The High-Energy Photoproduction at GlueX: The States and Outlook

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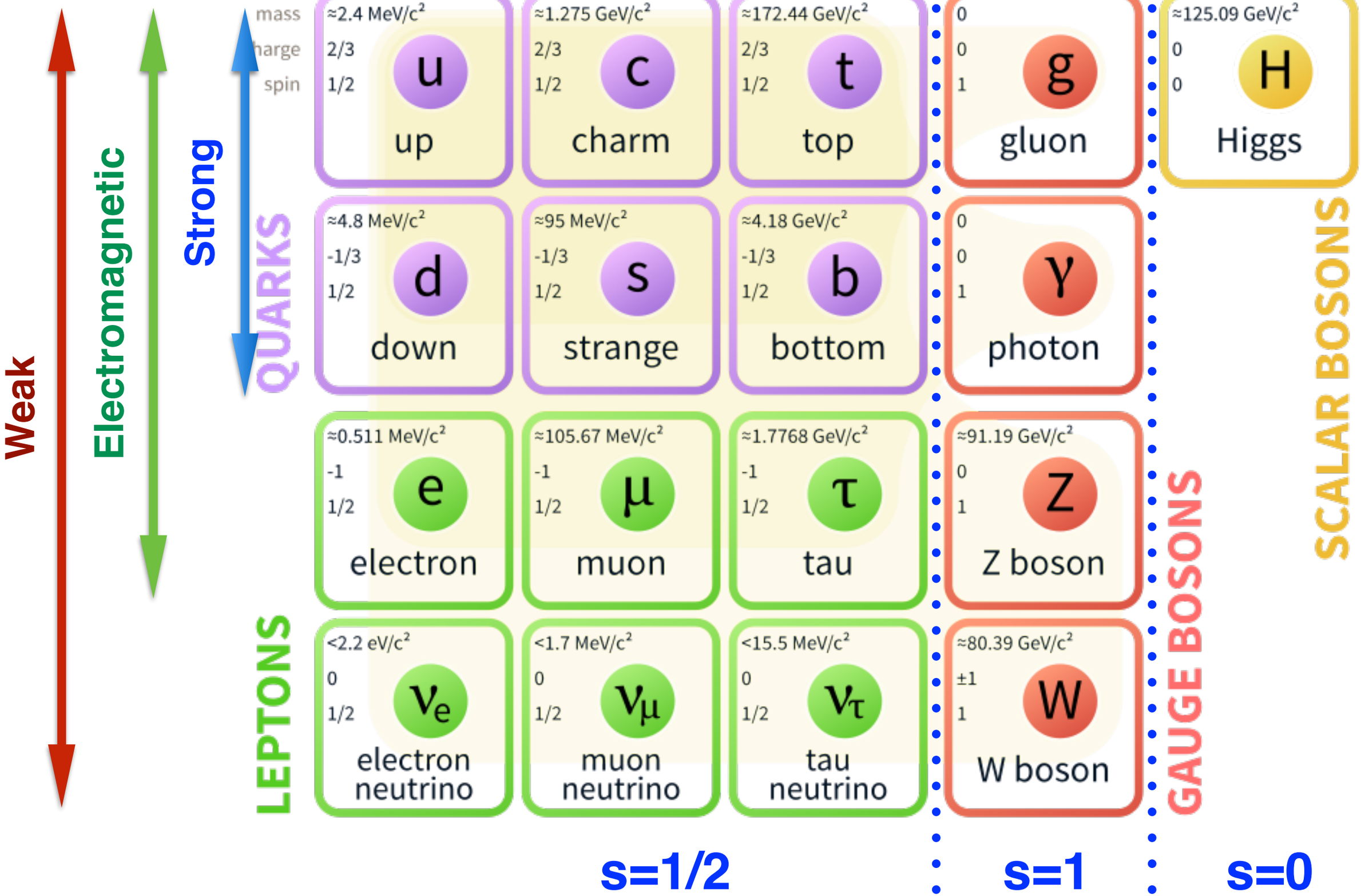
Jefferson Lab GLUEX

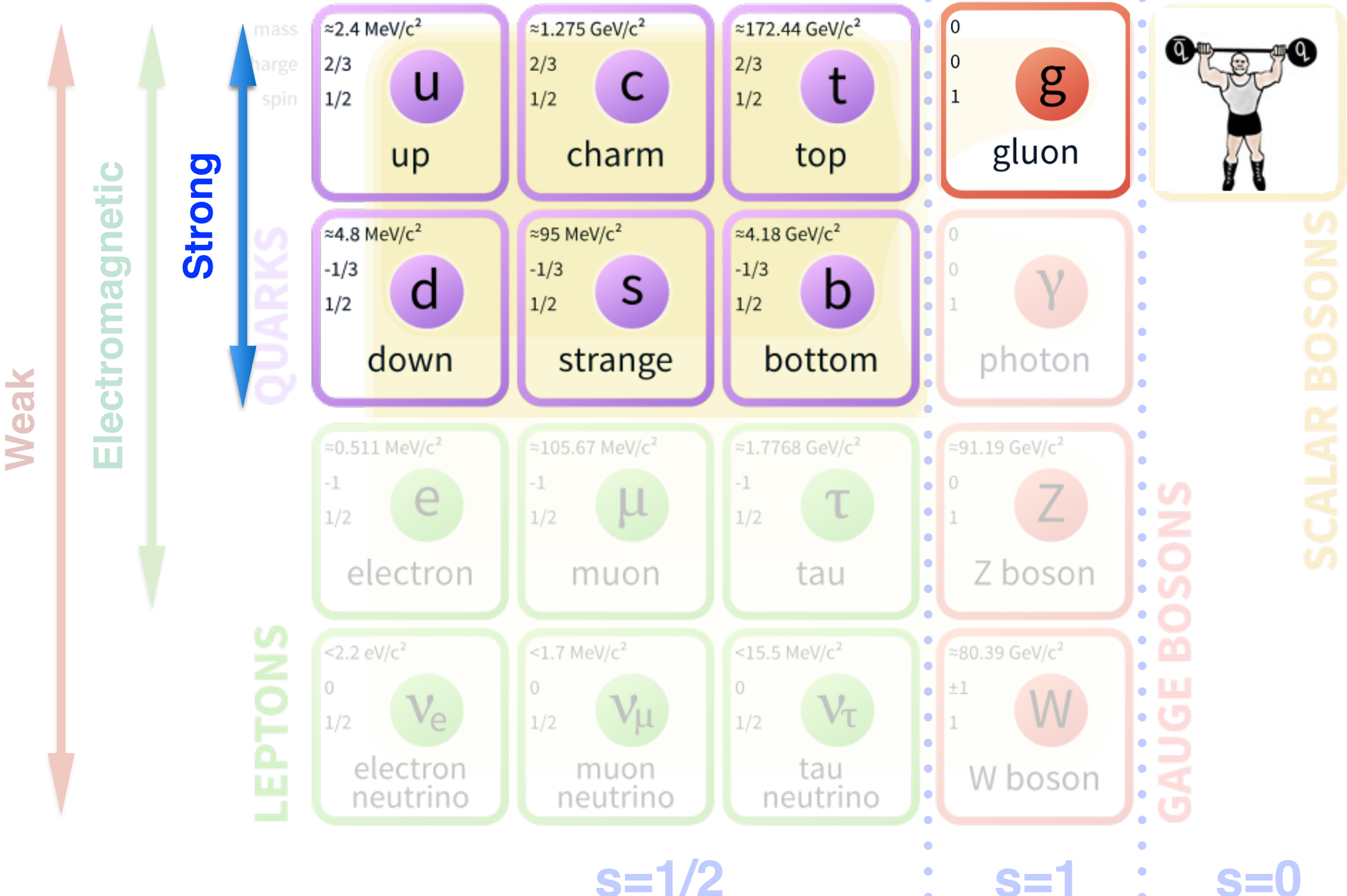
OUTLINE

- Introduction
- GlueX experiment and performance
- Meson photoproduction at GlueX
- Future plans and outlook

Standard Model

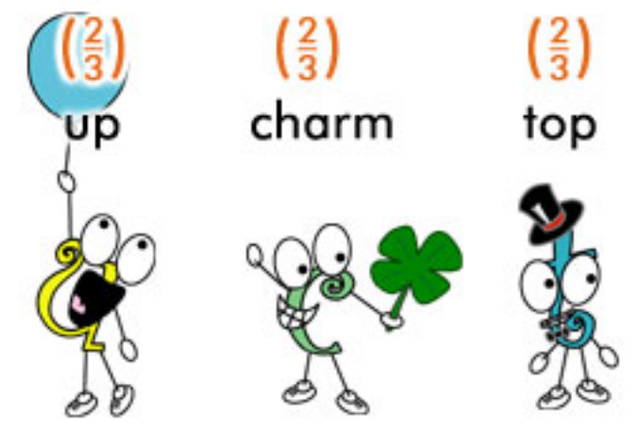


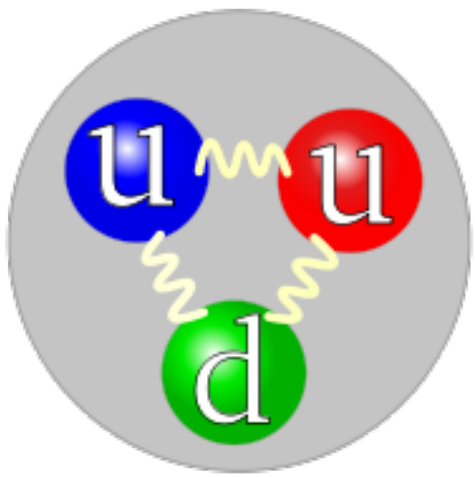
Quark, Gluons, and Strong Force

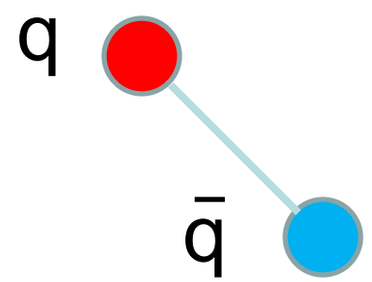


Hadron Physics and Quark Model

Quarks





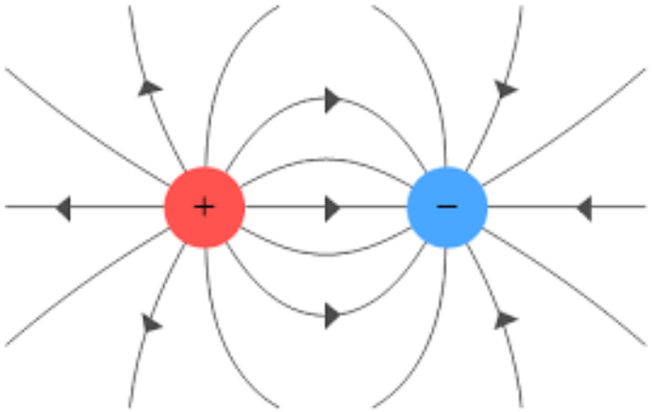


Baryons **Mesons**

Ordinary hadrons

QCD vs QED

QED
Electromagnetic interaction



Charge

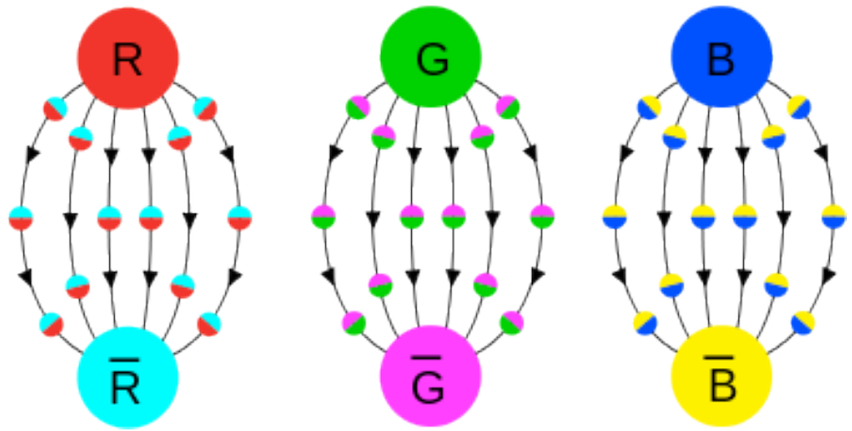
+ and -

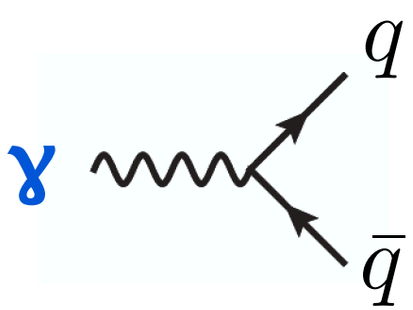
QCD
Strong interaction

Color

red, green, blue

anti-red, anti-green, anti blue





Photon

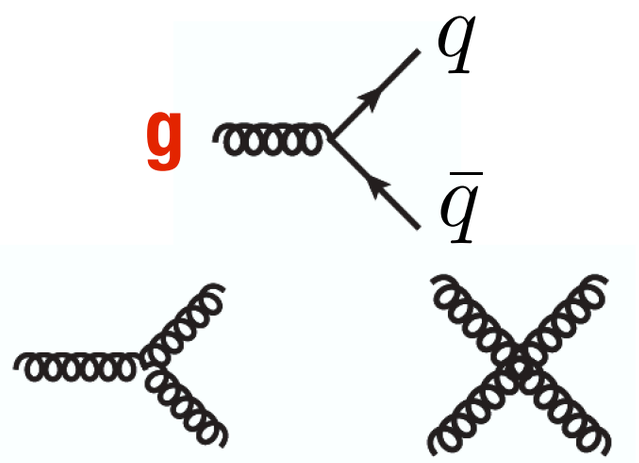
No charge

No direct interaction

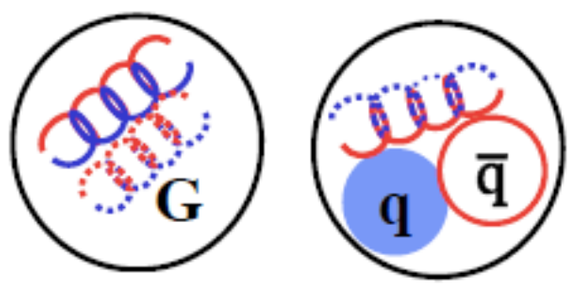
Gluon

color and anti-color

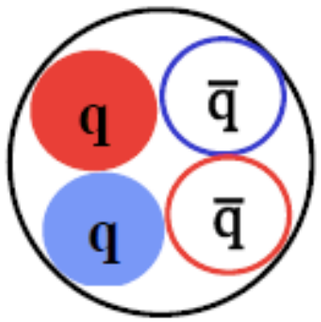
3 gluons and 4 gluons interactions

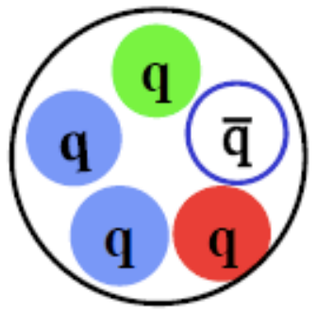


The exotic states can be strong proof for the existence of gluon predicted by QCD as the strong interaction mediator.

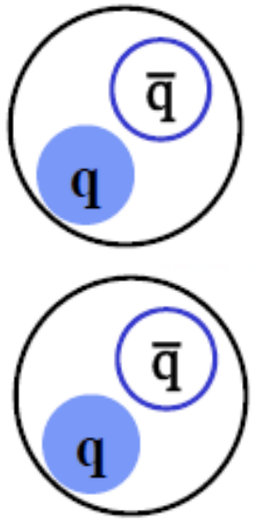


QCD Exotic States



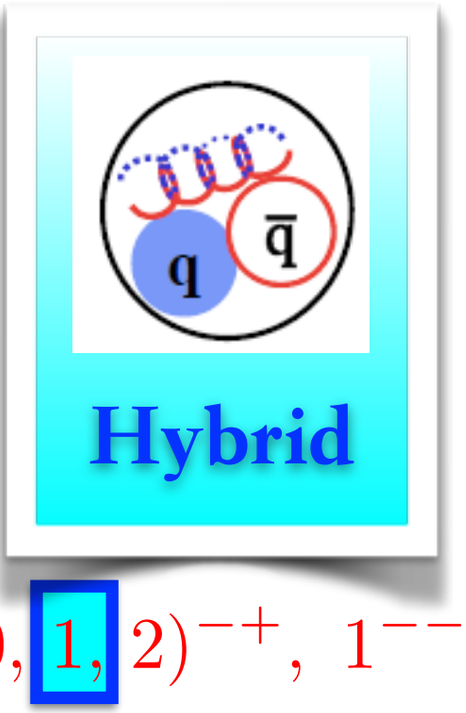


Multi-quark states



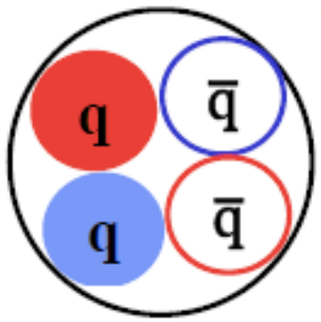
Hadron modular states

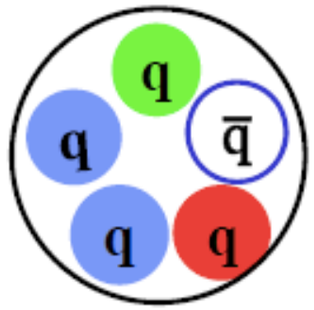
GlueBalls



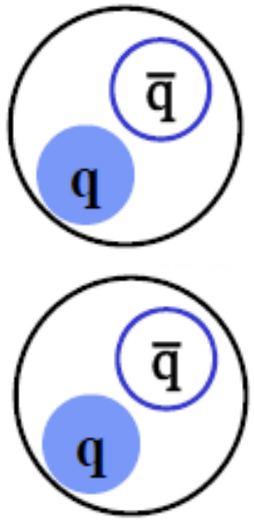
In 1984, Prof. Jueping Liu constructed baryon current operators composed of five-quark field to investigate the resonance Lambda(1405) in the framework of QCD sum rules.

