Antiprotons in the Galaxy and at colliders: perspectives from AMS02-AMBER interplay

Nicolò Masi – 13/02/2023 EMMI Workshop

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ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

The astroparticle perspective: explaining $Z \leq 28$ CRs physics by means of GALPROP and HelMod

- Thanks to AMS-02 high precision data we can constrain CRs production and propagation **at the % level**;

- AMS-02 published data are fitted in the combined framework of GALPROP and HelMod (for Galactic and Heliosphere propagation, respectively) **with a single model**, capable of reproducing all primary and secondary spectra at the same time time (see ApJ 840:115 No 2, 2017; ApJ 854:94 No 2, 2018; ApJ 858:61 No 1, 2018; ApJ 889:167, 2020; ApJS 250 27, 2020; ApJ 913 5, 2021; ApJ 925 108, 2022; ApJ 933 147, 2022);

- The proposed local interstellar spectra fit Voyager 1, ACE, Pamela, AMS-02 (and many other experiments) and recent CALET and DAMPE data, from 10 MeV/n up to 200 TeV/n, representing a **reference model for AMS-02 collaboration** and a **forecasting tool for astroparticle and solar physics;**

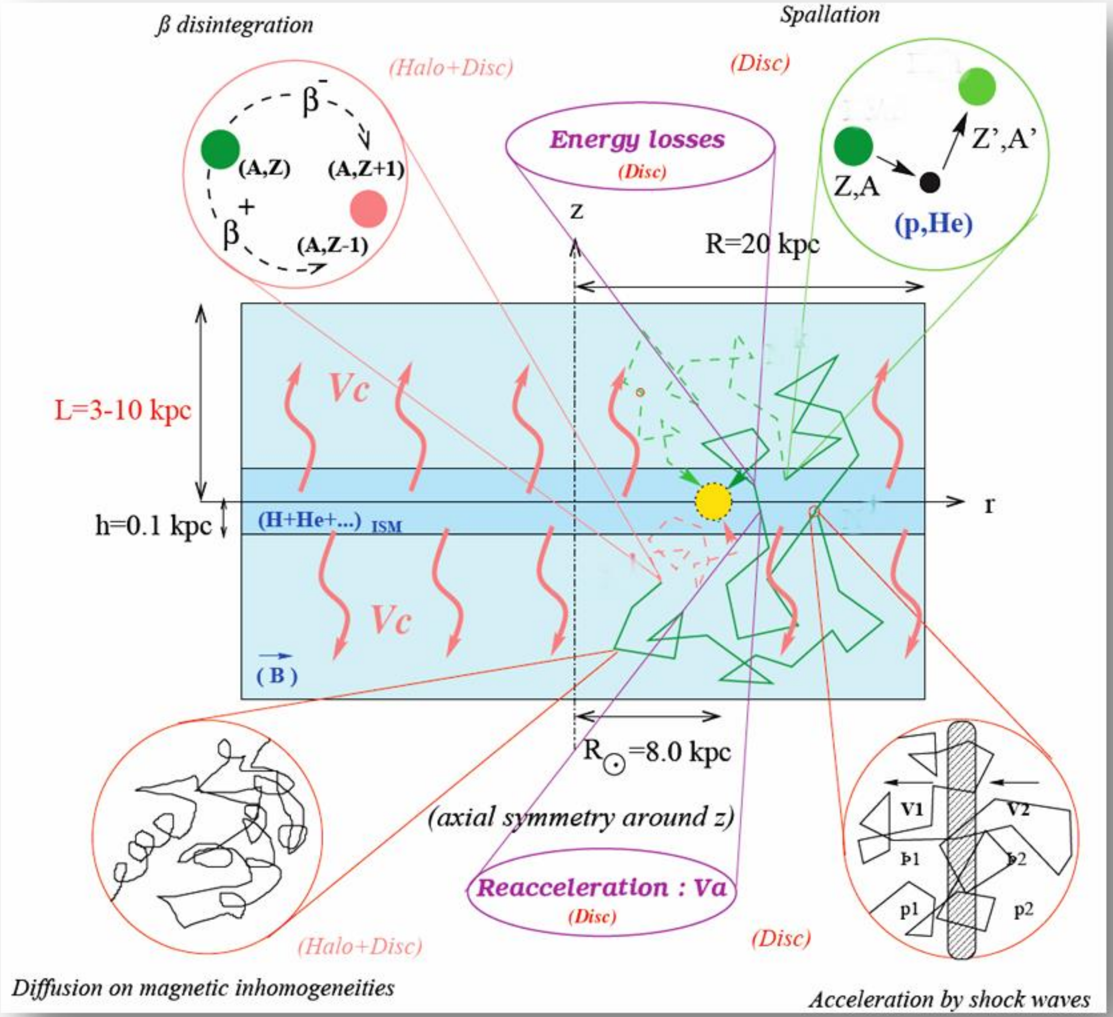
- The overall model has a strong **prediction capability** for what concerns the resulting cosmic rays **antimatter content**, especially antiprotons.

The Propagation Scheme in the Milky Way

Diffusion · Reacceleration · Energy Loss in ISM · Fragmentation

$$\frac{\partial \psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Source · Convection · Adiabatic Expansion · Decay

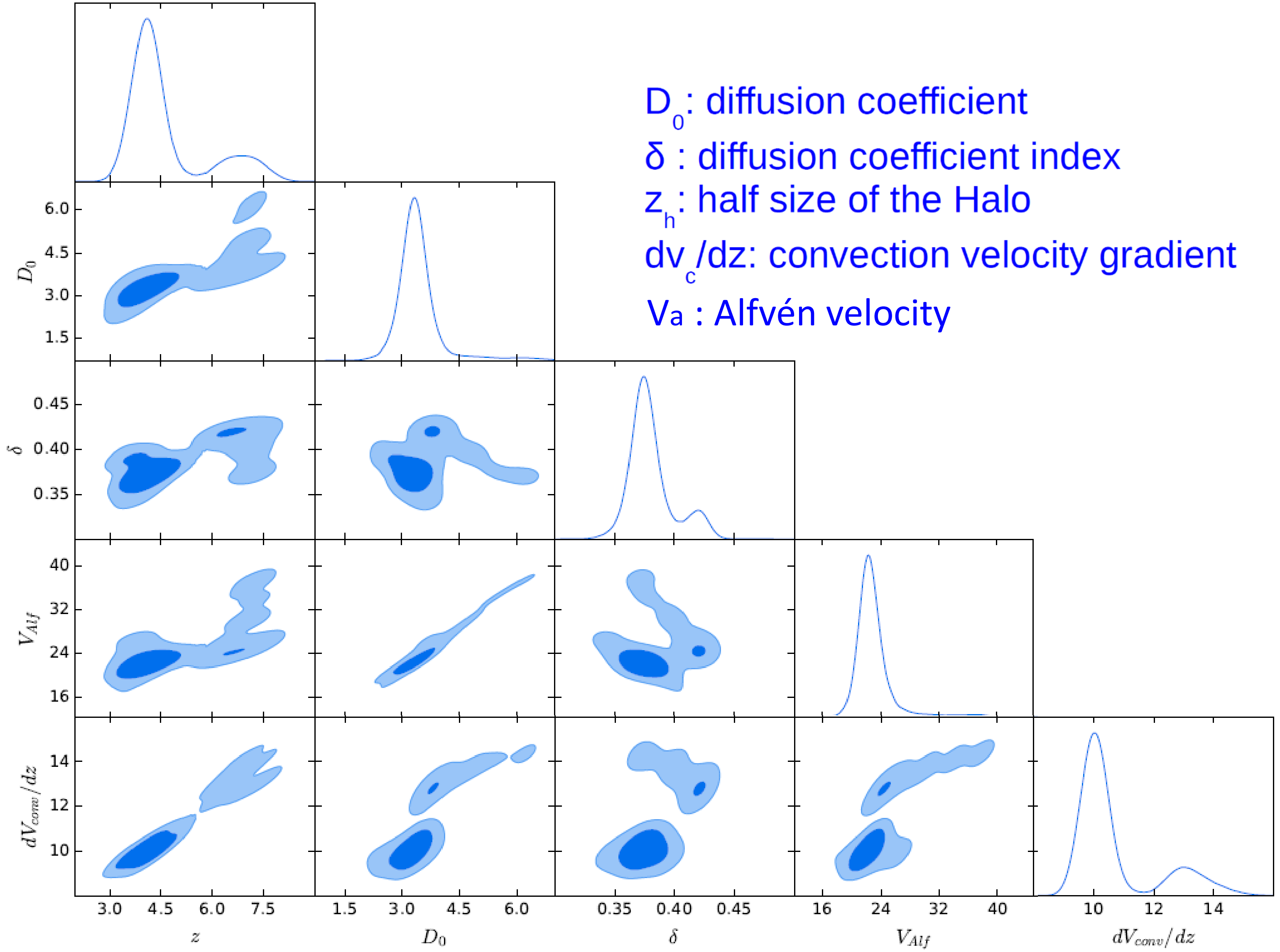


- **Geometry**: halo of thickness z
- **Diffusion**: diffusion in the galactic magnetic field inhomogeneities, propagating through the ISM (D_0, δ)
- **Convection**: galactic wind with velocity gradient dV_c/dz
- **Reacceleration**: interstellar turbulence with Alfvén velocity V_A

→ 5 fundamental parameters space to fix CR propagation

MCMC Matrix Approach

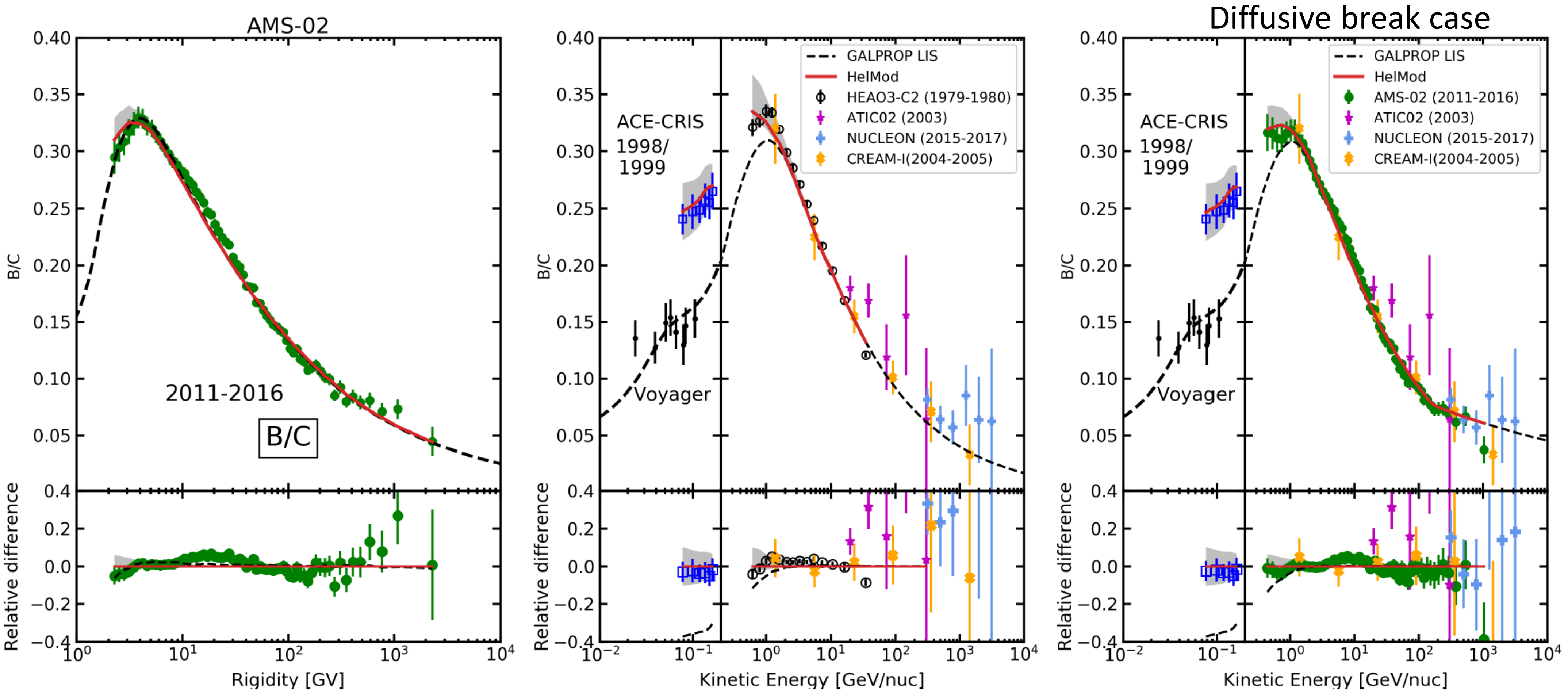
M. Boschini, S. della Torre, N. Masi, I. Moskalenko, L. Quadrani, P.G. Rancoita *et al.*,
Solution Of Heliospheric Propagation: Unveiling The Local Interstellar Spectra Of Cosmic Ray Species,
The Astrophysical Journal **840**:115 No 2, 2017, arXiv:1704.06337



1. The Monte-Carlo-Markov-Chain interface to **GALPROP v56** was **developed in Bologna** from CosRay-MC and COSMOMC package, embedding GALPROP framework into the MCMC scheme;
2. The simulations run on Ravenna pc farm;
3. The solar modulation is made using **HelMod**;
4. The experimental observables used in the MCMC scan include **all primary CRs AMS-02 data and B/C ratio, not the secondaries produced by spallation**

