Probes for Fundamental Symmetries and a Dark Gauge Boson via Light Meson Decays

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Outline

1. Introduction
   → challenges in physics

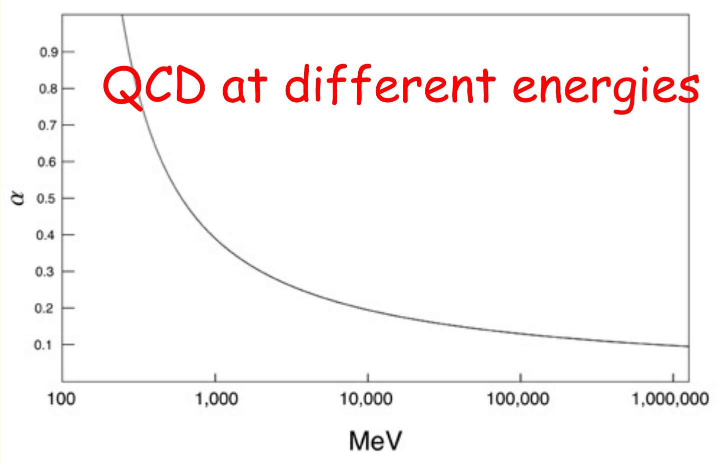
2. PrimEx experiments on π^0, η, η'
   → test confinement QCD symmetries

3. Jlab Eta Factory (JEF) Program on $\eta \rightarrow 3\pi$ and rare decays
   → determine light quark mass ratio and search for new physics

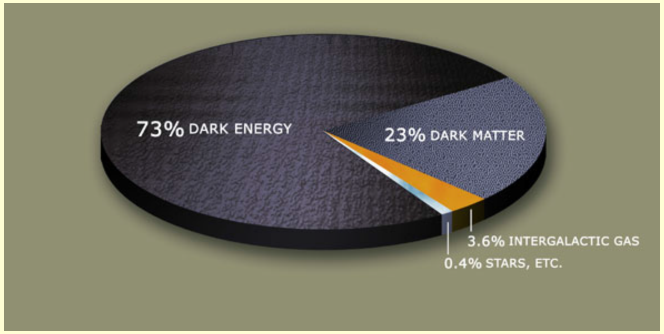
4. Summary

Challenges in Physics

- Confinement QCD
  - QCD confinement and its relationship to the dynamical chiral symmetry breaking



- New physics beyond the Standard Model (SM)
  - Dark matter and dark energy
  - New sources of CP violation



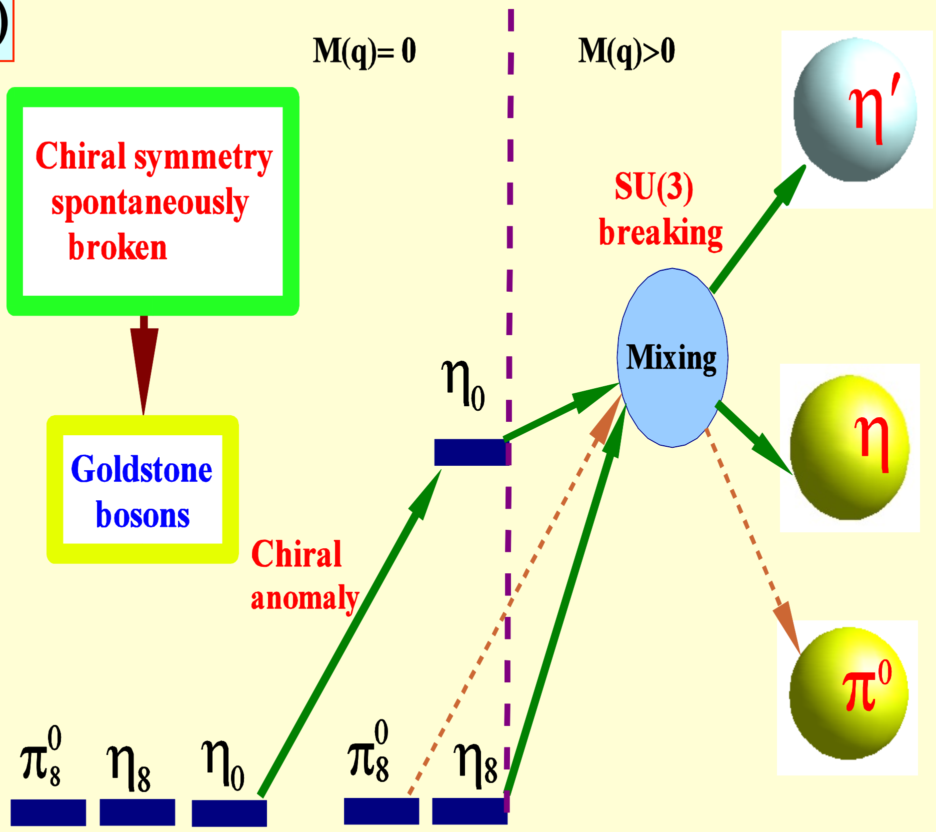
"As far as I see, all priori statements in physics have their origin in symmetry". By H. Weyl

QCD Symmetries and light mesons

- QCD Lagrangian in Chiral limit ($m_q \to 0$) is invariant under:

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

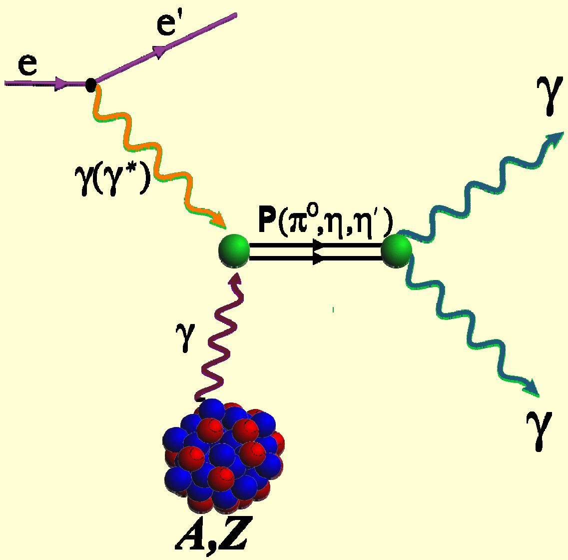
- Chiral symmetry $SU_L(3) \times SU_R(3)$ spontaneously breaks to $SU(3)$
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Mass of η_0
- $SU_L(3) \times SU_R(3)$ and $SU(3)$ are explicitly 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.

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

Input to Physics:

- 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 GeV^2/c^2):

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

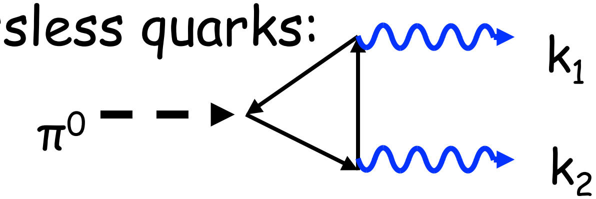
Input to Physics:

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

Axial Anomaly Determines 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:

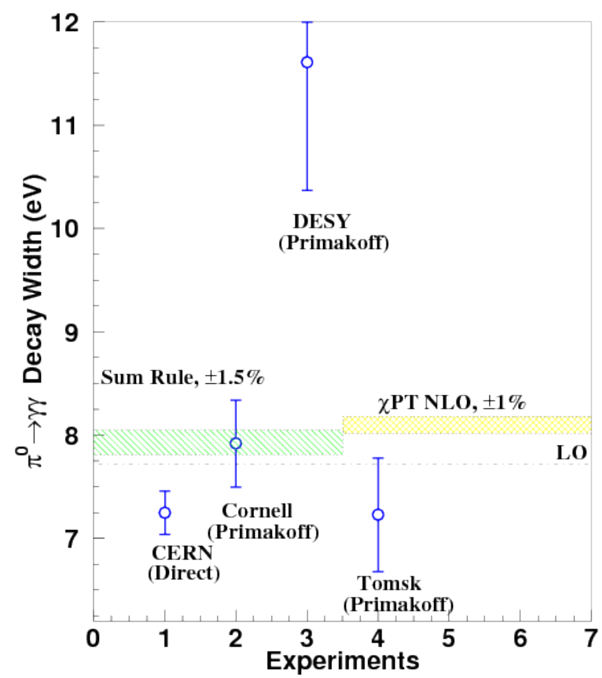
$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \frac{\alpha^2 N_c^2 m_\pi^3}{576\pi^3 F_\pi^2} = 7.725\ eV$$



- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at ~1% level to higher orders!

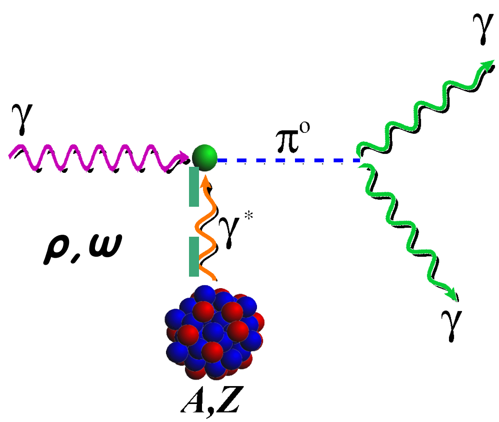
  - Corrections to the chiral anomaly prediction:
    Calculations in NLO ChPT:
    - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10eV \pm 1.0\%$
      (J. Goity, et al. Phys. Rev. D66:076014, 2002)
    - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.06eV \pm 1.0\%$
      (B. Ananthanarayan et al. JHEP 05:052, 2002)

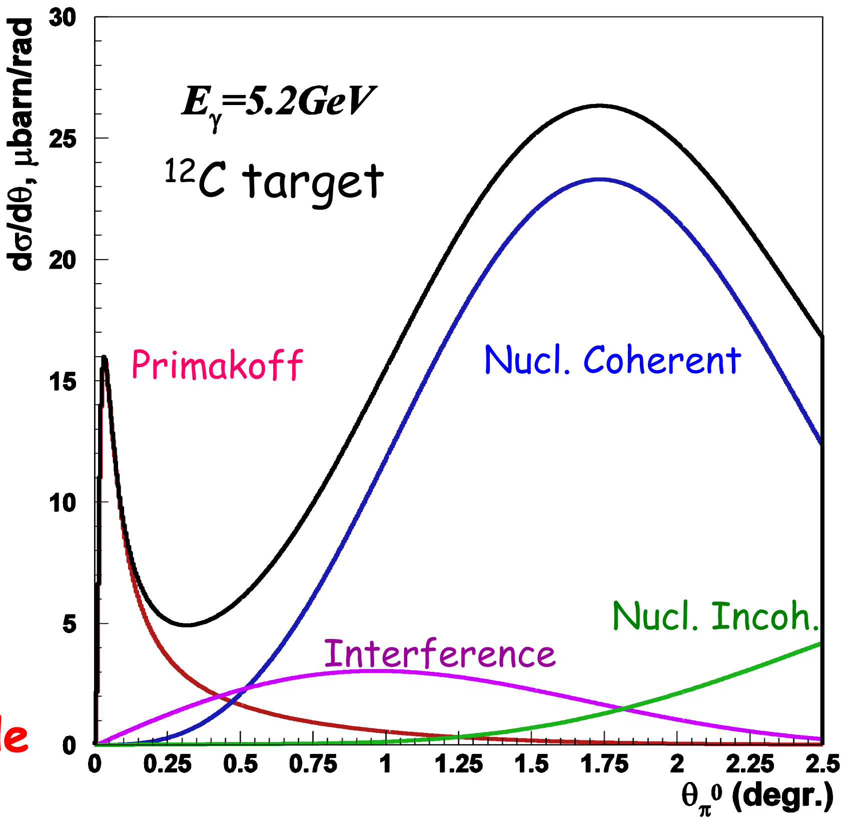
    Calculations in NNLO SU(2) ChPT:
    - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.09eV \pm 1.3\%$
      (K. Kampf et al. Phys. Rev. D79:076005, 2009)
  - Calculations in QCD sum rule:
    - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.93eV \pm 1.5\%$
      (B.L. Ioffe, et al. Phys. Lett. B647, p. 389, 2007)



- Precision measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ at the percent level will provide a stringent test of low energy QCD.

Primakoff Method





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

Challenge: Extract the Primakoff amplitude

Requirement:

- Photon flux
- Beam energy
- π^0 production angle resolution
- Compact nuclear target

Features of Primakoff cross section:

- Peaked at very small forward angle:

$$\langle\theta_{\text{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2}$$

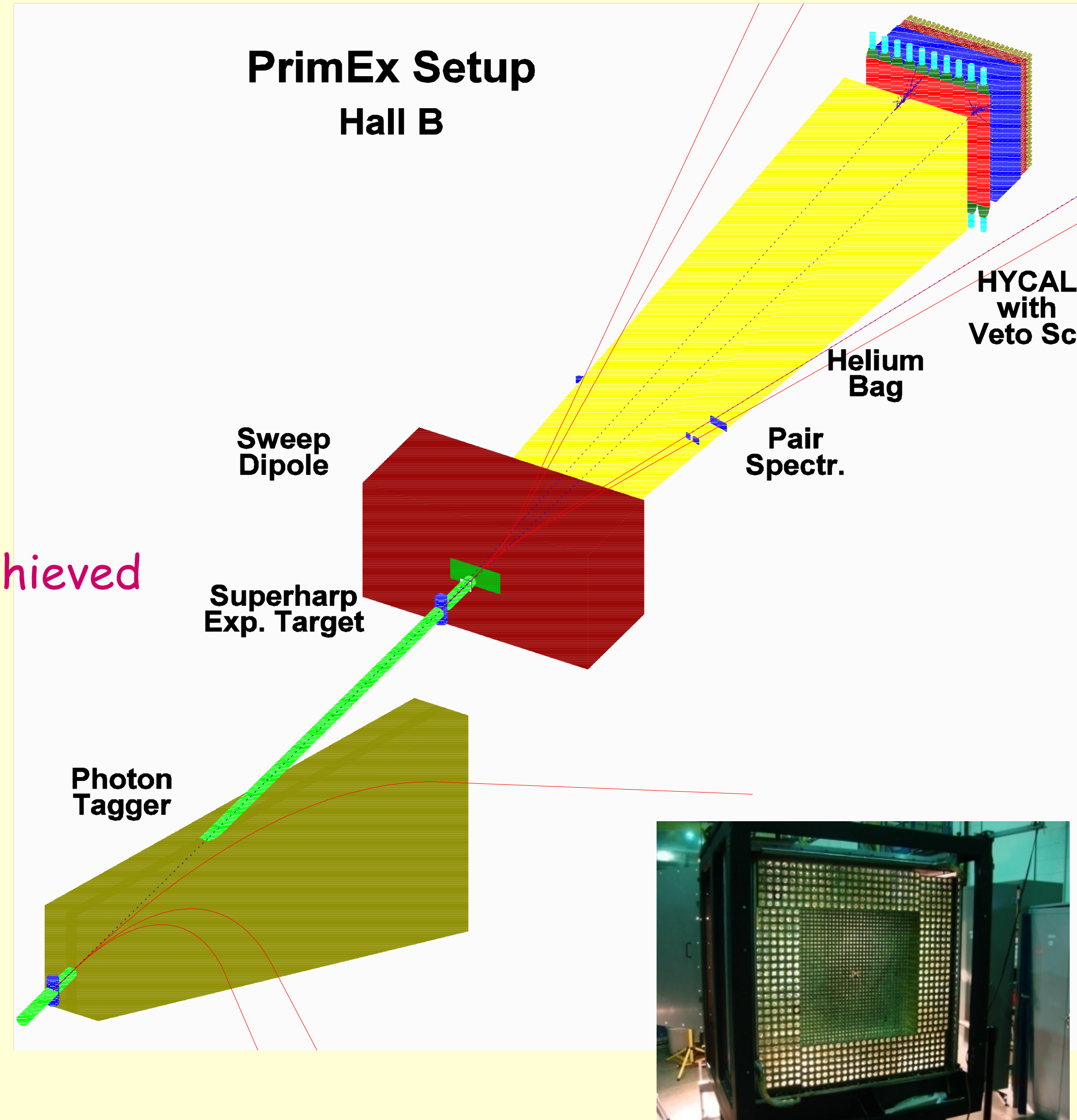
- Beam energy sensitive:

