Numerical modeling of galactic cosmic ray proton and helium observed by AMS-02 during the solar maximum of Solar Cycle 24

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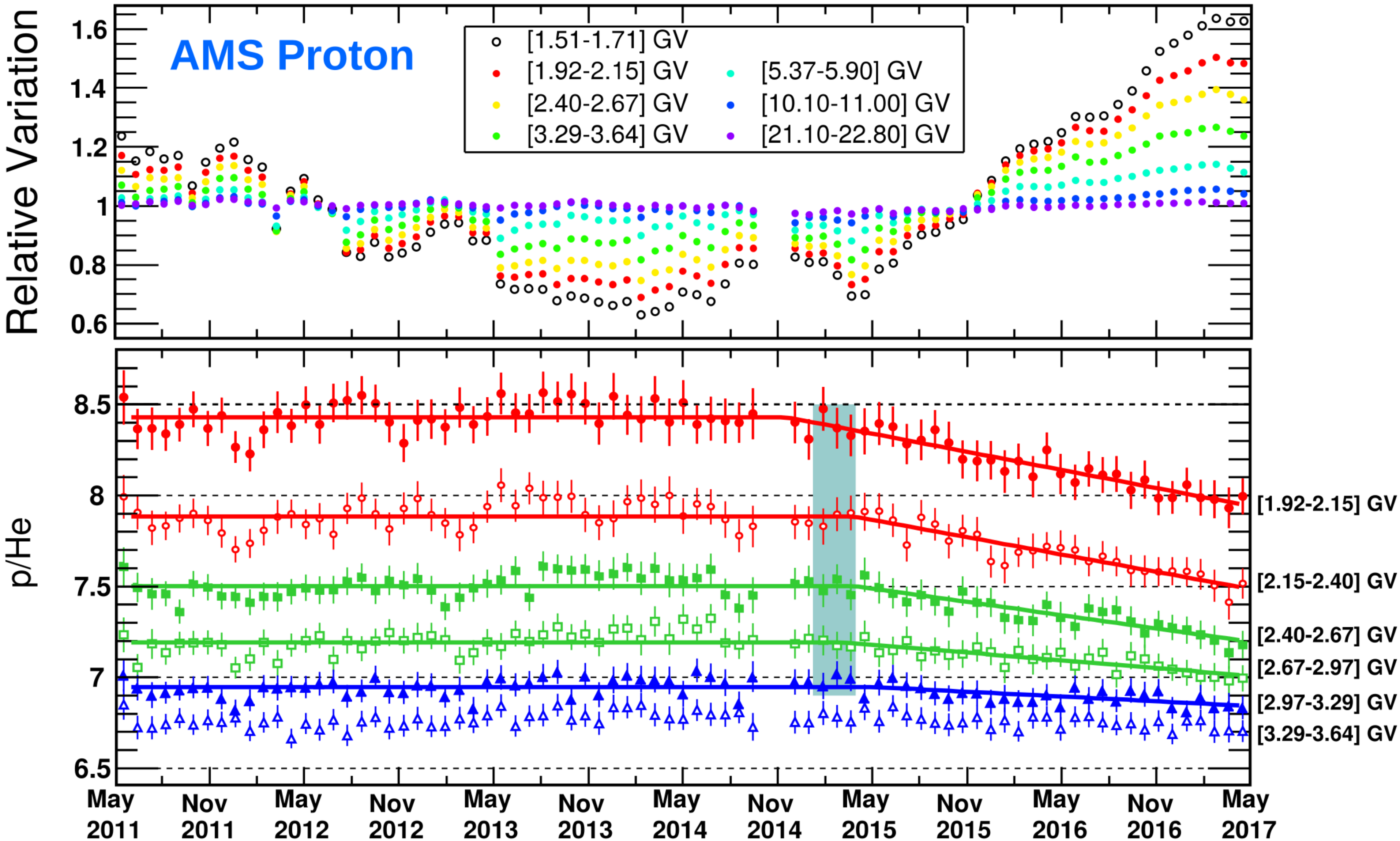
Outline

