Accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ fit for UB and UUB

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Abstract

From the installation of the Upgraded Unified Board (UUB) is expected to have a better accuracy for the estimation of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values respect of the previous Unified Board (UB). Here, the process to calculate the accuracy of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values for the UUB and UB is presented, and the results of its application on 80 UUB stations, and their respective UB version, are showed.

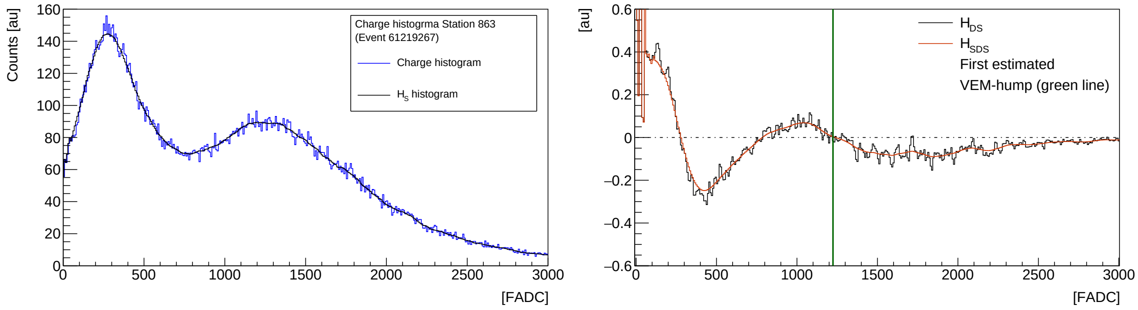

Figure 1: Algorithm's steps applied to get the $Q_{\text{VEM}}^{\text{Peak}}$ from the calibration histograms. Left: typical charge calibration histogram, where the black line represents the smoothing histogram (H_S) after applying 15-bin sliding window. Right: first derivative histogram (H_{DS}) in black, and smoothing of this last one in red (H_{SDS}); here, the green vertical line shows the maximum or the first approach of $Q_{\text{VEM}}^{\text{Peak}}$.

1 Fitting histograms

The $Q_{\text{VEM}}^{\text{Peak}}$ value is obtained from the charge calibration histogram, an algorithm based on the first derivative has been implemented and applied. The goal of this procedure is to estimate the $Q_{\text{VEM}}^{\text{Peak}}$ as the maximum of a second order polynomial, fitting the respective hump muon. In this sense, the first derivative of the histogram works as first approach to locate this hump, and from there to estimate the fit range. This algorithm is described below, and showed in figure 1:

1. Smoothing the histogram using a 15-bin sliding window, H_S.
2. Obtaining the first derivative of the H_S, by

$$\frac{f(x+1)-f(x-1)}{2h}, \tag{1}$$

   which is called H_{DS}.

3. Smoothing H_{DS}, by 15-bin sliding window, and obtaining H_{SDS}.
4. Searching for the estimated $Q_{\text{VEM}}^{\text{Peak}}$, i.e. first bin for H_{SDS} equal to zero, from right to left.
5. Fixing the fitting range using n-bin leftward and n-bin rightward from the estimated $Q_{\text{VEM}}^{\text{Peak}}$.

The last algorithm' step requires an extra procedure in order to fixed the number of n-bin. Using a set of histograms, the stability of the fit (in terms of RMS/$\left\langle Q_{\text{VEM}}^{\text{Peak}} \right\rangle$) was plotted as a function of the n-bin. For this, the estimated $Q_{\text{VEM}}^{\text{Peak}}$ from the derivative (step 4.) was used as initial parameter, and from this point, a number of n-bin was fixed with an extra condition of not reaching the valley of the histogram. Finally, the RMS/$\left\langle Q_{\text{VEM}}^{\text{Peak}} \right\rangle$ vs n-bin was plotted, and it is presented in the first row of figure 2. There, the stability of the fit is seen at and after 30-bin, and this last one is chosen as the number of n-bin for the algorithm' step 5. In the bottom row of figure 2, an example of applying this procedure is presented. Section 5 contains the $Q_{\text{VEM}}^{\text{Peak}}$ values obtained by this method from 75 UUB stations and for the same stations but in UB version (using the same algorithm).

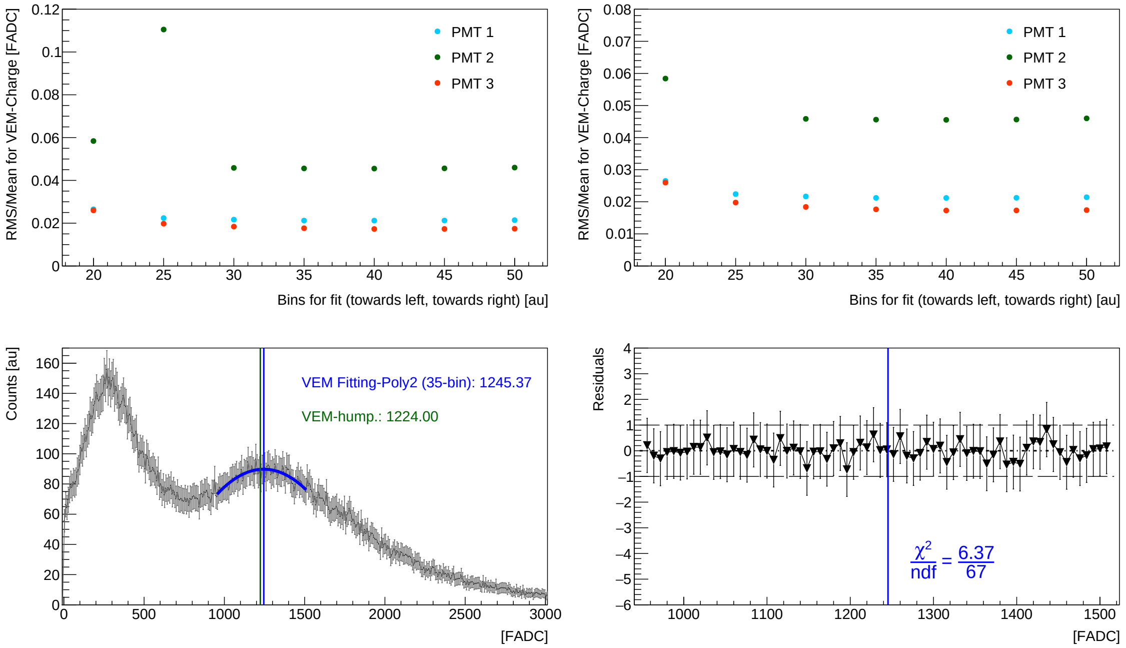

Figure 2: Top row, results for the stability of fitting the hump muon (RMS/$\left\langle Q_{\mathrm{VEM}}^{\mathrm{Peak}} \right\rangle$) as function of the n-bin. After 30 bins the stability is reached. Bottom row, an example of applying the algorithm; here the vertical green line shows the hump VEM obtained from the first derivative (step 4.), and the vertical blue line shows the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ obtained as the maximum of the fitted second order polynomial.

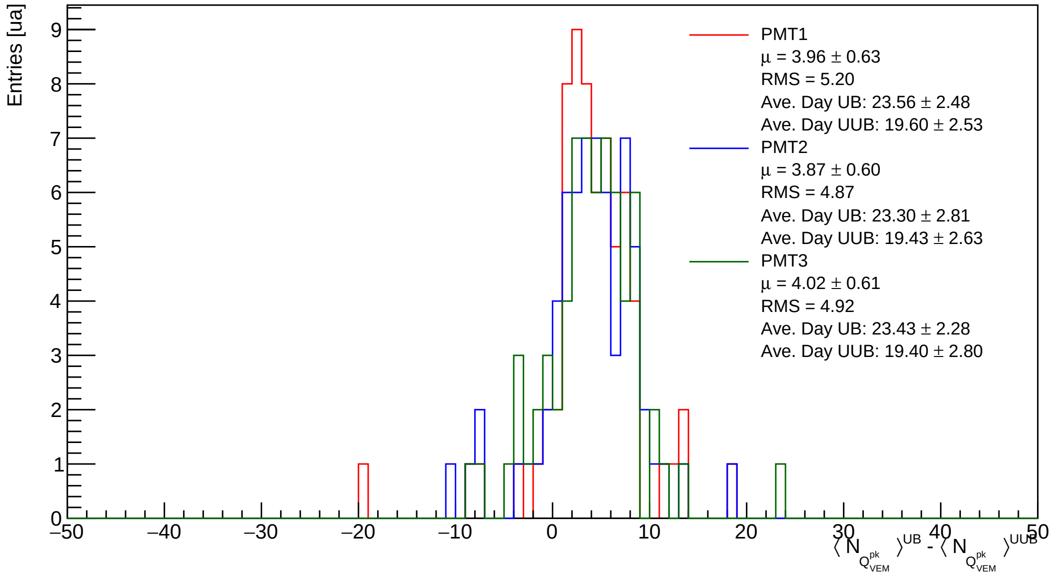

Figure 3: Average of number of histograms fitted per day, $< N_{Q_{VEM}^{pk}} >$, for UB and UUB, from August to November, 2018 and 2021 respectively. In global, the UUB version produces $\sim$ 19.5 T3 triggers per day, around 4 less than the same ones for UB.

2 Sliding window algorithm

The strategy followed to calculate the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ accuracy is based on the selection of a time window in which the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ as a function of time was stable, i.e. $Q_{\mathrm{VEM}}^{\mathrm{Peak}}(t) \sim$ constant. In this sense, as first step the average of number of histograms fitted per day, $< N_{Q_{VEM}^{pk}} >$, was calculated by PMT for UB and UUB, and the distribution for the difference of this averages (UB minus UUB) is presented in figure 3. There is possible to see that the mean of each distribution is positive and around 4 histograms per day, which imply that, in average, the UUB version is producing four T3 triggers less per day than UB; in global, the UUB version produces $\sim$ 19.5 charge histograms per day while UB produces 23.5 of these same.

The time window has been chosen as six days, i.e. 5% of total days in four months (August to November). To identify the stable window into the four months, a sliding window algorithm was applied for each PMT as follows

1. Starting with the first day of August, an average of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ is calculate per day for six days, getting a first six-day-series.
2. A linear fit is applied to previous six-day-series, and the respective slope and χ^2 are stored.
3. After the first [six-day-series]$_0$, a new [six-day-series]$_1$ is building replacing the sixth day in [six-day-series]$_0$ by the next day in the respective month.
4. A check in the [six-day-series]$_i$ continuity is applied, i.e. checking the six days are consecutive, if not a new series is build starting for the first day after the discontinuity; for instance, if series i has a discontinuity in day 3 jumping to day 5, so the new six-day-series is calculated starting from the day 5.

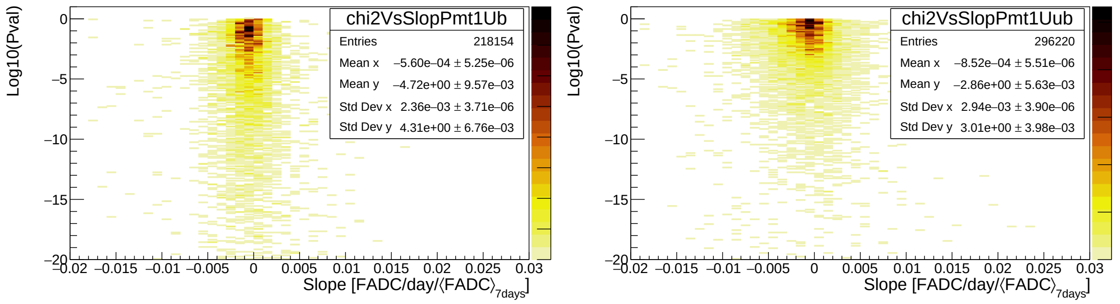

Figure 4: χ^2 Vs Slope. PMT1

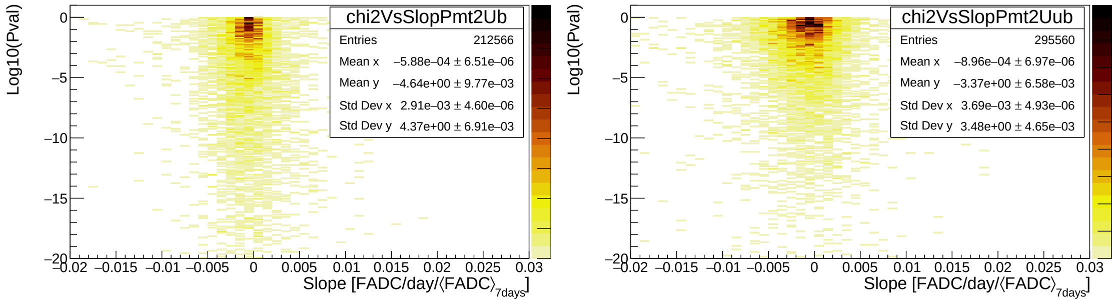

Figure 5: χ^2 Vs Slope. PMT2

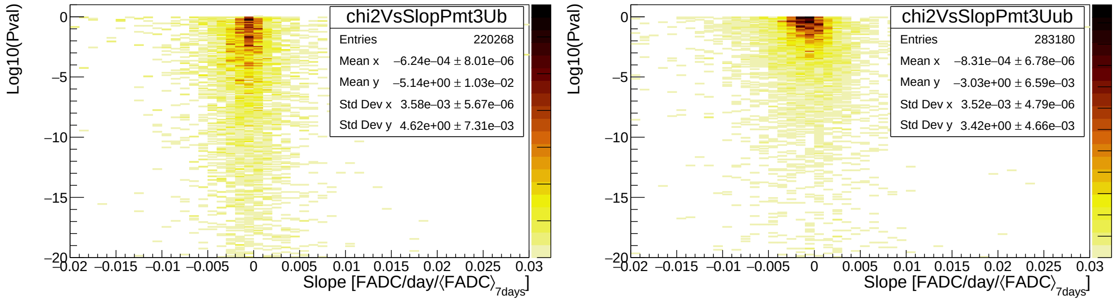

Figure 6: χ^2 Vs Slope. PMT3

The results of this algorithm are shown in figures 4 to 6, where the distribution of the χ^2 versus the slope obtained from each [six-day-series] is presented per PMT, for both UB and UUB. There, it is seen that for the three PMTs, the slope distribution is narrower for UB than UUB, with a clear hot-region seen for UB PMTs but which it is not observable in UUB. On the other hand, the mean of the slopes is close to zero for UB, but close to -1 for UUB. This means that, in average, the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values for UUB are decreasing at a rate of one FADC per day. Regarding the quality of the fits, in average the χ^2 is better for UUB stations, $\langle\chi^2\rangle \sim 15$, than UB, $\langle\chi^2\rangle \sim 22$.

