Search for CP violation in τ decays.

Yurii Maravin, SMU/CLEO

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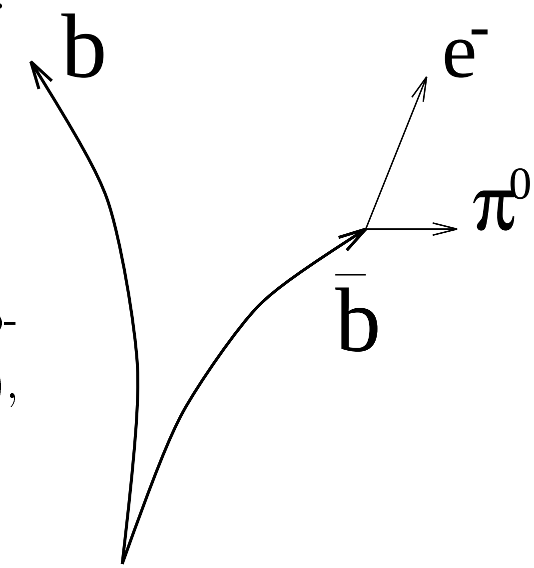
Motivation

Universe is matter dominated!

- initial conditions ("...it does not satisfy me to shift the empirically established asymmetry to one of the initial state...", Pauli, 1933)
- mechanism that breaks matter-antimatter equivalence.



Sakharov criteria: [A. D. Sakharov JETP Lett. **5**, 24 (1967)]

- baryon number violating processes (GUTs),
- broken symmetry between matter and antimatter (violation of C and CP symmetries in the Standard Model),
- out of equilibrium conditions (Expanding Universe).

Standard Model CPV is too small to generate matter dominance in the Universe!

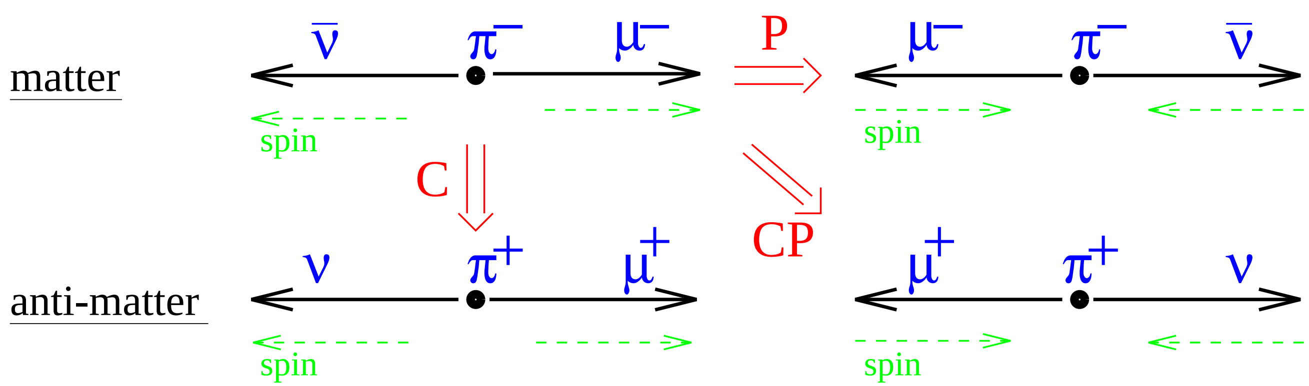
[P.Huet and E.Sather Phys. Rev. D **51**, 379 (1995)]

Symmetry

- "Sum metria" (same measure), Polykleitos (5th century B.C.),
- invariance under the set of changes/transformations

Three important discrete transformations:

- C - charge conjugation [particle ↔ anti-particle],
- P - parity [(x,y,z) → (-x,-y,-z)],
- T - time reversal [t → -t].



Violation of symmetries with respect to C and CP transformations distinguish between matter and anti-matte ⇒ C and P are maximally violated.

Motivation

- perhaps baryogenesis is wrong,
- or more CP violation beyond the Standard Model (SM)
  - ∗ SM mechanism of CP violation is build on CP non-conservation in the kaon decays only, no CPV in lepton sector,
  - ∗ no fundamental reason to have CP symmetry in the lepton sector,
  - ∗ evidence for massive neutrinos suggests CP violation in the lepton sector,
  - ∗ almost any SM extension has new sources of CP violation (SUSY, MHDMs) including lepton sector.

