Experiment GlueX: Early Results and Future Plans

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JLab, for **GlueX** collaboration

Presented at

XVI International Workshop on Hadron Structure and Spectroscopy

IWHSS 19, Aveiro, Portugal, June 24-26 2019

Outline

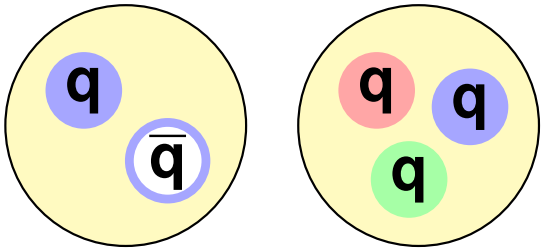
1. GlueX experiment in Hall D at Jefferson Lab
   - Main goal: spectroscopy - search for exotic hybrid mesons
   - Very large photoproduction data sample allows other studies
   - Linearly polarized photon beam and a hermetic spectrometer
   - Data taking and analysis:
     - Phase 1 (GlueX-I) data taking complete 2016-1018 (200 days) 20% of data processed and analyzed (70% processed)
     - Phase 2 (GlueX-II) with a DIRC for PID, double the beam rate scheduled to start in 2019 (400 days)
2. Early Results based on 20% of the GlueX-I sample:
   - J/ψ photoproduction close to threshold
     - Probes high-x gluons in proton
     - Search for the LHCb pentaquark
   - Polarization effects: beam-driven asymmetries for various reactions
3. Prospects: search for hybrid mesons
4. Prospects: studies of strange particles

Spectroscopy of Hadrons

- Quark Model was a big success!
  - "Constituent" quarks: flavor SU(3)
  - Postulated observables: $(q\bar{q})$ & (qqq)
- QCD: exact color SU(3) symmetry
  - Asymptotic freedom; Confinement
  - The masses are generated dynamically.

Initial ansatz

based on flavor SU(3)



color SU(3) singlets

Further Insights from Spectroscopy?

QCD does not limit the bound states to $(q\bar{q})$ & (qqq). Do others exist?

- LQCD predicts states like "hybrids"
- Probing our understanding of the mass scale and the binding energy

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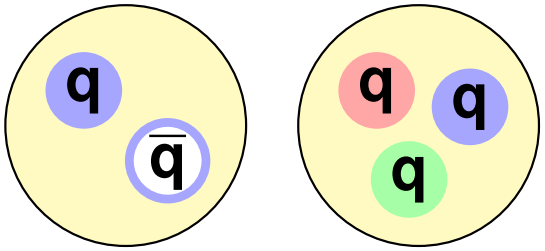

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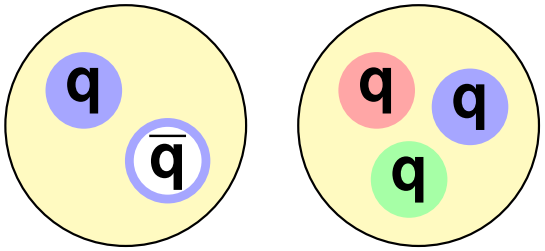

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QCD does not limit the bound states to $(q\bar{q})$ & (qqq). Do others exist?

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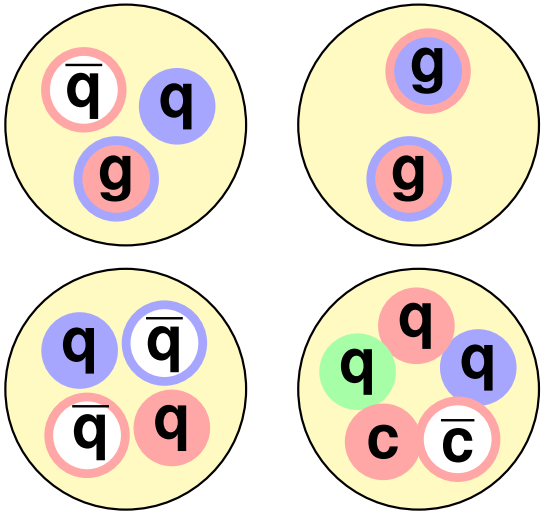
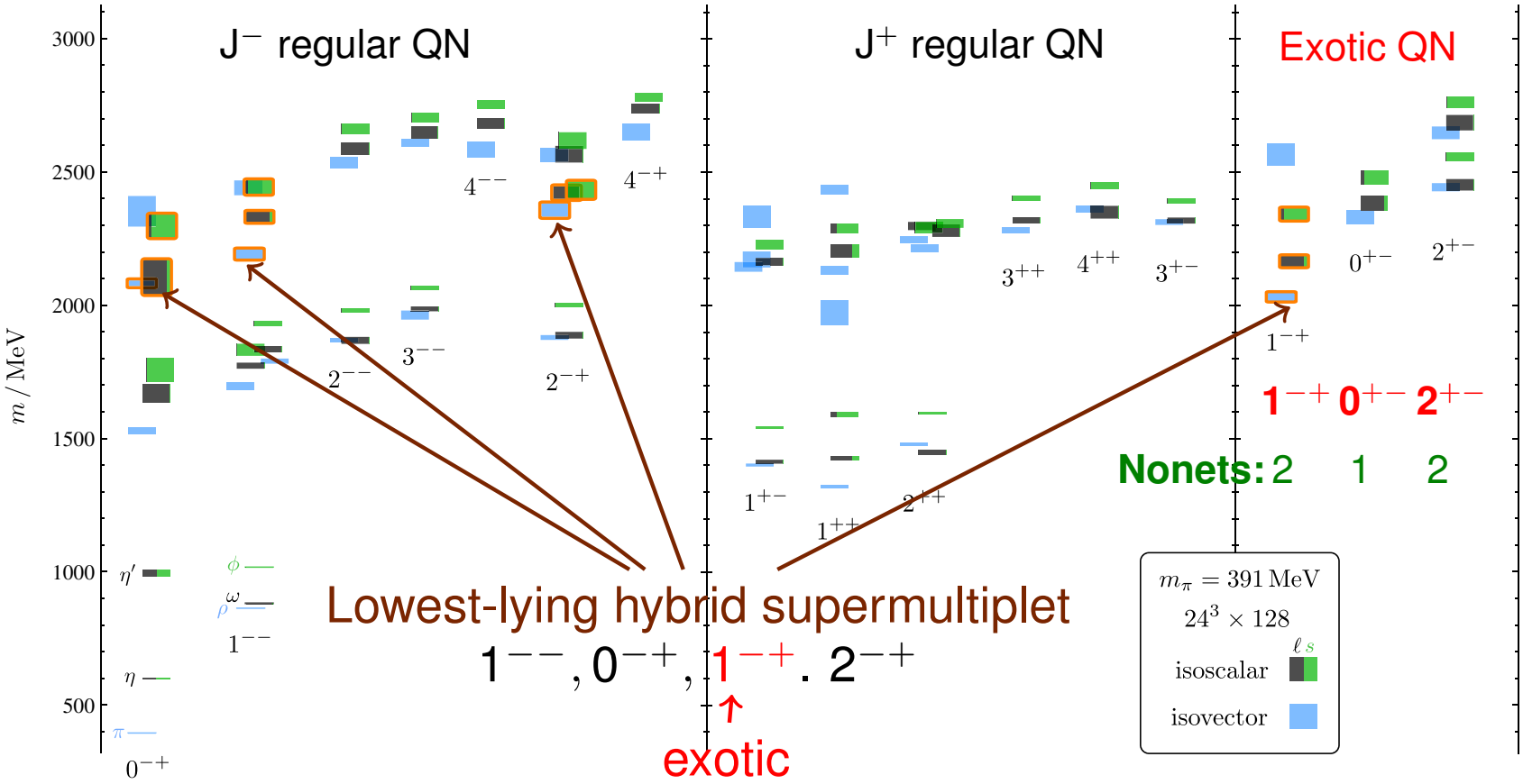
QCD-possible
but not established
"exotic" hadrons



Lattice QCD - the Meson Spectra

J.Dudek et al PRD 83 (2011); PRD 84 (2011), PRD 88 (2013)

Hybrids identified: States with non-trivial gluonic fields



Calculations for $m_\pi \sim 400 MeV$

Orange frames - lightest hybrids

Lower-lying exotic hybrids: masses, widths, decays

LQCD: masses

1^{-+} $\sim$2.0 – 2.4 GeV/c^2
0^{+-} $\sim$2.3 – 2.5 GeV/c^2
2^{+-} $\sim$2.4 – 2.6 GeV/c^2

Models: widths and decays

$\Gamma \sim$0.1-0.5 GeV/c^2,
$\Gamma(1^{-+}) \sim \Gamma(2^{+-}) < \Gamma(0^{+-})$

easy $\Rightarrow$ *statistics* $\Rightarrow$ *hard*
reach *needed*

1^{-+}
$\pi_1 \to \rho\pi$, $b_1\pi$, $f_1\pi$, $\eta\pi$, $\eta'\pi$, $a_1\eta$
$\eta_1 \to f_2\eta$, $a_2\pi$, $f_1\eta$, $\eta'\eta$, $\pi(1300)\pi$, $a_1\pi$
$\eta'_1 \to K^*\overline{K}$, $K(1270)\overline{K}$, $K(1410)\overline{K}$, $\eta'\eta$,

2^{+-}
$b_2 \to \omega\pi$, $a_2\pi$, $\rho\eta$, $f_1\rho$, $a_1\pi$, $h_1\pi$, $b_1\eta$
$h_2 \to \rho\pi$, $b_1\pi$, $\omega\eta$, $f_1\omega$
$h'_2 \to K_1(1270)\overline{K}$, $K(1410)\overline{K}$, $K_2\overline{K}$, $\phi\eta$, $f_1\phi$

0^{+-}
$b_\circ \to \pi(1300)\pi$, $h_1\pi$, $f_1\rho$, $b_1\eta$
$h_\circ \to b_1\pi$, $h_1\eta$
$h'_\circ \to K_1(1270)\overline{K}$, $K(1410)\overline{K}$, $h_1\eta$

Final states:
$(p,n)+3\pi$, 4π, $3\pi\eta$, $4\pi\eta$...
70% $\geq 1\pi^\circ$
50% $\geq 2\pi^\circ$

Lower-lying exotic hybrids: masses, widths, decays

		easy ⇒ statistics ⇒ hard reach needed
	$\pi_1 \to$	$\rho\pi$, $b_1\pi$, $f_1\pi$, $\eta\pi$, $\eta'\pi$, $a_1\eta$
1^{-+}	$\eta_1 \to$	$f_2\eta$, $a_2\pi$, $f_1\eta$, $\eta'\eta$, $\pi(1300)\pi$, $a_1\pi$
	$\eta'_1 \to$	$K^*\overline{K}$, $K(1270)\overline{K}$, $K(1410)\overline{K}$, $\eta'\eta$,

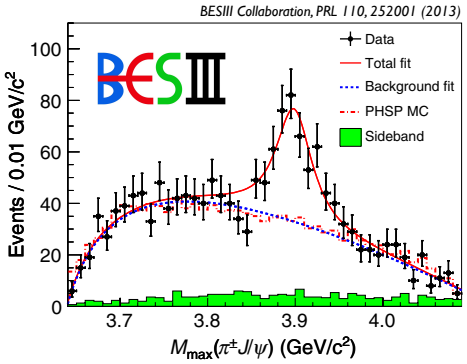
Experimental evidence for “Exotic” hadrons

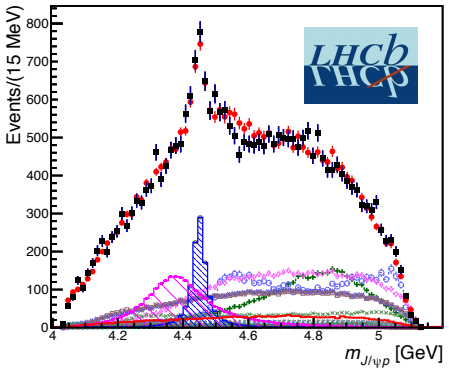
Multi-quark candidates

- Numerous narrow signals $X, Y, Z \to J/\psi$ or Υ
- Experimentally well established: Belle, BaBar, CDF, BES, LHCb etc
- Typically close to thresholds $M_c\overline{M_c}$
- Interpretation?
  - Threshold cusps, triangular diagrams
  - “Molecules” of color singlets
  - Color multiplets $P \to pJ/\psi$

$Z_c^{\pm} \to \pi^{\pm} J/\psi$

BESIII Collaboration, PRL 110, 252001 (2013)

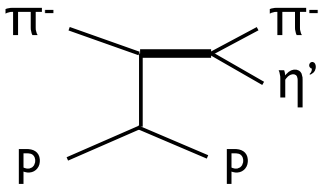


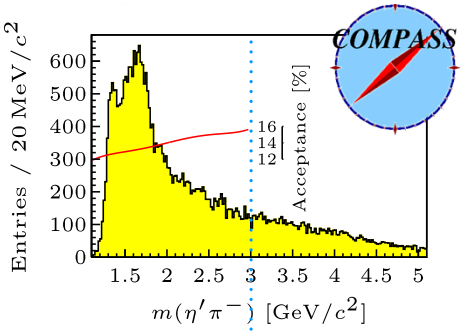


Hybrid candidates

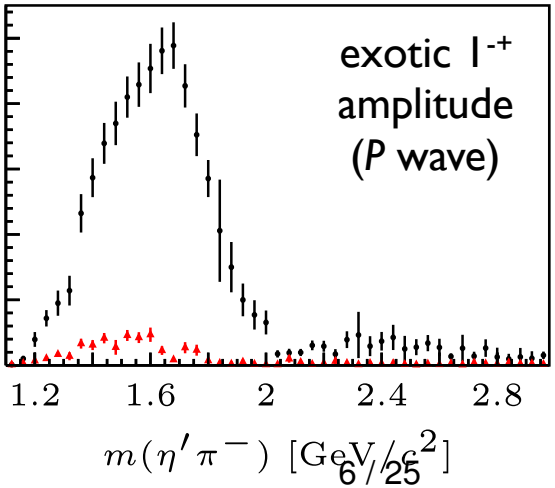
- Identifiable by exotic J^{PC}
- Relatively weak evidence
- Experiments: LEAR, E852, VES, COMPASS etc $p\overline{p}, \pi^- p$

COMPASS





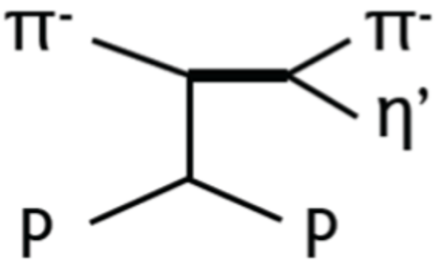
COMPASS Collab., PLB 740, 303 (2015)



COMPASS: Evidence for Exotic Hybrid Mesons

Many studies, strongest evidence for 1^{-+} π_1 in $\eta\pi$ and $\eta'\pi$ P-waves:

- COMPASS *PLB 740, 303 (2015)*
- JPAC *PRL 122, 042002 (2019)* COMPASS data are described by a model with a 1^- pole at $M = 1590 \pm 100$ MeV, $\Gamma = 500 \pm 100$ MeV



