(Anti)matter propagation in the Galaxy

Istituto Nazionale di Fisica Nucleare

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Nicolò Masi – 13/01/2022

Explaining Z ≤ 28 CRs physics by means of GALPROP and HelMod

- 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 (*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));

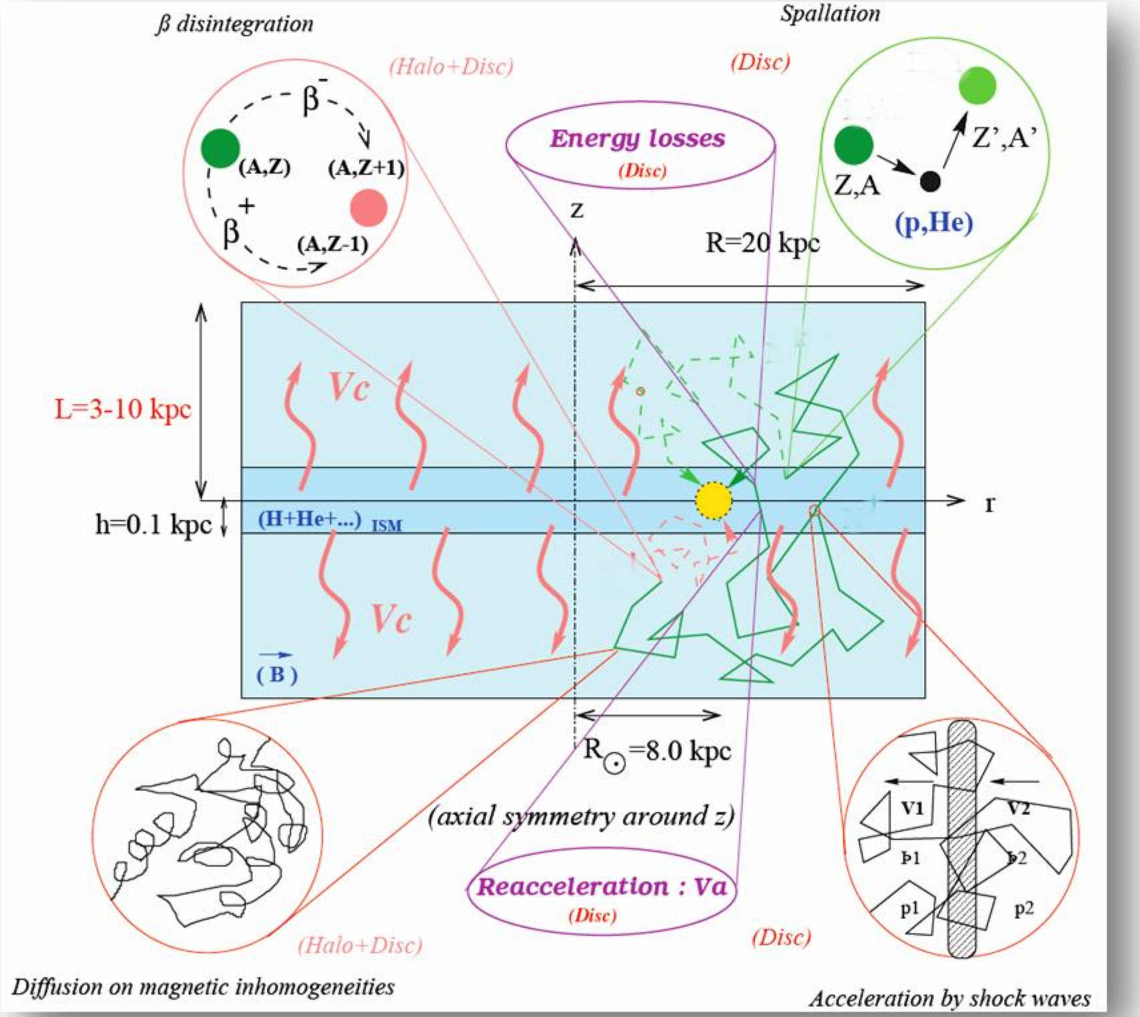
- The 28 proposed LISs fit Voyager 1, ACE, Pamela, AMS-02 (and many other experiments) and recent CALET and DAMPE data, from 10 MeV/n up to 200 TeV/n, representing a **reference model for the Collaboration** and a **forecasting tool for astroparticle and solar physics;**

- 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

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

Source, Diffusion, Convection, Reacceleration, Energy Loss in ISM, Adiabatic Expansion, Fragmentation, Decay

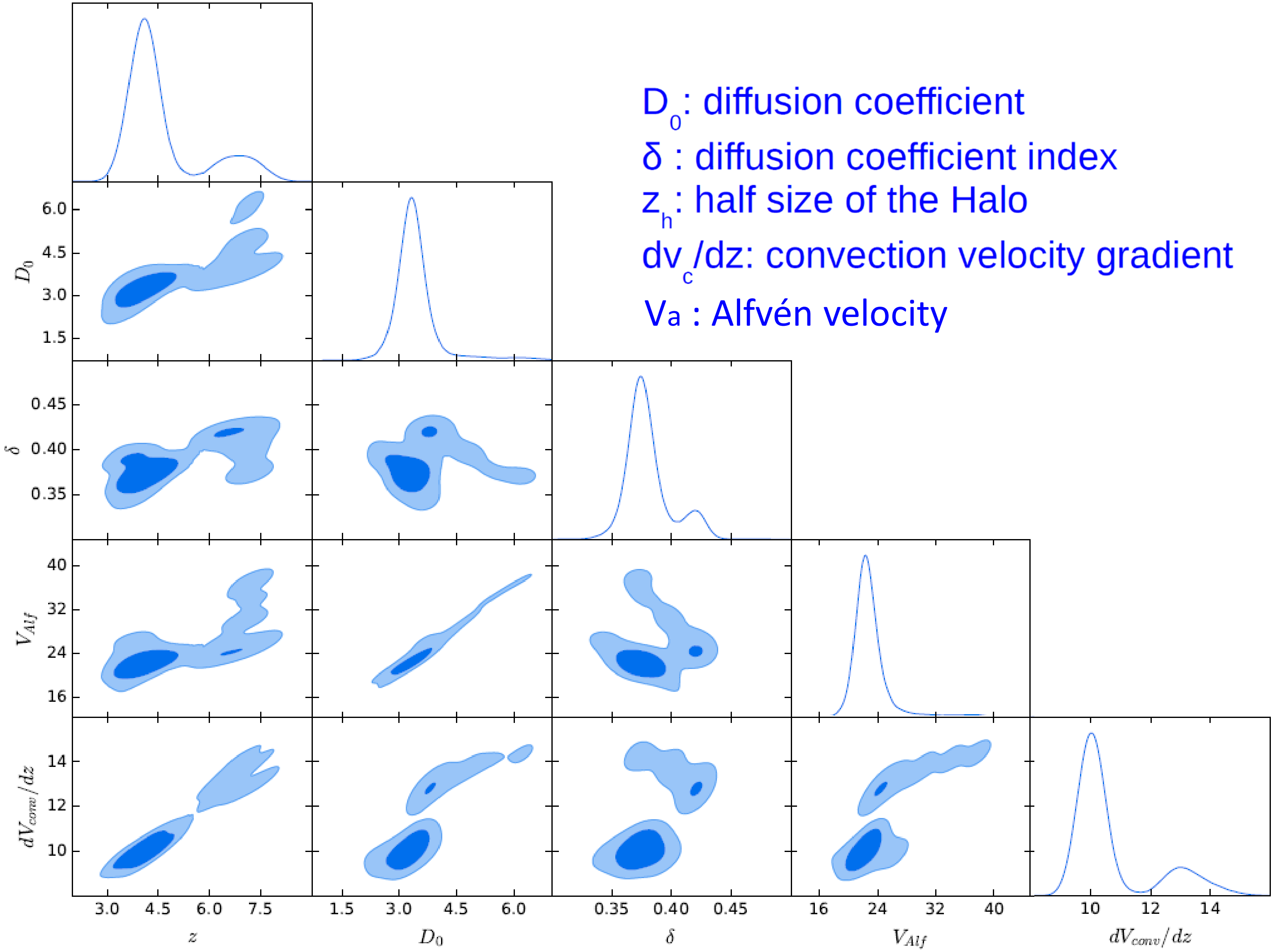


- **Geometry**: halo of thickness z
- **Diffusion**: diffusion in the galactic magnetic field inhomogeneities, propagating through the ISM (D_0, δ)
- **Convection**: galactic wind with velocity gradient dV_c/dz
- **Reacceleration**: interstellar turbulence with Alfvén velocity V_A

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



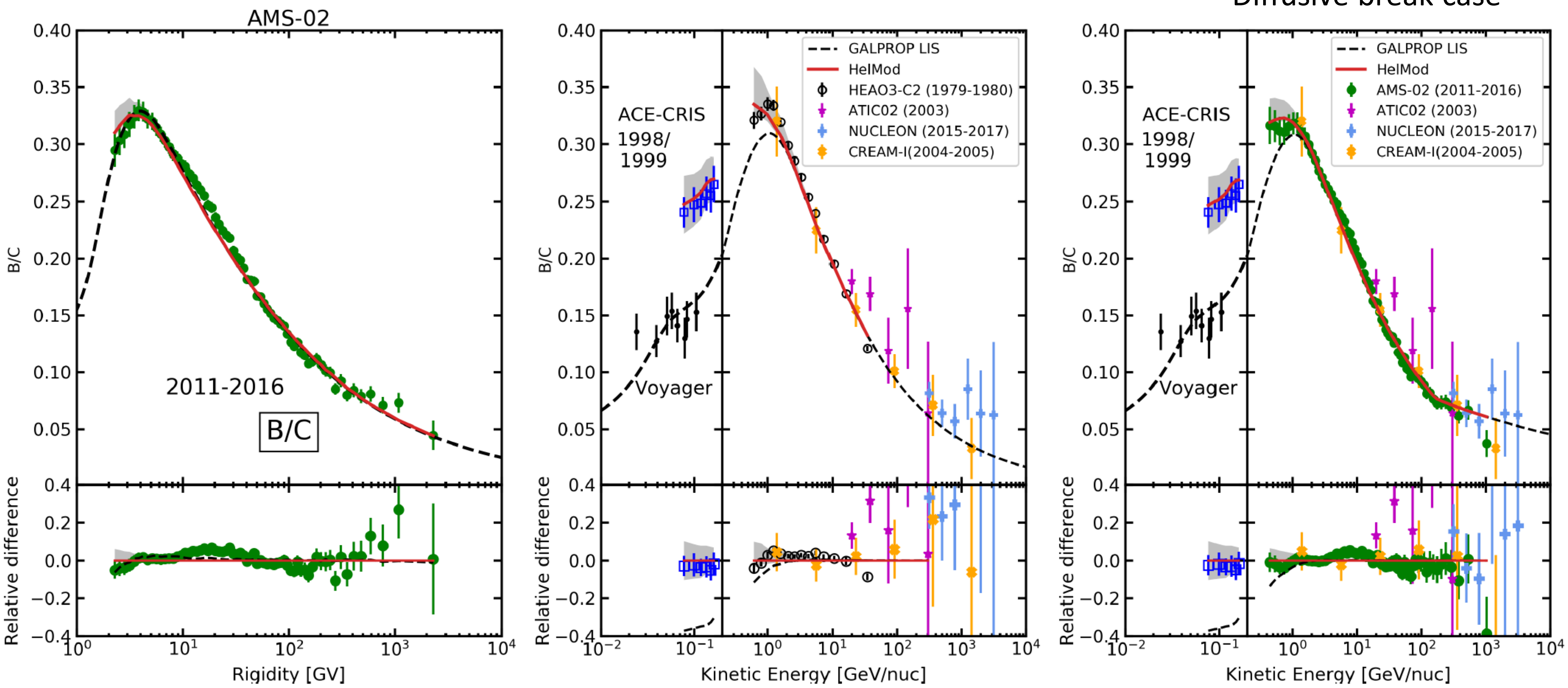
D_0: diffusion coefficient
δ : diffusion coefficient index
z_h: half size of the Halo
dv_c/dz: convection velocity gradient
Va : Alfvén velocity

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.**

One order of magnitude of improvement for fundamental parameters uncertainties

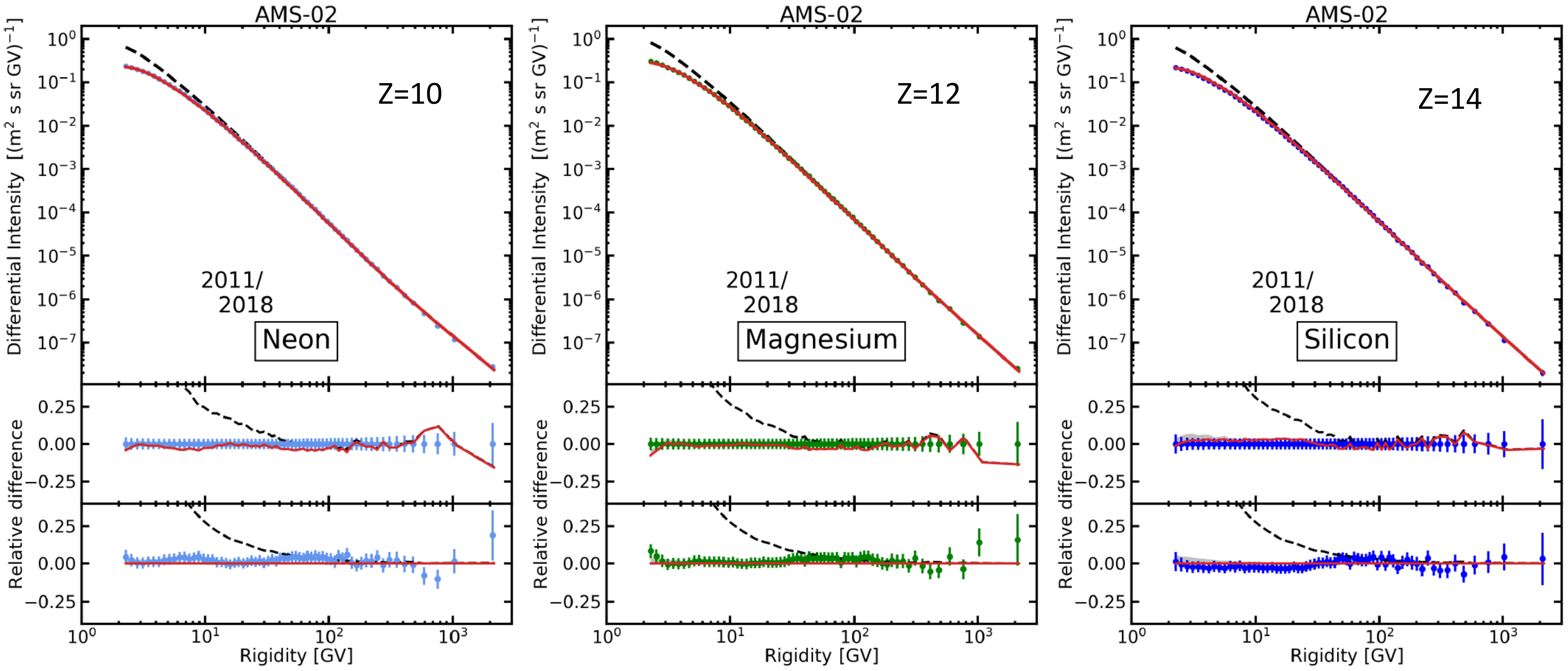
Updated secondary over primary ratio: B/C