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

- Coherent process

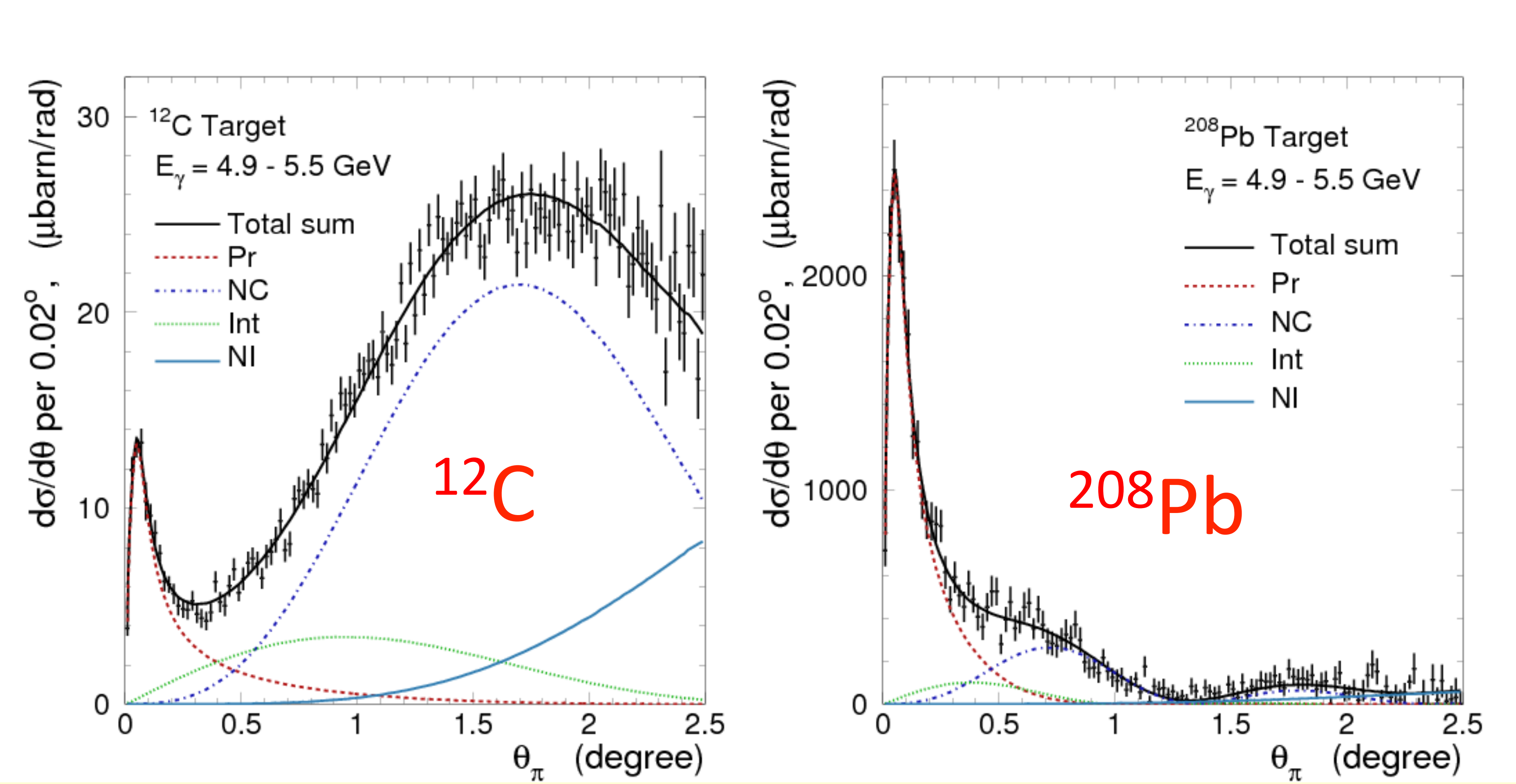
PrimEx Experimental Setup

- JLab Hall B high resolution, high intensity photon tagging facility
- New pair spectrometer for photon flux control at high beam intensities
  ➡ 1% accuracy has been achieved
- New high resolution hybrid multi-channel calorimeter (HyCal)

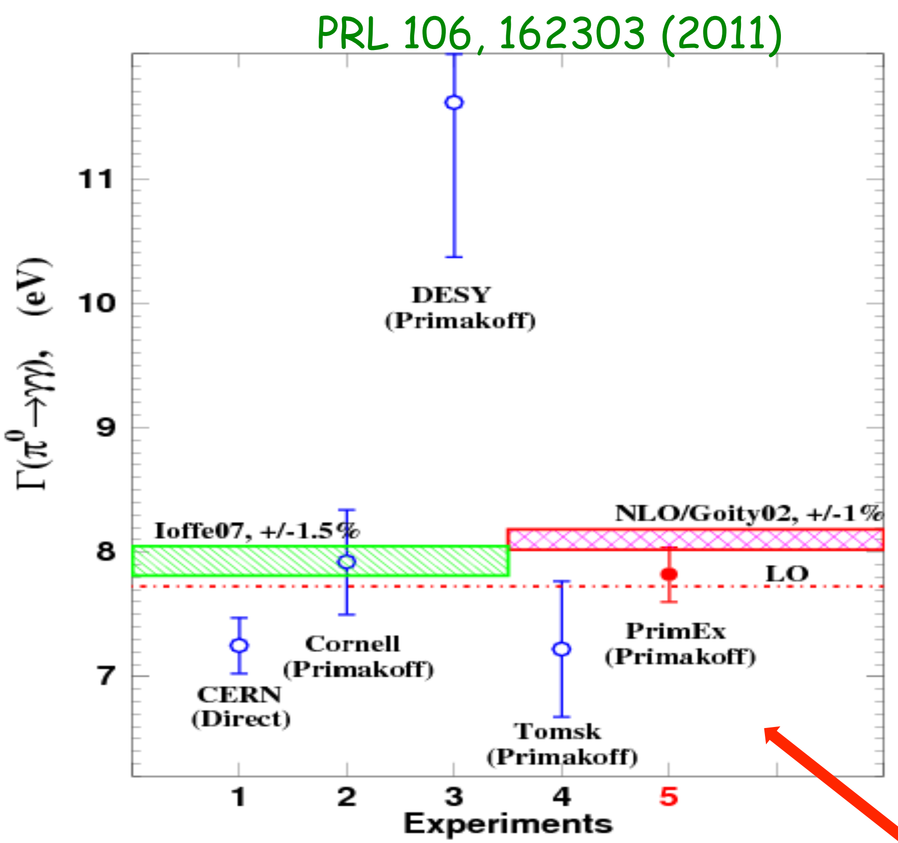


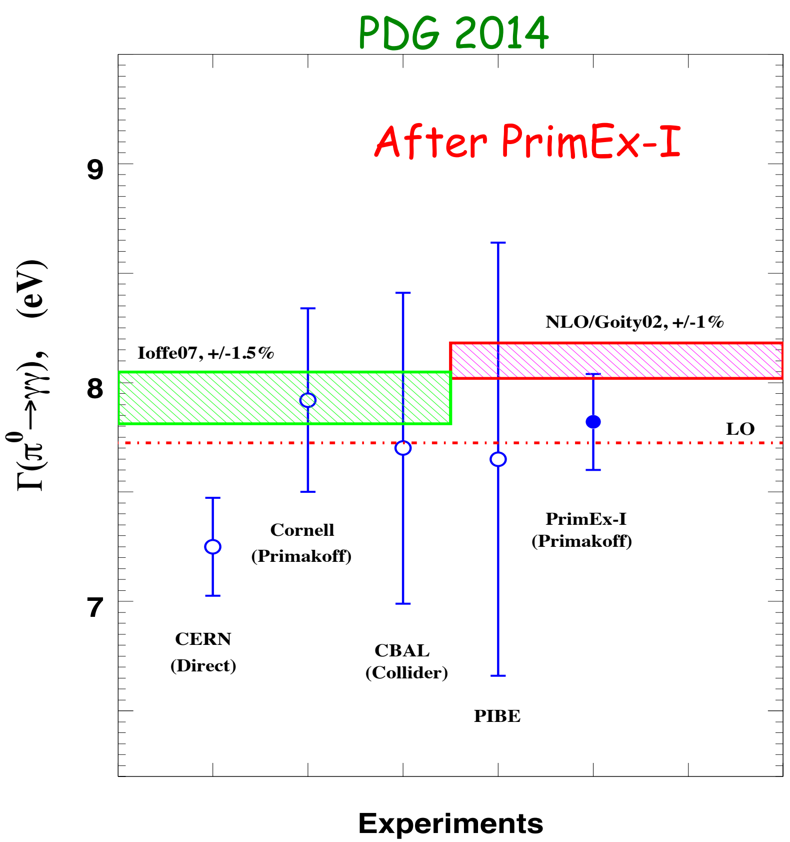
The first experiment: PrimEx-I (2004)

Theoretical angular distributions smeared with experimental resolutions are fit to the data on two nuclear targets to extract $\Gamma(\pi^0 \rightarrow \gamma\gamma)$



PrimEx-I Result

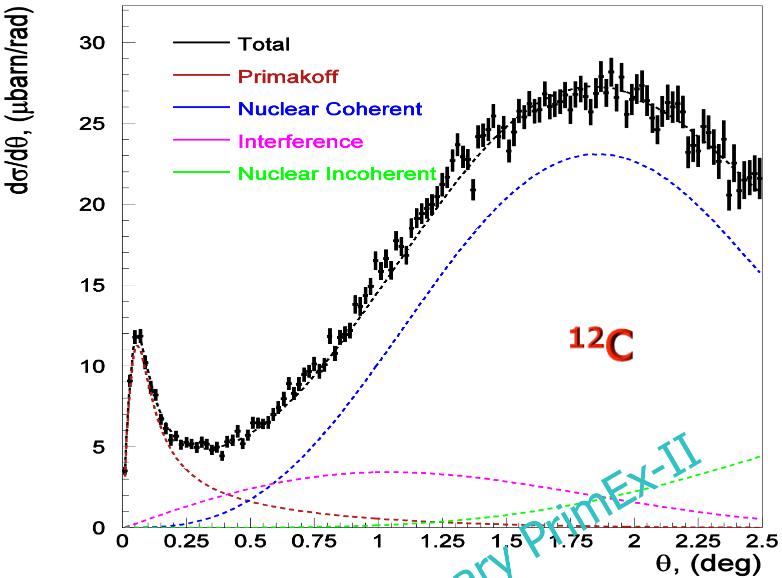


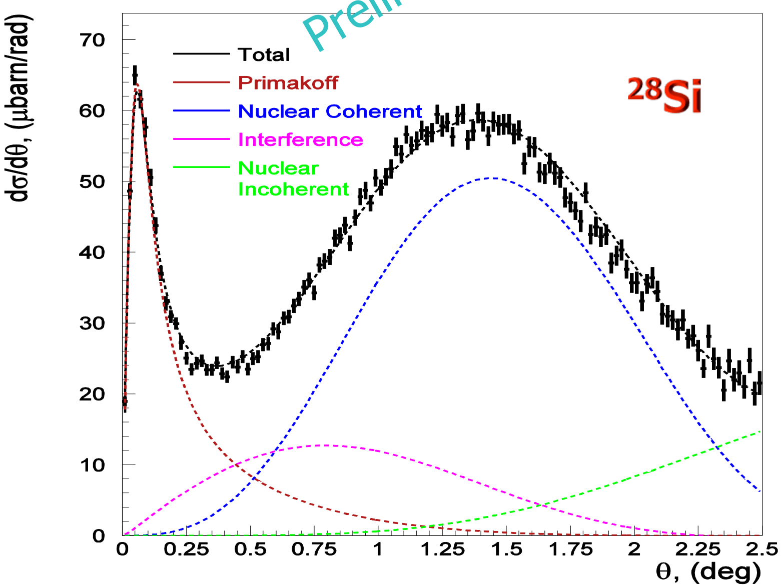


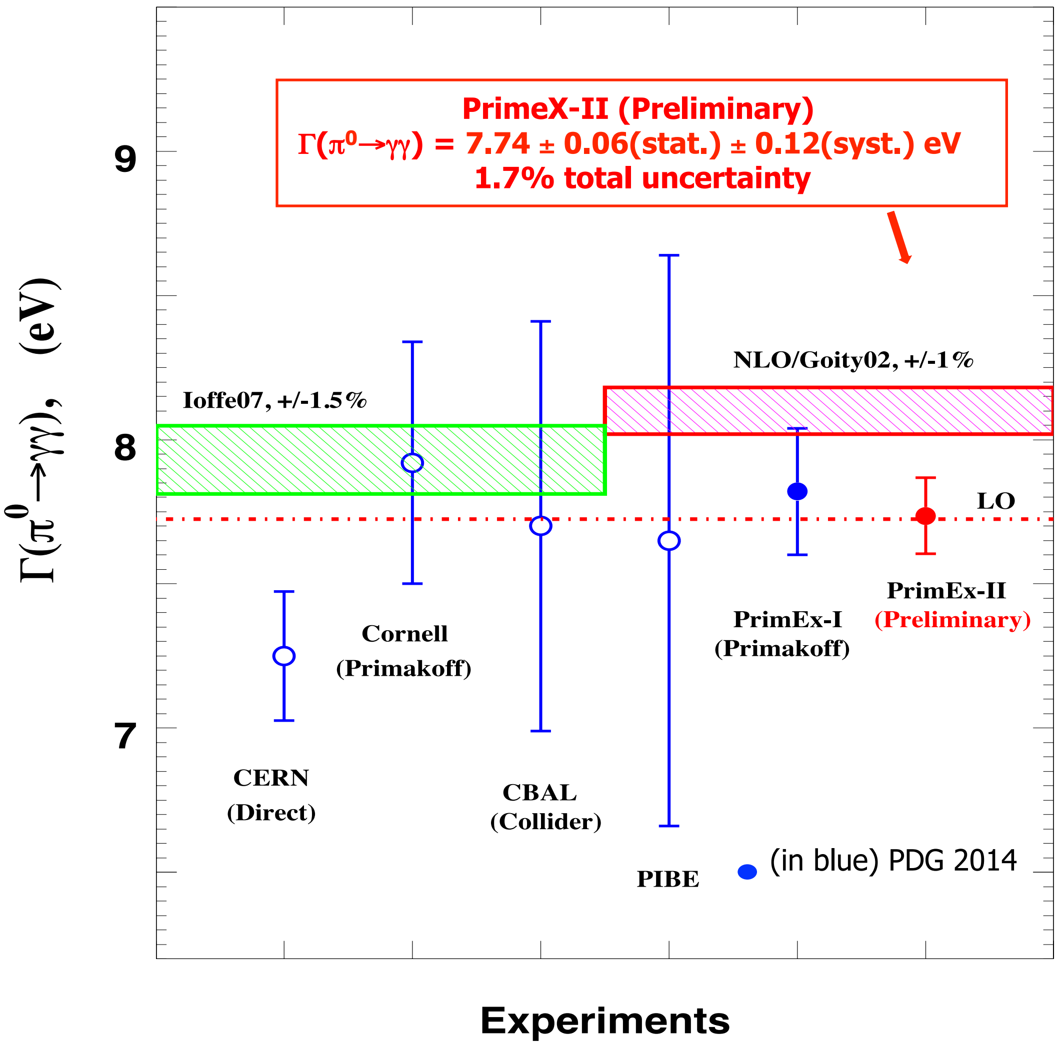
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty

PrimEx-I improved the precision of PDG average by more than a factor of 2

The second experiment: PrimEx-II

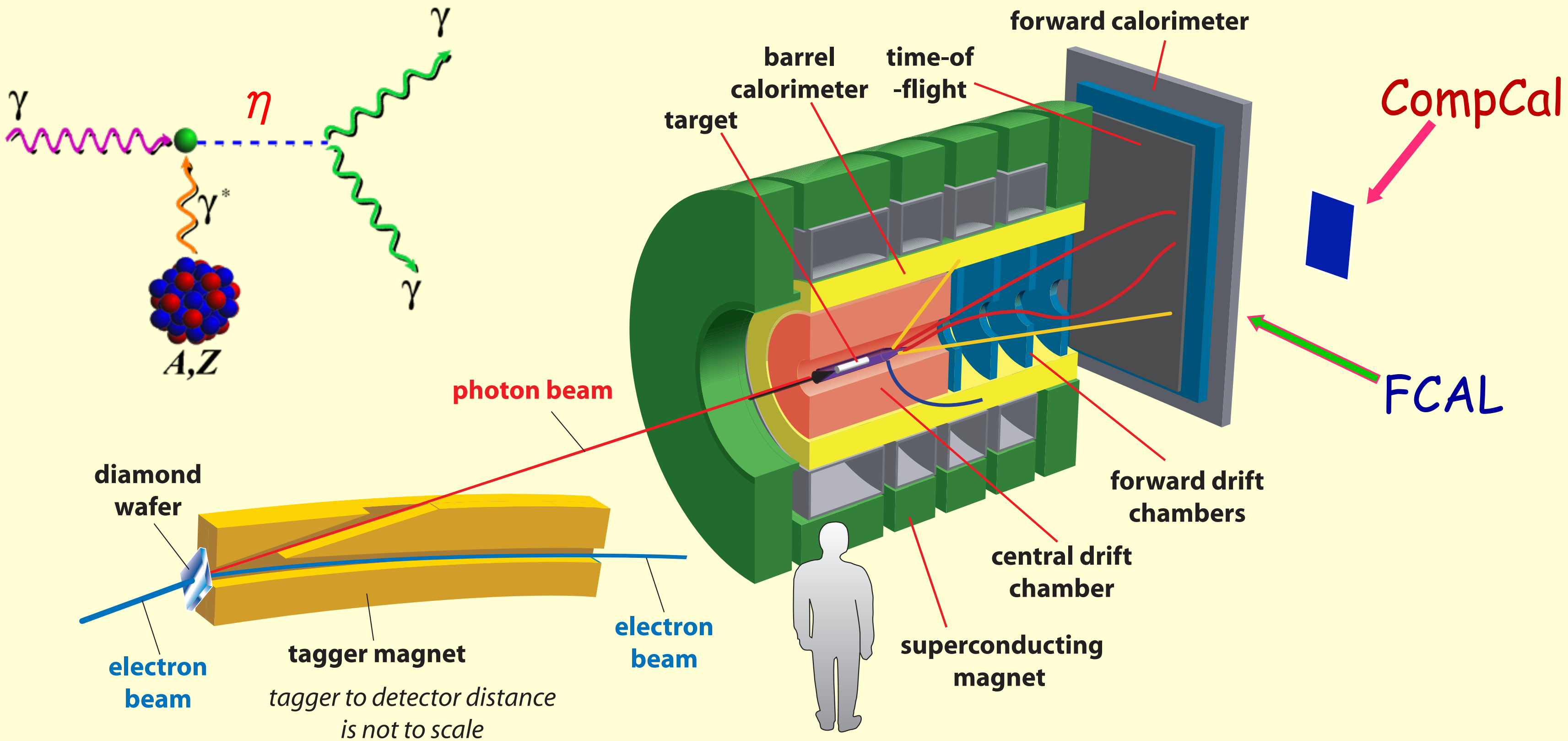






Details will be given by A. Gasparian
in Parallel Session 6 - Goldstone Boson

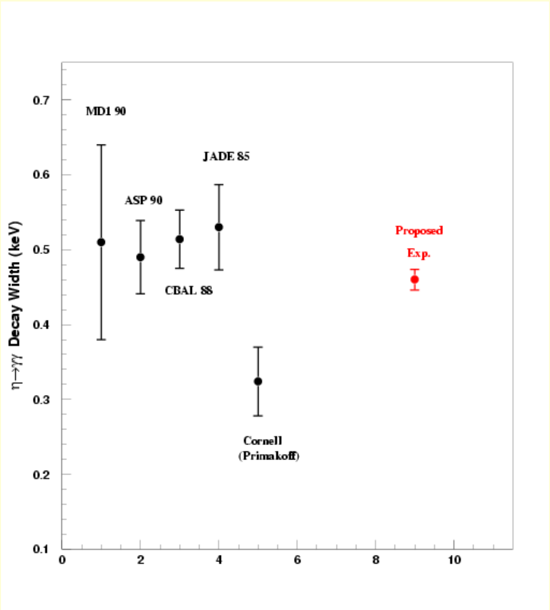
Measurement of $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D at 12 GeV



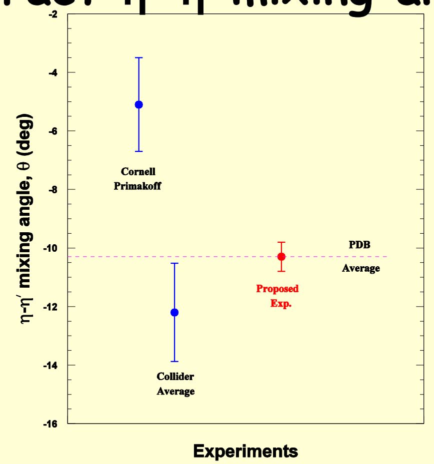
- Incoherent tagged photon beam (~10.5-11.5 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- 30 cm liquid Hydrogen and ^{4}He targets (~3.6% r.l.)
- Forward Calorimeter (FCAL) for $\eta\rightarrow\gamma\gamma$ decay photons
- CompCal and FCAL to measure well-known Compton scattering for control of overall systematic uncertainties.
- Solenoid detectors and forward tracking detectors (for background rejection)

Γ(η→γγ) Experiment @ 12 GeV

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

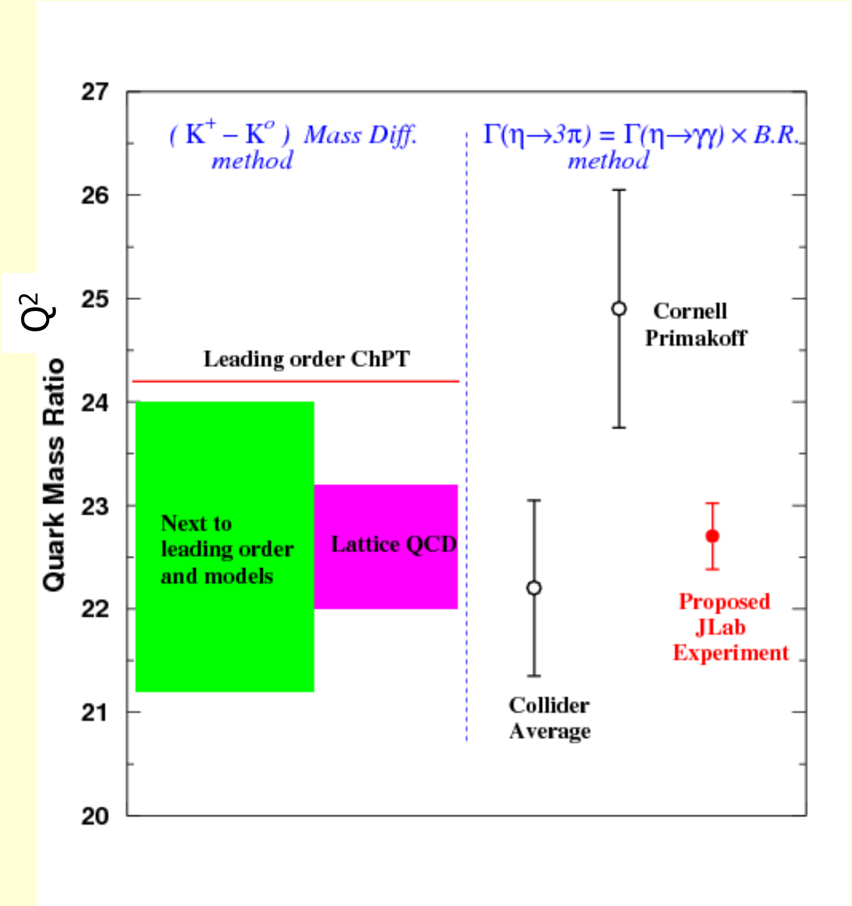


2. Extract η-η' mixing angle:



3. Determine Light quark mass ratio:

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



H. Leutwyler Phys. Lett., B378, 313 (1996)

Challenges in the η→γγ Primakoff experiment

Compared to π^0:

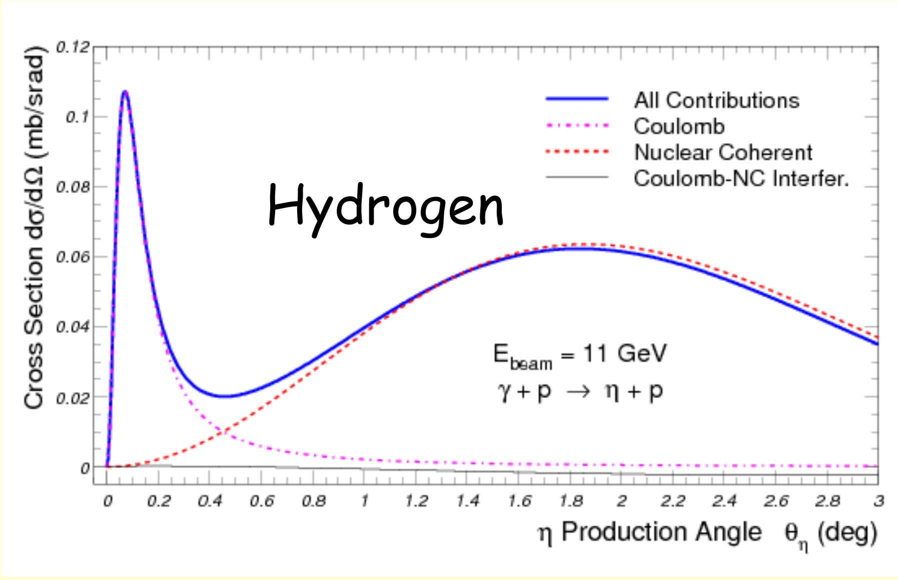
- η mass is a factor of 4 larger than π^0 and has a smaller cross section

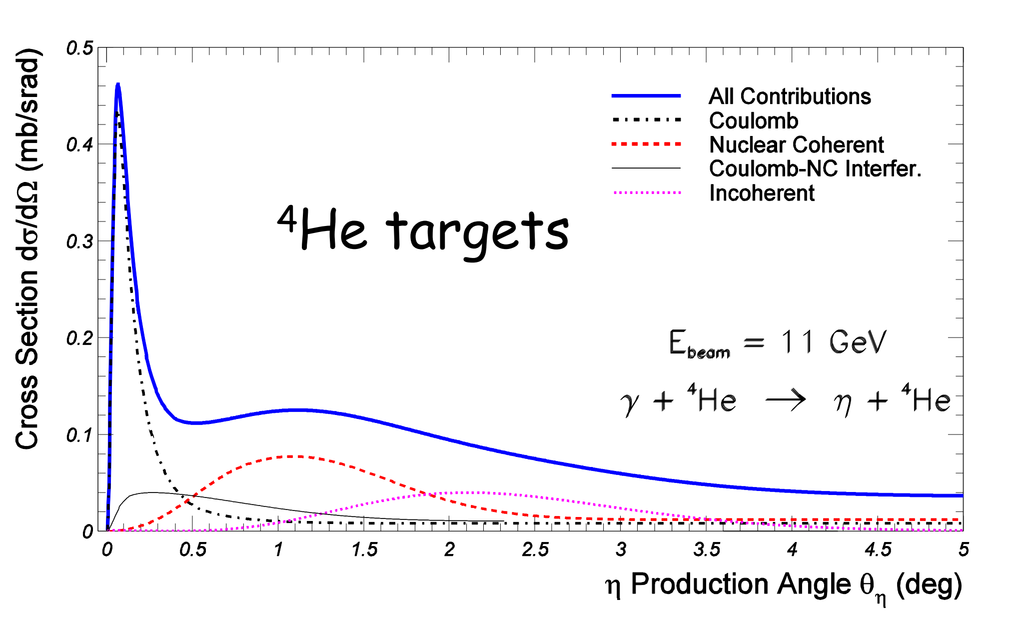
$$\left(\frac{d\sigma_{\mathrm{Pr}}}{d\Omega}\right)_{\mathrm{peak}} \propto \frac{E^4}{m^3}$$

- larger overlap between Primakoff and hadronic processes;

