Memorandum

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To: LEM group

cc: LEM user

Background in LE-μSR decay histograms

This memo explains the contributions to the measured background bkg per bin in low-energy μ^+ (LE-μ^+ or LEM) raw decay histograms, with no post-pileup rejection of trigger detector (TD, the "start" detector for the LE-μSR measurement) and positron (e^+) signals. The motivation to have the post-pileup rejection disabled in the data acquisition logic arises from the fact that the TD signals have correlated after-pulses, see Fig. 4. However, the absence of TD-post-pileup rejection results in an additional contribution to the background at times $t > t_0$, where t_0 denotes the *mean* implantation time of the low-energy μ^+. As will be shown below, the ratio $r = bkg(t > t_0)/bkg(t < t_0)$ can be used to determine the detection efficiency ε_{TD} of the trigger detector, therefore giving the possibility to continuously monitor ε_{TD} (which is an important issue since the number of holes in the carbon foil of TD increases with time...). Furthermore, the background $bkg(t > t_0)$ can be calculated in an easy way to be compared with fit results.

On the other hand for data analysis it is of advantage to have $r = 1$, since in this case the background can be determined independently from the interval at $t < t_0$, which at present has a width of about 400 ns in the LEM experiment. This is achieved by rejecting those events which have i) a TD post-pileup, ii) a e^+ post-pileup and, iii) where a 2nd e^+ detector was hit at the same time. At the moment, histograms with these additional cuts can be generated offline from the event-by-event data file. Starting in 2007 a 2nd set of histograms with post-pileup rejection enabled will be created by the LEM analyzer program, thus providing both sets of histograms online. The effect of post-pileup rejection on background and signal rates: in 2006, measured with s-N_2 moderator, the raw event rate drops to 73.0%, whereas the background-corrected muon rate decreases to 84.7% (Run 1133, applied cuts: reject TD post-pileup, 2nd positron, require only one positron).

The following definitions are used in the derivation of the equations describing the different background contributions:

- the positron rate of coincidences is denoted by e^+, and its run average is written for each positron detector pair to the run summary file.
- the positron rate consists of two components:
  $e^+ = e^+_{uncorr} + e^+_{\mu}$, where
  - e^+_{uncorr} is the rate of uncorrelated positrons from scattered beam positrons. This rate can be measured experimentally by switching off the Mirror of the transport system.

  - e^+_μ is the rate of positrons from muons decaying in the sample region. Experimentally, it is derived by measuring e^+_{uncorr} as described above:
    $e^+_\mu = e^+ - e^+_{uncorr}$.

- Δt is the bin width in the decay histogram.
- $\sum(TD_{clean})$ denotes the total number of TD_{clean} hits (a TD without pre-pileup) in a run, which is the number of "starts" for the data acquisition logic. This number is available in the summary file (or in the "VME_STATS" section of ODB, accessible on the Midas Status page).

The background consists of the three components:

1. uncorrelated background due to e^+_{uncorr}, contributing for all t.
2. correlated background, where the μ^+ was not detected by TD, but another hit on TD started the measurement:
   $\propto (1-\varepsilon_{TD}) \cdot e^+_\mu$, contributing for all t.
3. correlated background, where a μ^+ is detected in TD, but as a post-pileup, i.e., the start hit in TD is from an ion or beam positron (see Fig. 2):
   $\propto \varepsilon_{TD} \cdot e^+_\mu$, contributing only at $t > t_0$.

Then, the background in the raw LEM decay histograms can be written, for $\Delta t \cdot e^+ \ll 1$ (see also Fig. 1):

$$\begin{aligned} bkg(t > t_0) &= \sum(TD_{clean}) \cdot \Delta t \cdot [e^+_{uncorr} + (1-\varepsilon_{TD}) \cdot e^+_\mu + \varepsilon_{TD} \cdot e^+_\mu] \\ &= \sum(TD_{clean}) \cdot \Delta t \cdot e^+, \qquad (1) \\ bkg(t < t_0) &= \sum(TD_{clean}) \cdot \Delta t \cdot [e^+_{uncorr} \cdot + (1-\varepsilon_{TD}) \cdot e^+_\mu]. \qquad (2) \end{aligned}$$

