Sez. Milano-Bicocca

Cosmic Rays backtracing in the Earth Magnetic Field: the importance for AMS-02 of the External Models during the last solar period data taking (from 2011 to 2013)

Davide Grandi

INFN – Milano Bicocca

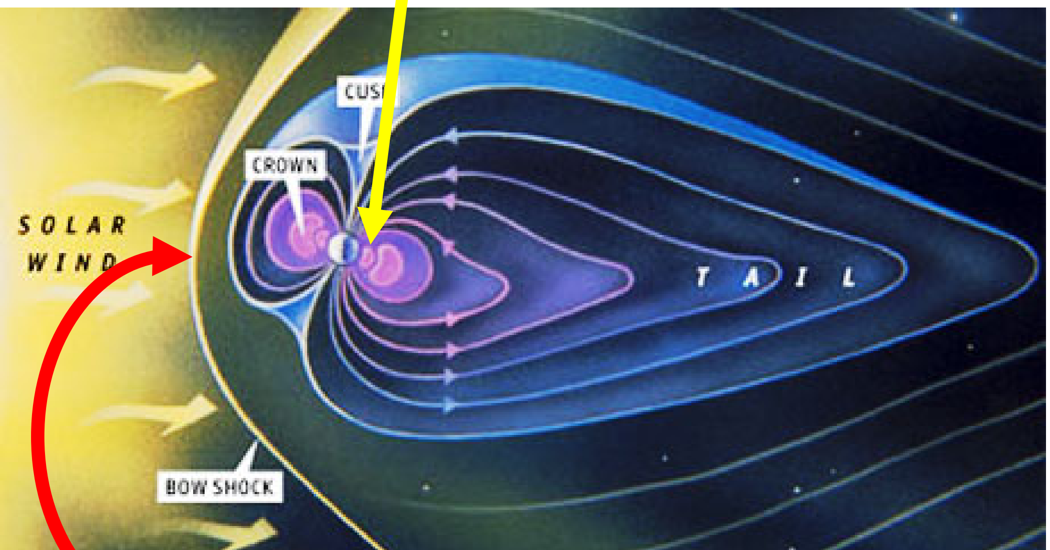
Summary

- The Earth Magnetic field Field
  - Internal & External Field (TS96 & TS05) GOES & Cluster Magnetic Field data
  - Our Magnetic Field model
- CR trajectory reconstruction
  - Particle nature Primary vs Secondary
- Back Tracing with/without TS05
  - Internal vs External Magnetic Field
  - Simulation
  - AMS-02 data & solar flares
- Conclusions

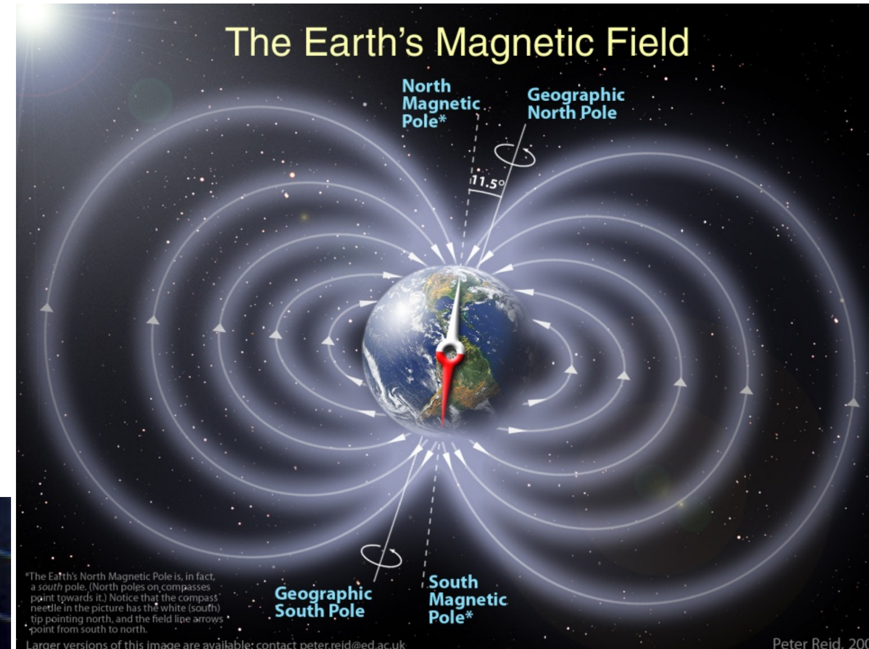
The Earth Magnetic Field

The Earth magnetic field can roughly be considered as a dipole, whose axis is tilted with respect to the rotation axis and whose center is shifted with respect to the Earth's center.

B_e = 0,5 Gauss



B_{IMF} = few nT



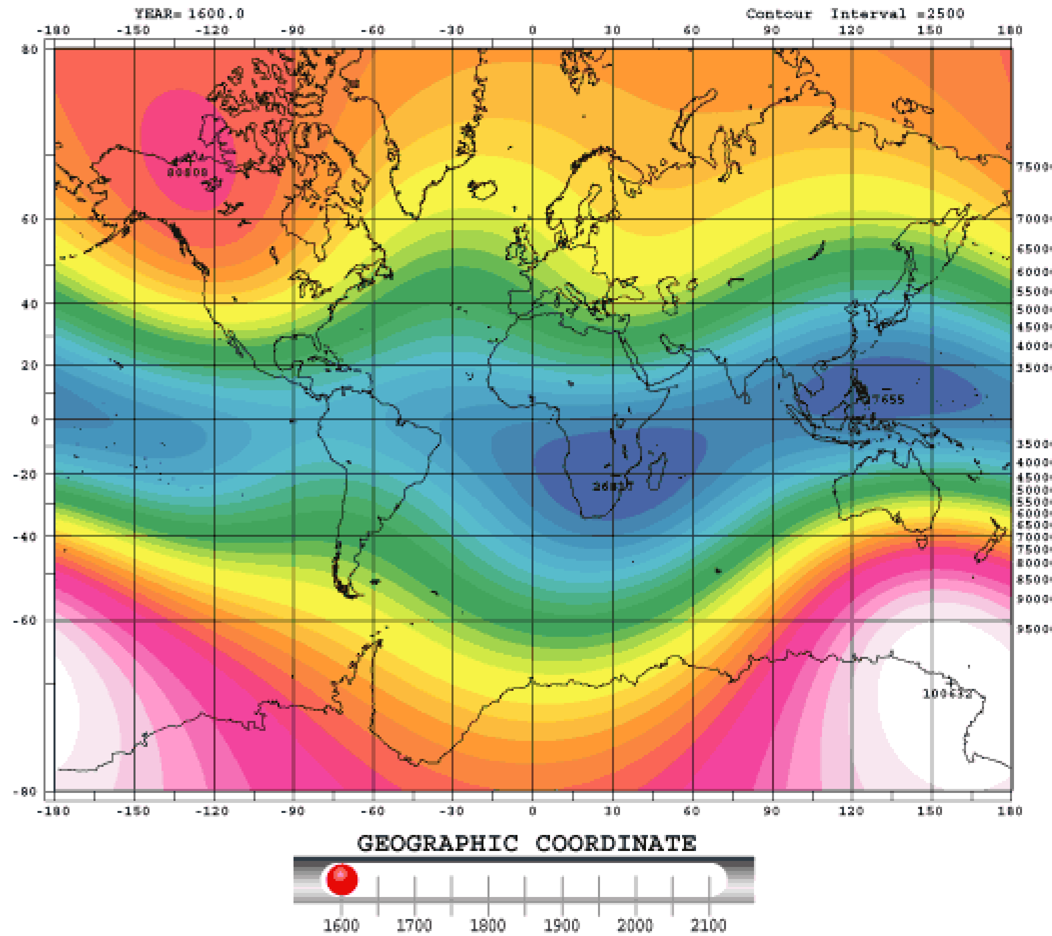
Due to the compression of the solar wind it becomes widely asymmetric with a long tail opposite to the Sun

Internal Field

IGRF 11 latest model is a standard mathematic description of the Earth main magnetic field and its annual rate of change (secular variation).

In source free regions this main field is the negative gradient of a scalar potential V, represented by a truncated series of spherical (13^{th} order) harmonic expansion

$B = - \nabla V$



$$V = R_e/\Sigma\, \Sigma (R_e/r)^{n+1} [g_n^m(t) \cos m\phi + h_n^m(t) \sin m\phi]\, P_n^m(\cos \vartheta)$$

http://www.ngdc.noaa.gov/IAGA/vmod/igrf.ht

External Field

Tsyganenko model:s

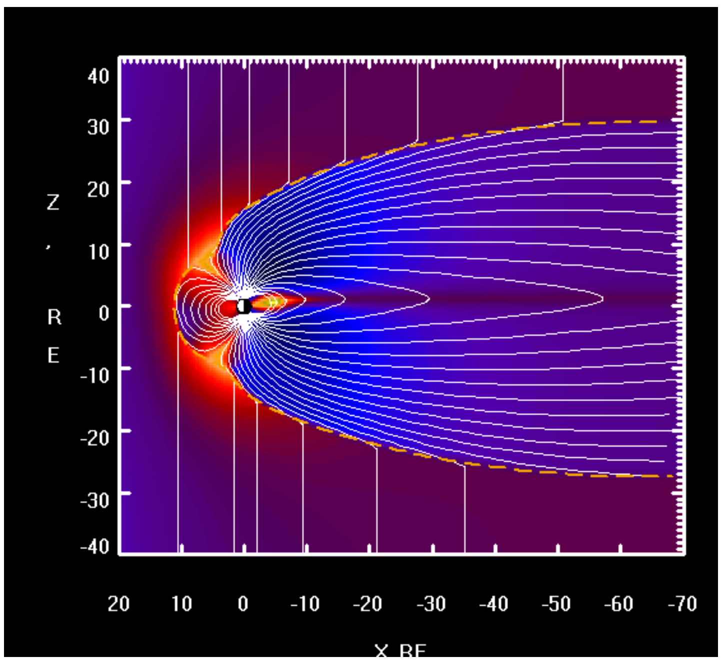
•Data base approach from over 3 decades of measurements…

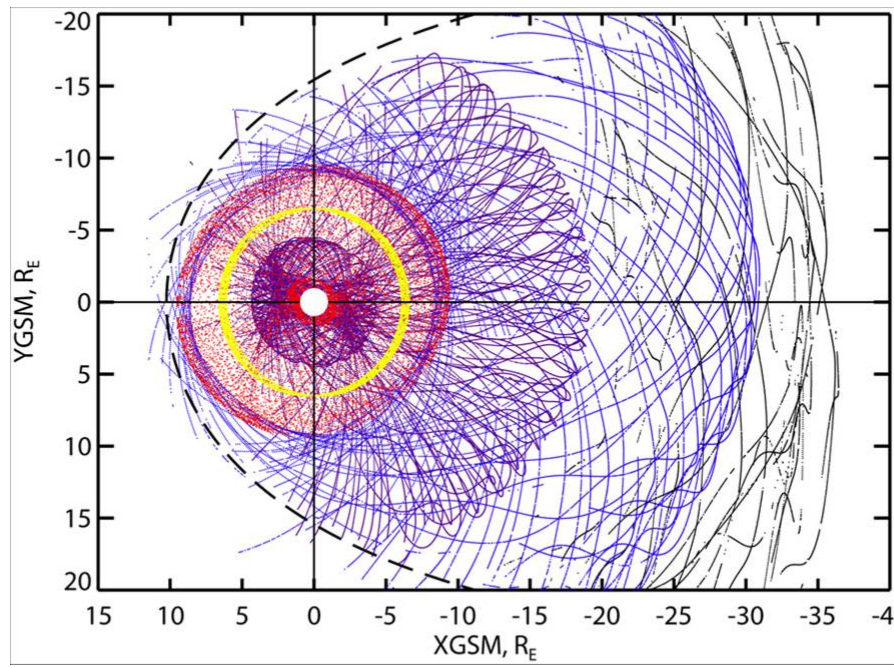
•All external currents contributions to external magnetic field

•1996 model (solar wind controlled magnetopause Sibeck)

•2001 and 2005 models (for SEP and CME events)

http://geo.phys.spbu.ru/~tsyganenko/modeling.html





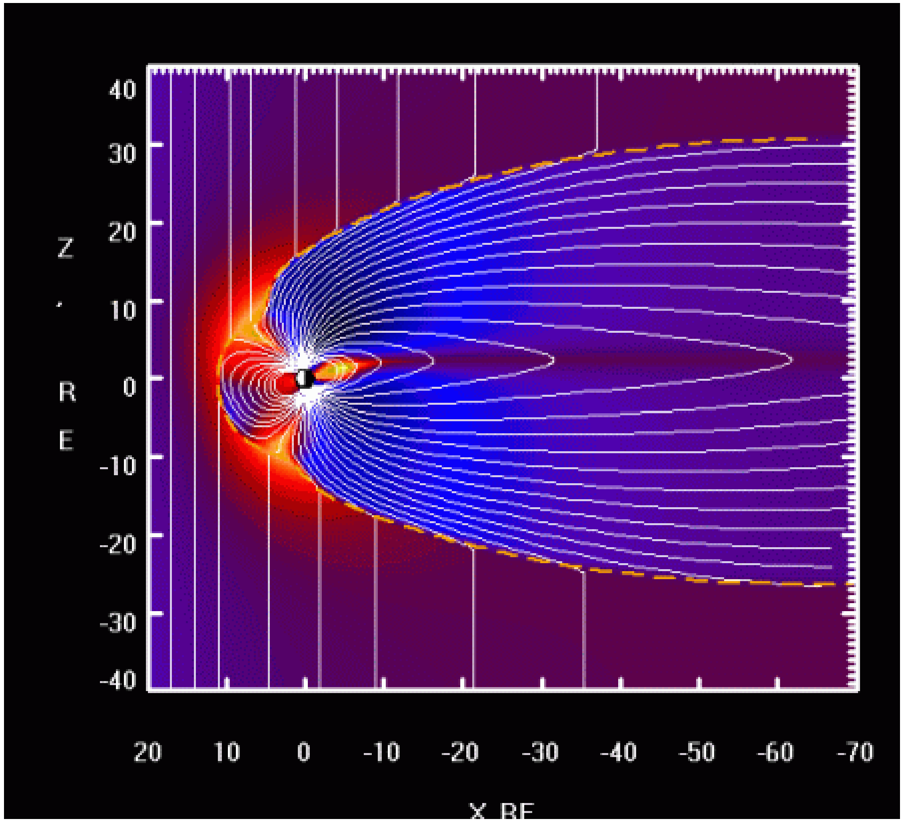
Tsyganenko 96

Depends on 4 main parameters: Dst, Pdyn By and Bz of IMF)

Contains these main Magnetic field contribution:

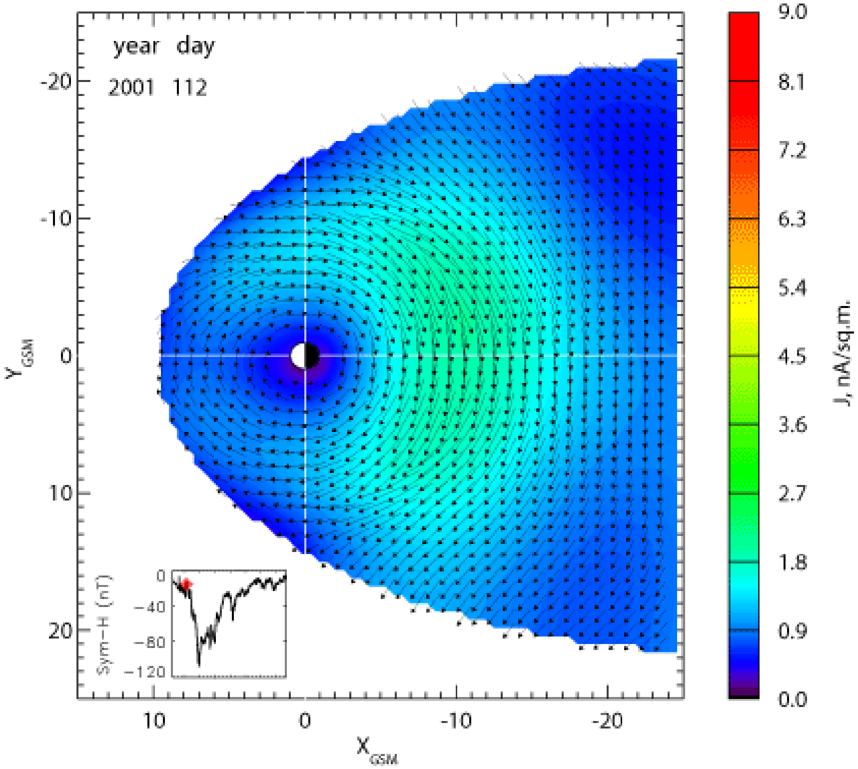
- Magnetopause
- Ring Current (trapped)
- Tail current
- Bierkeland region 1
- Bierkeland region 2
- Interconnection field

All fields are empirically obtained by the 4 main parameters



http://geo.phys.spbu.ru/~tsyganenko/modeling.html

Tsyganenko 05



New data from 1996 to 2000 (37 major events)

All components from 3 main parameters:

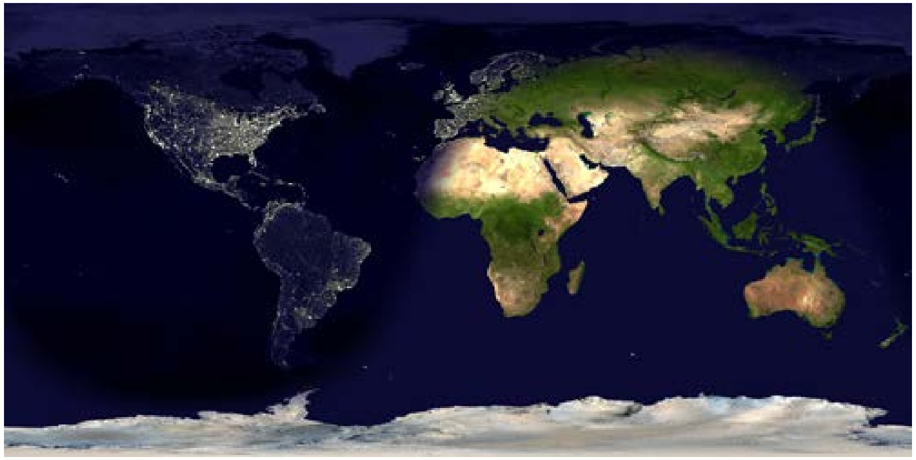
1. N density of SW
2. V speed of SW
3. B southward IMF components

Time scale of Tsyganenko 2001 is 1 hour, (symmetric rise and decay of solar event) while with Tsyganenko 2005 becomes asymmetric.

