Primakoff Program at Jlab 6 GeV, 12 GeV, and future e-p Collider

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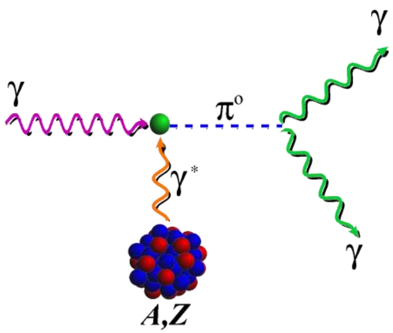
Outline

- **What is the Primakoff Effect?**
- **Current Primakoff Experimental Program at Jlab**
- **Expansion of Primakoff Program with e-p Collider**
- **Summary**

What is the Primakoff Effect?



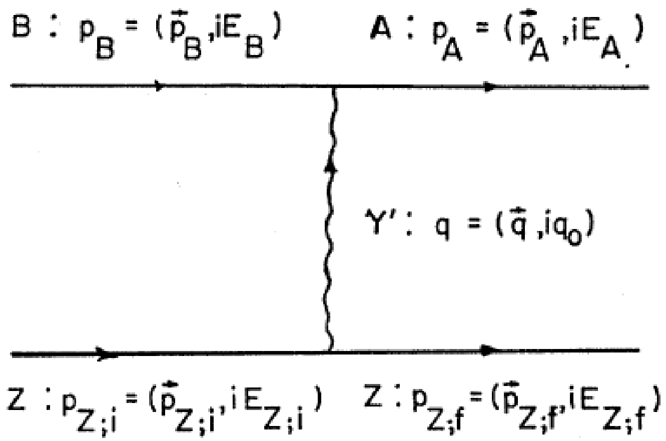


Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. Primakoff†
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts

January 2, 1951

It has now been well established experimentally that neutral π-mesons (π^0) decay into two photons.[1] Theoretically, this two-photon type of decay implies zero π^0 spin;[2] in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton anti-proton pair.[3] Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the π^0 wave field, φ, and the electromagnetic wave field, **E**, **H**, representable in the form:

$$\text{Interaction Energy Density} = \eta(\hbar/\mu c)(\hbar c)^{-\frac{1}{2}}\varphi\mathbf{E}\cdot\mathbf{H}. \quad (1)$$

Here φ has been assumed pseudoscalar, the factors $\hbar/\mu c$ and $(\hbar c)^{-\frac{1}{2}}$ are introduced for dimensional reasons ($\mu \equiv$ rest mass of π^0),

H. Primakoff, Phys. Rev. 81, 899 (1951)

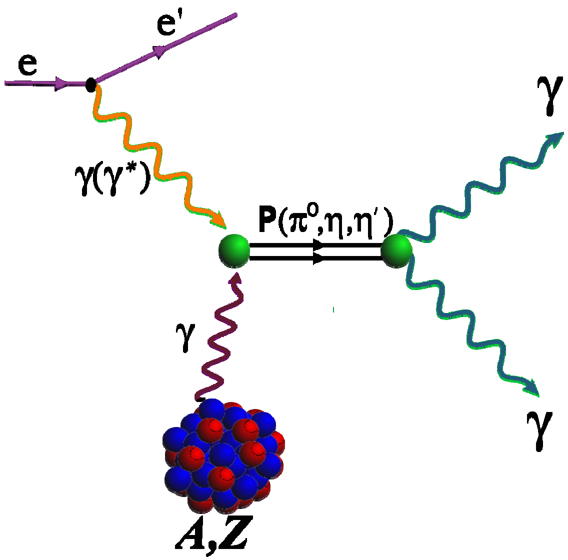
Features of Primakoff Effect

1. Cross section is peaked at extremely small *t*
2. Coherent process
3. Sensitive to the beam energy

$$\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2},\ \left(\frac{d\sigma_{\mathrm{Pr}}}{d\Omega}\right)_{peak} \propto E^4,\ \int d\sigma_{\mathrm{Pr}} \propto Z^2\log(E)$$

Primakoff Program at Jlab 6&12 GeV

Precision measurements of electromagnetic properties of π^0, η, η' via Primakoff effect.



a) Two-Photon Decay Widths:

1) $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ @ 6 GeV
2) $\Gamma(\eta \rightarrow \gamma\gamma)$
3) $\Gamma(\eta' \rightarrow \gamma\gamma)$

<u>Input to Physics:</u>

- precision tests of Chiral symmetry and anomalies
- determination of light quark mass ratio
- η-η' mixing angle

b) Transition Form Factors at low Q^2 (0.001-0.5 GeV²/c²):

$F(\gamma\gamma^* \rightarrow \pi^0)$, $F(\gamma\gamma^* \rightarrow \eta)$, $F(\gamma\gamma^* \rightarrow \eta')$

<u>Input to Physics:</u>

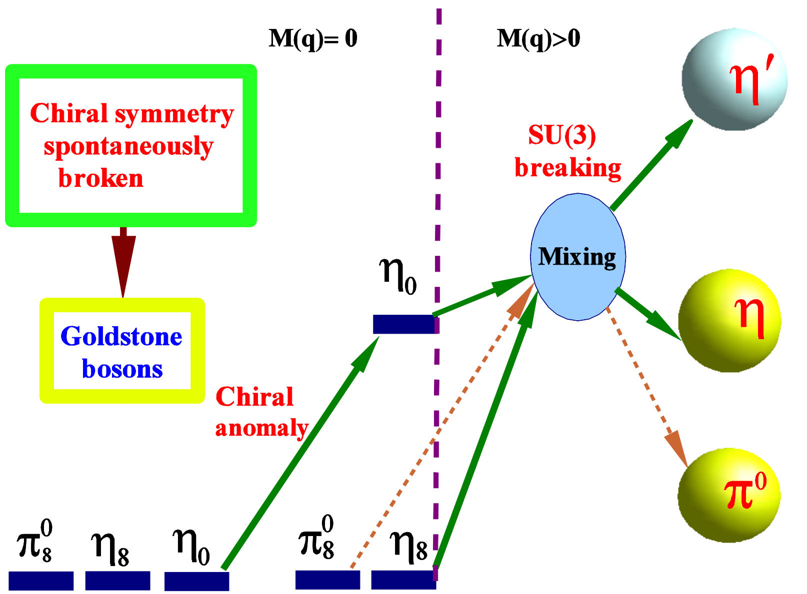
- π^0, η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?

Symmetries in QCD

- QCD Lagrangian in Chiral limit is invariant under:

$$SU_L(3)\times SU_R(3)\times U_A(1)\times U_B(1)$$

- Chiral symmetry $SU_L(3)xSU_R(3)$ spontaneously broken:
  - 8 Goldstone Bosons (π,K,η)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$
  - Mass of η_0
- Massive quarks, SU(3) broken:
  - GB are massive
  - Mixing of π^0 η η'



The π^0, η, η' system provides a rich laboratory to study the symmetry structure of QCD at low energies.

Status of PrimEx at JLab

- PrimEx-I Experiment in Hall B for $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ was approved in 1999 and reapproved in 2002.
  - The experiment performed in 2004 with 6 GeV beam.
  - Publication is in progress.

- PrimEx-II for $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ was approved by PAC33 in Jan 2008, is under preparation to be run in Hall B with 6 GeV.

- The 12 GeV Primakoff program was reviewed by 3 special high energy PAC's. It was included in Jlab 12 GeV upgrade White paper and CDR.

  PAC18 (2000)
  PAC23 (2003)
  PAC27 (2005)

- The first 12 GeV Primakoff experiment on $\Gamma(\eta \rightarrow \gamma\gamma)$ in Hall D was recently approved by PAC35 in Jan 2010.

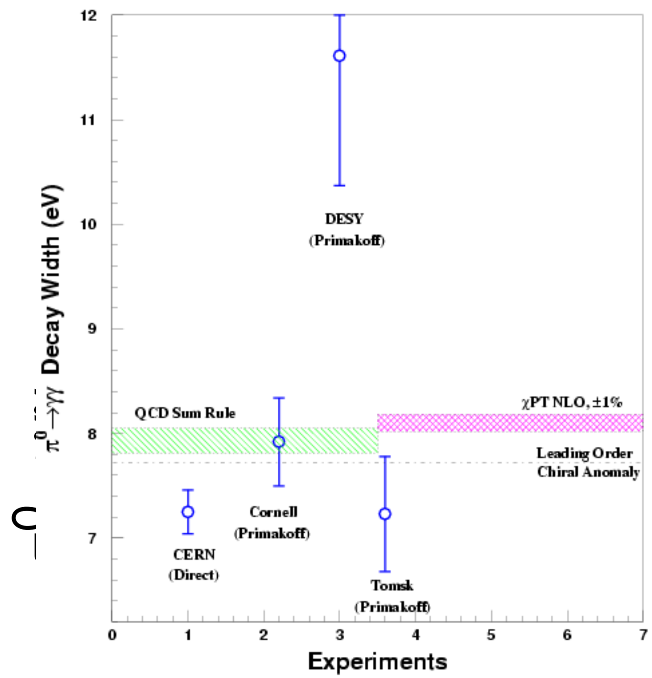
First Jlab Primakoff Experiment: π^0 Lifetime

- $\pi^0 \rightarrow \gamma\gamma$ decay proceeds primarily via the chiral anomaly in QCD.
- The chiral anomaly prediction is exact for massless quarks:

$$\Gamma\left(\pi^0 \rightarrow \gamma\gamma\right) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.725\ eV$$

