Test Confinement QCD and Search for new Physics via Light Meson Decays

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Outline

1. Introduction ⟶ challenges in physics

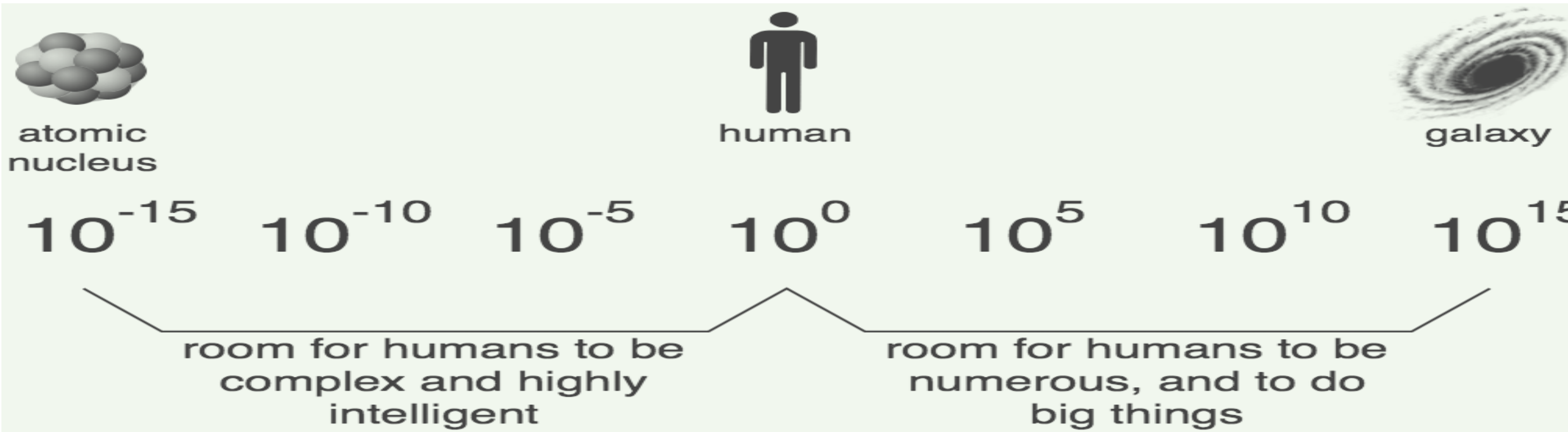
2. Primakoff experiments on π^0, η, η' ⟶ precision tests of confinement QCD

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

4. Summary

This project is supported by USA NSF 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

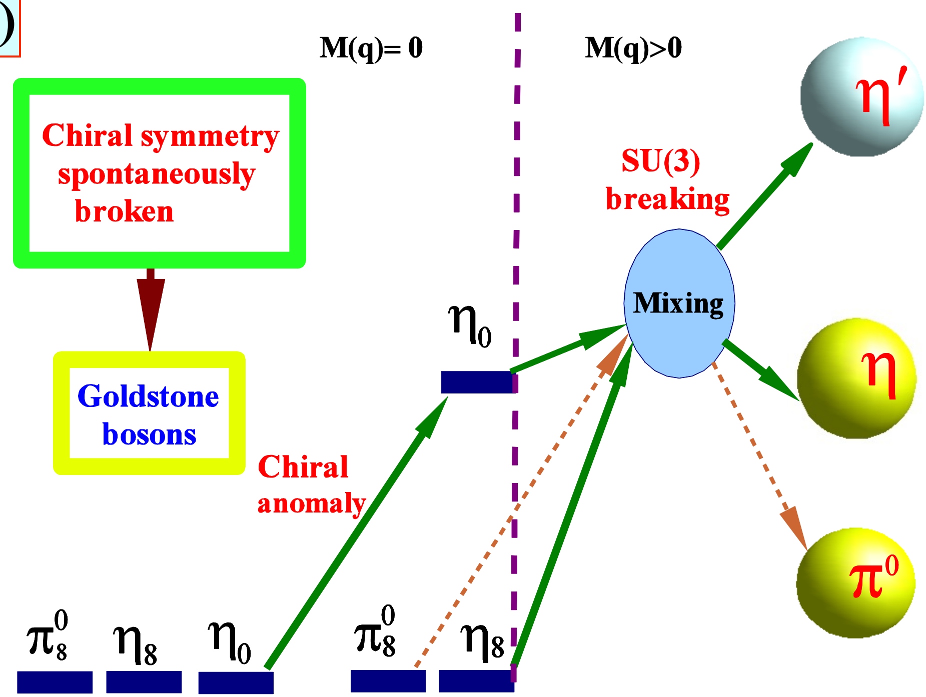
Decays of π^0, η, η' provide sensitive probes for both fundamental challenges

Low-Energy QCD Symmetries and Light Mesons

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

$$\boxed{SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)}$$

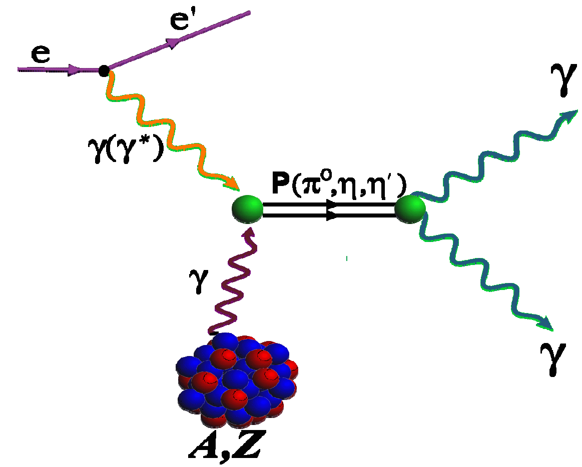
- Chiral symmetry $SU_L(3)xSU_R(3)$ spontaneously breaks to $SU(3)$
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma)$, $\Gamma(\eta \to \gamma\gamma)$, $\Gamma(\eta' \to \gamma\gamma)$
  - Mass of η_0
- $SU_L(3)xSU_R(3)$ and $SU(3)$ are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

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

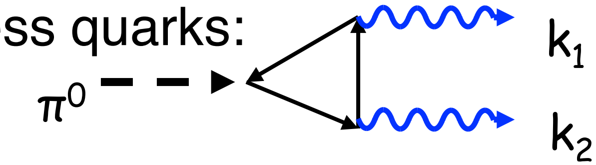
Input to Physics:

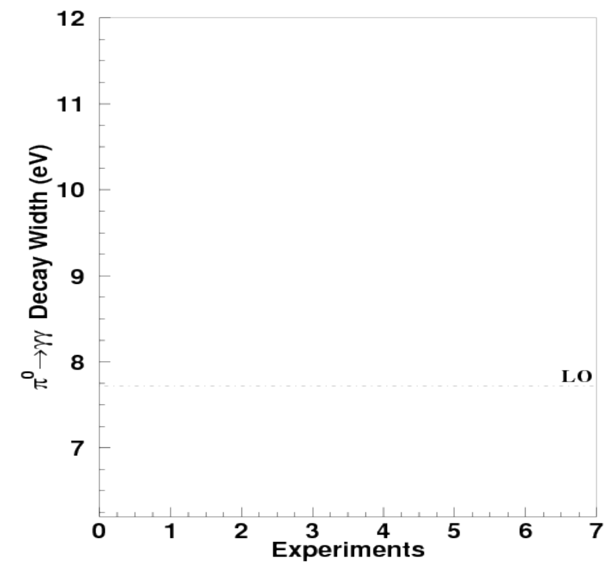
- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- inputs to a_μ(HLbL) calculations

Axial Anomaly Determines π^0 Lifetime

- $\pi^0 \rightarrow \gamma\gamma$ 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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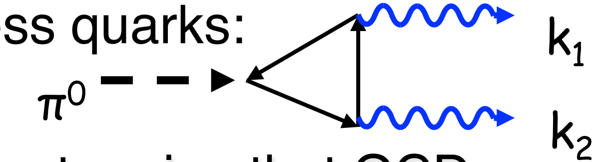

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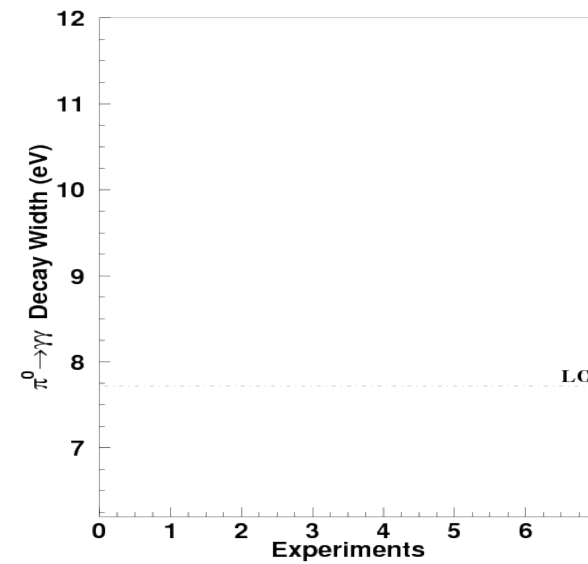

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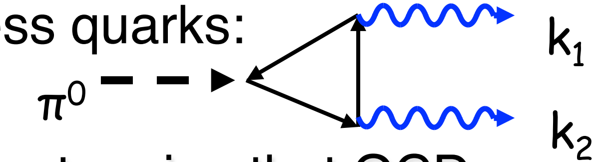

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  - Corrections to the chiral anomaly prediction:

    Calculations in NLO ChPT:

    - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10\text{eV} \pm 1.0\%$
      (J. Goity, et al. Phys. Rev. D66:076014, 2002)
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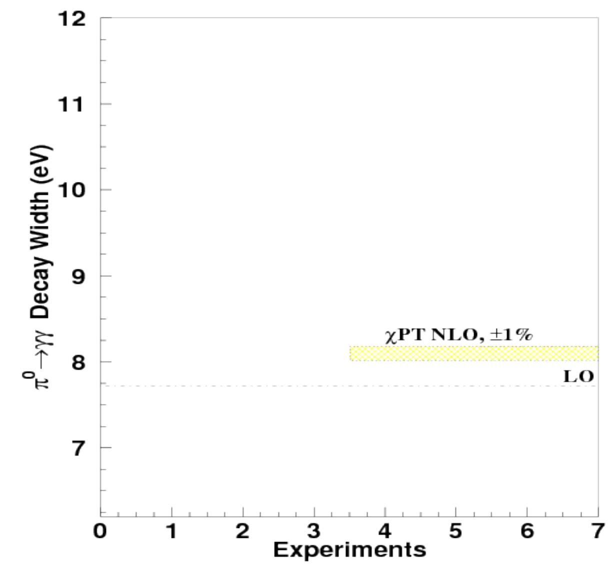

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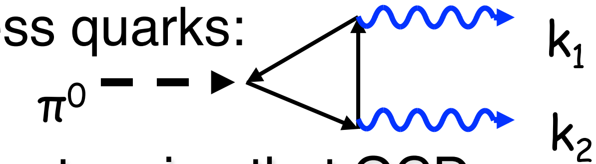

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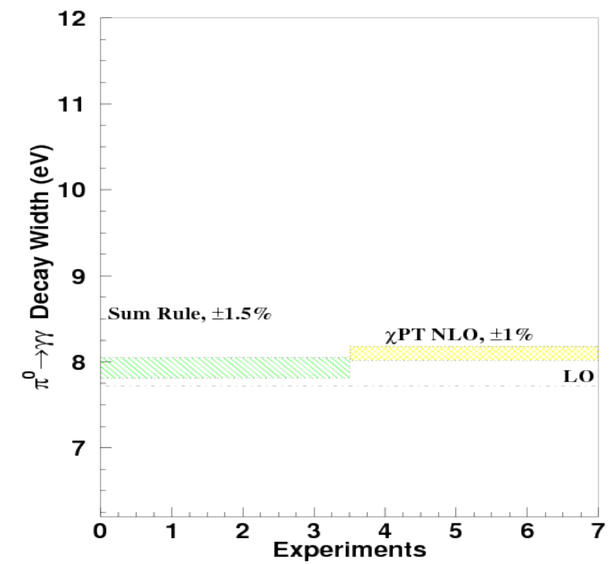

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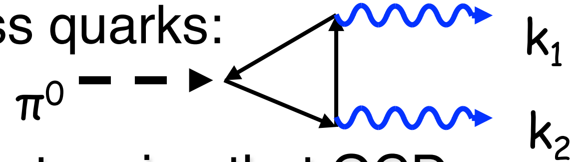

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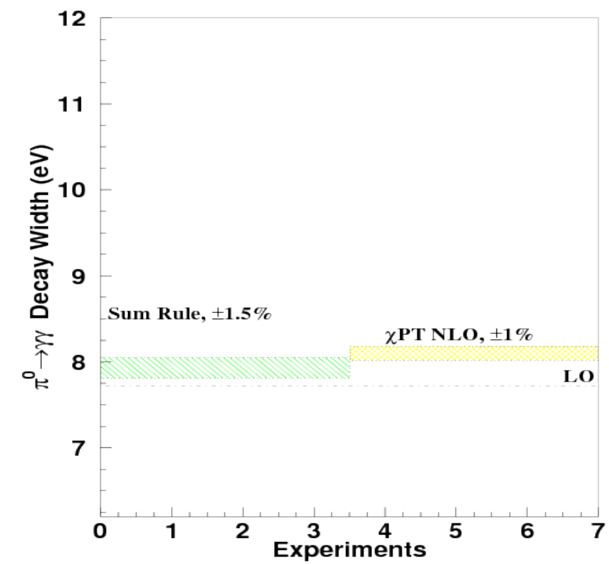

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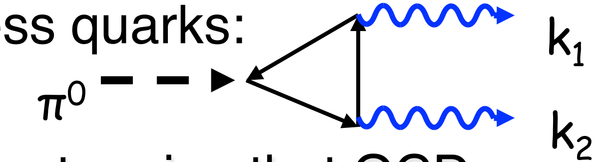

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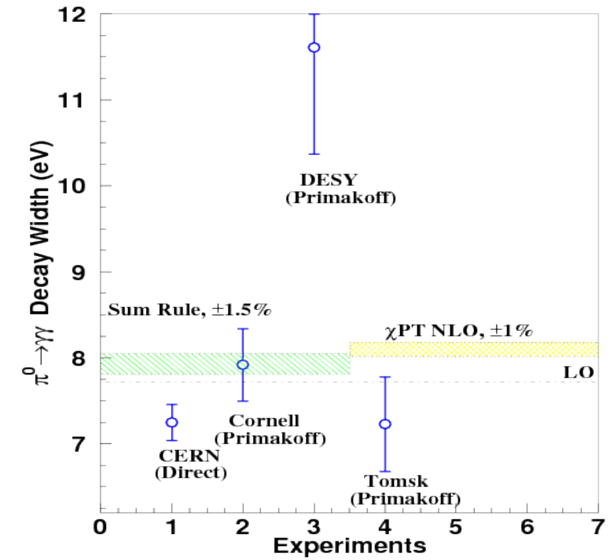

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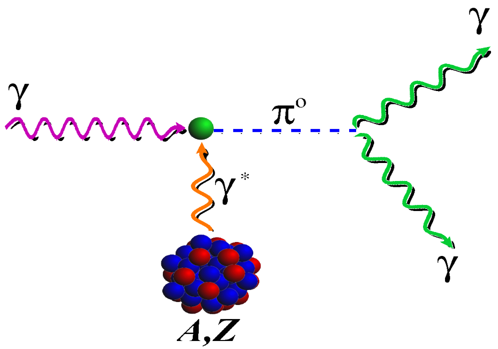
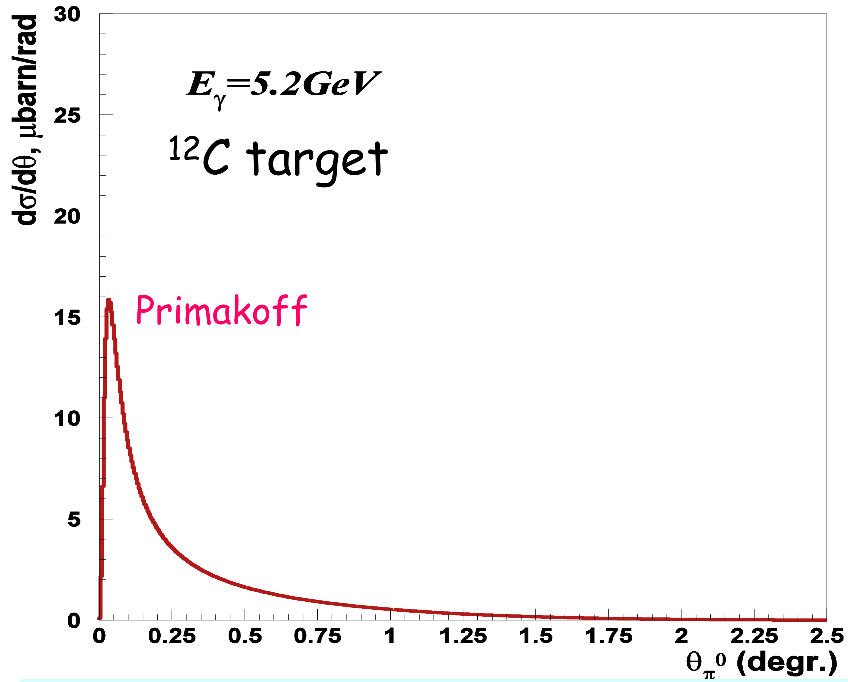
Primakoff Method