Diffusive break case



New AMS-02 Z>8 Nuclei

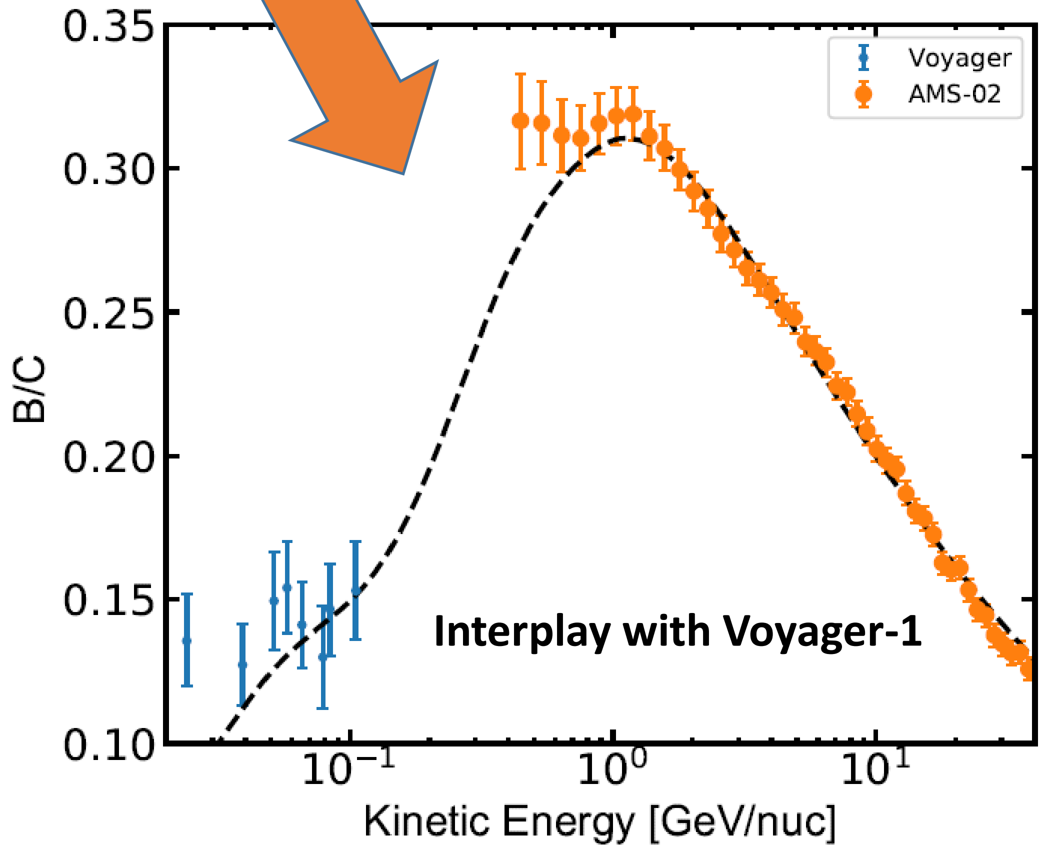
AMS-02 data from PHYSICAL REVIEW LETTERS **124**, 211102 (2020)

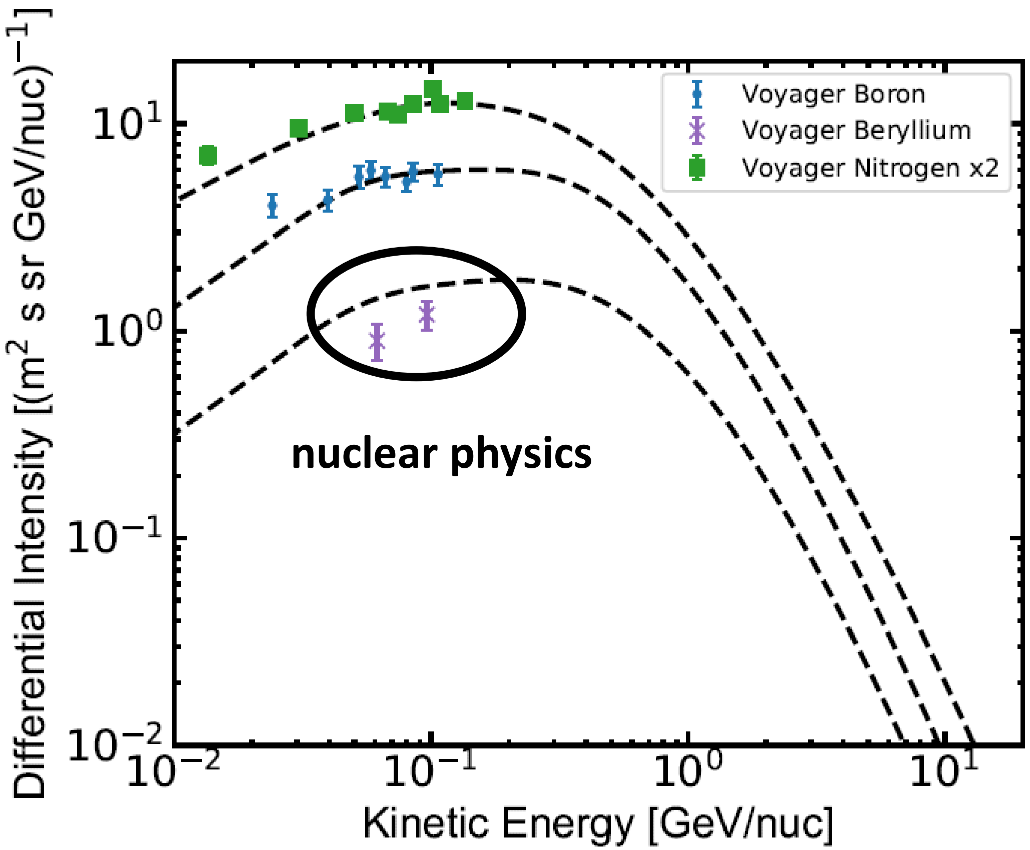


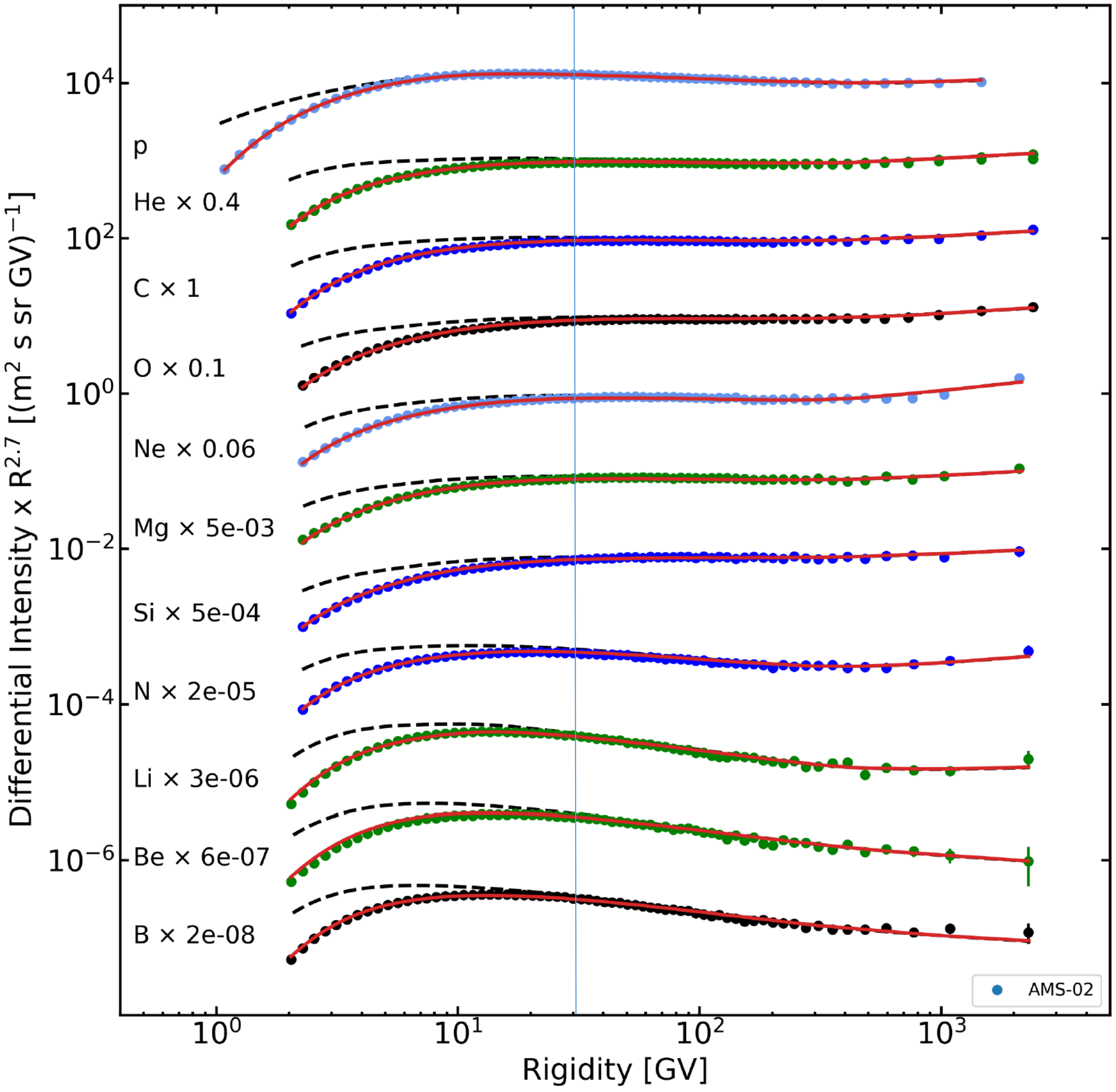
Per cent/few per cent level precision

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	$V_{\rm Alf}$	km s^{-1}	30	3
5	$dV_{\rm conv}/dz$	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.







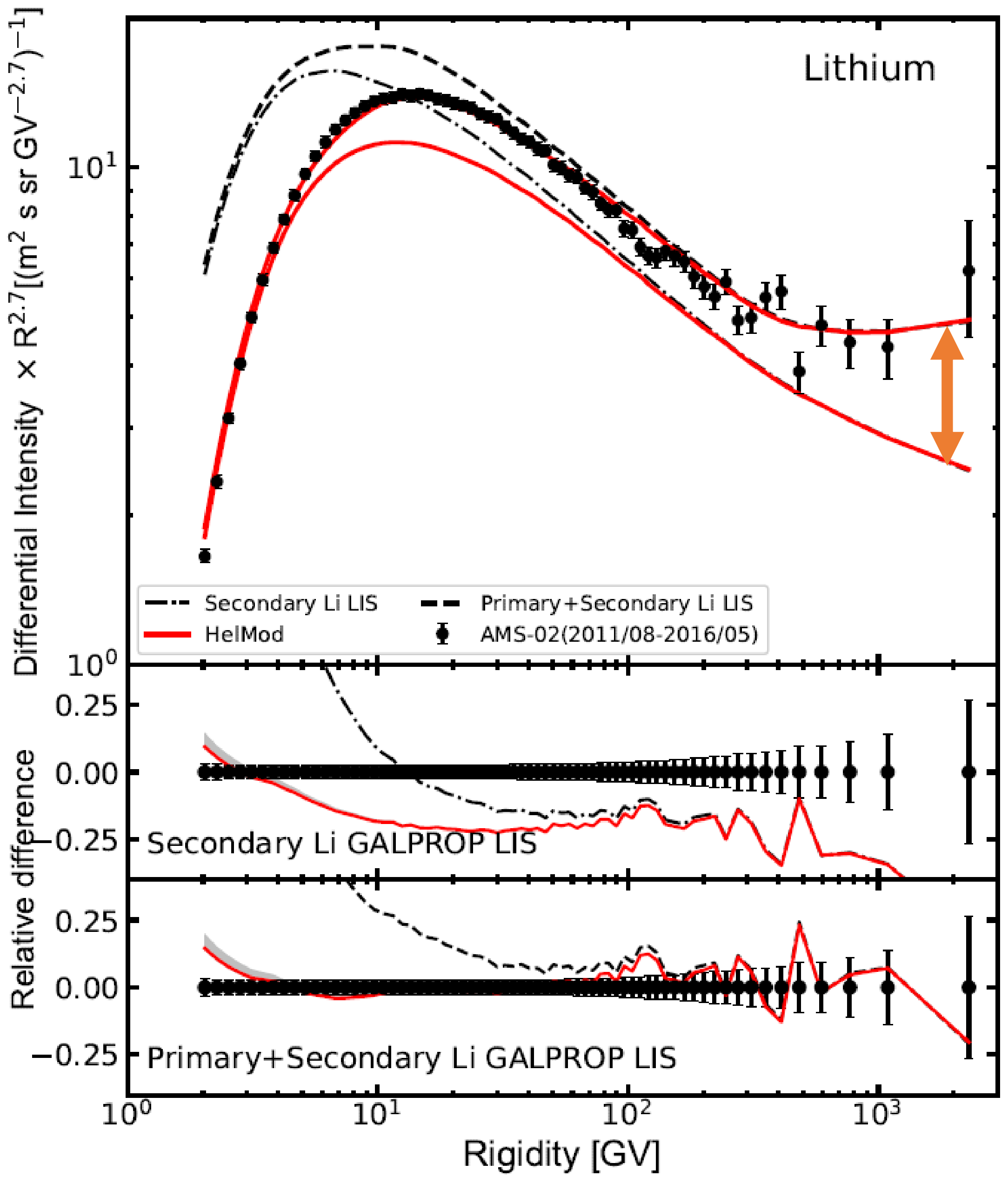
The Model confirms its prediction capability for all AMS-02 species with a single set of parameters