Figures 7 to 9 show the projection for the slope distribution, where is clear that, for the three PMTs, this distribution is narrow ($\sigma \sim 1$), with $\mu \sim 0\,\mathrm{FADC/day}$ for UB, while for UUB it is wide ($\sigma \sim 5$) and $\mu \sim -1\,\mathrm{FADC/day}$. The projections for χ^2 distributions are presented in figures from 10 to 12 together with the respective cumulative distribution, which one has been include with the aim to set a criteria to reject $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ according with its fit quality, this due to the extended tail of the distribution and that its maximum cover less than 30 % of the counts.

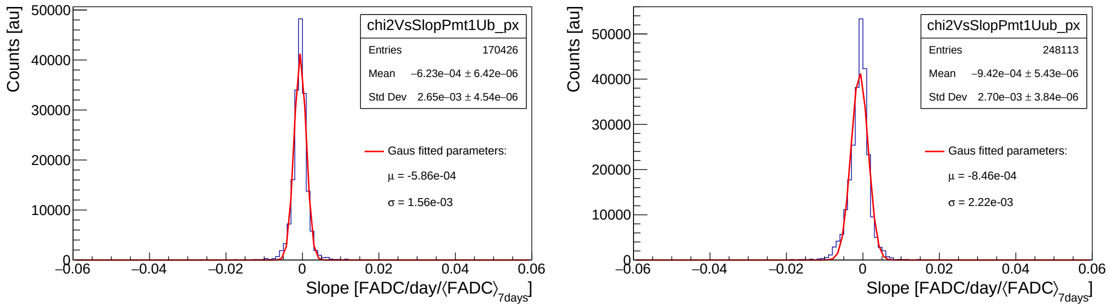

Figure 7: Slope distribution for PMT1, left UB and right UUB.

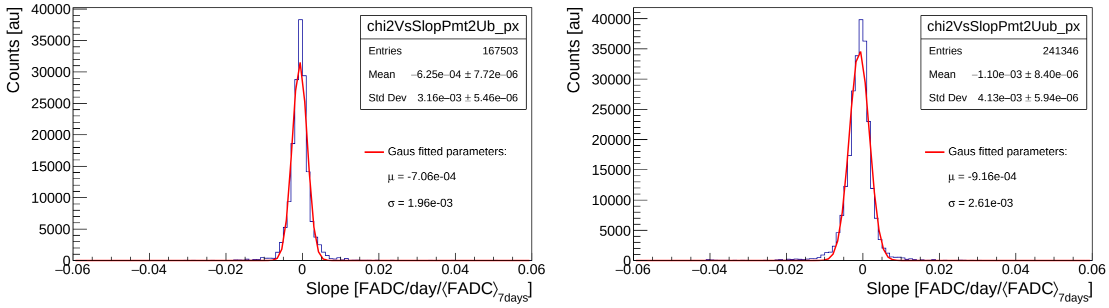

Figure 8: Slope distribution for PMT2, left UB and right UUB.

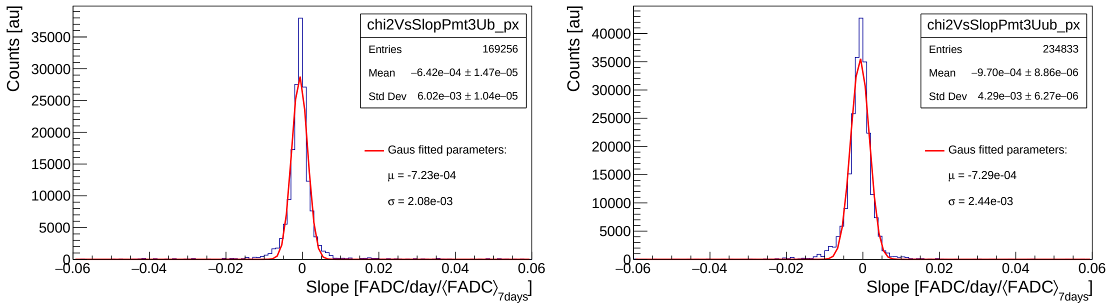

Figure 9: Slope distribution for PMT3, left UB and right UUB.

In this sense, a χ^2 of 18 for UB, and 12 for UUB, has been chosen as cut, values including the 60 % of the counts, as it can be seen in the respective plots.

3 Accuracy calculation

For the calculation of the accuracy, a set of $Q^{\text{Peak}}_{\text{VEM}}$ values, per PMT, were used. This set corresponds to the [six-day-series] with the minimum χ^2 among the ones with slope between -0.5 and 0.5, for both UB and UUB. This range is inside one sigma of the slope distributions, as figures from 7 to 9. This imply that some PMTs, from some stations, were discarded because there was not a [six-day-series] with a slope into the former range. For instance, if the PMT$_i$ from the UB station A was discarded, so the same PMT$_i$ for UUB version was discarded too.

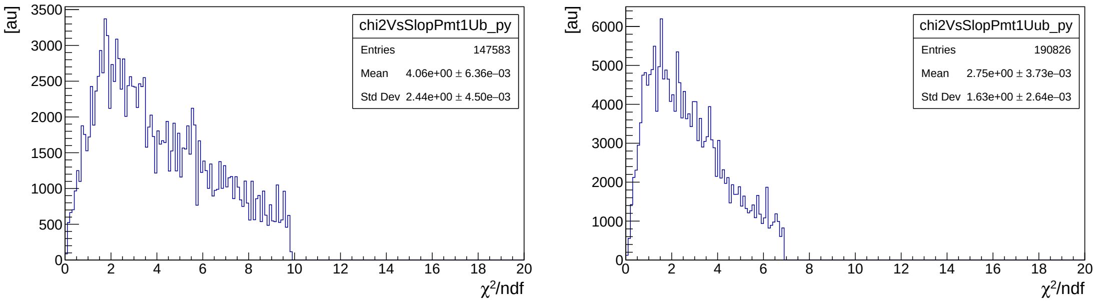

Figure 10: χ^2 distribution PMT1, left UB, right UUB. In red, the cumulative of the distribution is presented.

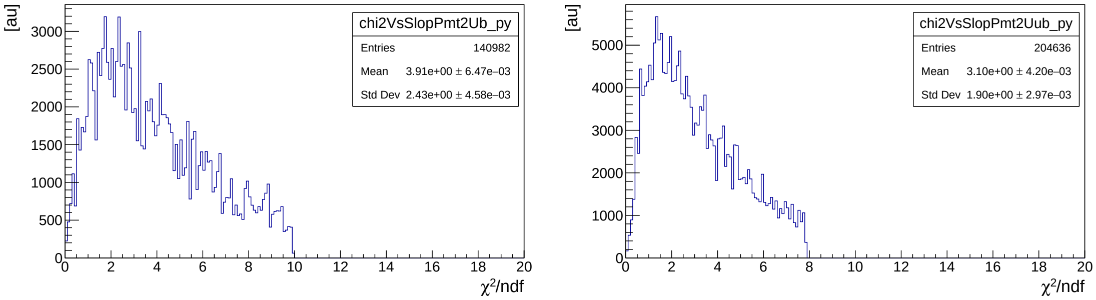

Figure 11: χ^2 distribution for PMT2, left UB, right UUB. In red, the cumulative of the distribution is presented.

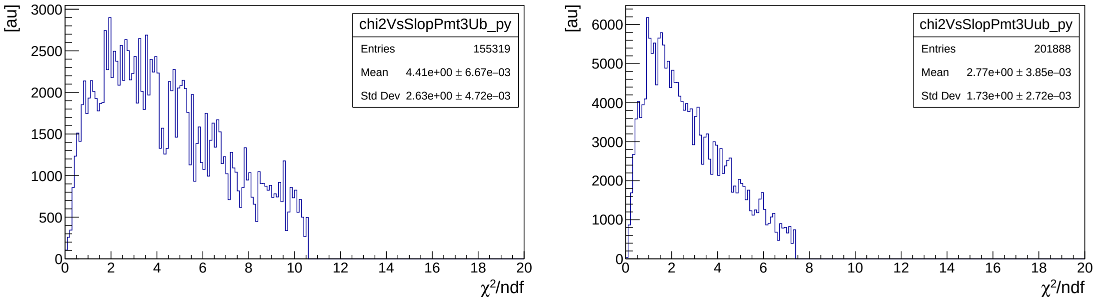

Figure 12: χ^2 distribution for PMT3, left UB, right UUB. In red, the cumulative of the distribution is presented

Using the [six-day-series] selected, and for the respective PMT, the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ were normalized, respect the average of the set, and a single distribution is built by summing the distributions of the respective PMTs.

In this way, we obtain a distribution that represents the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ normalized for each station. A Gauss function is fitted to this last distribution in order to the get the first two moments of the distribution, which are used to determine the accuracy, σ/μ. The figure 13, top row, shows an example for the distribution of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values ($Q_{\mathrm{Dist}}^{\mathrm{Pk}}$) for station 1208, UUB and UB version, meanwhile bottom row shows the distribution for the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ normalized.

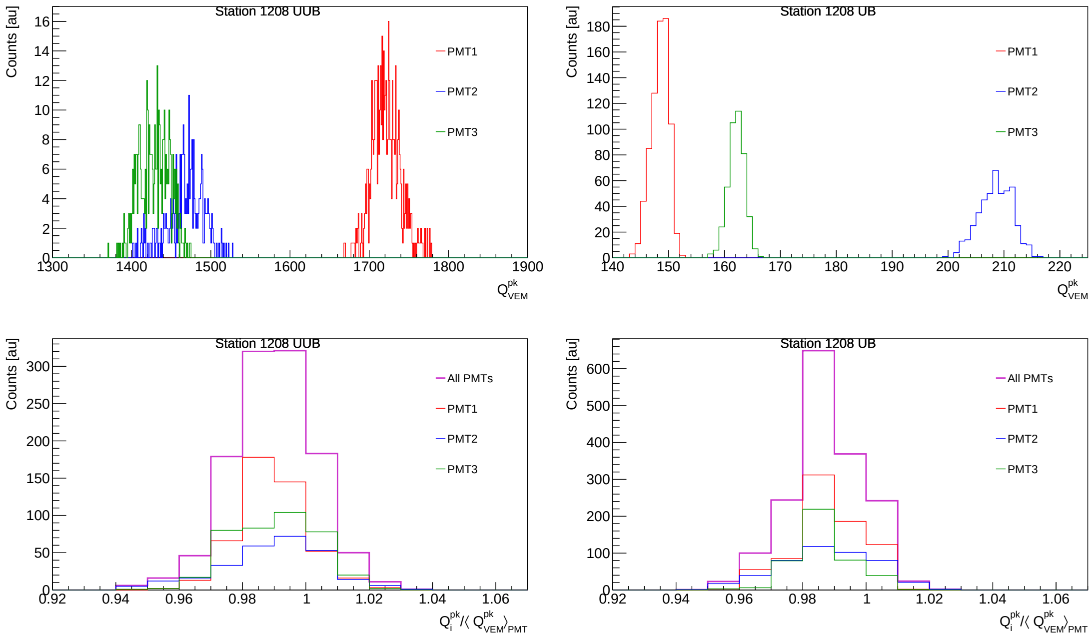

Figure 13: Upper row, distribution of the fitted $Q^{\mathrm{Peak}}_{\mathrm{VEM}}$ values ($Q^{\mathrm{Pk}}_{\mathrm{Dist}}$, in the plot) for station 1747, for each PMT (red PMT1, blue PMT2, and green PMT3), UUB (left) and UB (right) version. Lower row, For same station, results for $Q^{\mathrm{Peak}}_{\mathrm{VEM}}$ normalized respect the average of the respective PMTs. The magenta line represents the $Q^{\mathrm{Pk}}_{\mathrm{NormDist}}$, i.e. the sum of $Q^{\mathrm{Pk}}_{\mathrm{Dist}}$ with a RMS lower or equal to 1.3 times the σ of the preliminary distribution (see text for details). In red, a Gauss function fitted to $Q^{\mathrm{Pk}}_{\mathrm{NormDist}}$.

The figure 14 shows the results for the accuracy of the fitted $Q^{\mathrm{Peak}}_{\mathrm{VEM}}$, applying the algorithm presented in section **??**. There, the distribution of the accuracy for UB, and UUB are presented, with a means of 1.40 % ± 0.06 % and 1.97 % ± 0.17 %, respectively.

