CLEO CONTRIBUTIONS TO TAU PHYSICS

A semi-critical review of the strengths and weaknesses of tau physics at CLEO – Past, Present, Future

- Tau pair production
- Branching fractions for major decay modes
- Rare decays
- Forbidden decays
- Michel parameters, spin physics
- Hadronic sub-structure, resonance parameters
- Tau mass, tau lifetime, tau neutrino mass
- CPV in decay
- production: dipole moments, CPV EDM
- Tau physics at CLEO-II and at CLEO-c

TAU PRODUCTION AT 10 GEV

- In e^+e^- collisions, can study taus in *production* and/or *decay*.
- $e^+e^- \to \gamma^* \to \tau^+\tau^-$ is governed by well-understood QED; not terribly interesting (or at least, nowhere near as interesting as studying $e^+e^- \to \gamma^*/Z^{(*)} \to \tau^+\tau^-$ at LEP I and LEP II)
- Can measure $e^+e^- \to \Upsilon(nS) \to \tau^+\tau^-$ (*e.g.*, for $\Upsilon(1S)$, see CLEO, PLB340:129,1994).
- In addition to overall rate, can search for small anomalous couplings.
- Rather generally, can parameterize these with anomalous magnetic, and (CPV) electric, dipole moments.
- With $\tau^+\tau^-$ final states, can study spin structure of final state; perhaps the most sensitive way to search for anomalous couplings.
- More on anomalous couplings, later.

TAU PRODUCTION AT 10 GEV, 2

- Measuring the *production* rate at CLEO is only interesting if it's precise: $< 1\%$. This has proven to be difficult:
- Tau selection: hard to do an inclusive selection of $\tau^+\tau^-$ final states.
  - backgrounds from $q\bar{q}$, e^+e^-, $\mu^+\mu^-$ and two-photon are less easily distinguishable from $\tau^+\tau^-$ than at LEP, and they depend on tau decay mode.
  - It's not really hard, but it's hard to get *precise* efficiency
- Then, need precise luminosity (error $<< 1\%$)
  - Use large angle Bhabhas (e^+e^-), $\mu^+\mu^-$, $e^+e^- \to \gamma\gamma$
  - To get luminosity, need accurate QED-predicted cross-section times selection efficiency from precision MC (radiative corrections).
  - Much less effort has gone into this at 10 GeV than at LEP!
  - Each of these measurements has negligible statistical errors, systematic errors $\sim 2\%$

  - CLEO gets agreement between the 3 QED processes at the level of 1%, discrepancies likely to be in the MCs. CLEO quotes 1% systematic error on luminosity (Heltsley, NIMA.345:429,1994)

- Moral: need *precision* QED MCs!
- **KKMC** (Jadach, Was, *et al.*) promises precision results, but it *must* be validated with careful computational *and experimental* cross-checks.
- Consistent results for e^+e^-, $\mu^+\mu^-$, $e^+e^- \to \gamma\gamma$ are a good first step!
- Must validate all-important spin-dependence!

Tau decay physics at CLEO

What we can learn from Tau decays:

$\tau \to e\nu\nu$	$\approx 18\%$	Br, universality, Michel Parameters
$\tau \to \mu\nu\nu$	$\approx 17\%$	Br, universality, Michel Parameters
$\tau \to \pi\nu$, $K\nu$	$\approx 12\%$	Br, universality
$\tau \to \pi\pi\nu$	$\approx 25\%$	Br, ρ Propagator, ρ', CVC, Π
$\tau \to K\pi\nu$	$\approx 1.4\%$	Br, K^* Propagator, $K^{*\prime}$
$\tau \to 3\pi\nu$	$\approx 18\%$	Br, a_1 Propagator, a_1', substructure, h_{ν_τ}
$\tau \to K\pi\pi\nu$	$\approx 0.8\%$	Br, K_1 Propagator, K_{1b}, W-Z, substructure
$\tau \to 4\pi\nu$	$\approx 5\%$	Br, ρ' Propagator, substructure, CVC
$\tau \to$ rare	$\approx 2\%$	5π, 6π, KK, $KK\pi$, $K3\pi$, $\eta\pi\pi$, $\eta3\pi$
$\tau \to \eta\pi\nu, b_1\nu$	$\ll 1\%$	second-class currents
$\tau \to$ forbidden	$\ll 1\%$	limits on neutrinoless decays

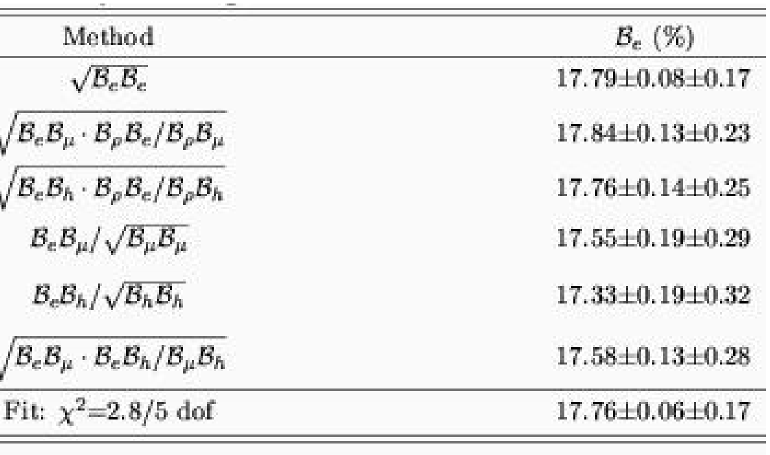
MAJOR DECAY MODES

- In the early 90's, the "tau one-prong" problem was raging;
  BR's for exclusively reconstructed tau decays didn't add up to 1.
- Resolution required precision (sub-1%) BR measurements
- CLEO-II was a new detector; acceptances, in/efficiencies, detector simulation needed to be understood well
- Detection of π^0's: they rarely merged into one shower, great $m_{\gamma\gamma}$ resolution ($\sim$ 6 MeV). BUT, soft photons could get lost.
  "Splitoffs" from hadronic showers could fake photons.
  Overall detection efficiency $\sim 50(1 \pm 0.03)\%$.
- Also, CLEO had poor K/π separation over most of the interesting momentum range.
  We made progress using K^0_S, with detection efficiency $\sim 50\%$.
- *Hard* to know efficiency, after backgrounds, to better than 1%.

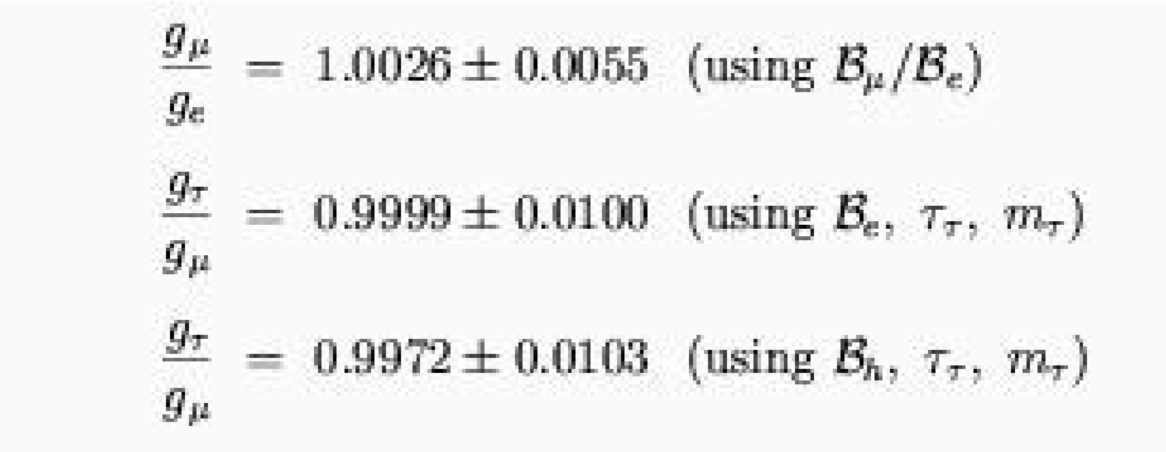
MAJOR DECAY MODES, 2

- Ultimately, BR's were limited by knowledge of luminosity (1%), cross-section (KORALB, $\sim 1\%$), detection eff and bkgnds ($\sim 1-2\%$)
- BUT, with millions of produced $\tau^+\tau^-$, what we lacked in efficiency we made up for in statistics.
- By 1995, we made ($\sim 1-2\%$) measurements of BRs to $e\nu\nu$, $\mu\nu\nu$, $\pi/K\nu$, $\pi\pi^0\nu$, $\pi n\pi^0\nu$, *etc.*.
- Reduced the "tau one-prong" problem to insignificance by PDG 1996.
- Tested $e/\mu/\tau$ charged-current coupling universality at 1% level.
- By then, LEP was measuring branching fractions with total errors much smaller than 1%. Quite a shock to CLEO!
- LEP knew $N_{\tau\tau} = \sigma\mathcal{L}$ quite well, as by-product of EW program.