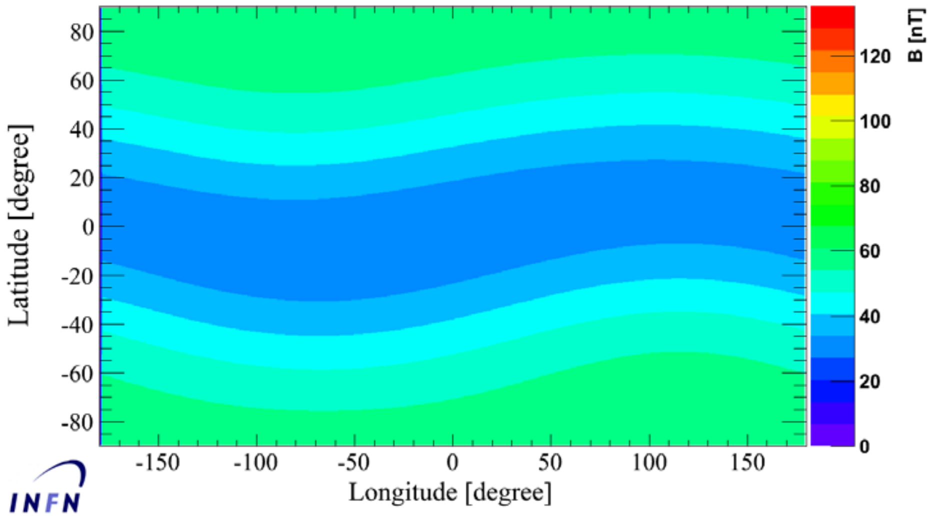
Plus in addition there is a Fast and Slower response of each Magnetic field component to the Storm

http://geo.phys.spbu.ru/~tsyganenko/modeling.html

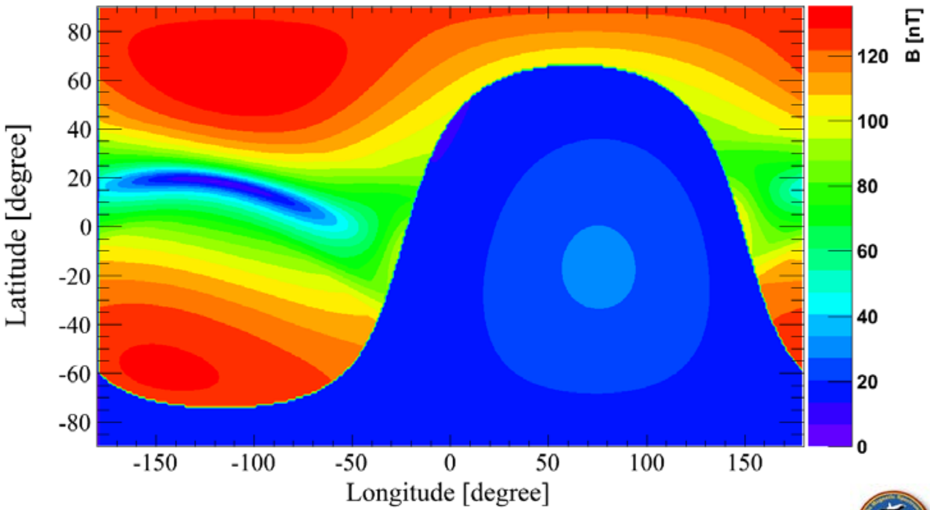
Outer Magnetic Field



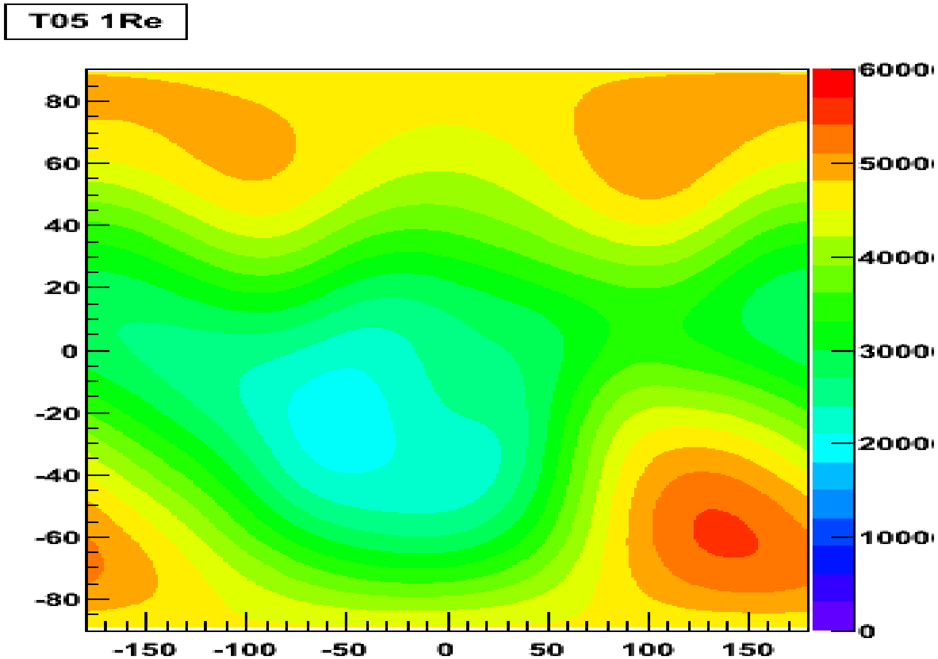
IGRF only @ 10 R_e

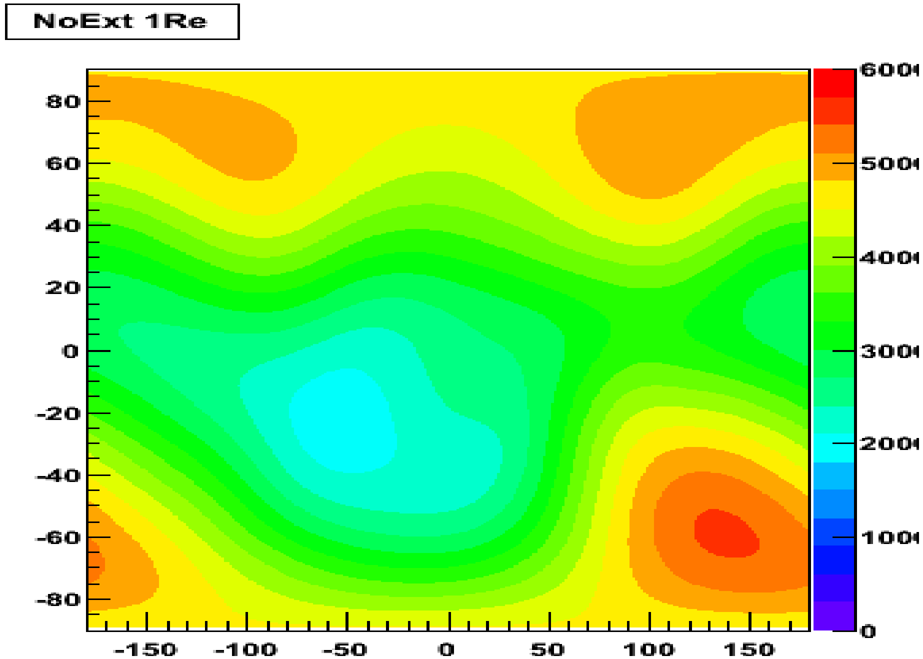


IGRF + TS05 @ 10 R_e



Variation of Magnetic Field with r





External Field for GOES data

- GOES measurements compared with External field models T96, T02 and TS05) during solar storms
- Added IGRF and compared Bz (long Dst minimum -213 nT)
- TS05 is better (residuals are smaller) and not anomalously strong negative Bz

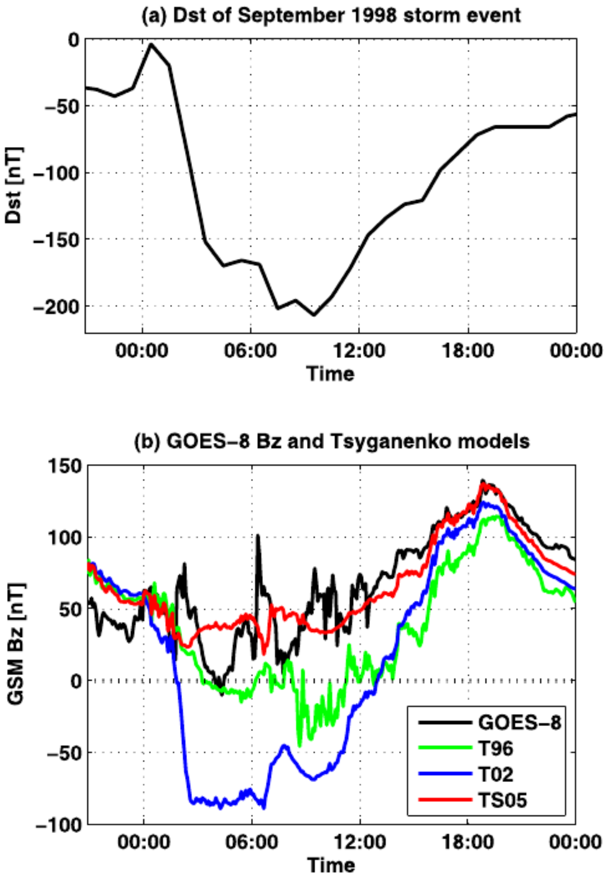


Figure 1. D_{st} and geostationary magnetic field during a major storm on 25 September 1998 in universal time. Panel (b) shows the GOES-8 GSM B_z magnetic field (in black) and the Tsyganenko model predictions at GOES-8's position (T96 in green, T02 in blue, and TS05 in red). The predicted B_z value include the IGRF and the model external field.

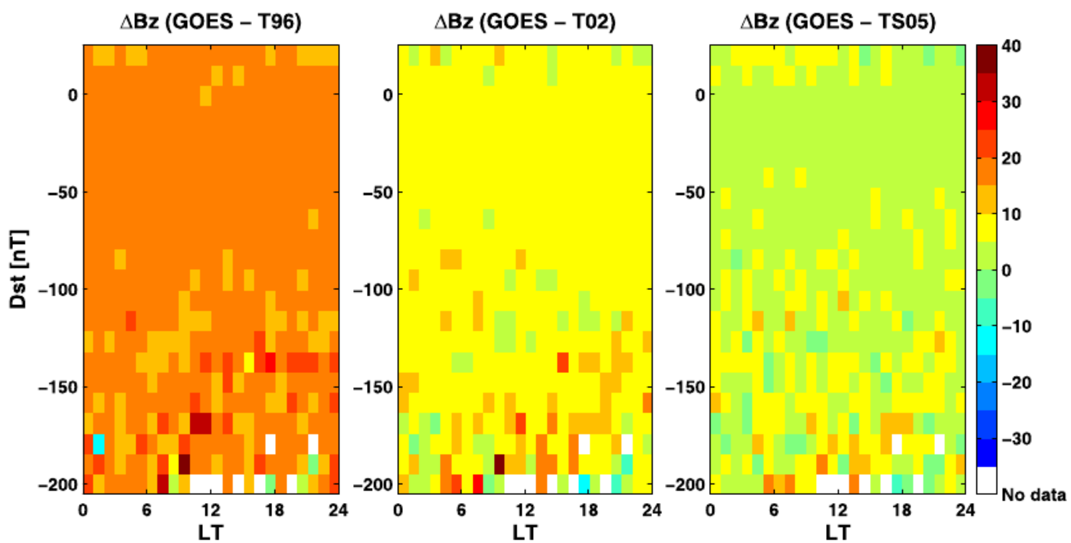


Figure 4. The residual fields (ΔB_z) between GOES data and Tsyganenko model outputs in different local time and D_{st} bins (T96, T02, and TS05, from left to right, respectively). The median data value is picked to represent all data points in each bin. The color scales of each panel are identical, from −35 to +40 nT. A white pixel marks a bin with no data.

Huang et al. **Test Magnetic Field Models** Jou. Of Geoph. Res. – 113 - 2008

External Field for Cluster data

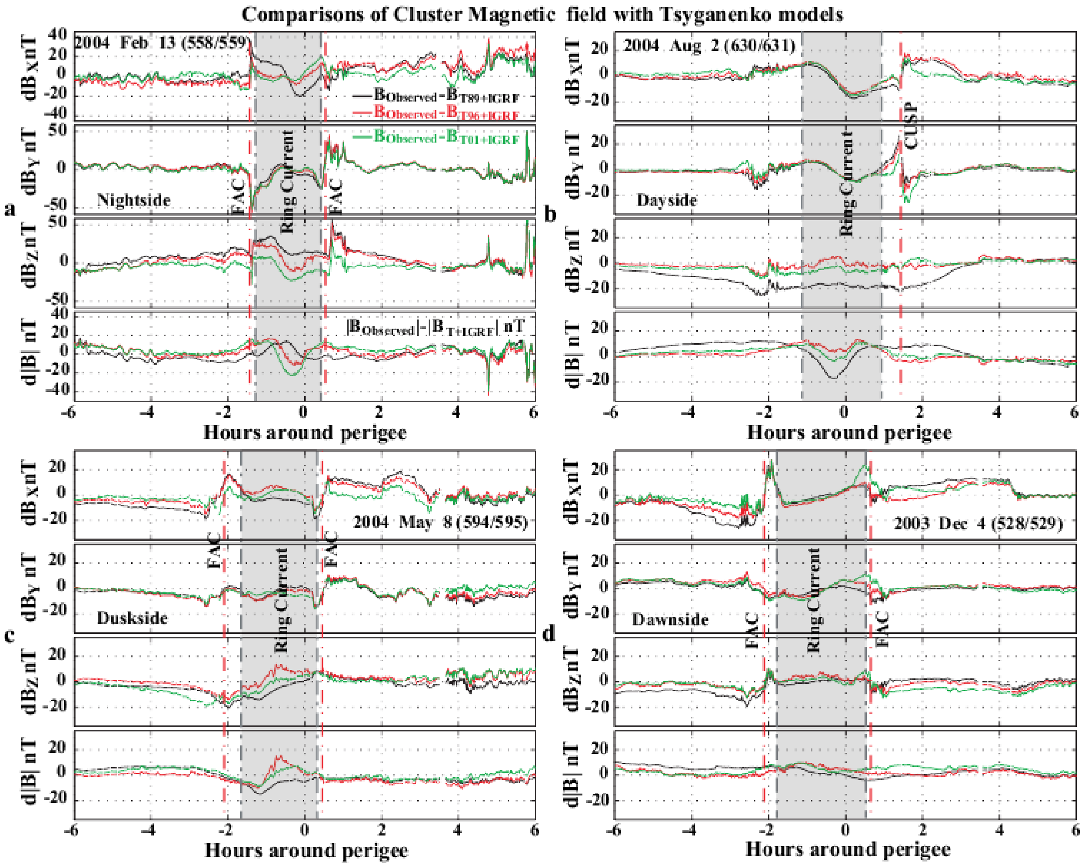
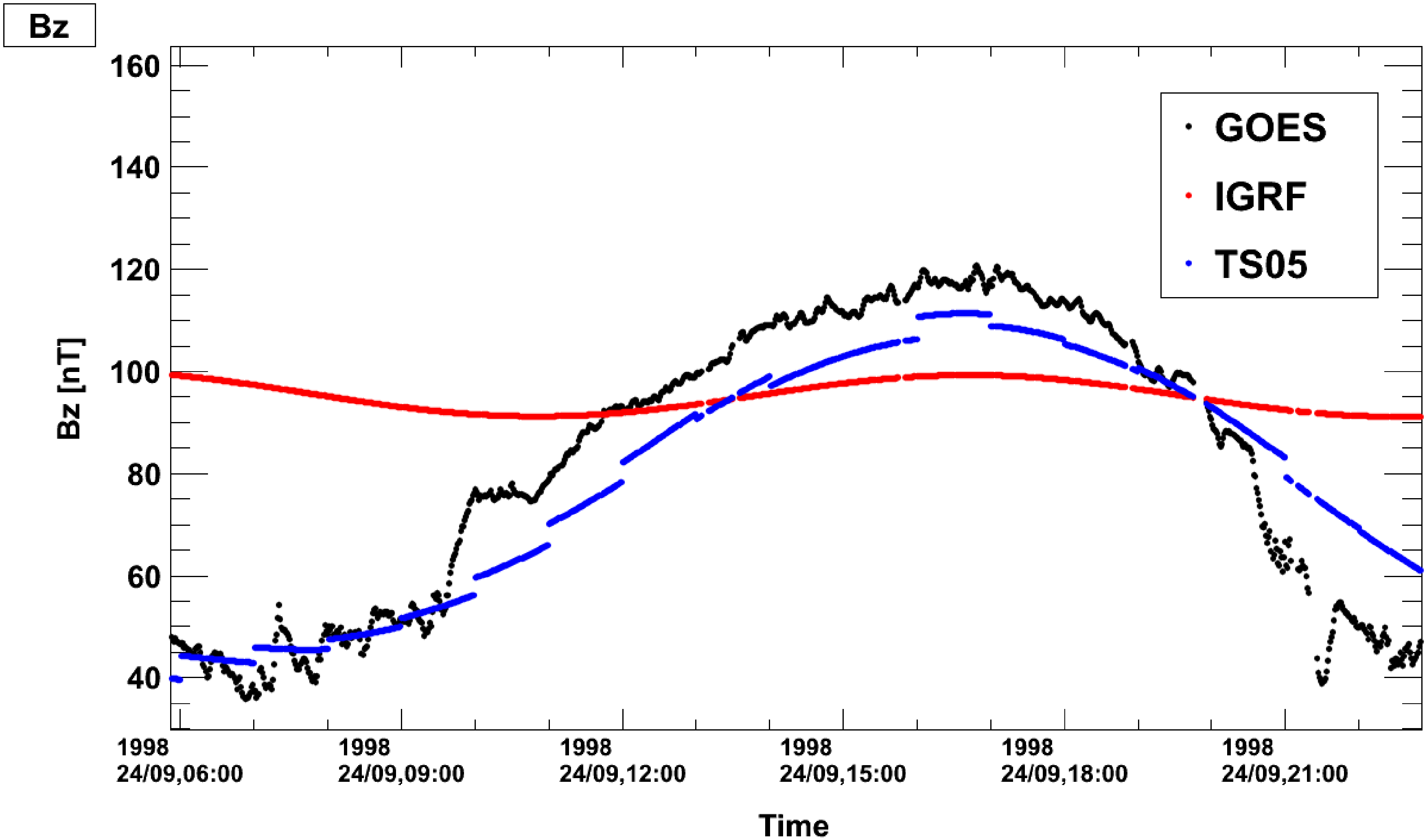


Fig. 4. Residuals from the comparisons of Cluster S/C 1 observations with T89 (black), T96 (red) and T01 (green) and IGRF (magenta) models for the nightside pass on 13 February 2004 **(a)**, dayside pass on 2 August 2004 **(b)**, duskside pass on 8 May 2004 **(c)** and dawnside pass on 4 December 2003 **(d)**. From top to bottom panels of Fig. 5a–d are for the dB_{XGSM}, dB_{YGSM}, dB_{ZGSM} and the magnitude of the field. The black vertical lines show the ring current region crossing.

