Current Status of *Hadronic Physics* *with*

GlueX *at* Jefferson Lab

*Igor Strakovsky**
The George Washington University
(for GlueX Collaboration)

Բարև Ձեզ!

Road to Tatev Monastery, 9th-century

- GlueX Project: Motivation.
- GlueX Experiment.
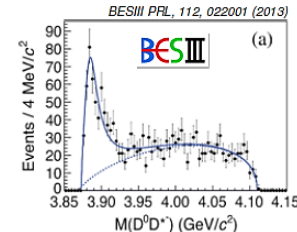 - Pseudoscalars.
  - Scalars & Tensors.
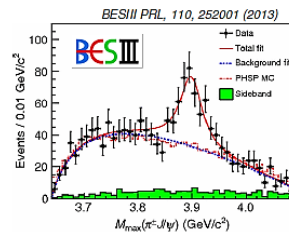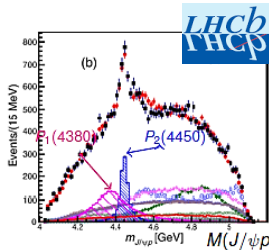 - Vectors.
  - Cascades.
- Summary.

GlueX Project

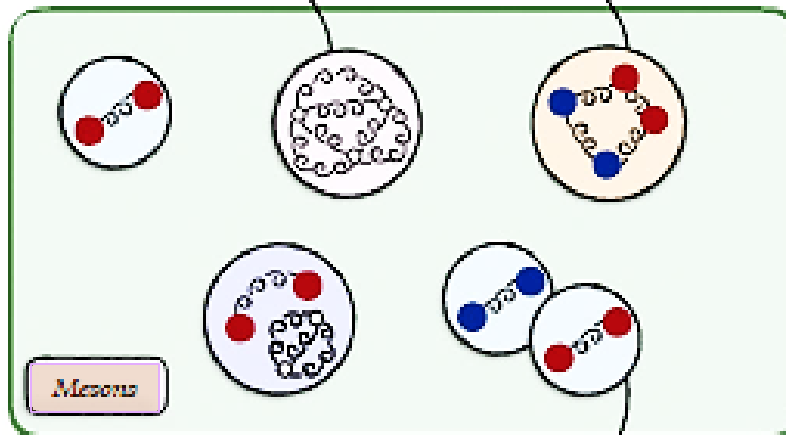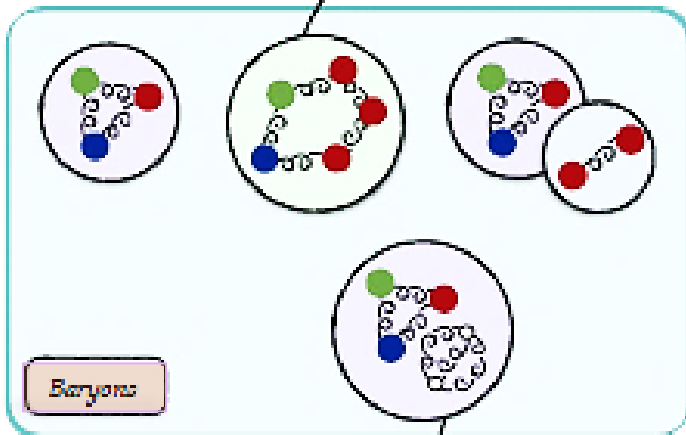*125+* members
from *26* institutions

Hadrons
QCD's rich spectrum

pentaquarks - LHCb (2015)

glueballs

tetraquarks - Belle (2003)

Baryons

Mesons

exotics & hybrids

molecules

JLab searches: CLAS12 GLUEX

CPHI, Yerevan, Armenia, September 2018   Igor Strakovsky   3

Primary goal of **GlueX** experiment is to search for & ultimately map out **spectrum** of **light quark hybrid mesons**.

Lightest Hybrid mesons
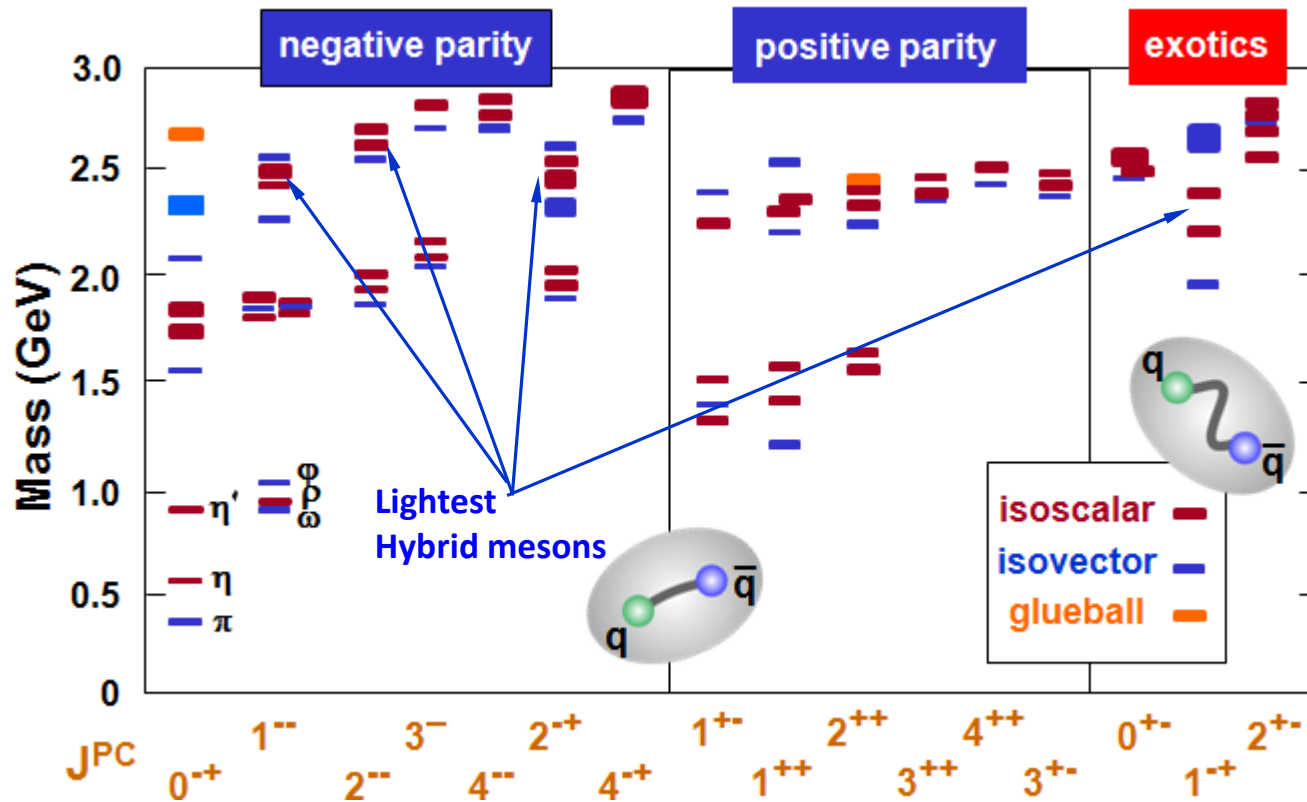
isoscalar
isovector
glueball

Low- & High-Energy Dynamics for Meson Photoproduction
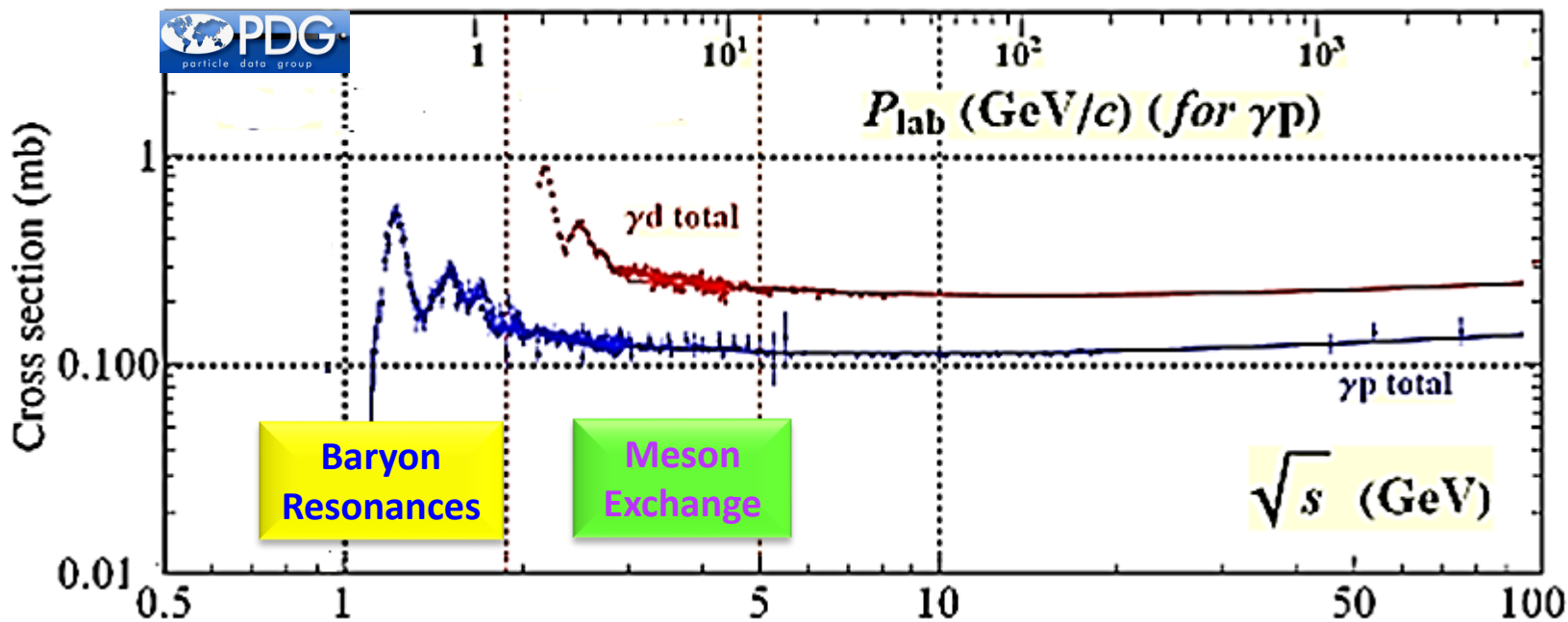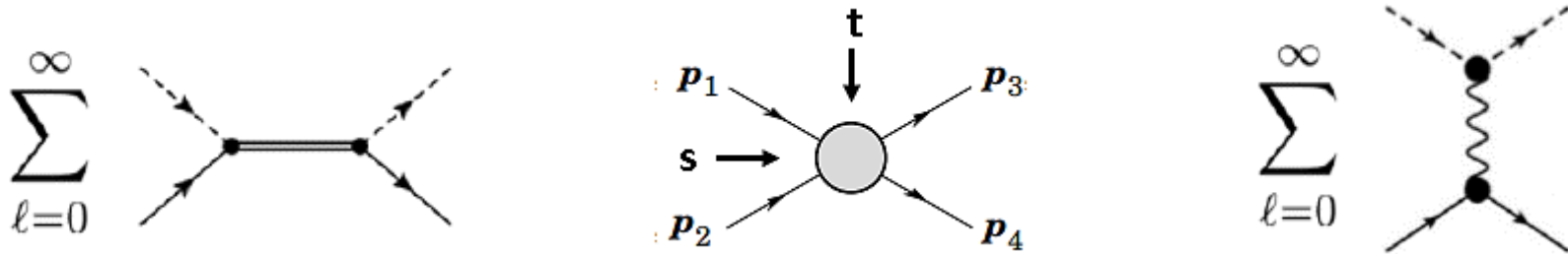
GlueX Experiment

Current Status: Begin by understanding non-exotic production mechanisms.