TEST OF UNIVERSALITY



Method	$\mathcal{B}_e$ (%)
$\sqrt{\mathcal{B}_e\mathcal{B}_e}$	17.79±0.08±0.17
$\sqrt{\mathcal{B}_e\mathcal{B}_\mu \cdot \mathcal{B}_\rho\mathcal{B}_e/\mathcal{B}_\rho\mathcal{B}_\mu}$	17.84±0.13±0.23
$\sqrt{\mathcal{B}_e\mathcal{B}_h \cdot \mathcal{B}_\rho\mathcal{B}_e/\mathcal{B}_\rho\mathcal{B}_h}$	17.76±0.14±0.25
$\mathcal{B}_e\mathcal{B}_\mu/\sqrt{\mathcal{B}_\mu\mathcal{B}_\mu}$	17.55±0.19±0.29
$\mathcal{B}_e\mathcal{B}_h/\sqrt{\mathcal{B}_h\mathcal{B}_h}$	17.33±0.19±0.32
$\sqrt{\mathcal{B}_e\mathcal{B}_\mu \cdot \mathcal{B}_e\mathcal{B}_h/\mathcal{B}_\mu\mathcal{B}_h}$	17.58±0.13±0.28
Fit: χ^2=2.8/5 dof	17.76±0.06±0.17



$$\frac{g_\mu}{g_e} = 1.0026 \pm 0.0055 \quad (\text{using } \mathcal{B}_\mu/\mathcal{B}_e)$$

$$\frac{g_\tau}{g_\mu} = 0.9999 \pm 0.0100 \quad (\text{using } \mathcal{B}_e,\ \tau_\tau,\ m_\tau)$$

$$\frac{g_\tau}{g_\mu} = 0.9972 \pm 0.0103 \quad (\text{using } \mathcal{B}_h,\ \tau_\tau,\ m_\tau)$$

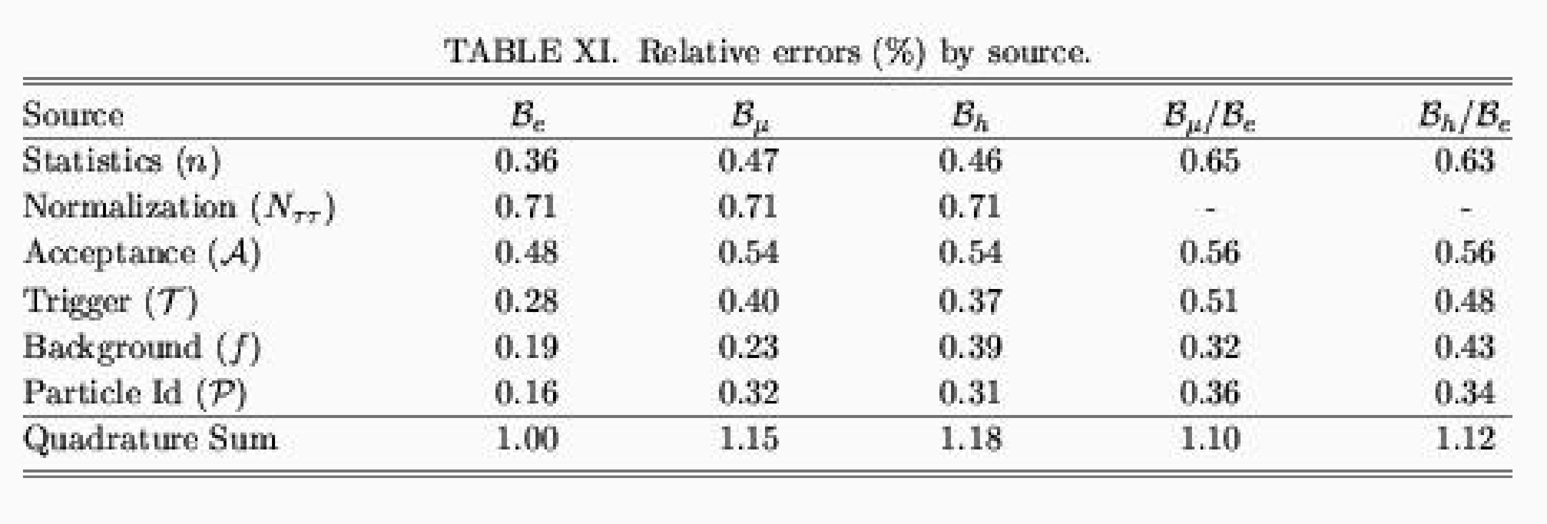


TABLE XI. Relative errors (%) by source.

Source	$\mathcal{B}_e$	$\mathcal{B}_\mu$	$\mathcal{B}_h$	$\mathcal{B}_\mu/\mathcal{B}_e$	$\mathcal{B}_h/\mathcal{B}_e$
Statistics (n)	0.36	0.47	0.46	0.65	0.63
Normalization ($N_{\tau\tau}$)	0.71	0.71	0.71	-	-
Acceptance ($\mathcal{A}$)	0.48	0.54	0.54	0.56	0.56
Trigger ($\mathcal{T}$)	0.28	0.40	0.37	0.51	0.48
Background (f)	0.19	0.23	0.39	0.32	0.43
Particle Id ($\mathcal{P}$)	0.16	0.32	0.31	0.36	0.34
Quadrature Sum	1.00	1.15	1.18	1.10	1.12

CLEO, Phys. Rev. Lett.78:4686 (1997)

RARE MODES - $(n\pi)^{-}\nu$

- With the world's largest sample of tau pairs, here's where CLEO shines!
- Rare modes like 5π, 6π, 7π, $\eta\pi\pi$, $\eta 3\pi$, are relatively easy to reconstruct.
- The big problem is background from $q\bar{q}$. Lepton tags can clean that up reasonably well. But there's an irreducible background.

$$\begin{aligned}
\mathcal{B}(2\pi^-\pi^+2\pi^0\nu_\tau) &= (5.3 \pm 0.4) \times 10^{-3} \\
\mathcal{B}(3\pi^-2\pi^+\nu_\tau) &= (7.8 \pm 0.6) \times 10^{-4} \\
\mathcal{B}(2\pi^-\pi^+3\pi^0\nu_\tau) &= (2.2 \pm 0.5) \times 10^{-4} \\
\mathcal{B}(3\pi^-2\pi^+\pi^0\nu_\tau) &= (1.7 \pm 0.3) \times 10^{-4} \\
\mathcal{B}(\pi^-2\pi^0\omega\nu_\tau) &= (1.5 \pm 0.5) \times 10^{-4} \\
\mathcal{B}(2\pi^-\pi^+\omega\nu_\tau) &= (1.2 \pm 0.3) \times 10^{-4} \\
\mathcal{B}(3\pi^-2\pi^+2\pi^0\nu_\tau) &\quad < 1.1 \times 10^{-4} \\
\mathcal{B}(7\pi^\pm(\pi^0)\nu_\tau) &\quad < 2.4 \times 10^{-6}.
\end{aligned}$$

- rich and complicated sub-structure!

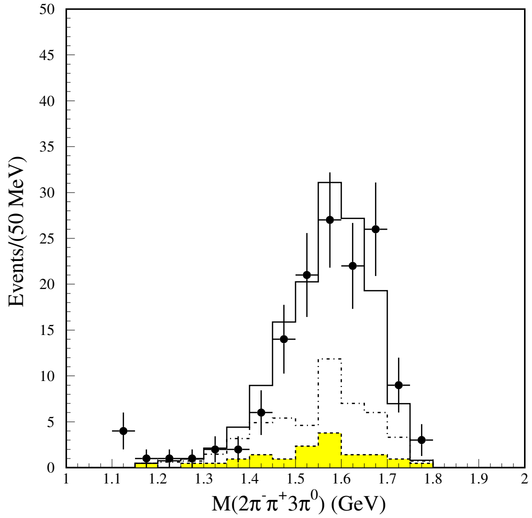
RARE MODES - $\eta X^-\nu$

- Modes with η's:

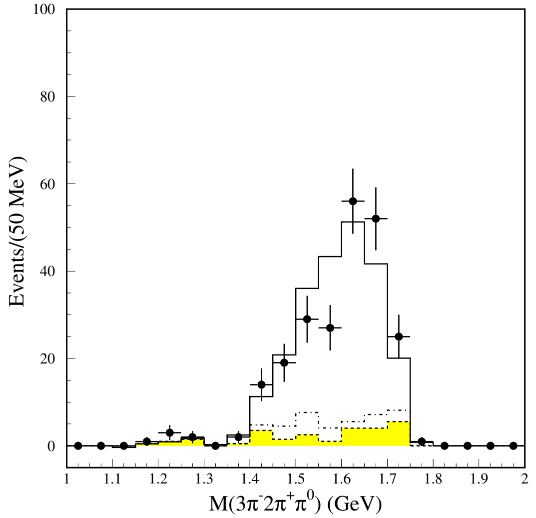
$$\begin{aligned}
\mathcal{B}(\nu_\tau \eta \pi^-) &< 1.4 \times 10^{-4} \text{at 95\% CL (2nd-class current)} \\
\mathcal{B}(\nu_\tau \eta K^-) &= (2.6 \pm 0.5) \times 10^{-4} \text{ (SU(3)}_f\text{-violation)} \\
\mathcal{B}(\nu_\tau \eta \pi^- \pi^0) &= (1.7 \pm 0.3) \times 10^{-3} \text{ (W-Z)} \\
\mathcal{B}(\nu_\tau \eta \pi^- \pi^+ \pi^-) &= (3.4 \pm 0.8) \times 10^{-4} \\
\mathcal{B}(\nu_\tau \eta \pi^- \pi^0 \pi^0) &= (1.4 \pm 0.6) \times 10^{-4} \\
\mathcal{B}(\nu_\tau K^{*-} \eta) &= (2.90 \pm 0.80 \pm 0.42) \times 10^{-4}.
\end{aligned}$$

- Can even delve into substructure, in 5π, 6π, $\eta 3\pi$.
- Even saw $\tau^- \to e^- e^+ e^- \nu\nu$ (5 events) and $\tau^- \to \mu^- e^+ e^- \nu\nu$ (1 event)