- Cluster measurements compared with T89, T96 and T01
- subtracted static IGRF to obtain only the external component.
- all models have some "problem" for the Ring Current (grey zone in the figure)
- T01 (precursor of TS05) performs better (the residuals are much smaller)

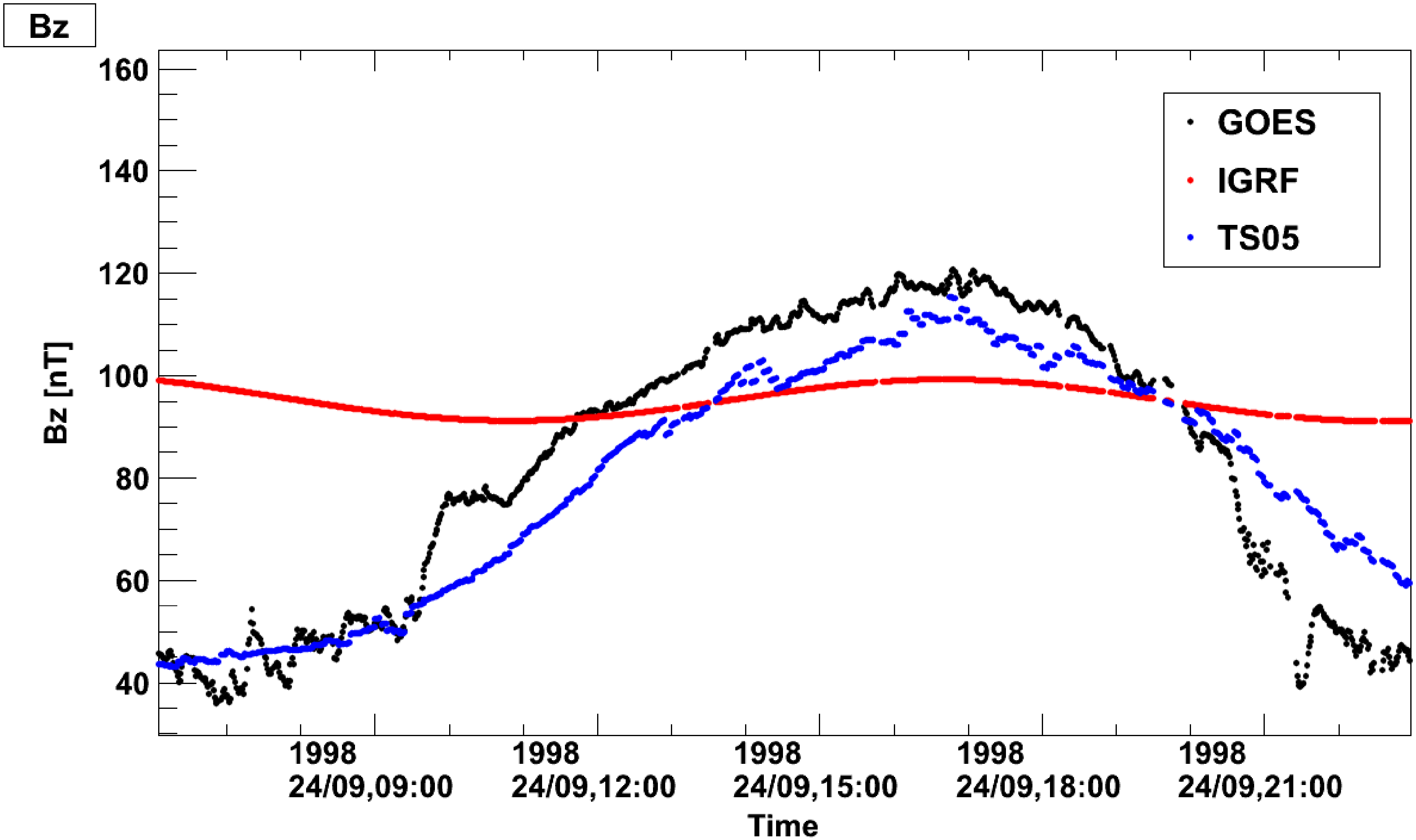
Q. –H. Zhang et al. **Comparison of magnetic field data from Cluster with Tsyganenko models** Ann. Geophys. ,28, 309-326. 2010

