Backgrounds to τ studies below charm threshold

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Abstract

Using DELCO data obtained at SPEAR, we evaluate the backgrounds to $\tau^+\tau^-$ data samples below open charm threshold at the τ-charm Factory (τcF). With a single-tagging signature (electron and missing energy, E_{miss}), which is unique to the τcF, the backgrounds are found to be below 0.1%.

1 Requirements for future τ data samples

In order to make significant progress in τ physics, future data samples must have:

1. high statistics,
2. low backgrounds, and
3. reduced systematic biases.

The precisions of current measurements are limited by one or more of these aspects. For example, searches for rare decays are generally limited only by statistics, whereas an improved sensitivity to the ν_τ mass requires both more statistics and a reduction of heavy-flavour backgrounds. On the other hand, present measurements of the exclusive one-prong branching ratios are limited by systematics and backgrounds and by the need for better detector performance, rather than by statistics.

The τ-charm Factory attacks each of these three present limitations as follows:

1. **Large increase in statistics**: the yearly rate exceeds the *total* present data by two orders of magnitude.
2. **Elimination of heavy flavour backgrounds** by operating below $D\bar{D}$ threshold (3.73 GeV); at these energies, τ decay is the only source of prompt leptons. Furthermore, **all non-τ backgrounds are internally calibrated** by taking data below $\tau^+\tau^-$ threshold (3.57 GeV).
3. **Single-tagging of $\tau^+\tau^-$ events**, e.g. $e + E_{miss}$. This imposes no requirements on the decay of the second τ, thereby permitting a bias-free study of its decay. Furthermore, single-tagging allows absolute branching ratios to be measured, without the need for assumptions of the $\tau^+\tau^-$ cross-section or measurements of the luminosity.

The combination of these features, which are described below in more detail, provides the τ-charm Factory with a sensitivity to precise and rare τ physics that is unmatched elsewhere.

E_{cm} GeV	$\sigma(\tau^+\tau^-)$ nb	$\sigma(c\bar{c})$ nb	$\sigma(u\bar{u},d\bar{d},s\bar{s})$ nb	# $\tau^+\tau^-$ events per year
3.55	0	0	15.8	0
3.57	0.22	0	15.7	$2\,10^6$
3.67	2.3	0	14.8	$2\,10^7$
3.69 (ψ': standard optics)	4.6	0	700	$5\,10^7$
: monochromator)	14.0	0	3500	$1.5\,10^8$
4.25	3.5	4.2	11.0	$3\,10^7$

Table 1: Operating energies for τ studies

2 Event selection

2.1 Operating points

The optimum beam energies for τ physics[1] (Table 1) are as follows:

- **3.55 GeV**. This energy, which is just below τ threshold, provides a direct measurement of all non-τ backgrounds: hadronic ($u\bar{u}$,$d\bar{d}$ and $s\bar{s}$), two-photon, QED and beam-gas.
- **3.57 GeV**. A recent calculation[2] has shown that the $\tau^+\tau^-$ cross section has a finite value (0.223 nb) precisely at threshold, due to a Coulomb interaction between the τ^+ and τ^-. This introduces an important new operating point for τ physics, with the following features:
  - Monochromatic two-body decays e.g. $\pi\nu_\tau$, $K\nu_\tau$ and $\rho\nu_\tau$. The τ velocity is simply determined by the beam energy spread ($\sigma_E = 1.1$ MeV) i.e. $\beta_\tau = 0.025$. The momentum spread of the two-body decays is therefore only $\pm$ 2.5%. This implies that the $\pi\nu_\tau$ and $K\nu_\tau$ decays are *kinematically* separated ($\bar{p}_\pi = 887$ MeV/c and $\bar{p}_K = 824$ MeV/c) and can be precisely measured. Furthermore, $\tau^+\tau^-$ events can be tagged, with 15% efficiency, by a monochromatic $\pi + E_{miss}$.
  - Capability to make a precise measurement of the τ mass. It should be possible to measure the τ mass to 10% of the beam energy spread, i.e. 0.1 MeV/c^2. This may be reduced by approximately a factor of 5 if monochromator optics can be successfully implemented[3].
  - Absence of large radiative corrections to the kinematics of the $\tau^+\tau^-$ events. This applies to the τ threshold region in general and provides a significant advantage in certain experiments, such as the precise measurement of the $\tau \to e\nu_e\,\nu_\tau$ electron spectrum.
- **3.67 GeV**. This energy provides the highest $\tau^+\tau^-$ cross section below $\psi'(3.69)$ and charm thresholds. The τ cross section is 65% of its maximum value in the continuum. The τ velocity is small ($\beta_\tau = 0.23$) and so the effects of Lorentz smearing on momentum distributions etc. are also small.

