The current status and some future plans at GlueX

Zhenyu Zhang Wuhan University
for the GlueX Collaboration

Topical Workshop on Parton Distributions on Modern Era
Peking University, Beijing, China
2017. 7. 14

武漢大學 WUHAN UNIVERSITY

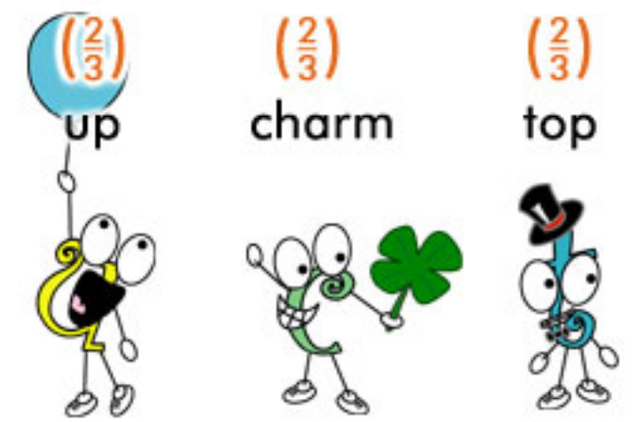
Jefferson Lab GLUEX

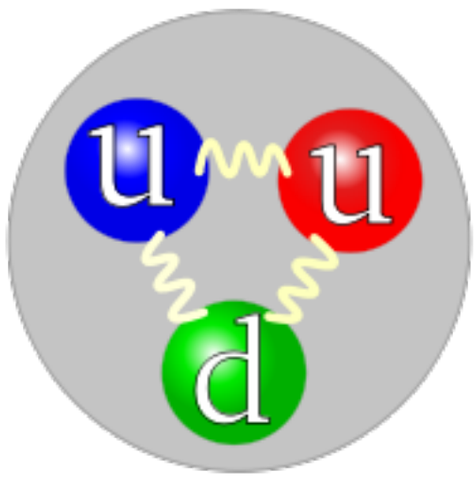
OUTLINE

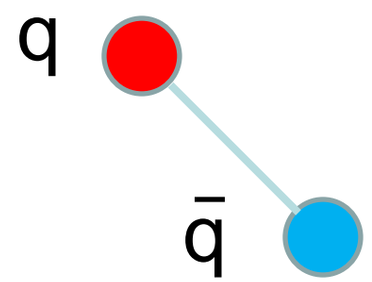
- Introduction
- GlueX experiment and performance
- Meson photoproduction at GlueX
- Future plans and outlook

Hadron Physics and Quark Model

Quarks







Baryons **Mesons**

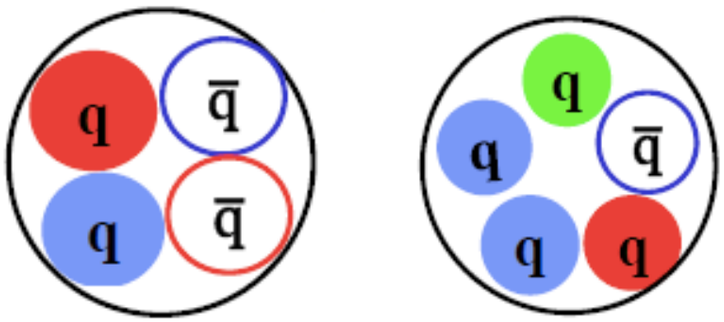
Ordinary hadrons

QCD Exotic States

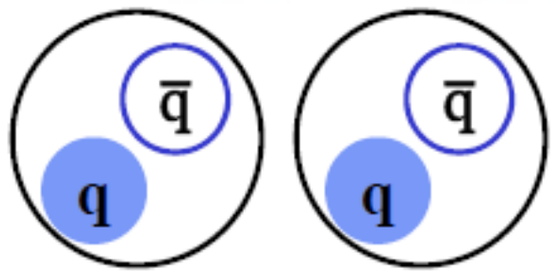
Multi-quark states **Hadron modular states**

- In 1964, Gell-Mann's original paper alludes to the possibility of exotic hadrons
- 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
- A number of exotic states candidates are found in recent years

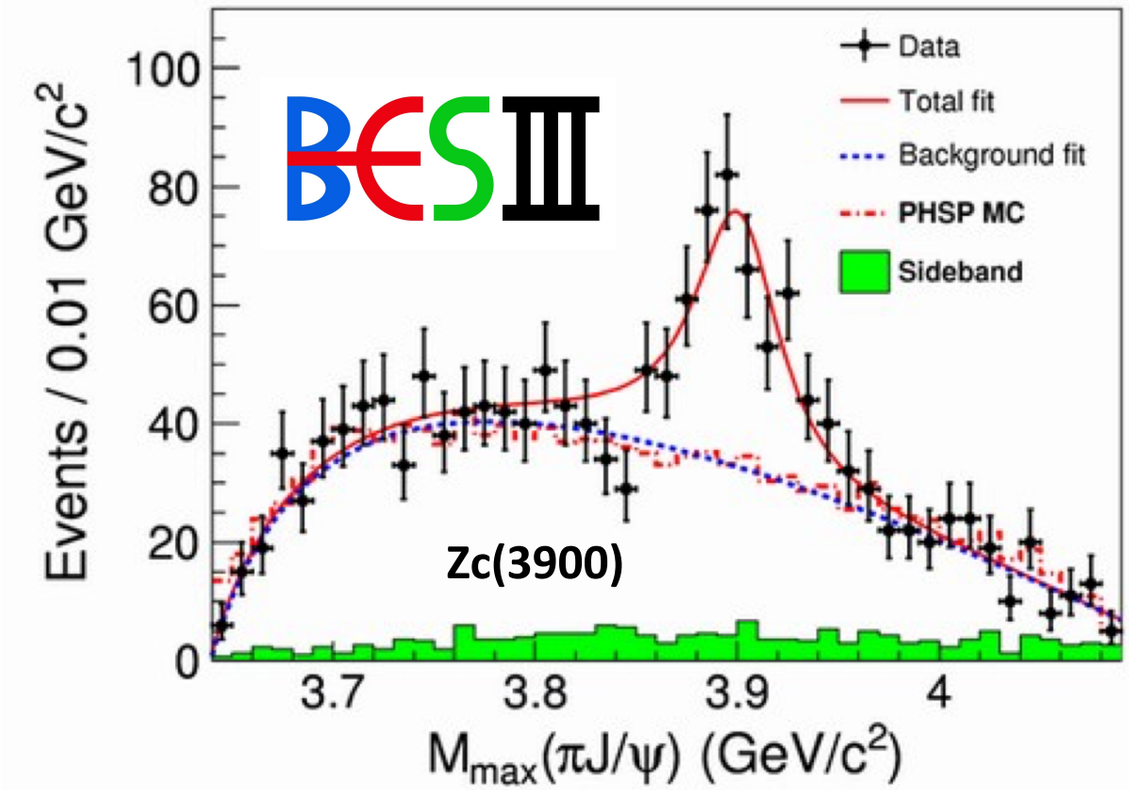
QCD Exotic States

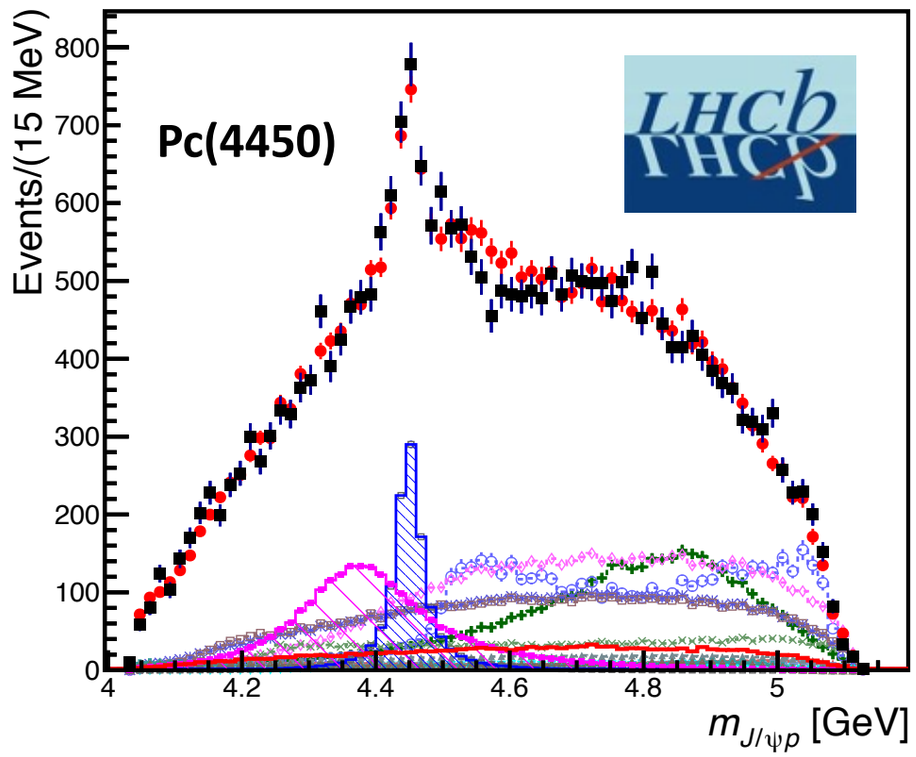


Multi-quark states

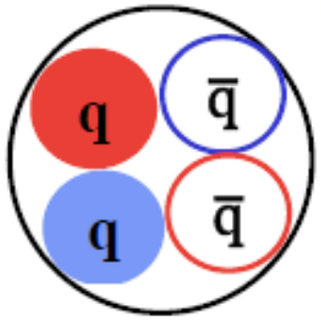


Hadron modular states

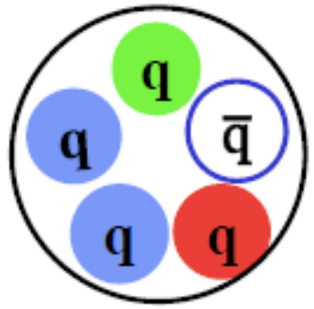


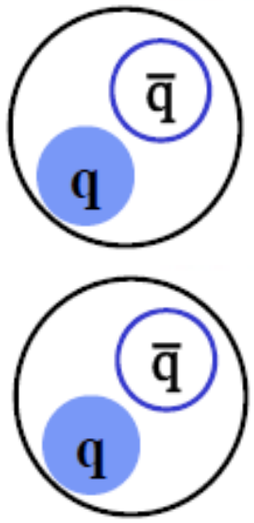


QCD Exotic States

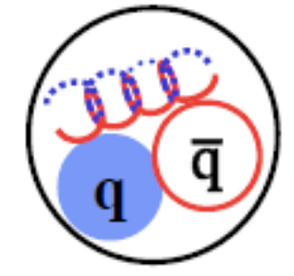


Multi-quark states



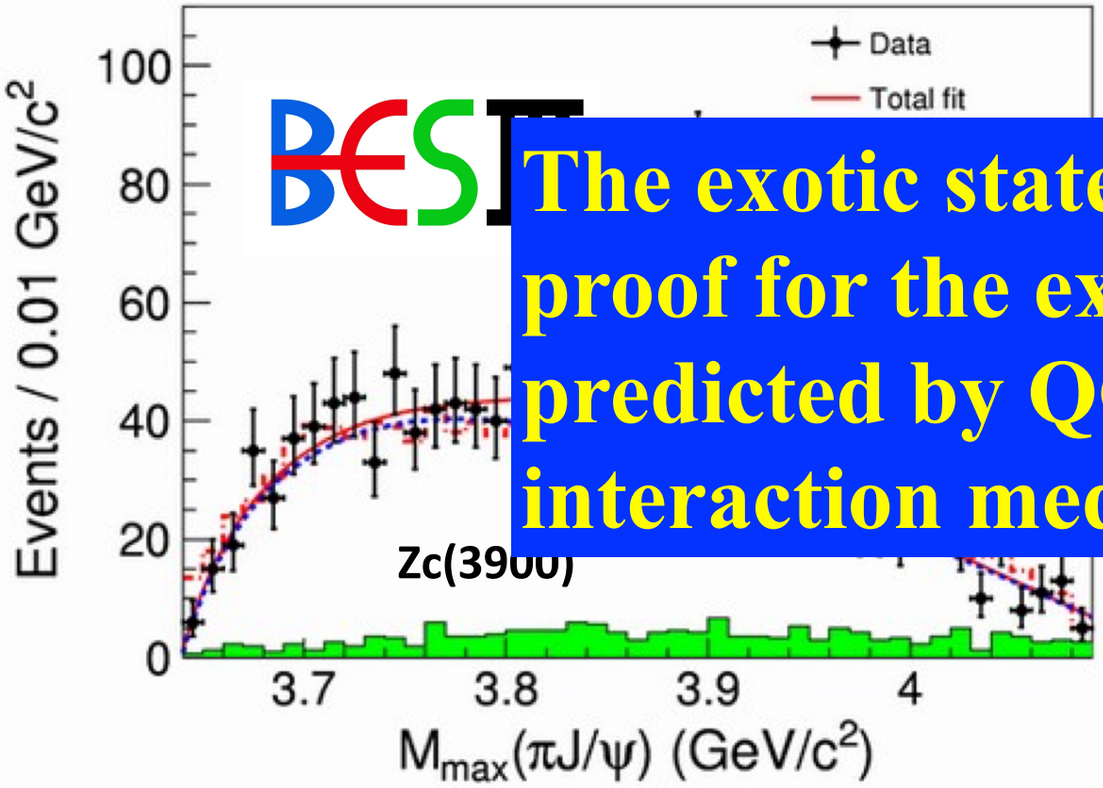


GlueBalls

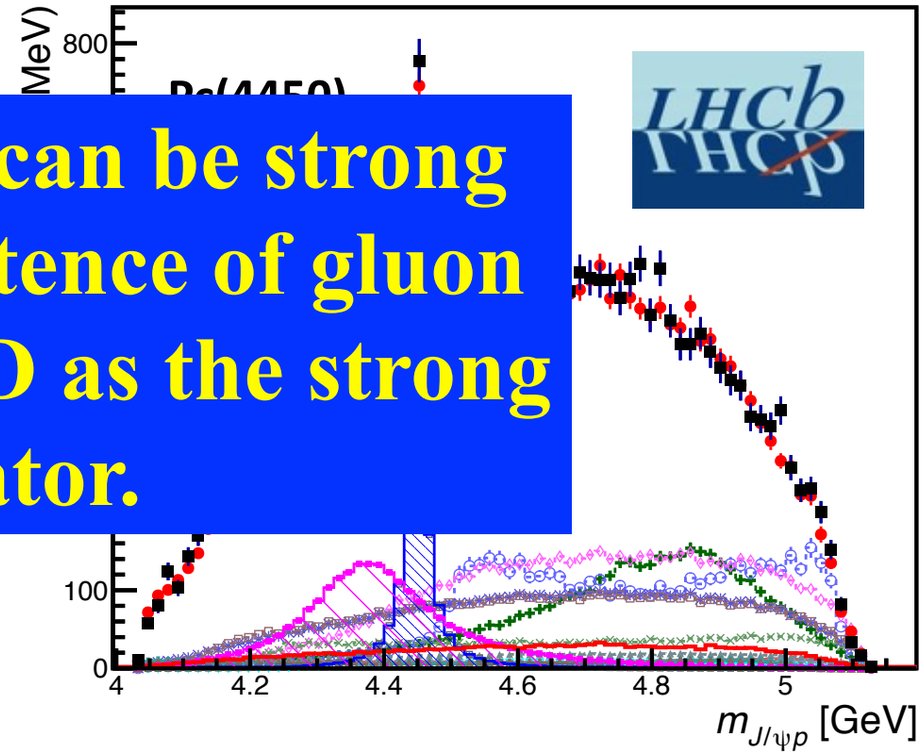


Hybrid

Hadron modular states

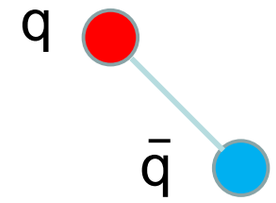


The exotic states can be strong proof for the existence of gluon predicted by QCD as the strong interaction mediator.



Classifying Mesons

——Mass, Electric Charge, Quark Flavor…

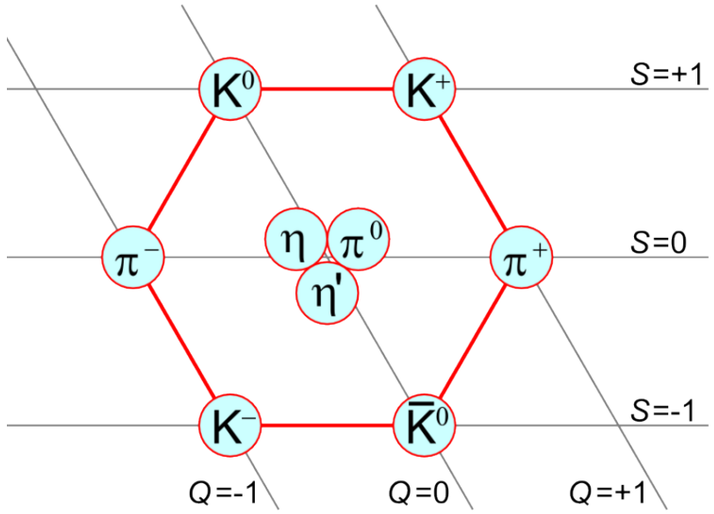


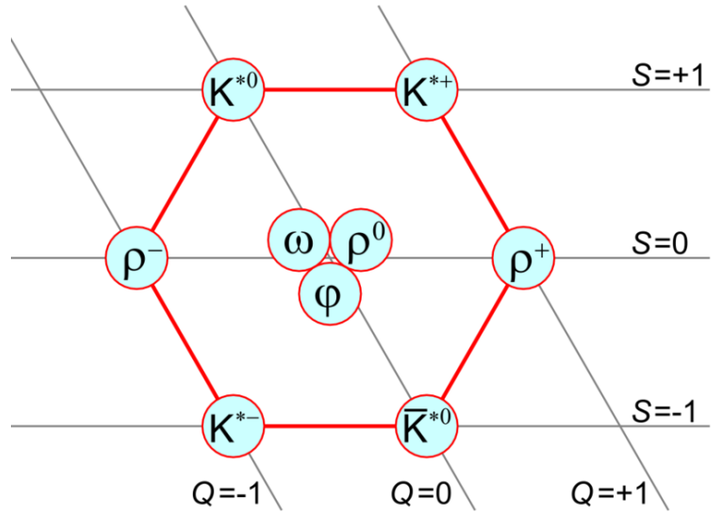
Quantum numbers: J^{PC}

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

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

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





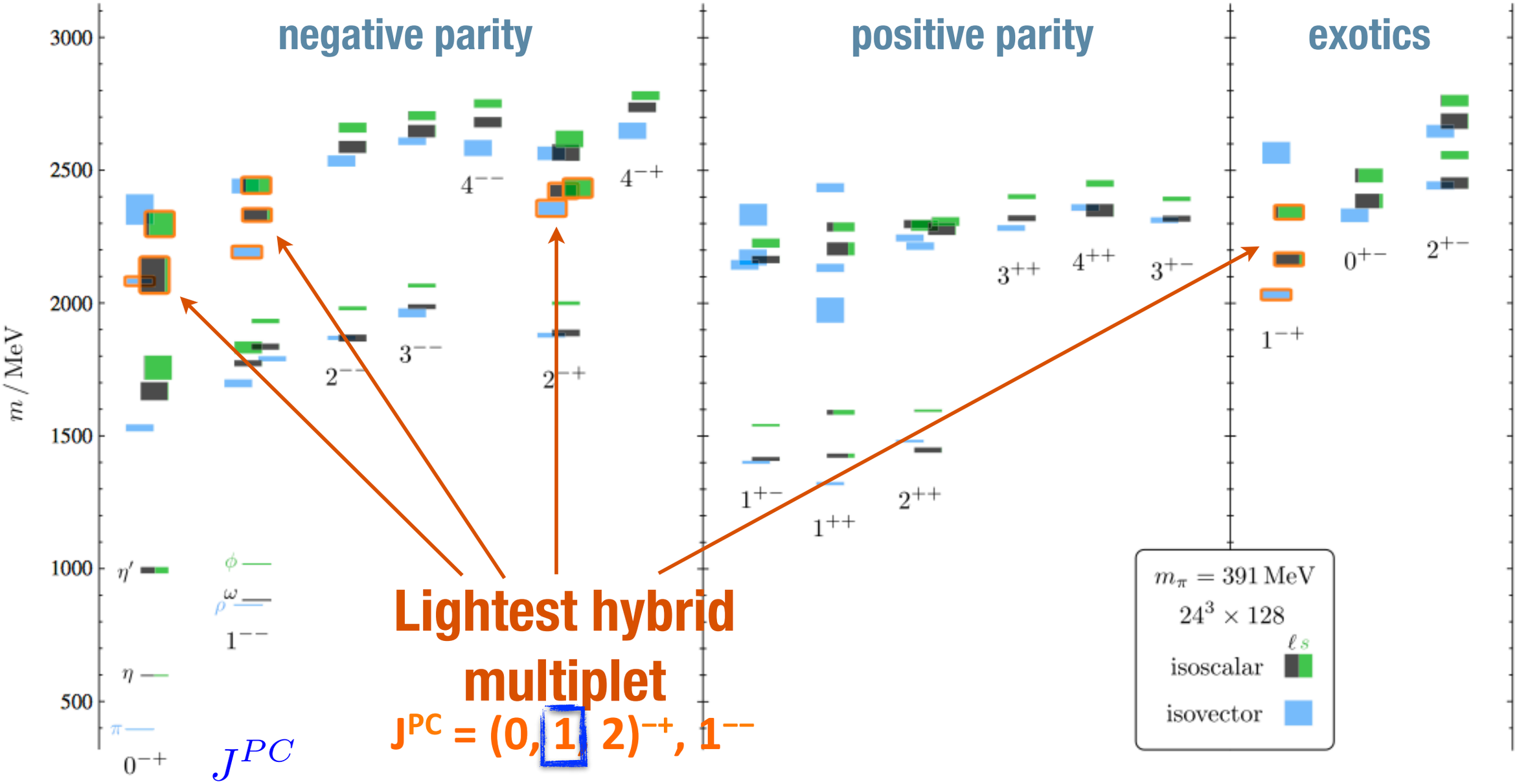
Allowed J^{PC} for $q\bar{q}$ mesons:

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

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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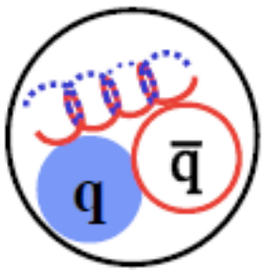
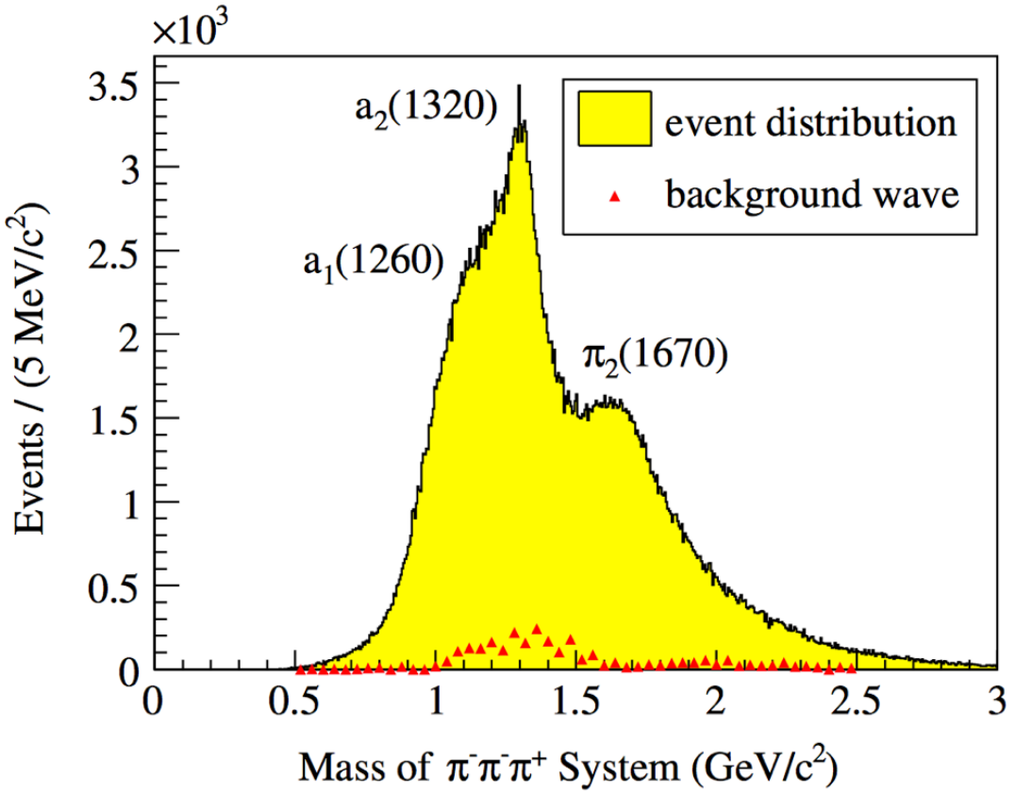
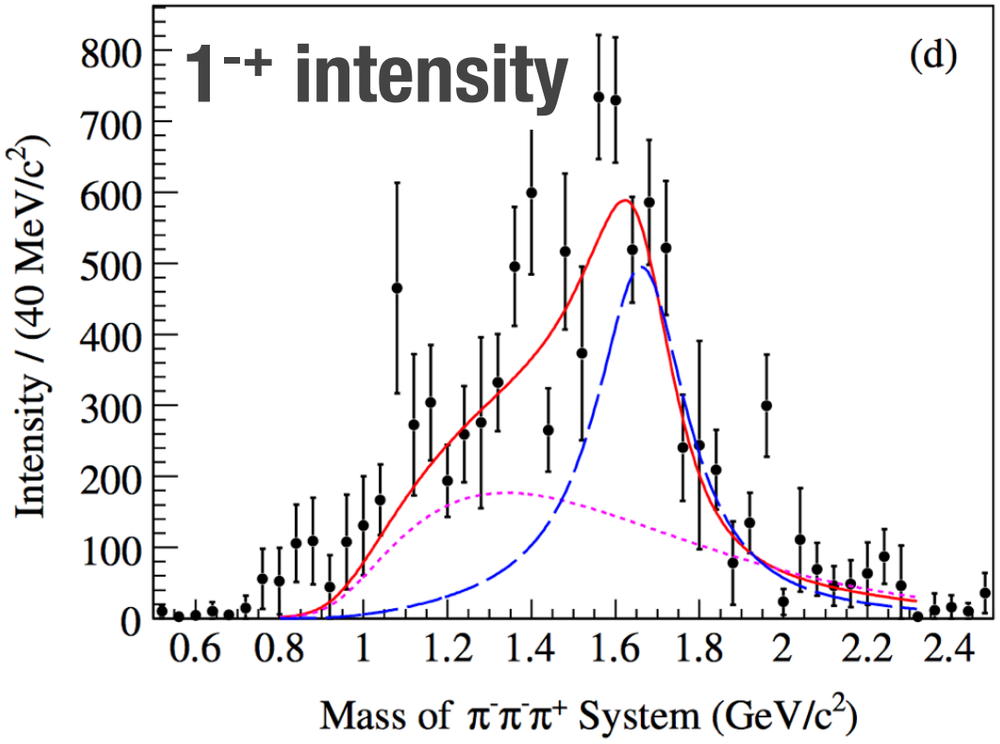
Search for hybrids

