

Nuclear Physics

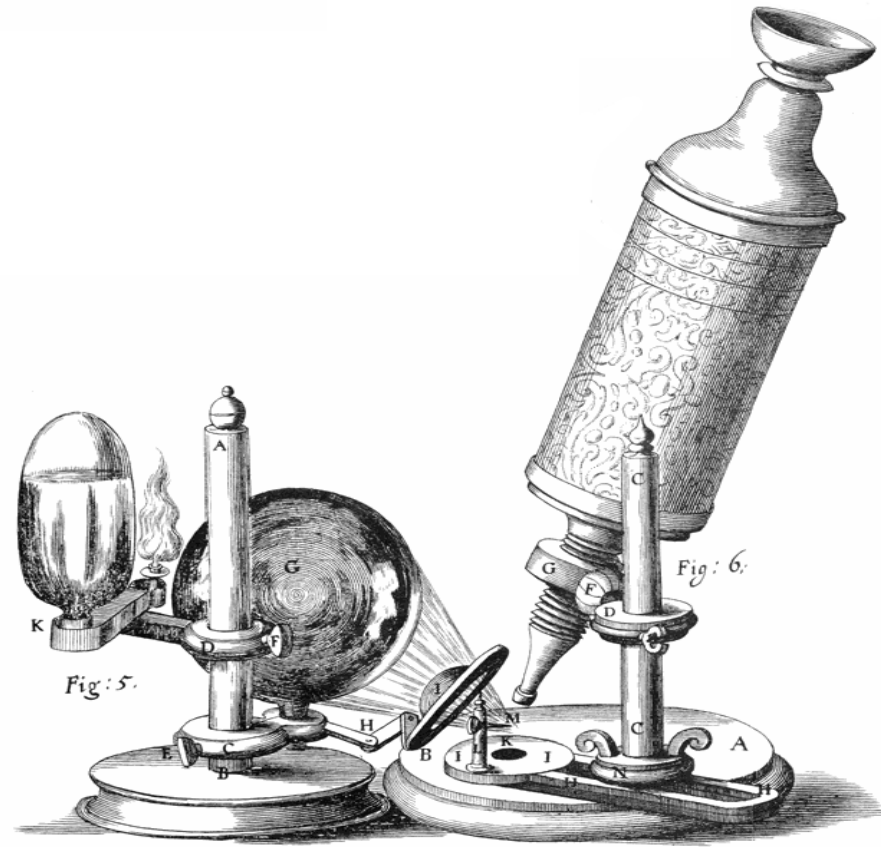
Exploring the Heart of Matter

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With slides provided by Latifa Elouadrhiri and Alex Barnes

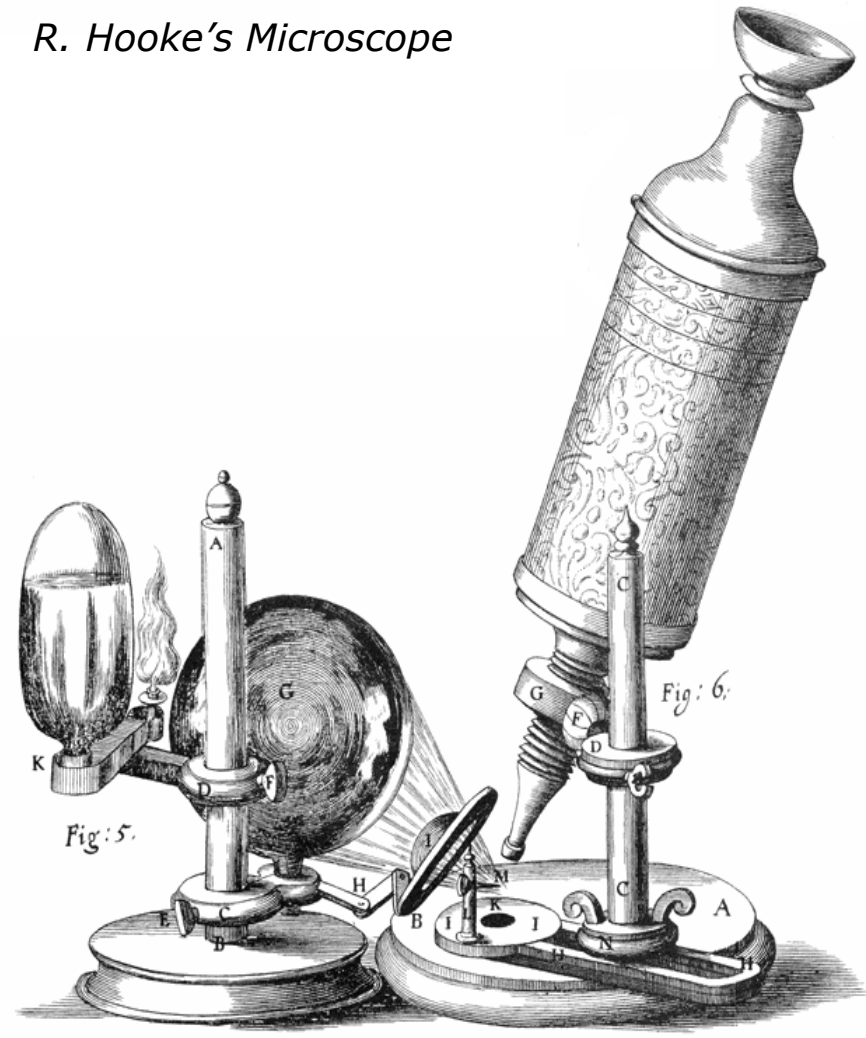
Part –II Particle Scattering Microscope on the world of quarks



The Microscope

In the past, scientists tried to study microscopic objects invisible to the human eye, using magnifying glasses first and then ever more sophisticated tools

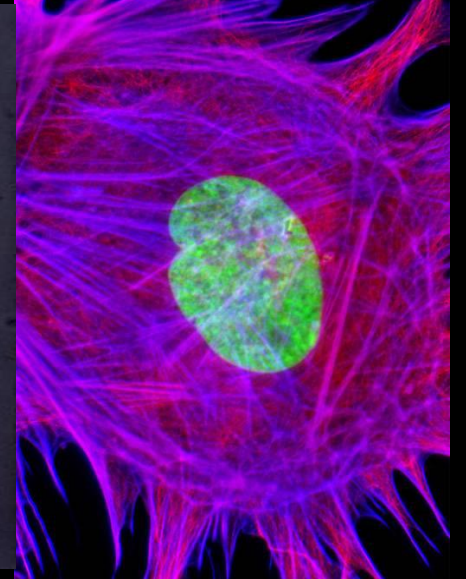
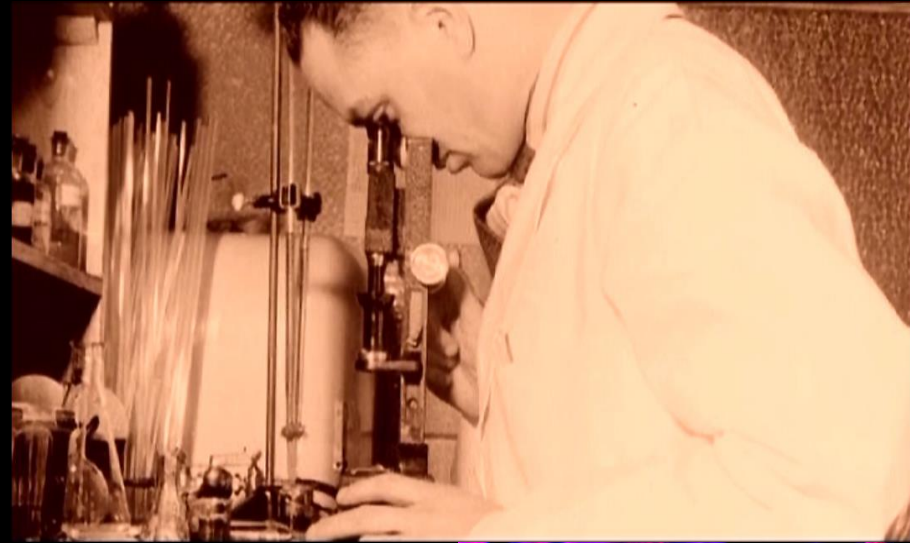
R. Hooke's Microscope



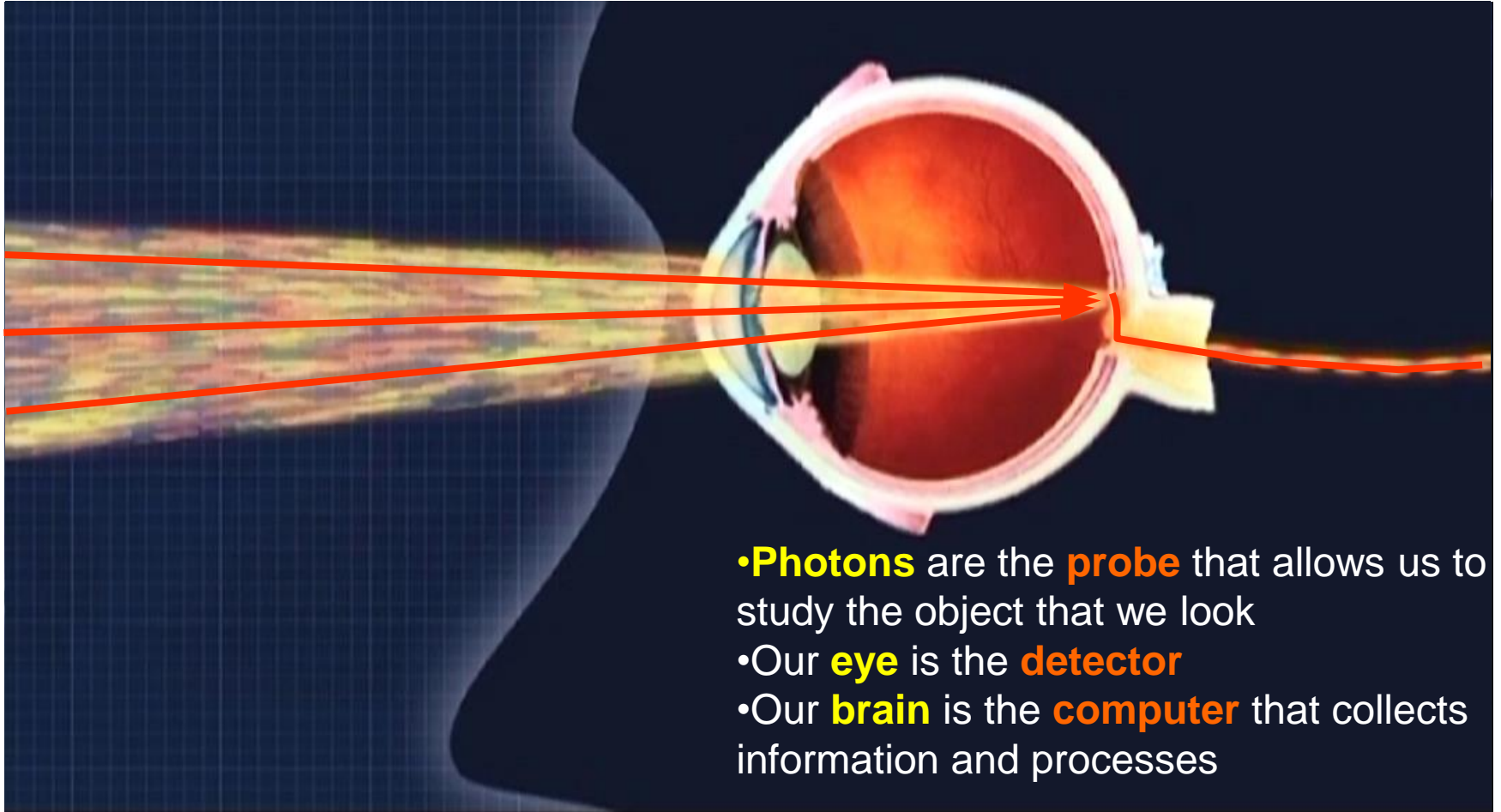
The Microscope

In the past, scientists tried to study microscopic objects invisible to the human eye, using magnifying glasses first and then ever more sophisticated tools

The optical microscope allowed the discovery of the existence of microscopic organisms and to study the organic fabric



The Microscope



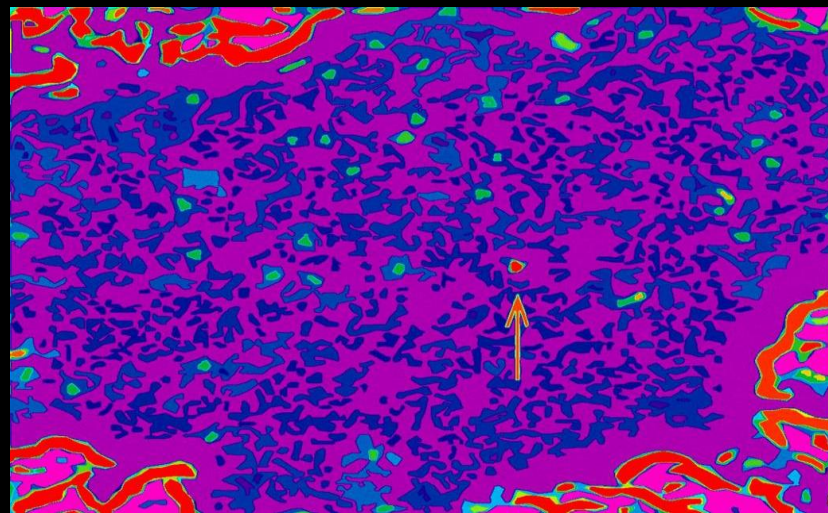
- **Photons** are the **probe** that allows us to study the object that we look
- Our **eye** is the **detector**
- Our **brain** is the **computer** that collects information and processes

The Microscope

Today, more sophisticated microscopes achieved a very high resolution

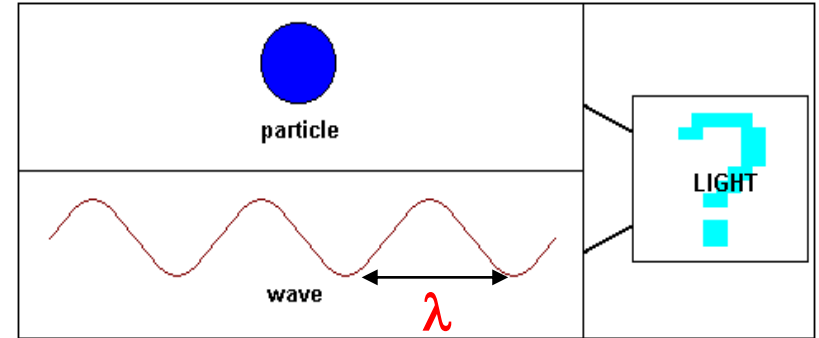
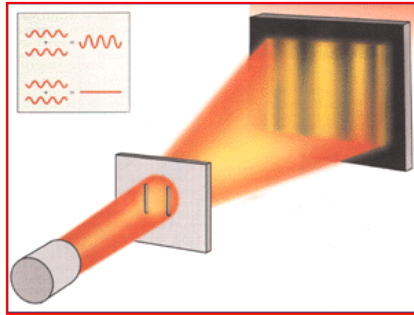
the electron microscope allows you to see objects the size of the atom

But how can we get to "see" quarks?



