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

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Motivation

- Electro (α_π) and Magnetic (β_π) Polarizabilities represent fundamental properties of the charged pion in the low-energy sector of QCD
- α_π and β_π are related to the charged pion weak form factors F_V and F_A :

$$\alpha_\pi = -\beta_\pi = \frac{4\alpha_{EM}}{m_\pi F_\pi^2}(L_9^r + L_{10}^r) \propto \frac{F_A}{F_V}$$

where the low-energy constants L^r_{10} and L^r_9 are part of the Gasser-Leutwyler effective Lagrangian

- Measuring the polarizabilities of the charged pion can be used to test the even-parity part of the Chiral Lagrangian
(as opposed to the odd-parity sector which is tested via anomalous processes such as $\pi^o \to \gamma\gamma$)

- Improved measurement of $\alpha_\pi - \beta_\pi$ would reduce uncertainty contribution of hadronic light-by-light scattering to SM prediction of anomalous magnetic moment of the μ: $(g_\mu-2)/2$

    (see K. Engel, H. Patel, M. Ramsey-Musolf, arXiv:1201.0809v2 [hep-ph] and arXiv:1309.2225 [hep-ph])

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

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

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

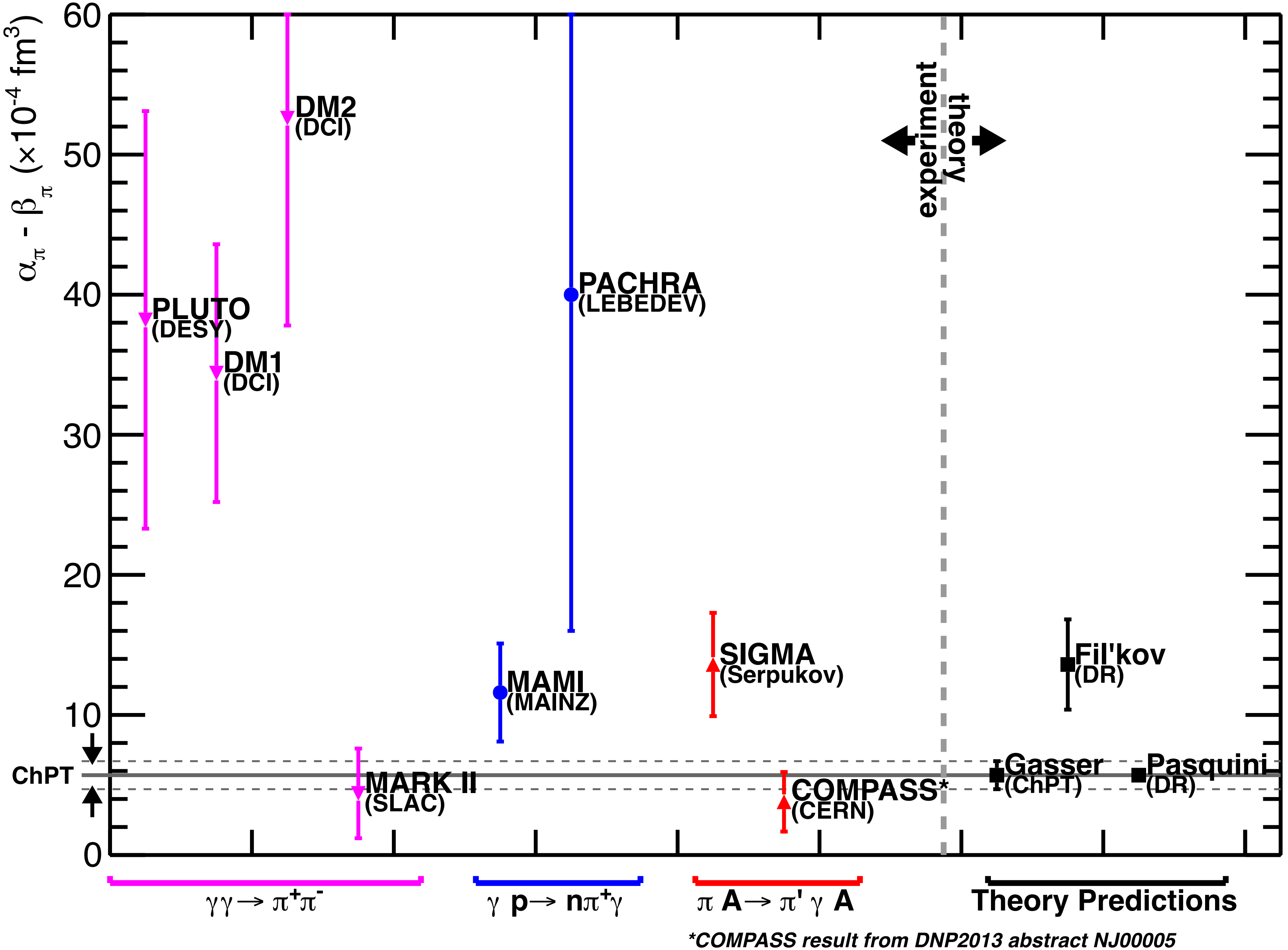
$$\alpha_\pi + \beta_\pi = 0.16 \pm 0.1 \times 10^{-4}\ \text{fm}^3$$