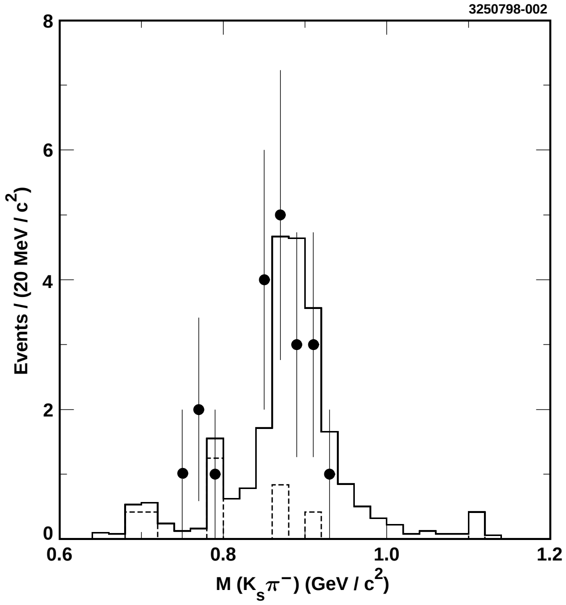
RARE SEMI-HADRONIC DECAYS



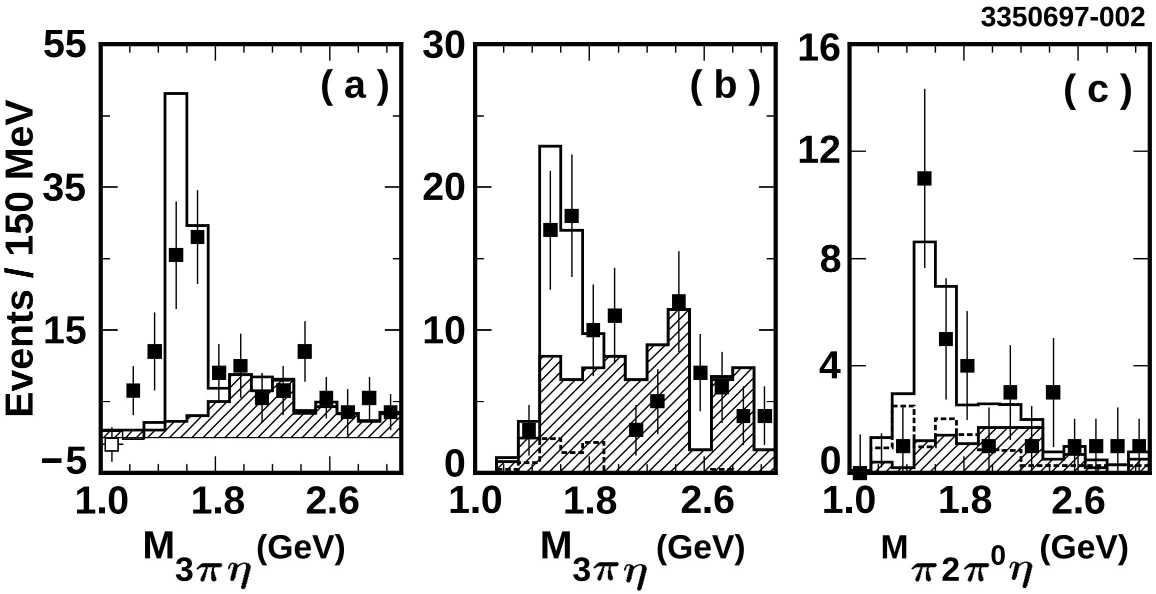
$2\pi^-\pi^+3\pi^0\nu_\tau$



$3\pi^-2\pi^+\pi^0\nu_\tau$



$\tau^- \to K^{*-}\eta\nu_\tau$



$\tau^- \to (3\pi)^-\eta\nu_\tau$

RARE MODES - $X_S^- \nu$

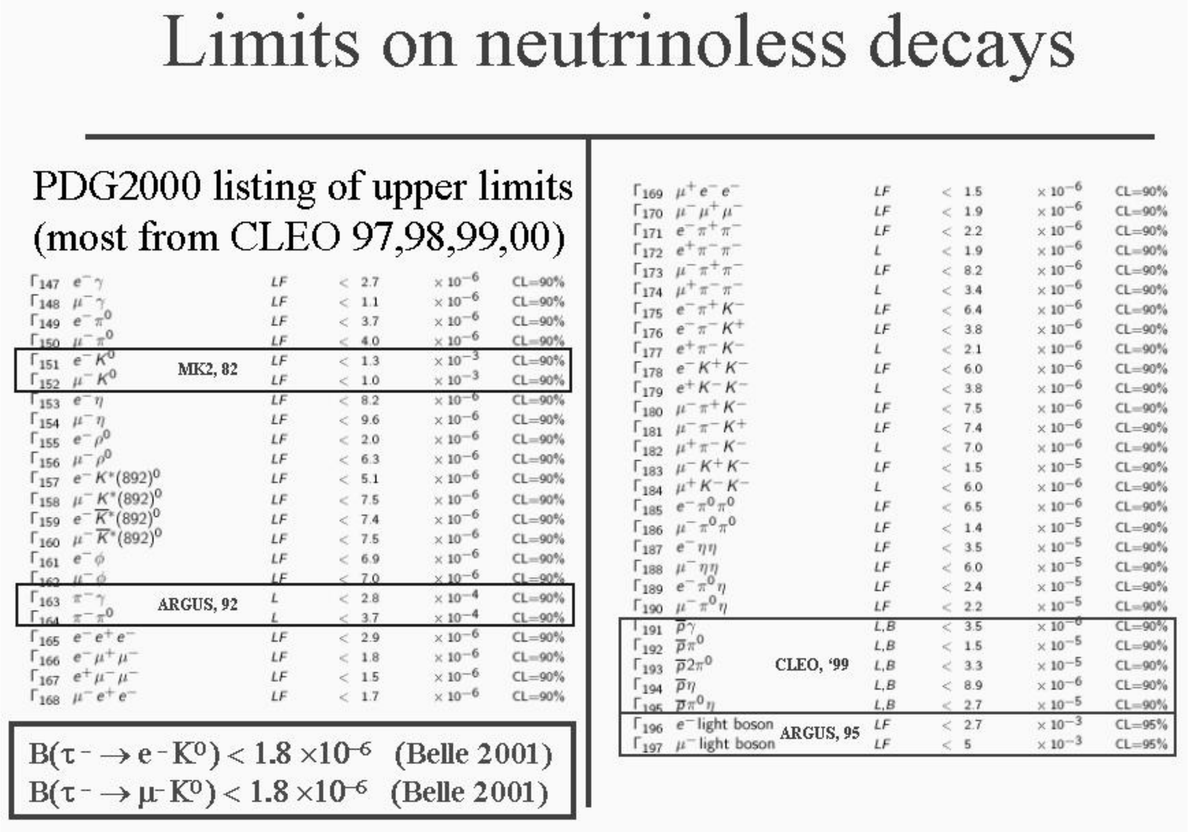
- Modes with K_S^0 are also accessible;
  Even with poor K/π separation ($\sim< 2\sigma$), we can identify KK, $KK\pi$, $K3\pi$, $K\eta$, *etc.*at a statistical level.

τ decay mode	Measurement	Branching fraction, 10^{-2}
$\tau^- \to \bar{K}^0 \pi^- \pi^0 \nu_\tau$	CLEO 96	$0.417 \pm 0.058 \pm 0.044$
$\tau^- \to K^- \pi^+ \pi^- \nu_\tau$	CLEO 98	$0.345 \pm 0.023 \pm 0.055$
$\tau^- \to K^- \pi^0 \pi^0 \nu_\tau$	CLEO 94	$0.14 \pm 0.10 \pm 0.03$
$\tau^- \to K^- K^0 \pi^0 \nu_\tau$	CLEO 96	$0.145 \pm 0.036 \pm 0.020$
$\tau^- \to K^- K^+ \pi^- \nu_\tau$	CLEO 98	$0.144 \pm 0.013 \pm 0.028$
$\tau \to K_S^0 K_S^0 \pi^- \nu_\tau$	CLEO 96	$0.023 \pm 0.005 \pm 0.003$
$\tau^- \to K^- \pi^+ \pi^- \pi^0 \nu_\tau$	CLEO 98	$0.075 \pm 0.026 \pm 0.017$
$\tau^- \to K^- K^+ \pi^- \pi^0 \nu_\tau$	CLEO 98	$0.033 \pm 0.018 \pm 0.007$

- But, LEP-I produced terrific results on modes with kaons, including K_L^0!

FORBIDDEN (NEUTRINOLESS) DECAYS

- Starting with $\mathcal{B}(\tau \to \mu\gamma) < 4.2 \times 10^{-6}$ (90% CL) in 1992
- Improved to 3.0×10^{-6} by 1996 (4.3×10^{6} tau pairs);
  then 1.1×10^{-6} by 1999 (12.6×10^{6} tau pairs).
- Starting to hit background!
- 22 neutrinoless modes in 1994; BR UL's around 10^{-5}.
- Updated in 1997, 28 modes, including resonances; BR UL's $\sim$ few 10^{-6}
- Added 10 more modes with π^0's and/or η's in 1997.
- Five more modes in 1998: $\tau^- \to \bar{p}X^0$.
- Forgot the modes with K^0's!
  New for this conference (PRD accepted), (12.7×10^{6} $\tau^+\tau^-$), at 90% CL:
  $\mathcal{B}(e^-K^0_S) < 9.1 \times 10^{-7}$ $\qquad$ $\mathcal{B}(\mu^-K^0_S) < 9.5 \times 10^{-7}$
  $\mathcal{B}(e^-K^0_SK^0_S) < 2.2 \times 10^{-6}$ $\qquad$ $\mathcal{B}(\mu^-K^0_SK^0_S) < 3.4 \times 10^{-6}$



Limits on neutrinoless decays

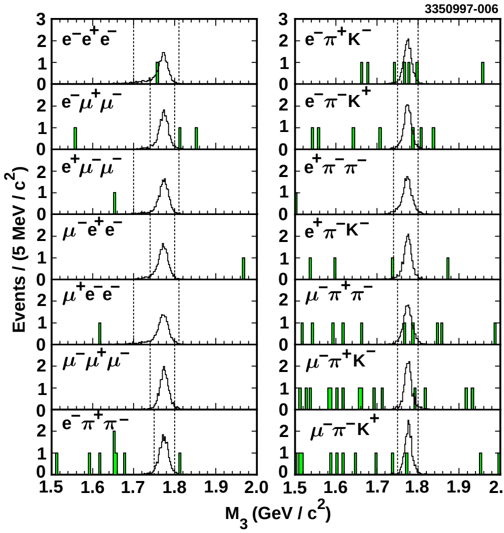
PDG2000 listing of upper limits (most from CLEO 97,98,99,00)