Wave-particle duality of Nature

Central concept of quantum mechanics:
all particles present **wave-like** properties



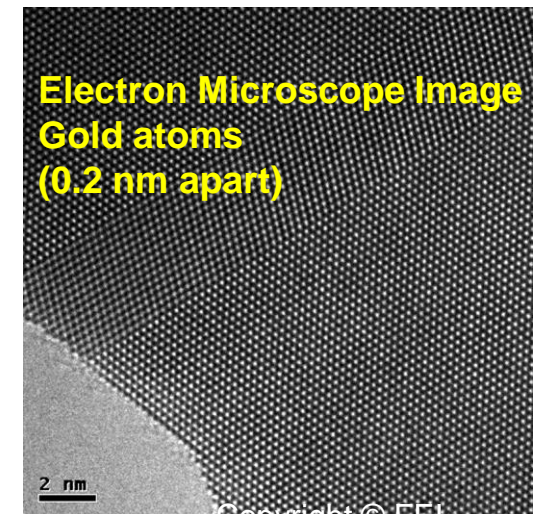
Not only light has a dual nature

De Broglie showed that moving particles have an equivalent wavelength λ

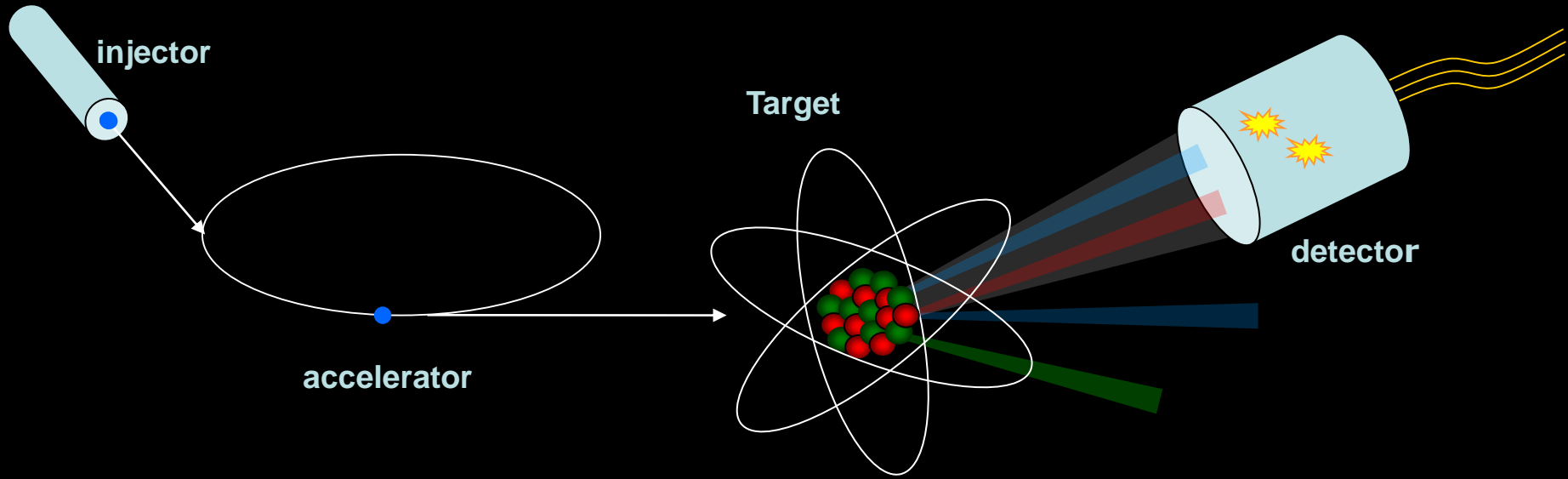
$$\lambda \propto \frac{1}{p}$$

So high momentum gives us short wavelengths so we can make out small details

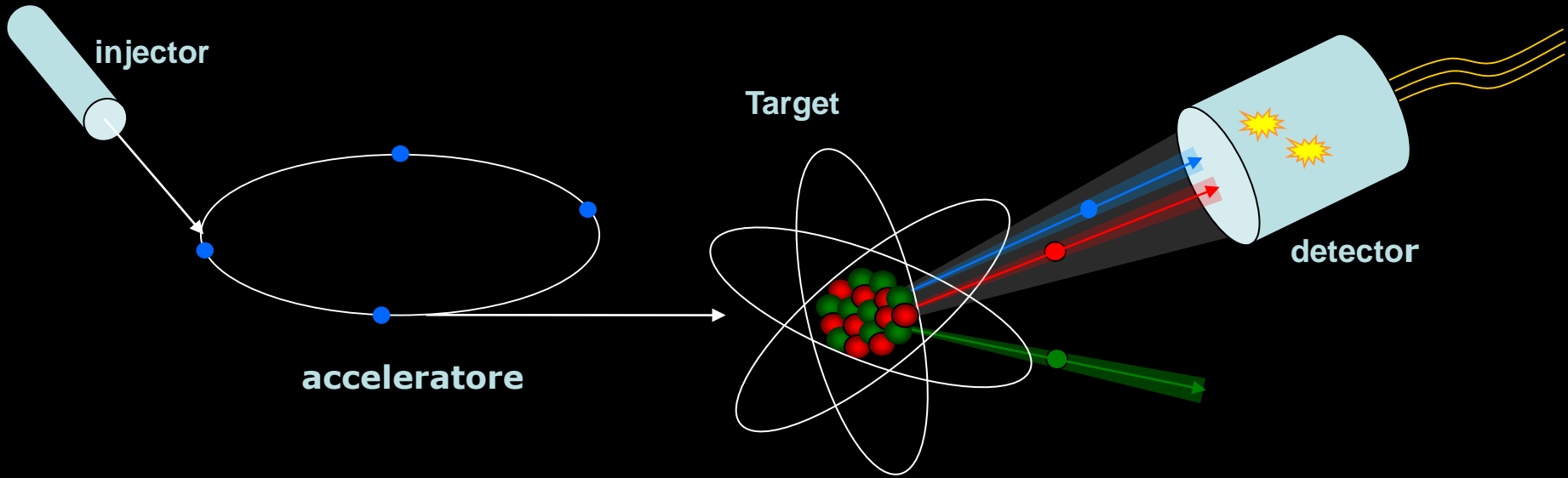
Example: electron microscope



Electron Scattering

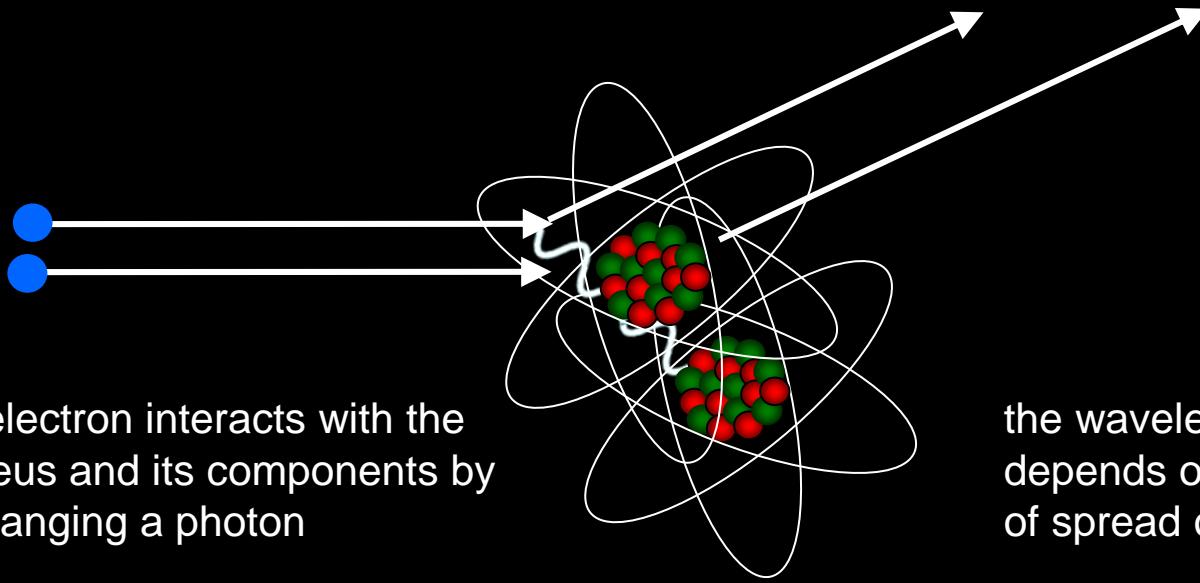


Electron Scattering



but what happens when an electron interacts
with the nucleus and with the protons and
neutrons inside?

Electron Scattering

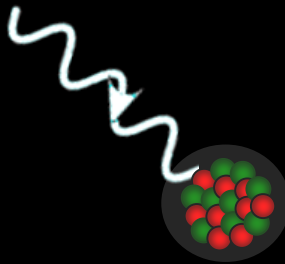


the electron interacts with the nucleus and its components by exchanging a photon

the wavelength of the photon depends on the energy and the angle of spread of the electron

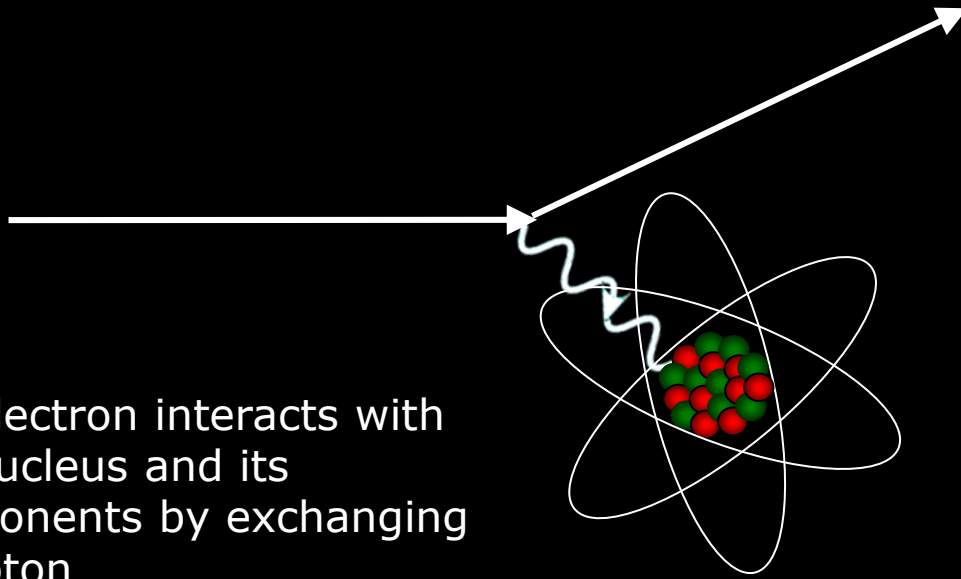
At wavelengths comparable to the size of the nucleus

$$\lambda \gg 10^{-15} \text{ m}$$



the photon interacts with the entire core and it is not possible to distinguish its components

Electron Scattering

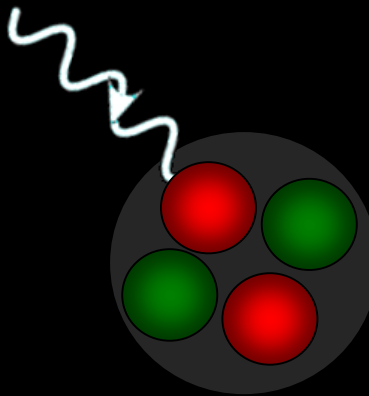


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the wavelength of the photon depends on the energy and the angle of the electron

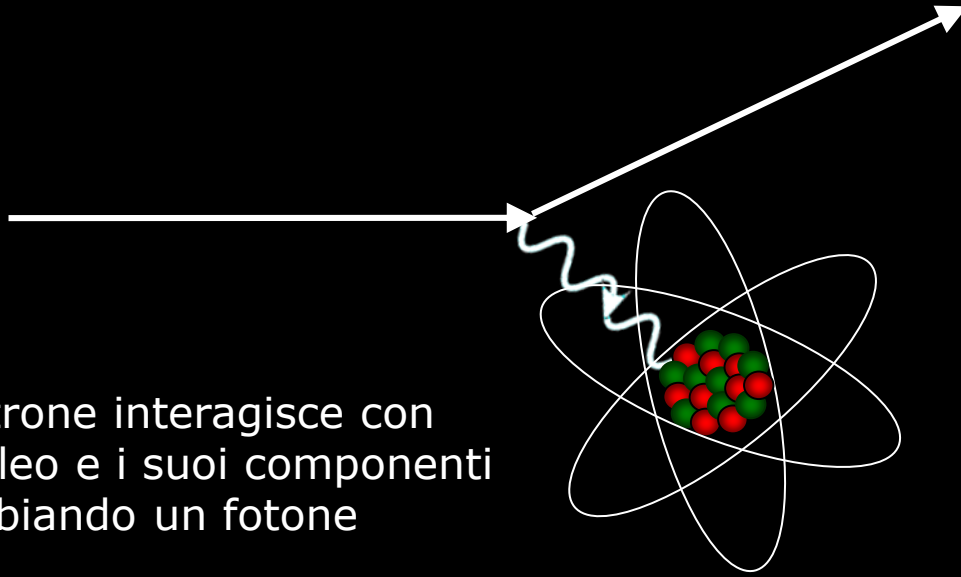
At intermediate wavelength the order of the size of the nucleon

$$\lambda \sim 10^{-15} \text{ m}$$



the photon interacts with the individual protons and neutrons that make up the nucleus

Electron Scattering

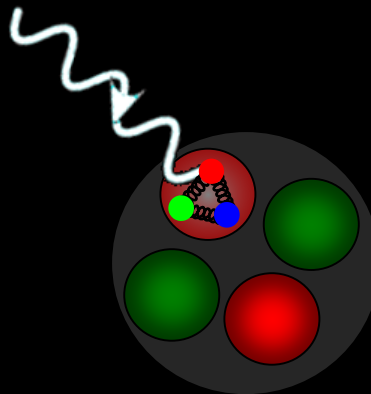


l'elettrone interagisce con il nucleo e i suoi componenti scambiando un fotone

the wavelength of the photon depends on the energy and the angle the electron

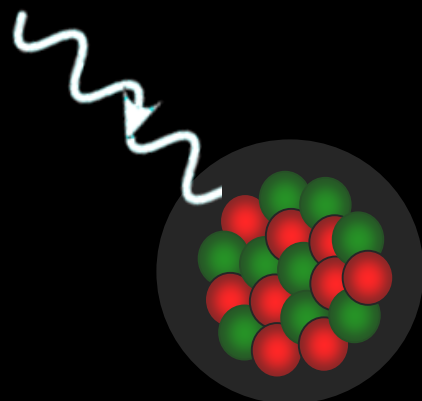
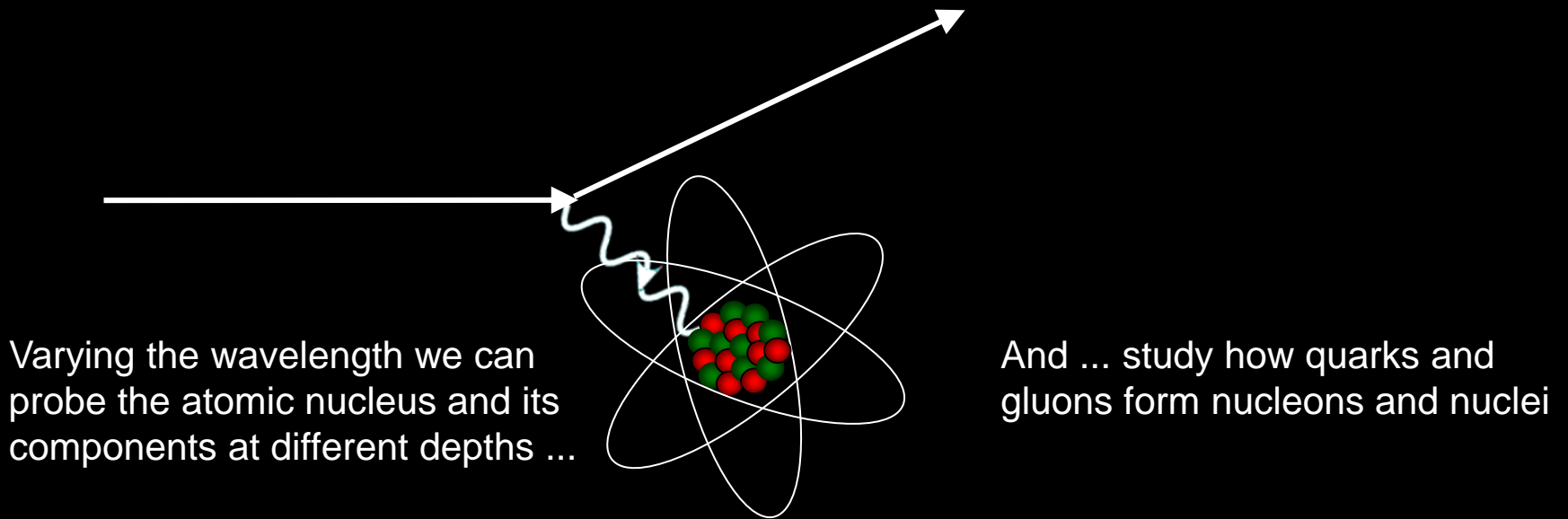
At short wavelength, smaller than the size of the proton

$$\lambda \ll 10^{-15} \text{ m}$$

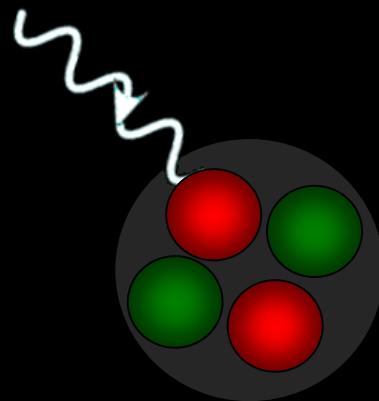


the photon interacts with the constituents of the individual nucleons, ie quarks and gluons