Bürgi 1996,
Gasser et al. 2006

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

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

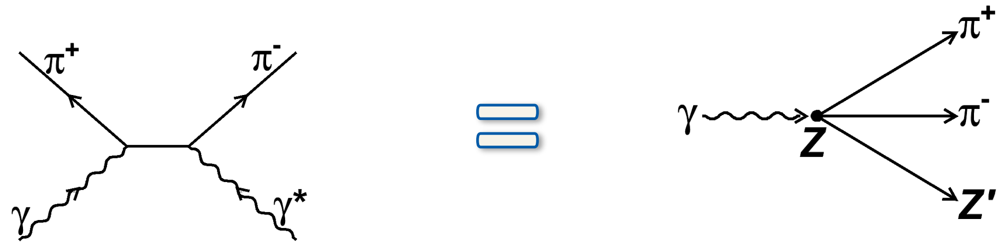
$$\alpha_\pi - \beta_\pi = 5.7 \times 10^{-4}\ \text{fm}^3$$ *Pasquini et al. 2008*



$\alpha_\pi - \beta_\pi$ ($\times 10^{-4}$ fm^3)
60
50
40
30
20
10
0
ChPT
PLUTO
(DESY)
DM1
(DCI)
DM2
(DCI)
MARK II
(SLAC)
MAMI
(MAINZ)
PACHRA
(LEBEDEV)
SIGMA
(Serpukov)
COMPASS*
(CERN)
experiment
theory
Gasser
(ChPT)
Fil'kov
(DR)
Pasquini
(DR)
$\gamma\gamma \to \pi^+\pi^-$
γ p $\to$ n$\pi^+\gamma$
π A $\to$ π' γ A
Theory Predictions
*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

