Hadron Probes for Fundamental Symmetries and Dark Gauge Bosons

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Outline

1. Introduction
   → challenges in physics

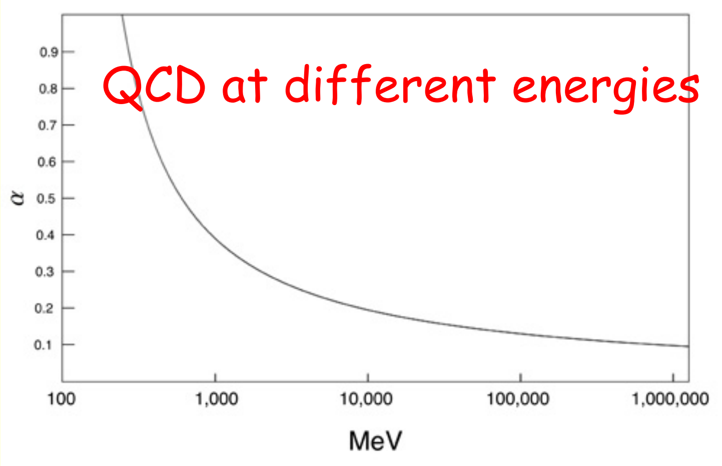
2. PrimEx experiments on π^0, η, η'
   → test confinement QCD symmetries

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

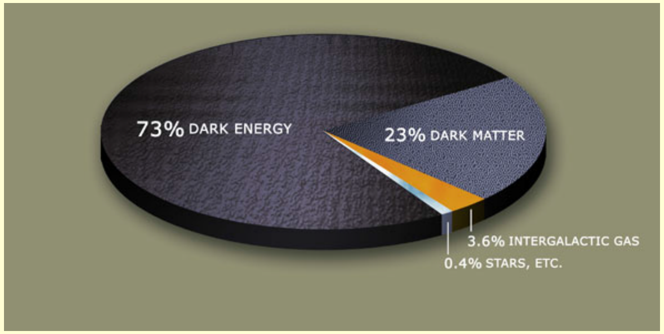
4. Summary

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



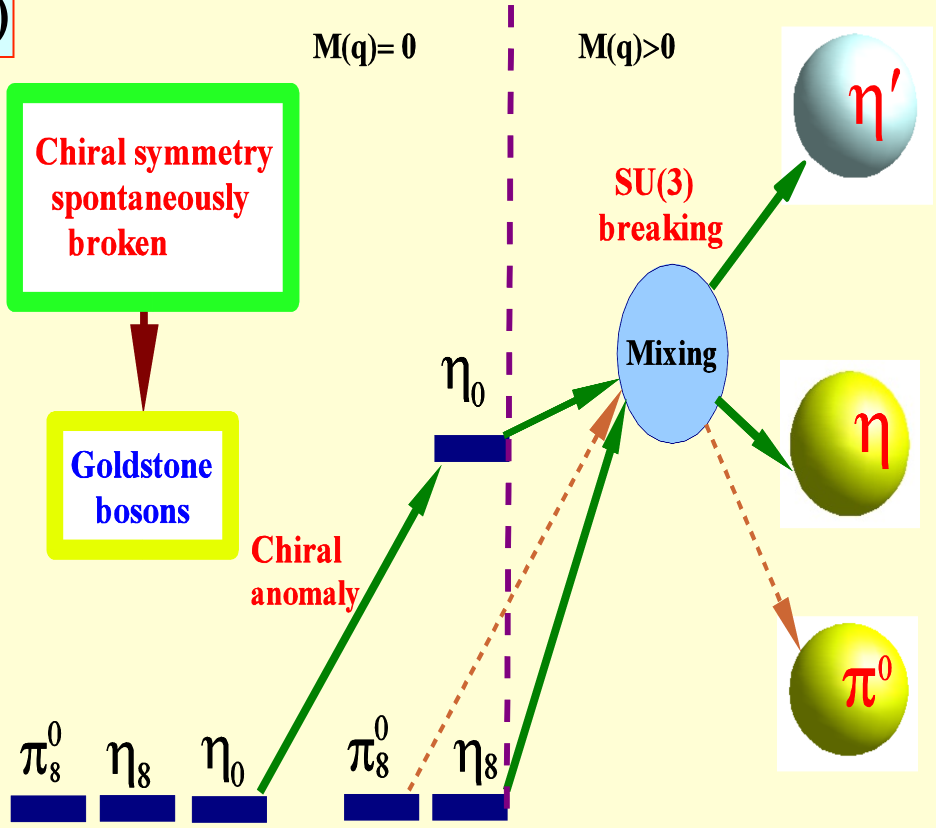
"As far as I see, all priori statements in physics have their origin in symmetry". By H. Weyl

QCD Symmetries and light mesons

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

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

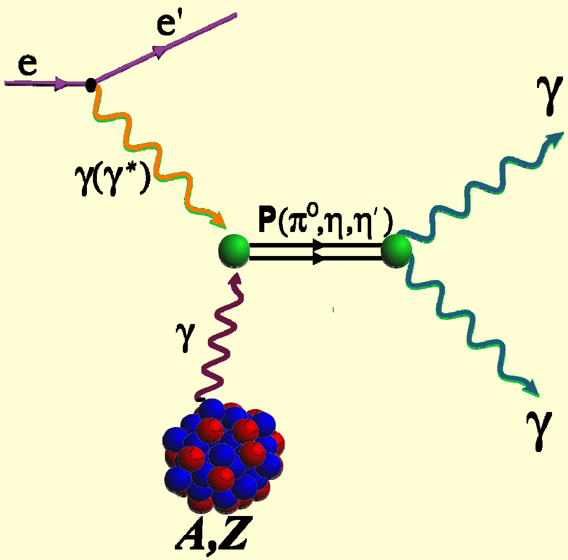
- Chiral symmetry $SU_L(3) \times SU_R(3)$ spontaneously breaks to $SU(3)$
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Mass of η_0
- $SU_L(3) \times SU_R(3)$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

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

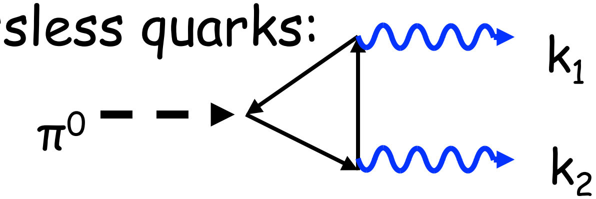
Input to Physics:

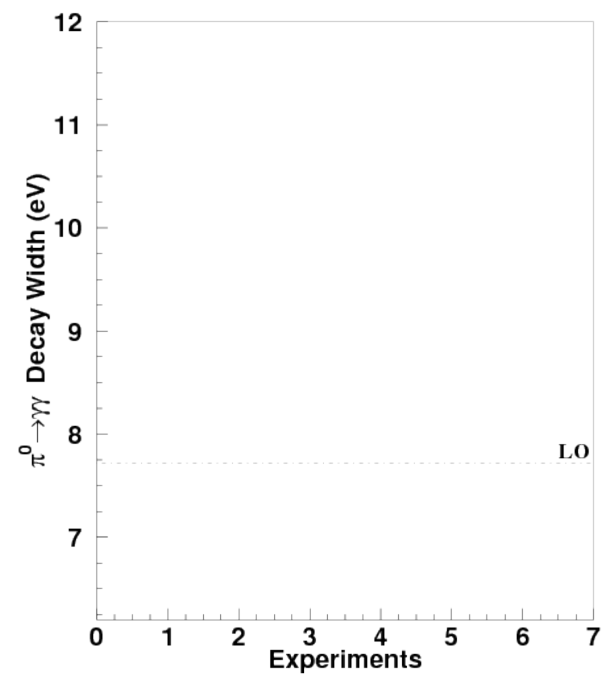
- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?

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:

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





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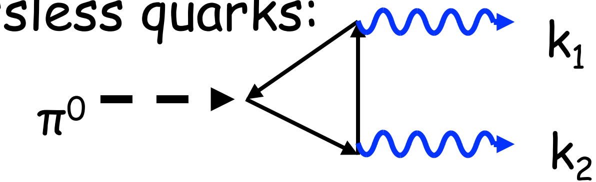

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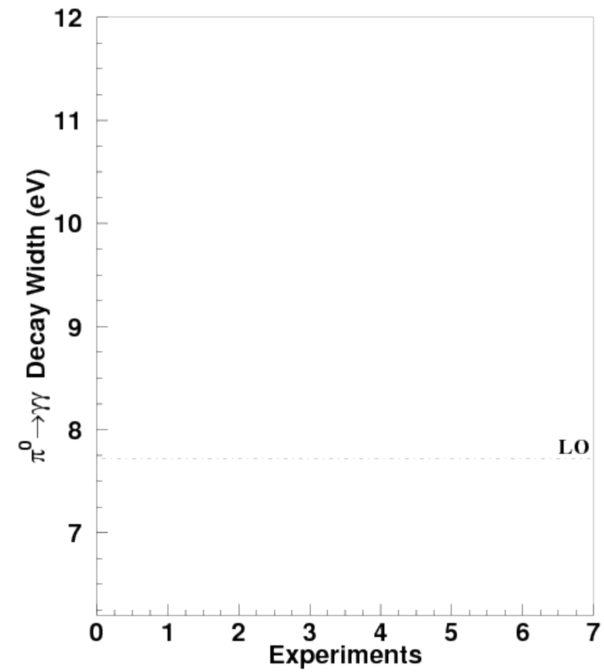

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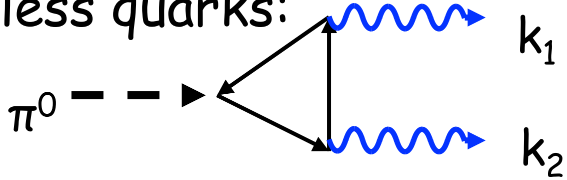

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➢ Corrections to the chiral anomaly prediction:

Calculations in NLO ChPT:

- ❑ $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.10eV ± 1.0%
  (J. Goity, et al. Phys. Rev. D66:076014, 2002)
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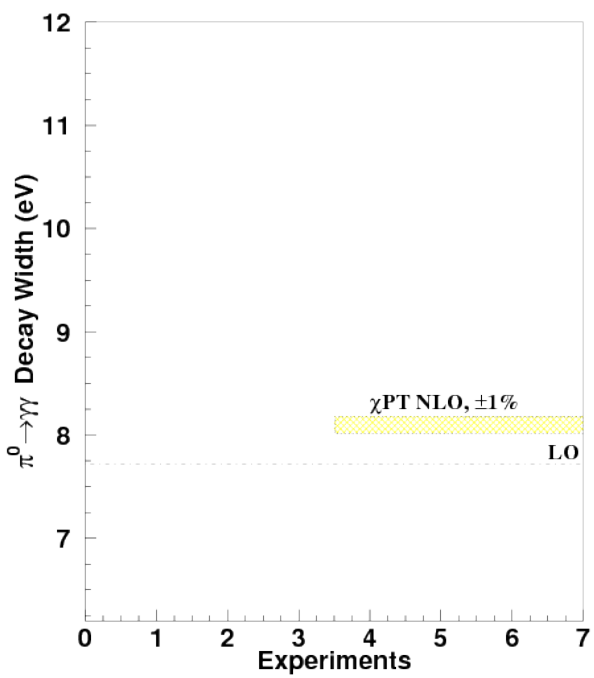

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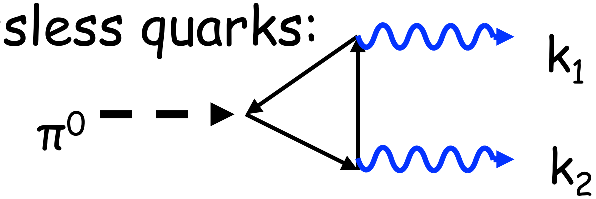

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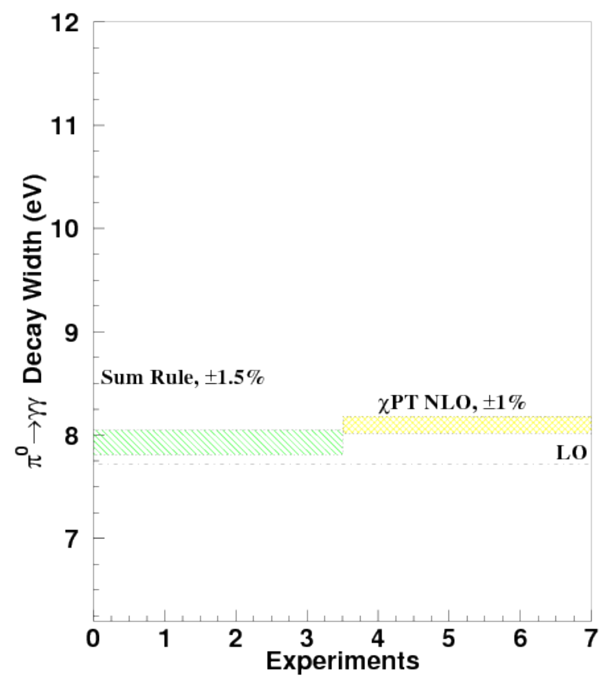

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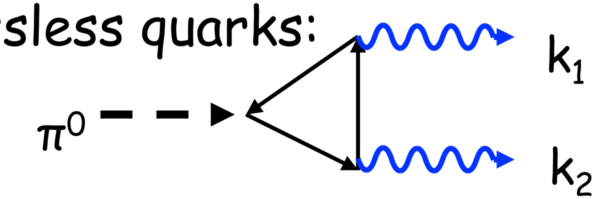

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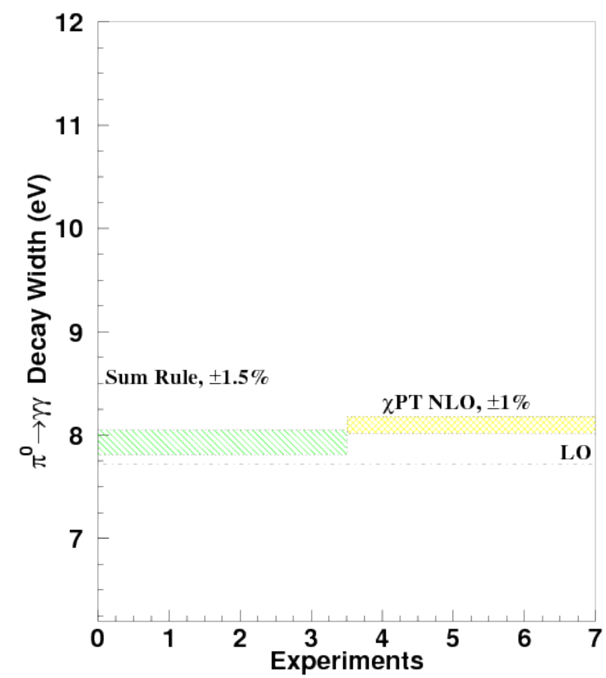

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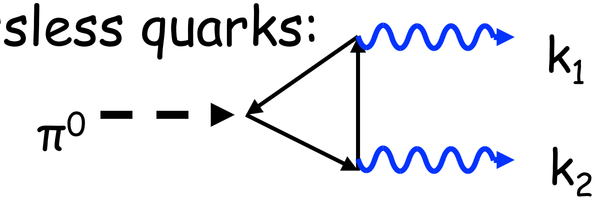

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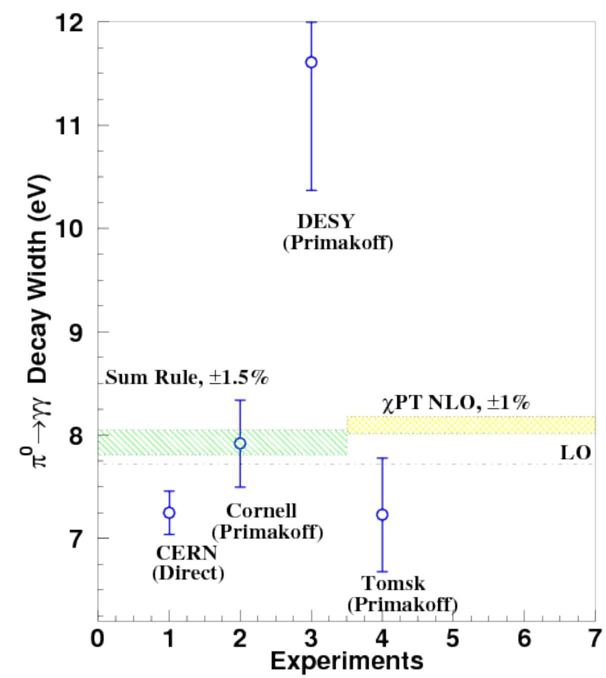

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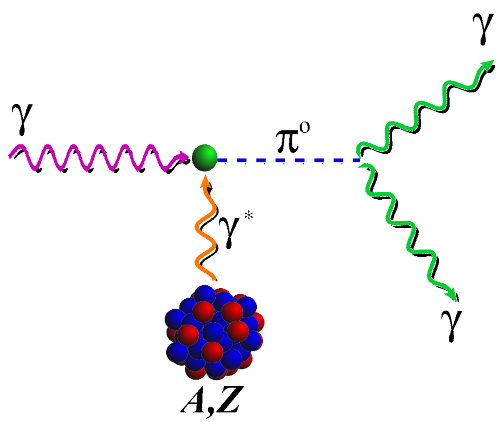
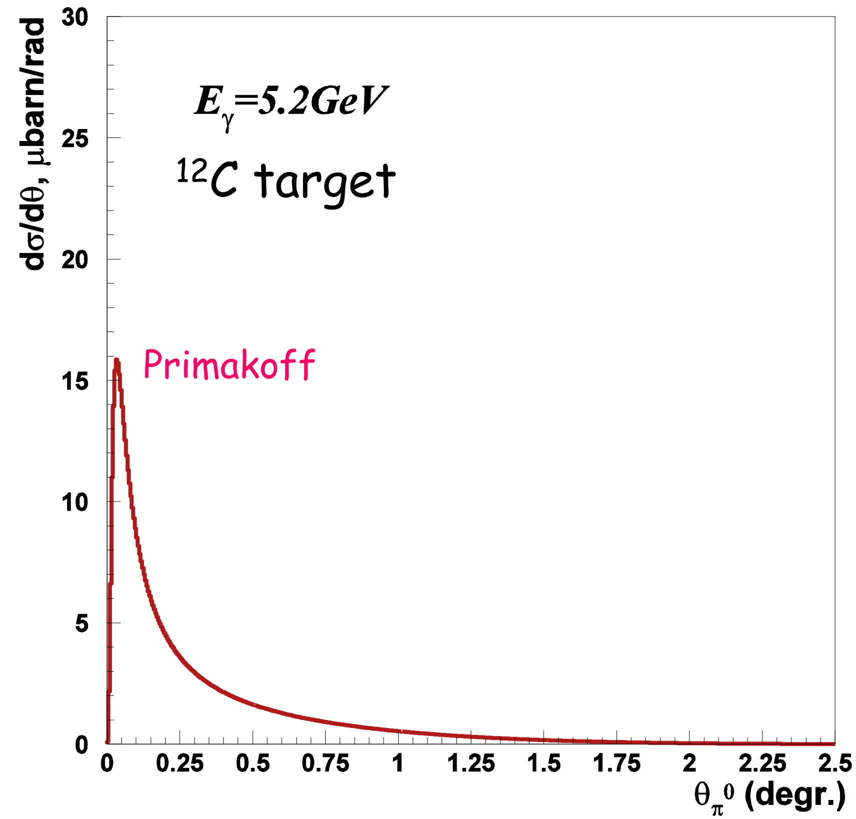
Primakoff Method