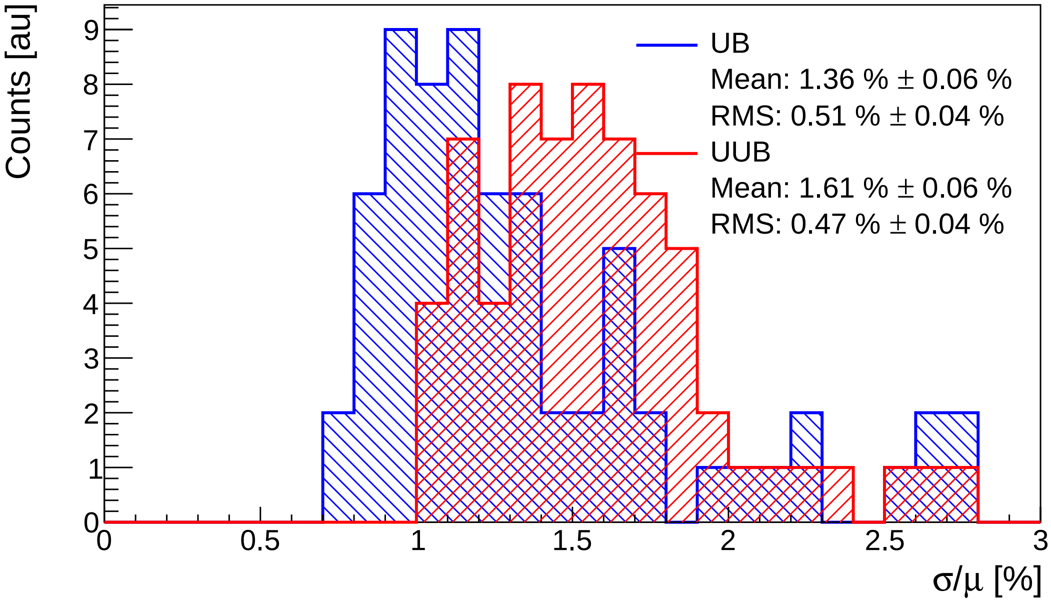

Figure 14: Results for the accuracy calculation of the $Q_{\text{VEM}}^{\text{Peak}}$ fitting, using the algorithm describe in section 2. In the right side, the distribution of the σ/μ values is presented for both version, UUB (red) and UB (blue). Here, it is possible to see that the accuracy for UUB is better than the one for UB.

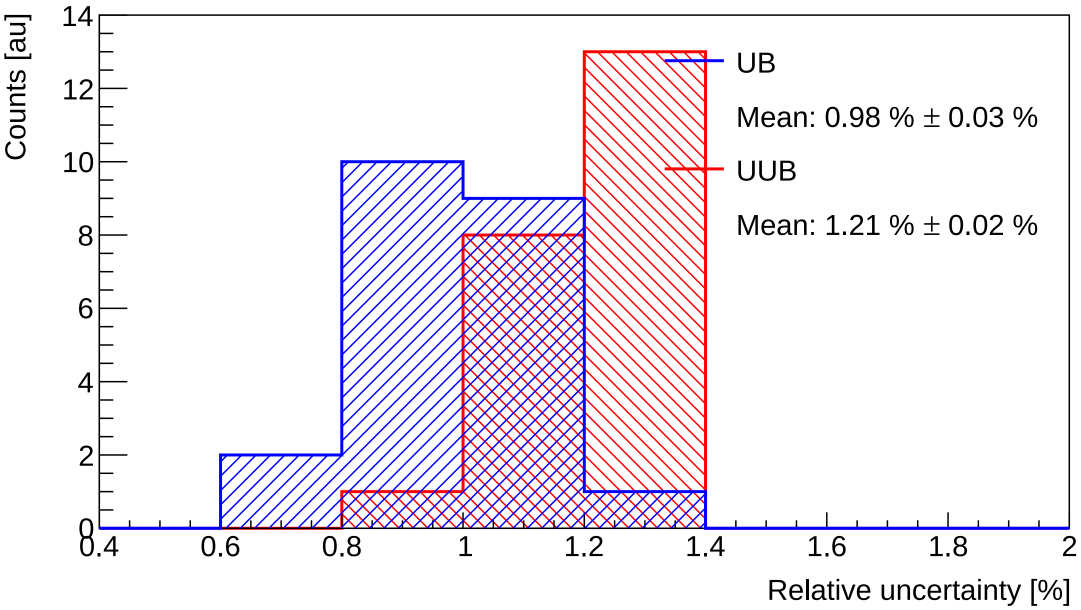

Figure 15: Results for the accuracy calculation of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ fitting, selecting the [n-day-series] by hand. In the right side, the distribution of the σ/μ values is presented for both version, UUB (red) and UB (blue). Here, it is possible to see that the accuracy for UUB is better than the one for UB.

4 Results hand-selection

The figure 15 shows the results for the accuracy of the fitted $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$, selecting the [n-day-series] by hand. The respective intervals are shown on figures in section 5, horizontal black line. There, the distribution of the accuracy for UB, and UUB are presented, with a means of $1.40\,\% \pm 0.06\,\%$ and $1.97\,\% \pm 0.17\,\%$, respectively.

5 $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ as function of time

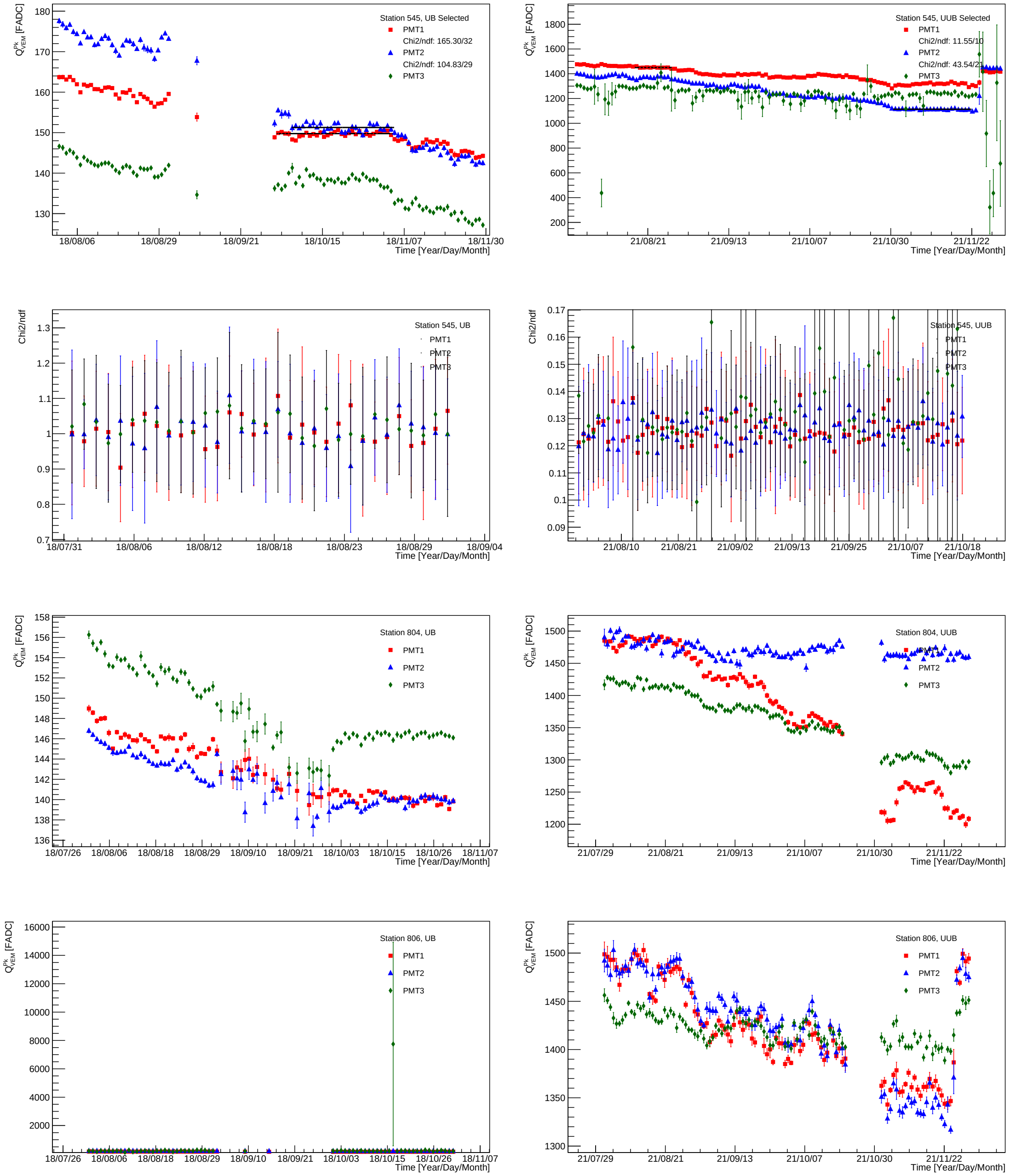

Figure 16: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. The first row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, for the station 545, left UB, and right UUB version. In the second raw, the quality of the respective fit (the average of χ^2/ndf per day), same station, is plotting as function of time. The third and fourth row present the same results as row 1, for stations 804 and 806. if the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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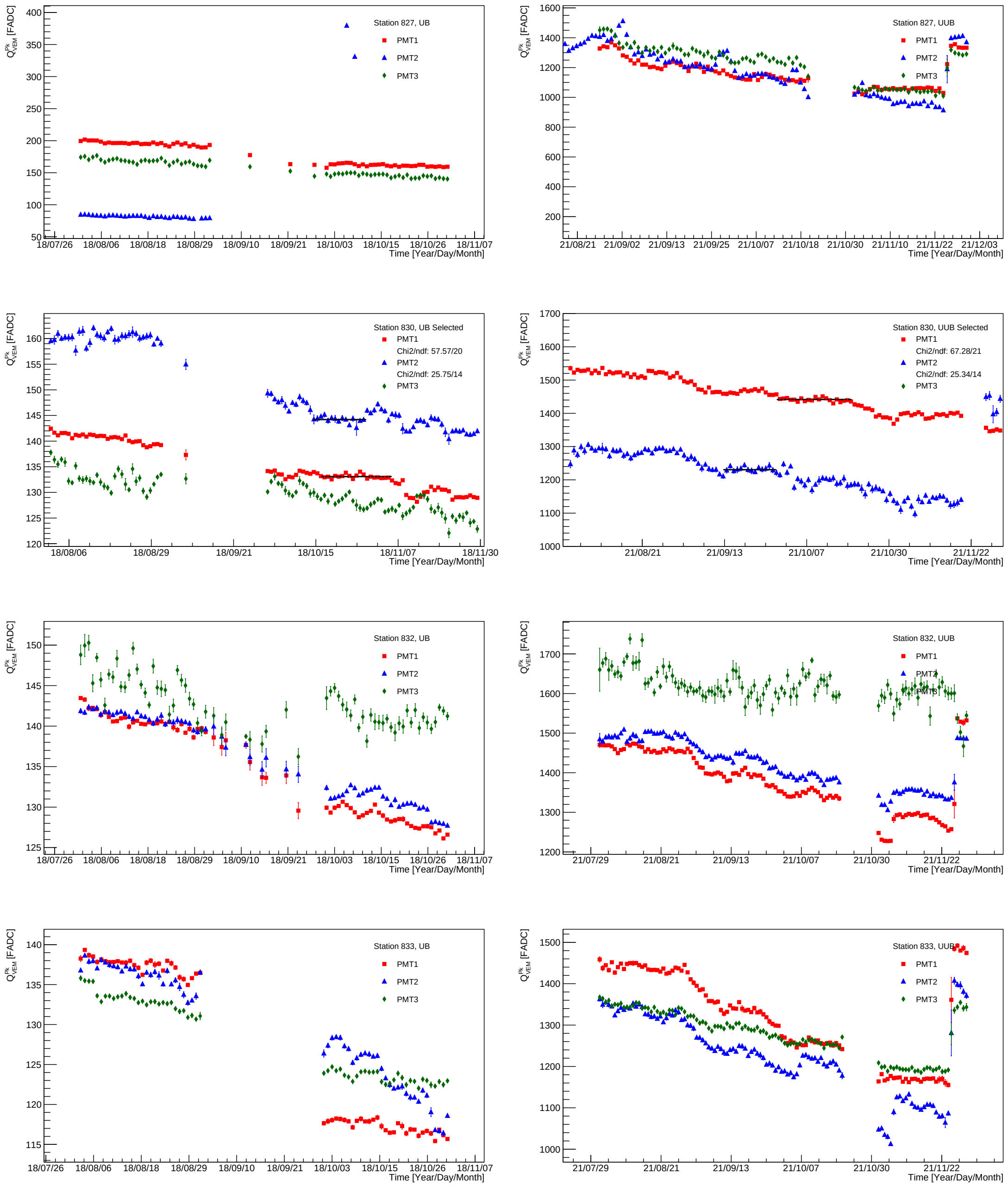

Figure 17: $Q_{\text{VEM}}^{\text{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\text{VEM}}^{\text{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label “Selected” is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\text{VEM}}^{\text{Peak}}$.