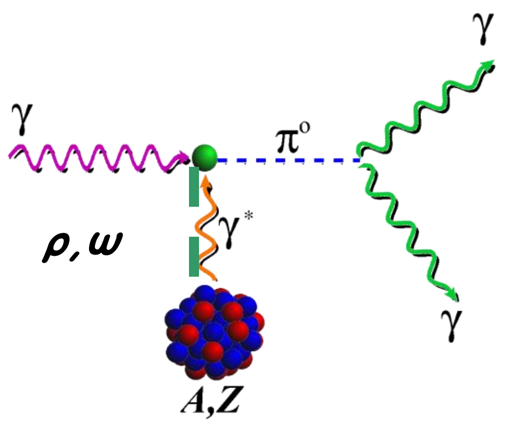
- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at higher orders!
  - Corrections to the chiral anomaly prediction: (u-d quark masses and mass differences)
    Calculations in NLO ChPT:
    - $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.10eV $\pm$ 1.0%
      (J. Goity, at al. Phys. Rev. D66:076014, 2002)
    - $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.09eV $\pm$ 1.3%
      (K. Kampt at al. Phys. Rev. D79:076005, 2009)
  - Calculations in QCD sum rule:
    (B.L. Ioffe, et al. Phys. Lett. B647, p. 389, 2007)
    1. $\Gamma(\eta \rightarrow \gamma\gamma)$ is the only input parameter
    2. π^0-η mixing included

    $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.93eV $\pm$ 1.5%

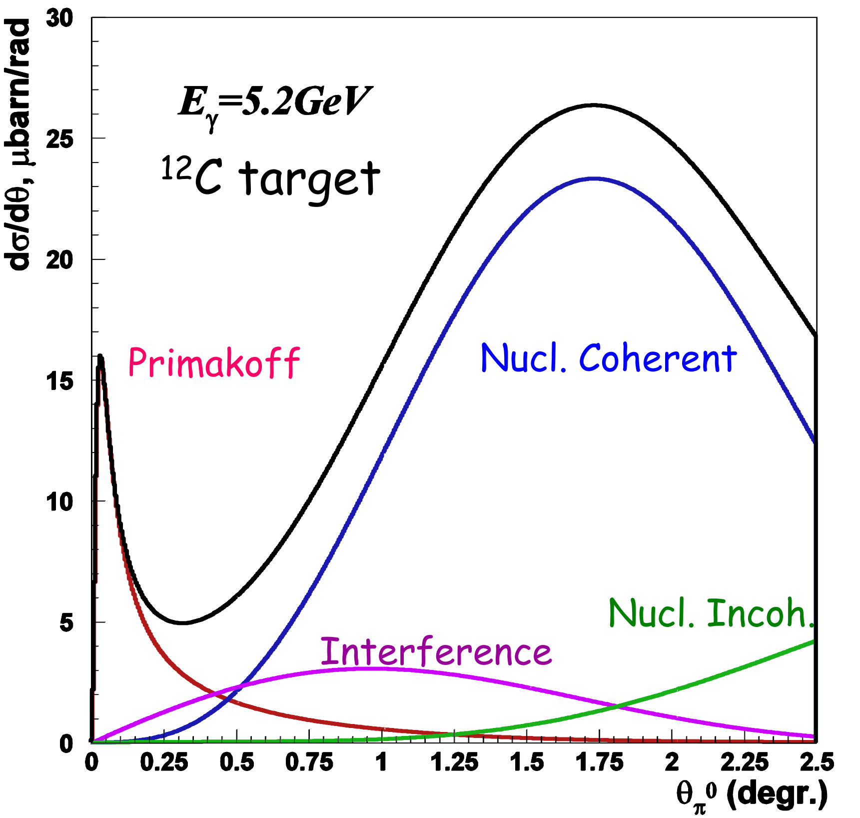


- Precision measurements of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ at the percent level will provide a stringent test on a fundamental prediction of QCD.

Primakoff Method



$$\frac{d\sigma_{\rm Pr}}{d\Omega} = \Gamma_{\gamma\gamma}\frac{8\alpha Z^2}{m_\pi^3}\frac{\beta^3 E^4}{Q^4}\left|F_{e.m.}(Q)\right|^2 \sin^2\theta_\pi$$

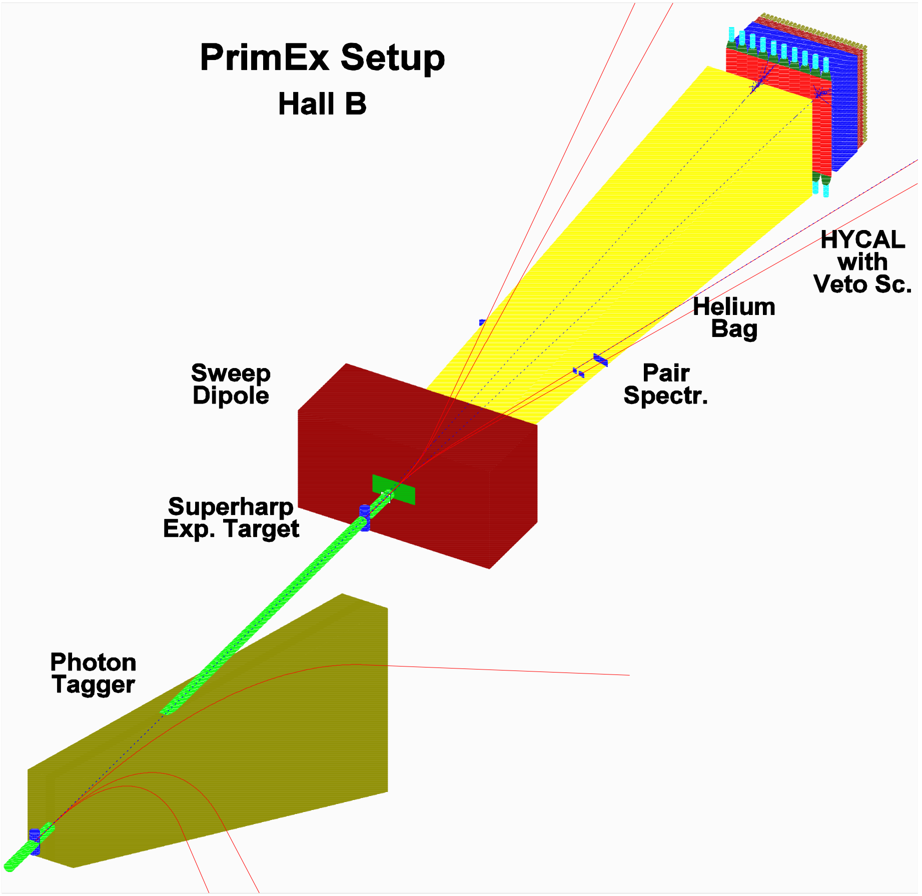


$$\langle\theta_{\rm Pr}\rangle_{peak} \propto \frac{m_\pi^{\ 2}}{2E^2}, \left(\frac{d\sigma_{\rm Pr}}{d\Omega}\right)_{peak} \propto E^4, \int d\sigma_{\rm Pr} \propto Z^2\log(E)$$

Extract the Primakoff amplitude based on different angular dependences

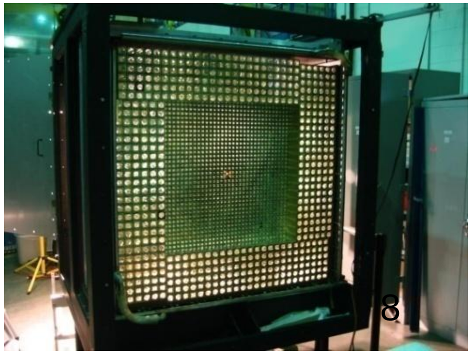
Experiment on $\Gamma(\pi^0 \to \gamma\gamma)$ at 6 GeV

- ❑ JLab Hall B high resolution, high intensity photon tagging facility

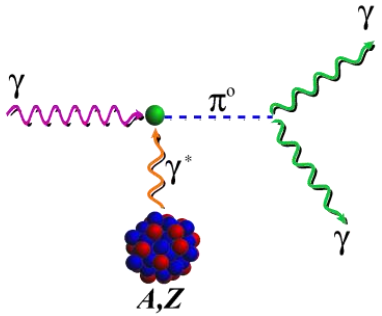


- ❑ New pair spectrometer for photon flux control at high intensities

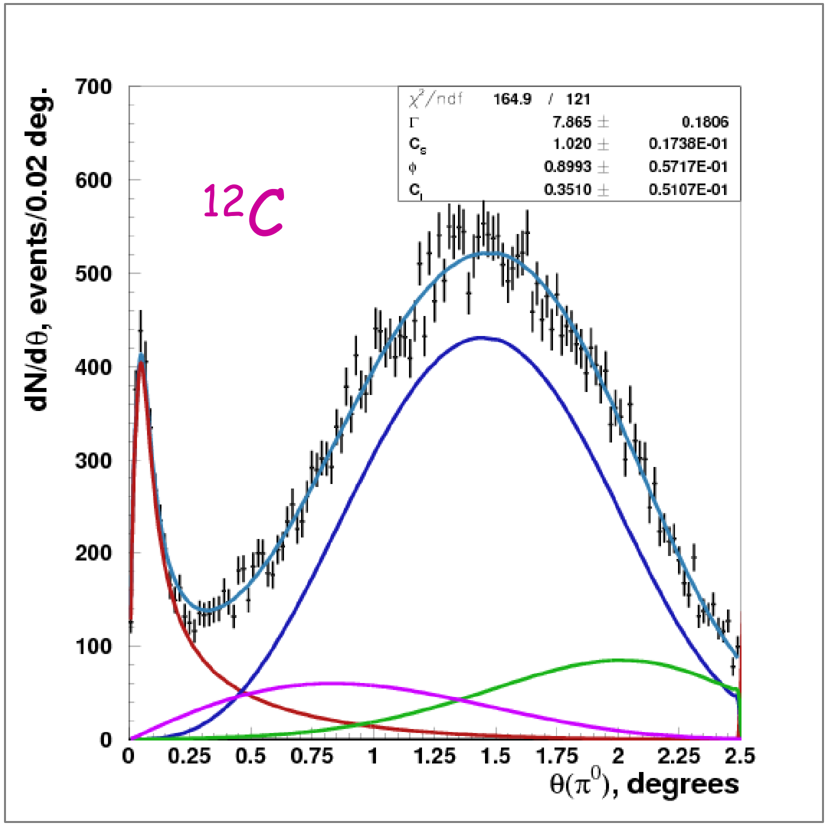
- ❑ New high resolution hybrid multi-channel calorimeter