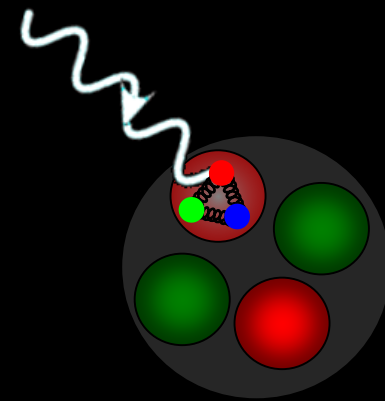
Electron Scattering



$\lambda \gg 10^{-15} \text{ m}$



$\lambda \sim 10^{-15} \text{ m}$



$\lambda \ll 10^{-15} \text{ m}$

Aerial photo taken April 2011

Hall-D

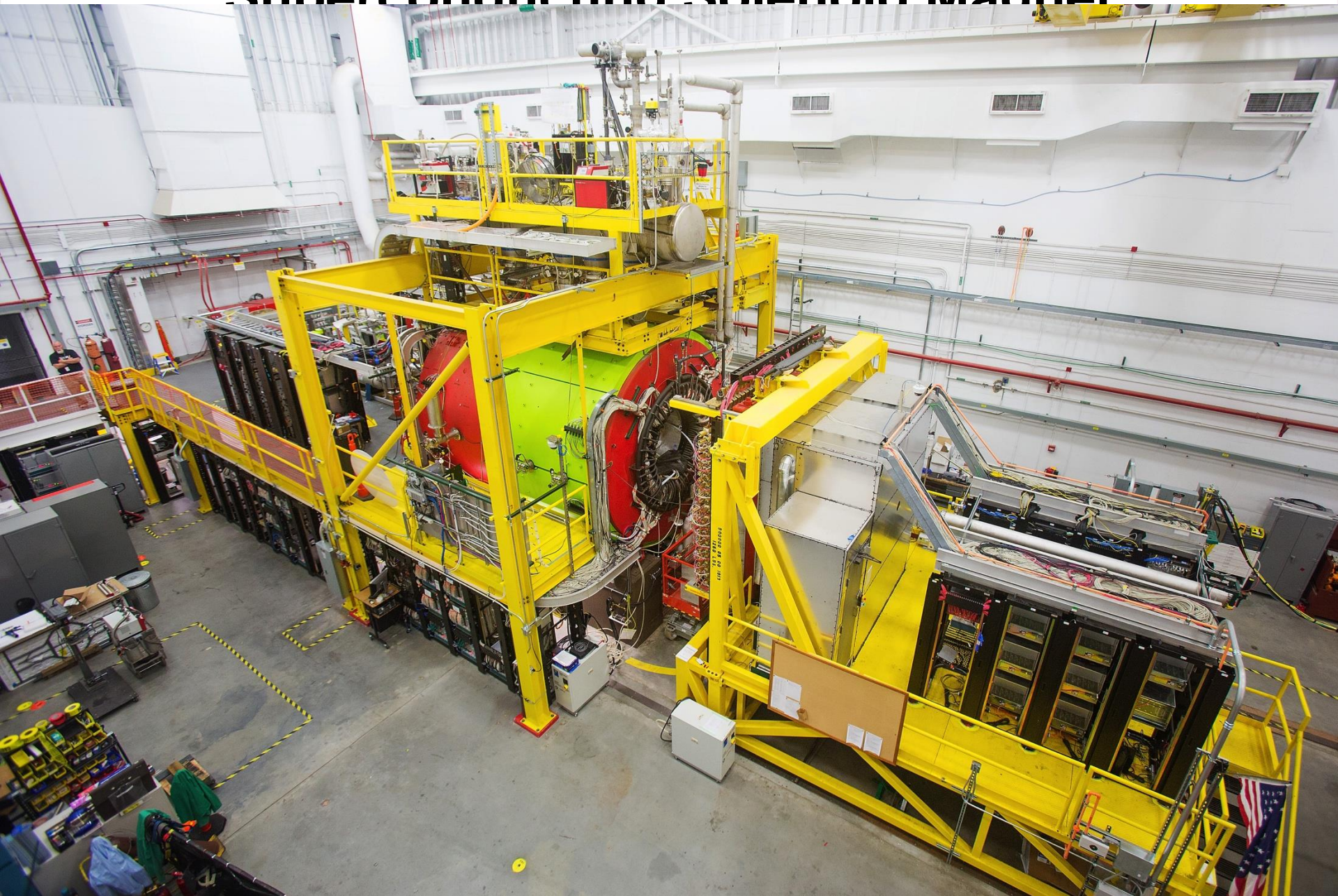


**Thomas Jefferson National Accelerator Facility (JLab)
Newport News, Virginia, USA**

Electron beam

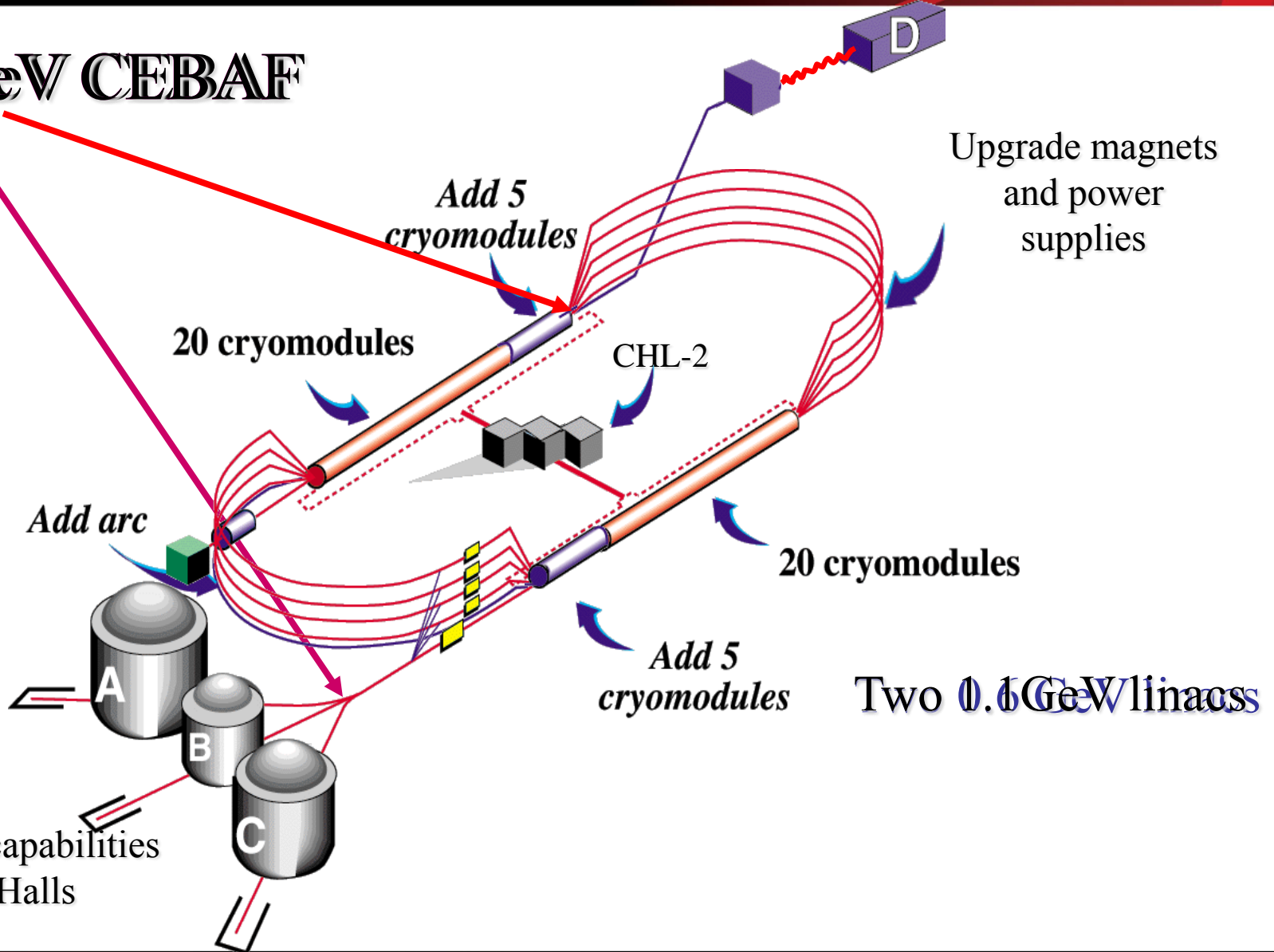
- continuous (1497MHz, structure in)
- Polarized beam
- Upgraded (from 6GeV)
- 70 μ A max (200 μ A max)

Superconducting Solenoid Magnet



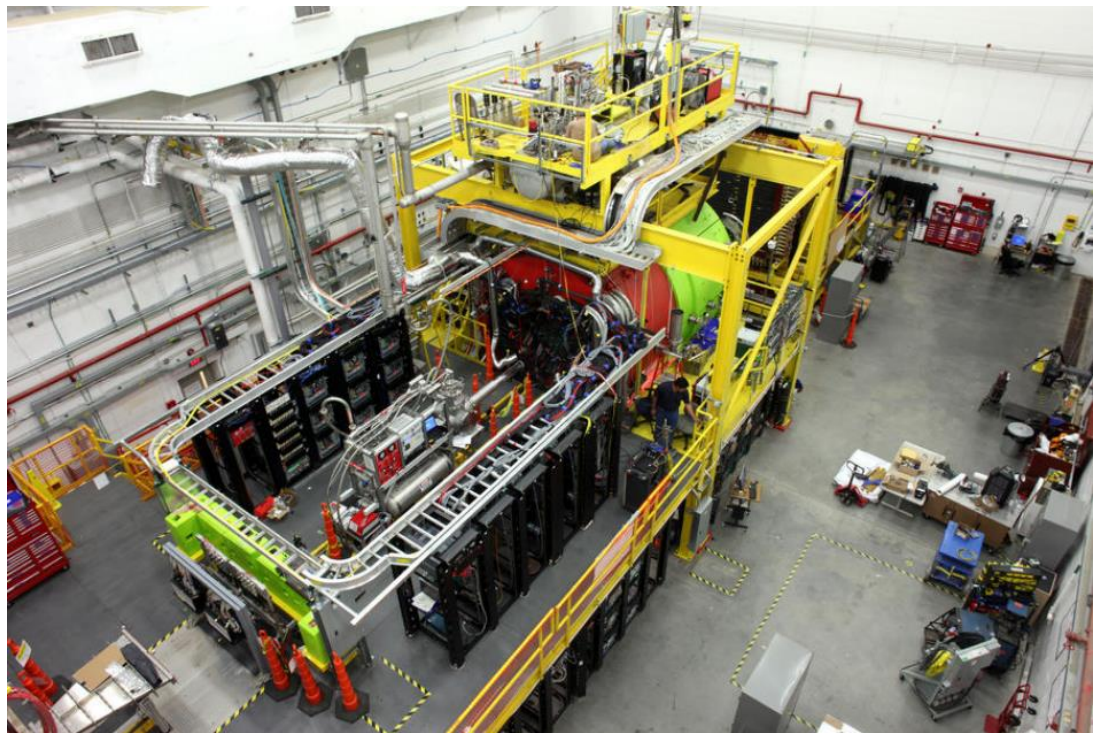
The JLab 12GeV Upgrade

12 GeV CEBAF



Hall D Experiments

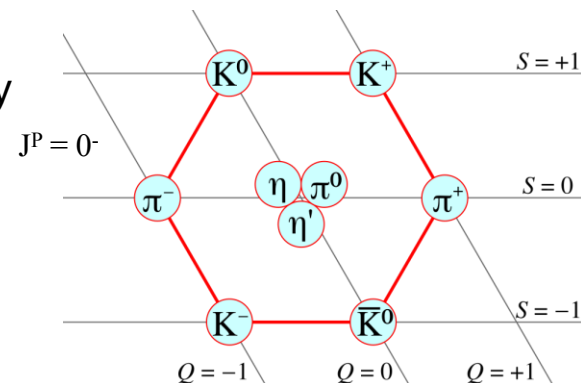
- GlueX
 - E12-06-102, C12-12-002, E12-13-003
 - 540 PAC days
- PrimEx-eta
 - E12-10-011
 - 79 PAC days
- Pion polarizability
 - E12-13-008
 - 25 PAC days
- JLab Eta Factory (JEF): Rare eta decays
 - C12-14-004
 - Conditionally approved



Exotic Hybrid Mesons

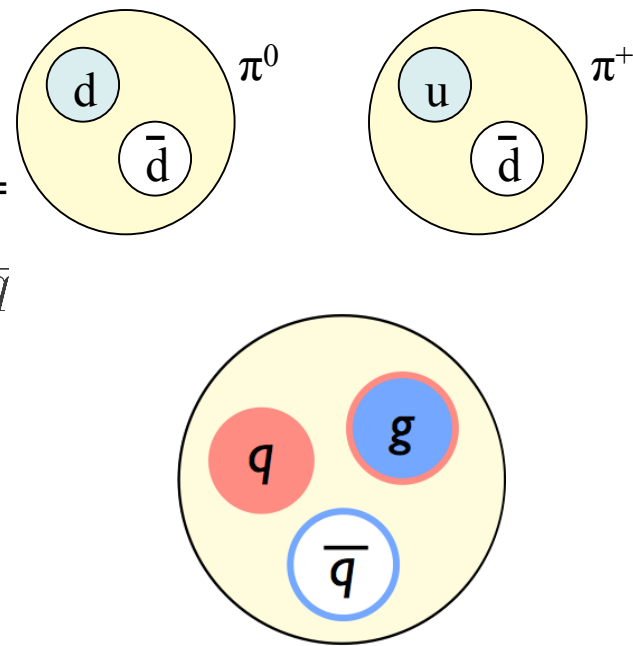
Quark model

- The spectrum of conventional mesons is described by the quark model
- Mesons are grouped in nonets of J^P with different quark flavor content
- Allowed $q\bar{q}$ states: 0^+ , 1^- , 1^+ , 0^{++} , 2^{++} , ...



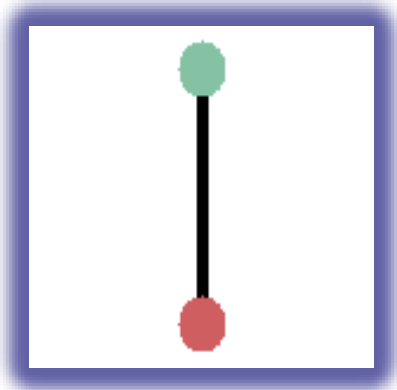
Hybrids

- Excited gluonic field coupled to $q\bar{q}$ pair
- Spectrum of hybrids predicted by lattice QCD
 - Can be modeled as “constituent gluon” with $J^{PC} = 1^+$ and mass = 1-1.5 GeV
- Some have “exotic” J^{PC} which cannot be formed by $q\bar{q}$
 - $J^{PC} = 0^{+-}$, 1^{-+} , 2^{+-} , ...
 - Exotic J^{PC} provide good signal for hybrids

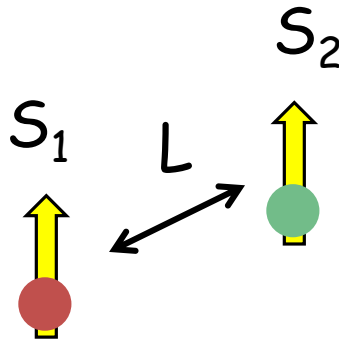


Exotic Hybrid Mesons

Conventional meson has quantum numbers determined only by constituent quarks

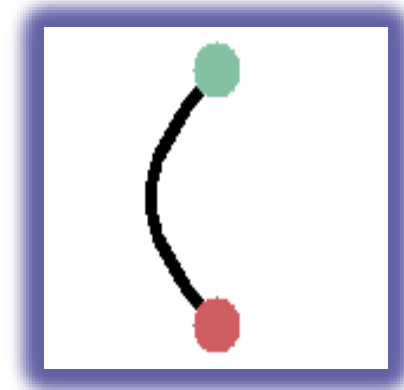


$$J^{PC} = 0^+, 0^{++}, 1^{++}, 1^{+-}, 2^{-+}, 2^{++}$$



$$\begin{aligned} S &= S_1 + S_2 \\ J &= L + S \\ P &= -(-1)^L \\ C &= (-1)^{L+S} \end{aligned}$$

Hybrid meson has some quantum properties due to contributions from the “glue”

