Hadron Spectroscopy at Jefferson Lab

GlueX & CLAS12

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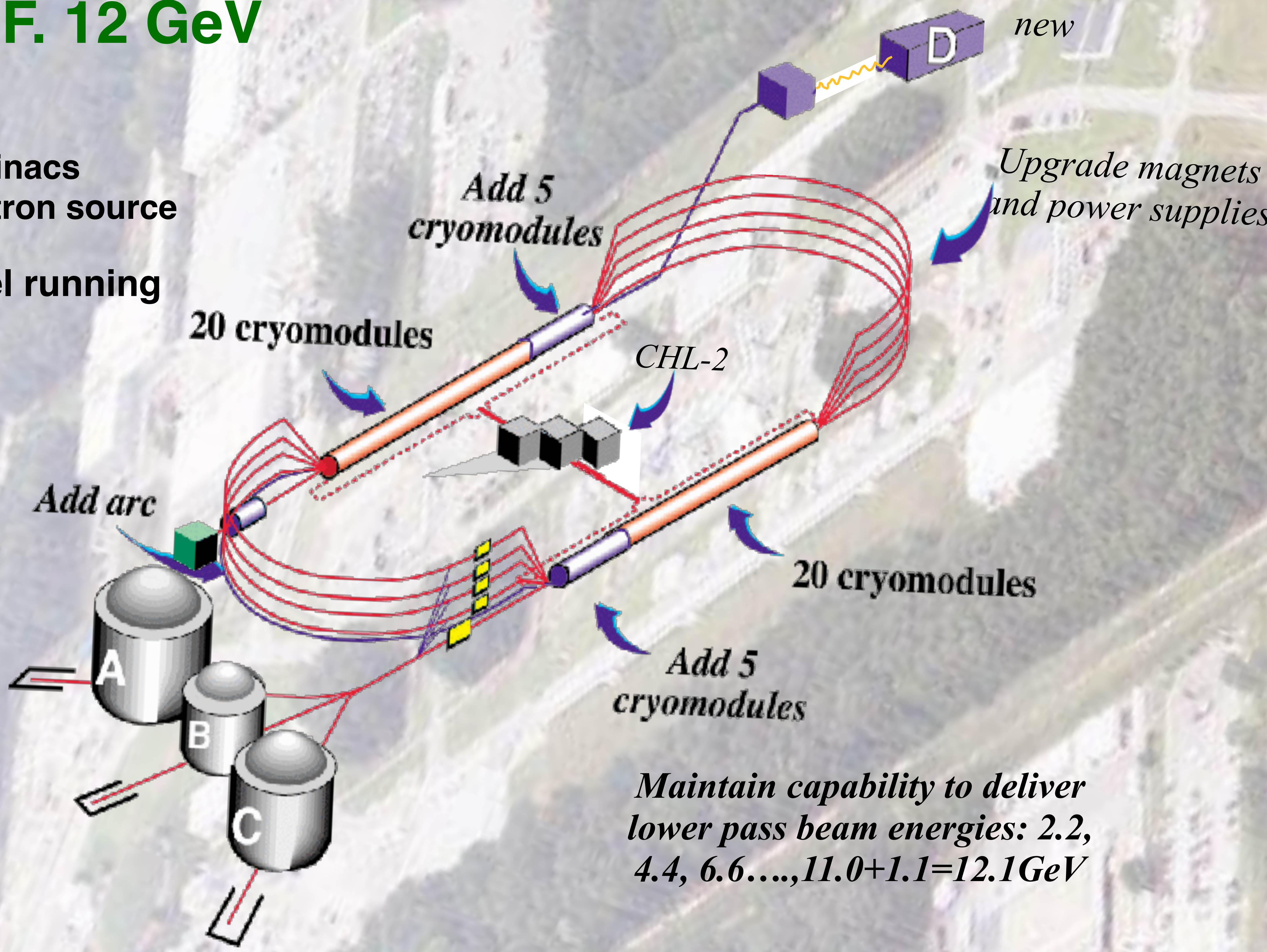
Outline

- **Jefferson Lab**
- **Hadron Spectroscopy and QCD**
- **CLAS12**
- **GlueX**
- **Summary and Near Future Plans**

C.E.B.A.F. 12 GeV

Two 1.1 GeV Linacs
Polarized electron source

- 4 halls parallel running
- I_{max} = 90 μA
- Pol = 90%



Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….,11.0+1.1=12.1GeV

Very high luminosities ~10^{39} cm^{-2}sec^{-1}

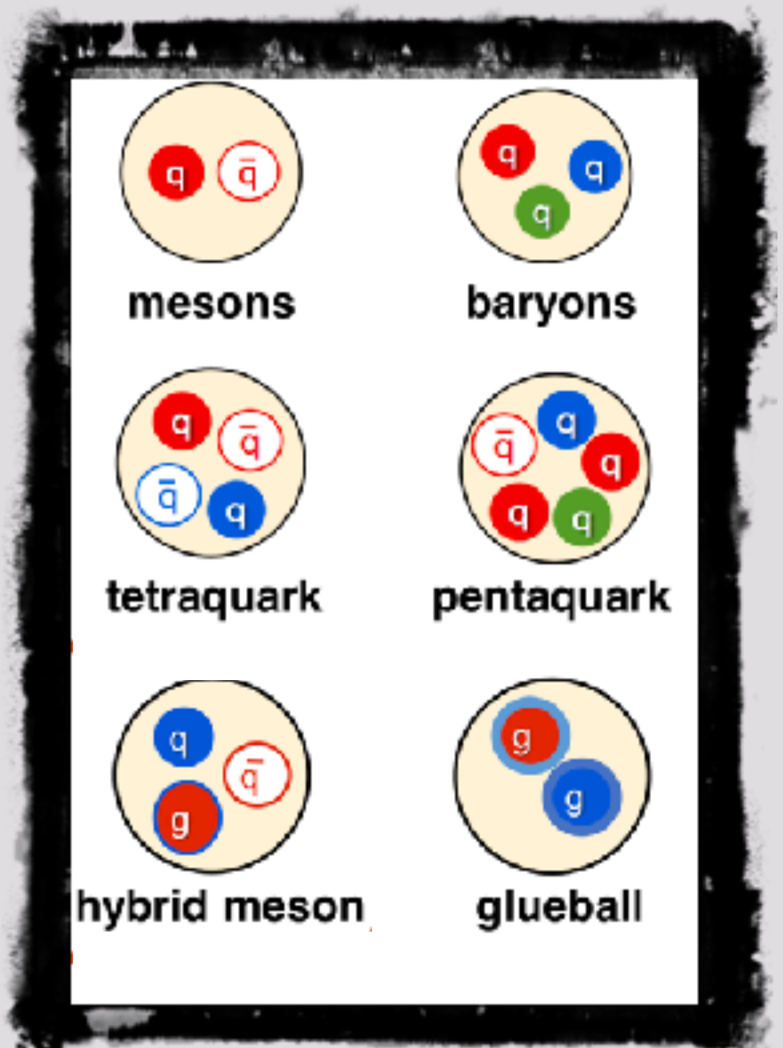
Jefferson Lab Main Goal: To study QCD at the nucleon scale.

↳ Confinement - Role of the gluon in the mass and spin of nucleon

- Nucleon Structure (PDF, GPD, TMD,…)
- Light-Hadron Spectroscopy

of **Baryons**
Mesons

Masses ~ 1-3 GeV



spectrum, structure, production

Outside the original quark model

➤ Hybrids(gluonic rich) and Multi(>3)-quark states

☆ **Exotics** (J^{PC}: 1^{-+},2^{+-},…) ☆
Explicitly forbidden quantum numbers.

Main Experimental Topics on (Light)-Hadron Spectroscopy

Mesons: Identification of Hybrids (Exotics) Mesons
Identification of the Strangeonia excited states (ssbar)

- Exotics Predicted by several phenological models (flux tube,…)
- Validate LQCD predictions on hybrids.
- Of about 22 strangeonia resonances expected below a mass of 2.5 GeV, only 7 are "relatively" well established.
- Strangeonia hybrids have been predicted just above a mass of 2 GeV.

Baryons: N* spectrum ("missing" resonances = previously unobserved).
Hyperons, Excited cascades (Ξ*) …

- Understanding the relevant degrees of freedom to describe hadrons (di-quark clustering,…)
- Electrons beams provide important Q2 dependence
- Validate LQD predictions
- Baryons beyond QM (e.g. Pentaquarks…)

But ... How you recognize (experimentally) a resonance? How you search? When are you sure that you found one?

Not every bump is a resonance and not every resonance is a bump

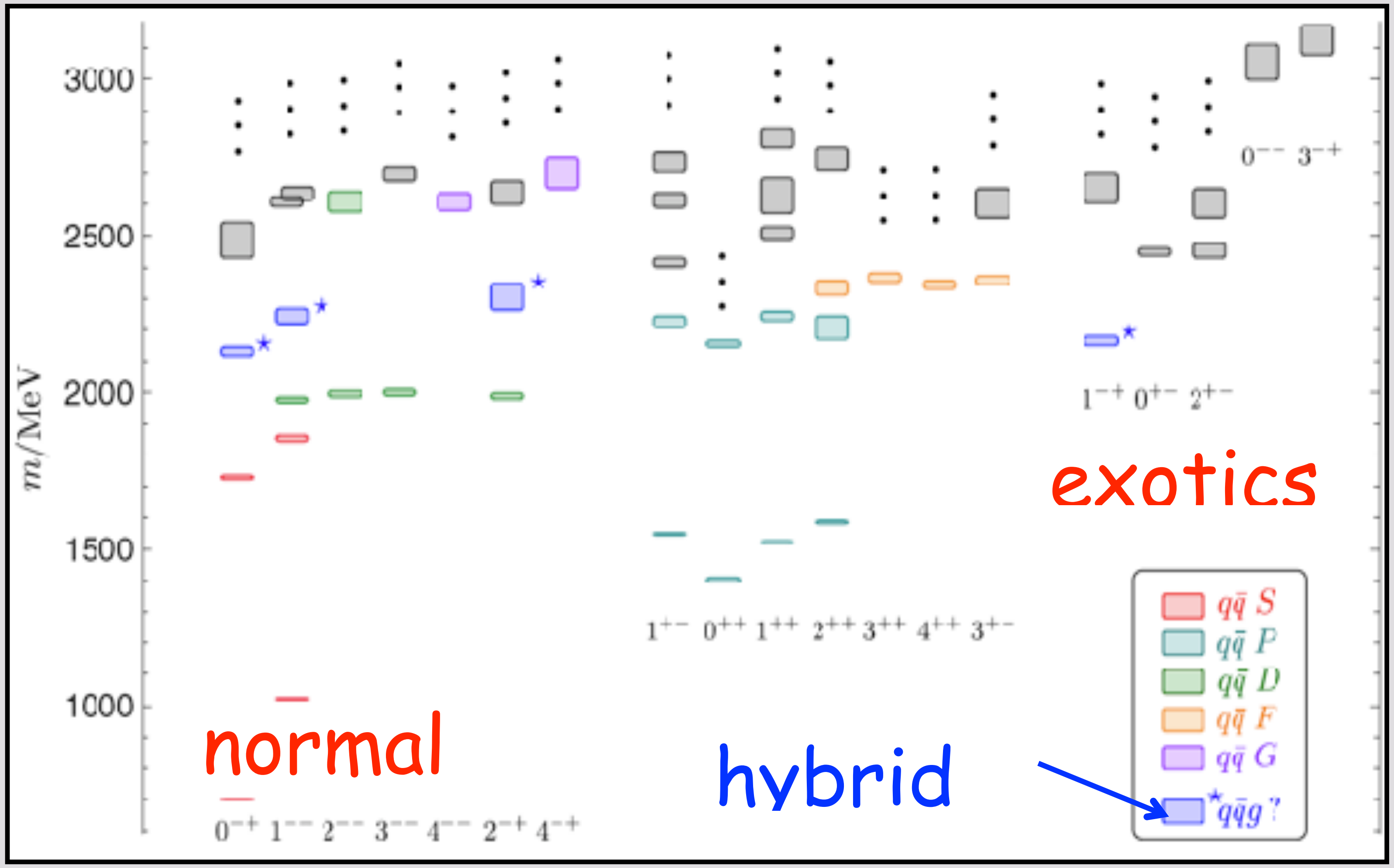
Related Jlab Theory Groups

J.P.A.C.

For identifying the Hadron Spectrum we use Amplitude/PW Analysis.
To find new resonances we need to search for poles of the S-Matrix (in the complex-Riemann surfaces).
The S-Matrix will be constrained by: Analyticity and Unitarity … current calculations use Regge Theory, ChPT, Dispersion Relations, …

Hadron Spectrum Collaboration (**HadSpec**)
Lattice QCD calculations to study the spectrum of Hadrons.

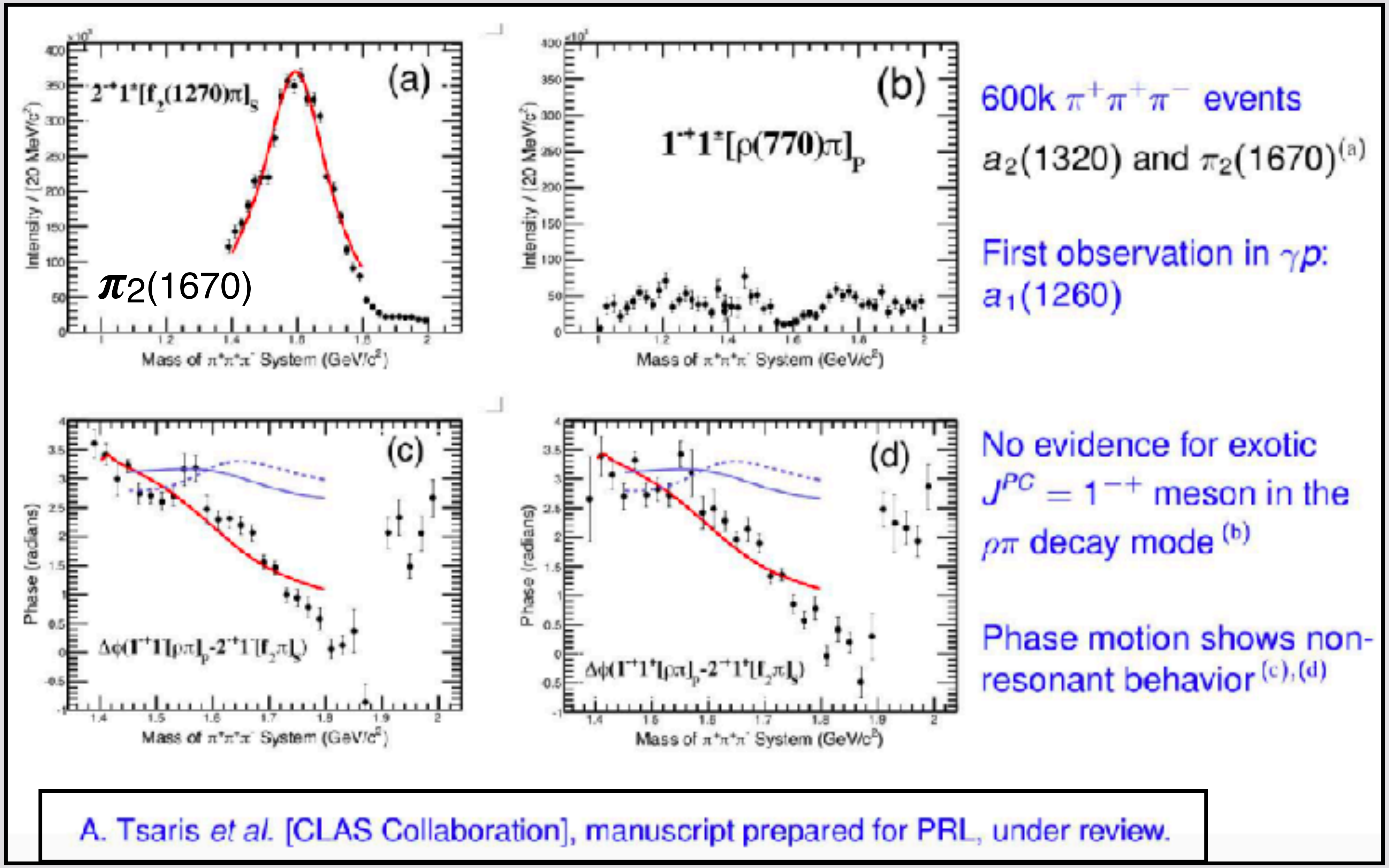
Light-Meson Spectrum from Lattice-QCD



Dudek el al PRD 83

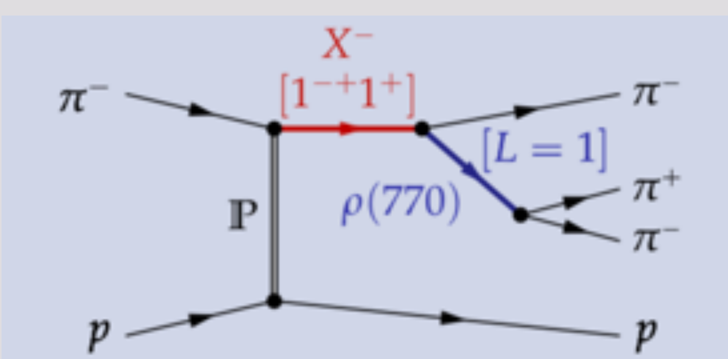
Isovector mesons, m_π~700 MeV

An example: $\pi_1(1600)$ (1^{-+}) was observed in Hadro-production (E852, COMPASS…)



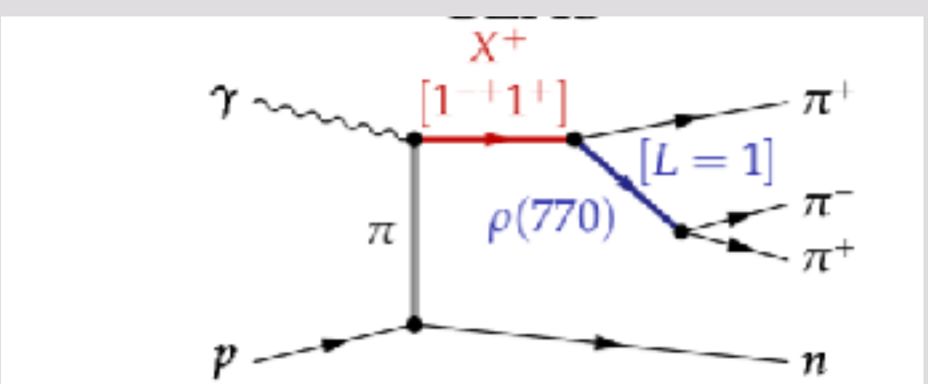
$\gamma p \to n\pi^+\pi^+\pi^-$

CLAS(6)-g12



Hadroproduction

$\pi_1(1600)$ is not observed in Photo-production.

