Status update on geomagnetic Analysis

Davide Grandi

On behalf of
INFN Milano Bicocca group

Bologna, 20 December 2022

Summary

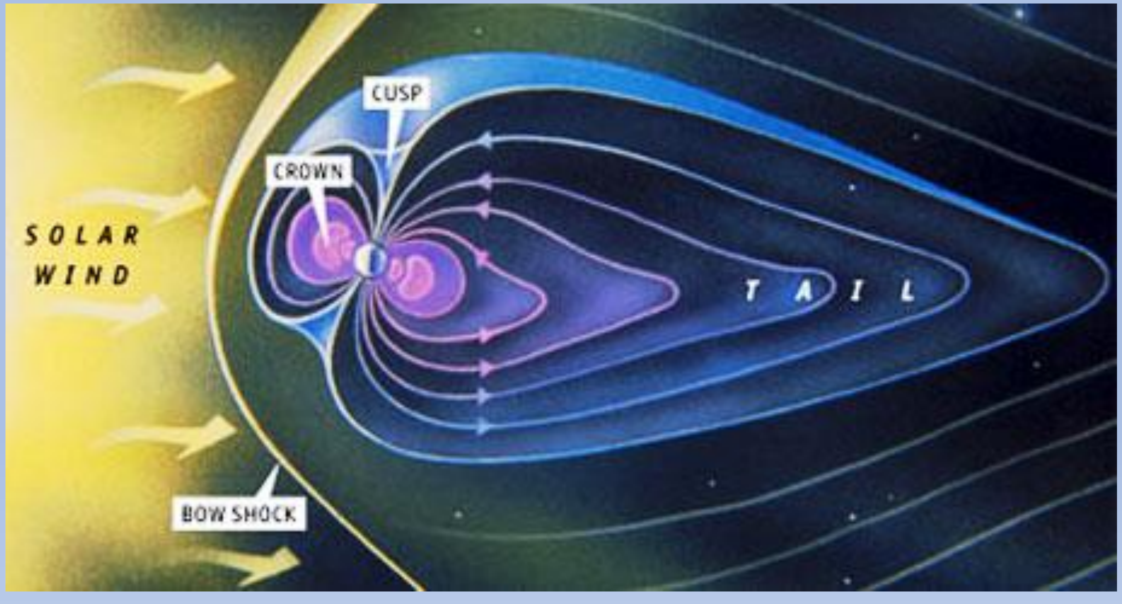
- IGRF Correction Factors from backtracing with TS05
- Possible application to AMS-02 Analisys
  - Average values
  - Solar parameter dependent values
- Secondary Particles
- Solar Flares
- Trapped Ions
- Trapped Protons
- Future developments & ideas

Back-tracing in the geomagnetic field

Our GOAL: find IGRF cut-off corrections based on OUR particle back-tracing.

- We performed the back-tracing using **GeoMagSphere** model (http://www.geomagsphere.org/) developed within the AMS-02 INFN – Milano Bicocca group

- **GeoMagSphere** is a back-tracing numerical code running IGRF internal field with external **Tsyganenko models** (in particular *Tsyganenko 1996* for quiet periods and *Tsyganenko 2005,* specifically developed to reproduce the magnetosphere during magnetic storms)
  - Tsyganenko models showed to **reproduce with good accuracy the geomagnetic field observations during quiet and disturbed periods.**



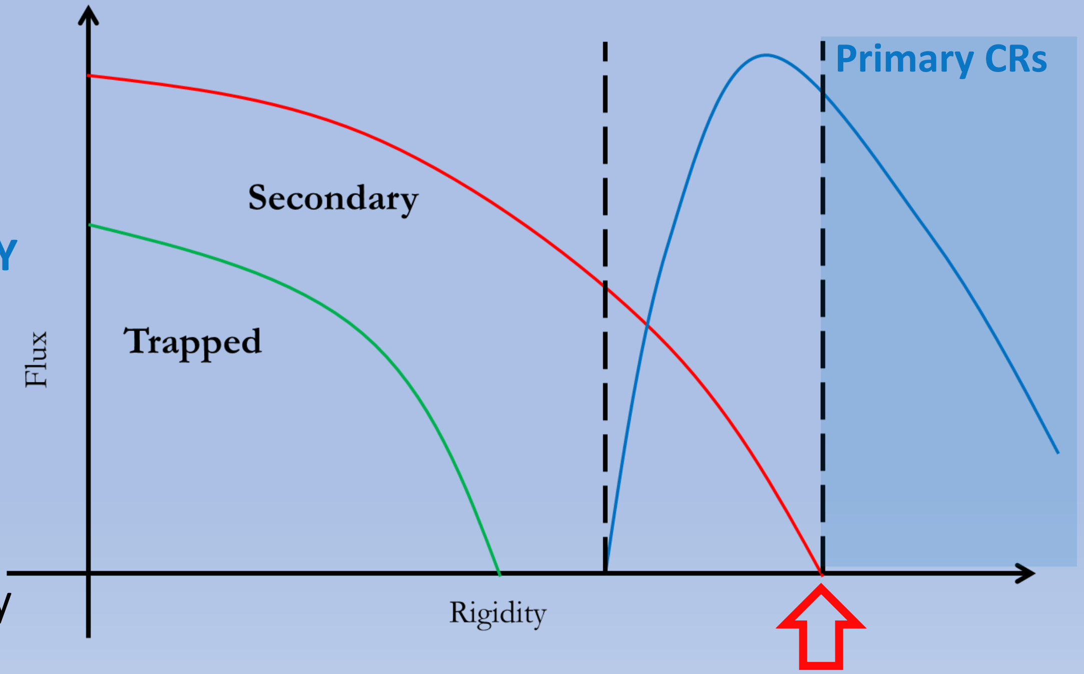
The Tsyganenko cut-off

In order to determine the cut-off, we used real selected events (in place of generated MC events) in the detector field of view.

- We selected AMS-02 protons between 0.8 GV < R < 100 GV, during **quiet** and **disturbed** periods of the solar activity.

- Using **GeoMagSphere** we back-traced all the selected particles, determining the rigidity distribution of:
  - ➢ particles coming from the outer magnetosphere → **PRIMARY**
  - ➢ particles created in the atmosphere → **SECONDARY**
  - ➢ particles trapped in the magnetic field lines → **TRAPPED**

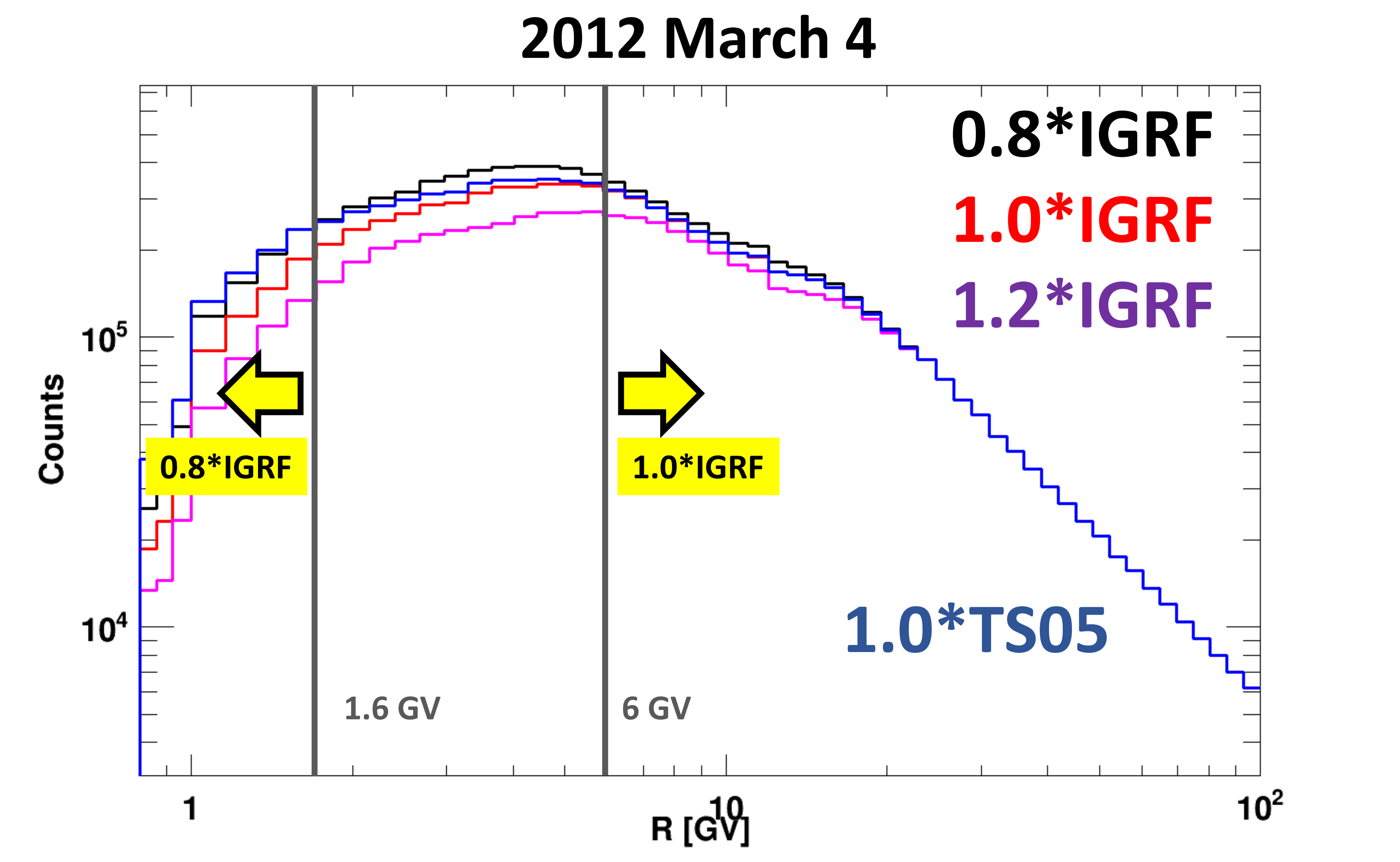
- **The Tsyganenko rigidity cut-off** is the upper rigidity cut-off, defined as the highest rigidity for particles identified as secondary
- **SO NO PENUMBRA!**



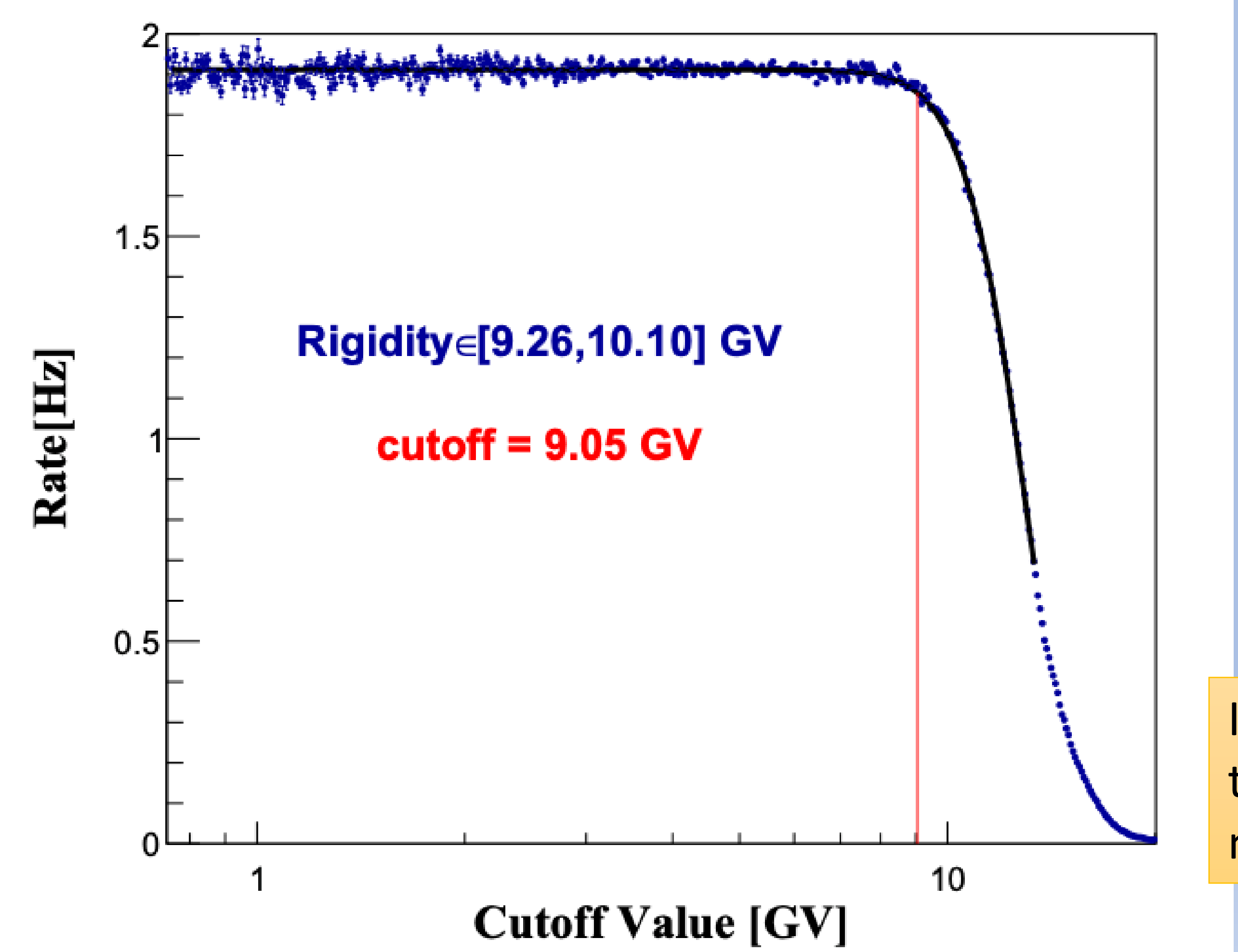
Operative definition of cut-off rigidity:
the highest rigidity for secondary particles
hereafter referred to as the *Tsyganenko cut-off*

Tsyganenko vs IGRF – SF?

- Analysis of AMS-02 protons and evaluation of possible safety factor to increase statistics



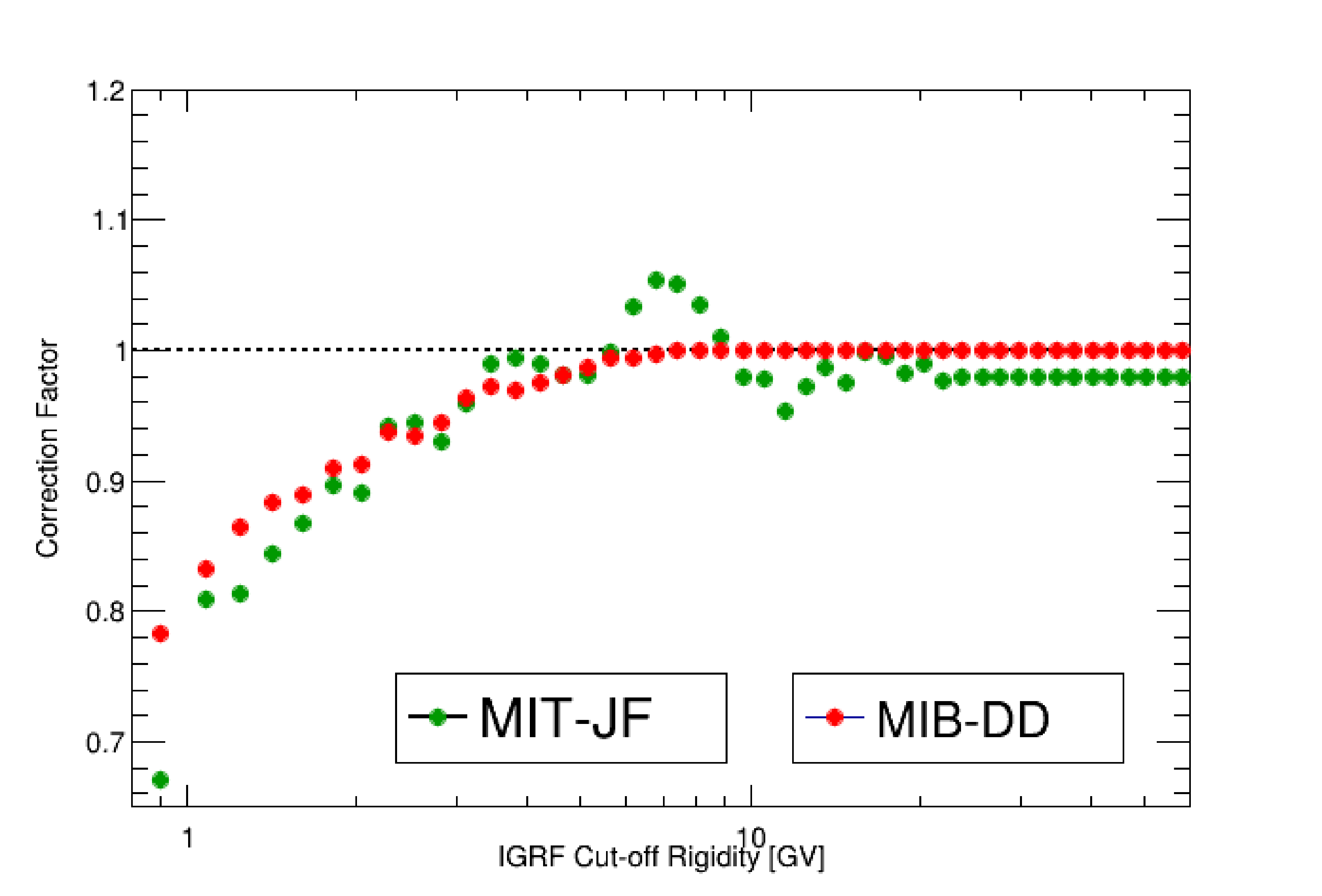
Cutoff Estimation Method – J. Feng



- **At different geomagnetic cut-offs or locations, we measure the corresponding rates.**
- **We fit the Rate distribution to measure the cutoff value.**
- **In this way, we correct the IGRF cut-off model with AMS by Safe Factor = Rigidity/cutoff.**

In the present study the correction factor derived in the Inner+L1 geometry, for the Choutko rigidity, maximum value of p and He, has been used.

Geomagnetic cut-off correction factor



Data Selection and strategy

- We selected AMS-02 protons in 2 Bartel Rotations a **quiet one** June/July 2016 and **disturbed one** March/April 2012.

- Using **GeoMagSphere** we back-traced all the selected particles, with different models:
  - Tsyganenko 2005 and Tsyganeno 96
  - IGRF

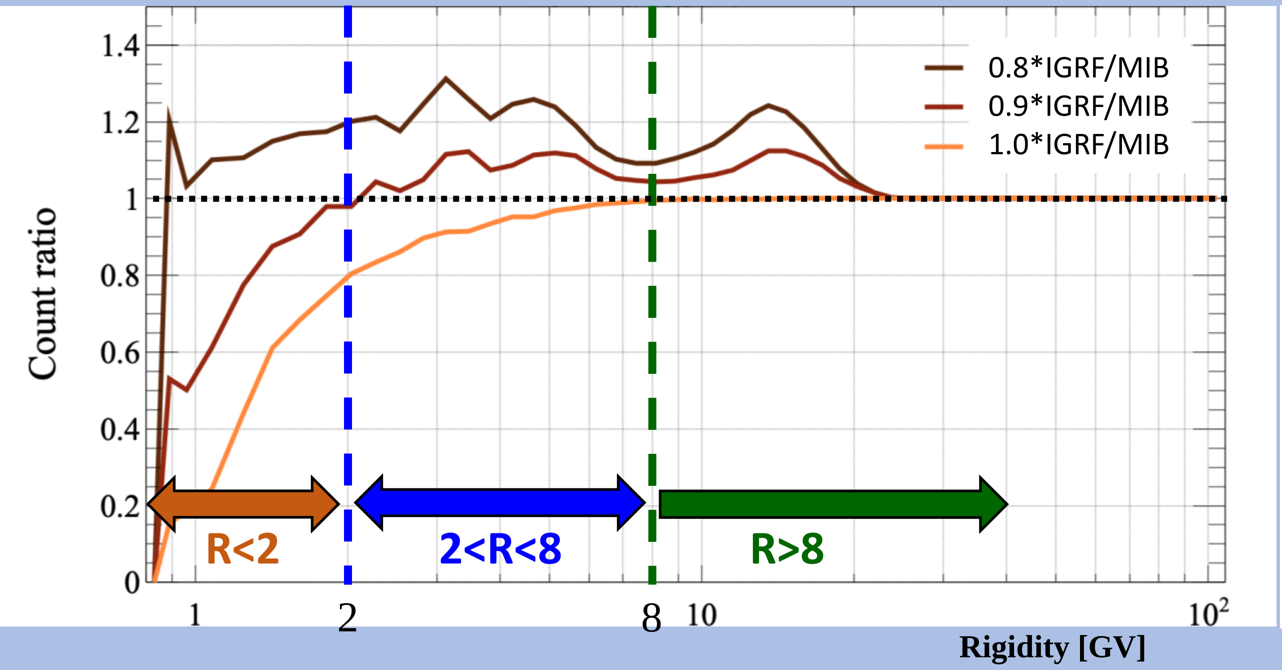
- **The Tsyganenko rigidity cut-off** is taken as REFERENCE
- **IGRF counts are compared with TS05 ones**
- **Exposure and Rate are then obtained**

Which is the factor to be applied to the IGRF cut-off in order to obtain the same event count as using the Tsyganenko cut-off?

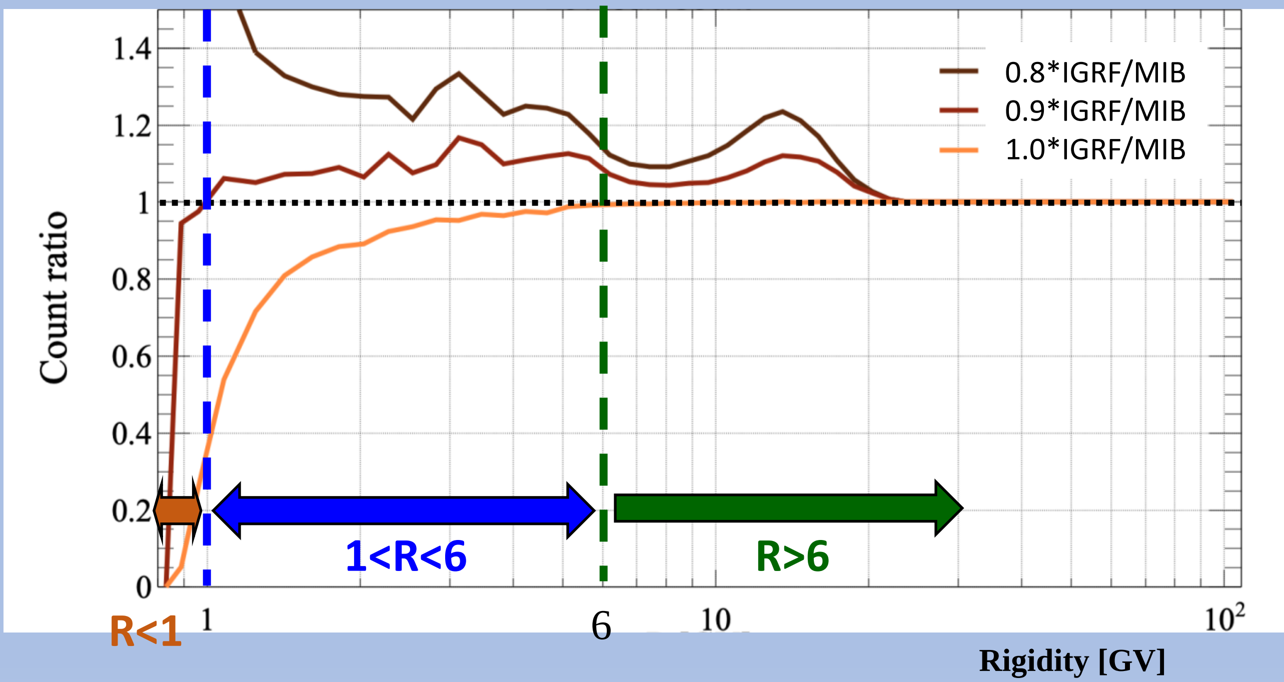
Cut-off optimization: IGRF vs. Tsyganenko cut-off

For each rigidity bin, the **correction factor** is the factor to be applied to the IGRF cut-off in order to **match (within 1,2 max 3%) the event count obtained using the Tsyganenko cut-off**.

Inner Tracker + L1 geometry



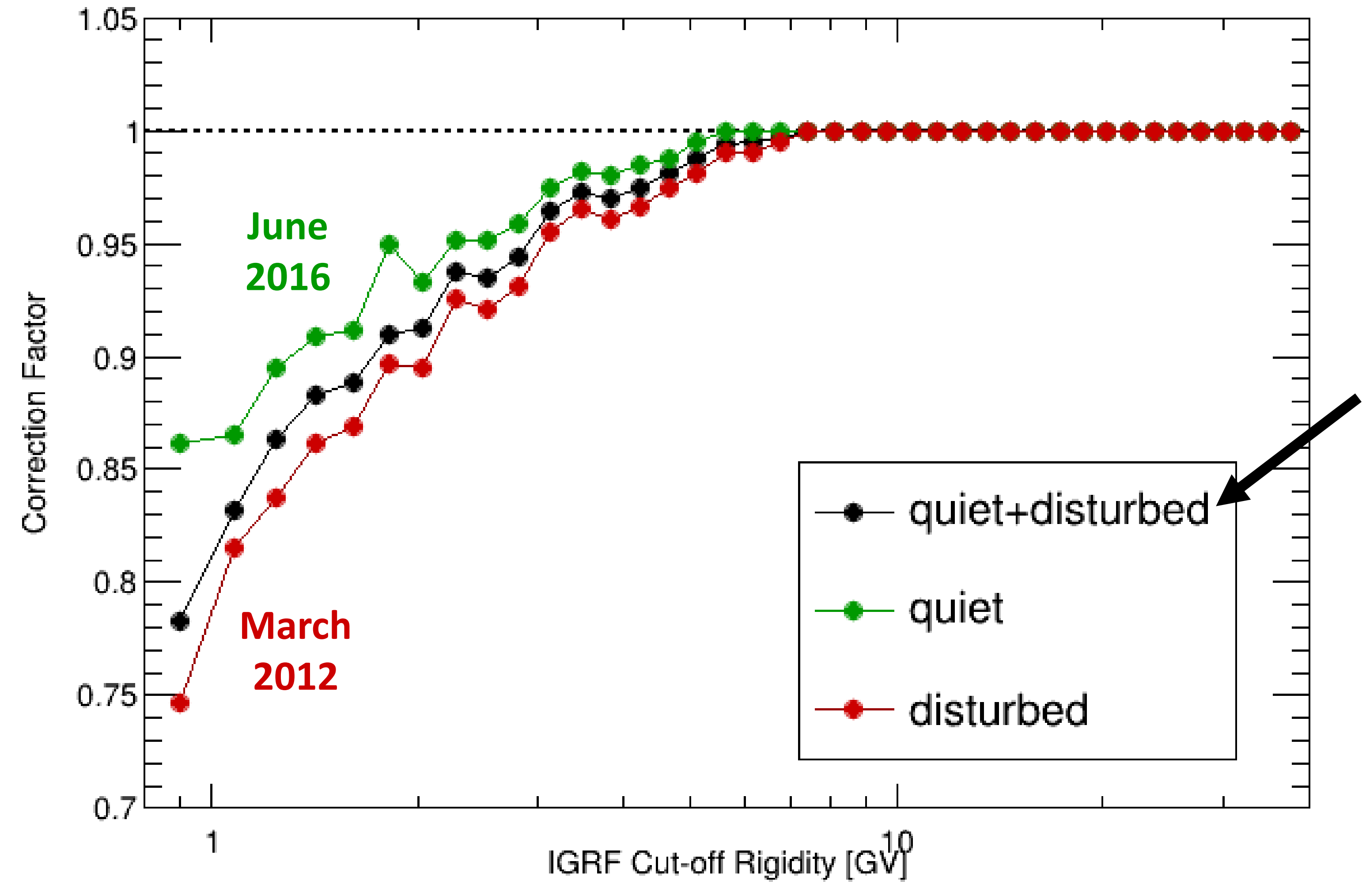
A disturbed period – March 2012



A quiet period – June 2016

The correction factor is rigidity dependent.
Moreover it varies according to geomagnetic disturbances.

Geomagnetic cut-off correction factor



Inner Tracker + L1 geometry

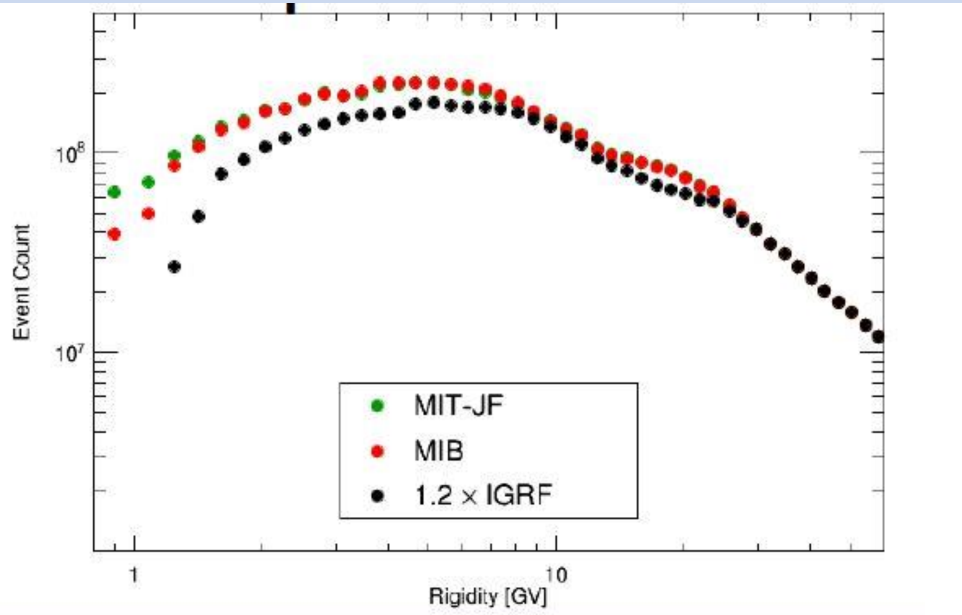
For the present study the "averaged" correction factor has been used

Quiet
Bartel 2495

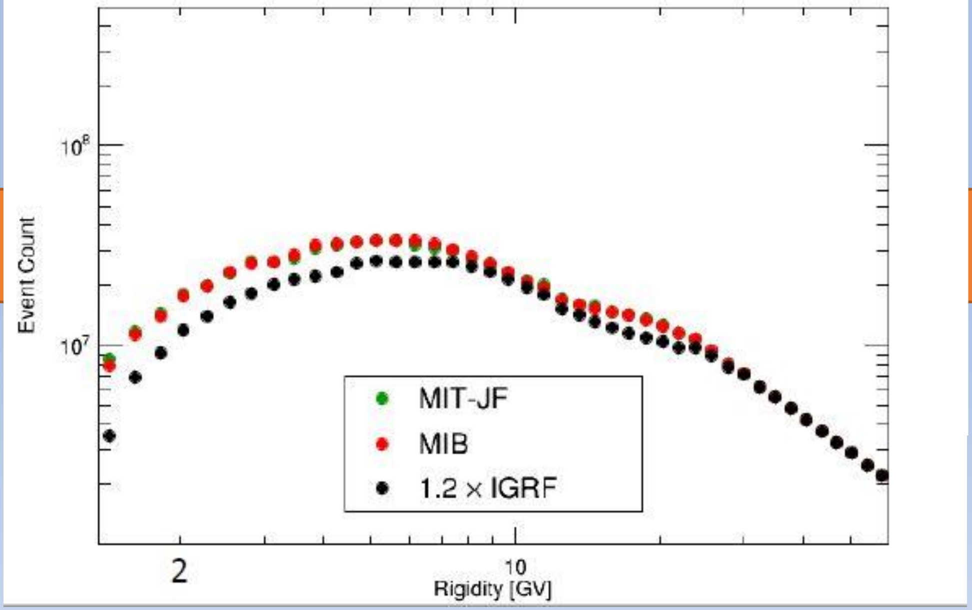
Disturbed
Bartel 2437

Event Counts: direct comparison

Proton

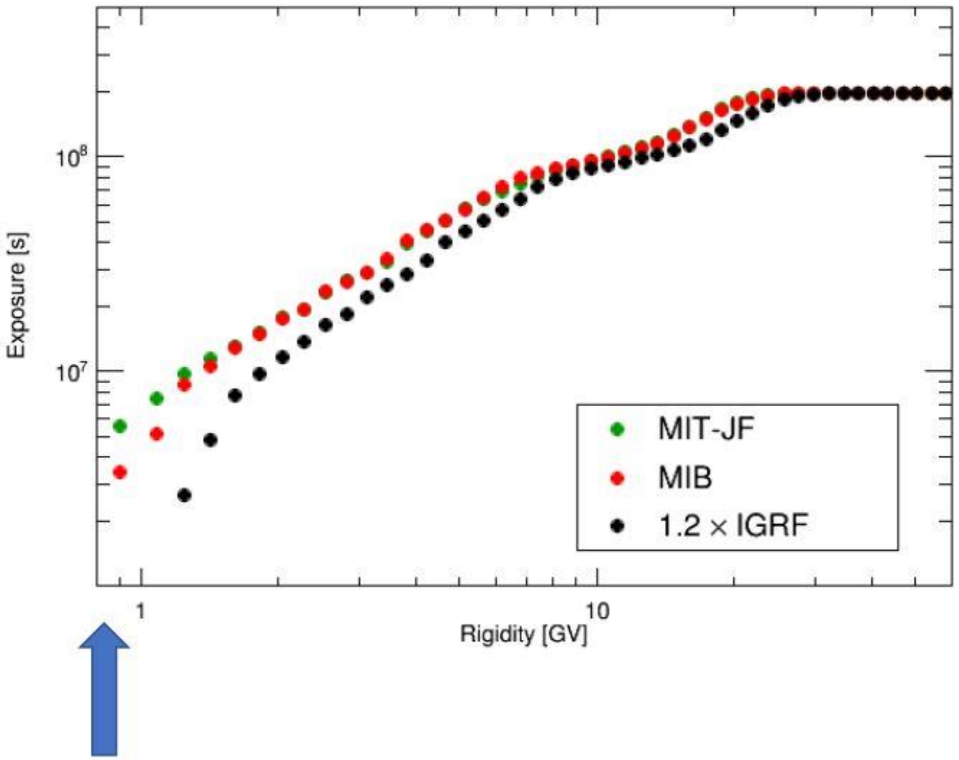


Helium



Protons

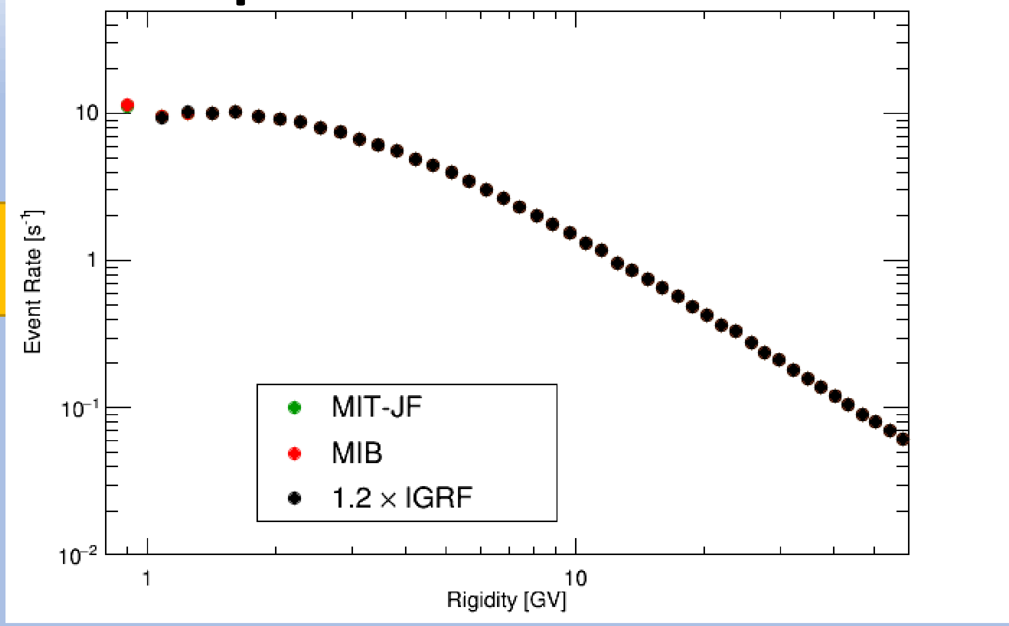
Exposure



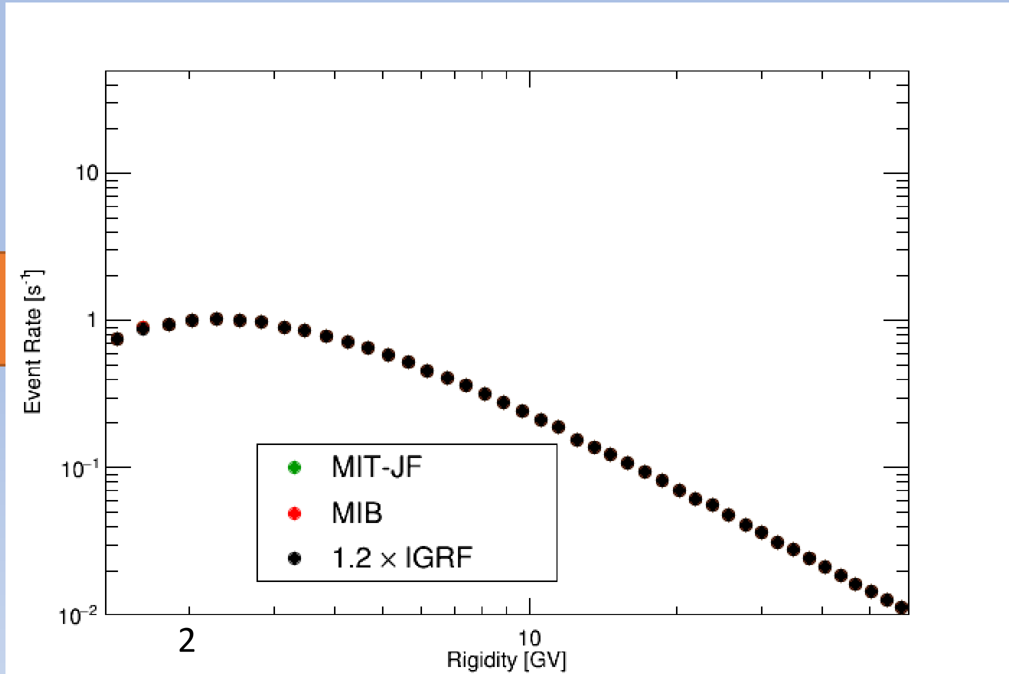
[0.8,1.0]GV
Bin not allowed
using IGRF cut-off

