Test of discrete symmetries with the WASA detector at COSY

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II SYMPOSIUM ON APPLIED NUCLEAR PHYSICS AND INNOVATIVE TECHNOLOGIES
September 24 - 27, 2014, Collegium Maius Jagiellonian University, Kraków, Poland
JAGIELLONIAN UNIVERSITY IN KRAKOW
FNP Foundation for Polish Science
KNOW

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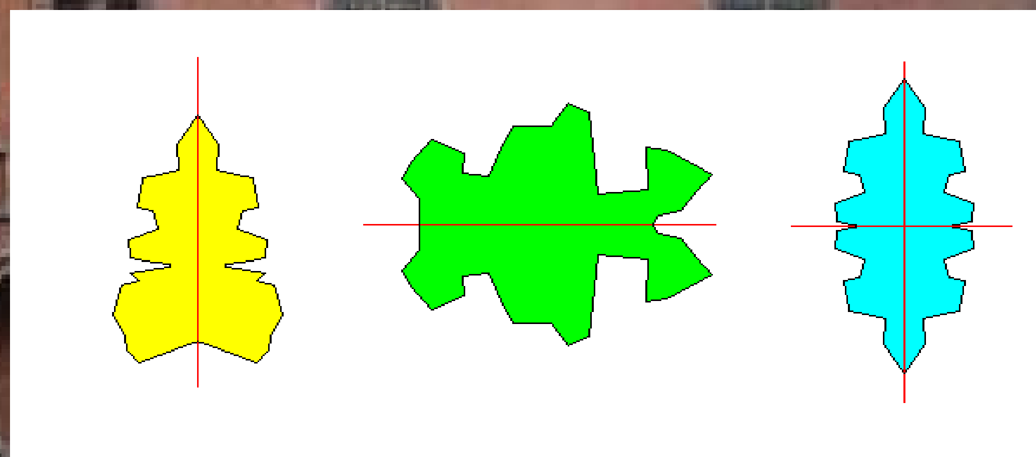
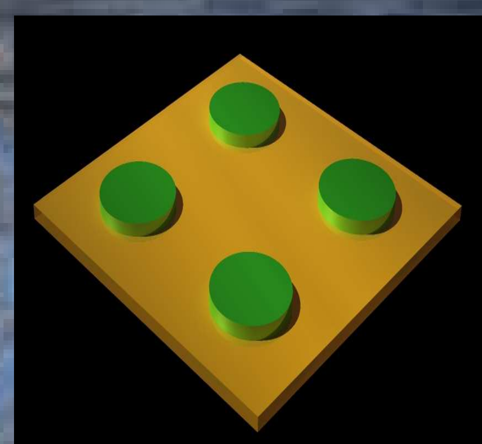
Discrete Symmetry ≡

Symmetry describing non-continuous changes in a system





A.Ferrando, M.A.Garcia-March, Journal of Optics (2014)

Discrete Symmetry ≡

Symmetry describing non-continuous changes in a system

Examples from Particle Physics (in this talk):

C   Charge Conjugation Symmetry

CP combined C and P(arity) Symmetry

(Rare) Decays of light mesons and symmetries

Rare decays are rare since

- Standard Model mechanisms are small
- symmetries are violated

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Rare decays are rare since

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$\Rightarrow$ window for searches for new physics beyond the SM

...this means searches for

- rare or forbidden decays
- asymmetries between decay particles in not-so-rare decays
- light dark-matter particles