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



- Peaked at very small forward angle

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

- Beam energy sensitive:

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

- Coherent process

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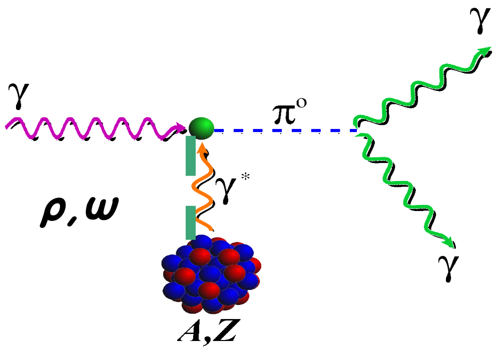

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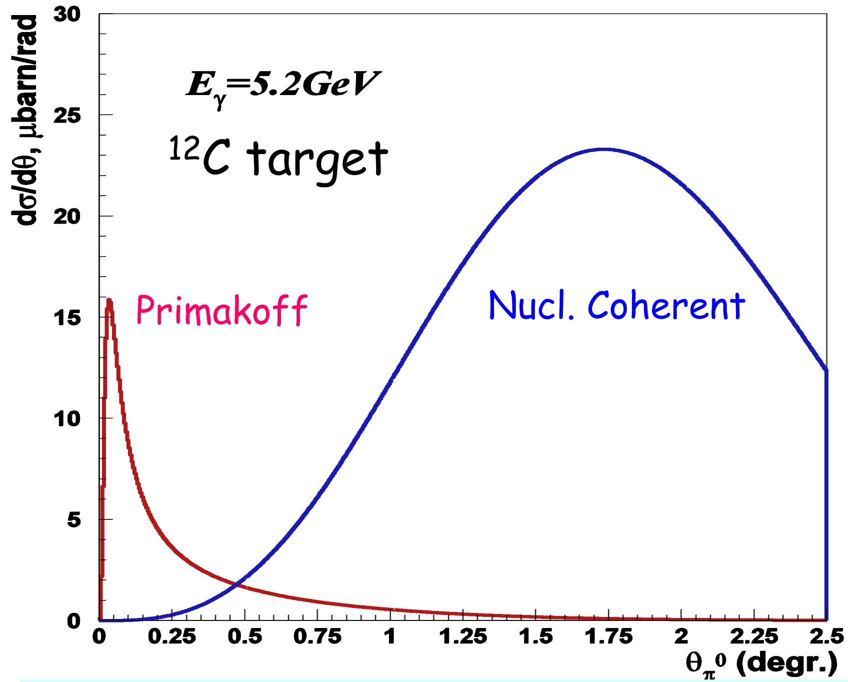

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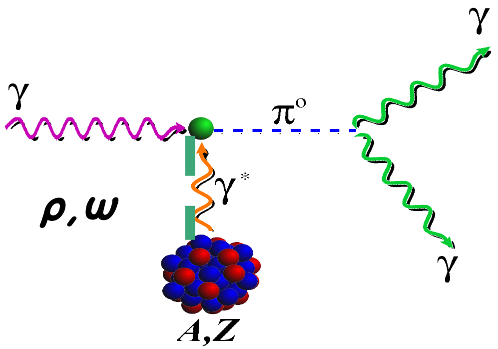

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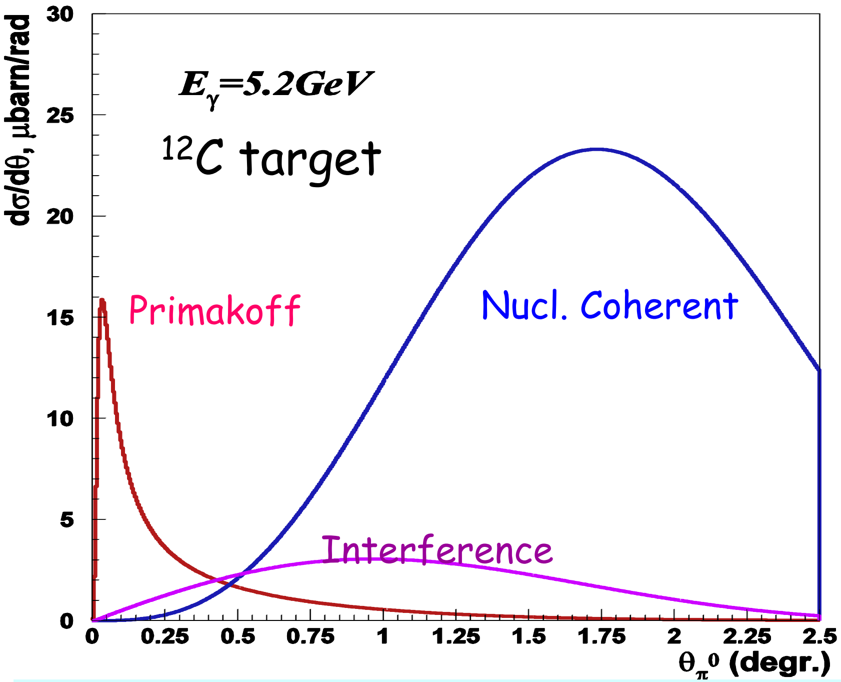

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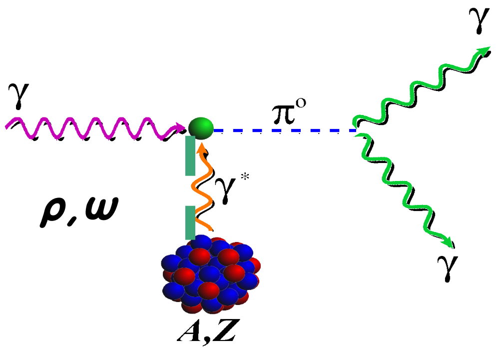

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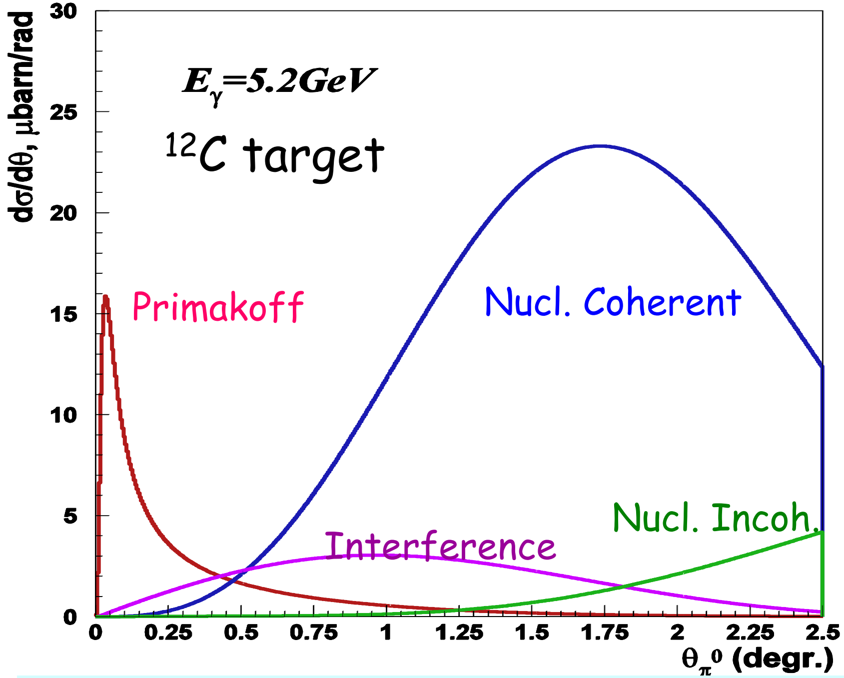

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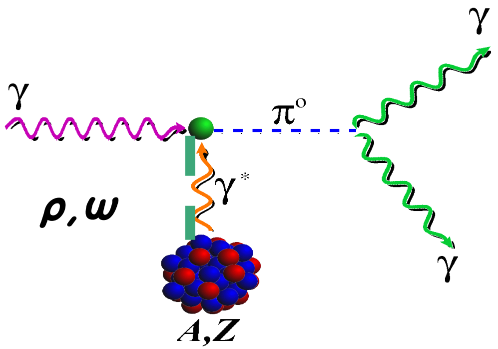

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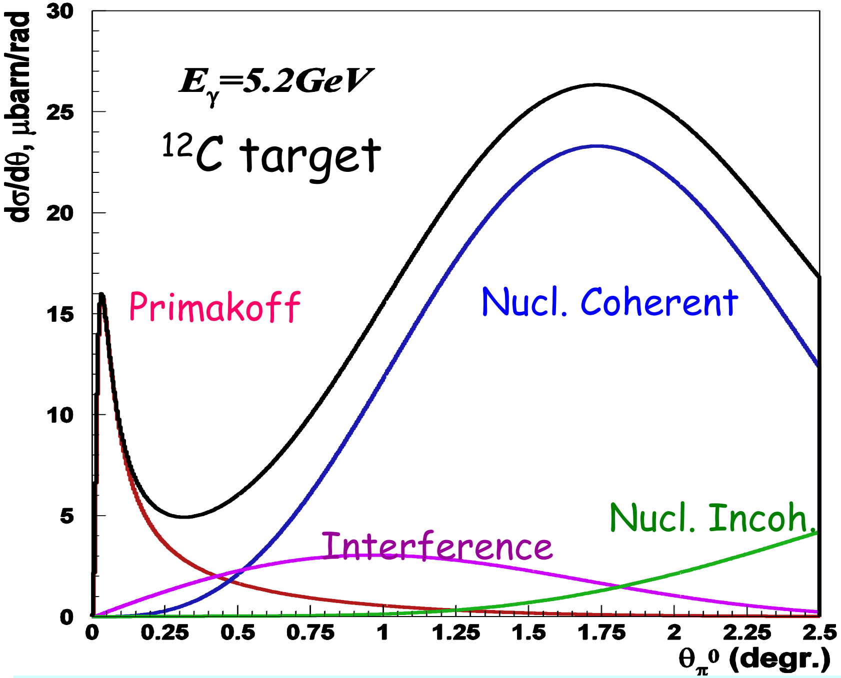
Challenge: Extract the Primakoff amplitude



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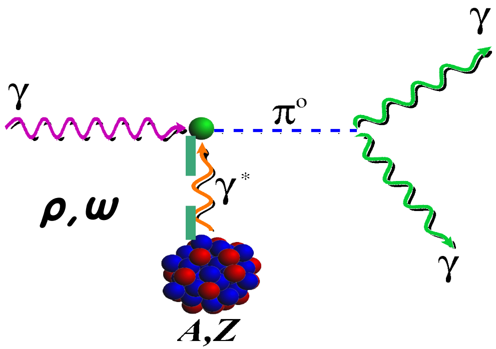

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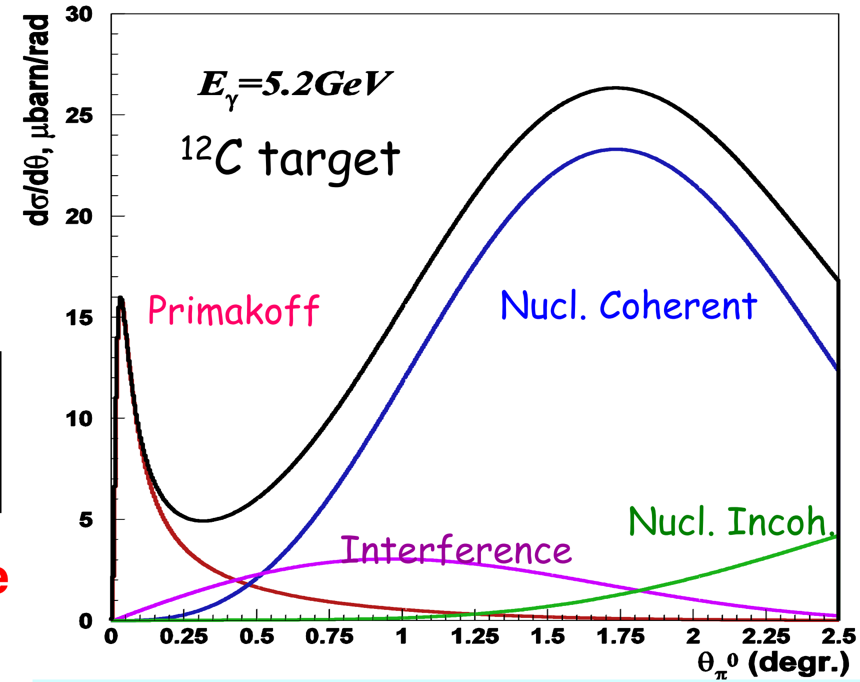

Requirement:

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

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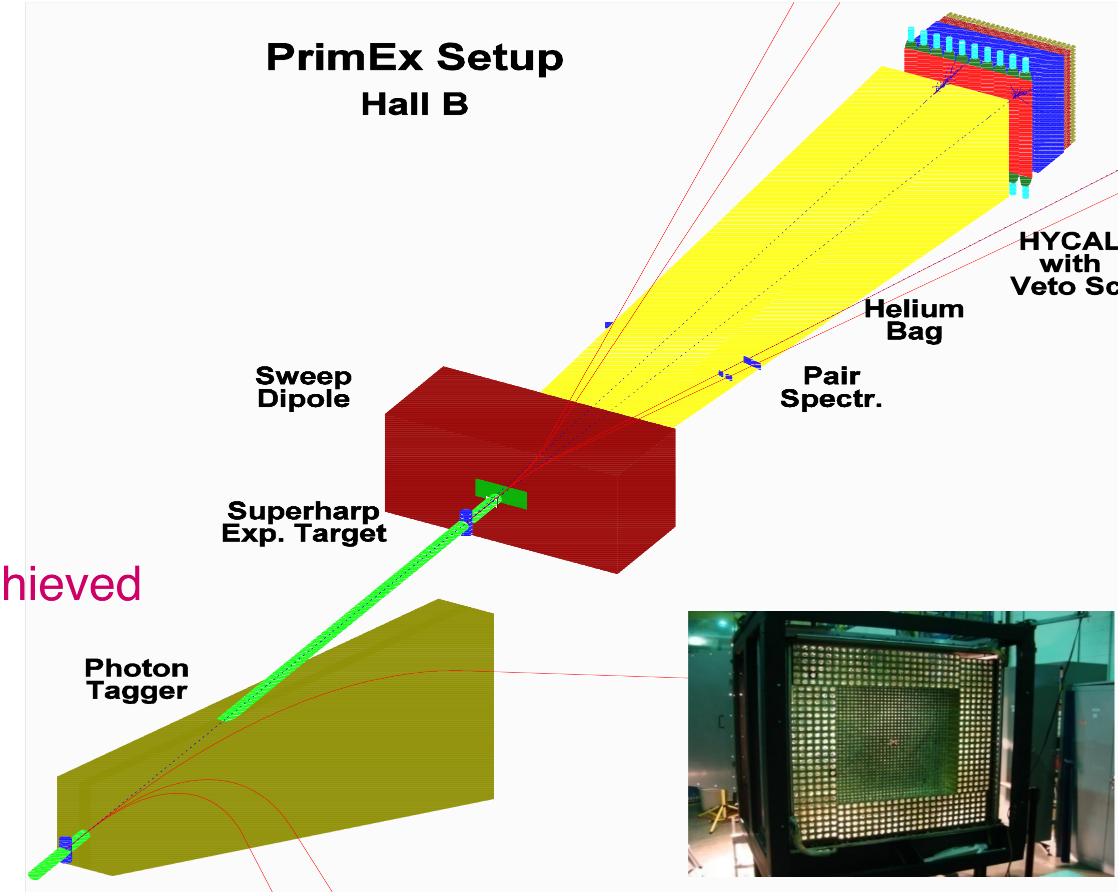
PrimEx Experimental Setup

