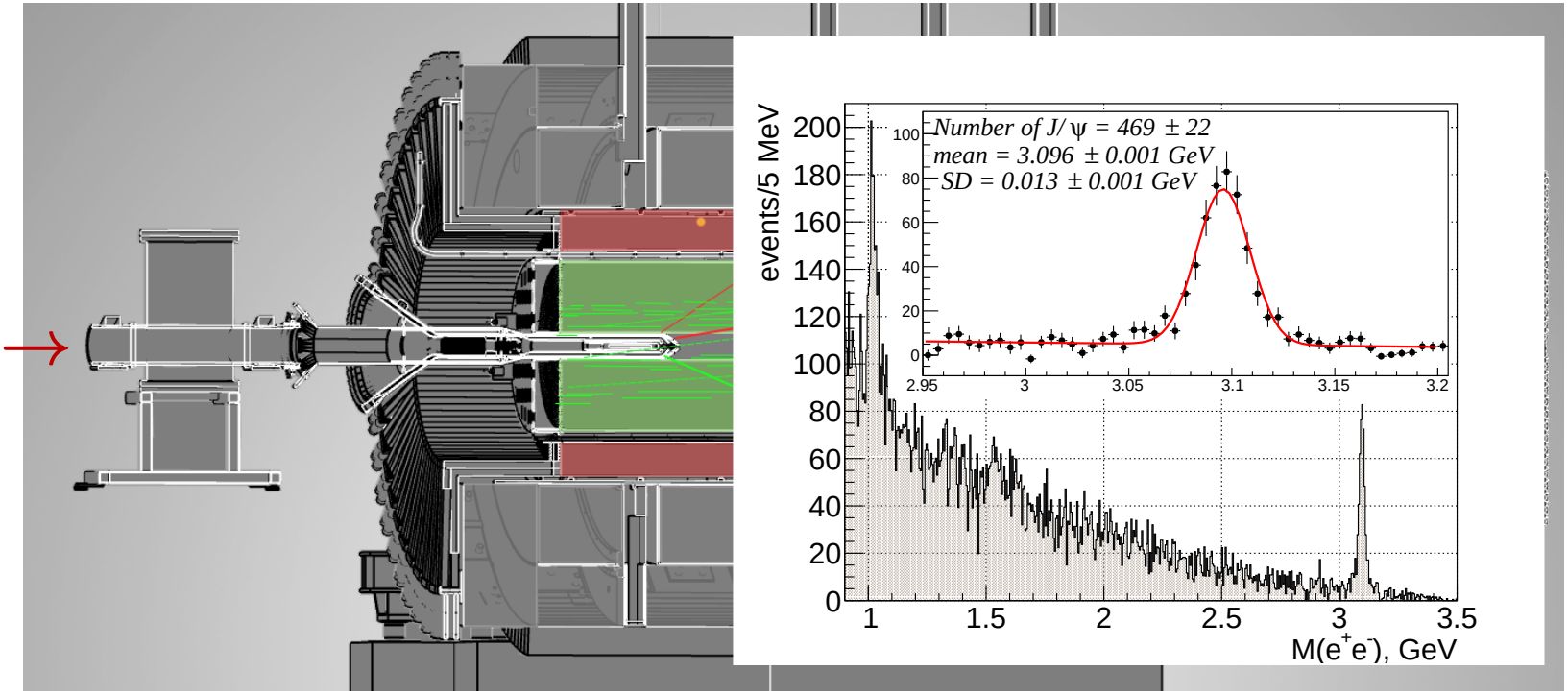

- Electron identification: E/p in calorimeters, pion background suppression by 10^{-4}
- Kinematic Fit with 0.1% precision on photon beam energy
- Cross section normalized by non-resonant e^+e^- production (Bethe-Heitler)

J/ψ Cross Section at Threshold

PRL 123, 072001 (2019): Editor's Suggestion!

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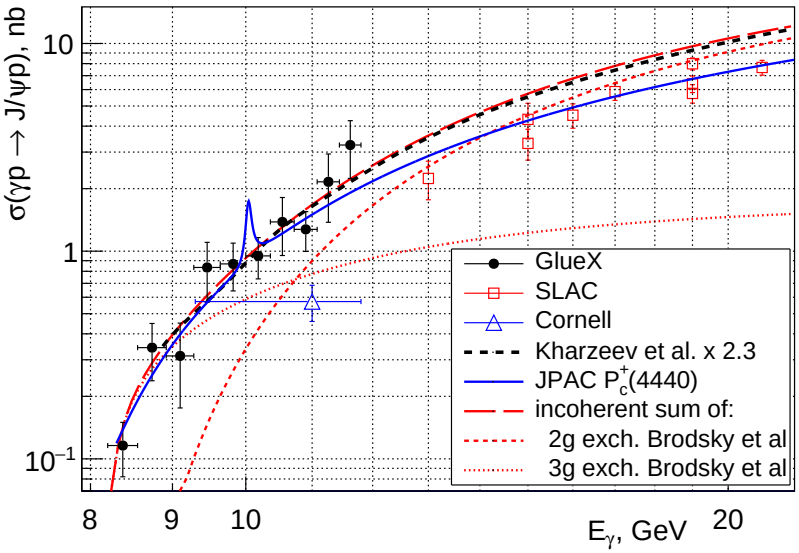

Energy dependence probes

- Production dynamics
  Brodsky et al. [PRL 498 (2001)]
- Gluon distribution in proton
  Kharzeev et al. [NPA 661, 568 (1999)]

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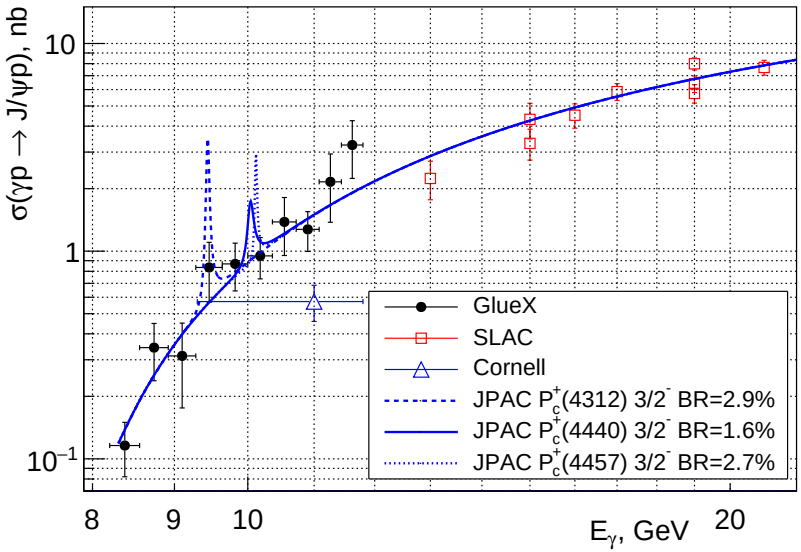
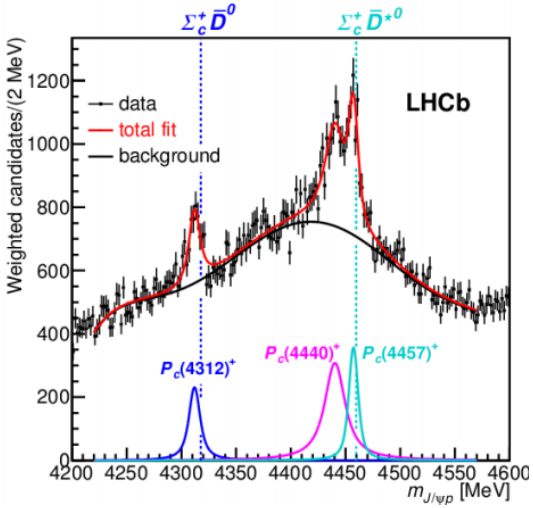
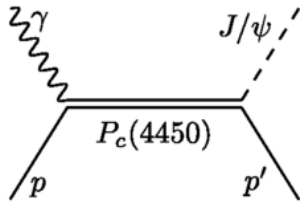




