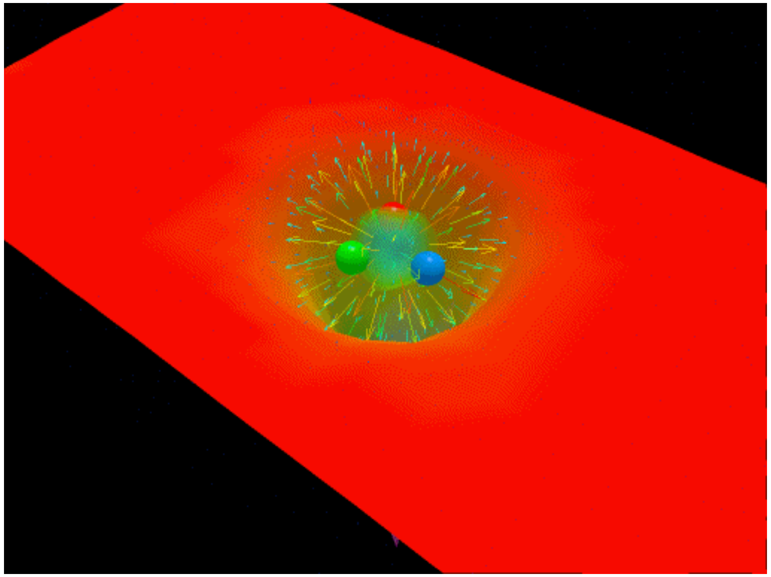
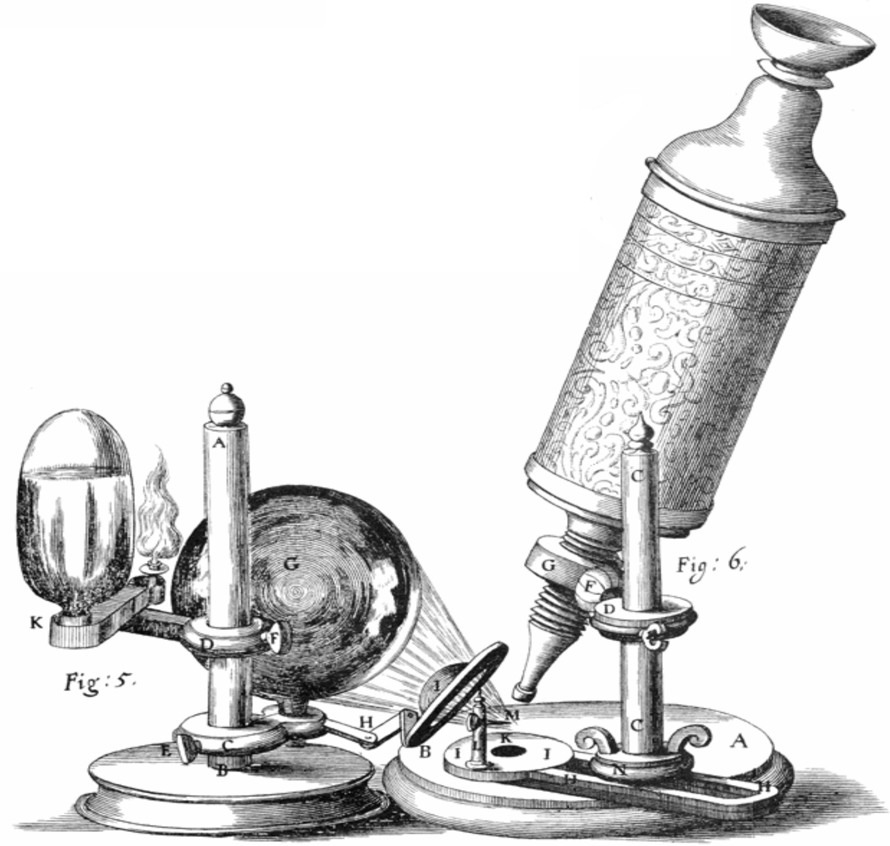


Nuclear Physics

Exploring the Heart of Matter

David Lawrence
Jefferson Lab Newport News VA, USA

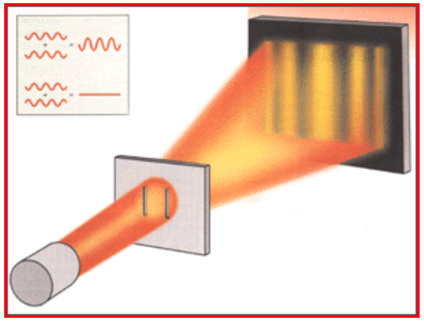
With slides provided by Latifa Elouadrhiri and Alex Barnes

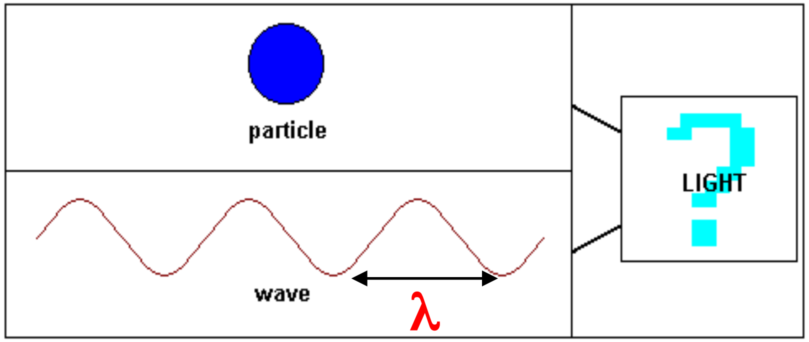


Part –II
Particle Scattering Microscope on the world of quarks

Wave-particle duality of Nature

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





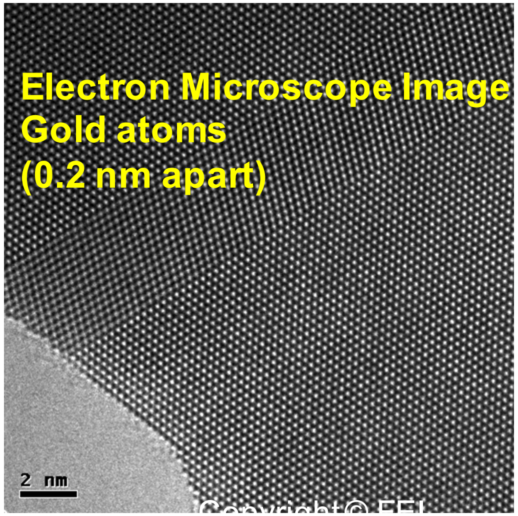
Not only light has a dual nature

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

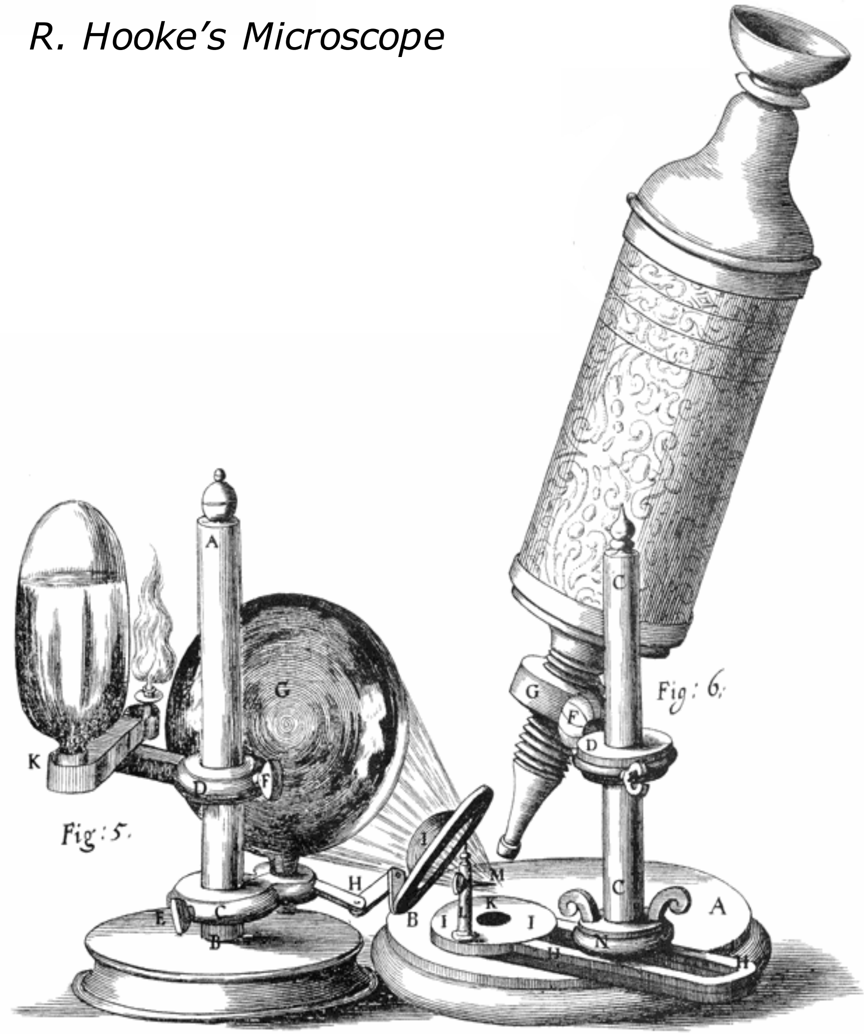
Example: electron microscope



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

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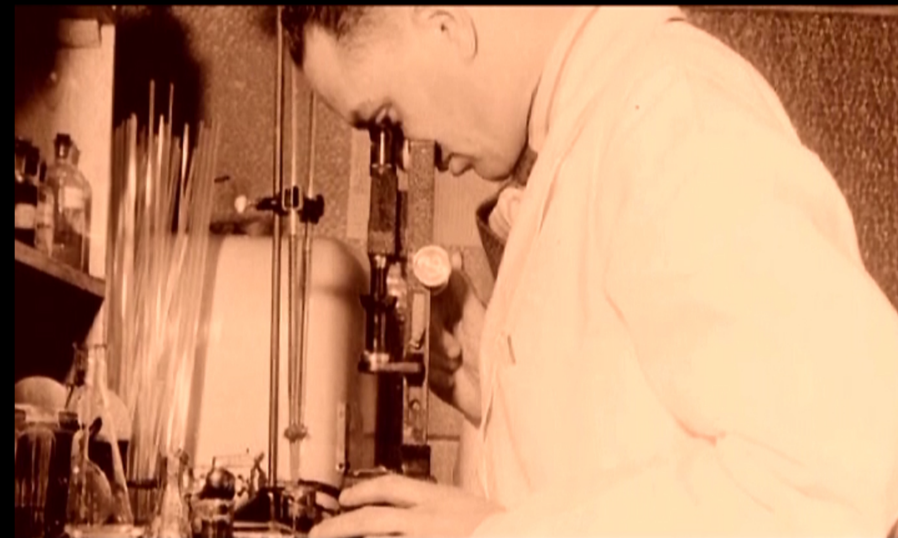
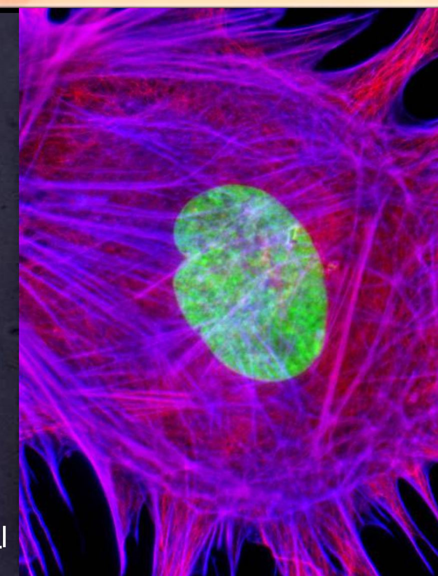
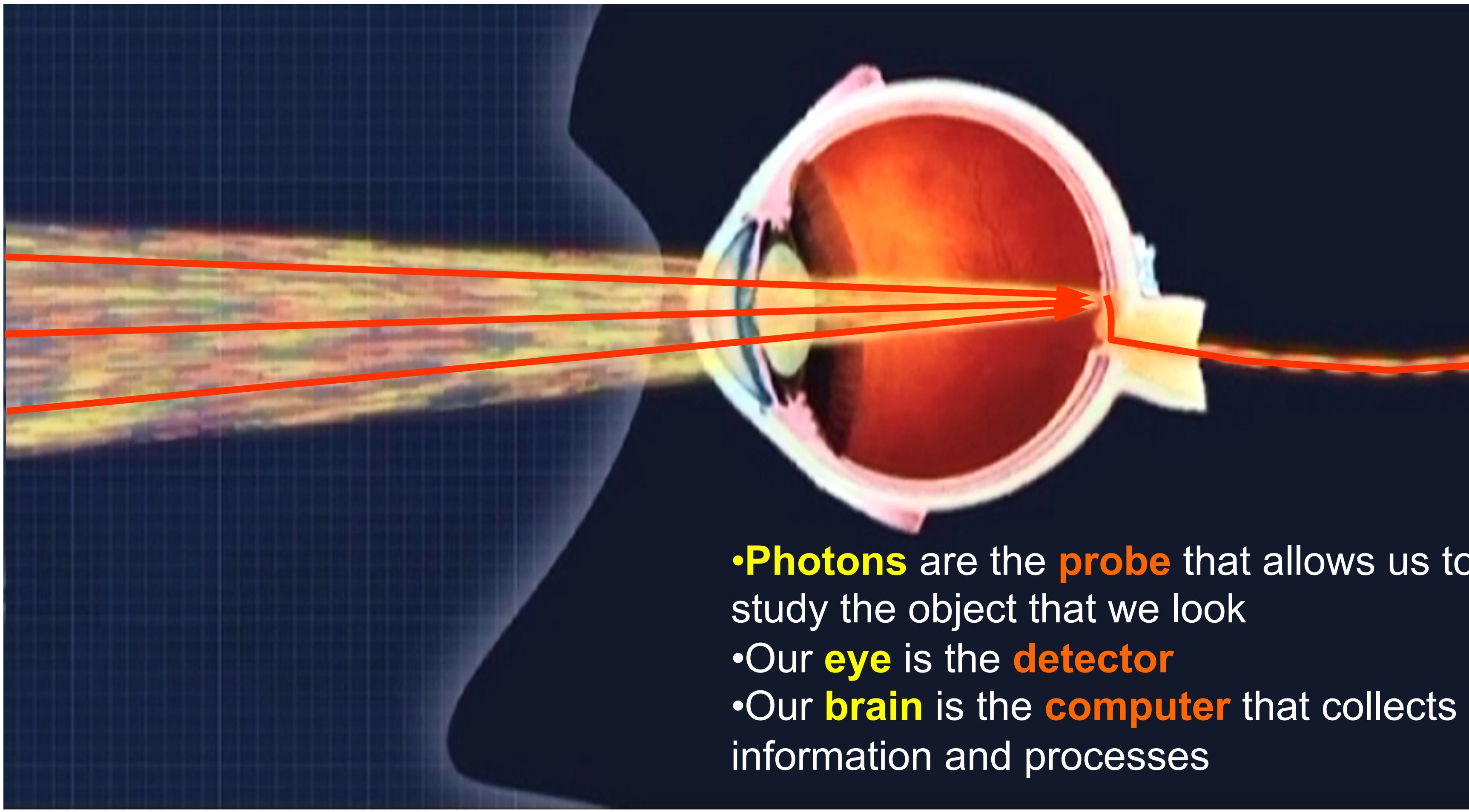


The optical microscope allowed the discovery of the existence of microscopic organisms and to study the organic fabric



