The Next Grand Challenge: Finding $\not{CP}$ in Leptodynamics

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WG3 Subgroup on "$\not{CP}$ with charged leptons" with input from: M. Felcini, W. Fetscher, J. Imazato, M. Roney, J. Kuehn, W. Bernreuther

$\not{CP}$ found in (down-type) quark dynamics

$\not{CP}$ `demystified': phases can be large!

☞ Demystification completed if $\not{CP}$ found also in leptodynamics

☞ Baryogensis from leptogenesis?

Need $\not{CP}$ in leptons!

Importance well recognized as evidenced by

- projects for probing $\not{CP}$ in ν oscillations
- heroic efforts in finding an EDM for the electron

Next best bet:

- $\not{CP}$ in τ decays

More unconventional avenues:

- T *odd* correlation in μ decays
- T *odd* correlation in decays of polarized positronium
- T *odd* correlation in $K \rightarrow \mu\nu\pi/\mu\nu\gamma$ decays

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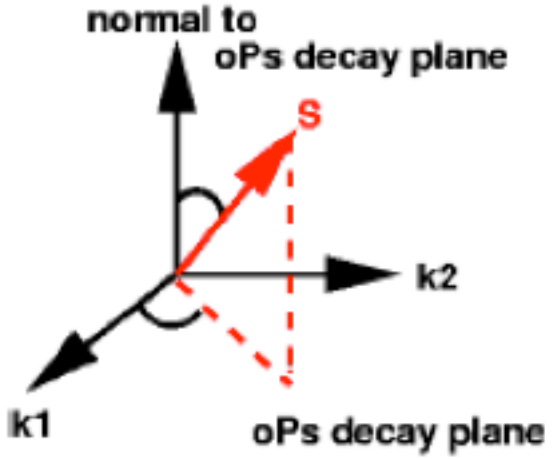
I T *odd* correlation in μ decays (Fetscher)

$\mu \rightarrow e\nu\nu$

ETH-Zuerich-Cracow-PSI Collab.:

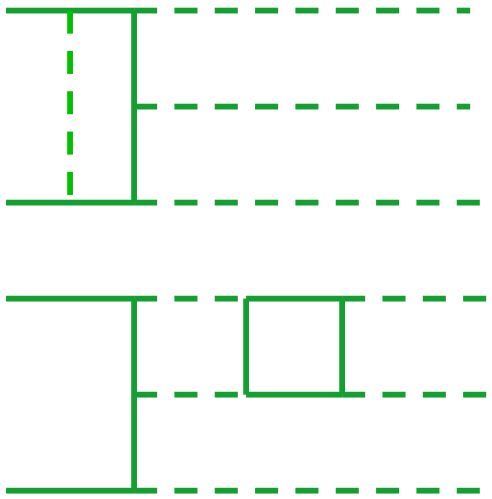
$$|\langle Pol_t^{(e)} \rangle| = |\langle \mathbf{s}^{(e)} \cdot (\mathbf{s}^{(\mu)} \times \mathbf{p}^{(e)}) / |\mathbf{s}^{(\mu)} \times \mathbf{p}^{(e)}| \rangle| = (3.7 \pm 7.7 \pm 3.4) \times 10^{-3}$$

II T *odd* correl. in decays of polarized positronium (+Felcini)



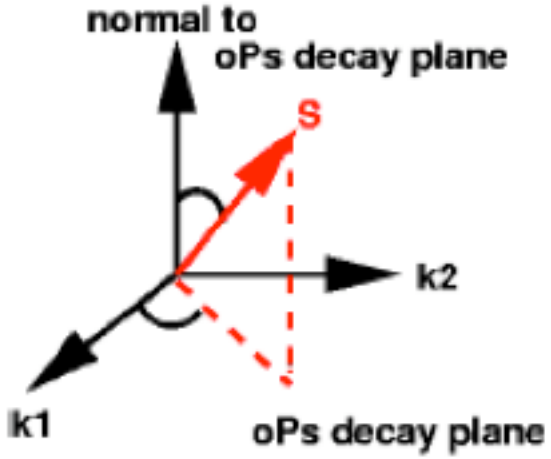
$\langle S\cdot(k_1 \times k_2)/|k_1 \times k_2|\rangle$