- **3.69 GeV.** With the standard machine optics, decays of $\psi'(3.69)$ contribute a $\tau^+\tau^-$ production rate that is approximately equal to the continuum rate. Monochromator optics could potentially increase the $\psi'(3.69)$ rate by a factor of five, to give $\sigma(\tau^+\tau^-) \approx 14$ nb. This represents the optimum operating point for τ studies in which the limiting sensitivity is due to statistics and not backgrounds.

- **4.25 GeV.** At this energy the τ continuum rate has its maximum value, coinciding with a minimum in the charm cross section. The possible advantages here include a finite τ flight path (60 μm) and large polarization correlations for $\tau^+\tau^-$[1]. The presence of backgrounds from charm decays, however, limits the range of experiments that are feasible.

2.2 Single-tagging of $\tau^+\tau^-$ events

All previous τ measurements have employed global event selection criteria that impose restrictions on *both* τ decays in each event. The observed number of events is then,

$$N_{ij} = 2\, N_{\tau\bar{\tau}}\, B_i\, B_j\, \epsilon_{ij}$$

where $N_{\tau\bar{\tau}}$ is the number of $\tau^+\tau^-$ events, B_i is the branching ratio to a final state i and ϵ_{ij} is the detection efficiency for the combined final state ij. This technique allows *relative* branching ratios to be determined without knowledge of $N_{\tau\bar{\tau}}$. However, *absolute* branching ratios depend on a determination of $N_{\tau\bar{\tau}} = \sigma_{\tau\bar{\tau}} \int L\, dt$. This requires a calculation of $\sigma_{\tau\bar{\tau}}$ and a measurement of luminosity, which limits the accuracy to a few percent.

A better technique, which has been used to great advantage in the study of D decays at $\psi''(3.77)$, is to tag the $\tau^+\tau^-$ event by means of a *single* τ decay, leaving the second τ to decay in an unbiased way. This technique – known as single-tagging – provides a parent τ data sample with zero normalization uncertainty. It also ensures that the remaining particles in the event must all originate from the same parent τ. The observed number of events in which the second τ decays to a state i is,

$$N_i = N_\tau\, B_i\, \epsilon_i$$

where N_τ is the number of events in the single-tagged sample.

Of course, the application of single-tagging requires a signature from a single τ decay that is very clean. With the unique capability of the τ-charm Factory to produce $\tau^+\tau^-$ events near threshold and without any contamination from heavy flavour decays, several signatures fulfill this requirement, as follows:

1. $e + E_{miss}$
2. $\mu + E_{miss}$
3. Monochromatic $\pi + E_{miss}$ (at 3.57 GeV). This may also be extended to include a monochromatic ρ or $a_1(1260)$.

In the remainder of this paper, we will discuss only the first of these tags, $e + E_{miss}$, which is particularly clean and has a high efficiency ($\approx 22\%$ of all $\tau^+\tau^-$ events).

E_{cm} (GeV)	$J/\psi(3.10)$	3.51	3.67	$\psi''(3.77)$
Luminosity (pb^{-1})	0.12	0.66	1.4	2.4
Observed events:				
$N(hadron)$	185K	8.3K	16K	44K
$N(hadron + e, \geq 3\, prongs)$	1140	70	200	1200
Electron backgrounds:				
$N(Dalitz + \gamma\ conversion)$	425	19	38	103
$N(Compton)$	21	1	2	5
$N(K_{e3})$	25	1	2	7
$N(2-photon)$	2	10	20	33
Total	473	31	62	148
Hadron backgrounds:				
$N(h \rightarrow e)$	576	29	58	186
Background-subtracted events:				
$N(hadron + e, \geq 3\, prongs)$	89±34	10±8	80±14	869±35
Residual sources	unaccounted bgds.		τ	$\tau + D$

Table 2: DELCO multiprong electron data in the τ-charm threshold region.

