Proton flux analysis and solar modulation with the AMS-02 detector and neutron monitors.

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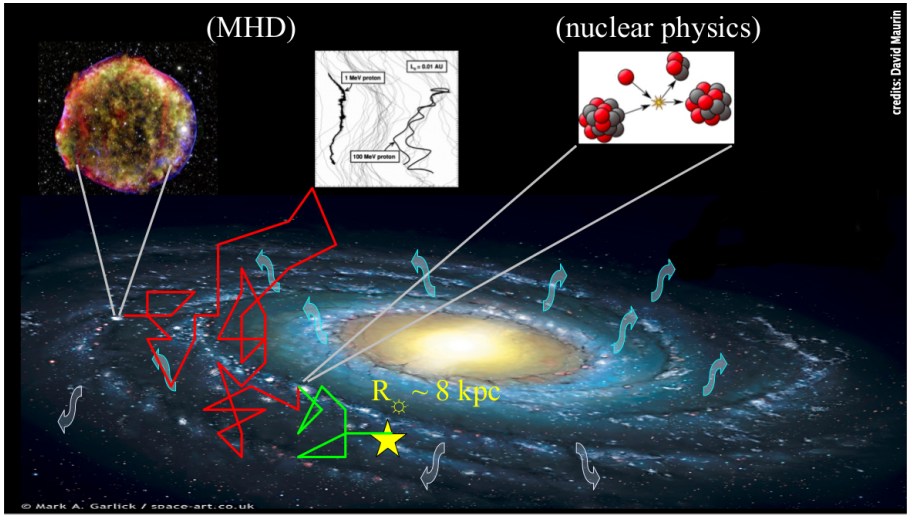
Introduction & Motivations

Galactic cosmic rays (GCR) and solar modulation



Propagation of CRs in the Galaxy

- Synthesis and acceleration.
- Transport in the Galaxy (≈20 Myr).
  - Diffusion on magnetic fields.
  - Energy gains/losses.
  - Nuclear interactions.

Introduction & Motivations

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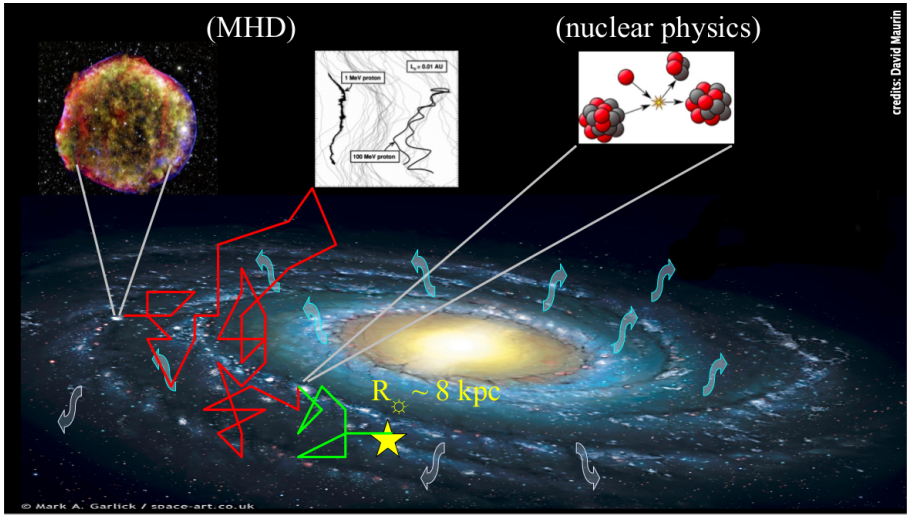

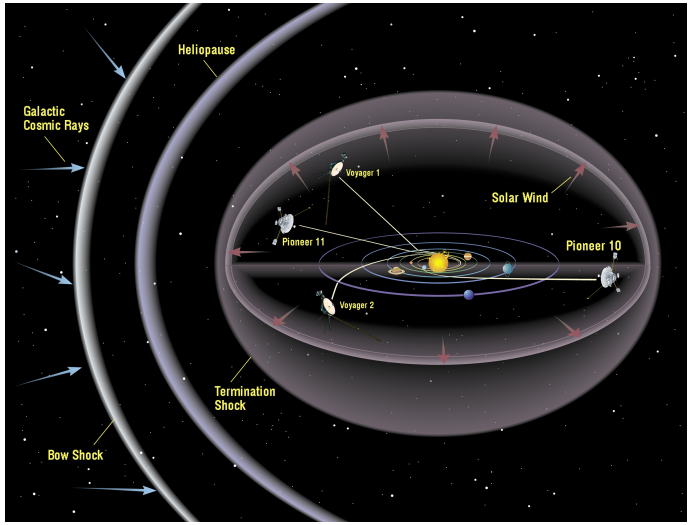

Propagation of CRs in the Galaxy

- Synthesis and acceleration.
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Solar modulation

- CR interaction with the solar plasma.
- Modulation correlated with the Sun activity (sunspots).
- Time dependent (11 yr cycle).

Introduction & Motivations

Galactic cosmic rays (GCR) and solar modulation

Motivations

Galactic scale:

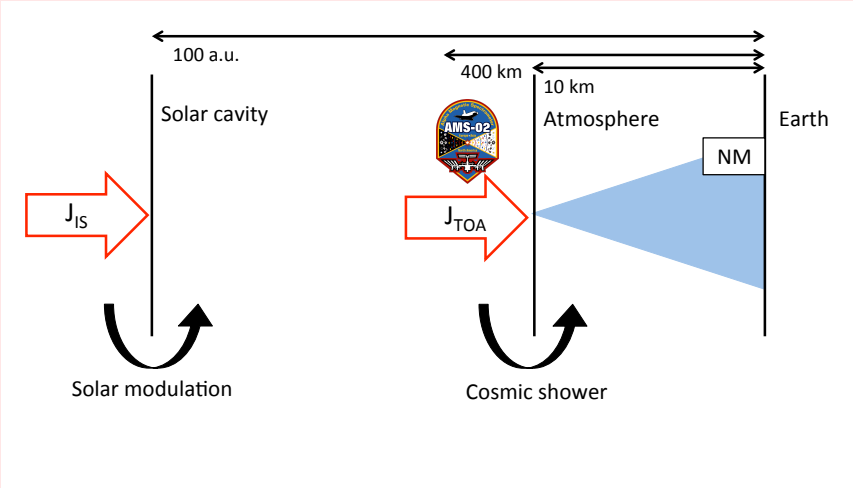
- CR sources (abundances, spectrum).
- CR transport.
- Dark matter.

Local scale:

- Interstellar fluxes (J_{IS}) needed for GCR data interpretations.
- Understand solar physics and transport in solar cavity.

Which data can be used?

- Top of atmosphere (TOA) CR experiments.
  - **AMS-02**, PAMELA, BESS.
- Count rate from ground based experiments.
  - **Neutron monitors** (**NM**), muon monitors.



