Test Fundamental Symmetries via π^0, η, η' Decays

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Outline

1. Introduction
   → challenges in physics

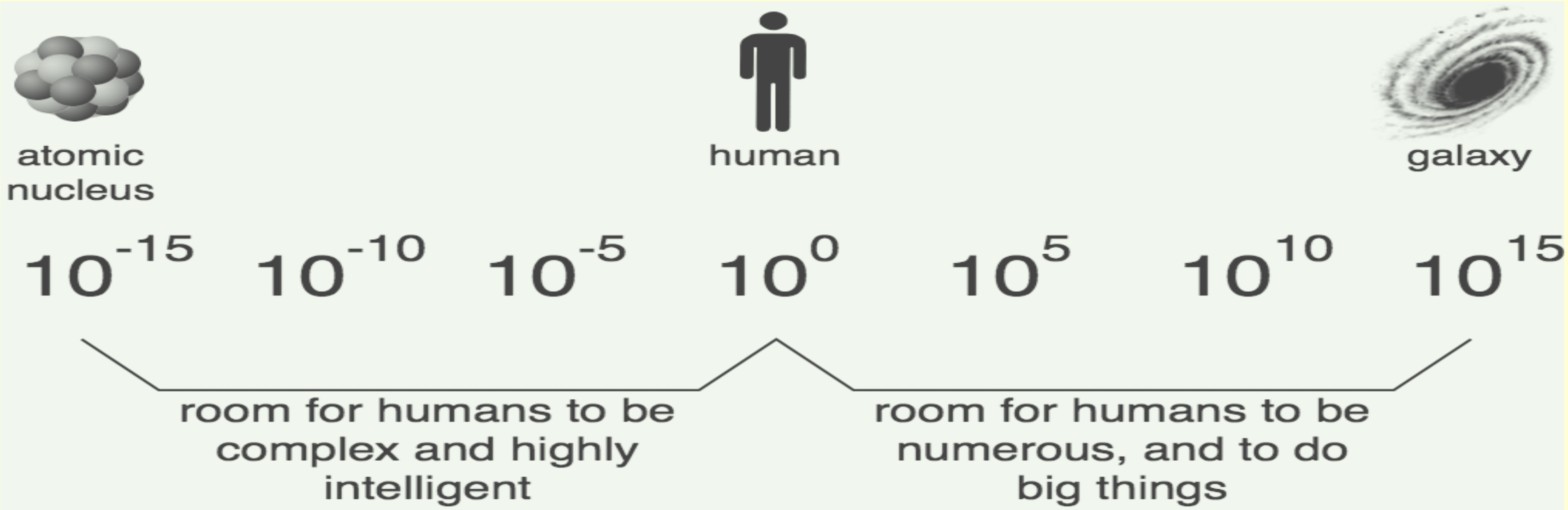
2. Primakoff experiments on π^0, η, η'
   → precision tests confinement QCD symmetries

3. JLab Eta Factory (JEF) Program for rare η decays
   → search for BSM new physics

4. Summary

This project is supported by NSF PHY-1206043 and PHY-1506303 awards.

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

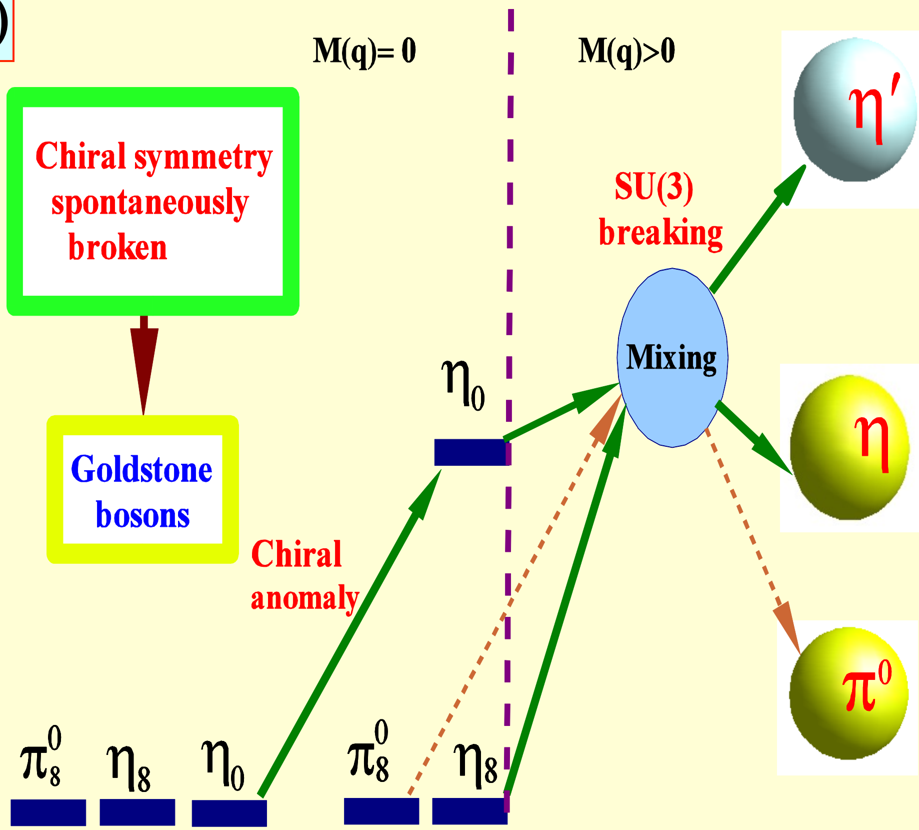
"As far as I see, all priori statements in physics have their origin in symmetry". By H. Weyl

QCD Symmetries and Light Mesons

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

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

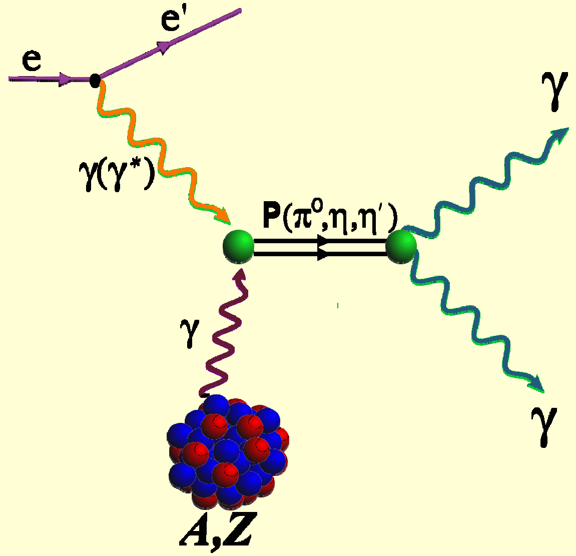
- Chiral symmetry $SU_L(3) \times SU_R(3)$ spontaneously breaks to $SU(3)$
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Mass of η_0
- $SU_L(3) \times SU_R(3)$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

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

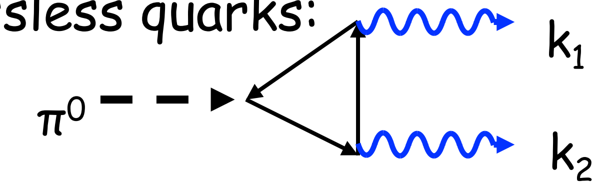
Input to Physics:

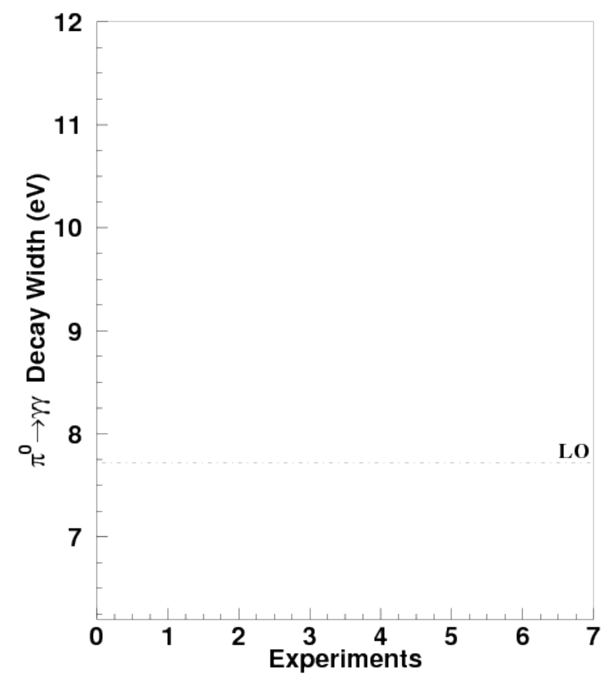
- π^0, η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- inputs to a_μ(HLbL) calculations

Axial Anomaly Determines π^0 Lifetime

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

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





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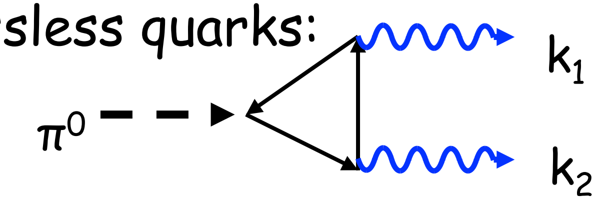
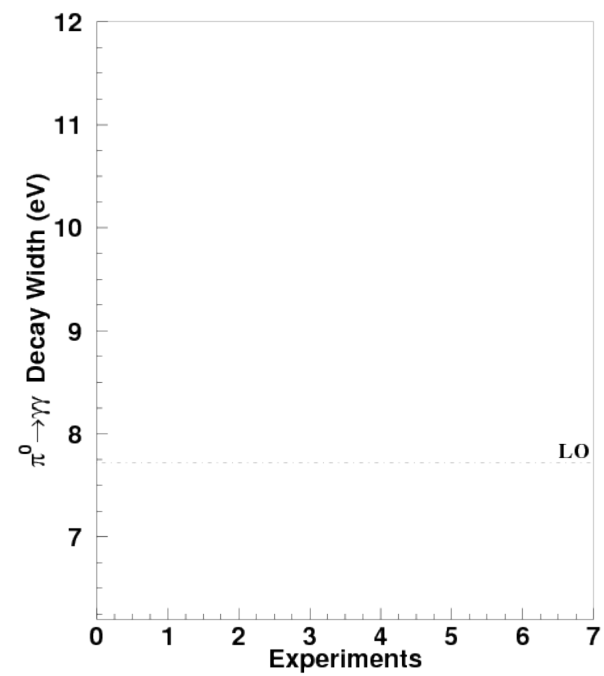


- $\Gamma(\pi^0 \to \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at ~1% level to higher orders!



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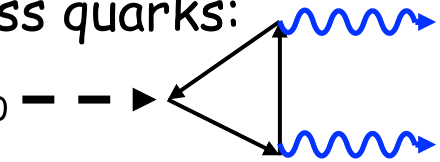

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➢ Corrections to the chiral anomaly prediction:

Calculations in NLO ChPT:

- ❑ $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.10eV ± 1.0%
  (J. Goity, et al. Phys. Rev. D66:076014, 2002)
- ❑ $\Gamma(\pi^0 \to \gamma\gamma)$ = 8.06eV ± 1.0%
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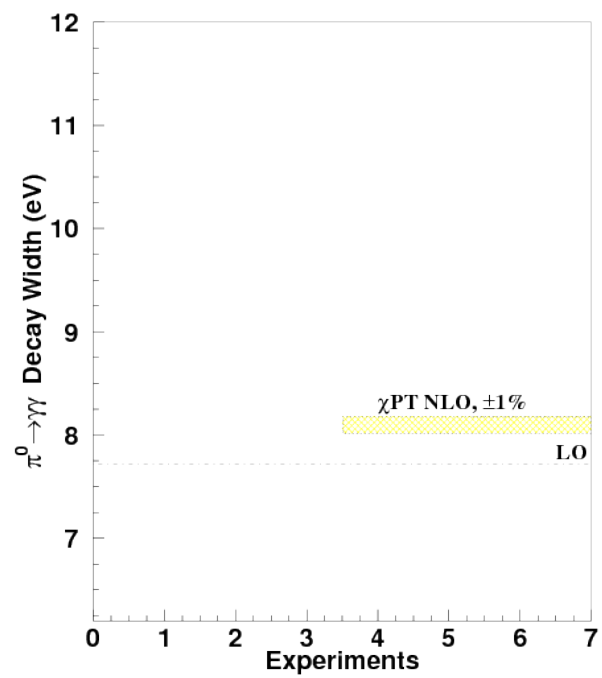

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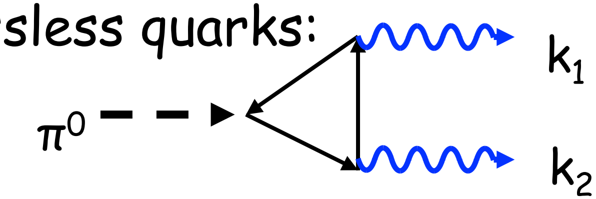

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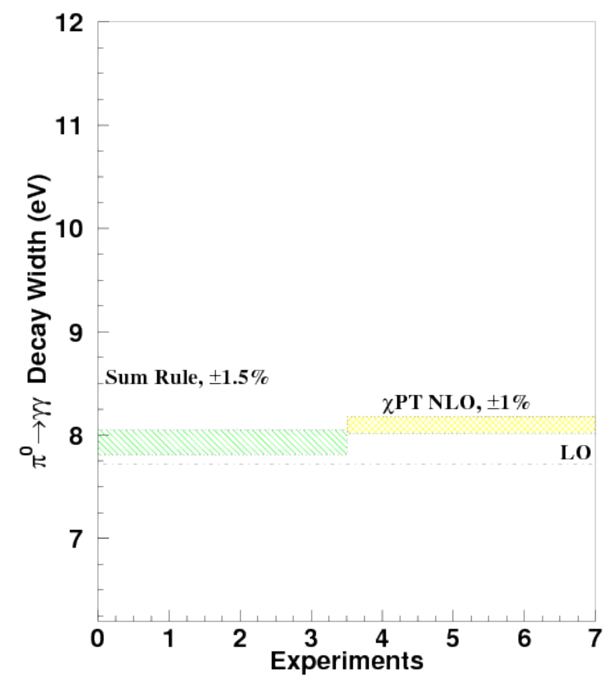

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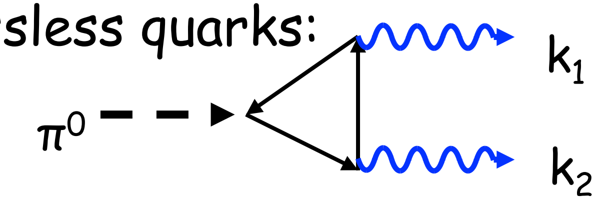

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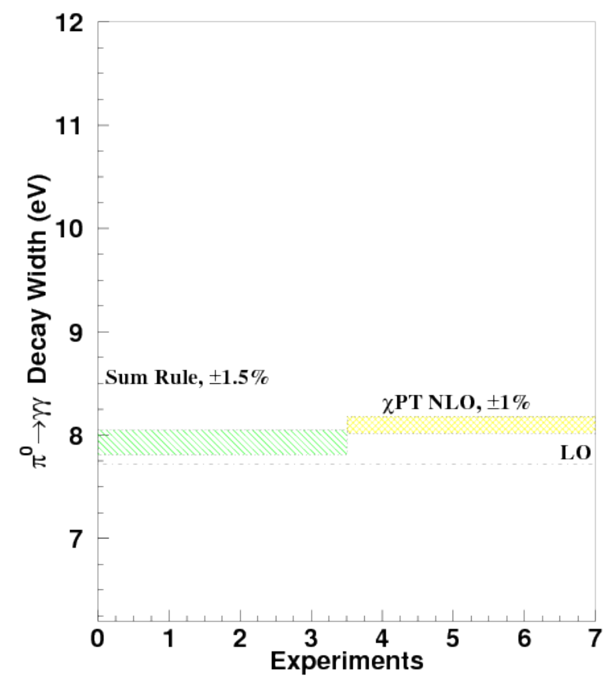

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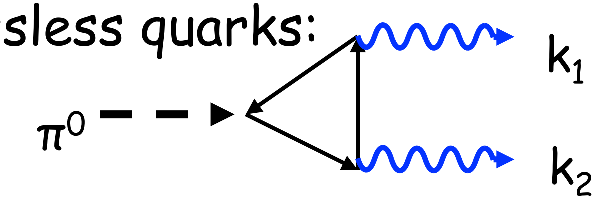