Event Rate: comparison with 1.2×IGRF cut-off

Proton



Helium



First Conclusions

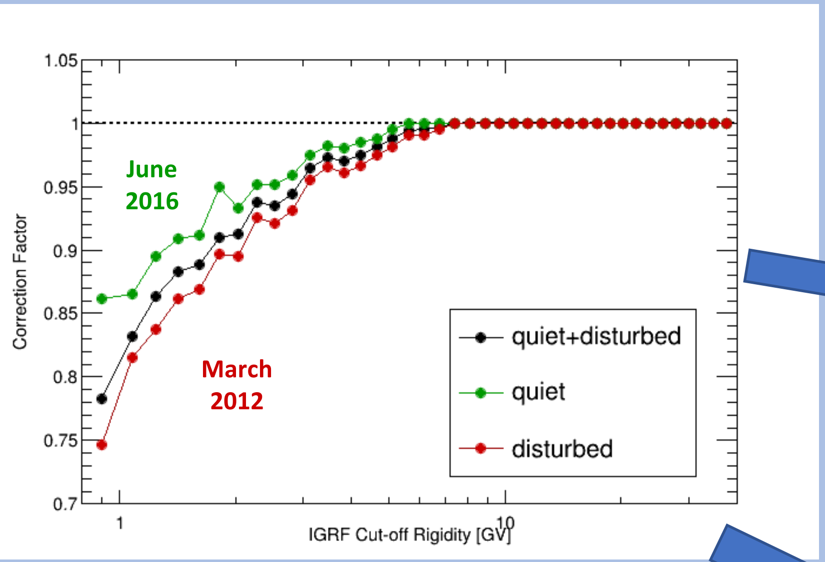
- We back-traced real events by means of the **GeoMagSphere** code, in order to estimate the cut-off in the AMS field of view, using realistic models of the geomagnetic field, such as the Tsyganenko models;
- We determined the **correction factor** to be applied to the IGRF cut-off in order to **match (at 1% level) the event count obtained using the Tsyganenko cut-off**. The present study as been performed considering two Bartel rotations, during a quiet (June 2016) and a disturbed (March 2012) period;

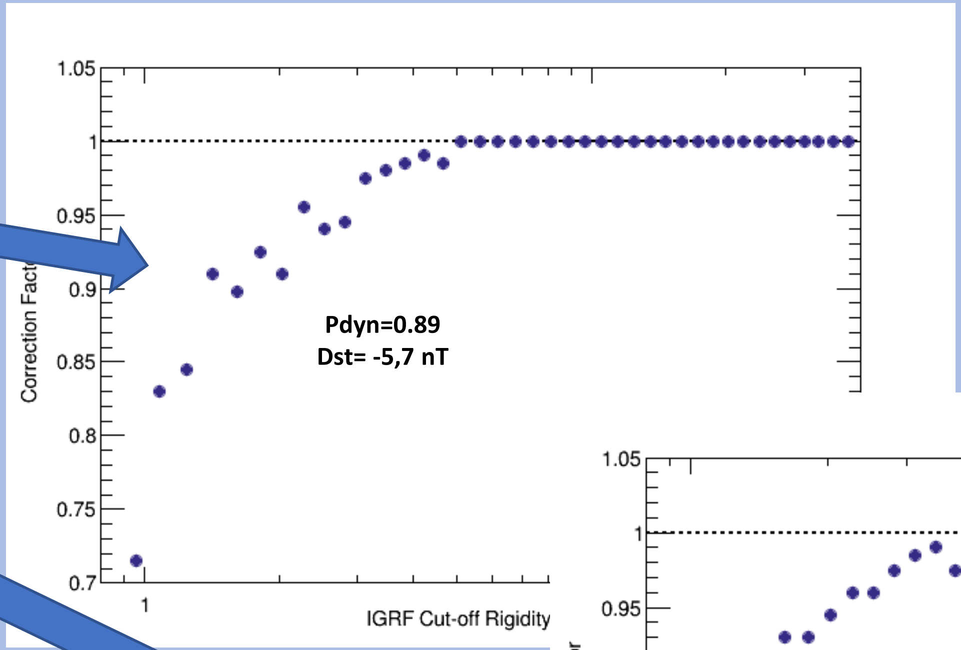
- **The increment in p & He statistics** using the corrected cut-off can reach **a factor larger than 10 at low rigidities**, with respect to the 1.2×IGRF cut-off**;**
- **The agreement between MIB and MIT-JF rate is <0.5% above 1.0GV;**

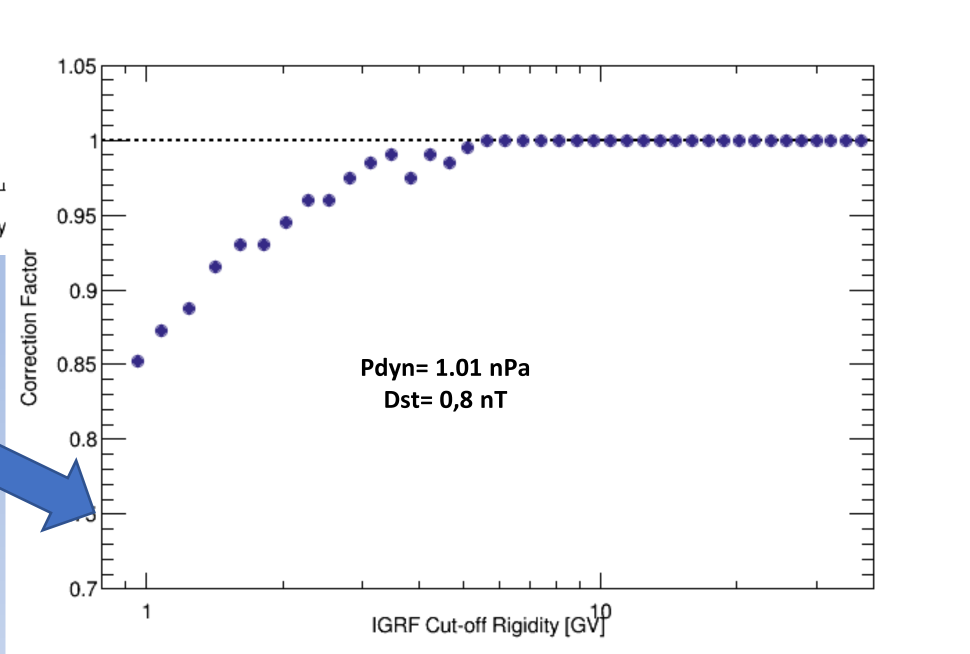
- In addition, peculiar periods with **solar energetic particles (SEPs),** need a suitable treatment, *i.e.* **back-tracing the full sample** with Tsyganenko magnetospheric field model.

www.geomagsphere.org

Data analysis
Geomagnetic cut-off correction factor







After the study performed considering two Bartel rotations, during a quiet (June 2016) and a disturbed (March 2012) period

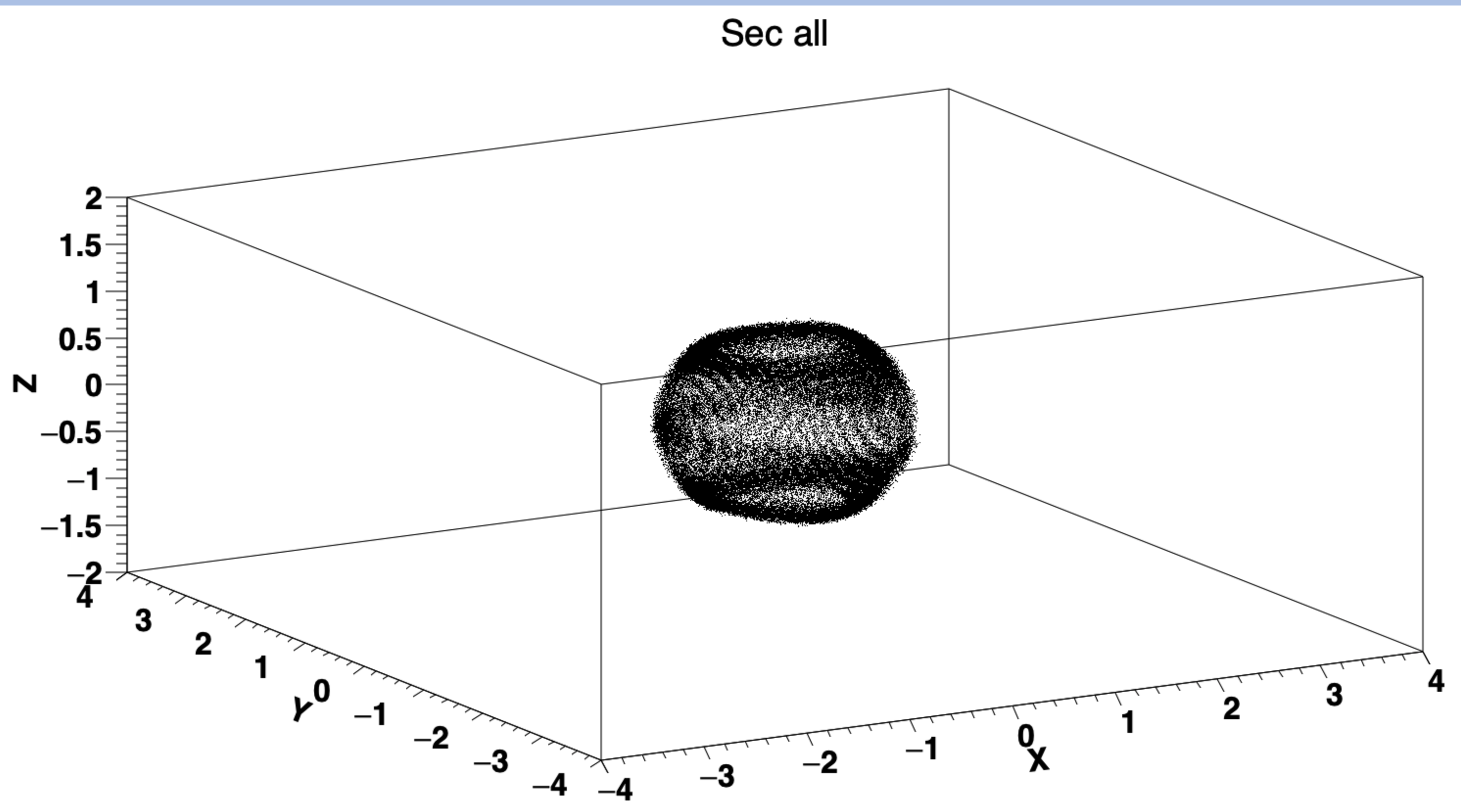
New Correction Factors depending on "daily average" **Solar Parameters (Pdyn)** and **magnetic disturbancies (Dst)**

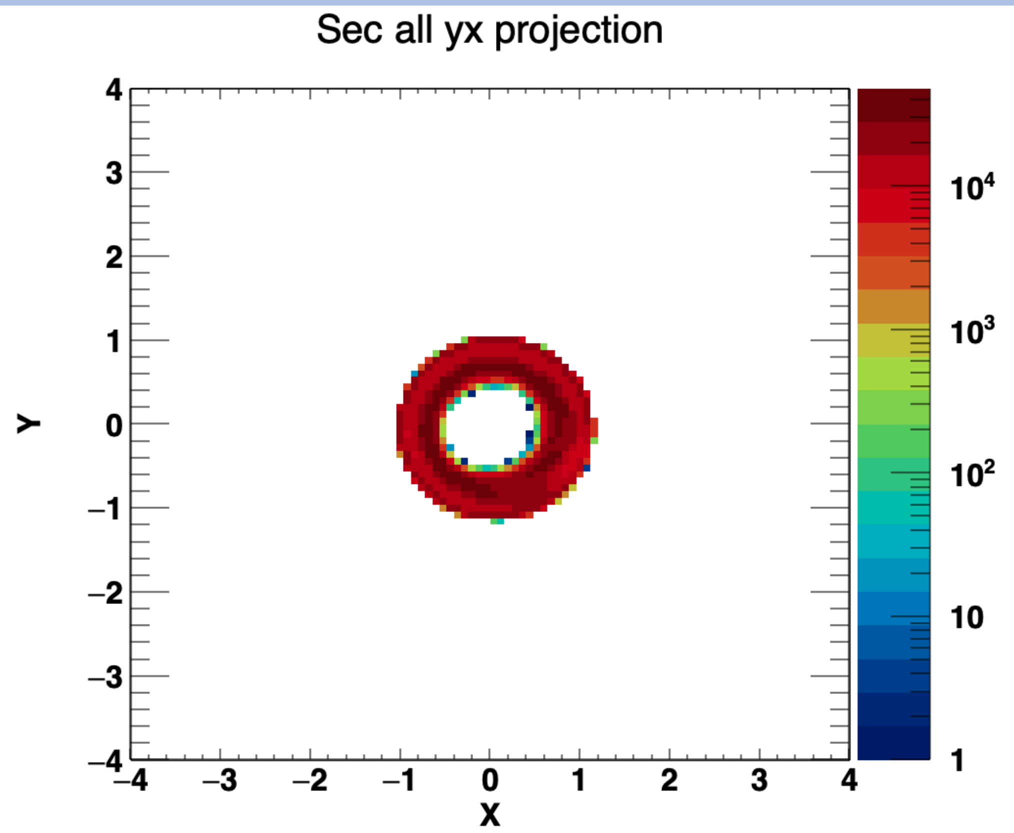
AMS-02 data analysis

SECONDARY PROTONS

- Back-tracing of secondary protons during March 2012 using GeoMagSphere
- Starting points of secondary trajectories detected close to magnetic equator and magnetic poles
- All graphs are in Geomagnetic coordinates

All Sec final point after BkT; 25° opening angle; days: March 4-12, 2012



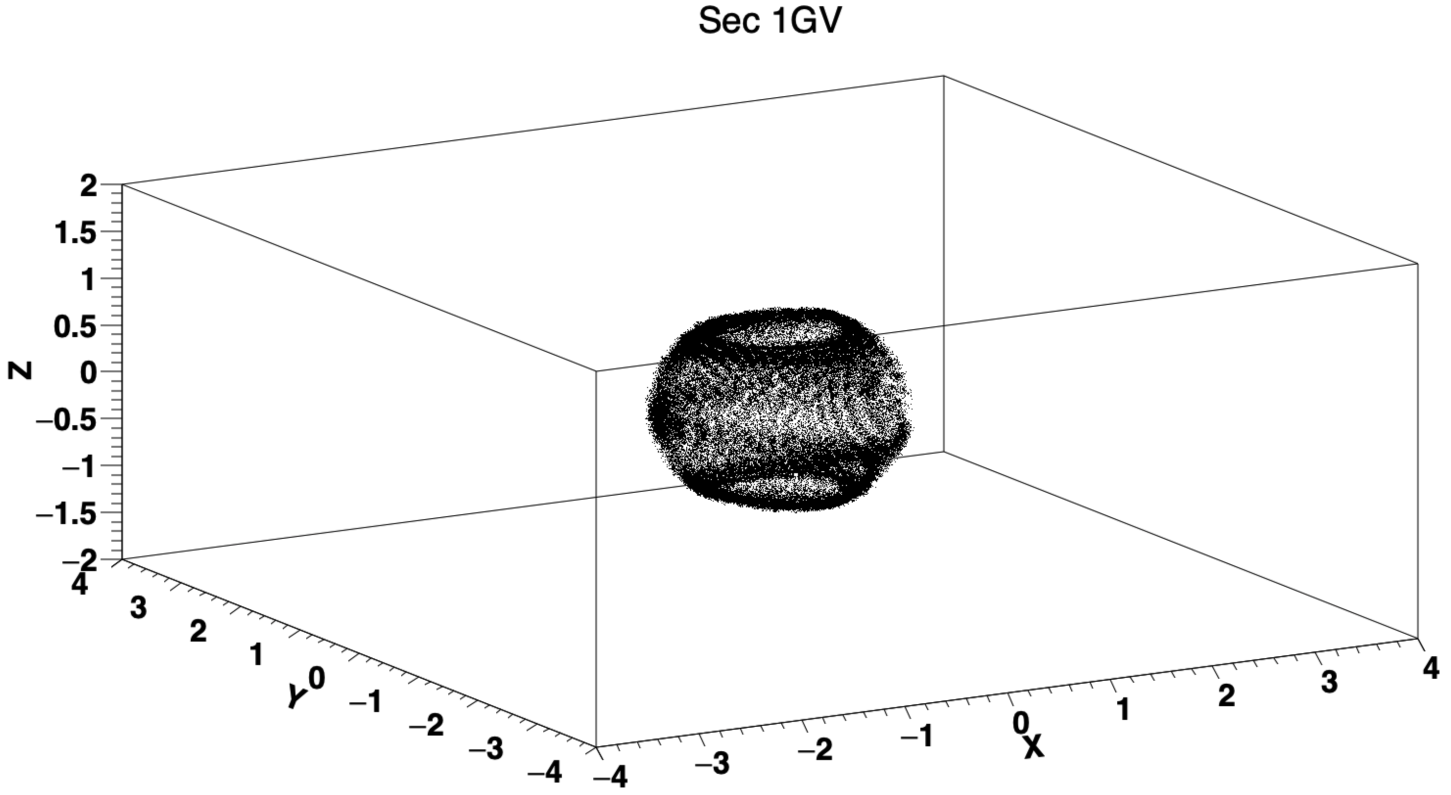


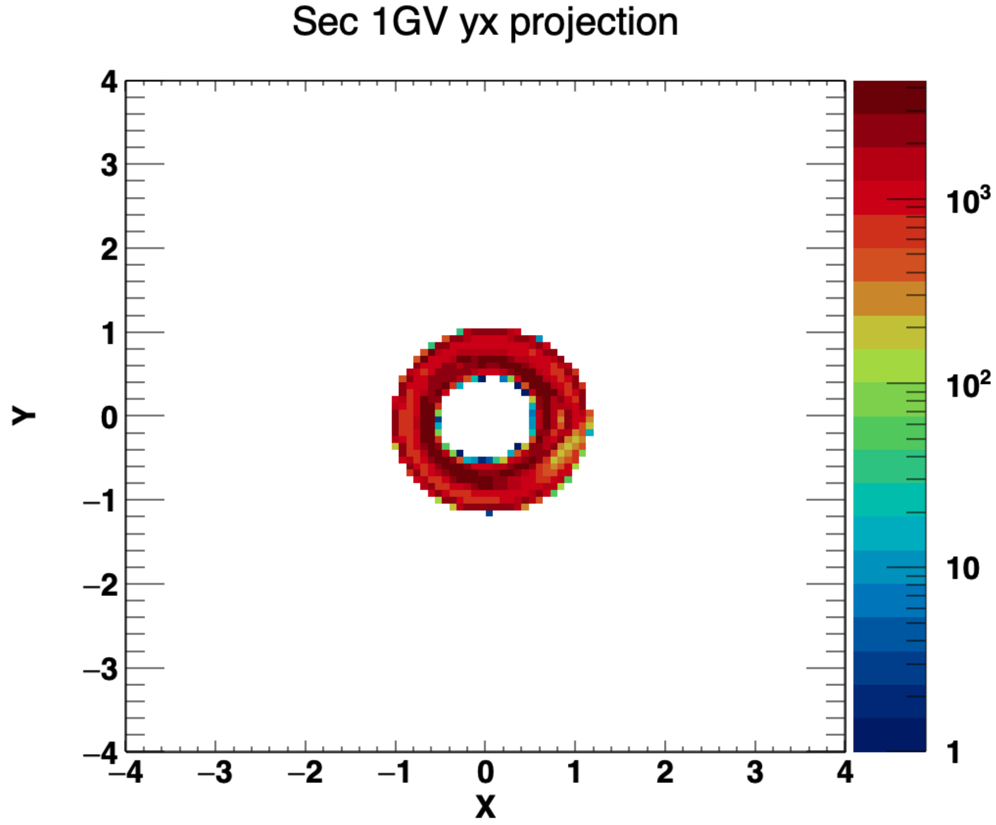
FINAL POINT = SAME SHOOTING ALTITUDE (AMS02 ONE)

Secondary CR detected at magnetic equator

Close to magnetic equator

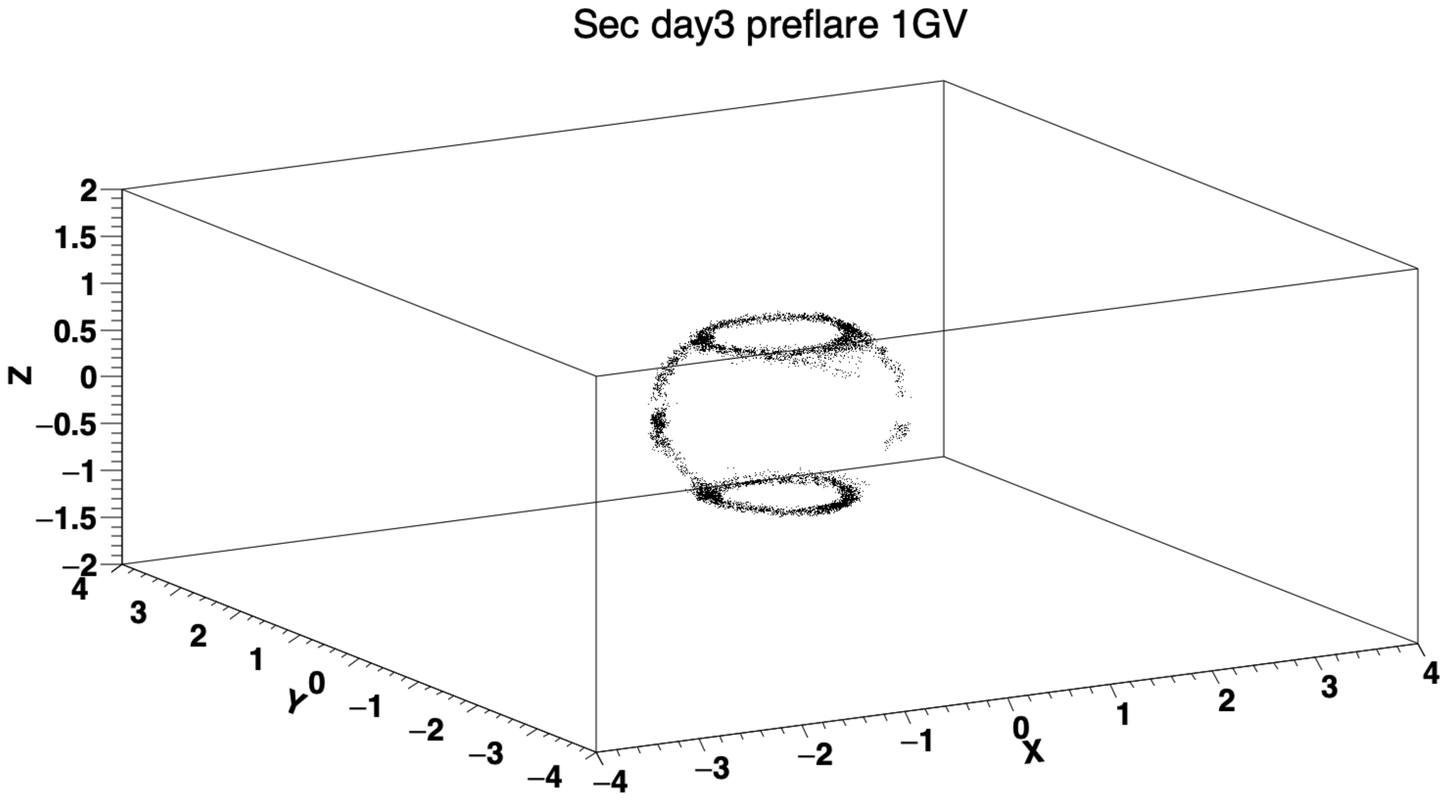
Sec final point after BkT; Sec detected in: -5°<λ_{mag}<+5°; 25° opening angle; day: March 4, 2012; R<1GV

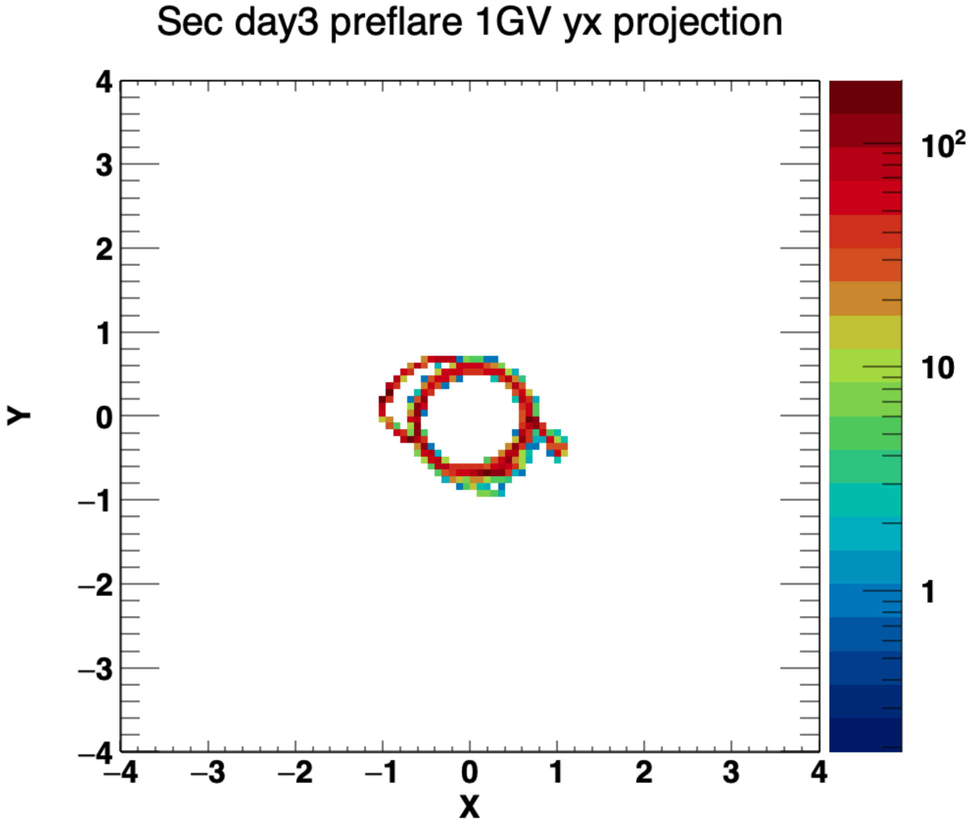




Close to magnetic equator

Sec final point after BkT; Sec detected in: -5°<λ_{mag}<+5°; 25° opening angle; day: March 6, 2012; R<1GV
t=90min