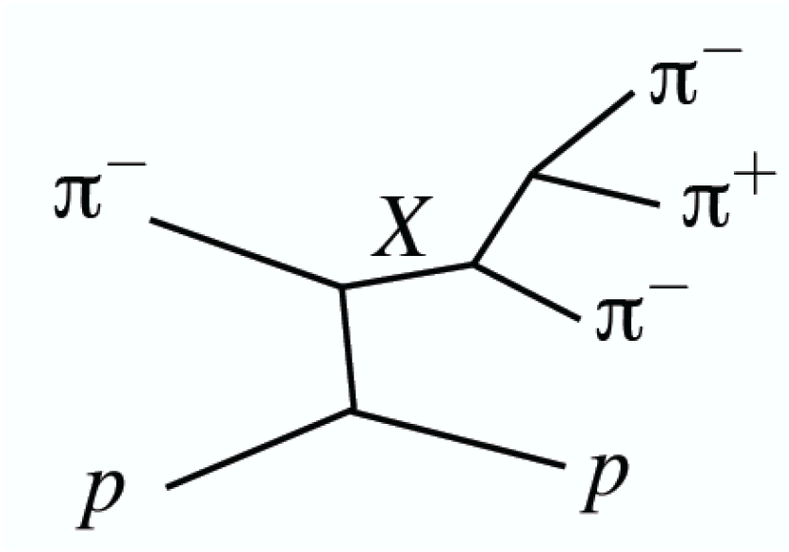


COMPASS: $\pi^- p \to \pi^- \pi^+ \pi^- p$

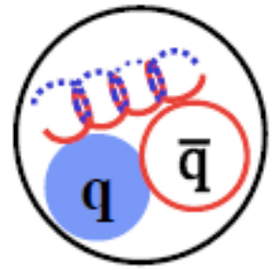




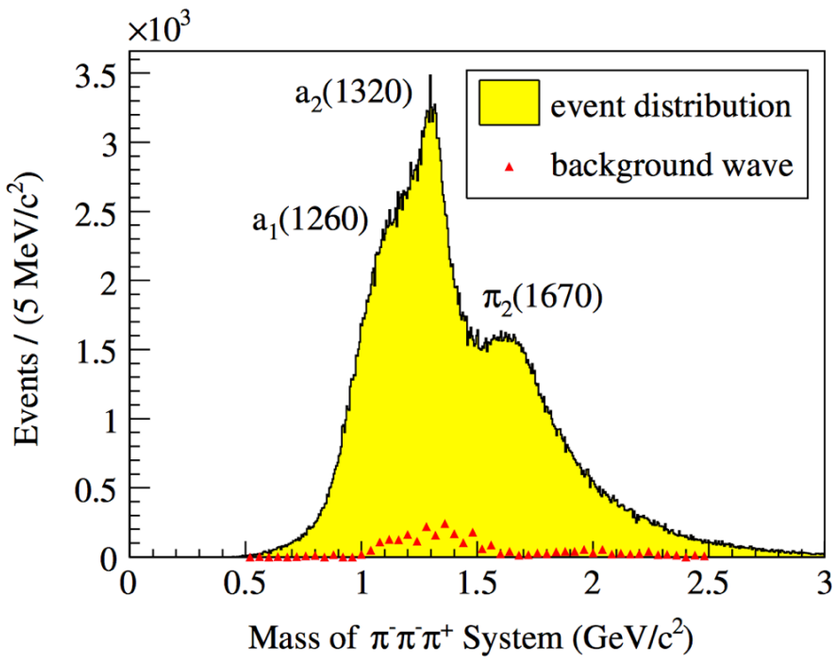
PRL 104, 241803 (2010)



Search for hybrids

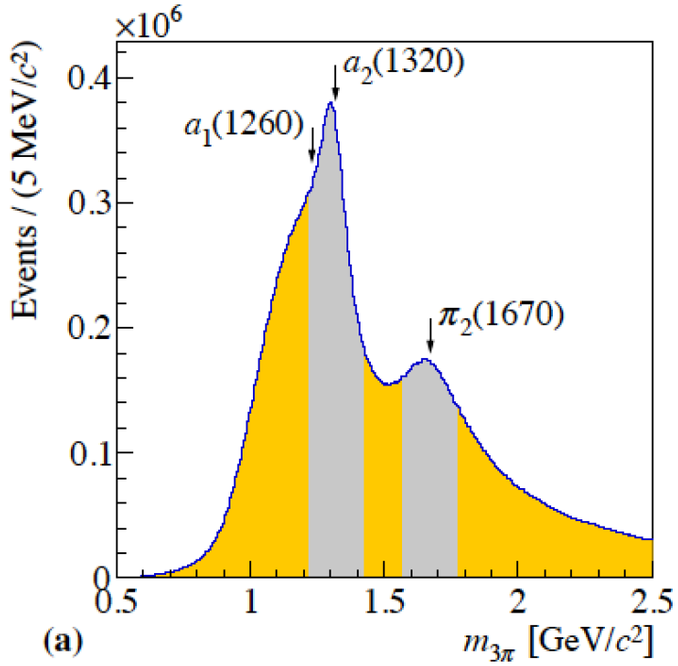


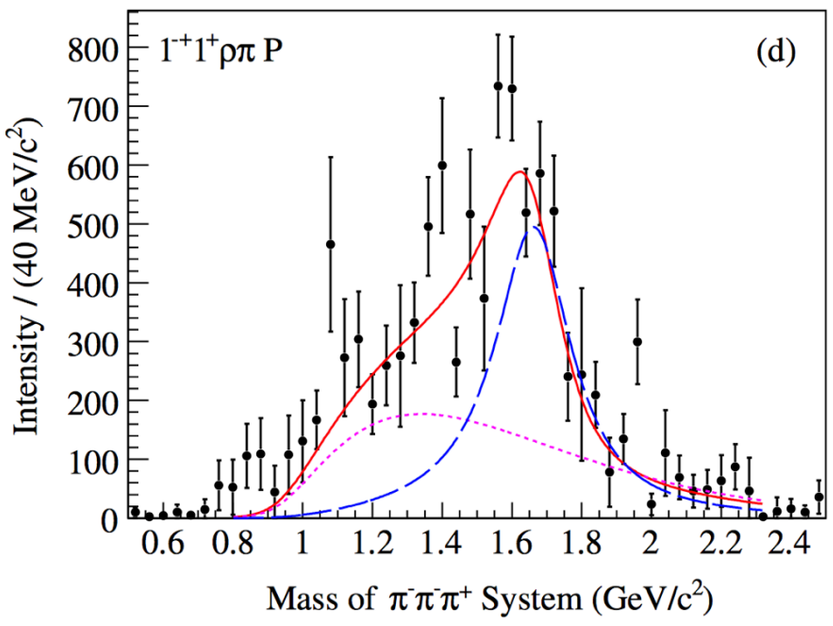
Compass: PRL 104, 241803 (2010)

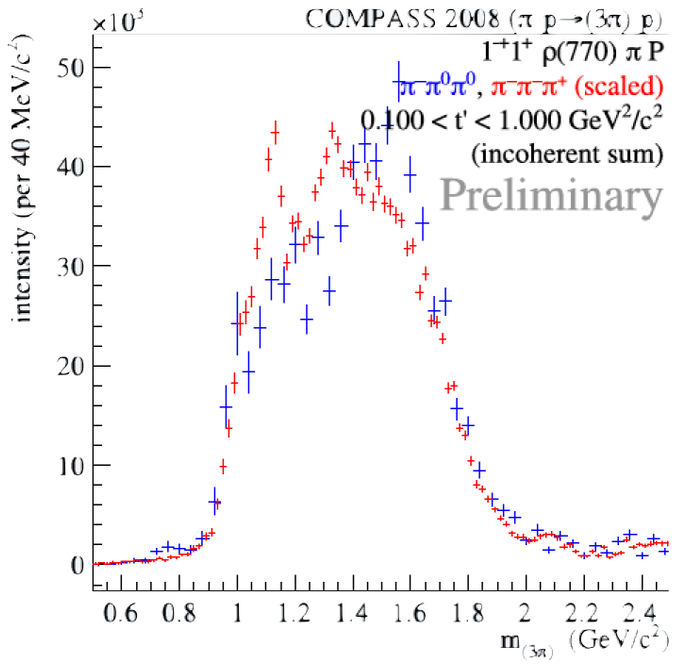


Unprecedented statistics

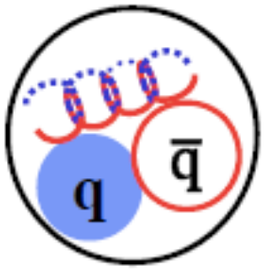
Compass: 1509.00992



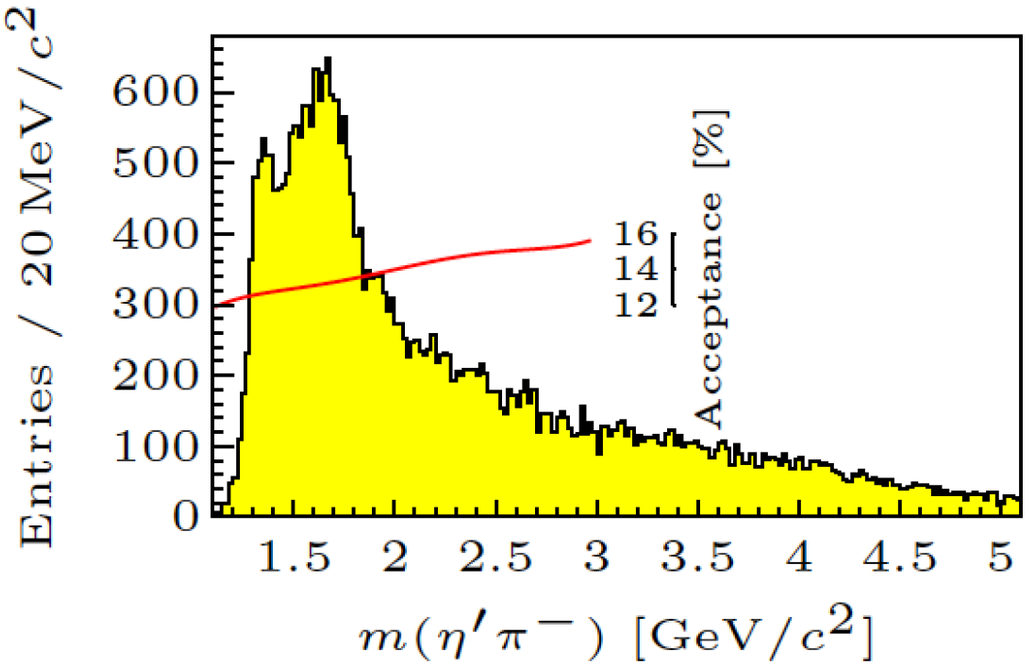


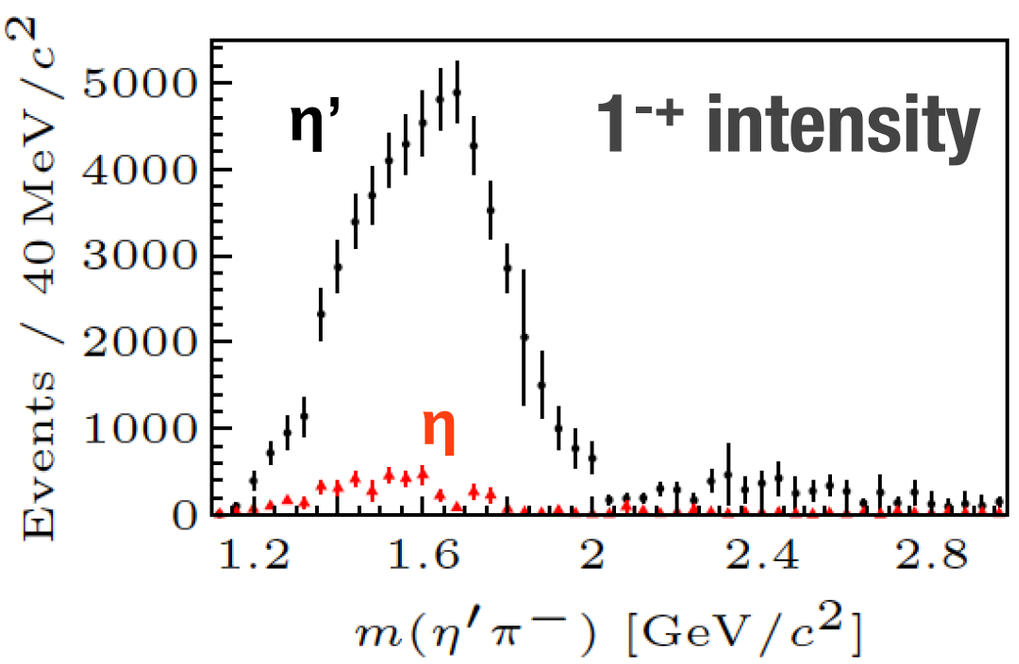


Search for hybrids

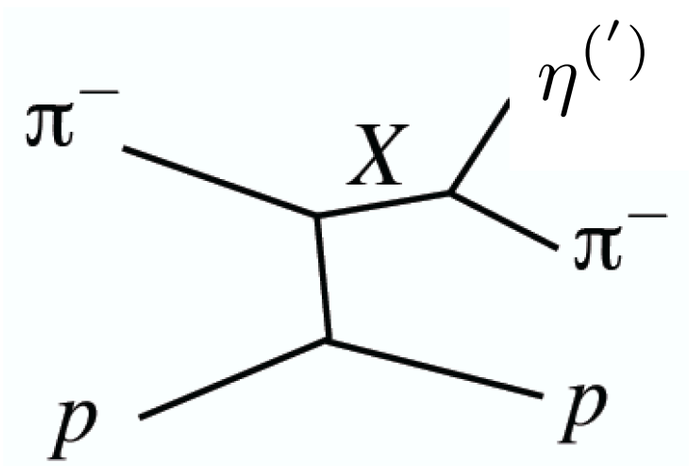


COMPASS: $\pi^- p \to \eta^{(\prime)} \pi^- p$

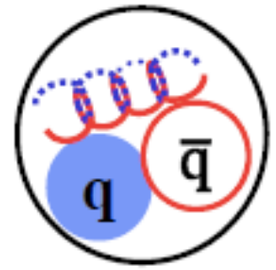




PLB 740 (2015) 303



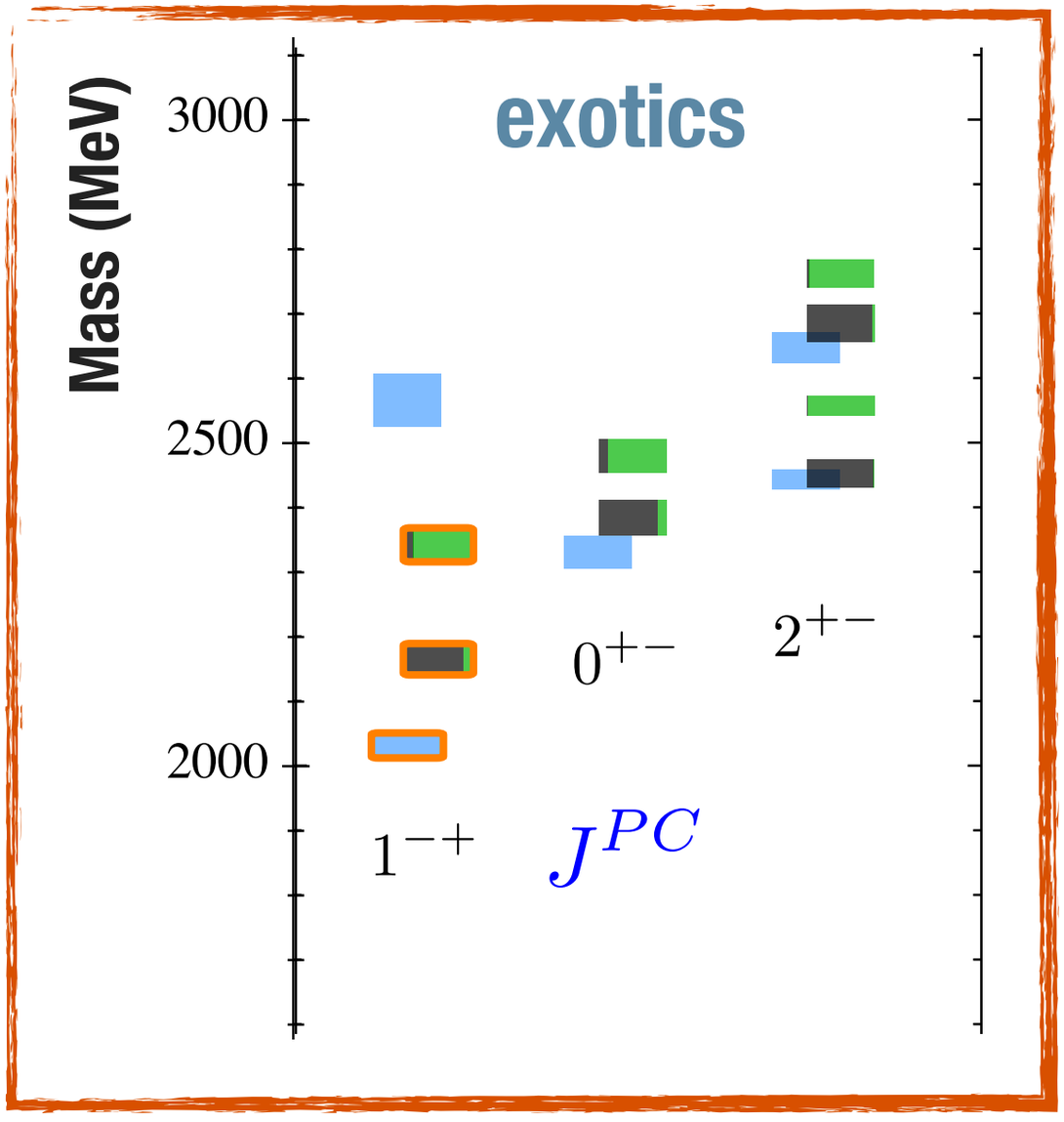
Search for exotic hybrids



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	1^{-+}	$\omega\pi\pi^\dagger$, $3\pi^\dagger$, 5π, $\eta 3\pi^\dagger$, $\eta'\pi^\dagger$
η_1	1^{-+}	4π, $\eta 4\pi$, $\eta\eta\pi\pi^\dagger$
η_1'	1^{-+}	$KK\pi\pi^\dagger$, $KK\pi^\dagger$, $KK\omega^\dagger$
b_0	0^{+-}	4π
h_0	0^{+-}	$\omega\pi\pi^\dagger$, $\eta 3\pi$, $KK\pi\pi$
h_0'	0^{+-}	$KK\pi\pi^\dagger$, $\eta 3\pi$
b_2	2^{+-}	4π, $\eta\pi\pi^\dagger$
h_2	2^{+-}	$\omega\pi\pi^\dagger$, $3\pi^\dagger$
h_2'	2^{+-}	$KK\pi\pi^\dagger$, $KK\pi^\dagger$

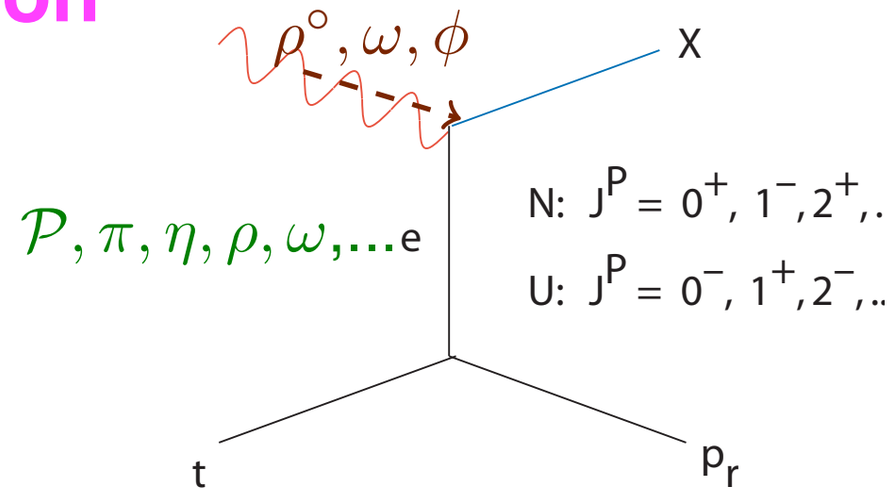


Hybrid Meson Search Strategy

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**

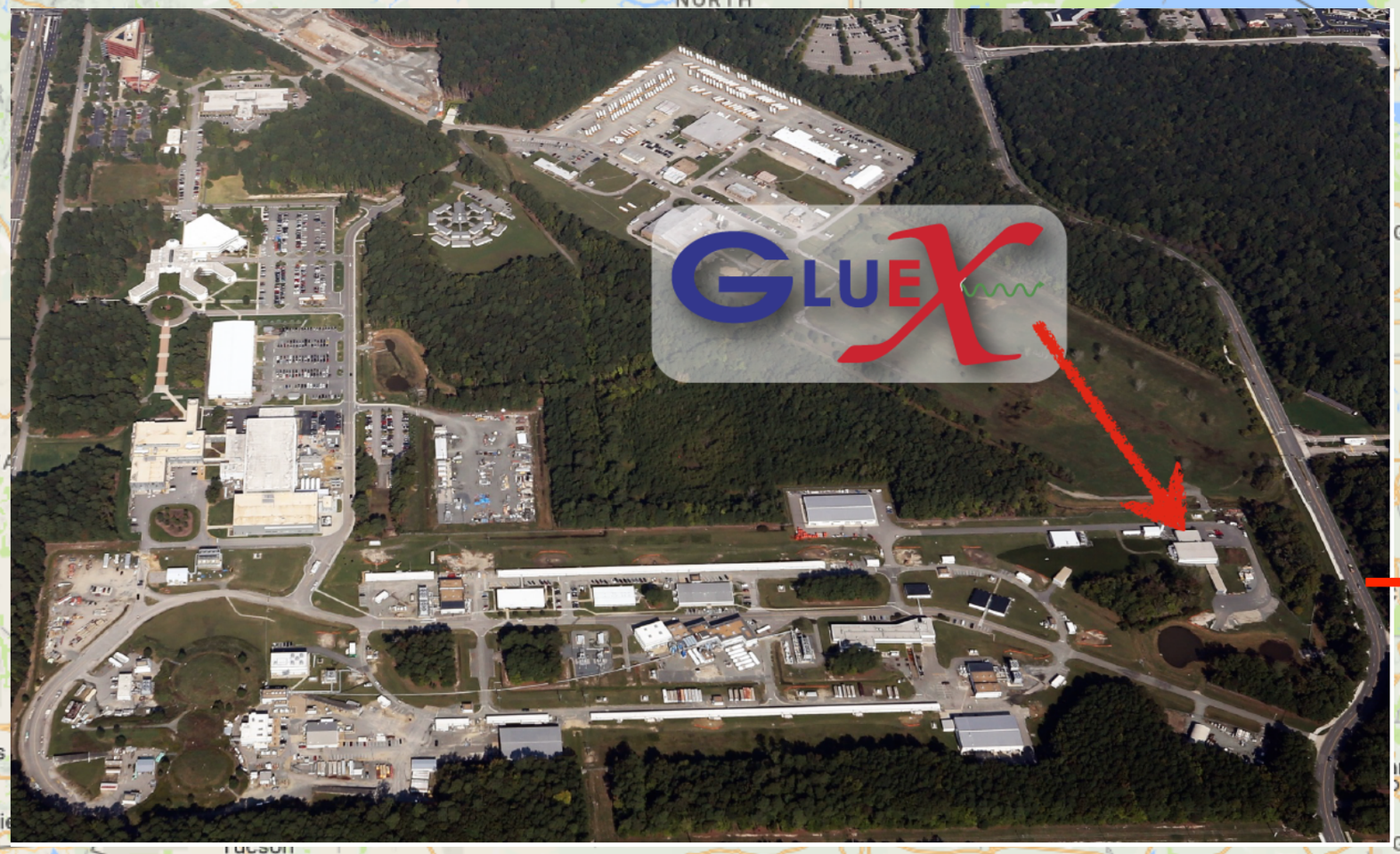


Exchange particle		Final states	
$\mathcal{P}$	0^{++}	$2^{+-}, 0^{+-}$	b°, h, h'
π°	0^{-+}	2^{+-}	b_2°, h_2, h_2'
$\pi^\pm$	0^{-+}	1^{-+}	$\pi_1^\pm$
ω	1^{--}	1^{-+}	π_1, η_1, η_1'

Can couple to all 3 exotic nonets

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

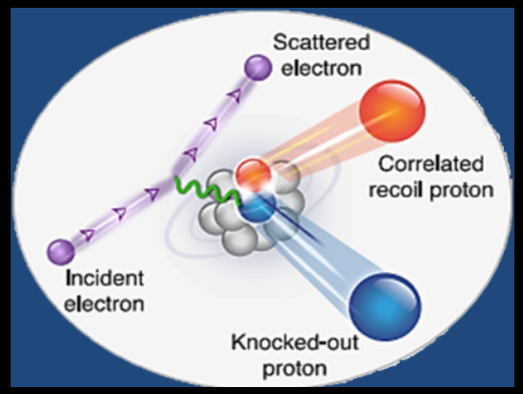
Thomas Jefferson National Accelerator Facility
(Jefferson Lab)