One order of magnitude of improvement for fundamental parameters uncertainties

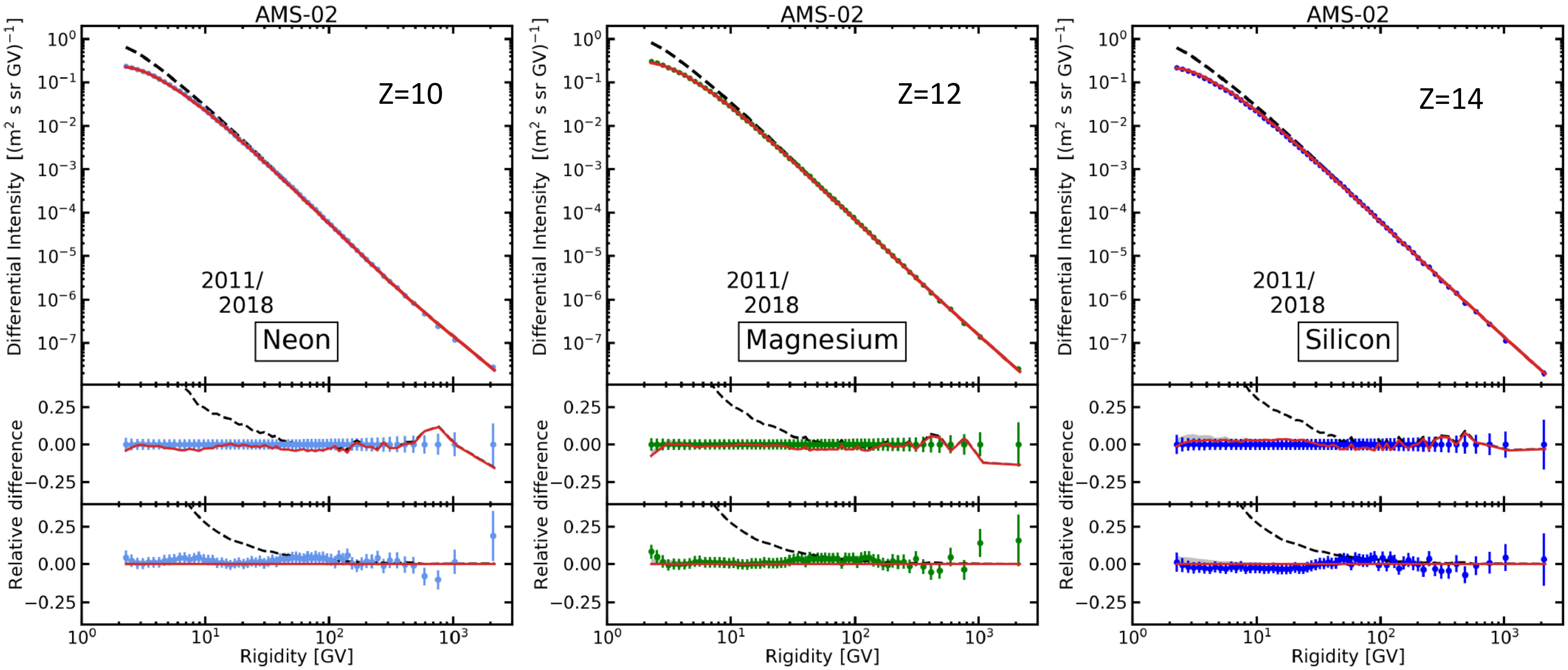
Updated secondary over primary ratio: B/C



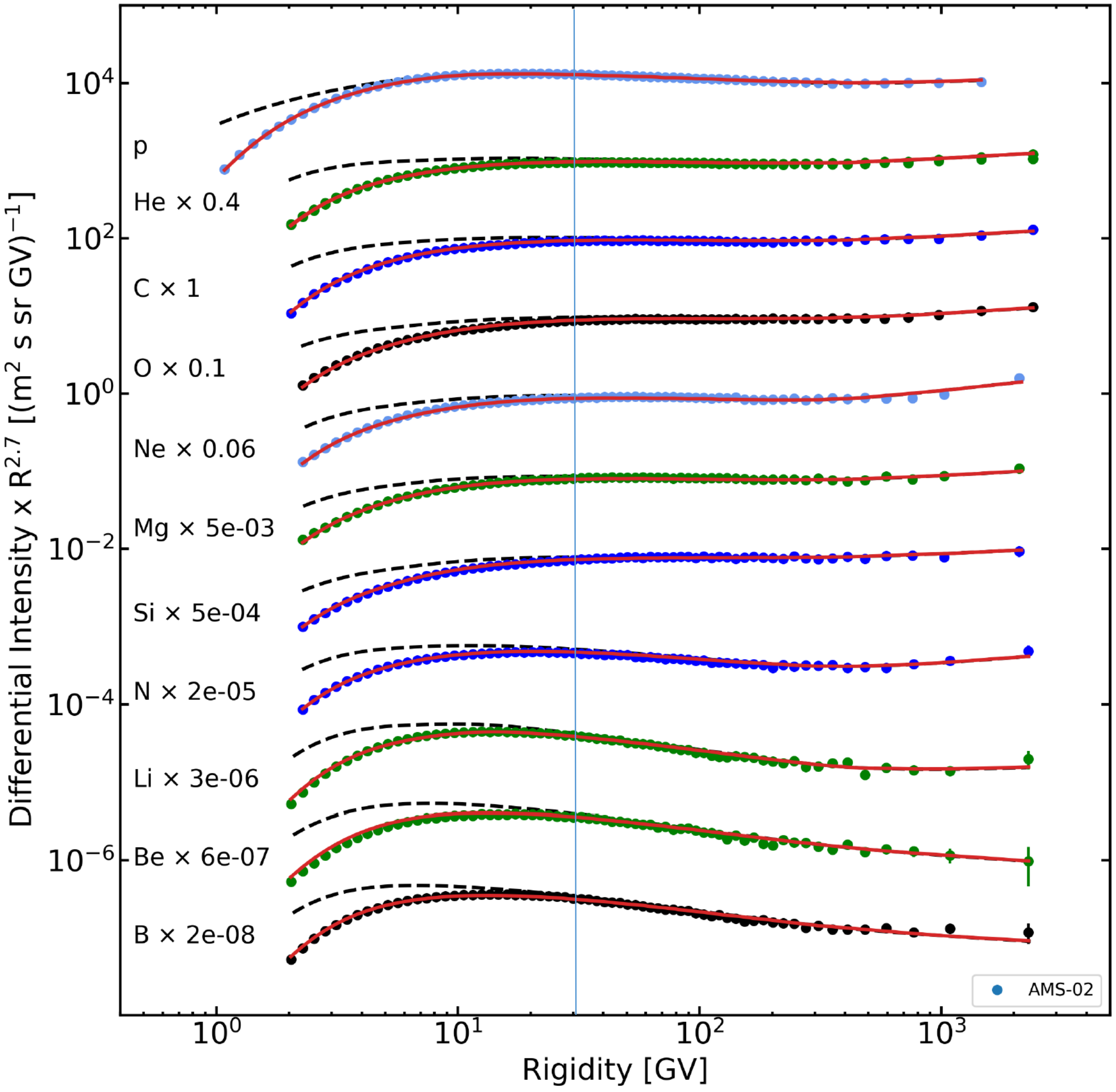
- We can deduce from B/C the **diffusion features**. The B/C ratio does not rise at high energies: **hadrons SNRs reacceleration models in the Galaxy are ill-favored.**
- **The antiproton channel for DM indirect search will represent the most significant signal of new particle physics**, cleaner and clearer than the leptonic one, which can be mimicked by pulsars.

AMS-02 Z>8 Nuclei

AMS-02 data from PHYSICAL REVIEW LETTERS **124**, 211102 (2020)



Per cent/few per cent level precision

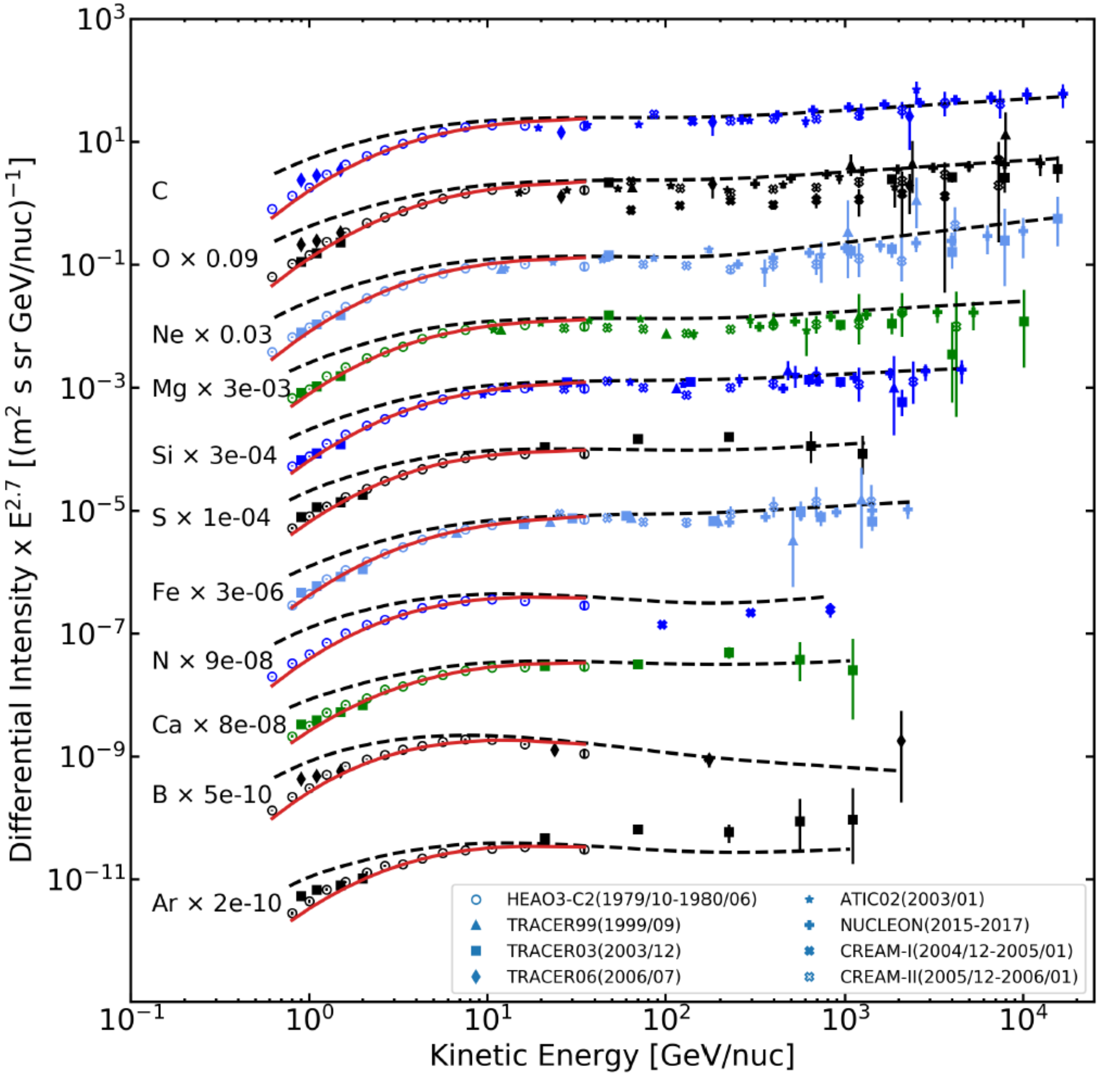


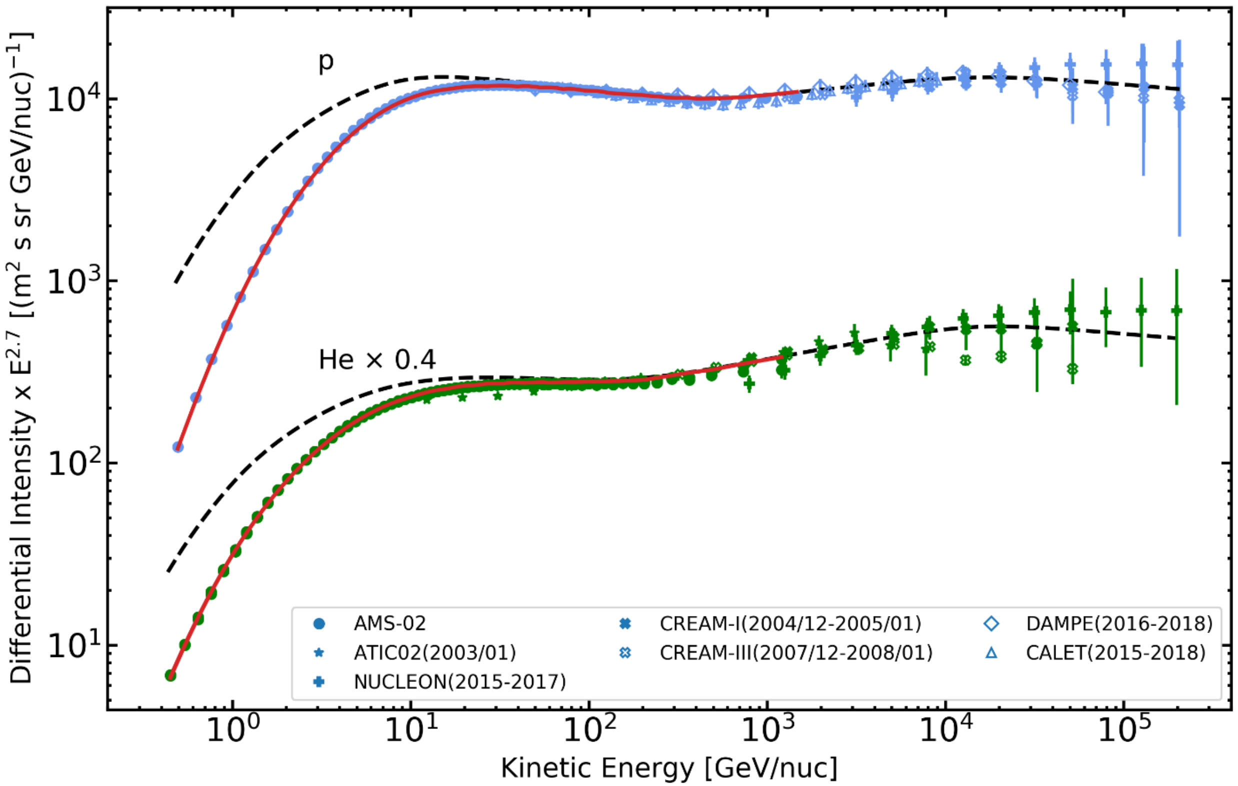
N	Parameter	Units	Best Value	Error
1	z_h	kpc	4.0	0.6
2	D_0	10^{28} cm^2 s^{-1}	4.3	0.7
3[a]	δ_1		0.415	0.025
4	V_{Alf}	km s^{-1}	30	3
5	dV_{conv}/dz	km s^{-1} kpc^{-1}	9.8	0.8

[a] For the *P*-scenario : $\delta_2 = 0.15 \pm 0.03$ for $R \geq 370 \pm 25$ GV.