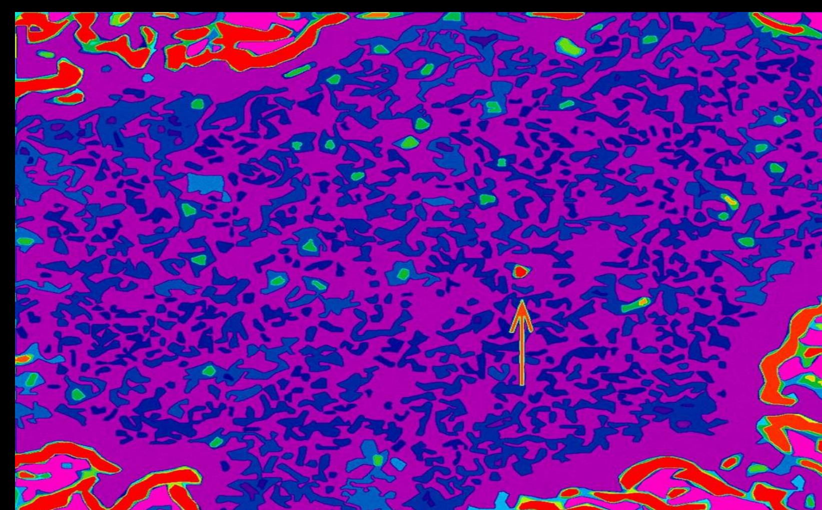
The Microscope



The Microscope

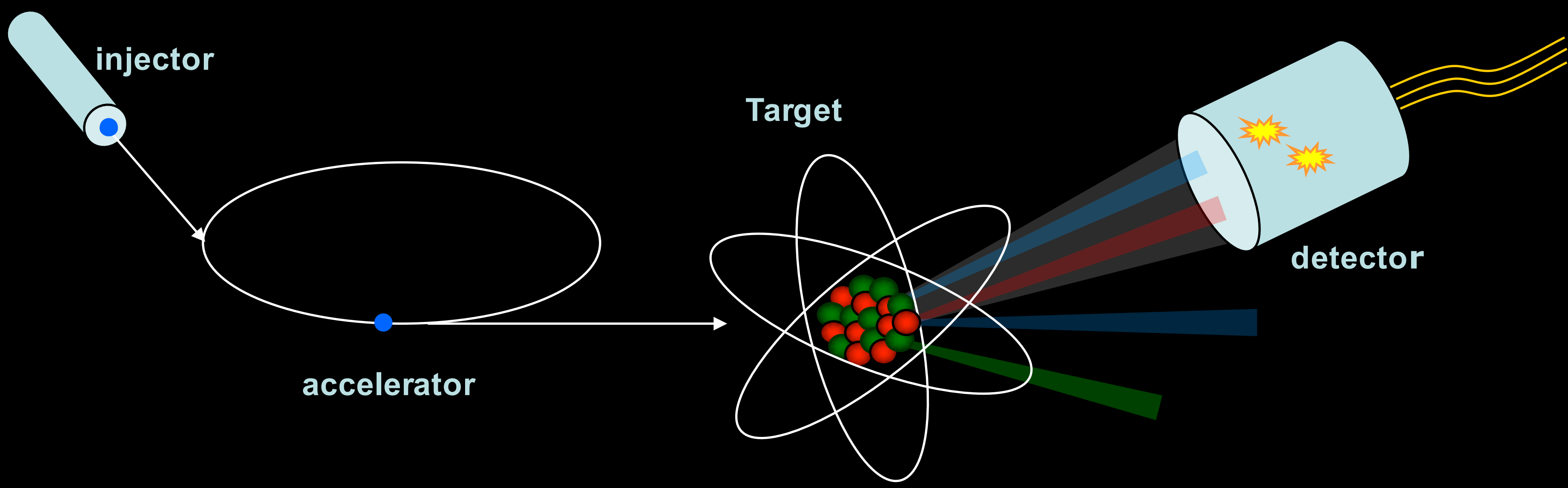
Today, more sophisticated microscopes achieved a very high resolution

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

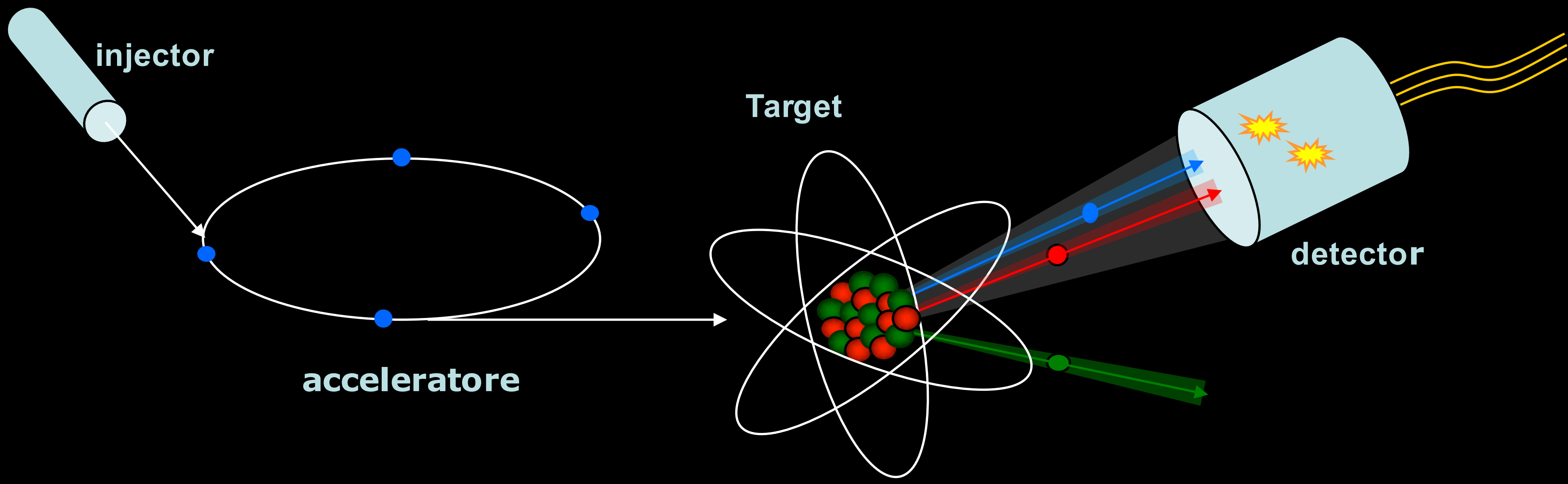


But how can we get to "see" quarks?

Electron Scattering

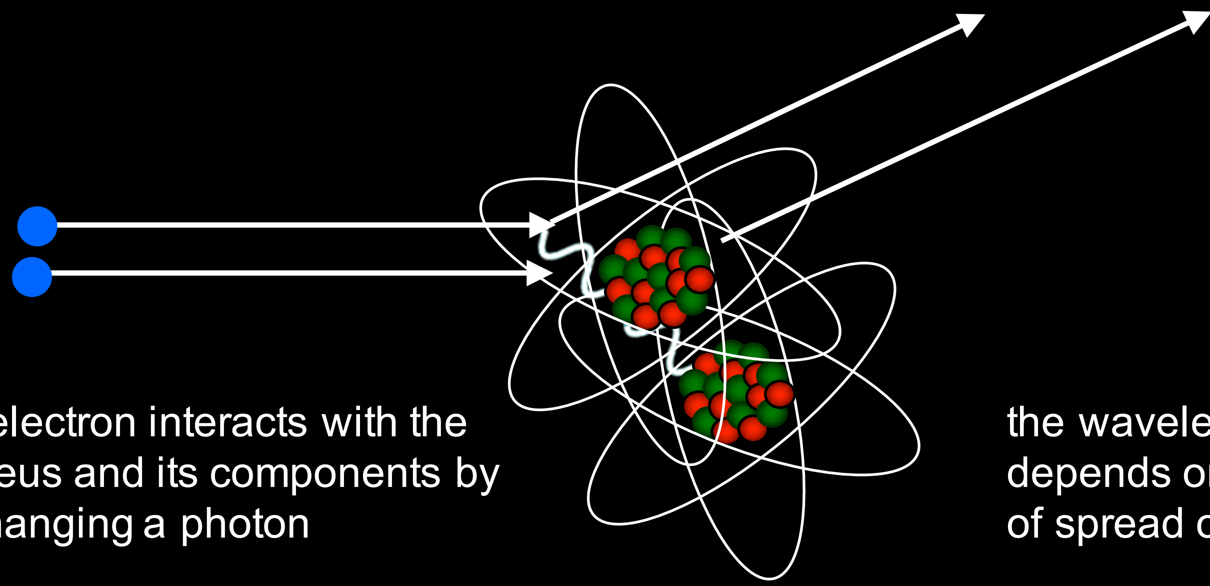


Electron Scattering



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

Electron Scattering

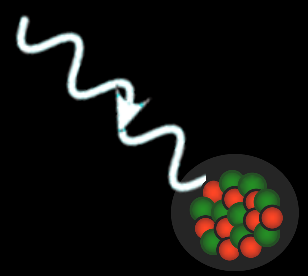


the electron interacts with the nucleus and its components by exchanging a photon

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

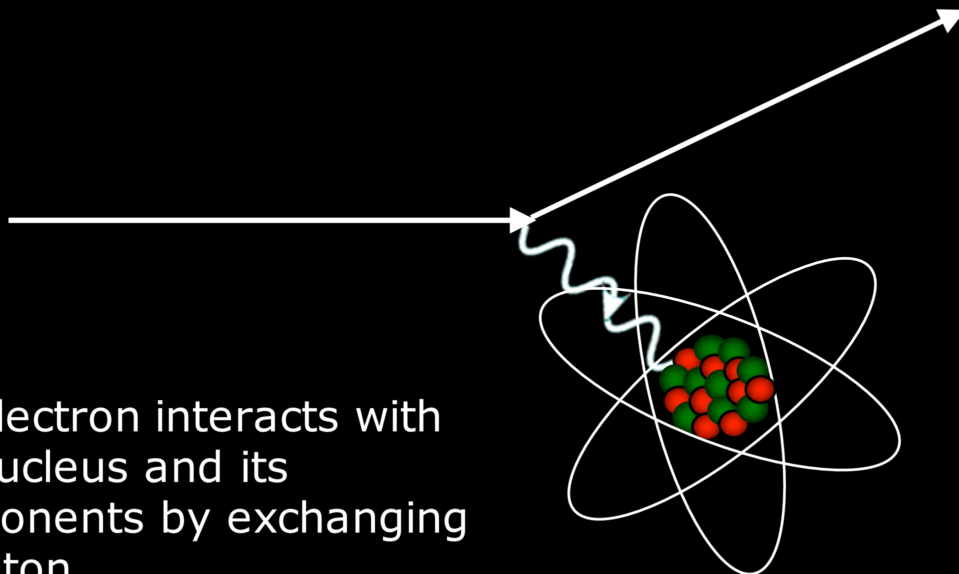
At wavelengths comparable to the size of the nucleaus

$\lambda >> 10^{-15}$ m



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

Electron Scattering



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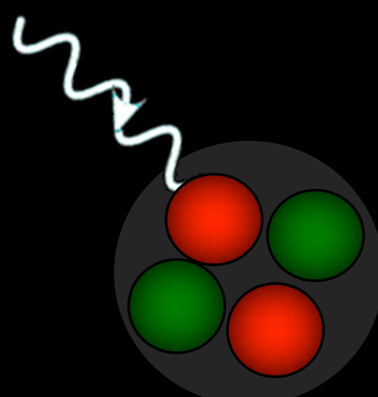
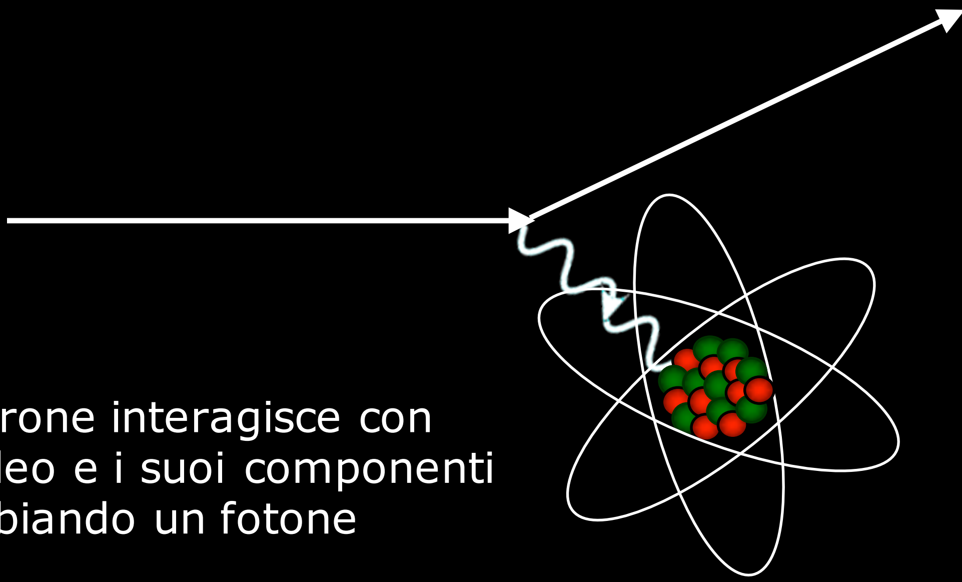


At intermediate wavelength the order of the size of the nucleon

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

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

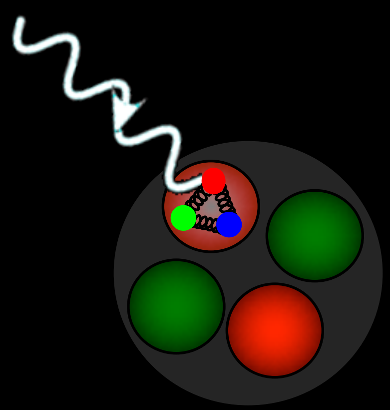
Electron Scattering



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

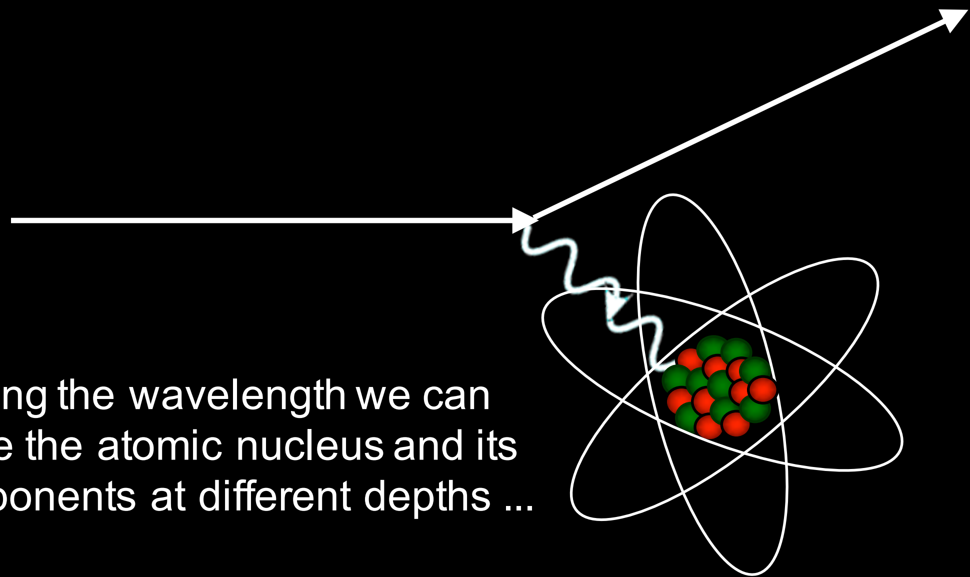
At short wavelength, smaller
than the size of the proton



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

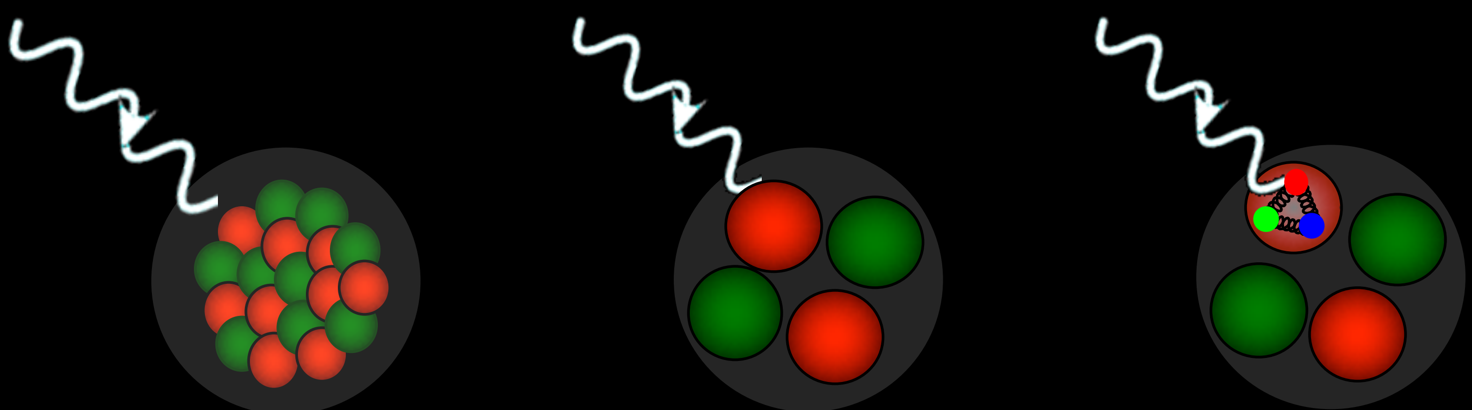
$\lambda << 10^{-15}$ m

Electron Scattering



Varying the wavelength we can probe the atomic nucleus and its components at different depths ...