Search for CP violation is one of the most promising directions in the search for New Physics beyond the Standard Model.

Search for CPV in lepton sector!

CP violation

- CP is violated by CP-odd term in the lagrangian
- example: Standard Model CPV
  - ∗ accounts for CP violation in the kaon system,
  - ∗ CP is broken by complex, CP-odd elements of quark mixing matrix

Coupling of $W^{\pm}$ to quarks and its CP-conjugated one are

$$g V_{ij} \bar{u}_i \gamma_\mu W^{+\mu}(1-\gamma_5) d_j + g V^*_{ij} \bar{d}_j \gamma_\mu W^{-\mu}(1-\gamma_5) u_i$$

$$CP: \quad g V^*_{ij} \bar{u}_i \gamma_\mu W^{+\mu}(1-\gamma_5) d_j + g V_{ij} \bar{d}_j \gamma_\mu W^{-\mu}(1-\gamma_5) u_i$$

These terms are identical (CP symmetric) only if $V^*_{ij} \equiv V_{ij}$.
CKM matrix is 3x3 unitary matrix, which has $(3-1)^2$ physical parameters:

- $\frac{3(3-1)}{2} = 3$ moduli,
- $\frac{(3-1)(3-2)}{2} = 1$ phase.

- V_{ij} is complex $\Rightarrow$ CPV,
- In SM all CPV is in V_{ij}, along with Flavor Mixing,
- CPV in leptons $\Rightarrow$ SM extensions.

CPV in the Multi-Higgs-Doublet Models

- Higgs sector of the SM consists of a single Higgs doublet,
- possibility of an extended Higgs sector does not contradict with data,
- one of the most general model is 3HDM with three Higgs doublets

Y. Grossman, Nucl. Phys. **B426**, 355 (1994).

Rotation of the interaction eigenstates into the mass eigenstates

$$\begin{pmatrix} G^+ \\ H_2^+ \\ H_3^+ \end{pmatrix} = U \begin{pmatrix} \Phi_1^+ \\ \Phi_2^+ \\ \Phi_3^+ \end{pmatrix}$$

- U is unitary, 3x3 matrix $\Rightarrow$ has $(3-1)^2$ parameters
  - $\frac{3(3-1)}{2} = 3$ moduli,
  - $\frac{(3-1)(3-2)}{2} = \underline{1 \text{ phase}}$.

U is complex, thus CP violating!

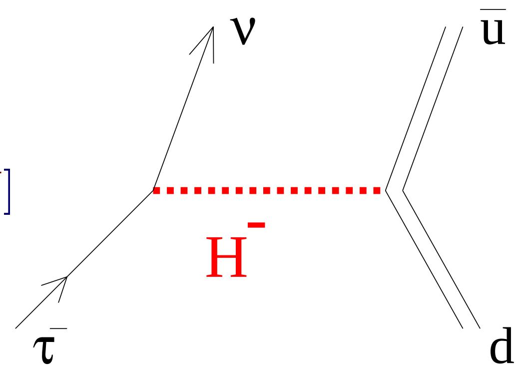
CPV in the Multi-Higgs-Doublet Models

Therefore,

$$\mathcal{L}_H \sim \left\{ X\bar{u}_L M_d V d_R + Y\bar{u}_R M_u V d_L + Z\bar{l}_L M_l l_R \right\} H^+ + h.c.$$

X, Y, and Z are complex coupling of the charged Higgs to down-, up-type quarks, and leptons

$$\Lambda = \frac{m_\tau}{m^2_{Higgs}}[m_u Z^* X - m_d Z^* Y]$$

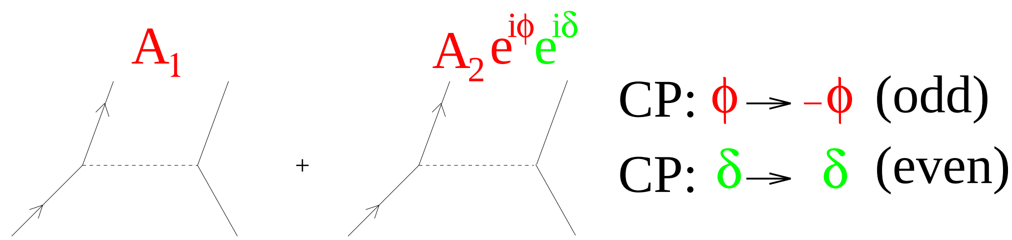


- coupling is proportional to fermion mass ⇒ largest effects in τ decays.