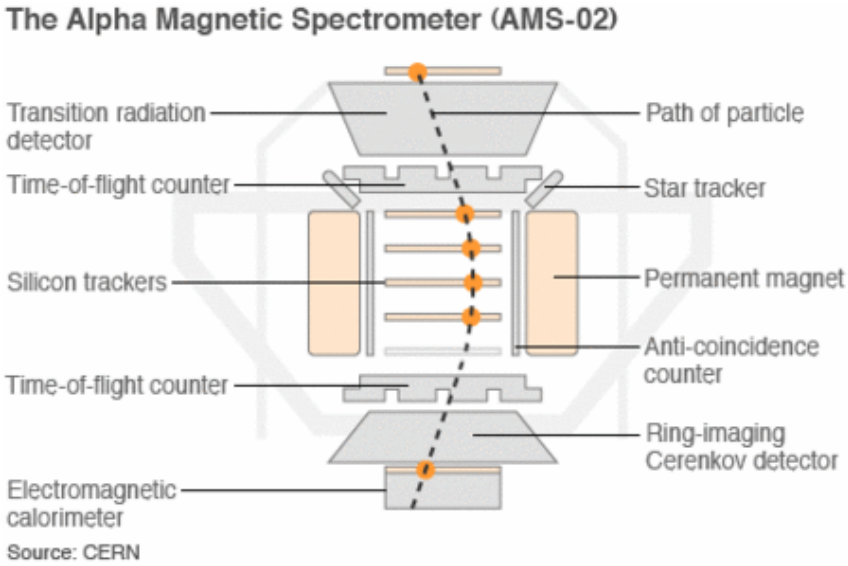
Outline

1. Introduction & Motivations.
2. AMS-02 proton analysis.
   - What is AMS-02?
   - From count rates to flux.
   - Proton selection.
   - **Unfolding**.
   - **Caracterisation of the proton flux**.
3. Solar modulation study.
   - What is solar modulation?
   - The force field model.
   - What is a neutron monitor?
   - **Reconstruction of solar modulation levels.**
4. Conclusion & Perspectives.

AMS-02 proton analysis

What is AMS-02?

- On the ISS since may 2011.
  - Continuous data taking.
  - Large statistics (3×10^8 protons detected over 30 months).
- Composed of 6 sub-detectors.
  - Multi-purpose detector (from H to Fe + leptons).
  - Redundant measurements of detected particle's properties.
- Core: permanent magnet and silicon tracker.
  - Identify the sign of the particle.
  - Measure magnetic rigidity $R = \frac{p}{Z} = Br_L$



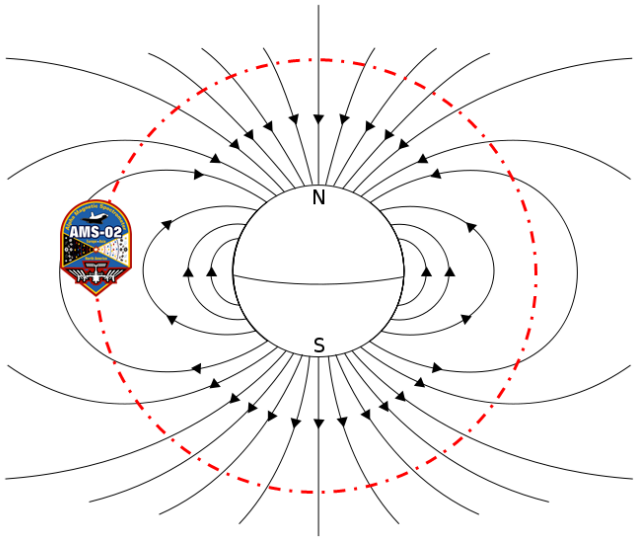
- Very good identification of particles.
- Large acceptance + long duration experiment: huge statistics.

AMS-02 proton analysis

From count rates to flux

$$J_i = \frac{N_i}{Acc_i \times \epsilon_i^{trigger} \times T_i \times \Delta R_i}$$

- i: rigidity bin $[R_i; R_i + \Delta R_i]$.
- N_i: number of particle detected in rigidity bin i.
- Acc_i: effective acceptance (estimated from MC simulation).
- $\epsilon_i^{trigger}$: trigger efficiency (estimated from data).
- T_i: exposure time (from data).

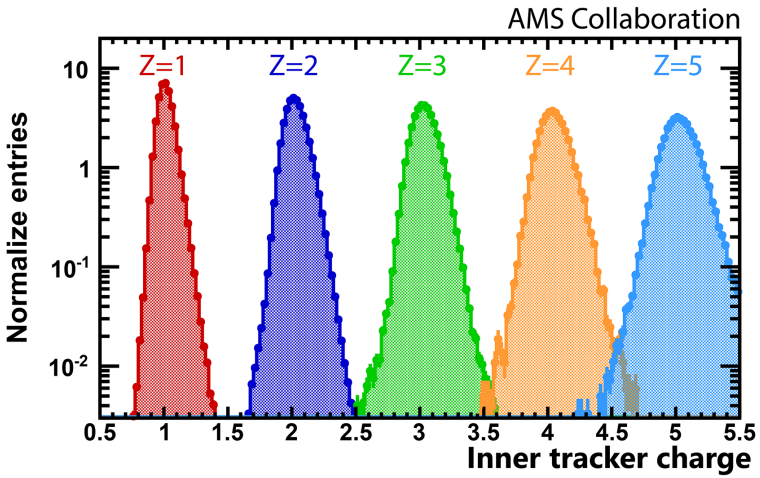


Acceptance from MC, the rest from data.

AMS-02 proton analysis

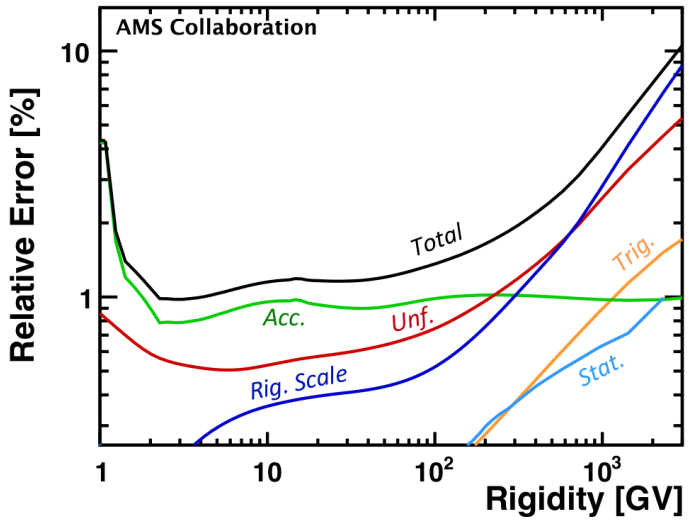
Proton selection

1. Selection criteria:
   - Downgoing particles: $\beta > 0.3$.
   - Charged $+1$ particles: $|Z| < 1.4$ and $Z > 0$.
   - Particle above the geomagnetic cutoff: $R > 1.4 \times R_{cut}$.
   - Clear signal: $N_{track} > 0$ and 4/4 ToF layers hit.



Clean selection of proton events.

2. Systematic uncertainties.
   - Estimated from MC simulation and in-flight data.
   - Syst (4% @1TV) $>$ Stat (0.5% @1TV).



