SLAC-PUB-13003

Study of the $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ decays using the *BABAR* Detector

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The $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ decays have been studied with the *BABAR* detector. Preliminary branching fractions on the two modes are presented. The $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ mode is found to have a large contribution from the $\tau^- \to \omega\pi^-\nu_\tau$ decay. The $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ decay is studied using the $\eta \to \gamma\gamma$ mode and the $\tau^- \to f_1(1285)\pi^-\nu_\tau$ decay is seen to be the primary source of these decays. A 90% confidence level upper limit is placed on the $\tau^- \to \eta'(958)\pi^-\nu_\tau$ decay which proceeds through a second-class current and is expected to be forbidden in the limit of perfect isospin symmetry.

1. Introduction

The semi-leptonic decays of the τ lepton are an ideal area for studying strong interaction effects (for example, see Ref. [1]). The decay mode $\tau \to X^-\nu_\tau$ probes the matrix element of the left-handed current between the vacuum and the hadronic state X^-. This work presents a preliminary study of the $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ decays using the *BABAR* detector [2].

This analysis is based on data recorded at the PEP-II asymmetric-energy e^+e^- storage ring operated at the Stanford Linear Accelerator Center. The sample used in these analyses correspond to 210-230 fb^{-1} of data recorded at center-of-mass energy ($\sqrt{s}$) of 10.58 GeV and 10.54 GeV between 1999 and 2003. With an expected cross section for τ-pair production at the luminosity-weighted $\sqrt{s}$ of $\sigma_{\tau\tau} = (0.89 \pm 0.02)$ nb [3], this data sample contains approximately 400 million τ decays.

Monte Carlo simulation is used to evaluate the background contamination and selection efficiency. The τ pair production is simulated with the KK2f Monte Carlo event generator [3] and the τ decays modeled with Tauola [4].

Non-τ Monte Carlo samples used in this work include samples of $q\overline{q}$ ($q = u, d, s, c, b$). The samples were scaled to the luminosity of the data using the known cross sections.

In addition, dedicated samples of $\tau^+\tau^-$ events were created using EvtGen [5] where one of the τ leptons can decay to a generic mode and the other τ decays to a $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ final state.

2. Data selection

The τ pairs are produced back-to-back in the e^+e^- CM frame. As a result it is convenient to divide the event into two hemispheres based on the plane perpendicular to the thrust axis, each containing the decay products of a single τ lepton. The analysis procedure selects events with one track in one hemisphere (tag hemisphere) and three tracks in the other hemisphere (signal hemisphere).

The reduction of the non-τ background is made by requiring that the track in the tag hemisphere be identified as an electron or a muon with the momentum required to be less than approximately 4 GeV/c^2. In the $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ selection, the track and neutrals are accepted if they reconstruct to a ρ meson. Background from non-τ^- events was further reduced in both selections by requirements on the magnitude of the thrust in the event.

Contributed to 9th International Workshop on Tau Lepton Physics (Tau06), 09/19/2006--9/22/2006, Pisa, Italy

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

2.1. $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ selection

Events are required to have overall charge balance, a $1-3$ topology of charged tracks and at least one π^0 candidate reconstructed in the signal hemisphere. The charged tracks in the signal hemisphere are required to be identified as pions and are fitted to a common vertex.

Candidate π^0's are constructed from pairs of photons, with the requirement that one have energy greater than 200 MeV and the other have energy greater than 100 MeV. The π^0 candidates must also have a two-photon mass between 100 MeV/c^2 and 160 MeV/c^2. Events with two or more π^0 candidates on the signal side are discarded. The selected π^0 candidates are mass constrained to the π^+ π^- π^- vertex.

The events are separated into three different tag samples (e-tag, μ-tag and ρ-tag). These three samples are independent as no event passes more than one of these sets of selection criteria.

Further selection cuts are imposed in order to reduce the background level. These include requirements on the residual amount of neutral energy in the signal hemisphere, the total energy of the event, and the angle of the thrust axis. Tracks from photon conversions are removed if the invariant mass of the two tracks is less than 0.005 GeV/c^2 assuming both tracks are electrons.

2.2. $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ selection

The $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ decays were also selected with a 1-3 topology. The event was rejected if any of the tracks in the signal hemisphere are identified as an electron or if any pair of oppositely charged tracks was consistent with originating from a photon conversion. The reconstructed mass of the three tracks and the η meson was required to be less than 1.8 GeV/c^2. It is also required that there be no π^0 candidates in the signal hemisphere.