Primary Lithium Discovery

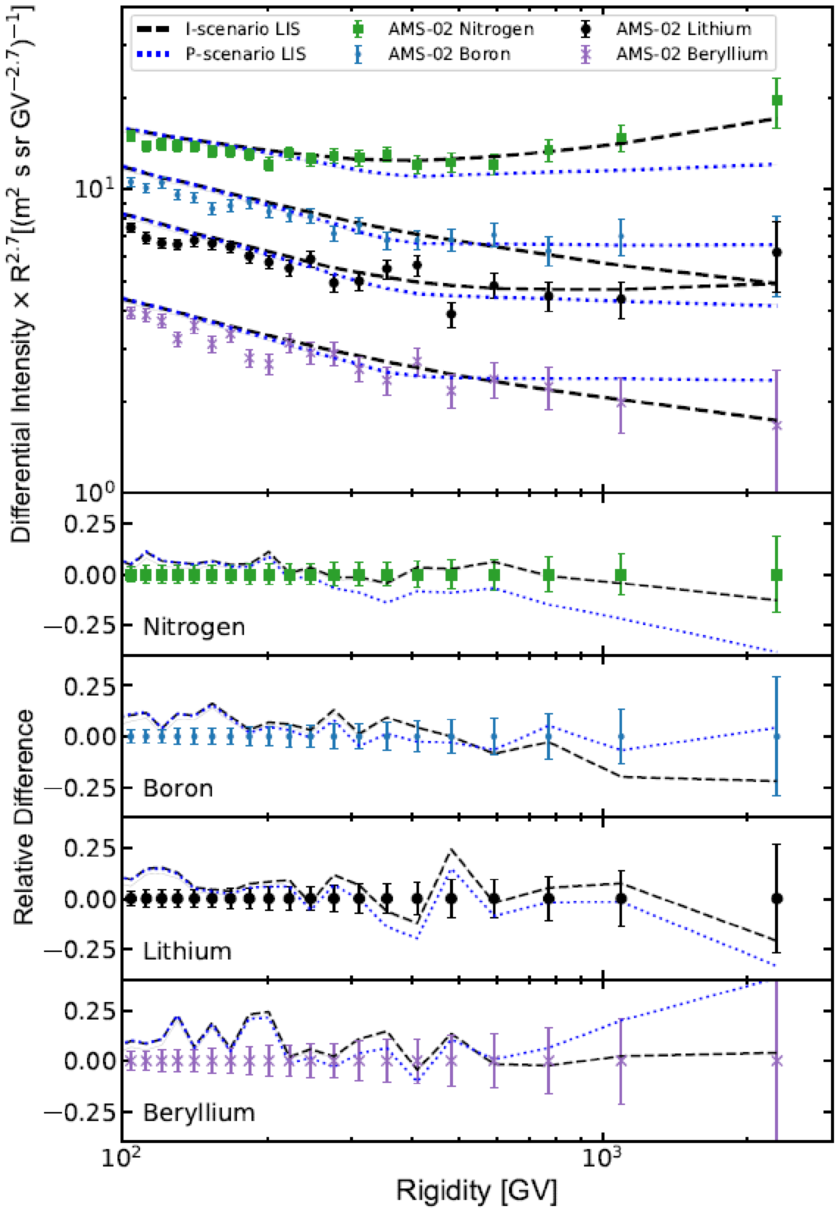
Primary Lithium from Novae/Wolf Rayet stars is mandatory to explain AMS-02 measurement

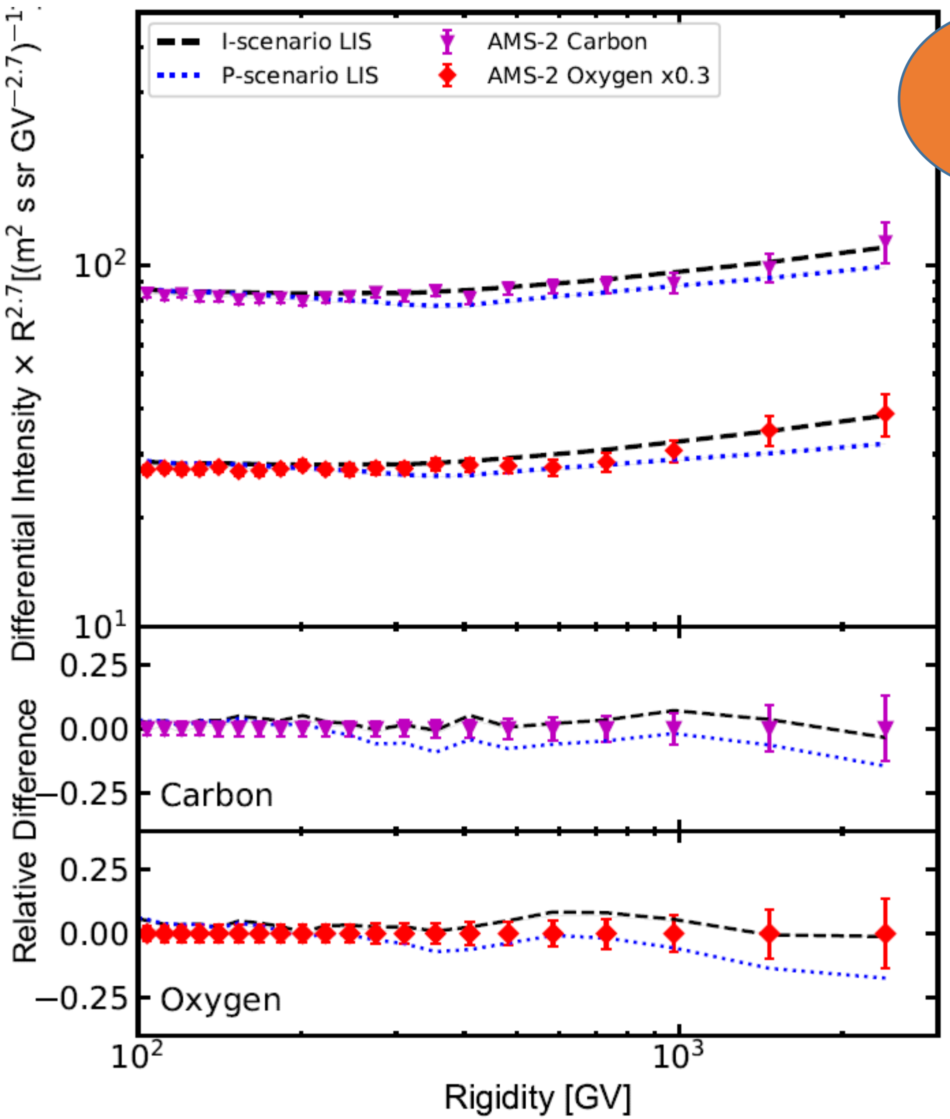
the observed stellar lithium abundances indicate that some proportion of lithium is also produced in low-mass stars and nova explosions. Indeed, the alpha-capture reaction of ^{7}Be production ^{3}He$(\alpha,\gamma)^7$Be was proposed a while ago (Cameron 1955; Cameron & Fowler 1971). A subsequent decay of ^{7}Be with a half-life of 53.22 days yields ^{7}Li isotope. To ensure that produced ^{7}Li is not destroyed in subsequent nuclear reactions, ^{7}Be should be transported into cooler layers where it can decay to ^{7}Li, the so-called Cameron-Fowler mechanism.

Recent observation of blue-shifted absorption lines of partly ionized ^{7}Be in the spectrum of a classical novae V339 Del about 40-50 days after the explosion (Tajitsu et al. 2015) is the first observational evidence that the mechanism proposed in 1970s is working indeed (Hernanz 2015)



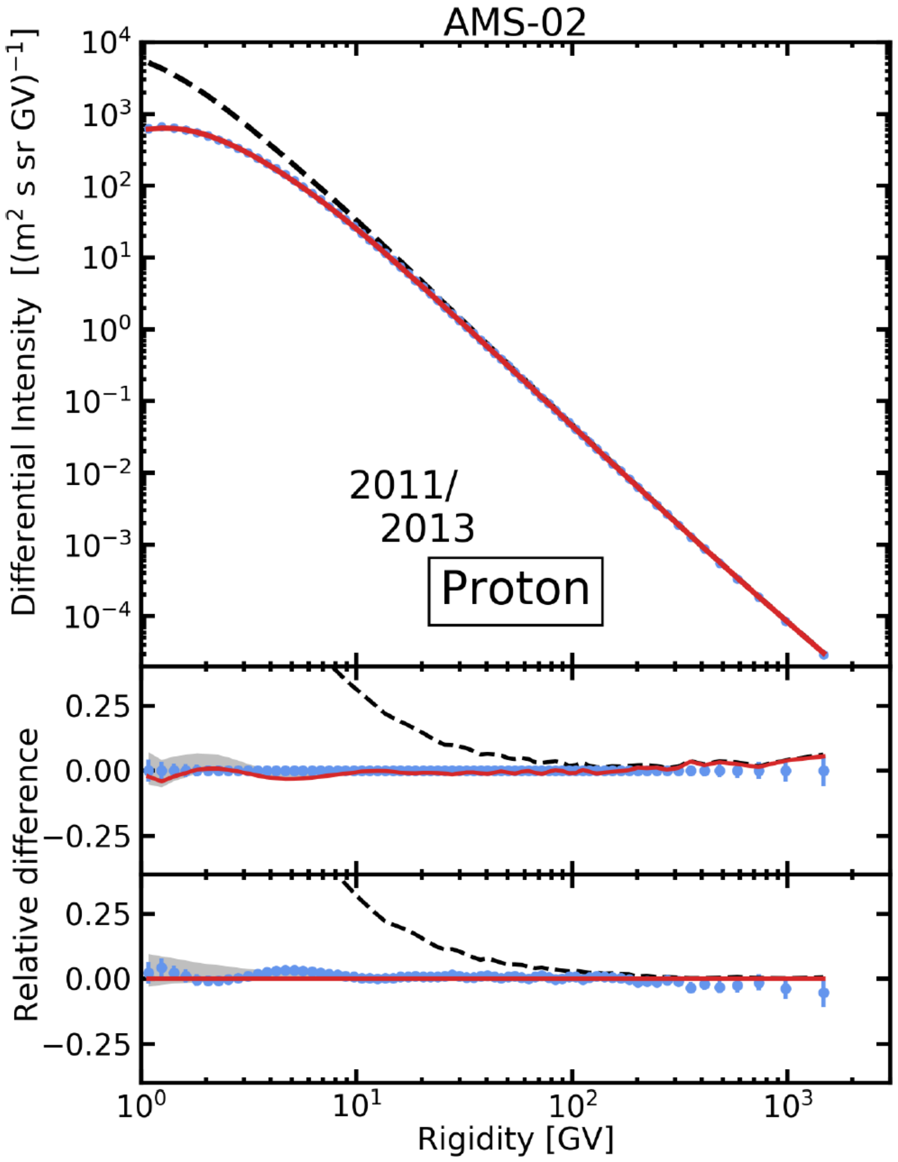
Injection versus Propagation scenarios to explain CRs hardening above 300 GV

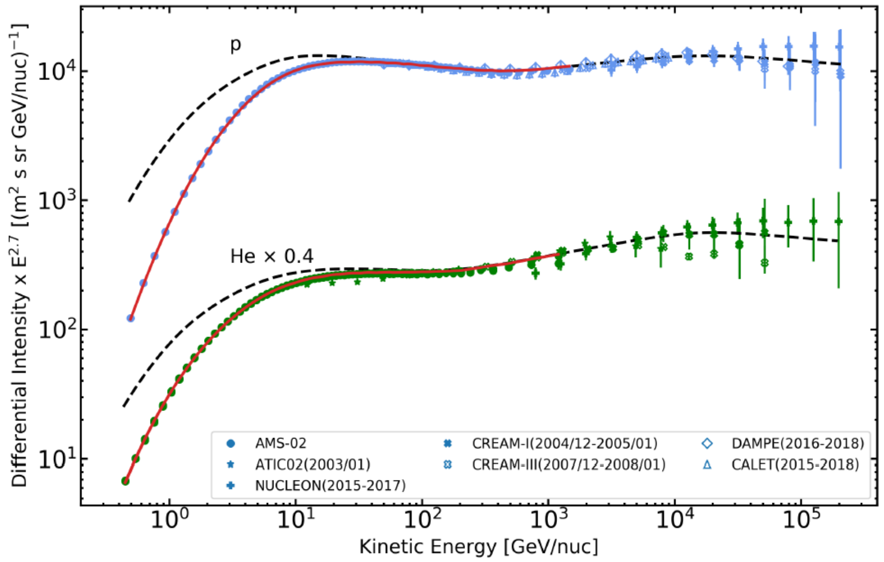


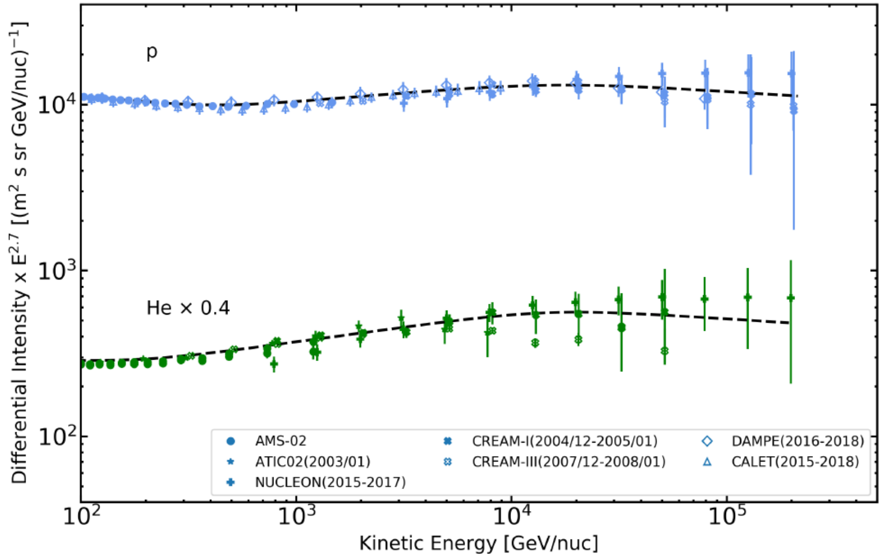


I or P?