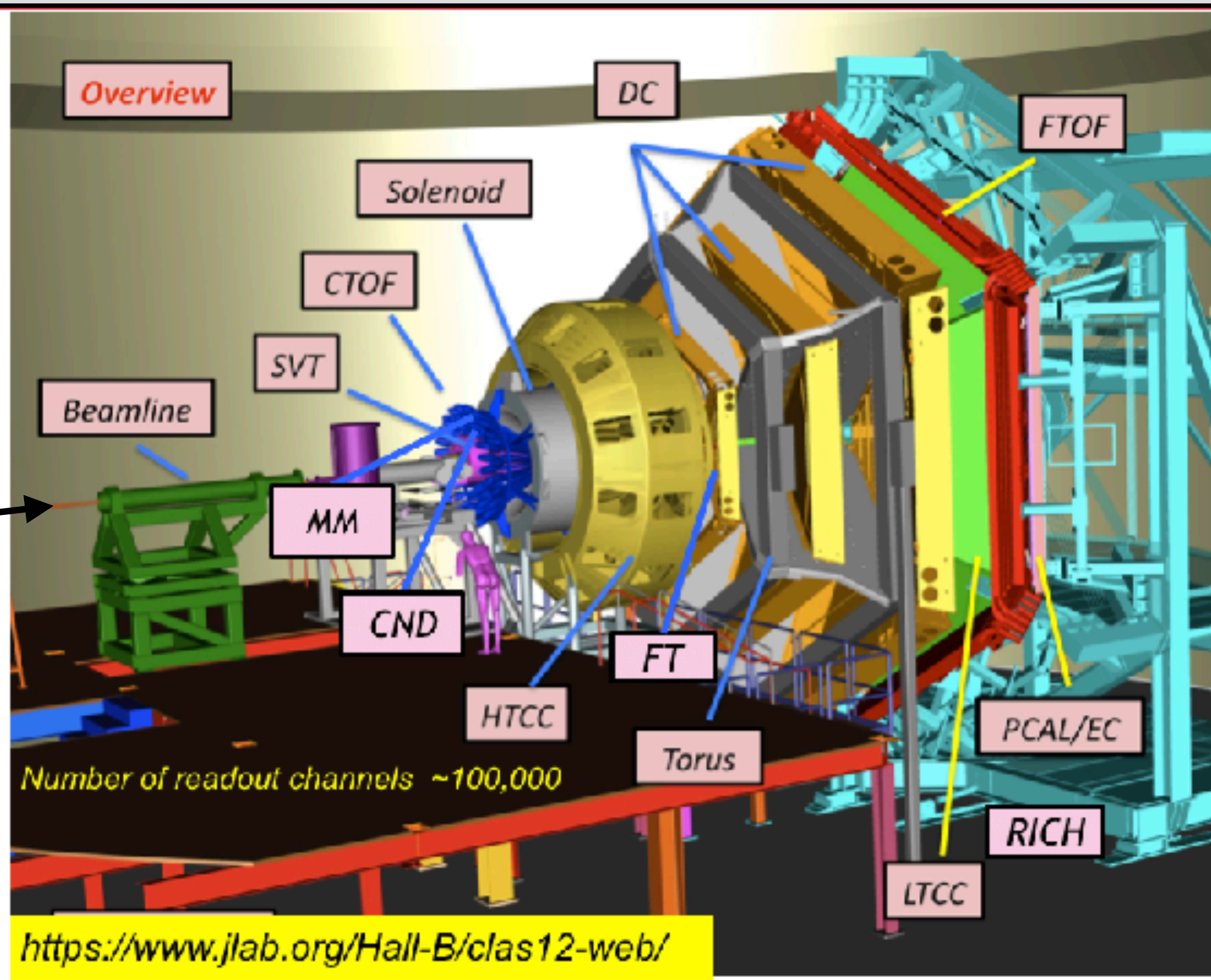


Photoproduction

Hall B: CLAS12

Central Detector:
- SOLENOID magnet
- Barrel Silicon Tracker
- Micromegas
- Central ToF system
- Neutron detector
- Backward Angle Neutron detector

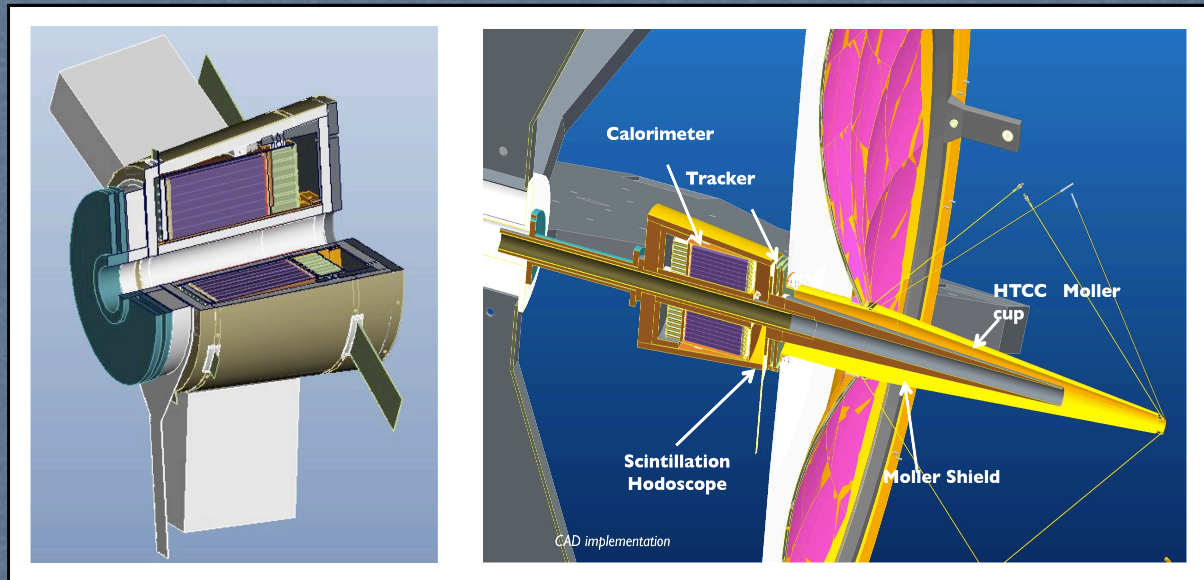
e Beam



Forward Detector:
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- RICH detector
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter (EC)
- Forward Tagger

- **targets:**
  - **proton, deuteron and nuclei**
  - **unpolarized, longitudinally and transversally polarized**
  - **solid, liquid and gas**
- **beam:**
  - **highly polarized electron beam**
  - **linearly polarized quasi-real photons**
- **final states: inclusive, semi-inclusive and exclusive**
- **luminosity up to 10^{35} cm^{-2}s^{-1}**

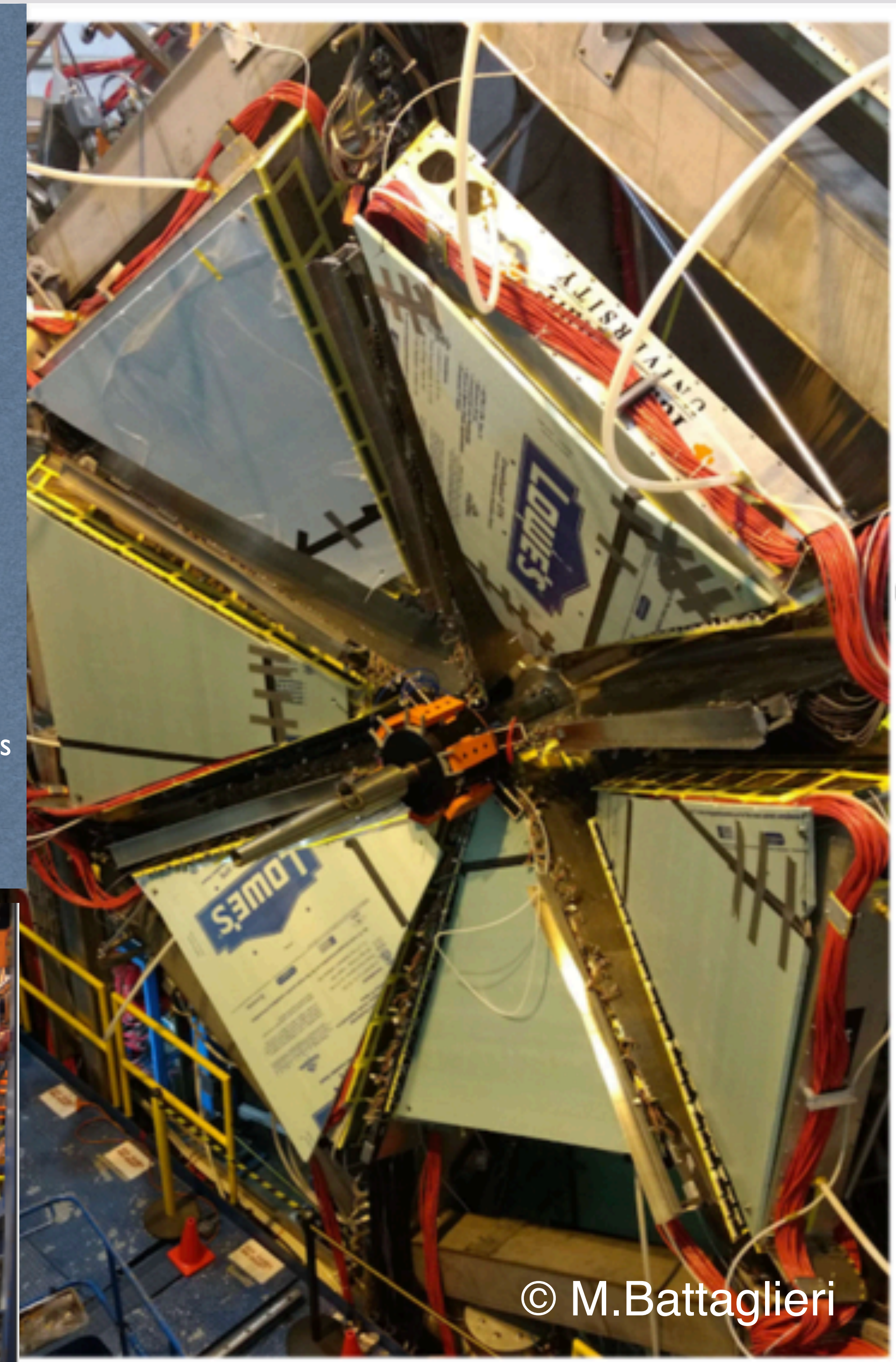
The Forward Tagger for CLAS12

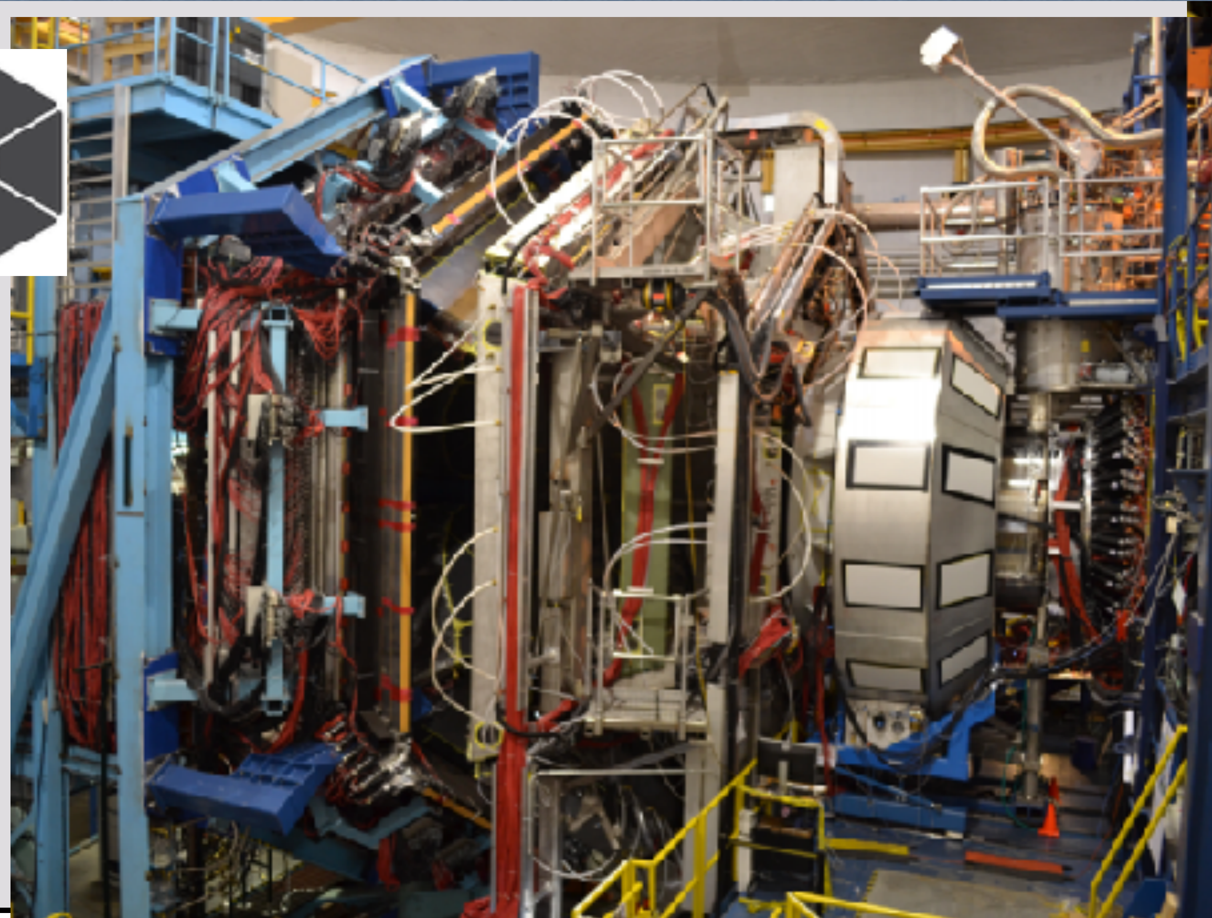


FT-Cal: $PbWO_4$ calorimeter
electron energy/momentum
Photon energy (ν=E-E')
Polarization $\varepsilon^{-1} \approx 1 + \nu^2/2EE'$

FT-Hodo: Scintillator tiles
veto for photons
Edinburgh+JMU+NSU

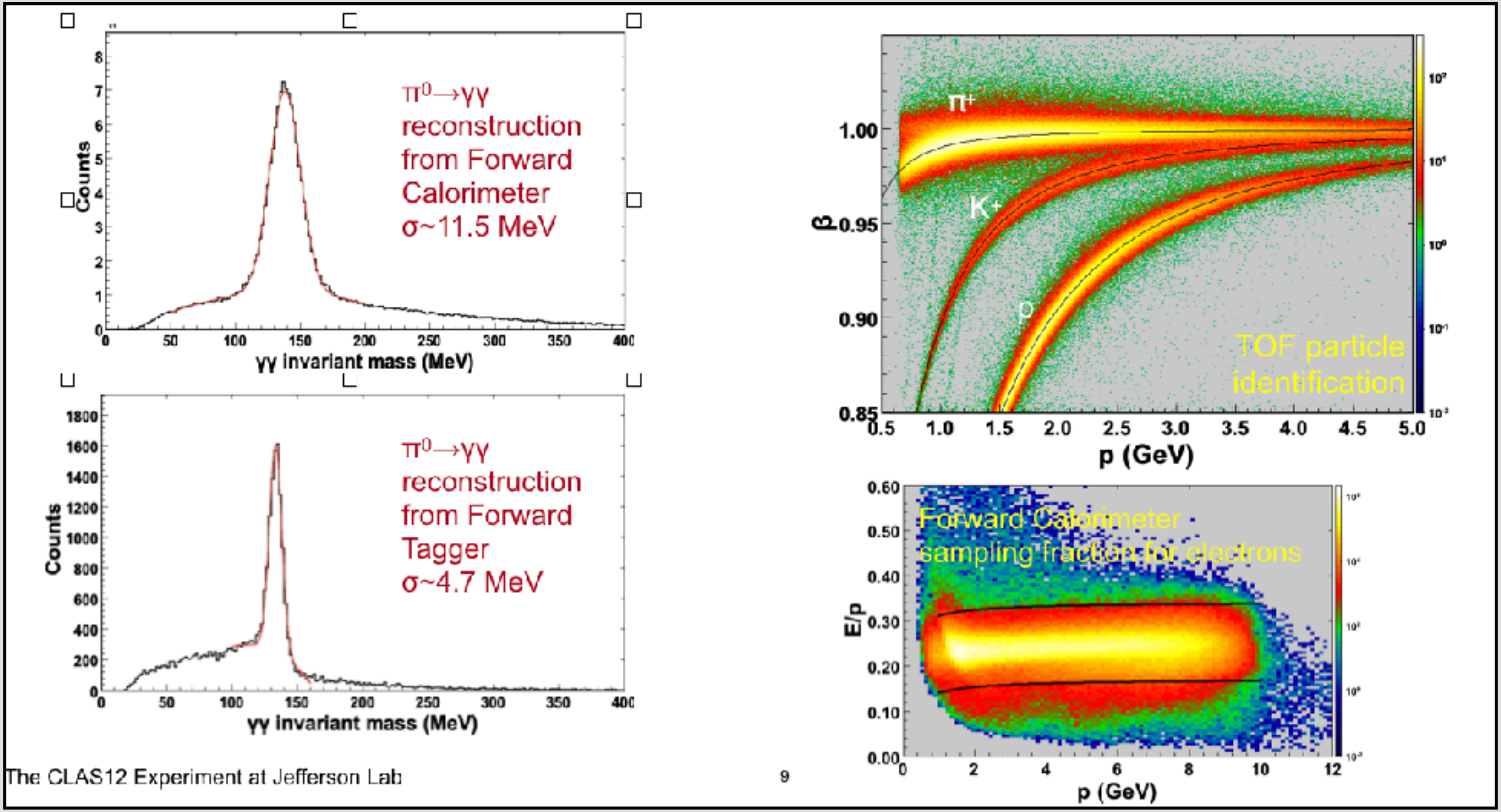
FT-Trck: MicroMegas detectors
electron angles and polarization plane
Saclay + Ohio





$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0^o - 360^o
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV

CLAS12- Physics program began taking data Feb'18 - 6% reconstructed - Very preliminary physics results presented at DNP19 ...