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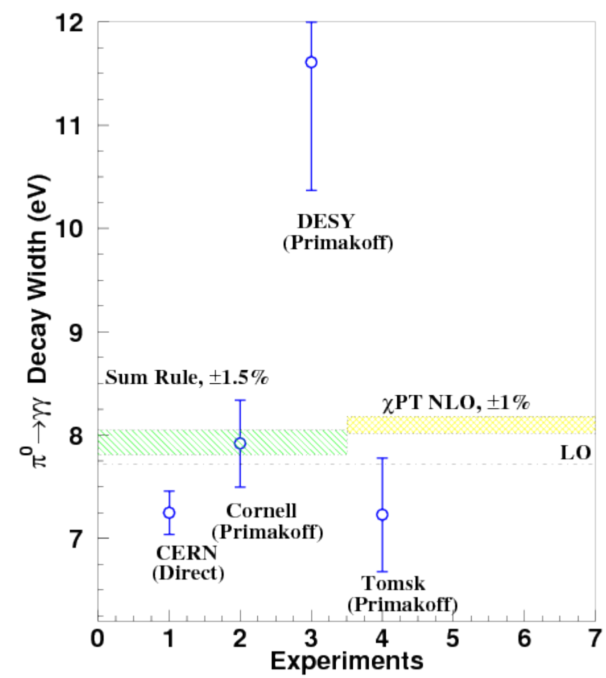

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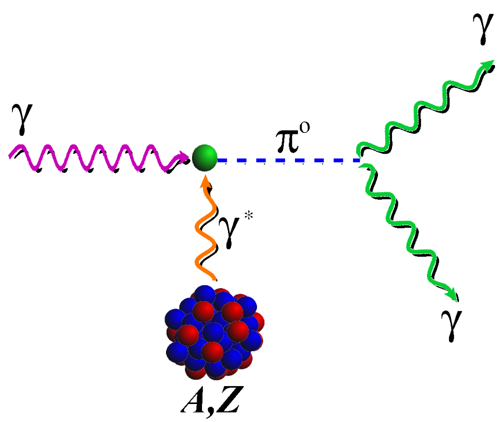
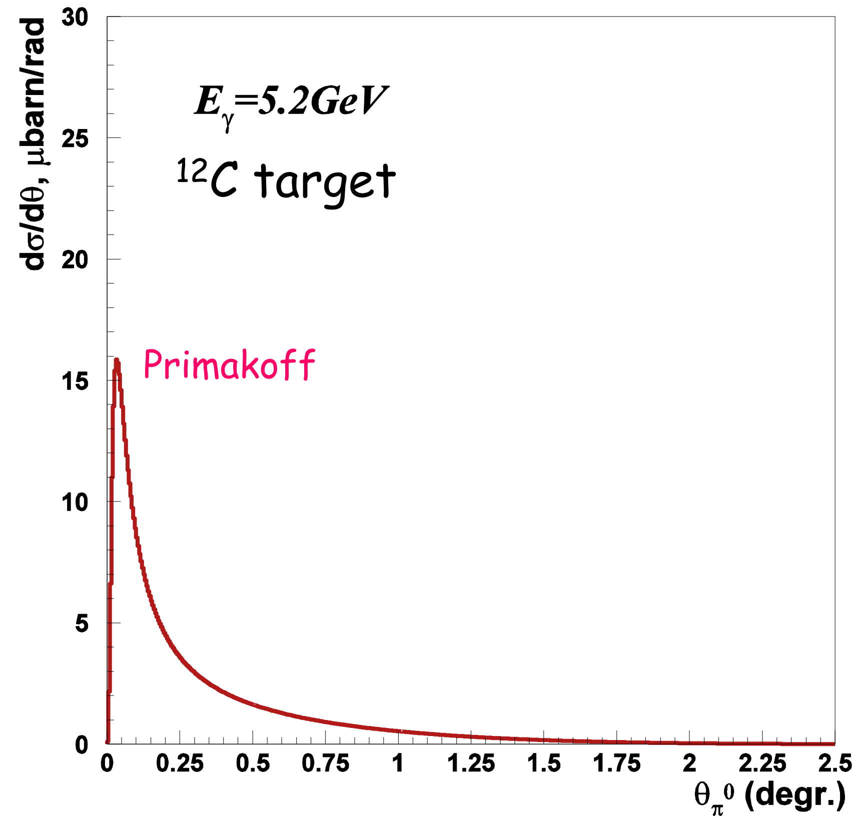
Primakoff Method



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



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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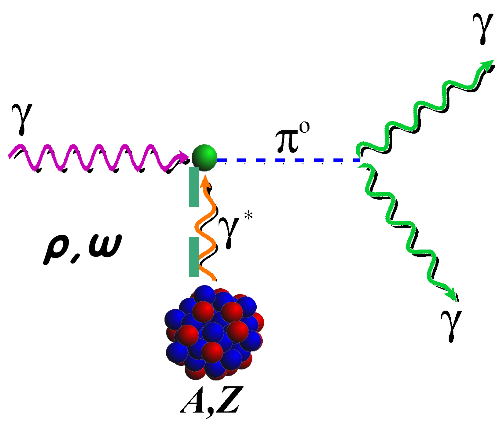

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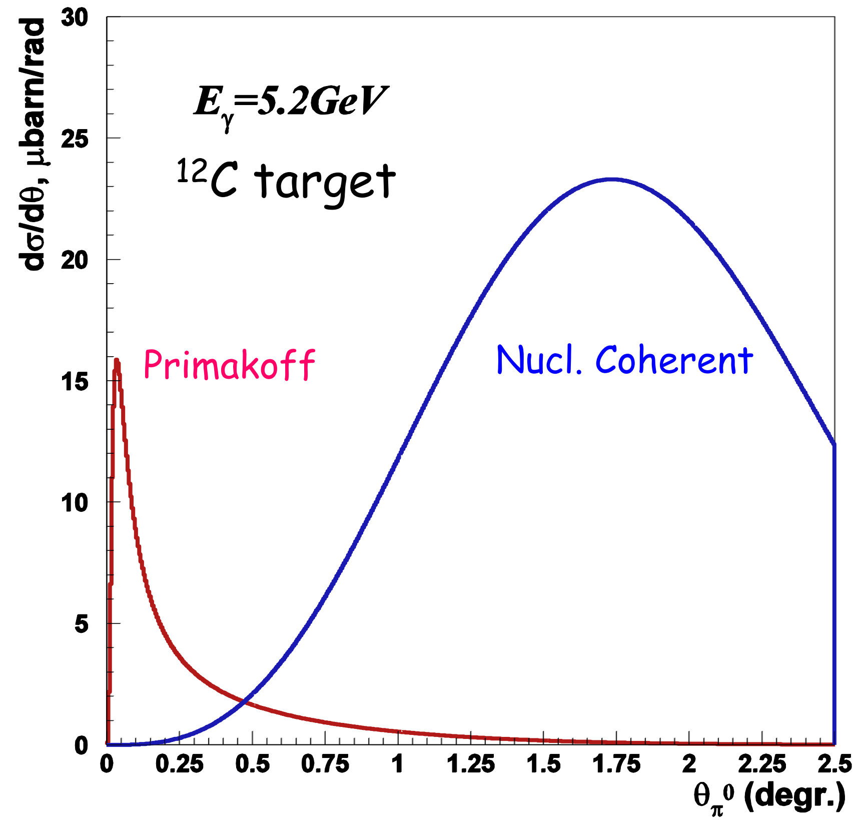

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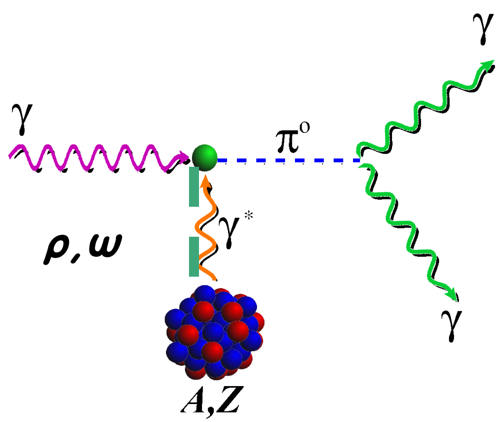

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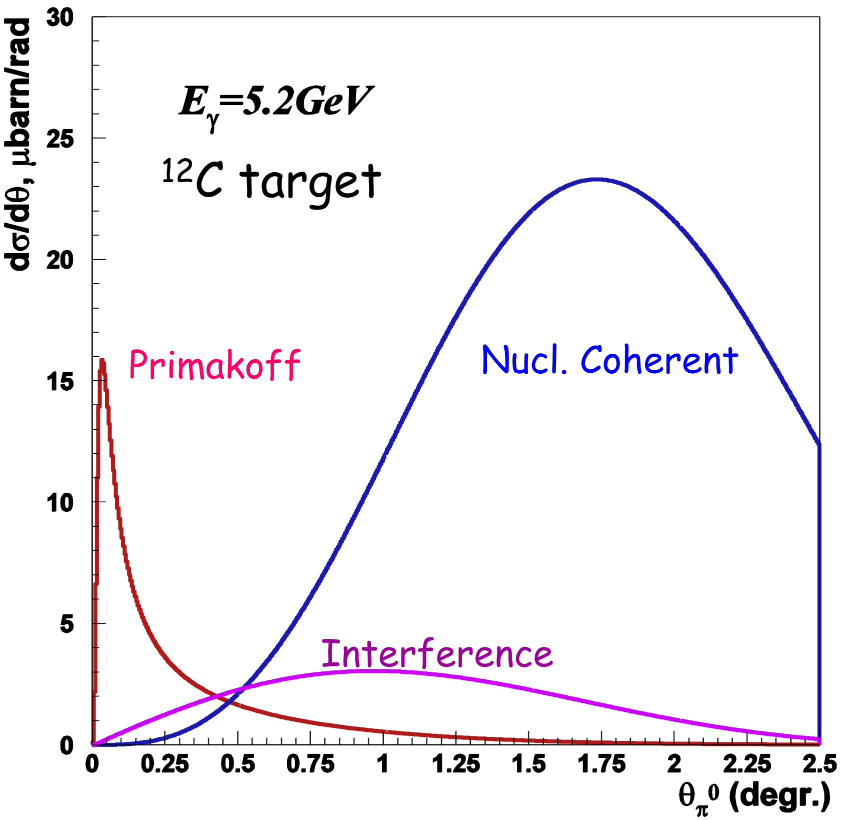

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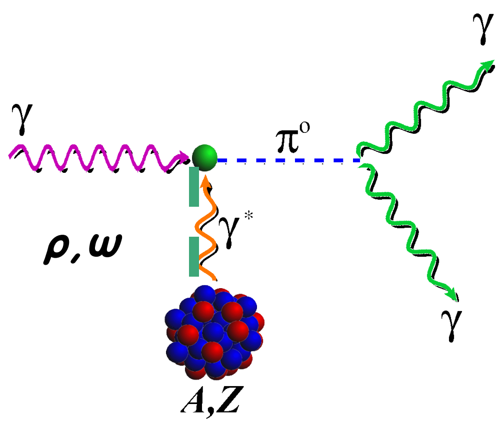

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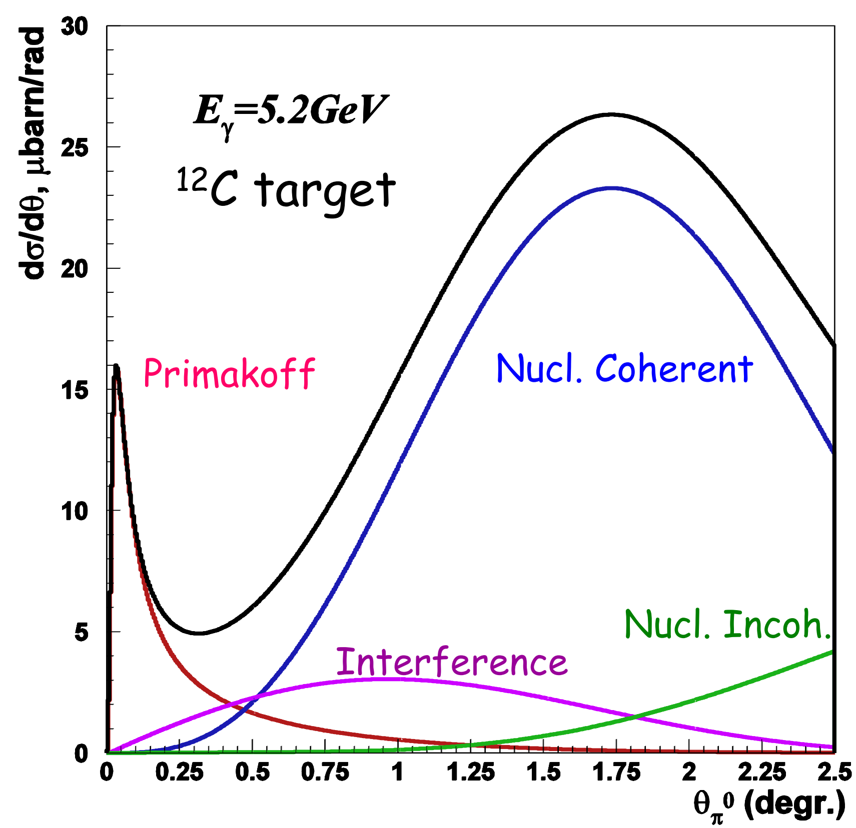

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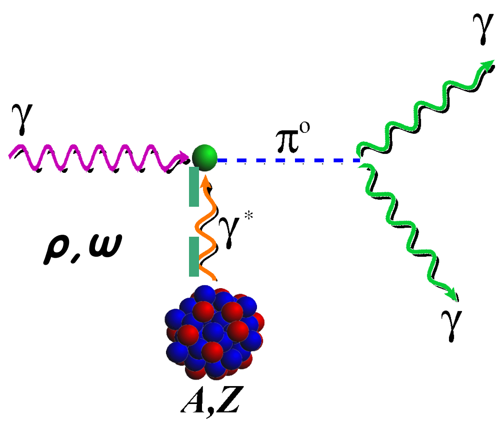

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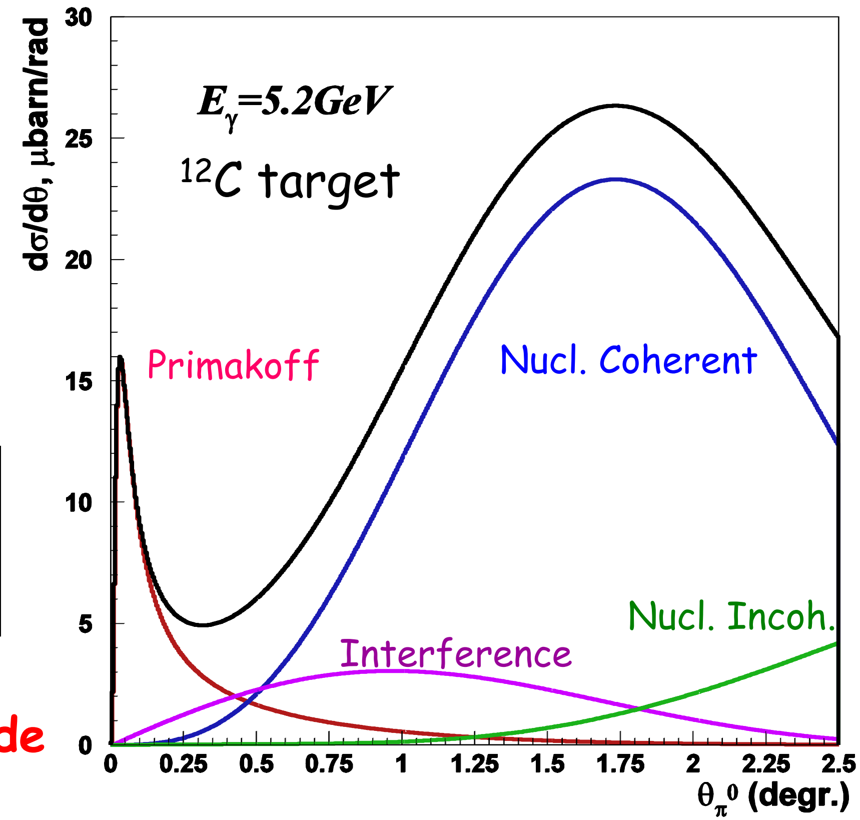
Challenge: Extract the Primakoff amplitude



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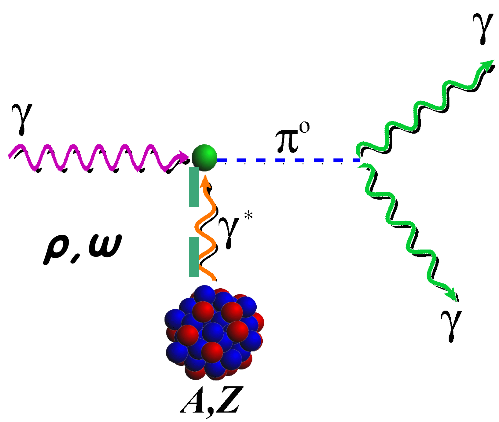

