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

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Outline

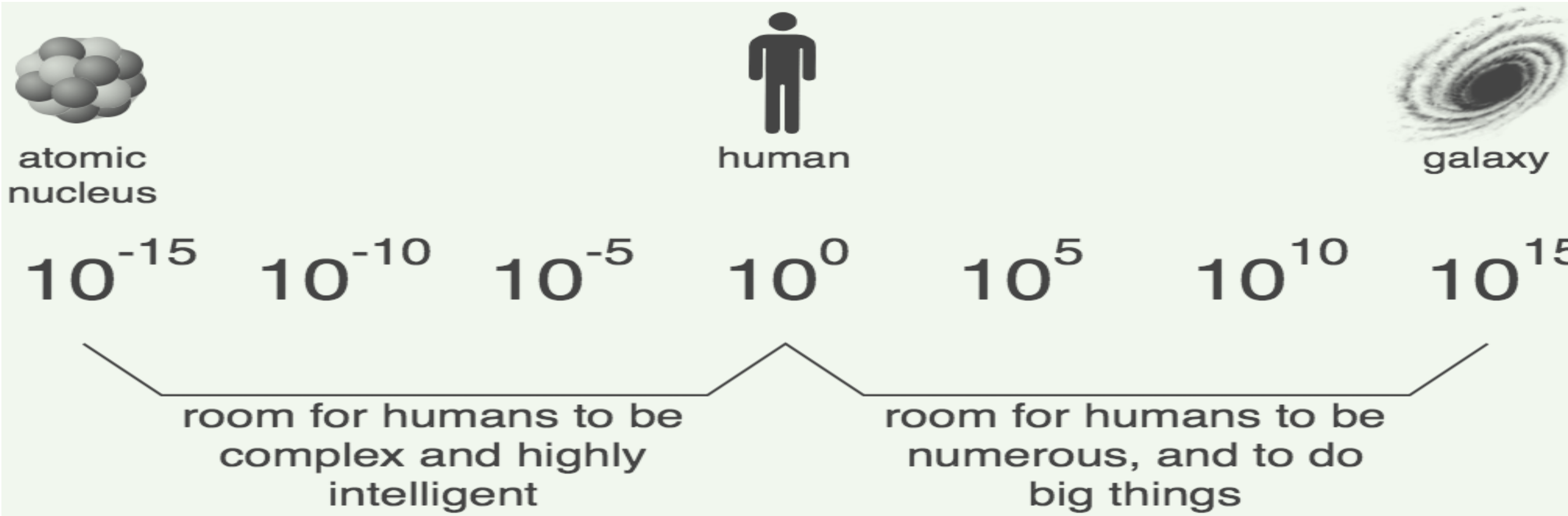
1. Introduction
   ⟶ challenges in physics

2. PrimEx experimental program on π^0, η, η'
   ⟶ precision tests confinement QCD symmetries

3. Jlab Eta Factory (JEF) experiment for rare η decays
   ⟶ search for BSM 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

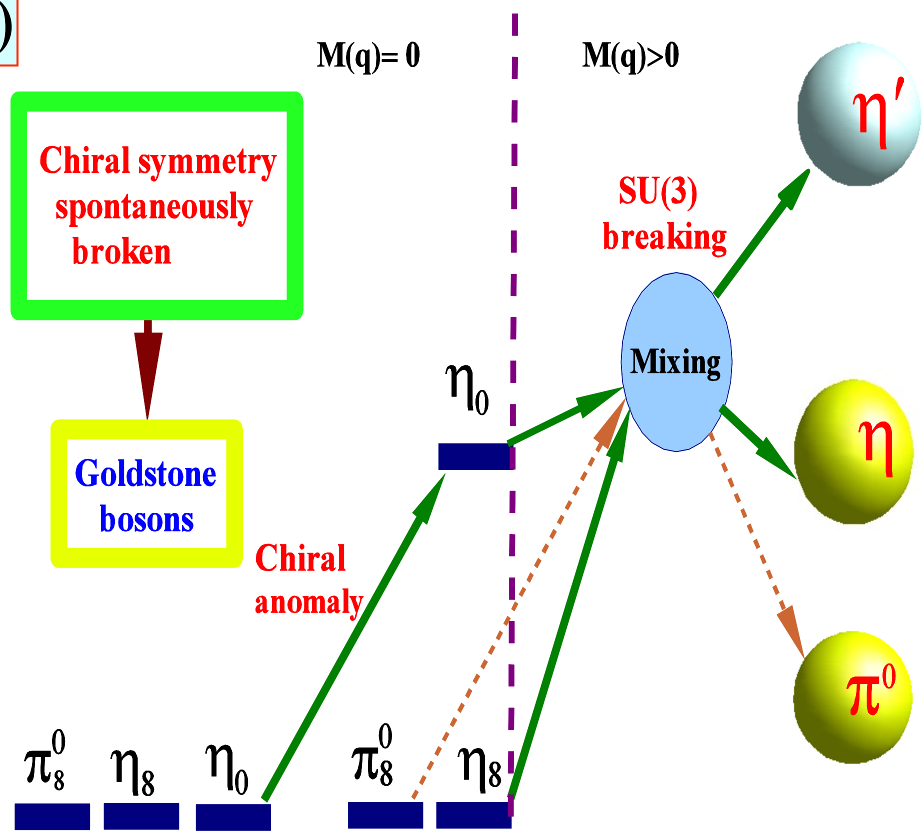
"As far as I see, all priori statements in physics have their origin in symmetry". By H. Weyl

QCD Symmetries and Light Mesons

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

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

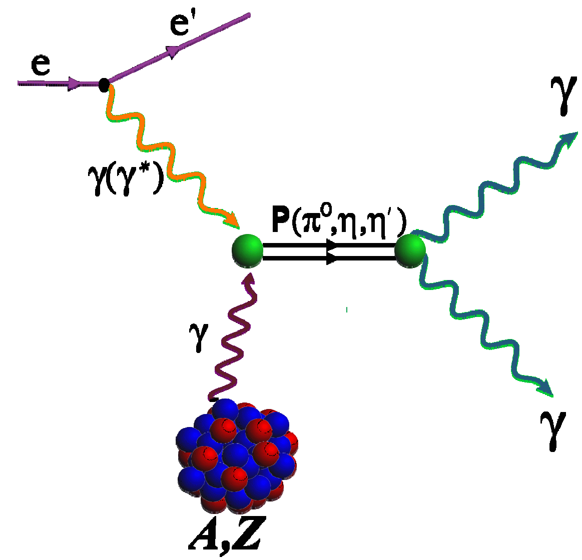
- Chiral symmetry $SU_L(3)xSU_R(3)$ spontaneously breaks to $SU(3)$
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken: (Chiral anomalies)
  - $\Gamma(\pi^0\to\gamma\gamma)$, $\Gamma(\eta\to\gamma\gamma)$, $\Gamma(\eta'\to\gamma\gamma)$
  - Mass of η_0
- $SU_L(3)xSU_R(3)$ and $SU(3)$ are explicitly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

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:

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

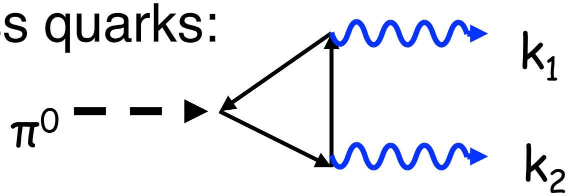
Input to Physics:

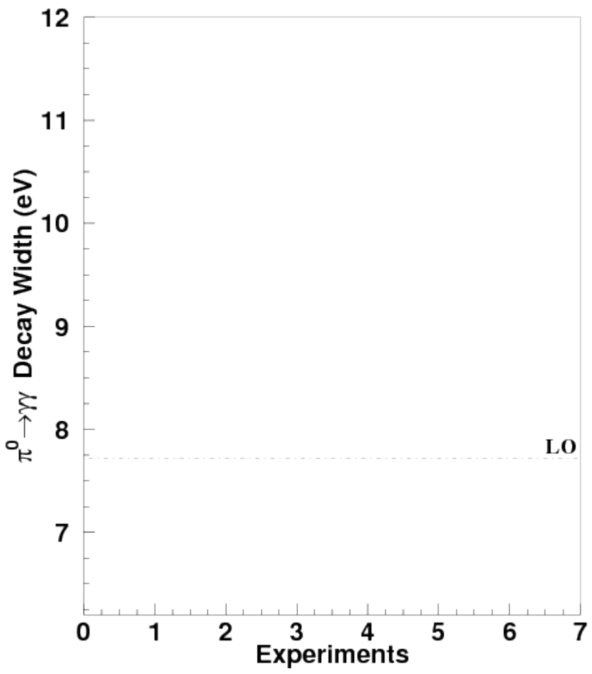
- π^0,η and η' electromagnetic interaction radii
- is the η' an approximate Goldstone boson?
- inputs to $(g-2)_\mu$(HLbL) calculations

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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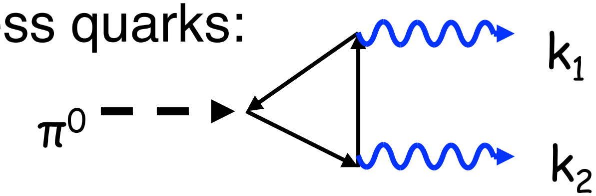

- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at ~1% level to higher orders!

➢ Corrections to the chiral anomaly prediction:

Calculations in NLO ChPT:

- ❑ $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.10eV ± 1.0%
  (J. Goity, et al. Phys. Rev. D66:076014, 2002)
- ❑ $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.06eV ± 1.0%
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Calculations in NNLO SU(2) ChPT:

- ❑ $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.09eV ± 1.3%
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➢ Calculations in QCD sum rule:

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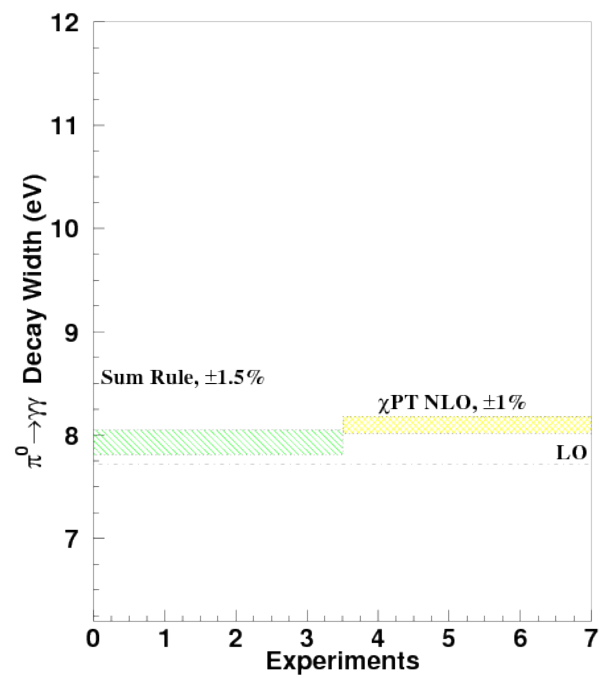

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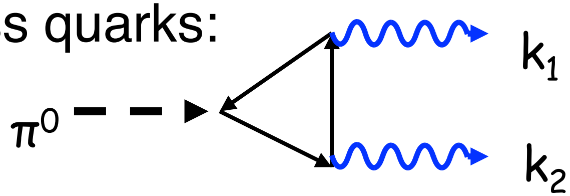

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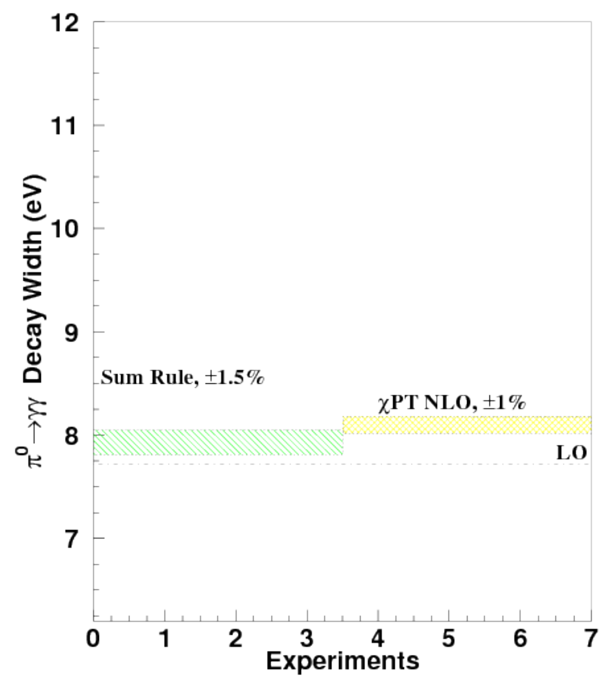

- Precision measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ at the percent level will provide a stringent test of low energy QCD.