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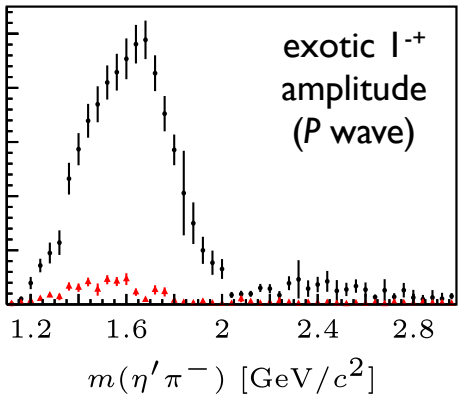
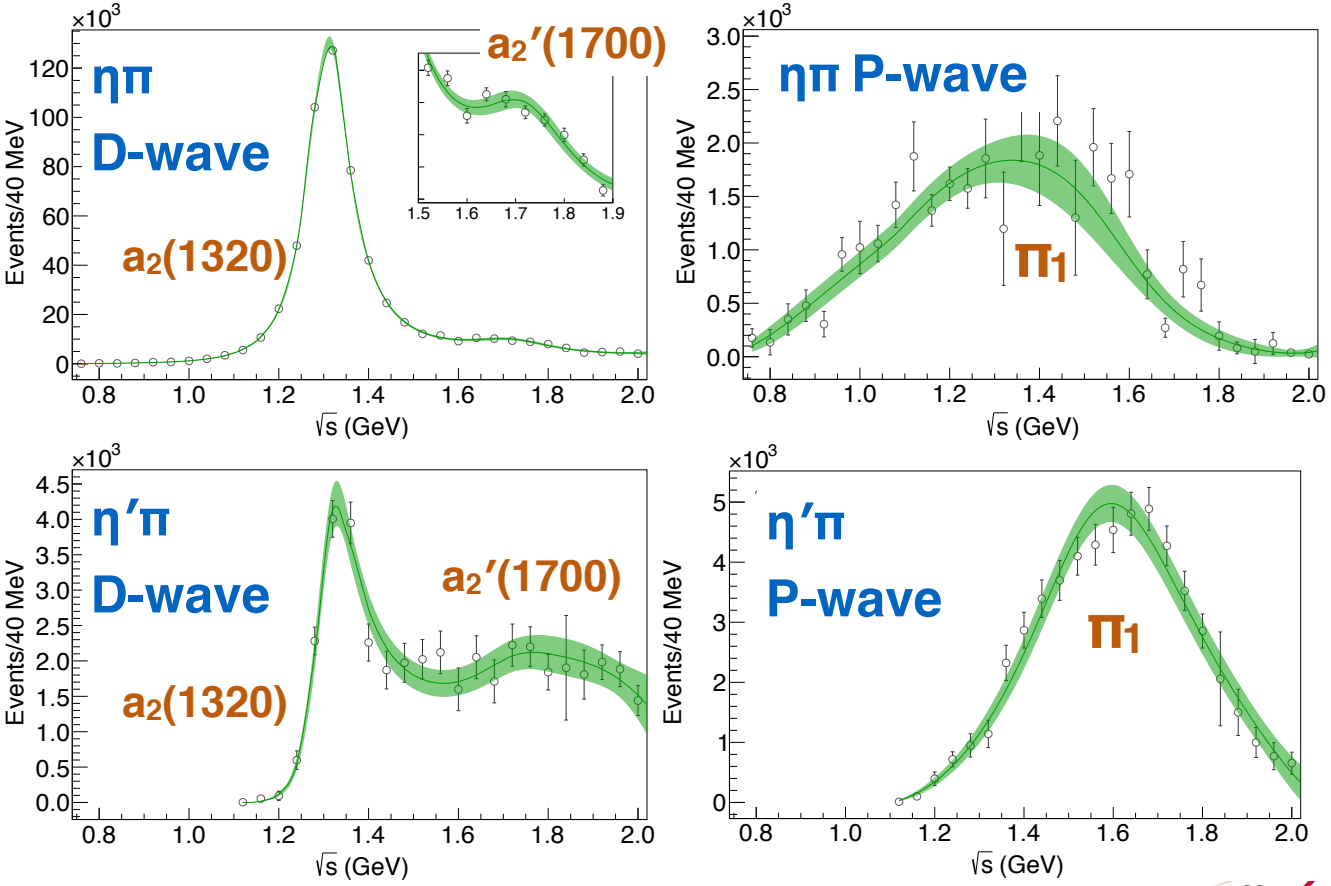
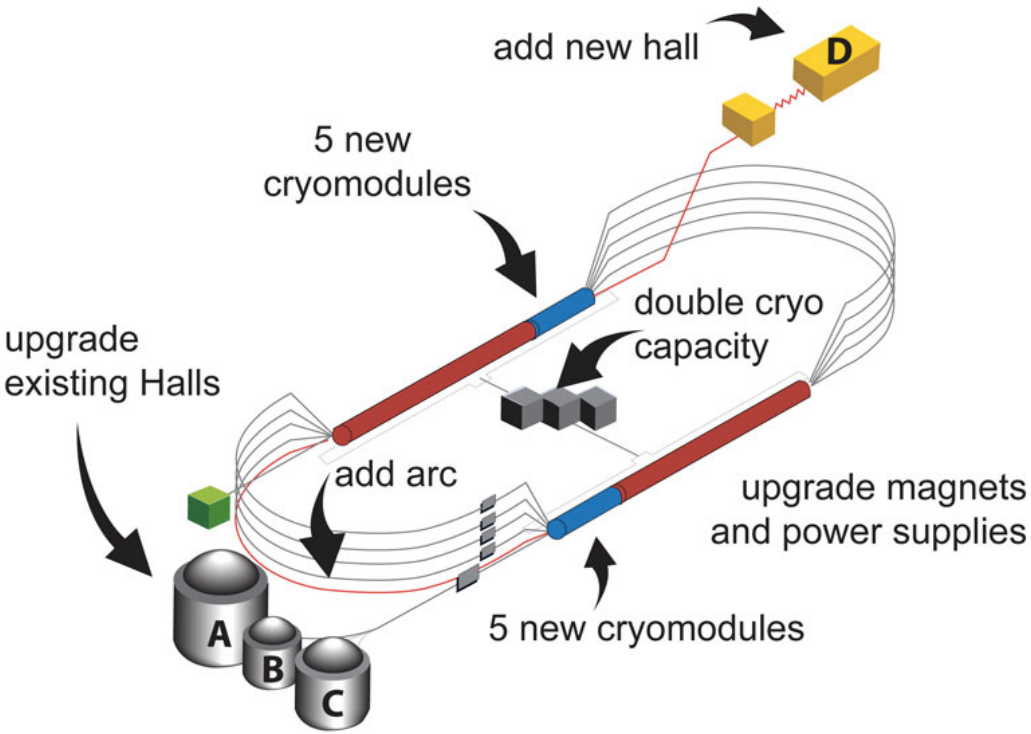
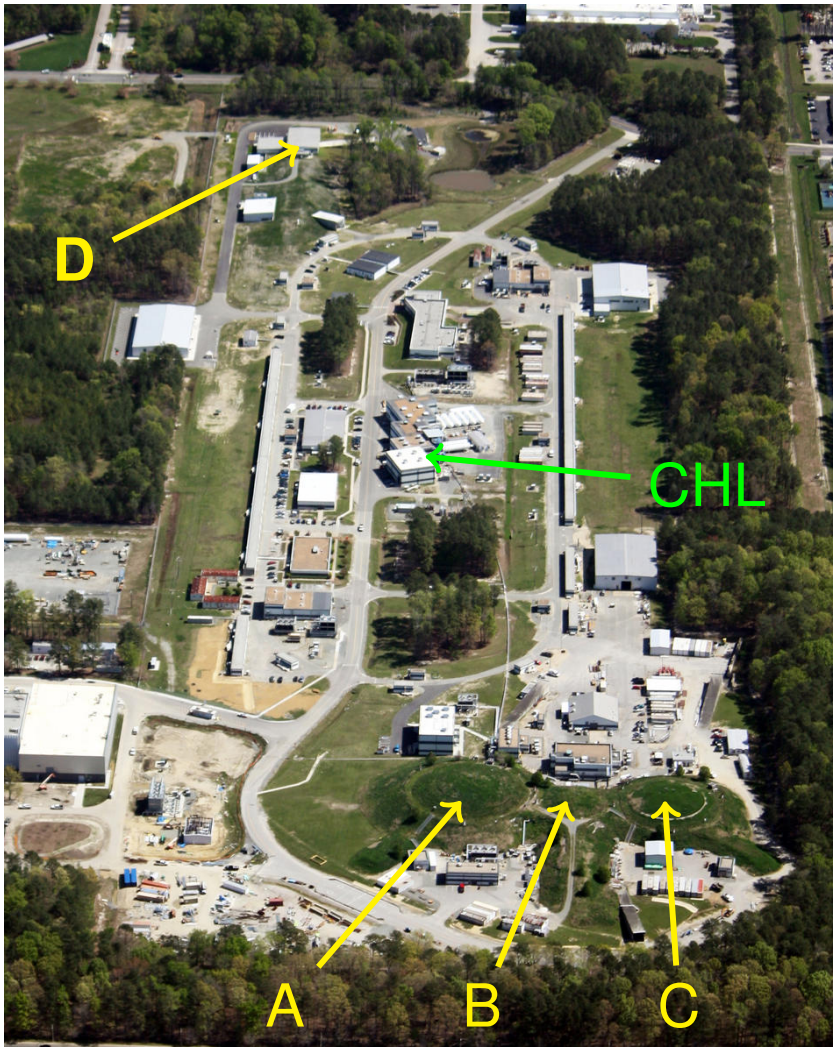




Jefferson Lab

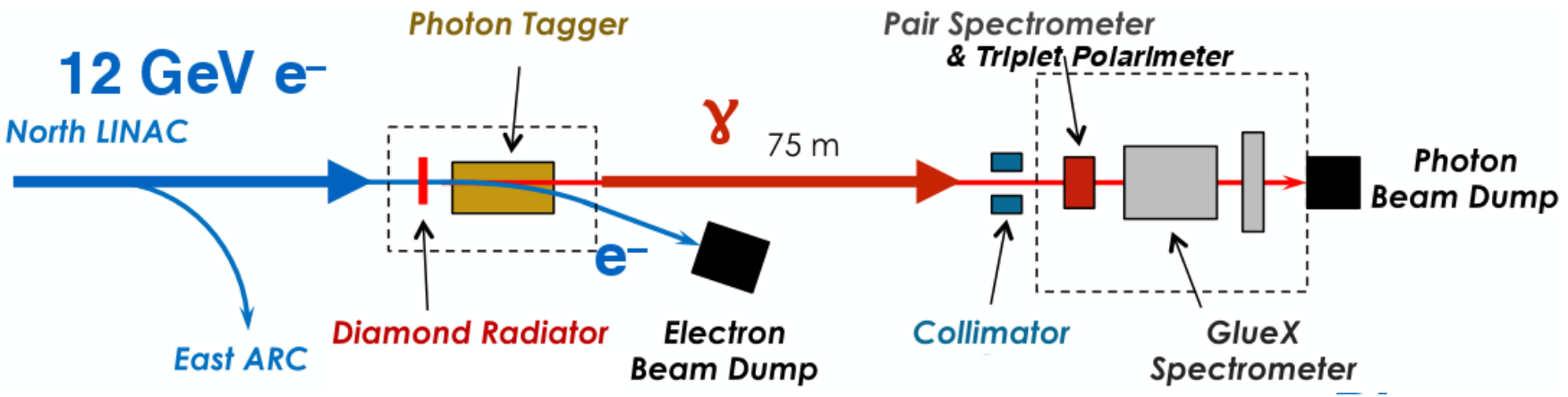
CEBAF at 12 GeV



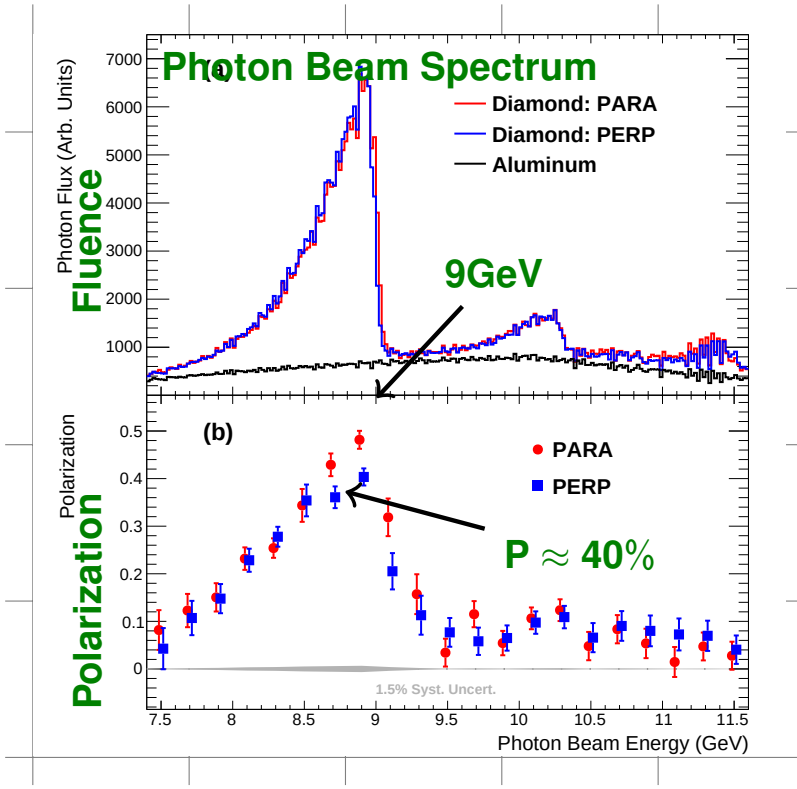


- Accelerator: $\leq$2.2 GeV/pass
- Accelerator: full current $<$80 μA
- Halls A,B,C: e^- 1-5 passes $\leq$11 GeV
- Hall D: e^- 250 MHz 5.5 passes $\leq$12 GeV γ-beam
- Beam extraction to 4 halls in parallel

