What the Upsilon Scans Teach Us About CESR at 5 GeV

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Abstract

We present fit results of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ lineshape scans that are relevant for studies of CESR. The beam energy spread (σ_E/E) is 20% narrower than expected, though its relationship with beam energy is linear, with a slope of $(119 \pm 75) \times 10^{-6}$ GeV^{-1}. We also find that the beam energy measurement varies by $\sim$0.3 MeV/5 GeV from week to week, but less than 0.07 MeV within a 10-hour scan period (68% C.L.). Measured Υ masses/2 are lower than PDG masses/2 by (0.20 $\pm$ 0.14) MeV, (-0.46 $\pm$ 0.20) MeV, and (-1.51 $\pm$ 0.33) MeV for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ respectively.

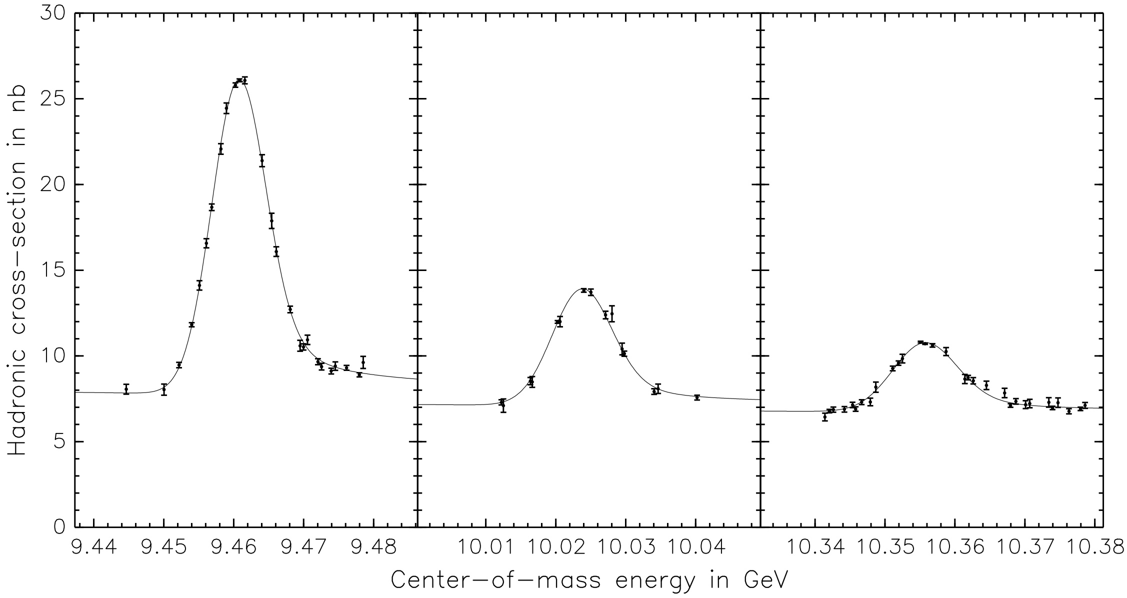

FIG. 1: Fits to the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ (left to right) including the initial state radiation tail. The three plot windows are equally wide. The "hadronic cross-section" background contains some radiative bhabhas.

I. INTRODUCTION

From November 2001 to August 2002, CESR performed detailed scans of the three narrow Υ resonances to precisely measure their di-electron widths, Γ_{ee}. Because these resonances are very narrow (25–50 keV), they can also be used as delta-function probes of the CESR beams. We used their fitted widths to measure the beam energy spread directly, and their fitted masses to correct the beam energy measurement, since the Υ masses are very well known.

For the Γ_{ee} analysis, we fit the three resonances to a convolution of a Breit-Wigner peak, an initial state radiation (ISR) tail, and a Gaussian beam energy spread (see Figure 1) [1]. This three-way convolution accounts for a widening of the peak due to the ISR tail (and, to a tiny extent, the Breit-Wigner width) and a shift in the peak maximum toward higher energies, due to the ISR tail. In this document, we will quote beam energy spreads as single-beam spreads σ_E with the ISR tail (and Breit-Wigner width) removed, and Υ masses in terms of single-beam energies with the ISR tail removed. Since we perform all fits in the center-of-mass, this means that we divide our fitted widths by $\sqrt{2}$ and our fitted masses by 2. (With the exception of Figure 1, we only quote single-beam quantities in this document.)

The data were acquired in small, independent, weekly scans (defined in terms of run numbers and dates in Appendix A). In principle, one could fit each week separately, but this would not be an optimal use of the data, particularly the continuum ($\sim$10 MeV below resonance) and high-energy tail (25–50 MeV above resonance) points, which are not sensitive to small shifts in beam energy. Instead, we fit all scans of a given resonance in a single fit, with separate Υ mass parameters for each weekly scan, i.e., the "calibration" of each week's beam energy measurement is allowed to float. The following is an exhaustive list of floating fit parameters: lineshape area (Γ_{ee}), background level, beam energy spread (σ_E), and a parameter representing M_Υ(PDG) $-$ M_Υ(measured) for each weekly scan (12 for $\Upsilon(1S)$, 6 for $\Upsilon(2S)$, and 7 for $\Upsilon(3S)$).

Cross-section measurements are described in [2]. The most pertinent result from that analysis is the conclusion that cross-section measurements are very reproducible: the largest cross-section jitter the data can support is ± 0.03 nb (68% C.L. upper bound), whereas the statistical error in most cross-section measurements is 0.2 nb. Therefore, we will treat all cross-section measurements as being limited only by statistical errors.

In this note, we will present measurements of beam energy spreads (Section II), reproducibility of the beam energy measurement from one week to the next (Section III A), and within a 10-hour scan (Section III B). We hope this will provide useful information about the CESR beams at 5 GeV.

II. MEASUREMENTS OF BEAM ENERGY SPREAD

Single-beam energy spreads, expressed as a fraction of beam energy (σ_E/E), were measured to be $(565 \pm 4) \times 10^{-6}$, $(587 \pm 12) \times 10^{-6}$, and $(616 \pm 14) \times 10^{-6}$ for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, respectively (beam energies are 4.7302, 5.0116, and 5.1776 GeV). These are plotted in Figure 2, along with the CESRV prediction, extrapolated from the `CESRC_3S_V2 lattice`. Although the predicted beam energy spread is 20% too high, the three measurements are consistent with proportional scaling ($\sigma_E/E \propto E$), with a slope of $(119 \pm 75) \times 10^{-6}$ GeV^{-1}.

To see if the beam energy spread changes between scans, we replaced the single parameter σ_E with a separate beam energy spread for each weekly scan. The results of this fit are plotted in Figure 3 and listed in Table I. All beam energy spreads seem to be consistent with a single σ_E except for `apr03`.

The `apr03` scan only includes measurements on the low-energy side of the peak (see Figure 13 in Appendix A). This is not because any runs were lost, but the high-side points differ from their design energy by a factor of two (e.g. 13 MeV above the resonance mass instead of 6 MeV). (This may have been due to a miscommunication about single-beam energies and center-of-mass energies.) The beam energy spread in this scan can not be adequately measured, though it is surprising that the fitted uncertainty does not compensate for this effect. (These are MINOS errors; they are allowed to be asymmetric and non-linear.)

Removing this outlier (2.6σ), the reduced χ^2 of $\Upsilon(1S)$ beam energy spreads is $13.9/10 = 1.4$. The reduced χ^2 of $\Upsilon(2S)$ and $\Upsilon(3S)$ beam energy spreads is $4.6/5 = 0.92$ and $8.7/6 = 1.5$, respectively. The reduced χ^2 for all three is $27.2/21 = 1.3$, which is consistent with a single beam energy spread (with a 16% C.L.).

III. BEAM ENERGY MEASUREMENT REPRODUCIBILITY

A. From Week to Week

As previously mentioned, our fits for Γ_{ee} allow M_Υ from each week to float, so the reproducibility of the beam energy measurement can be read directly from the fit values. These are plotted in Figure 4 and listed in Table II as differences from the PDG Υ mass.