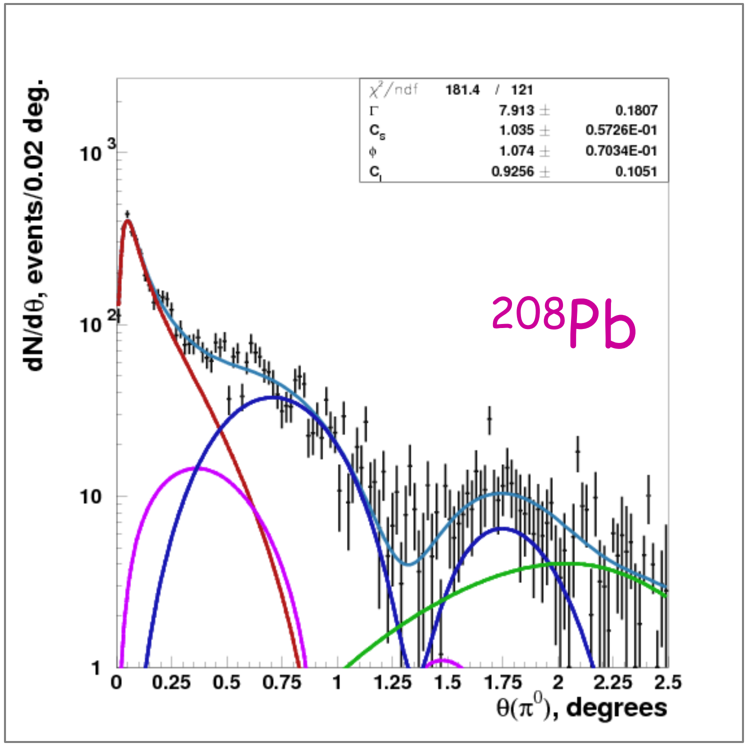


PrimEx-I Experiment: $\Gamma(\pi^0 \to \gamma\gamma)$ Decay Width

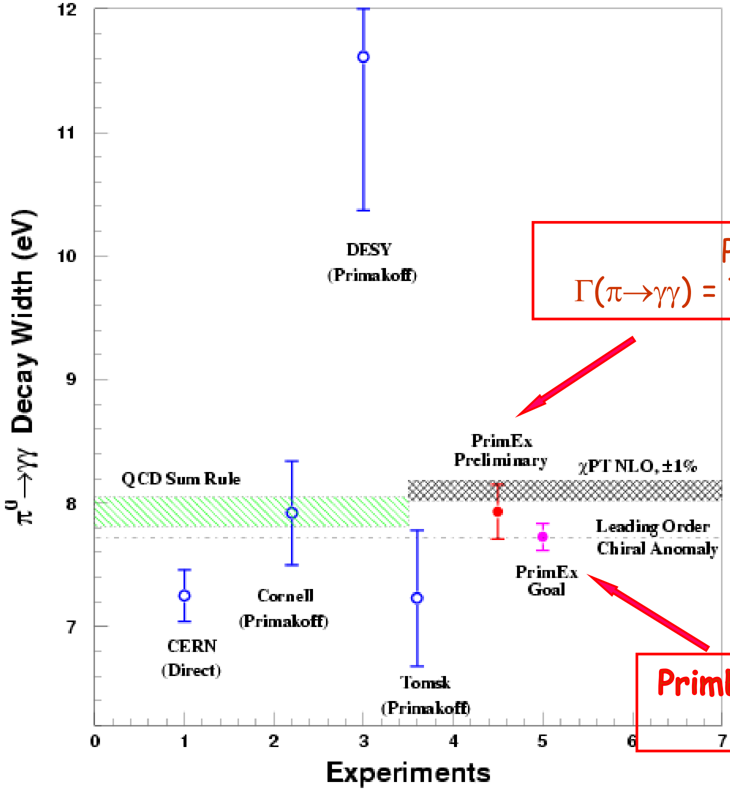


- Nuclear targets: ^{12}C and ^{208}Pb;
- 6 GeV Hall B tagged beam;
- experiment performed in 2004





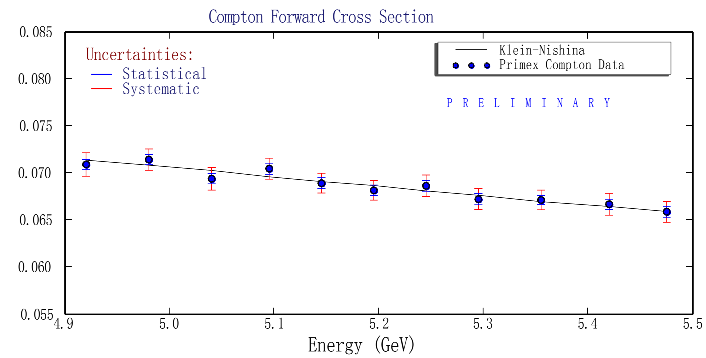
PrimEx-I Result, New PrimEx-II Experiment

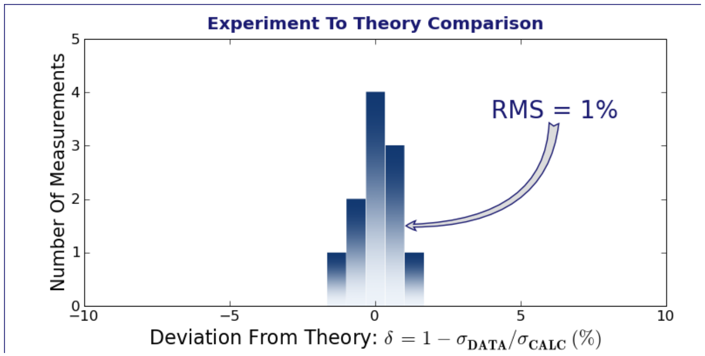


PrimEx-I
$\Gamma(\pi \to \gamma\gamma)$ = 7.82eV±1.8%±2.1%

PrimEx-II projected ±1.4%

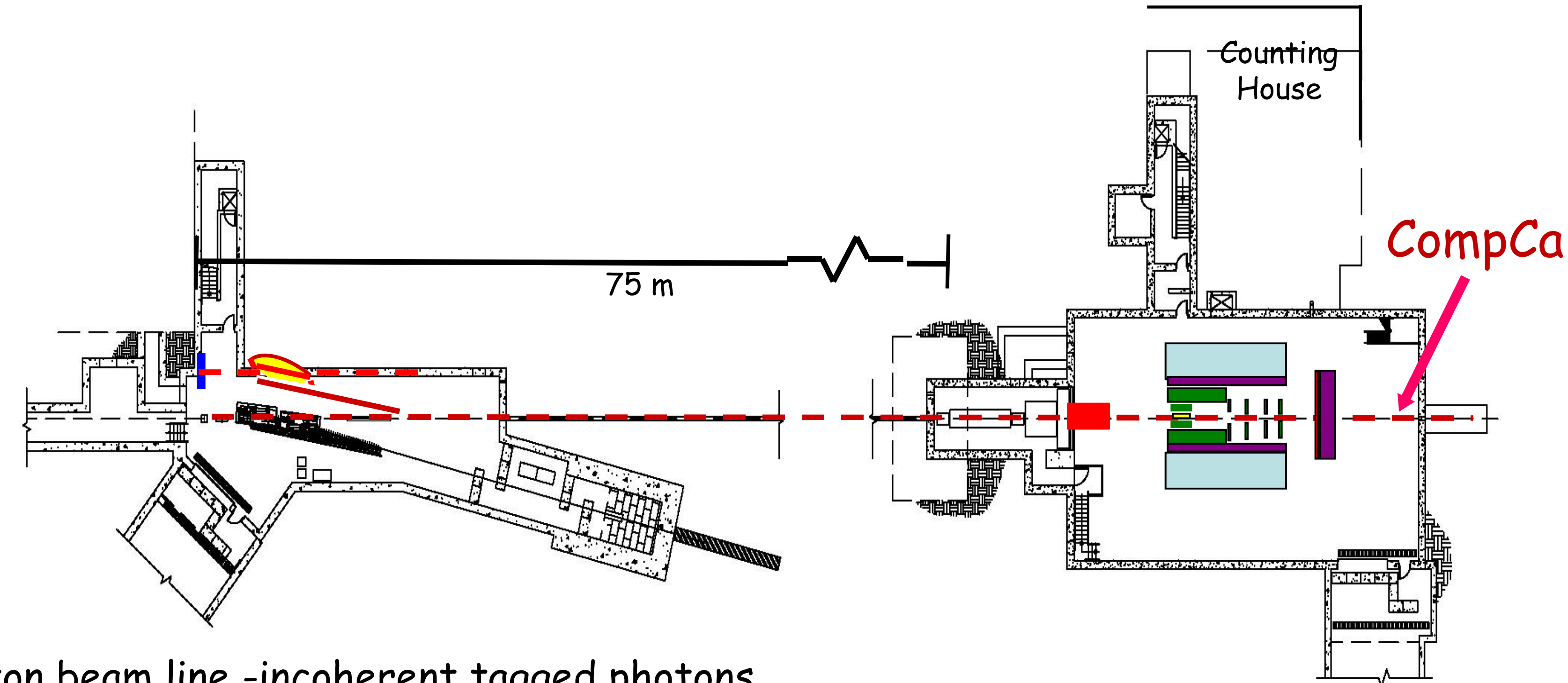
Control of overall systematic uncertainty by the $\gamma + e \to \gamma + e$
Compton cross section measurement





Measurement of $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D at 12 GeV

- We propose to use GlueX standard setup for this measurement:



- Photon beam line -incoherent tagged photons
- Pair spectrometer
- Solenoid detectors (for background rejection)
- 30 cm LH2 and LHe4 targets (~3.6% r.l.)
- Forward tracking detectors (for background rejection)
- Forward Calorimeter (FCAL) for $\eta\rightarrow\gamma\gamma$ decay photons
- Additional CompCal detector for overall control of systematic uncertainties.