The Model confirms its prediction capability for all AMS-02 species with a single set of parameters

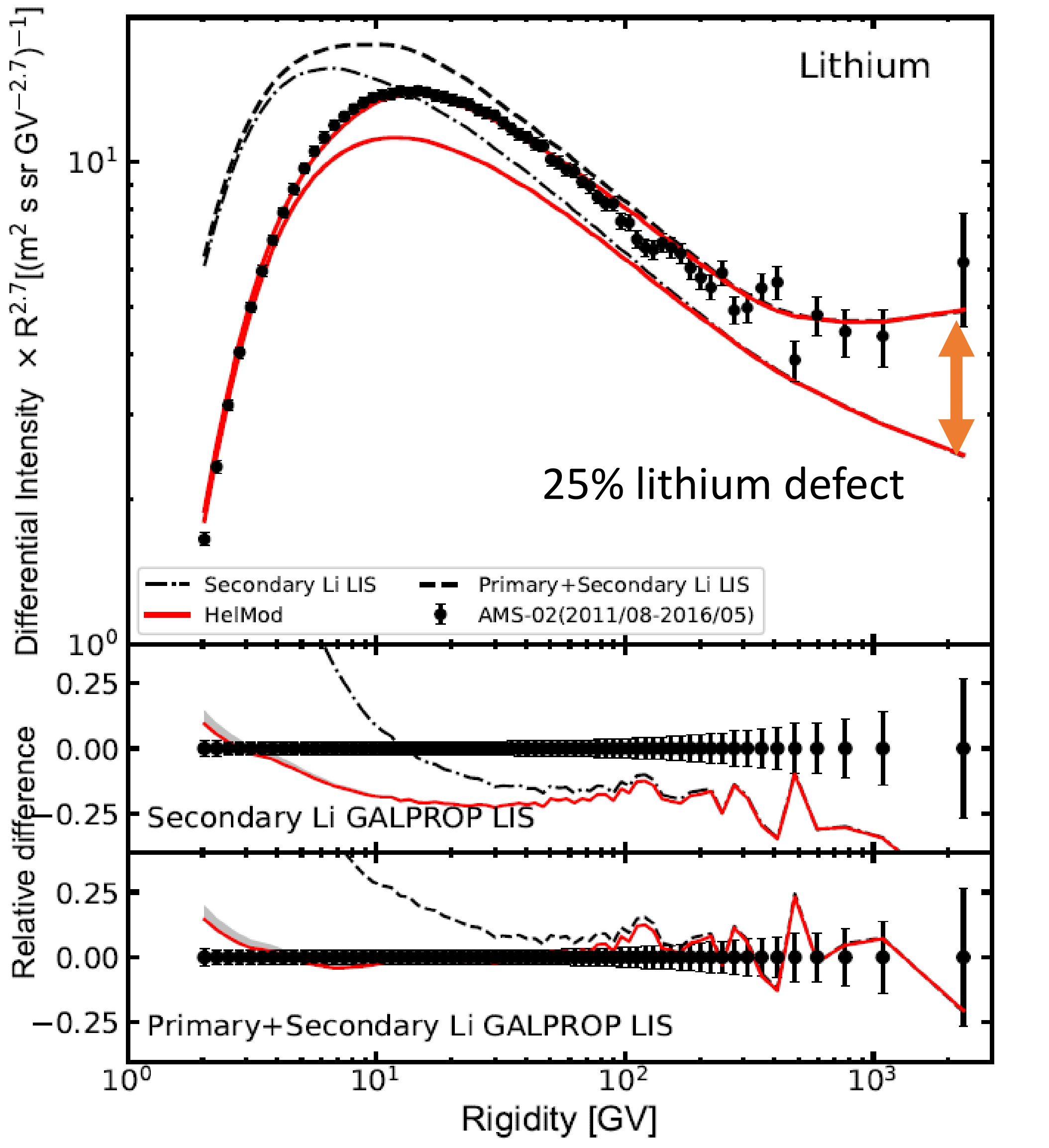
LISs validity is extended up to tens (and hundreds) TeV/n





Primary Lithium: cross section vs astrophysical sources

Boschini *et al* ApJ **889**:167 2020



Li isotopes main production channels (from C and O) are well-constrained and a 20% nuclear error in one of them would correspond to only 2%–3% correction.
It is rather unlikely that cross-section errors are all biased on the same side leading to the observed 25% excess.

Primary ^{7}Li through the Cameron-Fowler mechanism for intermediate-mass AGB (asymptotic giant branch) stars and Novae:

alpha-capture ^{3}He(α,γ) ^{7}Be

transport of ^{7}Be into cooler layers

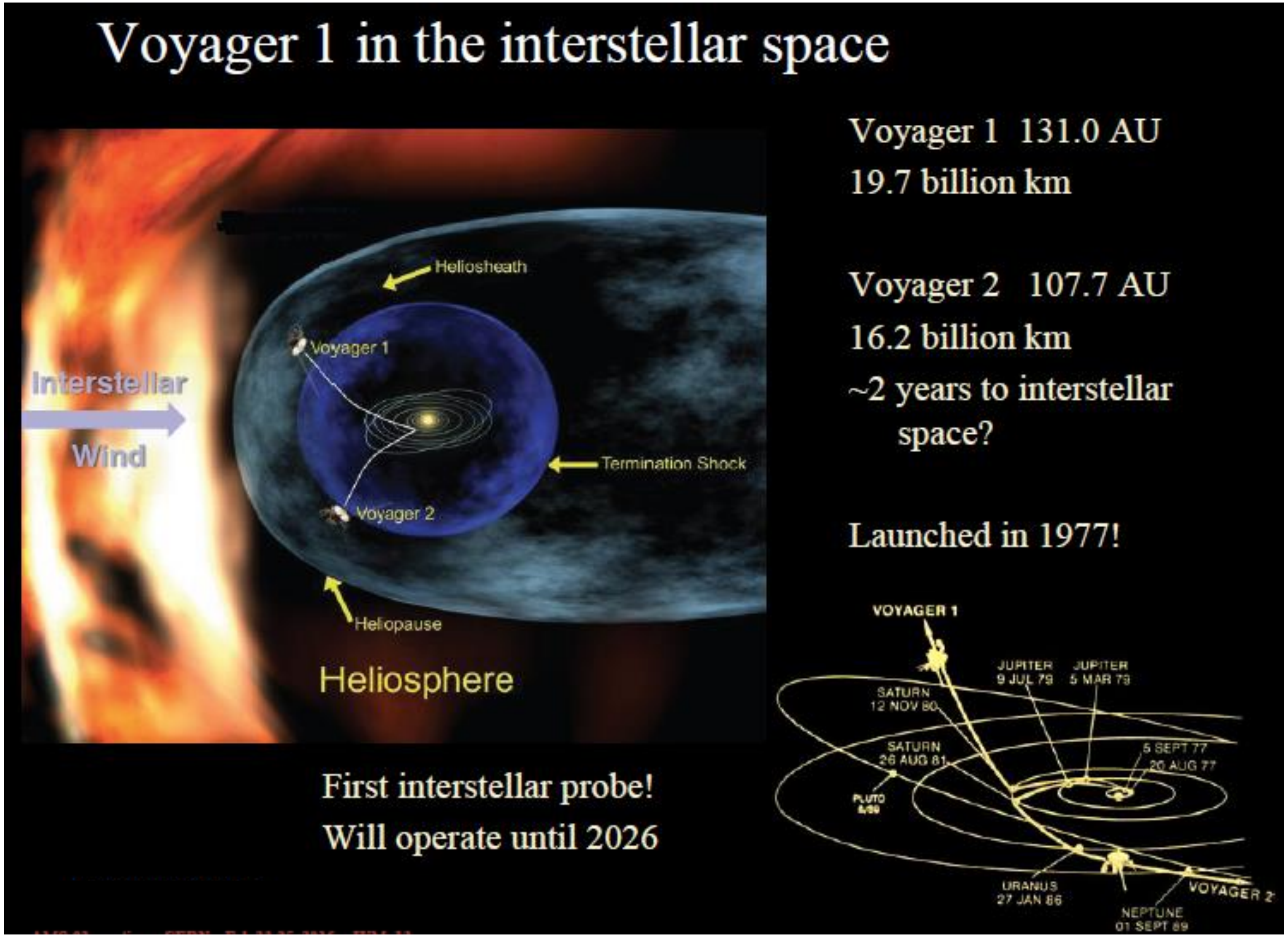
^{7}Be decay (53.22 days) → ^{7}Li

- **Observation of blue-shifted absorption lines of partly ionized ^{7}Be in the spectrum of a classical nova V339 Del** about 40-50 days after the explosion is the first observational evidence that the mechanism proposed in 1970s is working indeed

- **Consequent observations of other stars** (V1369 Cen, V5668 Sgr and V2944 Oph, ASASSN-16kt [V407 Lupi], V838 Her) **also reveal the presence of ^{7}Be lines**

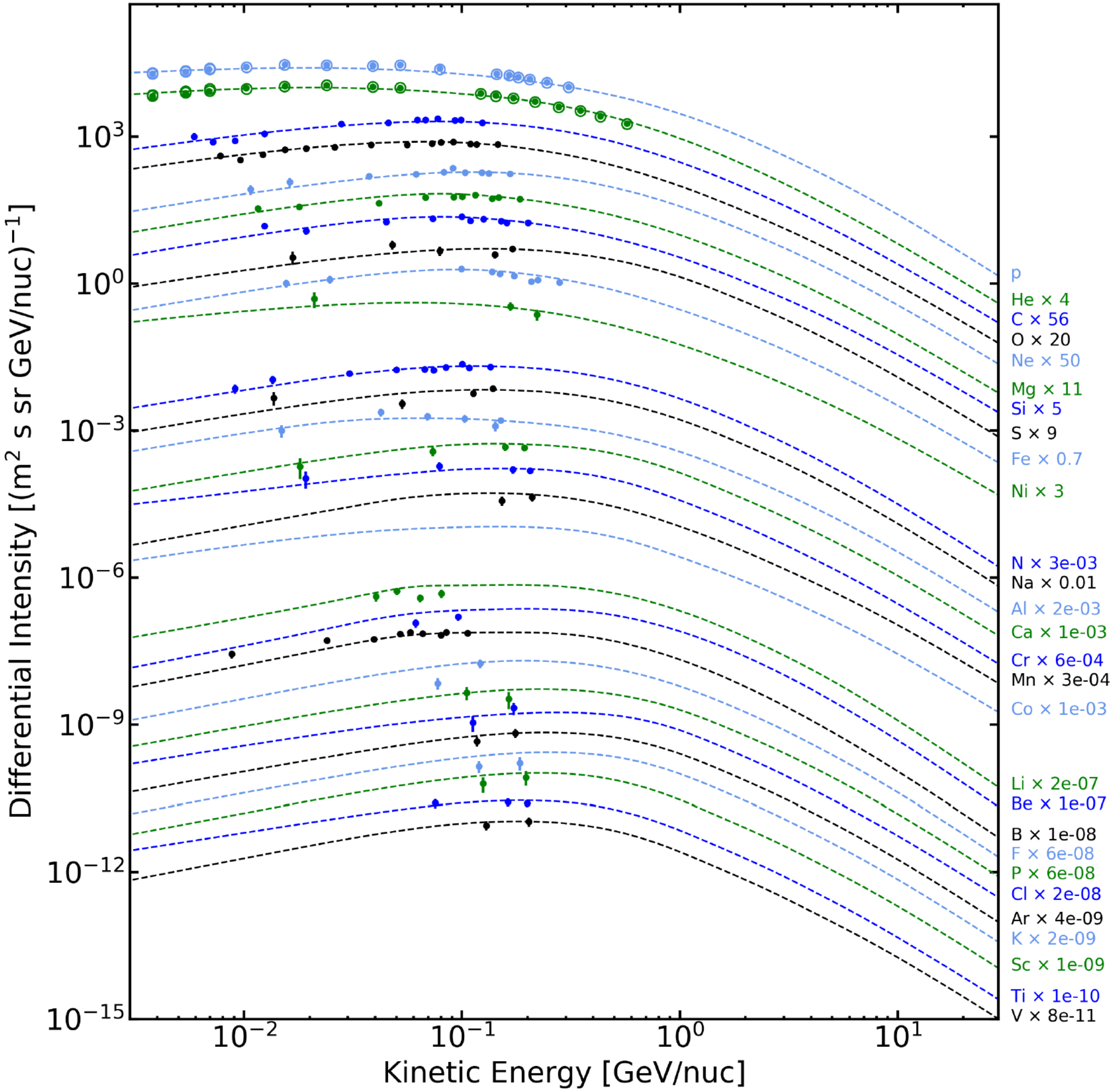
- **Primary Lithium from new stars processes is mandatory to explain AMS-02 measurement**

AMS – Voyager1 interplay



Simulated proton and He LISs have been successfully compared to Voyager1

Interstellar spectra measured by Voyager-1



All Z ≤ 28 are well reproduced

Our website provides numerical LISs, analytical formulas and plots

Website Search

Search ...