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



Features of Primakoff cross section:

- Peaked at very small forward angle:

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

- Beam energy sensitive:

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

- Coherent process

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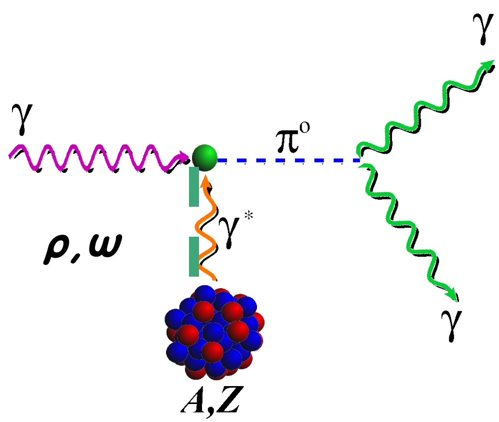

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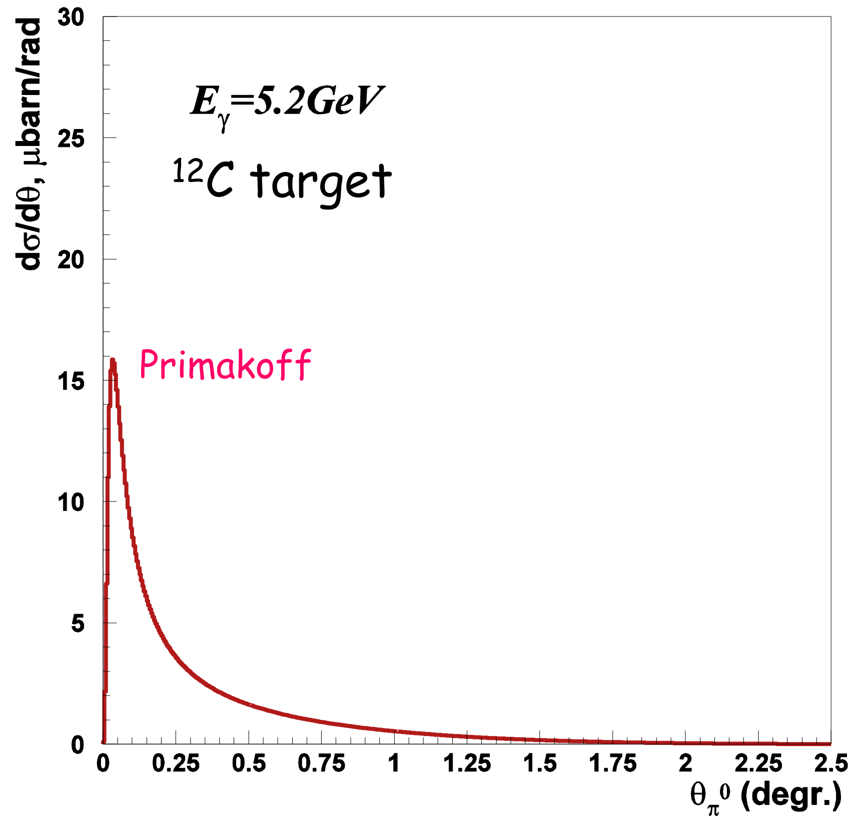

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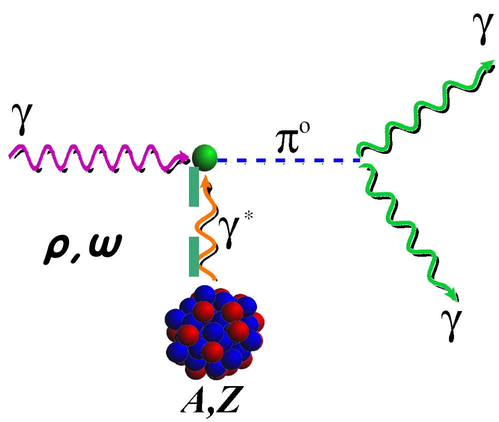

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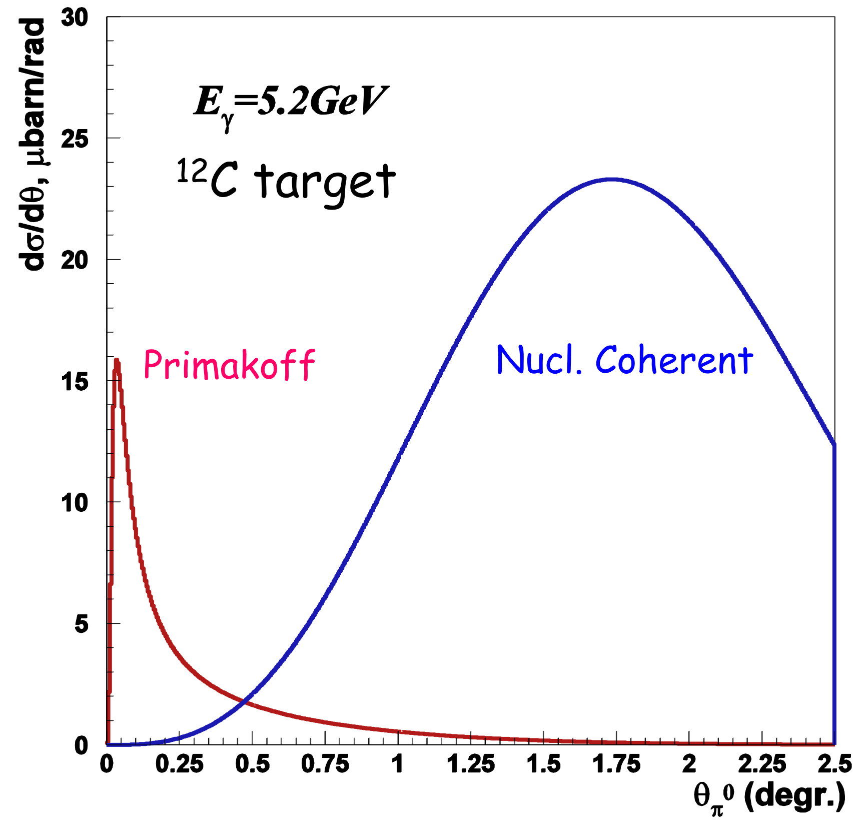

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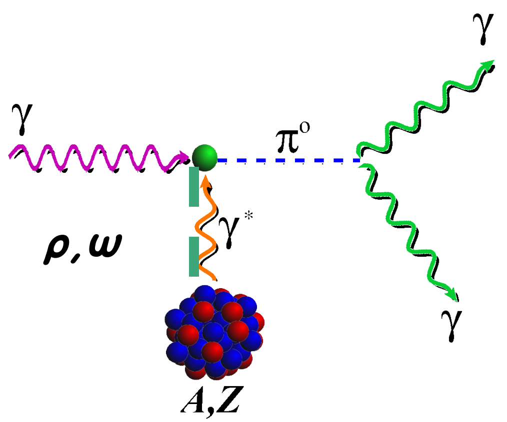

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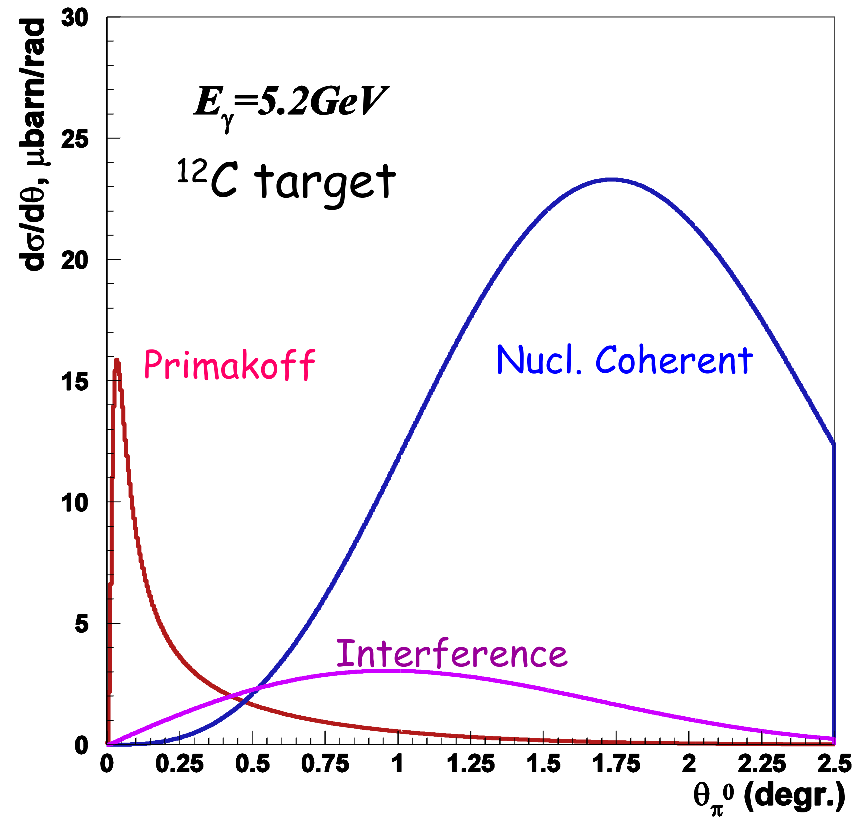

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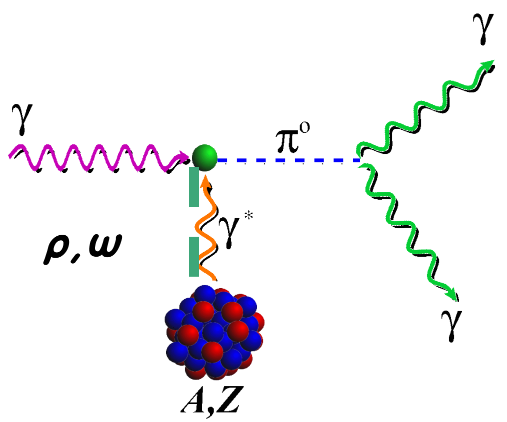

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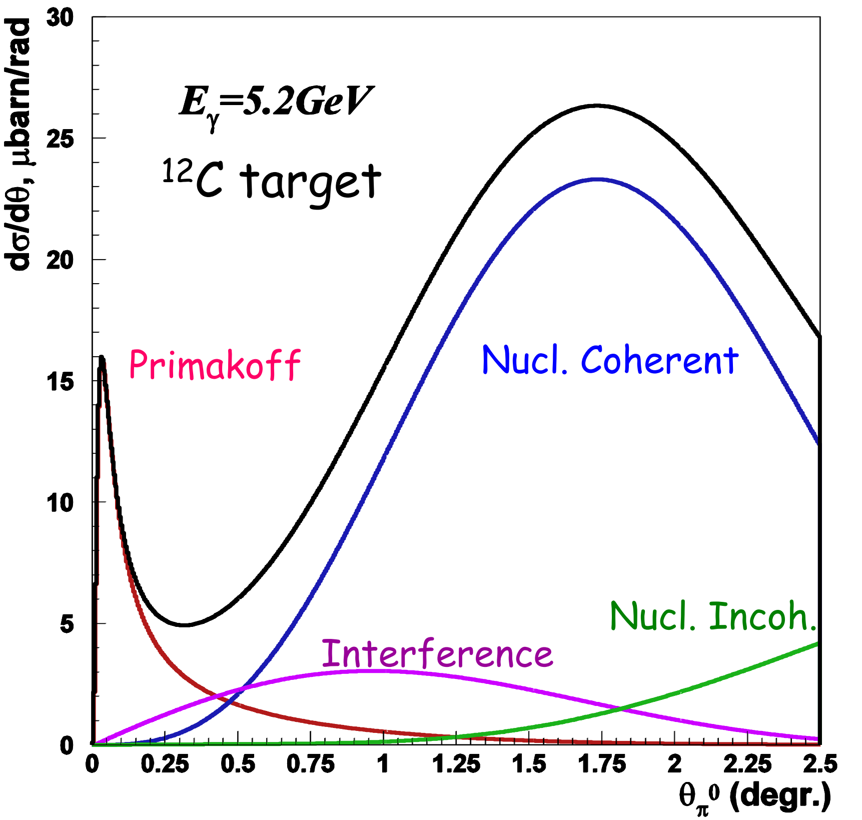

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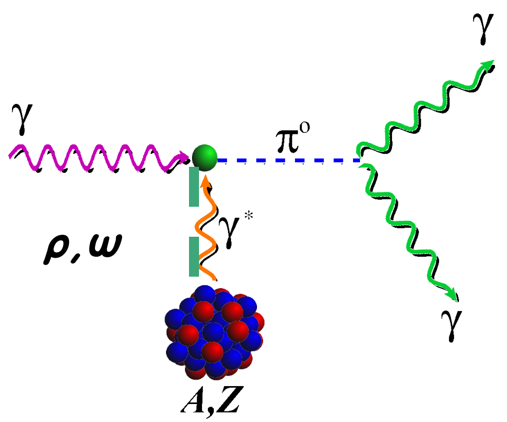

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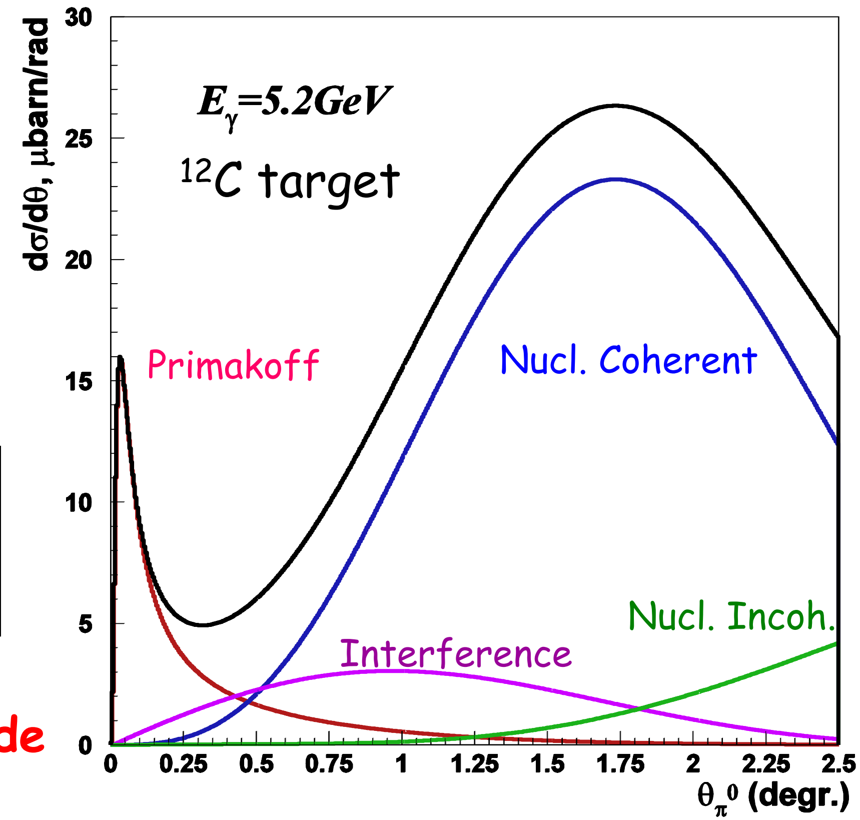
Challenge: Extract the Primakoff amplitude



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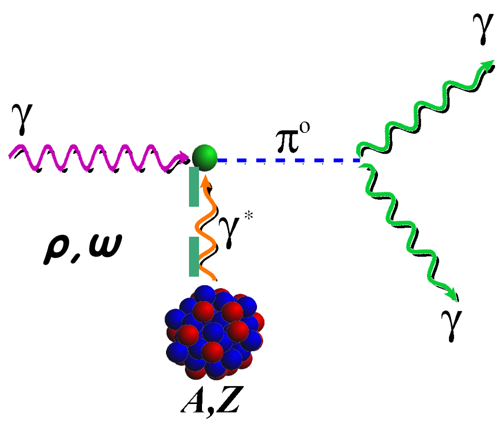

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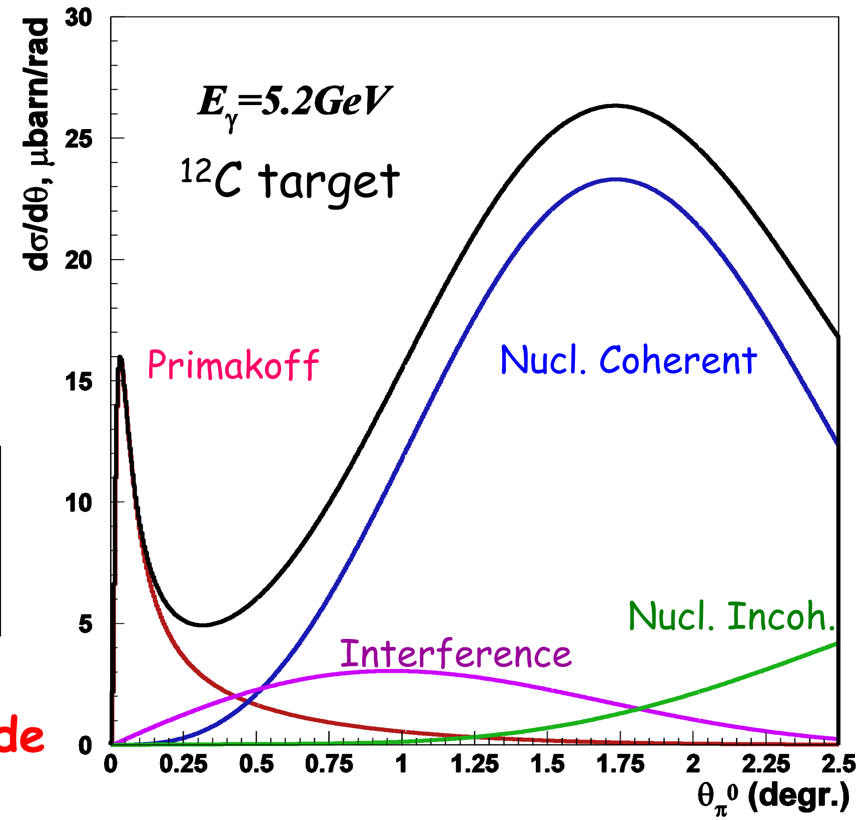

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Requirement:

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

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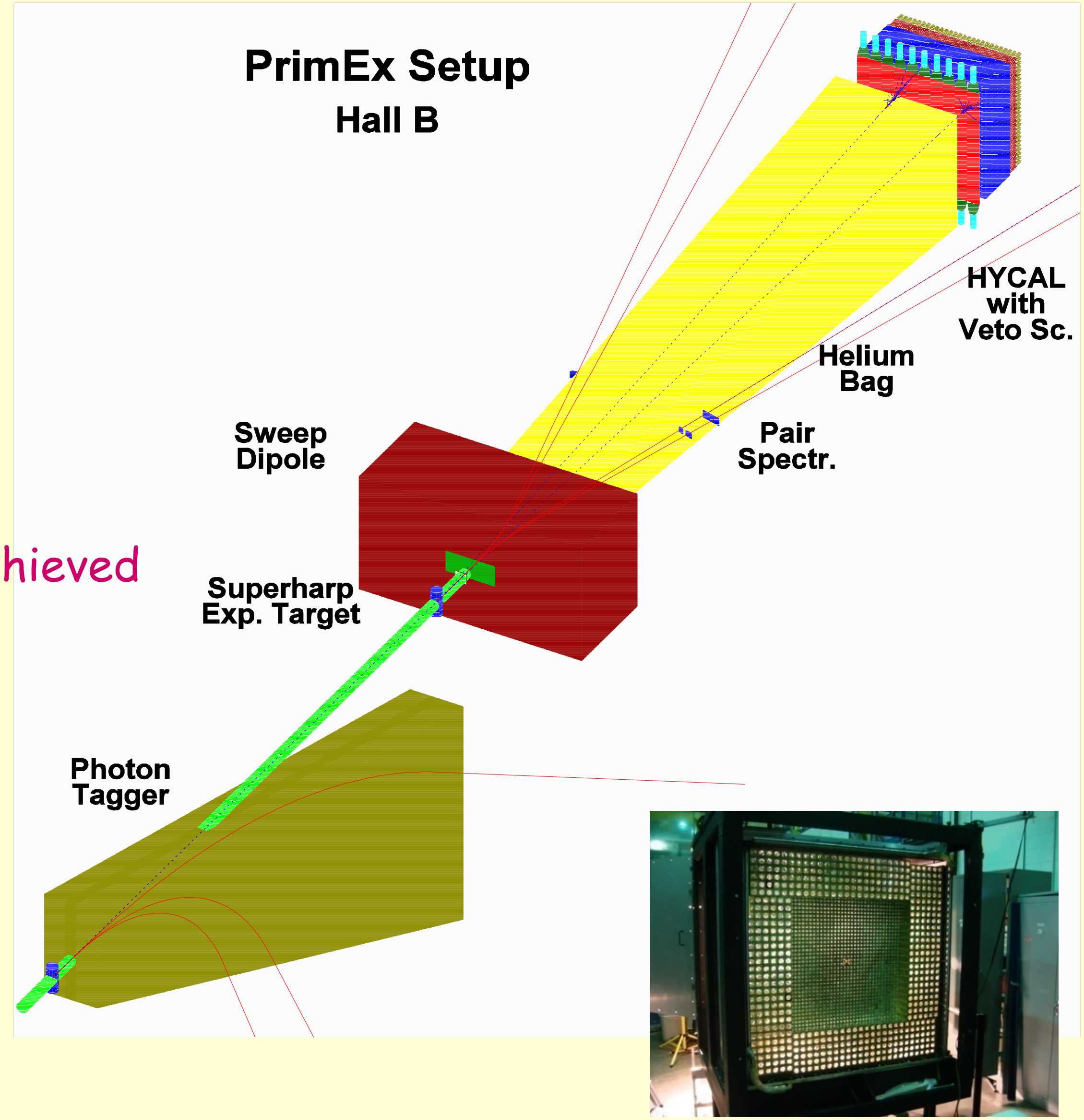
PrimEx Experimental Setup

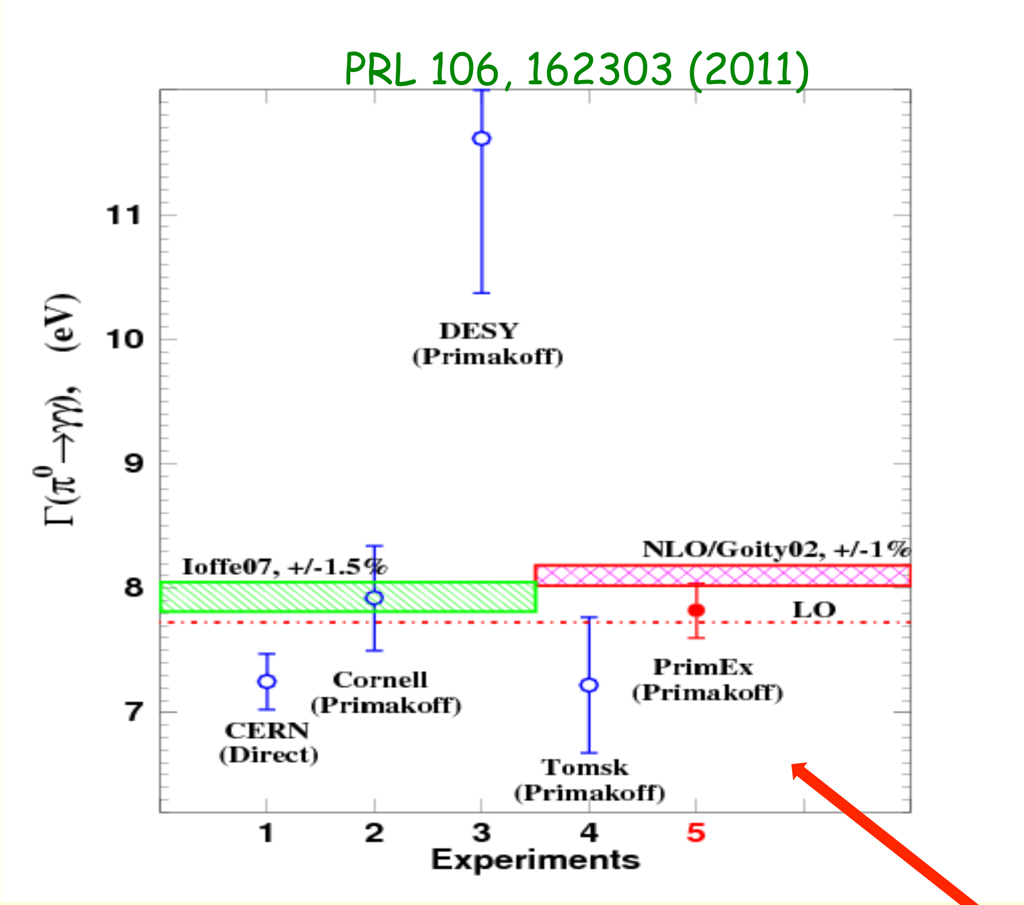
- JLab Hall B high resolution, high intensity photon tagging facility

- 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 Result



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2.8% total uncertainty

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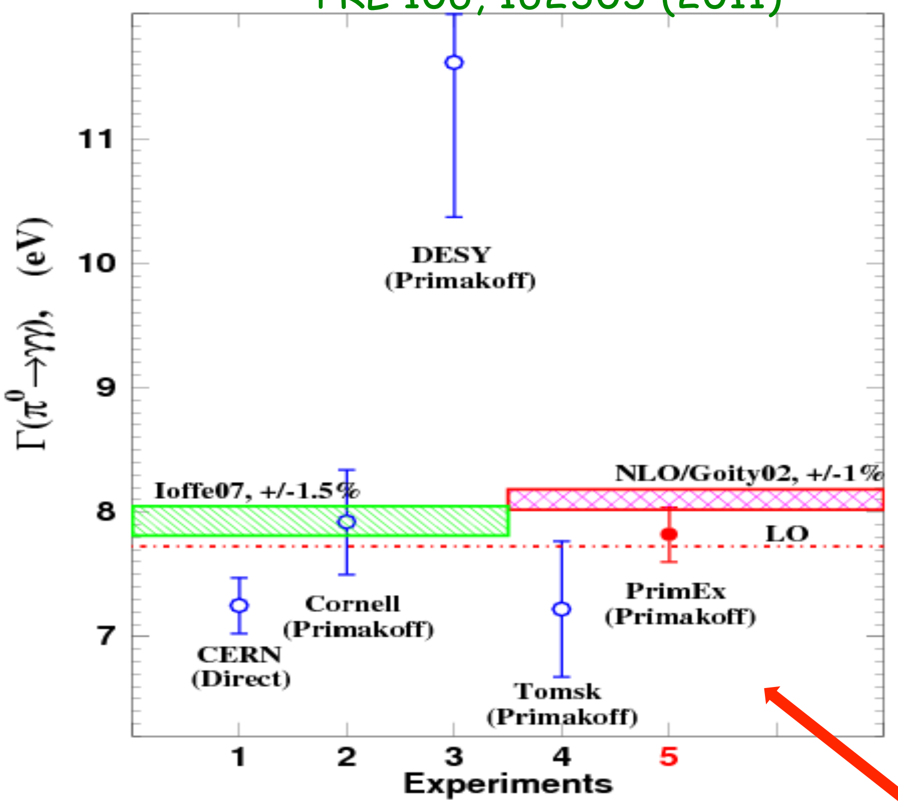
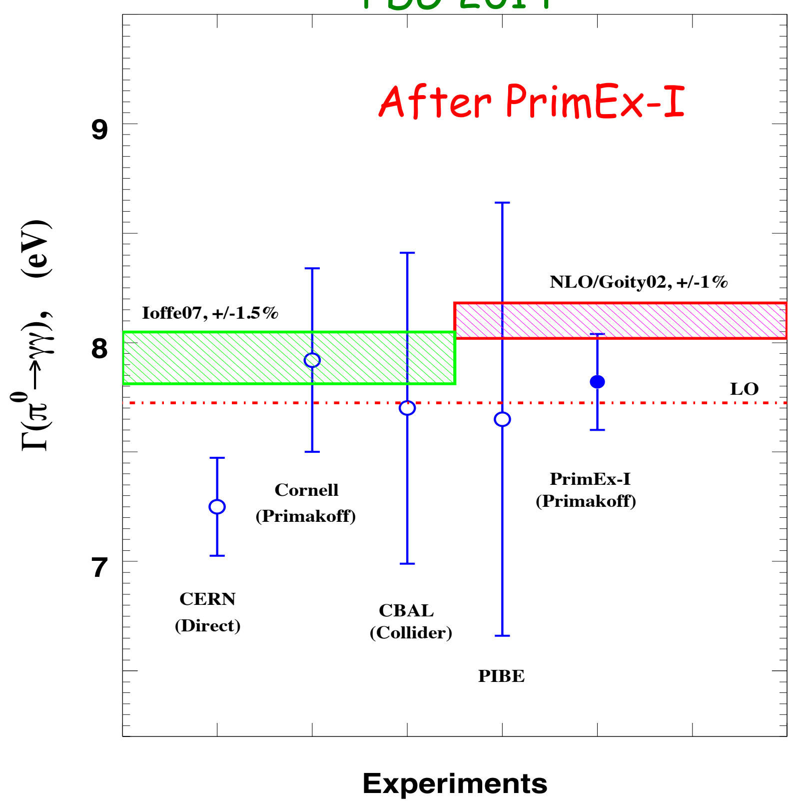
PRL 106, 162303 (2011)



PDG 2014



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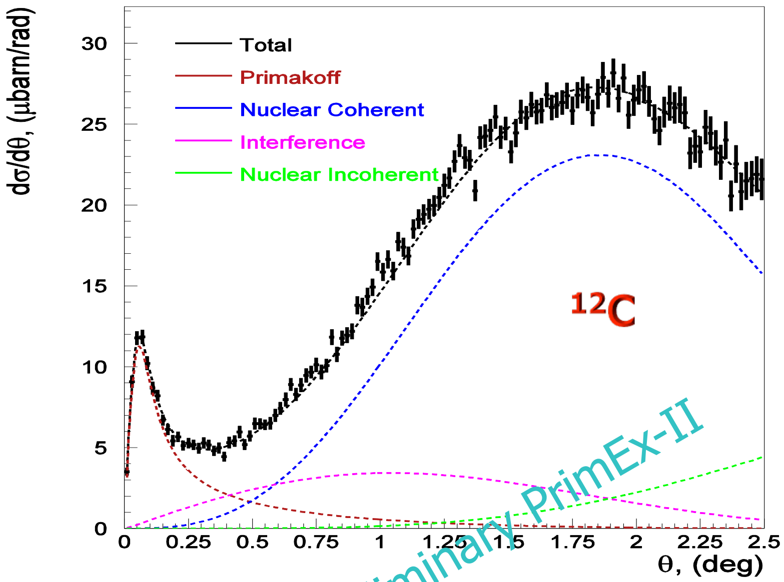
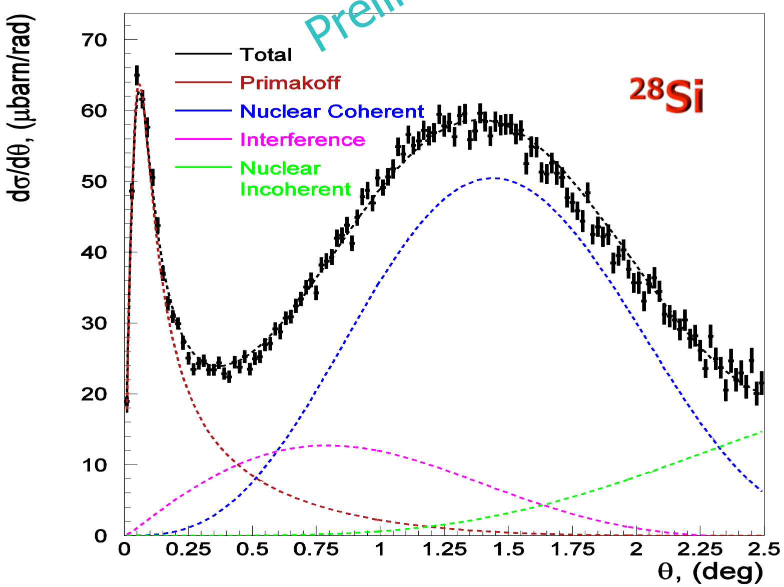
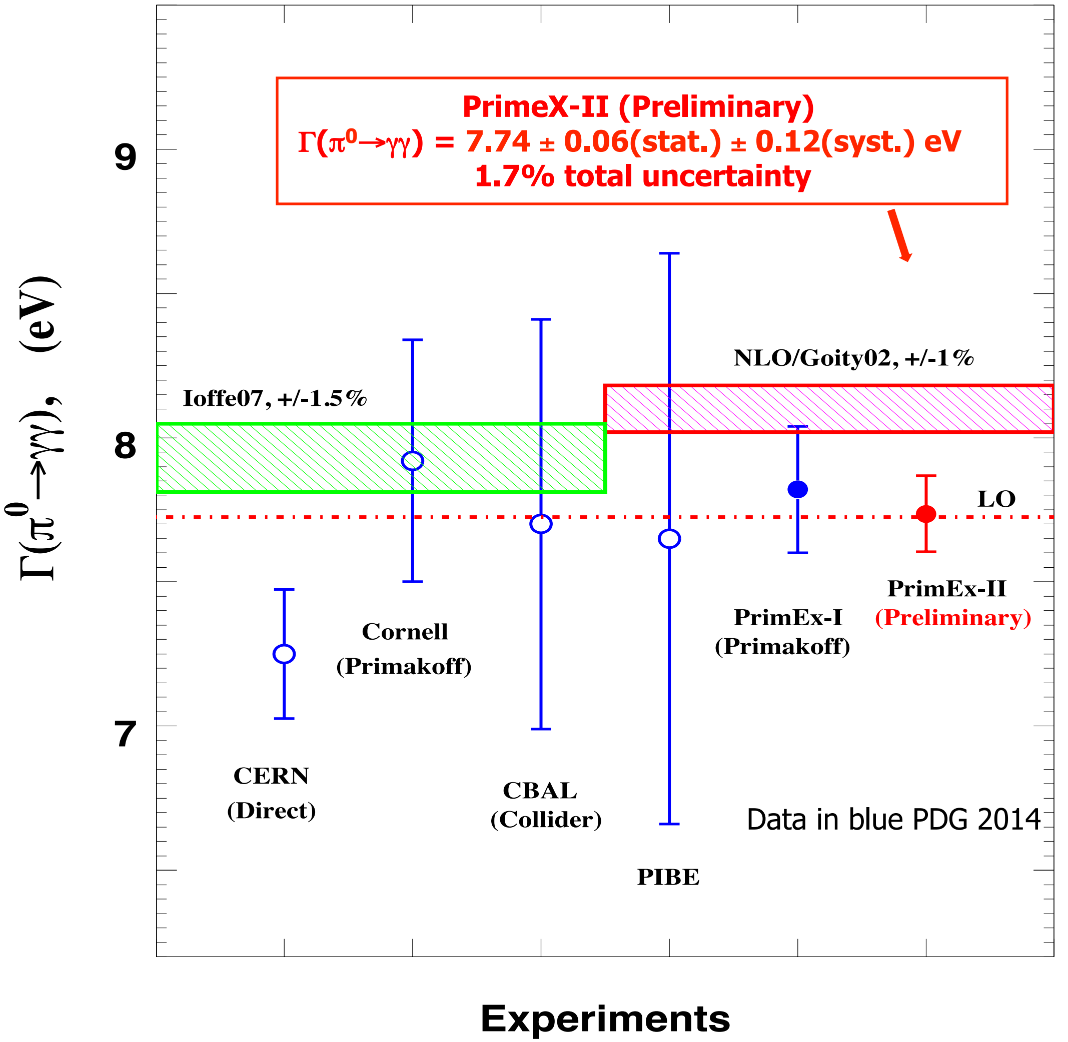
PrimEx-I improved the precision of PDG average by more than a factor of 2

The second experiment: PrimEx-II
(analysis #1 by I. Larin and L. Ma)