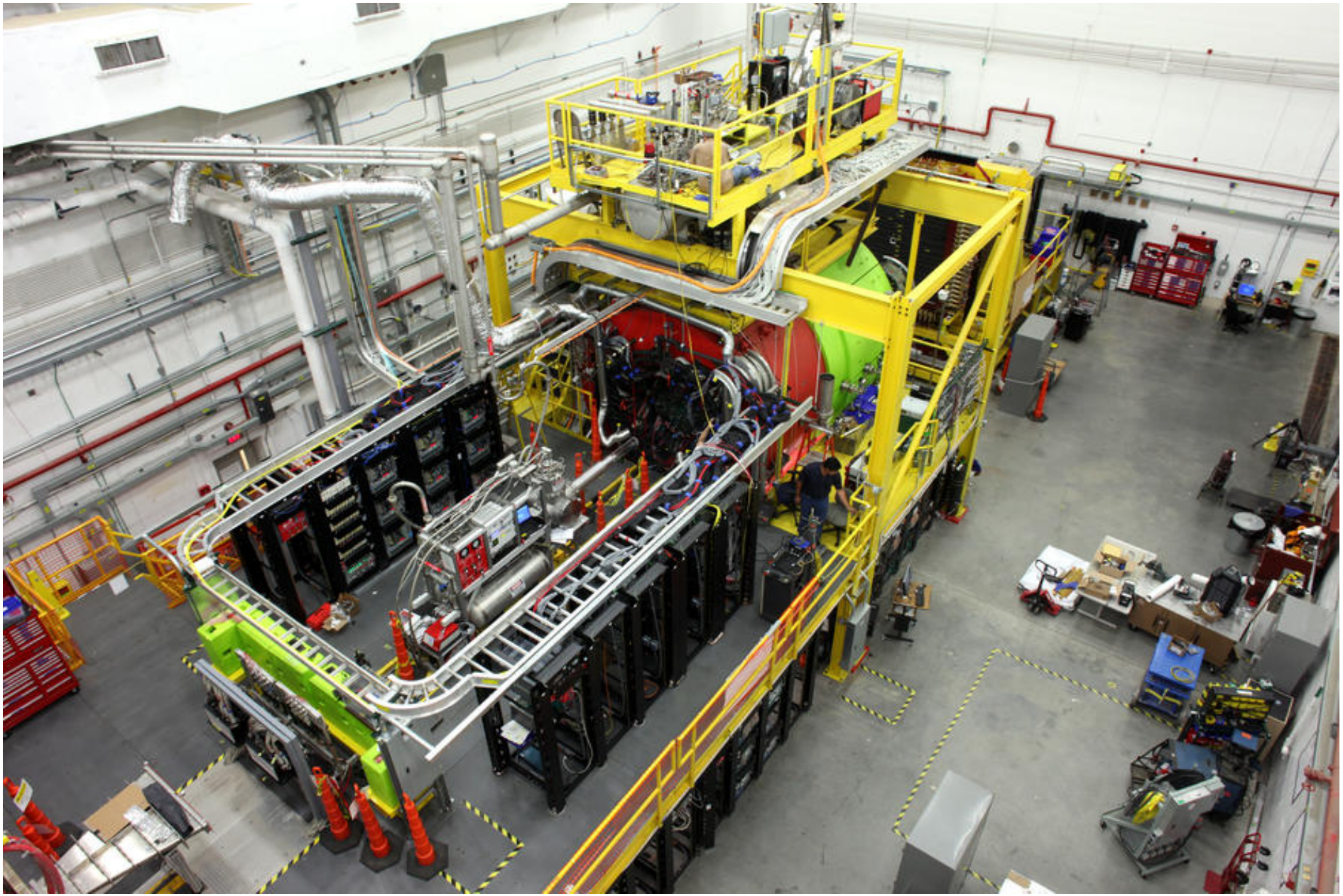
Photon beam and Hall D Facility



- 12 GeV e^- beam $0.001 - 5\ \mu$A
- Coherent Bremsstrahlung
- 3.4/5 mm collimator
- In peak $\mathcal{P} \sim 40\%$
- Flux $<$100 MHz in 7 - 12 GeV
- Energy/polarization measured:
  - Tagger spectrometer $\sim 0.2\%$
  - Polarimeter $\gamma e^- \to e^- e^+ e^-$ $\sigma_{\mathcal{P}}/\mathcal{P} \sim 2\%$



Hall D



Hall D/GlueX Spectrometer and DAQ

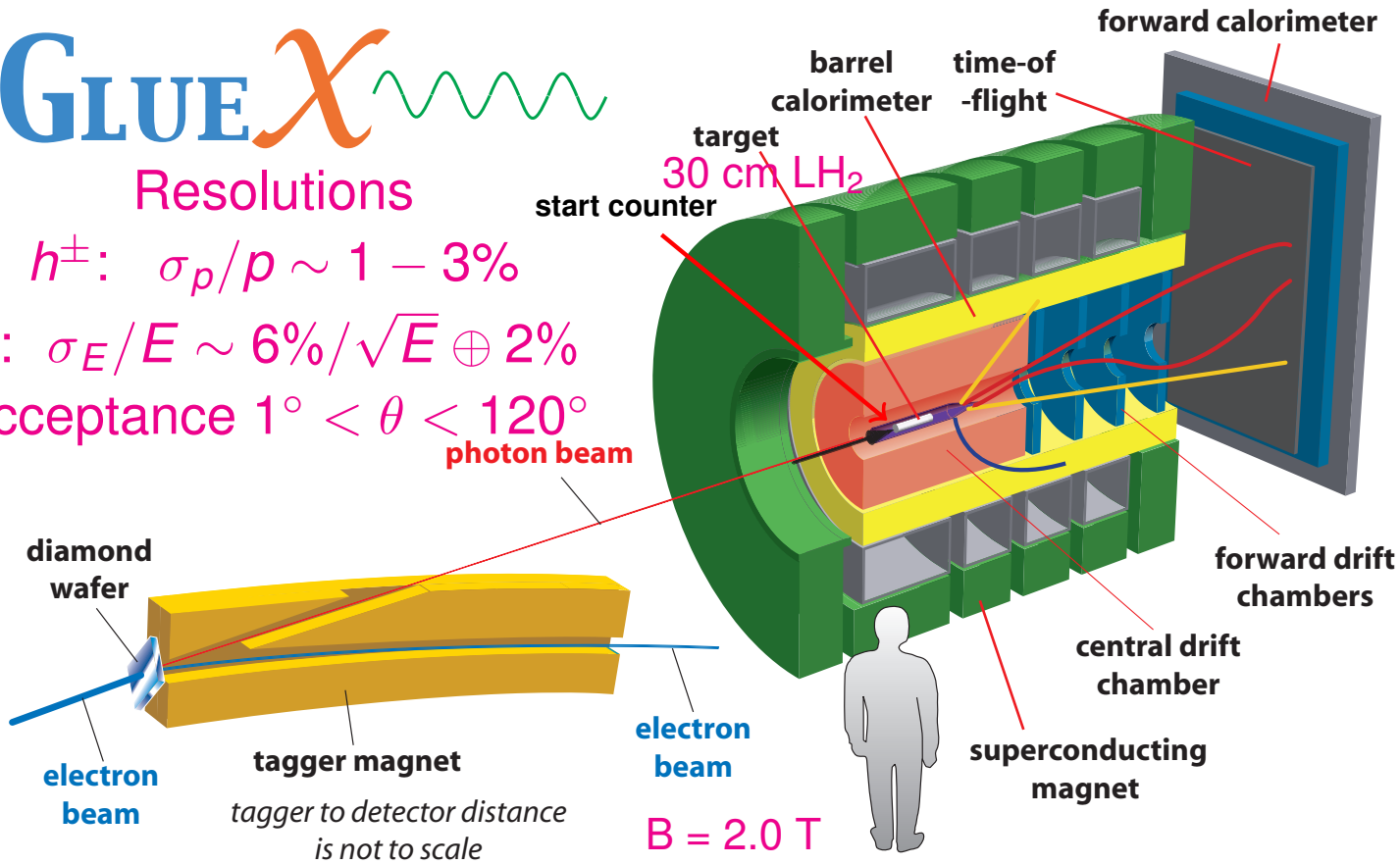
GlueX

Resolutions

$h^{\pm}$: $\sigma_p/p \sim 1-3\%$

γ: $\sigma_E/E \sim 6\%/\sqrt{E} \oplus 2\%$

Acceptance $1^\circ < \theta < 120^\circ$



Detectors

- CDC, FDC
- BCAL, FCAL
- TOF, ST

Upgrades

- DIRC
- FCAL insert

Open trigger takes nearly all photoproduction at $E_\gamma > 5GeV$

Beam 25 MHz/peak: trigger 40 kHz $\Rightarrow$ DAQ $\Rightarrow$ 0.6 GB/s $\Rightarrow$ tape

5 PB of GlueX-I data

Early Results: J/ψ photoproduction close to threshold

Measured: $\sigma(E_\gamma)$ for $\gamma + p \to J/\psi + p$ at $8.22 < E_\gamma < 12$ GeV
Older data: two experiments from 1975 at $E > 11$ GeV

1. Photoproduction dynamics
   - $\sigma(E_\gamma)$ is sensitive to high-x gluons in the nucleon
2. Spectroscopy: search for the LHCb pentaquark
   - s-channel production $\gamma + p \to P_c(4450) \to J/\psi + p$ at 10.1 GeV
   - The P_c production would manifest itself as a peak in $\sigma(E_\gamma)$

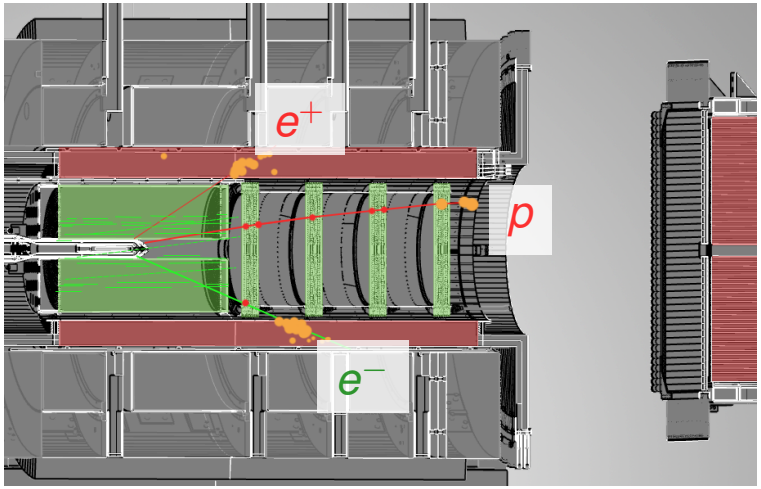
Event selection

Detected decay $J/\psi \to e^+e^-$

EM Calorimeters - PID for e^+e^-

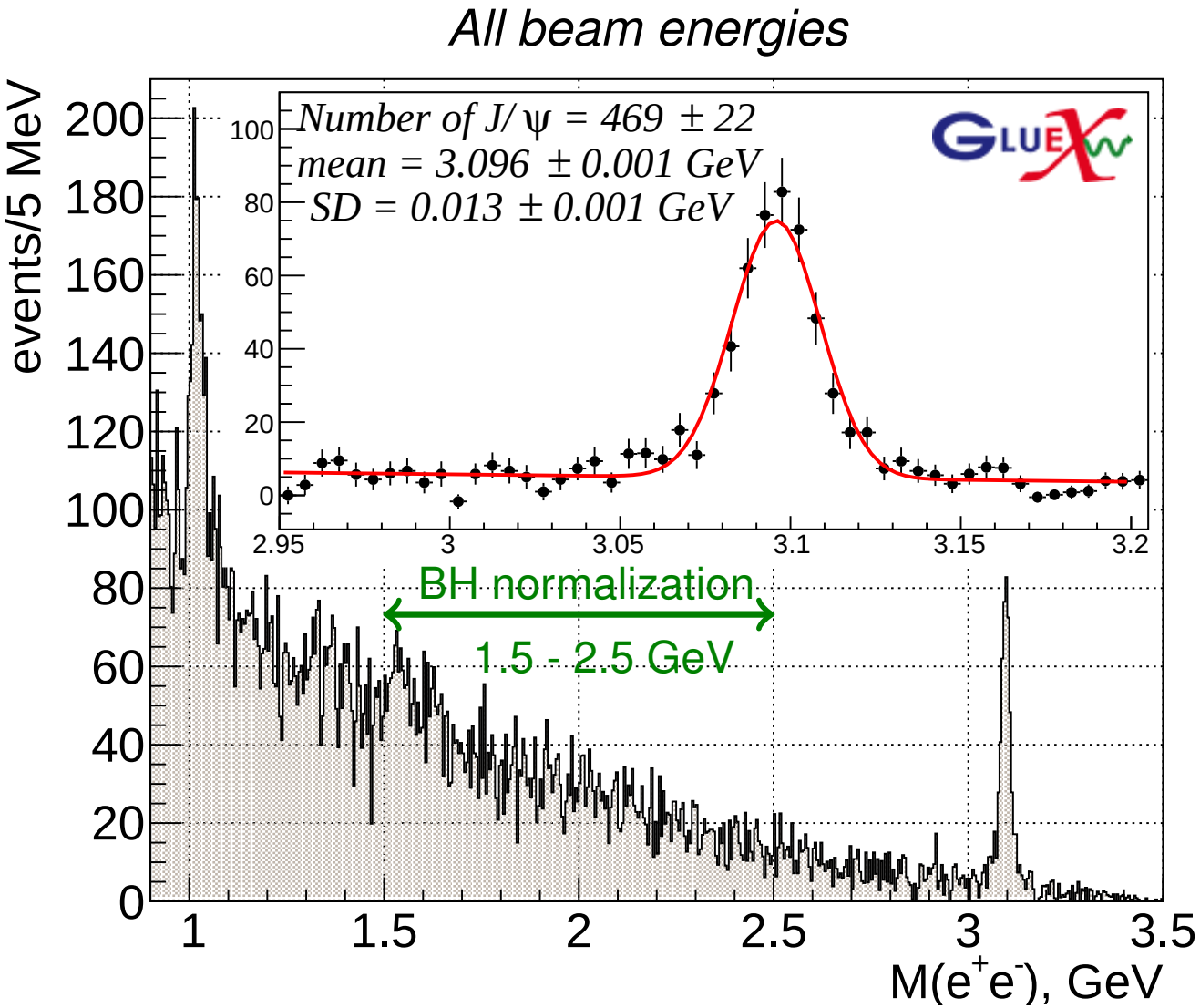
$\frac{dE}{dx}$, TOF - PID for p

The Bethe-Heitler reaction $\gamma\, p \to (e^+e^-)p$ is used for normalization of the cross section



