PrimEx Experiments and the Prospects of Rare η Decays at GlueX

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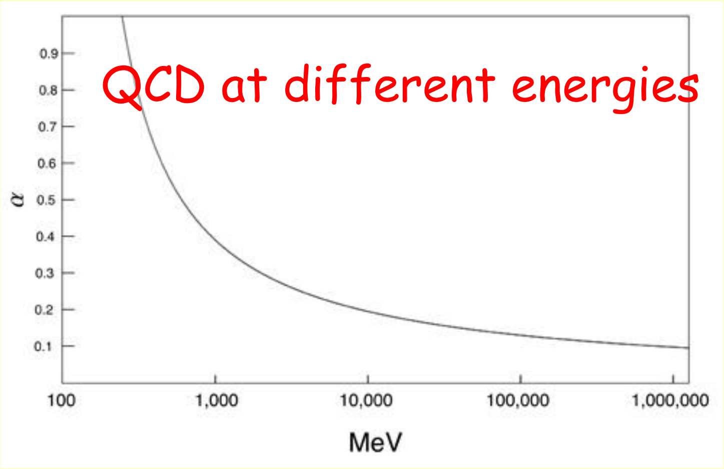
Outline

- Challenges in Physics
- Precision tests of continuous symmetries of confinement QCD via the PrimEx experiments
- Testing discrete symmetries and searching for new physics via the η rare decays
- Summary

Challenges in Physics

- Confinement QCD
  - Lattice QCD
  - Chiral perturbation theory



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

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

Continuous symmetries of confinement QCD

chiral limit: is the limit of vanishing quark masses $m_q \to 0$.

QCD Lagrangian with quark masses set to zero:

$$L_{QCD}^{(o)} = \bar{q}_L \gamma_\mu i D_\mu q_L + \bar{q}_R \gamma_\mu i D_\mu q_R - \frac{1}{4} G_{\mu\nu}^{\alpha} G^{\alpha\mu\nu}$$

$$D_\mu = \partial_\mu - g_s \lambda_\alpha / 2 G_\mu^\alpha$$

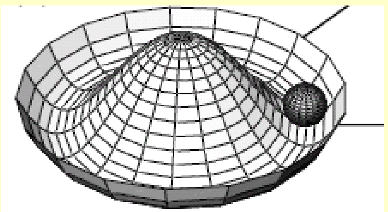
$$q = \begin{pmatrix} u \\ d \\ s \end{pmatrix} \qquad q_{R,L} = \frac{1}{2}(1 \pm \gamma_5) q$$

Large global symmetry group:

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

Fate of QCD symmetries

$m_q = 0$



Classical QCD Lagrangian

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

- $SU_L(3) \times SU_R(3)$
  - $<\bar{q}q> \neq 0 \longrightarrow$ Chiral symmetry spontaneously broken,
  - 8 massless Goldstone Boson
  - $\pi^+ \; \pi^- \; \pi^0 \; K^+ \; K^- \; K^0 \; \bar{K}^0 \; \eta_8$
  - SU(3) symmetry of QCD vacuum
- $U_A(1)$ explicitly broken by Axial anomaly
  - Axial anomaly and $<\bar{q}q> \neq 0$
  - quasi-Goldstone Boson η_o if Nc can be taken as large
  - $m_{\eta_o} \neq 0$
- $U_B(1)$ holds

$m_q = 0$

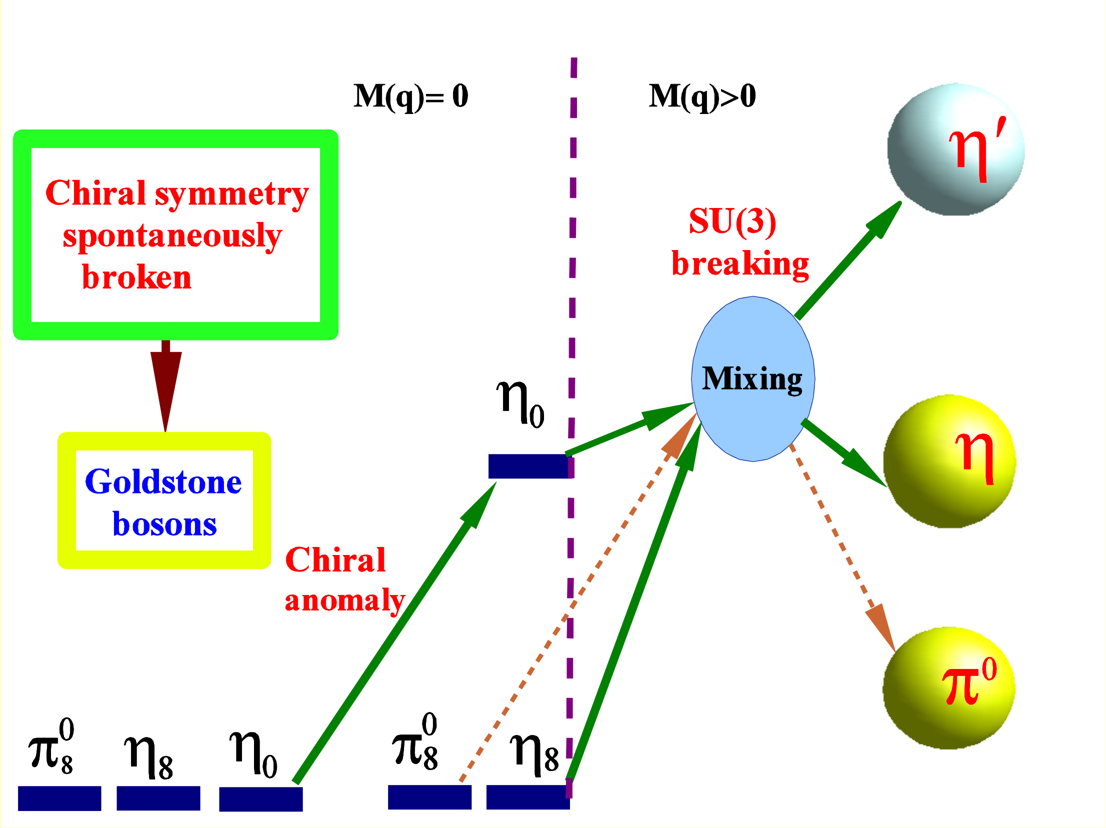
$m_q \neq 0$

- Chiral symmetry explicitly broken
  SU(3) is broken
  - massive Goldstone bosons
  - unequal quark masses: mixing of states
  - $\pi^+ \; \pi^- \; \pi^0 \; K^+ \; K^- \; K^0_s \; K^0_L \; \eta$
- massive η' Bosons
- conservation of Baryon number

$m_q \neq 0$

Lightest pseudoscalar mesons

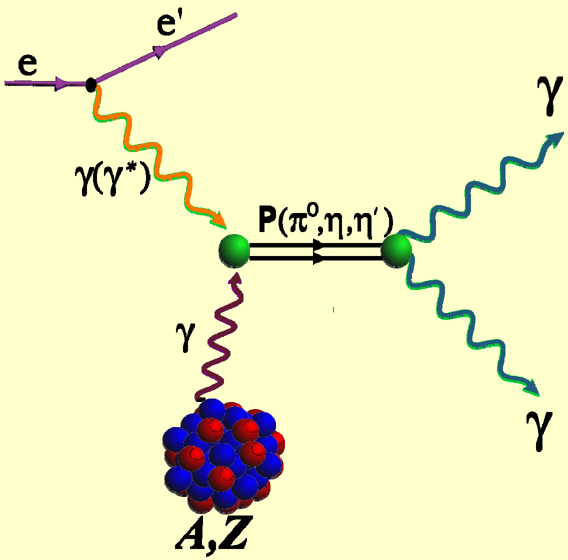
- Chiral $SU_L(3) X SU_R(3)$ spontaneously broken
  → Goldstone mesons π^0, η_8
- Chiral anomalies
  → Mass of η_0
  → $P \rightarrow \gamma\ \gamma$
  (P: π^0, η, η')
- Quark flavor SU(3) breaking
  → The mixing of π^0, η and η'



The π^0, η and η' system provides a rich laboratory to study the symmetry structure of QCD at low energy.

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):

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

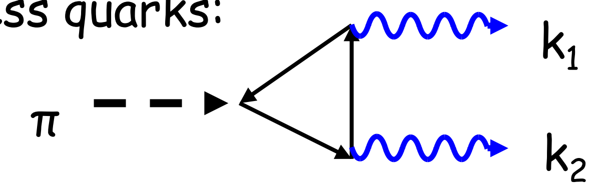
Input to Physics:

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

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Experiments @ 6 GeV

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

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



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

> Corrections to the chiral anomaly prediction:

Calculations in NLO ChPT:

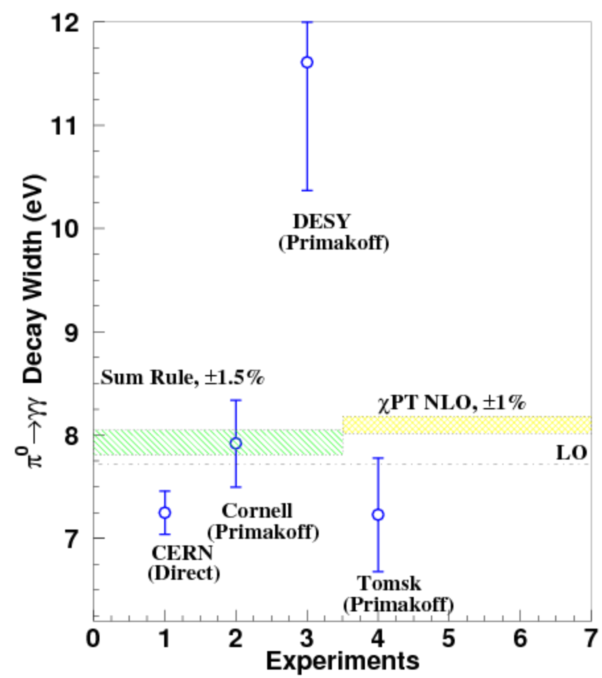
- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.10eV ± 1.0%
  (J. Goity, et al. Phys. Rev. D66:076014, 2002)
- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.06eV ± 1.0%
  (B. Ananthanarayan et al. JHEP 05:052, 2002)

Calculations in NNLO SU(2) ChPT:

- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 8.09eV ± 1.3%
  (K. Kampf et al. Phys. Rev. D79:076005, 2009)

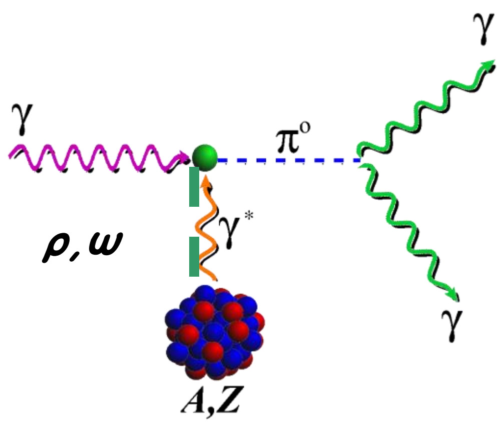
> Calculations in QCD sum rule:

- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.93eV ± 1.5%
  (B.L. Ioffe, et al. Phys. Lett. B647, p. 389, 2007)

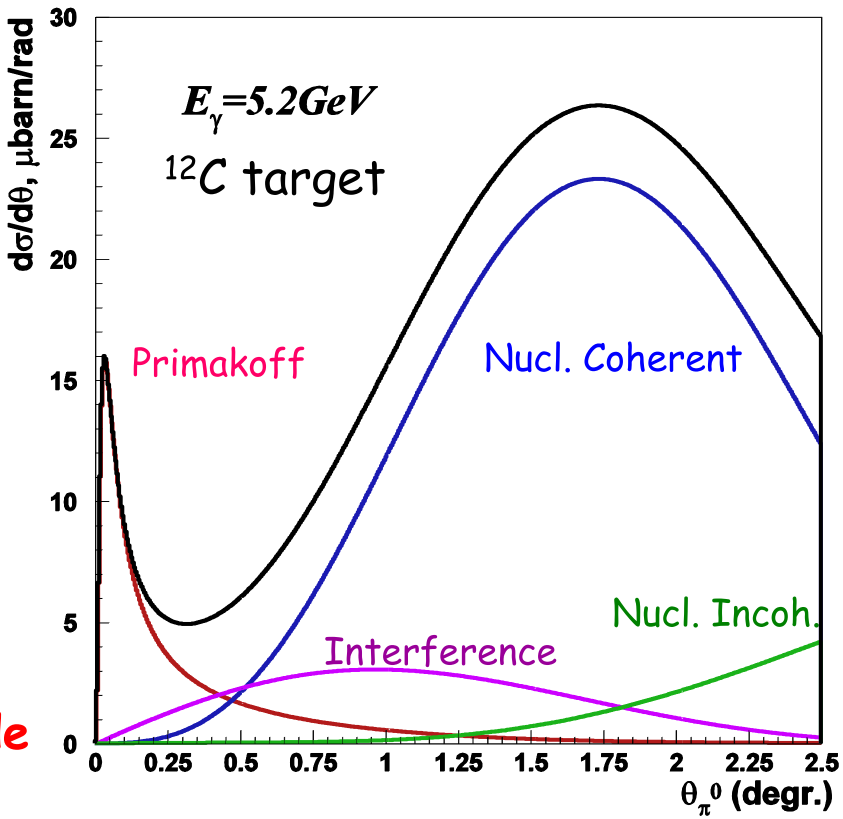


- Precision measurements of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ at the percent level will provide a stringent test of a fundamental prediction of QCD.

Primakoff Method



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



Challenge: Extract the Primakoff amplitude

Requirement:

- ➢**Photon flux**
- ➢**Beam energy**
- ➢**π^0 production Angular resolution**

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:

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

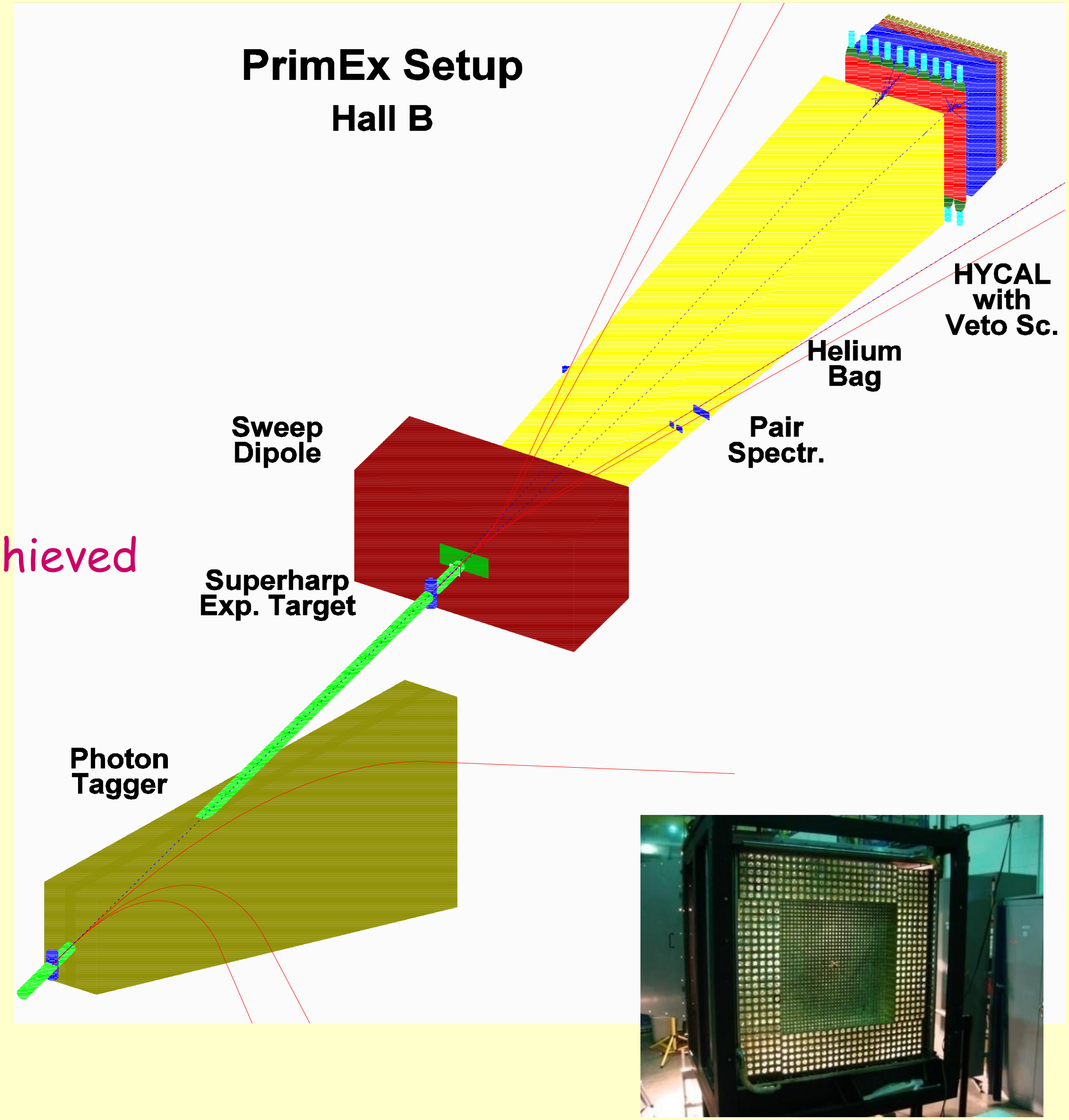
- Coherent process

PrimEx-I (2004)

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

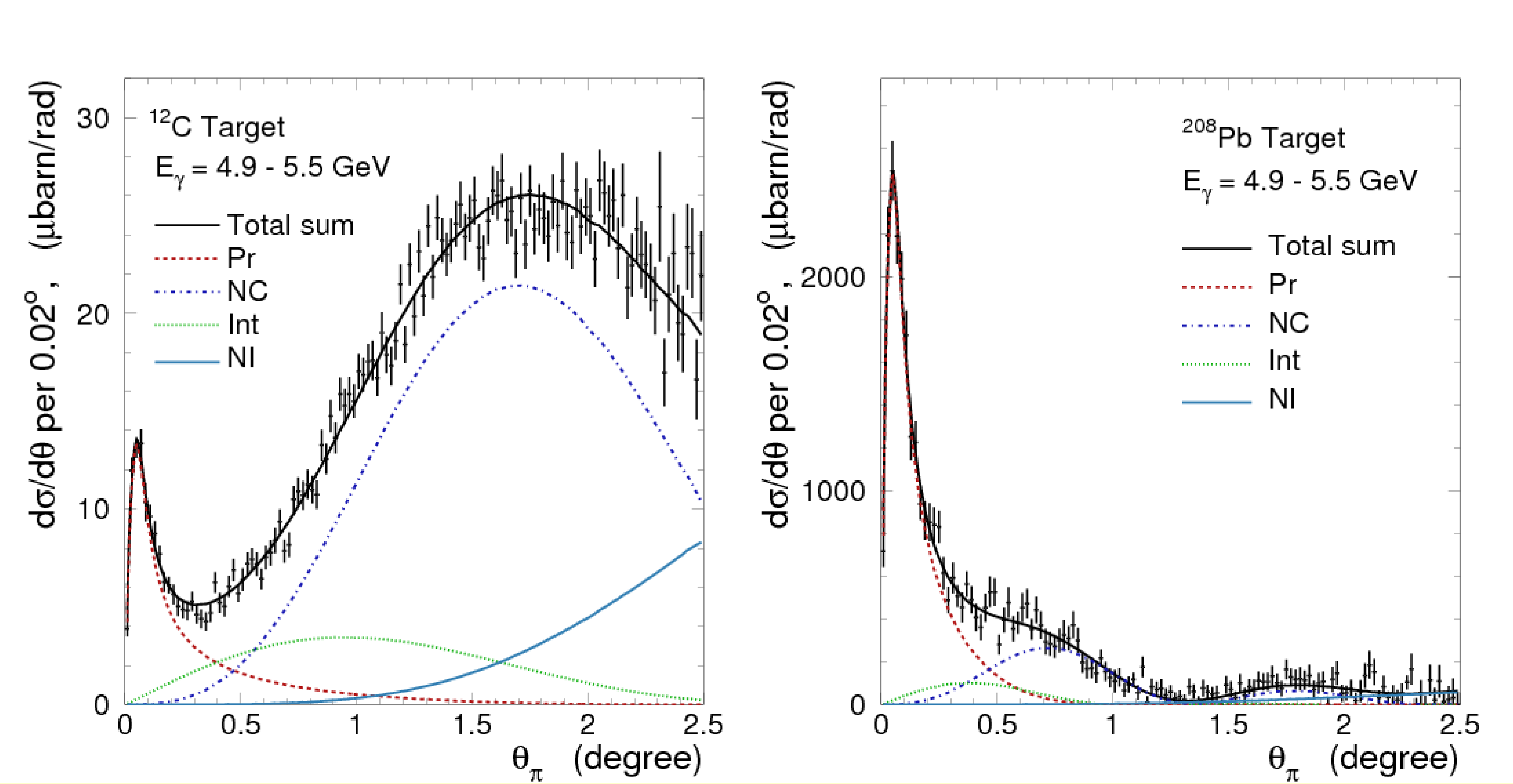
- New pair spectrometer for photon flux control at high beam intensities
  ➡ 1% accuracy has been achieved