Physics Outcome from New $\eta \to \gamma\gamma$ Experiment

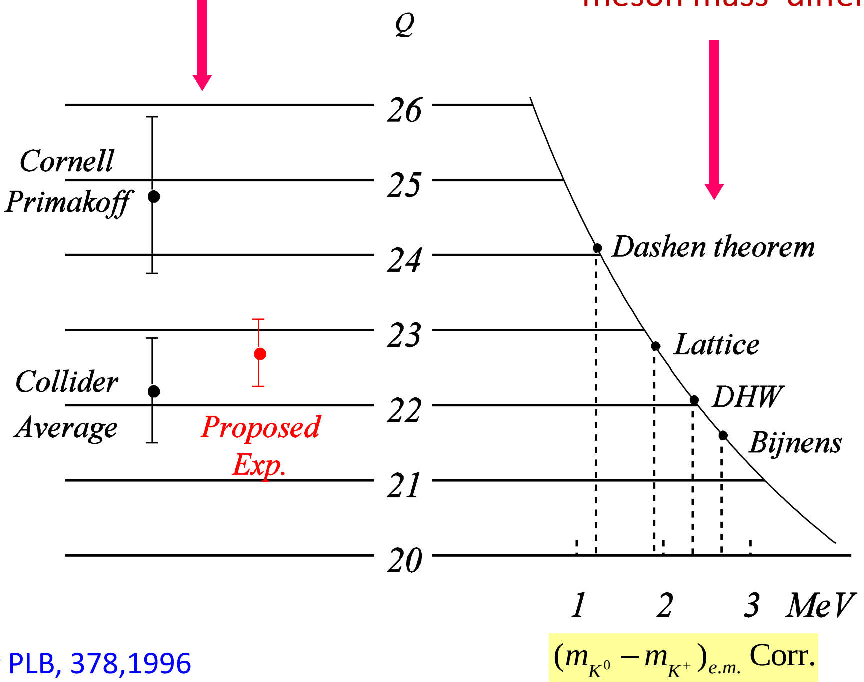
- **3. Determine Light quark mass ratio:**

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \qquad \text{where } \hat{m} = \frac{1}{2}(m_u + m_d)$$

$\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}$

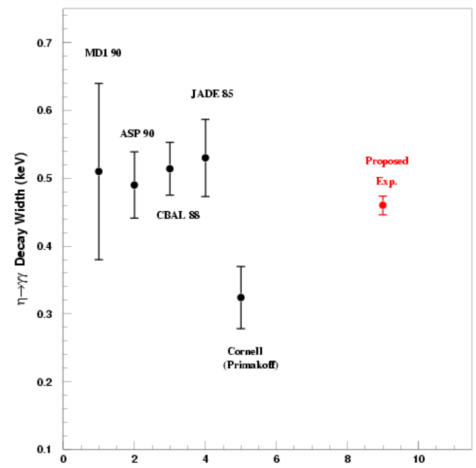
$\Gamma(\eta \to 3\pi) = \Gamma(\eta \to \gamma\gamma) \times BR(3\pi)/BR(\gamma\gamma)$

$(K^+ - K^0)_{e.m.}$
meson mass difference

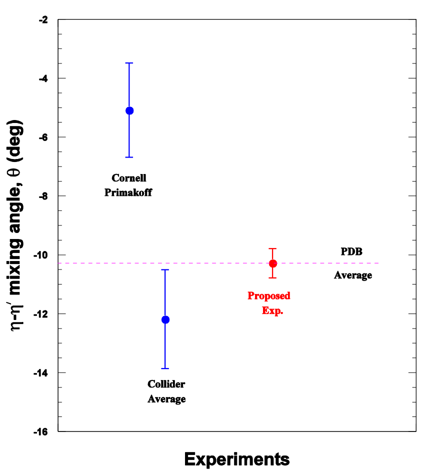


H. Leutwyler PLB, 378,1996

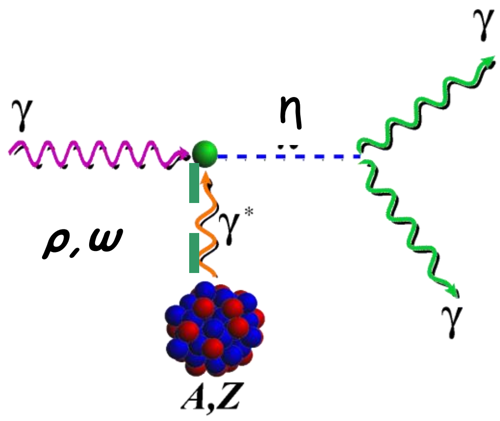
- **1. Resolve long standing discrepancy between collider and Primakoff measurements:**



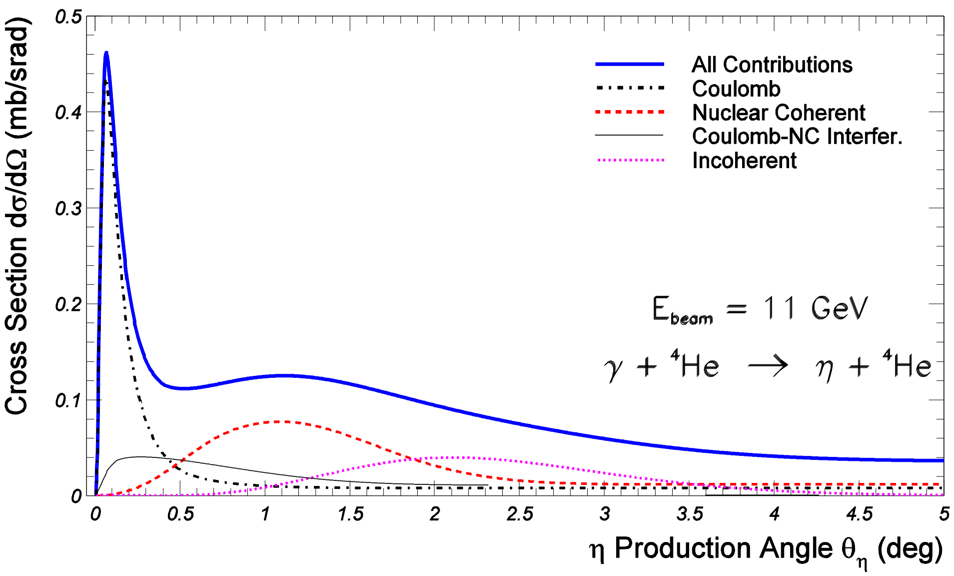
- **2. Extract η-η'mixing angle:**



Challenges in η→γγ Experiment



$$\frac{d^3\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m_\eta^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2\theta_\eta$$



- Difficulties of η→γγ experiment:
  - η mass factor of 4 larger than π^0;
  - cross section is smaller;
  - larger overlap between Primakoff and hadronic processes;

$$\langle\theta_{Pr}\rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \theta_{NC} \propto \frac{2}{E \bullet A^{1/3}}$$

  - larger momentum transfer: (coherency, form factors, FSI,…)

Challenge: Separate Primakoff amplitude from hadronic processes.

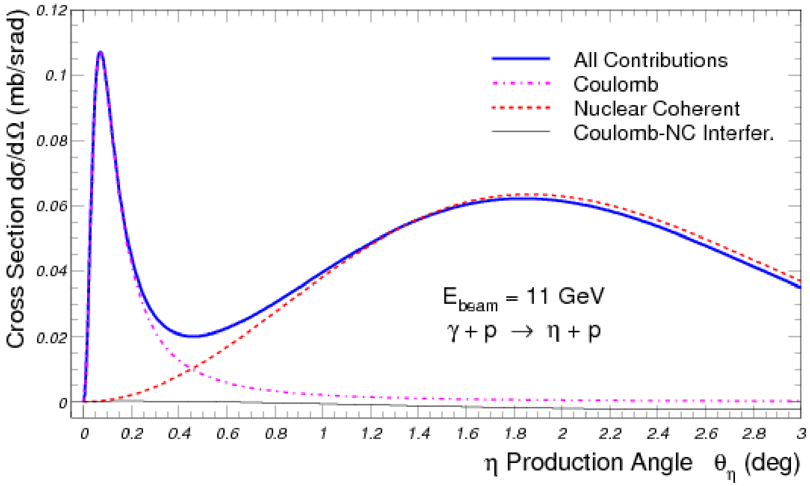
We propose to use LH2 and LHe4 targets to address all those issues.