LHCb, PRL 122, 222001 (2019)



JPAC, PRD 94, 034002 (2016)

Energy dependence probes

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  Brodsky et al. [PRL 498 (2001)]
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Search for Resonance in J/ψp

- No evidence for P_c^+ states
- Upper limit for $J^{PC} = 3/2^-$

State	BR
$P_c^+(4312)3/2$-	$< 2.9\%$
$P_c^+(4440)3/2$-	$< 1.6\%$
$P_c^+(4457)3/2$-	$< 2.7\%$

- Disfavors hadrocharmonium and some molecular models

J/ψ Cross Section at Threshold

Search for LHCb P_c^+ states continued

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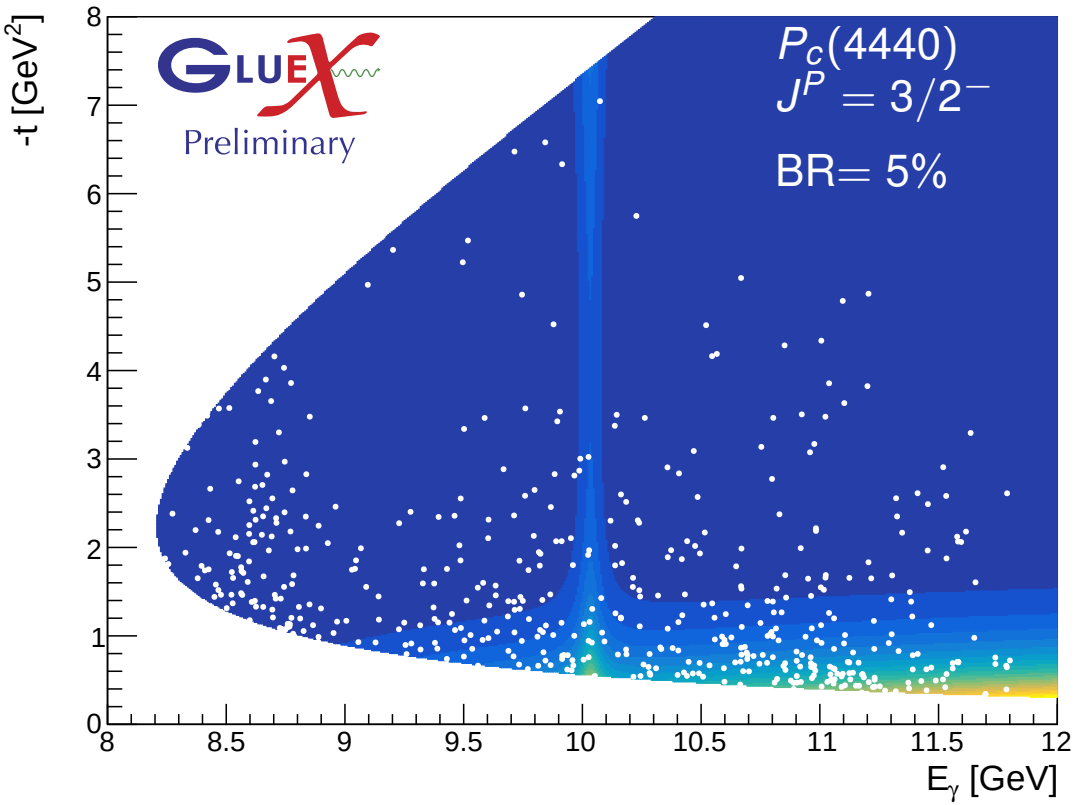
- Beam energy resolution $\ll$ energy bins
- 3x larger data set available
- Resonance has characteristic t distribution



$\Rightarrow$ **Unbinned analysis in E_γ and t**

- Higher sensitivity
- Requirement: detailed understanding of beam spectrum and acceptance
- No clear evidence for s-channel production

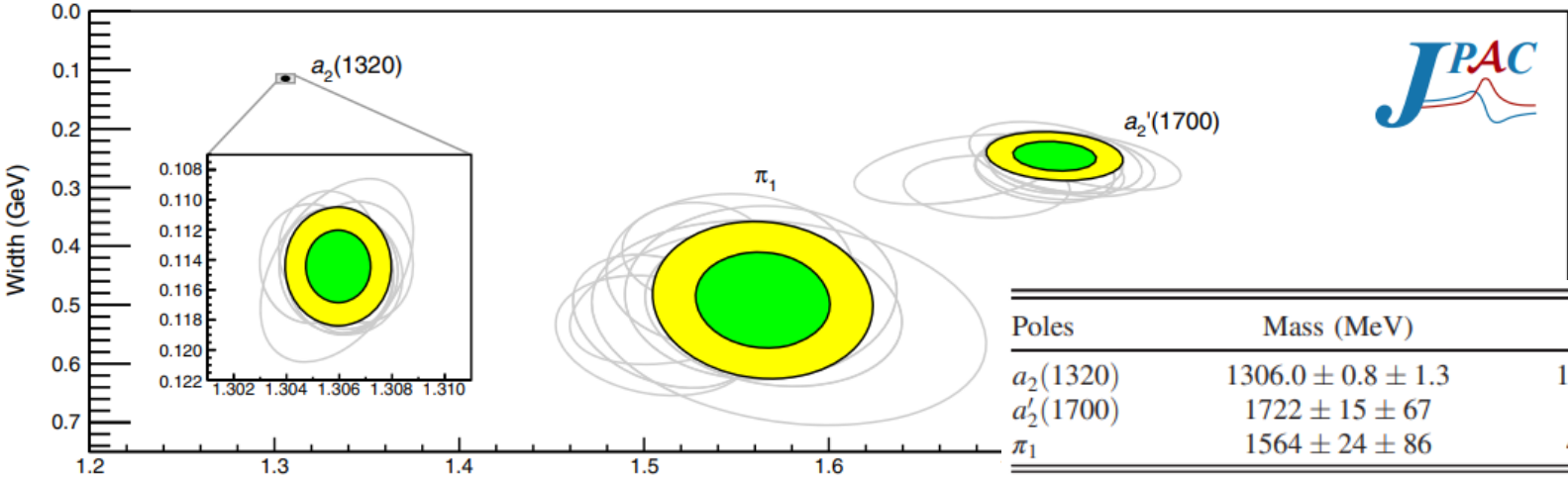
The $\eta^{(\prime)}\pi$ System

- Possible quantum number for the neutral $\pi\eta^{(\prime)}$ system:

L	S	**P**	D	**F**	G	...
J^{PC}	0^{++}	**1^{-+}**	2^{++}	**3^{-+}**	4^{++}	...

- High priority final state, recent developments from COMPASS + JPAC:

A. Rodas et al. [Joint Physics Analysis Center], PRL 122, 042002 (2019)



Poles	Mass (MeV)	Width (MeV)
$a_2(1320)$	$1306.0 \pm 0.8 \pm 1.3$	$114.4 \pm 1.6 \pm 0.0$
$a_2'(1700)$	$1722 \pm 15 \pm 67$	$247 \pm 17 \pm 63$
π_1	$1564 \pm 24 \pm 86$	$492 \pm 54 \pm 102$

- GlueX analysis ongoing, with multiple decay modes:
  $\eta\pi^0 : \eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ $\quad$ $\eta\pi^- : \eta \to \gamma\gamma, \pi^+\pi^-\pi^0$
  $\eta'\pi^0 : \eta' \to \eta\pi^+\pi^-$ $\quad$ $\eta'\pi^- : \eta' \to \eta\pi^+\pi^-$
  (AA, Carlos Salgado, Colin Gleason, Stuart Fegan, ...)

