The GlueX Program at Jefferson Lab

- Spectrum of Mesons
  - Quark model, lattice calculations
- The GlueX experiment
- Early physics
  - Asymmetries, SDMEs, Charm at threshold
- Summary

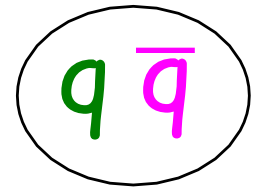
Elton S. Smith, Jefferson Lab

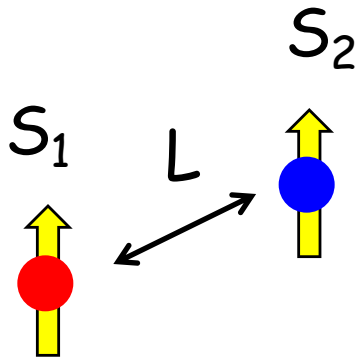
APCTP Workshop on "The Nature of Hadron Mass and Quark-Gluon Confinement from JLab Experiments in the 12-GeV Era"

Pohang, Korea, July 1-4, 2018

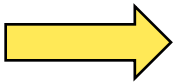
QCD ↔ Spectroscopy

- Quark model is amazingly successful at describing the hadron spectrum.
- Yet most of the hadron mass is not due to quarks
- Search for glue using non-$q\bar{q}$ degrees of freedom





$S = S_1 + S_2$
$J = L + S$
$P = -(-1)^L$
$C = (-1)^{L+S}$



$J^{PC} = 0^{-+}\ 0^{++}\ 1^{--}\ 1^{+-}\ 2^{++}\ \ldots$

Allowed combinations

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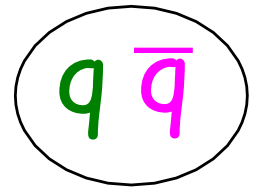

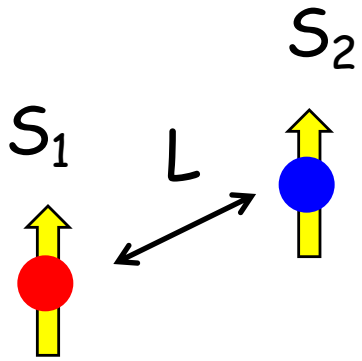

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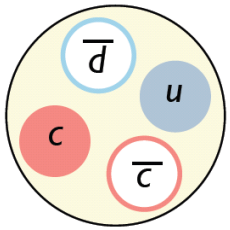
Allowed combinations

$J^{PC} = 0^{--}\ 0^{+-}\ 1^{-+}\ 2^{+-}\ \ldots$

Not-allowed: exotic

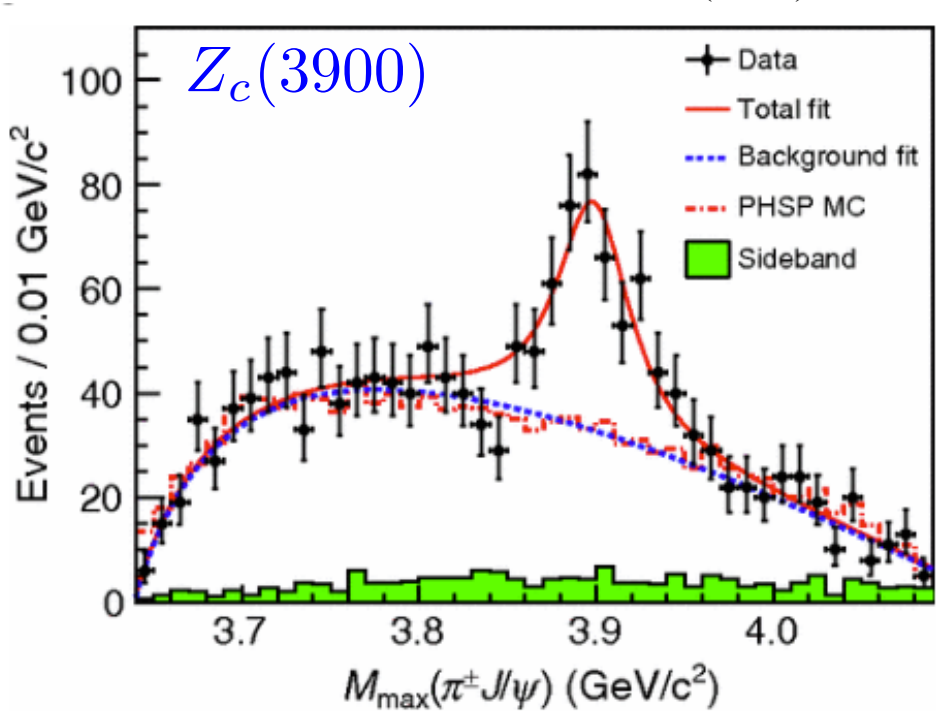
Tetraquarks and Pentaquarks (Heavy Quarks)

$$e^+e^- \to \pi^+\pi^- J/\psi$$



BESIII PRL 110 (2013) 252001

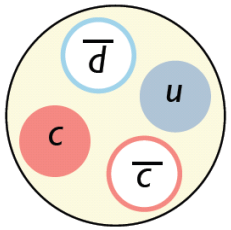
BELLE PRL 110 (2013) 252002



Tetraquarks and Pentaquarks (Heavy Quarks)

$e^+e^- \to \pi^+\pi^- J/\psi$

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



BESIII PRL 110 (2013) 252001

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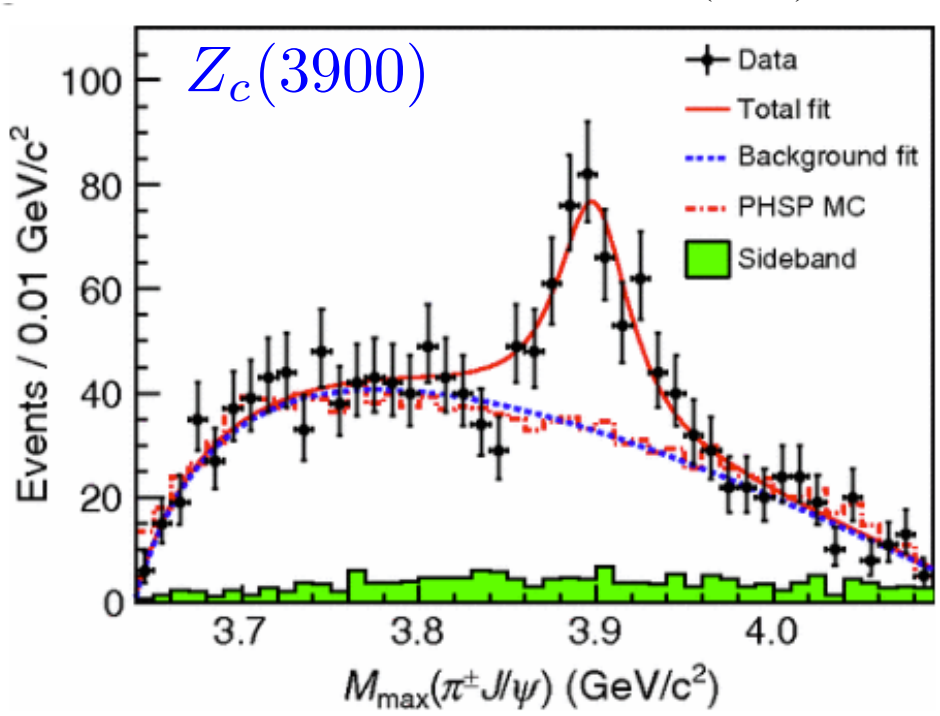
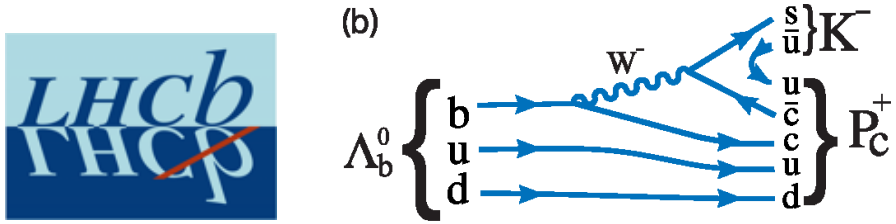
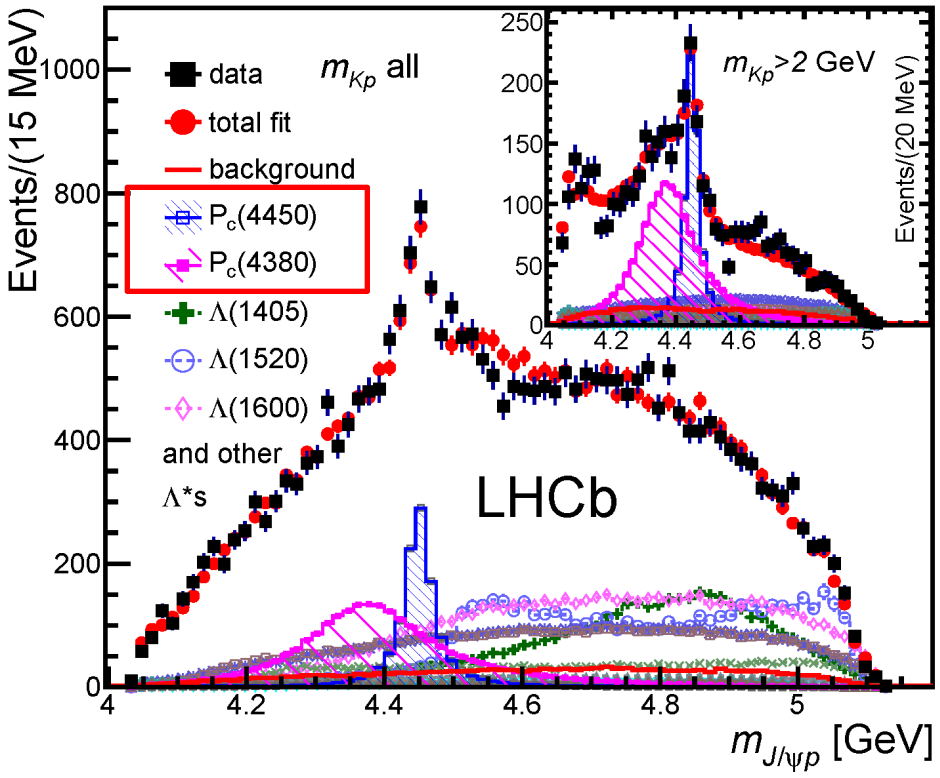
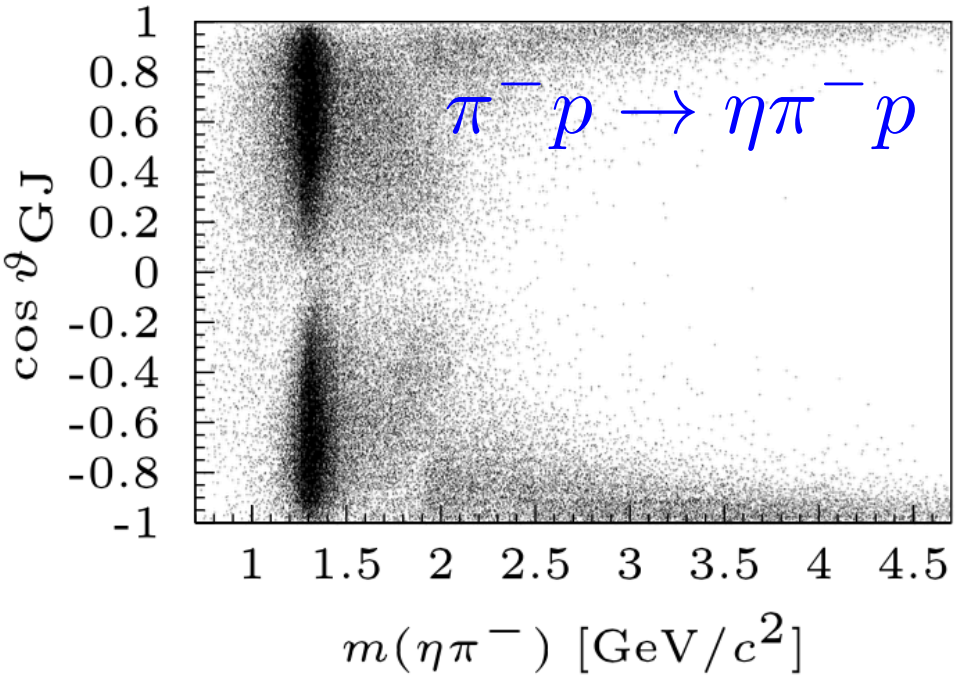


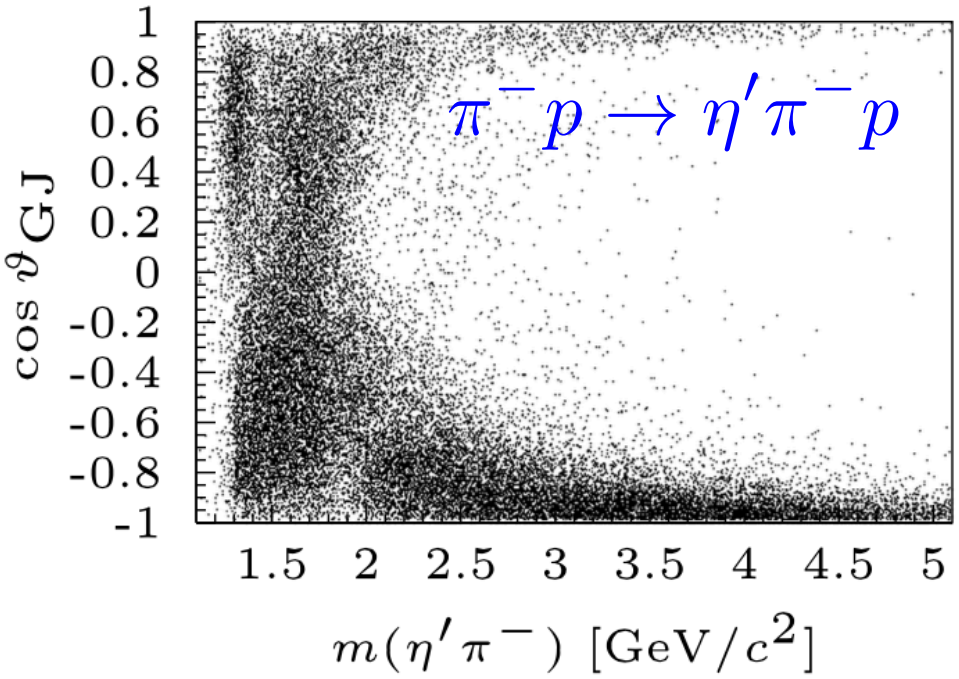


LHCb PRL 115 (2015) 072001

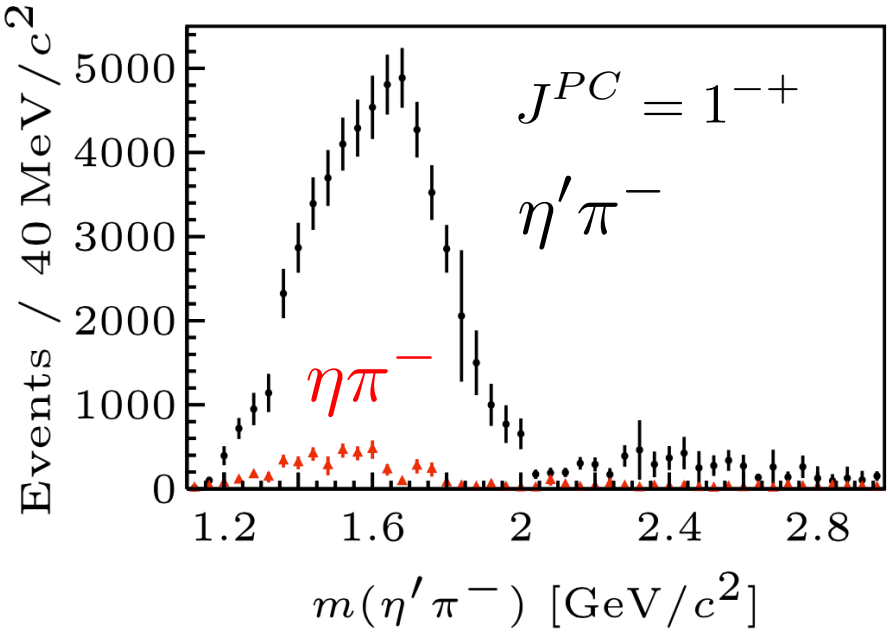


COMPASS: Exotic π_1, η_1, η'_1?





- Asymmetry in cosθ is a result of interference between even and odd partial waves
- Exotic 1^{-+} larger in $\eta'\pi^-$ than $\eta\pi^-$
- No resonance parameters are presented for the exotic L odd-waves

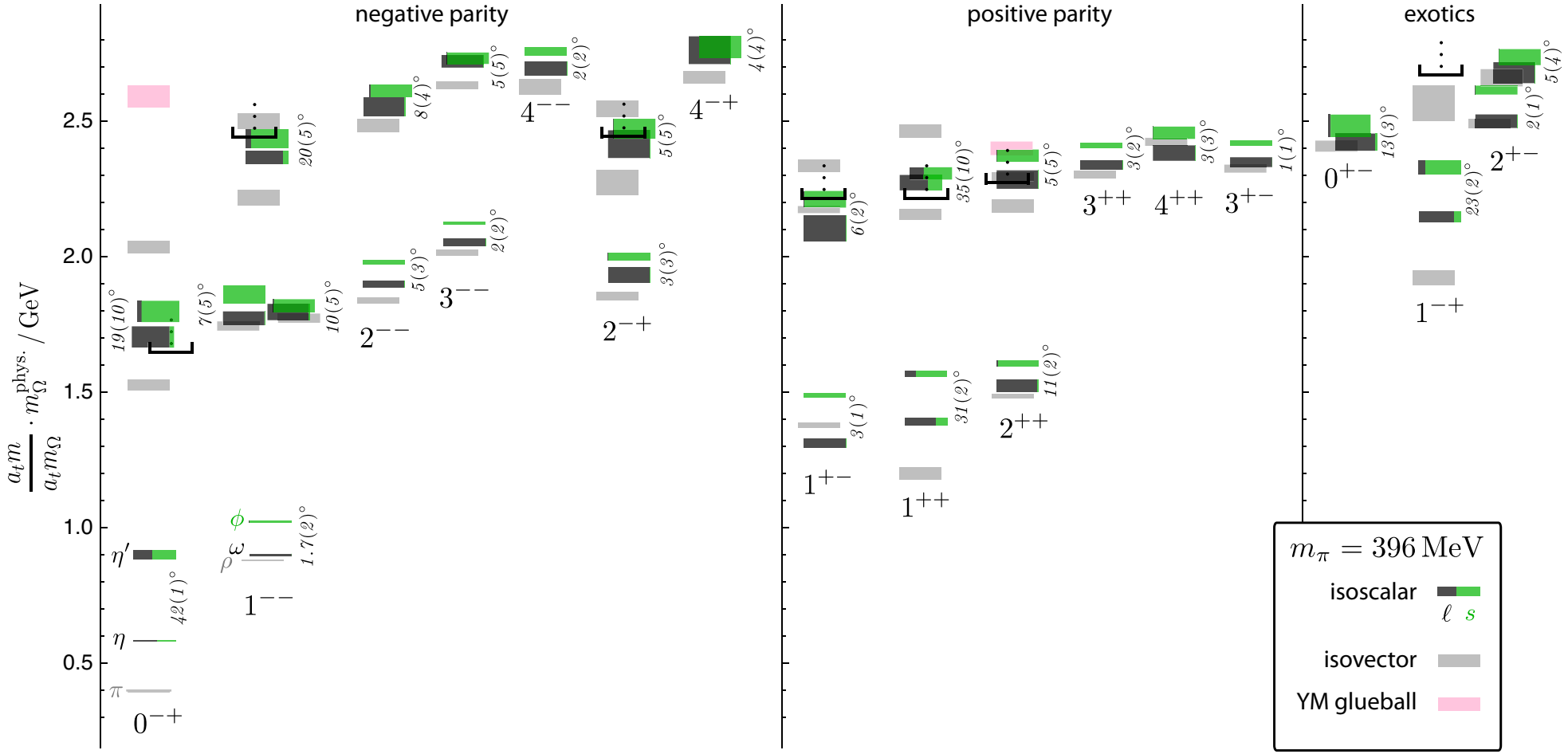


COMPASS PLB 740 (2015) 303

LQCD Meson spectrum for light quarks

Dudek PRD 83 (2011) 111502
Dudek PRD 84 (2011) 074023

M_π~400 MeV



$\frac{1}{\sqrt{2}}\left(u\overline{u} - d\overline{d}\right)$ $\frac{1}{\sqrt{2}}\left(u\overline{u} + d\overline{d}\right)$ $\left(s\overline{s}\right)$