Advantages of the Proposed Targets

- Precision measurements require low A targets to control:
  - coherency
  - contributions from nuclear processes

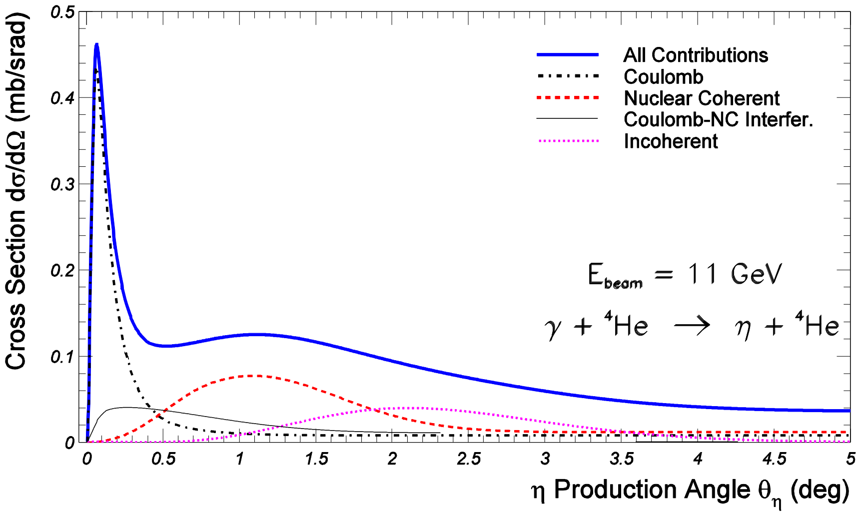
- **Hydrogen:**
  - ✓ no inelastic hadronic contribution
  - ✓ no nuclear final state interactions
  - ✓ proton form factor is well known
  - ✓ better separation between Primakoff and nuclear processes
  - ✓ new theoretical developments of Regge description of hadronic processes

J.M. Laget, Phys. Rev. C72, (2005)
A. Sibirtsev, et al. hep-ph/0902.1819 (2009)



- **^{4}He:**
  - ✓ higher Primakoff cross section
  - ✓ the most compact nucleus
  - ✓ form factor well known
  - ✓ new theoretical developments for FSI

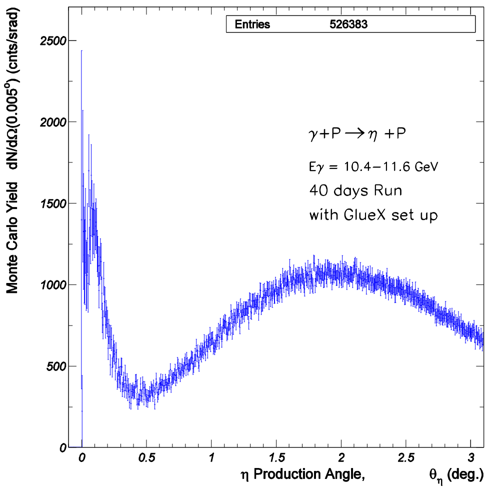
S. Gevorkyan et al., Phys. Rev. C 80, 2009

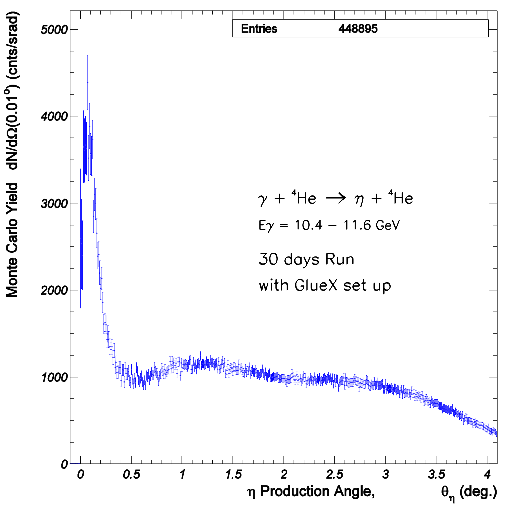


Estimated Error Budget

- **Systematical errors:**
  (added quadratically)

Contributions	Estimated Error
Photon flux	1.0%
Target thickness	0.5%
Background subtraction	2.0%
Event selection	1.7%
Acceptance, misalignment	0.5%
Beam energy	0.2%
Detection efficiency	0.5%
Branching ratio (PDG)	0.66%
Total Systematic	**3.02%**





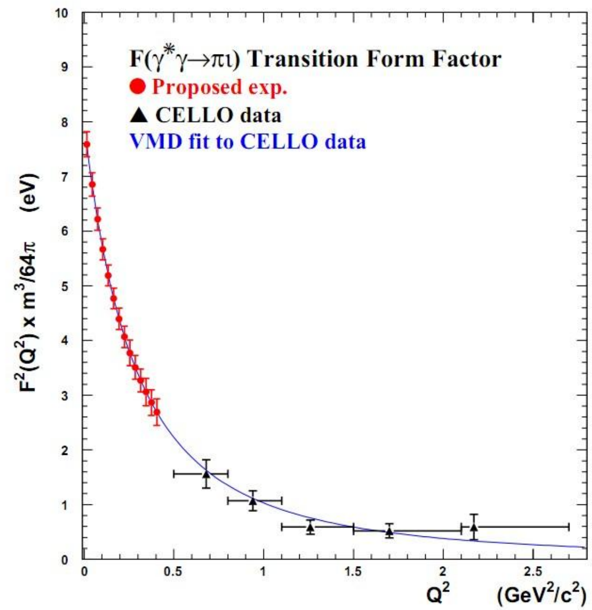
- **Total error:**
  (added quadratically)

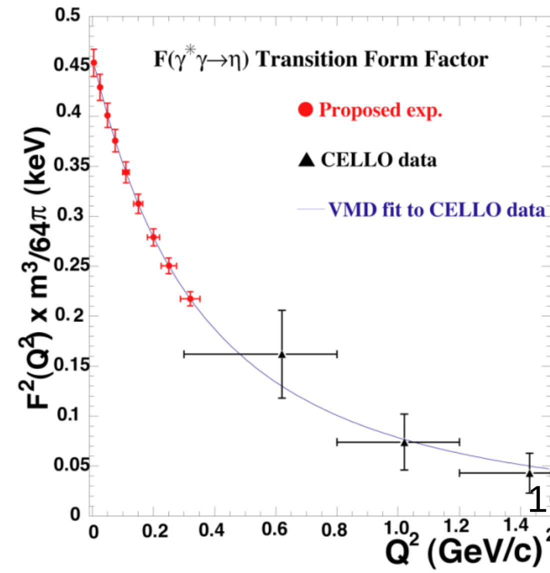
Statistical error	1.0%
Systematic error	3.02%
Total Error	**3.2%**

Transition Form Factors of π^0, η and η' at Low Q^2

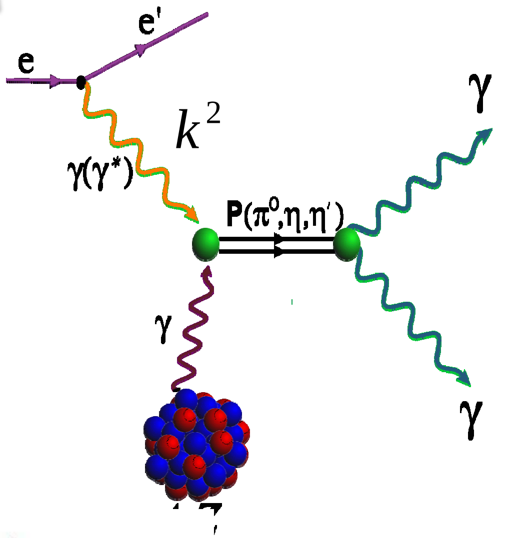
Q^2 (0.001-0.5 GeV^2/c^2)

- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian
- Test different models
- Test of future lattice calculations





Transition Form Factors: Primakoff Method



Hadjimicle and Fallieros, phys.Rev.C39,1438 (1989)

Use electro-Primakoff method to measure transition form factors.

$$\frac{d^3\sigma}{d\epsilon_2 d\Omega_2 d\Omega_P} = \frac{Z^2\eta^2}{\pi}\sigma_M \frac{\vec{q}_P^{\,4}}{\vec{k}^{\,4}} \frac{\beta_P^{-1}}{\omega_P} |F_N(K^2)|^2 |F_{\gamma^*\gamma P^0}(q_\mu^2)|^2 \sin^2\frac{\theta_e}{2} \sin^2\theta_P$$

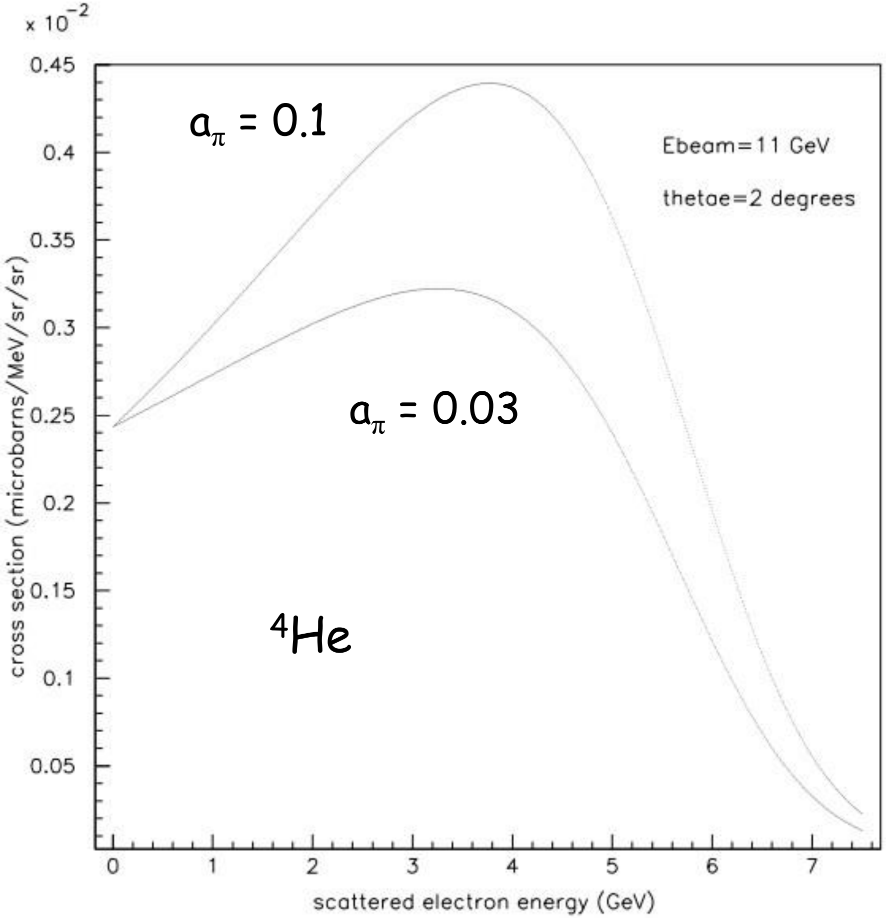
$$\times[4\epsilon_1\epsilon_2 \sin^2\phi_P + |\vec{q}|^2 / \cos^2\frac{\theta_e}{2}]$$