Our model : GOES data - 1998



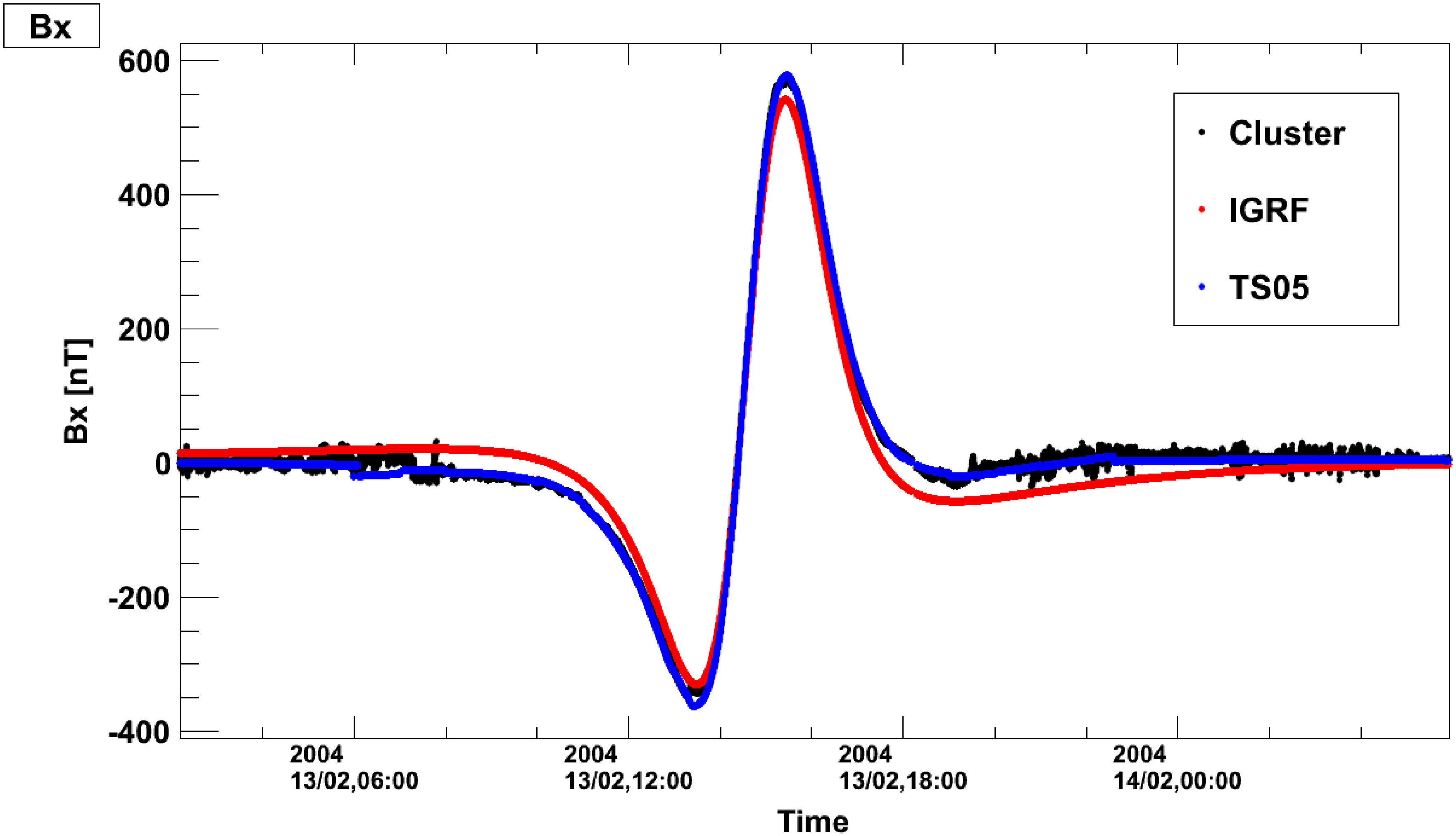
1 hour averaged parameters

Our model : GOES data - 1998



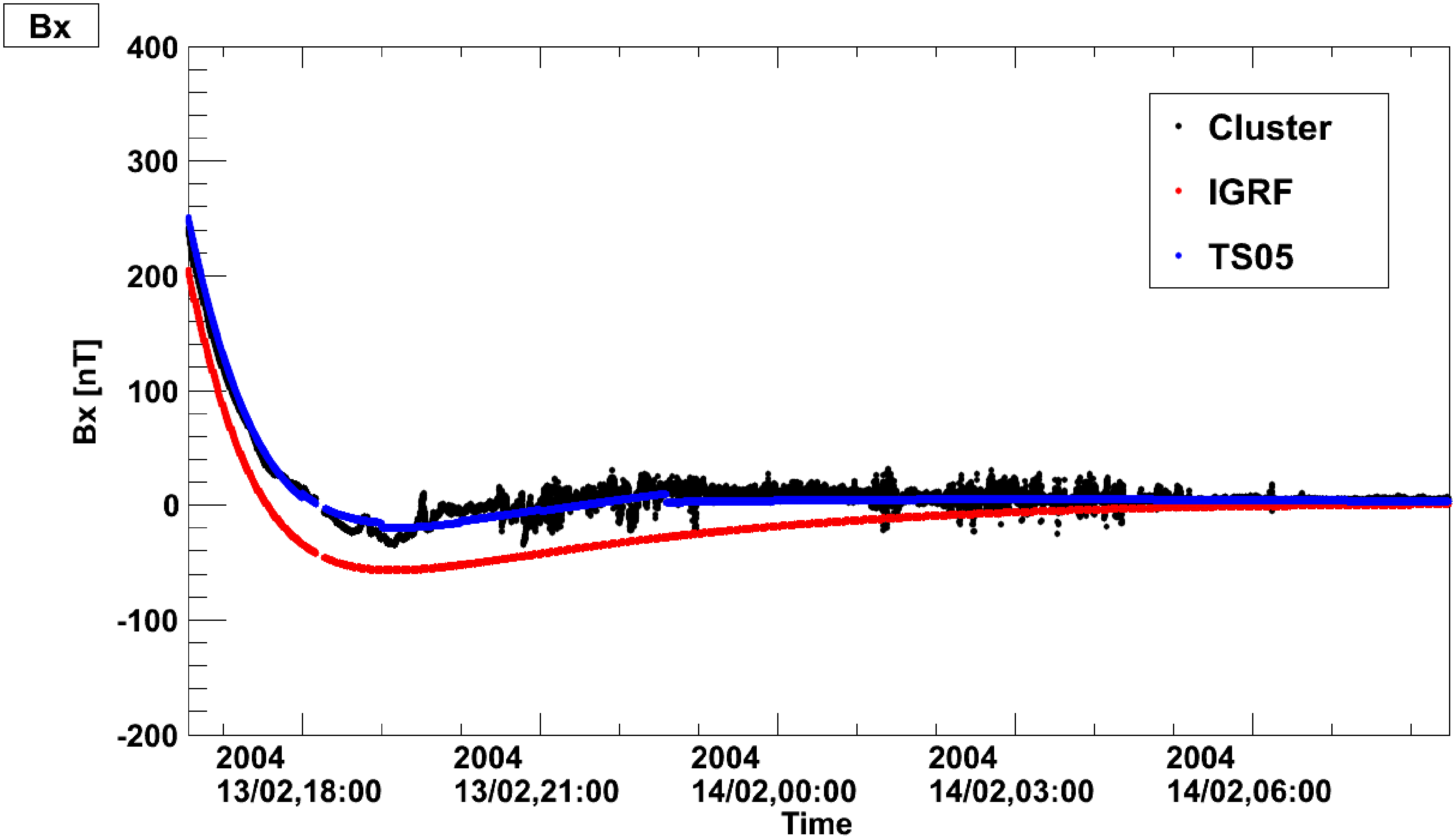
5 min averaged parameters

Our model : Cluster data - 2004



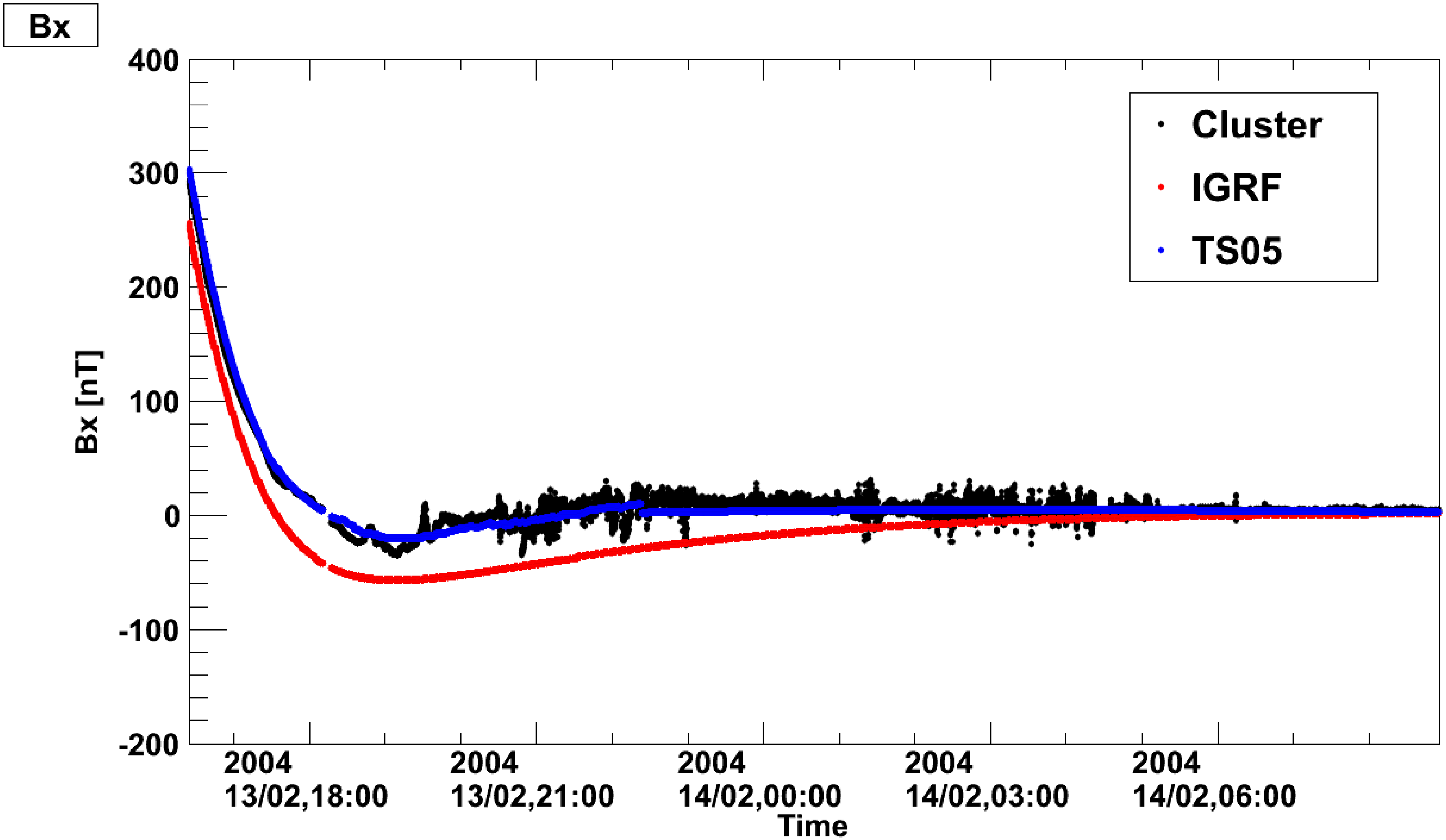
1 hour averaged parameters

Our model : Cluster data- 2004



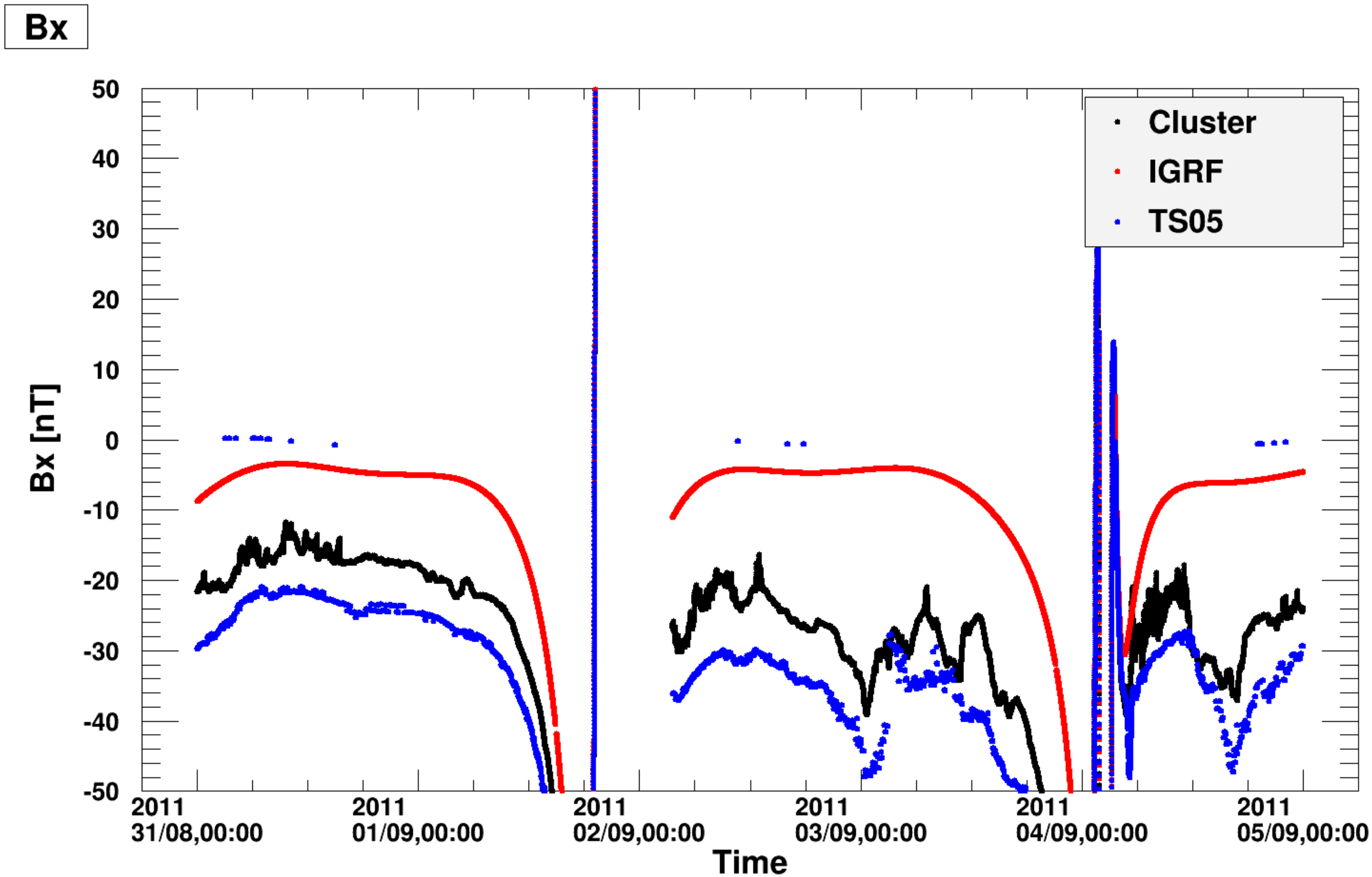
1 hour averaged parameters

Our model : Cluster data - 2004

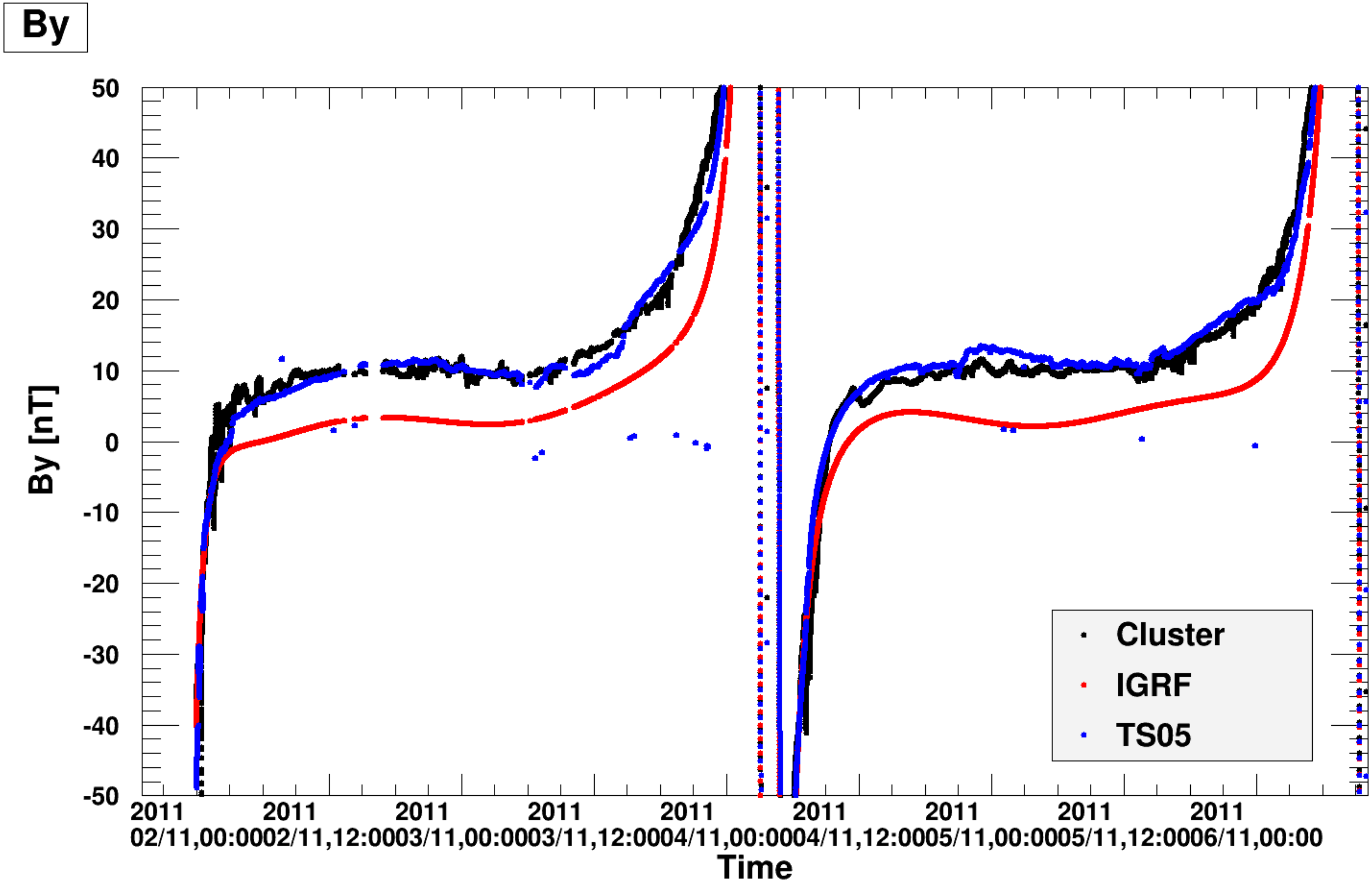


5 min averaged parameters

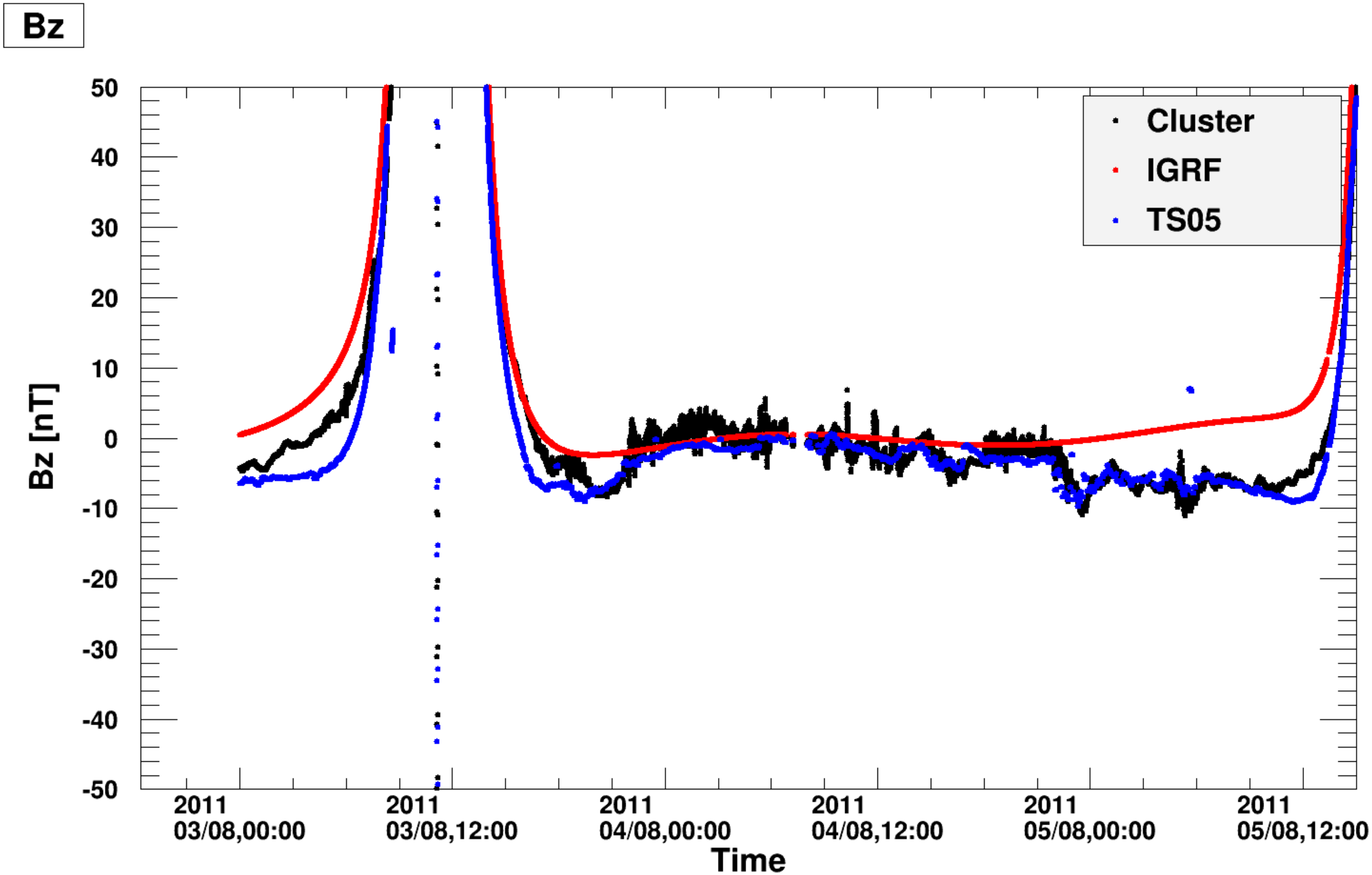
Our model : Cluster data – AMS mission



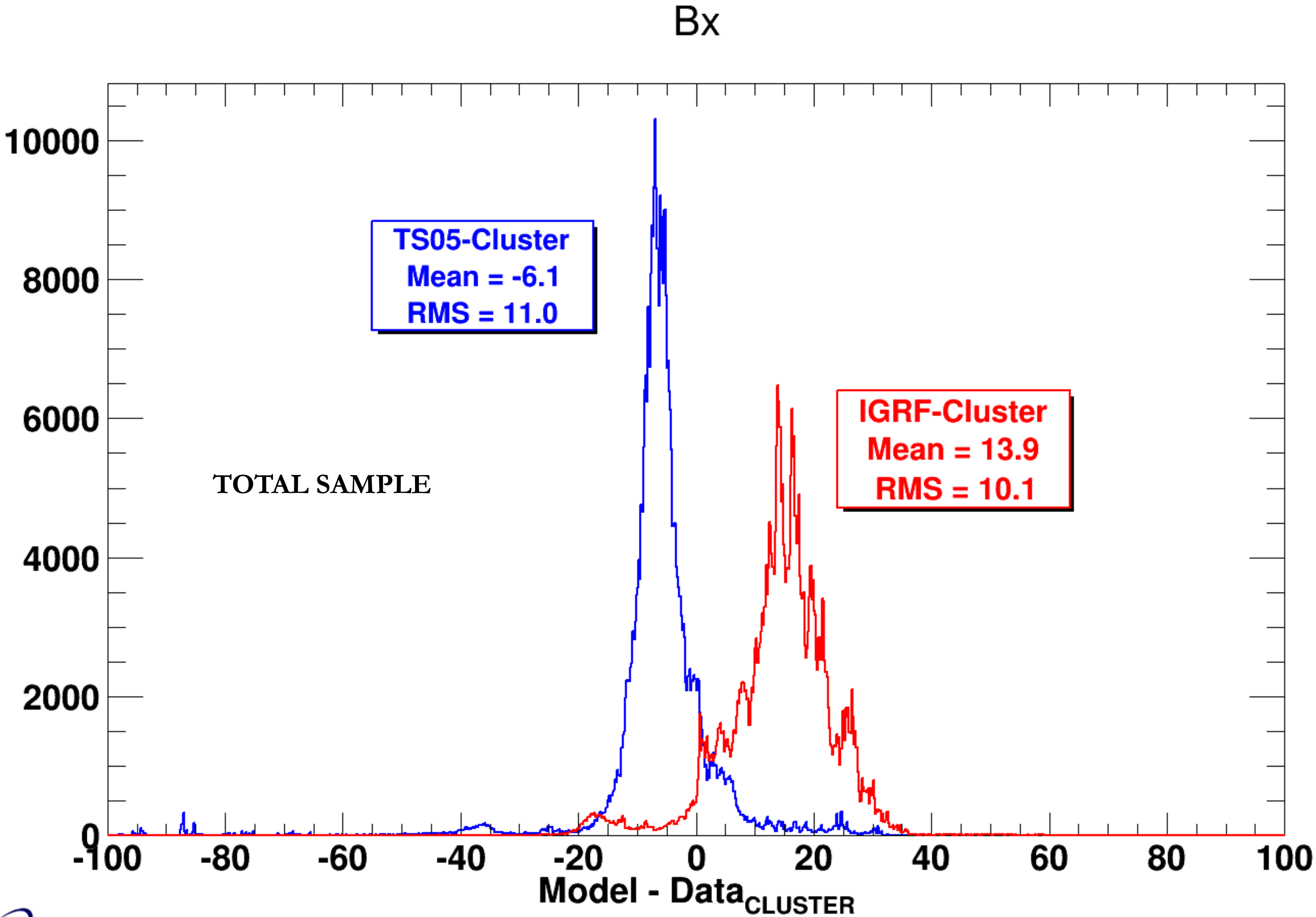
Our model : Cluster data – AMS mission



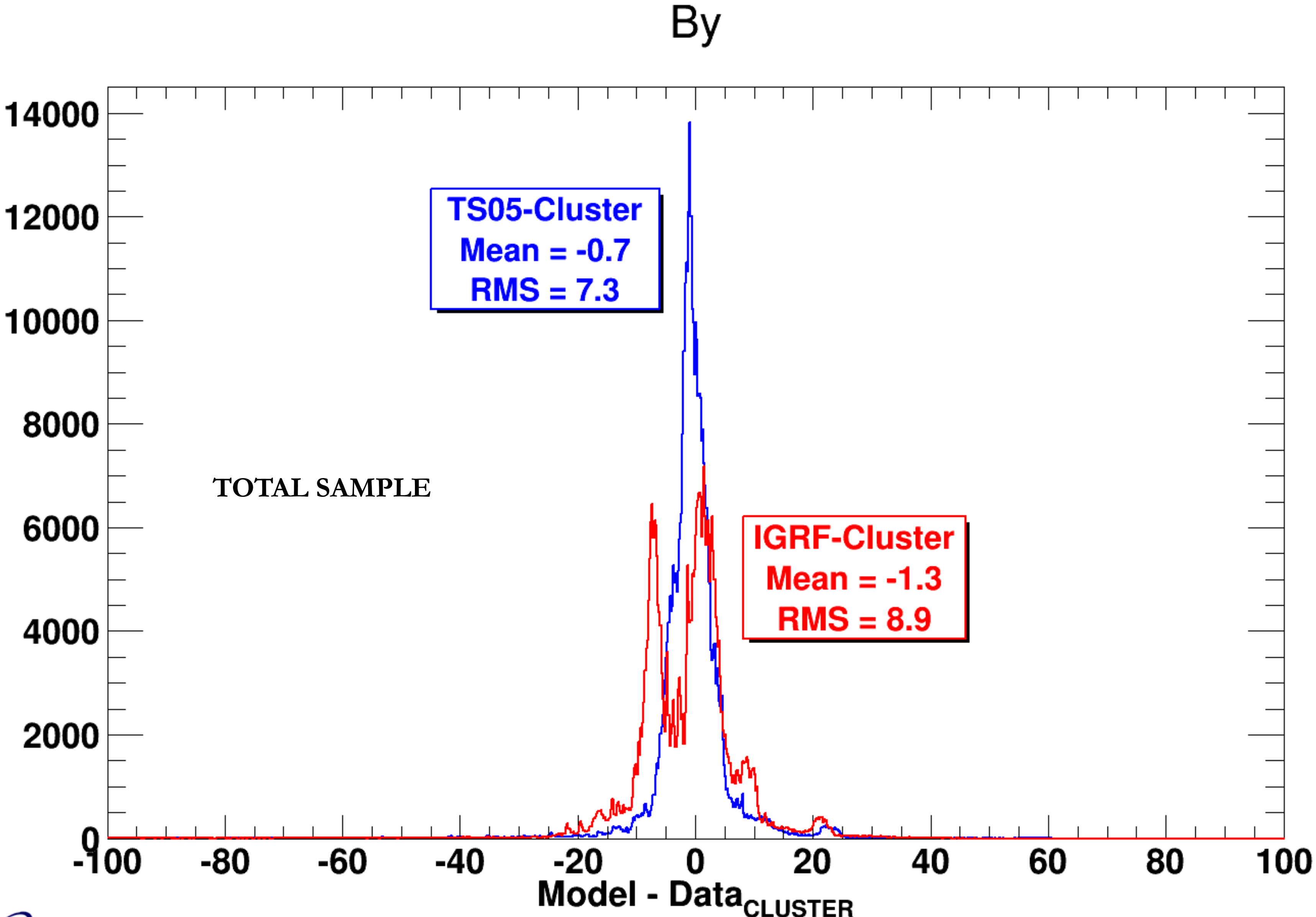
Our model : Cluster data – AMS mission



Our model : Cluster data – AMS mission

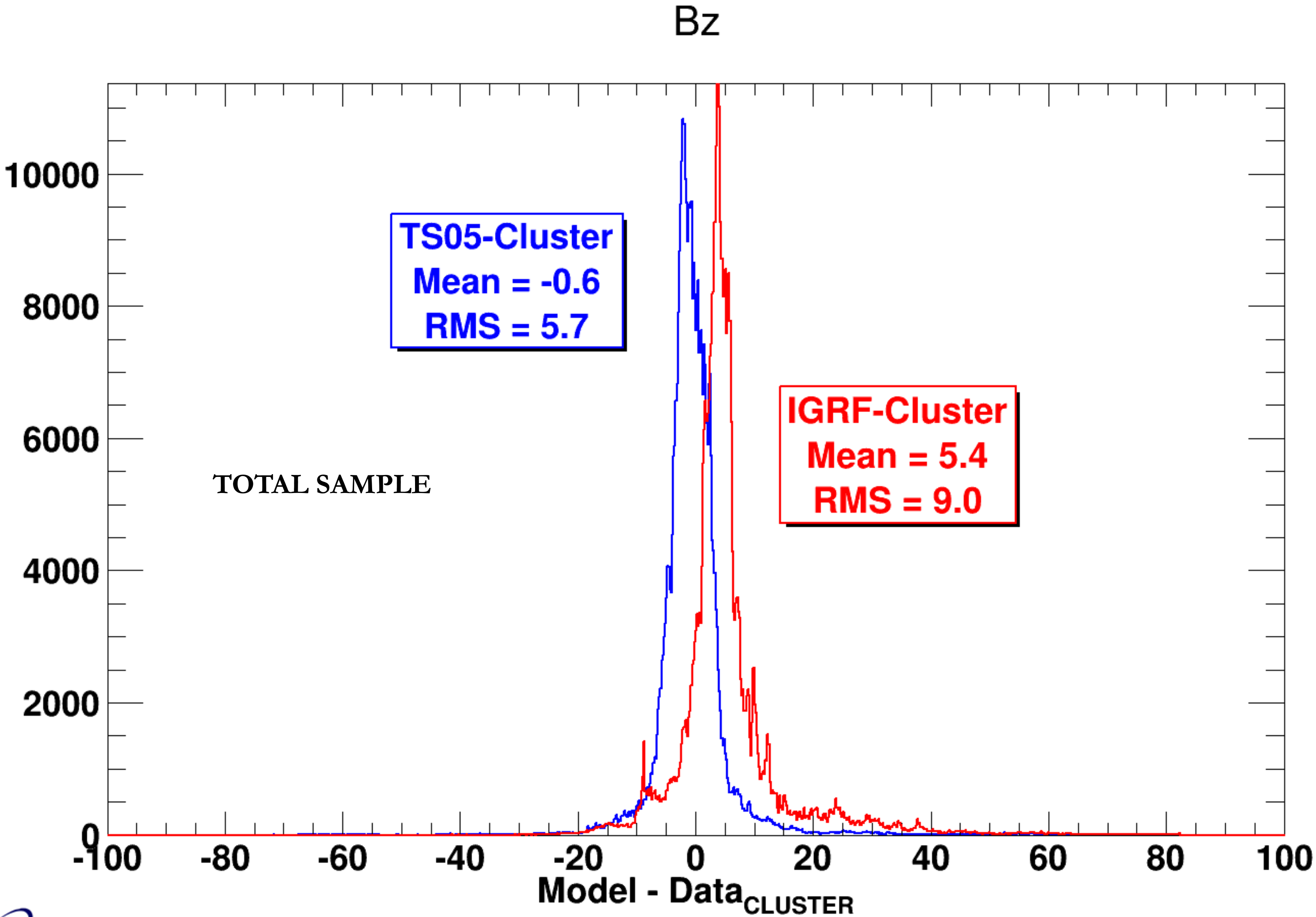


Our model : Cluster data – AMS mission

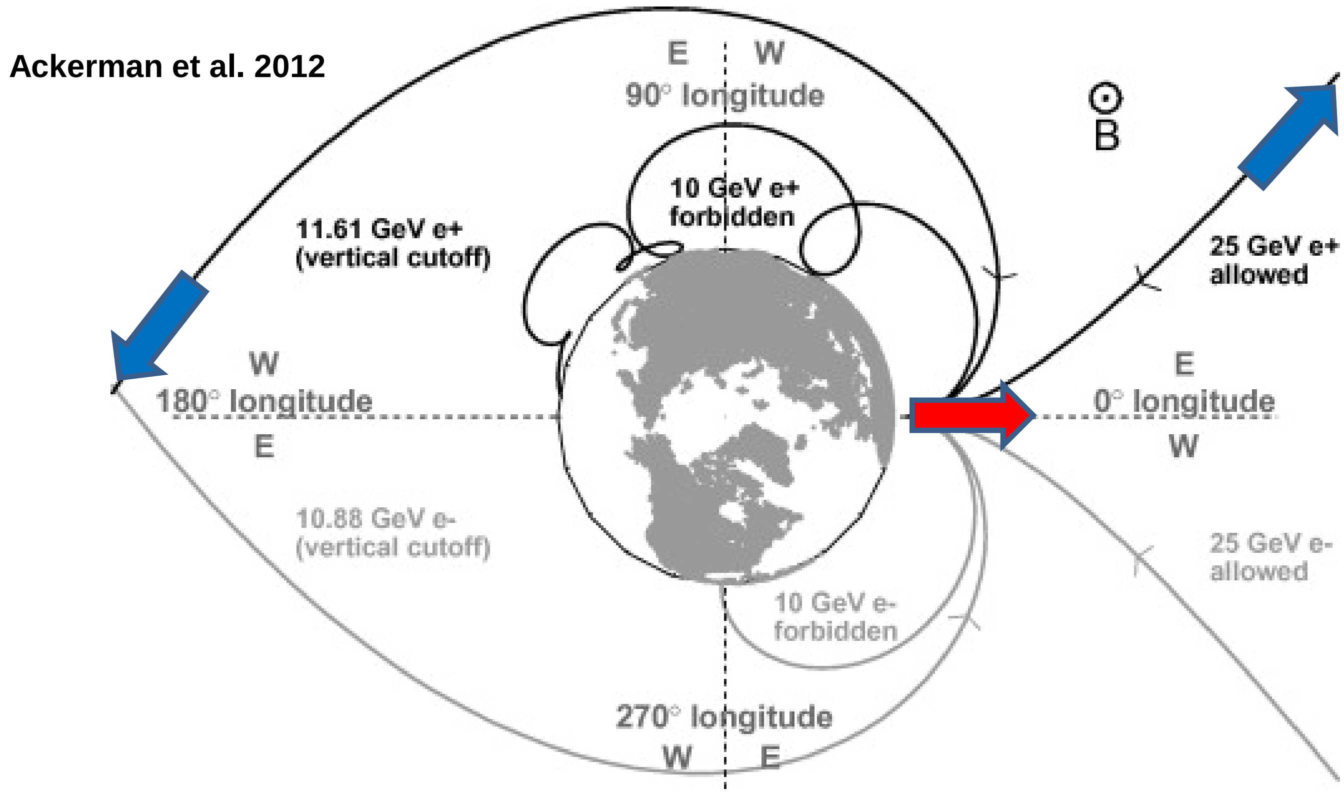


INFN
Sez. Milano-Bicocca

Our model : Cluster data – AMS mission



CR trajectory reconstruction



Particle trajectory is reconstructed back in time with "actual" magnetic field model to distinguish between allowed and forbidden trajectories (i.e. primaries and secondaries CR)

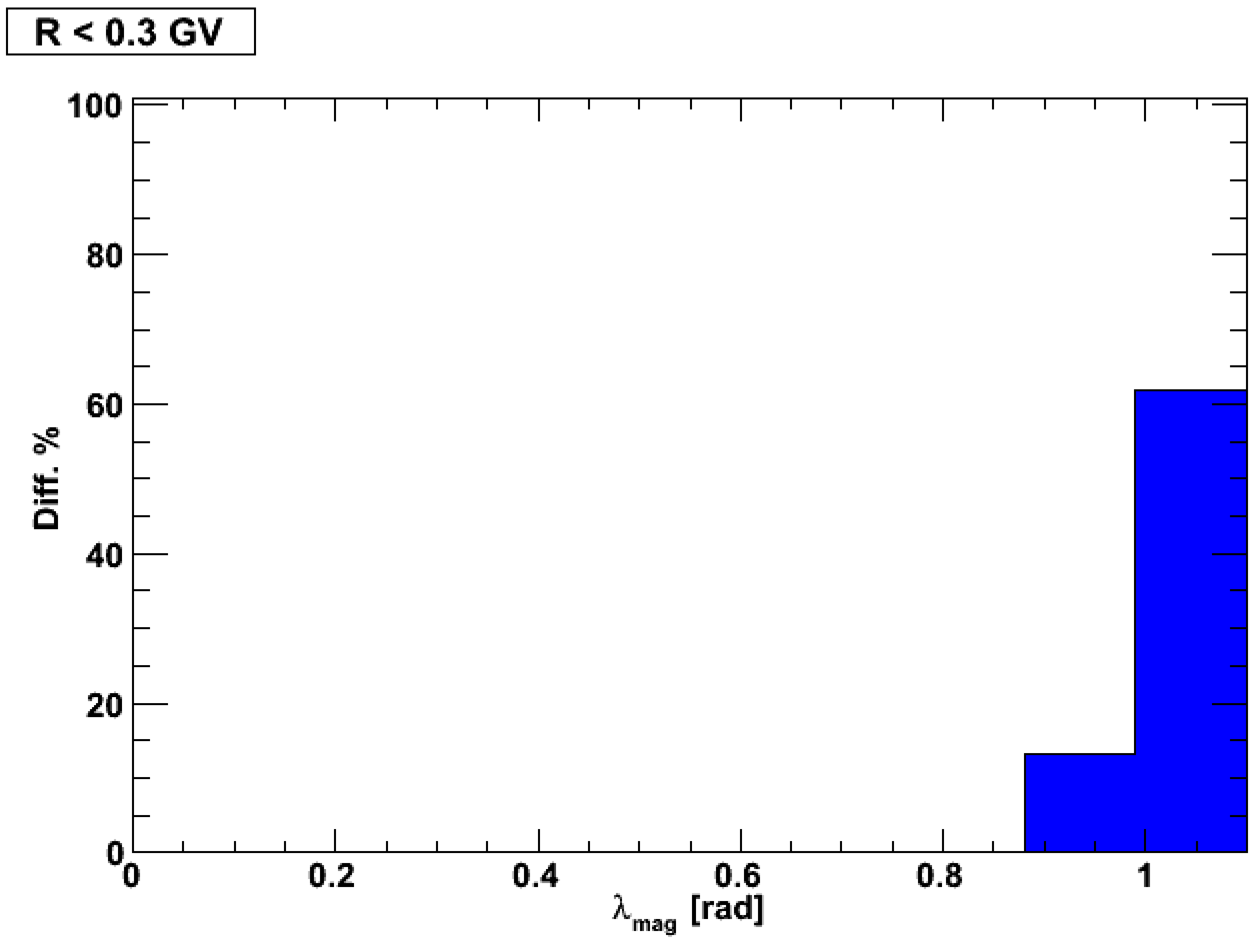
CR trajectory reconstruction

Parameters of the test:

1. 20 energy bins from 300 MV to 200 GV
2. From -50 to +50 in lat and 360 in long (756 pos)
3. 13 bins in incoming lat and 13 in incoming long (inside a cone of 60° from zenith this considering a situation AMS-02 like)