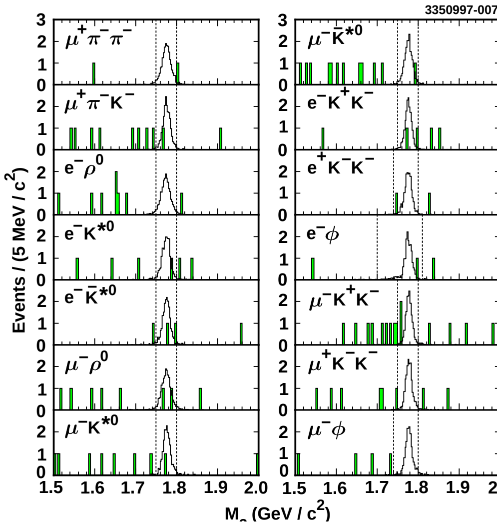
Γ_{147}	$e^- \gamma$		LF	< 2.7	$\times 10^{-6}$	CL=90%
Γ_{148}	$\mu^- \gamma$		LF	< 1.1	$\times 10^{-6}$	CL=90%
Γ_{149}	$e^- \pi^0$		LF	< 3.7	$\times 10^{-6}$	CL=90%
Γ_{150}	$\mu^- \pi^0$		LF	< 4.0	$\times 10^{-6}$	CL=90%
Γ_{151}	$e^- K^0$	MK2, 82	LF	< 1.3	$\times 10^{-3}$	CL=90%
Γ_{152}	$\mu^- K^0$		LF	< 1.0	$\times 10^{-3}$	CL=90%
Γ_{153}	$e^- \eta$		LF	< 8.2	$\times 10^{-6}$	CL=90%
Γ_{154}	$\mu^- \eta$		LF	< 9.6	$\times 10^{-6}$	CL=90%
Γ_{155}	$e^- \rho^0$		LF	< 2.0	$\times 10^{-6}$	CL=90%
Γ_{156}	$\mu^- \rho^0$		LF	< 6.3	$\times 10^{-6}$	CL=90%
Γ_{157}	$e^- K^*(892)^0$		LF	< 5.1	$\times 10^{-6}$	CL=90%
Γ_{158}	$\mu^- K^*(892)^0$		LF	< 7.5	$\times 10^{-6}$	CL=90%
Γ_{159}	$e^- \overline{K}^*(892)^0$		LF	< 7.4	$\times 10^{-6}$	CL=90%
Γ_{160}	$\mu^- \overline{K}^*(892)^0$		LF	< 7.5	$\times 10^{-6}$	CL=90%
Γ_{161}	$e^- \phi$		LF	< 6.9	$\times 10^{-6}$	CL=90%
Γ_{162}	$\mu^- \phi$		LF	< 7.0	$\times 10^{-6}$	CL=90%
Γ_{163}	$\pi^- \gamma$	ARGUS, 92	L	< 2.8	$\times 10^{-4}$	CL=90%
Γ_{164}	$\pi^- \pi^0$		L	< 3.7	$\times 10^{-4}$	CL=90%
Γ_{165}	$e^- e^+ e^-$		LF	< 2.9	$\times 10^{-6}$	CL=90%
Γ_{166}	$e^- \mu^+ \mu^-$		LF	< 1.8	$\times 10^{-6}$	CL=90%
Γ_{167}	$e^+ \mu^- \mu^-$		LF	< 1.5	$\times 10^{-6}$	CL=90%
Γ_{168}	$\mu^- e^+ e^-$		LF	< 1.7	$\times 10^{-6}$	CL=90%

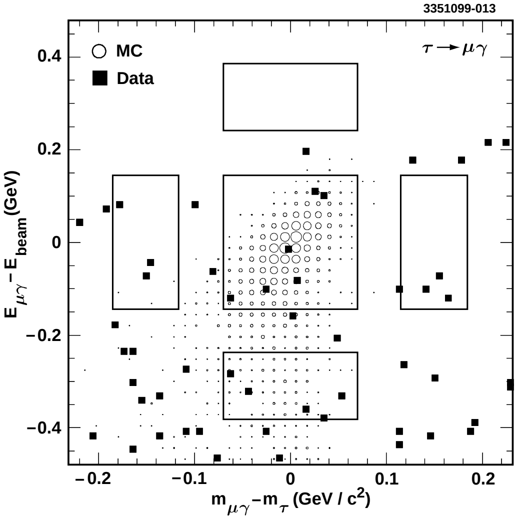
$B(\tau^- \rightarrow e^- K^0) < 1.8 \times 10^{-6}$ (Belle 2001)

$B(\tau^- \rightarrow \mu^- K^0) < 1.8 \times 10^{-6}$ (Belle 2001)

Γ_{169}	$\mu^+ e^- e^-$		LF	< 1.5	$\times 10^{-6}$	CL=90%
Γ_{170}	$\mu^- \mu^+ \mu^-$		LF	< 1.9	$\times 10^{-6}$	CL=90%
Γ_{171}	$e^- \pi^+ \pi^-$		LF	< 2.2	$\times 10^{-6}$	CL=90%
Γ_{172}	$e^+ \pi^- \pi^-$		L	< 1.9	$\times 10^{-6}$	CL=90%
Γ_{173}	$\mu^- \pi^+ \pi^-$		LF	< 8.2	$\times 10^{-6}$	CL=90%
Γ_{174}	$\mu^+ \pi^- \pi^-$		L	< 3.4	$\times 10^{-6}$	CL=90%
Γ_{175}	$e^- \pi^+ K^-$		LF	< 6.4	$\times 10^{-6}$	CL=90%
Γ_{176}	$e^- \pi^- K^+$		LF	< 3.8	$\times 10^{-6}$	CL=90%
Γ_{177}	$e^+ \pi^- K^-$		L	< 2.1	$\times 10^{-6}$	CL=90%
Γ_{178}	$e^- K^+ K^-$		LF	< 6.0	$\times 10^{-6}$	CL=90%
Γ_{179}	$e^+ K^- K^-$		L	< 3.8	$\times 10^{-6}$	CL=90%
Γ_{180}	$\mu^- \pi^+ K^-$		LF	< 7.5	$\times 10^{-6}$	CL=90%
Γ_{181}	$\mu^- \pi^- K^+$		LF	< 7.4	$\times 10^{-6}$	CL=90%
Γ_{182}	$\mu^+ \pi^- K^-$		L	< 7.0	$\times 10^{-6}$	CL=90%
Γ_{183}	$\mu^- K^+ K^-$		LF	< 1.5	$\times 10^{-5}$	CL=90%
Γ_{184}	$\mu^+ K^- K^-$		L	< 6.0	$\times 10^{-6}$	CL=90%
Γ_{185}	$e^- \pi^0 \pi^0$		LF	< 6.5	$\times 10^{-6}$	CL=90%
Γ_{186}	$\mu^- \pi^0 \pi^0$		LF	< 1.4	$\times 10^{-5}$	CL=90%
Γ_{187}	$e^- \eta \eta$		LF	< 3.5	$\times 10^{-5}$	CL=90%
Γ_{188}	$\mu^- \eta \eta$		LF	< 6.0	$\times 10^{-5}$	CL=90%
Γ_{189}	$e^- \pi^0 \eta$		LF	< 2.4	$\times 10^{-5}$	CL=90%
Γ_{190}	$\mu^- \pi^0 \eta$		LF	< 2.2	$\times 10^{-5}$	CL=90%
Γ_{191}	$\overline{p} \gamma$		L,B	< 3.5	$\times 10^{-6}$	CL=90%
Γ_{192}	$\overline{p} \pi^0$		L,B	< 1.5	$\times 10^{-5}$	CL=90%
Γ_{193}	$\overline{p} 2\pi^0$	CLEO, '99	L,B	< 3.3	$\times 10^{-5}$	CL=90%
Γ_{194}	$\overline{p} \eta$		L,B	< 8.9	$\times 10^{-6}$	CL=90%
Γ_{195}	$\overline{p} \pi^0 \eta$		L,B	< 2.7	$\times 10^{-5}$	CL=90%
Γ_{196}	e^- light boson	ARGUS, 95	LF	< 2.7	$\times 10^{-3}$	CL=95%
Γ_{197}	μ^- light boson		LF	< 5	$\times 10^{-3}$	CL=95%





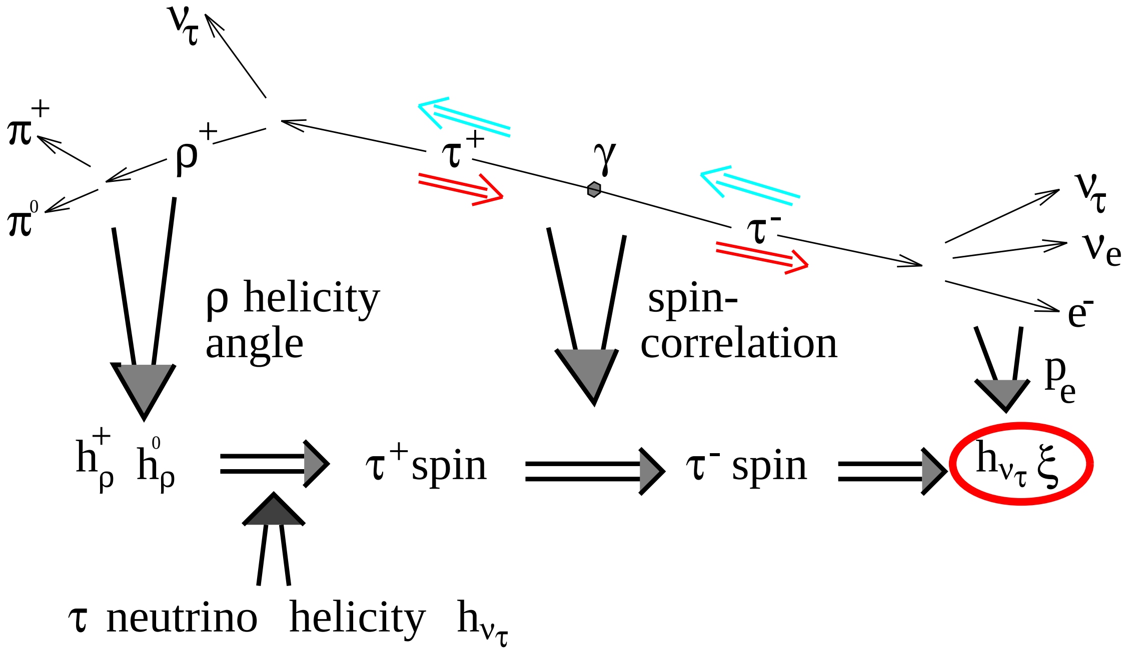


FOUR CLEO MICHEL PARAMETER ANALYSES

- Select $\ell^- \overline{\nu} \nu_\tau$ *vs.* $\pi^+ \pi^0 \, \overline{\nu}_\tau$;
  Use $\pi^\pm \pi^0$ as tag. Lepton energy spectrum ⇒ ρ, η
- Select $\pi^- \nu_\tau$ *vs.* $\pi^+ \overline{\nu}_\tau$;
  spin correlations ⇒ $|h_{\nu_\tau}|^2$
- Select $\ell^- \overline{\nu} \nu_\tau$ *vs.* $\pi^+ \pi^0 \, \overline{\nu}_\tau$;
  Use $\pi^\pm \pi^0$ as spin analyzer.
  Full event kinematics ⇒ ρ, η, ξ, δ, $|h_{\nu_\tau}|$
- Select $\ell^- \overline{\nu} \nu_\tau$ *vs.* $\pi^+ \pi^0 \, \pi^0 \, \overline{\nu}_\tau$;
  Exploit interference between two $\rho\pi$ amplitudes;
  Full event kinematics ⇒ PV-signed h_{ν_τ}
- Limits on Lorentz couplings, $W_R^\pm$, $H^\pm$ masses

