Search for CPV in tau decays.

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Motivation

Search for the CP violation is interesting because of many reasons:

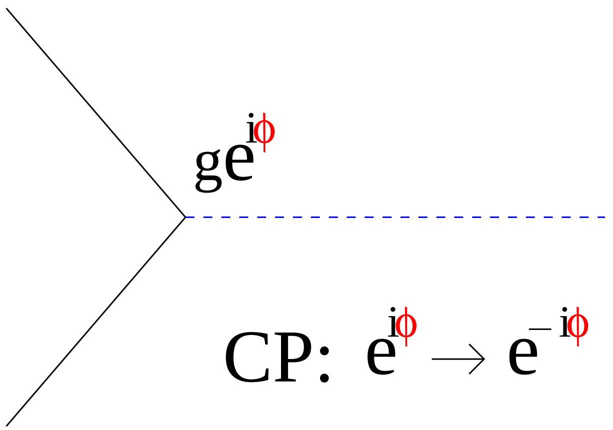
- matter asymmetry of the Universe,
- CPV was found only in K decays

  (Standard Model: V_{CKM} CPV in quark mixing only),
- no fundamental reason not to have CP violation in lepton sector,
- recent discovery of the neutrino masses,
- MHDM can provide CPV in lepton sector.

Search for CP violation in lepton decays.

Gauge theory and CPV

* CP symmetry can be broken by a CP-odd phase in the Lagrangian:
Phase cannot be rotated out by using a different gauge.



- SM: CP-odd phase comes from V_{CKM} =>
  * CPV in quark interactions,
  * no CPV in lepton sector,

- If $m_\nu \neq 0$ => CPV in leptons
  * suppressed by $(m_\nu/m_{lepton})^2$,

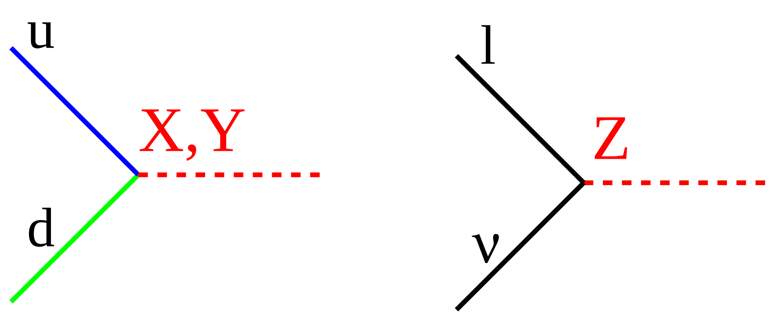
- extension of SM: MHDM,
  * scalar Higgs can have complex coupling.

Consider MHDM as a candidate theory for CPV in lepton sector

MHDM and CP violation in a lepton decays

Possible SM extension which can provide CP violation in lepton sector is MHDM.

- SM: one Higgs doublet (no CP violation),
- 2HDM: neutral coupling can be complex (tau production),
- 3HDM: complex coupling (tau decays).

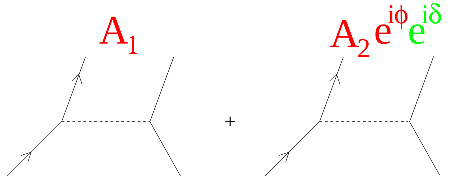


(natural FCNC) Three doublets, coupling to up, down quarks and leptons with complex couplings X, Y and Z can provide CP-odd phase ϕ.

CP violation in lepton decays

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

* observe interfering effects,
* need two amplitudes with CP-odd phase ϕ and CP-even phase δ:



CP: $\phi \to -\phi$ (odd)
CP: $\delta \to \delta$ (even)

$$|A|^2 = (A_1 + A_2 e^{i\phi} e^{i\delta})(A_1 + A_2 e^{-i\phi} e^{-i\delta}) = A_1^2 + A_2^2 + 2A_1A_2 \cos\phi \cos\delta + \underbrace{2A_1A_2 \sin\phi \sin\delta}_{CP odd}$$