And ... study how quarks and gluons form nucleons and nuclei



$\lambda >> 10^{-15}$ m $\lambda \sim 10^{-15}$ m $\lambda << 10^{-15}$ m

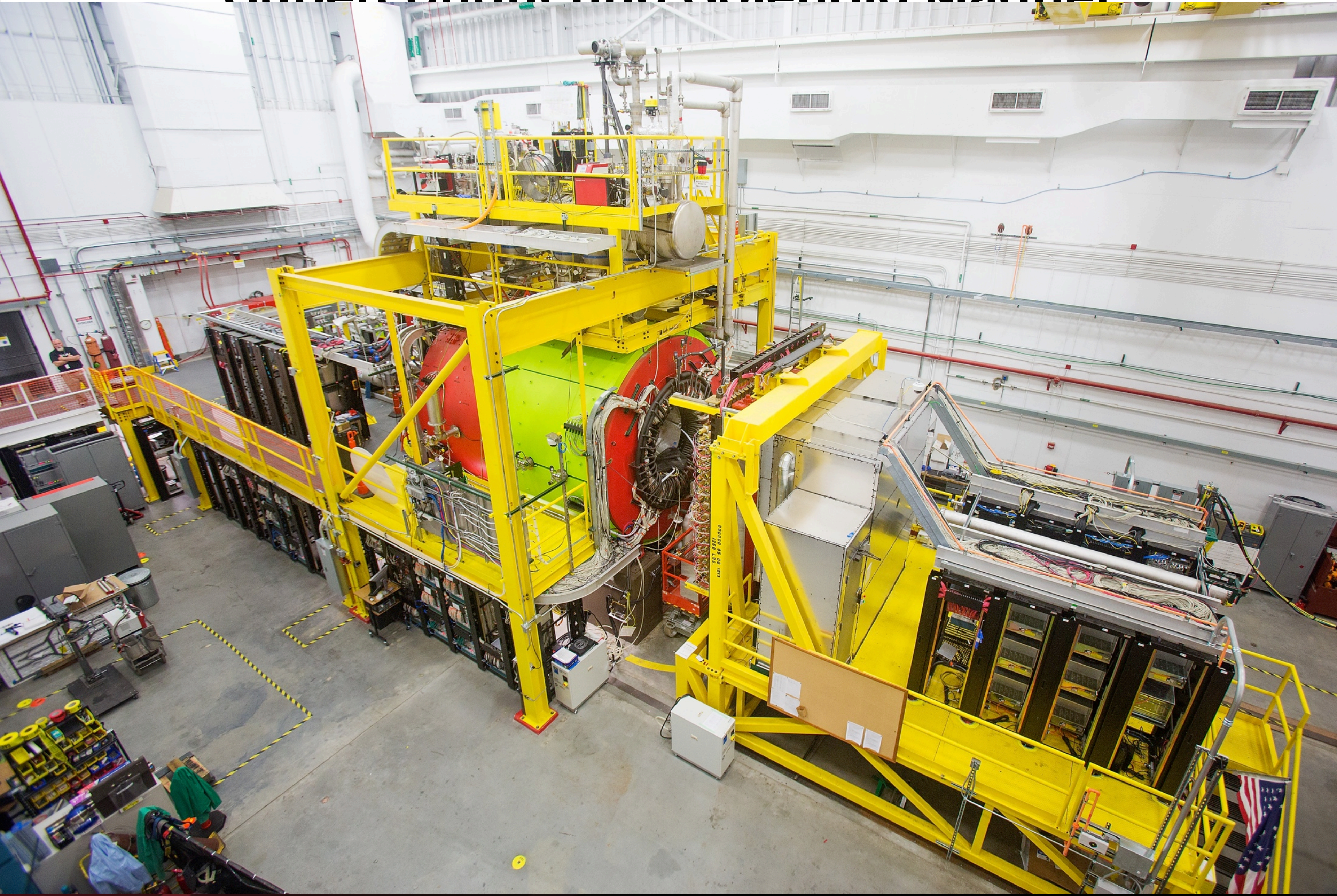
Aerial p
taken Apr

Hall-D

Electron beam

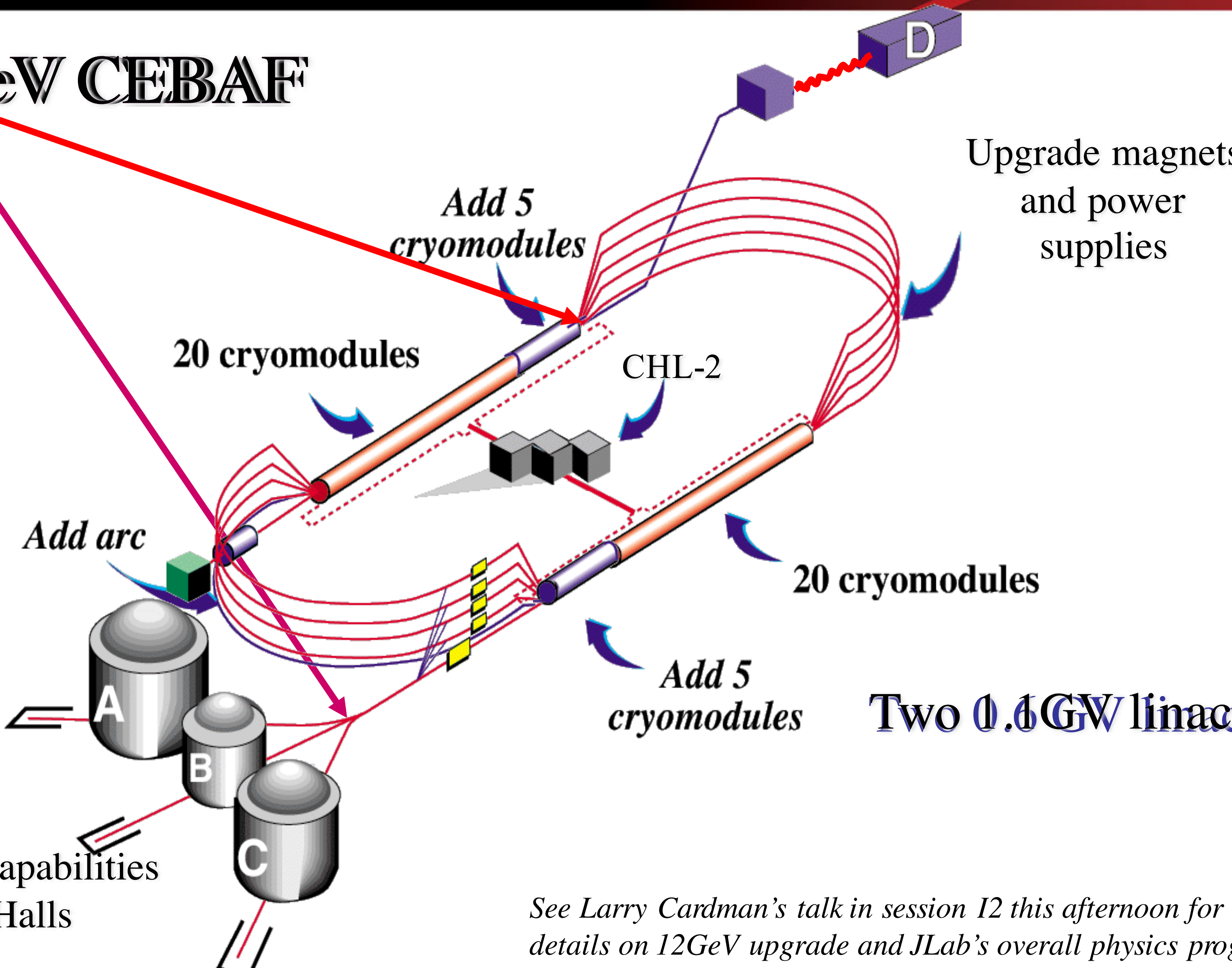
- continuou
  (1497MHz,
  structure in
- Polarized
  beam
- Upgraded
  (from 6GeV
- 70 μA ma
  (200μA ma

Superconducting Solenoid Magnet



The JLab 12GeV Upgrade

12 GeV CEBAF



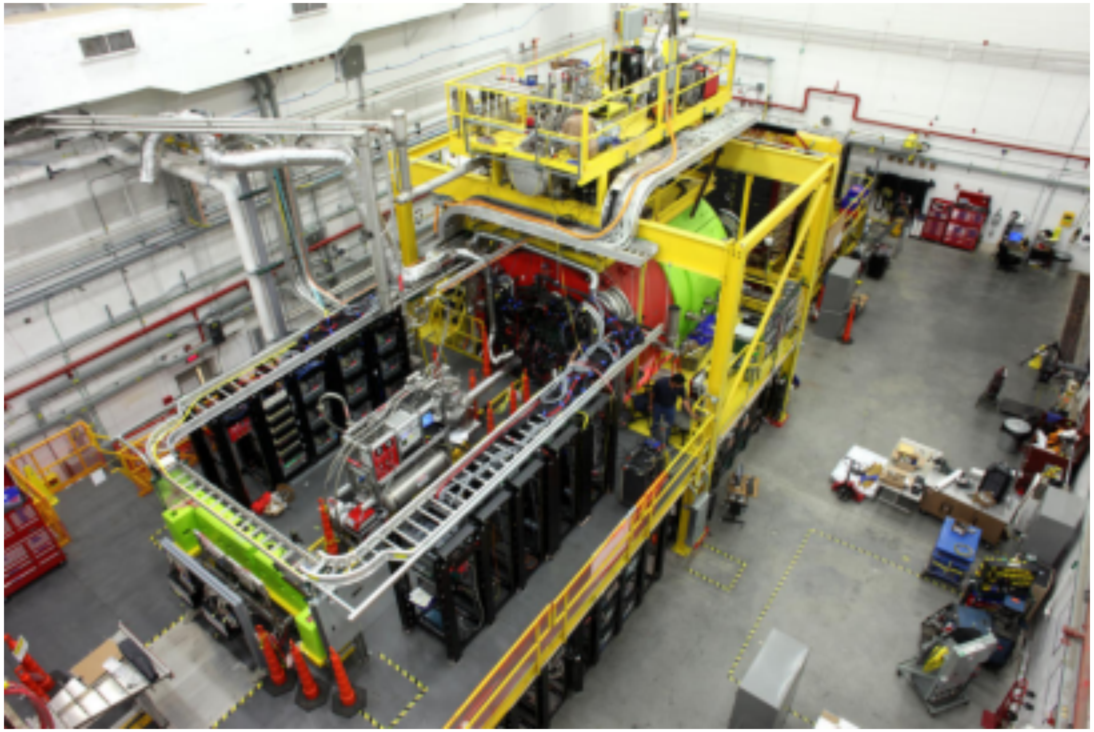
Two 1.1GV linacs

Enhanced capabilities in existing Halls

See Larry Cardman's talk in session I2 this afternoon for more details on 12GeV upgrade and JLab's overall physics program

Hall D Experiments

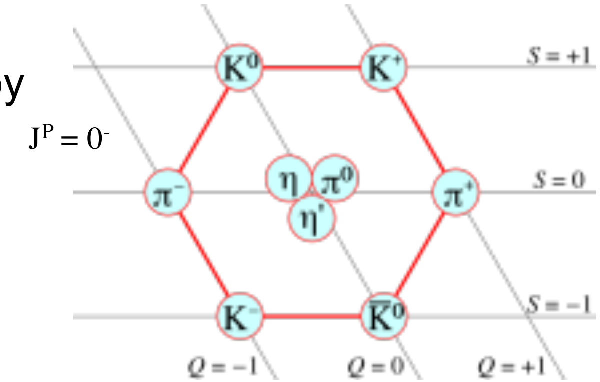
- GlueX
  - E12-06-102, C12-12-002, E12-13-003
  - 540 PAC days
- PrimEx-eta
  - E12-10-011
  - 79 PAC days
- Pion polarizability
  - E12-13-008
  - 25 PAC days
- JLab Eta Factory (JEF): Rare eta decays
  - C12-14-004
  - Conditionally approved



Exotic Hybrid Mesons

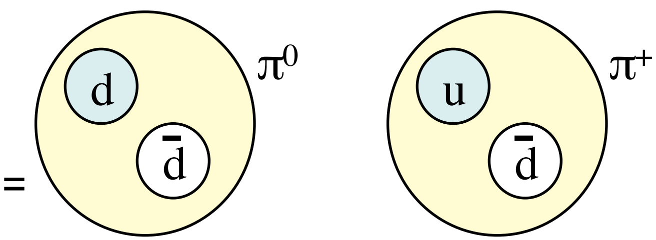
Quark model

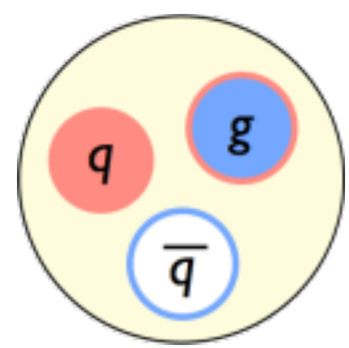
- The spectrum of conventional mesons is described by the quark model
- Mesons are grouped in nonets of J^P with different quark flavor content
- Allowed $q\bar{q}$ states: 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 2^{++}, …



Hybrids

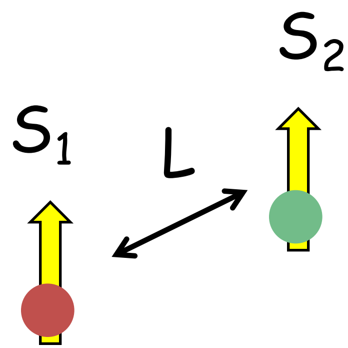
- Excited gluonic field coupled to $q\bar{q}$ pair
- Spectrum of hybrids predicted by lattice QCD
  - Can be modeled as "constituent gluon" with $J^{PC} = 1^{+-}$ and mass = 1-1.5 GeV
- Some have "exotic" J^{PC} which cannot be formed by $q\bar{q}$
  - $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, \ldots$
  - Exotic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



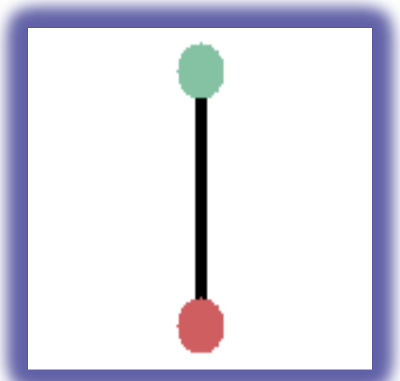


Exotic Hybrid Mesons

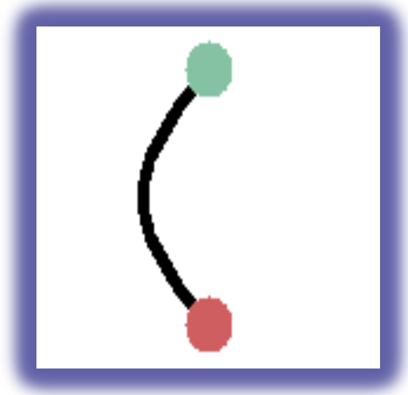
Conventional meson has quantum numbers determined only by constituent quarks