These measurements are not consistent with a single mass, so we can infer that the calibration of the single-beam energy measurement does shift by about 0.3 MeV from one

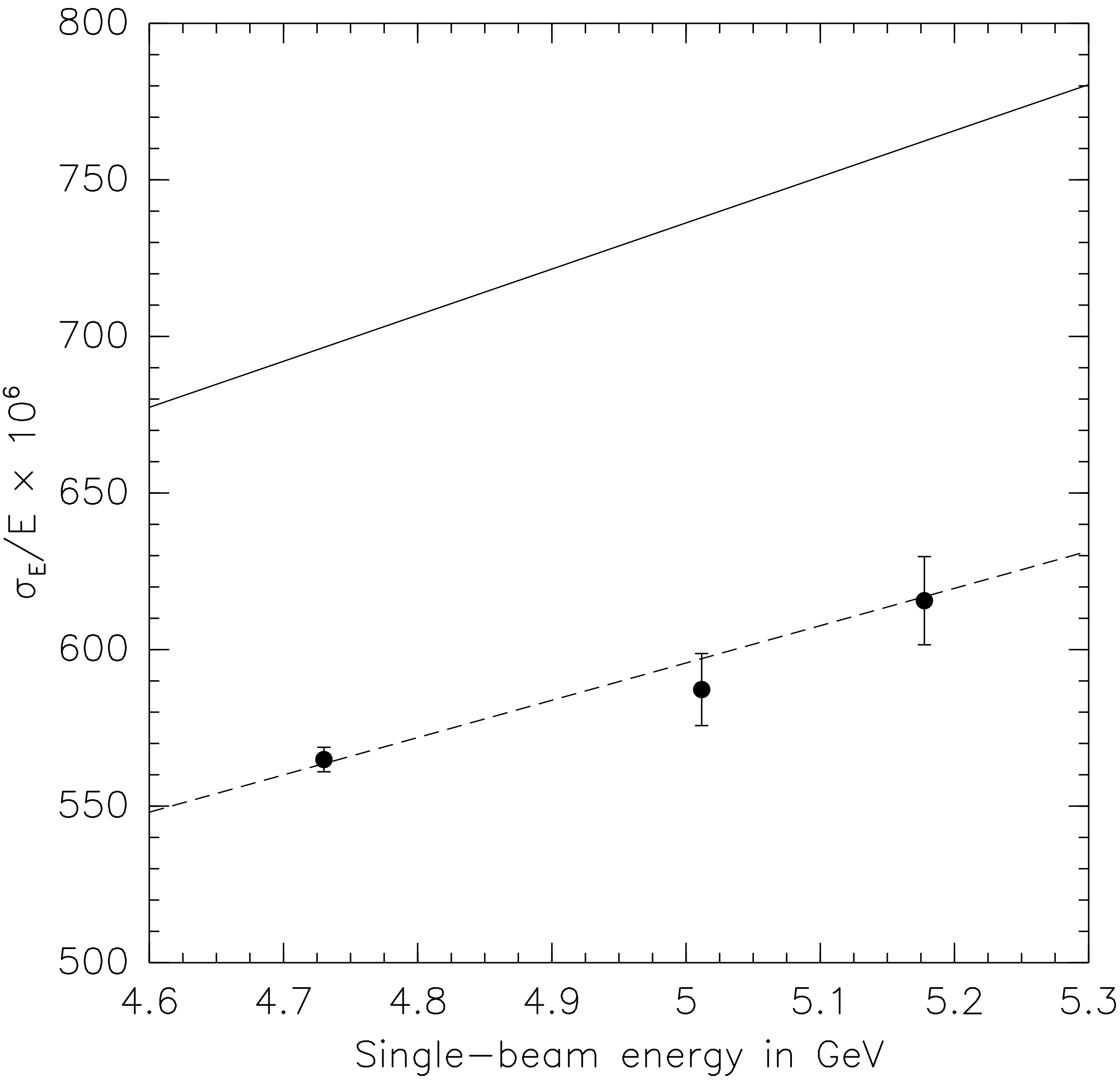

FIG. 2: Beam energy spread versus beam energy, compared to the CESRV prediction (solid line, extrapolated from $\Upsilon(3S)$) and a fit (dotted line).

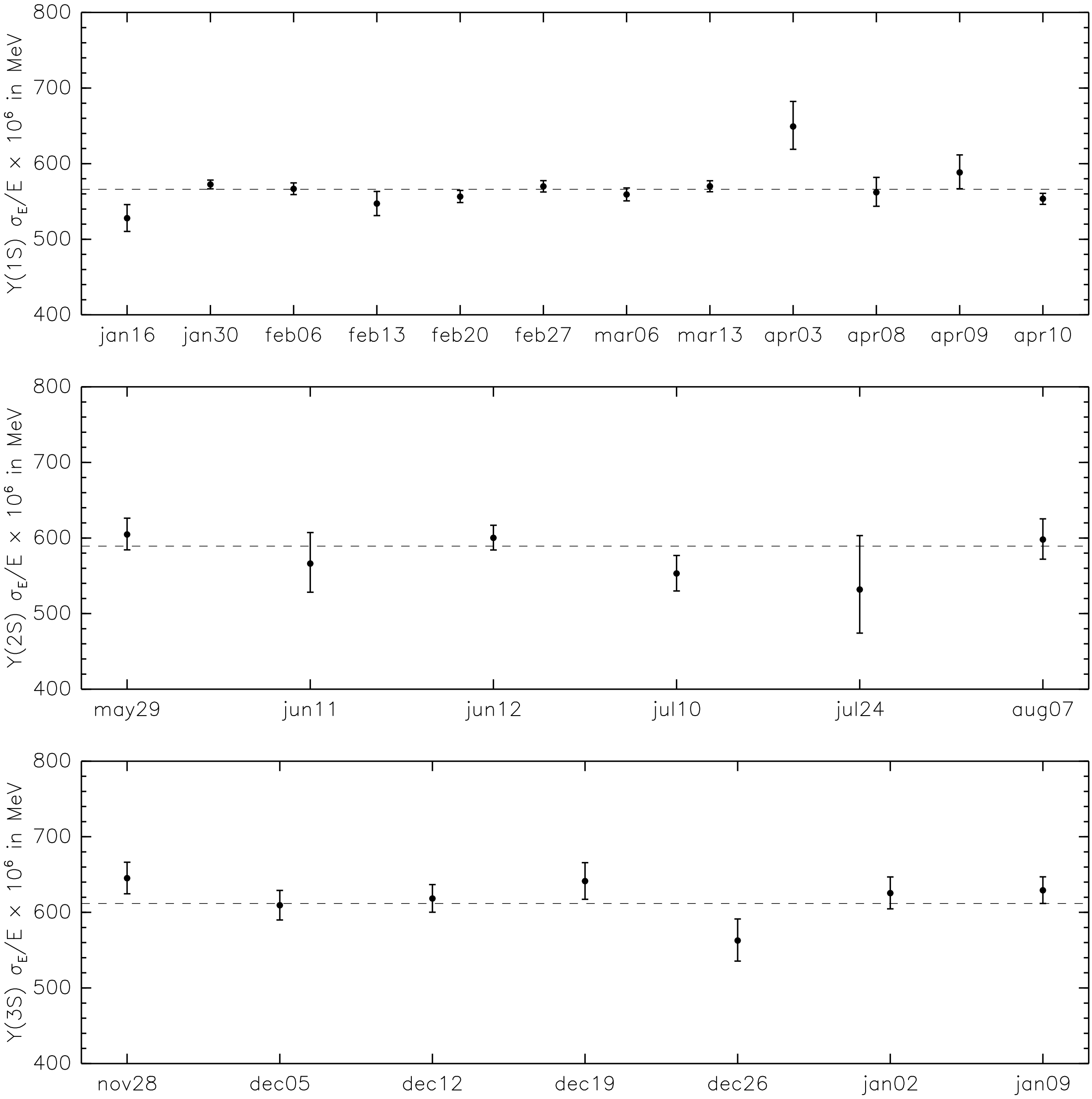

FIG. 3: Beam energy spread (σ_E/E) of each weekly scan (points), compared to the output of a combined fit for σ_E/E (dotted lines). The `apr03` scan is missing measurements on the high-energy side of the peak (see Figure 13).