$\eta^2 = (4/\pi m^3)/\tau$, with τ is the life time of meson

$$\langle\theta_{Pr}\rangle_{peak} \propto \frac{-k^2 + m_\pi^{\ 2}}{2E_\pi^{\ 2}} \qquad \langle\theta_{NC}\rangle_{peak} \propto \frac{2}{E_\pi \bullet A^{1/3}}$$

Electro-Primakoff peak is at relatively larger angle than real photon primakoff

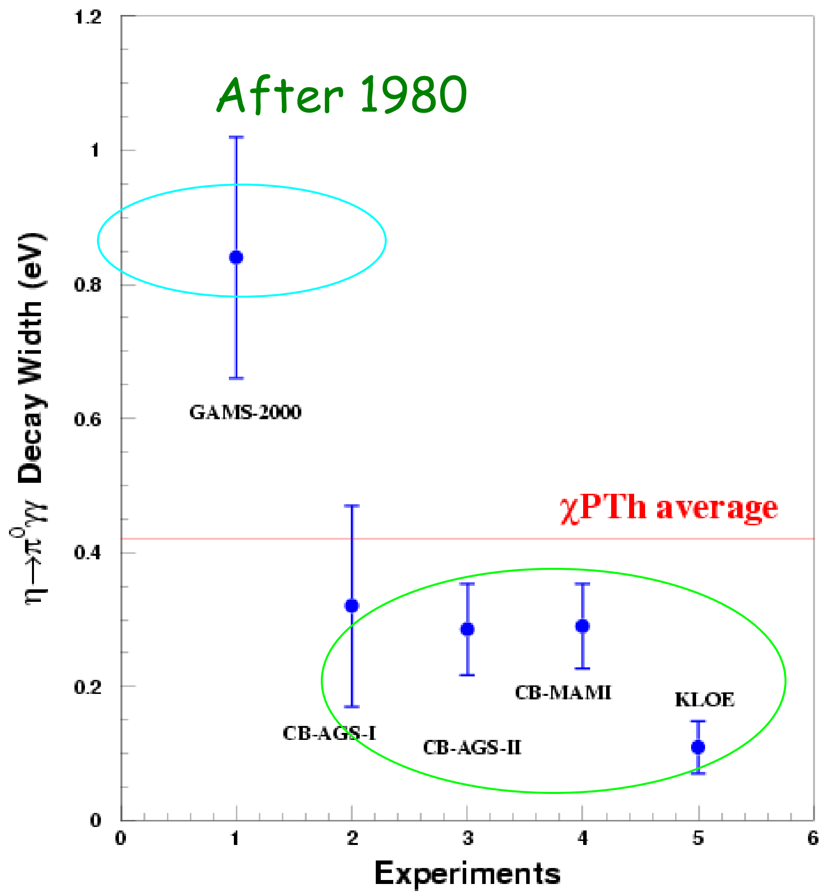
Primakoff Method: Sensitivity to Slope Parameter



Study QCD symmetries via η and η′ Rare Decays

Mode	Branching Ratio	Physics Highlight
$\pi^0 \pi^0$	$<3.5 \times 10^{-4}$	CP, P
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh, O(p^6)
$\pi^+ \pi^-$	$<1.3 \times 10^{-5}$	CP, P
$\pi^0 \pi^0 \gamma$	$<5 \times 10^{-4}$	C
3γ	$<1.6 \times 10^{-5}$	C
$\pi^0 \pi^0 \pi^0 \gamma$	$<6 \times 10^{-5}$	C
$\pi^0 e^+ e^-$	$<4 \times 10^{-5}$	C
$4\pi^0$	$<6.9 \times 10^{-7}$	CP, P

History of the $\eta \to \pi^0 \gamma\gamma$ Measurements

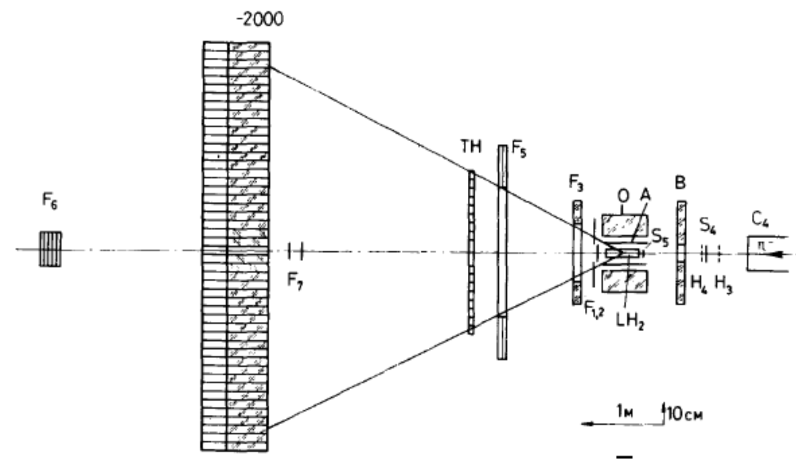


A long standing "η" puzzle is still un-settled

High Energy η Production
GAMS Experiment at Serpukhov

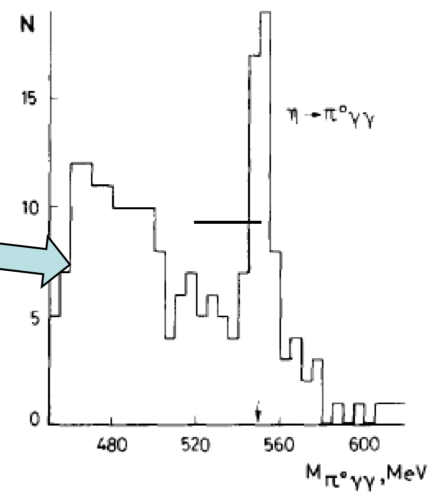
D. Alde et al., Yad. Fiz 40, 1447 (1984)

- Experimental result was first published in 1981
- The η's were produced with 30 GeV/c π^- beam in the $\pi^- p \rightarrow \eta n$ reaction
- Decay γ's were detected by lead-glass calorimeter



Major Background

- $\pi^- p \rightarrow \pi^0 \pi^0 n$
- $\eta \rightarrow \pi^0 \pi^0 \pi^0$



Final result:

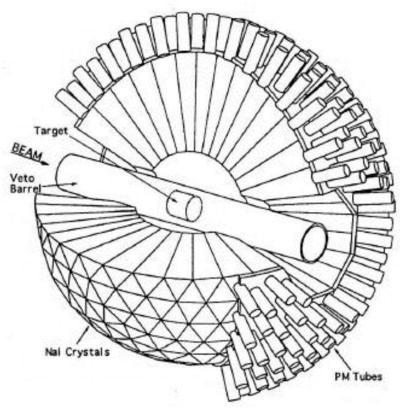
$\Gamma(\eta \rightarrow \pi^0 \gamma\gamma) = 0.84 \pm 0.17$ eV

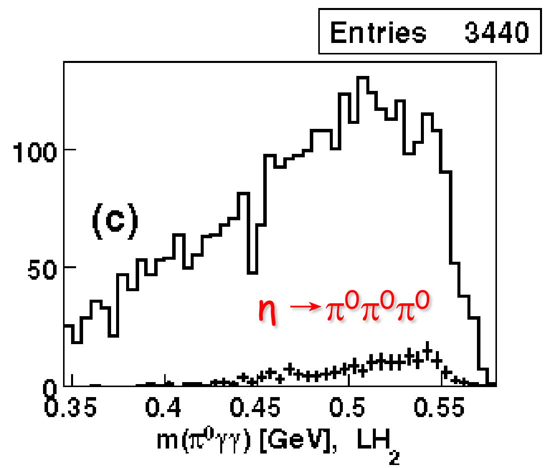
Low energy η production

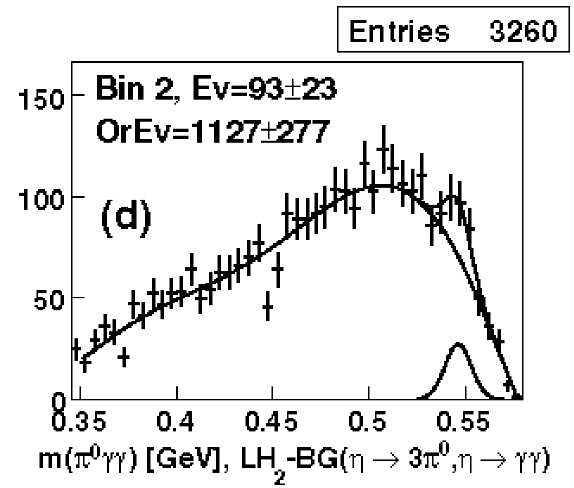
CB experiment at AGS

S. Prakhov et al. Phy.Rev.,C78,015206 (2008)

The Crystal Ball







- The η's were produced with 720 MeV/c π^- beam through the $\pi^- p \rightarrow \eta n$ reaction
- Decay γ's energy range: 50-500 MeV

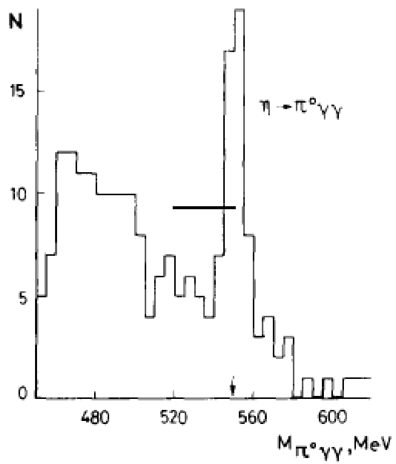
Final result:

$\Gamma(\eta \rightarrow \pi^0 \gamma\gamma) = 0.285 \pm 0.031 \pm 0.061$ eV

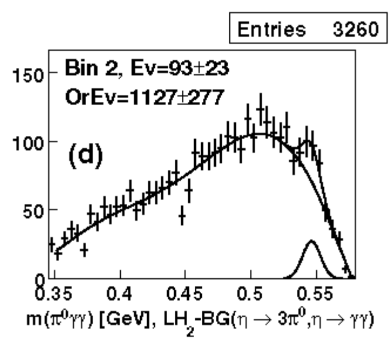
What can be improved with 12 GeV

- High energy photo-production $\gamma + p \rightarrow \eta + p$ to reduce the background from $\eta \rightarrow 3\pi^0$
  - Lower relative threshold for γ-ray detection
  - Improve calorimeter resolution
- High resolution, high granularity Calorimeter
  - Higher energy resolution → improve $\pi^0\gamma\gamma$ invariance mass
  - Higher granularity → better position resolution and less overlap clusters
- Large statistics to provide a precision measurement of Dalitz plot

$E_\pi = 30$ GeV/c

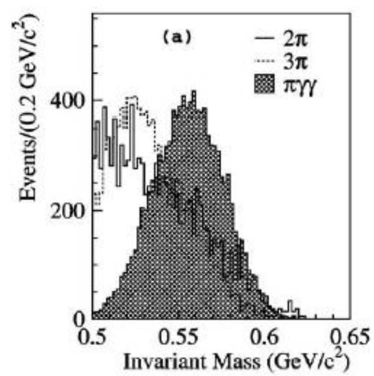


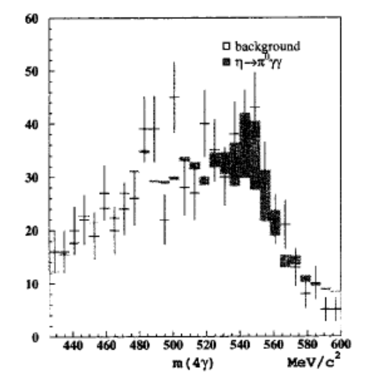
$E_\pi = 720$ MeV/c



ϕ production $\sqrt{s} = 1020$ MeV

$\phi \rightarrow \gamma\eta$





Primakoff Production with an e-p Collider

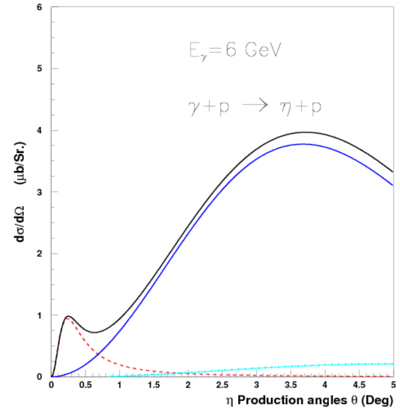
- A high energy electron beam on a proton target.
  For a 5-10 GeV electron and 30-60 GeV proton collider, it is equivalent to a 320-1279 GeV electron beam on the proton at rest.

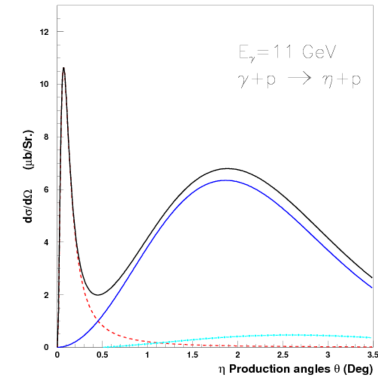
- Polarized virtual photons or polarized protons

Advantages of High Energy e-p Collider

- Increase Primakoff cross section:

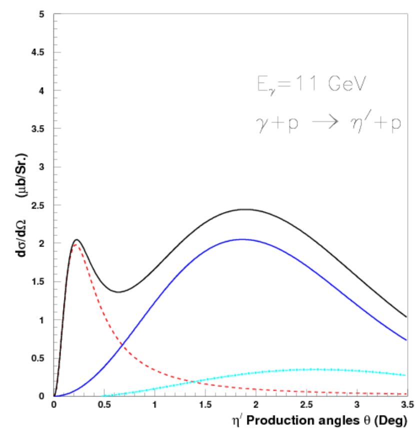
$$\left(\frac{d\sigma_{\mathrm{Pr}}}{d\Omega}\right)_{peak} \propto \frac{E^4}{m^3} \qquad \int d\sigma_{\mathrm{Pr}} \propto \frac{Z^2}{m^3}\log(E)$$

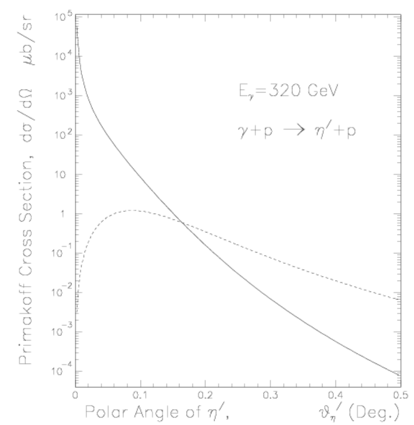




- Better separation of Primakoff reaction from nuclear processes:

$$\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \langle\theta_{NC}\rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}$$



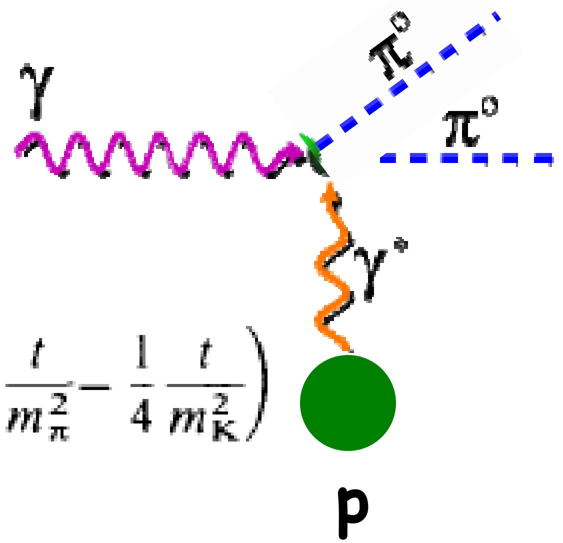


Primakoff Program with e-p Collider

- Expand the current PrimEx program to include more heaver mesons, such as $f_0(980)$, $f_2(1270)$, $a_2(1320)$, $f_0(1370)$
  - Radiative decay widths $\Gamma(\gamma\gamma)$
  - Transition form factors $F(\gamma\gamma^* \rightarrow p)$

Hadron Polarizabilities

- Study hadron polarizabilities by $\gamma\gamma \to$ pp reaction, P represents π, η, and other mesons
- Hadron electric and magnetic polarizabilities characterize the induced transient dipole moments of hadron subjected to external electromagnetic fields. For t→0,



$$\left(\frac{d\sigma}{d\Omega}\right)^{\chi PT}_{\gamma\gamma\to\pi^0\pi^0} \simeq \frac{1}{2}\frac{m_\pi^2}{4}\frac{\beta_v}{2}\left|\bar{\alpha}^*_{\pi^0}(s)\right|^2 s \qquad \bar{\alpha}^*_{\pi^0} \approx \bar{\alpha}_{\pi^0}\left(1-\frac{13}{15}\frac{t}{m_\pi^2}-\frac{1}{4}\frac{t}{m_K^2}\right)$$

where $\bar{\alpha}_{\pi^0} = -\bar{\beta}_{\pi^0}$

- The Primakoff cross section for two pion production is

$$\frac{d^2\sigma}{d\Omega dE_{\pi\pi}} = \frac{\alpha Z^2}{\pi^2}\sigma(\gamma\gamma\to\pi\pi)\frac{\beta^2 E^4}{E_{\pi\pi}^2 Q^4}\left|F(Q)\right|^2 \sin^2\theta_{\pi\pi} K_\pi$$

Neutral Axial Coupling of Proton

J. Bernabeu et al., phys. Lett., B305, 392 (1993); Z. phys., C69, 431 (1996)

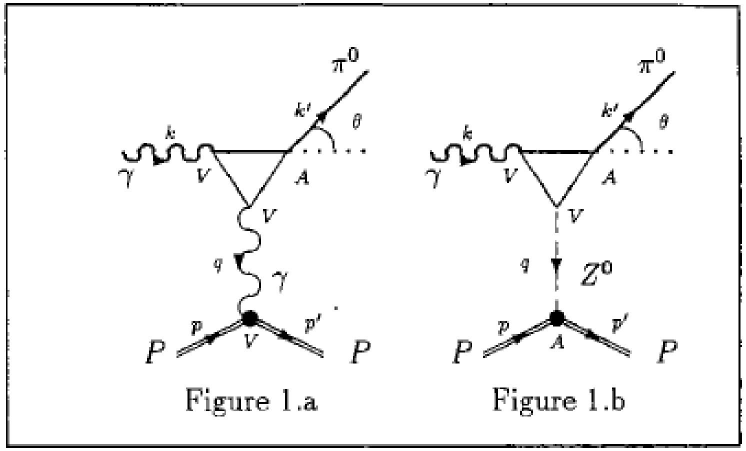
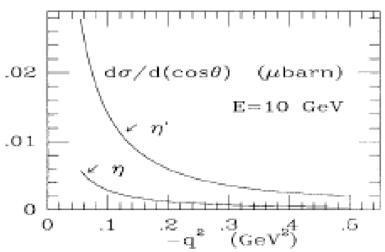
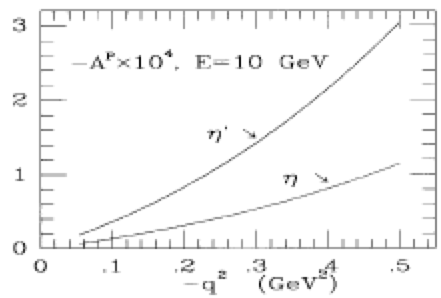
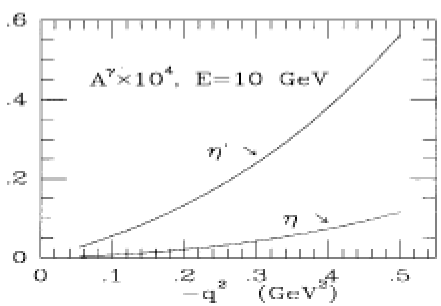


Figure 1.a Figure 1.b







- Axial coupling is $G_A = \Delta u - \Delta d - \Delta s$
- The neutral vector coupling of the proton is filtered out in the Primakoff effect and only G_A is left in the observables.
- For circularly polarized photons:

$$A^\gamma \equiv \frac{d\sigma(h=+) - d\sigma(h=-)}{d\sigma(h=+) + d\sigma(h=-)}$$

$$\approx \frac{1-4s_w^2}{4\pi}\frac{G_F}{\sqrt{2}}\frac{(-t)}{\alpha}\frac{G_A G_M}{G_E^2 - \frac{t}{4M^2}G_M^2}\frac{t-m_\pi^2}{2ME}$$

- For longitudinally polarized protons:

$$A^p \equiv \frac{d\sigma(s=+) - d\sigma(s=-)}{d\sigma(s=+) + d\sigma(s=-)}$$

$$\simeq \frac{1-4s_w^2}{4\pi}\frac{G_F}{\sqrt{2}}\frac{(-q^2)}{\alpha}\frac{G_A G_E}{G_E^2 - \frac{q^2}{4M^2}G_M^2}$$

Summary

- The Primakoff effect is a powerful tool for precision measurements to test QCD symmetries and search for new physics beyond standard model

- A comprehensive Primakoff program has been developed at Jlab 6@12 GeV to perform precision measurements on the radiative decay widths and transition form factors of π^0, η, and η'.