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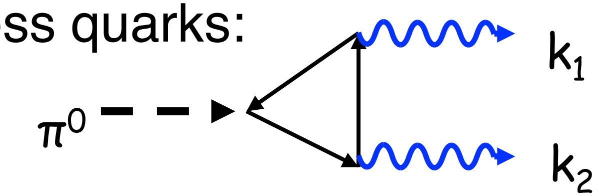

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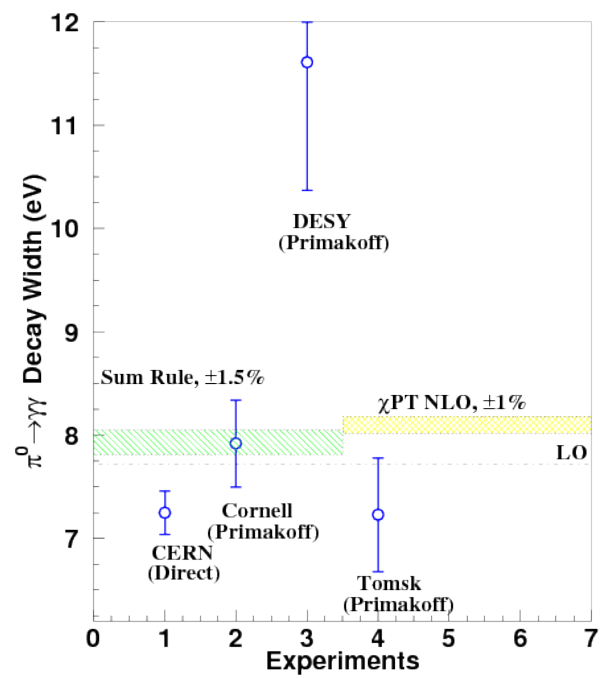

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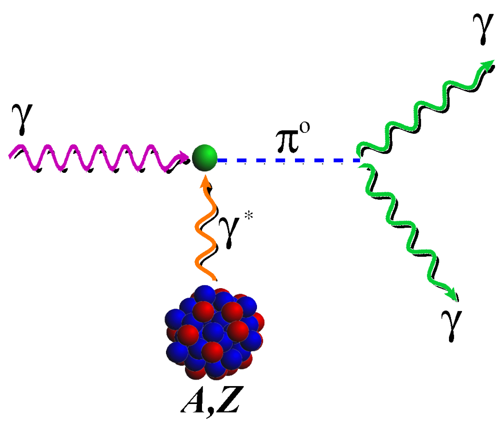
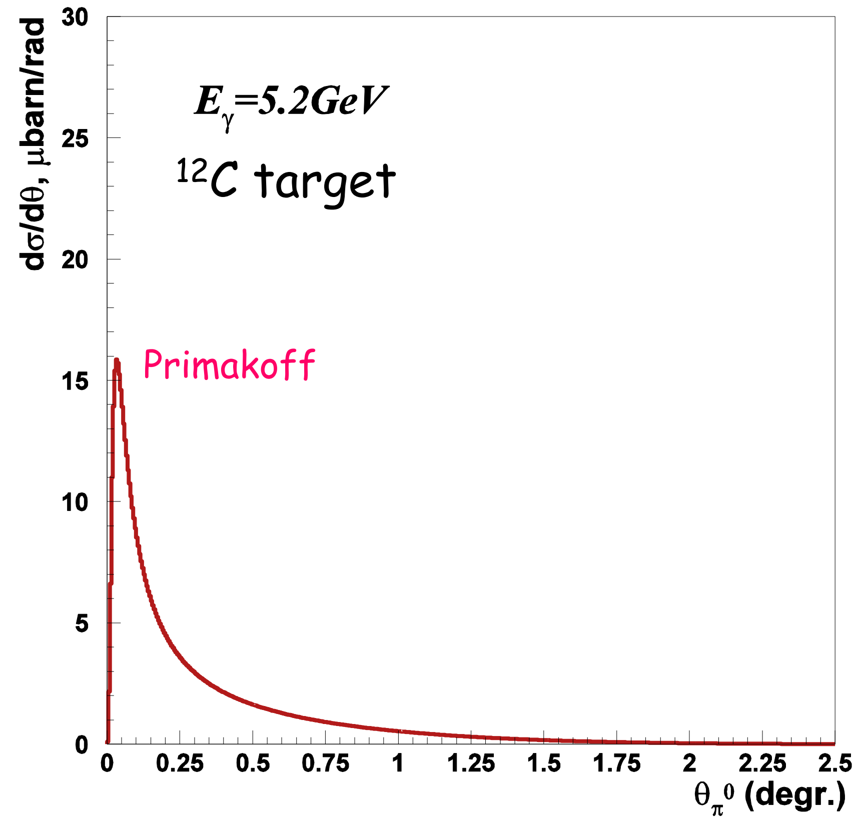
Primakoff Method



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



Features of Primakoff cross section:

- 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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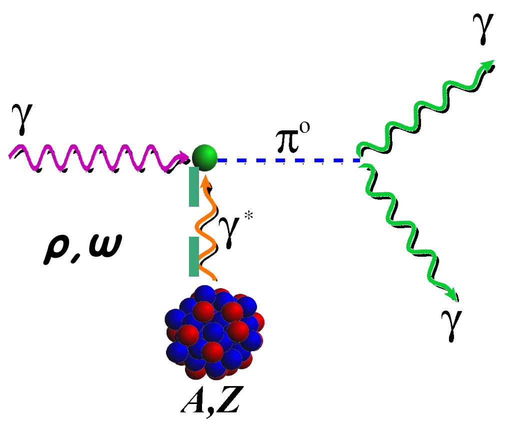

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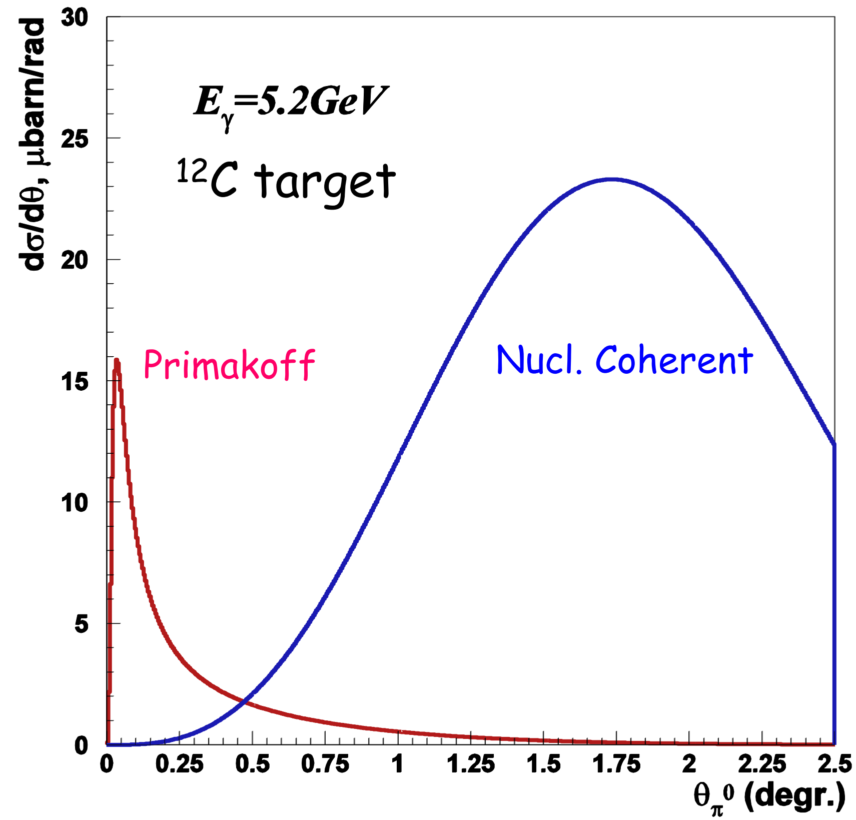

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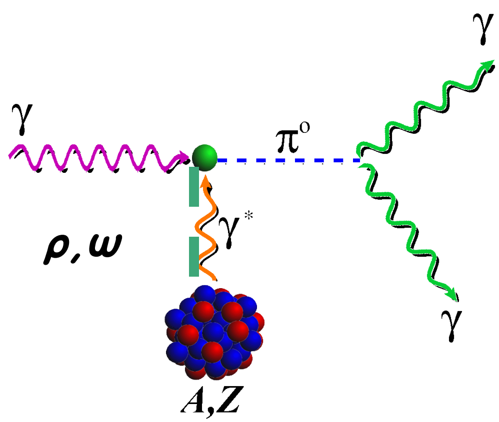

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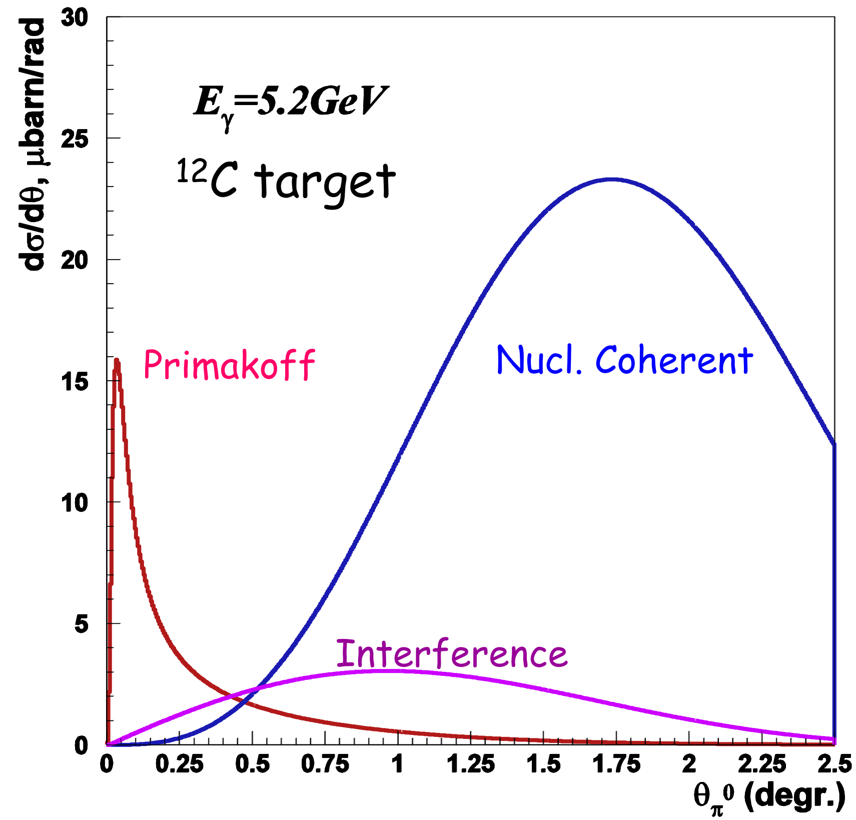

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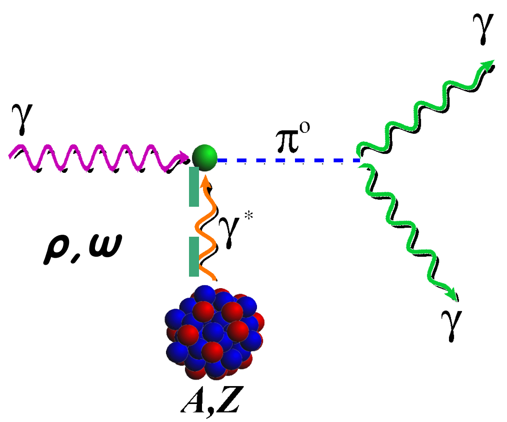

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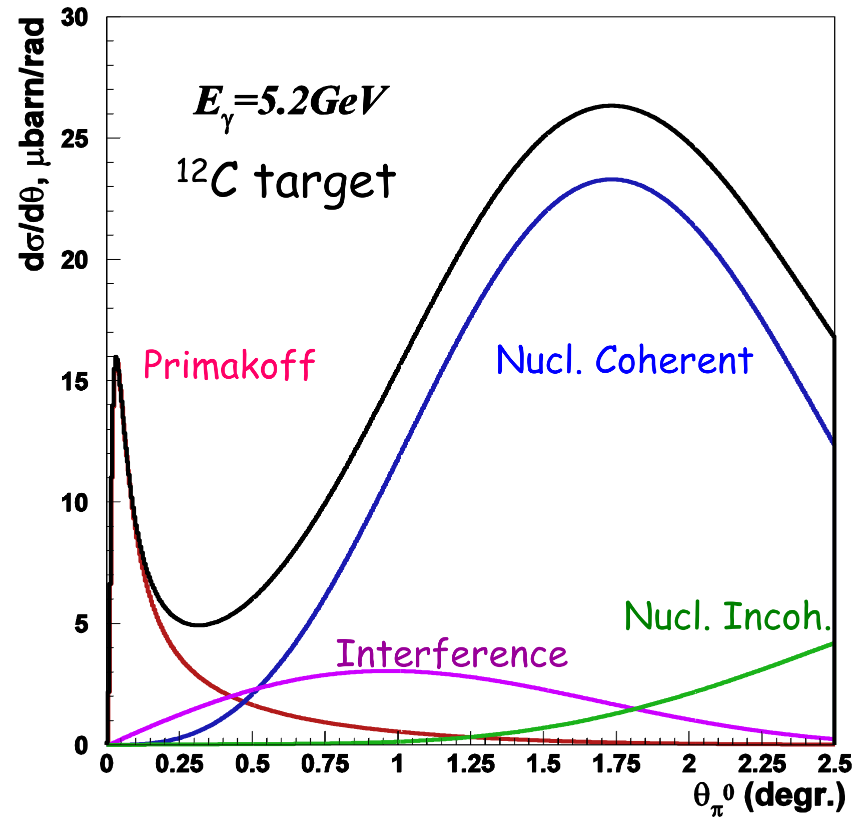