Extension of AMS-02 based LISs for p and He up to tens (and hundreds) TeV/n with CALET and DAMPE

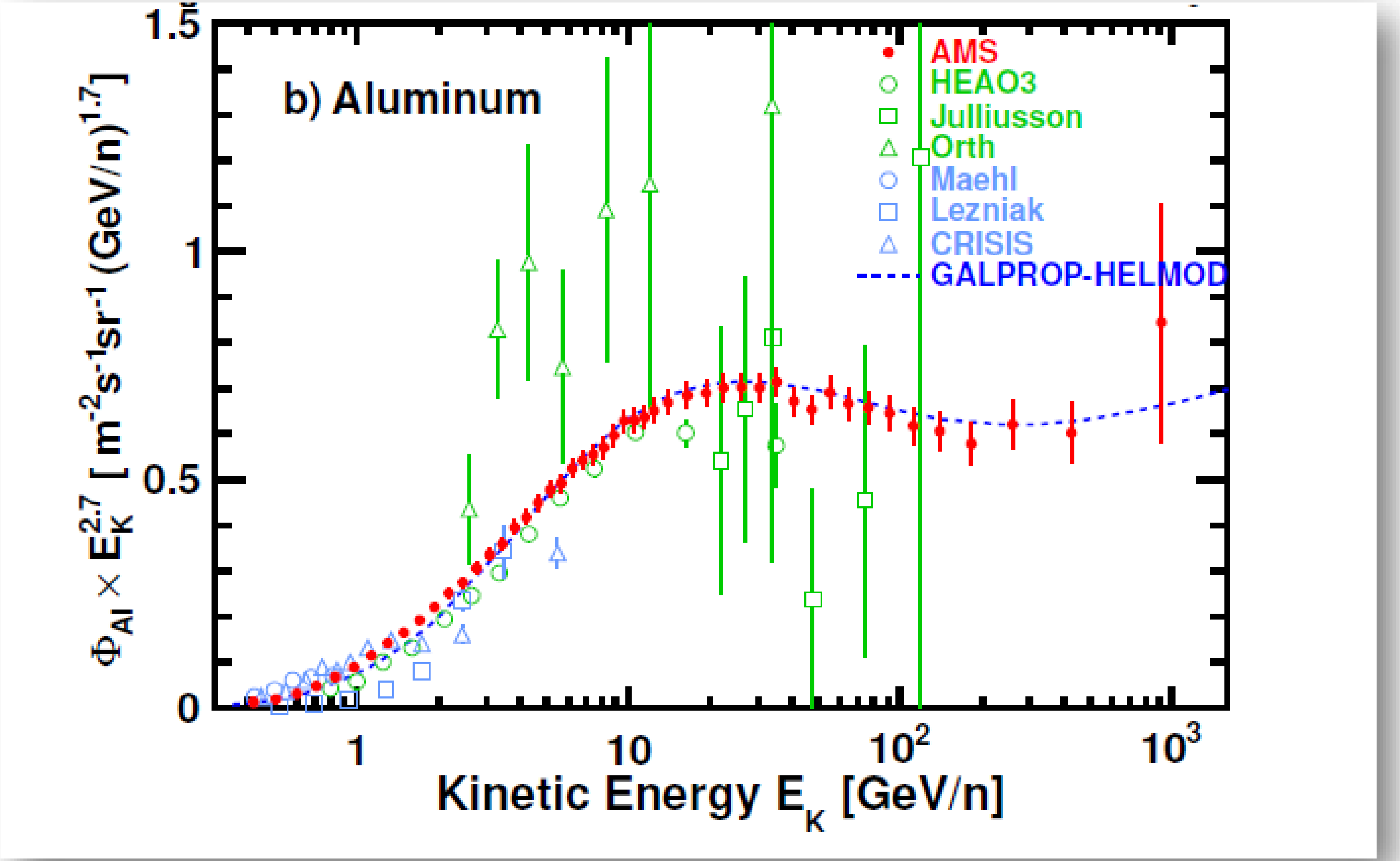




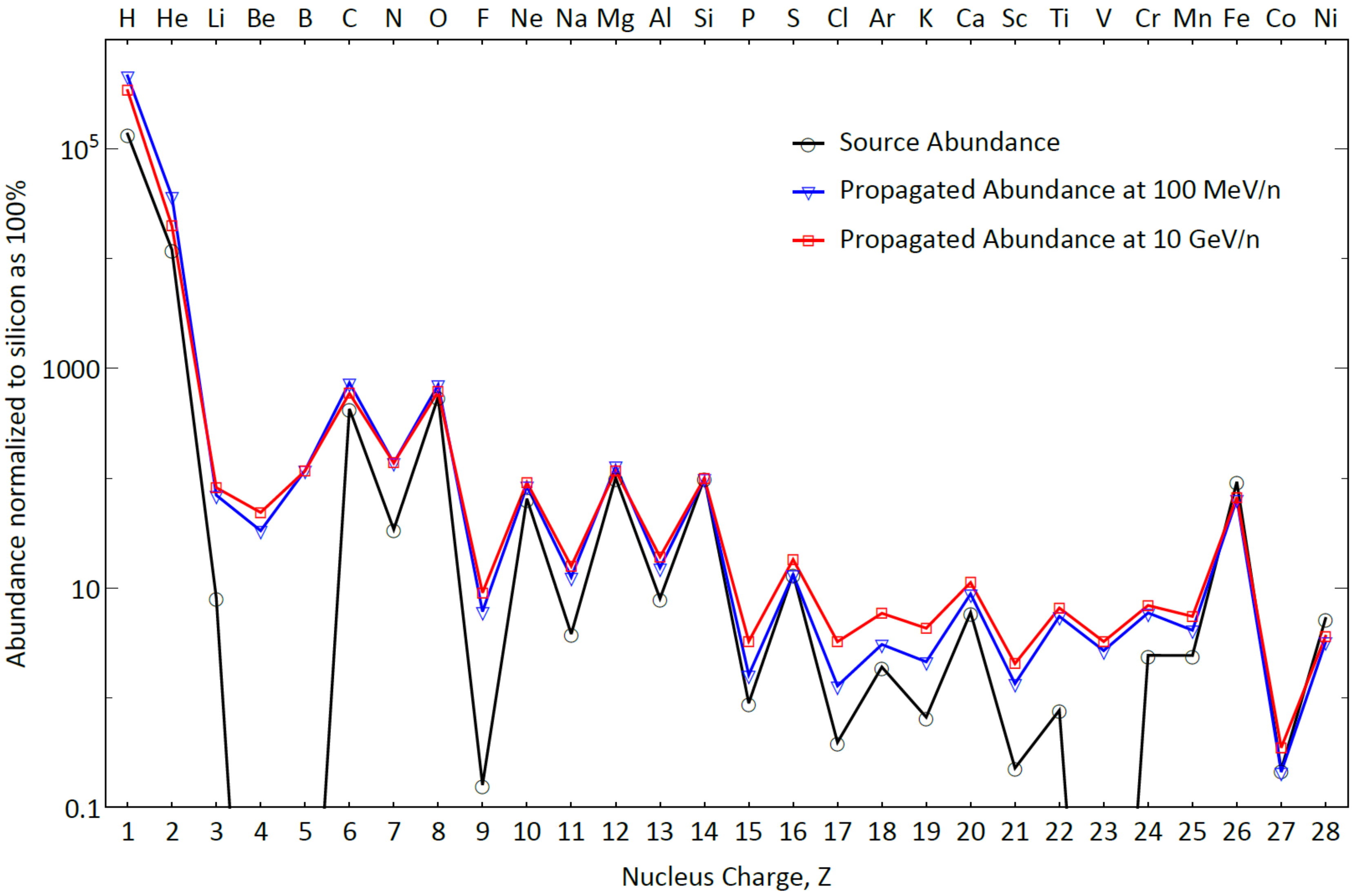


New universal behaviour with a 20 TeV/n break?

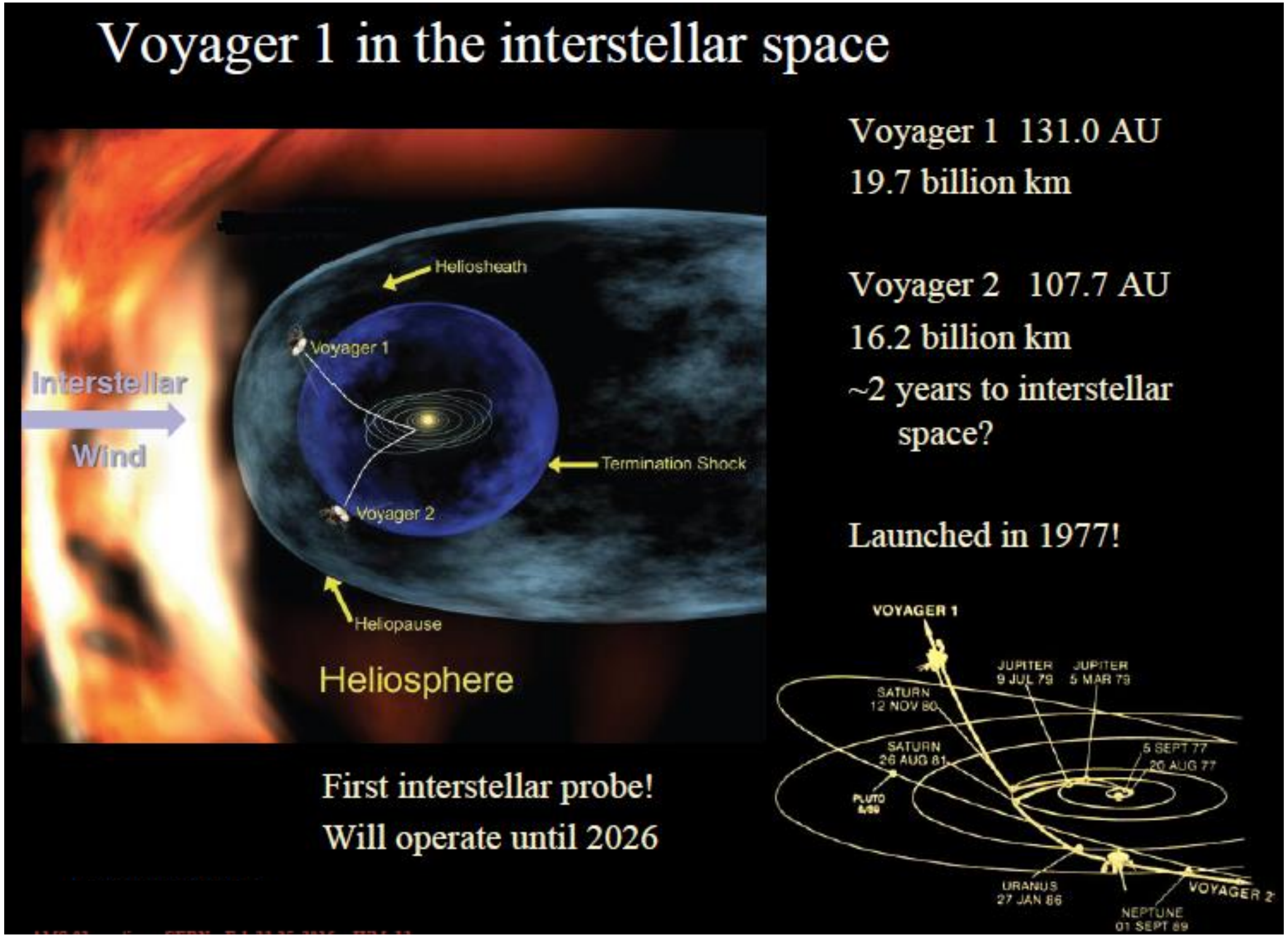
Aluminum forecasting!