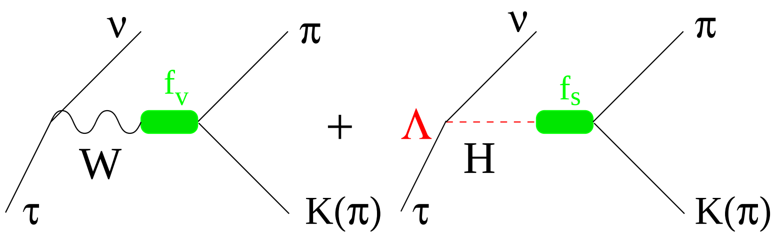
$$= P_{even} + P_{odd}.$$

- Search for CPV in interference between standard W and scalar Higgs exchanges,
- X, Y and Z are complex => $\sin\phi \neq 0$,
  * any scalar exchange with complex coupling can break CP symmetry.
- CP-even phase δ may arise from QCD final state interaction between quarks.
- Mass dependence of the couplings => taus favored.

CPV in single tau decays

Search for CPV in a single tau decay into hadronic final state plus a neutrino.

* $\tau \rightarrow K\pi\nu_\tau$, CLEO collaboration, (Phys. Rev. Lett. **81**, 3823, (1998)).
* $\tau \rightarrow \pi\pi^0\nu_\tau$, Belle collaboration, analysis in progress. (Osaka 2000)



$$\Lambda = \frac{m_\tau}{m_{Higgs}}(m_{s(d)} YZ^* - m_u XZ^*)$$

Comparing two modes:

	$\tau^- \rightarrow \bar{u}d\nu_\tau$	$\tau^- \rightarrow \bar{u}s\nu_\tau$
Resonance	$\rho^- \rightarrow \pi\pi^0$	$K^* \rightarrow K\pi$
Statistics	largest branching fraction	Cabbibo suppressed (1/20)
Isospin	suppressed (1/30)	-
Higgs* coupling	mass suppressed (1/15)	-

Comparable sensitivity

Analysis method

- For the decays of unpolarized taus (Phys. Lett.**B398**, 407 (1997)):

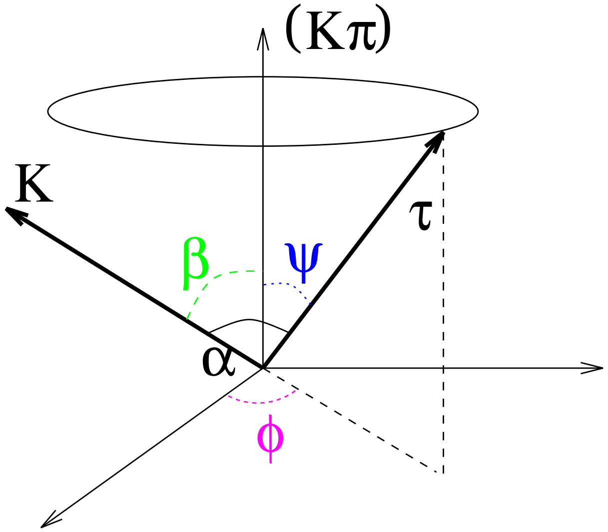
$$P_{odd} = f(q)\ \Im(\Lambda)\ \Im(e^{i\delta})\ \cos\alpha.$$

- α is an angle between τ and K in a hadronic rest frame,
- use $\cos\alpha$ as an observable,

$$\frac{dN(\tau^-)}{d\cos\alpha} \sim P_{even} + const \cdot \Im(\Lambda)\ \cos\alpha$$

$$\frac{dN(\tau^+)}{d\cos\alpha} \sim P_{even} - const \cdot \Im(\Lambda)\ \cos\alpha$$