The $\eta\pi^0$ System

Example: $\gamma p \to \eta\pi^0 p$, $\eta \to \pi^+\pi^-\pi^0$ [AA]

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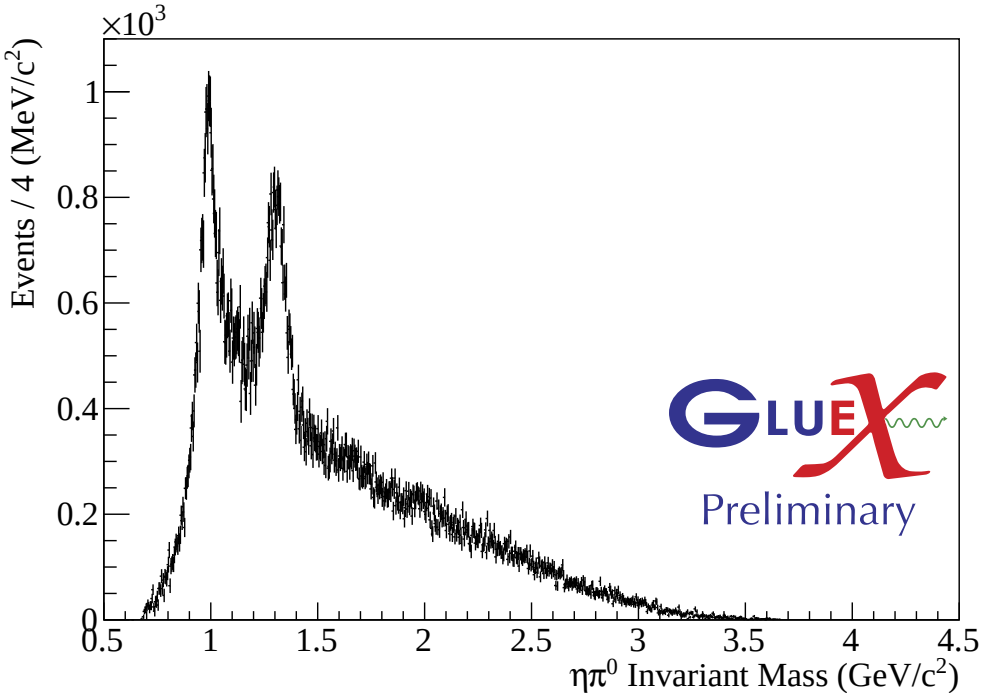
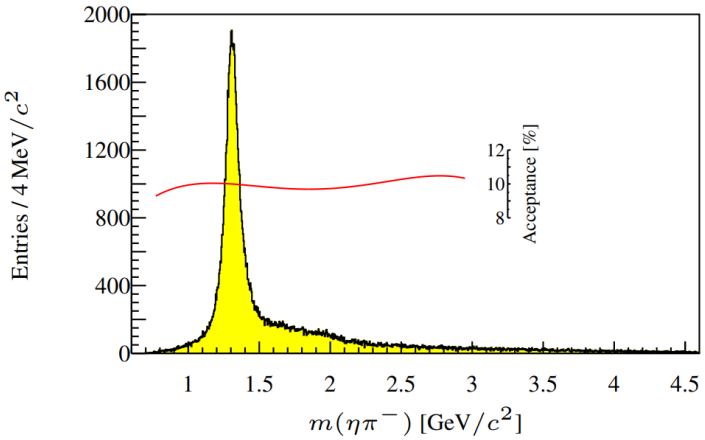


COMPASS, PLB 740, 303 (2015)



- Comparable statistical precision, but different production and multiple decay modes

The $\eta\pi^0$ System

Example: $\gamma p \to \eta\pi^0 p, \quad \eta \to \pi^+\pi^-\pi^0$ [AA]

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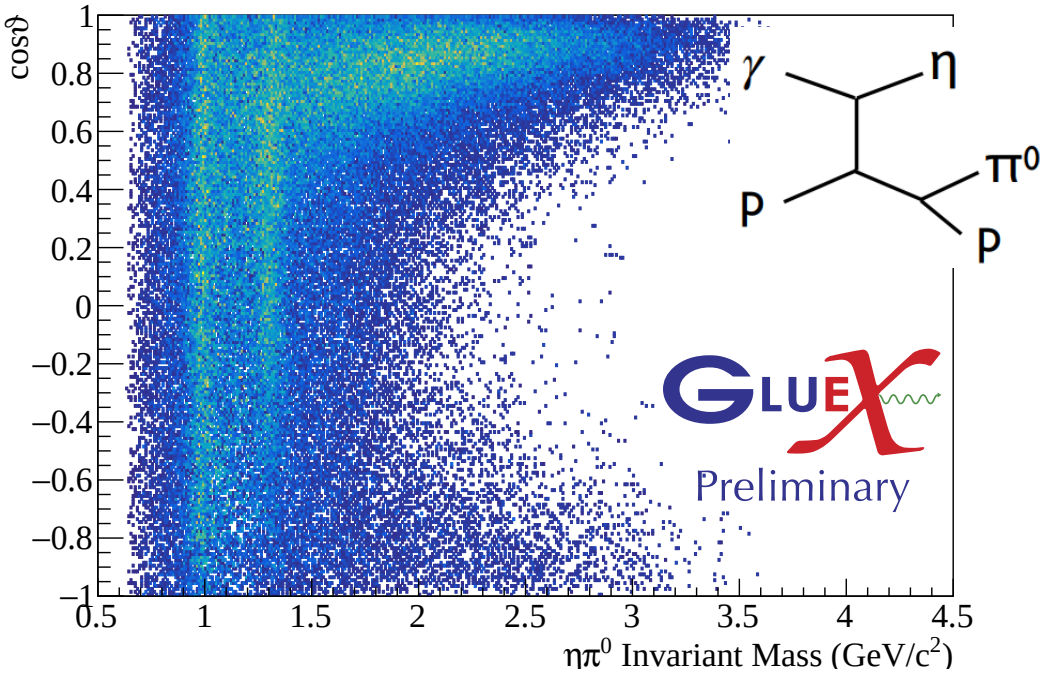
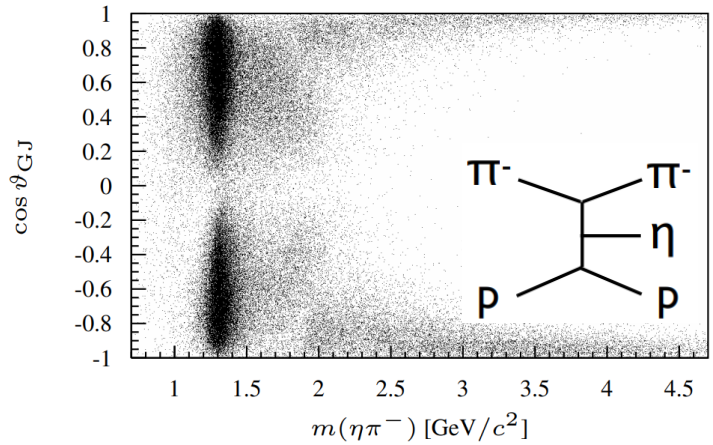


COMPASS, PLB 740, 303 (2015)



- Comparable statistical precision, but different production and multiple decay modes
- Same exotic signal in presence of different backgrounds?
- Linear beam polarization provides enhanced sensitivity