No particle identification algorithm is applied to the charged tracks in the signal hemisphere to distinguish charged pions from kaons. Note that energy-momentum conservation would not permit a $\tau^- \to f_1(1285)K^-\nu_\tau$ decay.

It is required that there be one $\eta \to \gamma\gamma$ candidate in the signal hemisphere consisting of two neutral clusters in the electromagnetic calorimeter. The $\eta \to \gamma\gamma$ candidates are preselected by requiring the momentum and energy of the $\gamma\gamma$ system to be greater than 0.2 GeV/c and 0.05 GeV, respectively. The two clusters must have a combined invariant mass $M_{\gamma\gamma}$ between 0.47 and 0.62 GeV/c^2. Background is reduced by requiring that at least one of the clusters is required to have an energy of at least 0.7 GeV and the other cluster at least 0.3 GeV.

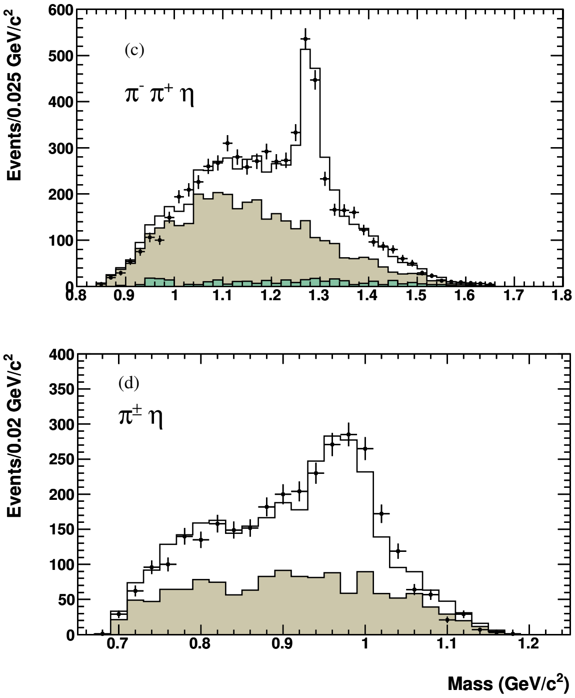

Figure 1. The invariant masses of the $\pi^-\pi^+\eta$ and $\eta\pi$ final states are shown. The unshaded histograms are the simulated signal events, the lightly-shaded histograms are the simulated τ background and the darker-shaded histograms are the simulated $q\overline{q}$ background. Note that the plots have two entries per event. All selection criteria are applied. It is required that the invariant mass of the $\gamma\gamma$ system is between 0.50 and 0.58 MeV/c^2. In the $\eta\pi$ mass plot it is required that the invariant mass of the associated $\pi^-\pi^+\eta$ system is between 1.23 and 1.32 GeV/c^2.

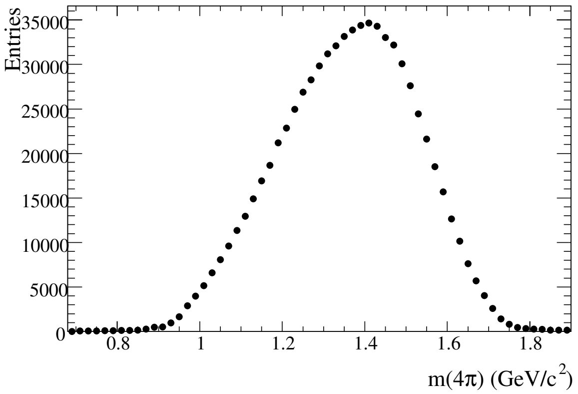

Figure 2. $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ mass spectrum for data after combining all tags and subtracting background.

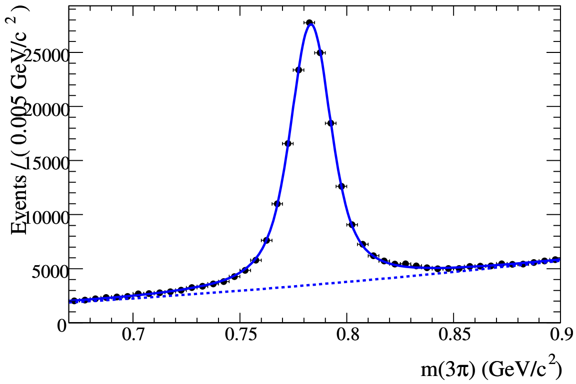

Figure 3. Fit to the $\pi^-\pi^+\pi^0$ invariant mass spectrum for the $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ decays. Shown is the fit to the data for e-tag events.