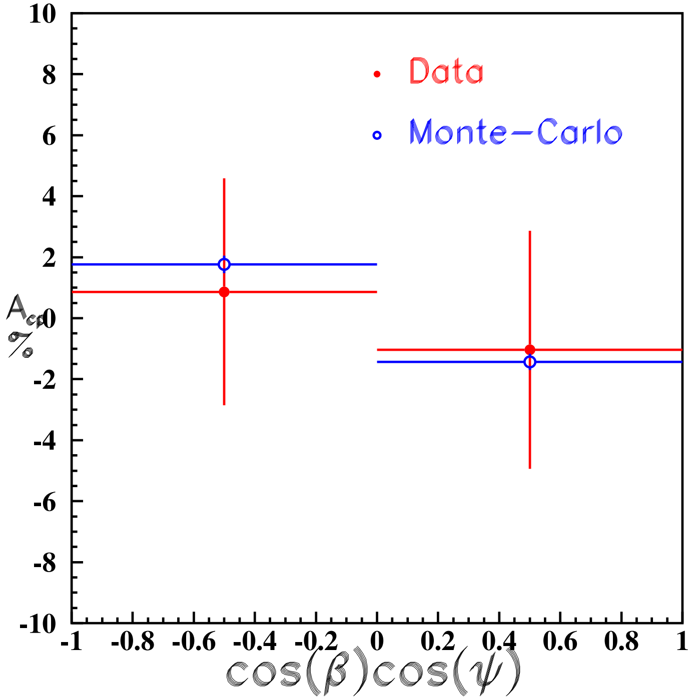
Difference $\sim 2\ const\ \Im(\Lambda)\ \cos\alpha$



- No τ direction => use less sensitive $\cos\beta\cos\psi$ as an observable,
- difference $\sim const\Im(\Lambda)\ \cos\beta\cos\psi$,
- non-zero slope indicates CP violation
- calibration constant $const$ can be obtained from CPV Monte Carlo.

CLEO $\tau \to K\pi\nu_\tau$ PRL(1998)

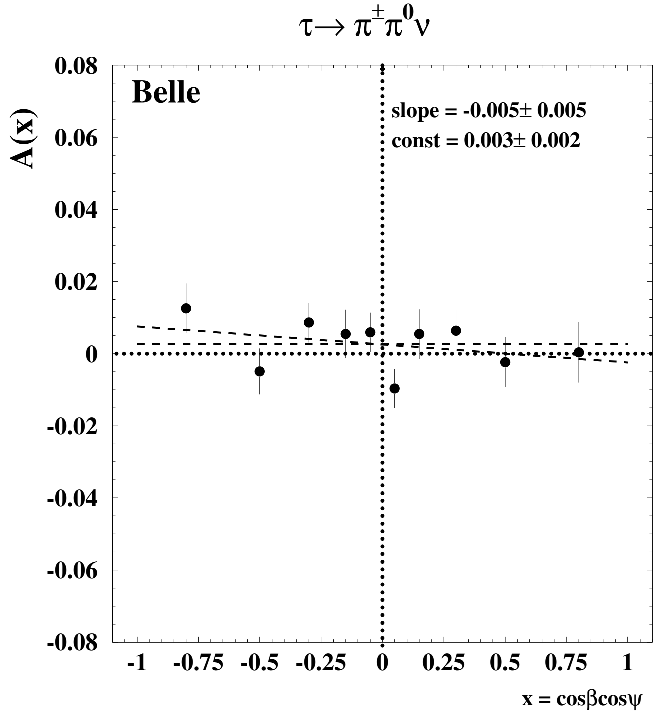
$$N_{\tau\tau} = 4.4 \cdot 10^6, \; N_{sig} = 4169$$



- No evidence for the slope,
- $|\Im(\Lambda)| < 1.7$ at 90% C.L.

Belle $\tau \to \pi\pi^0\nu_\tau$ Osaka 2000

$$N_{\tau\tau} = 6.2 \cdot 10^6, \; N_{sig} = 260,000$$



- slope is consistent with zero (no CPV),
- *const* $\Im(\Lambda) = (-5.0 \pm 5.0) \cdot 10^{-3}$,
- normalization constant *const* is unknown (work in progress).

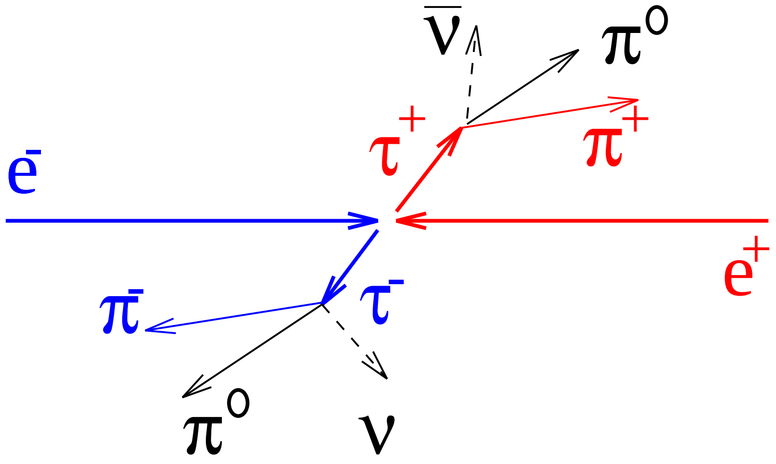
Summary of single decay results

- CLEO result provides the first restriction on CP violation in tau lepton decays,