3 Backgrounds to prompt electron + E_{miss} (ν) tag

3.1 DELCO experience with prompt electron tag

The DELCO detector recorded extensive data in the $\tau^+\tau^-$ threshold region during 1978-79 in the course of an experiment to measure the τ mass. These measurements[4] provide a useful indication of the electron backgrounds to be expected at the τ-charm Factory operating in the same energy region. A summary of the relevant data is given in Table 2.

For data taken below τ and charm thresholds, the probability per hadronic event (P) to observe a candidate prompt electron was $P(hadron + e) = 6\ 10^{-3}$. These candidate electrons were well described, both in rate and momentum distributions, by the background processes indicated in Table 2. Two background classes were identified:

1. **Electron backgrounds**, involving a real electron in the tracking chambers. This was dominated by π^0 Dalitz decays and γ conversions where the second $e^\pm$ was undetected. The observed rate, $P = 3\ 10^{-3}$, corresponds to $\approx 10\%$ probability to miss the second track.

2. **Hadron backgrounds**, involving a misidentified electron in the tracking chambers. The observed rate, $P = 3\ 10^{-3}$, corresponds to 10^{-3} $h \rightarrow e$ misidentification probability.

A second contribution to the class 1 backgrounds came from 2-photon events (largely $e^+e^-\mu^+\mu^-$), which had a background rate of 10^{-3} relative to hadronic events in the continuum.

We can estimate the implications of these data on the τcF detector [5] as follows. Firstly, the τ-charm Factory should have far better rejection of class 1 electron backgrounds. DELCO had a relatively massive inner tracker (0.018 r.l.) and vacuum chamber (0.013 r.l.), and only 6 layers of central tracking. In consequence the conversion rate, and the probability of failing to observe the second e, were quite high. With less material and vastly improved tracking relative to DELCO, the τcF detector should reduce such backgrounds by a further factor $\approx 10^{-2}$. Improvements in the material, tracking and particle identification will also reduce Compton and K_{e3} backgrounds, by at least an order of magnitude. Finally, 2-photon events will be reduced by at least 10^{-2} relative to DELCO (which had a modest μ detector subtending 20% of 4π str. and limited resolution to identify the characteristic kinematics of such events). In summary, class 1 electron backgrounds in the τcF detector will have a probability, $P \leq 10^{-4}$.

In the case of class 2 backgrounds, we expect the τ-charm Factory and DELCO to have similar performance, i.e. $P = 3\,10^{-3}$. DELCO relied on a threshold gas Cerenkov counter, whereas the τcF will use a precise matching of momentum (tracking) and energy (crystal calorimeter) measurements, together with ToF, dE/dX and an analysis of shower shapes and positions.

The electron data in Table 2 are multiprong events, i.e. ≥ 3 charged particles. In the case of 2-prong events, DELCO observed 2 events at $E_{cm} = 3.51$ GeV that contained an electron and a second track that was not an electron. This corresponds to a background probability of 2-prong electron events, $P = 2\,10^{-4}$, which is small in comparison with the multiprong electron rates.

Combining all sources, we therefore estimate for the τ-charm Factory a probability per hadronic event to observe a background electron,

$$P(hadron + e) = 3\,10^{-3}.$$

This rate, which applies to events recorded below charm threshold, is dominated by $h \rightarrow e$ misidentification. Note that, above charm threshold ($\psi''(3.77)$ in Table 2) the electron background rate to τ samples increases by an order of magnitude.

3.2 Calculated backgrounds in the τ-charm Factory

We evaluate here the τ signal-to-background ratio at $E_{cm} = 3.67$ GeV for events that are selected with the $e + E_{miss}$ tag. [The corresponding figures at $E_{cm} = 3.57$ GeV, using the same tag, are obtained simply by reducing the signal rate by a factor of 10 (Table 1)]. First we consider the prompt e tag alone, based on the DELCO experience discussed above, and then we estimate the effect of including the E_{miss} tag.