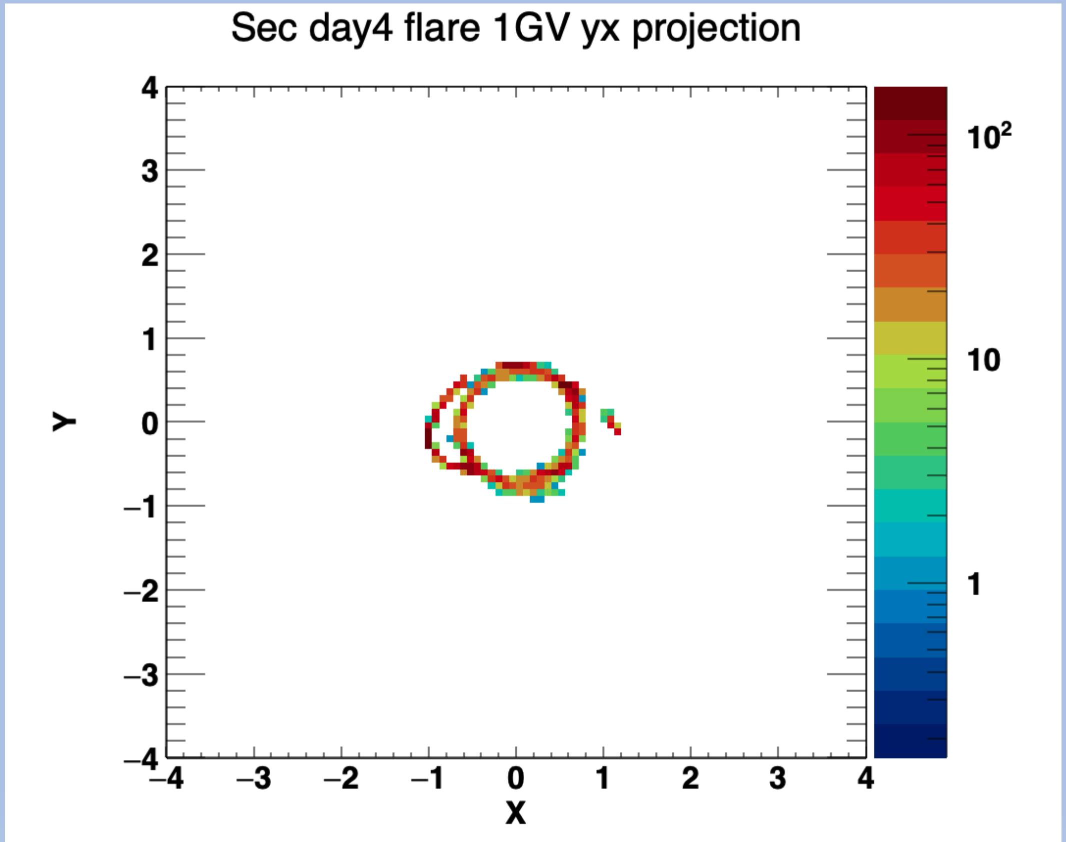




Close to magnetic equator

Sec final point after BkT; Sec detected in: -5°<λ_{mag}<+5°; 25° opening angle; day: March 7, 2012; R<1GV

t=90min



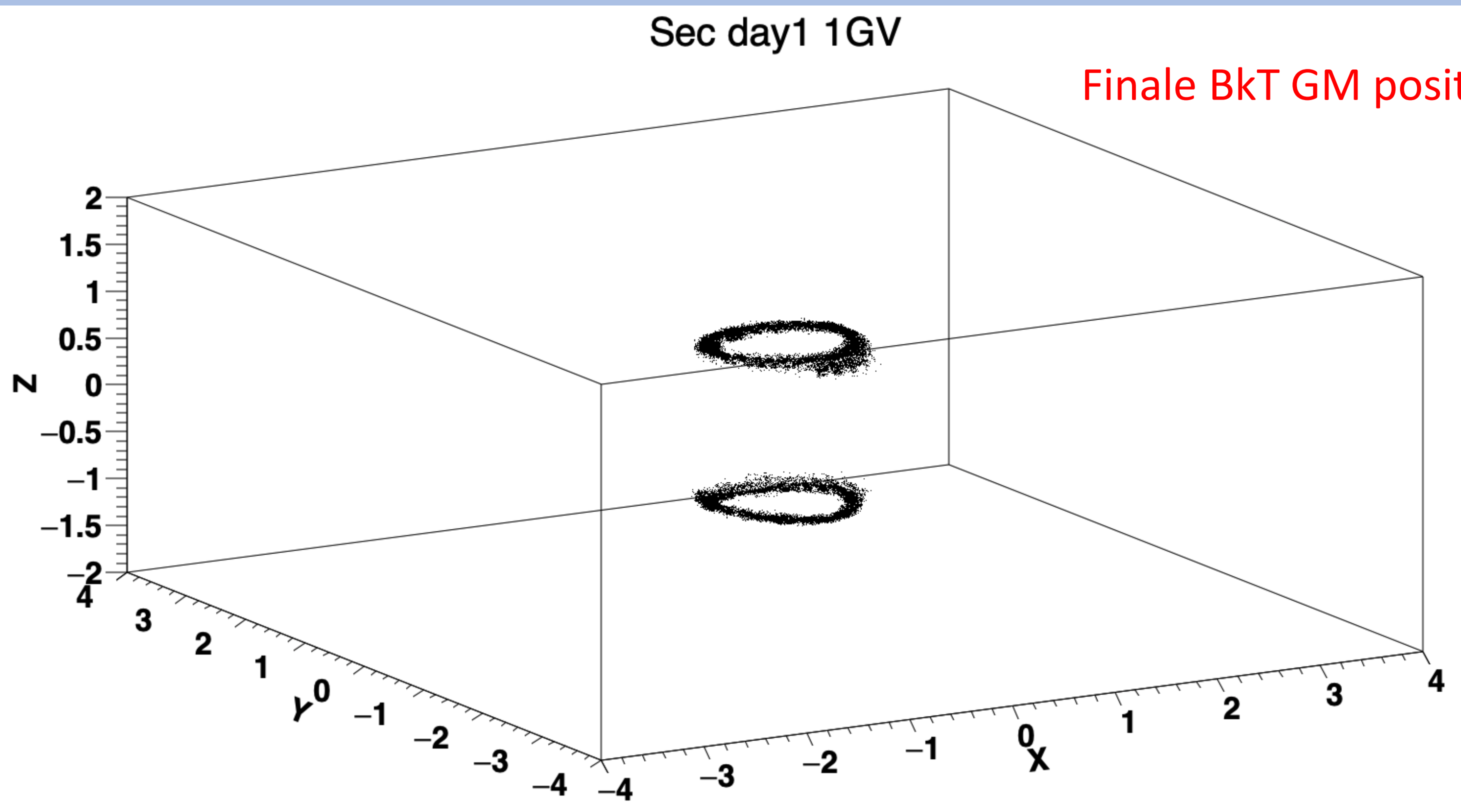
Secondary CR detected at magnetic poles

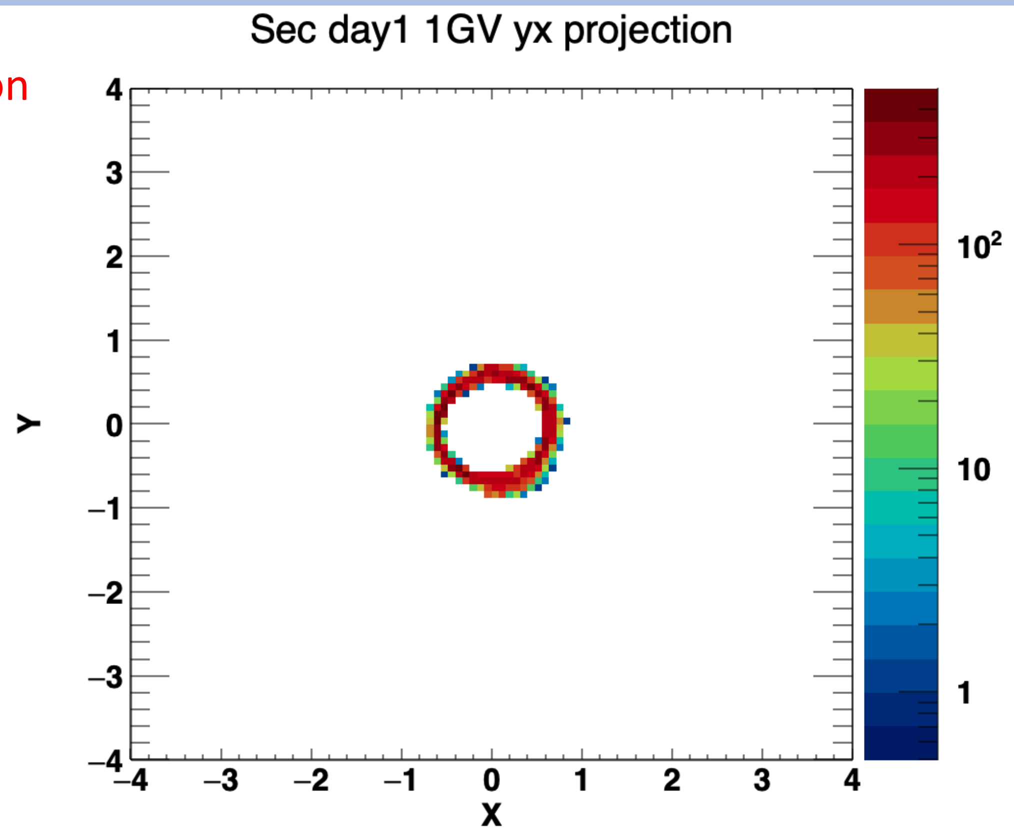
Close to magnetic poles

Sec final point after BkT; Sec detected in: λ_{mag}<-50° && λ_{mag}>+50°; 25° opening angle; day: March 4, 2012

R<1GV – full day

Finale BkT GM position

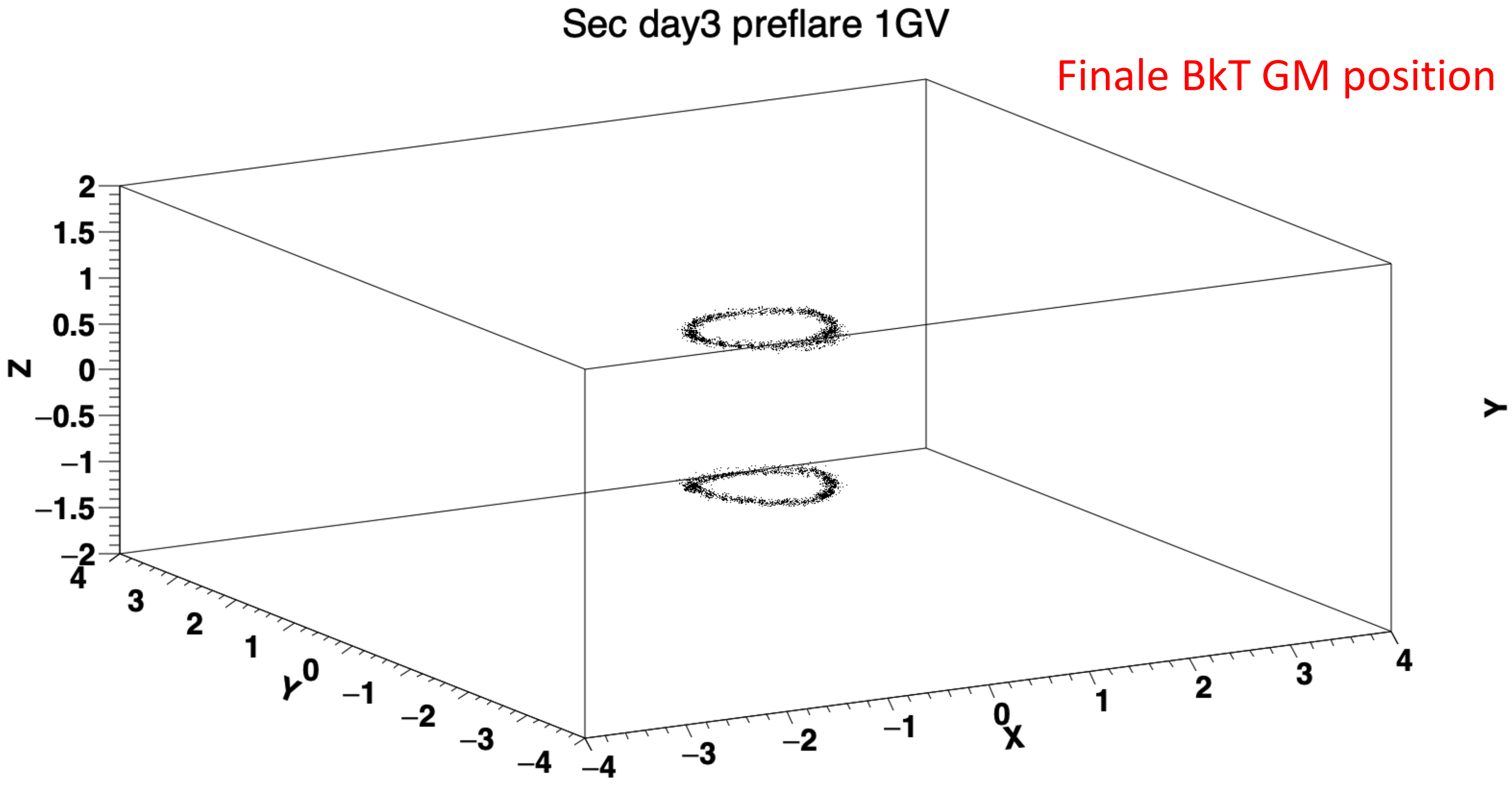


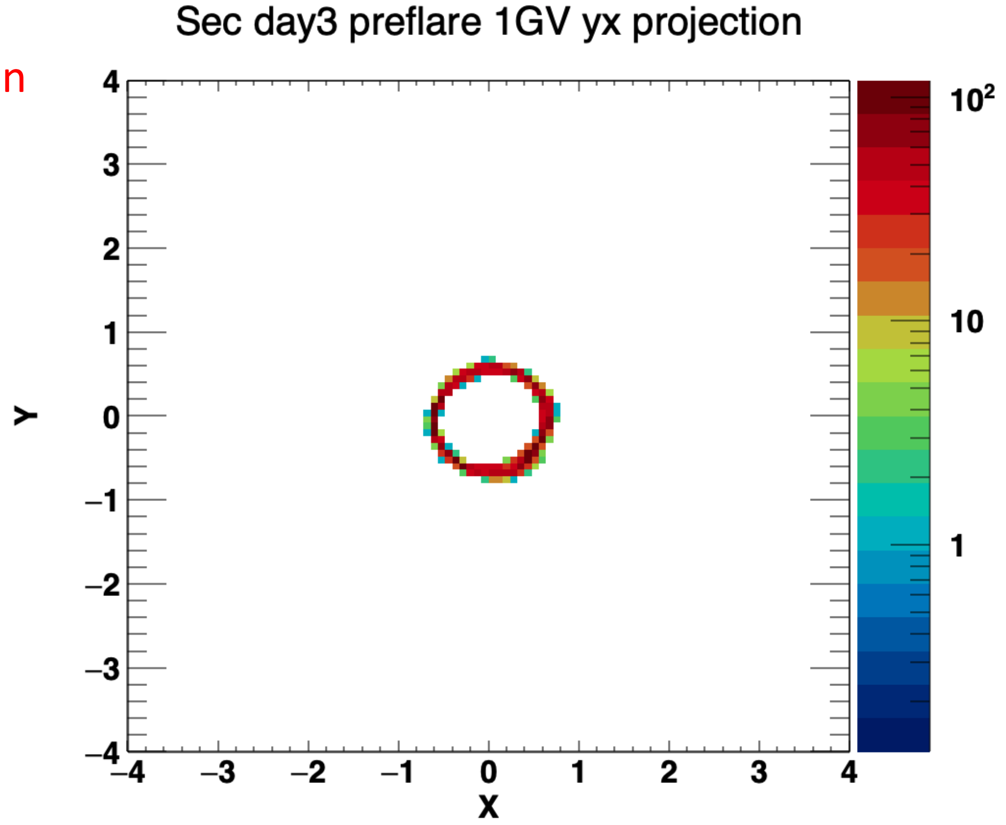


Close to magnetic poles

Sec final point after BkT; Sec detected in: λ_{mag}<-50° && λ_{mag}>+50°; 25° opening angle; day: March 6, 2012

R<1GV; t=90min



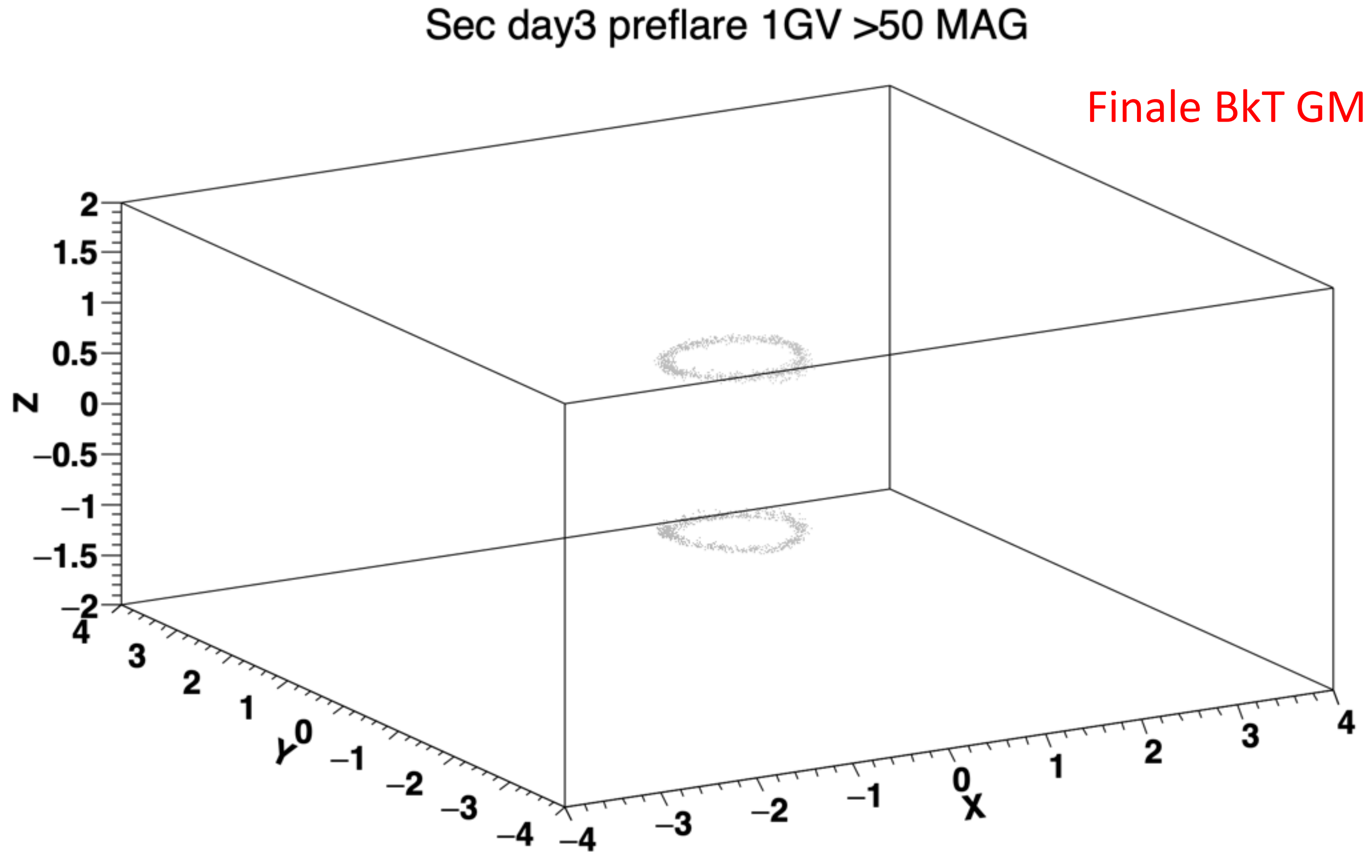


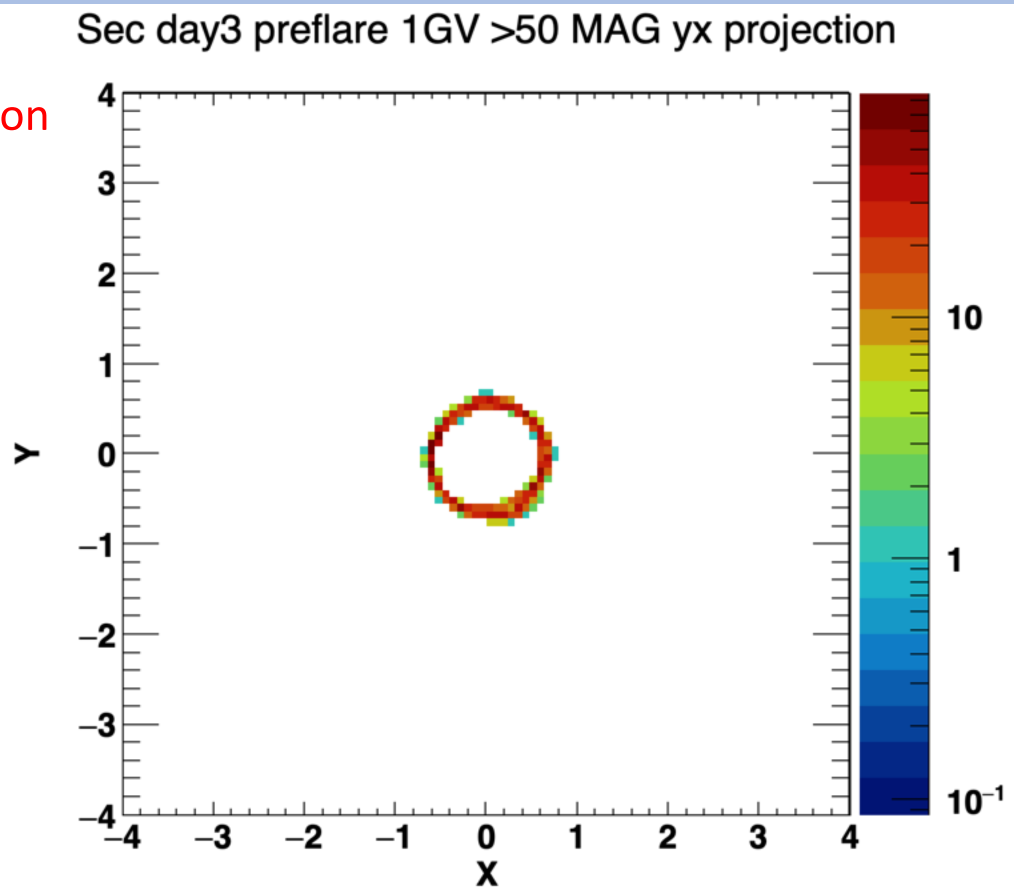
Close to magnetic poles

Sec final point after BkT; Sec detected in: λ_{mag}>+50°; 25° opening angle; day: March 6, 2012

R<1GV; t=90min

Finale BkT GM position

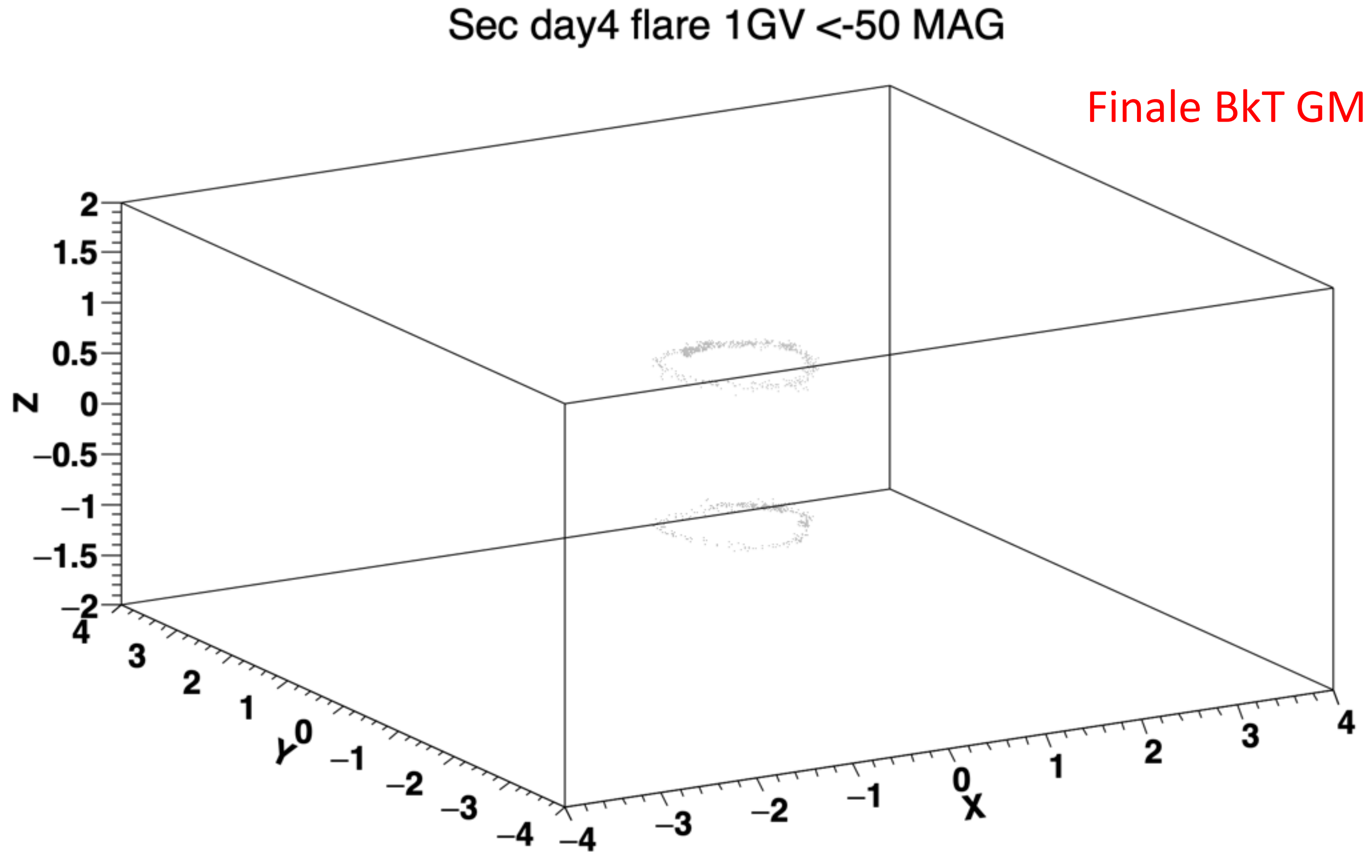




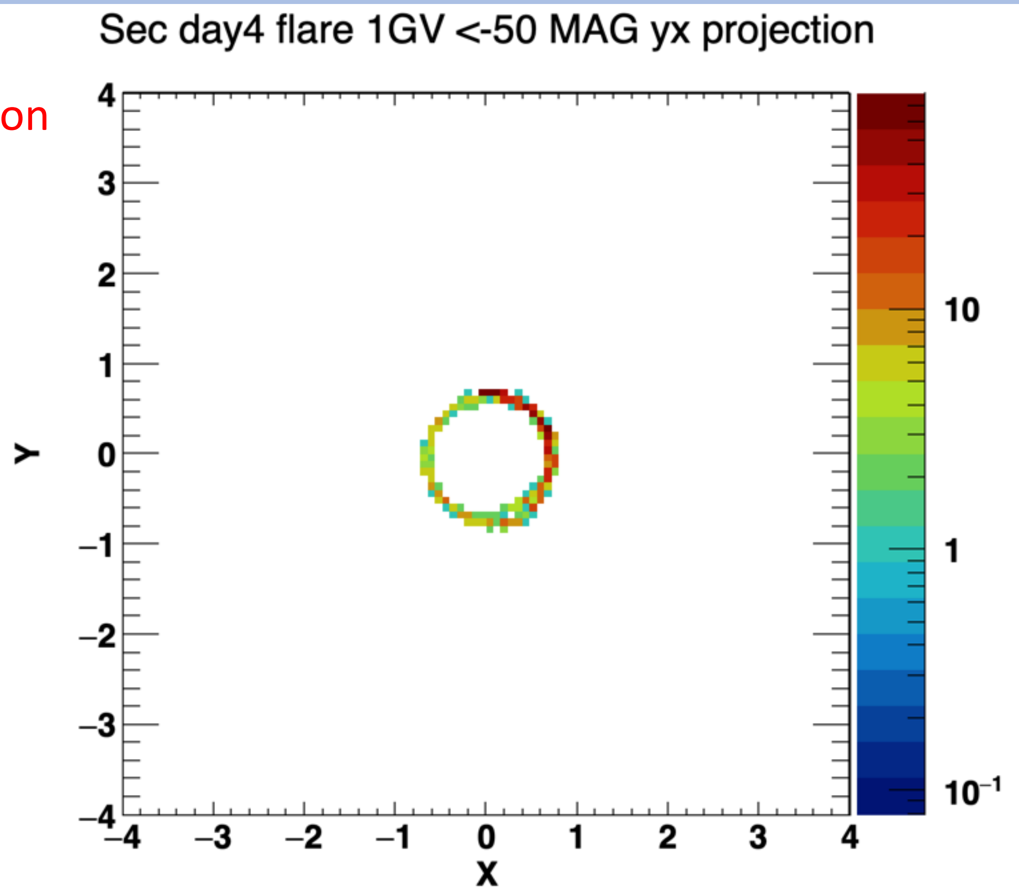
Close to magnetic poles

Sec final point after BkT; Sec detected in: λ_{mag}<-50°; 25° opening angle; day: March 7, 2012

R<1GV; t=90min



Finale BkT GM position



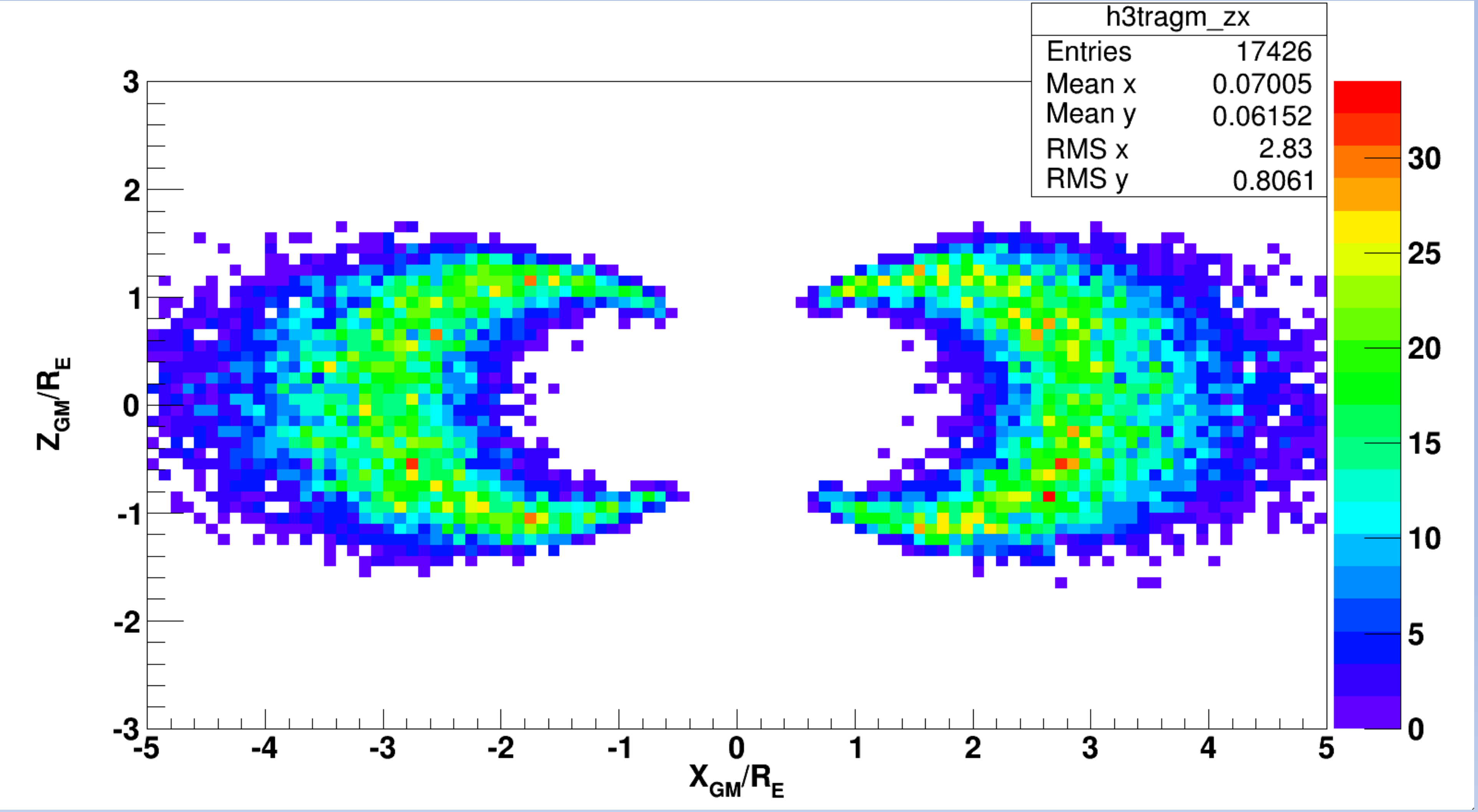
The Magnetosphere & Solar Flares - 2016

March Solar Flares Analysis

- Total of 9 days data taking
- Inside 25° FOV
- Livetime > 0.1
- Primary Protons
  - $4,5 \times 10^{7}$ Particles
- Secondary Protons
  - $7,9 \times 10^{6}$ Particles
- Trapped Protons
  - $3,1 \times 10^{5}$ Particles