Exploiting spin correlations

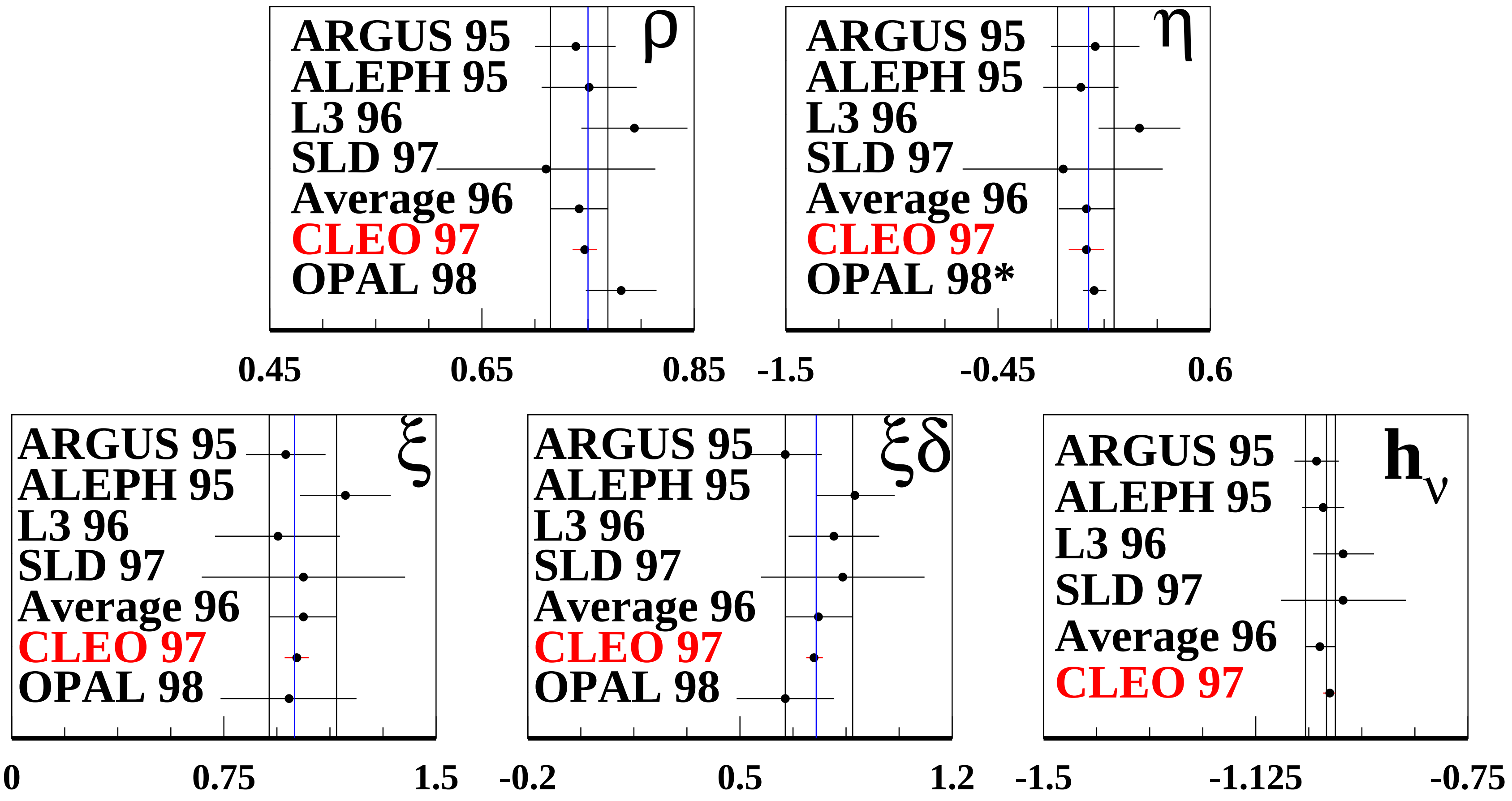
To make full use of kinematical information,
do full multi-dimensional likelihood fit:



$$
\begin{aligned}
|\mathcal{M}|^2 \quad = \quad & H_1 \times P \times [L_1 + \rho L_2 + \eta L_3] \\
& + h_{\nu_\tau} H'_{1\alpha} \times C^{\alpha\beta} \times [\xi L'_{1\beta} + \xi\delta L'_{2\beta}]
\end{aligned}
$$

Combined fit to e *vs.* ρ, μ *vs.* ρ, and ρ *vs.* ρ $\Longrightarrow$ ρ, (η), $|h_{\nu_\tau}\xi|$, $|h_{\nu_\tau}\xi\delta|$, $|h_{\nu_\tau}|^2$

RESULTS FOR ALL MICHEL PARAMETERS

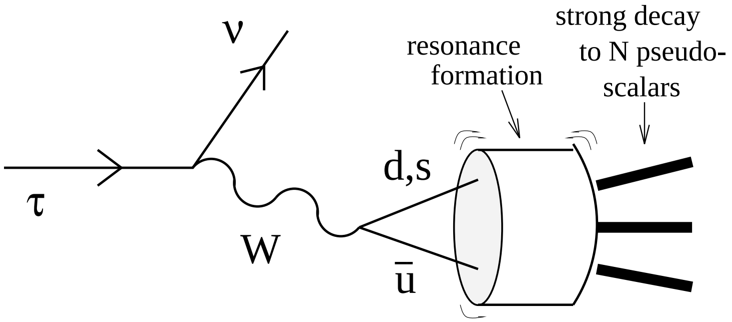


ρ and η: Phys. Rev. Lett. 78, 4686 (1997);

ρ (updated), ξ, $\xi\delta$ and h_{ν_τ}: Phys. Rev. D. 56, 5320 (1997).

(* η constrained by branching fraction)

HADRONIC SUBSTRUCTURE IN TAU DECAYS

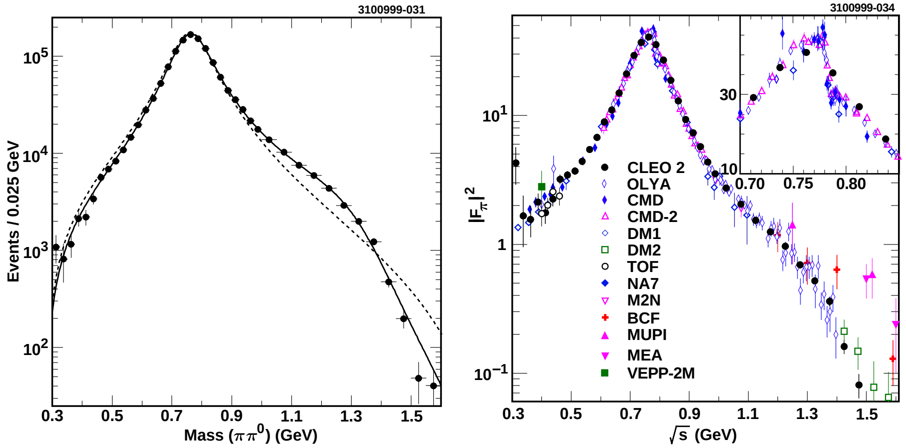


- a clean probe of low energy meson dynamics
- Strong dynamics is the weakest part of the SM!
- No fundamental theory to characterize hadronic structure in detail: must rely on models, symmetries and conservation laws, CVC, sum rules, Chiral perturbation theory, QCD on the lattice
- momentum transfer small in τ decays $\Longrightarrow$ Resonance dominance $\Longrightarrow$ Models
- Parameterized in tau decays via $v(q^2)$, the 'spectral fnctn' containing strong dynamics.
- CLEO can measure $v(q^2)$ using exclusive final states; more problematic to do inclusive studies

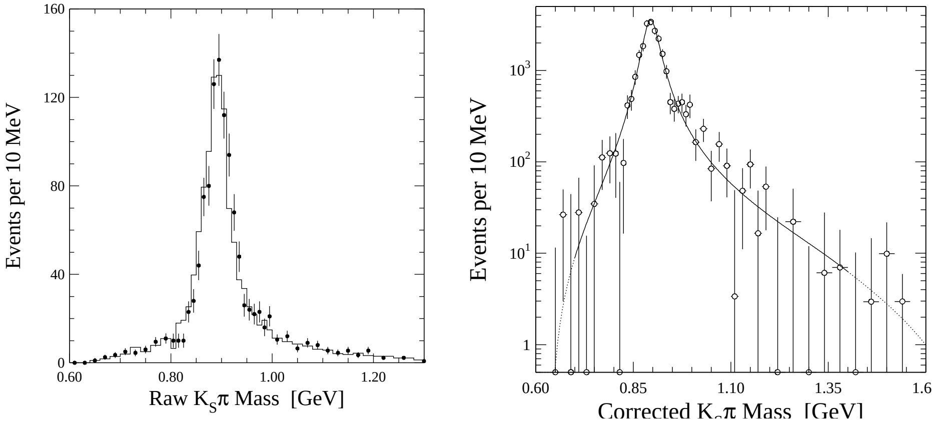
- $\tau^- \to \pi^- \pi^0 \nu_\tau$
- $\tau^- \to (3\pi)^- \nu_\tau$
- $\tau^- \to (4\pi)^- \nu_\tau$
- $\tau^- \to (5\pi)^- \nu_\tau, \ (6\pi)^- \nu_\tau$
- $\tau^- \to (K\pi\pi)^- \nu_\tau$
- $\tau^- \to \eta(K\pi)^- \nu_\tau$
- $\tau^- \to \eta\pi^- \pi^0 \nu_\tau$

TAU → HADRONS RESONANT STRUCTURE, 1

- $\tau^- \to \pi^- \pi^0 \nu_\tau$:
  Mass and width of ρ^- meson,
  pion form factor $|F_\pi(q^2)|$;
  Mass/width/coupling of ρ'^- meson,
  tests of CVC in comparison with $e^+e^- \to \pi^+\pi^-$

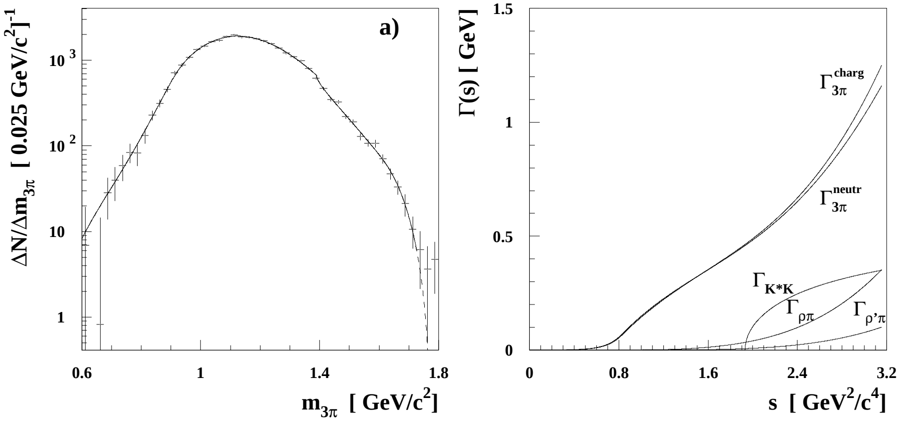


- $\tau^- \to \pi^- K^0 \nu_\tau$:
  Mass and width of K^{*-} meson,
  decay constant f_{K^*};
  Mass/width/coupling of $K^{*\prime-}$
  TAU96 (NPB), never published.
  Note K^* mass shift!