4. Total particles simulated 2.5×10^6

- Almost 18% of the particles were recognized as secondaries CR (forbidden trajectories) only with IGRF-11 while they were primaries if External field was applied, 2% of the cases is the viceversa.
- The difference was dominant in the "polar" regions where it could
- Reach 100% of the sample., for rigidities below 10 GV
- The test was done in quiet solar periods .

CR trajectory reconstruction

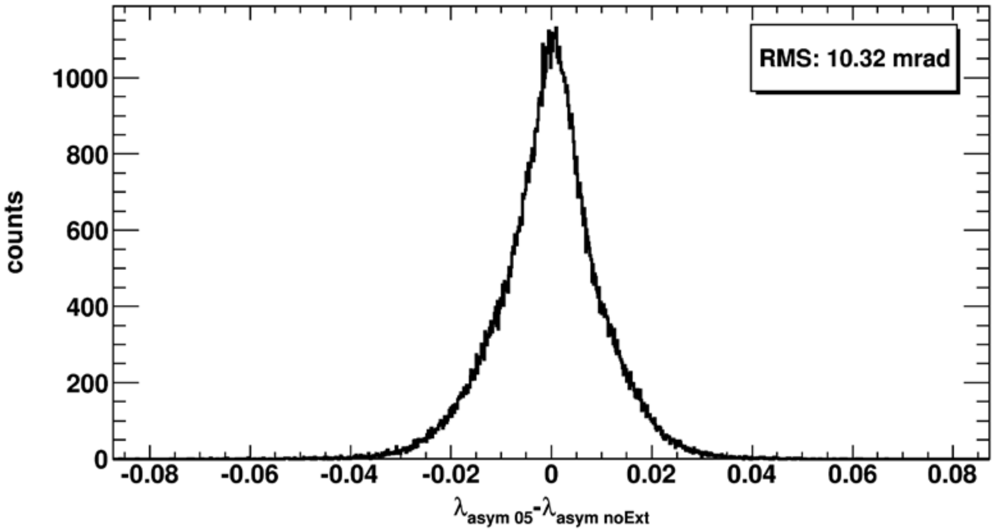


Latitudine magnetica

Internal vs External– Final point difference

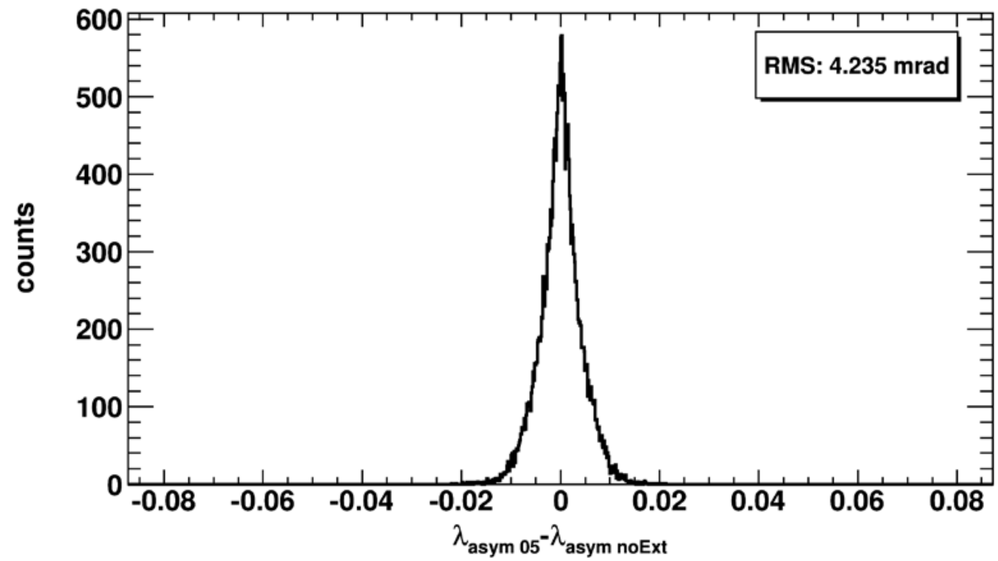
- Test we performed with primary CR (May 2011- dec 2012)
- Precision of the reconstructed trajectory at the border of the magnetosphere.
- Used the last magnetopause model of Shue (whose boundary size depends on SW pressure and IMF)
- Sample for this analysis is 2.2 x 10^5 AMS electrons.
- Evaluated the difference between last point direction (magneosphere) for different rigidity bins separated for Latitude and Longitude
- This decrease increasing the rigidity and is bigger with and without the external field

IGRF –TS05 : Latitude difference

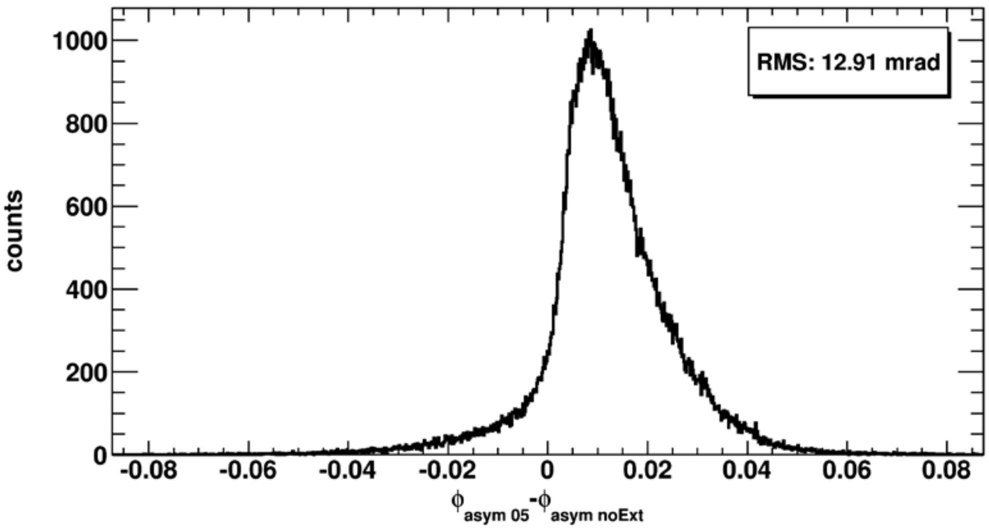


20<R<30 GV

R>50 GV



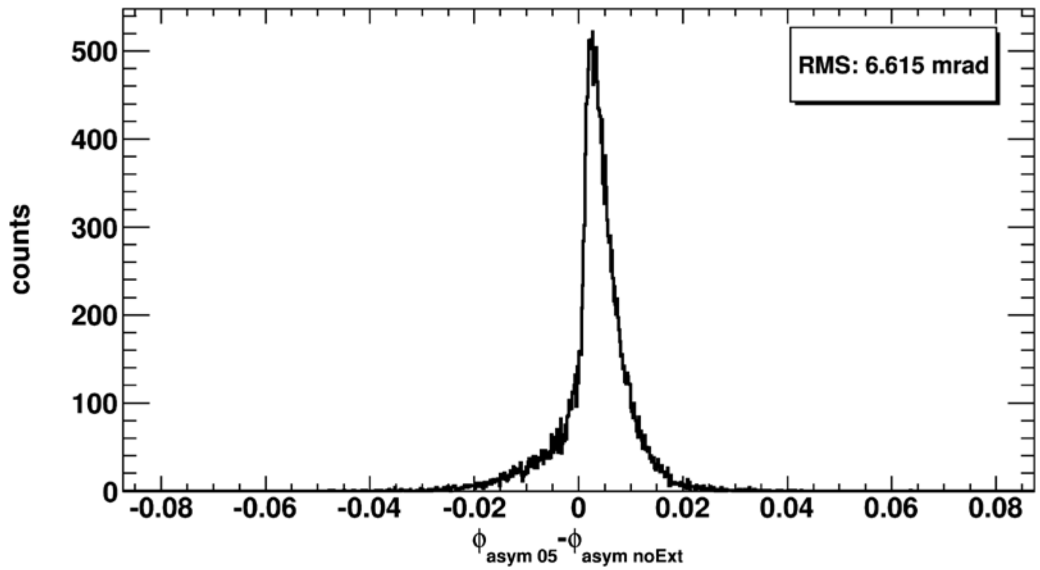
IGRF –TS05 : Longitude difference



20<R<30 GV

Asimmetry: due to dipolar field and negaitively charged particles (electrons) curvature is mainly westward..

R>50 GV



Internal vs External

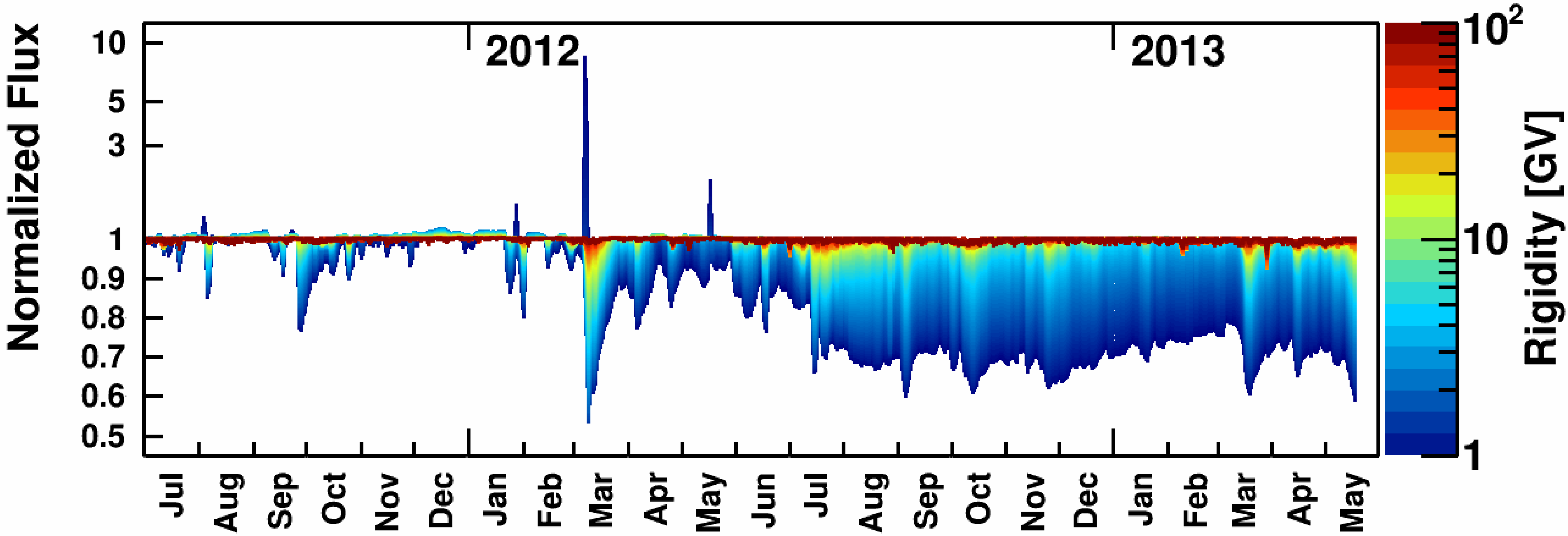
TS05 or IGRF?