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

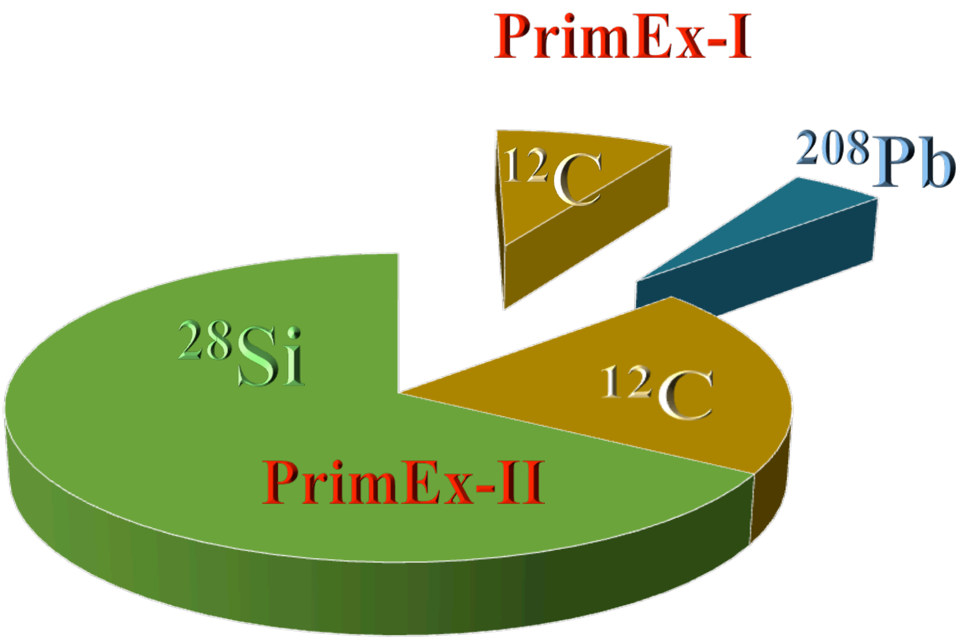
- A pair spectrometer for photon flux control at high beam intensities

→ 1% accuracy has been achieved

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



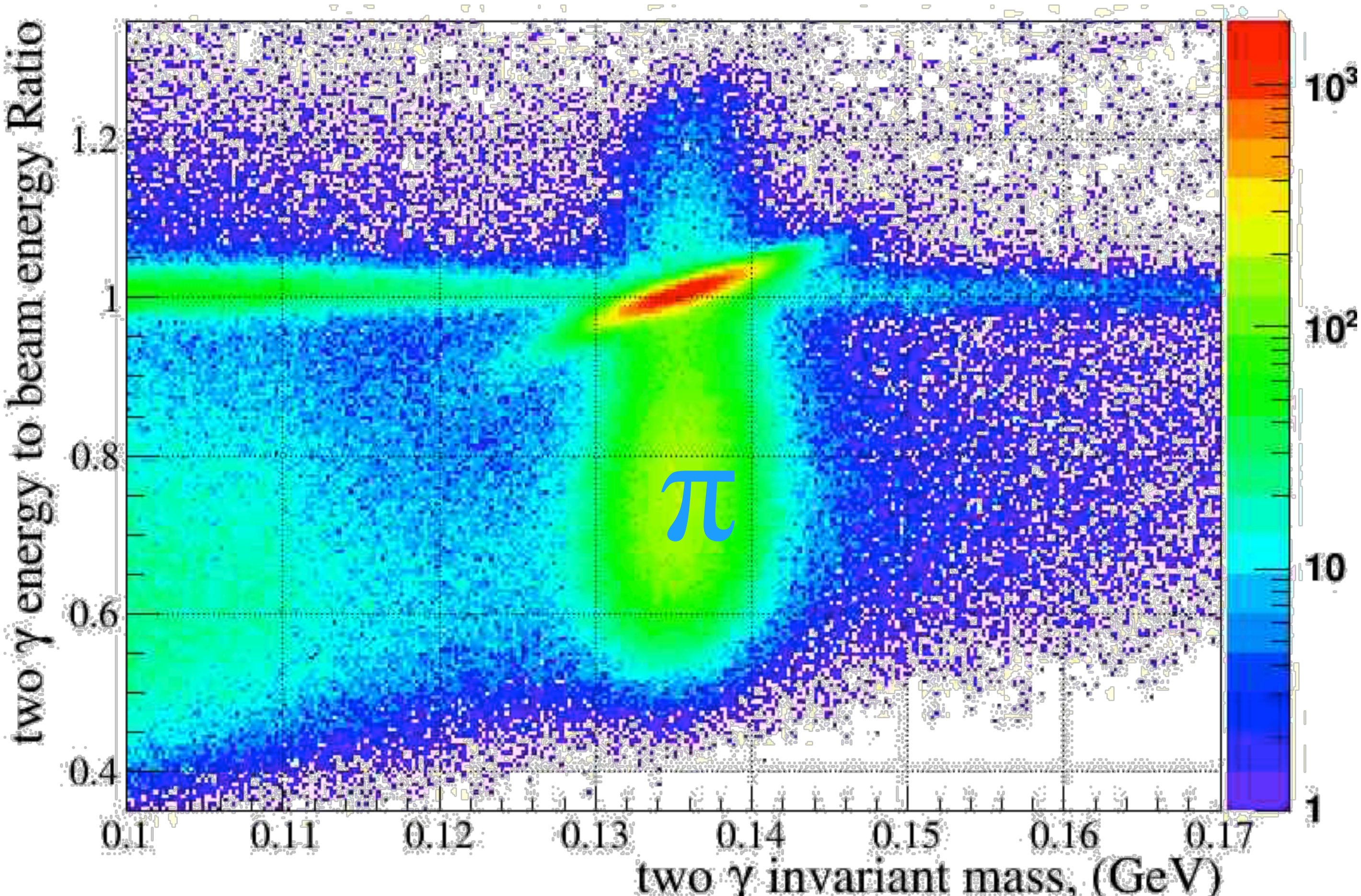
Two Experiments on $\Gamma(\pi^0 \rightarrow \gamma\gamma)$: PrimEx I & II

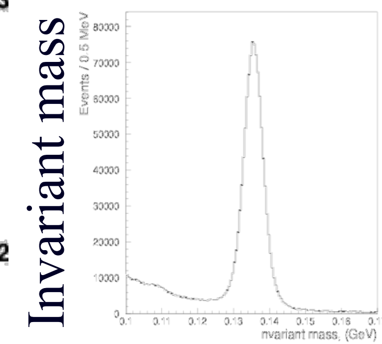


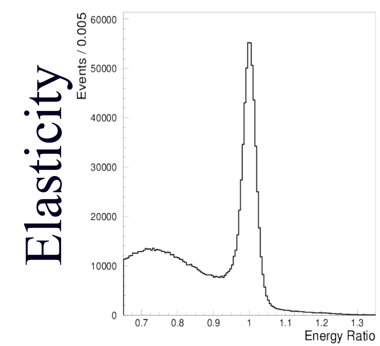
- PrimEx I was performed on ^{12}C and ^{208}Pb targets, and the result was published in 2011.
  PRL 106, 162303 (2011)

- PrimEx II was performed on ^{12}C and ^{28}Si targets. The result is recently finalized

$\pi^0 \to \gamma\gamma$ Event Selection







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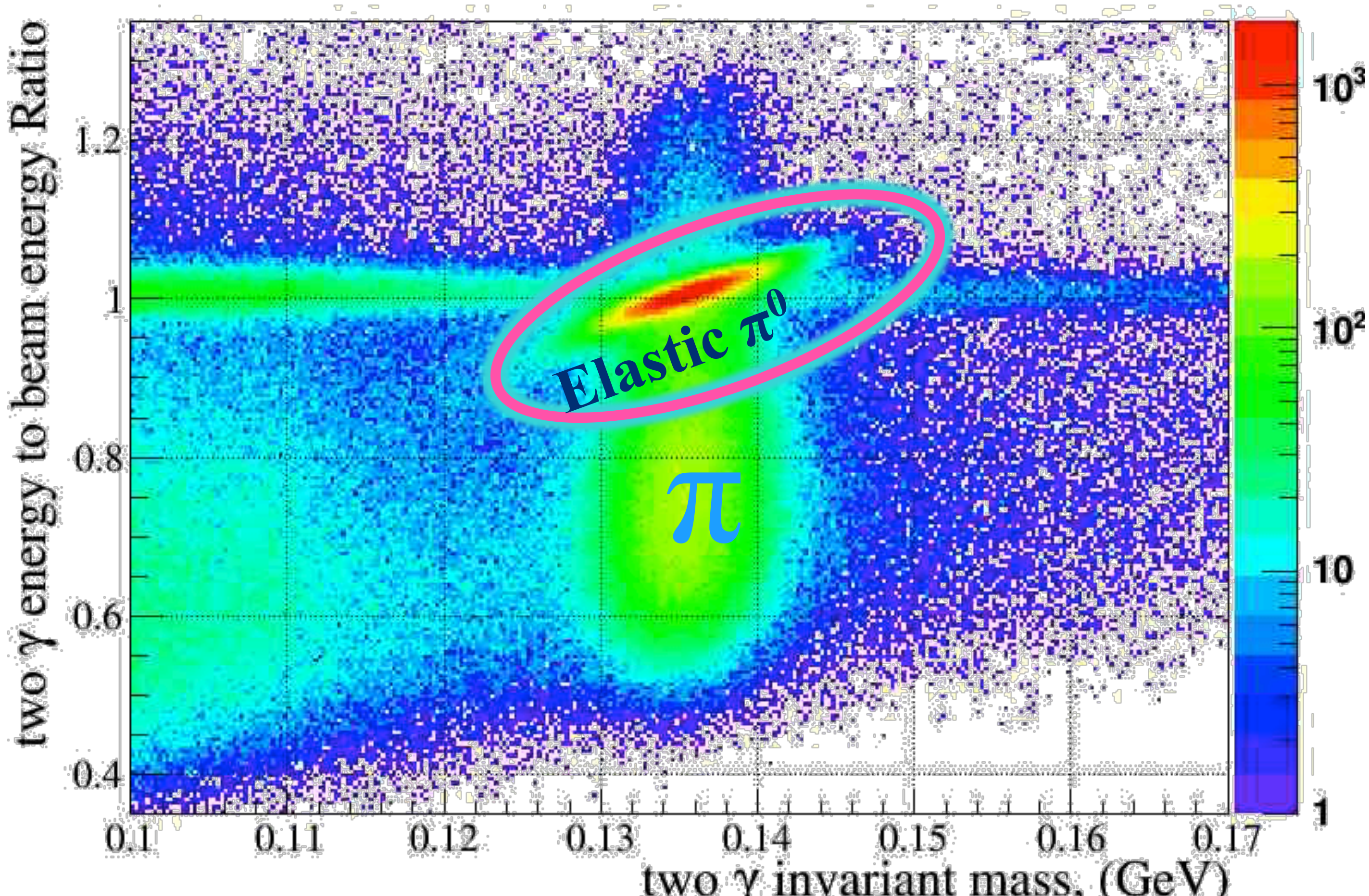
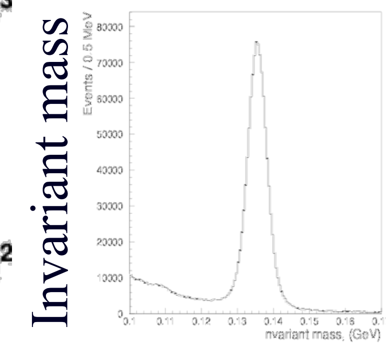
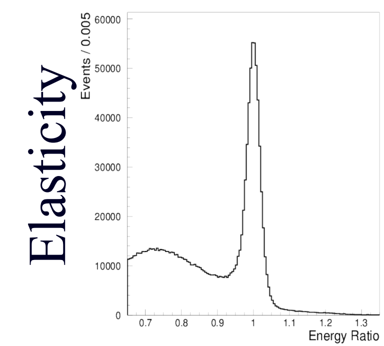
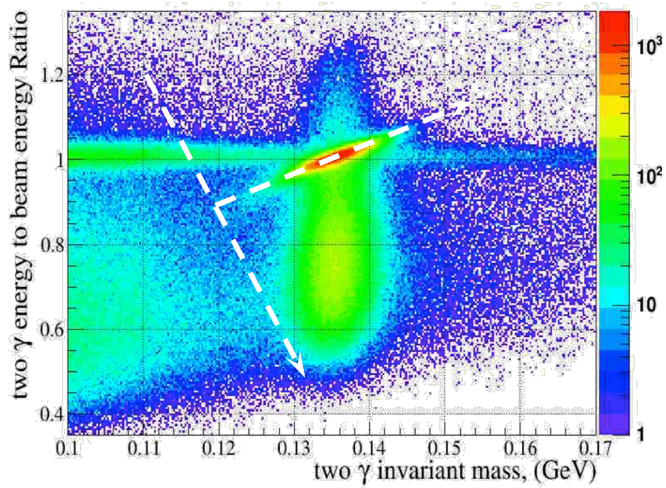






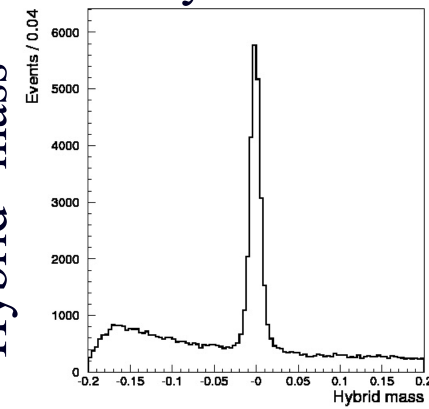
Two methods for π^0 yield extraction

- **Hybrid mass (H):**
  Y. Zhang, Duke Univ.

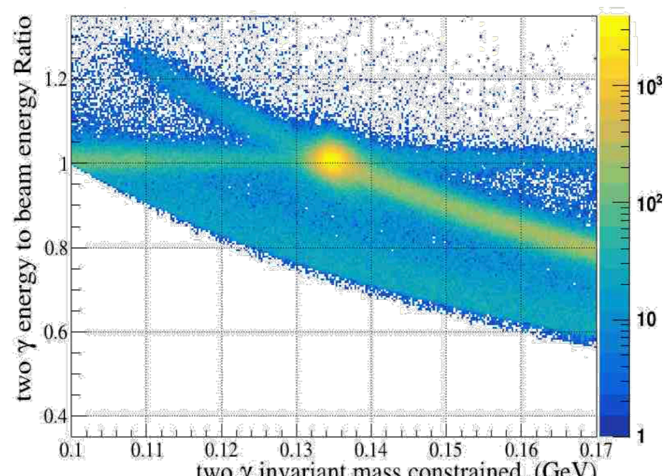


Analysis H

“Hybrid” mass

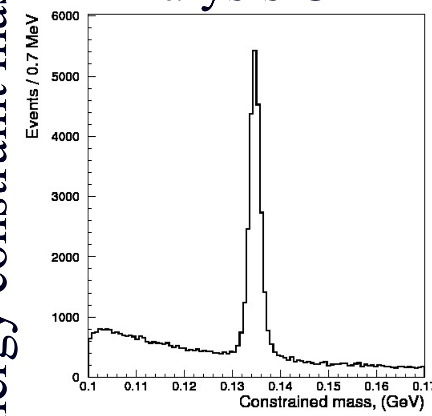


- **Constraint mass (C):**
  I. Larin, UMass

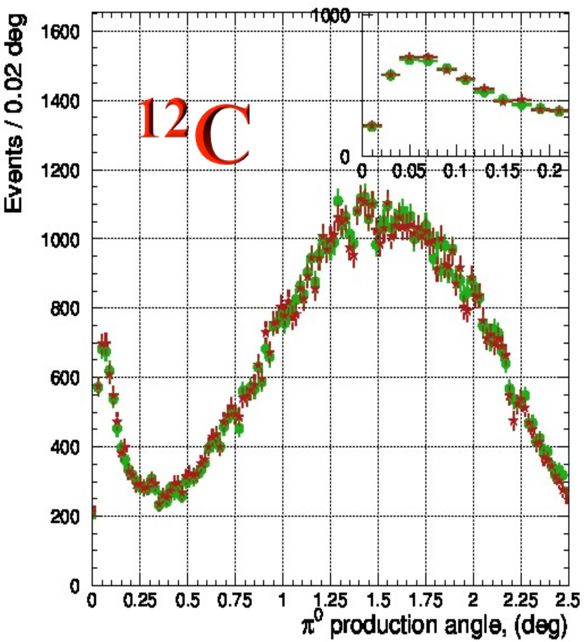


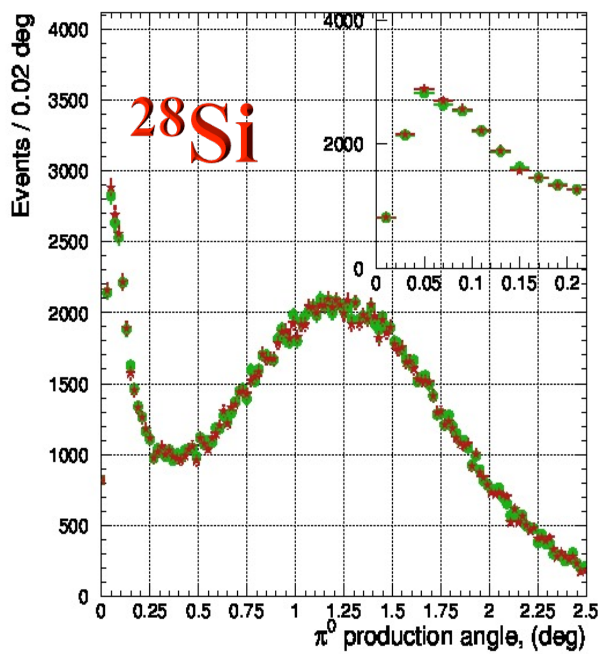
Analysis C

Energy constraint mass



Comparison of two extraction methods (PrimEx-II)