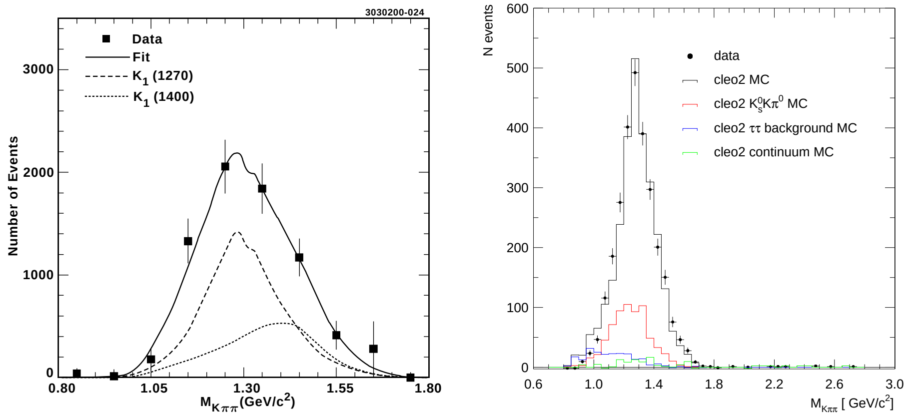


TAU → HADRONS RESONANT STRUCTURE, 2

- $\tau^- \to 3\pi\nu_\tau$:
  RICH structure: scalars, tensors; coupling of tau (decay constant f_{a_1});
  Neutrino helicity h_{ν_τ}
  Model-dependent analysis *and*
  Model-indep. structure functions.

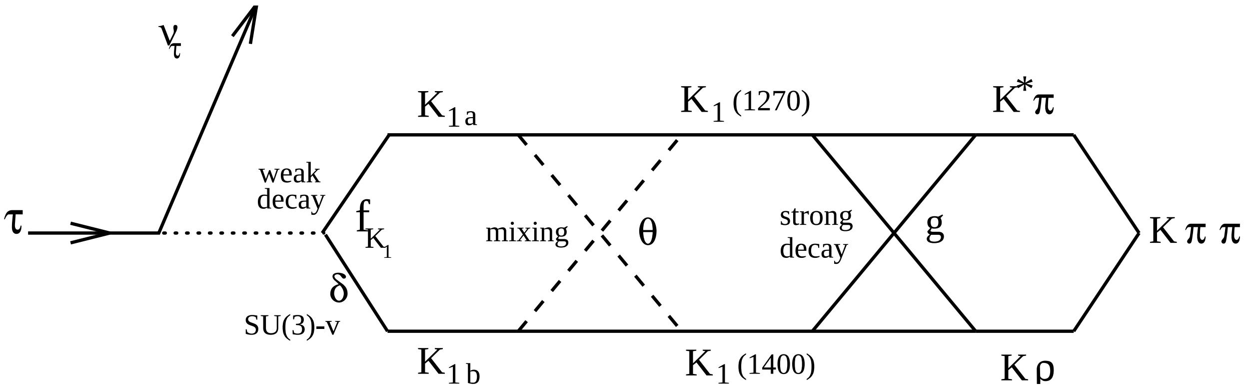


- $\tau^- \to (K\pi\pi)^-\nu_\tau$:
  Mass, width, BR's of K_1 mesons, mixing, SU(3) violating couplings, coupling of tau
  (decay constant f_{K_1}).
  $K^-\pi^+\pi^-\nu_\tau$ published in 2000;
  $K^0_S\pi^-\pi^0\nu_\tau$ *still* in progress



$\tau^- \to K_1^- \nu_\tau$ STRUCTURE

- observed in the final states $K^-\pi^+\pi^-\nu_\tau$ and $K_S^0\pi^-\pi^0\nu_\tau$
- There are two axial-vector ($J^P = 1^+$) states:
  K_a in the ${}^3P_1$ octet, strange partner of the $a_1(1260)$;
  K_b in the ${}^1P_1$ octet, strange partner of the $b_1(1235)$.
  K_b couples to W as SU(3)-violating "second-class" current.
- Both decay to $K\pi\pi$ via $K^*\pi$ and $K\rho$, mix into $K_1(1270)$, $K_1(1400)$
- So, we have weak coupling, SU(3)-violation, and mixing.
- Also, vector current via Wess-Zumino: $K^{*\prime} \to (K^*\pi, K\rho) \to K\pi\pi$.



K_a-K_b MIXING IN $\tau^- \to K^-\pi^+\pi^-\nu_\tau$

- $K_{1a} \leftrightarrow K_{1b}$ mixing:
  $K_1(1400) = K_a \cos\theta_K - K_b \sin\theta_K$
  $K_1(1270) = K_a \sin\theta_K + K_b \cos\theta_K$
- $SU(3)_f$ symmetry breaking in $\tau \to W \to |K_a\rangle - \delta|K_b\rangle$
  $|\delta| = (m_s - m_u)/\sqrt{2}(m_s + m_u) \approx 0.18$

$$\frac{\mathcal{B}(\tau \to K_1(1270)\nu)}{\mathcal{B}(\tau \to K_1(1400)\nu)} = \left|\frac{\sin\theta_K - \delta\cos\theta_K}{\cos\theta_K + \delta\sin\theta_K}\right|^2 \times \Phi^2$$

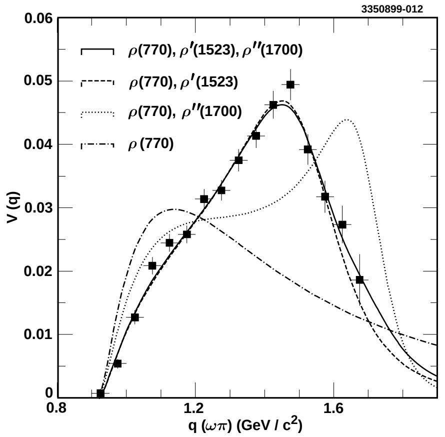
- Two possible solutions, depending upon the sign of δ:

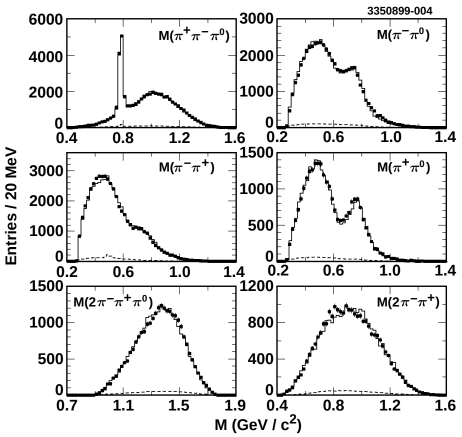
$$\theta_K = (69 \pm 16 \pm 19)^\circ \quad (\delta = 0.18),$$
$$\theta_K = (49 \pm 16 \pm 19)^\circ \quad (\delta = -0.18).$$

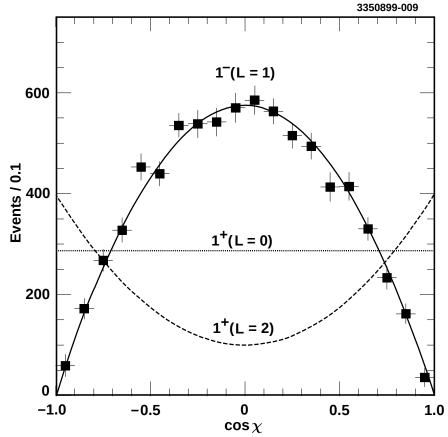
- Suzuki (PRD47, 1252, 1993) finds 57° and 33° from K_1 widths and BRs.

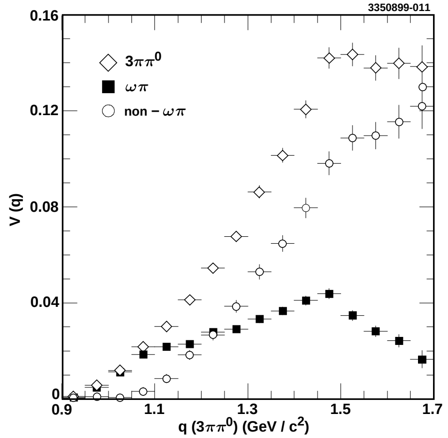
$\tau^- \to (4\pi)^- \nu_\tau$

- $\tau \to 4\pi\nu$ through vector current $(J^P = 1^-)$
- J^μ is dominated by ρ, ρ', ρ''... resonances
- resonant decomposition of 4π system
  $(\omega\pi,\ \eta\pi,\ a_1\pi)$
- search for second class (axial) currents
  e.g., $\tau \to b_1\nu_\tau$, $b_1 \to \omega\pi$ (G-parity viol)
- Must know spectral function
  for m_{ν_τ} measurements
  (CLEO 1999: $m_{\nu_\tau} < 28$ MeV/c^2, 95% CL
- CVC tests,
  comparing $e^+e^- \to 2\pi^+2\pi^-$, $\pi^+\pi^-2\pi^0$
  to $\tau^- \to \nu_\tau 2\pi^-\pi^+\pi^0$, $\pi^- 3\pi^0$