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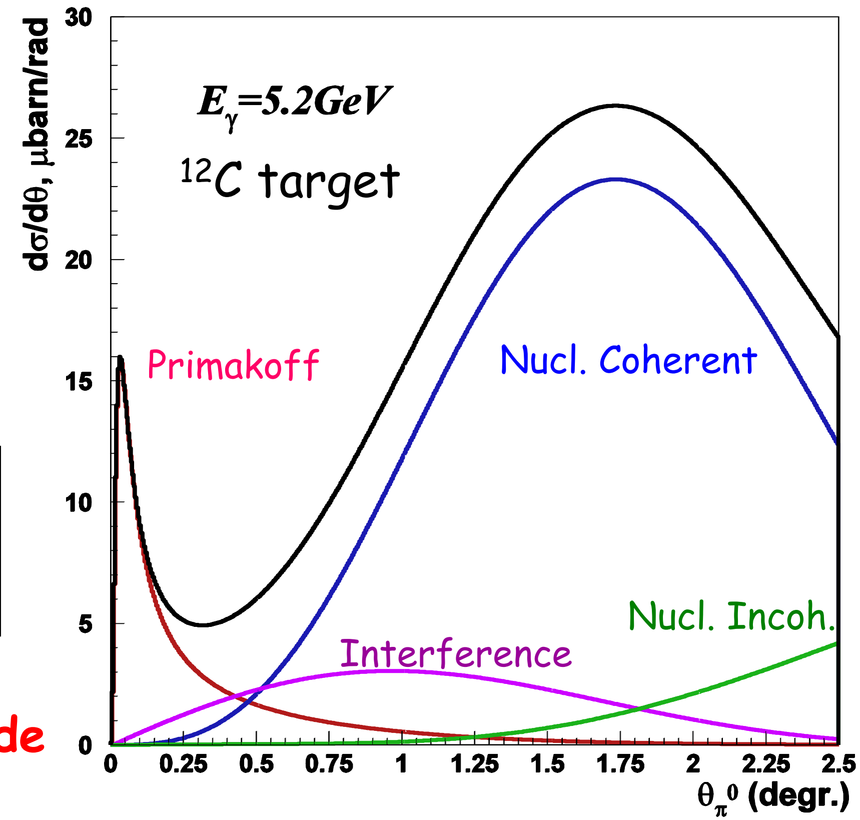

Challenge: Extract the Primakoff amplitude

Requirement:

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

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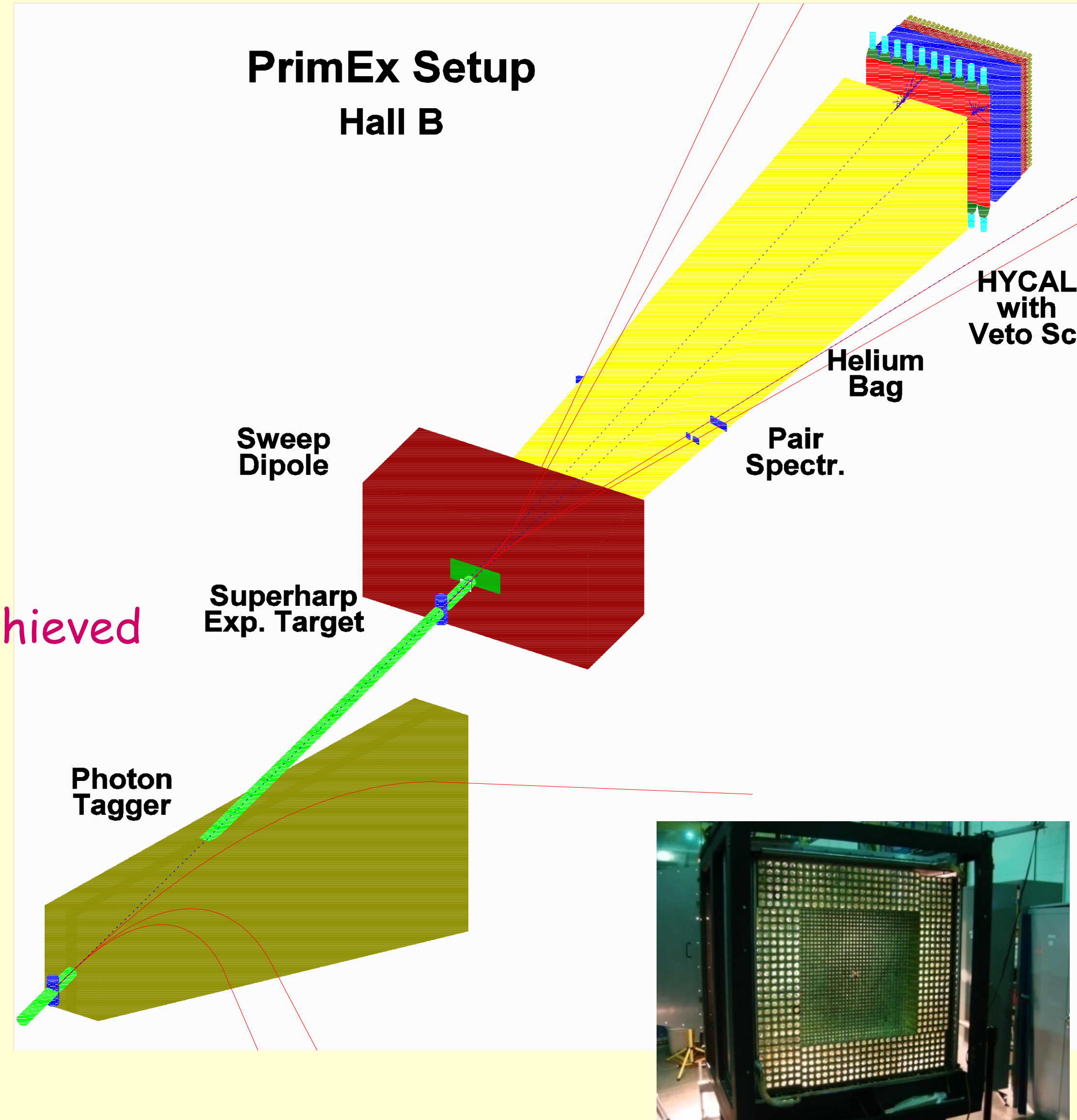
PrimEx Experimental Setup

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

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

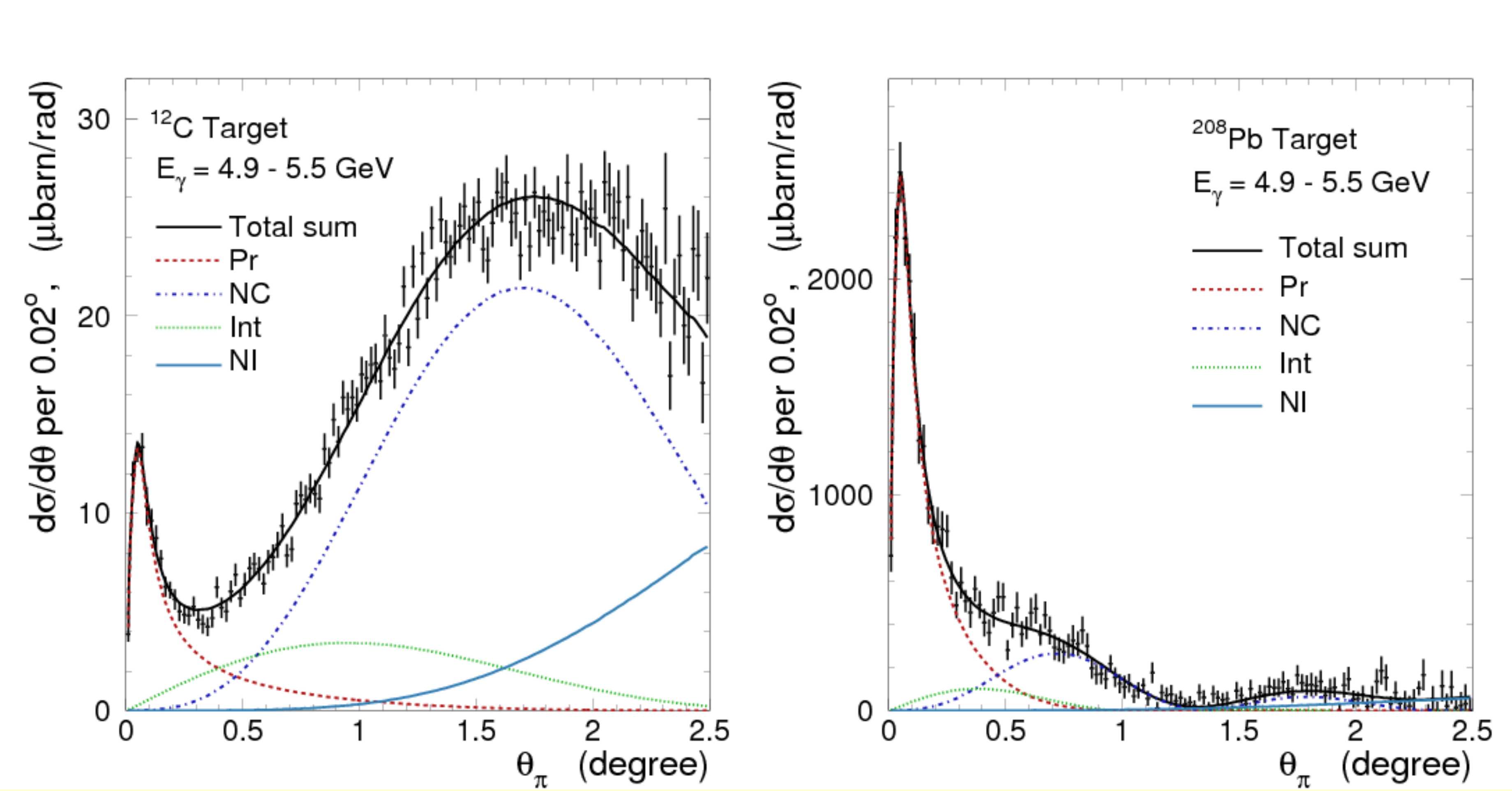
➡ 1% accuracy has been achieved

- ❑ New high resolution hybrid multi-channel calorimeter (HyCal)

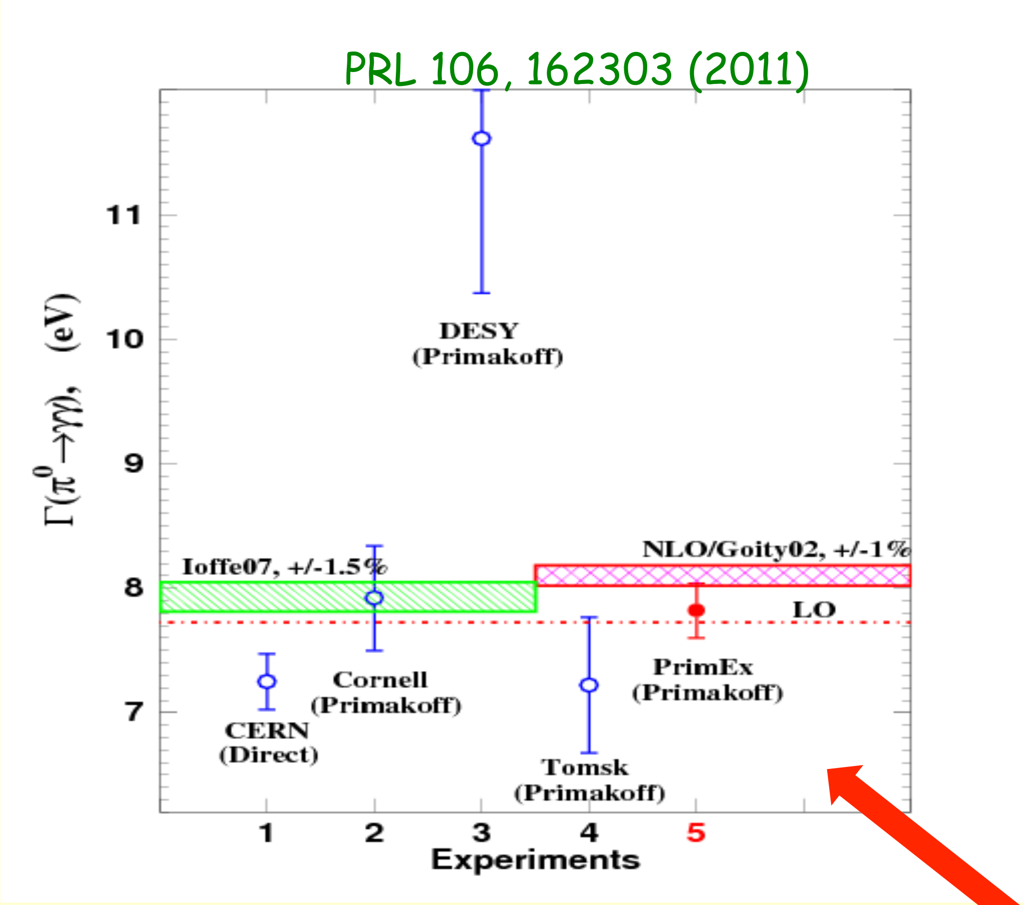


The First Experiment: PrimEx-I (2004)

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



The First Experiment: PrimEx-I Result



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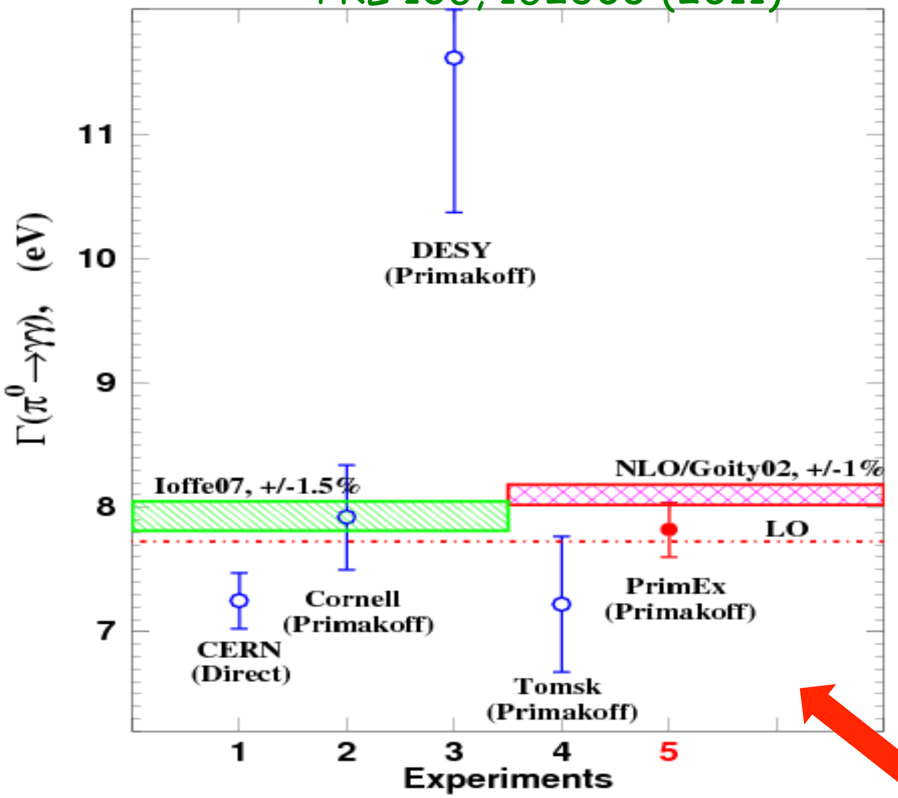
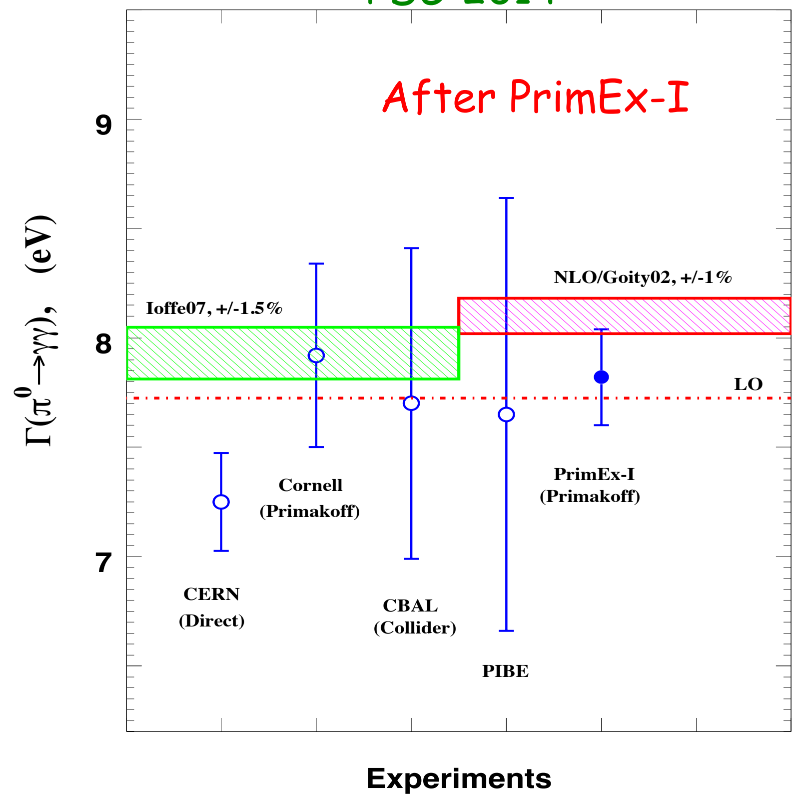
2.8% total uncertainty