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



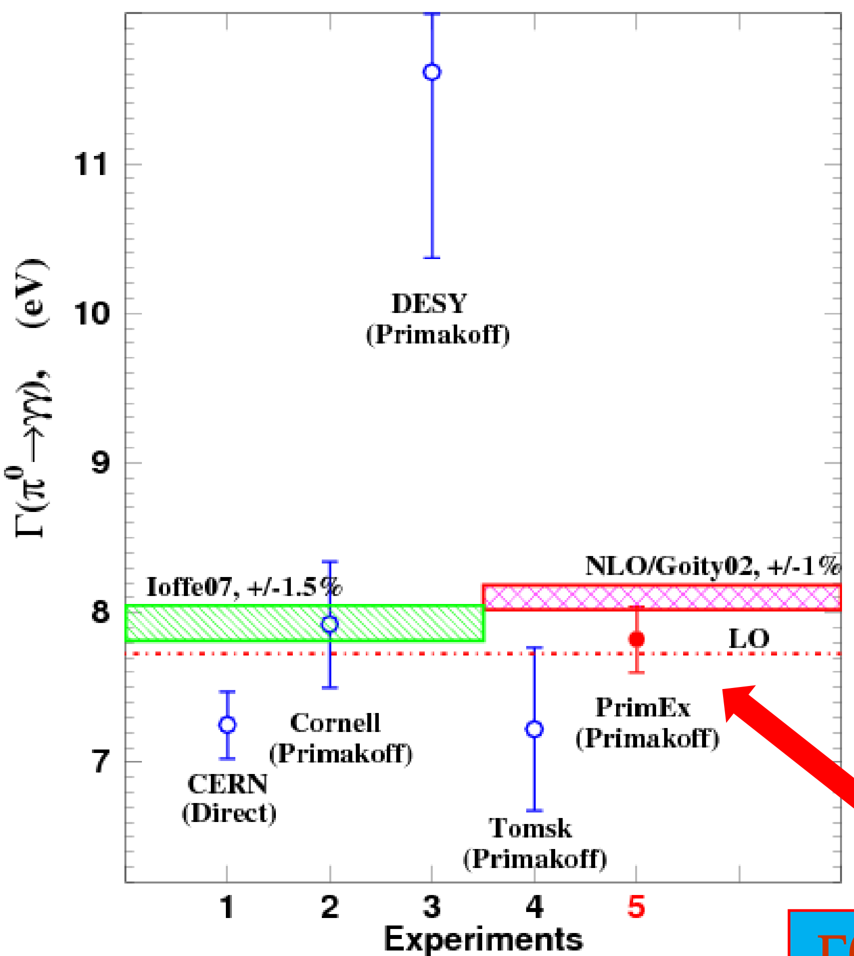
Fit Differential Cross Sections to Extract $\Gamma(\pi^0 \rightarrow \gamma\gamma)$

Theoretical angular distributions smeared with experimental resolutions are fit to the data on two nuclear targets:

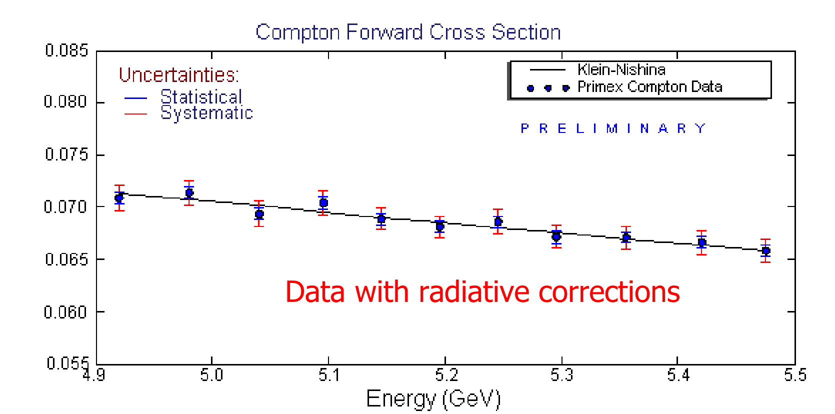


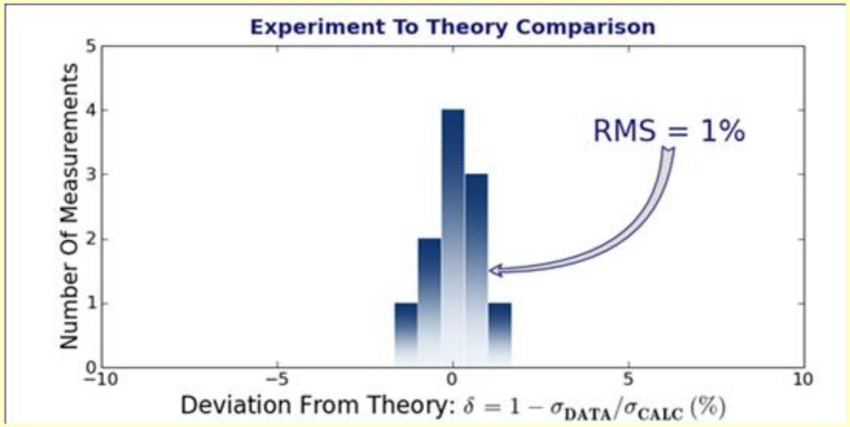
PrimEx-I Result

PRL 106, 162303 (2011)



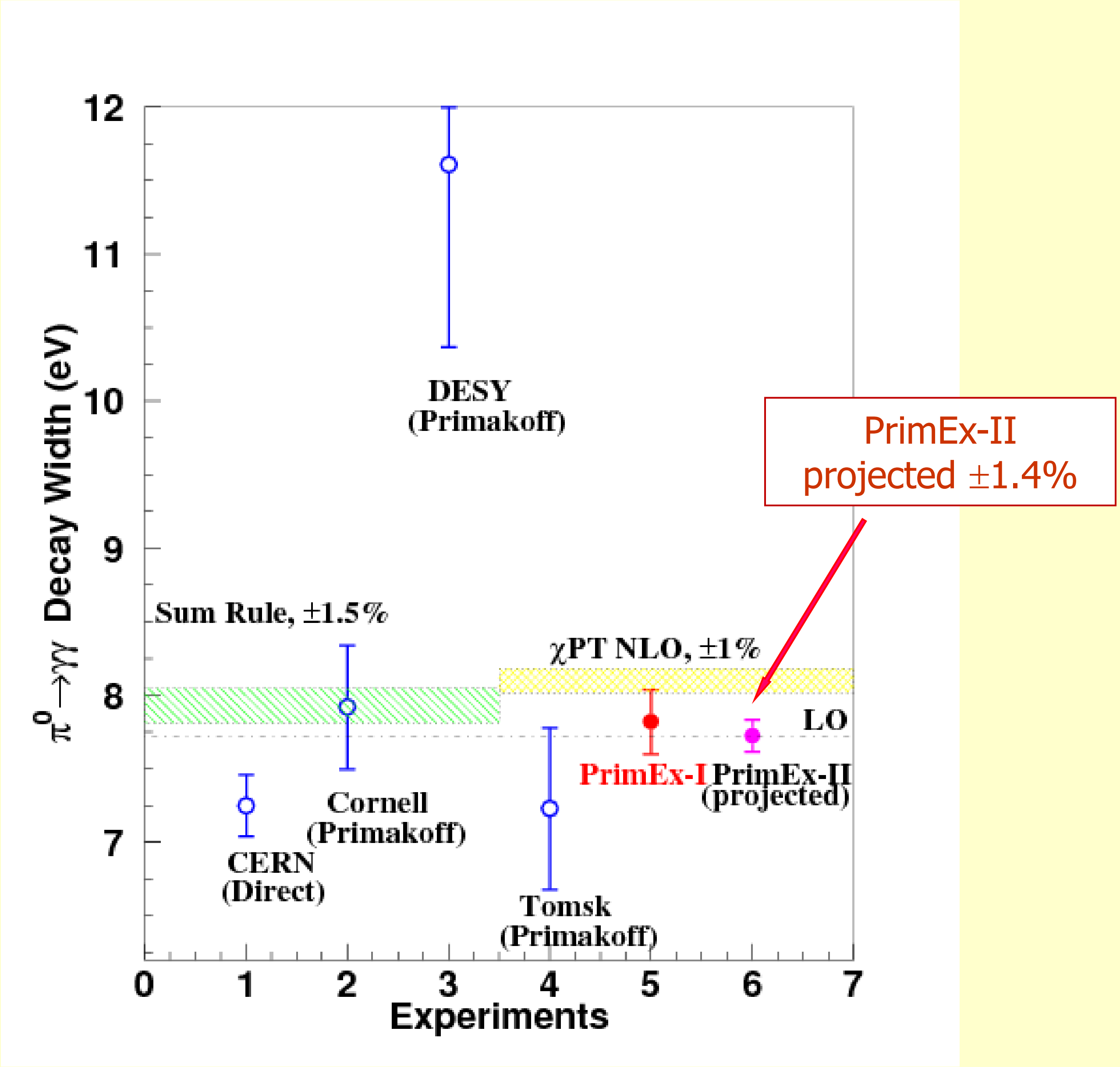
Systematical uncertainty verification:
Compton Cross Section Measurement





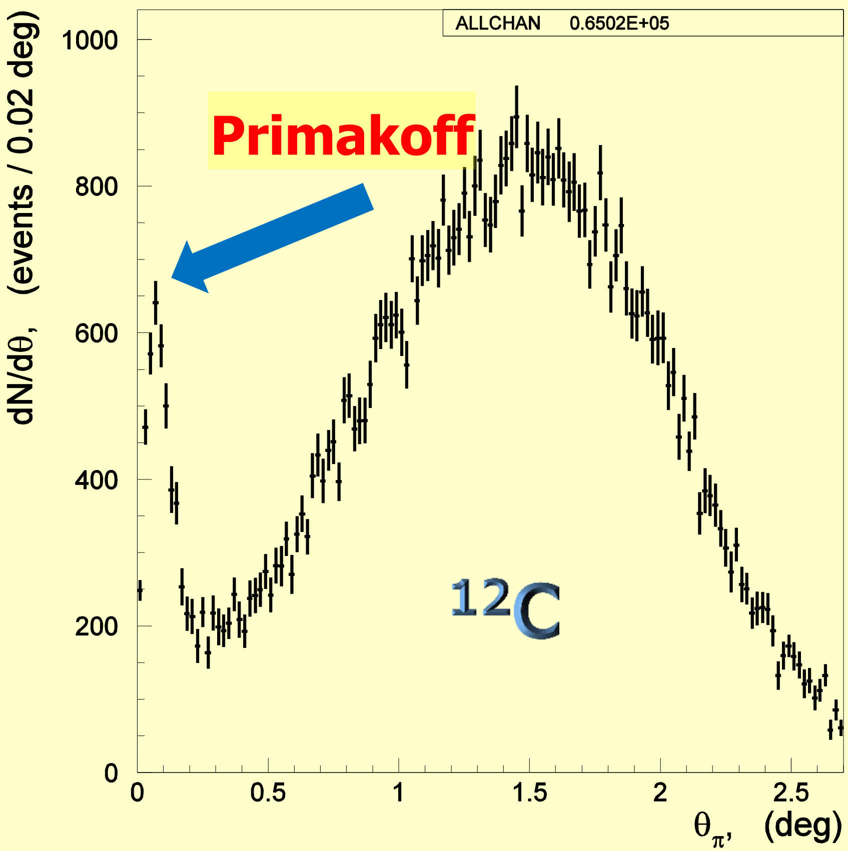
$\Gamma(\pi^0\rightarrow\gamma\gamma)$ = 7.82±0.14(stat)±0.17(syst) eV
2.8% total uncertainty

