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Cosmic ray modulation error for 2D SDE SOLARPROP model

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Abstract

For comprehensive global modeling of cosmic rays modulation in the heliosphere, it is essential to have a sound transport theory, and reliable numerical schemes with appropriate boundary conditions. For the description of the solar modulation process, and the propagation of the particles inside the heliosphere, Parkers transport equation is widely used. The correct and precise solution of this equation also must take into consideration errors. That's why the presented work particularly focused on the estimation of the errors of the SOLARPROP model, based on the input parameters range, and statistical errors for these numerical solutions of 2D Parkers equation by stochastic differential equation method to suggest the safe simulation strategy for spectra evaluation at 1 AU.

Method Description 1D

In the previous work for the estimation of the 1D model statistical error [1], we simulated ten separate sets of one million quasiparticles with energy 5GeV at 1AU to illustrate how an error in the backward in time method change with a number of injected particles.

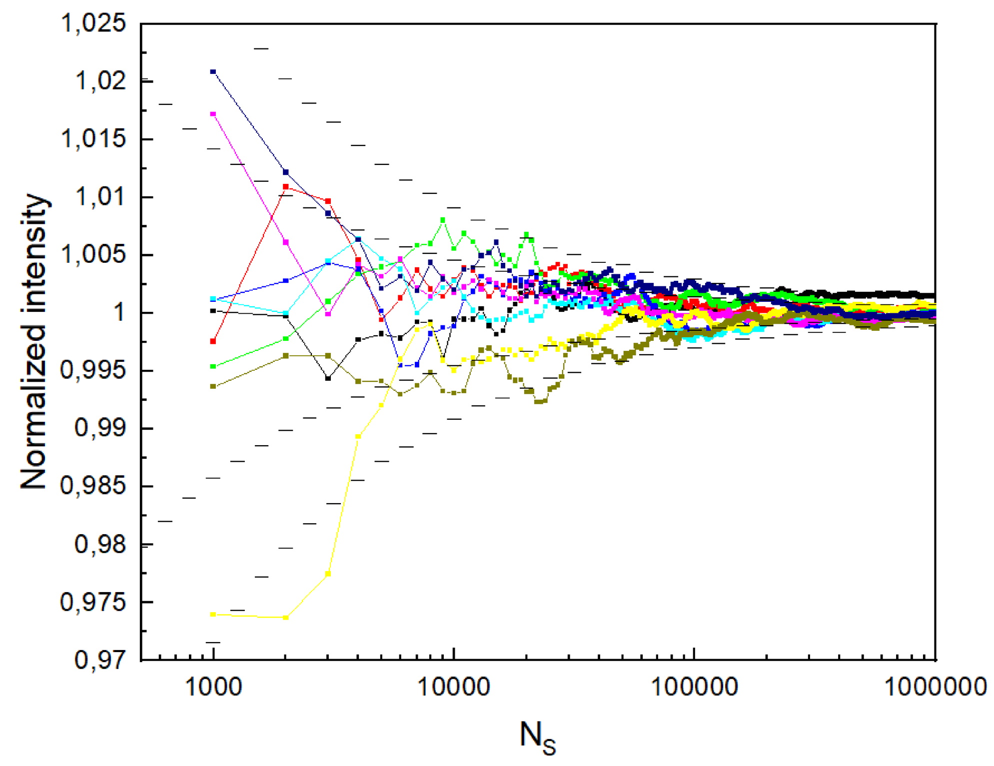

Fig. 1. Dependence of intensity on number of simulated quasiparticles for 10 separate set of quasiparticles signed by different colors.

To show statistical error, we divided obtained set of 10 million quasiparticles to subsets with Ns quasiparticles. From every subset with Ns = 1000 quasiparticles we evaluate average value of intensity I_{NS}