$$|\Im(\Lambda)| < 1.7 \text{ at } 90\% \text{ C.L.}$$

- Belle result will be available soon,
- searches not optimized,
- sensitive only to spin-independent CP-odd terms of matrix element.

Search for CPV in correlated τ decays



Use tau pair decays into $\pi^{\pm}\pi^{0}\nu_{\tau}$ final state each =>

- advantage : sensitive to all CP-odd terms in matrix element via spin-correlation, less prone to systematic errors due to detector reconstruction.

Optimal observable

Statistics is limited => use optimal method to search for CP violation.

- Derived by D. Atwood and A. Soni (Phys.Rev.**D45**:2405,(1992))

  * if a process has a probability density of a form:

$$P = P_{even} + P_{odd},$$

  * then, statistically optimal observable is:

$$\xi = \frac{P_{odd}}{P_{even}}; \text{ and } <\xi>= \int \xi(P_{even} + P_{odd})\, dLips = \int \frac{P_{odd}{}^2}{P_{even}}\, dLips$$

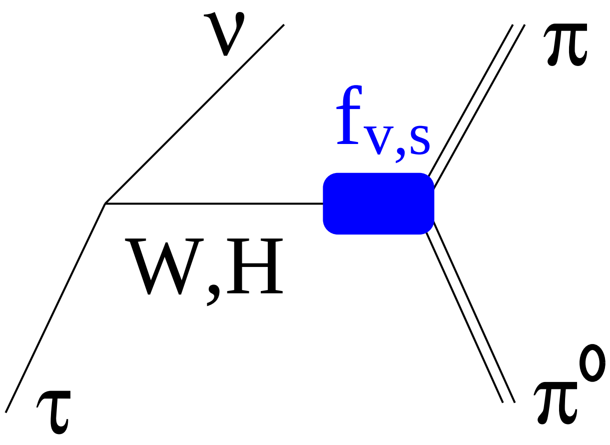
- Function of the decay parameters: p_i, f_v and f_s

  * f_v parameterized by ρ Breit-Wigner,
  * for f_s we use three choices:

    $f_s = 1$,

    $f_s = BW(a0(980))$,

    $f_s = BW(a0(1450))$

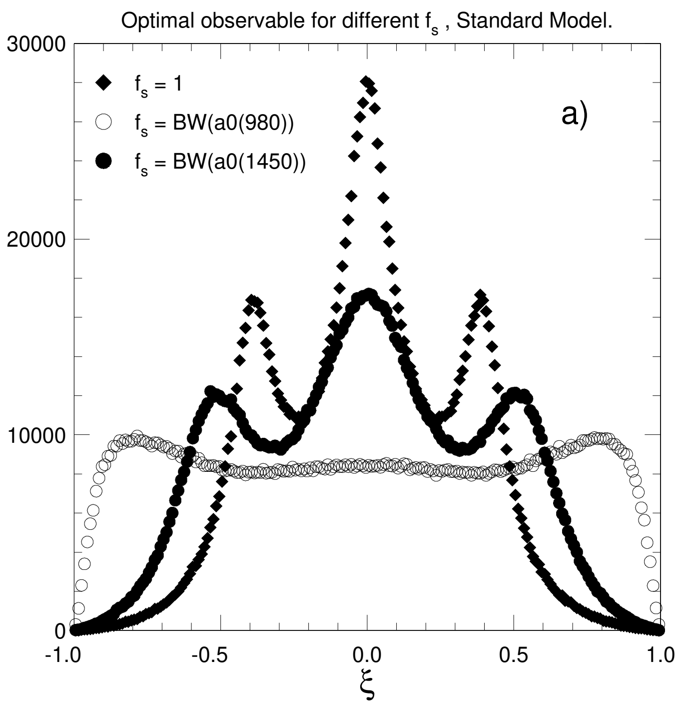


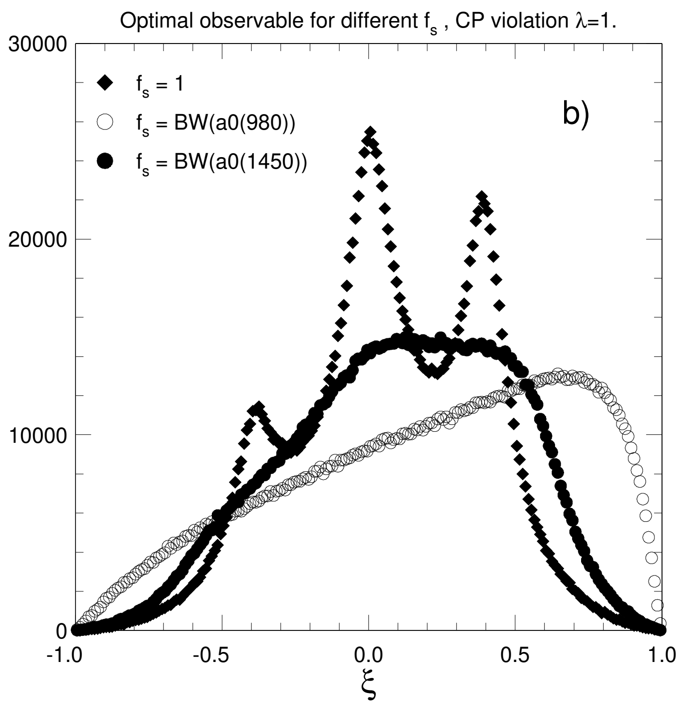
Monte Carlo studies

- Modify TAUOLA decay package to simulate W-Higgs interference:
- study distribution of optimal variable (expect $<\xi>\neq 0$ for CPV).

No CP violation ($\Im(\Lambda) = 0$)

'Maximal' CP violation ($\Im(\Lambda) = 1$)





- Shapes depend on choice of f_s (shapes are not important, but $<\xi>$,
- strong asymmetry for CPV.

