The recent results from the GlueX experiment

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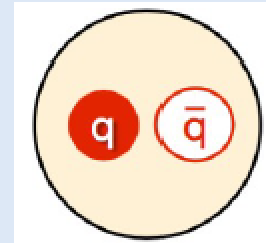
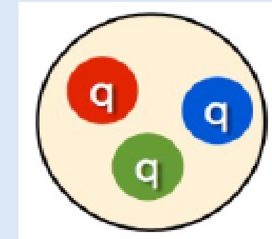
Yerevan, Armenia, June 5, 2018

- Physics motivation
- GlueX experiment: Apparatus & first results
  - Photoproduction by linearly polarized photons: asymmetries
  - J/ψ photoproduction near threshold
  - Observation of various known resonances
- Outlook

QCD: masses of hadrons

- Quark Model ⟶ describes hadron spectrum
  Flavor SU(3) symmetry for "constituent" quarks
  $q\bar{q}$ & qqq - most of visible matter in universe

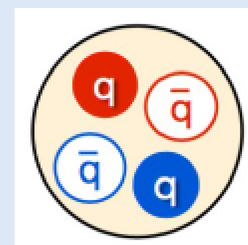


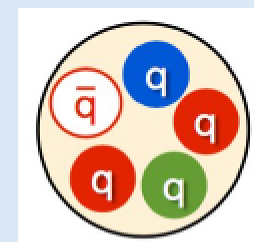


color SU(3) singlets

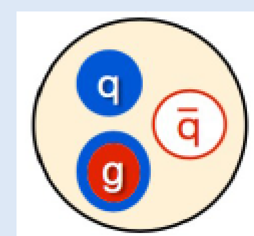
- QCD: exact color SU(3) symmetry
  Asymptotic freedom; Confinement
  The masses are generated dynamically.

- Other configurations are allowed in QCD:
  "Exotic" hadrons





- Lattice QCD predicts states like "hybrids"



Experimental evidence of ``exotic“ hadrons

Multi-quark candidates

- Numerous narrow signals X;Y; Z ⟶ J/ψ or ϒ
- Experimentally well established: Belle, BaBar, CDF, BES, LHCb etc
- Interpretation:

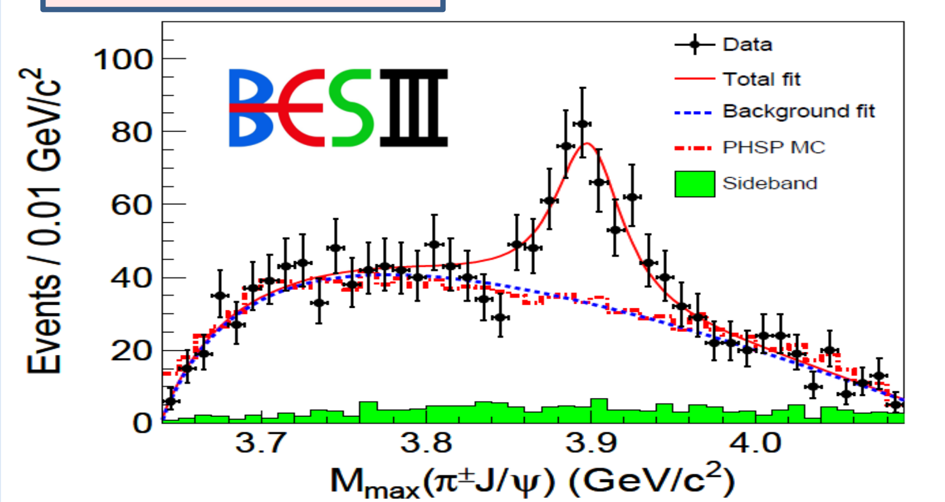
  Threshold cusps;

  ``Molecules” of color singlets;

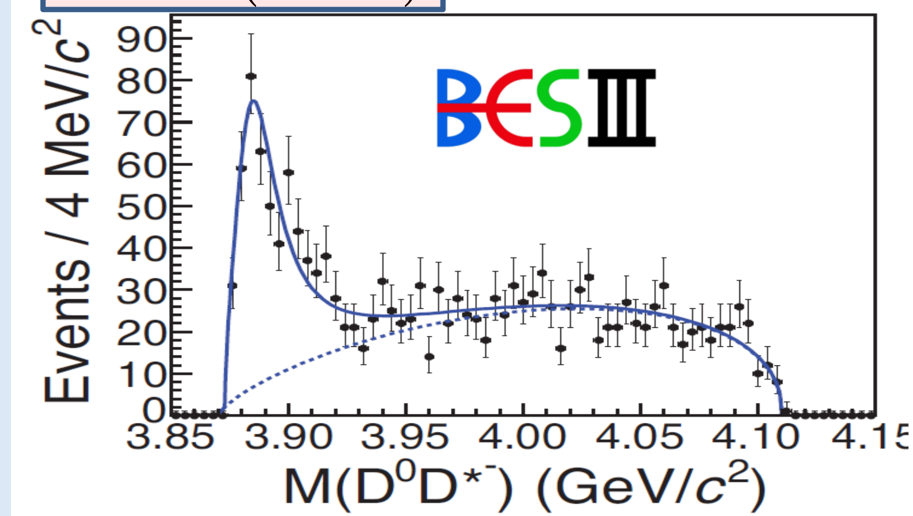
  Color multiplets.

$$\mathrm{e}{+}\mathrm{e}^{-} \rightarrow \pi^{\mp} Z_{\mathrm{c}}^{\pm}$$

$Z_{\mathrm{c}}^{\pm} \rightarrow \pi^{\pm} J/\psi$ PRL 110 252001 (2013)



$Z_{\mathrm{c}}^{\pm} \rightarrow \left(\bar{D}^{0} D^{*}\right)^{\pm}$ PRL 112 022001 (2013)



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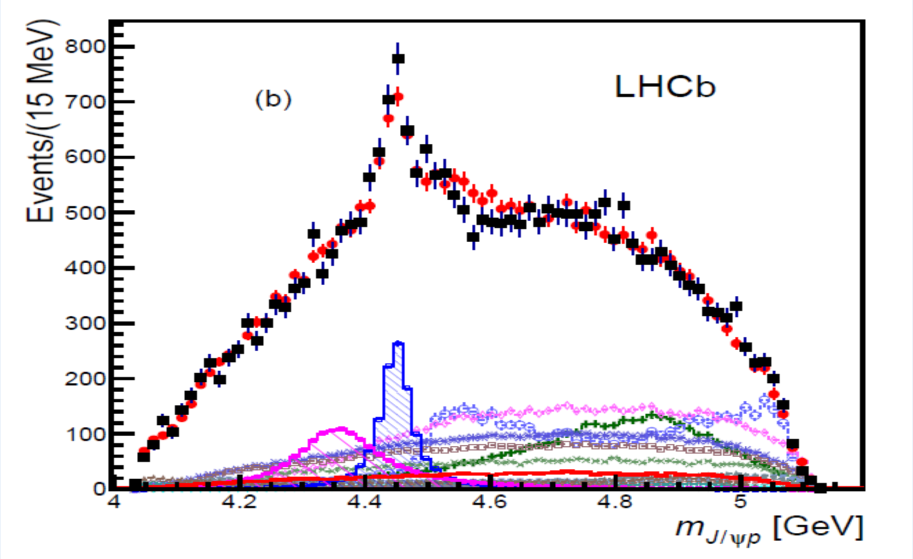
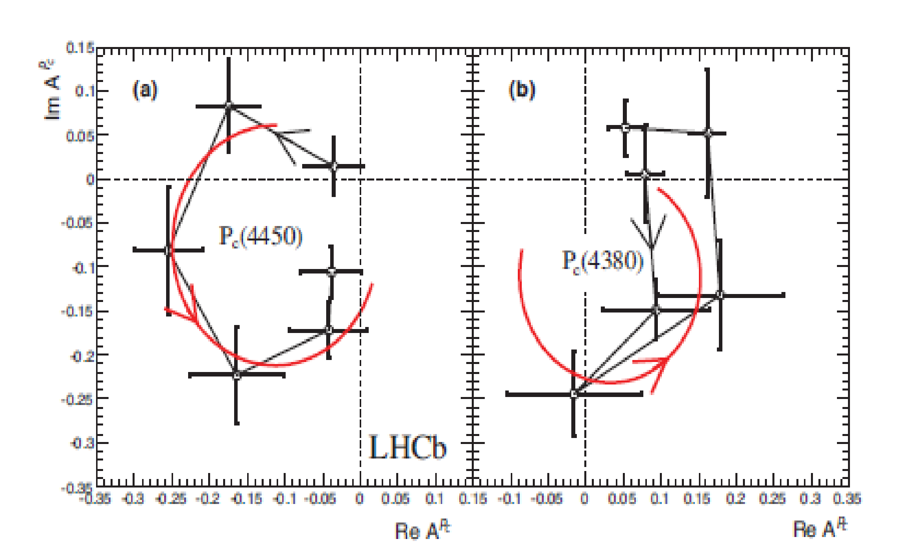
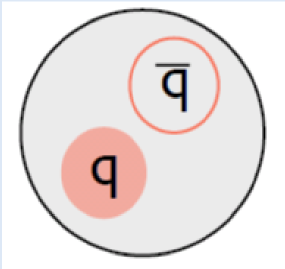
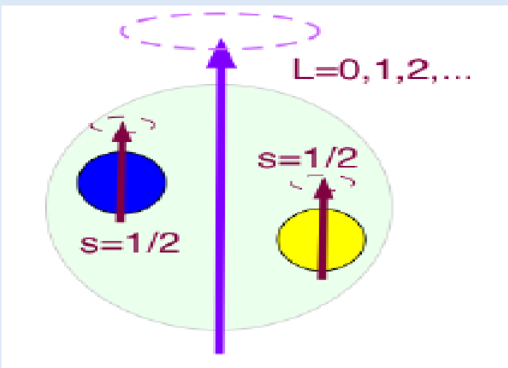
B → p K J/ψ

PRL 115 072001 (2015)





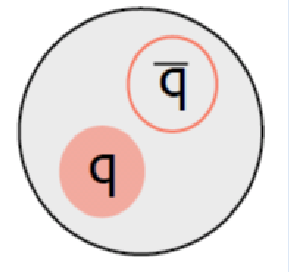


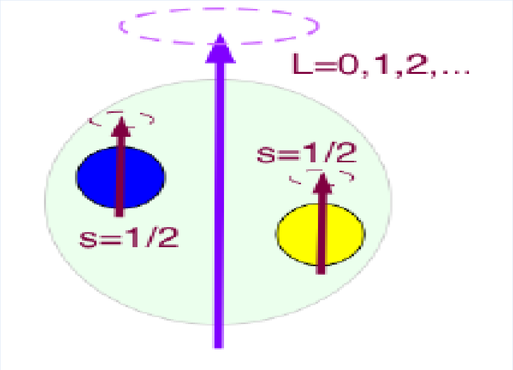


- ✓ Ordinary mesons are built from the lightest quarks **u**, **d** and **s** and their **antiquarks**.
- ✓ Combine two spin ½ objects to S=**0** or S=**1**
- ✓ Orbital angular momentum of two quarks: **L=0,1,2,3,…**
- ✓ Total angular momentum, **J=L⊕S**
  J=0,1,2,3,…

J^{PC}, $P=-(-1)^L$, $C=(-1)^{L+S}$

L=0, S=0, $J^{PC}=0^{-+}$	L=1, S=0, $J^{PC}=1^{+-}$	L=2, S=0, $J^{PC}=2^{-+}$	L=3, S=0, $J^{PC}=3^{+-}$
L=0, S=1, $J^{PC}=1^{--}$	L=1, S=1, $J^{PC}=2^{++}$ $J^{PC}=1^{++}$ $J^{PC}=0^{++}$	L=2, S=1, $J^{PC}=3^{--}$ $J^{PC}=2^{--}$ $J^{PC}=1^{--}$	L=3, S=1, $J^{PC}=4^{++}$ $J^{PC}=3^{++}$ $J^{PC}=2^{++}$





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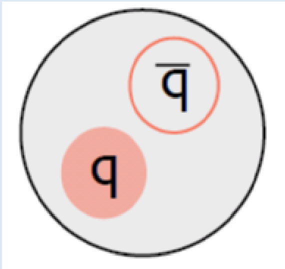
Each J^{PC} corresponds to nine quark-antiquark states, nonets :

$$u\bar{s}\ ,\ d\bar{s}$$

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

$$s\bar{d}\ ,\ s\bar{u}$$



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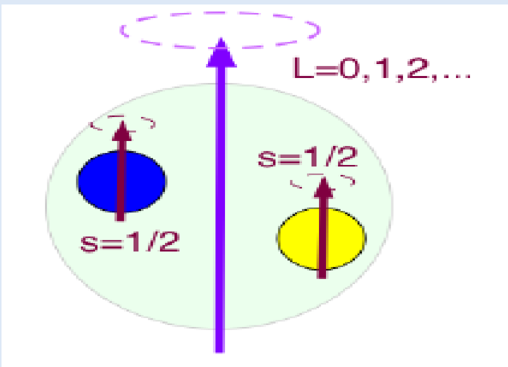

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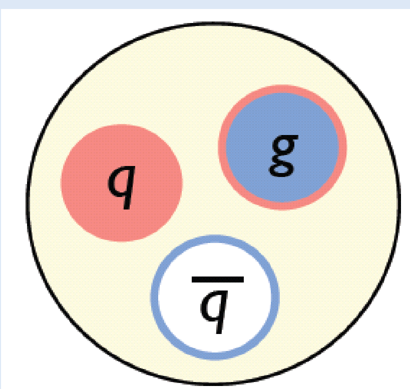
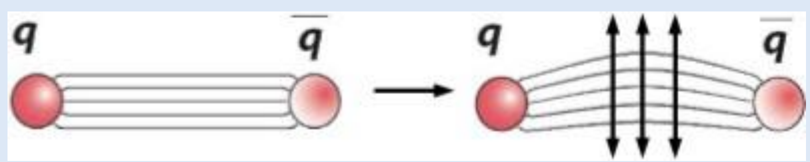


"Constituent gluon" behaves like $J^{PC} = 1^{+-}$ with a mass of 1-1.5 GeV

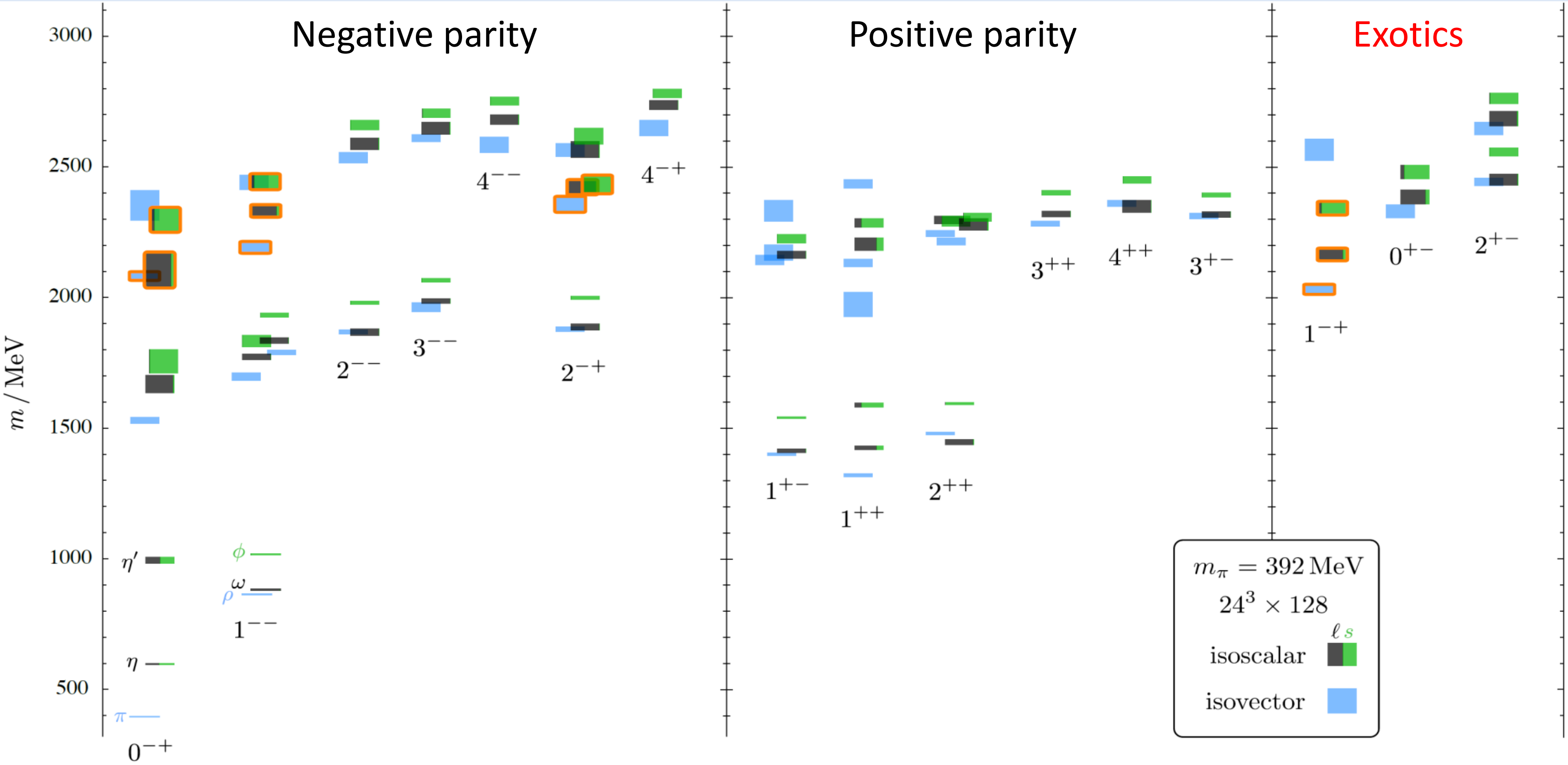


Exotic Quantum Numbers:

0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}

Predictions from lattice QCD (light quarks – u,d,s)

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



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

Orange frames – lightest hybrids

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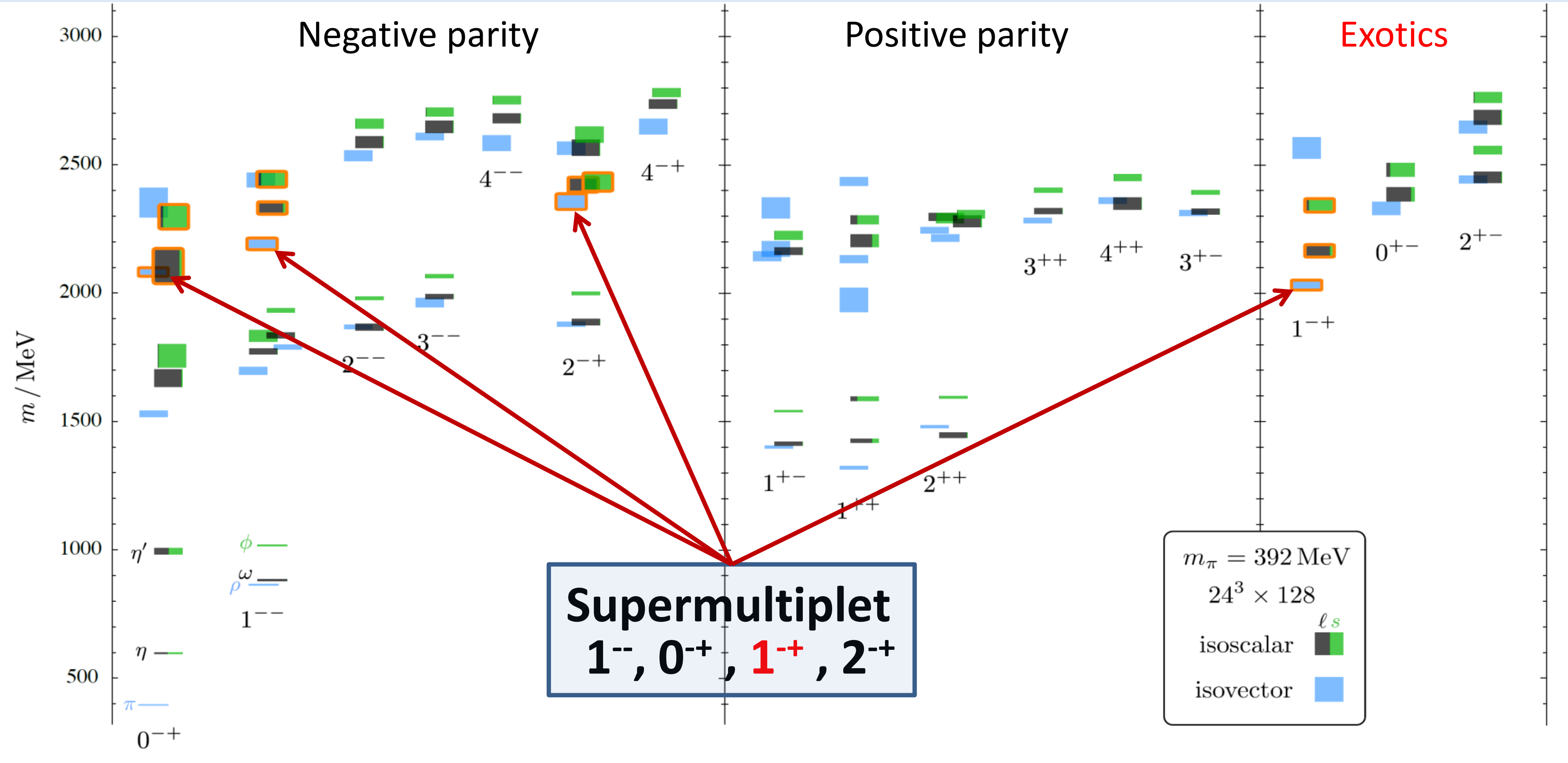


$$\frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \qquad \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \qquad (s\bar{s})$$

Orange frames – lightest hybrids

Lattice QCD: Masses

2 nonets: 1^{-+} π_1; η_1 ... ~ 2.0 – 2.4 GeV/c^2

1 nonet: 0^{+-} b^0; h ... ~ 2.3 – 2.5 GeV/c^2

2 nonets: 2^{+-} b_2^0; h_2 ... ~ 2.4 – 2.6 GeV/c^2

Models: Decays

$\Gamma^{tot} \approx 0.1 - 0.5$ GeV/c^2

Final states: multiple $\pi^{\pm}$ and γ

No calculations for the decay widths, couplings or cross sections so far.

How to detect the hybrids?

- Detect the final states (exclusive reactions)
- Identify the QN using the Partial Wave Analysis (PWA)

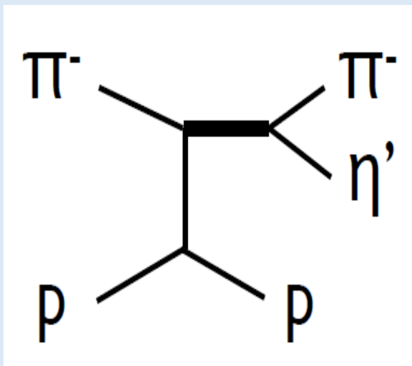
- The $\pi_1(1600)$ has been observed by several experiments, mostly in $\pi^- p$ experiments. It has been seen in a number of decay modes, some of which are controversial.

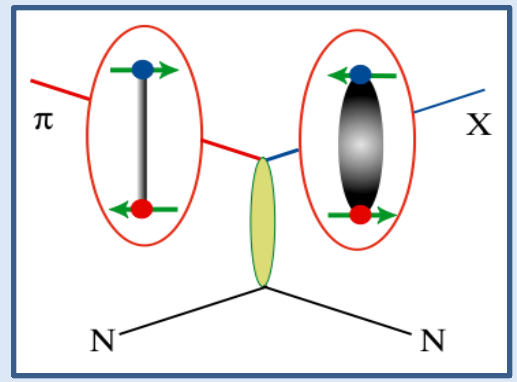
- The $\pi_1(2015)$ has been observed by a single low-statistics experiment. Confirmation is needed.

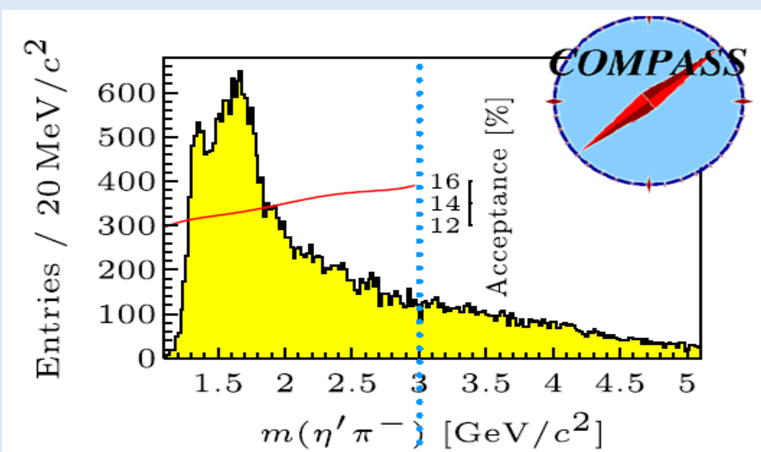
Experimental evidence of ``exotic“ hadrons

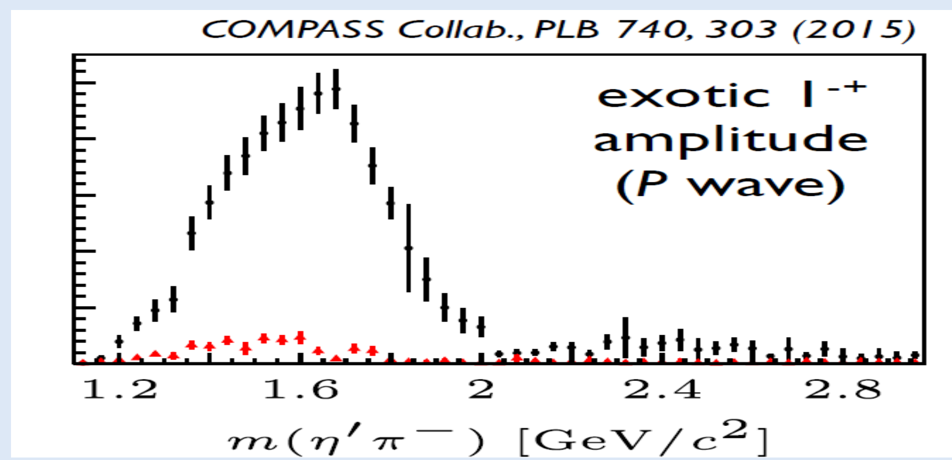
Hybrid candidates

- Relatively weak evidence
- Experiments: LEAR, E852, VES, COMPASS etc.
- $p\bar{p}$ & $\pi^{-}p$ interactions

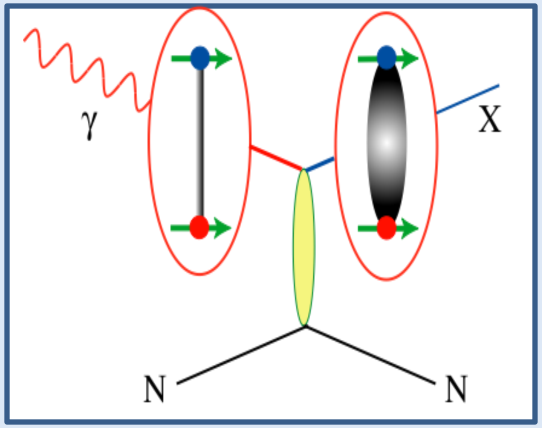






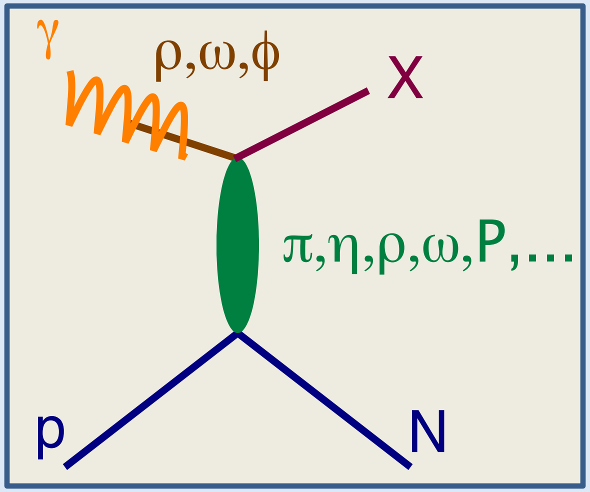


Photoproduction by linearly polarized photons



- Photoproduction is poorly-studied.
- Photon can fluctuate into a spin-1 particle.

Do not need charge exchange or isospin 1 final states. Linear polarization filters the exchange mechanisms.



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

Decay of ``Hybrid" mesons

J^{PC}	
----	————————————————————————————————
1^{-+}	$\pi_1 \rightarrow \pi\rho, \pi b_1, \pi f_1, \pi\eta', \eta a_1$
	$\eta_1 \rightarrow \eta f_2, a_2\pi, \eta f_1, \eta\eta', \pi(1300)\pi, a_1\pi$
	$\eta_1' \rightarrow K^*K, K_1(1270)K, K_1(1410)K, \eta\eta'$
2^{+-}	$b_2^0 \rightarrow \omega\pi, a_2\pi, \rho\eta, f_1\rho, a_1\pi, h_1\pi, b_1\eta$
	$h_2 \rightarrow \rho\pi, b_1\pi, \omega\eta, f_1\omega$
	$h'_2 \rightarrow K_1(1270)K, K_1(1410)K, K_2^*K, \phi\eta, f_1\phi$
0^{+-}	$b_0 \rightarrow \pi(1300)\pi, h_1\pi, f_1\rho, b_1\eta$
	$h \rightarrow b_1\pi, h_1\eta$
	$h' \rightarrow K_1(1270)K, K(1460)K, h_1\eta$
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large BR: early reach   need statistics   small BR: much harder

- Broad survey for hybrid mesons: large acceptance detector with good PID for both charged particles and photons.

The GlueX experiment

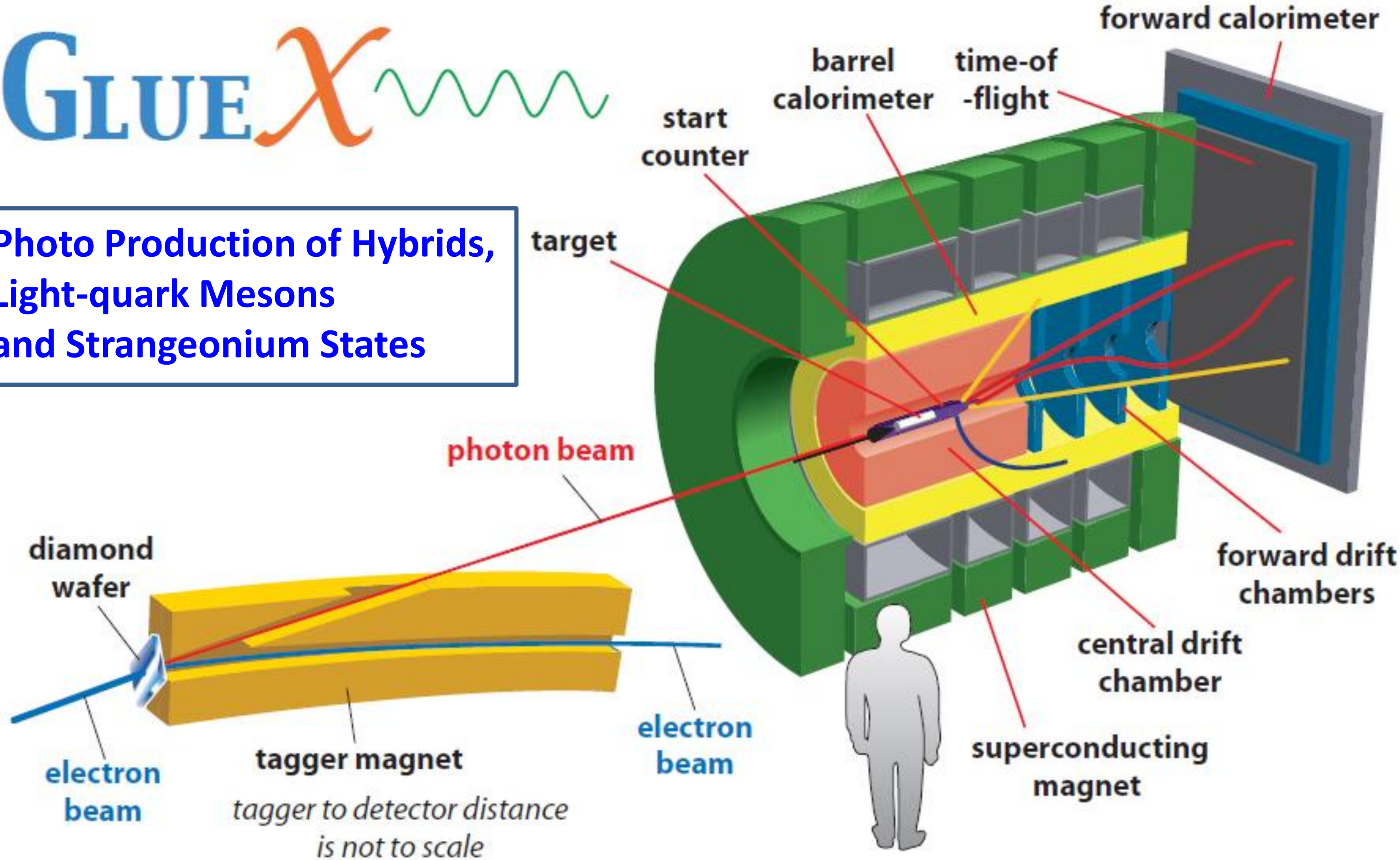


Photo Production of Hybrids, Light-quark Mesons and Strangeonium States

The GlueX spectrometer

Acceptance θ = 1–120°

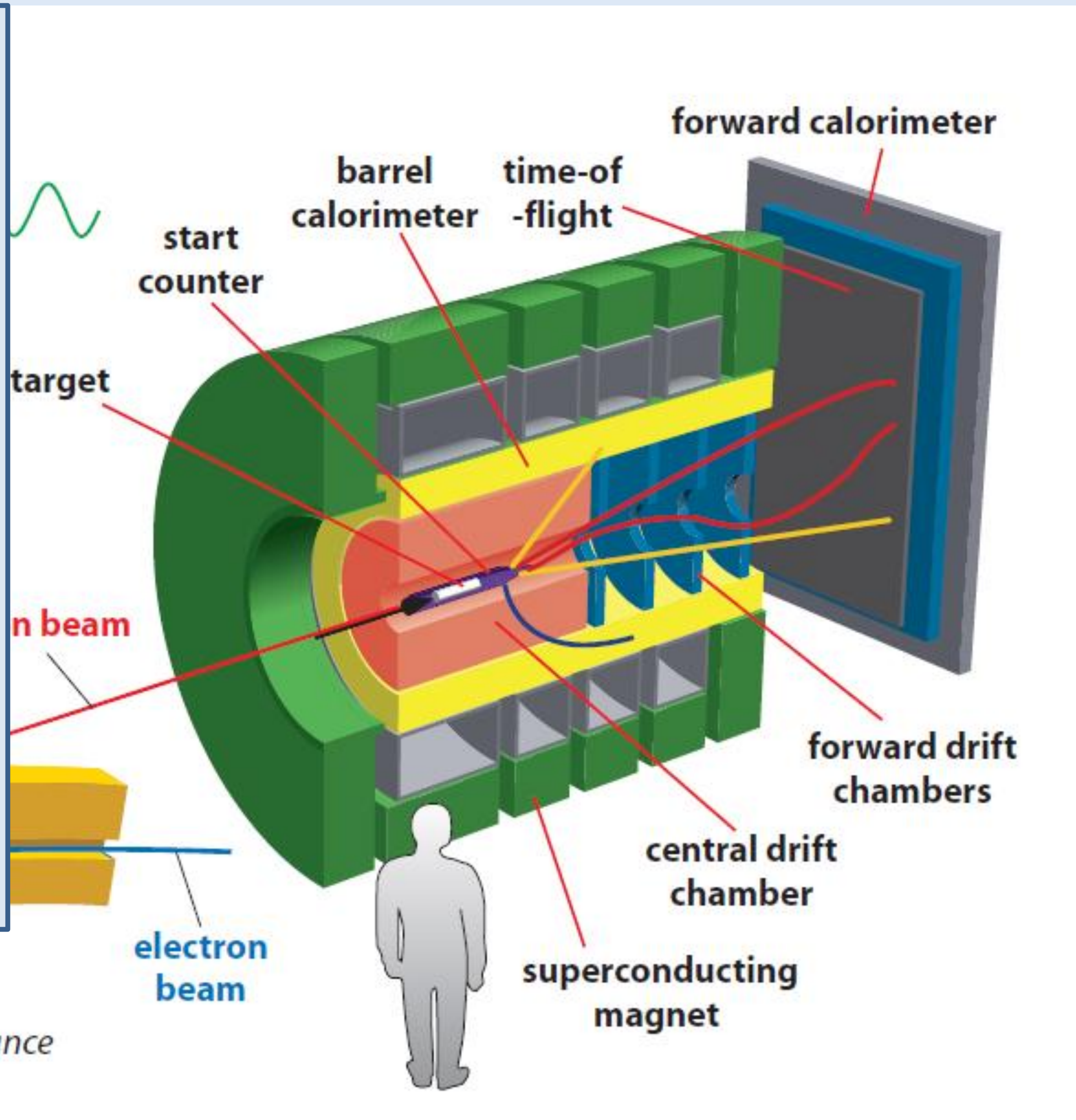
Charged particles:
drift chambers σ_p/p ~ 1-3%

