A Statistical Study of Solar Particle Events in Flux and Dose

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Abstract

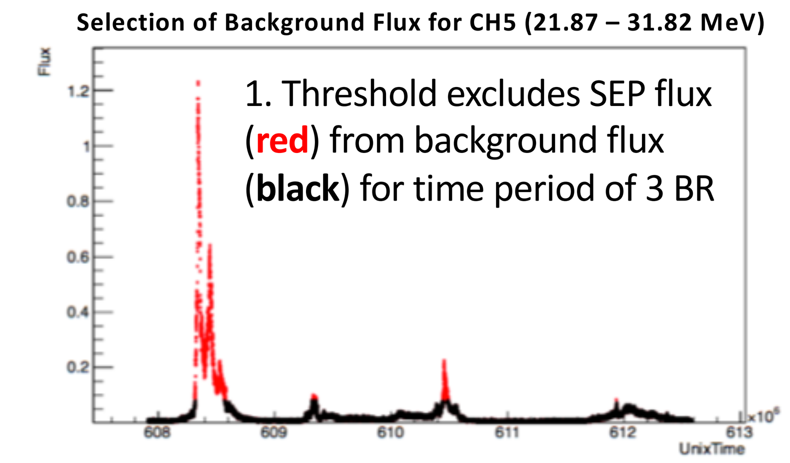
The high-energy protons from solar energetic particle (SEP) events present a hazard to space systems: damage to science instruments/electronics/materials or to astronauts. A reliable estimate of the high-energy proton environment is critical to assure mission success. Important characteristics of an SEP event are fluence, peak flux, energy spectrum, time to reach the peak flux, time to reach peak dose, and properties of the cumulative dose profile after an event starts. All of these characteristics are important to understand in order to design space missions properly for both robotic and human missions.

Because of the unpredictable and sporadic nature of SEP events, statistical models are often used to represent the SEP parameters described above. In a study by Jun et al. (2007), the statistics of event fluences, durations, and time intervals between events were investigated using the then-available historical SEP dataset obtained from the instruments onboard the IMP-8 spacecraft. Since then, a more comprehensive SEP dataset based off of IMP-8 and GOES called Reference Data Set Version 2.0 (RDSv2.0) has become available covering the SEP events up to Year 2015 under a framework of the European Space Agency's (ESA's) Solar Energetic Particle Environment Modelling (SEPEM) project (Jiggens et al., 2018). The main objectives of this statistical study of SEP events are two-fold: First, the statistics of peak fluxes, event fluences, durations, and time intervals will be re-visited by using RDSv2.0; Second, the statistical analyses of flux and dose timing will be performed using the same dataset RDSv2.0. The results of this study will address the statistical properties of all key parameters for designing a spacecraft or a human mission where the SEP environment is an important consideration.

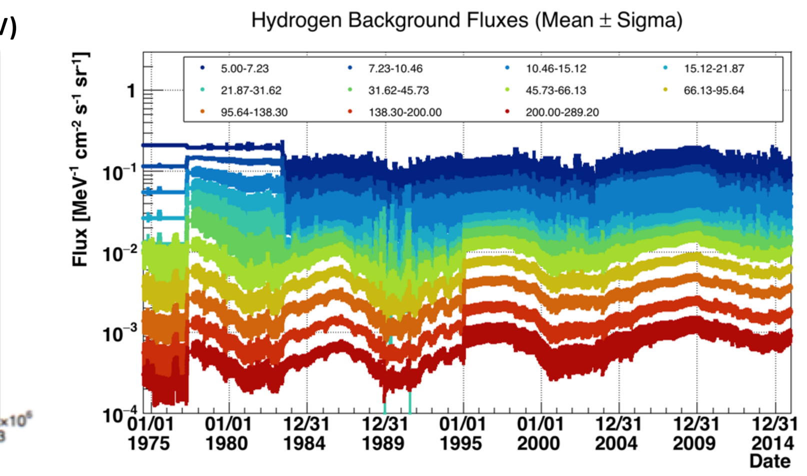
1. SEP Background Subtraction Methodology