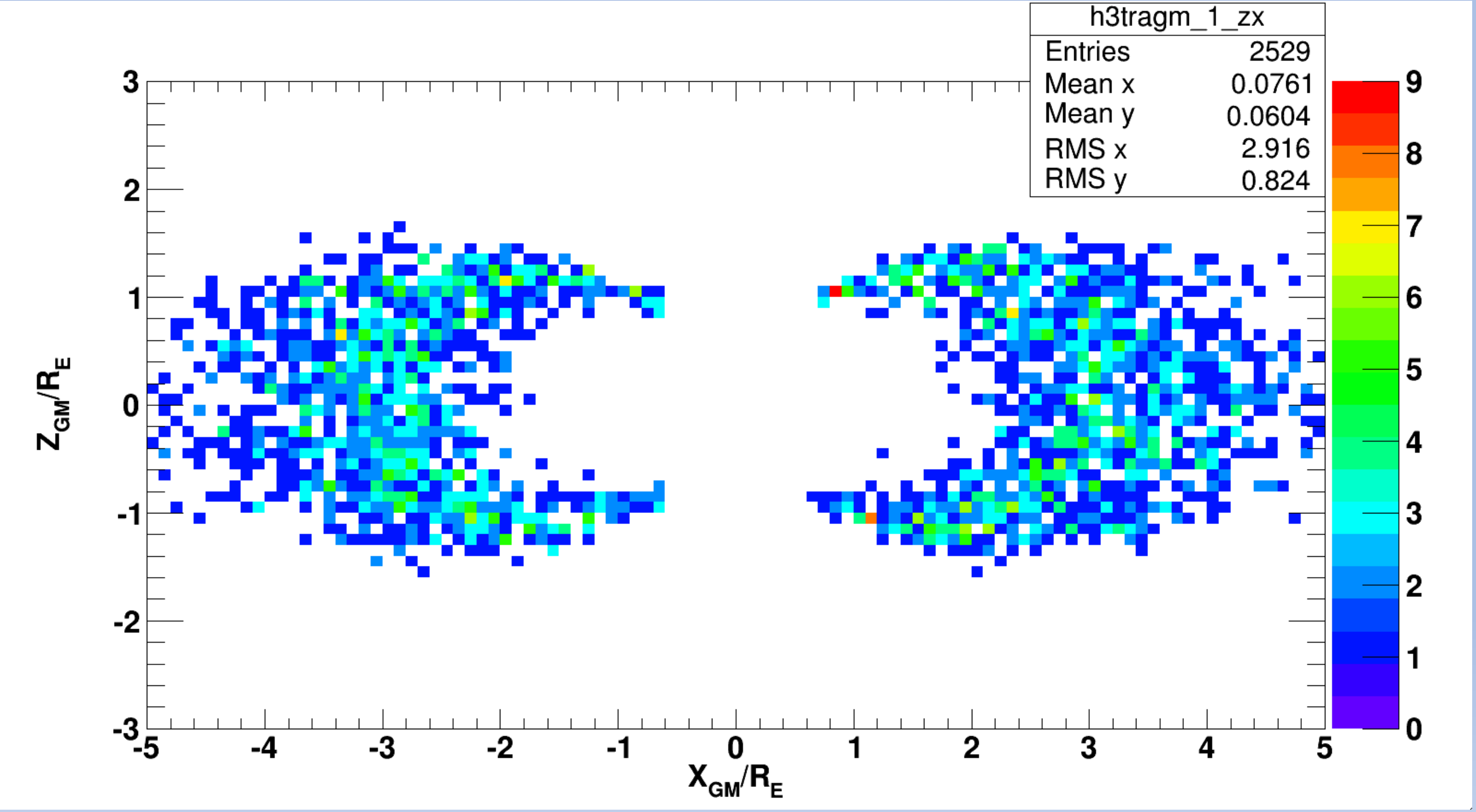
March 2012 Analysis

Trapped Particles – all days from 04/03 to 12/03

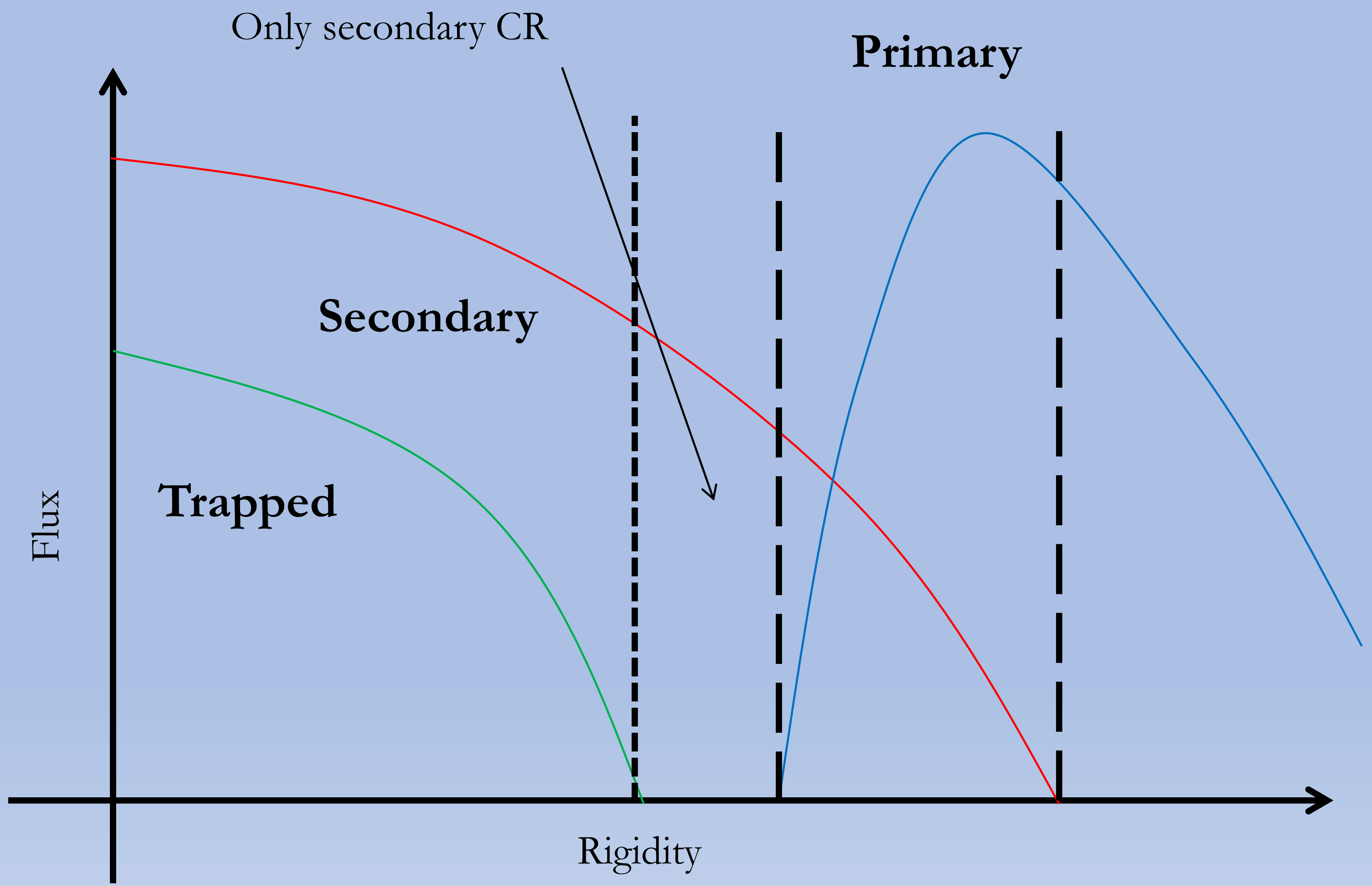


March 2012 Analysis

Trapped Particles – one day 04/03

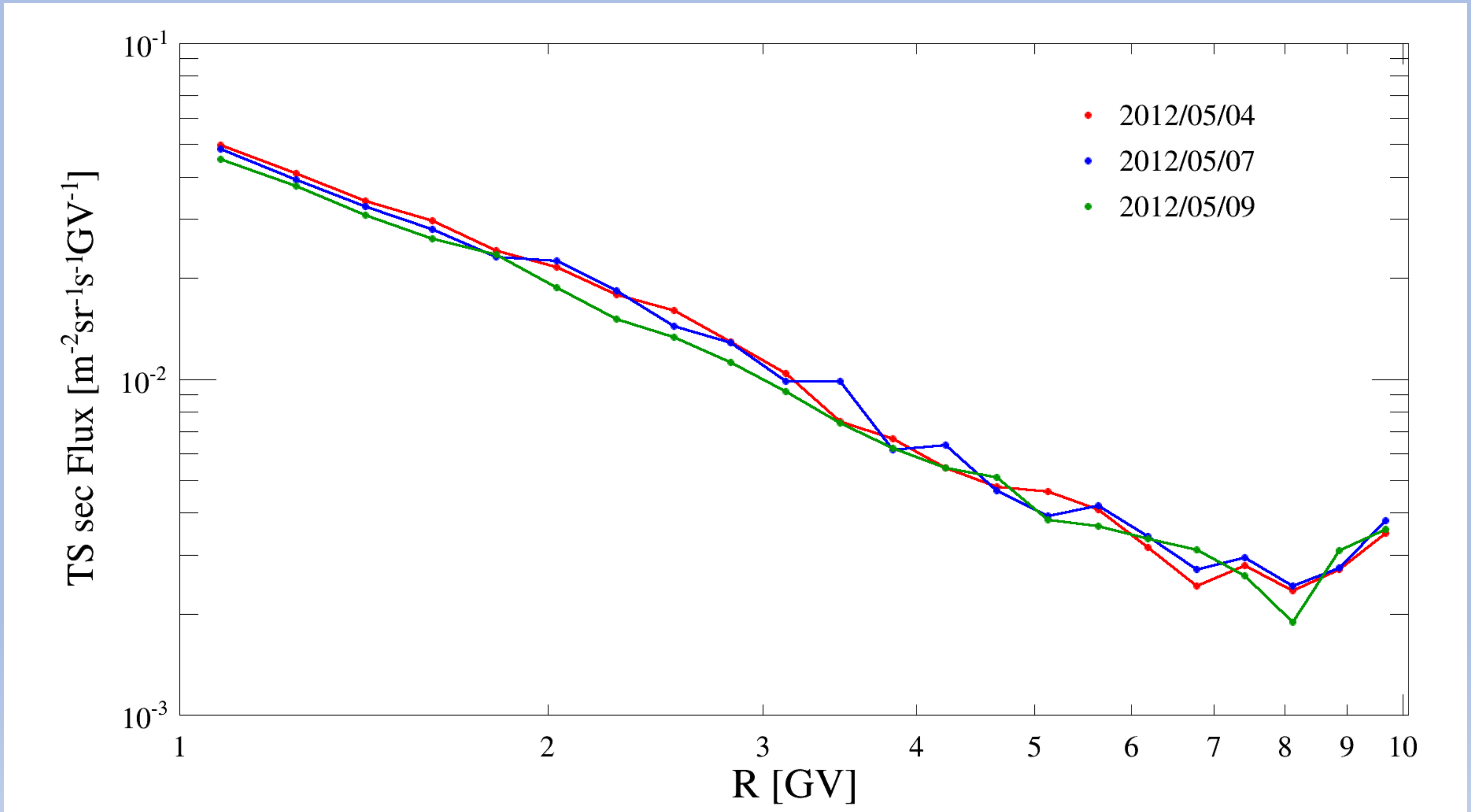


March 2012 Analysis



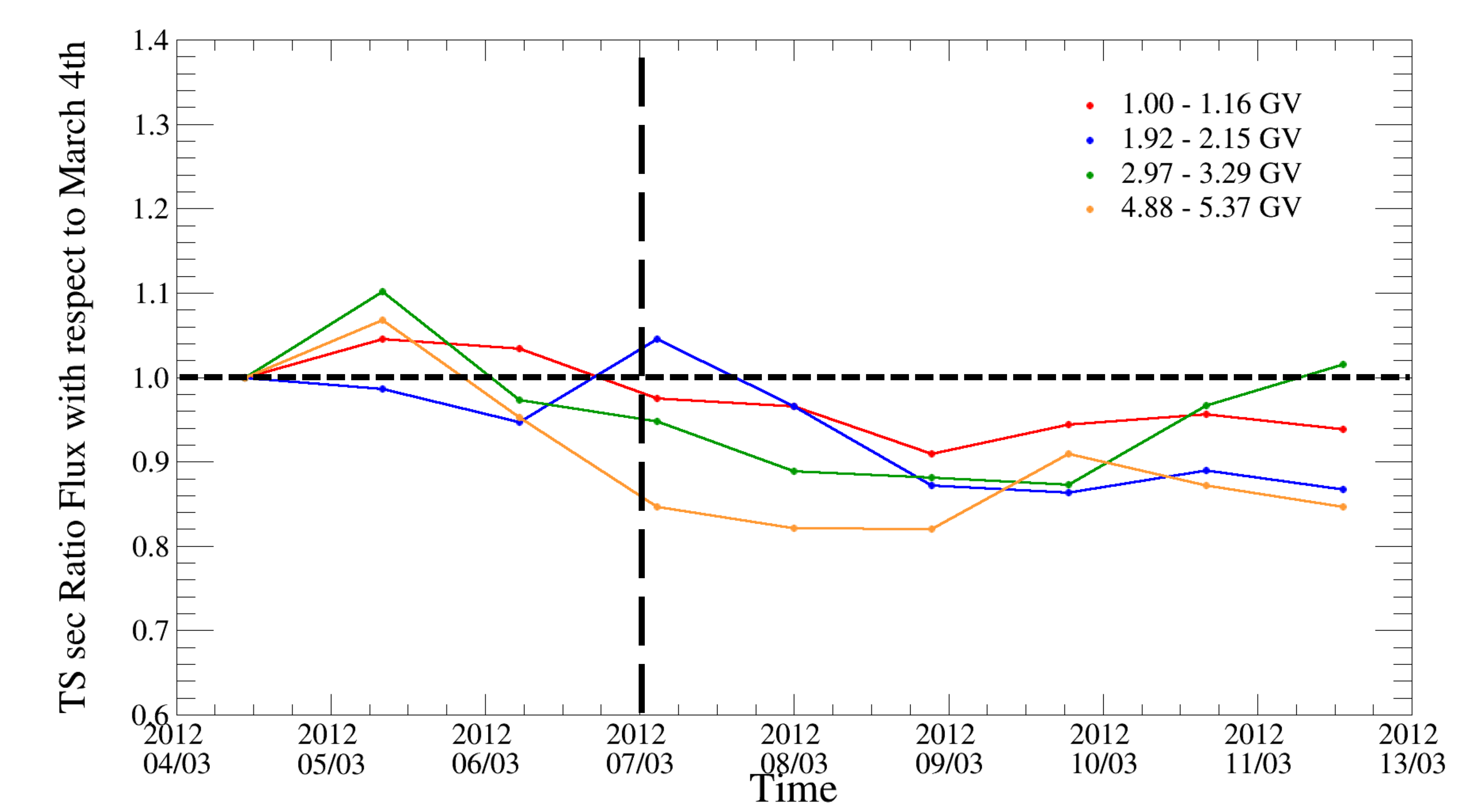
March 2012 Analysis

Secondary RAW proton Flux



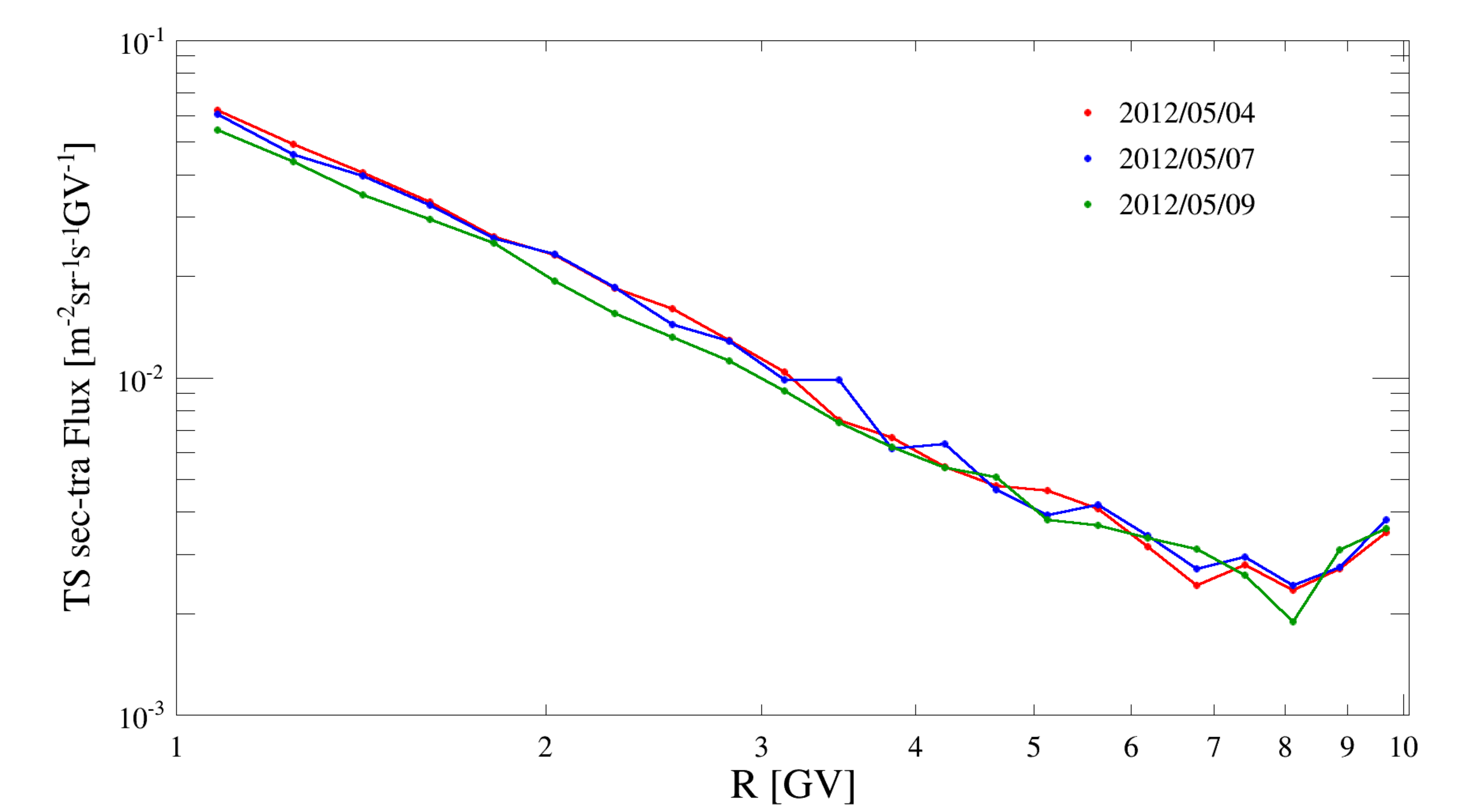
March 2012 Analysis

Ratio of Secondary Proton Flux



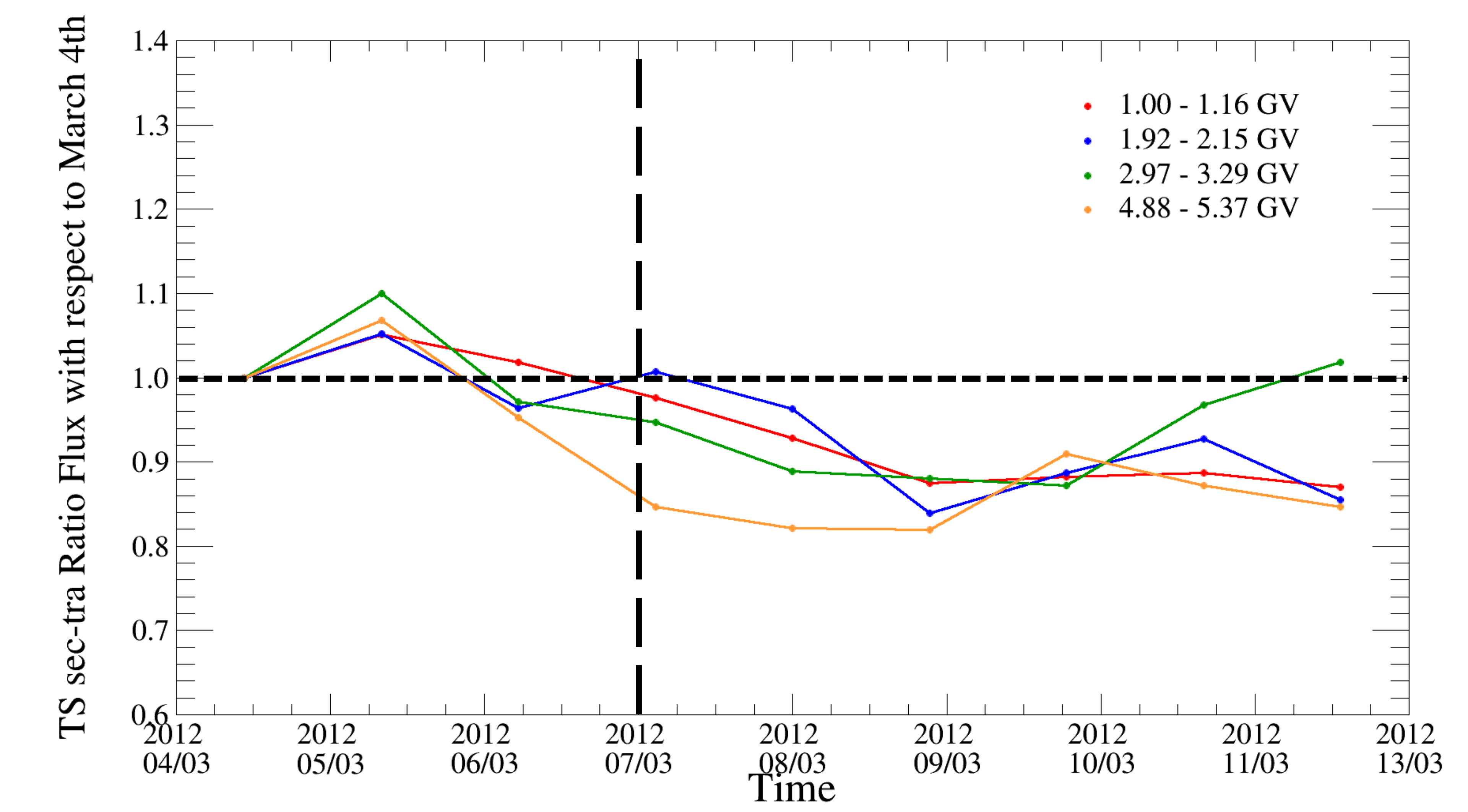
March 2012 Analysis

Trapped and Secondary Proton Flux

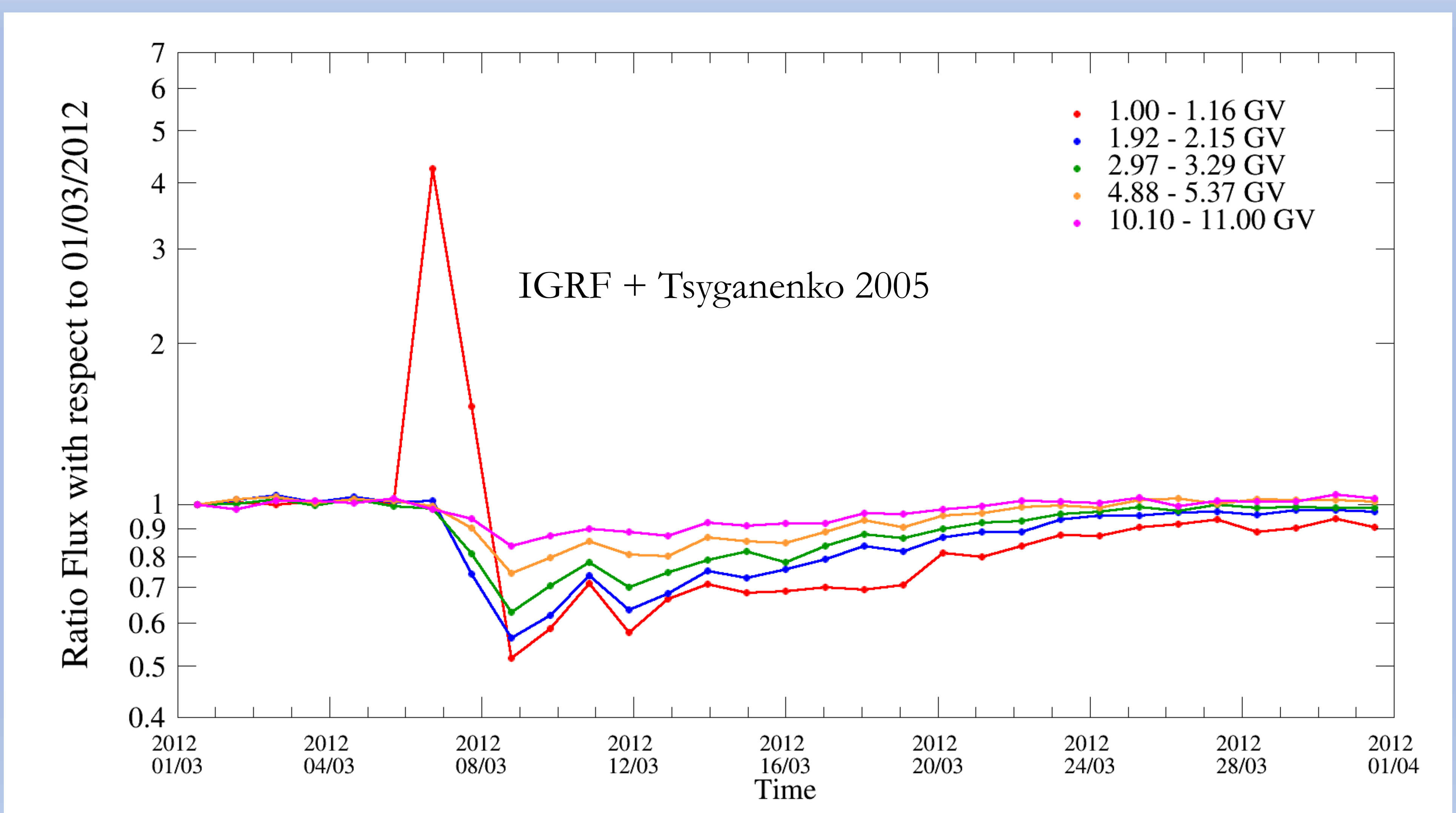


March 2012 Analysis

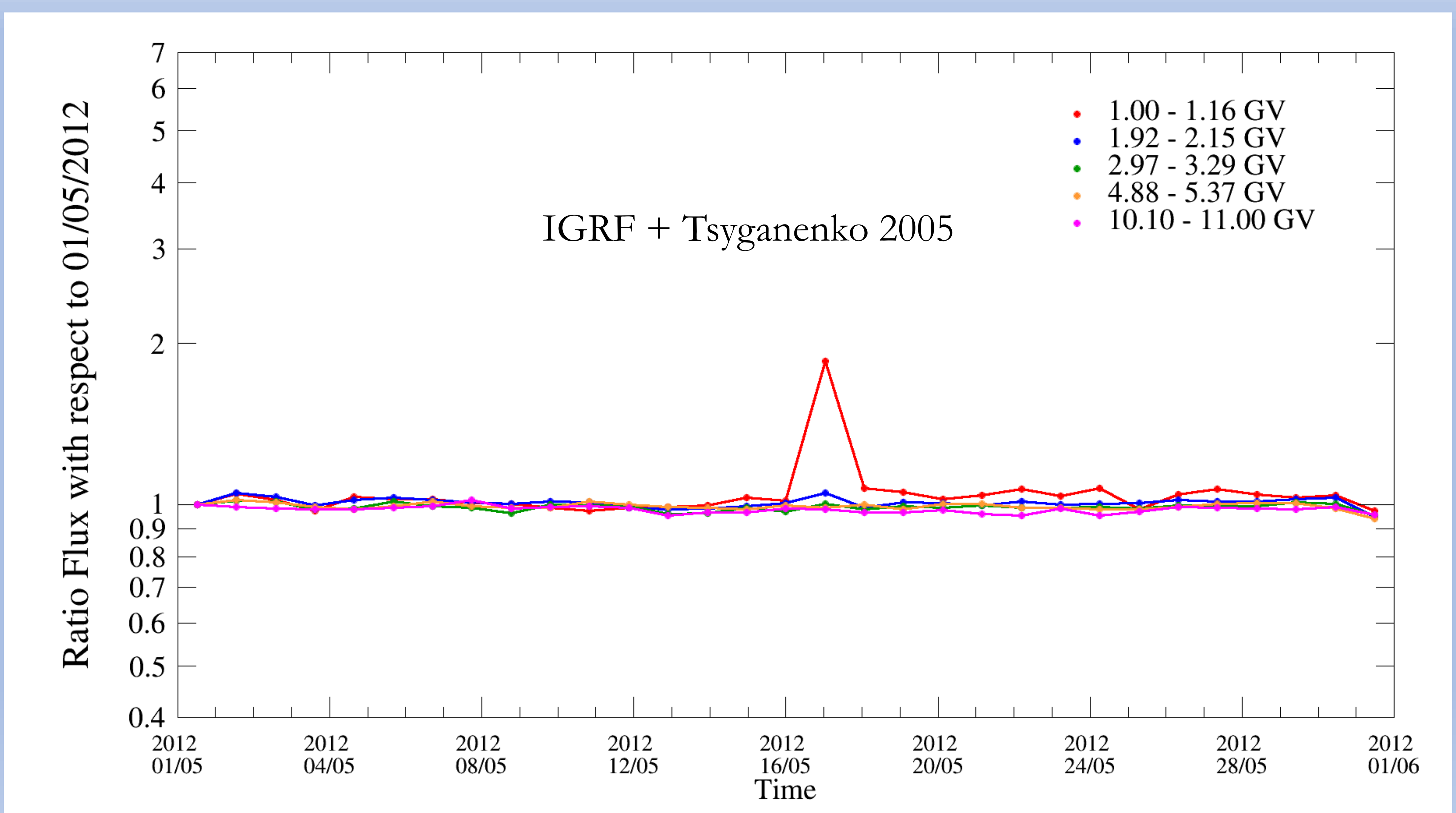
Ratio of Trapped and Secondary Proton Flux



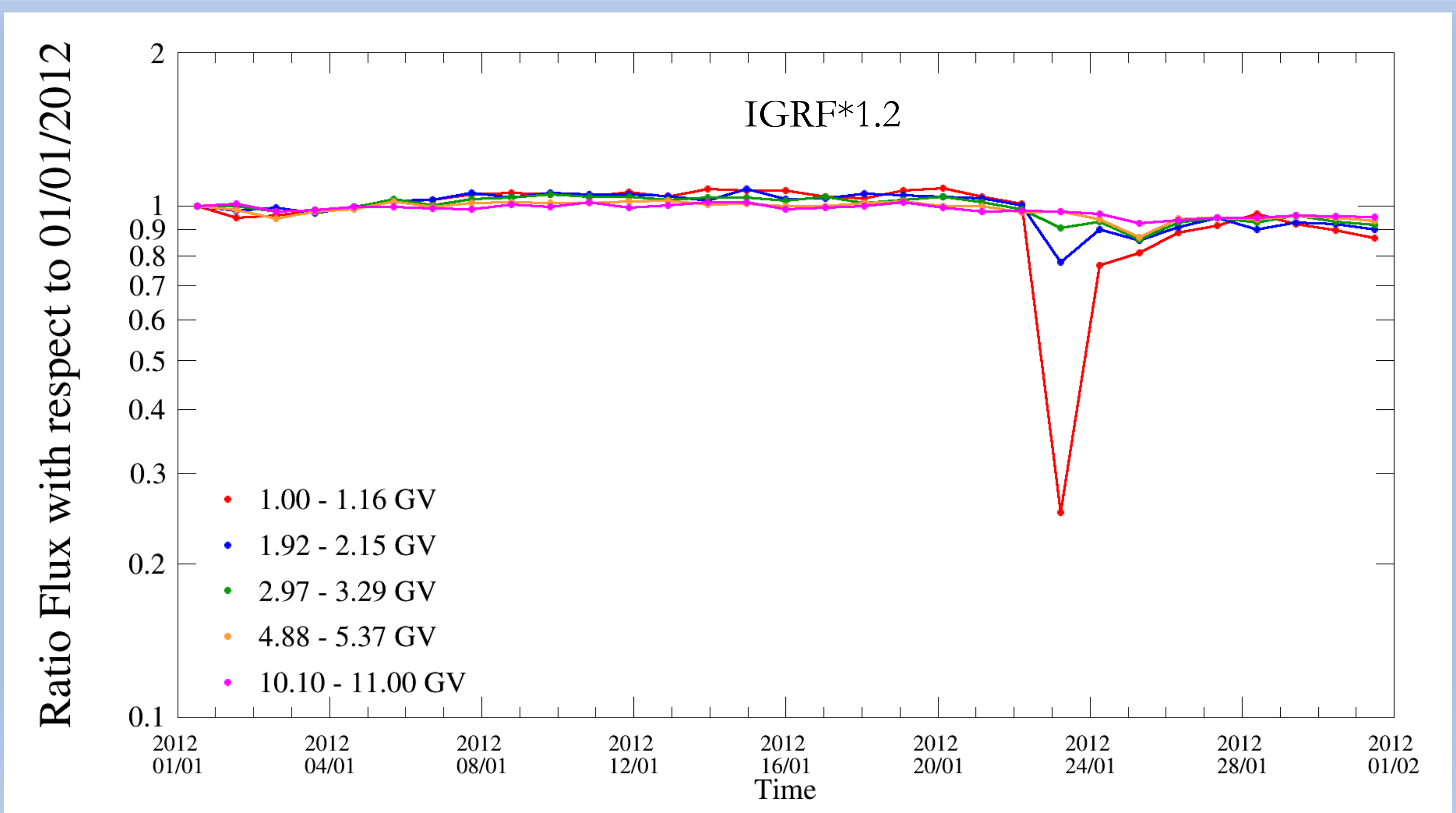
Ratio of Fluxes vs time



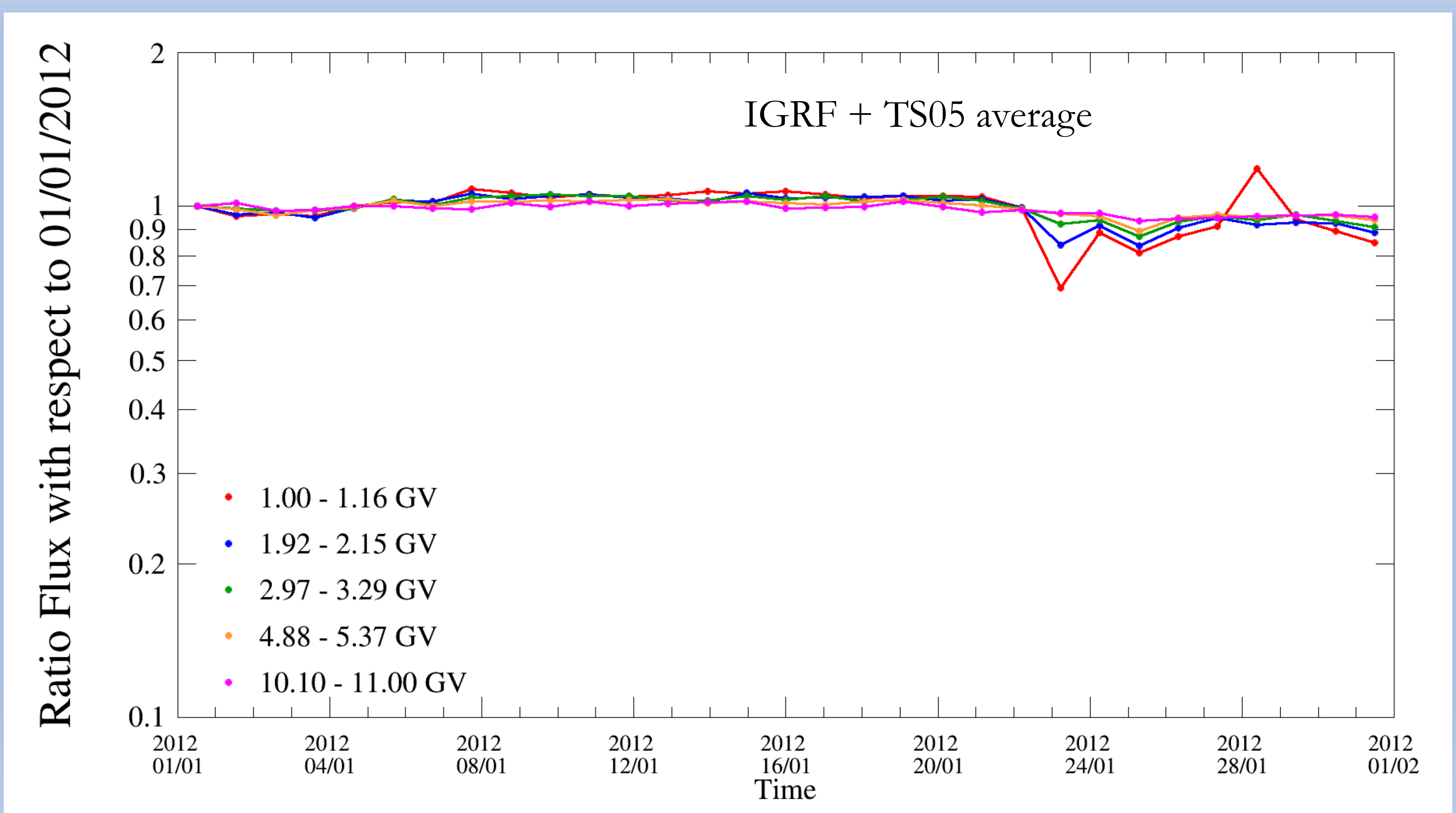
No Forbush in May even with TS05



January 2012



January 2012



List of Candidates SEP Events

AMS-02 Event	Solar Event Date	Flare Class	CME Vel. (km/s)
1	06/07/11	M2.5	1255
2	08/04/11	M9.3	1315
3	08/09/11	X6.9	1610
4	01/23/12	M8.7	2175
5	01/27/12	X1.7	2508
6	03/07/12	X5.4, X1.3	2684, 1825
7	03/13/12	M-class	1884
8	05/17/12	M5.1	1582
9	07/19/12	M7.7	1631
10	07/23/12	-	2003
11	04/11/13	M6.5	861
12	05/22/13	M5.8	1466
13	10/28/13	M5.1, M2.8, M4.4	1201, 1073, 812
14	11/02/13	C8.2*	828
15	12/28/13	-	1118
16	01/06/14	-	1118
17	01/07/14	X1.2	1830
18	02/25/14	X4.9	2147
19	09/01/14	-	1404
20	09/10/14	X1.6	1267

Confirmed

From J. Hoffman presentation Dec. 2015

All the events observed by AMS-02 are associated with M- and X-class Flares, followed by very high speed halo CMEs

This reinforce the Solar Origin of these temporary Excess/Lack

Photon Observation (X-band)
Of Solar Photosphere
e.g. using GOES satellite

Photon Observation (optical band)
Of Solar Corona
e.g. using SOHO satellite

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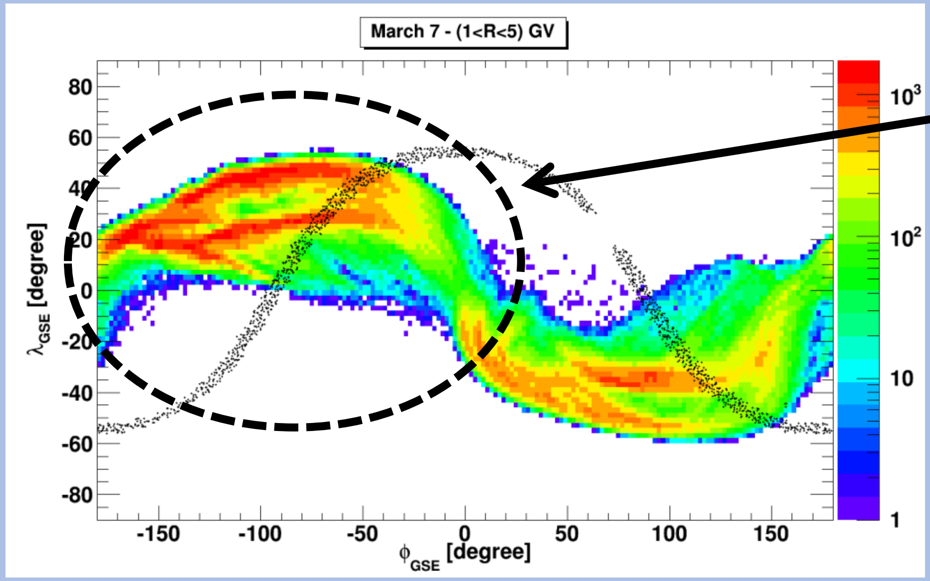
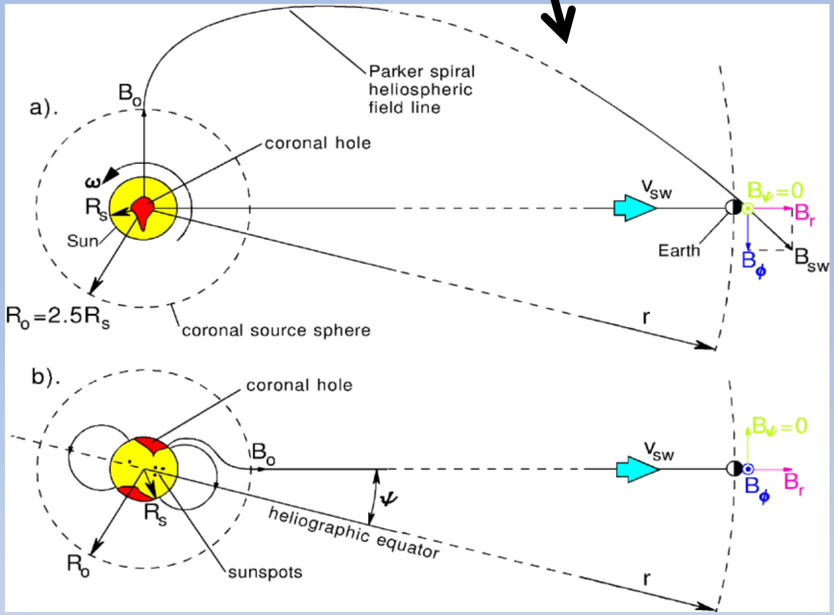
Anisotropy?