Full knowledge of CR abundances: Source vs Propagated

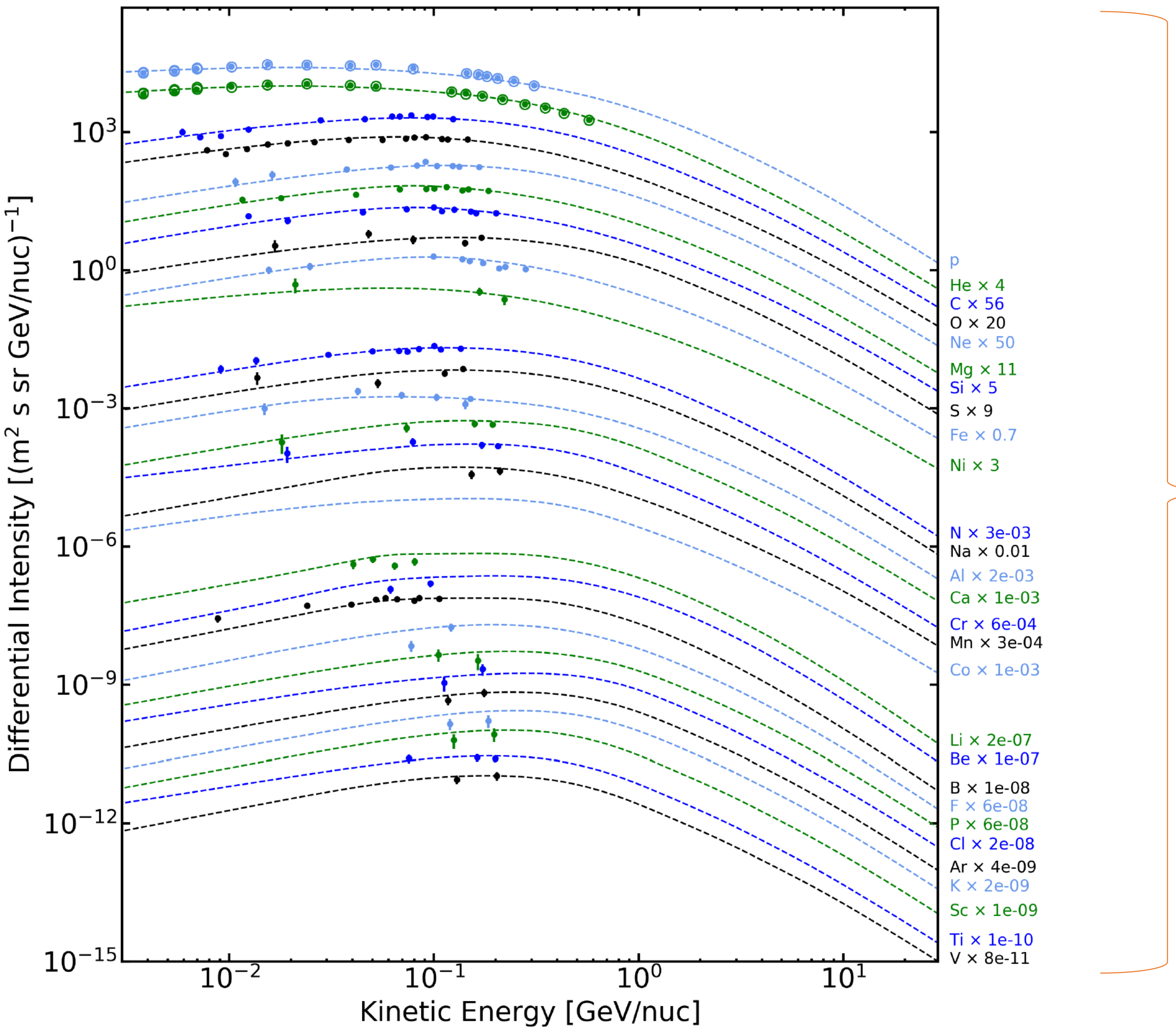


AMS – Voyager1 interplay



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
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- Current and Historical Values of default parameters
- Interpolation Functions for Local Interstellar Spectra
- HelMod Results
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Related Link

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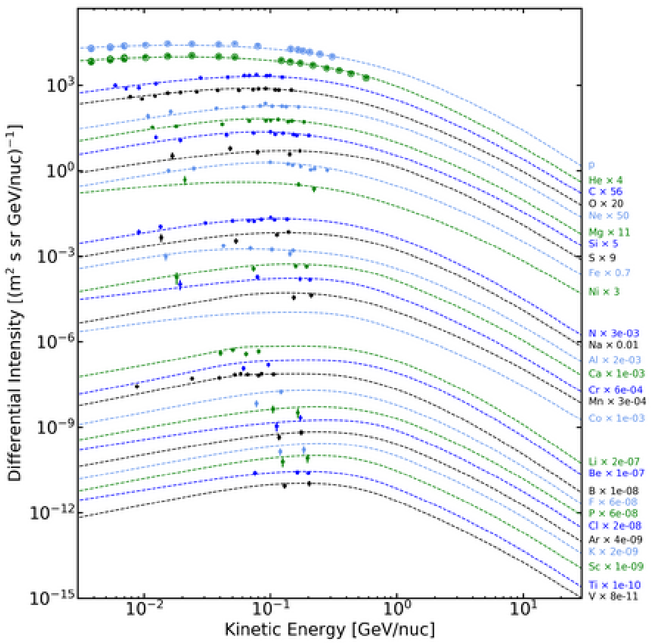
- SR-NIEL web calculator
- SR-NIEL physics handbook
- ASIF - ASI Supported Irradiation Facilities

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.

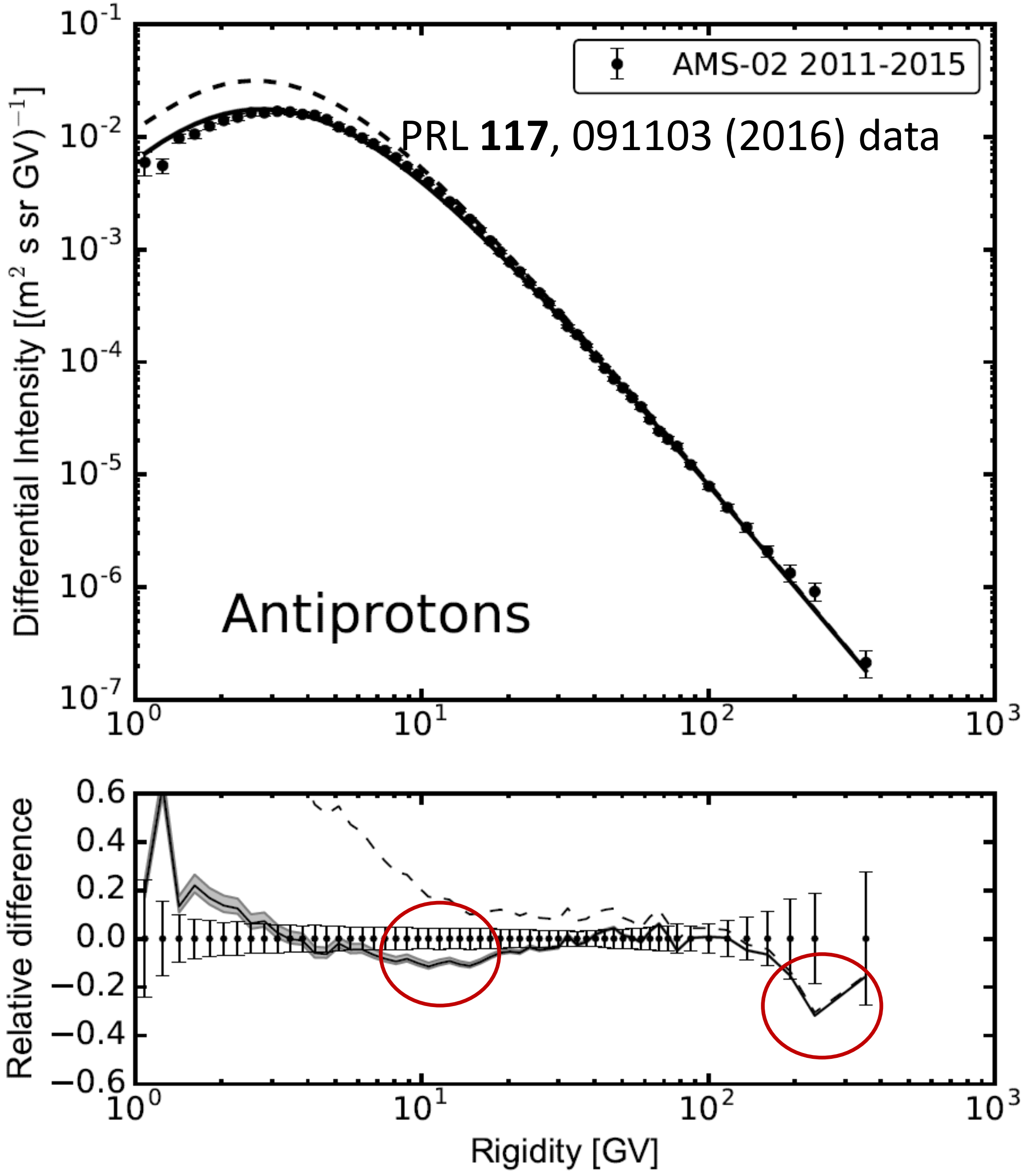
LISs will be futher fine-tuned and updated on the website using incoming AMS-02 measurements

2020-2021 Achievements

- ✓ All cosmic rays species with $Z \leq 28$ predicted with GALPROP plus HelMod
- ✓ General reference framework for astroparticle community
- ✓ Extension of LISs validity up to 100 TeV/n scale
- ✓ Study of high mass nuclei, abundances and possible anomalous secondaries
- ✓ Iron spectrum and its fine features
- ✓ High mass primary/half-primary (Na-Al) and secondaries (Fluorine)
- ✓ Iron/sub Iron predictions and study of the past SNe activity in the solar neighborhood with Iron isotopes
- ✓ Fundamental propagation mechanisms tests: injection vs diffusive breaks scenarios, possible nearby sources….
- ✓ Isotopes physics (deuterium, Li, Be, B…- ongoing)

So we are touching the «cross section wall»

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 (60-90 GeV or 200-400 GeV mass DM)

Low energy DM candidates

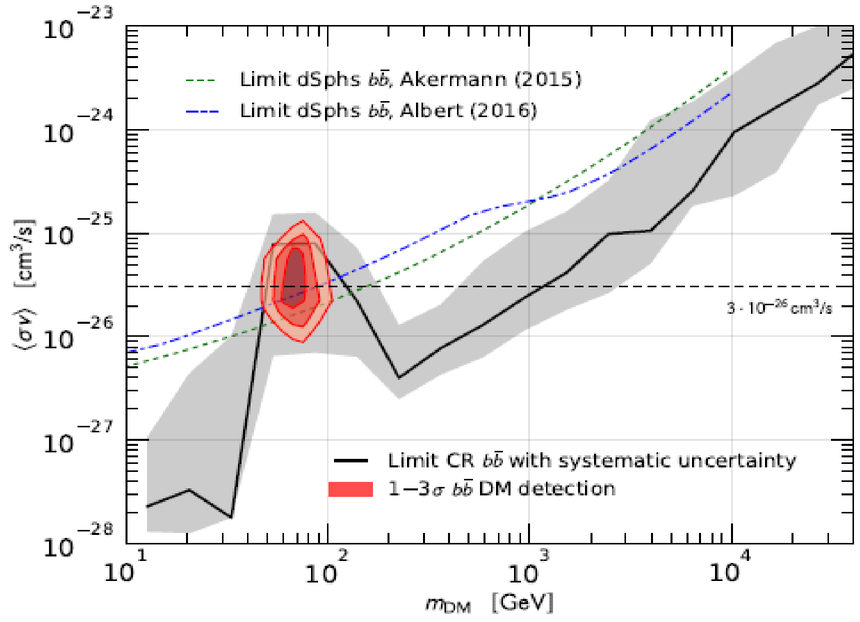
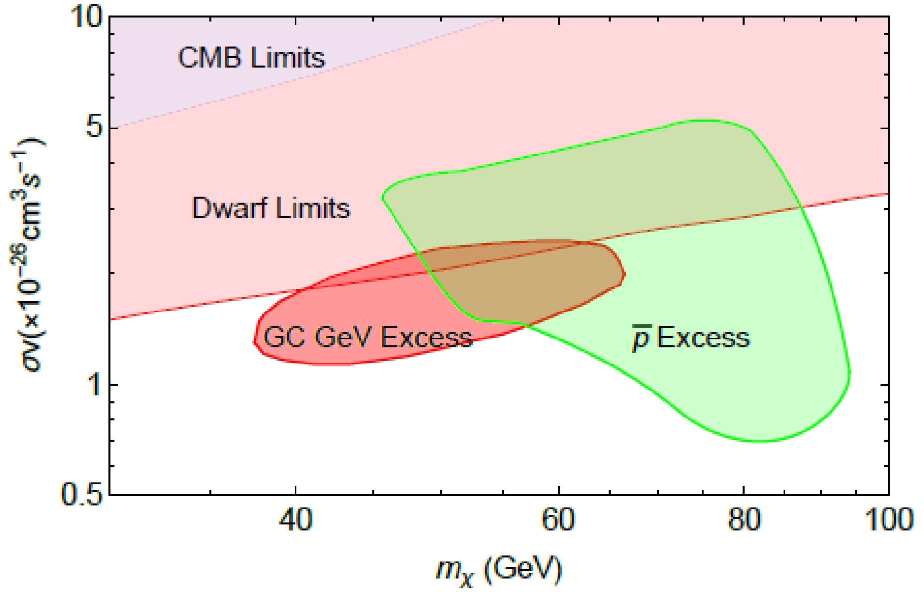
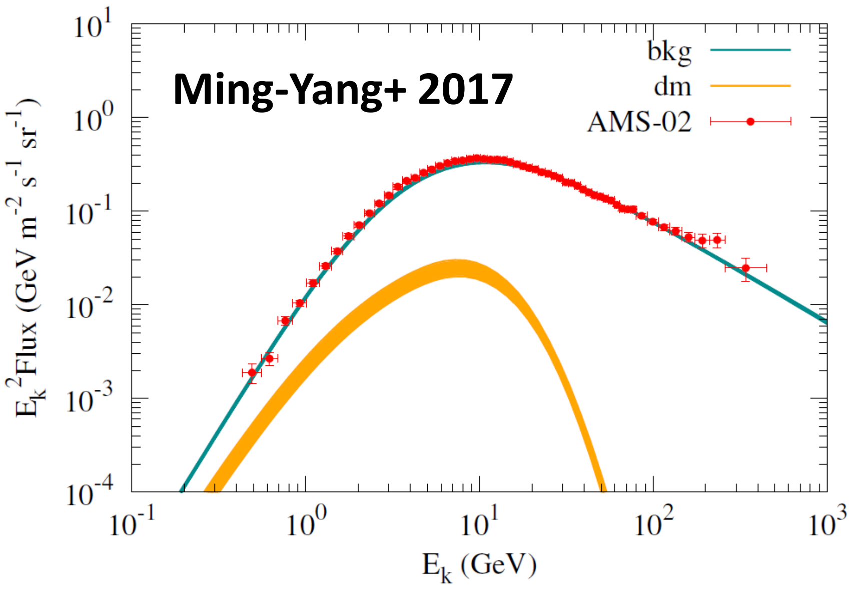