Photons:
electromagnetic calorimeters
$\sigma_E/E = 6\% / \sqrt{E} \oplus 2\%$

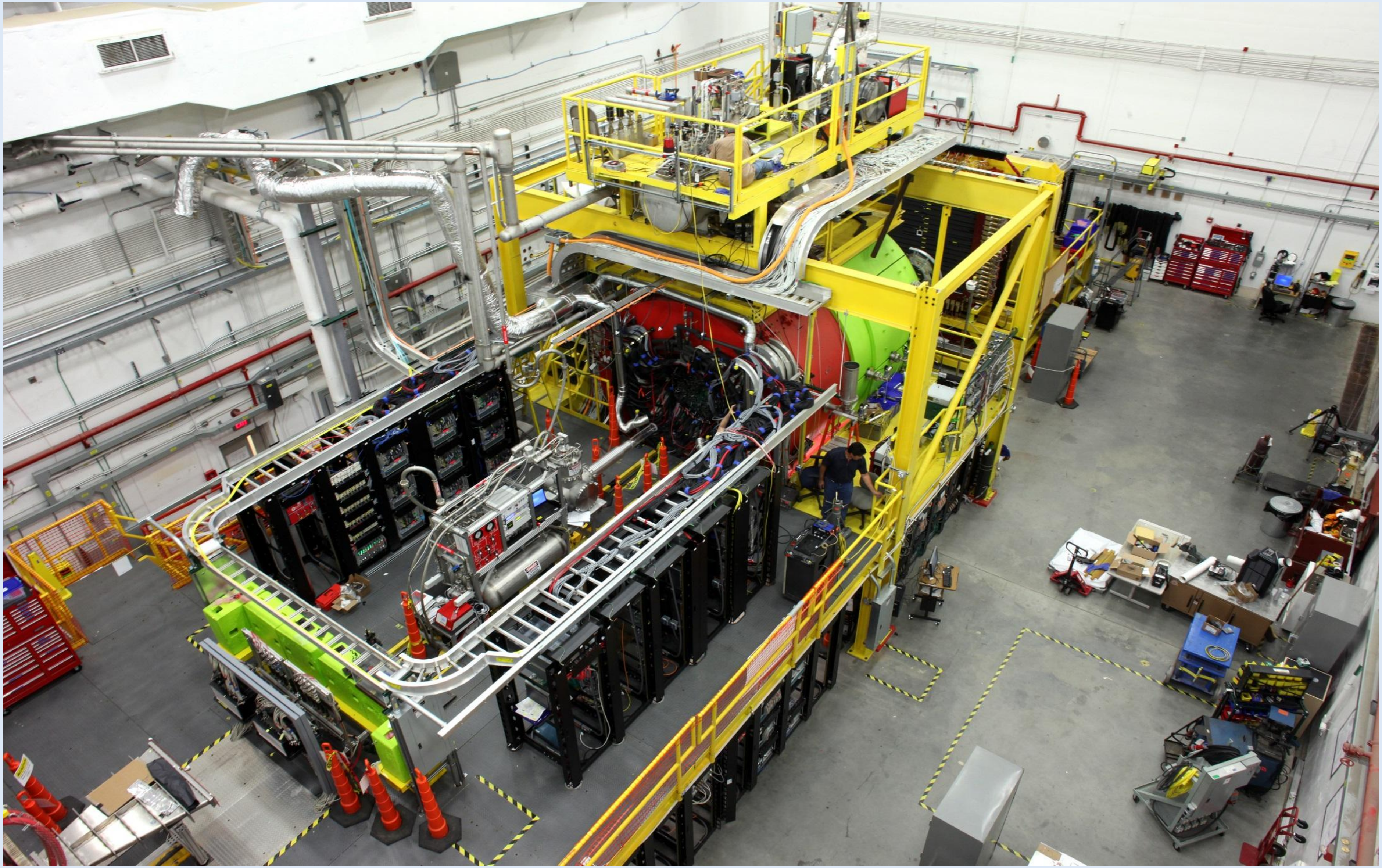
Timing:
start counter, time-of-flight

PID: all (dE/dx, E/p, β)

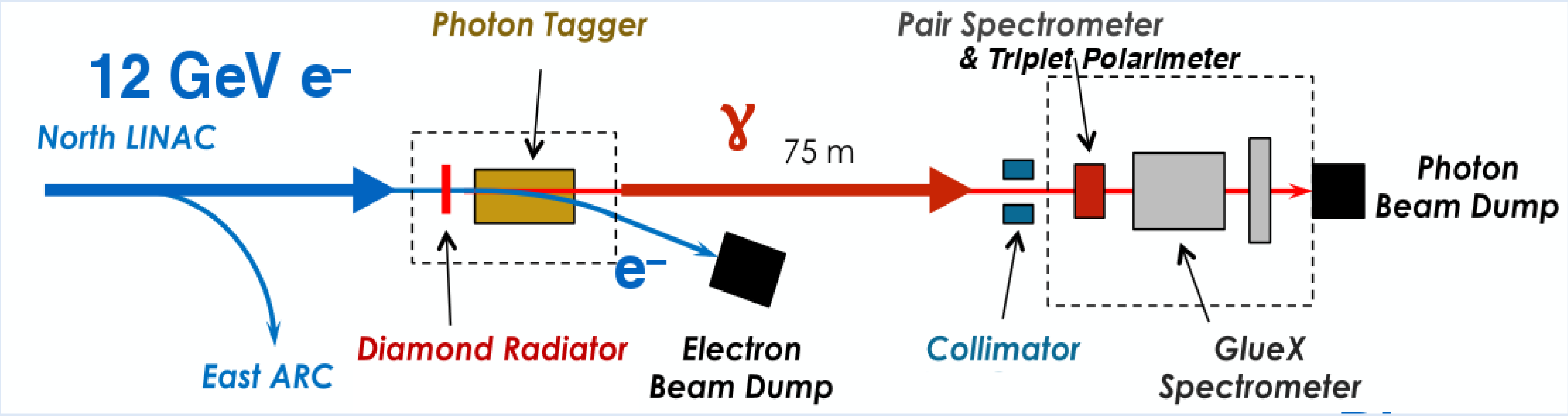
Trigger:
hadronic, minimum bias,
from calorimeters



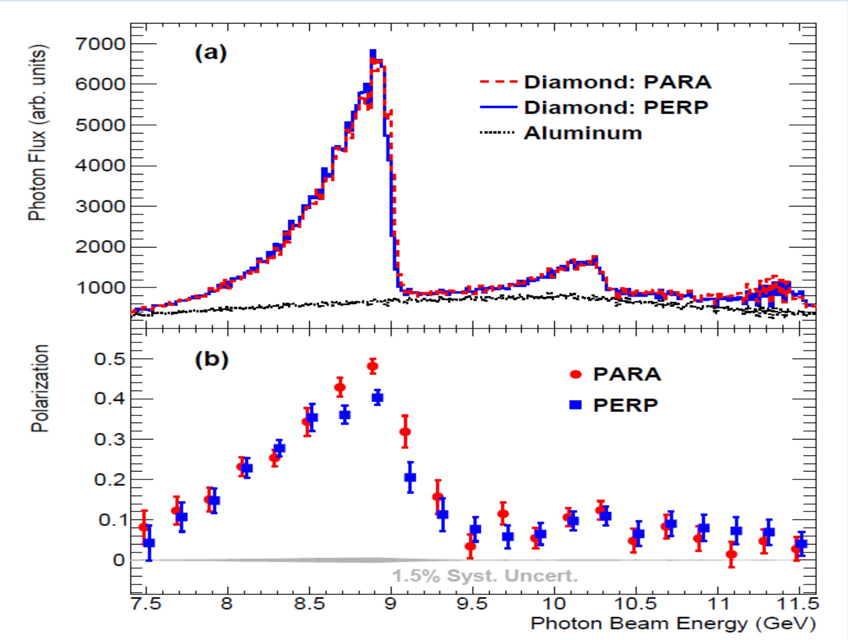
GlueX spectrometer in HALL D



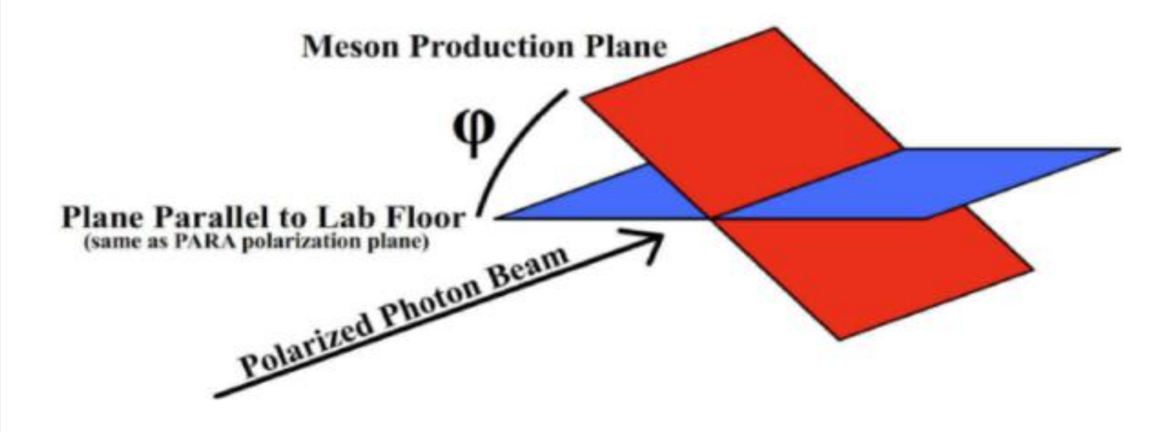
Photon beam: Coherent Bremsstrahlung



- 12 GeV e^- beam 0.05 – 2.2 μA
  Diamond thickness: 20 – 50 μm
- Collimator suppresses the incoherent part:
  $\theta < 25\ \mu r$
- Coherent peak: 8.4 – 9.0 GeV in the peak
- Tagger Spectrometer measures the energy:
  σ_E/E ~0.1%
- Triplet Polarimeter ($\gamma\ e^- \rightarrow e^-\ e^+\ e^-$)
  measures the polarization: σ_p/p~2%



Pseudoscalar meson: beam asymmetry



$\gamma\, p \rightarrow p\, \pi^0\, (\eta)$

$$\frac{d\sigma}{d\varphi_{\parallel}} \propto \left(1 - P\Sigma\cos(2\varphi)\right)$$

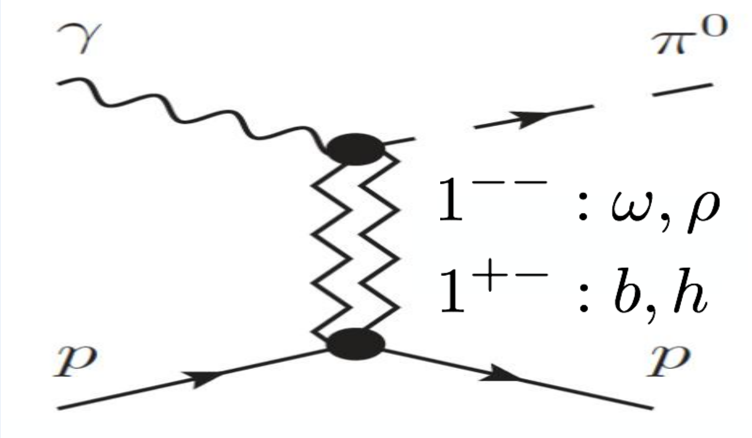
$$\frac{d\sigma}{d\varphi_{\perp}} \propto \left(1 - P\Sigma\cos(2\varphi - \pi)\right)$$

Measured asymmetry: the systematic effects cancel

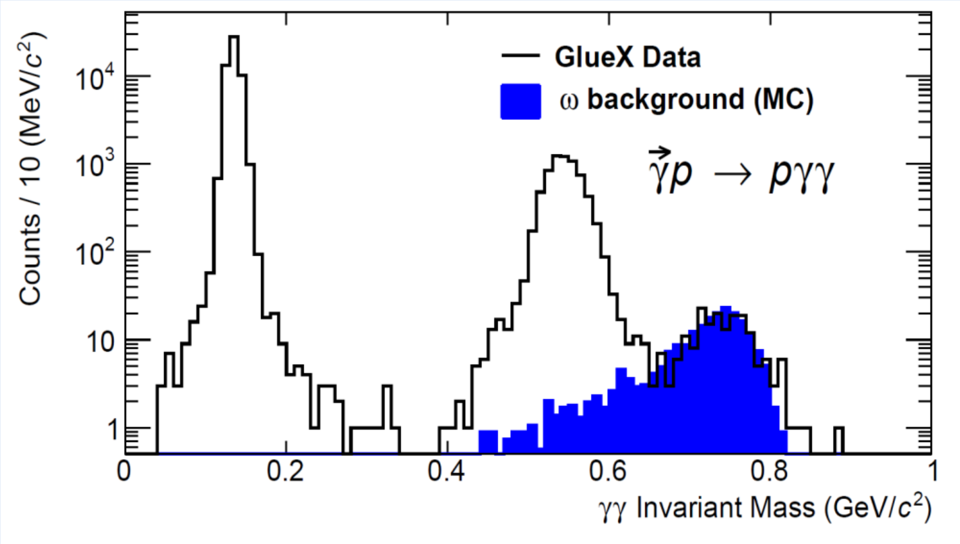
$$\mathrm{A}(\varphi) = \frac{\frac{d\sigma}{d\varphi_{\perp}} - \frac{d\sigma}{d\varphi_{\parallel}}}{\frac{d\sigma}{d\varphi_{\perp}} + \frac{d\sigma}{d\varphi_{\parallel}}} \approx P\Sigma\cos(2\varphi)$$

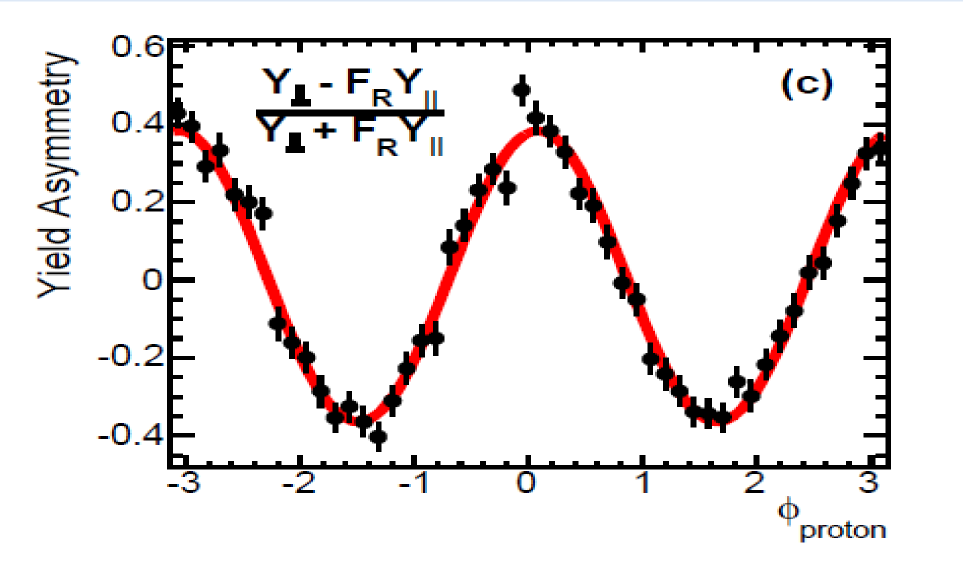
Beam asymmetry of π^0 & η

PRD 92 074013 (2015)



