From Observations near the Earth
to the Local Interstellar Spectra

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Towards a unified picture of CRs production and propagation by means of GALPROP and HelMod for solar modulation:

- Astrophysical uncertainties: the MCMC approach to GALPROP v55
- Protons, Helium and Antiprotons LIS from GALPROP + HelMod synergy
- Interstellar Spectra: AMS-02 vs Voyager-1
The Propagation Scheme in the Milky Way

- **Geometry**: halo of thickness \( z \)
- **Diffusion**: diffusion in the galactic magnetic field inhomogeneities, propagating through the ISM \((D_0, \delta, R_0)\)
- **Convection**: galactic wind with velocity \( V_c \) and gradient \( dV_c/dz \)
- **Reacceleration**: interstellar turbulence with Alfvén velocity \( V_A \)
- **Sources**: SNe shocks produce power law spectra in energy \((\gamma_{1,2} \text{ indices})\)

7 fundamental parameters space to fix CR propagation + N specific injection indices

**Propagation models uncertainties**: almost two orders of magnitude, one above one below the often called in literature MED propagation values set
1. The Monte-Carlo-Markov-Chain interface to **GALPROP v55** was developed in Bologna from CosRay-MC and COSMOMC package, embedding GALPROP framework into the MCMC scheme;

2. An iterative procedure is used to sample GALPROP cosmic rays production and propagation parameters using AMS-02 data as observational constraints, exploring a very large parameter space;

3. The solar modulation is made using numerical functions based on HelMod;

4. GALPROP accuracy was tested at the % level, checking solution stability and introducing new “smoothing features”;

5. The experimental observables used in the MCMC scan include all published AMS-02 data on protons, Helium, **B/C** ratio and electrons, while positrons and antiprotons are excluded.

*Precision measurement of Boron-to-Carbon Ratio with AMS-02...*, Valerio Formato
Using AMS-02 high precision data we can easily constrain, for the first time, CR propagation and the galactic physics.

- $D_0$: diffusion coefficient
- $\delta$: diffusion coefficient index
- $z_h$: half size of the Halo
- $dv_c/dz$: convection velocity gradient
- $V_a$: Alfvén velocity
- $V_c$: convection velocity
- $R_0$: diffusion break position
CR Physics Improvements

Before AMS-02

<table>
<thead>
<tr>
<th>Unit</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z$</td>
<td>50%</td>
</tr>
<tr>
<td>$D_{0}/10^{28}$</td>
<td>100%</td>
</tr>
<tr>
<td>$\delta$</td>
<td>60%</td>
</tr>
<tr>
<td>$V_{Alfven}$</td>
<td>90%</td>
</tr>
<tr>
<td>$V_{0\text{conv}}$</td>
<td>100%</td>
</tr>
<tr>
<td>$dV_{C}/dz$</td>
<td>100%</td>
</tr>
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</table>

After AMS-02

<table>
<thead>
<tr>
<th>Error (%)</th>
<th>Improvement factor $\varepsilon_{\text{before}}/\varepsilon_{\text{after}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>10</td>
</tr>
<tr>
<td>5%</td>
<td>20</td>
</tr>
<tr>
<td>5%</td>
<td>12</td>
</tr>
<tr>
<td>7%</td>
<td>13</td>
</tr>
<tr>
<td>6%</td>
<td>16</td>
</tr>
<tr>
<td>5%</td>
<td>20</td>
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</table>

- Before AMS-02 we were not able to fix the CR propagation physics: the parameters lied in very wide ranges.
- With AMS-02 data is finally possible to achive a consistent best fit: the errors associated to the fundamental propagation parameters $z, D_{0xx}, \delta_{1,2}$ are greatly reduced.
- We still have some degeneracies/uncertainties which afflict secondaries predictions.

A factor 10-20 of improvement for fundamental parameters
Simultaneous inclusion of diffusion, convection and reacceleration is required to reproduce AMS-02 measurements.

<table>
<thead>
<tr>
<th>N</th>
<th>Parameters</th>
<th>Best Value</th>
<th>Units</th>
<th>1σ Mean Error</th>
<th>% Error</th>
<th>Scan Range</th>
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<tbody>
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<td>1</td>
<td>z</td>
<td>4.0</td>
<td>kpc</td>
<td>0.2</td>
<td>5</td>
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<td>4.3</td>
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<td>[1-10]</td>
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<tr>
<td>3</td>
<td>$\delta$</td>
<td>0.36</td>
<td>-</td>
<td>0.02</td>
<td>5</td>
<td>[0.3-0.9]</td>
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<td>4</td>
<td>$R_D$</td>
<td>4.2</td>
<td>GV</td>
<td>0.4</td>
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<td>5</td>
<td>$V_{Alfven}$</td>
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<tr>
<td>7</td>
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<td>km$\cdot$s$^{-1}$kpc$^{-1}$</td>
<td>0.5</td>
<td>5</td>
<td>[0-20]</td>
</tr>
</tbody>
</table>