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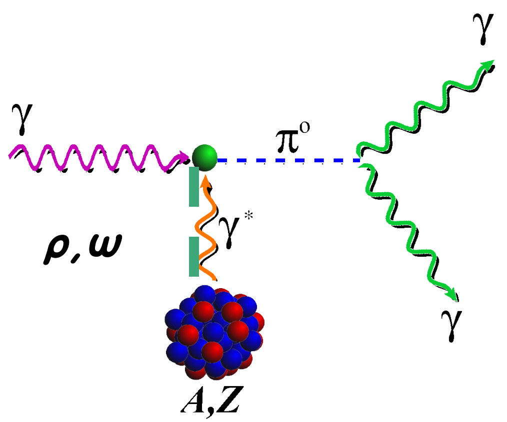

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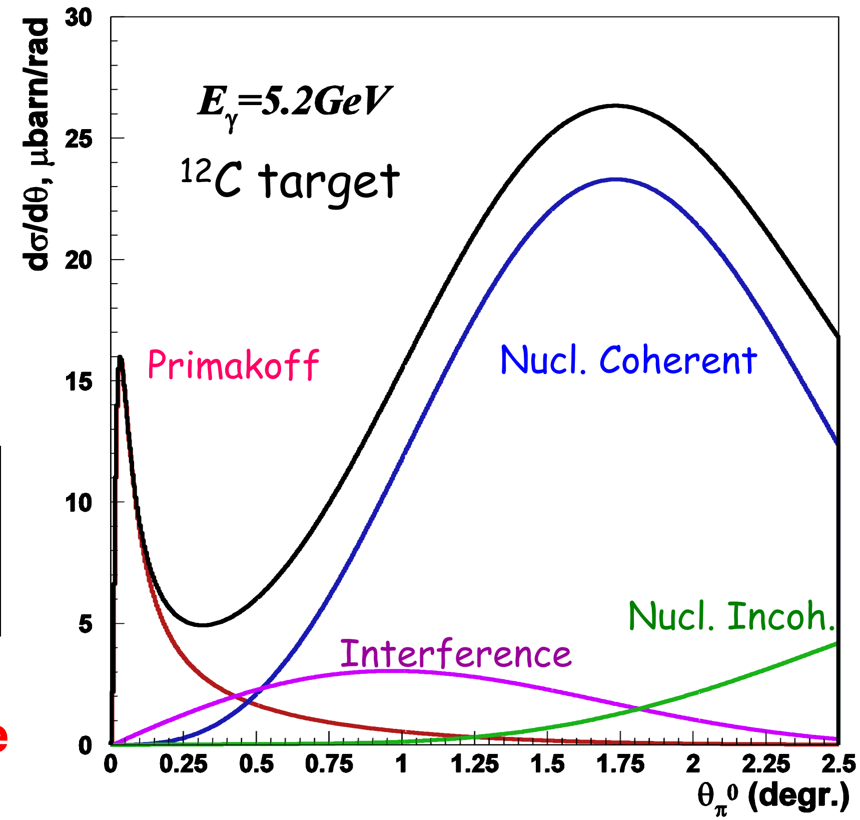
Challenge: Extract the Primakoff amplitude



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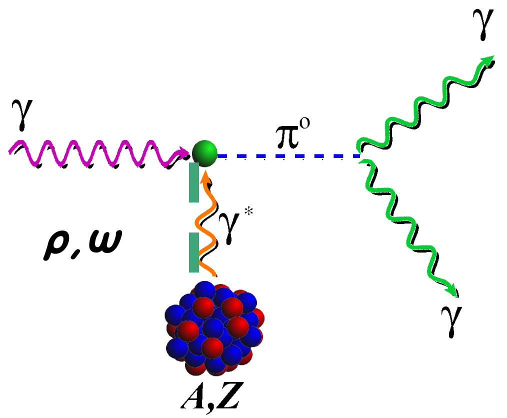

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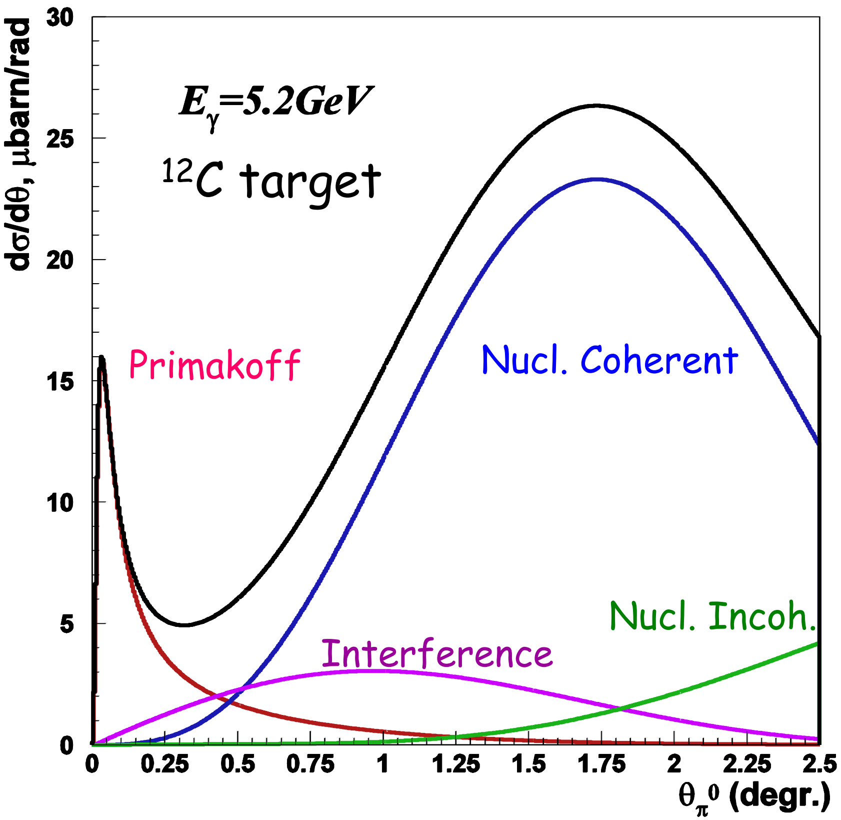

Challenge: Extract the Primakoff amplitude

Requirement:

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

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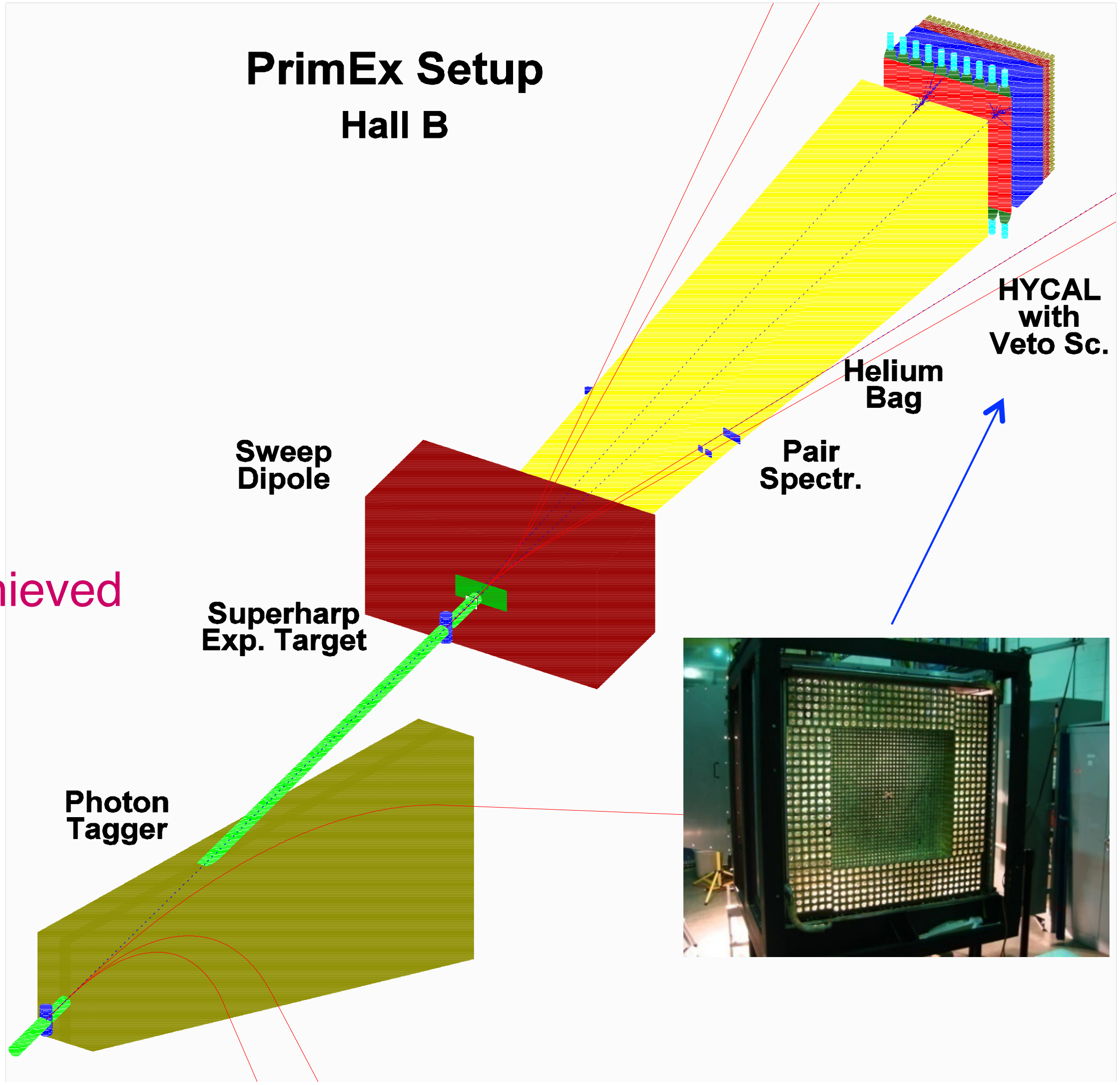
- Coherent process

PrimEx Experimental Setup in Hall B

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

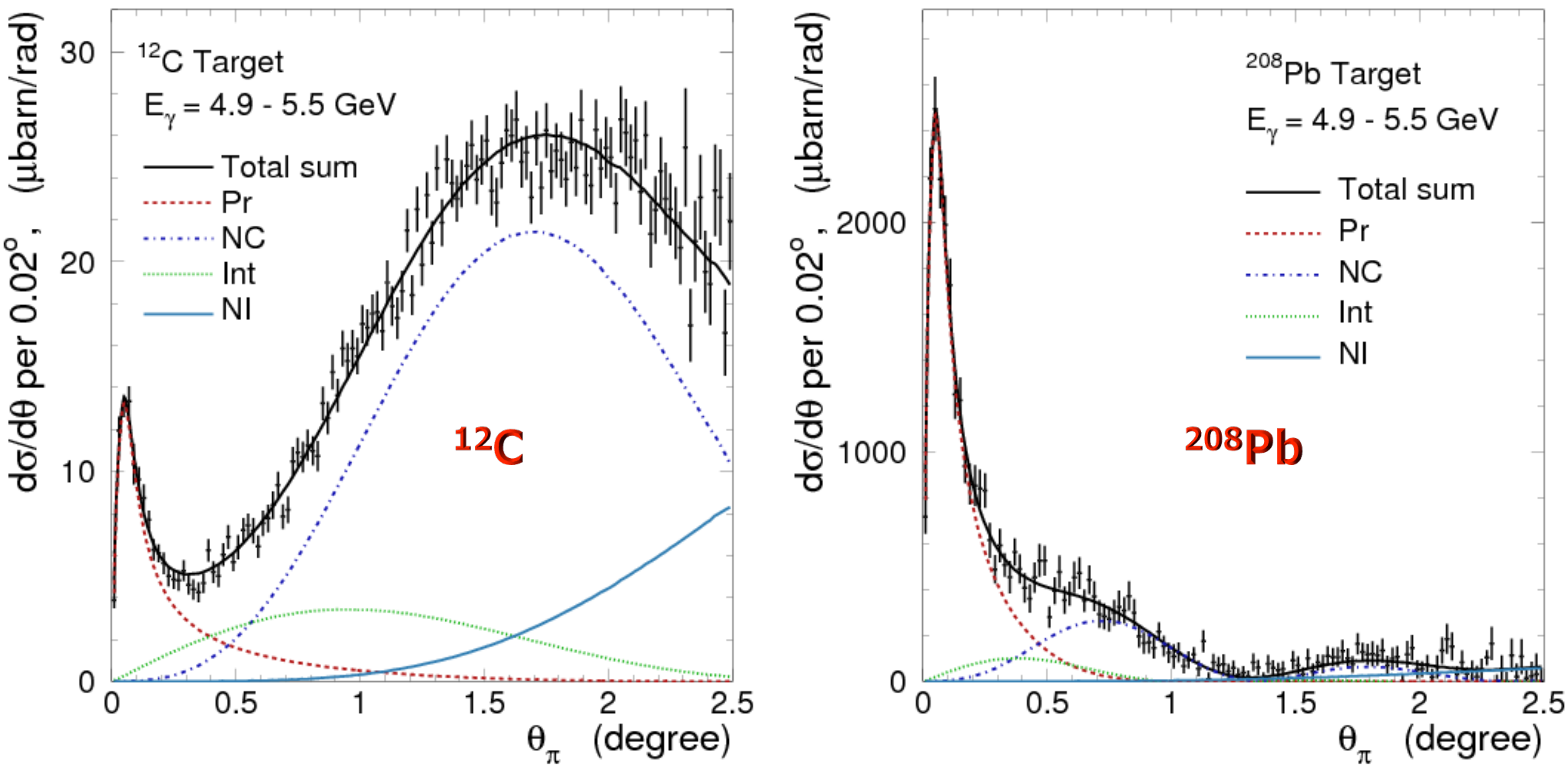
- New pair spectrometer for photon flux control at high beam intensities
  - 1% accuracy has been achieved