Phys. Rev. C 95 042201 (2017)





Asymmetry is sensitive to J^{PC} of the exchanged particle

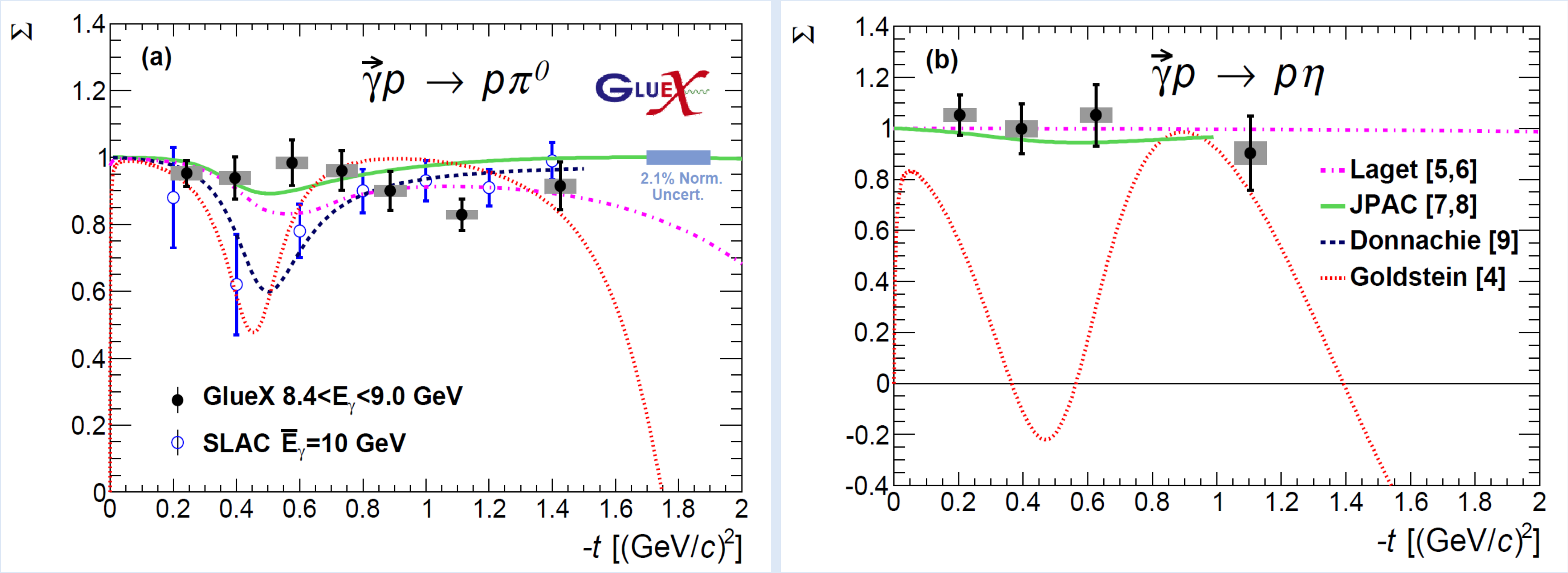
$$\Sigma = \frac{|\omega+\rho|^2 - |h+b|^2}{|\omega+\rho|^2 + |h+b|^2}$$

Σ ≈ +1 for 1^{--} exchange

Σ ≈ −1 for 1^{++} exchange

Beam asymmetry of π^0 & η

Phys. Rev. C 95 042201 (2017)



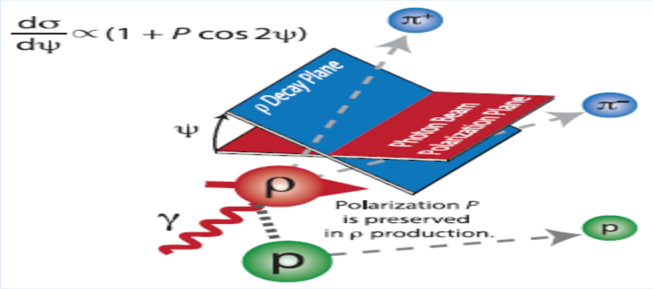
The results:

- $\Sigma \approx +1$;
- Vector exchange 1^{-} dominates;
- No dip observed at $-t = 0.5\ (GeV/c)^2$;
- Models: Laget, JPAC, Donnachie, Goldstein;
- First measurement for η at this energy.

Beam asymmetry of vector mesons

$\gamma\, p \rightarrow p\, \rho\, (\omega)$

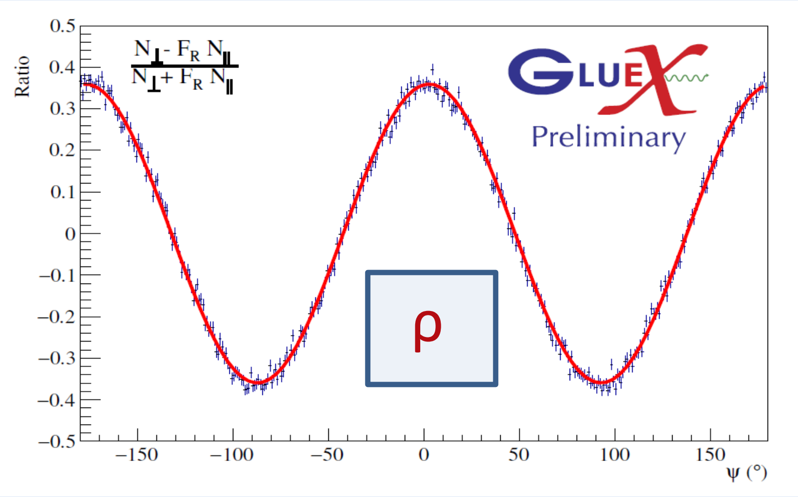
arXiv: 1512.03699 [nucl-ex]

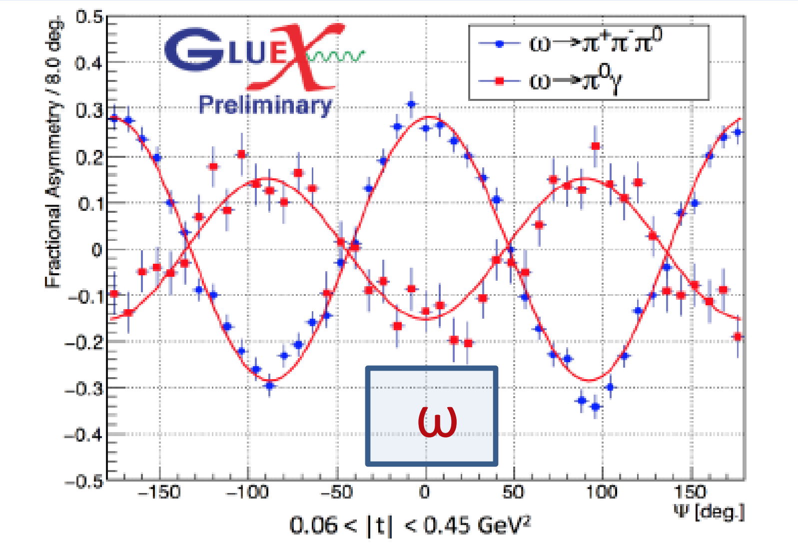


$$\begin{cases} d\sigma_\perp \propto 1 - P_\perp \Sigma \cos 2\phi \\ d\sigma_\parallel \propto 1 + P_\parallel \Sigma \cos 2\phi \end{cases}$$

$$P\Sigma \cos 2\phi = \frac{N_\parallel - N_\perp}{N_\parallel + N_\perp}$$

arXiv: 1801.05332





- Huge increase in statistics for ρ and ω over the existing data from SLAC.
- Expectations: $\Sigma_{3\pi} / \Sigma_{\pi^0\gamma} = -2$
- Measurement: $\Sigma_{3\pi} / \Sigma_{\pi^0\gamma} = -1.88 \pm 0.13$

Photoproduction of J/ψ close to threshold

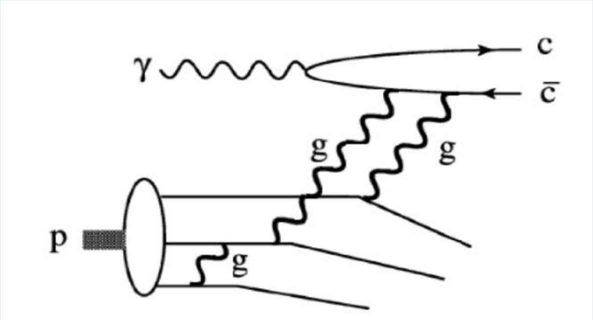
$\gamma\, p \rightarrow J/\psi\, p$

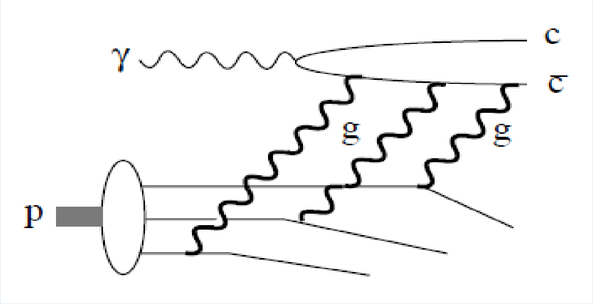
- Gluon distributions in proton

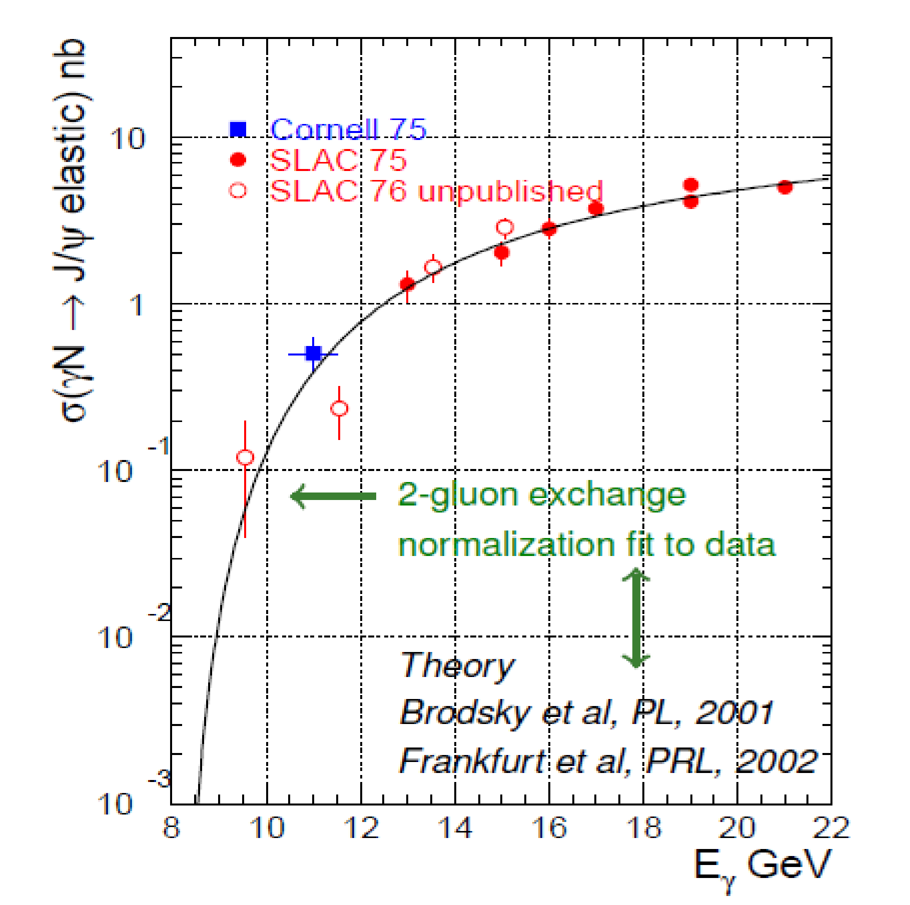
Kharzeev et al., NPA 661, 568 (1999)

- Multiquark correlations

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







The two mechanisms have different energy dependences near threshold.

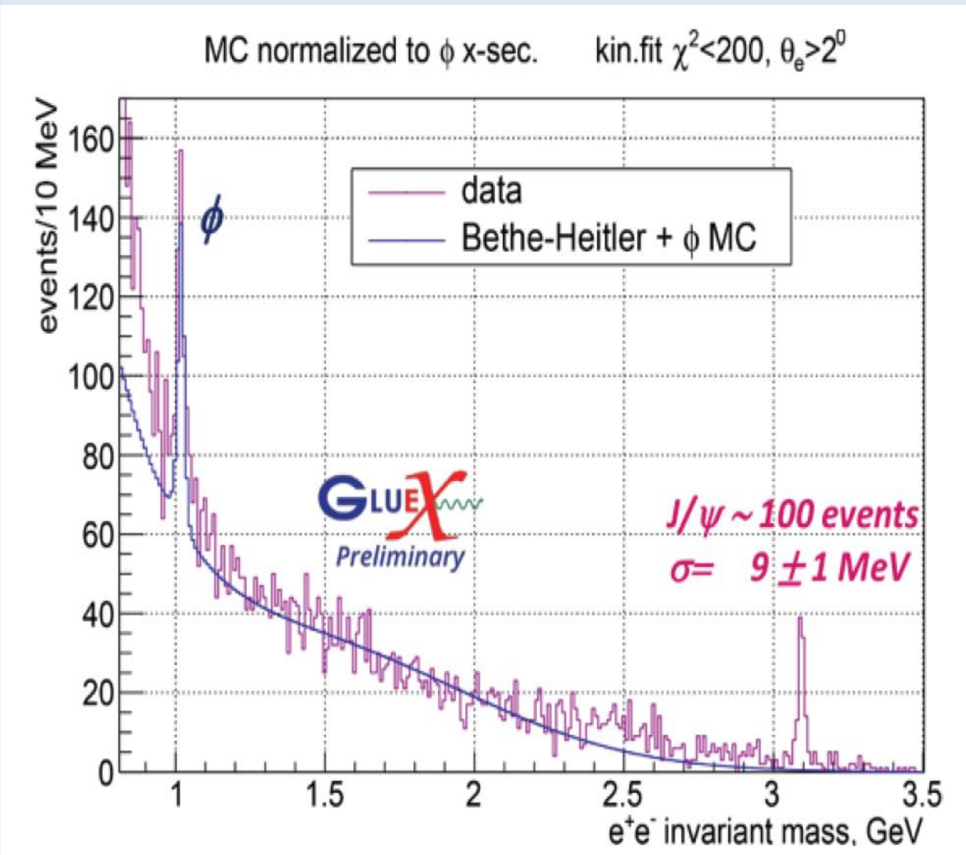
Photoproduction of J/ψ close to threshold

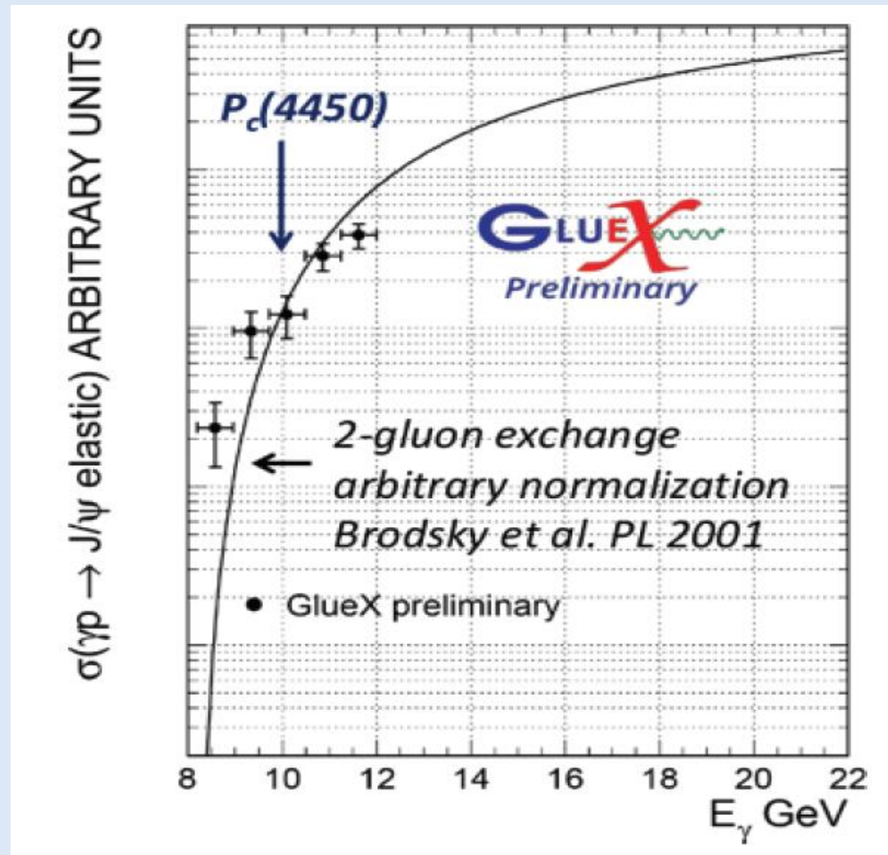
- Detect J/ ψ through its e^+e^- decay
- e^+e^-: PID using the electromagnetic calorimeters BCAL & FCAL
- Kinematic fit with the beam energy from the tagger

$\gamma\, p \to J/\psi\, p$

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

arXiv: 1712.07214 [nucl-ex]