CLAS12 : Analyses in Progress

6% of data taken

Meson Spectroscopy
(MesonX)

- $\gamma^* p \to p\pi^+\pi^-$
- $\gamma^* p \to pK^+K^-$
- $\gamma^* p \to (n)\pi^+\pi^+\pi^-$

Baryon Spectroscopy

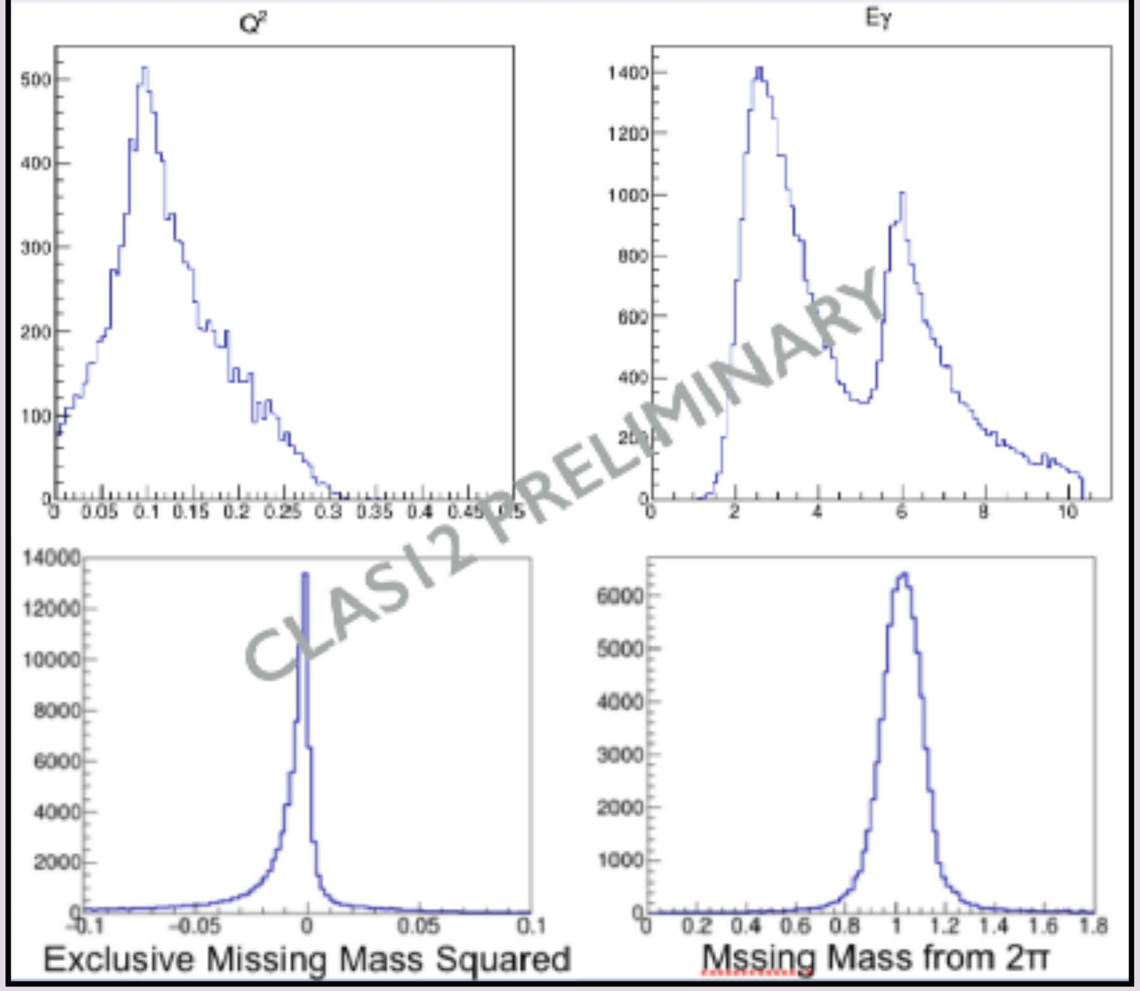
$\gamma^* p \to K^+K^+K^0\Omega^-$ (Very Strange group)

$\gamma^* p \to K^+Y$ (Λ and Σ)

$\gamma^* D(n) \to D(n)$ ppbar (RG-B)

CLAS12 data taking

- **First commissioning run** (KPP) in February 2017
- **Engineering run** in December 2017-February 2018
- Physics data taking start in February 2018:
  - Run Group A:
    - 13 experiments
    - 10.2-10.6 GeV polarized electrons
    - Liquid-hydrogen target
    - ~300 mC, ~50% of approved beam time
  - Run Group K:
    - 3 experiments
    - 6.5, 7.5 GeV polarized electrons
    - Liquid-hydrogen target
    - ~45 mC, ~12% of approved beam time
  - Run Group B:
    - 7 experiments
    - 10.2-10.5 GeV polarized electrons
    - Liquid-deuterium target
    - ~84 mC, ~24% of approved beam time

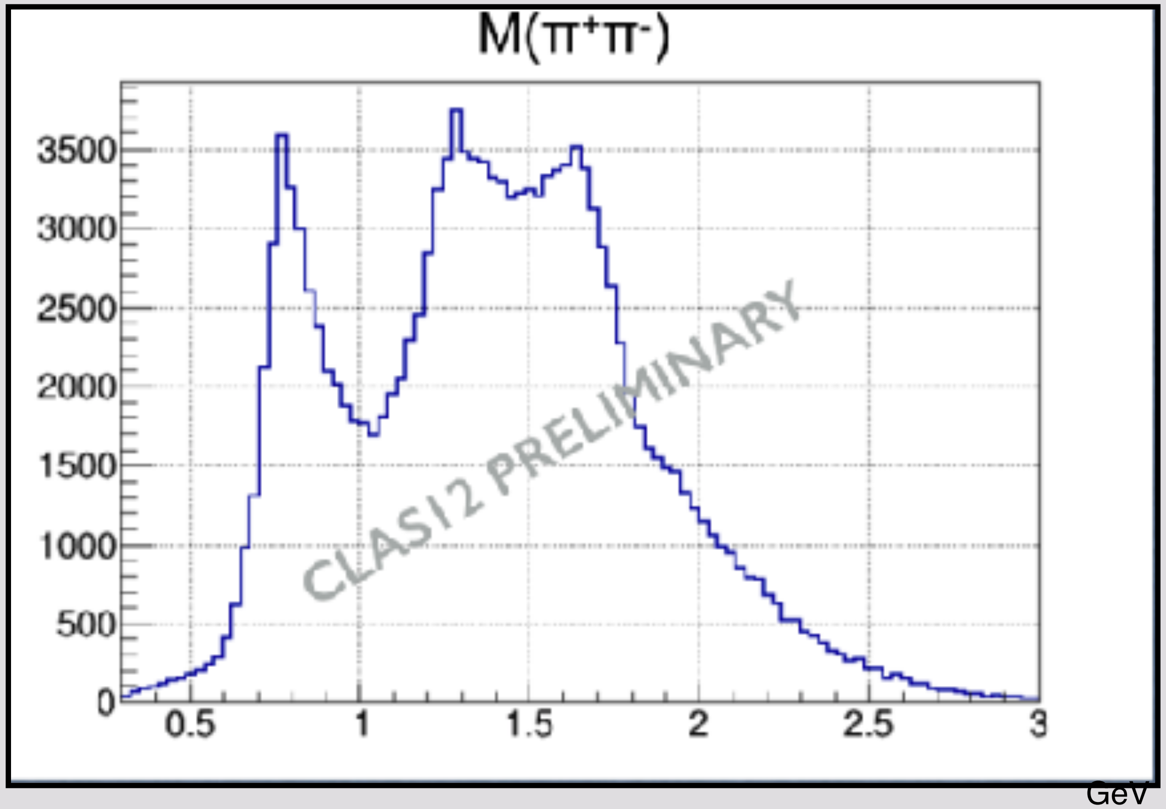


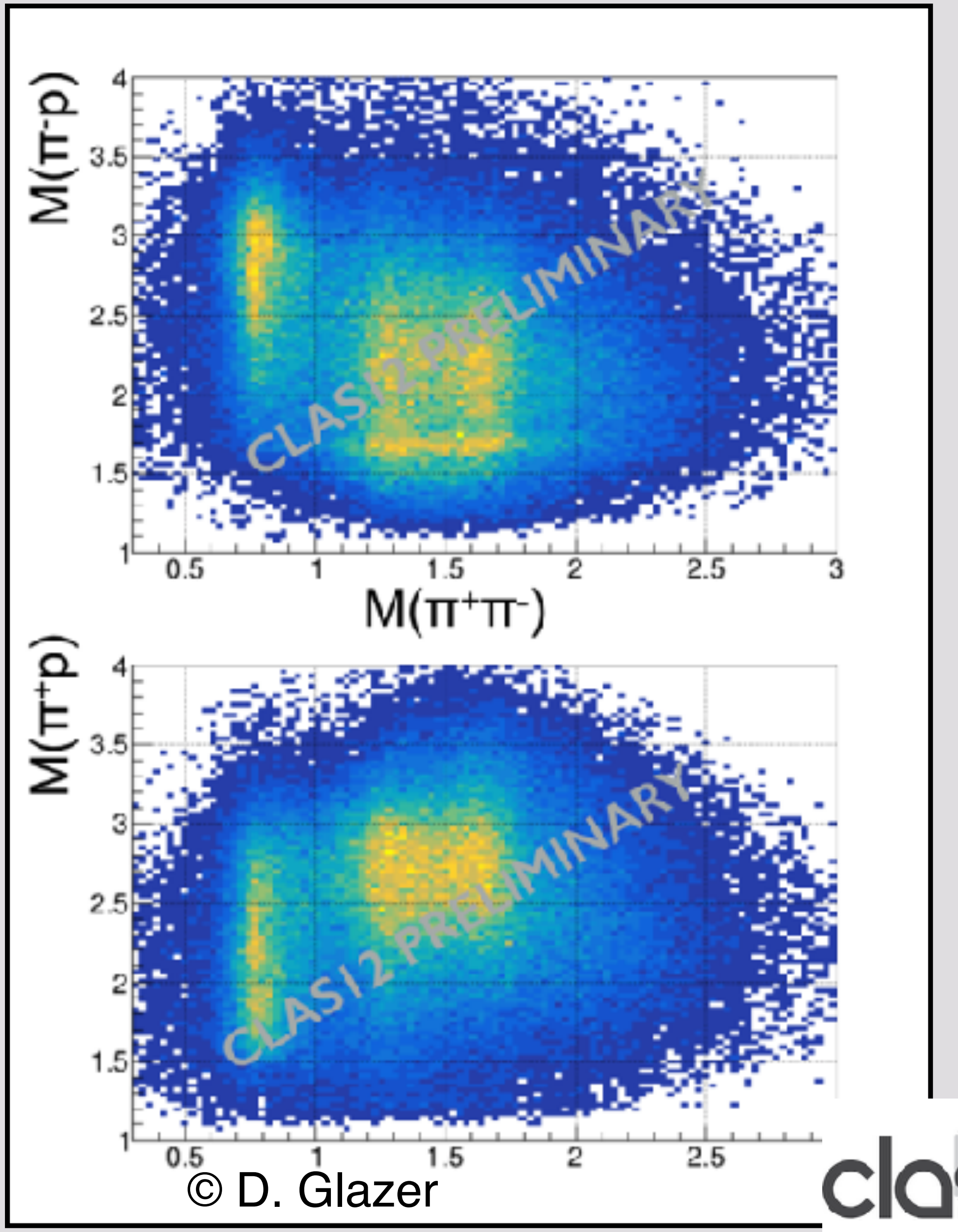
ALL TRIGGERS

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

(exclusive)

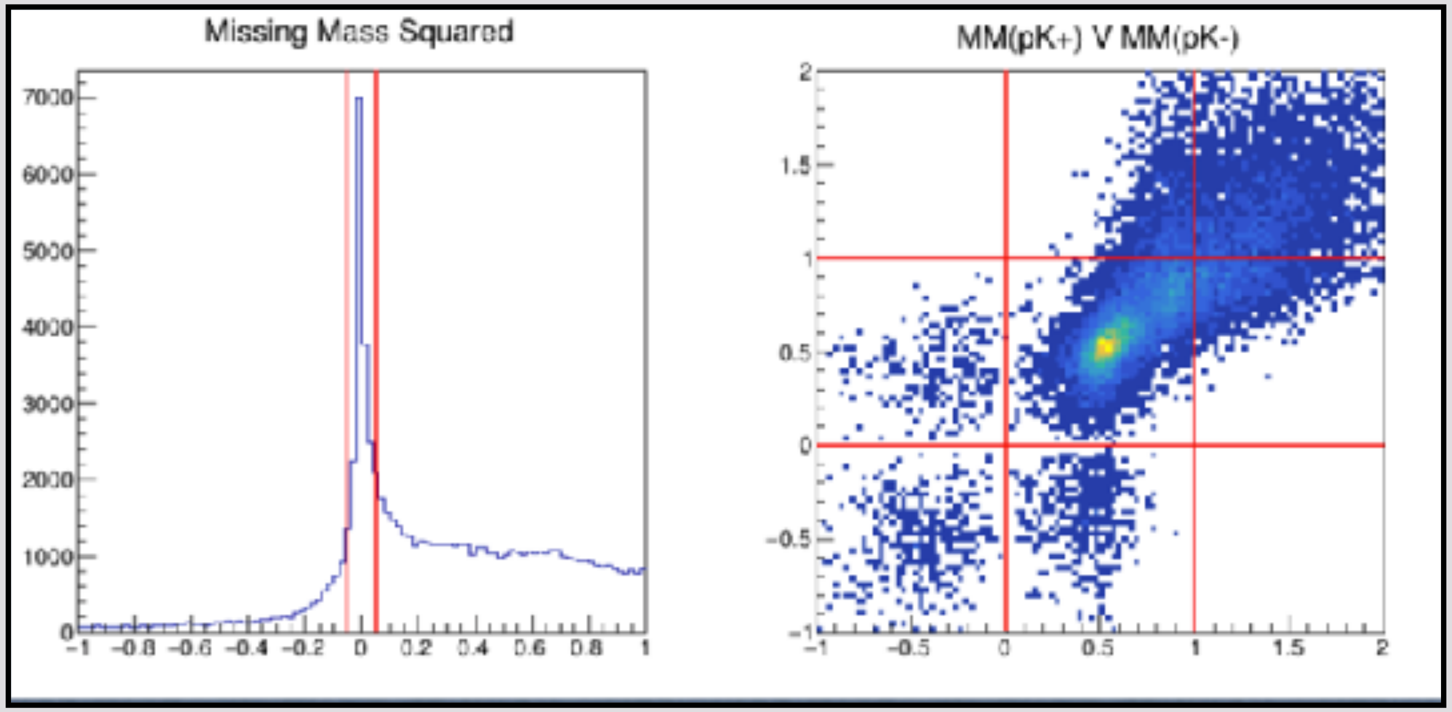
- **Goal to study Moments**
- **Contributions from Δ/N* will need to be accounted for.**