Fig. 1 shows the invariant mass of the $\pi^-\pi^+\eta$ system and the invariant mass of the $\pi^-\eta$ and $\pi^+\eta$ systems with the requirement that the invariant mass of the $\pi^-\pi^+\eta_{\gamma\gamma}$ systems is between 1.23 and 1.32 GeV/c^2 (consistent with being an $f_1(1285)$ meson). In the latter plot only the π mesons forming the $f_1(1285)$ meson are shown in this plot. The peak near 1 GeV/c^2 is attributed to the $f_1(1285) \rightarrow a_0(980)\pi$ decay.

3. Results

3.1. $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$

The number of $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ events is obtained by counting the number of events in the 4π mass spectrum below the τ mass after subtracting the expected background contributions (see fig. 2). The branching fraction is calculated using

$$\mathcal{B} = \frac{N_{data} - N_{bkg} - N_{q\overline{q}}}{2N_{\tau\tau}\ \epsilon}$$

where N_{data} is the number of events in data; N_{bkg} is the number of τ-background events; $N_{q\overline{q}}$ is the number of $q\overline{q}$ events; ϵ is the efficiency for selecting signal events. $N_{\tau\tau}$ is the number of τ pair events in data, calculated using $N_{\tau\tau} = L \times \sigma_{e^+e^- \rightarrow \tau^+\tau^-}$ where L is the data sample luminosity and $\sigma_{e^+e^- \rightarrow \tau^+\tau^-}$ is the τ pair production cross section (0.89 nb) at $\sqrt{s} = 10.58$ GeV.

A total of 411225, 217788 and 220262 events are selected in the e-tag, μ-tag and ρ-tag samples, respectively. The selection efficiencies are 2.22%, 1.15% and 1.17%, respectively. Background levels are 10-20%. The branching fraction of the $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ decay is measured $(4.39 \pm 0.01(stat) \pm 0.21(syst)) \times 10^{-2}$ for the e-tag sample. The branching fractions obtained from the μ-tag and ρ-tag samples are consistent with the experimental uncertainties.

For the study of $\tau^- \rightarrow \omega\pi^-\nu_\tau$, candidate signal events were required to have the invariant mass of the 4π system to be less than the τ mass. The total number of $\tau^- \rightarrow \omega\pi^-\nu_\tau$ events is obtained by a fit to the $\pi^+\pi^-\pi^0$ invariant mass spectrum (see fig. 3). Both the $q\overline{q}$ and τ backgrounds have contributions that peak at the ω mass. The number of background events in the ω peak is found by fitting the 3π mass spectra of the background Monte Carlo samples. The branching fraction can then be calculated using

$$\mathcal{B} = \frac{N_{data} - N_{bkg} - N_{q\overline{q}}}{2N_{\tau\tau}\ \epsilon} \frac{1}{\mathcal{B}_\omega}$$

where N_{data} is the number of ω events in data; N_{bkg} and $N_{q\overline{q}}$ are the numbers of ω events in the τ

background MC and $q\overline{q}$ background, respectively; $N_{\tau\tau}$ is the number of τ pairs in data; ϵ is the efficiency for selecting signal events; and $\mathcal{B}_\omega$ is the branching fraction of $\omega \to \pi^+\pi^-\pi^0$.

The function used to fit the ω resonance in the 3π mass spectrum is a Breit-Wigner shape convoluted with a Gaussian function for the resonance and a second order polynomial for the background. The resolution is found to be 6.1 MeV.

Figure 3 shows the fit to the e-tag data. A total of 144305, 78261 and 78306 events were obtained in the e-tag, μ-tag and ρ-tag samples, respectively. Background in the ω peak from other τ decays and non-tau backgrounds are approximately 6% and 0.5-2.0%, respectively. The branching fraction for the decay $\tau^- \to \omega\pi^-\nu_\tau$ is measured to be $(1.97 \pm 0.01(stat) \pm 0.10(syst)) \times 10^{-2}$ using the e-tag sample. We find the ratio of the branching fractions $\tau^- \to \omega\pi^-\nu_\tau$ to $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ to be $0.449 \pm 0.002(stat) \pm 0.007(syst)$.

The systematic errors in both branching fractions are dominated by the π^0 reconstruction efficiency (3.0%), the luminosity and cross section uncertainty (2.3%), the track reconstruction efficiencies (2.0%). Other smaller terms include particle identification, background estimate and MC statistical errors. The total systematic error is approximately 5% for the e-tag and μ-tag samples and 7% for the ρ-tag sample.