Type	S	L	J^P
Pseudoscalar	0	0	0^-
Pseudovector	0,1	1	1^+
Vector	1	0,2	1^-
Scalar	1	1	0^+
Tensor	1	1,3	2^+

Tatev Monastery, 9th-century

Hall D
(GlueX)
D

North
Linac

South
Linac

A
B
C

Experimental
Halls A/B/C

D

CHL

A   B   C
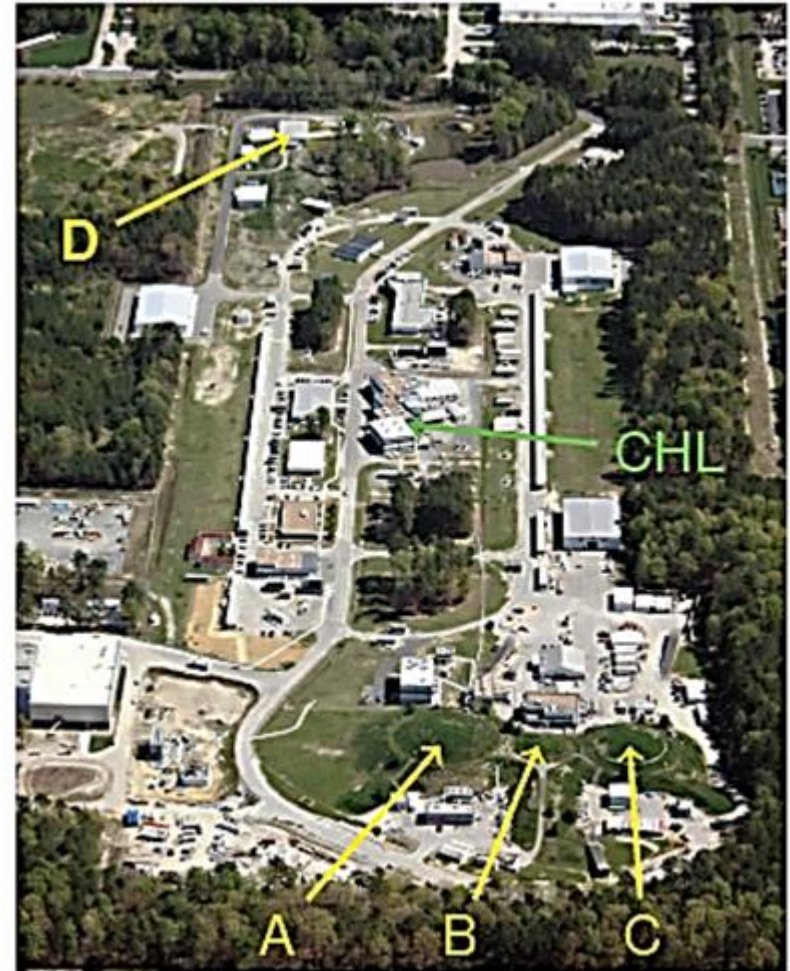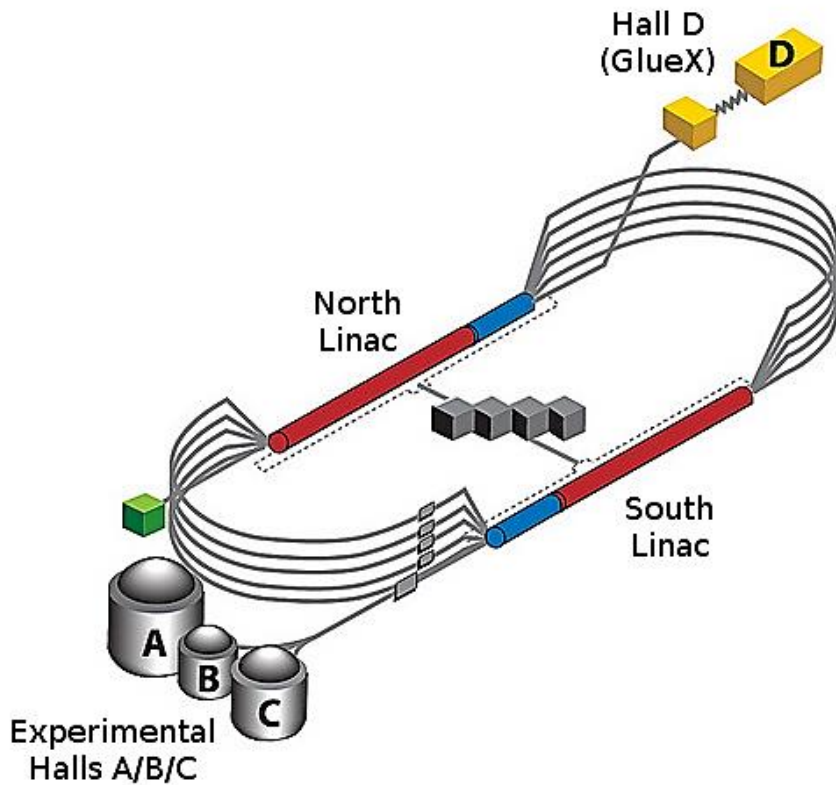
- Accelerator: 2.2 GeV/pass
- Halls A,B,C: e^- 1-5 passes $\leq$11 GeV
- Hall D: e^- 5.5 passes 12 GeV $\Rightarrow$ γ-beam
- Runs 2017-2018: 5.5 passes 11.7 GeV

12 GeV e⁻
North LINAC

East ARC

Photon Tagger

Diamond Radiator

Electron Beam Dump

γ 75 m

Pair Spectrometer & Triplet Polarimeter

Collimator

GlueX Spectrometer

Photon Beam Dump

Photon Beam Spectrum

(a)
Photon Flux (Arb. Units)
— Diamond: PARA
— Diamond: PERP
— Aluminum

9GeV

Flux

(b)
Polarization
• PARA
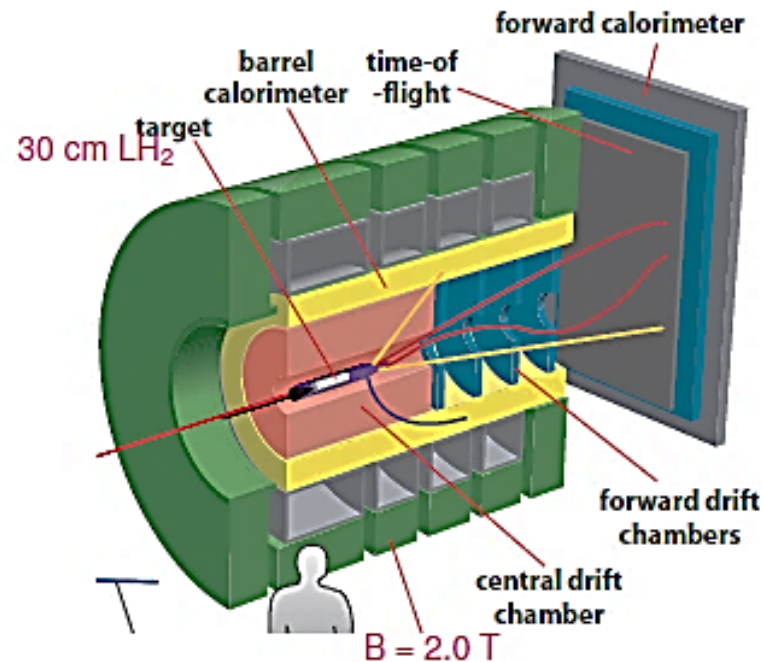■ PERP

$P \approx 40\%$

1.5% Syst. Uncert.

Photon Beam Energy (GeV)

30 cm LH₂ target

barrel calorimeter

time-of-flight

forward calorimeter

forward drift chambers

central drift chamber

B = 2.0 T
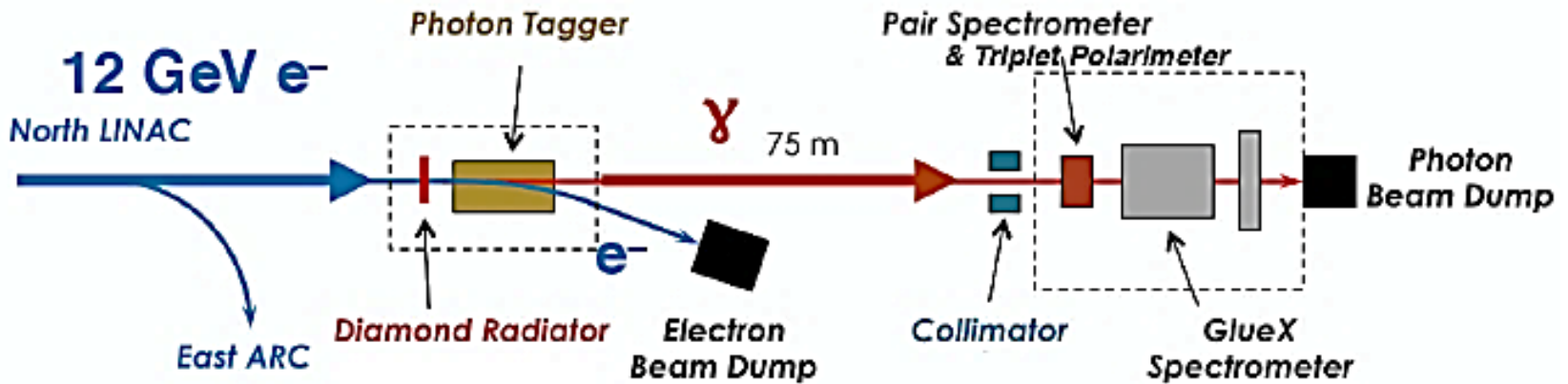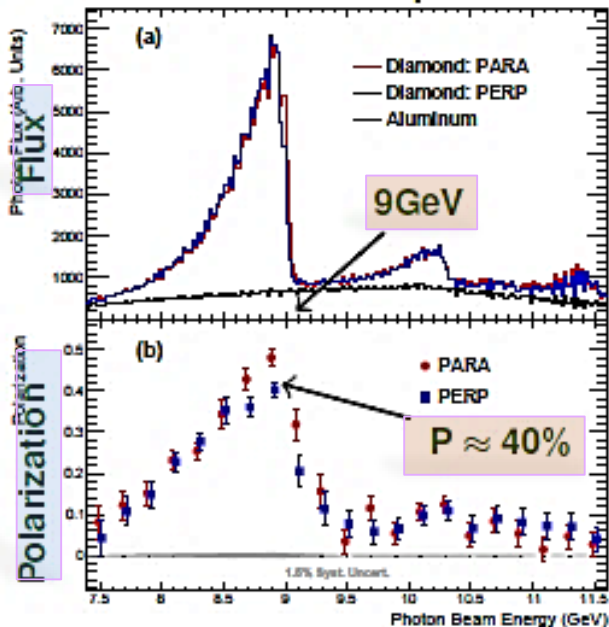
Hall D

RAPID COMMUNICATIONS

1st paper

PHYSICAL REVIEW C 95, 042201(R) (2017)

Measurement of the beam asymmetry Σ for π^0 and η photoproduction on the proton at $E_\gamma = 9$ GeV
(GlueX Collaboration)
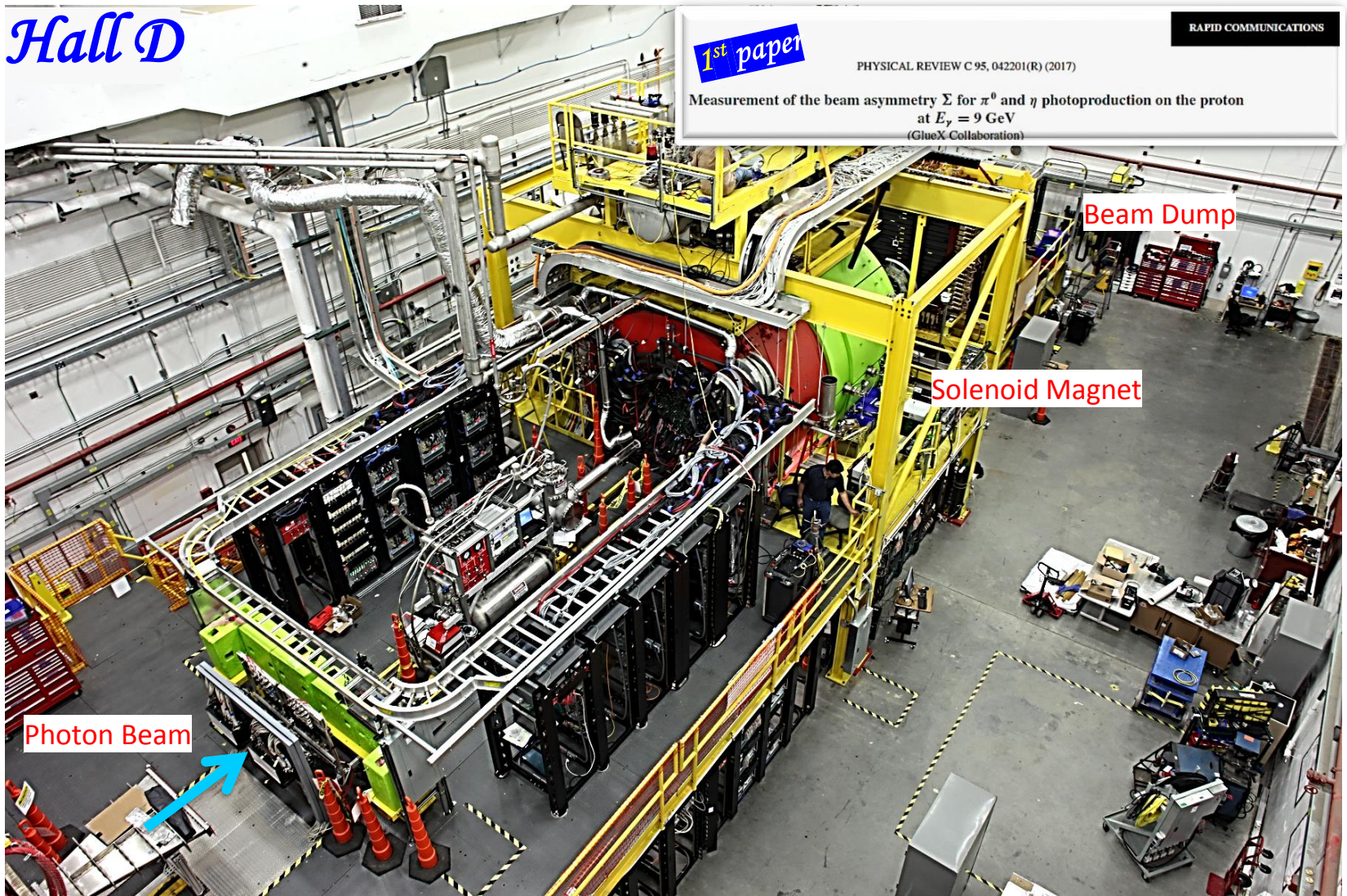
Beam Dump