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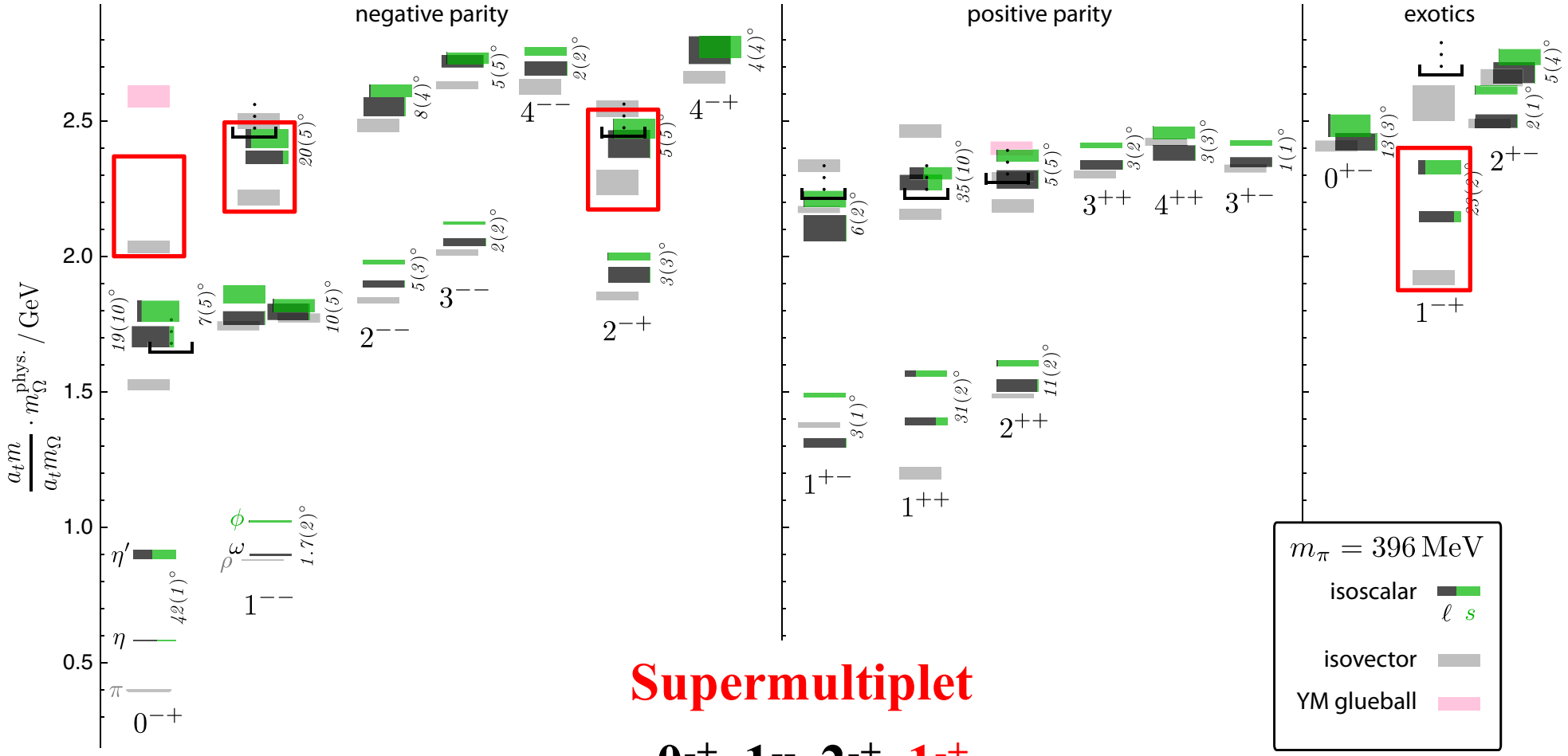


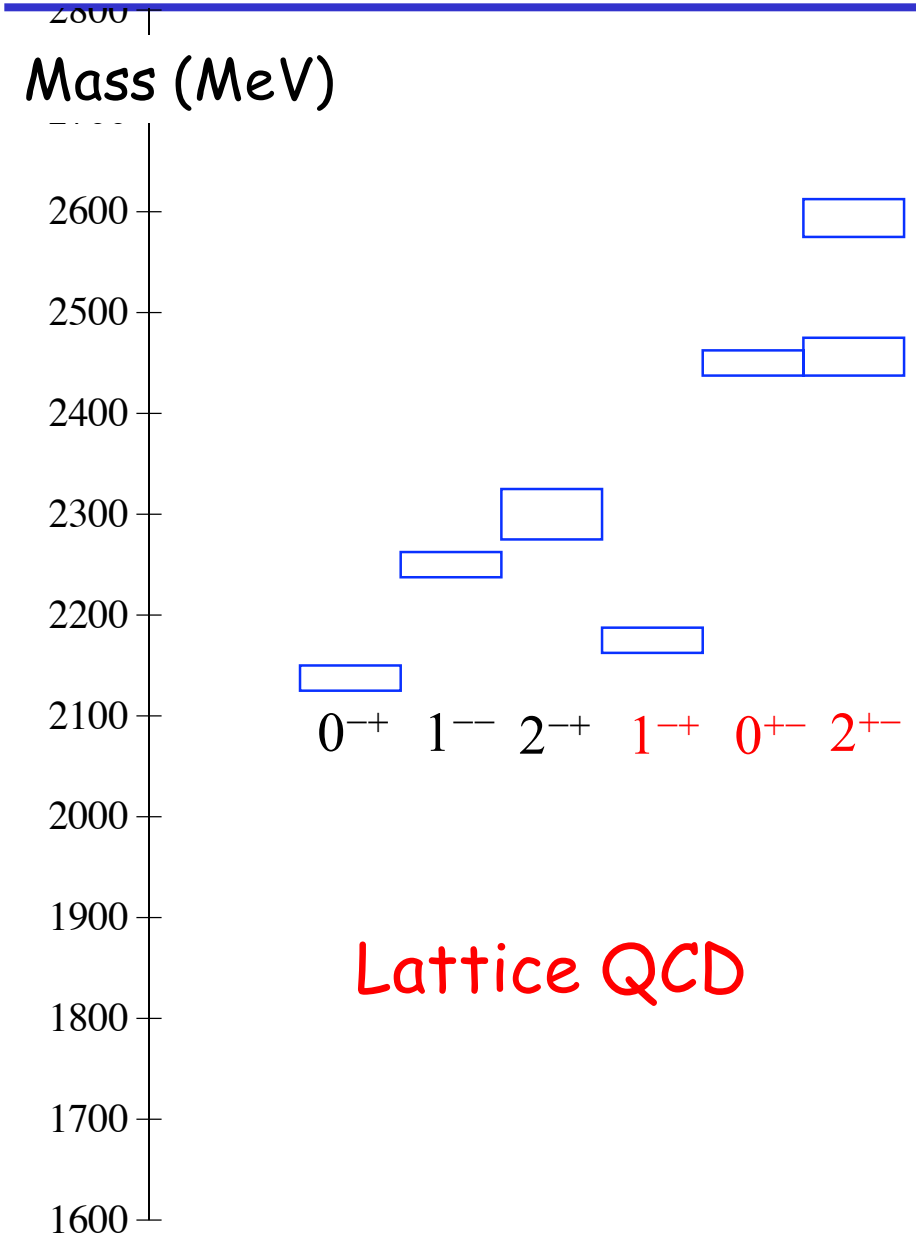
Supermultiplet

0^{-+}, 1^{--}, 2^{-+}, 1^{-+}

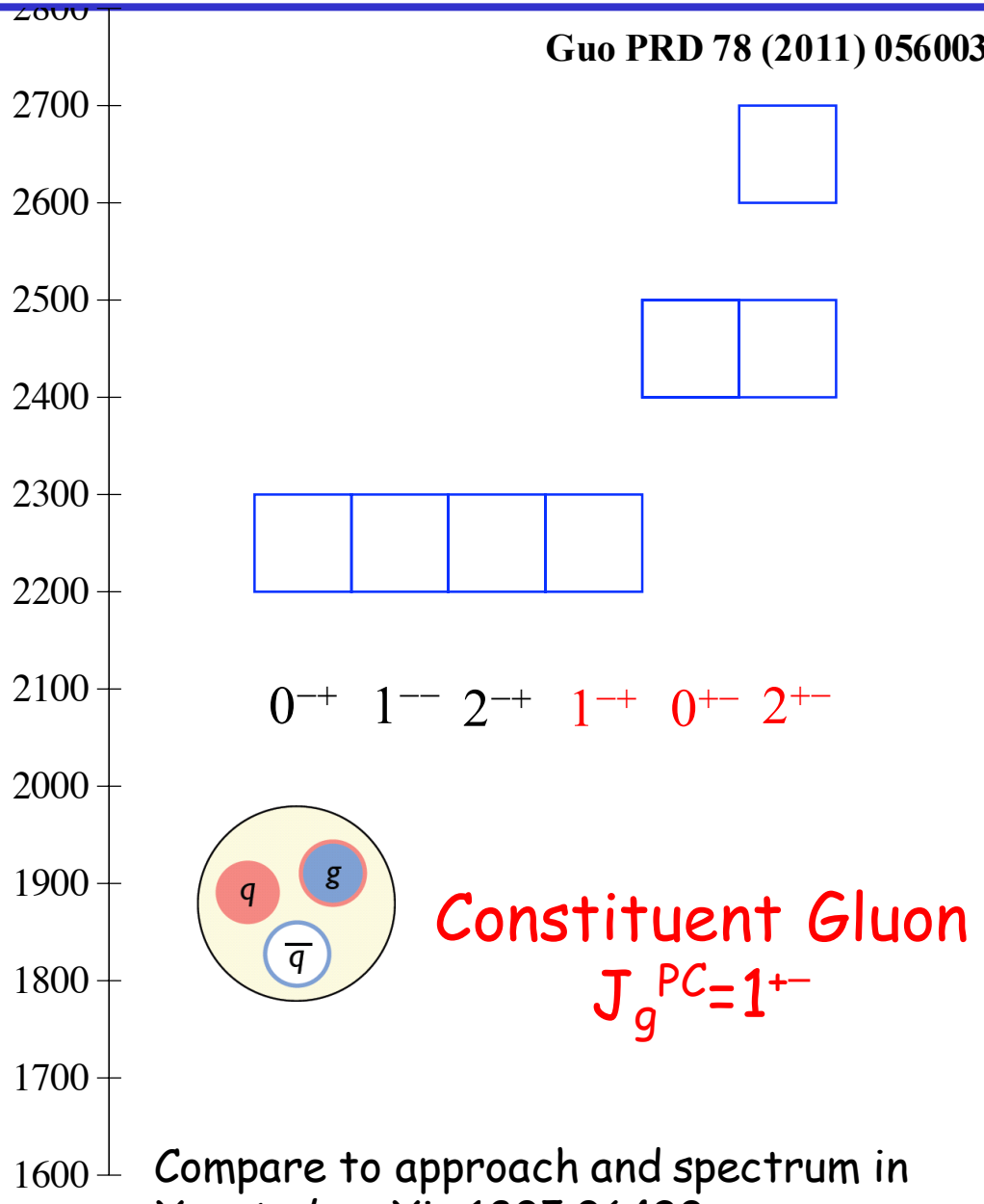
$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ $\quad$ $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$ $\quad$ $(s\bar{s})$

States with non-trivial gluonic fields $\mathbf{F_{j,\mu\nu}\, F_j^{\mu\nu}}$

Models for hybrid mesons



Lattice QCD

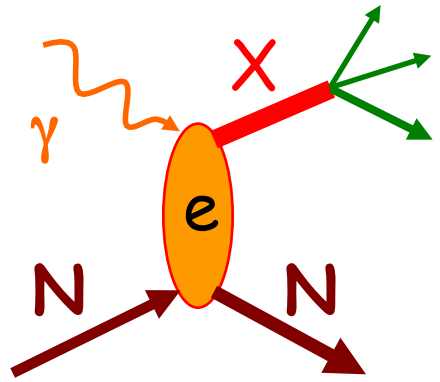


Constituent Gluon
$J_g^{PC}=1^{+-}$

Compare to approach and spectrum in
Xu *et al.*, arXiv:1805.06430

Photoproduction

- Very little photoproduction data in this energy range
- Approximately the 70% of total cross section in the energy region Eγ ~ 7-12 GeV has multiple neutrals and is completely unexplored
- Polarized photons may help disentangle different production mechanisms



γ ⇔ ρ,ω,ϕ

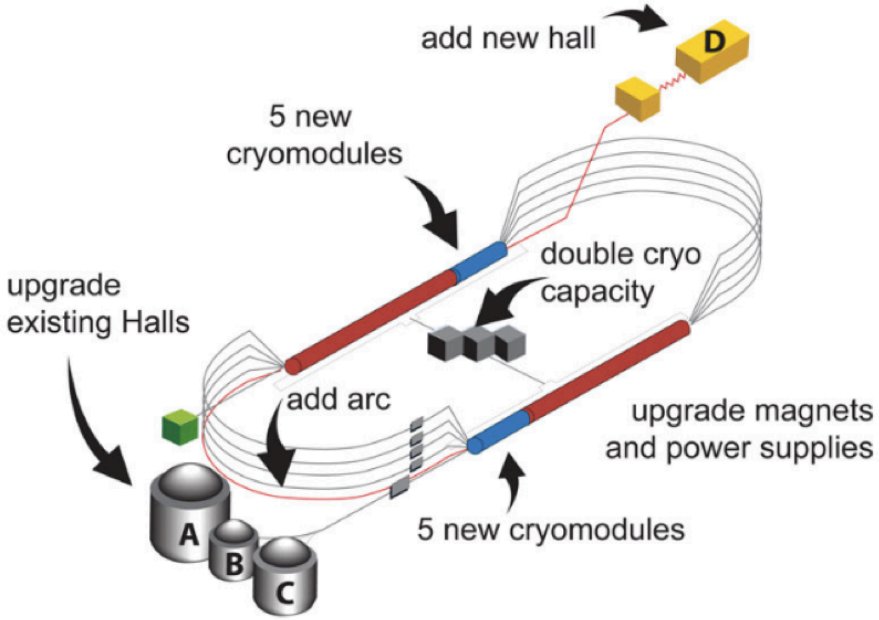
Possible decay modes

$$\pi_1 \to \rho\pi,\ \eta'\pi$$

$$\eta_1 \to \eta f_2,\ a_2\pi$$

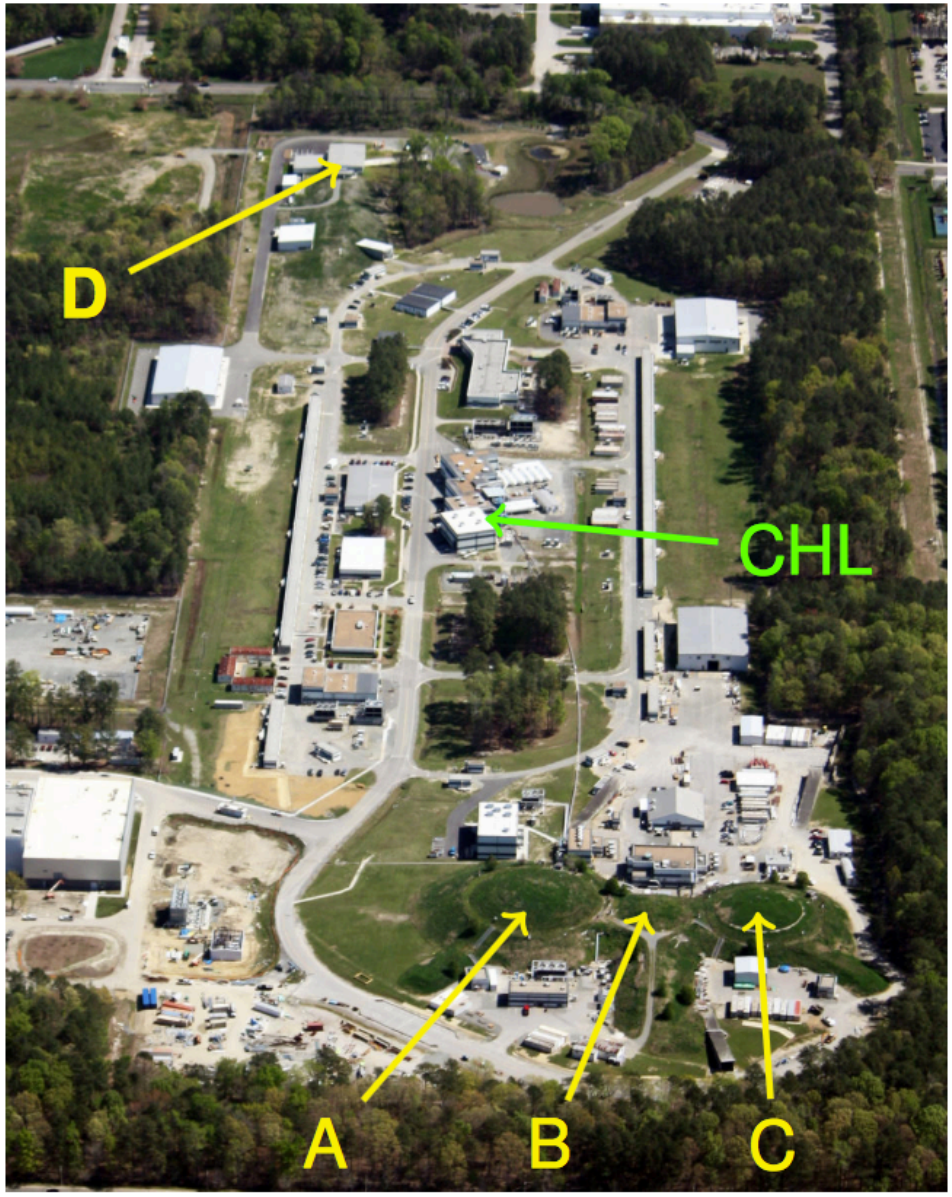
$$\eta_1' \to K^*K$$

Jefferson Lab site

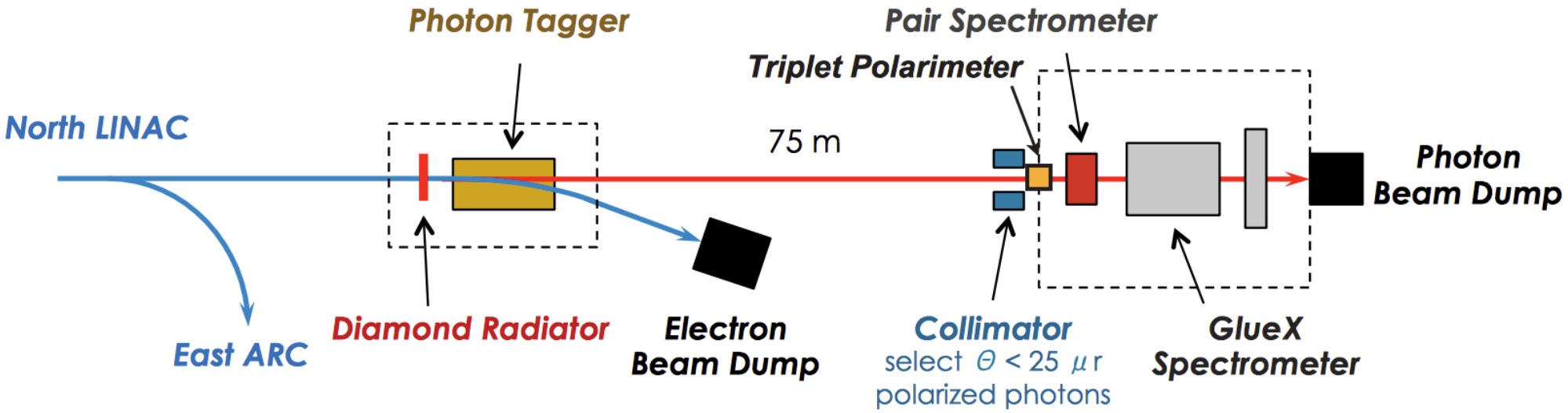


Upgrade Goals

- Accelerator: 6 GeV ⇒ 12 GeV
- Halls A,B,C: e^- <11 GeV, < 100 μA
- Hall D: e^- 12 GeV ⇒ γ-beam