RMS in mrad

	All	P<4nPa	P>4nPa
Latititude NoExt-T05	10.9	10.3	18.2
Longitude NoExt-T05	13.6	12.9	21.6
Latititude T96-T05	3.5	3.3	6.7
Longitude T96-T05	5.0	4.5	8.8

T05 for disturbed periods and T96 for "quiet" ones

Solar modulation effects with AMS02 data



Solar Flares

Analysis on 3 periods

March 2012

Mon, 05 Mar 2012 20:45:52 GMT
Tue, 13 Mar 2012 05:39:12 GMT

May 2012

Sat, 12 May 2012 04:20:16 GMT
Wed, 23 May 2012 23:55:44 GMT

August 2011

Sat, 28 July 2011 00:00:00 GMT
Wed, 14 Aug 2011 24:00:00 GMT

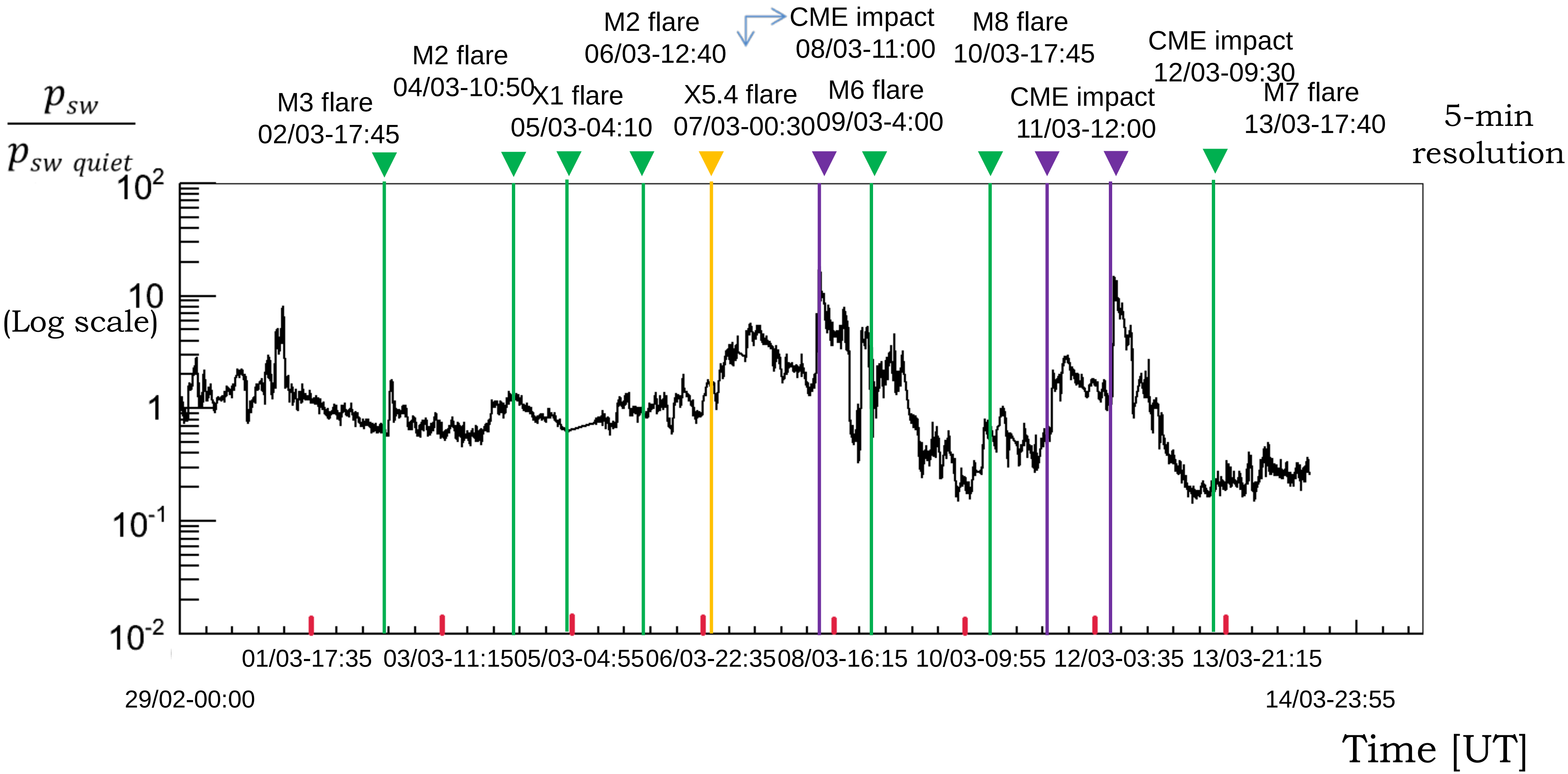
Main Parameters

- Solar & Earth Parameters

AMS -02 mission values

PARAMETER	P_DYN	DST
MAX VALUE	37.98 nPa	95 nT
MIN VALUE	0.03 nPa	-143 nT
AVERAGE	1.78 nPa	-8.1 nT

March Solar Wind pressure

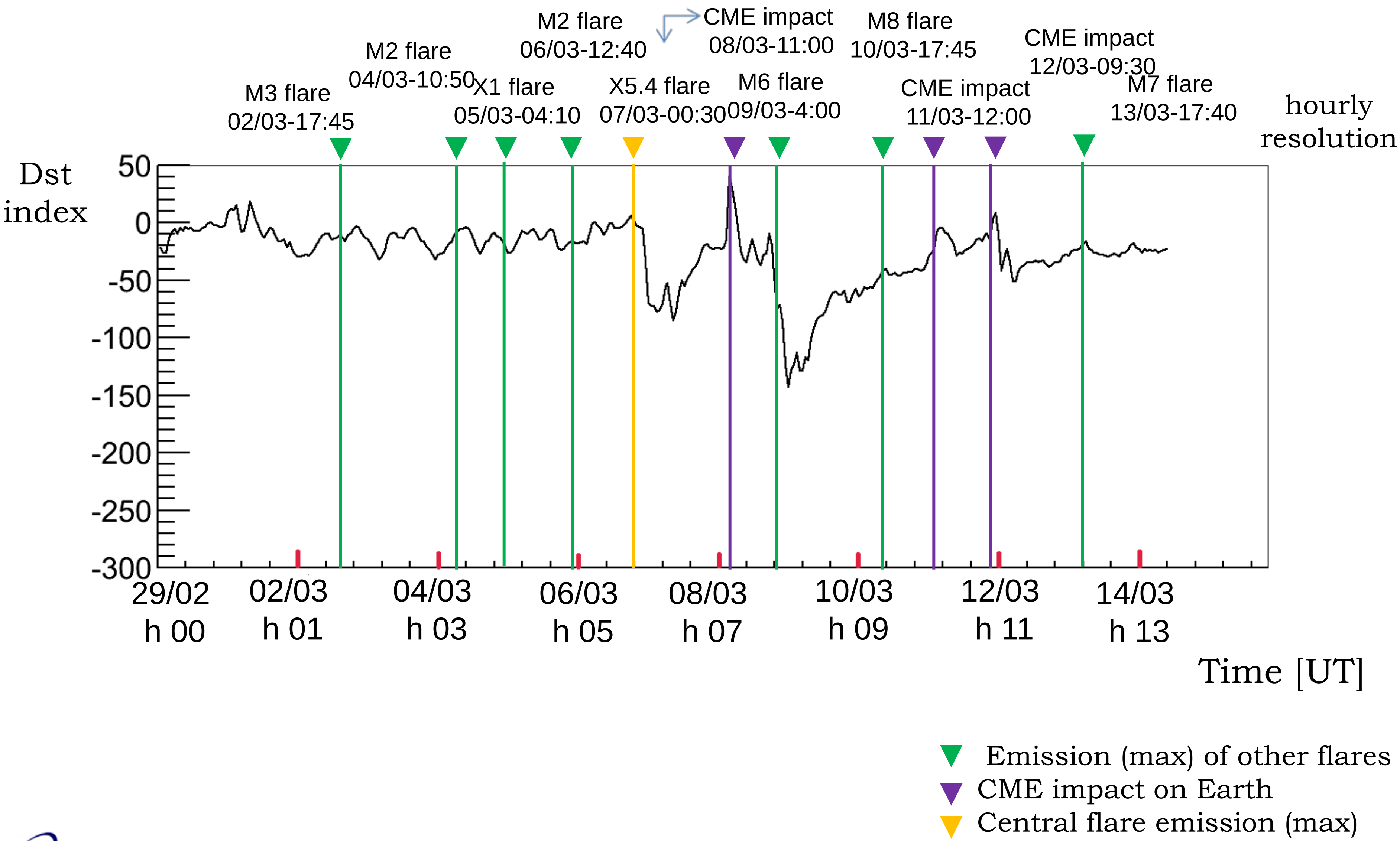


p_{sw_quiet} = 1,64 nPa

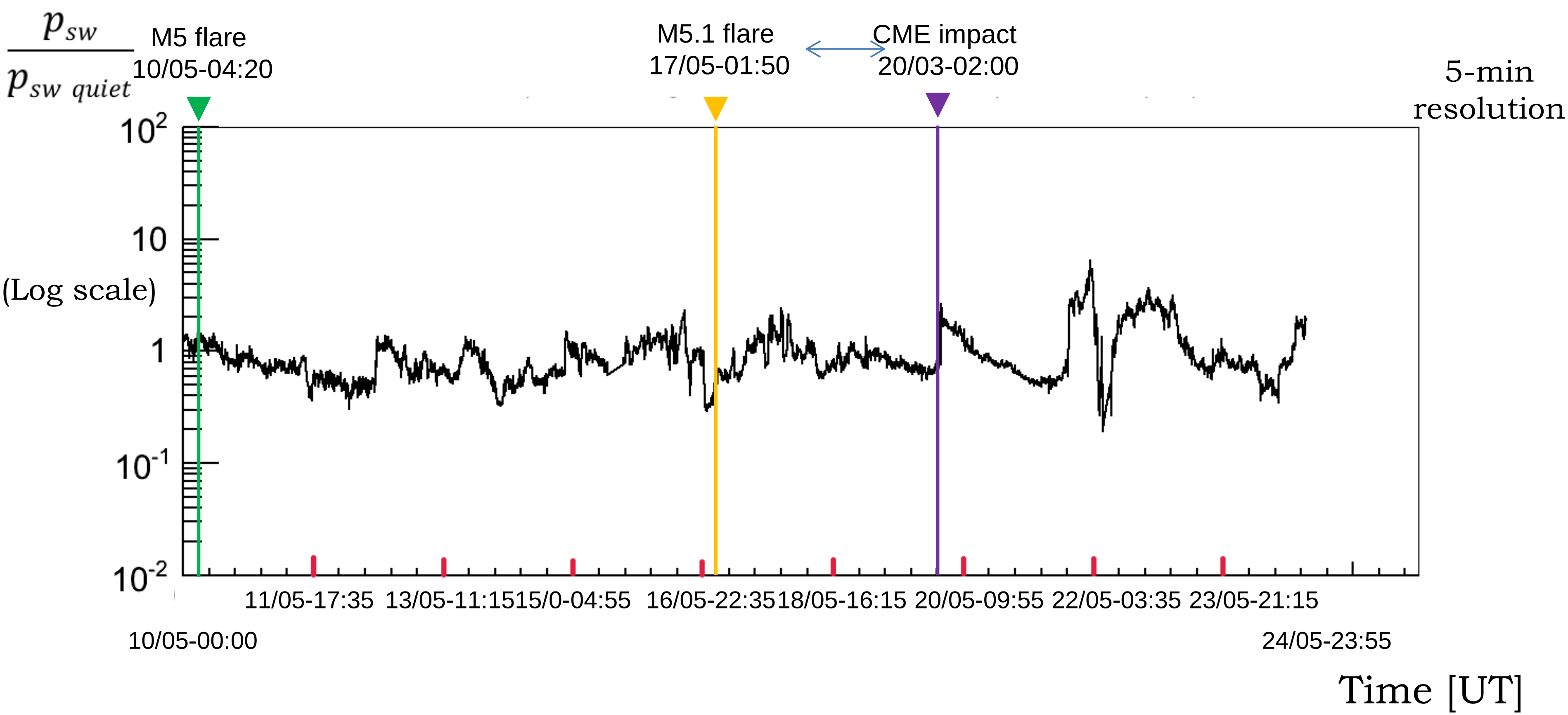
Computed on a quiet period in 2008

- Emission (max) of other flares
- CME impact on Earth
- Central flare emission (max)

March Dst Index



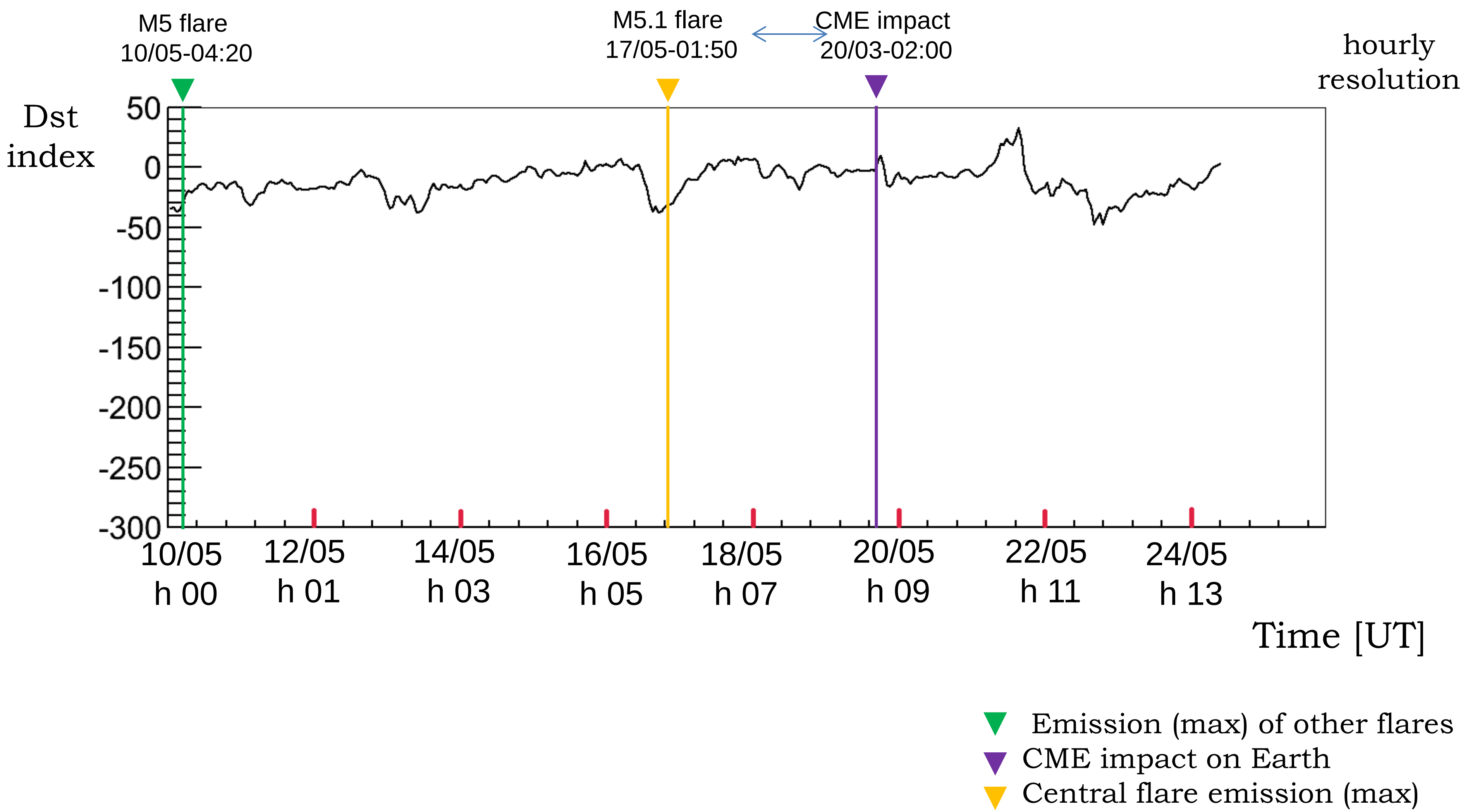
May Solar Wind pressure



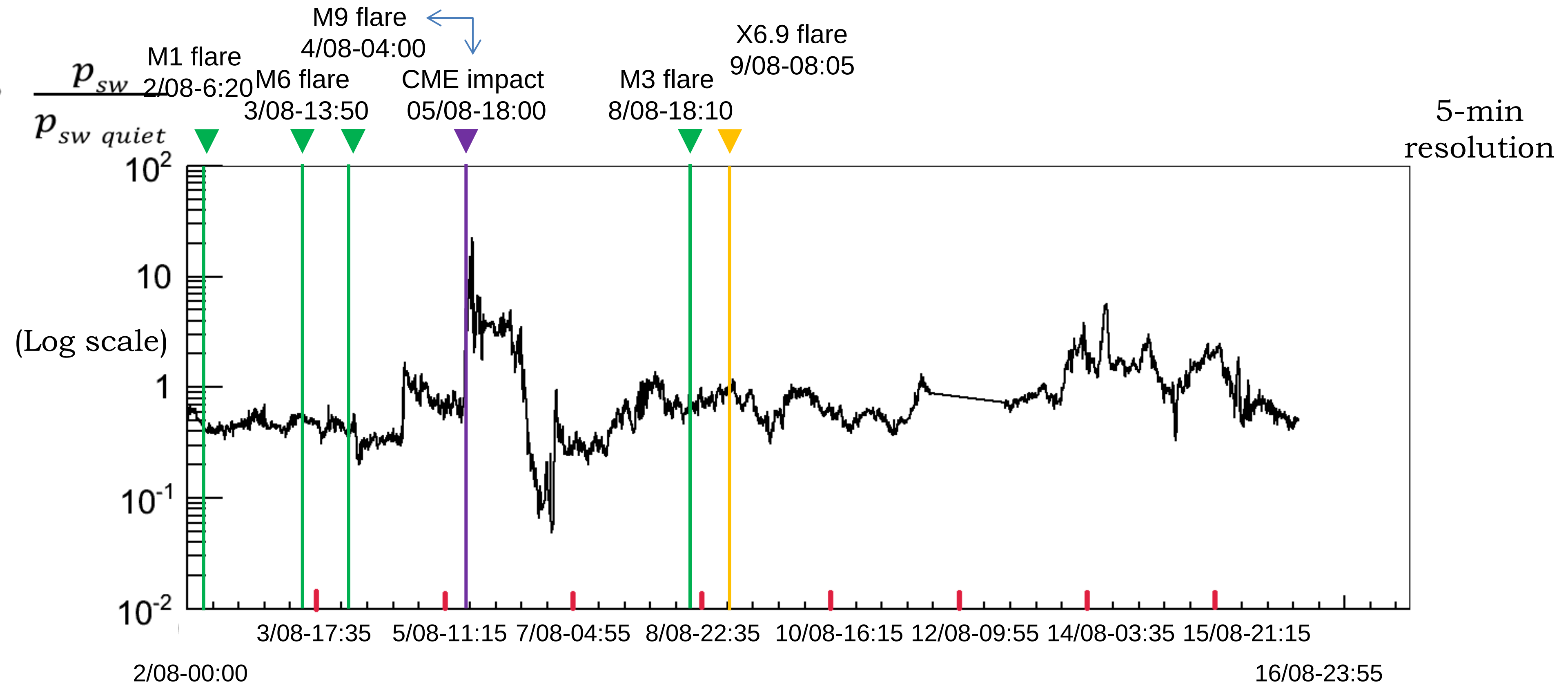
p_{sw_quiet}= 1,64 nPa
Computed on a quiet period in 2008

▼ Emission (max) of other flares
▼ CME impact on Earth
▼ Central flare emission (max)