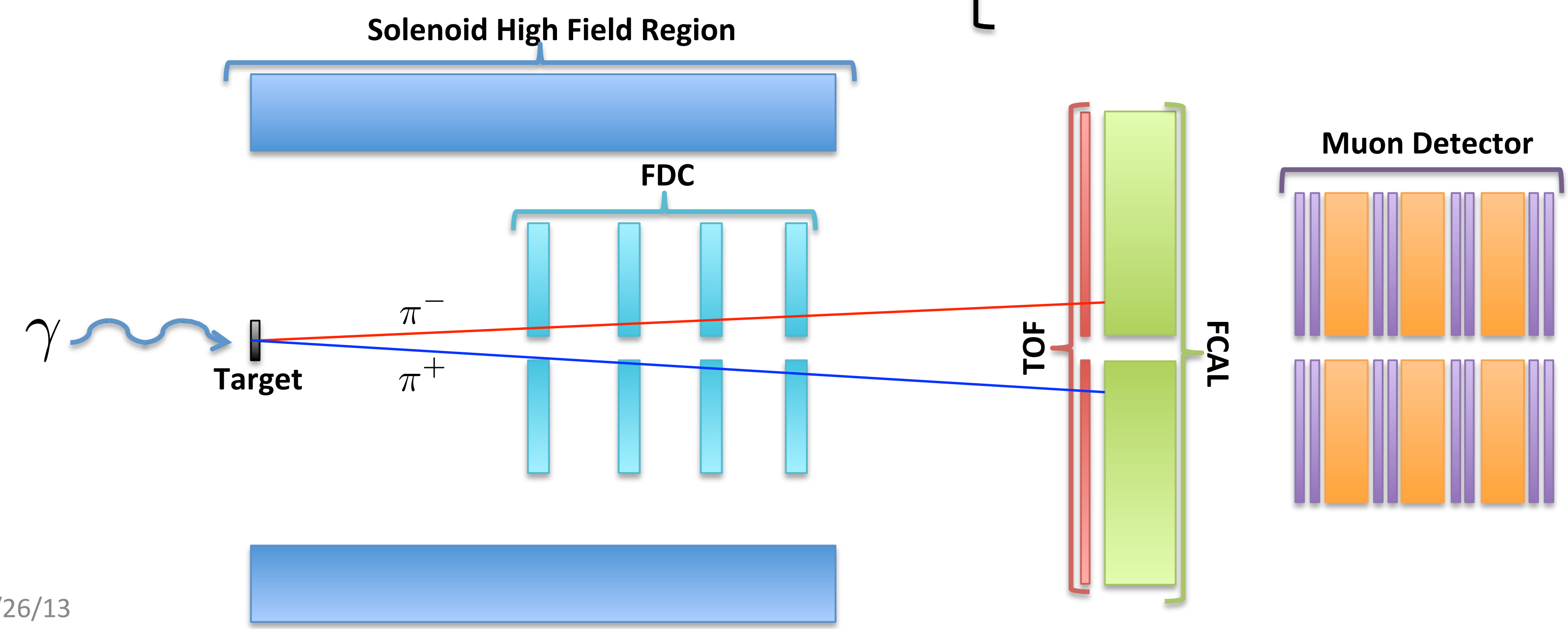
Experimental Setup

$$\gamma\gamma \rightarrow \pi^+\pi^- \quad Z(\gamma,\pi^+\pi^-)Z$$ Signal reaction

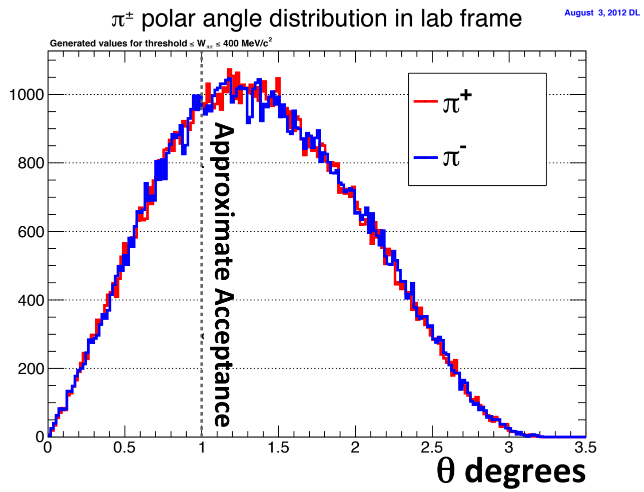
$$\gamma\gamma \rightarrow \mu^+\mu^- \quad Z(\gamma,\mu^+\mu^-)Z$$ Normalization

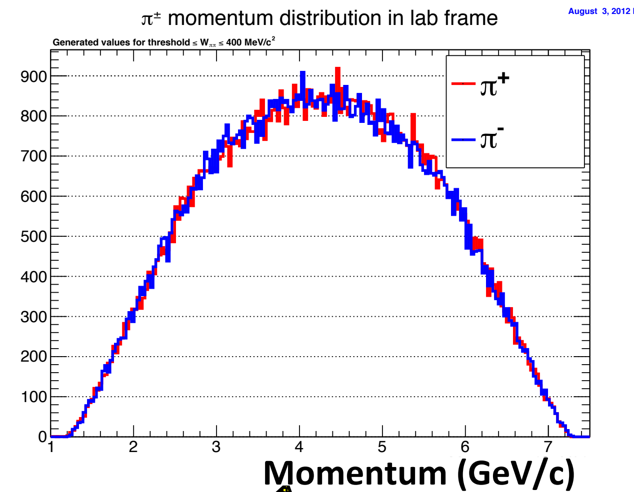
$$\gamma\gamma \rightarrow \pi^o \quad Z(\gamma,\pi^\circ)Z$$ Beam polarization

- 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)