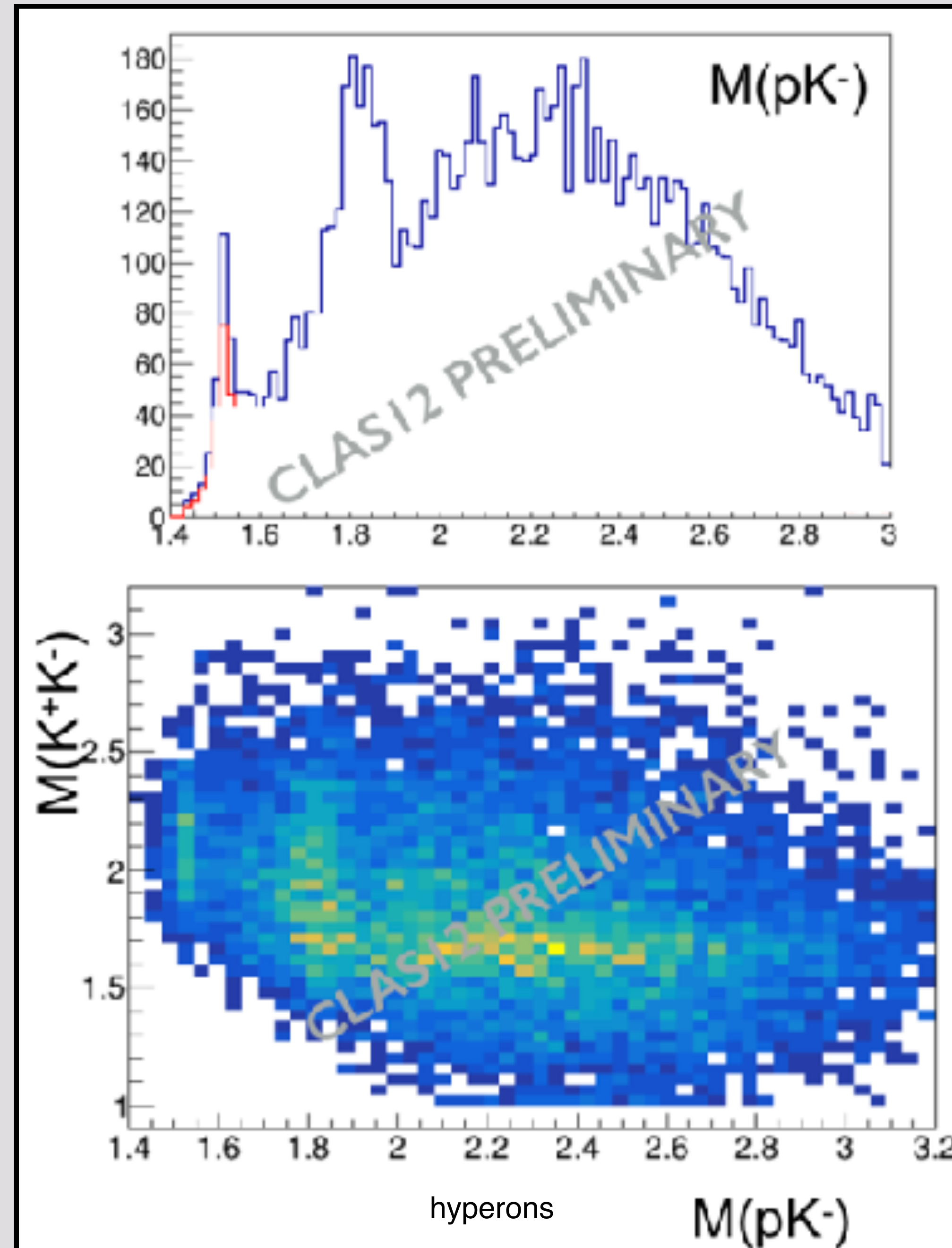




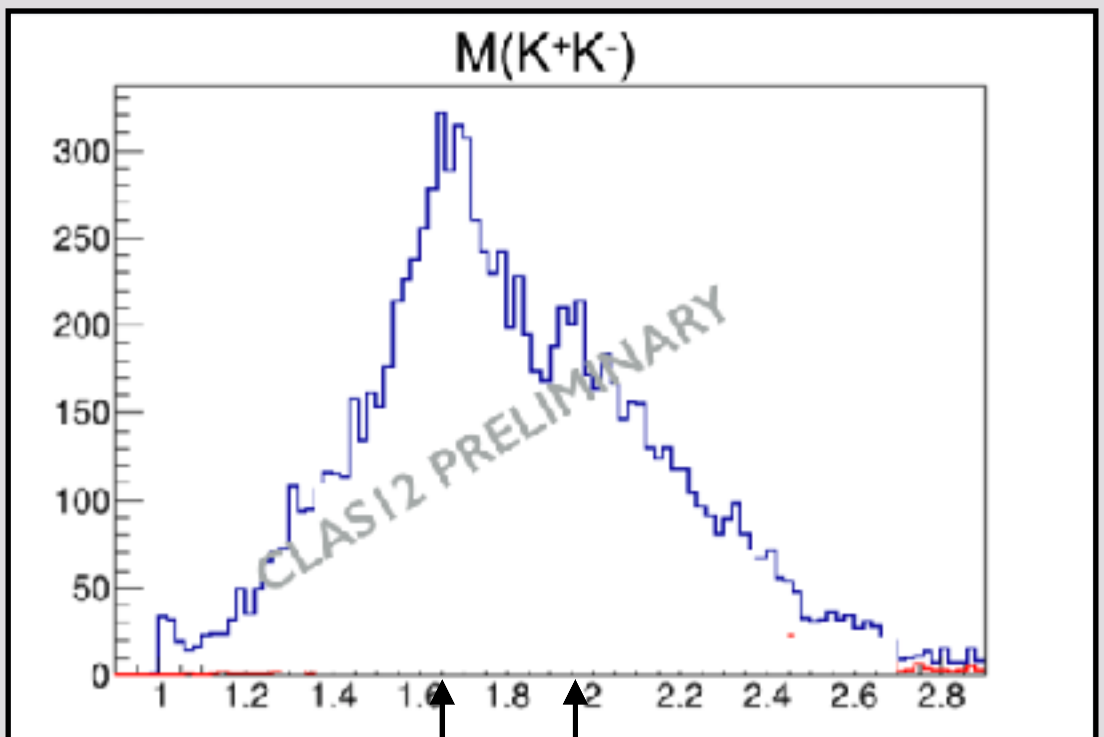
$\gamma^* p \rightarrow pK^+K^-$

ALL TRIGGERS





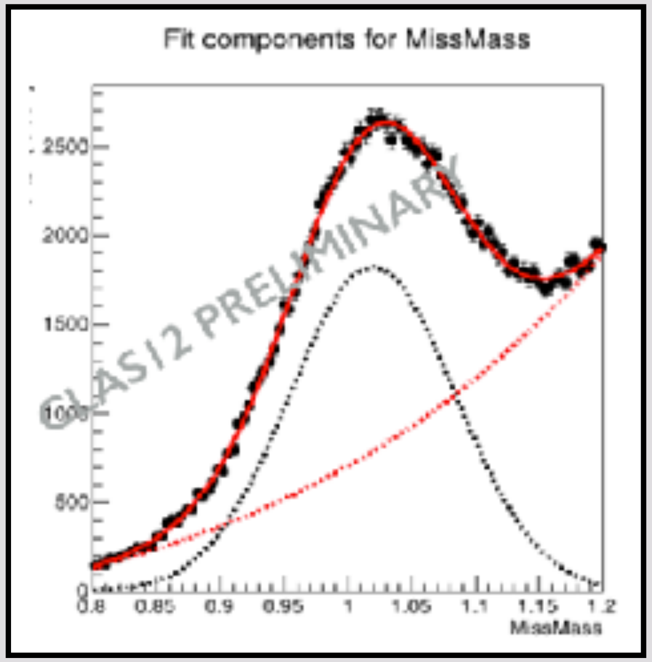
Excited Strangeonia

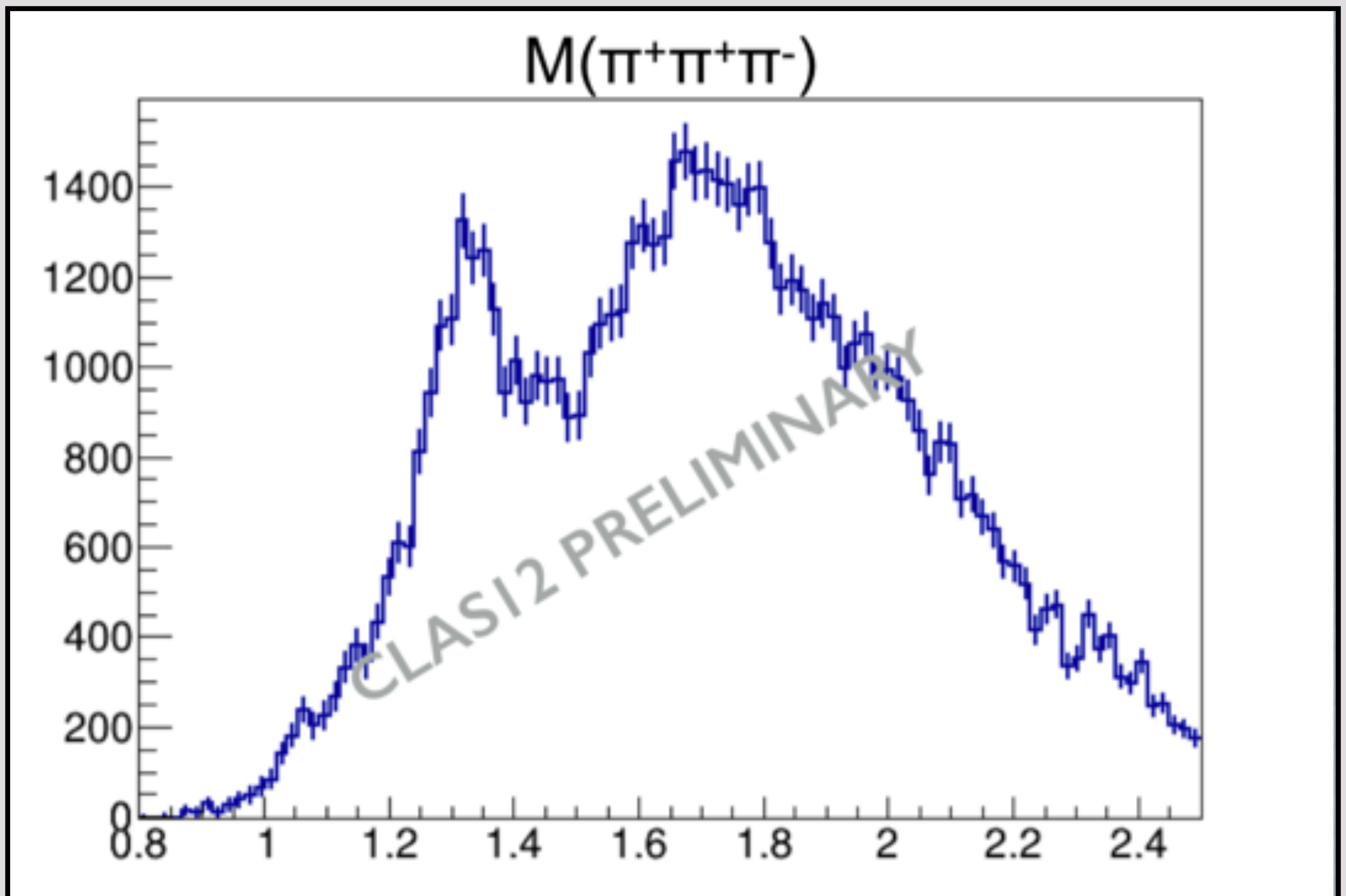


φ(1680)?? φ(1850)??

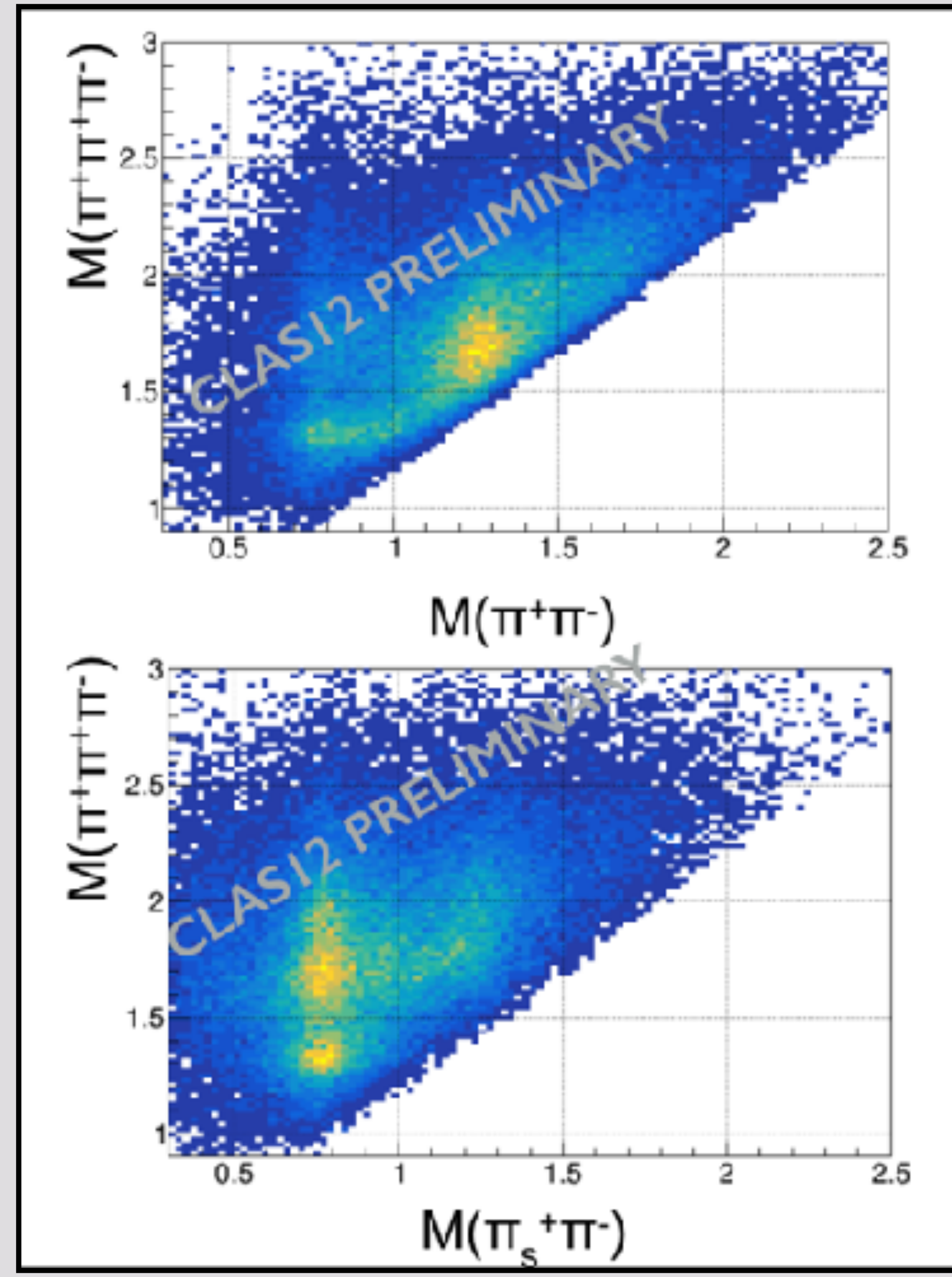
ALL TRIGGERS

$\gamma^{*}p \rightarrow (n)\pi^{+}\pi^{+}\pi^{-}$





a_2 **(1320)** $\pi_2(1670)$



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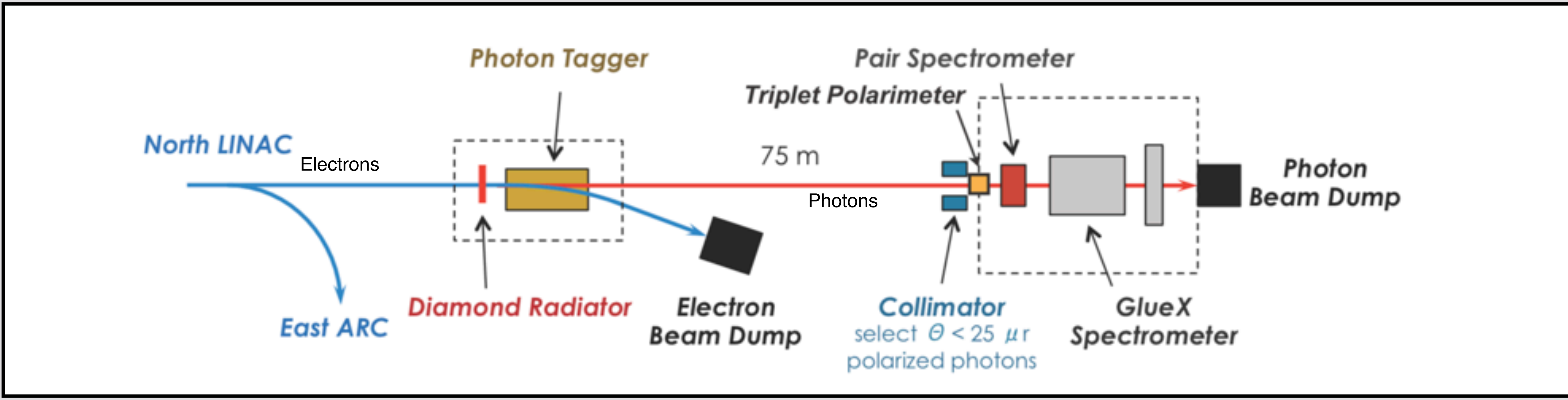
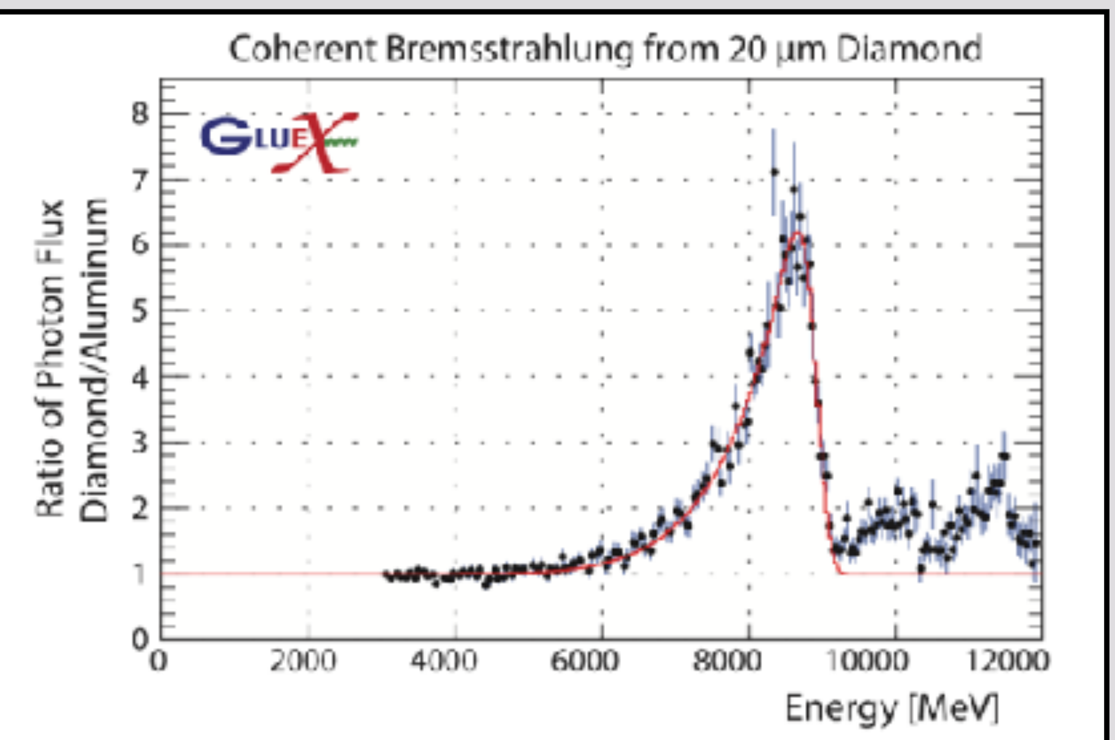
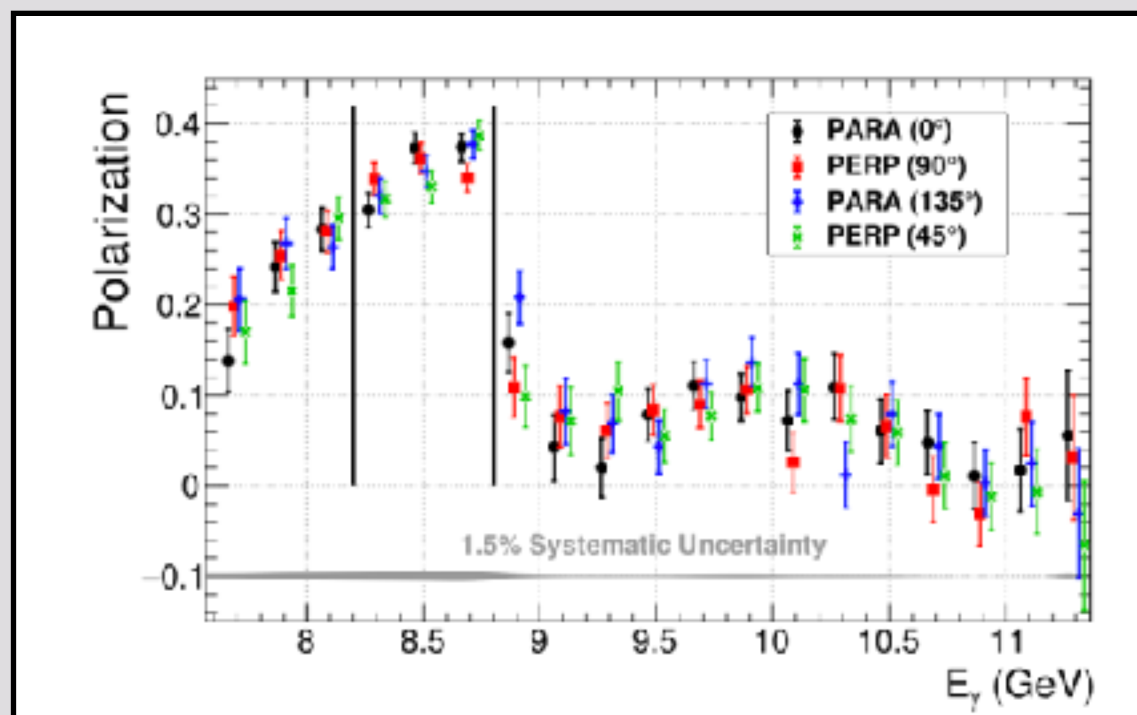
Hall D: Tagger Spectrometer