The $\eta\pi^-$ System

Example: $\gamma p \to \eta\pi^-\Delta^{++}$, $\eta \to \gamma\gamma$ [C. Gleason]

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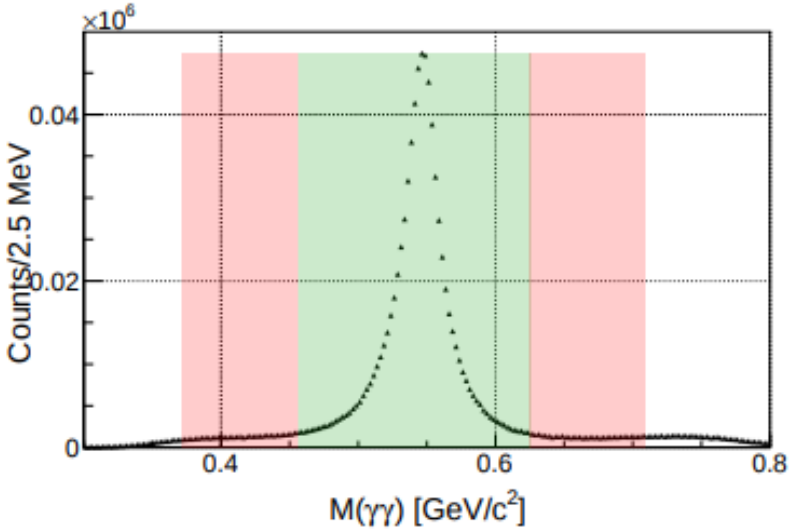
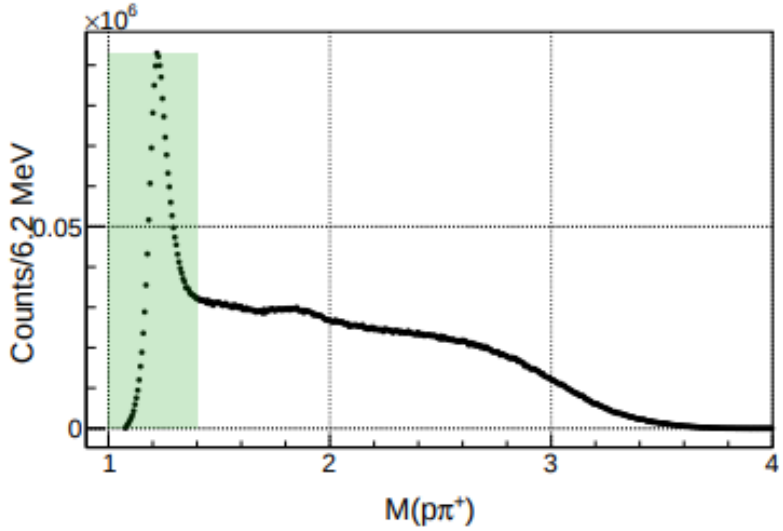
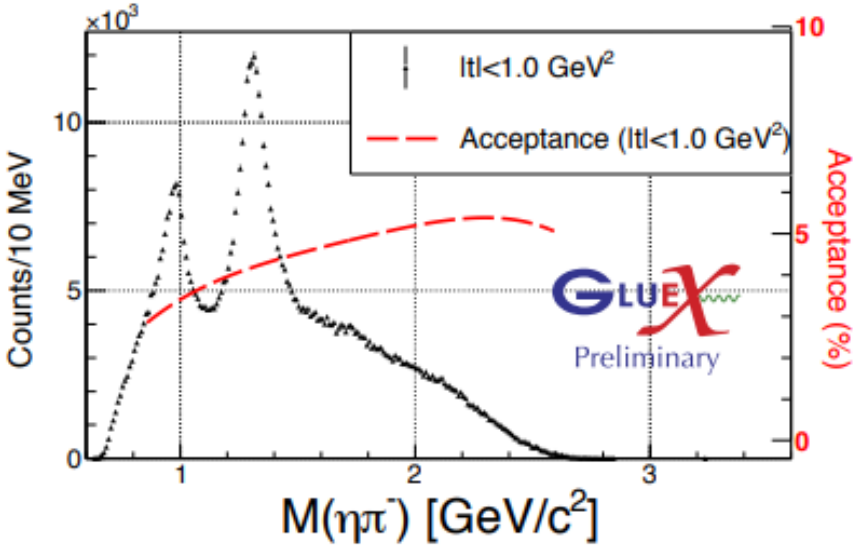
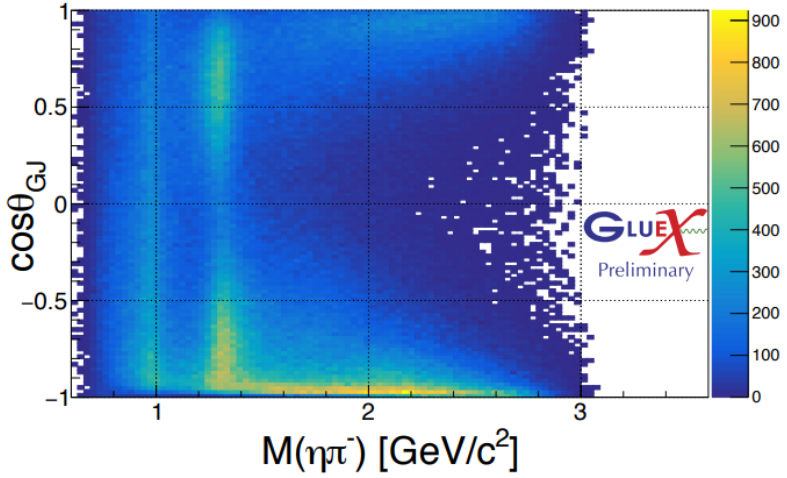