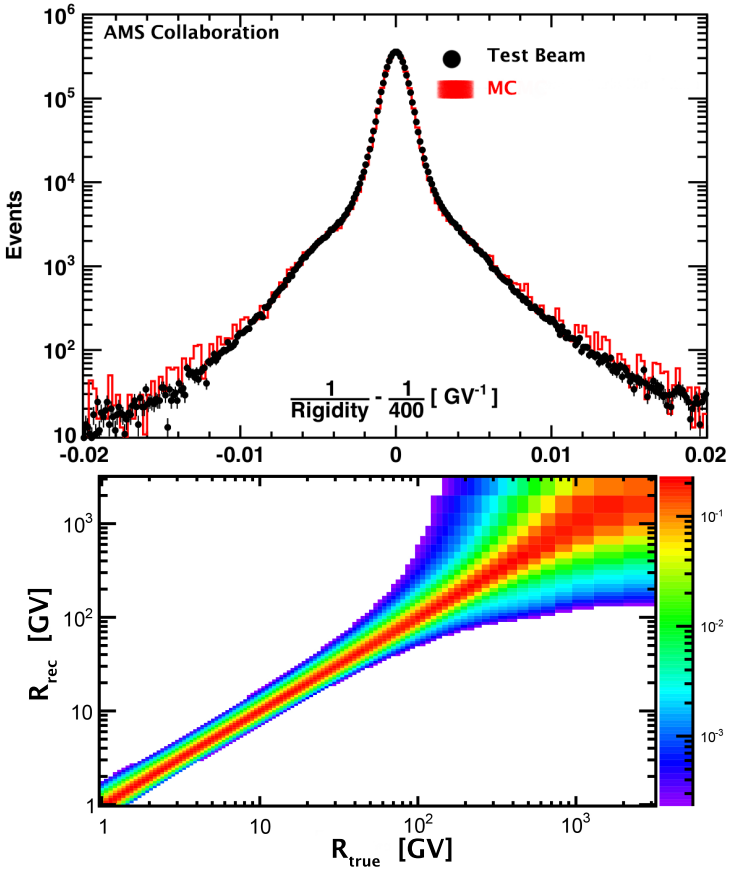
Energy resolution is the dominant source of systematics at high energy.

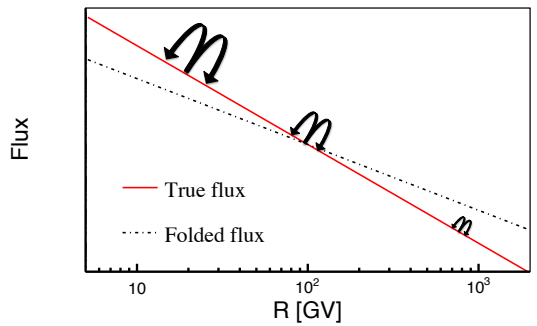
AMS-02 proton analysis

Unfolding - Problematic

- Finite energy resolution.
  - $R_{rec} \neq R_{true}$
- Migration matrix (from MC simulation): migration probability.
  - Migration depends on rigidity.
  - Maximum detectable rigidity MDR = 2 TV ($\Delta R = 100\%$).
- Illustration on a power-law flux.
  - Flux distorsion (change of spectral index).
  - Important consequences for data interpretation.

Given AMS-02 data precision, migration has to be corrected.





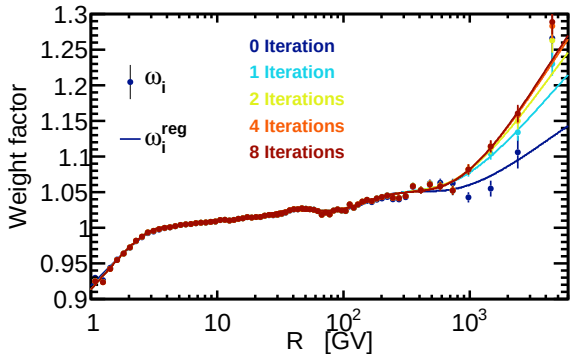
AMS-02 proton analysis

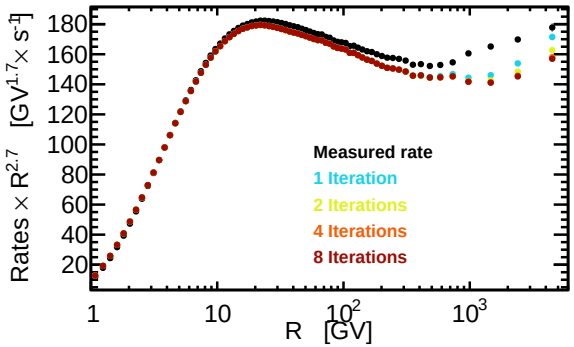
Unfolding - Correction from finite energy resolution [*Ghelfi, Proceeding CRISM 2014*]

1. **Algorithm:**
   - X_j: Unfolded rate at the j^{th} iteration.
   - Y_j: Folded rate.
   - Y_{mes}: measured rate.
   - ω_j: weight factor.
   - ω_j^{reg}: regularised weight factor.

$$
\begin{aligned}
Y_{mes} &= M \cdot X_{true} \\
Y_j &= M \cdot X_j \\
\omega_j &= \frac{Y_j}{X_j} \\
\omega_j^{reg} &= Spline(\omega_j) \\
X_{j+1} &= \frac{Y_{mes}}{\omega_j^{reg}}
\end{aligned}
$$

2. **Regularisation**: Avoid propagation of statistical fluctuations in the process.