- Separate Solar Particles from GCR
- Study arrival directions

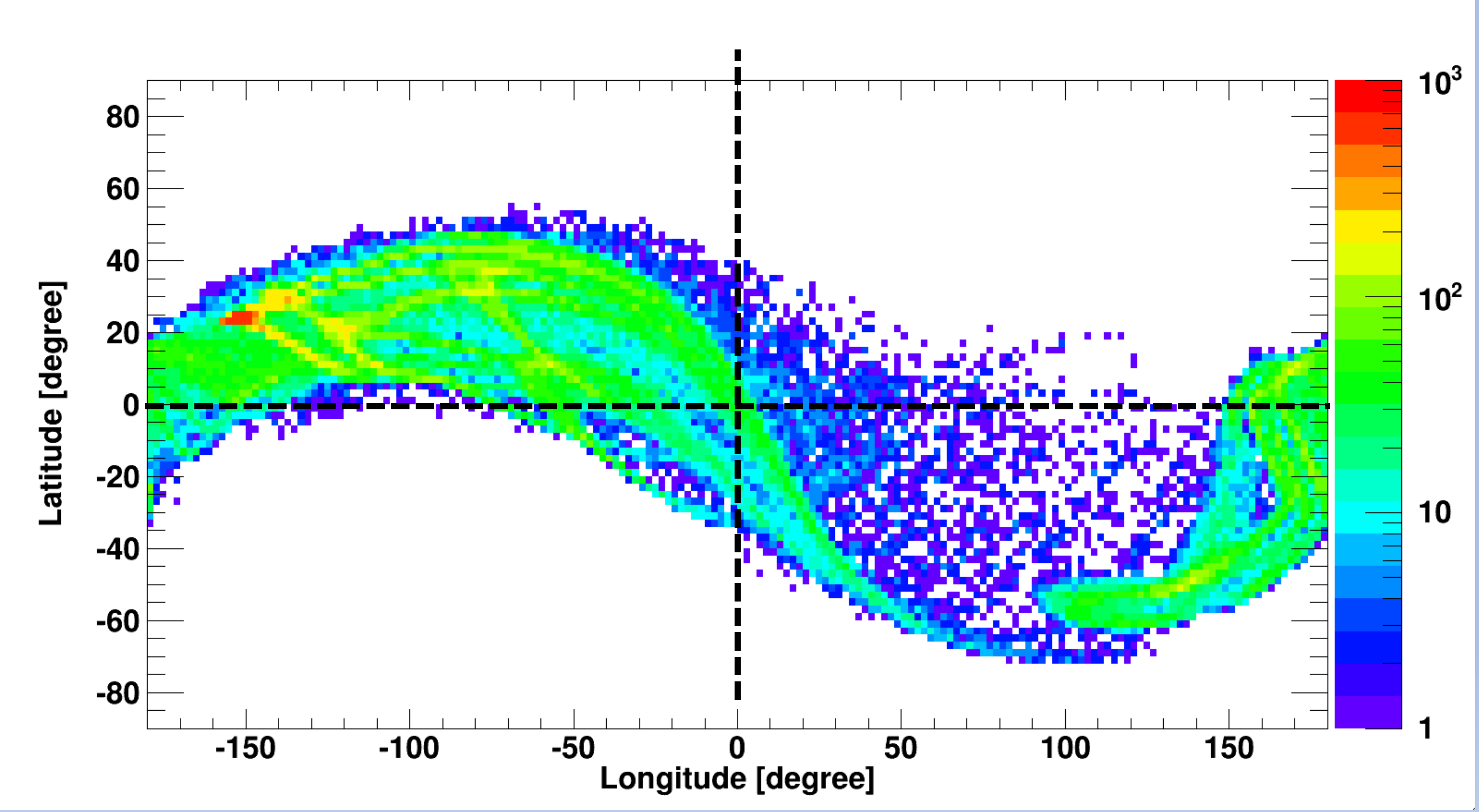


Primary Solar protons should follow the Solar Magnetic field spiral



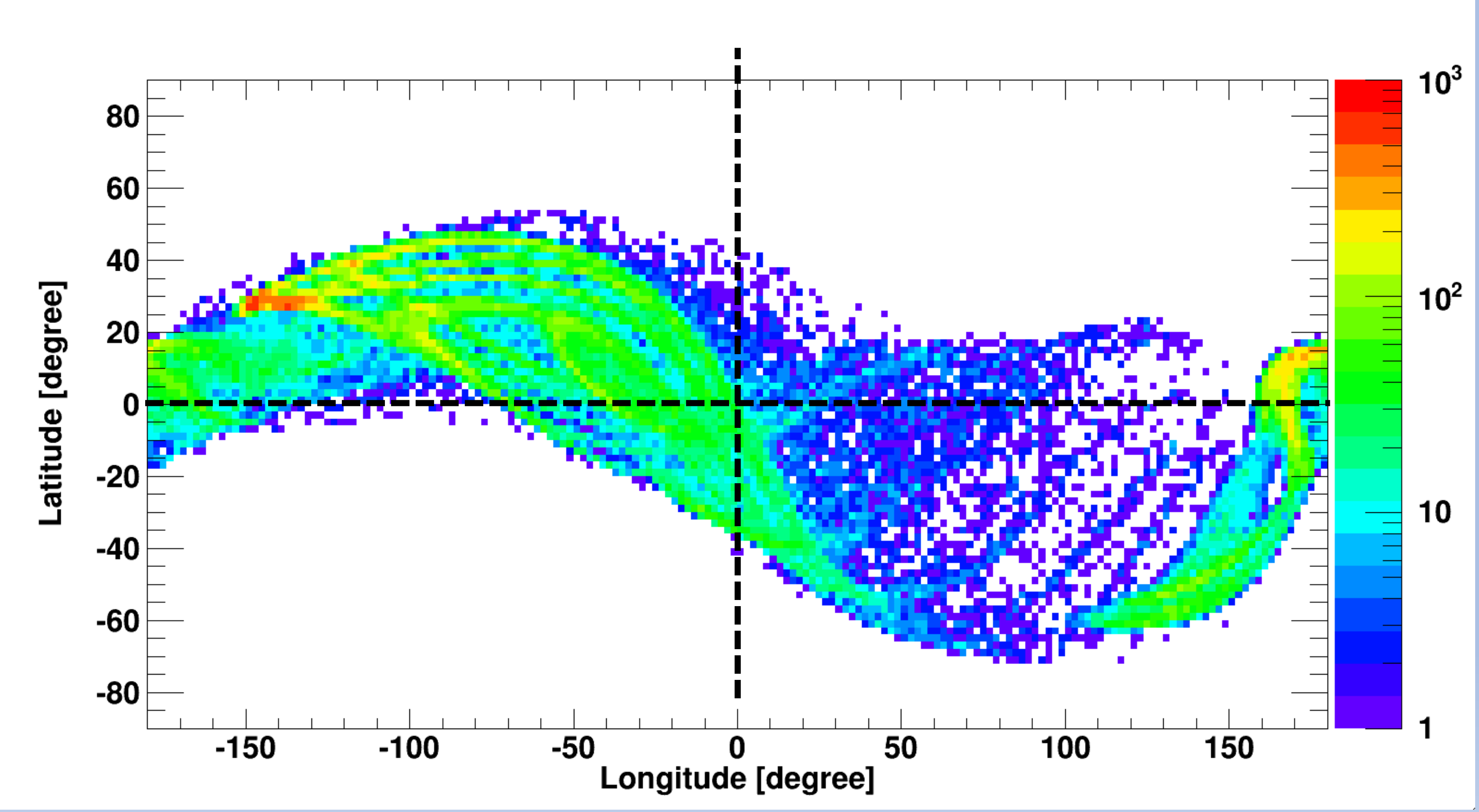
Anisotropy?

1-1.16 GV rigidity bin – March 4 2012



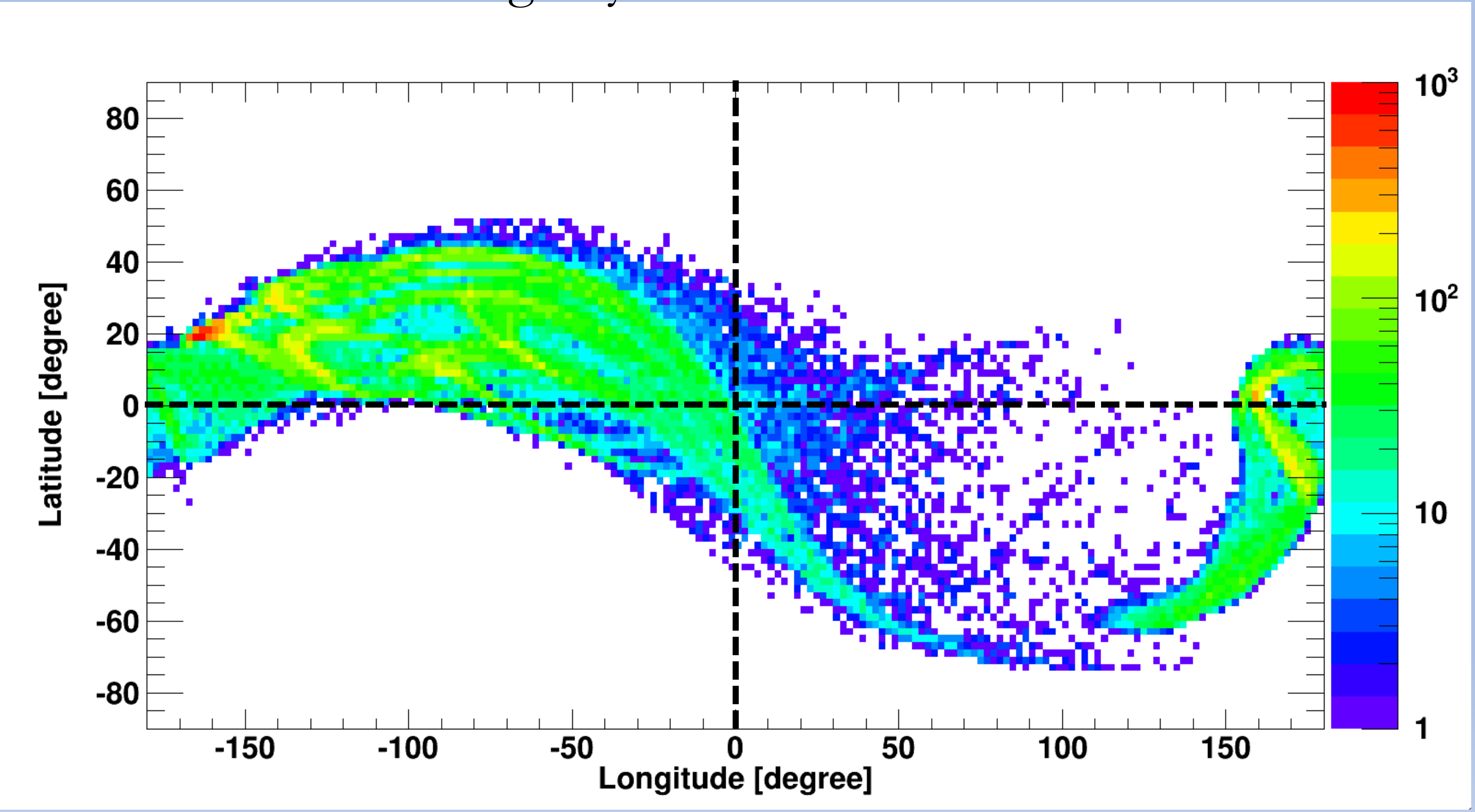
Anisotropy?

1-1.16 GV rigidity bin – March 5 2012



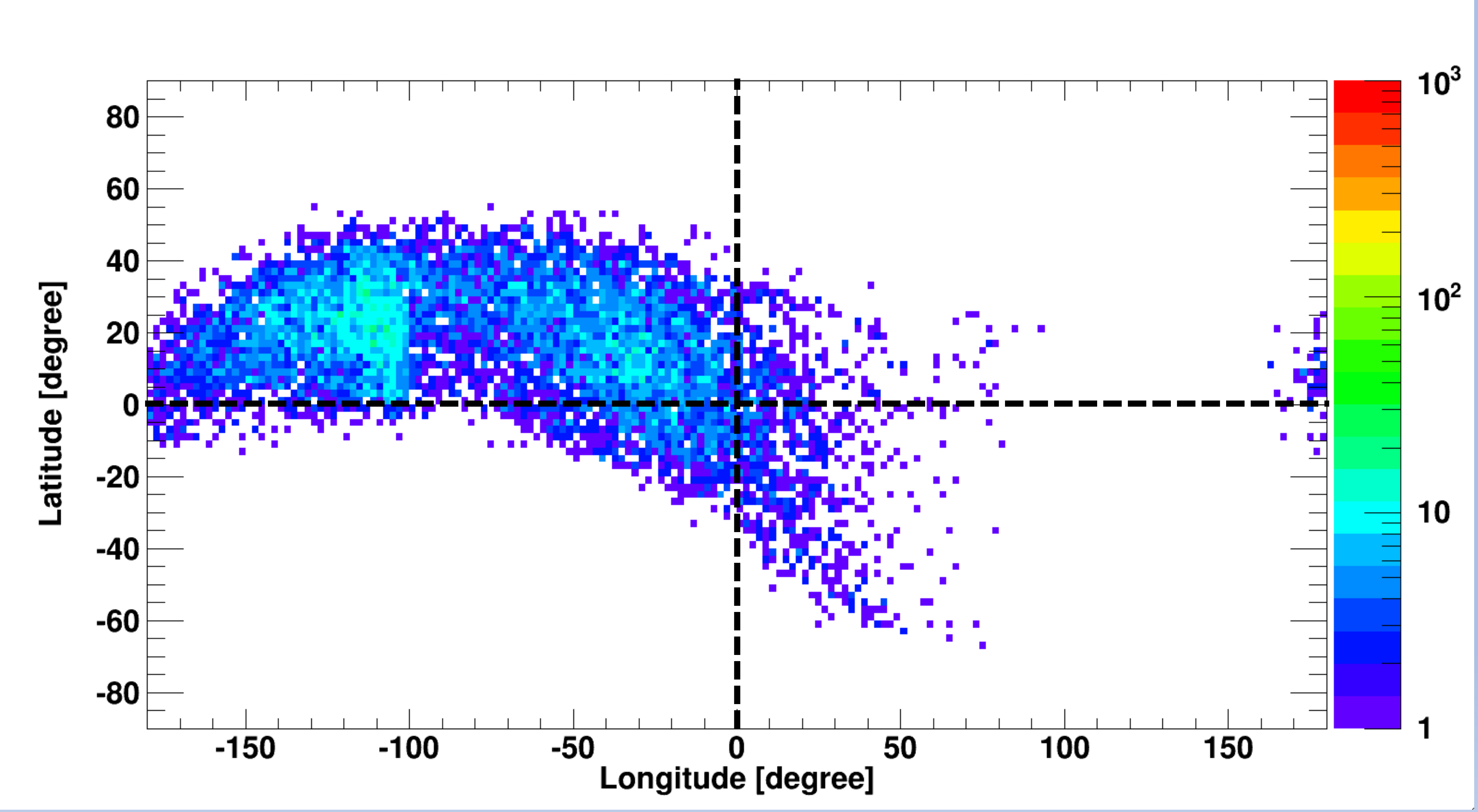
Anisotropy?

1-1.16 GV rigidity bin – March 6 2012



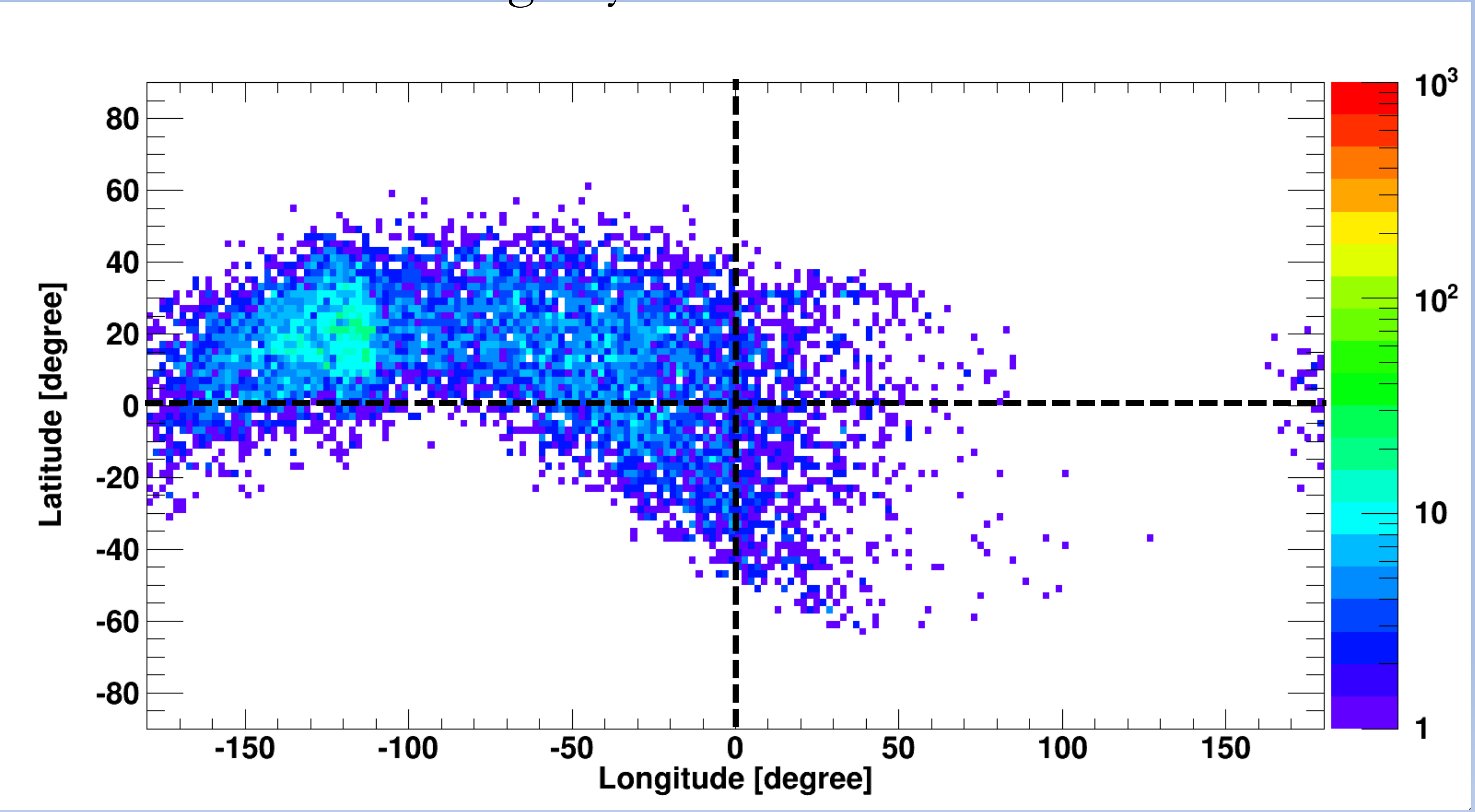
Anisotropy?

1-1.16 GV rigidity bin – March 7 2012 - !!!!!



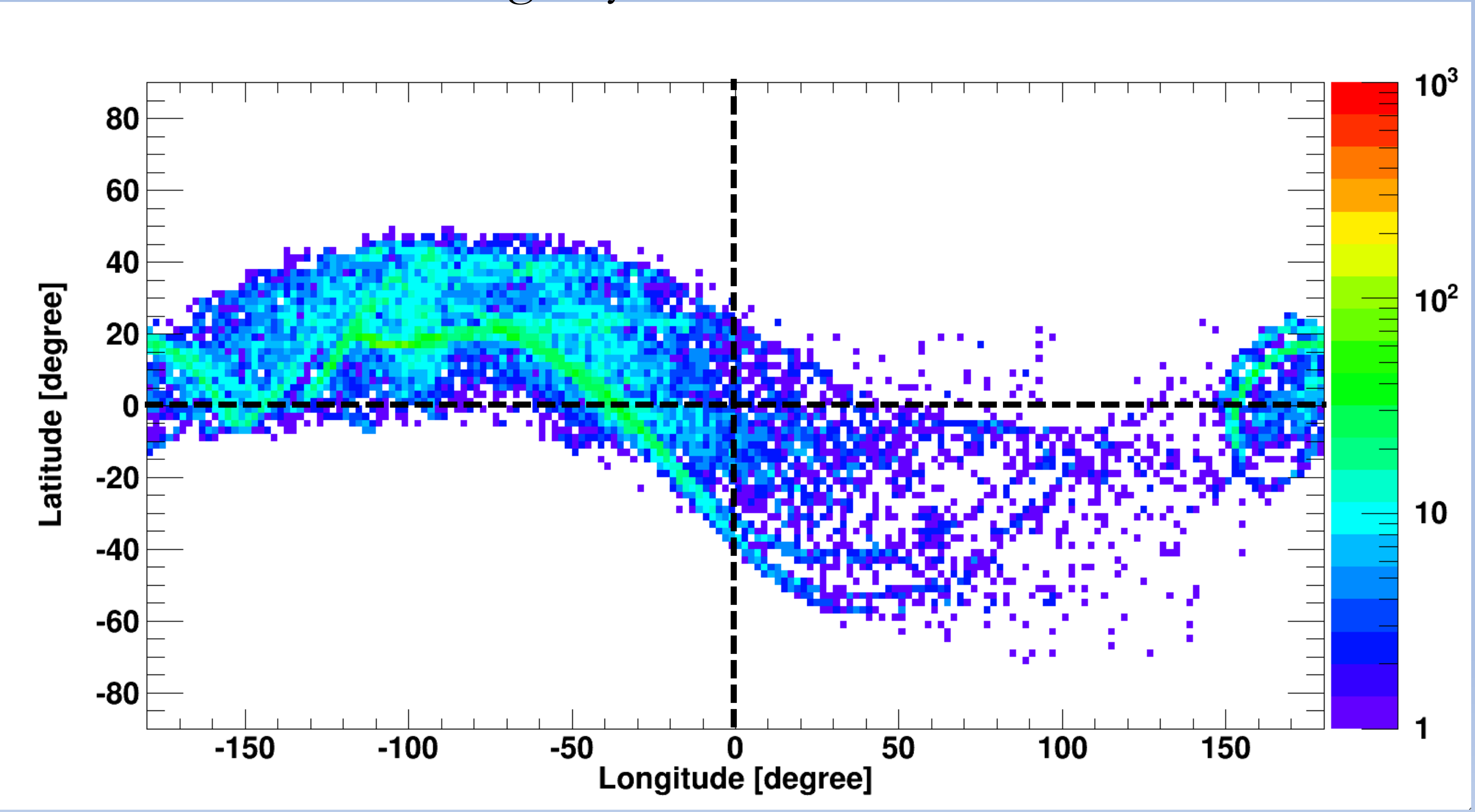
Anisotropy?

1-1.16 GV rigidity bin – March 8 2012



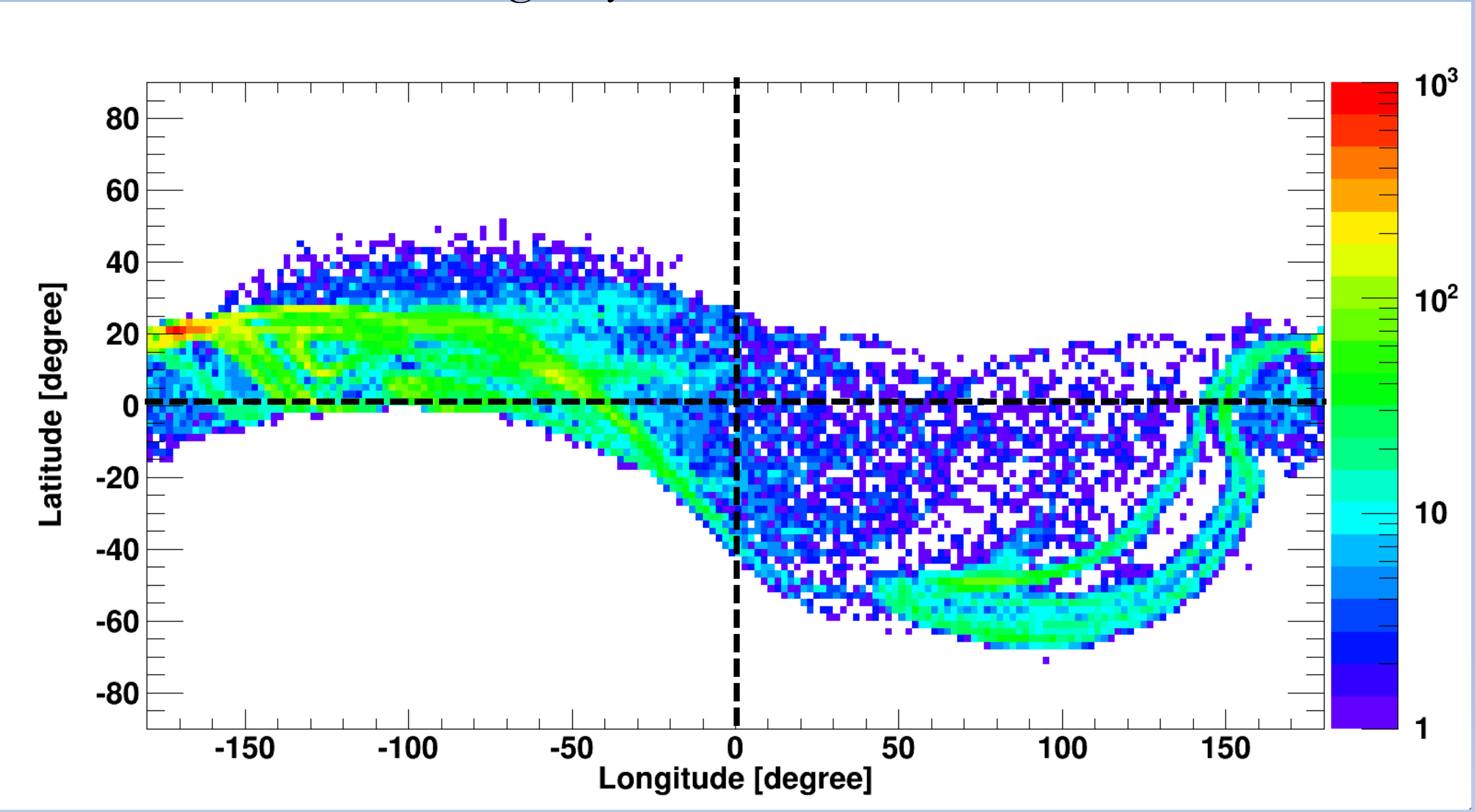
Anisotropy?

1-1.16 GV rigidity bin – March 9 2012



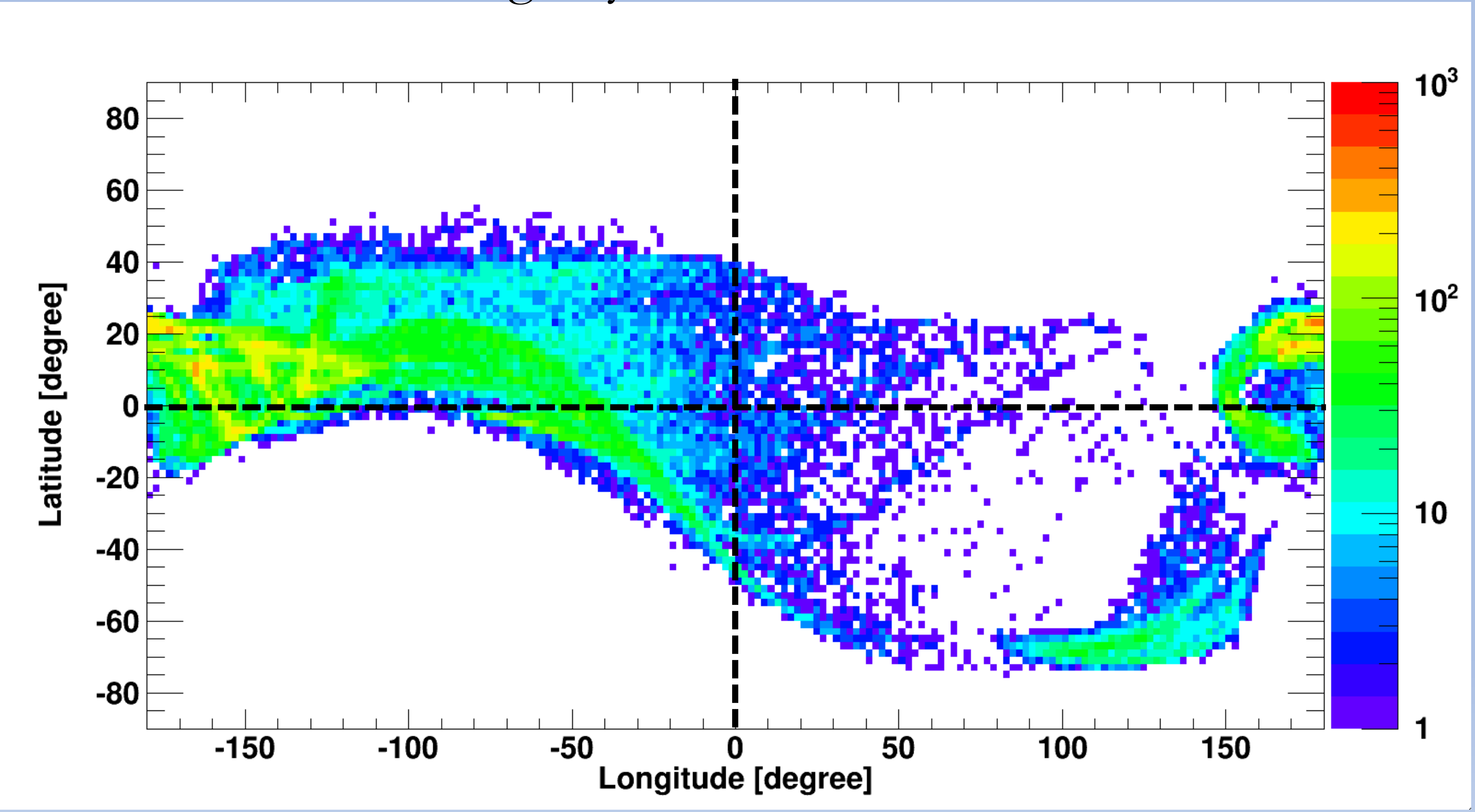
Anisotropy?

1-1.16 GV rigidity bin – March 10 2012



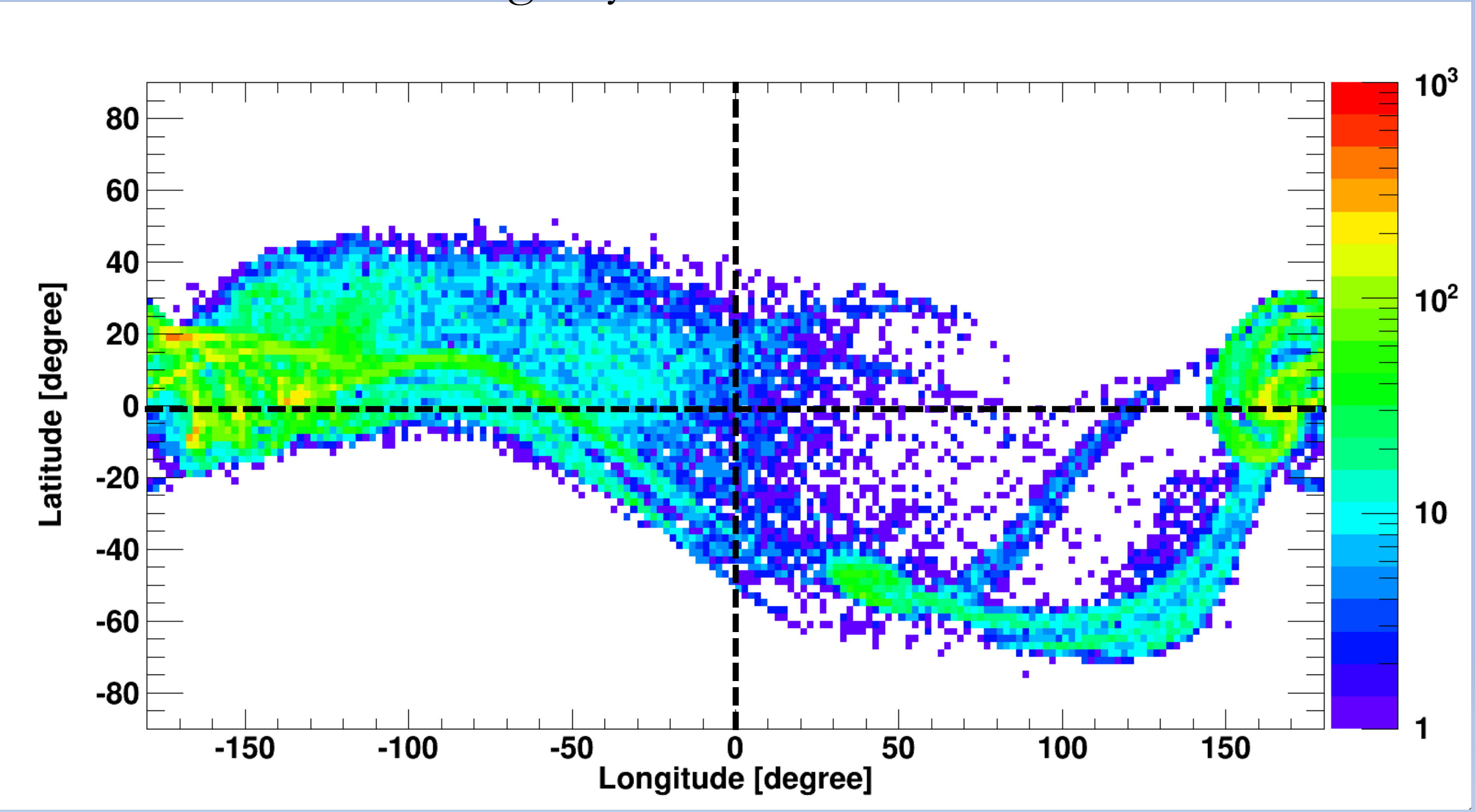
Anisotropy?