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



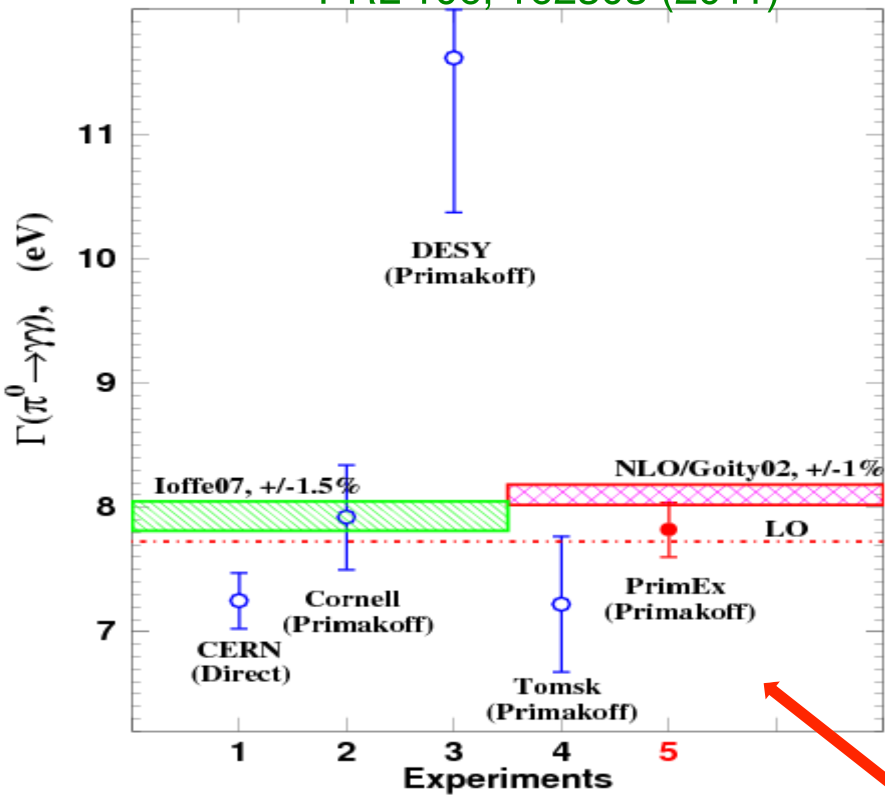
The First Experiment: PrimEx-I (2004)

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



PrimEx-I Result

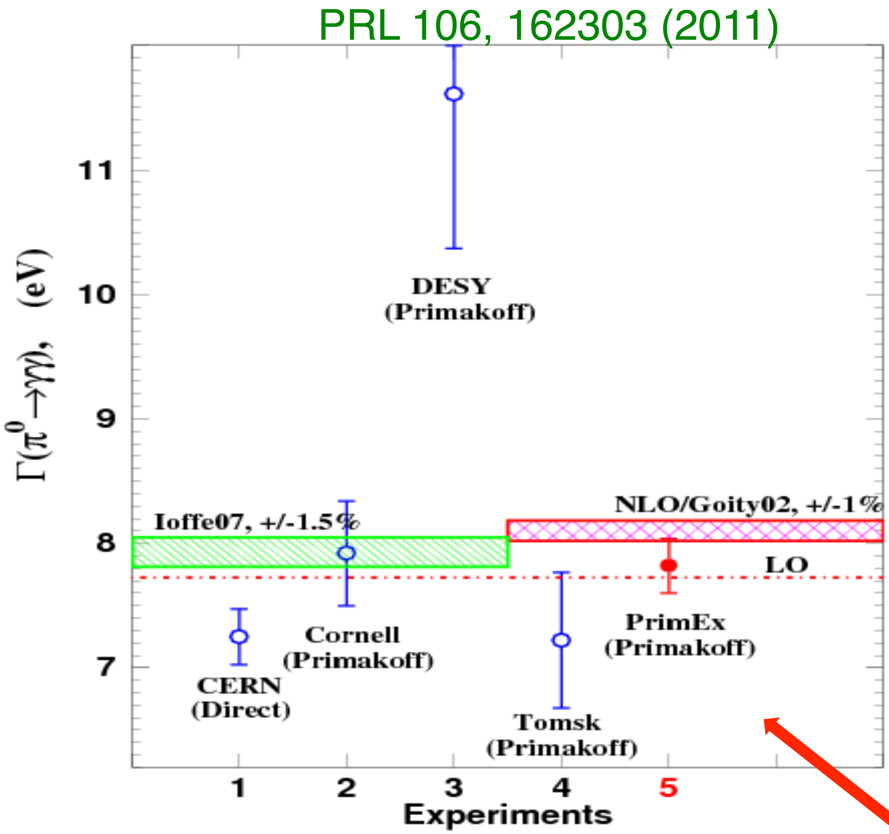
PRL 106, 162303 (2011)

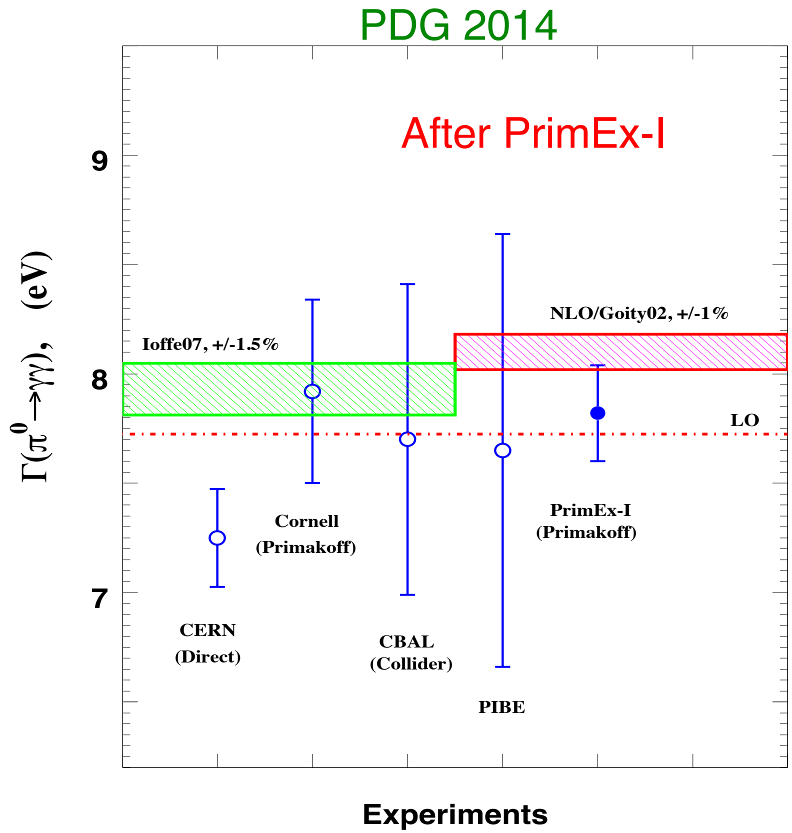


$\Gamma(\pi^0\to\gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty

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

PrimEx-I Result





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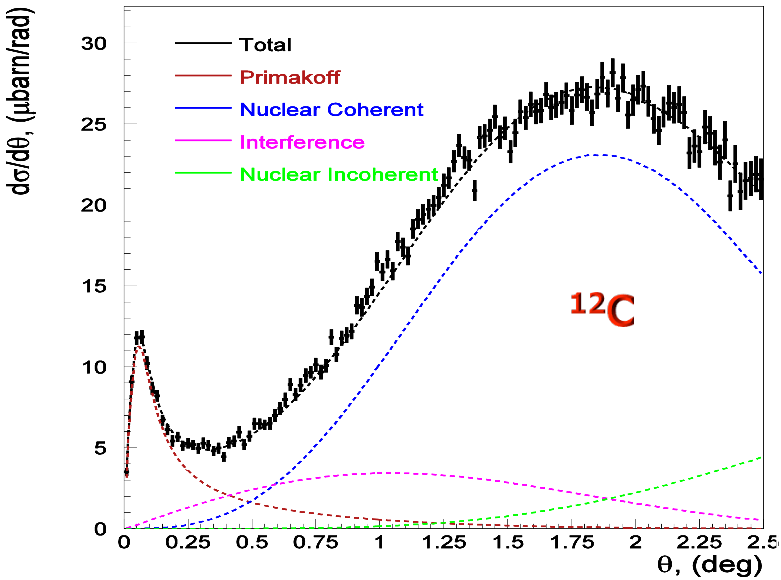
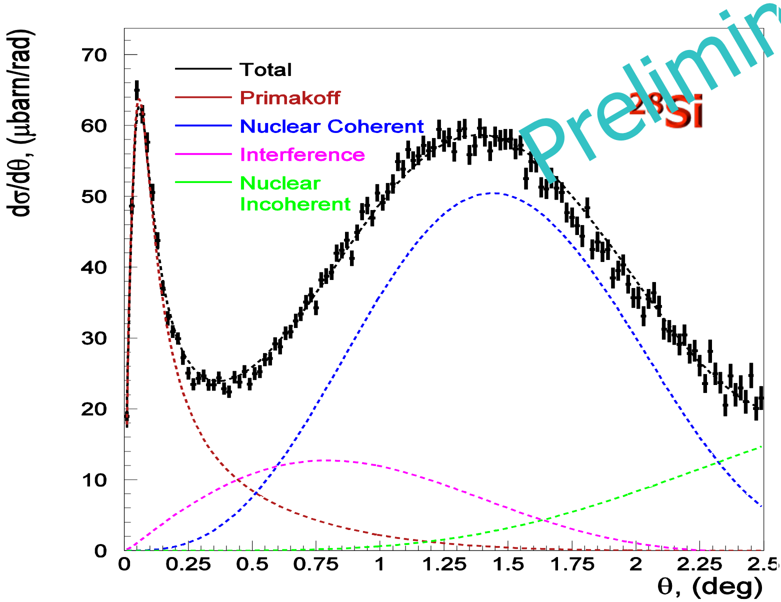
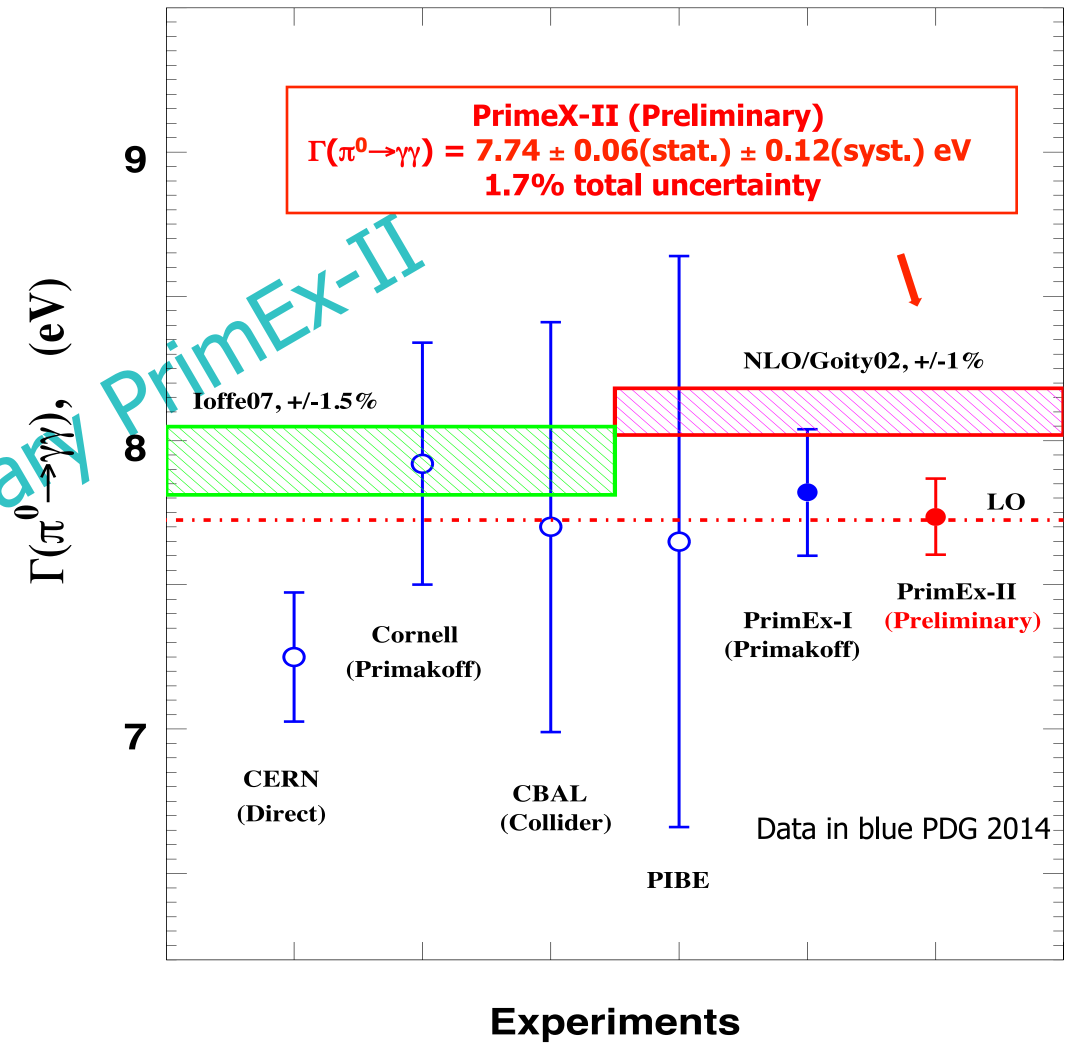
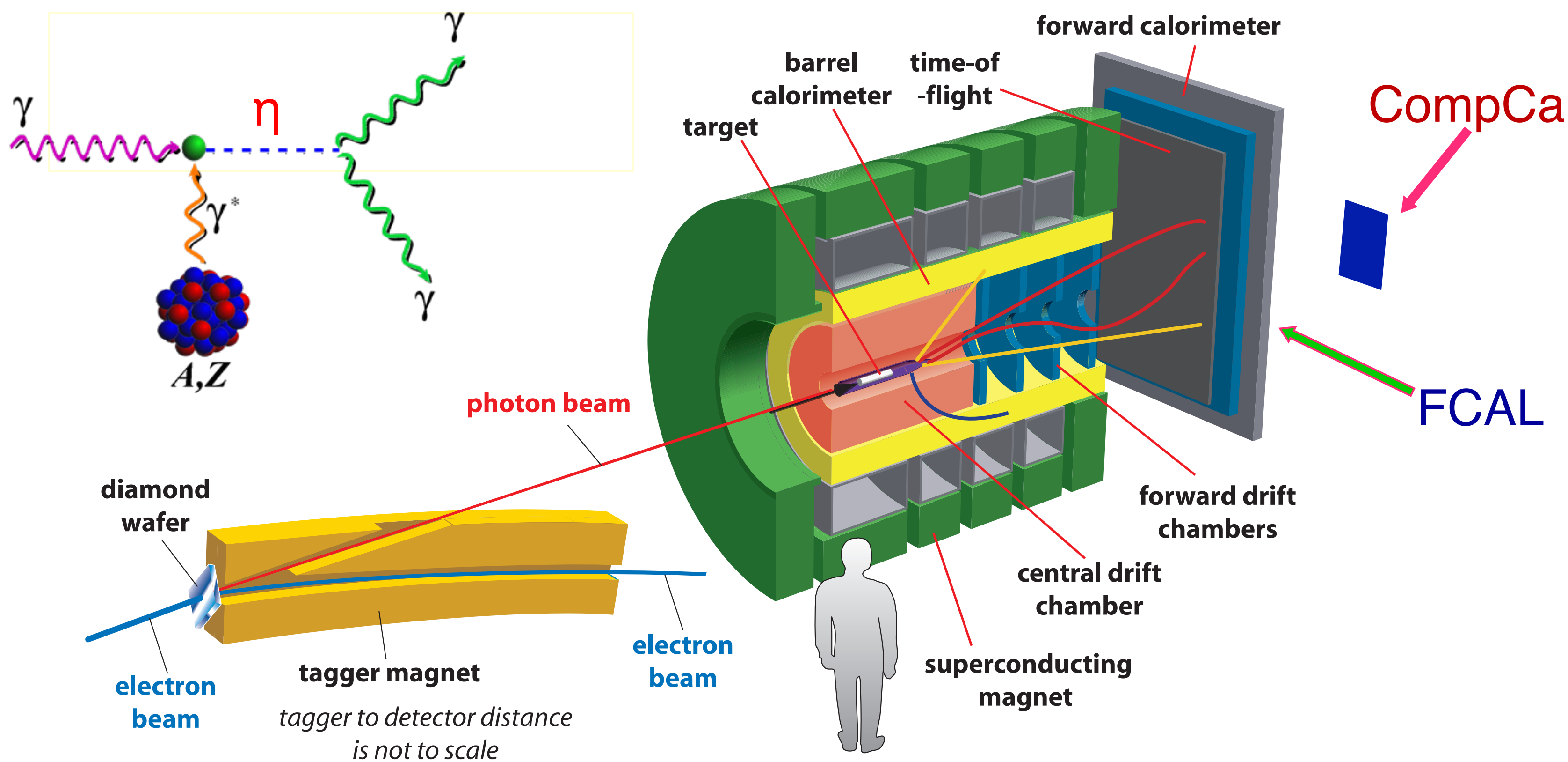
Preliminary PrimEx-II Result