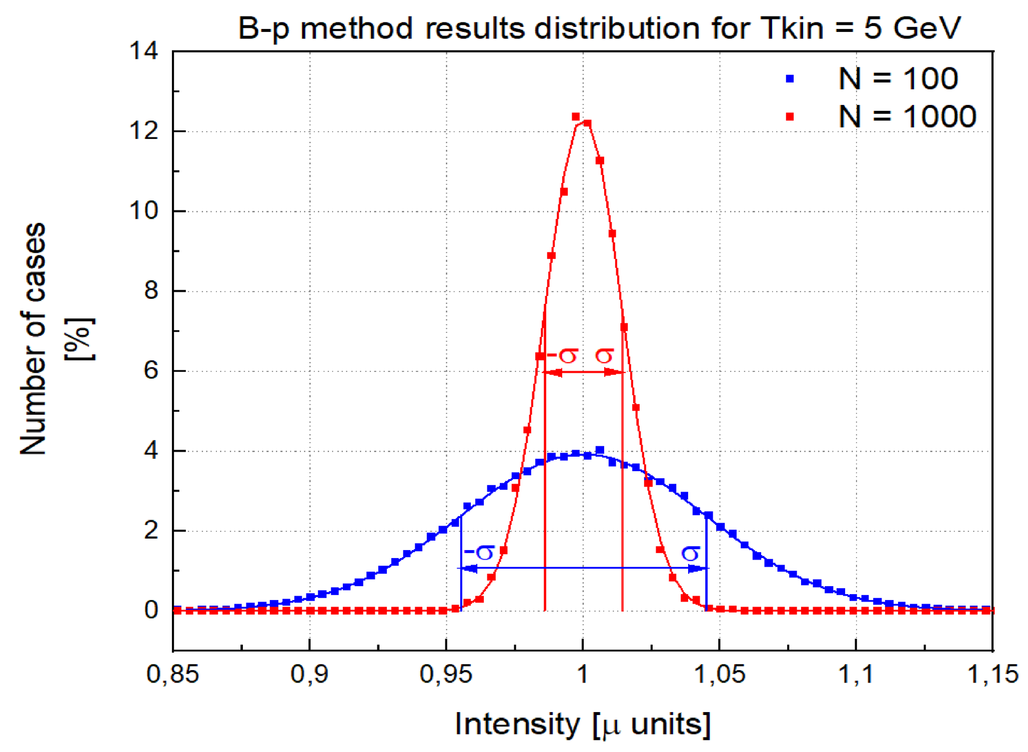

Fig. 2. Comparison of I_{NS} values histogram with probability distribution function with μ_{NS} and σ_{NS} of histogram. Red points sign case for $N_s = 1000$, blue for $N_s = 100$. Ranges $\pm 1\sigma$ are shown for both cases.

The dependency of σ at N_s for sets with normal distribution (consequence of central limit theorem) should have power law shape with slope $-1/2$. To show it we evaluated a σ_{NS} for set of different Ns with logarithmical step. In figure 3. we show dependency of σ on Ns for evaluation of intensities for two energies Tkin equal 5GeV and 1GeV.

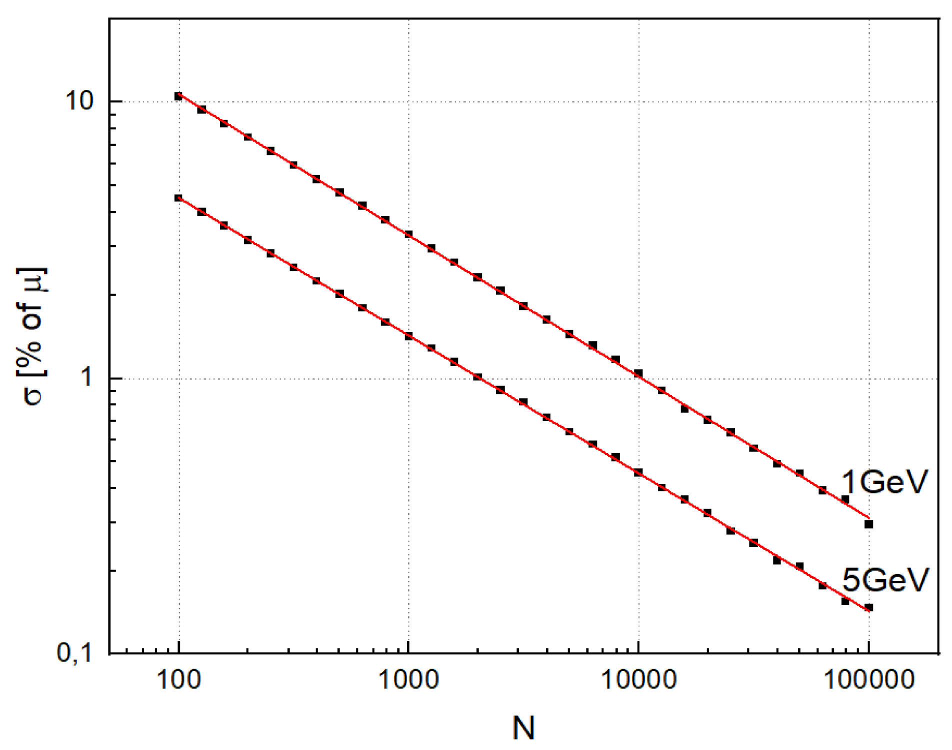

Fig. 3. Dependency of σ on Ns for energies Tkin equal 5 GeV and 1 GeV.

Results 2D SOLARPROP model

We used the SOLARPROP model [2] to investigate statistical error dependency on the number of injected quasiparticles for 2D models. The procedure described in the previous section for the 1D backward in time model was used.