- P & CP even
- T odd
- final state interactions can generate T odd moments with T invariant dynamics



$O(\alpha/2\pi) \leq 10^{-3}$ (Bernreuther)

$O(\alpha^2) \sim 5 \times 10^{-5}$



$$(\hat{S}\cdot\hat{k}_1)(\hat{S}\cdot\hat{k}_1\times\hat{k}_2)$$

$$N(\cos\theta) = N_0(1 + C_{CP}\cos\theta)$$

$$\cos\theta \equiv \cos\theta_1 \cos\theta_2$$

- P, T & CP odd

- final state interactions cannot generate CP odd moments with CP invariant dynamics

i.e. bona fide CP violation!

Previous experim. (Skalsey, Van House '91):

$$C_{CP} = -0.0056 \pm 0.0154$$

Suggestion by M. Felcini:

$$\text{Can reach } \Delta C_{CP} = 5 \times 10^{-6}!$$

weak effects ~ $O([G_F(2m_e)^2] \sim 10^{-11}$

interesting New Physics scenarios?

III T *odd* correlation in $K \to \mu\nu\pi/\mu\nu\gamma$ decays (+ Imazato)

$K \to \mu\nu\pi$ $\quad Pol_t(\mu) = \langle \mathbf{s}_\mu \cdot (\mathbf{p}_\mu \times \mathbf{p}_\pi)/|\mathbf{p}_\mu \times \mathbf{p}_\pi| \rangle$ -- T odd moment

$K_L \to \mu^+\nu\pi^-$ $\quad Pol_t^{SM}(\mu) \sim 10^{-3}$ ($\sim \alpha/2\pi$) -- Coulomb FSI!

$K^+ \to \mu^+\nu\pi^0$

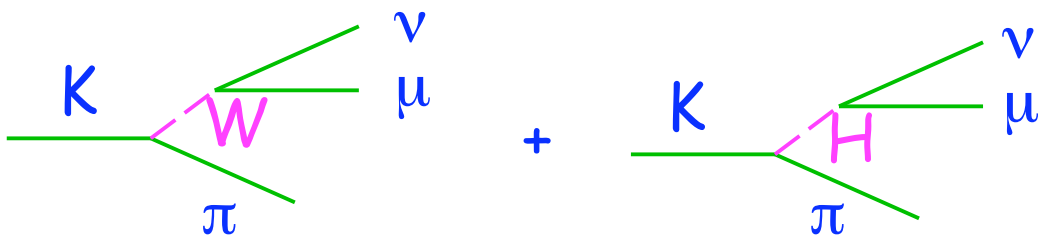
E246 (KEK)

$Pol_t(\mu) = (-1.7 \pm 2.3 \pm 1.1) \times 10^{-3}$ **vs.** $Pol_t^{SM}(\mu) < 10^{-6}$

$Pol_t(\mu) \propto Im\ \xi$, $\xi = f_-/f_+$,

$f_{-[+]}$ helicity violating[conserving] amplitude

➥ a clean search for ~~CP~~ via Higgs dyn.



generic guestimate:
direct ~~CP~~ presumably unsuppressed by $\Delta I = 1/2$ rule:

$5 \times 10^{-6} \times 20 \sim 10^{-4}$

-- unless enhanced couplings to leptons!