The ratio r of background before and after t_0 can be derived from Eq. 1 and Eq. 2:

$$r := \frac{bkg(t > t_0)}{bkg(t < t_0)} = \frac{e^+}{e^+_{uncorr} + (1-\varepsilon_{TD})e^+_\mu}, \qquad (3)$$

from which the efficiency ε_{TD} of the TD detector is obtained:

$$\varepsilon_{TD} = \frac{e^+ \cdot (r-1)}{r \cdot e^+_\mu}. \qquad (4)$$

If we write $e^+_\mu = x \cdot e^+$ eqs. 3 and 4 can be rewritten as

$$r := \frac{bkg(t > t_0)}{bkg(t < t_0)} = \frac{1}{(1-x) + x \cdot (1-\varepsilon_{TD})} = \frac{1}{1 - x \cdot \varepsilon_{TD}}, \qquad (5)$$

and

$$\varepsilon_{TD} = \frac{(r-1)}{x \cdot r}. \qquad (6)$$

Figure 3 illustrates, how ε_{TD} can be determined by a fit of Eq. 5 to the data.

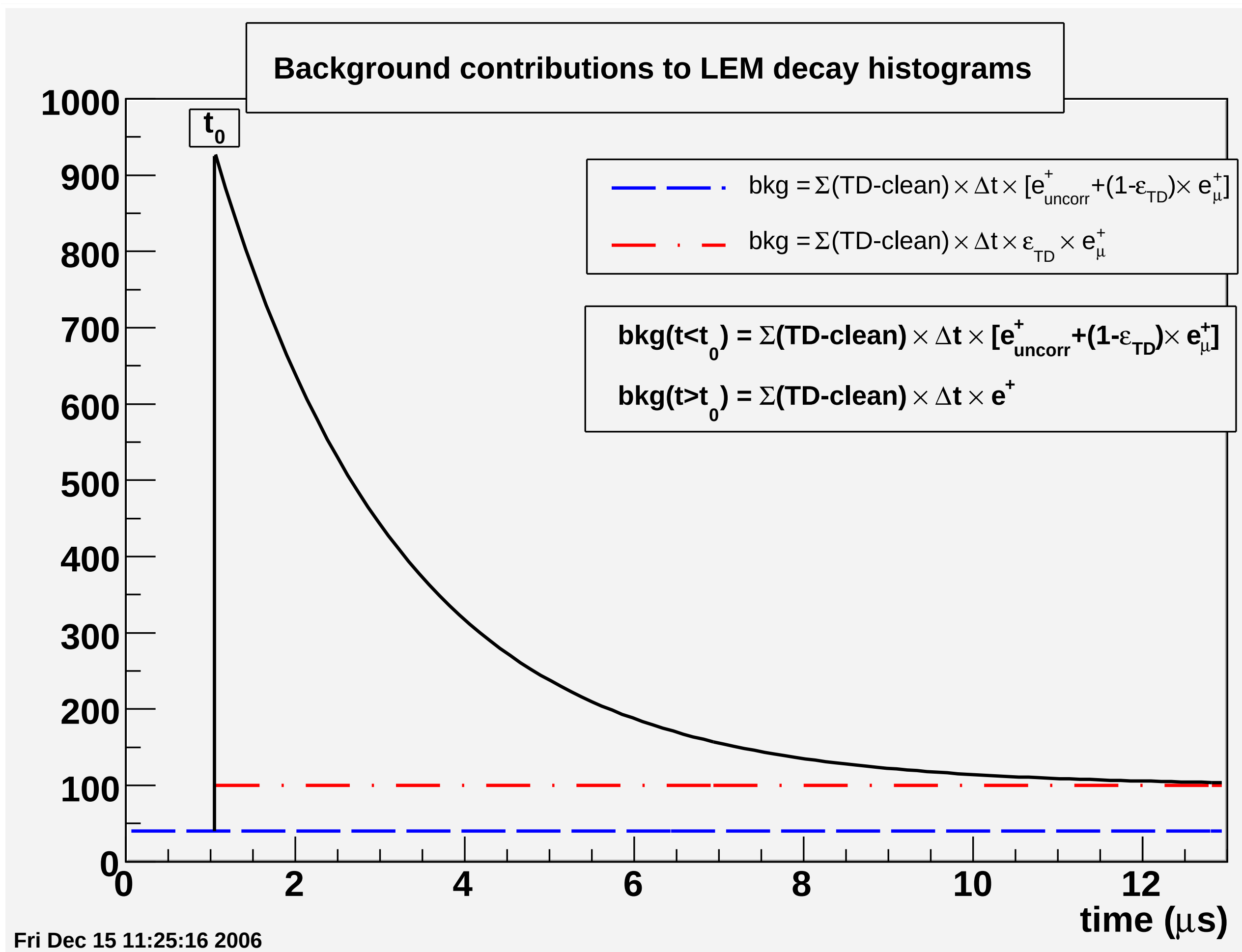

Figure 1: Background contributions to the LEM raw decay histograms. The difference in background between $t < t_0$ and $t > t_0$ arises from the non-rejection of post-pileups in the LEM data acquisition logic, as described in the text. Here, $\Sigma(TD_{clean})$ is the total number of TD_{clean} in a run, Δt is the bin width, $e^+ = e^+_{uncorr} + e^+_{\mu}$ is the measured positron rate, and ε_{TD} is the detection efficiency of TD.