The First Experiment: PrimEx-I Result

PRL 106, 162303 (2011)



PDG 2014



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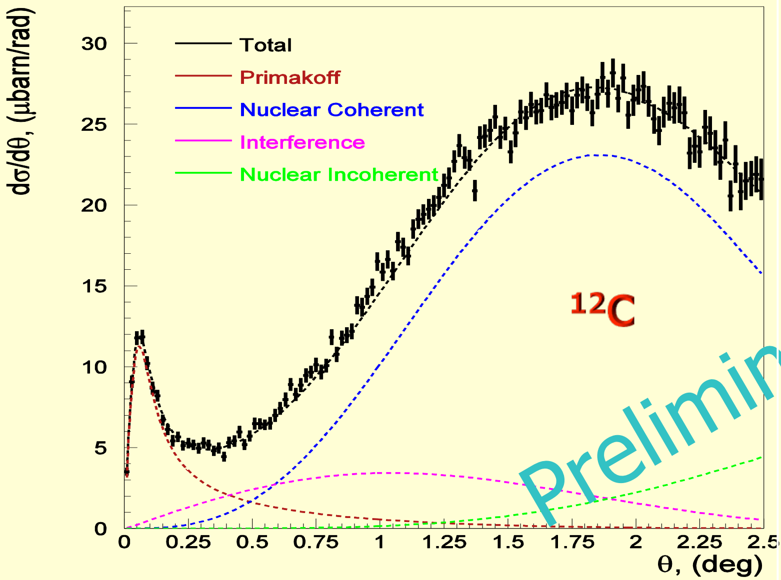
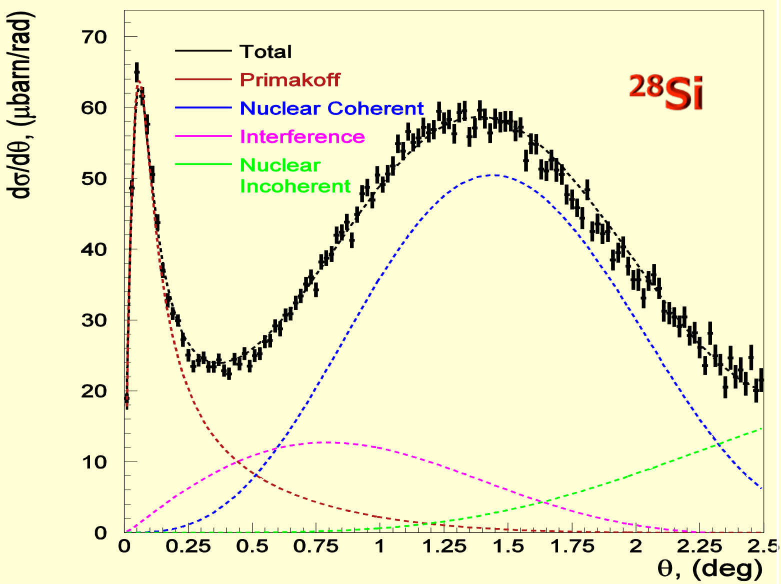
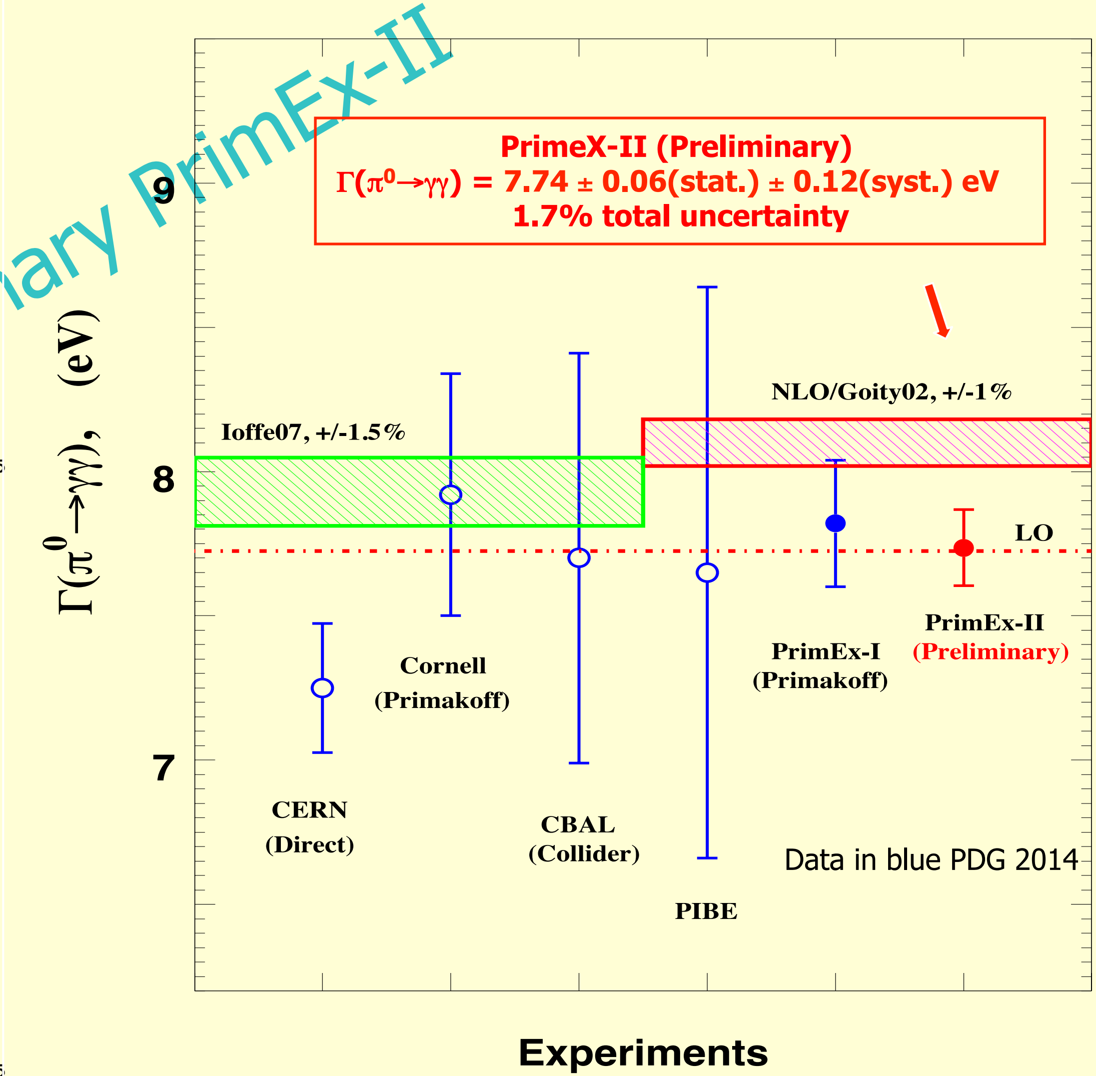
PrimEx-I improved the precision of PDG average by more than a factor of two

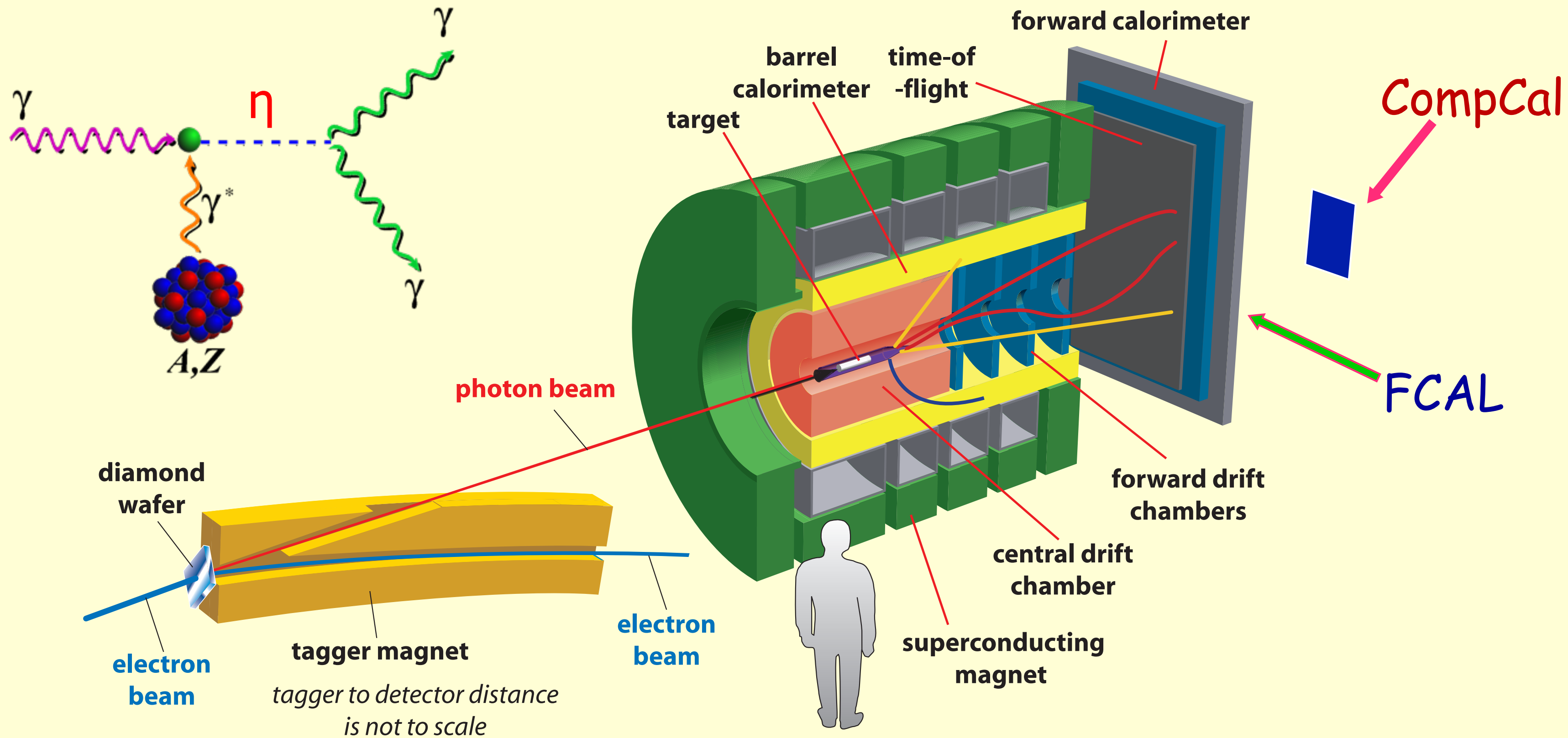
Preliminary PrimEx-II Results from Analysis
(L. Ma, Y. Zhang and I. Larin)







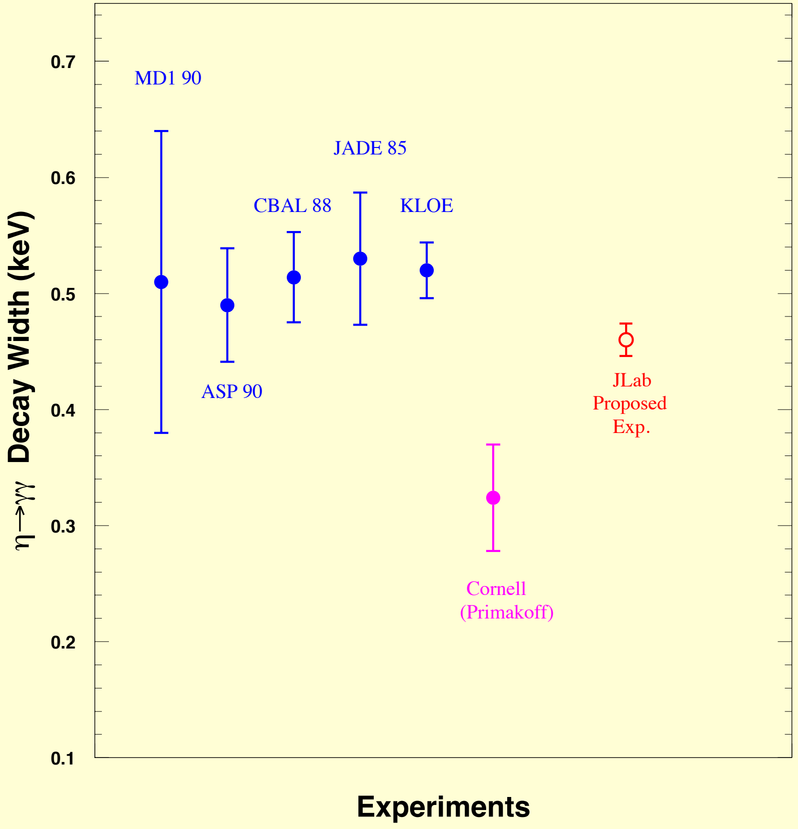
Measurement of $\Gamma(\eta\to\gamma\gamma)$ in Hall D at 12 GeV



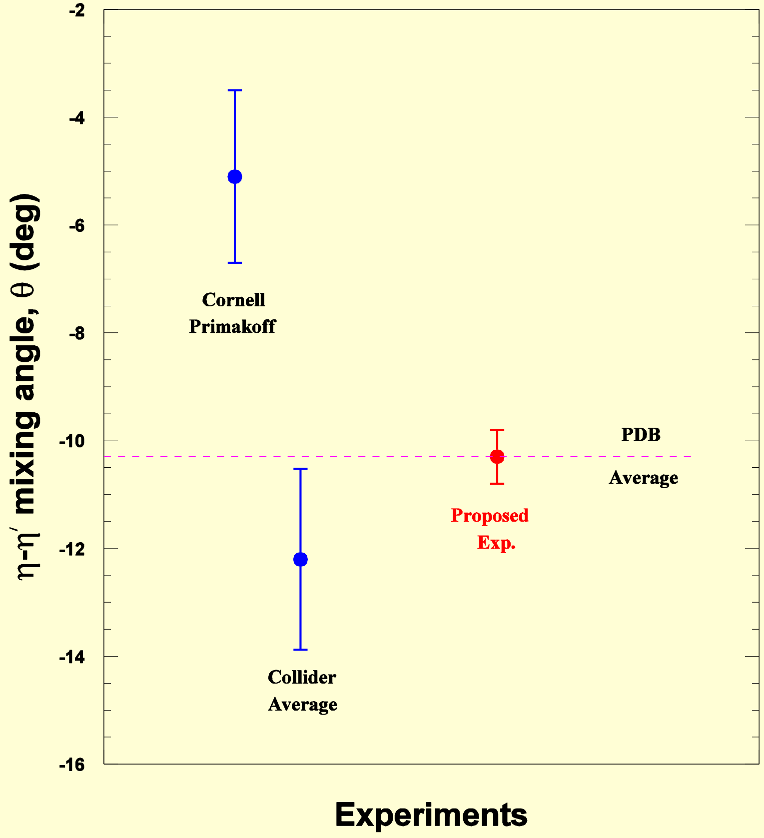
- Incoherent tagged photon beam (~10.5-11.5 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- 30 cm liquid Hydrogen and ^{4}He targets (~3.6% r.l.)
- Forward Calorimeter (FCAL) for $\eta\to\gamma\gamma$ decay photons
- CompCal and FCAL to measure well-known Compton scattering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

Physics Impact of $\Gamma(\eta\rightarrow\gamma\gamma)$ Measurement

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



2. Extract η-η' mixing angle:

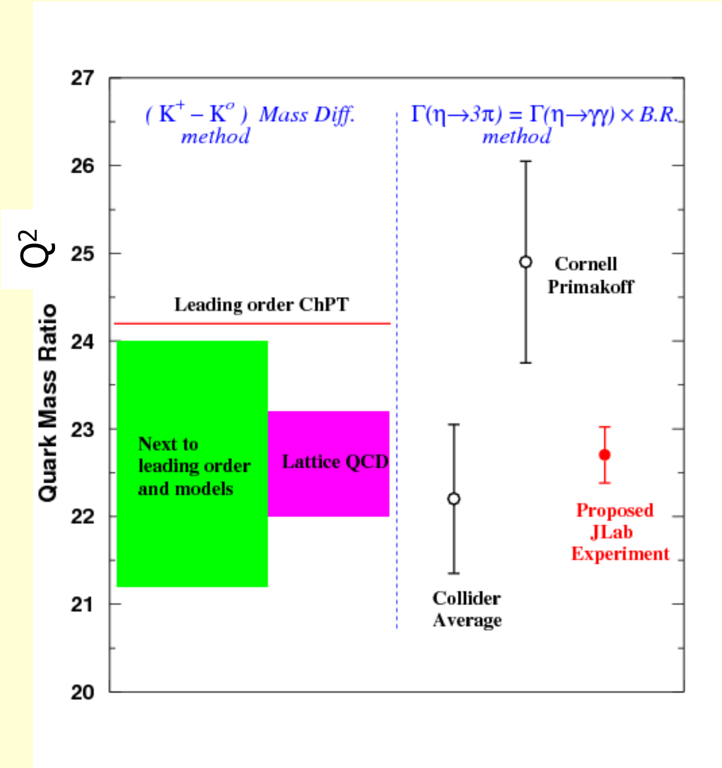


3. Improve all partial decay widths in the η-sector

Precision Determination Light Quark Mass Ratio

A clean probe for quark mass ratio: $Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}$, where $\hat{m} = \frac{1}{2}(m_u + m_d)$