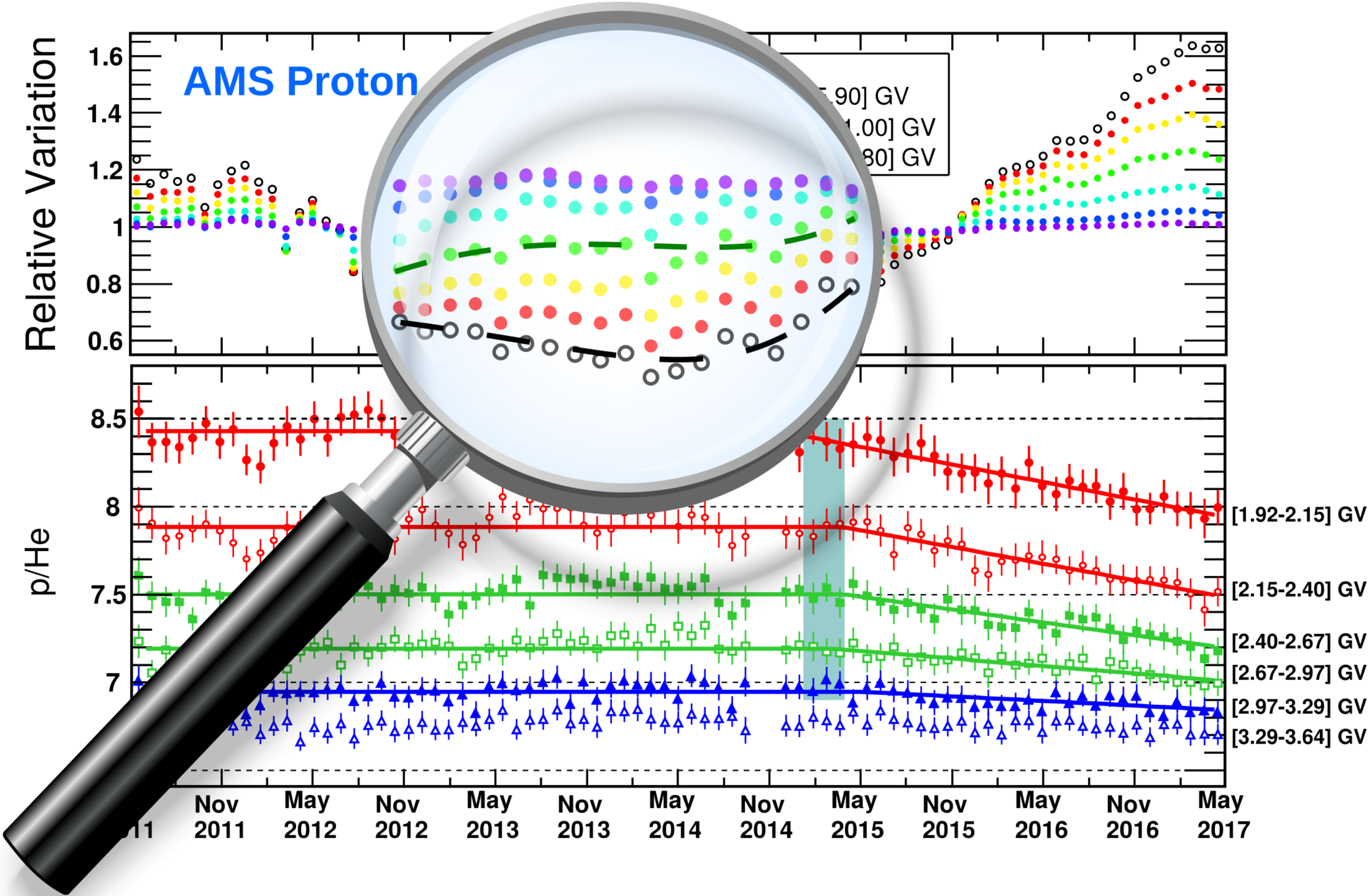
- Numerical model for GCR transport in the heliosphere
- Fitting of AMS-02 monthly proton fluxes
- Comparison of numerical model prediction for p/He with AMS-02 monthly data

Explaining AMS-02 monthly fluxes



Aguilar et al. PRL 051101, 2018

Explaining AMS-02 monthly fluxes



Transport equation of GCRs

GCR propagation in the heliosphere is described by the Parker equation:

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind plasma convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drift}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Energy losses}} + \underbrace{Q}_{\text{Sources/sinks}}$$

K = diffusion tensor
f = omnidirectional distribution function of GCRs

Particle drifts due to heliospheric magnetic field gradients and heliospheric current sheet.

Adiabatic energy losses due to expansion of solar wind.

Numerical model description

- Created in South Africa (Burger, Potgieter) in FORTRAN (1998), then translated in C (2010) and C++/ROOT (2016)
- Nvidia CUDA (2010) and OpenMP (2017) support to run in parallel
- Three-dimensional steady-state model solving numerically the Parker transport equation of galactic cosmic rays in the heliosphere with the ADI (Alternating Direction Implicit) method
- All processes included
- Termination shock: diffusion barrier, but no reacceleration (should be negligible for p, He above 1 GV at Earth)

Diffusion and drift coefficients

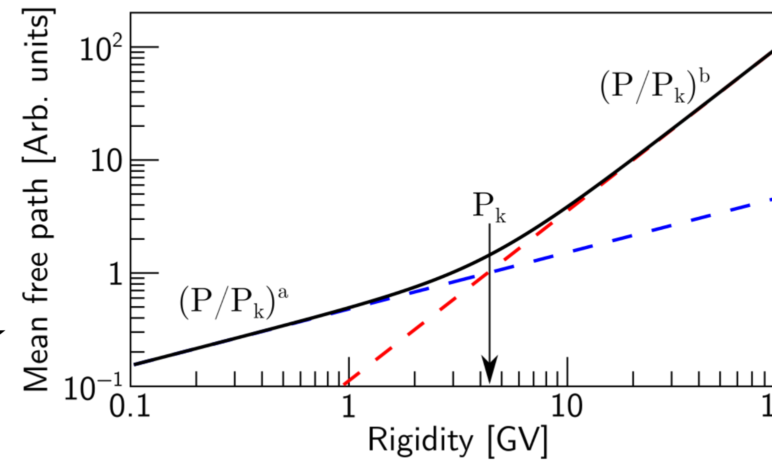
Parallel diffusion

$6\text{x}10^{20}$ cm^2 s^{-1}

Parametrization: $k_{\parallel} = k_{\parallel,0}\,\beta\,\frac{B_0}{B}\left(\frac{P}{P_k}\right)^{a}\left[1+\left(\frac{P}{P_k}\right)^{c}\right]^{\frac{b-a}{c}}$