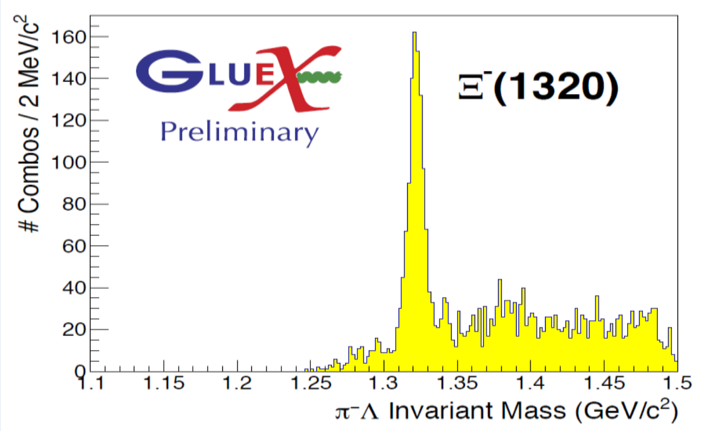
Double strange barions

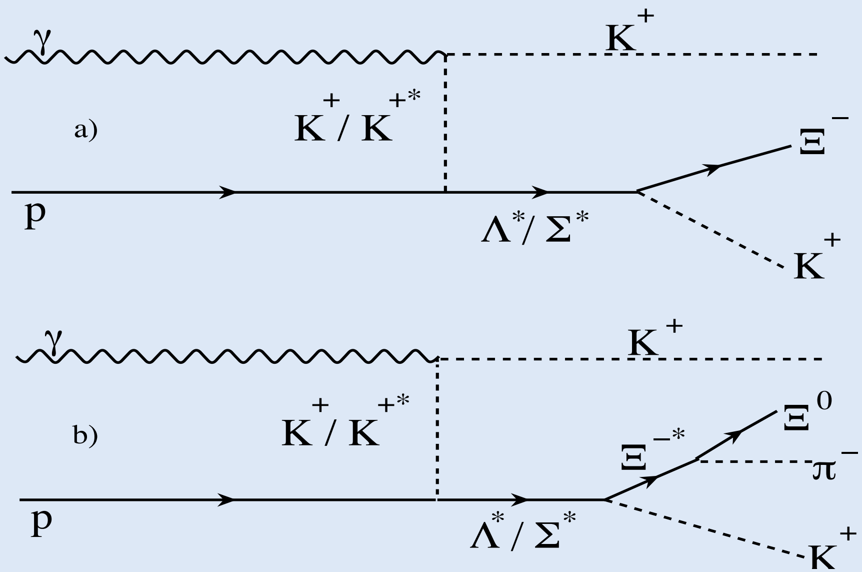
Double-strange baryons: ssu (Ξ^0) & ssd (Ξ^-)   arXiv: 1712.07214 [nucl-ex]

$\Xi(1320)$ $(1/2)^+$ ****
$\Xi(1530)$ $(3/2)^+$ ****
$\Xi(1690)$ ***
$\Xi(1820)$ $(3/2)^-$ ***
$\Xi(1950)$ ***
$\Xi(2030)$ ***

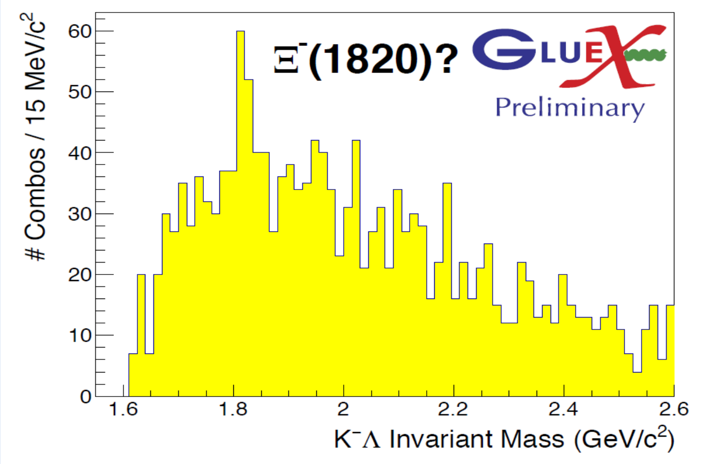
CLAS observed the lightest two at lower energies.

$\gamma\, p \to \Xi^- K^+ K^-$ $\Xi^- \to \Lambda\, \pi^-$



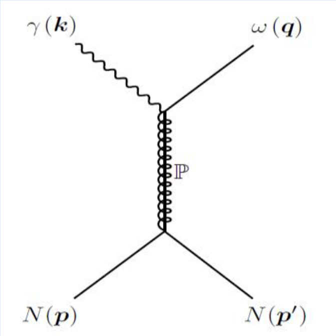


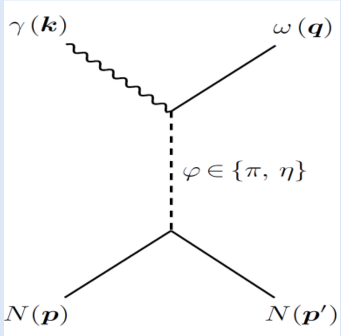
$\Xi^{*-} \to \Lambda\, K^-$



SDMEs of vector mesons

- Spin Density Matrix Elements (SDMEs) measure the spin transfer from the polarized photon to the vector meson.
- SDMEs are sensitive to the production mechanism.
- SDMEs of vector mesons are obtained by fitting complicated angular distributions.





Oh, Titov & Lee (OTL) model:
Phys. Rev. C 63 025201 (2001)

In the OTL model, the SDMEs are sensitive to the relative amounts of Pomeron and pseudoscalar (PS) meson exchange (mostly π^0)

Hadronic decay:

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

$$
\begin{aligned}
W_h^0(\cos\theta, \phi, \rho^0) &= \frac{3}{4\pi}\left[\frac{1}{2}\left(1-\rho^0_{00}\right) + \frac{1}{2}\left(3\rho^0_{00}-1\right)\cos^2\theta \right. \\
&\quad \left. -\sqrt{2}\,\mathrm{Re}\rho^0_{10}\sin 2\theta\cos\phi - \rho^0_{1-1}\sin^2\theta\cos 2\phi\right] \\
W_h^1(\cos\theta, \phi, \rho^1) &= \frac{3}{4\pi}\left[\rho^1_{11}\sin^2\theta + \rho^1_{00}\cos^2\theta - \sqrt{2}\,\mathrm{Re}\rho^1_{10}\sin 2\theta\cos\phi \right. \\
&\quad \left. -\rho^1_{1-1}\sin^2\theta\cos 2\phi\right] \\
W_h^2(\cos\theta, \phi, \rho^2) &= \frac{3}{4\pi}\left[\sqrt{2}\,\mathrm{Im}\rho^2_{10}\sin 2\theta\sin\phi + \mathrm{Im}\rho^2_{1-1}\sin^2\theta\sin 2\phi\right] \\
W_h^3(\cos\theta, \phi, \rho^3) &= \frac{3}{4\pi}\left[\sqrt{2}\,\mathrm{Im}\rho^3_{10}\sin 2\theta\sin\phi + \mathrm{Im}\rho^3_{1-1}\sin^2\theta\sin 2\phi\right].
\end{aligned}
$$

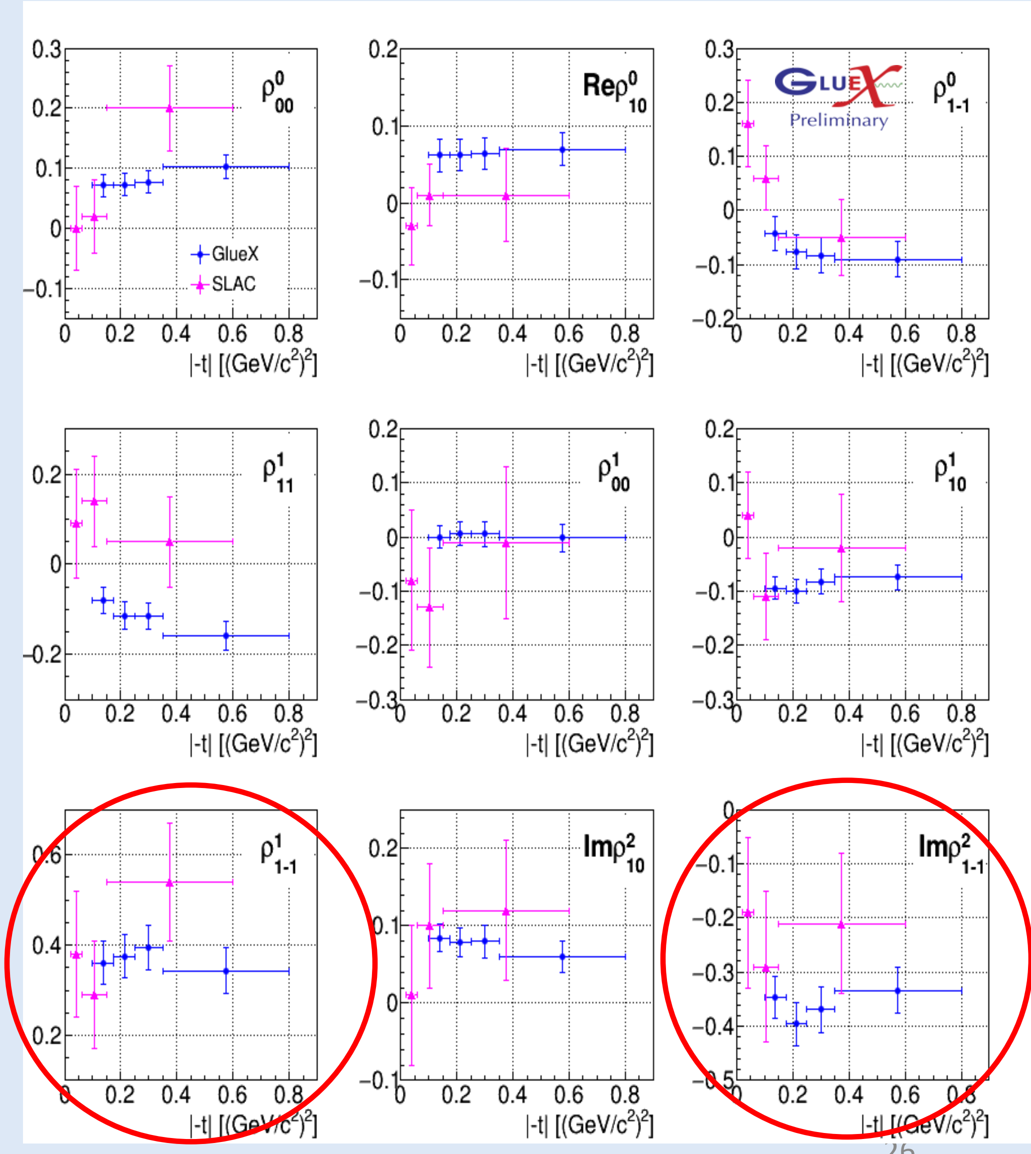
SDMEs of ω mesons

M. Staib, Ph.D. Thesis 9/2017

- Two of the elements ρ^1_{1-1} and Im ρ^2_{1-1} are very sensitive to the transfer of spin from the photon to the ω meson.

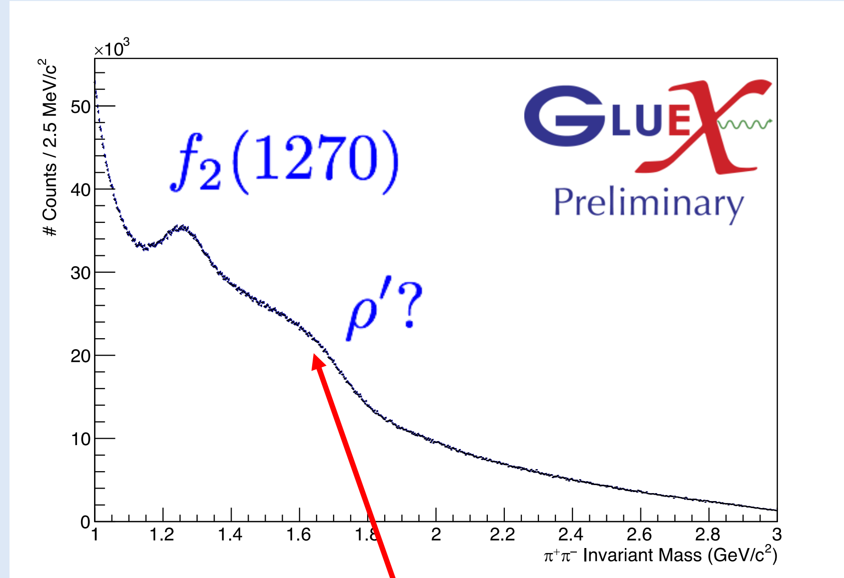
- If the exchange is pure "Pomeron", +½ and –½. If it is pure pion exchange, – ½ and +½. We obtained: ~ 0.35 and –0.35.

- results are consistent with the dominance of "Pomeron" exchange at our beam energy and range of –t.

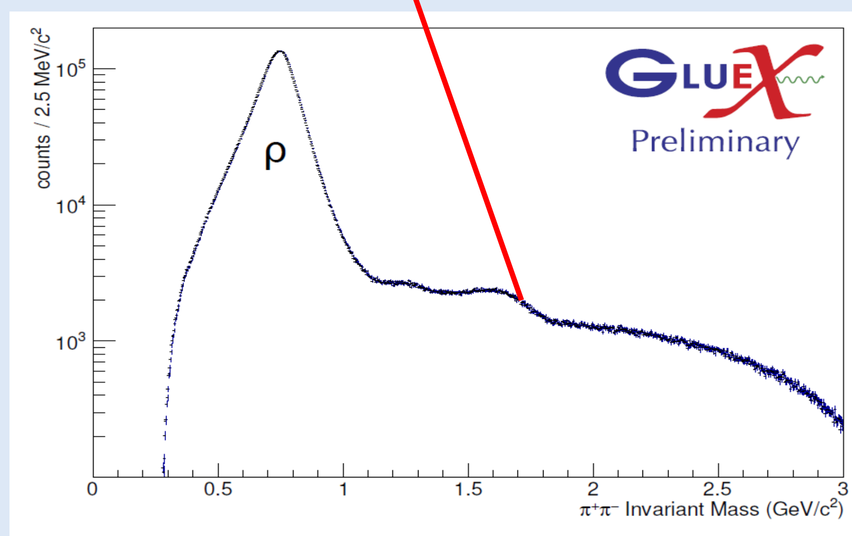


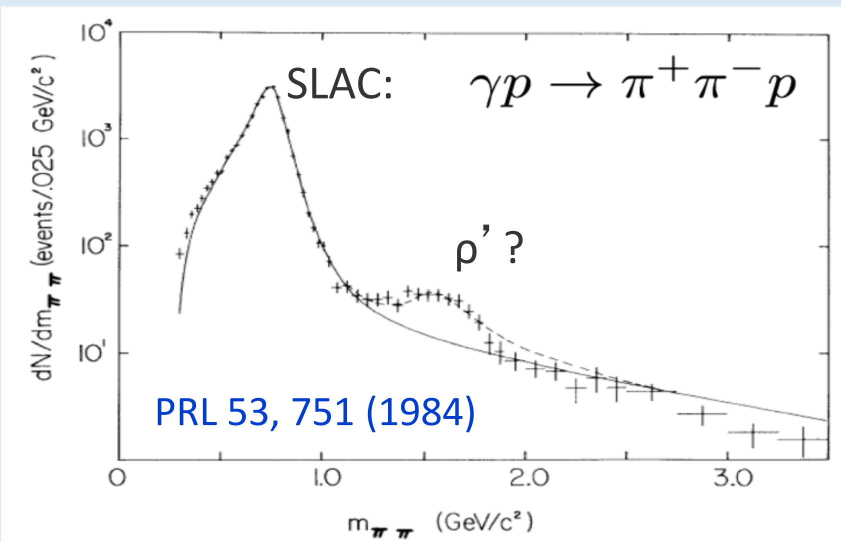
Observed signals (known states)

In the ρ event sample, we can look for higher-mass vector mesons. We observe an enhancement around 1.6 GeV with significantly more statistics than existed; we should be able to measure polarization observables.