1-1.16 GV rigidity bin – March 11 2012



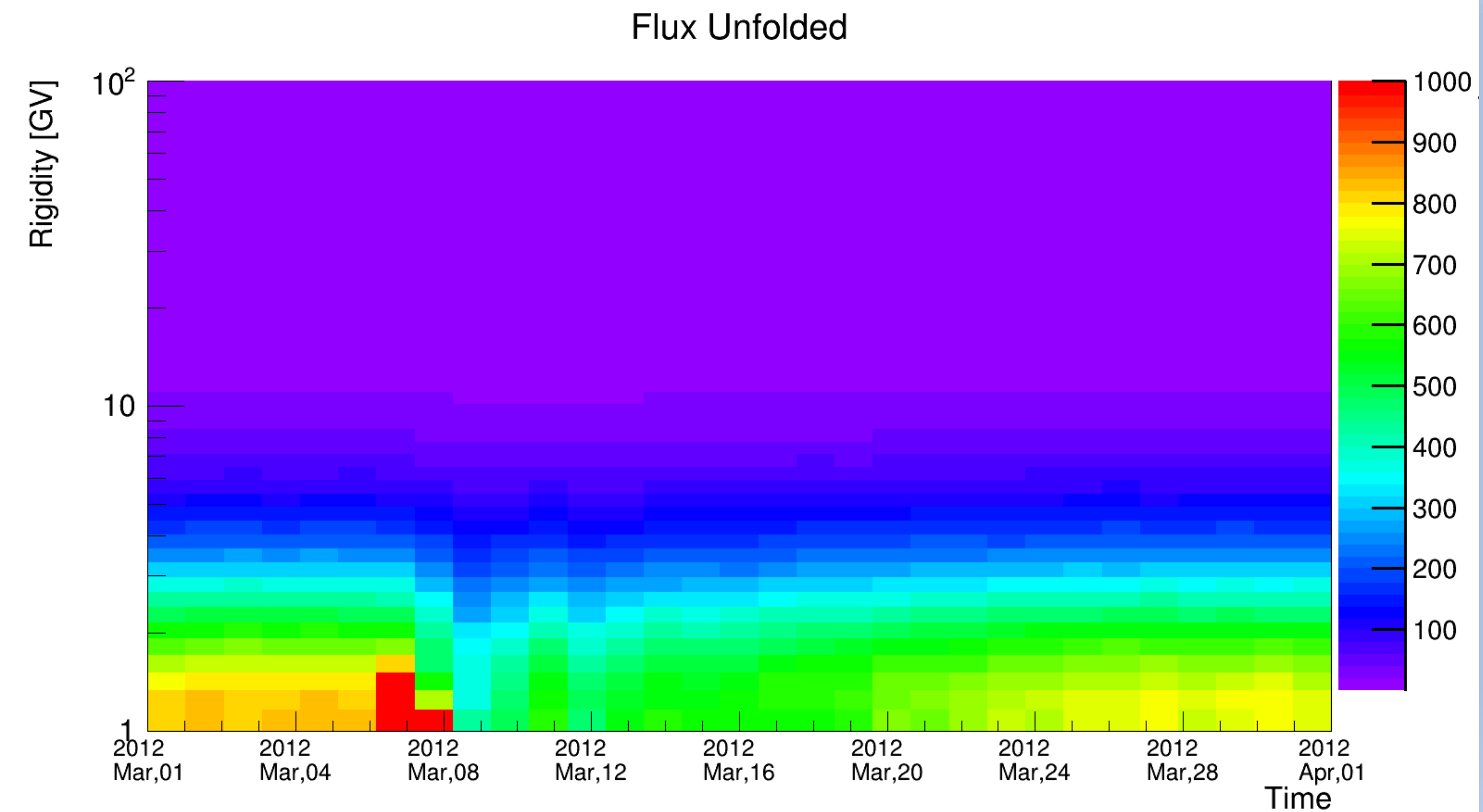
Anisotropy?

1-1.16 GV rigidity bin – March 12 2012



Rigidity Cutoff

IGRF + Tsyganenko 2005



Anisotropy?

- Fake or real?
- Problem of FOV?
- Problem of position and inclination?
- Problem of pile up and livetime?

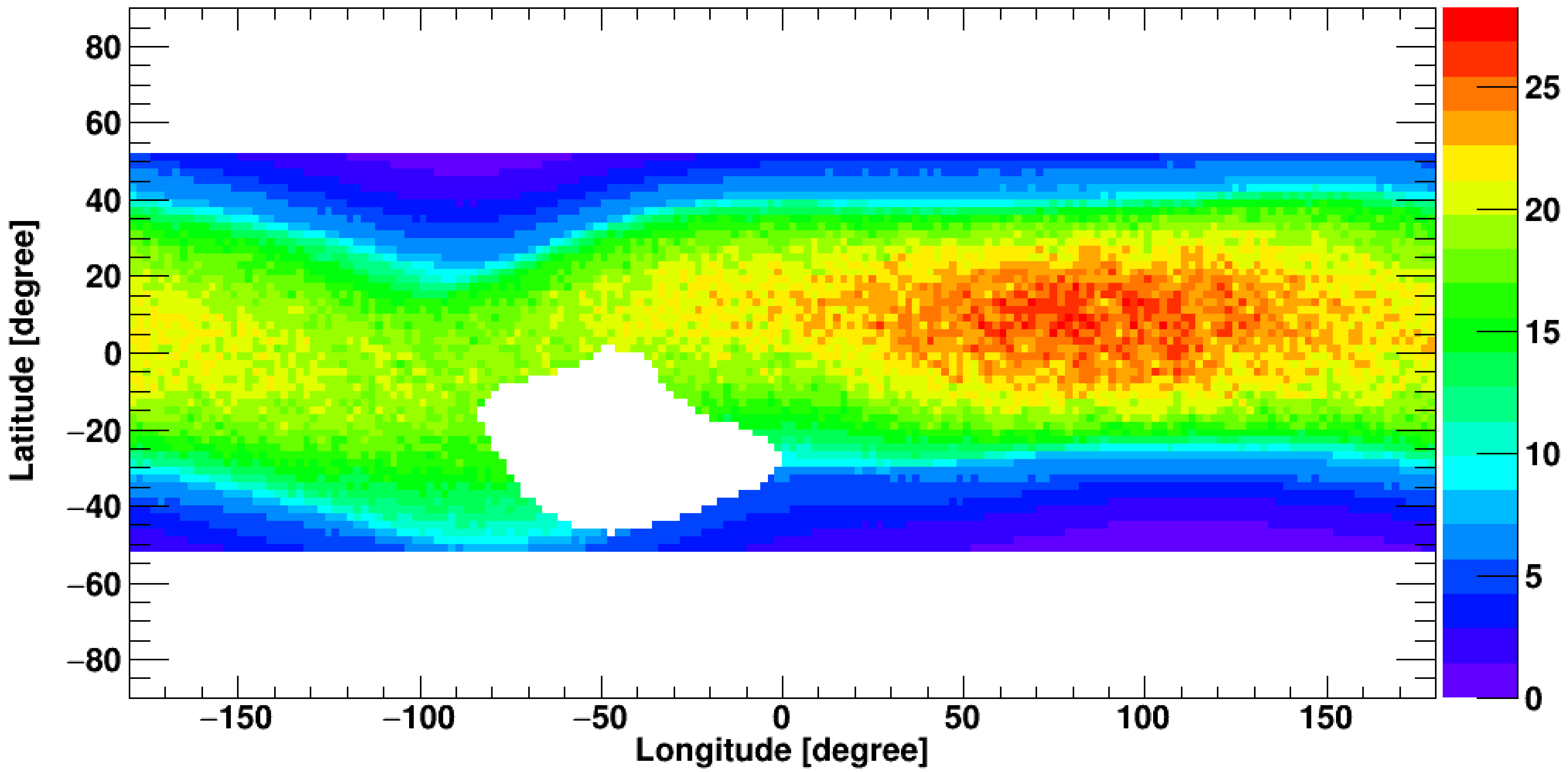
Preliminary Analysis of Protons detected by AMS-02 inside the South Atlantic Anomaly - 2017

Summary:

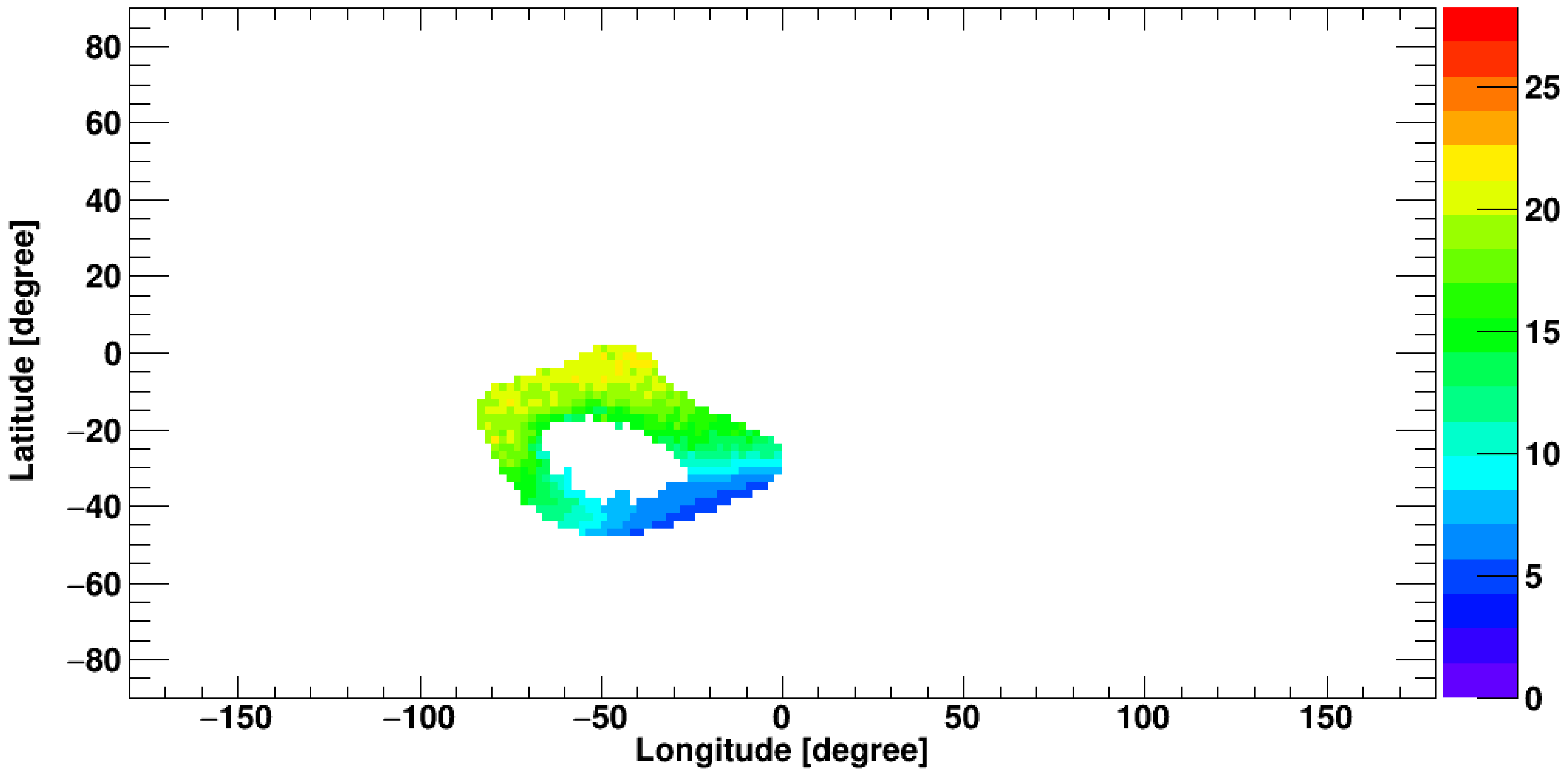
- Analysis of CR protons inside SAA region;

- Primary, Trapped and Secondary CR behaviour;

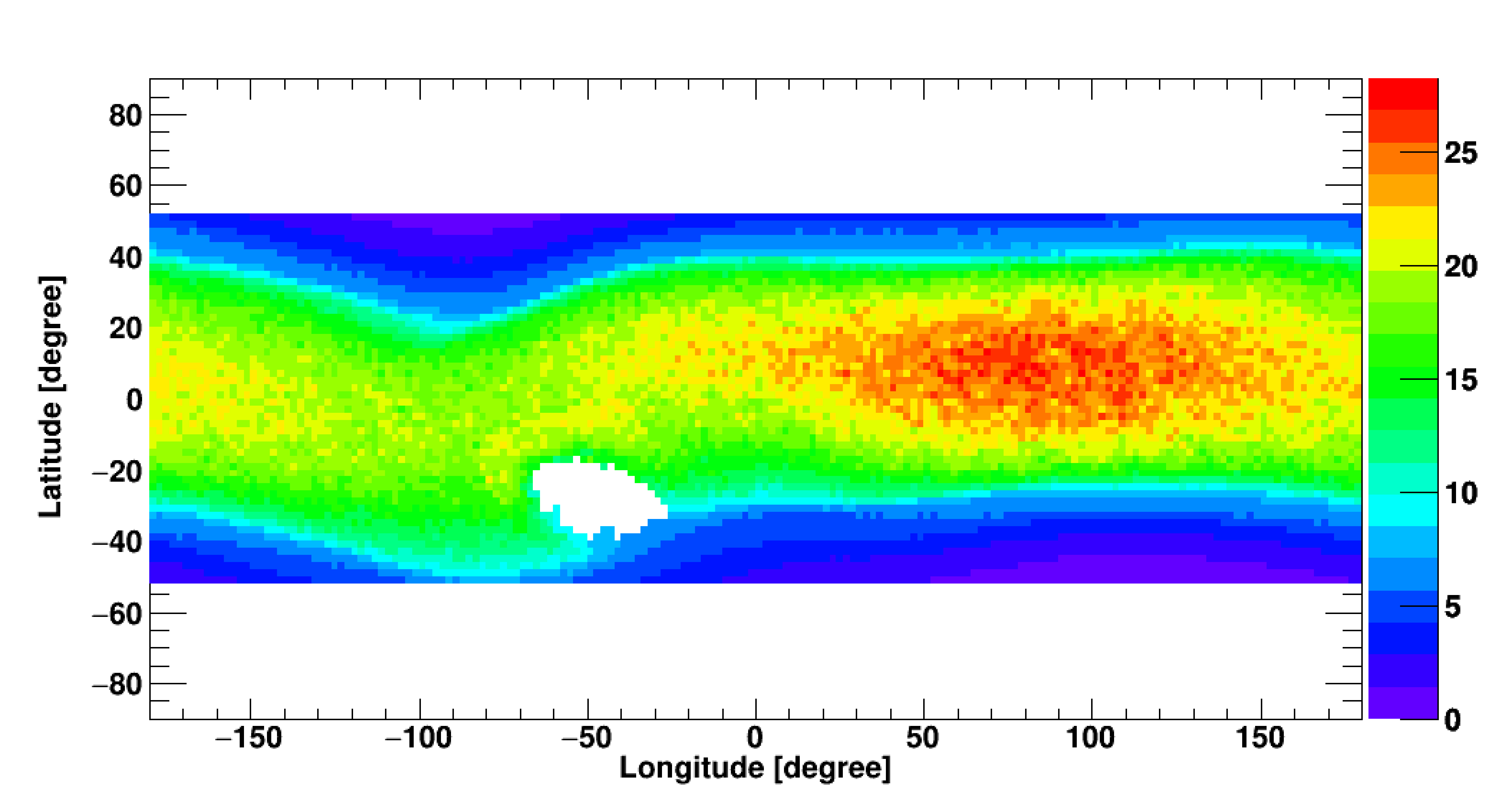
Primary CR: Upper cutoff map outside SAA



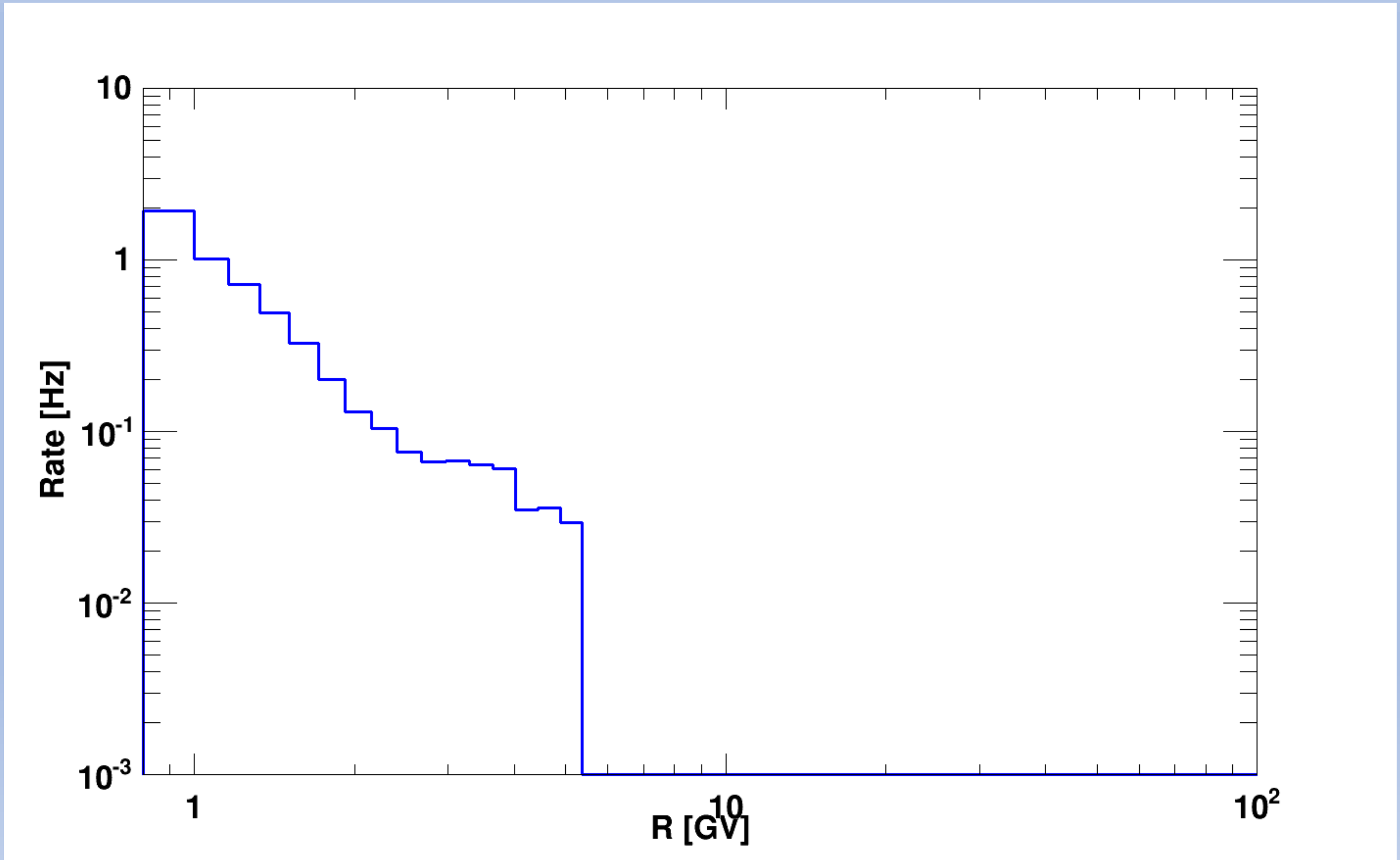
Primary CR: Upper cutoff map inside SAA



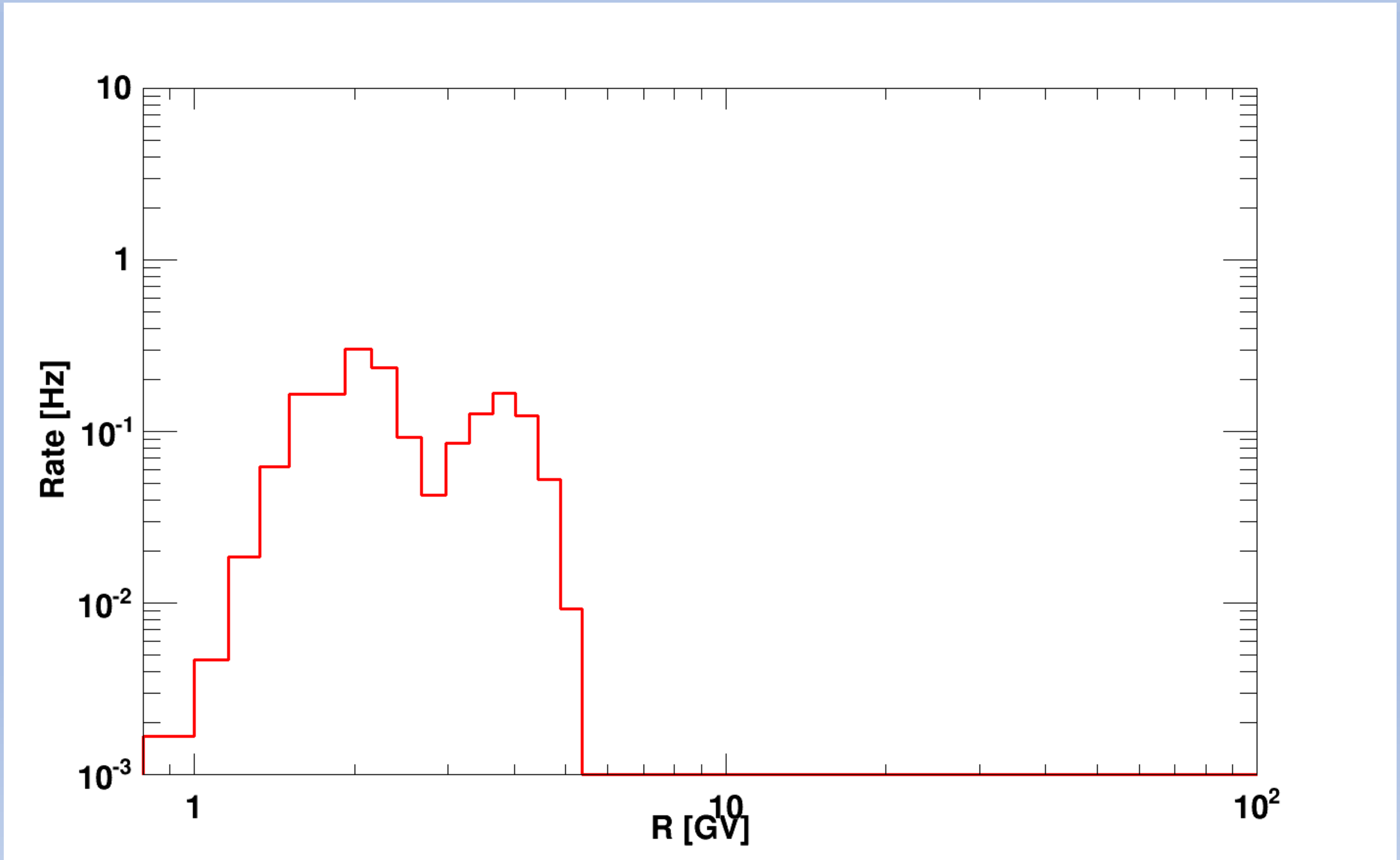
Primary CR: Upper cutoff map outside + inside SAA



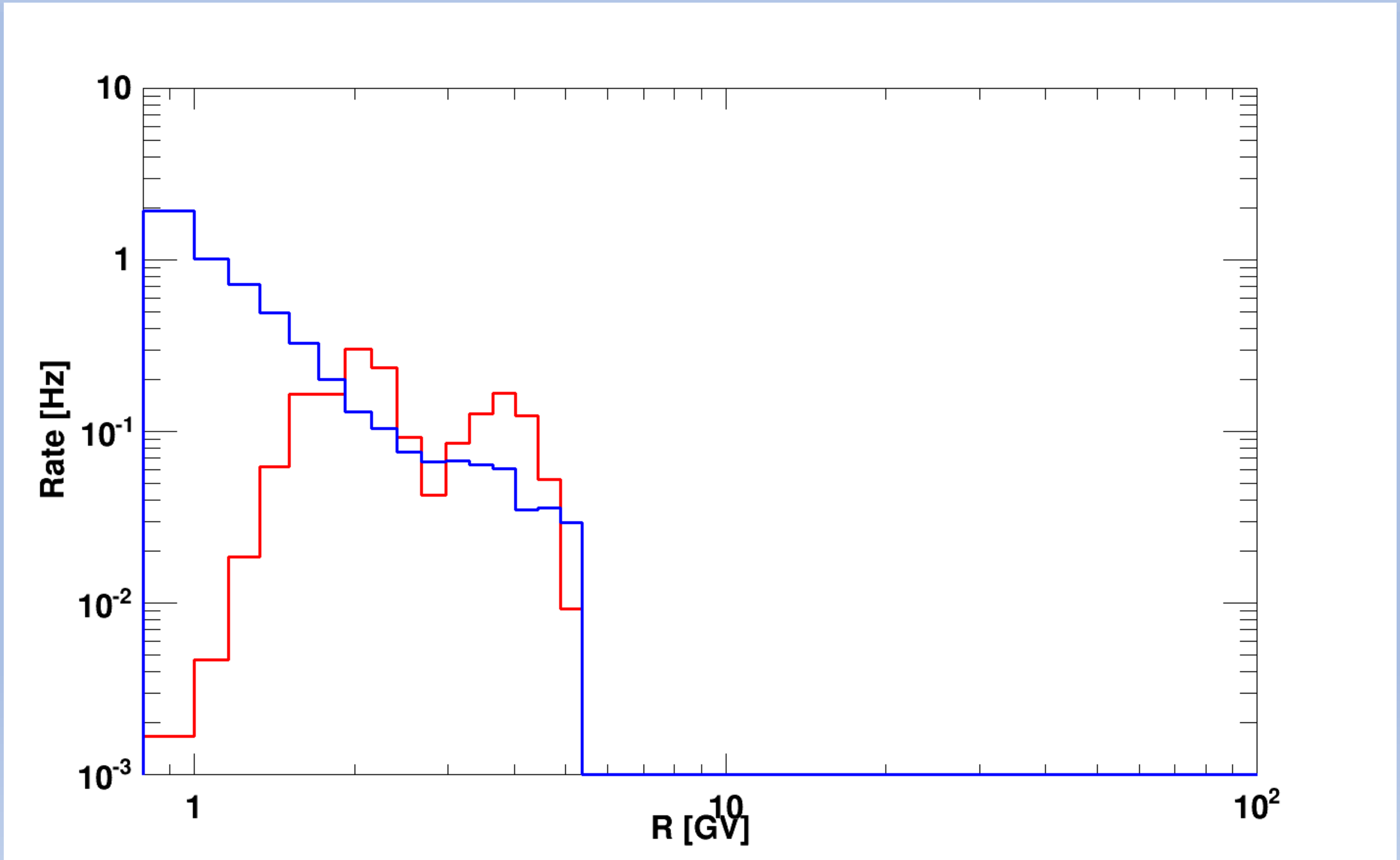
Trapped CR: RATE outside SAA



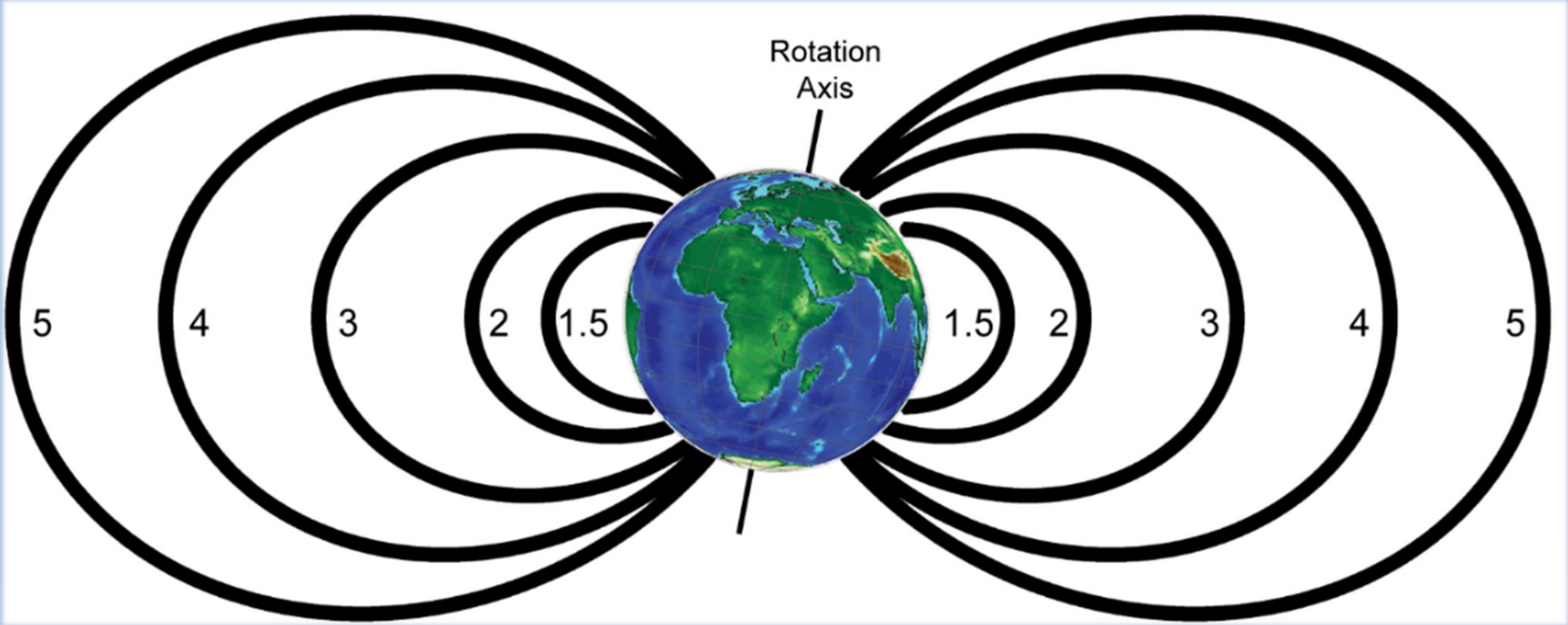
Trapped CR: RATE inside SAA



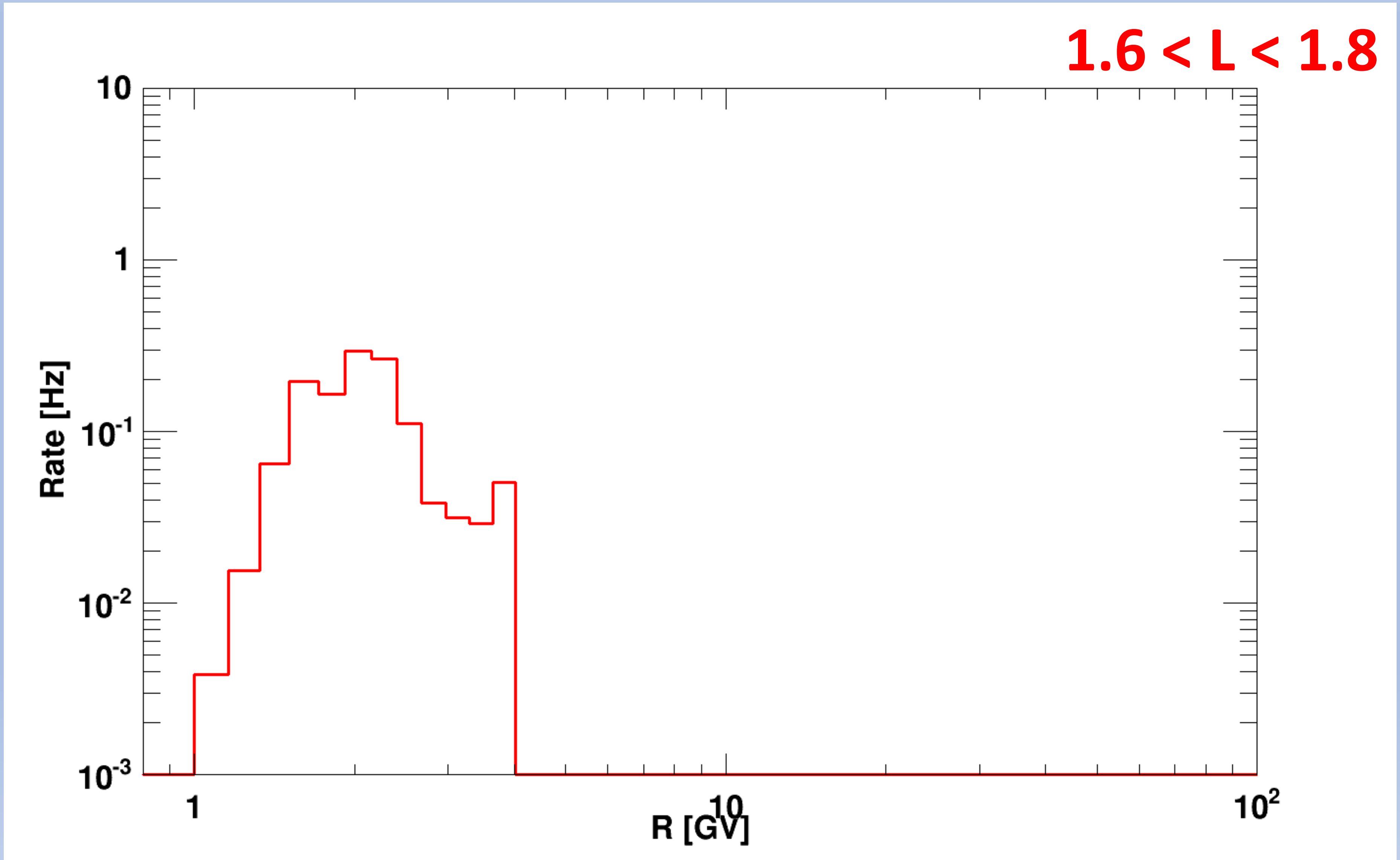
Trapped CR: RATE outside + inside SAA



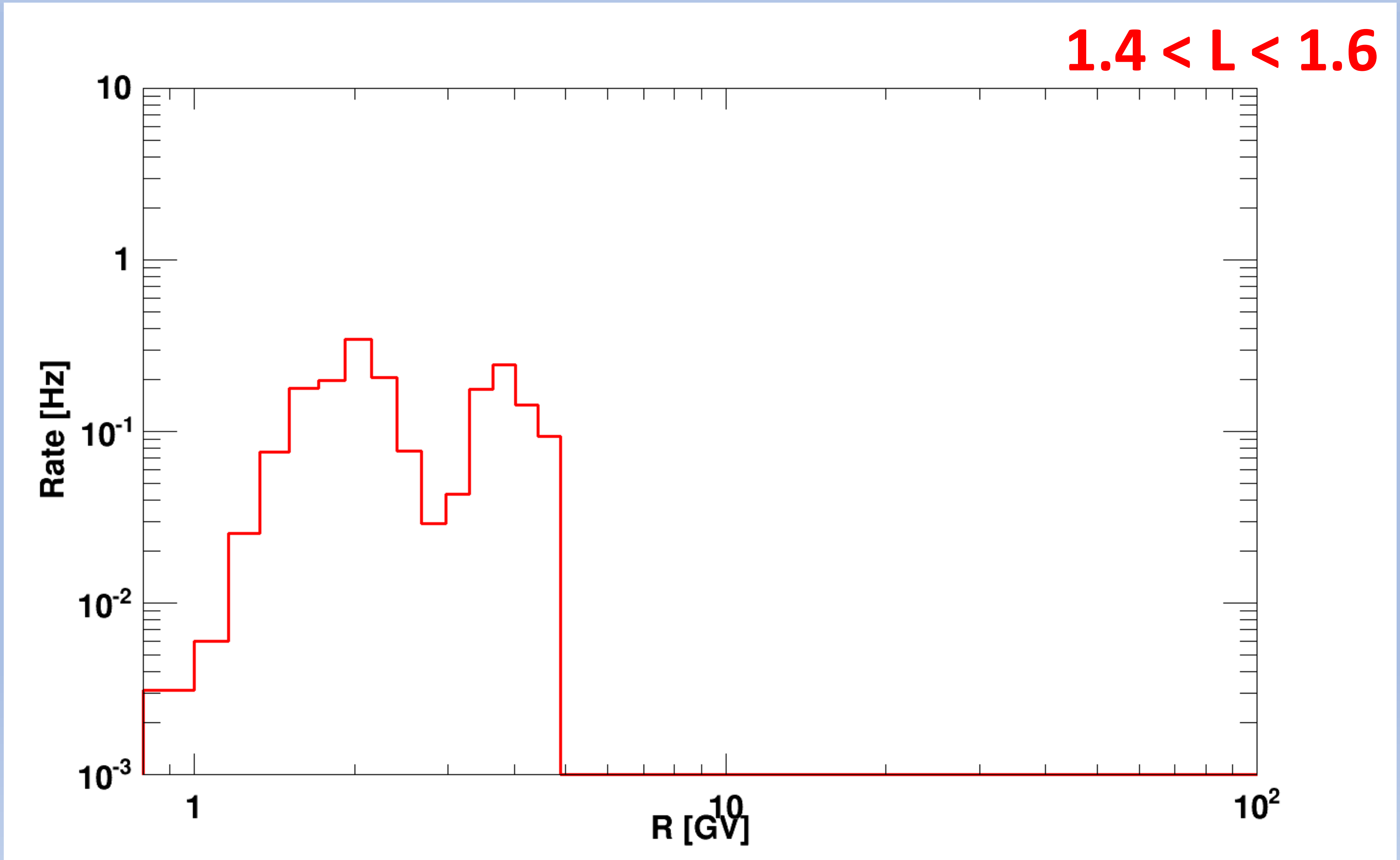
L - shell → $r = L\,cos^2(\lambda_{geomag})$