Spatial dependence

Rigidity dependence



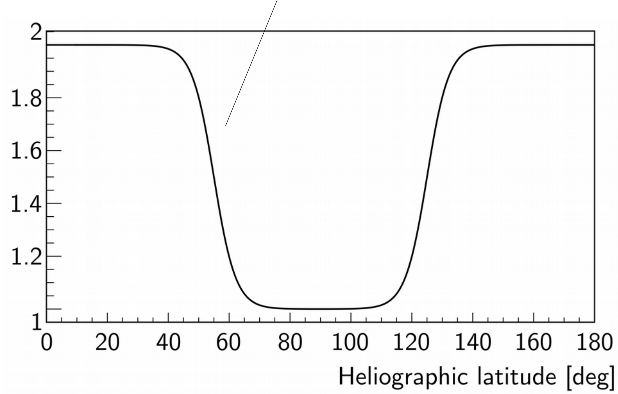
Perpendicular diffusion

$$\kappa_{\perp,r} = \kappa^0_{\perp,r}\kappa_{\parallel}$$

$$\kappa_{\perp,\theta} = f(\theta)\kappa^0_{\perp,\theta}\kappa_{\parallel}$$

2%

1%



Drifts

$$\langle \mathbf{v}_A \rangle = \frac{pv}{3q}\frac{(\omega\tau_A)^2}{1+(\omega\tau_A)^2}\nabla\times\frac{\mathbf{B}}{B^2} = \nabla\times\kappa_A\mathbf{e}_B$$

$$\kappa_A = \kappa_{A,0}\frac{v}{3}r_L\frac{\left(\frac{P}{P_{A,0}}\right)^2}{1+\left(\frac{P}{P_{A,0}}\right)^2}$$