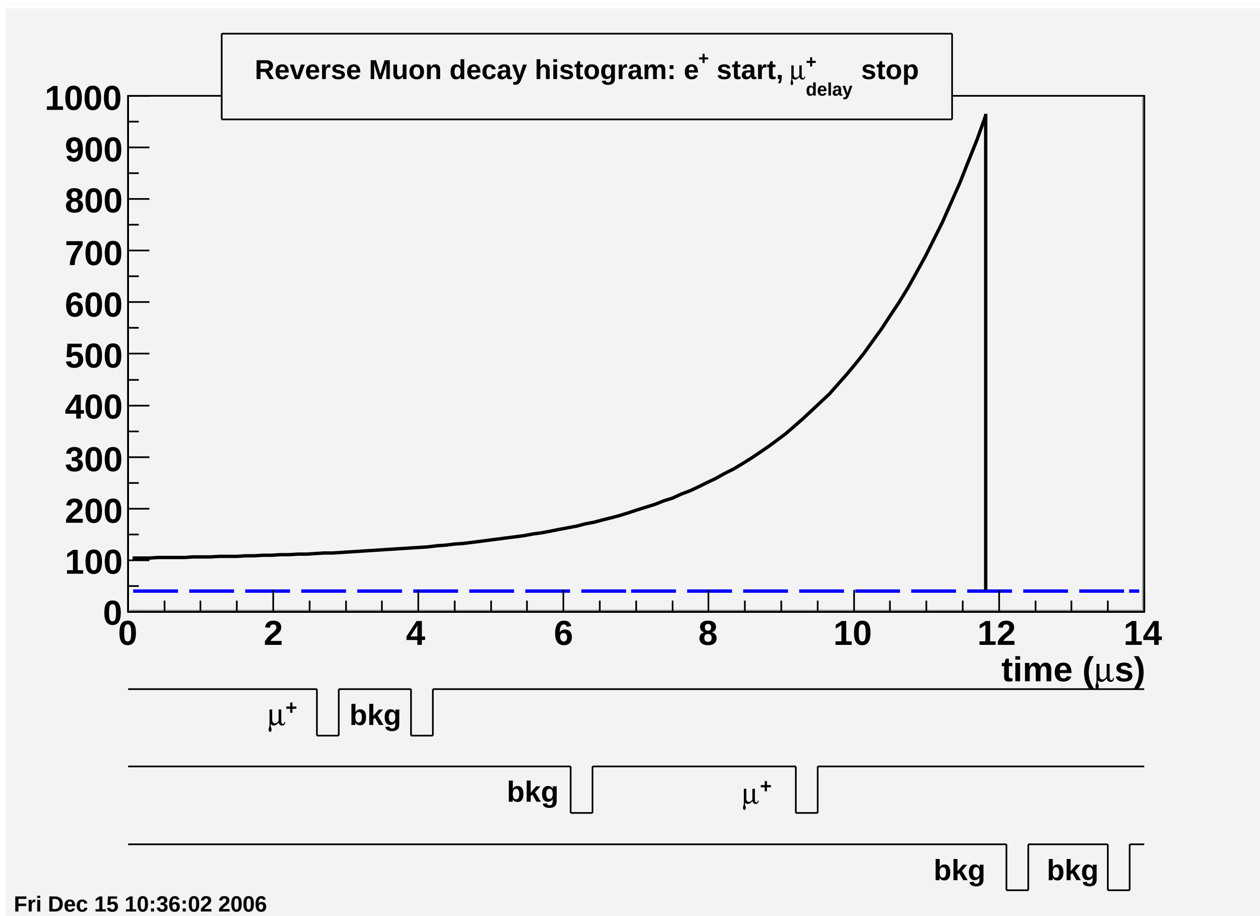

Figure 2: This figure illustrates, how and why a missing TD post-pileup rejection yields additional background in the region of the signal, i.e. the exponential part. Considering it with respect to the e^+ hit makes it more clear (at least for me...): the hypothetical histogram show the muon decay where the start is given by the decay e^+, and the stop by the delayed TD hit. Beneath the histogram three pulse sequences with TD post-pileup are shown, which all do contribute to the histogram entries. The 1st sequence with the μ^+ at 2.5 μs followed by a background (bkg) hit at 4 μs is a good event which would have been lost if pileup rejection were enabled. The 2nd sequence shows that the stop at 6 μs is made by the wrong bkg hit which is followed by a μ^+ hit at 9 μs; so, we got the wrong stop, i.e. a real contribution to background. This background event were rejected if post-pileup rejection were enabled. At $t > 11.8$ μs no μ^+ do contribute to the background ($\varepsilon_{TD} = 100\%$ assumed), only uncorrelated TD hits, as is illustrated by the 3rd sequence. Therefore, the bkg in this region is smaller than in the region with signal, i.e. the part with the exponential decay.