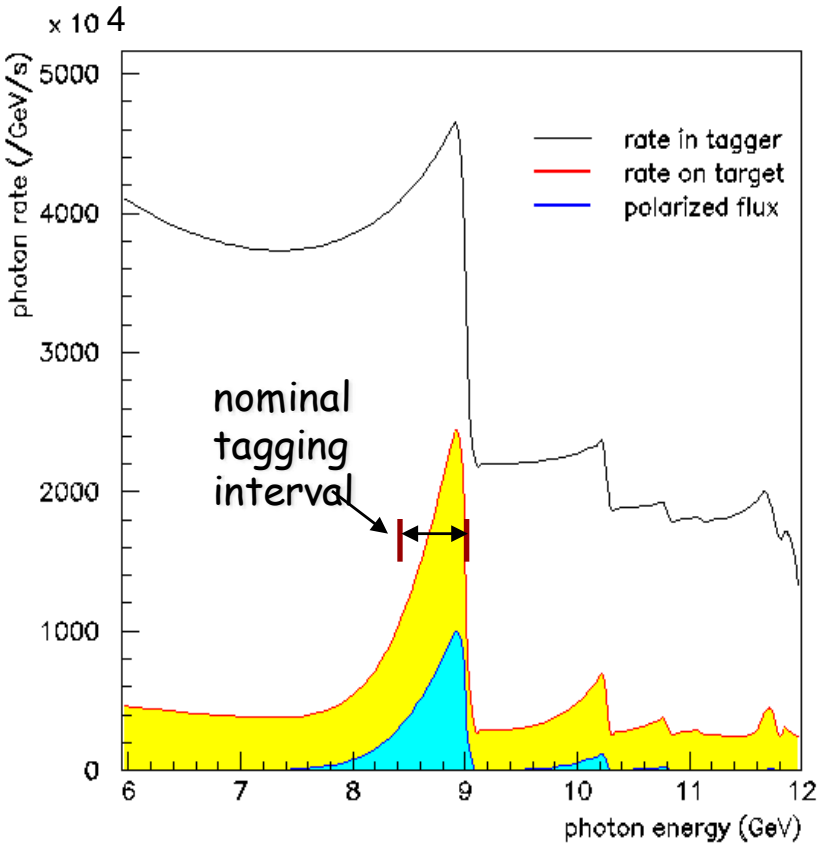


Photon beam and experimental area

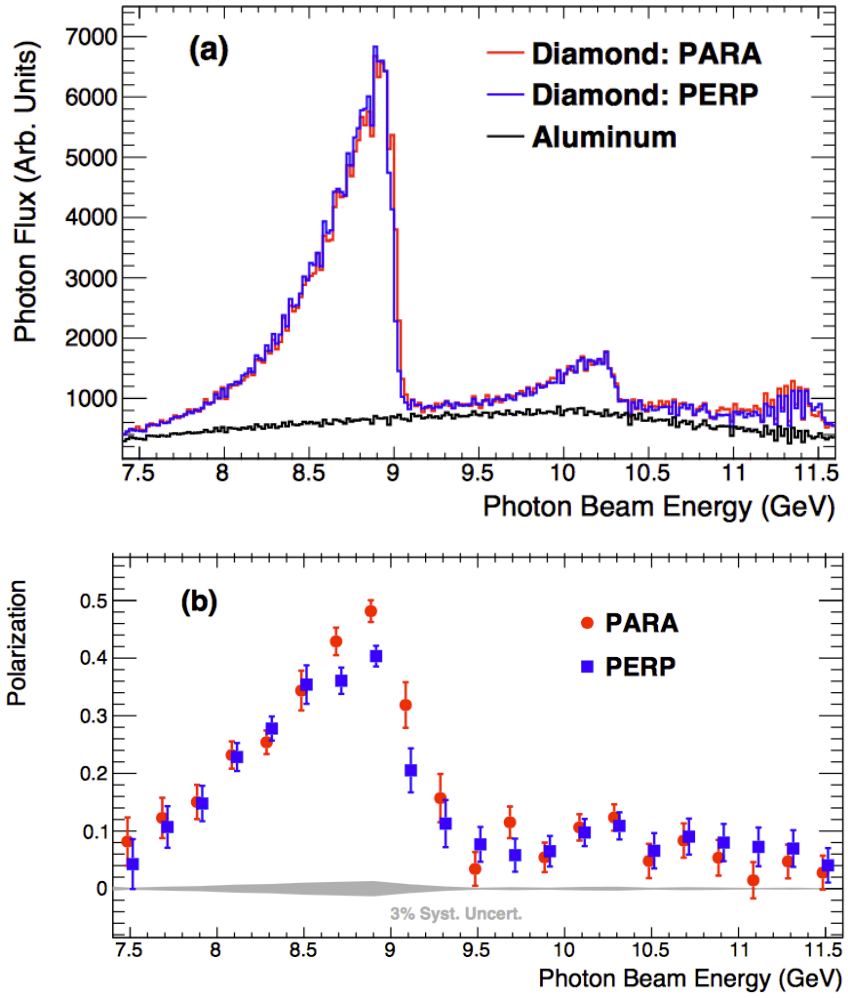


Linearly Polarized Photon Beam

Calculated Spectrum (12 GeV beam)



Measured Spectrum (over PS acceptance)

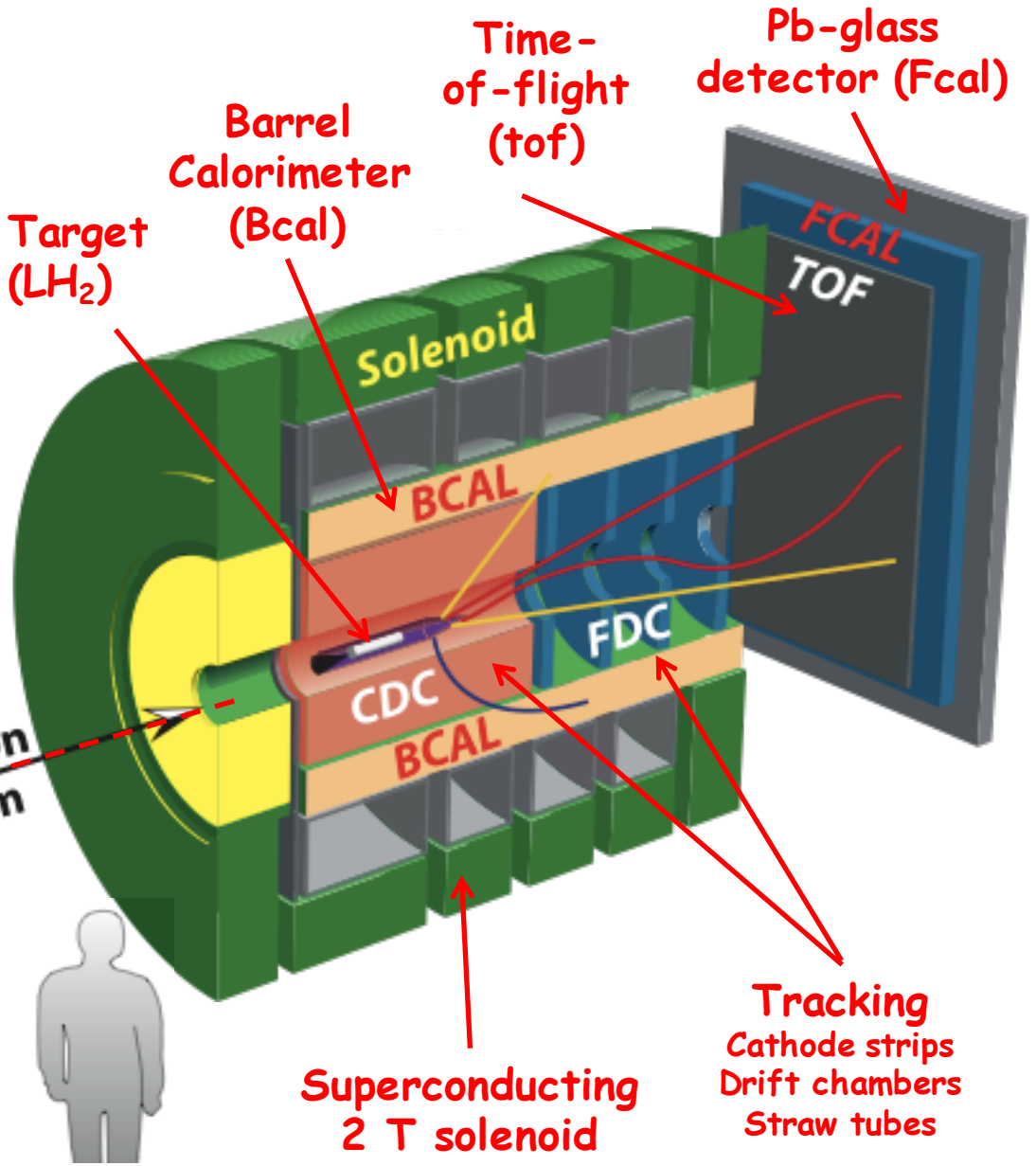


GlueX PRC95 (2017) 042201

Hall D – GlueX detector

Hermetic detection of charged and neutral particles in solenoid magnet

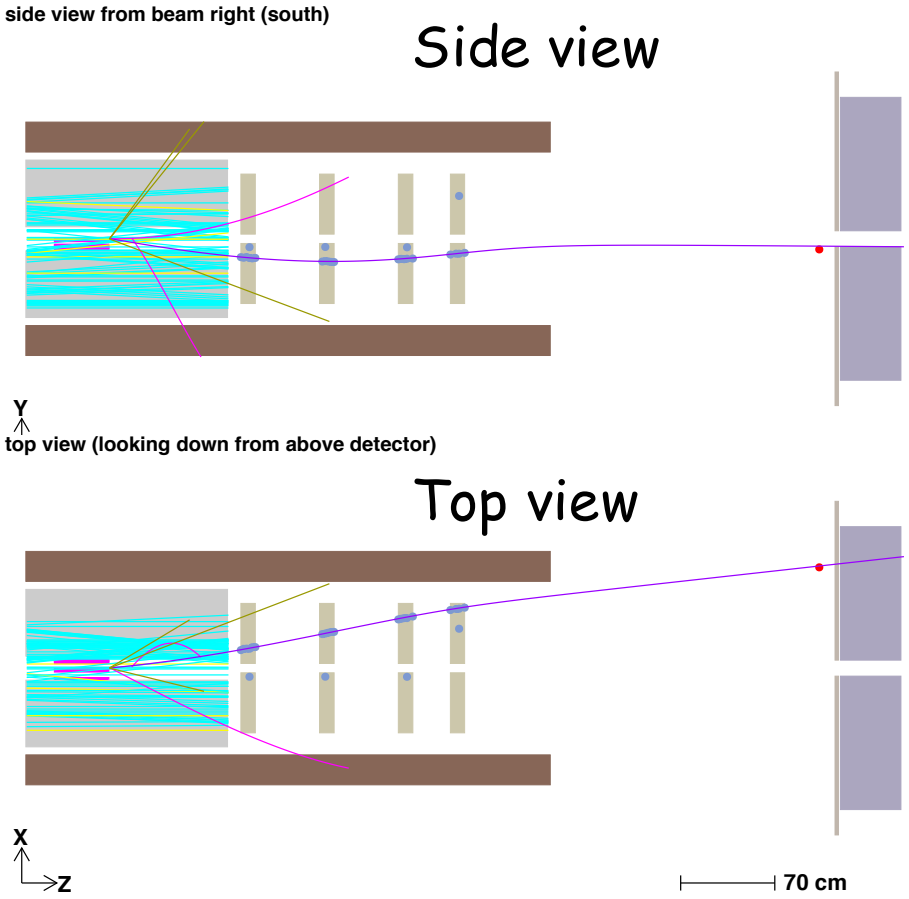
Flux (peak) ~ 2×10^7 γ/s
18,000 FADCs
4,000 pipeline TDCs
50 KHz L1 trigger
600 MB/s to tape

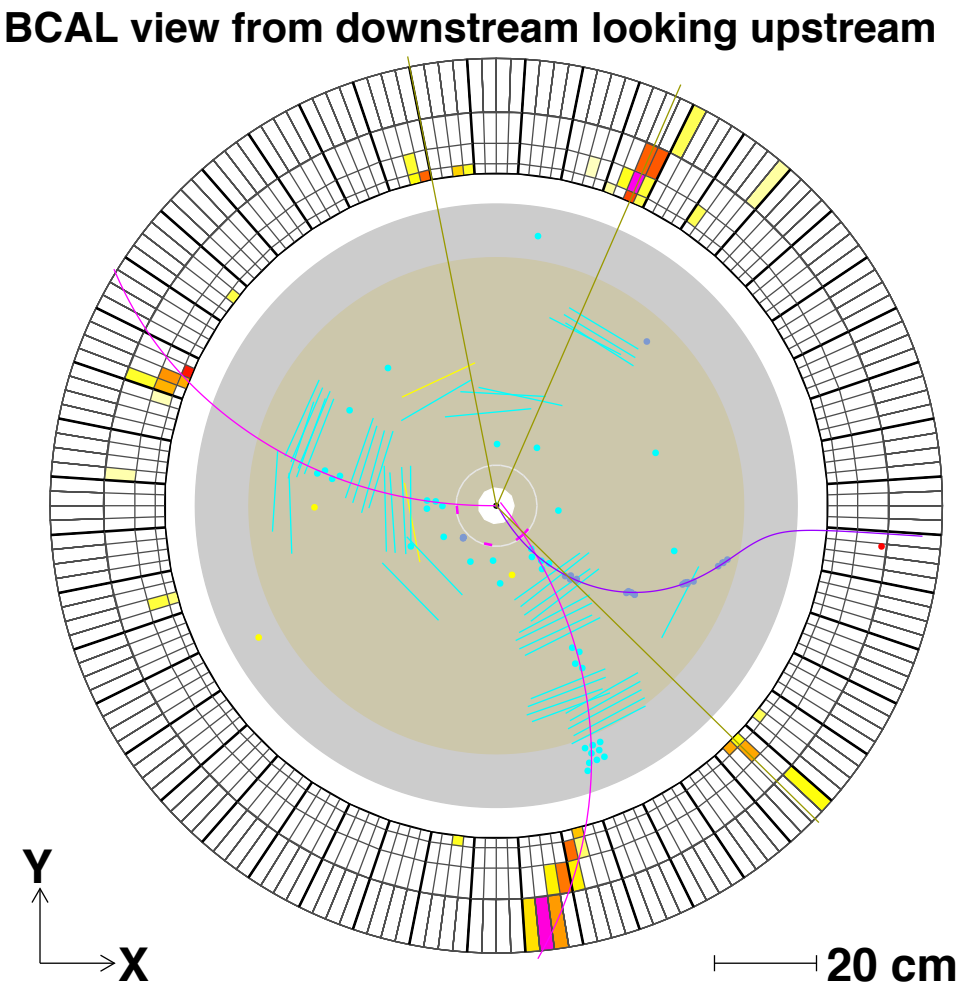


Tagger Spectrometer (Upstream)

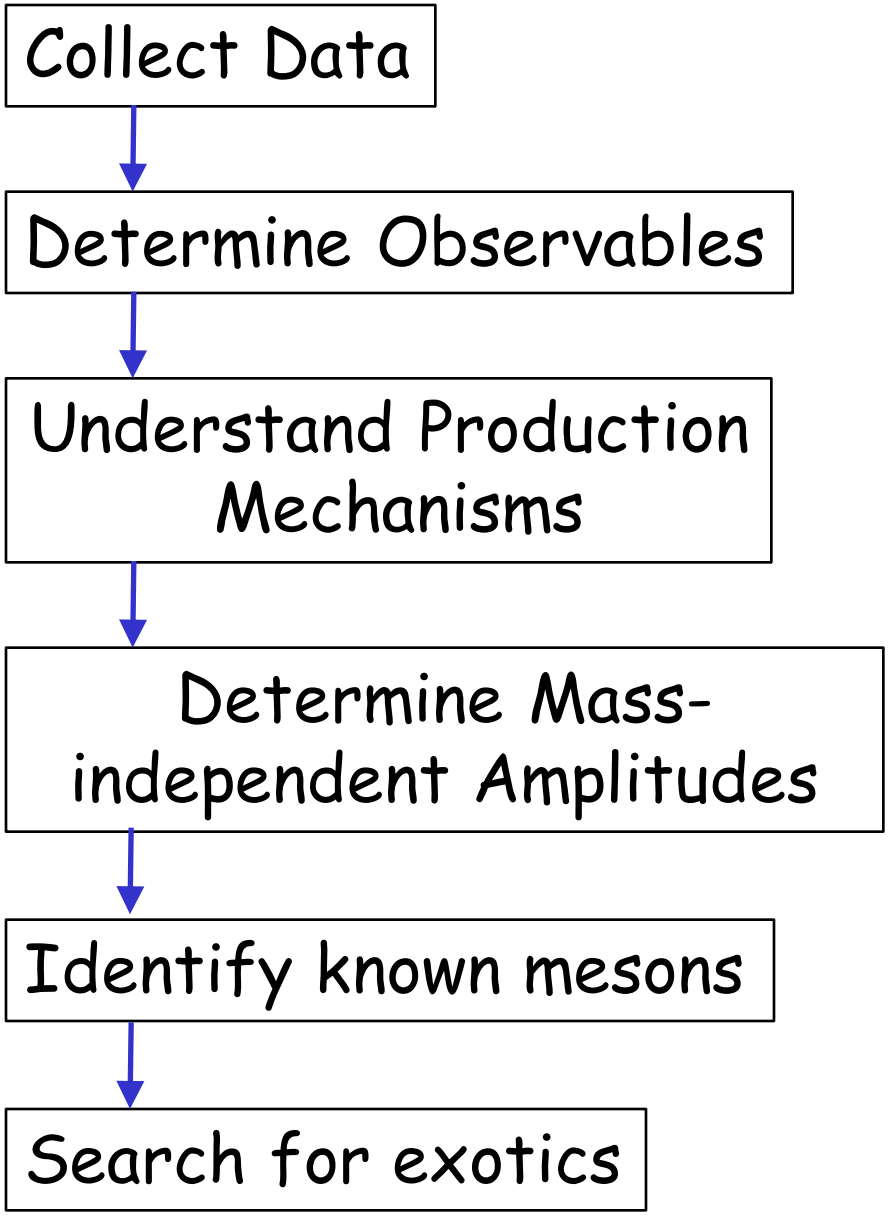
Viewer single-event

- Tracks, calorimeter showers reconstructed





Program to study meson spectrum



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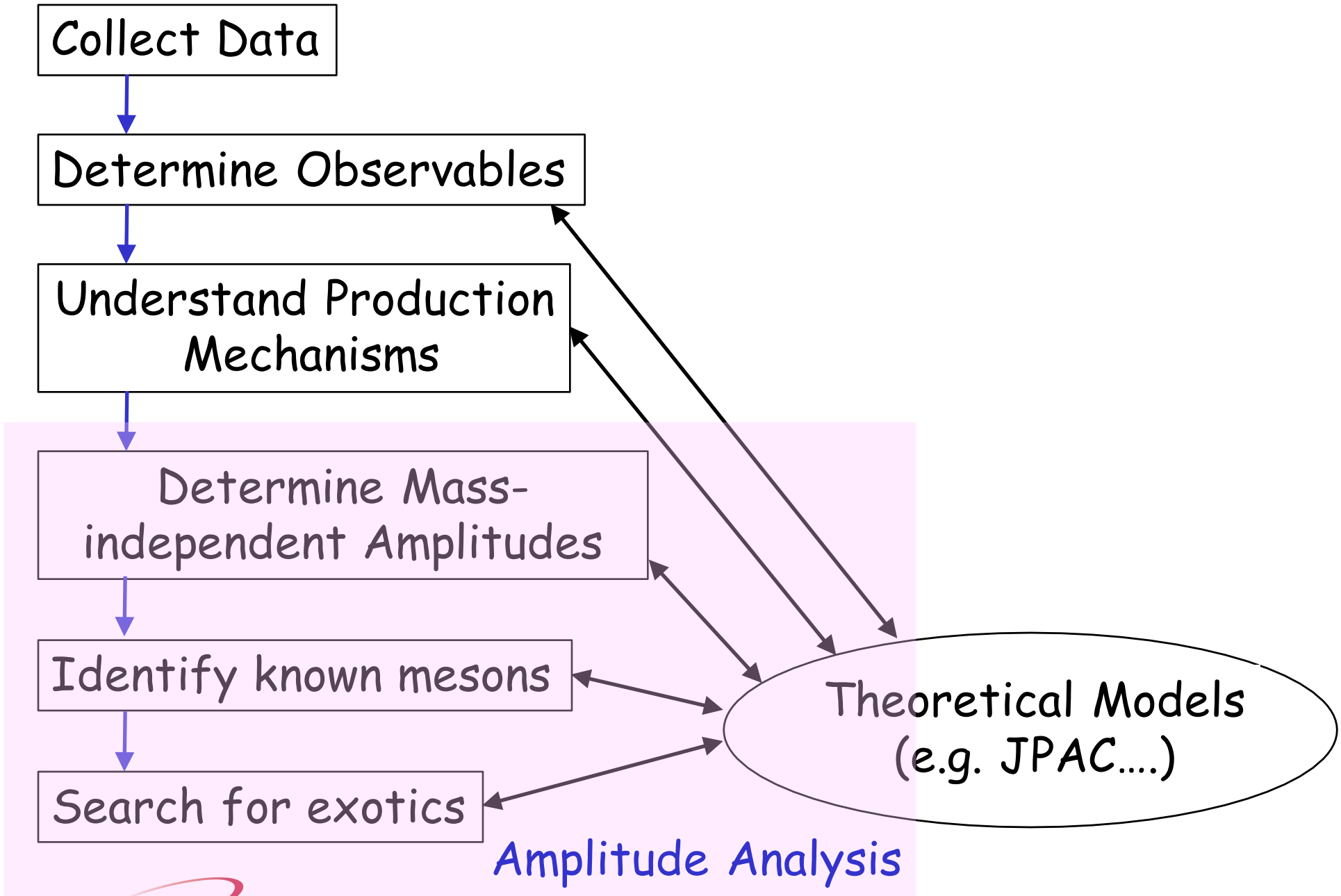