★ - Hybrid mass

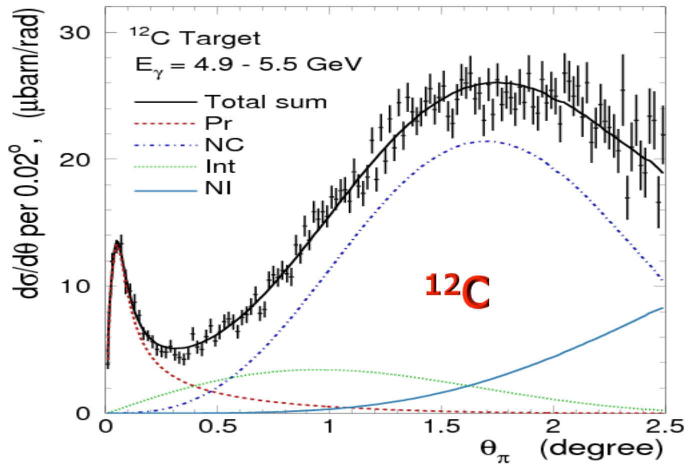
● - Constrained mass

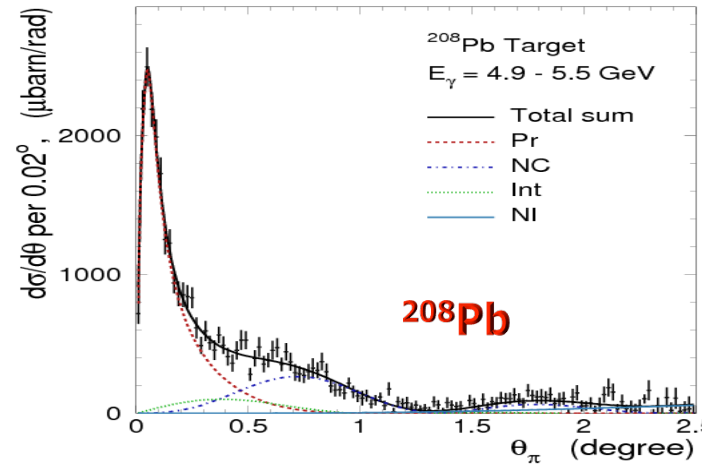
method	^{12}C	^{28}Si
Hybrid mass	**83,751**	**165,329**
Constr. mass	**84.015**	**165,736**

Extracted π^0 yield up to 2.5 deg.

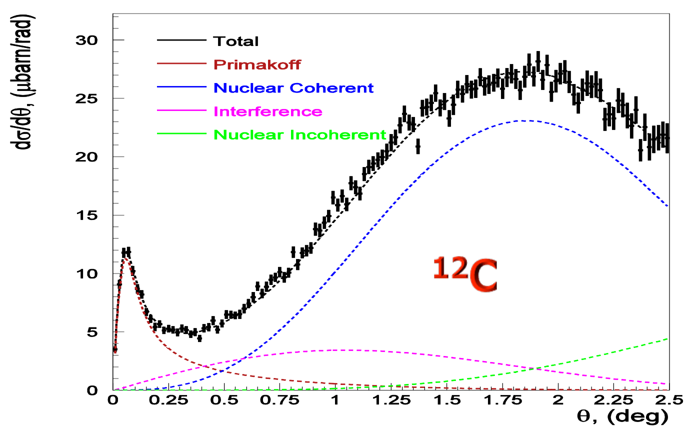
Differential Cross Sections

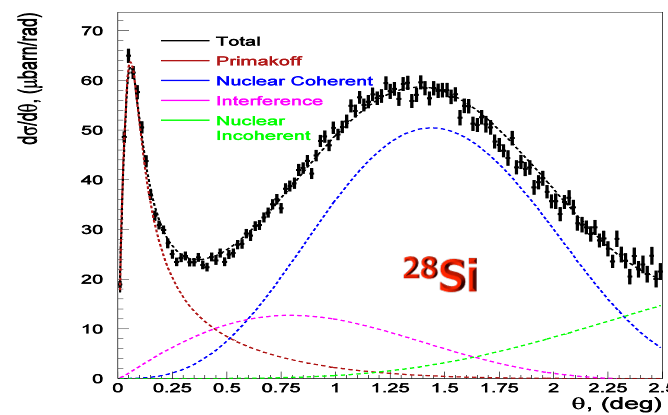
PrimEx I:





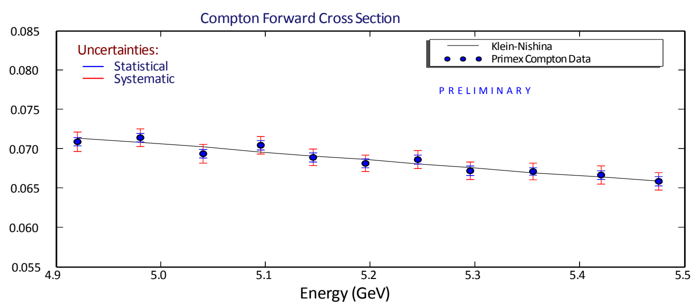
PrimEx II:

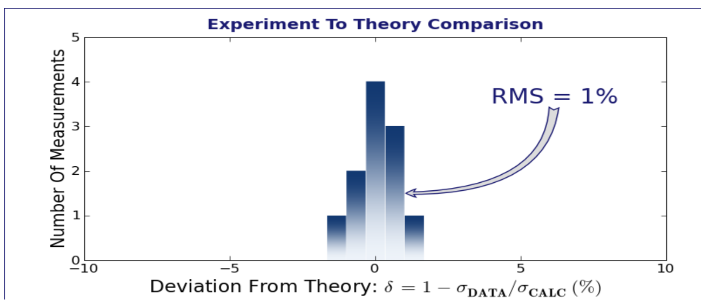




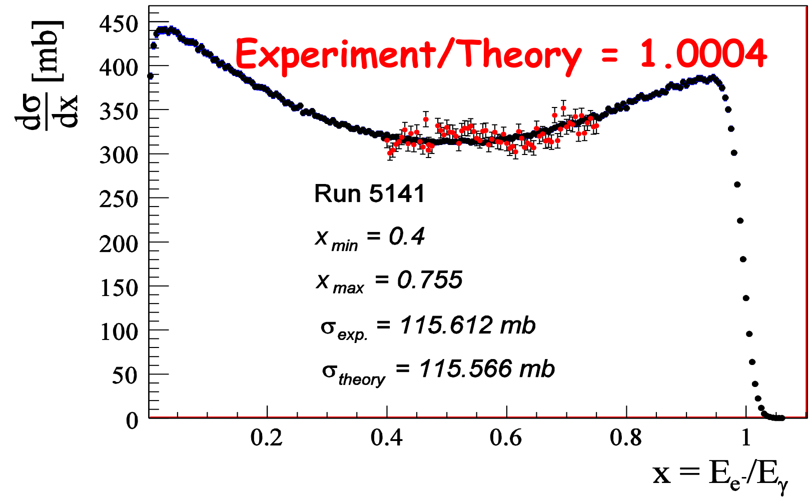
Verification of Overall Systematical Uncertainties

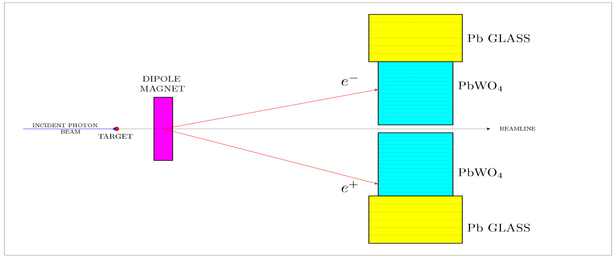
- $\gamma + e \rightarrow \gamma + e$ Compton cross section measurement





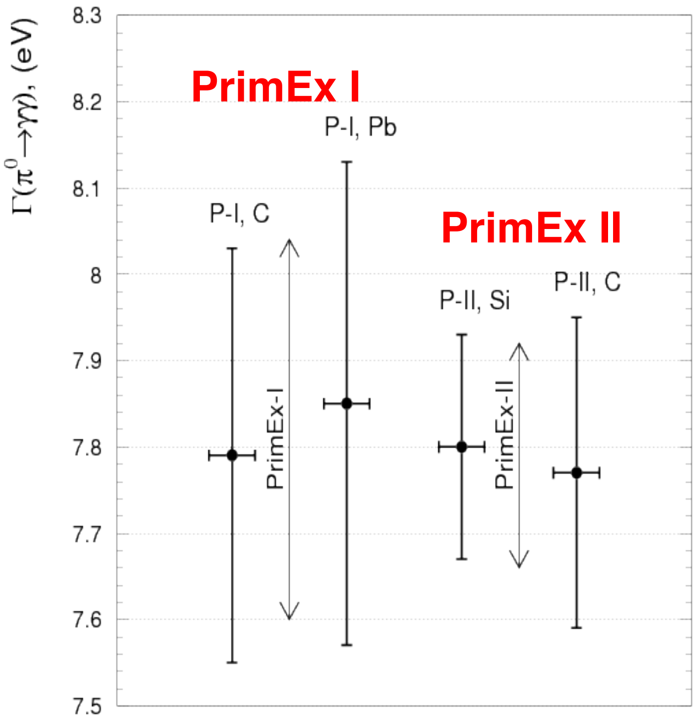
- e^+e^- pair-production cross section measurement:





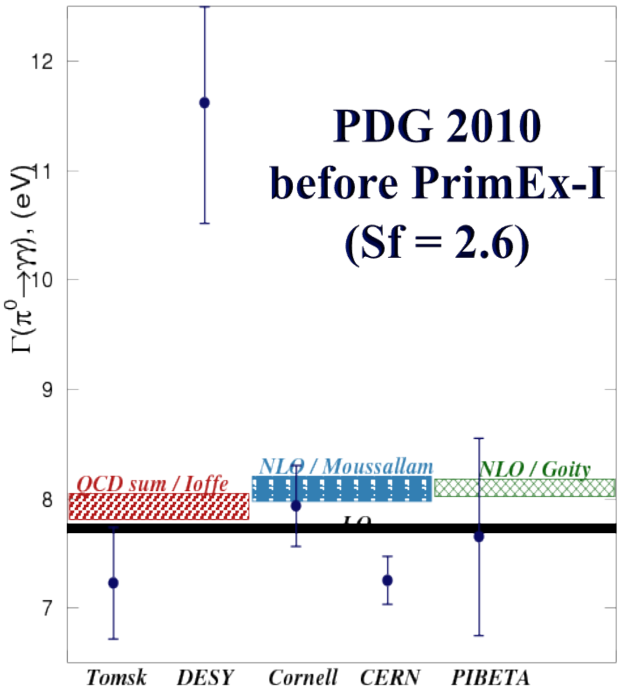
Systematic uncertainties on cross section are controlled under 1.3%

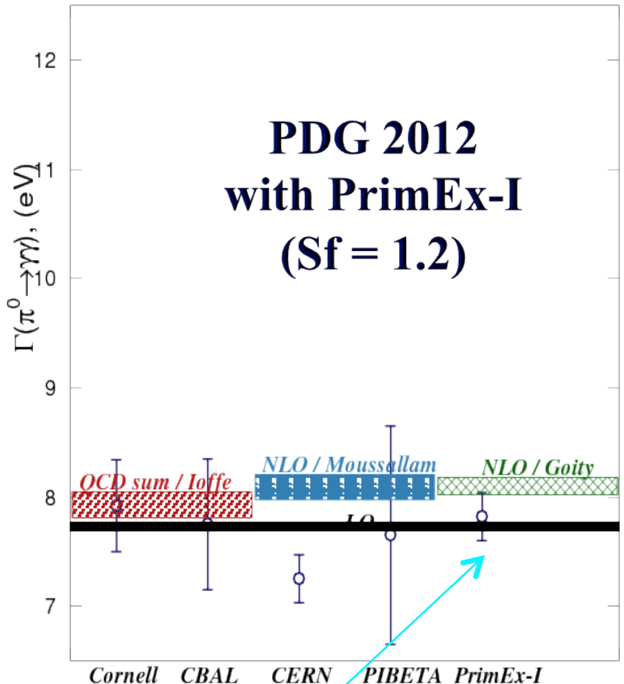
PrimEx I and II results



Exp.	Target	$\Gamma(\pi^0 \to \gamma\gamma)$, eV
PrimEx-I	^{12}C	7.79±0.24
PrimEx-I	^{208}Pb	7.85±0.28
PrimEx-II	^{28}Si	7.80±0.13
PrimEx-II	^{12}C	7.77±0.18

Impact of PrimEx results

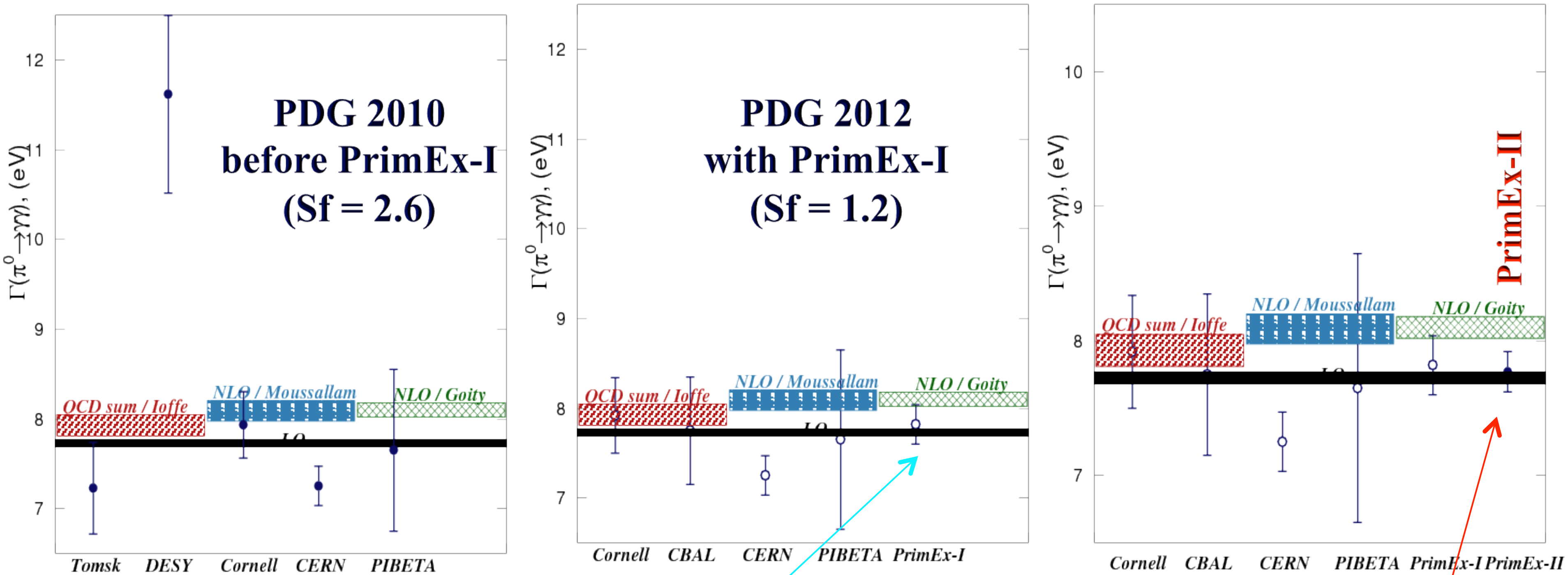




PrimEx I
$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty

PRL 106, 162303 (2011)