3.2. $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$

The invariant mass distribution of the $(\gamma\gamma)$ system is fitted with a Novosibirsk function [6] (Gaussian distribution with a tail parameter) for the η meson plus a polynomial function for the background. The observed width of the η is dominated by the experimental resolution (14 MeV/c^2). The resolution and the tail parameters in the fit to the data are fixed to the values obtained from a fit to the signal Monte Carlo. The peak and normalization parameters of the Novosibirsk function are allowed to vary in the fit. A total of 1260 ± 56 decays are obtained from the fit which is shown in fig. 4(a).

The inclusive $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ branching fraction is measured using

$$B = \frac{N_{obs} - N_{bkgd}}{2N_{\tau^+\tau^-}} \frac{1}{\epsilon} \frac{1}{B(\eta \to \gamma\gamma)}$$

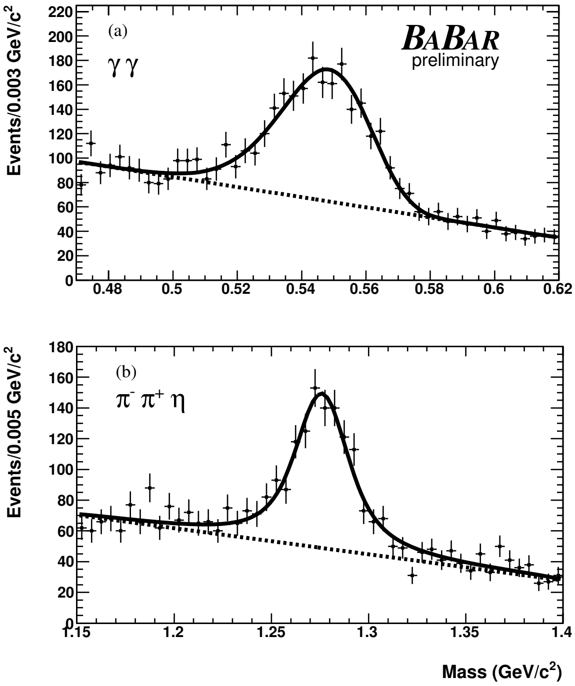

Figure 4. The invariant mass of the $\gamma\gamma$ system is shown in plot (a). The fit to the data uses a Novosibirsk function and a first-order polynomial for the background. Plot (b) shows the invariant mass of the $\pi^-\pi^+\eta$ system where the fit to the $f_1(1285)$ resonance uses a Breit-Wigner convoluted with a Gaussian distribution plus a second-order polynomial distribution.

where N_{obs} is the number of events obtained from the fit (1260 ± 56), N_{bkgd} is the number of events with an η meson from $q\overline{q}$ events (54 ± 16), $N_{\tau^+\tau^-}$ is the number of τ leptons, ϵ is the efficiency for selecting the signal events (4.00 ± 0.07)%, and $B(\eta \to \gamma\gamma)$ is 0.3943 ± 0.0026 [7]. The branching fraction is measured to be $(1.84 \pm 0.09 \pm 0.13) \times 10^{-4}$. where the first error is the statistical error and the second is the systematic.

The systematic errors are similar to those presented in the previous section. Additional contributions arise from uncertainties associated with the fit as well as the $f_1(1285)$ decay model.

The $f_1(1285)\pi$ candidates are selected using the criteria specified above together with the requirement that the η candidates have $0.50 < M_{\gamma\gamma} < 0.58$ GeV/c^2. The invariant mass of the $(\pi^-\pi^+\eta)$ system (fig. 1) is fit with a Breit-Wigner convoluted with a Gaussian distribution and a polynomial function for the background (see fig. 4(b)). The expected mass resolution for the $(\pi^+\ \pi^-\ \eta)$ system is approximately 7 MeV/c^2. The normalization, peak parameter and width of the Breit-Wigner function were allowed to vary. The resolution parameter of the Gaussian was fixed to 7 MeV/c^2 during the fit.

The $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ and $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau$ branching fractions are determined using

$$B = \frac{N_{obs}}{2N_{\tau^+\tau^-}}\frac{1}{\epsilon}\frac{1}{B(\eta\rightarrow\gamma\gamma)}$$

$$B = \frac{N_{obs}}{2N_{\tau^+\tau^-}}\frac{1}{\epsilon}\frac{1}{B(\eta\rightarrow\gamma\gamma)}\frac{1}{B(f_1(1285)\rightarrow\pi^+\pi^-\eta)}$$