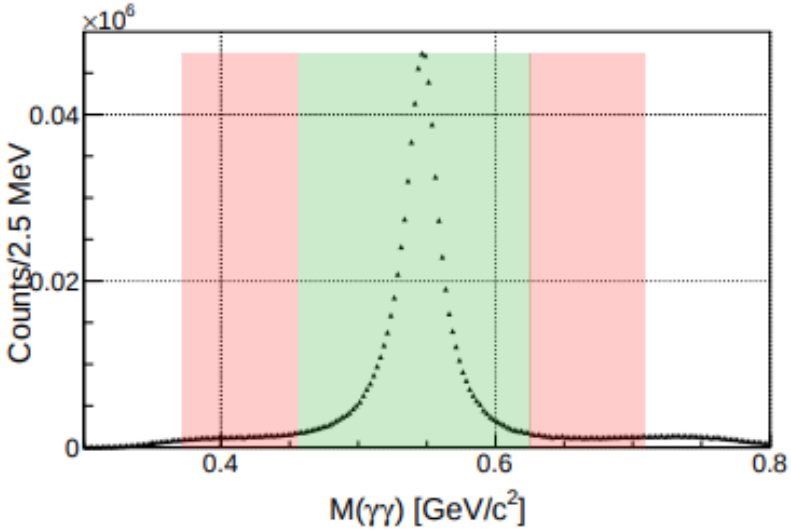


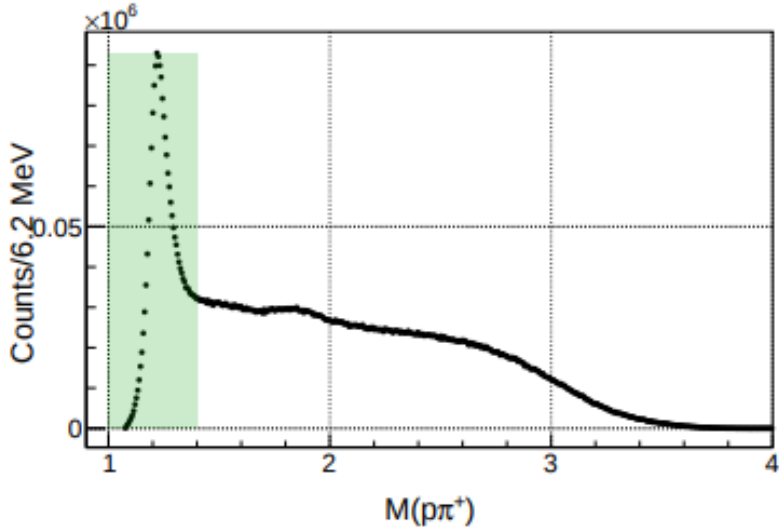


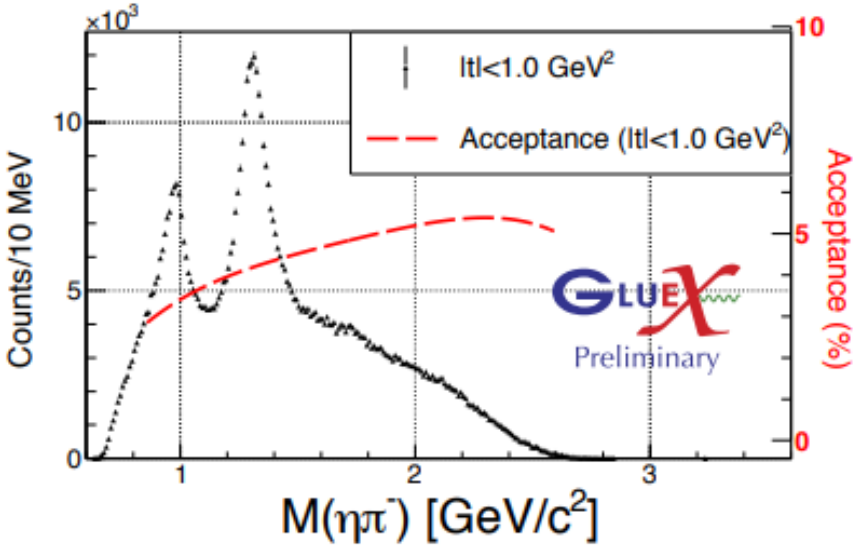
The $\eta\pi^-$ System

Example: $\gamma p \to \eta\pi^-\Delta^{++}$, $\eta \to \gamma\gamma$ [C. Gleason]

Carnegie Mellon University





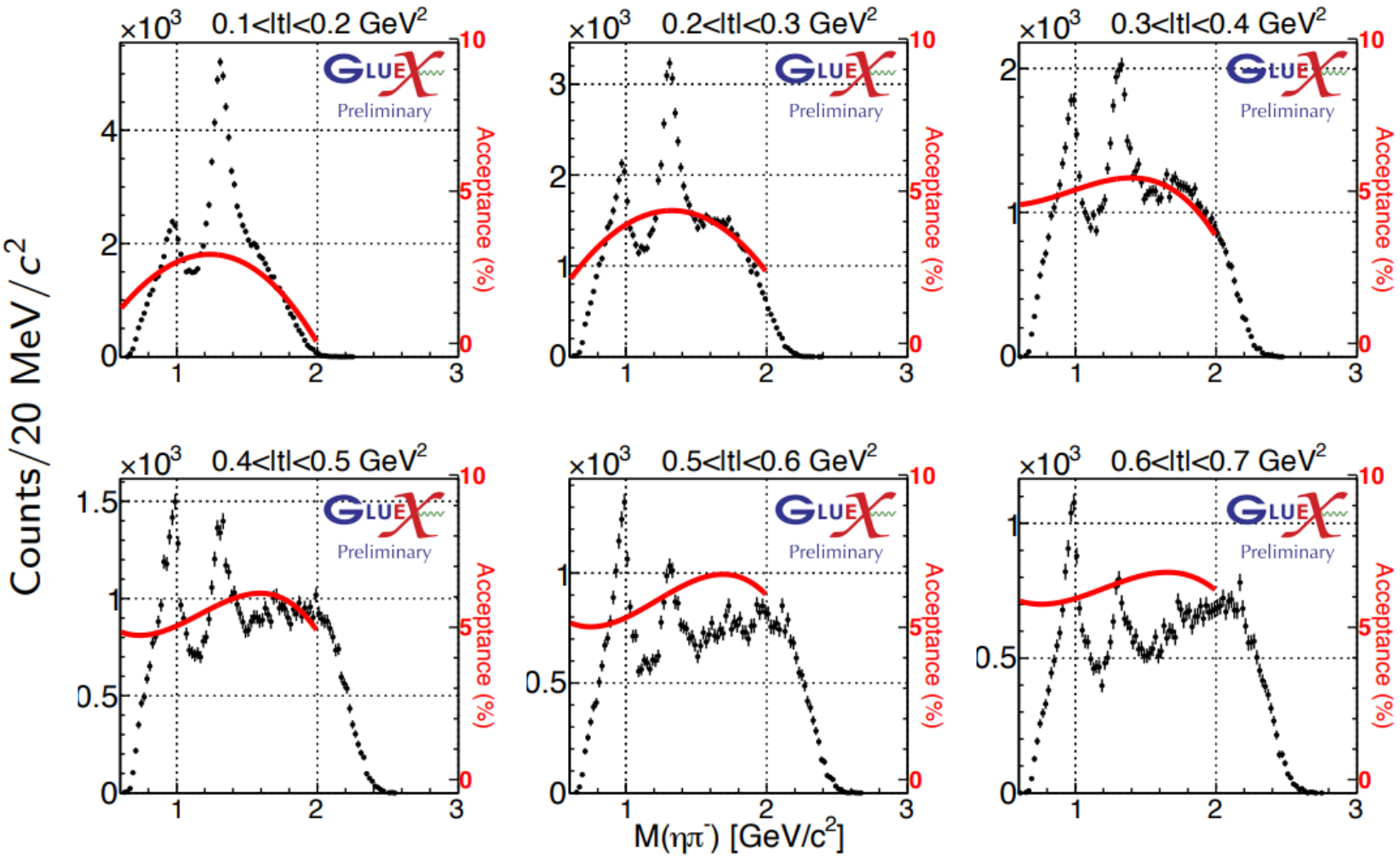


- Complimentary channel
- Different backgrounds
- Charge exchange reaction: *t*-dependence

The $\eta\pi^-$ System

Example: $\gamma p \to \eta\pi^-\Delta^{++}$, $\eta \to \gamma\gamma$ [C. Gleason]

Carnegie Mellon University



Different contributions from natural and unnatural parity exchange?