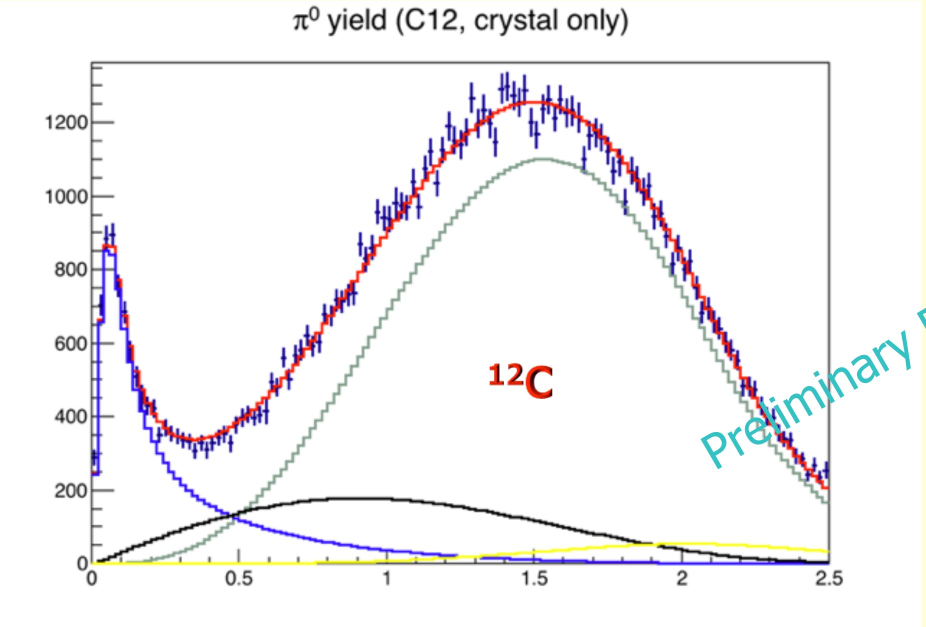


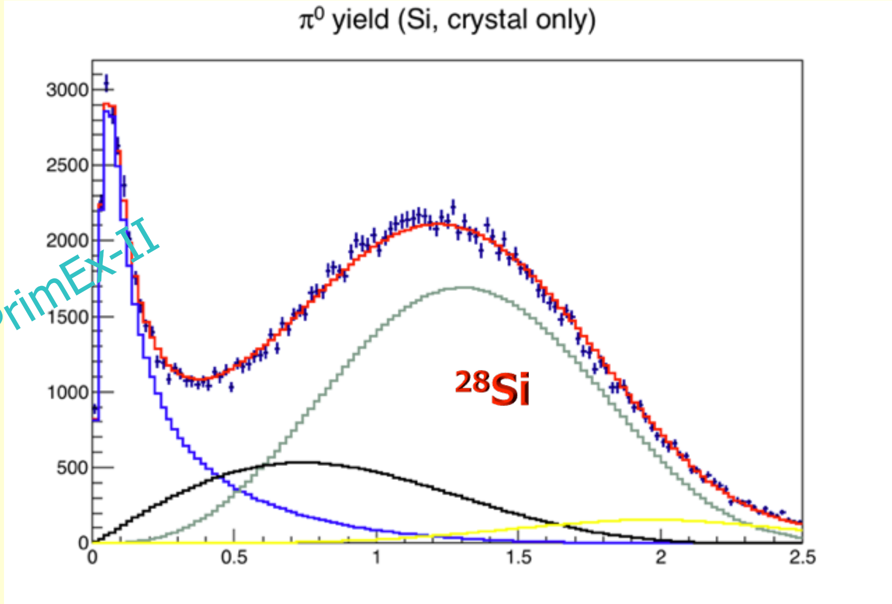




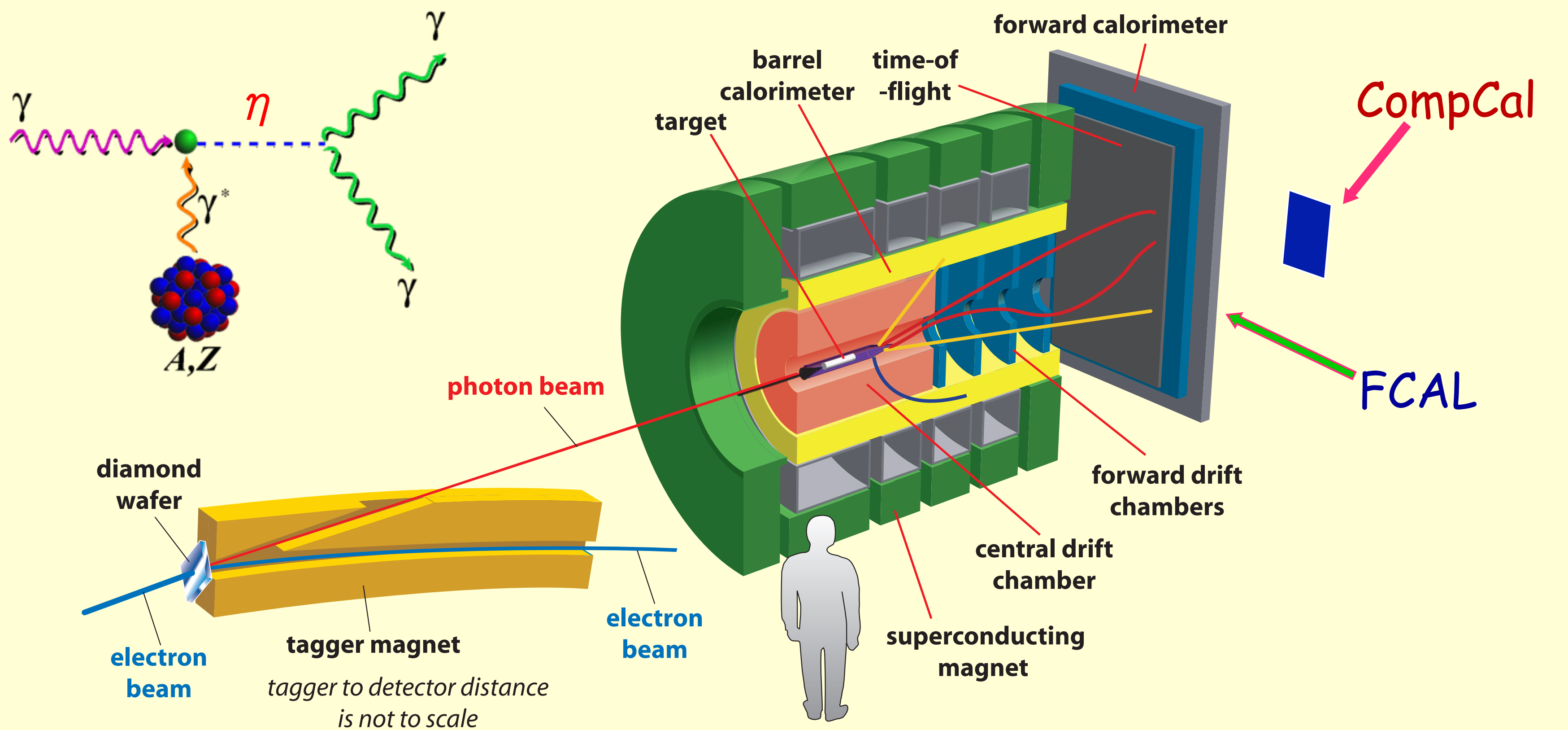
PrimEx-II

(analysis #2 by Y. Zhang)





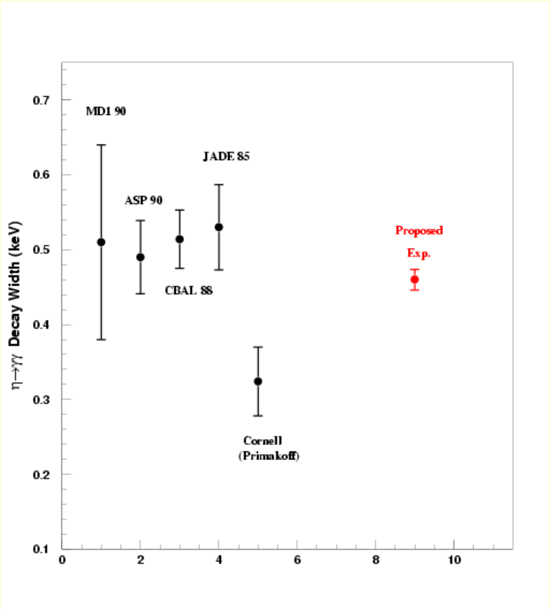
Measurement of Γ(η→γγ) in Hall D at 12 GeV



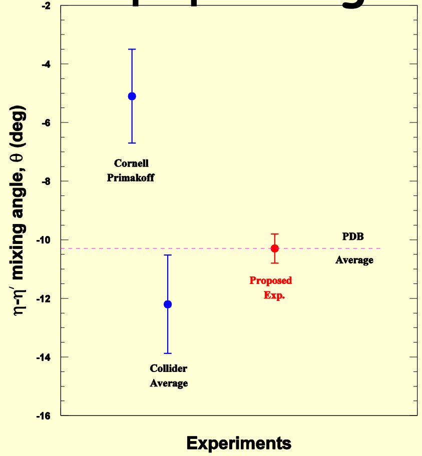
- Incoherent tagged photon beam (~10.5-11.5 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- 30 cm liquid Hydrogen and ^{4}He targets (~3.6% r.l.)
- Forward Calorimeter (FCAL) for η→γγ decay photons
- CompCal and FCAL to measure well-known Compton scattering for control of overall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

$\Gamma(\eta\rightarrow\gamma\gamma)$ Experiment @ 12 GeV

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

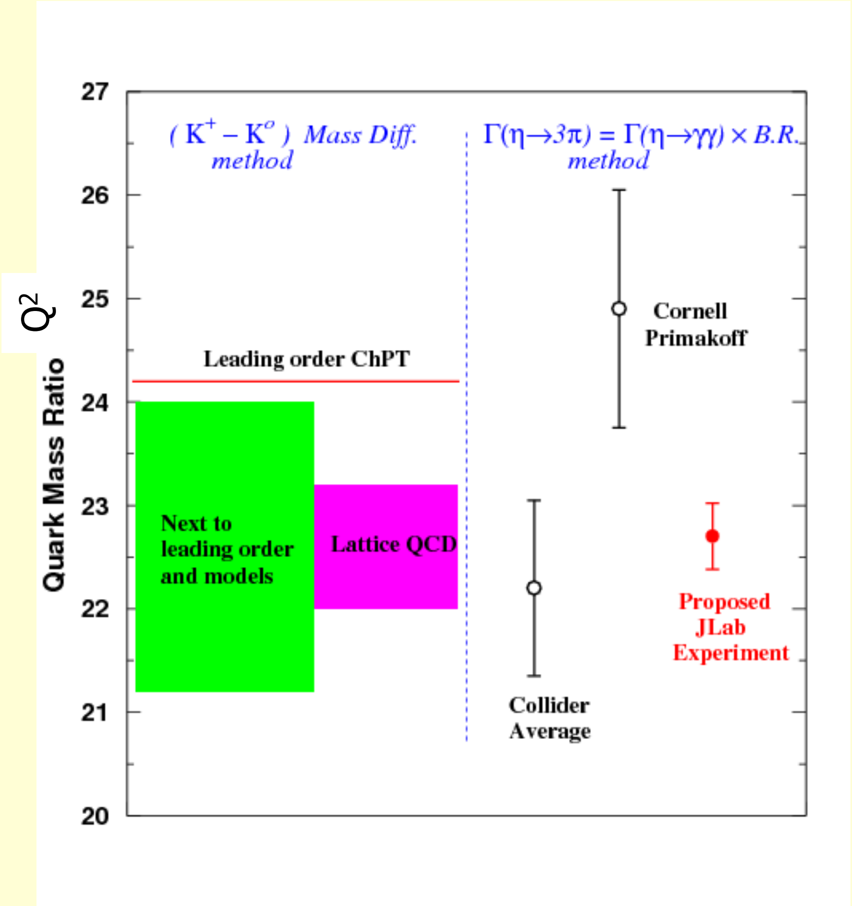


2. Extract η-η' mixing angle:



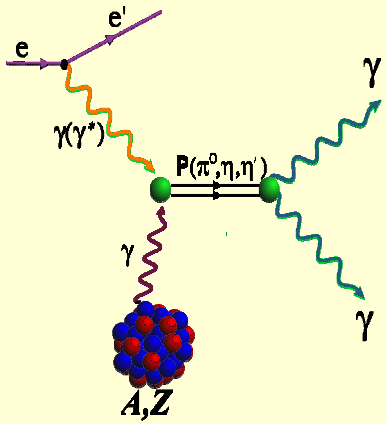
3. Determine Light quark mass ratio:

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

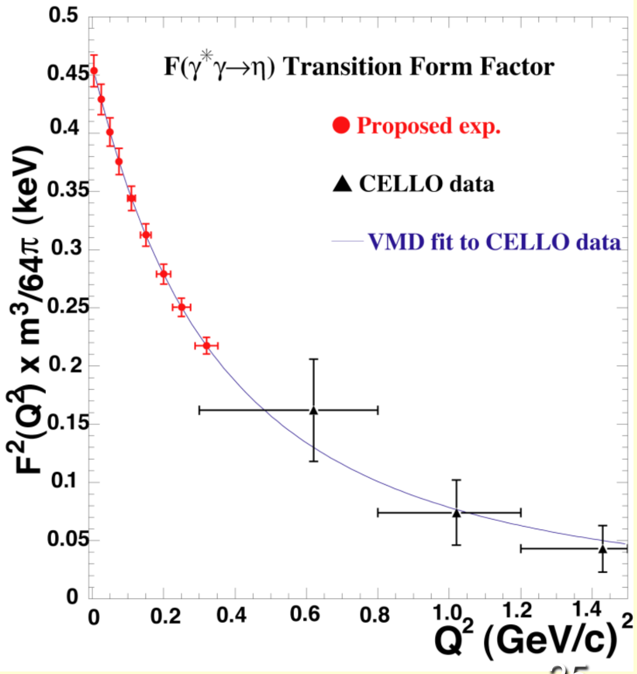


H. Leutwyler Phys. Lett., B378, 313 (1996)

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

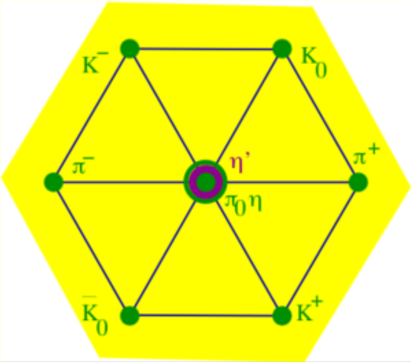


- Direct measurement of slopes
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2)\approx 1-1/6 \cdot \langle r^2\rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian
- Input for light-by-light scattering for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

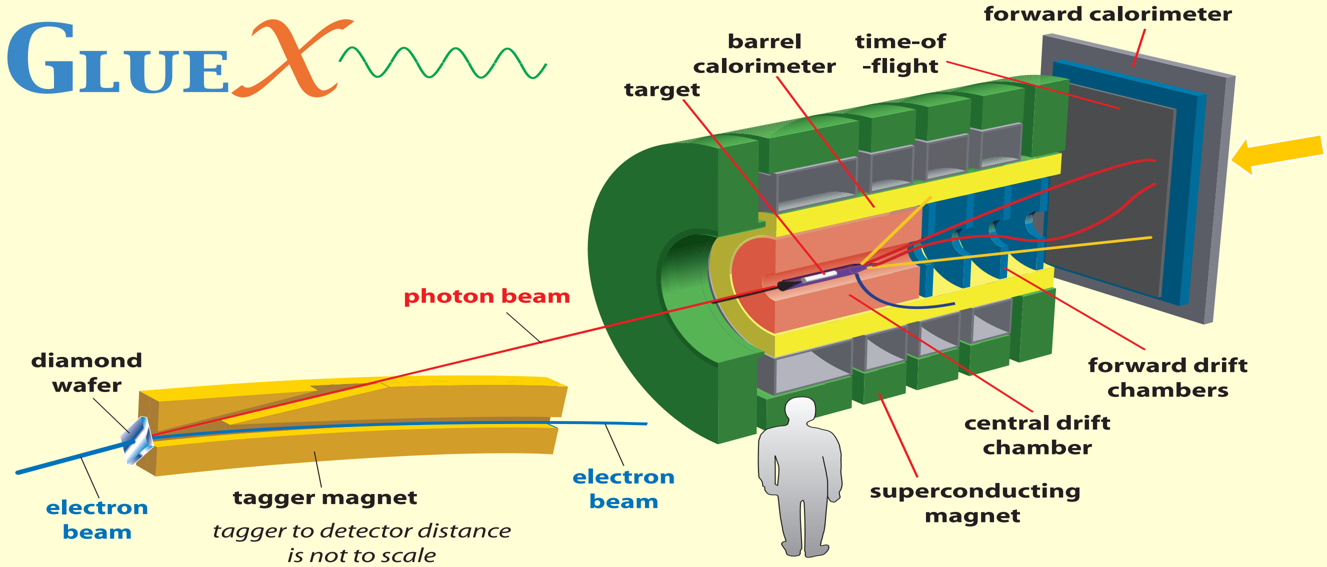
Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$\gamma + B$	beyond SM	leptophobic dark boson	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	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. Search for a leptophobic dark boson (B).
2. Directly constrain CVPC new physics
3. Determine the light quark mass ratio
4. Probe the role of scalar dynamics in ChPT to calculate LEC's in the chiral Lagrangian.