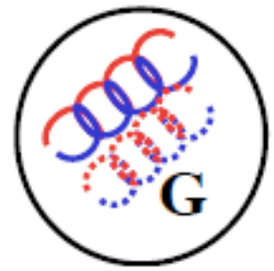
QCD Exotic States





Multi-quark states



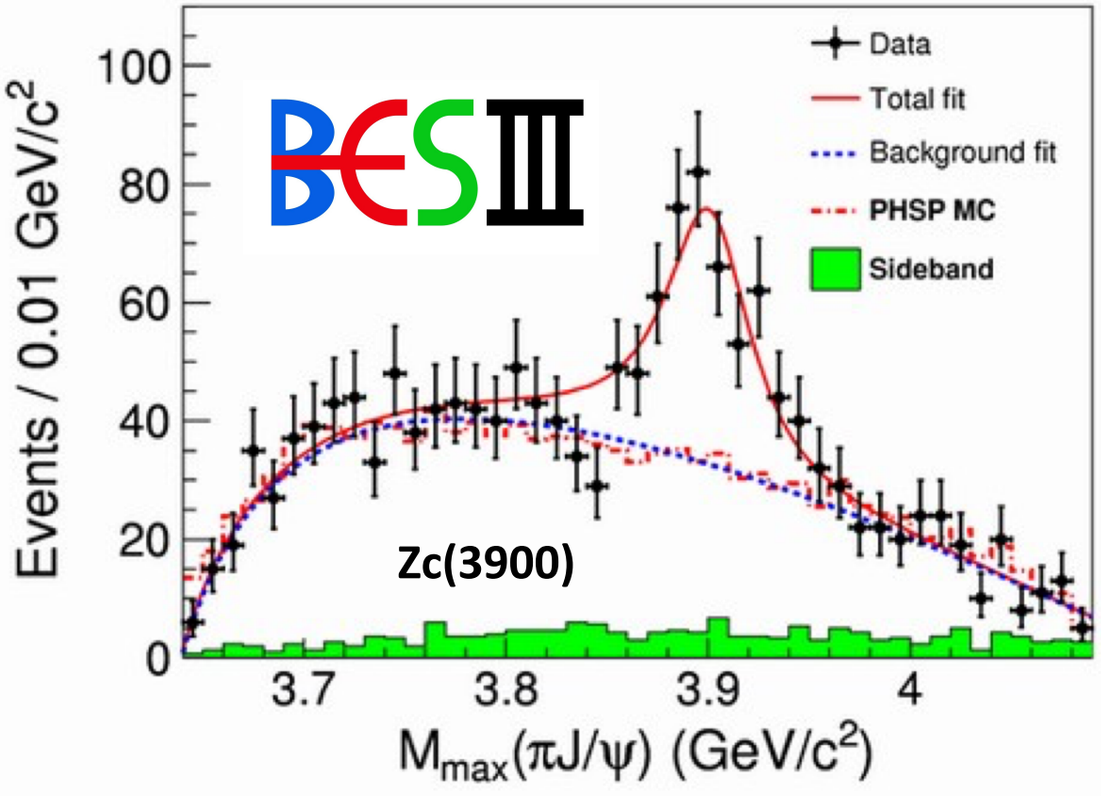


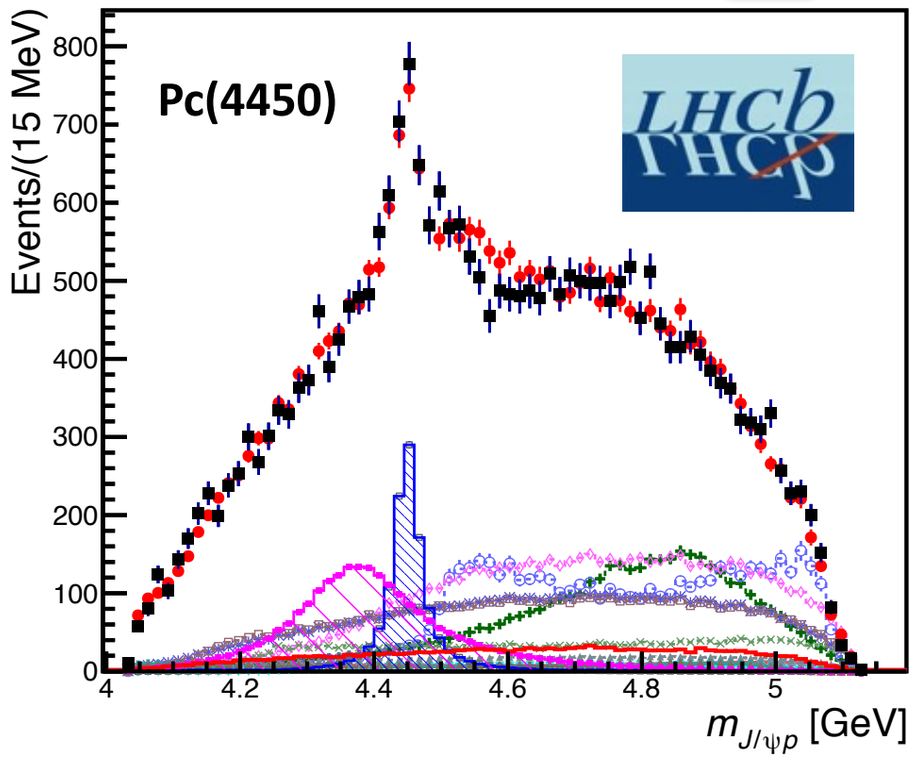
GlueBalls

Hybrid

$(0, \boxed{1}, 2)^{-+},\ 1^{--}$

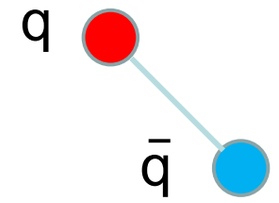
Hadron modular states





Classifying Mesons

——Mass, Electric Charge, Quark Flavor…

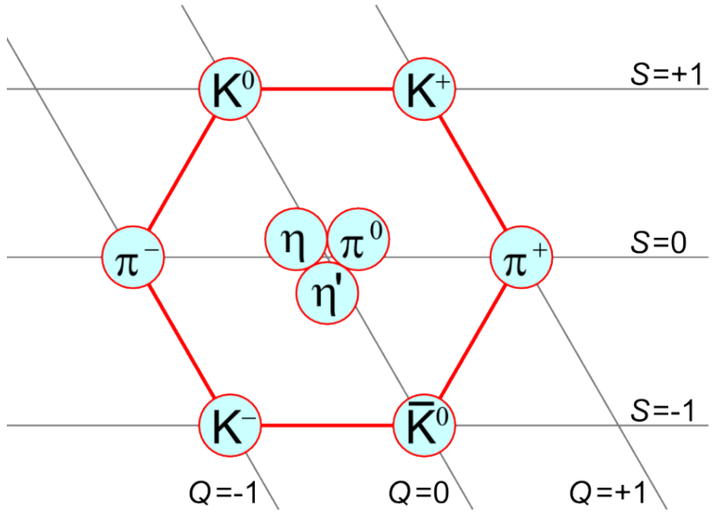


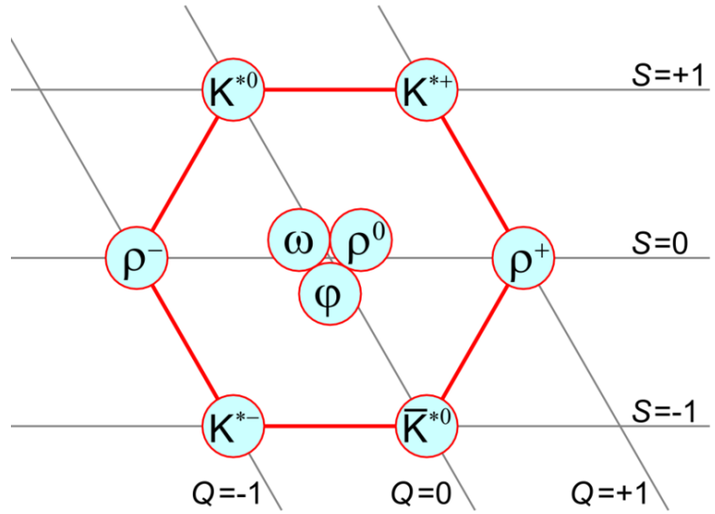
Quantum numbers: J^{PC}

$$\vec{J} = \vec{L} + \vec{S}$$

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

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





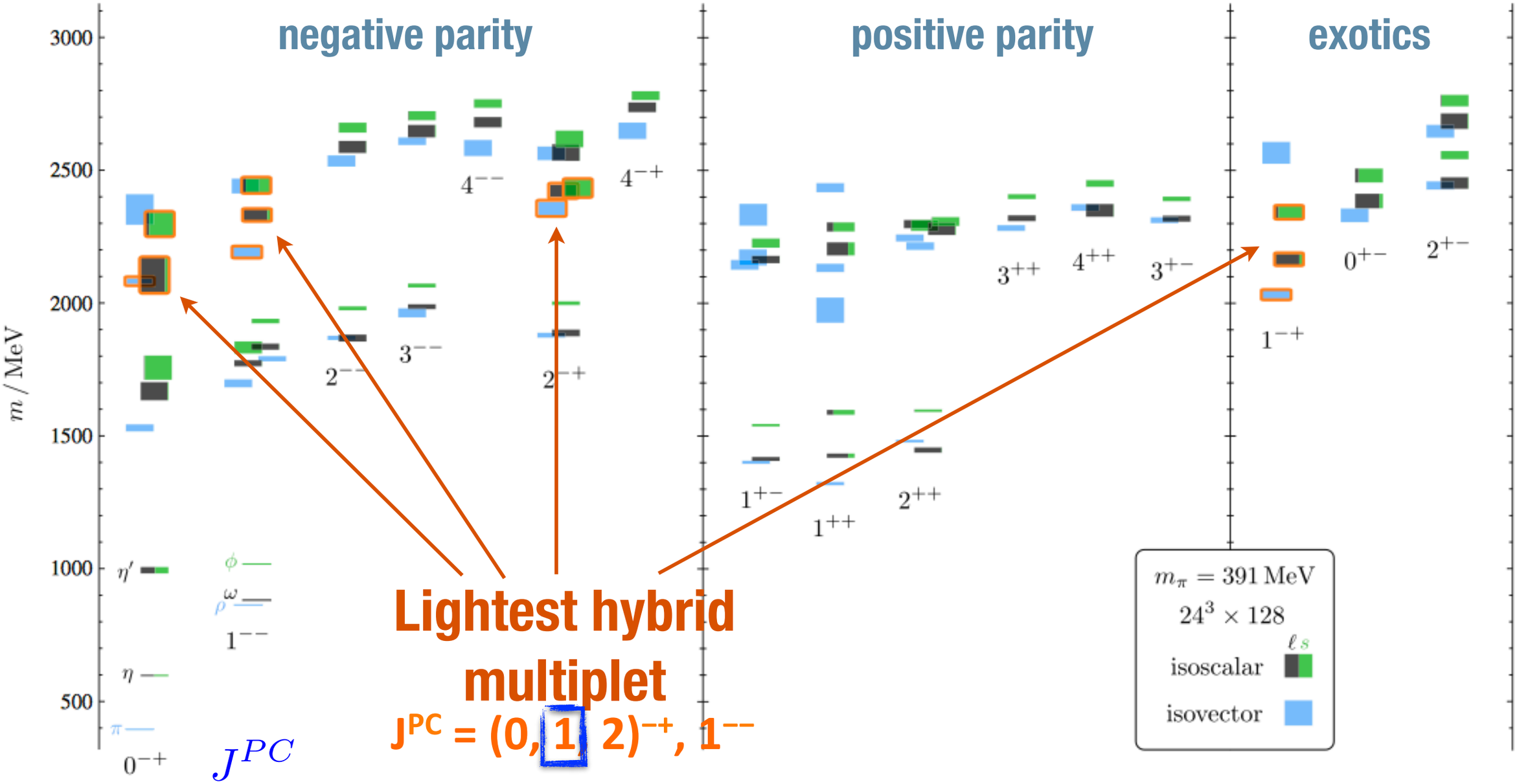
Allowed J^{PC} for $q\bar{q}$ mesons:

$$0^{-+},\ 1^{--},\ 1^{+-},\ 0^{++},\ 2^{++}\ \textbf{...}$$

J^{PC} not allowed for $q\bar{q}$ mesons:

$$0^{+-},\ 1^{-+},\ 2^{+-}...$$

LQCD Meson Spectrum for Light Quarks



Lightest hybrid multiplet

J^{PC} = $(0, 1, 2)^{-+}$, 1^{--}

J^{PC}

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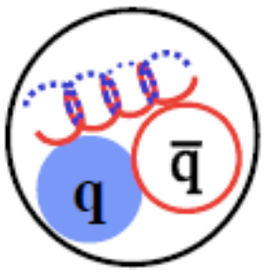
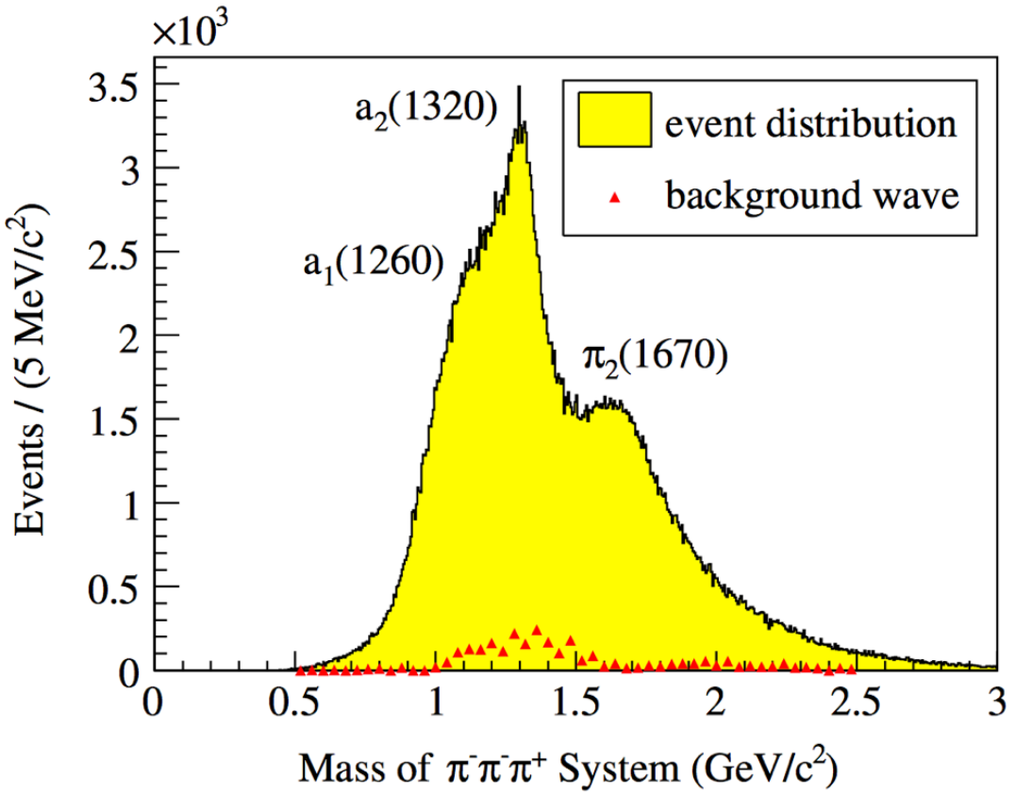
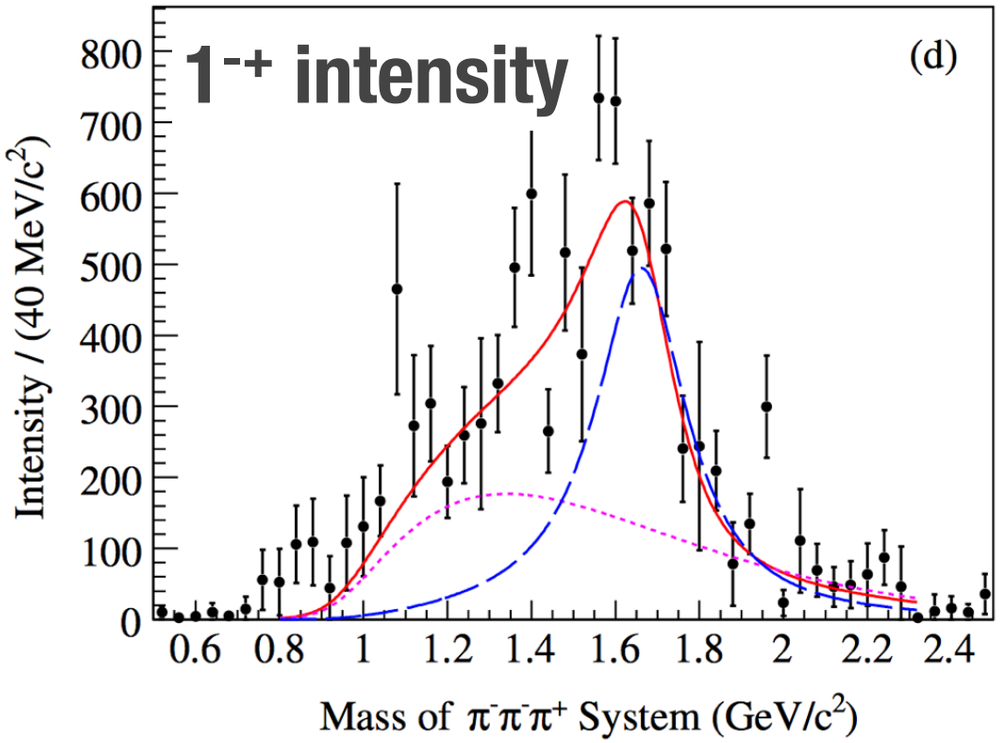
Search for hybrids

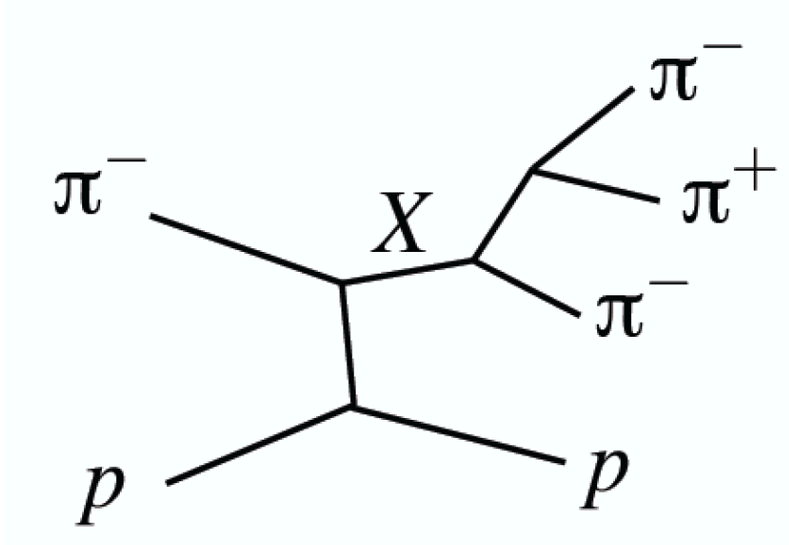


COMPASS: $\pi^- p \to \pi^- \pi^+ \pi^- p$

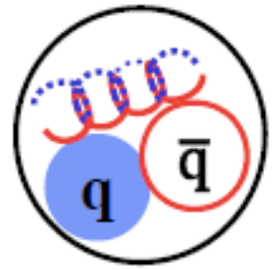




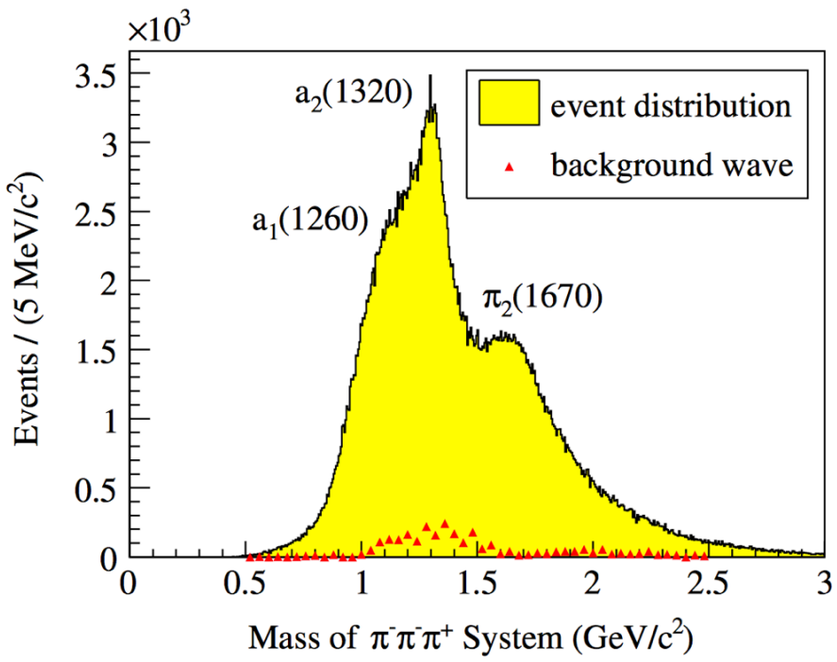
PRL 104, 241803 (2010)



Search for hybrids

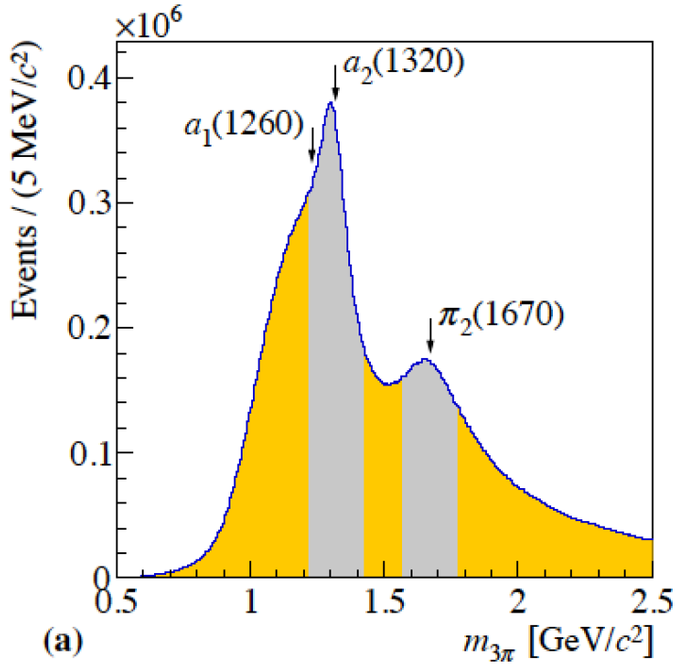


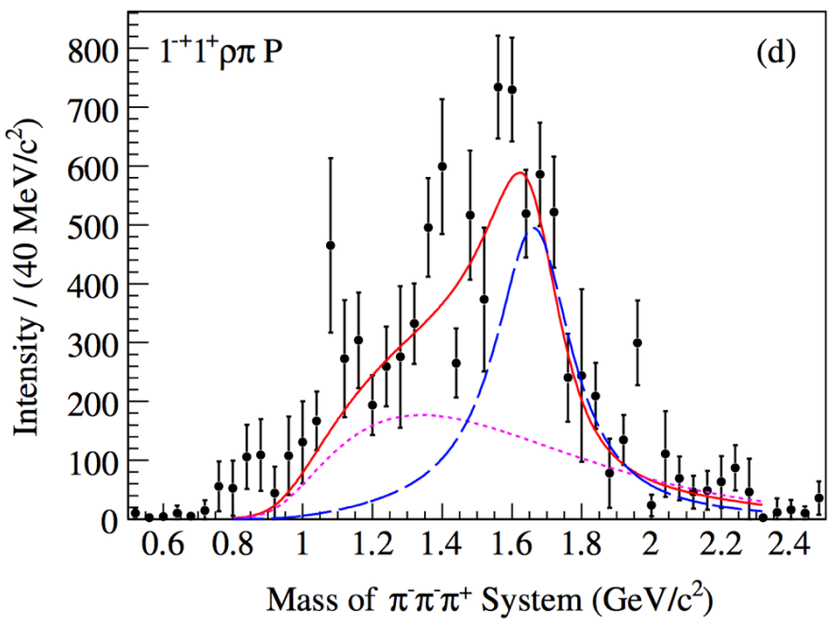
Compass: PRL 104, 241803 (2010)

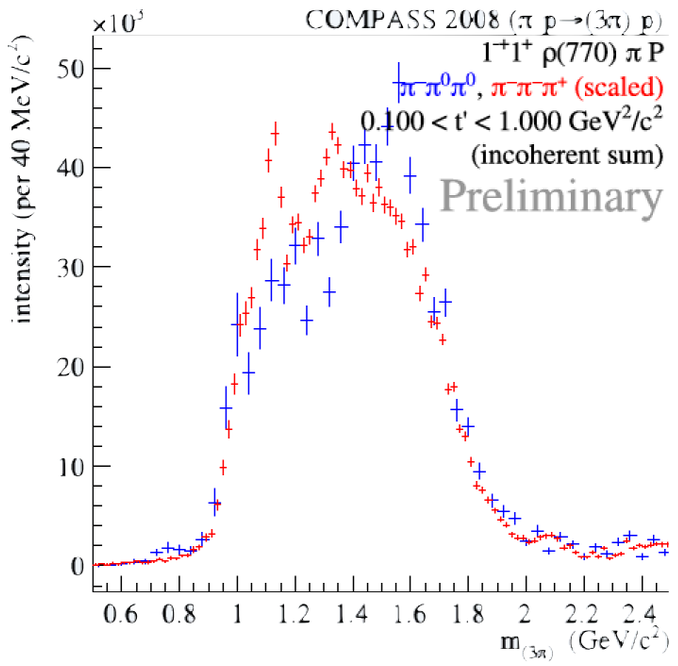


Unprecedented statistics

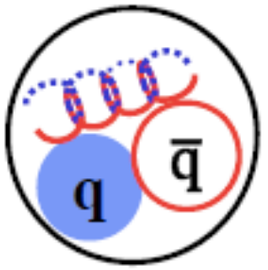
Compass: 1509.00992



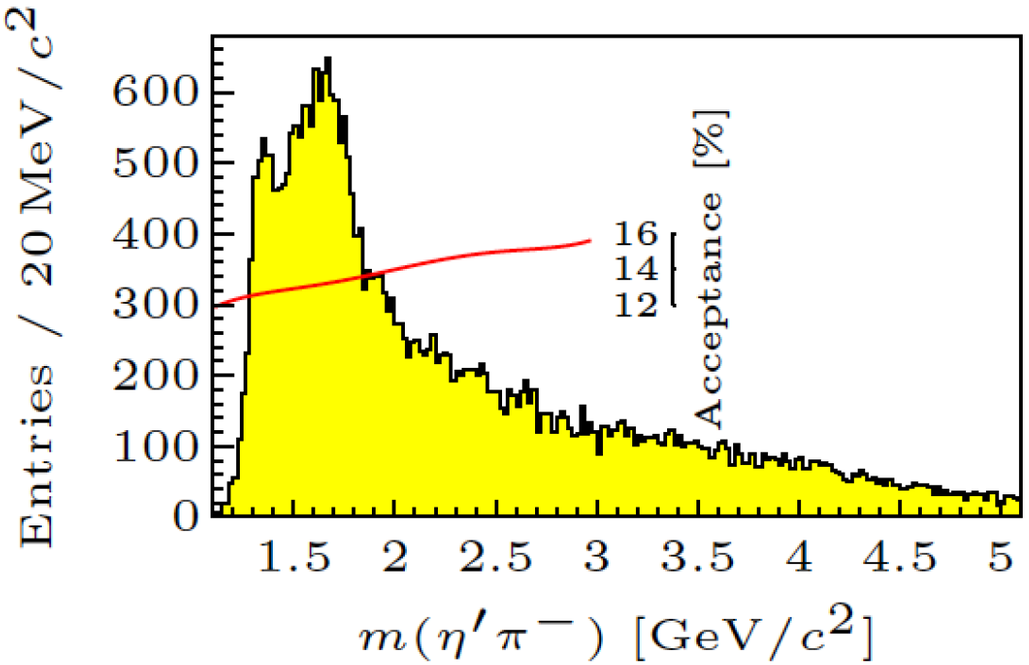


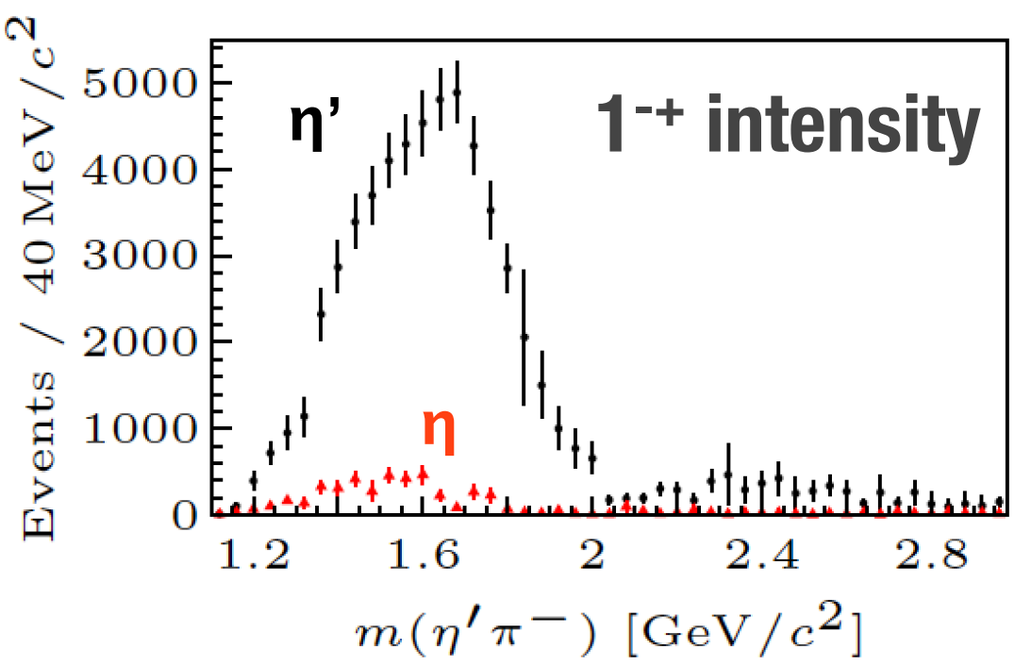


Search for hybrids

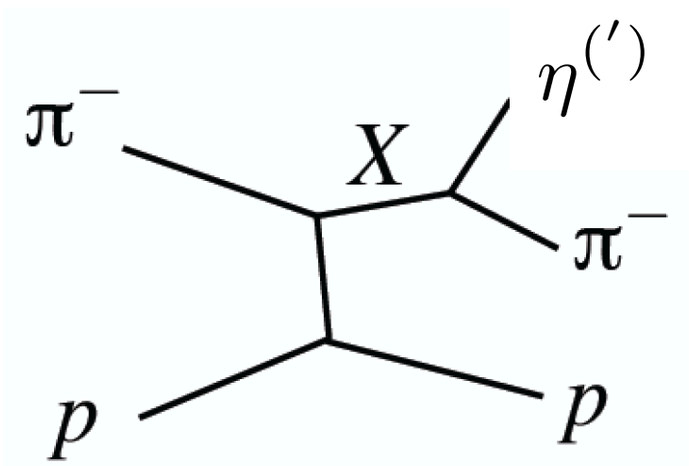


COMPASS: $\pi^- p \to \eta^{(\prime)} \pi^- p$





PLB 740 (2015) 303



The Photoproduction Mechanisms and the Decay Modes of Exotic Hybrids

$\rho\pi,\rho\omega \longrightarrow \pi_1$

$\omega\omega,\rho\rho \longrightarrow \eta_1$

$\omega\omega,\rho\rho,\phi\omega \longrightarrow \eta'_1$

$\rho P \longrightarrow b_0$

$\omega P \longrightarrow h_0$

$\omega P,\ \phi P \longrightarrow h'_0$

$\omega\pi,\rho\eta,\rho P \longrightarrow b_2$

$\rho\pi,\omega\eta,\omega P \longrightarrow h_2$

$\rho\pi,\omega\eta,\phi P \longrightarrow h'_2$

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

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

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

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

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

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

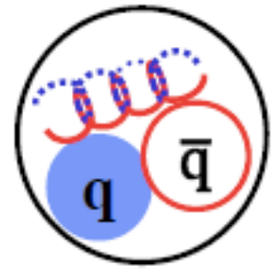
$b_0 \rightarrow \pi(1300)\pi,\ h_1\pi,\ f_1\rho,\ b_1\eta$

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

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

The meson photoproduction is a promising experimental technique to search for exotic hybrid mesons.