HelMod Long Write Up

- The HelMod Model
- HelMod Heliosphere
- Heliospheric boundaries in HelMod
- Heliospheric Magnetic Field
- Diffusion Parameter
- Diffusion tensor
- Monte Carlo Integration
- Current and Historical Values of default parameters
- Interpolation Functions for Local Interstellar Spectra
- HelMod Results
- HelMod Forecasting

HelMod Web Calculators

- Mission Integrated Differential Intensity and Forecast
- Stand-Alone Module (offline)

News

Updated Offline Archives to v4.1

released 4.1 version

Related Link

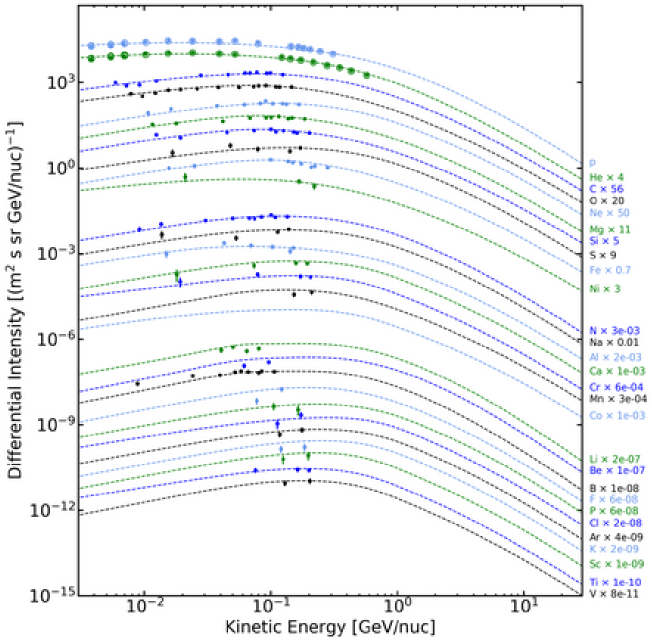
- GALPROP
- Wilcox Solar Observatory
- SILSO
- OMNIWeb
- Geomagsphere
- SR-NIEL web calculator
- SR-NIEL physics handbook
- ASIF - ASI Supported Irradiation Facilities

Local Interstellar Spectra from Galprop-HelMod join effort

By exploiting experimental results, the combined effort of the physicists involved with the Galprop model for propagation in galaxy and HelMod for the propagation in heliosphere, the local interstellar spectra (LIS) for Galactic Cosmic Rays species up to Z=28 (Nickel) were derived. These spectra are available and accessible from the current webpage.

Selected LIS: 26: Iron

Some of the currently available LIS's were derived accounting for AMS-02 data published up to TV rigidity region. The exploitation of AMS-02 data allowed one to approach the procedure with high statistic data of unprecedent accuracy. Currently, the observation data at Earth on cosmic rays species from HEAO3-C2 (from october 1979 to June 1980) and AMS-02 were employed for absolute scale normalization of fluxes (see Sects. 3-3.2 in Boschini et al. 2020).

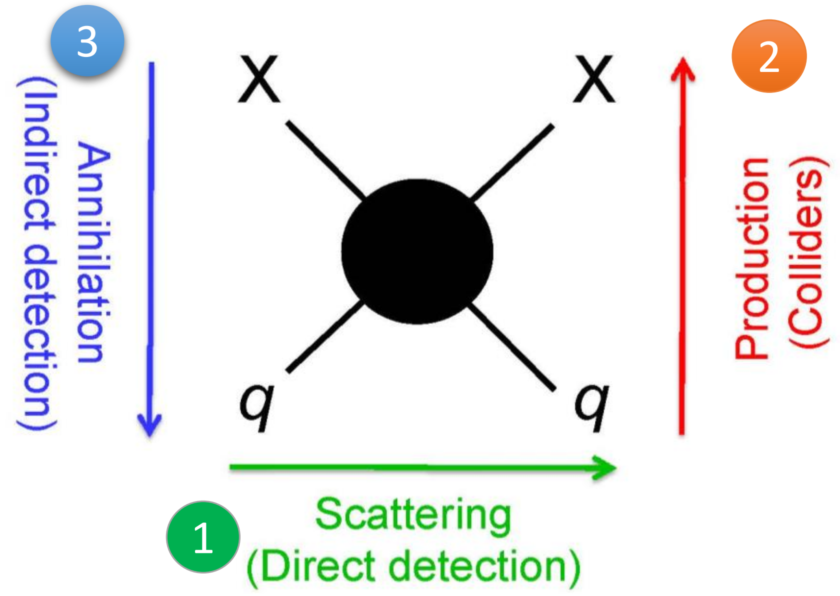


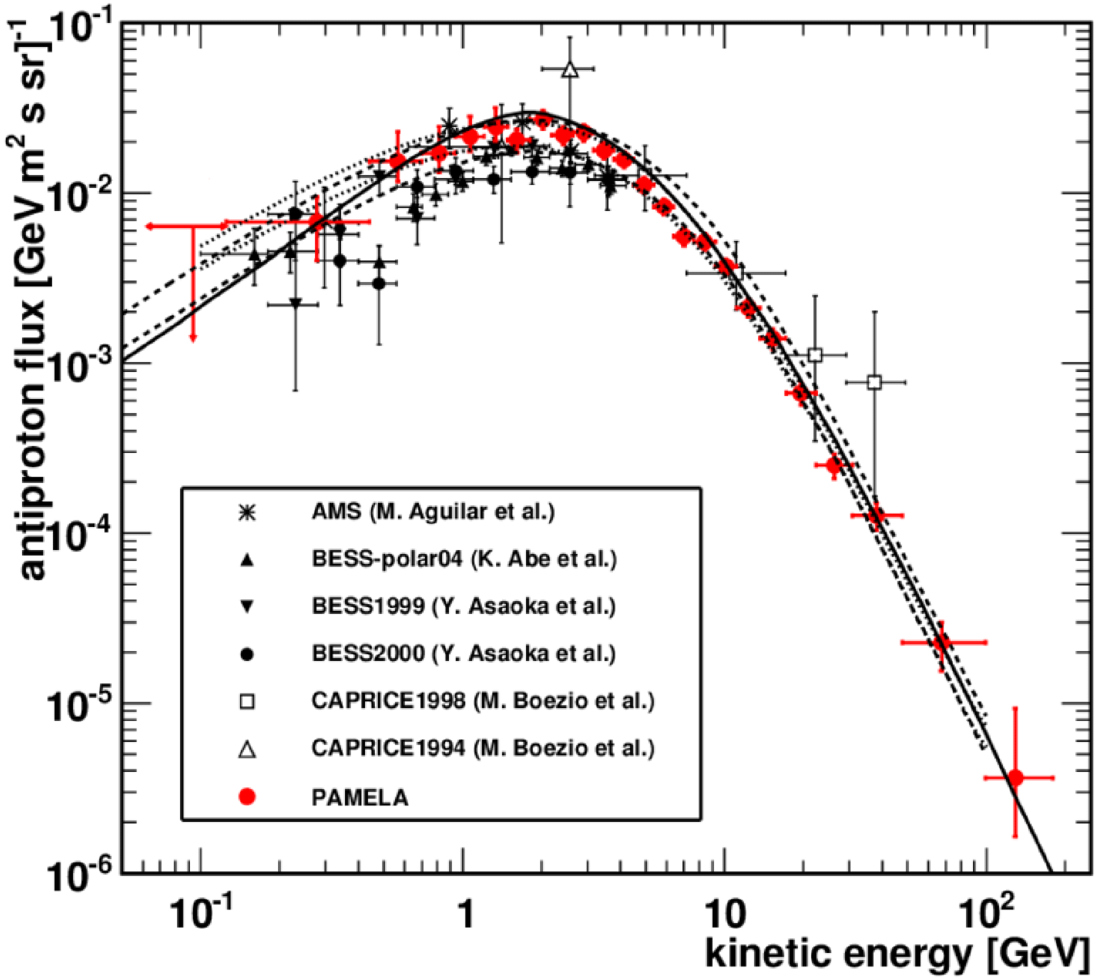
The GALPROP LIS for all CR species (dashed lines) are compared to the Voyager 1 data (filled circles, Cummings et al 2016). We also show updated Voyager 1 data for H and He (open circles) taken from September 1, 2012 to November 13, 2019. The elements are sorted by approximate amount of primary contribution: first group is mostly primary, second – with significant primary contribution, and third – mostly secondary.

LISs will be futher fine-tuned and updated on the website using incoming AMS-02 measurements

...Antimatter and isotopes measurements: we are touching the «cross section wall», where astroparticle measurements are too precise w.r.t. theory and the possibility of new discoveries lies in nuclear physics accuracy

How to detect Dark Matter

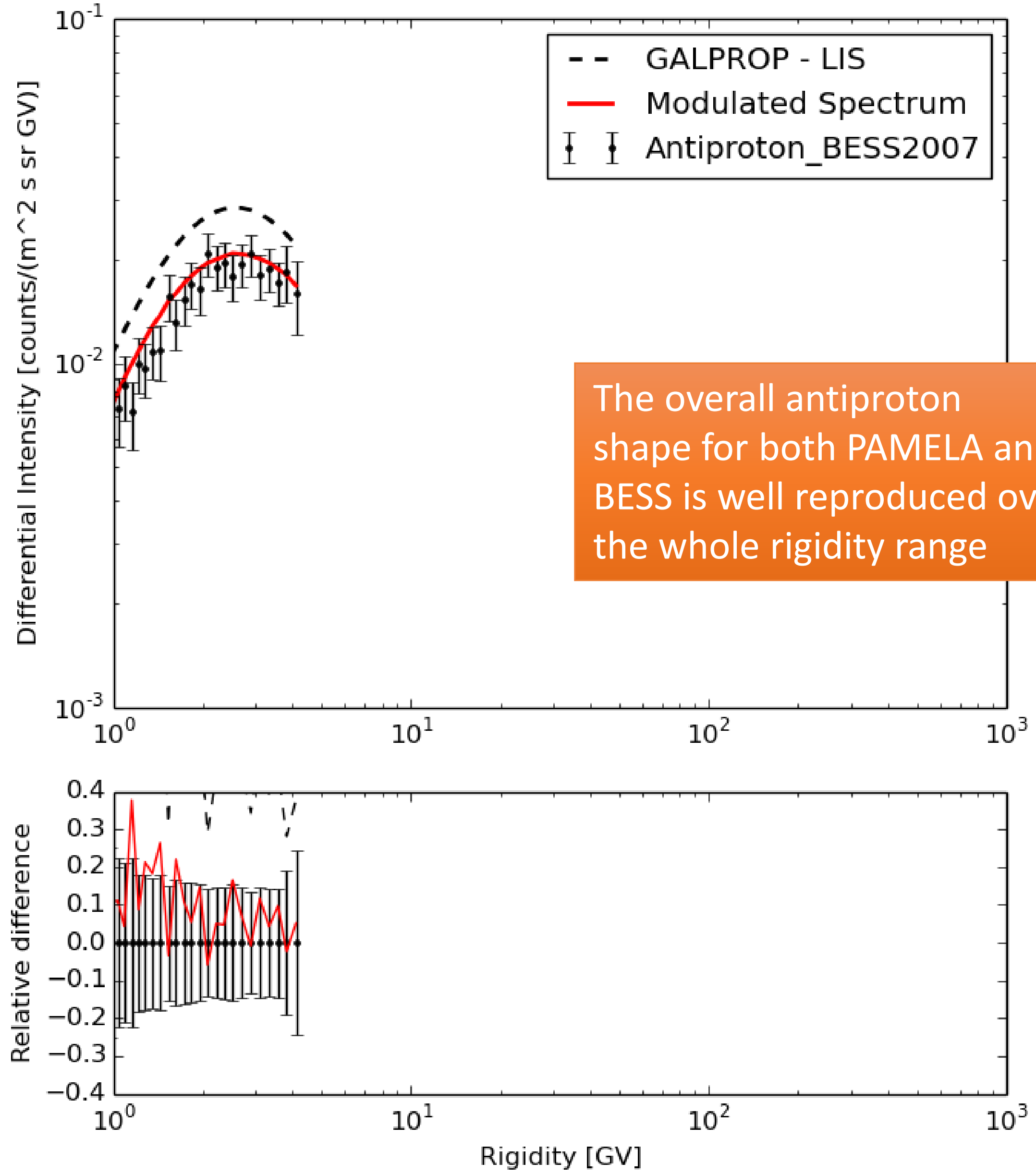




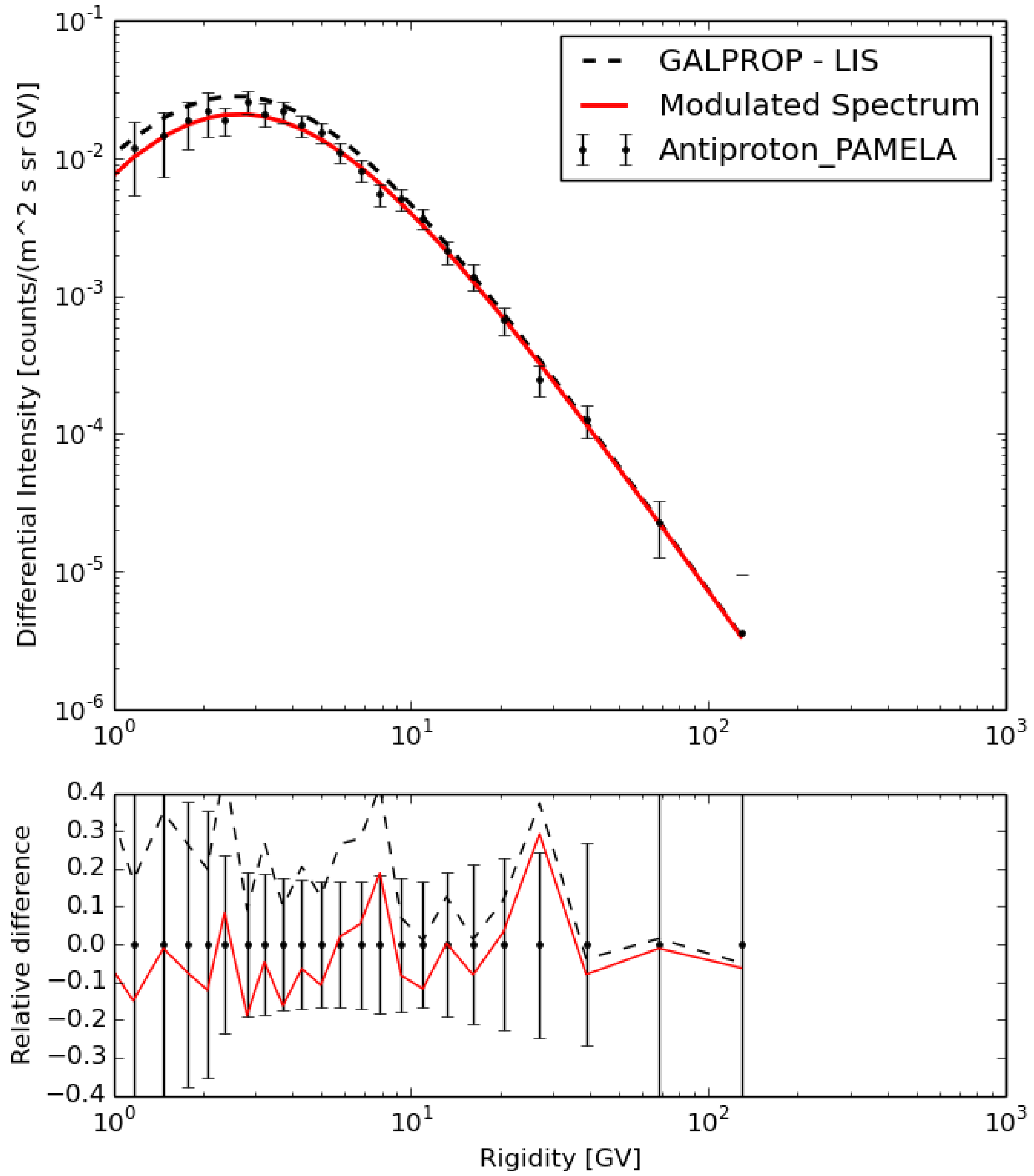
<u>Indirect Cosmic Rays Anomalies</u>:

WIMP-like Dark Matter self-annihilates in the galactic halo and injects into CRs detectable products: $\gamma, \nu, e^+, \bar{p}, \bar{d}$. They progate in the Milky Way, according to a Standard Model, and arrive at the top of Earth atmosphere, where they can be detected by space experiment, such as FERMI, PAMELA, AMS-02, DAMPE, CALET…

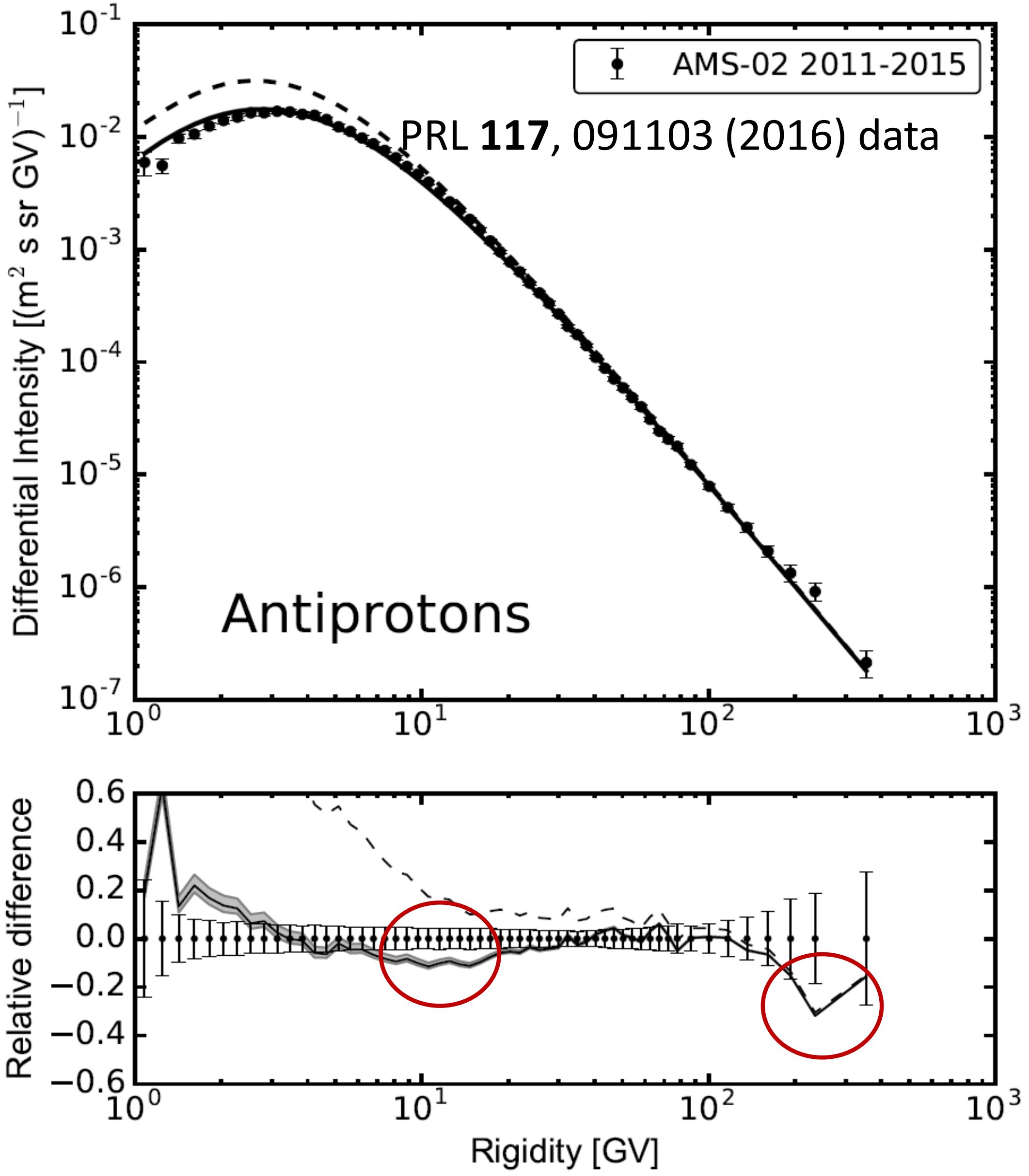
Low Solar Activity Antiprotons



The overall antiproton shape for both PAMELA and BESS is well reproduced over the whole rigidity range



Antiprotons



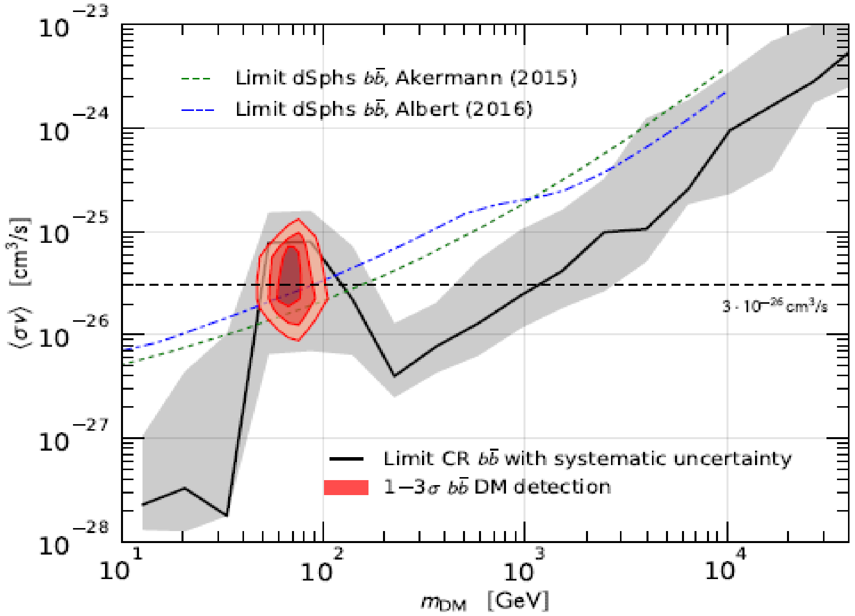
The Antiproton LIS is substantially compatible with AMS-02 within 2σ

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

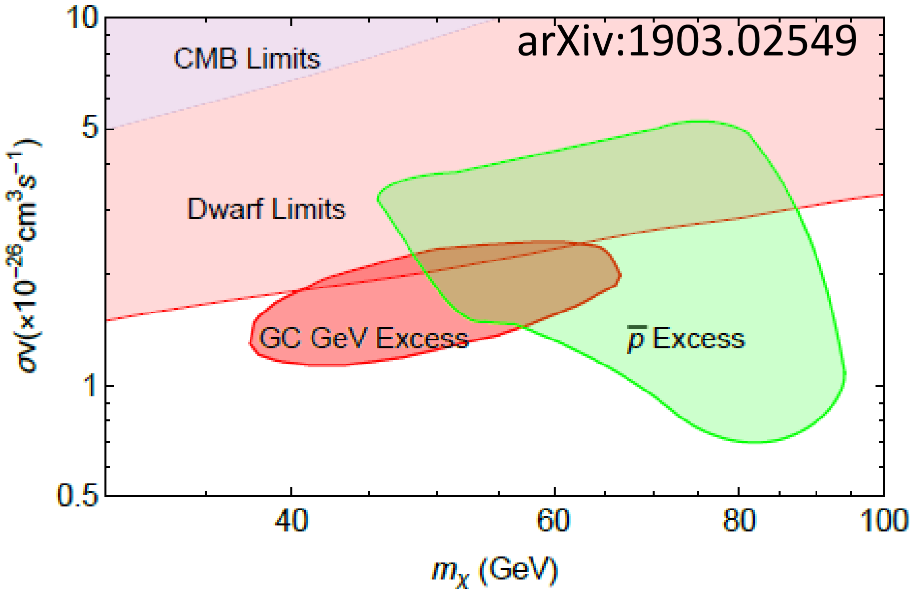
- nuclear cross section uncertainties
- peculiar propagation effects or variation of primary p and He spectra in the Galaxy
- eventually, DM annihilation in the galactic halo (40-90 GeV or 200-400 GeV mass DM)

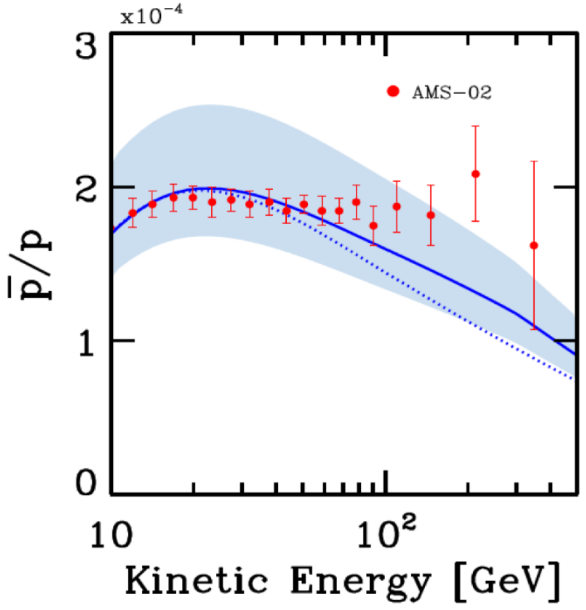
ApJ 840:115 No 2, 2017

Low energy DM candidates



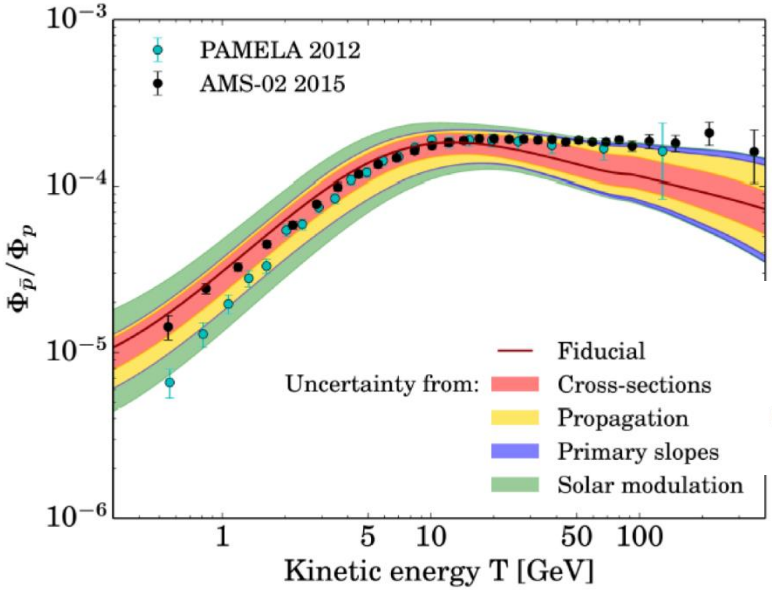
Phys. Rev. Lett. **118**, 191102 (2017)





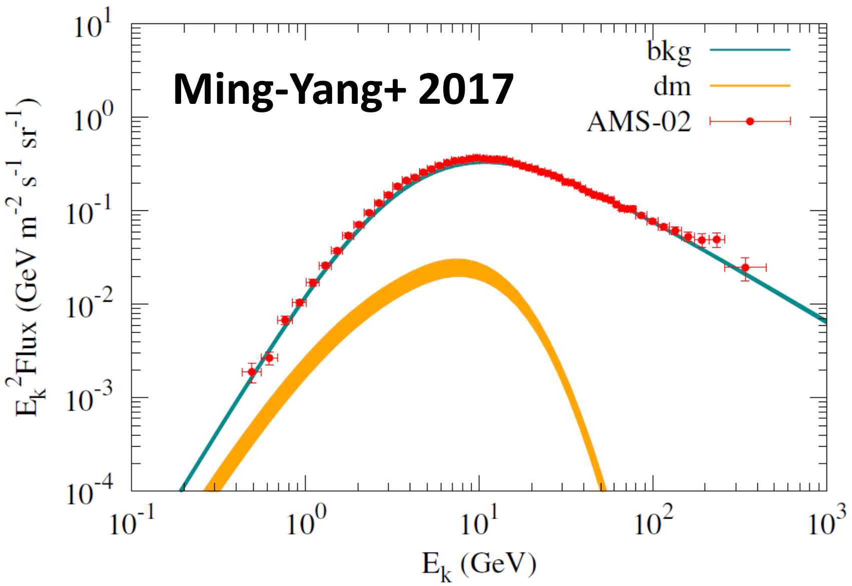
Secondary antiprotons as a Galactic Dark Matter probe