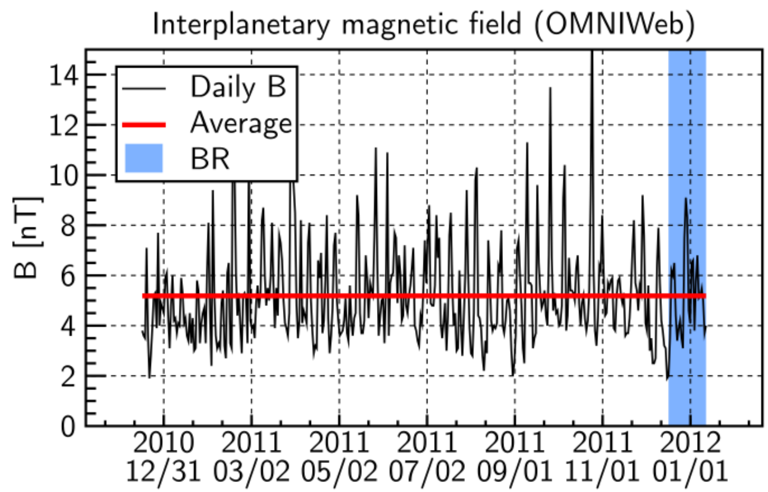
Scattering correction

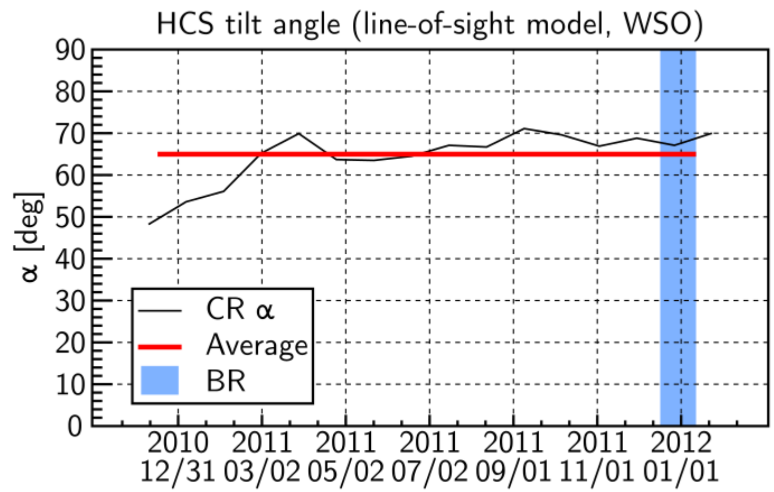
Weak scattering limit

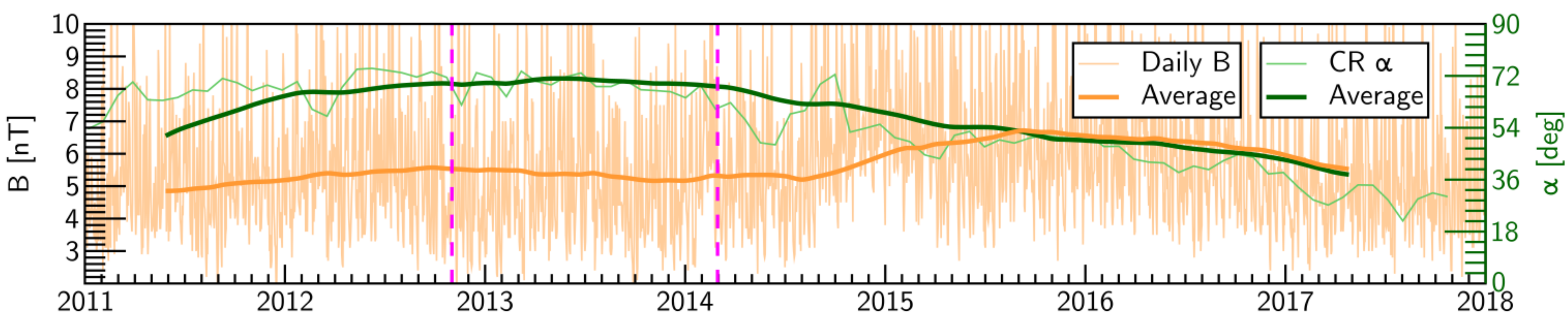
$r_L = P/B$

Fixing the heliosphere status

For each AMS-02 BR flux, tilt angle and magnetic field strength fixed to the average value of the preceding 12 months.