- $\eta \to 3\pi$ decays through isospin violation: $A = (m_u - m_d)A_1 + \alpha_{em}A_2$
- α_{em} is small
- Amplitude: $A(\eta \to 3\pi) = \frac{1}{Q^2}\frac{m_K^2}{m_\pi^2}(m_\pi^2 - m_K^2)\frac{M(s,t,u)}{3\sqrt{3}F_\pi^2}$



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

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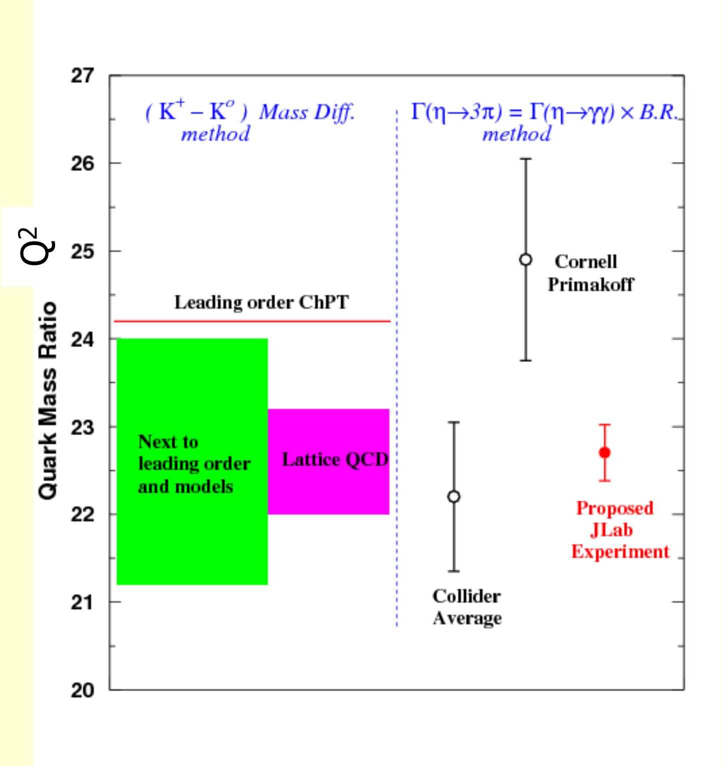
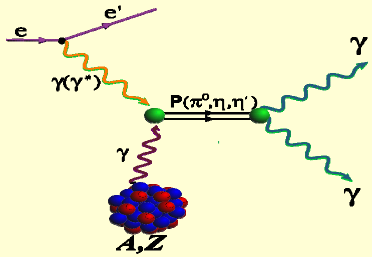


- Critical input to extract Cabibbo Angle, $V_{us} = \sin(\theta_c)$ from kaon or hyperon decays.
- V_{us} is a cornerstone for test of CKM unitarity:

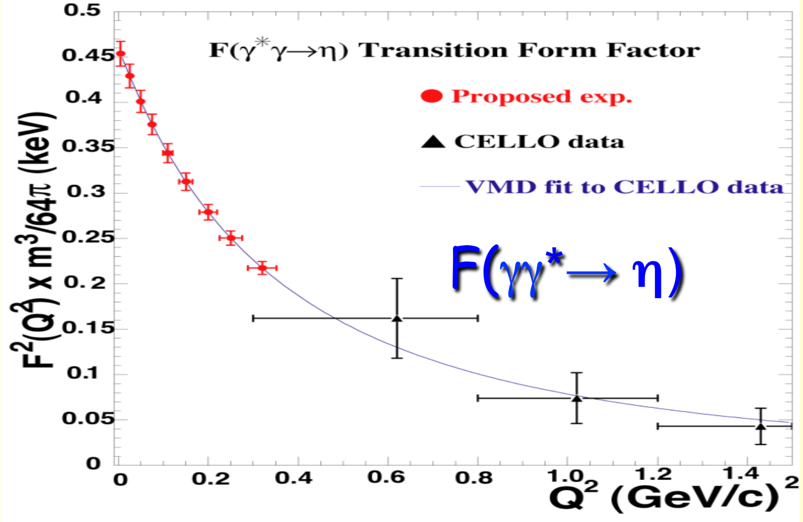
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

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

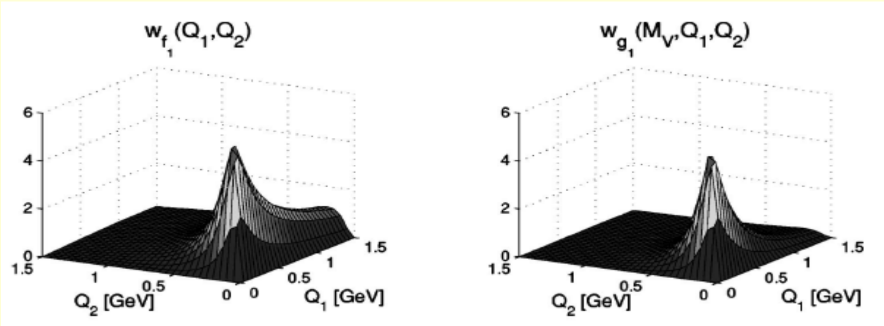
Transition Form Factors $F(\gamma\gamma^* \to P)$
(at low Q^2 : 0.001-0.5 GeV^2/c^2)



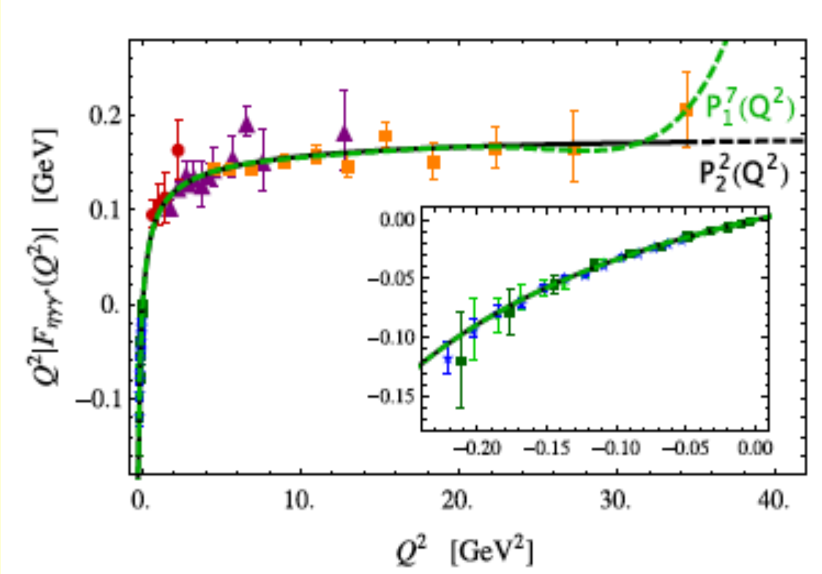
- **Direct measurement of slopes**
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



- **Input for hadronic light-by-light calculations in muon (g-2)**

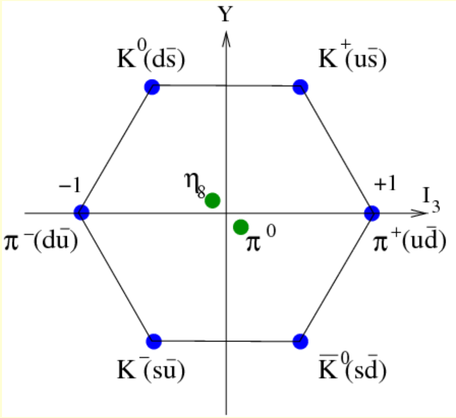


Phys.Rev.D65,073034



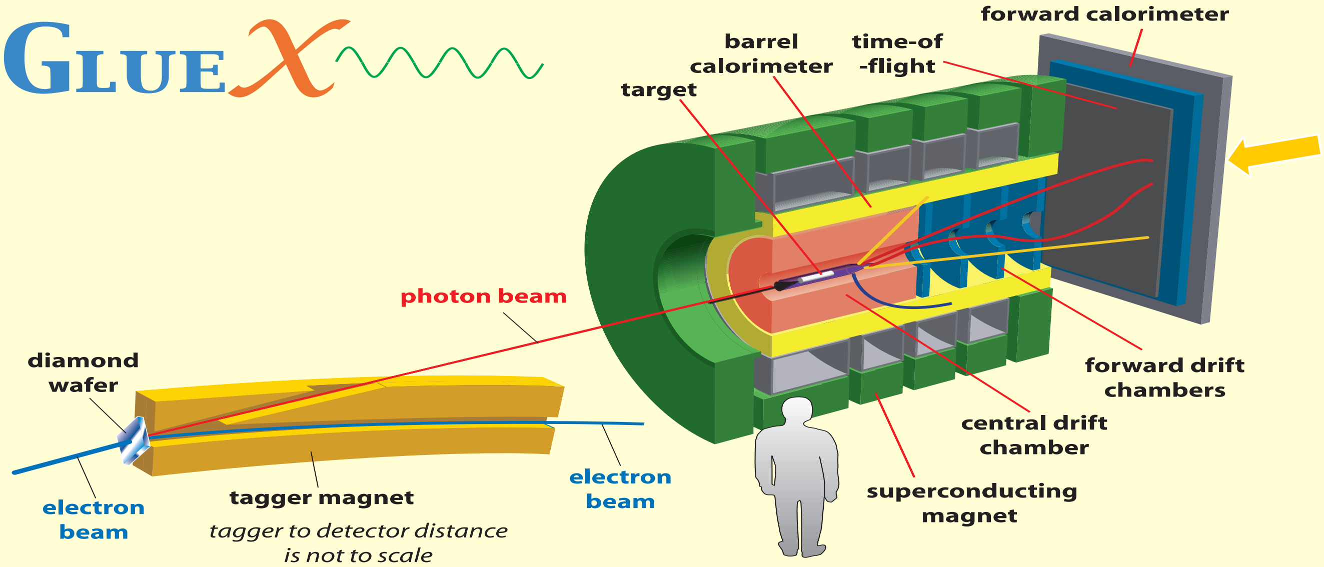
Eur.Phys.J. C75, 414 (2015)

η is a unique probe for new physics



- 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.

JLab Eta Factory (JEF) Experiment



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

- 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%)

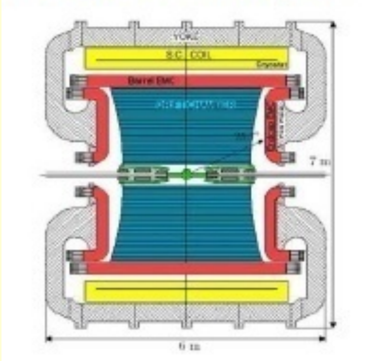
- Upgraded Forward Calorimeter with **High resolution, high granularity $PbWO_4$** insertion (**FCAL-II**) to detect multi-photons from rare η decays