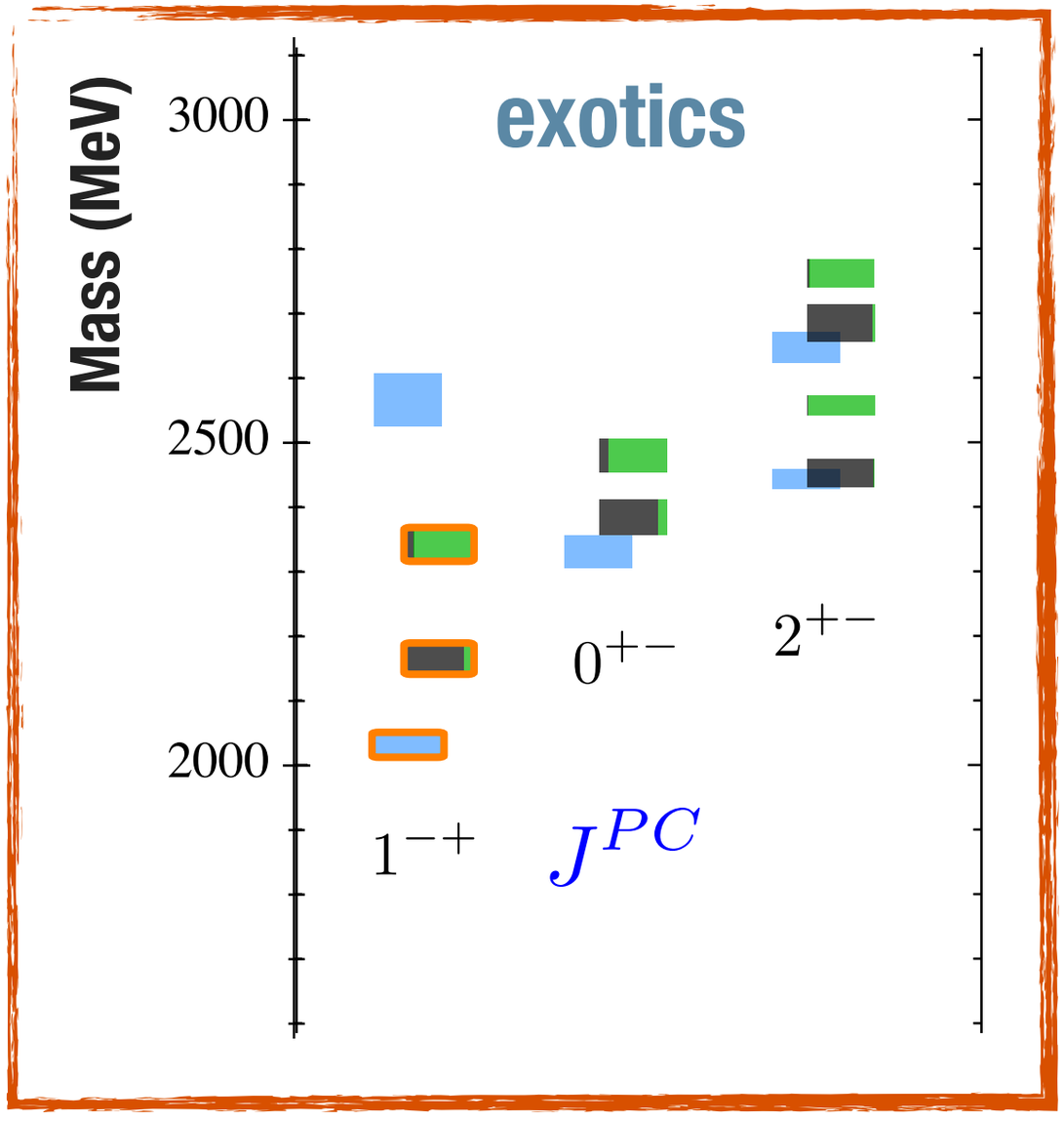
Search for exotic hybrids



Evidence exists for $J^{PC}=1^{-+}$ amplitudes, but interpretation clearly not conclusive

Search for a pattern of hybrid states in many final states

	Approximate Mass (MeV)	J^{PC}	Final States
π_1	1900	1^{-+}	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	2100	1^{-+}	4π, $\eta 4\pi$, $\eta\eta\pi\pi^\dagger$
η_1'	2300	1^{-+}	$KK\pi\pi^\dagger$, $KK\pi^\dagger$, $KK\omega^\dagger$
b_0	2400	0^{+-}	4π
h_0	2400	0^{+-}	$\omega\pi\pi^\dagger$, $\eta 3\pi$, $KK\pi\pi$
h_0'	2500	0^{+-}	$KK\pi\pi^\dagger$, $\eta 3\pi$
b_2	2500	2^{+-}	4π, $\eta\pi\pi^\dagger$
h_2	2500	2^{+-}	$\omega\pi\pi^\dagger$, $3\pi^\dagger$
h_2'	2600	2^{+-}	$KK\pi\pi^\dagger$, $KK\pi^\dagger$

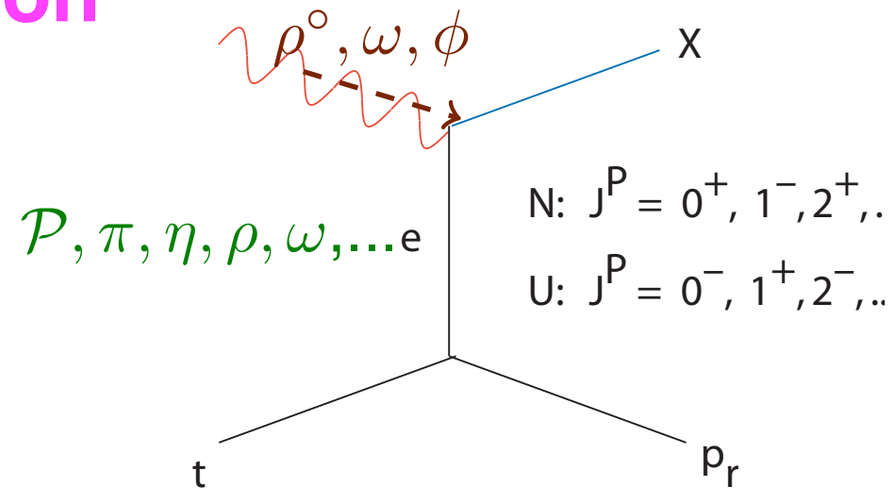


Hybrid Meson Search Strategy

The High-Energy Photoproduction

GLUEX

- **Unique production mechanism with access to exotic J^{PC}**
- **Access to hybrid masses up to ~2.8 GeV**
- **Large acceptance for multi-particle final states**
- **Identification of exotic JPC through amplitude analyses**
- **Ability to study many final states simultaneously**

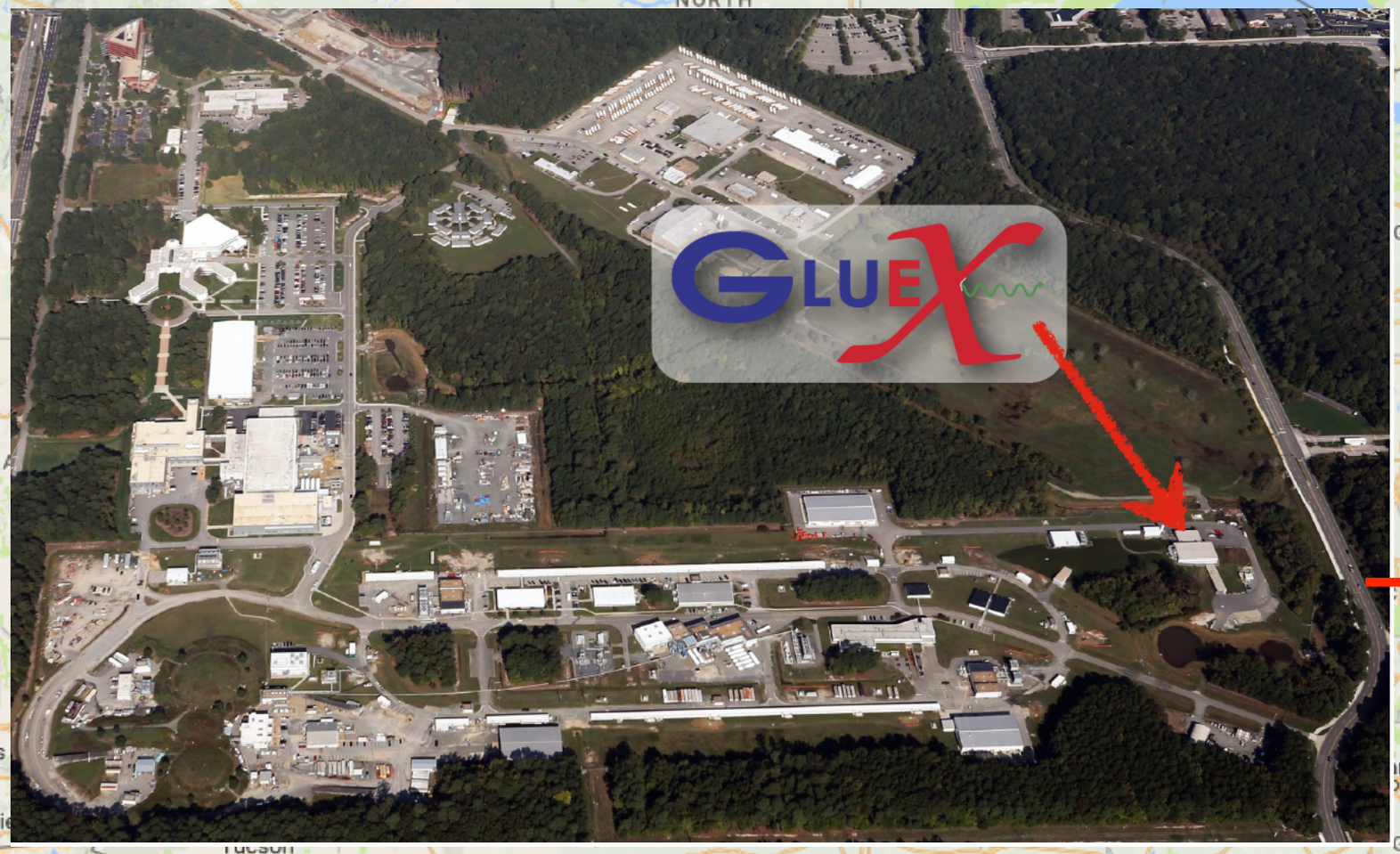


Exchange particle		Final states	
$\mathcal{P}$	0^{++}	$2^{+-}, 0^{+-}$	b°, h, h'
π°	0^{-+}	2^{+-}	b_2°, h_2, h_2'
$\pi^\pm$	0^{-+}	1^{-+}	$\pi_1^\pm$
ω	1^{--}	1^{-+}	π_1, η_1, η_1'

Can couple to all 3 exotic nonets

1^{-+} $\pi_1, \eta_1 \ldots$ $\sim$2.0 – 2.4 GeV/c^2
0^{+-} $b_\circ, h_\circ \ldots$ $\sim$2.3 – 2.5 GeV/c^2
2^{+-} $b_2, h_2 \ldots$ $\sim$2.4 – 2.6 GeV/c^2

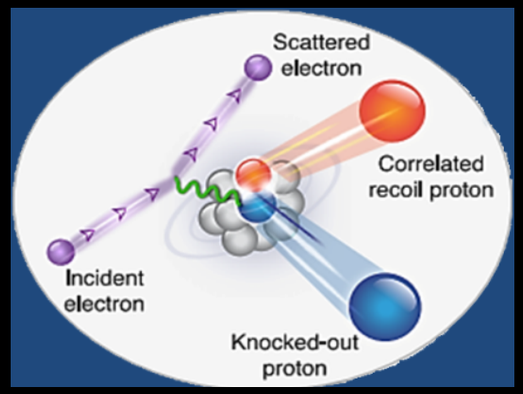
Thomas Jefferson National Accelerator Facility
(Jefferson Lab)



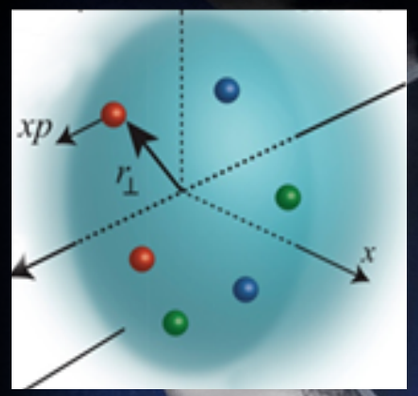
Thomas Jefferson
(1743–1826)

托马斯·杰斐逊国家加速器装置
（杰斐逊实验室）

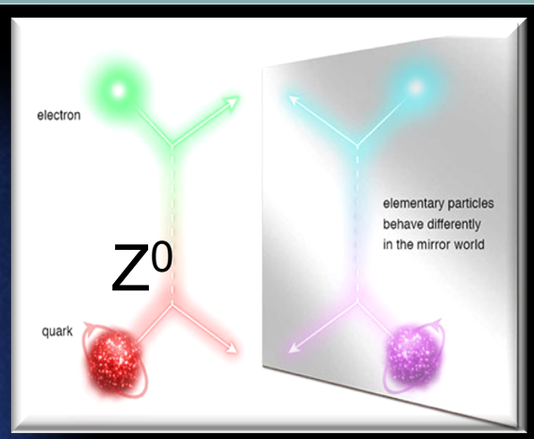
JLab: A Laboratory for Nuclear Science



Nuclear Structure

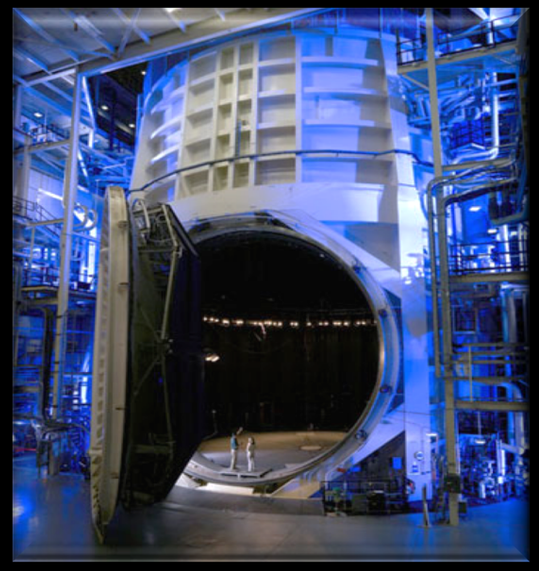


Structure of Hadrons



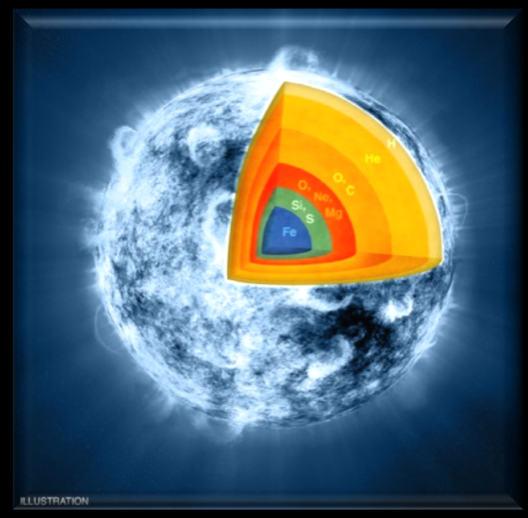
Fundamental Forces & Symmetries

Medical Imaging



Cryogenics

Accelerator S&T



Nuclear Astrophysics

Theory & Computation

The 12-GeV upgrade at Jefferson Lab

Hall D: The new experiment hall at JLab

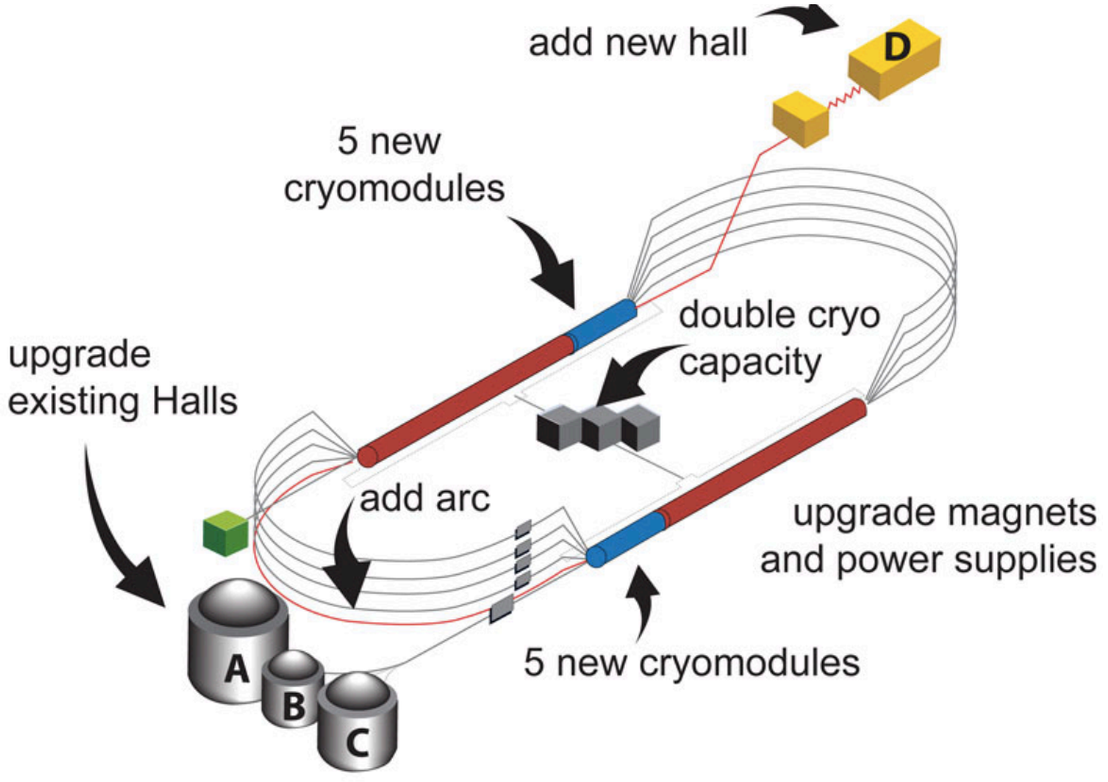
GlueX: The spectrometer in the Hall D

The long-term aim:

Understand quark-gluon interactions

search for exotic hybrid mesons

- The 12-GeV upgrade is completed in Feb. 2016
- Accelerator: 2.2 GeV/pass
- Halls A, B, C: 1-5 turns <11 GeV
- Hall D: 5.5 turns →12 GeV
- Halls A&D started data taking in 2016 spring
- Halls B&C started data taking in 2017 spring



The 2015 LONG RANGE PLAN for NUCLEAR SCIENCE

Here are the recommendations of the 2015 Long Range Plan.

RECOMMENDATION I

The progress achieved under the guidance of the 2007 Long Range Plan has reinforced U.S. world leadership in nuclear science. The highest priority in this 2015 Plan is to capitalize on the investments made.

- *With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.*

GlueX Collaboration

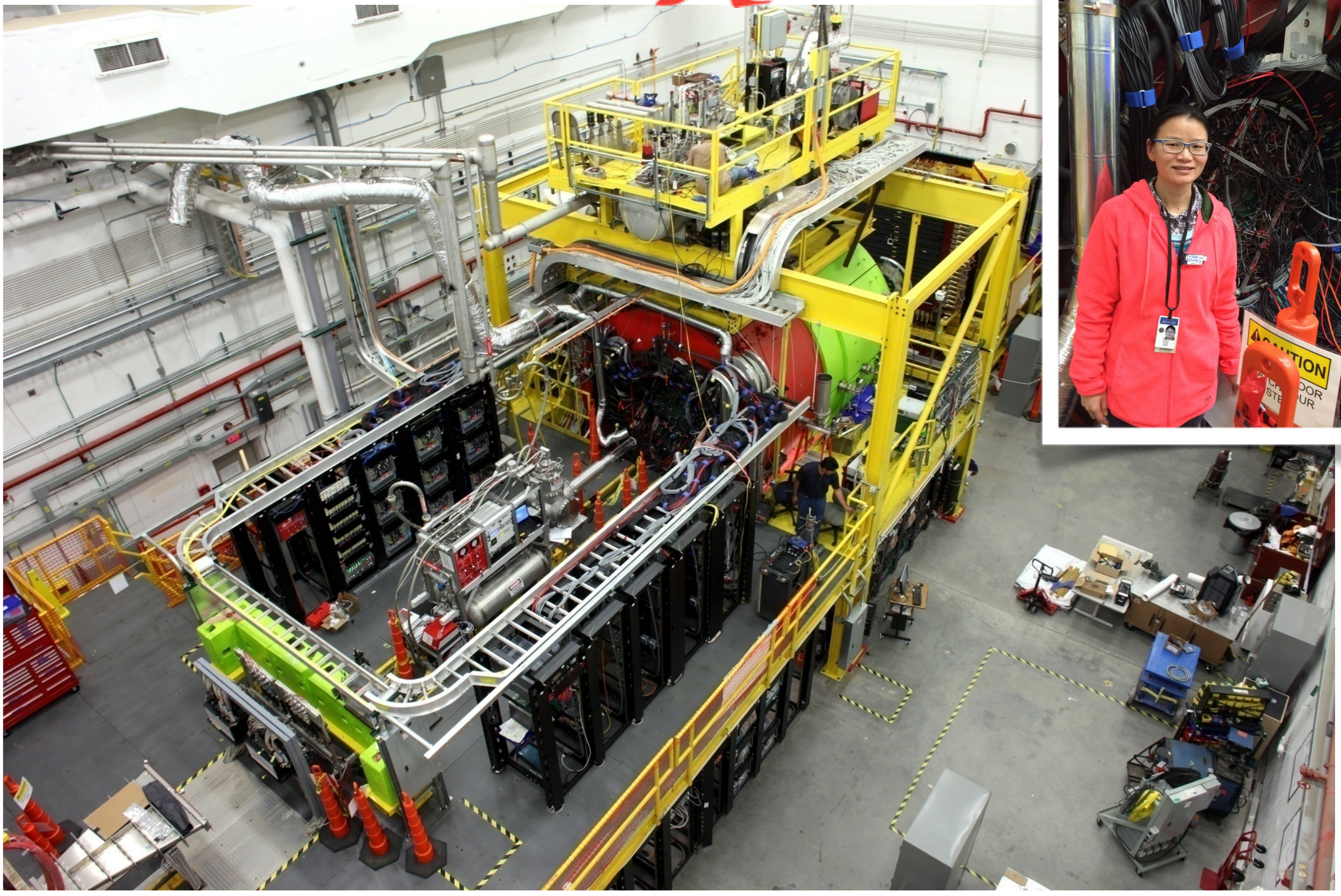
http://portal.gluex.org/GlueX/Home.html

~120 members from 25 institutions of 8 counties

GlueX Collaboration

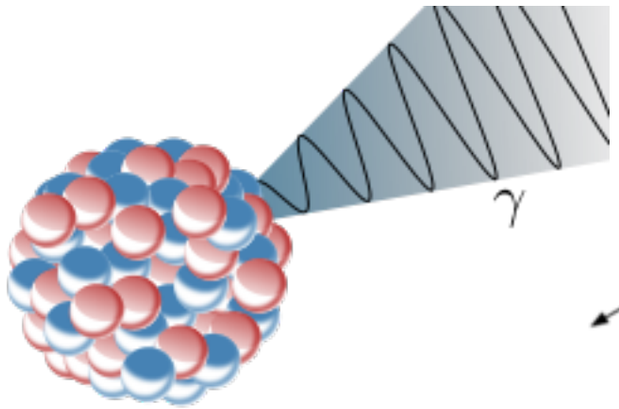
http://portal.gluex.org/GlueX/Home.html ~120 members from 27 institutions of 9 counties

In 2016, Wuhan University became the first GlueX member from Asia.