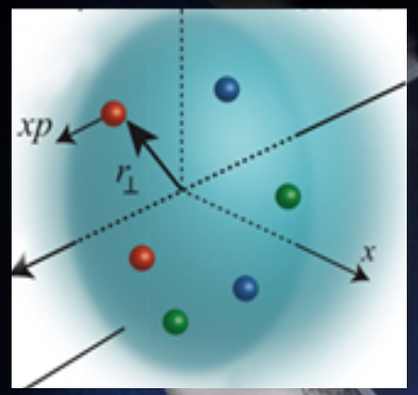
Thomas Jefferson
(1743–1826)

托马斯·杰斐逊国家加速器装置
（杰斐逊实验室）

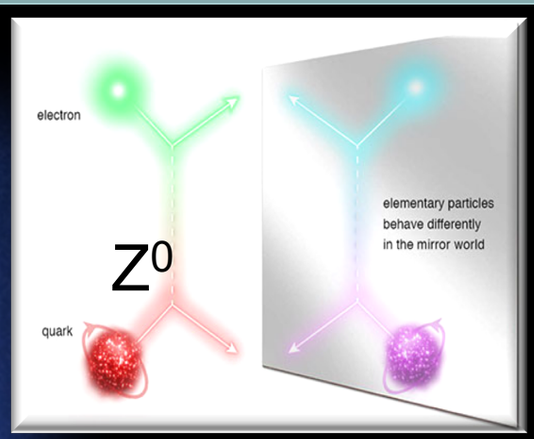
JLab: A Laboratory for Nuclear Science



Nuclear Structure

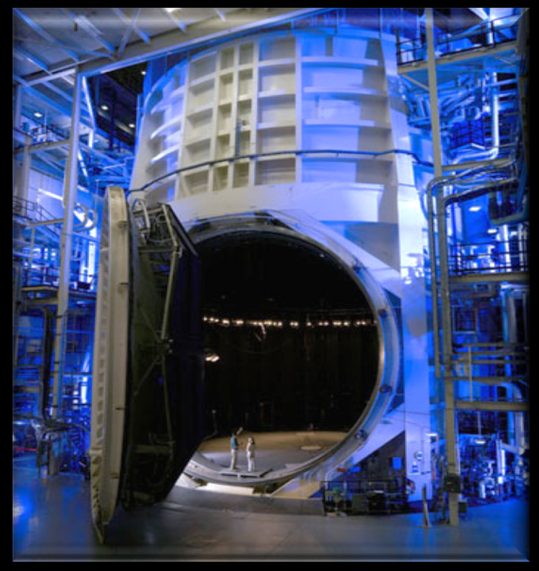


Structure of Hadrons



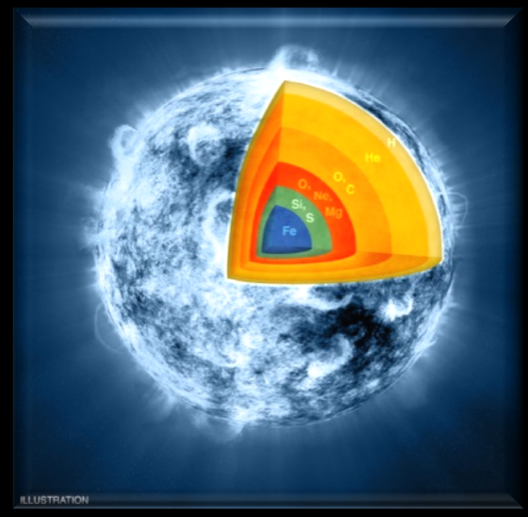
Fundamental Forces & Symmetries

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

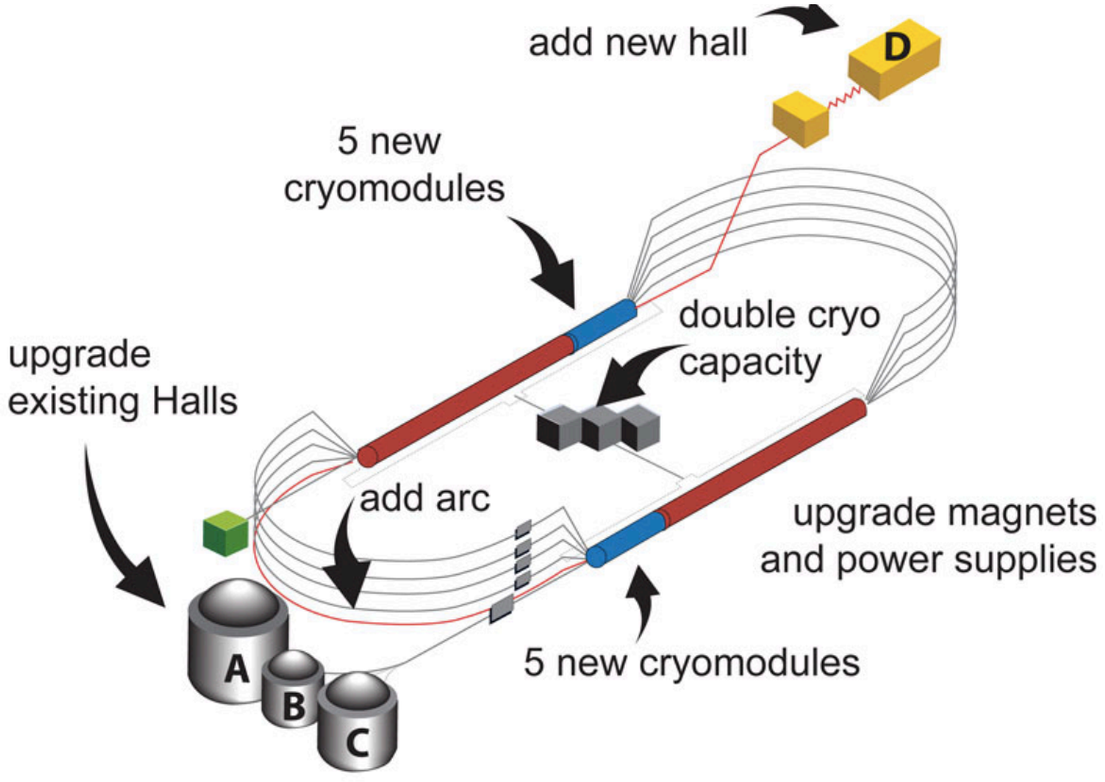
GlueX: The spectrometer in the Hall D

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

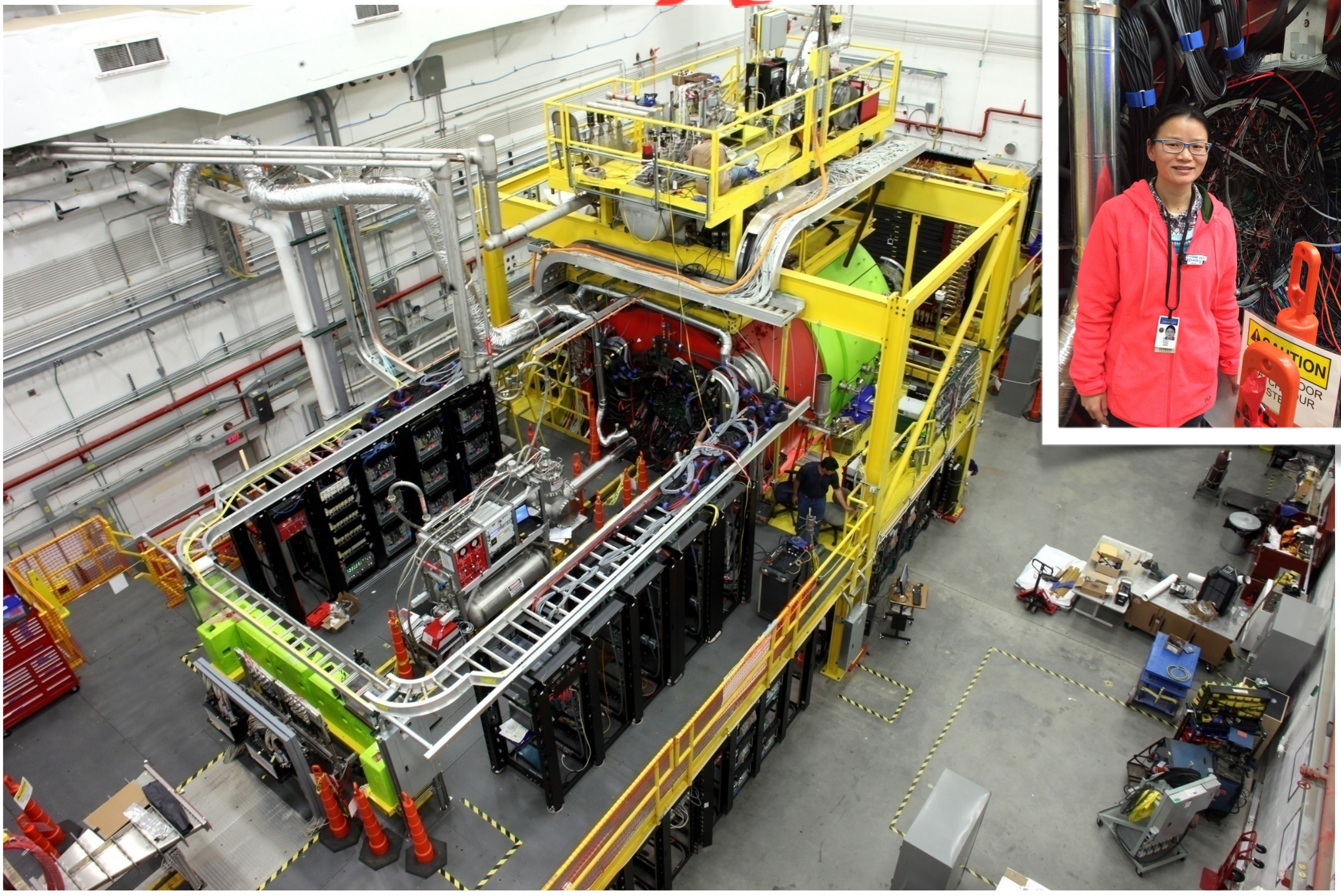
http://portal.gluex.org/GlueX/Home.html

~120 members from 25 institutions of 8 counties

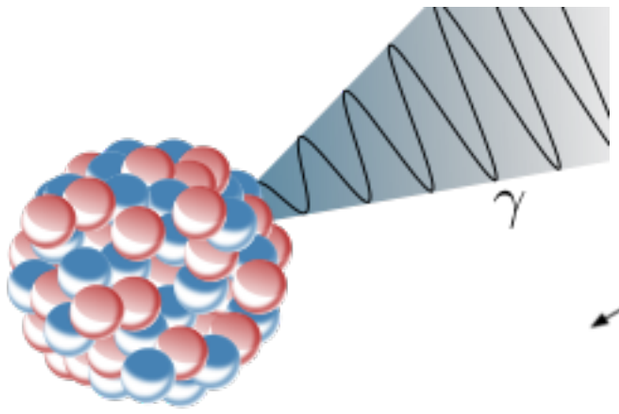
GlueX Collaboration

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

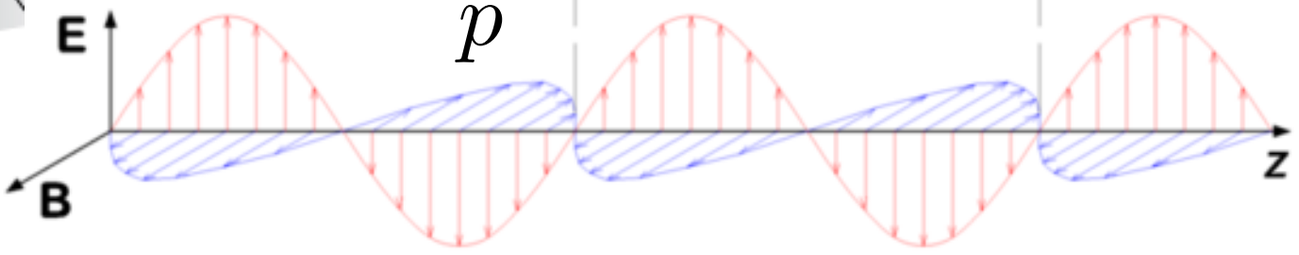
In 2016, Wuhan University became the first GlueX member from Asia.

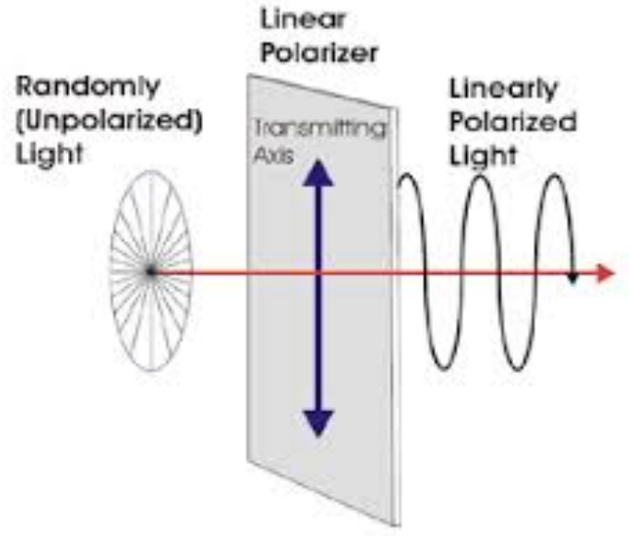


Linearly polarised photon beam

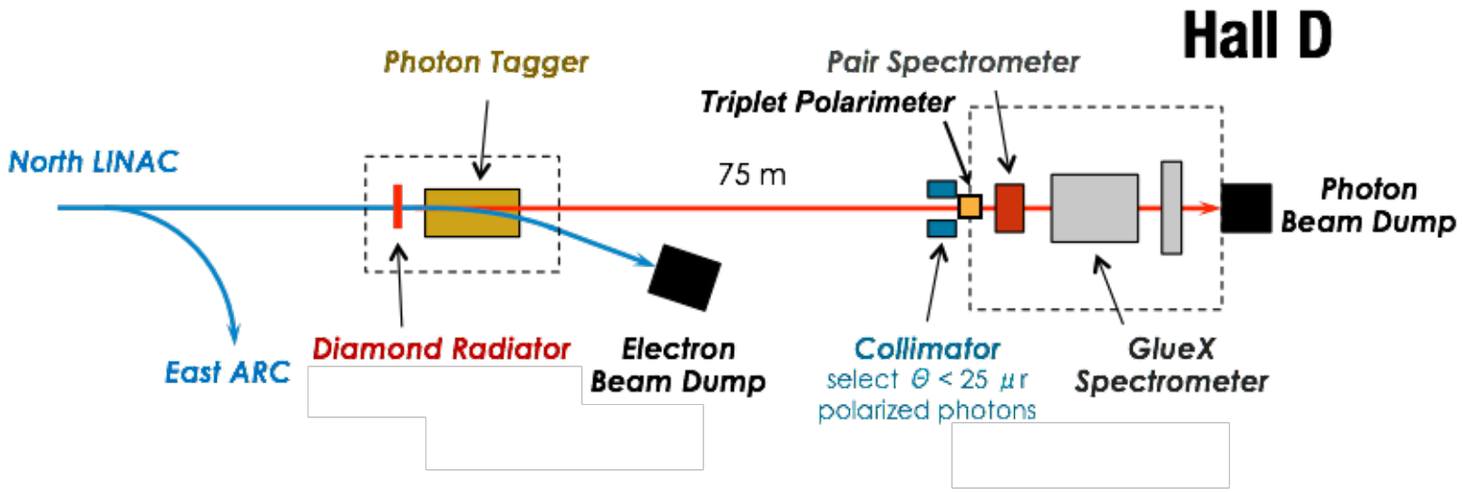


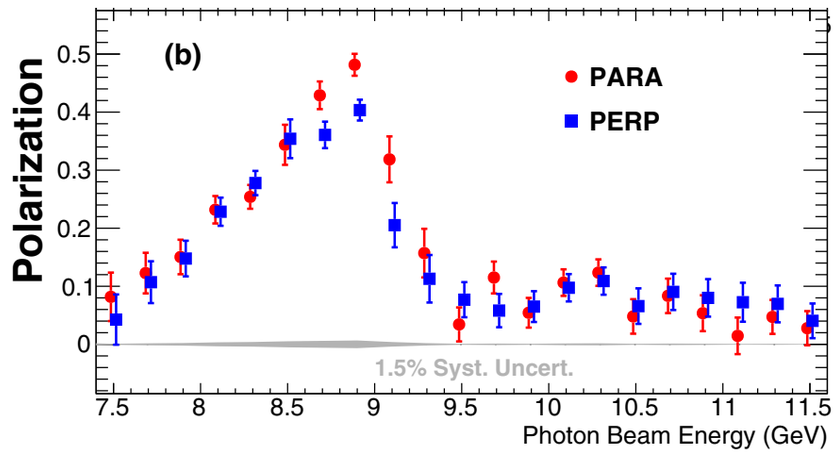
$$\lambda = \frac{h}{p}$$





Photon flux 10-100 MHz in the peak





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

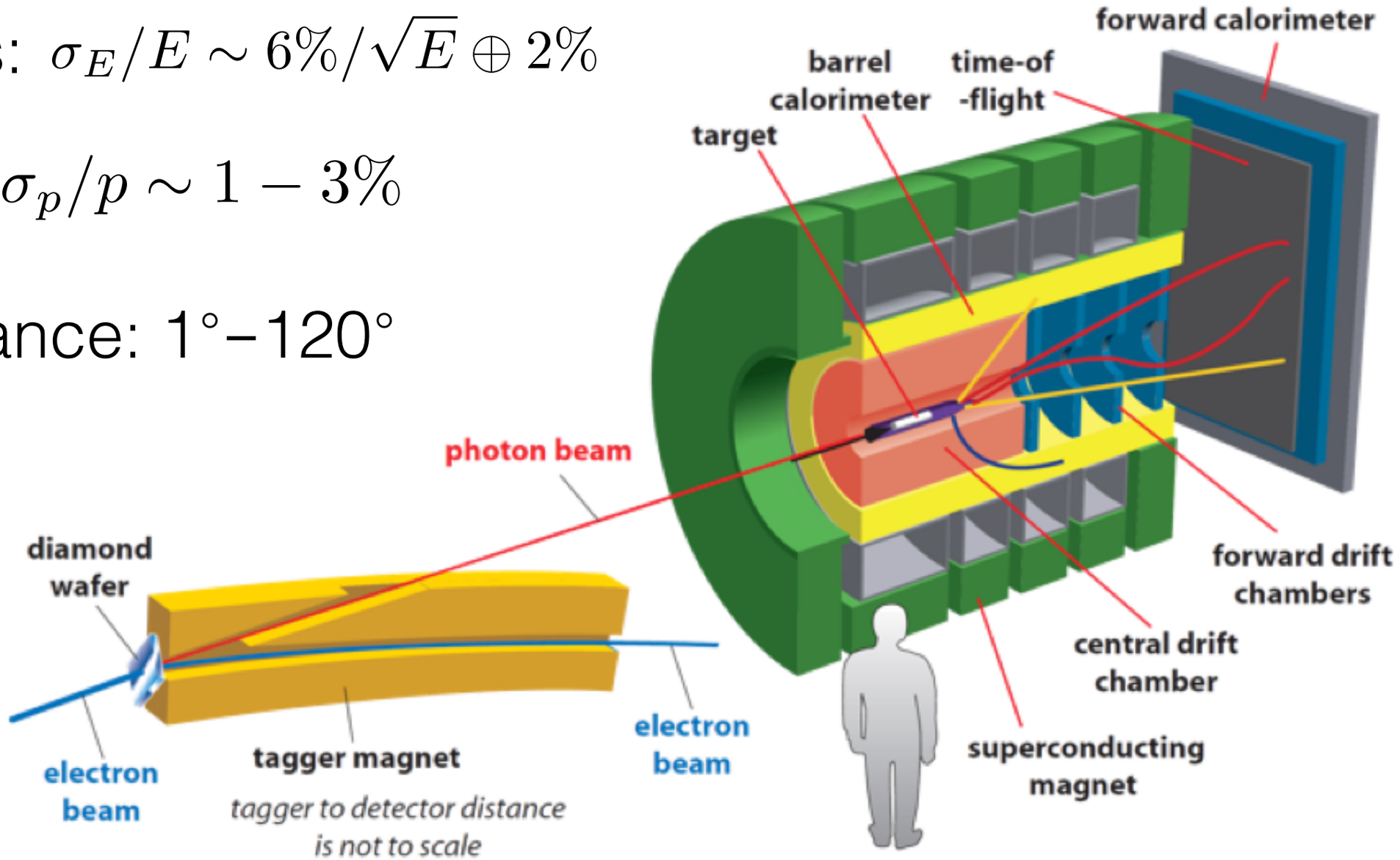
GlueX detector

Detector resolutions:

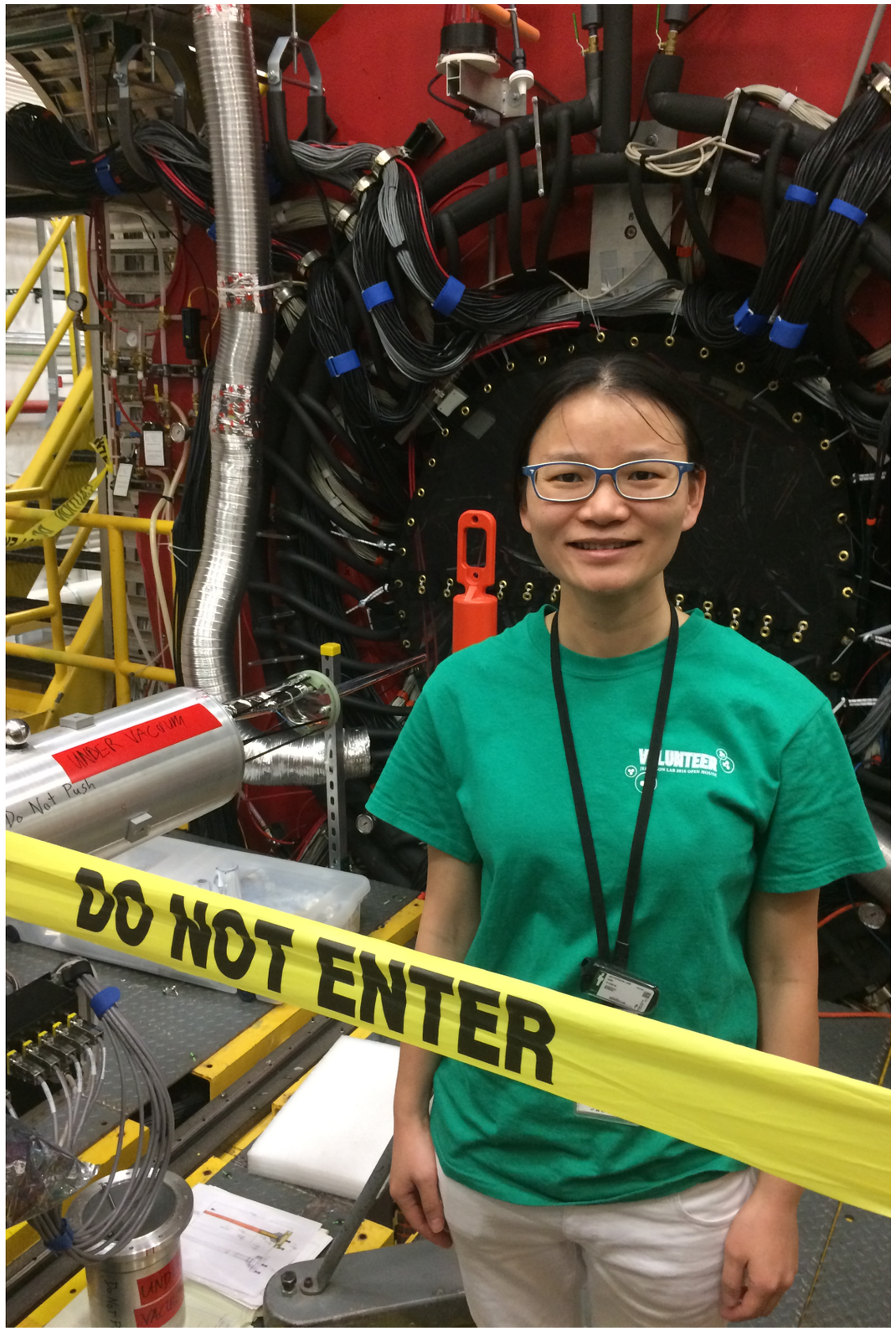
Photons: $\sigma_E/E \sim 6\%/\sqrt{E} \oplus 2\%$