May Dst Index



August Solar Wind pressure

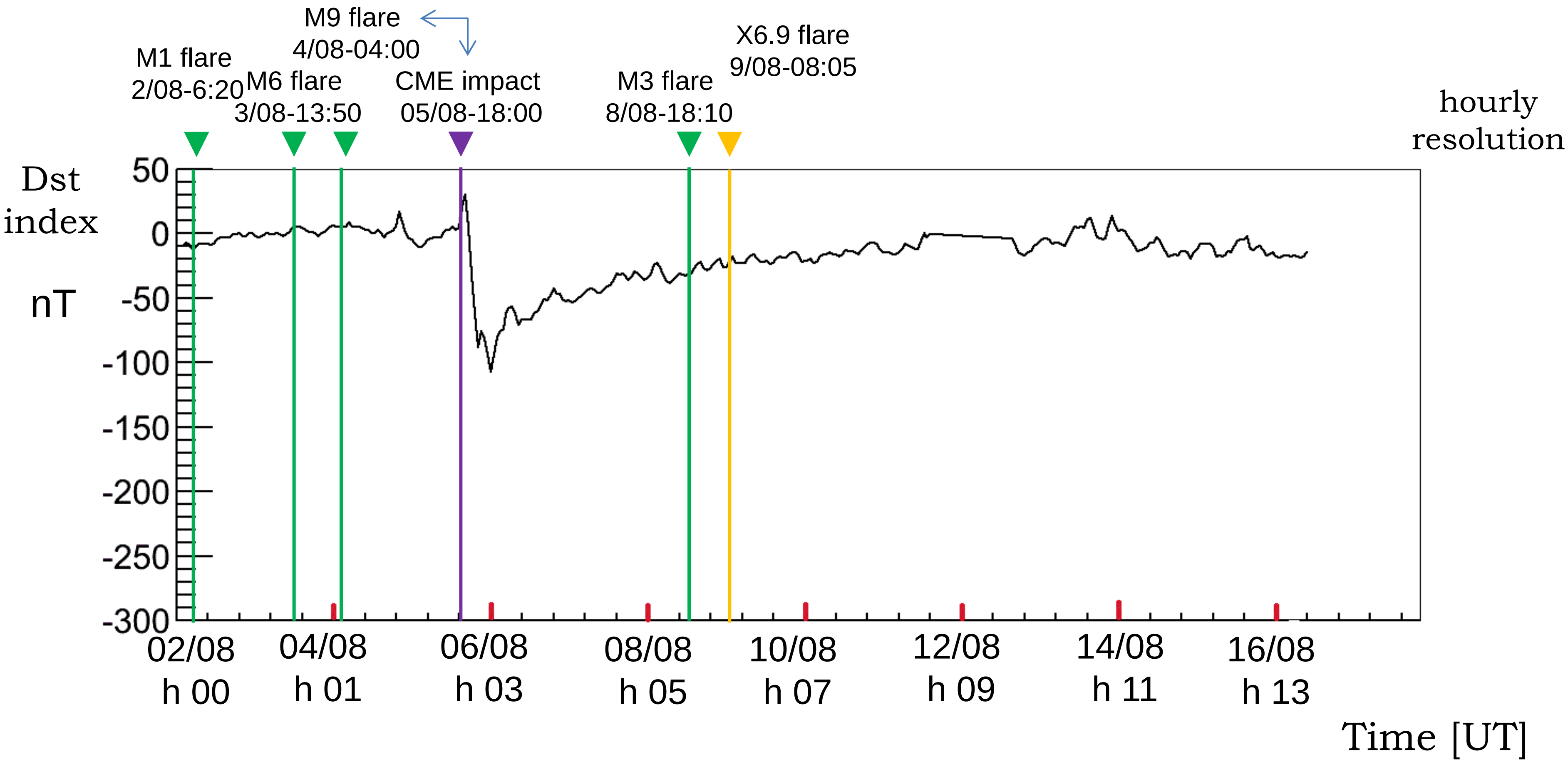


p_{sw_quiet} = 1,64 nPa

Computed on a quiet period in 2008

- ▼ Emission (max) of other flares
- ▼ CME impact on Earth
- ▼ Central flare emission (max)

August Dst Index

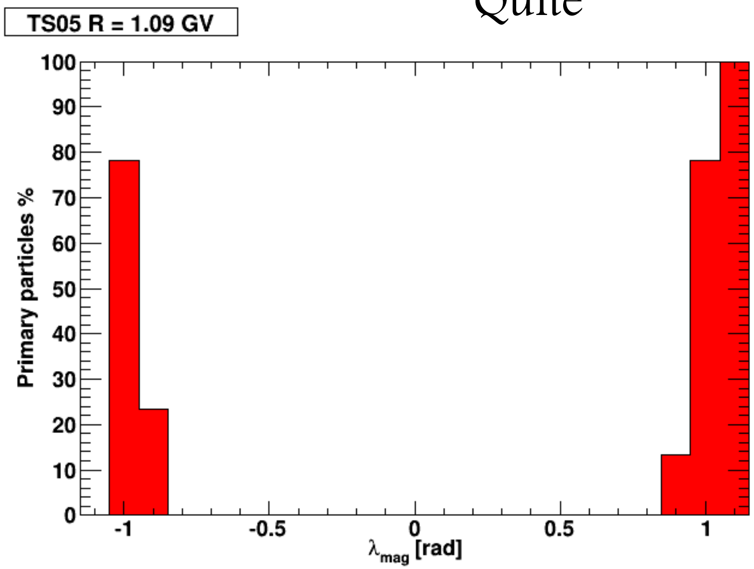


▼ Emission (max) of other flares
▼ CME impact on Earth
▼ Central flare emission (max)