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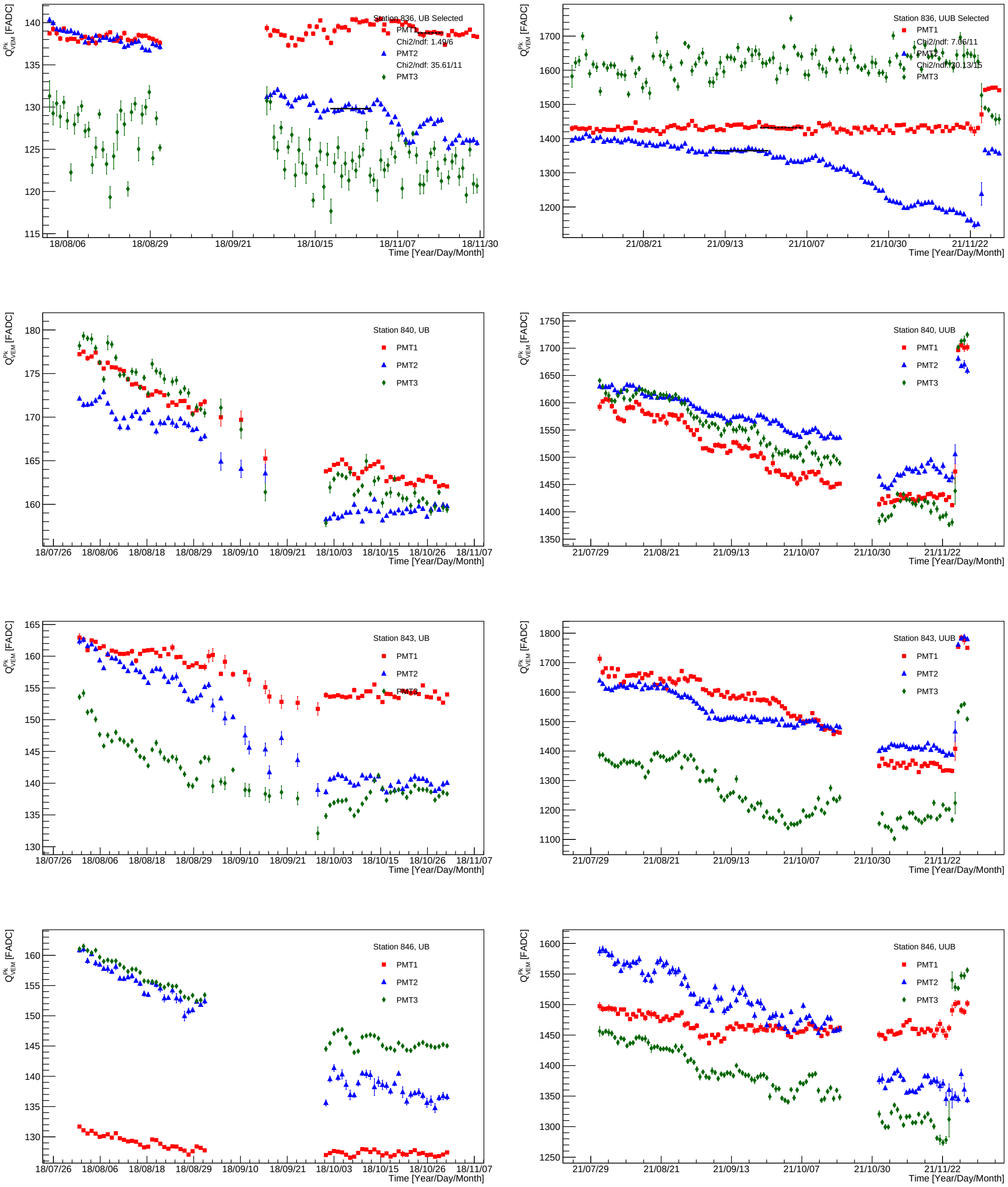

Figure 18: $Q^{\text{Peak}}_{\text{VEM}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q^{\text{Peak}}_{\text{VEM}}$ per day plotting as function of time, left UB, and right UUB version. If the label “Selected” is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q^{\text{Peak}}_{\text{VEM}}$.

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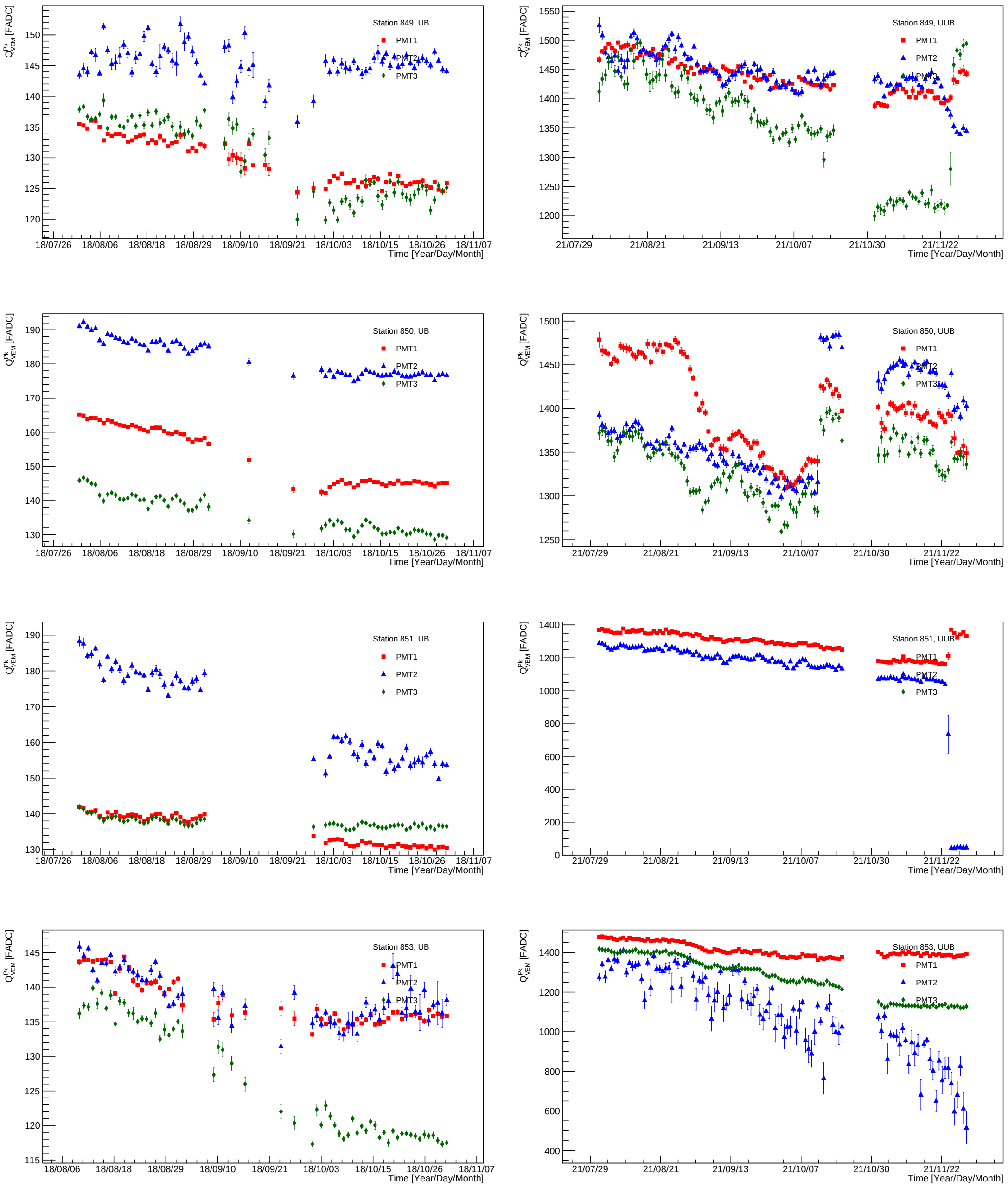

Figure 19: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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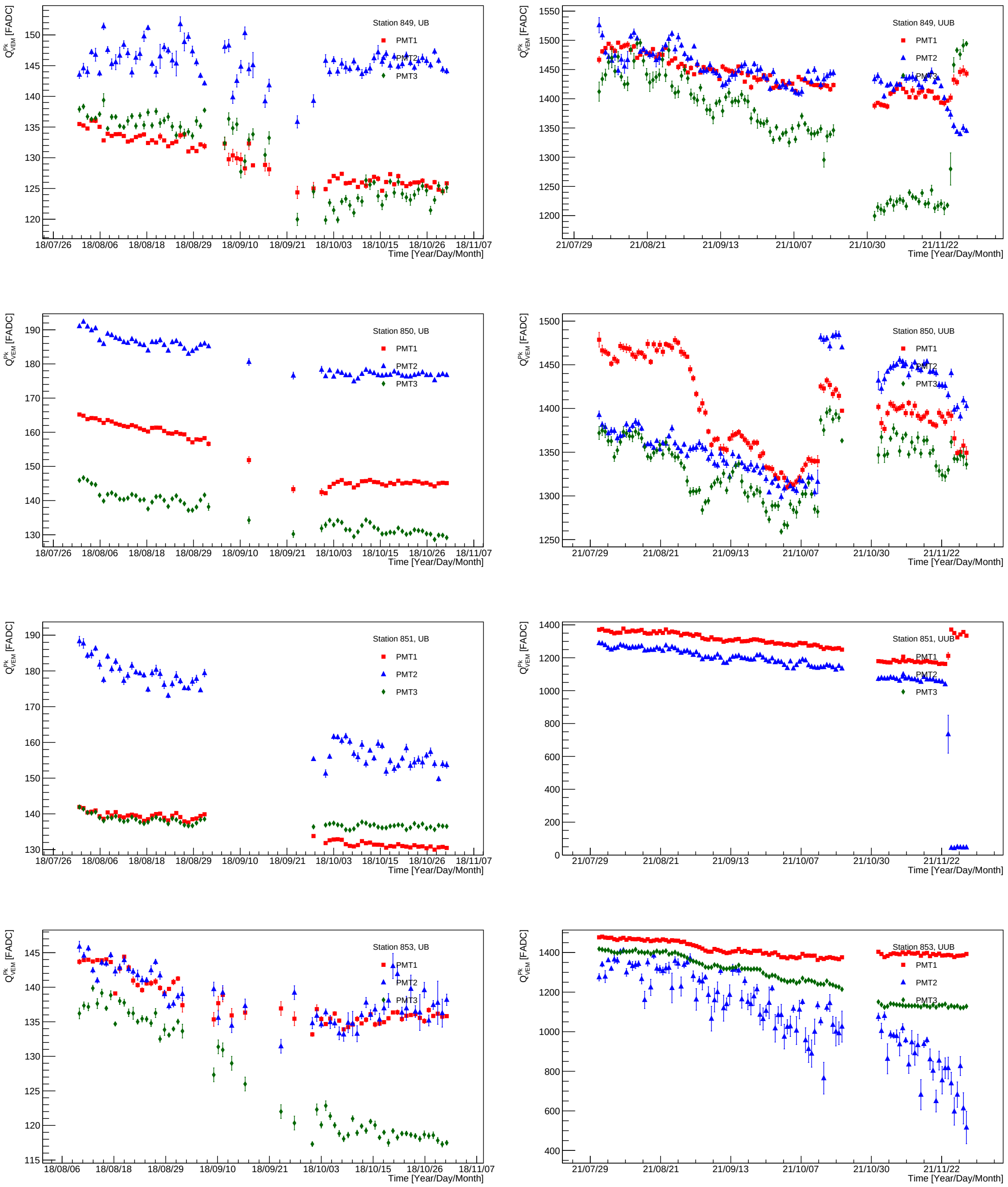

Figure 20: $Q_{\text{VEM}}^{\text{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\text{VEM}}^{\text{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\text{VEM}}^{\text{Peak}}$.

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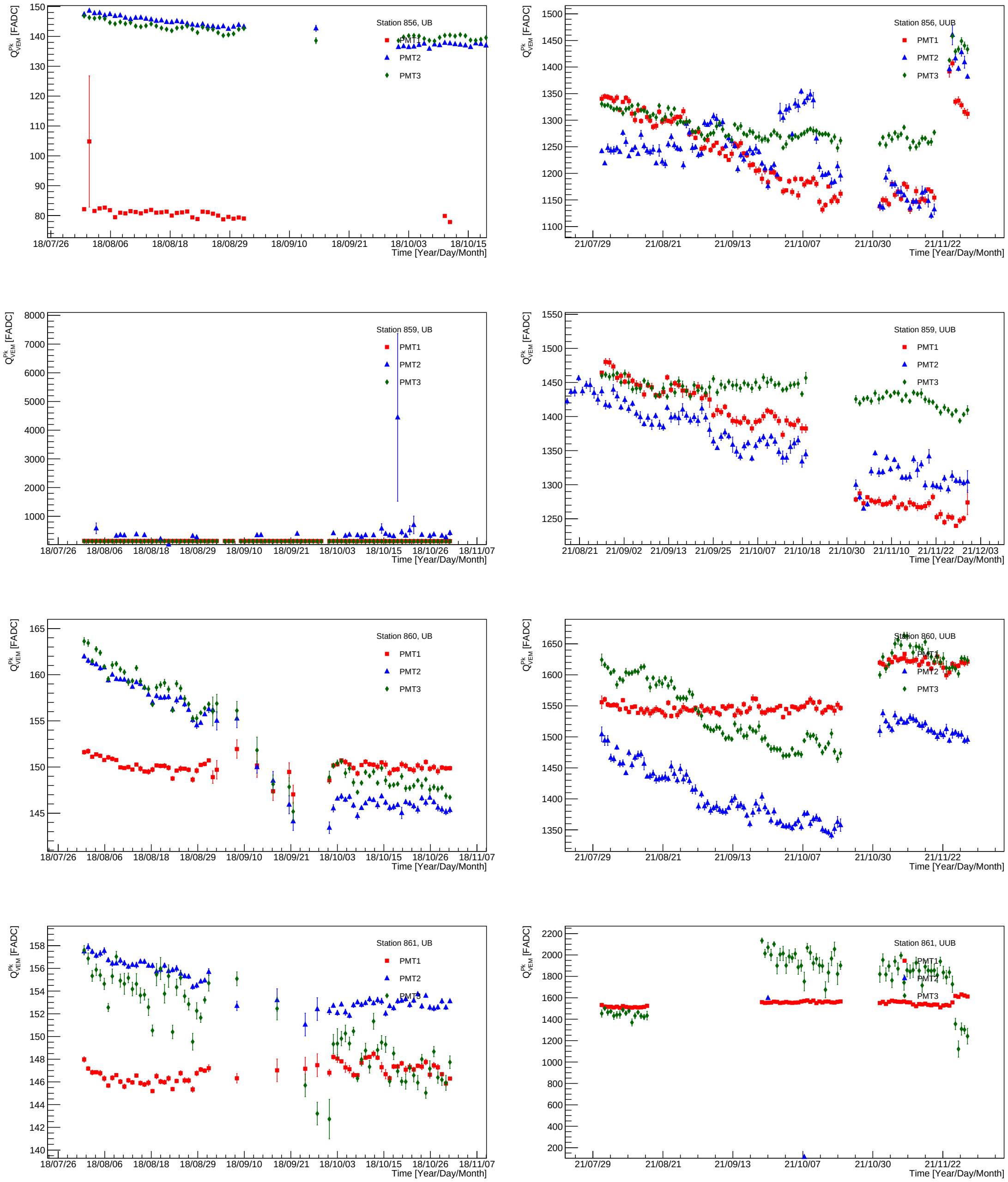

Figure 21: $Q^{\text{Peak}}_{\text{VEM}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q^{\text{Peak}}_{\text{VEM}}$ per day plotting as function of time, left UB, and right UUB version. If the label “Selected” is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q^{\text{Peak}}_{\text{VEM}}$.