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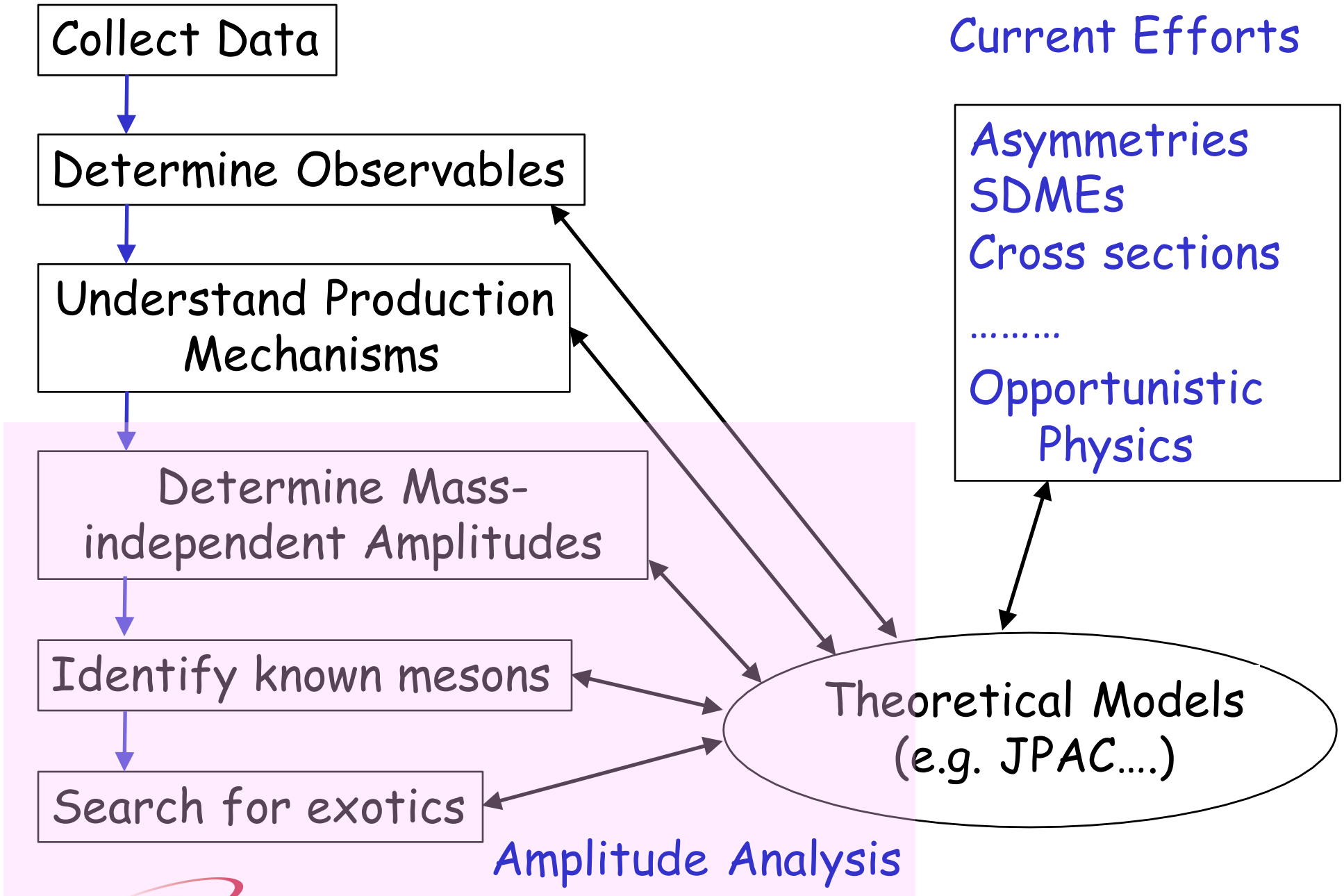
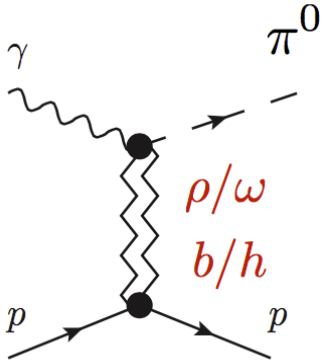


π^0 and η azimuthal asymmetry

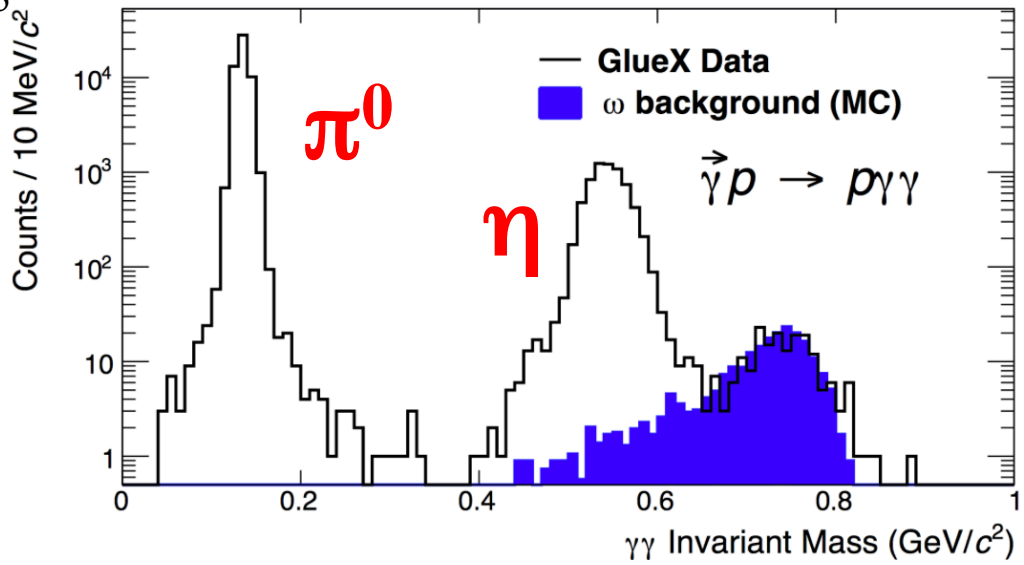


JPAC PRD 92 (2015) 074013

Exchange J^{PC}

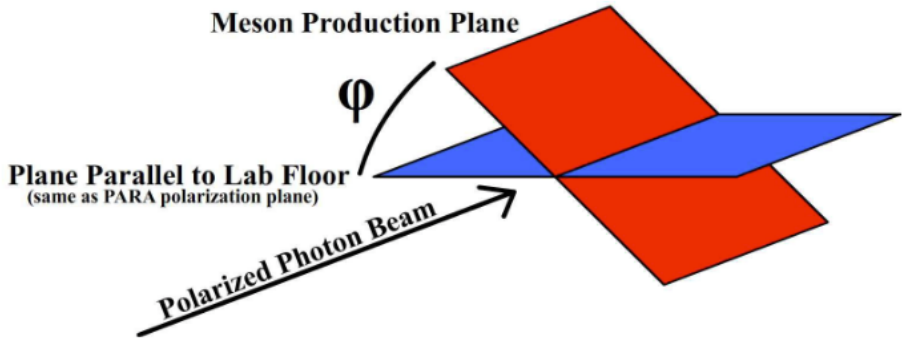
$1^{--} : \omega, \rho$

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

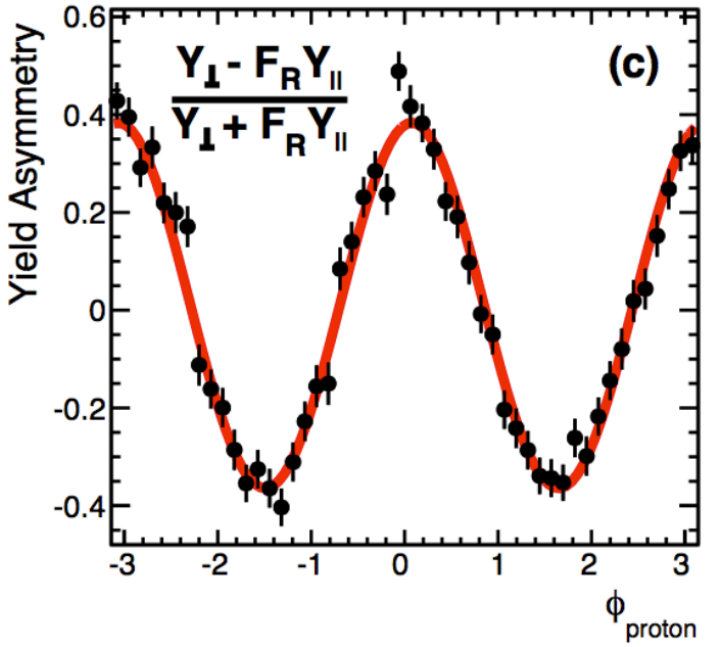


$$\frac{d\sigma}{dt} = \sigma_\perp + \sigma_\parallel = |\rho + \omega|^2 + |b + h|^2$$

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



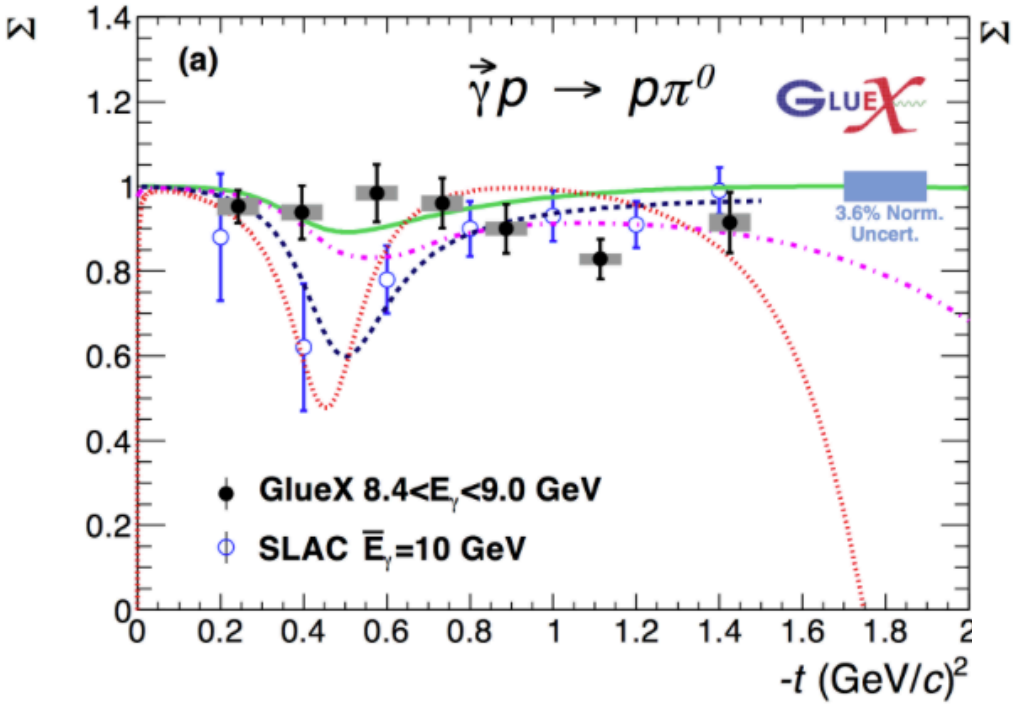
$$\frac{d\sigma}{d\phi_{\text{proton}}} \propto 1 - P\Sigma \cos 2(\phi_{\text{proton}} - \phi_\gamma)$$

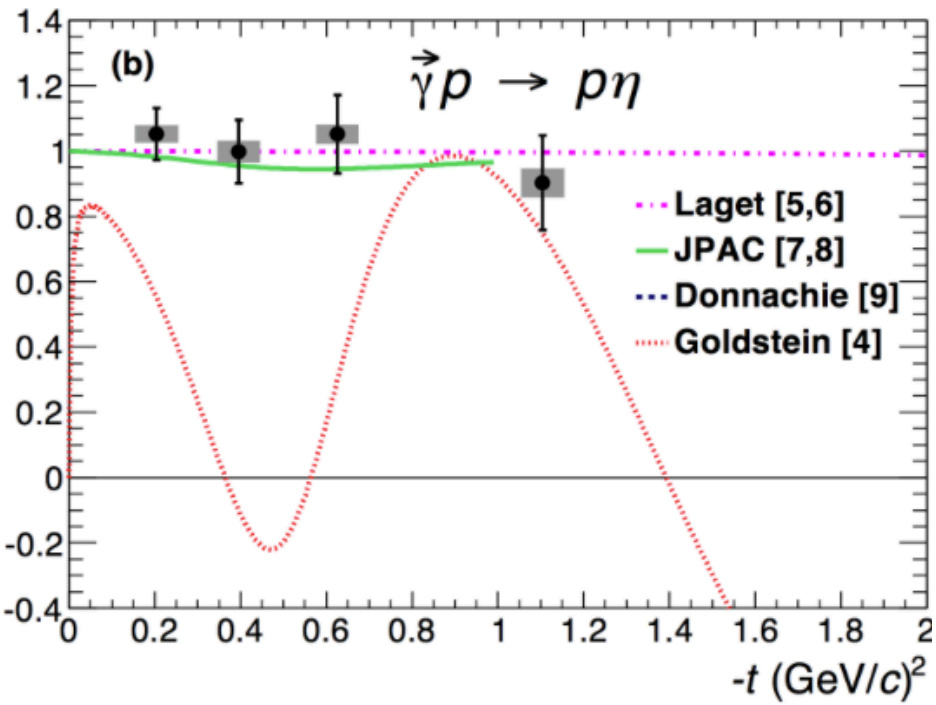


π^0 and η asymmetries

$\vec{\gamma}p \rightarrow \gamma\gamma p$

GlueX PRC95 (2017) 042201



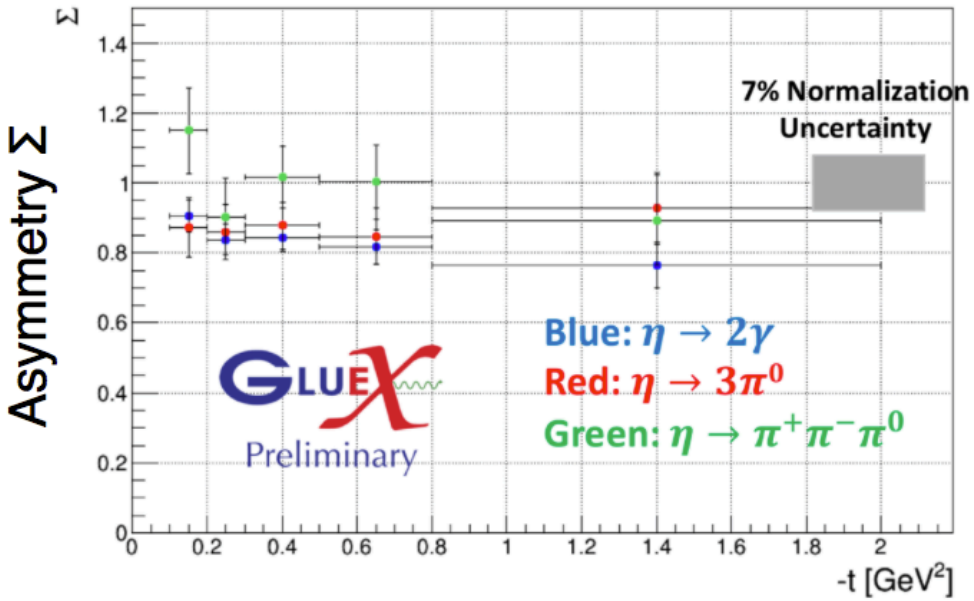


- π^0 and η azimuthal asymmetries measured for 0 < -t < 1.5 GeV^2
- Measurements are being compared to model calculations to understand particle exchange mechanisms
- First asymmetry measurements for η at this energy