A. Kupsc, A. Wirzba,
DISCRETE 2010, J Phys Conf Ser 335 (2011) 012017

Facilities

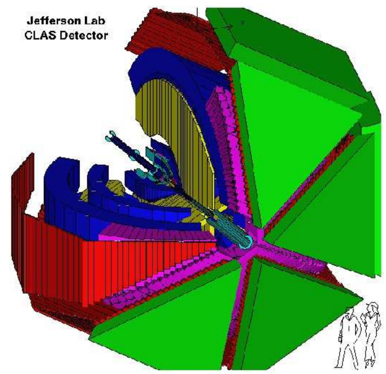
photoproduction

fixed target experiments

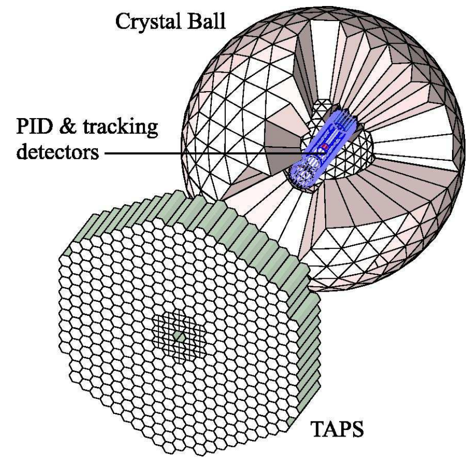
hadroproduction

e^+e^- collider

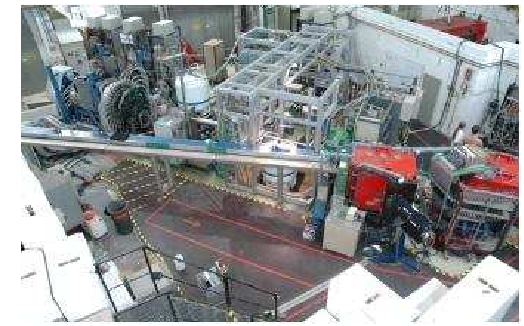
CLAS at JLAB



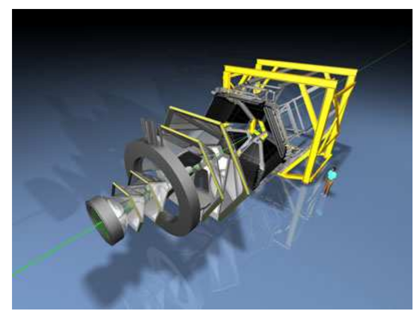
Crystal Ball at MAMI



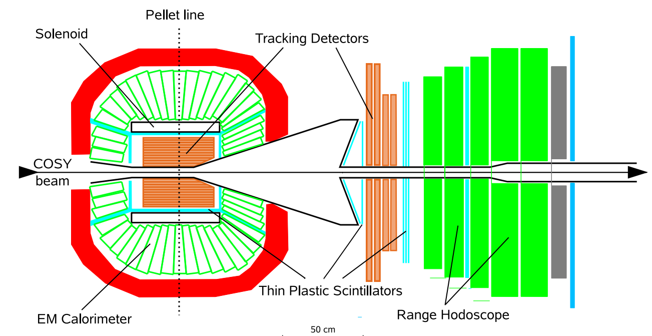
Crystal Barrel at ELSA



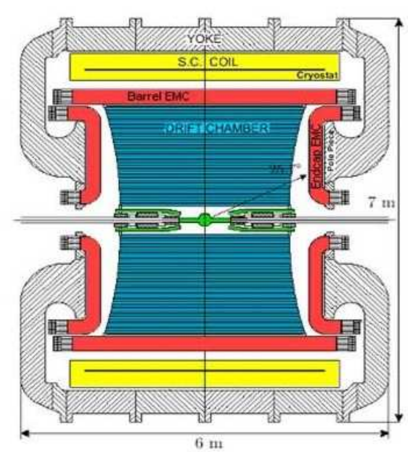
HADES at GSI



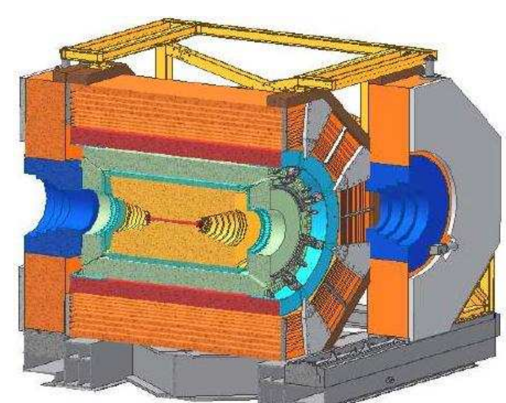
WASA at COSY



KLOE-2 at DAϕNE



BESIII at BEPCII



Charge Conjugation Symmetry (C parity)

- C operator ≡ full switch in sign of **all** additive quantum numbers
  (baryon number, lepton number, isospin, strangeness, charm, ..., charge)
- other quantities remain unchanged
  (mass, momentum, spin)
- transforms particles into antiparticles
  ($C|e^-\rangle = |e^+\rangle$; $C|\pi^-\rangle = |\pi^+\rangle$; $C|p\rangle = |\bar{p}\rangle$)
- eigenstates: only neutral particles or particle-antiparticle systems
  ($C|\eta\rangle = |\eta\rangle$; $C|\pi^0\rangle = |\pi^0\rangle$; $C|\gamma\rangle = -|\gamma\rangle$; $C|e^+e^-\rangle = (-1)^{L+S}|e^-e^+\rangle$)

C parity is violated in weak interactions, but (believed to be) conserved in strong and electromagnetic interactions

What is special about the η meson?

- heaviest of octet Goldstone bosons $\Rightarrow$ many open decay channels

- mass and all interactions vanish in the chiral limit
  $\Rightarrow$ basis for effective field theory approach (ChPT)

- eigenstate of P, C, CP, and G, $I^G(J^{PC}) = 0^+(0^{-+})$
  $\Rightarrow$ first order strong and electromagnetic decays forbidden
  $\Rightarrow$ laboratory to study (non-)conservation of these discrete symmetries

Tests of C symmetry in rare η decays

η decays into neutrals with an odd number of photons

- simplest case: $\eta \to 3\gamma$

  $\eta \to \gamma + (\gamma\gamma)_{J=0}$ forbidden for real γ ($0 \to 0$ transition)

  $\eta \to \gamma + (\gamma\gamma)_{J=1}$ forbidden by Bose symmetry

  $\Rightarrow$ each $(\gamma\gamma)$ pair hase to have at least J=2

  $BR(\eta \to 3\gamma) \leq 1.6 \times 10^{-5}$

  KLOE PLB 591 (04) 49

- $\eta \to \pi^0\gamma$ $0 \to 0$ transition

  $BR(\eta \to \pi^0\gamma) \leq 9 \times 10^{-5}$

  Crystal Ball PRC 72 (05) 035212

- $\eta \to \pi^0\pi^0\gamma,\ \eta \to 3\pi^0\gamma, \ldots$

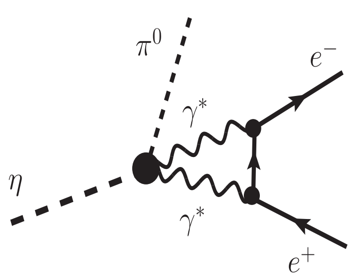
η decays into neutrals with an odd number of l^+l^-

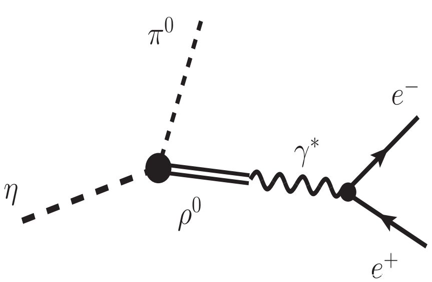
- $\eta \to \pi^0 e^+ e^-$

Tests of C symmetry in rare η decays

η decays into neutrals with an odd number of $l^+ l^-$

Standard Model C conserving contribution:

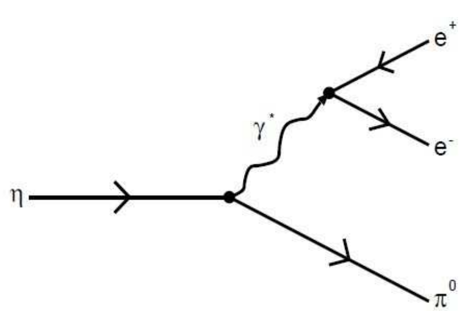




$BR(\eta \to \pi^0 e^+ e^-) \approx 1.1 \times 10^{-8}$

T.P.Cheng, PR 162 (67) 1734

C invariance violating process:



experiment:

$BR(\eta \to \pi^0 e^+ e^-) \leq 4.5 \times 10^{-5}$

M.R.Jane et al., PLB 59 (75) 99

PDG:

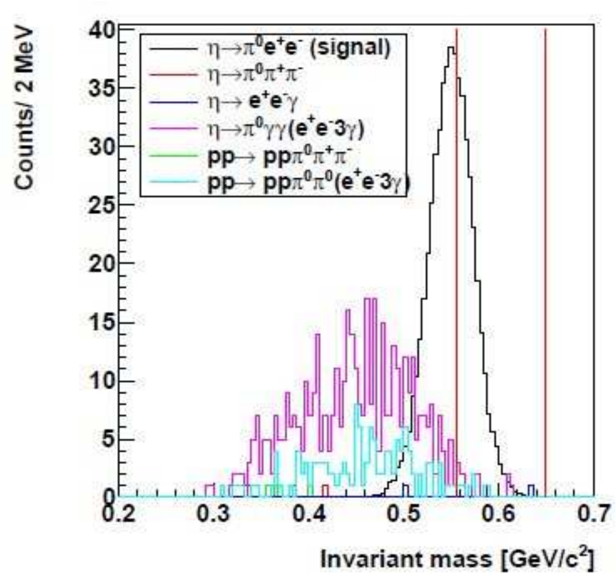
$BR(\eta \to \pi^0 e^+ e^-) \leq 4.0 \times 10^{-5}$

$\eta \to \pi^0 e^+ e^-$ with WASA-at-COSY

M. Zielinski, PhD thesis, arXiv: 1301.0098 [hep-ex]

invariant mass of $\pi^0 e^+ e^-$

simulation:



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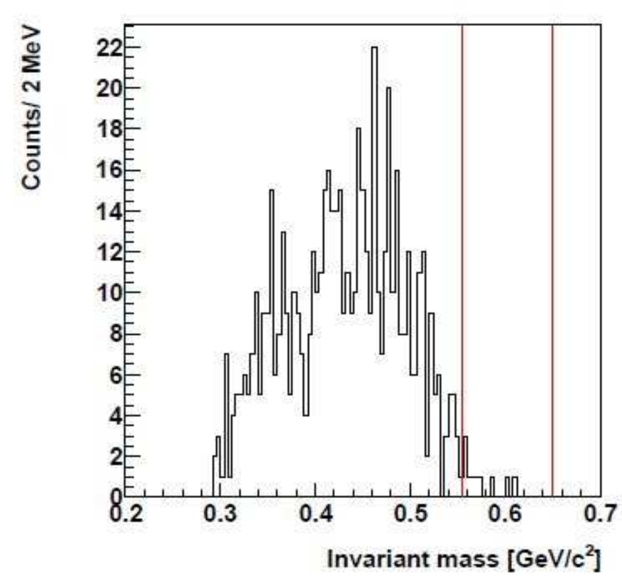

Standard Model prediction:

$BR(\eta \to \pi^0 e^+ e^-) \approx 1.1 \times 10^{-8}$

PDG:

$BR(\eta \to \pi^0 e^+ e^-) \leq 4.0 \times 10^{-5}$

this work:

$BR(\eta \to \pi^0 e^+ e^-) \leq 3.7 \times 10^{-5}$

⇒ new upper limit below present PDG value

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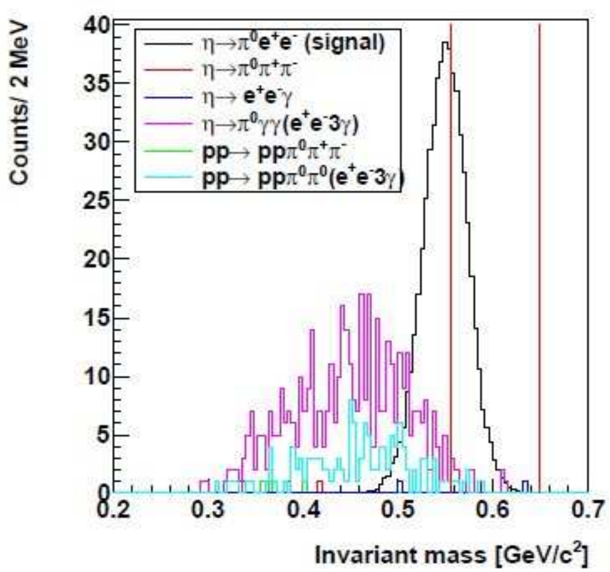

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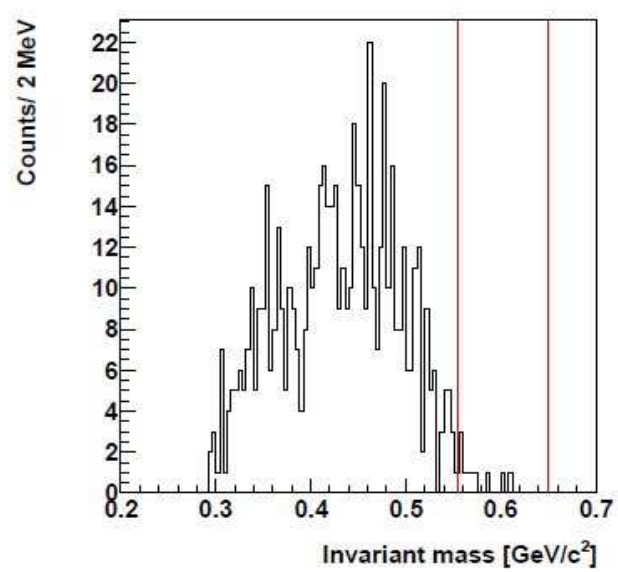