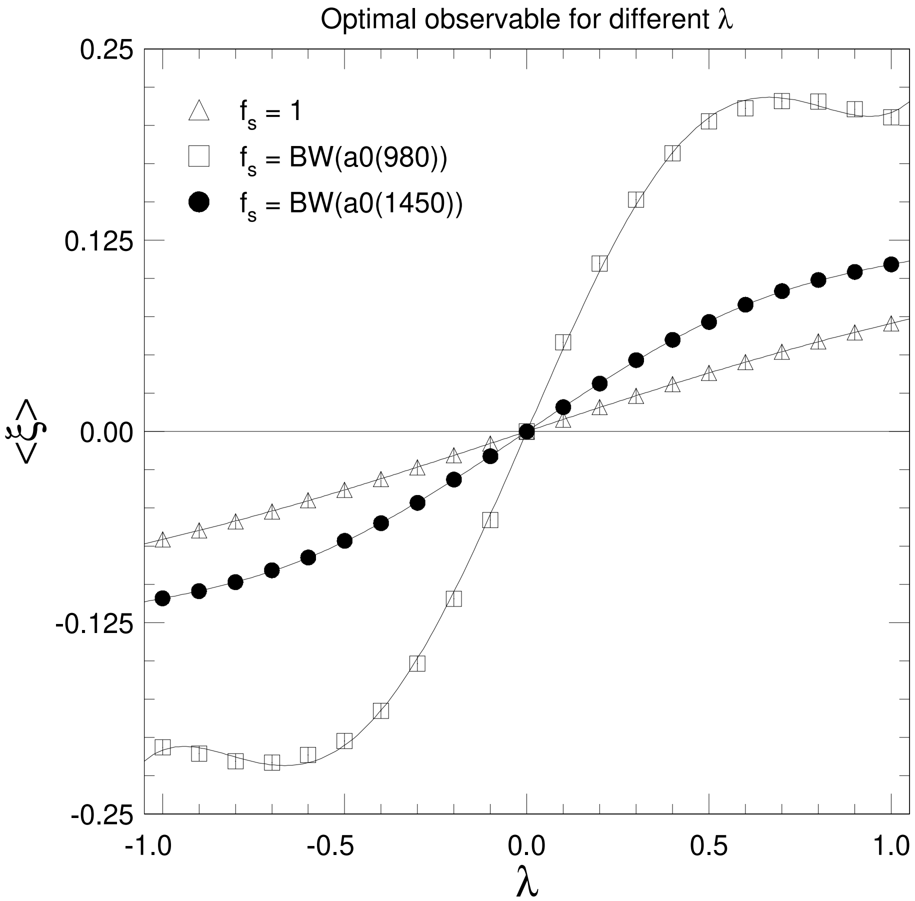
Calibration

- Mean value $<\xi>\neq 0$ indicates CPV,
- One can the relate observed value of $<\xi>$ to $\Im(\Lambda)$:

$$<\xi>= c_1\Im(\Lambda) + c_2\Im(\Lambda)^3 + c_3\Im(\Lambda)^5$$

- calibration is provided by CPV MC with different values of $\Im(\Lambda)$.

Calibration curves



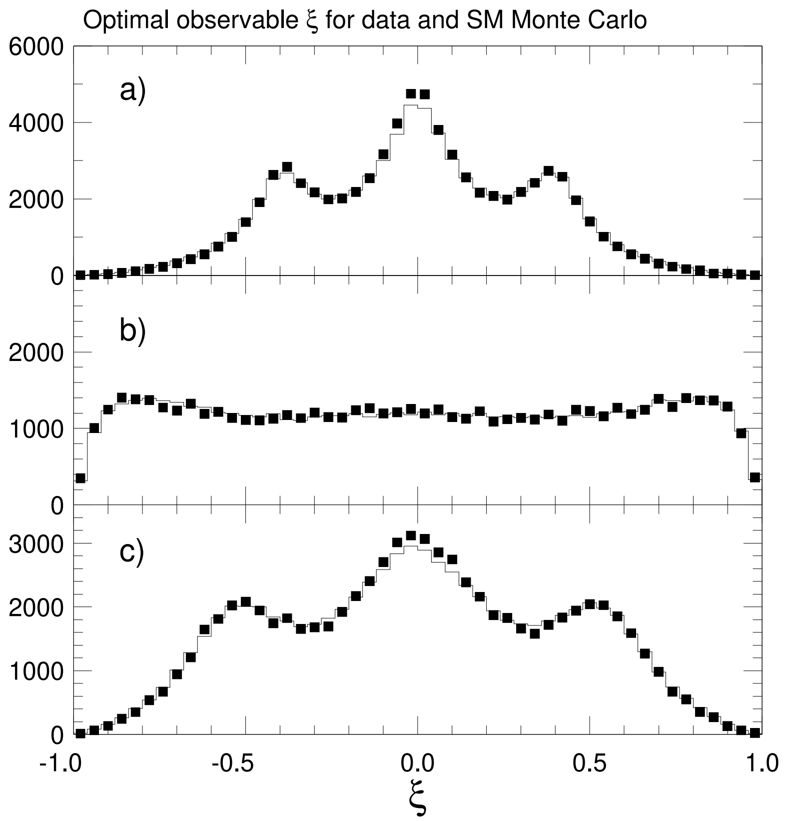
Data sample and selection criteria

$$\tau^+\tau^- \to \pi^+\pi^0\bar{\nu}_\tau + \pi^-\pi^0\nu_\tau$$

- Use 13.2 fb^{-1} luminosity at $E_{cm} \sim 10.52$ GeV $(12.2 \cdot 10^6$ tau pairs),
- we use standard selection criteria used by CLEO in previous analyses,
  - backgrounds from $q\bar{q}$, $B\bar{B}$ and two-photon physics are estimated using Monte Carlo and found to be negligible,
  - most background comes from τ physics ($\tau \to \pi\pi^0\nu_\tau$ $.vs.$ $\tau \to a_1\nu_\tau$),
  - total background is estimated to be 9.9%,
- background does not bias $<\xi>$ measurement.

Data

Shapes of ξ depends on choice of f_s (not important),



- The following values of $< \xi >$ observed:

f_s	$< \xi >$
1	-0.0008 ± 0.0014
BW(a0(980))	-0.0006 ± 0.0024
BW(a0(1450))	0.0002 ± 0.0017

- Mean values $< \xi >$ are small => use first order term of the expansion:

$$< \xi > = c_1 \Im(\Lambda)$$

- obtain normalization constant c_1 from CPV MC samples with different values of $\Im(\Lambda)$.