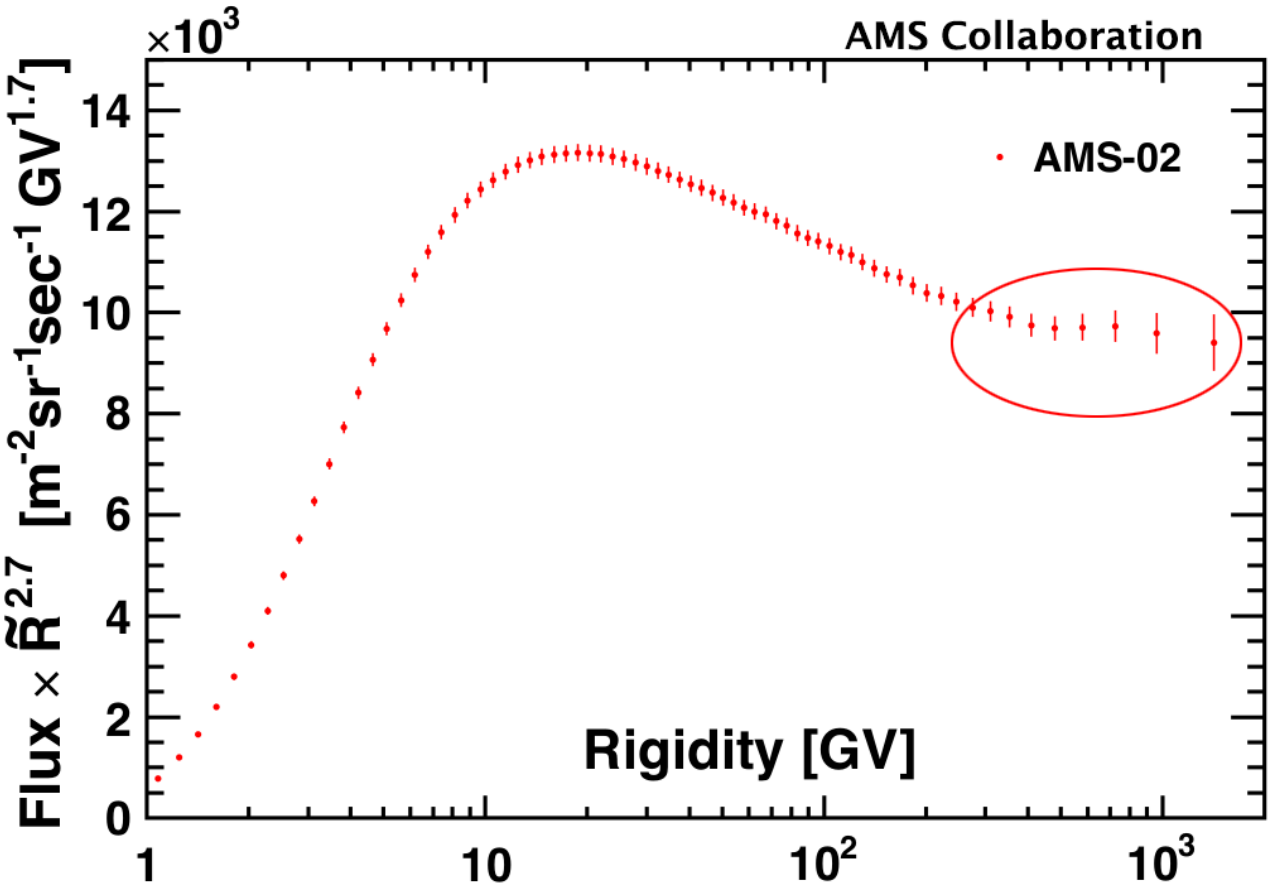


- Fast and robust convergence.
- Validated on simulated data.
- Official method in AMS-02 analysis.

AMS-02 proton analysis

Proton flux

LPSC analysis selected, PRL publication accepted.



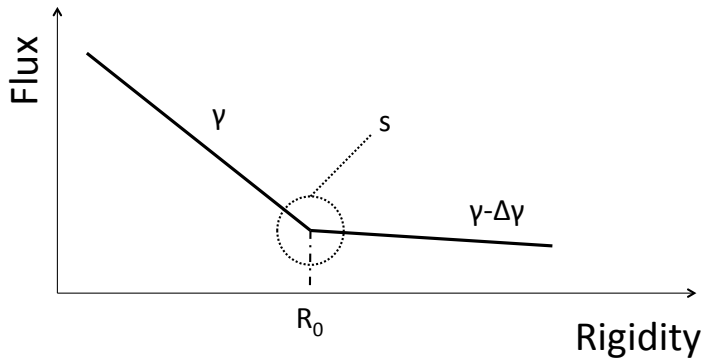
High energy change of slope?

AMS-02 proton analysis

Characterisation of the proton flux

- **Motivations**
  - Hint of a break around 200 GV [*Adriani et al, 2011*], [*Yoon et al, 2011*].
  - Structure at high energy (source spectrum, transport...?).
- Fit a double power-law with smooth transition.

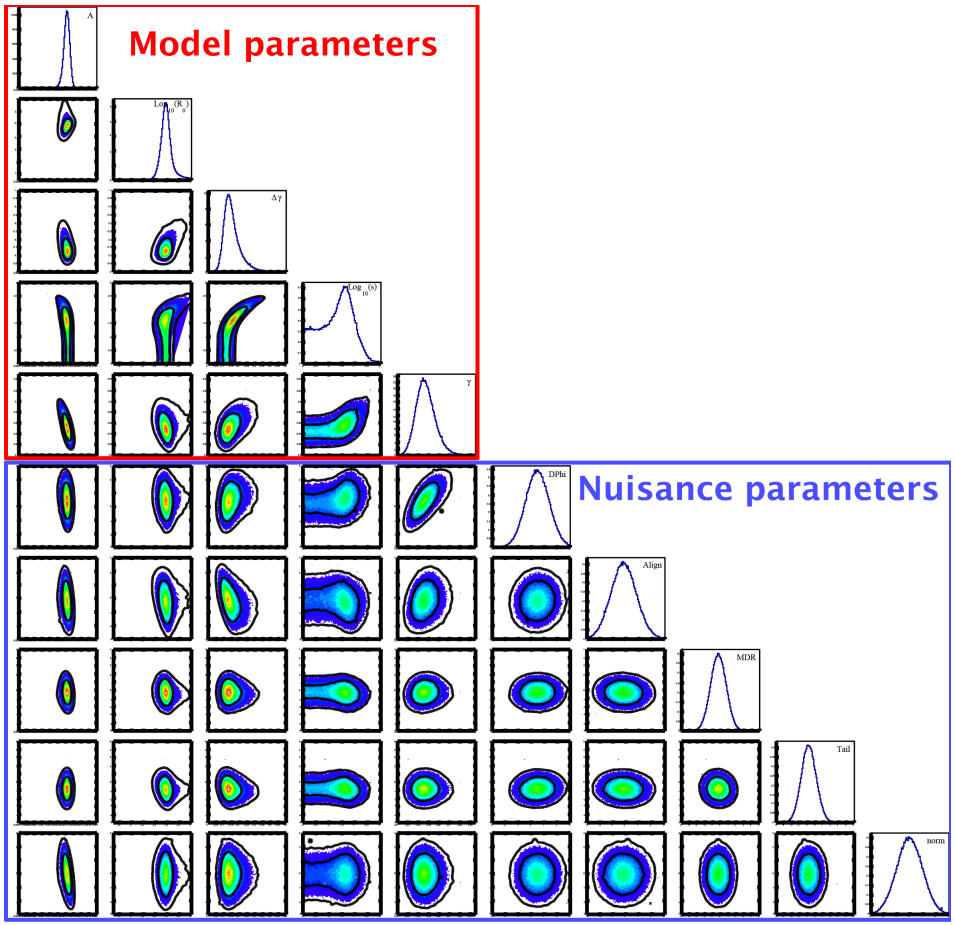
$$J(R) = C \times R^{-\gamma} \left[1 + \left(\frac{R}{R_0} \right)^{\Delta\gamma/s} \right]^{s}$$



- Estimation of non-gaussian parameters errors (needed for testing hypothesis).
  - Profile likelihood.
  - Markov chain Monte Carlo (MCMC).

AMS-02 proton analysis

Characterisation of the proton flux - Analysis



- Access PDFs (1D and 2D).
- Asymmetric errors.