$\pi^0\pi^0$ and $\eta\eta$ Systems

[A. Thiel]

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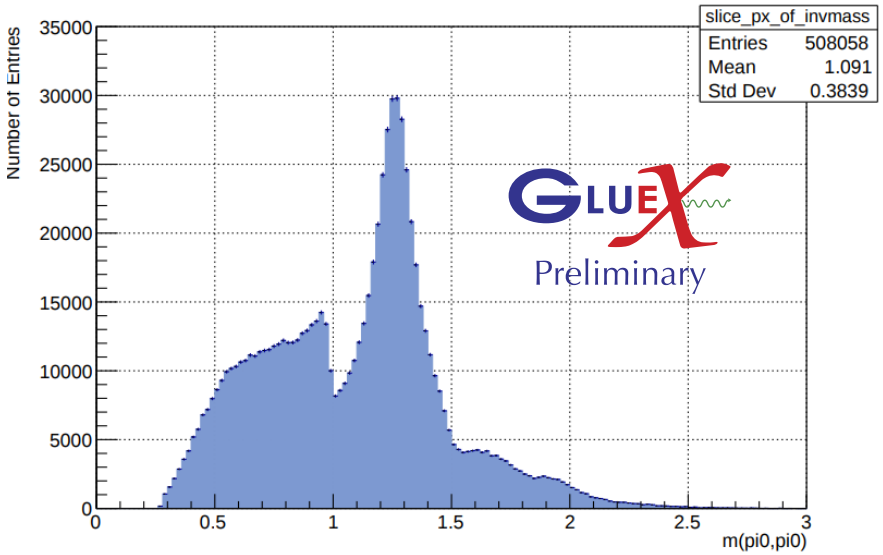
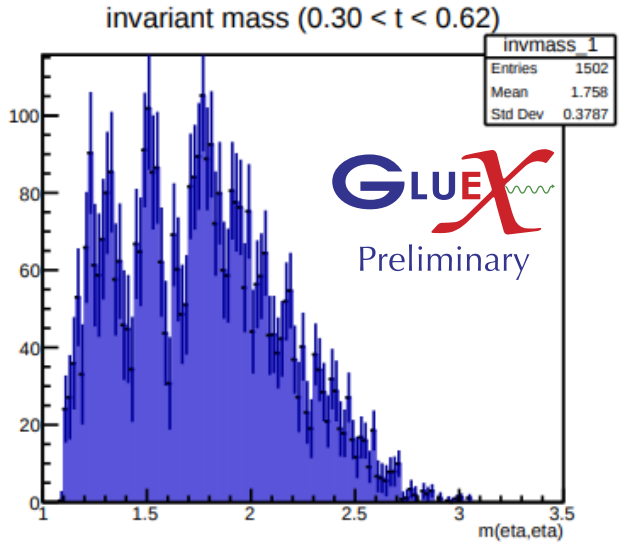
$\gamma p \to \pi^0\pi^0 p$



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

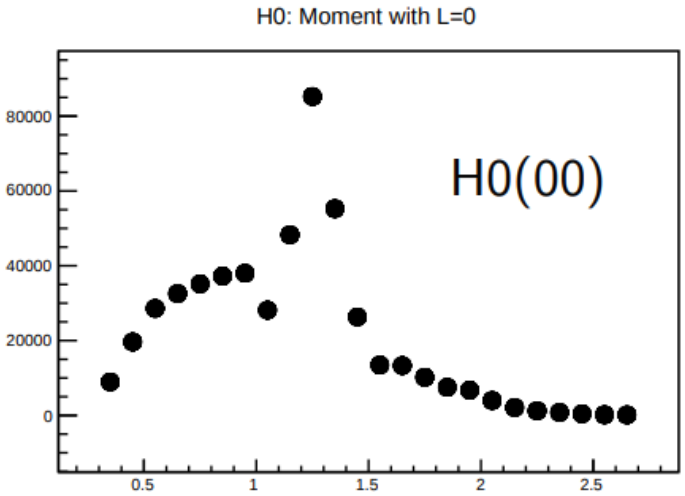


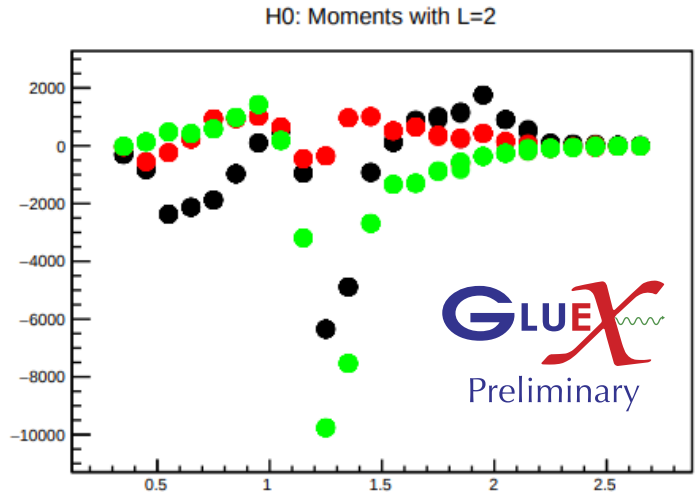
- Develop methods with $\pi^0\pi^0$, limited data for $\eta\eta$ so far
- Similar intermediate states: $f_0(980)$, $f_2(1275)$, $f_0(1500)$, ...
- Two identical particles: only even partial waves allowed

Moment Analysis

$\pi^0\pi^0$ System [A. Thiel]

Carnegie Mellon University

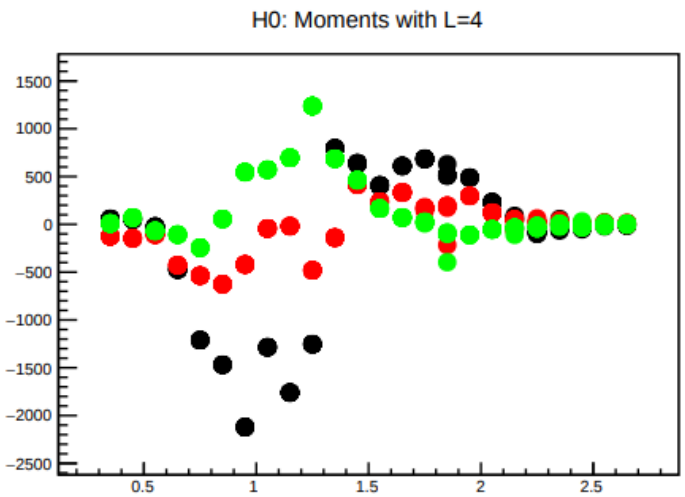




H0(20): black

H0(21): red

H0(22): green



H0(40): black

H0(41): red

H0(42): green

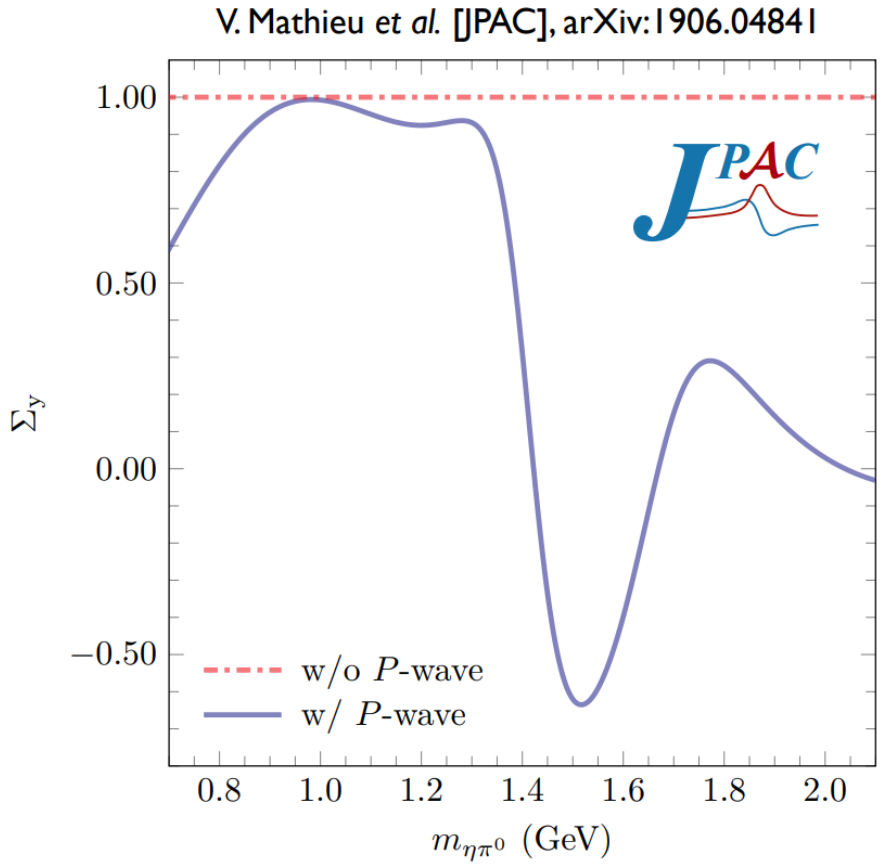
- Unpolarized Moments
- Fits with Haspect
- Formalism based on V. Mathieu [arXiv:1906.04841]