28

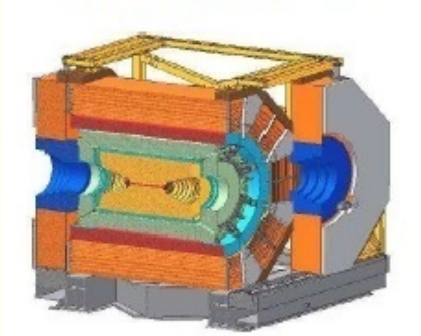
World competition in η decays

e^+e^- Collider

KLOE-2 at DAΦNE

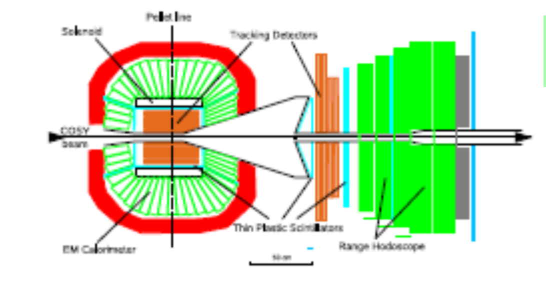


BESIII at BEPCII



Fixed-target

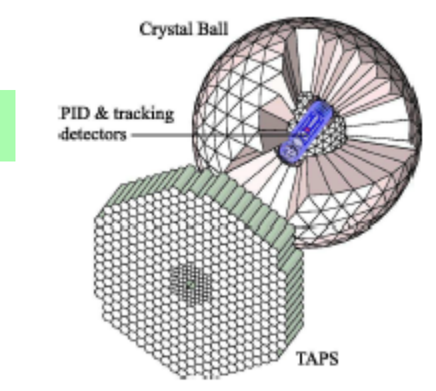
WASA at COSY



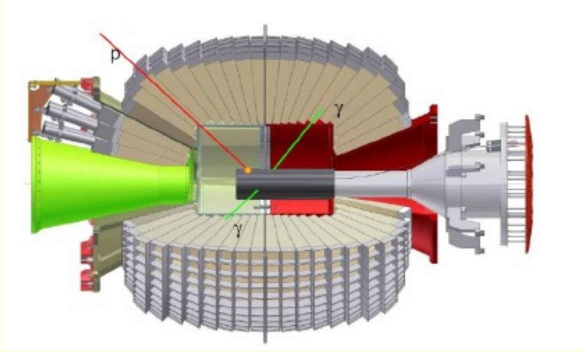
hadroproduction

photoproduction

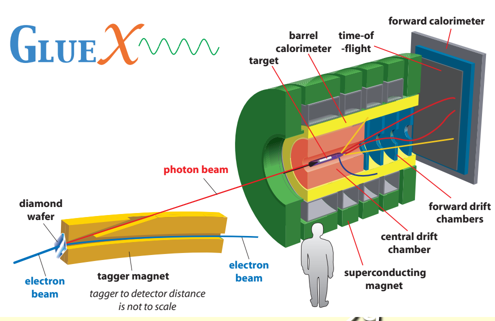
Crystall Ball at MAMI



CBELSA/TAPS at ELSA

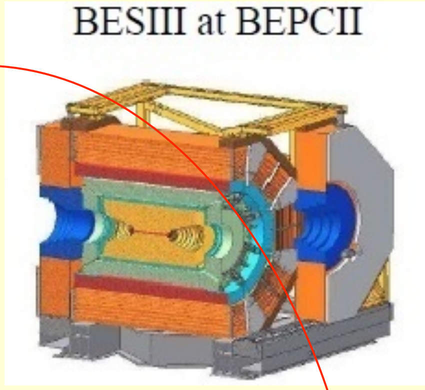


JEF at JLab



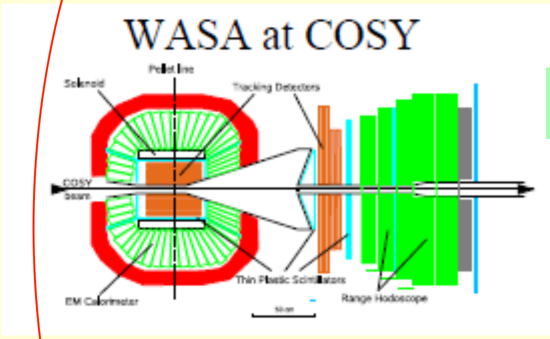
World competition in η decays

e^+e^- Collider



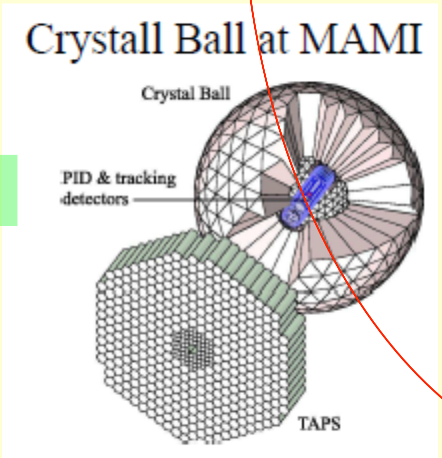
Low energy η-facilities

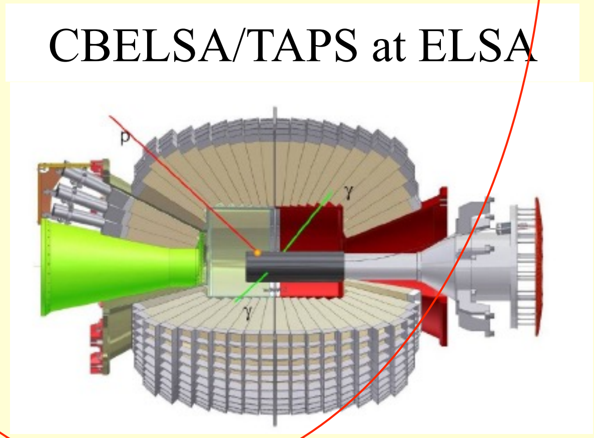
Fixed-target

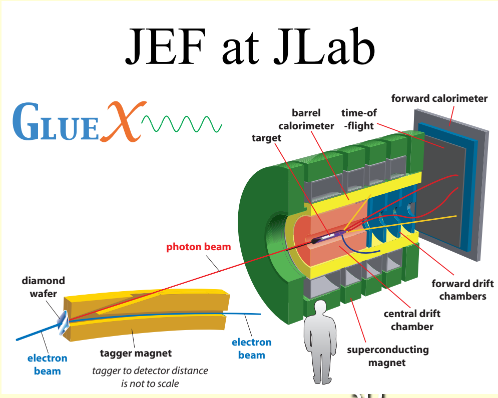


hadroproduction

photoproduction



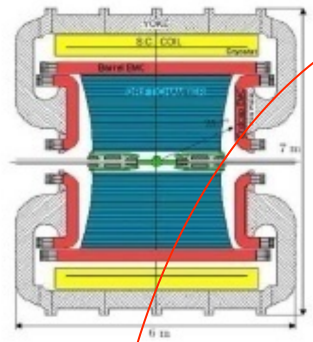




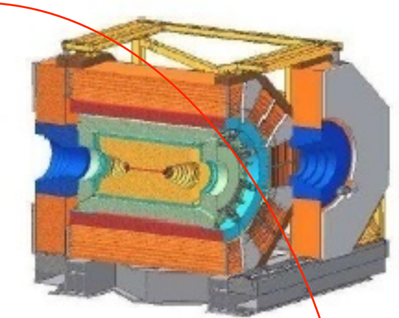
World Competition in η Decays

e^+e^- Collider

KLOE-2 at DAΦNE



BESIII at BEPCII



Low energy η-facilities

Fixed-target

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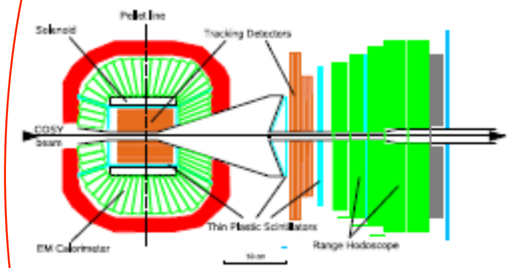
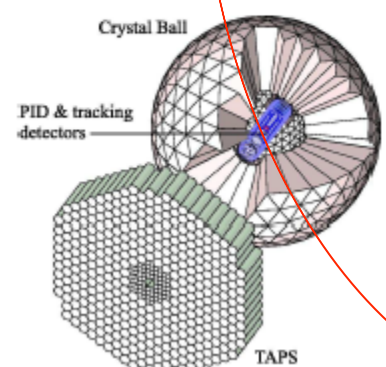


hadroproduction

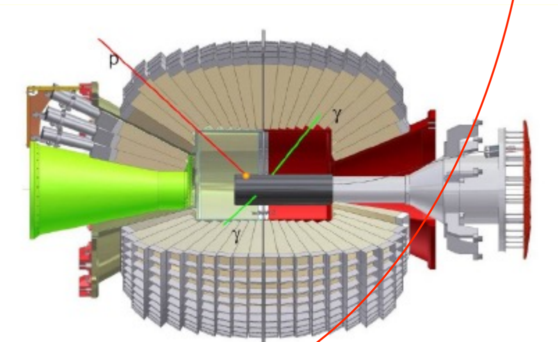
High energy η-facility

photoproduction

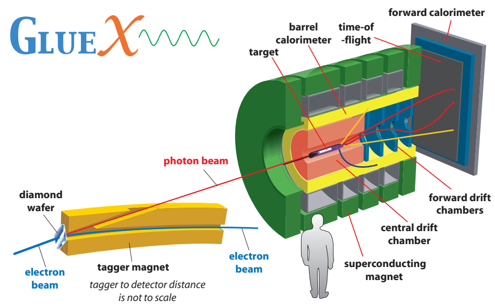
Crystall Ball at MAMI



CBELSA/TAPS at ELSA

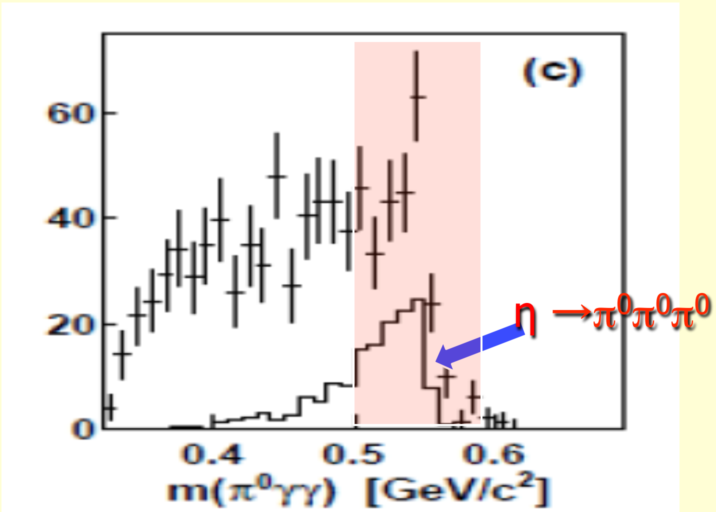


JEF at JLab

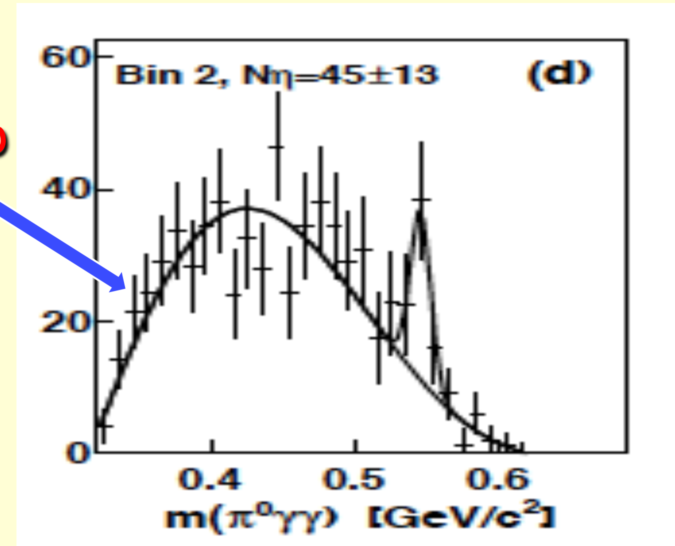


Filter Background with η Energy Boost ($\eta \to \pi^0\gamma\gamma$)

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

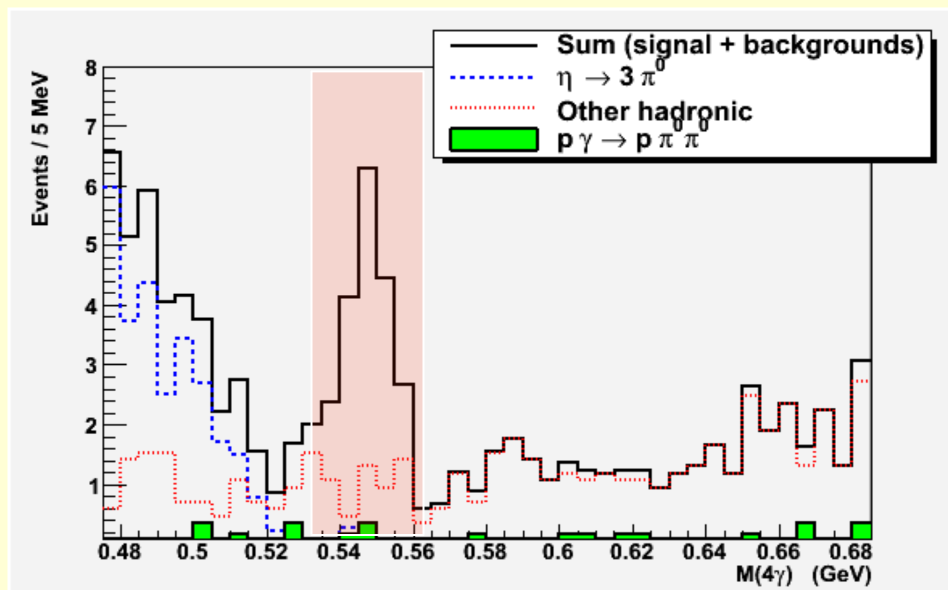


γp→ π⁰π⁰ + p



JLab:

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



Overview of the JLab Eta Factory (JEF) Project

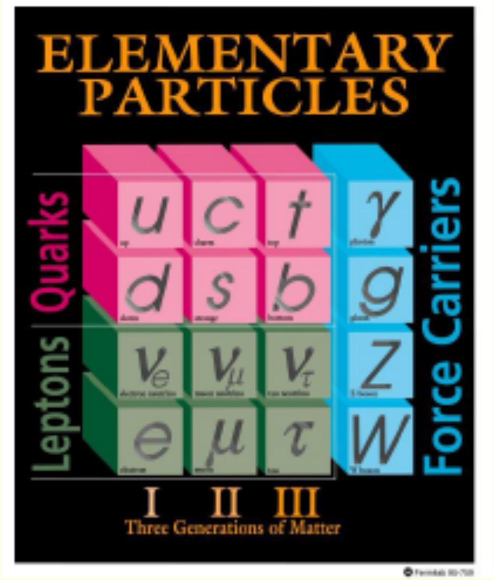
Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	4
$\gamma + B$	beyond SM	leptophobic dark boson	4
$3\pi^0$	$(32.6 \pm 0.2)\%$	$m_u - m_d$	6
$\pi^+\pi^-\pi^0$	$(22.7 \pm 0.3)\%$	$m_u - m_d$, CV	2
3γ	$< 1.6 \times 10^{-5}$	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:

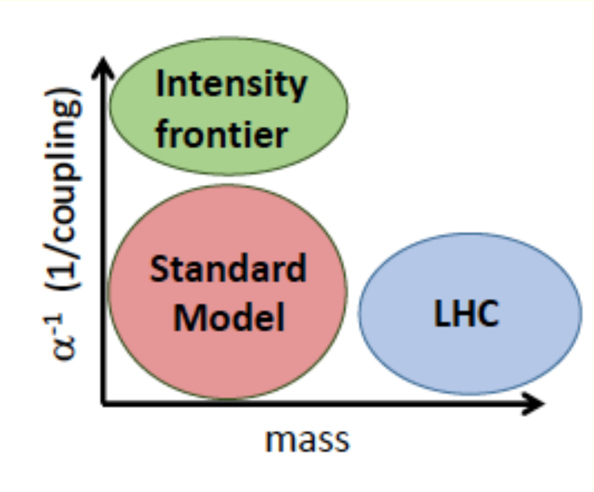
1. Search for a leptophobic dark gauge boson (B).
2. Directly constrain CVPC new physics
3. Probe interplay of VMD & scalar resonances in ChPT.
4. Improve the light quark mass ratio

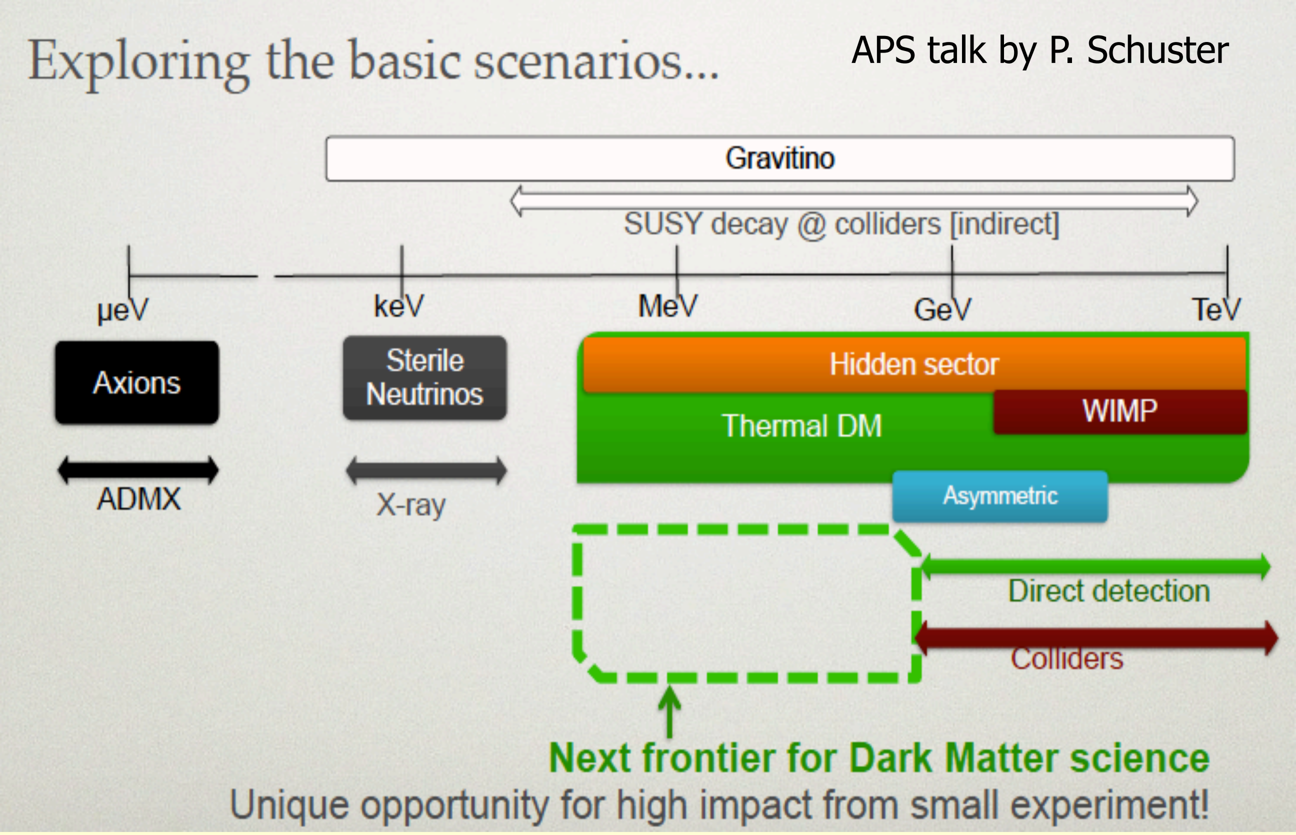
FCAL-II is required for the rare decays

Search for Dark Forces



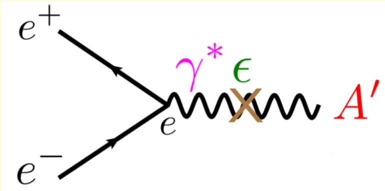
SM based on $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry. Are there any additional gauge symmetries? Look for new gauge bosons.