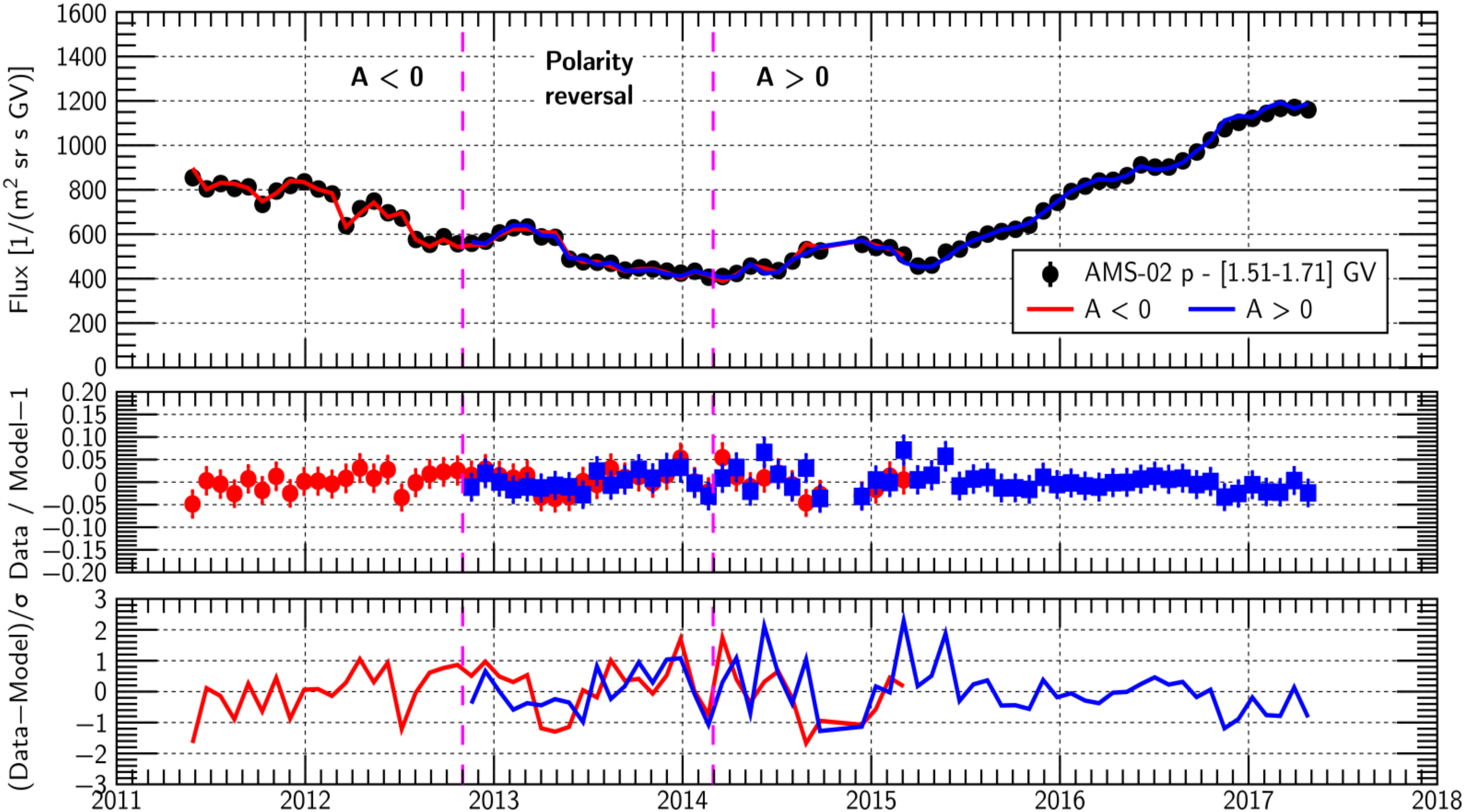






Fit results

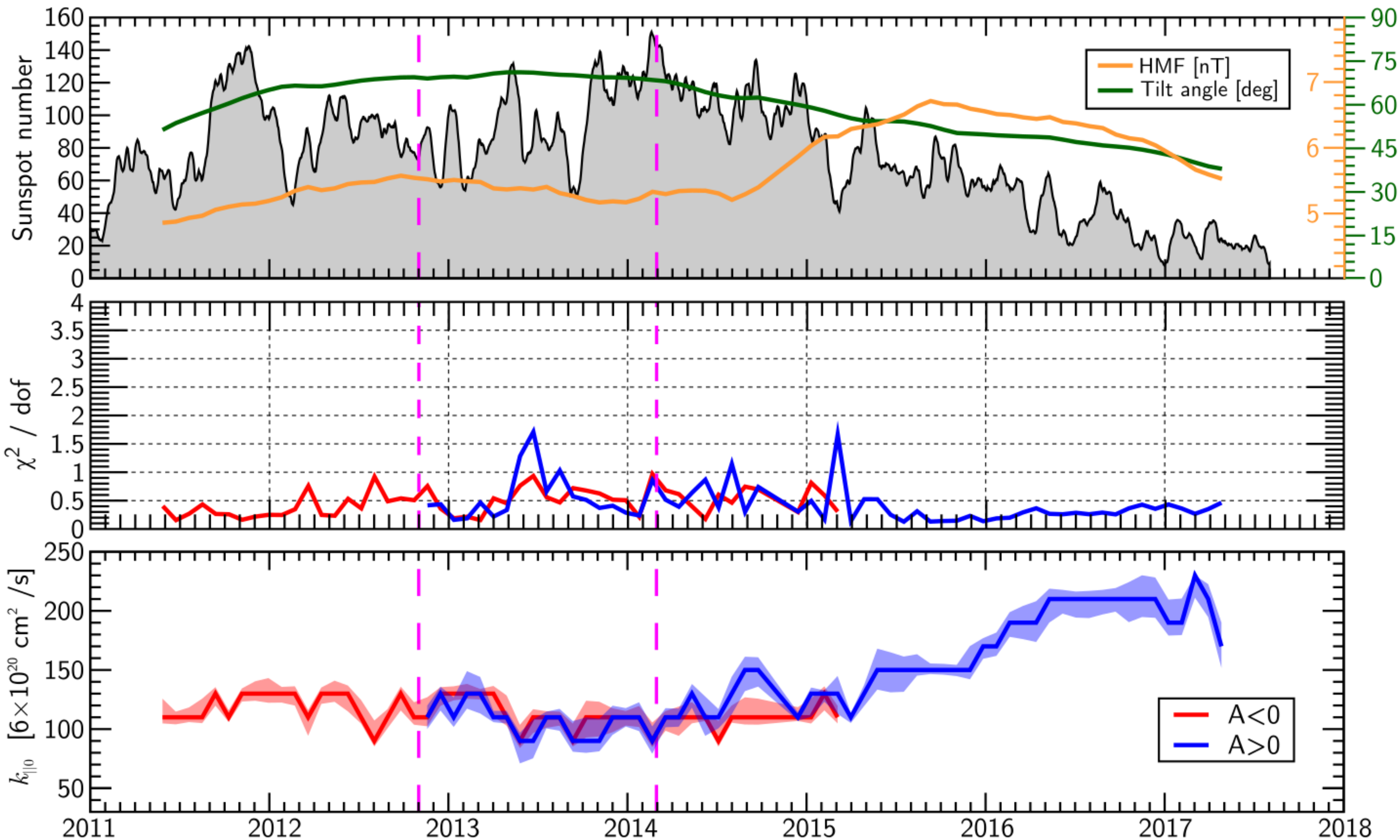
The residuals fluctuate less than 5%, within 1 or 2 sigma from zero.



Fit results

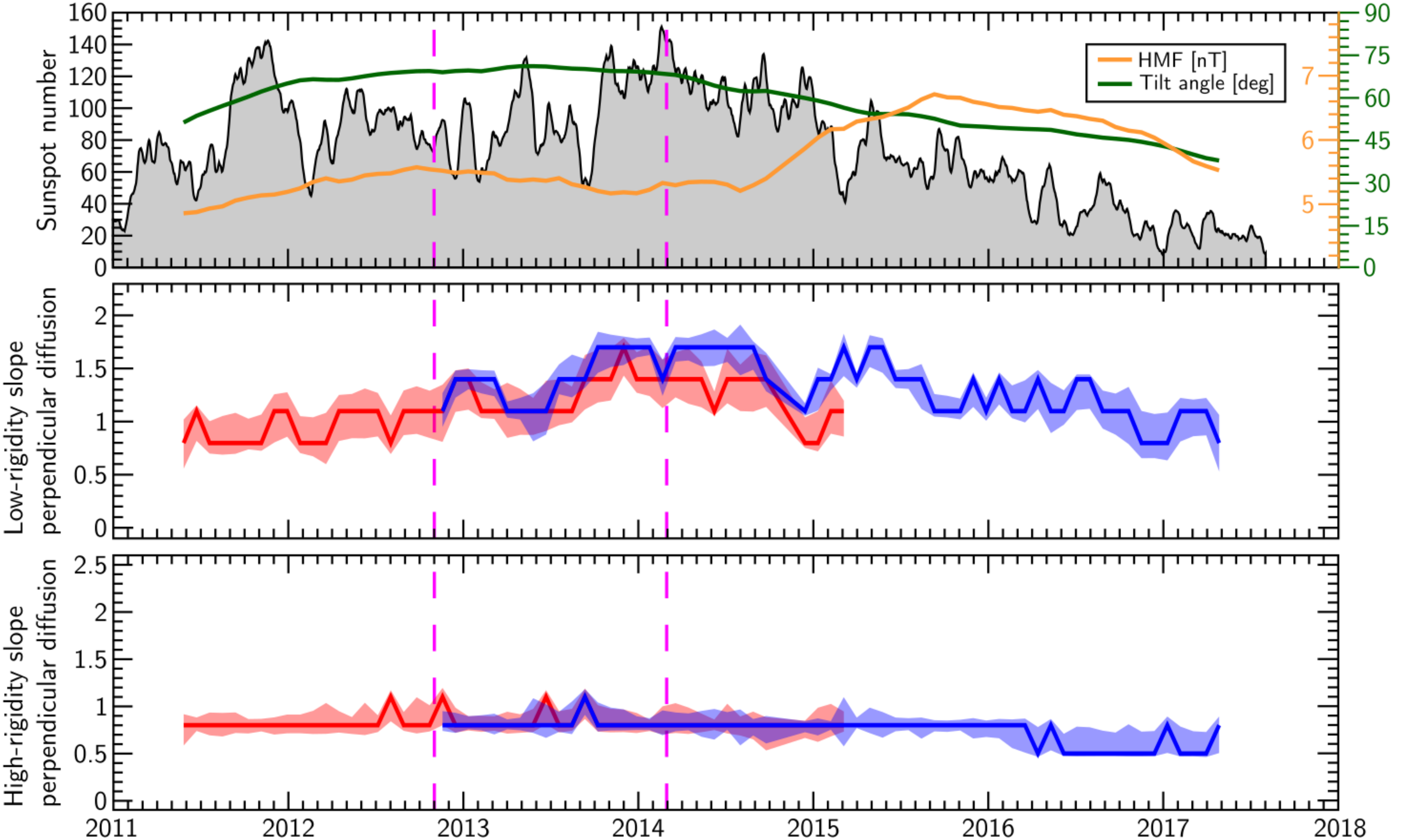
Very good agreement for all Bartels Rotations.