Solenoid Magnet

Photon Beam

GlueXcitations Xperiment **Statistics:** **above 8.2 GeV**

Spring **2016**: **10 pb^{-1}** ⟹ Source for the 1st paper

Spring **2017**: **45 pb^{-1}**

Spring **2018**: **100 pb^{-1}**

Fall **2018**: in progress

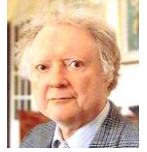# *Photoproduction of Pseudoscalar Mesons*
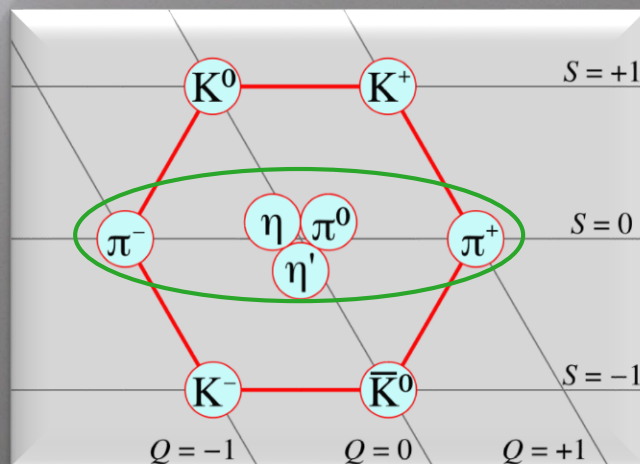
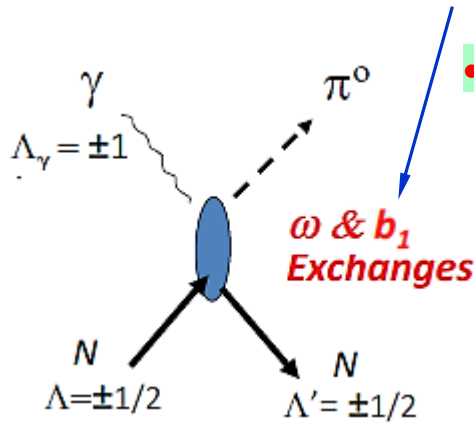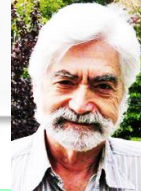$J^P = 0^-$

Regge Pole Model
with Regge-cut corrections

IL NUOVO CIMENTO VOL. XXXII, N. 3 1º Maggio 1964

The Reaction $\gamma + N \rightarrow \pi + N$ at High Energies

G. ZWEIG

γ
$\Lambda_\gamma = \pm 1$
π^0
ω & b_1 **Exchanges**
N
$\Lambda = \pm 1/2$
N
$\Lambda' = \pm 1/2$

- There were no b_1 mesons back to **1964**.

- **Regge cut** amplitudes are incorporated into some models & are interpreted as re-scattering of on-shell meson-nucleon amplitudes.
- ω-exchange is dominant in π^0 photoproduction. That is unique case in **meson photoproductions** – **single** trajectory.
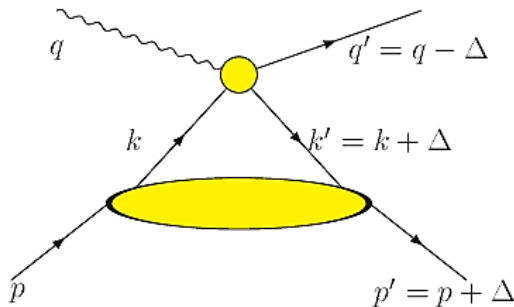
Handbag Model
with twist-3 contribution

H.W. Huang & P. Kroll, Eur Phys J C **17**, 423 (2000)

q
$q' = q - \Delta$
k
$k' = k + \Delta$
p
$p' = p + \Delta$

- Reaction is factorized into **two** parts:
  - One quark from incoming & one from outgoing nucleon participate in hard sub-process, which is calculable using **pQCD**.
  - Soft part consists of all other **partons** that are spectators & can be described in terms of **GPD**s.

Σ *Beam Asymmetry* *for* $\vec{\gamma}p \rightarrow p\pi^0$

$$\gamma p \rightarrow p\gamma\gamma$$
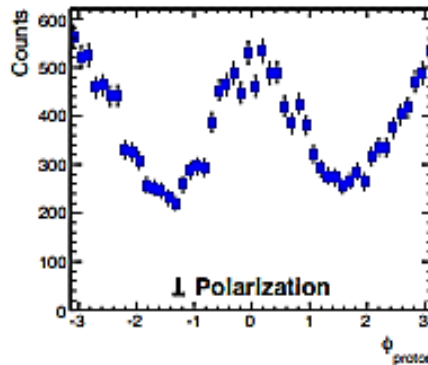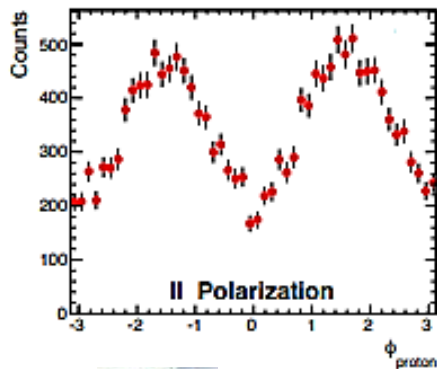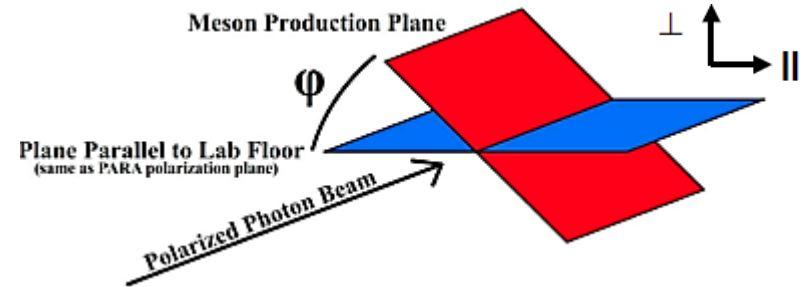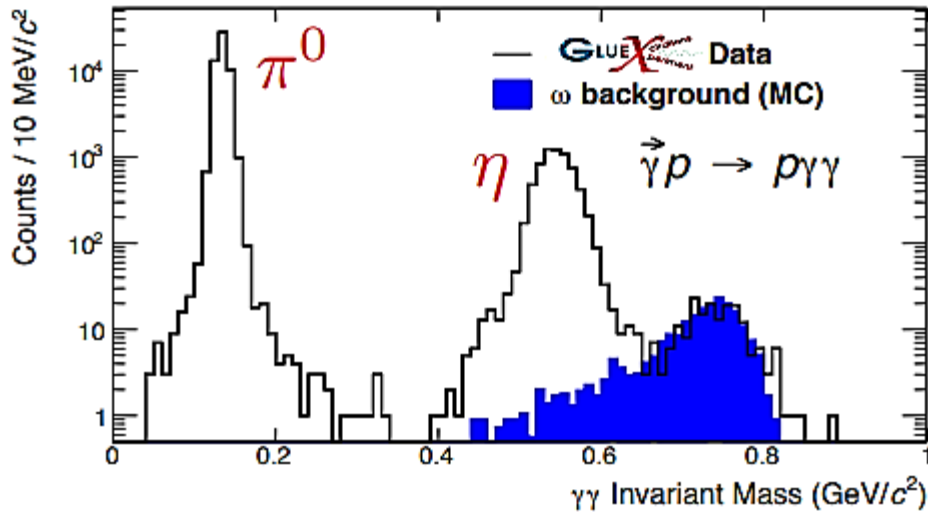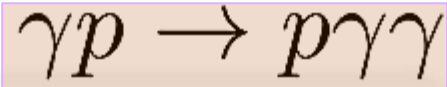
$$\sigma = \sigma_0 \left(1 - P_\gamma \Sigma \cos 2(\phi_p - \phi_\gamma^{\text{lin}})\right)$$

Courtesy of Justin Stevens, 2017
Courtesy of Zhenyu Zhang, 2017

$\vec{\gamma}p \rightarrow p\pi^0$

2016

GlueX

2.1% Norm. Uncert.

GlueX $8.4 < E_\gamma < 9.0$ GeV [2017]
SLAC $E_\gamma = 10$ GeV [1971]

$-t$ [(GeV/c)^2]

$s^7 d\sigma/dt$ (μb GeV^{12})

5425 MeV

CLAS

10^3

$\cos\theta_\pi$

6 ⟵ t ⟶ 2 (GeV/c)^2
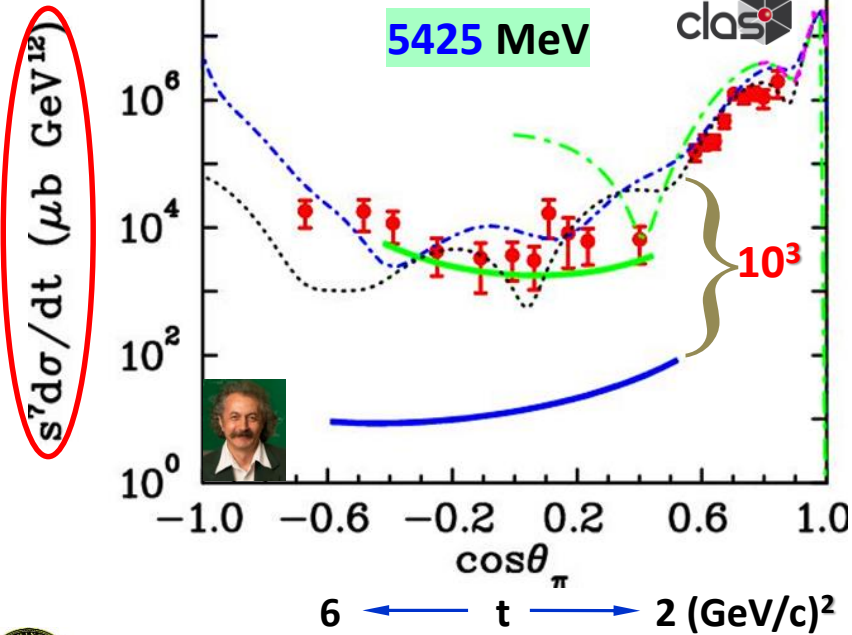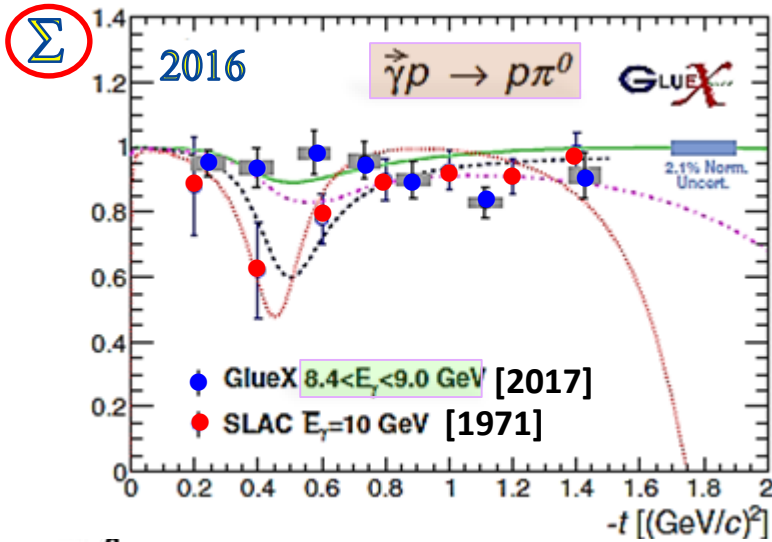
- GlueX Σ closes to **unity**.