FCAL-II is required for the rare decays

Jlab Eta Factory (JEF) experiment



Simultaneously measure η decays: $\eta\rightarrow\pi^0\gamma\gamma$, $\eta\rightarrow3\gamma$, and …

- η produced on LH_2 target with **9-11.7 GeV tagged photon beam:**
  $\gamma+p \rightarrow \eta+p$
- 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

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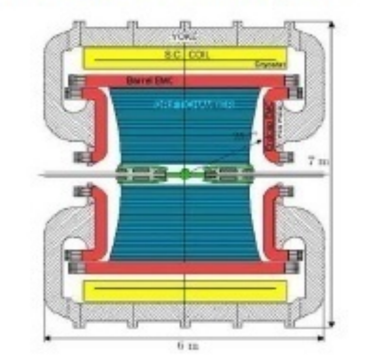
World competition in η decays

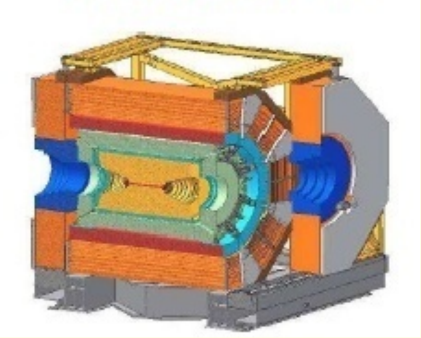
World competition in η decays

e^+e^- Collider

KLOE-2 at DAϕNE



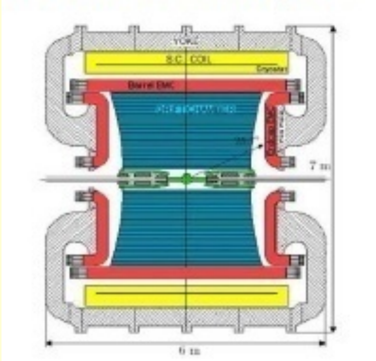
BESIII at BEPCII



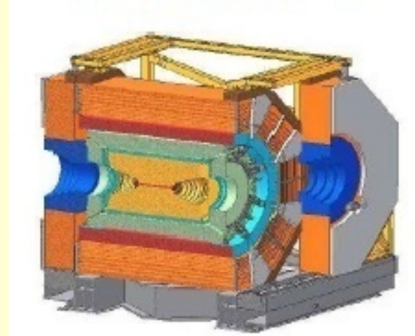
World competition in η decays

e^+e^- Collider

KLOE-2 at DAΦNE

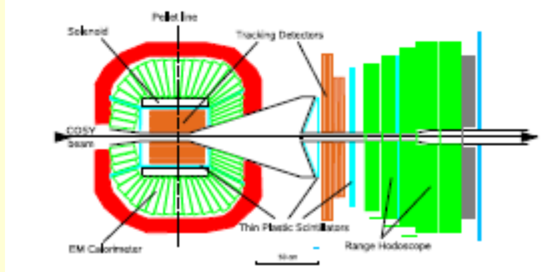


BESIII at BEPCII



Fixed-target

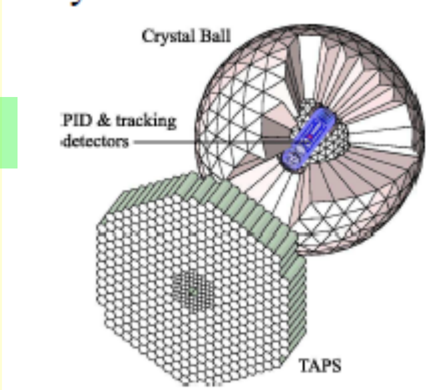
WASA at COSY



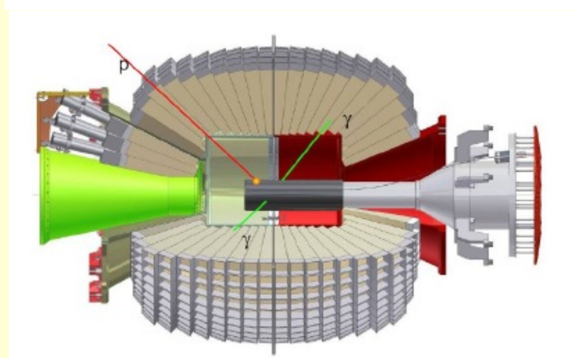
hadroproduction

photoproduction

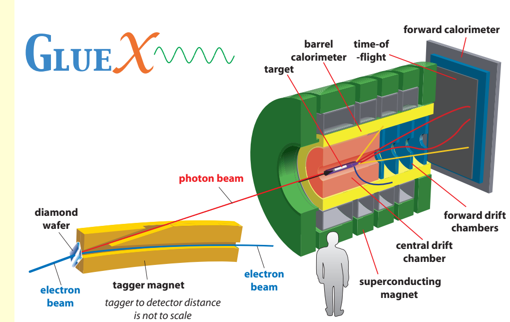
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



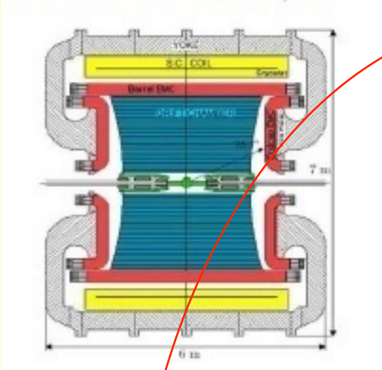
JEF at Jlab



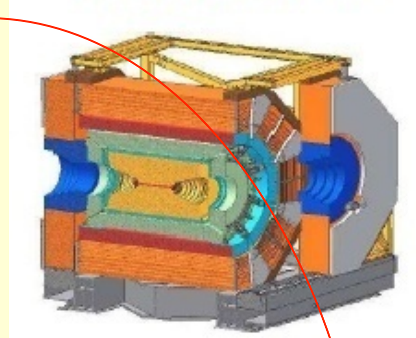
World competition in η decays

e^+e^- Collider

KLOE-2 at DAΦNE



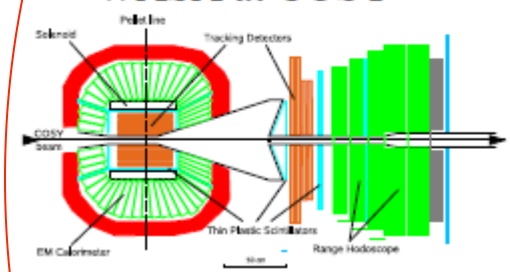
BESIII at BEPCII



Low energy η-facilities

Fixed-target

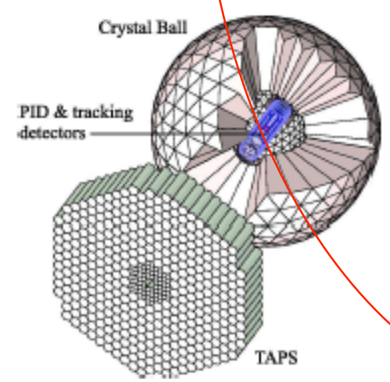
WASA at COSY



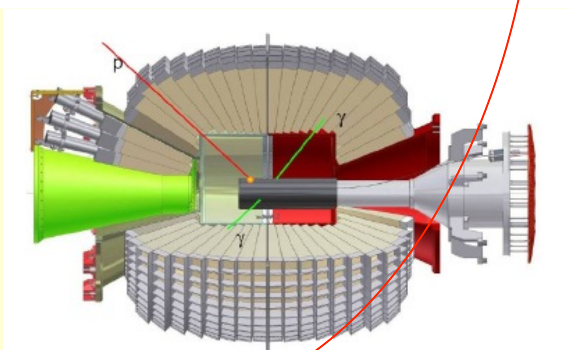
hadroproduction

photoproduction

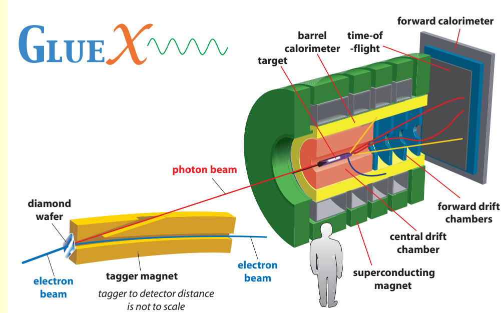
Crystall Ball at MAMI



CBELSA/TAPS at ELSA



JEF at Jlab

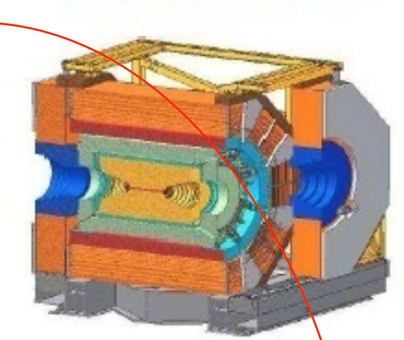


World competition in η decays

e^+e^- Collider

KLOE-2 at DAΦNE

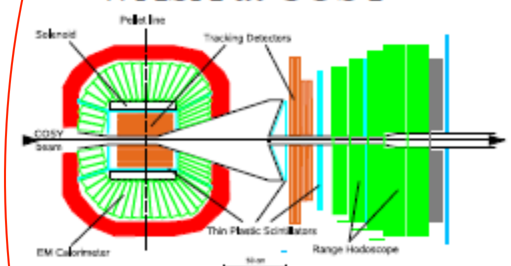
BESIII at BEPCII



Low energy η-facilities

Fixed-target

WASA at COSY

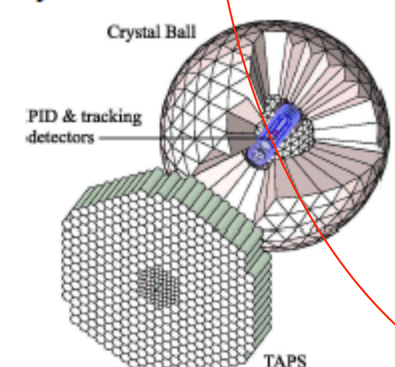


hadroproduction

High energy η-facility

photoproduction

Crystall Ball at MAMI



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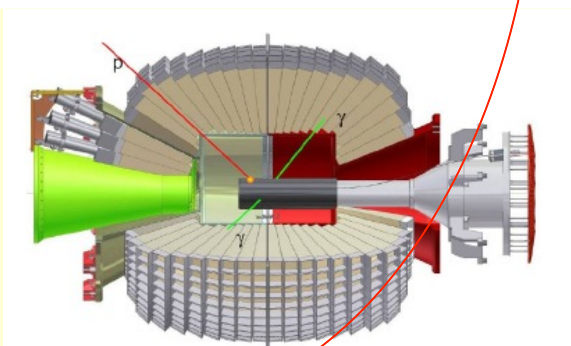
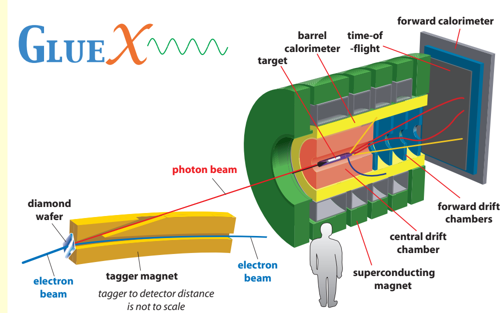
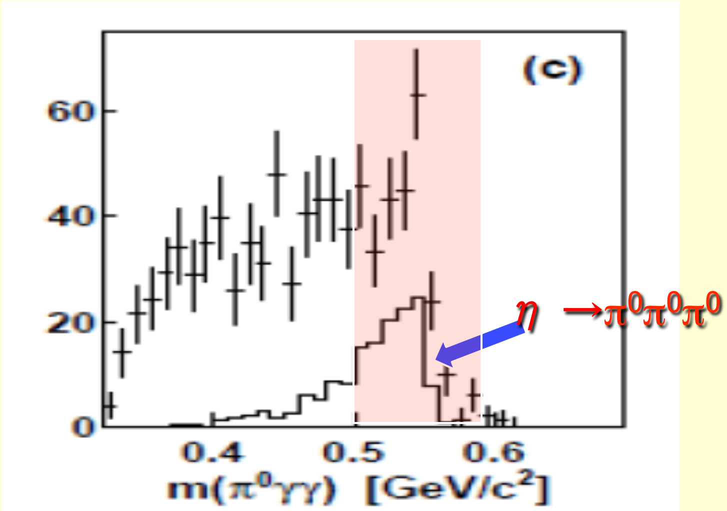


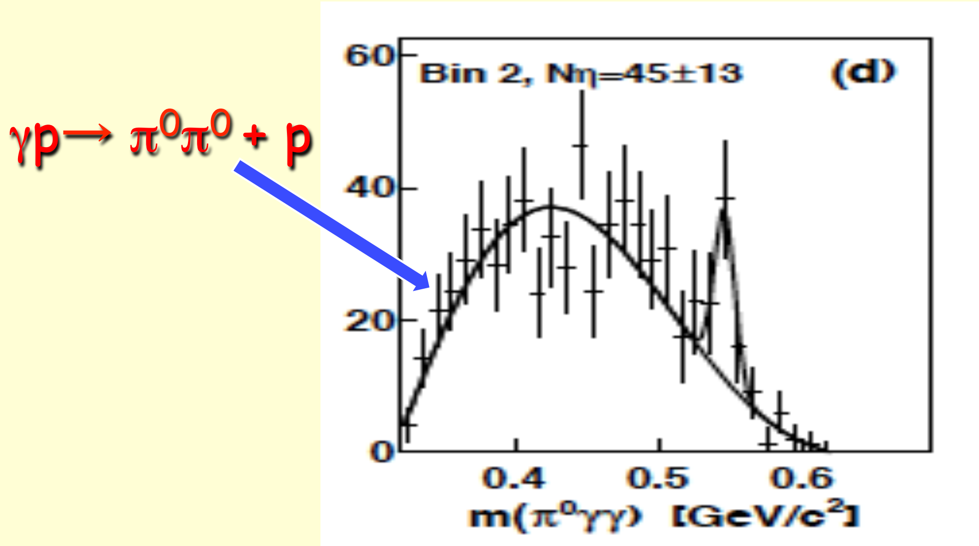
JEF at Jlab



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

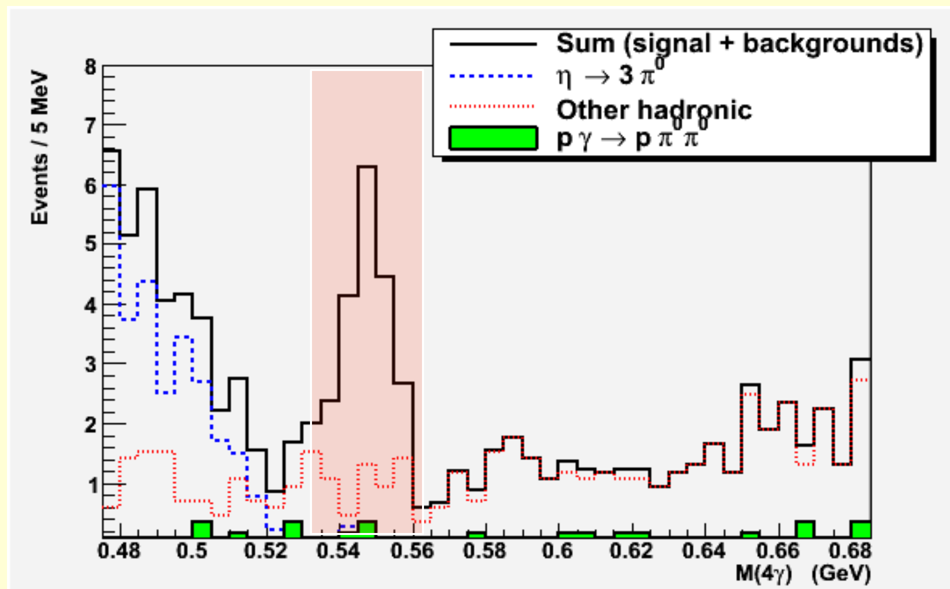
A2 at MAMI (Phys.Rev. C90 (2014) 025206): $\gamma p \to \eta p$ (E_γ=1.5 GeV)



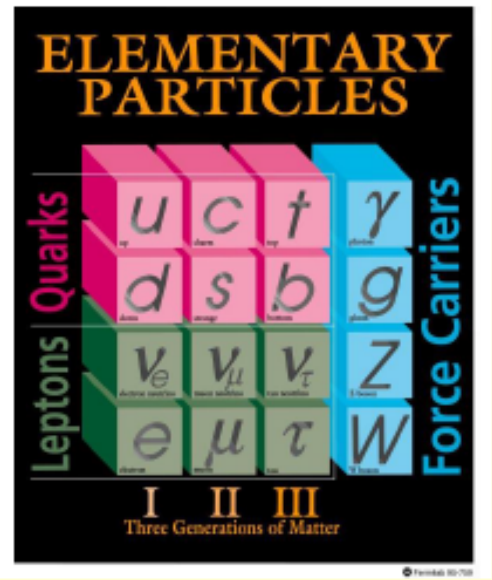


Jlab:

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



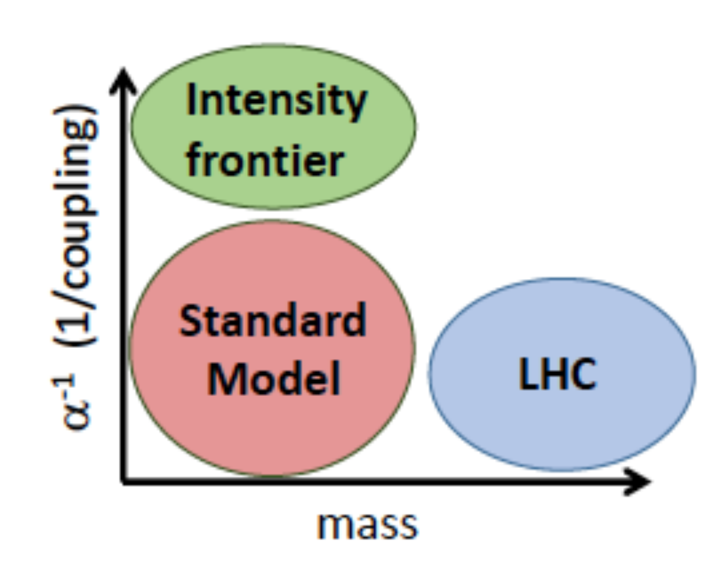
Search for Dark Forces



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:

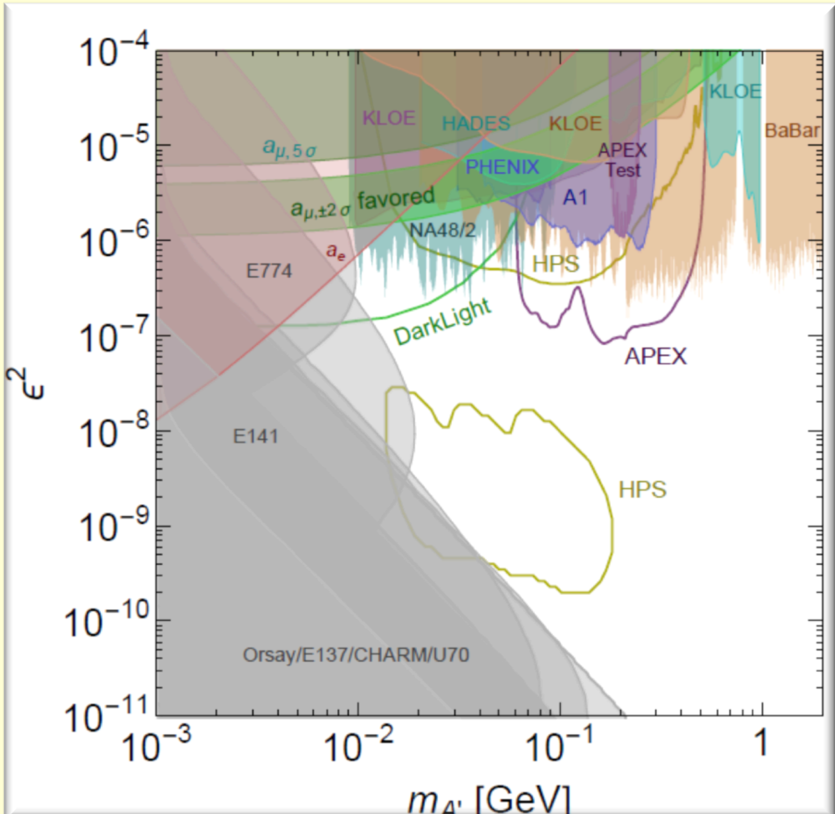
1. **Grand unified theories:** Generically have additional gauge bosons, but typically very heavy (10^{16} GeV).
2. **Dark matter:** Stability of dark matter related to new gauge symmetry?
   Can also give the right relic density.