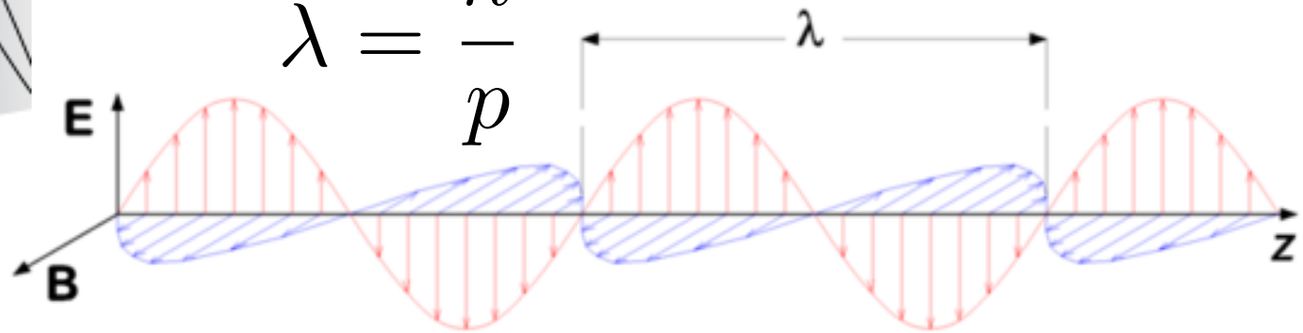


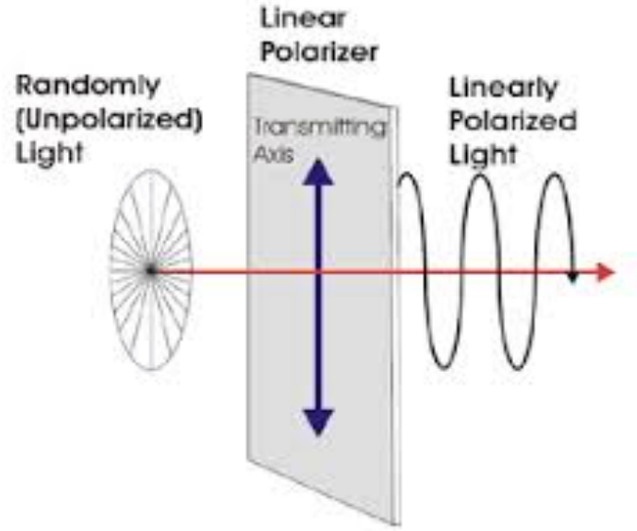
CAUTION

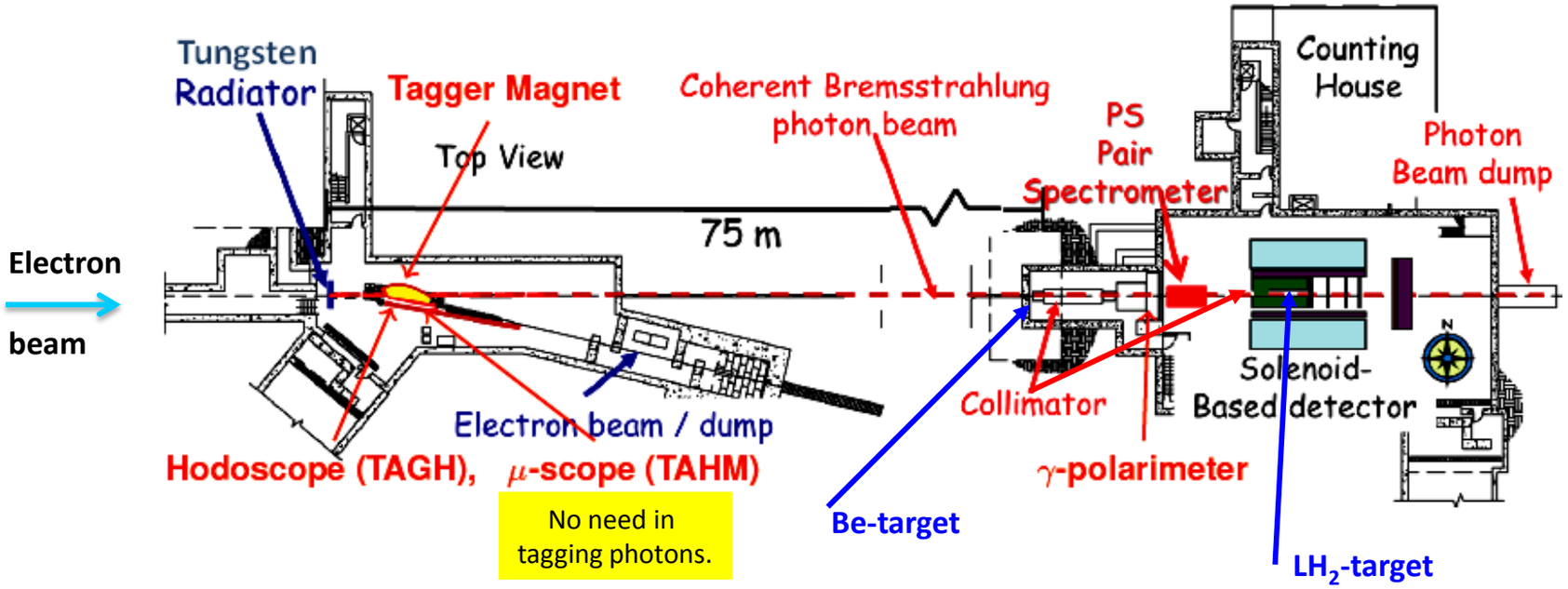
Linearly polarised photon beam

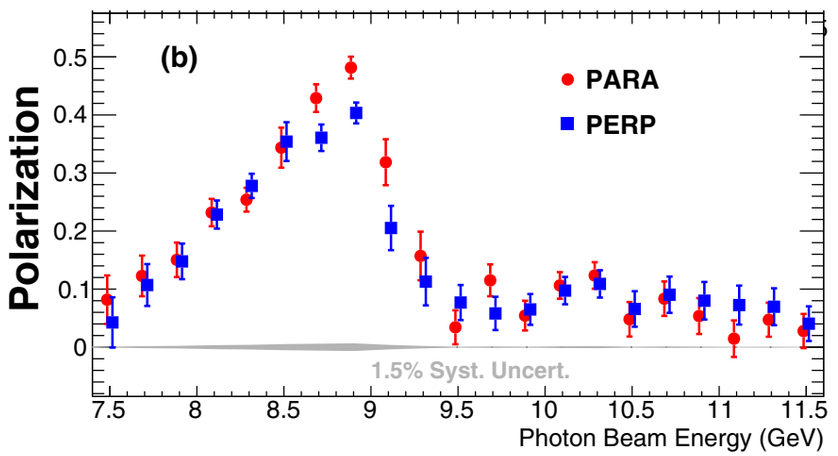


$$\lambda = \frac{h}{p}$$









Linearly polarized photons via coherent bremsstrahlung from diamond radiator off liquid hydrogen peaking at 9 GeV

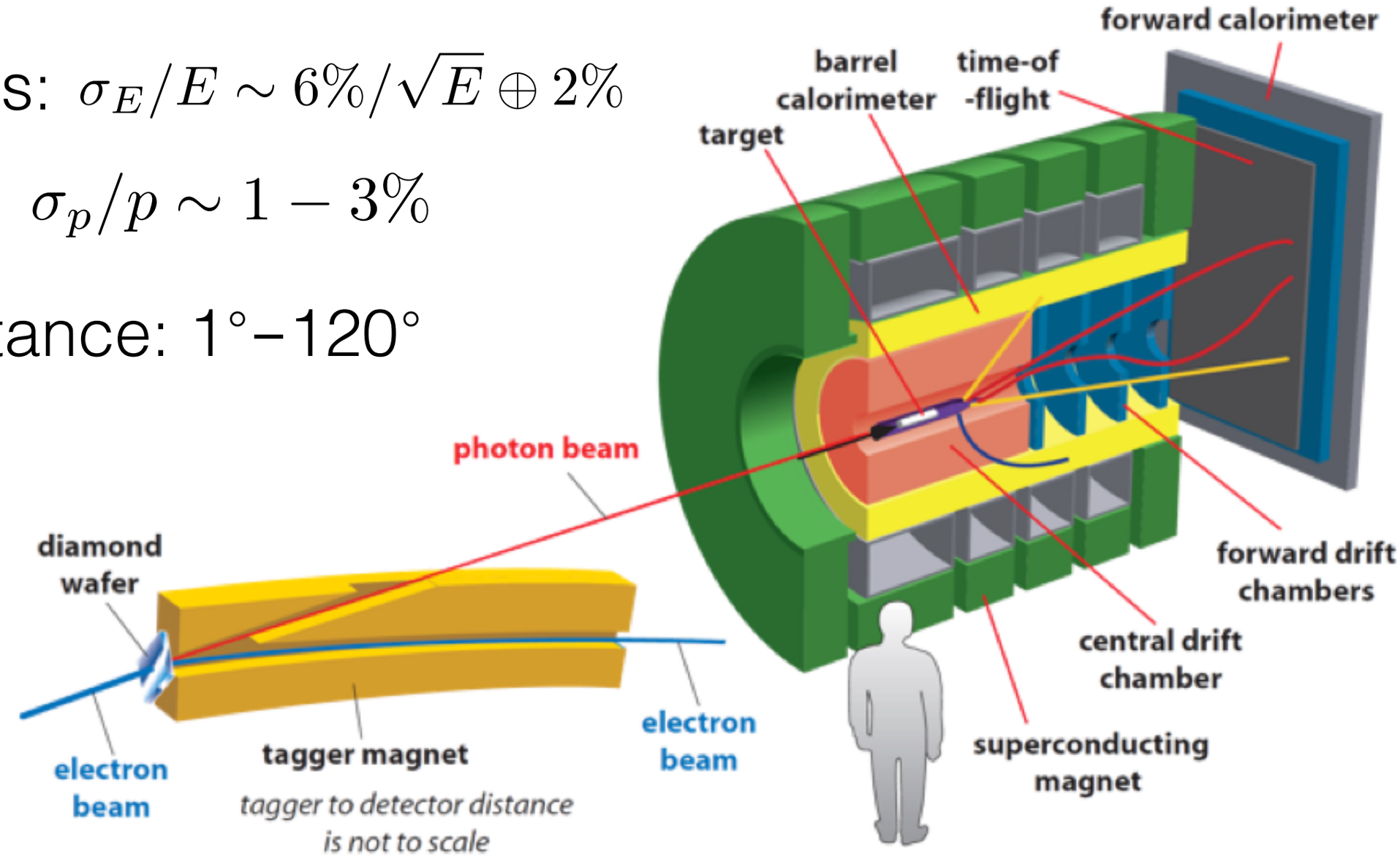
GlueX detector

Detector resolutions:

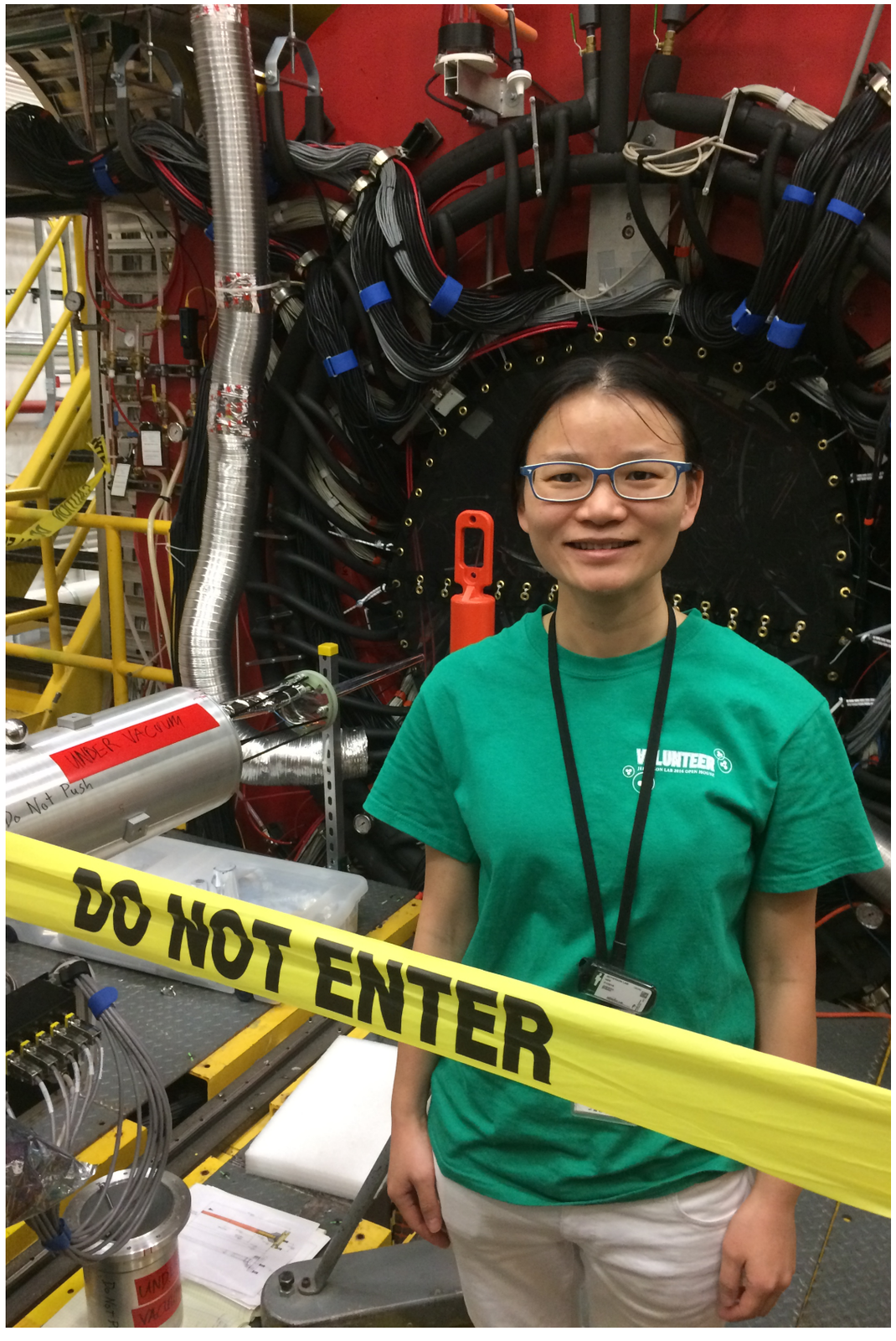
Photons: $\sigma_E/E \sim 6\%/\sqrt{E} \oplus 2\%$