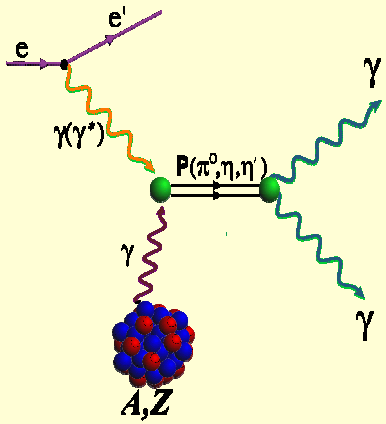
$$\langle\theta_{\mathrm{Pr}}\rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \theta_{NC} \propto \frac{2}{E \bullet A^{1/3}}$$

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

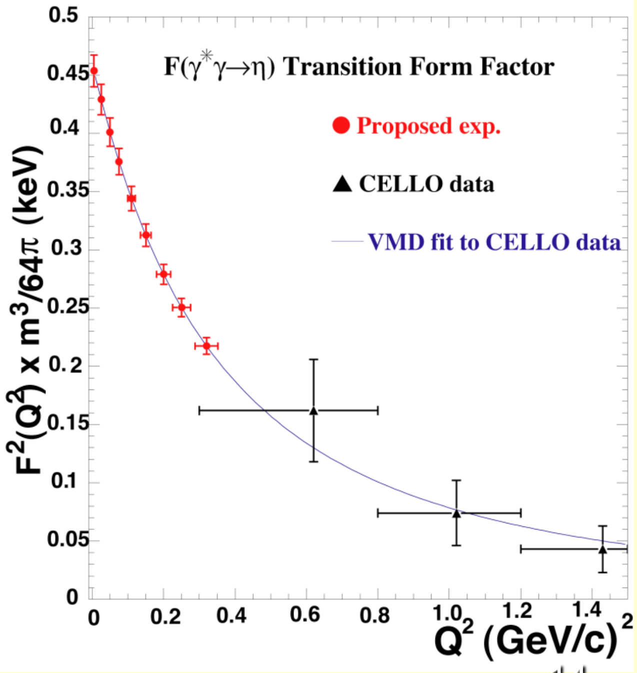




Transition Form Factors $F(\gamma\gamma^* \rightarrow p)$
(at Low Q^2)

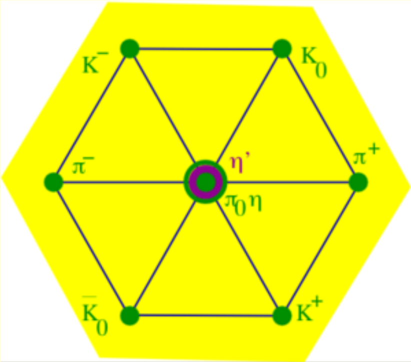


- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^* P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian
- Input for light-by-light scattering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



η is a unique probe for fundamental symmetries

- The most massive member in the octet of pseudoscalar Goldstone mesons (547.9 MeV/c2)
  ➡ Many open decay channels
  ➡ Sensitive to symmetry breakings



- η decay width Γ_η =1.3KeV is narrow (relative to Γ_ω=8.5 MeV)
  ➡ The lowest orders of η decays are filtered out, enhancing the contributions from higher orders (by a factor of ~7000 compared to ω decays).

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  ➡ Study violations of discrete symmetries

- The η decays are flavor-conserving reactions effectively free of SM backgrounds for new physics search.

Overview of the JEF project

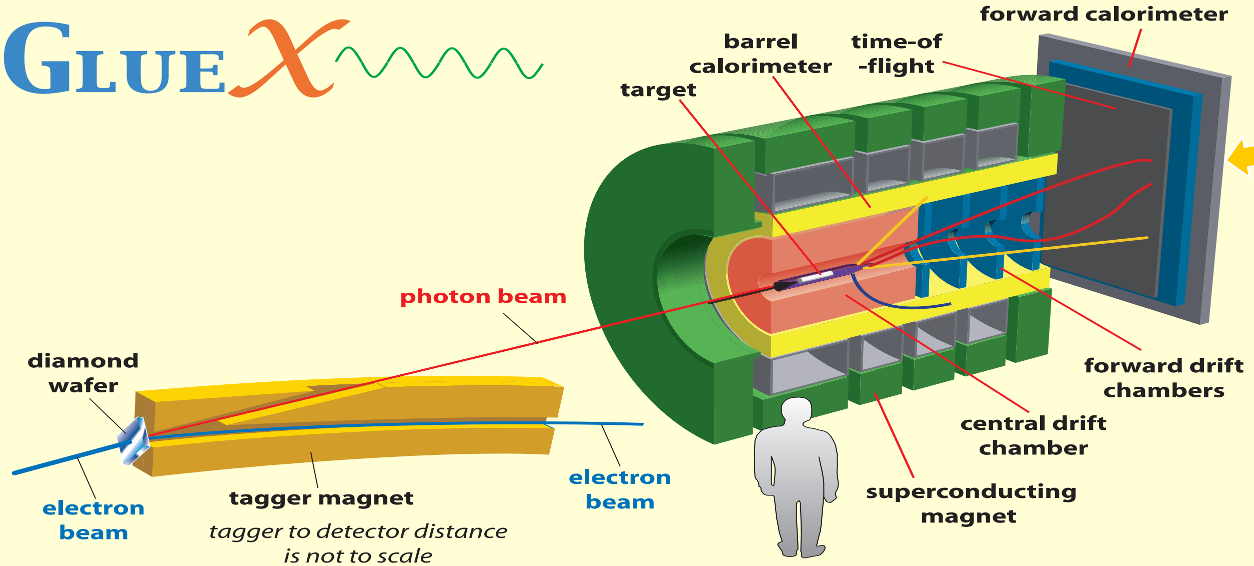
Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$\gamma + B$	beyond SM	leptophobic dark boson	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	CV, CPV	3
ancillary:			
4γ	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[112]	4
$2\pi^0$	$< 3.5 \times 10^{-4}$	CPV, PV	4
$2\pi^0\gamma$	$< 5 \times 10^{-4}$	CV, CPV	5
$3\pi^0\gamma$	$< 6 \times 10^{-5}$	CV, CPV	6
$4\pi^0$	$< 6.9 \times 10^{-7}$	CPV, PV	8
$\pi^0\gamma$	$< 9 \times 10^{-5}$	CV, Ang. Mom. viol.	3
normalization:			
2γ	$(39.3 \pm 0.2)\%$	anomaly, η-η' mixing PR12-10-011	2

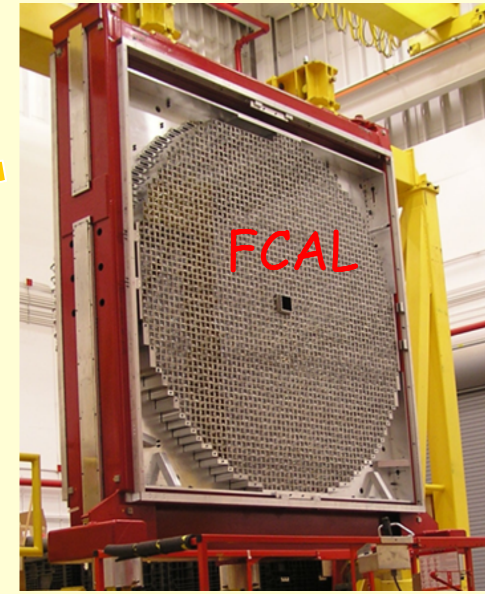
Main physics goals:

1. Determine the light quark mass ratio
2. Probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian.
3. Search for a leptophobic dark boson (B).
4. Directly constrain CVPC new physics

FCAL-II is required for the rare decays

Jlab Eta Factory (JEF) experiment





Simultaneously measure η decays: $\eta\to\pi^0\gamma\gamma$, $\eta\to3\gamma$, and …

- η produced on LH_2 target with **9-11.7 GeV tagged photon beam:**

  $\gamma+p \to \eta+p$

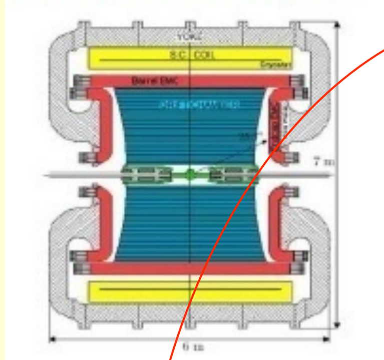
- Reduce non-coplanar backgrounds by **detecting recoil p's** with GlueX detector (ε~75%)

- Upgraded Forward Calorimeter with **High resolution, high granularity** **$PbWO_4$** insertion (**FCAL-II**) to detect multi-photons from rare η decays

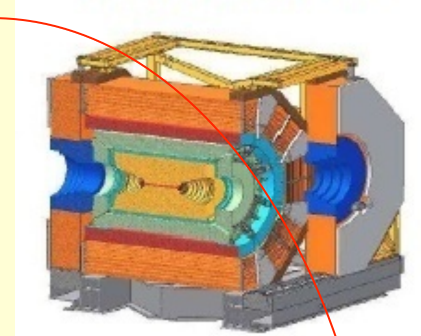
World competition in η decays

e⁺e⁻
Collider

KLOE-2 at DAφNE



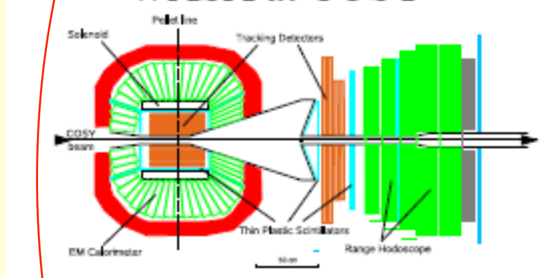
BESIII at BEPCII



Low energy η-facilities

Fixed-target

WASA at COSY

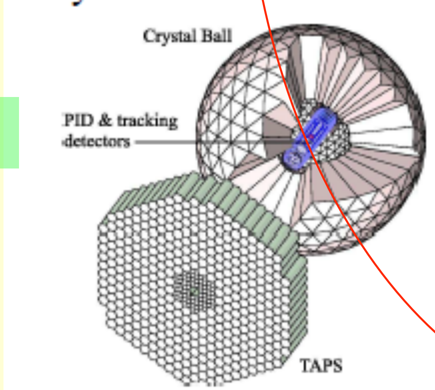


hadroproduction

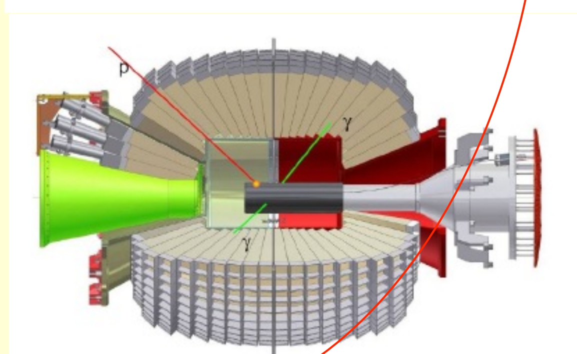
High energy η-facility

photoproduction

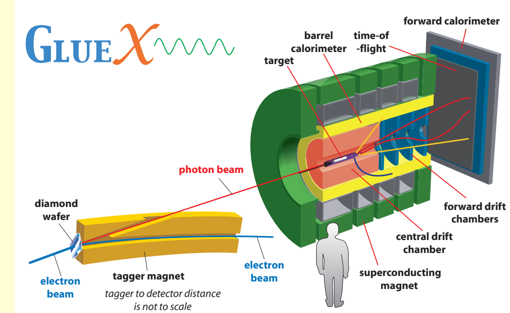
Crystall Ball at MAMI



CBELSA/TAPS at ELSA

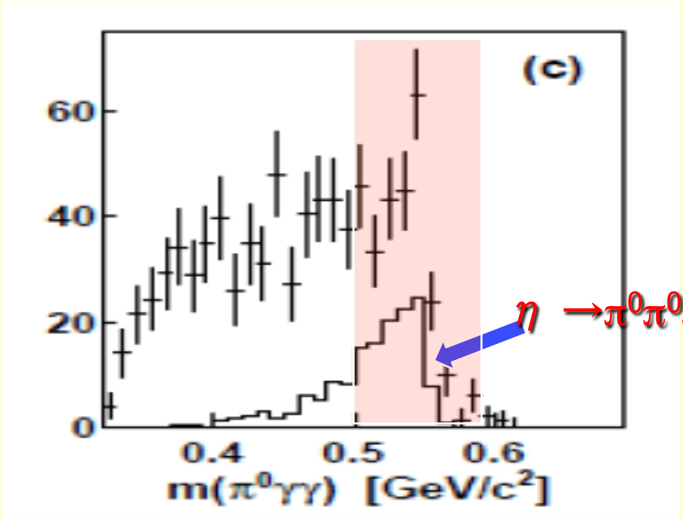


JEF at Jlab

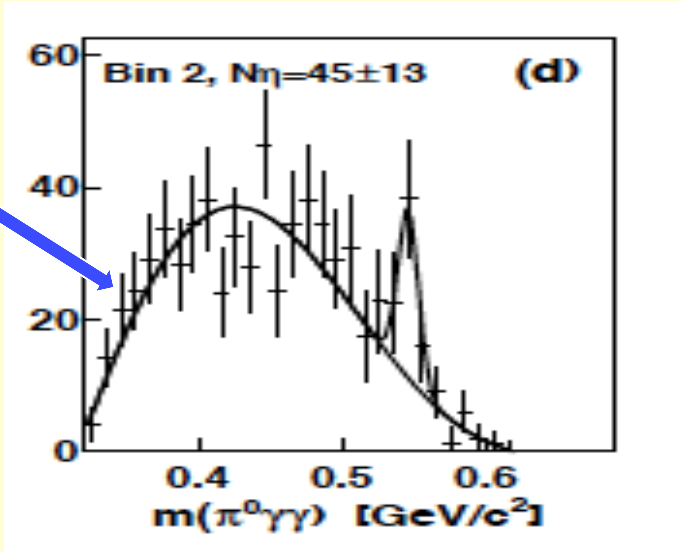


Filter Background with η Energy Boost ($\eta \to \pi^0\gamma\gamma$)

A2 at MAMI (Phys.Rev. C90 (2014) 025206): $\gamma p \to \eta p$ (E_γ=1.5 GeV)