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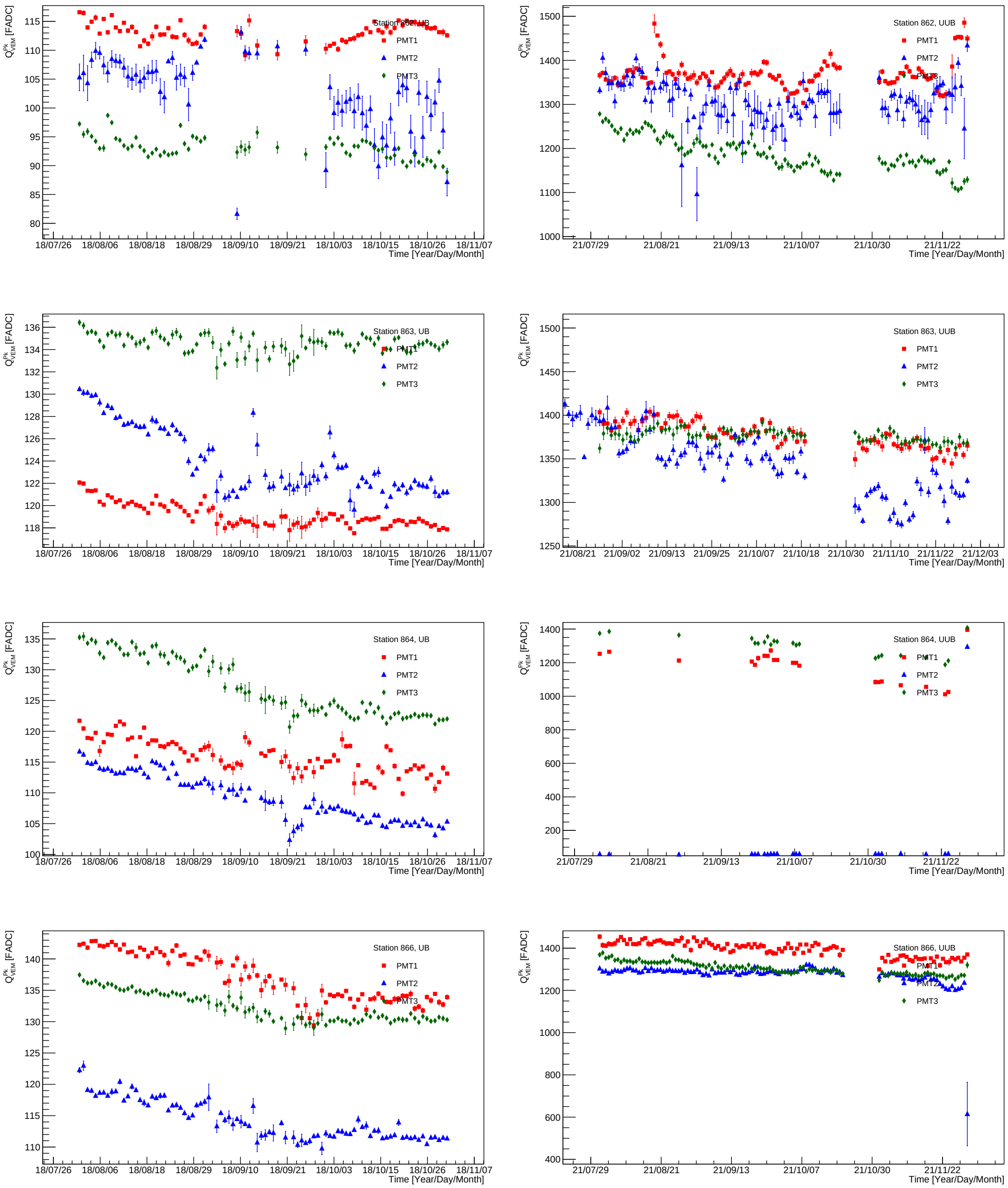

Figure 22: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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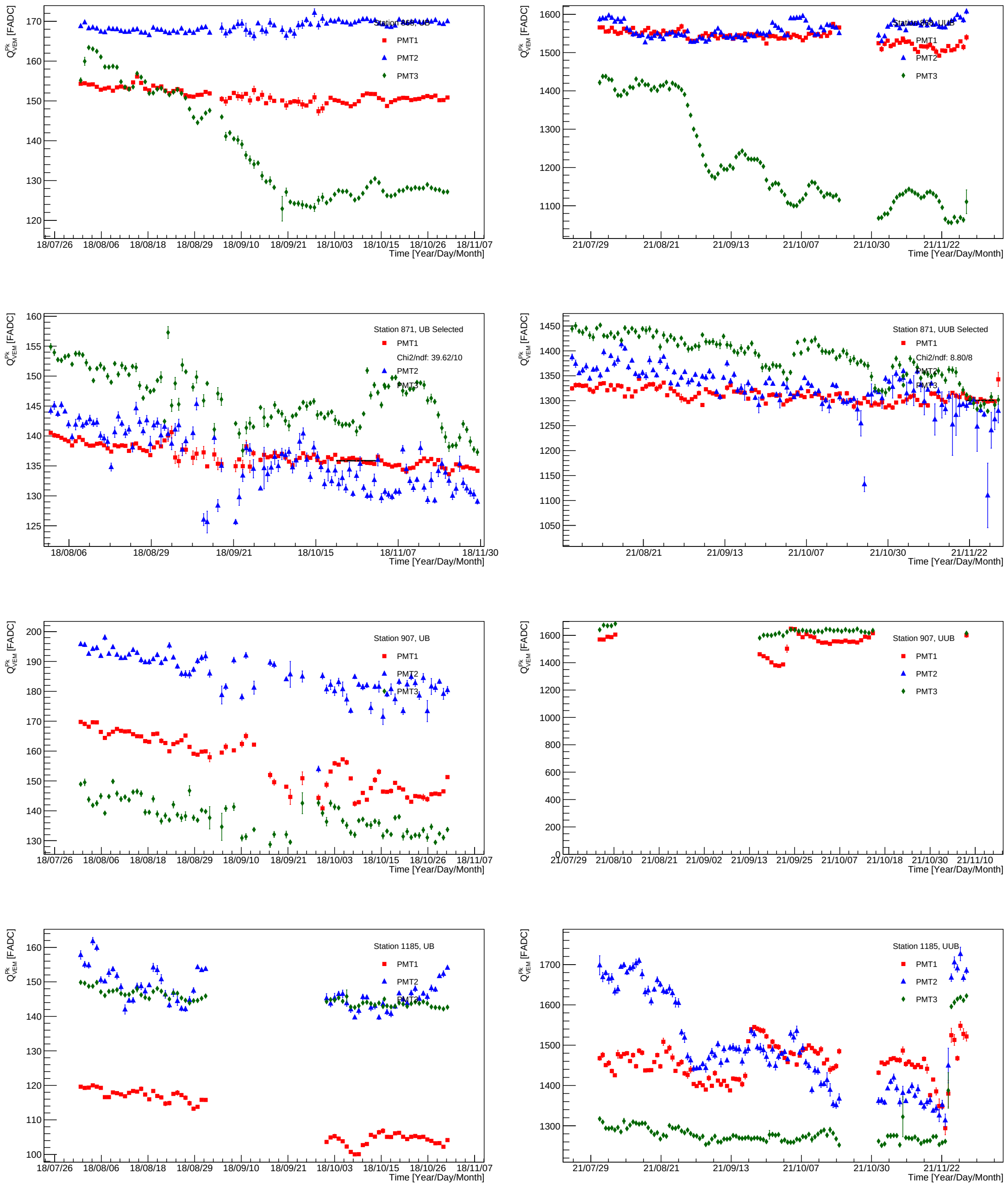

Figure 23: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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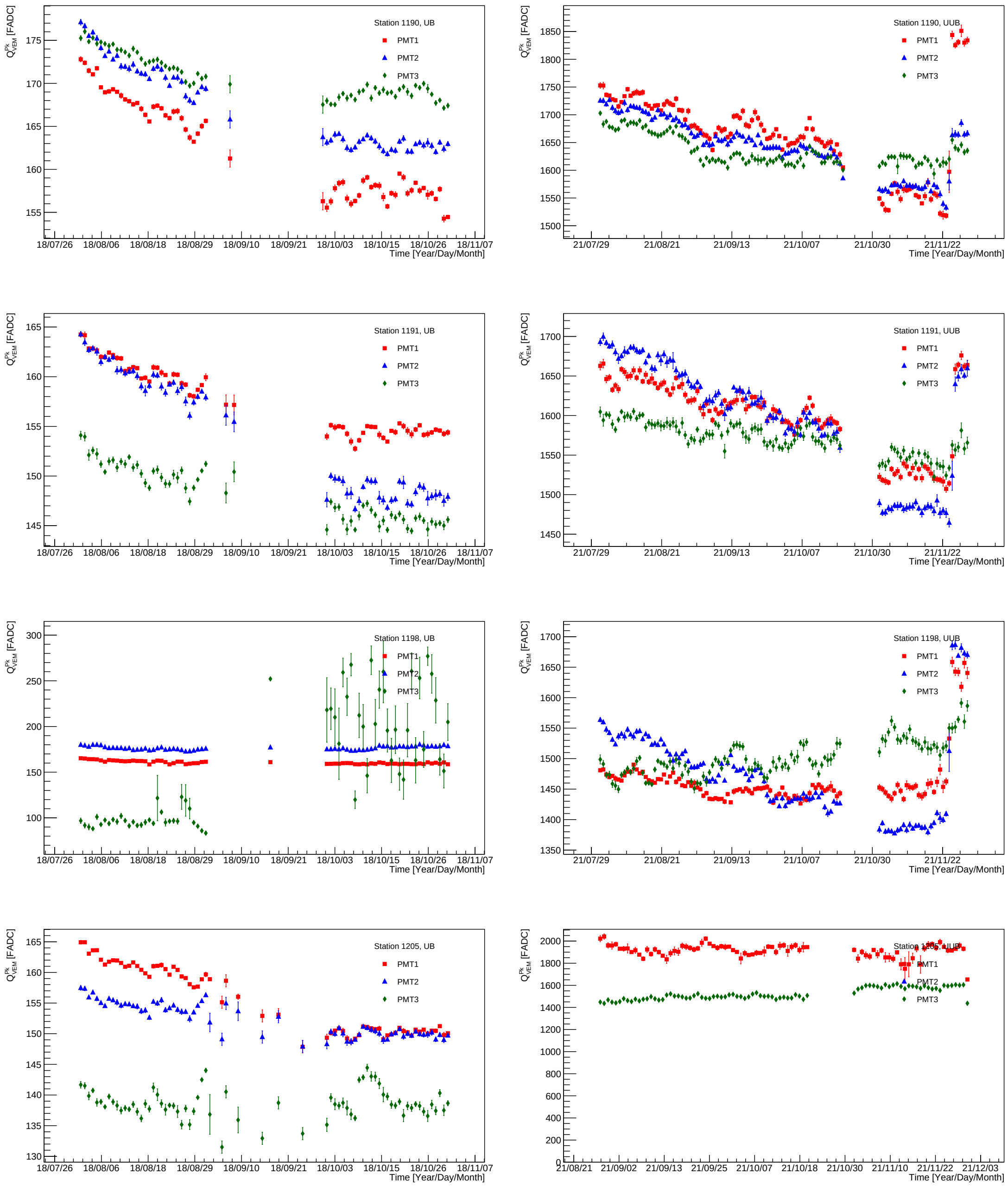