Scan	Single beam energy spread in MeV	$\sigma_E/E \times 10^6$
jan16	2.50 ± 0.08	527 ± 17
jan30	2.71 ± 0.03	572 ± 5
feb06	2.68 ± 0.04	566 ± 7
feb13	2.59 ± 0.08	547 ± 15
feb20	2.63 ± 0.04	556 ± 8
feb27	2.70 ± 0.04	569 ± 7
mar06	2.65 ± 0.04	559 ± 8
mar13	2.70 ± 0.03	570 ± 7
apr03	3.07 ± 0.15	649 ± 31
apr08	2.66 ± 0.09	562 ± 19
apr09	2.78 ± 0.11	588 ± 22
apr10	2.62 ± 0.03	553 ± 7
may29	3.03 ± 0.11	604 ± 20
jun11	2.84 ± 0.20	566 ± 39
jun12	3.01 ± 0.08	600 ± 16
jul10	2.77 ± 0.12	553 ± 23
jul24	2.67 ± 0.32	531 ± 64
aug07	3.00 ± 0.13	597 ± 26
nov28	3.34 ± 0.11	645 ± 20
dec05	3.16 ± 0.10	609 ± 19
dec12	3.20 ± 0.09	618 ± 18
dec19	3.32 ± 0.13	641 ± 24
dec26	2.91 ± 0.14	562 ± 27
jan02	3.24 ± 0.11	625 ± 21
jan09	3.26 ± 0.09	629 ± 17

TABLE I: The data plotted in Figure 3. The three blocks are $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, top to bottom.

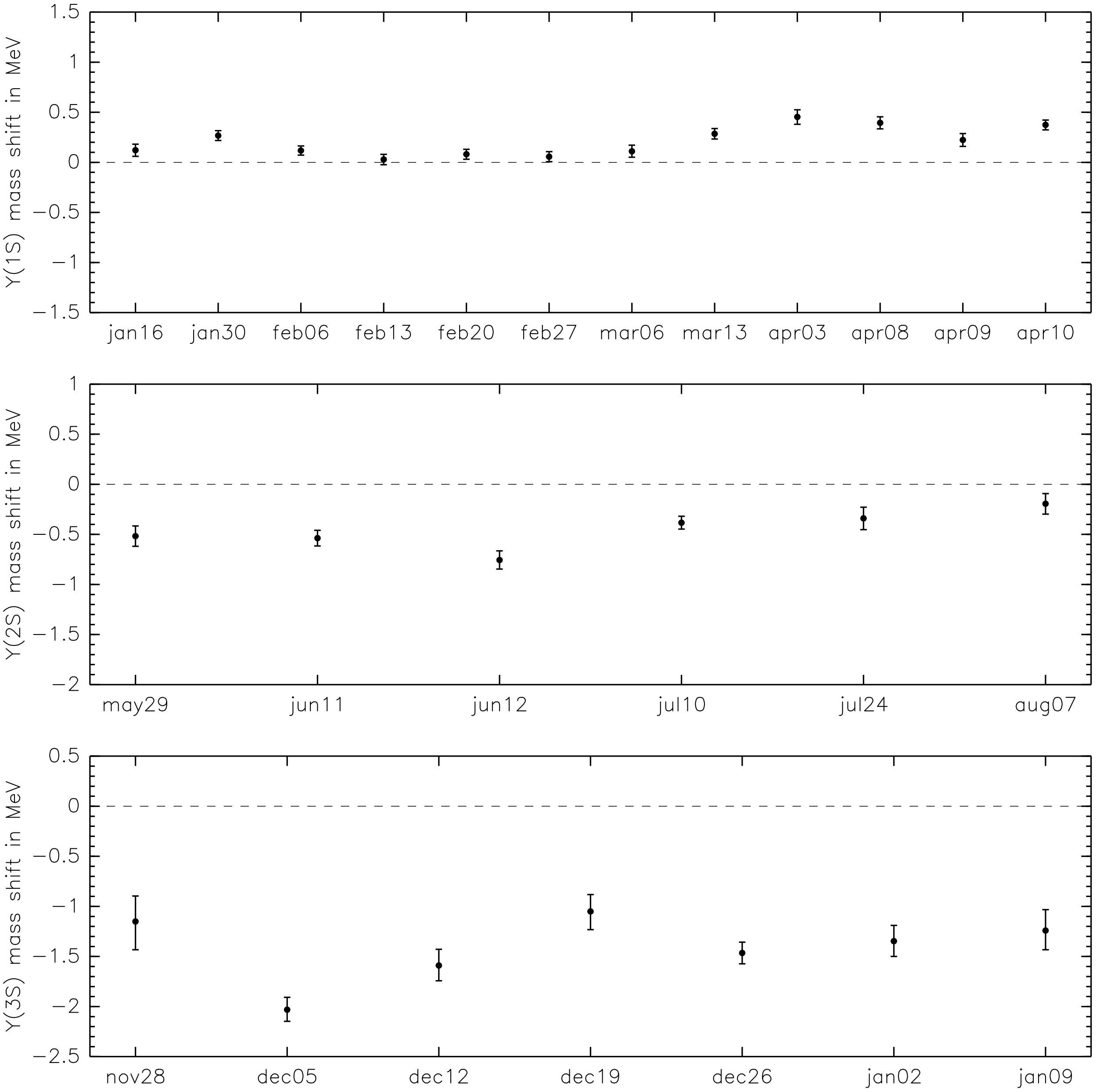

FIG. 4: Weekly scan measurements of M_Υ as a difference from the PDG M_Υ, divided by 2 for single-beam energy measurement shifts in MeV. These are corrections that need to be *added* to beam energy measurements.

Scan	$(M_\Upsilon(\text{PDG}) - M_\Upsilon(\text{measured}))/2$ in MeV
jan16	0.12 ± 0.06
jan30	0.27 ± 0.05
feb06	0.12 ± 0.05
feb13	0.03 ± 0.05
feb20	0.08 ± 0.05
feb27	0.06 ± 0.05
mar06	0.11 ± 0.06
mar13	0.28 ± 0.05
apr03	0.45 ± 0.07
apr08	0.39 ± 0.06
apr09	0.22 ± 0.06
apr10	0.37 ± 0.05
may29	-0.52 ± 0.10
jun11	-0.54 ± 0.08
jun12	-0.76 ± 0.09
jul10	-0.38 ± 0.06
jul24	-0.34 ± 0.11
aug07	-0.19 ± 0.10
nov28	-1.15 ± 0.27
dec05	-2.03 ± 0.12
dec12	-1.59 ± 0.16
dec19	-1.05 ± 0.17
dec26	-1.47 ± 0.11
jan02	-1.35 ± 0.15
jan09	-1.24 ± 0.20

TABLE II: The data plotted in Figure 4. The three blocks are $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, top to bottom.

week to the next. (The RMS shift is 0.3 MeV; the beam energy measurement sometimes appears to drift smoothly over long timescales.)

The average $M_\Upsilon(\text{PDG}) - M_\Upsilon(\text{measured})$ is not zero, so we can also infer a correction to the beam energy measurement. Beam energy measurements in the $\Upsilon(1S)$ region need to be increased by (0.20 ± 0.02 ± 0.14) MeV, measurements in the $\Upsilon(2S)$ region need to be decreased by (0.46 ± 0.04 ± 0.20) MeV, and measurements in the $\Upsilon(3S)$ region need to be decreased by (1.51 ± 0.06 ± 0.33) MeV, where the first uncertainty is statistical and the second is the RMS of week-by-week variations. These corrections are plotted in Figure 5 and are

$$\text{correct beam energy}(E_\text{beam}) = E_\text{beam} + (15 \pm 3)\text{ MeV} + (-0.0031 \mp 0.0007) \times E_\text{beam} \quad (1)$$

if fitted to a line, where E_beam is the output of the beam energy program. The uncertainties in the intercept and slope are almost exactly anticorrelated. (We are not recommending the application of this extrapolation far from the Υ region!)