1. **Select only fluxes that are considered "background" with a static threshold**
   Using thresholds specified for each energy channel, exclude fluxes that are too high (SEPs) to be background
2. **Create a distribution of background fluxes for time periods of 3 Bartels Rotations (BR) and each channel individually**
3. **Calculate the mean and standard deviation of each distribution**
   μ = average background flux
   σ = measure of fluctuations expected in the background
4. **Use the background in step 3 as a changing threshold, iterate steps 1 – 3; Calculate background for each day using the previous 27 days**
5. **Set all flux less than $\mu + 3\sigma$ to zero; assume μ = background flux and subtract from RSDv2.0 data set to get SEP flux (plots below)**

Selection of Background Flux for CH5 (21.87 – 31.82 MeV)

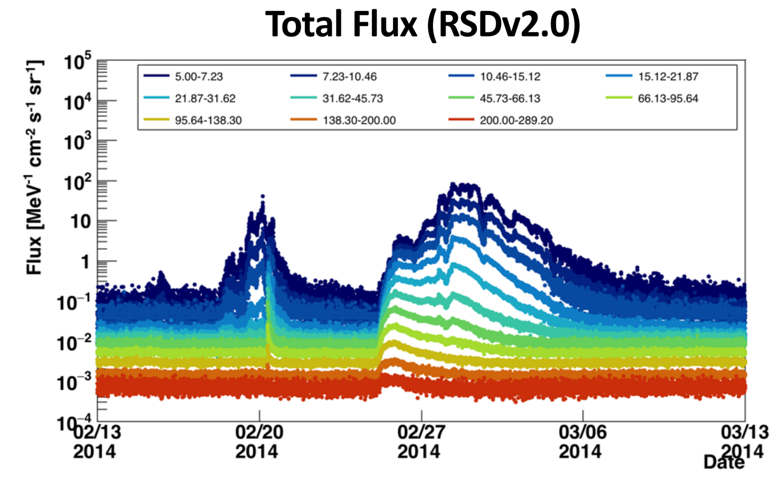


Hydrogen Background Fluxes (Mean ± Sigma)



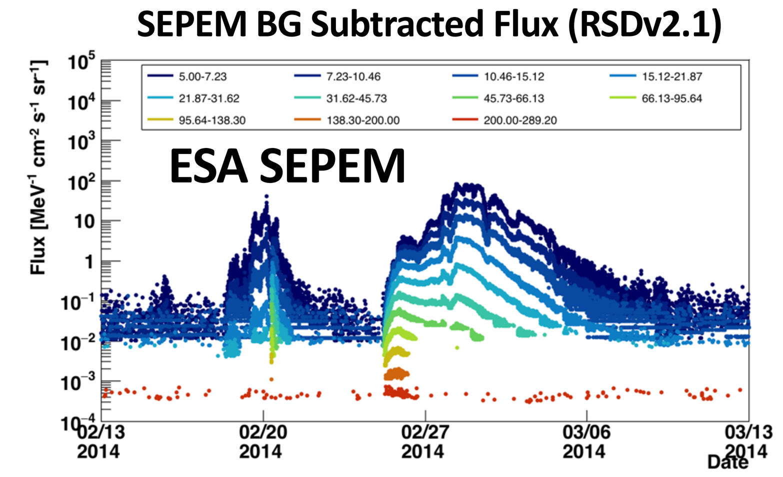
Above Left: Fluxes selected as background (black) are put into a distribution for each period of 3 BR for an initial estimate of the background μ and σ.
Above right: After iterating, the final background flux values (μ) for every day in the RSDv2.0 data set. The error bars (σ) indicate the amount of fluctuation expected in the background. μ and σ were calculated using the 27 days prior to each day.