Figure 24: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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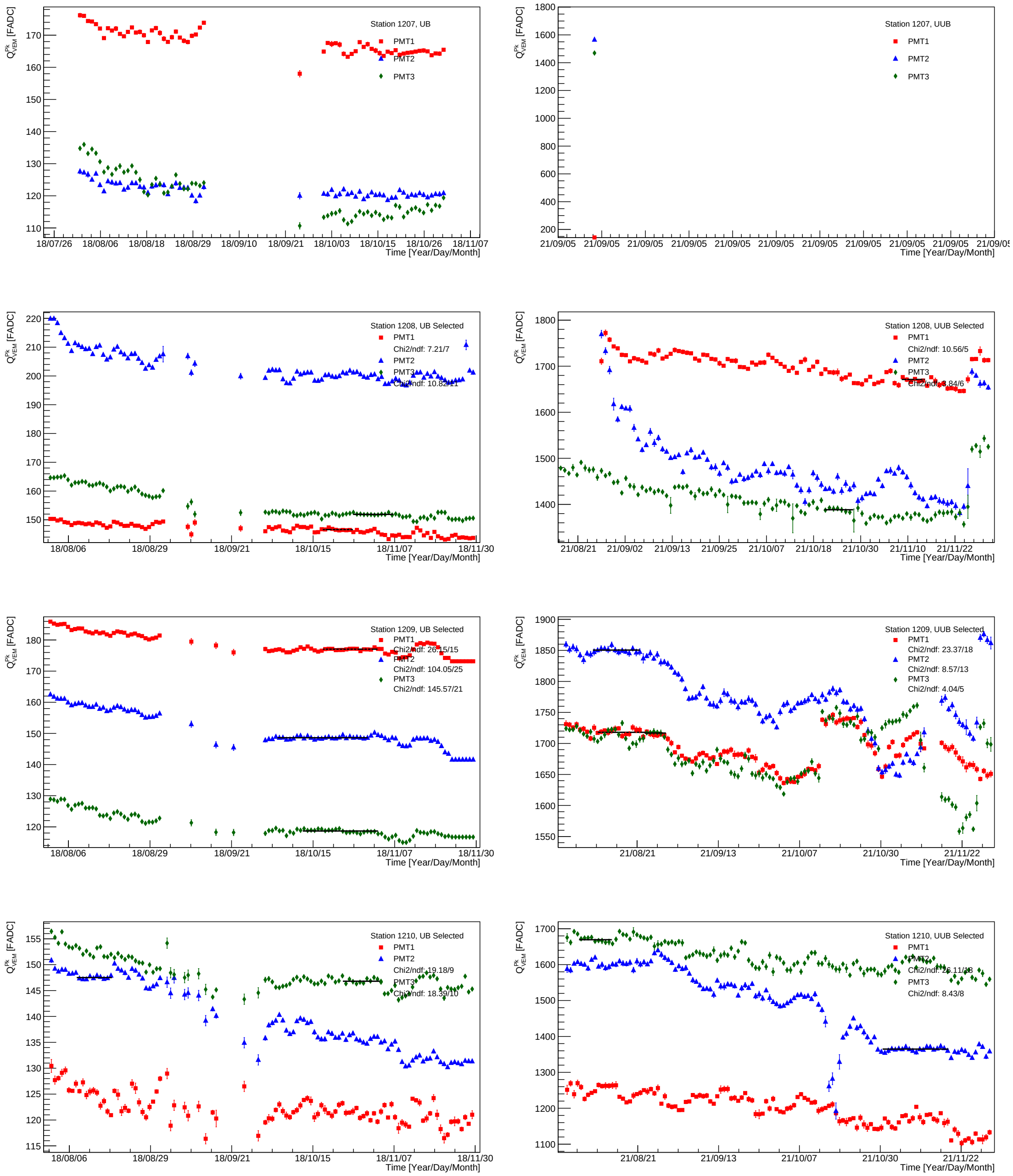

Figure 25: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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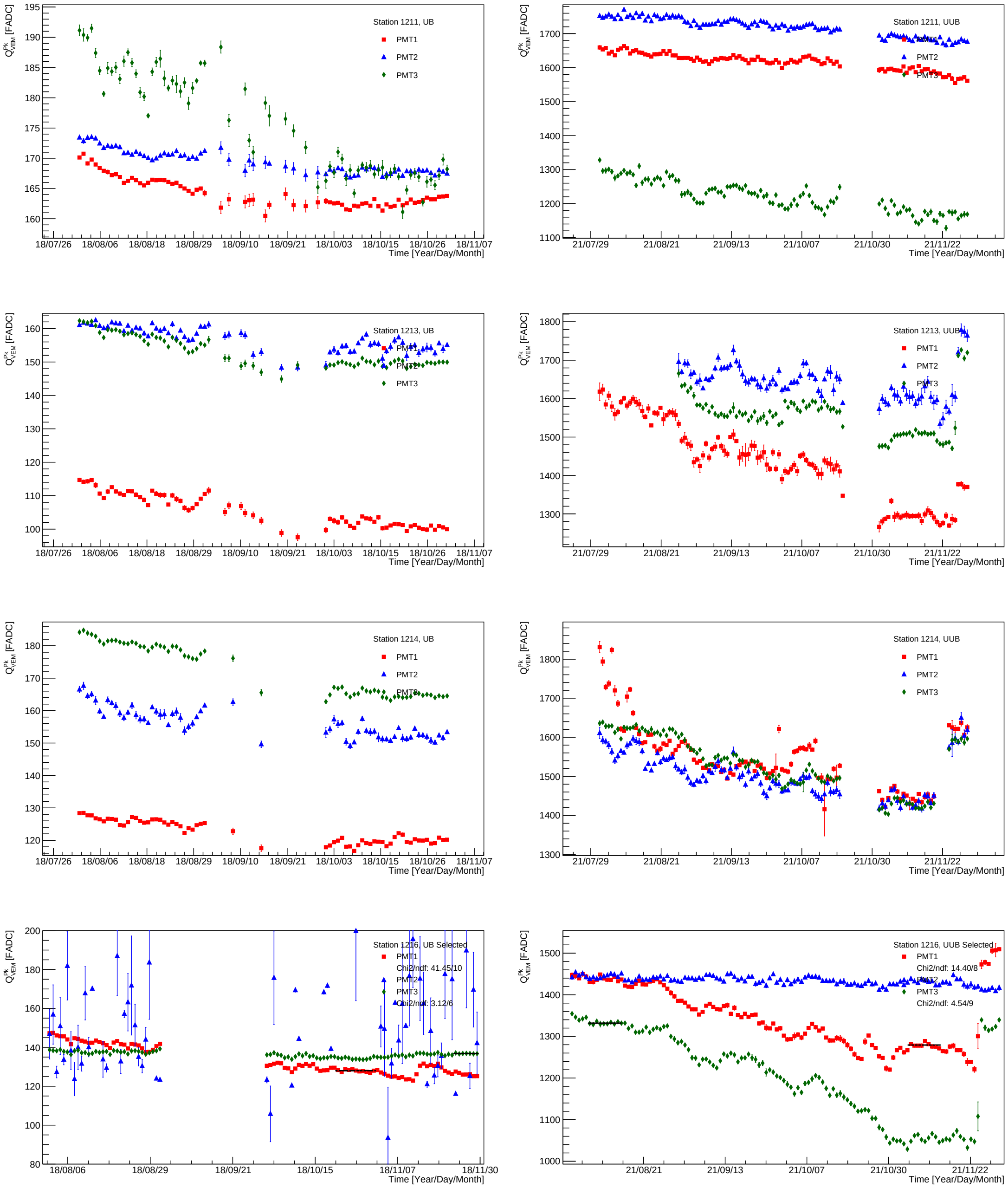

Figure 26: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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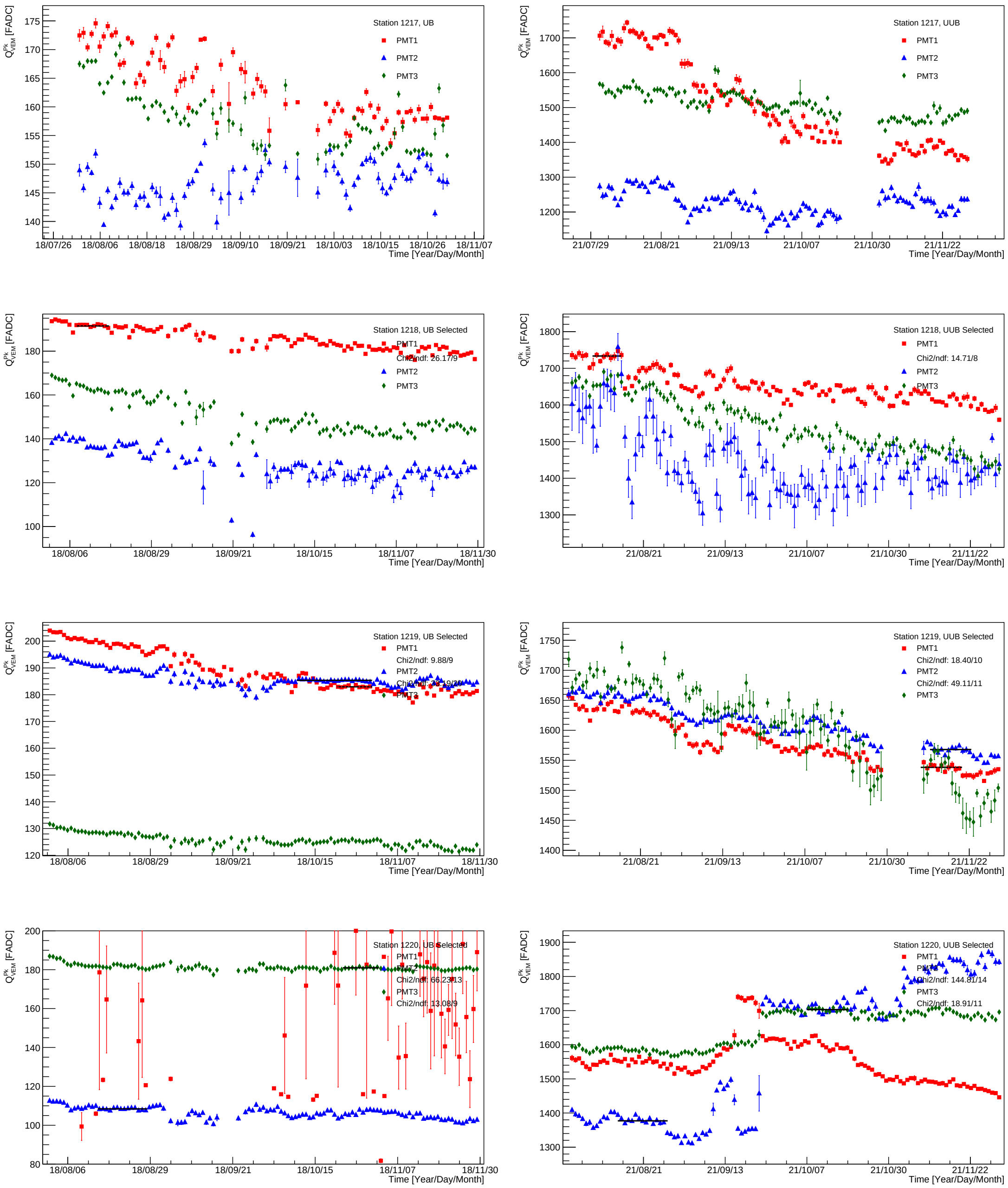

Figure 27: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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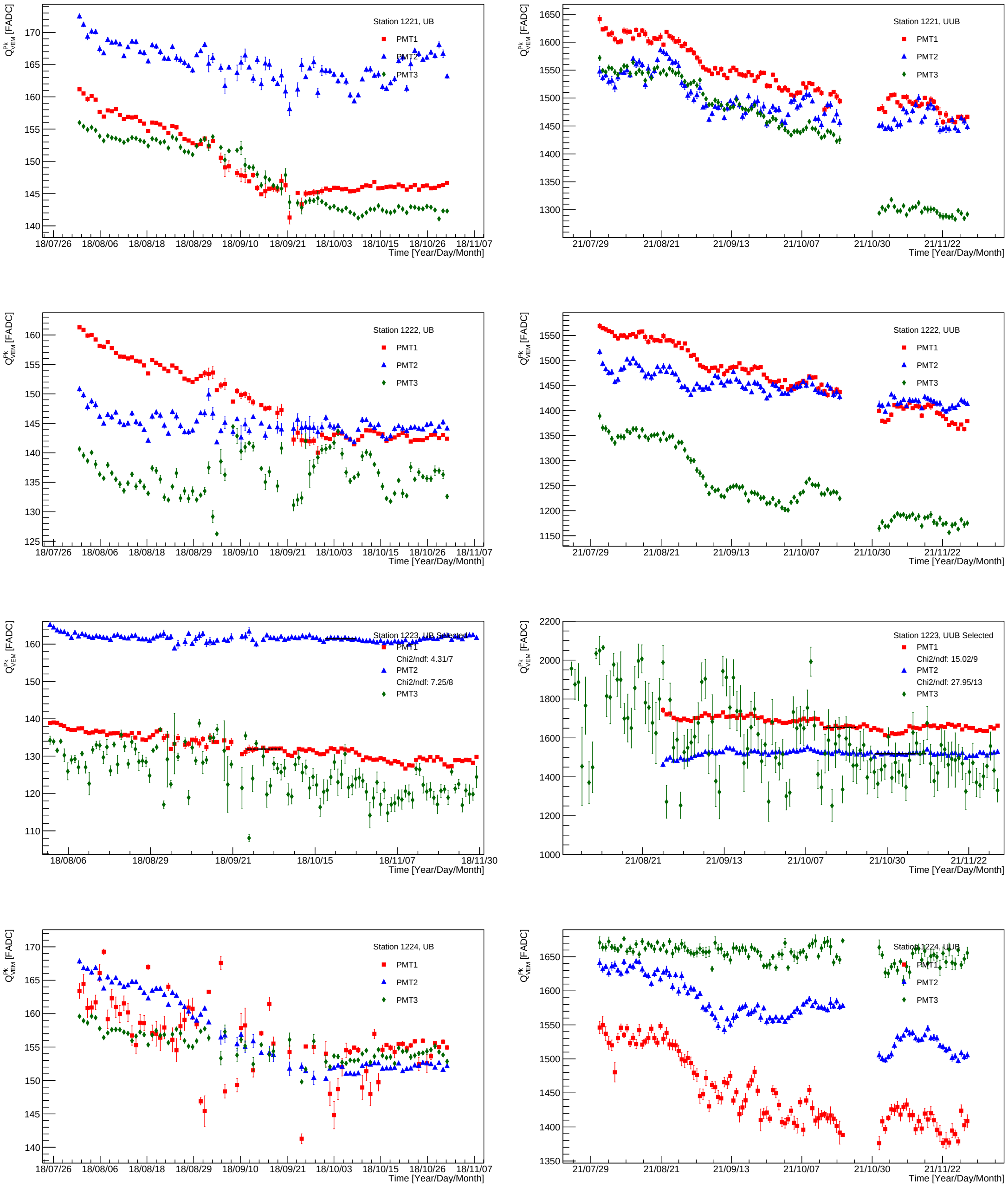

Figure 28: $Q^{\mathrm{Peak}}_{\mathrm{VEM}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q^{\mathrm{Peak}}_{\mathrm{VEM}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q^{\mathrm{Peak}}_{\mathrm{VEM}}$.