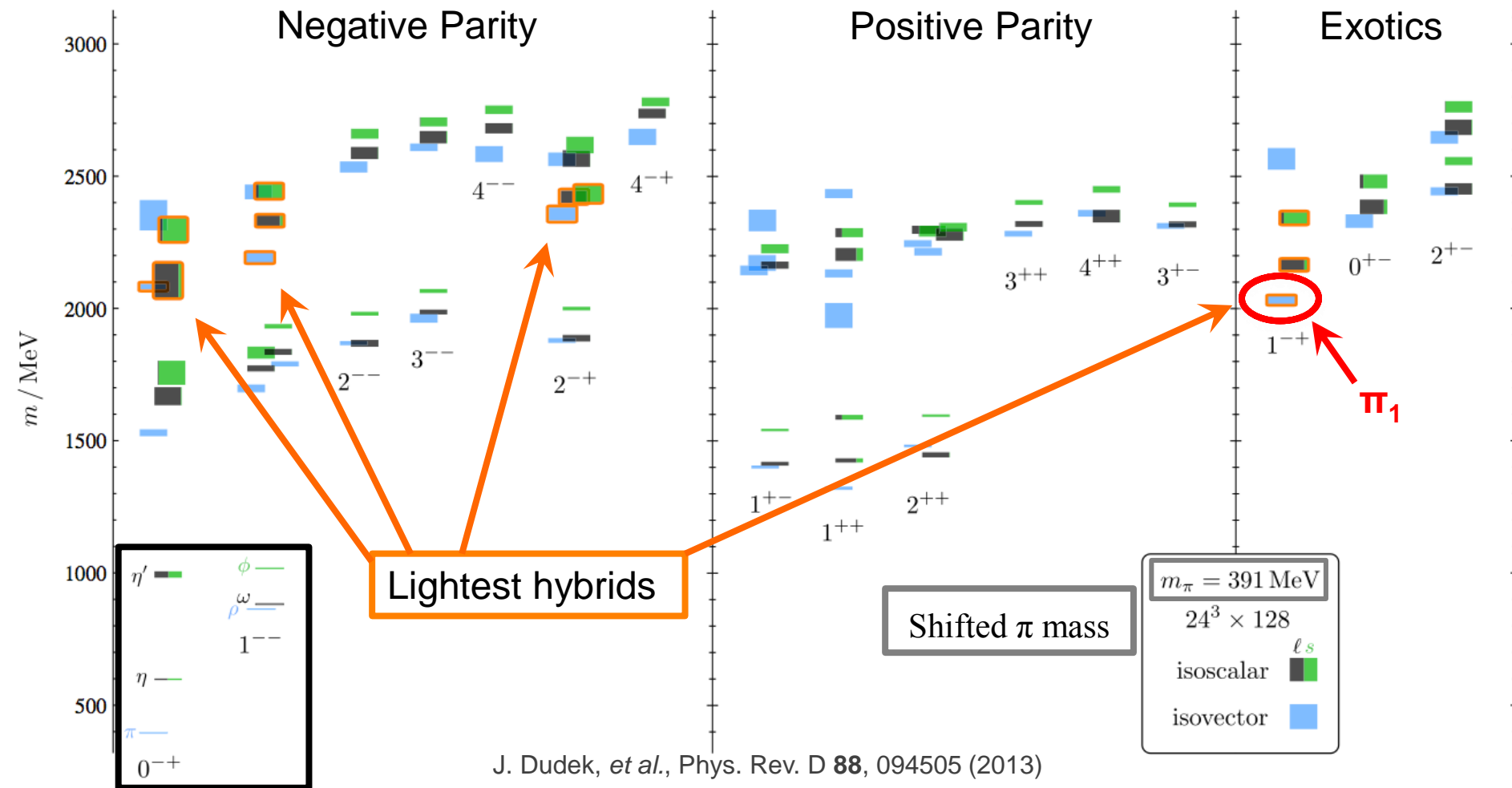


$$J^{PC} = 0^+, 0^{++}, 0^{+-}, 1^{++}, 1^{+-}, 1^{+-}, 2^{-+}, 2^{++}, 2^{+-}$$

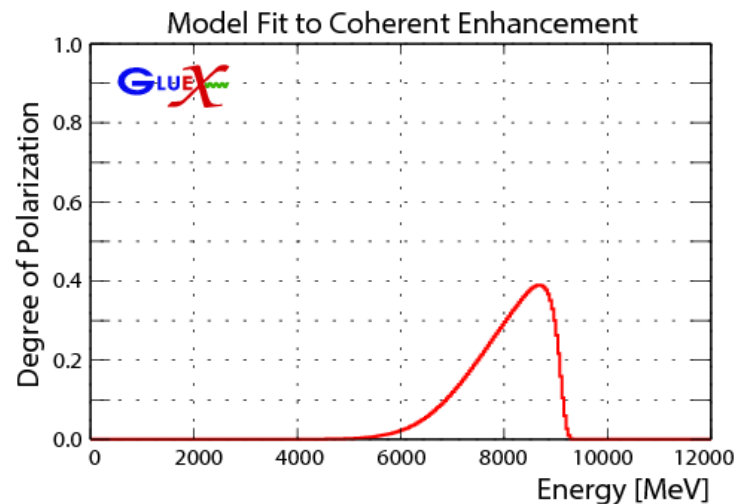
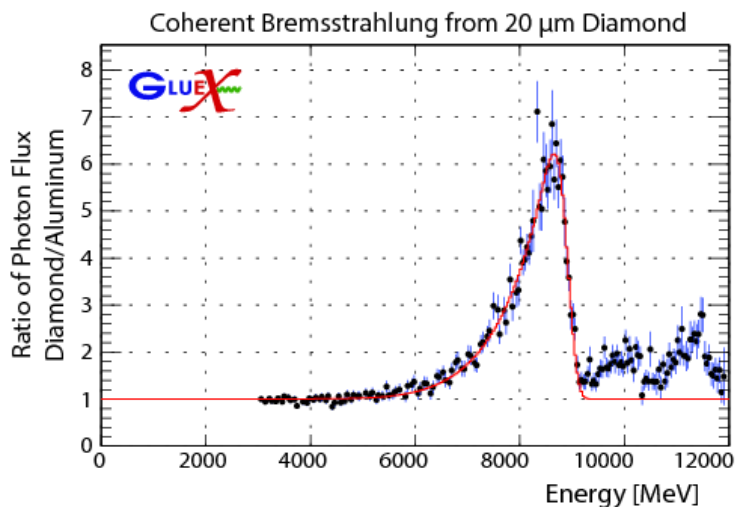
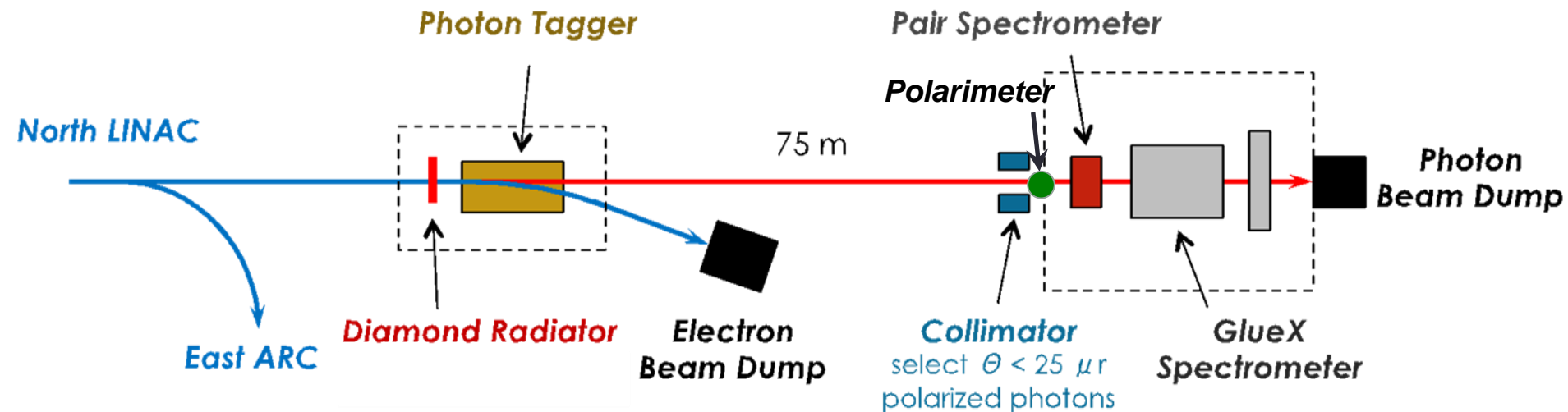
“exotic” states

Lattice QCD predictions

- Search for pattern of hybrid states in many final states
- Most evidence for π_1 ($J^{PC} = 1^{-+}$)



GlueX Experiment - beamline (UConn)



Exotic J^{PC} Decays

- Lattice predictions for the mass of hybrids
- Decay predictions are model dependent
- Reported $J^{PC} = 1^{-+}$: $\pi\rho \rightarrow 3\pi$, $\pi\eta' \rightarrow 3\pi\eta$, $\pi b_1 \rightarrow 2\pi\omega$
- Early reach
- With statistics

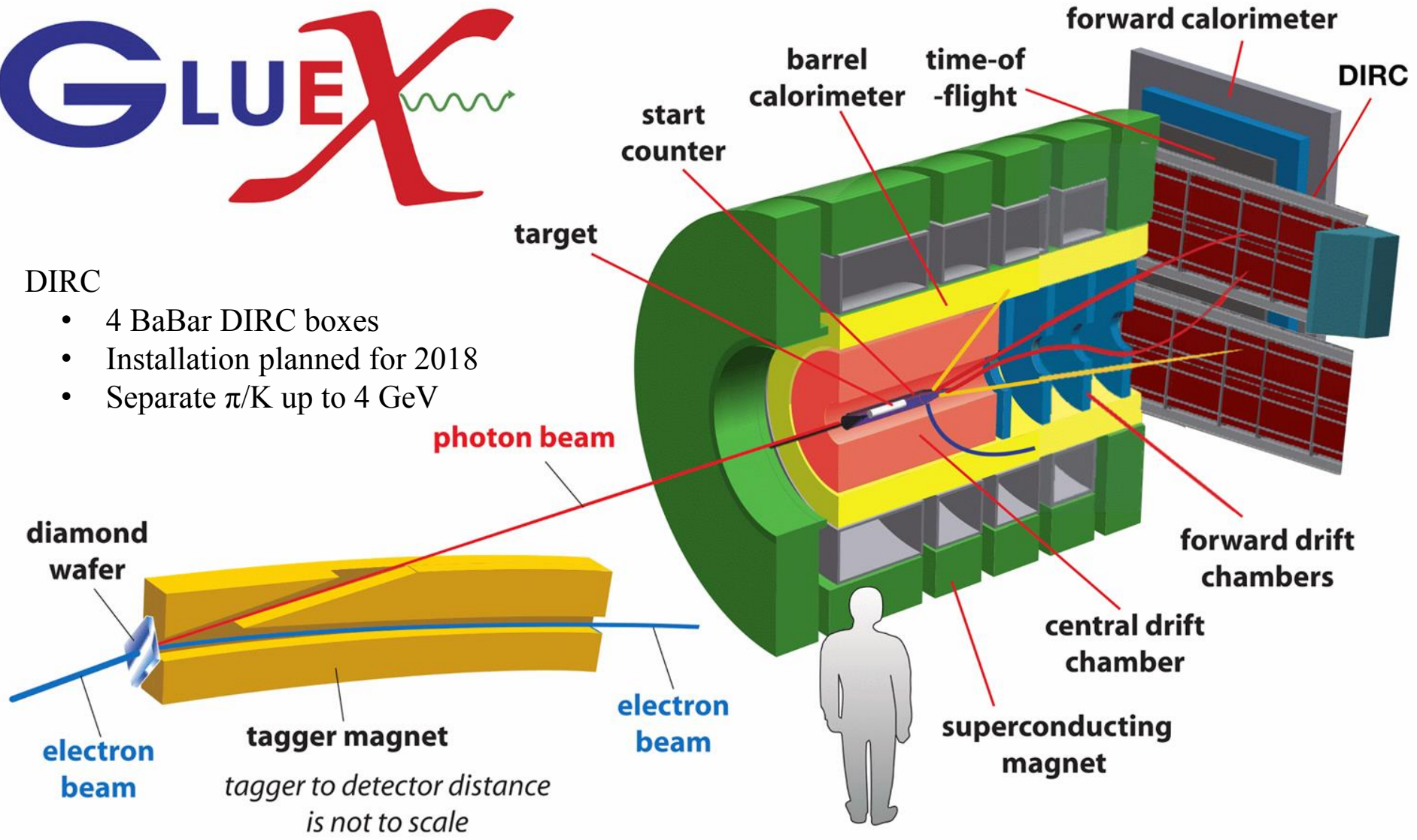
Name	J^{PC}	Total width MeV (Model)		Allowed decay modes	$K_1^A(1270)$ $K_1^B(1400)$
		PSS	IKP		
π_1	1^{-+}	81-168	117	$b_1\pi$, $\pi\rho$, πf_1 , $\pi\eta$, $\pi\eta'$, ηa_1 , $\pi\eta(1295)$	
η_1	1^{-+}	59-158	107	πa_1 , πa_2 , ηf_1 , ηf_2 , $\pi\pi(1300)$, $\eta\eta'$, KK_1^A , KK_1^B	
η'_1	1^{-+}	95-216	172	KK_1^B , KK_1^A , KK^* , $\eta\eta'$	
b_0	0^{+-}	247-429	665	$\pi\pi(1300)$, πh_1 , ρf_1 , ηb_1	
h_0	0^{+-}	59-262	94	πb_1 , ηh_1 , $KK(1460)$	
h'_0	0^{+-}	259-490	426	$KK(1460)$, KK_1^A , ηh_1	
b_2	2^{+-}	5-11	248	πa_1 , πa_2 , πh_1 , $\eta\rho$, ηb_1 , ρf_1	
h_2	2^{+-}	4-12	166	$\pi\rho$, πb_1 , $\eta\omega$, ωb_1	
h'_2	2^{+-}	5-18	79	KK_1^B , KK_1^A , KK_2^* , ηh_1	

C. A. Meyer and E. S. Swanson, Progress in Particle and Nuclear Physics B82, 21, (2015)

GLUEX

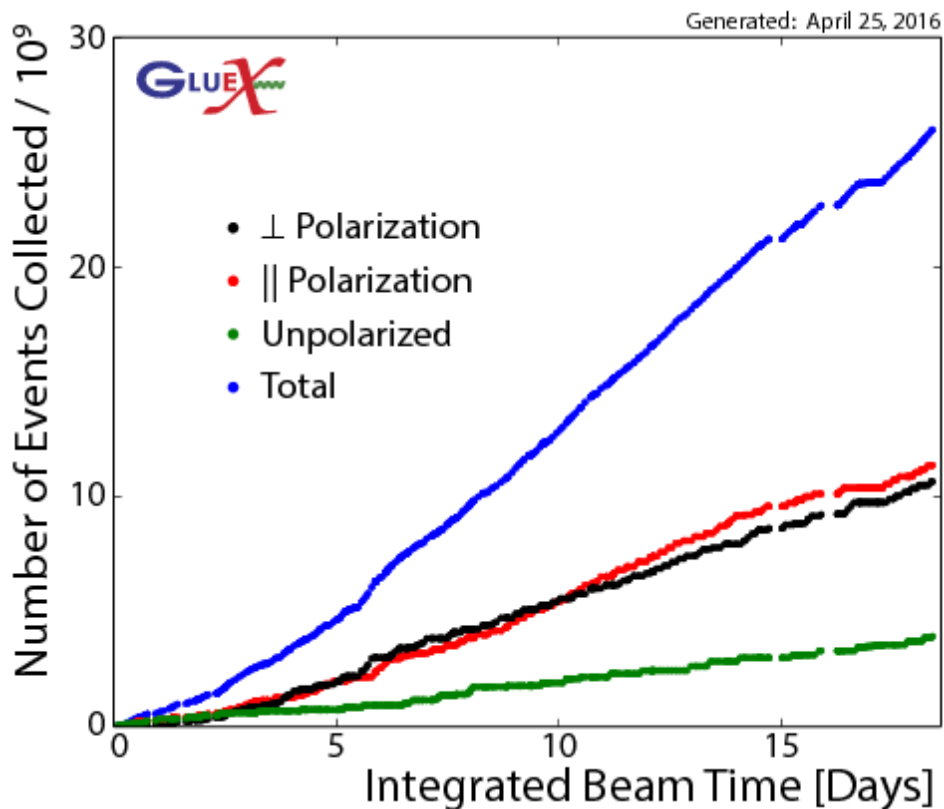
DIRC

- 4 BaBar DIRC boxes
- Installation planned for 2018
- Separate π/K up to 4 GeV

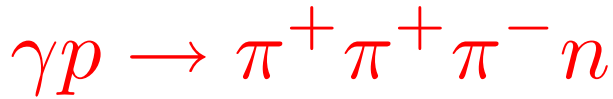


GlueX - Spring 2016 Commissioning Data

- Typical acquisition rate
 - 30 kHz
 - 90% live time
 - 750 MB/s
- Approximate production volume: 550 TB, raw data



Amplitude Analysis



generated waves

$$a_1(1260) \rightarrow \rho\pi \quad (\text{S - wave})$$

$$a_2(1320) \rightarrow \rho\pi \quad (\text{D - wave})$$

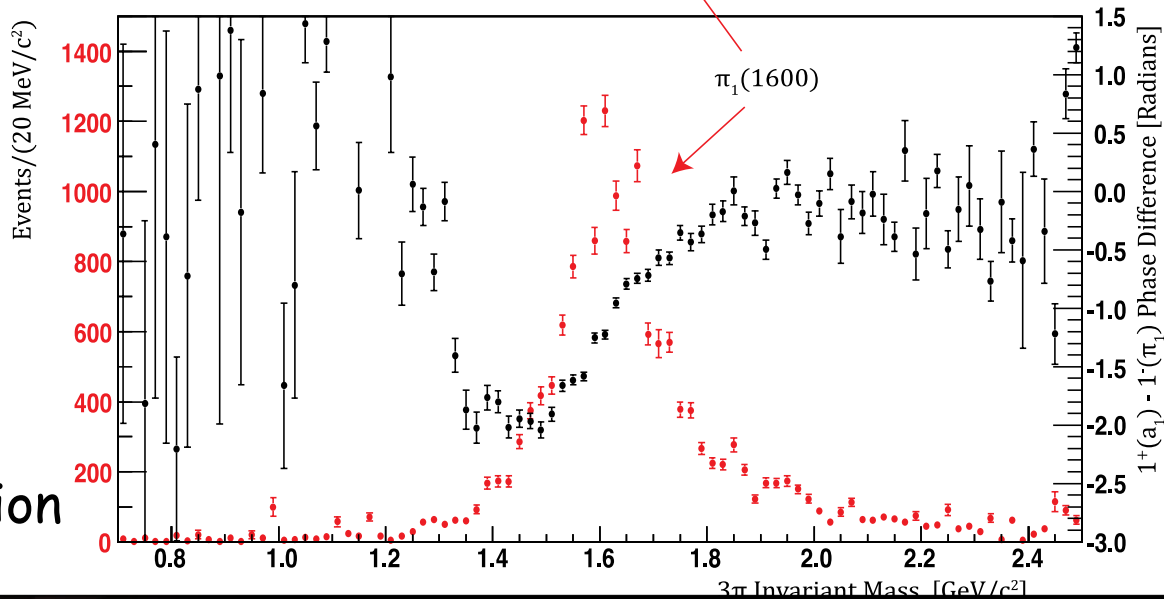
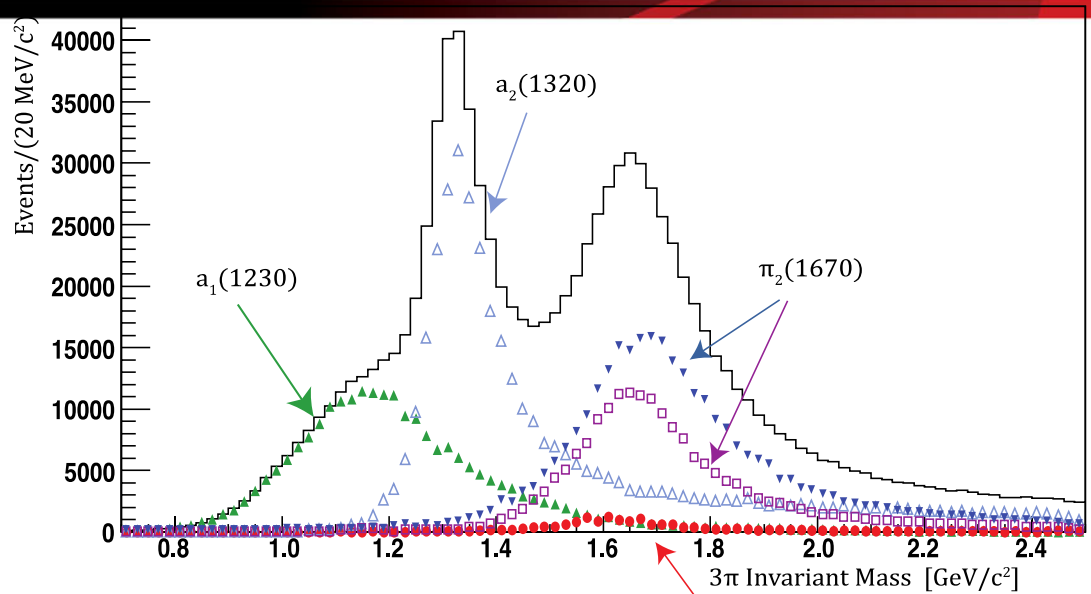
$$\pi_1(1600) \rightarrow \rho\pi \quad (\text{P - wave})$$

$$\pi_2(1670) \rightarrow f_2\pi \quad (\text{S - wave})$$

$$\pi_2(1670) \rightarrow \rho\pi \quad (\text{P - wave})$$

1^- exotic wave
generated with 1.6%
relative strength

Corresponds to 3.5 hours
GlueX data, full detector
simulation and reconstruction



June 3,

Exotic Hybrid Spectroscopy

Summary

- Measuring smaller things requires more momentum
- Testing models requires looking for signatures that are often buried deep under backgrounds
- Some measurements may only yield results that a statistical sample contains the signal. (You'll never know which elements in the sample are the actual ones!)