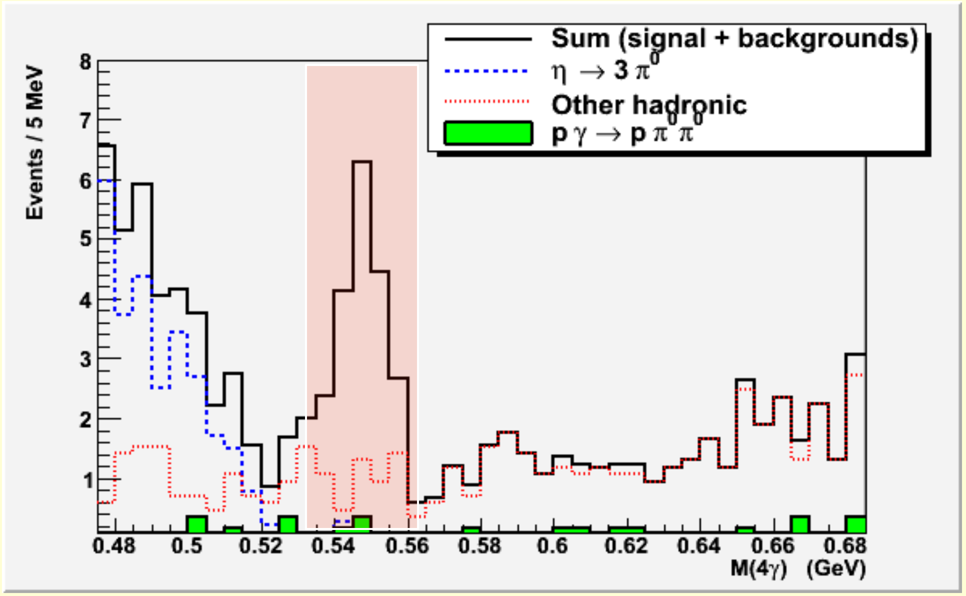


$\gamma p \to \pi^0\pi^0 + p$



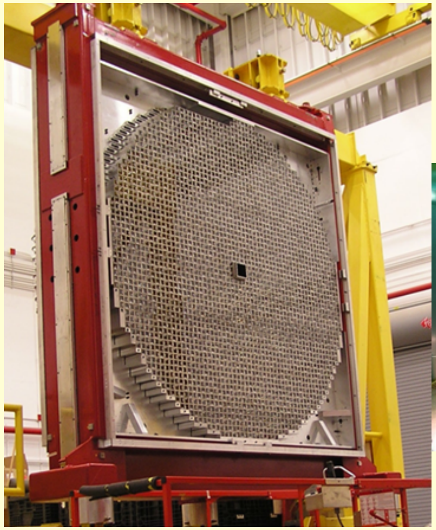
Jlab:

$\gamma p \to \eta p$ ($E\gamma$ = 9-11.7 GeV)

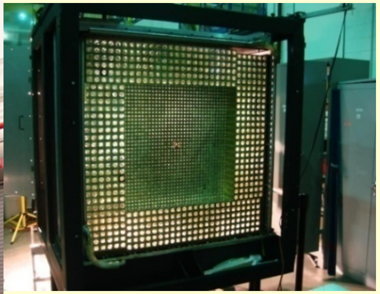


New Equipment: FCAL-II

FCAL



HyCal

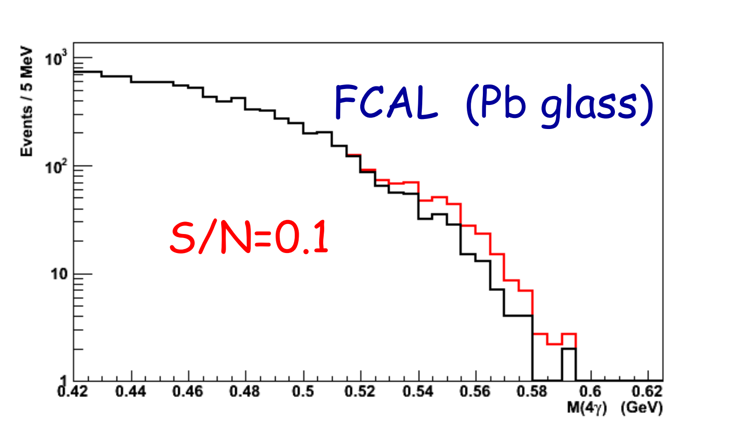


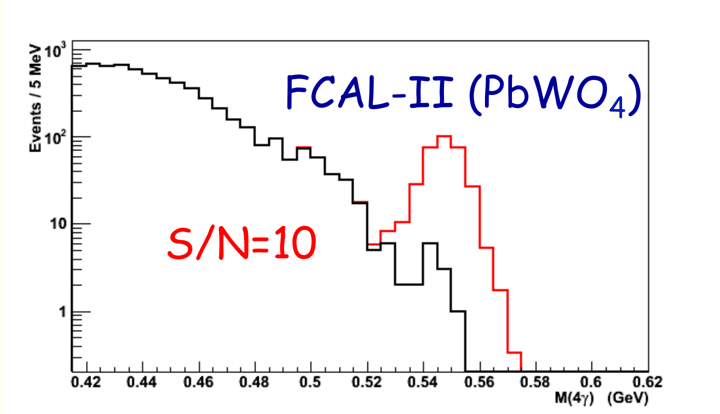
FCAL with PWO insertion:

- 118x118 cm^2 in Size (3445 $PbWO_4$)
- 2cm x 2cm x 18cm per module

S/N Ratio vs. Calorimeter Types

signal: $\eta \to \pi^0\gamma\gamma$, background: $\eta \to 3\pi^0$



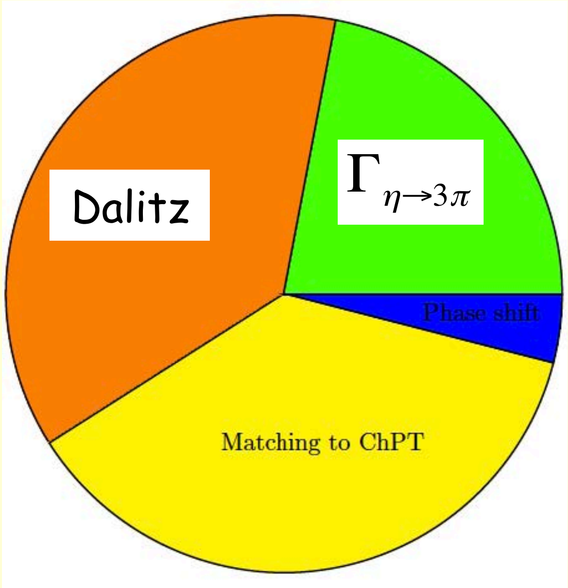


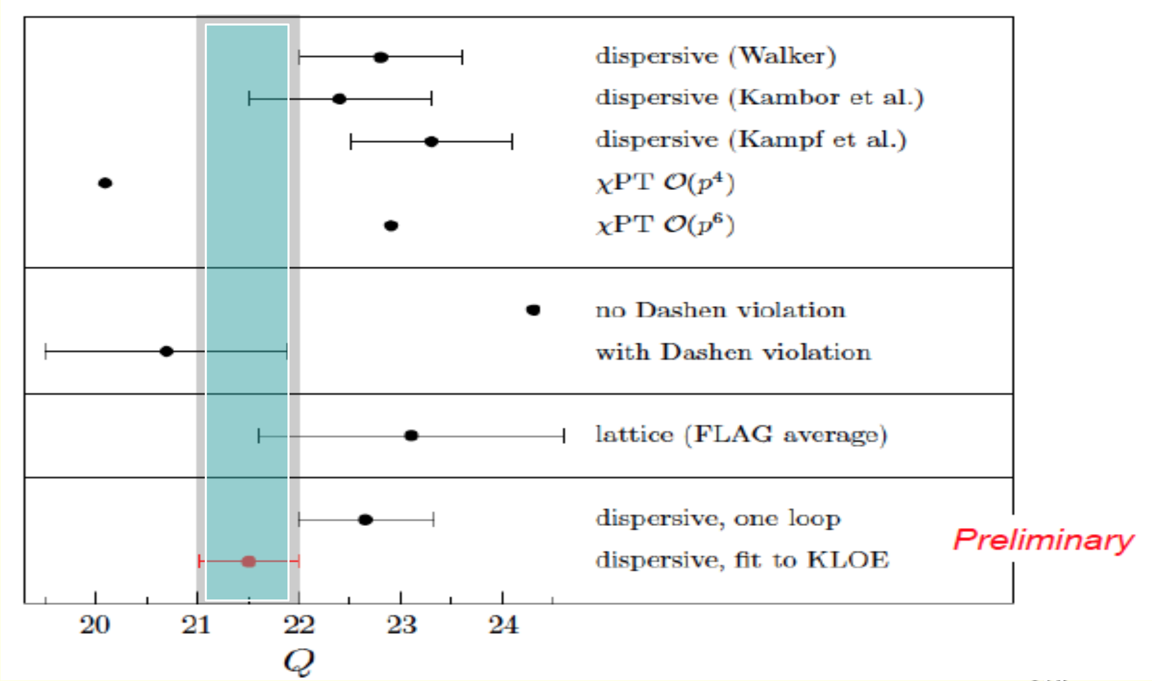
FCAL-II ($PbWO_4$) vs. FCAL (Pb glass)

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

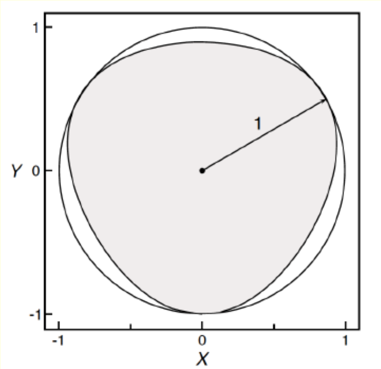
Determine Light Quark Mass Ratio via $\eta\to3\pi$

- **A clean probe for quark mass ratio:** $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$ $\hat{m} = \frac{m_u + m_d}{2}$
  - decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
  - α_{em} is small
  - Amplitude: $A(s,t,u) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{\mathcal{M}(s,t,u)}{3\sqrt{3}F_\pi^2}$,
- Uncertainties in quark mass ratio (E. Passemar, talk at AFCI workshop)





Experimental Measurements of $\eta\rightarrow3\pi$

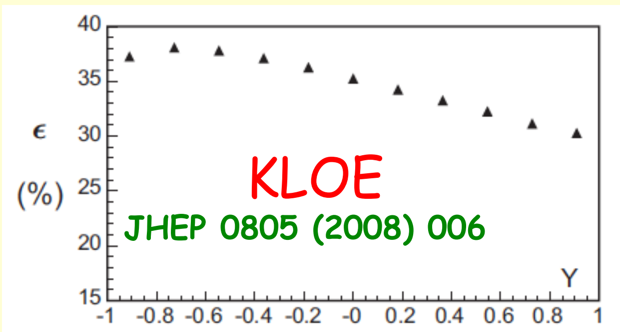


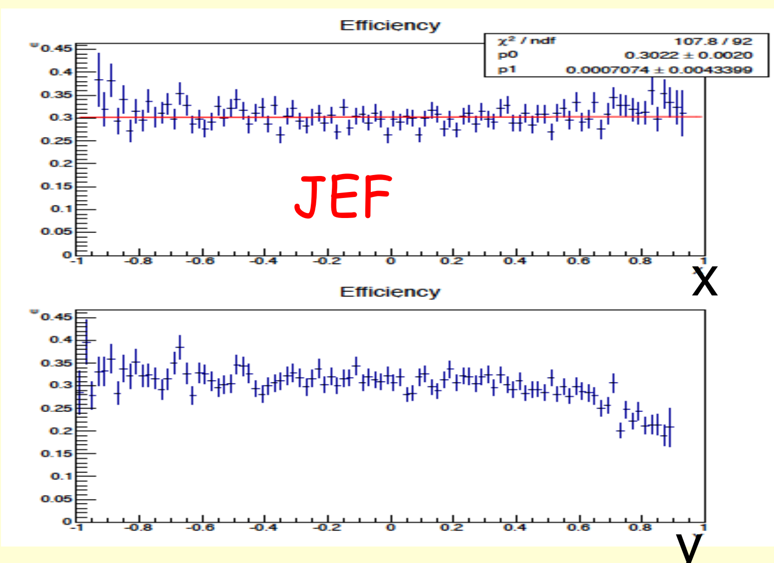
$$X = \frac{\sqrt{3}}{2M_\eta Q_c}(u-t)$$

$$Y = \frac{3}{2M_\eta Q_c}\left(\left(M_\eta - M_{\pi^0}\right)^2 - s\right) - 1$$

$$Z = X^2 + Y^2$$

$$Q_c \equiv M_\eta - 2M_{\pi^+} - M_{\pi^0}$$





Exp.	$3\pi^0$ Events (10^6)	$\pi^+\pi^-\pi^0$ Events (10^6)
Total world data (include prel. WASA and prel. KLOE)	6.5	6.0
GlueX+PrimEx-η +JEF	20	19.6

- Existing data from the low energy facilities are sensitive to the detection threshold effects
- JEF at high energy has uniform detection efficiency over Dalitz phase space
- JEF will offer large statistics and improved systematics

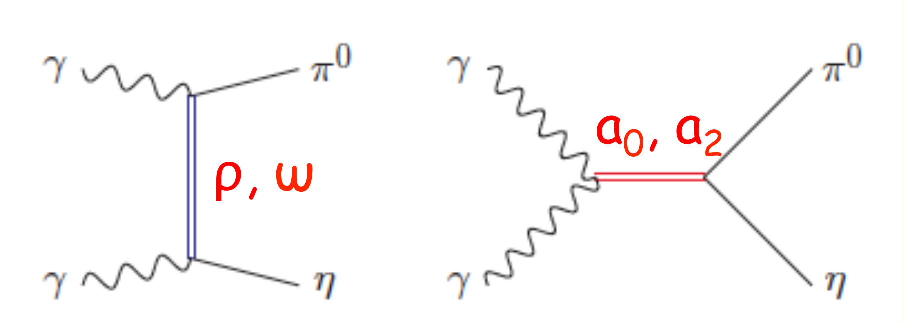
SM allowed $\eta\to\pi^0\gamma\gamma$

➡ A rare window to probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian
(J. Bijnens, talk at AFCI workshop)

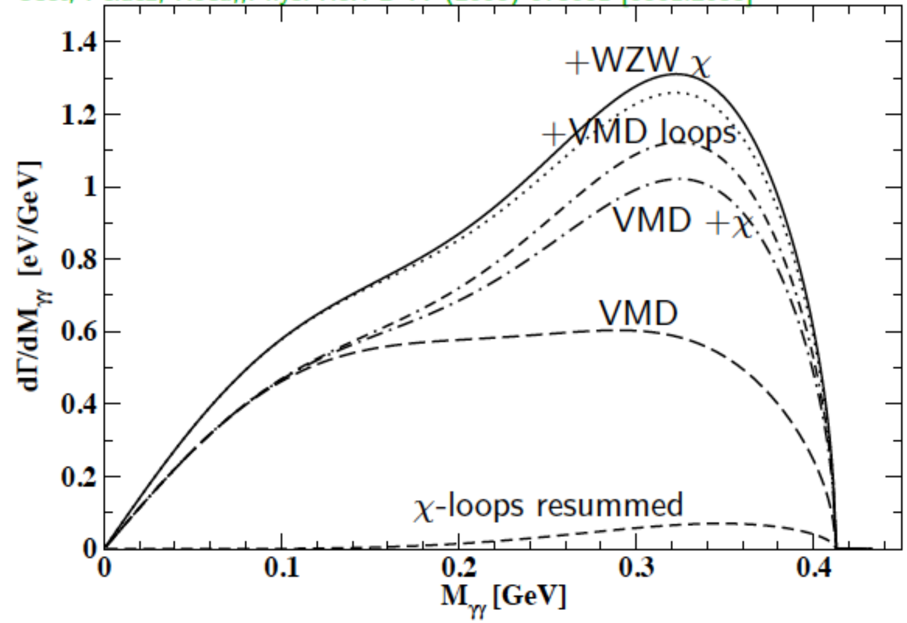
◆ The major contributions to $\eta\to\pi^0\gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian ➡ an unique probe for the high order ChPT.
L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

◆ Shape of Dalitz distribution is sensitive to the role of scalar resonances.