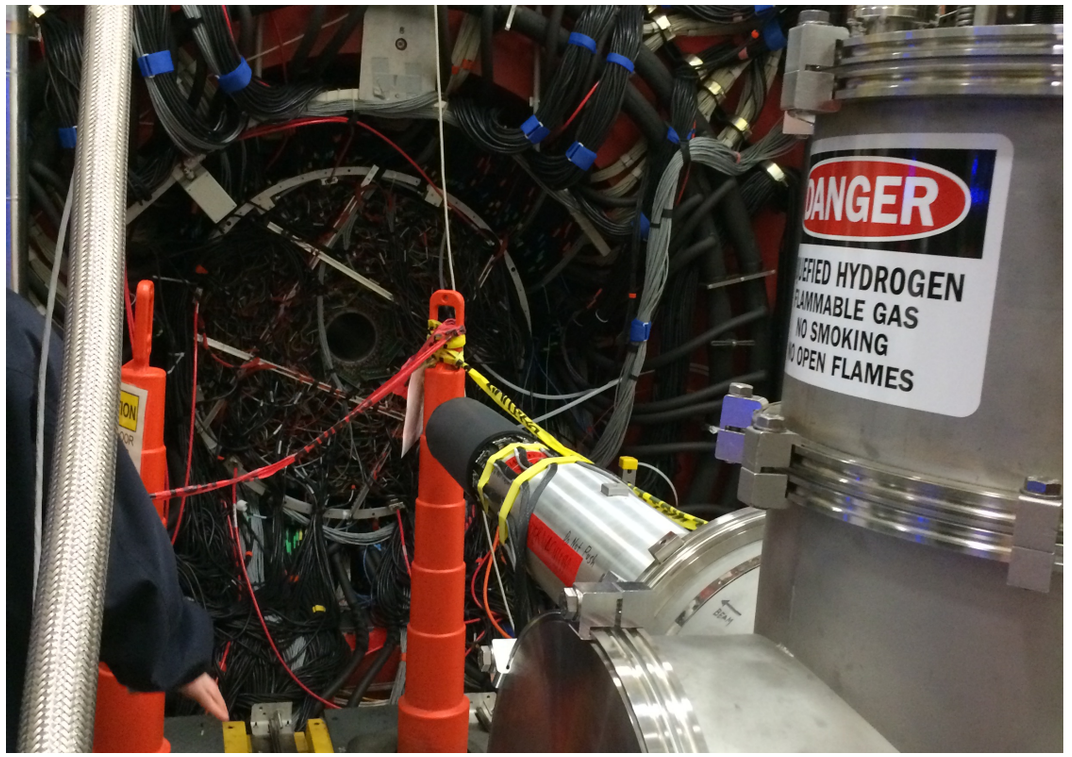
Tracks: $\sigma_p/p \sim 1 - 3\%$

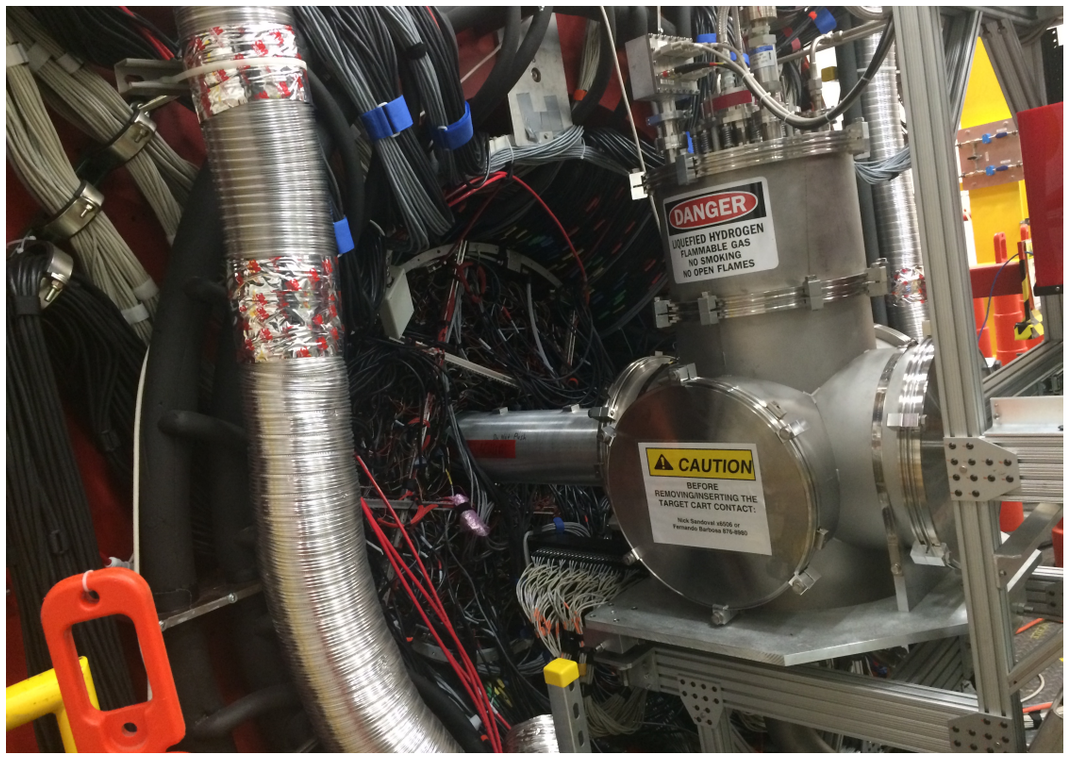
Receptance: 1°–120°



Liquid hydrogen target and start counter

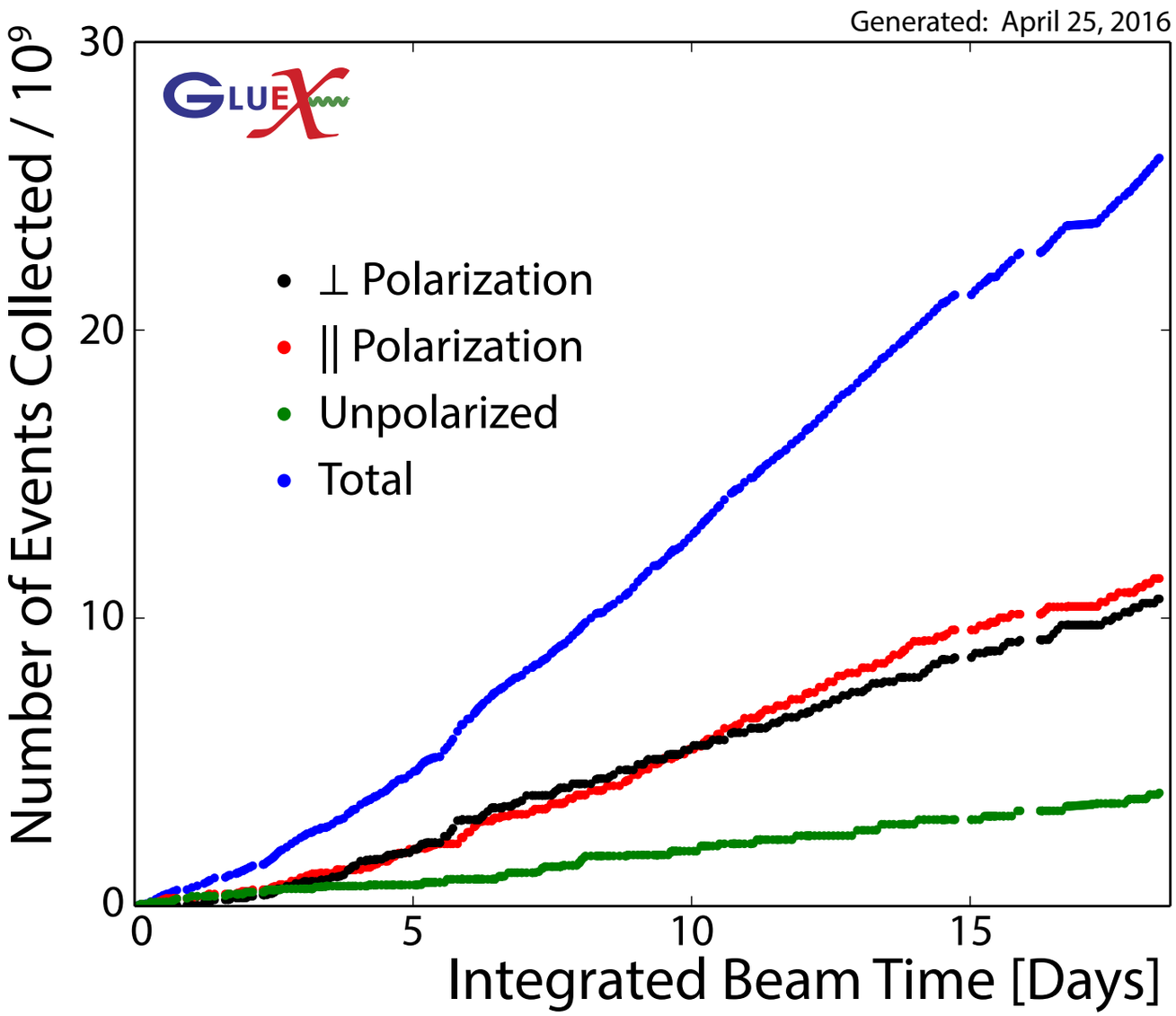






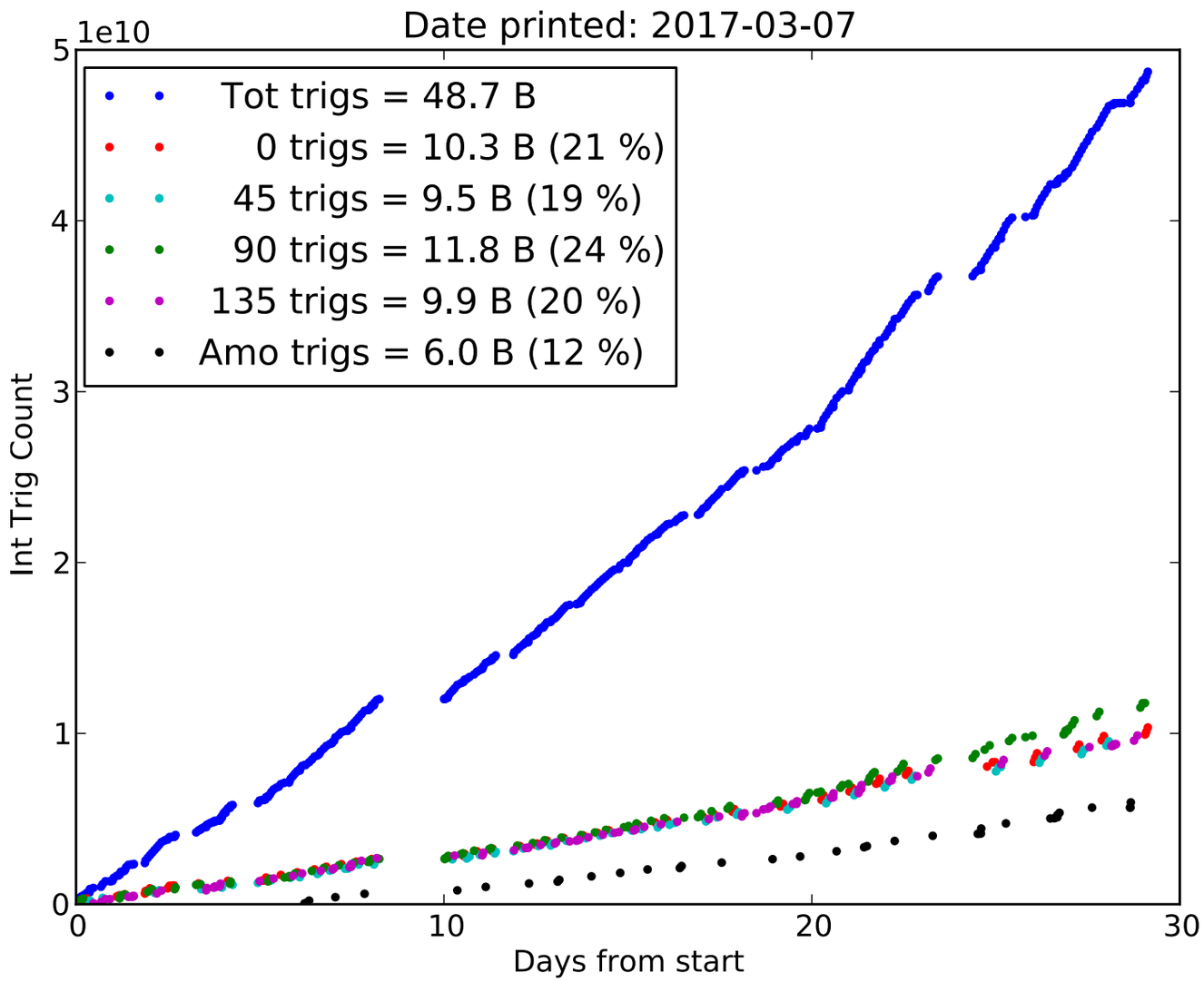
Spring 2016:

Detector commissioning and engineering runs



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

Spring 2017:
The first physics runs



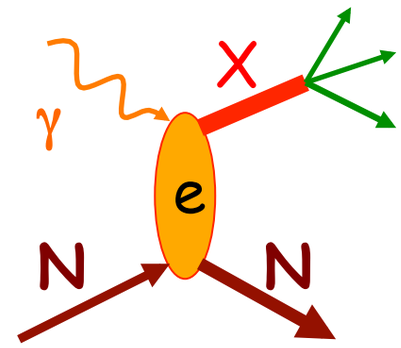
GlueX-I [low-intensity]: 2017-18

Physics at GlueX

- **Early Physics:**
  - **Beam asymmetry and polarization transfer measurements in the meson/bayon photoproduction**
- **Long-term Physics:**
  - **Search for exotic hybrids (PWA analysis)**
  - **Spin-density matrix elements to understand production mechanisms.**
  - **Cross section measurements**
  - **Generalized Parton Distributions measurement from time-like Compton scattering**

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



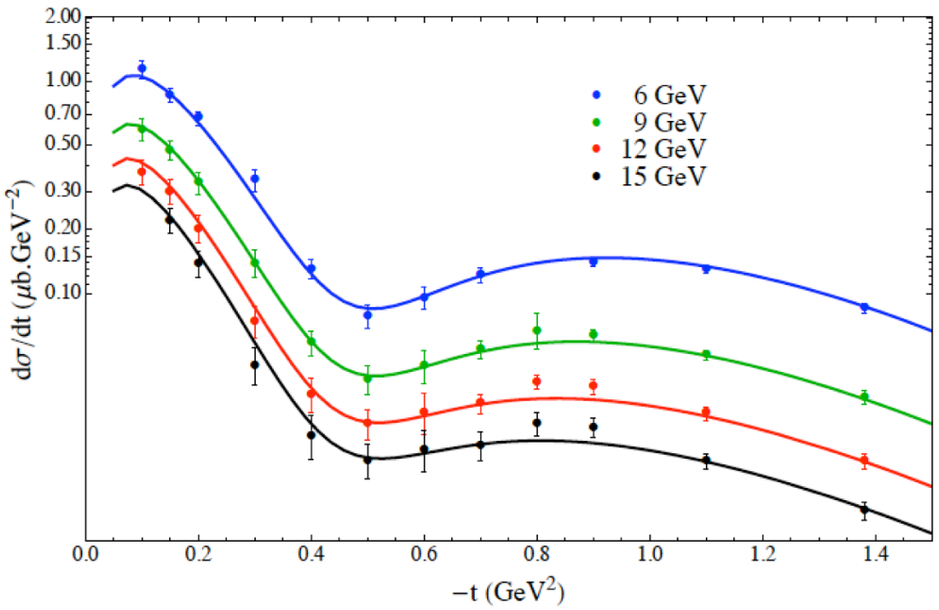
$\gamma \Leftrightarrow \rho, \omega, \phi$

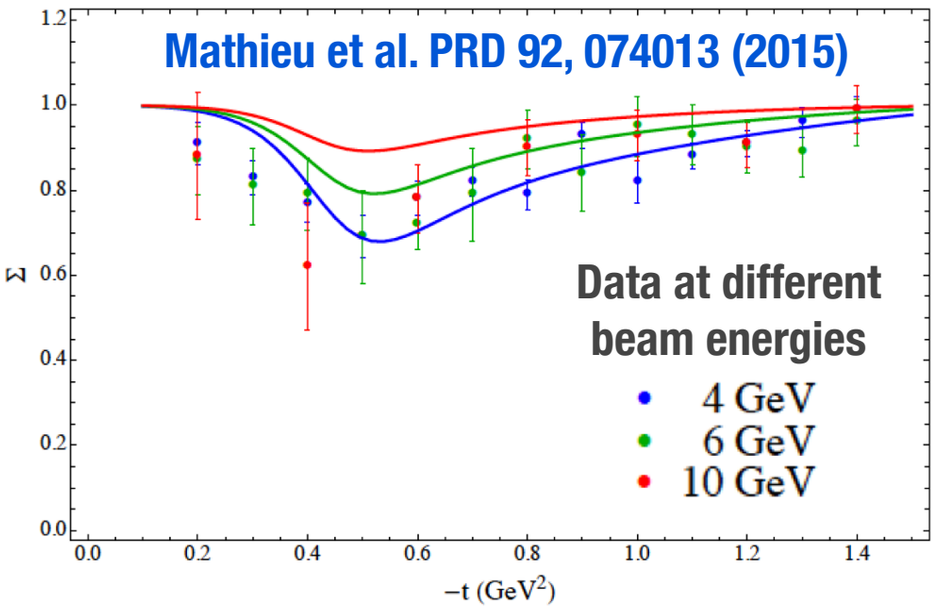
High-Energy Meson Photoproduction: VMD & Regge-cut phenomenology

GlueX & JPAC: Experiment & Theory

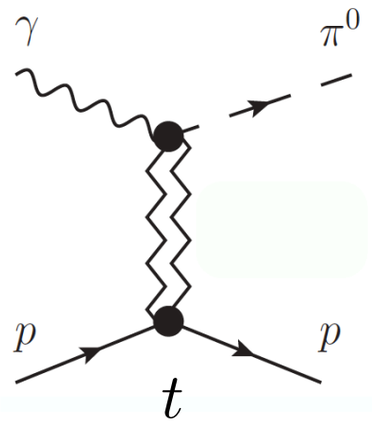
Psuedoscalar mesons π^0/η Photoproduction

JPAC Regge Model





SLAC: PRD 4, 1937 (1971)



Exchange J^{PC}

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

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

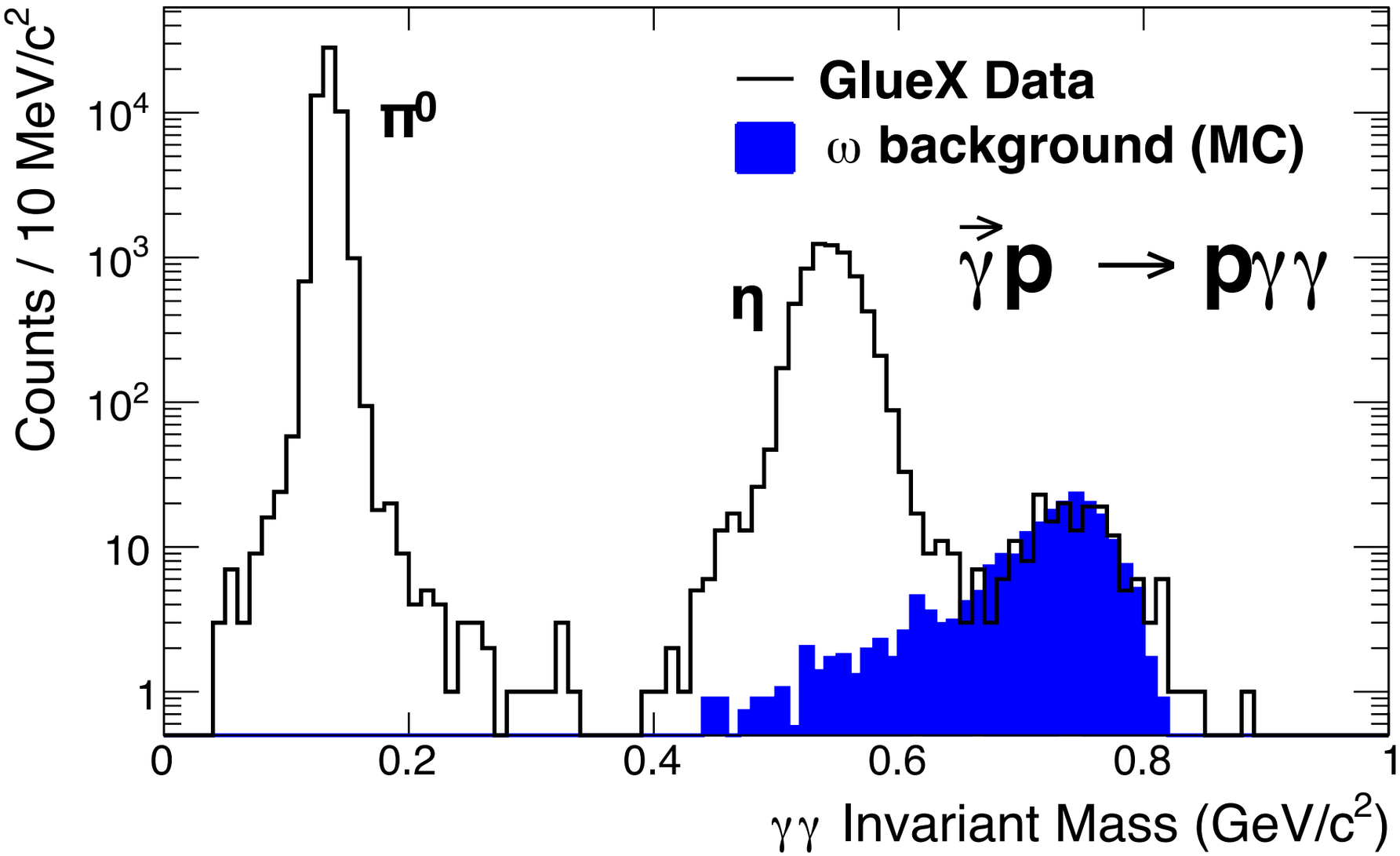
$$\frac{d\sigma}{dt} = \sigma_\perp + \sigma_\parallel = |\rho + \omega|^2 + |b + h|^2$$

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

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

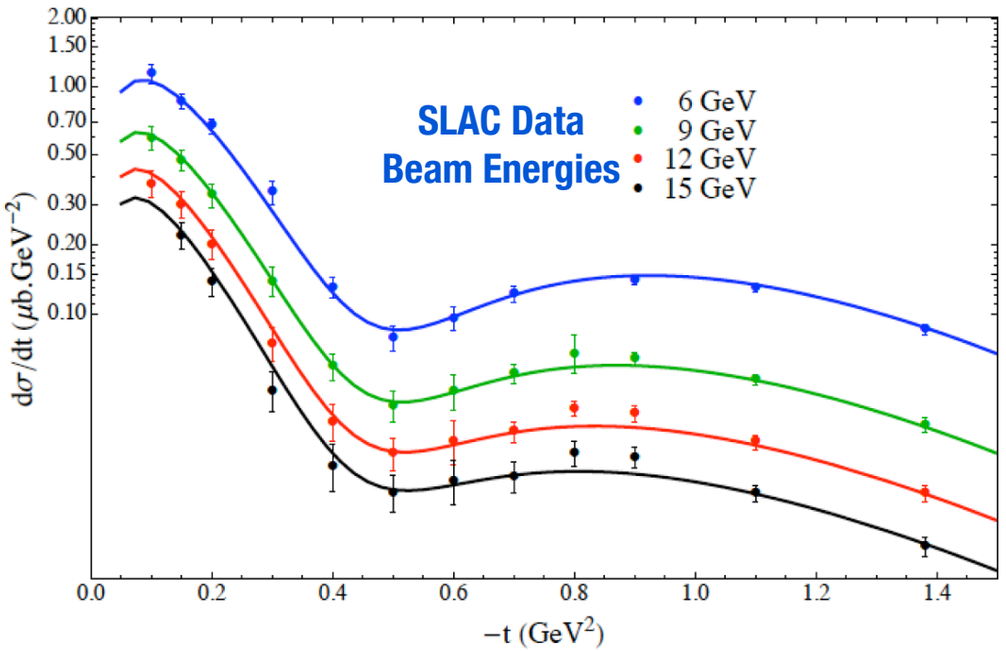
ω Backgrounds



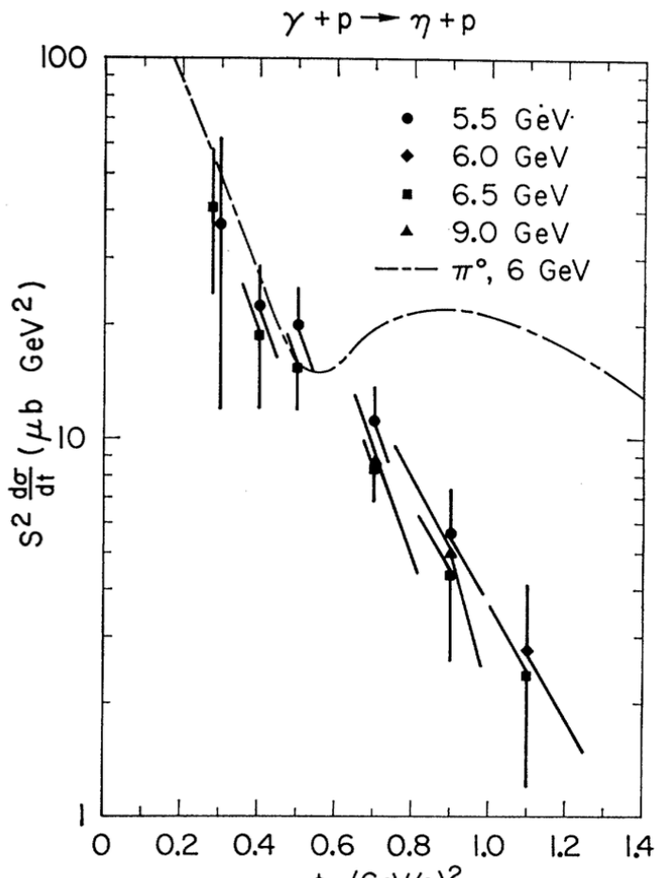
- **Continuum background between π^0 and η is negligible.**
- **The largest background is γp→ωp, ω→π^0γ with a missing photon. To get the background shape, we simulated this reaction then normalized to the ω leakage peak.**
- **Our exclusive measurements and cuts ensure very low backgrounds: for the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