Backup Slides

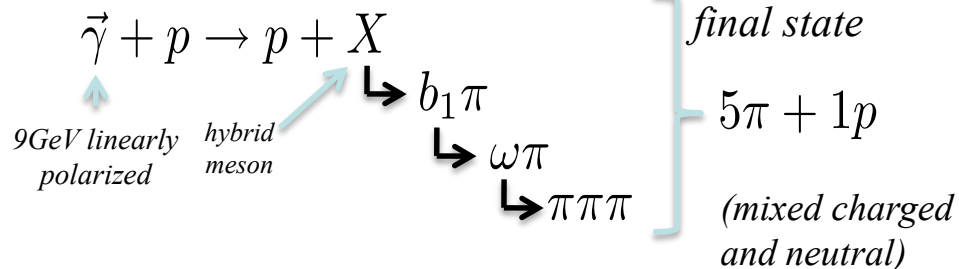
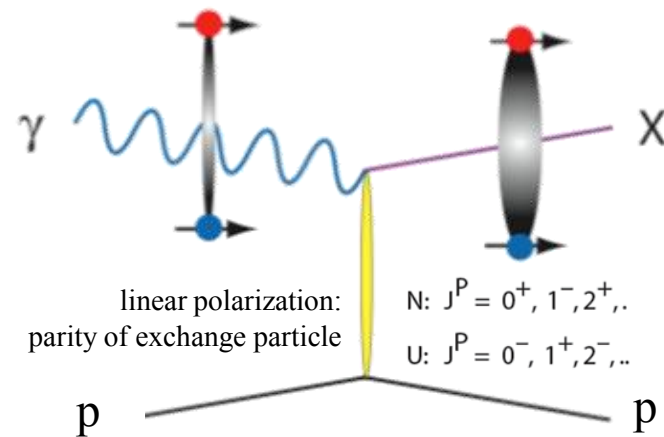


Photo-production of Exotic Hybrids

- High energy real* photons incident on a liquid Hydrogen target
- Recent LQCD calculations indicate similar radiative decay widths for charmonium hybrids as for normal mesons**
(i.e. photo-production rates of hybrids should be similar to that of non-hybrid mesons)

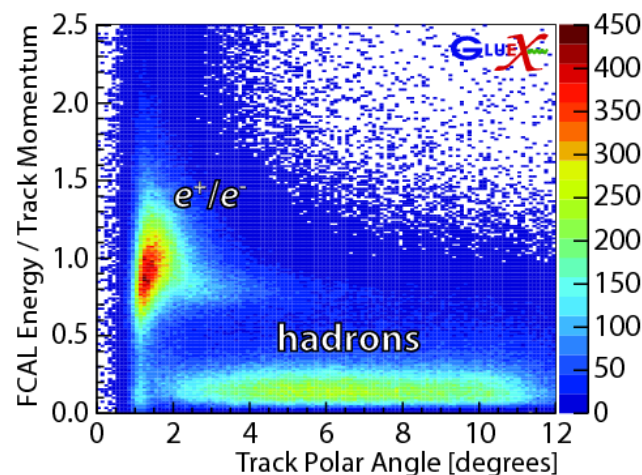
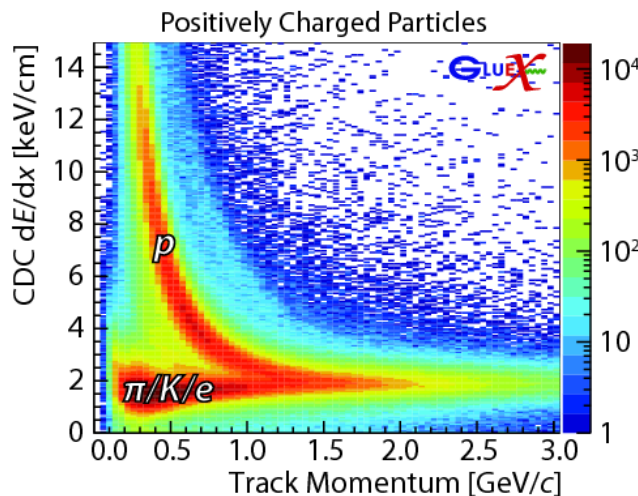
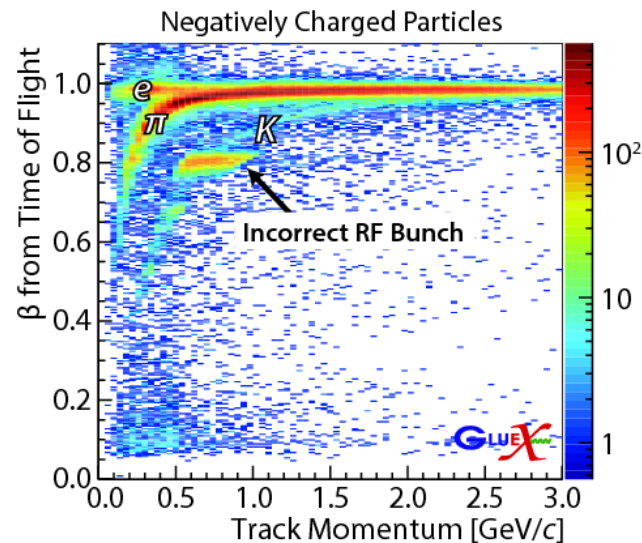
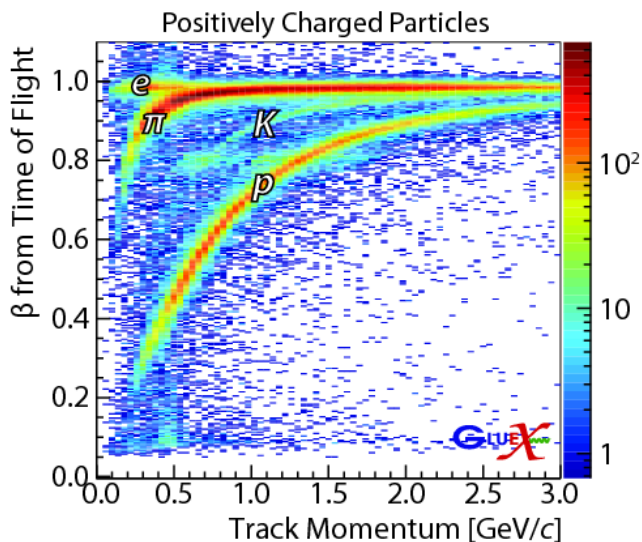
$$\Gamma(\eta_{c1} \rightarrow J/\psi \gamma) \sim 100 \text{ keV}$$

- Photons have spin-1 component allowing easier production of exotics compared to pion beams where a spin flip must occur
- Linear polarization of incident photon allows us to distinguish naturalities of the exchange particle



* not virtual
**Dudek PRD 79 (2009) 094504

GlueX - Particle Identification



Physics in GlueX

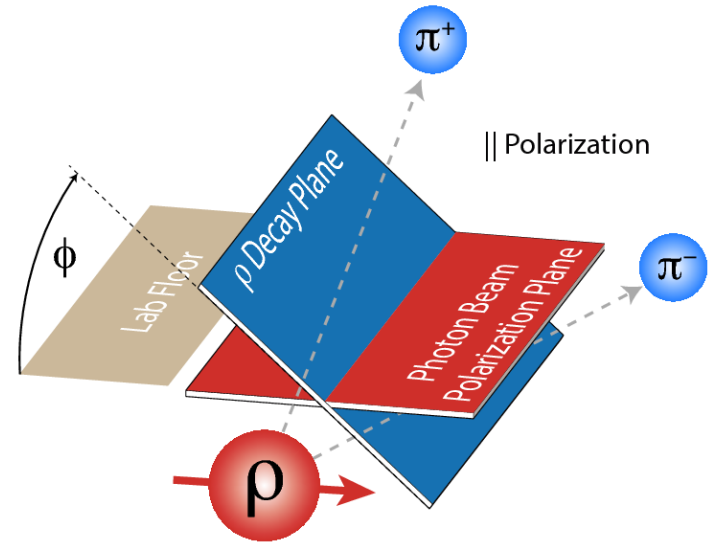
- Currently processing data into condensed data format
 - 25% processed, less analyzed
 - More currently on the farm

- Short term using commissioning data
 - Polarization transfer and beam asymmetry
 - $\gamma p \rightarrow (\pi^0, \eta, \eta') p$
 - $\gamma p \rightarrow (\rho^0, \omega, \phi) p$
 - Initial analyses for:
 - 1.6 GeV enhancement in $\pi^+ \pi^-$ mass distribution
 - Signals in the 4γ final state

- Long term
 - Spin-density matrix elements to understand production mechanisms
 - Cross sections measurements

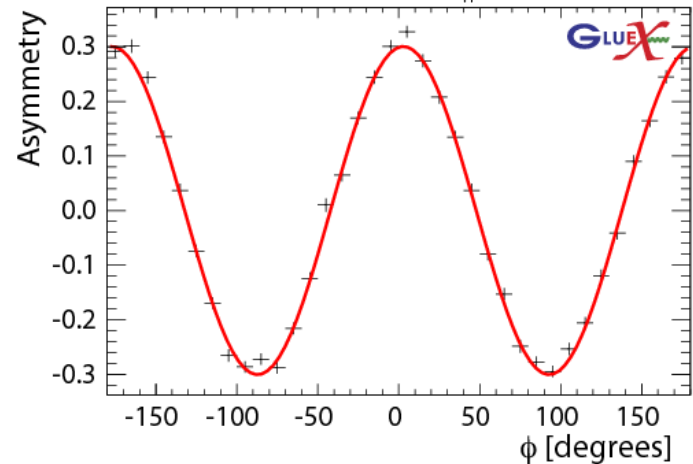
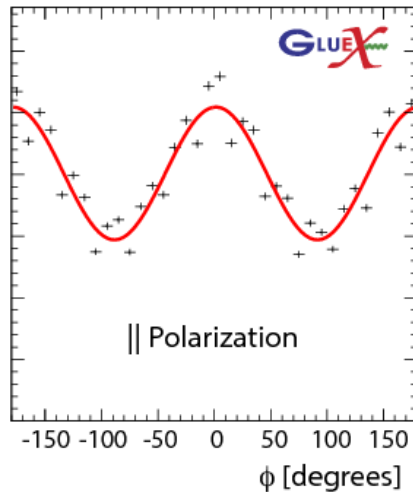
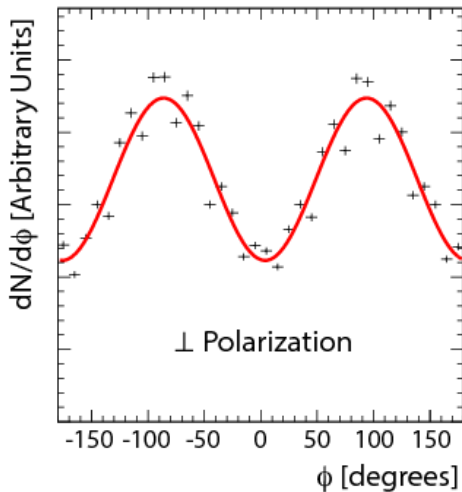
Beam Asymmetry in ρ Photoproduction

- Useful monitor of photon beam polarization
- Have 100 times the existing world data for all energies
- Working with the Joint Physics Analysis Center (JPAC) on models for analysis



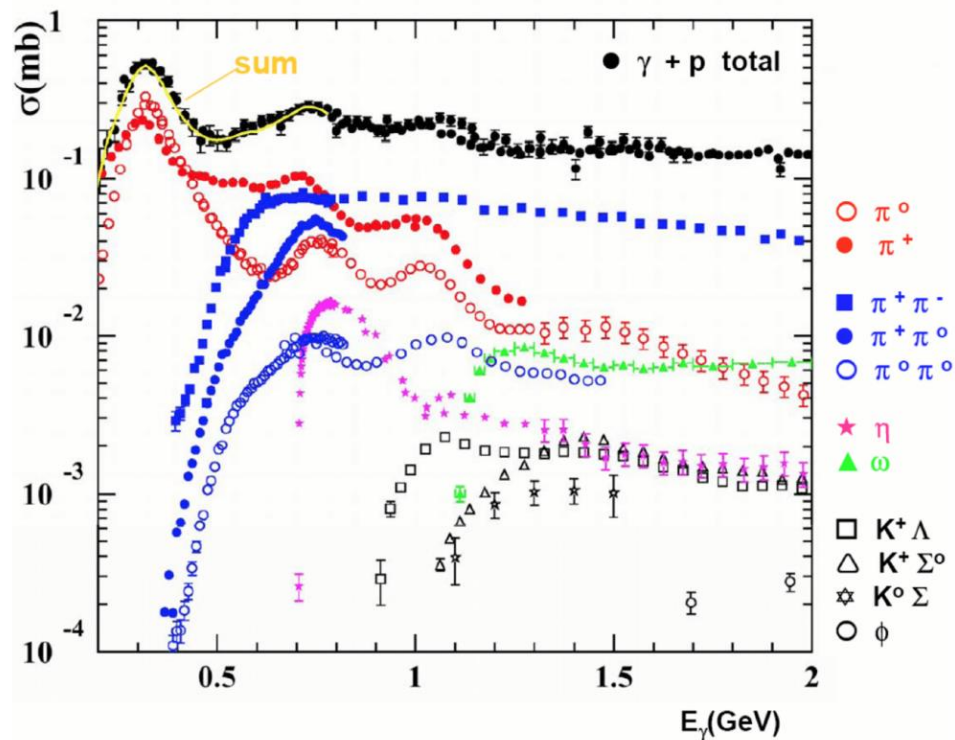
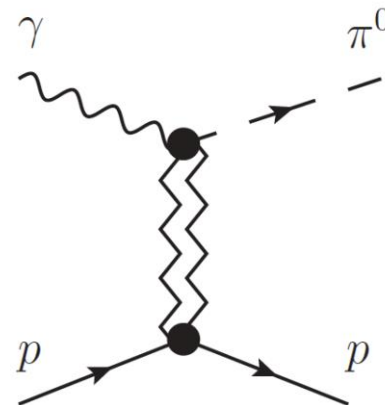
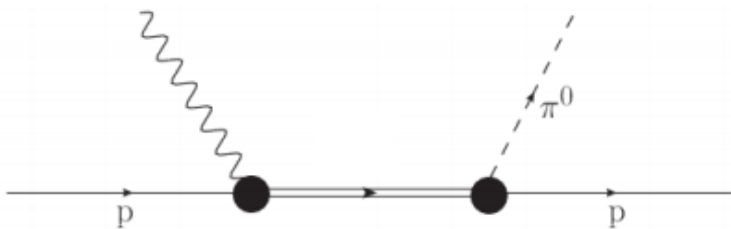
$$P \Sigma \cos 2\phi = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

• Large polarization transfer to the



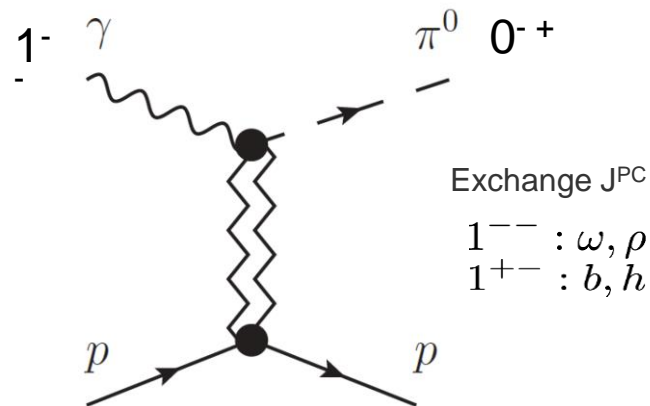
~~π^0 beam asym~~

- Provides constraints on “background” to baryon resonance extraction in low energy regime
 - Constrains PWA amplitudes through Finite Energy Sum

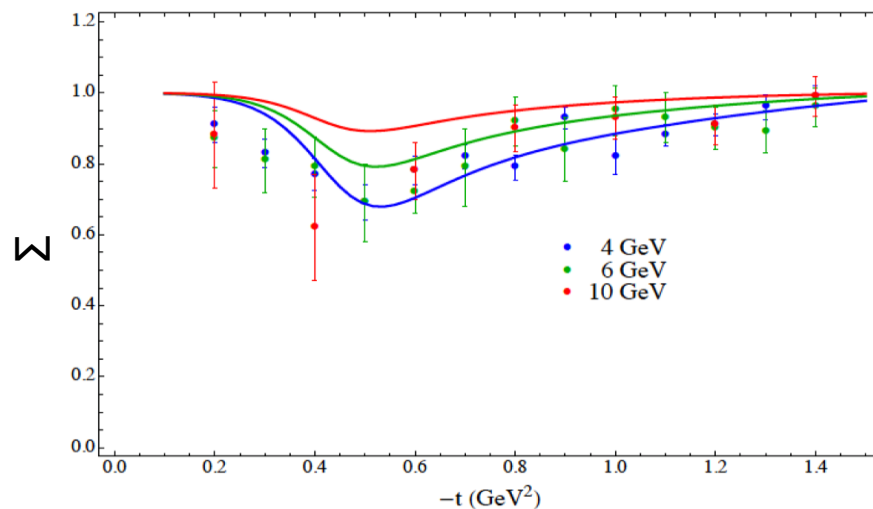


π^0 beam asymmetry

- Provides constraints on “background” to baryon resonance extraction in low energy regime
 - Constrains PWA amplitudes through Finite Energy Sum Rule