Search for CP violation in decay

Absolute value of a CP-odd phase has no physical meaning =>

- observe in interference effects
- need two amplitudes with relative CP-odd phase ϕ and CP-even phase δ:

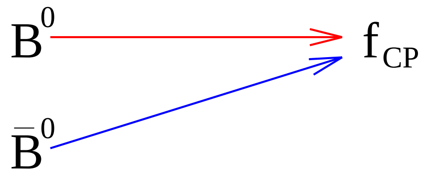


$$|\mathcal{A}|^2 = (\mathcal{A}_1 + \mathcal{A}_2 e^{i\phi} e^{i\delta})(\mathcal{A}_1 + \mathcal{A}_2 e^{-i\phi} e^{-i\delta}) = \mathcal{A}_1^2 + \mathcal{A}_2^2 + 2\mathcal{A}_1\mathcal{A}_2 \cos\phi \cos\delta + \underbrace{2\mathcal{A}_1\mathcal{A}_2 \sin\phi \sin\delta}_{\text{CP odd}}$$

- $\sin\phi \neq 0 \Rightarrow$ complex CP-odd phase
- $\sin\delta \neq 0 \Rightarrow$ complex CP-even phase

<u>What is the CP-even phase?</u>

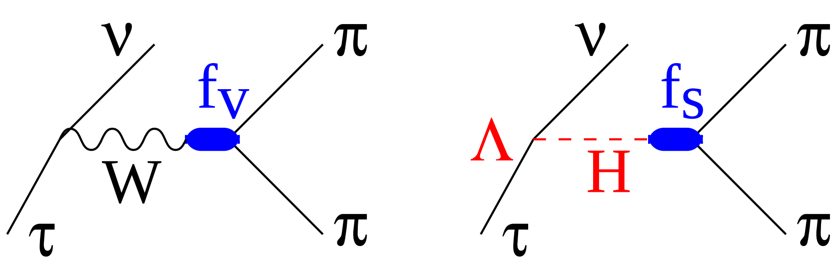
CP violation in interference between mixing and decay