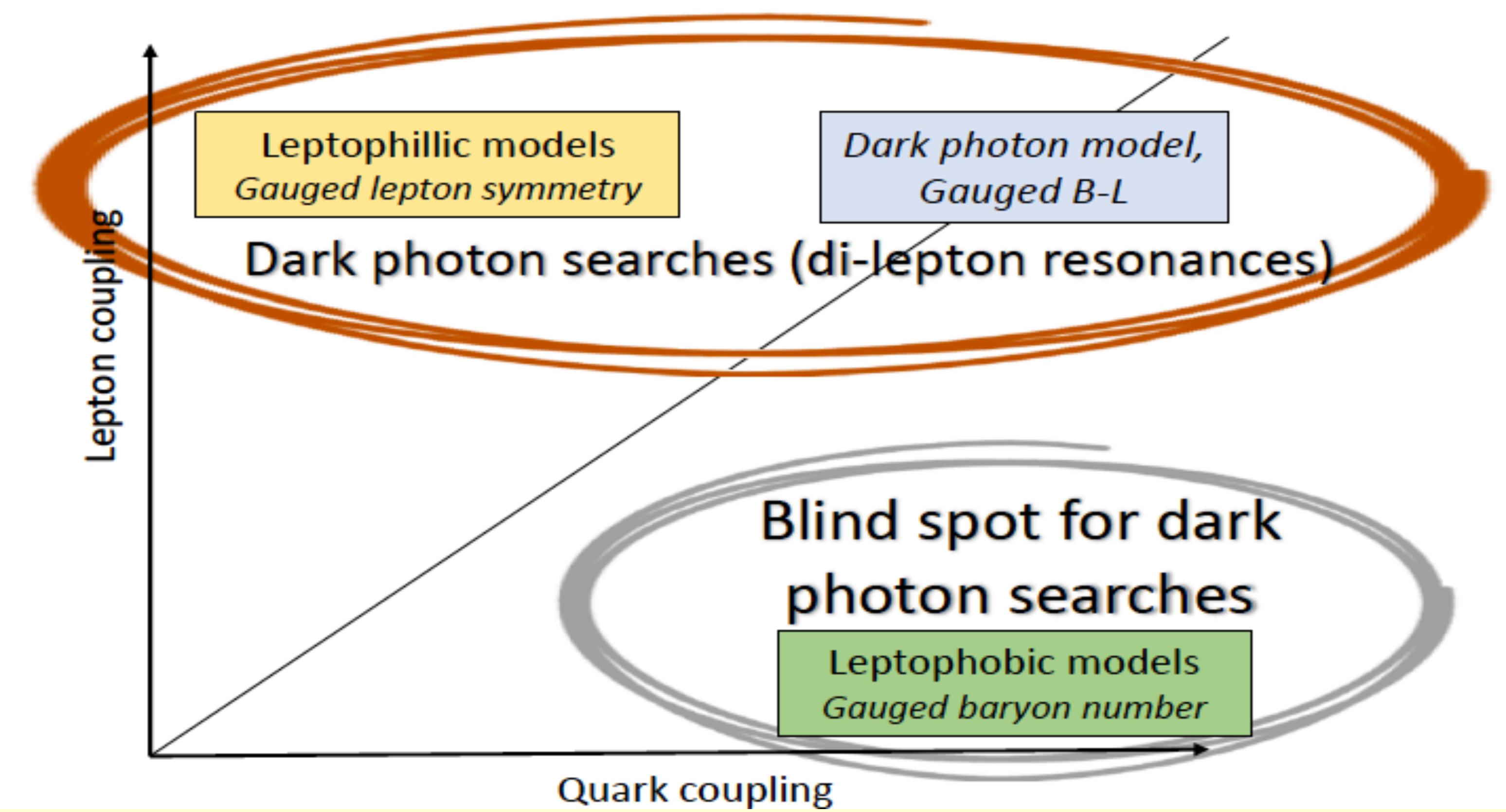


"Vector Portal" to Dark Sector

1. Dark photon A′



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

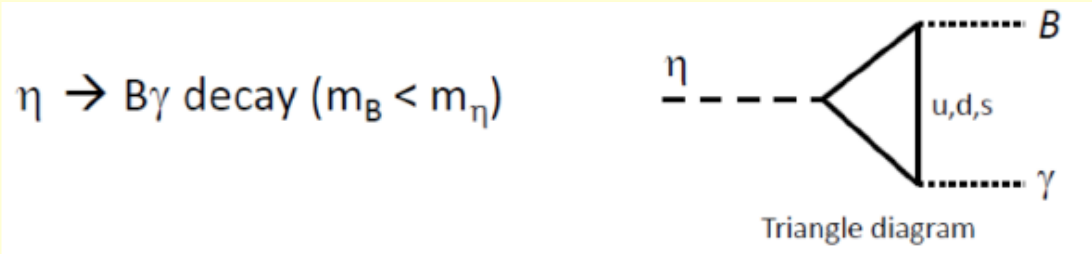


2. Leptophobic B-boson (dark ω, γ_B , or Z′):

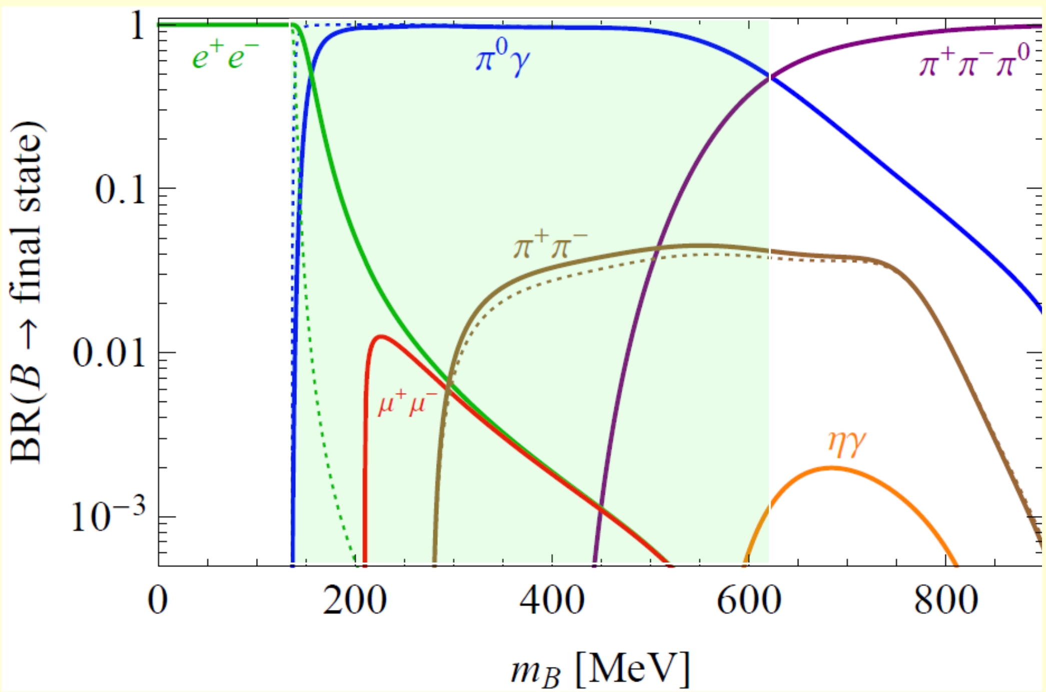
$$\frac{1}{3}g_B\bar{q}\gamma^\mu qB_\mu$$ Gauged baryon number symmetry $U(1)_B$

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



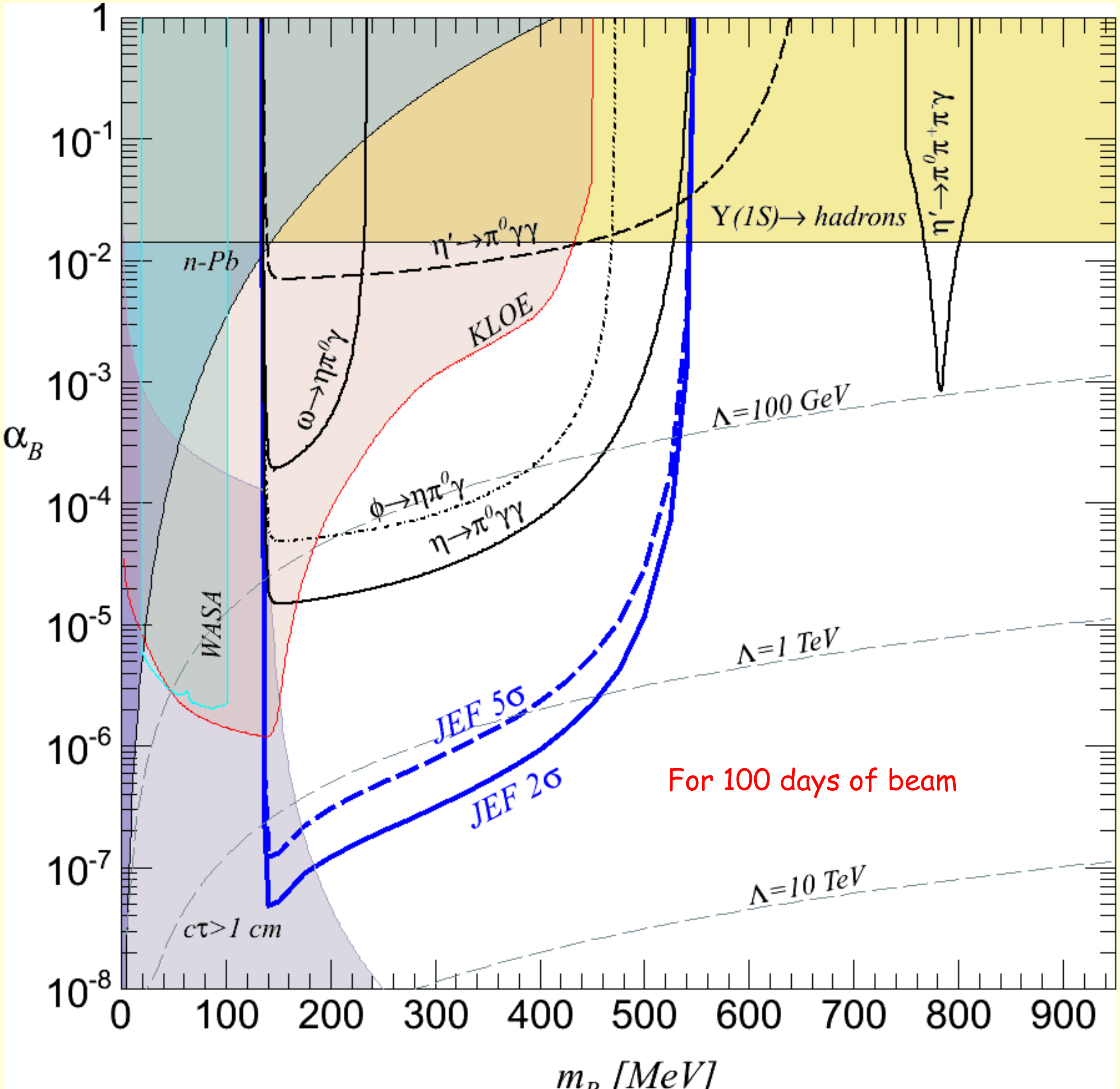
$\eta \to \gamma B \to \gamma + \pi^0 \gamma$

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

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

- $\Gamma(\eta \to \pi^0 \gamma\gamma) \sim 0.3 eV$ ⟶ 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:

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

Summary

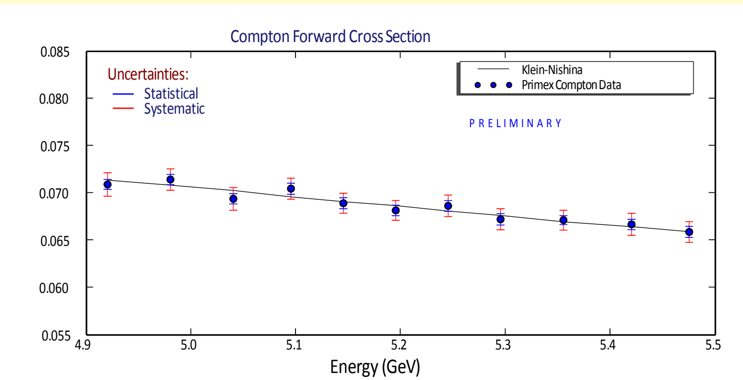
- The π^0, η and η' decays are sensitive probes for the fundamental symmetries.

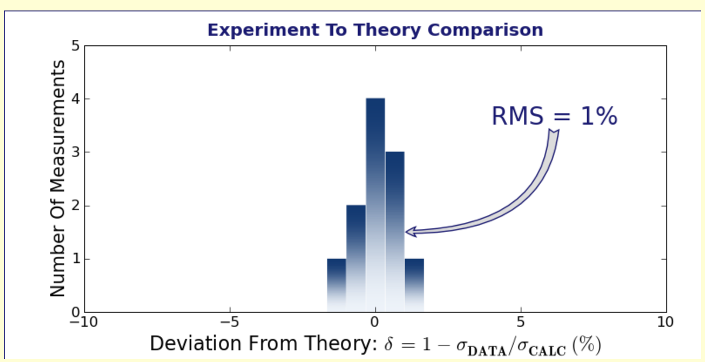
- A comprehensive Primakoff program has been developed at JLab to measure $\Gamma(P \rightarrow \gamma\gamma)$ and $F(\gamma\gamma^* \rightarrow P)$ of π^0, η and η' to test the confinement QCD symmetries.
  - tests of chiral symmetry and anomalies
  - light quark mass ratio and η-η' mixing angle
  - π^0,η and η' electromagnetic interaction radii
  - Inputs for a_μ(HLbL) calculations

- The JEF experiment will measure the rare η decays as well as non-rare decays with low experimental backgrounds to test the SM symmetries and search for BSM new physics.
  - Probe a leptophobic dark B-boson in 140-550 MeV range via $\eta \rightarrow B\gamma \rightarrow \pi^0\gamma\gamma$
  - 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 $\eta \rightarrow \pi^0\gamma\gamma$

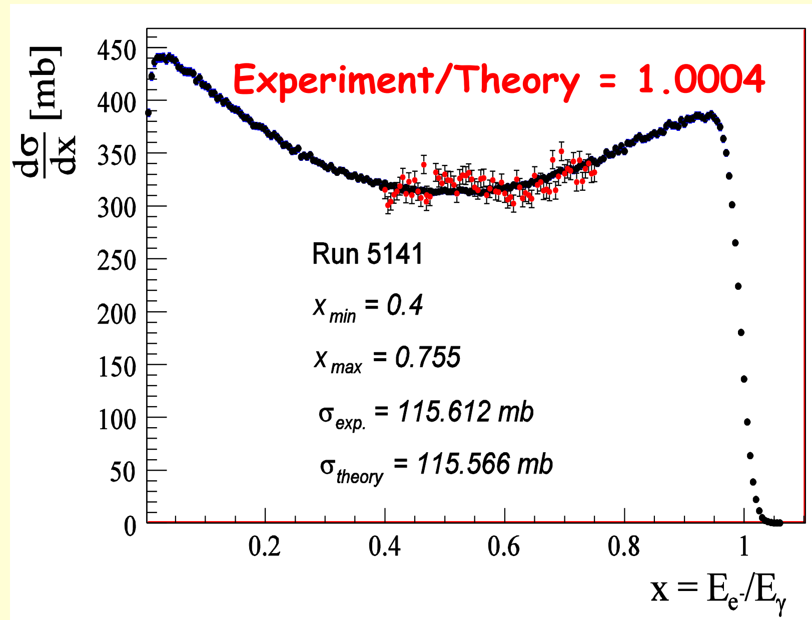
Verification of Overall Systematical Uncertainties

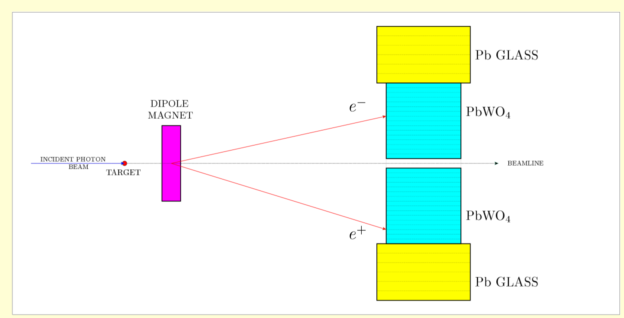
- $\gamma + e \rightarrow \gamma + e$ Compton cross section measurement





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





Systematic uncertainties on cross section are controlled under 1.3%

Challenges in the $\Gamma(\eta\to\gamma\gamma)$ Experiment

Compared to π^0:

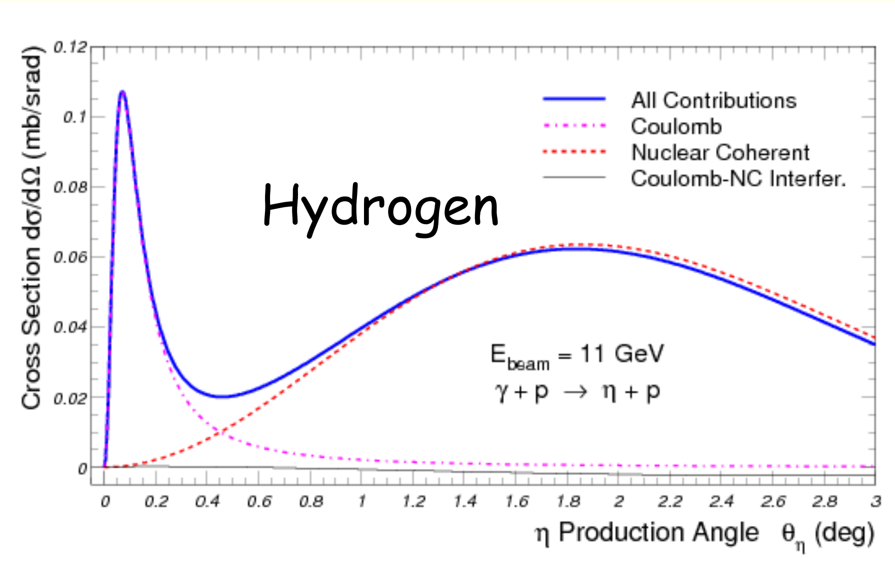
- η mass is a factor of 4 larger than π^0 and has a smaller cross section