Goal for PrimEx-II (2010)

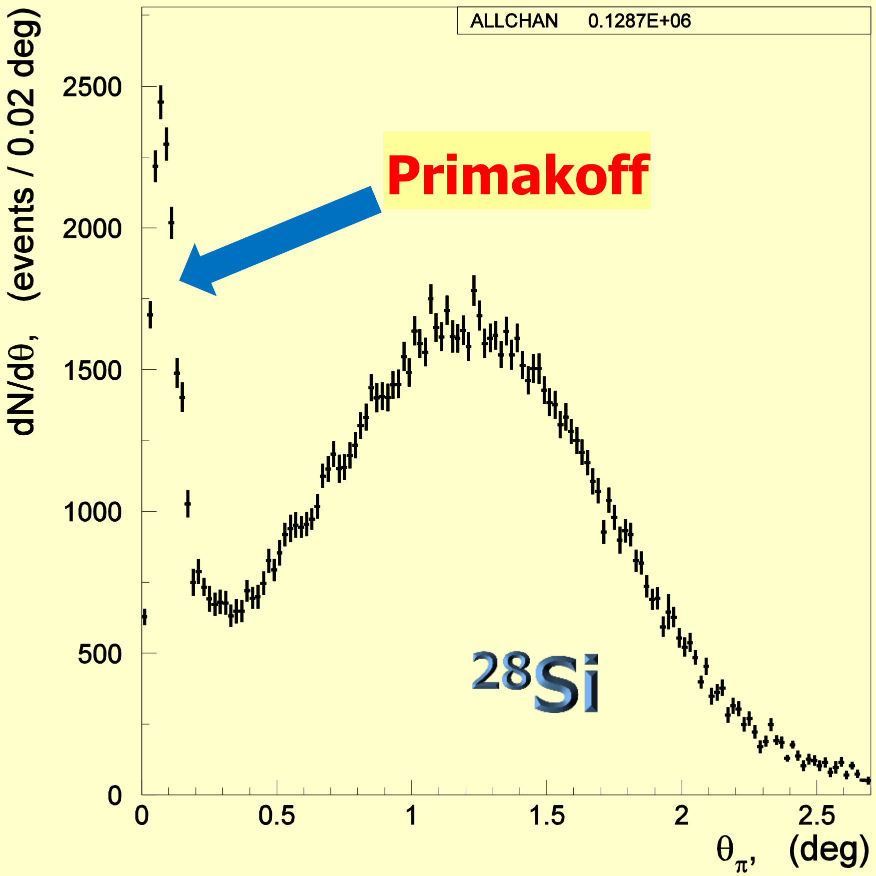


PrimEx-II Experimental Yield (preliminary)

($E\gamma$ = 4.4-5.3 GeV)



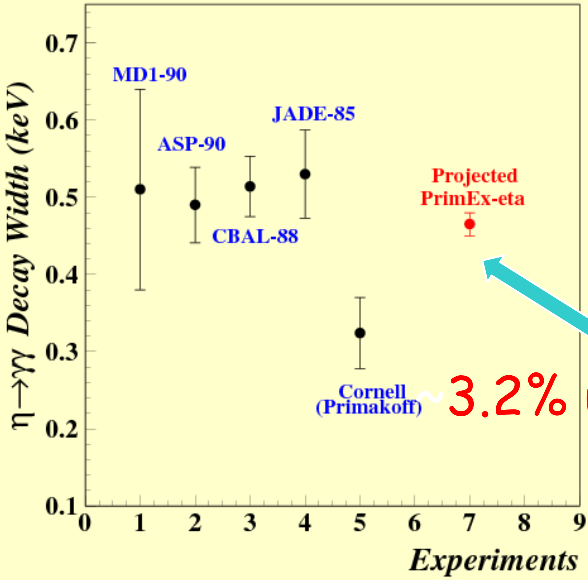
~8K Primakoff events



~20K Primakoff events

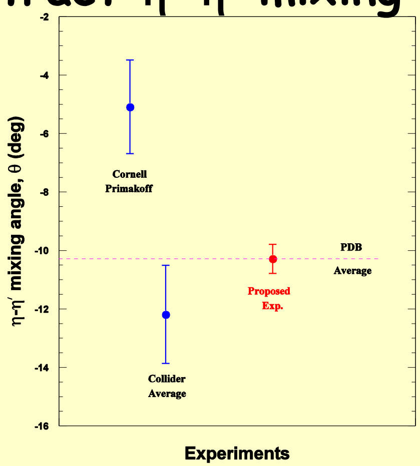
Outcomes from Γ(η→γγ) Experiment @ 12 GeV

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



~3.2% uncertainty

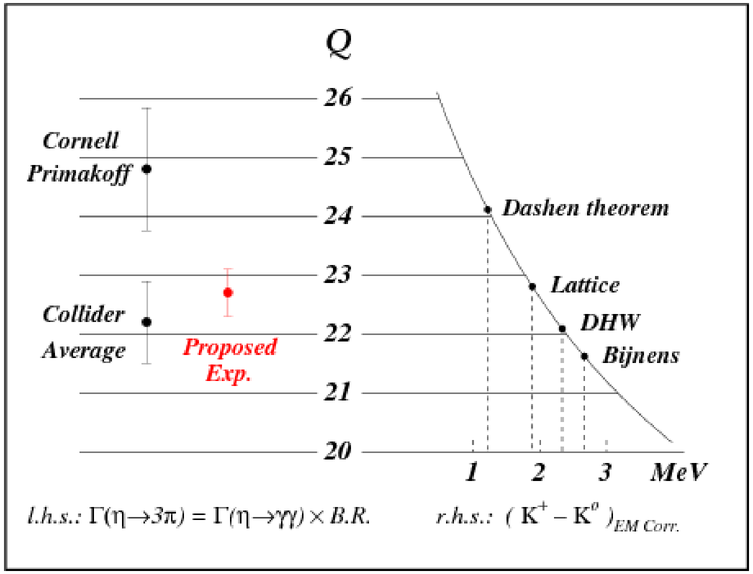
2. **Extract η-η' mixing angle:**



3. **Determine Light quark mass ratio:**

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

$\Gamma(\eta \to 3\pi) \propto |A|^2 \propto Q^{-4}$



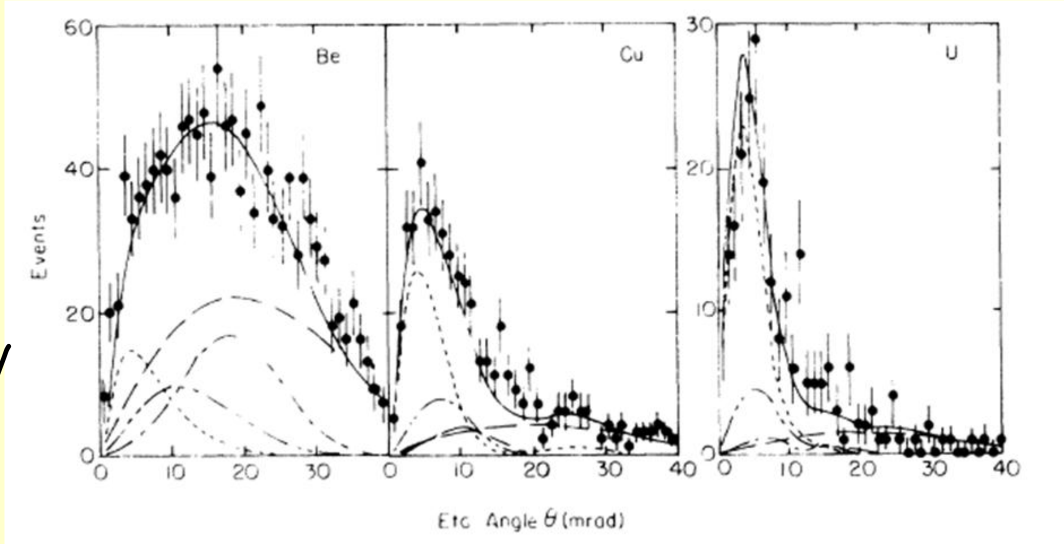
H. Leutwyler Phys. Lett., B378, 313 (1996)

Challenges in the η→γγ experiment

η

Cornell experiment (PRL, 1974):

- untagged bremsstrahlung γ beam, E_γ=5.8, 9.0, 11.45 GeV
- targets: Be, Al, Cu, Ag, U
- Pb-glass calorimeter
- Result: $\Gamma(\eta\to\gamma\gamma)$=(0.324±0.046) keV
  ±14.2% total uncertainty



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,…)

Advantages of the Proposed Light Targets

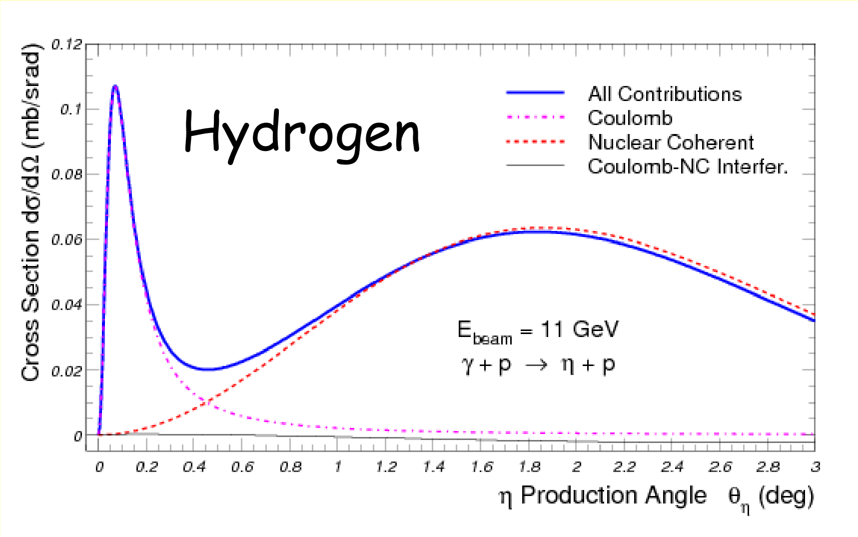
- Precision measurements require low A targets to control:
  - contributions from nuclear processes
  - coherency