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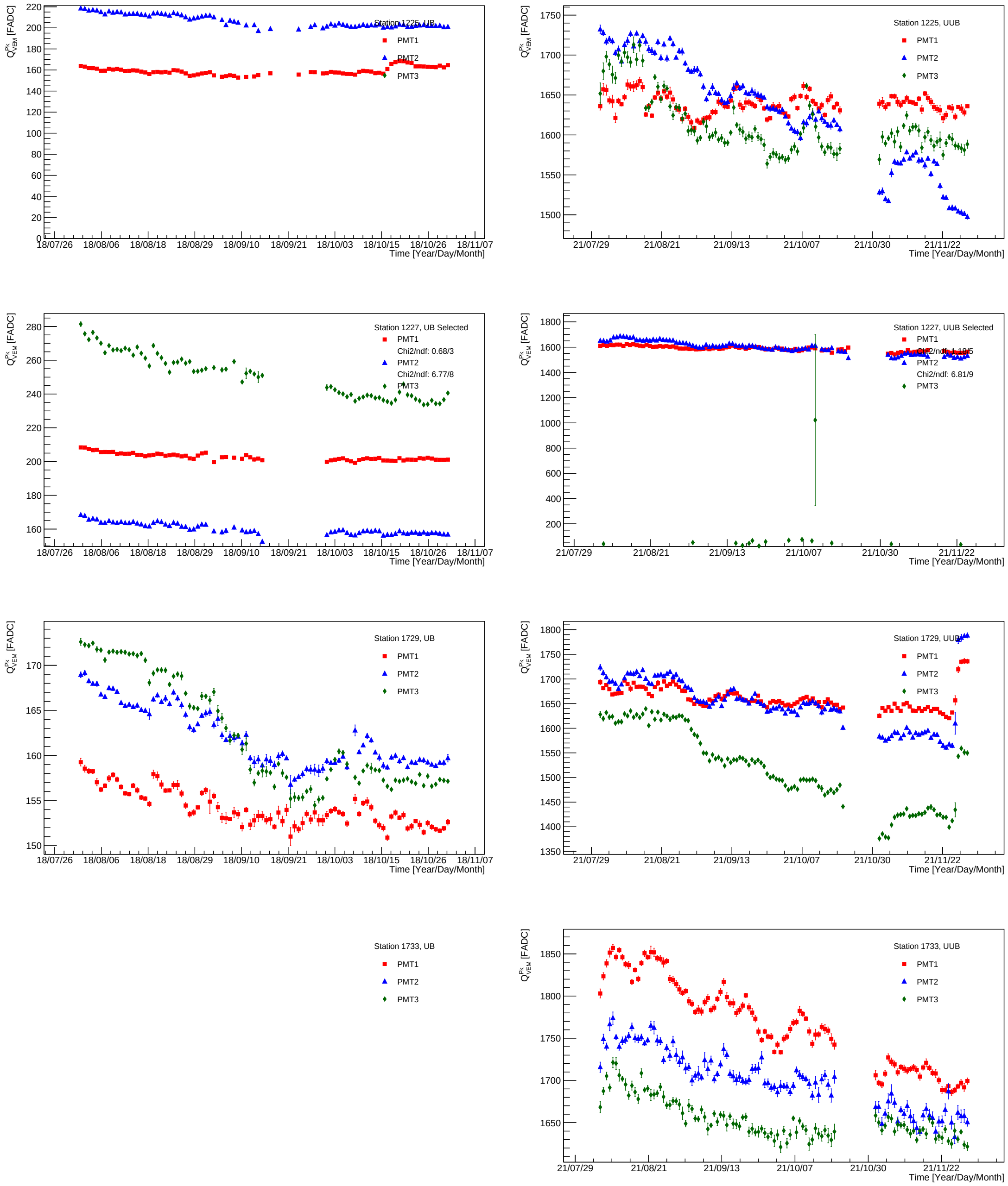

Figure 29: $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\mathrm{VEM}}^{\mathrm{Peak}}$.

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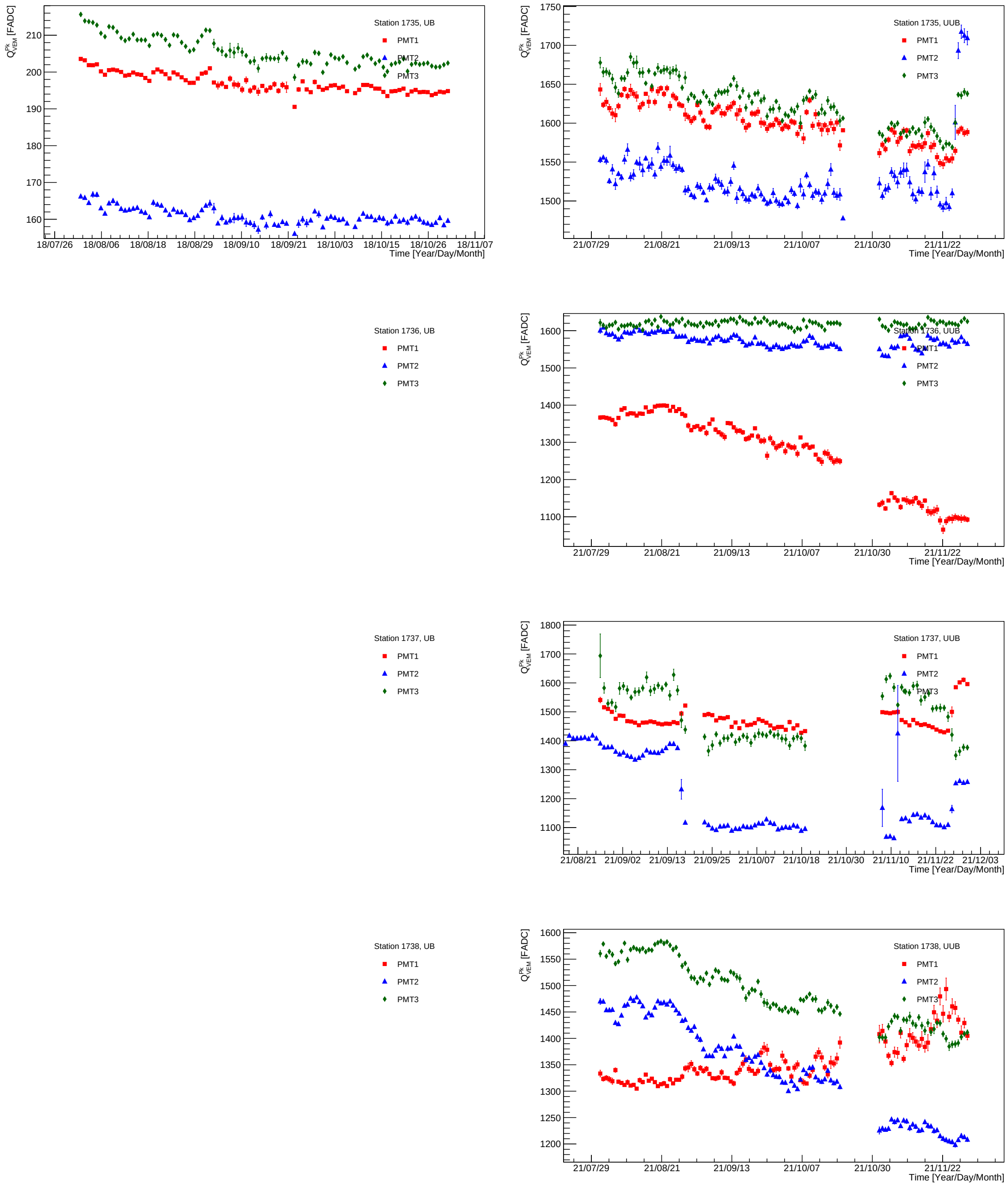

Figure 30: $Q^{\text{Peak}}_{\text{VEM}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q^{\text{Peak}}_{\text{VEM}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q^{\text{Peak}}_{\text{VEM}}$.

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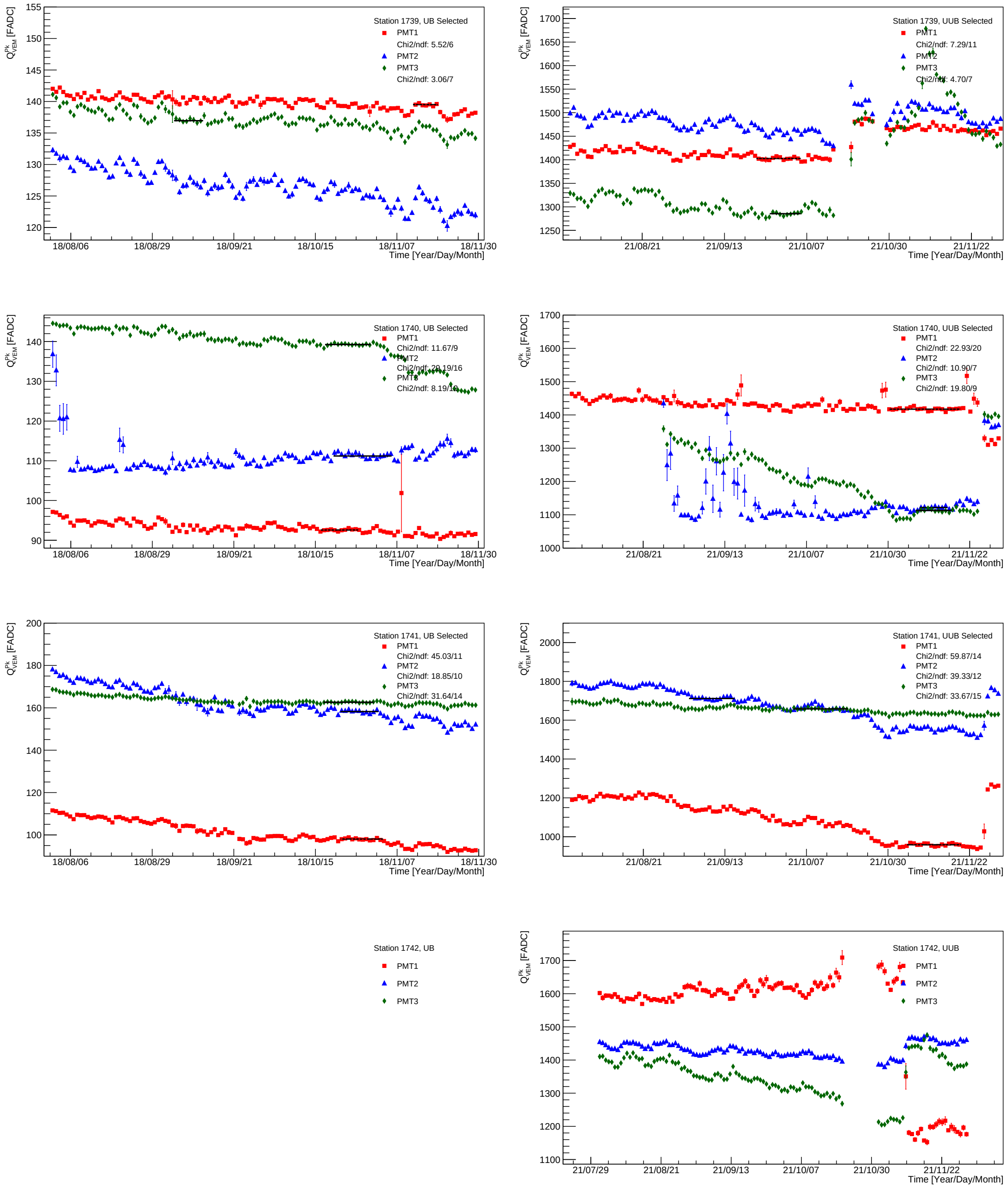

Figure 31: $Q_{\text{VEM}}^{\text{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\text{VEM}}^{\text{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\text{VEM}}^{\text{Peak}}$.

hi

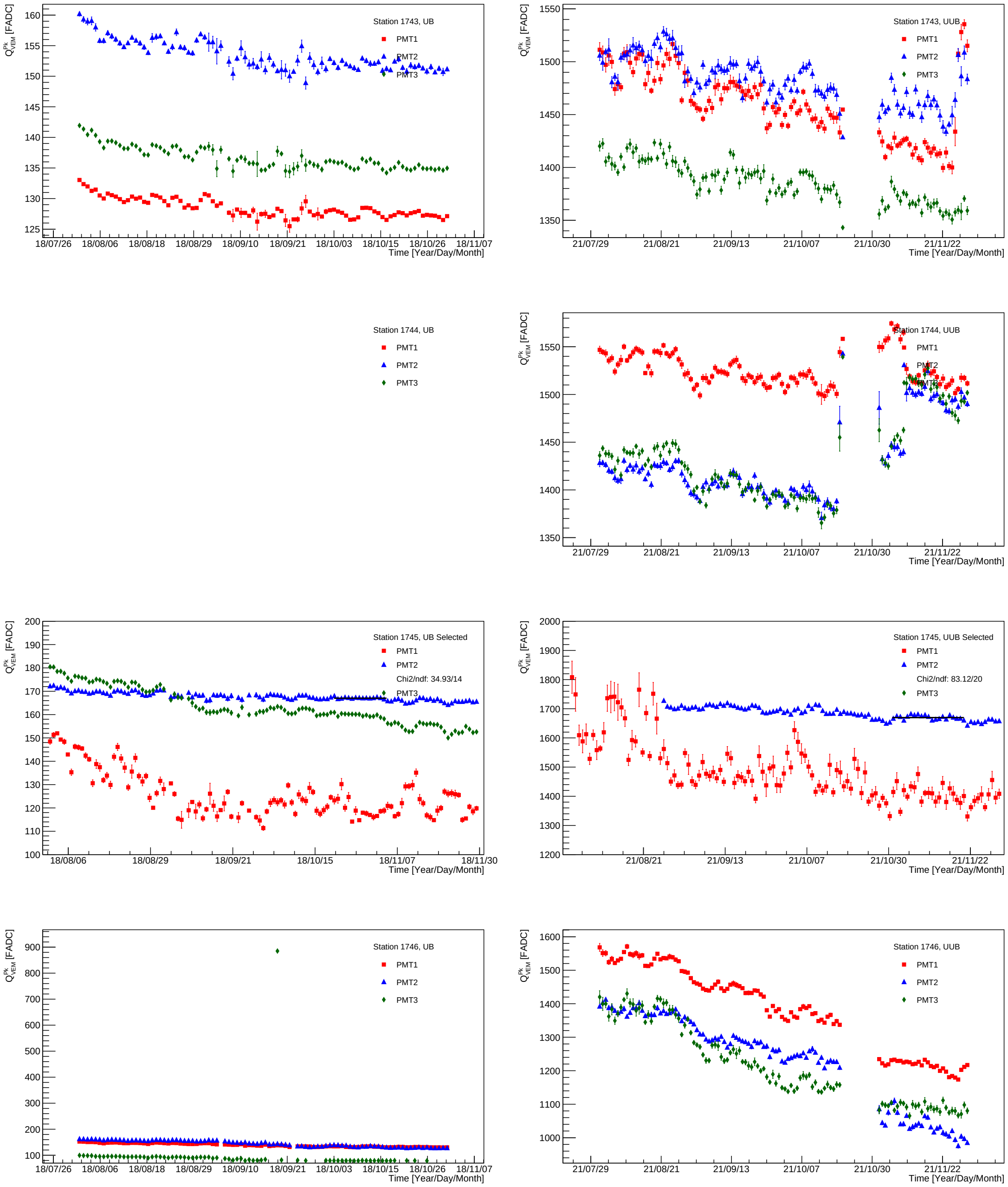

Figure 32: $Q_{\text{VEM}}^{\text{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\text{VEM}}^{\text{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label “Selected” is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\text{VEM}}^{\text{Peak}}$.