- Experiments to study η and η′ rare decays at 12 GeV is under development

- Possible future electron-proton collider will open exciting new opportunities: expand the current existing Primakoff program to include more heaver mesons; access to hadron polarizabilities via double meson Primakoff productions; measure the Neutral Axial Coupling of Proton via the parity violating asymmetries in the Primakoff production.

The End

Transition Form Factors
Previous Experiments: Time-like region

- **Dalitz decay of mesons:** $P \rightarrow \gamma\, e^{+} e^{-}$

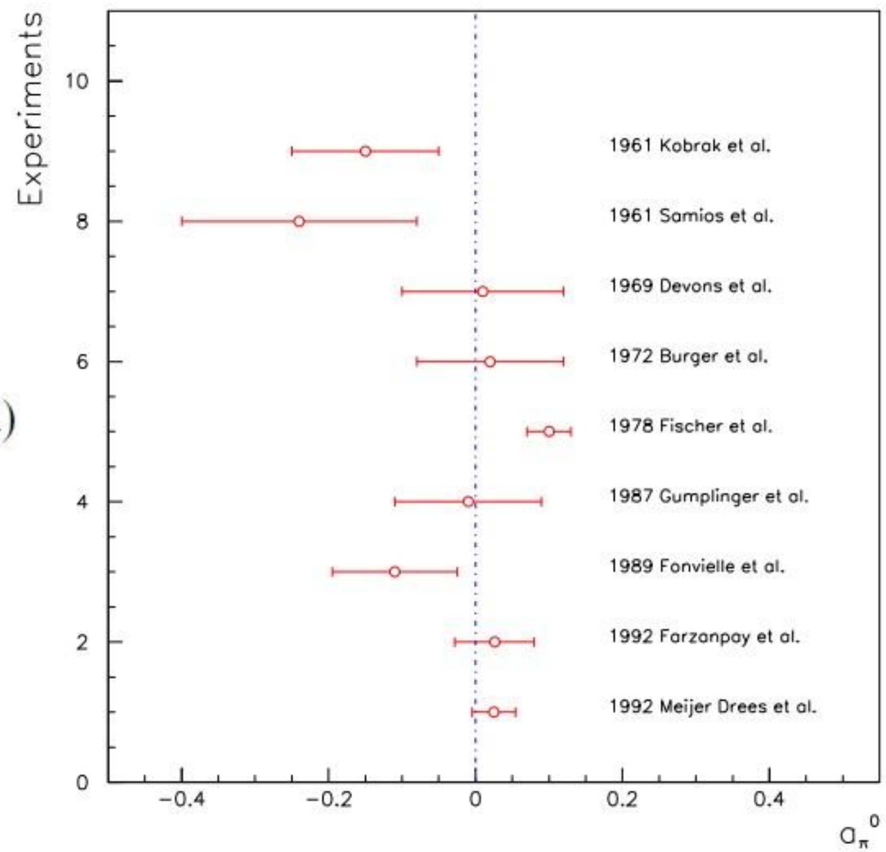
Problems;

- small kinematical range;
- significant background;
- large rad. Corrections;
- low statistics

$$F_{\gamma^*\gamma^*\pi^0}(0, Q^2) = F_{\gamma^*|\gamma^*\pi^0}(0,0)(1 - a_\pi Q^2/m_\pi^2)$$

Results:

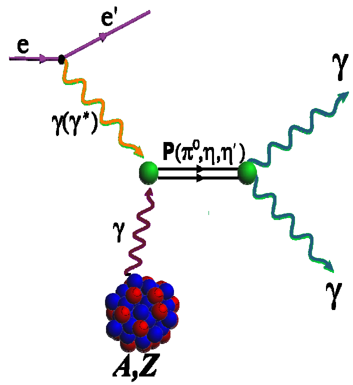
a_π = [- 0.24 to + 0.12]

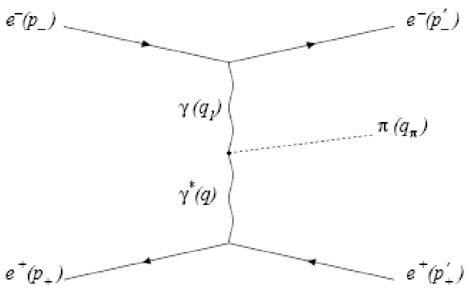


Primakoff Production with an e-p Collider

- A high energy electron beam on a proton target.

  For a 5-10 GeV electron and 30-60 GeV proton collider, it is equivalent to a 320-1279 GeV electron beam on the proton at rest.
- Differences between Promakoff productions @ e-p collider and $\gamma^*\gamma^*$ **reaction @** e+e- Collider





- Primakoff cross section is peaked forward along the beam line. Its phase space is different from other production processes in lab frame
- Decay products from light particles are energetic in the lab frame

- The mesons are produced at rest in the lab frame. The phase spaces for different processes are overlap in lab frame
- Decay products from light particles have relatively low energies

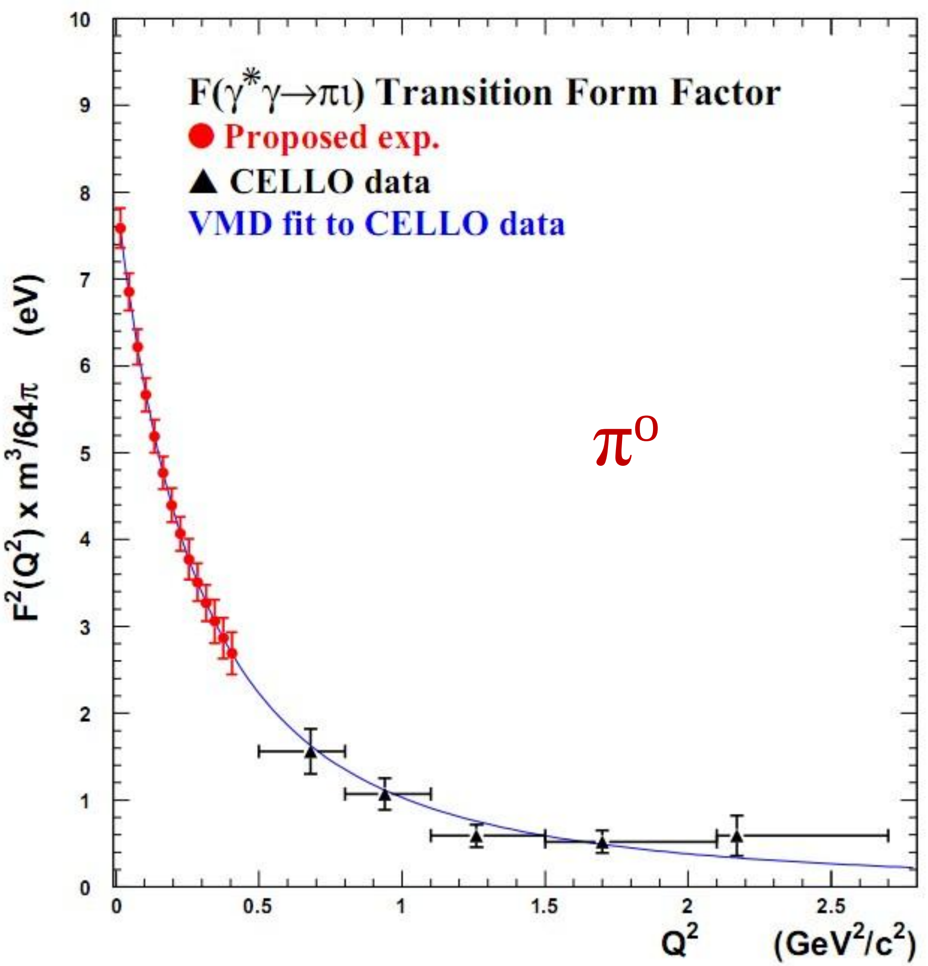
Transition Form Factors
Previous Experiments: Space-like region

- Collider experiments: $e^+e^- \rightarrow e^+e^- P$
  only one lepton detected to control Q^2

Experiments: CELLO @ PETRA at $Q^2 = 0.62 - 2.17\ (GeV/c)^2$

Results (from VMD fit):

a_π = 0.0325 +/- 0.0026



Transition Form Factors
Previous Experiments: Space-like region

- Collider experiments: $e^+e^- \to e^+ e^- P$
  only one lepton detected to control Q^2

Experiments: CELLO @ PETRA
at $Q^2 = 0.62 - 2.17\ (GeV/c)^2$

Results (from VMD fit):

$a_\eta = 0.428 +/- 0.063$

Also for η' :
$a_{\eta'} = 1.46 +/- 0.16$