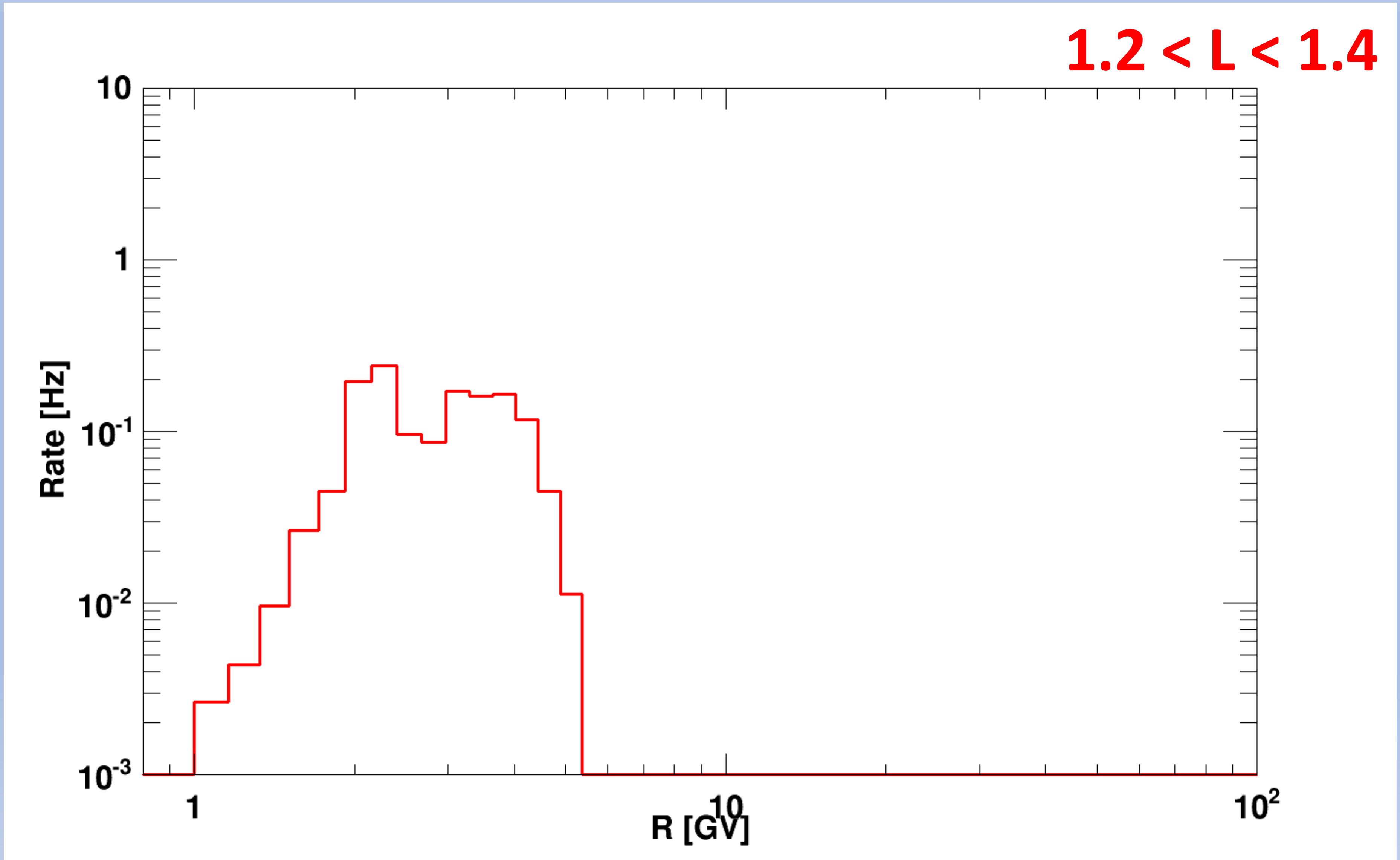
Trapped CR: RATE as a function of the L-shell inside SAA



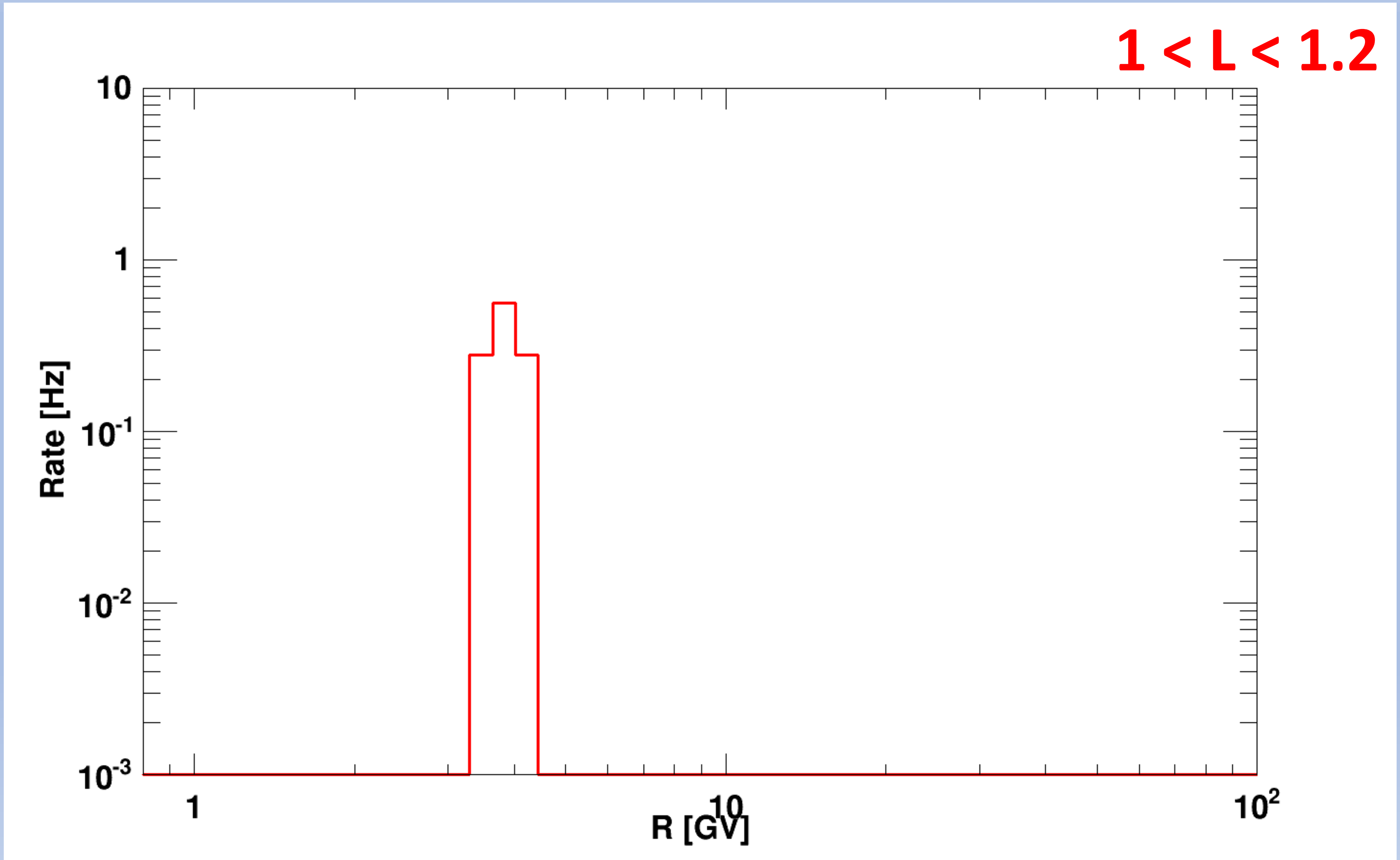
Trapped CR: RATE as a function of the L-shell inside SAA



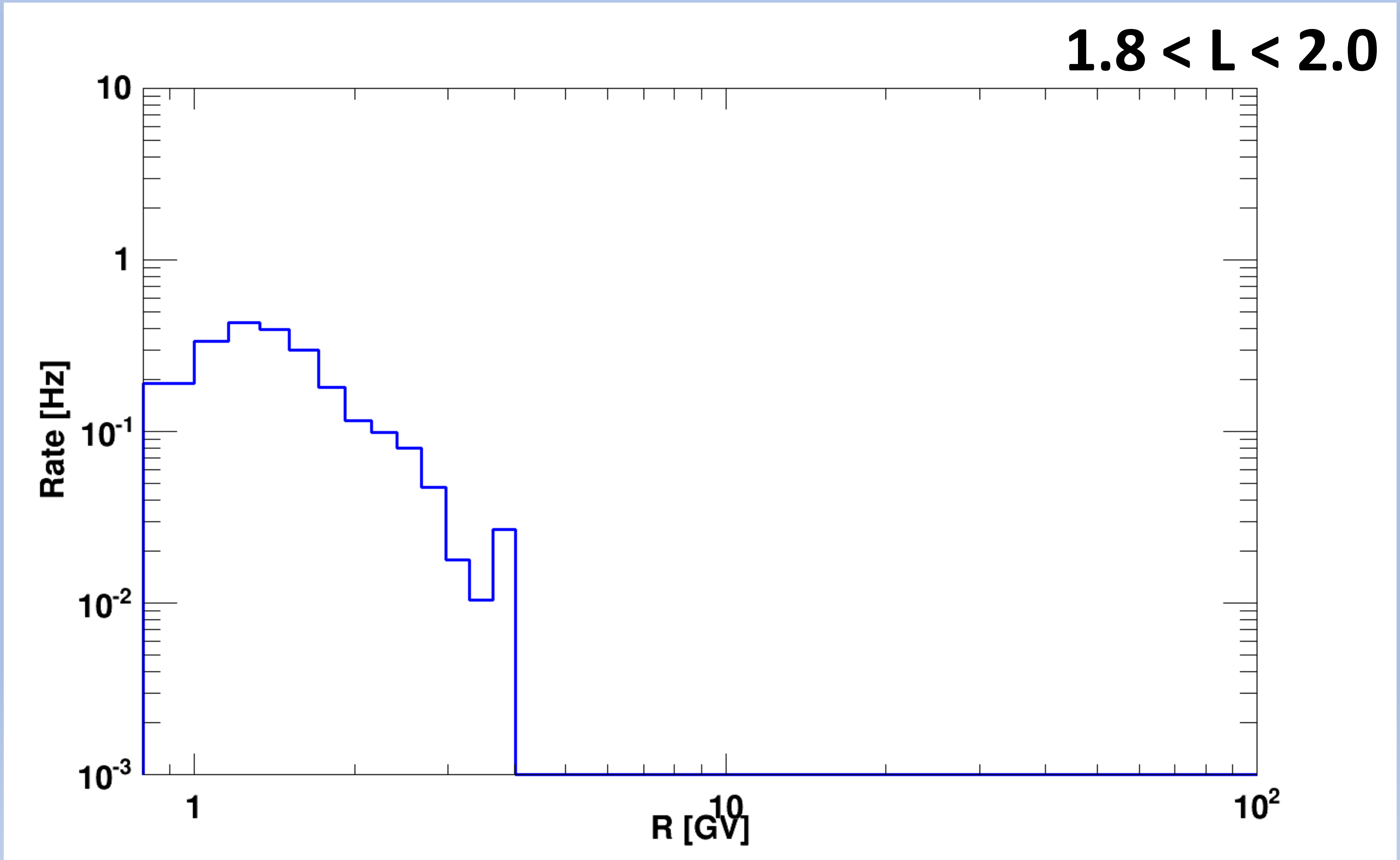
Trapped CR: RATE as a function of the L-shell inside SAA



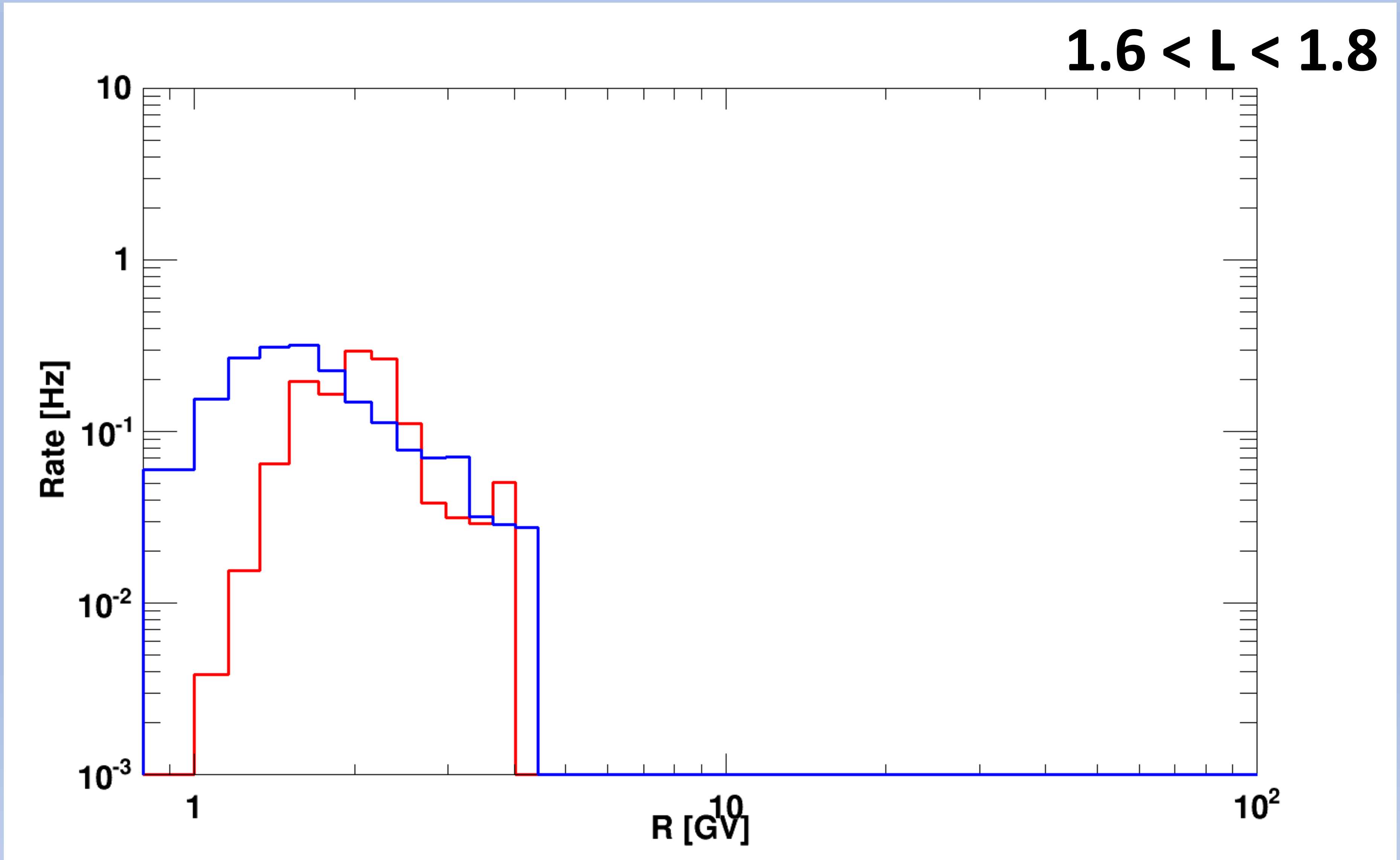
Trapped CR: RATE as a function of the L-shell inside SAA



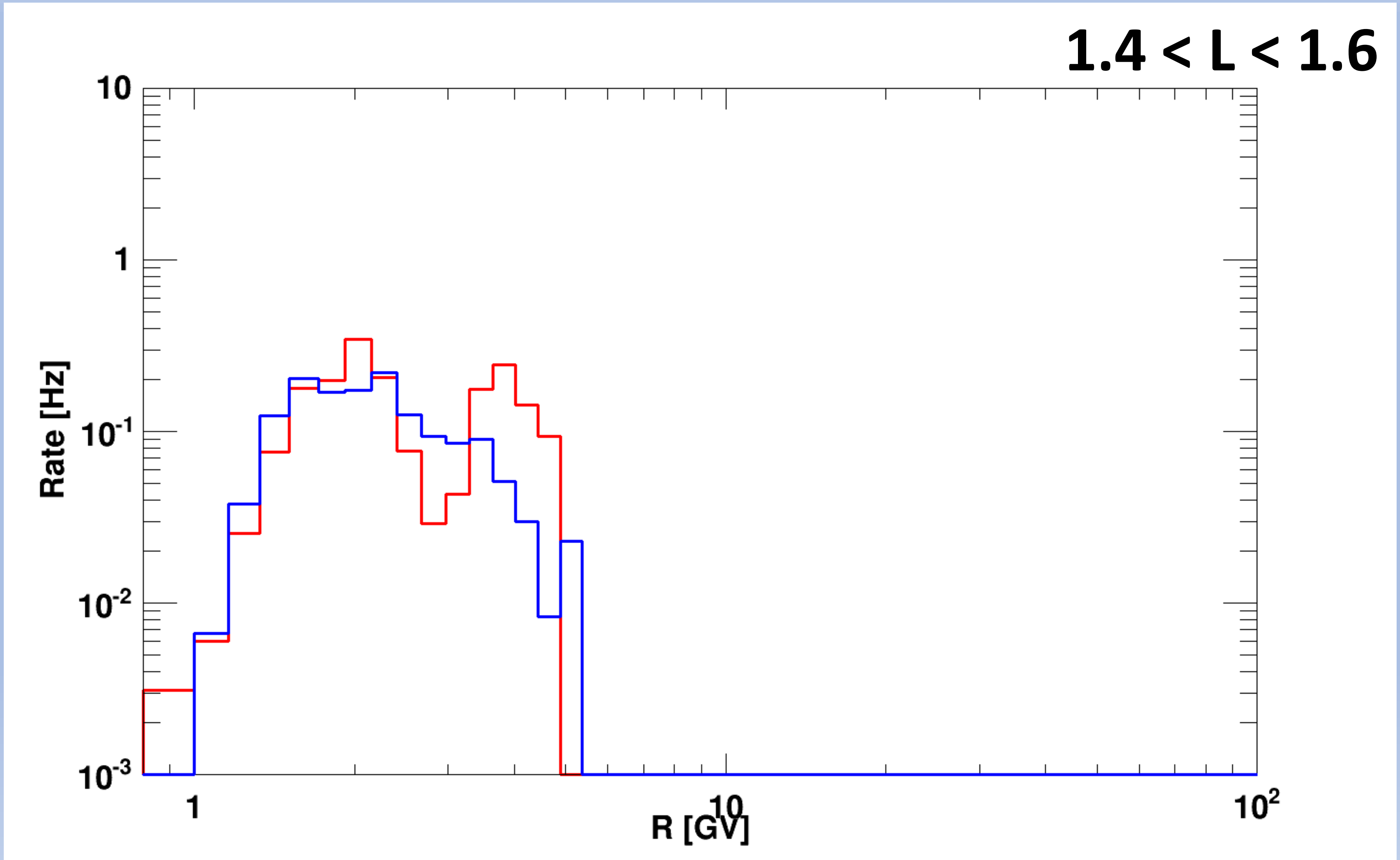
Trapped CR: RATE as a function of the L-shell outside + inside SAA



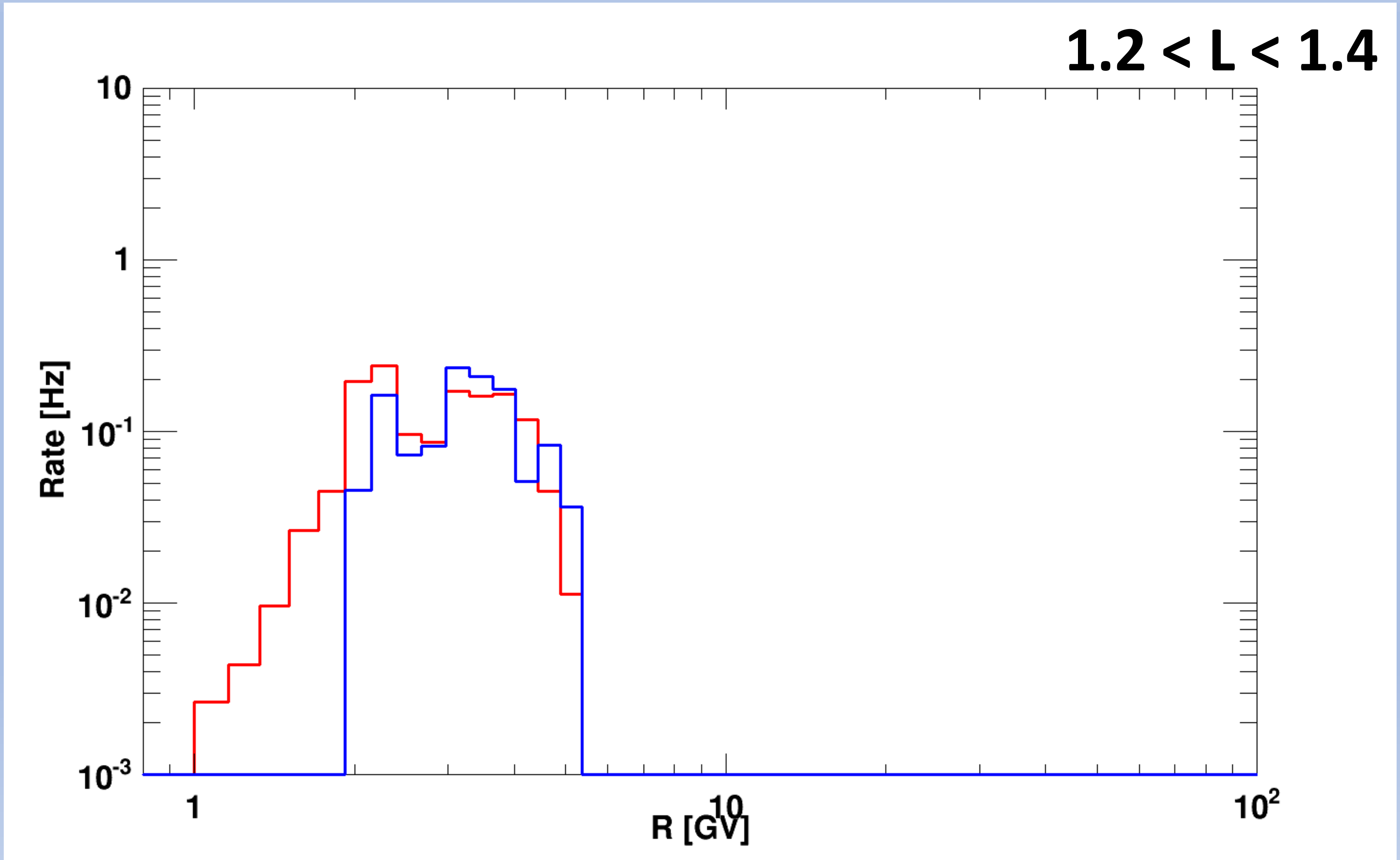
Trapped CR: RATE as a function of the L-shell outside + inside SAA



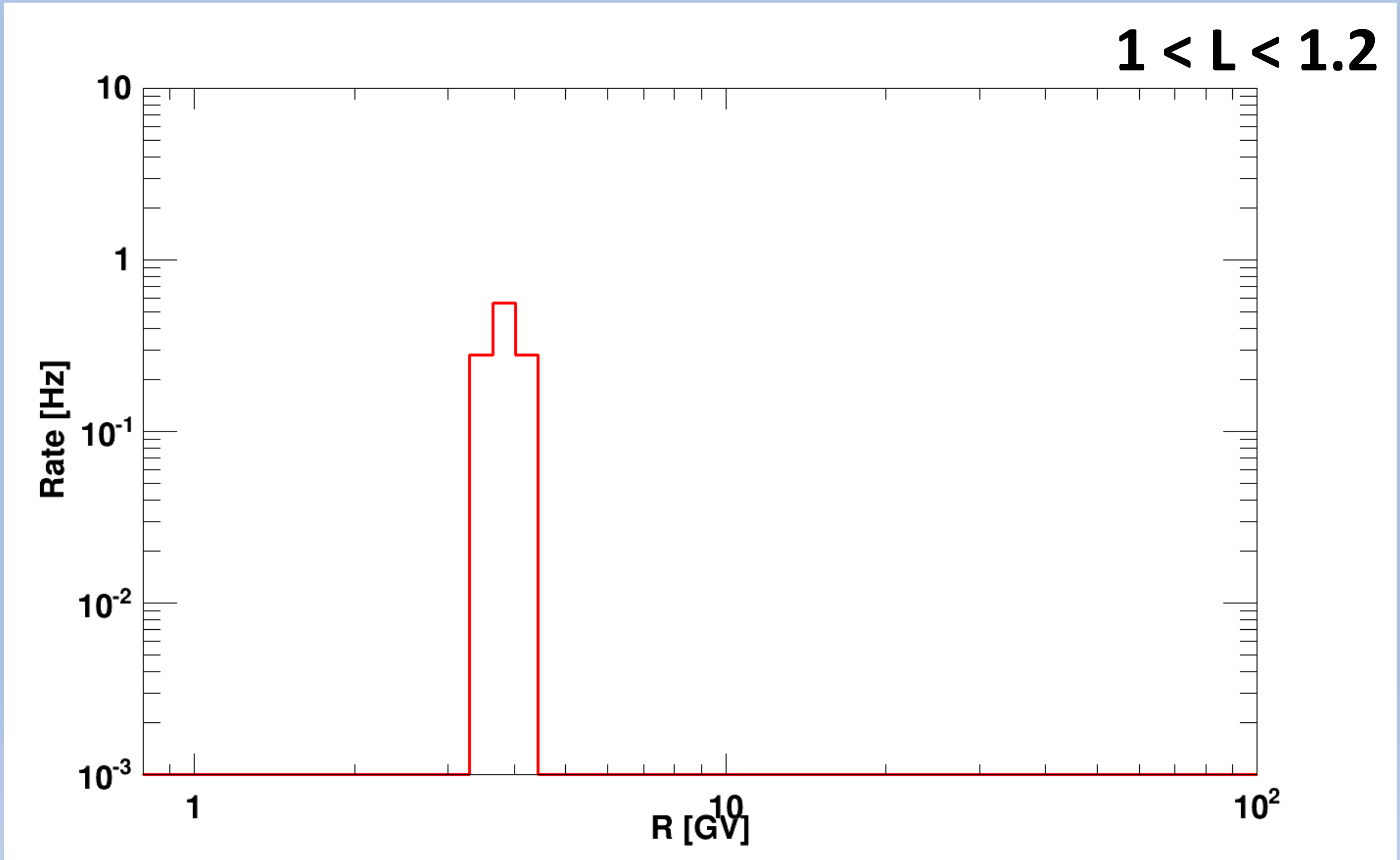
Trapped CR: RATE as a function of the L-shell outside + inside SAA



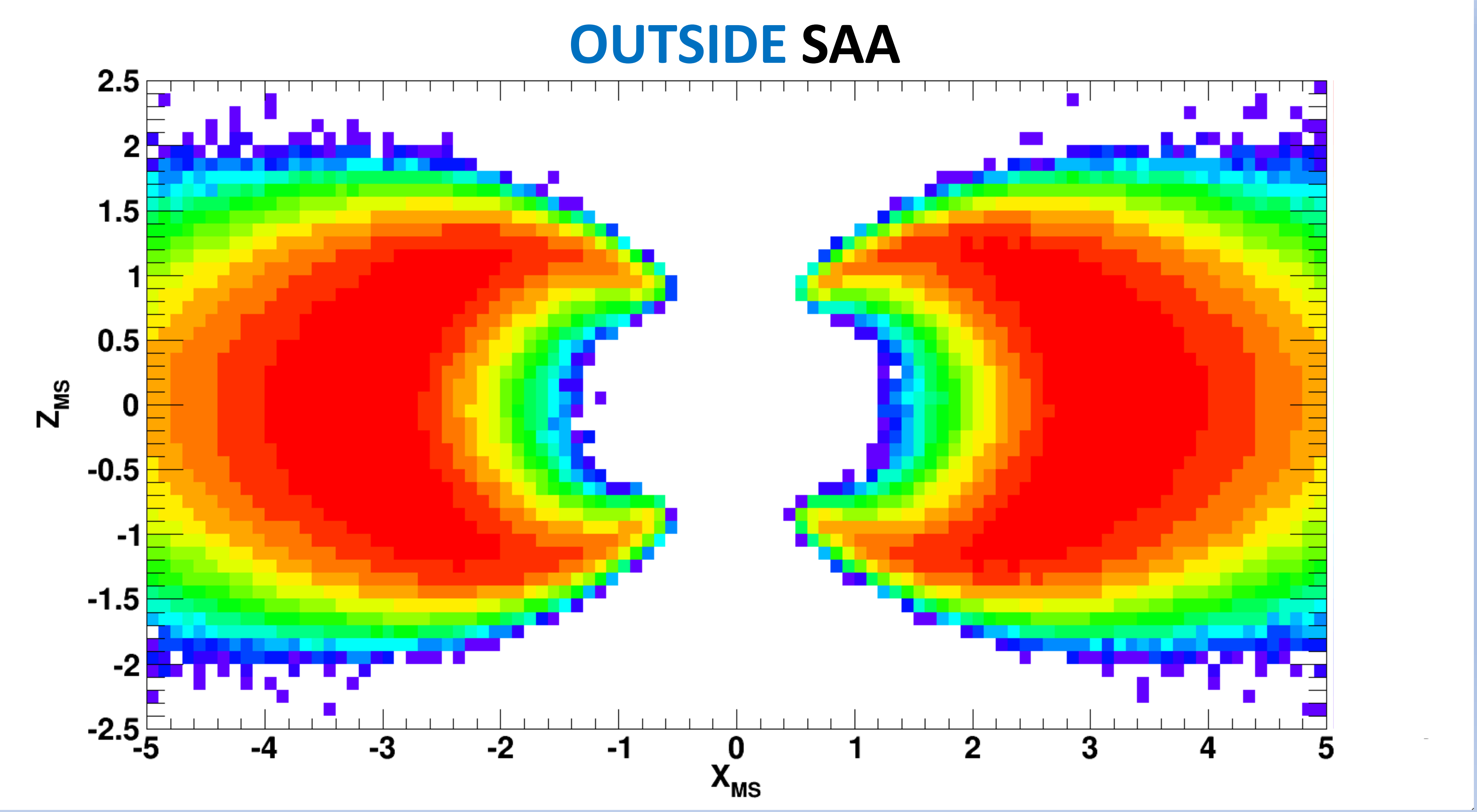
Trapped CR: RATE as a function of the L-shell outside + inside SAA