Once defined a consistent parameter space, a methodical calibration employing the HelMod Model was performed, involving injection spectra and solar parameters.
Forthcoming Results:
Protons LIS
Low Solar Activity

Local Interstellar Spectrum

Differential Intensity [counts/(m^2 s sr GV)]

- GALPROP LIS
- HelMod
- AMS-01 Aguilar et al. 2002

Proton

Heliosphere Uncertainty Band

Relative difference

Rigidity [GV]

Differential Intensity [counts/(m^2 s sr GV)]

- GALPROP LIS
- HelMod
- PAMELA 12/2007 Adriani et al. 2013

Proton

Relative difference

Rigidity [GV]
Recent AMS-02 results: impressive agreement between data and HelMod-modulated LIS from GALPROP

Analytic Formula for 0.45 GV < R < 20000 GV:

\[ F(R) \cdot R^{2.7} = a + \frac{b}{R} + \frac{c}{d + R} + \frac{e}{f + R} + \frac{g}{h + R} \]
High Energy Comparison

Good agreement with CREAM-I
Helium LIS
Low Solar Activity

![Graphs showing differential intensity of Helium over rigidity with comparison to models and measurements.](image)

- **GALPROP LIS**
- **HelMod**
- **BESS07 Abe et al. 2016**

![Graphs showing relative difference over rigidity.](image)

- **PAMELA Adriani et al. 2011.**
Recent AMS-02 results: impressive agreement between data and HelMod-modulated LIS from GALPROP

Analytic Formula for 1.5 GV < R< 20000 GV:

\[ F(R) \cdot R^{2.7} = a + b \cdot R + \frac{c}{R} + \frac{d}{e+R} + \frac{f}{g+R} + \frac{h}{k+R} \]
High Energy Comparison

Compatible with CREAM-I

![Graph showing high energy comparison with CREAM-I]
Antiproton LIS
The overall antiproton shape for both PAMELA and BESS is well reproduced over the whole rigidity range.
High Solar Activity

The Antiproton LIS is substantially compatible with AMS-02.

Tiny discrepancies w.r.t. AMS-02 high precision data could be due to:

• residual astrophysical uncertainties
• nuclear cross section uncertainties
• peculiar propagation effects or variation of primary p and He spectra in the Galaxy
Ultra-low energy physics
AMS – Voyager1 interplay

Voyager 1 in the interstellar space

Voyager 1 131.0 AU
19.7 billion km

Voyager 2 107.7 AU
16.2 billion km
~2 years to interstellar space?

Launched in 1977!

First interstellar probe!
Will operate until 2026

Simulated proton and He LISs have been successfully compared to Voyager1
The means of six months data; the error associated to each point is chosen as the variation of the monthly measured point.
The LISs show a good agreement with Voyager-1 data:

- Helium perfectly reproduces the shape of the interstellar measurements
- Protons fit Voyager-1 very well, in particular in the region above 100-200 MeV

Low energy physics effects at this scale are not included nor calibrated in GALPROP, so this overall agreement is very encouraging and susceptible to future improvements.
A new era for astroparticle physics

- AMS-02 data allow a deeper understanding of the «High Energy Universe» and do put the models to the test, highlighting theoretical inaccuracies and driving the models to a precision astroparticle physics;

- Fitting AMS-02 data with the ultimate GALPROP framework together with the HelMod Model of Heliosphere, a precise and almost univocal propagation scheme was achieved, granting a unitary description of CR physics at the 1-2 % level for protons and Helium;

- Once fixed the CR propagation parameters, the secondary background for DM (and exotic) searches can be removed;

- The proposed LISs accommodate both the very low energy interstellar CR spectra measured by Voyager 1 and the high energy observations at Earth publicly released by BESS, Pamela, AMS-01 and AMS-02;

- Forthcoming papers will be devoted to the description of electrons and positrons LISs, Boron over Carbon ratio and Boron, Carbon and Oxygen spectra, when available from AMS-02.
backup
The overall antiproton shape for both PAMELA and BESS is well reproduced over the whole rigidity range.
Once modulated, the LISs correctly reproduce AMS-02 (and also PAMELA, BESS, AMS-01...)

AMS – Voyager1 interplay

Simulated proton and He LISs have been compared to Voyager1
Results: Spectra and Ratios Fits @ % level