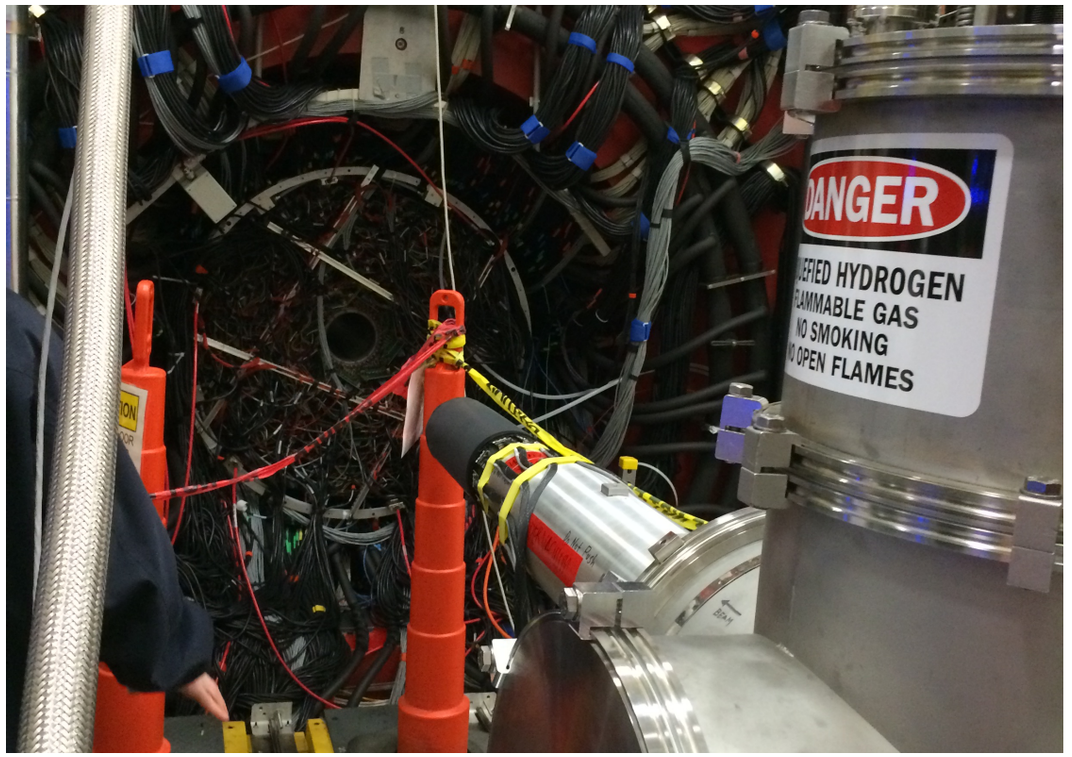
Tracks: $\sigma_p/p \sim 1 - 3\%$

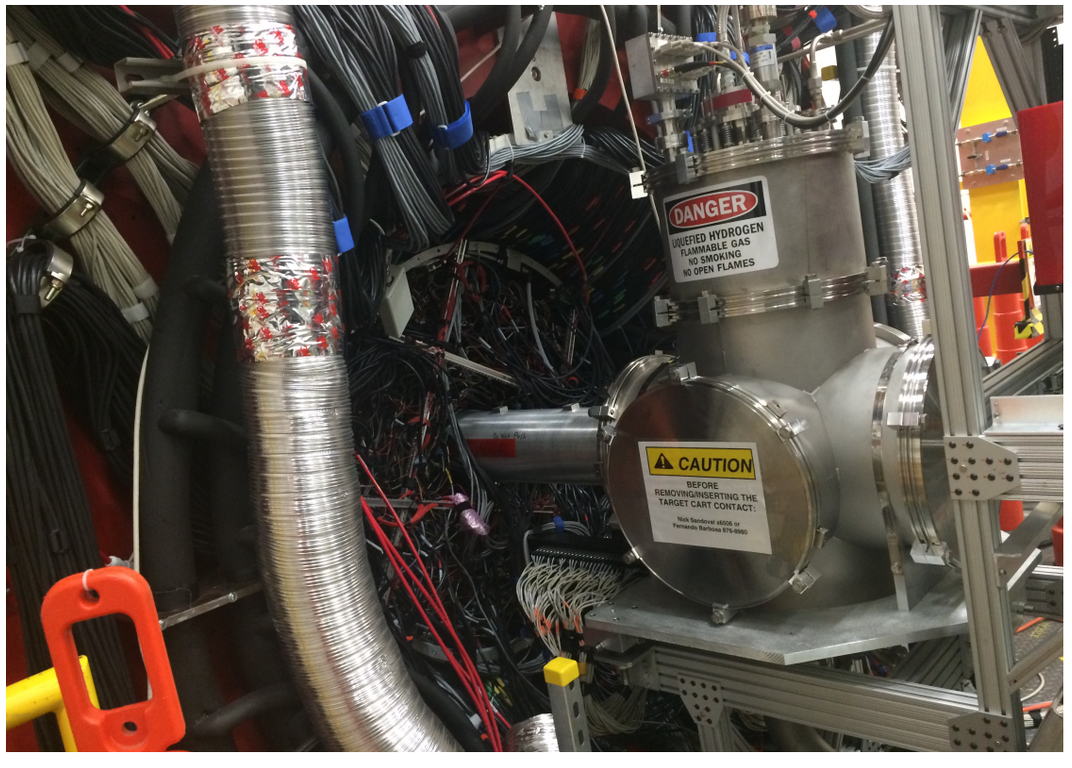
Receptance: 1°–120°



Liquid hydrogen target and start counter

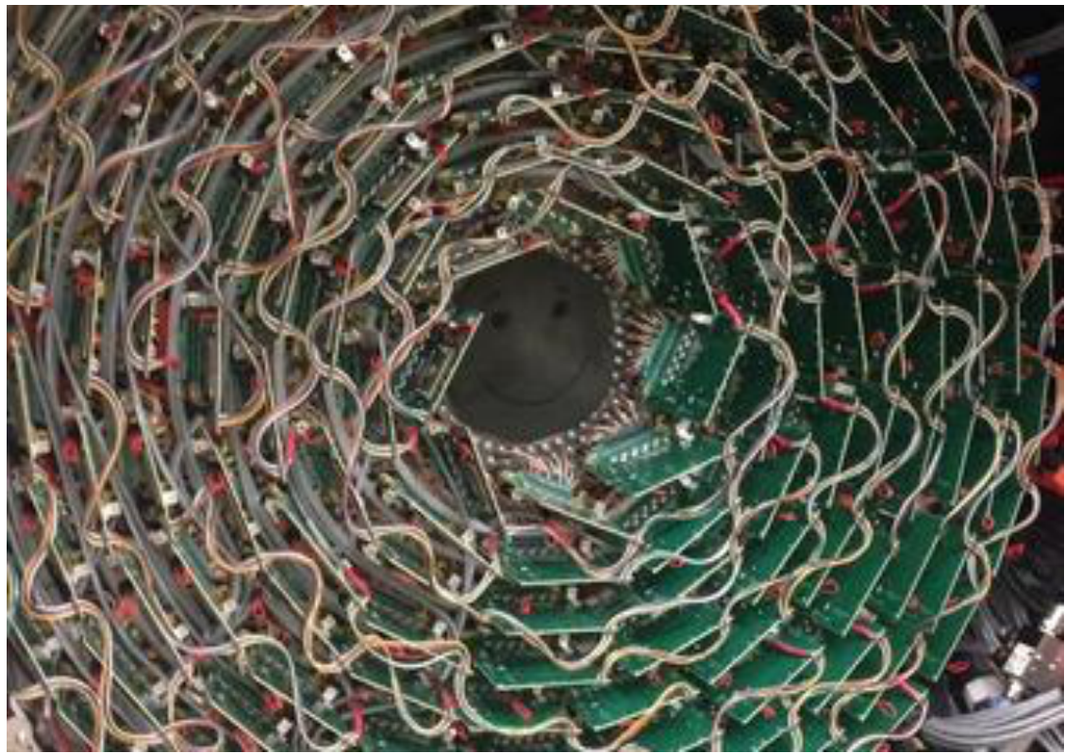




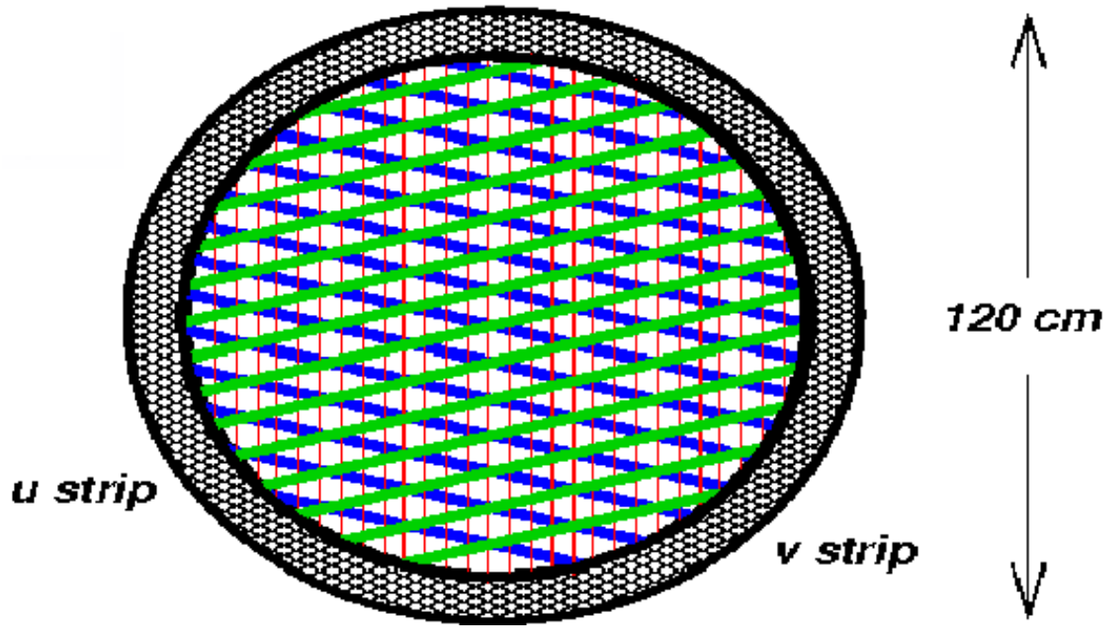


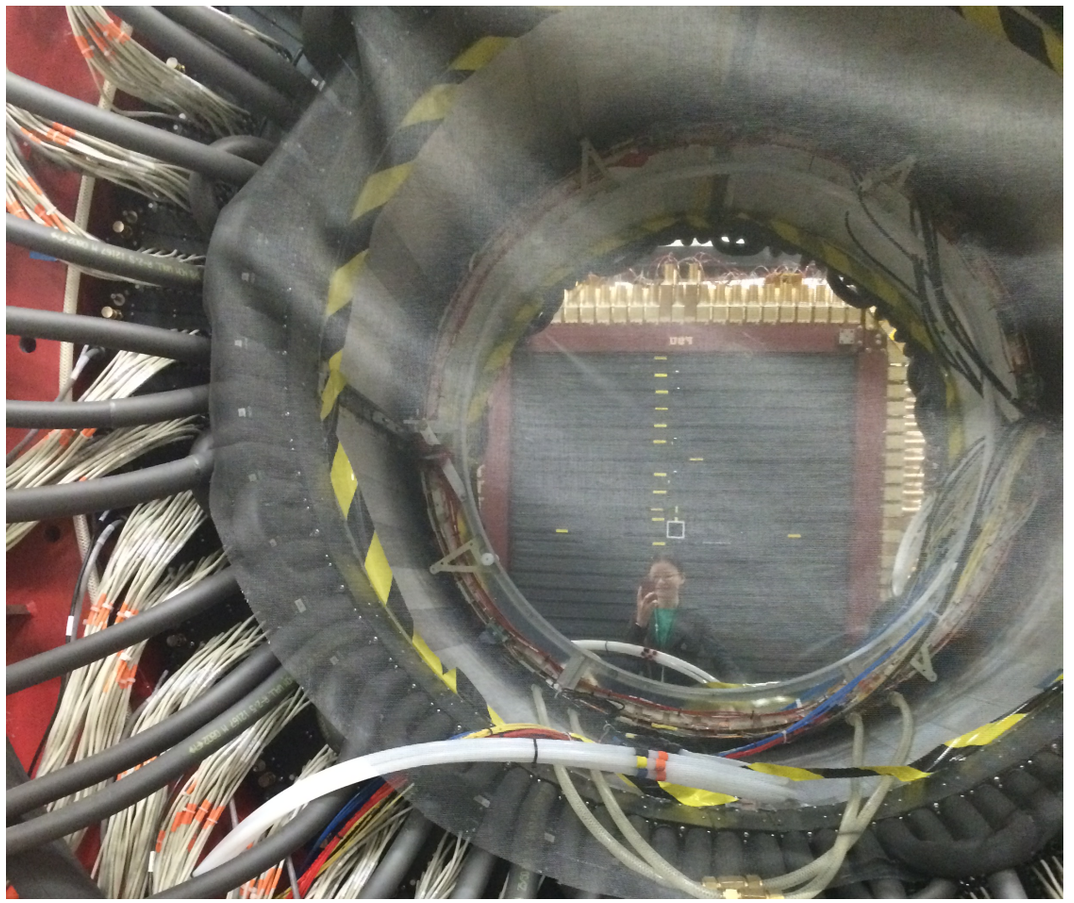
CDC and FDC

Straw tube drift chamber



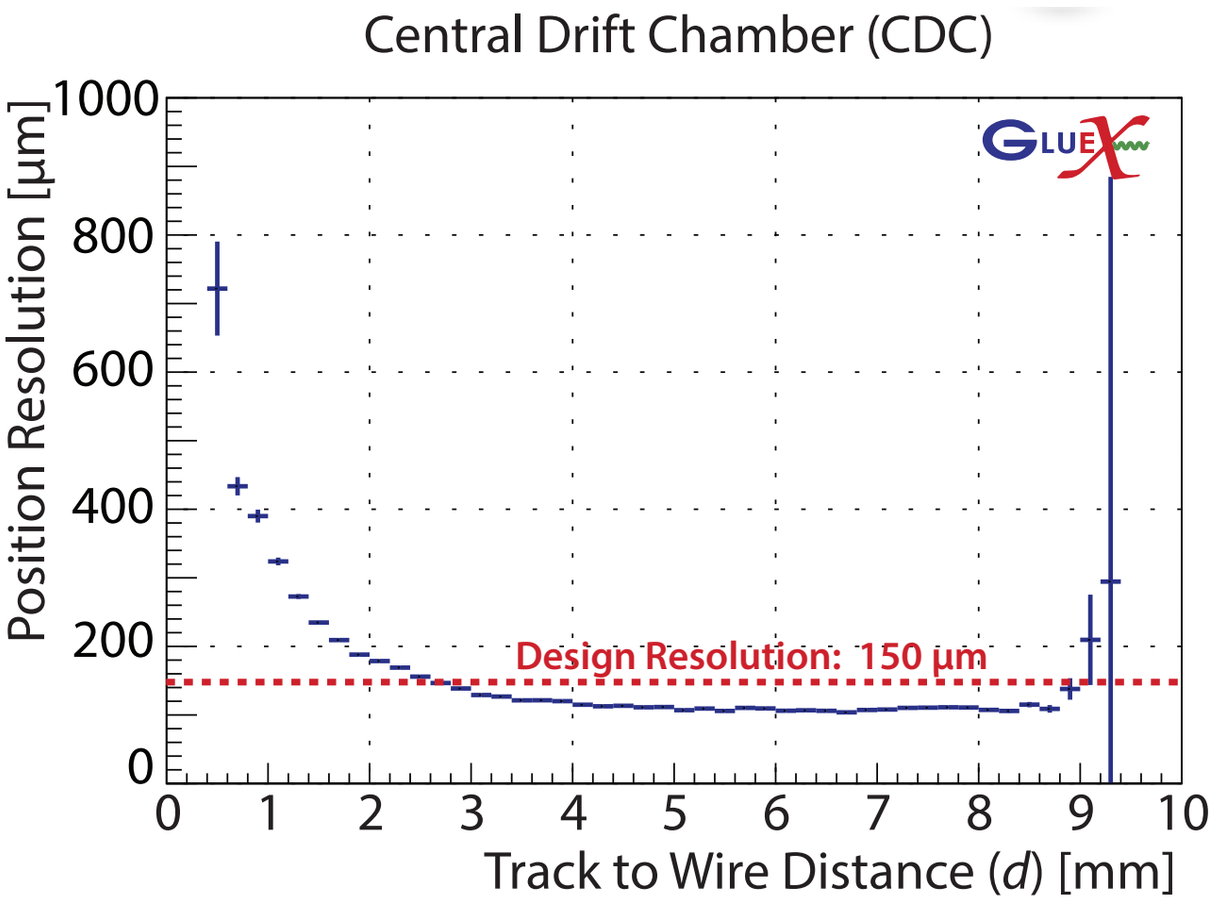
Interleaved planes of field/sense wires and planes of cathode strips

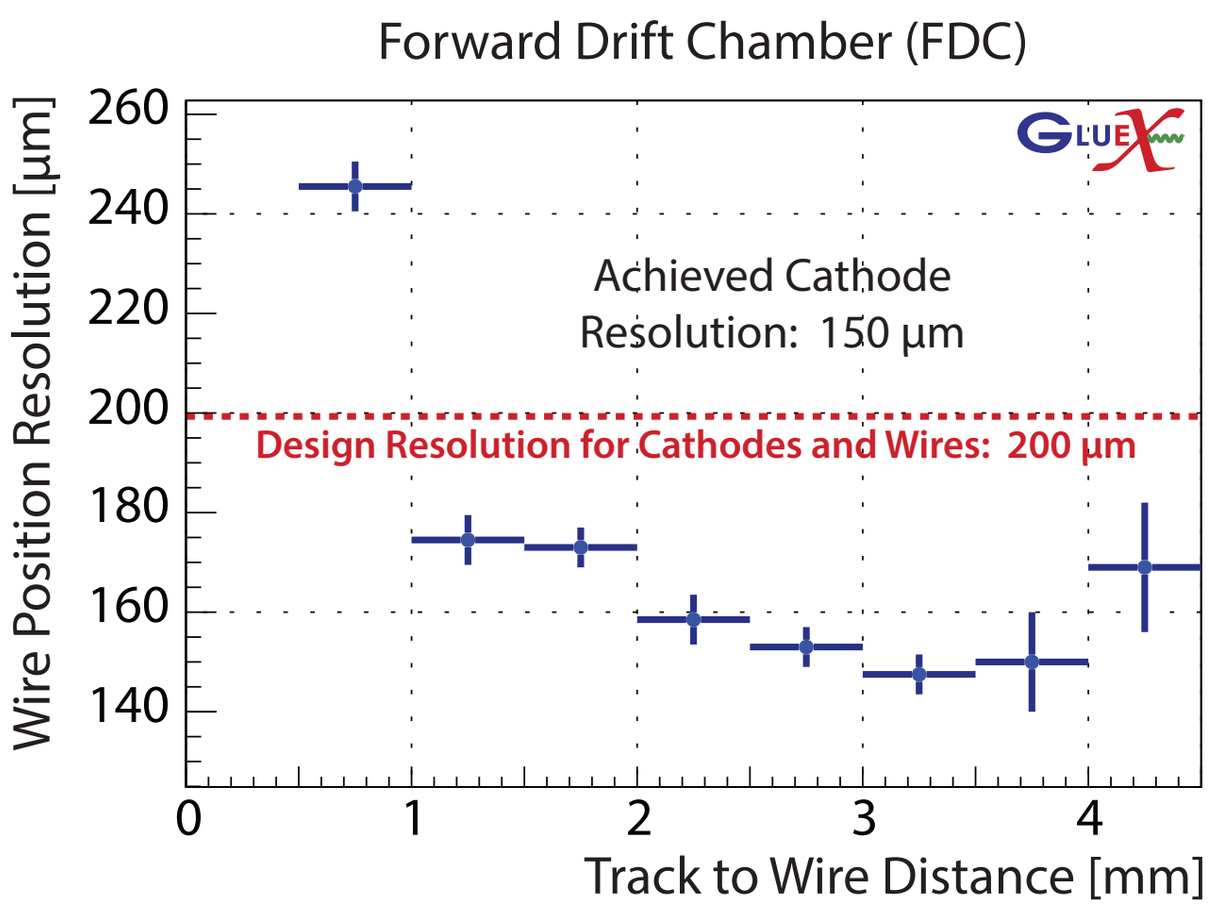




Detector Performance

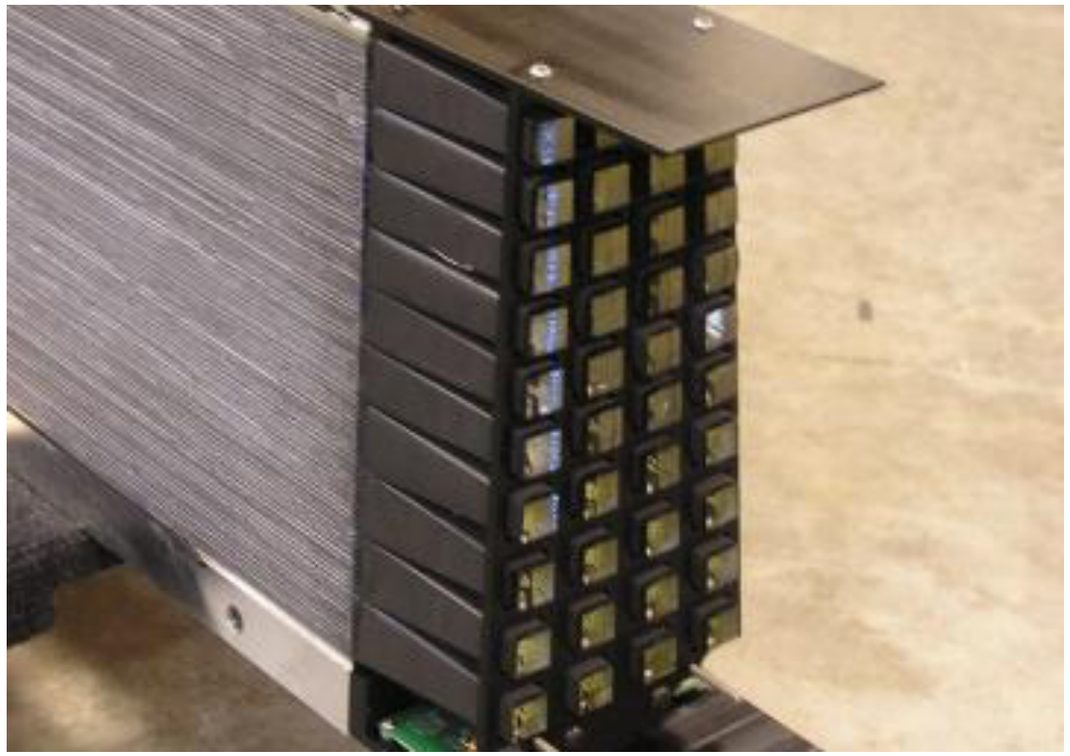
Drift chambers exceed design position resolution



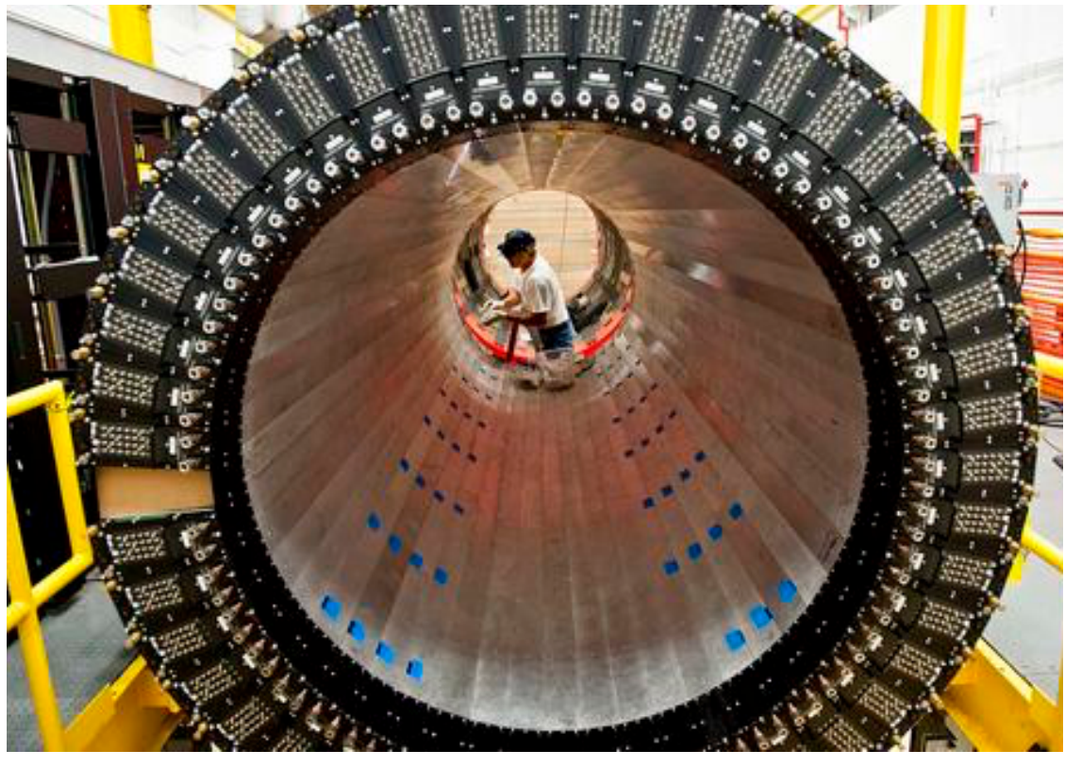


BCAL and FCAL

Scintillating fibers in the interstitial layers of lead



Fast silicon photomultipliers (SiPMs)