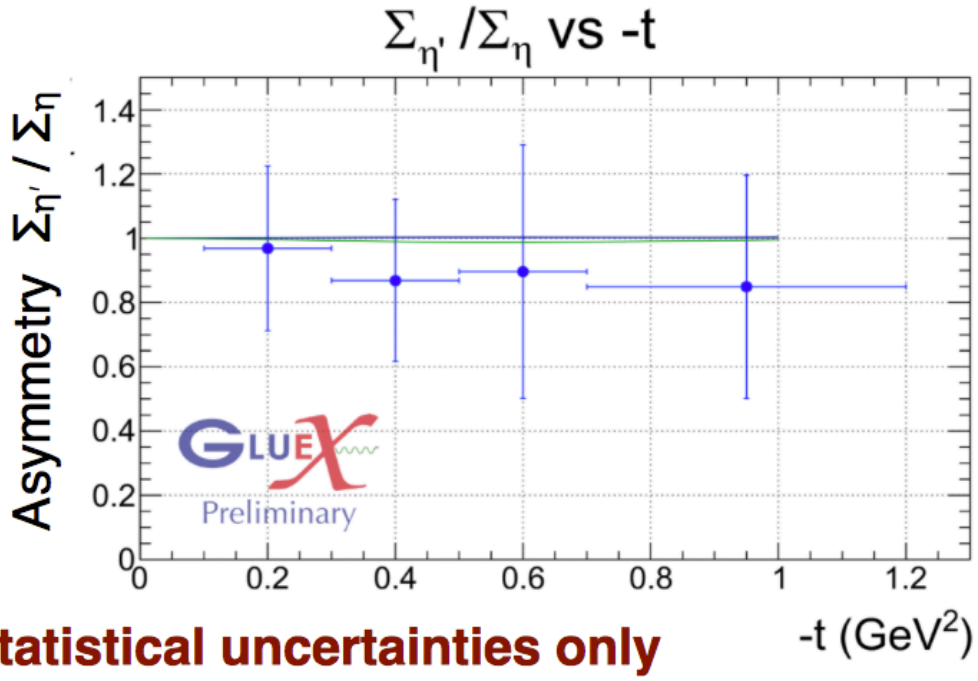
Pseudo-scaler asymmetries

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

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



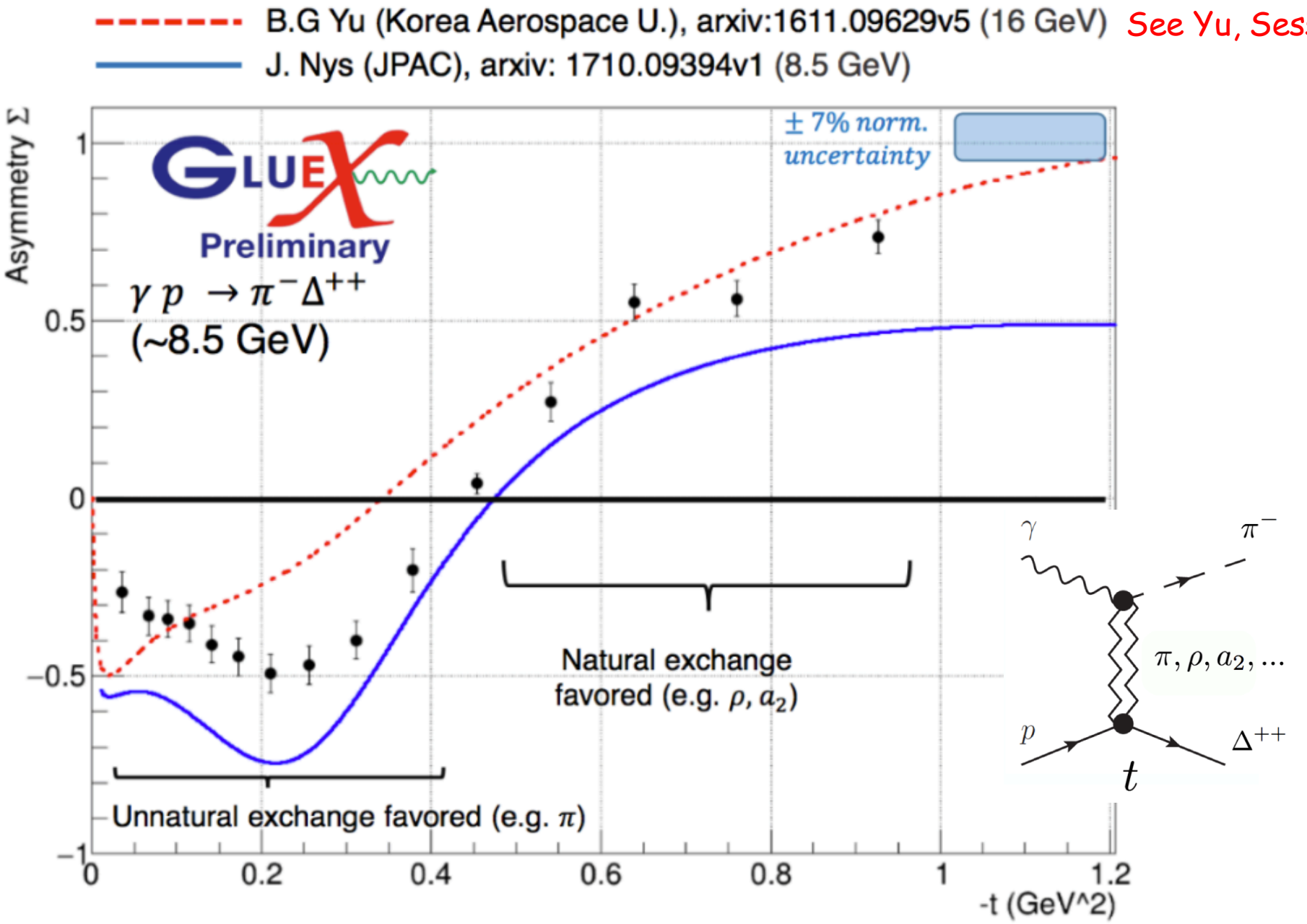
$$\vec{\gamma}p \rightarrow \eta' p$$



- Production is consistent with vector exchange dominance
- Expect similar mechanism for exotics

Statistical uncertainties only

γp -> π⁻ Δ⁺⁺ Asymmetry



Spin density matrix elements (SDMEs)

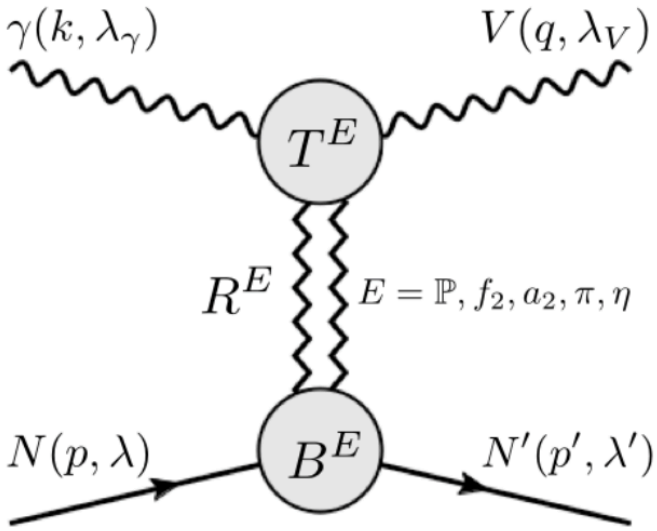
See McGinley, JLab User's Meeting 2018

SDMEs measure the transfer polarization from the photon to the vector meson V

$$\rho(V) = T\,\rho(\gamma)\,T^{\dagger}$$
$$\rho(\gamma) = \frac{1}{2}I + \frac{1}{2}\mathbf{P}_{\gamma}\cdot\sigma$$
$$\mathbf{P}_{\gamma} = P_{\gamma}(-\cos 2\Phi, -\sin 2\Phi, 0)$$

Φ is the angle between the photon polarization and the production plane

JPAC PRD 97 (2018) 094003



Helicity Conservation: $\rho(V) = \rho(\gamma)$

$\Rightarrow$

$$\rho^{\alpha}_{ik} = 0, \text{ except}$$
$$\rho^{1}_{1-1} = -\,Im\,\rho^{2}_{1-1} = \frac{1}{2}$$

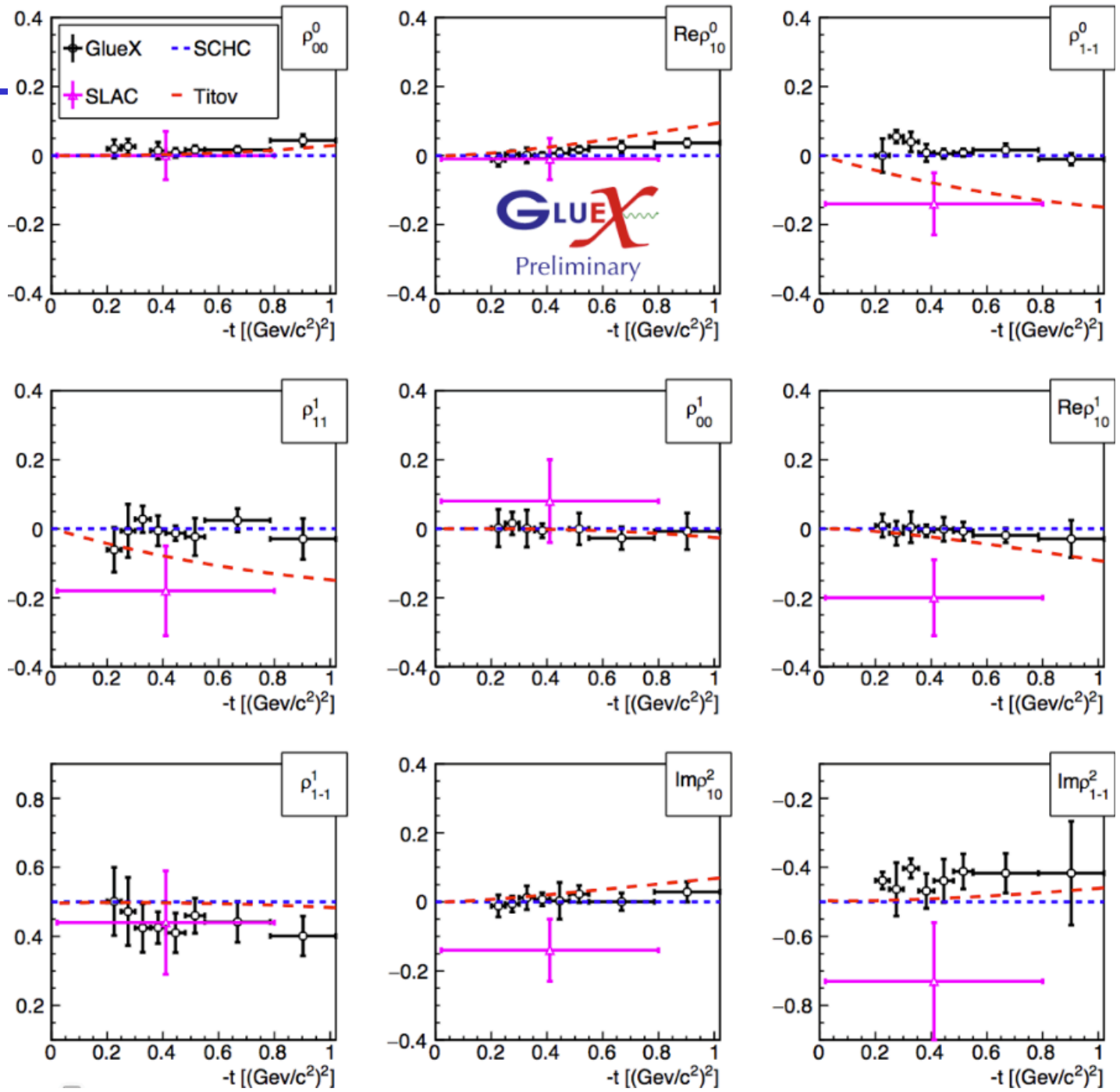
Standard Decomposition

$$\rho(V) = \rho^{0} + \sum_{\alpha=1}^{3} P^{\alpha}_{\gamma}\,\rho^{\alpha}$$

γp -> ϕp

$\phi \rightarrow K^+K^-$

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

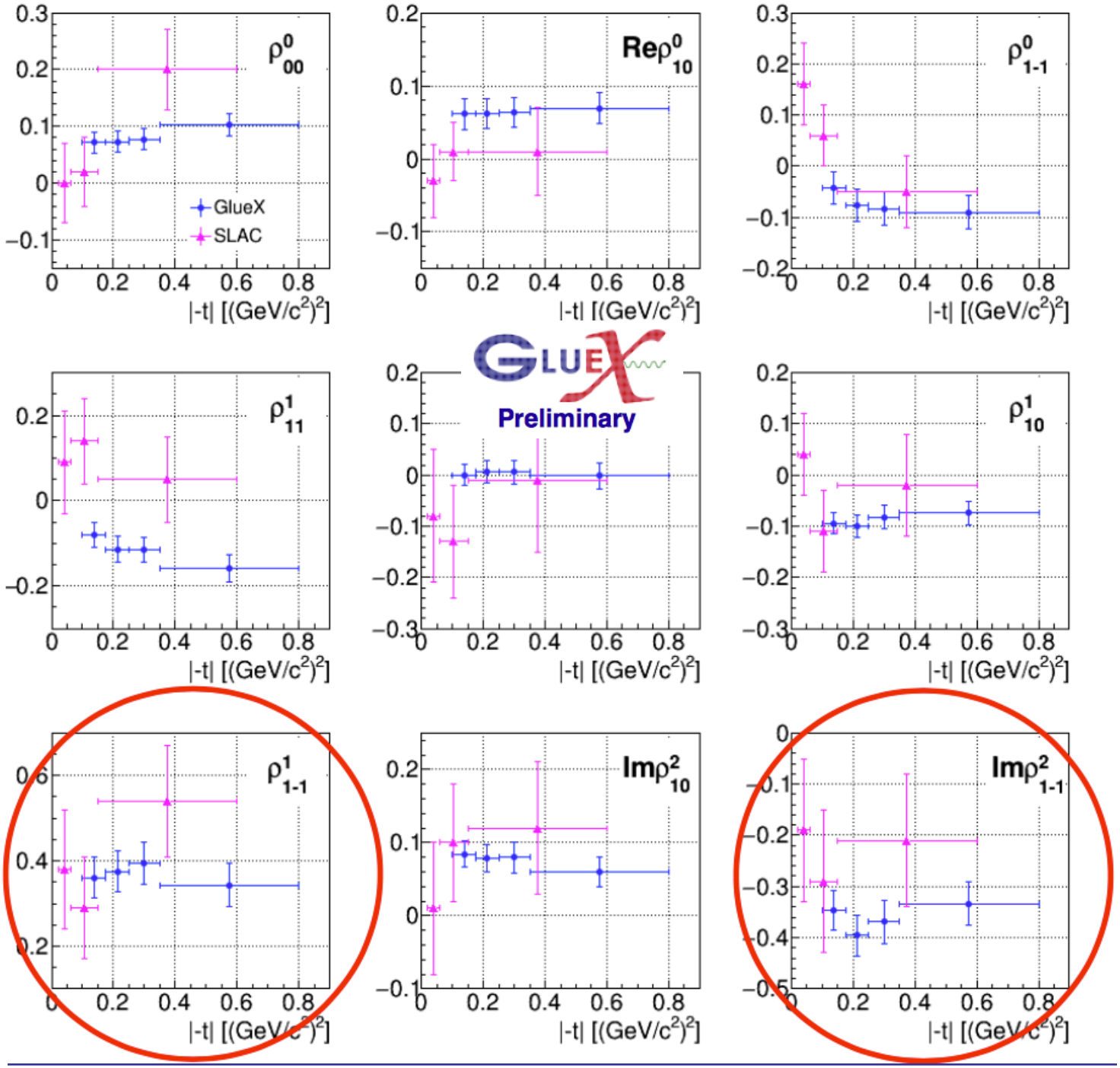


A. Barnes, Ph.D. UConn, 2017

γp -> ω p

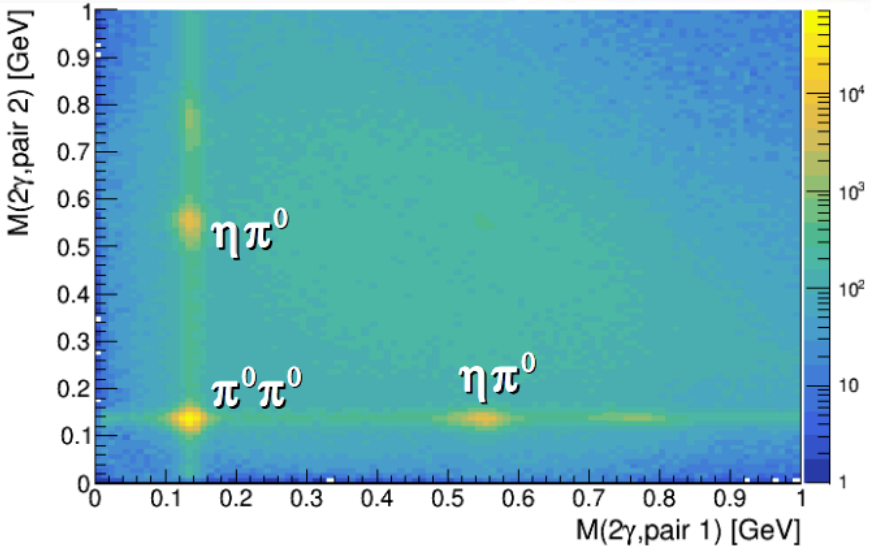
$\omega \rightarrow \pi^+\pi^-\pi^0$

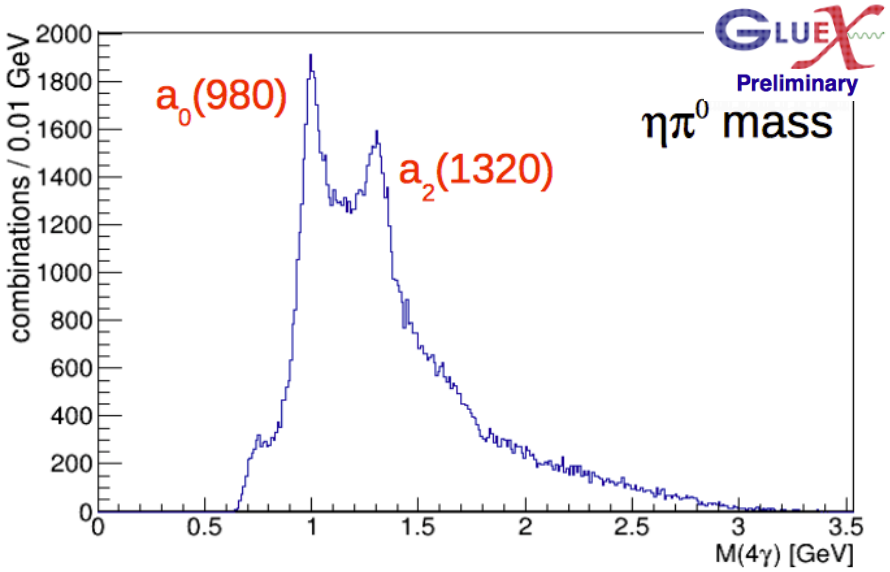
- Expect contributions from pseudo-scalar exchange
- Consistent with previous SLAC results
- Provides insight into the exchange mechanisms