Impact of PrimEx results



PrimEx I

$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV

2.8% total uncertainty

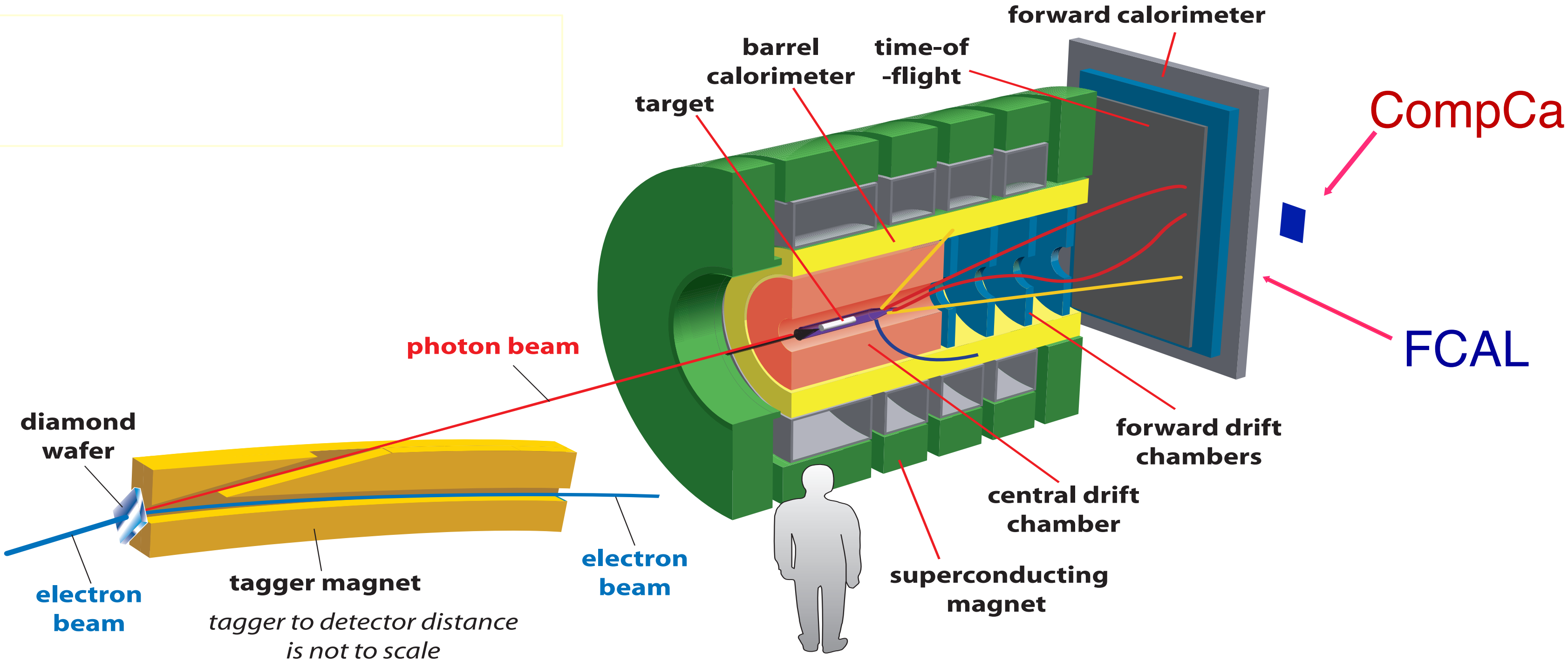
PRL 106, 162303 (2011)

PrimEx II

$\Gamma(\pi^0 \to \gamma\gamma)$ = 7.79±0.06(stat)±0.12(syst) eV

1.6% total uncertainty

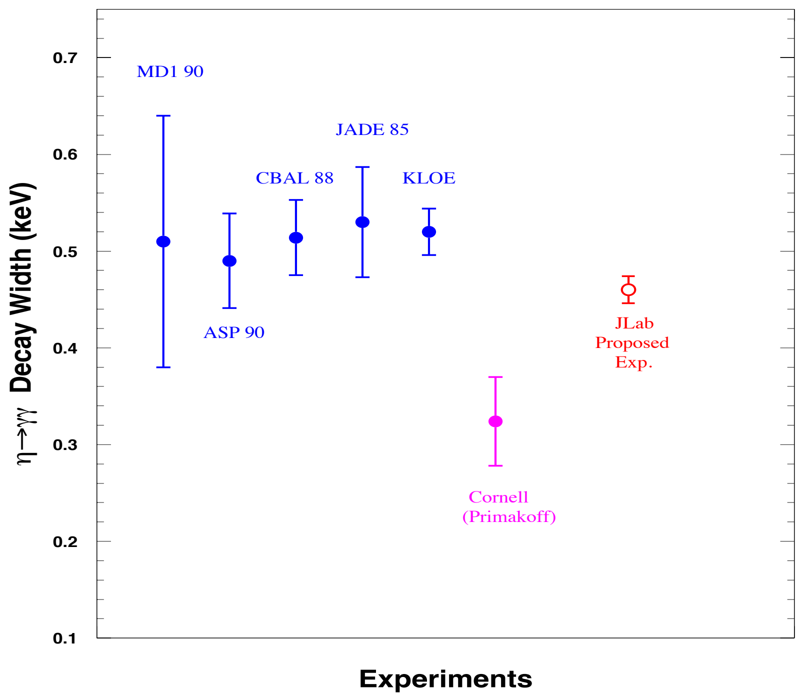
Measurement of $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D at 12 GeV



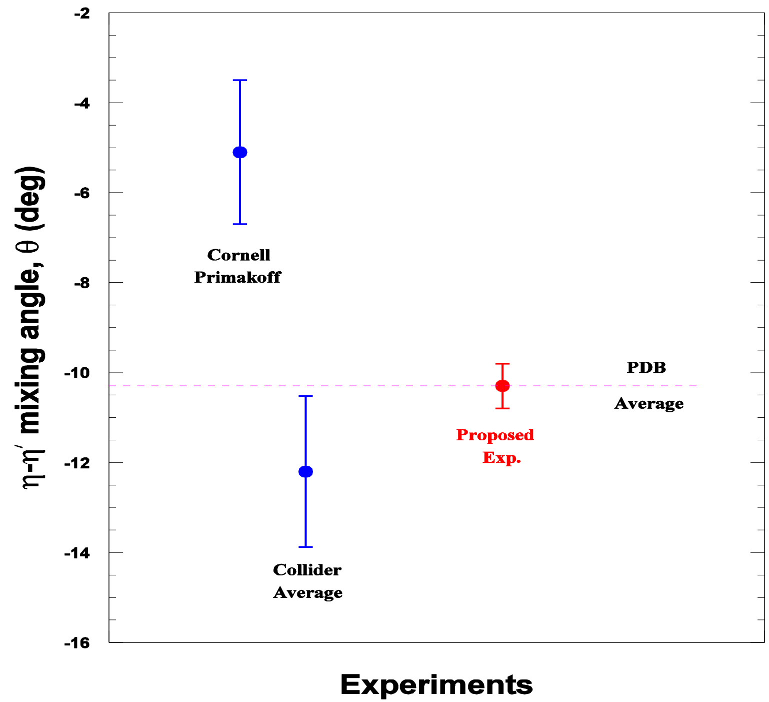
- Tagged photon beam (~9.5-11.7 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- Liquid Hydrogen (3.5% R.L.) and ^{4}He targets (~4% R.L.)
- Forward Calorimeter (FCAL) detects the $\eta\rightarrow\gamma\gamma$ decay photons
- CompCal and FCAL to measure electron Compton scattering for control of overall systematics.

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:**



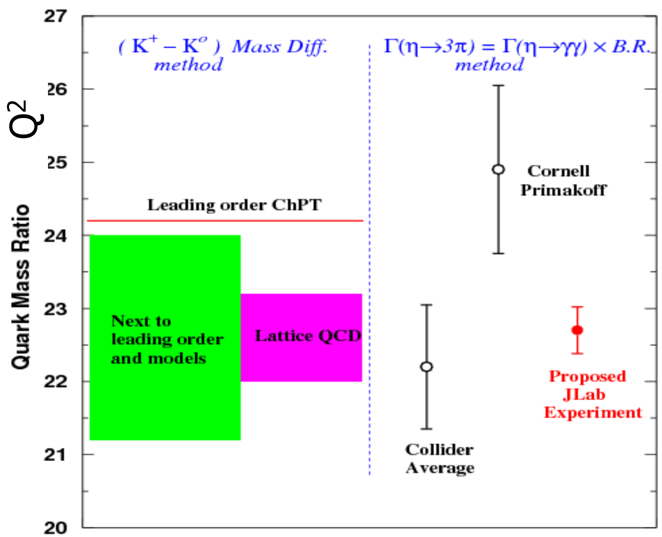
3. **Improve all partial decay widths in the η-sector**

Precision Determination Light Quark Mass Ratio

A clean probe for quark mass ratio:

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

- $\eta \to 3\pi$ 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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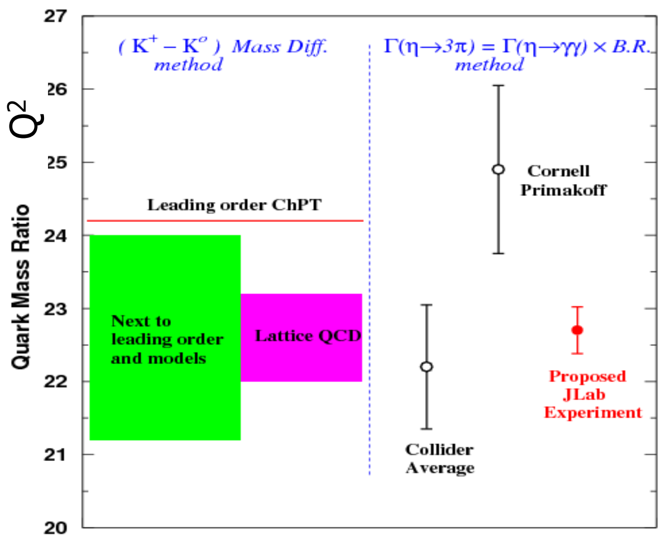


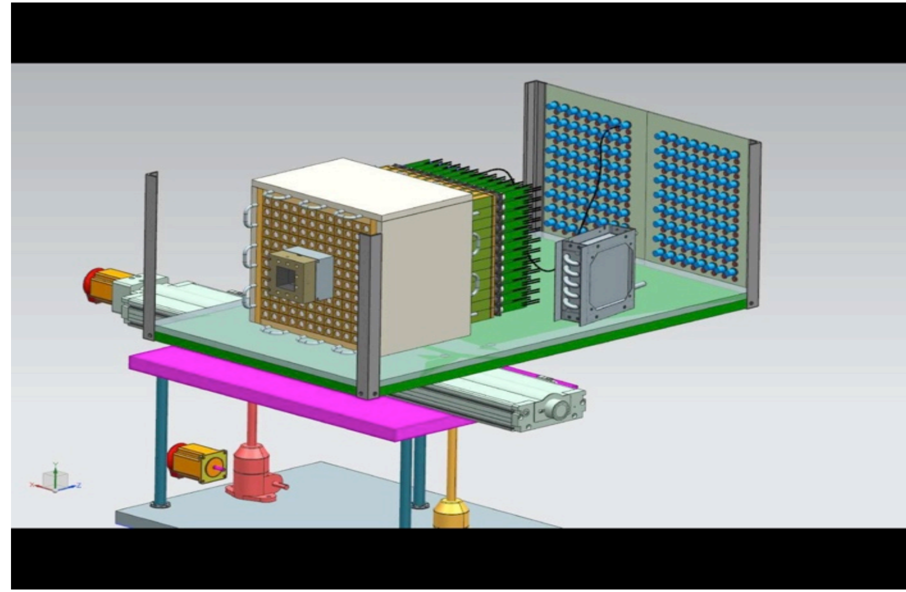
- Critical input to extract Cabibbo Angle, $V_{us} = \sin(\theta_c)$ from kaon or hyperon decays.
- V_{us} is a cornerstone for test of CKM unitarity:

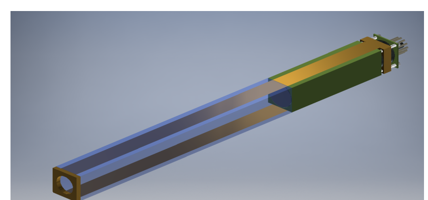
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

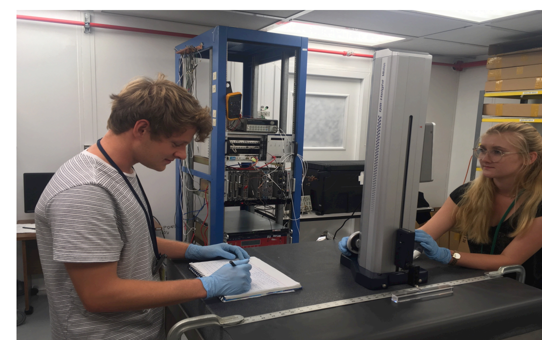
H. Leutwyler Phys. Lett., B378, 313 (1996)

Current Status

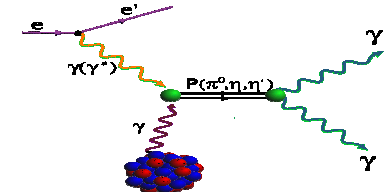
- CompCal is currently under construction
- A engineering run in fall 2018
- Physics production run will start in spring 2019.



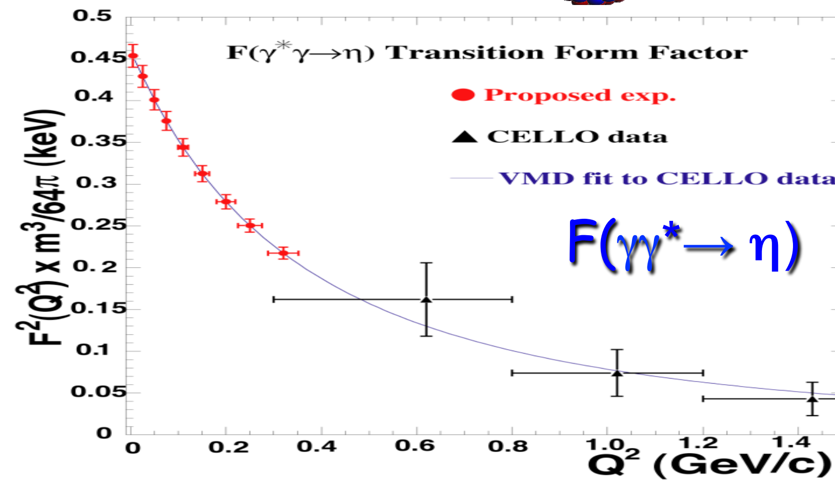




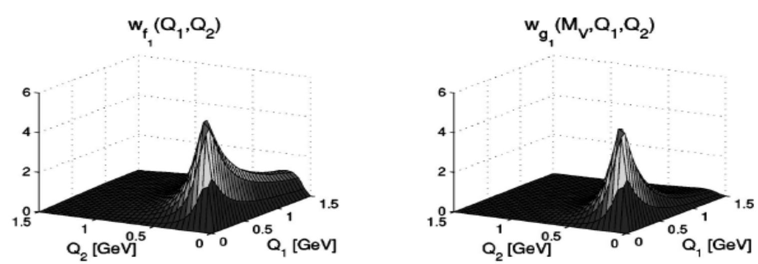
Transition Form Factors $F(\gamma\gamma^* \rightarrow P)$
(at low Q^2 : 0.001-0.5 GeV^2/c^2)