Total Flux (RSDv2.0)

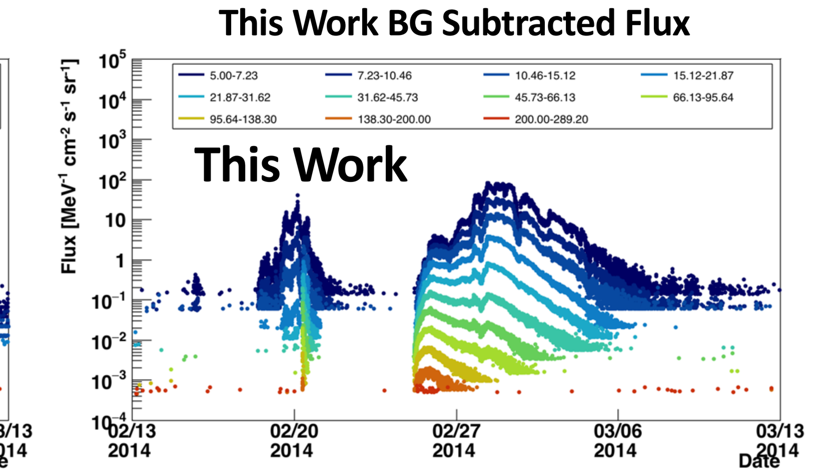


Left: Total flux in the ESA SEPEM RSDv2.0 data set.
Middle: SEPEM BG-subtracted flux, provided by ESA as the RSDv2.1 dataset. They used an average of 3 days before and after SEP event for background.
Right: BG-subtracted flux using method in this work.

SEPEM BG Subtracted Flux (RSDv2.1)



This Work BG Subtracted Flux



2. Automated SEP Event Start and Stop Times

SEP START in specified channel – each channel treated independently:

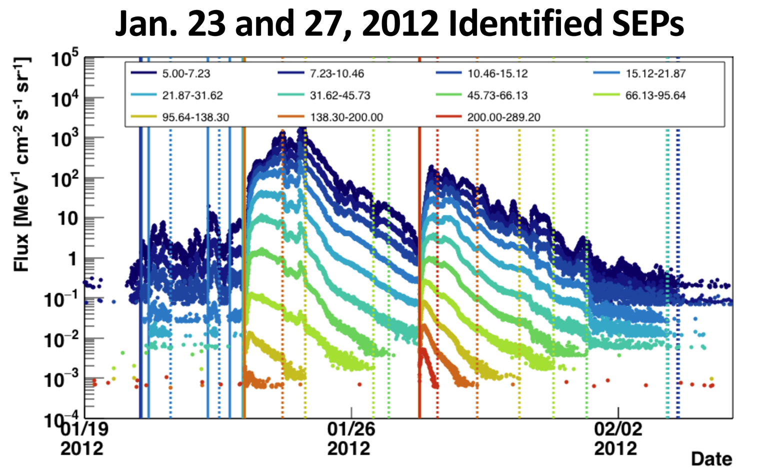
- ✓Require flux above background (non-zero flux) in specified channel
- ✓Require any 2 other channels to also see an increase (3 channels total)
- ✓Require a consecutive increase in 3 channels for 4 hours
- ✓Allow 50 minutes worth of gap in that initial time period
- ✓If all requirements are met, then the SEP event start time is recorded as the first point where conditions are satisfied

After SEP event starts, allow a gap (dwell time) of up to 3 hours

SEP END in specified channel:

- ✓If specified channel and 2 other channels do not record an increase during the allowed gap, SEP event ends at last point where all requirements were met