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

Hydrogen:

- ✓ no inelastic hadronic contribution
- ✓ no nuclear final state interactions
- ✓ proton form factor is well known
- ✓ better separation between Primakoff and nuclear processes
- ✓ new theoretical developments of Regge description of hadronic processes

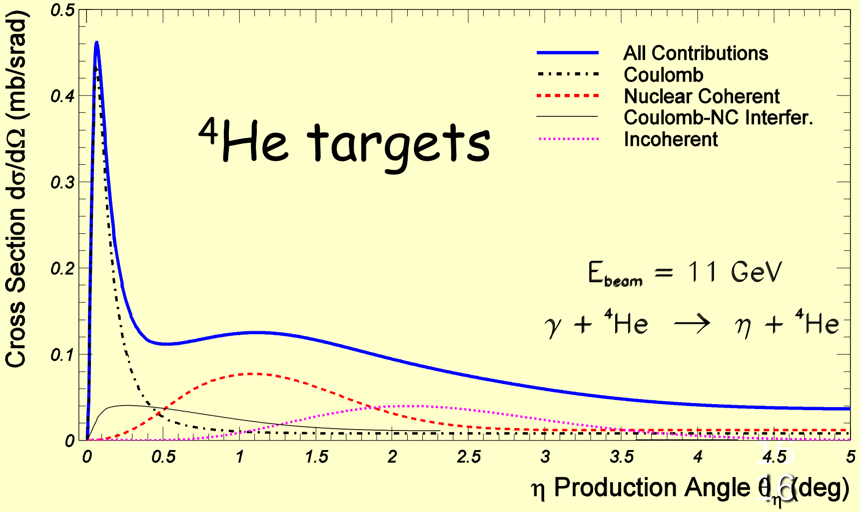
J.M. Laget, Phys. Rev. C72, (2005)
A. Sibirtsev, et al. arXiv:1001.0646, (2010)



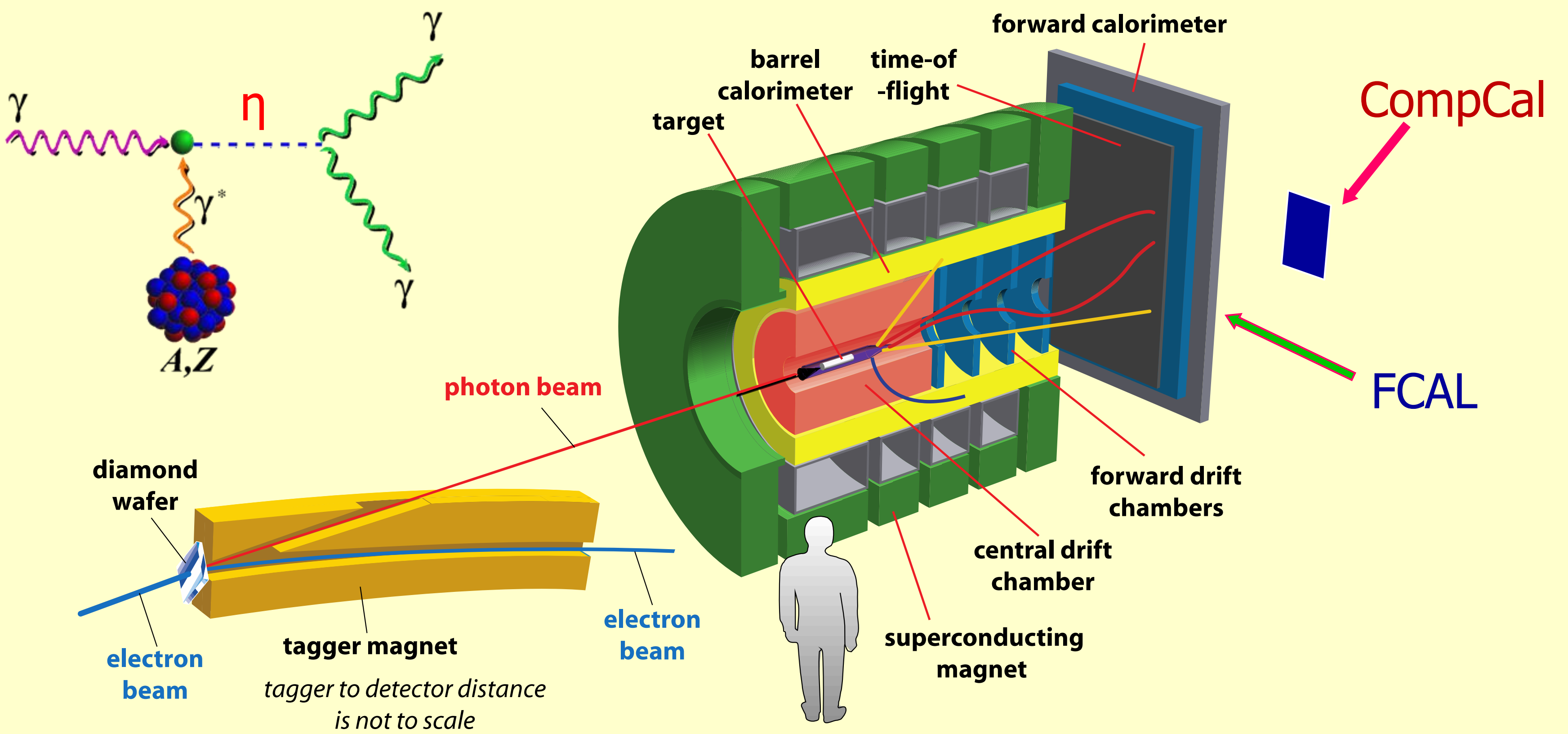
^{4}He:

- ✓ higher Primakoff cross section: $\sigma_{Pr} \propto Z^2$
- ✓ the most compact nucleus
- ✓ form factor well known
- ✓ new theoretical developments for FSI

S. Gevorkyan et al., Phys. Rev. C 80, (2009)

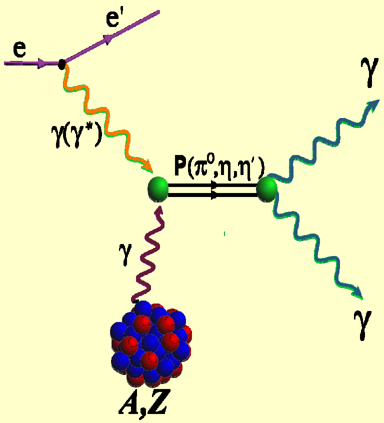


Measurement of $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D at 12 GeV

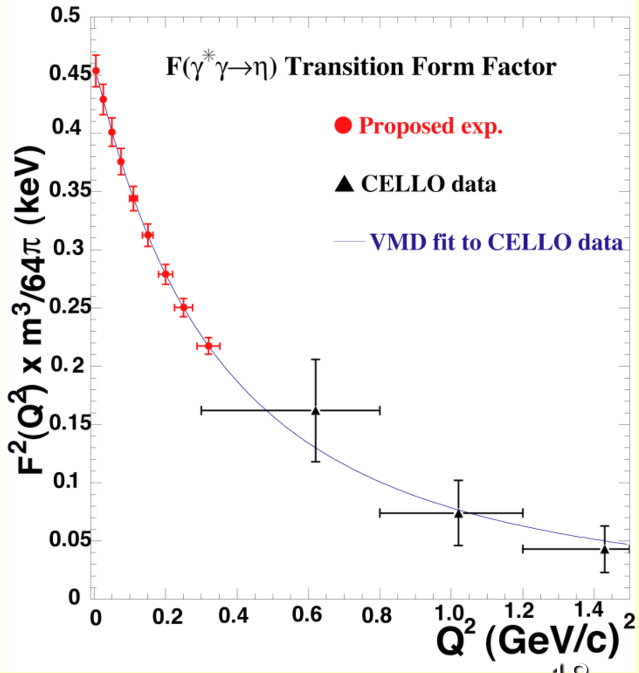


- Incoherent tagged photon beam (~10.5-11.5 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- 30 cm liquid Hydrogen and ^{4}He targets (~3.6% r.l.)
- Forward Calorimeter (FCAL) for $\eta\rightarrow\gamma\gamma$ decay photons
- CompCal and FCAL to measure well-known Compton scattering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

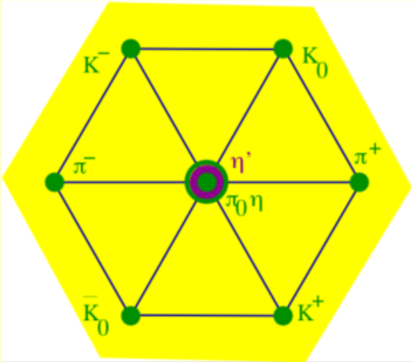
Transition Form Factors $F(\gamma\gamma^*\to p)$
(at Low Q^2)



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



Why η is an 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 QCD symmetry breakings

- Due to the symmetries in the strong and EM interactions, the η decay width Γ_η =1.3KeV is extremely narrow (relative to Γ_ρ=149MeV)
  - ➡ The lowest orders of η decays are filtered out in the strong and EM interactions, enhancing the contributions from higher orders by a factor of ~100,000.

- 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 which are effectively free of SM backgrounds for new physics search.

η decays is a unique probe to test SM and to search for new physics beyond SM: (1) test higher order χPTh and future lattice QCD predictions; (2) new sources of fundamental symmetry violations; (3) light dark matter.

η Neutral Rare Decay Channels

Mode	Branching Ratio (PDG)	Physics Highlight
$\pi^0 2\gamma$	$(2.7 \pm 0.5) \times 10^{-4}$	χPTh @ $O(p^6)$, Lattice QCD
$2\pi^0$	$<3.5 \times 10^{-4}$	CP, P
3γ	$<1.6 \times 10^{-5}$	C
$\pi^0 \gamma$	$<9 \times 10^{-5}$	C, L, gauge inv.
4γ	$<2.8 \times 10^{-4}$	Suppressed ($<10^{-11}$)
$\pi^0 \pi^0 \gamma$	$<5 \times 10^{-4}$	C
$\pi^0 \pi^0 \pi^0 \gamma$	$<6 \times 10^{-5}$	C
$4\pi^0$	$<6.9 \times 10^{-7}$	CP, P

Status of $\eta \to \pi^0 \pi^0$

theoretical predictions:

	$BR(\eta \to \pi\pi)$
CKM (SM)	$\leq 2 \times 10^{-27}$ (G_F^2, cancellation) C.Jarlskog, E.Shabalin, PS T 99 (02) 23
θ (QCD)	$\leq 3 \times 10^{-17}$ (d_n) C.Jarlskog, E.Shabalin, PR D 52 (95) 6327
extended Higgs	$\leq 1.2 \times 10^{-15}$ C.Jarlskog, E.Shabalin, PR D 52 (95) 6327
general	$\leq 3.5 \times 10^{-14}$ (d_n) M.Gorchtein, hep-ph 0803.2906

experimental limits:

$$BR(\eta \to \pi^0\pi^0) \leq 3.5 \times 10^{-4}$$

GAMS-4π, PAN 70 (07) 693

Detection at any level would be signature of P and PC violations from new sources!