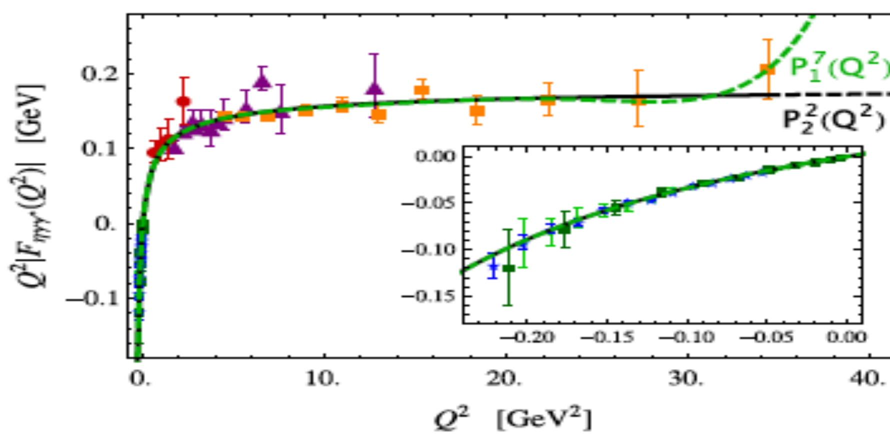
- **Direct measurement of slopes**
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2) \approx 1 - 1/6 \cdot \langle r^2 \rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



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

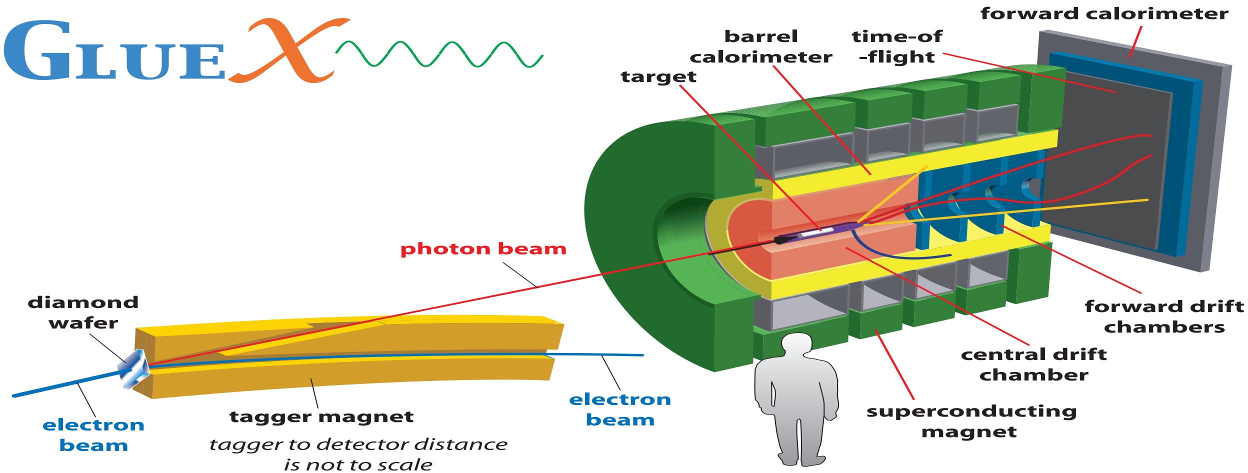


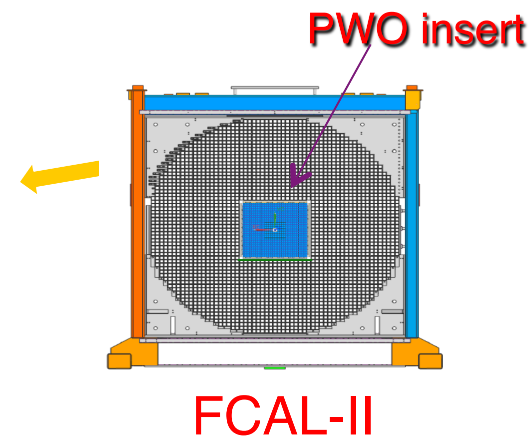
Phys.Rev.D65,073034



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

Jlab Eta Factory (JEF) experiment





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

- η/η' produced on LH_2 target with 8.4-11.7 GeV tagged photon beam

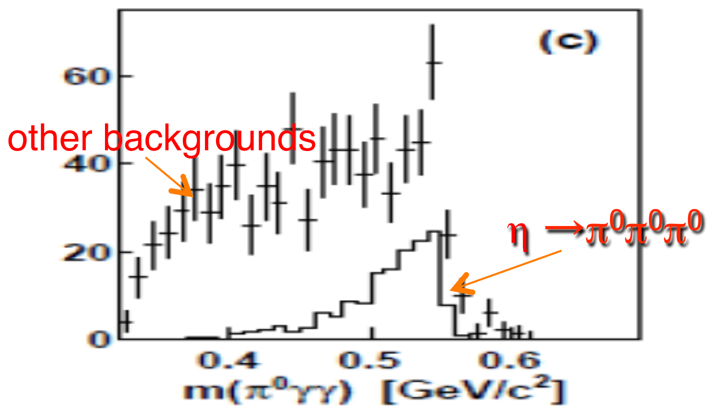
  $\gamma+p \rightarrow \eta/\eta' + p$
- Reduce non-coplanar backgrounds by detecting recoil protons with GlueX detector
- Upgraded Forward Calorimeter with High resolution, high granularity PWO insertion (FCAL-II) to detect multi-photons from the η/η' decays

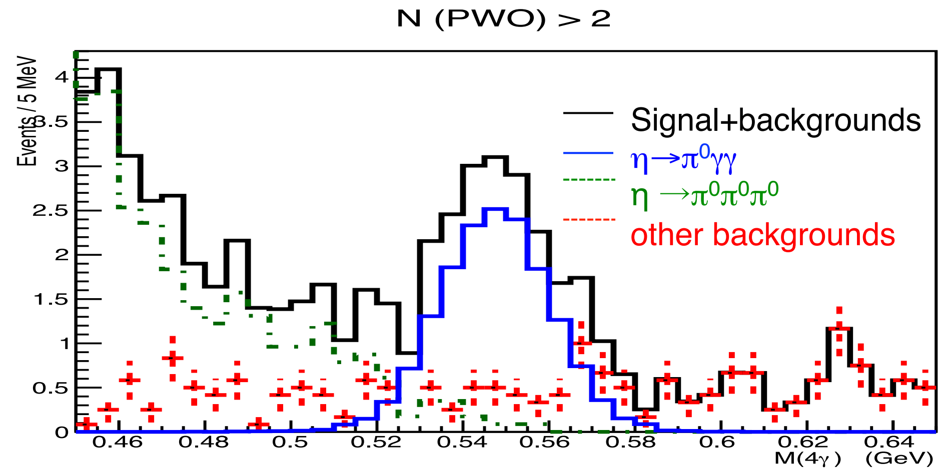
Uniqueness of JEF Experiment

1. Highly suppressed background with:
   a) η/η' energy boost; b) FCAL-II; c) exclusive detections

A2 at MAMI: $\gamma p \to \eta p$ (E_γ=1.5 GeV)
(P.R. C90, 025206)

JEF: $\gamma p \to \eta p$ (E_γ=8.4-11.7 GeV)



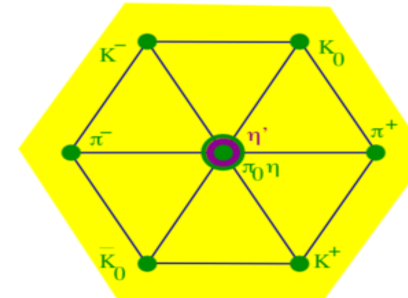


2. Simultaneously produce η and η' with similar rates

	η/100 days	η'/100 days
Tagged mesons	6.5×10^7	4.9×10^7

3. Capability of running in parallel with GlueX and other experiments in Hall D ⟶ potential for high statistics

Why η is a unique probe for QCD and BSM physics?



- A Goldstone boson due to spontaneous breaking of QCD chiral symmetry
  → η is one of key mesons bridging our understanding of low-energy hadron dynamics and underlying QCD

- All its possible strong and EM decays are forbidden in the lowest order so that η has narrow decay width (Γ_η =1.3KeV compared to Γ_ω=8.5 MeV)
  → Enhance the higher order contributions (by a factor of ~7000 compared to ω decays). Sensitive to weakly interacting forces.

- Eigenstate of P, C, CP, and G: $I^G J^{PC} = 0^+ 0^{-+}$
  → tests for C, CP

- All its additive quantum numbers are zero and its decays are flavor-conserving
  → effectively free of SM backgrounds for new physics search.

Overview of JEF Physics

Mode	Branching Ratio	Physics Highlight	Photons
priority:			
$\gamma + B'$	beyond SM	leptophobic vector boson	4
$\pi^0 + \phi'$	beyond SM	electrophobic scalar boson	4
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh at $\mathcal{O}(p^6)$	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	$< 2.8 \times 10^{-4}$	$< 10^{-11}$[4]	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 E12-10-011	2

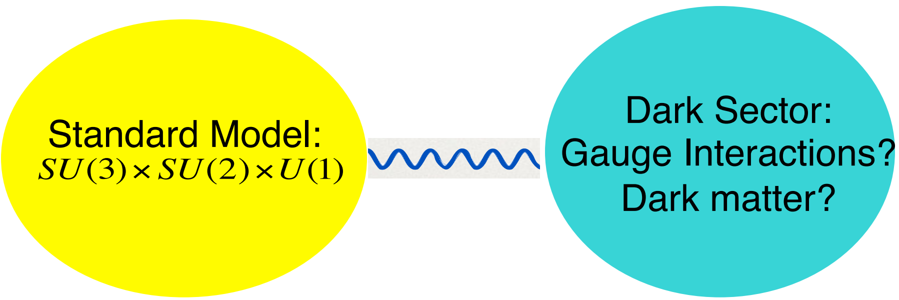
Main physics goals:

1. Search for sub-GeV gauge bosons: leptophobic vector B′ and electrophobic scalar Φ′
2. Directly constrain CVPC new physics
3. Probe interplay of VMD & scalar resonances in ChPT to calculate LEC's in the chiral Lagrangian
4. Improve the quark mass ratio via $\eta \to 3\pi$

FCAL-II is required

Key Channel: $\eta\to\pi^0\gamma\gamma$

1. New physics:



Portal: $(n=4)$

vector $\kappa B^{\mu\nu}V_{\mu\nu}$

scalar $H^{+}H(\varepsilon S+\lambda S^{2})$

fermion ξLHN

2. Confinement QCD:

- **Search for sub-GeV gauge bosons**
  - A leptophobic vector B′:
    $\eta\to\gamma B'$, $B'\to\pi^0\gamma$ PR,D89,114008
  - An electrophobic scalar Φ′:
    $\eta\to\pi^0\Phi'$, $\Phi'\to\gamma\gamma$
    → electrophobic scalar can solve proton radius and $(g\text{-}2)_\mu$ puzzles.

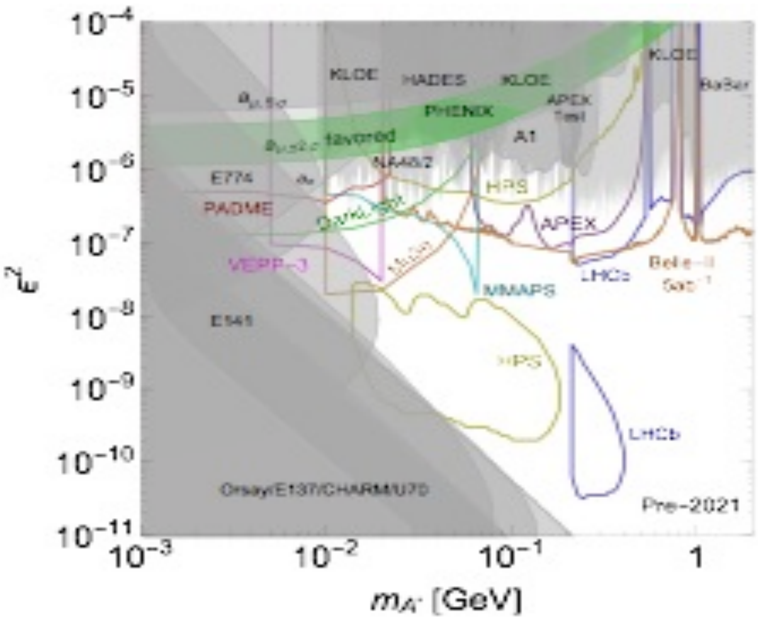
PRL 117,101801 (2016); PL B740,61(2015)
arXiv:1805.01028

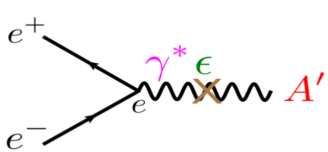
- **A rare window to probe interplay of VMD & scalar resonance in ChPT**

“Vector Portal” to Dark Sector

1. Dark photon A′

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





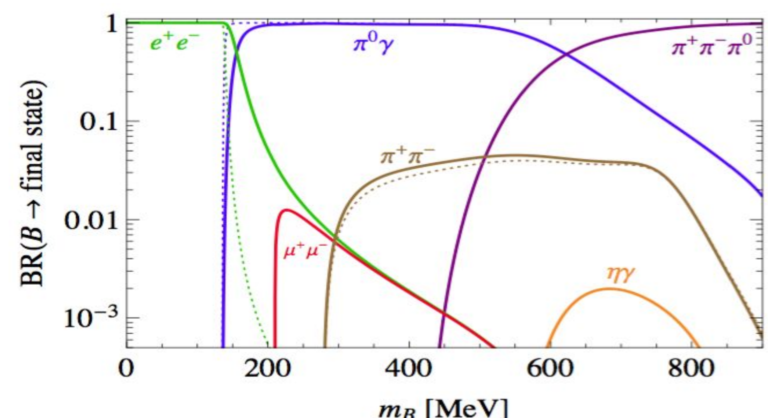
Most A′ searches look for A′→l^+l^-, relying on the leptonic coupling of new force

2. Leptophobic B′ (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)

- $m_B<m_\pi$ is strongly constrained by long-range forces searches; the $m_B>50$ GeV has been investigated by the collider experiments.
- GeV-scale domain is nearly untouched, a discovery opportunity!



PR,D89,114008

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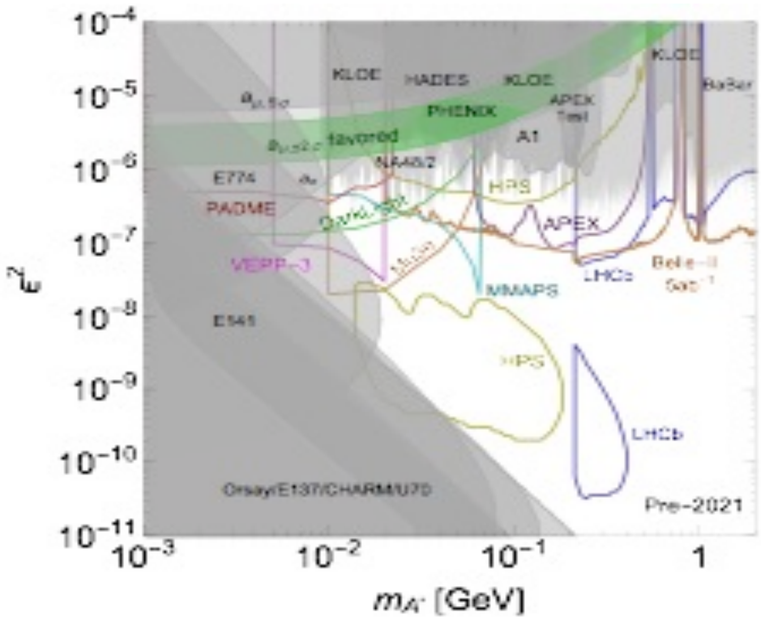