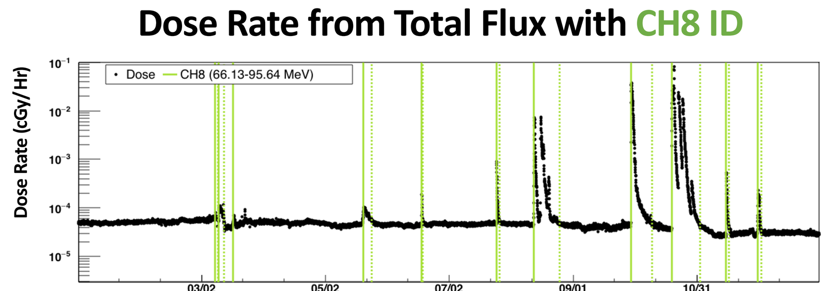
Jan. 23 and 27, 2012 Identified SEPs



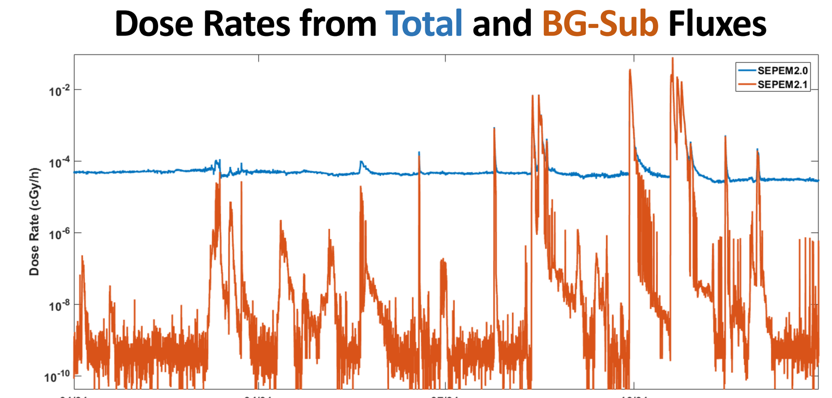
Left: Solid lines indicate identified SEP event start times and dashed lines indicate SEP event stop times. Each channel is treated independently, and colors correspond to the energy range in MeV. In some cases, lower energy channels may identify a single SPE, while higher energy channels may indicate multiple SPEs in the same time period.

3. Identification of Dose-Significant SEP Events

Dose Rate from Total Flux with CH8 ID



Dose Rates from Total and BG-Sub Fluxes



The top and bottom plots show the hourly *dose rates inside of a sphere of 10 g/cm² Aluminum* for 1989 calculated from the total flux in the RSDv2.0 data set (**black** top, **blue** bottom). The bottom plot shows the hourly dose rate for 1989 calculated from background-subtracted flux (**orange**). Even though many events occurred, only a subset of these events resulted in an increase in dose above background.

It was found that SPE start and stop times derived from Channel 8 (66.13 – 95.64 MeV, green lines on top plot) successfully identified the dose-significant events (10g/cm² Al) and were appropriate start and stop times to capture the full event dose.