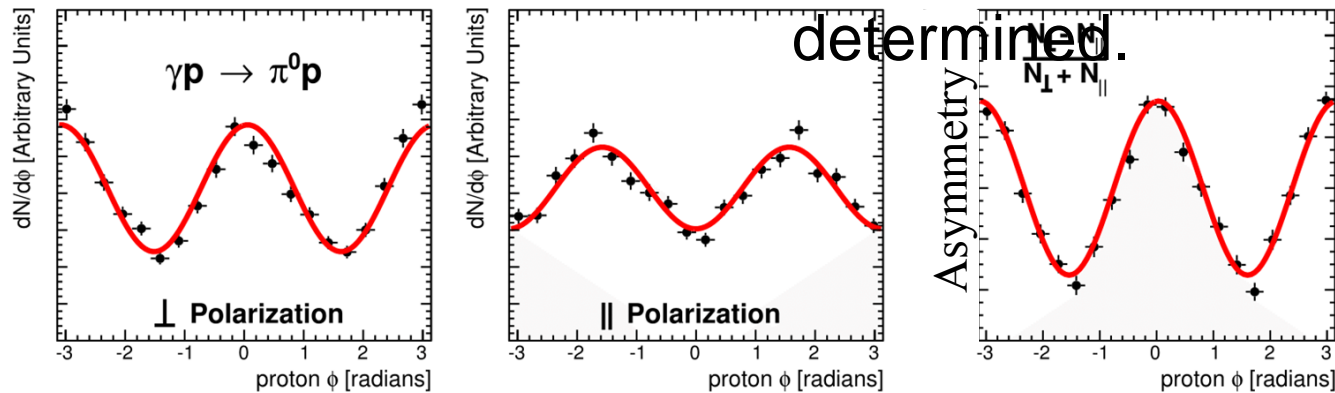


- $\frac{d\sigma}{dt} = \sigma_{\perp} + \sigma_{\parallel} = |\rho + \omega|^2 + |b + h|^2$
- $\frac{d\sigma_{\perp}}{dt} = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$
- $\frac{d\sigma_{\parallel}}{dt} = \frac{2\text{Re}(\omega + \rho)(h + b)^*}{|\omega + \rho|^2 + |h + b|^2}$
- $\frac{d\sigma_{\perp}}{dt} = 0$ produce neutral $C = +1$, need a $C = -1$ exchange particle

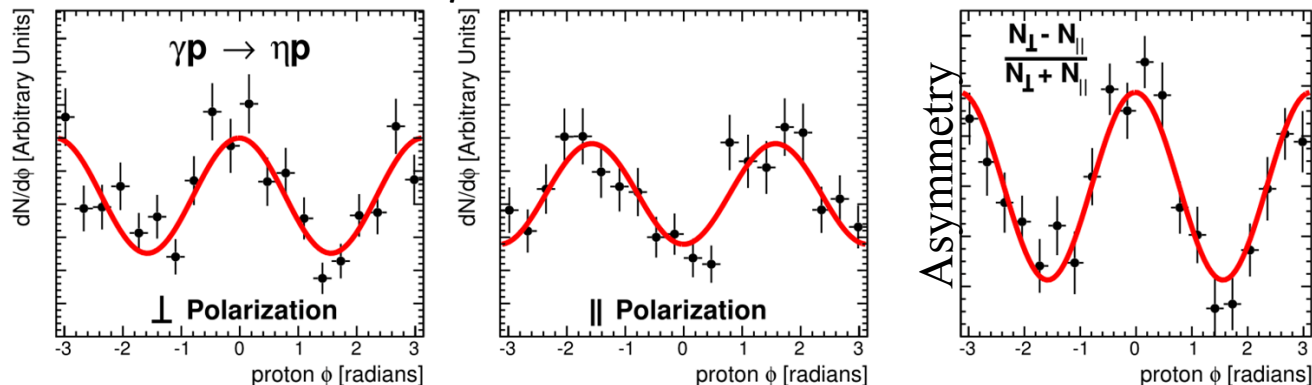


Pseudoscalar Beam Asymmetries

- From a subset of available data Polarization not yet determined.



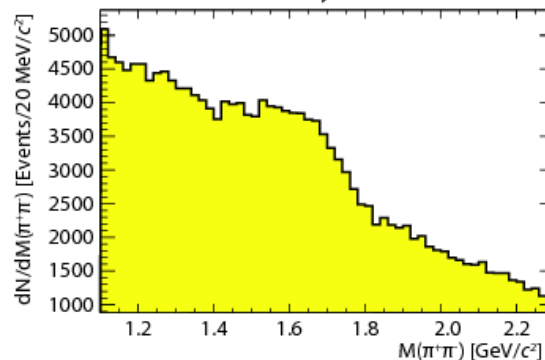
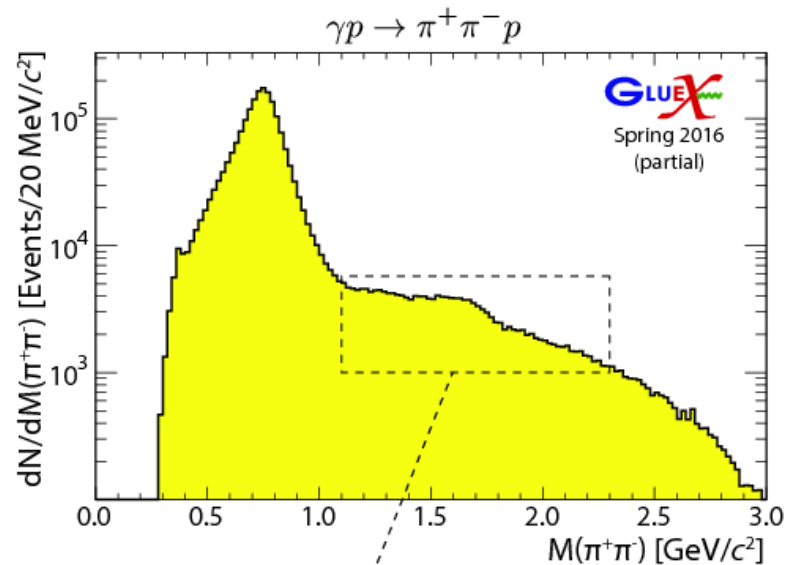
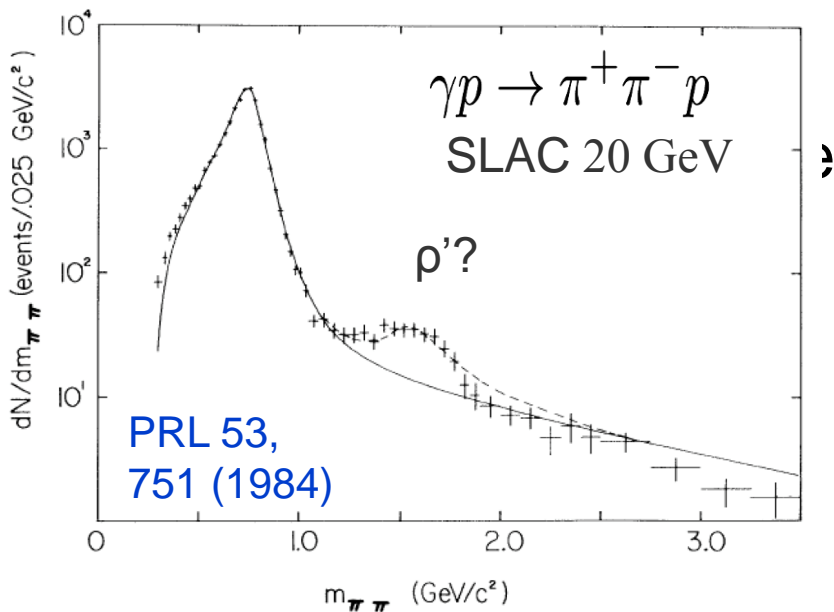
$$E_{\gamma} = 8.4 - 9.0 \text{ GeV}$$



No previous measurements for $\gamma p \rightarrow \eta p$

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

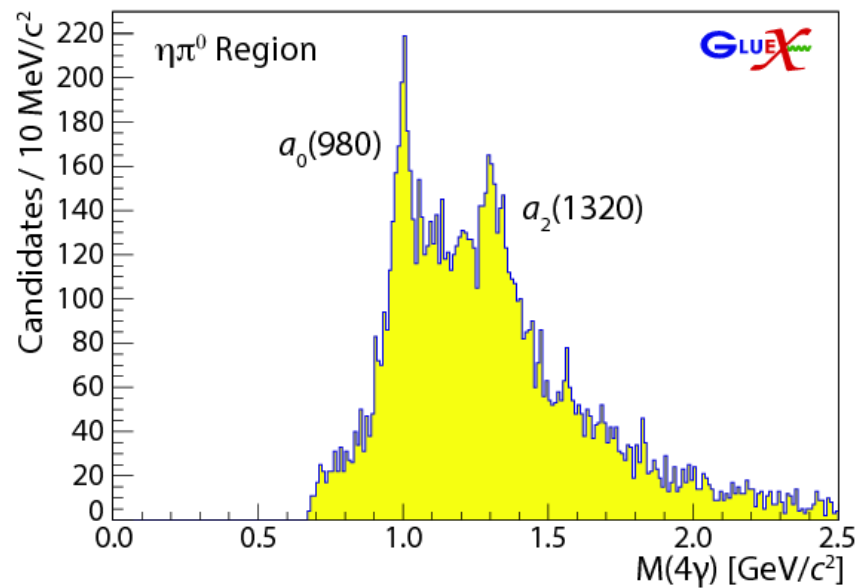
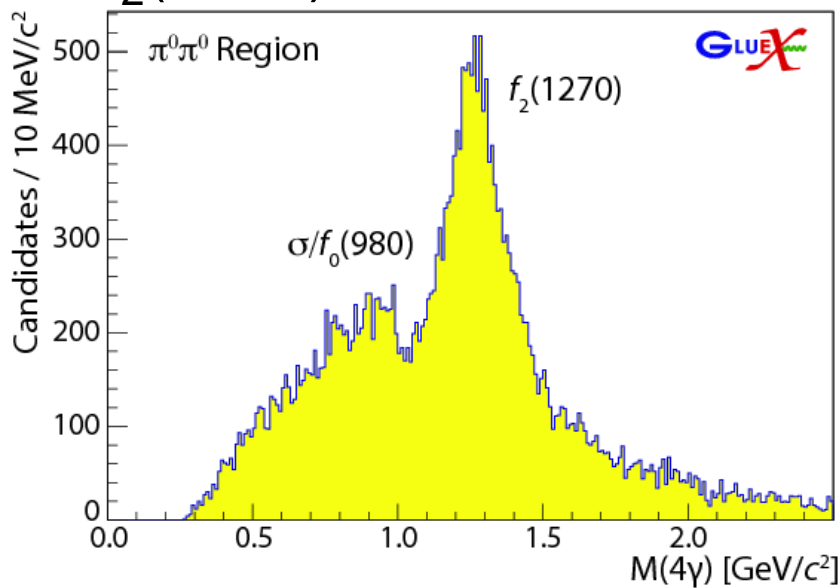
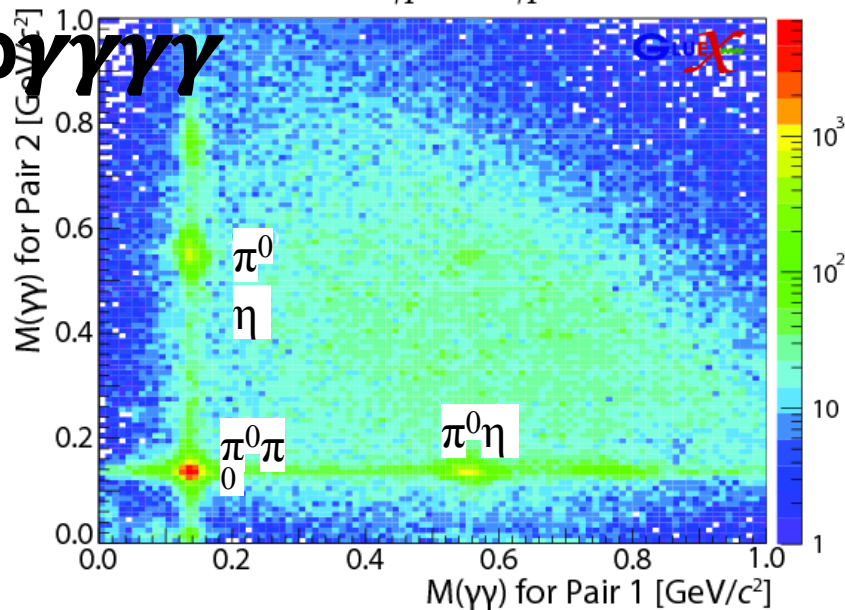
- In the $\pi^+ \pi^-$ invariant mass spectrum we can look for higher-mass vector mesons
- We observe an enhancement at 1.6 GeV with significantly more statistics than existing data



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

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

- About 6% of the spring 2016 statistics
- Preliminary production run
- Signals for σ , $f_0(980)$, $f_2(1270)$, $a_0(980)$ and $a_2(1320)$



Summary

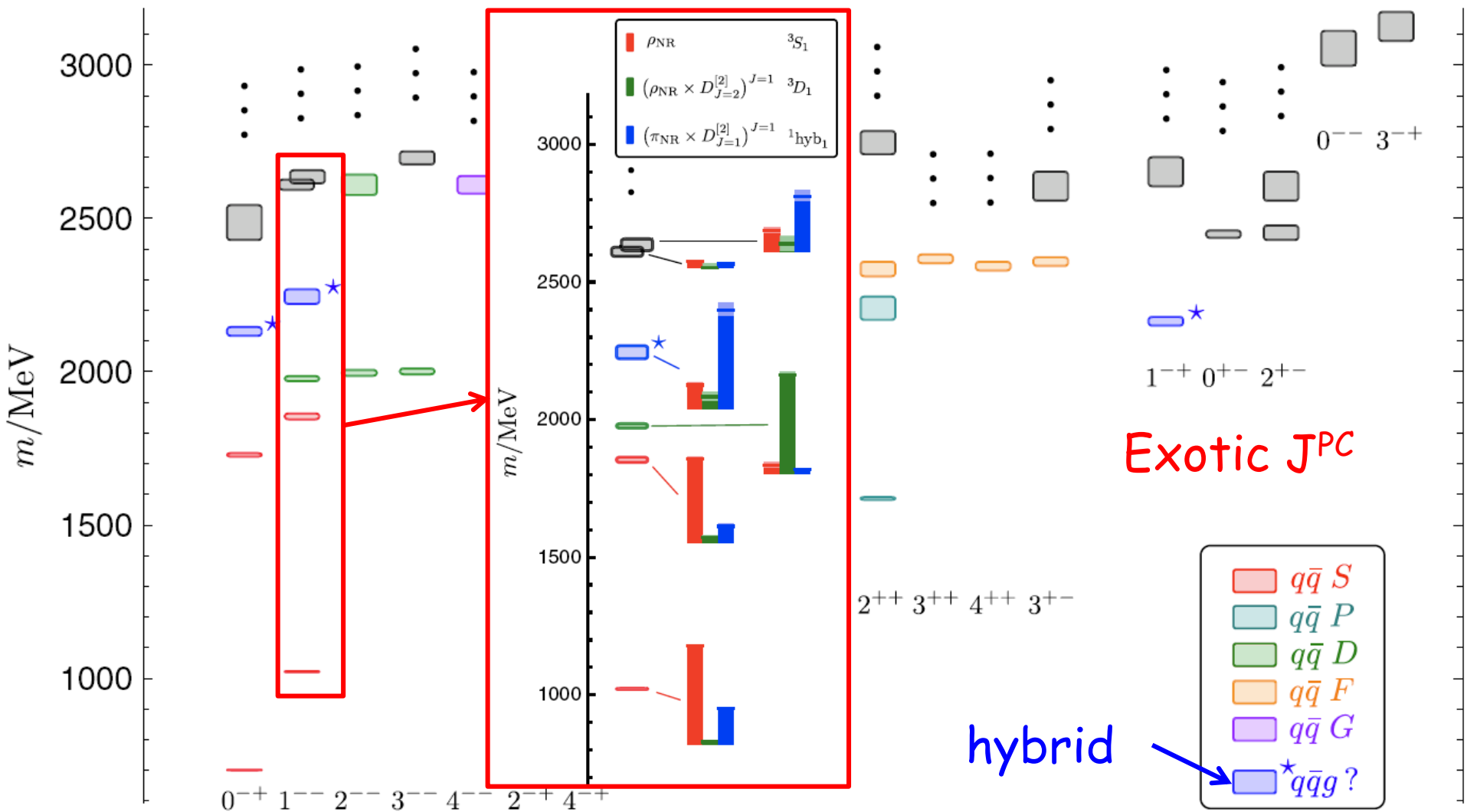
- Commissioning running finished successfully
- All detector systems are near design specifications
- Iterative calibration improvements expected
- Initial physics running fall 2016 - 2018
- We have made significant progress towards our first physics measurements
- The addition of the BaBar DIRC bar boxes and 5x higher intensity are planned in 2018 to allow us to cover all parts of the GlueX exotic hybrid program
- There is an extensive physics program beyond GlueX and we are excited to have new ideas and new collaborators

Hall D GlueX Collaboration

- Arizona State
- Athens
- Carnegie Mellon
- Catholic University
- Univ. of Connecticut
- Florida International
- Florida State
- George Washington
- Glasgow
- GSI
- Indiana University
- ITPP
- Jefferson Lab
- Univ. Mass Amherst
- MIT
- MEPhI
- Norfolk State
- North Carolina A&T
- Univ. North Carolina Wilmington
- Northwestern
- University of Regina
- Santa Maria
- Tomsk
- Yerevan Physics Institute.