- There is some **disagreement** between GlueX & SLAC measurements.

- **Mike Dugger**:
  At **dip**, SLAC had huge background from **Compton**.

- Preliminary 2017 confirms 2016 data sample.

- **Dip** at $|t| \sim$ **0.5** (GeV/c)^2 in multiple **Regge** predictions observed.

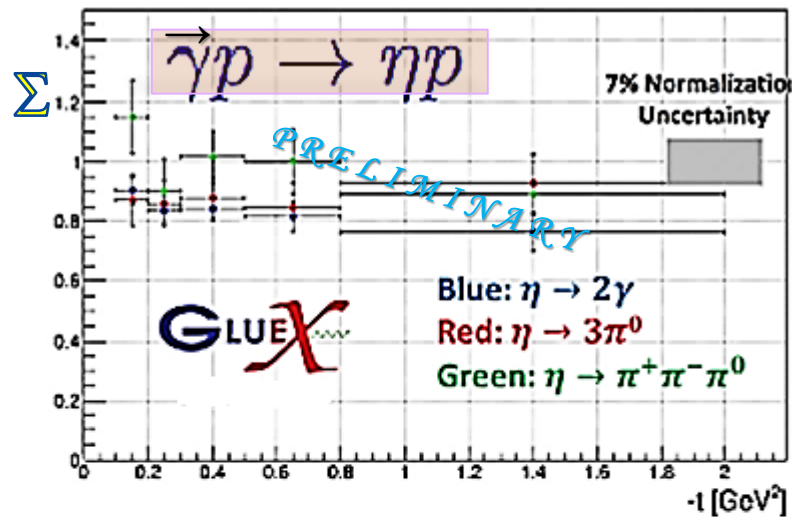|		
··········	**Goldstein73**	H. Al Ghoul *et al,*
— · — · —	**Laget11**	Phys Rev **95**, 042201(R) (2017)
————	**Mathieu15**	
- - - - -	**Donnachie16**	

- **Regge** exchange based models for π^0 photoproduction are more consistent with CLAS experimental data.

- **Size** of angular distribution of measured CLAS cross sections is greatly **underestimated** by **QCD** based **GPD** mechanism at **s = 11** GeV^2.

- Numerical studies **reveal** dominance of **twist-3** contribution.

··········	**Goldstein73**		————	**Kroll00**
— · — · —	**Laget11**		————	**Kroll18**
— · — · —	**Mathieu15**			M. Kunkel *et al,*
— · — · —	**Donnachie16**			Phys Rev C **98**, 015207 (2018)

Σ *Beam Asymmetry for* $\vec{\gamma}p \to \eta p$ & $\vec{\gamma}p \to \eta'p$

$\vec{\gamma}p \to \eta p$

PRELIMINARY

Blue: $\eta \to 2\gamma$
Red: $\eta \to 3\pi^0$
Green: $\eta \to \pi^+\pi^-\pi^0$

7% Normalization Uncertainty

-t [GeV²]

$\vec{\gamma}p \to \eta'p$

PRELIMINARY

Normalization Uncertainty (7%)

-t (GeV²)

- **First** high-energy measurements.
- **Σ** closes to **unity**.
- Preliminary 2017 confirms 2016 data η sample.
- Dominated by **vector**-meson exchange.
- Consistent with J^{PAC} predictions.

V. Mathieu *et al,* Phys Lett B **774**, 362 (2017)

$\eta, \ \eta'$
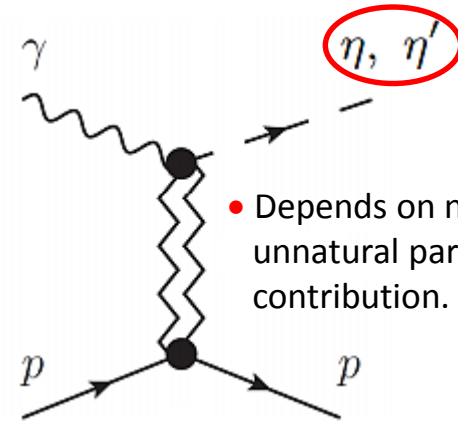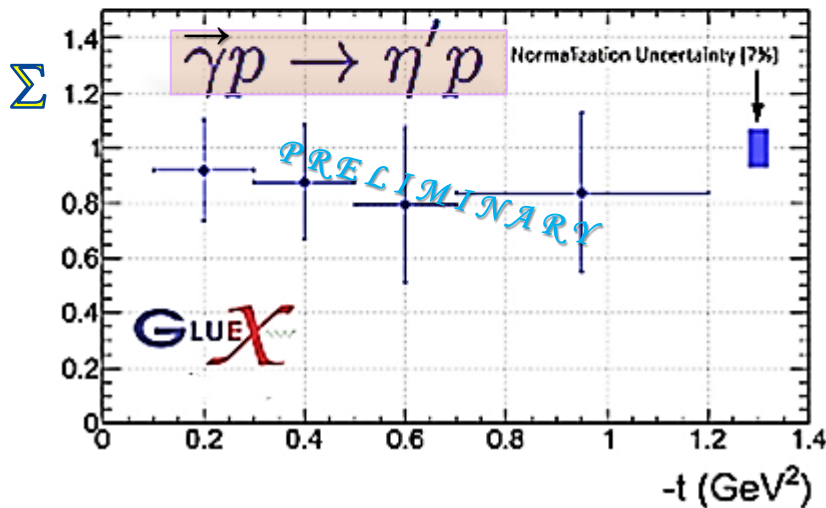
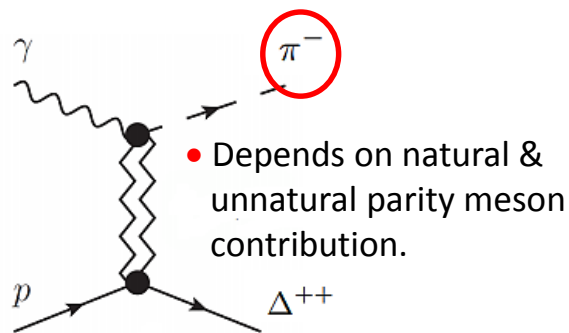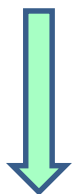- Depends on natural & unnatural parity meson contribution.

Courtesy of William McGinley, 2018
Courtesy of Teagan Beattie, 2018

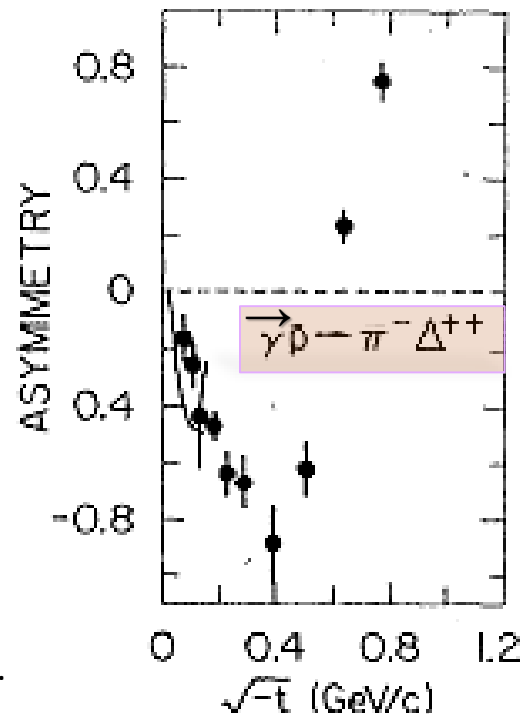$\vec{\gamma}p \rightarrow \pi^-(\pi^+ p)$ or $(\pi^- \pi^+)p$

Early Spectroscopy Opportunity

- Depends on natural & unnatural parity meson contribution.

SLAC @16 GeV

B.-G. Yu *et al,* Phys Lett B **769**, 262 (2017)

J. Nys *et al,* Phys Lett B **779**, 77 (2018)

J^{PAC}

Σ

- More complicated **t**-dependence.

D. J. Quinn *et al,* PRD **20**, 15553 (1979)

Courtesy of Jonathan Zarling, 2018

$$\vec{\gamma}p \rightarrow \pi^-(\pi^+p) \text{ or } (\pi^-\pi^+)p$$

Early Spectroscopy Opportunity

SLAC @ 20 GeV

$f_2(1270)$?

ρ' ?

$\rho(770)$
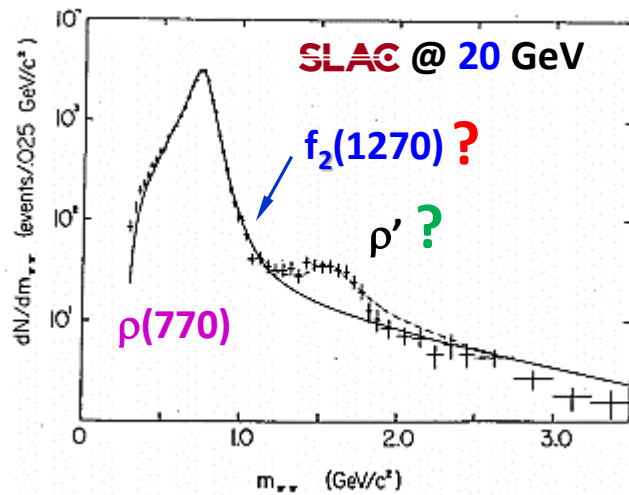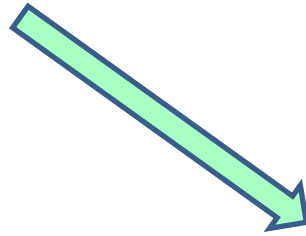
K. Abe *et al.* Phys Rev Lett **53**, 751 (1984)

$f_2(1270)$

GlueX

ρ'?

PRELIMINARY

$\rho(770)$
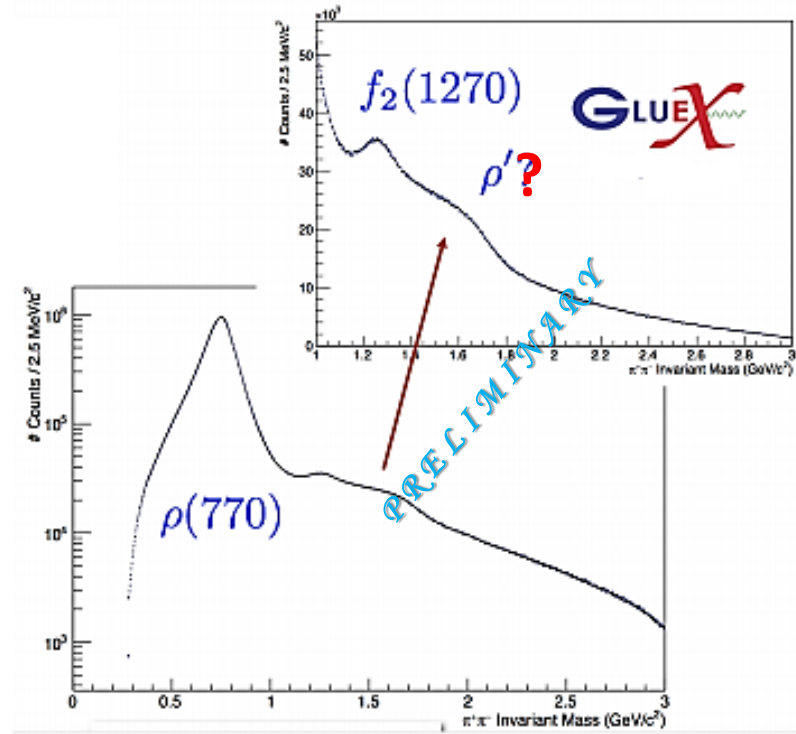
Courtesy of Jonathan Zarling, 2018

- Enhancement of GlueX consistent with early SLAC measurements but **1000x** more statistics.