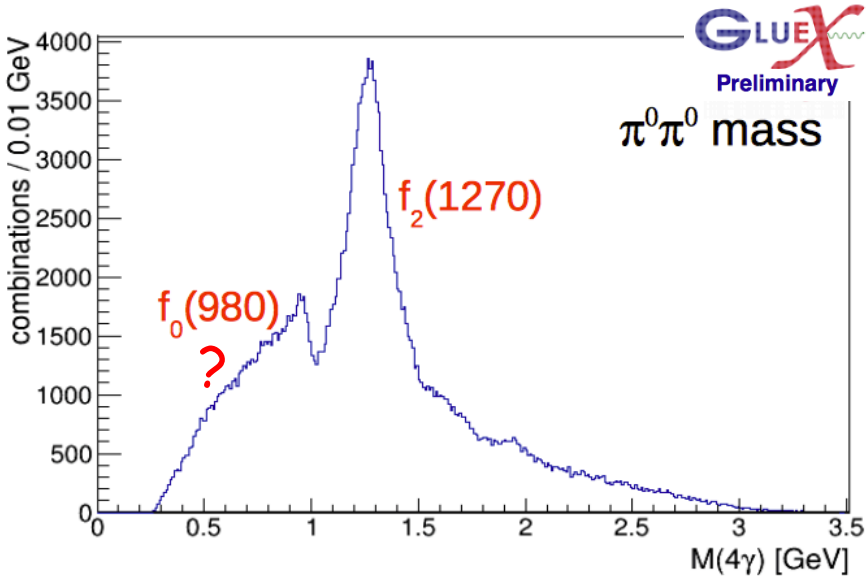


M. Staib, Ph.D. CMU, 2017

Opportunities in spectroscopy: 4γ systems

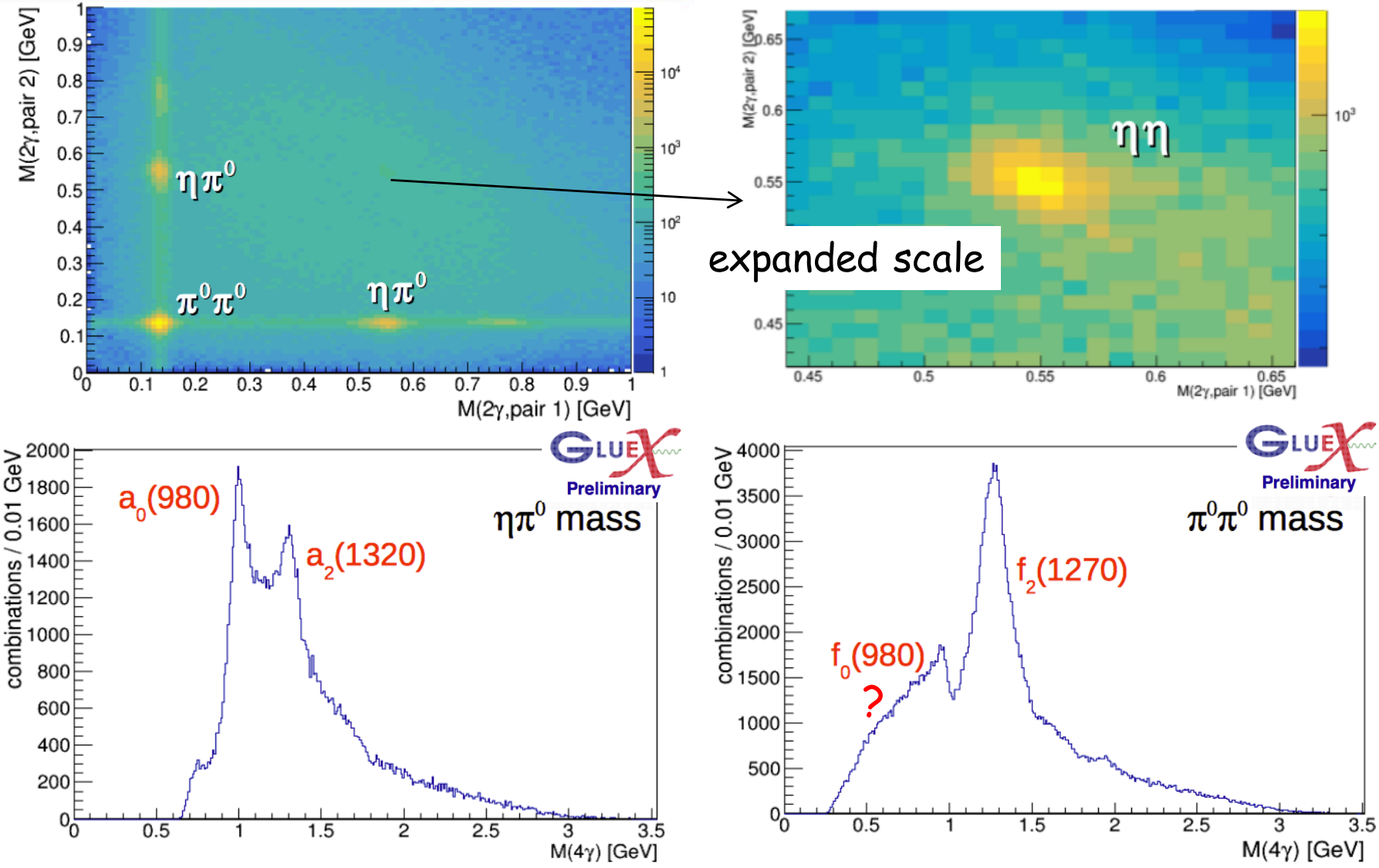






- Previous photoproduction data with multiple neutrals is very limited
- Systems decaying with L=odd to ηπ have exotic J^{PC}.

Opportunities in spectroscopy: 4γ systems



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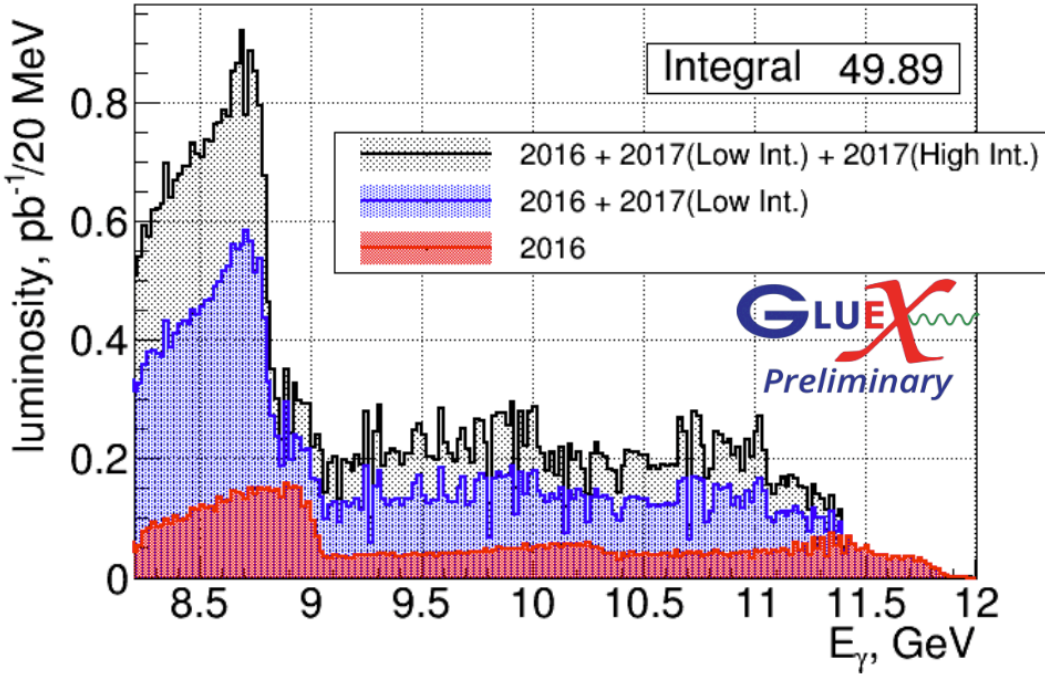
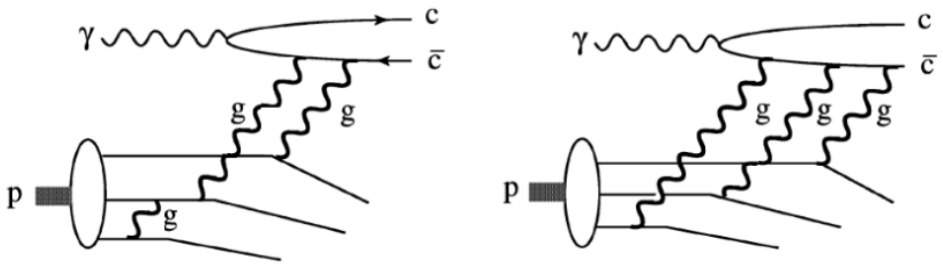
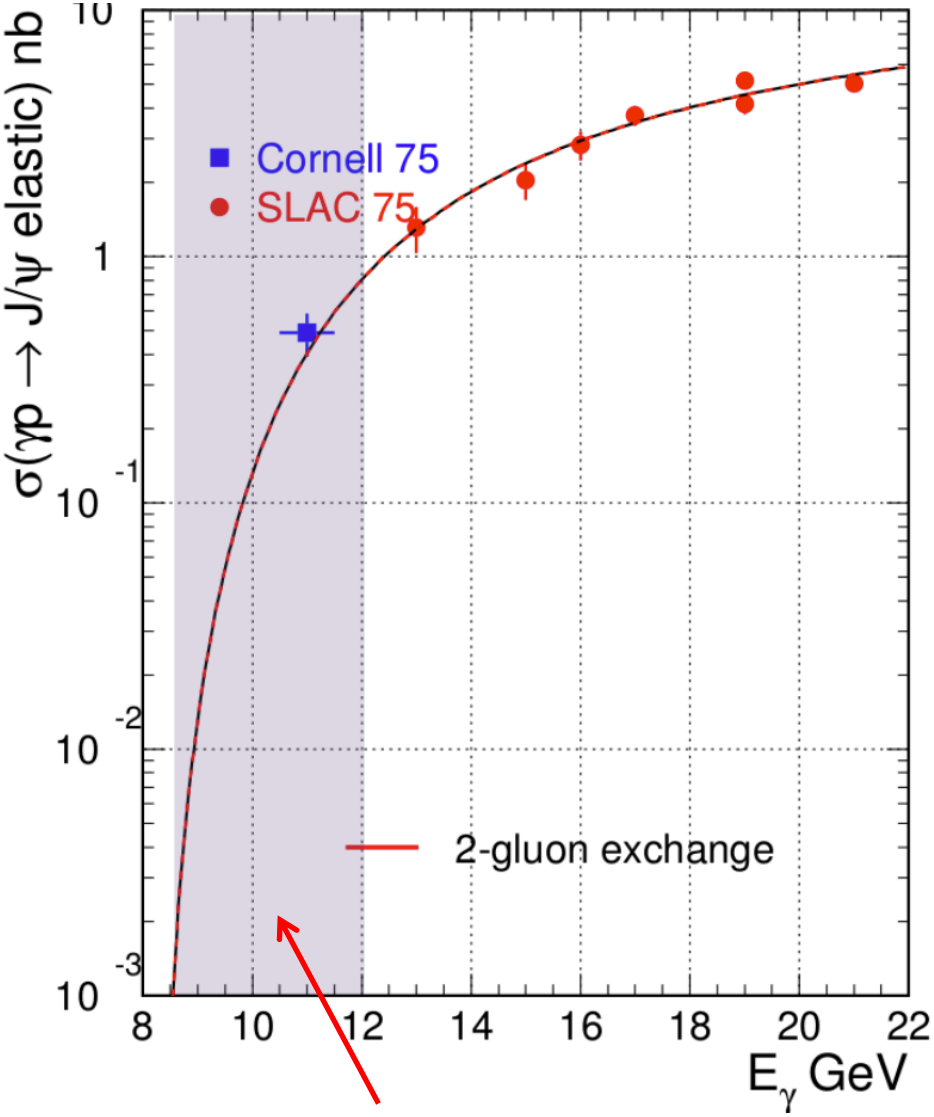
Charm production near threshold

See Pentchev, JLab User's Meeting 2018





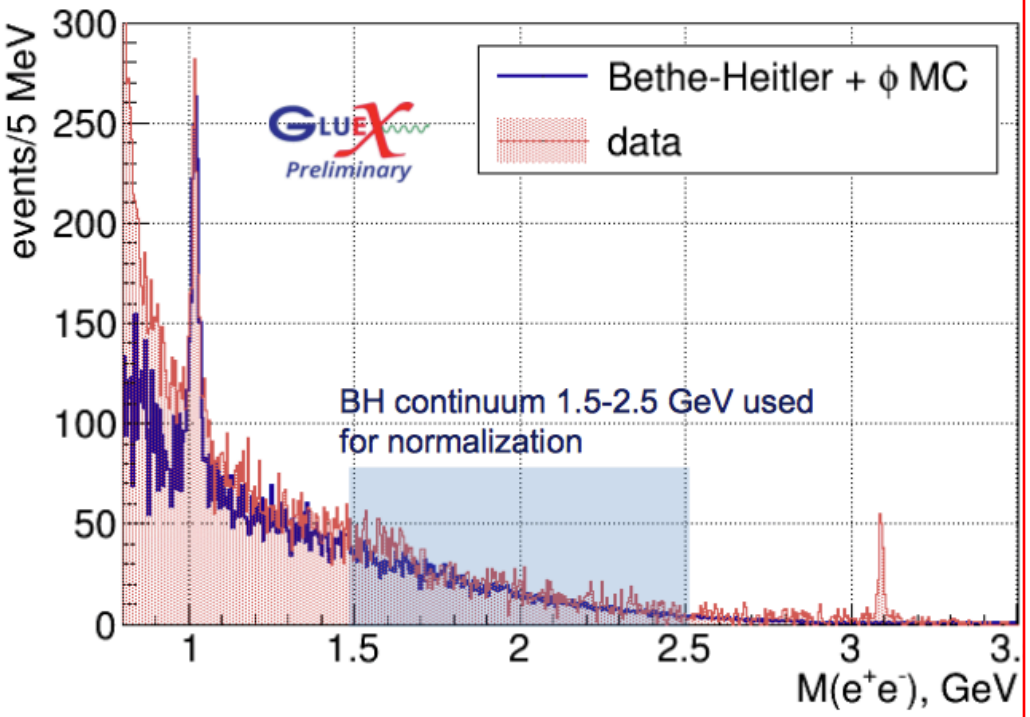
Brodsky *et.al.* PLB 498 (2001) 23

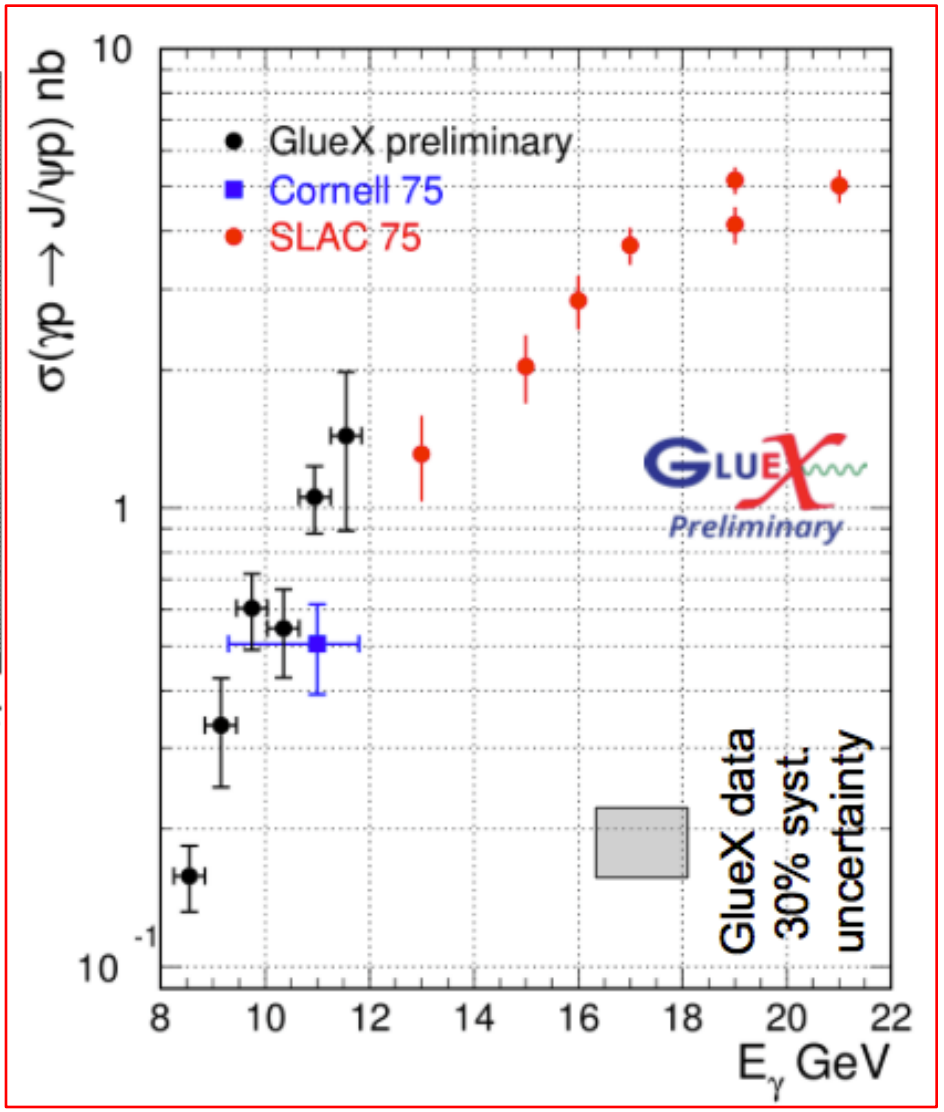


GlueX Energy Range

Preliminary J/ψ results

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

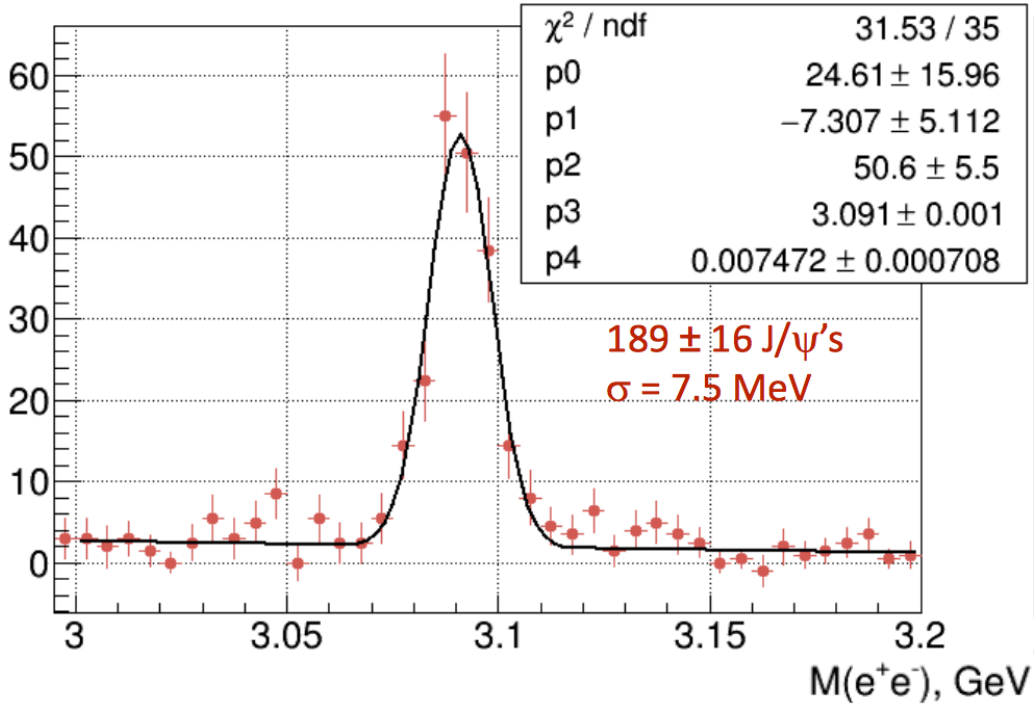




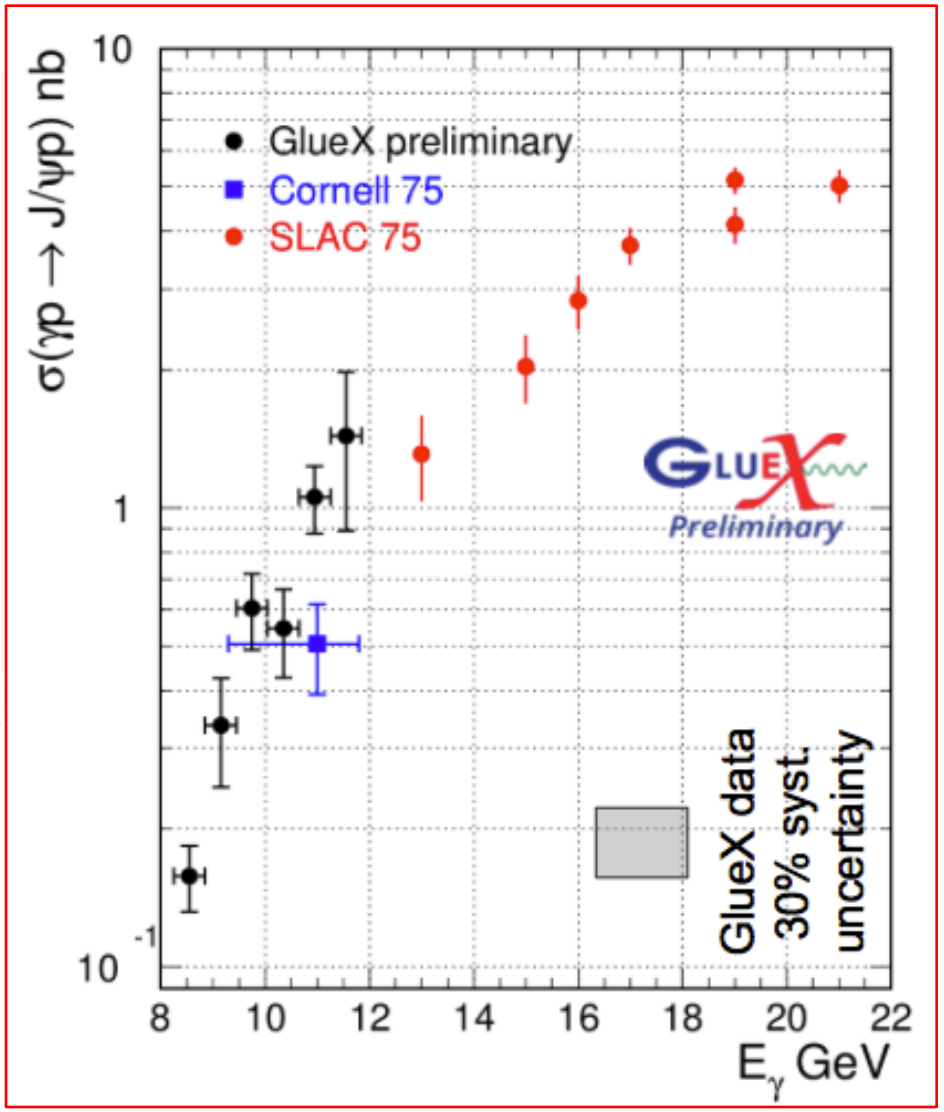
- Preliminary cross sections E_γ~8-12 GeV