where N_{obs} is the number of $f_1(1285)$ mesons obtained in the fit (951±78), $N_{\tau^+\tau^-}$ is the number of τ pairs obtained from the luminosity and $e^+e^- \rightarrow \tau^+\tau^-$ cross section, ϵ is the efficiency for selecting a $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau$ event $(4.36 \pm 0.09)\%$, $B(\eta \rightarrow \gamma\gamma)$ is the $\eta \rightarrow \gamma\gamma$ branching fraction (0.3943 ± 0.0026) and $B(f_1(1285) \rightarrow \pi^+\pi^-\eta)$ is (0.35 ± 0.11) [7]. The reason for splitting the branching fraction for the $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ decay mode is because of the large uncertainty (30%) in the $f_1(1285) \rightarrow \pi^+\pi^-\eta$ branching fraction. The Particle Data Group lists both decay modes [7].

The $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ and $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau$ branching fractions are measured to be $(1.33 \pm 0.11 \pm 0.07) \times 10^{-4}$ and $(3.83 \pm 0.32 \pm 0.20 \pm 1.18) \times 10^{-4}$, respectively, where the first error is statistical and the second is systematic. The third error quoted on the $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau$ branching fraction is due to the large error on the $f_1(1285) \rightarrow \pi^+\pi^-\eta$ branching fraction. The systematic errors for these branching fractions are nearly identical to the ones listed for the $\tau^- \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ branching fraction.

We observe that the $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau$ decay alone cannot account for the observed $\tau^- \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ branching fraction. The fraction of the $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ branching fraction to the inclusive $\tau^- \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ branching fraction is found to be $0.723 \pm 0.012 \pm 0.042$ where the first error is statistical and the second is systematic (taking into account the correlation between the various components).

3.3. Limit on the $\tau^- \rightarrow \eta'(958)\pi^-\nu_\tau$ branching fraction

A limit on the $\tau^- \rightarrow \eta'(958)\pi^-\nu_\tau$ branching fraction can be set by searching for decays of the $\eta'(958)$ to the $\pi^-\pi^+\eta$ final state. This decay proceeds through a forbidden second-class current and is not expected to produce an observable signal.

A fit is performed using a Gaussian function for the $\eta'(958)$ and a polynomial function for the background. The mean of the Gaussian is fixed to the mass of the $\eta'(958)$ meson. The standard deviation of the Gaussian distribution is fixed to the value obtained in a fit to a data sample containing $\eta'(958)$ mesons. This data sample is created by using a hadron tag which has a single track that is not an electron or a muon. All other tag selection criteria are applied.

We observe an excess of events (26 ± 10) over the background fit near the mass of the $\eta'(958)$ meson in the data. To set a conservative limit, we assume that all the events in the $\eta'(958)$ peak are due to signal events.

We also assume that the efficiency for selecting $\tau^- \rightarrow \eta'(958)\pi^-\nu_\tau$ events is identical to the $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau$ selection efficiency. The systematic uncertainty is dominated by a 17% error due to the uncertainty in the resolution of the $\eta'(958)$. The remaining systematic errors are identical to those obtained for the $\tau^- \rightarrow f_1(1285)\pi^-\nu_\tau \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ branching fraction. The results give a conservative 90% confidence level upper limit on the $\tau^- \rightarrow \eta'(958)\pi^-\nu_\tau$ branching fraction of 1.2×10^{-5}.

4. Summary

The $\tau^- \rightarrow \pi^-\pi^+\pi^-\pi^0\nu_\tau$ and $\tau^- \rightarrow \pi^-\pi^-\pi^+\eta\nu_\tau$ decays have been studied with the *BABAR* detector. Preliminary branching fractions on the two modes have been presented. The $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ mode is found to have a large contribution from the $\tau^- \to \omega\pi^-\nu_\tau$ decay. The $\tau^- \to \pi^-\pi^-\pi^+\eta\nu_\tau$ decay is studied using the $\eta \to \gamma\gamma$ mode and the $\tau^- \to f_1(1285)\pi^-\nu_\tau$ decay is seen to be the primary source of these decays. A 90% confidence level upper limit is placed on the $\tau^- \to \eta'(958)\pi^-\nu_\tau$ decay which proceeds through a second-class current and is expected to be forbidden in the limit of perfect isospin symmetry.

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6. The Novosibirsk function is defined as $f(E) = A\exp(-0.5\left\{\ln^2\left[1 + \Lambda\tau\cdot(m - m_0)\right]/\tau^2 + \tau^2\right\})$, where $\Lambda = sinh(\tau\sqrt{\ln 4})/(\sigma\tau\sqrt{\ln 4})$, the peak position is x_0, the width is σ and τ is the tail parameter.
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