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this work:

$BR(\eta \to \pi^0 e^+ e^-) \leq 3.7 \times 10^{-5}$

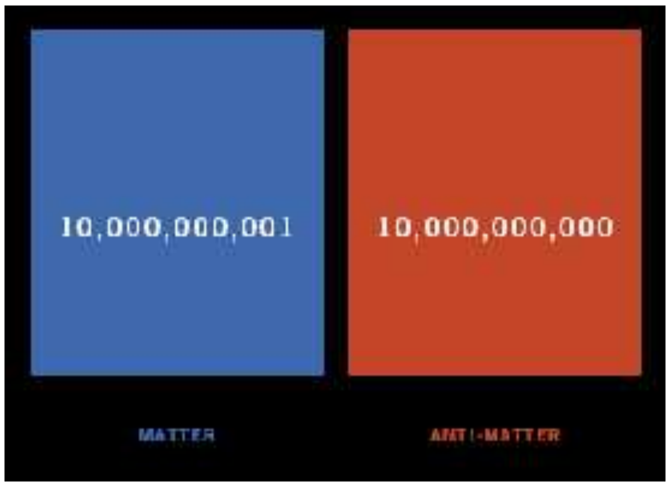
⇒ new upper limit below present PDG value

and: result based only on few per cent of the available data

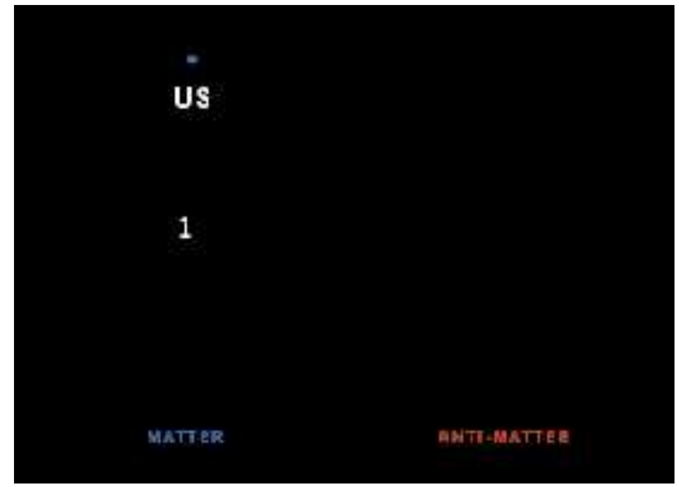
⇒ WASA data should reach one order of magnitude lower

CP symmetry and Matter-Antimatter asymmetry

early universe



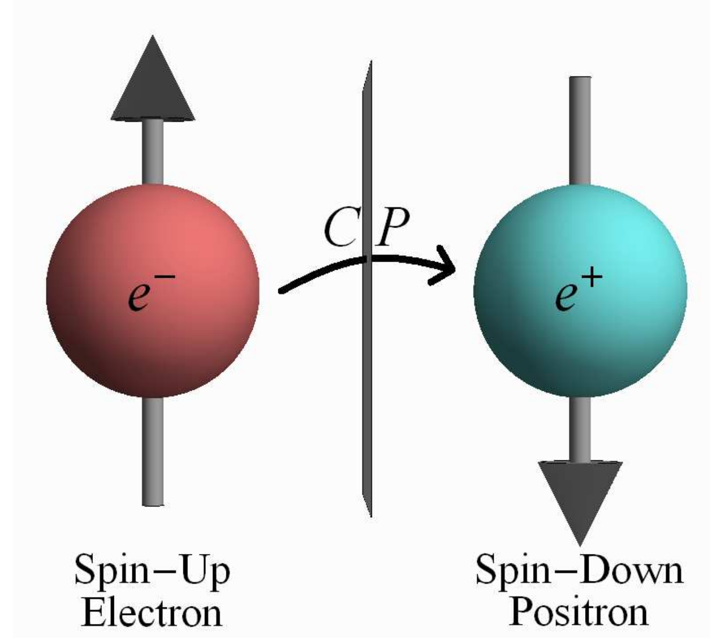
today



Sakharov conditions (1967)

1. baryon number violation
2. C and CP violation
3. departure from thermodynamic equilibrium

CP violation in K_L decays (1964)



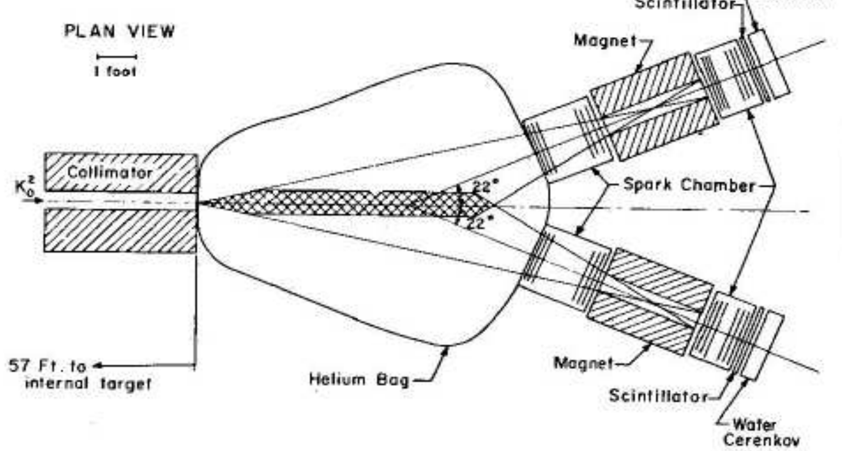
- Non-strange particles: $(\pi,\rho,\ldots)_{I=1}: u\bar{d},\ (u\bar{u}-d\bar{d})/\sqrt{2}$; $(\eta,\omega,\ldots)_{I=0}: (u\bar{u}+d\bar{d})/\sqrt{2}+\ldots$ — Neutral particles are eigenstates of C operator
- Strange particles: $(K,K^*,\ldots)_{I=1/2}: K^+=u\bar{s},\ K^-=\bar{u}s,\ K^0=d\bar{s},\ \bar{K}^0=\bar{d}s$ — Neutral strange particles are not eigenstate of C operator