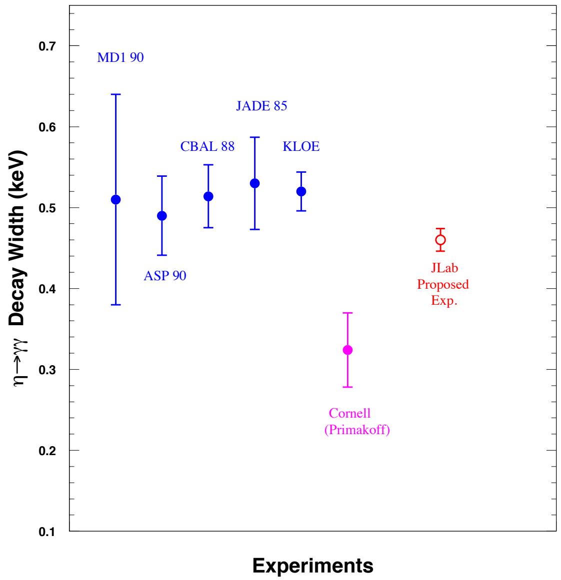
Measurement of Γ(η→γγ) in Hall D at 12 GeV



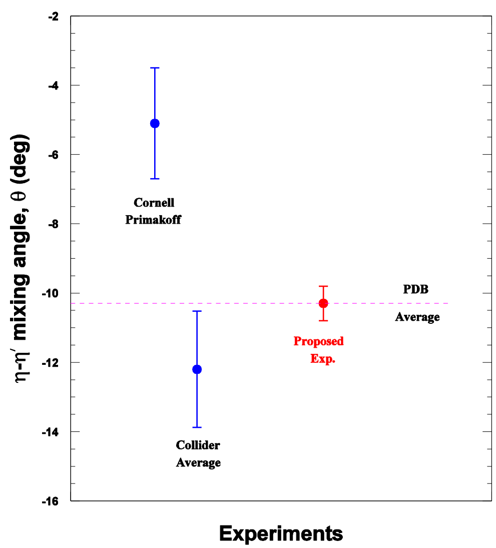
- Incoherent tagged photon beam (~10.5-11.5 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- 30 cm liquid Hydrogen and ^{4}He targets (~3.6% r.l.)
- Forward Calorimeter (FCAL) for $\eta\rightarrow\gamma\gamma$ decay photons
- CompCal and FCAL to measure well-known Compton scattering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

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

1. Improve all decay widths in η-sector

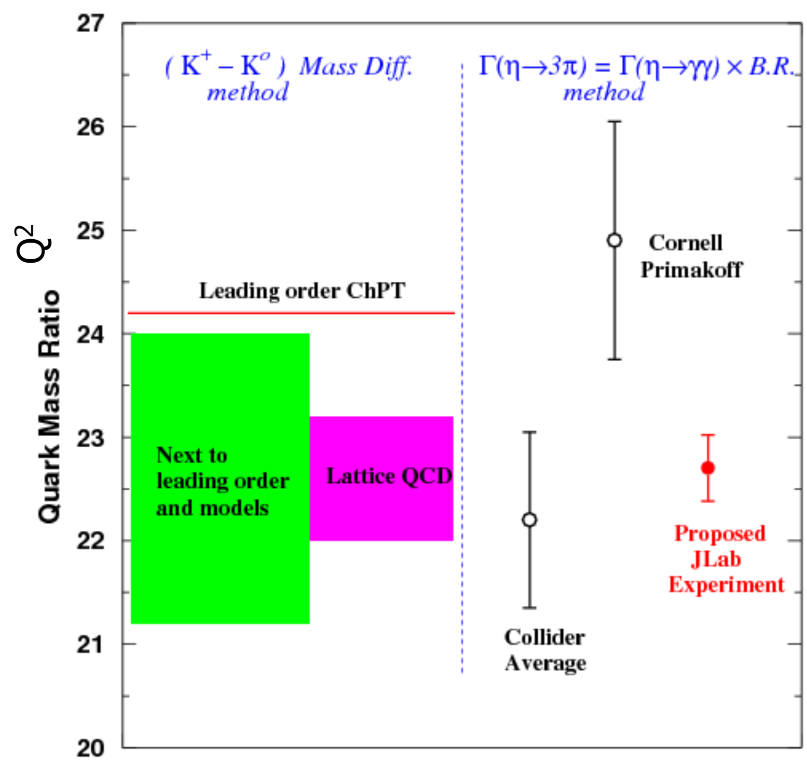


2. Extract η-η' mixing angle:



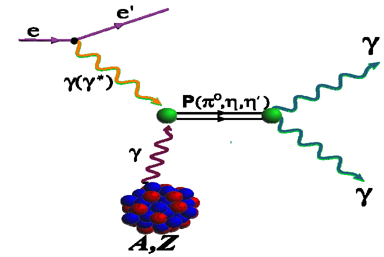
3. Determine light quark mass ratio:

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

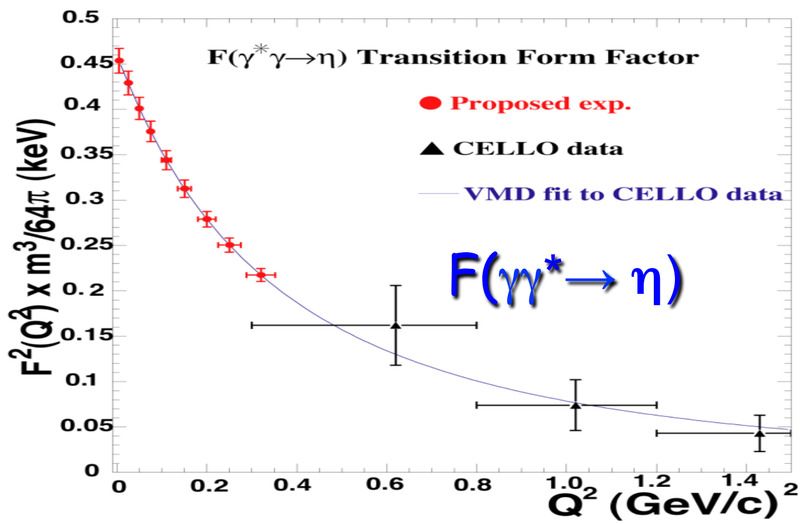


H. Leutwyler Phys. Lett., B378, 313 (1996)

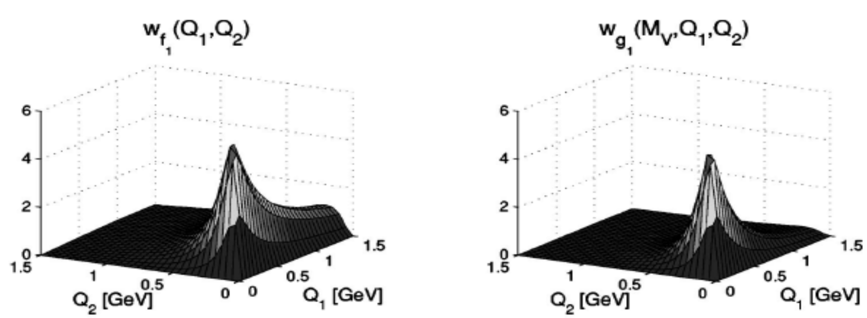
Transition Form Factors $F(\gamma\gamma^*\rightarrow p)$
(Q^2 : 0.001-0.5 GeV^2/c^2)



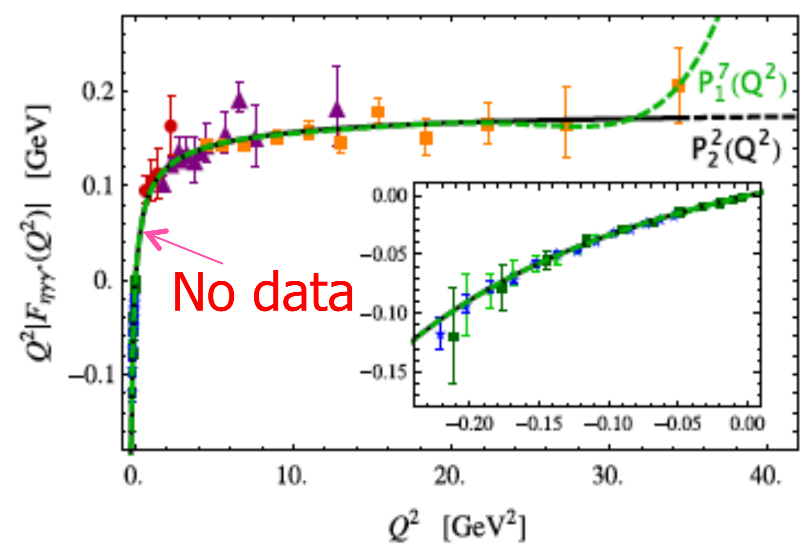
- **Direct measurement of slopes**
  - Interaction radii: $F_{\gamma\gamma^*P}(Q^2)\approx 1-1/6\blacksquare\langle r^2\rangle_P Q^2$
  - ChPT for large N_c predicts relation between the three slopes. Extraction of $O(p^6)$ low-energy constant in the chiral Lagrangian