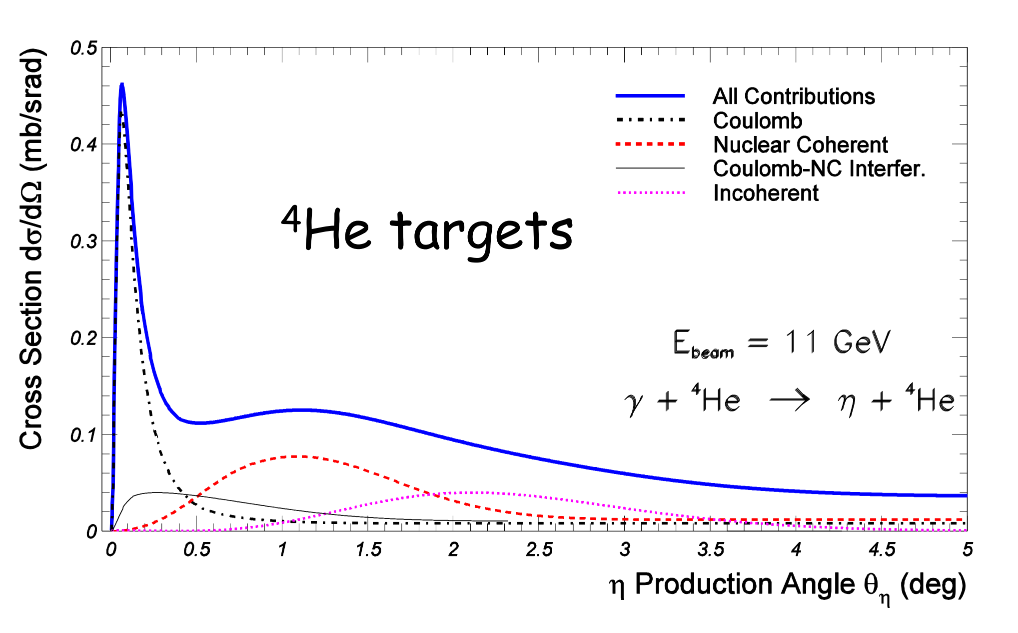
$$\left(\frac{d\sigma_{\text{Pr}}}{d\Omega}\right)_{\text{peak}} \propto \frac{E^4}{m^3}$$

- larger overlap between Primakoff and hadronic processes;

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

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





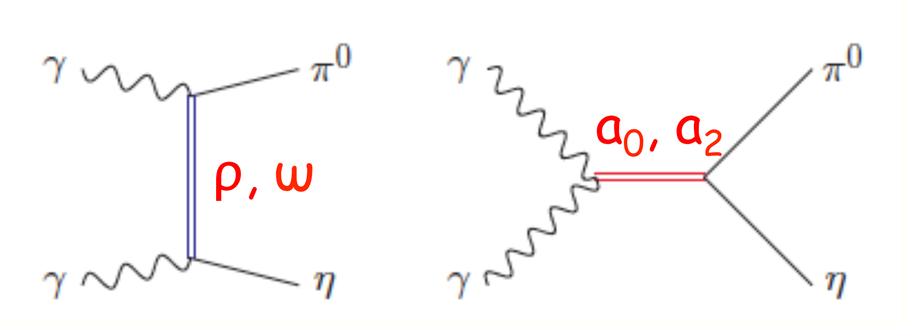
SM Allowed $\eta \to \pi^0 \gamma\gamma$

→ 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)

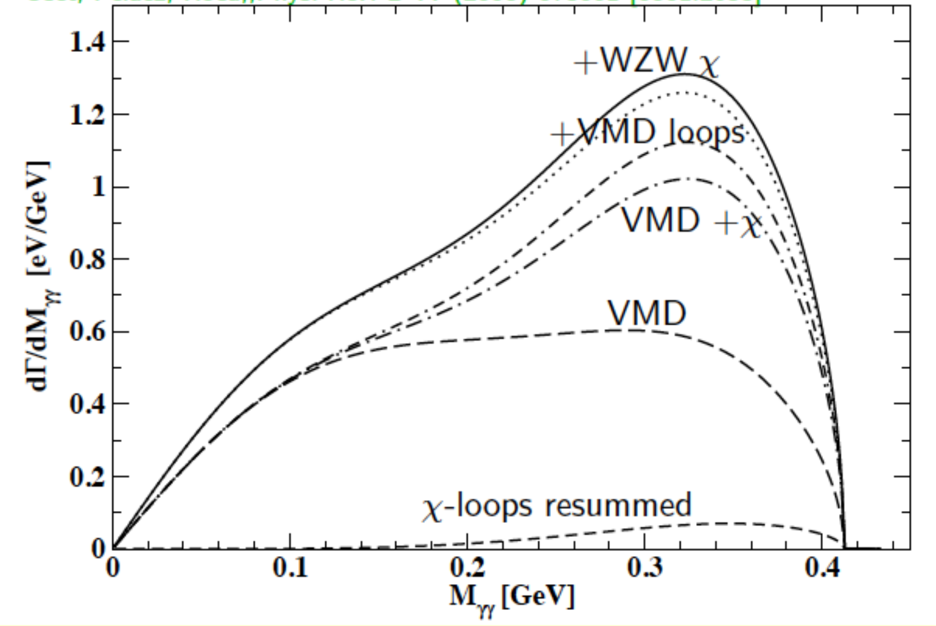
- The major contributions to $\eta \to \pi^0 \gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian → an unique probe for the high order ChPT.
  L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

- 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

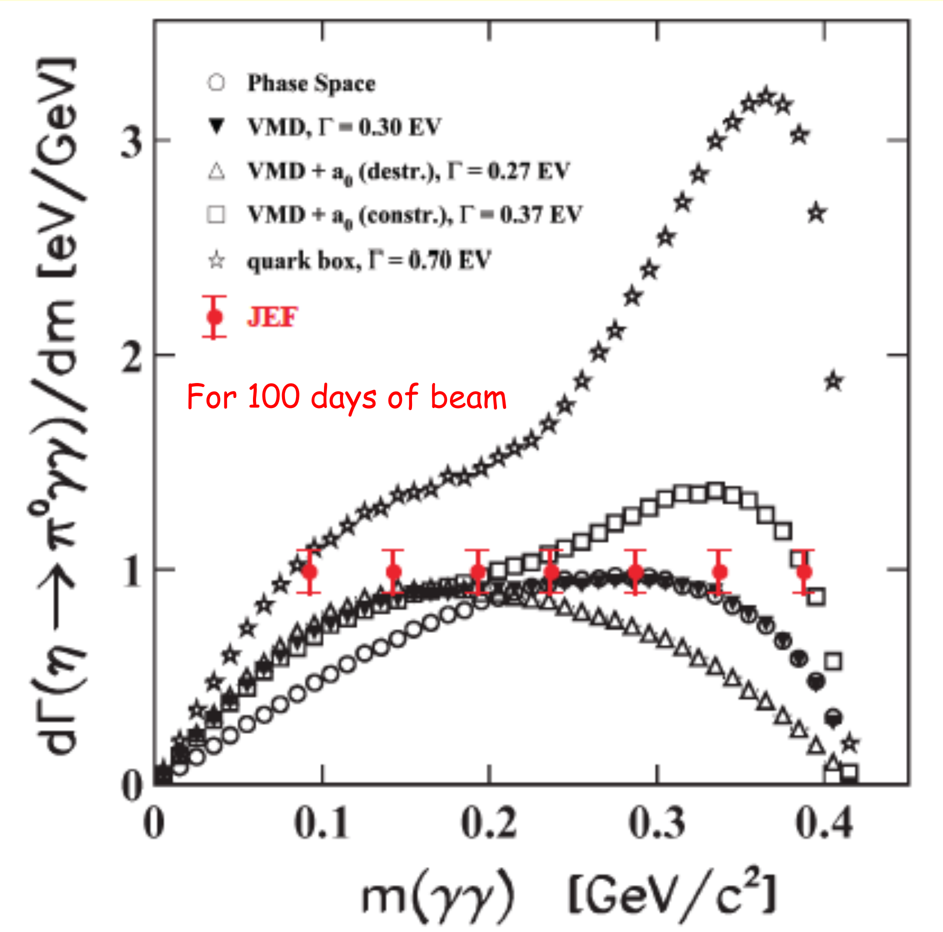


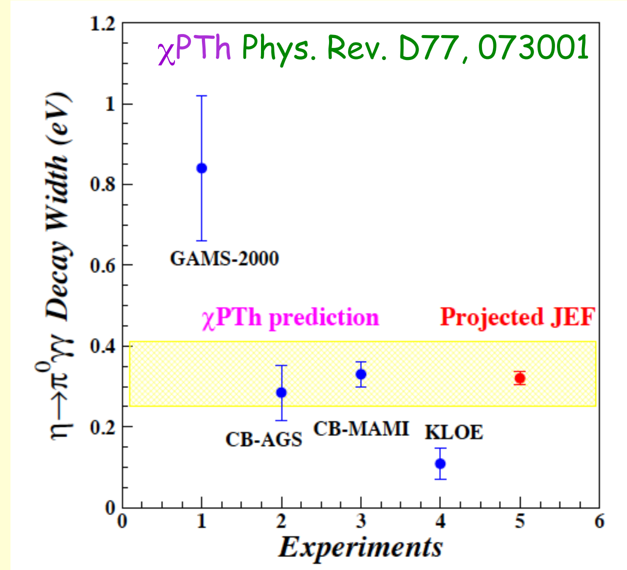
Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]

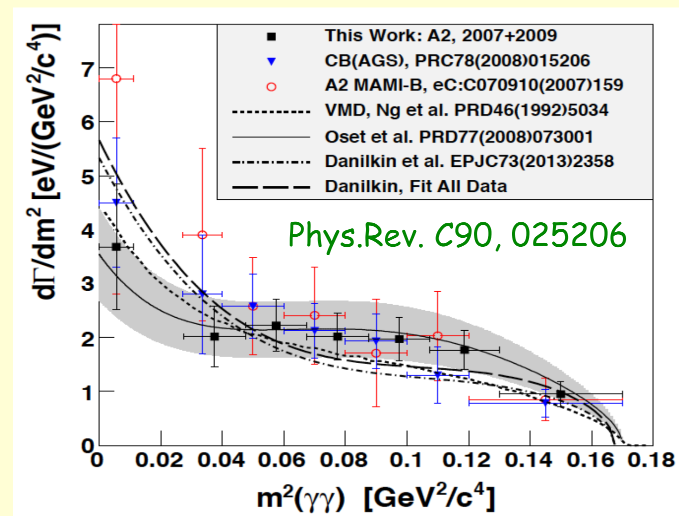


Projected JEF Results on $\eta\to\pi^0\gamma\gamma$

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

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

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β-decays,
K-, B-, D-meson decays
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17 C-tests involving η, η', π^0, ω, J/ψ decays

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Experimental tests

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

EDM, $\eta \to$ 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	

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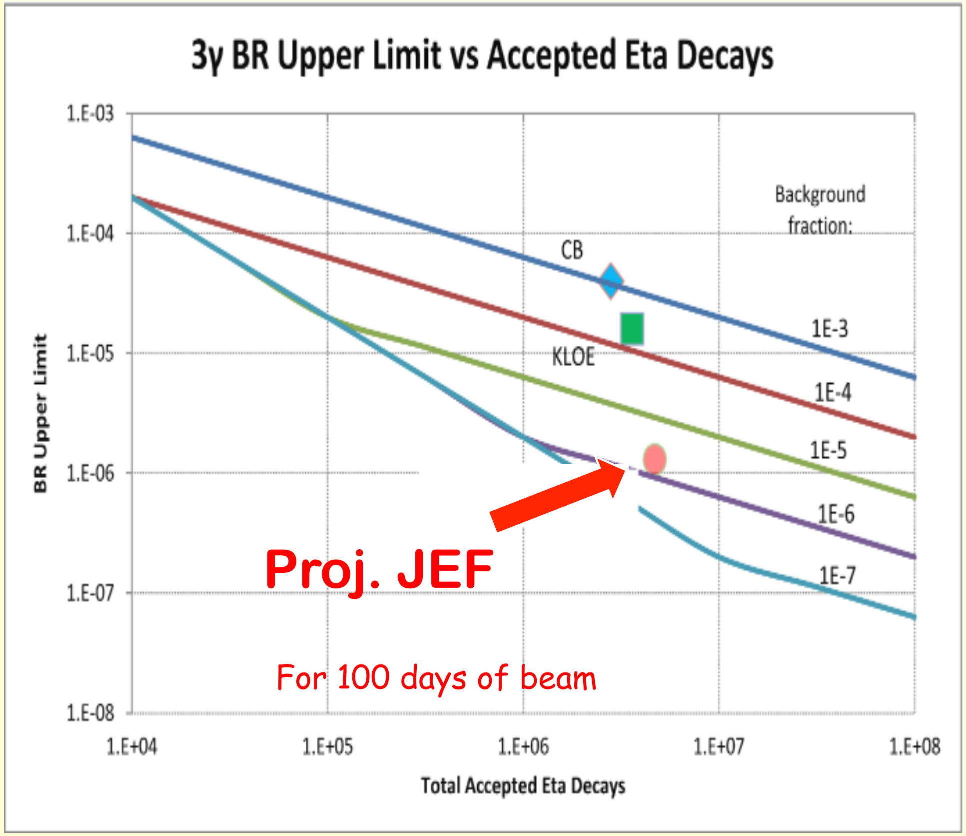
Experimental Improvementon in $\eta \to 3\gamma$

- SM contribution: BR($\eta \to 3\gamma$) <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($\eta \to 3\gamma$)< 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

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 $\left|[\pi^+(\mathbf{p})\,\pi^-(-\mathbf{p})]_I\,\pi^0(\mathbf{p}')_I\right\rangle$ final states of 0^- meson decay.

It is linear in a CP-violating parameter.

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

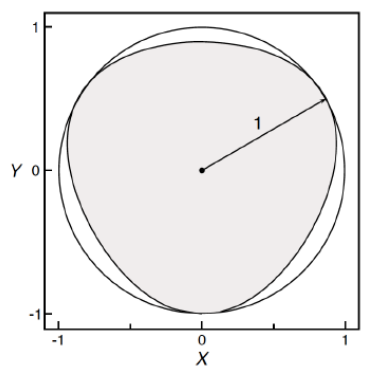
"C violation" [Lee and Wolfenstein, 1965; Lee, 1965, Nauenberg, 1965; Bernstein, Feinberg, and Lee, 1965]

C-even, P-odd

This can be generated by the interference of amplitudes which distinguish $\left|[\pi^-(\mathbf{p})\,\pi^0(-\mathbf{p})]_I\,\pi^+(\mathbf{p}')_I\right\rangle$ from $\left|[\pi^+(\mathbf{p})\,\pi^0(-\mathbf{p})]_I\,\pi^-(\mathbf{p}')_I\right\rangle$ 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.

Measurement of $\eta \rightarrow 3\pi$ Dalitz Distribution



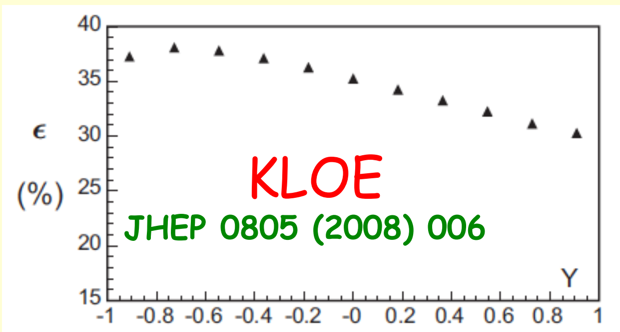
$$X = \frac{\sqrt{3}}{2M_\eta Q_c}(u-t)$$

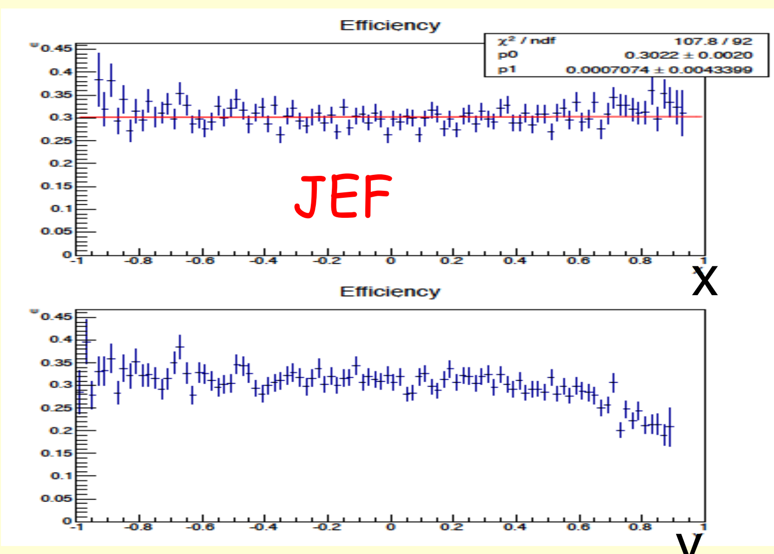
$$Y = \frac{3}{2M_\eta Q_c}\left(\left(M_\eta - M_{\pi^0}\right)^2 - s\right) - 1$$

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

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

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	10.0
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