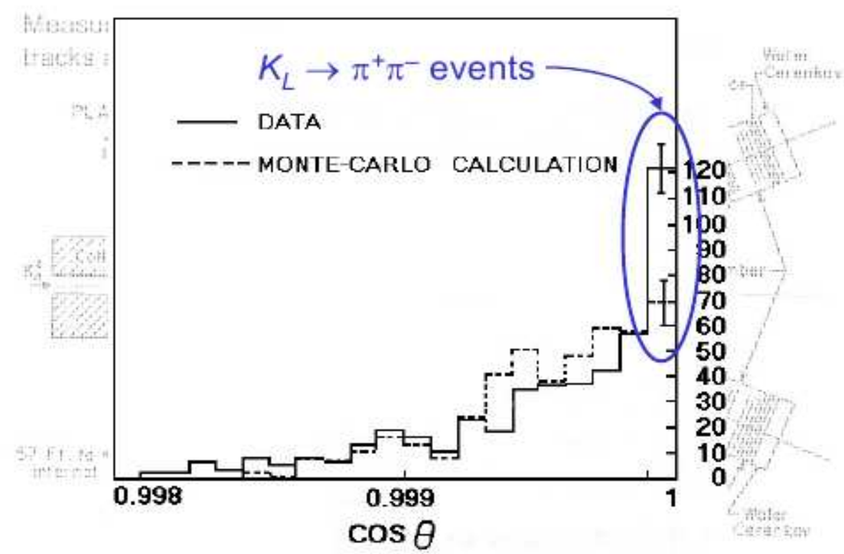
experimentally observed: short- and long-lived neutral states K_S and K_L

- Their observed pionic decays are: $K_S \to (\pi\pi)^0$ and $K_L \to (\pi\pi\pi)^0$
- And it was believed that: $CP|K_S\rangle = +|K_S\rangle$ and $CP|K_L\rangle = -|K_L\rangle$

Cronin, Fitch et al. observe the CP violating $K_L \to \pi^+\pi^-$ decay

Measurement of opening angle of pion tracks and their invariant mass:





CP violation in the Standard Model

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$\Rightarrow$ CP violation in flavour changing weak processes

$\Rightarrow$ included in the Standard Model by Cabibbo-Kobayashi-Maskawa formalism

but: amount of CP violation is too small to explain the observed matter-antimatter asymmetry

$\Rightarrow$ **search for additional sources of CP violation**

Tests of CP symmetry in η decays

- Mostly modeled in anology to K_L decays

- Flavor conserving
  → not constrained by CKM mechanism

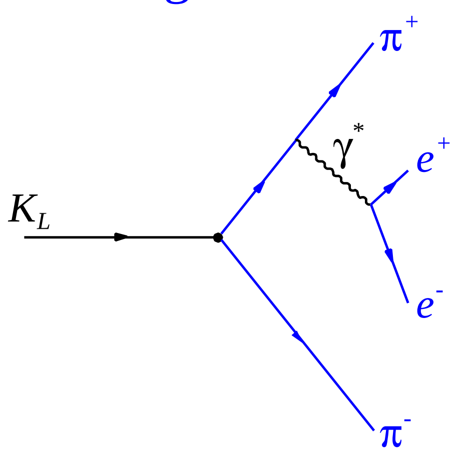
- Search scenarios:
  - rare decays, which would be forbidden if CP exact symmetry
  - asymmetries among decay products in not-so-rare decays

CP violation in $K_L \to \pi^+\pi^-e^+e^-$

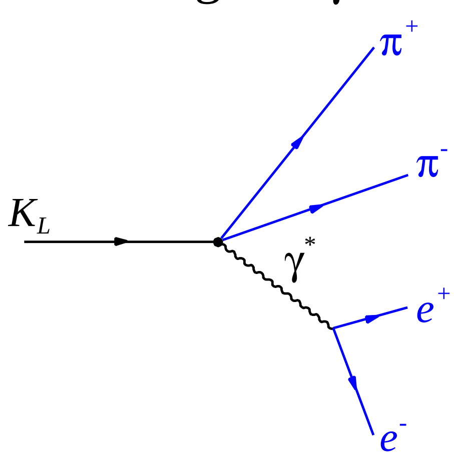
L.M. Sehgal, M. Wanninger, PRD 46 (1992) 1035
P. Heiliger, L.M. Sehgal, PRD 48 (1993) 4146

dominant amplitudes

CP violating bremsstrahlung



CP conserving M1 γ emission



interference of amplitudes

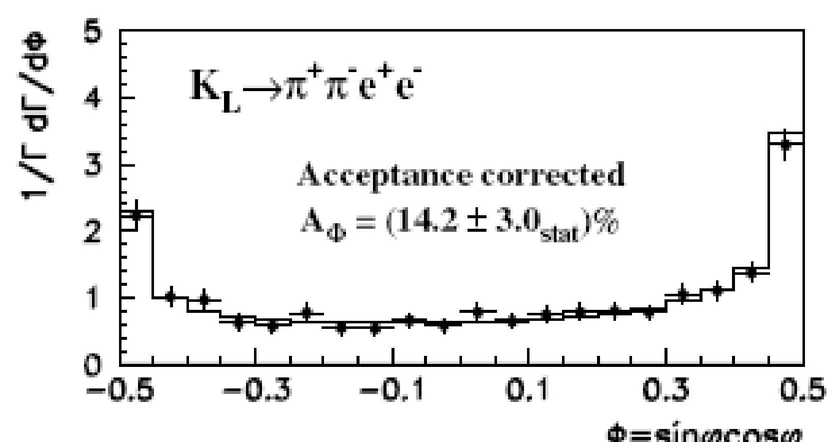
⇒ CP violating linear photon polarisation