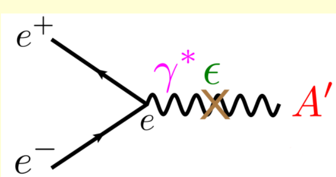


"Vector Portal" to Dark Sector

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'):

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

Gauged baryon symmetry $U(1)_B$

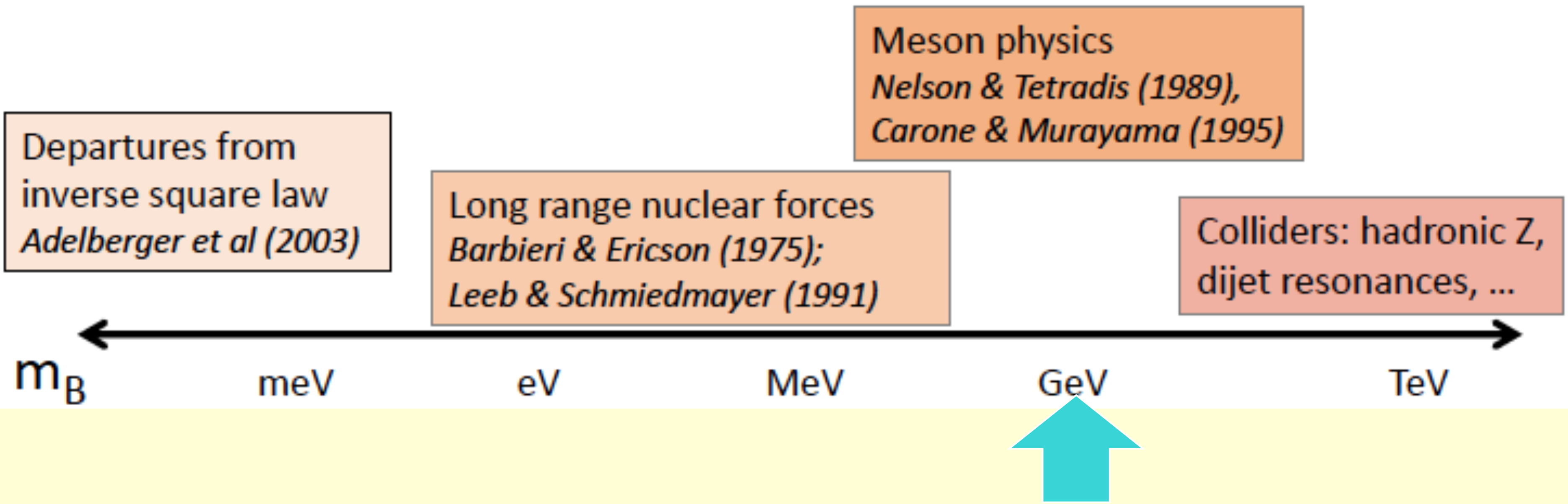
T.D. Lee and C.N. Yang, Phys.Rev.,98, 1501 (1955)

- 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:

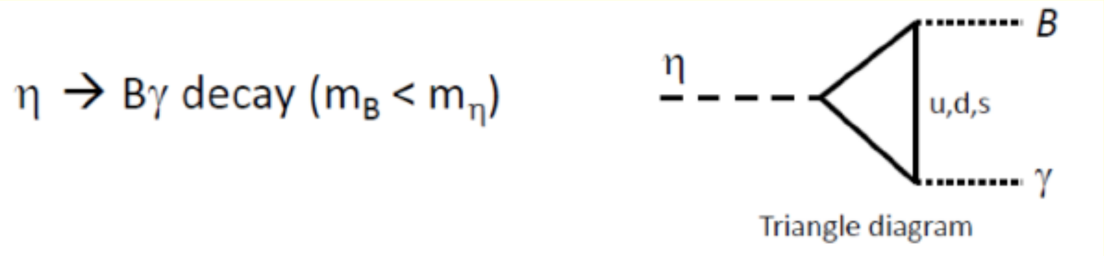
- the $m_B < m_\pi$ region is strongly constrained by long-range forces search and nuclear scattering experiments.
- the $m_B > 50 GeV$ region has been investigated by the collider experiments.
- GeV-scale domain is nearly untouched.



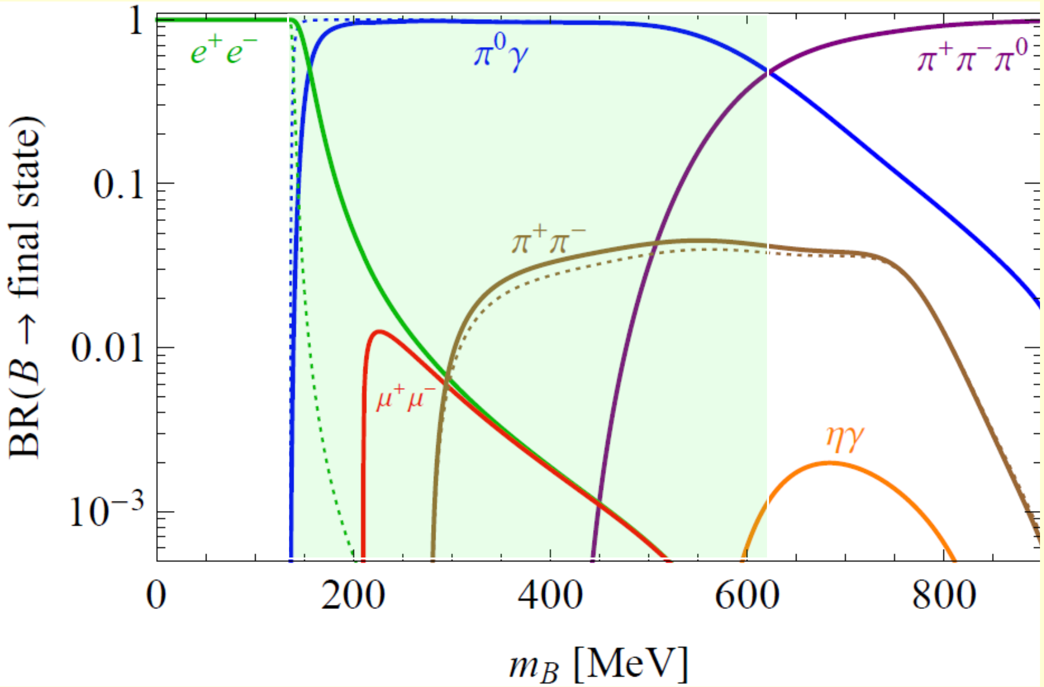
a discovery opportunity hiding in nonperturbative QCD regime!

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



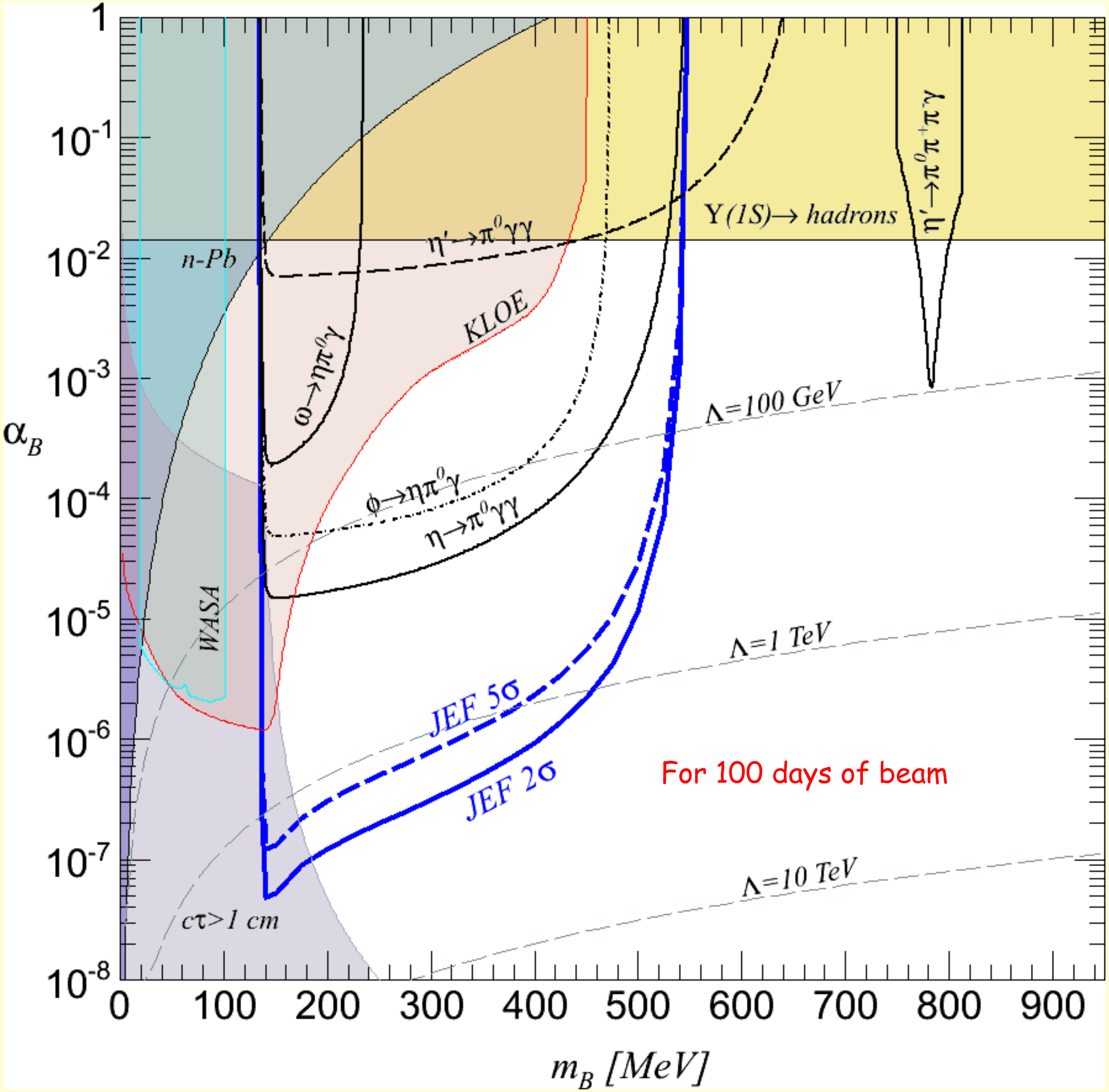
$\eta \to \gamma B \to \gamma + \pi^0\gamma$

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	$C,\ T,\ CP,\ PT$	$P,\ CT$

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Experimental tests

Class	Violated	Valid
1	C, P, CT, PT	T, CP
2	C, P, T, CP, CT, PT	
3	P, T, CP, CT	C, PT
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3	P, T, CP, CT	C, PT	EDM, $\eta \to$ even π's
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Experimental tests

P-violating exp.,
β-decays,
K-, B-, D-meson decays
EDM, $\eta \rightarrow$ even π's

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Experimental tests

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

EDM, $\eta \to$ even π's

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

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Class	Violated	Valid
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2	C, P, T, CP, CT, PT	
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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	

C Invariance

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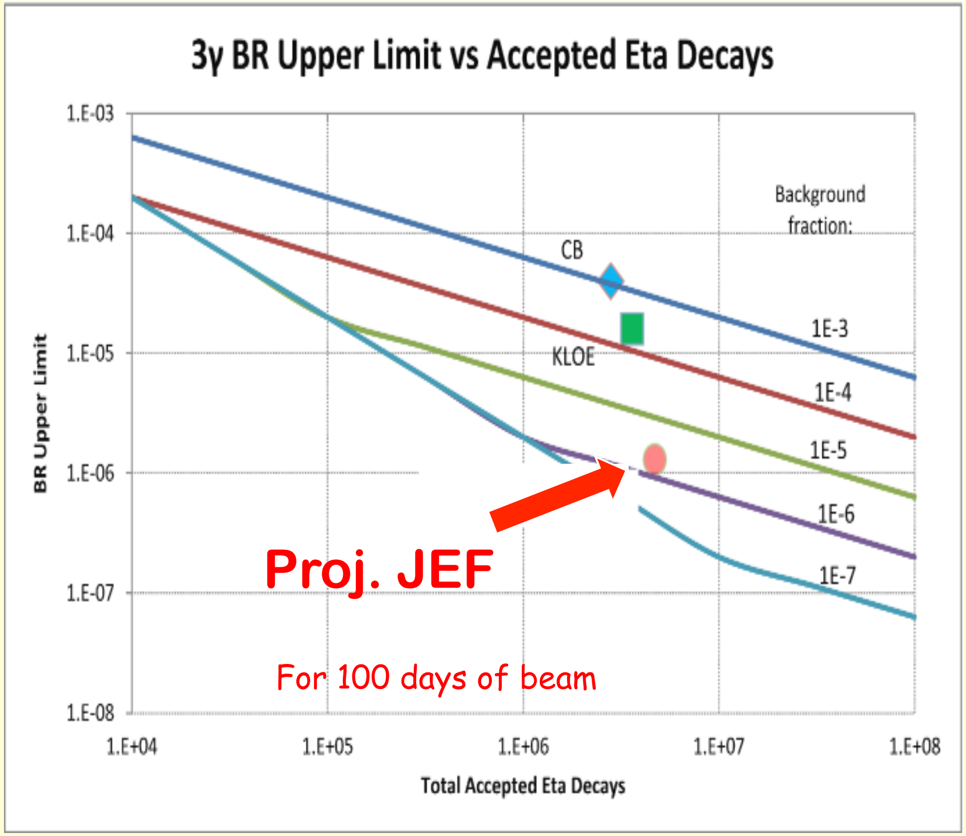
$3\gamma\pi^0$	Nothing published	
$3\pi^0\gamma$	$< 6 \cdot 10^{-5}$	7
$3\gamma 2\pi^0$	Nothing published	

Experimental Improvementon in $\eta \rightarrow 3\gamma$

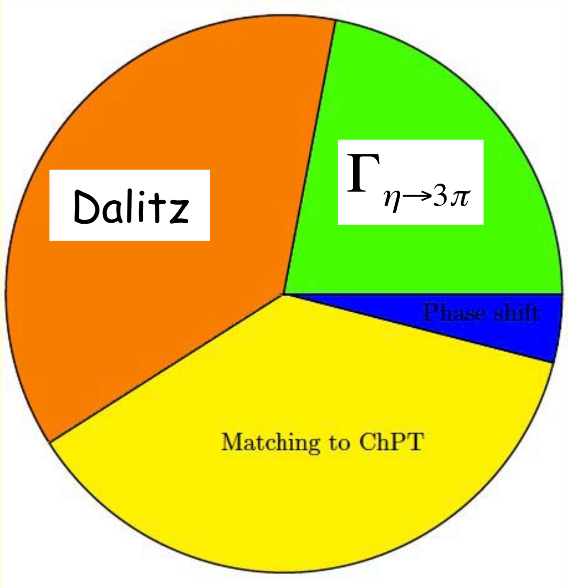
- SM contribution: BR($\eta \rightarrow 3\gamma$) <10^{-19} via P-violating weak interaction.
- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee Phys. Rev.,139, B1965 (1965)
- A calculation due to such new physics by Tarasov suggests: BR($\eta \rightarrow 3\gamma$)< 10^{-2} Sov.J.Nucl.Phys.,5,445 (1967)
- A new investigation by M. Ramsey-Musolf and two Ph.D. students is in progress

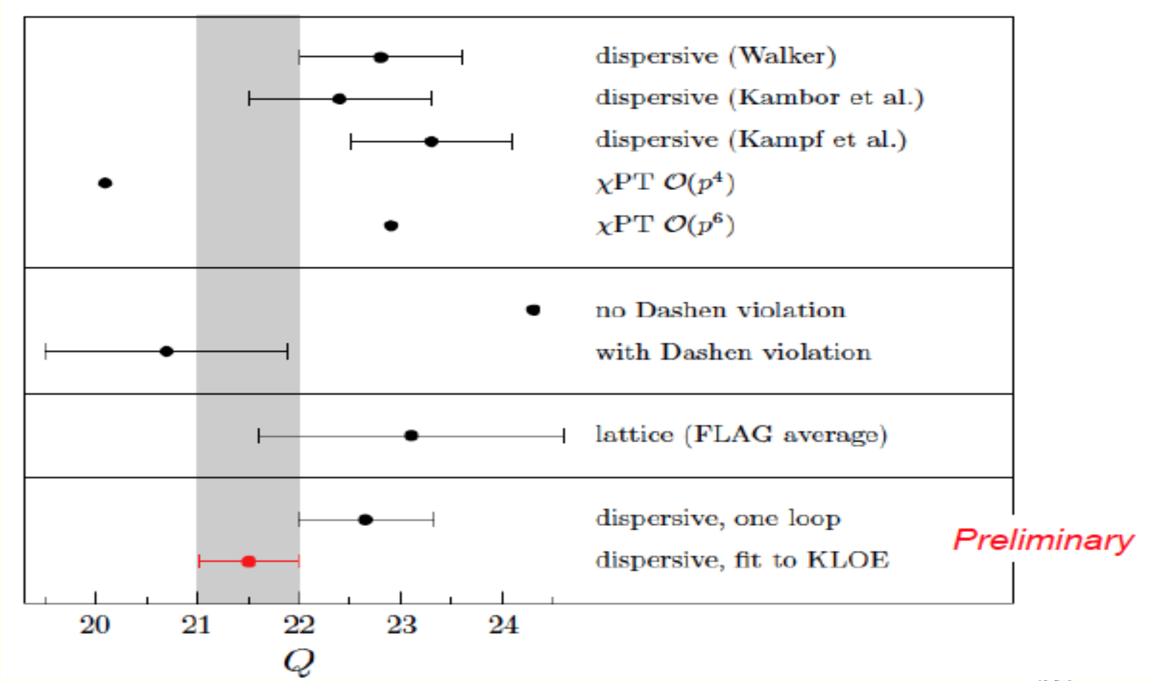


Improve BR upper limit by one order of magnitude to directly tighten the constraint on CVPC new physics