LEC's are dominated by meson resonances
Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael 1989; Donoghue, Ramirez, Valencia 1989

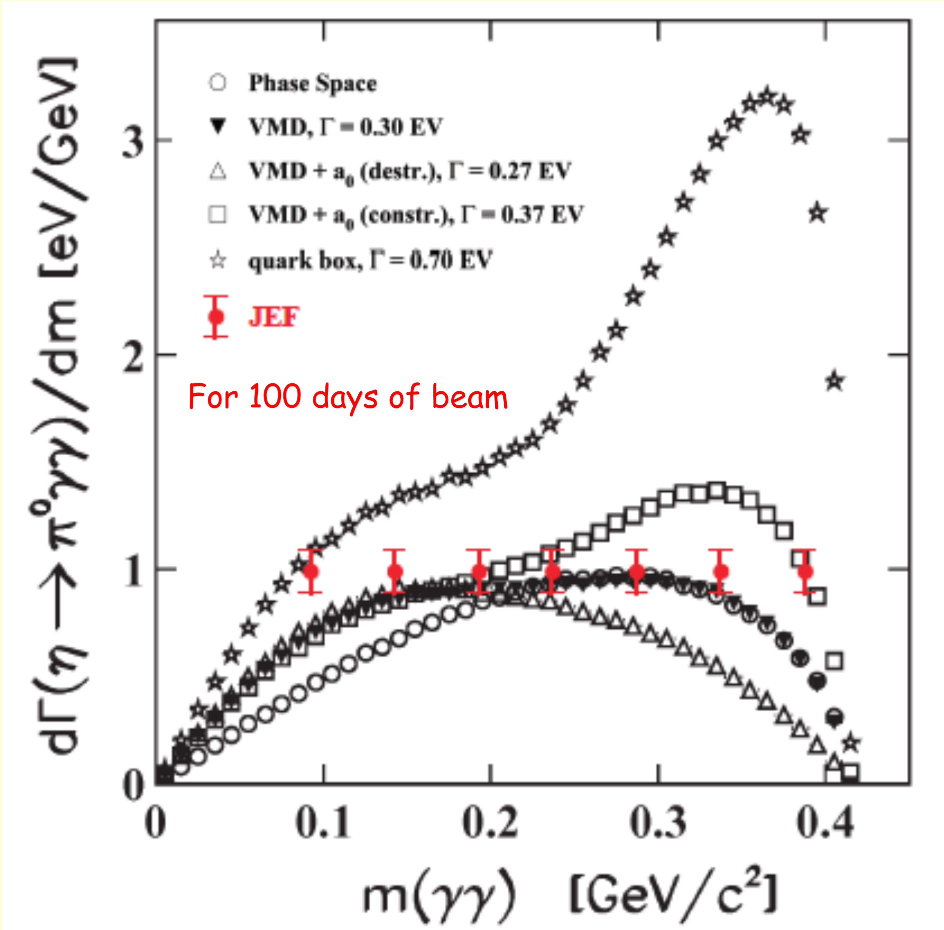


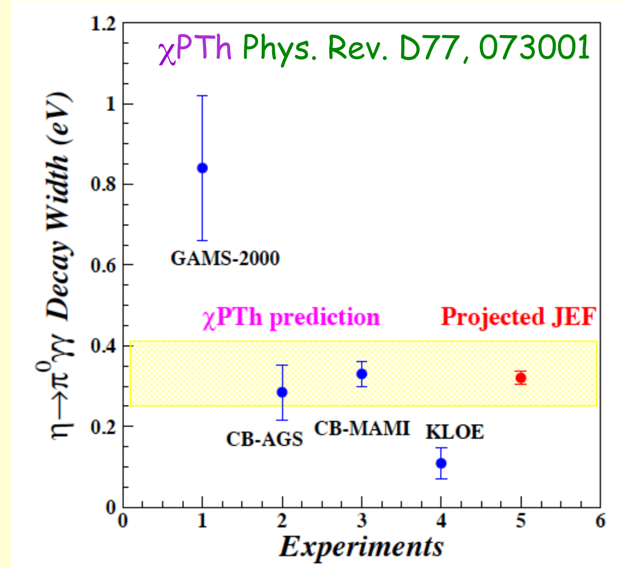
Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]

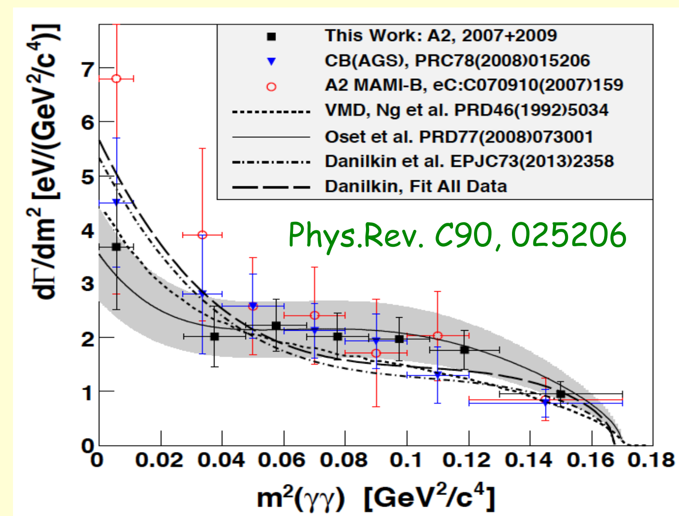


Projected JEF results on $\eta \to \pi^0\gamma\gamma$

J.N. Ng and D.J. Peters, Phys. Rev. D47, 4939





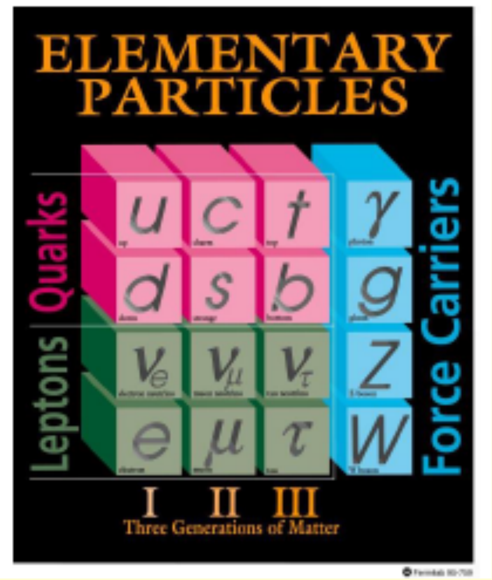


We measure both BR and Dalitz distribution

- model-independent determination of two LEC's of the $O(p^6)$ counter- terms
- probe the role of scalar resonances to calculate other unknown $O(p^6)$ LEC's

J. Bijnens, talk at AFCI workshop

Search for Dark Forces

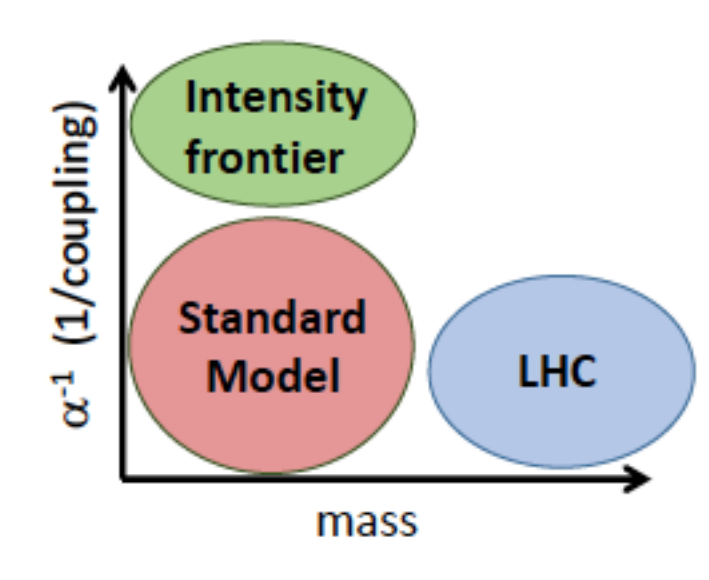


SM based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. Are there any additional gauge symmetries? Look for new gauge bosons.

Motivations:

1. **Grand unified theories:** Generically have additional gauge bosons, but typically very heavy (10^{16} GeV).
2. **Dark matter:** Stability of dark matter related to new gauge symmetry?

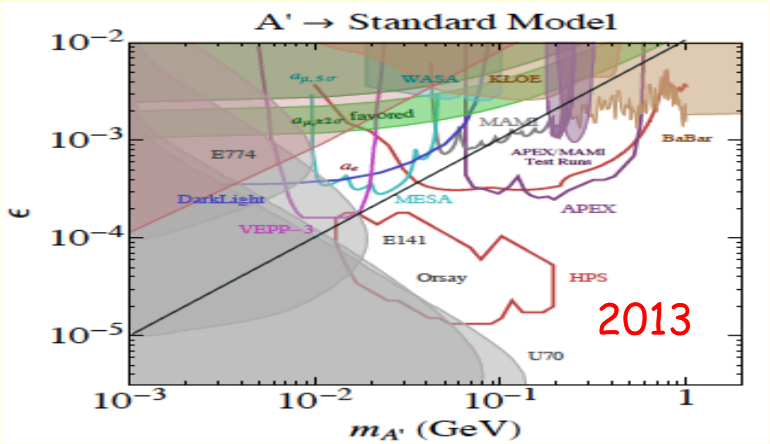
   Can also give the right relic density.

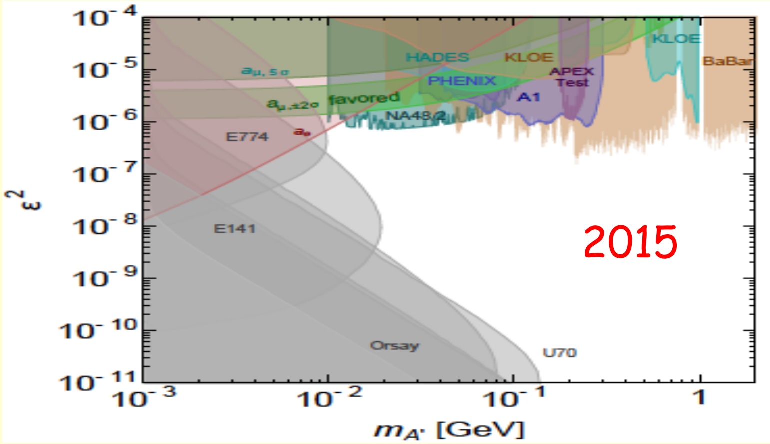


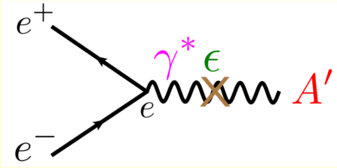
"Vector Portal" to Dark Sector

1. Dark photon A'

$-\frac{1}{2}\varepsilon F^{\mu\nu}F'_{\mu\nu}$ Kinetic mixing and U(1)'







Most A' searches look for $A' \to l^+ l^-$, relying on the leptonic coupling of new force

2. Dark leptophobic B-boson (dark ω, γ_B , or Z'):

$$\frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu$$

Gauged baryon symmetry $U(1)_B$

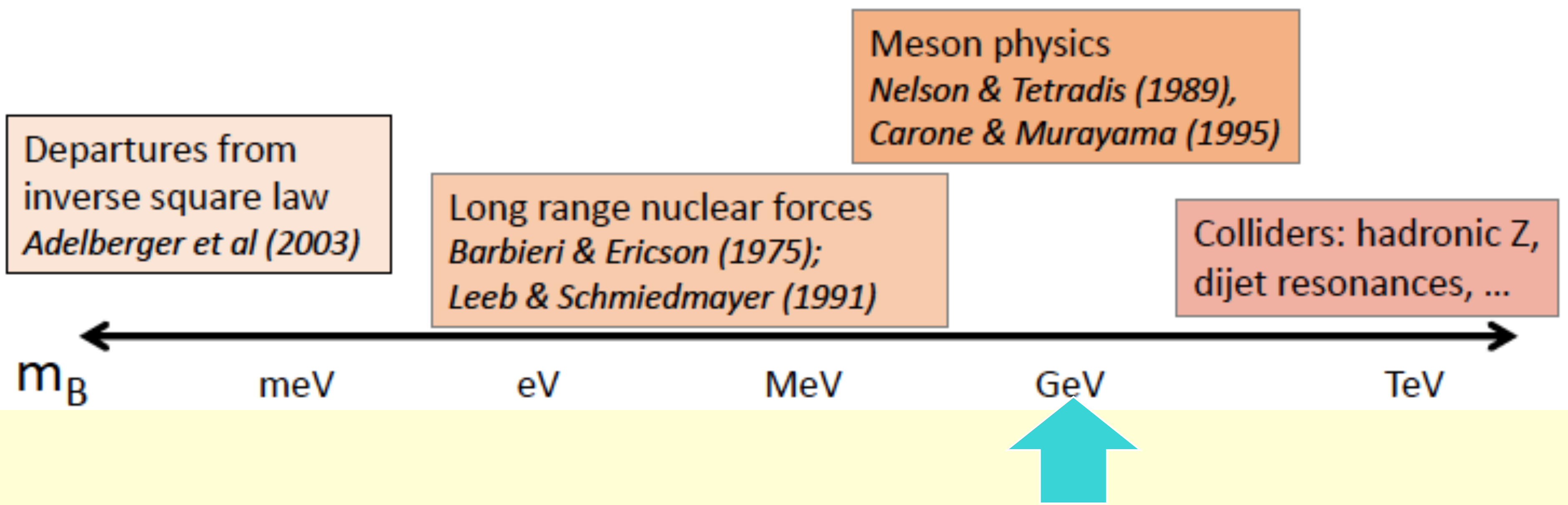
T.D. Lee and C.N. Yang, Phys.Rev.,98, 1501 (1955)

- the stability of baryonic and dark matter
- a unified genesis of baryonic and dark matter M.Graesser, I. Shoemaker and L. Vecchi, arXiv:1107.2666
- a natural framework for resolving "Strong CP problem" in QCD

Experimental probes for B-boson

Discovery signals depend on the B mass:

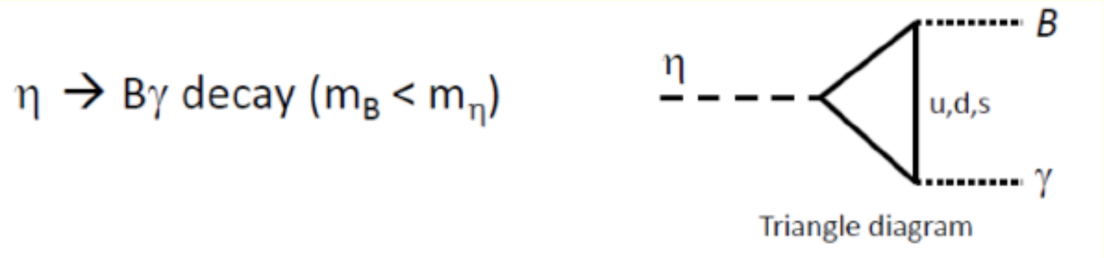
- the $m_B < m_\pi$ region is strongly constrained by long-range forces search and nuclear scattering experiments.
- the $m_B > 50 GeV$ region has been investigated by the collider experiments.
- GeV-scale domain is nearly untouched.