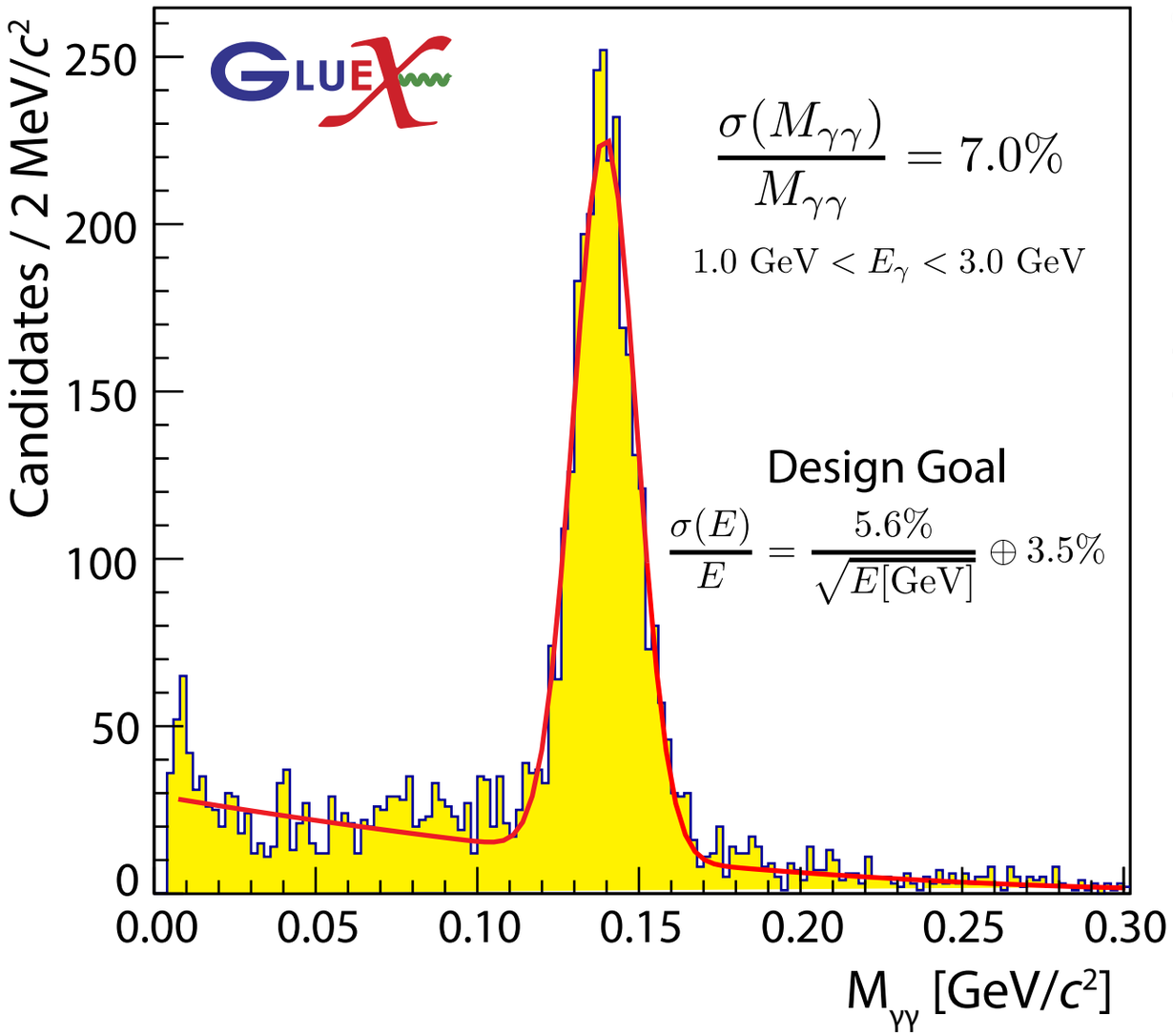


F8-00 lead glass, 4 × 4 × 45 cm

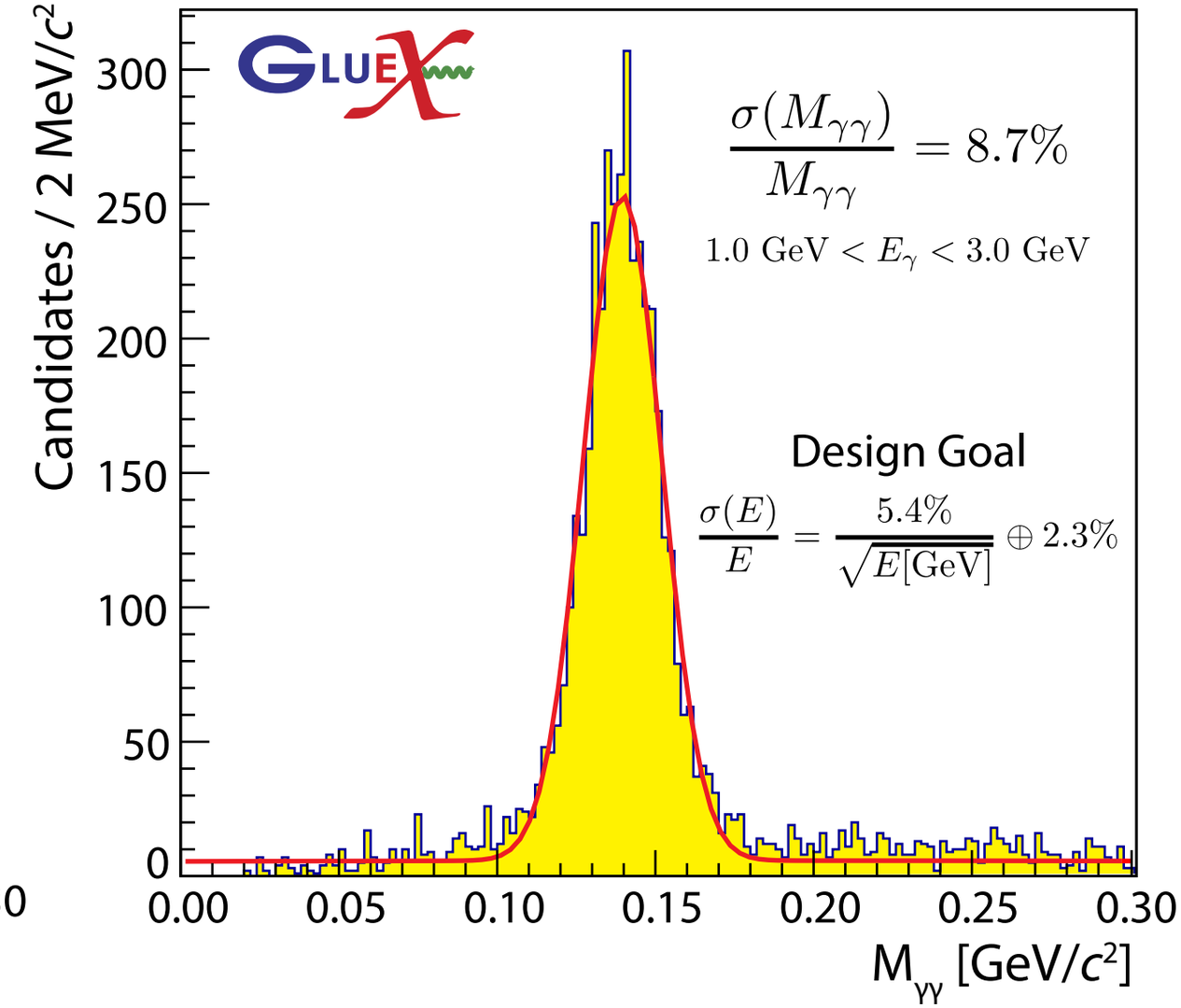
Detector Performance

Calorimeters approaching design energy resolution

Forward Lead Glass Calorimeter

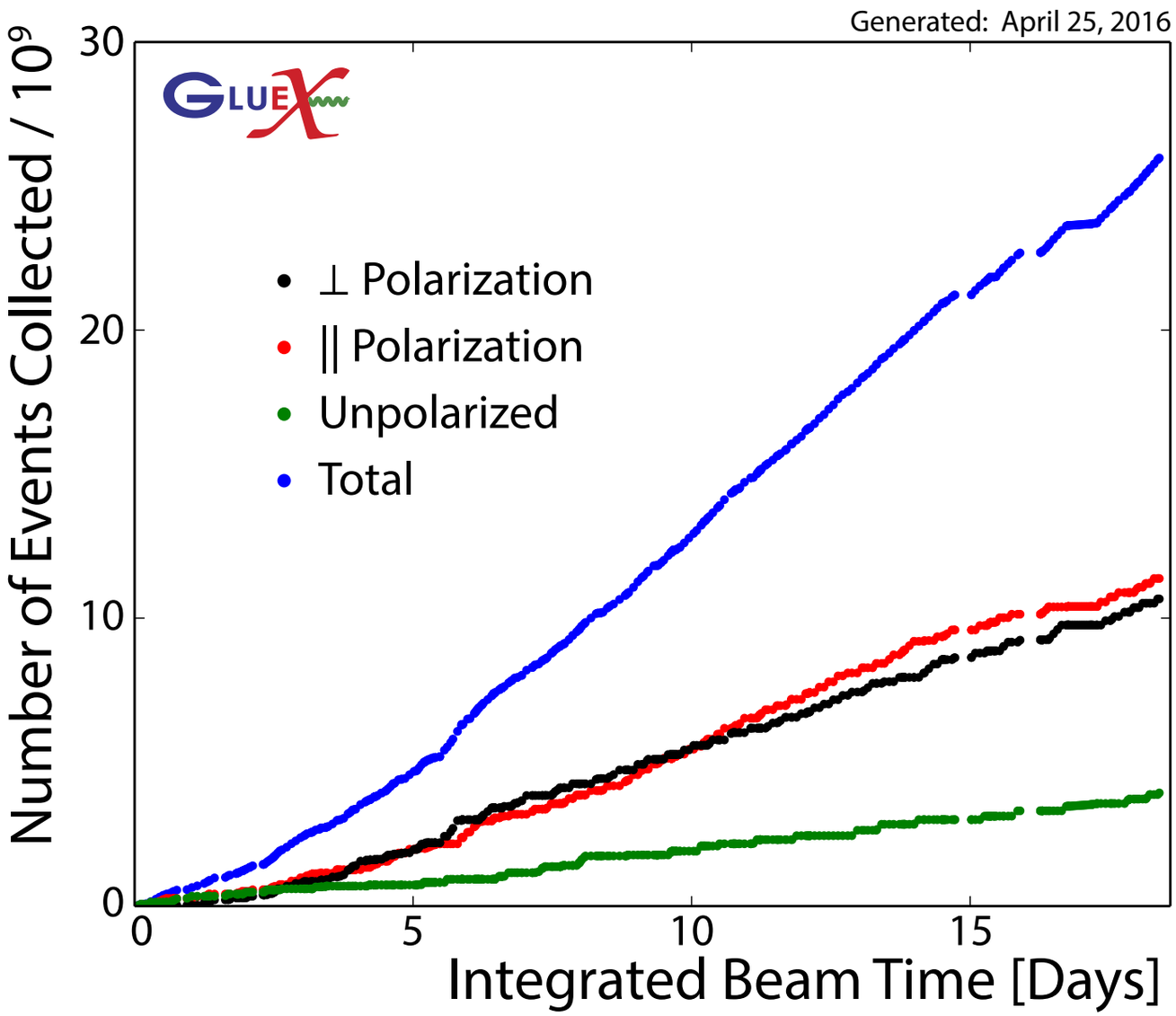


Barrel Lead-Scintillating Fiber Calorimeter



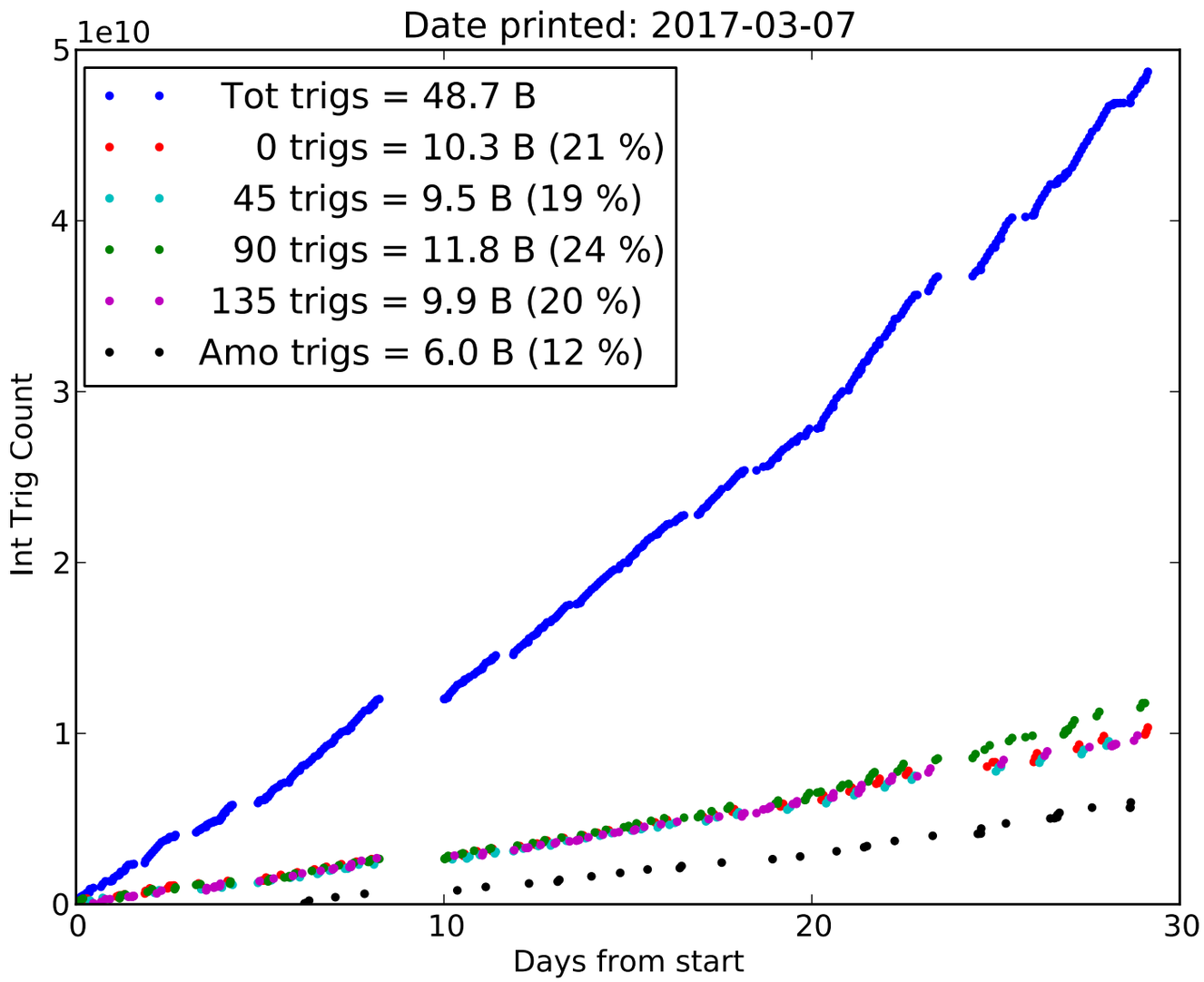
Spring 2016:

Detector commissioning and engineering runs



Initial physics data (≈ 80 h)
First results presented here

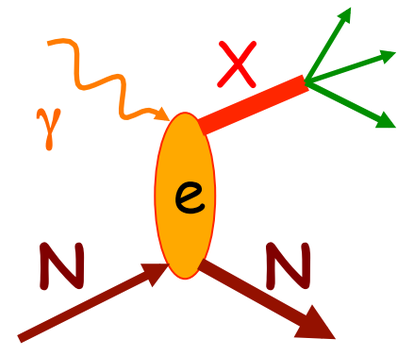
Spring 2017:
The first physics runs



GlueX-I [low-intensity]: 2017-18

Meson Photoproduction

- **Meson photoproduction: almost 50 years at SLAC, DESY, and Cambridge**
- **Growing vigorously recently： JLab, ELSA, and MAMI**
- **Understanding the properties of strong interaction in the nonperturbative regime**
- **Search for exotic hybrid mesons**
- **Provide constraints on “background” to baryon resonance extraction in the low energy regime**
- **Beam asymmetry Σ provides insight into dominant production mechanism**



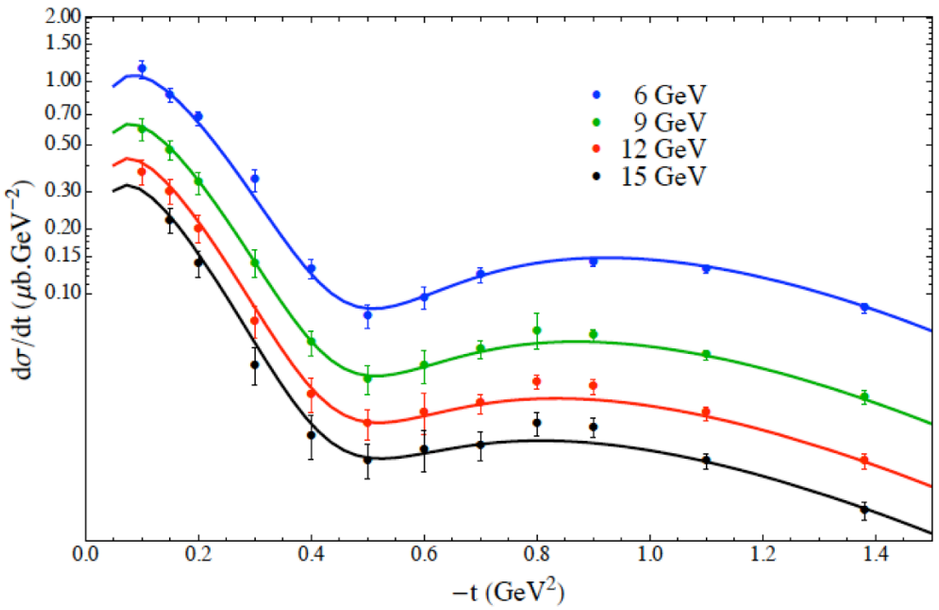
$\gamma \Leftrightarrow \rho, \omega, \phi$

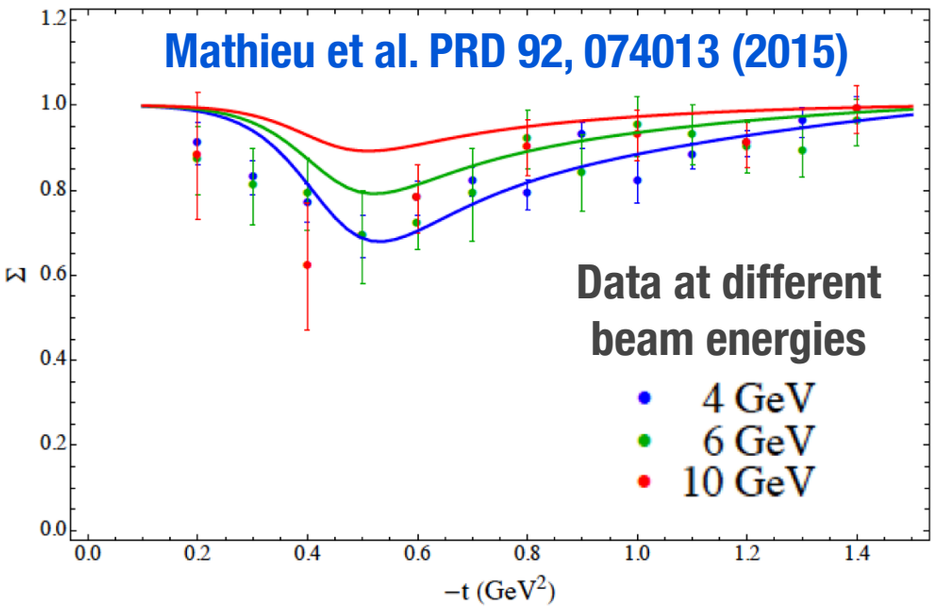
High-Energy Meson Photoproduction: VMD & Regge-cut phenomenology

GlueX & JPAC: Experiment & Theory

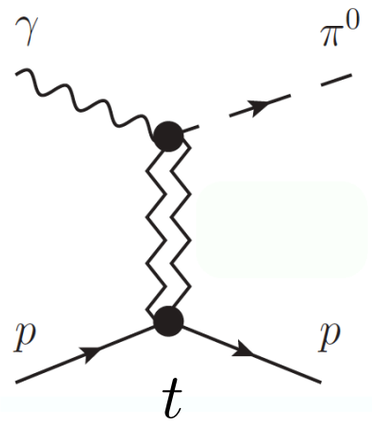
Psuedoscalar mesons π^0/η Photoproduction

JPAC Regge Model





SLAC: PRD 4, 1937 (1971)



Exchange J^{PC}

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

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

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

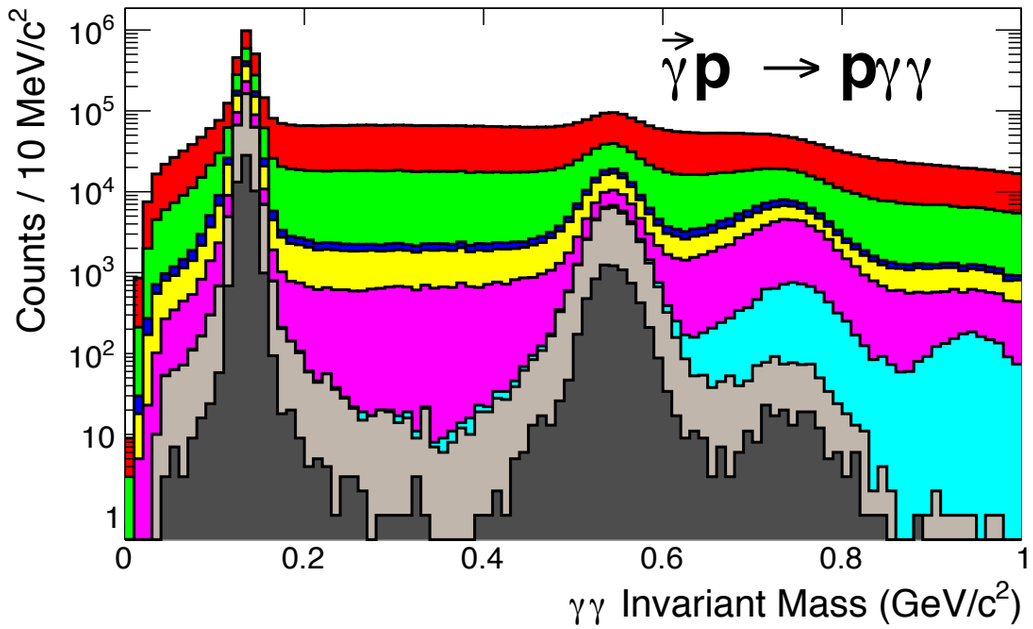
$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$

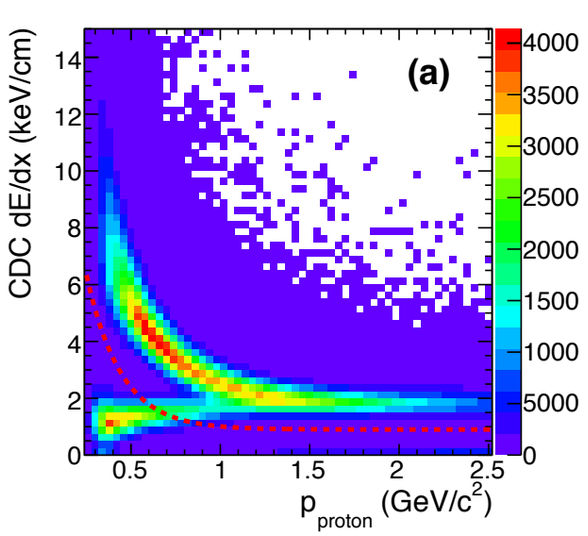
The high intensity, linearly polarized photon beam of GlueX/Hall D will provide important new constraints on Regge models

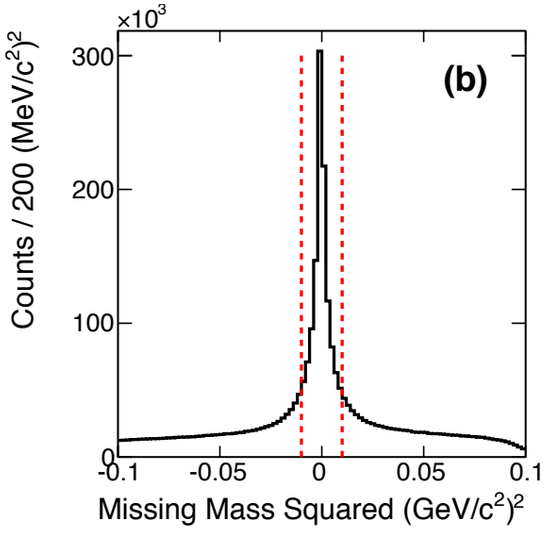
There are no previous measurements of the Σ asymmetry for $\gamma p \to \eta p$ with $E_\gamma > 3$ GeV

Event Selection

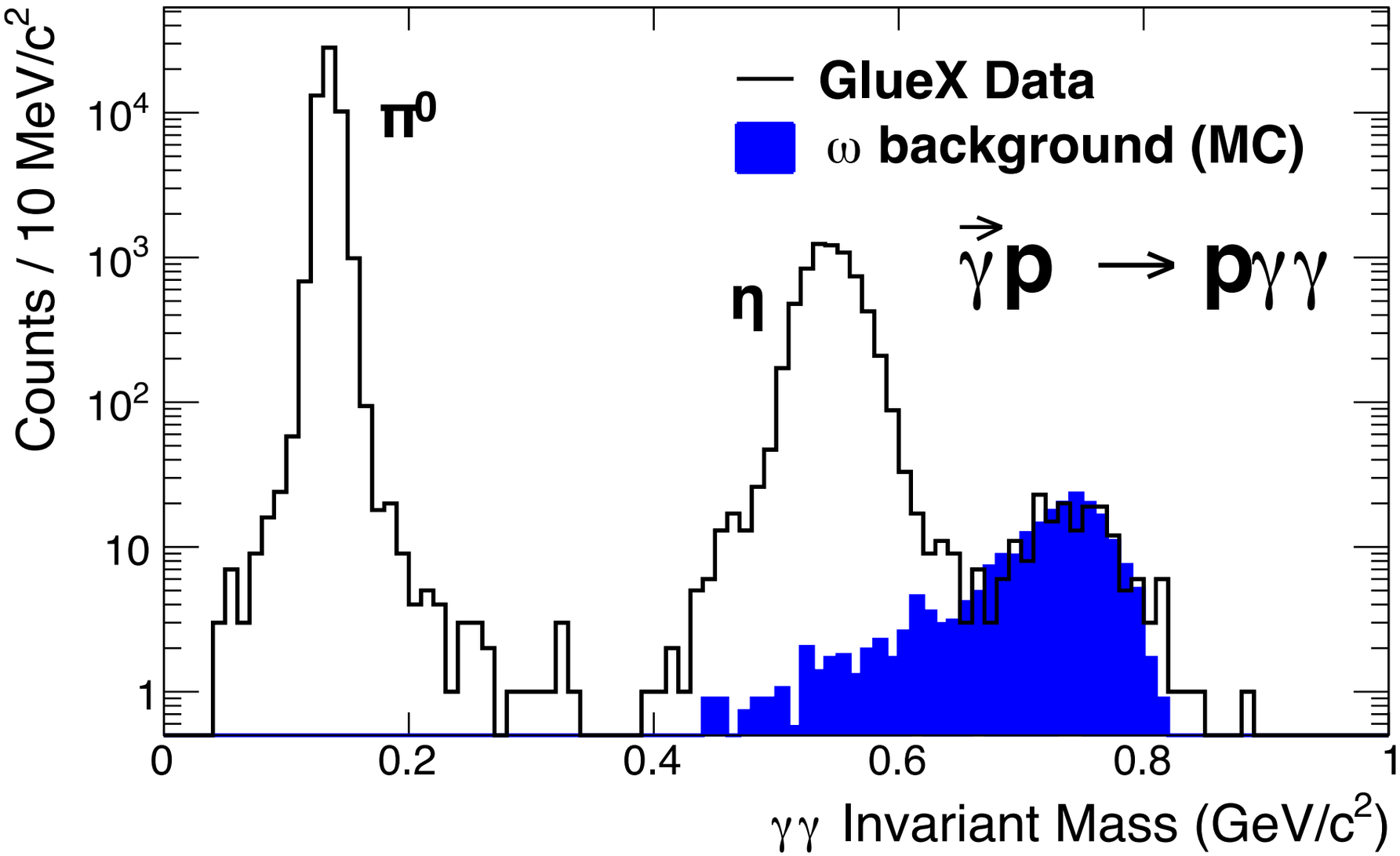
- **Loose timing cuts**
- **Proton requirements:**
  - **p_{proton} > 250 MeV**
  - **Originates from target region**
  - **CDC dE/dx contour**
- **γp→pγγ cuts**
  - **Δϕ, Missing Mass squared, Missing energy, beam energy (E_γ>4.0GeV), only two photons reconstructed, Missing mass off proton, coherent beam energy(8.4<E_γ<9.0GeV)**