$k_{\parallel 0}$ correlated with solar activity, polarity-independent in the overlapping period.



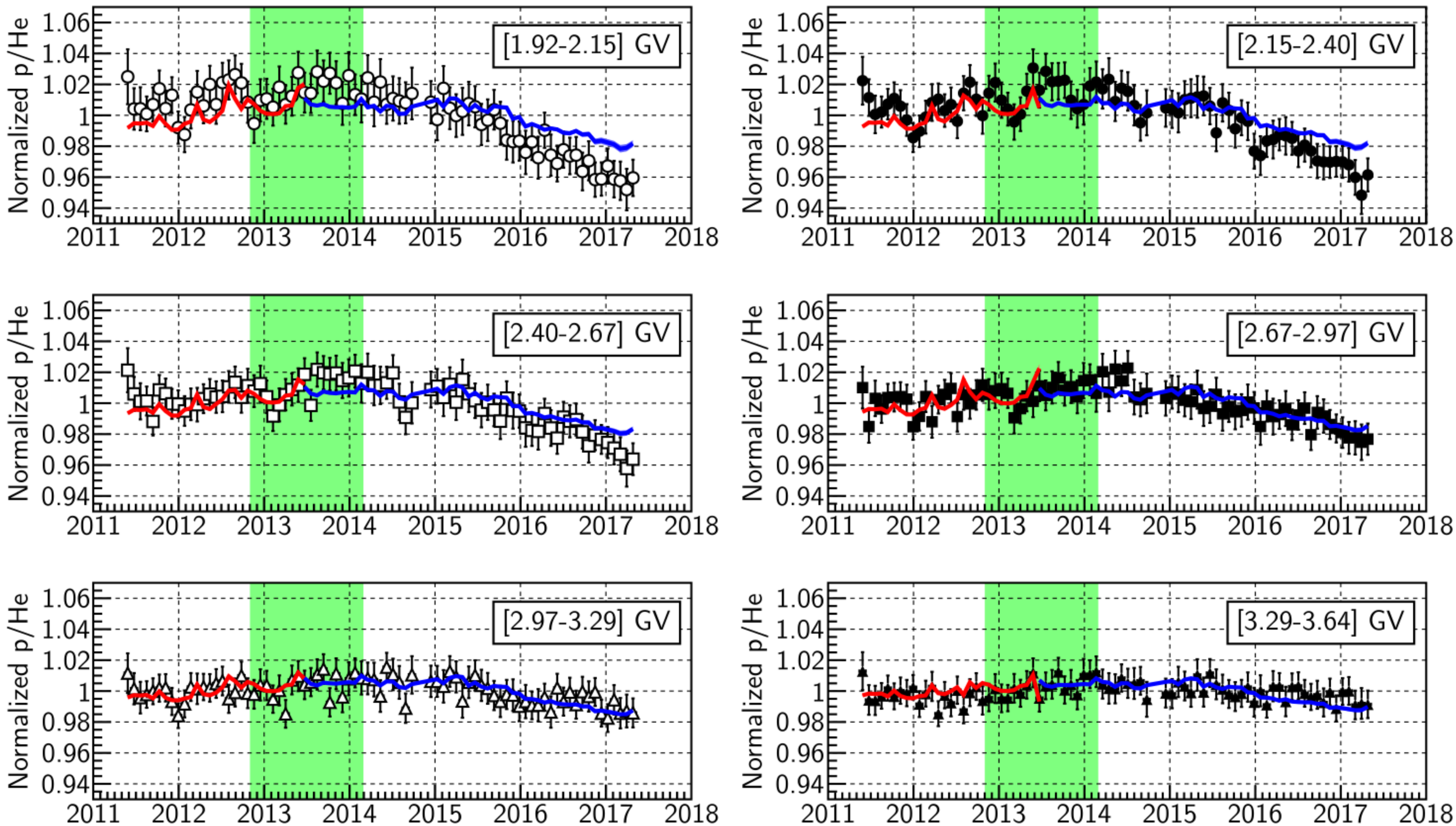
Fit results

Low-rigidity slope of the perpendicular diffusion increases during solar maximum. High-rigidity slope remain basically constant.



p/He model predictions

Same parameters as the one derived from the fit on AMS-02 p.
The model predicts a slightly less steep decrease with respect to data.