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



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



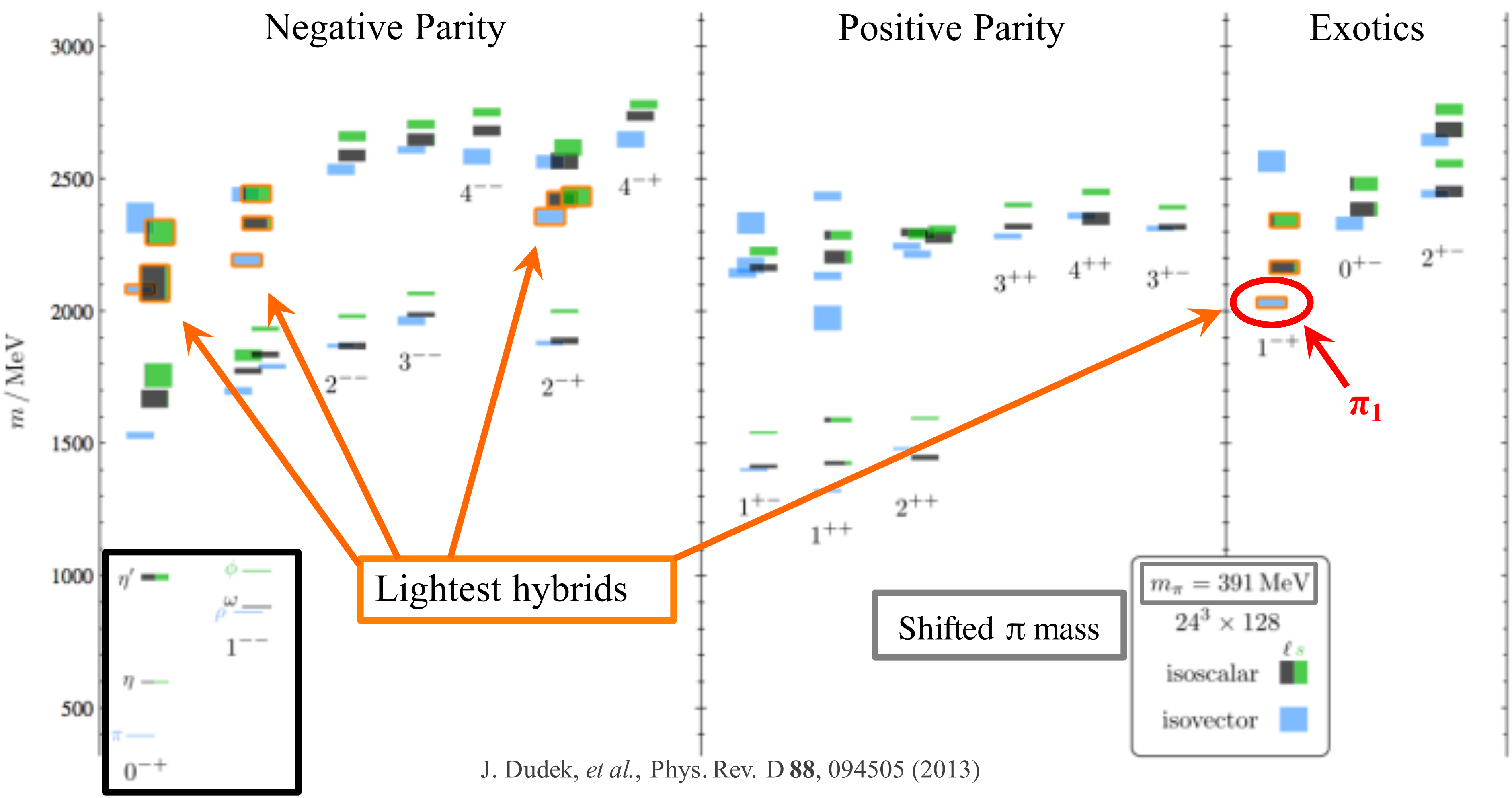
$J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 1^{+-}, 2^{-+}, 2^{++}$

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

"exotic" states

Lattice QCD predictions

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



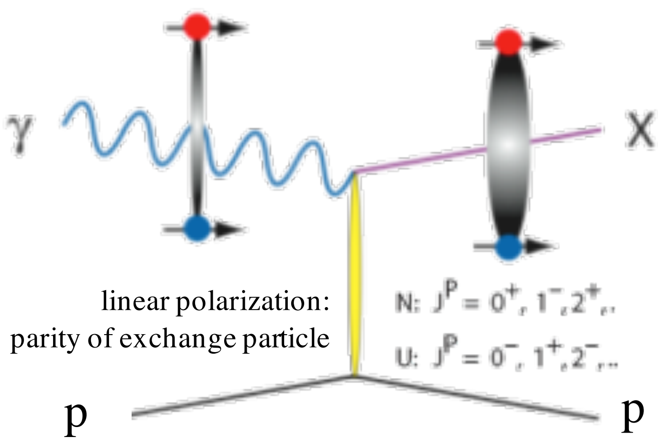
J. Dudek, *et al.*, Phys. Rev. D **88**, 094505 (2013)

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)

$$\Gamma\left(\eta_{c1} \to J/\psi\,\gamma\right) \sim 100\,\mathrm{keV}$$



- **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

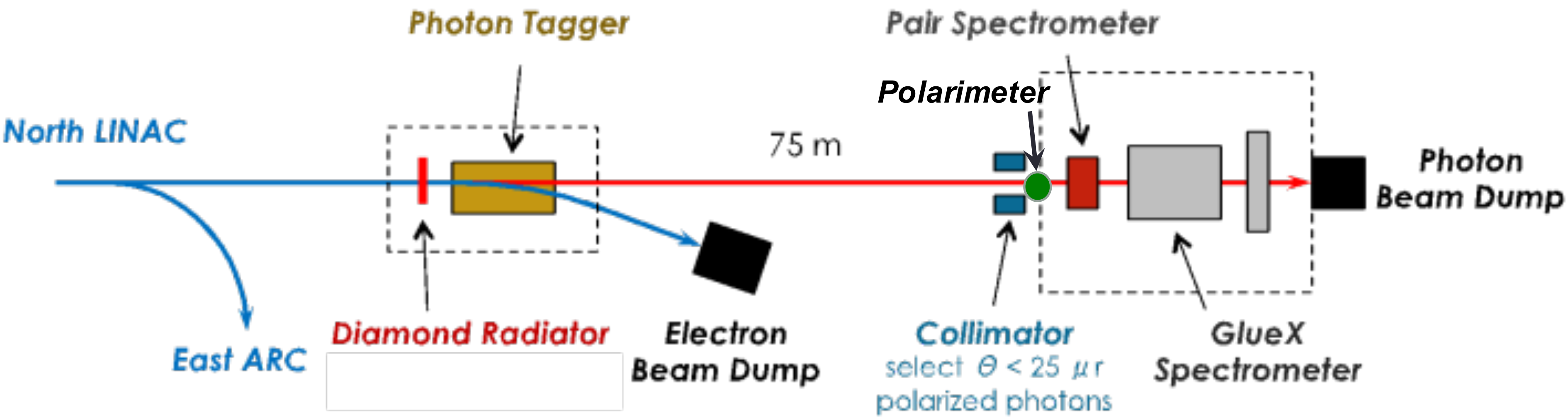
$$\vec{\gamma} + p \to p + X$$
$\hookrightarrow b_1\pi$
$\hookrightarrow \omega\pi$
$\hookrightarrow \pi\pi\pi$

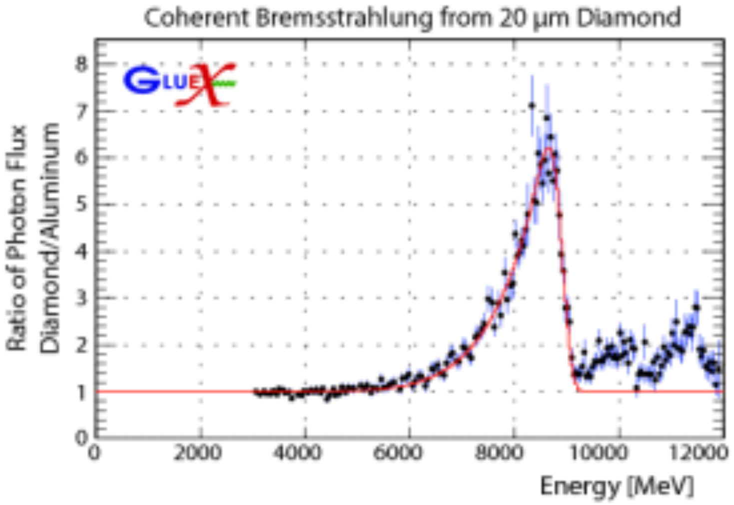
9GeV linearly polarized ($\vec{\gamma}$); *hybrid meson* (X)

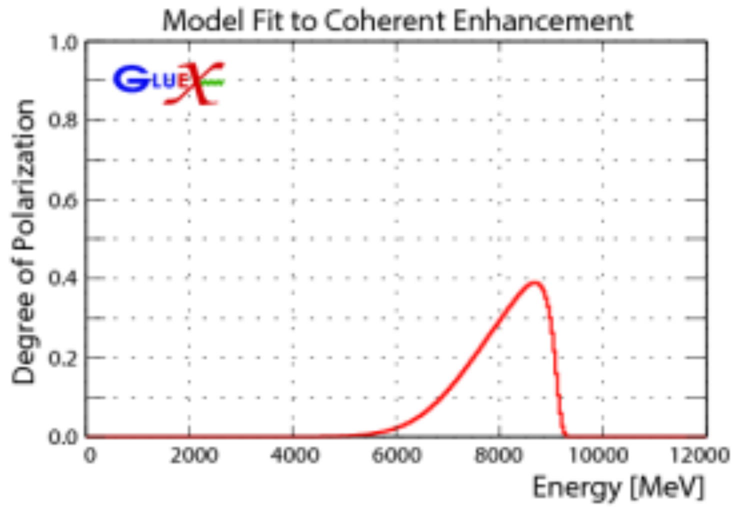
detectable final state: $5\pi + 1p$ *(mixed charged and neutral)*

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

GlueX Experiment - beamline (UConn)







Exotic J^{PC} Decays

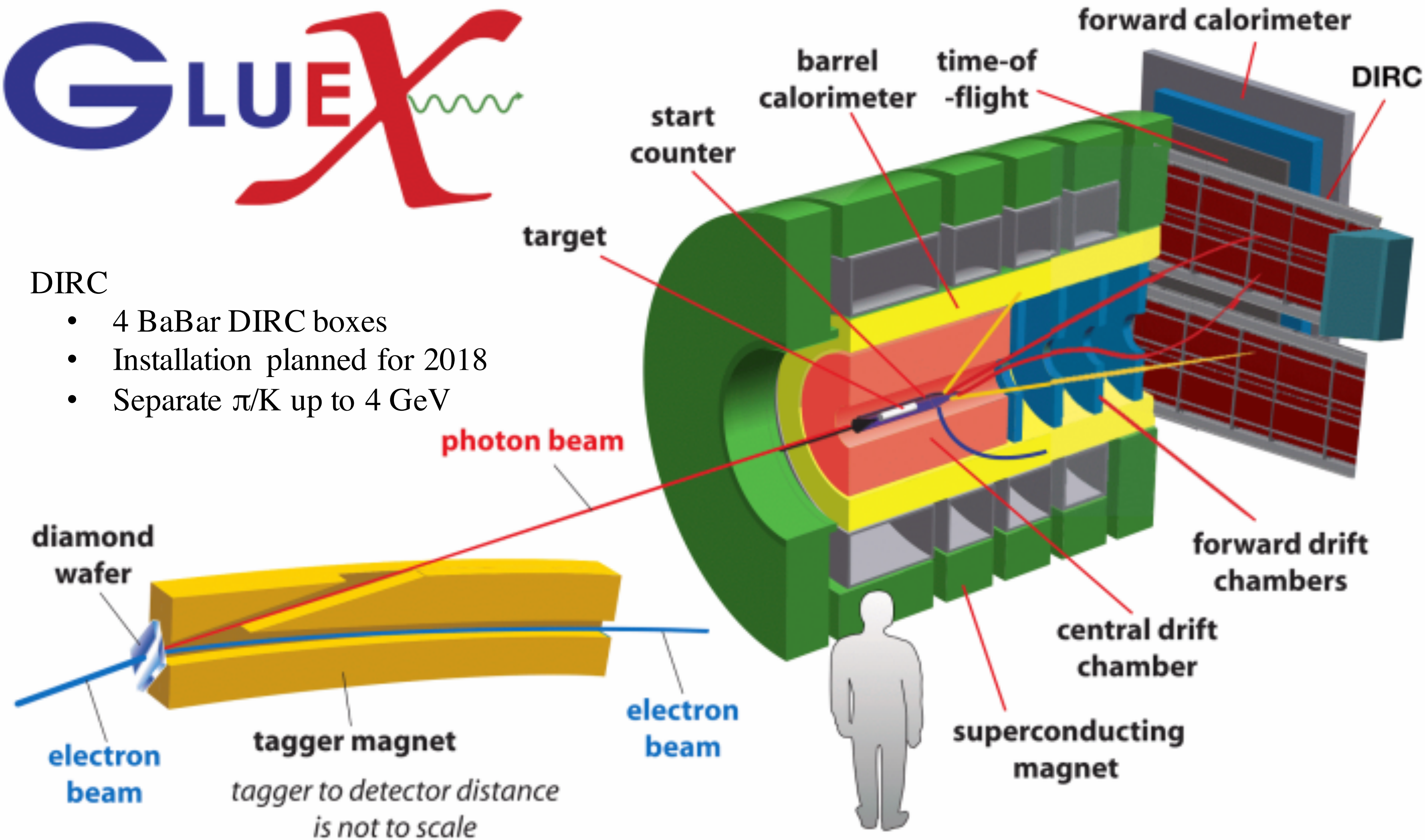
- Lattice predictions for the mass of hybrids
- Decay predictions are model dependent
- Reported $J^{PC} = 1^{-+}$: $\pi\rho \rightarrow 3\pi$, $\pi\eta' \rightarrow 3\pi\eta$, $\pi b_1 \rightarrow 2\pi\omega$
- Early reach
- With statistics

$K_1^A(1270)$
$K_1^B(1400)$

Name	J^{PC}	Total width MeV (Model) PSS	IKP	Allowed decay modes
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

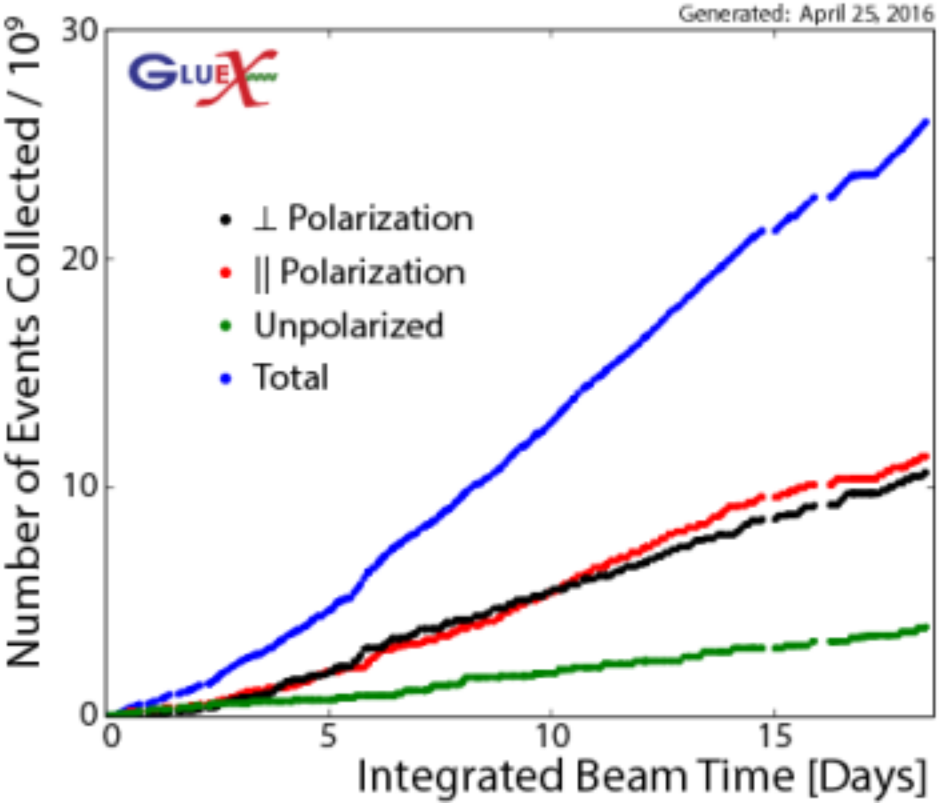
C. A. Meyer and E. S. Swanson, Progress in Particle and Nuclear Physics B82, 21, (2015) DIRC

- 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

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

generated waves

$a_1(1260) \rightarrow \rho\pi$ (S – wave)

$a_2(1320) \rightarrow \rho\pi$ (D – wave)