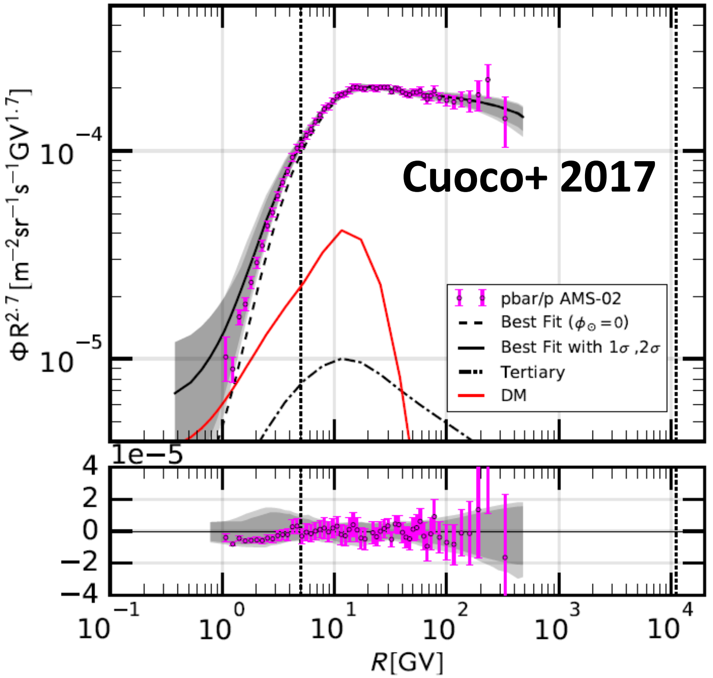
Carmelo Evoli[a] Daniele Gaggero[b] Dario Grasso[c]

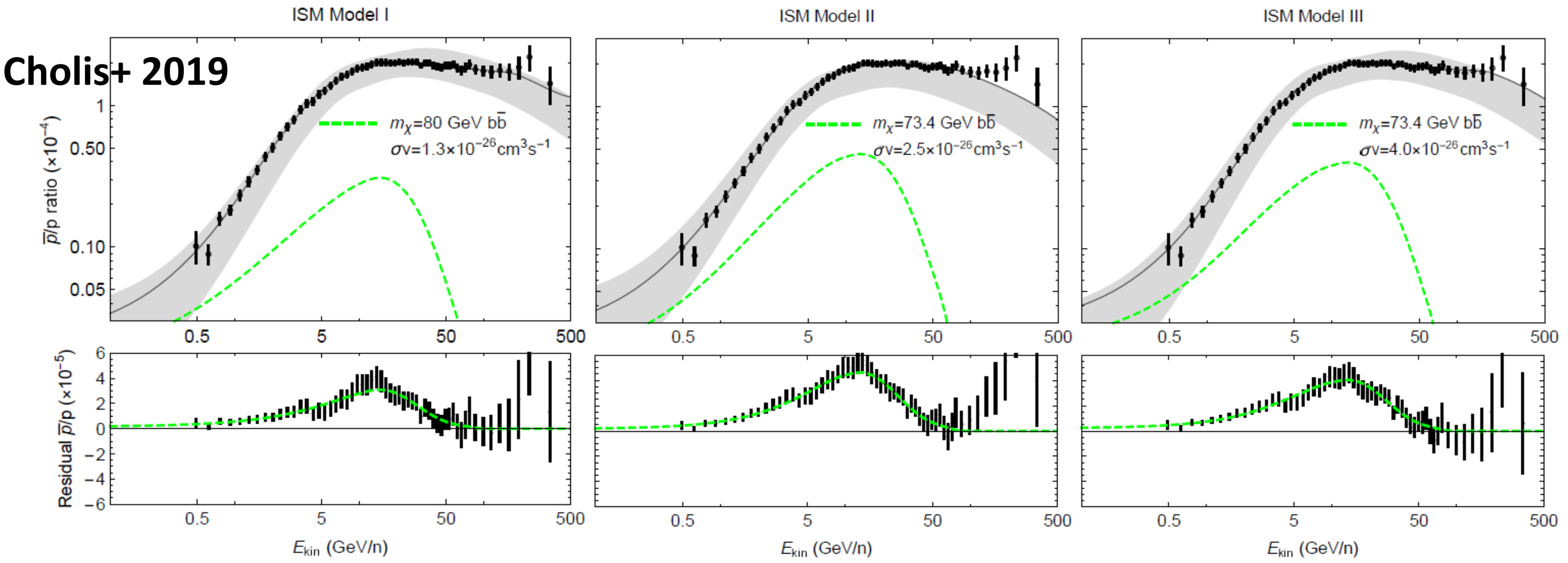


AMS-02 antiprotons, at last!
Secondary astrophysical component and immediate implications for Dark Matter

Gaëlle Giesen[a,*], Mathieu Boudaud[b], Yoann Génolini[b], Vivian Poulin[b,c], Marco Cirelli[a], Pierre Salati[b], Pasquale D. Serpico[b]

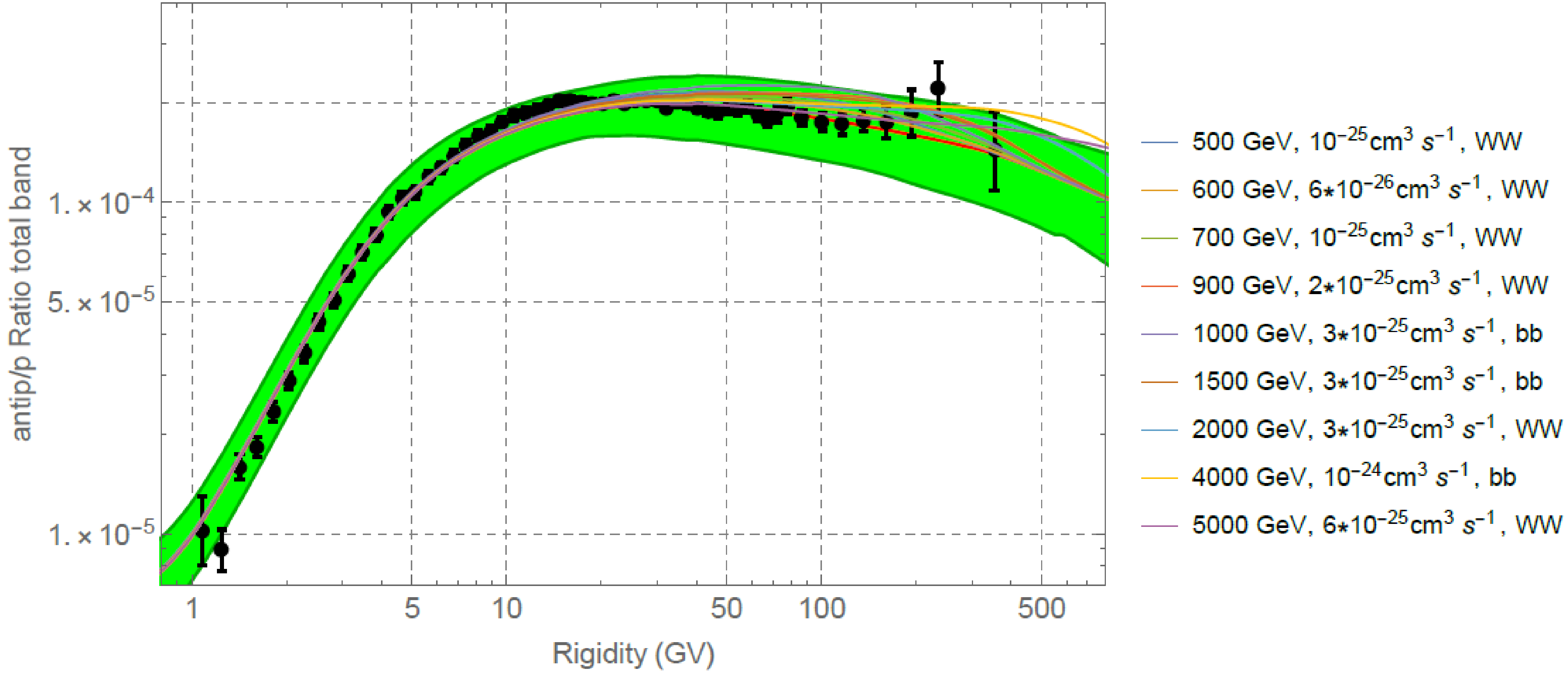

Ming-Yang+ 2017
bkg
dm
AMS-02
E_k^2Flux (GeV m^{-2} s^{-1} sr^{-1})
E_k (GeV)


Cuoco+ 2017
$\Phi R^{2.7}$ [$m^{-2} sr^{-1} s^{-1} GV^{1.7}$]
pbar/p AMS-02
Best Fit ($\phi_{\odot}=0$)
Best Fit with 1σ, 2σ
Tertiary
DM
1e−5
R[GV]


Cholis+ 2019
ISM Model I
ISM Model II
ISM Model III
m_χ=80 GeV $b\bar{b}$
σv=1.3×10^{-26}cm^{3}s^{-1}
m_χ=73.4 GeV $b\bar{b}$
σv=2.5×10^{-26}cm^{3}s^{-1}
m_χ=73.4 GeV $b\bar{b}$
σv=4.0×10^{-26}cm^{3}s^{-1}
$\bar{p}/p$ ratio (×10^{-4})
Residual $\bar{p}/p$ (×10^{-5})
E_{kin} (GeV/n)

Total uncertainty (astrophysics&nuclear) for heavy DM candidates

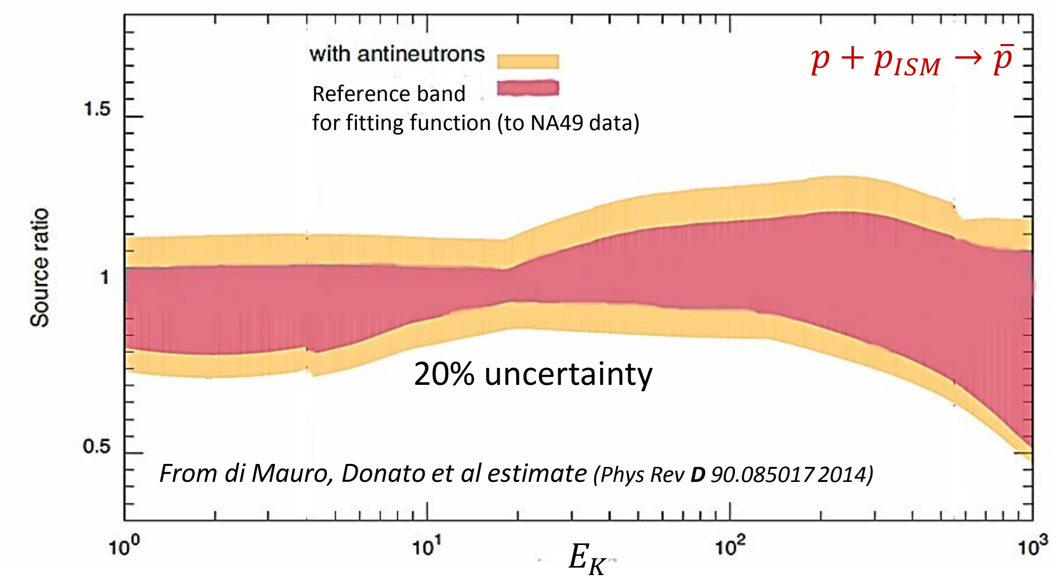
BETTER CANDIDATES: m > 1 TeV, 0.6 TeV < m < 1 TeV and $\langle\sigma v\rangle < 10^{-25} cm^3/s$

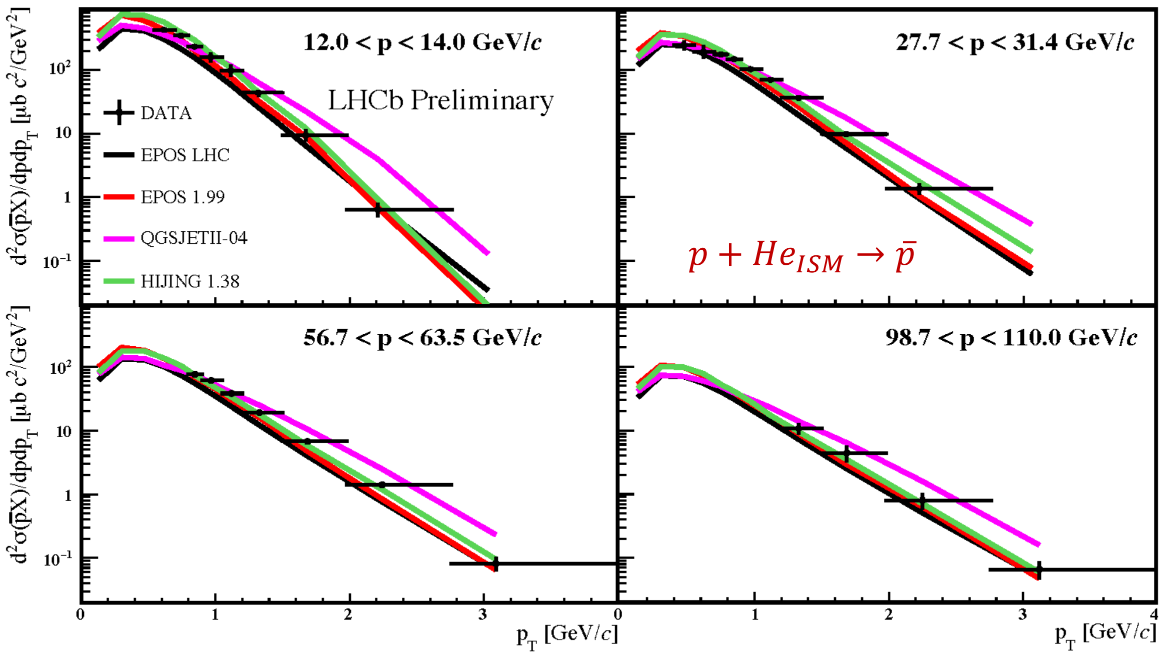


- **AMS-02 results are still compatible with a secondary production but DM signals could in principle still hide within the overall error band.**
- With the nuclear measurements effort we will be capable of extracting a possible DM signal.