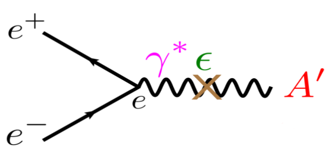

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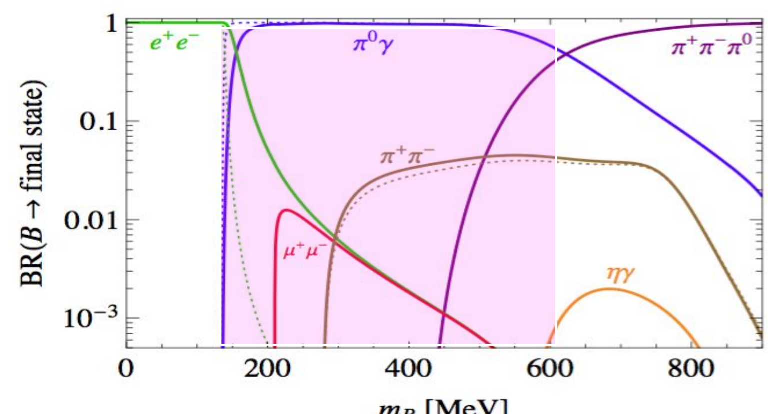
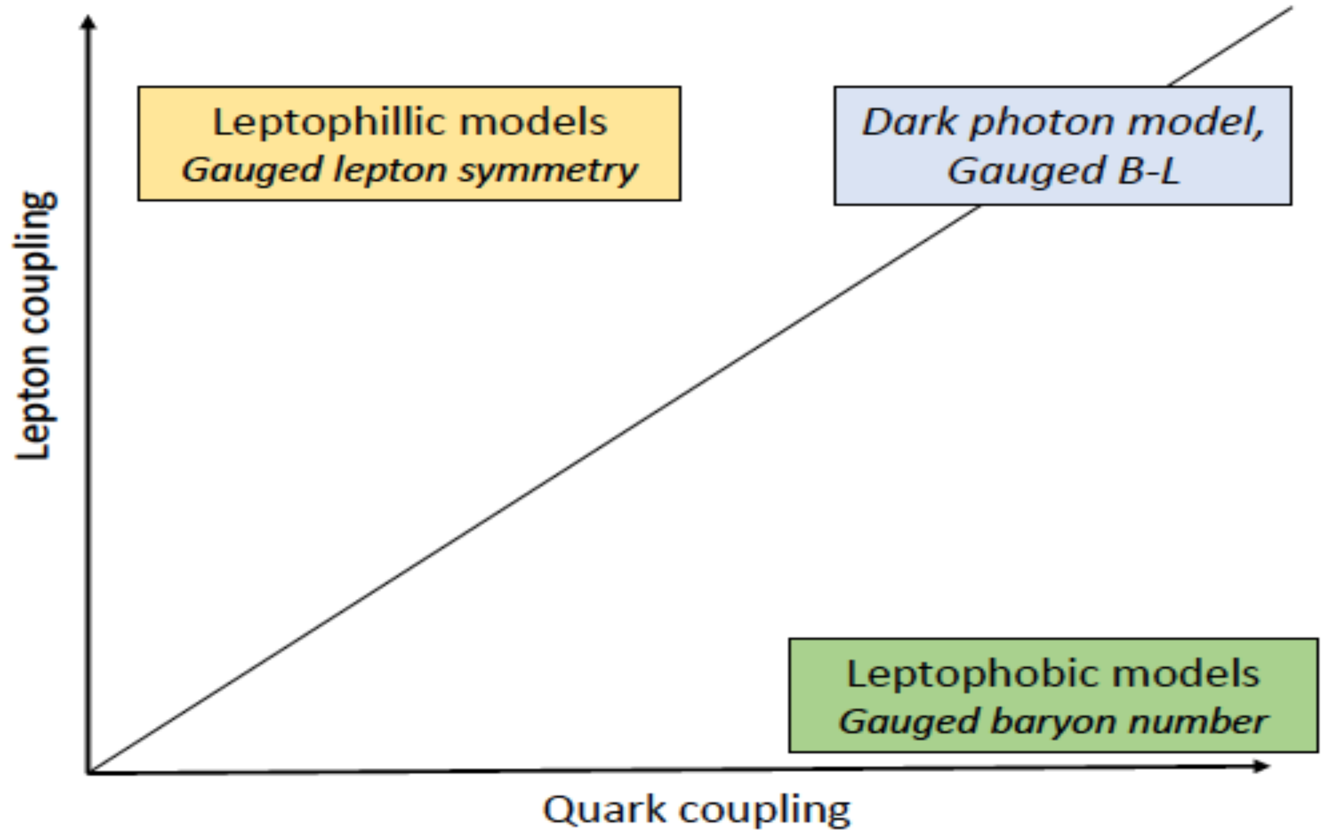


PR,D89,114008

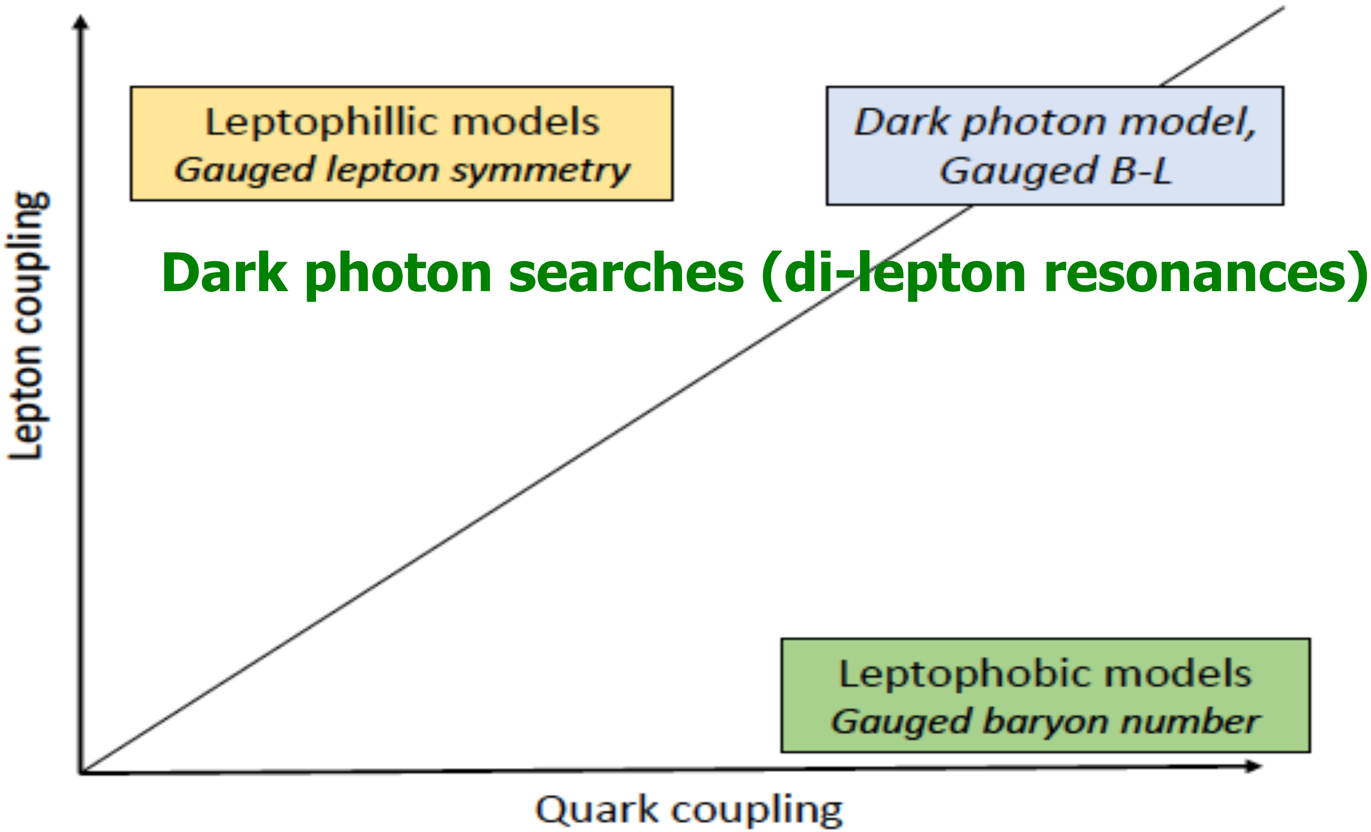
Landscape of New GeV-Scale Forces



Also a third axis: decays to invisible states (neutrinos, light dark matter)

Davoudiasl et al (2012), Batell et al (2009), deNiverville et al (2011,2012)

Landscape of New GeV-Scale Forces



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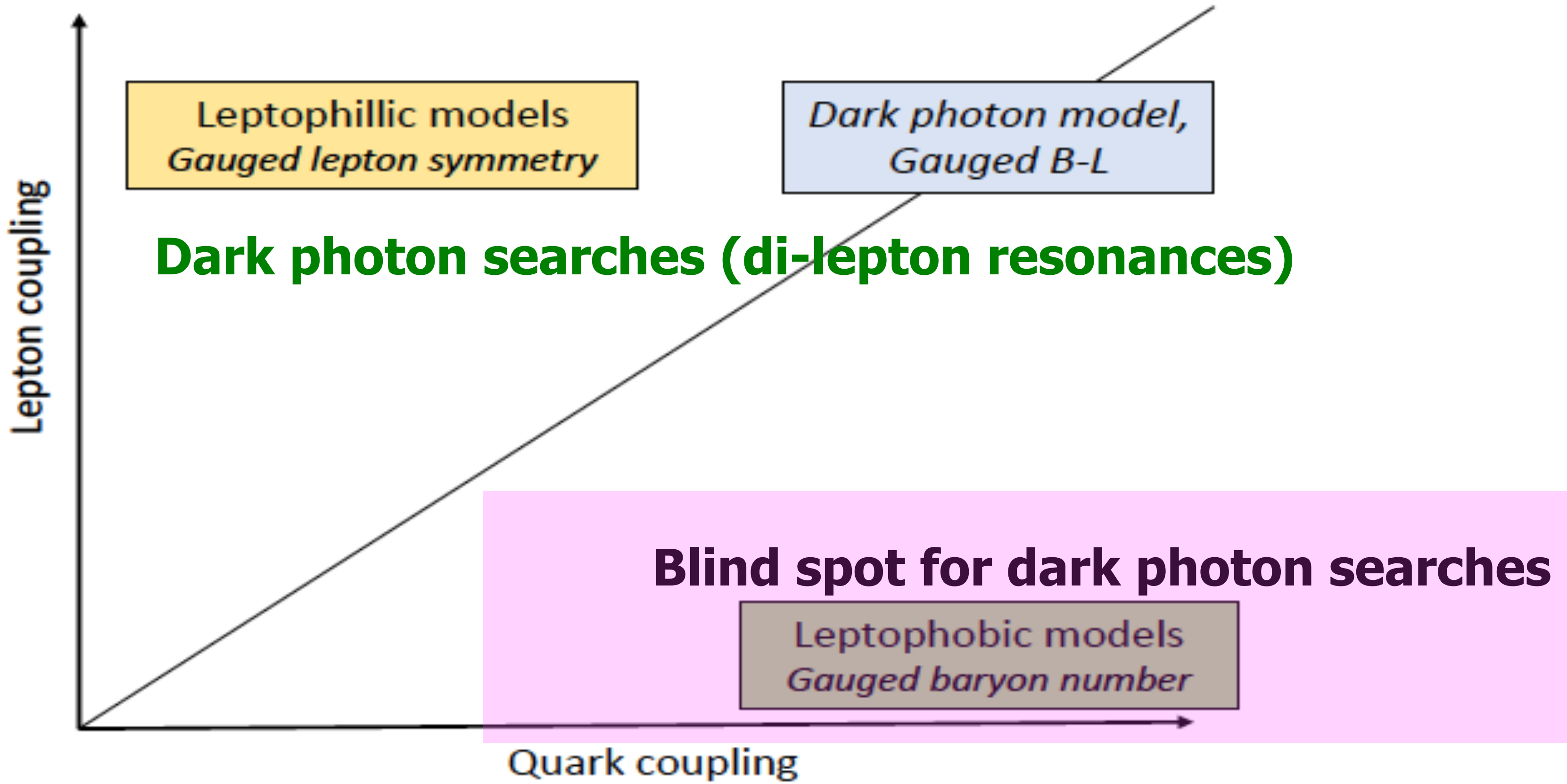
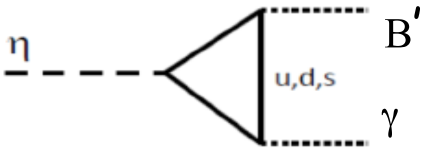


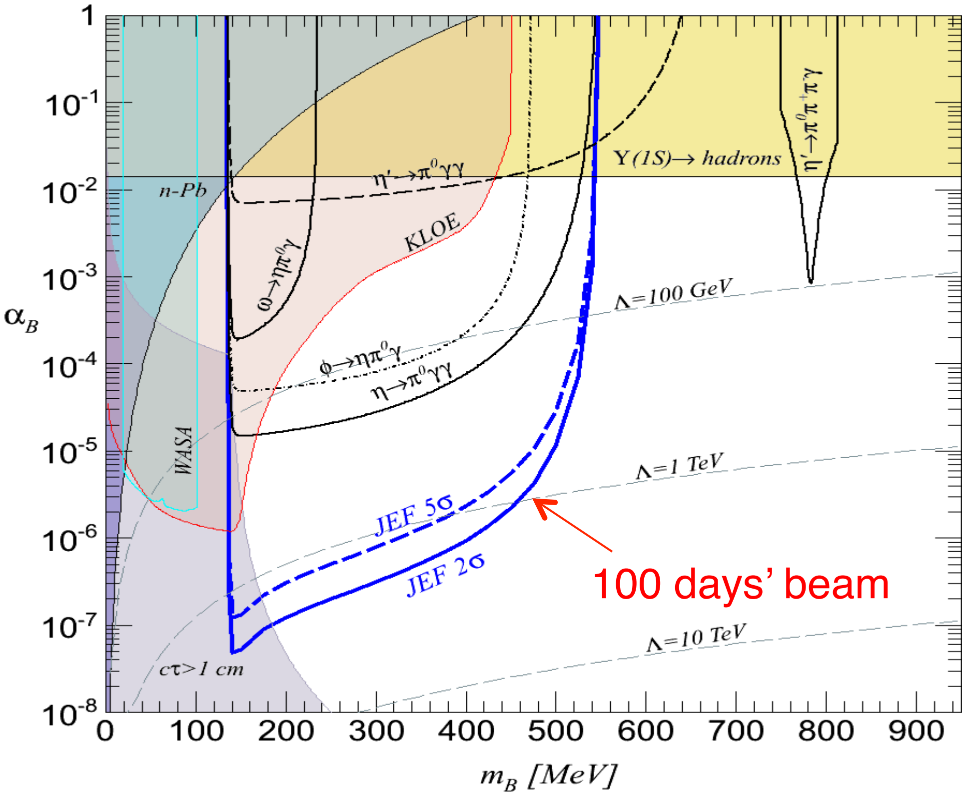
Also a third axis: decays to invisible states (neutrinos, light dark matter)
Davoudiasl et al (2012), Batell et al (2009), deNiverville et al (2011,2012)

JEF Experimental Reach for B′

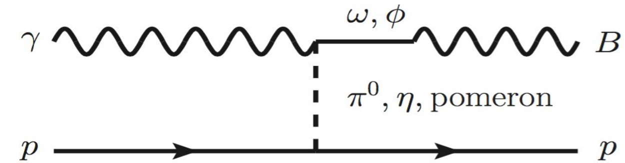
1. Meson decay $\eta \rightarrow B'\gamma \rightarrow \pi^0\gamma\gamma$

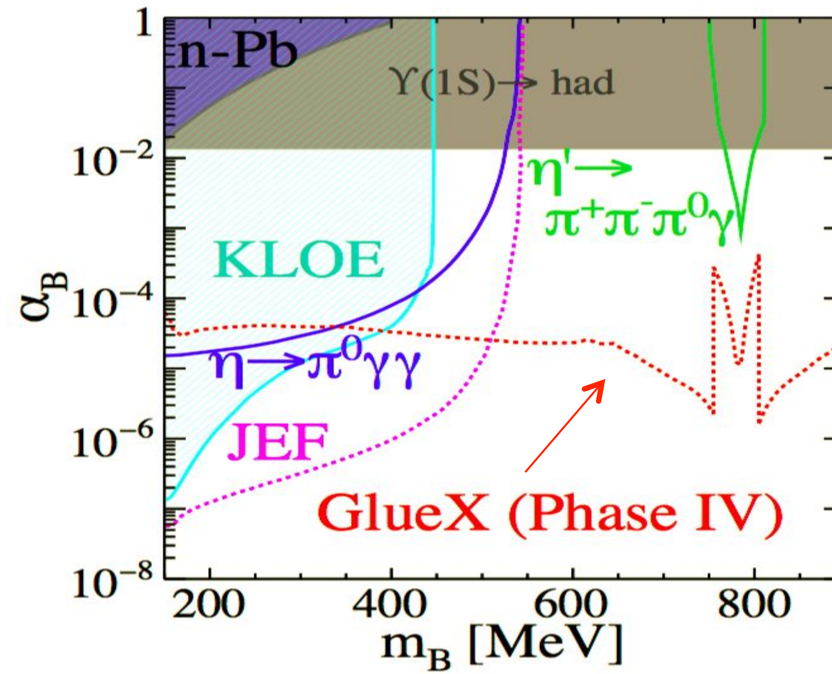


PL, B221, 80 (1989)
PR,D89,114008



2. Photoproduction $\gamma p \rightarrow B'p$





arXiv:1605.07161

Impact of the SM allowed $\eta\to\pi^0\gamma\gamma$ measurement

→ A rare window to probe interplay of VMD & scalar resonances in ChPT to calculate $O(p^6)$ LEC's in the chiral Lagrangian

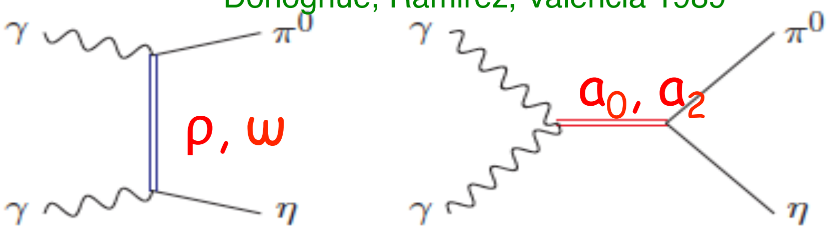
◆ The major contributions to $\eta\to\pi^0\gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian → an unique probe for the high order ChPT.