B. Within a 10-Hour Scan

The Γ_{ee} analysis would be sensitive to mismeasurements of beam energy during a scan, so we chose a scan technique that would allow us to check the beam energy measurement with the scan data itself. Most weekly scans included a repeated energy point (sometimes more than one), on the shoulder of the Υ lineshape where the derivative is at a maximum, usually at the beginning and end of the scan. If the calibration of the beam energy measurement shifts during a scan, the second cross-section measurement will differ from the first. We calculate an "energy calibration shift" from a pair of measurements by

$$\text{calibration shift} = \frac{\sigma_2 - \sigma_1}{f'(E_\text{beam})} - (E_{\text{beam }2} - E_{\text{beam }1}) \quad (2)$$

where $f'(E_\text{beam})$ is the derivative of the lineshape at the pair's (average) beam energy, σ_1 and σ_2 are cross-section measurements, and $E_{\text{beam }1}$ and $E_{\text{beam }2}$ are the measured beam energies (2 is always later in time than 1). Since the cross-section measurements are statistics-limited, the calibration shift measurements will be as well.

The scan data contain 30 pairs of repeated measurements, which we translate into 30 beam energy calibration shifts using Equation 2 (plotted in Figure 6 and listed in Table III). They are all consistent with zero shift, as their pulls (shift divided by uncertainty in shift) form a unit Gaussian (see Figure 7). There is also no apparent dependence on the time between measurements.

We applied two methods to set an upper limit on beam energy measurement jitter. First, we defined a negative log likelihood for the 30 measurements by

$$\text{-log likelihood}(\delta_E) = \sum_{i=1}^{30} - \ln\left(\frac{1}{\sqrt{2\pi({\delta_{s_i}}^2 + {\delta_E}^2)}} \exp\left(-s_i^2/2/({\delta_{s_i}}^2 + {\delta_E}^2)\right)\right) \quad (3)$$

where $s_i \pm \delta_{s_i}$ are the calibration shift measurements listed in Table III, and δ_E is a hypothetical random jitter in the measurement. To raise $L(\delta_E)$ above $L(0)$ by 0.5, a δ_E of 0.05 MeV is needed.

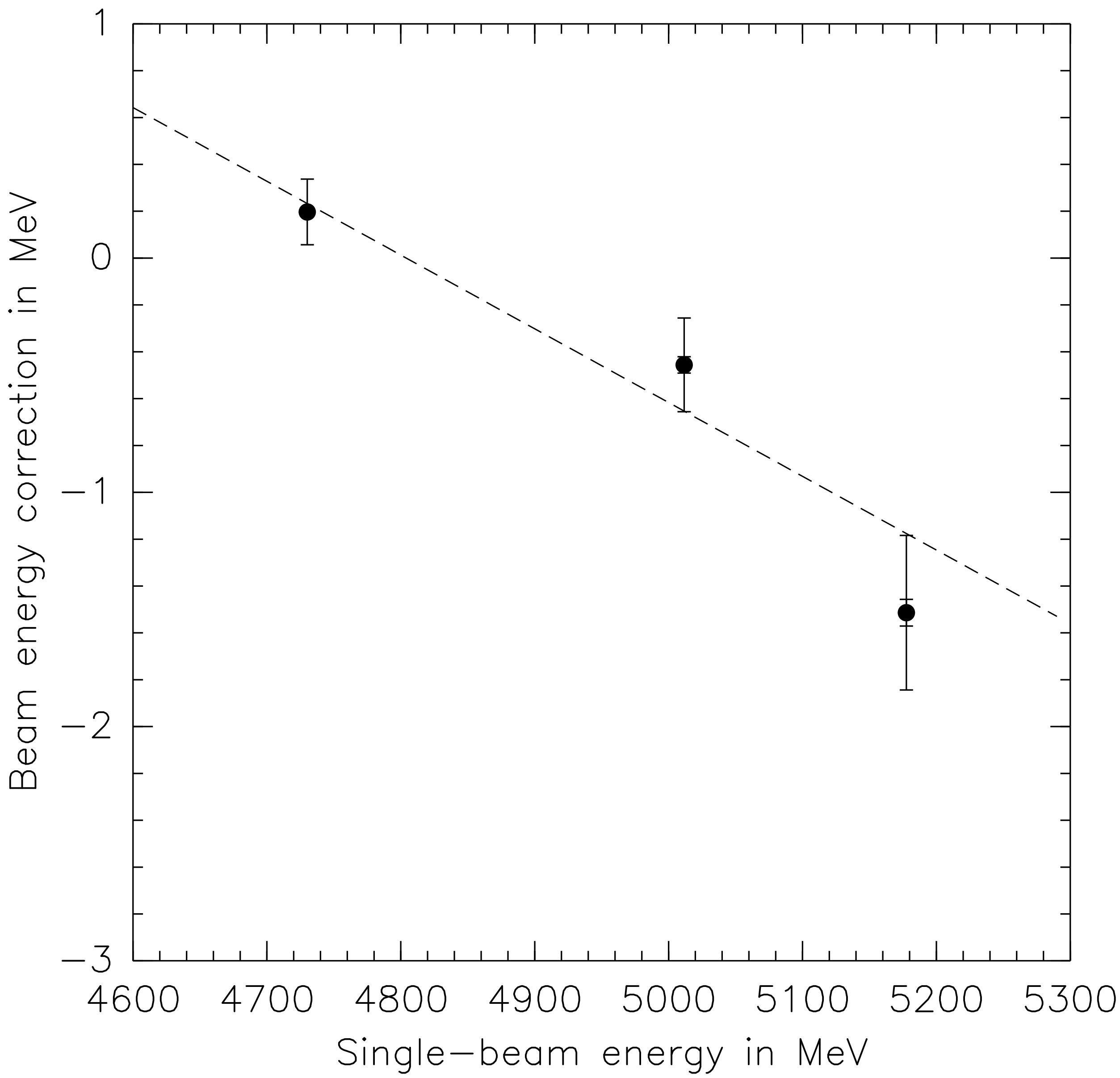

FIG. 5: A fit to the beam energy correction. Inner error bars are purely statistical, outer error bars represent the RMS spread in measurement from week to week. This correction should be *added* to the single-beam energy measurement (see Equation 1).

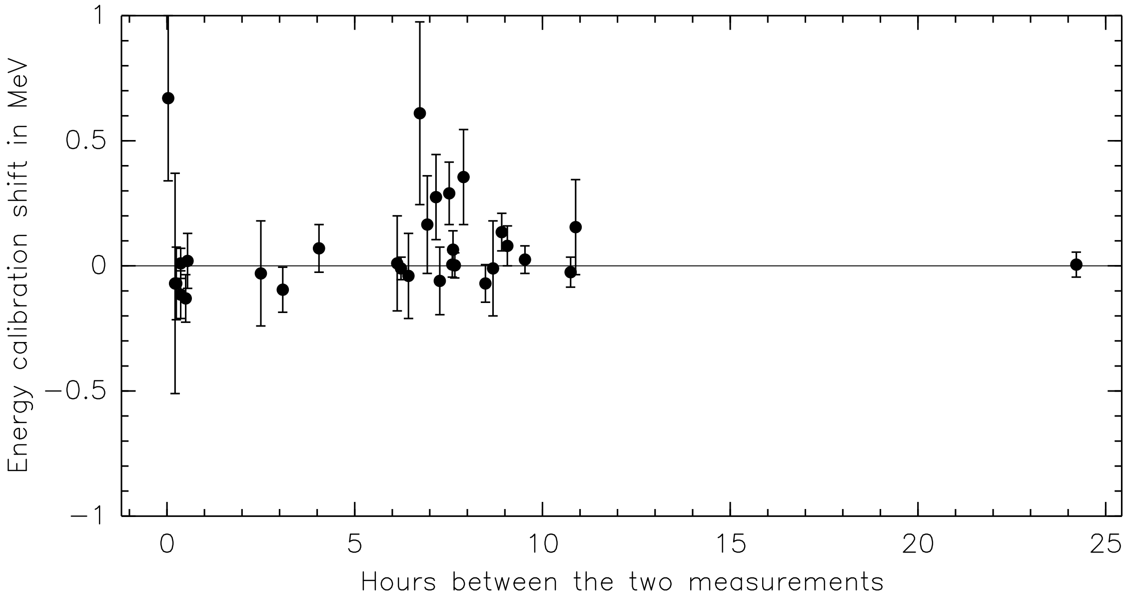

FIG. 6: Beam energy calibration shifts, as determined from thirty pairs of repeated cross-section measurements (plotted versus time).