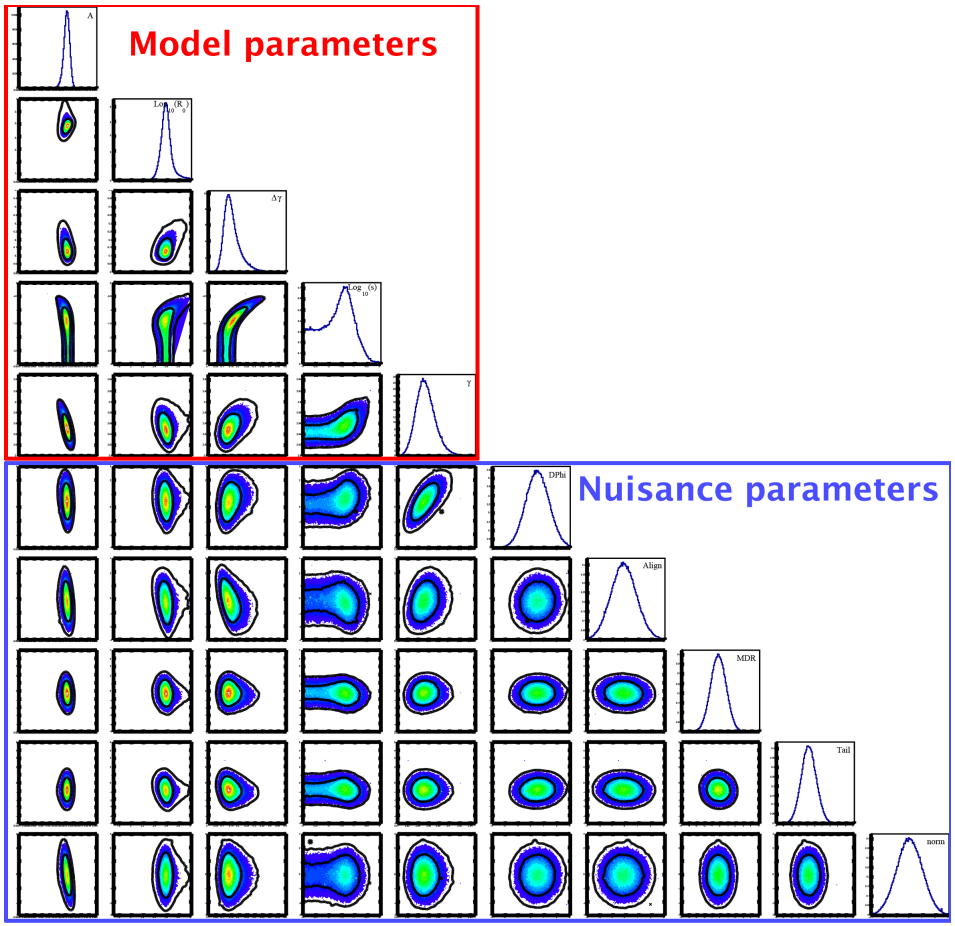
- MCMC principle.
  - Based on the Bayes theorem.

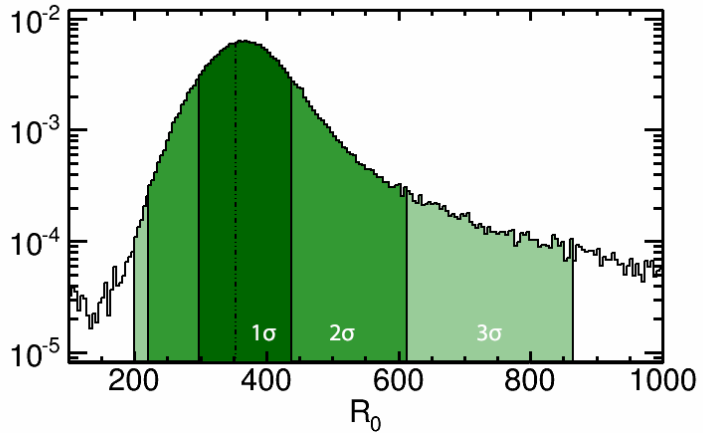
$$\underbrace{P(\vec{\theta}|data)}_{PDFs} \propto \underbrace{P(data|\vec{\theta})}_{Likelihood} \times \underbrace{P(\vec{\theta})}_{Prior}$$

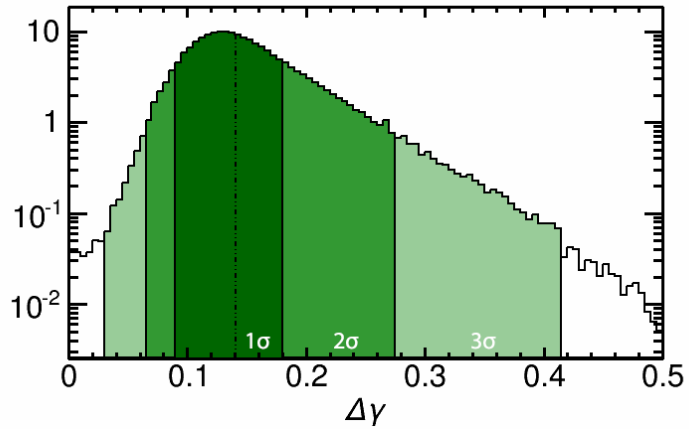
  - MCMC: Intelligent sampling of the likelihood and natural marginalisation.
- Systematic uncertainties ([*SOS 2014, W. Verkeke*]).
  - Goal: Propagate systematics from analysis into the fit.
  - Each source of systematics described by a model and some parameters (nuisance parameters NP) constrained by external measurement (calibration).

AMS-02 proton analysis

Caracterisation of the proton flux - Analysis





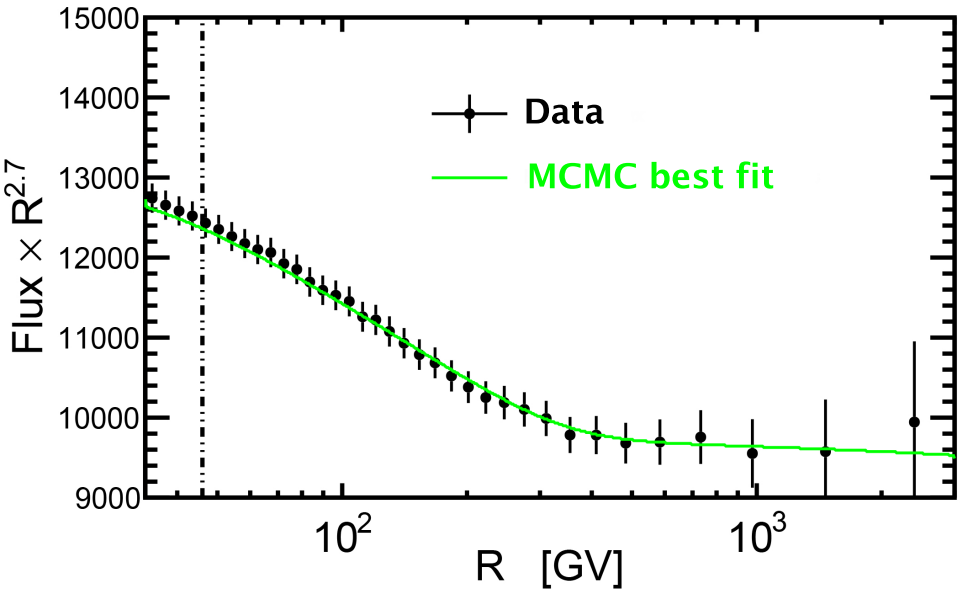


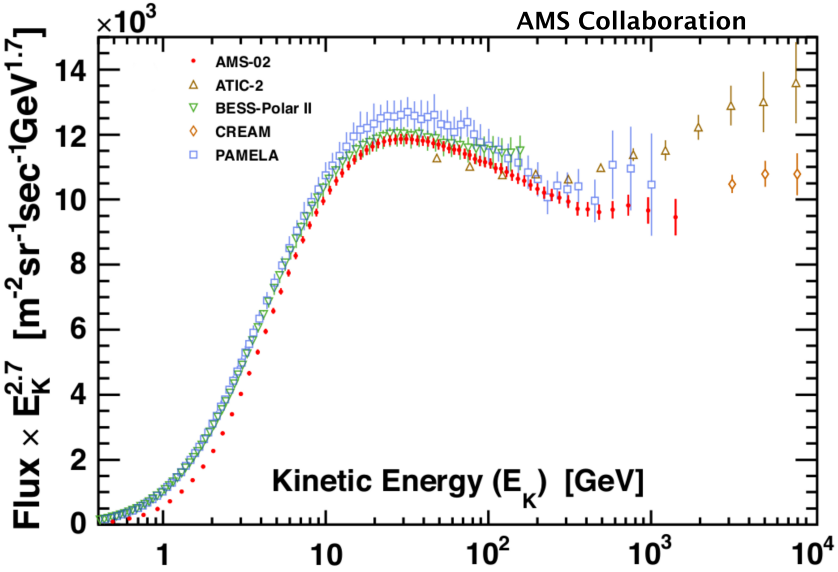
- $R_0 = 353^{+82}_{-53}$.
- $\Delta\gamma = 0.151^{+0.037}_{-0.048}$.