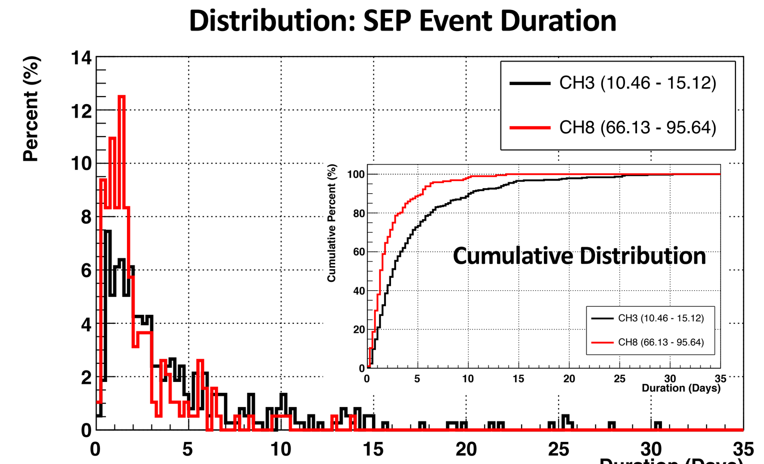
4. Results: SEP Event Statistics

Values for Largest SEP Events in Dose

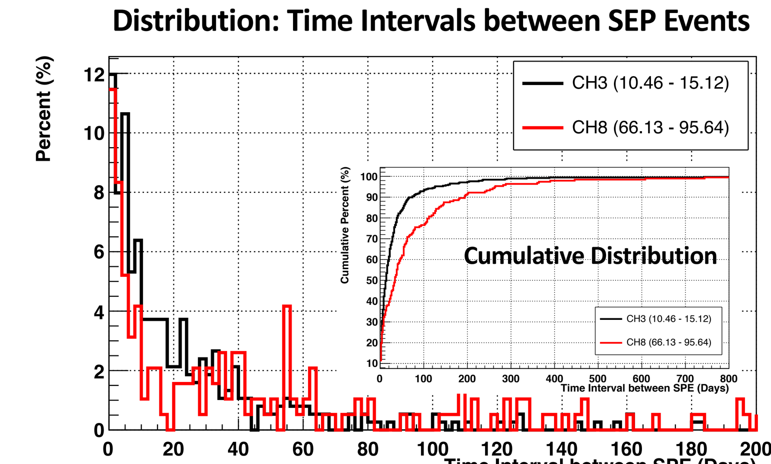
SEP Event Date	Onset Time	Duration (Days)	Peak Flux (66.13 – 95.64 MeV)	Fluence >66.13 MeV	Fluence >95.64 MeV	Peak Dose Rate (cGy/Hr)	Total Dose (cGy)	Time to Peak Flux (66.12 – 95.64 MeV) (Hr)	Time to Peak Dose Rate (Hr)	Time to 10% Dose (Hr)	Time to 50% Dose (Hr)	Time to 90% Dose (Hr)
1989/08/12	15:25:00	12.92	1.52	5.40e7	1.71e7	0.026	2.36	13.1	85.8	11.8	86.3	119.25
1989/09/29	11:50:00	10.45	3.72	1.64e8	7.38e7	0.145	9.18	8.0	8.1	3.8	11.8	28.8
1989/10/19	13:05:00	13.96	10.90	3.96e8	1.80e8	0.288	21.86	26.3	26.6	9.8	29.8	134.1
1991/03/23	6:50:00	6.45	4.97	3.35e7	6.48e6	0.065	1.08	21.0	21.1	12.8	19.3	22.3
2000/07/14	10:35:00	5.67	10.70	2.79e8	8.66e7	0.297	13.24	5.8	2.6	1.8	7.3	23.8
2000/11/08	23:40:00	5.93	11.10	2.42e8	6.30e7	0.239	10.65	4.0	4.3	2.5	7.5	16.8
2001/09/24	11:40:00	6.44	1.18	5.03e7	1.09e7	0.022	1.94	20.3	20.8	11.5	22.8	39
2001/11/04	16:45:00	5.10	9.83	1.61e8	3.84e7	0.168	6.52	33.6	33.7	5.2	29.4	36.2
2003/10/28	11:20:00	3.93	6.86	2.05e8	5.66e7	0.120	9.11	12.9	13.1	5.1	14.3	42.3
2005/01/15	23:55:00	8.28	10.19	1.14e8	4.87e7	0.511	6.37	103.3	103.3	52.5	104.5	113.75

Above: The statistics calculated in this study are tabulated for the 10 largest SEPs in dose. Event timing and duration were derived from Channel 8 (see Sec. 3). The dose values were calculated inside an Aluminum sphere of 10 g/cm². Flux and fluence units are [MeV^{-1} cm^{-2} s^{-1} sr^{-1}] and [cm^{-2}].