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

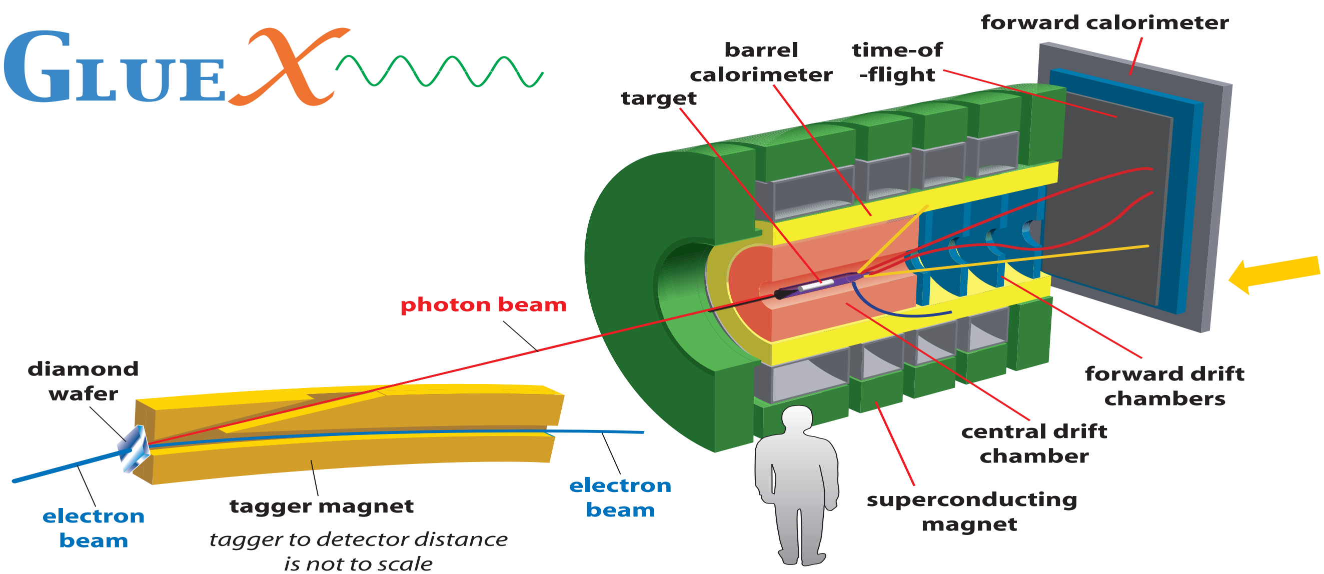


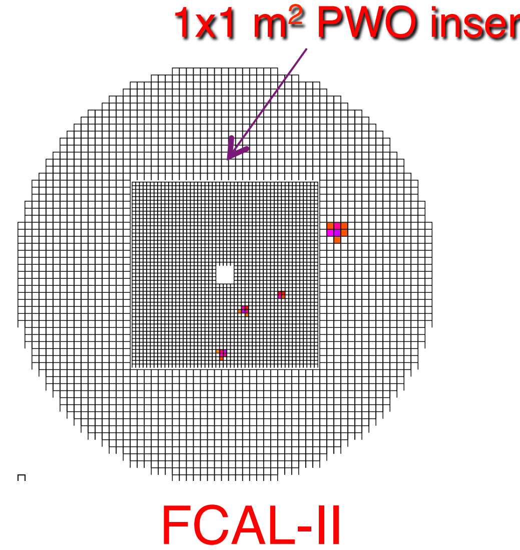
Phys.Rev.D65,073034



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

JEF experiment in Hall D





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

- η produced on LH_2 target with 8.4-11.7 GeV tagged photon beam:
  $\gamma+p \to \eta/\eta' + p$
- 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

Tagged η and η' Production Rates

JEF for 100 days of beam:

	η	η'
Tagged mesons	6.5×10^7	4.9×10^7

Previous Experiments:

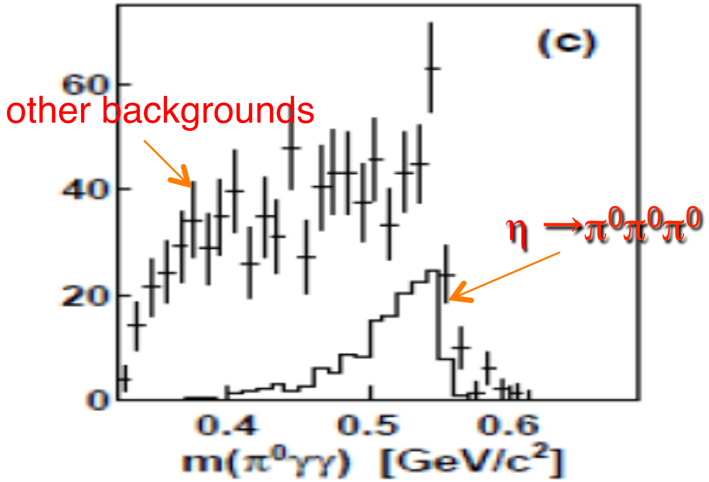
Experiment	Total η	Total η'
CB at AGS	10^7	-
CB MAMI-B	2×10^7	-
CB MAMI-C	6×10^7	-
WASA-COSY	$\sim 10^9$	-
KLOE	10^8	5×10^5
BESIII	10^6	6×10^6

JEF offers a competitive η/η' factory

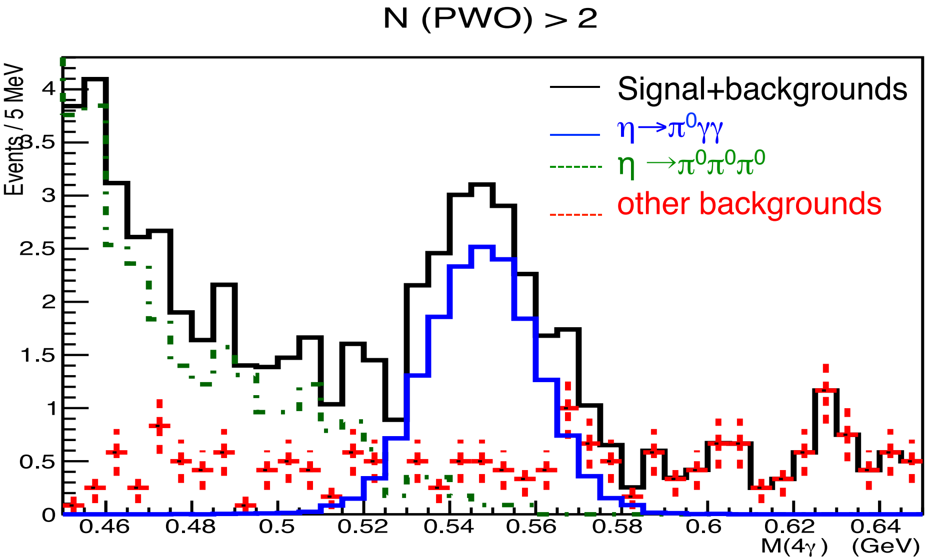
Unique of JEF Experiment

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)

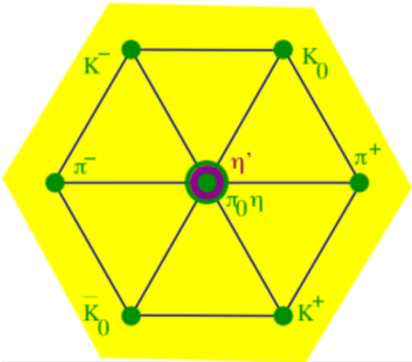


2. Simultaneously produce η and η' with similar rates

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

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:

i. Search for sub-GeV gauge bosons: a leptophobic vector B′ and an electrophobic scalar Φ′

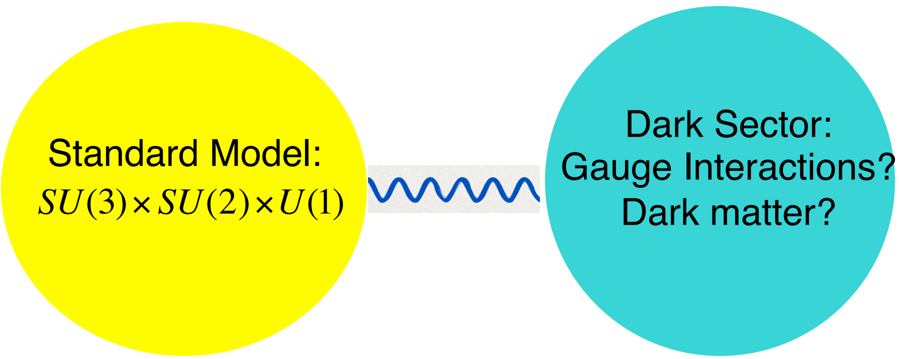
ii. Directly constrain CVPC new physics

iii. Probe interplay of VMD & scalar resonances in ChPT to calculate LEC's in the chiral Lagrangian

iv. Improve the quark mass ratio via $\eta \rightarrow 3\pi$

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

- **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′:
    $\eta \to \pi^0 \Phi'$, $\Phi' \to \gamma\gamma$
    → A 100 keV-100 MeV electrophobic scalar can solve proton radius and $(g\text{-}2)_\mu$ puzzles.

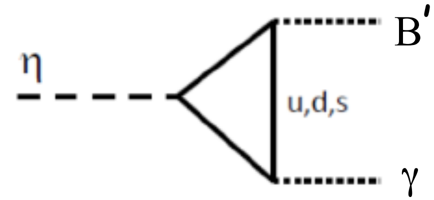
PRL 117,101801 (2016); PL B740,61(2015)

2. Confinement QCD:

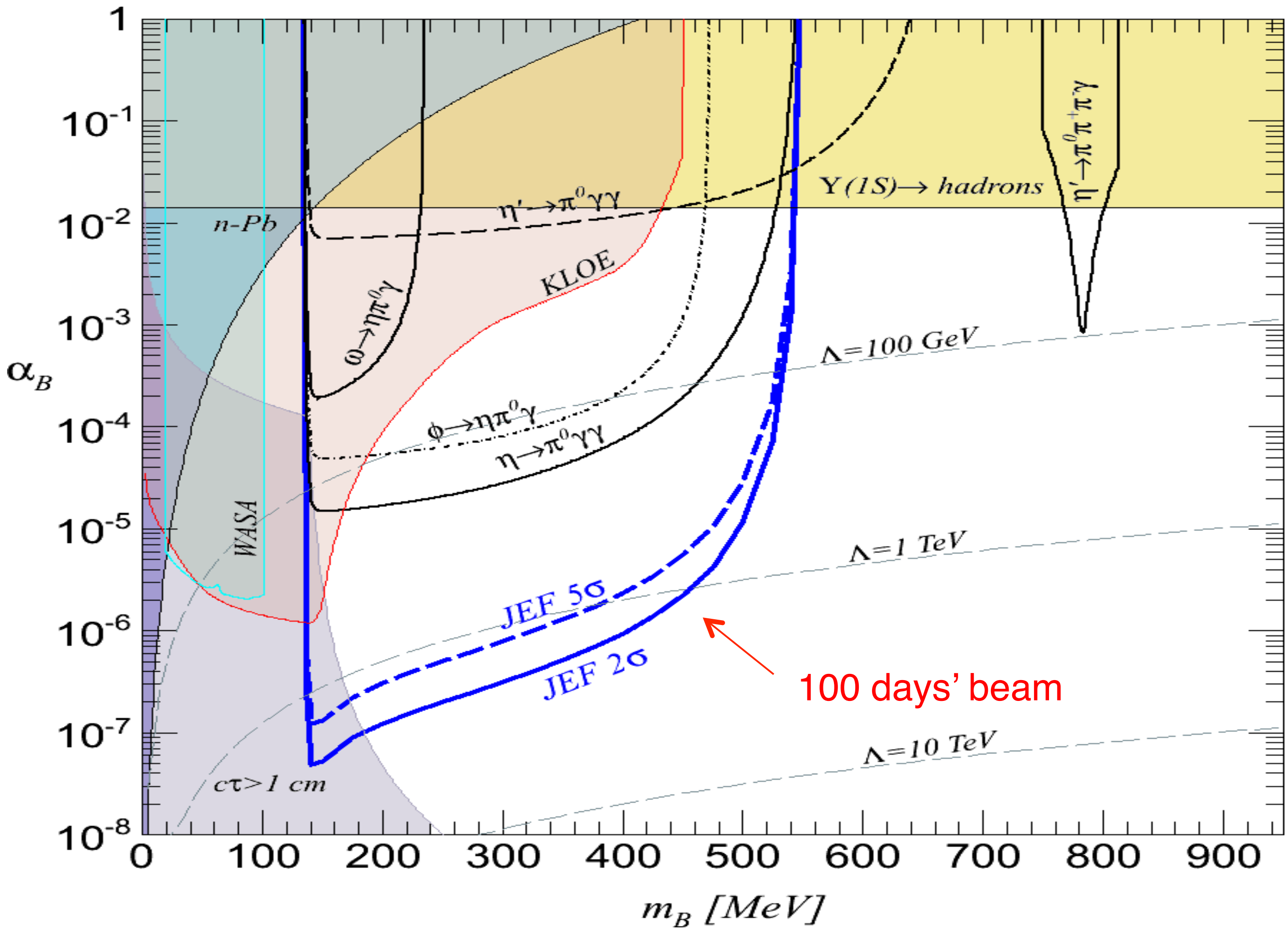
- **A rare window to probe interplay of VMD & scalar resonance in ChPT via the shape of Dalitz distribution**

JEF Experimental Reach for B′

Meson decay $\eta \to B'\gamma \to \pi^0\gamma\gamma$



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



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

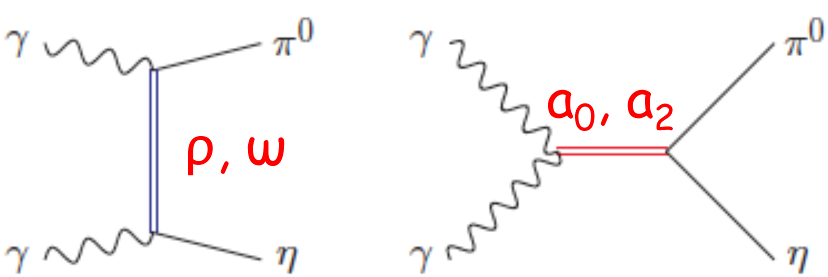
- The major contributions to $\eta \to \pi^0 \gamma\gamma$ are two $O(p^6)$ counter-terms in the chiral Lagrangian ➡ an unique test for high order ChPT.