"No break" hypothesis rejected at 3 sigma.

AMS-02 proton analysis

Characterisation of the proton flux - Results





- MCMC approach: validation of the official fit (profile likelihood).
- Break origin: source spectrum, transport...? $\Rightarrow$ Other CR fluxes needed!

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   - What is a neutron monitor?
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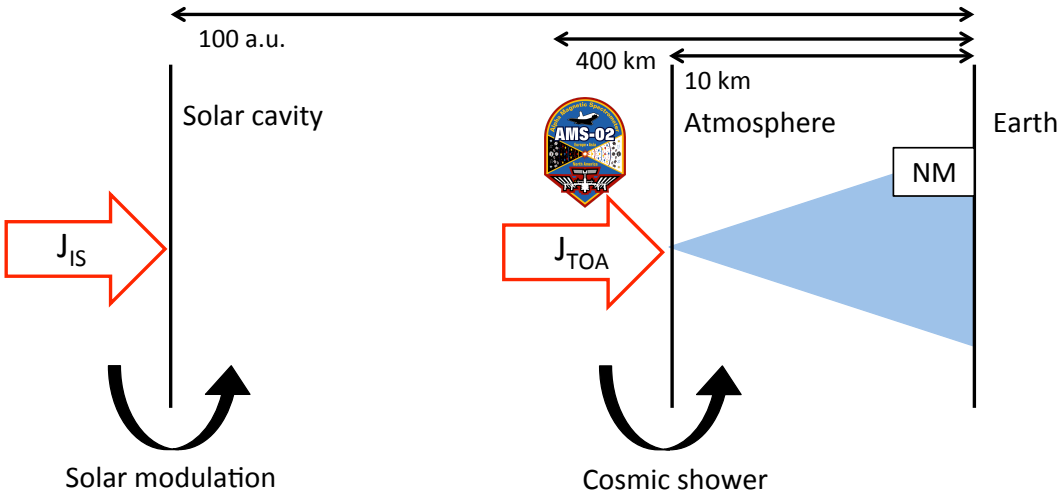
Solar modulation study

What is solar modulation?

- Interaction between solar plasma and GCR particles (MHD).
- Flux variations correlated with solar activity (11 years cycle).
- Affect all charged CR data at low energy.
- Link between J_{IS} and J_{TOA}.



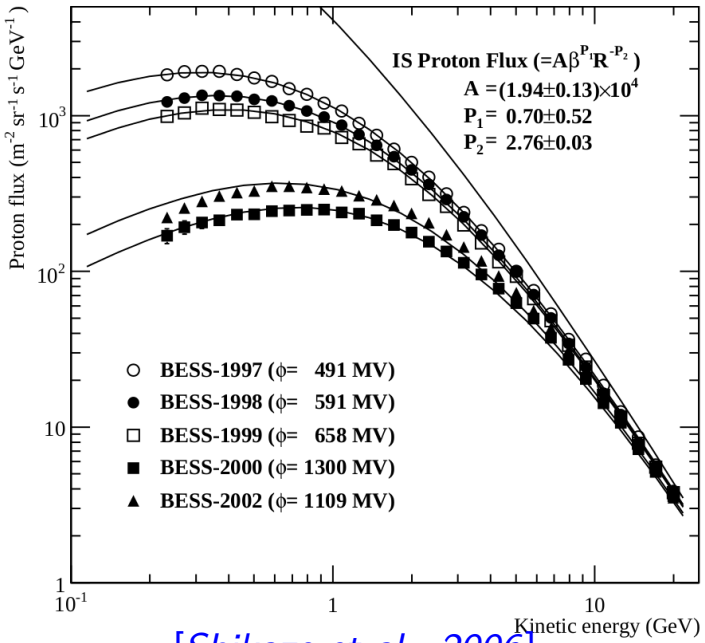
J_{IS} not directly measured.

Solar modulation study

The Force field model [*Gleeson and Axford, 1967*]

- Simple link between J_{IS} and J_{TOA}.
- One parameter $\phi(t)$, typical values between 200 MV and 1500 MV.

$$\begin{cases} E_{TOA} & = & E_{IS} - Z\phi, \\ J_{TOA}\left(E_{TOA}\right) & = & \dfrac{E_{TOA}^2 - m^2}{(E_{TOA} + Z\phi)^2 - m^2} \times J_{IS}\left(E_{TOA} + Z\phi\right). \end{cases}$$



[*Shikaze et al., 2006*]

- Reproduce well TOA data.
- Still widely used nowdays.
  $\Rightarrow \phi$ from TOA fit.

Solar modulation study

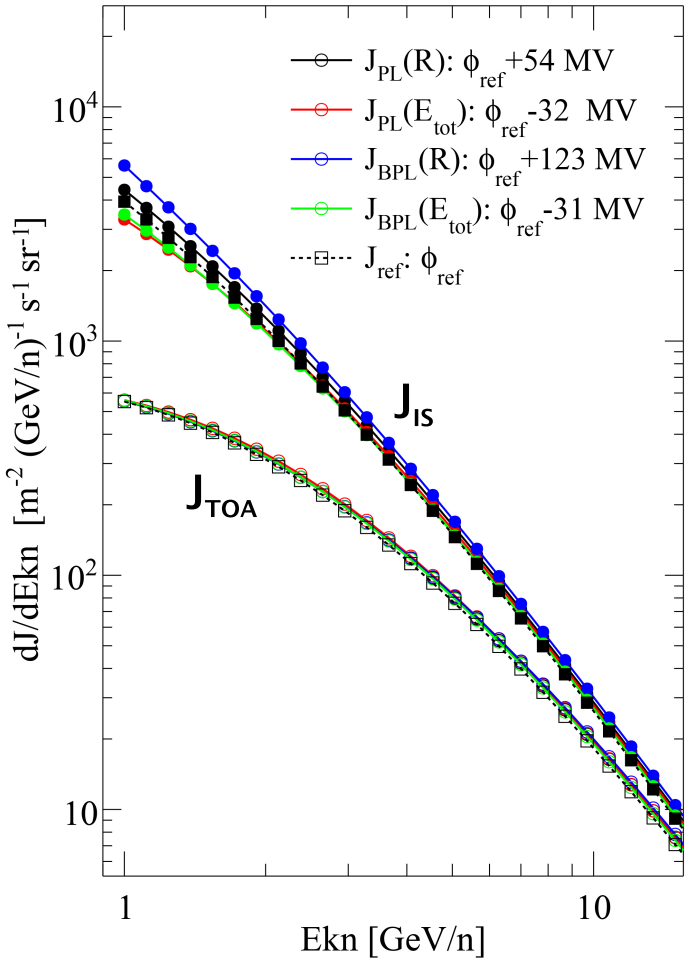
How do we reconstruct solar modulation levels? - TOA analysis

Methodology

- Assume a IS flux parametrisation.
- Choose a set of TOA data (over m time periods)$\rightarrow$ CRDB (lpsc.in2p3.fr/cosmic-rays-db).
- Fit **one** IS flux and m solar modulation parameters on the TOA data.