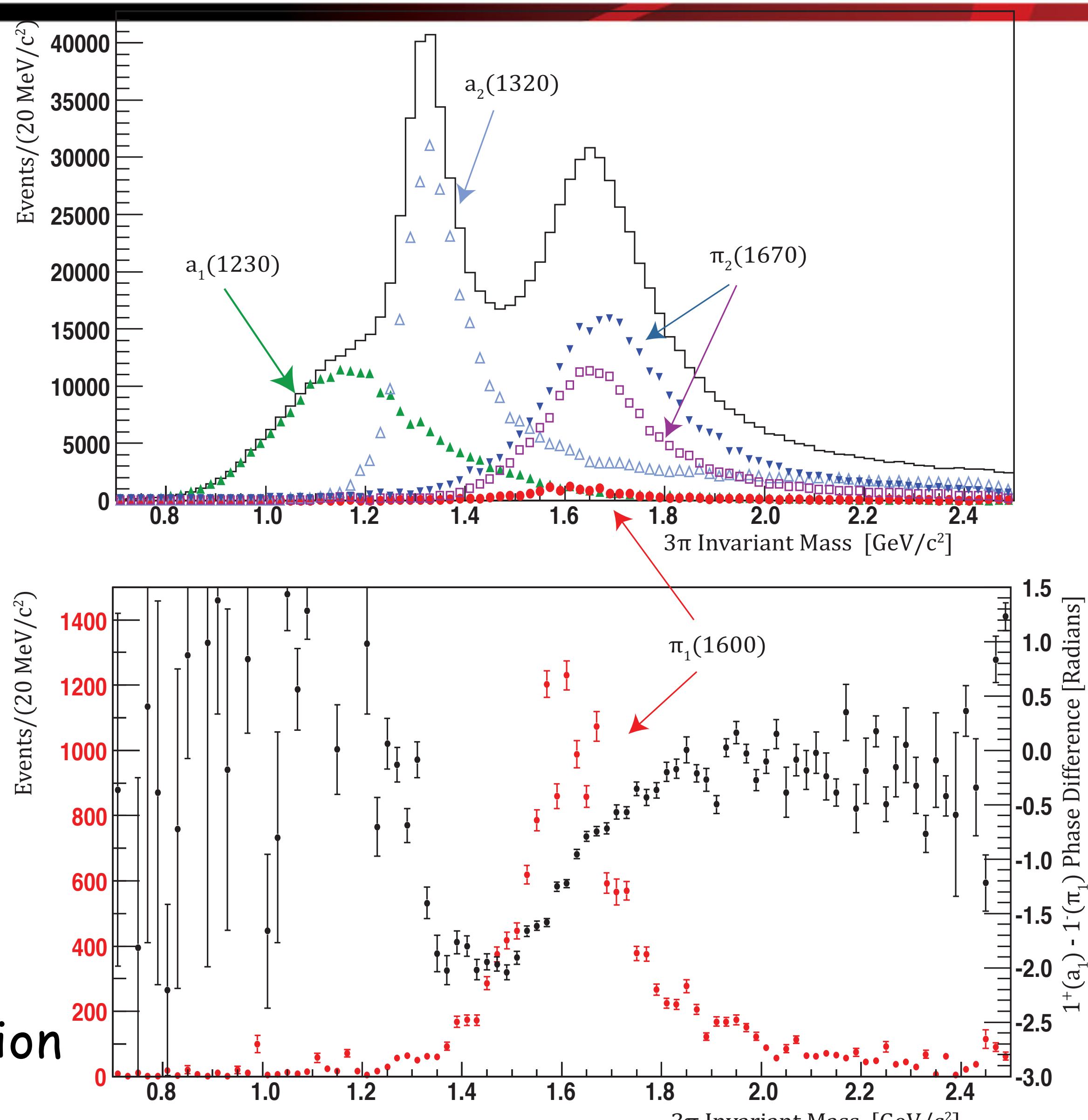
$\pi_1(1600) \rightarrow \rho\pi$ (P – wave)

$\pi_2(1670) \rightarrow f_2\pi$ (S – wave)

$\pi_2(1670) \rightarrow \rho\pi$ (P – wave)

1^{-+} exotic wave generated with 1.6% relative strength

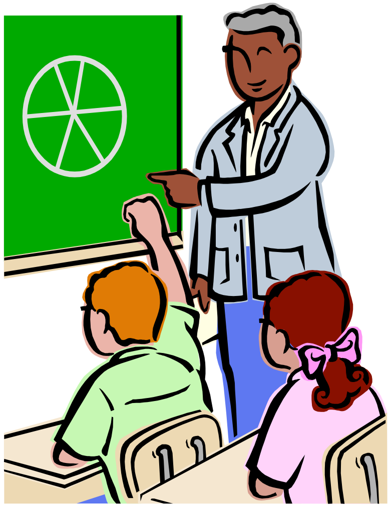
Corresponds to 3.5 hours GlueX data, full detector simulation and reconstruction



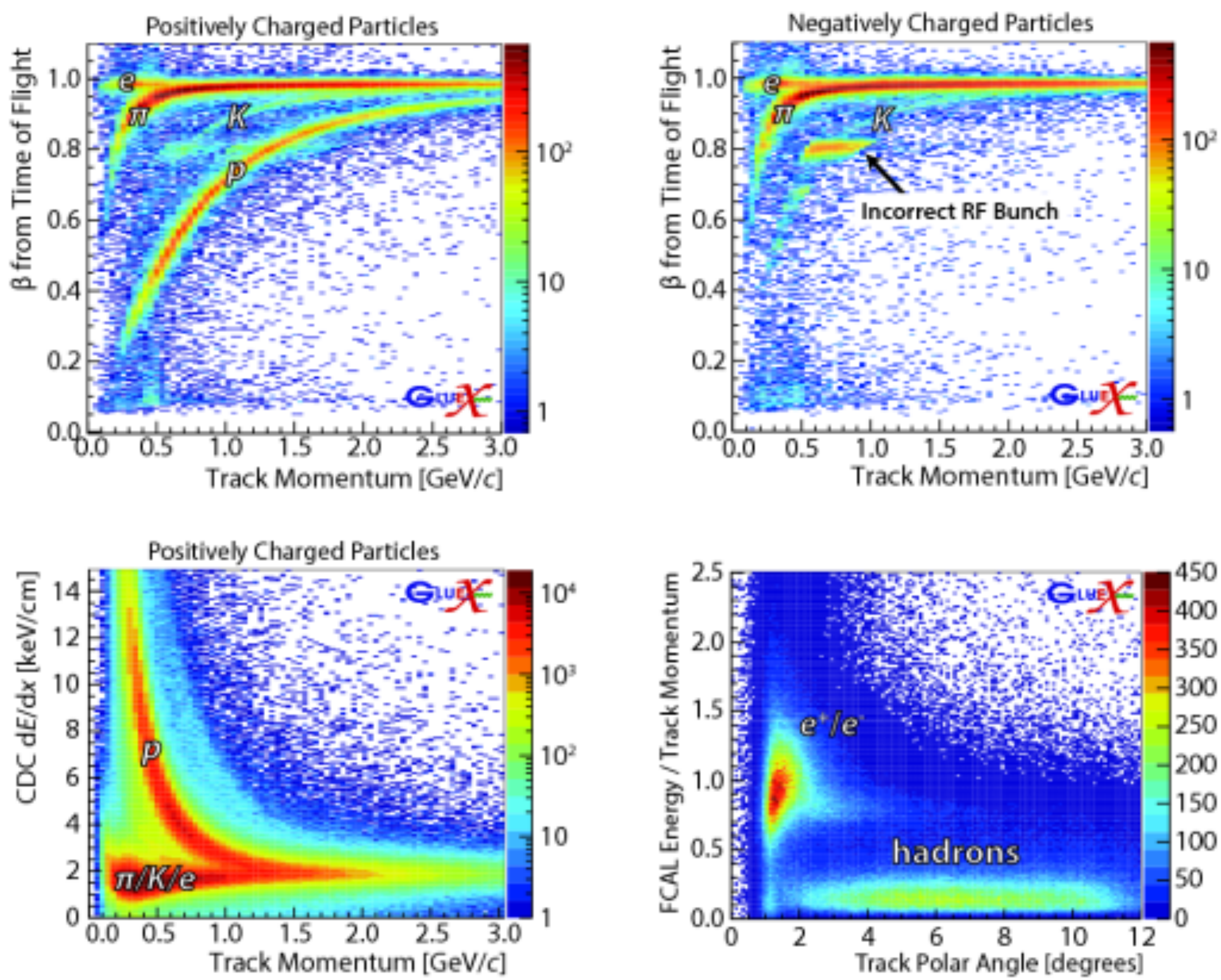
Summary

- 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



GlueX - Particle Identification



Physics in GlueX

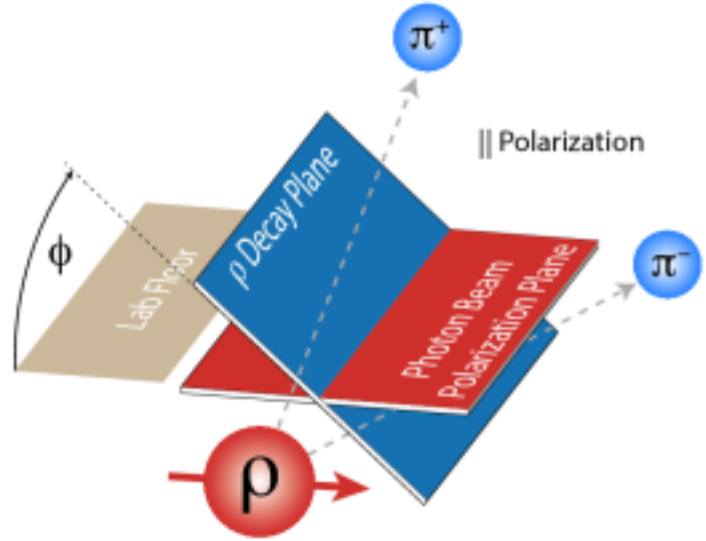
- Currently processing data into condensed data format
  - 25% processed, less analyzed
  - More currently on the farm

- 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

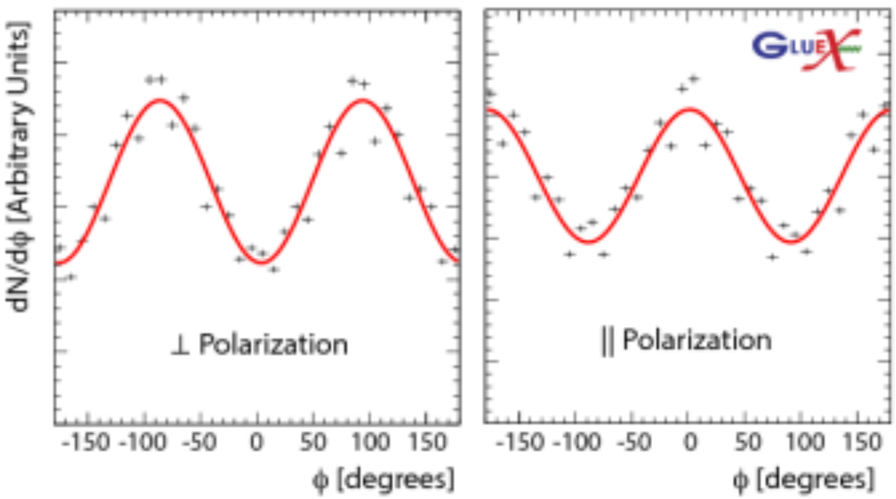
- Long term
  - Spin-density matrix elements to understand production mechanisms
  - Cross sections measurements

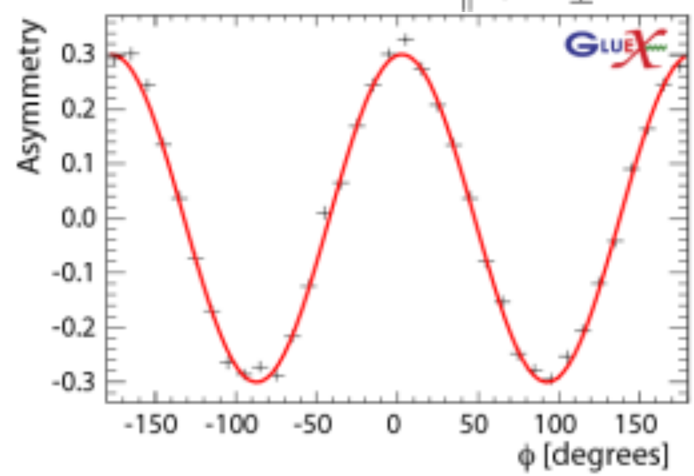
Beam Asymmetry in ρ Photoproduction

- 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
- Large polarization transfer to the

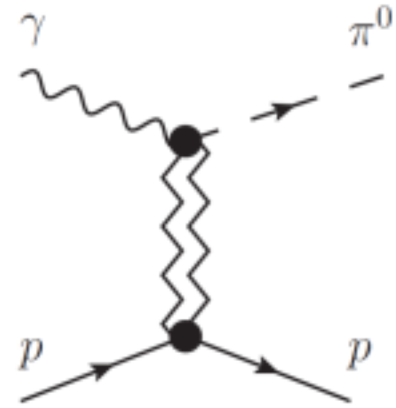


$$P\Sigma cos2\phi = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}$$

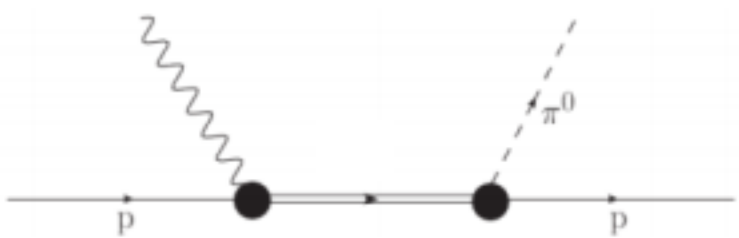


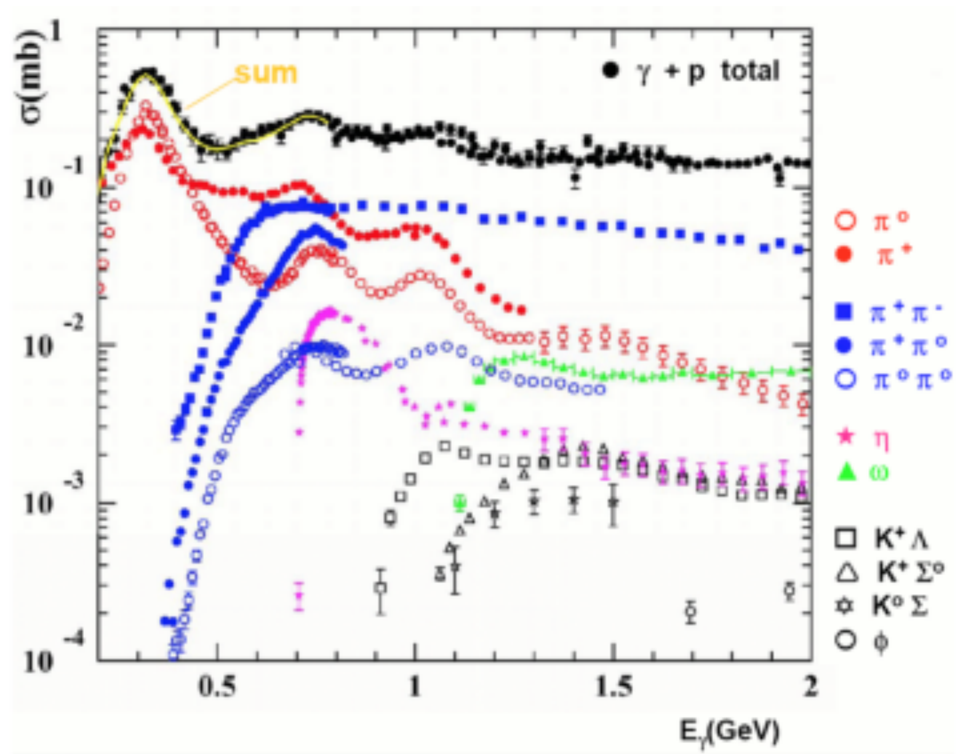


π^0 beam asymm



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





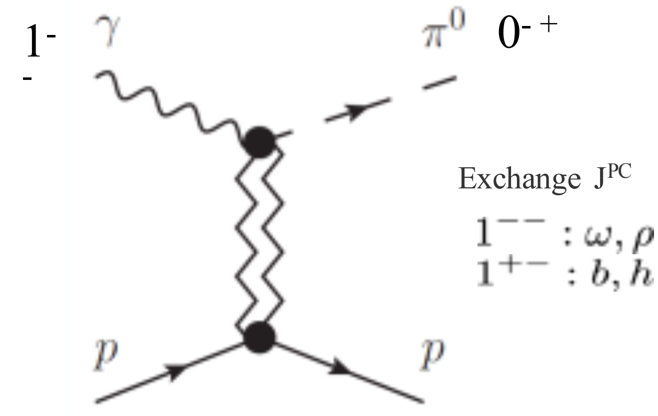
π^0 beam asymmetry

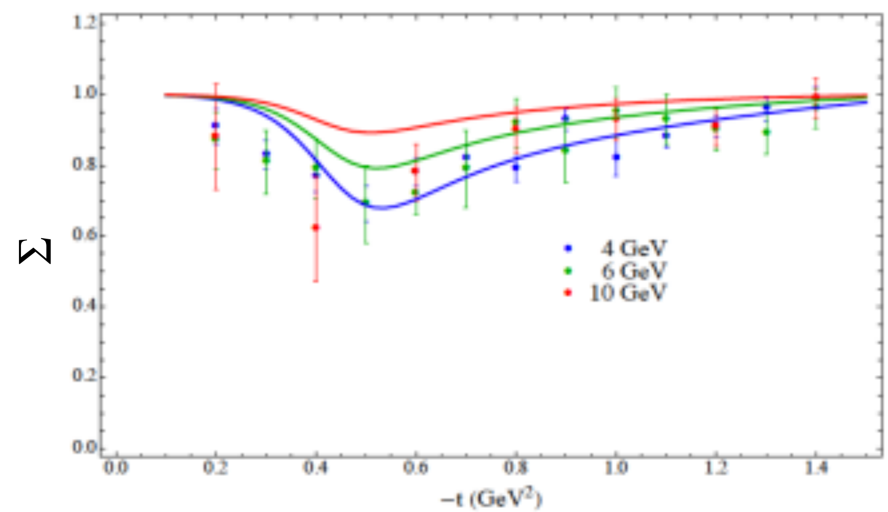
- Provides constraints on “background” to baryon resonance extraction in low energy regime
  - Constrains PWA amplitudes through Finite Energy Sum Rule