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

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





Determine Light Quark Mass Ratio via $\eta \to 3\pi$

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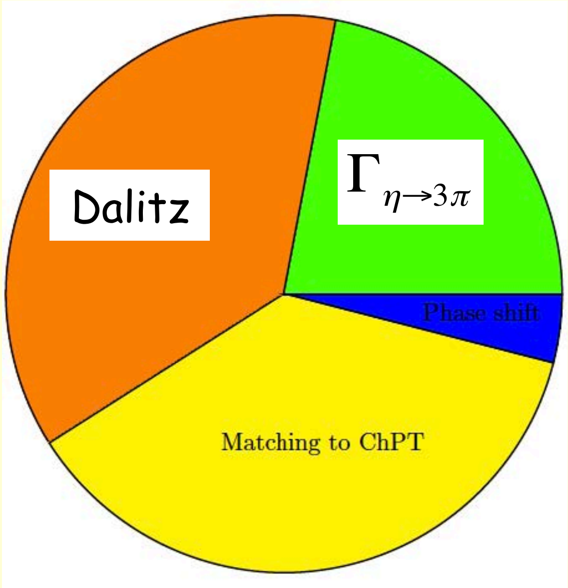
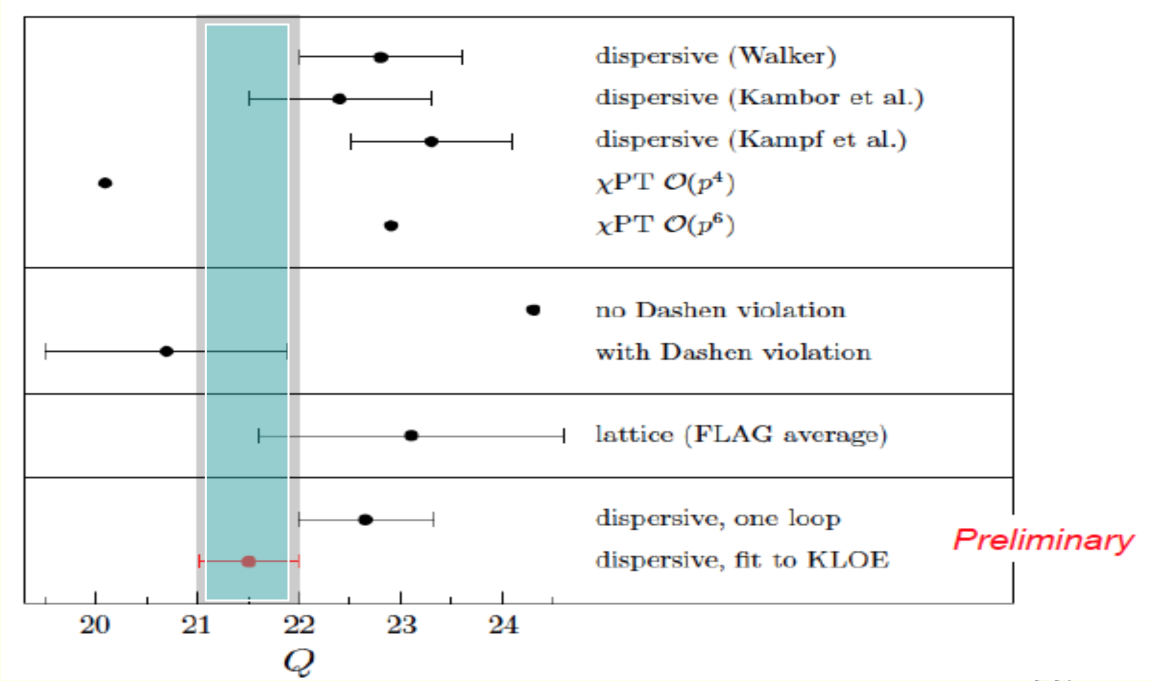
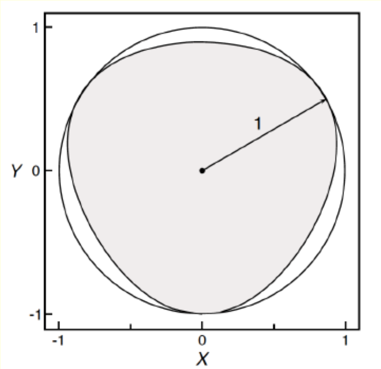




Experimental Measurements of $\eta \rightarrow 3\pi$



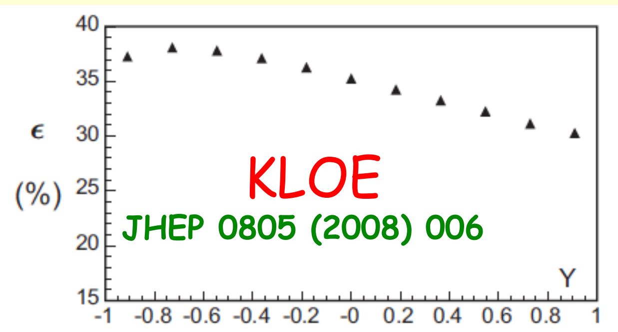
$$X = \frac{\sqrt{3}}{2 M_\eta Q_c}(u - t)$$

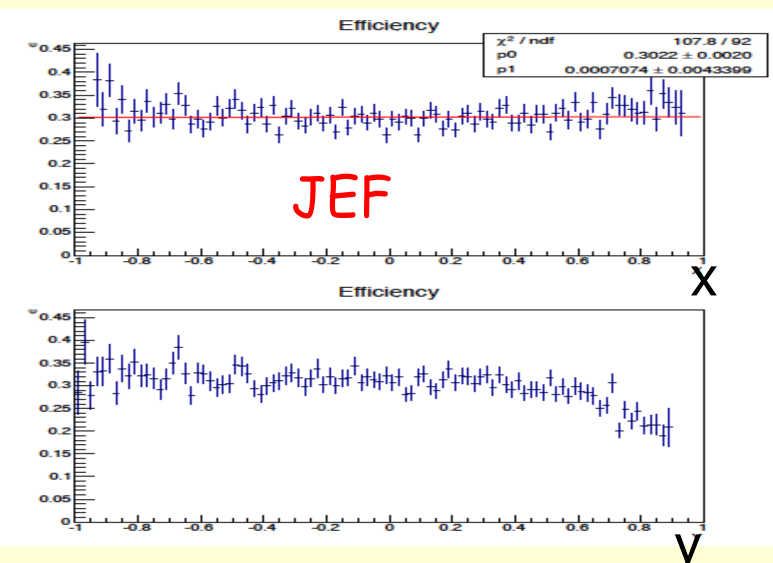
$$Y = \frac{3}{2 M_\eta Q_c}\left(\left(M_\eta - M_{\pi^0}\right)^2 - s\right) - 1$$

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

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

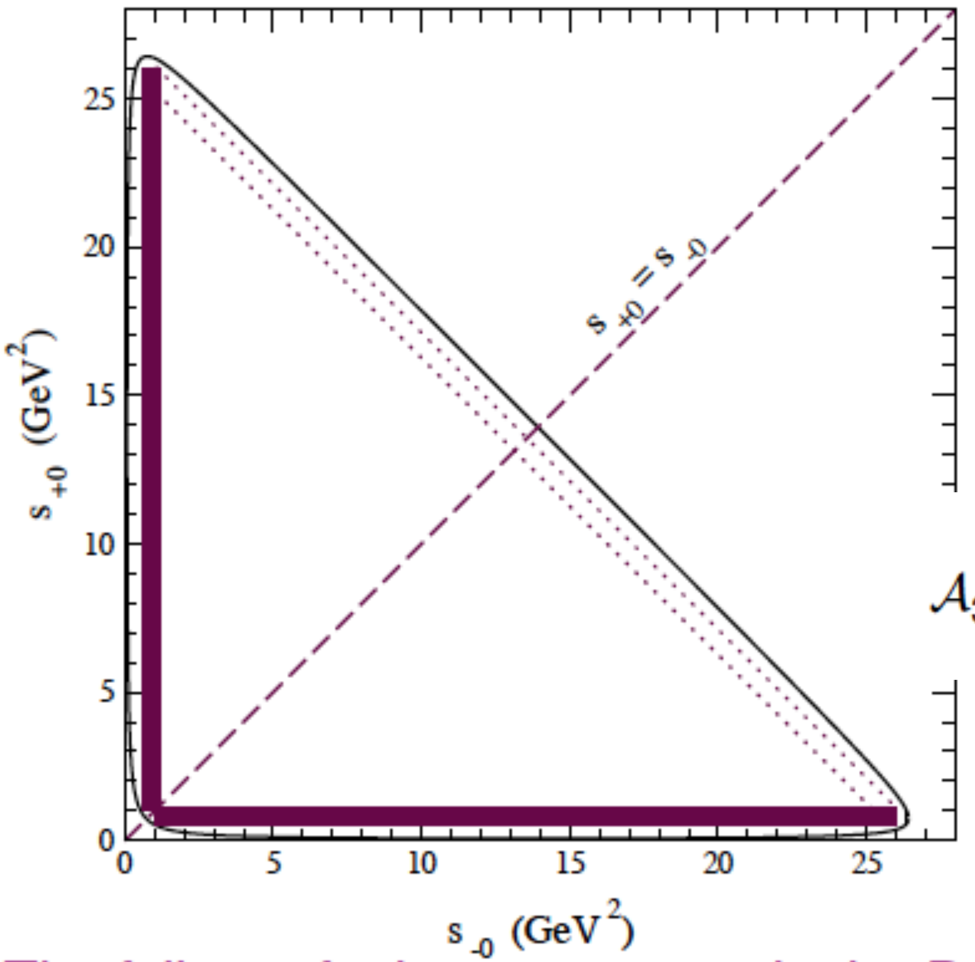
Exp.	$3\pi^0$ Events (10^6)	$\pi^+ \pi^- \pi^0$ Events (10^6)
Total world data (include prel. WASA and prel. KLOE)	6.5	6.0
GlueX+PrimEx-η +JEF	20	19.6





- 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

Dalitz Studies of CP Violation in $\eta^{(\prime)} \to \pi^+\pi^-\pi^0$



$$\mathcal{A}_{3\pi} \equiv \frac{\Gamma_{3\pi}[s_{+0}>s_{-0}] - \Gamma_{3\pi}[s_{+0}<s_{-0}]}{\Gamma_{3\pi}[s_{+0}>s_{-0}] + \Gamma_{3\pi}[s_{+0}<s_{-0}]}$$

The failure of mirror symmetry in the Dalitz plot in η or η' decay (or of the **untagged** decay rate in $B, \bar{B}$ or $D, \bar{D}$ decay) to $\pi^+\pi^-\pi^0$ signals the presence of CP violation.

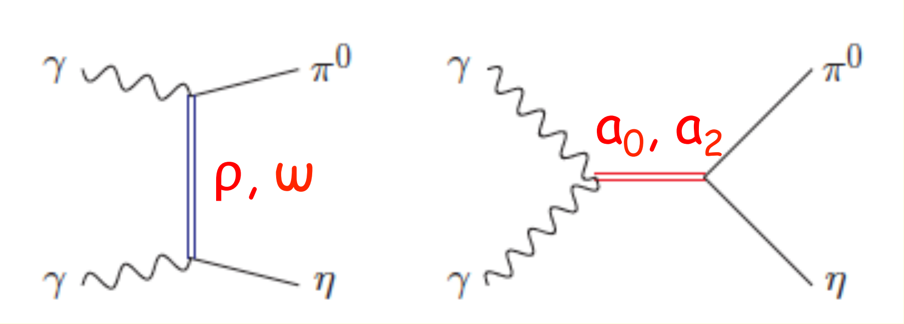
SM allowed $\eta \to \pi^0 \gamma\gamma$

→ 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)

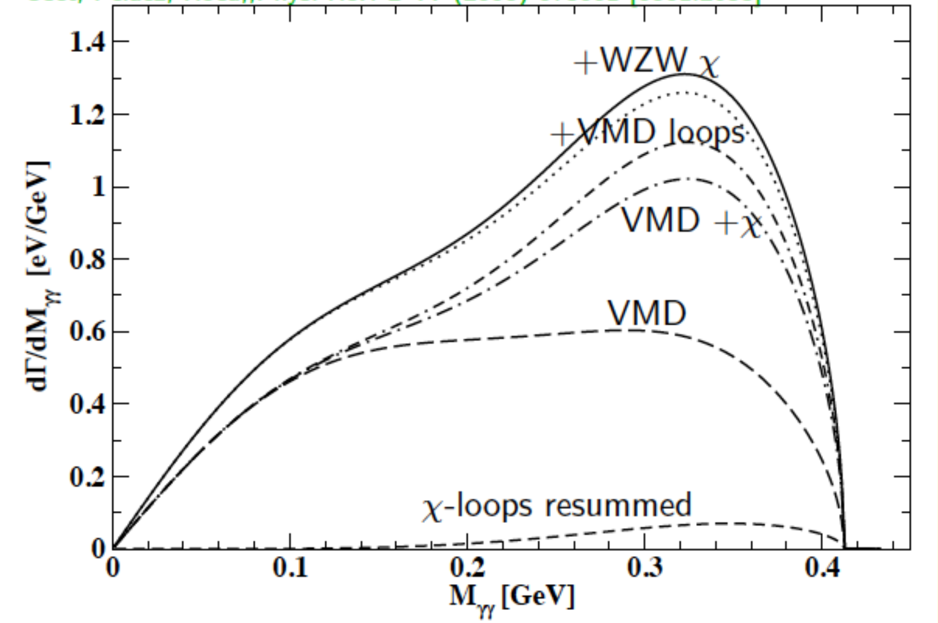
- The major contributions to $\eta \to \pi^0 \gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian → an unique probe for the high order ChPT.
  L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

- 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

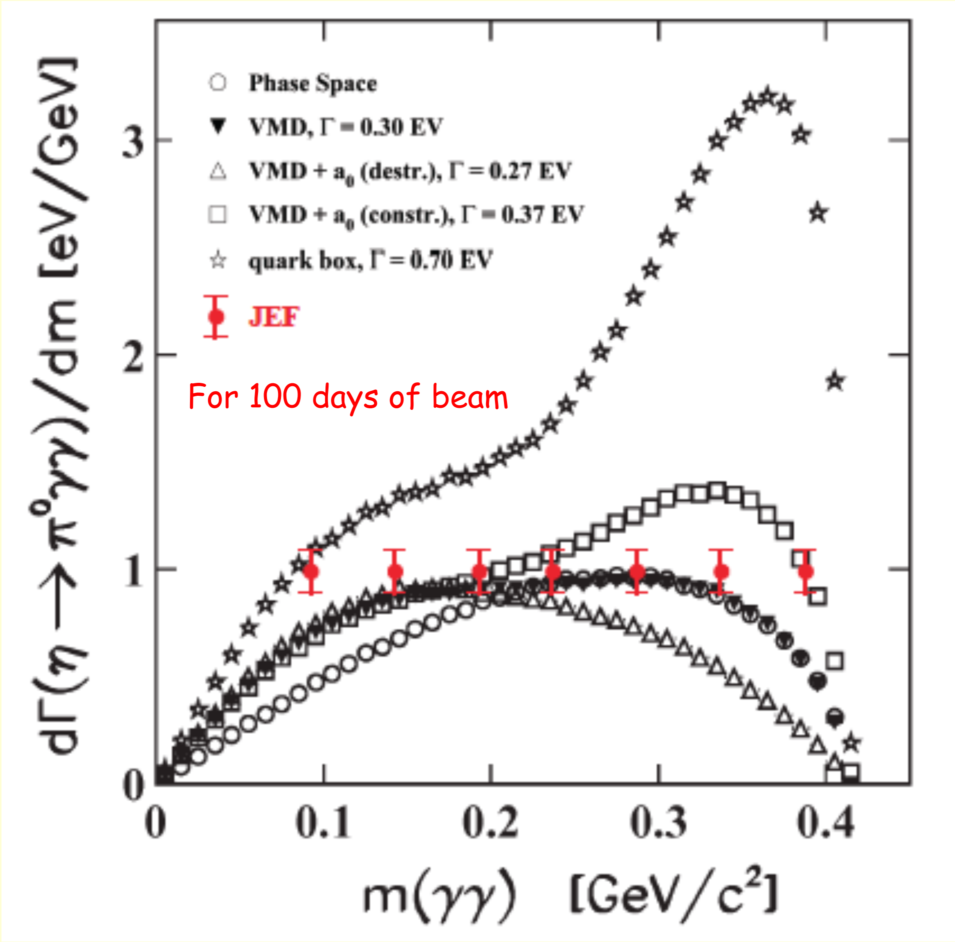


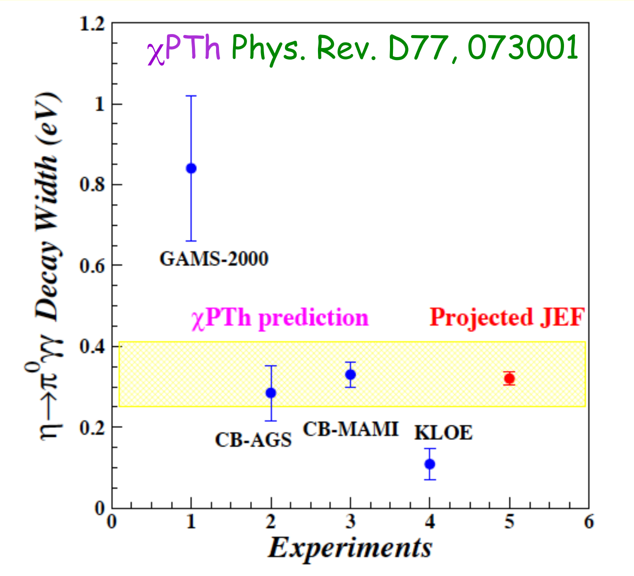
Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]

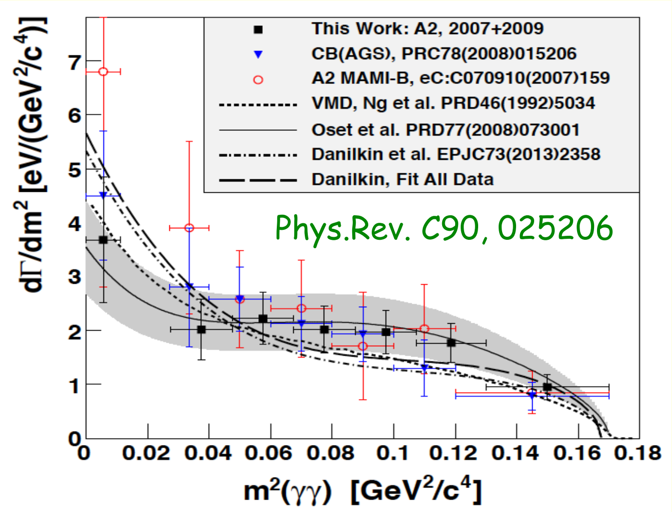


Projected JEF results on $\eta \to \pi^0 \gamma\gamma$

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

Summary

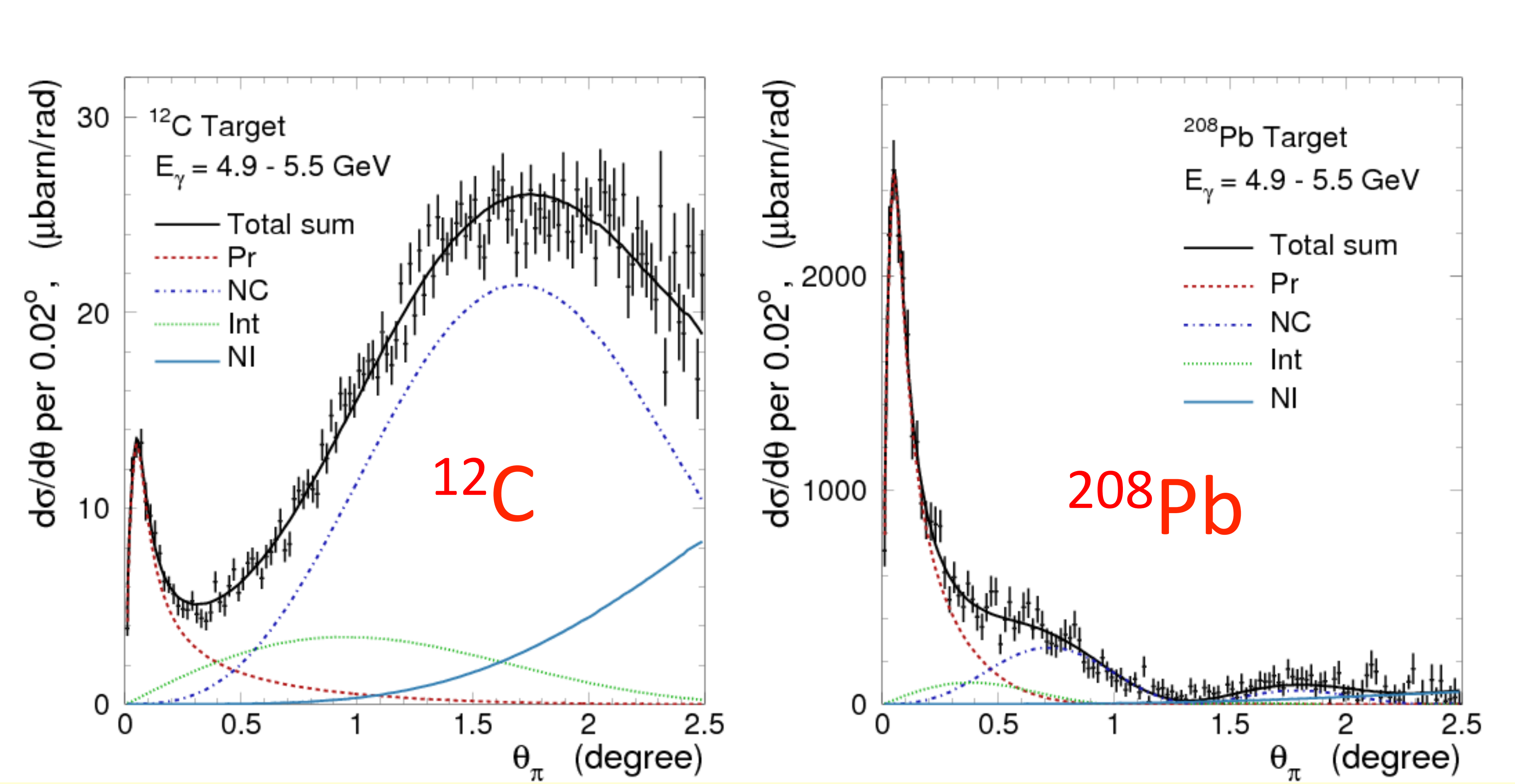
- **A comprehensive Primakoff program has been developed at Jlab to measure $\Gamma(p \rightarrow \gamma\gamma)$ and $F(\gamma\gamma^* \rightarrow p)$ of π^0, η and η′. These results will provide rich data sets to test the fundamental symmetries of QCD at low energy.**
  - tests of chiral symmetry and 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.**
  - 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 $\eta \rightarrow 3\gamma$ and other C-violating channels
  - A clean determination of the light quark mass ratio via $\eta \rightarrow 3\pi$
  - Test the role of scalar dynamics in ChPT through $\eta \rightarrow \pi^0\gamma\gamma$