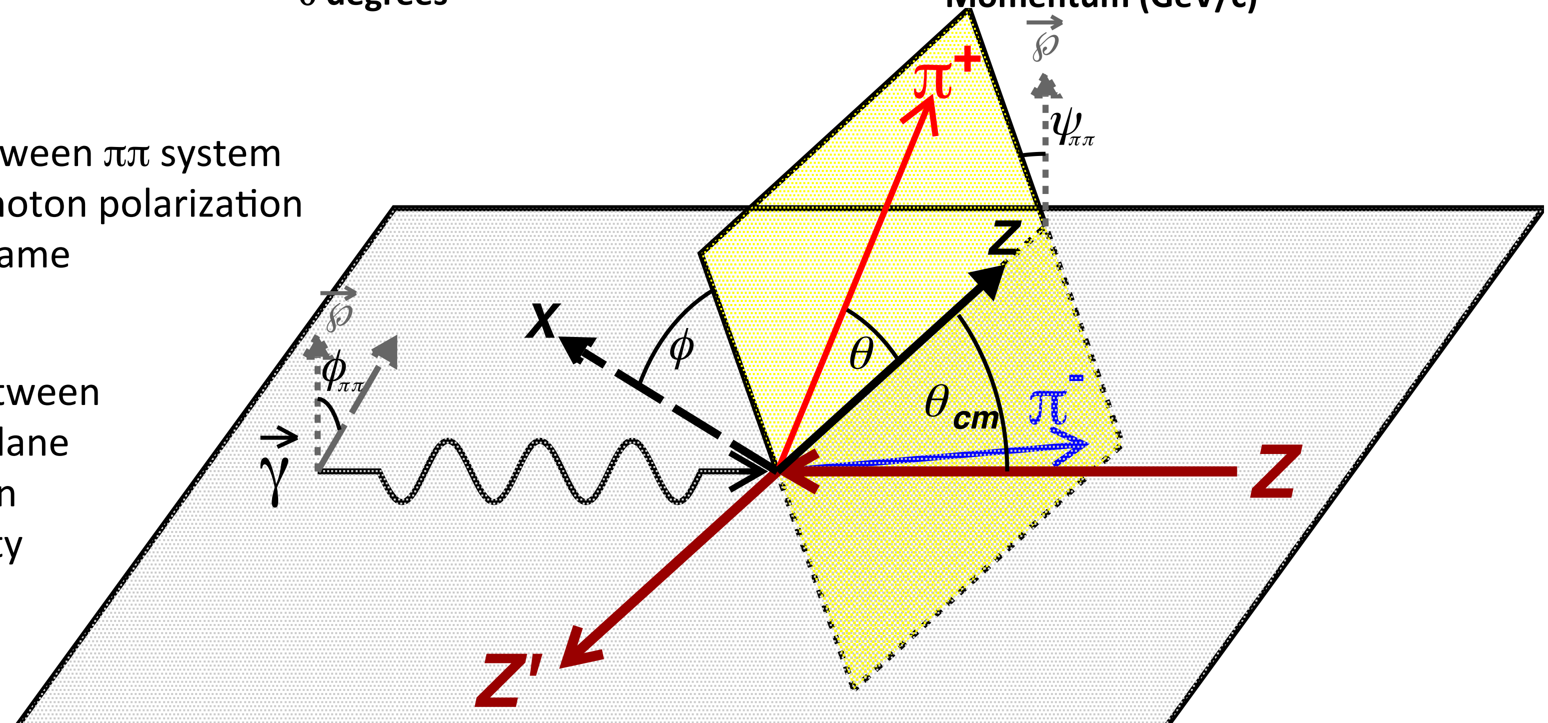
Kinematics of Experiment





$\phi_{\pi\pi}$ 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

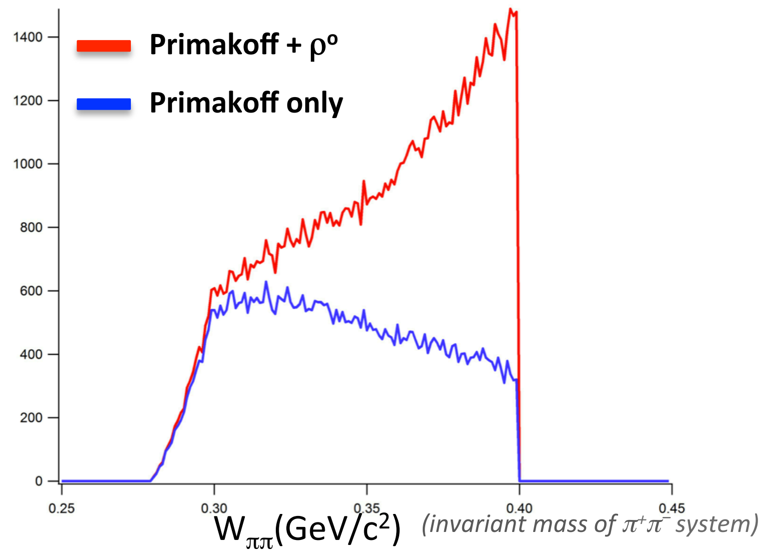


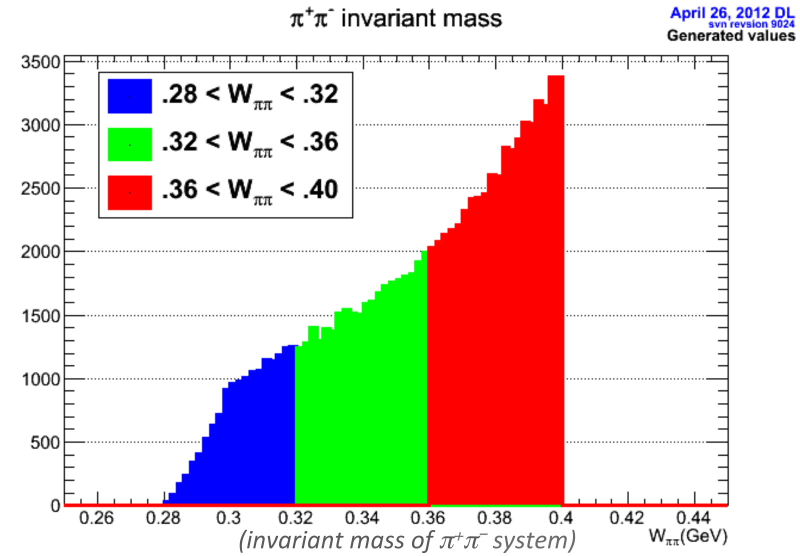
Backgrounds

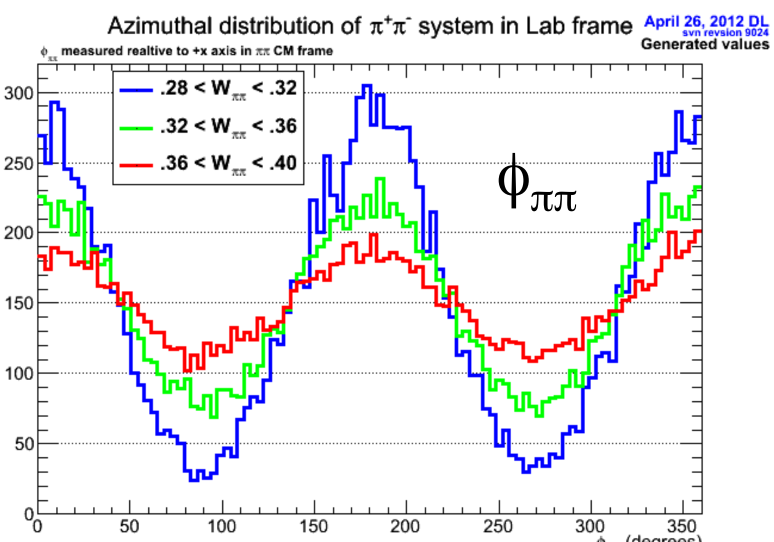
- Experiment will measure reaction:

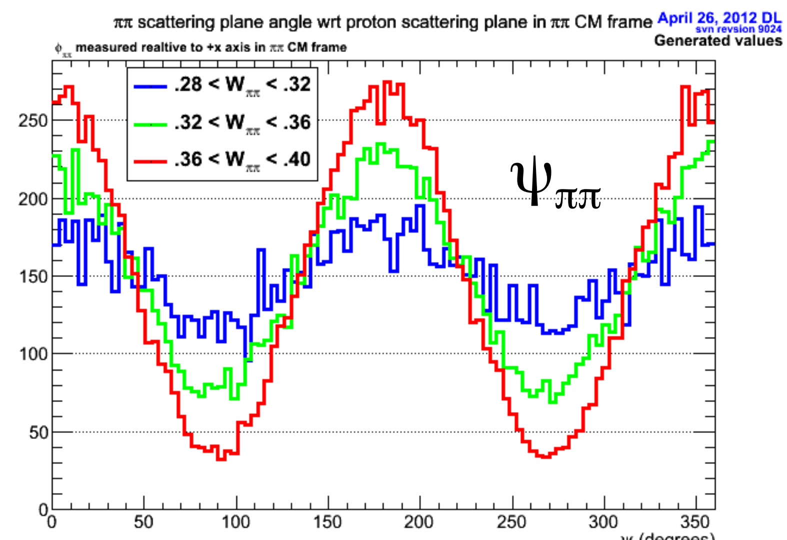
  $^{116}Sn\,(\gamma\,,\,\pi^+\,\pi^-)\,^{116}Sn$ *(signal of interest: $\gamma\,\gamma^* \to \pi^+\,\pi^-$)*
- Primary backgrounds will be:
  - coherent ρ^o production followed by $\rho \to \pi\pi$ decay
    - Will use angular distributions to separate Primakoff from coherent ρ^o production *(see later 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 photon beam helps distinguish Primakoff from coherent ρ^o production