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

- Understand production mechanism in high energy physics
  - To produce neutral C = +1, need a C = -1 exchange particle

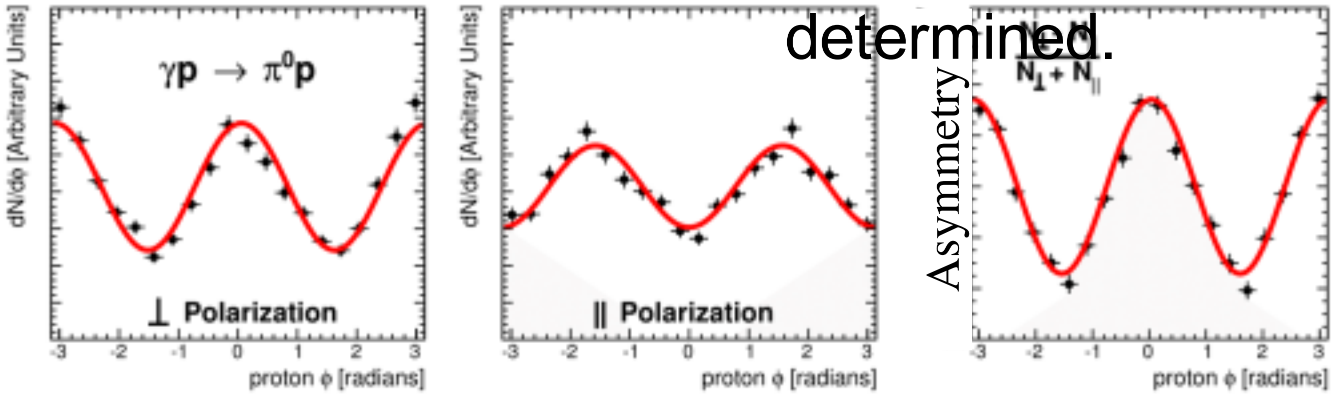
$$\Sigma = \frac{|\omega + \rho|^2 - |h + b|^2}{|\omega + \rho|^2 + |h + b|^2}$$



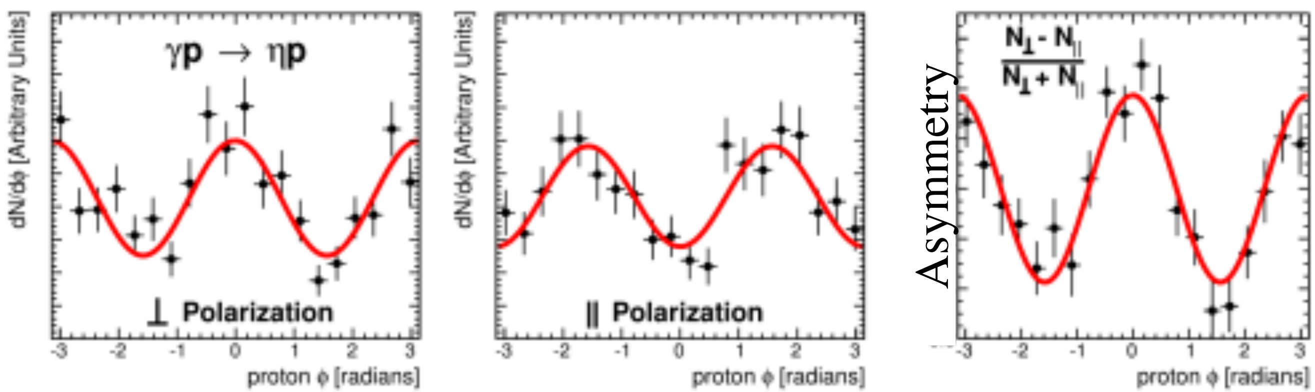


Pseudoscalar Beam Asymmetries

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



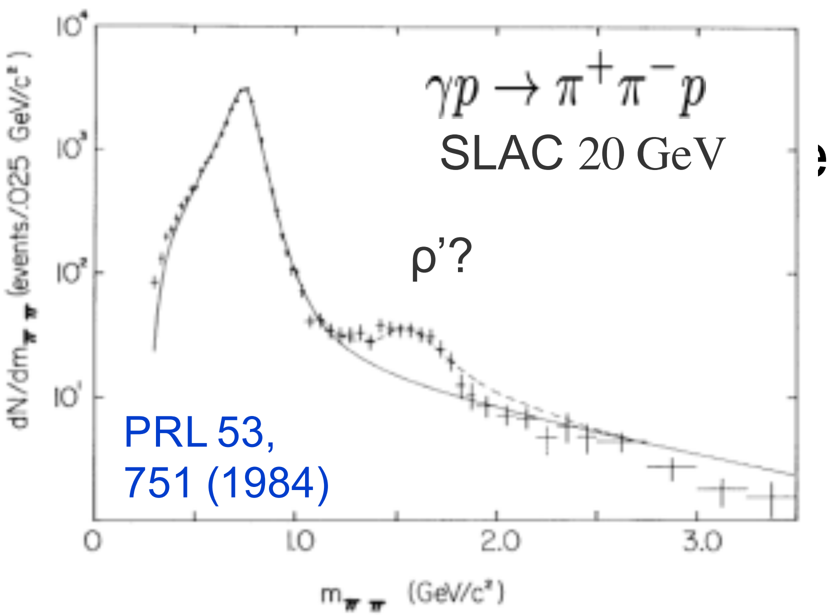
E_γ = 8.4 - 9.0 GeV

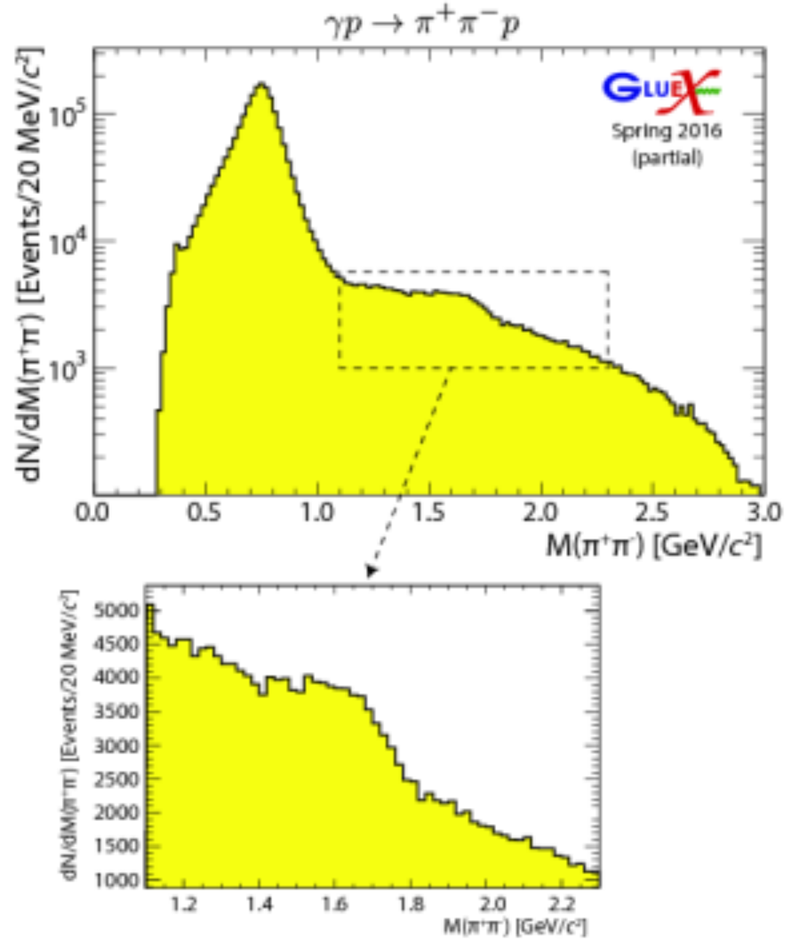


No previous measurements for $\gamma p \rightarrow \eta p$

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

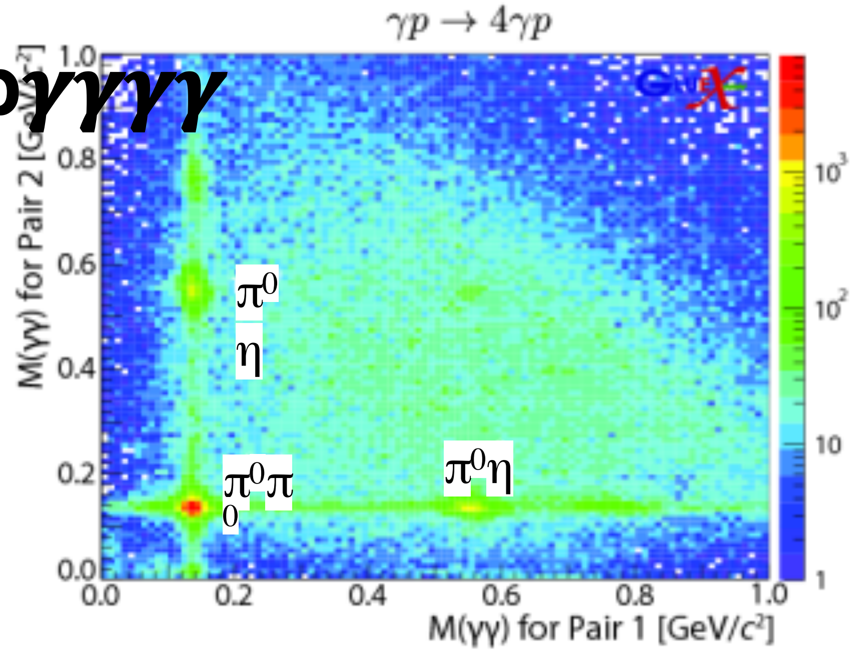
- In the $\pi^+\pi^-$ invariant mass spectrum we can look for higher-mass vector mesons
- We observe an enhancement at 1.6 GeV with significantly more statistics than existing data