Issues

- J_{IS} and solar modulation ϕ highly degenerated.
- Solutions:
  $\Rightarrow$ Make simultaneous fit for different species and different time periods.
  $\Rightarrow$ Use other tracers of solar modulation.



$\Rightarrow \Delta\phi \approx 100$ MV.

Solar modulation study

What is a neutron monitor? [Simpson, Space Sci. Rev. 93 (2000) 11-32]

- Simple detectors.
  - Sensitive to neutrons from cosmic showers.
  - Continuous data taking (from 1960).
- Worldwide network.
  - Measurements at different R_c.

- Independant measurement of $\phi(t)$.
- Very fine time resolution ($\approx$ min).

Solar modulation study

How do we reconstruct solar modulation levels? - NM analysis

Methodology

$$N(\vec{r},t) = \int_{R_c}^{\infty} \sum_{i=CRs} \mathcal{Y}_i(R,h) \, \frac{dJ_i^{\mathrm{TOA}}}{dR}(R,\phi(t)) \, dR.$$

Link between J_{IS} and J_{TOA} similar to TOA analysis.

- Link between J_{IS} and J_{TOA}: Force field model.
- Link between J_{TOA} and NM count rates: **Yield function** $\mathcal{Y}$.
  - Modelisation of the earth atmosphere and the detector.

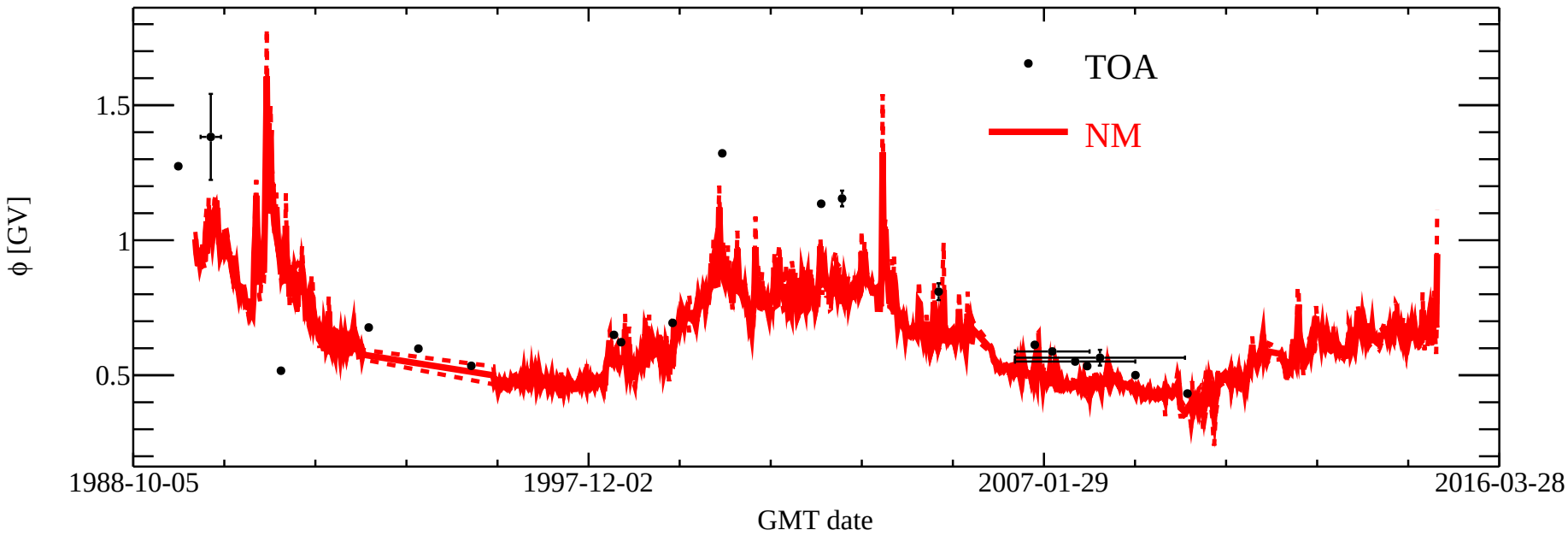
Issues

- Integrated measurement (energy and species).
- Large systematics[*Maurin et al*].
- **Solution**: Huge network of NM.

One $\phi(t)$ for each stations.

Solar modulation study

How do we reconstruct solar modulation levels? - NM analysis



Ongoing work:

- Compare $\phi(t)$ for different NM stations, yield functions, J_{IS}.
- Provide reference phi values for the CR community.
- [*Ghelfi et al*]in preparation.

Conclusion & Perspectives

Conclusion

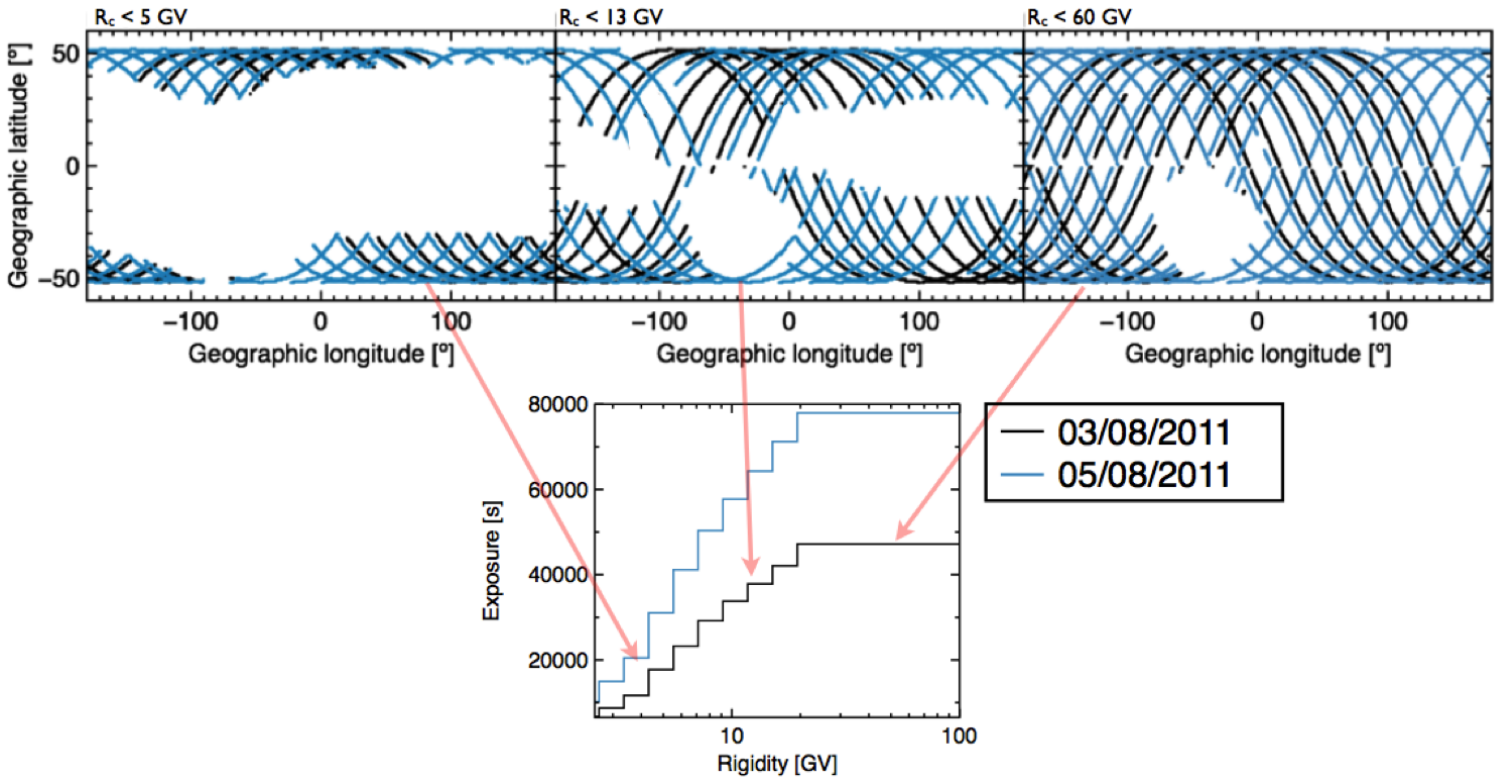
- AMS-02.
  - Involved in the Grenoble proton analysis (selected for proton flux publication).
  - Unfolding method selected as the official one.
- Solar modulation.
  - Analysis chain developped and tested for $\phi(t)$ reconstruction.
  - Coherent $\phi(t)$ over 50 years.