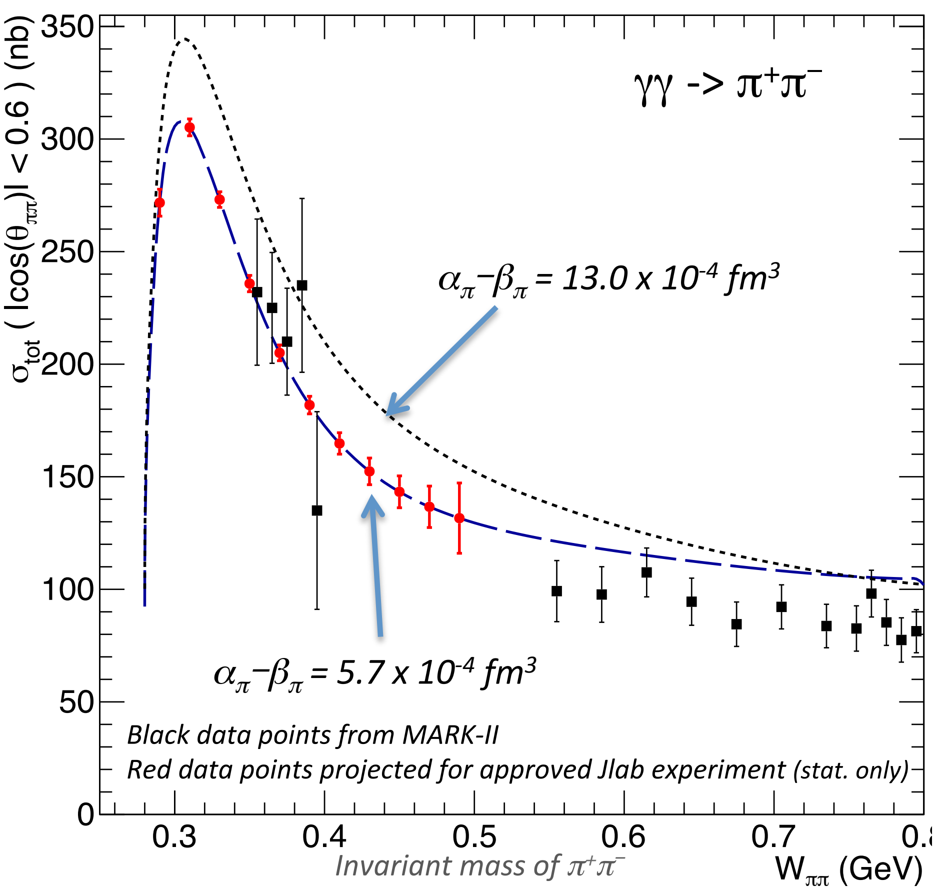






Relating cross-section to $\alpha_\pi-\beta_\pi$

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

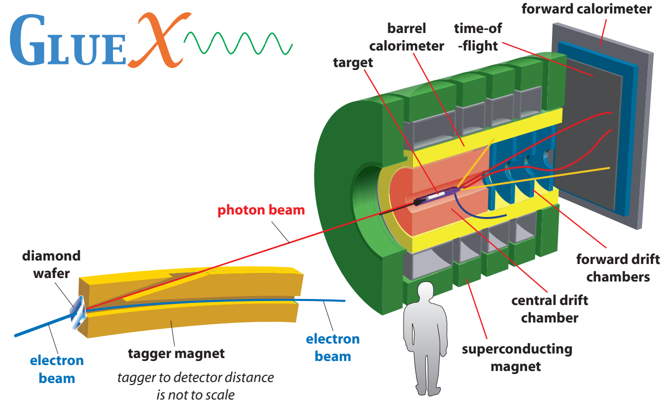
Errors and correction factors	Correction factor	Statistical uncertainty in correction factor
Overall statistical error		0.6 %
Normalization to $\mu^+\mu^-$ and relative trigger efficiency		1 %
$\mu^+\mu^-$ background in $\pi^+\pi^-$ yield	0.03 %	0 %
Polarization	70%	0.2 %
Pion identified as muon, and 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: $(g_\mu-2)/2$


Backups

The GlueX Detector in Hall-D

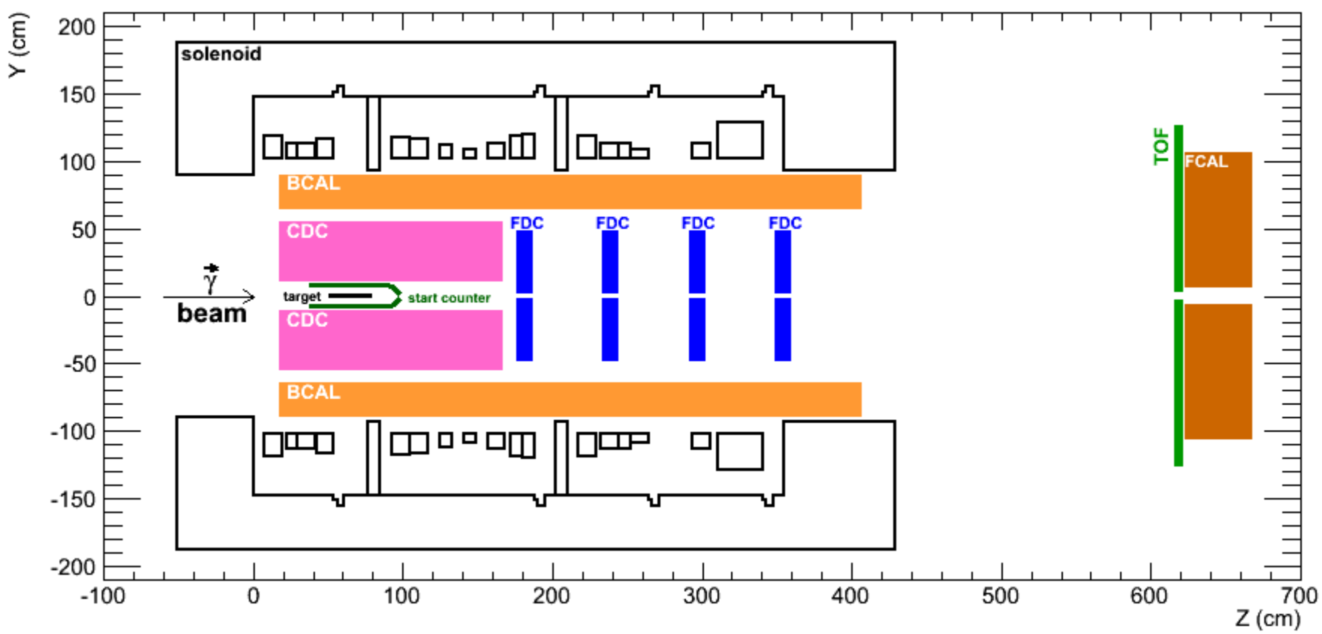


New Proposal will use GlueX detector in Hall-D:

- 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?



Anomalous magnet moment of the μ: $(g_\mu-2)/2$

- Experimental uncertainty of ~ 63×10^{-11}
- SM calculation has uncertainty of ~ 49×10^{-11}
  - Hadronic light-by-light (HLBL) scattering is one of two major contributors to SM uncertainty
    (other is hadronic vacuum polarization)
  - π polarizability is potentially significant contribution to HLBL that is currently omitted from current SM calculation
- g-2 collaboration at Fermilab is preparing a measurement that will reduce experimental uncertainty by a factor of 4
- A measurement of the π polarizability could help reduce the SM uncertainty significantly

For detailed info on planned Fermi-lab experiment, see http://gm2.fnal.gov/public_docs/proposals/Proposal-APR5-Final.pdf