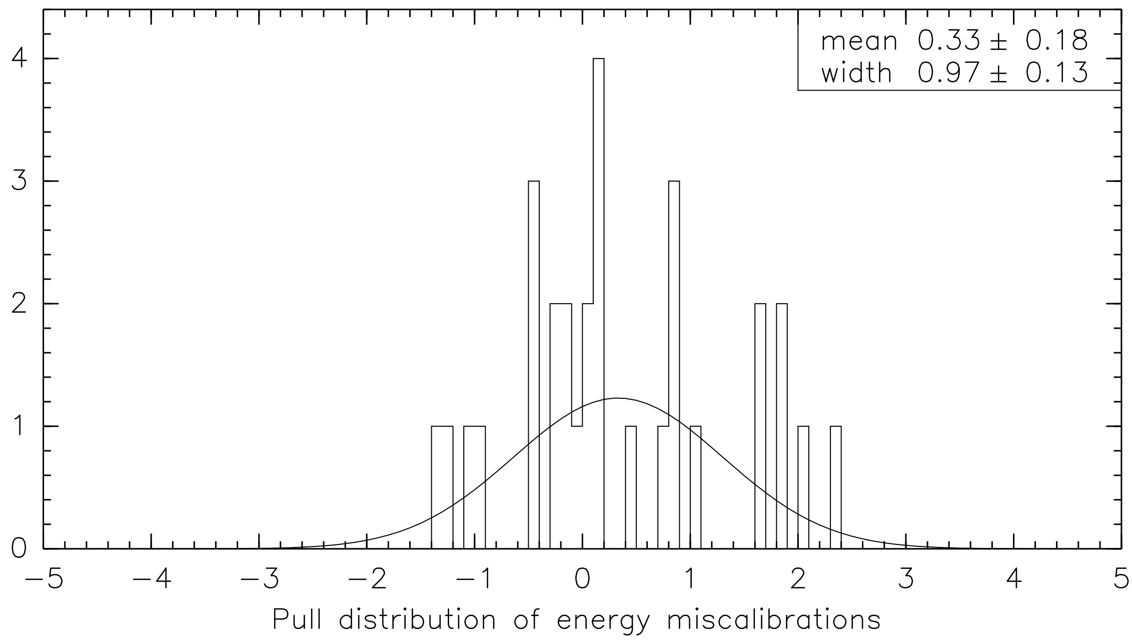

FIG. 7: Pull distribution of beam energy calibration shifts.

Minutes between measurements	Energy calibration shift	Weekly scan
2	0.67 ± 0.33	jan02
13	-0.07 ± 0.44	jan09
15	-0.07 ± 0.145	aug07
22	0.01 ± 0.06	apr03
22	-0.115 ± 0.095	may29
30	-0.13 ± 0.095	jul24
33	0.02 ± 0.11	jan16
150	-0.03 ± 0.21	dec05
185	-0.095 ± 0.09	jan30
243	0.07 ± 0.095	feb06
368	0.01 ± 0.19	dec26
374	-0.01 ± 0.045	feb20
386	-0.04 ± 0.17	dec26
404	0.61 ± 0.365	dec26
416	0.165 ± 0.195	dec26
430	0.275 ± 0.17	jan02
436	-0.06 ± 0.135	apr08
451	0.29 ± 0.125	apr09
456	0.005 ± 0.05	feb06
457	0.065 ± 0.075	mar06
460	0.002 ± 0.05	feb13
474	0.355 ± 0.19	dec19
509	-0.07 ± 0.075	feb27
521	-0.01 ± 0.19	jan09
535	0.135 ± 0.075	jan16
544	0.08 ± 0.08	mar13
572	0.025 ± 0.055	jan30
645	-0.025 ± 0.06	jul10
653	0.155 ± 0.19	dec12
1453	0.005 ± 0.05	jun11, jun12

TABLE III: The data plotted in Figure 6.

Another way to calculate the same thing is to define an S factor in analogy to the PDG's,

$$S(\delta_E) = \sum_{i=1}^{30} \frac{s_i}{{\delta_{s_i}}^2 + {\delta_E}^2} \frac{1}{30-1}. \tag{4}$$

The value of δ_E needed for $S(\delta_E) = 1$ is 0.07 MeV. Because these two methods agree relatively well, we claim that the 68% C.L. upper limit on beam energy measurement shifts (in a 10-hour period) is 0.07 MeV.

IV. SUMMARY

We learned from these studies that

1. the CESRV beam energy spread prediction is 20% too wide,
2. the calibration of the beam energy measurement drifted on the order of 0.3 MeV from week to week,
3. if one desires $\lesssim$ 0.03% errors in Υ beam energy measurements, one must apply the correction in Equation 1, and
4. the calibration of the beam energy measurement drifted less than about 0.07 MeV during a 10-hour scan.

[1] K. Berkelman, *Primer on Onium Widths,* CBX 02-10, and *Onium Line Shape Fitting,* CBX 03-12.

[2] J. Pivarski, R. Patterson, and K. Berkelman, *Di-electron Widths of the Upsilon(1S,2S,3S) Resonances,* CBX 05-41.

APPENDIX A: DEFINITION OF WEEKLY SCANS

The 25 weekly scan periods referred to throughout this document are defined in Table IV and presented graphically in Figures 8–12. Mini-plots of each scan are available in Figure 13, just to show what energy points are available to each.

We defined these periods conservatively by dividing any scan with a gap of more than 6 hours (during which the beam energy measurement might shift) into two scans. In both cases (apr08, apr09, apr10, and jun11, jun12), we see no significant shift. Also, all scans, including on-resonance data, are limited to a total of 48 hours. (Data beyond 48 hours would only be at the top of the resonance peak, where the extra statistical precision has diminishing returns for Γ_{ee}.)

Scan	CLEO run range (inclusive)	StartRun Date	EndRun Date
jan16	123164 – 123178	15 Jan 21:21	16 Jan 10:07
jan30	123596 – 123645	30 Jan 18:44	01 Feb 19:01
feb06	123781 – 123836	06 Feb 21:24	08 Feb 21:41
feb13	124080 – 124092	19 Feb 22:23	20 Feb 08:29
feb20	124102 – 124159	20 Feb 22:09	22 Feb 22:29
feb27	124279 – 124338	27 Feb 22:08	01 Mar 22:03
mar06	124436 – 124495	06 Mar 22:48	08 Mar 22:20
mar13	124625 – 124681	13 Mar 22:34	15 Mar 22:37
apr03	125119 – 125127	02 Apr 21:58	03 Apr 06:11
apr08	125254 – 125262	08 Apr 21:44	09 Apr 06:41
apr09	125285 – 125295	09 Apr 23:02	10 Apr 07:58
apr10	125303 – 125358	10 Apr 20:39	12 Apr 20:44
may29	126449 – 126508	29 May 18:20	31 May 18:28
jun11	126776 – 126783	11 Jun 20:04	12 Jun 05:51
jun12	126814 – 126871	12 Jun 18:57	14 Jun 19:16
jul10	127588 – 127615	10 Jul 19:42	11 Jul 18:28
jul24	127924 – 127933	23 Jul 22:01	24 Jul 07:37
aug07	128303 – 128316	07 Aug 18:41	08 Aug 04:43
nov28	121884 – 121940	28 Nov 22:44	30 Nov 22:23
dec05	122069 – 122126	06 Dec 00:29	08 Dec 01:21
dec12	122245 – 122298	12 Dec 23:40	14 Dec 23:15
dec19	122409 – 122452	19 Dec 23:37	22 Dec 00:14
dec26	122535 – 122579	25 Dec 08:49	26 Dec 22:18
jan02	122766 – 122821	02 Jan 18:32	04 Jan 18:30
jan09	122993 – 123044	09 Jan 22:17	11 Jan 22:11

TABLE IV: Beginning and end of each weekly scan. The three blocks are $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$, top to bottom. Dates are in 2002 except for Nov and Dec, which are in 2001 ($\Upsilon(3S)$ only).