Analysis with Beam Polarization

Carnegie Mellon University

Moment Analysis

- Model-independent
- Sensitive to exotic *P*-wave through interference
- Generalization of beam asymmetry



Analysis with Beam Polarization

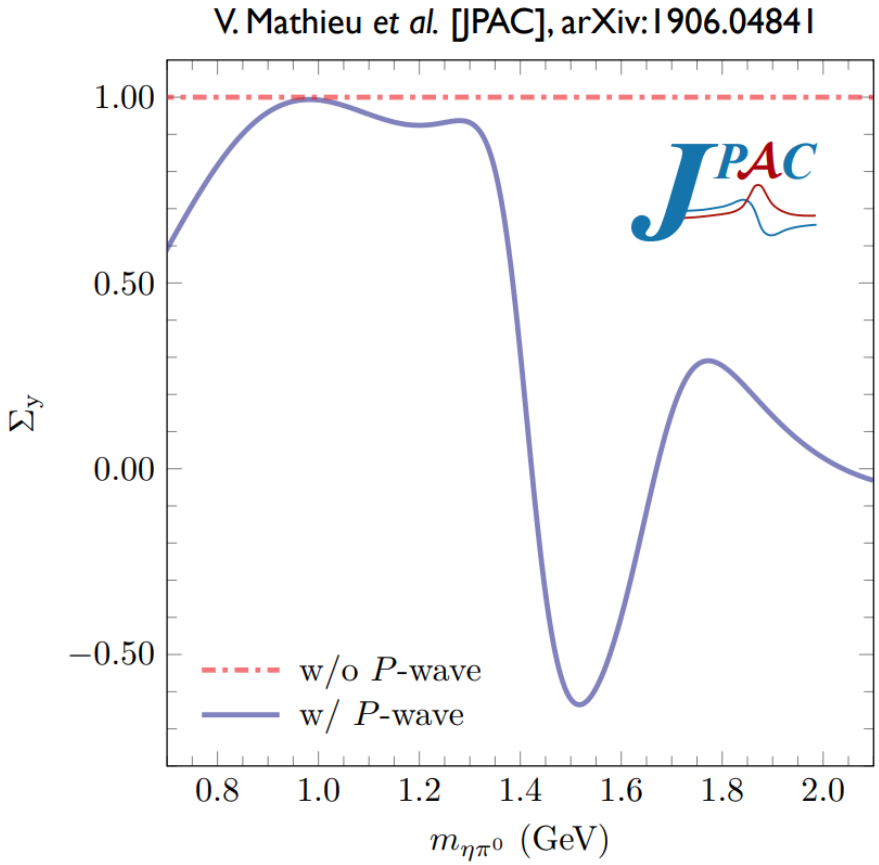
Carnegie Mellon University

Moment Analysis

- Model-independent
- Sensitive to exotic *P*-wave through interference
- Generalization of beam asymmetry

Amplitude Analysis

- Chung-Truman parametrization has to be extended with polarized beam
  [PRD 11, 633 (1975)]
- Collaboration with JPAC to develop new analysis techniques
- Test new methods on known systems (e.g. vector meson SDMEs)



More Ongoing Analyses

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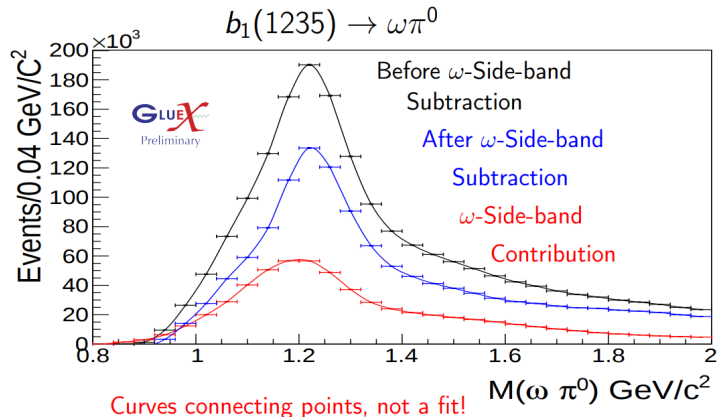
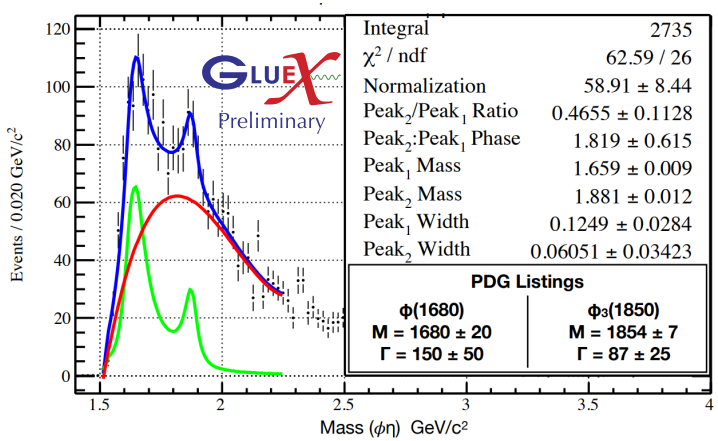
Exotic Searches with PWA

- $\gamma p \to \omega \pi^0 p$ (Ahmed Foda)
- $\gamma p \to \omega \pi^+ \pi^- p$ (Amy Schertz)
- $\gamma p \to \eta \pi^+ \pi^- p$
- $\gamma p \to \eta K^+ K^- p$
- ...



Cross Section Measurements ($E_\gamma \in [3, 12]$ GeV)

- Single pseudoscalar mesons (π^0, η, η', ...)
- Vector mesons (ρ, ω, ϕ)