L. Ametller, J, Bijnens, and F. Cornet, Phys. Lett., B276, 185 (1992)

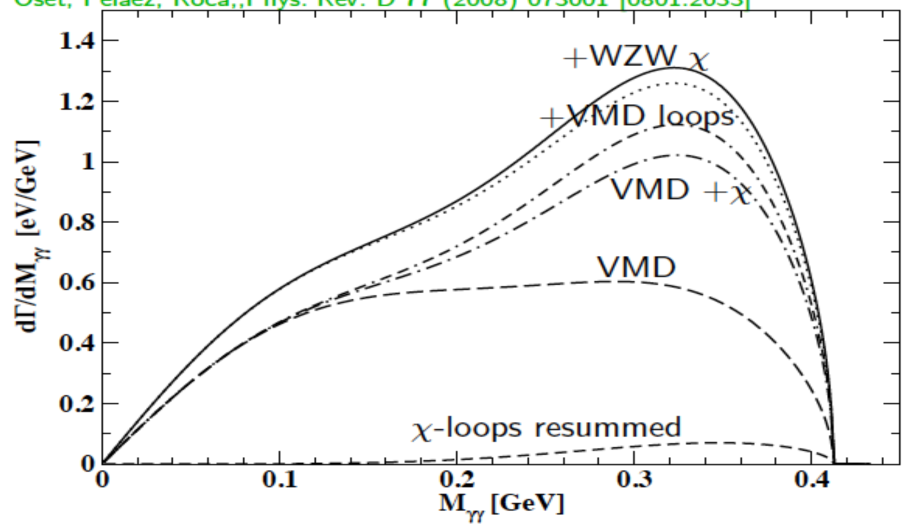
◆ Shape of Dalitz distribution is sensitive to the role of scalar resonances.

LEC's are dominated by resonances

Gasser, Leutwyler 84; Ecler, Gasser, Pich, de Rafael1989
Donoghue, Ramirez, Valencia 1989

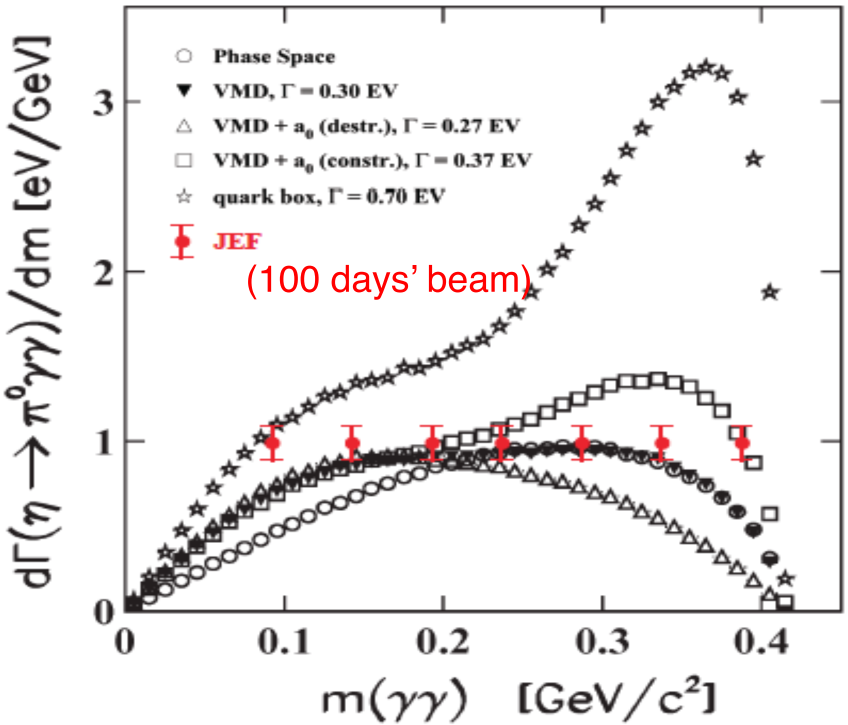


Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]

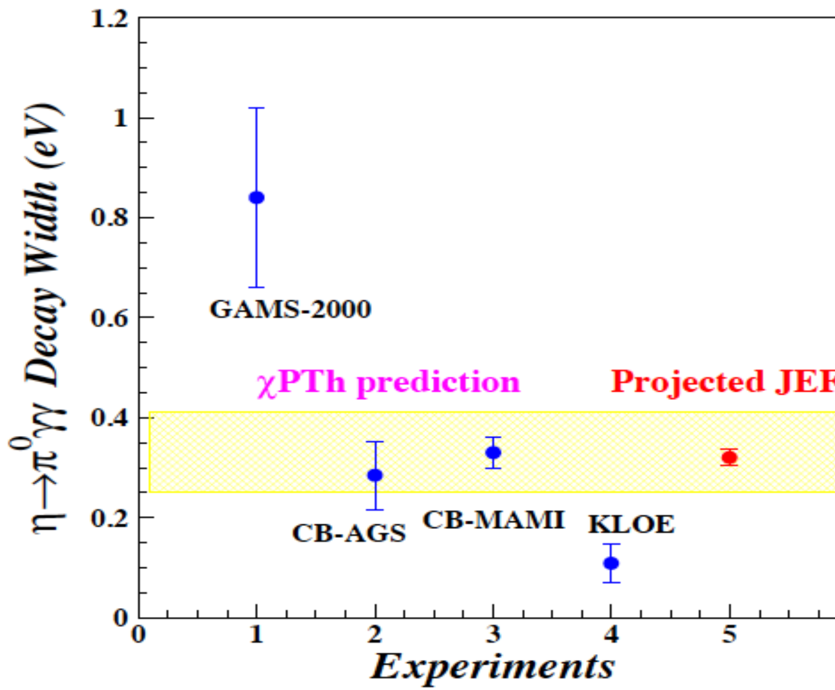


Projected JEF on SM Allowed $\eta\to\pi^0\gamma\gamma$

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



χPTh by Oset et al., Phys. Rev. D77, 073001



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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Experimental tests

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

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

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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.

Charge Conjugation 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

(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

Mode	Branching Ratio (upper limit)	No. γ's
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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$3\gamma 2\pi^0$	Nothing published	

Experimental Improvement on η→3γ

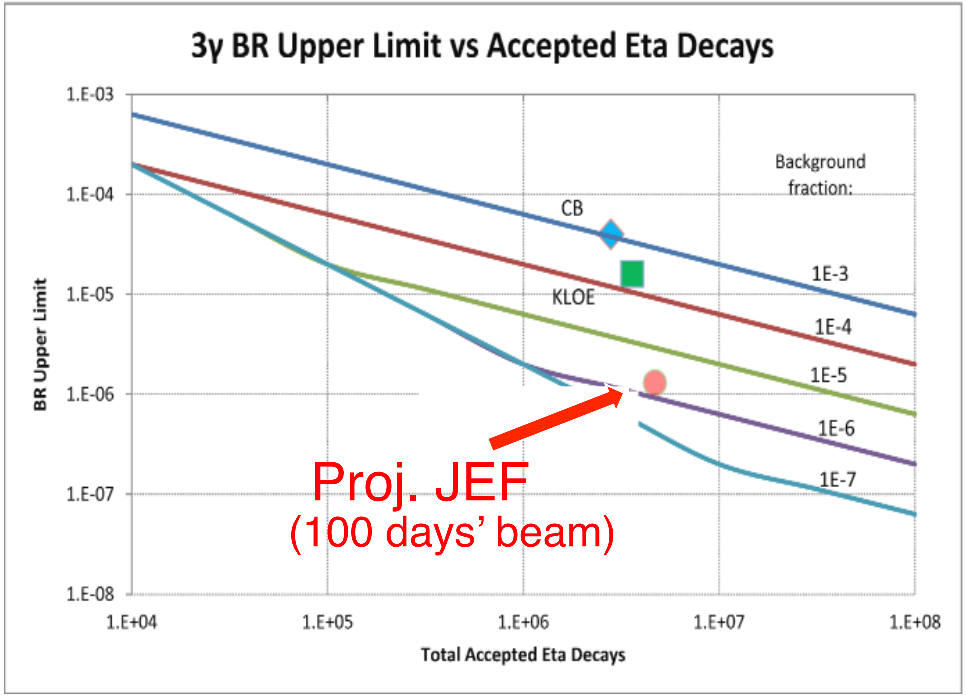
- SM contribution: BR($\eta \to 3\gamma$) $<10^{-19}$ via P-violating weak interaction.

- A new C- and T-violating, and P-conserving interaction was proposed by Bernstein, Feinberg and Lee

  Phys. Rev.,139, B1650 (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)



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

Summary

- **A comprehensive Primakoff program has been developed at JLab to measure $\Gamma(p \to \gamma\gamma)$ and $F(\gamma\gamma^* \to p)$ 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/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 sub-GeV leptophobic vector B' and an electrophobic scalar Φ' through $\eta \to \pi^0\gamma\gamma$
  - Directly constrain CVPC new physics via $\eta \to 3\gamma$ and other C-violating channels
  - A clean determination of the light quark mass ratio via $\eta \to 3\pi$
  - Test the role of scalar dynamics in ChPT through $\eta \to \pi^0\gamma\gamma$

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

Compared to π^0:

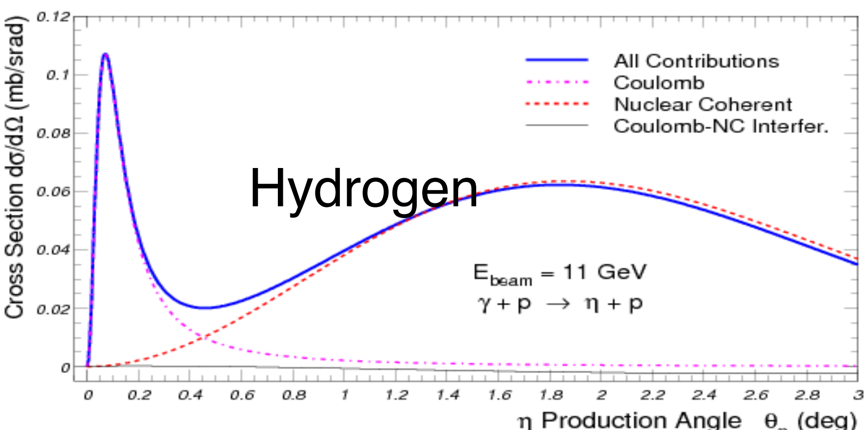
- η mass is a factor of 4 larger than π^0 and has a smaller cross section

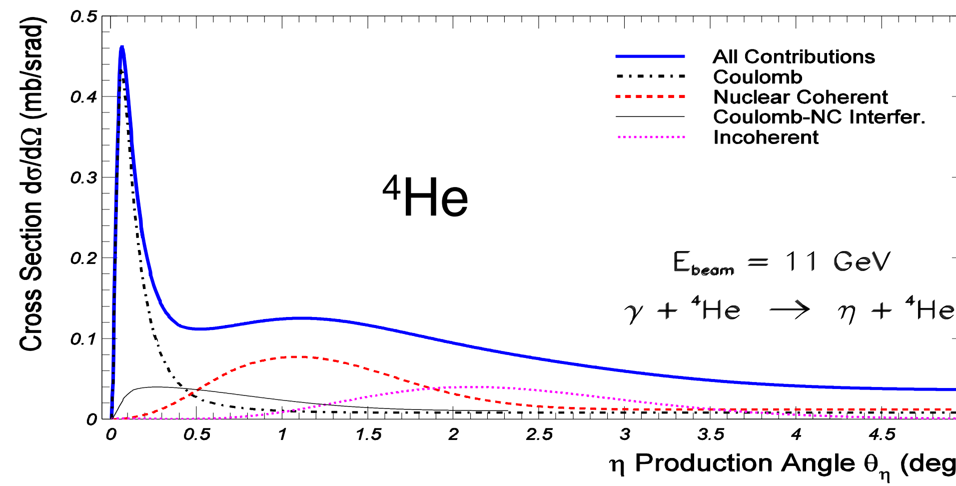
$$\left(\frac{d\sigma_{\mathrm{Pr}}}{d\Omega}\right)_{\mathrm{peak}} \propto \frac{E^4}{m^3}$$

- 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,…)





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

It is linear in a CP-violating parameter.

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

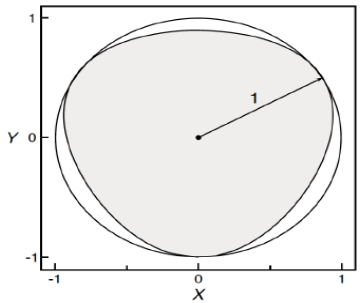
"C violation" [Lee and Wolfenstein, 1965; Lee, 1965, Nauenberg, 1965; Bernstein, Feinberg, and Lee, 1965]

C-even, P-odd

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

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



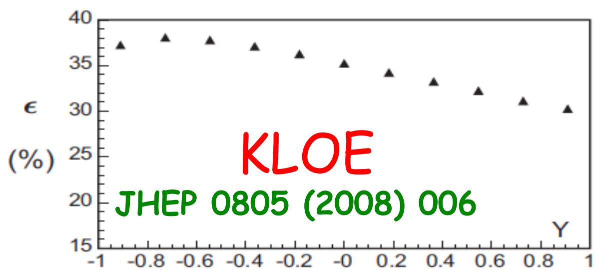
$$X = \frac{\sqrt{3}}{2M_\eta Q_c}(u-t)$$

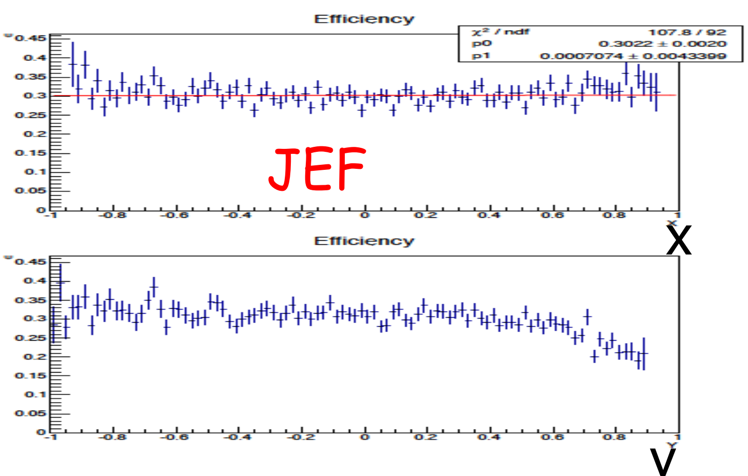
$$Q_c \equiv M_\eta - 2M_{\pi^+} - M_{\pi^0}$$

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

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

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

Tagged η and η' Production Rate

JEF for 100 days of beam:

	η	η'
Tagged mesons	$6.5\text{x}10^7$	$4.9\text{x}10^7$

Previous Experiments:

Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	$2\text{x}10^7$	-
CB MAMI-C	$6\text{x}10^7$	-
WASA-COSY	$\sim 10^9$	-
KLOE	10^8	$5\text{x}10^5$
BESIII	10^6	$6\text{x}10^6$

Some interesting η' decays:

Decays	B.R.	Physics highlight
$\pi^0\gamma\gamma$	$<8\times10^{-4}$	leptophobic B', electrophobic Φ'
$2\pi^0$	$<5\times10^{-4}$	PV, CPV
3γ	$<1.1\times10^{-4}$	CV, CPV
$\pi^0e^+e^-$	$<1.4\times10^{-3}$	CV, CPV
ηe^+e^-	$<2.4\times10^{-3}$	CV, CPV
γe^+e^-	$(4.73 \pm 0.30) \times 10^{-4}$	ChPT, dark A'

JEF offers a competitive η/η' factory