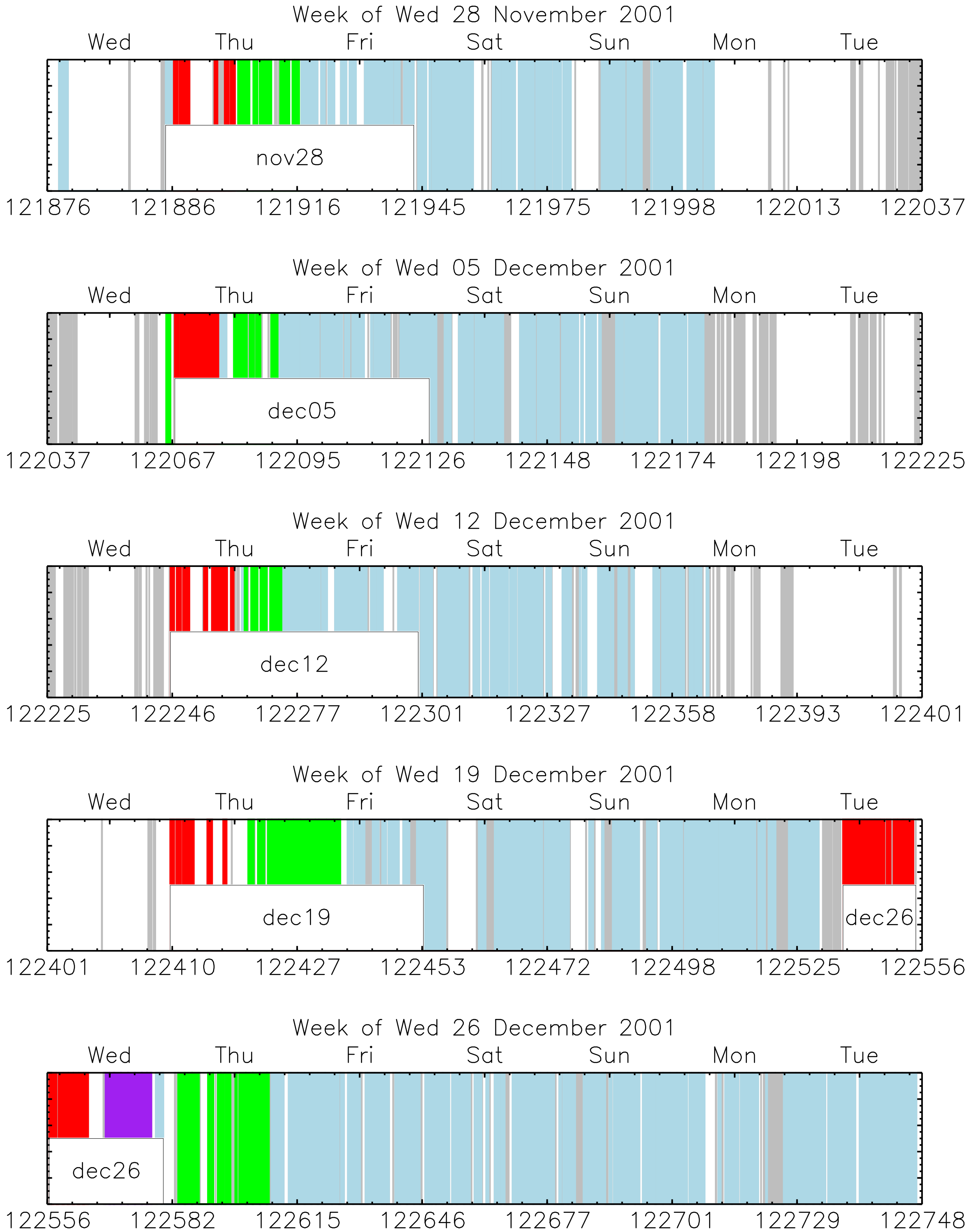

FIG. 8: Run periods by date and run number (1). Red regions are off-resonance scan, blue are on the top of the resonance peak (± 0.8 MeV), green are off-resonance continuum (∼10 MeV below resonance), purple are high-energy tail measurements (25–50 MeV above resonance), grey are not DataTaking runs in the Υ region, and white spaces are between runs or are runs without StartRun/EndRun timestamps.

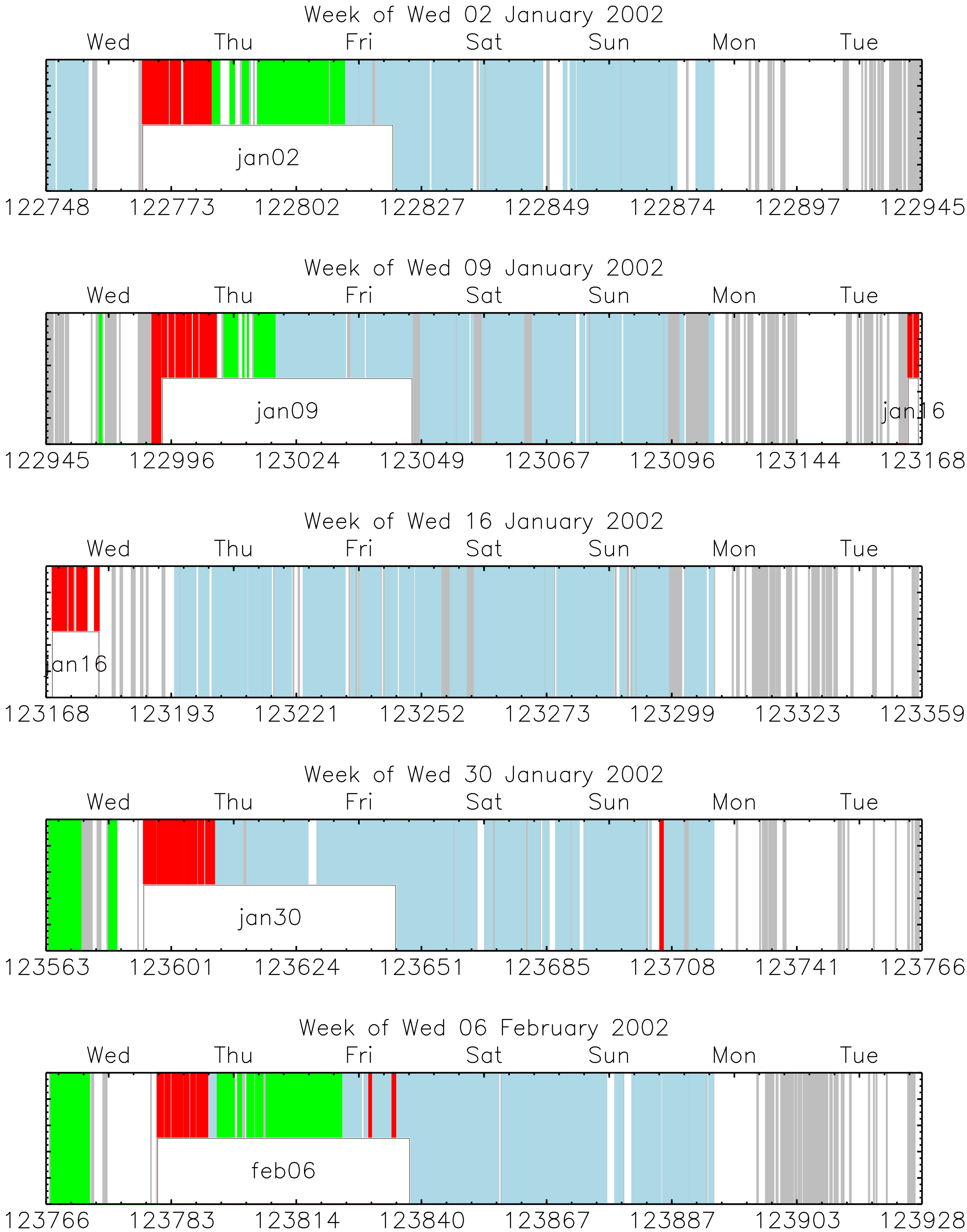

FIG. 9: Run periods by date and run number (2). See Figure 8 caption for color designations. The red region just before jan09 was an $\Upsilon(1S)$ test.