3.2.1 Electron tag

The relative production cross-section at $E_{cm} = 3.67$ GeV (Table 1) is,

$$\sigma(hadron)/\sigma(\tau\bar{\tau}) = 14.8/2.3 = 6.4$$

The tagging efficiency for $\tau^+\tau^-$ events with an electron is,

$$\epsilon(\tau\bar{\tau} \to X + e) = 2\, B_e\, \epsilon_e = 2 \text{ x } 0.175 \text{ x } 0.8 = 0.28$$

where X is all final states. Therefore the background contamination of inclusive electron data is,

$$N(hadron + e)\ /\ N(\tau\bar{\tau} \to X + e) = 6.4\,(\,3.10^{-3}\,/\,0.28\,)\ =\ 0.07$$

where $N(i)$ is the number of events of type i.

3.2.2 Electron + E_{miss} tag

The electron tag alone is insufficient to select a clean sample of $\tau^+\tau^-$ events. It is therefore applied together with an E_{miss} tag, which takes advantage of the large energy carried off by ν's. For a single electronic decay, the neutrino energy is simply $E_{miss} = E_\tau - E_e \approx E_{beam} - E_e$. This demonstrates another advantage of operating close to $\tau^+\tau^-$ threshold: the small Lorentz boost implies that *each* τ gives rise to a large $E_{miss} \approx m_\tau/2$, and a strong cut ($E_{miss} \geq 0.5$ GeV) can be applied which is, nevertheless, satisfied with high efficiency by a single τ decay.

Before cutting on E_{miss}, it is first necessary to require $\vec{p}_{miss}$ does not point near the beam axis, in order to eliminate events (especially 2–photon events) in which the missing energy was carried off by a particle in this direction. With a suitable cut that ensures a minimum $p^{\perp}_{miss}$, it is possible to *guarantee* that the measured E_{miss} could not be due to missing particles along the beam direction, since their momentum required to balance $p^{\perp}$ would imply a total event energy exceeding E_{cm}. Overall, we estimate an E_{miss} tag efficiency of 0.8 for τ events.

The E_{miss} sources in hadronic events are as follows:

1. **Charged and neutral energy smearing.** In order to estimate the event energy resolution, we make the following simple assumptions:

$$\begin{aligned} \bar{N}(ch) &= 4 \\ \bar{N}(\pi^0) &= 2 \\ \bar{N}(K^\pm) &= 0.3 \\ \bar{N}(K^0_L) &= 0.15 \\ \bar{N}(n,\bar{n}) &= 0.15 \end{aligned}$$

   $\bar{N}(i)$ is the mean number of particles of type i, per event, and each particle is assumed to have a a mean momentum 0.5 GeV/c. For those events involving only charged particles and γ's, the energy resolutions[5] in the τcF detector are,

$$\begin{aligned} \sigma(E_{ch}) &= \sqrt{4} \text{ x } (0.5\%) \text{ x } 500 = 5 \text{ MeV} \\ \sigma(E_\gamma) &= \sqrt{4} \text{ x } (1.5\%/\sqrt{0.25}) \text{ x } 250 = 15 \text{ MeV} \\ \text{i.e. } \sigma(E_{tot}) &= 16 \text{ MeV} \end{aligned}$$

   It is evident, for a high–resolution detector like the τcF, that energy smearing is negligible and the main contribution from this source will be γ detection inefficiencies caused by cracks, etc. (There is a negligible probability of losing an isolated energetic charged particle at wide angles.) For an undetected γ above 500 MeV, we assume the probability per hadronic event is below 10^{-3}, i.e. $\approx 1\%$ detection inefficiency inside the em. calorimeter fiducial volume.

2. K_L^0 **production**. On the conservative assumption of 5% inefficiency for K_L^0 detection in the outer hadron tagger/μ detector, the probability per hadronic event to miss a K_L^0 is $P = 0.15 \text{ x } 0.05 = 7\,10^{-3}$.

3. $n, \bar{n}$ **production**. Since neutrons must appear in final states containing a baryon *and* anti-baryon ($n+\bar{n}+X$, $n+\bar{p}+X$, or $\bar{n}+p+X$), the overall detection inefficiency will be small. We assume the same 5% detection inefficiency for n as for K_L^0, and 1% inefficiency to identify $p, \bar{p}$. The mean inefficiency to detect the presence of $n, \bar{n}$ in an event is therefore $\approx 10^{-3}$, i.e. small in comparison with K_L^0 production.