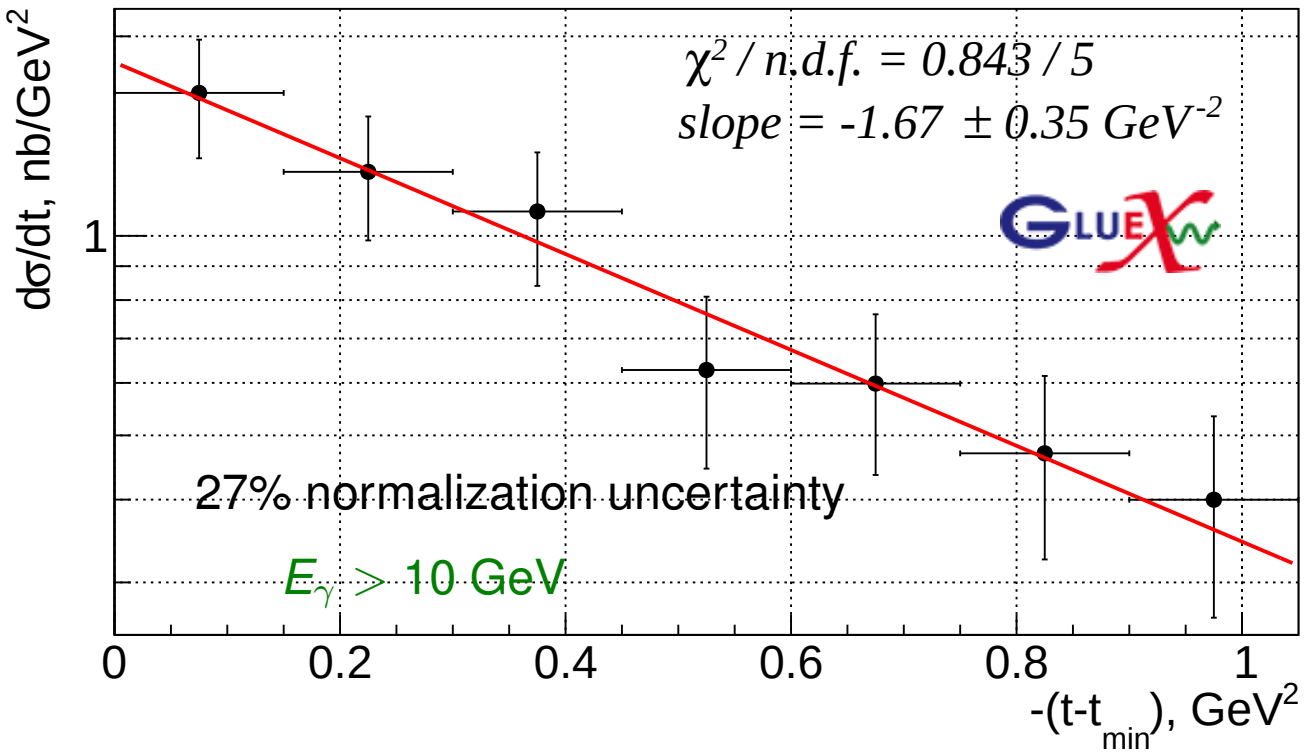
Mass Spectrum of e^+e^-

GlueX Collaboration A. Ali et al,arXiv:1905.10811 May 2019 submitted to PRL



Differential Cross Section

GlueX Collaboration A. Ali et al,arXiv:1905.10811 May 2019 submitted to PRL



Theory

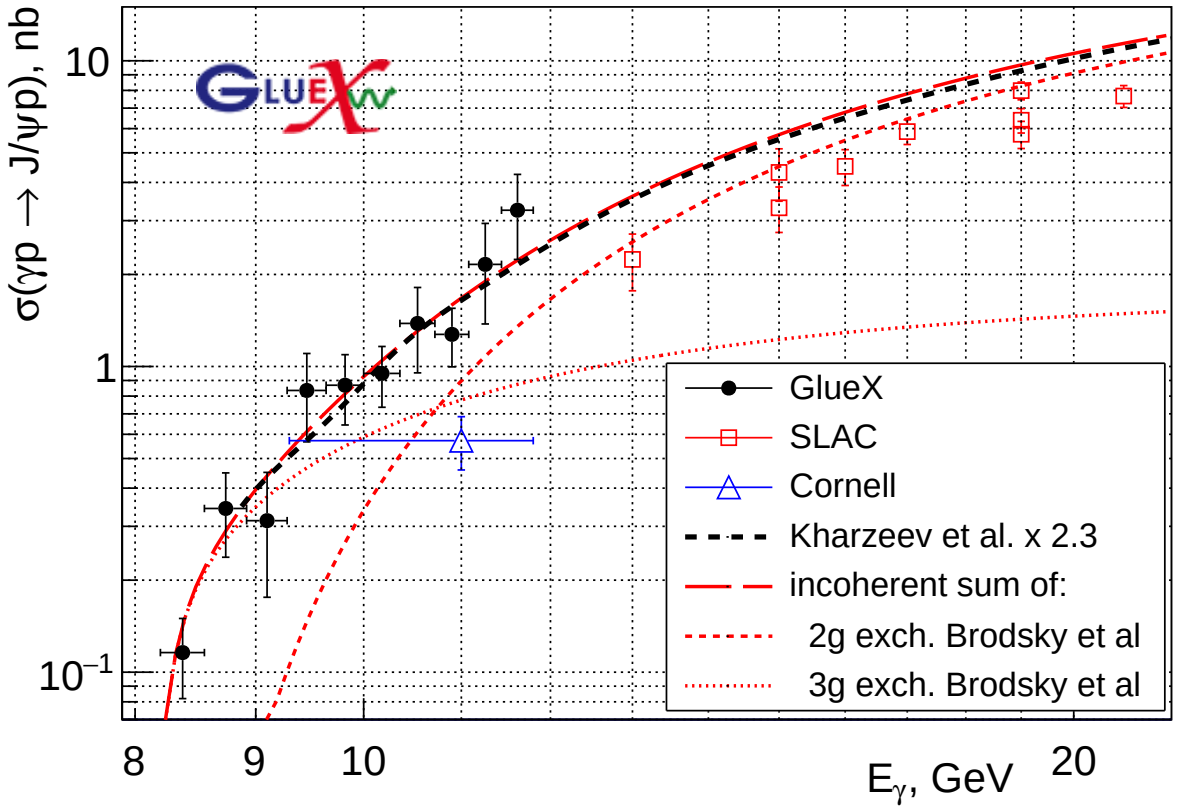
- Ansatz:
  $\frac{d\sigma}{dt} \propto e^{a \cdot t}$
- Proton gluonic FF
  M.Strikman et al, PRD 66
  $\frac{d\sigma}{dt} \propto (1 - t/m_\circ^2)^{-4}$
  $m_\circ \approx 1.1$ GeV

Measured slope *a*

- 1.67 ± 0.35 GeV^{-2} at $10 < E_\gamma < 11.8$ GeV GlueX
- 1.25 ± 0.2 GeV^{-2} at $E_\gamma \approx 11.$ GeV Cornell *B.Gittelman et al, PRL 35 (1975)*
- 2.9 ± 0.3 GeV^{-2} at $E_\gamma = 19$ GeV SLAC *U.Camerini et al, PRL 35 (1975)*

Energy Dependence of the Cross Section

GlueX Collaboration A. Ali et al,arXiv:1905.10811 May 2019 submitted to PRL



Old experiments

- SLAC 13-21 GeV

U.Camerini, PRL 35 (1975)

γD, inclusive

- Cornell ∼11 GeV

B.Gittelman, PRL 35 (1975)

γBe, inclusive, large BG

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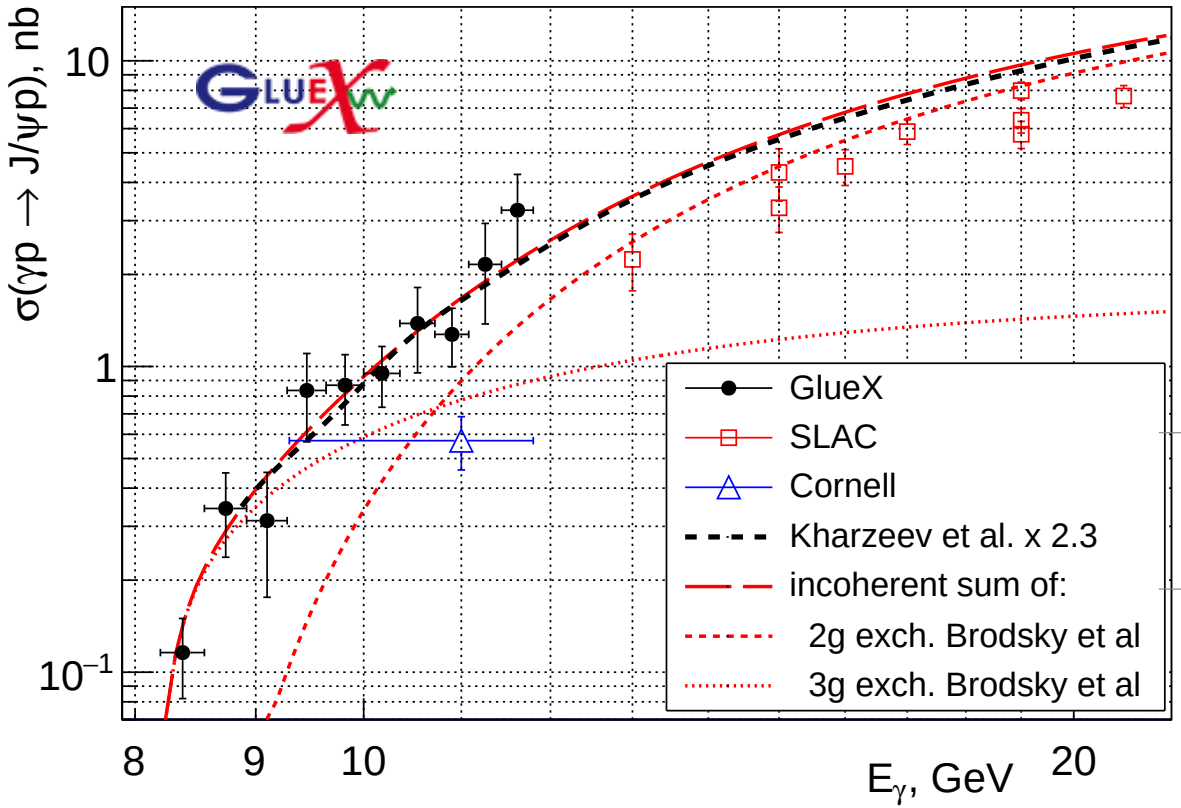


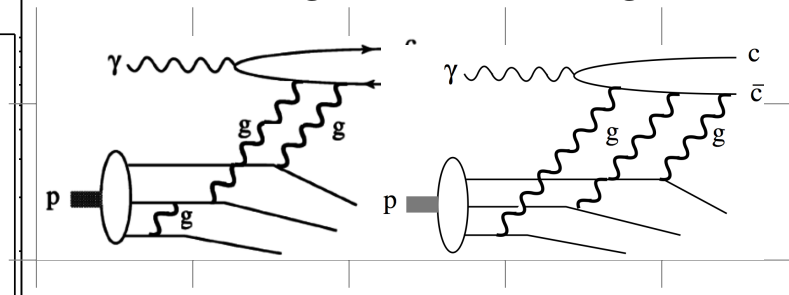
Theory

production at threshold

Brodsky et at PLB 498 (2002)

# of spectators involved

# of hard gluons exchanged



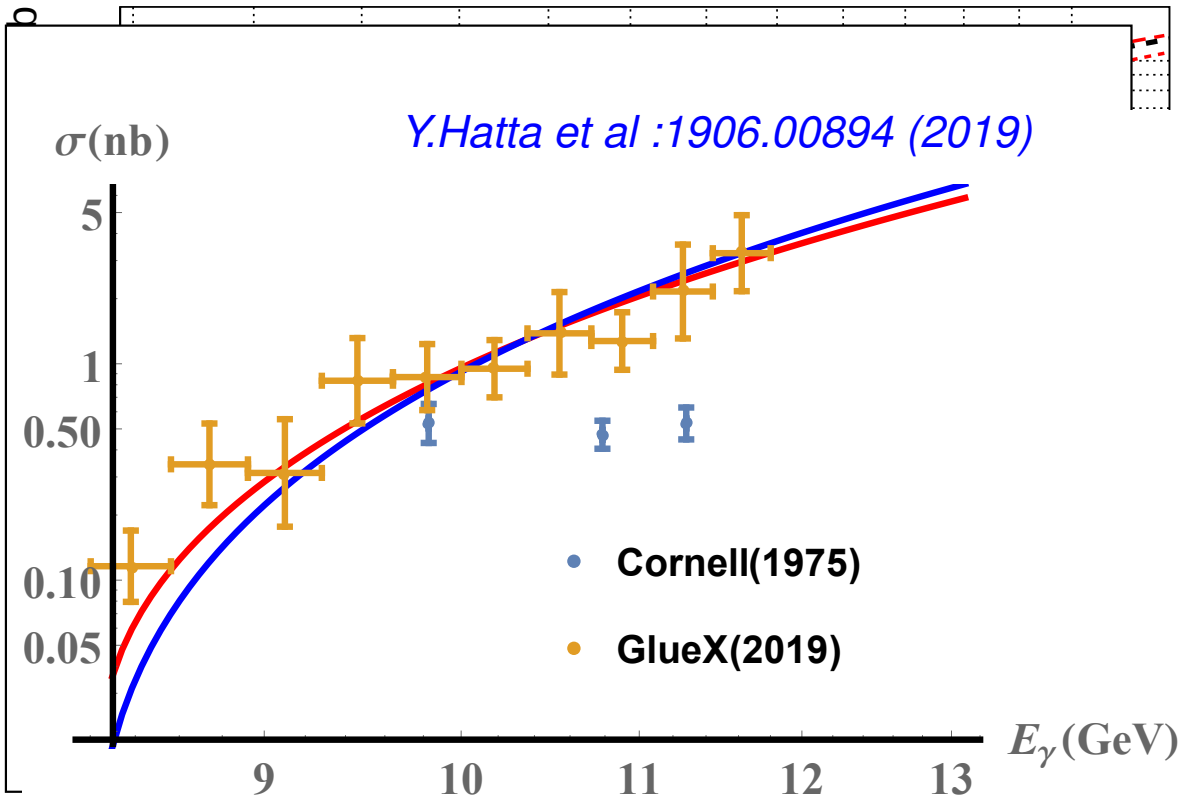
Scaling rules: $\sigma \propto f(E_\gamma)$

Interpretation of the results

- 3-gluon exchange (no spectator in proton) dominates close to threshold

Energy Dependence of the Cross Section

GlueX Collaboration A. Ali et al,arXiv:1905.10811 May 2019 submitted to PRL



Theory

production at threshold

Kharzeev et at NPA 661 (1999)

Gluon distribution

$Re(A)$ of $J/\psi p$ scattering is related to *trace anomaly*

TA related to proton mass

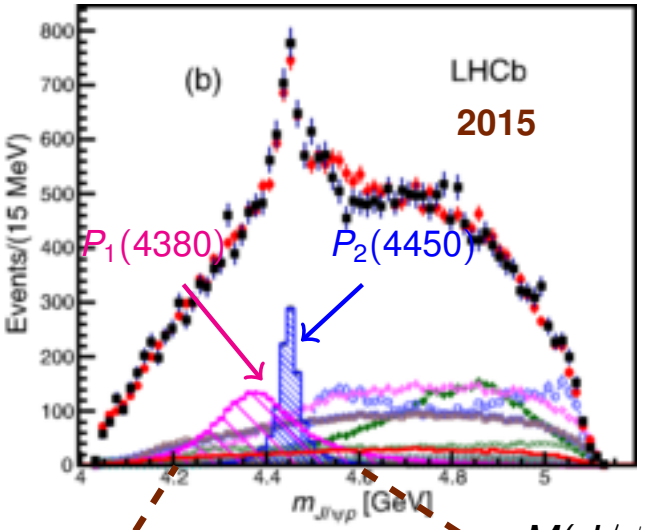
Y.Hatta et al :1906.00894 (2019) included our results

Interpretation of the results

- Implies a large contribution from gluons to the proton mass

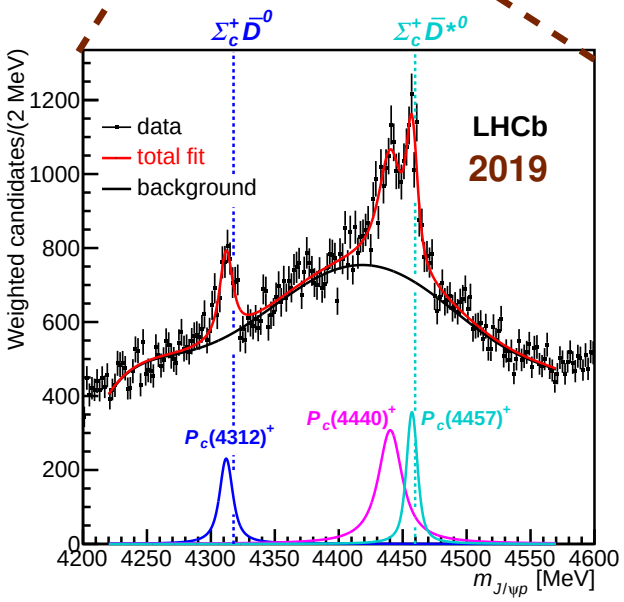
LHCb Pentaquark

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

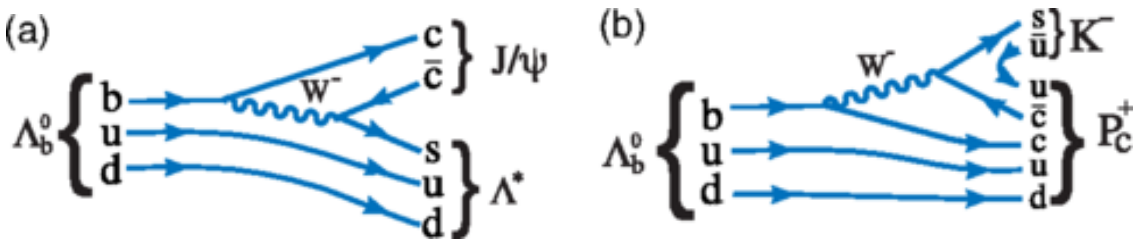


PRL 115,072001 (2015)