Thus by using the so-called *Standard 2D* SOLARPROP model, sets of one thousand injected quasiparticles for every energy bin (i.e. for whole spectrum) were simulated, for every month for years from 1991 – 1999 (i.e. 108 months). Firstly we evaluated the standard deviation σ distribution in the percent of mean value μ units for every month, and for four different energy bins at 1 AU.

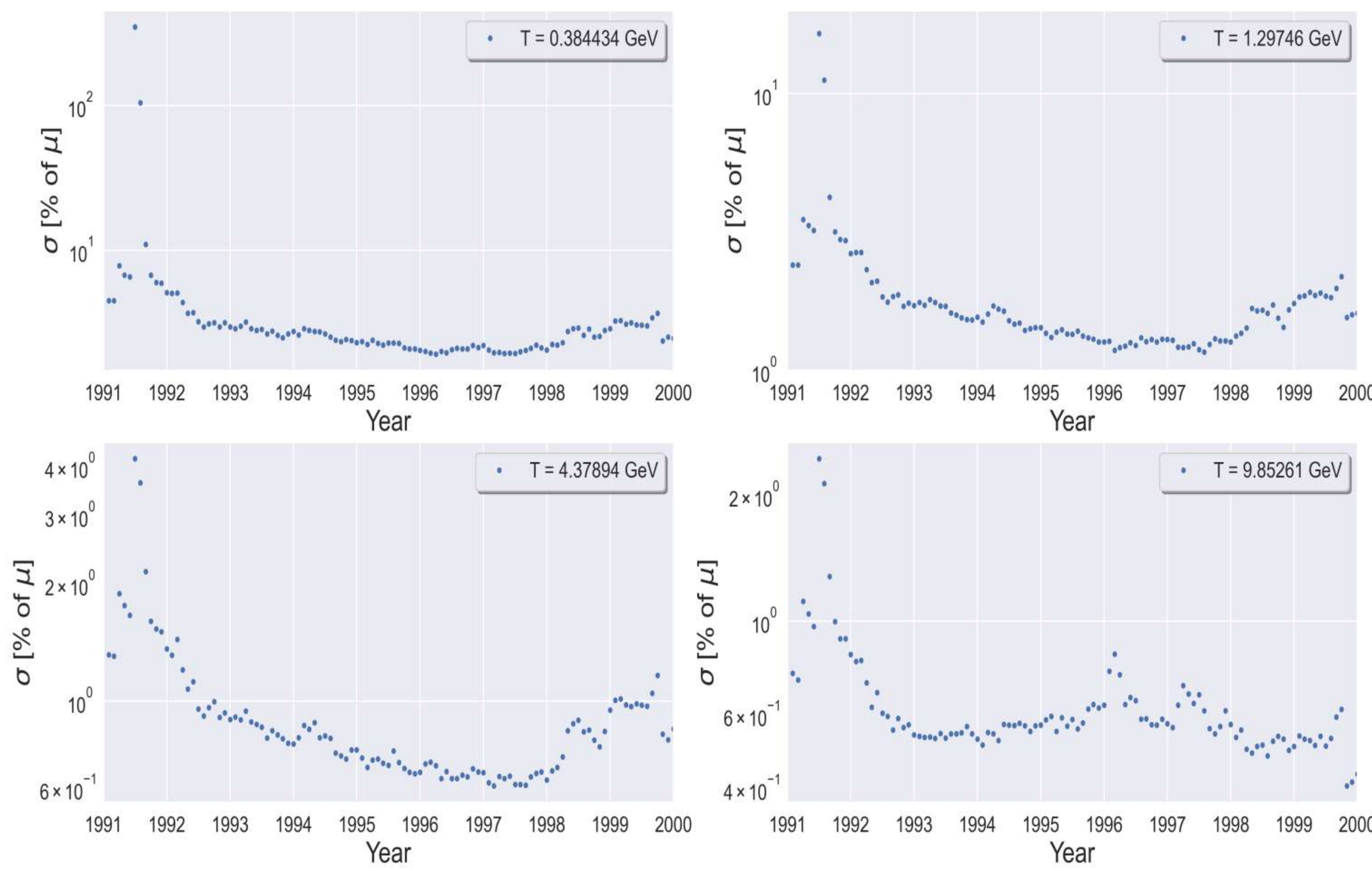

Fig. 4. Standard deviation distribution in percent of mean value units with respect to different months, for four energy bins at 1 AU.

Further, with the knowledge that statistical error has a power law shape with slope $-1/2$, the number of injected quasiparticles needed to reach 1% statistical error (i.e. σ equal to 1 in the percent of μ) was calculated for every month, for four energy bins.