Why p/He is time dependent?

Below 3 GV, p/He at a given rigidity is not flat with time, but the mean free paths of p, ^{3}He and ^{4}He are assumed to be exactly the same in rigidity.

Where is the time dependence coming from?

Two hypothesis:

1) A/Z dependence of the diffusion coefficient: $k(r,R) = \beta k_1(r) k_2(R)$
   Even if k_2 is the same for all nuclei, the beta multiplying it will change the divergence of the diffusive flux term in the Parker equation for nuclei with different A/Z.
   A/Z(p) = 1; A/Z(^{3}He) = 3/2; A/Z(^{4}He) = 2

$$\frac{\partial f}{\partial t} = \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drifts}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy changes}}$$

Why p/He is time dependent?

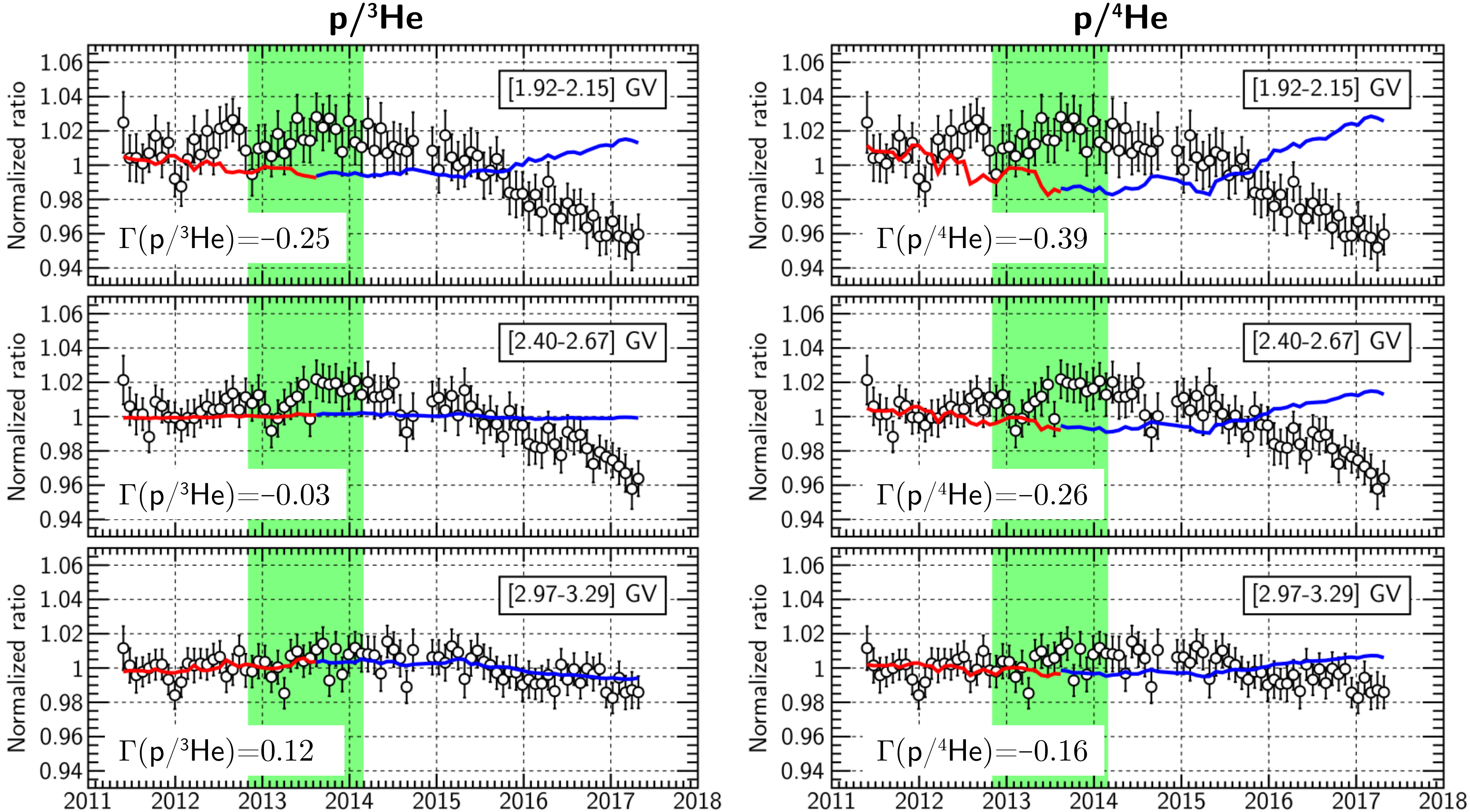
2) Difference in the LIS shape: the adiabatic energy change term in the Parker equation depends on the spectral index, so if two nuclei have the same A/Z, but different spectral index, the last term will be different.

$$\underbrace{\frac{\partial f}{\partial t}}= \underbrace{-\vec{V}_{SW}\cdot\vec{\nabla} f}_{\text{Solar wind convection}} \underbrace{-\vec{V}_{D}\cdot\vec{\nabla} f}_{\text{Particle drifts}} + \underbrace{\vec{\nabla}\cdot(K\cdot\vec{\nabla} f)}_{\text{Particle diffusion}} + \underbrace{\frac{1}{3}\vec{\nabla}\cdot\vec{V}_{SW}\frac{\partial f}{\partial \ln R}}_{\text{Adiabatic energy changes}}$$

Both effects are physically present, but which one is most important?