$M(J/\psi p)$



PRL 122,222001 (2019)



2015

- No reflection $\Lambda^* \to K^- p \Rightarrow J/\psi p$ observed
- PWA leads to two states for $P_c^+ \to J/\psi p$:

Mass, MeV	Γ,MeV	J^{PC}	
4380 ± 30	205 ± 90	$3/2^{\mp}$	$5/2^{\mp}$
4450 ± 3	39 ± 20	$5/2^{\pm}$	$5/2^{\pm}$

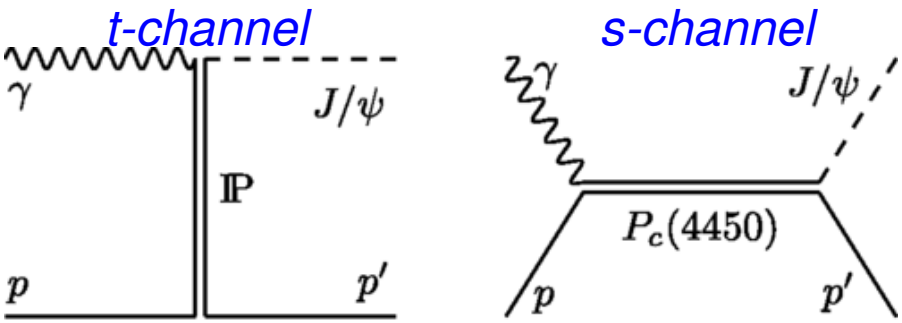
2019

3 narrow peaks $P_c^+ \to J/\psi p$:

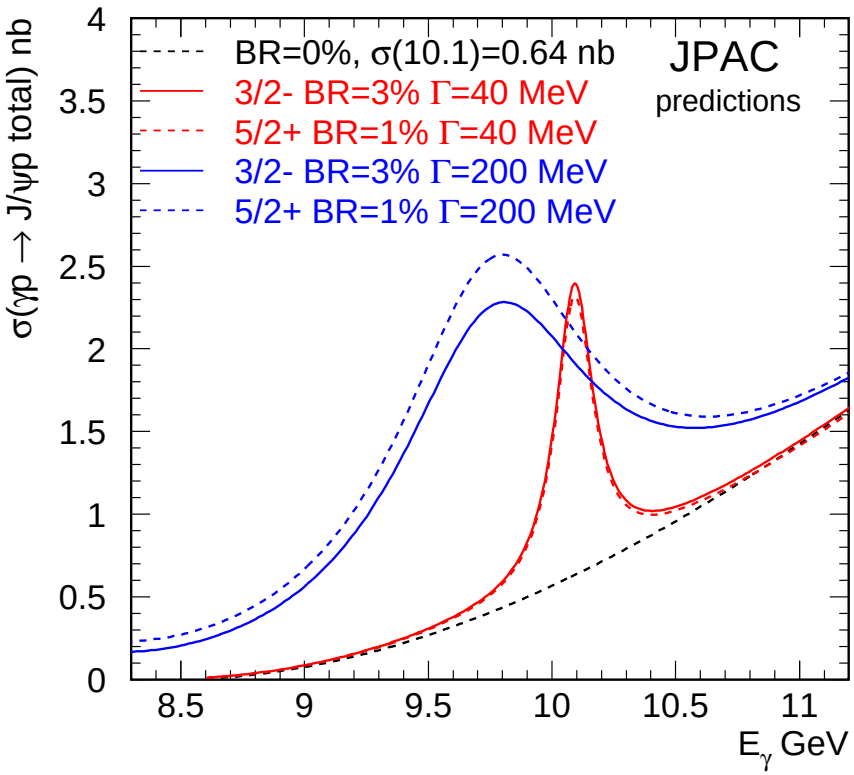
Mass, MeV	Γ,MeV	R, %
$4312 \pm 0.7^{+6.8}_{-0.6}$	$10 \pm 3^{+4}_{-5}$	0.3 ± 0.1
$4440 \pm 1.3^{+4.1}_{-4.7}$	$20 \pm 5^{+9}_{-10}$	1.1 ± 0.3
$4457 \pm 0.6^{+4.1}_{-1.7}$	$6 \pm 2^{+6}_{-2}$	0.5 ± 0.2

$R = (\Lambda_b \to P_c K^-) \cdot (P_c \to J/\psi p)/(\Lambda_b \to K^- J/\psi p)$

Photoproduction of the Pentaquark: Predictions



$E_\gamma \sim 10$ GeV



http://cgl.soic.indiana.edu/jpac/PentaQ_JPsi.php

In a *Broad-band photon beam*

$\gamma + p \to J/\psi + p$ may include

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

Addressed in a number of papers:

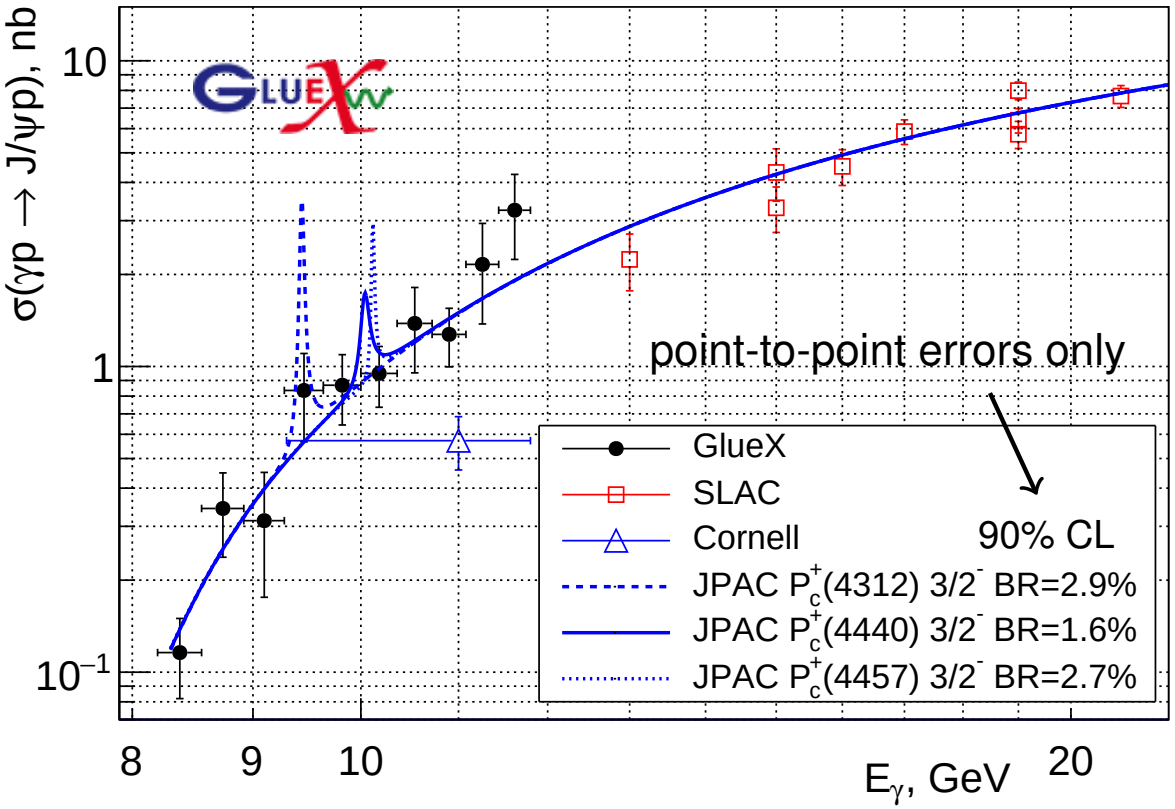
V. Kubarovsky et al PRD 92, 031502 (2015)
Q. Wang et al PRD 92, 034022 (2015)
M. Karliner et al PL 752, 329 (2016)
A. Hiller Blin et al PRD 94, 034002 (2016) JPAC

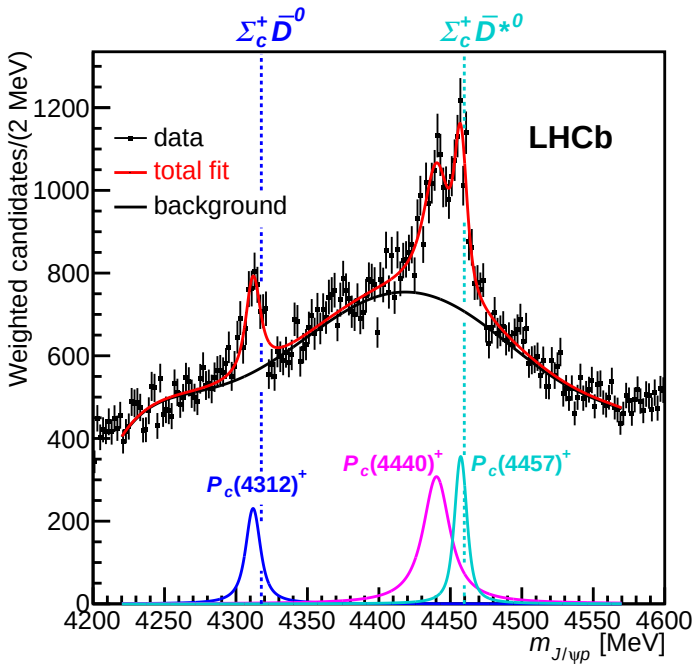
- $P_c \to J/\psi\, p \overset{VMD}{\Rightarrow} \gamma\, p \to P_c$
- Interference of *t*- and *s*-channels
- Using the measured $\Gamma(P_c)$ the full cross section is calculable with one free parameter:

$$\sigma_{\gamma p \to J/\psi p}(E_{peak}) \propto BR(P_c \to J/\psi p)^2$$

Limit on the Pentaquark Production

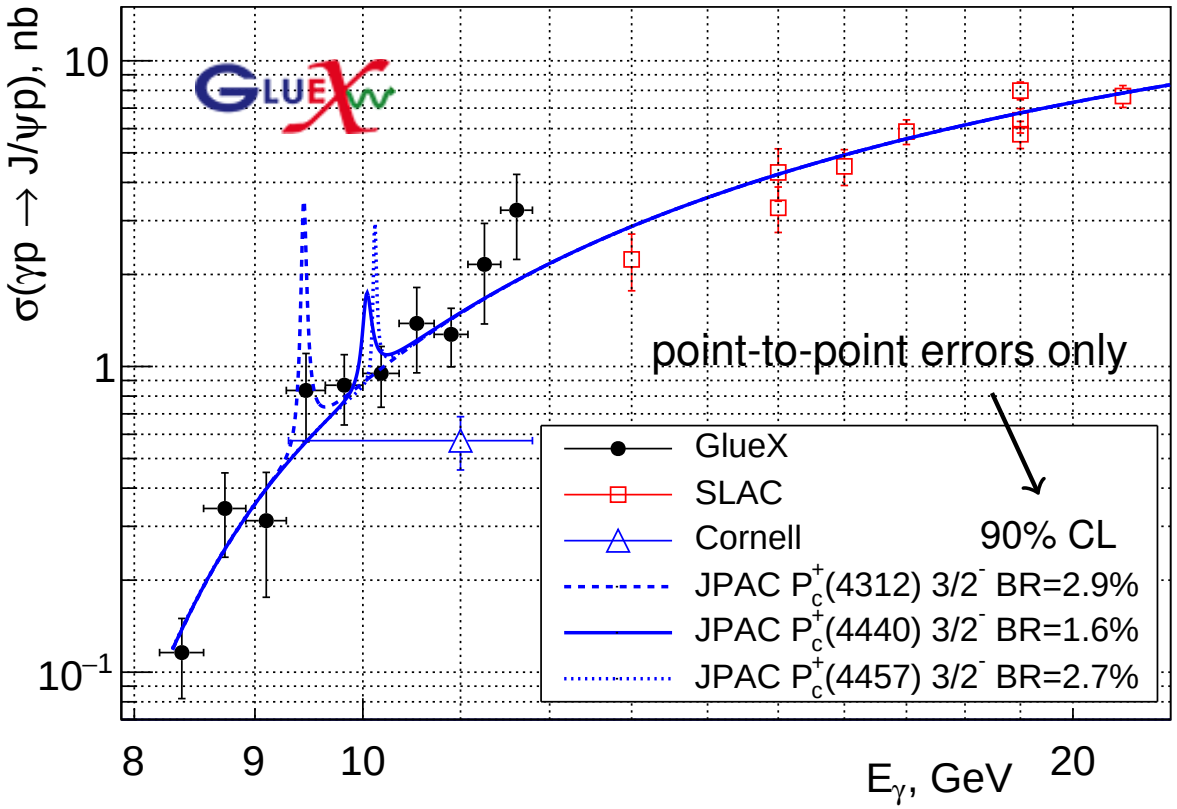
GlueX Collaboration A. Ali et al,arXiv:1905.10811 May 2019 submitted to PRL





Limit on the Pentaquark Production

GlueX Collaboration A. Ali et al,arXiv:1905.10811 May 2019 submitted to PRL



Evaluation of $BR(P_c^+ \to J/\psi p)$

JPAC model *PRD 94, 034002*
for $J = 3/2$, $\Gamma \Leftarrow$ LHCb

all the uncertainties are included
Limits at 90% CL

P_c	Γ,MeV	BR
$P_c(4312)$	10±3	$< 4.6\%$
$P_c(4440)$	20±5	$< 2.3\%$
$P_c(4457)$	6±2	$< 3.8\%$

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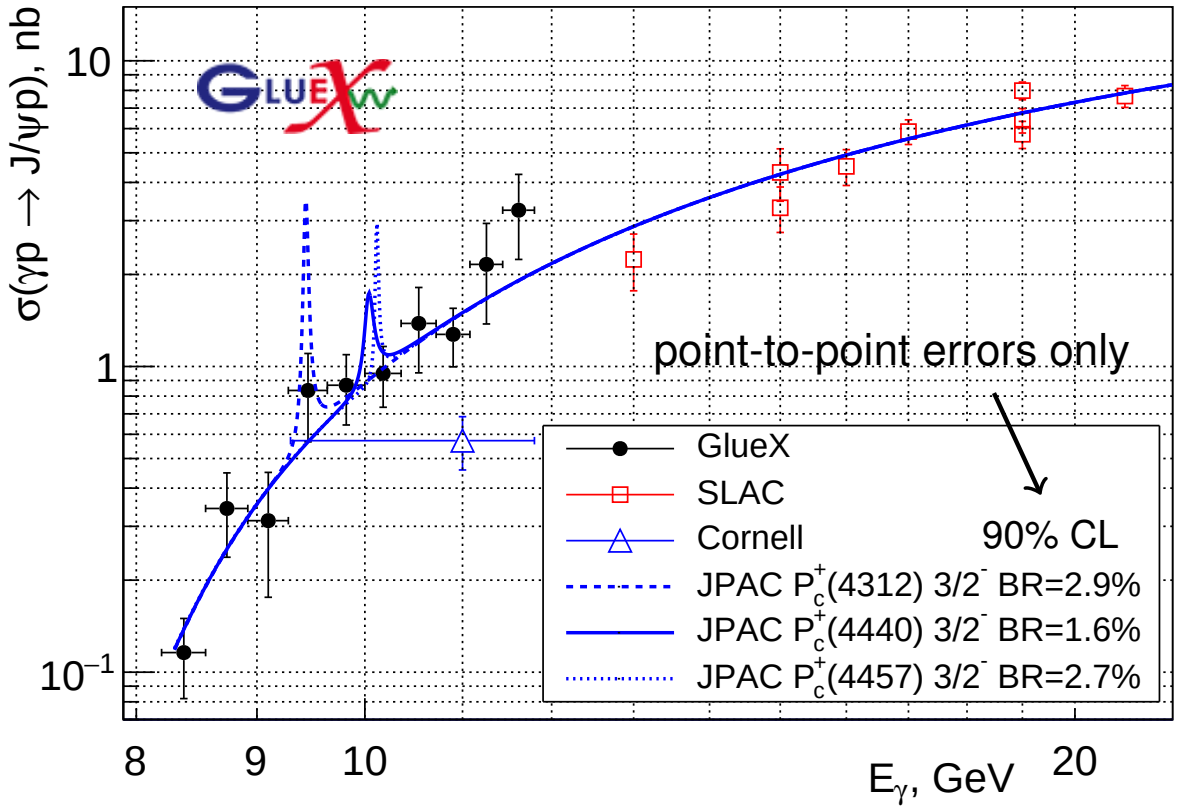

model	Ref.	$BR(J/\psi p)$
hadrocharm.	*Eides 1904.11616*	25-70%
molecule	*Guo PLB 793*	50-80%
molecule	*Eides PRD 98*	0.1%
diquarks	*Ali PLB 793*	small

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Lower than expected!