Perspectives

- Solar modulation.
  - $\phi(t)$ analysis with AMS-02 data (H and He analysis already done in the group).
- AMS-02.
  - Isotopic separation for the Lithium (Lithium analysis ongoing in the group).

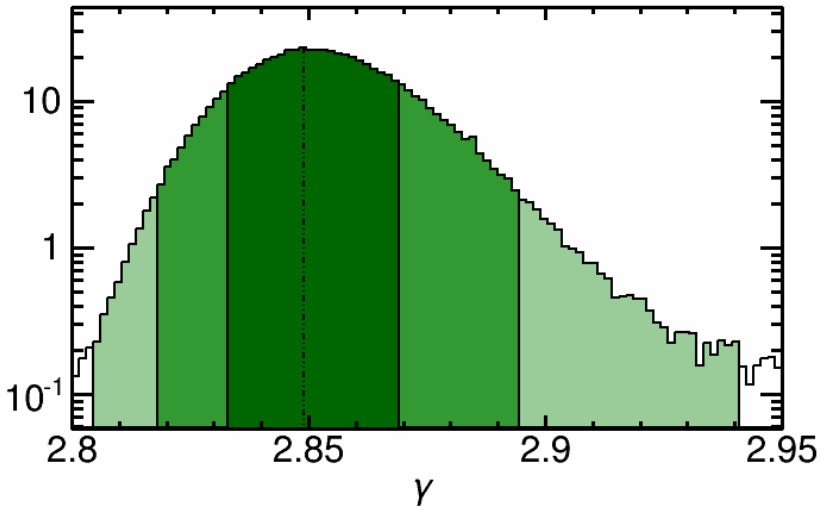
Back-up slides.

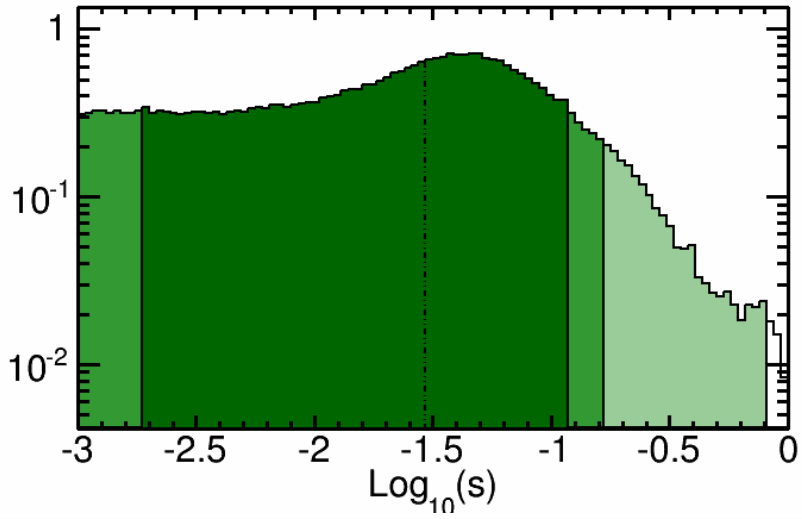
Exposure time.

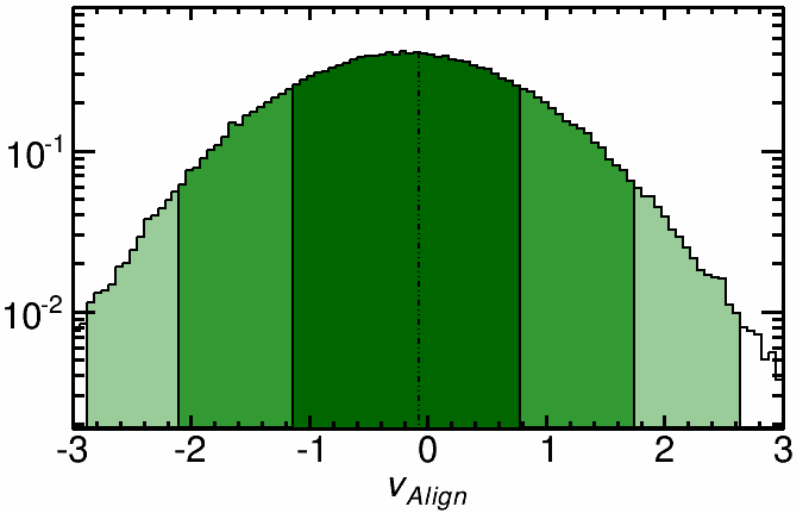


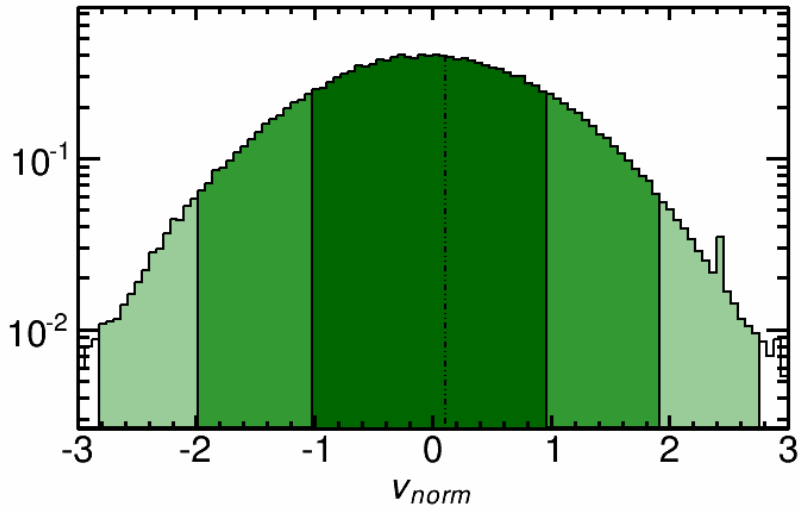
Back-up slides.

Fit parameters.









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