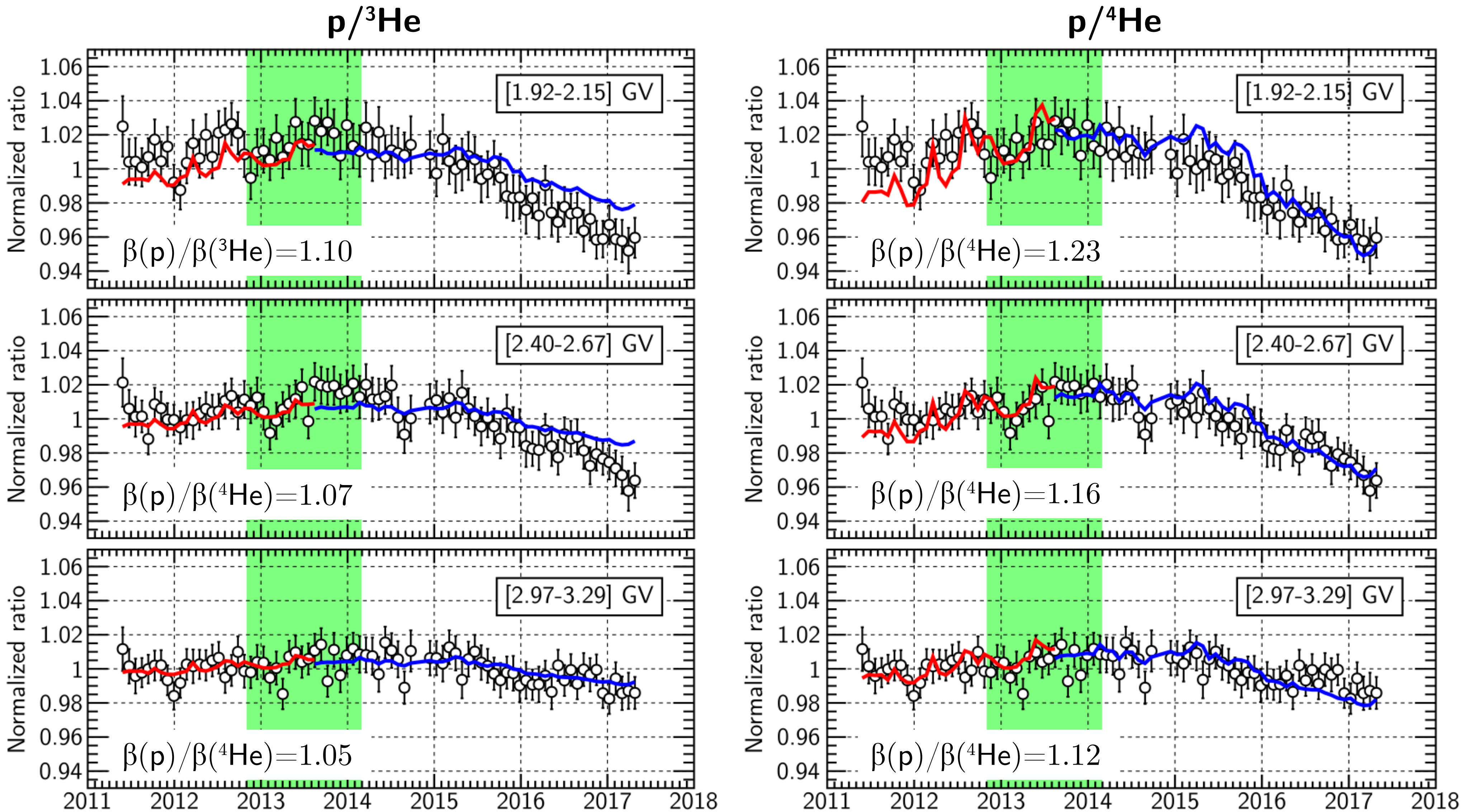
p/He vs time: LIS dependence

Same A/Z=1 for all particles; p LIS; ^{3}He LIS; ^{4}He LIS.



p/He vs time: A/Z dependence

Same LIS for all particles; A/Z(p) = 1; A/Z(^{3}He) = 3/2; A/Z(^{4}He) = 2.



Conclusions

- A 3D numerical model for solving the Parker equation has been tuned to match the AMS-02 proton monthly fluxes from May 2011 to May 2017
- The slopes of the parallel diffusion coefficient are not constrained by AMS-02 data
- The behavior of the fluxes below and above few GV is determined by the low- and high-rigidity slope of the perpendicular diffusion coefficient
- The tuned models reproduce the time trend of the AMS-02 He monthly fluxes and p/He
- The decrease in p/He after 2015 is due to the A/Z dependence of the diffusion coefficient