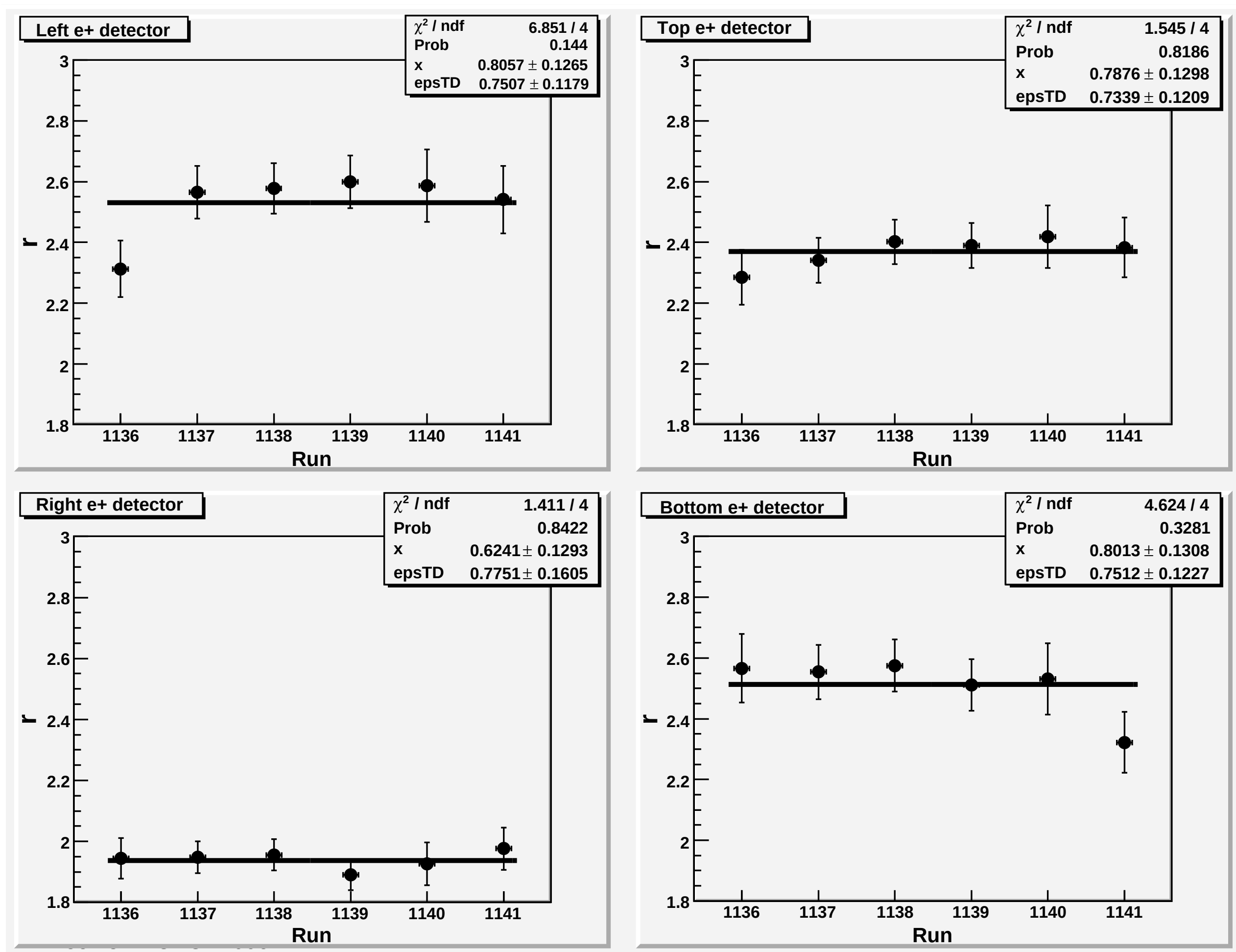

Figure 3: Fit of Eq. 5 to the data to determine ε_{TD}. Due to the strong correlation with the 2nd fit parameter x (which in principal could be fixed, because it can be determined experimentally) the errors of the fit are large. But this figure is just to demonstrate, how it works.