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

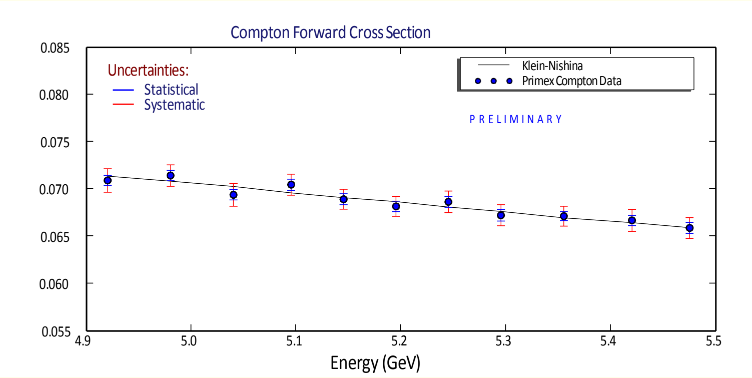
The first experiment: PrimEx-I (2004)

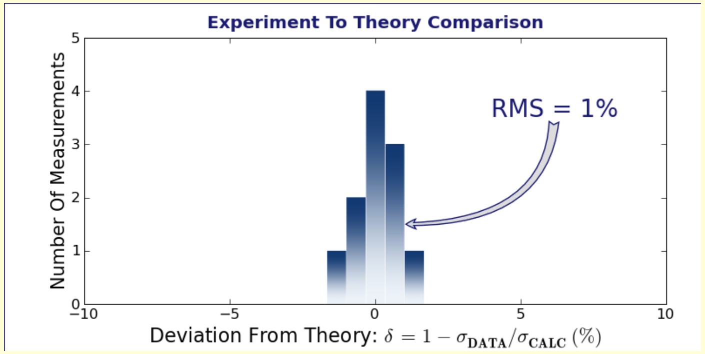
Theoretical angular distributions smeared with experimental resolutions are fit to the data on two nuclear targets to extract $\Gamma(\pi^0 \rightarrow \gamma\gamma)$



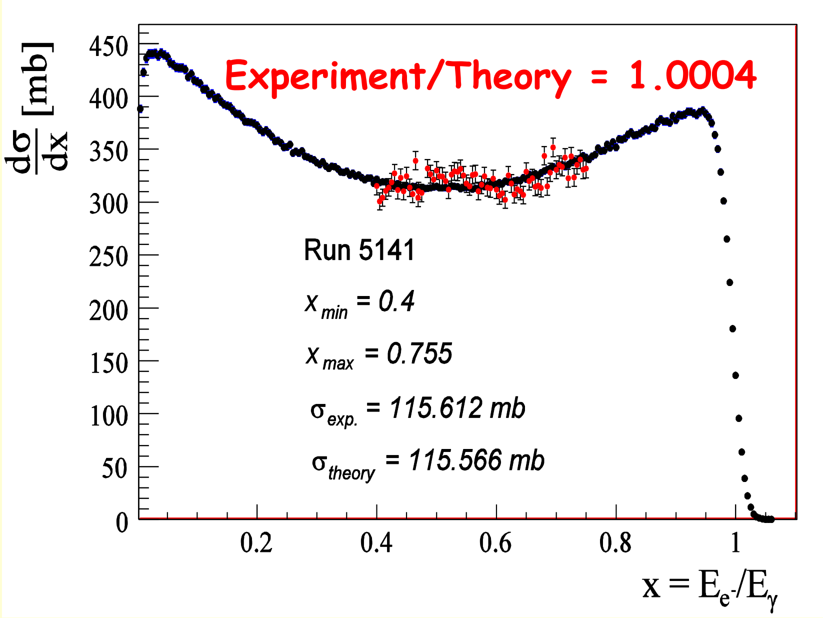
Verification of Overall Systematical Uncertainties

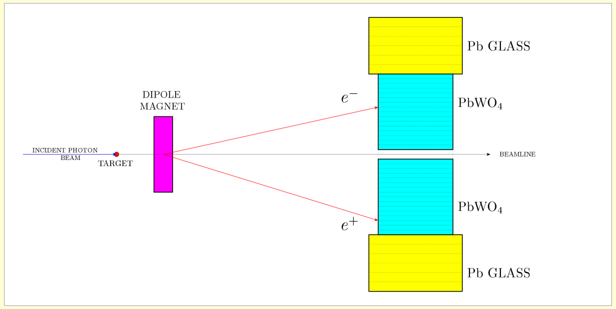
- $\gamma + e \rightarrow \gamma + e$ Compton cross section measurement





- 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**

Challenges in the $\eta\to\gamma\gamma$ Primakoff experiment

Compared to π^0:

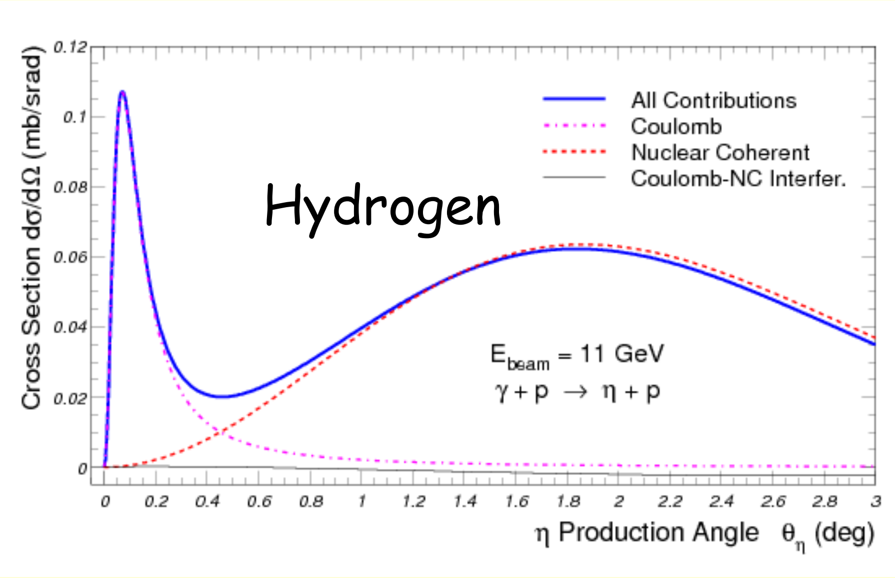
- η mass is a factor of 4 larger than π^0 and has a smaller cross section

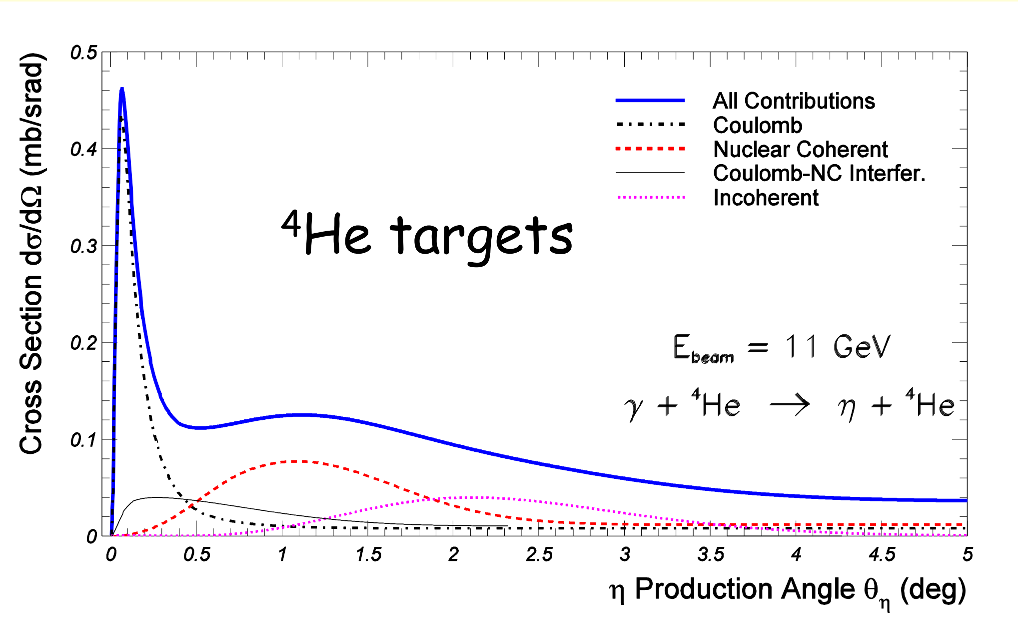
$$\left(\frac{d\sigma_{\rm Pr}}{d\Omega}\right)_{\rm peak} \propto \frac{E^4}{m^3}$$

- larger overlap between Primakoff and hadronic processes;

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

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





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 $\gamma+p \to \eta/\eta'+p$ 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)

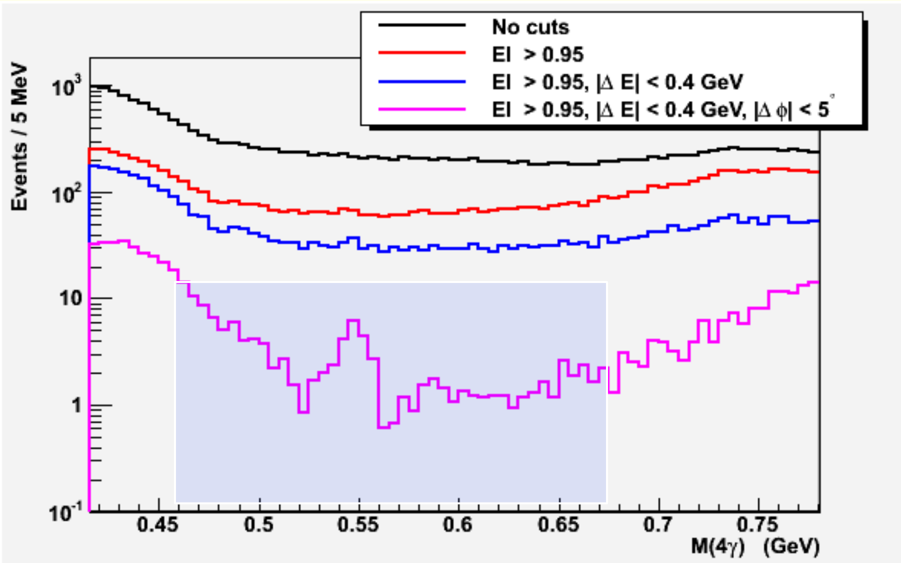
Photon beam intensity N_γ ~5x10^7 Hz (for E_γ ~9-11.7 GeV)

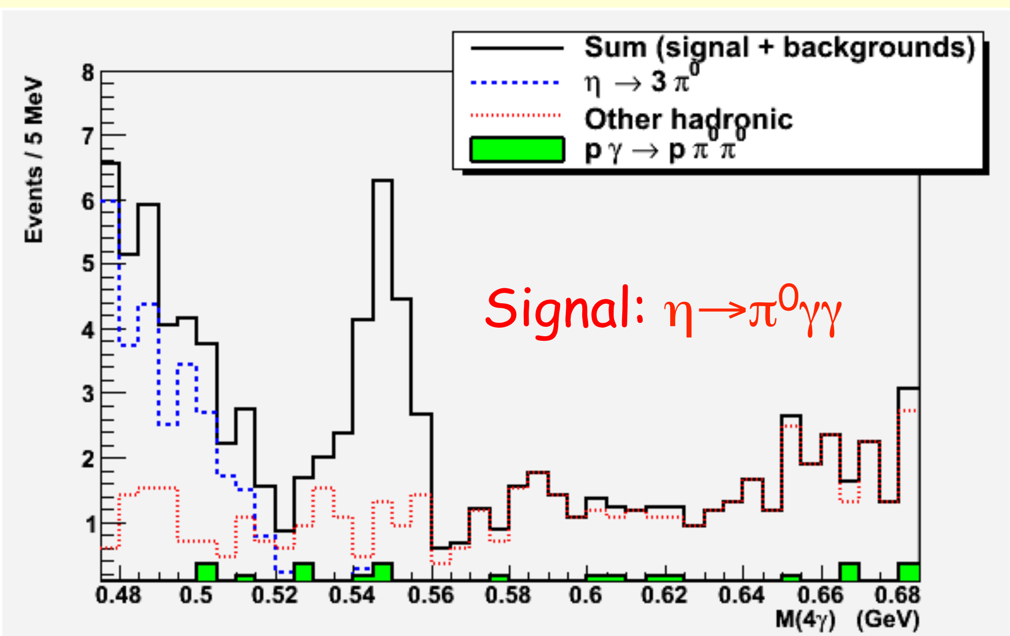
$$N_\eta = N_\gamma N_p \sigma = 5 \times 10^7 \times 1.28 \times 10^{24} \times 70 \times 10^{-33}$$
$$= 4.5 \text{ Hz}$$
$$\approx 3.9 \times 10^5 \ (\eta\text{'s/day})$$

Jlab Eta Factory (JEF)

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

Hadronic Backgrounds Reduction in 4γ States





Event Selection

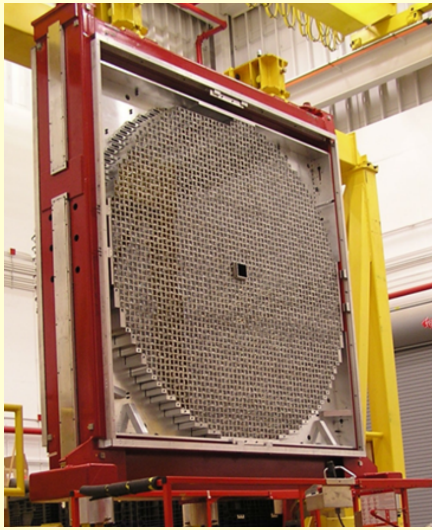
- Elasticity is $EL=\Sigma E_{\gamma}/ E_{tagged\text{-}\gamma}$
- Energy conservation for $\gamma+p \to \eta+p$ reaction: $\Delta E=E(\eta)+E(p)-E(beam)-M(p)$
- Co-planarity $\Delta\phi= \phi(\eta)- \phi(p)$

Note:

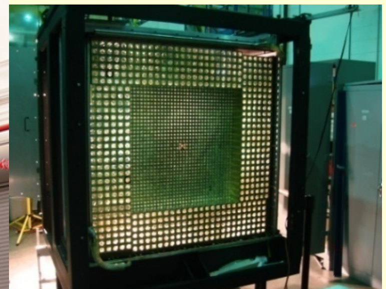
- Statistics is normalized to 1 beam day.
- BG will be further reduced by requiring that only one pair of γ's have the π^0 invariant mass.

New Equipment: FCAL-II

FCAL



HyCal

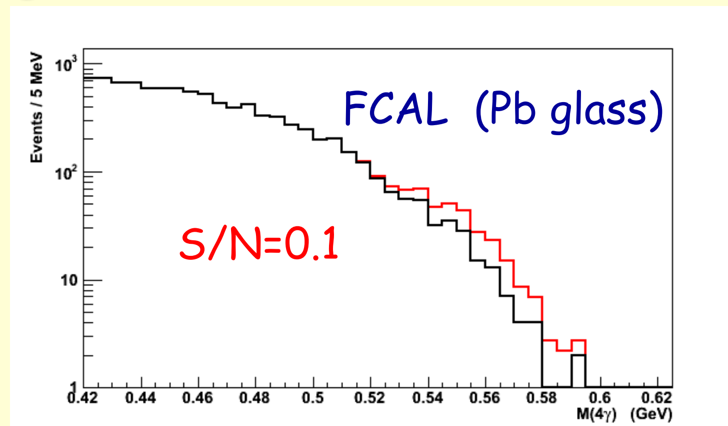


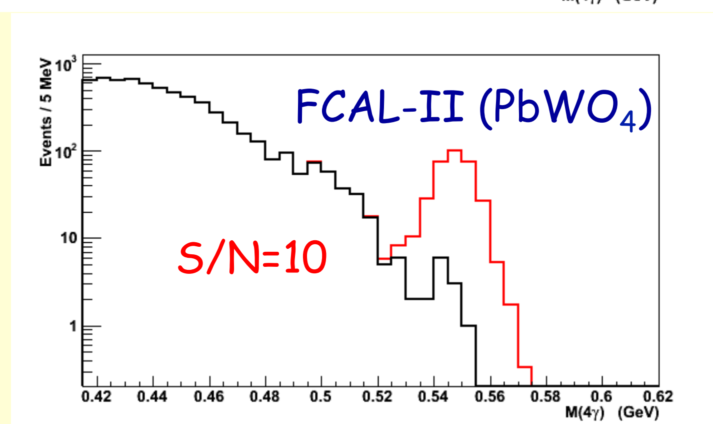
FCAL with PWO insertion:

- 118×118 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

Jlab and GlueX