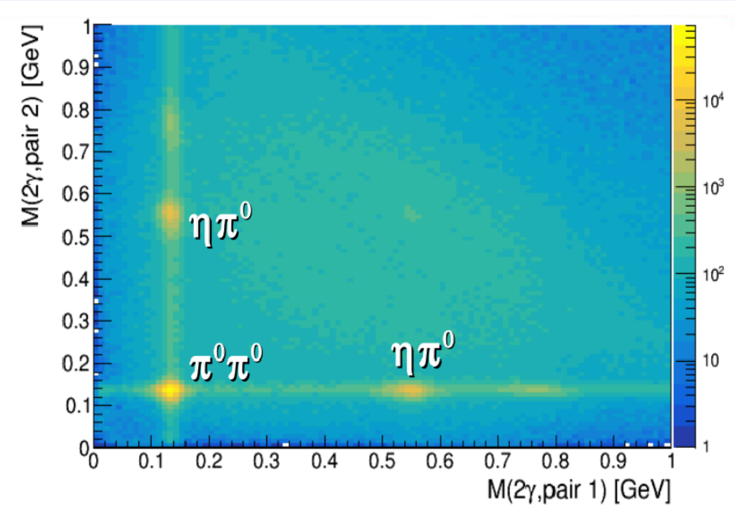


arXiv: 1801.05332





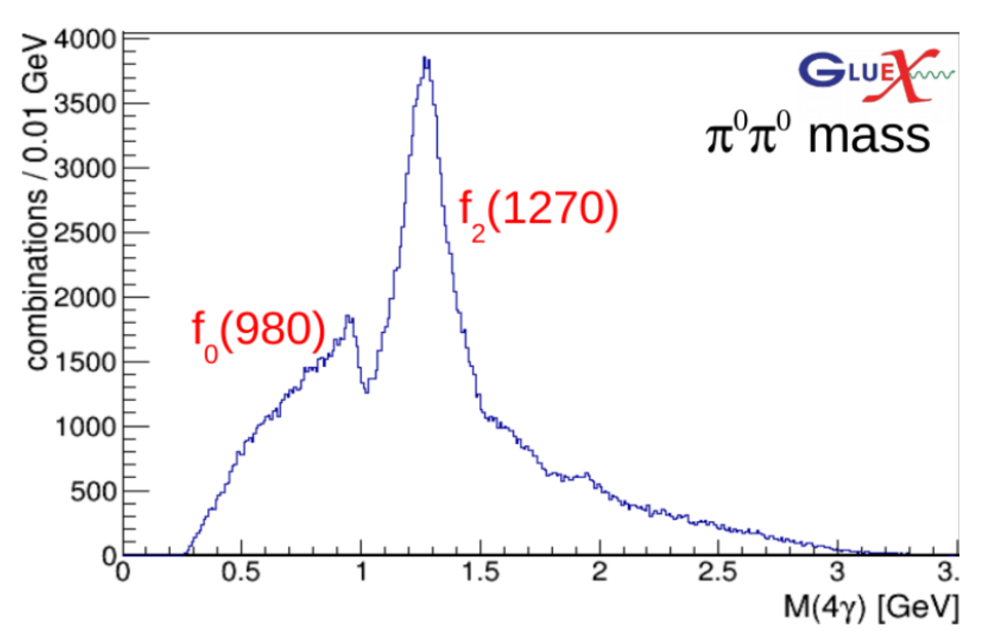
Observed signals (known states)

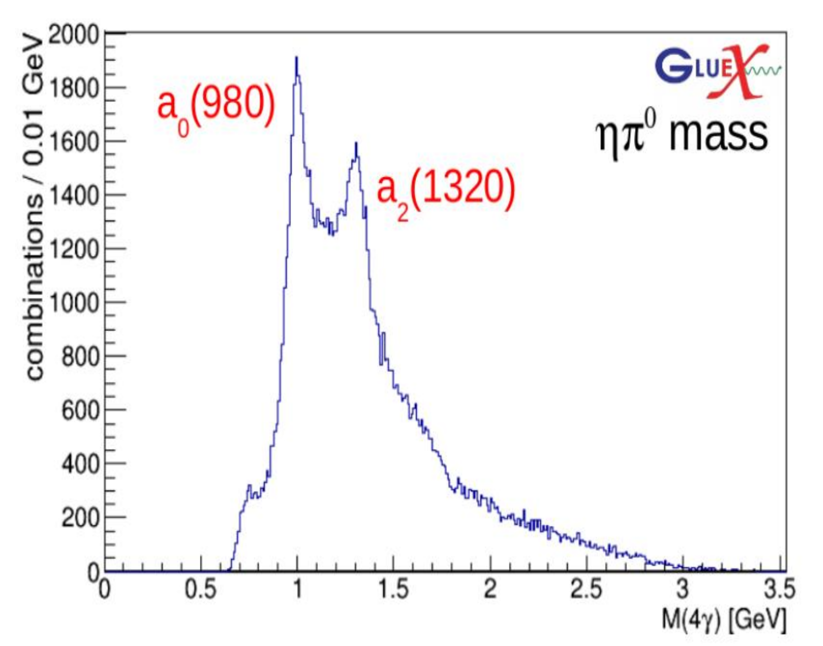


$\gamma\, p \rightarrow 4\,\gamma\, p$

Clear signals for $f_0(980)$, $f_2(1270)$, $a_0(980)$ and $a_2(1320)$ are observed.

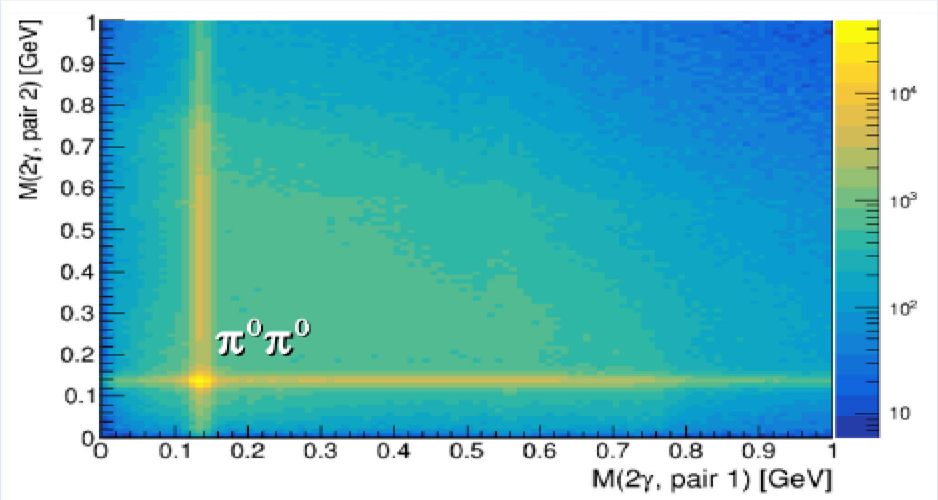
arXiv: 1712.07214 [nucl-ex]

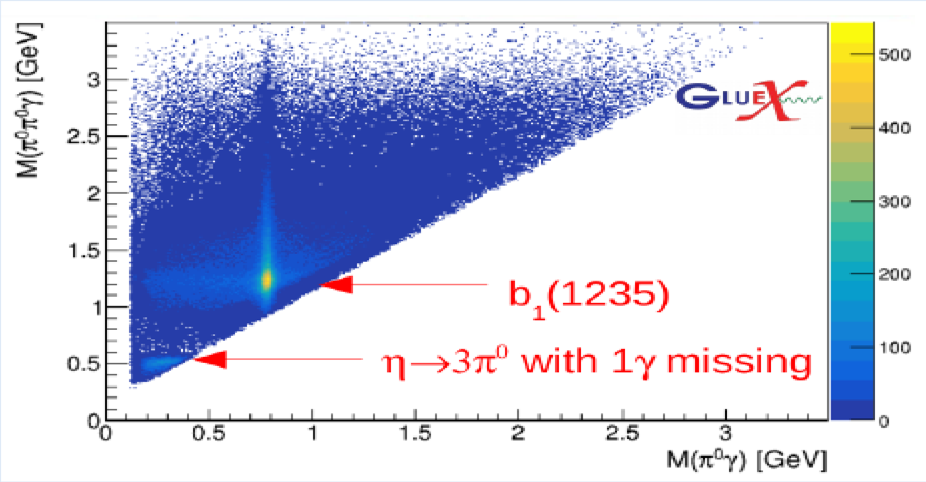


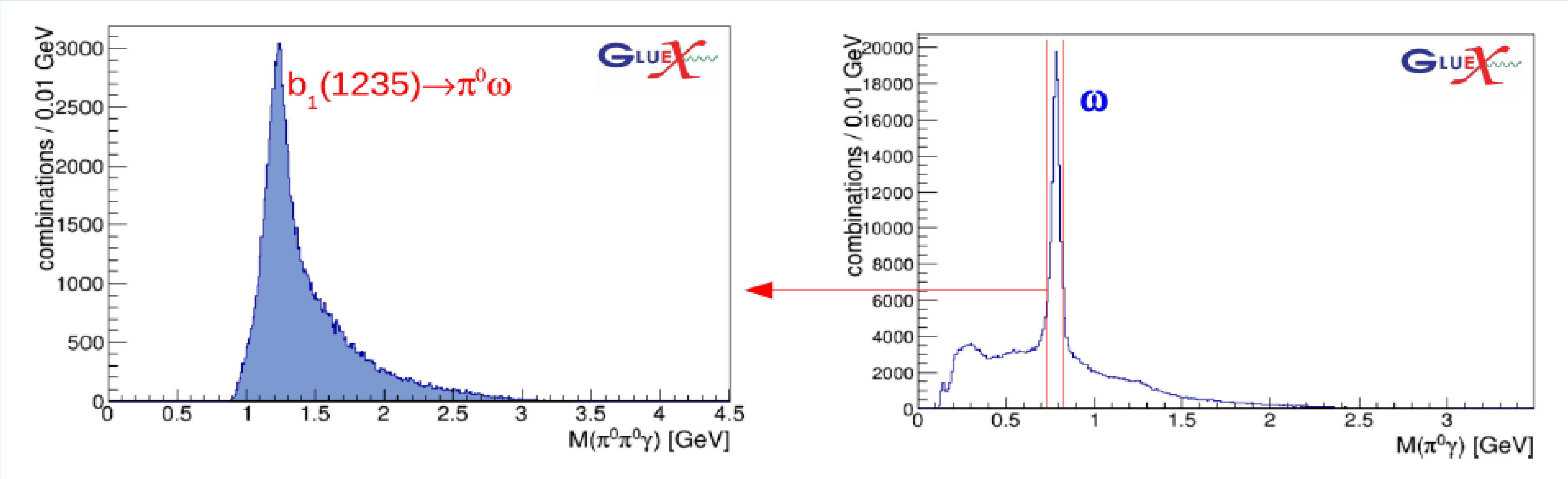


Observed signals (known states)

$\gamma\, p \rightarrow 5\, \gamma\, p$







Interesting Hybrid channels

$\gamma\, p \rightarrow p\eta\pi^+\pi^-$

$\gamma p \rightarrow p\eta_1$ → $\eta f_2,\ a_2\pi$

$\gamma p \rightarrow pb_2$ → $a_2\pi,\ \rho\eta$

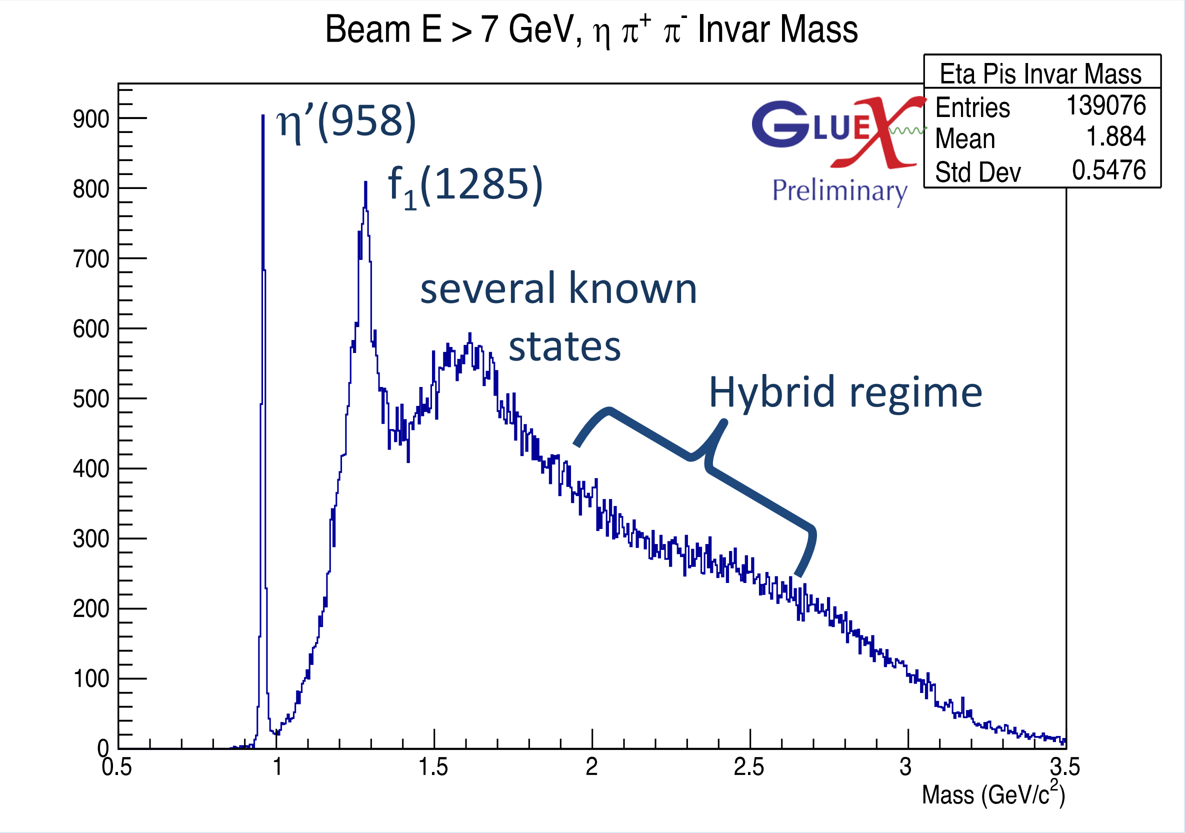
$f_2 \rightarrow \pi\pi,\ a_2 \rightarrow \eta\pi,\ \rho \rightarrow \pi\pi$

Look for these reactions:

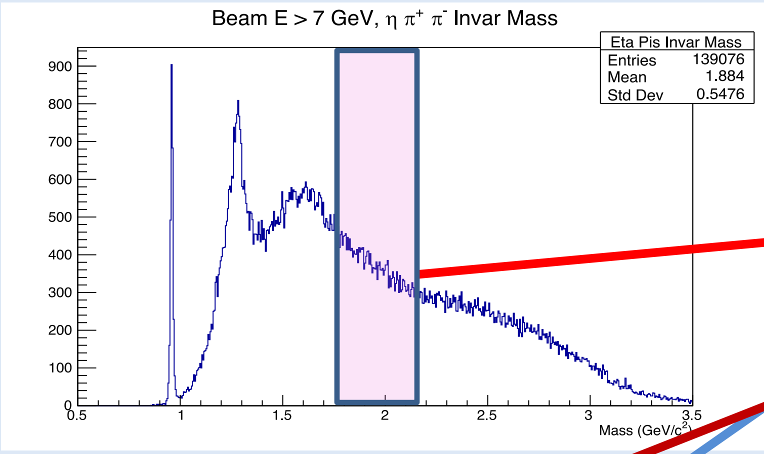
$$\gamma p \rightarrow p a_2^{\pm}\pi^{\mp}$$

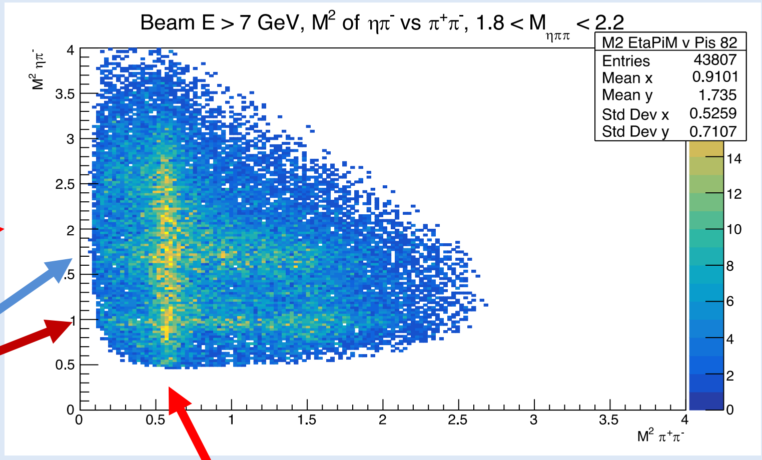
$$\gamma p \rightarrow p f_2 \eta$$

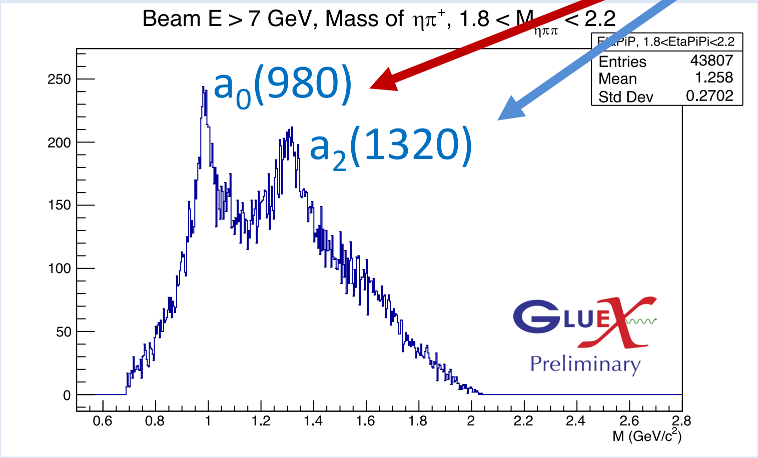
$$\gamma p \rightarrow p \rho \eta$$

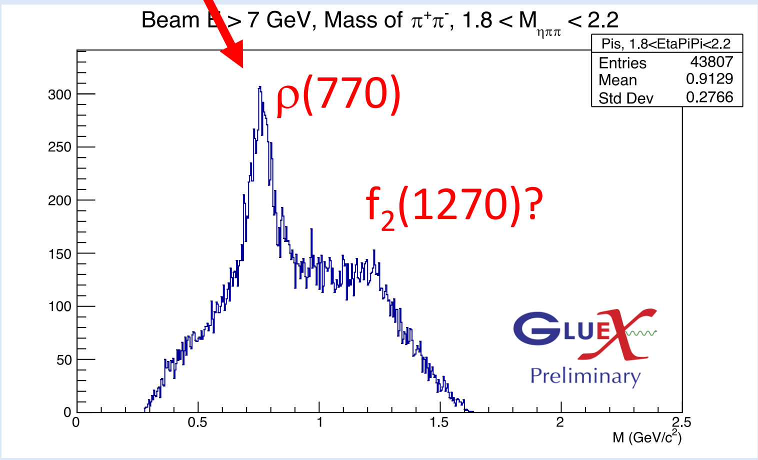


$\gamma\, p \rightarrow p\eta\pi^+\pi^-$









Clear signals for $\gamma p \rightarrow p a_2^{\pm} \pi^{\mp}$

$\gamma p \rightarrow p \rho \eta$

Weak signal for $\gamma p \rightarrow p f_2 \eta$

Outlook

- GlueX is installed, commissioned and started physics running in Spring 2017.
  All detector systems are near to or better than design specifications.