Nuclear uncertainties in the antiproton channel

$$p + ISM \rightarrow \bar{p} \ldots \begin{cases} p + p_{ISM} \rightarrow \bar{p} \ldots & \text{Few measurements (recent NA49, NA61 and LHC @ high energies)} \\ p + He_{ISM} \rightarrow \bar{p} \ldots & \text{No direct measurements until 2017 (SMOG @ 6.5 TeV)} \end{cases}$$



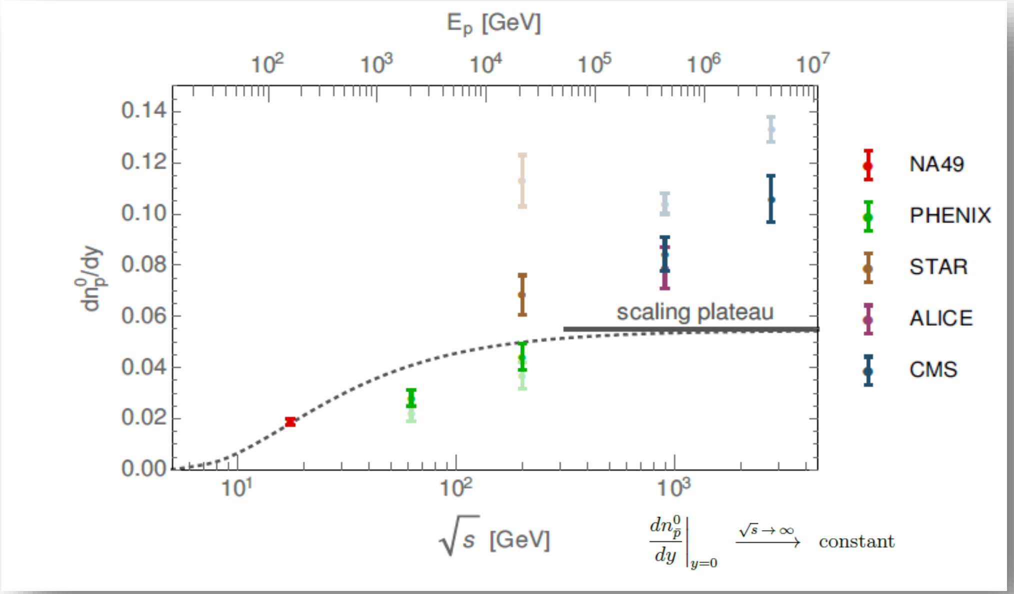


- Uncertainties in the pbar production spectrum are at least 10%.
- **Below 100 GeV the uncertainties for $pp \rightarrow \bar{p}$ are about 10-20%**
- **Above 100 GeV extrapolations lead to errors larger than 30%**

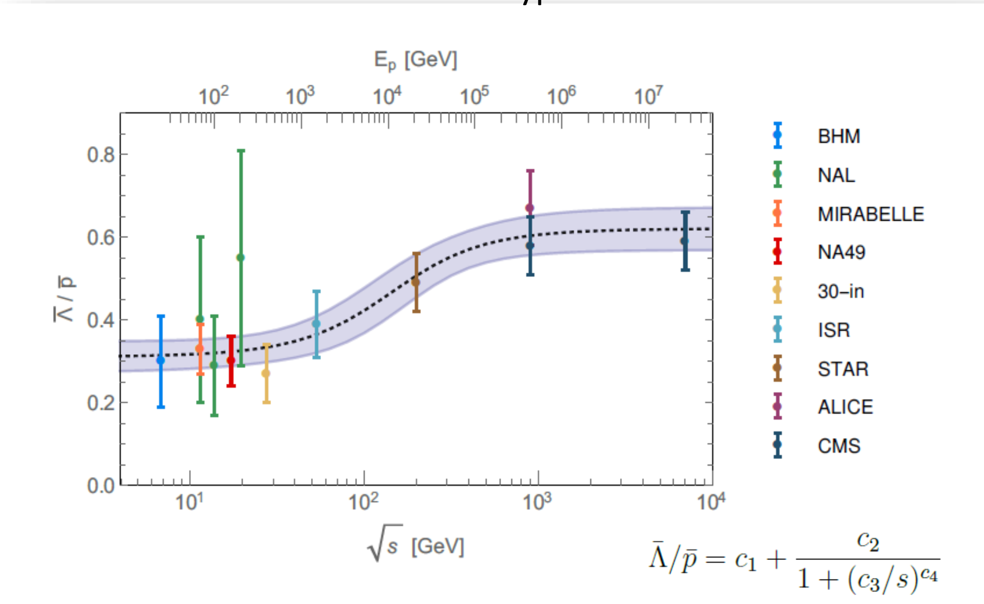
In March 2017 LHCb has performed the first measurement of the antiproton cross-section in p-He collisions at 6.5 TeV using fixed He target @ SMOG. A precision of around 10% is attained

Compilation of Measurements: LHC contributions

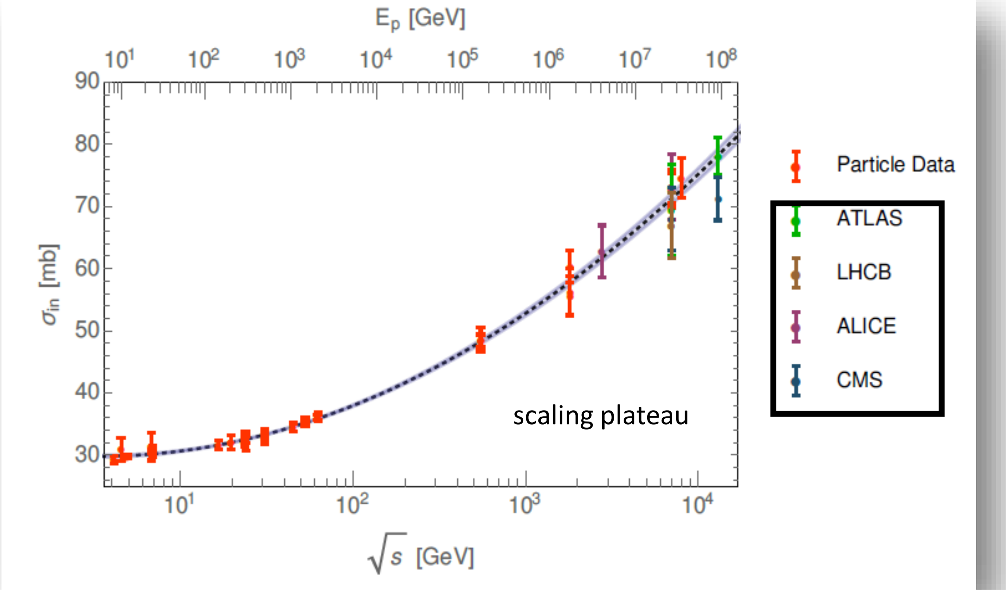
Antiproton multiplicity at central rapidity



Antihyperons



Total inelastic cross section in proton proton scattering



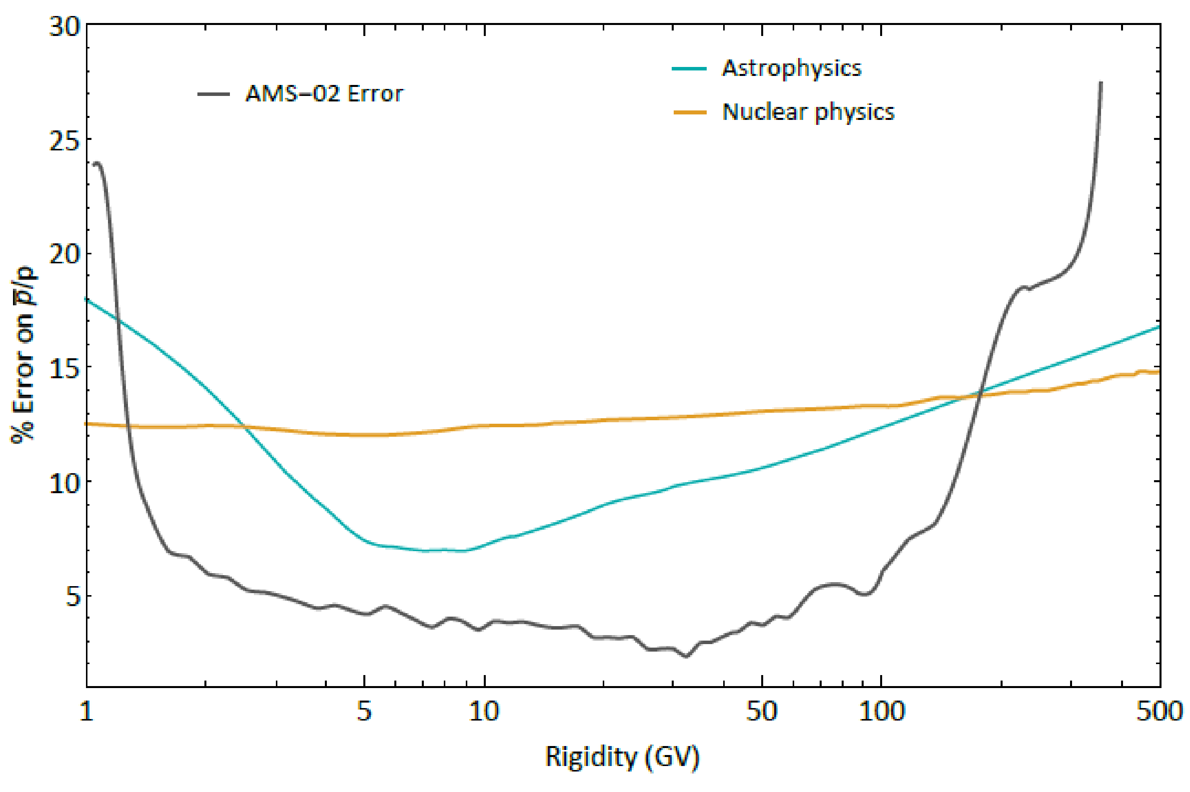
Winkler, JCAP **02**(2017)048

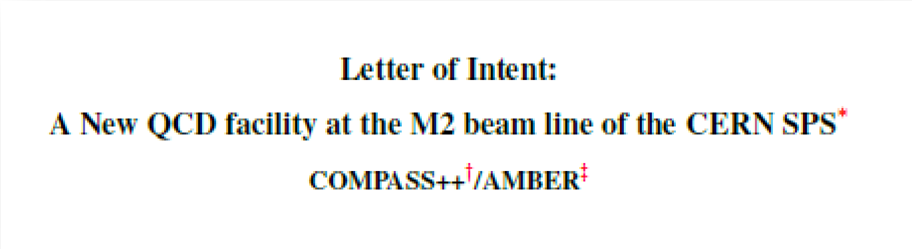
- There are new improved calculation of secondary antiproton production, with a particular focus on the high energy regime, **employing the most recent collider data**.
- A substantial **increase of antiproton cross sections with energy, driven by the violation of Feynman scaling as well as by an enhanced strange hyperon production**.
- **This violation could lead to more antiprotons than expected at high energies**

Secondary background for exotic search

- We are involved in the analysis of the **nuclear uncertainties which afflict secondary antiprotons production** in the ISM
- Thanks to the AMS-02 plus GALPROP/HelMod approach, **propagation uncertainties are now lower than nuclear ones**
- Bologna group has started a collaboration with **COMPASS/AMBER** experiment in order to add precise and up-to-date pHe (and pp) cross section measurements for the DM search in the antiproton channel

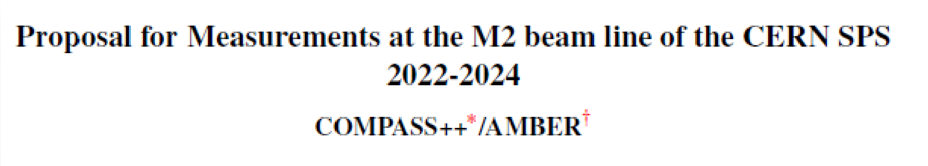
Comparison between uncertainties




Letter of Intent:

A New QCD facility at the M2 beam line of the CERN SPS*

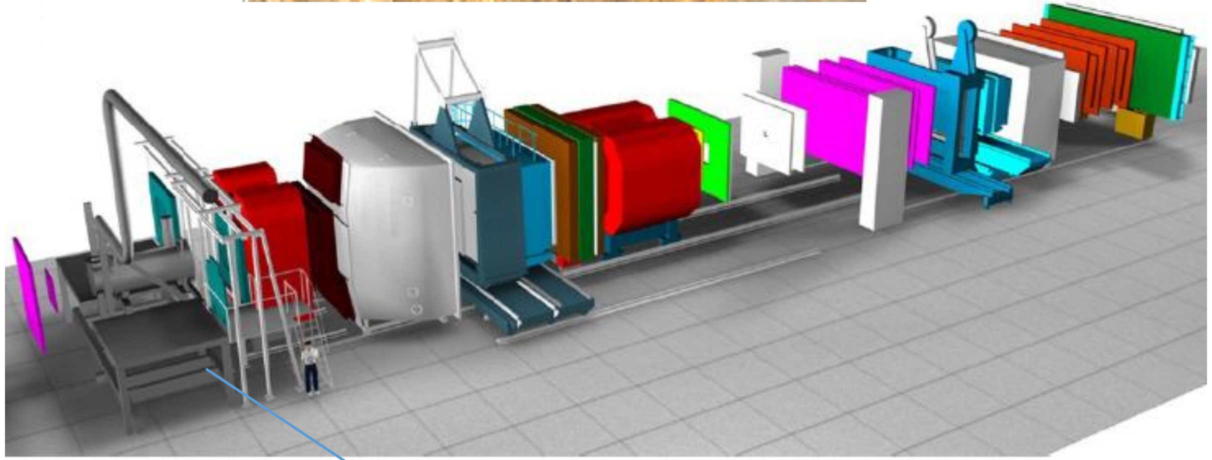
COMPASS++†/AMBER‡

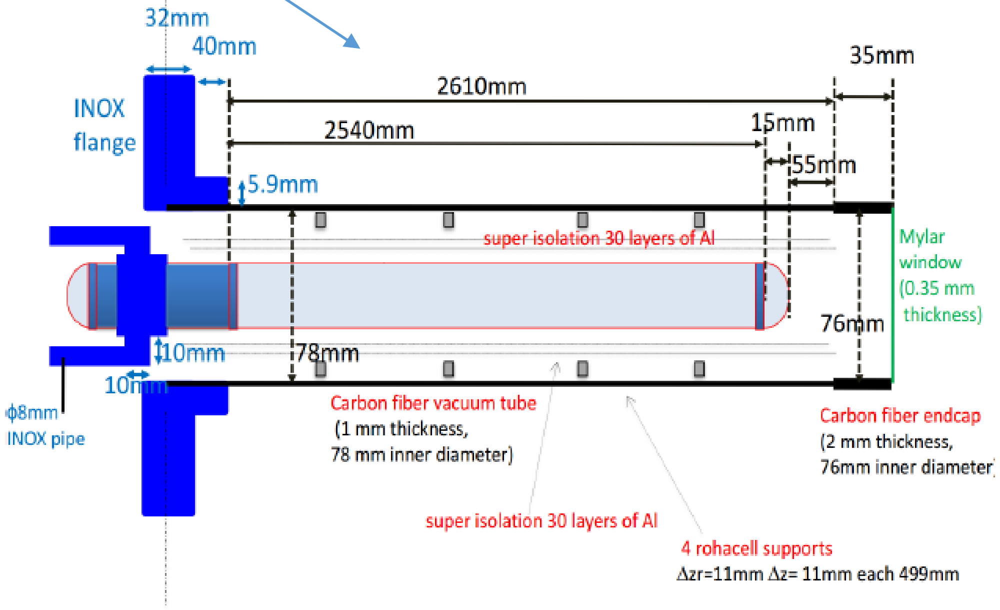

Proposal for Measurements at the M2 beam line of the CERN SPS 2022-2024

COMPASS++*/AMBER†

The COMPASS/AMBER experiment is a fixed-target experiment at located in the M2 beam-line of the SPS.

Apparatus for Meson and Baryon Experimental Research





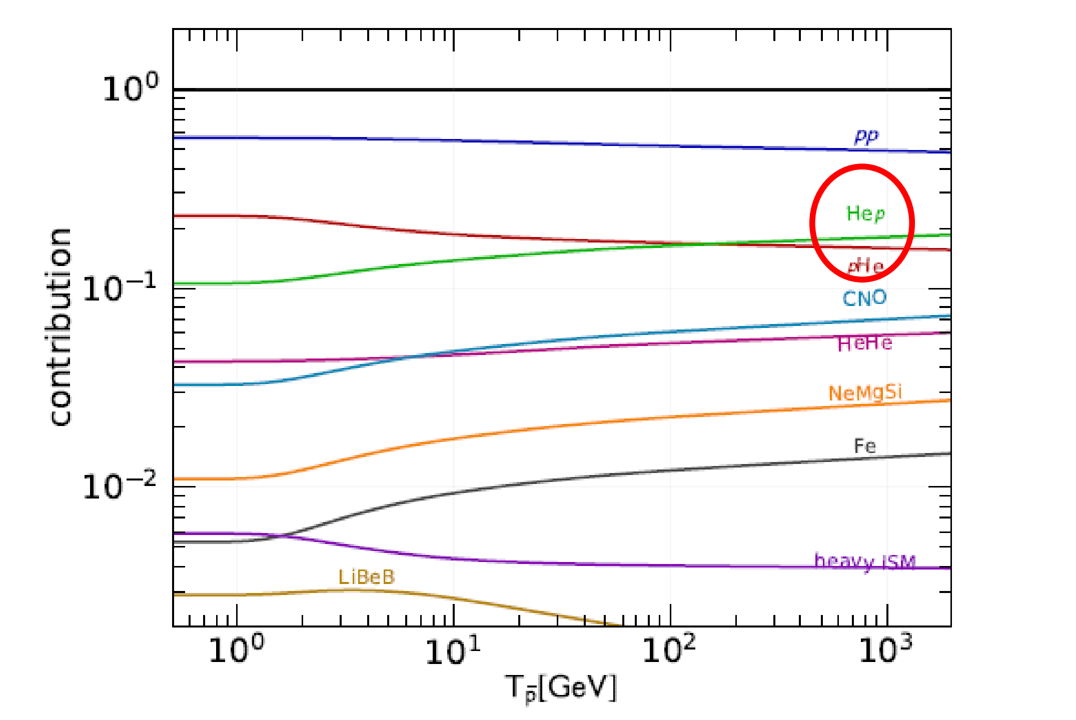
Profile of the COMPASS LH2 target

AMBER proton beam: from a 60 GeV/c up to 250 GeV/c.

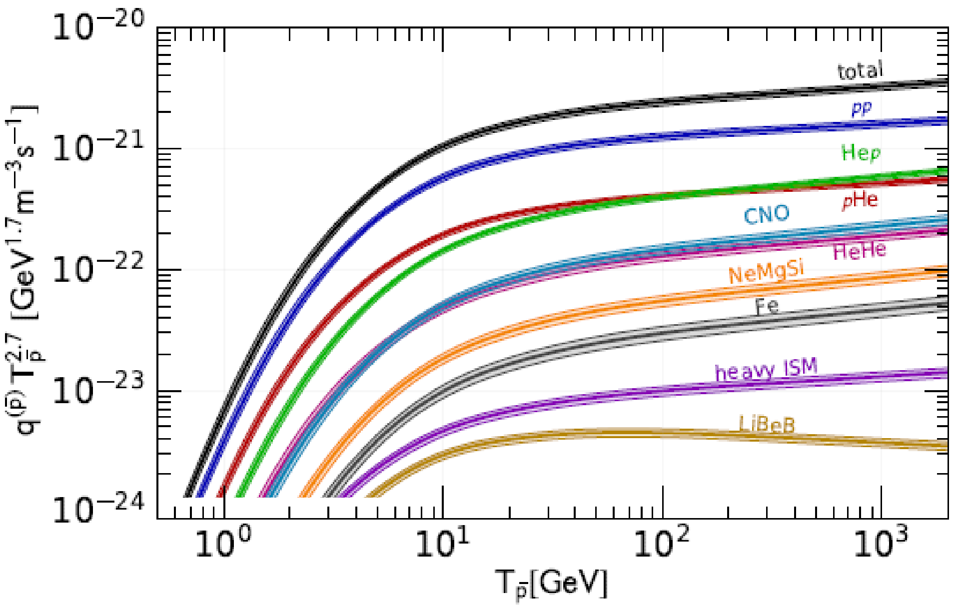
The goal is to measure the double differential (momentum and pseudo-rapidity) anti-p cross production from p+He (and p+H) at different proton momenta (60, 100, 150, 190, 250 GeV/c) on a fixed LHe (and LH2) target.

The calibration run occurred last May 2022 and the first test run in November. The first data taking is scheduled for May/June 2023.

Spallation channels contributions: the importance of helium



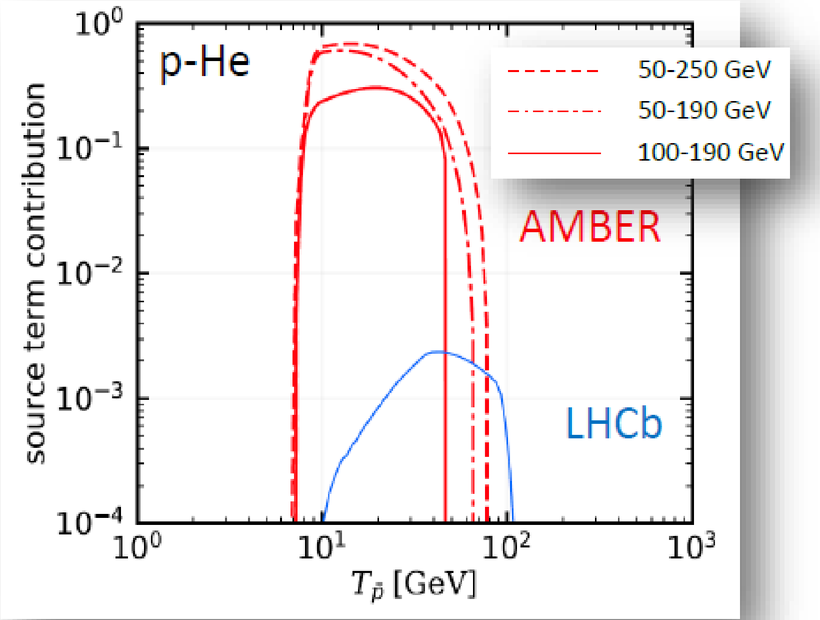
Cosmic spallation source term



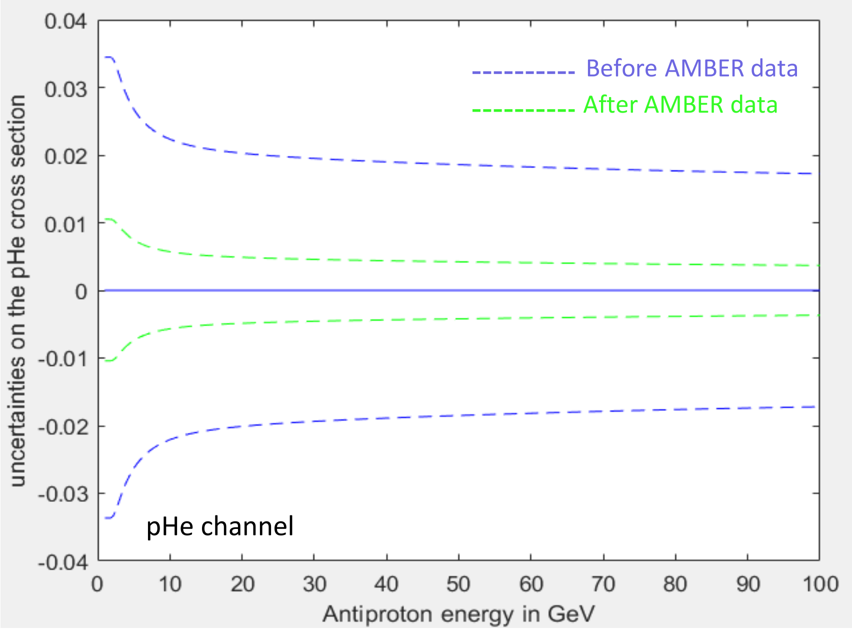
Korsmeier, Donato, di Mauro (PRD97, 103019 (2018))

- **Helium channels are responsible for almost 40%** of the antiproton production
- AMBER will improve our knowledge of the production of cosmic **antiprotons with kinetic energy up to 50 GeV:** with supposed 5% errors, the cross section uncertainties in the pHe (pp) channel will be sufficiently reduced
- AMBER phase-space is being studied with MC generators and analytical models to guide experimental set-up and measurements

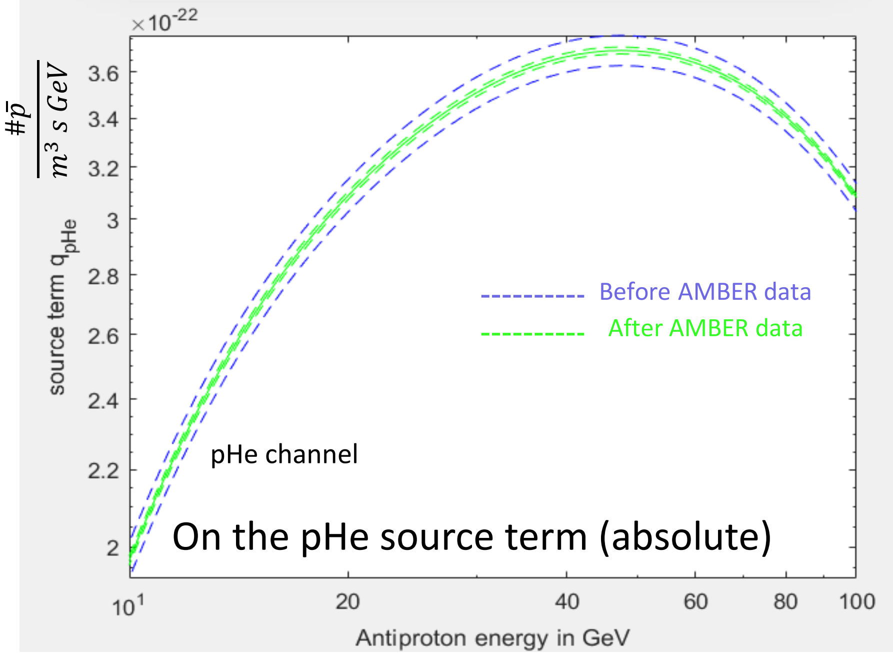
Impact of measurements on constraining the antiproton production: source-term contribution of the AMBER experiment to the total source term shown for three different beam energy ranges in the p–He channel (for comparison the contributions from the LHCb in blue line)



Few-Body Syst (2022) 63:72



Uncertainty on the pHe source term (percentage)



On the pHe source term (absolute)

A new era for astro-nuclear physics

- AMS-02 data allow a deeper understanding of the «High Energy Universe» and do put the models to the test, highlightning 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 propagation scheme was achieved, granting a unitary description of CR physics at the % level for primary cosmic rays;
- Once fixed the CR propagation parameters, the secondary astrophysical background for DM and exotic searches is greatly reduced;
- We cannot go much further in reducing astrophysical uncertainties, but we can certainly do it for nuclear ones;
- Nuclear uncertainties should be weigh, considering in details pHe, pA and AA reactions in the ISM, in order to understand how much we have to improve current measurements;
- The next step for antimatter study is to include deuterons, antideuterons, antihelium and antihyperons contributions in the GP-HelMod machine to predict their fluxes and guide the forthcoming measurements by AMS-02 and future experiments.