Photoproduction of
Scalar & Tensor Mesons

$J^P = 0^+$

$J^P = 2^+$

a₀(980) MASS

VALUE (MeV)	DOCUMENT ID	
980±20 OUR ESTIMATE	Mass determination very model dependent	

a₀(980) WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
50 to 100 OUR ESTIMATE		Width determination very model dependent			

a₀(980) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	$\eta\pi$	dominant
Γ_2	$K\overline{K}$	seen
Γ_3	$\rho\pi$	
Γ_4	$\gamma\gamma$	seen
Γ_5	e^+e^-	

Input: $\pi^- p \to \eta\pi^- p$ @ **191** GeV/c

A. Jackura *et al,* Phys Lett B **779**, 464 (2018)
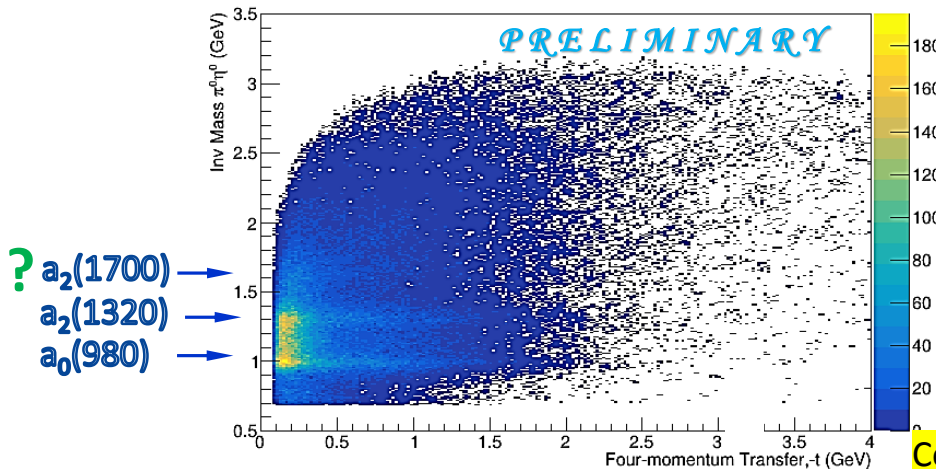
C. Adolph *et al,* Phys Lett B **740**, 303 (2015)

a₂(1320)
$M = 1305.8 \pm 0.9$ MeV
$\Gamma = 114.4 \pm 1.7$ MeV

a₂(1700)
$M = 1724 \pm 15$ MeV
$\Gamma = 247 \pm 19$ MeV

J^{PAC}

PRELIMINARY
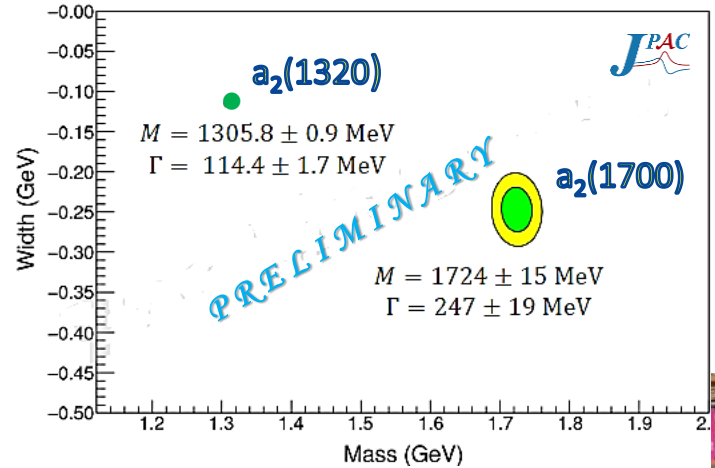
Courtesy of Alessandro Pilloni, 2018

$\gamma p \to p\pi^0\eta \to p4\gamma$

$\pi^0\eta$ invariant mass vs -t

PRELIMINARY

? a₂(1700)
a₂(1320)
a₀(980)

Courtesy of Stuart Fegan, 2018

Σ *Beam Asymmetry* for $\vec{\gamma}p \rightarrow a_0(980)p$

BROOKHAVEN NATIONAL LABORATORY

E852

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

@ 18 GeV/c

$a_2(1320)$

$a_0(980)$

$a_2(1700)$?
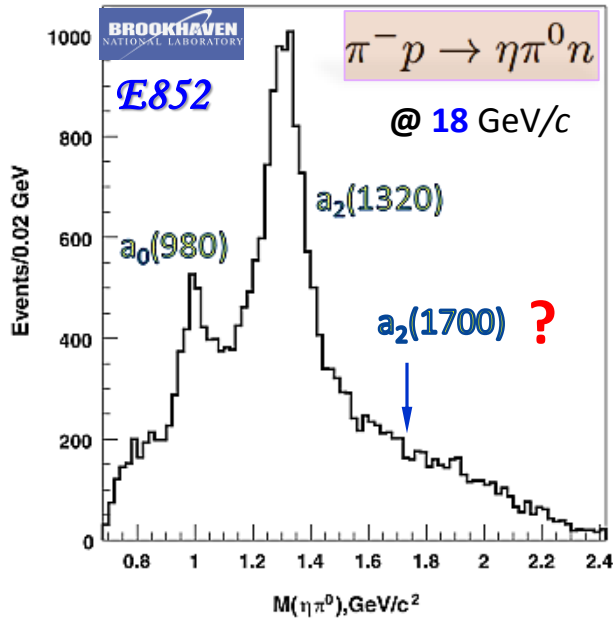
G.S. Adams *et al*, *Ph*ys Lett B **657**, 27 (2007)

$\gamma p \rightarrow p\pi^0\eta \rightarrow p4\gamma$

@ 9 GeV

$a_0(980)$

$a_2(1320)$

PRELIMINARY

$a_2(1700)$?

GLUEX citations Xperiment

Courtesy of Stuart Fegan, 2018


$\frac{d\sigma}{dt}$

3.5 GeV

5 GeV

9 GeV

- Model for **a_0** was extend π^0 one to incorporate **Regge cuts**, based on knowledge of π^0 photoproduction.
- One can expect that Σ for π^0 is similar to Σ for **a_0**.

- GLUEX citations Xperiment Data are coming in a month or so.
- Theoretical prediction is coming same time.

please stay tuned.
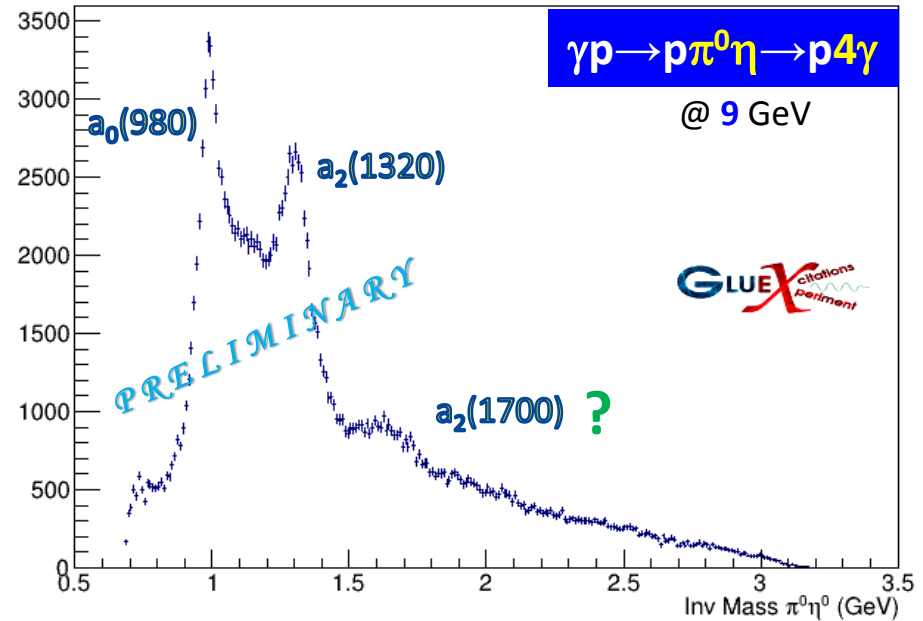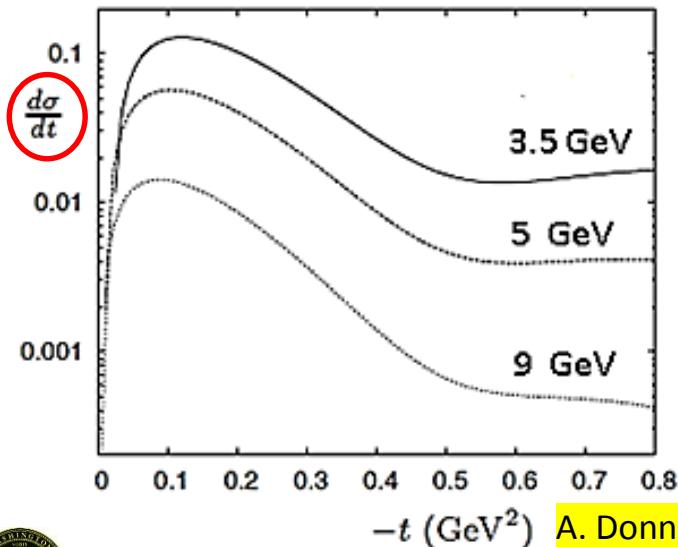
A. Donnachie & Yu. Kalashnikova, Phys Rev C **93**, 025203 (2016)

Photoproduction of Vector Mesons

$$J^P = 1^-$$

CPHI, Yerevan, Armenia, September 2018
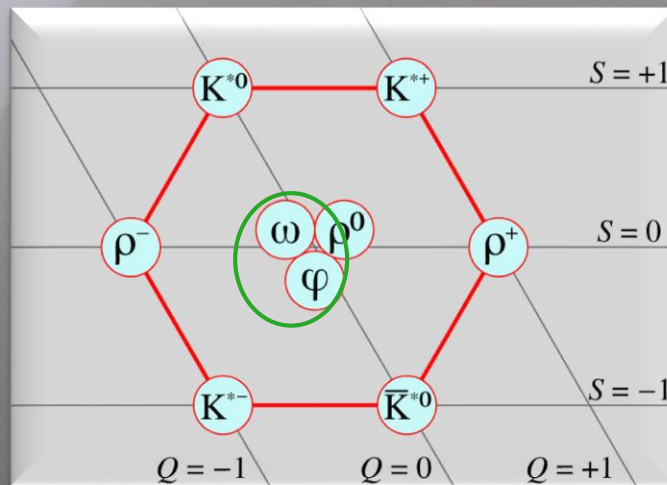
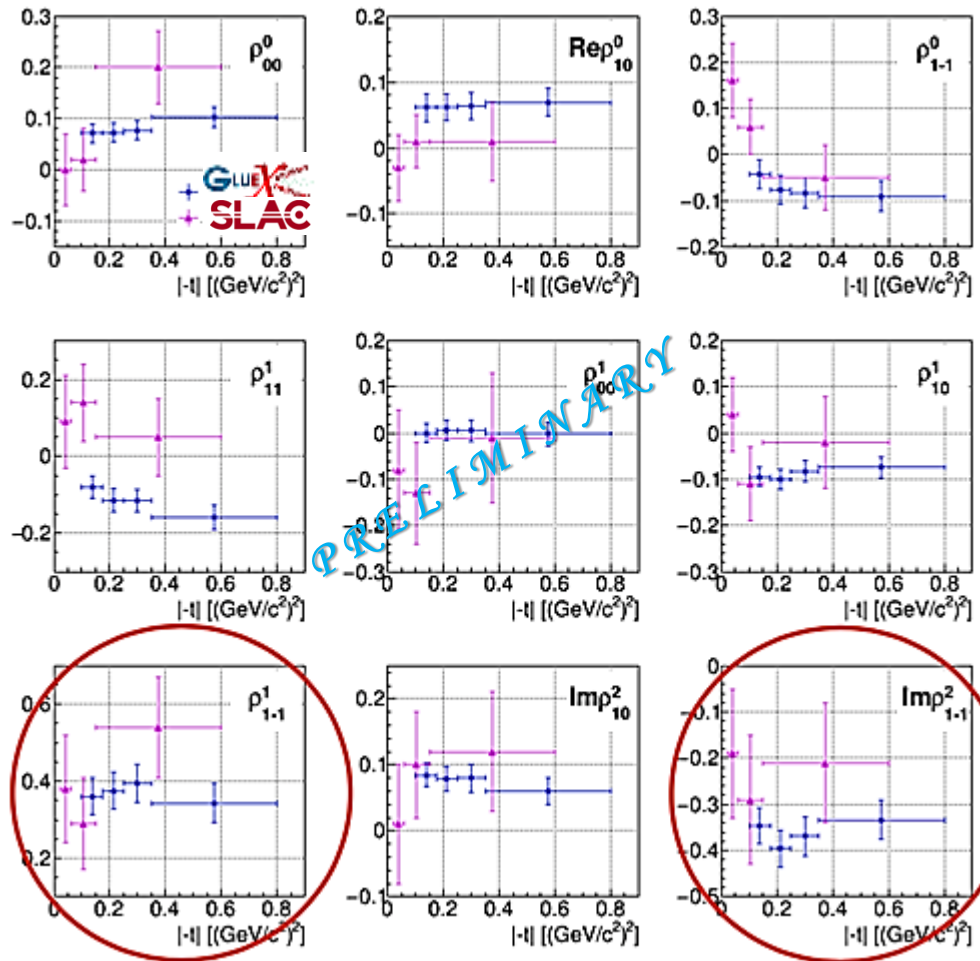# $\gamma p \rightarrow \omega p$ $\omega \rightarrow \pi^+\pi^-\pi^0$

- **Spin density matrix elements**: measure transfer polarization from **photon** to **vector meson**.