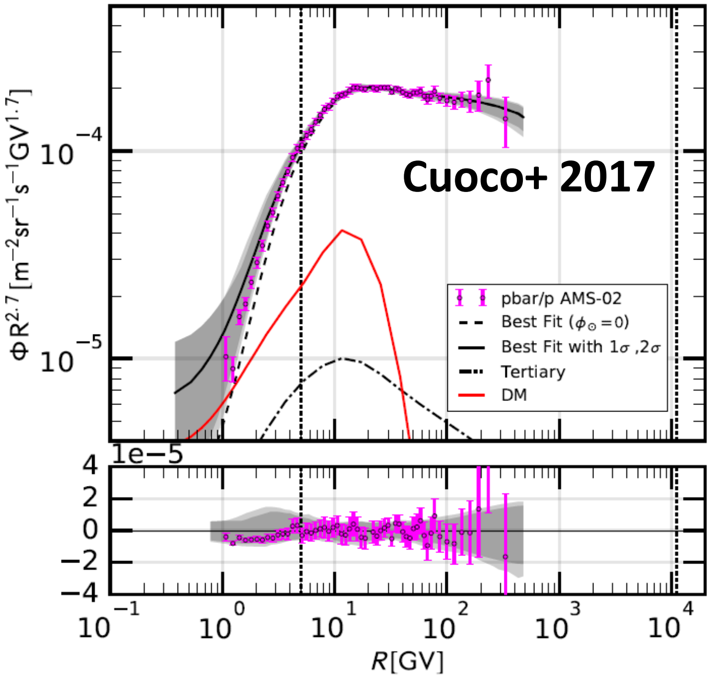
FIG. 4: Best fit regions (1, 2 and 3 σ) for a DM component of the antiproton flux, and limits on the DM annihilation cross-section into $b\bar{b}$ final states. The grey shaded uncertainty band is obtained from the envelope of the various fits presented in FIG. 3. For comparison we show limits on the annihilation cross-section obtained from gamma-ray observations of dwarf galaxies [49, 51], and the thermal value of the annihilation cross-section, $\langle\sigma v\rangle \approx 3 \times 10^{-26}$ cm^{3}s^{-1}.

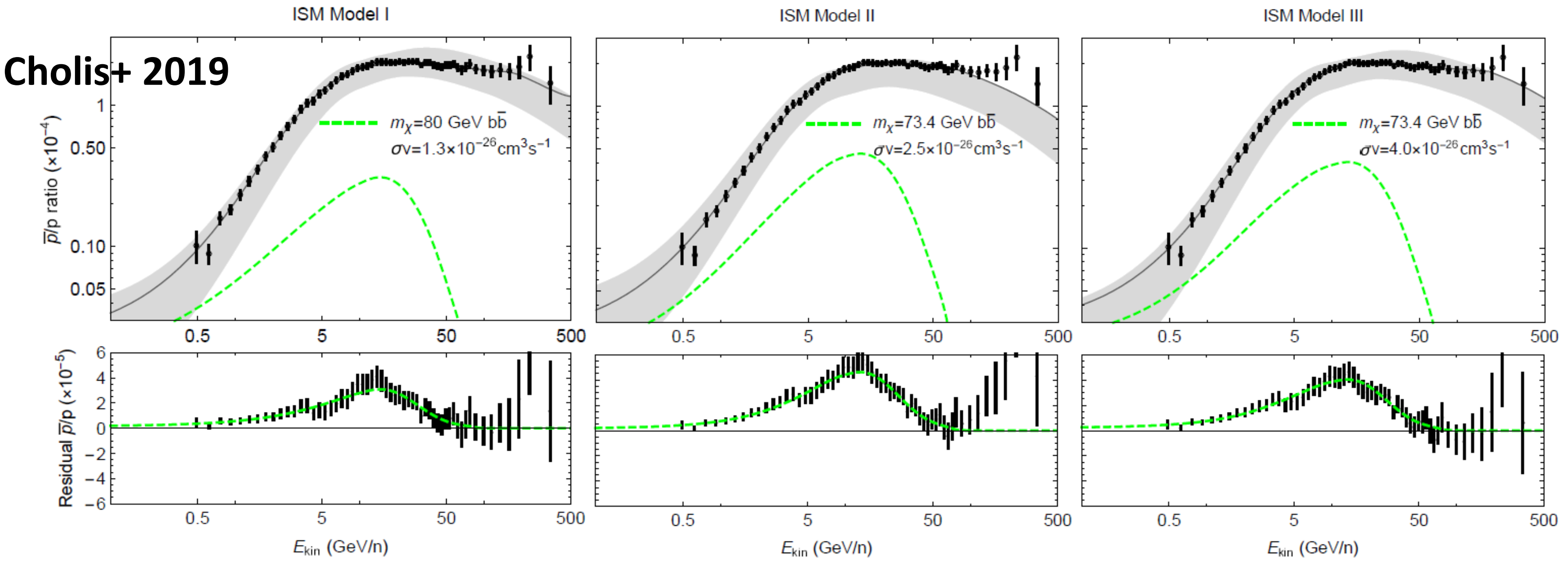
Phys. Rev. Lett. **118**, 191102 (2017)



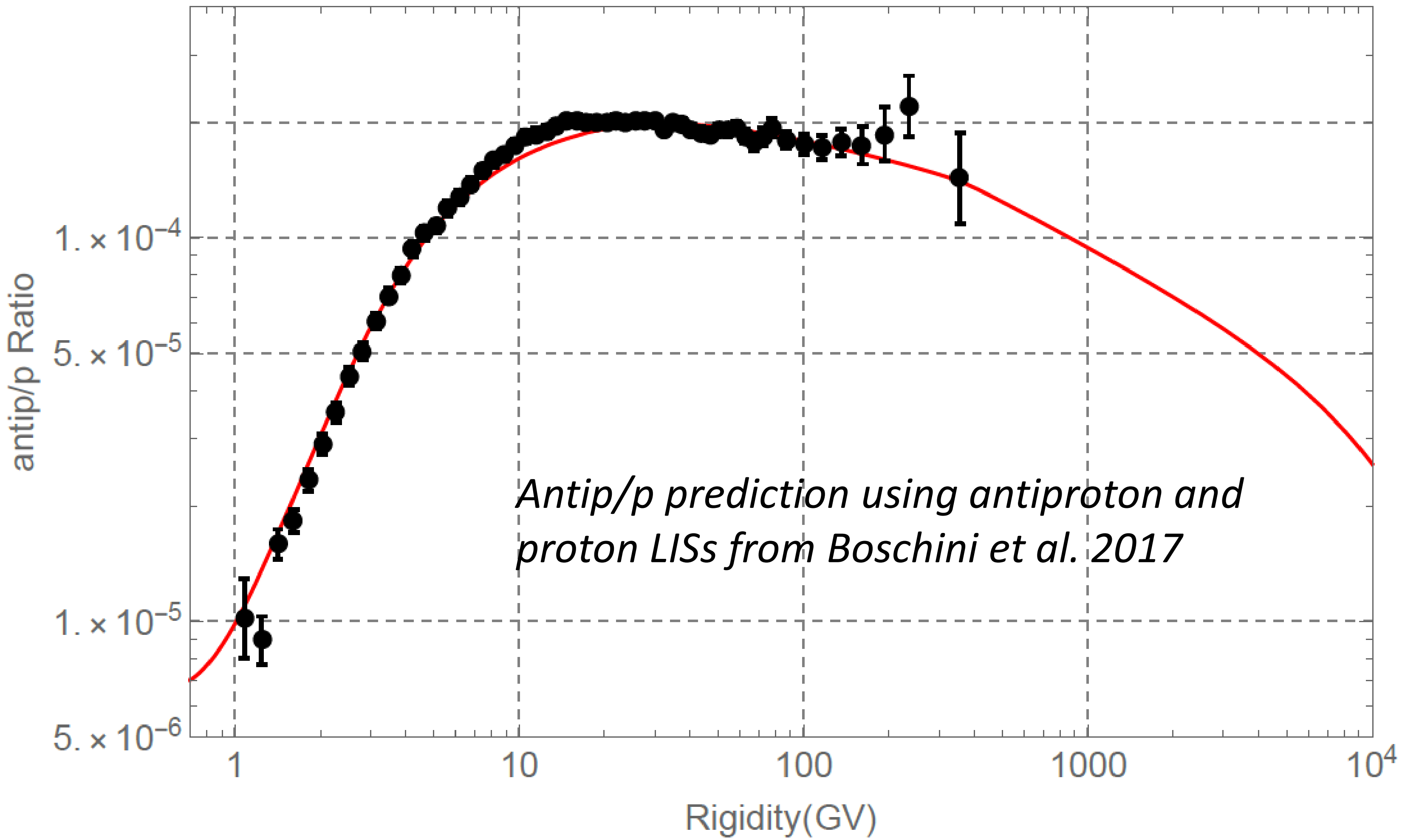
arXiv:1903.02549


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


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

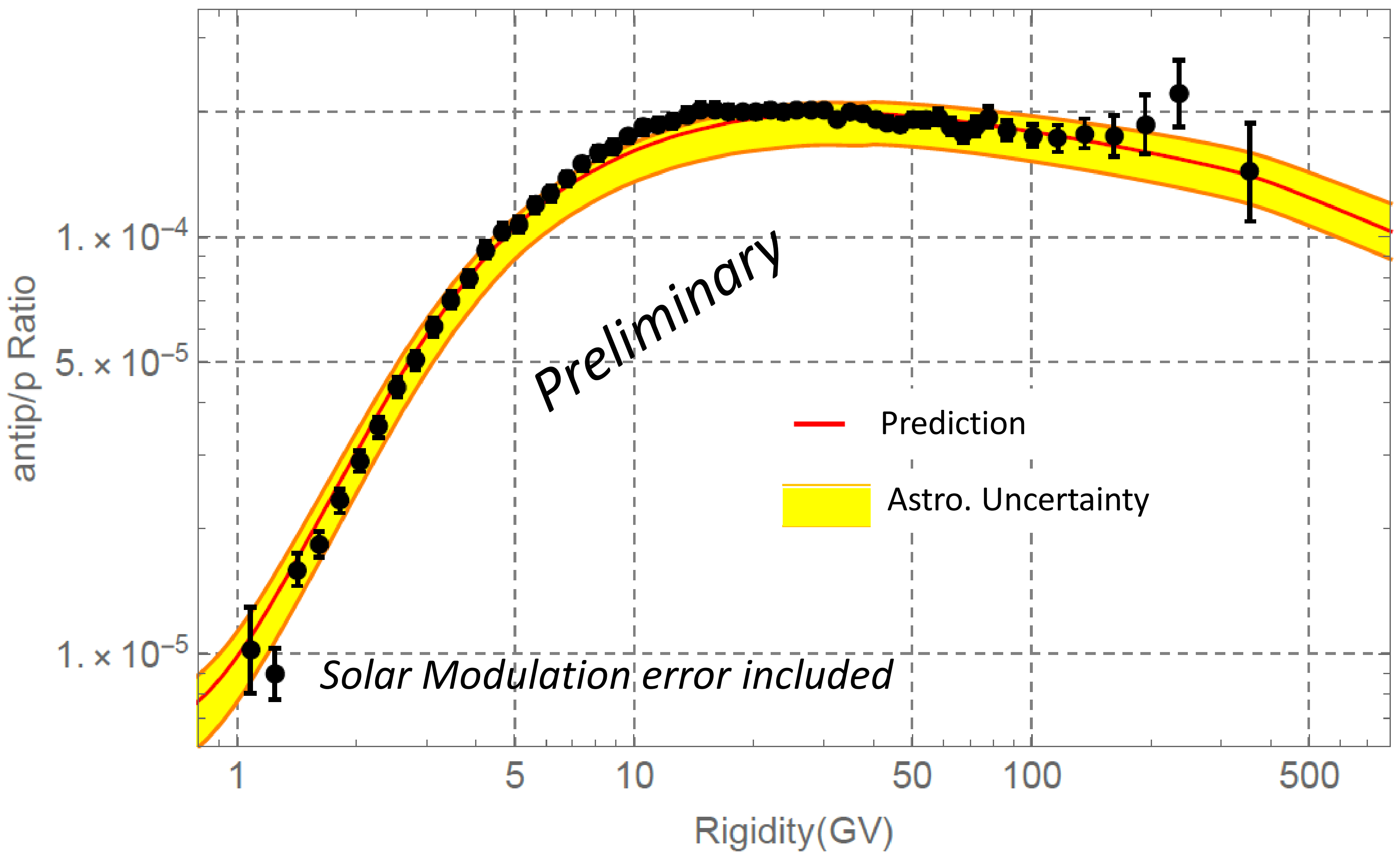
Antip/p Ratio and search for anomalies



- In standard GALPROP: analytic **parameterizations from Tan & Ng based on 70's data**: PRD **26** (1982) 1179; J.Phys.G:Nucl Phys **9** (1983) 227
- **Moskalenko has recently recalculated the $\overline{p}$ production in pp/pA/AA-interactions using EPOS-LHC and QGSJET-II-04 MC generators, tuned to accelerator data (ApJ, 803:54, 2015)**