Over 120 collaborators from 24 institutions, with others joining and more are welcome.

Meson Spectroscopy from LQCD



Isovector mesons, $m_\pi \sim 700$ MeV

Dudek PRD 83 (2011) 111502

Dudek PRD 84 (2011) 074023



June 3,

Exotic Hybrid Spectroscopy



Measuring the charged pion polarizability in the $e^+e^- \rightarrow \pi^+\pi^-$ reaction

David Lawrence, JLab

Rory Miskimen, UMass, Amherst

Elton Smith, JLab

Motivation

Electron (e^-) and Muon (μ^-) Polarizability

$$U = \exp\left(\frac{i}{f_\pi} T^a \pi^a\right) = \begin{bmatrix} \pi^0/\sqrt{2} + \eta_8/\sqrt{6} & \pi^+ & K^+ \\ \pi^- & -\pi^0/\sqrt{2} + \eta_8/\sqrt{6} & K^0 \\ K^- & \bar{K}^0 & -2\eta_8/\sqrt{6} \end{bmatrix}.$$

Since the dynamics of Goldstone modes is entirely fixed by the broken symmetry, one may write down the $SU_L(3) \times SU_R(3)$ invariant Lagrangian encoding this information by

$$\begin{aligned} \mathcal{L} = & \frac{f_\pi^2}{16} \text{Tr} D_\mu U D^\mu U^\dagger + \frac{f_\pi^2}{16} \text{Tr} \chi (U + U^\dagger) + L_1 [\text{Tr} (D_\mu U D^\mu U^\dagger)]^2 + L_2 (\text{Tr} D_\mu U D_\nu U^\dagger)^2 + L_3 \text{Tr} (D_\mu U D^\mu U^\dagger)^2 \\ & + L_4 \text{Tr} (D_\mu U D^\mu U^\dagger) \text{Tr} \chi (U + U^\dagger) + L_5 \text{Tr} D_\mu U D^\mu U^\dagger (\chi U^\dagger + U \chi) + L_6 [\text{Tr} \chi (U + U^\dagger)]^2 + L_7 [\text{Tr} \chi (U - U^\dagger)]^2 \\ & + L_8 \text{Tr} (\chi U \chi U + \chi U^\dagger \chi U^\dagger) - i L_9 \text{Tr} (F_{\mu\nu}^L D^\mu U D^\nu U^\dagger + F_{\mu\nu}^R D^\mu U^\dagger D^\nu U) + L_{10} \text{Tr} (F_{\mu\nu}^L U F^{R\mu\nu} U^\dagger). \end{aligned} \quad (4)$$

The parameters in the chiral perturbation theory of Eq. (4) are pion-decay constant f_π and the ten Gasser–Leutwyler (G-L) coefficients, L_i with $i = 1, \dots, 10$. These parameters are determined by fitting experimental data. Many models^[3] try to predict some of the ten coefficients. Recent review of the ChPT can be found in Ref. [4].

The chiral perturbation theory is rigorous and phe-

and arXiv:1309.2225 [hep-ph]

$$+ C_f g_s^2 \int \frac{d^4 k}{(4\pi)^4} \gamma^\mu S_f(k) \Gamma^\nu(k, p) G_{\mu\nu}(p - k), \quad (5)$$

where $S_f^0(p)$ is bare propagator of quark with flavor f and momentum p , $i(S_f^0(p))^{-1} = \not{p} - m_f$. The $C_f = 4/3$ stands for color factor and g_s is strongly coupling constant of QCD related to the so-called running coupling constant $g_s^2(\mu)$.

- **LO $O(p^4)$ ChPT calculations give:**

$$\alpha_\pi - \beta_\pi = 5.6 \pm 0.2 \times 10^{-4} \text{ fm}^3$$

with

$$\alpha_\pi + \beta_\pi = 0.0 \text{ fm}^3$$

} *Donoghue and Holstein, 1989*

- **NLO $O(p^6)$ corrections are relatively small**

$$\alpha_\pi - \beta_\pi = 5.7 \pm 1.0 \times 10^{-4} \text{ fm}^3$$

with

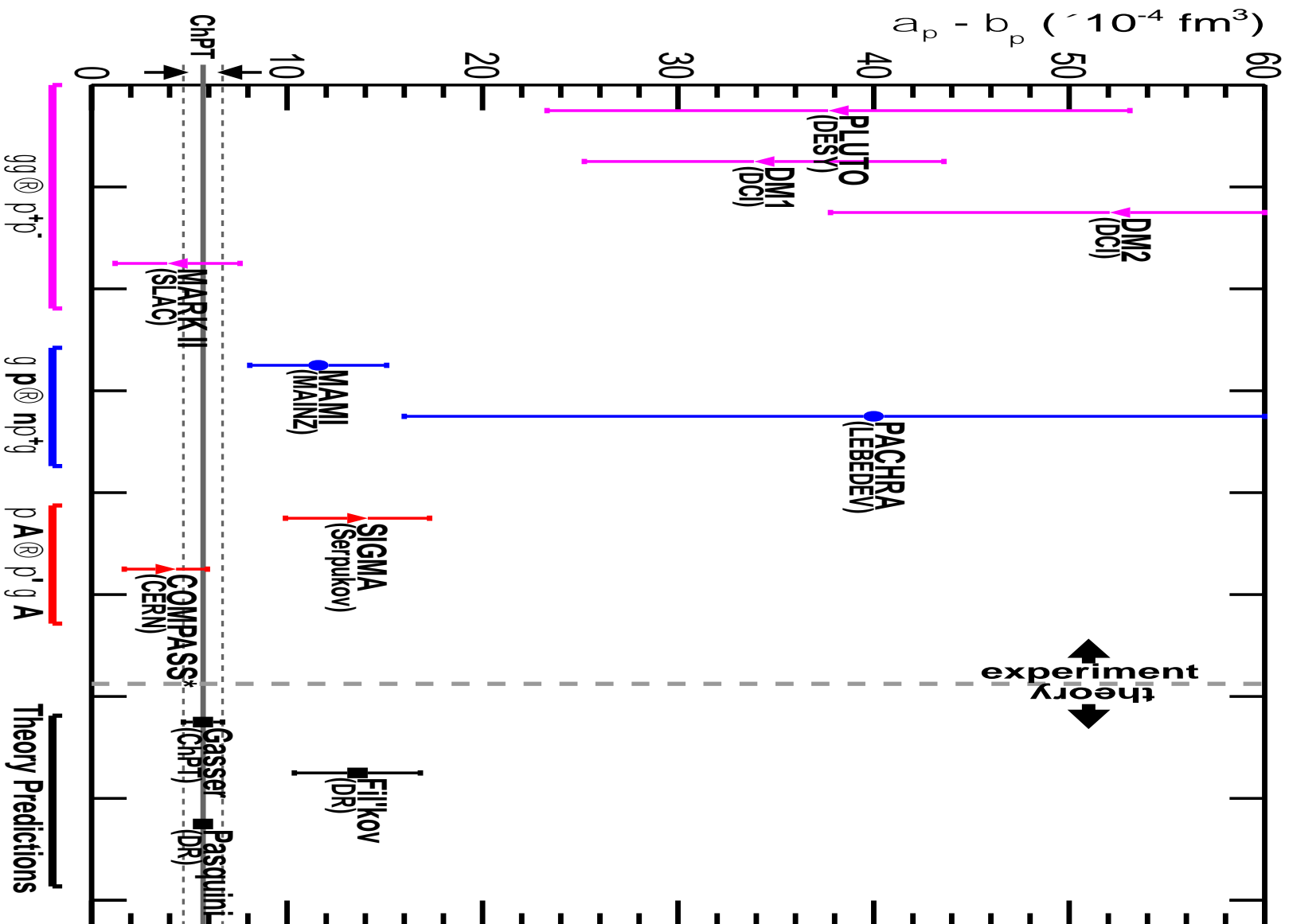
$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \times 10^{-4} \text{ fm}^3$$

} *Bürgi 1996,
Gasser et al. 2006*

- **Dispersion Relations have been used as well, but do not agree:**

$$\alpha_\pi - \beta_\pi = 13.0^{+2.6}_{-1.9} \times 10^{-4} \text{ fm}^3 \quad \textit{Fil'kov et al. 2006*}$$

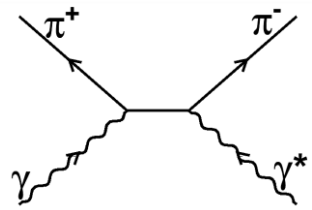
$$\alpha_\pi - \beta_\pi = 5.7 \times 10^{-4} \text{ fm}^3 \quad \textit{Pasquini et al. 2008}$$



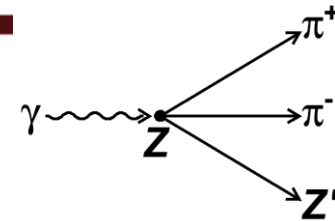
*COMPASS result from DNP2013 abstract N100005

Experimental Access

Primakoff effect

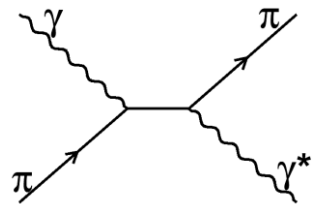


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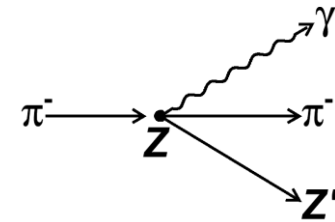


This experiment

Radiative pion photo-production

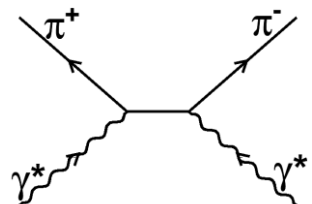


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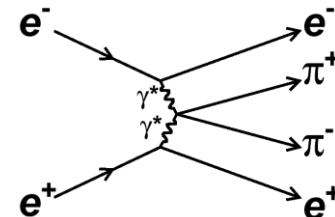


*SIGMA
COMPASS*

*Light by light scattering
(by crossing symmetry)*

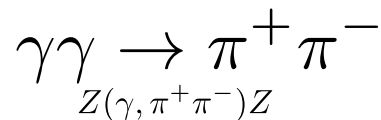


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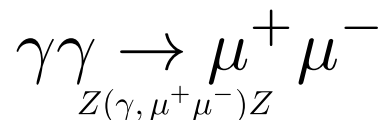


*PLUTO
DMI
DM2
MARK-II*

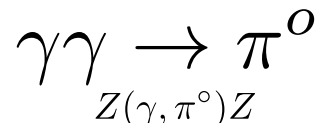
Experimental Setup



Signal reaction

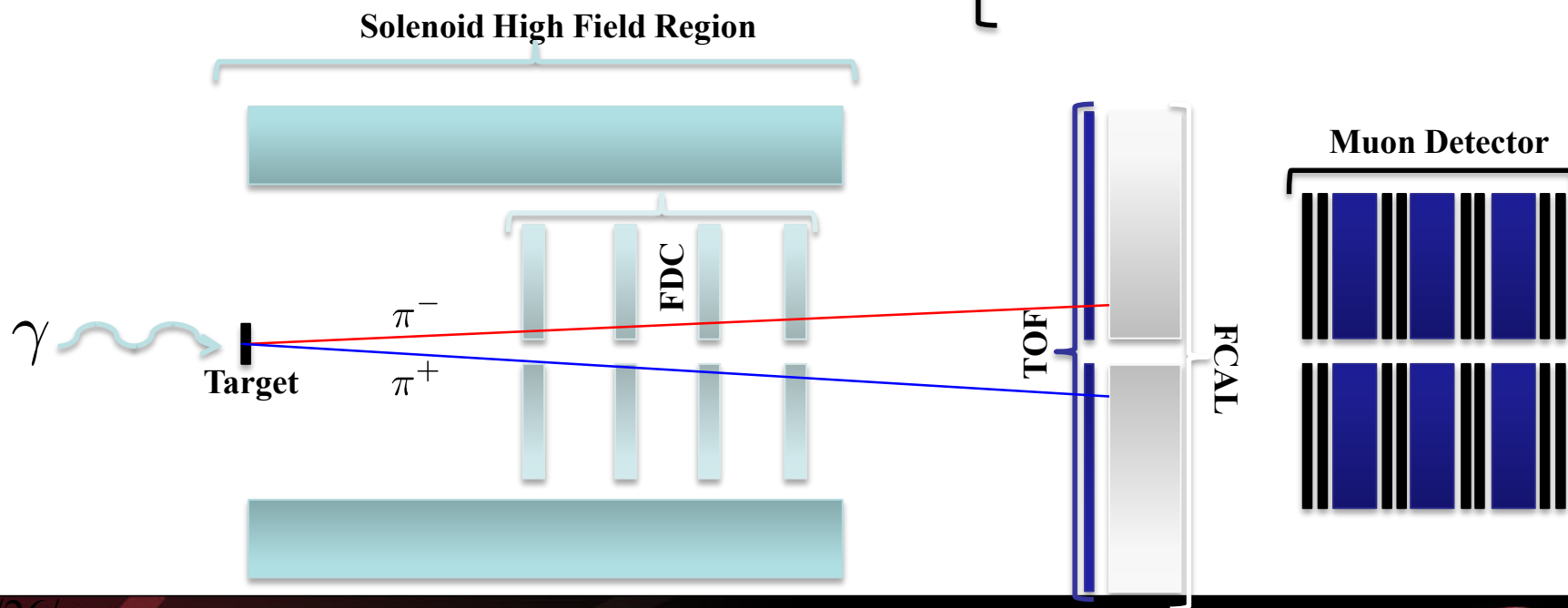


Normalization



Beam polarization

- All occur via the Primakoff effect (interaction with the Coulomb field of nucleus)
- All result in very forward going particles
- Low t ($-t < 0.005 \text{ GeV}^2$)



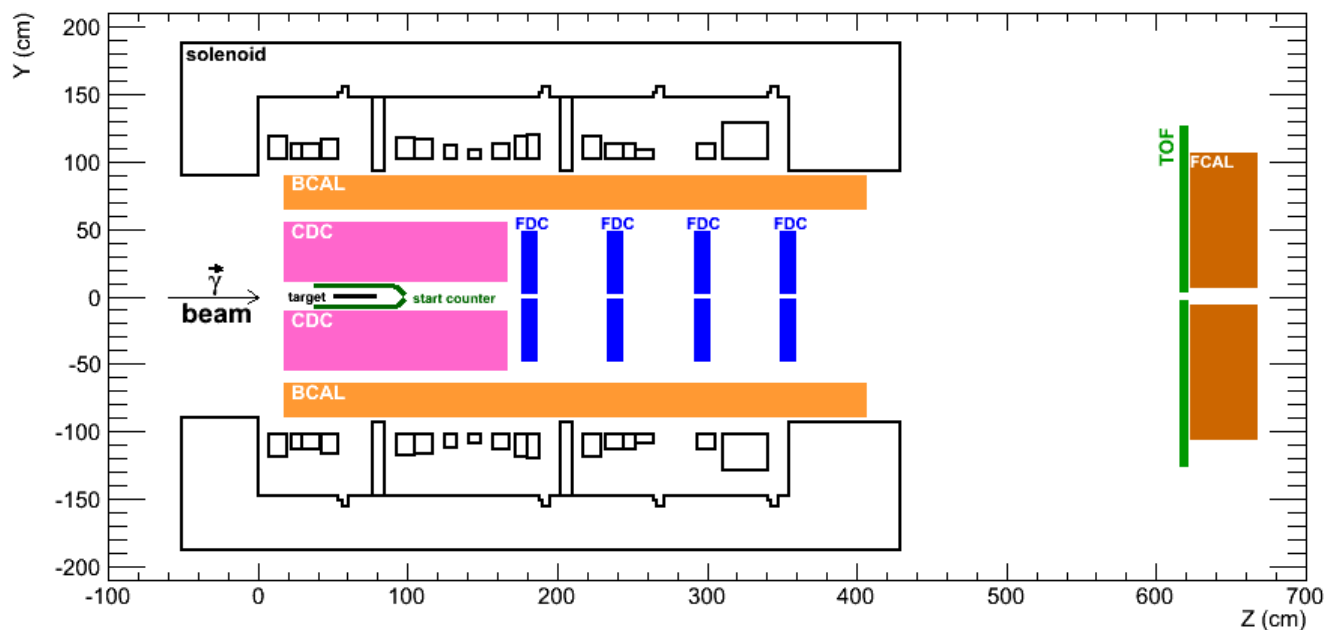
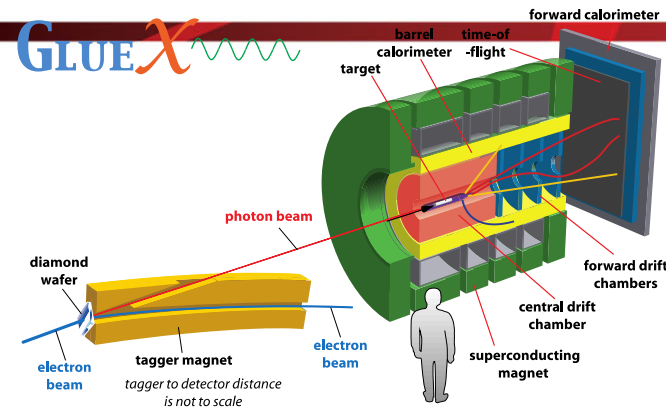
The GlueX Detector in Hall-D

New Proposal will use GlueX detector in Hall-D:

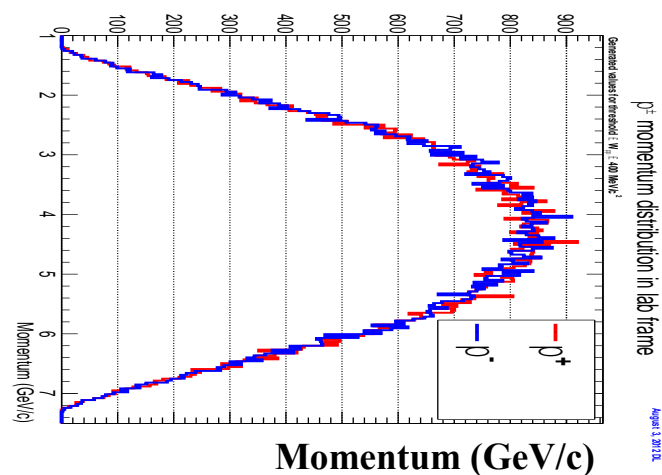
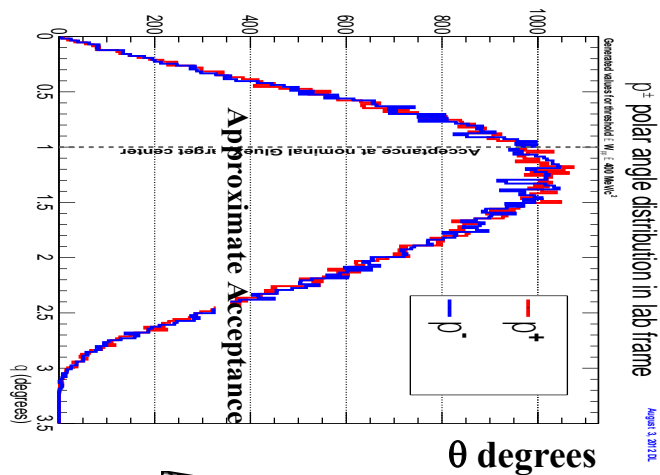
- Linearly polarized photon source ($\sim 9\text{GeV}$)
- 2T solenoidal magnetic field ($\delta p/p = \text{few } \%$)
- Drift chambers
- High resolution Time-of-flight detector

Modifications to standard GlueX setup:

- Replace LH2 target with thin Pb target
- Move target upstream to improve low-angle acceptance
- Alternate start-counter?