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

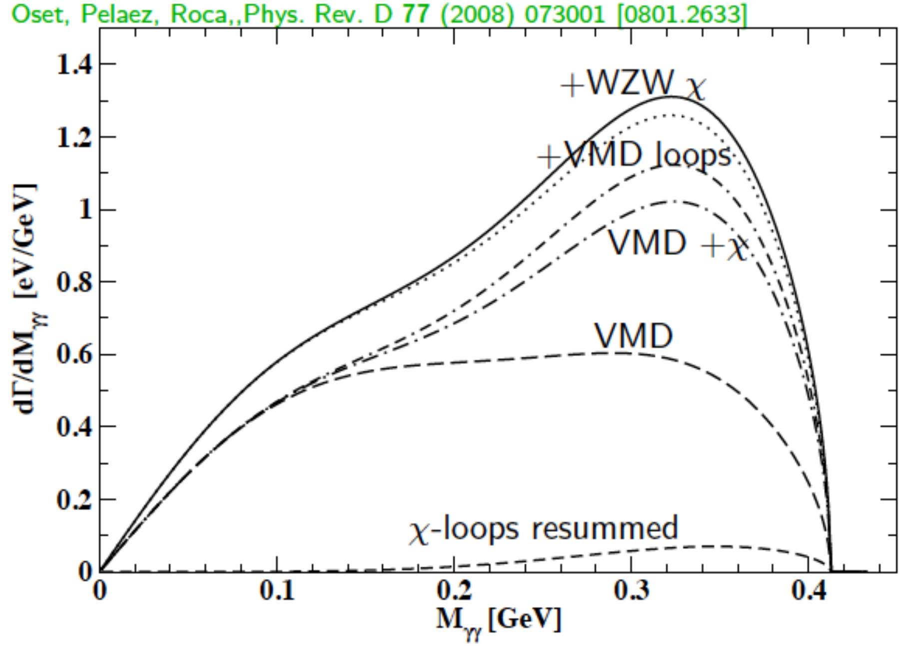
- Shape of Dalitz distribution is sensitive to the role of scalar resonances.

LEC's are dominated by resonances

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

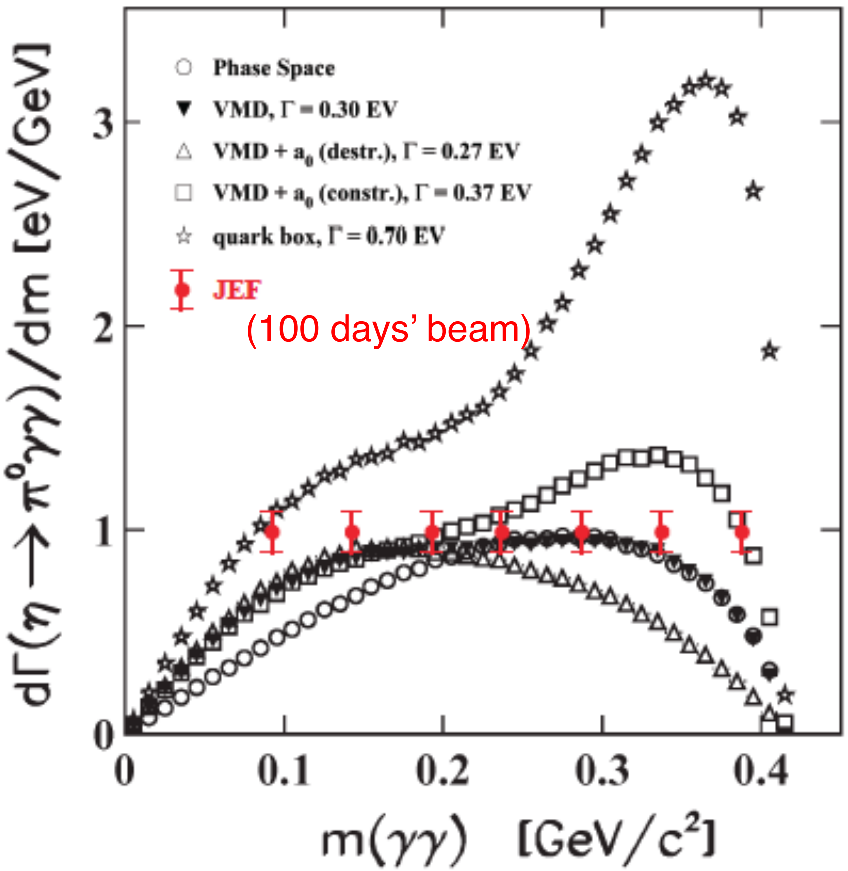


Oset, Pelaez, Roca,,Phys. Rev. D 77 (2008) 073001 [0801.2633]

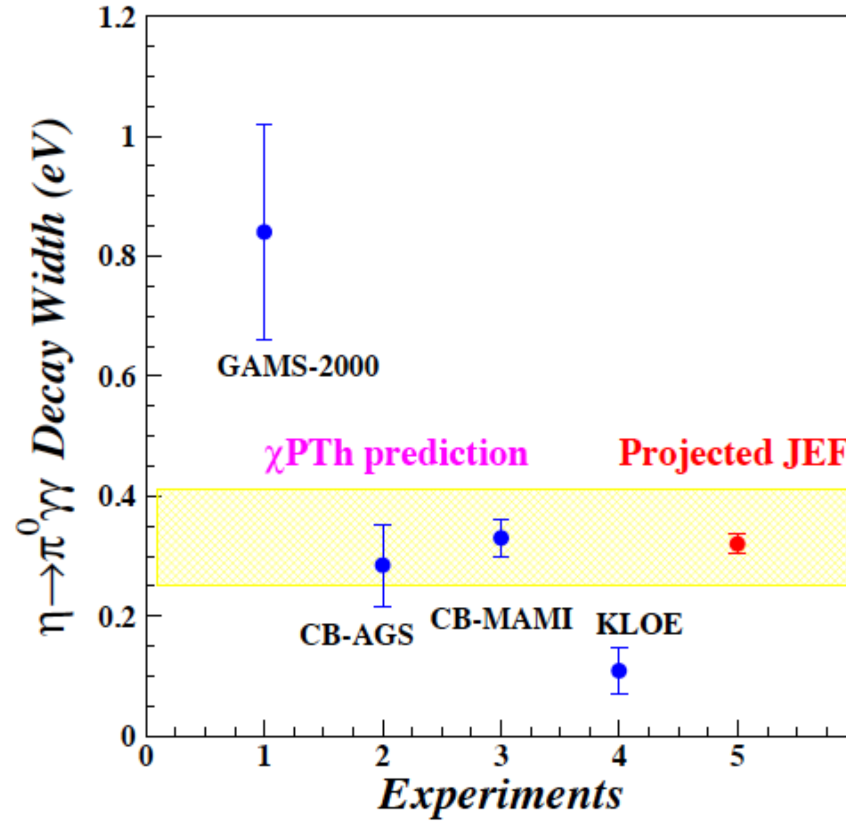


Projected JEF on SM Allowed $\eta \to \pi^0\gamma\gamma$

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

Charge Conjugation Invariance Test

- 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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Experimental Improvement on η→3γ

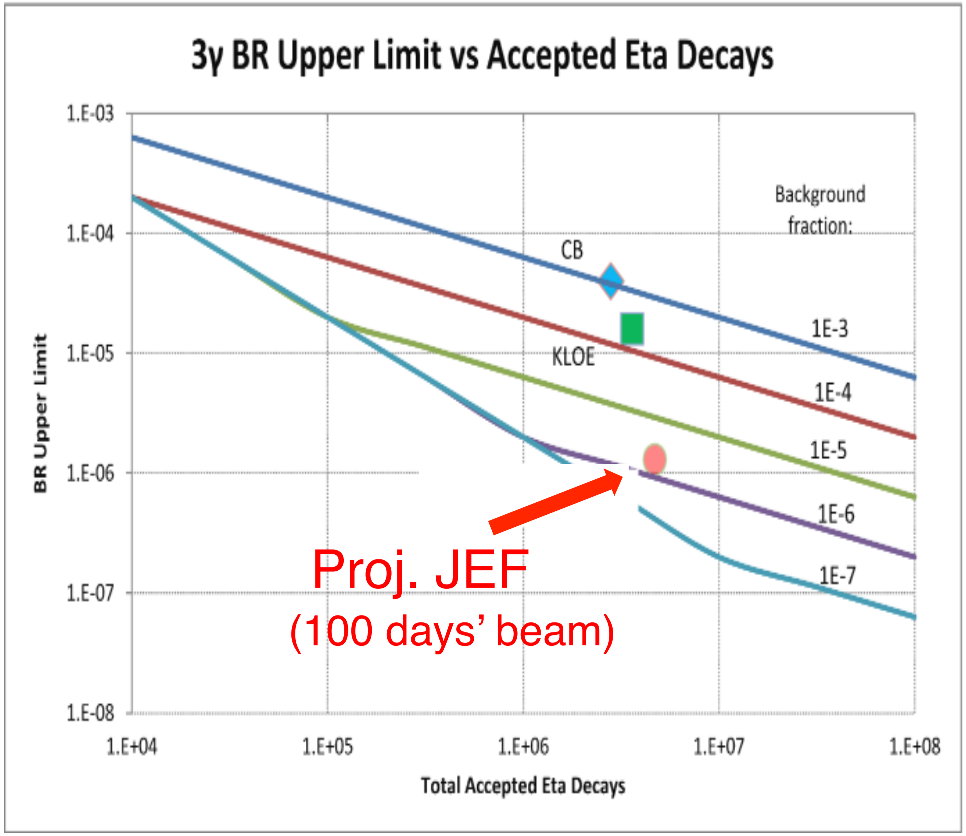
- SM contribution:
  BR(η→3γ) <10^{-19} via P-violating weak interaction.