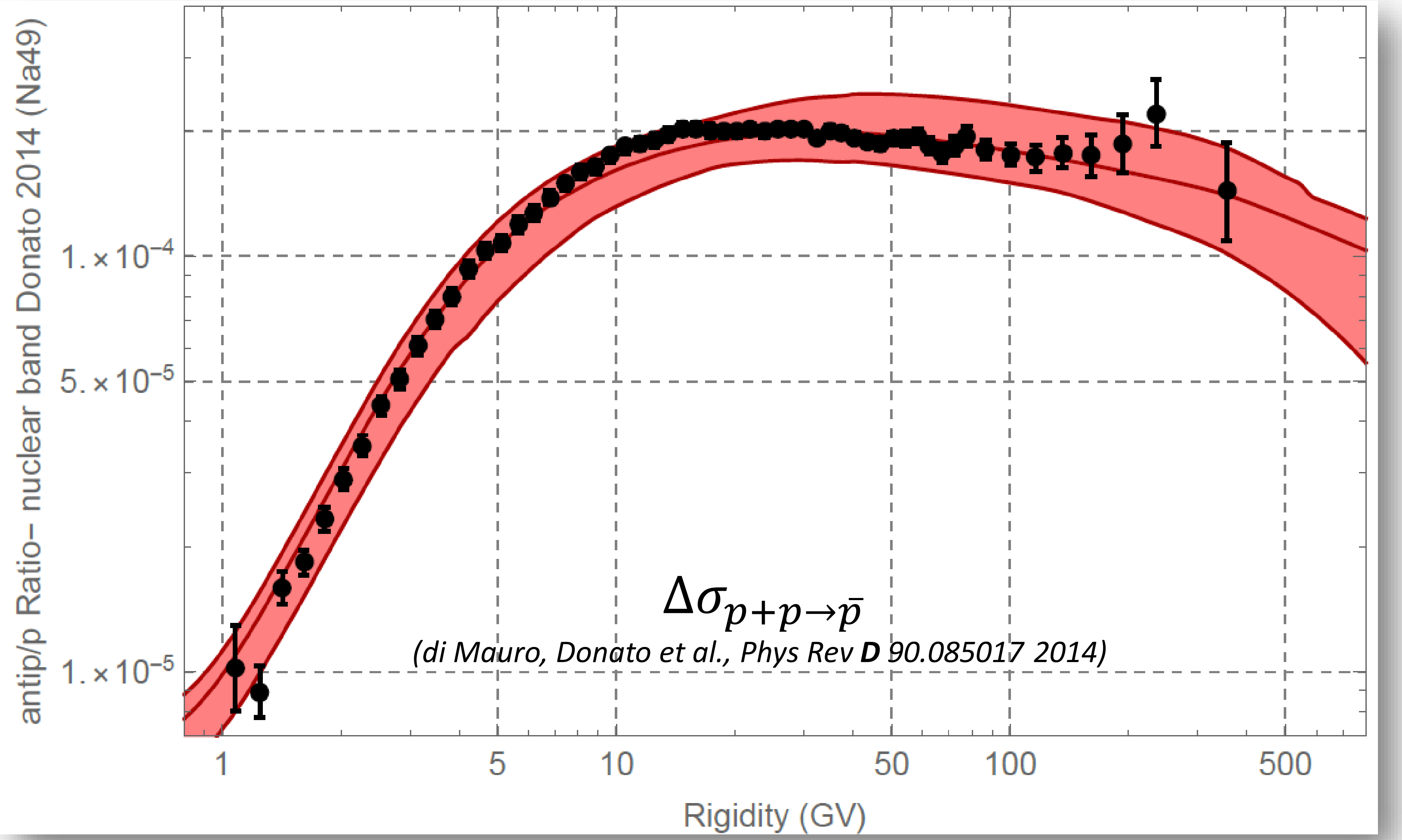
Astrophysical Uncertainty

With the AMS-02 based propagation scheme and the MCMC approach we compute $\bar{p}/p$ astrophysical uncertainties (remembering that z-D0 ratio is basically fixed by B/C)



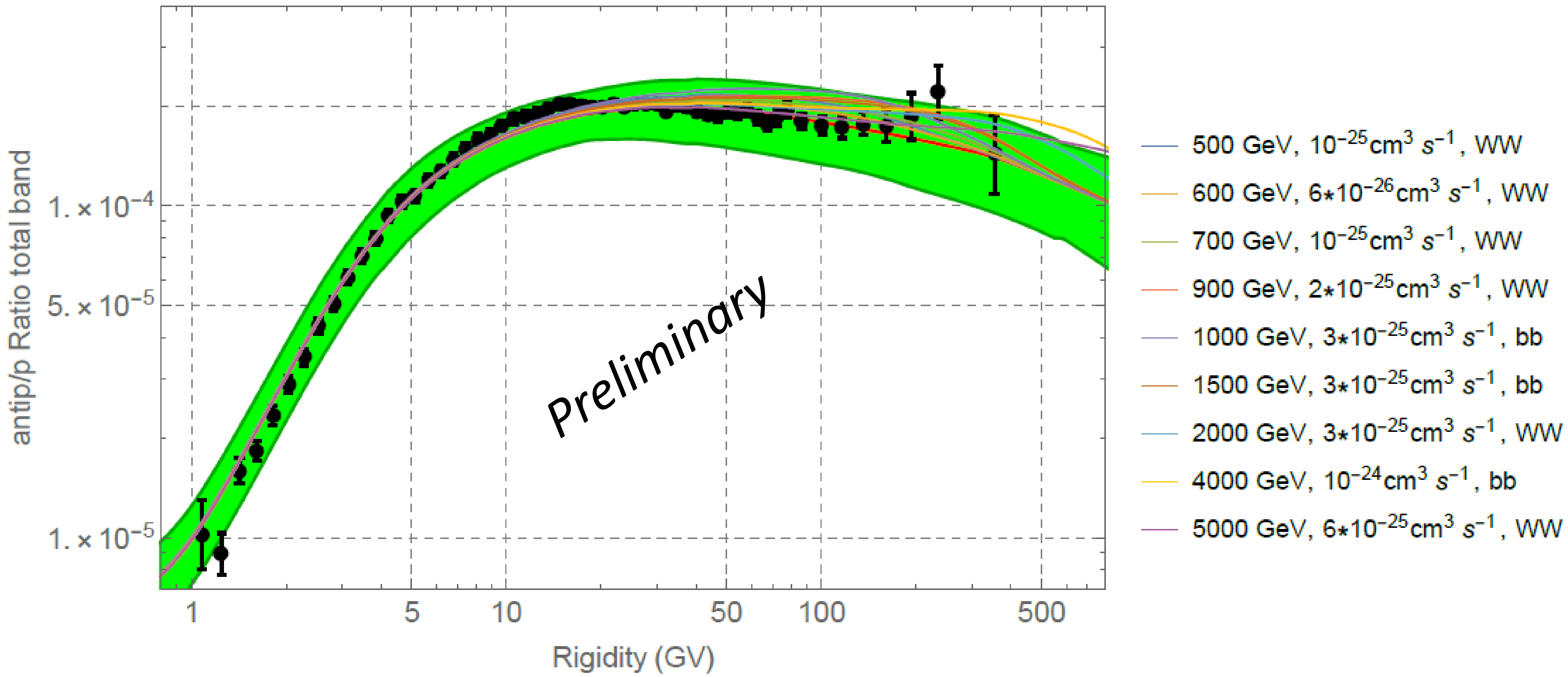
Nuclear uncertainty band for pp collisions

From NA49+BRAHMS analysis



Total uncertainty band (astro&Donato) + DM DarkSUSY simulations

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



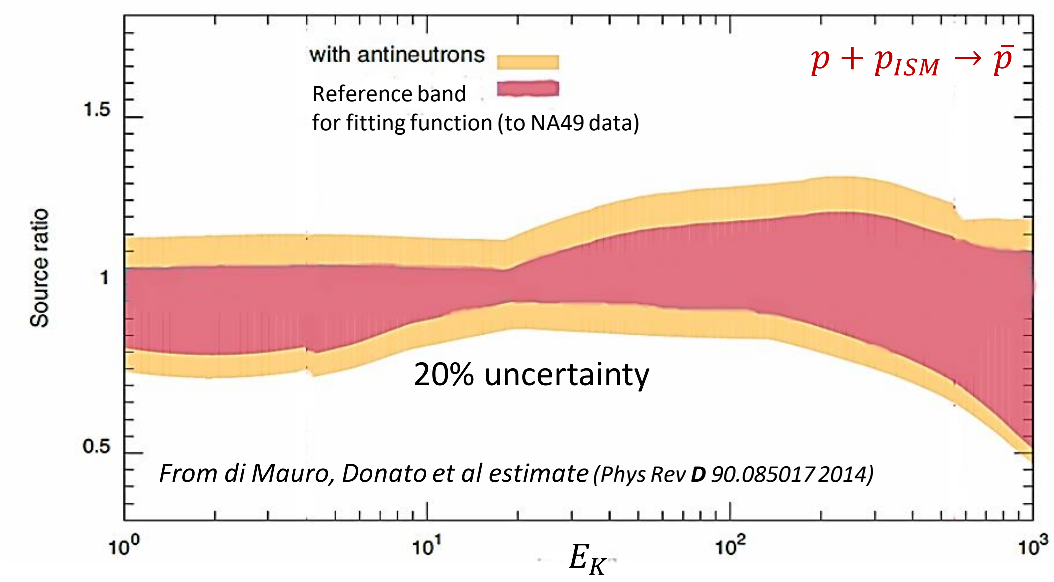
- **AMS-02 results are compatible with a secondary production but DM signals could in principle still hide within the overall error band.**
- With the nuclear measurements effort we will be capable of extracting a possible DM signal.

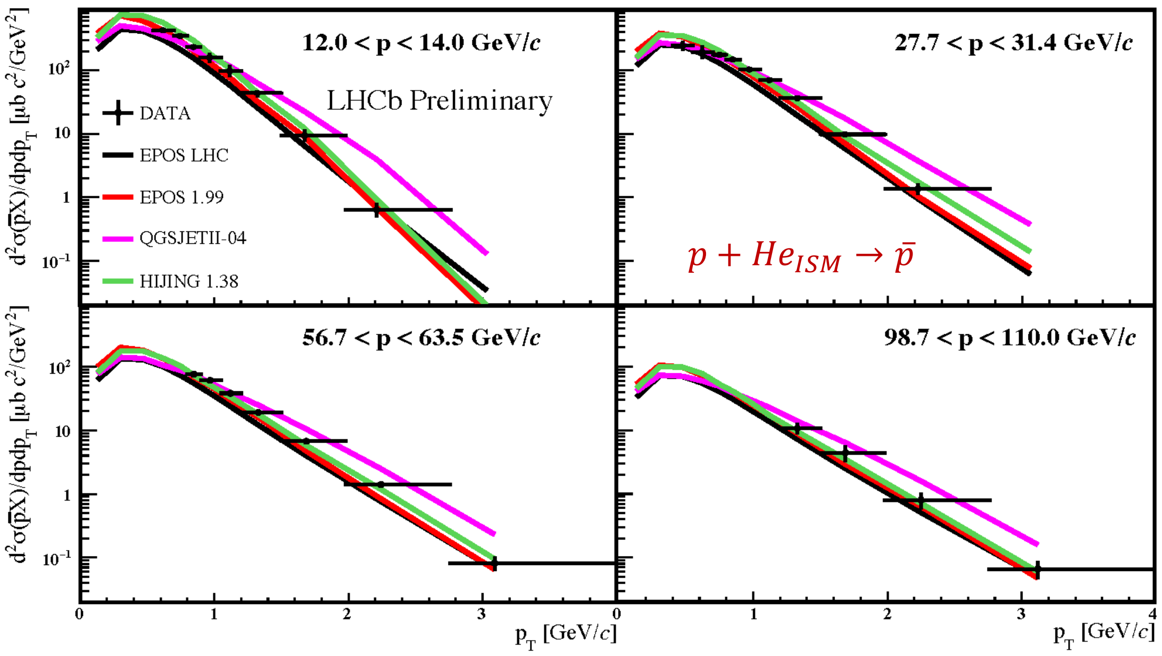
Nuclear uncertainties in the antiproton channel

$$p + ISM \rightarrow \bar{p} \ldots \begin{cases} p + p_{ISM} \rightarrow \bar{p} \ldots \\ p + He_{ISM} \rightarrow \bar{p} \ldots \end{cases}$$

Poor measurements (forthcoming COMPASS and SHINE data)

No direct measurements until 2017 (SMOG)



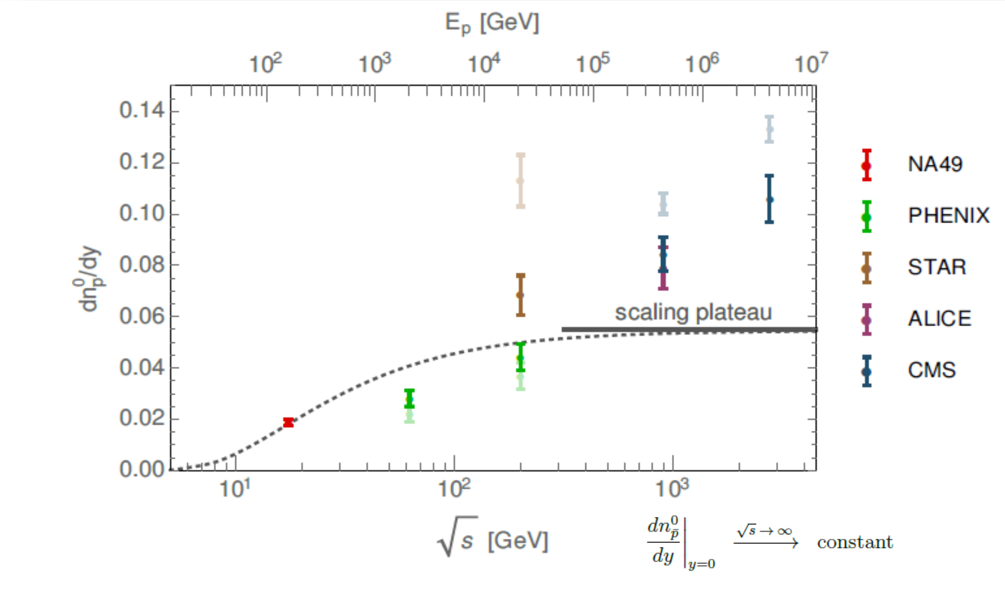


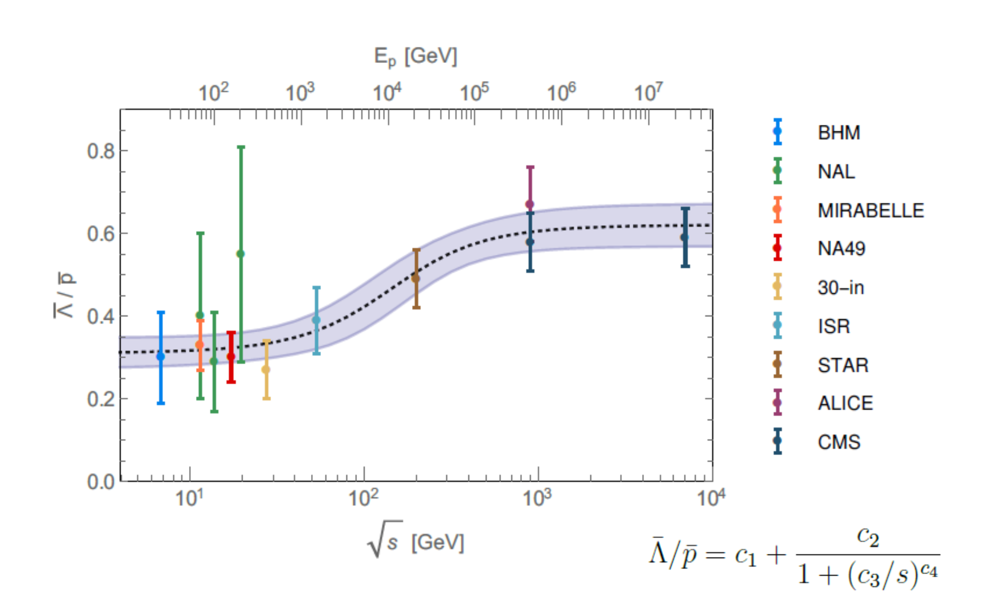
- Uncertainties in the pbar production spectrum are at least 10%.
- **Below 100 GeV the uncertainties for $pp \rightarrow \bar{p}$ are about 10-20%**
- **Above 100 GeV extrapolations lead to errors larger than 30%**