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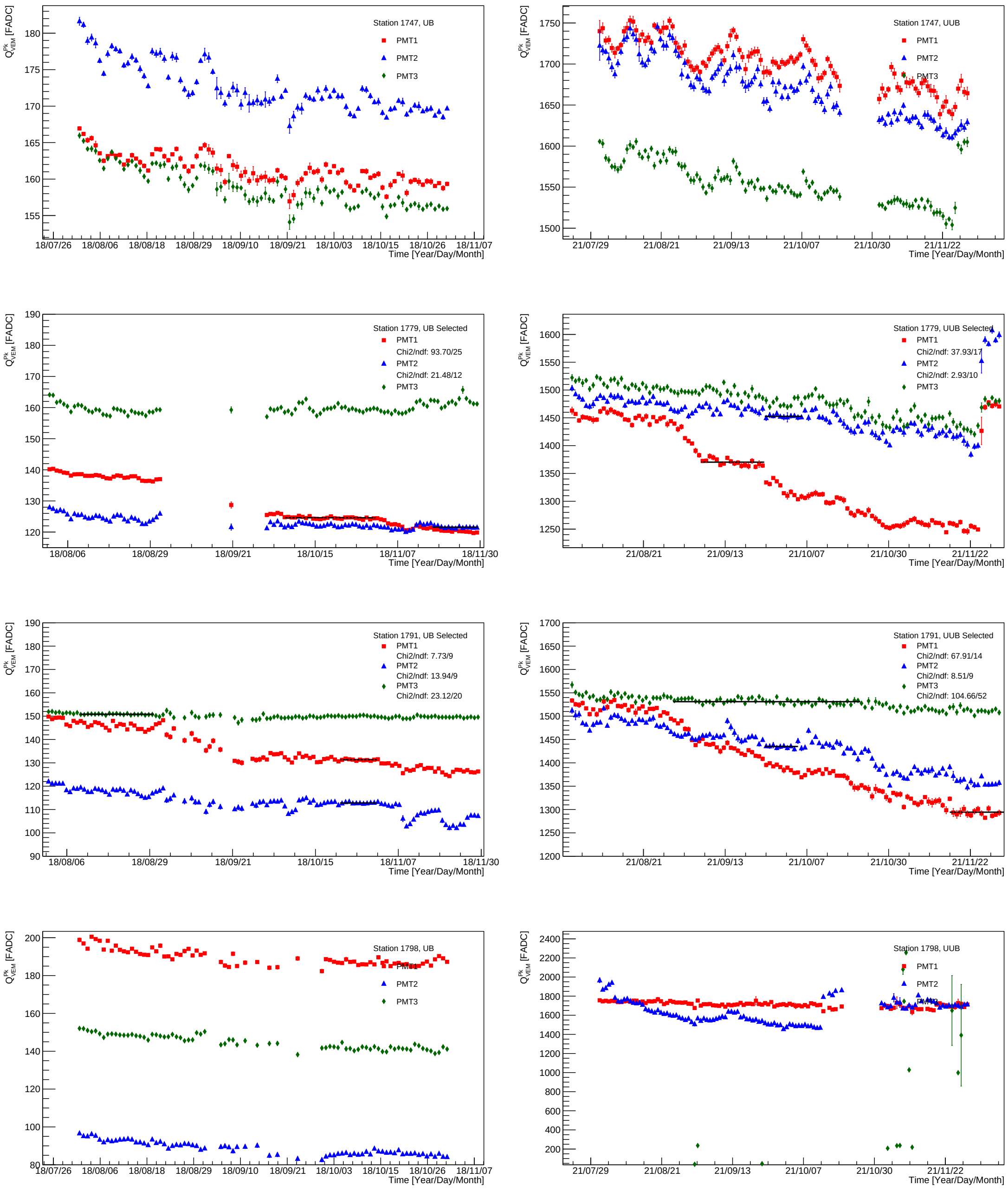

Figure 33: $Q_{\text{VEM}}^{\text{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\text{VEM}}^{\text{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\text{VEM}}^{\text{Peak}}$.

hi

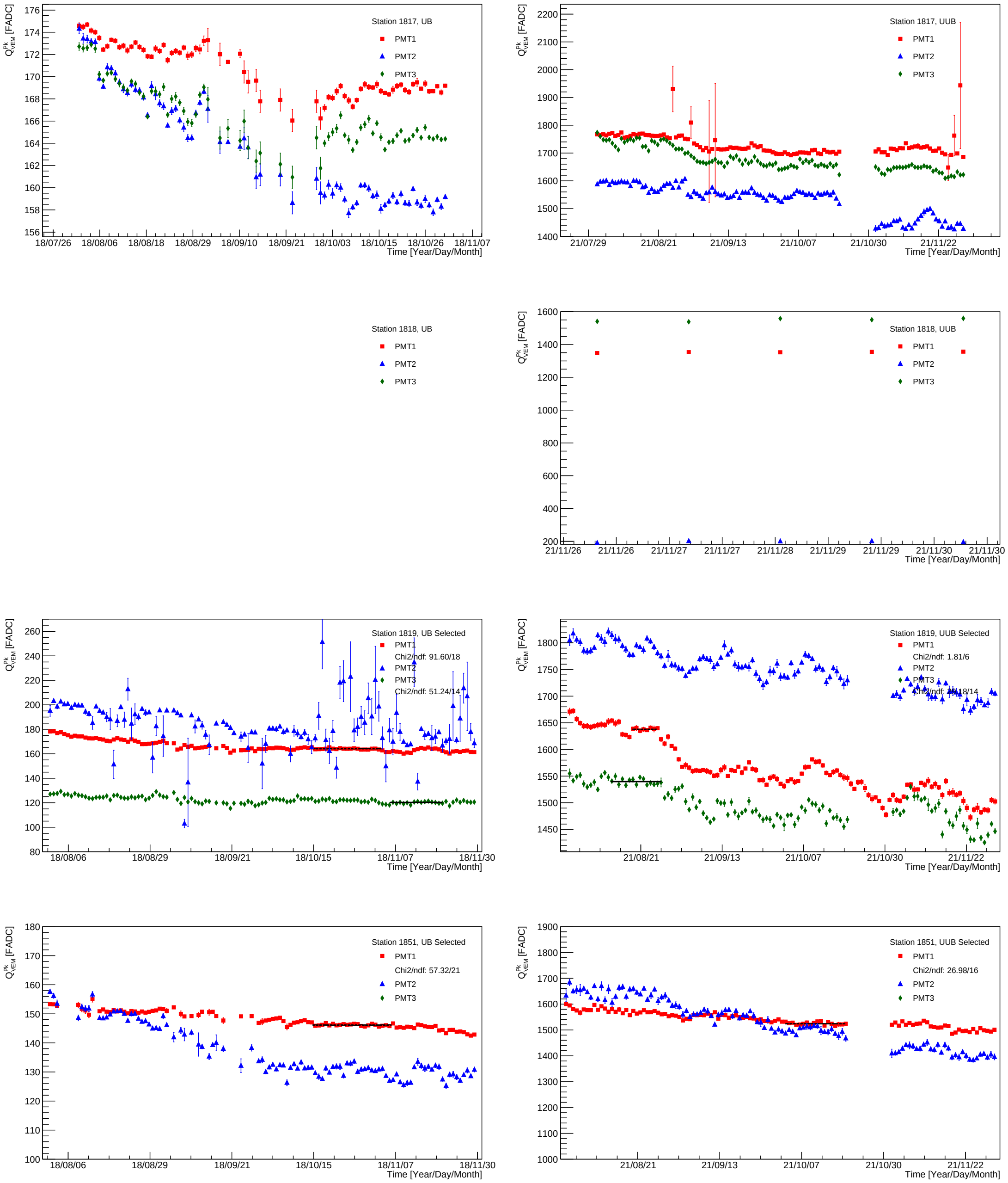

Figure 34: $Q^{\text{Peak}}_{\text{VEM}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q^{\text{Peak}}_{\text{VEM}}$ per day plotting as function of time, left UB, and right UUB version. If the label “Selected” is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q^{\text{Peak}}_{\text{VEM}}$.

hi

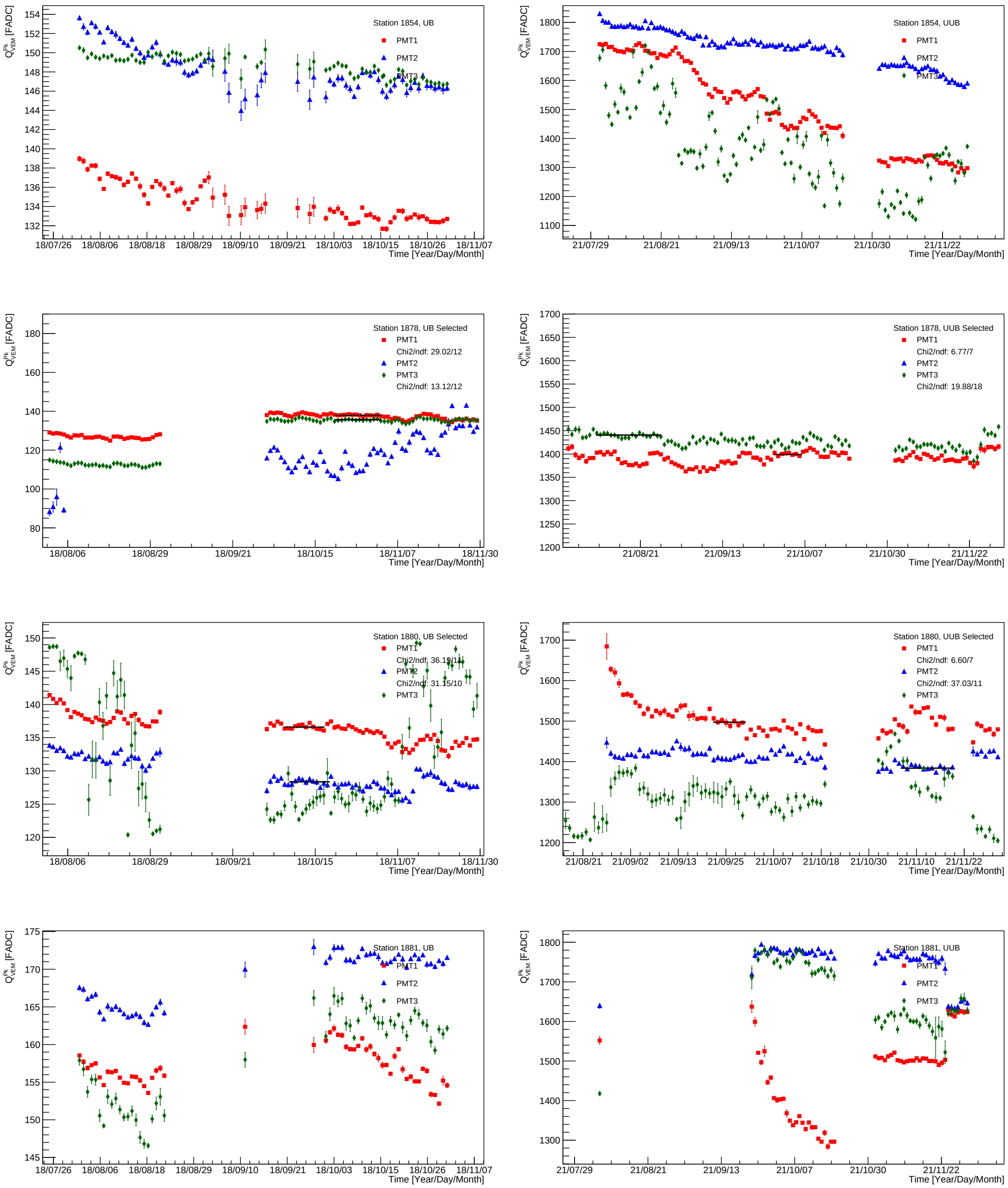

Figure 35: $Q_{\text{VEM}}^{\text{Peak}}$ values obtained applying the algorithm presented in section 1. Each row shows the average of the $Q_{\text{VEM}}^{\text{Peak}}$ per day plotting as function of time, left UB, and right UUB version. If the label "Selected" is seen, it means that some, or all, PMTs were chosen to calculate the accuracy of $Q_{\text{VEM}}^{\text{Peak}}$.