⇒ CP violating asymmetry in $\sin\varphi\cos\varphi$

$\varphi = \angle\,(\pi^+\pi^-), (e^+e^-)$ planes in K_L cms

$$A_\phi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$

NA48 result   A. Lai et al., EPJC 30 (2003) 33



CP violation in $\eta \to \pi^+\pi^- e^+e^-$

C.Q.Geng, J.N.Ng, T.H.Wu, MPLA 17 (2002) 1489
D.N.Gao, MPLA 17 (2002) 1583

dominant amplitudes

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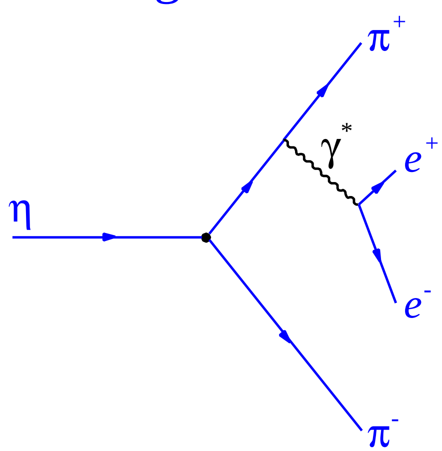
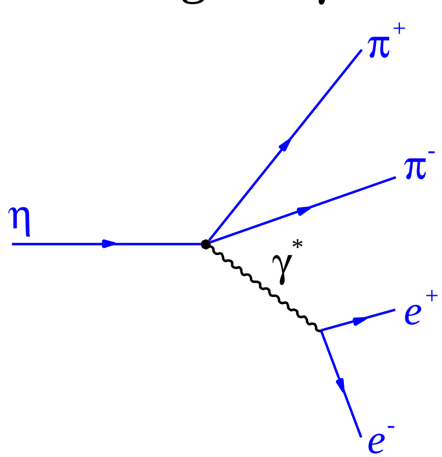


Standard Model constraint from BR($\eta \to \pi^+\pi^-$):

experimental upper bound $\Rightarrow A_\phi < 10^{-4}$

theoretical prediction $\Rightarrow A_\phi \sim 10^{-15}$

CP conserving M1 γ emission



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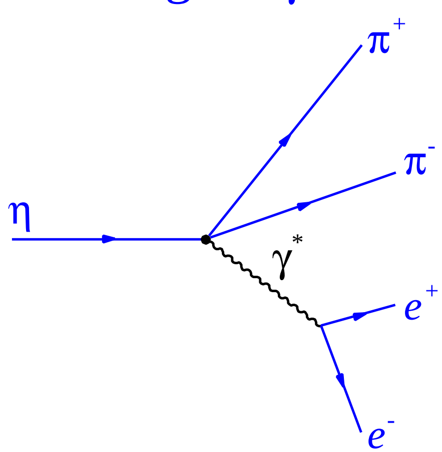

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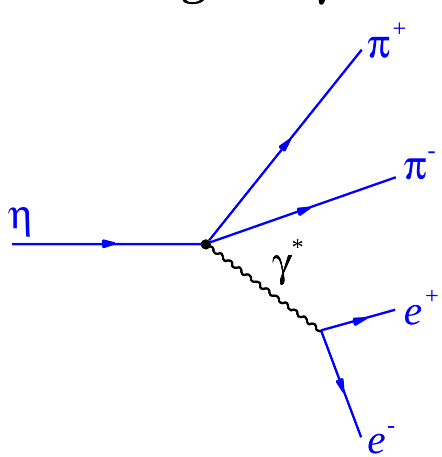

interference of amplitudes

$\Rightarrow$ CP violating linear photon polarisation

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$\varphi = \angle\,(\pi^+\pi^-), (e^+e^-)$ planes in η cms

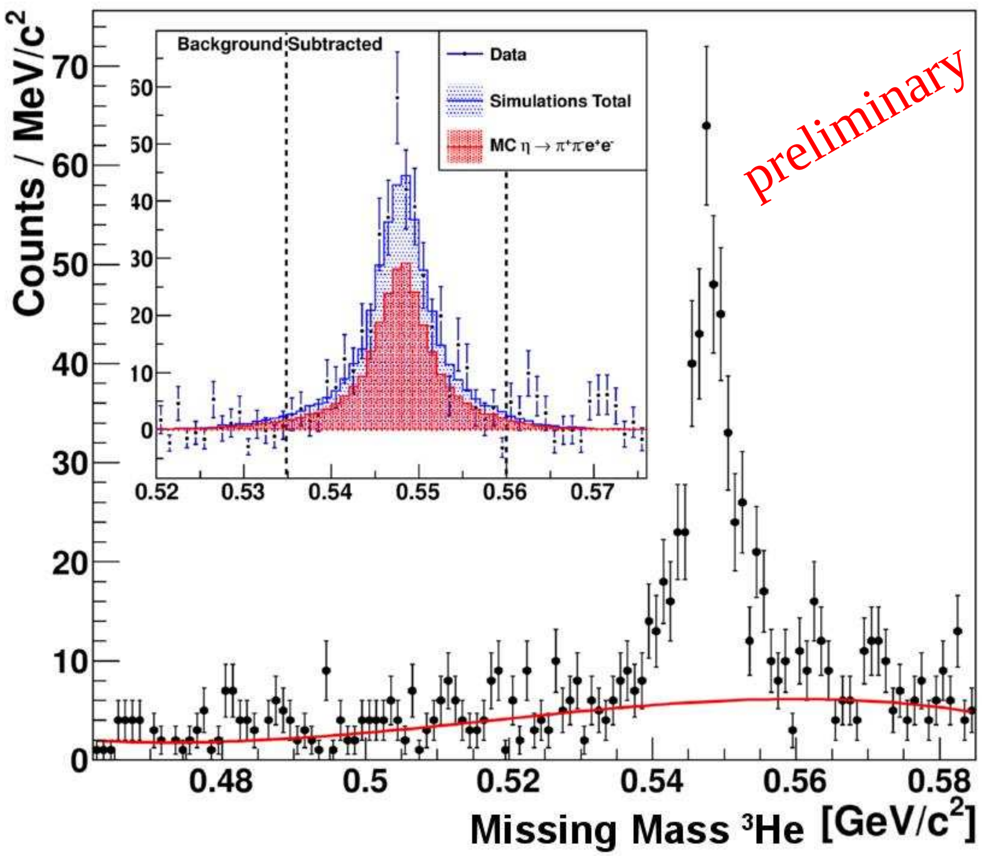
$$A_\phi = \frac{N_{\sin\varphi\cos\varphi>0} - N_{\sin\varphi\cos\varphi<0}}{N_{\sin\varphi\cos\varphi>0} + N_{\sin\varphi\cos\varphi<0}}$$