Strong CP Problem

- A term in QCD Lagrangian violates P, T, CP. It only manifests in flavor-conserving phenomena.

$$L_\theta = \theta_{QCD} \frac{g_s^2}{32\pi^2} G \cdot \tilde{G}$$

- When including electro-weak interaction in SM, the QCD vacuum angle becomes: $\bar{\theta} = \theta_{\mathrm{QCD}} + \arg\det(\mathrm{M}^{\mathrm{U}}\mathrm{M}^{\mathrm{D}})$

- Current experimental constraint on θ came from neutron EDM

  theoretical estimations: $d_n \sim (4 \cdot 10^{-17} \div 2 \cdot 10^{-15})\bar{\theta}\ e \cdot \mathrm{cm}$

  experimental limit: $d_n \le 2.9 \times 10^{-26}\bar{\theta}\ e \cdot \mathrm{cm}$ → $\bar{\theta} \sim 10^{-10 \pm 1}$

- Such constraint is sensitive to the tree level and loop term cancellation (K. Ottnad, et al., Phys.Lett.,B687, 42 (2010)):

$$d_n^{tree} = (2.9 \pm 1.1) \times 10^{-16}\bar{\theta}\ e \cdot \mathrm{cm} \qquad d_n^{loop} = -3.0^{+1.1}_{-0.8} \times 10^{-16}\bar{\theta}\ e \cdot \mathrm{cm}$$

- $\eta \to 2\pi^0$ may shed light on the Strong CP problem:

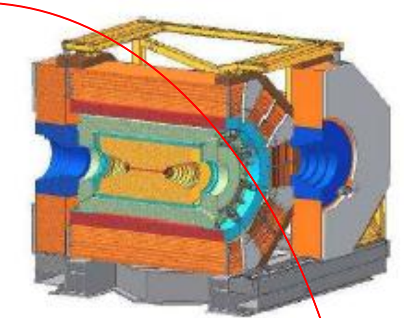
$$2\,Br(\eta \to 2\pi^0) \sim 180\,\bar{\theta}^2 \qquad \text{If } \bar{\theta} \sim 10^{-4}, \text{ then } Br(\eta \to 2\pi^0) \sim 10^{-6}$$

World competition in **Rare η Decays**

e⁺e⁻ Collider

KLOE-2 at DAΦNE

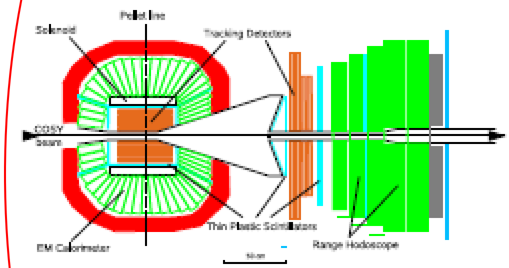
BESIII at BEPCII



Low energy η-facilities

Fixed-target

WASA at COSY

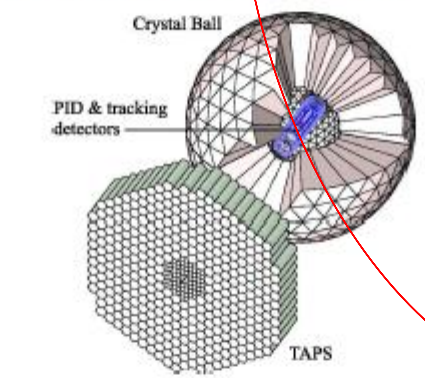


hadroproduction

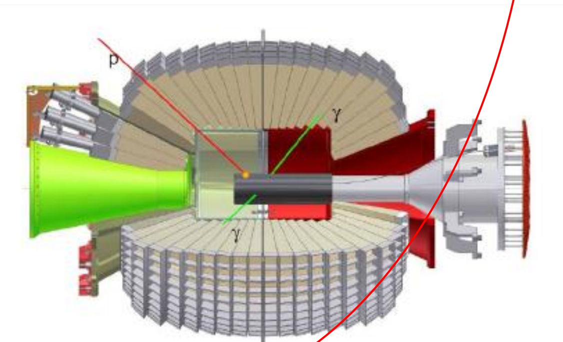
High energy η-facility

photoproduction

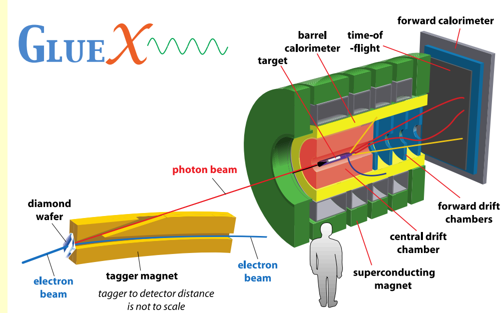
Crystall Ball at MAMI



CBELSA/TAPS at ELSA

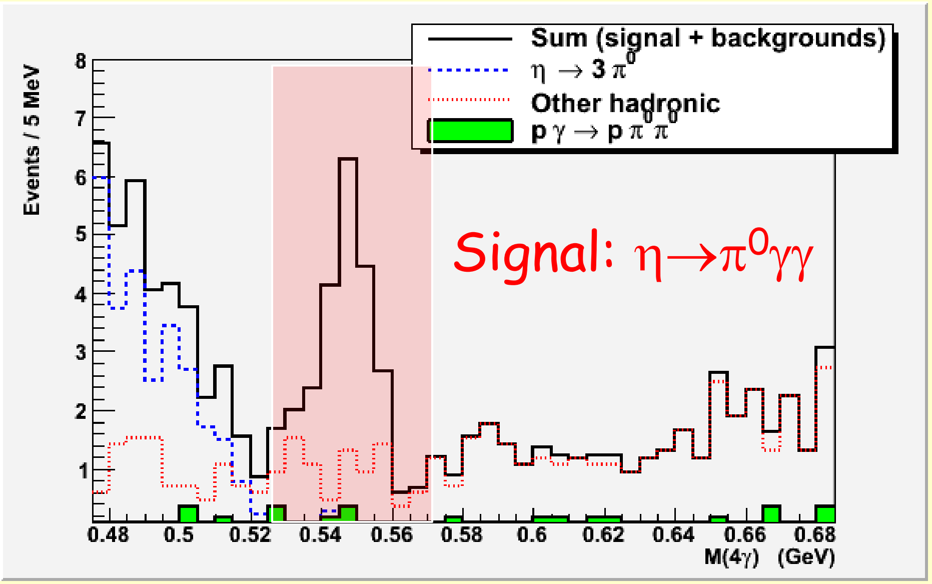


JEF at Jlab



Filter Background with η Energy Boost

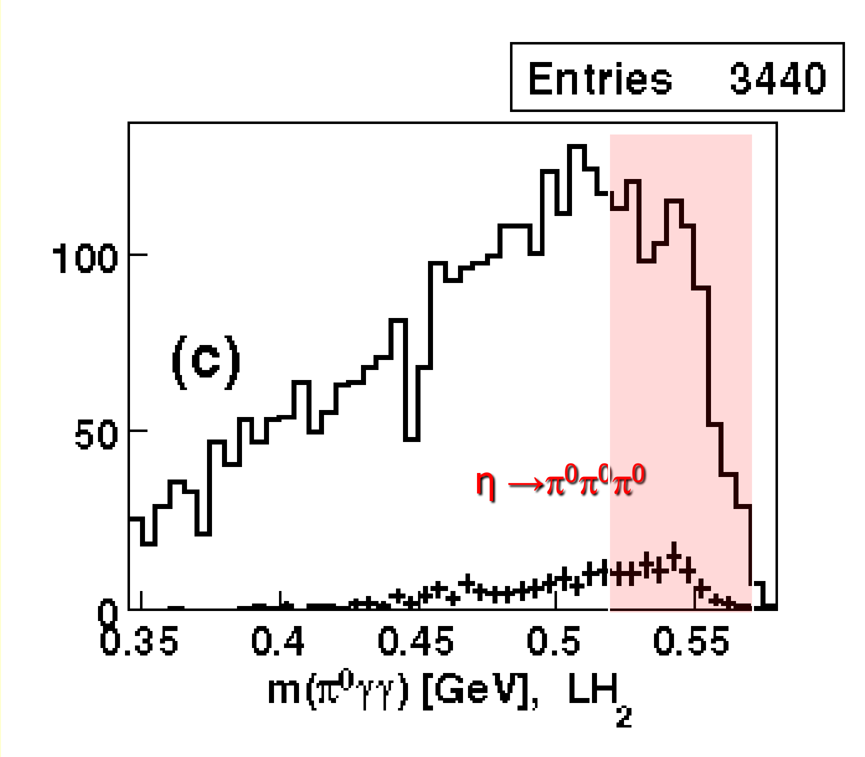
Jlab: high energy η production (E_γ = 9-11.7 GeV)



Note:

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

Other competitors (CB, KLOE, BES-III, WASA, CBELSA/TAPS) : low energy η production



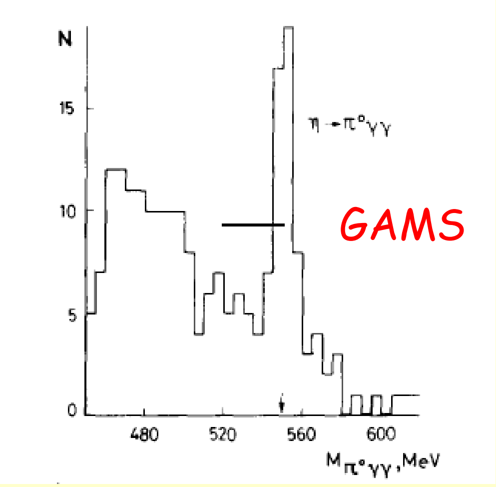
S. Prakhov *et al. Phy.Rev.,C78,015206 (2008)*

Advantages of JLab

- **High energy tagged photon beam** to reduce the background from $\eta \to 3\pi^0$
  - Lower relative threshold for γ-ray detection
  - Improved missing energy resolution
- **Recoil proton detection** to reduce non-coplanar backgrounds like non-resonant $\gamma p \to \pi^0\pi^0 p$
- **High resolution, high granularity $PbWO_4$ Calorimeter**
  - improved invariant mass, energy and position resolutions
  - fewer overlapping showers, thus reducing background from $\eta \to 3\pi^0$
  - Fast decay time (~20ns) and Flash ADCs → reduced pile-up
- **High statistics** to provide a precision measurement of Dalitz plot