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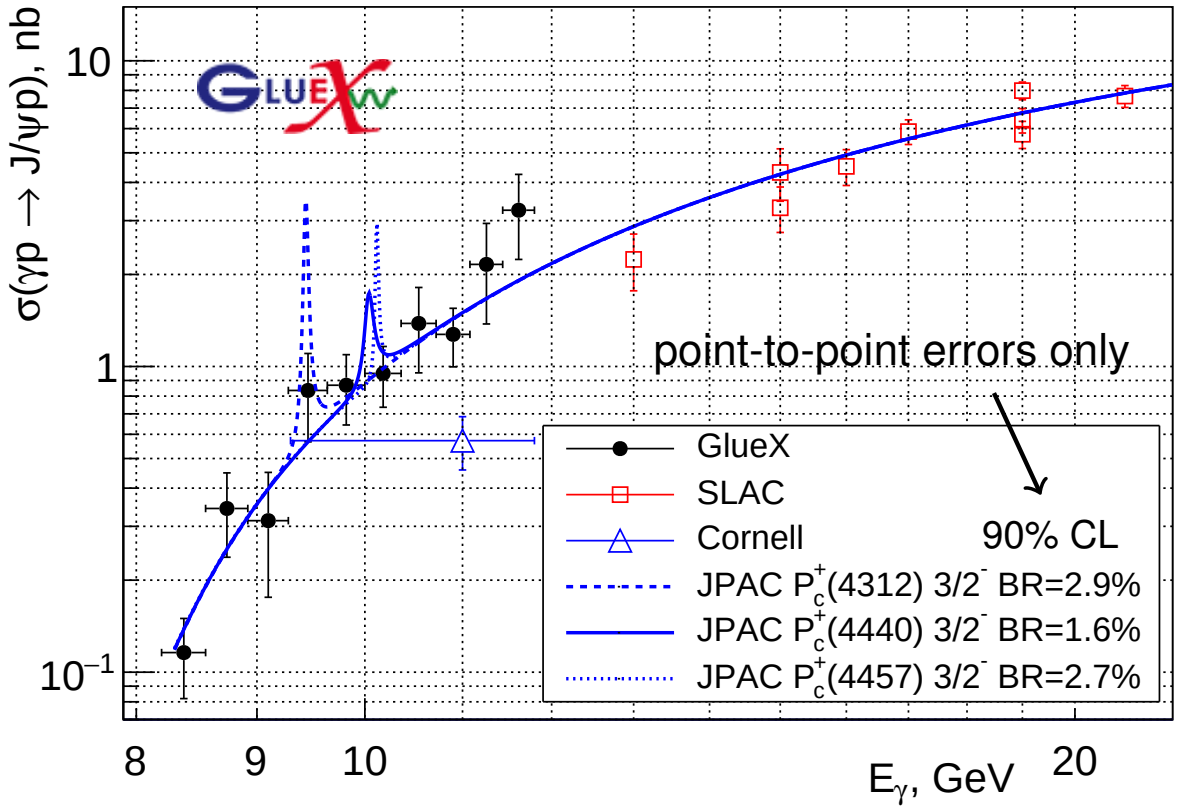

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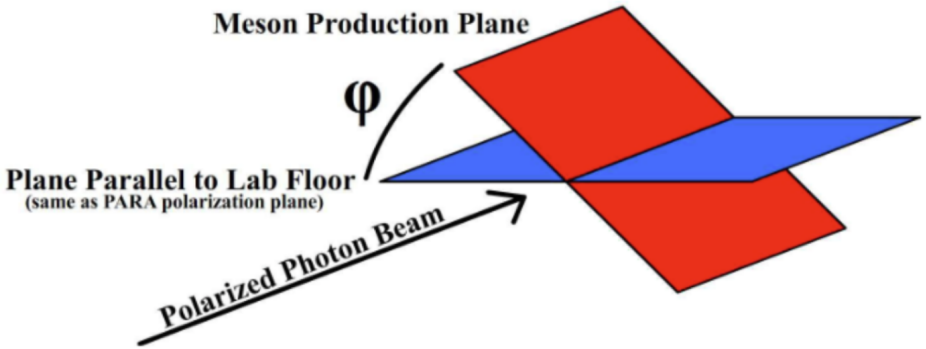
Interpretation

- *Wang 1906.04044* suppress photoproduction
- Diquarks?
- Triangular diagrams

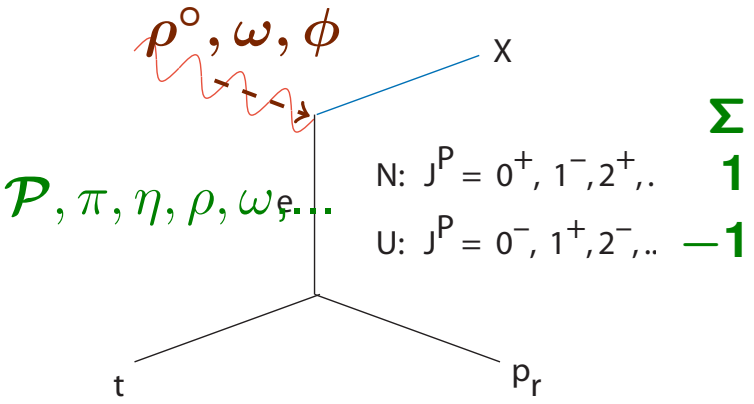
Photoproduction by linearly polarized beam

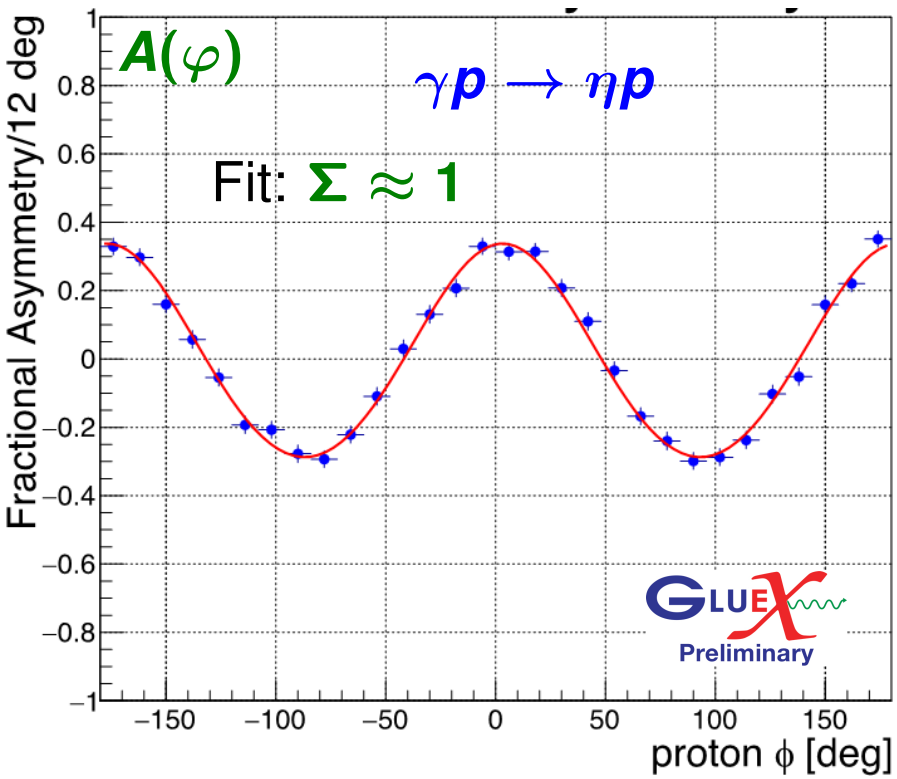


Two data sets with 90° between the polarization planes

$$A(\varphi) = \frac{\frac{d\sigma}{d\varphi}_{\perp} - \frac{d\sigma}{d\varphi}_{\parallel}}{\frac{d\sigma}{d\varphi}_{\perp} + \frac{d\sigma}{d\varphi}_{\parallel}} \approx P_{beam}\Sigma\cos(2\varphi)$$

Asymmetry - filter on *naturality*





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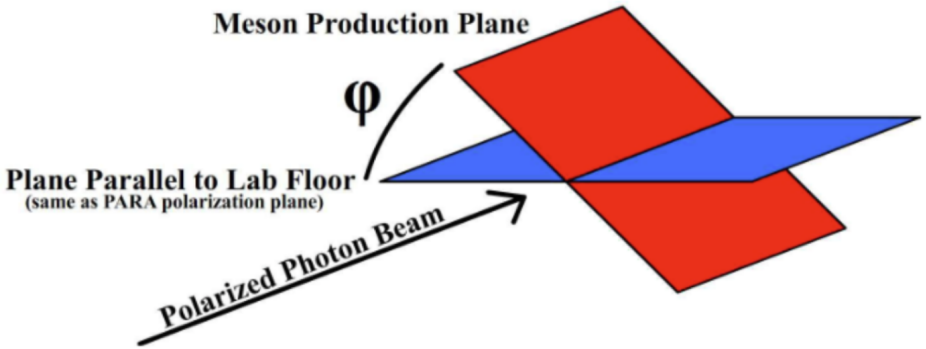

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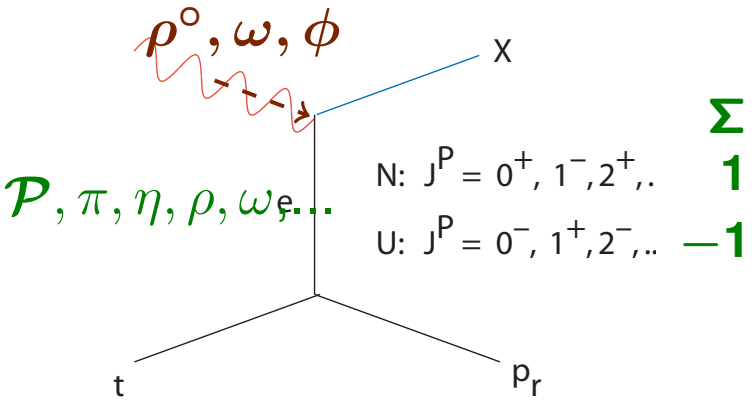
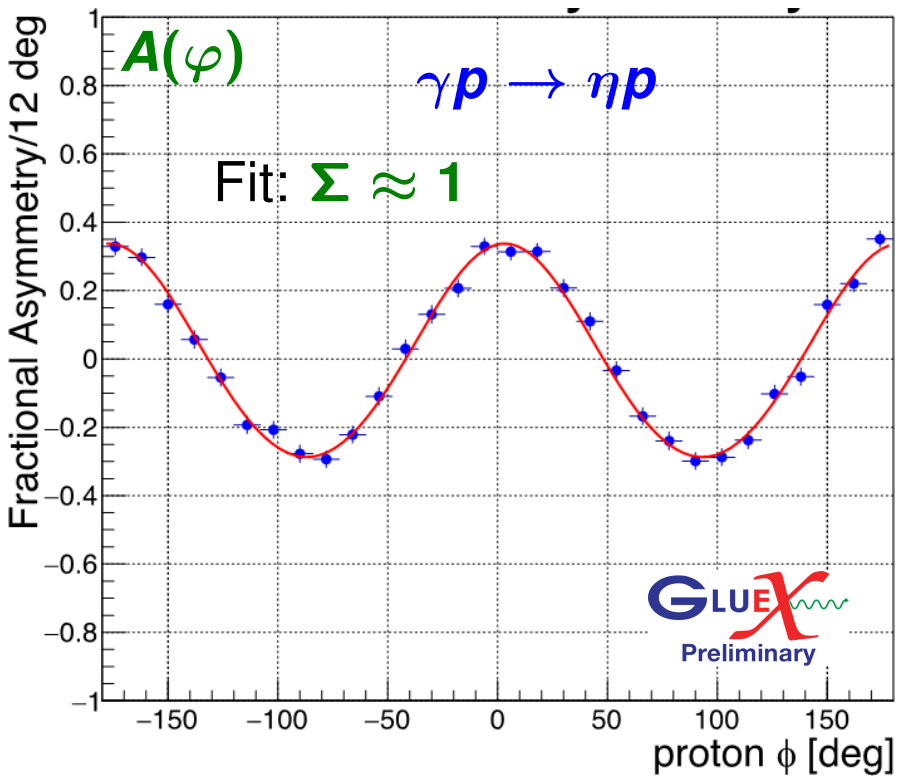
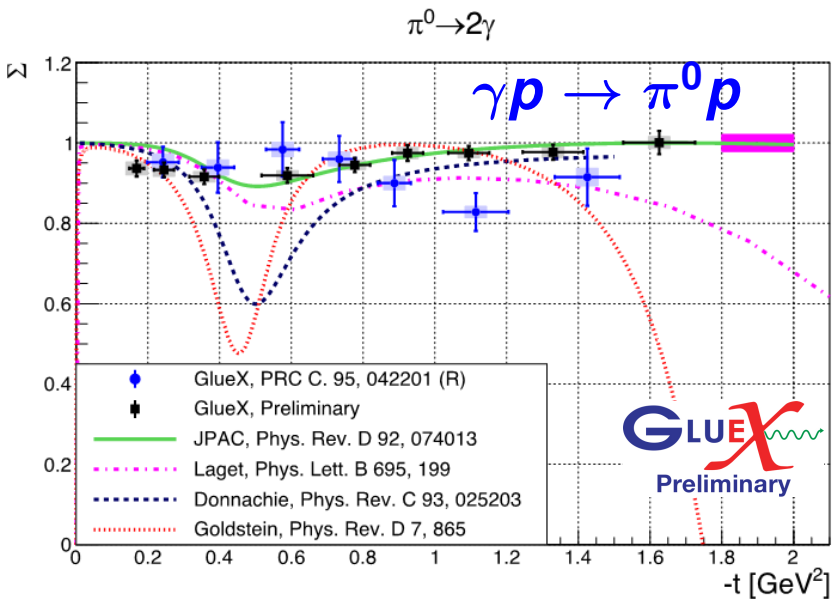