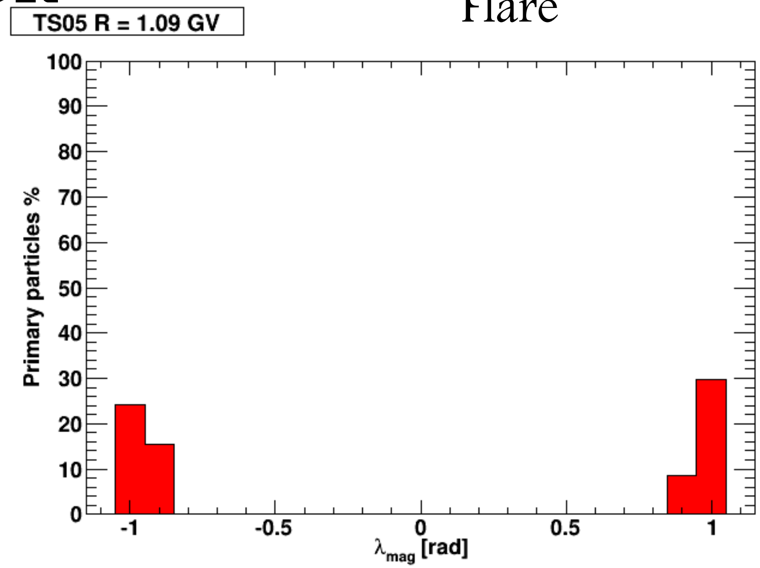
Solar Protons - March event

Primary CR

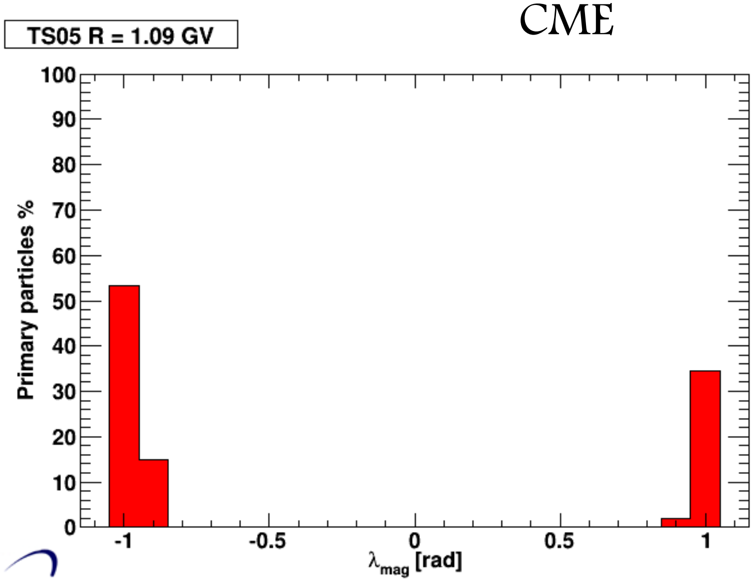
Quite



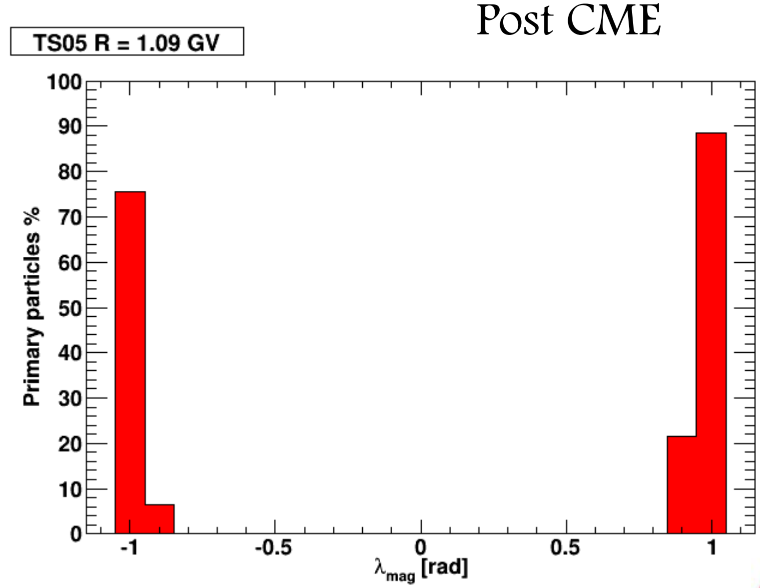
Flare



CME



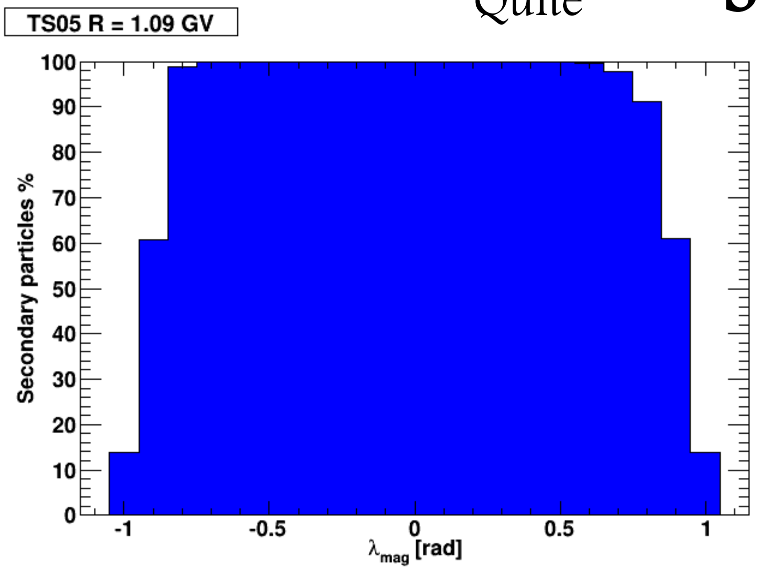
Post CME



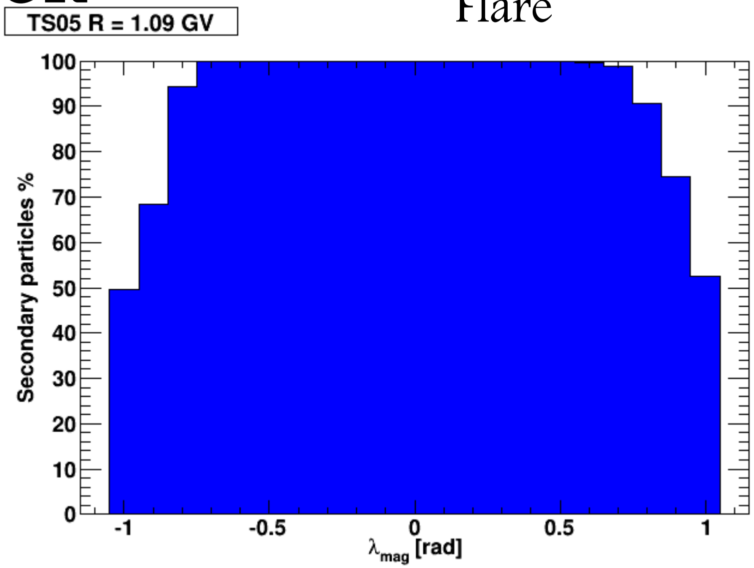
Solar Protons - March event

Secondary CR

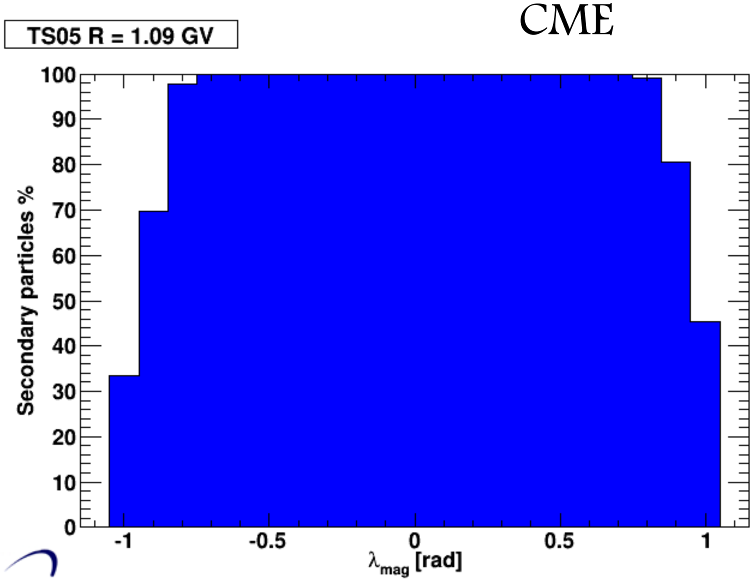
Quite



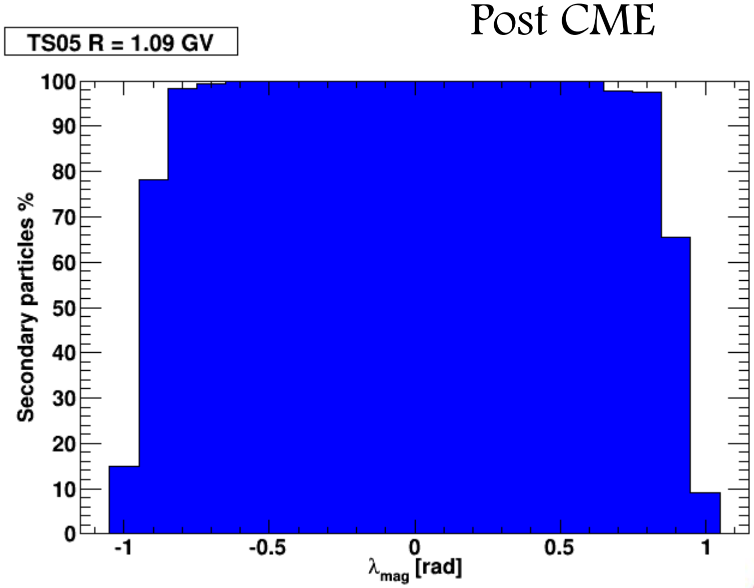
Flare



CME



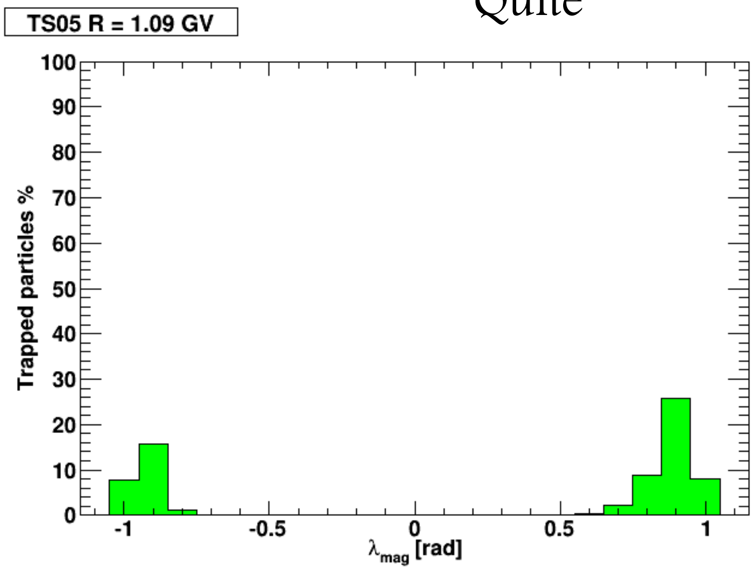
Post CME



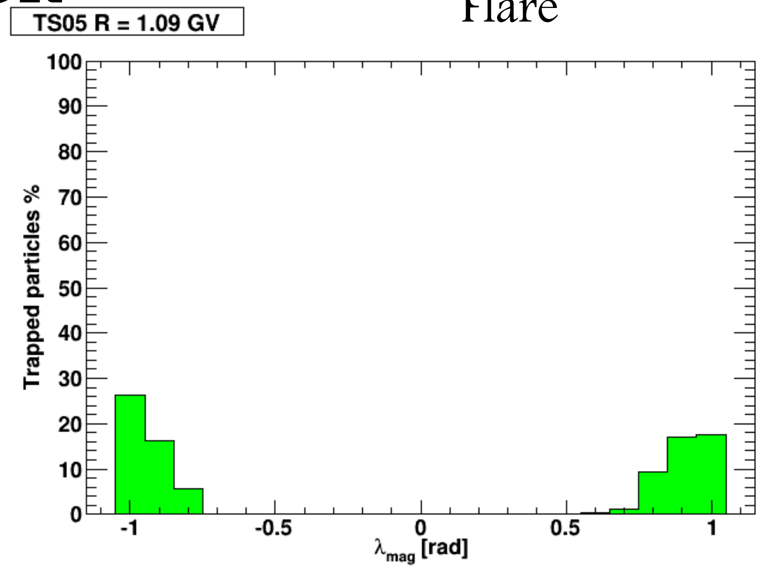
Solar Protons - March event

Trapped CR

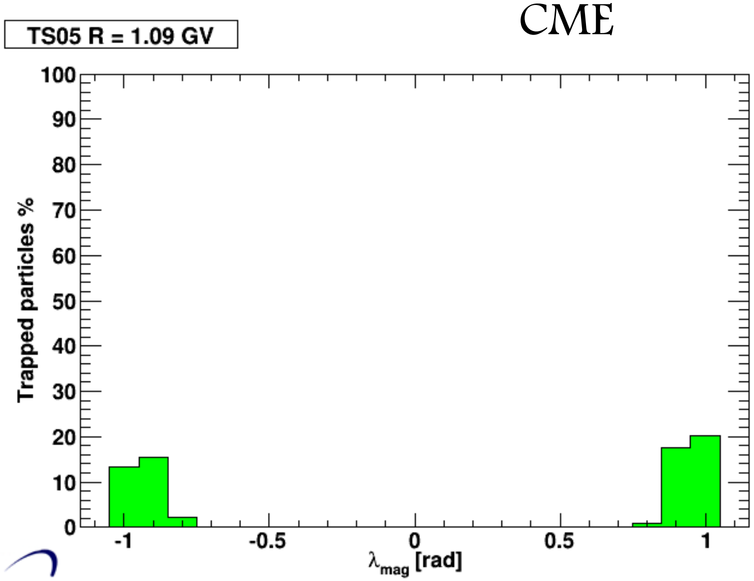
Quite



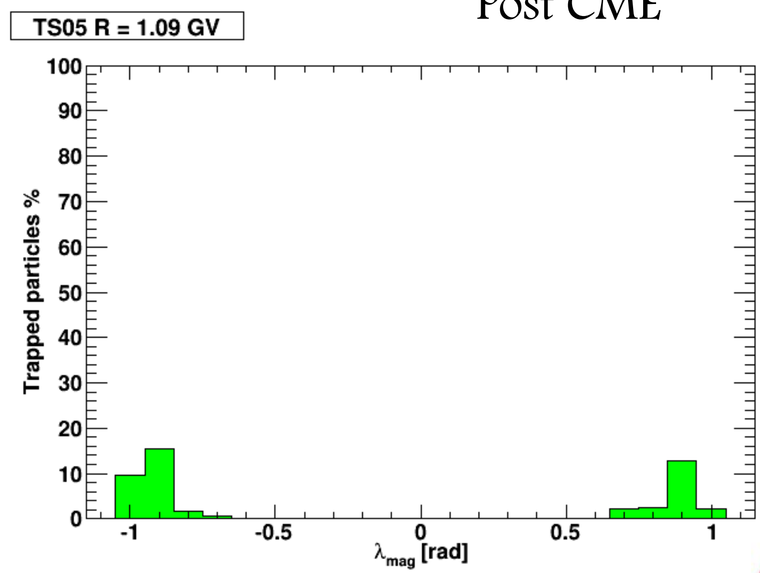
Flare



CME

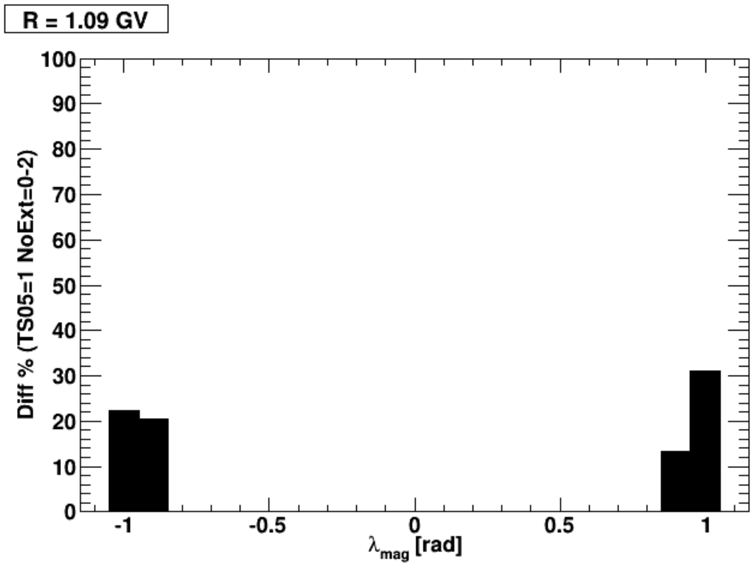


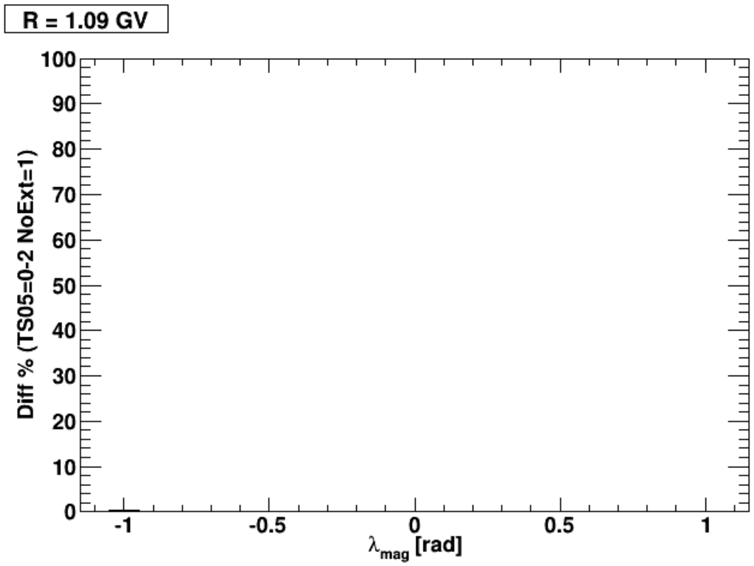
Post CME



Diff IGRF/TS05

QUITE

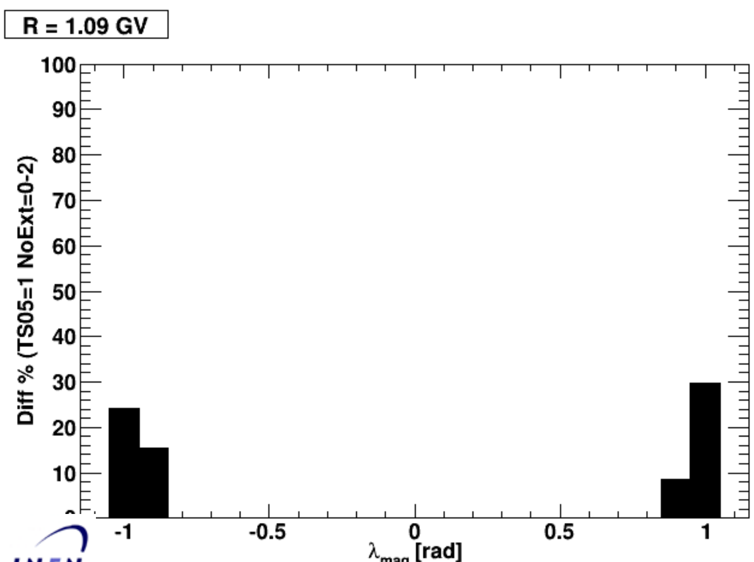


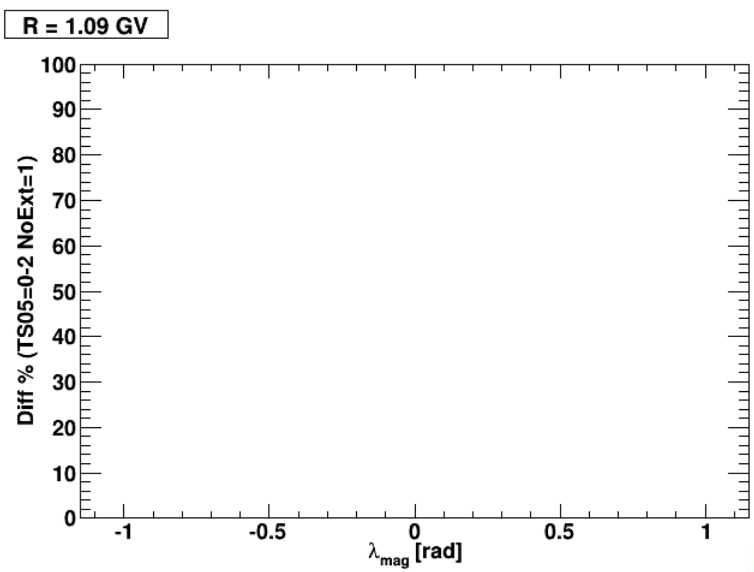


TS05 Primary; IGRF Secondary

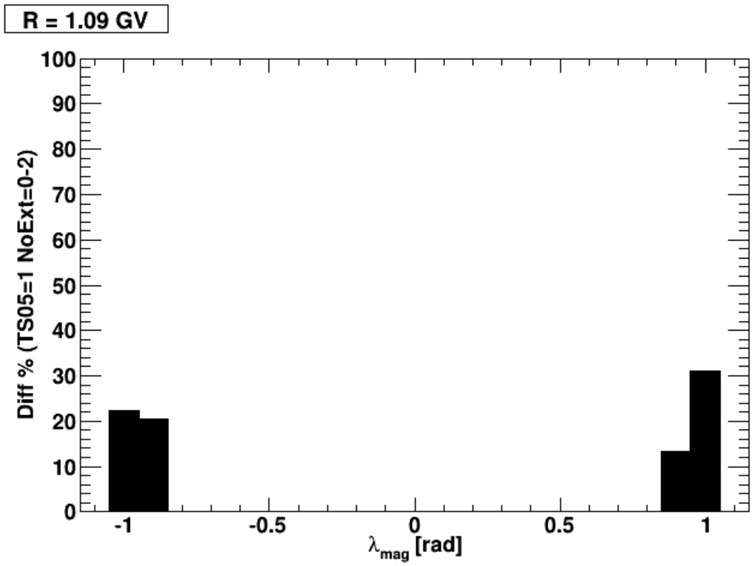
TS05 Secondary; IGRF Primary

FLARE

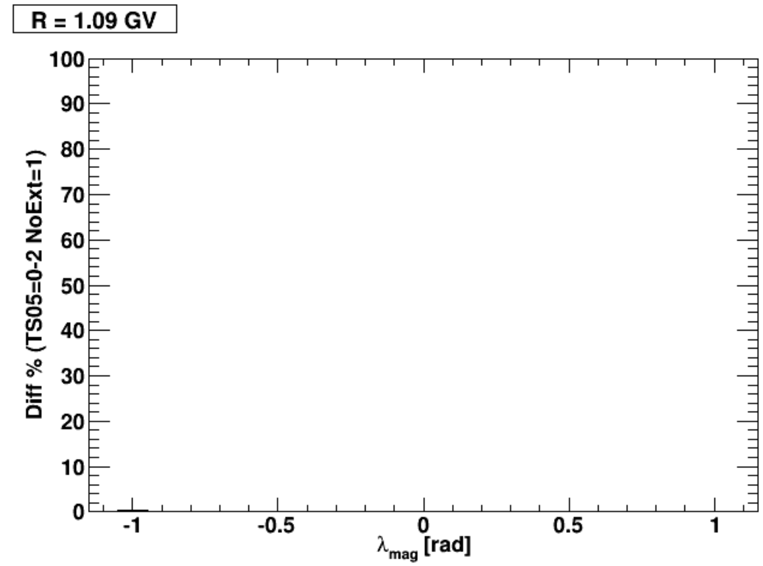




Diff IGRF/TS05

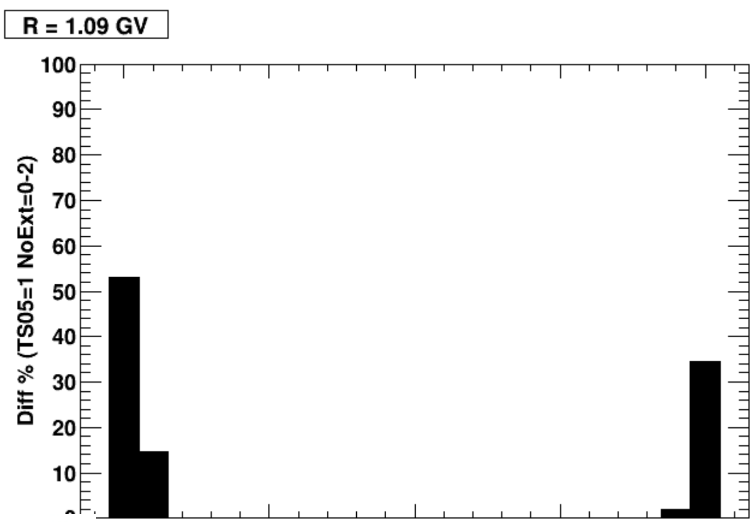


QUITE

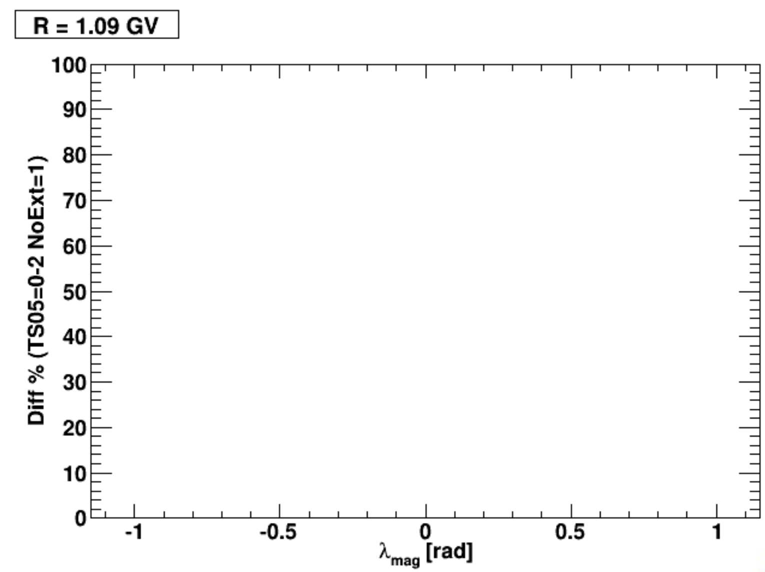


TS05 Primary; IGRF Secondary

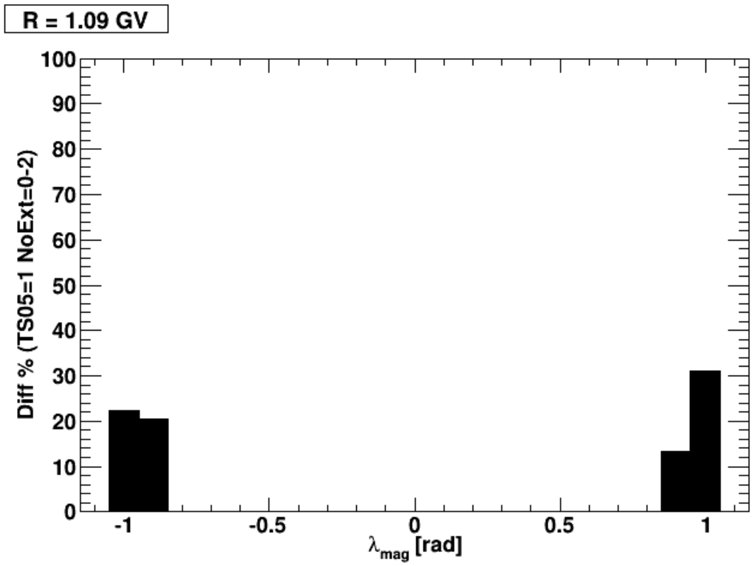
TS05 Secondary; IGRF Primary



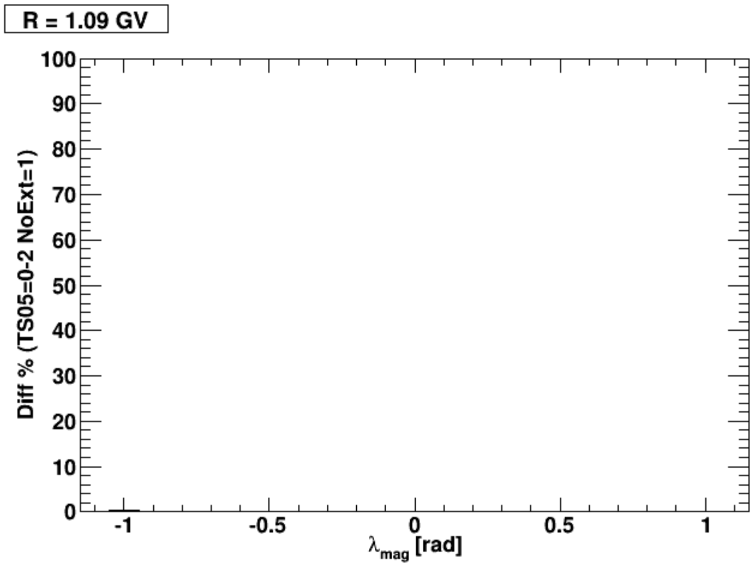
CME



Diff IGRF/TS05

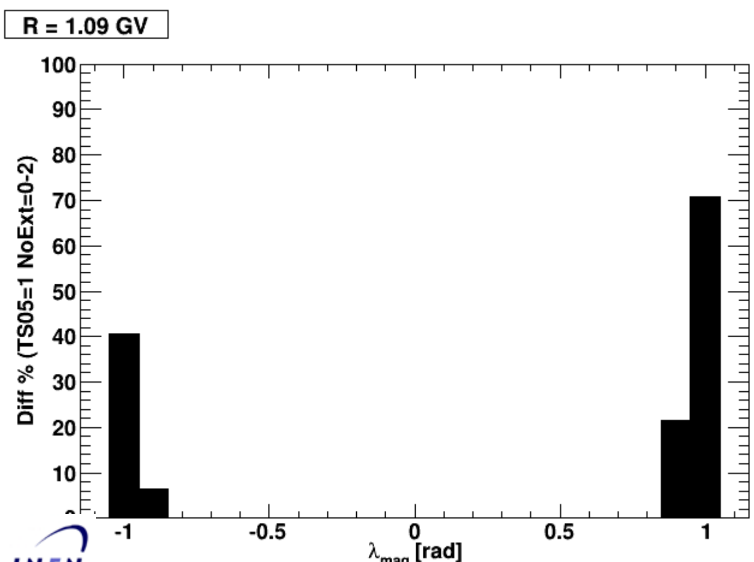


QUITE

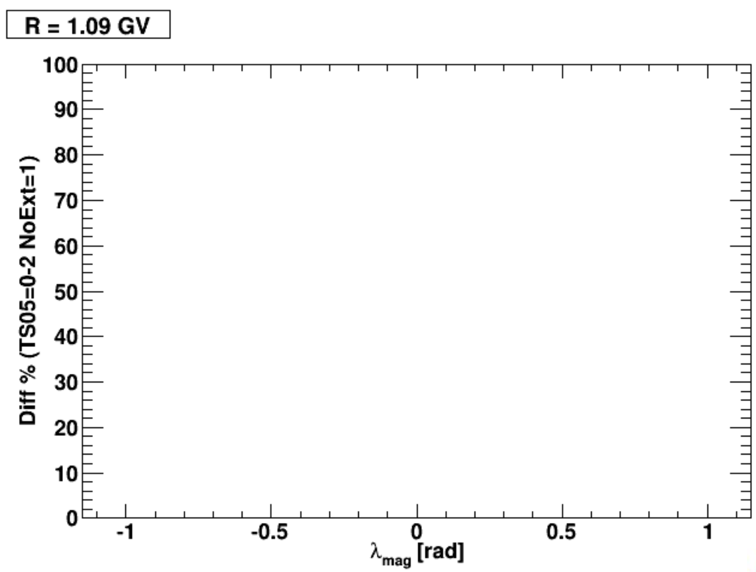


TS05 Primary; IGRF Secondary

TS05 Secondary; IGRF Primary



Post- CME



Conclusions

- With our study (and previous ones) we could verify that magnetic field measurements are in good agreement with predicted values with T05 (while simple IGRF is not precise enough especially in outer magnetosphere)
- T05, developed for storm periods, is even better in high solar activity periods like that one in which AMS-02 is taking data.
- The nature of Primary Cosmic rays highly depend on the magnetic field model, even up to 80-100% at high geomagnetic latitudes
- Even at high energy, so only for primary Cosmic Rays, the magnetosphere structure and an accurate Magnetic Model is important
- Our code, part of the AMS02 official one, has been used for the ongoing AMS-02 analysis for Solar Flares protons showing a big difference in separation of Primary and Secondary CR using or not the External Field (TS05)