Data (cont.)

- Using normalization constant c_1 obtained from CPV Monte Carlo yields the following values of $\Im(\Lambda)$:

f_s	$\Im(\Lambda)$
1	-0.012 ± 0.021
BW(a0(980))	-0.001 ± 0.004
BW(a0(1450))	0.001 ± 0.012

- two order of magnitude better than previous result (CLEO '98)

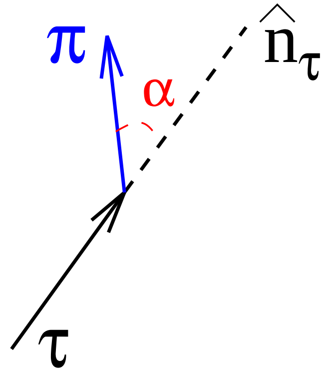
  - one order, assuming Higgs coupling mass dependence,

- use most conservative choice of f_s:

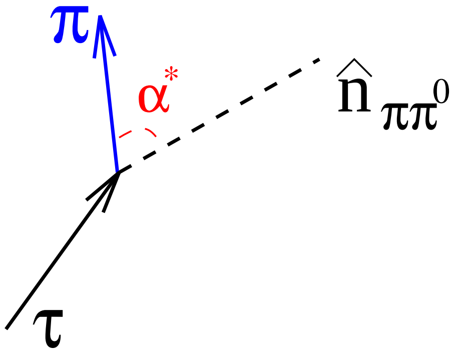
$$-0.046 < \Im(\Lambda) < 0.022 \text{ at } 90\% \text{ C.L.}$$

No CP violation is observed

Cross check (Pseudohelicity method)



τ rest frame



$\pi\pi^0$ rest frame

- Standard model vector exchange:

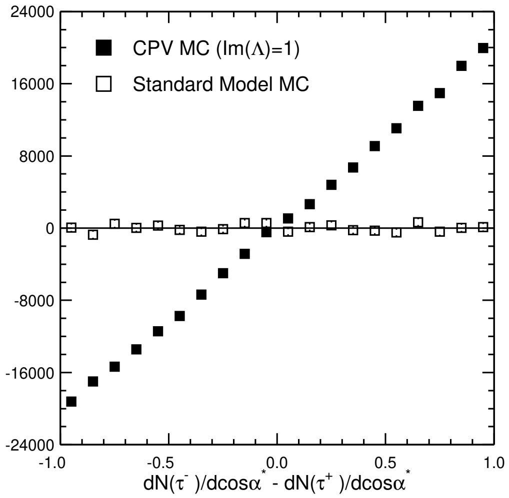
$$\frac{dN}{d\ \cos\alpha} \sim a + b\cos^2\alpha$$

- addition of scalar => S-P interference:

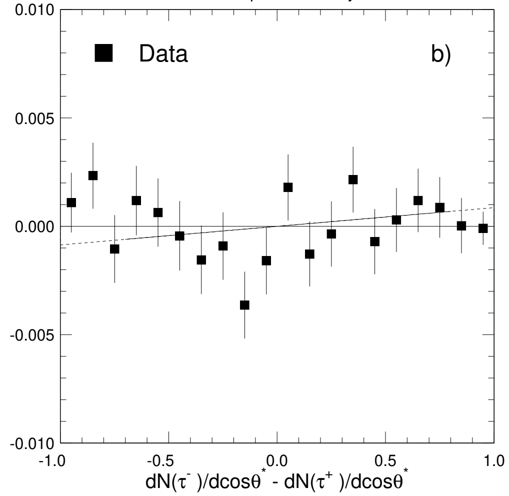
$$\frac{dN}{d\ \cos\alpha} \sim a + c_1\Re(\Lambda)\cos\alpha + c_2\Im(\Lambda)\cos\alpha + b\cos^2\alpha.$$

<u>Method</u>

- Search for interference terms linear in $\cos\alpha$.
- τ direction is unknown → use pseudohelicity angle α^*,
- MC studies show no bias ($\alpha^* \to \alpha$ if neutrino is either soft or collinear with $\pi\pi^0$),
- $\Im(\Lambda)$ - can be measured by difference of $\cos\alpha^*$ distribution for τ^- and τ^+,
- $\Re(\Lambda)$ - can be obtained by the sum.