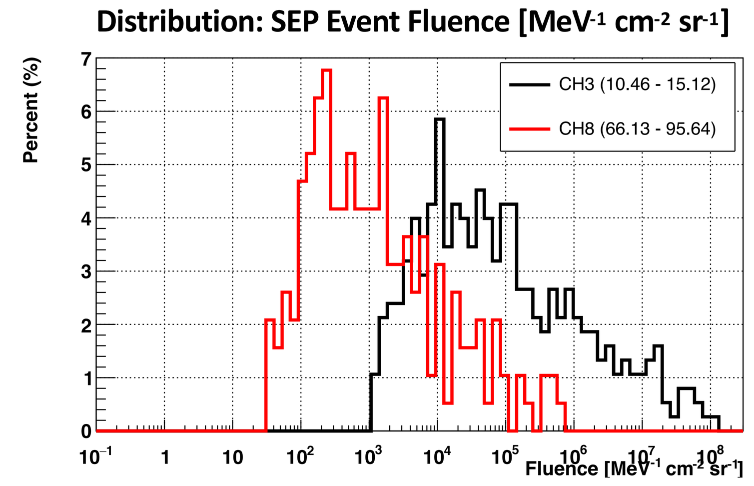
Distribution: SEP Event Duration



Distribution: Time Intervals between SEP Events

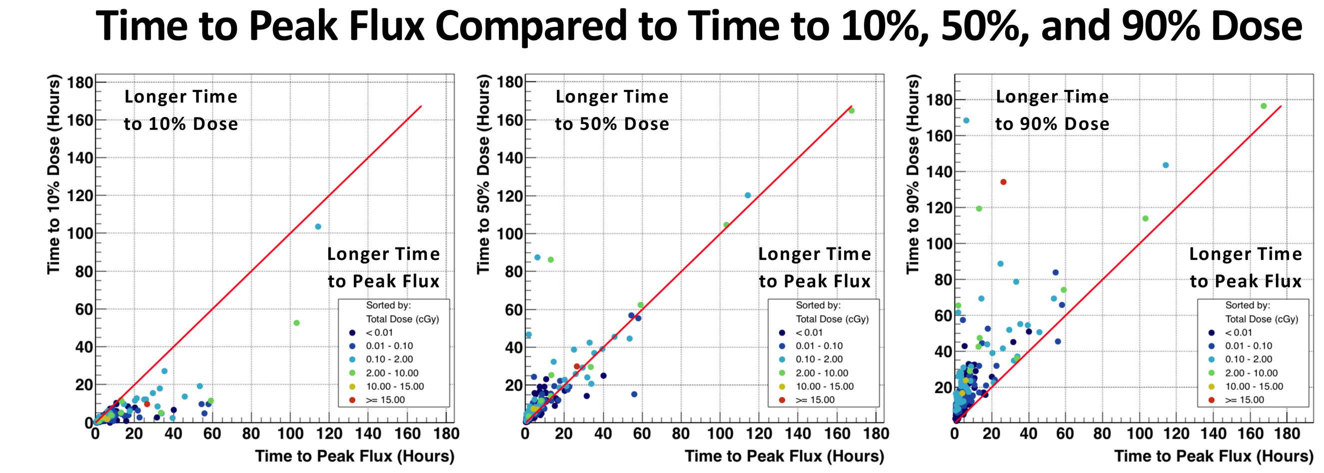


Distribution: SEP Event Fluence [MeV^{-1} cm^{-2} sr^{-1}]



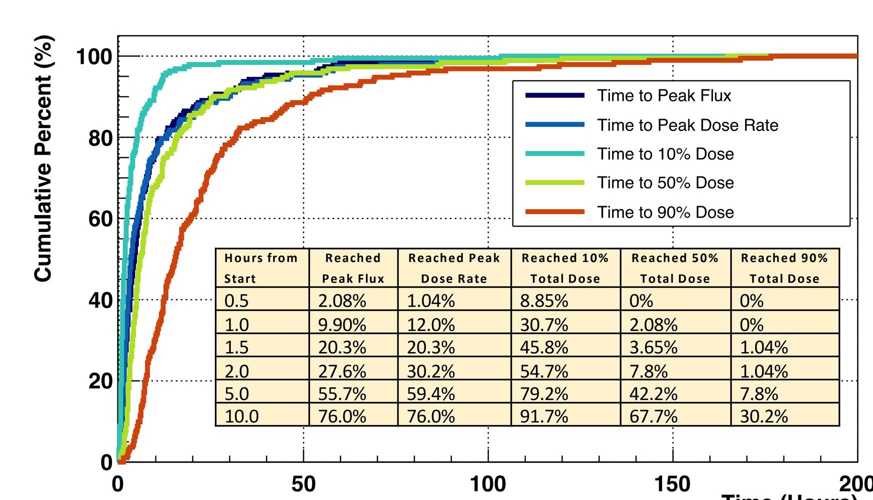
Example distributions of SEP event duration (**top left**), time intervals between events (**top right**), and fluence (**bottom left**) calculated in this study are shown for channels 3 and 8. *Each energy channel was treated independently*, resulting in different numbers of SEP events. The cumulative distributions are shown as insets for duration and time interval between events.