Preliminary J/ψ results

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

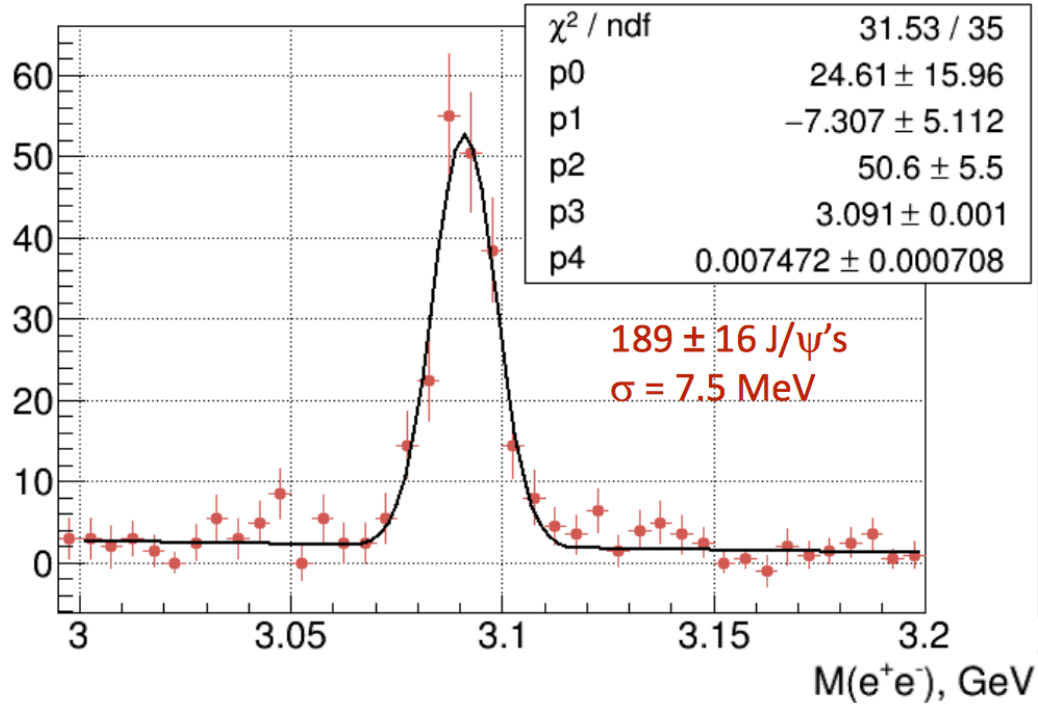


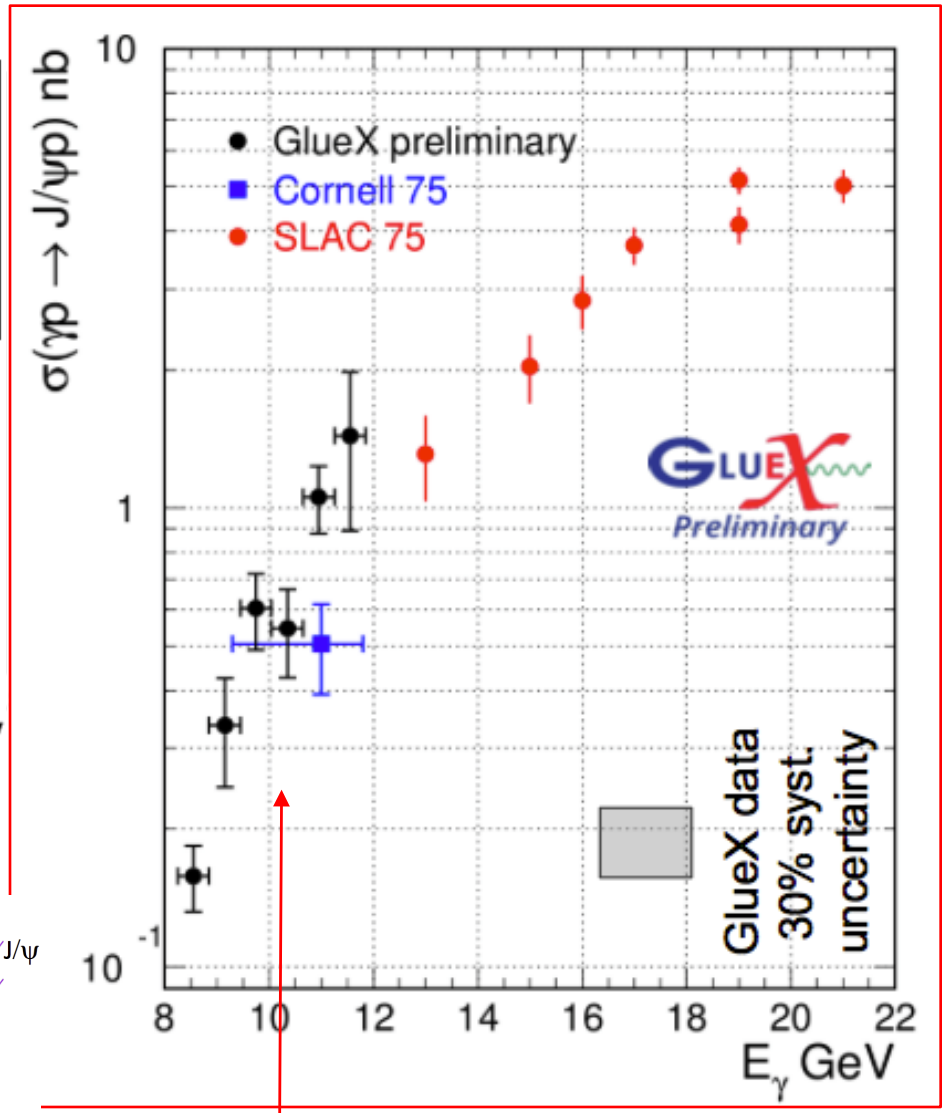
- Preliminary cross sections E_γ~8-12 GeV



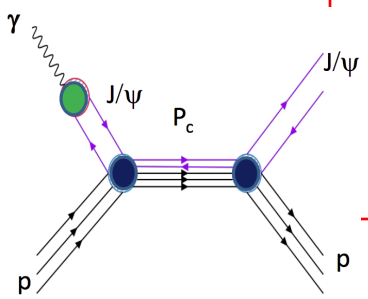
Preliminary J/ψ results

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





- Preliminary cross sections E_γ~8-12 GeV
- No indication of LHCB pentaquark



$P_c(4450)$

Summary

- We have mounted the GlueX experiment in Hall D at Jefferson Lab devoted to the study of hybrid mesons. Their existence and properties will yield fundamental information regarding the force that confines quarks.
- On the road toward finding exotic hybrids, we are
  - Measuring beam-spin asymmetries for several particles to understand production mechanisms
  - Measuring spin density matrices for vector mesons
  - Working on amplitude analysis of some simple systems such as $\eta\pi$ and $\eta'\pi$ (exotic J^{PC} for L=odd)
- Pursuing opportunistic physics such as J/ψ production at threshold

  - Upcoming experiments:
    - Primakoff η and rare η decays
    - High Intensity GlueX (with DIRC)
    - Charged Pion Polarizability

Also see Somov, Session 4

Backup Slides

Program and upgrades

Experiment	Description	Beam Time (days)
GlueX I	Study spectrum of light mesons and gluonic excitations (low intensity)	80
GlueX II	Study of hadron decays to strange final states (high intensity)	200+220(*)
Primakoff eta	Eta radiative decay width	79
CPP	Charged pion polarizability measurement	25
Jlab Eta Factory	Rare eta decays	42 (conditional)

(*) May run concurrently

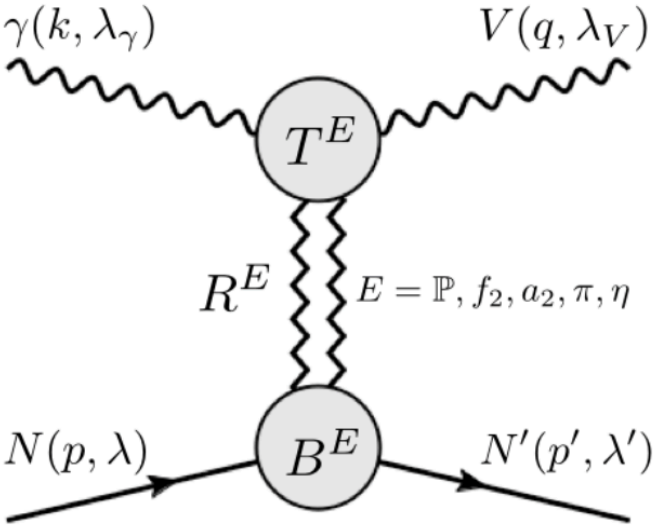
- DIRC detector for enhanced π/kaon identification will be installed starting this summer
- Online computer farm will be added for high intensity running
- High resolution calorimeter is needed for parts of the JEF program

Spin density matrix elements (SDMEs)

JPAC PRD 97 (2018) 094003

$$\begin{aligned} \rho(V) &= T\,\rho(\gamma)\,T^\dagger \\ \rho(\gamma) &= \frac{1}{2}I + \frac{1}{2}\mathbf{P}_\gamma \cdot \sigma \\ \mathbf{P}_\gamma &= P_\gamma(-\cos 2\Phi, -\sin 2\Phi, 0) \end{aligned}$$

Φ is the angle between the photon polarization and the production plane



$$\rho^0_{\lambda_V \lambda_{V'}} = \frac{1}{2N} \sum_{\lambda_\gamma \lambda_N \lambda_{N'}} T_{\lambda_V \lambda_{N'},\lambda_\gamma \lambda_N}\, T^*_{\lambda_{V'} \lambda_{N'},\lambda_\gamma \lambda_N}$$

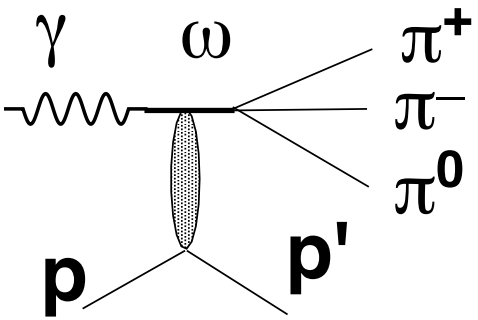
Sum over external helicities

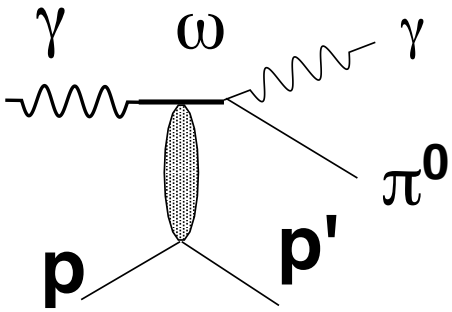
Helicity amplitudes

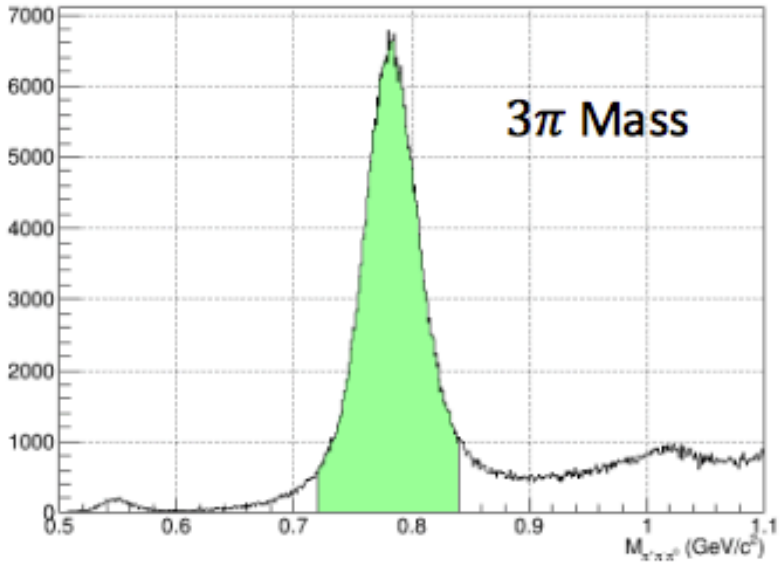
SDMEs measure the transfer polarization from the photon to the vector meson V

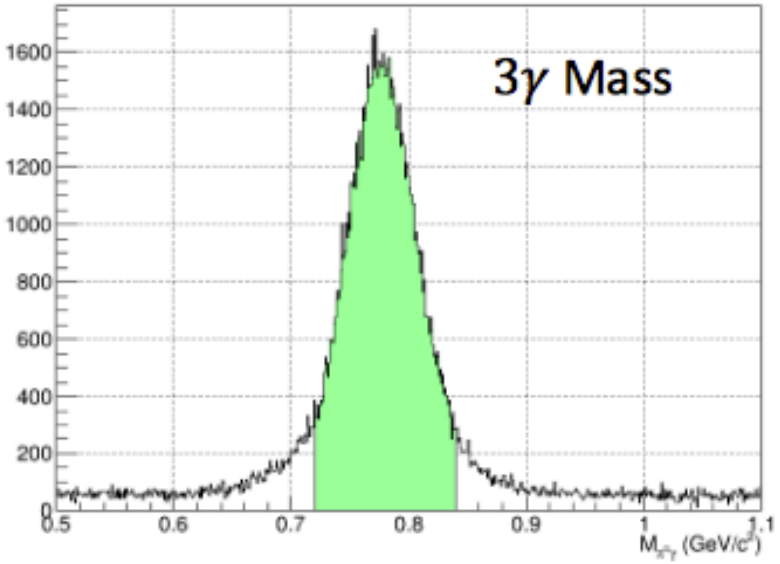
Omega production and decay

Use different decays to probe the same production mechanism









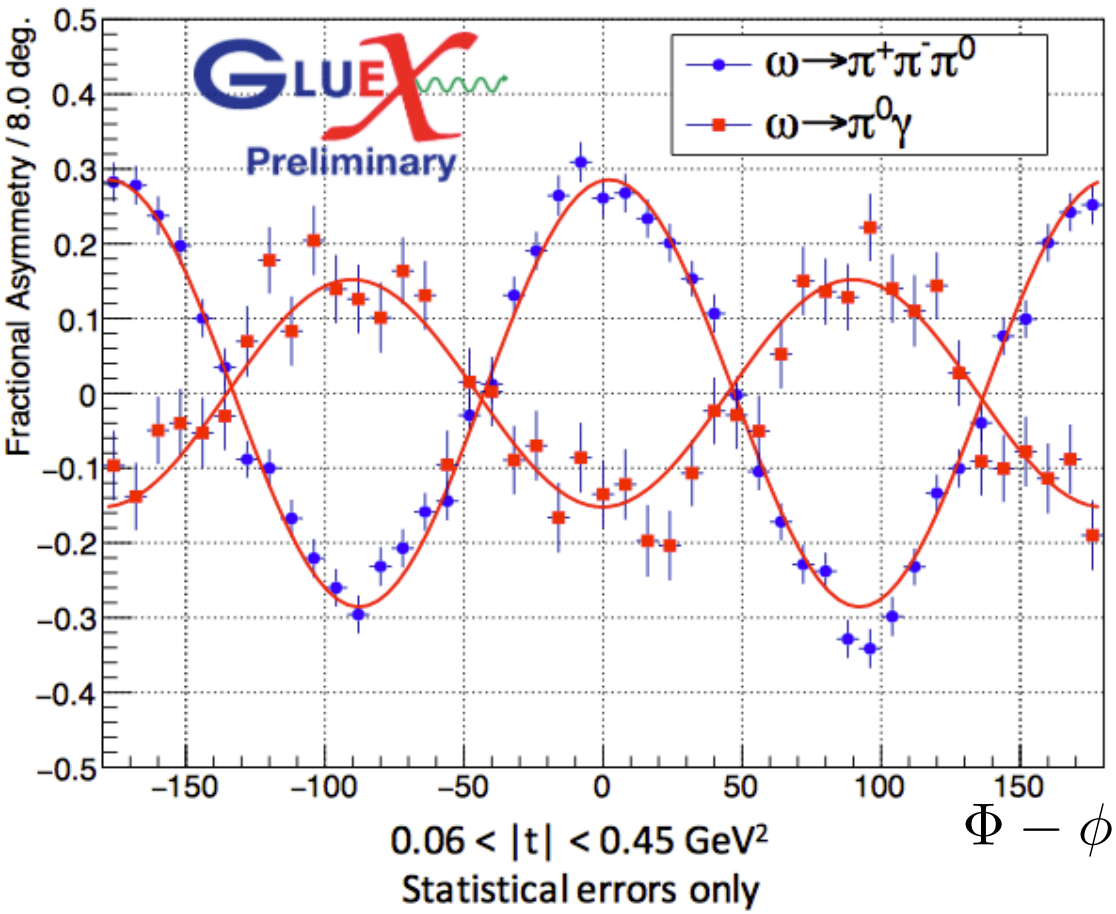
Titov PRC 78 (2008) 038201

Zhao PRC 71 (2005) 054004

ω asymmetry

Assuming Vector Meson Dominance (VMD), angles in helicity frame

$$\mathcal{A}^{\pi\gamma} = -\frac{1}{2} P \cos 2(\Phi - \phi) \qquad \mathcal{A}^{3\pi} = P \cos 2(\Phi - \phi)$$



$$\frac{\mathcal{A}^{3\pi}}{\mathcal{A}^{\pi\gamma}} = -1.88 \pm 0.13$$

- Preliminary data consistent with VMD
- Goal is to determine the Spin Density Matrix Elements (SDMEs) to probe the production mechanisms in more detail.