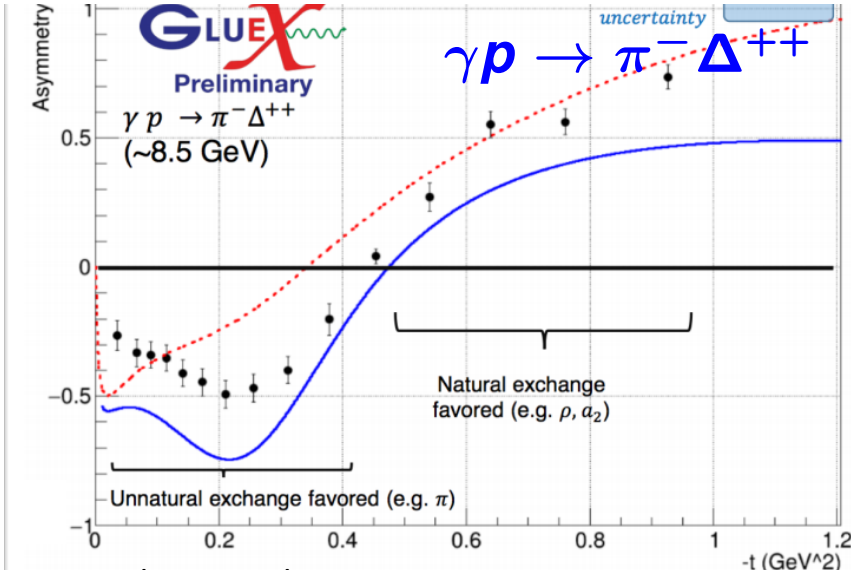
Allowed for hybrids:

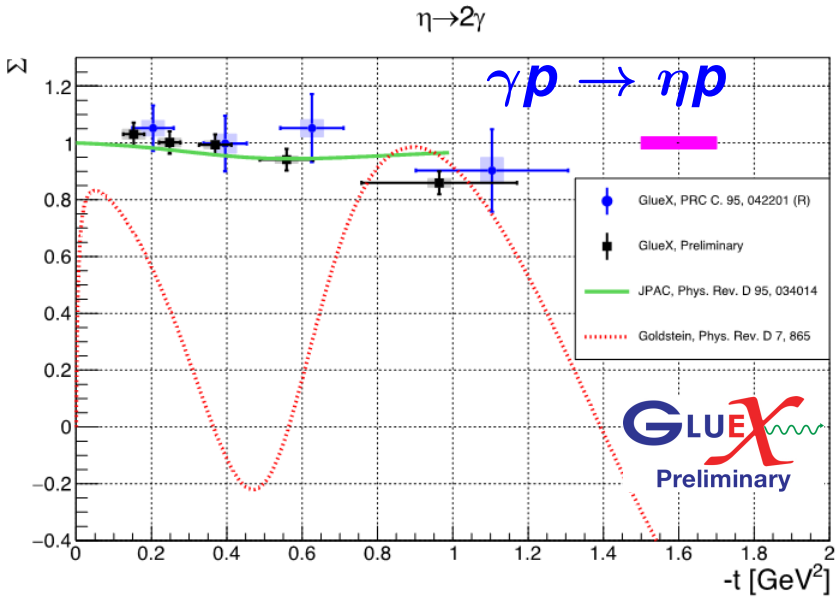
Exchange particle		Final states	
$\mathcal{P}$	0^{++}	$2^{+-}, 0^{+-}$	b°, h, h'
π°	0^{-+}	2^{+-}	b_2°, h_2, h_2'
$\pi^{\pm}$	0^{-+}	1^{-+}	$\pi_1^{\pm}$
ω	1^{--}	1^{-+}	π_1, η_1, η_1'

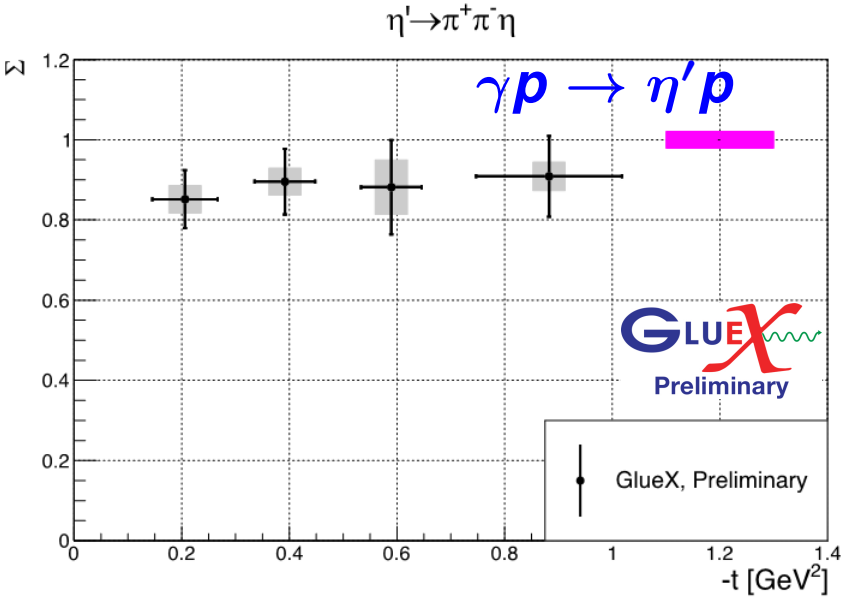


GlueX: Beam Asymmetries









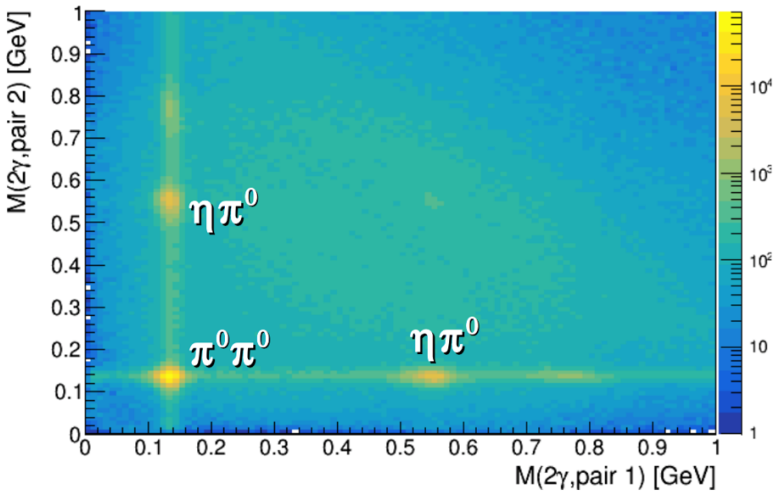
Jefferson Lab

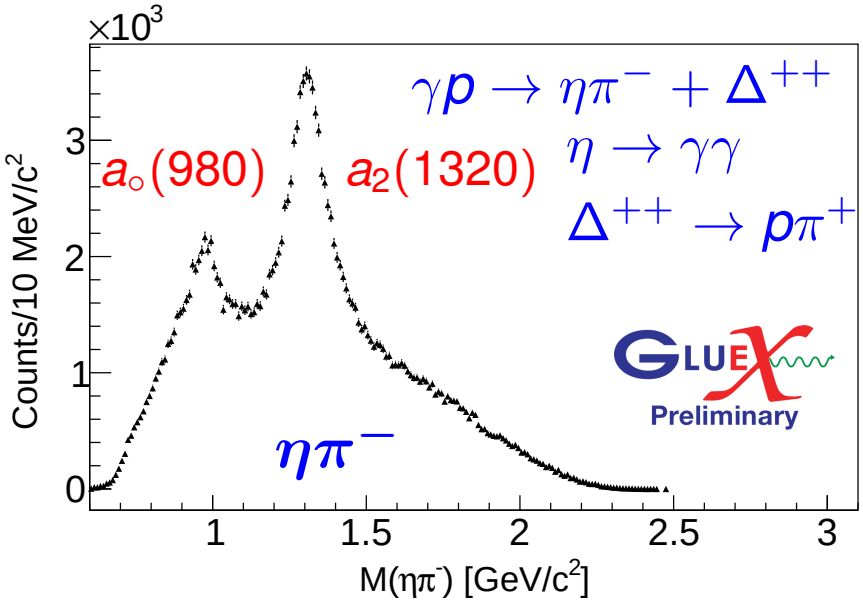
GlueX: Search for Hybrid Mesons - Status

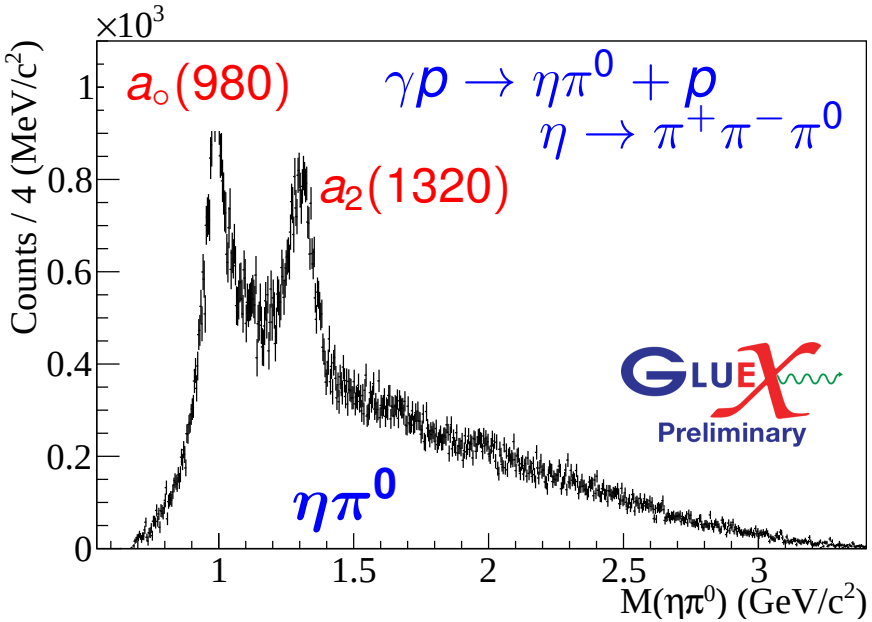
- Plans:
  - Start with looking for the lowest predicted multiplet $1^{-+}: \pi_1, \eta_1, \eta_1'$
  - Try 2-body decays first
- Requirements:
  - Understanding of the acceptance and efficiencies: in progress
  - Understanding of the beam polarization effects: well advanced
  - PWA application: in progress
- Current status:
  - 20% of the full data used
  - Well known meson resonances observed in relevant channels

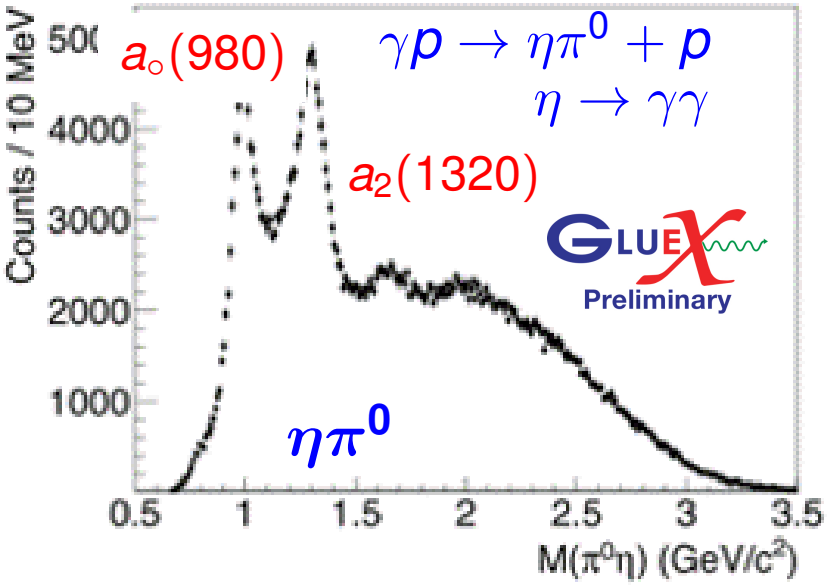
GlueX: Prospects for Spectroscopy in $\eta\pi$ Channels