- Expect contributions from **pseudoscalar** exchange.
- **Consistent** with previous SLAC results.
- Provides **insight** into exchange mechanisms.
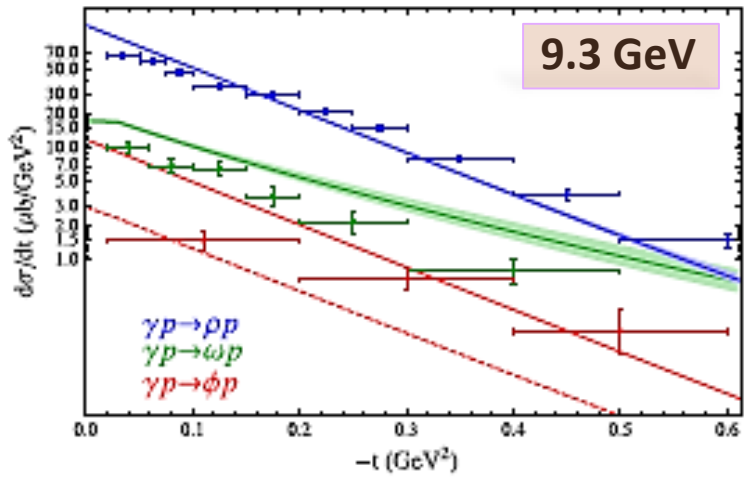- Consistent with **s**-channel **helicity** conservation.
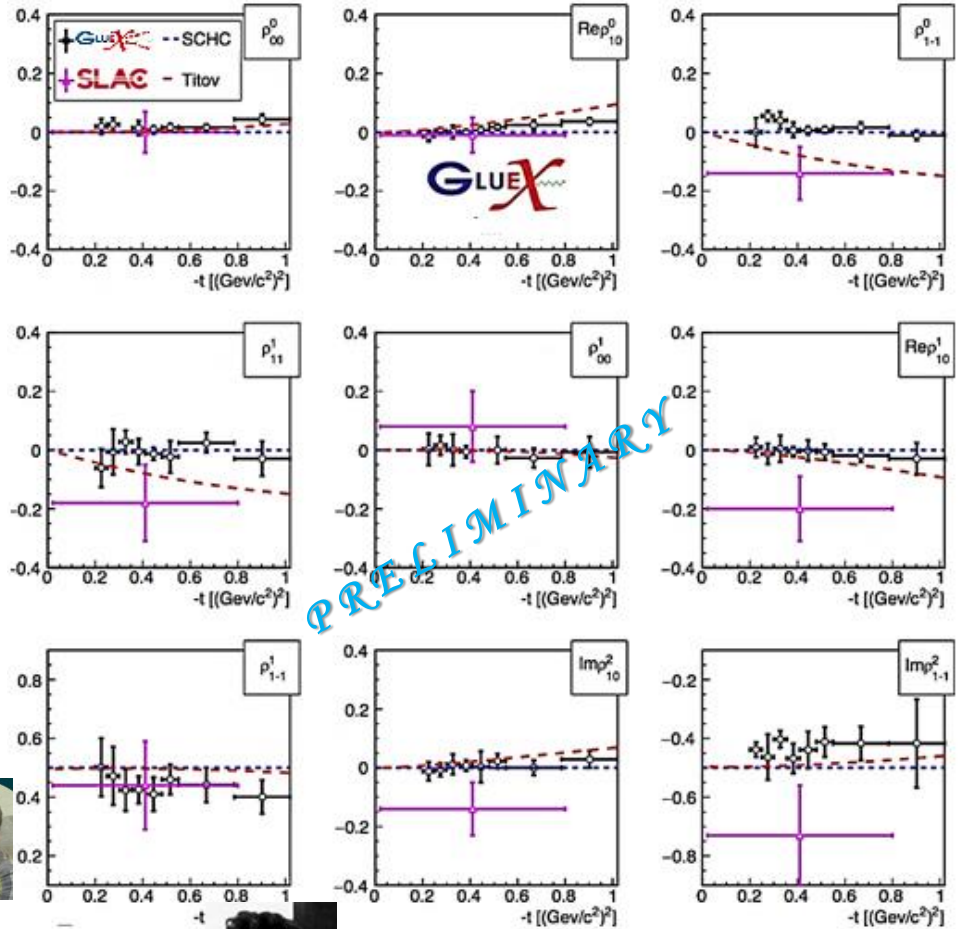

Courtesy of Michael Staib, 2018

$$\gamma p \longrightarrow \phi p \qquad \phi \to K^+ K^-$$

- **Spin density matrix elements**: measure transfer polarization from **photon** to **vector meson**.

SLAC J. Ballam *et al,* Phys Rev D **7**, 3150 (1973)

J^{PAC} V. Mathieu *et al,* Phys Rev D **97**, 094003 (2018)

9.3 GeV

$\gamma p \to \rho p$
$\gamma p \to \omega p$
$\gamma p \to \phi p$

Courtesy of Alex Barnes, 2018

PRELIMINARY

- Consistent with **s**-channel **helicity** conservation.
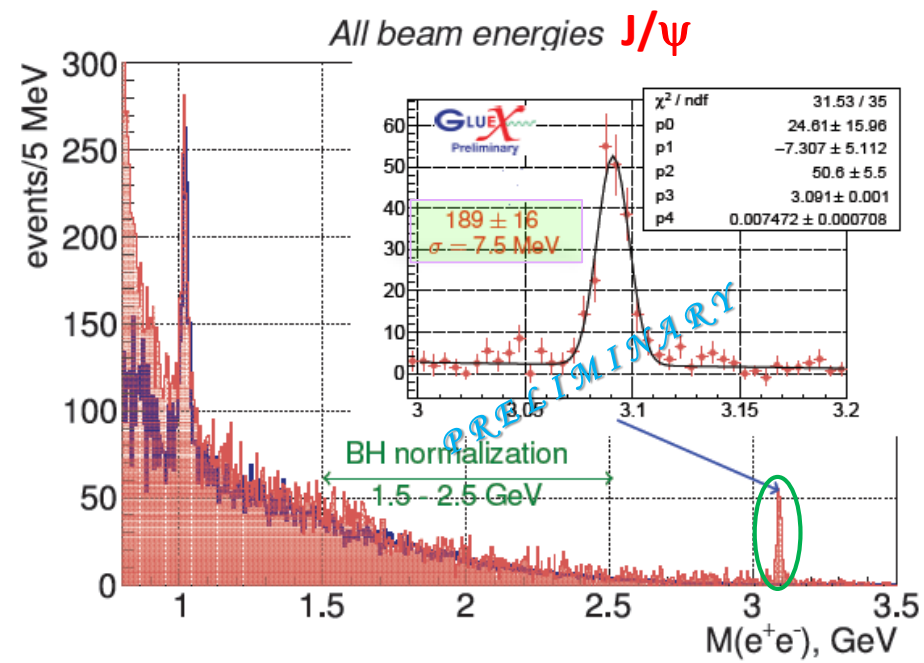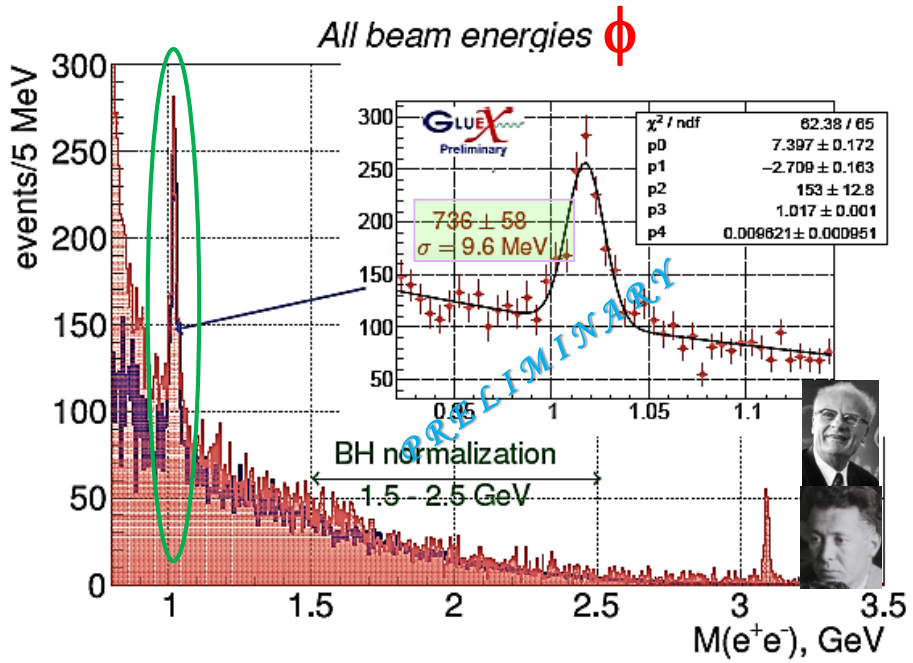
- Production mechanism dominated by **Pomeron** exchange.

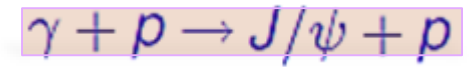# J/ψ Photoproduction at Threshold

$$J^P = 1^-$$

CPHI, Yerevan, Armenia, September 2018

$$\gamma p \rightarrow p e^+ e^-$$

- Preliminary **cross sections** measured for E_γ = **8.2–12 GeV**

- **Statistics**: **2016+2017** data sample (**70 %**)

All beam energies φ

All beam energies J/ψ

- Other experiments at **Jefferson Lab** (**CLAS** & Hall **C**) have been scheduled to near future to measure same process.

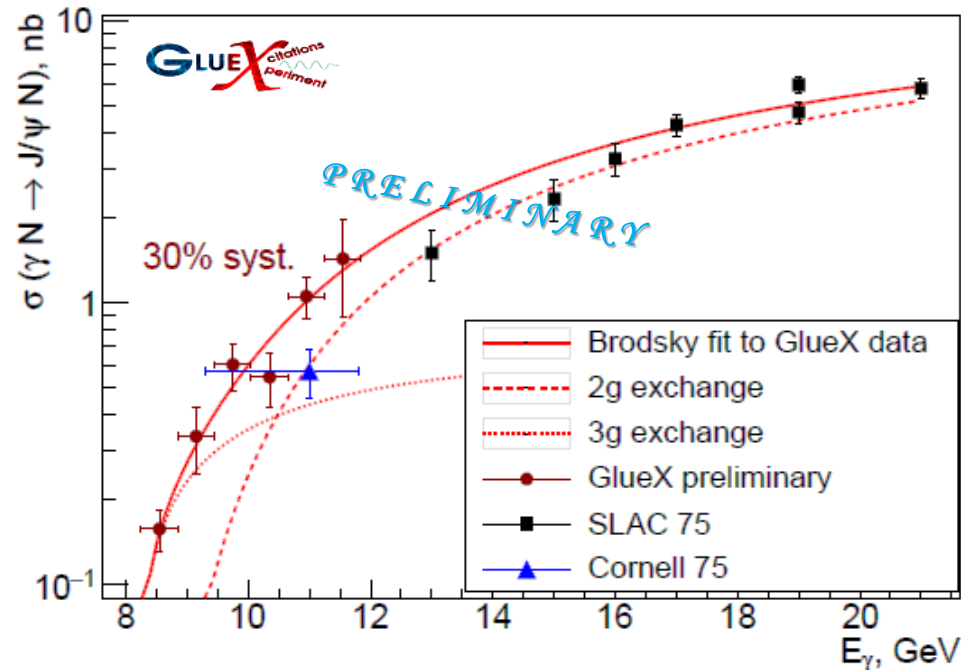$$\gamma + p \rightarrow J/\psi + p$$

- Threshold **J/ψ** provides info on
  - **Multiquark correlations**.