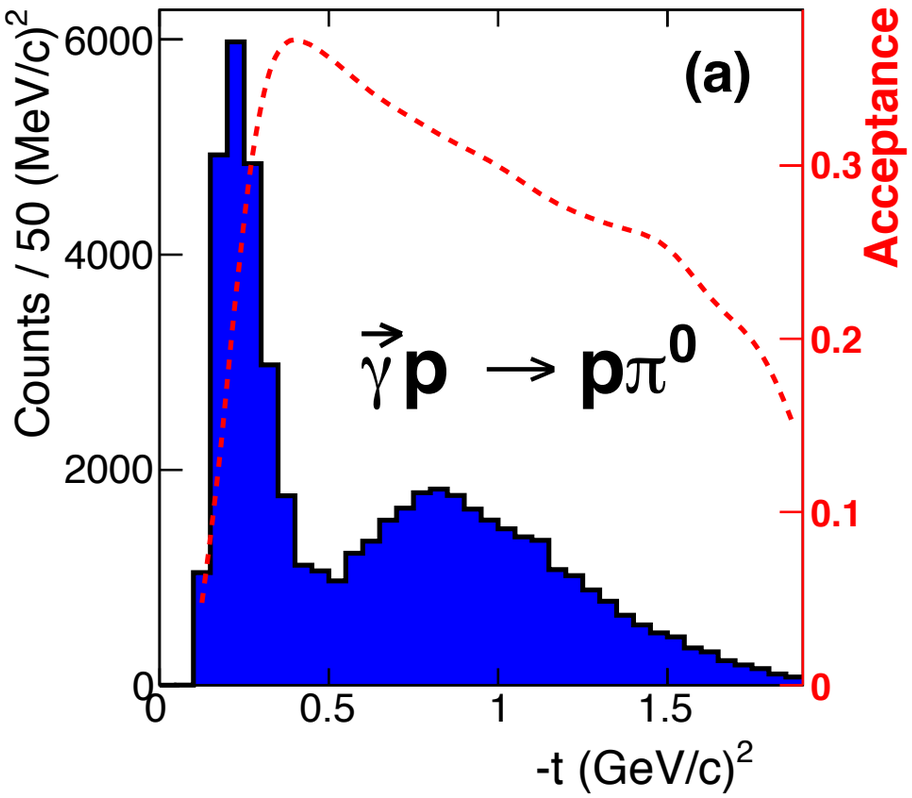
Final -t distributions

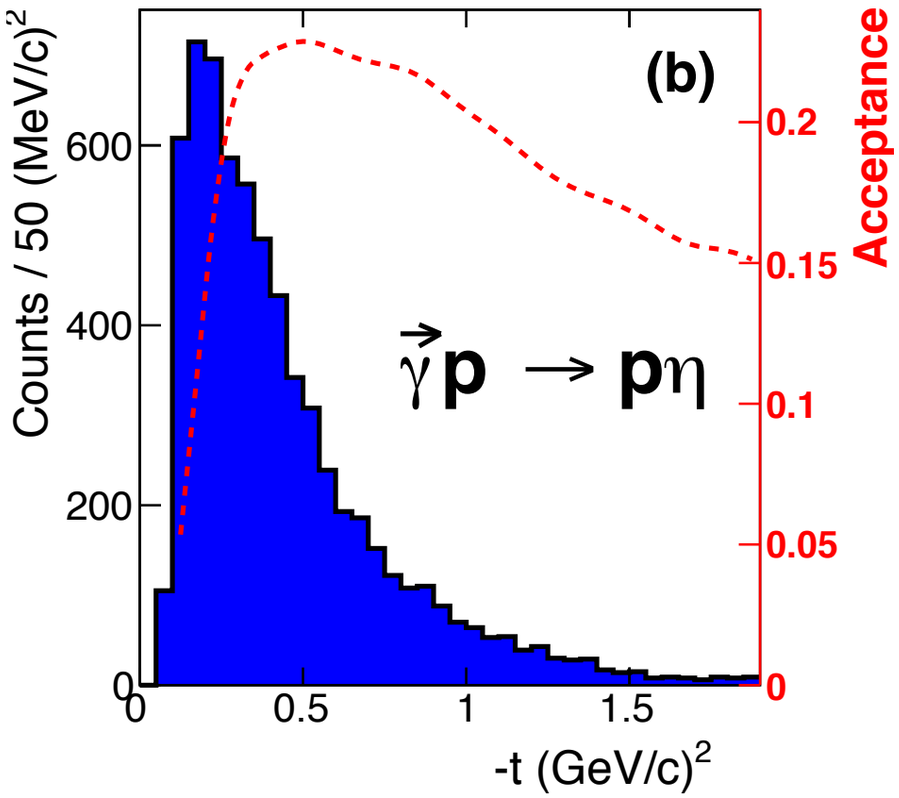
V. Mathieu (JPAC): PRD 92, 074013



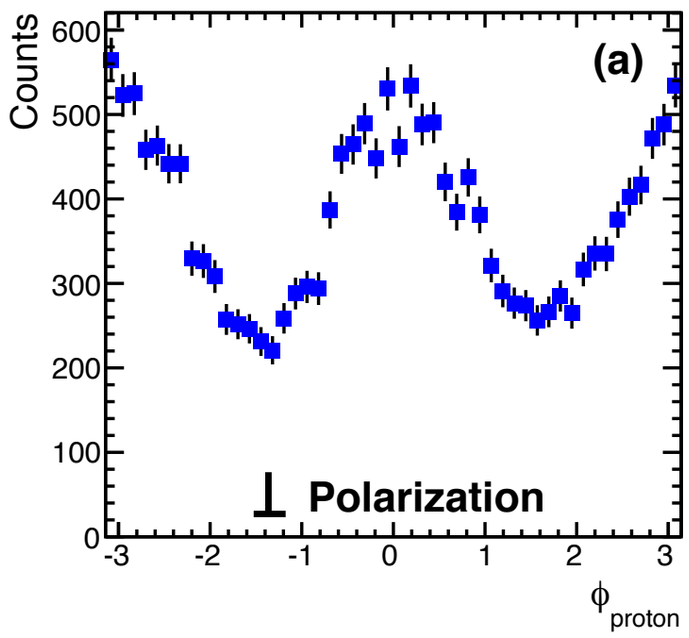
SLAC: PRD 1, 27 (1970)

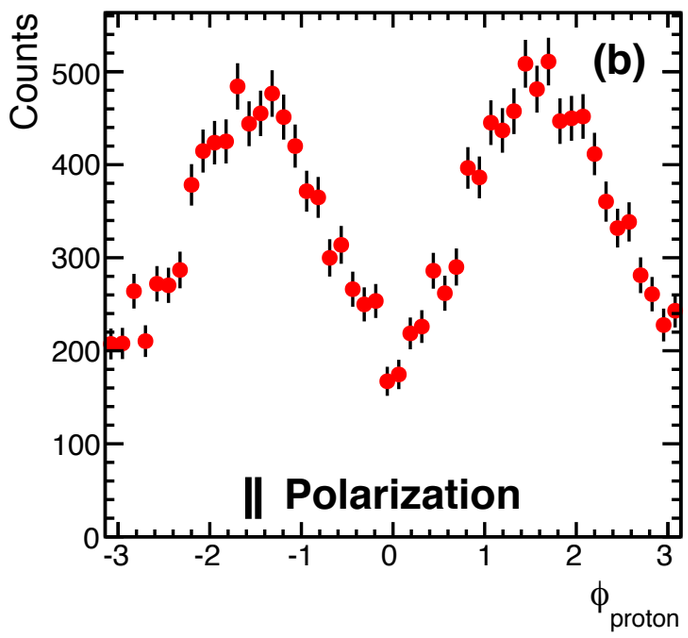


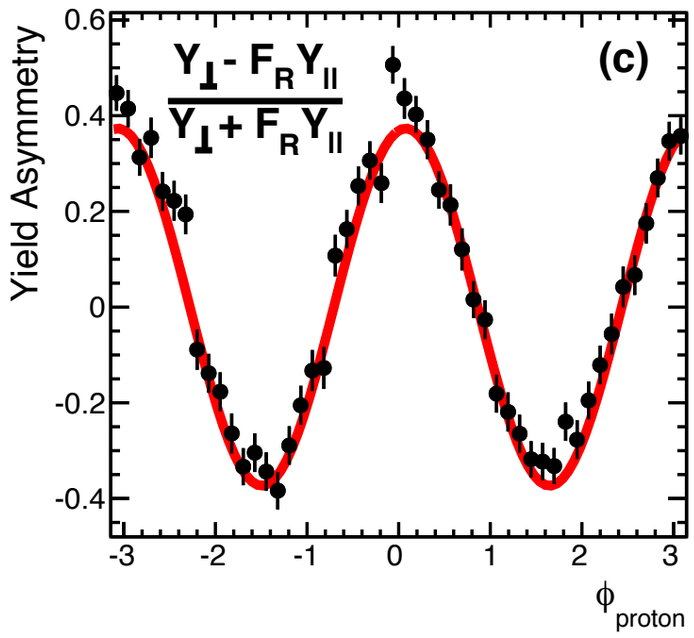




Beam Asymmetry: Method

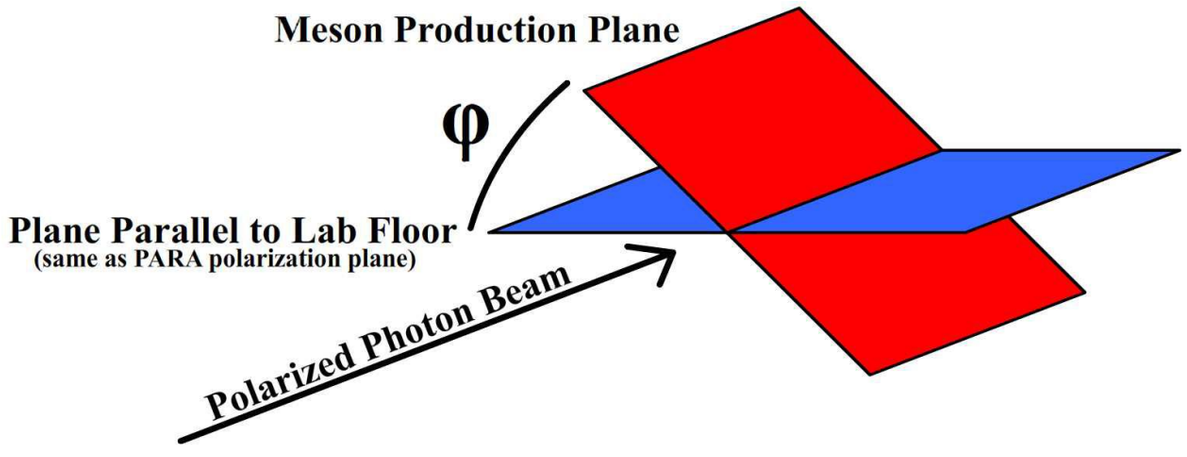




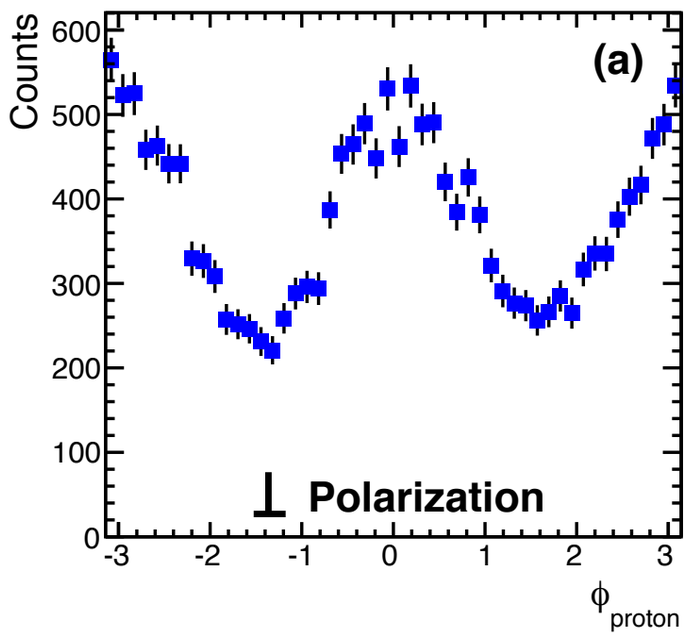


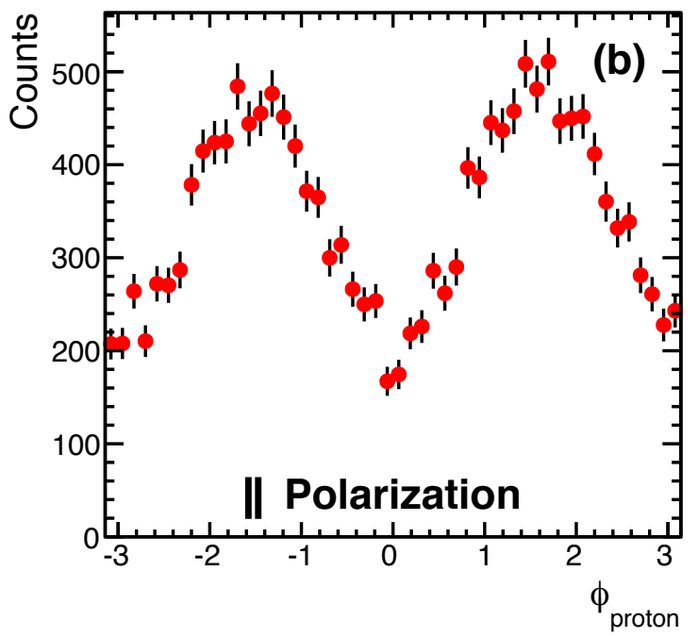
$$\frac{d\sigma}{d\phi_{\text{proton}}} \propto 1 - P\Sigma\cos 2(\,\phi_{\text{proton}} - \phi_\gamma\,)$$

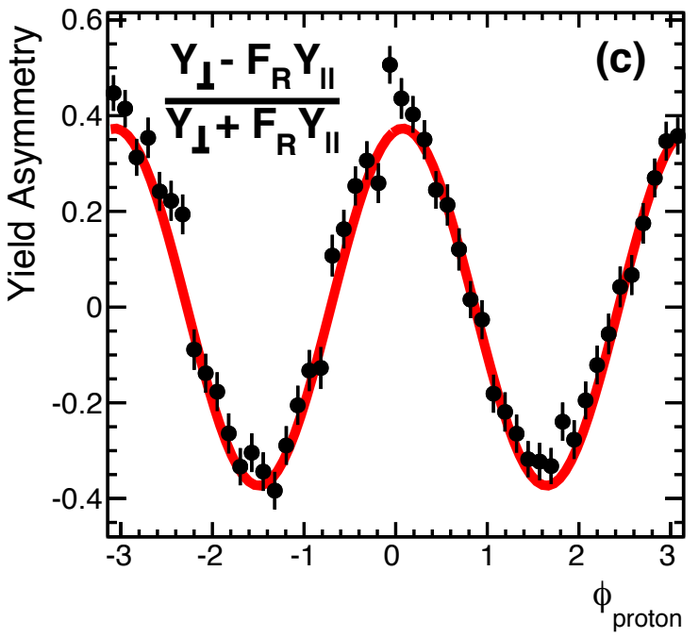
$$Y_\perp \propto N_\perp(1 + P_\perp\Sigma\cos 2\phi_{\text{proton}})\ \ \phi_\gamma = 90^\circ$$
$$Y_\parallel \propto N_\parallel(1 - P_\parallel\Sigma\cos 2\phi_{\text{proton}})\ \ \phi_\gamma = 0^\circ$$



Beam Asymmetry: Method







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

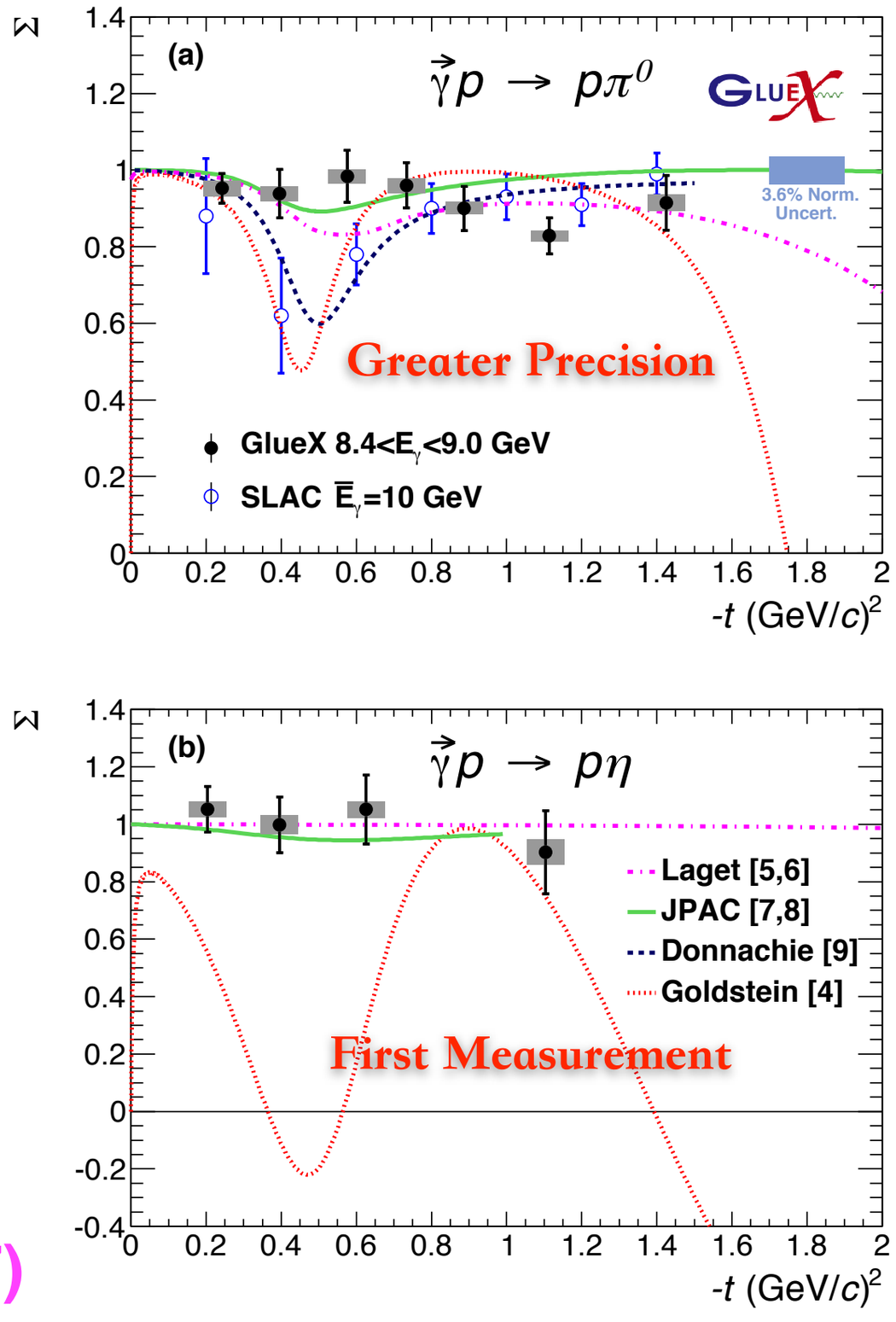
$$\frac{Y_\perp - F_R Y_\parallel}{Y_\perp + F_R Y_\parallel} = \frac{(P_\perp + P_\parallel)\Sigma \cos 2\phi_{\text{proton}}}{2 - (P_\perp - P_\parallel)\Sigma \cos 2\phi_{\text{proton}}}$$

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

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

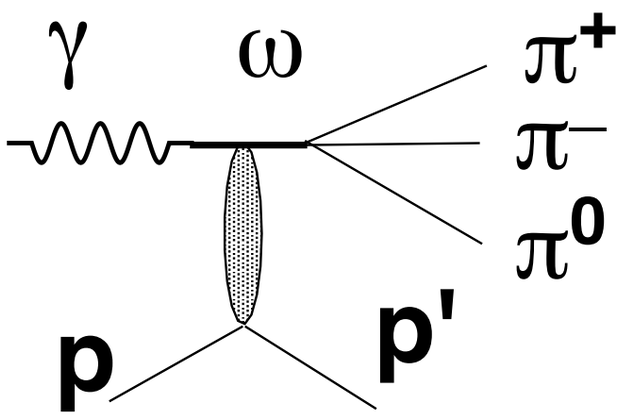
Beam Asymmetry: Results

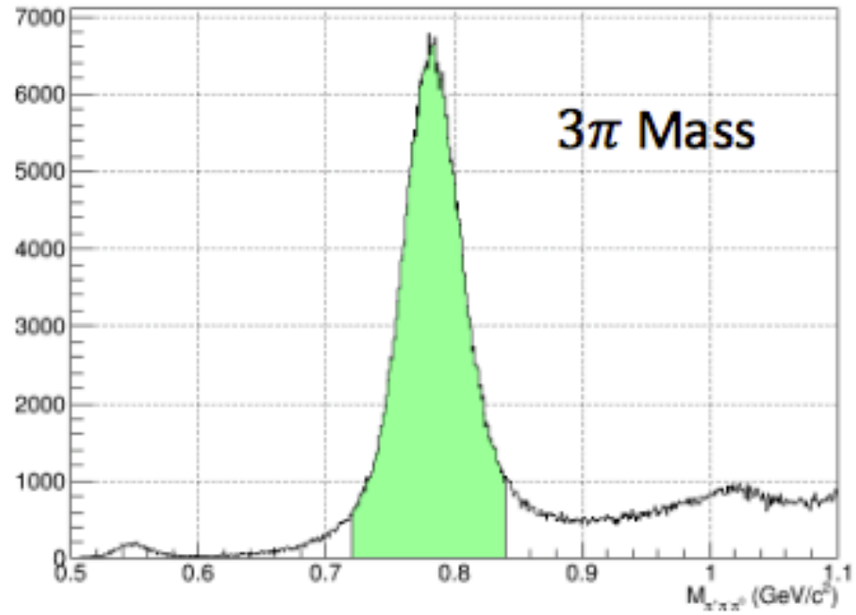
- **Measured asymmetries consistent with previous SLAC data**
- **Our measured Σ asymmetries are close to 1, with little evidence of -t dependence**
- **Don't observe prominent dip in beam asymmetry at -t = 0.5 (GeV/c)^2 as seen in the cross section**
- **Our data are somewhat consistent with the JPAC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

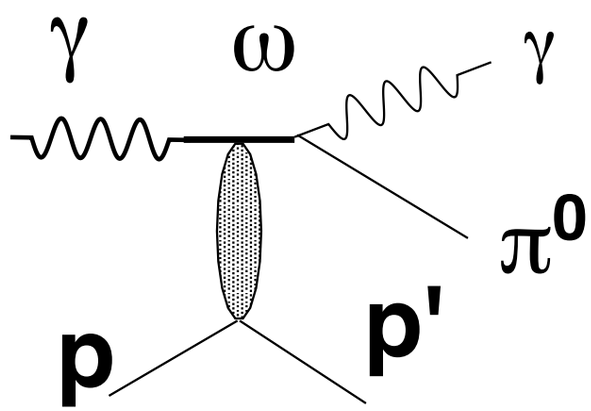


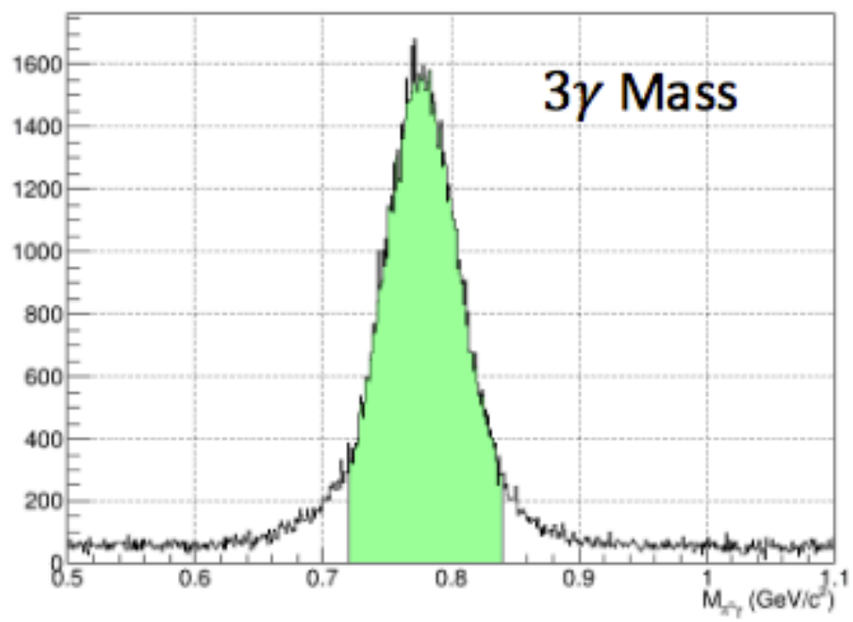
PHYS REV C 95, 042201(R) (2017)

Vector meson ω Photoproduction



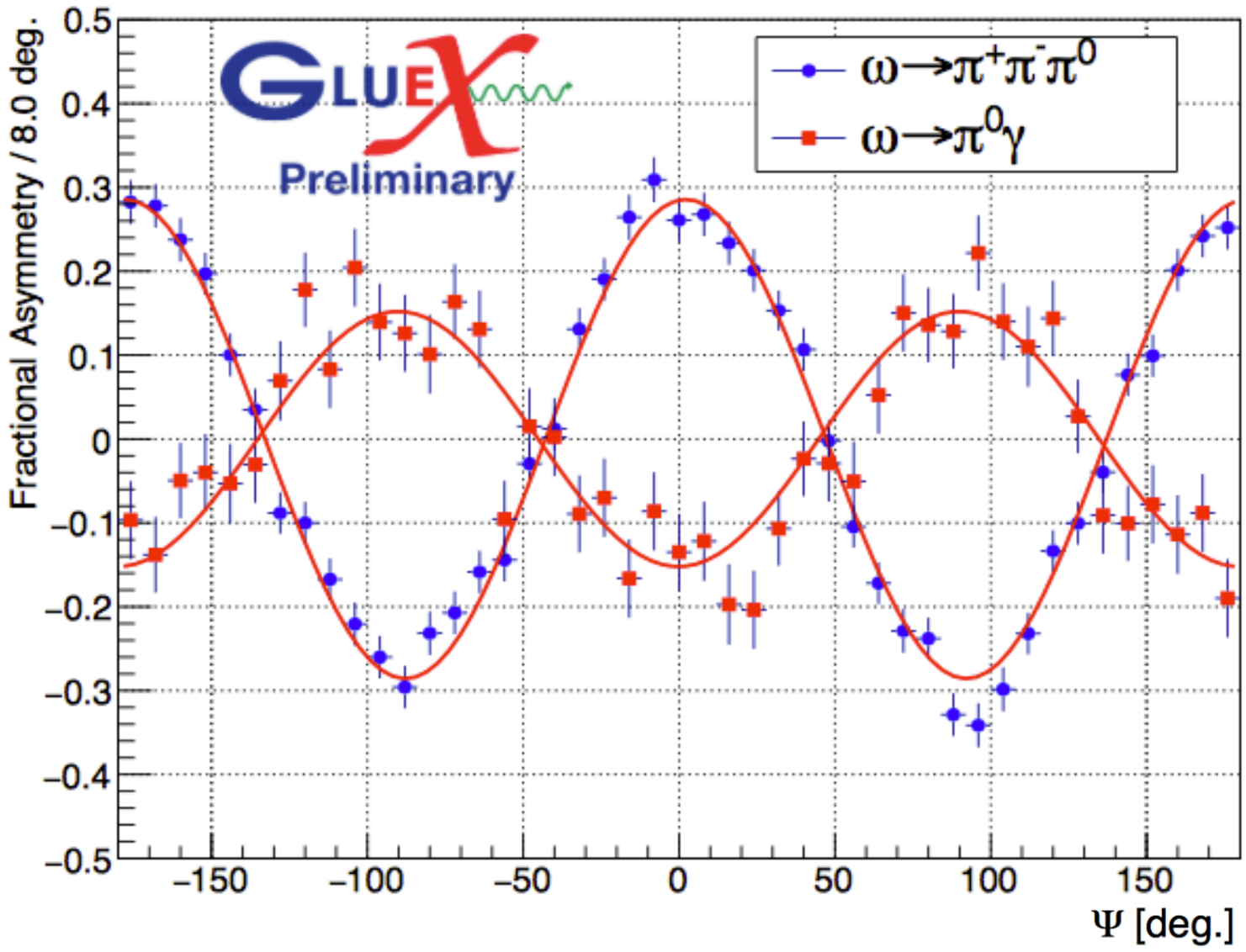






Vector meson ω Photoproduction

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



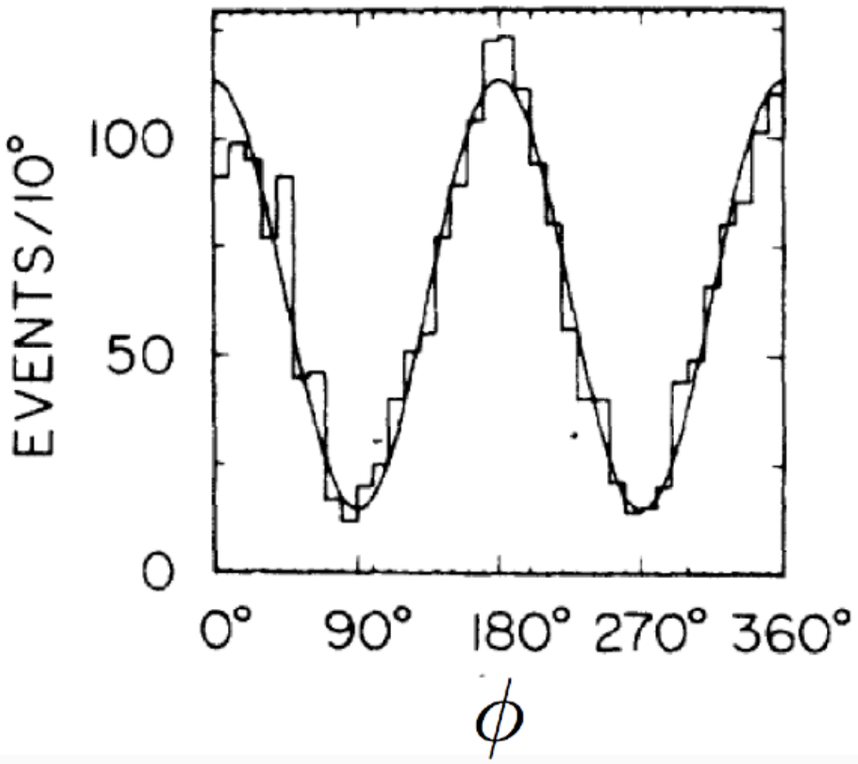
Expected:

Σ(π⁺ π⁻ π⁰) / Σ(π⁰ γ) = –2

Measured:

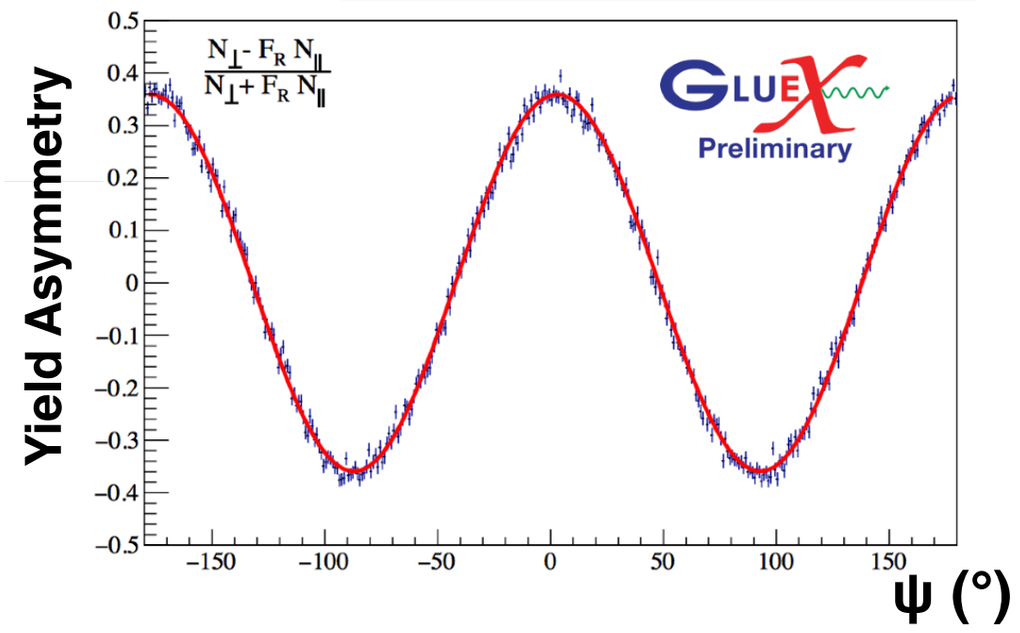
Σ(π⁺ π⁻ π⁰) / Σ(π⁰ γ) = –1.88 ± 0.13

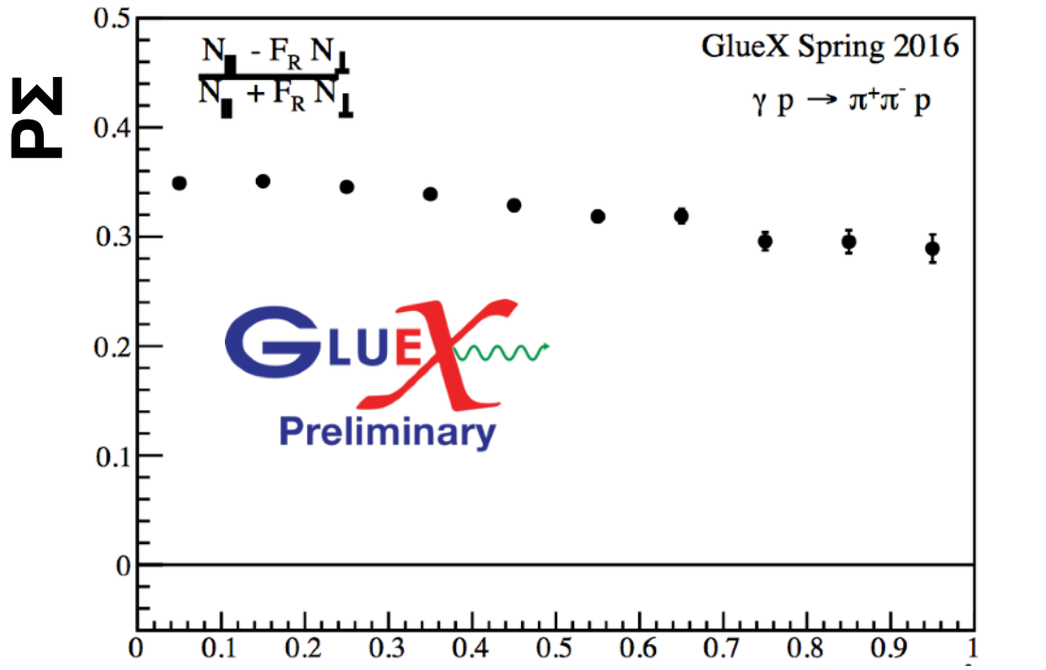
ρ Photoproduction



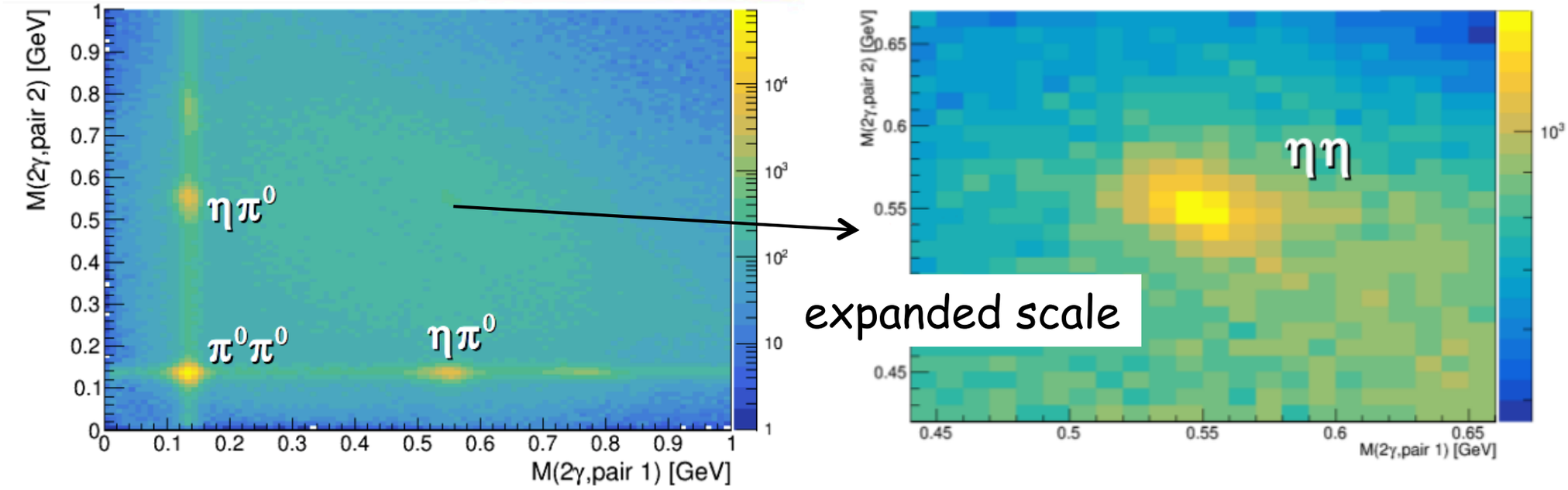
J. Ballam et al., PRD 7, 3150 (1973)

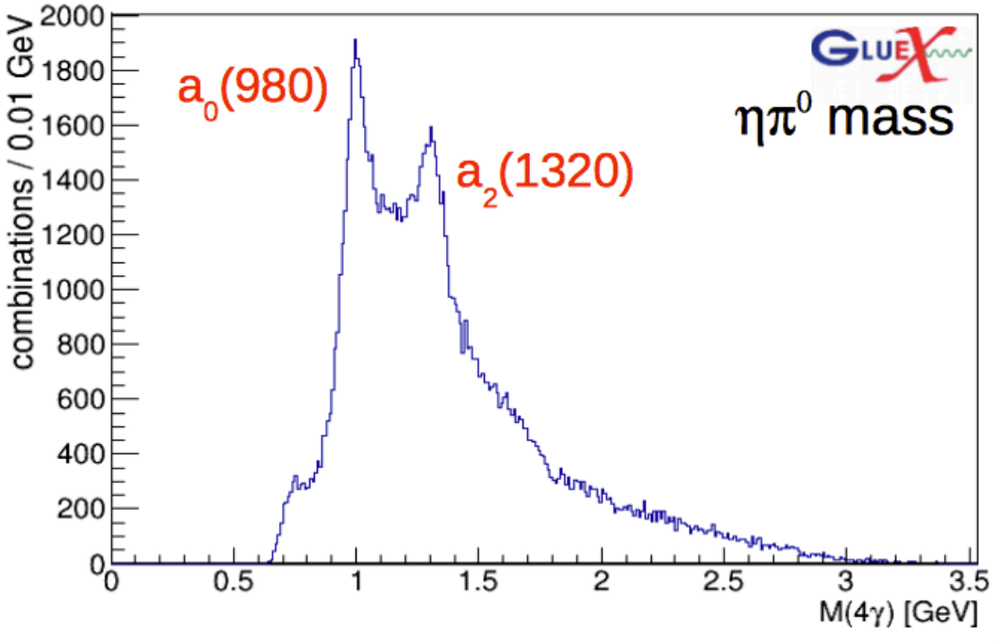
Full analysis of angular distributions is under way.

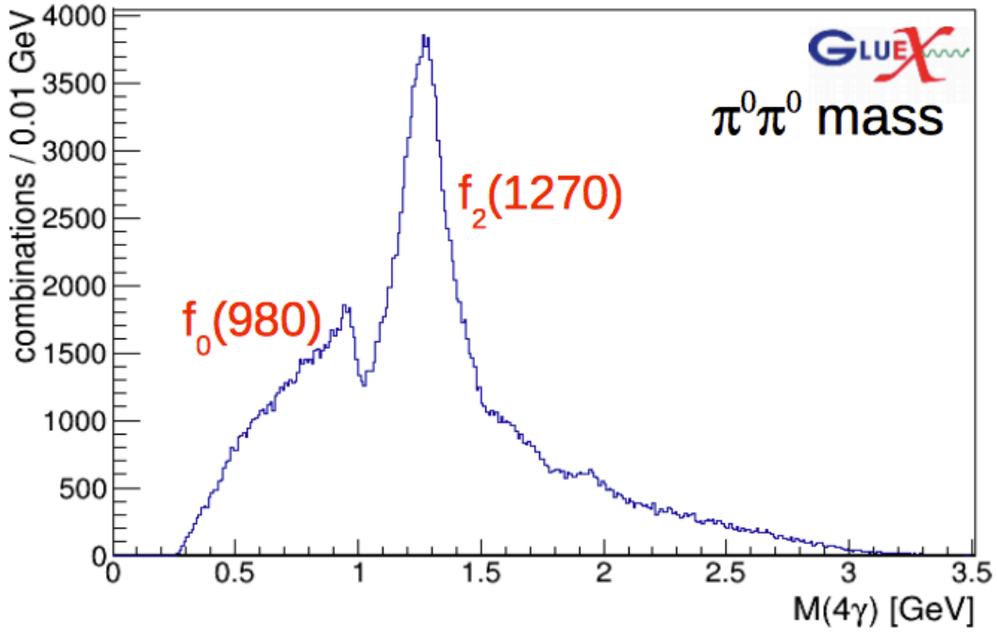




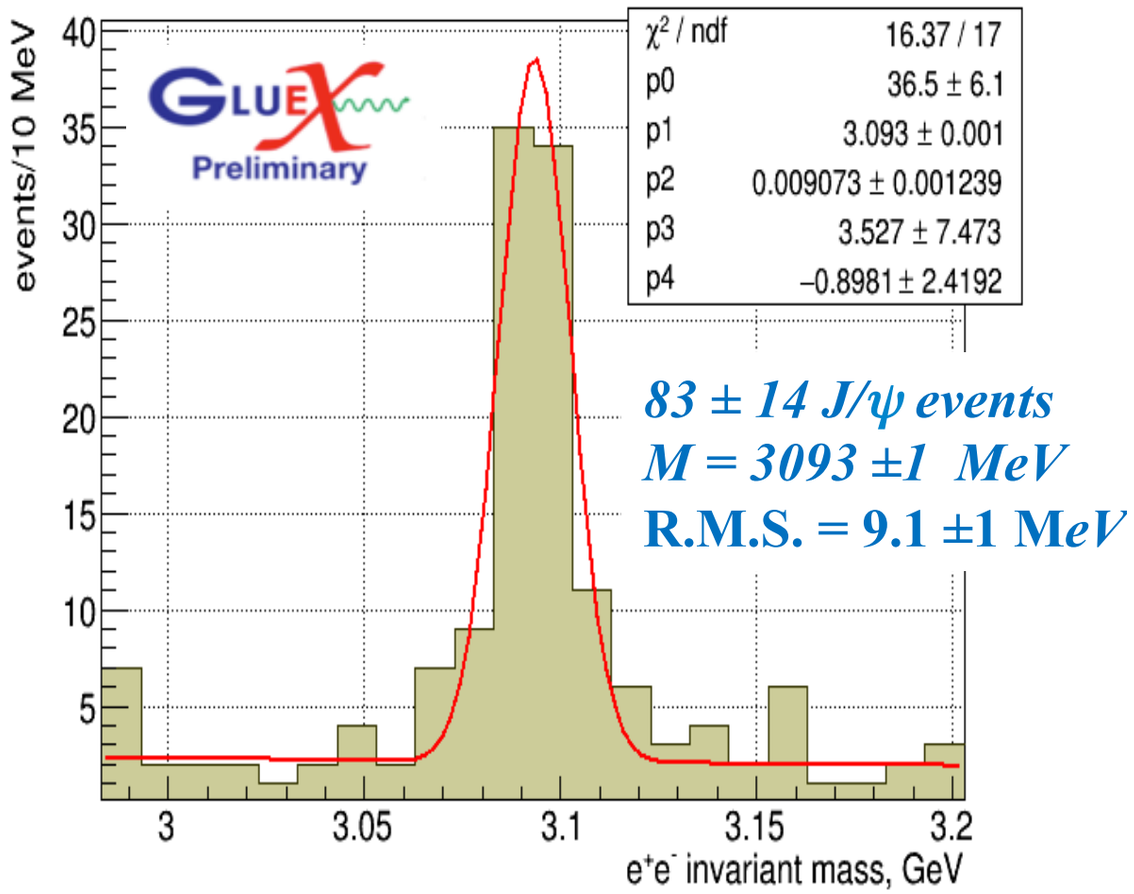
Four photon final states
scalar and tensor mesons Photoproduction

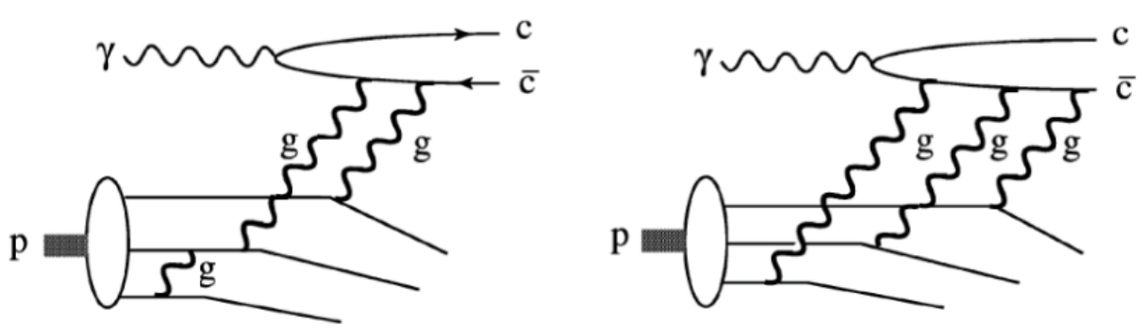


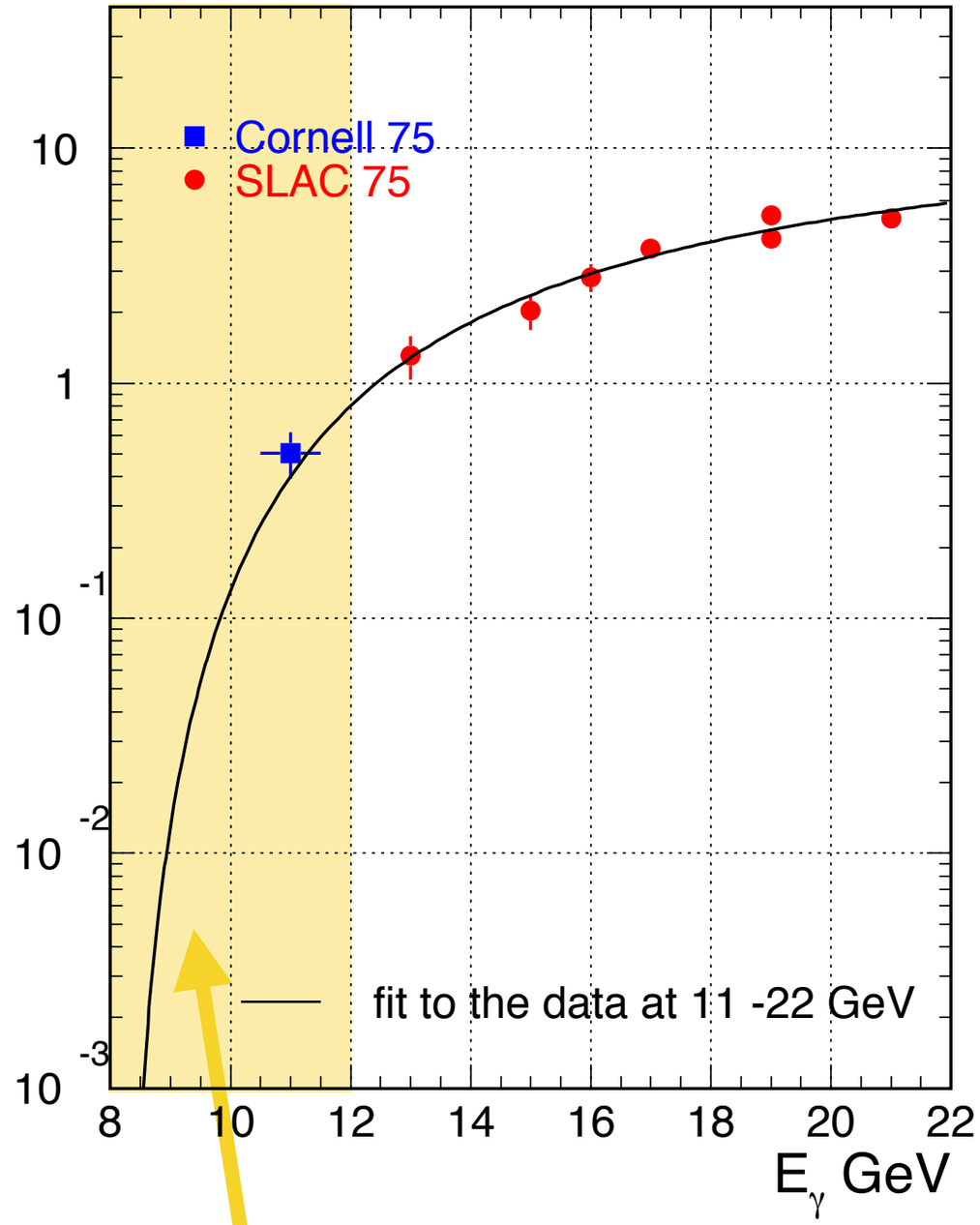




J/Ψ Photoproduction near threshold



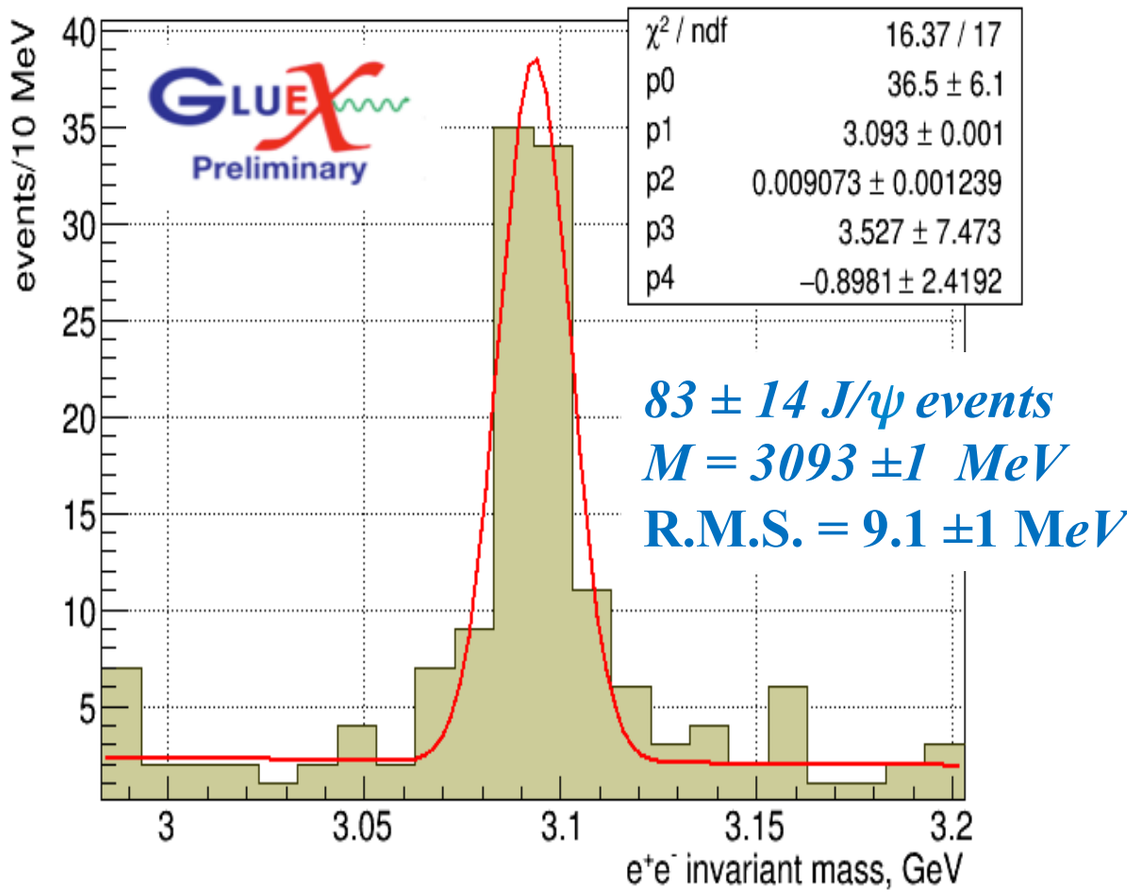


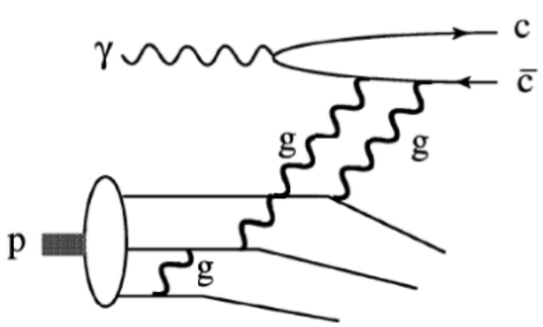


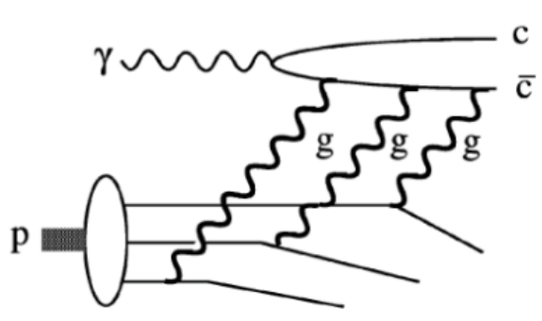
GlueX Energy Range

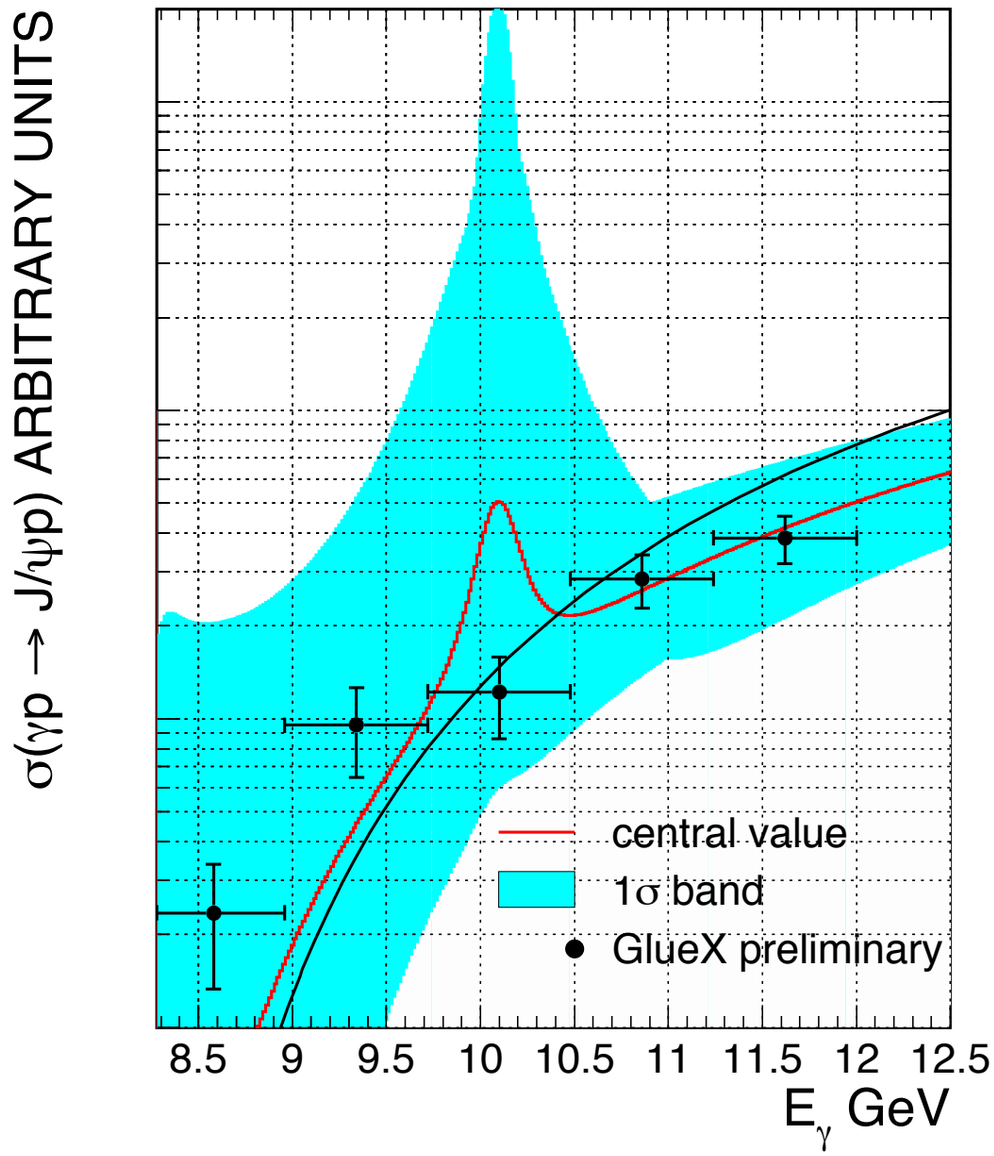
J/Ψ Photoproduction near threshold

JPAC: PRD 94 (2016) 034002









Upcoming measurements will set a limit on pentaquark 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	**130(*)**