Proposal TREK @ J-PARC

$\delta\, \mathrm{Pol}_t(\mu) \sim 10^{-4}$

$K^+ \rightarrow \mu^+\nu\gamma$

$\mathrm{BR}(K^+ \rightarrow \mu^+\nu\gamma) \approx 5.5 \times 10^{-3}$

but: $\mathrm{Pol}_t^{FSI}(\mu) \sim (1\text{-}2) \times 10^{-4}$ Isidori & Hiller '99

IV Historical Precedent

$K_L \rightarrow \pi^+\pi^- e^+e^-$ with BR ~ 3×10^{-7}

Φ angle between $\pi^+\pi^-$ & e^+e^- planes

- $d\Gamma/d\Phi = \Gamma_1 \cos^2\Phi + \Gamma_2 \sin^2\Phi + \Gamma_3 \sin\Phi \cos\Phi$
- $A = 2\Gamma_3/\pi(\Gamma_1+\Gamma_2)$ -- a *T odd* correlation
  - A~ 13% KTeV, NA48
- fully consistent with ~~CP~~ through ε_K
- for a while (arguably) largest observed ~~CP~~

☛ can trade BR for size of CP asymmetry!

V τ Decays (+Roney & Kuehn)

~~CP~~ in τ decays

most promising channels: $\tau \rightarrow \nu K \pi$, $\nu K \pi\pi$ [$\nu\pi\pi\pi$...]

- most sensitive to Higgs dynamics
- CP asymmetries possible also in final state distributions rather than integrated rates:
  - likely to be considerably larger
  - telling about detailed structure of underlying operator
  - better control over systematics
- $\tau \rightarrow \nu K \pi\pi$, $\nu\pi\pi\pi$...: more choices for final state distributions
  - ➥ can try to `maximize' CP asymmetry at expense of statistics -- memento $K_L \rightarrow \pi^+\pi^- e^+e^-$

Three unique advantages in $e^+e^- \rightarrow \tau^+\tau^-$

- can study CP conjugate transitions --
  FSI can induce T odd correlations, yet not ~~CP~~!
- pair produced with spins aligned:
  1 τ decays can `tag' the spin of the other
  - ➥ can probe spin-dependent ~~CP~~ with unpolarized beams!
- τ pair polarized, if e^- beam longitudinally polarized

➥ polarization dependent asymmetries provide

extra control over systematics

$\tau^- \to \nu\, K^-\pi^0 / K^0\pi^-$

CP odd ~ $|T^*_{SM}\, T_{NP}|$ vs. LFV ~ $|T_{NP}|^2$

i.e., 0.1 % ~~CP~~ in $\tau \to \nu K\pi$ ~ 10^{-8} BR for $\tau \to \mu\gamma$

- ☺ 3-body final state
  - ➥ ~~CP~~ in distributions in general — Kuehn & Mirkes '96,'97
    - ☺ possibly considerably larger than integrated ones
    - ☺ yield info on underlying transition operator
    - ☺ allows consistency checks
- ☺ presumably higher sensitivity to non-minimal Higgs dynamics
- energy distributions, angular correlations …
- *T odd* moments: $\langle \mathbf{s}_\tau . (\mathbf{p}_K \times \mathbf{p}_\pi) \rangle$
  - ✍ can extract info on $\mathbf{s}_\tau$ from τ pair spin alignment C.Nelson
  - ✍ can compare τ^+ with τ^-

Pioneering study by CLEO in '98:

~~CP~~ in angular distrib. < few %

an optimistic, yet not unrealistic NP domain starts ~ 1 %

(0.1 % a more realistic domain)

(need interference between $(K\pi)_{vector}$ & $(K\pi)_{scalar}$!)

$\tau \rightarrow \nu K\pi\pi$

☺ can form T odd moments without τ polarization

☺ can interfere $(K\pi\pi)_V$ with $(K\pi\pi)_A$

☺ more internal cross checks on `+' vs. `-' detection eff.

VI Summary

- $\not{CP}$ uncovered almost exclusively in partial rates
- we are just at the beginning of exploring unknown & novel territories of $\not{CP}$ in final state distributions
- those could provide specific info on the chirality of New Physics operators
- T odd moments in positronium decays:

enterprising QED theorists can establish (at least) bragging rights

- $K^+ \to \mu^+\nu\pi^0$ -- search window of 3 orders of magnitude in $P_t(\mu)$
  - ✍ natural place for non-minimal scalar dynamics to surface
- $\not{CP}$ ~ 0.1 - 1% in $\tau \to \nu K\pi$ / $K\pi\pi/\pi$'s --

there is fame within your grasp!