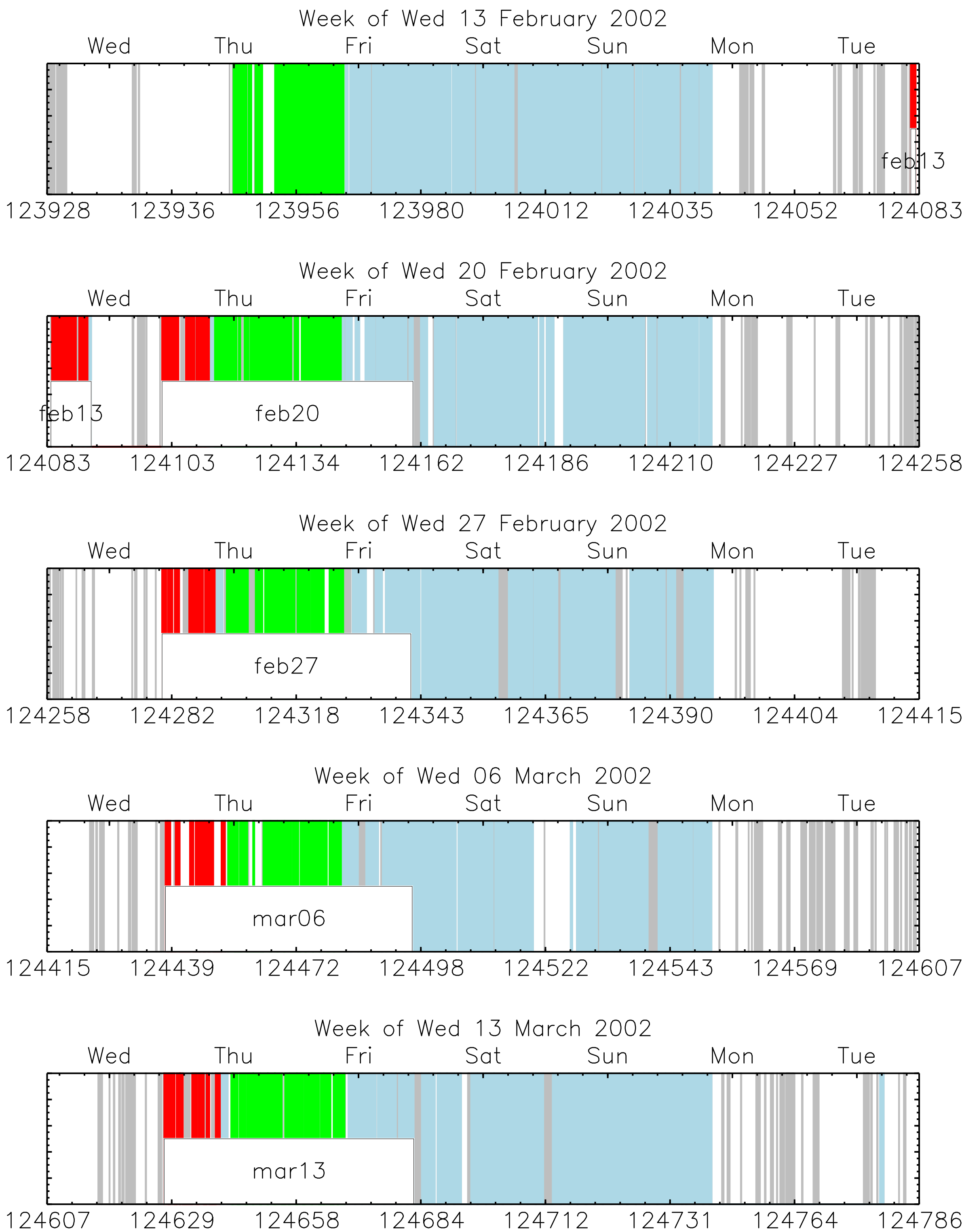

FIG. 10: Run periods by date and run number (3). See Figure 8 caption for color designations.

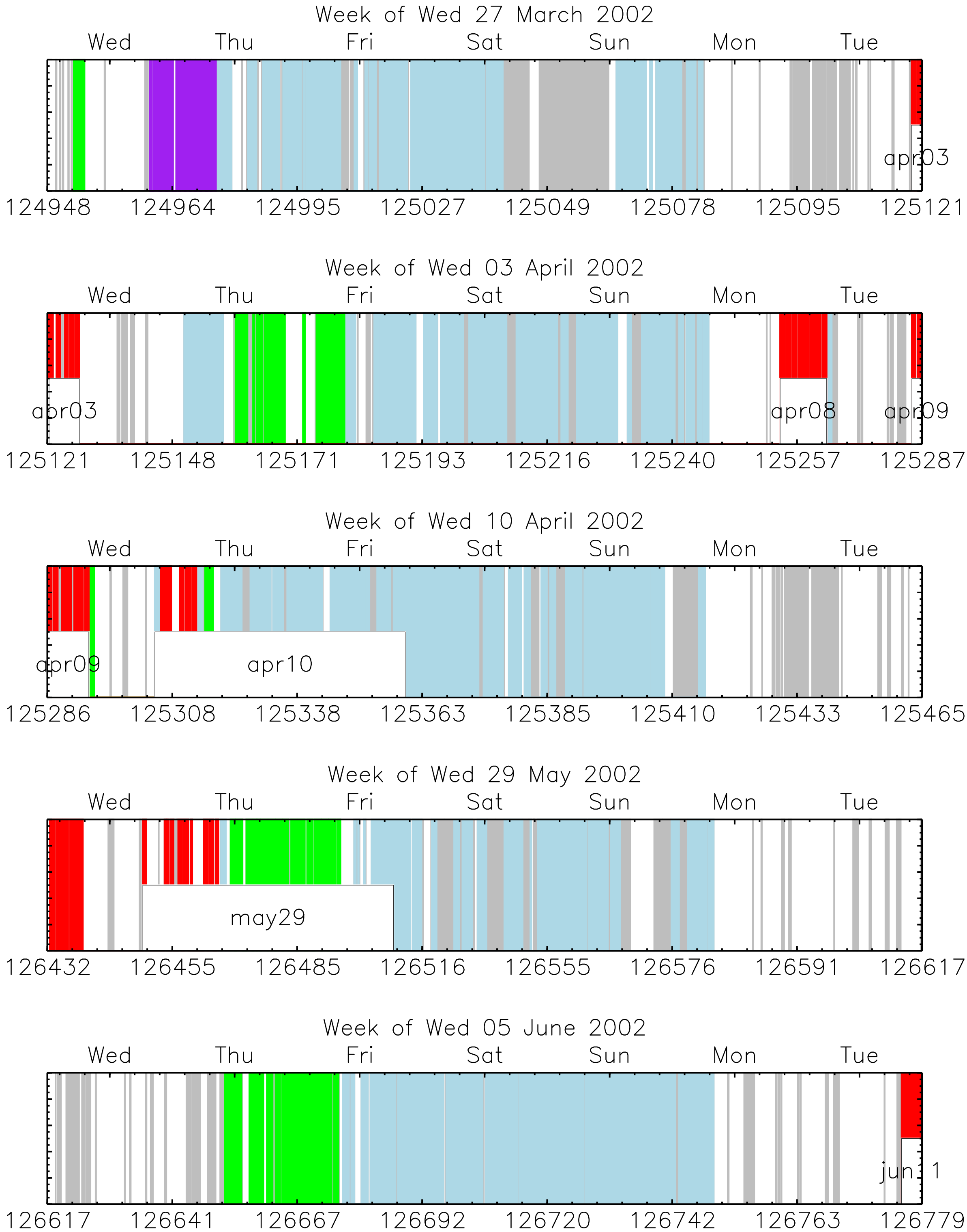

FIG. 11: Run periods by date and run number (4). See Figure 8 caption for color designations. The red region before may29 was a $\Upsilon(2S)$ test.