Hyperon Spectroscopy

- Excited Ξ spectrum (Ashley Ernst)
- Ω photoproduction

The Future of GlueX

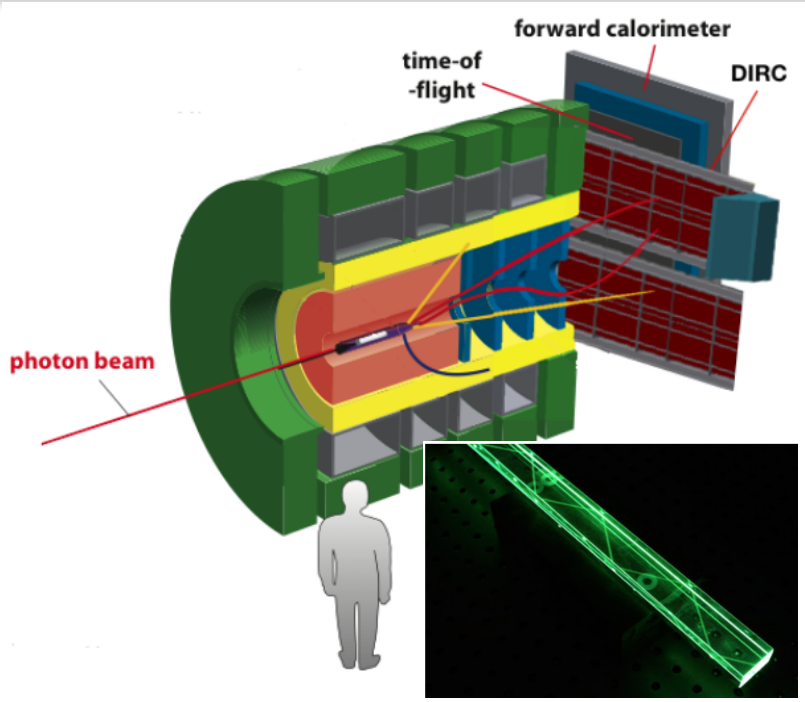
Carnegie Mellon University

Detector Upgrade: GlueX DIRC

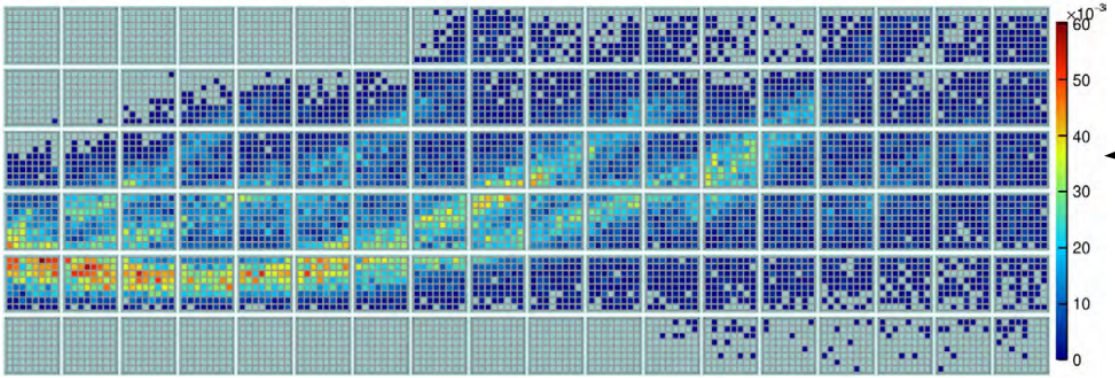
- Extend PID using 1/3 of BaBar DIRC
- New MAPMT photon cameras
- Partially commissioned in Spring 2019

Second data taking campaign

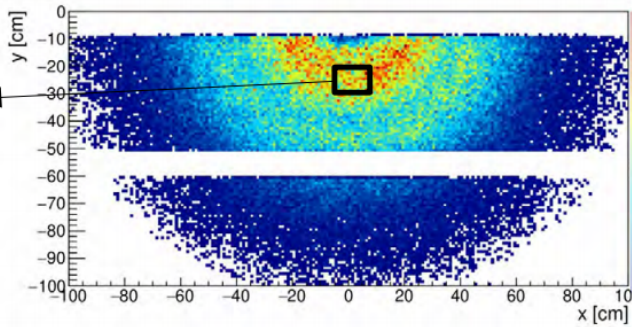
- Start Fall 2019, approved for at least 4 years
- Emphasis on final states with strangeness
- Higher luminosity: rare processes



[3.8,4.2] GeV/c pions from beam



Hit positions on the radiator wall:



Summary and Outlook

Carnegie Mellon University

Status

- Successful **commissioning** and **early physics** analyses
- Full data set for initial phase of GlueX **taken**
- Understanding of detector **acceptance** and **systematics**
  $\Rightarrow$ Comparison with previous measurements and models
- Study **production mechanism**
  $\Rightarrow$ Cross sections, beam asymmetries and spin-density matrix elements
- 2 paper published, 1 submitted, 2 more underway

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Ongoing Efforts

- **Precise measurement** of known resonances and ultimately hybrid candidates
- **Robust analysis framework** in collaboration with **theory**
- Second phase starts this fall: focus on meson spectrum with **strangeness** content

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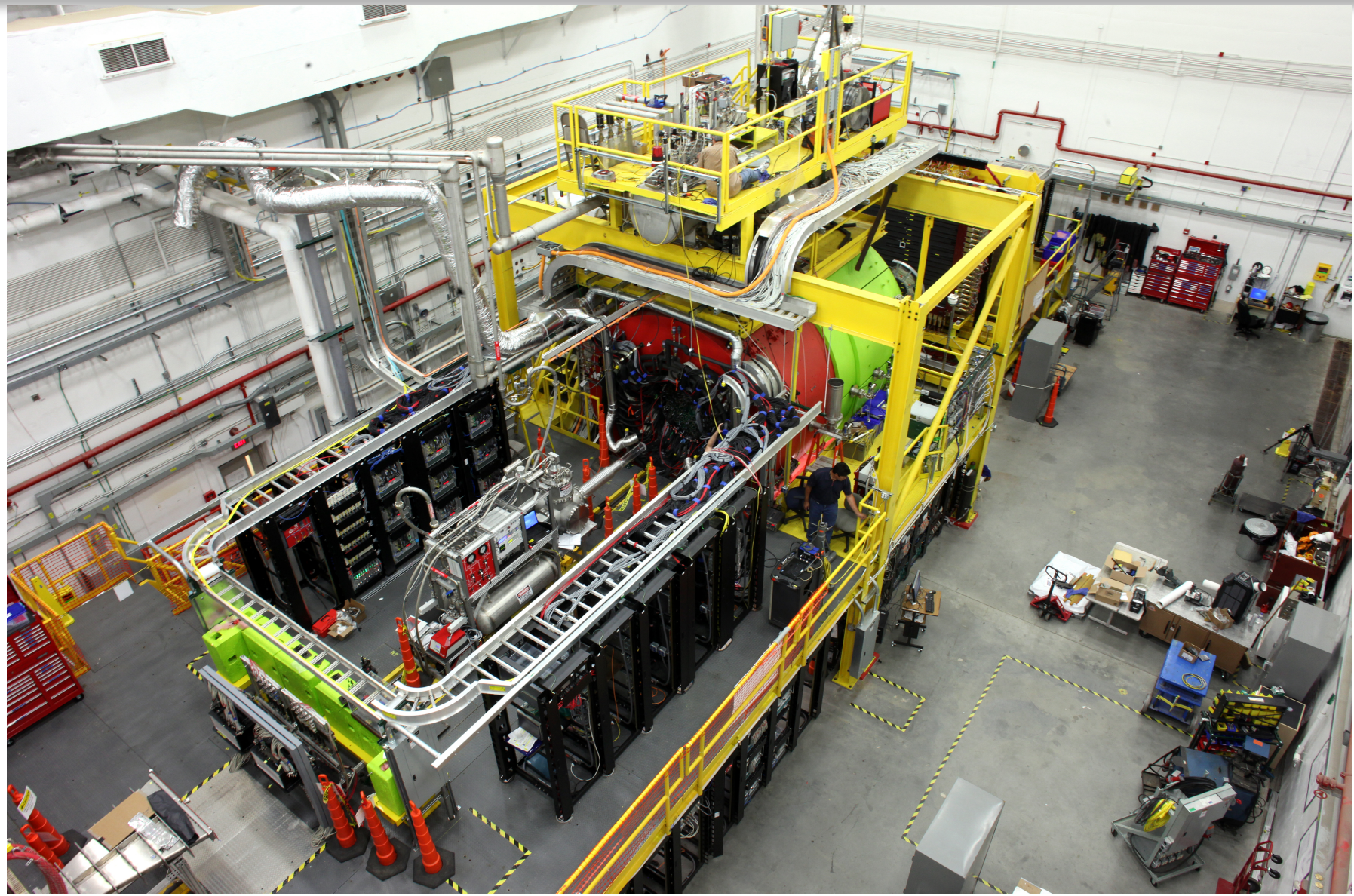
Thank You!

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