(*) May run concurrently

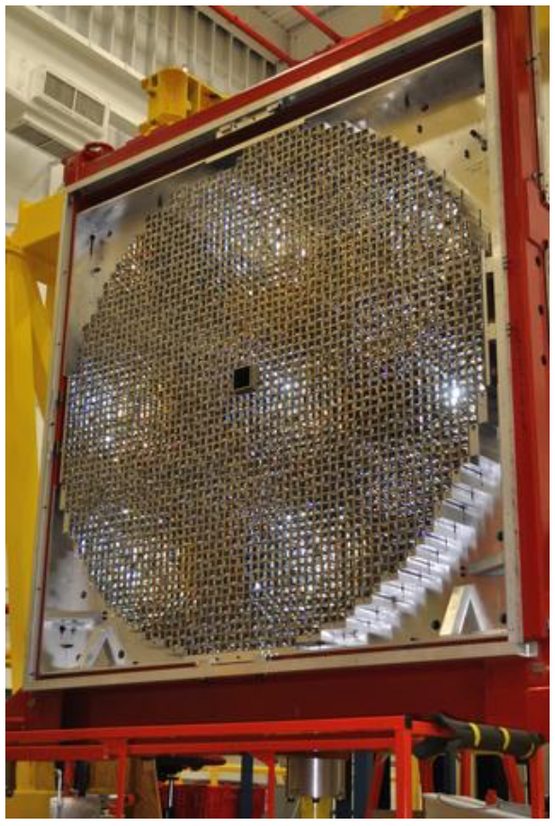
JEF Physics

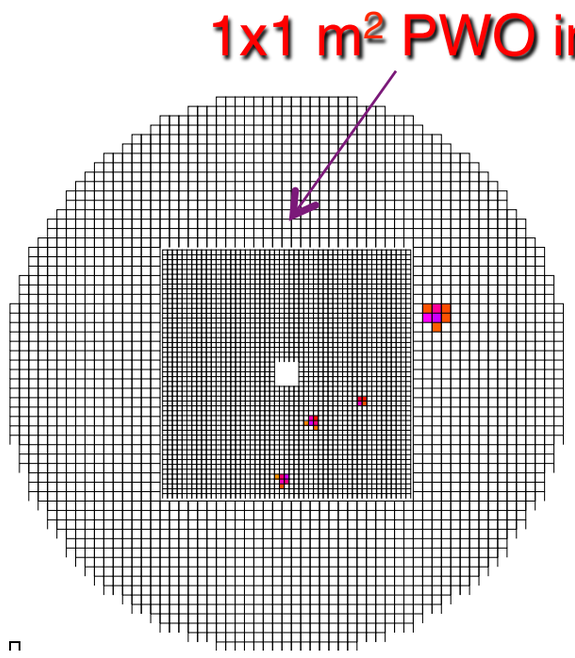
Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\gamma + B'$	beyond SM	leptophobic vector boson	4
$\pi^0 + \phi'$	beyond SM	electrophobic scalar boson	4
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[4]	4
$2\pi^0$	$< 3.5 \times 10^{-4}$	CPV, PV	4
$2\pi^0\gamma$	$< 5 \times 10^{-4}$	CV, CPV	5
$3\pi^0\gamma$	$< 6 \times 10^{-5}$	CV, CPV	6
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.3 \pm 0.2)\%$	anomaly, η-η' mixing E12-10-011	2

- **Probe for QCD and BSM physics by rare η decays**
  - **Search for sub-GeV gauge bosons (leptophobic B)**
  - **Directly constrain CVPC new physics**
  - **Tests of the ChPT predictions and understanding its links to QCD**
  - **Improve the quark mass ratio via η→3π**

Proposed JEF experiment

New Equipment: FCAL-II





2464 PWO crystal modules

PWO vs. lead glass

Property	Improvement factor
Energy σ	2
Position σ	2
Granularity	4
Radiation-resistance	10

PWO crystals may be bought from Shanghai Institute of Ceramics

QC of the PWO crystals can be performed in China

Upgraded Forward Calorimeter with High resolution, high granularity PWO insertion (FCAL-II) to detect multi-photons from the η decays

Summary and Outlook

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

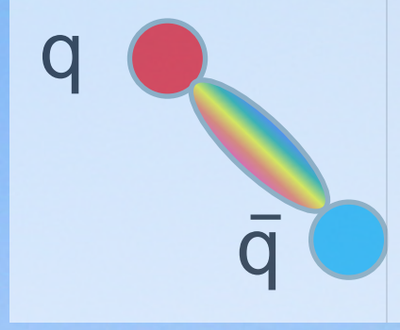
- The engineering and the first physics runs have been taken successfully.

- 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. 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!



Backup

The Photoproduction Mechanisms and the Decay Modes of Exotic Hybrids

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

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

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

$\rho P \longrightarrow b_0$

$\omega P \longrightarrow h_0$

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

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

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

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

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

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

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

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

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

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

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

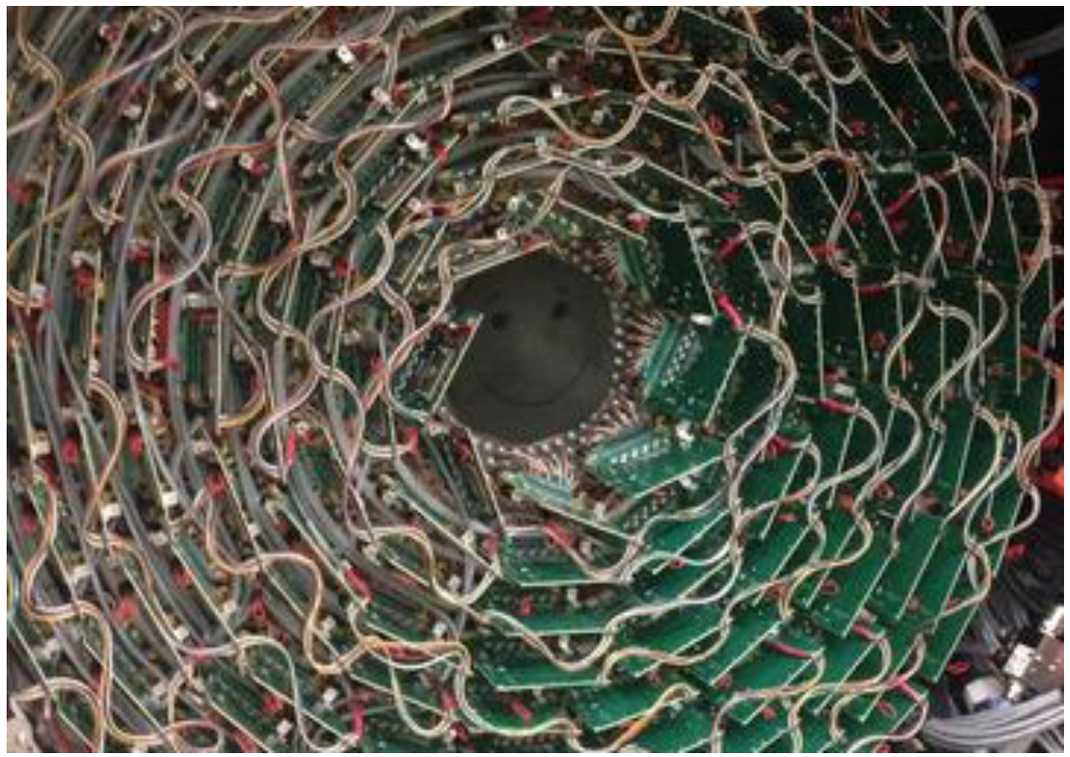
$h_0 \rightarrow b_1\pi\ ,\ h_1\eta$

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

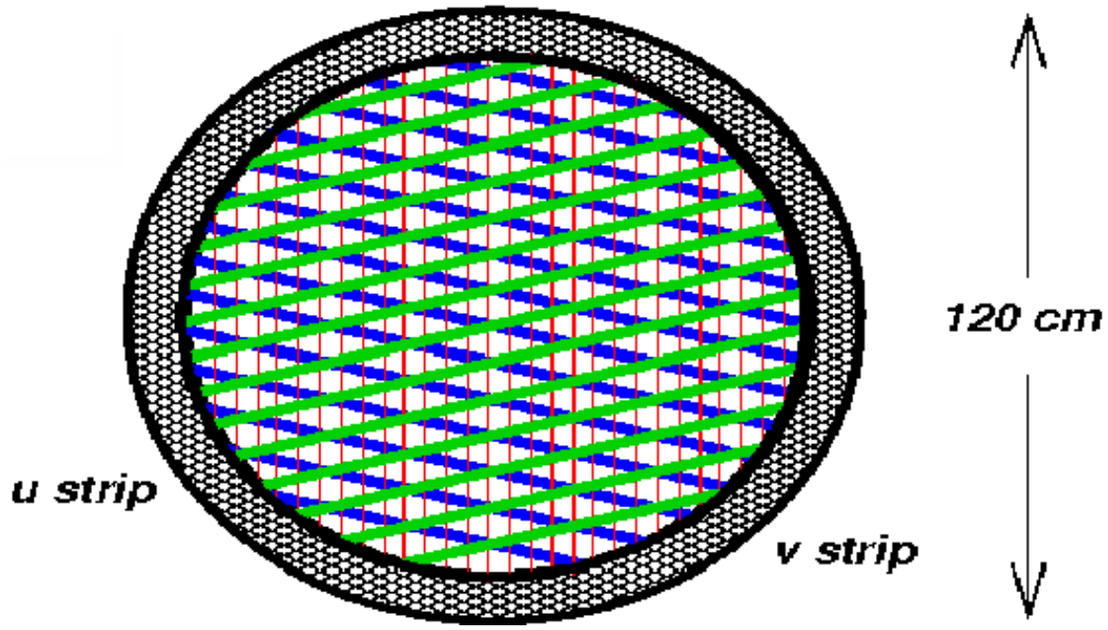
The meson photoproduction is a promising experimental technique to search for exotic hybrid mesons.

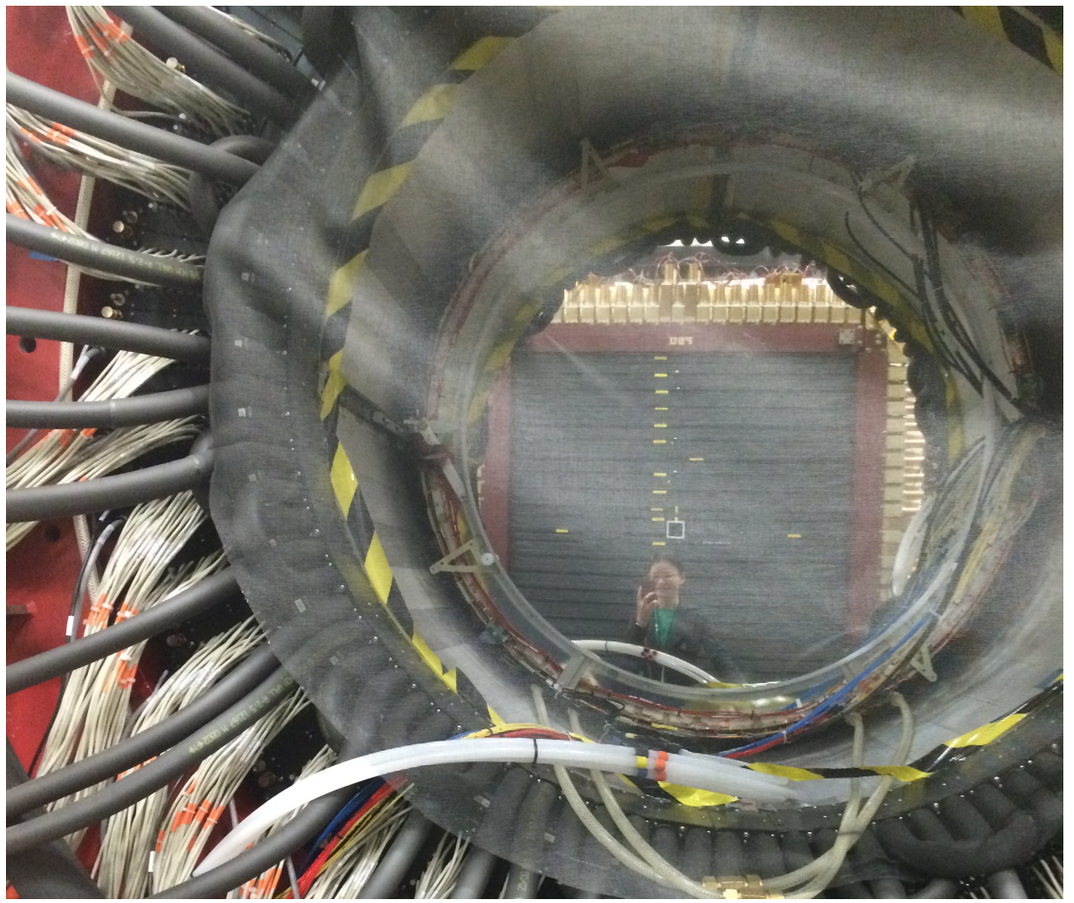
CDC and FDC

Straw tube drift chamber



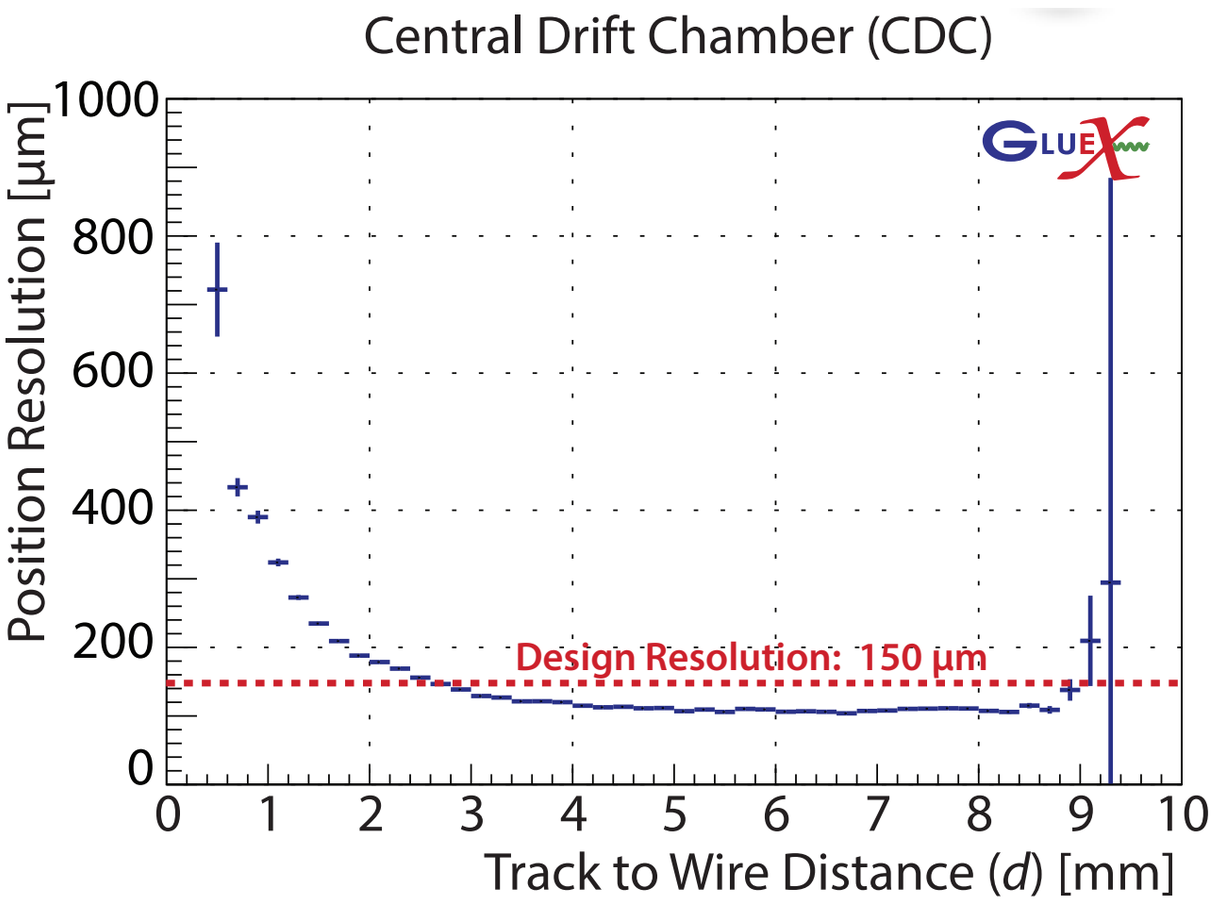
Interleaved planes of field/sense wires and planes of cathode strips

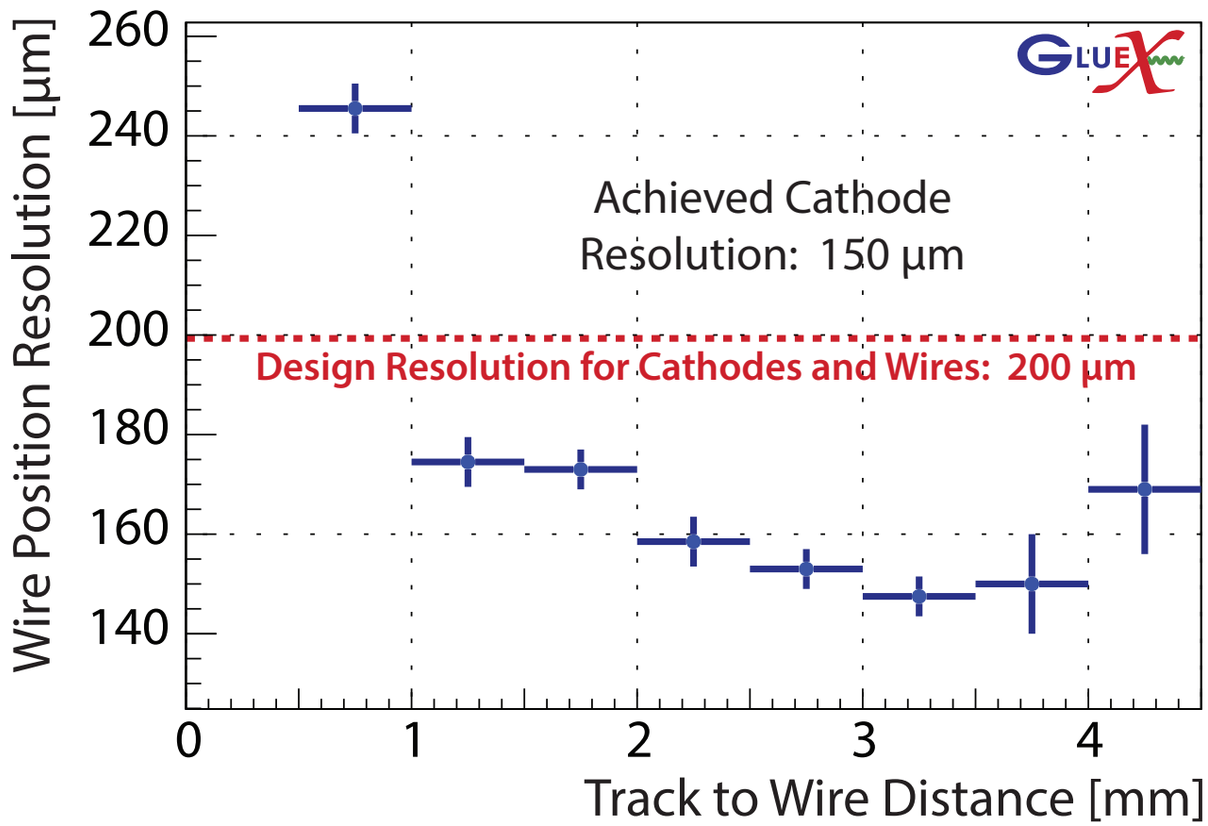




Detector Performance

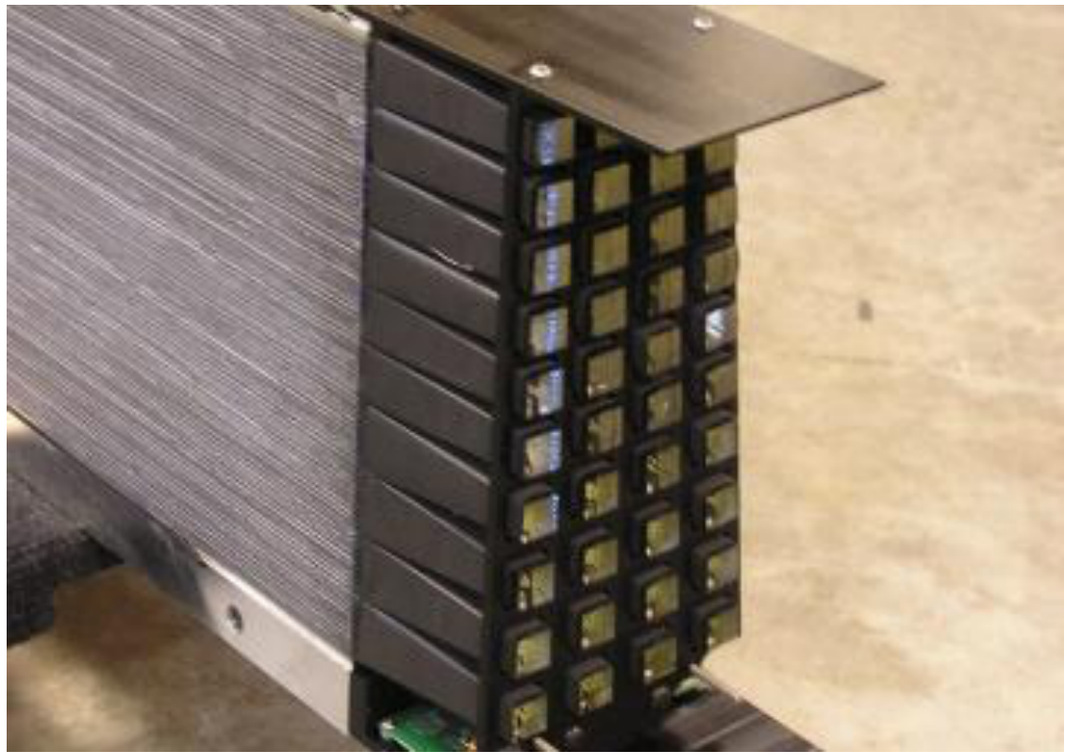
Drift chambers exceed design position resolution