GlueX Beam Line - Polarized Photons from Coherent Bremsstrahlung





Linear Pol.$_{peak}$ ~ 40%

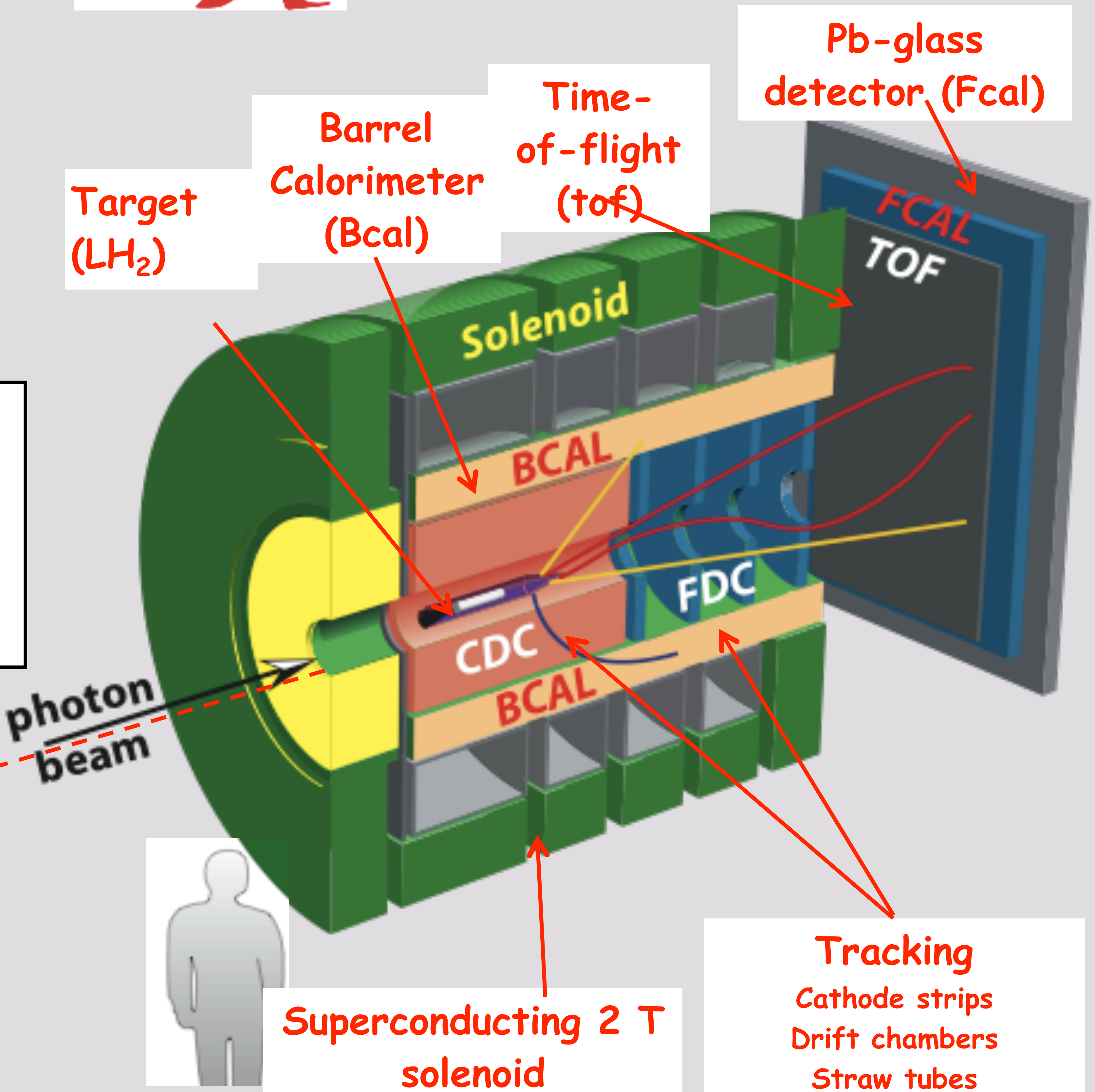


Hermetic detection of charged and neutral particles in a solenoid magnet

Coverage: $1^\circ < \theta < 120^\circ$, all ϕ
Tracking: $\sigma_p/p \approx 1\% - 5\%$
Calorimetry: $\sigma_E/E \approx 6\%/\sqrt{E} + 2\%$
Liquid Hydrogen Target

Tagger Spectrometer (Upstream)

All data reconstructed, completes GlueX - Phase I



GlueX Results

Meson Spectroscopy/Studies

Already Published

- $\gamma p \to p\pi^o, p\eta$ Pseudoscalar Beam Asymmetries
- $\gamma p \to pJ/\psi, \psi \to e^+e^-$ Cross Section/Pentaquark Search

$\gamma p \to p\eta, p\eta'$ Pseudoscalar Beam Asymmetries (submitted to PRC)

GlueX Analyses on Progress

$\gamma p \to \Delta^{++}\pi^-, K^+\Sigma^o$ ……

- $\gamma p \to p\rho^o$. Spin Density Matrix Elements
- $\gamma p \to p\pi^o\eta$ ($\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^o$)
- $\gamma p \to \Delta^{++}\pi^-\eta$ ($\eta \to \gamma\gamma$)

Baryon Spectroscopy

$\gamma p \to pK^+K^-$ Λ photoproduction

- $\gamma p \to K^+Y$ Excited Ξ states

GlueX data

- Spring 2016 - 2 pb^{-1}
- Spring 2017 - 21.8 pb^{-1}
- Spring 2018 - 58.4 pb^{-1}
- Fall 2018 - 39.2 pb^{-1}

Total to date: ~ 121 pb^{-1}

(coherent peak)

Over 250 billon events in more than 5 PB of data

$\gamma p \to p\pi^o, p\eta$ Pseudo-scalar Beam Asymmetry

Published: PRC 95, 042201 (2017)

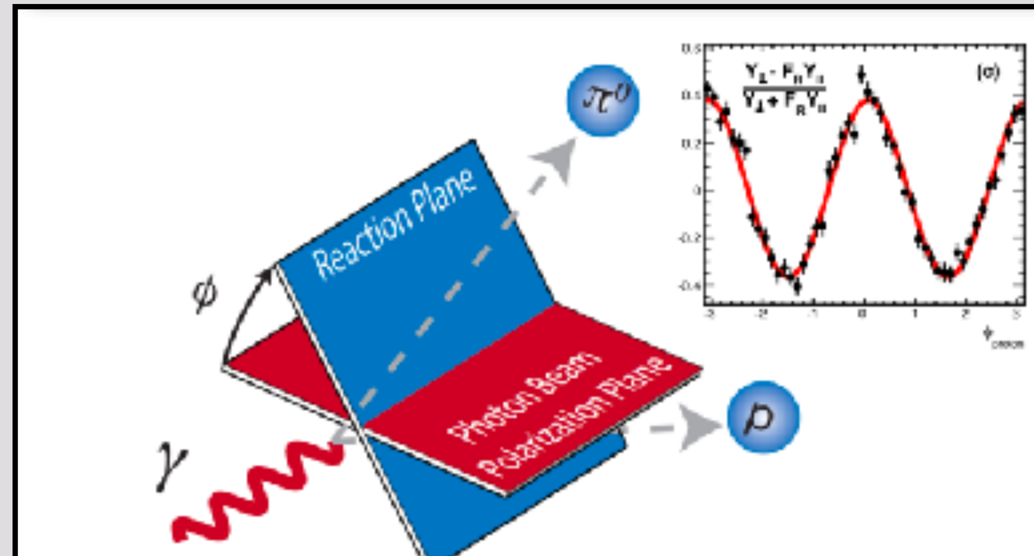
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = \frac{(P_\perp + P_\parallel)\Sigma\cos 2\phi_p}{2 + (P_\perp - P_\parallel)\Sigma\cos 2\phi_p},$$

Σ sensitive to exchanged *J^PC of exchange*

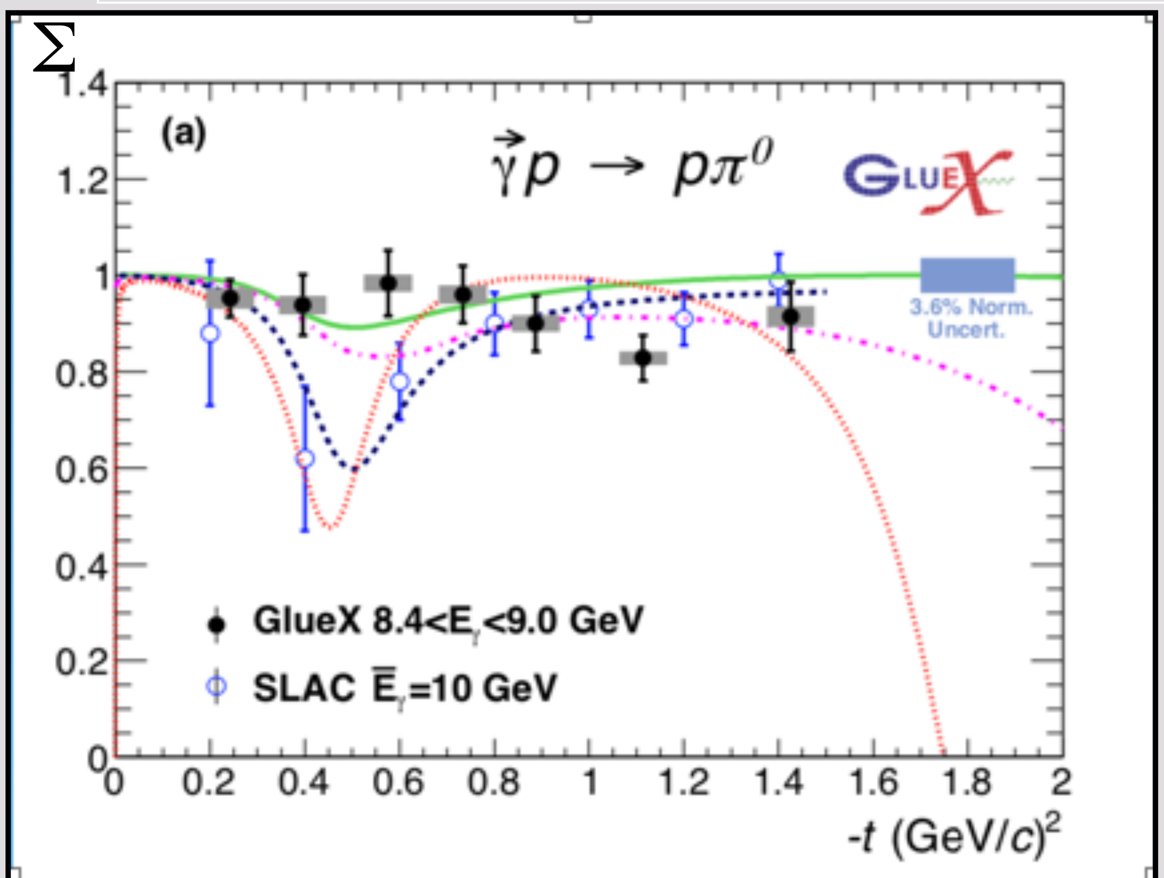
First measurement for η in this energy

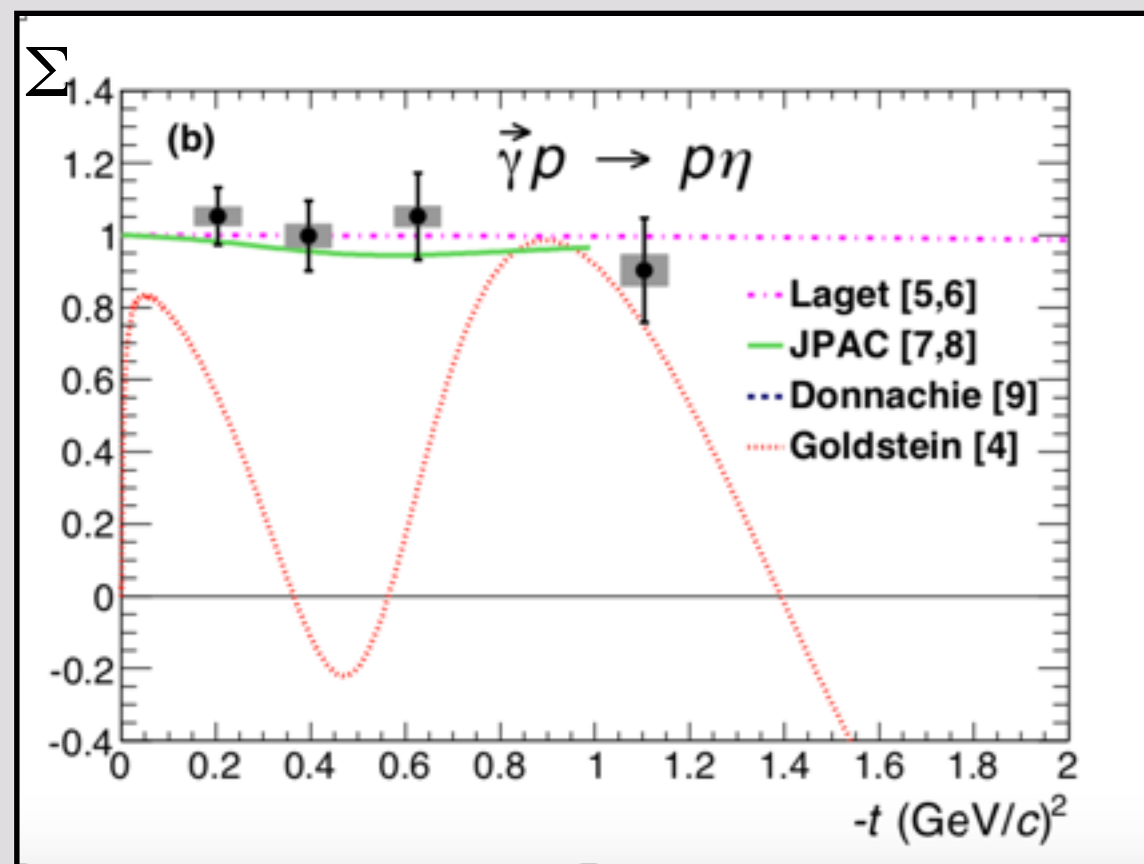
Weak dependance on t

Natural Parity exchange [P(-1)^J=+, J^P= 0^+,1^-,2^+,…] dominates at $\Sigma \sim 1$



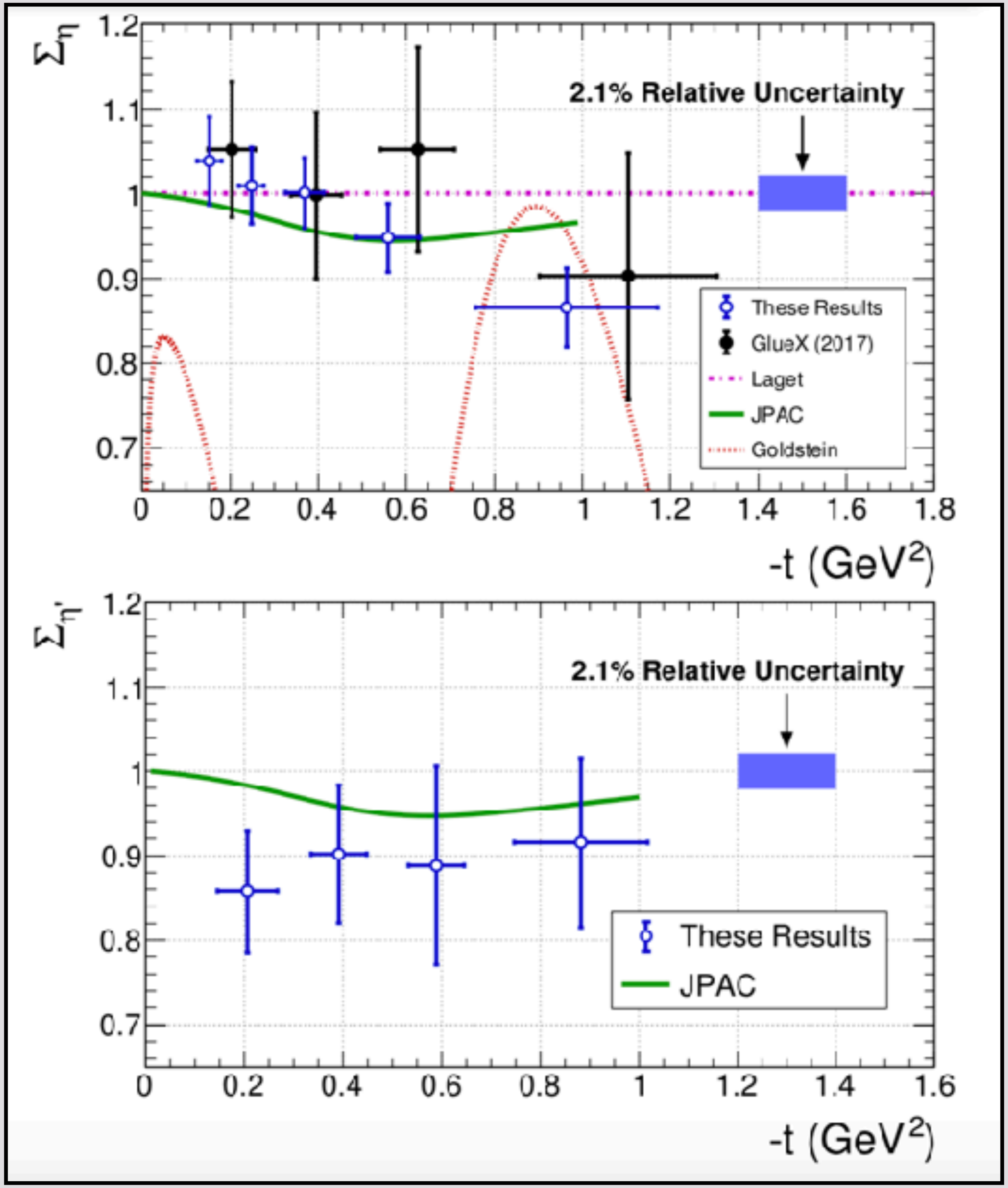
$$\sigma_{\text{pol}}(\phi) = \sigma_{\text{unpol}}\left[1 - P_\gamma \boldsymbol{\Sigma}\cos 2\phi\right]$$