    S. Brodsky *et al,* Phys Let B **498**, 23 (2001)
  - **Gluon distributions** in nucleon.

    D. Kharzeev *et al,* Eur Phys J C **9**, 459 (1999)

- Best fit using **Brodsky**'s parametrization reproduces **GlueX** & **SLAC** data well.

- **SLAC**

  U.Camerini et al, PRL 35 (1975)
  Calculated from the measured
  $\frac{d\sigma}{dt}|_{t=tmin}$ assuming
  $\frac{d\sigma}{dt} \propto e^{a \cdot t}$, $a = 2.9 \pm 0.3$ GeV^{-2}
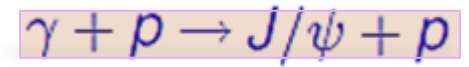 measured at 19 GeV

- B.Gittelman et al, PRL 35 (1975)
  t-slope $a = 1.25 \pm 0.2$ GeV^{-2}
  horizontal error bar represents
  the acceptance

$$\gamma + p \rightarrow J/\psi + p$$

- Threshold **J/ψ** provides info on
  - **Multiquark correlations**.
   S. Brodsky *et al*. Phys Let B **498**, 23 (2001)
  - **Gluon distributions** in nucleon.
    D. Kharzeev *et al*. Eur Phys J C **9**, 459 (1999)

- At **low energies** photoprod **amplitude** is proportional to matrix element of gluon part of trace of QCD energy-momentum tensor evaluated over nucleon state; this quantity arises from **scale anomaly** of QCD.

- Resulting contribution to photoprod **amplitude** is **real !**.

- Low-energy **J/ψ** photoprod data can thus be used to **extract fraction of nucleon's mass** arising from gluons, & corresponding spatial distribution.
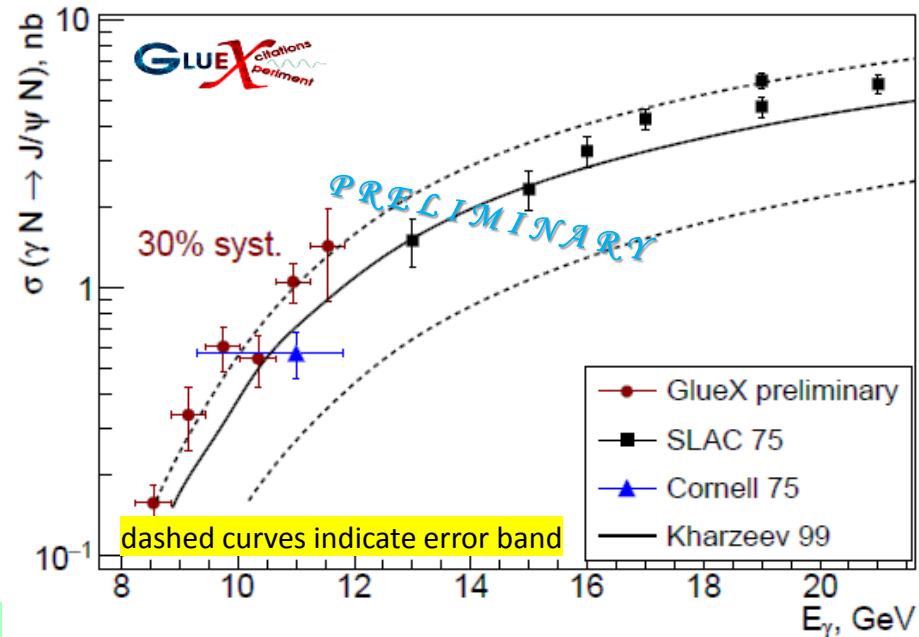
SLAC
U.Camerini et al, PRL 35 (1975)
Calculated from the measured
$\frac{d\sigma}{dt}\big|_{t=tmin}$ assuming
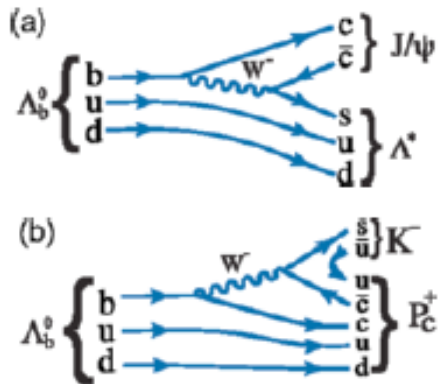$\frac{d\sigma}{dt} \propto e^{a \cdot t}$, $a = 2.9 \pm 0.3$ GeV^{-2}
measured at 19 GeV

B.Gittelman et al, PRL 35 (1975)
t-slope $a = 1.25 \pm 0.2$ GeV^{-2}
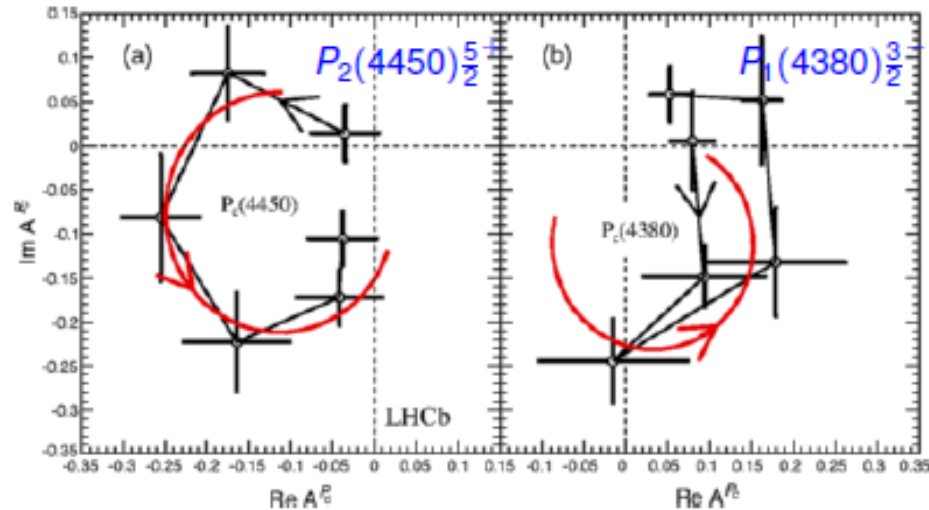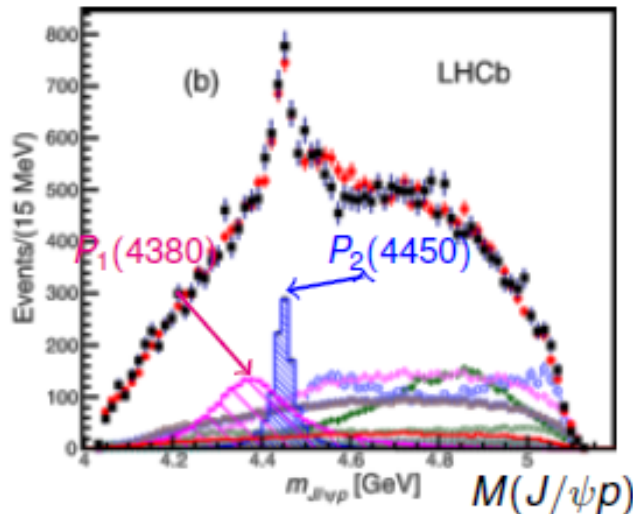horizontal error bar represents the acceptance

Courtesy of Lubomir Pentchev, 2018

$\Lambda_b^0 \to K^- (J/\psi p)$

- No indications of $\Lambda^* \to K^- p$ reflections to $J/\psi p$
- PWA leads to two states for $P_c^+ \to J/\psi p$:
  - $M_1 = 4380 \pm 30,\ \Gamma_1 = 205 \pm 90\ \text{MeV/c}^2$
  - $M_2 = 4450 \pm\ \ 3,\ \Gamma_2 =\ \ 39 \pm 20\ \text{MeV/c}^2$
- J^{PC}: $(\frac{3}{2}^-, \frac{5}{2}^+)$ or $(\frac{3}{2}^+, \frac{5}{2}^-)$ or $(\frac{5}{2}^+, \frac{3}{2}^-)$

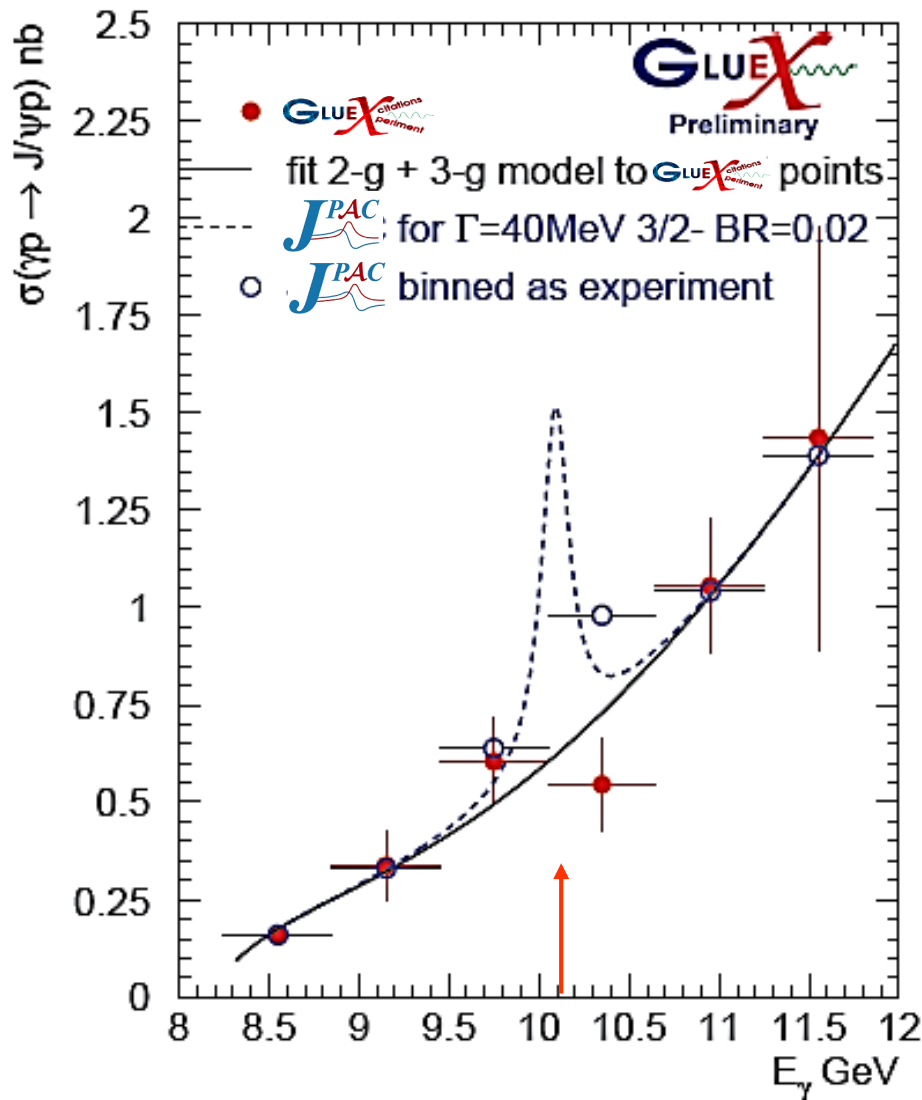Threshold of $\Sigma_c(2455)\bar{D}^*(2007) = 4462\ \text{MeV/c}^2$. The only mode detected J/ψ

Limit on *Pentaquark Production*

Fit: 2 + 3-gluon exchange

Brodsky et al, PL 498 (2001)