$\Rightarrow$ construct operators, that do not contribute directly to $\eta \to \pi^+\pi^-$ and K^0 decays

$\Rightarrow$ flavor conserving CP violating four-fermion operators involving two s-quarks

A_ϕ up to 2%

$\eta \to \pi^+\pi^-e^+e^-$ at WASA

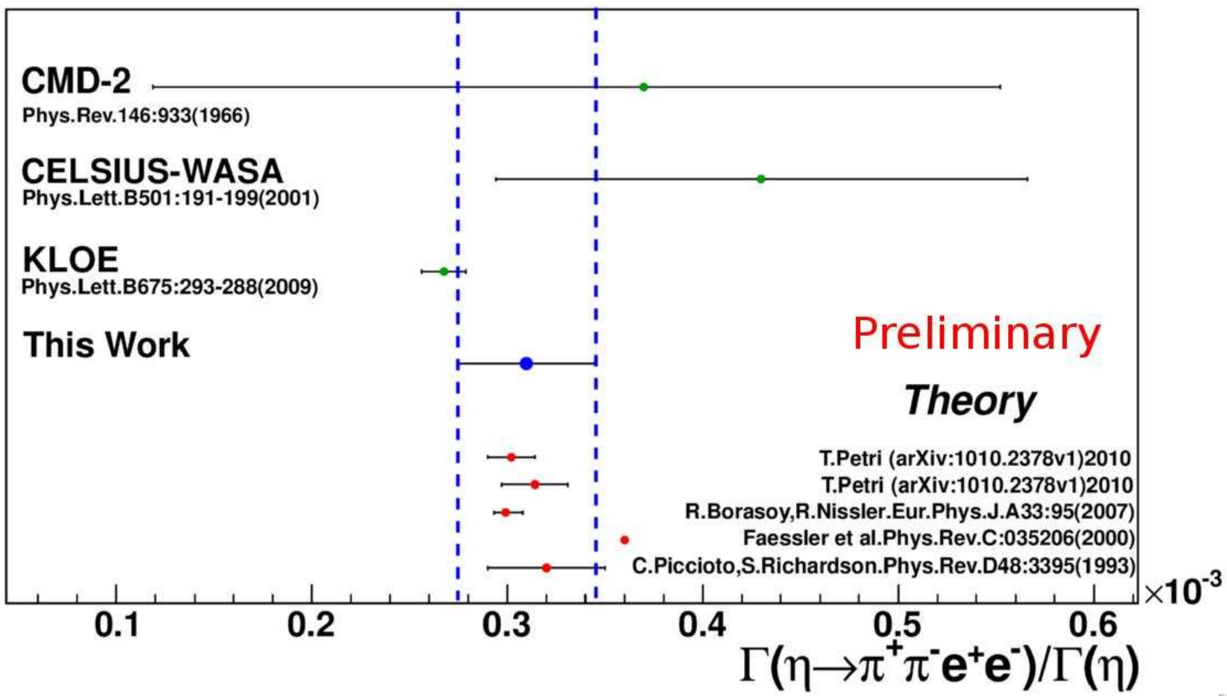


- 3×10^7 tagged $pd \to {}^3He\eta$ events
- $263\pm24_{stat}$ signal events

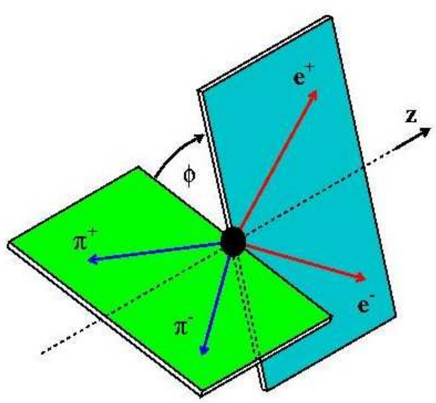
preliminary results: $BR(\eta \to \pi^+\pi^-e^+e^-) = (3.10 \pm 0.27_{stat} \pm 0.22_{sys}) \times 10^{-4}$

$A_\phi = (0.4 \pm 9.0_{stat} \pm 2.8_{sys}) \times 10^{-2}$

$\eta \rightarrow \pi^+\pi^-e^+e^-$



- branching ratio in agreement with previous measurements
- statistics benchmark KLOE: $1555 \pm 53_{stat}$ events