Difference between pseudo-helicity distributions



Data

$$\frac{dN(\tau^-)}{d\cos\alpha^*} - \frac{dN(\tau^+)}{d\cos\alpha^*} = \underbrace{const\,\Im(\Lambda)}_{Slope}\cos\alpha^*$$

- Expectation:
  - * No CPV – zero slope,
  - * CPV – non-zero slope $\sim \Im(\Lambda)$.
- use the same data sample, apply the same selection criteria,
- calculate the slope: Slope $= (4.2 \pm 3.6) \cdot 10^{-4}$
- derive $\Im(\Lambda)$ from the slope using CPV Monte Carlo for calibration:

$$\Im(\Lambda) = 0.028 \pm 0.037$$

$$-0.033 < \Im(\Lambda) < 0.089 \text{ at } 90\% \text{ C.L.}$$

- Result is less model dependent (no need for explicit matrix element).

Summary

BELLE Results in $\tau \to \pi\pi^0\nu_\tau$

- $|A_{CP}(cos\beta cos\psi)| < 0.010$ at 90% C.L.,
- no constraint on scalar coupling $\Im(\Lambda)$,
- analysis is progress.

CLEO Results in $\tau \to K(\pi)\pi^0\nu_\tau$

- Previous CLEO result ('98):

$$|\Im(\Lambda')| < 1.7 \text{ at } 90\% \text{ C.L.,}$$

- current analysis consists of two methods: 'optimal' and 'simplified':
- optimal methods provides the best constrain:

$$-0.046 < \Im(\Lambda) < 0.022 \text{ at } 90\% \text{ C.L.,}$$

- simplified method is more intuitive but less sensitive:

$$-0.033 < \Im(\Lambda) < 0.089 \text{ at } 90\% \text{ C.L.}$$

All present results are consistent with no CPV in tau decays.
No strong constraint on the theory so far (Belle, BaBar)

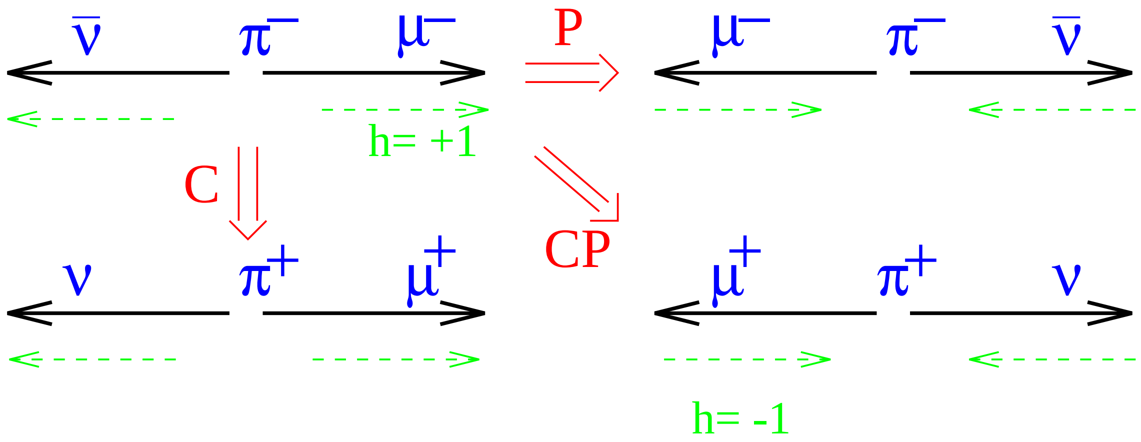
Discrete symmetries: C, P

Particle-antiparticle conjugation (C),

* transforms each particle into antiparticle (+q $\rightarrow$ -q),

Reflecting in space or Parity (P),

* changes sign of the coordinates (+x $\rightarrow$ -x).



Only $h_{\mu^-} = +1$ and $h_{\mu^+} = -1$ exist, therefore C and P are violated and CP is conserved.

* The combined CP operation connects two physical processes =>

* If these two processes are different, CP is violated!