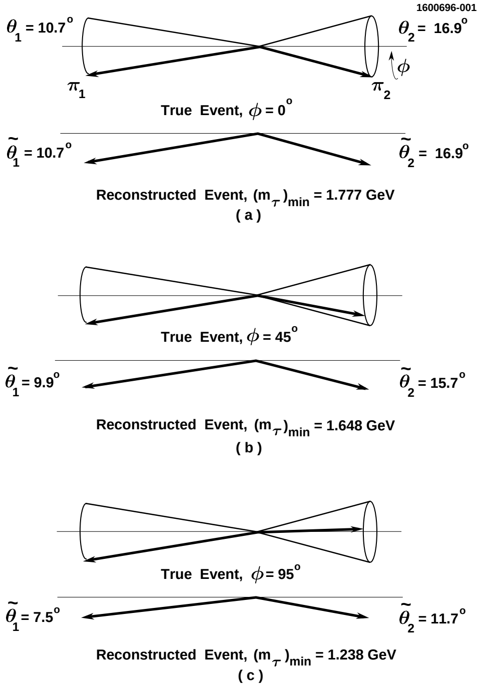


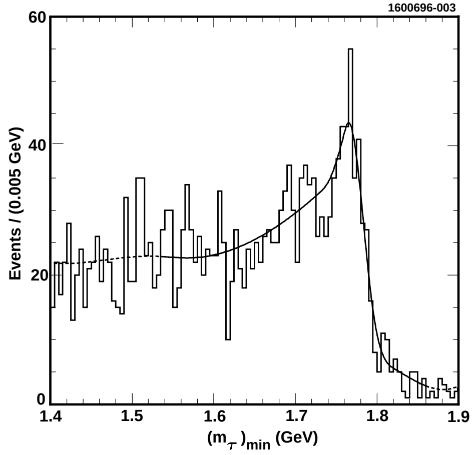




Tau mass and lifetime

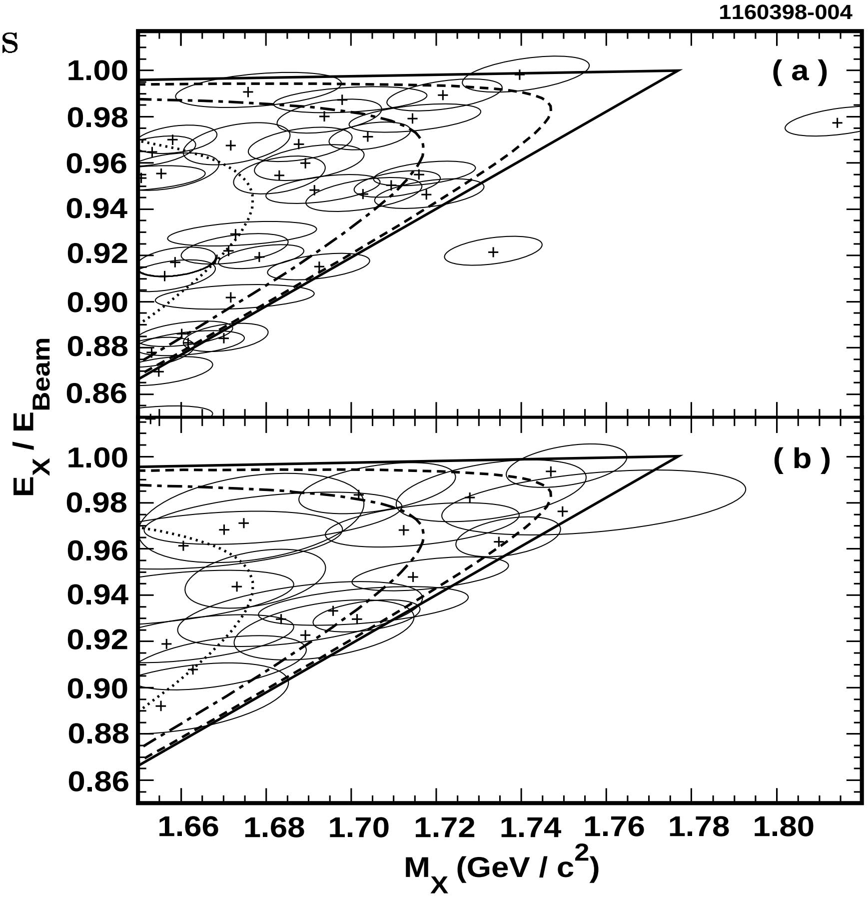
- CLEO used kinematic constraints to measure the tau mass $m_\tau = (1778.2 \pm 1.4)$ MeV
- When coupled with the (much better) mass measurement from BES, it constrains $m(\nu_\tau)$ as well: $m_\tau^{fit} \simeq m_\tau^{BES} - m_{\nu_\tau}^2/m_0$ $m(\nu_\tau) < 60$ MeV, 95% CL
- CLEO II used 1-v-3 and 3-v-3 events with vertex, beam position info, to measure: $\tau_\tau = 289.0 \pm 2.8 \pm 4.0$ fs
- CLEO II.V introduced precision SVD; ???





TAU NEUTRINO MASS

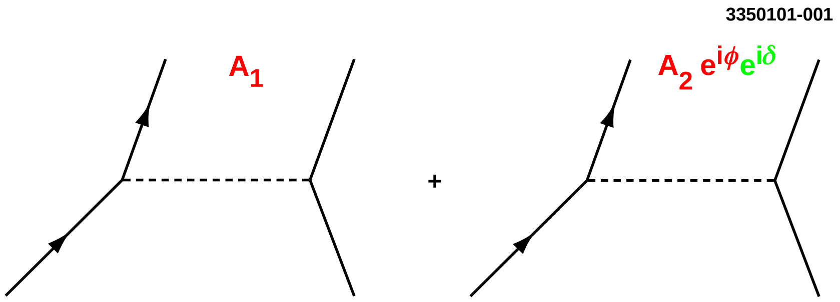
- Regardless of $m(\nu_\tau)$ constraints from ν-mixing and cosmology, constraining it kinematically in tau decays remains a worthy goal...
- ALEPH limit from 1998 still stands:
  $m^{eff}(\nu_\tau) < 18.2$ MeV (95% CL)
- CLEO has 3 limits:
  $m^{eff}(\nu_\tau) < 32.6$ MeV, 1993, $5\pi, 3\pi 2\pi^0$
  $m^{eff}(\nu_\tau) < 30$ MeV, 1998, $5\pi, 3\pi 2\pi^0$
  $m^{eff}(\nu_\tau) < 28$ MeV, 2000, $3\pi\pi^0$
  last 2 used 2-D technique from LEP
- To reach ~ 1 MeV level requires:
  - Lots of statistics
  - excellent, well-understood resolution
  - Good spectral function models
  - **Command** of statistics and systematics - there are many subtleties!

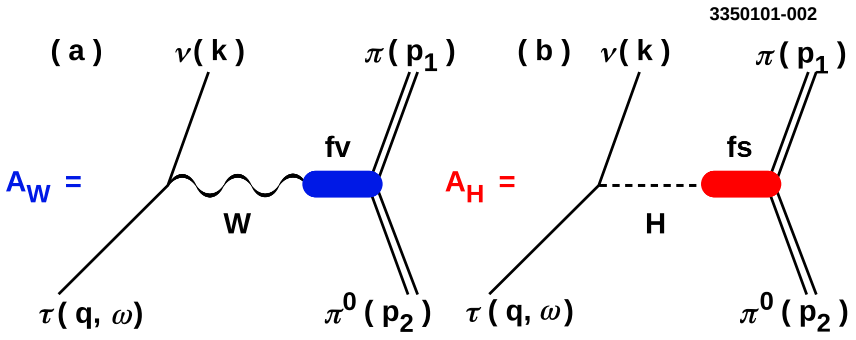


CPV IN DECAY

In tau decay via the charged weak current:

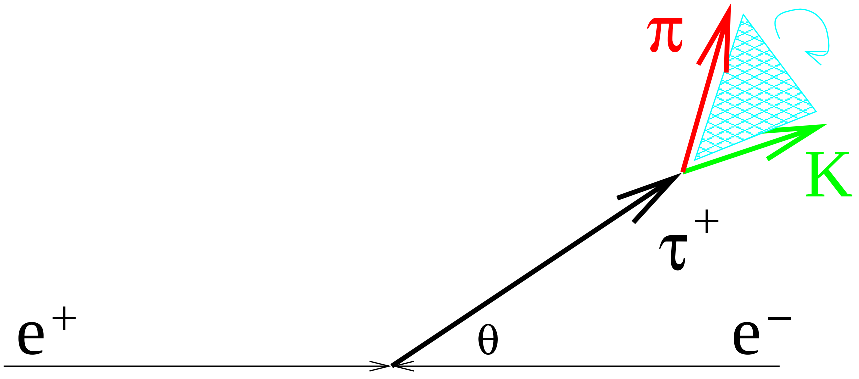
- NOT expected in leptonic decays (in SM)
  - need 2 or more interfering amplitudes, and weak phases ala CKM
  - μ, τ decay via one amplitude: $\tau^- \to W^- \nu_\tau$
  - leptons are fermions, no mixing
- $\tau \nu_\tau W$ coupling studied at CLEO, LEP.
- add 2nd amplitude (such as a charged Higgs: $\tau^- \to H^- \nu_\tau$); complex weak phase flips sign under CP, and strong phase supplied by $W \to \rho$ or K^*
- CLEO search using $\tau^- \to (K\pi)^- \nu_\tau$
- CLEO search using $\tau^+ \tau^- \to (\rho^- \nu_\tau)(\rho^+ \overline{\nu}_\tau)$.



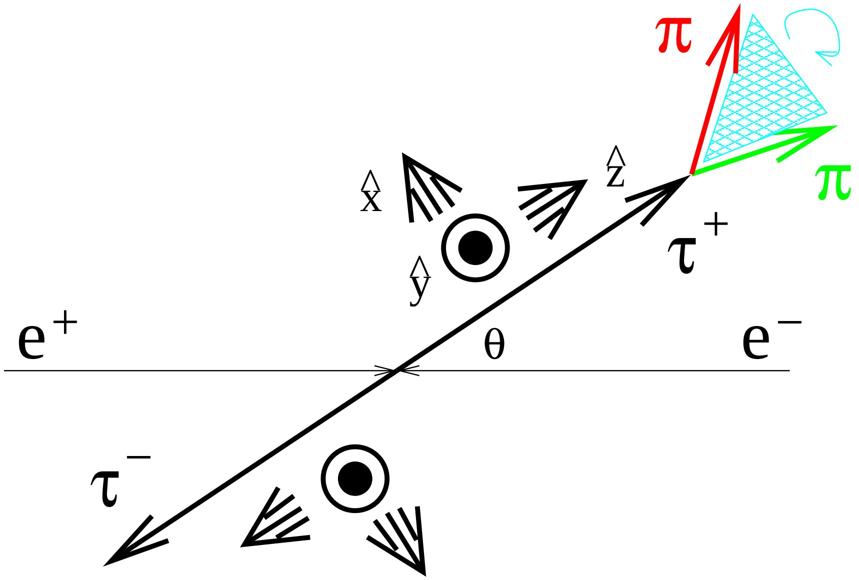


CPV IN DECAY

- CPv in single tau decays $\tau \rightarrow K\pi\nu_\tau$ (relies on violation of $\mathrm{SU}(3)_f$). Does the K preferentially lie above or below the $e^+\tau^+$ plane?