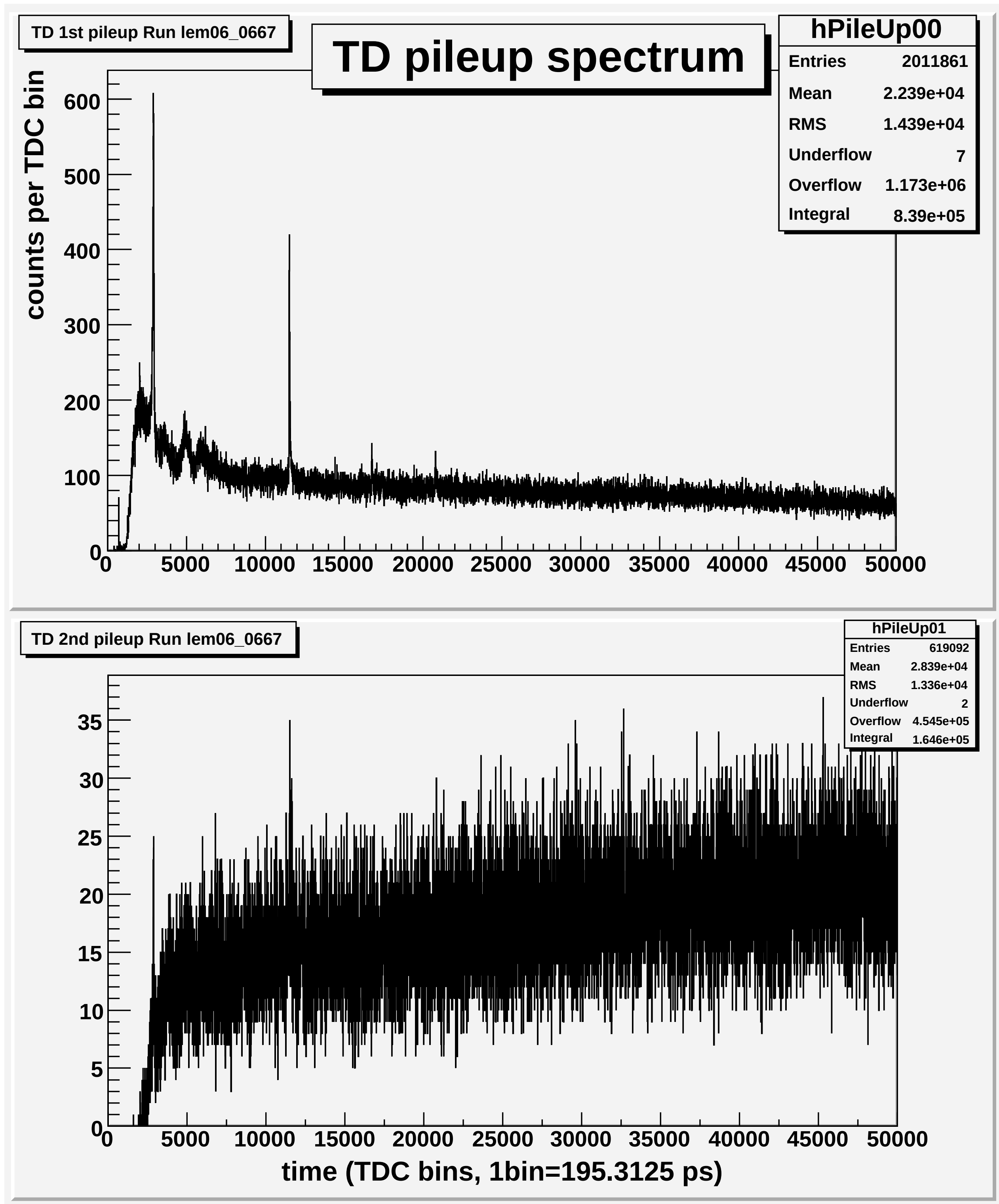

Figure 4: Measured post-pileup spectrum of the "trigger detector" TD. Shown are the spectra of the 1st and 2nd post-pileup hit. The peaks are partially *real*, i.e. they move when changing the transport energy of the LEM apparatus, and partially generated by the electronics.

Appendix

The background after post-pileup rejections reads

$$bkg(t) \;=\; \sum (TD^{acc}_{clean}) \cdot \Delta t \cdot [e^{+}_{uncorr} + (1-\varepsilon_{TD}) \cdot e^{+}_{\mu}], \qquad (7)$$

and is now independent on t. The integrated number $\sum(TD^{acc}_{clean})$ of accepted TD_{clean} will be provided in the summary file from 2007 on.

Further information:

- For more information on background contributions at continuous-particle beams, check, for example, Appendix B of [1]. The effect of non-post-pileup rejection on time-of-flight spectra has been discussed in [2] (the thereabouts derived equations are an approximation). Note, that the equations presented here are only valid for the case $\Delta t \cdot e^{+} \ll 1$.
- Used Root macros, available in LEM SVN repository in analysis/root/macros:
  - bkgTFFit.C to do a simple TF fit with gaussian relaxation to determine bkg at $t > t_0$ and at $t < t_0$, determine the ratio $r = bkg(t > t_0)/bkg(t < t_0)$.
  - bkgZFFit.C, analogous for ZF runs.
  - defineFit.C, used in the other two macros to define simple fit functions.

References:

[1] T. Prokscha, E. Morenzoni, M. Meyberg, T. Wutzke, B.E. Matthias, A. Fachat, K. Jungmann, and G. zu Putlitz, *Muonium formation by collisions of muons with solid rare-gas and solid nitrogen layers*, Phys. Rev. **A58**, 3739 (1998).

[2] T. Prokscha, PSI Memorandum *Nachweiseffizienz S1 für Myonen, Run IX,X*, 17-Mar-1998.