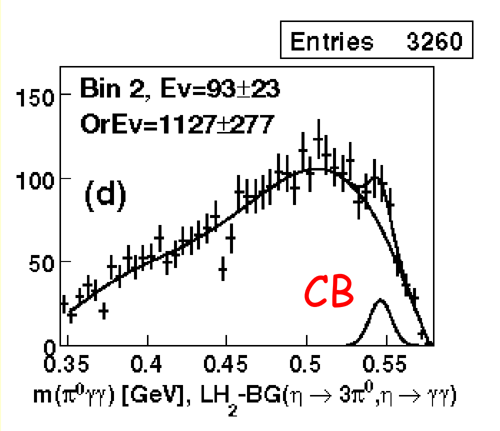
High energy η-production

$E_\pi = 30$ GeV/c



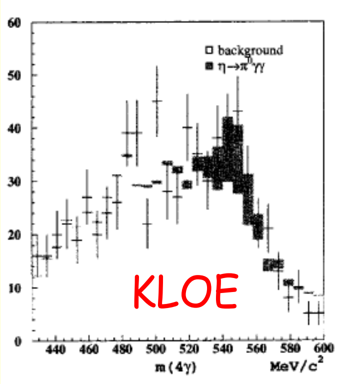
Low energy η-production

$E_\pi = 720$ MeV/c



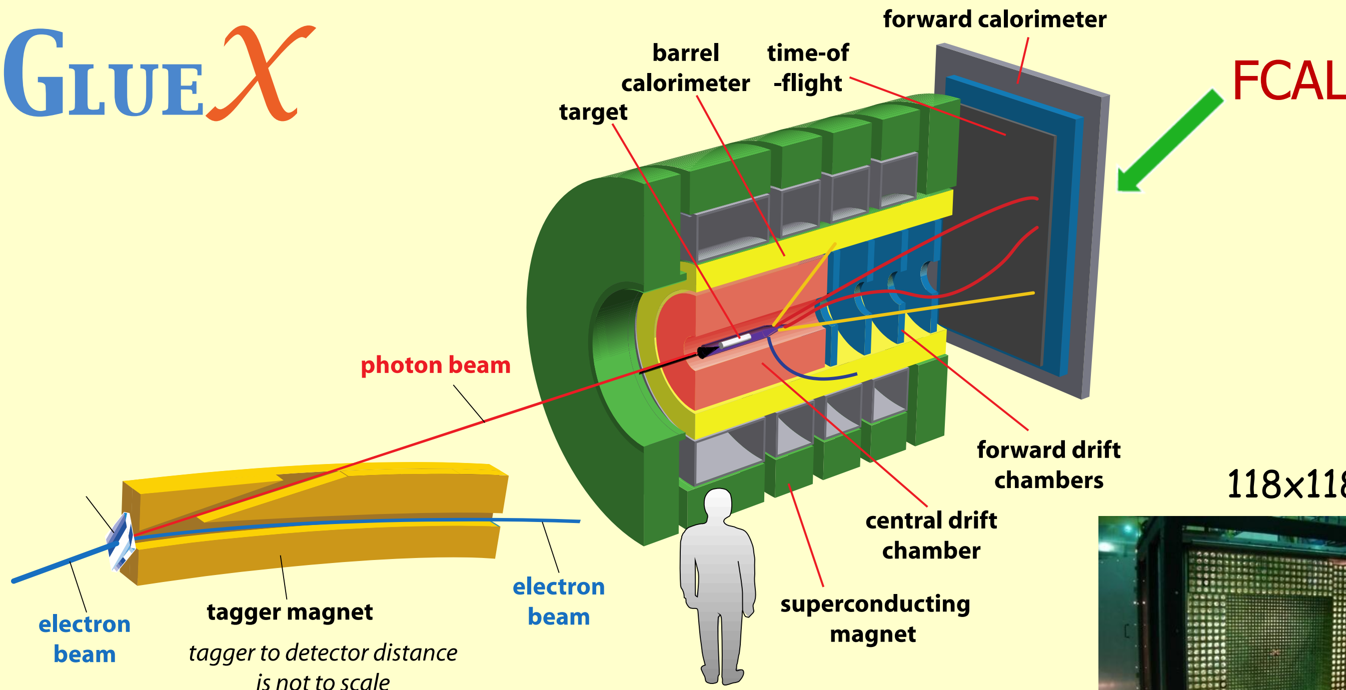
ϕ production $\sqrt{s} = 1020$ MeV

$\phi \to \gamma\eta$

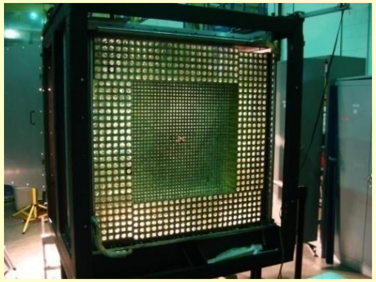


Proposed JEF Experiment in Hall D

GlueX



118×118 cm^2



Simultaneously measure the $\eta \to \pi^0\gamma\gamma$, $\eta \to \pi^0\pi^0$, $\eta \to 3\gamma$

- η produced on LH_2 target with **9-11.7 GeV tagged photon beam:** $\gamma+p \to \eta+p$
- Further reduce $\gamma p \to \pi^0\pi^0 p$ and other background by **detecting recoil p's** with GlueX detector
- Upgraded Forward Calorimeter with **$PbWO_4$** (**FCAL-II**) to detect multi-photons from the η decays

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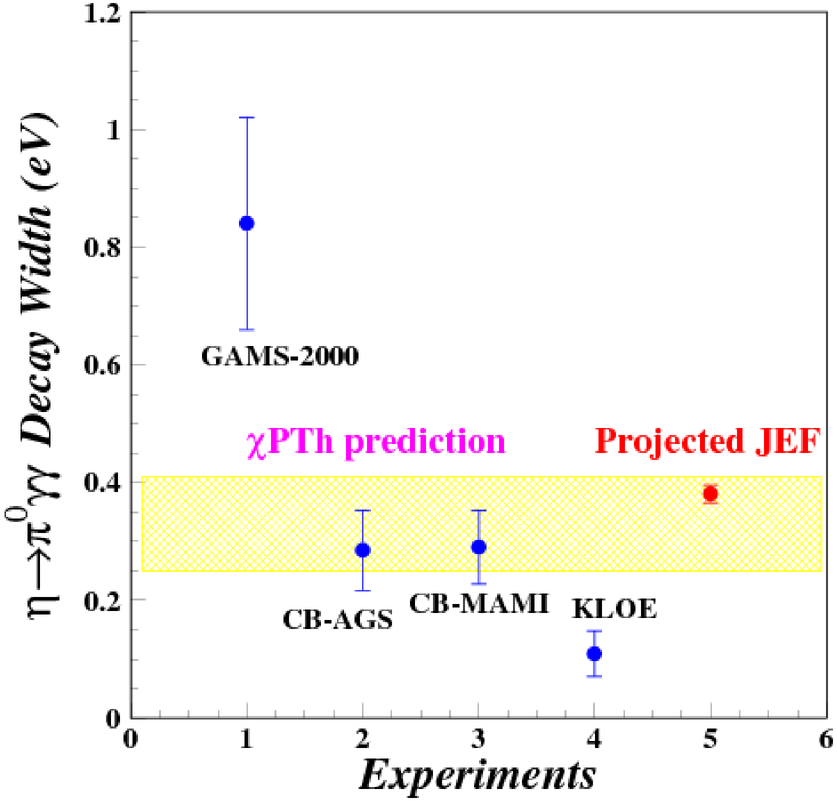
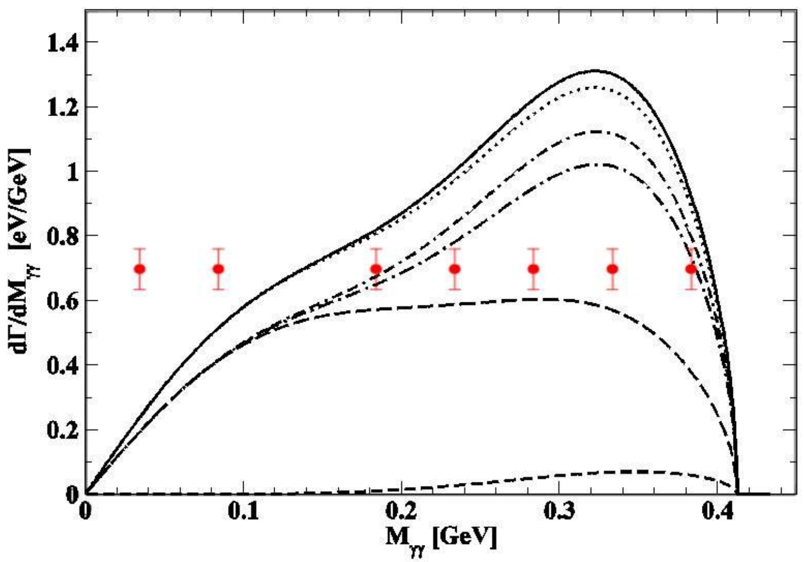
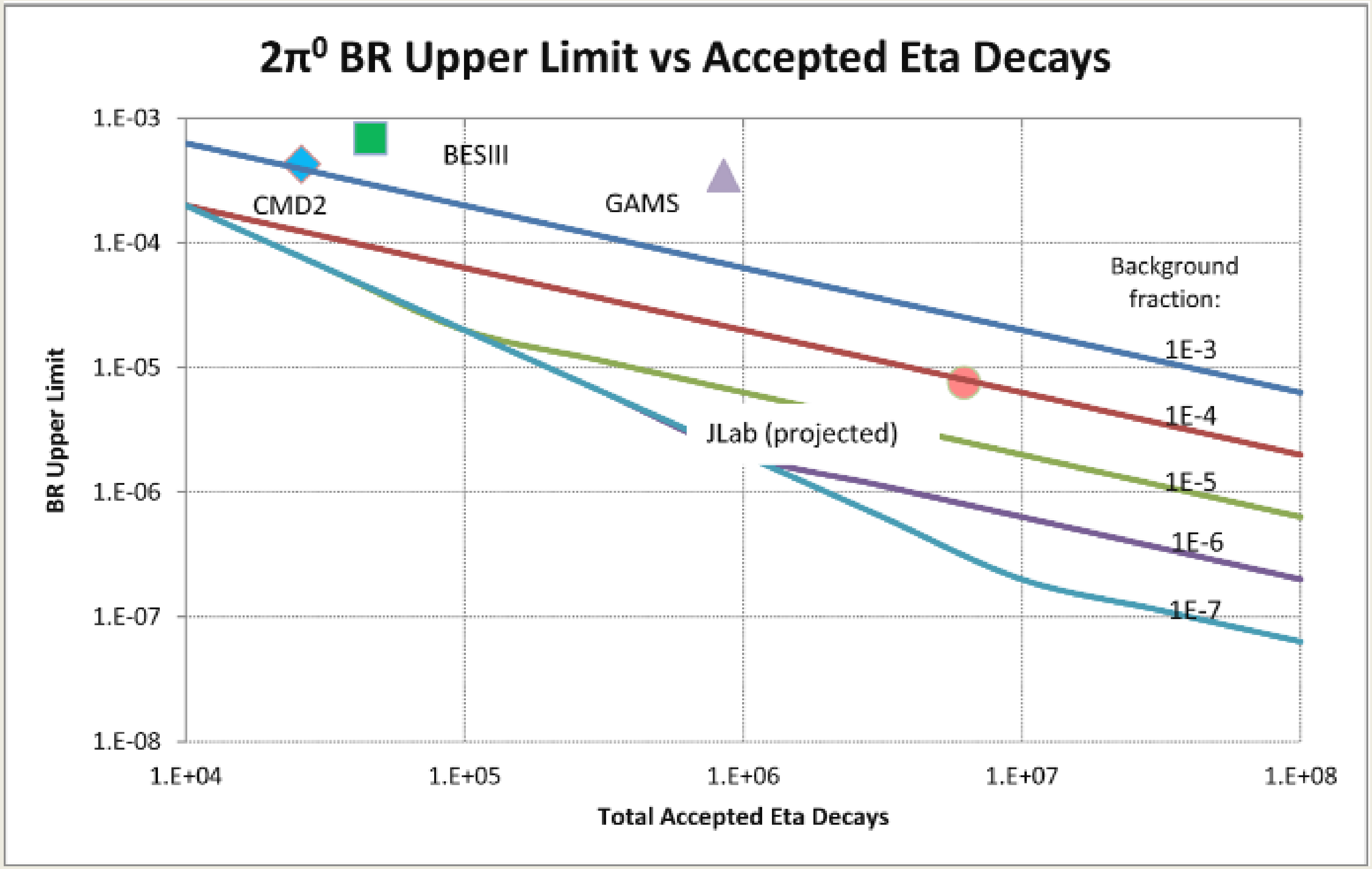
Projected JEF Measurement on $\eta \rightarrow \pi^0 2\gamma$