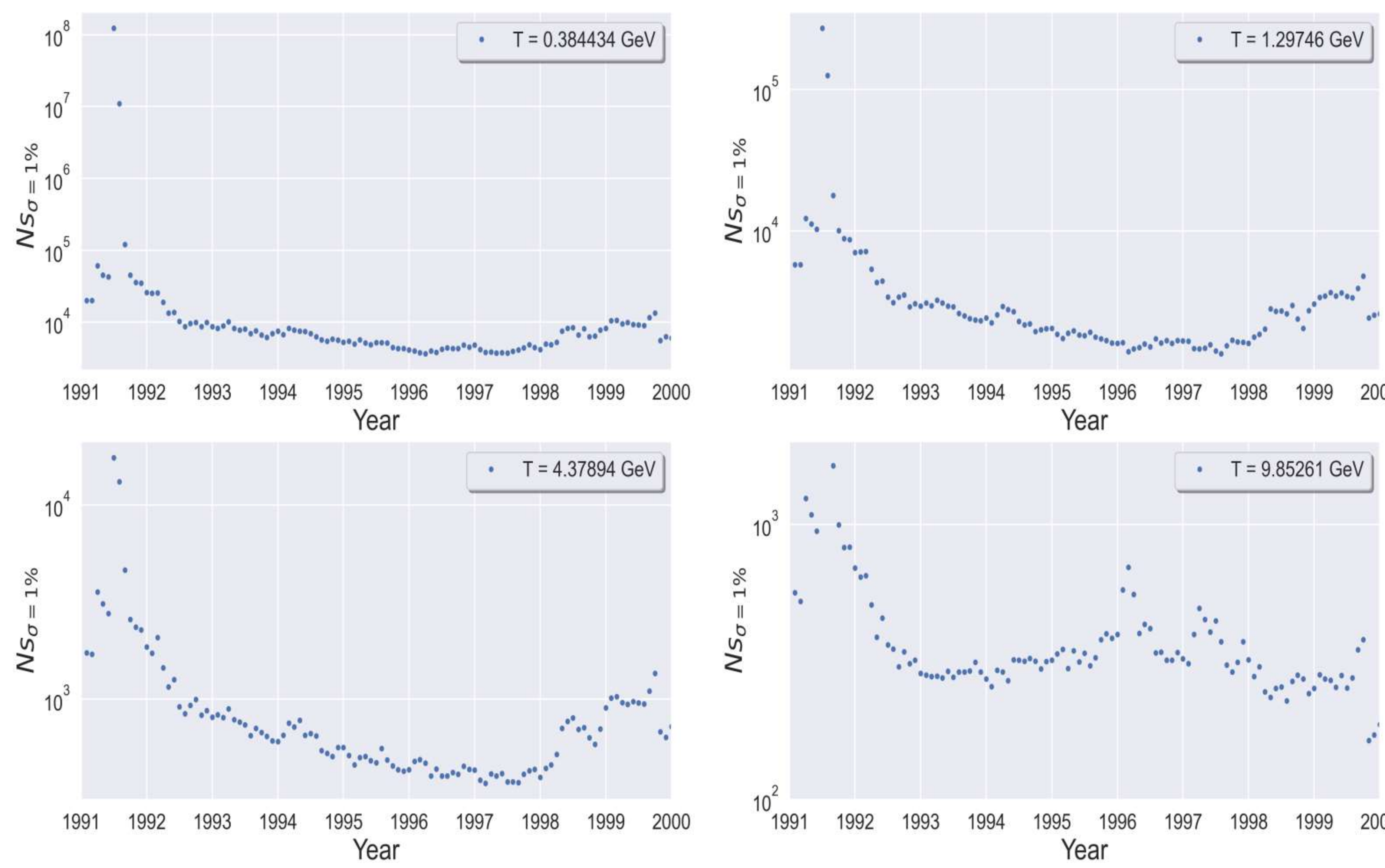

Fig. 5. Calculated number of injected needed to reach 1% statistical error with respect to different months, for four energy bins at 1 AU.

Conclusions

- Statistical error is much higher during the period of extreme solar modulation (for example June 1991).
- The previously suggested strategy $10^4/Tkin[in\ GeV]$ for number of injected particles in backward 1D method [1] is still valid for 2D SOLARPROP model for years without extreme solar modulation, i.e. 1993-2000.

References

[1] Mykhailenko, V.; Bobik, P. Statistical Error for Cosmic Rays Modulation Evaluated by SDE Backward in Time Method for 1D Model. *Fluids* **2022**, *7*, 46.
[2] Rolf Kappl, SOLARPROP: Charge-sign dependent solar modulation for everyone, Computer Physics Communications, Volume 207, 2016, Pages 386-399, ISSN 0010-4655.