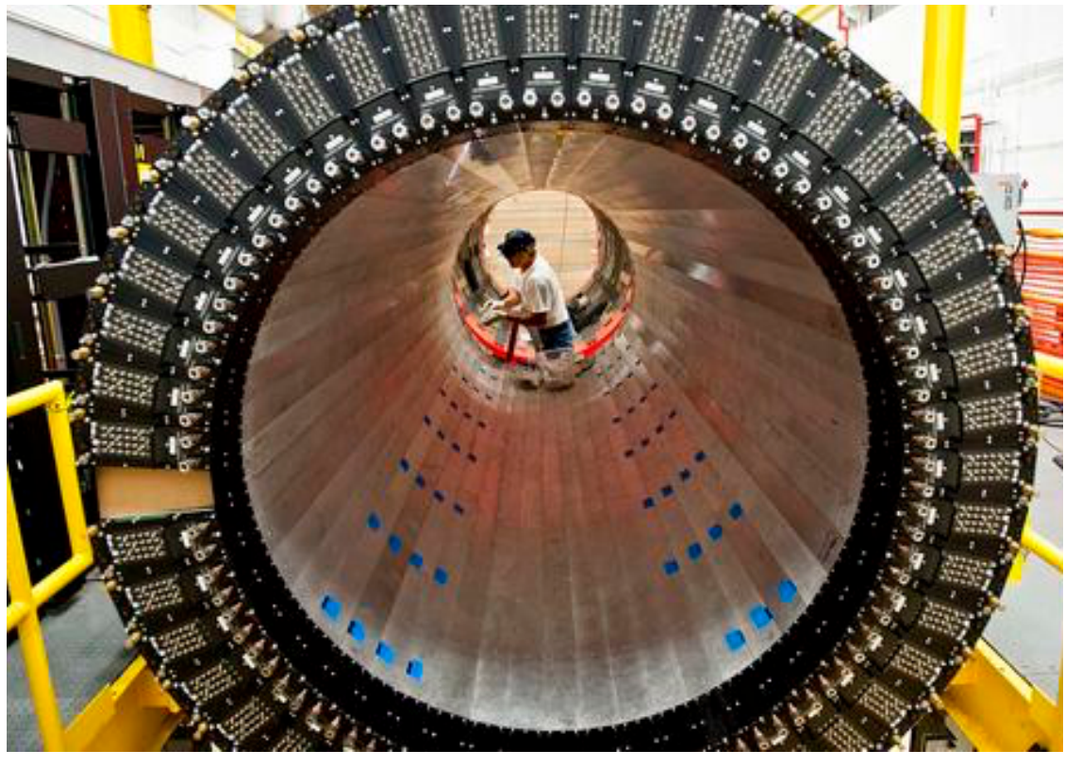


BCAL and FCAL

Scintillating fibers in the interstitial layers of lead



Fast silicon photomultipliers (SiPMs)

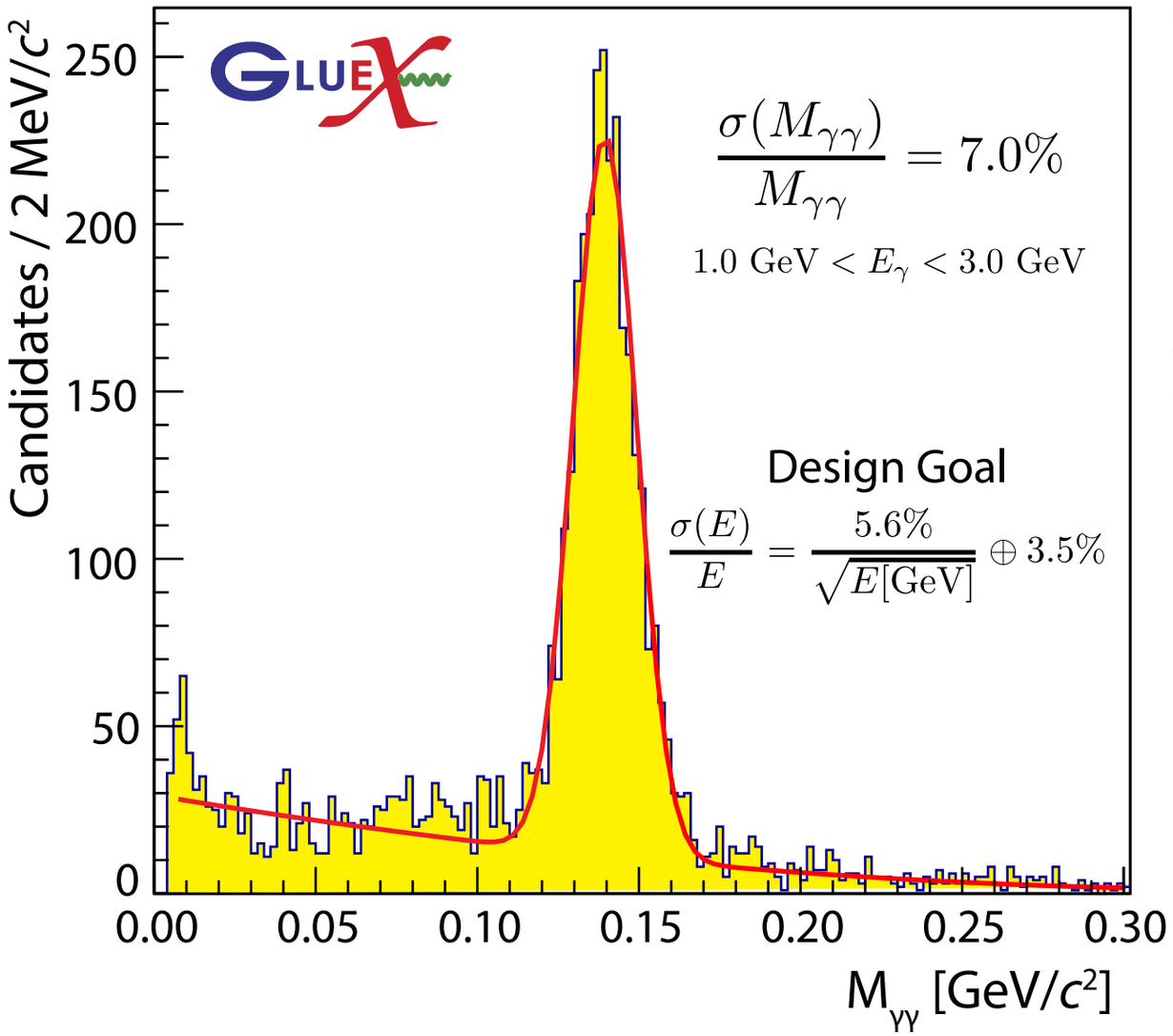


F8-00 lead glass, 4 × 4 × 45 cm

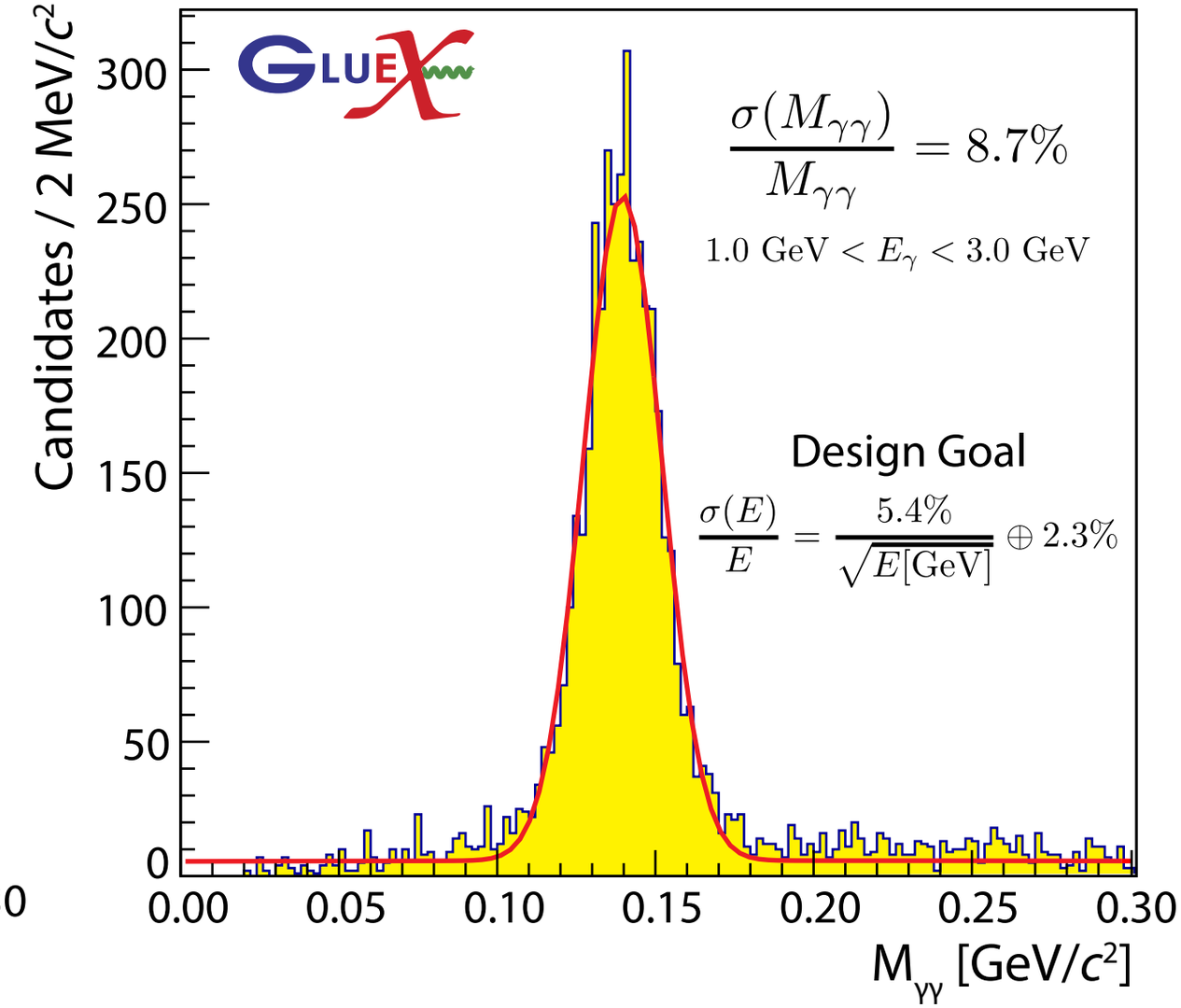
Detector Performance

Calorimeters approaching design energy resolution

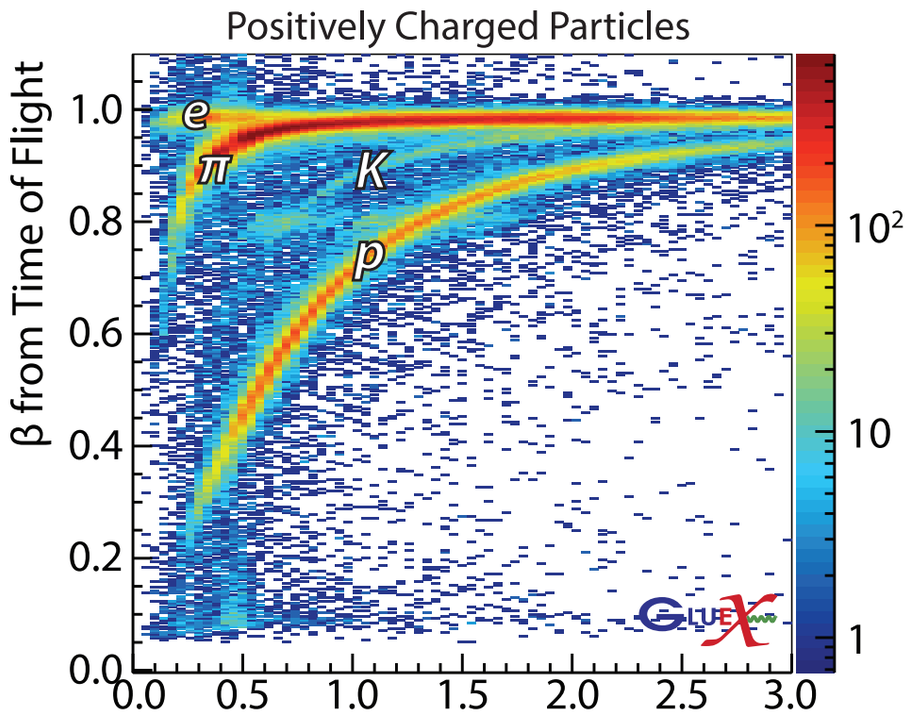
Forward Lead Glass Calorimeter

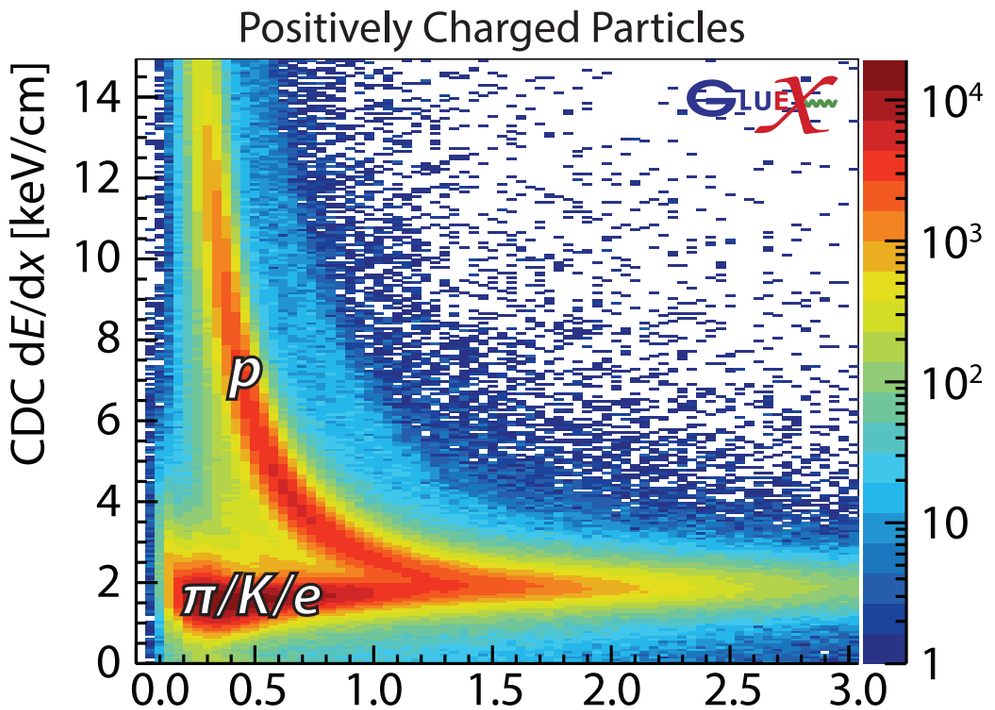


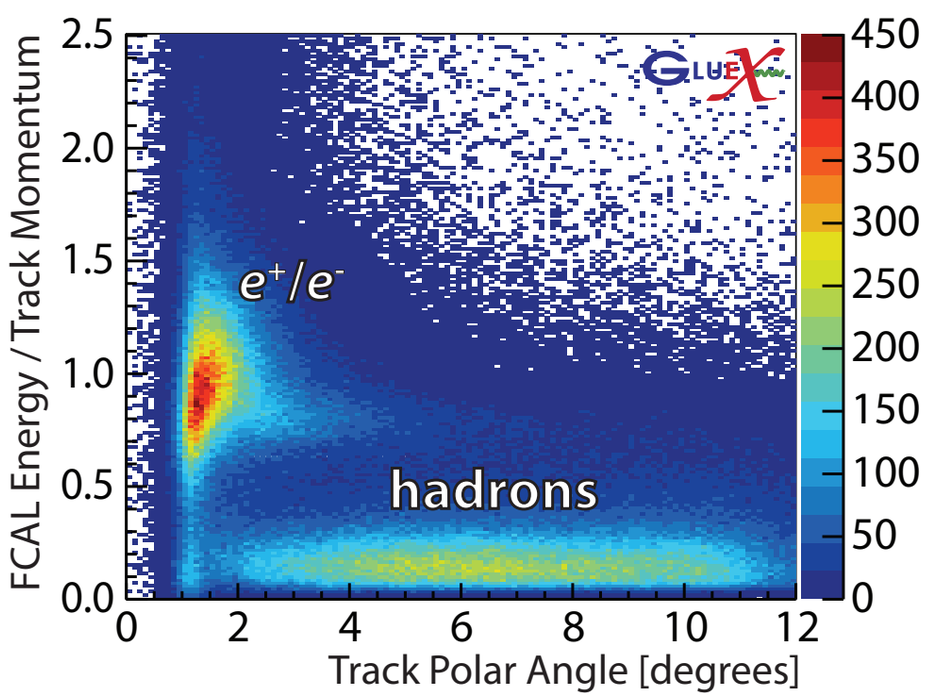
Barrel Lead-Scintillating Fiber Calorimeter



Particle Identification Performance

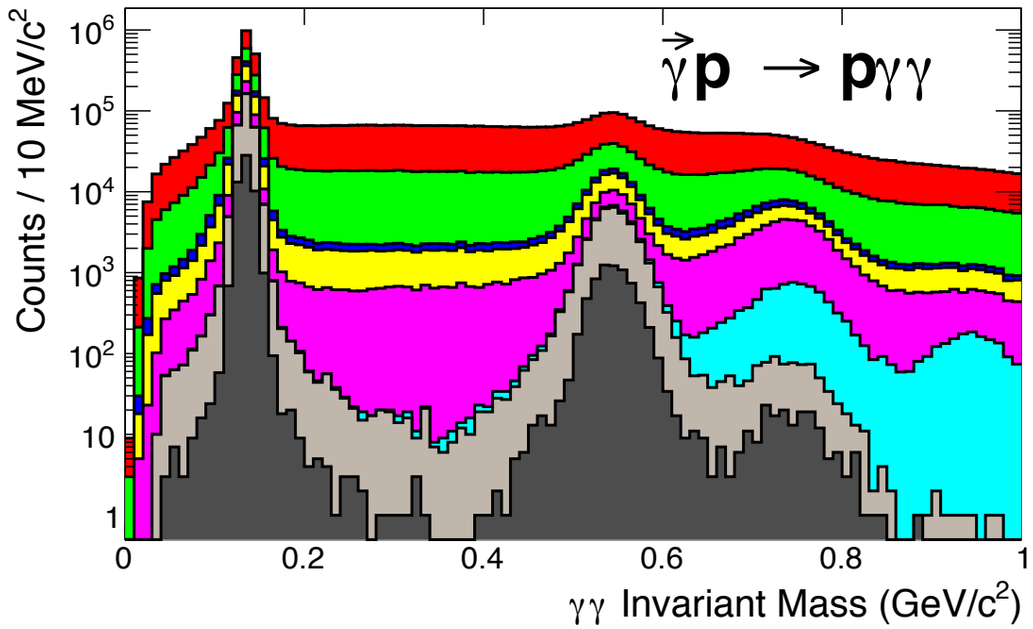


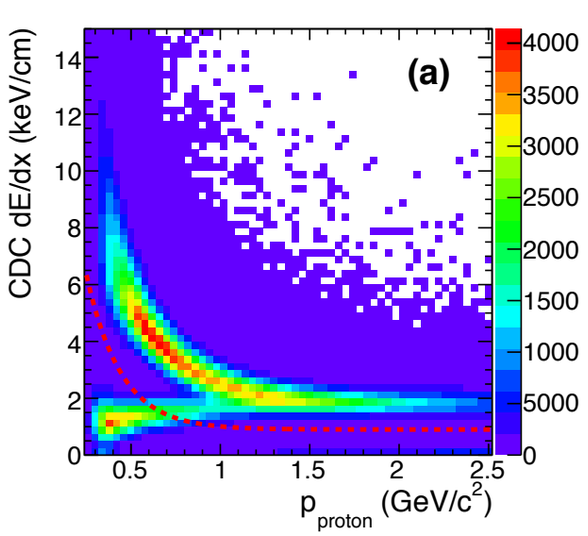


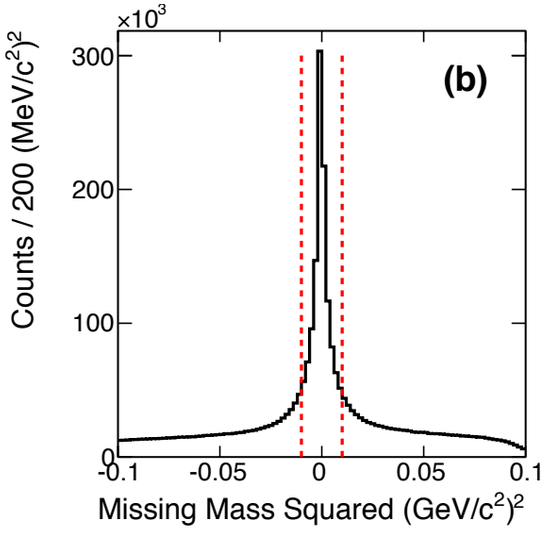


Event Selection

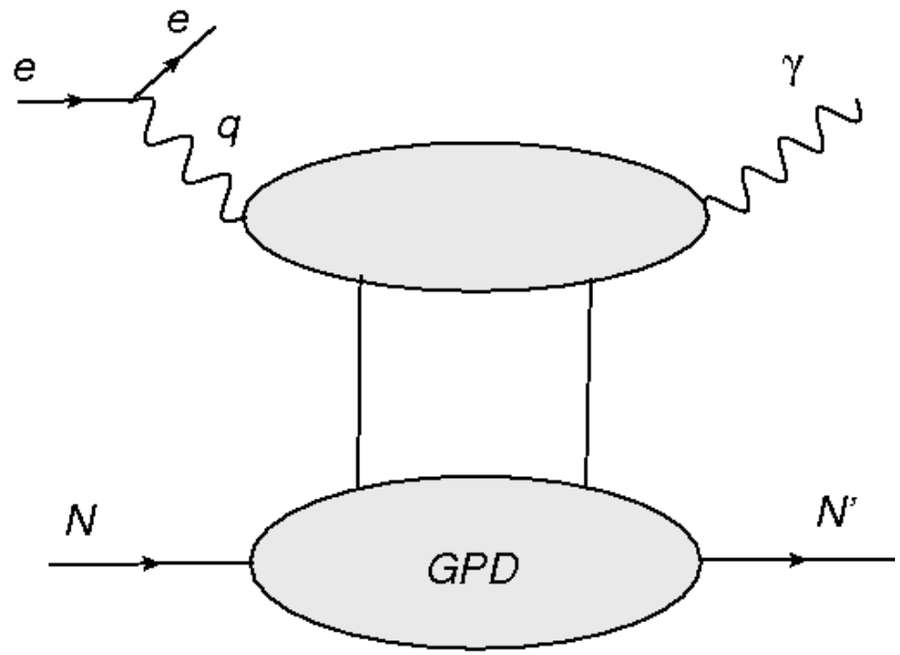
- **Loose timing cuts**
- **Proton requirements:**
  - **p_{proton} > 250 MeV**
  - **Originates from target region**
  - **CDC dE/dx contour**
- **γp→pγγ cuts**
  - **Δϕ, Missing Mass squared, Missing energy, beam energy (E_γ>4.0GeV), only two photons reconstructed, Missing mass off proton, coherent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



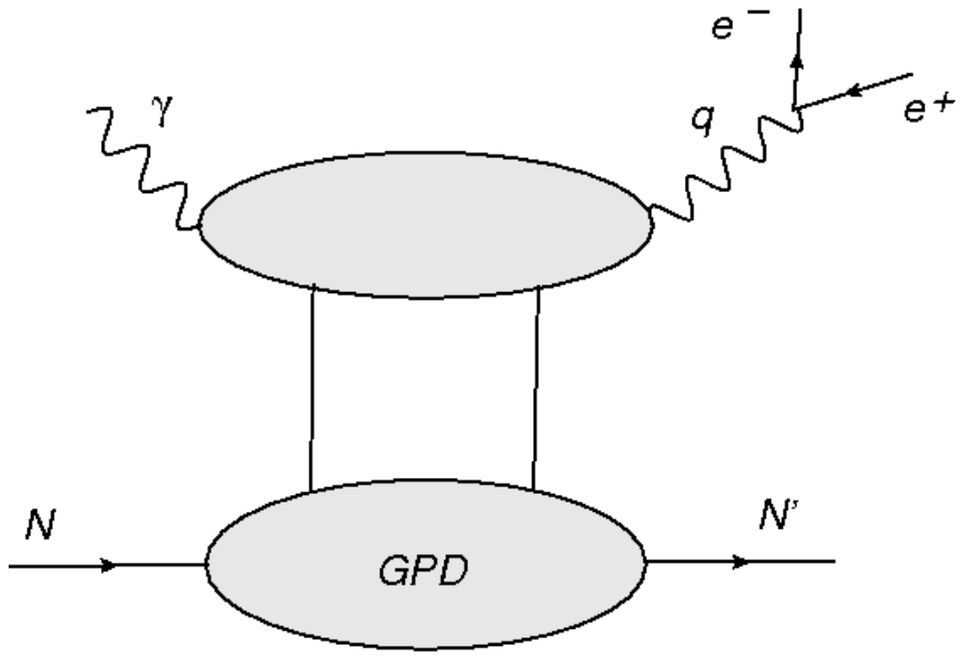




Deeply Virtual Compton Scattering



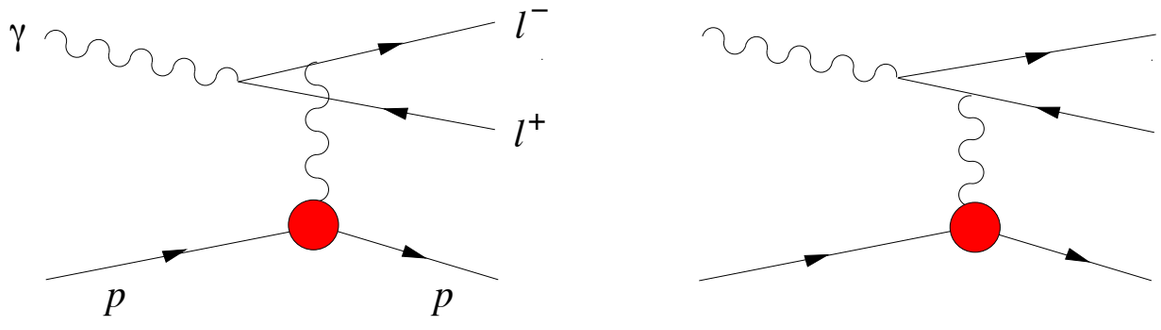
Time-like Compton Scattering



Inverse

Together obtain stronger constraints on the generalized parton distributions

Bethe-Heitler (BH)



- **BH contributes at the amplitude level in both case**
- **Always dominates over TCS**
- **The interference can be accessed through the angular distribution of the lepton pair**

arXiv:hep-ph/0110062