Combining these contributions, we estimate a probability per hadronic event to observe $E_{miss} \geq 0.5$ GeV,

$$P(hadron + E_{miss}) = 10^{-2}.$$

This rate is dominated by undetected K_L^0 and assumes careful attention is paid to eliminating cracks/detection inefficiencies in the crystal calorimeter of the τcF detector. Note that the presence of neutral hadron tagging is providing approximately one order of magnitude background reduction, i.e. without neutral hadron detection, $P(hadron + E_{miss}) \approx 0.1$.

Finally, we can estimate the background contamination in events recorded at $E_{cm} =$ 3.67 GeV and selected with the combined $e + E_{miss}$ tag,

$$N(hadron + e + E_{miss}) \; / \; N(\tau\bar{\tau} \to X + e + E_{miss}) = 0.07\,(\,0.01\,/\,0.8\,) \; = \; 10^{-3}$$

At $E_{cm} = 3.57$ GeV, the background increases to 1%. We point out that this tag is ineffective for selecting τ events above charm threshold, where it would produce a sample $\approx$ 1:1 τ:charm.

Our estimate assumes no correlation between a background e and E_{miss}, which is true in most cases. An exception is K_{e3} decay, for which the prompt electron rate in DELCO was $P = 10^{-4}$. With the additional requirement $E_{miss} \geq 0.5$ GeV, the final rate would be well below the uncorrelated $e + E_{miss}$ rate of $3\,10^{-3} \text{ x } 10^{-2} = 3\,10^{-5}$. Furthermore, events such as this, in which there is a *single* missing ν, can be identified by reconstruction of a K mass. We therefore expect a negligible contamination from K_{e3} decays.

Another exception is e^+e^- pairs from Dalitz decays or γ conversions in which the second e fails detection in the tracking chambers. Here the missed e has a very low energy ($\leq$20 MeV), which is well below the E_{miss} cut. In the very rare case of failing to detect a high energy e in the tracking chambers, no E_{miss} will be generated since the electron energy will be recorded in the electromagnetic calorimeter. Again we expect a negligible contamination from this source.

Finally, we comment that certain τ studies may wish to include the possiblity for τ decays into $K_L^0\ X$, which has a branching ratio $\approx 2\,10^{-3}$. For these studies it will be necessary to allow the presence of a detected neutral hadron and reject events in which its direction coincides with $\vec{p}_{miss}$.

3.2.3 τ backgrounds to τ's

The continuum backgrounds are small *and* internally calibrated, by taking data below $\tau^+\tau^-$ threshold. Consequently it is likely that the most significant backgrounds to τ studies will be due to confusion of one τ decay with another.

Separation between the τ decays relies largely on good particle identification, together with good photon detection efficiency and energy resolution. The kinematic range of secondary particles in the τ threshold region is ≤ 1 GeV, and so most particle identification is relatively unambiguous. As a specific example, the π contamination in a study of $\tau \rightarrow e\,\nu_e\,\nu_\tau$ is $(B_\pi \times 10^{-3})\,/\,B_e = 5\,10^{-4}$. In the case of $\tau \rightarrow \mu\,\nu_\mu\,\nu_\tau$, where the π–μ separation is weaker, the π kinematics (especially the monochromatic π at $E_{cm} = 3.57$ GeV !) can be used to identify the background events. As a further example, the study of the ν_τ mass will involve the 5-prong τ decay, which evidently has a vanishingly small background from other τ decays.

4 Summary

Using the single-tagging signature $e + E_{miss}$, which has an efficiency of ≈ 0.22 for $\tau^+\tau^-$ events, we calculate a rejection factor $3\,10^{-5}$ for hadronic events below charm threshold. This results in background levels $\leq 10^{-3}$ at $E_{cm} = 3.67$ GeV and $\leq 10^{-2}$ at $E_{cm} = 3.57$ GeV. Further tags for $\tau^+\tau^-$ events, such as a monochromatic π, ρ, or $a_1(1260)$ at $E_{cm} = 3.57$ GeV, can be used to increase the detection efficiency.

In view of the excellent rejection of hadronic events, in certain studies it is likely that a comparable source of background will be from τ decays themselves, in which particles are misidentified. The key to maintaining these backgrounds at a low level is good-quality particle identification in the τ-charm Factory detector.

References

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