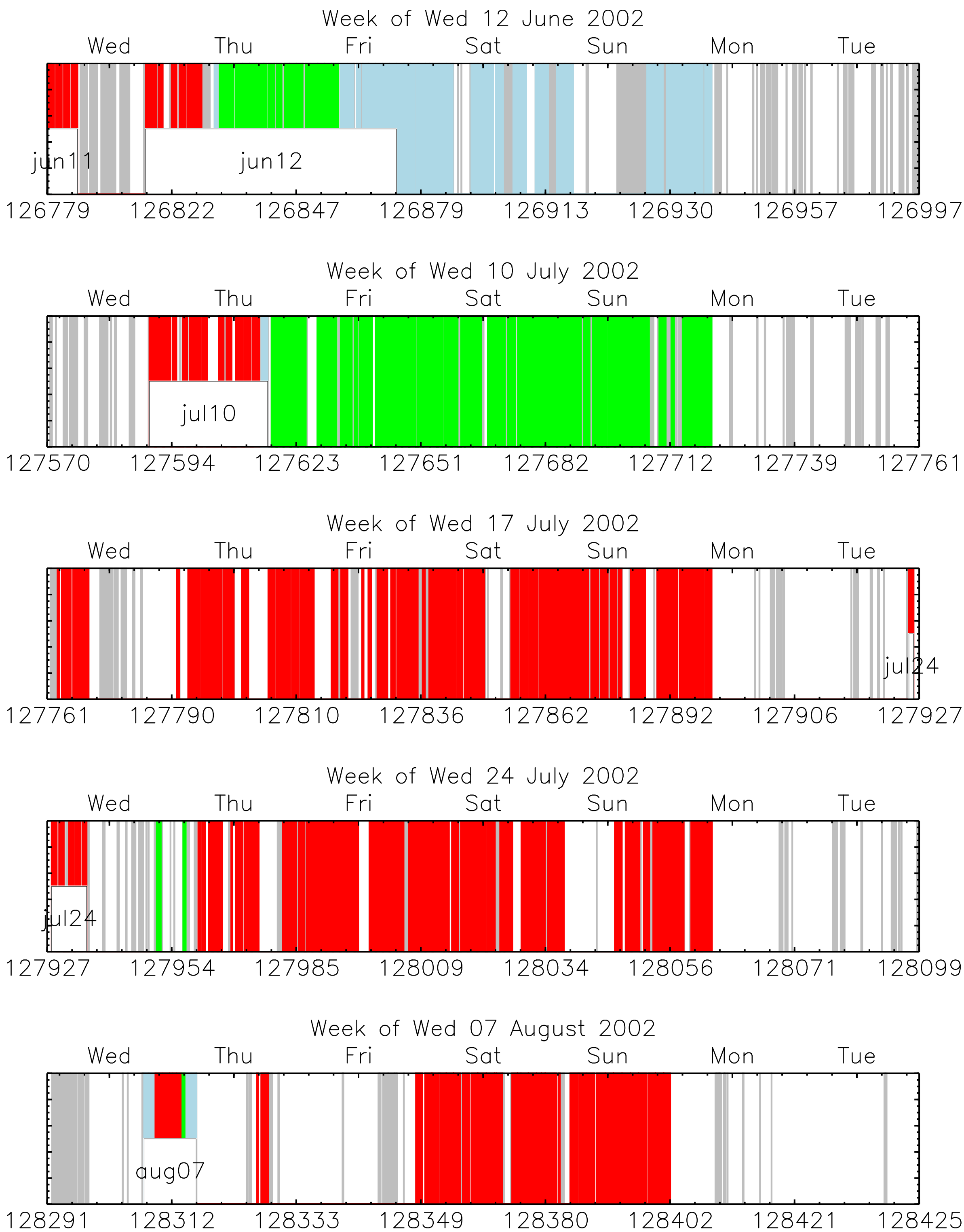

FIG. 12: Run periods by date and run number (5). See Figure 8 caption for color designations. The unassigned red regions on this plot are near the top of the $\Upsilon(3S)$ peak, and don't constitute a full scan.

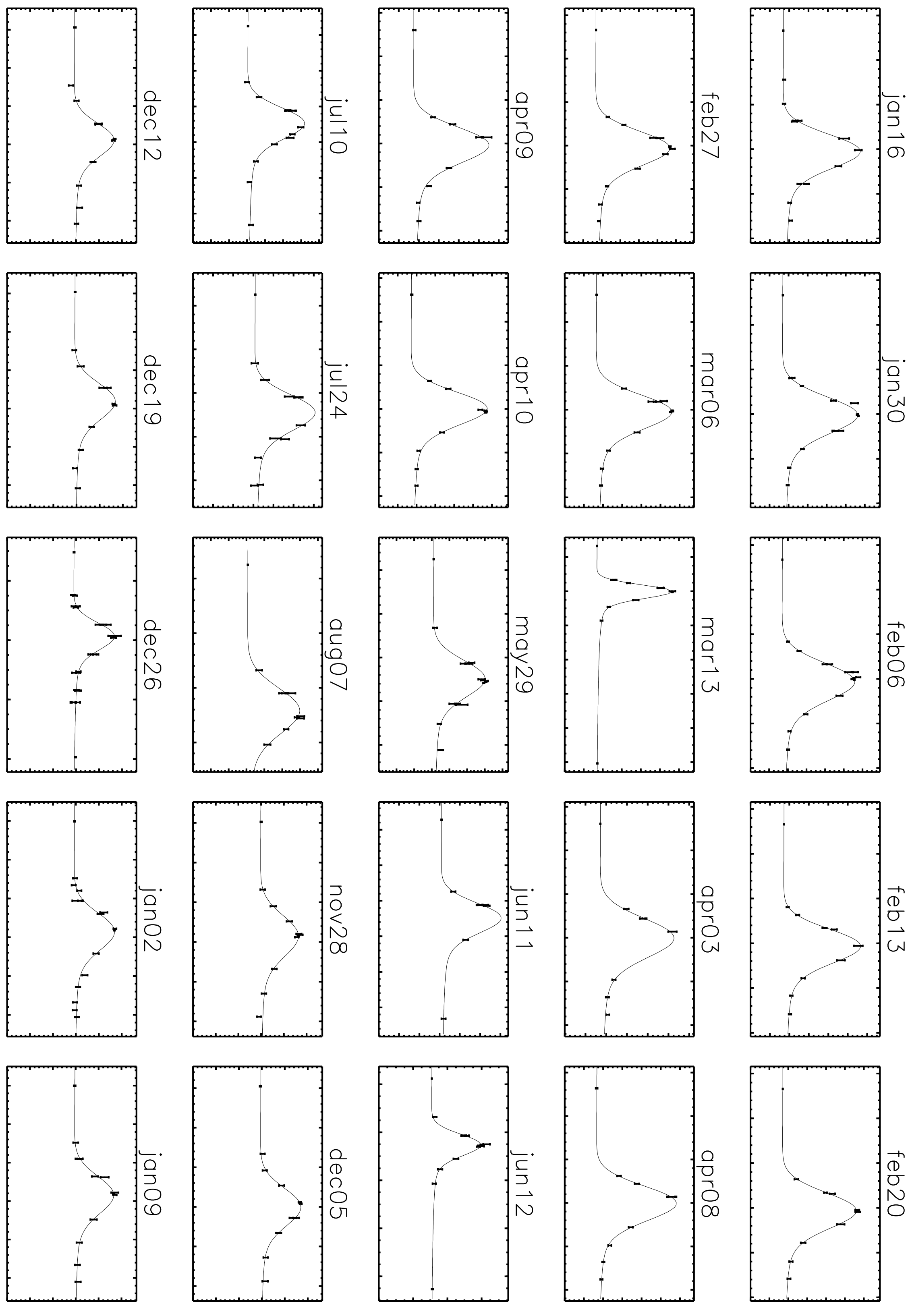

FIG. 13: Plots of individual scans, showing what energy points were available to each. The unlabeled axes do not share the same scale: for measured mass and beam energy spread values, see Figures 4 and Figure 3 and the text.