- Analysis of 2017 and spring 2018 data:
  Measurement of various beam asymmetries;
  Measurement of J/ψ cross section;
  Measurement of SDMEs for lower vector mesons;
  PWA of the lower known resonances (1.0 – 1.5 GeV/c^2).

- We have published our first results, and are moving ahead on other physics measurements.

- The broader program of exotic mesons is in sight.

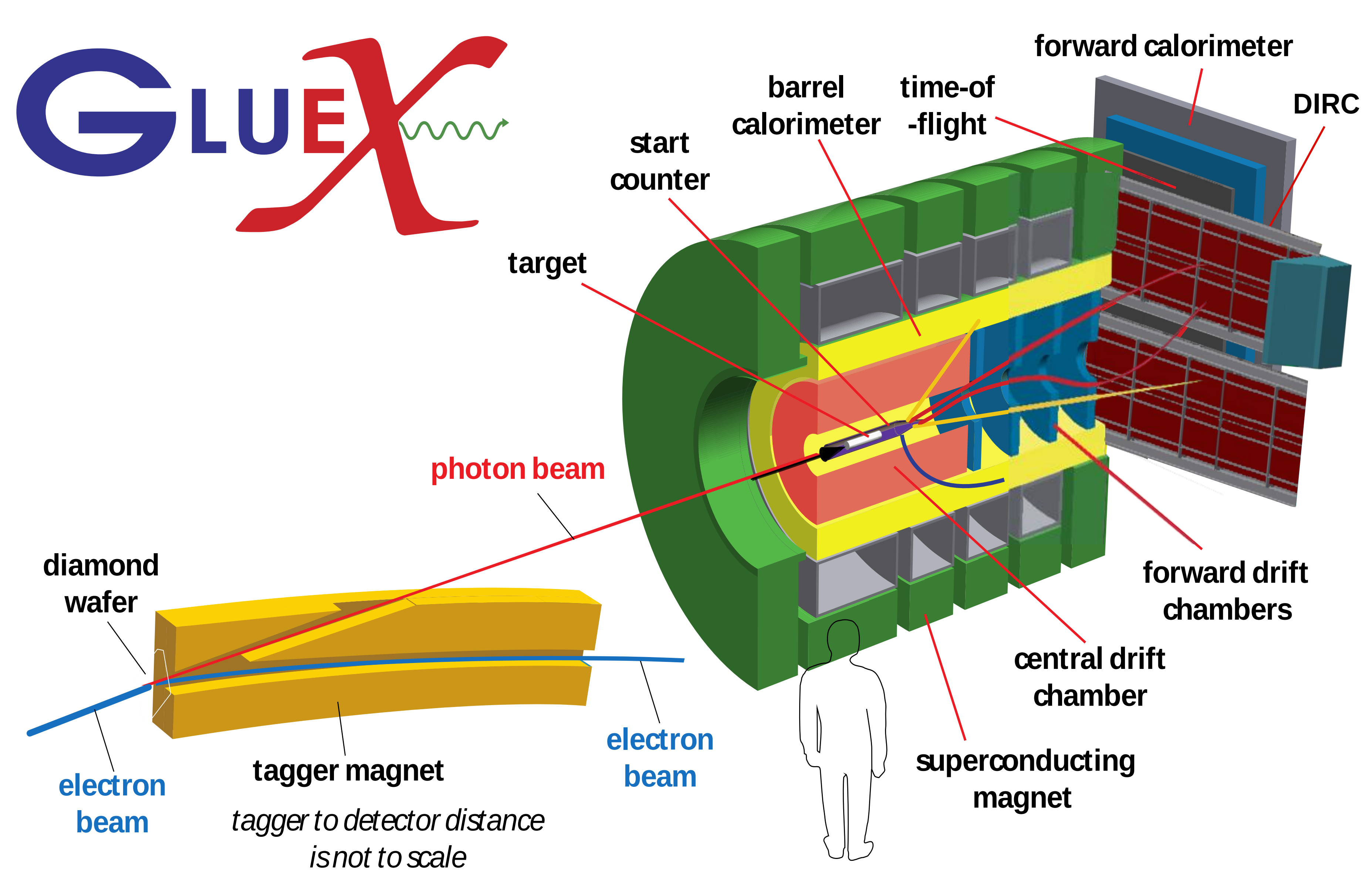
- Next run is scheduled for the fall 2018. In 2019-2022 GlueX will focus on hidden strangeness and hyperon resonances.

- Other approved experiments:
  η Radiative Decay Width via Primakoff Effect;
  Charged Pion Polarizability via Primakoff Effect.

- More Proposals and Letters of Intent are on the way.

Backup Slides

GlueX detector

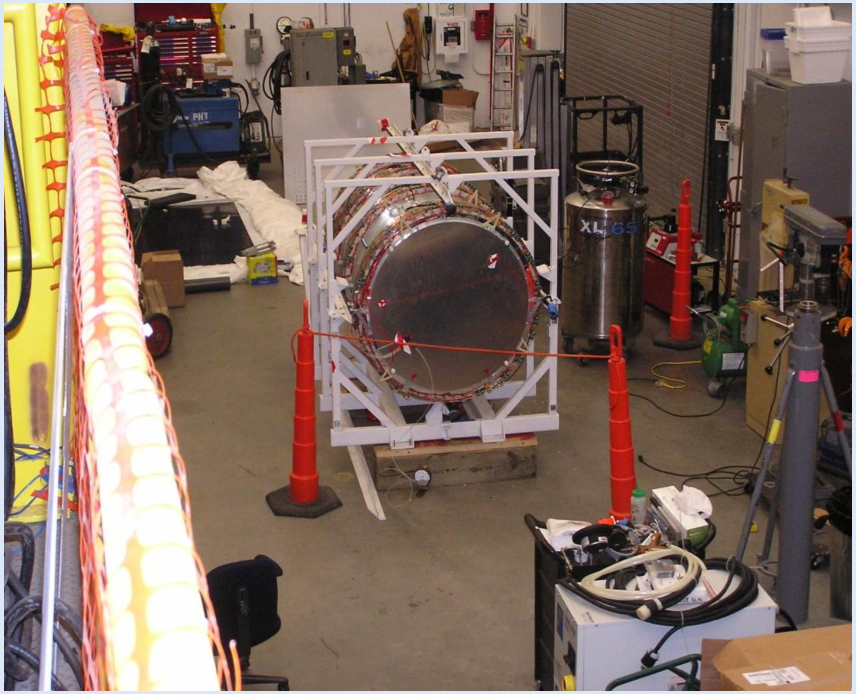


Central and Forward Drift Chambers

Central Drift Chamber (CDC)

✓Straw tube drift chamber:
28 layers; 12 straight + 16 stereo,
angular coverage $6^o < \vartheta < 155^o$

Forward Drift Chambers (FDC)



✓Cathode strip wire chambers:
4 packages of 6 chambers,
angular coverage $1^o < \vartheta < 30^o$

Electromagnetic Calorimeters

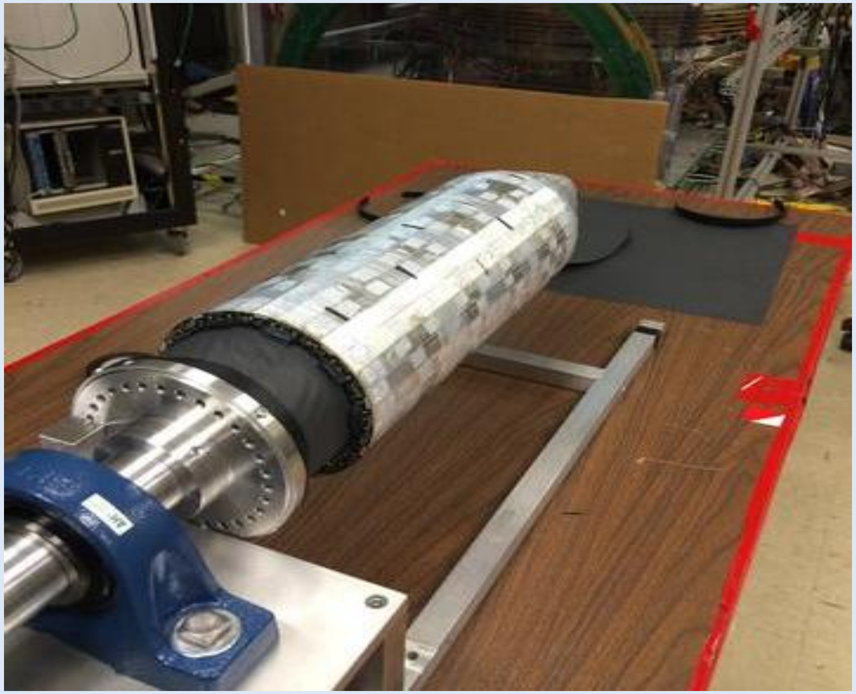
Barrel Calorimeter (BCAL)

✓Pb-scintillating fiber layers (185)
48 modules, segmented readout
from both ends with SiPMs (16)
angular coverage 11°<ϑ<120°

Forward Calorimeter (FCAL)

✓2800 Pb-glass blocks (F8-00)
blocks 4cmx4cmx45cm
PMT readout
angular coverage 2°<ϑ<11°

Start Counter (SC)

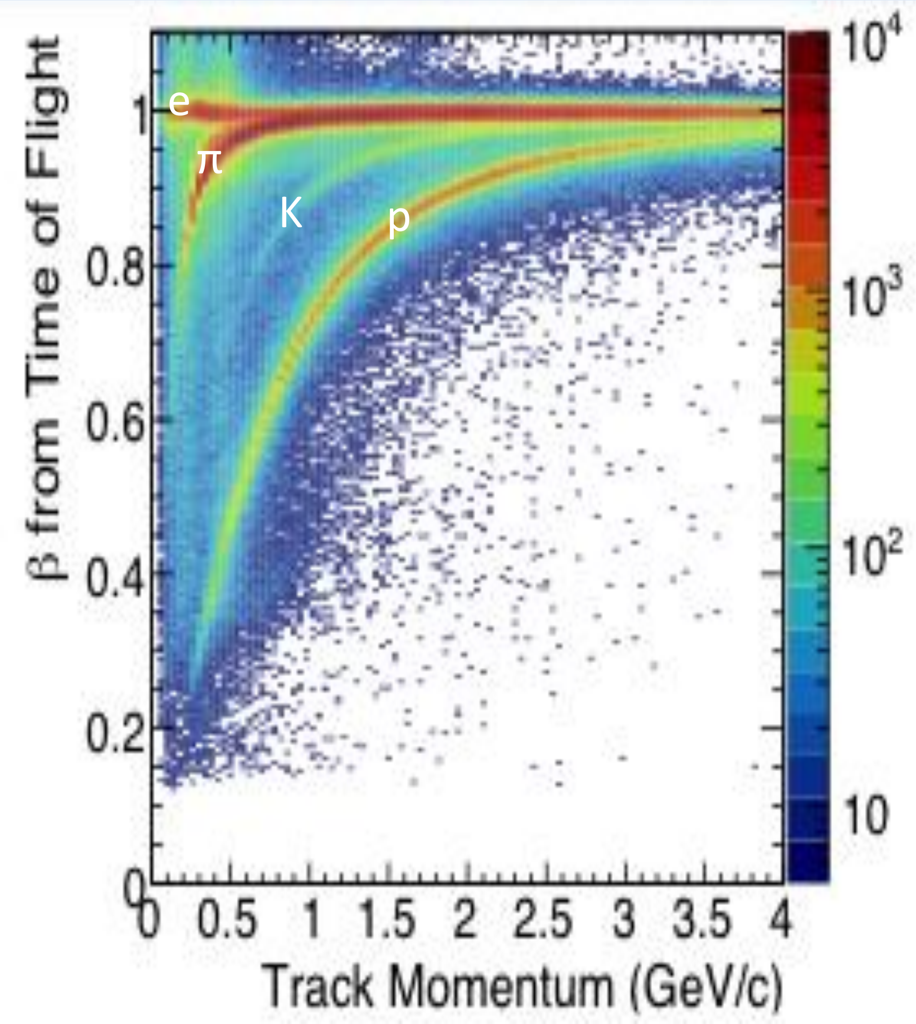


Time of Flight (TOF)

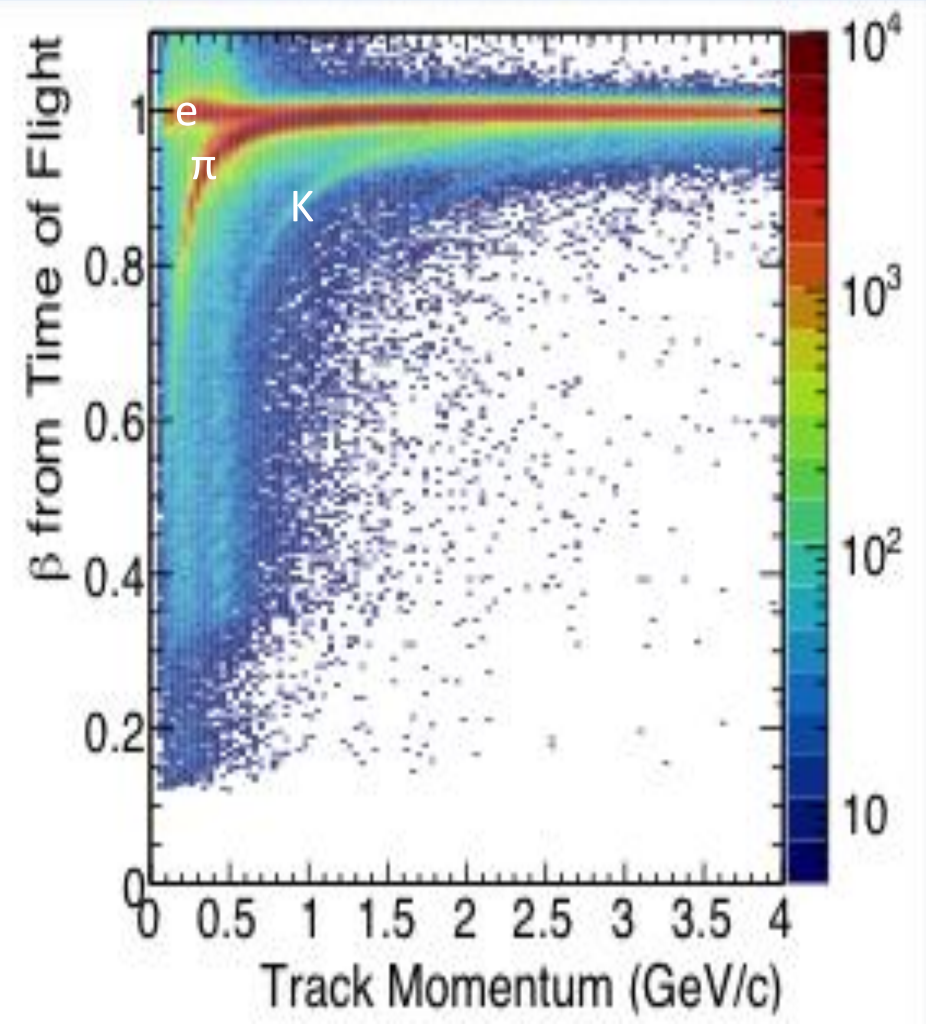
- ✓ 30 shaped scintillators: SiPM readout, time resolution ~300ps
- ✓ 92 scintillator paddles in 2 planes: 84 readout at both ends, time resolution ~100ps

Particle Identification (PID)