$\gamma p \rightarrow p\eta, p\eta'$ Beam Asymmetry

Submitted PRC (arXiv:1908.05563

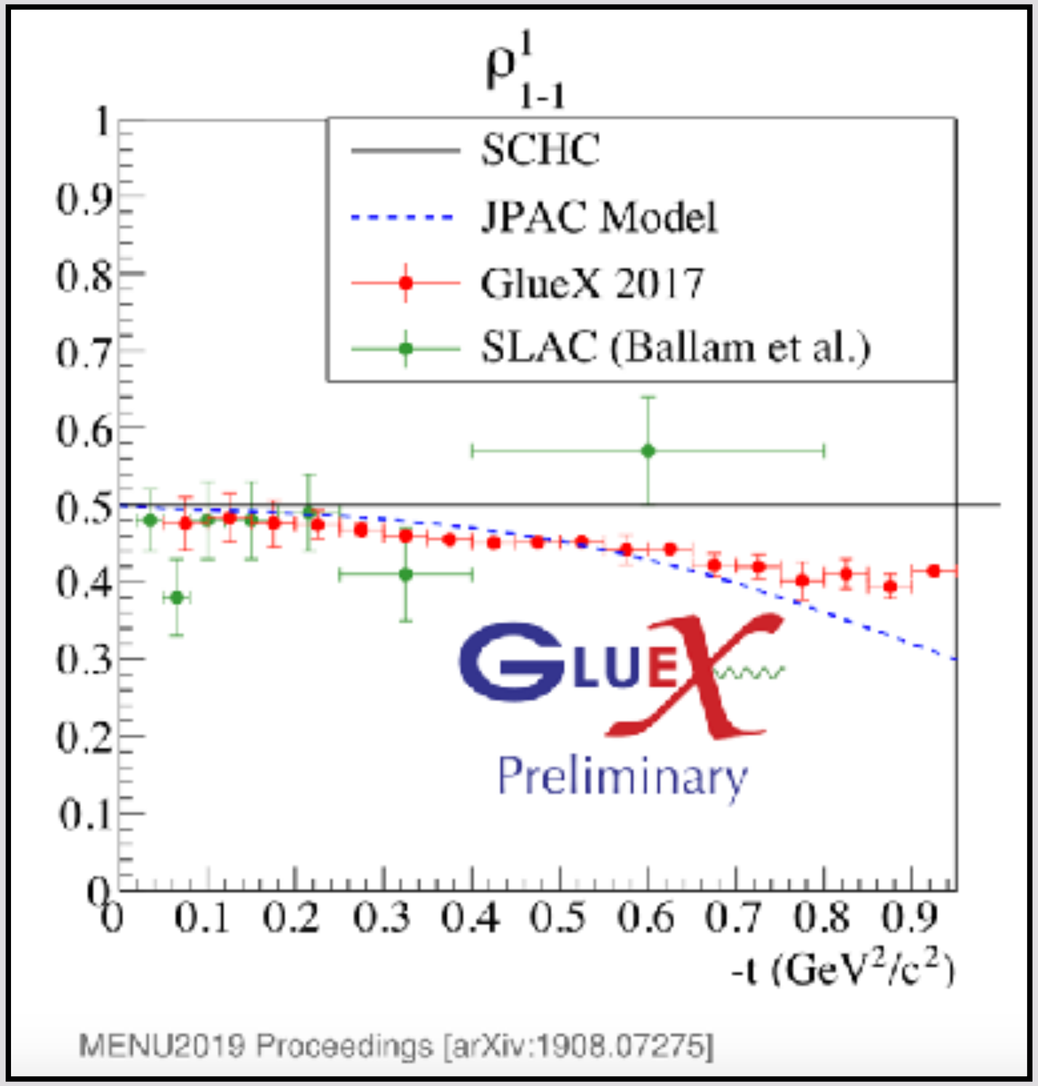


Production of η' is dominated by natural parity exchanges but there must be some unnatural parity exchange contributions as well.

Distribution suggests that ssbar exchanges (ϕ and h'$_1$) take part in the production. However, our data are not yet sensitive enough to draw a definitive conclusion.

$\gamma p \to p\rho^o(770)$ Spin Density Matrix Elements

- Nine linearly independent SDMEs
- Intensity W fit to angular dependence (reminiscent of a PWA)



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

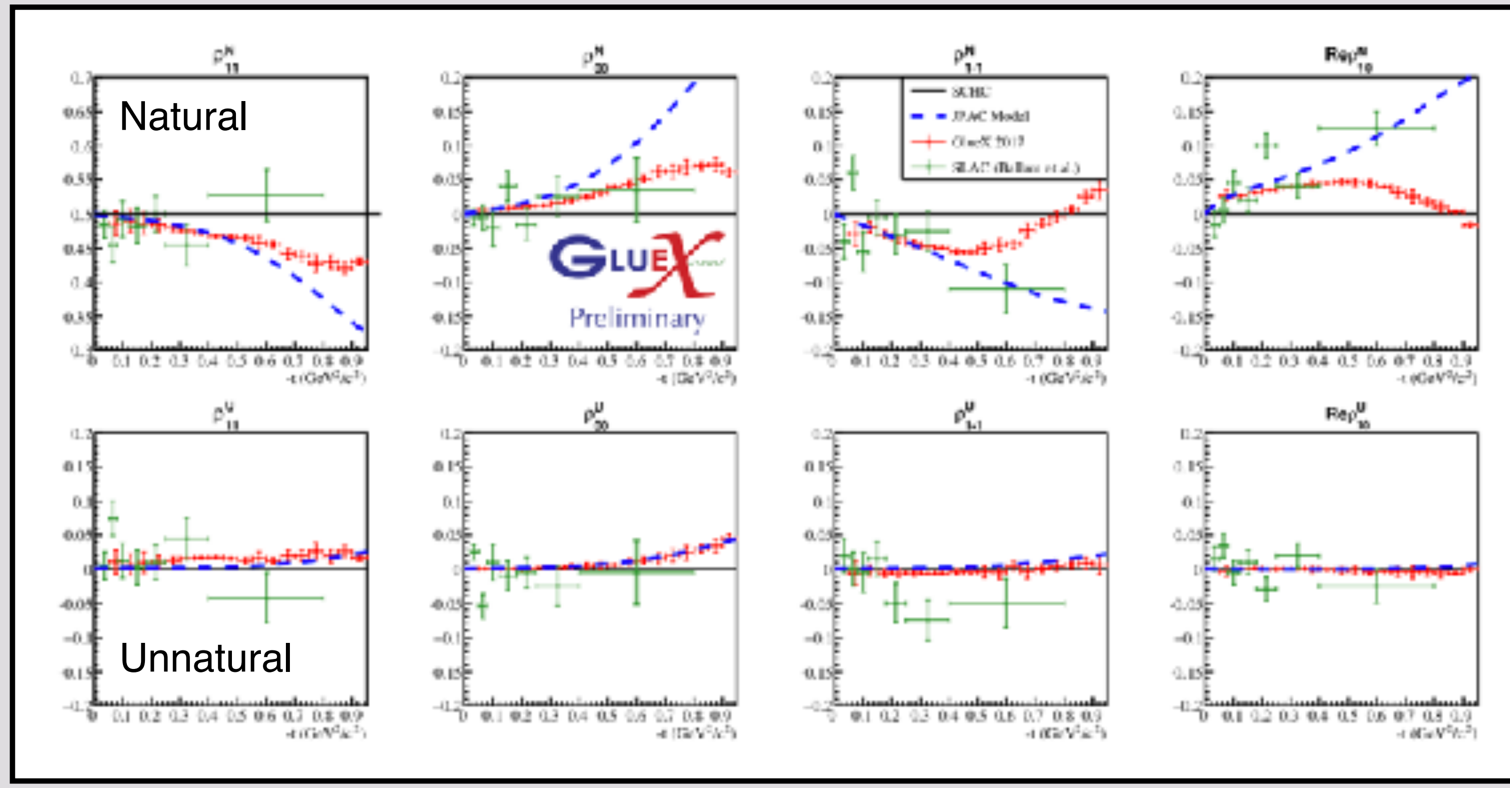
$$W^0(\cos\vartheta,\varphi) = \frac{3}{4\pi}\left(\frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\vartheta - \sqrt{2}\mathrm{Re}\rho^0_{10}\sin 2\vartheta\cos\varphi - \rho^0_{1-1}\sin^2\vartheta\cos 2\varphi\right)$$

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

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

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

use an extended-maximum likelihood fit to extract the SDMEs



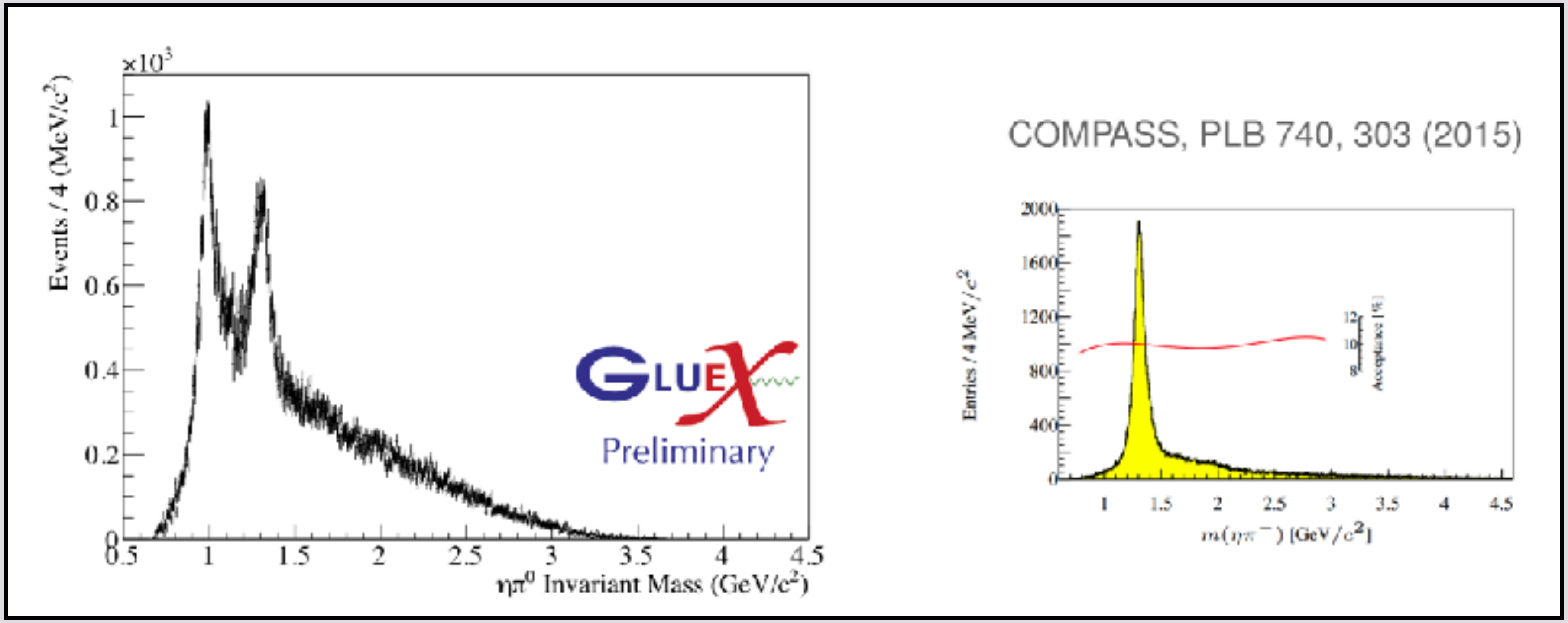
Production is consistent with *s*-channel helicity conservation only in the limit of –*t* → 0.

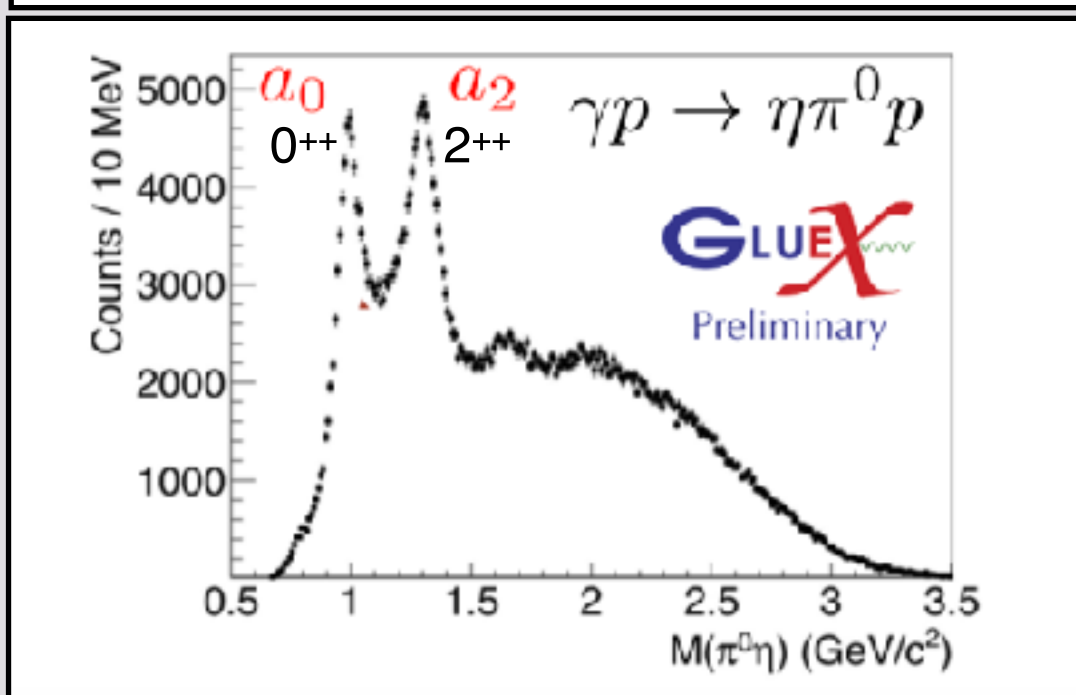
The decomposition of the spin-density matrix elements shows that natural parity exchanges dominate and the contribution from unnatural parity exchanges is small for the entire range in –*t*. This observation is consistent with predictions from Regge theory.