ω Backgrounds

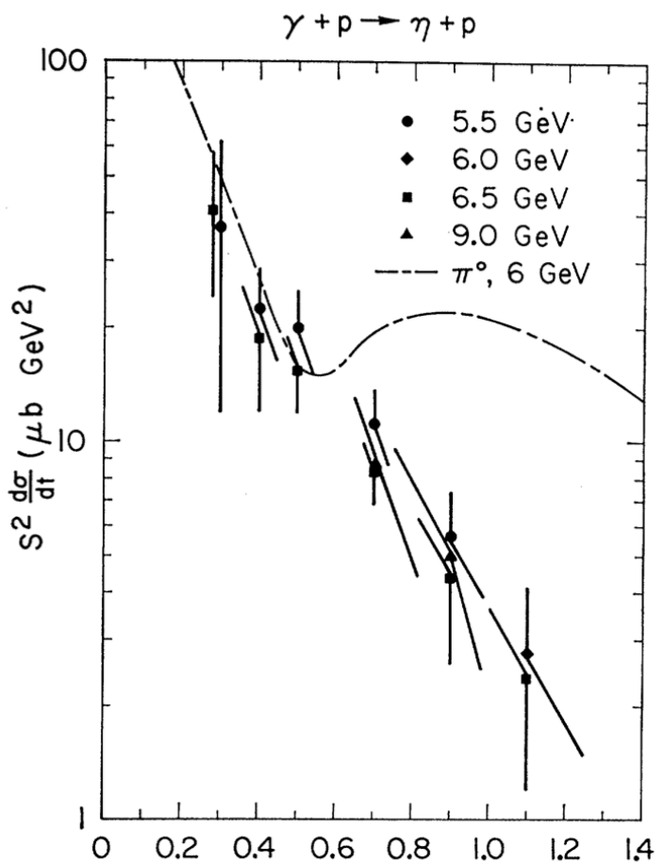


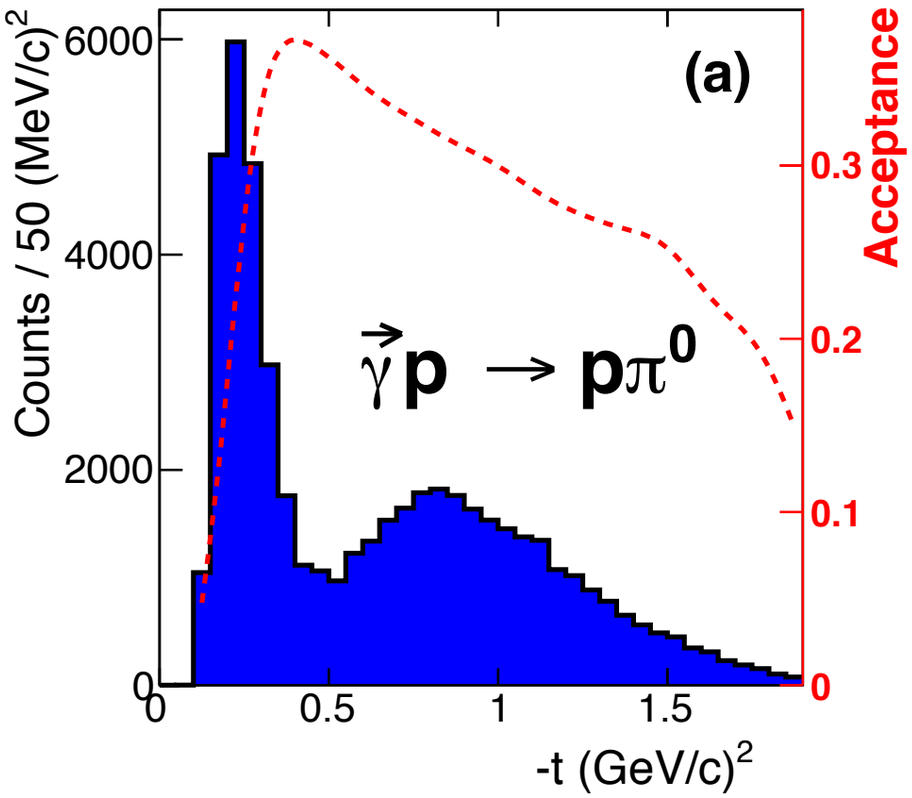
- **Continuum background between π^0 and η is negligible.**
- **The largest background is γp→ωp, ω→π^0γ with a missing photon. To get the background shape, we simulated this reaction then normalized to the ω leakage peak.**
- **Our exclusive measurements and cuts ensure very low backgrounds: for the eta the dilution is only 0.38%, while for the π^0 it is negligible.**

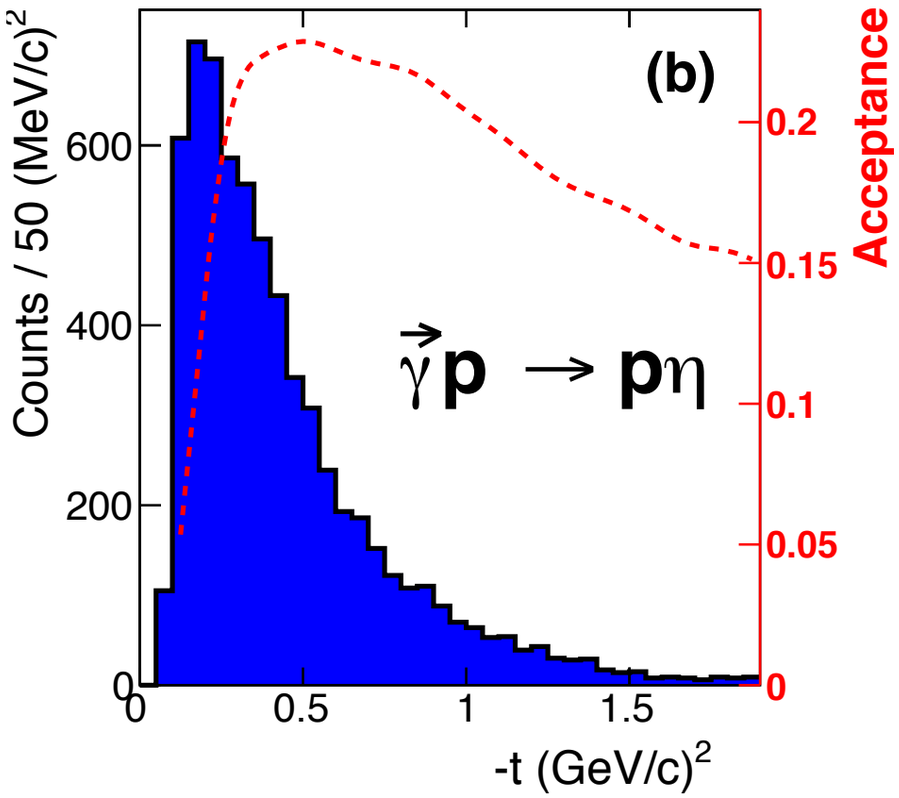
Final -t distributions

V. Mathieu (JPAC): PRD 92, 074013

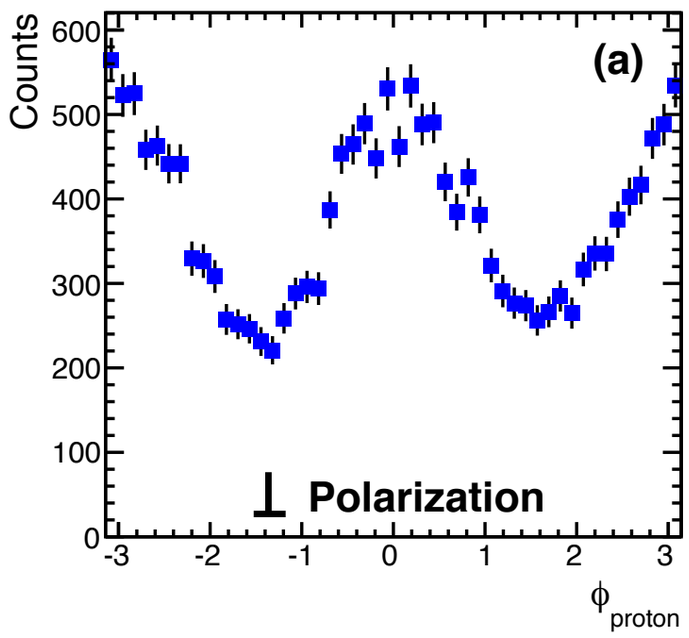
SLAC: PRD 1, 27 (1970)

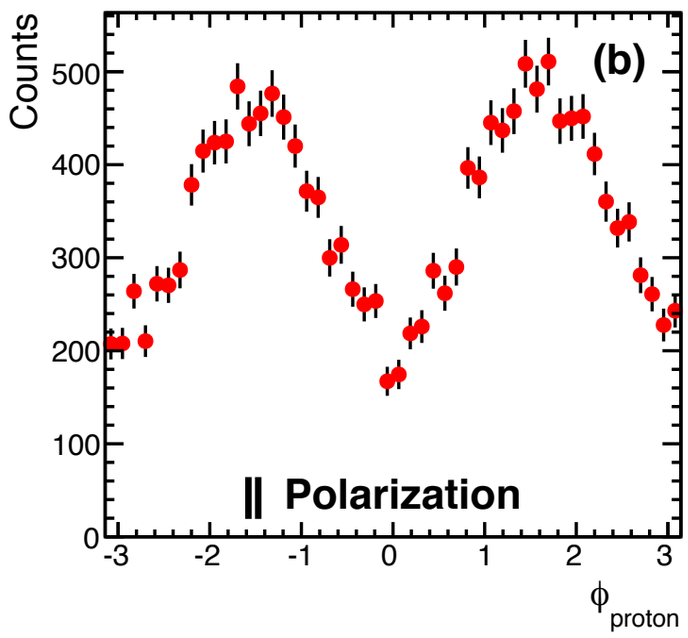


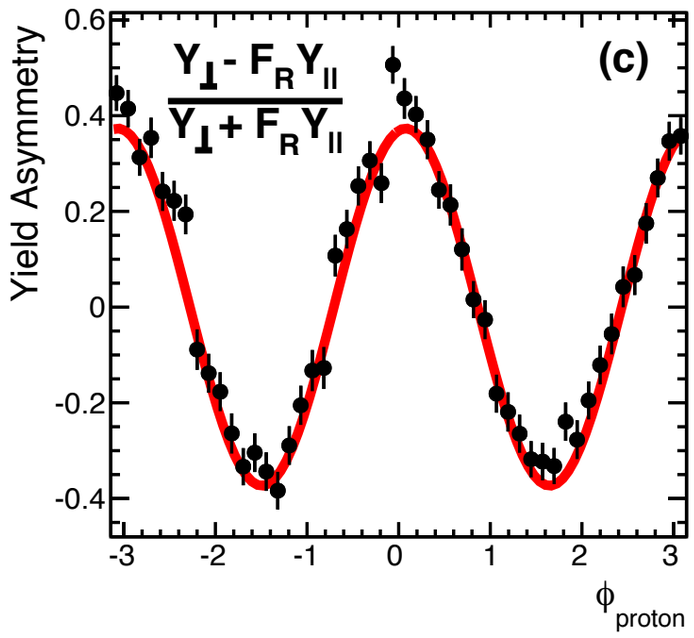




Beam Asymmetry: Method

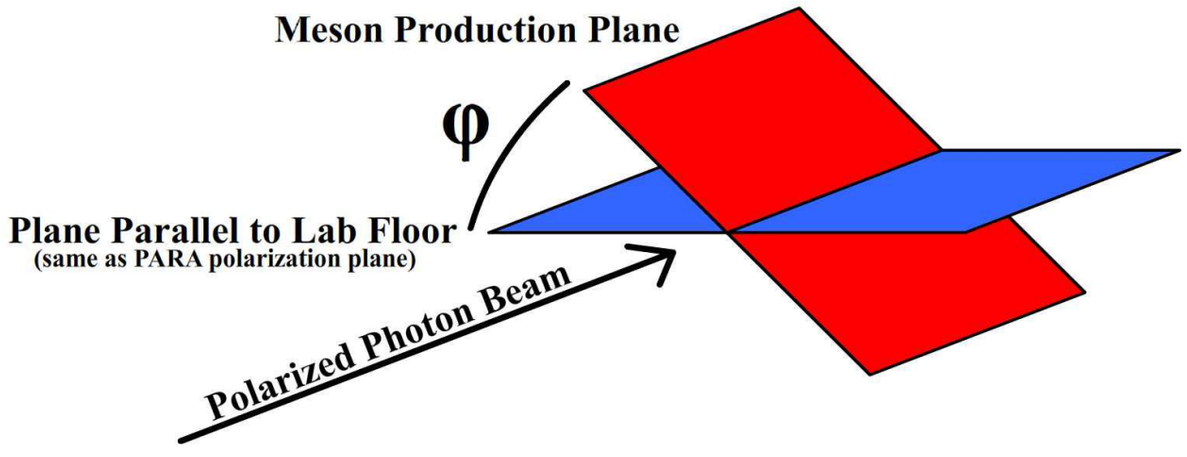




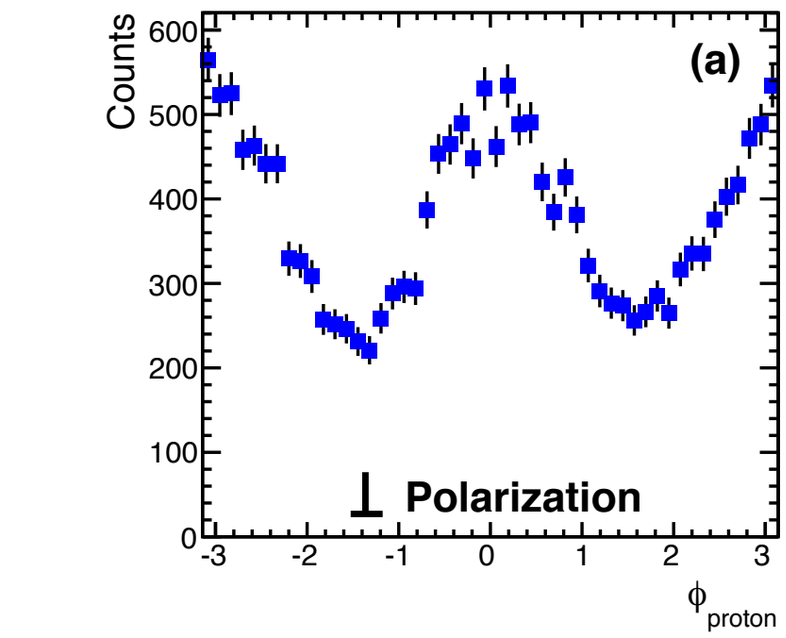


$$\frac{d\sigma}{d\phi_{\text{proton}}} \propto 1 - P\Sigma\cos 2(\,\phi_{\text{proton}} - \phi_\gamma\,)$$

$$Y_\perp \propto N_\perp(1 + P_\perp\Sigma\cos 2\phi_{\text{proton}})\ \ \phi_\gamma = 90^\circ$$
$$Y_\parallel \propto N_\parallel(1 - P_\parallel\Sigma\cos 2\phi_{\text{proton}})\ \ \phi_\gamma = 0^\circ$$



Beam Asymmetry: Method



$$Y_\perp \propto N_\perp(1 + P_\perp \Sigma \cos 2\phi_{\rm proton})\ \phi_\gamma = 90^\circ$$
$$Y_\parallel \propto N_\parallel(1 - P_\parallel \Sigma \cos 2\phi_{\rm proton})\ \ \phi_\gamma = 0^\circ$$

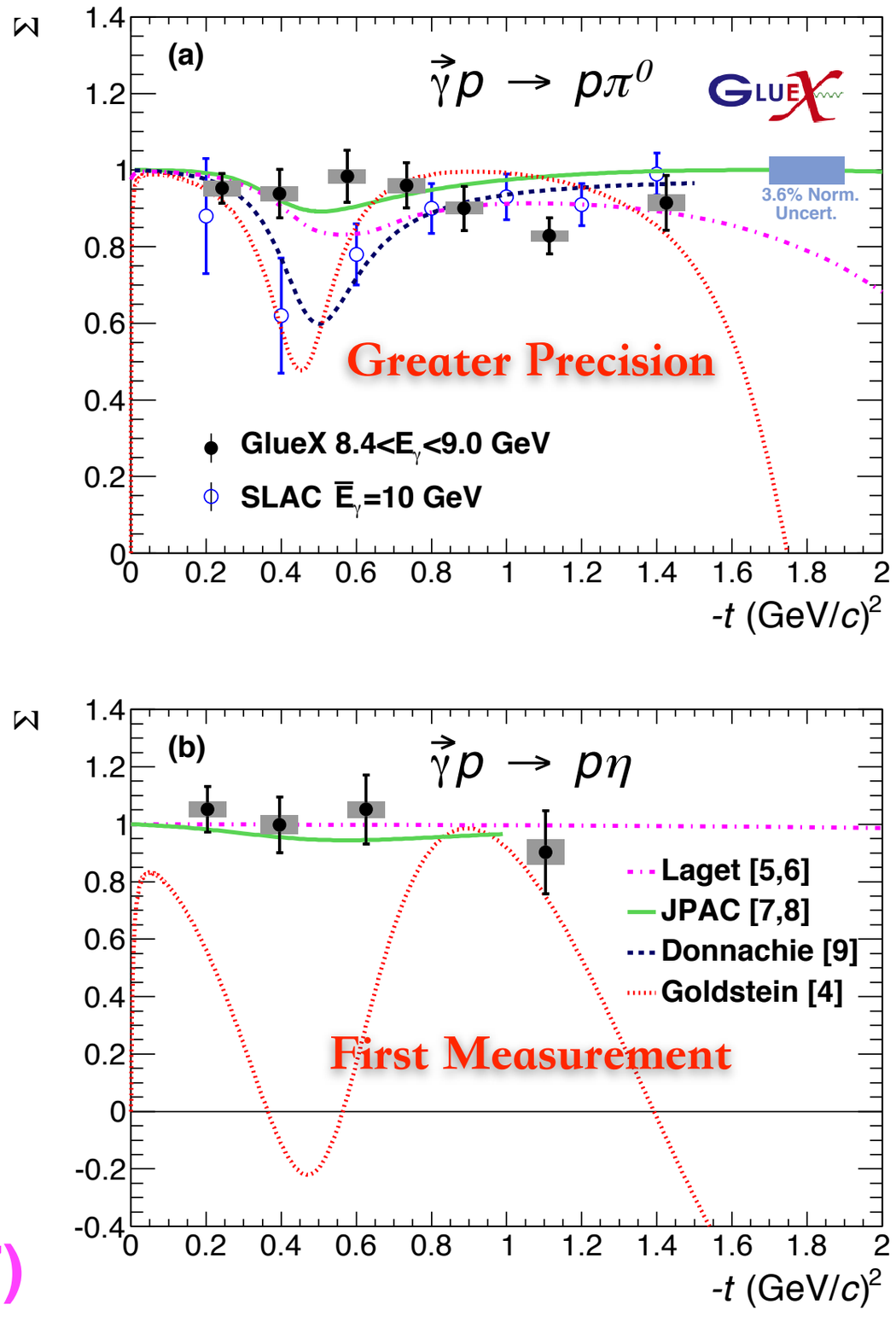
$$\frac{\boldsymbol{Y_\perp - F_R Y_\parallel}}{\boldsymbol{Y_\perp + F_R Y_\parallel}} = \frac{\boldsymbol{(P_\perp + P_\parallel)\Sigma \cos 2\phi_{\rm proton}}}{\boldsymbol{2 - (P_\perp - P_\parallel)\Sigma \cos 2\phi_{\rm proton}}}$$

Repeat in bins of -t for both π^0 and η

$$\boldsymbol{F_R = \frac{N_\perp}{N_\parallel}}$$

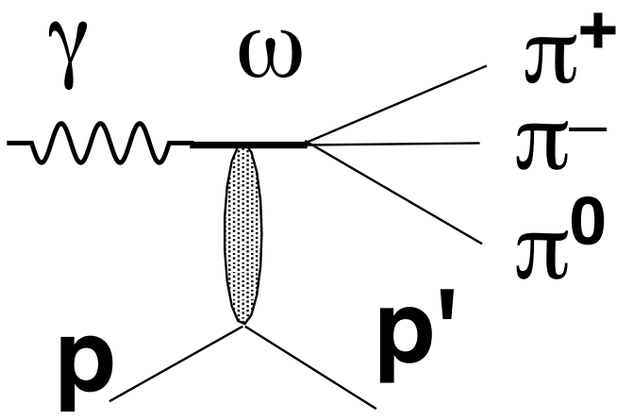
Beam Asymmetry: Results

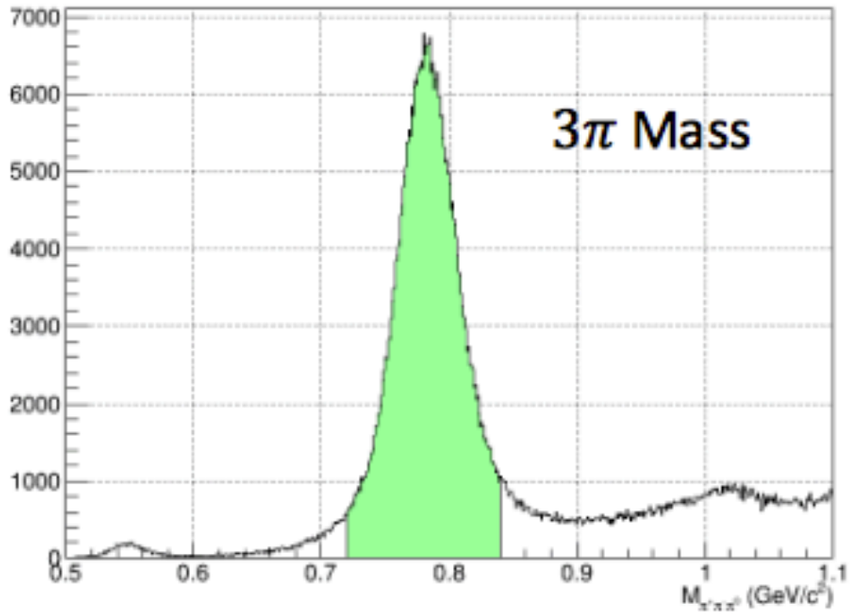
- **Measured asymmetries consistent with previous SLAC data**
- **Our measured Σ asymmetries are close to 1, with little evidence of -t dependence**
- **Don't observe prominent dip in beam asymmetry at -t = 0.5 (GeV/c)^2 as seen in the cross section**
- **Our data are somewhat consistent with the JPAC and Laget calculations**

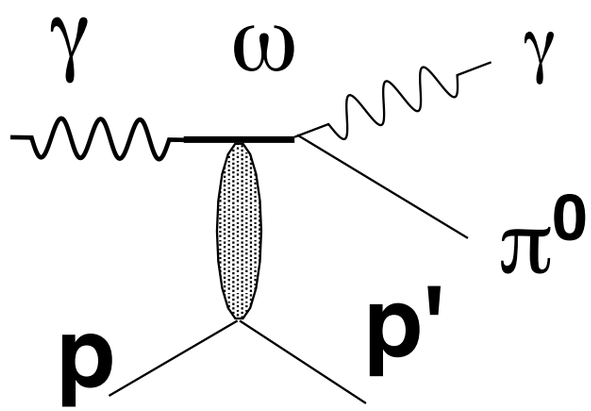


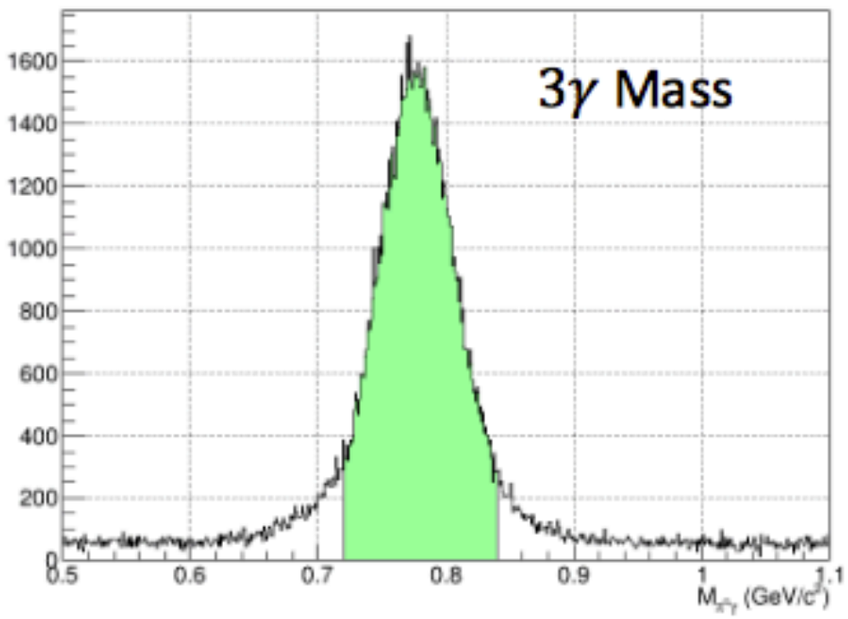
PHYS REV C 95, 042201(R) (2017)