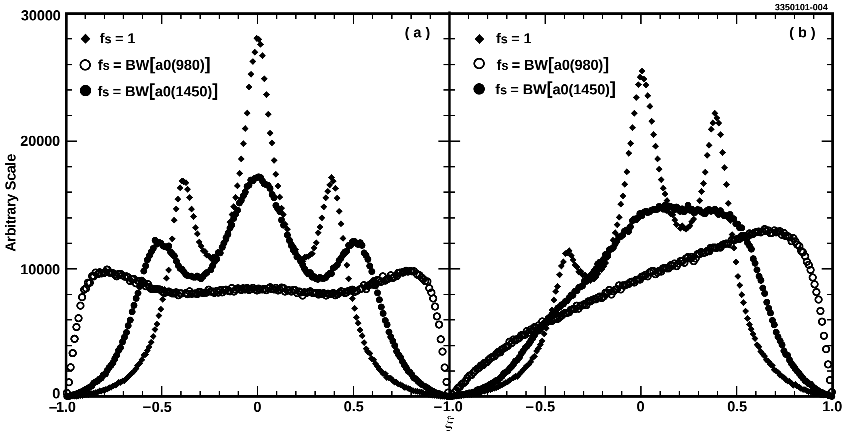


- CPv in tau pair decays $\tau \rightarrow \pi\pi\nu_\tau$ (relies on violation of isospin) . Does the π^+ preferentially lie above or below the planes normal to the tau spin direction, as measured using the other tau decay?

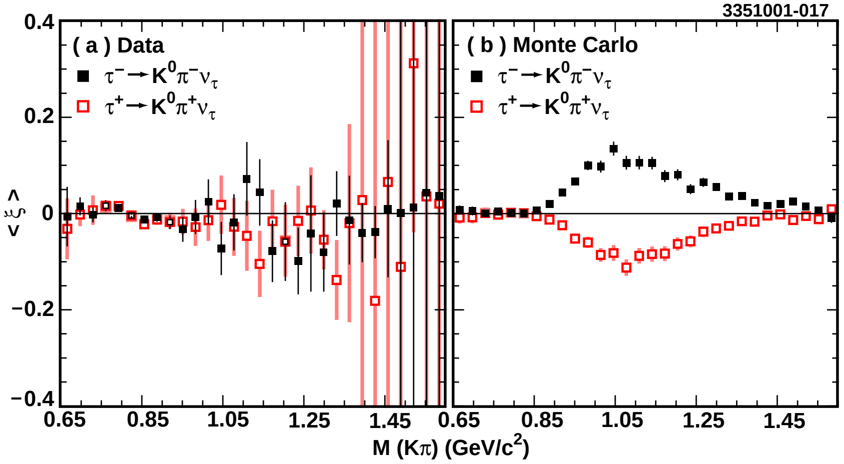


CPV IN DECAY

- 12.2M tau pairs
  $\pi^+\pi^0\bar{\nu}$ -vs- $\pi^-\pi^0\nu$
- Use all info in event;
  construct optimal CP-odd observable ξ (model-dependent)
- $<\xi>$ consistent with 0 $\Longrightarrow$
  $-0.033 < \Im(\Lambda) < 0.089$ 90

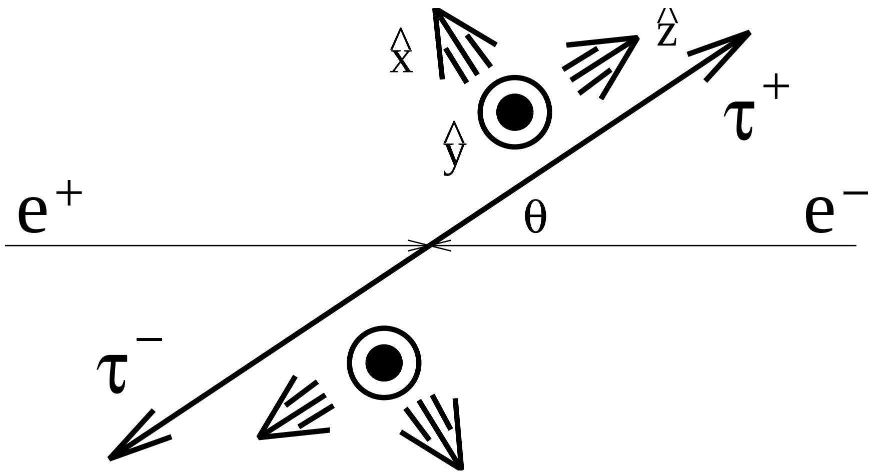


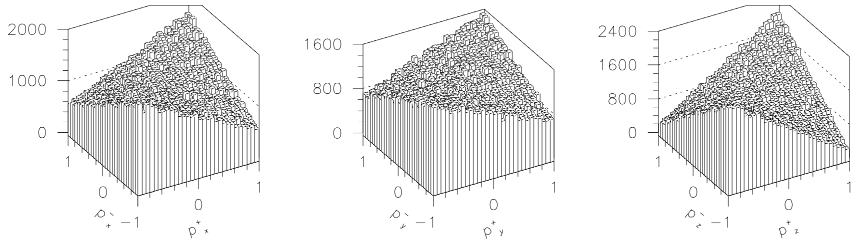
- 12.2M tau pairs
  $\pi^\pm K^0_S\nu$ -vs- any-tag
- construct optimal CP-odd observable ξ from CP-odd-signed interference between vector K^* and scalar $K^*_0(1430)$ (model-dependent)
- $<\xi>$ consistent with 0 $\Longrightarrow$
  $-0.172 < \Im(\Lambda) < 0.067$ 90



PRODUCTION: DIPOLE MOMENTS, CPV EDM

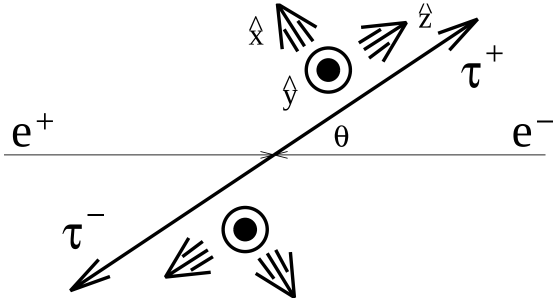
- Best sensitivity to anomalous dipole moments can be obtained by studying the spin correlations in $e^+e^- \to \gamma^* \to \tau^+\tau^-$ events.
- Work on this subject has been reported in (the last?) thesis with ARGUS data (Graf), and results from Belle.
- From CLEO ... nada!
- If the tau dipole moments are not anomalously large, then (far below the Z^0 peak) the taus in $\tau^+\tau^-$ events have very small net spin polarization.
- However, their spin polarizations are almost 100% correlated, in all three dimensions.
- Worthwhile to measure, as test of QED!



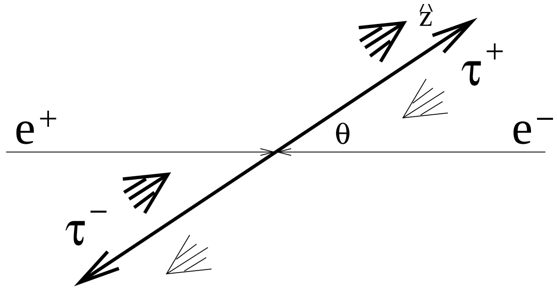


SPIN CORRELATIONS VS E_{cm}

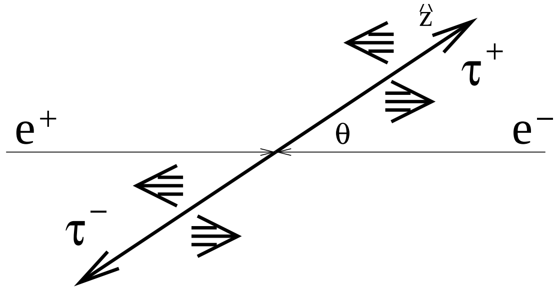
At 10 GeV, taupairs are produced via γ^*, P-conserving, at energies where the taus are relativistic but not extremely so. Both longitudinal and transverse spin correlations are maintained.



At LEP, taupairs are produced via Z^0, P-violating, at energies where the taus are extremely relativistic. Only longitudinal spin correlations are maintained, and there is a net polarization.



Near $\tau^+\tau^-$ threshold, taupairs are produced via γ^*, P-conserving, with taus nearly at rest. The spin correlations are dominantly along the direction of the e^+e^- beam axis.



Moral: Different beam energies $\Longrightarrow$

different optimal observables for anomalous dipole moments, CPV

TAU PHYSICS AT CLEO-III

- CLEO-III has 9×10^6 produced $\tau^+\tau^-$ near 10 GeV,
  with good K/π separation
- Also $\sim 3 \times 10^6$ fb^{-1} on $\Upsilon(nS)$ for $\mathcal{B}(\Upsilon(nS) \to \tau^+\tau^-)$
- rare decays, modes with kaons, precision measurements
- More tests of CP in τ system: $h_{\nu_\tau} = -h_{\bar{\nu}_\tau}$
- Rare decays may be seen: *e.g.*, 2nd class currents
- Limits (observation?) on LFV decays
- anomalous (eg, CPv) couplings in weak decay or in QED production
- exotica ($e.g.$, $\tau^- \to \pi^- \nu_{heavy}$, $e^- G^0$)
- keep testing and developing models of meson dynamics
  as a guide towards more fundamental theory:
  Structure of $\tau \to 4\pi\nu_\tau$, $K3\pi\nu_\tau$, $\eta 2\pi\nu_\tau$, $\eta 3\pi\nu_\tau$, *etc.*

TAU PHYSICS AT CLEO-C, NEAR/AT $\tau^+\tau^-$ THRESHOLD

- Everything on the CLEO-III list, with unique kinematical constraints
  - Monochromatic $\tau \to \pi\nu$ tag eliminates backgrounds
  - Branching fractions to sub-1% levels
- m_τ (to $\sim$ 0.1 MeV?), $m(\nu_\tau)$ (better than 10 MeV?)
- Spin correlations near $\tau^+\tau^-$ threshold:
  tests of QED, anomalous couplings
- Greater precision in Michel Parameters, esp η
  - Near $\tau^+\tau^-$ threshold, new techniques become available due to unique kinematics and spin correlations

CLEO-c tau-charm factory has a bright future in tau physics!