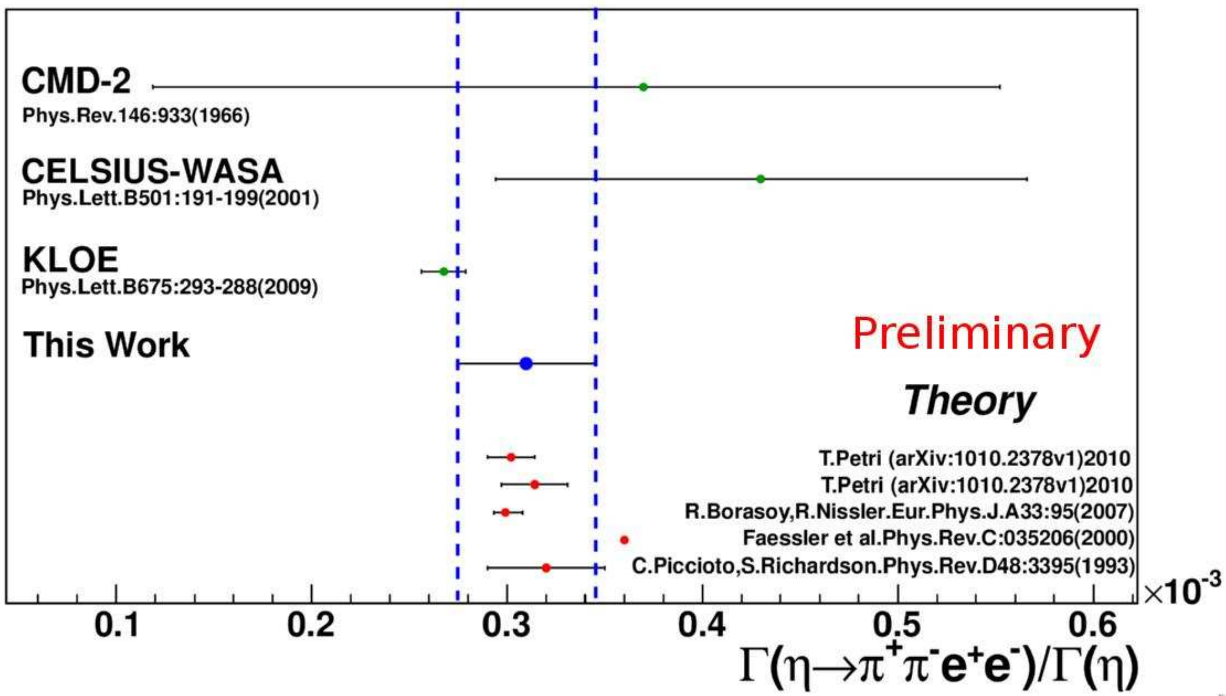


- A_ϕ limited by statistics

KLOE $A_\phi = (-0.6 \pm 2.5_{stat} \pm 1.8_{sys}) \times 10^{-2}$

WASA preliminary $A_\phi = (0.4 \pm 9.0_{stat} \pm 2.8_{sys}) \times 10^{-2}$

$\eta \rightarrow \pi^+\pi^-e^+e^-$



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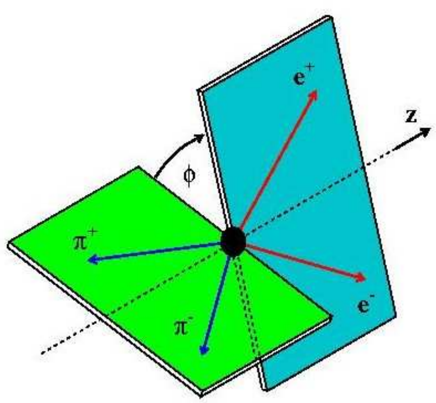

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⇒ one order of magnitude larger statistics in WASA pp data expected

⇒ KLOE-2 is expected to reduce statistical error by a factor of two

CP test without analog in K_L sector: $\eta(') \to 4\pi^0$

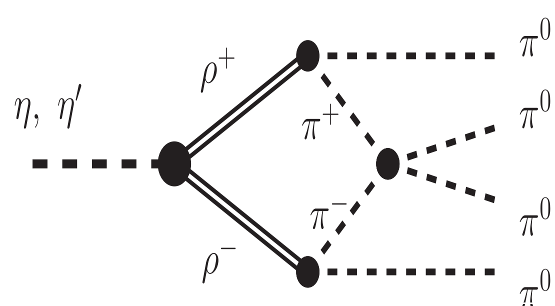
B.M.K.Nefkens (Dubna, 1994), Crystal Ball PRL 84 (00) 4802

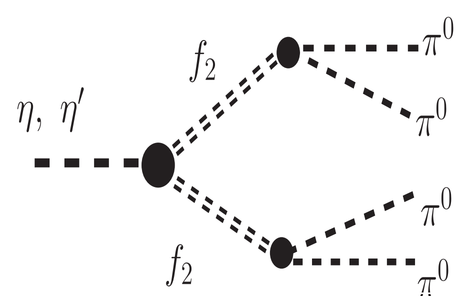
A.Kupsc, A.Wirzba, hep-ph 1103.3860 (DISCRETE 2010)

forbidden by P and CP if all π^0s are in relative s or p-wave

$\eta \to 4\pi^0$: only 7.9 MeV excess energy

$\eta' \to 4\pi^0$: two d-wave π pairs in relative p-wave possible $\to J^{PC} = 0^{-+}$





which are both of order $O(p^{10})$!

F.-K.Guo, B.Kubis, A.Wirzba, PRD 85 (12) 014014

estimates: $BR(\eta \to 4\pi^0) \leq 10^{-10}$ $\quad$ $BR(\eta' \to 4\pi^0) \leq 10^{-8}$

A.Kupsc, A.Wirzba, hep-ph 1103.3860 (DISCRETE 2010)

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experiment: unique 8 photon signal

$\eta \to 4\pi^0$: tiny background from direct π^0 production close to η threshold

present limits: $BR(\eta \to 4\pi^0) \le 6.9 \times 10^{-7}$ $BR(\eta' \to 4\pi^0) \le 3.2 \times 10^{-4}$

Crystal Ball PRL 84 (00) 4802   GAMS-4π 1406.5057 [hep-ex]

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Crystal Ball PRL 84 (00) 4802 GAMS-4π 1406.5057 [hep-ex]

⇧

as yet
highest sensitivity reached
on any η decay mode!

Detection at any level
above limits would signal
CP violation
from new sources!

Test of discrete symmetries with the WASA detector at COSY

Fundamental discrete symmetries can be probed in η decays

Large data samples are available for analysis from WASA-at-COSY and from complementary facilities

More to come in future: results from analysis and data of even larger statistical accuracy

Magnus Wolke