Time to Peak Flux Compared to Time to 10%, 50%, and 90% Dose



Above: Time to Peak Flux vs Time to 10% (**left**), 50% (**middle**), and 90% (**right**) Dose. The **red lines** indicate a 1:1 correspondence.

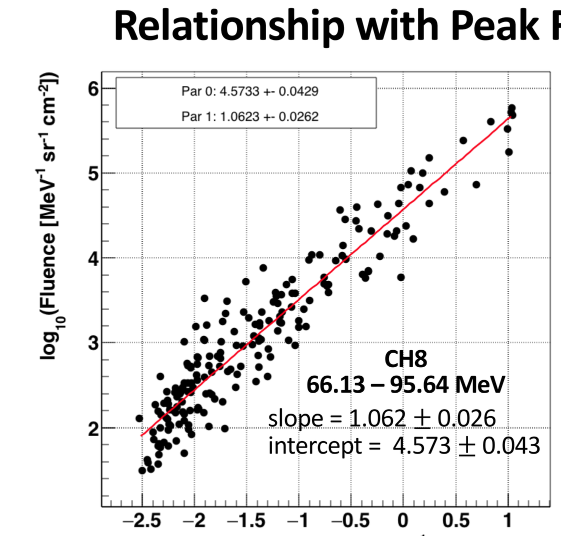
Cumulative Distributions: Flux and Dose Timing

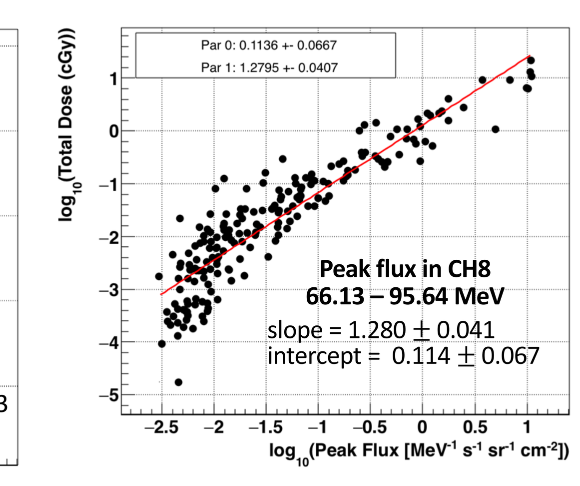


Hours from Start	Reached Peak Flux	Reached Peak Dose Rate	Reached 10% Total Dose	Reached 50% Total Dose	Reached 90% Total Dose
0.5	2.08%	1.04%	8.85%	0%	0%
1.0	9.90%	12.0%	30.7%	2.08%	0%
1.5	20.3%	20.3%	45.8%	3.65%	1.04%
2.0	27.6%	30.2%	54.7%	7.8%	1.04%
5.0	55.7%	59.4%	79.2%	42.2%	7.8%
10.0	76.0%	76.0%	91.7%	67.7%	30.2%

Cumulative distributions for the timing parameters in this study. The inset table lists the percent of SEP events that have reached peak flux, peak dose rate, 10%, 50%, and 90% dose within 0.5, 1, 1.5, 2, 5, and 10 hours. **SEP events behave similarly for time to peak flux, peak dose rate, and 50% dose.**

Relationship with Peak Flux: Fluence and Total Dose





Left: Fluence shows a clear relationship with peak flux for all channels (CH8 shown). **Right:** Total dose in CH8 (66.13 – 95.64 MeV) vs peak flux shows a linear relationship in log space.