Search for Exotics in the $\pi\eta$ and $\pi\eta'$ systems

$\gamma p \rightarrow p\pi^o\eta\ (\eta \rightarrow \pi^+\pi^-\pi^o)$

Previously: Two 1^{-+} states $\pi_1(1400)$ and $\pi_1(1600)$ were found on these channels. Recent COMPASS - JPAC Analysis (next speaker)

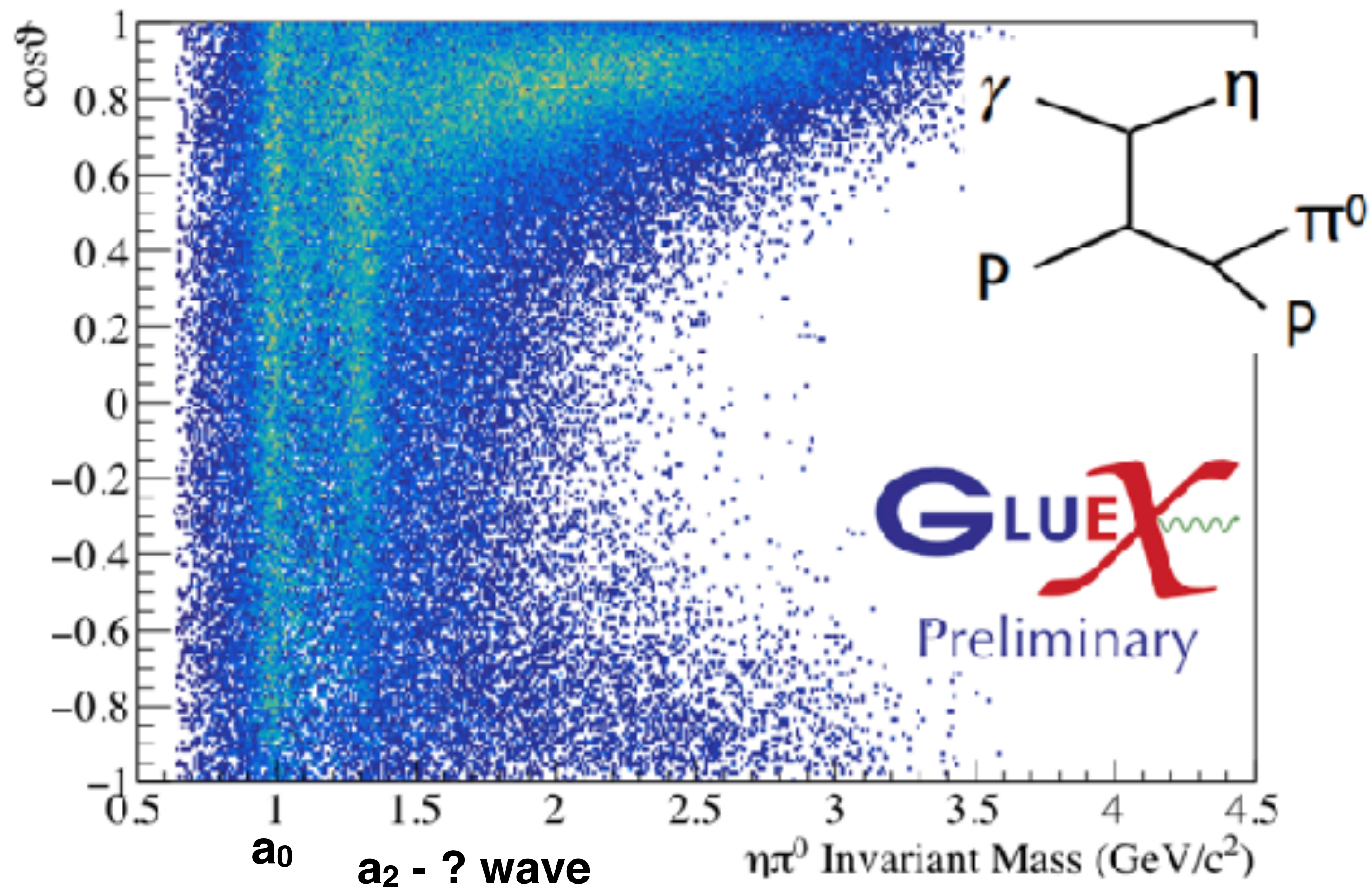


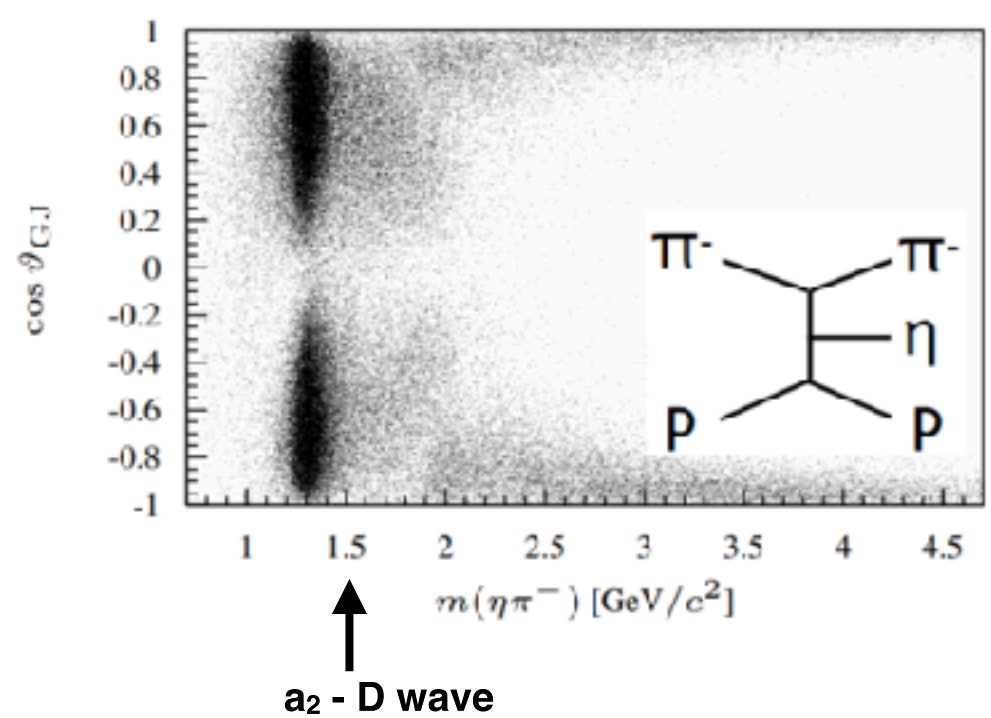


Currently: Studying backgrounds and effects on Angular distributions (P wave will be exotic)

$\gamma p \rightarrow p\pi^o\eta\ (\eta \rightarrow \gamma\gamma)$

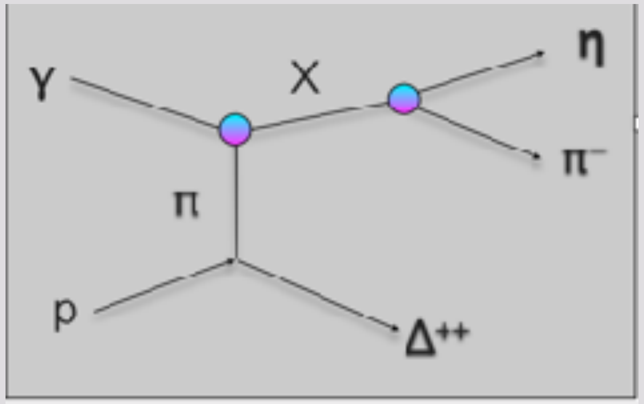
$\gamma p \to p\pi^o\eta$ ($\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^o$)



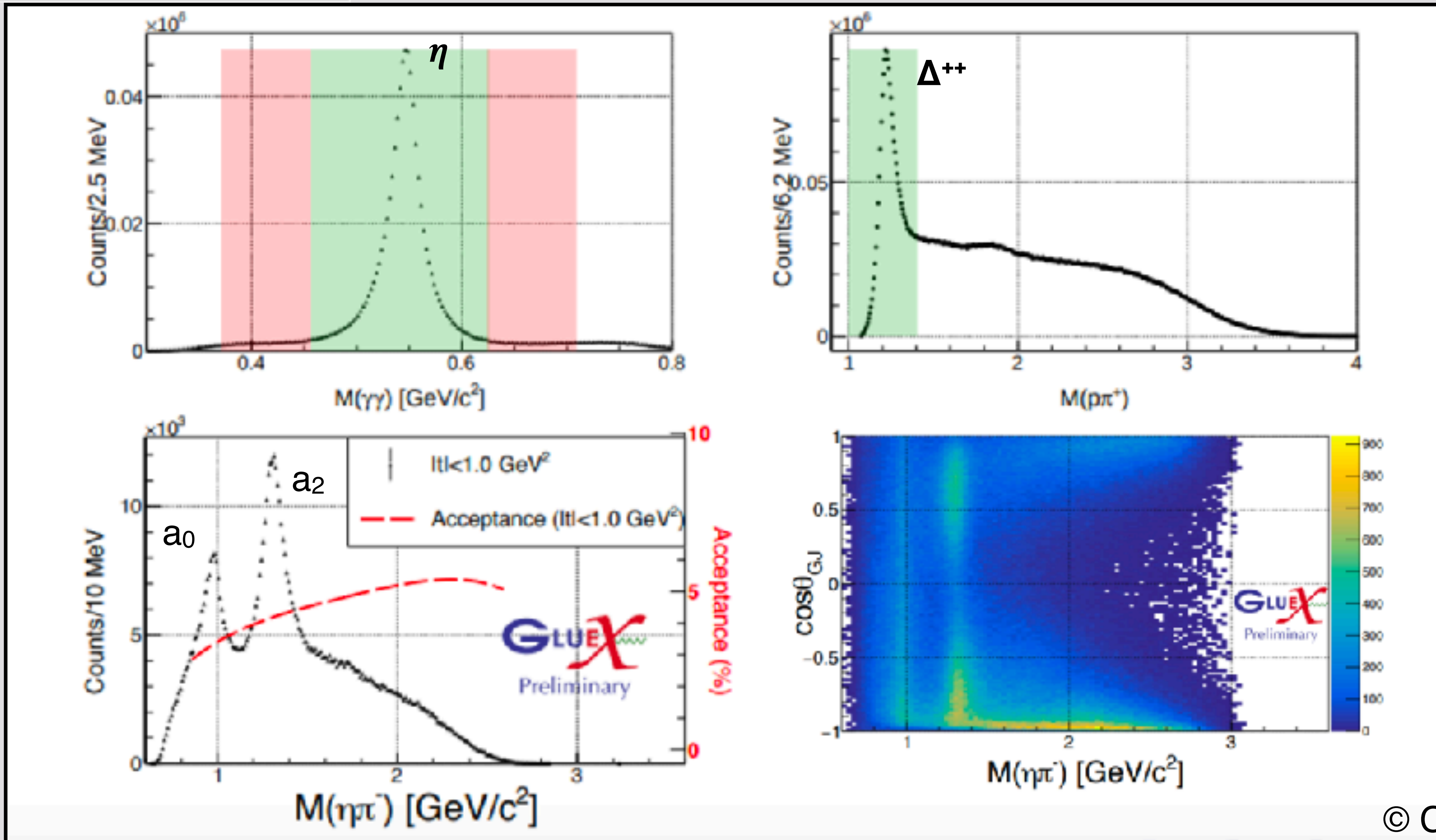


Angular distributions. **Cos(θ_{GJ}) vs Mass**

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



- The analysis goal is to select $\Delta^{++}\pi^{-}\eta$ events for PWA of the $\pi^{-}\eta$ system.
- The exchanged particle is constraint to $I^{G}=1^{-}$



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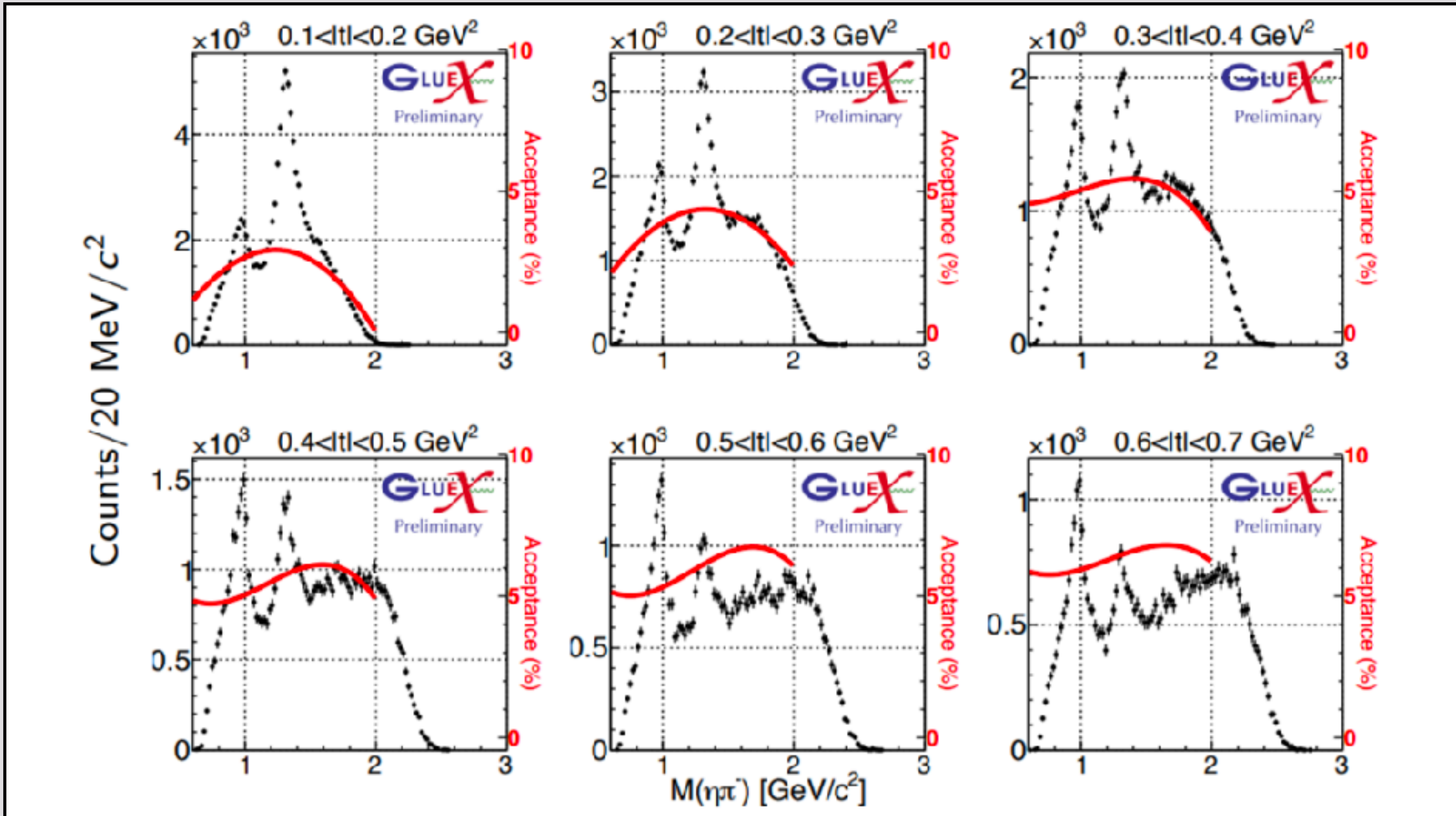
$\gamma p \rightarrow \Delta^{++}\pi^{-}\eta\ (\eta \rightarrow \gamma\gamma)$

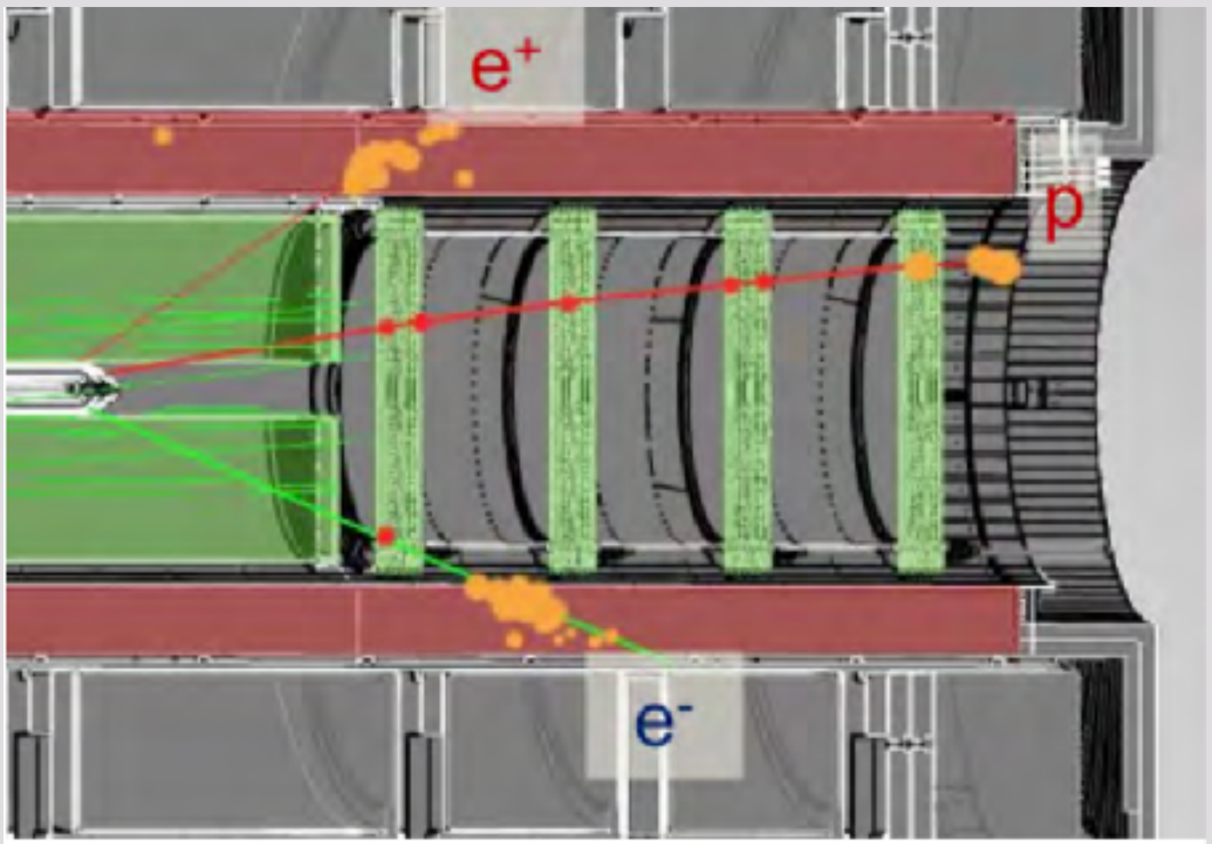


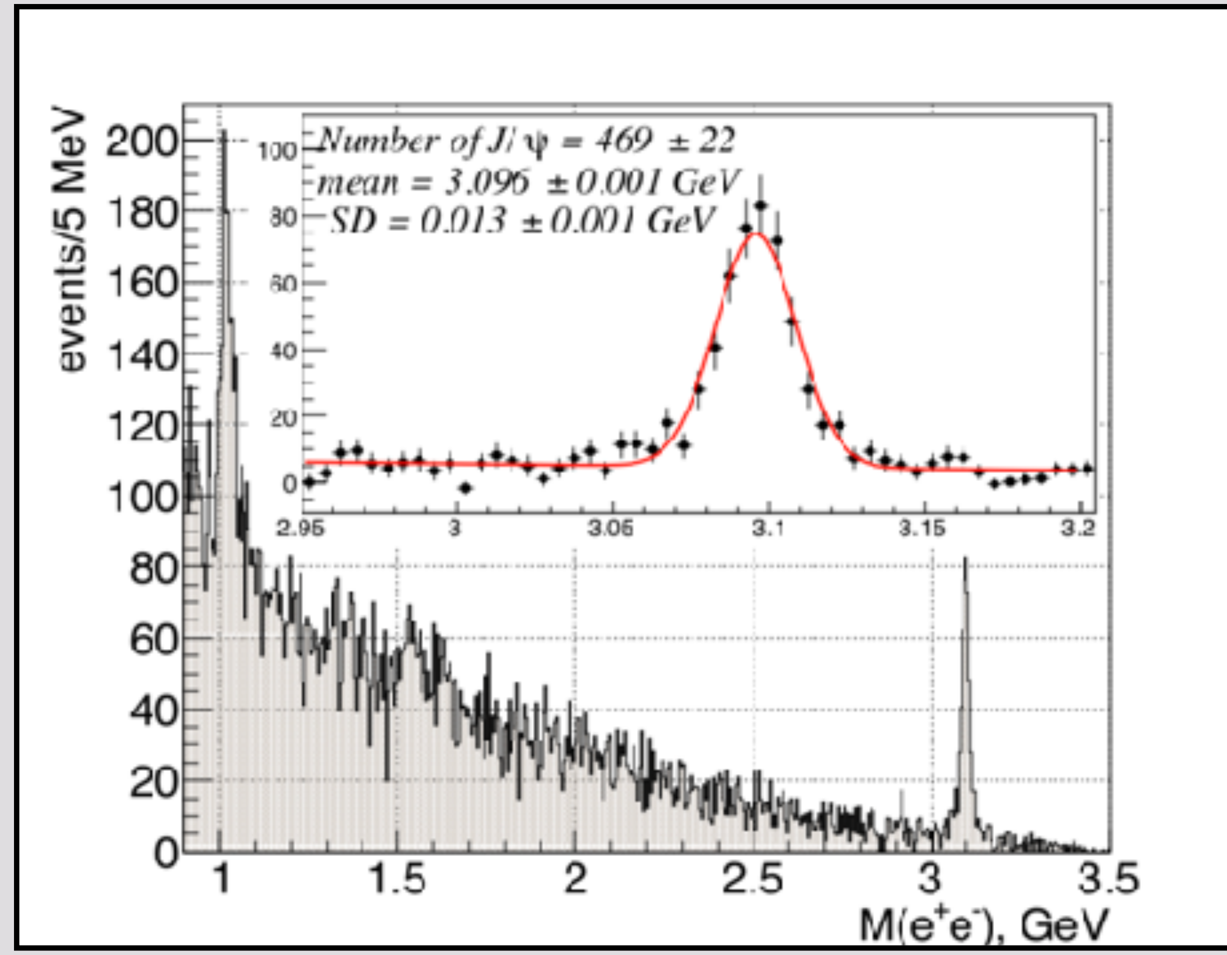
- Clear t dependence of $a_{0,2}$ production
- Extracting Moments will be a target for early physics