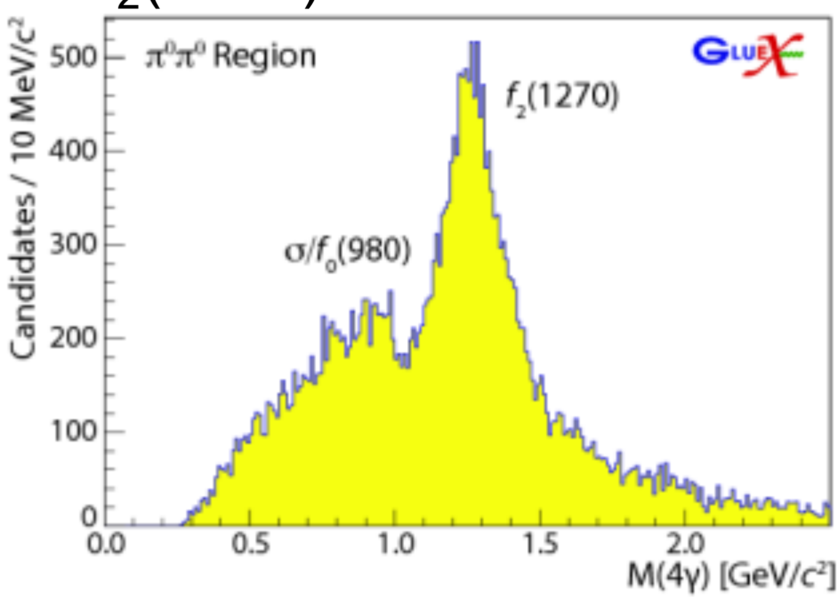


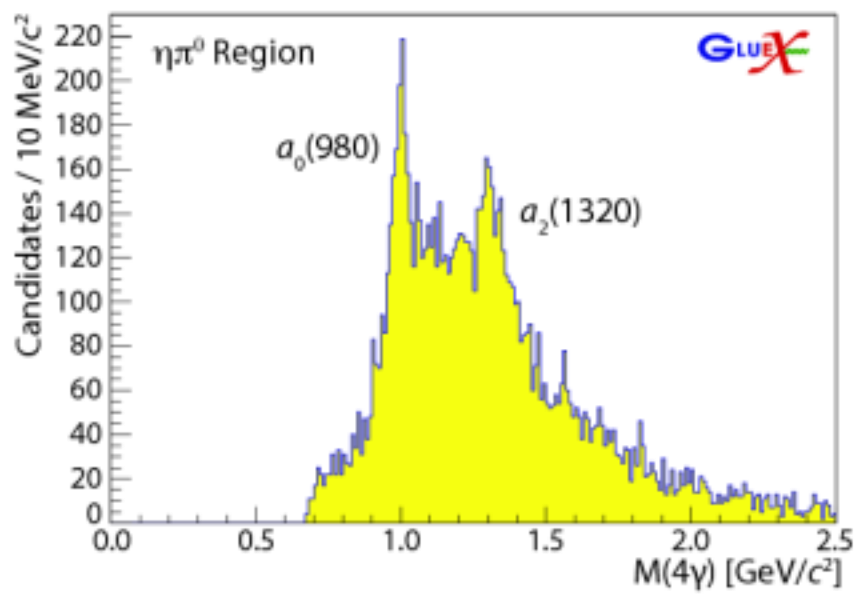


$\gamma p \rightarrow p\gamma\gamma\gamma\gamma$

- 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

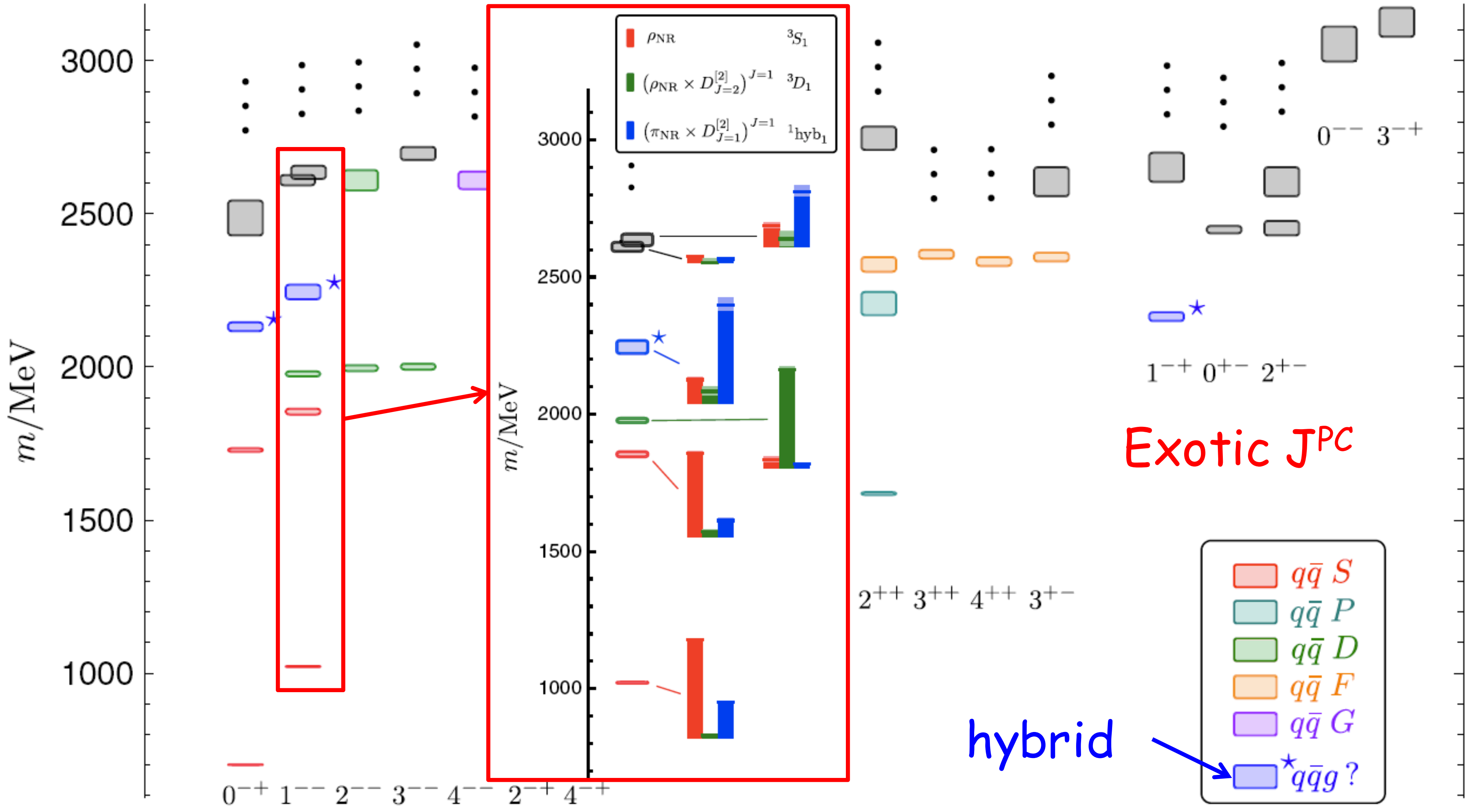
- Commissioning running finished successfully
- All detector systems are near design specifications
- Iterative calibration improvements expected
- Initial physics running fall 2016 - 2018
- We have made significant progress towards our first physics measurements
- The addition of the BaBar DIRC bar 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
- ITEP
- 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_π~700 MeV

Dudek PRD 83 (2011) 111502

Dudek PRD 84 (2011) 074023

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

David Lawrence, JLab
Rory Miskimen, UMass, Amherst
Elton Smith, JLab

Motivation

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

Since the dynamics of Goldstone modes is entirely fixed by the broken symmetry, one may write down the $\mathrm{SU}_L(3)\times\mathrm{SU}_R(3)$ invariant Lagrangian encoding this information by

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

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 $i = 1,\ldots,10$. 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-

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

where $S_f^0(p)$ is bare propagator of quark with flavor f and momentum p, $\mathrm{i}(S_f^0(p))^{-1} = \not{p} - m_f$. 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

and arXiv:1309.2225 [hep-ph])

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

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

with

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

Donoghue and Holstein, 1989

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

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

with

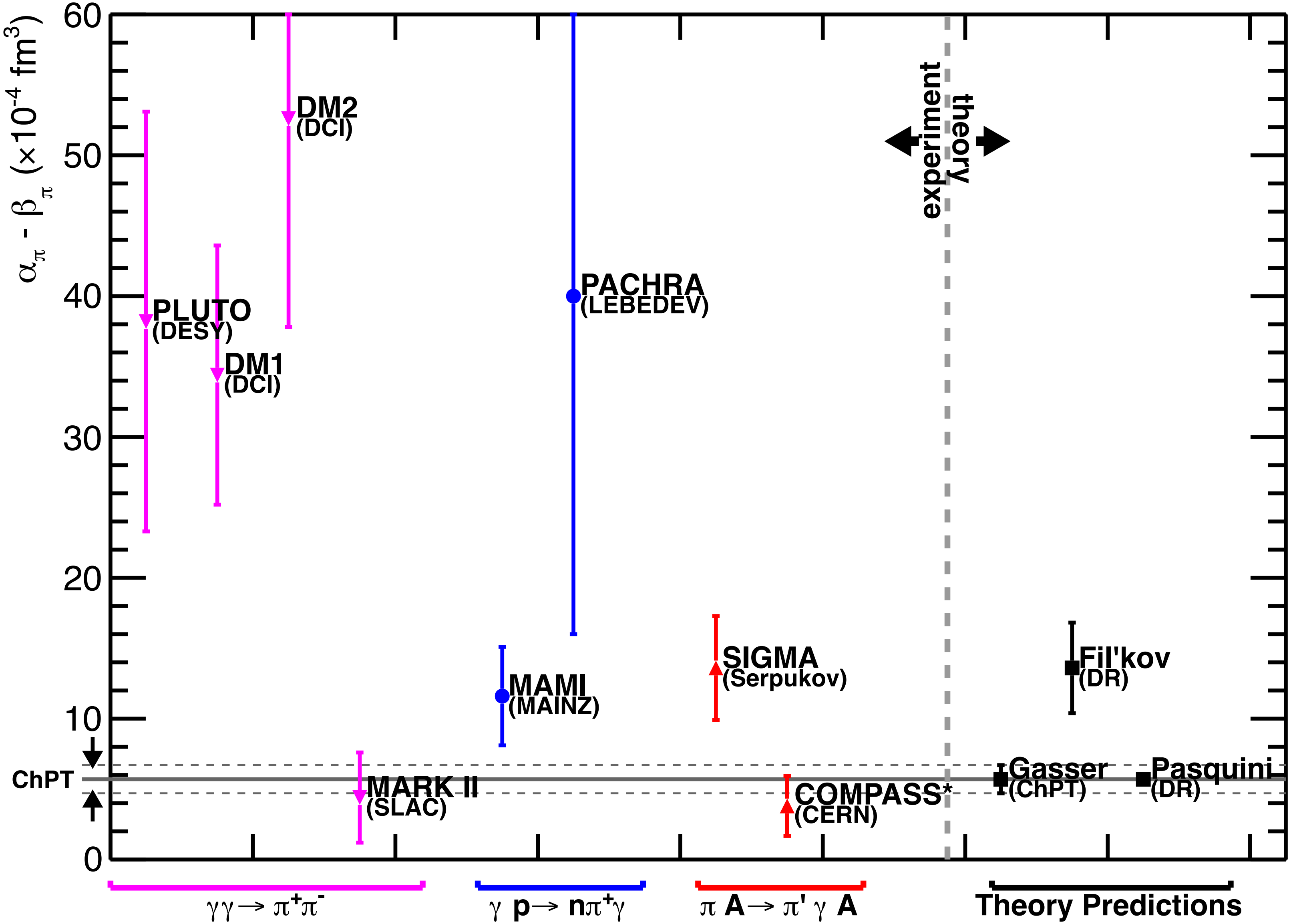
$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \times 10^{-4}\ \mathrm{fm}^3$$

Bürgi 1996,
Gasser et al. 2006

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

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

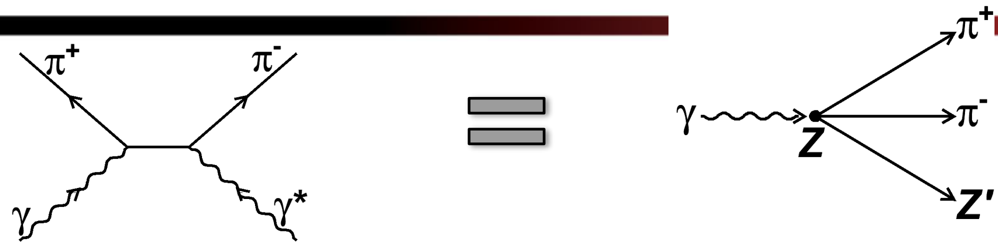
$$\alpha_\pi - \beta_\pi = 5.7 \times 10^{-4}\ \mathrm{fm}^3$$ *Pasquini et al. 2008*



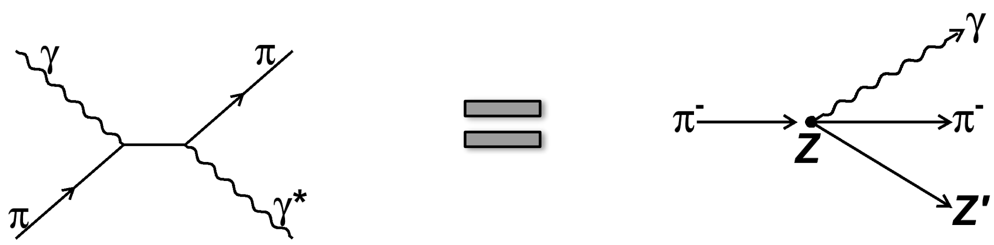
**COMPASS result from DNP2013 abstract NJ00005*

Experimental Access

Primakoff effect

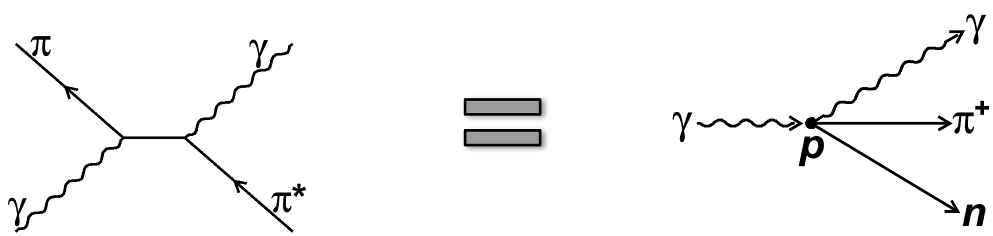


This experiment



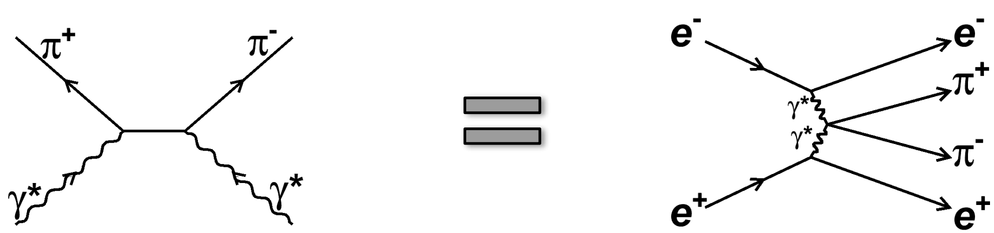
SIGMA
COMPASS

Radiative pion photo-production



MAMI
PACHRA

Light by light scattering
(by crossing symmetry)



PLUTO
DM1
DM2
MARK-II

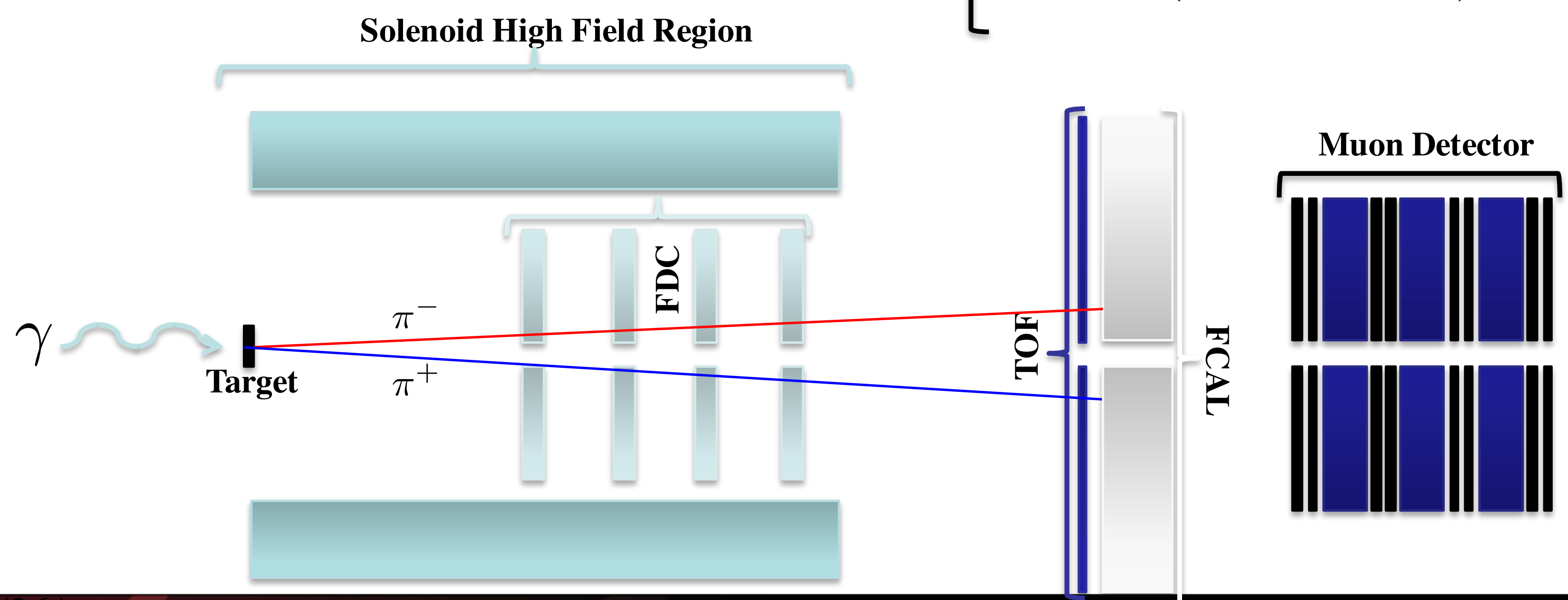
Experimental Setup

$$\gamma\gamma \xrightarrow[Z(\gamma,\pi^+\pi^-)Z]{} \pi^+\pi^-$$ Signal reaction

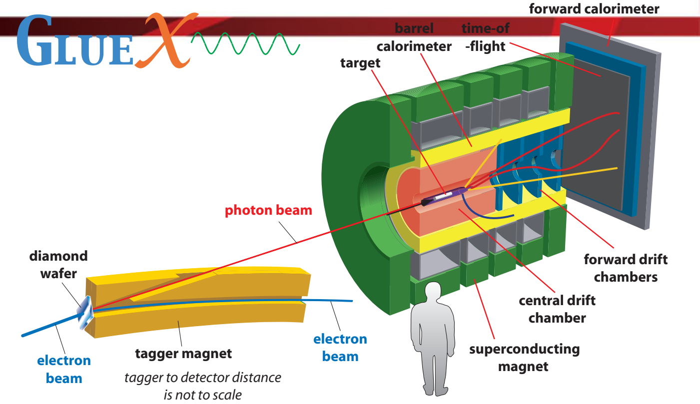
$$\gamma\gamma \xrightarrow[Z(\gamma,\mu^+\mu^-)Z]{} \mu^+\mu^-$$ Normalization

$$\gamma\gamma \xrightarrow[Z(\gamma,\pi^\circ)Z]{} \pi^o$$ Beam polarization

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



The GlueX Detector in Hall-D

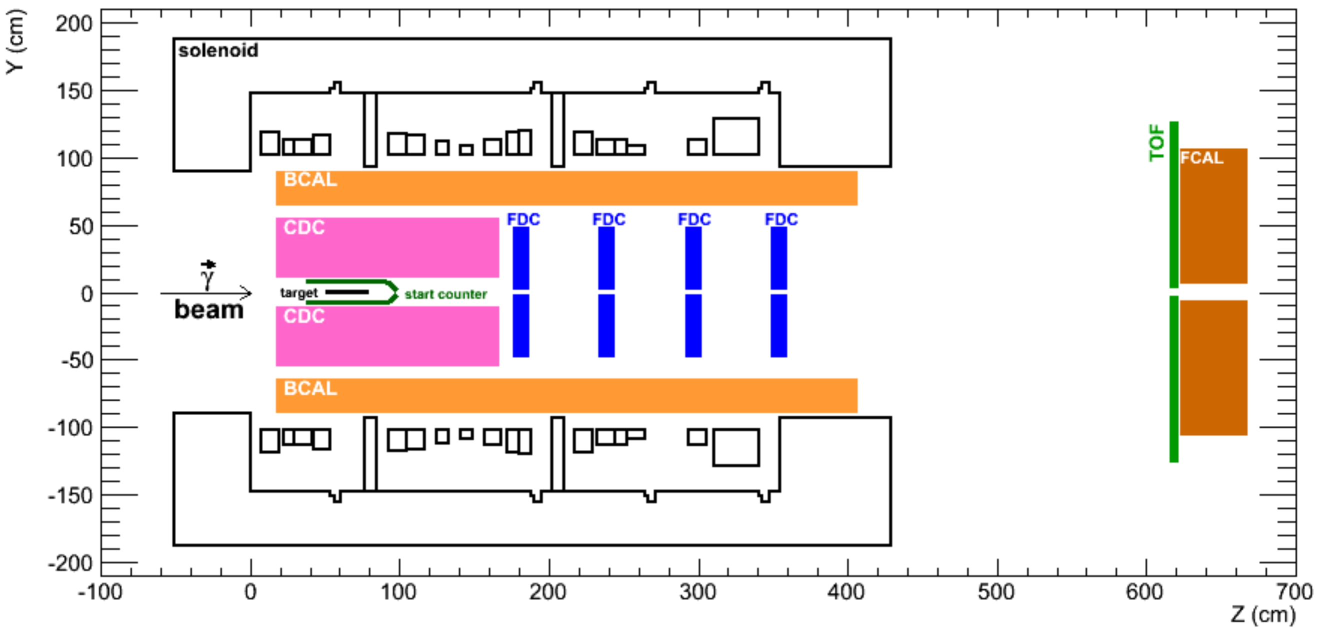


New Proposal will use GlueX detector in Hall-D:

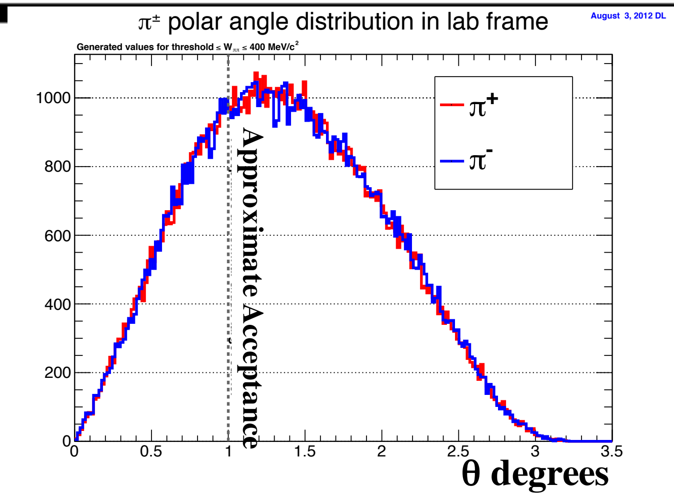
- Linearly polarized photon source (~9GeV)
- 2T solenoidal magnetic field ($\delta p/p$ = few %)
- Drift chambers
- High resolution Time-of-flight detector

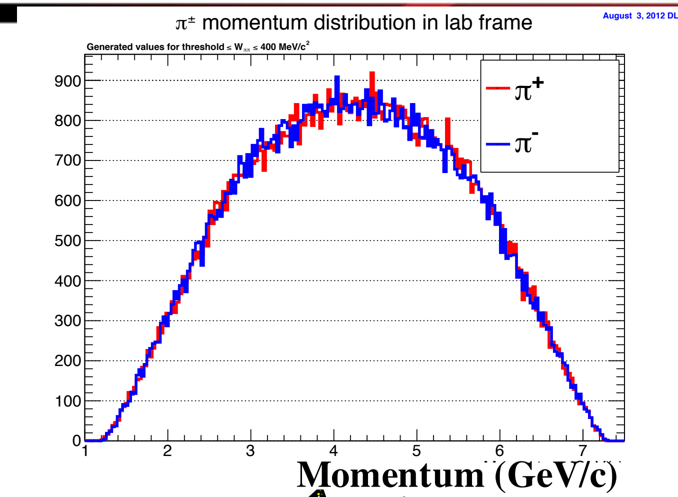
Modifications to standard GlueX setup:

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



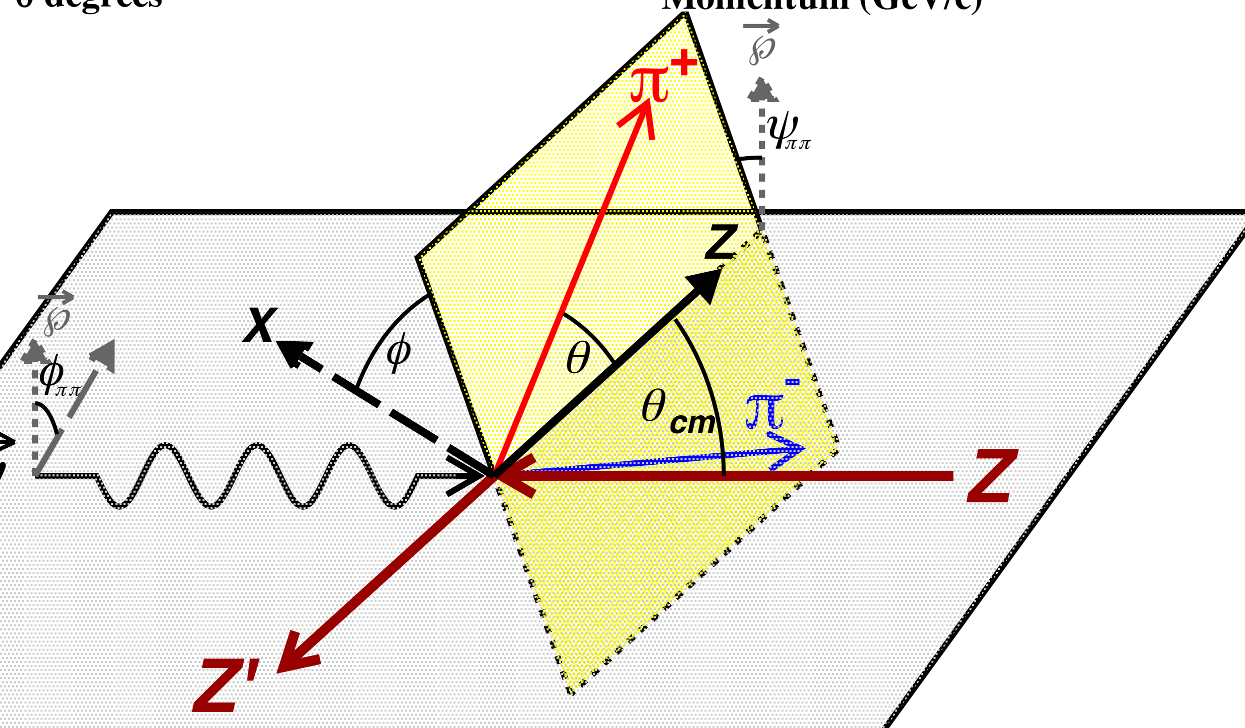
Kinematics of Experiment





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

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



Backgrounds

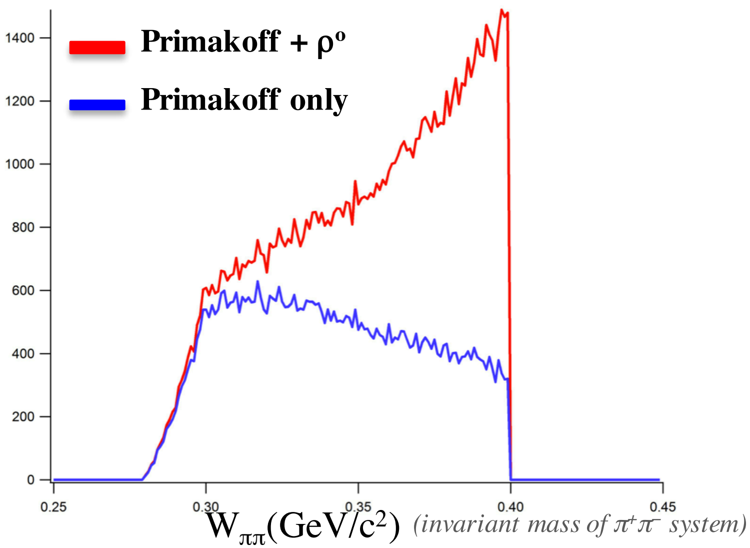
- Experiment will measure reaction:

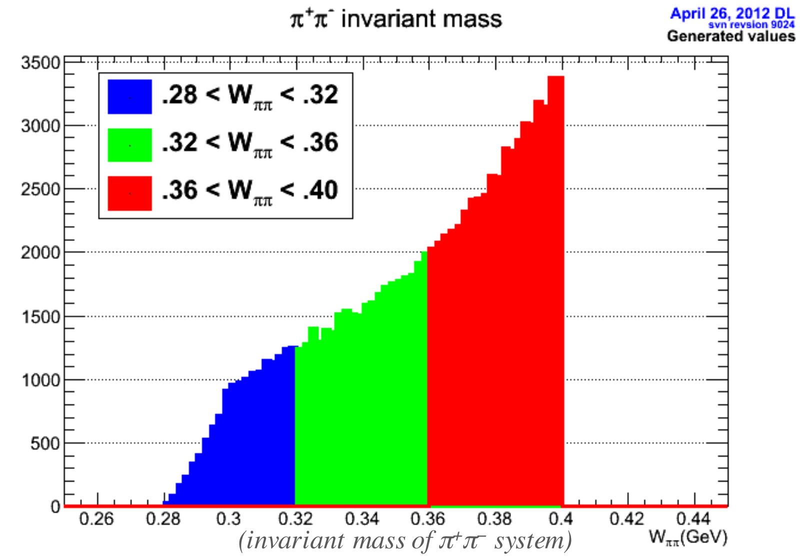
  $^{116}Sn\ (\gamma\ ,\ \pi^{+}\ \pi^{-})\ ^{116}Sn$ *(signal of interest: $\gamma\ \gamma^{*} \rightarrow \pi^{+}\ \pi^{-}$)*

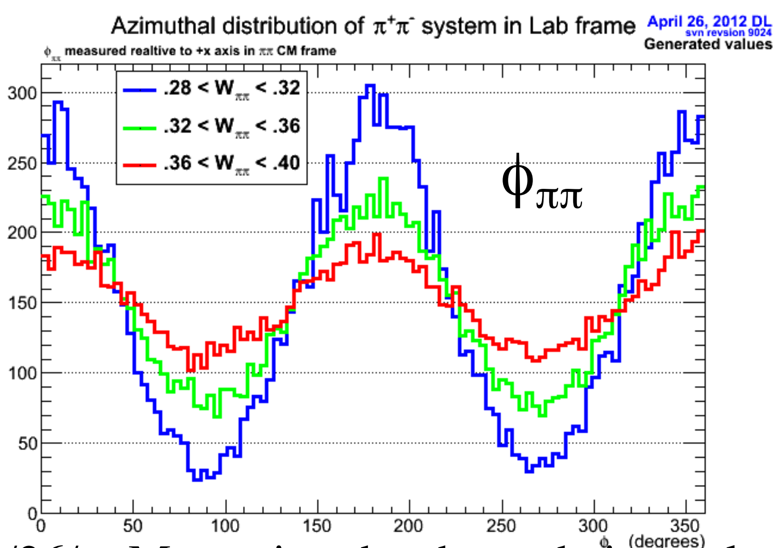
- Primary backgrounds will be:
  - coherent ρ^{o} production followed by $\rho \rightarrow \pi\pi$ decay
    - Will use angular distributions to separate Primakoff from coherent ρ^{o} production *(see later slides)*
  - Electromagnetic $\mu^{+}\mu^{-}$ production
    - Will use dedicated detector to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

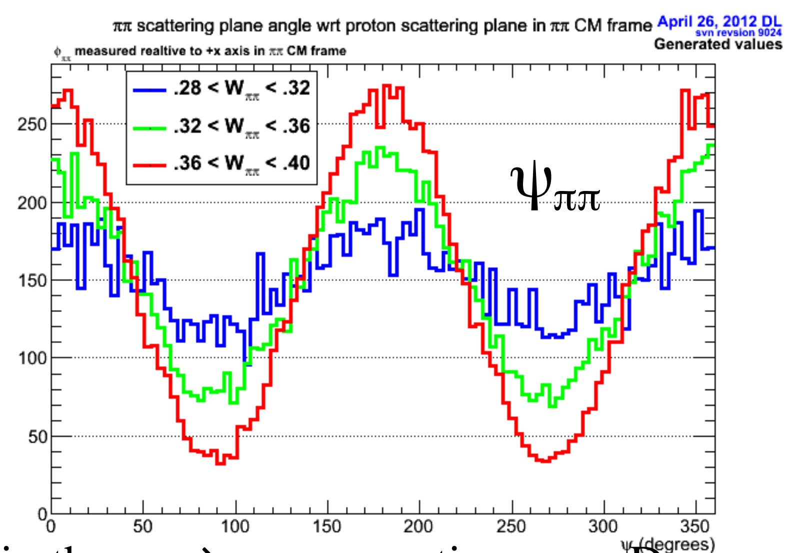
Linear Polarization of incident γ

helps distinguish Primakoff from coherent ρ° production



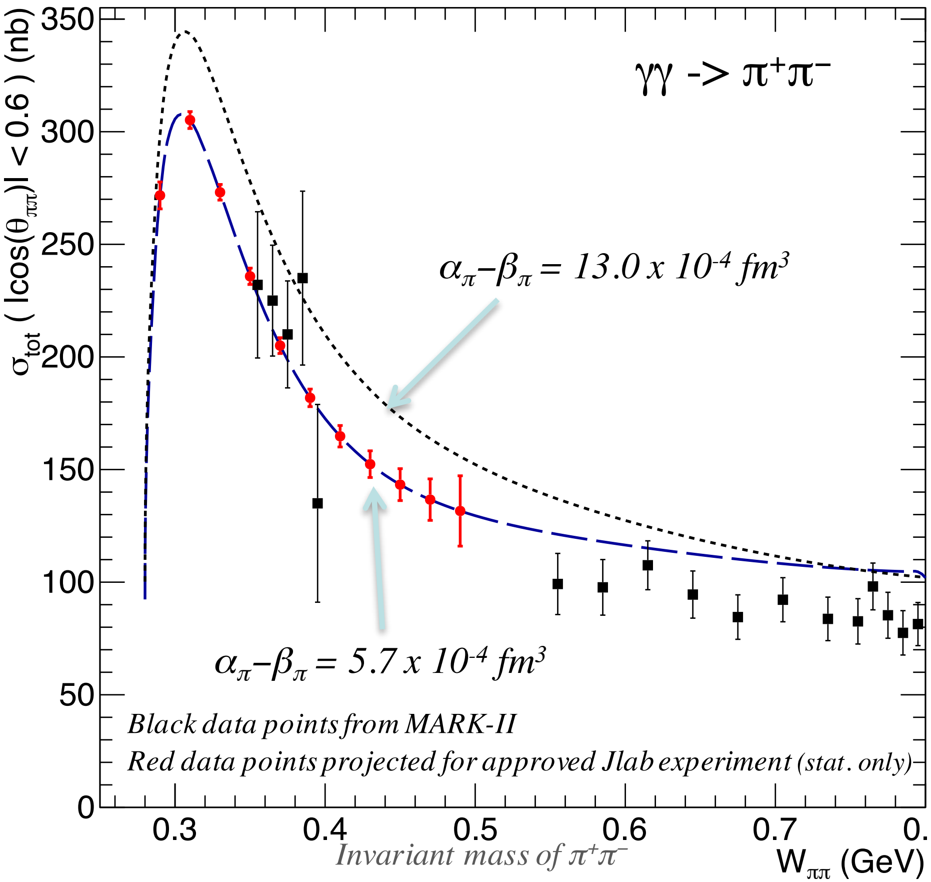






Relating cross-section to $\alpha_\pi - \beta_\pi$

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



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

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

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

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

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

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

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

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 ~320 MeV/c^2
- Estimated ~36k 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 α_π-β_π is 5.7 ± 1.0 x 10^{-4} fm^3
- Previous measurements of α_π-β_π range from 4.4 - 52.6 x 10^{-4} fm^3
- A newly approved experiment to measure the charged pion polarizability α_π-β_π via the $\gamma\gamma^*$->$\pi^+\pi^-$ reaction will be done using the GlueX detector at Jefferson Lab
  - *PR12-13-008*
- Total estimated uncertainty in α_π-β_π measurement is 10%

  (+/- 0.6 x 10^{-4} fm^3)
- An improved measurement of α_π-β_π would improve the SM prediction of the anomalous magnetic moment of the μ: $(g_\mu-2)/2$