100 days of beam time

Improvement on SM Forbidden Channels



The upper limit for the branching ratio at ~90% CL is estimated by:

$$\text{BR upper limit} \approx 2\sqrt{\frac{f_{bkg}}{N_{\eta} \bullet \varepsilon_{accep}}}$$

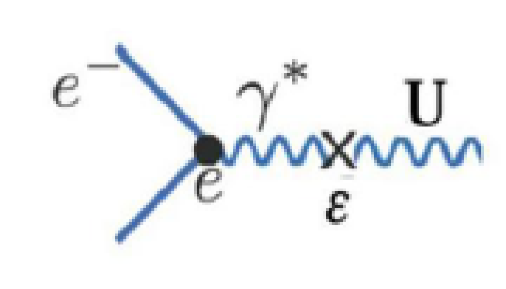
Improve the upper limits on the SM forbidden neutral decay channels by a factor of 1-1.5 orders of magnitude !

Neutral Vector U Boson (Dark Photon)

M.Reece, L.T.Wang, JHEP 07 (2009) 051

- Dark photon, a_u of $U(1)_{d,}$ couples to the SM photon by gauge kinetic mixing with $U(1)_Y$ of the SM:

$$\mathcal{L}_{\rm kin-mix} = -2\epsilon F_d^{\mu\nu} F_{\mu\nu}.$$



$$\varepsilon \propto 10^{-3} \text{ or less}$$

- Dark photon, a_u of $U(1)_{d,}$ coupling to SM weak currents is suppressed by m_U^2 / m_Z^2, $m_U \sim 1$ MeV - few GeV

- $U(1)_d$, is spontaneously broken, therefore U-boson has mass of $m_U \sim 1$ MeV - few GeV

U in Meson Decays

M.Reece, L.T.Wang, JHEP 07 (2009) 051

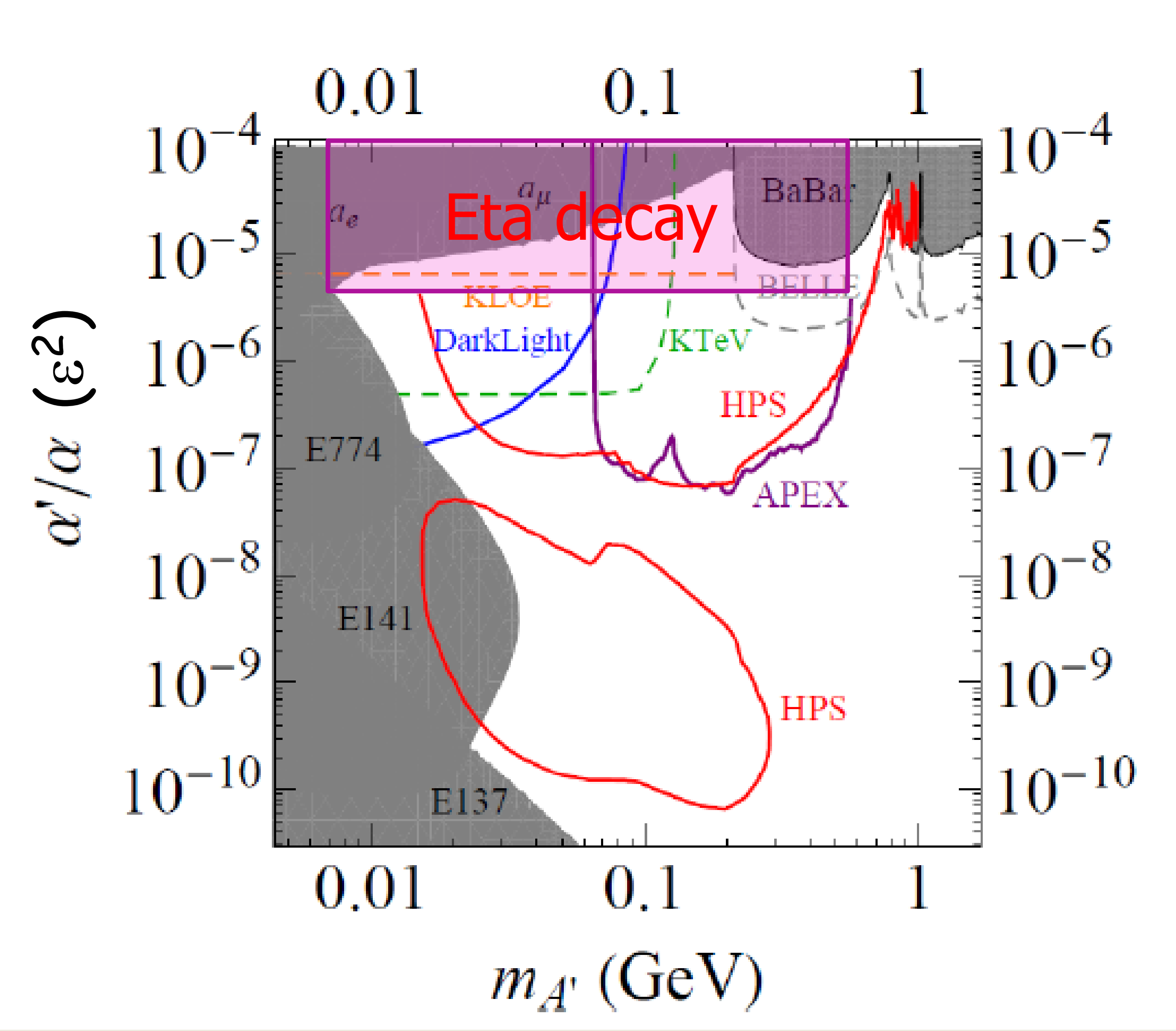
$X \rightarrow YU$, Followed by U $\rightarrow e^+e^-$

For $S/\sqrt{B} = 5$

$X \to YU$	n_X	$m_X - m_Y$ (MeV)	$\mathrm{BR}(X \to Y + \gamma)$	$\mathrm{BR}(X \to Y + \ell^+\ell^-)$	$\epsilon \leq$
$\eta \to \gamma U$	$n_\eta \sim 10^7$	547	$2 \times 39.8\%$	6×10^{-4}	2×10^{-3}
$\omega \to \pi^0 U$	$n_\omega \sim 10^7$	648	8.9%	7.7×10^{-4}	5×10^{-3}
$\phi \to \eta U$	$n_\phi \sim 10^{10}$	472	1.3%	1.15×10^{-4}	1×10^{-3}
$K_L^0 \to \gamma U$	$n_{K_L^0} \sim 10^{11}$	497	$2 \times (5.5 \times 10^{-4})$	9.5×10^{-6}	2×10^{-3}
$K^+ \to \pi^+ U$	$n_{K^+} \sim 10^{10}$	354	-	2.88×10^{-7}	7×10^{-3}
$K^+ \to \mu^+ \nu U$	$n_{K^+} \sim 10^{10}$	392	6.2×10^{-3}	7×10^{-8} [2]	2×10^{-3}
$K^+ \to e^+ \nu U$	$n_{K^+} \sim 10^{10}$	496	1.5×10^{-5}	2.5×10^{-8}	7×10^{-3}

Table 1. Reach in U-boson coupling in several competitive meson decay channels, assuming branching ratios to e^+e^-, $\mu^+\mu^-$ are similar if allowed by phase space. We take $m_U = 250$ MeV for this table. $m_X - m_Y$ is the largest m_U which can be probed in a particular channel, although reach will certainly reduce near kinematical boundary. Only $m_X - m_Y > 200$ MeV included. We elaborate on the treatment of the Kaon decay channels and discuss the decays of J/ψ and Υ in the text. Unless stated otherwise, the branching ratios are taken from the meson summary tables in ref. [40].

Experimental Sensitivity



Summary

- Testing the symmetries of SM will help us understanding fundamental issues in physics: confinement QCD and new physics beyond Standard Model.

- The PrimEx experiments will provide precision tests of continuous symmetries in confinement QCD by a study of electromagnetic properties of π^0, η and η' via the Primakoff effect.

- Measurements of various η rare decays with GlueX will be sensitive probes for testing the discrete symmetries of SM and searching for the evidences of new physics beyond: (1) test higher order χPTh and future lattice QCD predictions; (2) tighten the constrains on new sources of C, P and CP symmetry violations; (3) investigate the dark photon.

- Jlab offers great opportunities for precision experiments.

The End

Thanks you!