First measurement of near-threshold J/ψ exclusive photoproduction off the proton

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

Published: PRL 123, 072001 (2019)



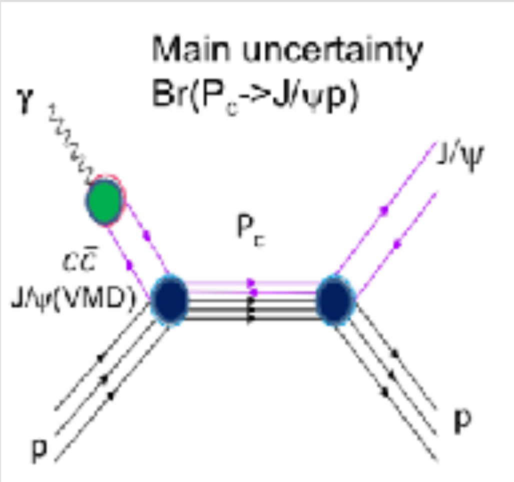


Electron identification: *E*/*p* in calorimeters, pion background suppression by 10^{-4} Kinematic

Fit with 0.1% precision on photon beam energy

Cross section normalized by non-resonant e^+e^- production (Bethe-Heitler)

The pentaquarks produced in the s-channel would appear as structures in the J/ψ photoproduction cross section as a function of energy, possibly interfering with the non-resonant continuum.

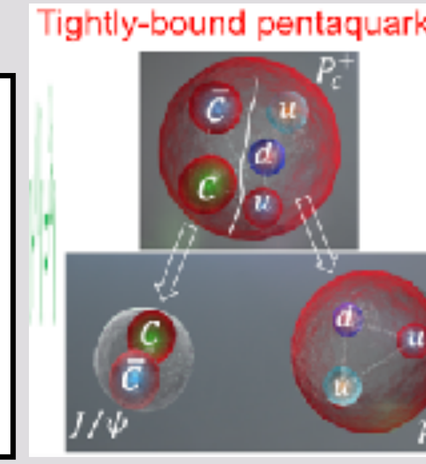


- V.Kubarovsky and M.B.Voloshin, PRD 92,031502 (2015).
- M.Karliner and J.Rosner, arXiv: PLB 752, 329 (2016).
- A.Blin, C.Fernandez-Ramirez, A.Jackura, V.Mathieu, V.Mokeev, A.Pilloni, and A.Szczepaniak, PRD 94,034002 (2016).

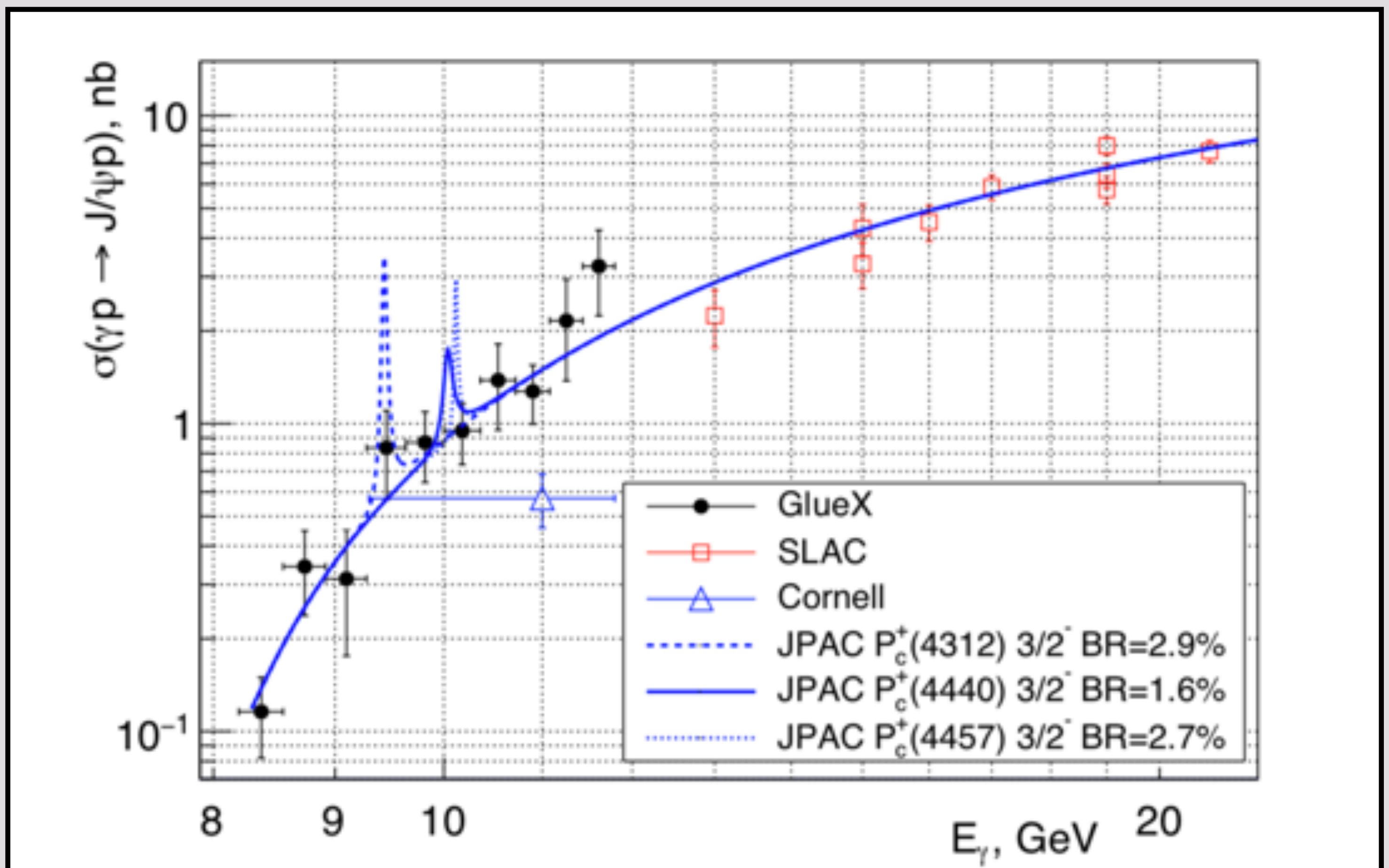
	$\mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, %		$\sigma_{\max} \times \mathcal{B}(P_c^+ \to J/\psi p)$ Upper Limits, nb	
	p.t.p. only	total	p.t.p only	total
$P_c^+(4312)$	2.9	4.6	3.7	4.6
$P_c^+(4440)$	1.6	2.3	1.2	1.8
$P_c^+(4457)$	2.7	3.8	2.9	3.9

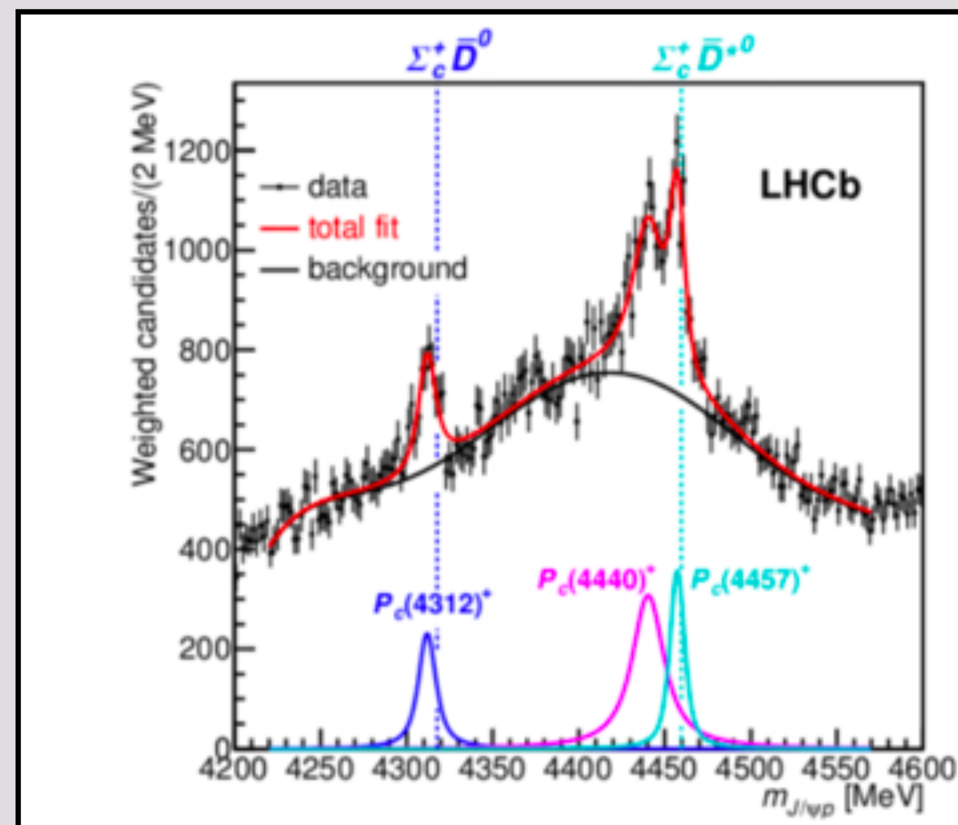
Upper limits at 90% confidence level

19



The measured cross section is used to set model-dependent upper limits on the branching fraction of the LHCb P_c^+ states, which allow to discriminate between different pentaquark models.

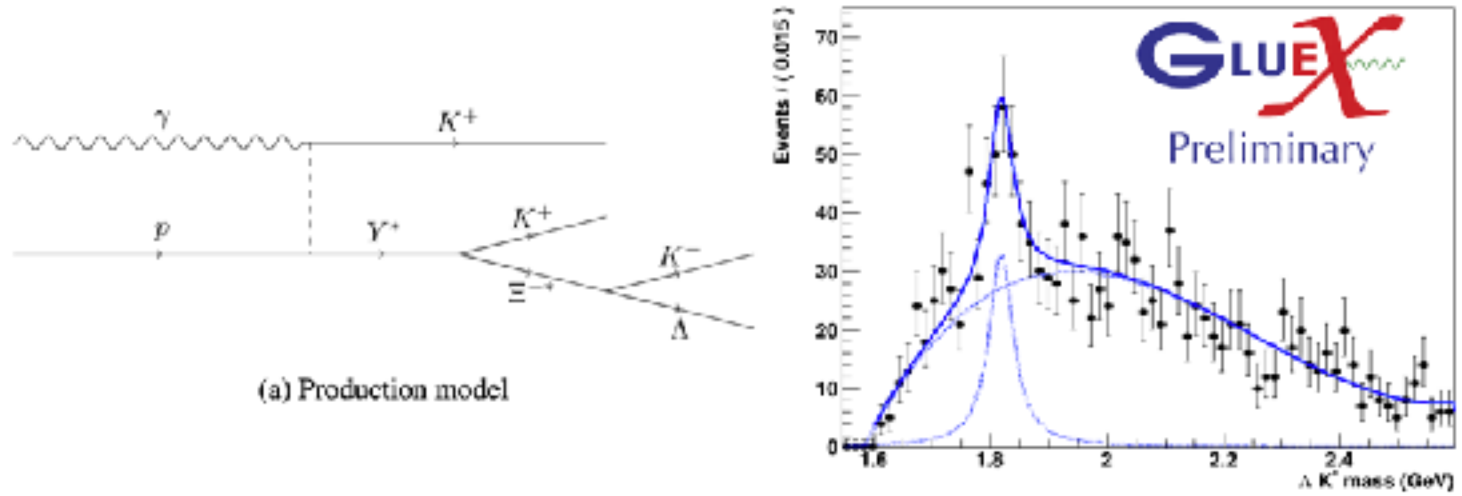




LHCb, PRL 122, 222001 (2019)

$\gamma p \to K^+ Y$

Excited Ξ states

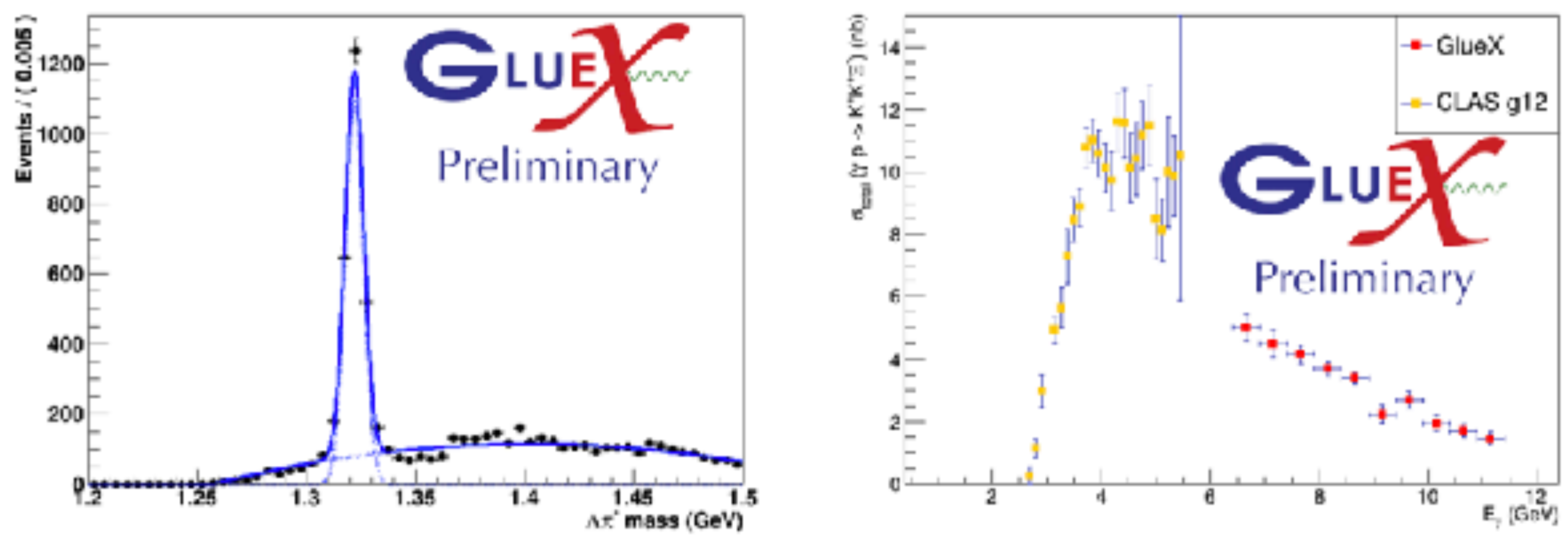


(a) Production model

(b) ΛK^- invariant mass

FIGURE 5: (a) The expected mode for the dominant decay mode of photoproduction of $\Xi^-(1820)$. (b) The invariant mass distribution of ΛK^- which shows a possible signal for $\Xi^-(1820)$. The peak has a significance of close to 5σ.

Of QM 33 excitations below 2.5 GeV only 6 states with ****
Production mechanism not well understood



(a) $\Lambda\pi^-$ invariant mass

(b) Total cross section

FIGURE 4: (a) The invariant mass distribution of $\Lambda\pi^-$ which shows a clear signal for $\Xi^-(1320)$. (b) Preliminary results for the cross section of $\Xi^-(1320)$ with statistical uncertainties only. The results are compared to data from the CLAS collaboration [6].

Ξ states spectrum not very well known

Summary and Near Future Plans

A Large Program on Hadron Spectroscopy at JLab provides high statistics data using electron, polarized real and quasi-real photon beams.

Two **JLAB High-statistics/Large Acceptance Experiments**

- CLAS12 using an electron beam (and “quasi-real” photons)
- GlueX using a linearly polarized real photon beam
- Both taking data as planned.
- **We expect the first results in hadron spectroscopy to become available in about a year and many more coming next.**

Also, we are improving Analysis Tools :

- Theory Groups at JLab: providing improved models - to include more “constraints” in PWA. LQCD “predictions”. (HadSpec and JPAC). Computing (more sophisticated PWA software).

NEAR Future

GLUEX: Upgraded PID adding DIRC detector in the forward direction. Phase-II start this Fall with emphasis in strangeonia and strange baryons.

CLAS12: After tuning alignments and calibrations, 50% of RG -A data (MesonEX and Very-Strange proposals) will be available for spectroscopy.