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

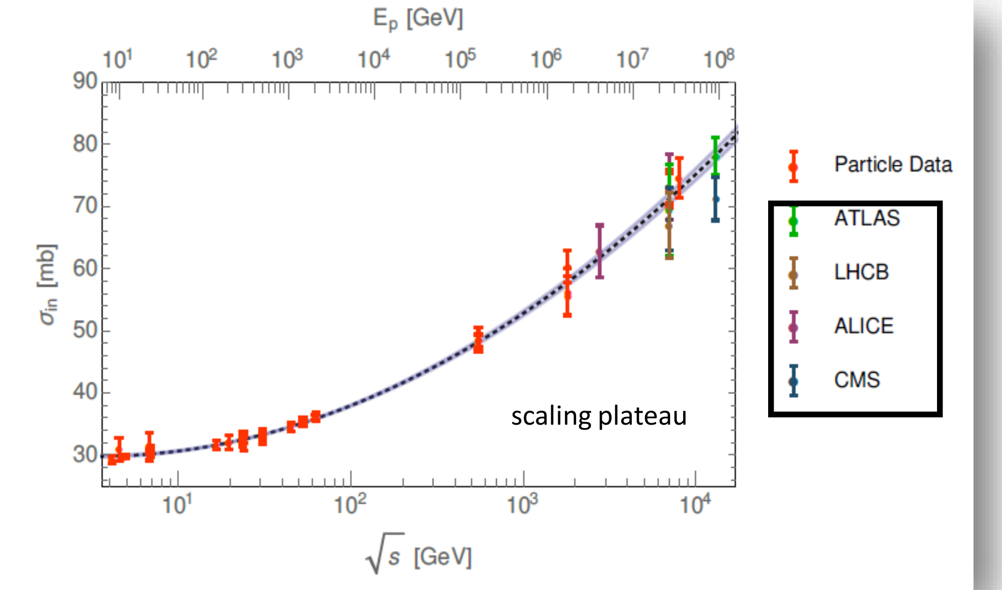
Antiproton multiplicity at central rapidity





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

Total inelastic cross section in proton proton scattering

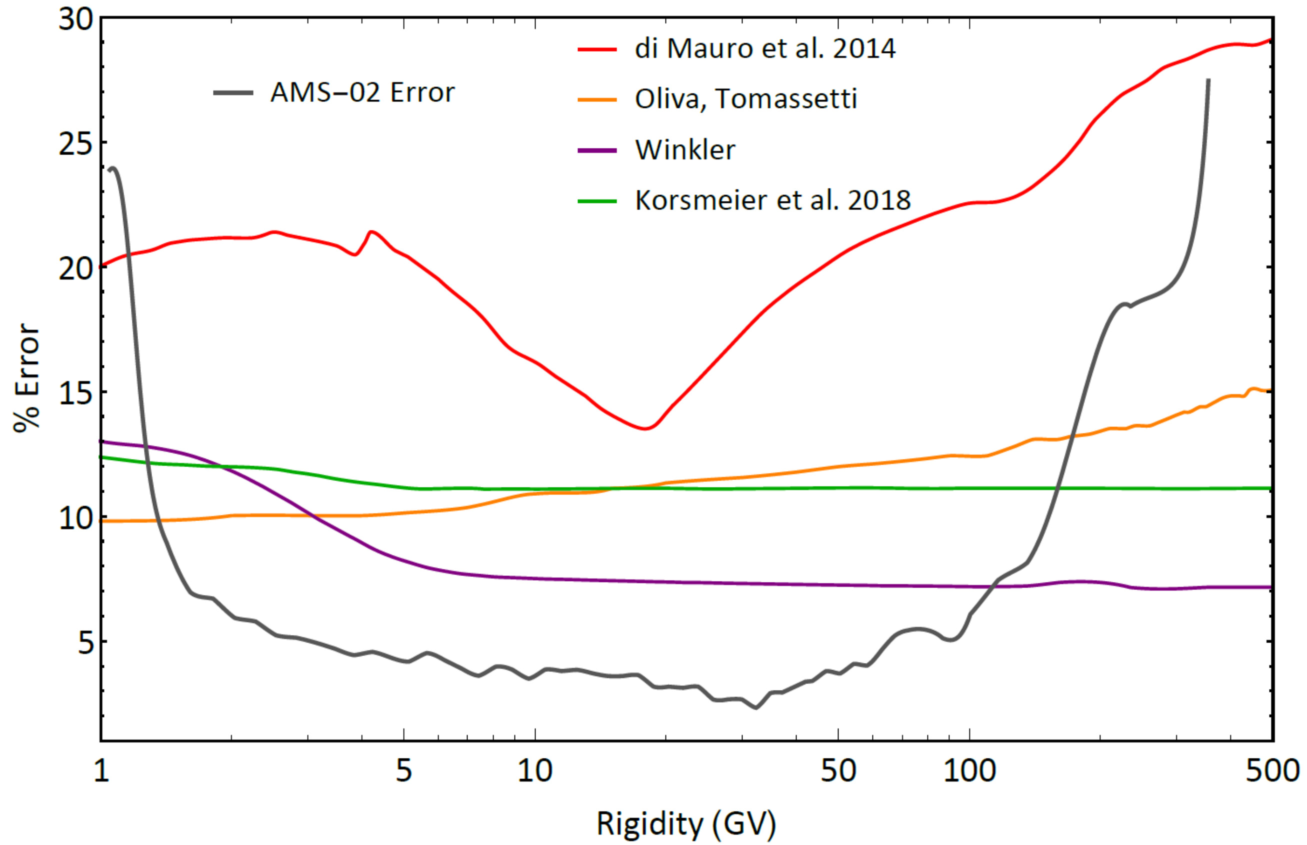


- There are new improved calculation of secondary antiproton production, with a particular focus on the high energy regime, **employing the most recent collider data**.
- A substantial **increase of antiproton cross sections with energy, driven by the violation of Feynman scaling as well as by an enhanced 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 lower than nuclear ones**
- Bologna group has started a collaboration with **COMPASS/AMBER** experiment in order to provide precise and up-to-date pp and pHe cross section measurements for the DM search in the antiproton channel

Comparison between nuclear uncertainties



Letter of Intent:

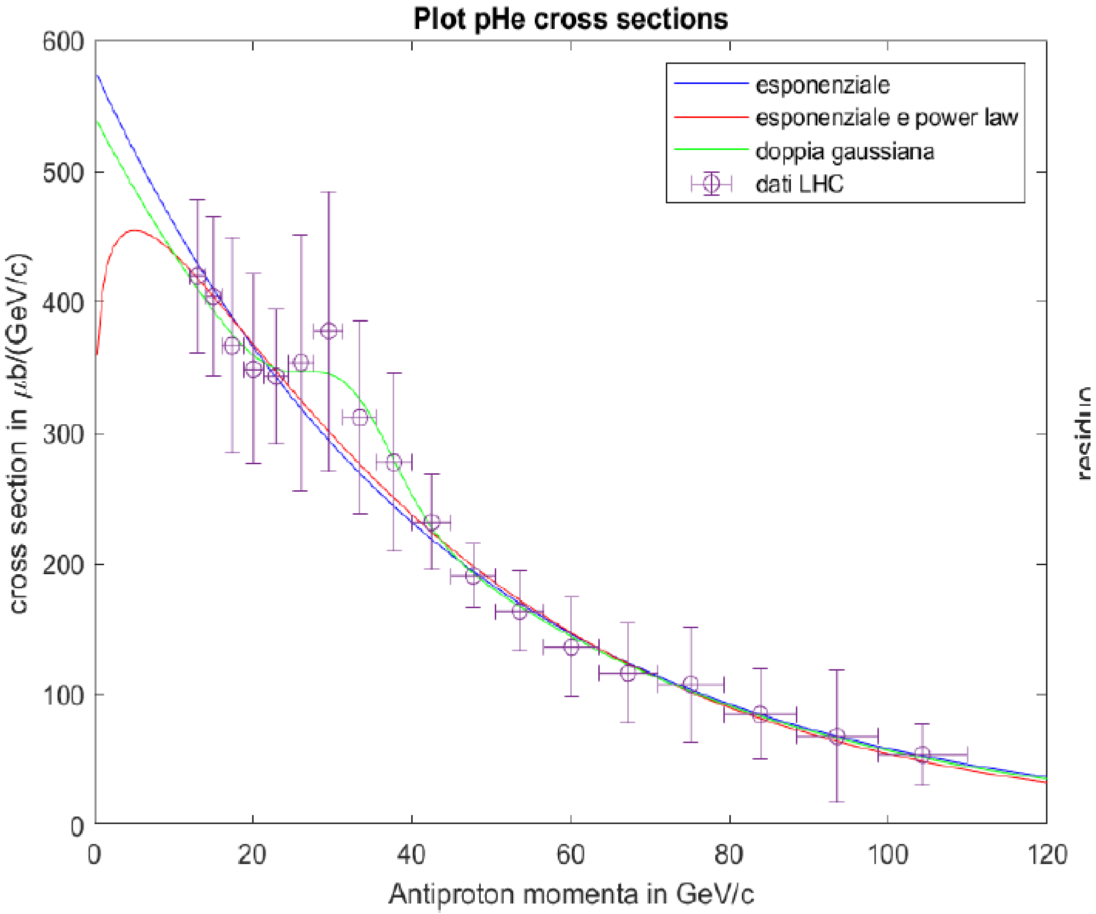
A New QCD facility at the M2 beam line of the CERN SPS[*]

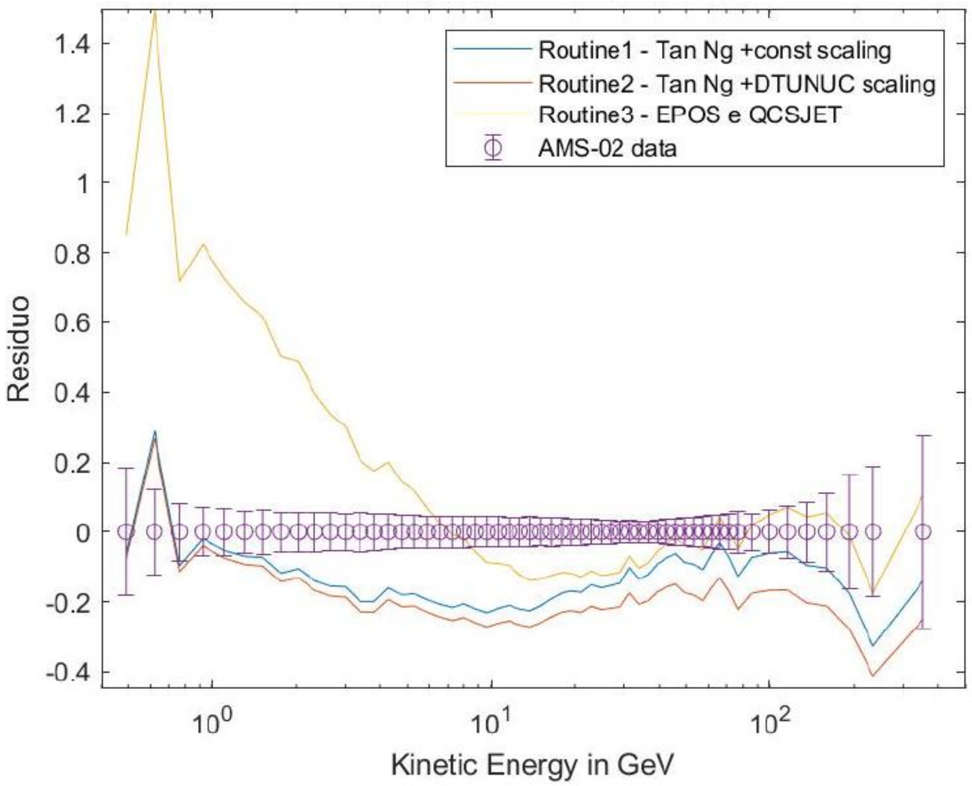
COMPASS++[†]**/AMBER**[‡]

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

COMPASS++[*]**/AMBER**[†]

Nuclear uncertanties: D'Angelo, Thesis 2021





p-He, He-p collision cross section from SMOG

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, 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 the measurements;
- The next step for antimatter study is to include deuterons, antideuterons and antihelium in the machine to predict their fluxes and guide the forthcoming measurements by AMS-02 and future experiments.