Naming Scheme for u,d Mesons

Name (I=1, I=0)	L	S	J^{PC}	$^{2S+1}L_J$	Examples
π, η	0	0	0^{-+}	$^1S_0$	π, η
ρ, ω	0	1	1^{--}	$^3S_1$	$\rho(770)$, $\omega(782)$
b, h	1	0	1^{+-}	$^1P_1$	$b_1(1235)$, $h_1(1170)$
a, f	1	1	0^{++}	$^3P_0$	$a_0(980)$, $f_0(980)$
a, f	1	1	1^{++}	$^3P_1$	$a_1(1260)$, $f_1(1285)$
a, f	1	1	2^{++}	$^3P_2$	$a_2(1320)$, $f_2(1270)$
π, η	2	0	2^{-+}	$^1D_2$	$\pi_2(1670)$
ρ, ω	2	1	1^{--}	$^3D_1$	$\rho_1(1700)$, $\omega_1(1600)$
ρ, ω	2	1	2^{--}	$^3D_2$	
ρ, ω	2	1	3^{--}	$^3D_3$	$\rho_3(1670)$
b, h	3	0	3^{+-}	$^1F_3$	
a, f	3	1	2^{++}	$^3F_2$	
a, f	3	1	3^{++}	$^3F_3$	
a, f	3	1	4^{++}	$^3F_4$	

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

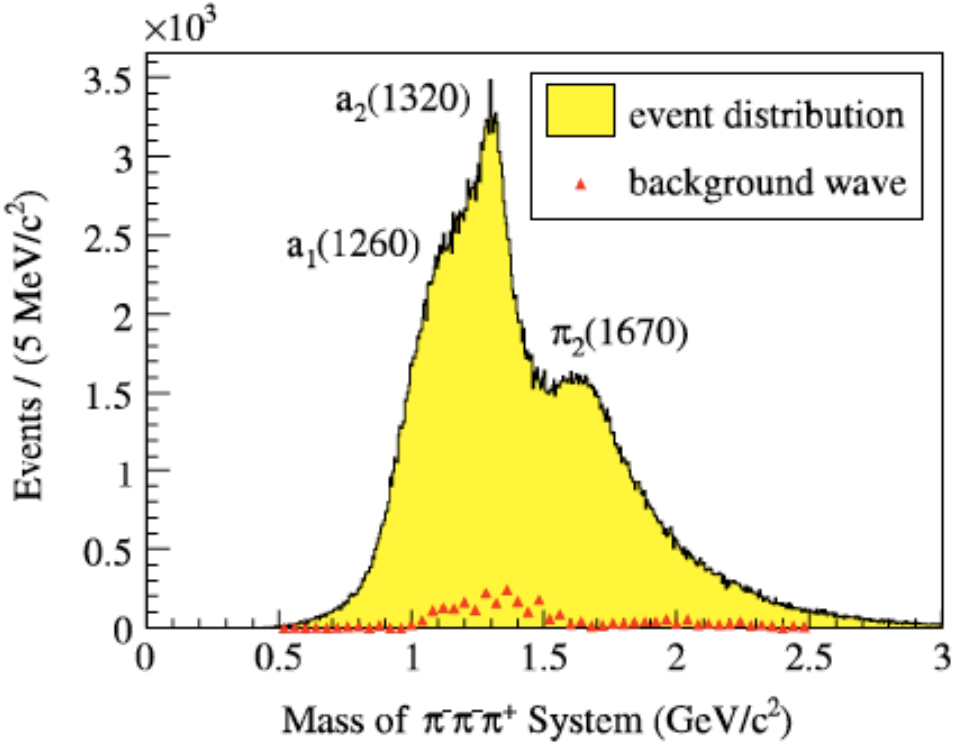
$PC = (-1)^{S+1}$

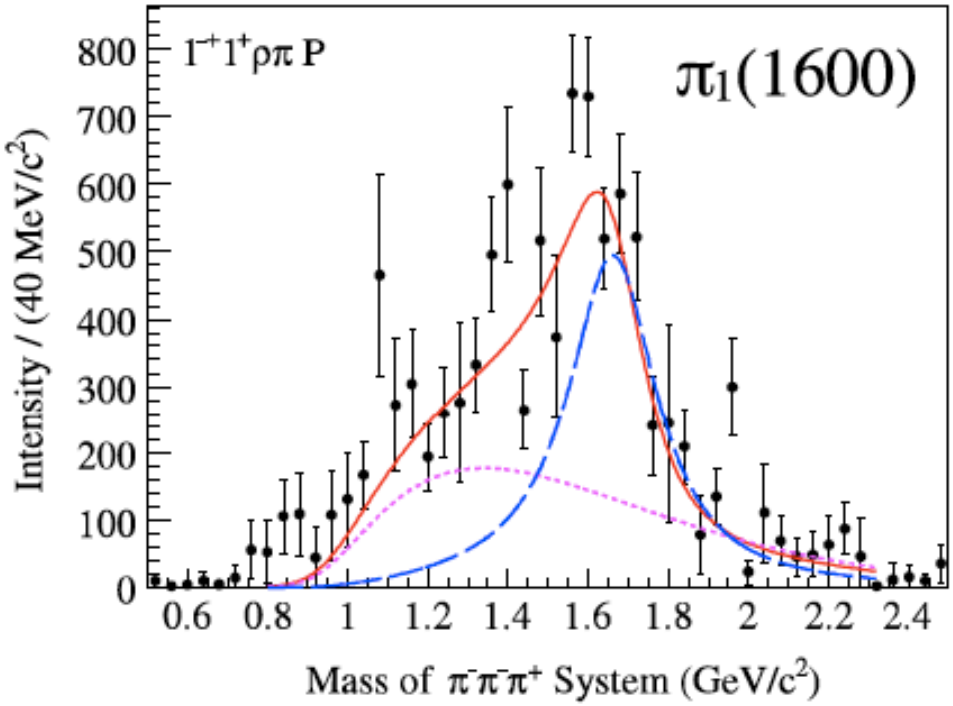
$G = C(-1)^I$

COMPASS: Exotic 1^{-+} $\pi_1(1600)$->$\pi^+\pi^-\pi^-$

Analysis of π^-Pb → $\pi^+\pi^-\pi^-$Pb at COMPASS

PRL 104, 241803 (2010)





~0.4 M events

Intensity =1.7% of total

COMPASS: Phase Motion of Exotic

COMPASS PRL 104 (2010) 241803

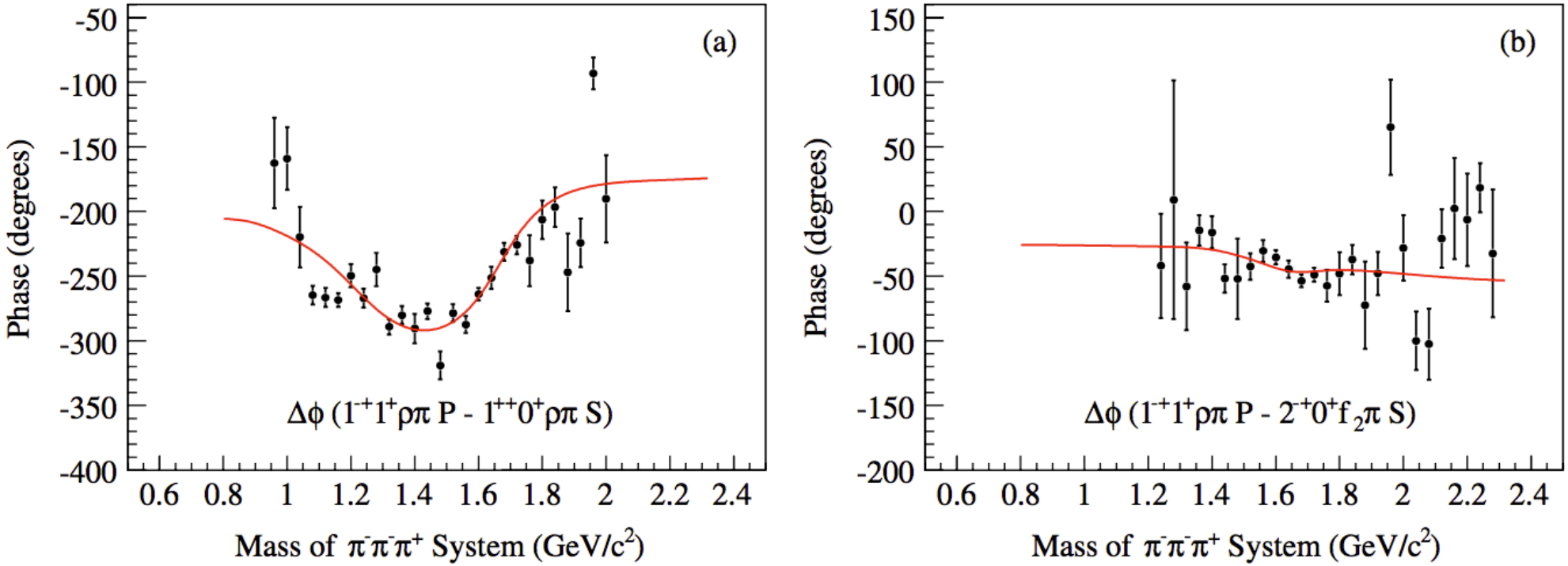


FIG. 3 (color online). Phase differences of the exotic $1^{-+}1^{+}\rho\pi P$ wave to the $1^{++}0^{+}\rho\pi S$ (a) and the $2^{-+}0^{+}f_2\pi S$ (b) waves. The data points represent the result of the fit in mass bins; the lines are the result of the mass-dependent fit.

COMPASS: $J^{PC}=1^{-+}$ $\eta\pi^-$, $\eta'\pi^-$

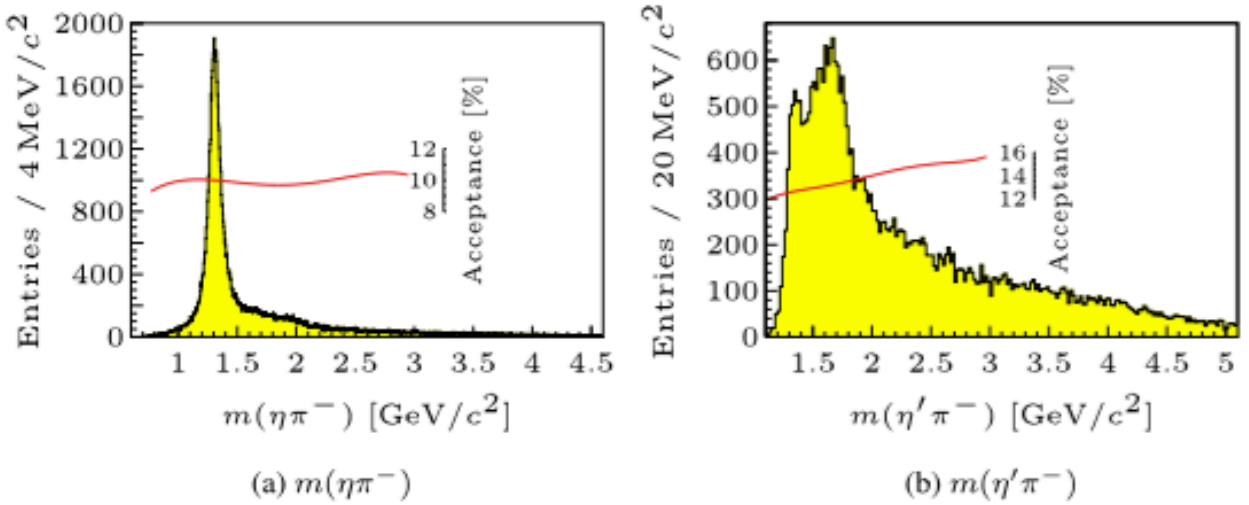


Fig. 1. Invariant mass spectra (not acceptance corrected) for (a) $\eta\pi^-$ and (b) $\eta'\pi^-$. Acceptances (continuous lines) refer to the kinematic ranges of the present analysis.

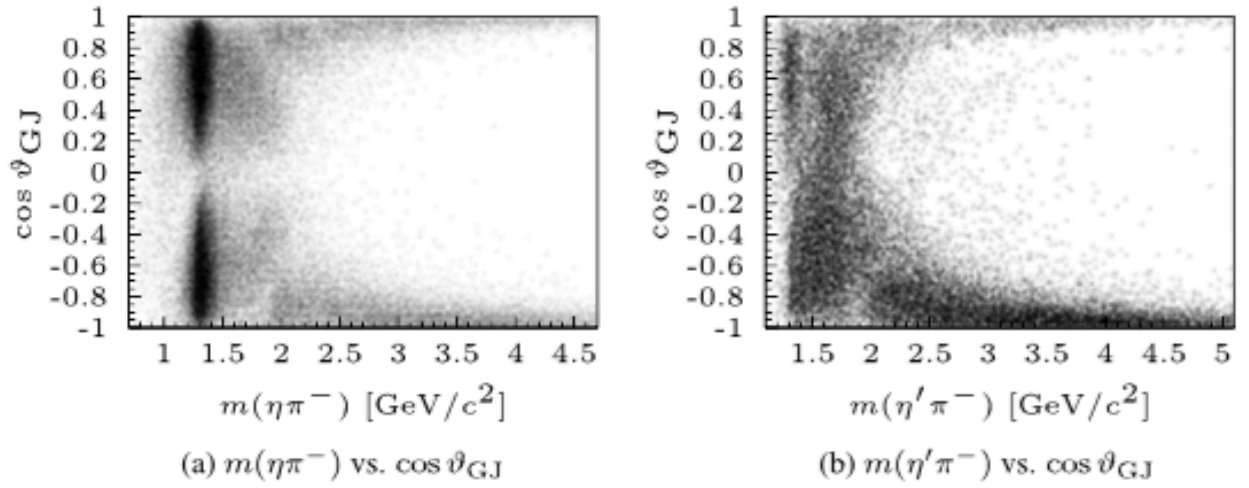
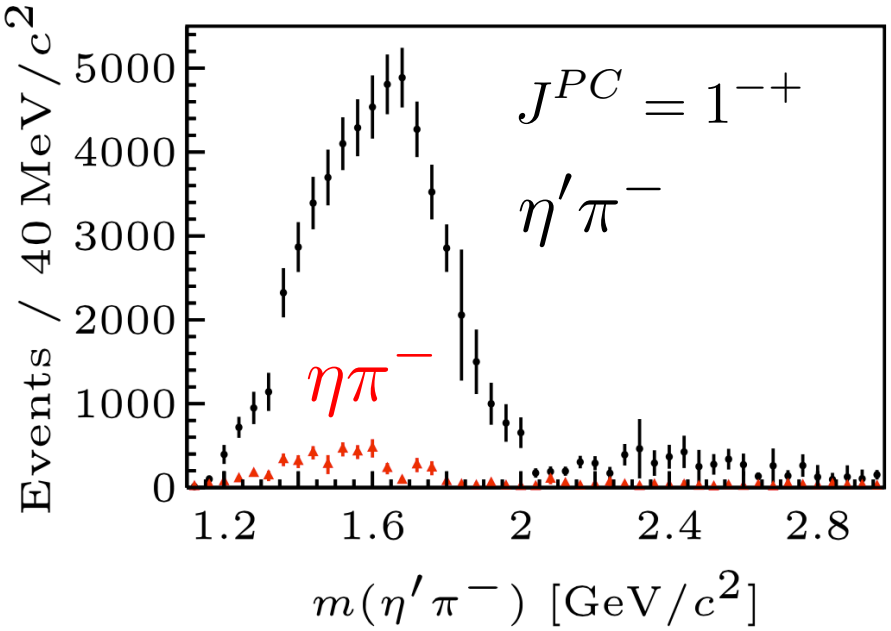


Fig. 2. Data (not acceptance corrected) as a function of the invariant $\eta\pi^-$ (a) and $\eta'\pi^-$ (b) masses and of the cosine of the decay angle in the respective Gottfried–Jackson frames where $\cos\vartheta_{GJ}=1$ corresponds $\eta^{(\prime)}$ emission in the beam direction. Two-dimensional acceptances can be found in Ref. [20].

COMPASS: $J^{PC}=1^{-+}$ $\eta\pi^-$, $\eta'\pi^-$

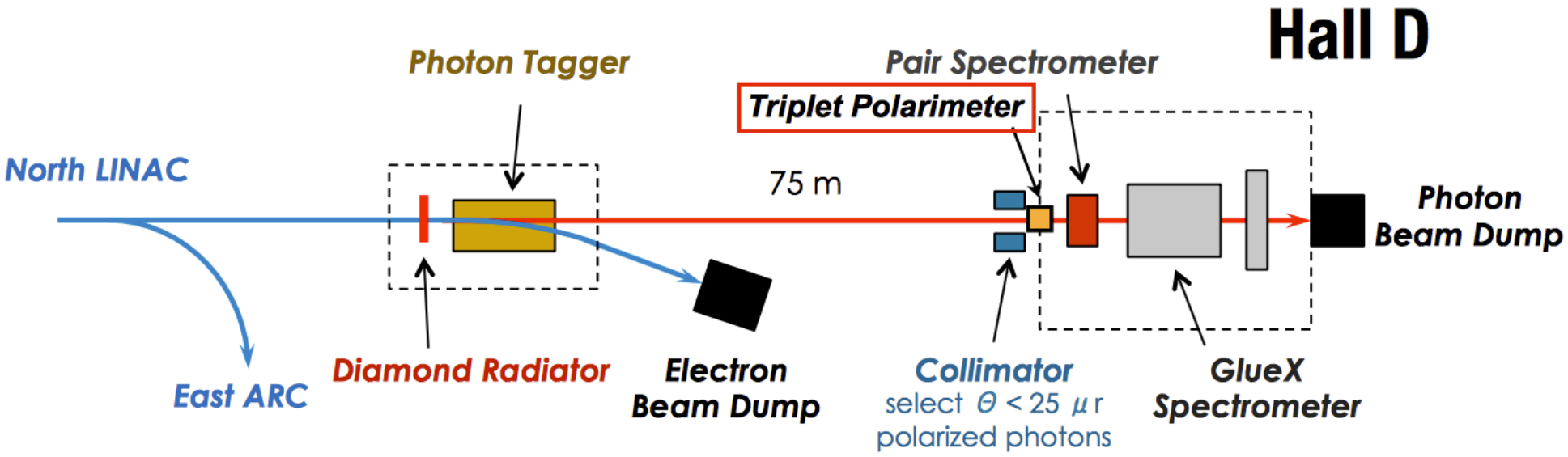
COMPASS PLB 740 (2015) 303



"The even partial waves with L=2,4,6 show a close similarity between the two channels, both in the intensities as a function of mass –after scaling by the phase-space and barrier factors- as well as in their phase behavior."

" The odd partial waves with L=1,3,5 carrying non-qqbar quantum numbers, are suppressed in $\eta\pi$- with respect to $\eta'\pi$-, underlining the importance of flavour symmetry."

Photon beam and experimental area



Decay modes for exotics

$\pi_1 \rightarrow \pi\rho,\ \pi b_1,\ \pi f_1, \pi\eta',\ \eta a_1$

$\eta_1 \rightarrow \eta f_2, a_2\pi, \eta f_1,\ \eta\eta', \pi(1300)\pi,\ a_1\pi,$

$\eta_1' \rightarrow K^*K,\ K_1(1270)K,\ K_1(1410)K\ ,\ \eta\eta'$

$b_2 \rightarrow \omega\pi,\ a_2\pi,\ \rho\eta,\ f_1\rho,\ a_1\pi,\ h_1\pi,\ b_1\eta$

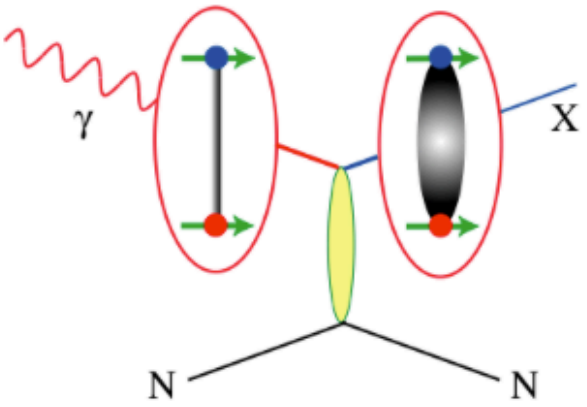
$h_2 \rightarrow \rho\pi, b_1\pi, \omega\eta,\ f_1\omega$

$h'_2 \rightarrow K_1(1270)K,\ K_1(1410)K,\ K_2^*K,\ \phi\eta,\ f_1\phi$

$b_0 \rightarrow \pi(1300)\pi\ ,\ h_1\pi,\ f_1\rho,\ b_1\eta$

$h_0 \rightarrow b_1\pi\ ,\ h_1\eta$

$h'_0 \rightarrow K_1(1270)K,\ K(1460)K,\ h_1\eta$



Early Reach **With Statistics** **Hard**

Hybrid kaons do not have exotic QN's

Models suggest narrower states are in the spin-1 and spin-2 nonets, while the spin-0 nonets are broad.