2 free parameters $\chi^2/ndf = 0.8$

Limit for $P_c(4450)$ $\Gamma = 40$ MeV J^{PAC} model, assumptions:
$\sigma(10.1) = 0.64$ nb non-reson.
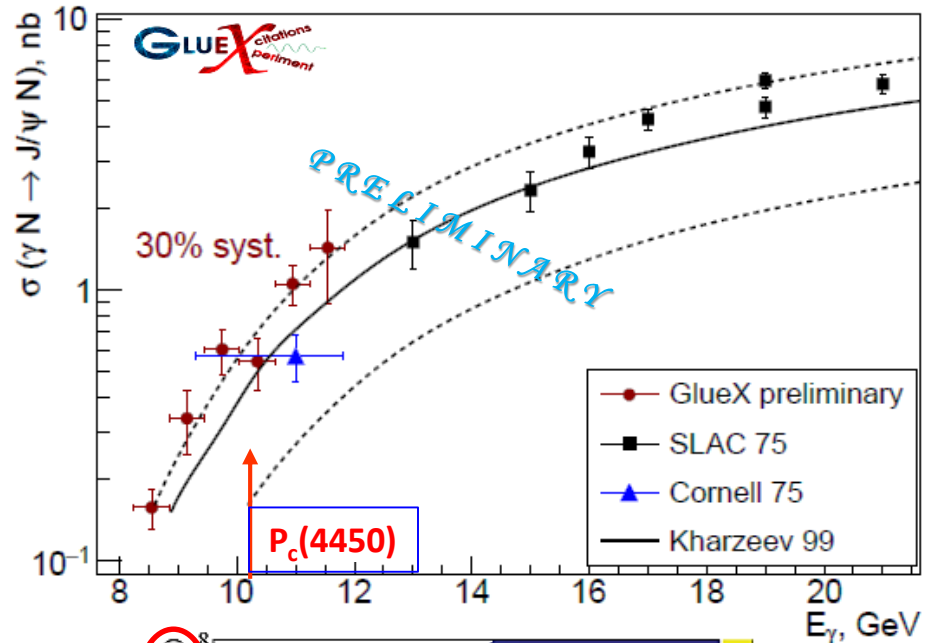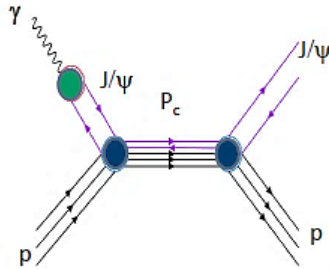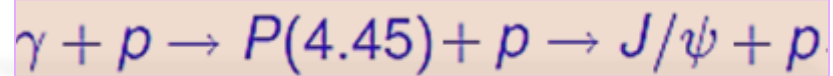no wide state $P_c(4380)$ added

J^{PC}	BR	10.1 ± 0.6 GeV		(2 bins)
		JPAC nb	experiment nb	sepa-ration $\sigma(stat)$
3/2-	2.0%	0.81	0.58 ± 0.08	2.9
5/2+	0.7%	0.81	0.58 ± 0.08	2.9

Systematic to be addressed:

- *t* and *s*-channel interference
- VMD model dependence
- The wide state influence

$$\gamma + p \rightarrow P(4.45) + p \rightarrow J/\psi + p$$
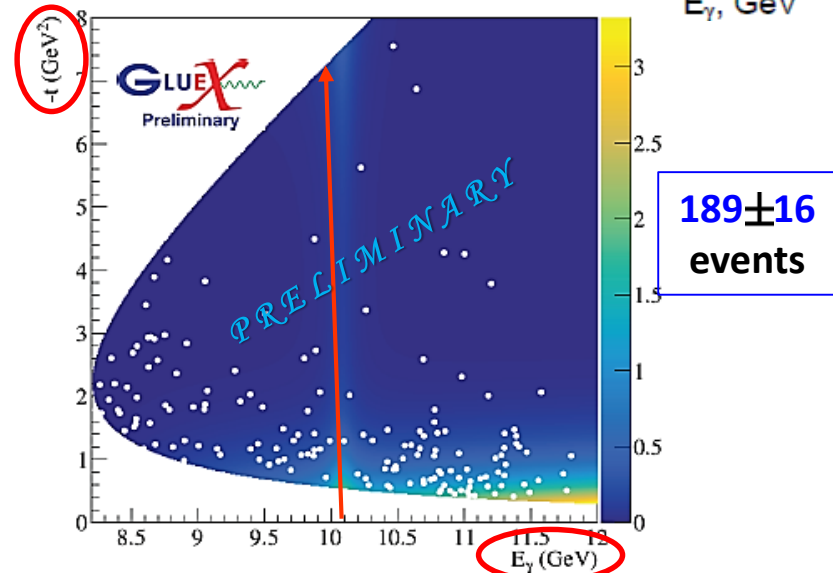

$P_c(4450)$

- **No indication** of LHCb **pentaquark**.
  R. Aaij *et al.* Phys Rev Lett **115**, 072001 (2015)

  While

- **Pentaquark** signal could present itself via **destructive interference** between **resonance** & **non-resonant** background in dominant partial wave.
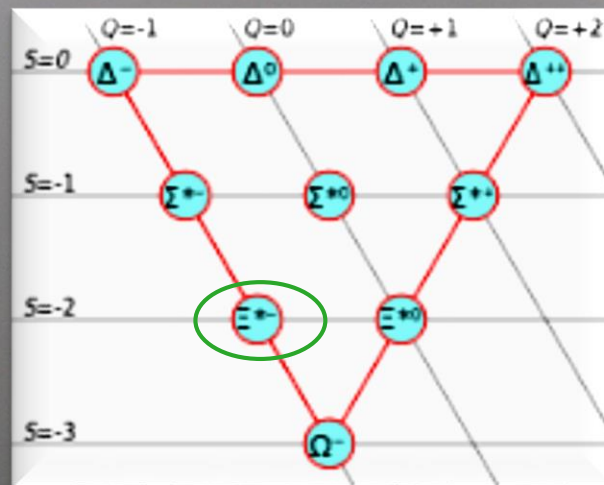
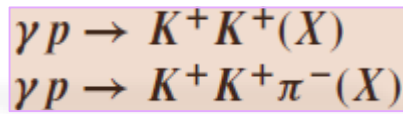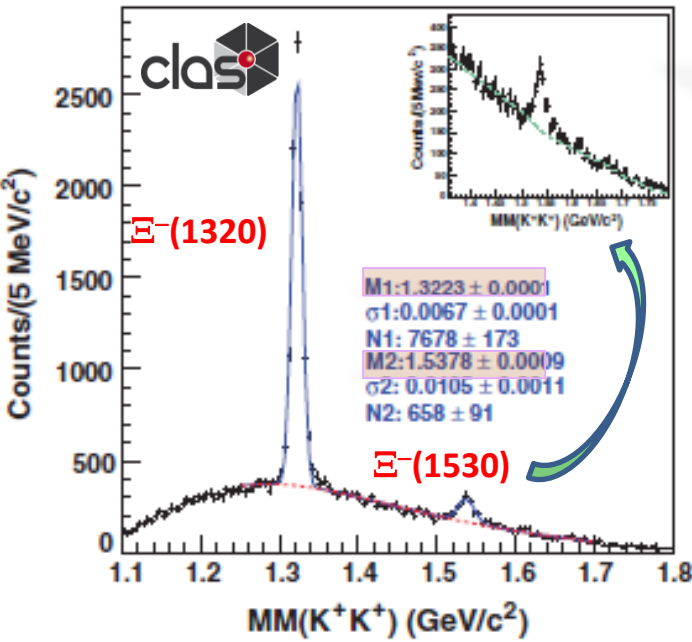$$\sigma \sim \sum |A_i|^2 \qquad A_i = BW_i + NR_i \times \exp(-i\phi)$$

189±16 events

Hyperon Spectroscopy

$$\gamma p \rightarrow K^+ K^+ (X)$$
$$\gamma p \rightarrow K^+ K^+ \pi^- (X)$$

@ **2.75 – 4.75** GeV

Ξ^-(1320)

M1:1.3223 ± 0.0001
σ1:0.0067 ± 0.0001
N1: 7678 ± 173
M2:1.5378 ± 0.0009
σ2: 0.0105 ± 0.0011
N2: 658 ± 91

Ξ^-(1530)

MM(K^+K^+) (GeV/c^2)
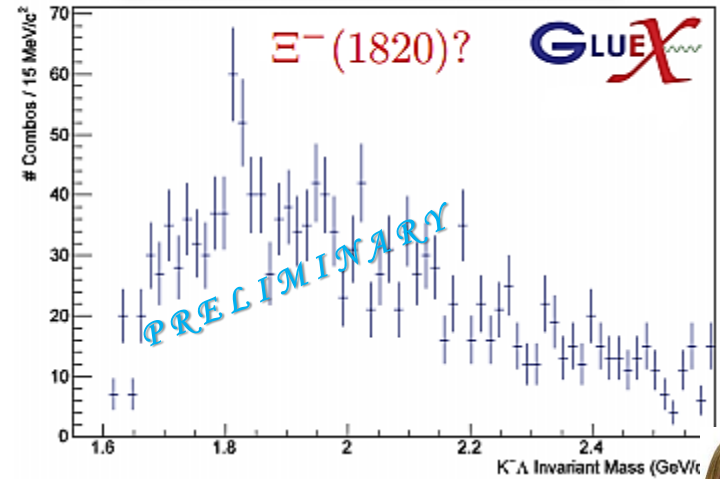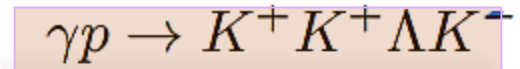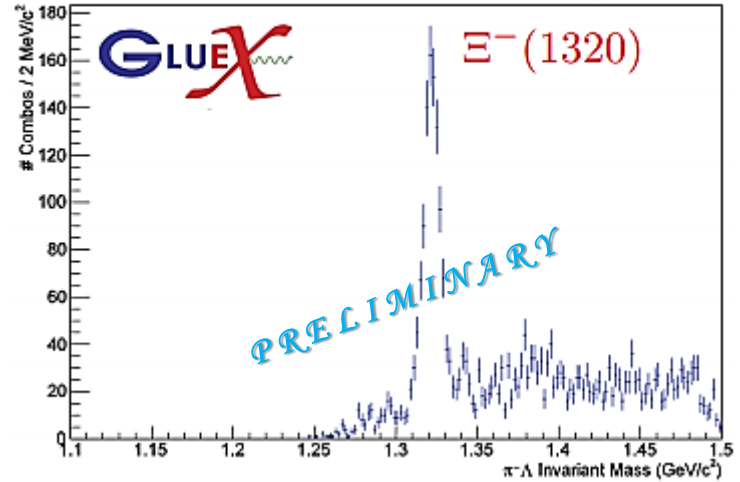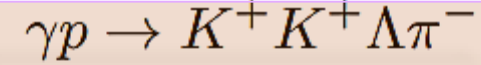
L. Guo *et al,* Phys Rev C **76**, 025208 (2007)

$$\gamma p \rightarrow K^+ K^+ \Lambda \pi^-$$

Ξ^-(1320)

PRELIMINARY

$$\gamma p \rightarrow K^+ K^+ \Lambda K^-$$

Ξ^-(1820)?

PRELIMINARY
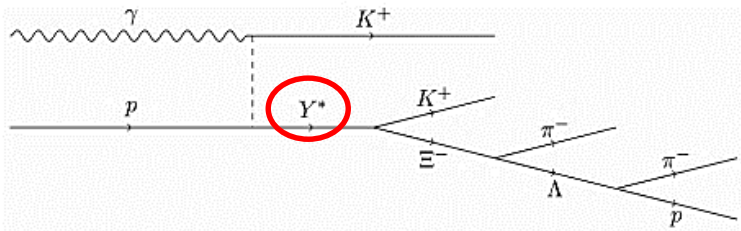
● **GlueX** can reconstruct these multi-step reactions.

● Searches in **CLAS12** by **Very Strange** Group.
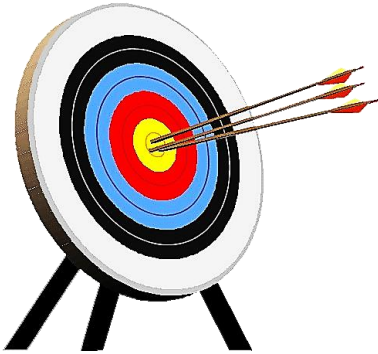
Courtesy of Ashley Ernst, 2018

Summary

``Low intensity" program (**GlueX I**), is expected to be completed in **2018**.

``High intensity" GlueX (**GlueX I**I with **DIRC**), will begin subsequently.

- **GlueX** experiment is commissioned & initial **meson** program is well underway.

- Early measurements aimed at understanding **meson production mechanism** through polarization observables.

- **First observation** of **charm** at **threshold**, potential limit on pentaquark production.

Haghartsin Monastery near Dilijan, 13th-century

Շնորհակալություն իրավերի
եւ Ձեր ուշադրության համար