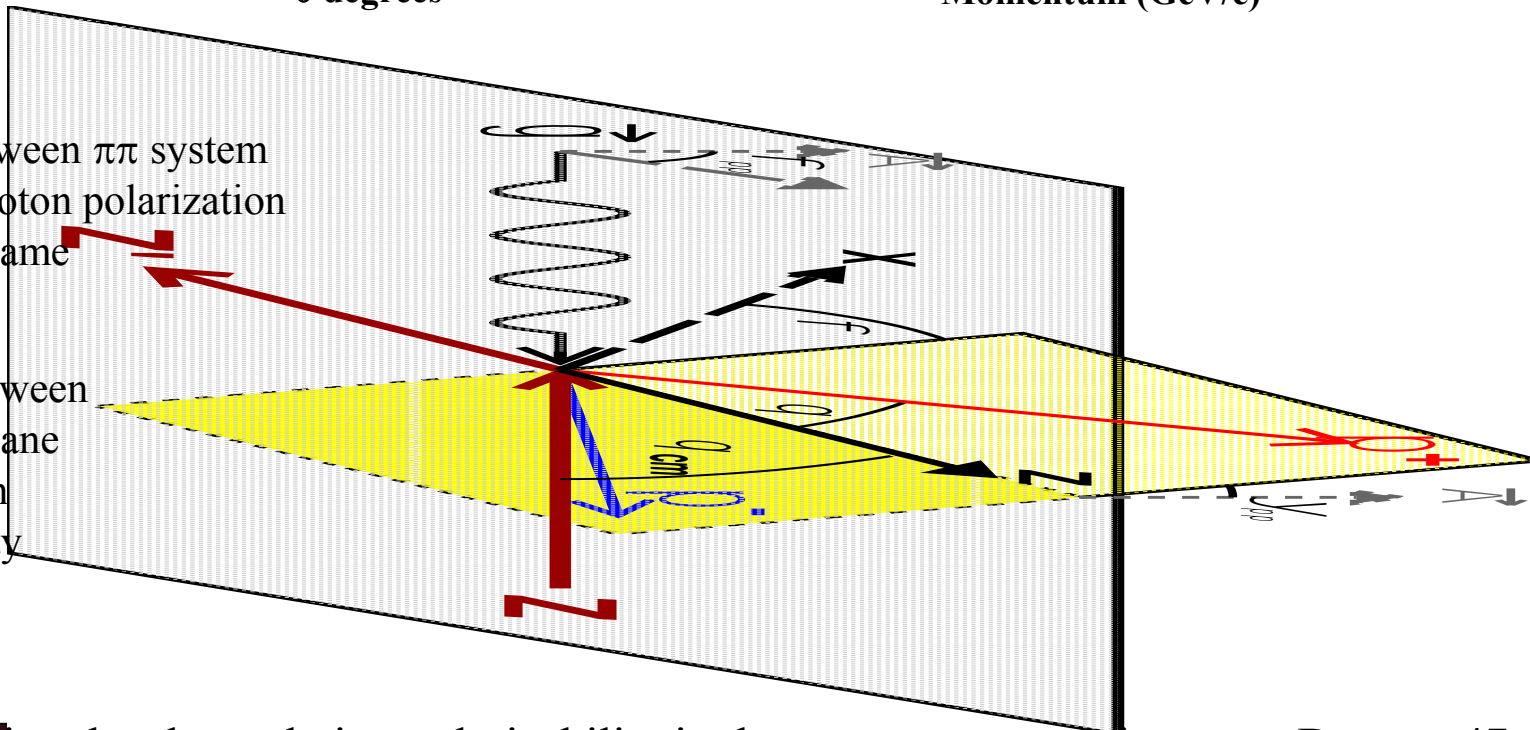


Kinematics of Experiment



$\phi_{\pi\pi}$ is angle between $\pi\pi$ system and incident photon polarization vector in CM frame

$\psi_{\pi\pi}$ is angle between $\pi\pi$ scattering plane and polarization vector in helicity frame



Backgrounds

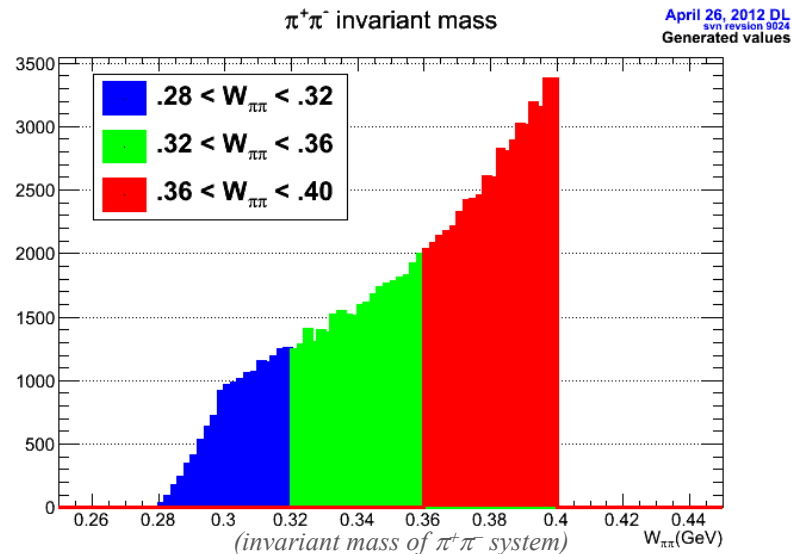
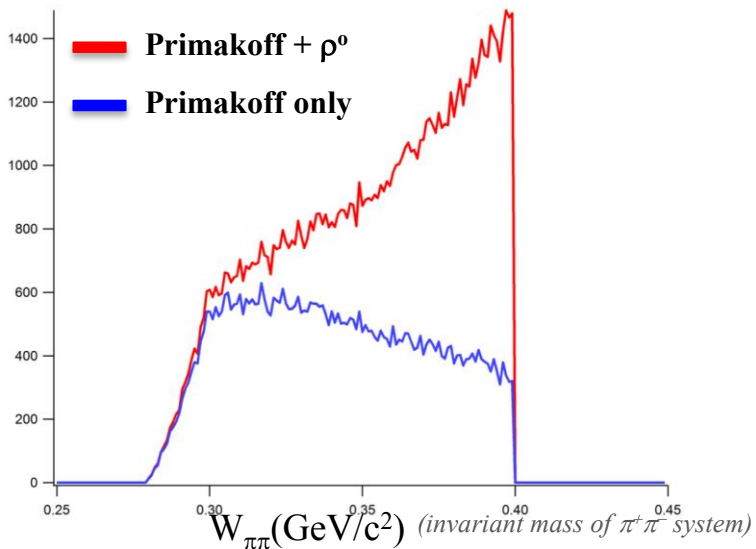
- Experiment will measure reaction:



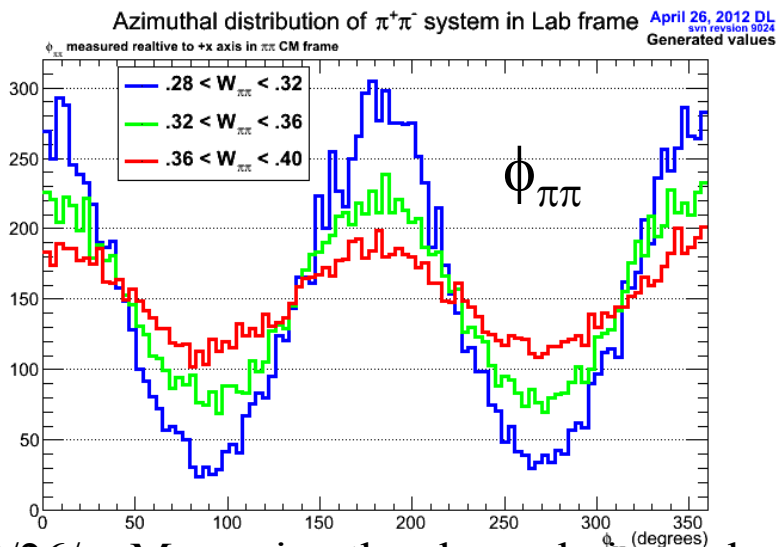
- Primary backgrounds will be:
 - coherent ρ^0 production followed by $\rho \rightarrow \pi\pi$ decay
 - Will use angular distributions to separate Primakoff from coherent ρ^0 production (see later slides)
 - Electromagnetic $\mu^+\mu^-$ production
 - Will use dedicated detector to identify hadron showers
- Other potentially relevant backgrounds include:
 - σ meson production (angular distributions same as Primakoff)
 - incoherent $\pi^+\pi^-$ production
 - ...

Linear Polarization of incident γ

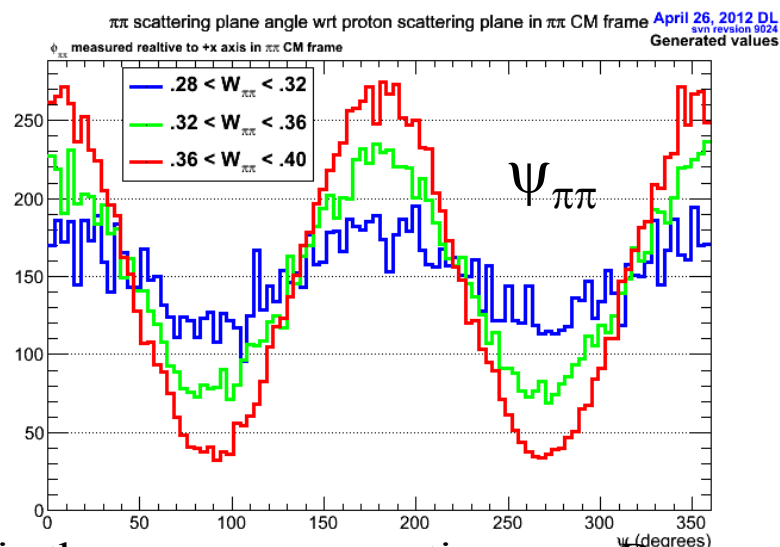
helps distinguish Primakoff from coherent ρ^0 production



April 26, 2012 DL
svn revision 9024
Generated values



April 26, 2012 DL
svn revision 9024
Generated values

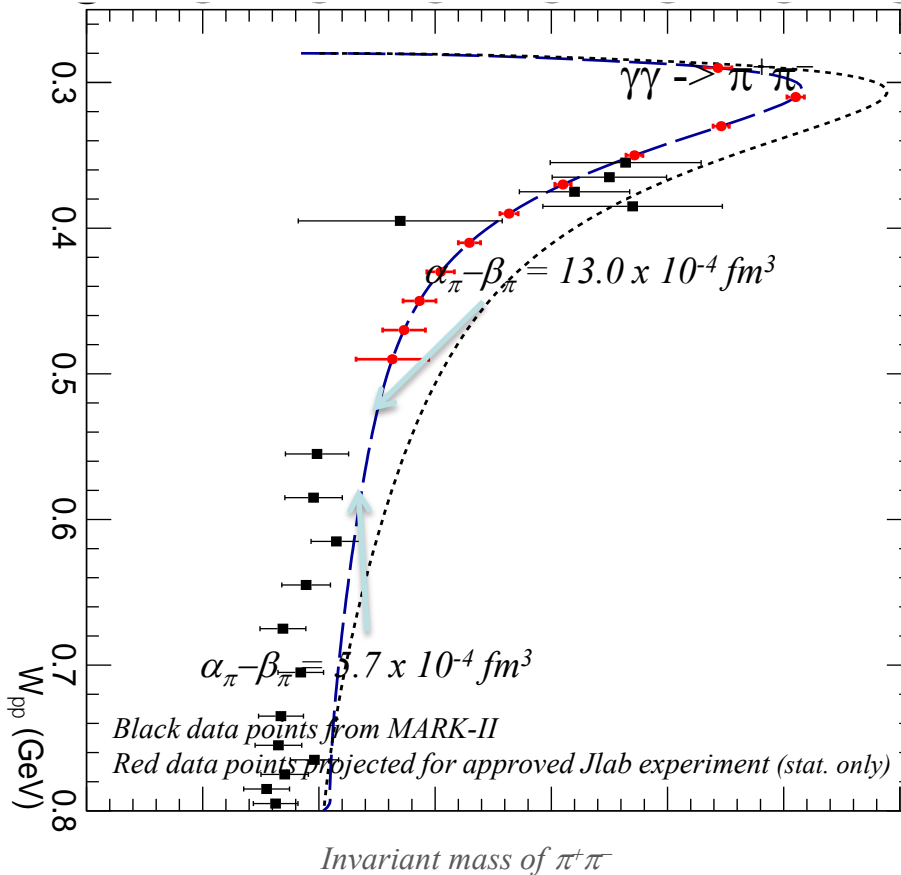


April 26, 2012 DL
svn revision 9024
Generated values



Relating cross-section to $\alpha_\pi - \beta_\pi$

Curves from figure 5. from Pasquini et al. Phys. Rev. C 77, 065211 (2008)



Cross-section for $\gamma\gamma \rightarrow \pi^+\pi^-$ calculated based on two values of $\alpha_\pi - \beta_\pi$:

$$\alpha_\pi - \beta_\pi = 13.0 \times 10^{-4} \text{ fm}^3 \text{ (top, dotted line)}$$

$$\alpha_\pi - \beta_\pi = 5.7 \times 10^{-4} \text{ fm}^3 \text{ (solid and dashed lines)}$$

Cross-section varies by $\sim 10\%$ for factor of 2 variation in $\alpha_\pi - \beta_\pi$

Need measurement of $\sigma(\gamma\gamma \rightarrow \pi^+\pi^-)$ at few percent level



dotted: subtracted DR calculation with $\alpha_\pi - \beta_\pi = 13.0$

dashed: subtracted DR calculation with $\alpha_\pi - \beta_\pi = 5.7$

Rates/Acceptance/Errors

- 500 hours of running
 - 10^7 tagged photons/second on 5% radiation length ^{116}Sn target
 - PAC approved 25 days (20 for production, 5 calibration)
- $W_{\pi\pi}$ acceptance down to $\sim 320 \text{ MeV}/c^2$
- Estimated $\sim 36\text{k}$ Primakoff events
(not including detector acceptance)

Error Budget

Errors and correction factors	Correction factor	Statistical uncertainty in correction factor
Overall statistical error		0.6 % 
Normalization to $\mu^+\mu^-$ and relative trigger efficiency		1 %
$\mu^+\mu^-$ background in $\pi^+\pi^-$ yield	0.03 %	0 %
Polarization	70%	0.2 %
Pion identified as muon, and pion decay	8 %	1%
Total systematic error		1.5 % 
Projected error in $\alpha - \beta$		10%

Summary

- Next to leading order ChPT prediction of $\alpha_\pi - \beta_\pi$ is $5.7 \pm 1.0 \times 10^{-4} \text{ fm}^3$
- Previous measurements of $\alpha_\pi - \beta_\pi$ range from $4.4 - 52.6 \times 10^{-4} \text{ fm}^3$
- A newly approved experiment to measure the charged pion polarizability $\alpha_\pi - \beta_\pi$ via the $\gamma\gamma^* \rightarrow \pi^+\pi^-$ reaction will be done using the GlueX detector at Jefferson Lab
 - *PR12-13-008*
- Total estimated uncertainty in $\alpha_\pi - \beta_\pi$ measurement is 10%
 - ($\pm 0.6 \times 10^{-4} \text{ fm}^3$)
- An improved measurement of $\alpha_\pi - \beta_\pi$ would improve the SM prediction of the anomalous magnetic moment of the μ : $(g_\mu - 2)/2$