About 20% of the GlueX-I data









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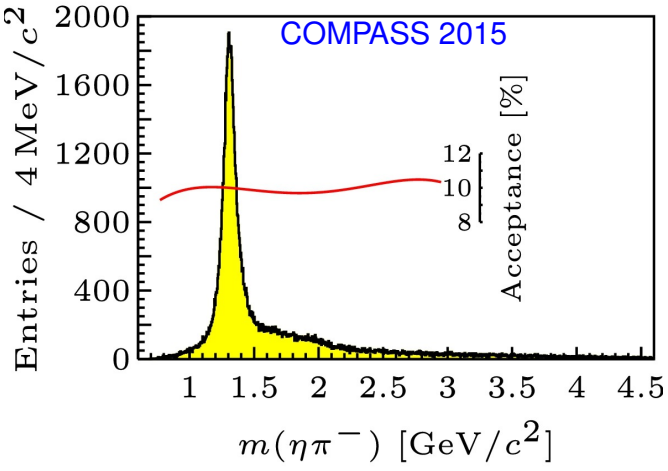
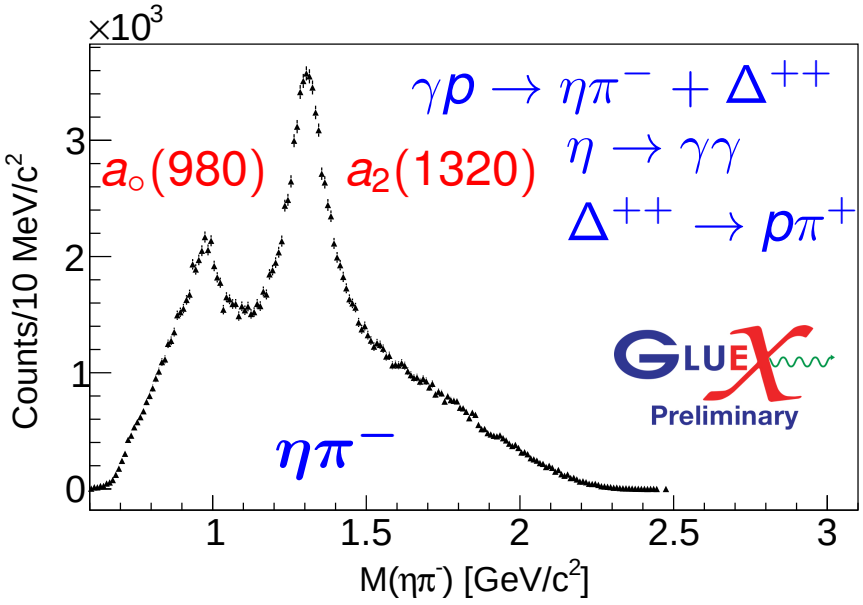
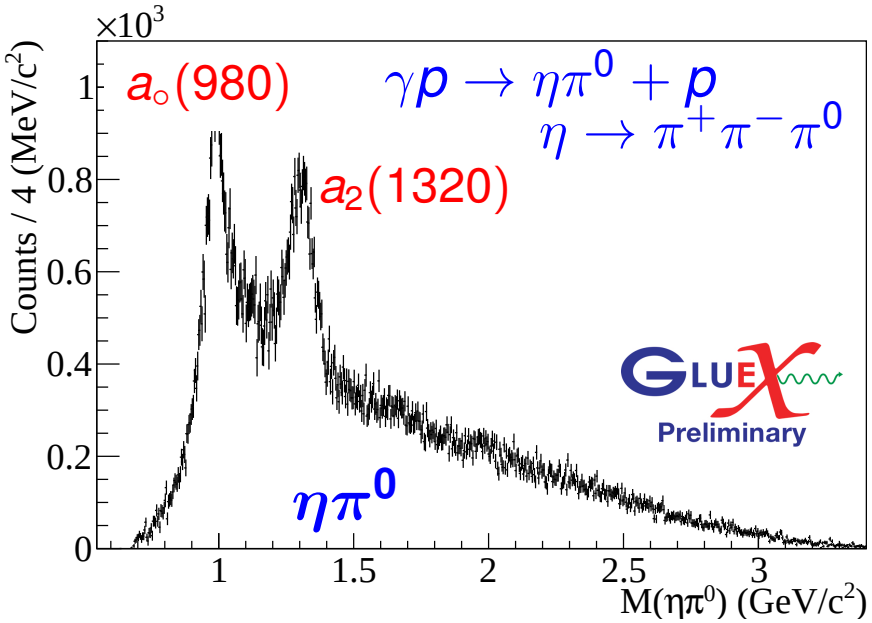
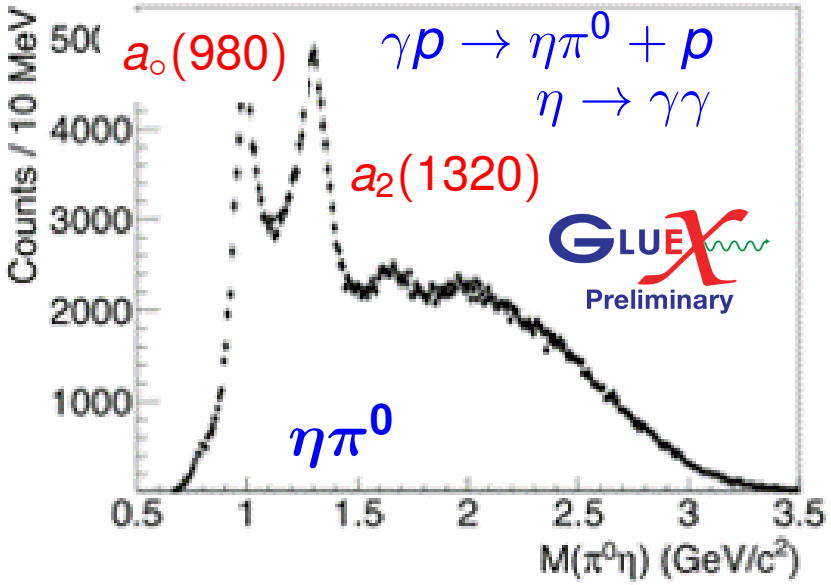




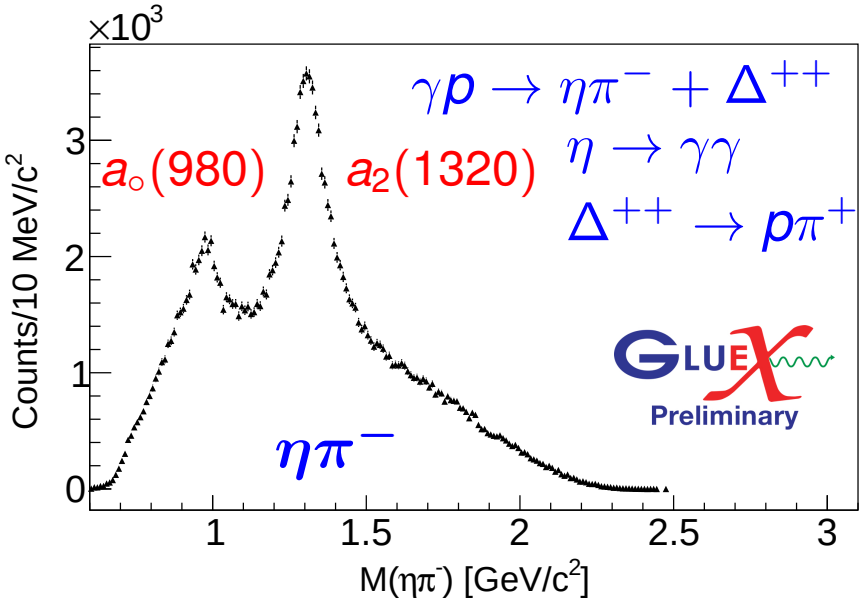


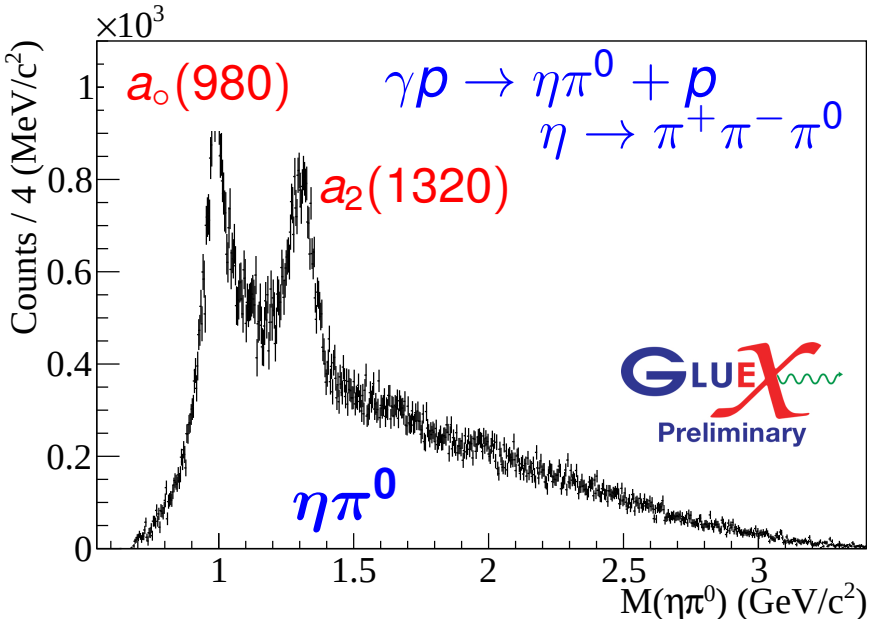


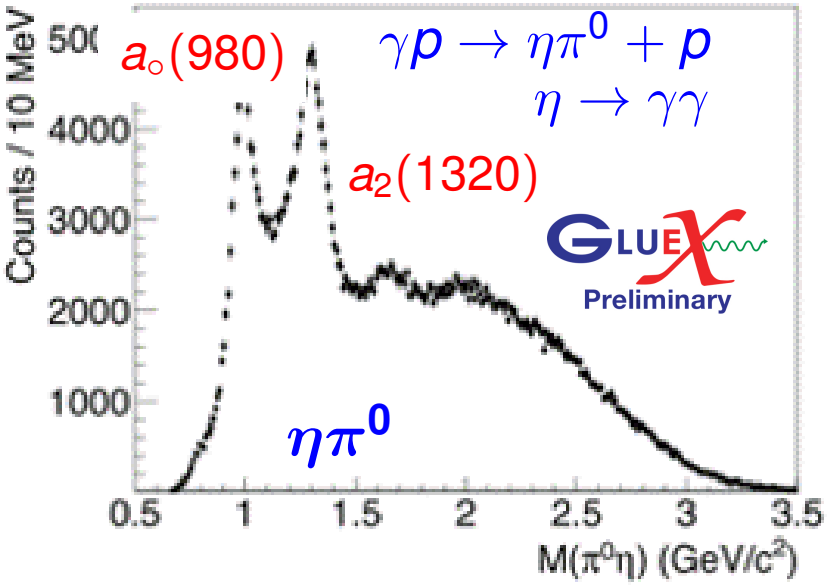
GlueX: Prospects for Spectroscopy in $\eta\pi$ Channels

About 20% of the GlueX-I data

- Analysis in progress for $\eta\pi$, $\eta'\pi$
- Well known states seen
- Expect a sample comparable to COMPASS(2015)



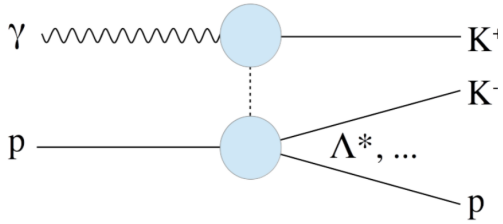


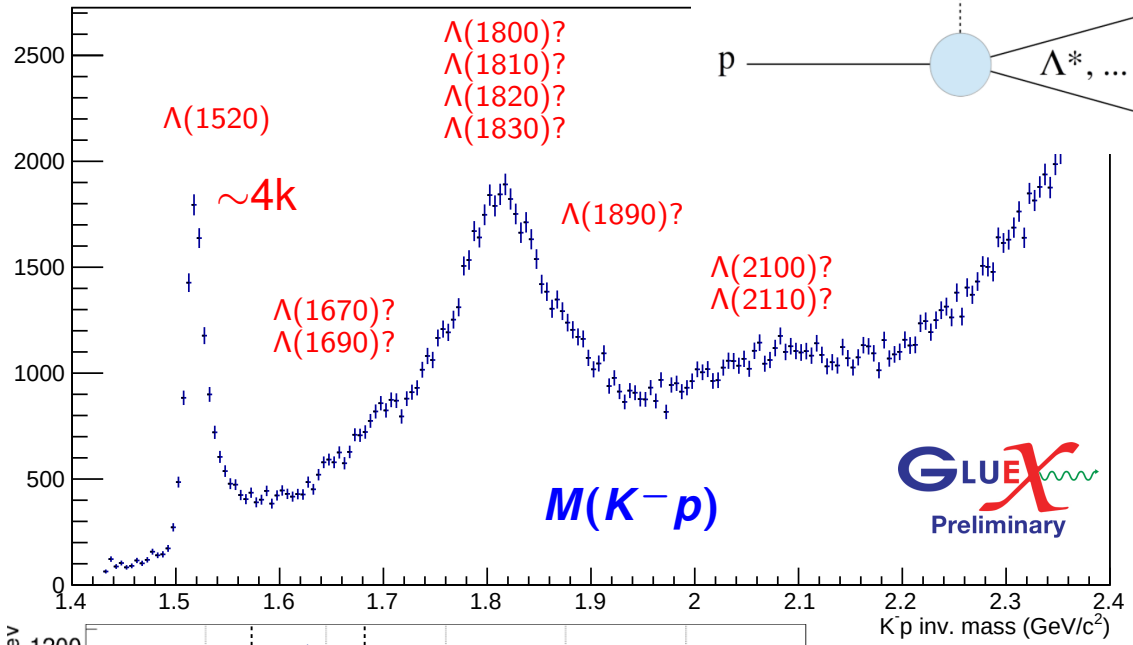


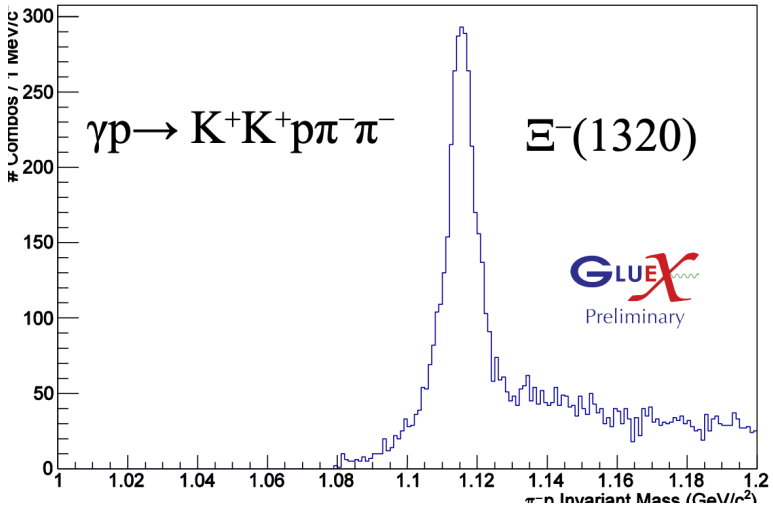
Hall D: Prospects for Studies of Strange Particles

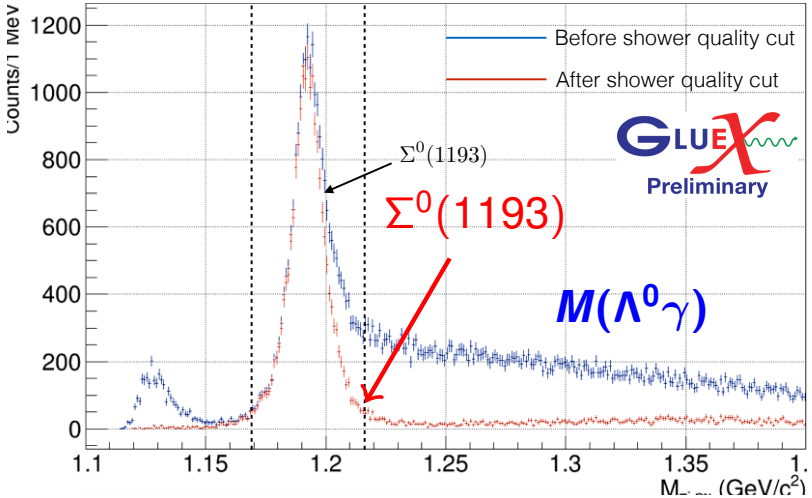
- GlueX-I experiment: data already taken
  - Statistics: $O(1\ M)$ of Λ^0
  - Beam asymmetries for reactions with $\Lambda^0, \Sigma^0, \Lambda(1520)$ etc
  - Cross sections for reactions with hyperons
- GlueX-II experiment: approved experiment, data taking 2019-2022
  - Statistics: $\times 4$ GlueX-I
  - New Cherenkov detector (DIRC) - $K^{\pm}$ identification improved
  - Search for hybrids decaying to kaons
  - Spectroscopy for strange mesons and hyperons
- KLF (K-Long Factory) proposal to PAC. If approved - running after 2024
  - Modification of the beam line $e^- \to \gamma \to K_L^0$, GlueX spectrometer
  - Expected 10 kHz of K_L^0 on LH_2 target
  - Search/identification of excited hyperons (PWA)
  - Study of poorly identified strange mesons as $0^{++}\kappa(800)$

GlueX-I: Strange Particles - Current Status









- 20% of the GlueX-I data
- Analysis in progress:
  beam asymmetry for $\Lambda(1520)$, Σ^0
  cross section for Ξ^-

Summary

- GlueX has accumulated a huge photoproduction data sample
- Early physics results from 20% of the data
  - First measurement of the reaction $\gamma p \to J/\psi p$ close to threshold
    Limits set on the LHCb pentaquarks $BR(P_c \to J\psi p)$
  - Measurements of beam-driven asymmetries for several reactions
- Prospects for further analysis
  - Full GlueX-I data sample: ready for analysis in the fall 2019:
    - Cross section measurements and calibration of the MC
    - Search for hybrids
    - Other opportunistic studies
- Next projects:
  - GlueX-II with better PID, next 3-4 years:
    hybrids, strange particles, other topics
  - Proposal for a K-Long beam