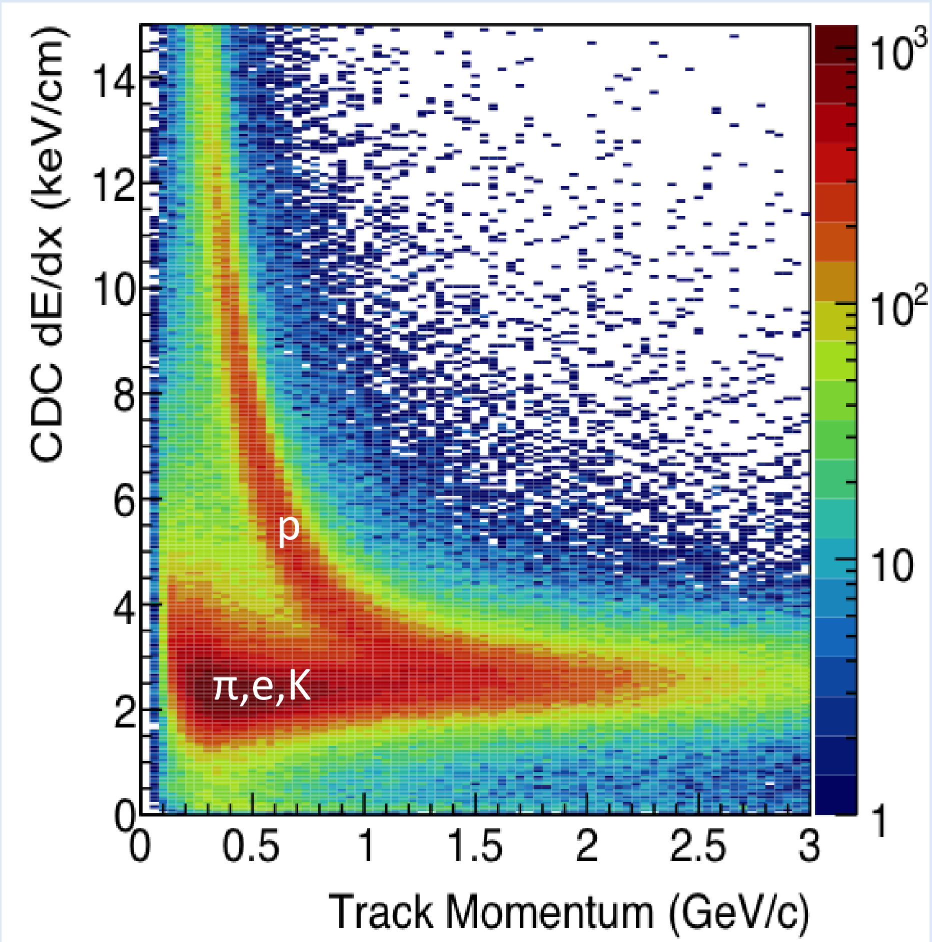
Positively Charged Particles



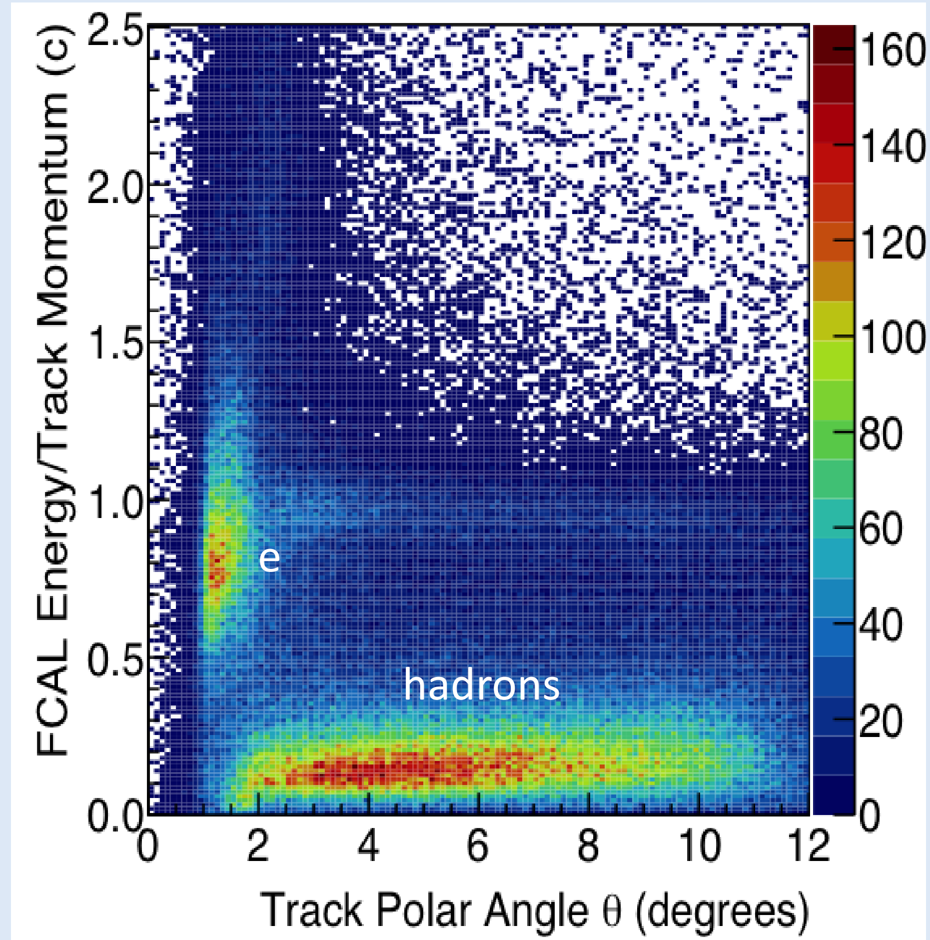
Negatively Charged Particles



Positively Charged Particles



Negatively Charged Particles



Searches for a Lepto-phobic Dark Vector Boson

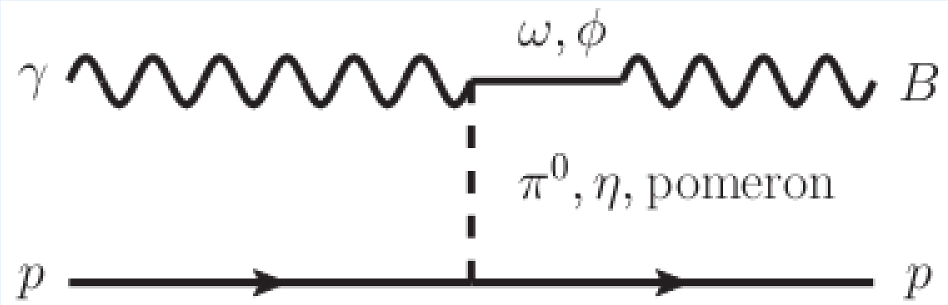
At the GeV scale, there has been relatively little progress searching for a dark boson with suppressed couplings to electrons and muons.

Recently Tulin considered a model with universal quark couplings, which preserves low energy symmetries of QCD. He focused on light meson decays producing dark omegas. PRD 89, 14008 (2014)

$$\mathscr{L}_{\text{int}} = (\tfrac{1}{3} g_B + \varepsilon Q_q e)\bar{q}\gamma^\mu q B_\mu - \varepsilon e \bar{\ell}\gamma^\mu \ell B_\mu$$

$$\alpha_B \equiv g_B^2/4\pi,$$

Fanelli and Williams then formalized direct ω_D production $\gamma + p \rightarrow \omega_D + p$. This has clear advantages in certain mass ranges. (But needs GlueX SDMEs data!)



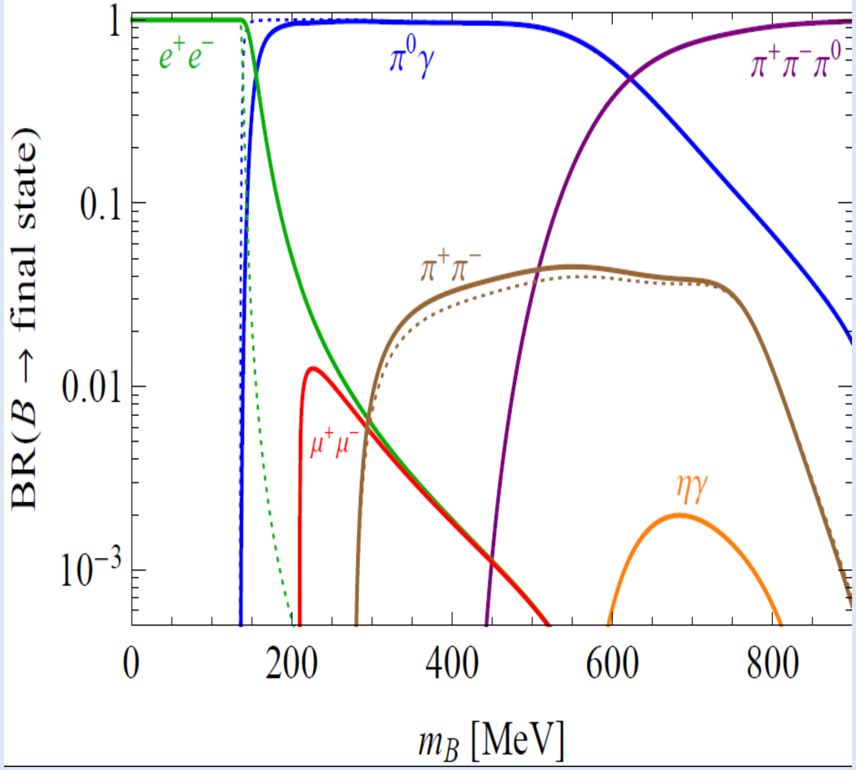
http://arxiv.org/abs/1605.07161

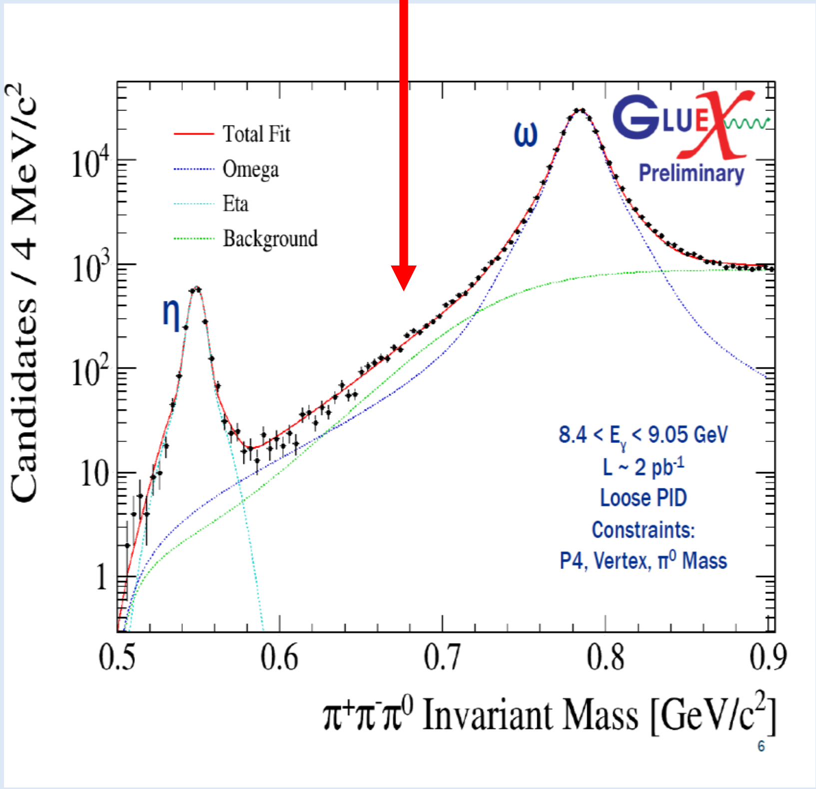
From the talk D. Mack (for the GlueX Collab.), HEP 2018 Valparaiso, Chile Jan 12, 2018

Direct Production
M_B = 600-900 MeV/c^2

In this mass range, Tulin predicts the dominant decay would be $\omega_D \rightarrow \pi^+\pi^-\pi^0$.

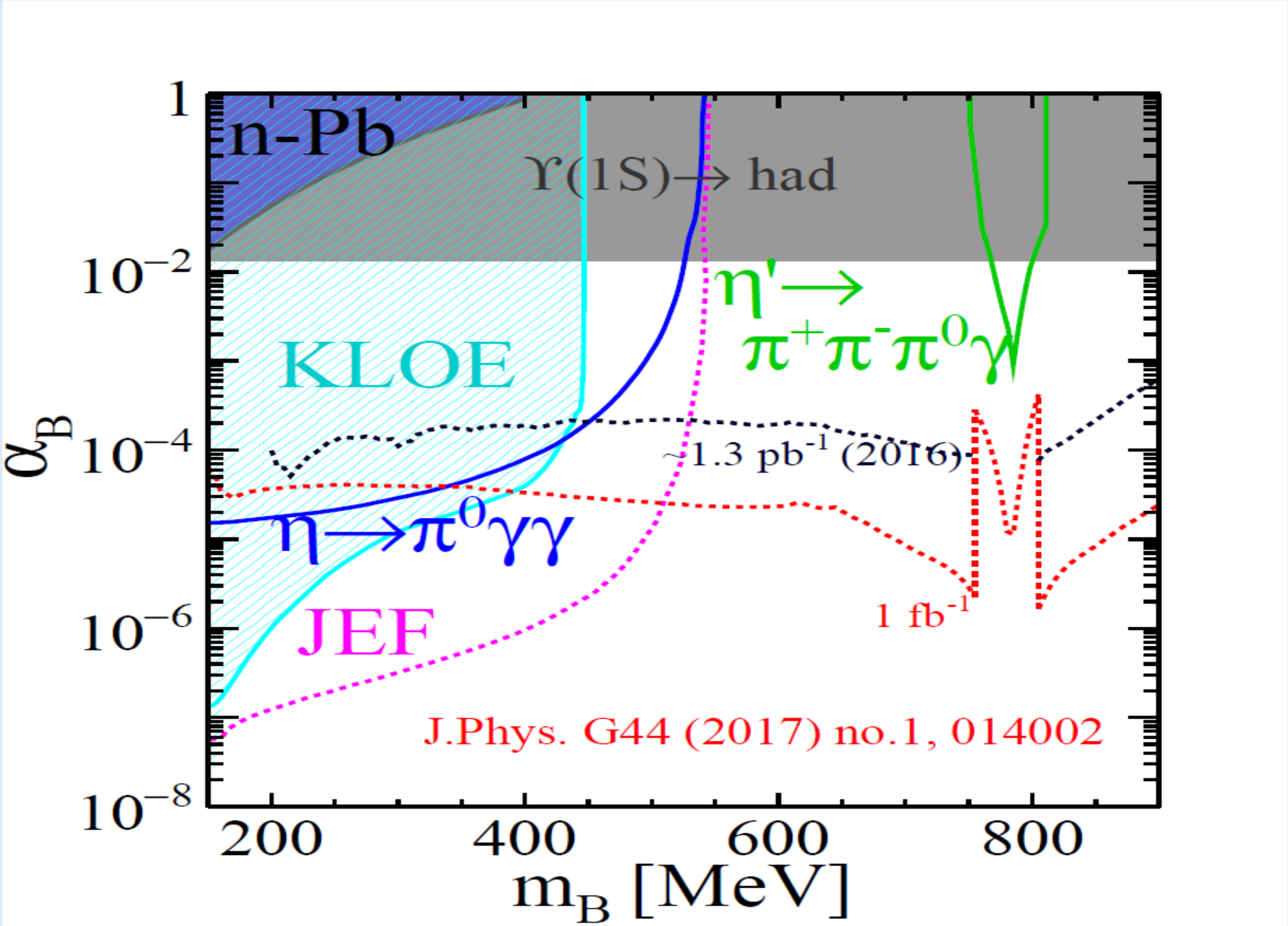
Looking for a bump in GlueX data.





From the talk D. Mack (for the GlueX Collab.), HEP 2018 Valparaiso, Chile Jan 12, 2018

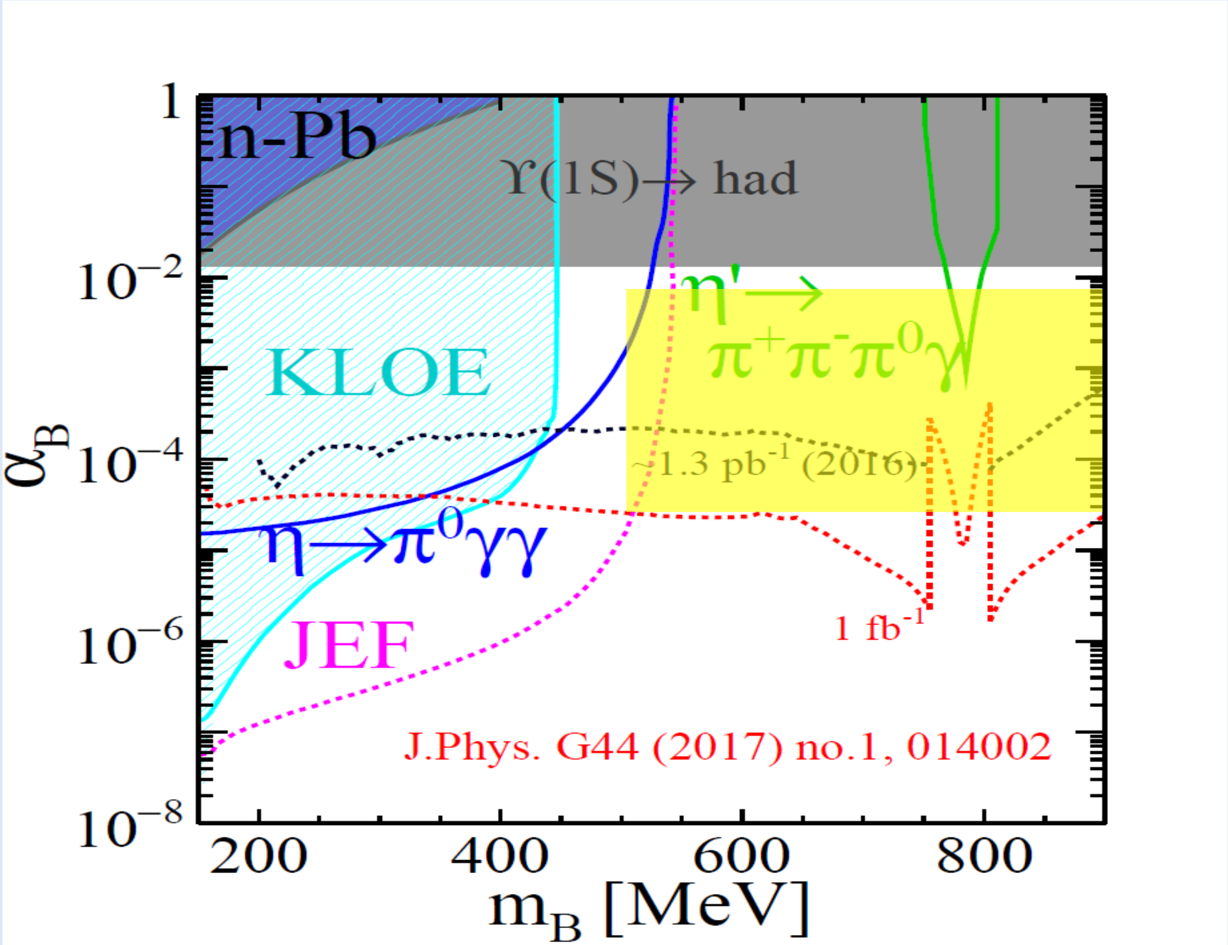
Expected Constraints on Lepto-phobic Dark Coupling and Mass Using Direct Production



A coupling $\alpha_B \sim \alpha_{EM}$ has not yet been excluded in the 0.5-1 GeV/c^2 mass range!

From the talk D. Mack (for the GlueX Collab.), HEP 2018 Valparaiso, Chile Jan 12, 2018

Expected Constraints on Lepto-phobic Dark Coupling and Mass Using Direct Production



Spring 2016 Preliminary

Entire GlueX program, only considering beam flux in the coherent peak.

From the talk D. Mack (for the GlueX Collab.), HEP 2018 Valparaiso, Chile Jan 12, 2018