Vector meson ω Photoproduction



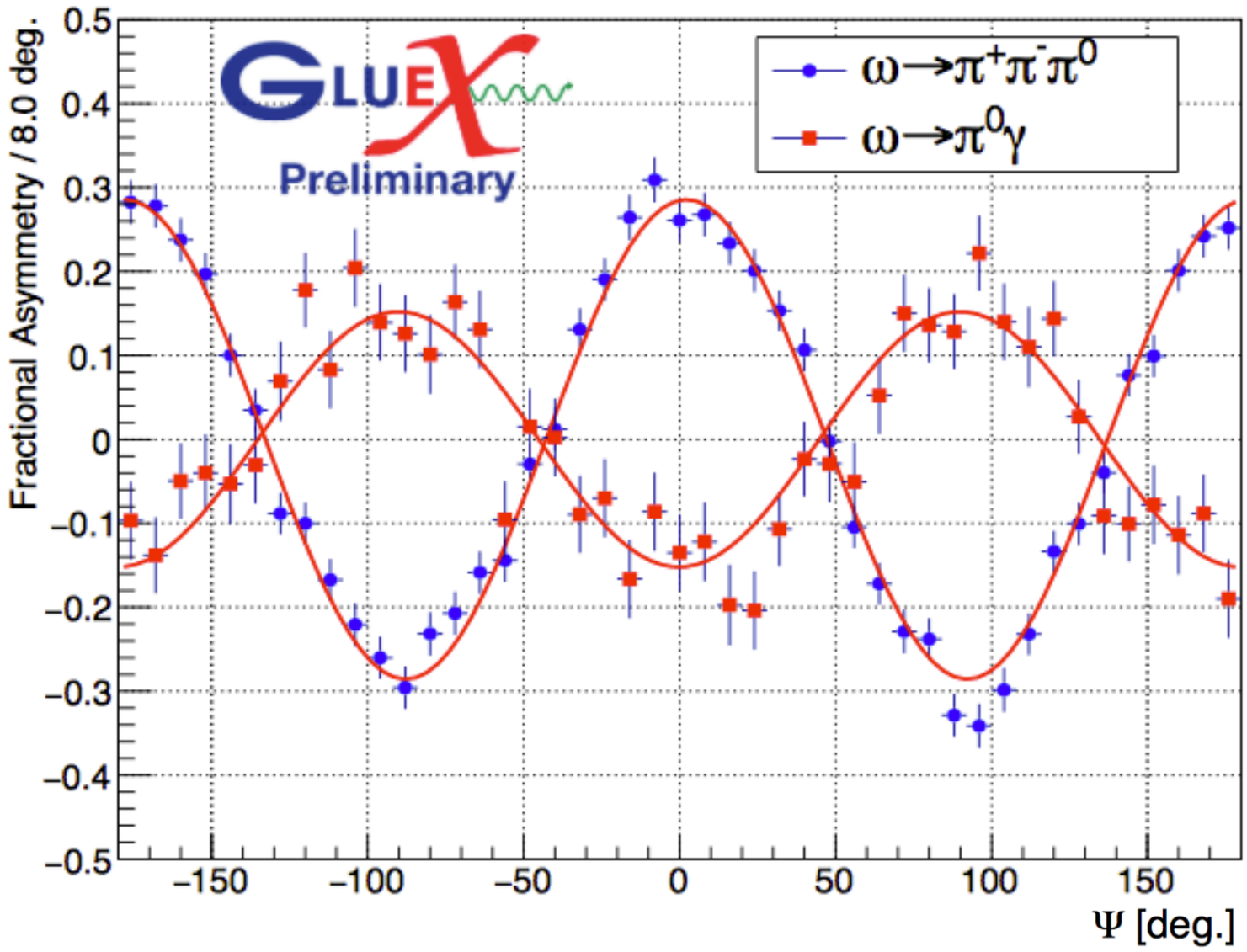






Vector meson ω Photoproduction

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



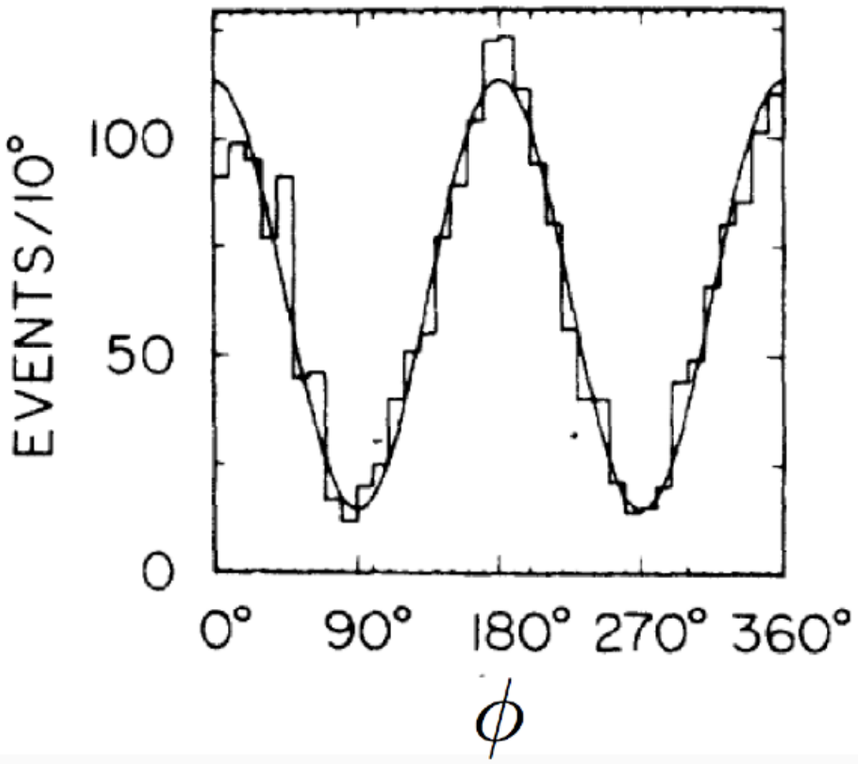
Expected:

Σ(π⁺ π⁻ π⁰) / Σ(π⁰ γ) = –2

Measured:

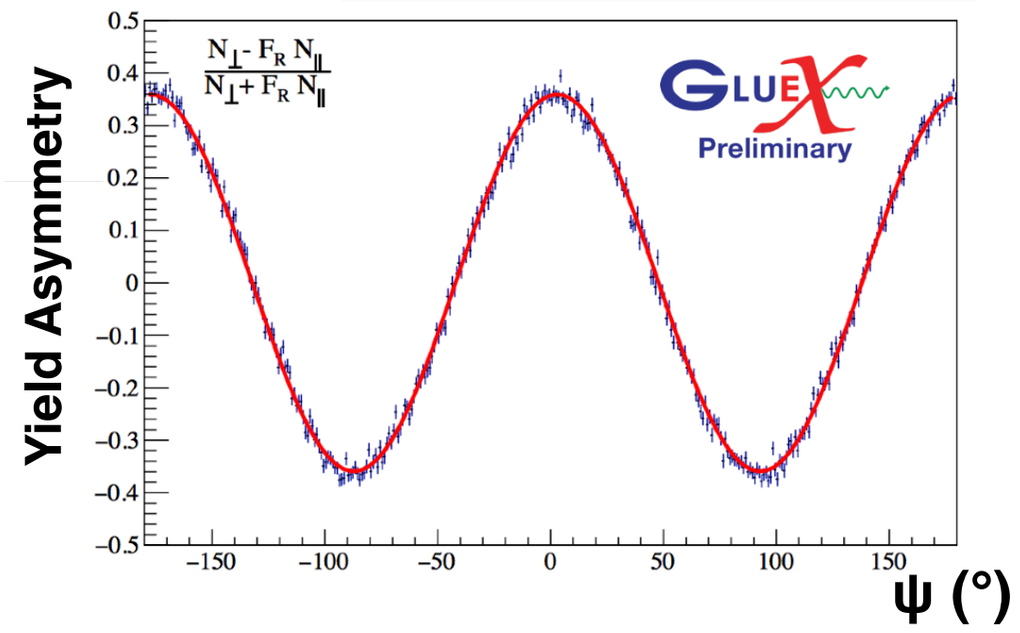
Σ(π⁺ π⁻ π⁰) / Σ(π⁰ γ) = –1.88 ± 0.13

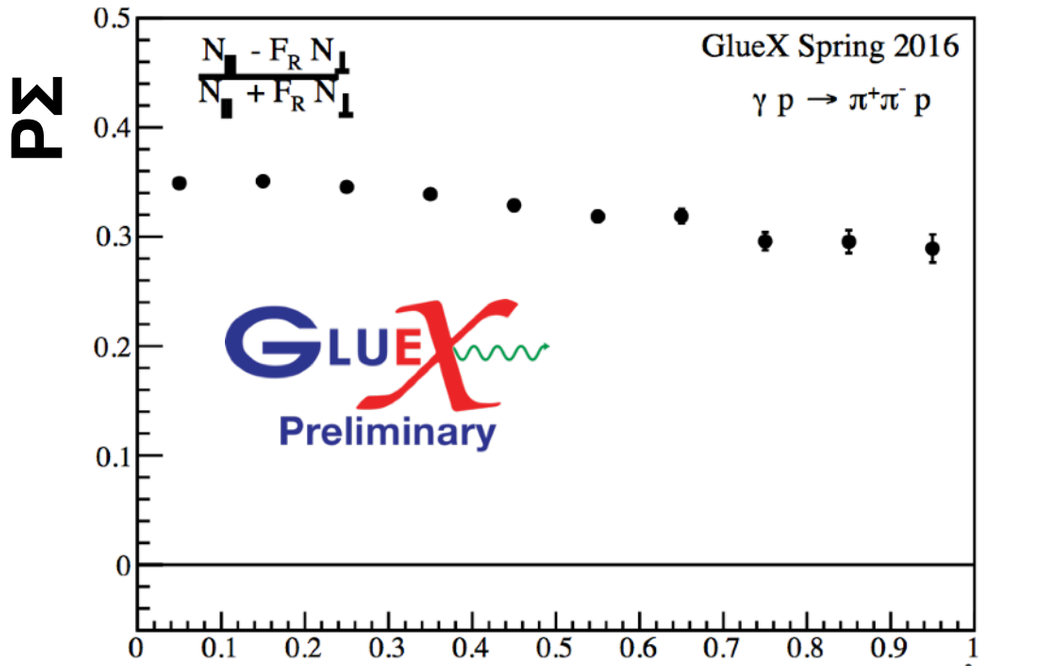
ρ Photoproduction



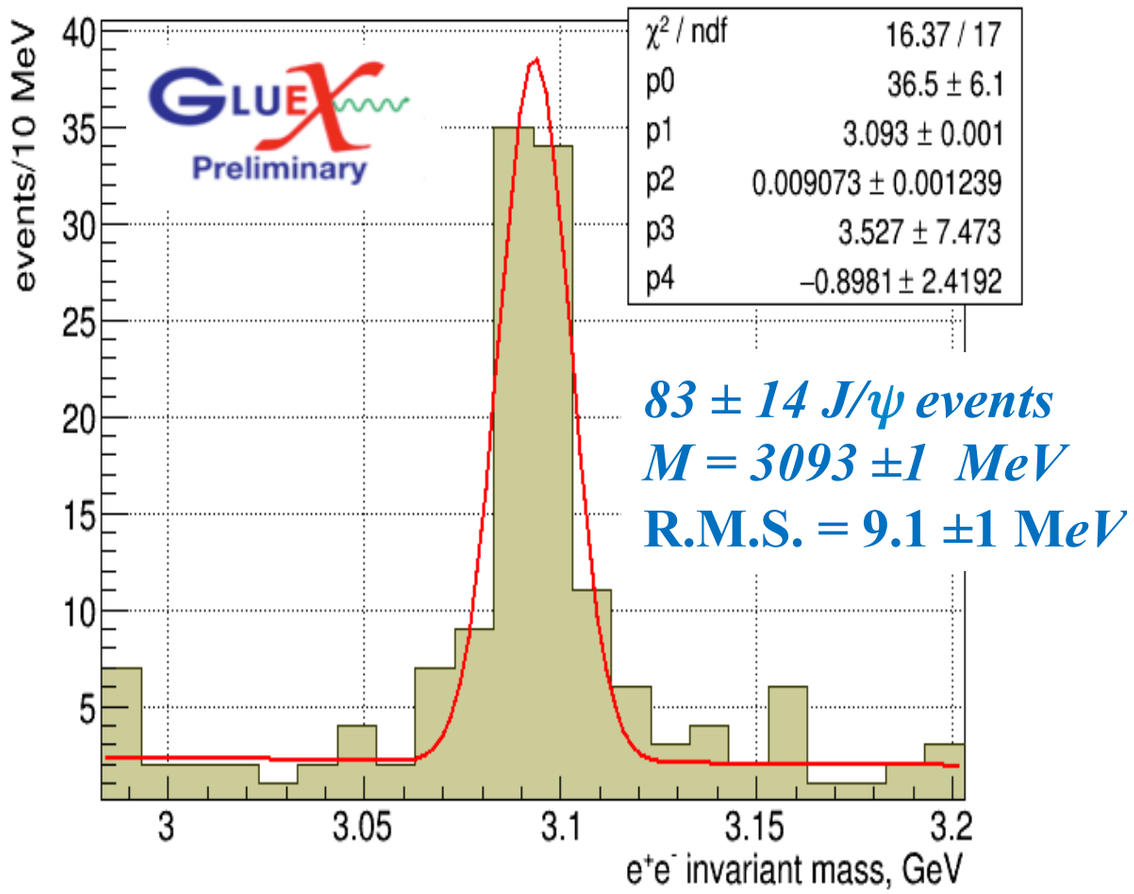
J. Ballam et al., PRD 7, 3150 (1973)

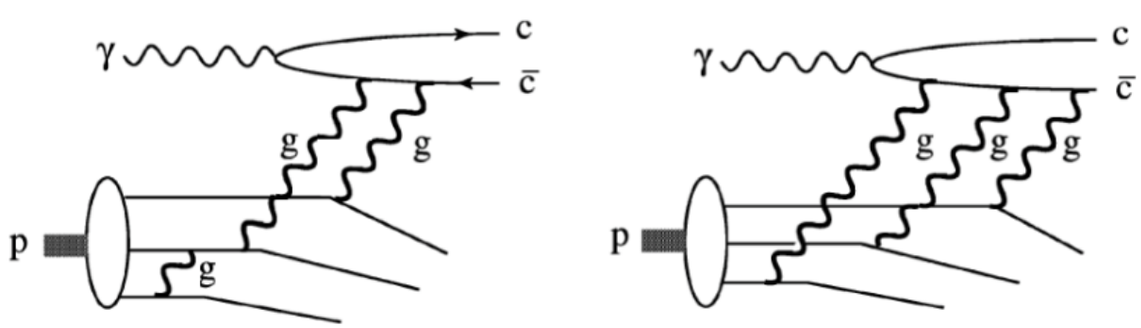
Full analysis of angular distributions is under way.

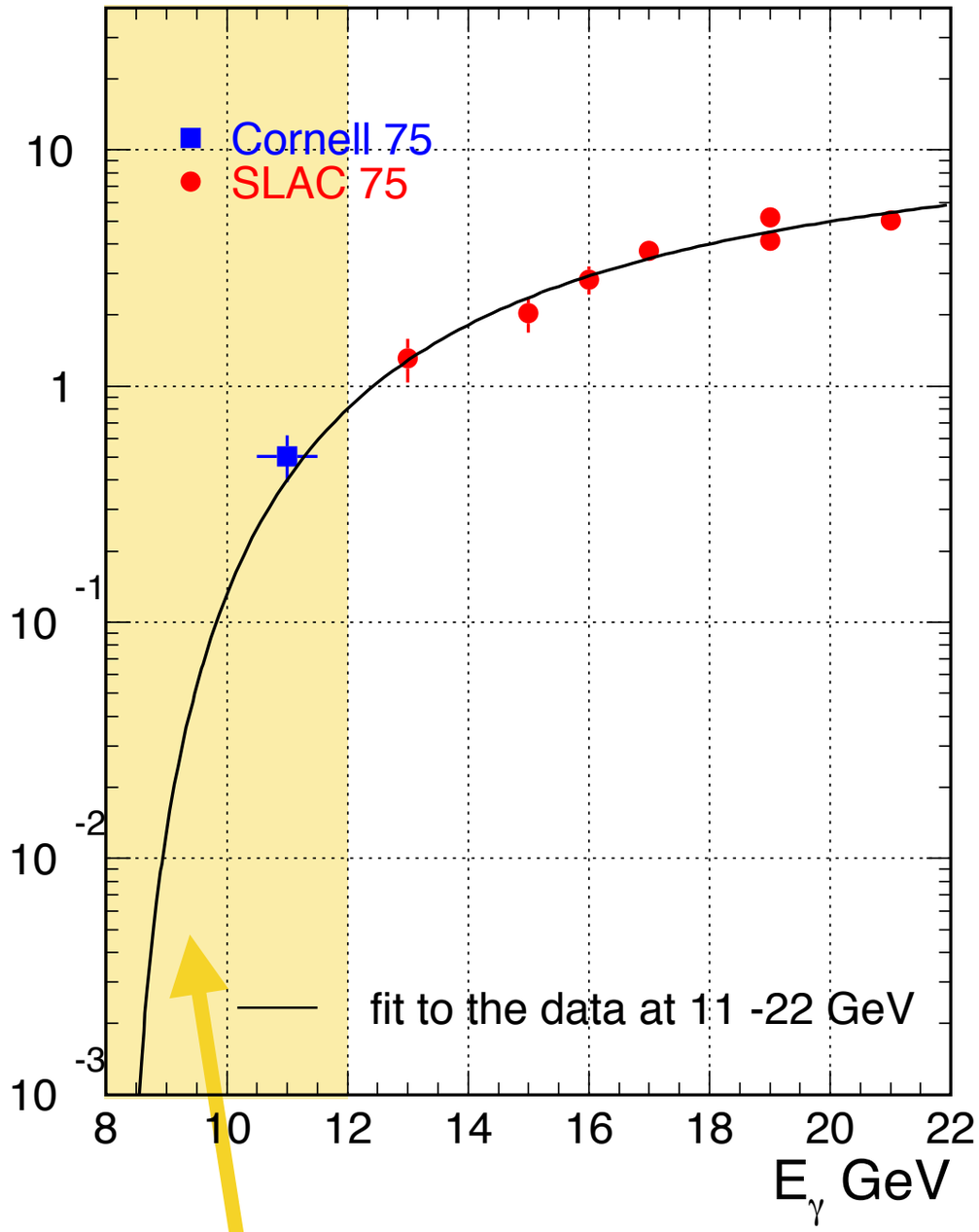




J/Ψ Photoproduction near threshold

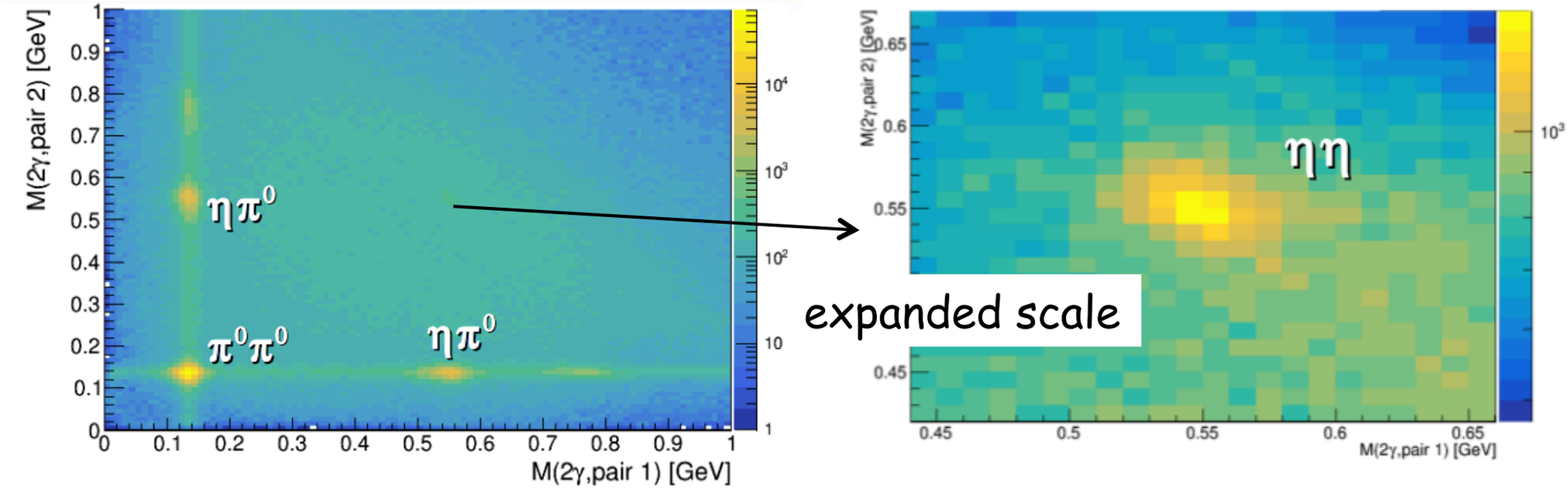


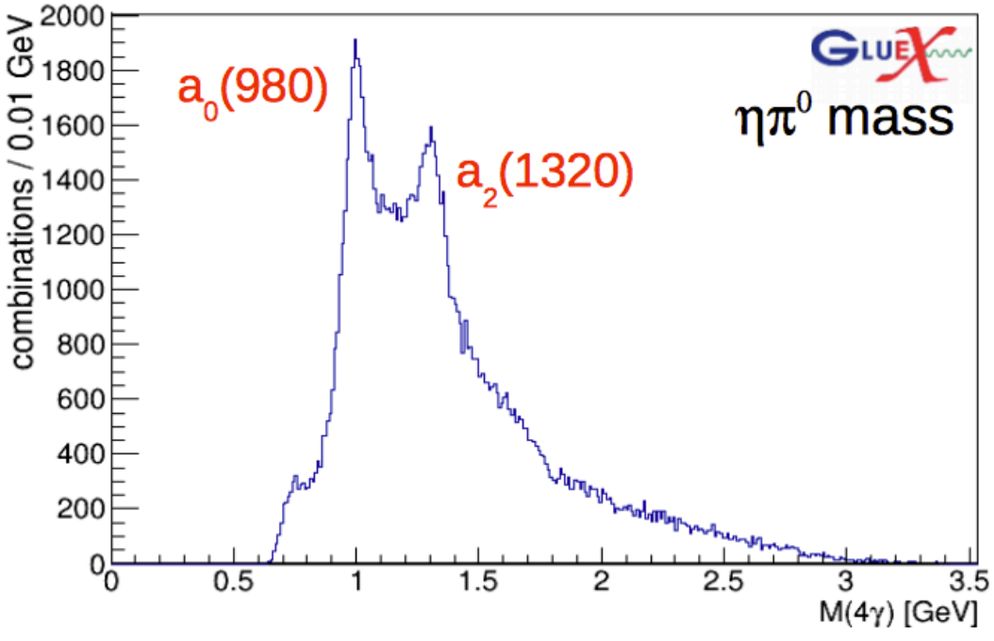


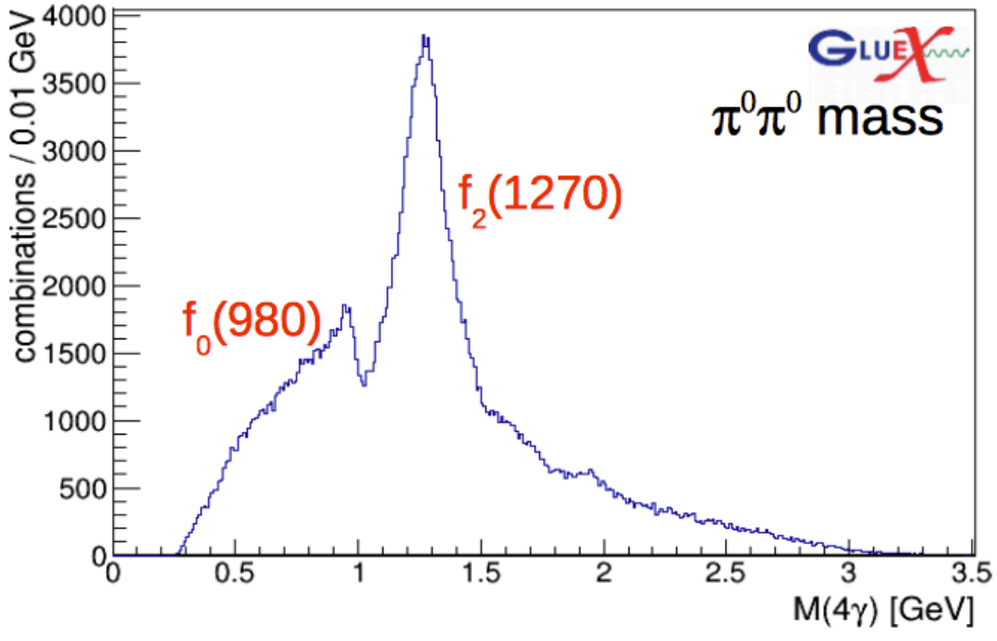


GlueX Energy Range

Four photon final states
scalar and tensor mesons Photoproduction







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

Summary and Outlook

- GlueX is installed, commissioned and all detector systems are exceed or near design specifications.

- The engineering and the first physics runs have been taken successfully.

- The linearly polarized photon beam asymmetry Σ for π^0/η photoproduction have measured. A broad meson photoproduction project is under way, including beam asymmetries, cross sections and spin density matrix elements analysis.

- DIRC detector for enhanced π/K separation 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.

- The broader program of exotic mesons is in sight. New ideas and new collaborators are welcome.

Thanks!