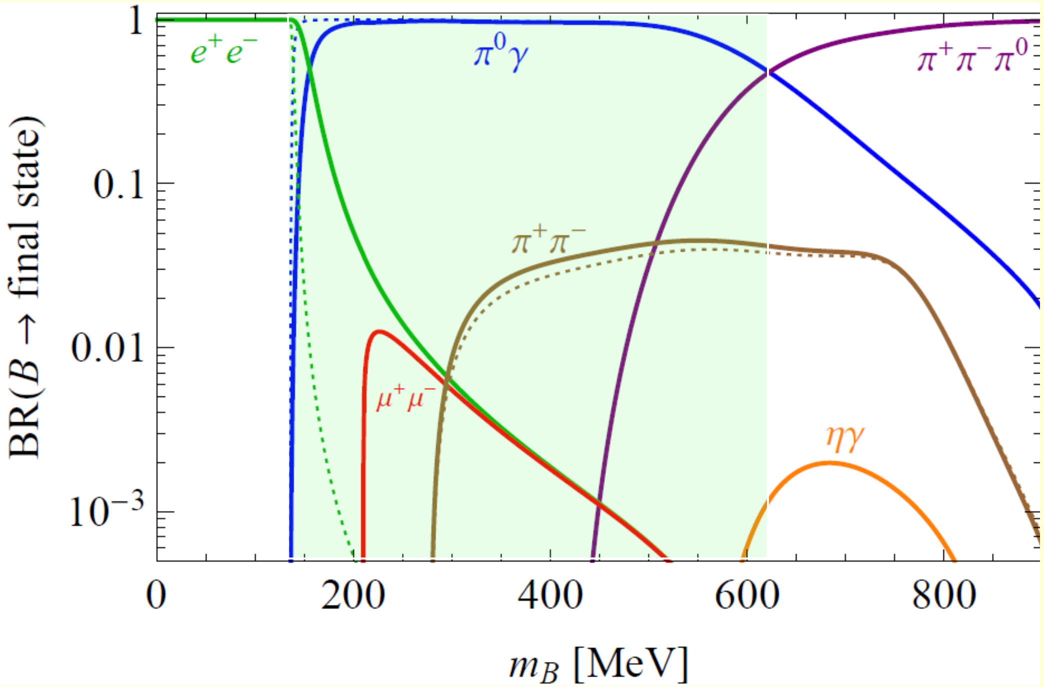
a discovery opportunity hiding in nonperturbative QCD regime!

Striking signature for B-boson in $\eta \to \pi^0\gamma\gamma$

- B production: A.E. Nelson, N. Tetradis, Phys. Lett., B221, 80 (1989)



- B decays: $B \to \pi^0\gamma$ in 140-620 MeV mass range



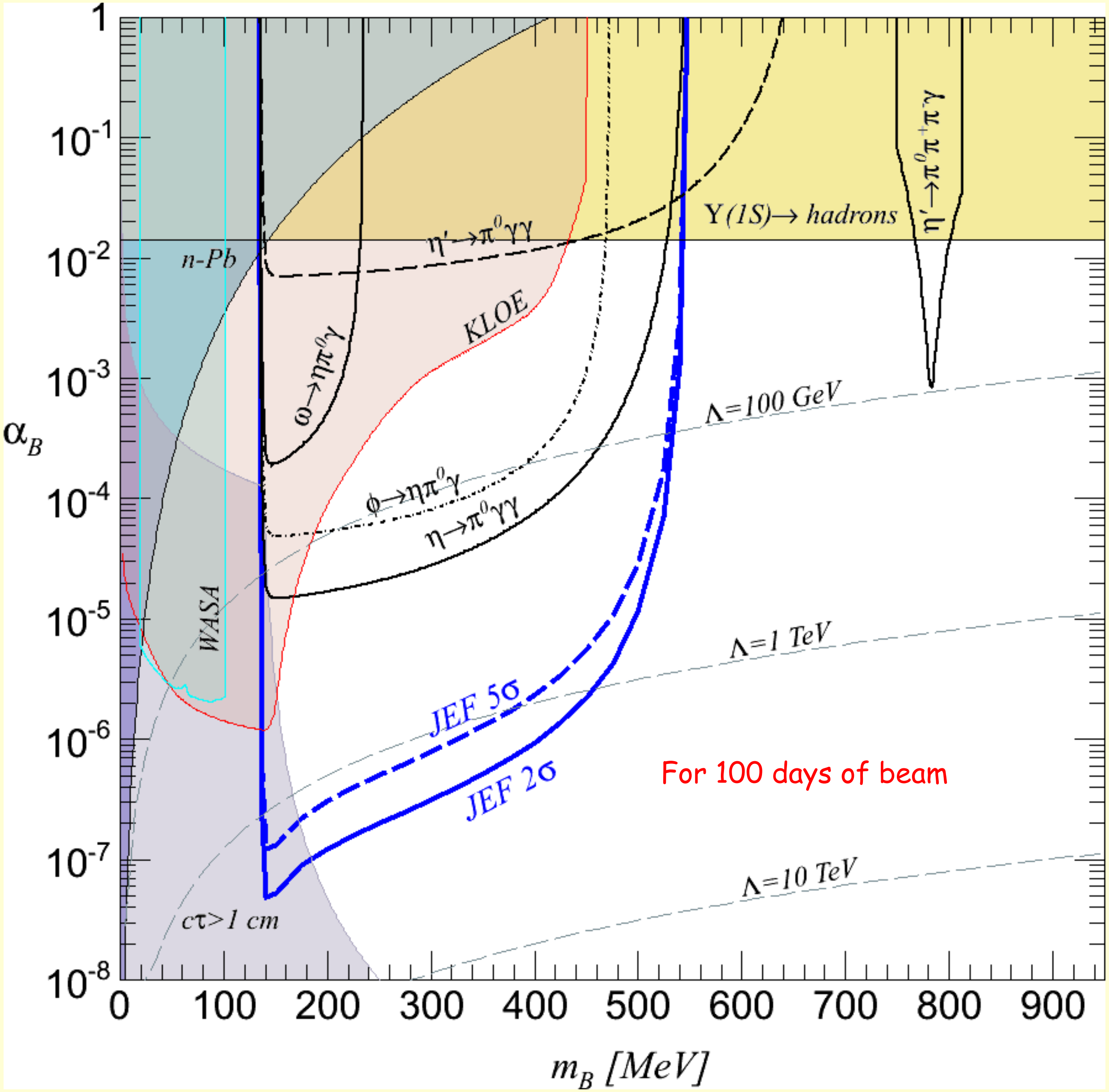
$\eta \to \gamma B \to \gamma + \pi^0\gamma$

Search for a resonance peak of $\pi^0\gamma$ for m_B ~140-550 MeV

S. Tulin, Phys.Rev., D89, 14008 (2014)

- $\Gamma(\eta \to \pi^0\gamma\gamma) \sim 0.3eV$ ⟶ highly suppressed SM background

JEF Experimental Reach ($\eta \to B\gamma \to \pi^0\gamma\gamma$)



- A stringent constraint on the leptophobic B-boson in 140-550 MeV range.
- A positive signal of B in JEF will **imply a new fermion with a mass up to a few TeV due to electro-weak anomaly cancellation.**
- Future η' experiment will extend the experimental reach up to 1 GeV

Constraints from A' search (KLOE and WASA) assumed:

$$\varepsilon \sim 0.1 \times e g_B / (4\pi)^2$$

The Four Classes of C, P, and T Violations Assuming CPT Invariance

B. Nefkens and J. Price, Phys. Scrip., T99, 114 (2002)

Class	Violated	Valid
1	C, P, CT, PT	T, CP
2	C, P, T, CP, CT, PT	
3	P, T, CP, CT	C, PT
4	C, T, CP, PT	P, CT

Experimental tests

P-violating exp.,
β-decays,
K-, B-, D-meson decays

EDM, $\eta \rightarrow$ even π's

17 C-tests involving η, η', π, ω, J/ψ decays

For class 4:

- a few tests available
- not well tested experimentally in EM and strong interactions
- less constrained by nEDM and parity-violating experiments.
- offer a golden opportunity for new physics search.

C Invariance

- Maximally violated in the weak force and is well tested.
- Assumed in SM for electromagnetic and strong forces, but **it is not experimentally well tested (The current constraint: $\Lambda \geq 1$ GeV)**
- EDMs place no constraint on CVPC in the presence of a conspiracy or new symmetry; **only the direct searches are unambiguous**.

(M. Ramsey-Musolf, phys. Rev., D63, 076007 (2001); talk at the AFCI workshop)

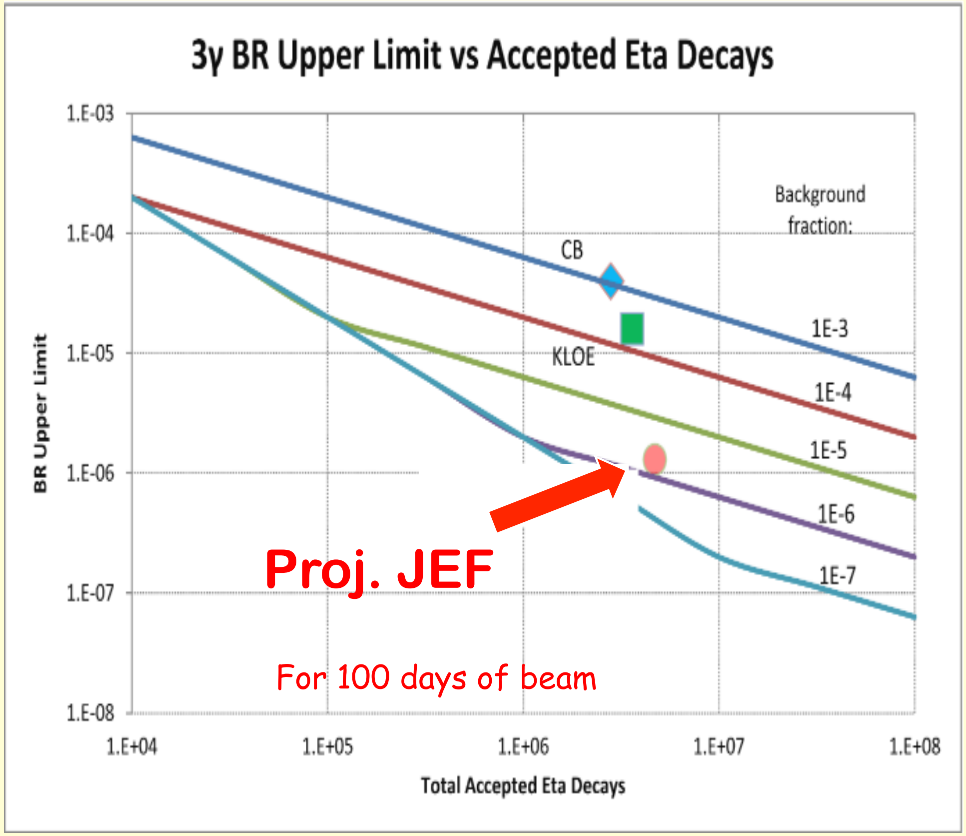
C Violating η neutral decays

Final State	Branching Ratio (upper limit)	Gammas in Final State
3γ	$< 1.6 \cdot 10^{-5}$	3
$\pi^0\gamma$	$< 9 \cdot 10^{-5}$	
$2\pi^0\gamma$	$< 5 \cdot 10^{-4}$	5
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

Experimental Improvementon in η→3γ

- SM contribution: BR(η→3γ) <10^{-19} via P-violating weak interaction.

- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee   Phys. Rev.,139, B1965 (1965)

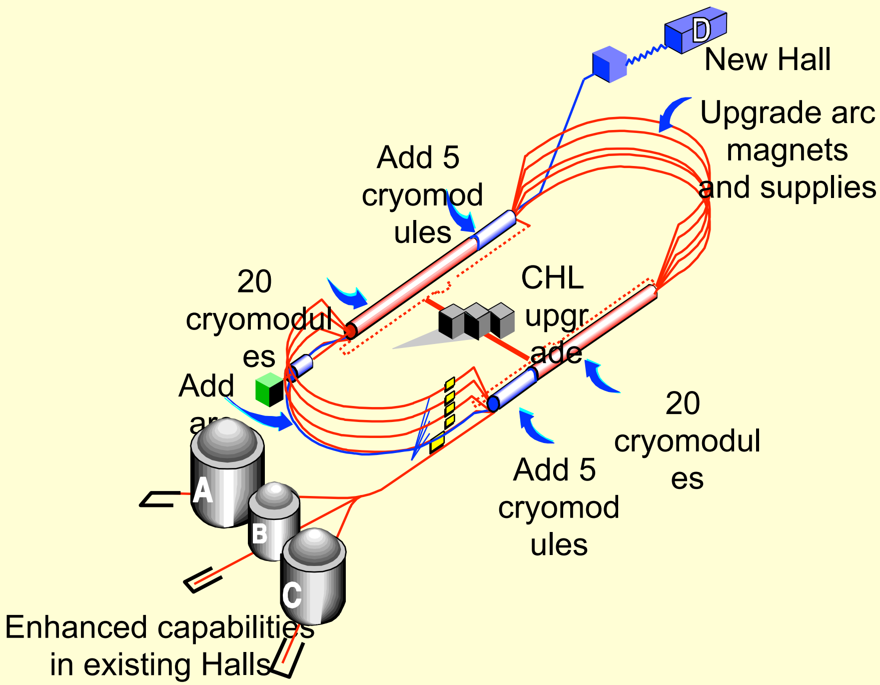


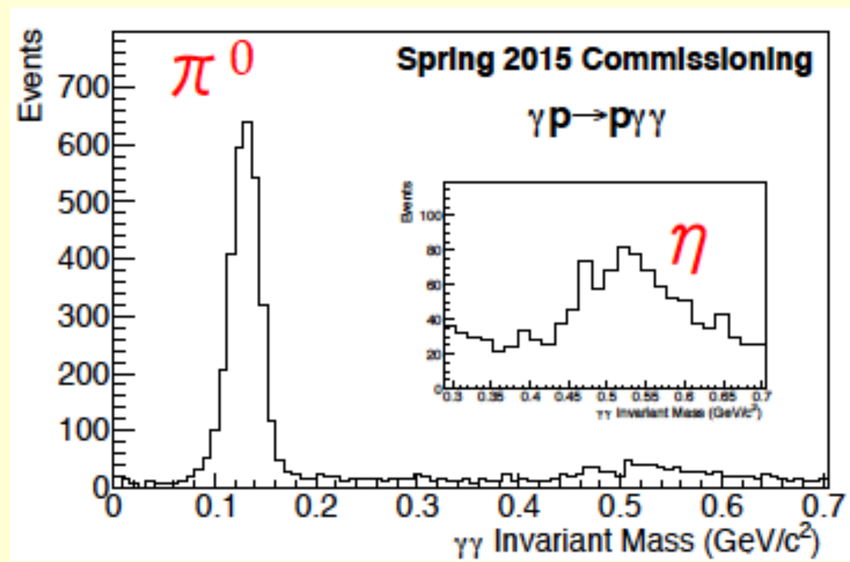
- A calculation due to such new physics by Tarasov suggests: BR(η→3γ)< 10^{-2} Sov.J.Nucl.Phys.,5,445 (1967)

- A new investigation by M. Ramsey-Musolf and two Ph.D. students is in progress

Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

Jlab and GlueX





Summary

- **A comprehensive Primakoff program has been developed at Jlab to measure $\Gamma(p\rightarrow\gamma\gamma)$ and $F(\gamma\gamma^*\rightarrow p)$ of π^0, η and η'. These results will provide rich data sets to test the fundamental symmetries of QCD at low energy.**
  - tests of chiral symmetry and anomalies
  - light quark mass ratio
  - η-η' mixing angle
  - π^0,η and η' electromagnetic interaction radii

- **12 GeV tagged photon beam with GlueX setup offers a unique η facility with two orders of magnitude in background reduction in the neutral rare η decays compared to other facilities in the world.**
  - A clean determination of the light quark mass ratio via $\eta\rightarrow3\pi$
  - Test the role of scalar dynamics in ChPT through $\eta\rightarrow\pi^0\gamma\gamma$
  - Probe a leptophobic dark B-boson in 140-550 MeV range via $\eta\rightarrow B\gamma\rightarrow\pi^0\gamma\gamma$ (complementary to ongoing A′ search)
  - Directly constrain CVPC new physics via $\eta\rightarrow3\gamma$ and other C-violating channels

This project is supported in part by US NSF MRI PHY-0079840 and research award PHY-1206043.

Special thanks to our theory colleagues:

G. Colangelo, B. Kubis, E. Passemar, J. Bijnens,
B. Holstein, M. Ramsey-Musolf, A.Aleksejevs,
S. Tulin, J. Goity, S. Barkanova, B. Martemyanov

η Production Rate Estimation

LH2 target length L=30cm, ρ=0.0708 g/cm^3

$$N_p = \frac{\rho L}{A} N_A = \frac{0.0708 \times 30}{1} \times 6.022 \times 10^{23} = 1.28 \times 10^{24} \ \text{p/cm}^2$$

The $\gamma + p \rightarrow \eta/\eta' + p$ cross section: ~70 nb for η; ~57 nb for η′

J.M. Laget , Phys.Rev. , C72, 022202 (2005) and A. Sibirtsev et al. Eur.Phys.J., A44, 169 (2010)

Photon beam intensity **N_γ ~5x10^7 Hz** (for E_γ ~9-11.7 GeV)

$$N_\eta = N_\gamma N_p \sigma = 5 \times 10^7 \times 1.28 \times 10^{24} \times 70 \times 10^{-33}$$

$$= 4.5 \ \text{Hz}$$

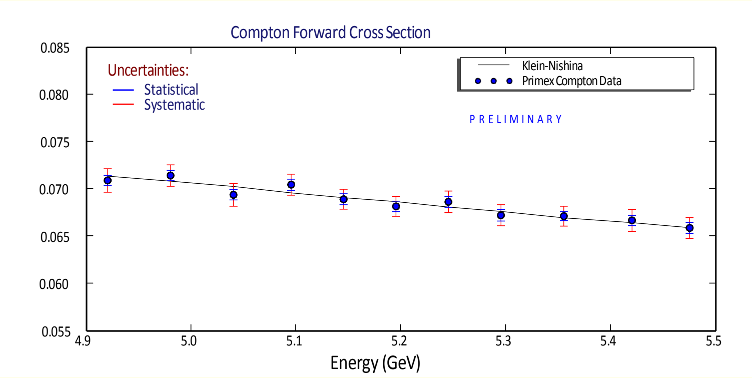
$$\approx \ 3.9 \times 10^5 \ (\eta\text{'s/day})$$

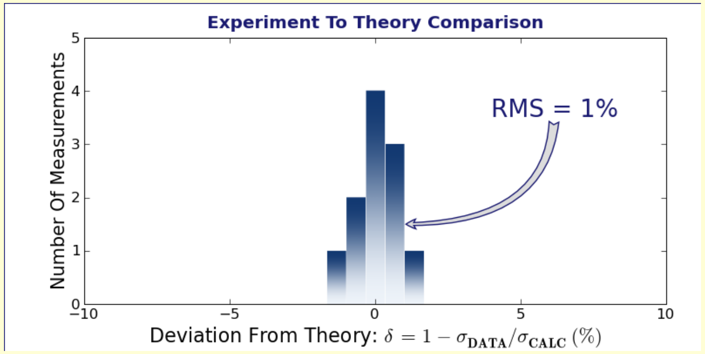
Jlab Eta Factory (JEF)

$$N_{\eta'} \approx 3.2 \times 10^5 \qquad (\eta' \ /\text{day})$$

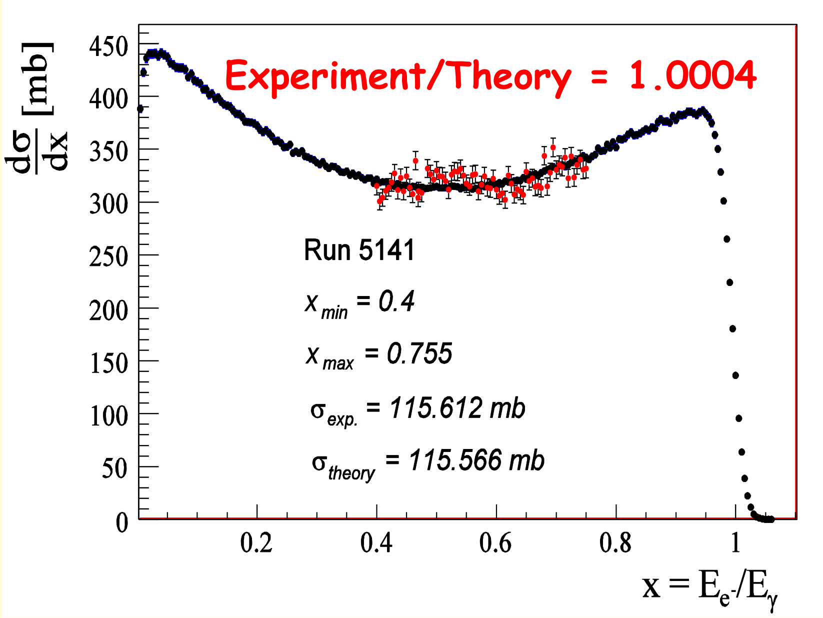
Verification of Overall Systematical Uncertainties

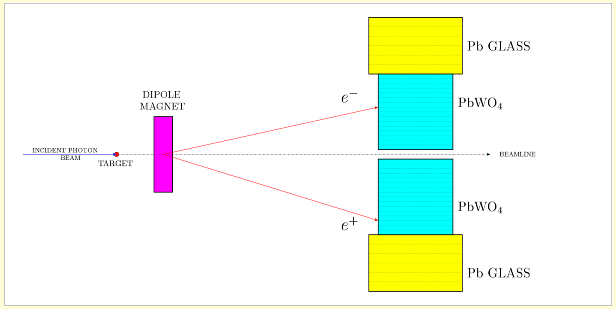
- $\gamma + e \rightarrow \gamma + e$ Compton cross section measurement





- e^+e^- pair-production cross section measurement:



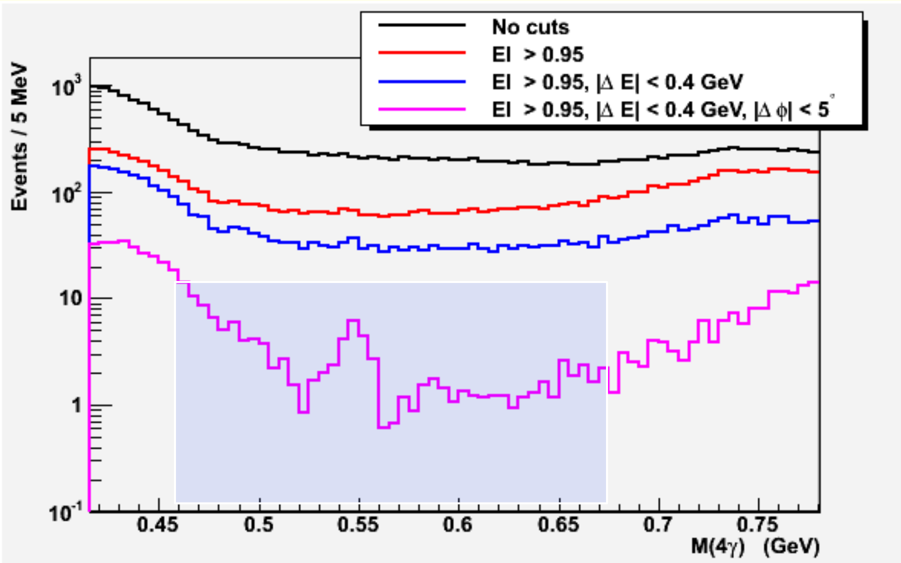


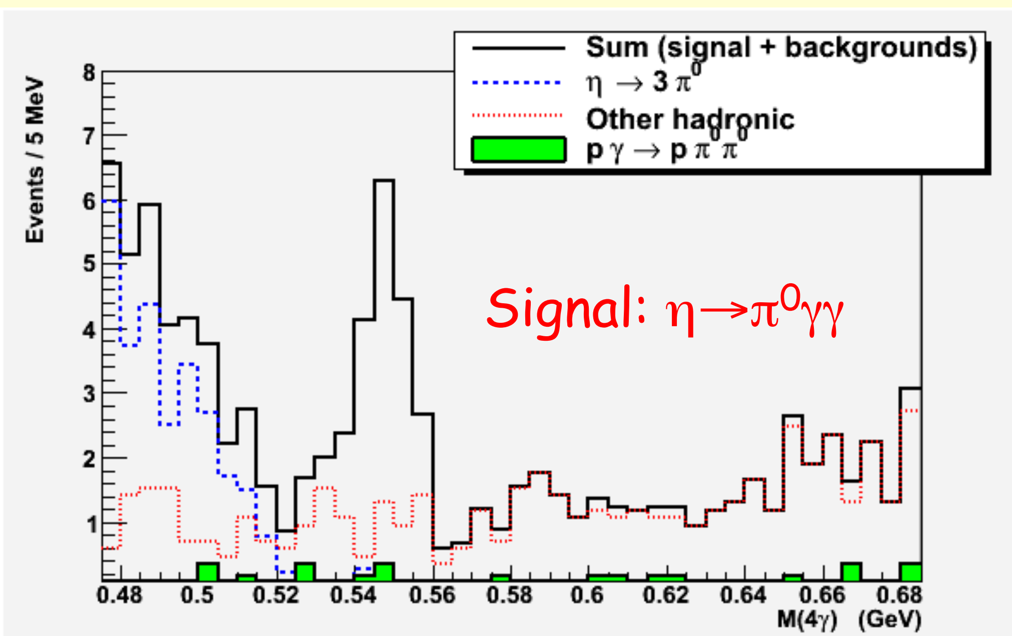
Systematic uncertainties on cross section are controlled under 1.3%

Estimated Systematic Uncertainties PrimEx-II (Preliminary)

Contributions	Uncertainty (%)
Photon flux	0.7
Beam parameters	0.4
Accidentals	0.1
Target parameters	0.2 ^{12}C; 0.4 ^{28}Si
Yield extraction	1.0
Acceptance	0.3
Trigger efficiency	0.3
Detector resolution	0.28
Model errors (theory)	0.5
Physics background	0.3
Branching ratio (PDG)	0.03
Total	**1.6**

Hadronic Backgrounds Reduction in 4γ States





Event Selection

- Elasticity is $EL = \Sigma E_\gamma / E_{tagged\text{-}\gamma}$
- Energy conservation for $\gamma+p \to \eta+p$ reaction: $\Delta E = E(\eta)+E(p)-E(beam)-M(p)$
- Co-planarity $\Delta\phi = \phi(\eta) - \phi(p)$

Note:

- Statistics is normalized to 1 beam day.
- BG will be further reduced by requiring that only one pair of γ's have the π^0 invariant mass.

Anatomy of CP Violation in $\Gamma(M_{C=+} \to \pi^+\pi^-\pi^0)$

C-odd, P-even

This can be generated by $s - p$ interference of $\left|[\pi^+(\boldsymbol{p})\,\pi^-(-\boldsymbol{p})]_I \pi^0(\boldsymbol{p}')_l\right\rangle$ final states of 0^- meson decay.

It is linear in a CP-violating parameter.

This contribution **cannot** be generated by $\bar{\theta}_{\rm QCD}$!

"C violation" [Lee and Wolfenstein, 1965; Lee, 1965, Nauenberg, 1965; Bernstein, Feinberg, and Lee, 1965]

C-even, P-odd

This can be generated by the interference of amplitudes which distinguish $\left|[\pi^-(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})]_I \pi^+(\boldsymbol{p}')_l\right\rangle$ from $\left|[\pi^+(\boldsymbol{p})\,\pi^0(-\boldsymbol{p})]_I \pi^-(\boldsymbol{p}')_l\right\rangle$ as in, e.g., $B \to \rho^+\pi^-$ vs. $B \to \rho^-\pi^+$. "CP-enantiomers" [SG, 2003]

This possibility is not accessible in $\eta \to \pi^+\pi^-\pi^0$ decay (but in η' decay, yes). Thus a "left-right" asymmetry in $\eta \to \pi^+\pi^-\pi^0$ decay tests C-invariance, too.