CP-odd : CKM

CP-even : $e^{i\Delta m t}$

CP violation in decay

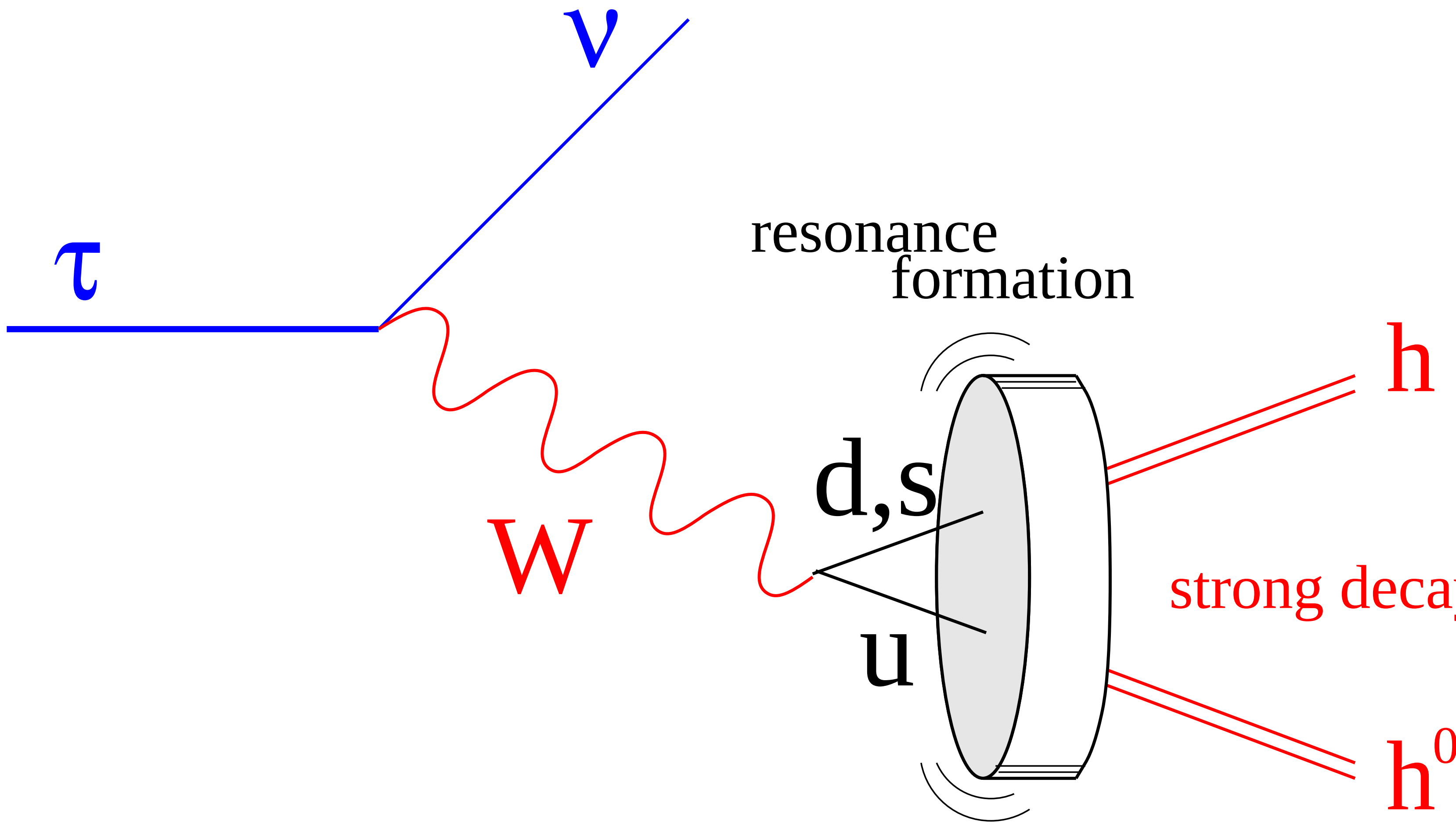


CP-odd : Λ

CP-even : *strong phases*

Strong phase arises from QCD final state interactions between quarks

$$A \sim \sum A_l e^{i\delta_l} P_l(\cos\psi_{scat})$$


ν
τ
resonance
formation
h
d,s
W
strong decay
u
h0

Two tau decay modes

Consider $\tau \to \pi\pi^0\nu_\tau$ and $\tau \to K\pi\nu_\tau$

	$\tau^- \to \bar{u}d\nu_\tau$	$\tau^- \to \bar{u}s\nu_\tau$
Statistics	largest branching fraction	Cabbibo suppressed (1/20)
Isospin	suppressed (1/30)	-
Higgs* coupling	mass suppressed (1/15)	-

*Within MHDM: $\Lambda = \frac{m_\tau}{m^2_{Higgs}}[m_u Z^* X - m_d Z^* Y]$

- $\tau \to \pi\pi^0\nu_\tau$ – most sensitive to the Λ (no mass dependence)
- $\tau \to K\pi\nu_\tau$ – most sensitive to X, Y and Z.

Method of searching for CP violation

If squared matrix element of the decay has a CP-odd term $\mathcal{M}^2_{\rm odd}$:

$$\mathcal{M}^2 = \mathcal{M}^2_{\rm even} + \mathcal{M}^2_{\rm odd},$$

CP is violated and may be observed:

- construct CP-odd observable ξ,
- observe an average value of such observable in data:

$$<\xi>= \int \xi(\mathcal{M}^2_{\rm even} + \mathcal{M}^2_{\rm odd}) dLips = \int \xi \mathcal{M}^2_{\rm odd} dLips \neq 0, \text{ if } \mathcal{M}^2_{\rm odd} \neq 0.$$

- $<\xi> \neq 0$ - CP violation (no model dependence!),
- interpretation of $<\xi>$ is model-dependent.

Optimal observable

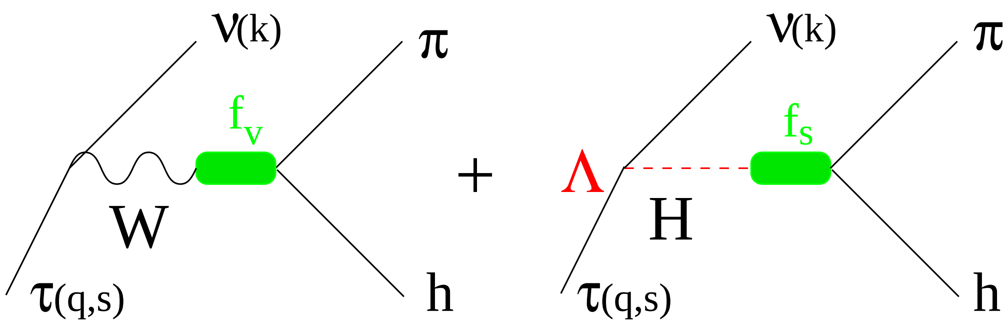
To increase the sensitivity use statistically optimal observable:

[D. Atwood and A. Soni, Phys. Rev. D **45**, 2405 (1992)]

$$\xi \equiv \frac{\mathcal{M}^2_{\rm odd}}{\mathcal{M}^2_{\rm even}} \Rightarrow \underline{\text{need explicit forms of } \mathcal{M}^2_{\rm odd} \text{ and } \mathcal{M}^2_{\rm even}}$$

- select a model,
- calculate $\mathcal{M}^2_{\rm odd}$ and $\mathcal{M}^2_{\rm even}$,
- construct CP-odd observable ξ (optimal within the selected model!),
- can relate observable $< \xi >$ to the CP-violating parameter in the model (Λ).

Squared matrix element for $\tau \to h\pi\nu_\tau$



$$\mathcal{M}_W = \frac{G_F}{\sqrt{2}}\bar{\nu}\gamma_\mu(1-\gamma_5)\tau V_{qQ} f_V Q^\mu,$$

where the vector hadronic current is parameterized as a product of

$$Q^\mu = [(p_\pi - p_h)^\mu - \frac{m_\pi^2 - m_h^2}{(p_\pi + p_h)^2}(p_\pi + p_h)^\mu].$$

and a vector form-factor f_V describing the resonance in the final state.

$$\mathcal{M}_H = \frac{G_F}{\sqrt{2}}\bar{\nu}(1-\gamma_5)\tau\Lambda V_{qQ} f_S M.$$

Here f_S is a scalar form-factor, M - normalization parameter.

What are the form-factors?

Can be approximated by the Breit-Wigner function describing the shape for the resonances in the final state: [S. Anderson *et al.*, Phys. Rev. D **61**, 112002 (2000)]

$$f = \frac{-m^2}{s - m^2 + im, (s)},$$

$$, (s) = \begin{cases} \frac{m}{\sqrt{s}} \left(\frac{s-4m_\pi^2}{m^2-4m_\pi^2} \right)^{n/2} & \text{if } s > (2m_\pi)^2 \\ 0 & \text{elsewhere,} \end{cases}$$

where $n \equiv 3$ for the vector and $n \equiv 1$ for the scalar.

- It is crucial to have the best possible approximation for the hadronic current,
- important for "optimal" observable construction

Squared matrix element for $\tau \to h\pi\nu_\tau$

$$|\mathcal{M}|^2 = \frac{G_F^2}{2} V_{qQ}^2 [K + s^\mu \omega_\mu]$$

where

$$K = 2|f_V|^2[2(qQ)(kQ) - (kq)Q^2] + 2|\Lambda|^2|f_S|^2 M^2(qk) + 4\mathrm{Re}(\Lambda)\mathrm{Re}(f_S f_V^*)Mm_\tau(Qk)$$
$$-\underline{4\mathrm{Im}(\Lambda)\mathrm{Im}(f_S f_V^*)Mm_\tau(Qk)},$$
$$s^\mu\omega_\mu = s^\mu\{-2|f_V|^2 M_\tau[2Q_\mu(kQ) - k_\mu Q^2] + 2|\Lambda|^2|f_S|^2M^2M_\tau k_\mu$$
$$-4\mathrm{Re}(\Lambda)\mathrm{Re}(f_S f_V^*)M[Q_\mu(kq) - k_\mu(qQ)]$$
$$+\underline{4\mathrm{Im}(\Lambda)\mathrm{Im}(f_S f_V^*)M[Q_\mu(kq) - k_\mu(qQ)]}$$
$$+4\mathrm{Re}(\Lambda)\mathrm{Im}(f_S f_V^*)M\epsilon_{\mu\alpha\beta\gamma}q^\alpha Q^\beta k^\gamma + \underline{4\mathrm{Im}(\Lambda)\mathrm{Re}(f_S f_V^*)M\epsilon_{\mu\alpha\beta\gamma}q^\alpha Q^\beta k^\gamma}\}.$$

- underlined terms are CP-odd.

At CESR beams are unpolarized:

- no spin information $\Rightarrow < s^\mu\omega_\mu >= 0$
- use spin correlation between τ's in the $\pi\pi^0\nu_\tau$ decay mode!