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

  Phys. Rev.,139, B1650 (1965)

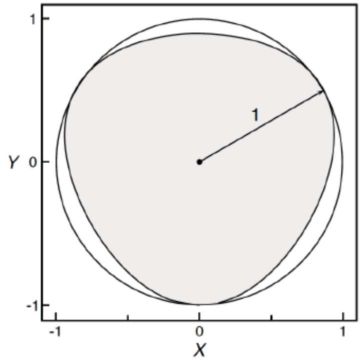
- A calculation due to such new physics by Tarasov suggests: BR(η→3γ)< 10^{-2}

  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

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



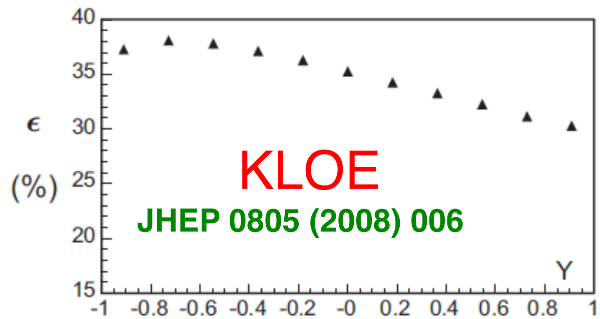
$$\boxed{X = \frac{\sqrt{3}}{2M_\eta Q_c}(u-t)}$$

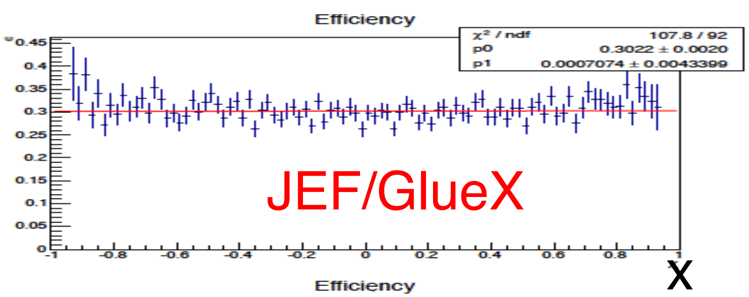
$$\boxed{Y = \frac{3}{2M_\eta Q_c}\left(\left(M_\eta - M_{\pi^0}\right)^2 - s\right) - 1}$$

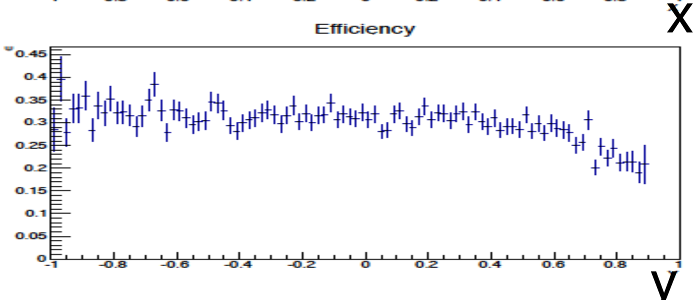
$$\boxed{Z = X^2 + Y^2}$$

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

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/JEF +PrimEx-η	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

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
  - inputs for a_μ(HLbL) calculations

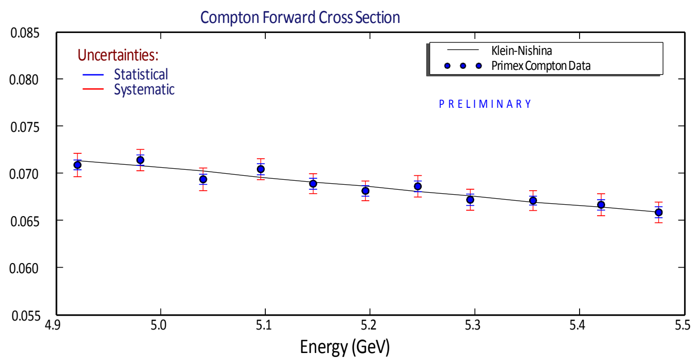
- **12 GeV tagged photon beam with GlueX setup offers a unique η/η′ facility with two orders of magnitude in background reduction in the neutral rare decays compared to other facilities in the world.**
  - Search for sub-GeV gauge bosons:

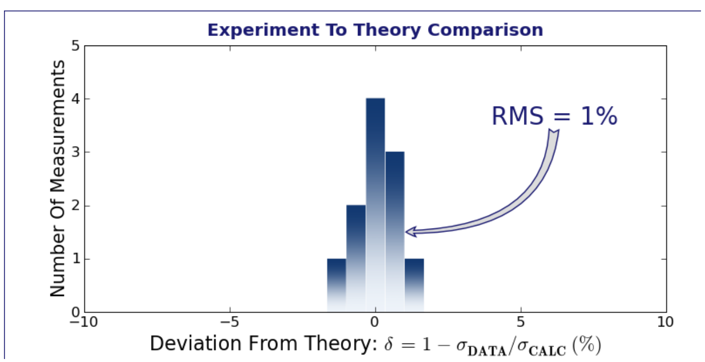
    a leptophobic vector B′ and an electrophobic scalar Φ′
  - Directly constrain CVPC new physics
  - Test the role of scalar dynamics in ChPT

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

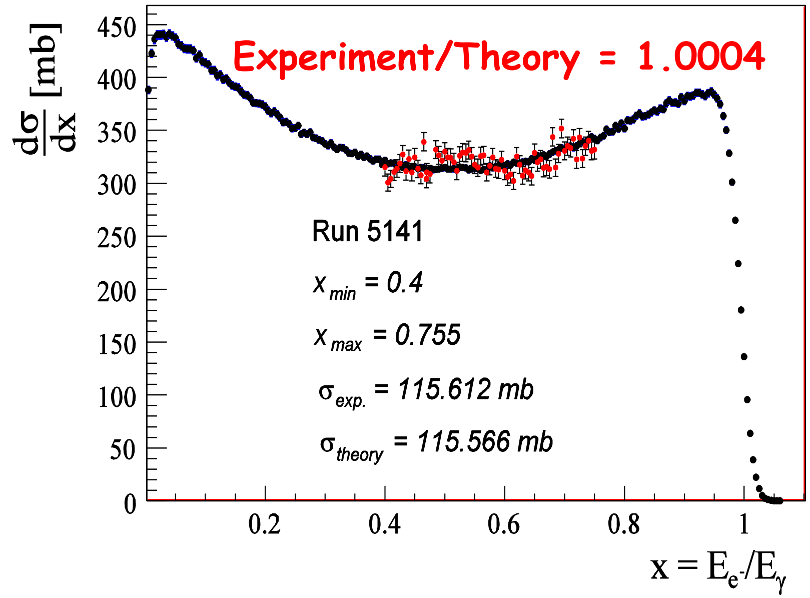
Verification of Overall Systematical Uncertainties

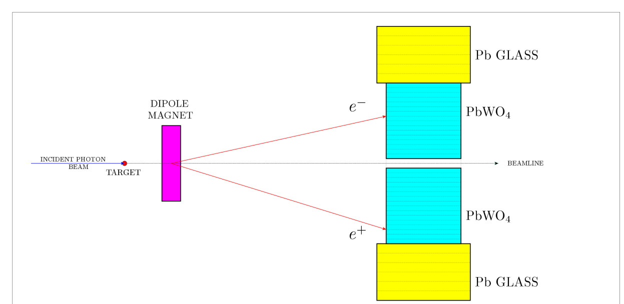
- ❑ $\gamma + e \rightarrow \gamma + e$ Compton cross section measurement





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





Systematic uncertainties on cross section are controlled under 1.3%

Experimental Challenges for $\Gamma(\eta\rightarrow\gamma\gamma)$

Compared to π^0:

- η mass is a factor of 4 larger
- smaller cross section

$$\left\langle \frac{d\sigma_{\mathrm{Pr}}}{d\Omega} \right\rangle_{peak} \propto \frac{E^4}{m^3}$$

- larger overlap between Primakoff and hadronic processes

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

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

1. Higher beam energy
2. Light targets

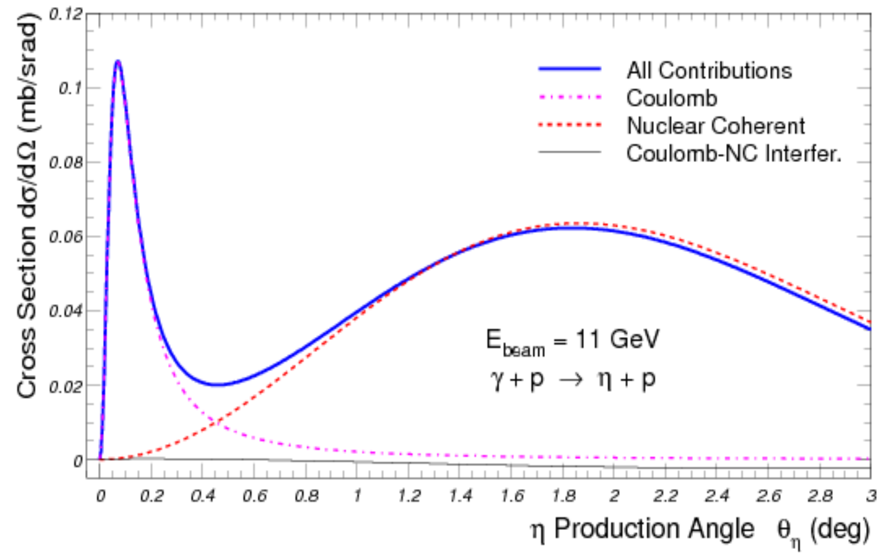
Advantage of Light Targets

Low A targets to control:

- Coherency: compact nucleus
- Separate background

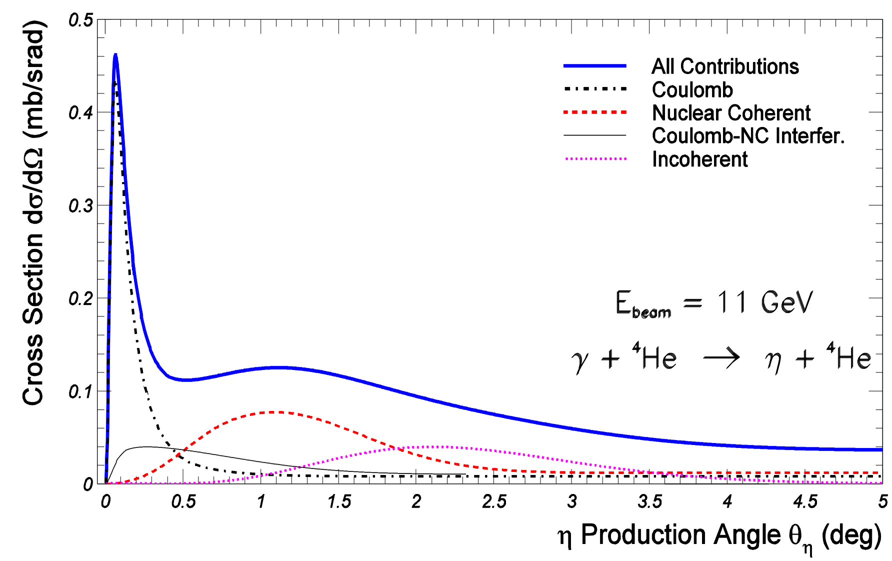
$$\langle \theta_{\mathrm{Pr}} \rangle_{peak} \propto \frac{m^2}{2E^2} \qquad \langle \theta_{NC} \rangle_{peak} \propto \frac{2}{E \bullet A^{1/3}}$$

- Well known form factors



Hydrogen:

- No inelastic hadronic contribution
- No nuclear final state interactions



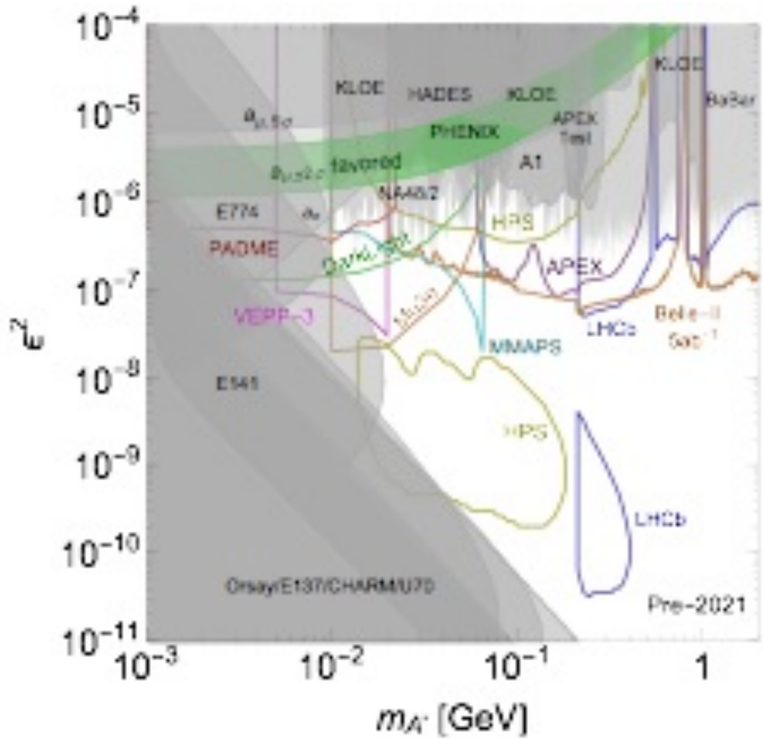
^{4}He:

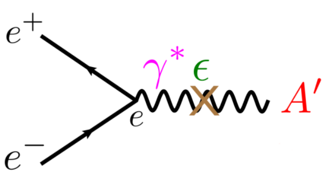
- Higher Primakoff cross section: $\sigma_{\mathrm{Pr}} \propto Z^2$

"Vector Portal" to Dark Sector

1. Dark photon A′

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





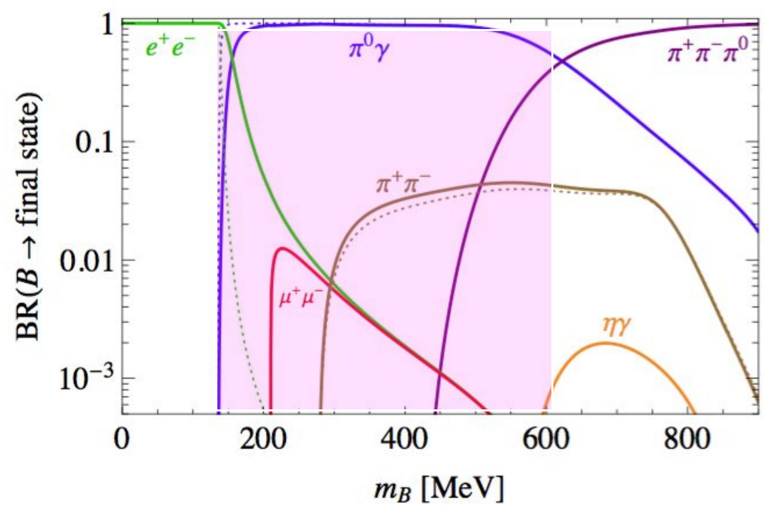
Most A′ searches look for $A' \to l^+l^-$, relying on the leptonic coupling of new force

2. 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!



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