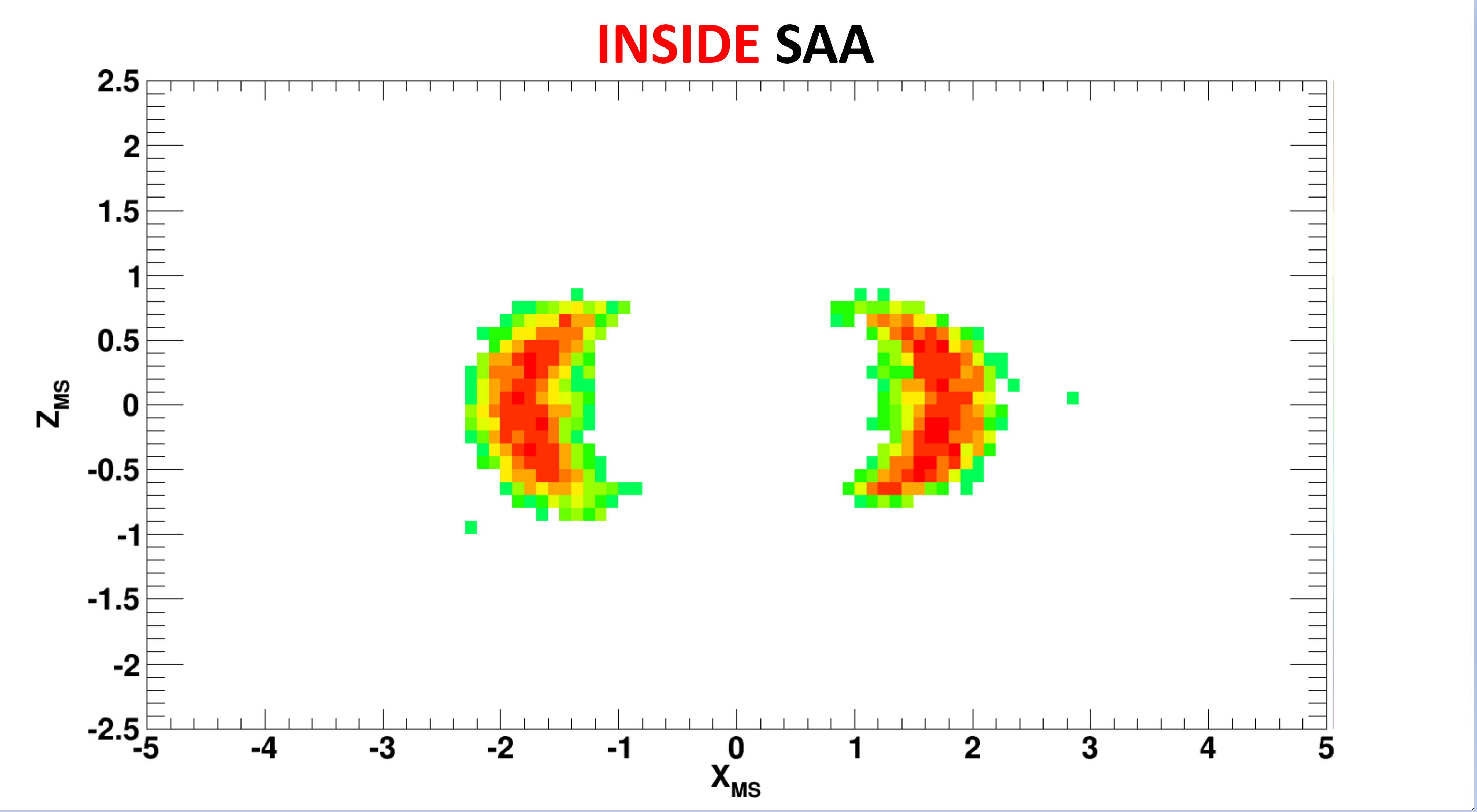
Trapped CR: RATE as a function of the L-shell outside + inside SAA



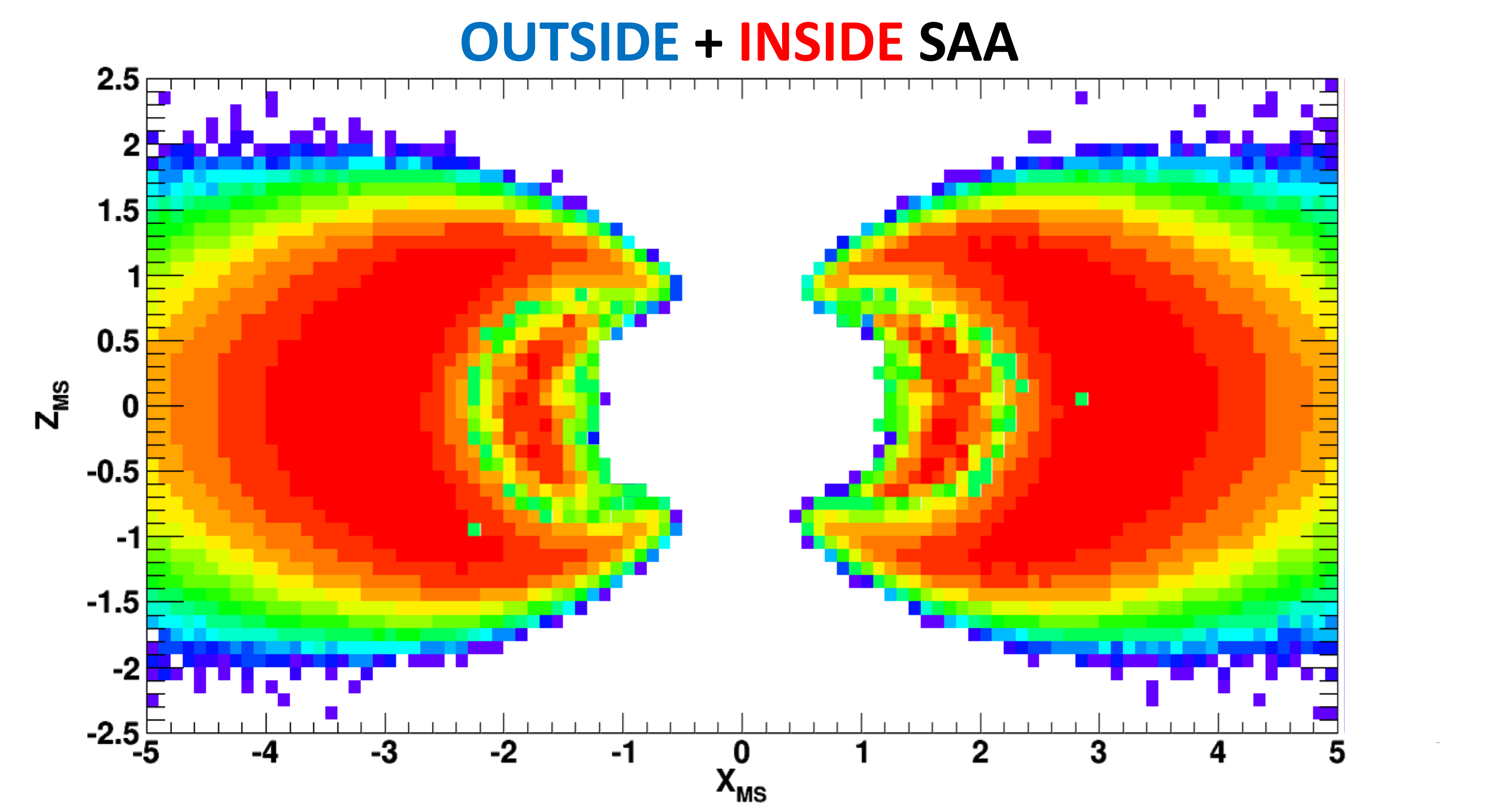
Trapped CR: Final position after 10 seconds of backtracing



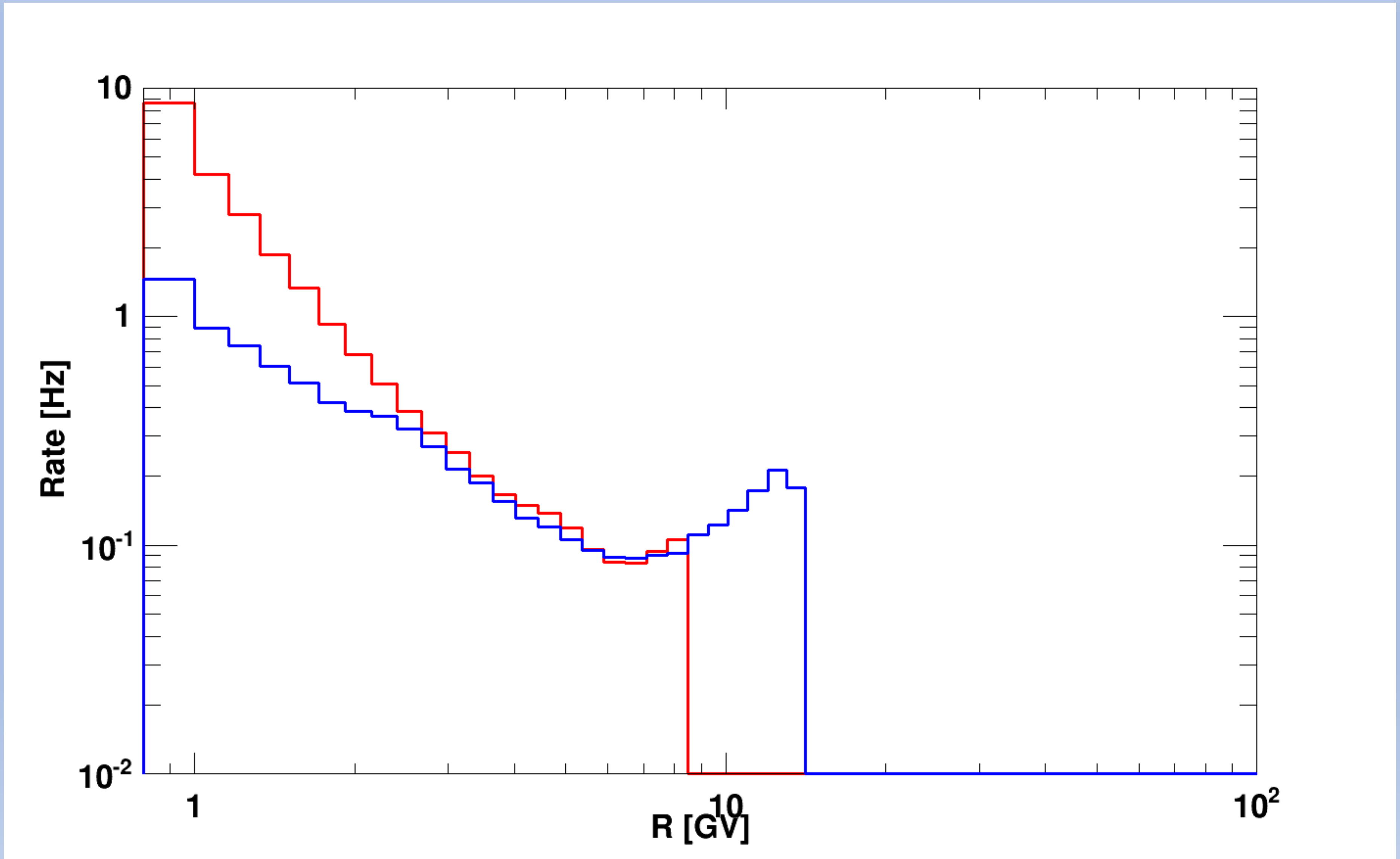
Trapped CR: Final position after 10 seconds of backtracing



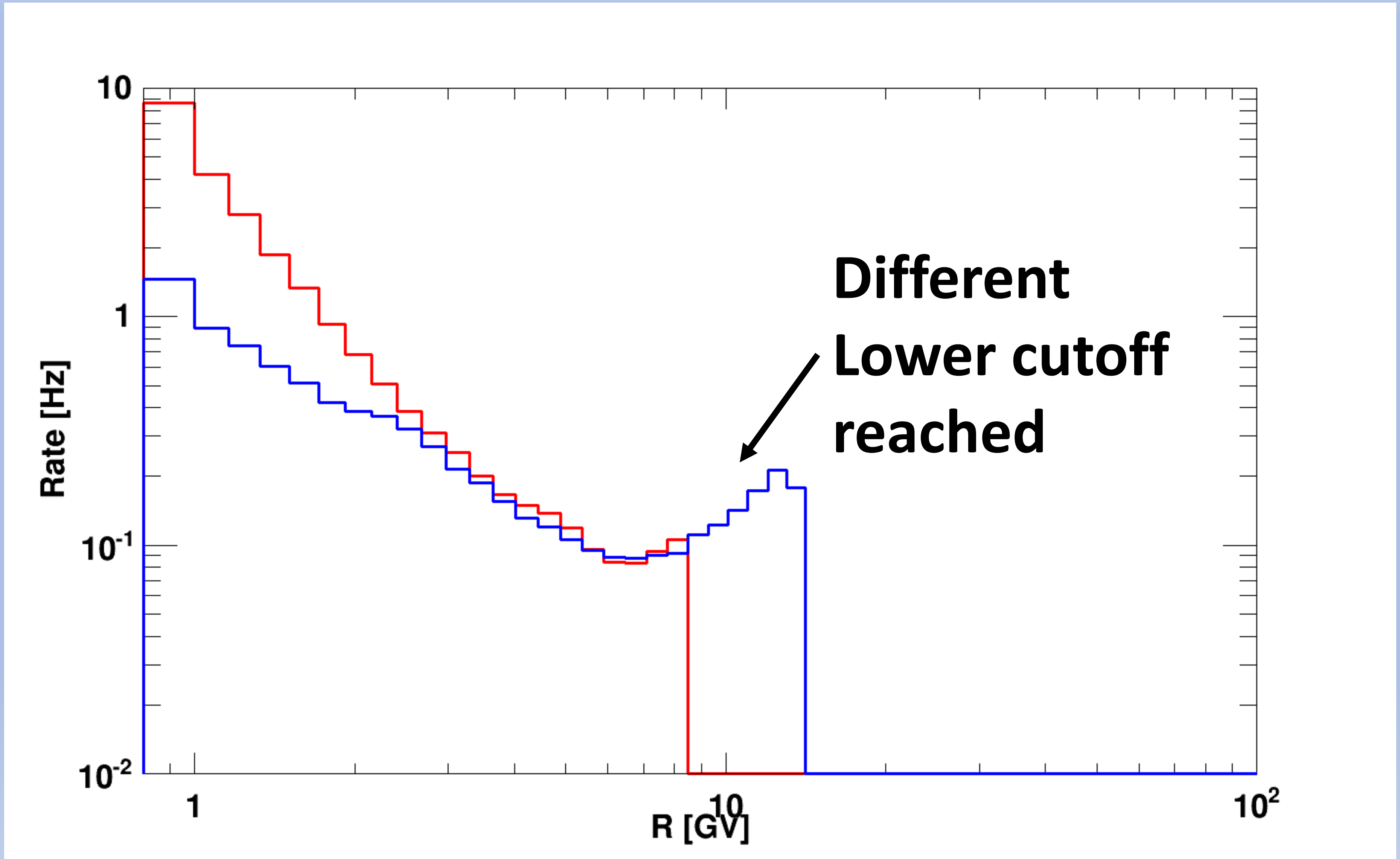
Trapped CR: Final position after 10 seconds of backtracing



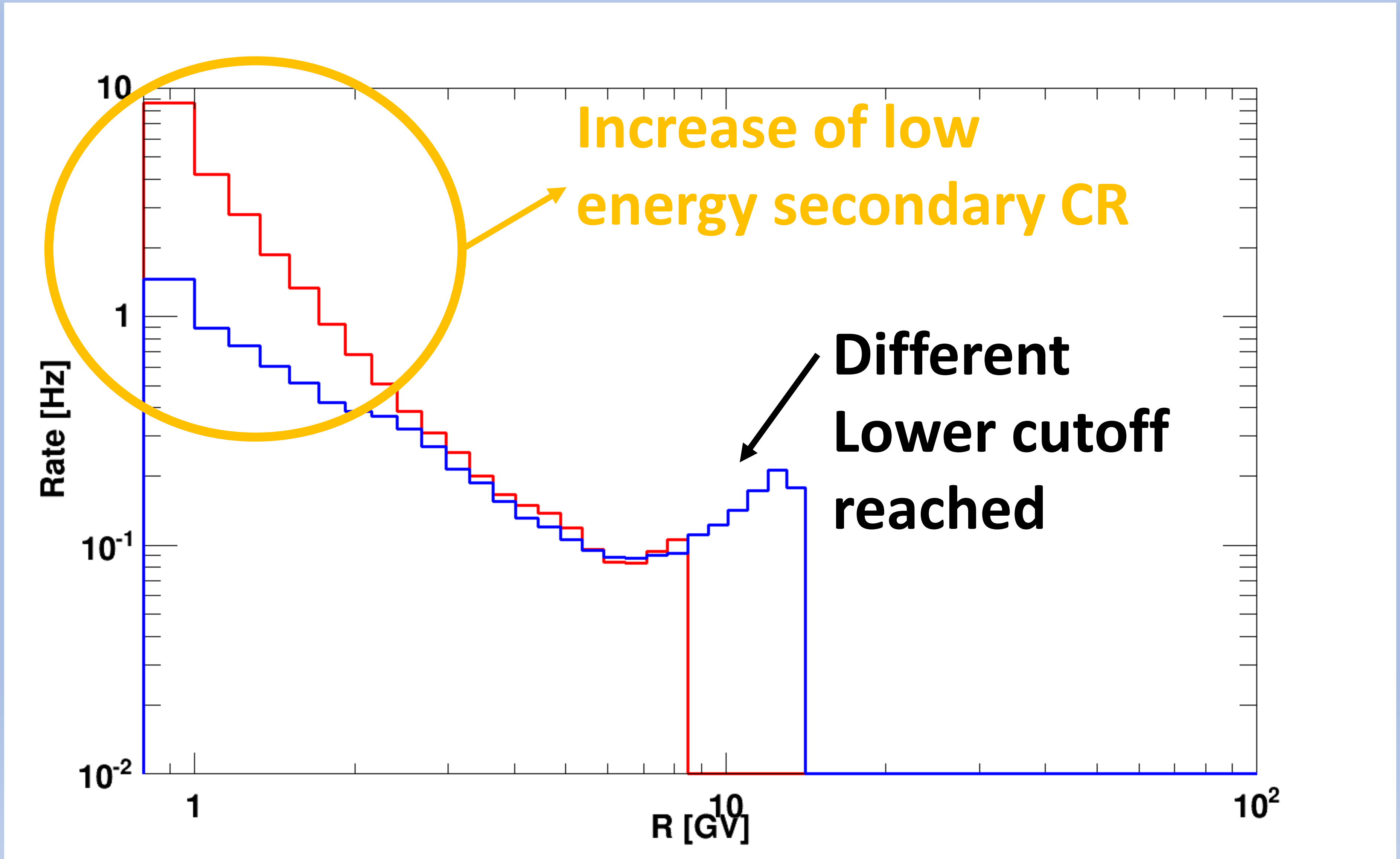
Secondary CR: Rate OUTSIDE vs INSIDE SAA



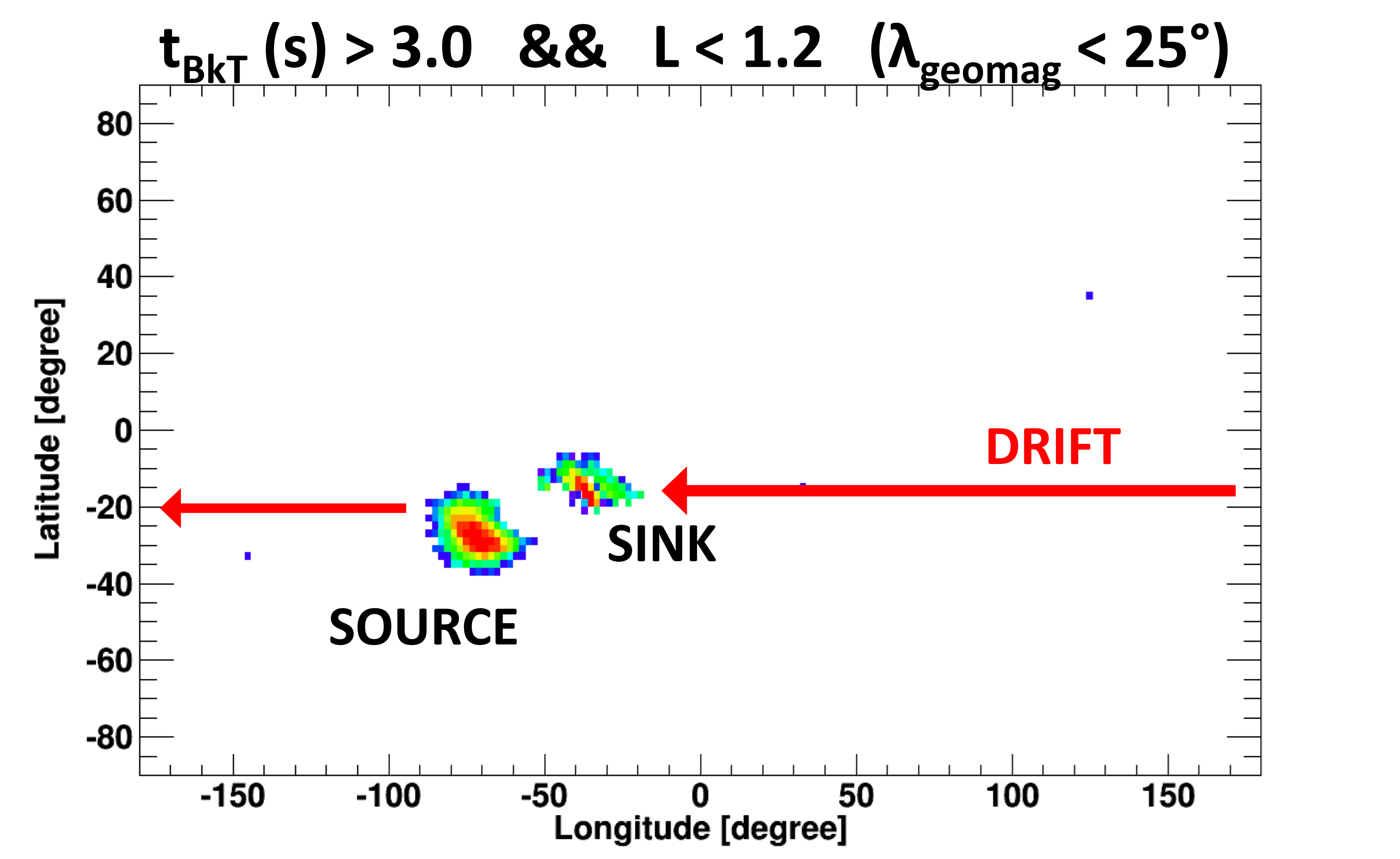
Secondary CR: Rate OUTSIDE vs INSIDE SAA



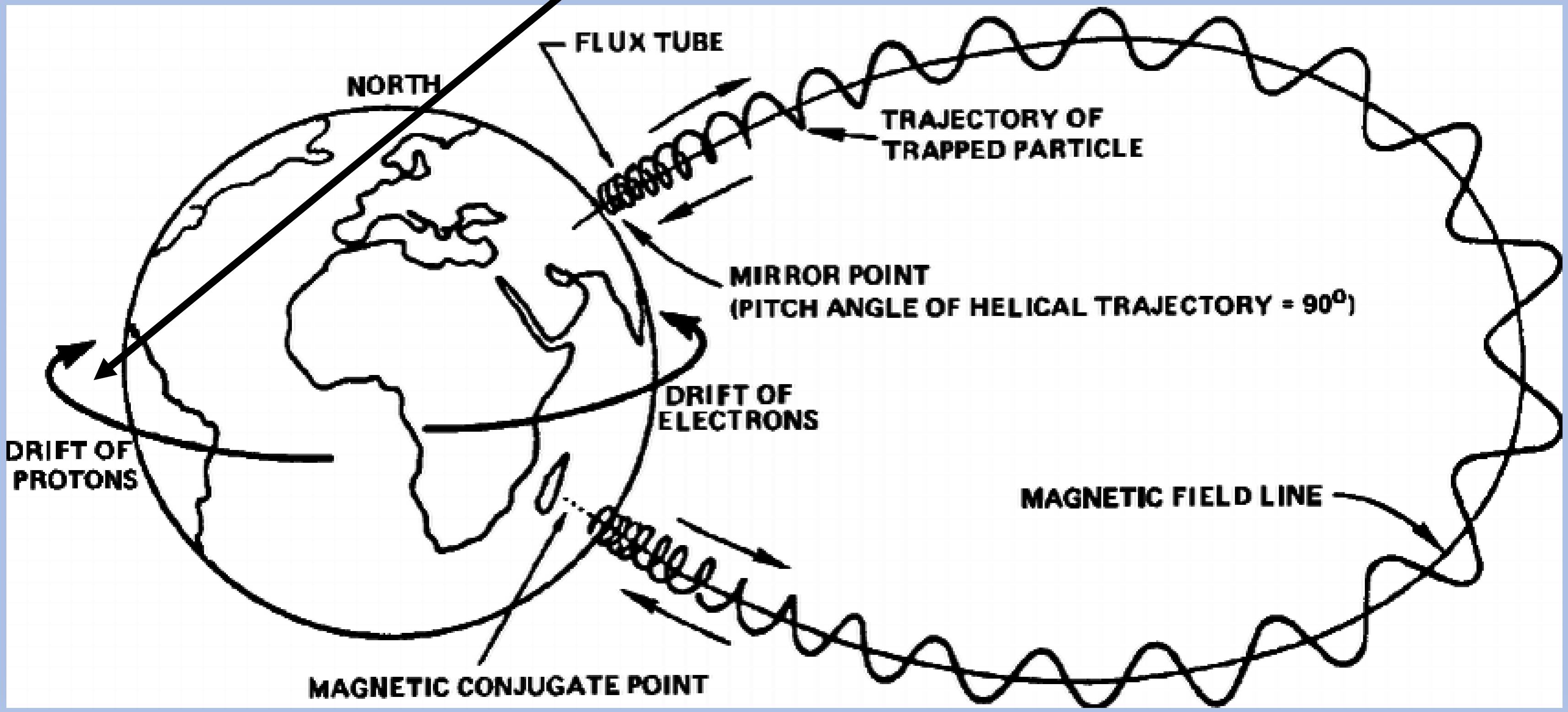
Secondary CR: Rate OUTSIDE vs INSIDE SAA



Secondary CR: Creation and Detection positions INSIDE SAA



Secondary CR: DRIFT of protons



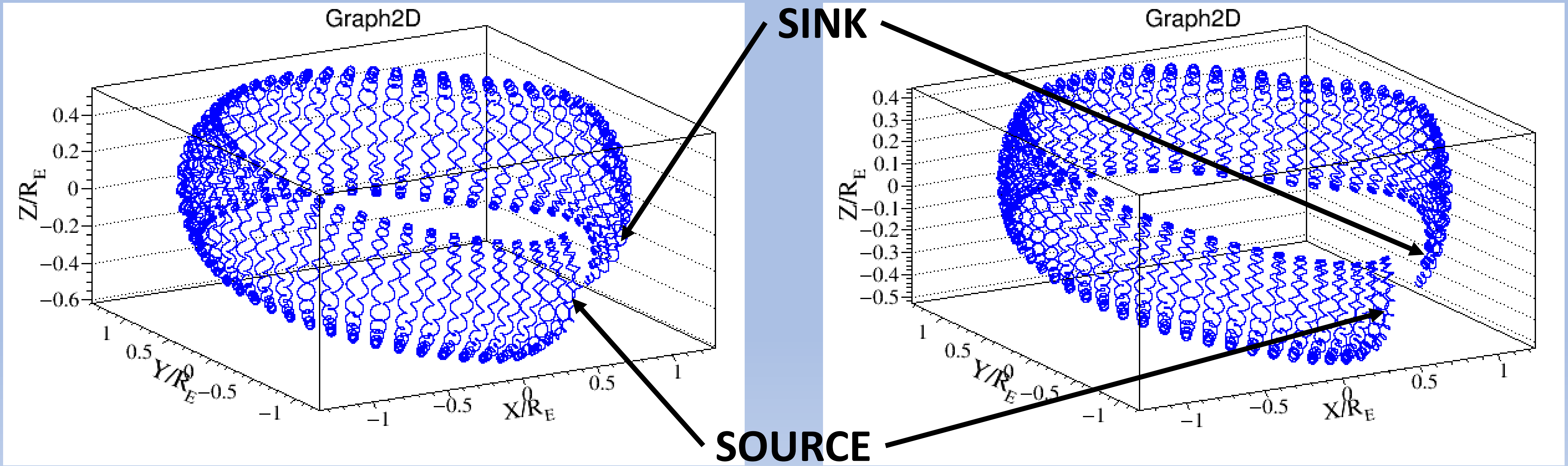
Secondary CR: DRIFT of protons

Sample of Secondary CR detected inside SAA with

t_{BkT} (s) > 3.0 && L < 1.2 (λ_{geomag} < 25°)

The paths were computed with GeoMagSphere (MIB-Backtracing code)

www.geomagsphere.org

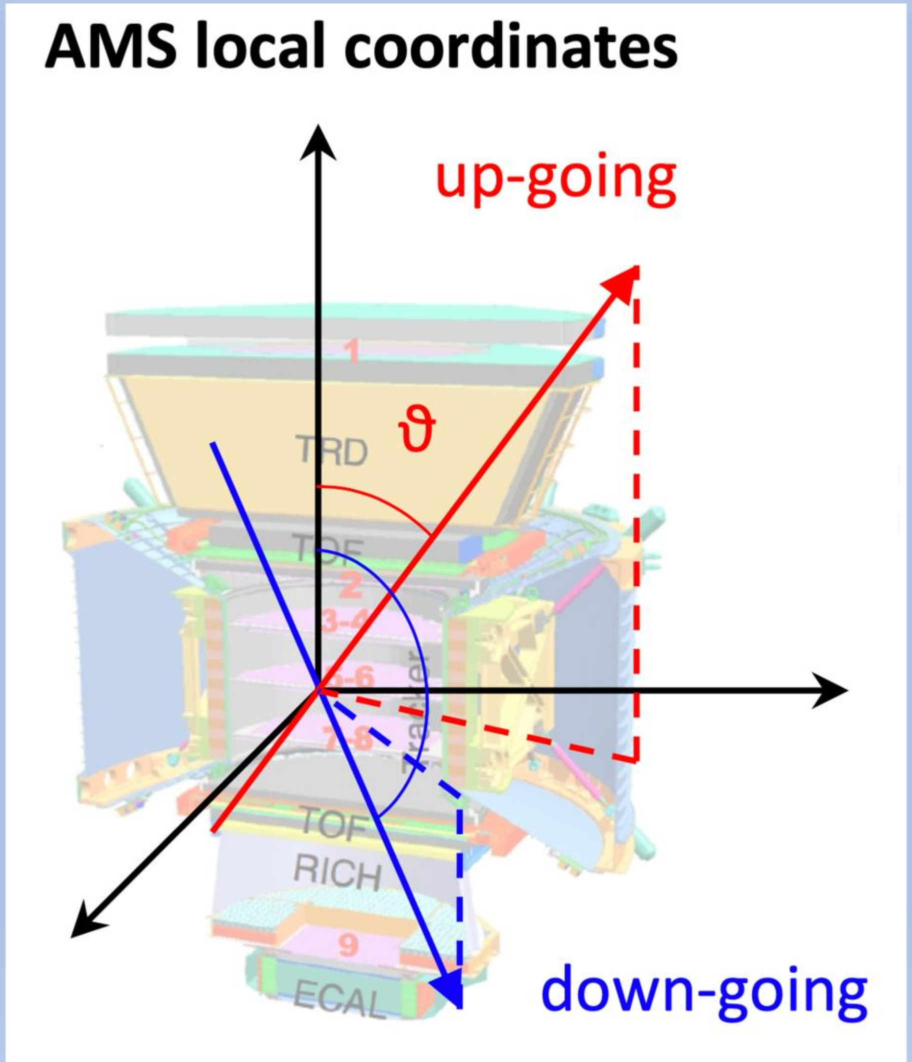


Analysis on AMS ions in magnetosphere

Data selected by A. Oliva and F. Giovacchini

Backtracing and analysis performed by D. Grandi and D. Rozza

Analysis performed on:

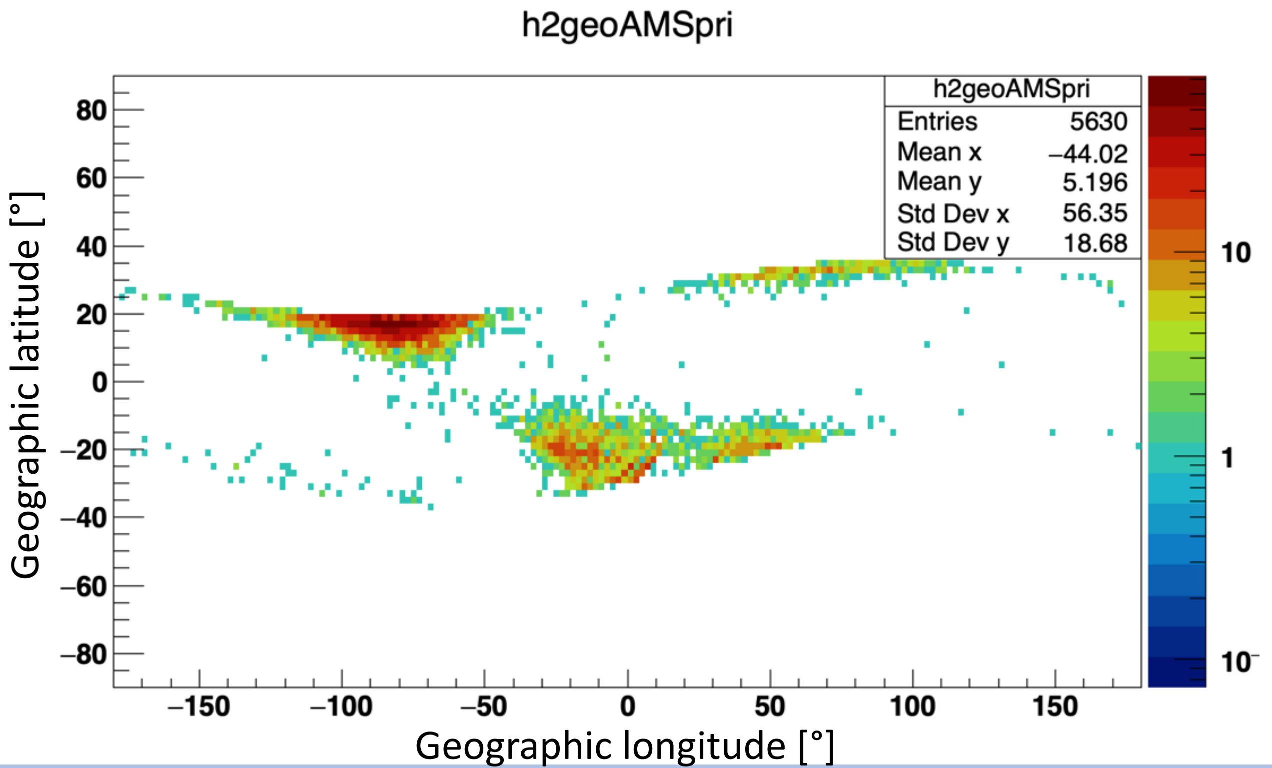


	upgo/down going	upgo3/down3 going
Precision	0.0001	0.0001
Time limit (s)	50	70
Atmosphere limit (km)	100	0
Step limit	500000	500000

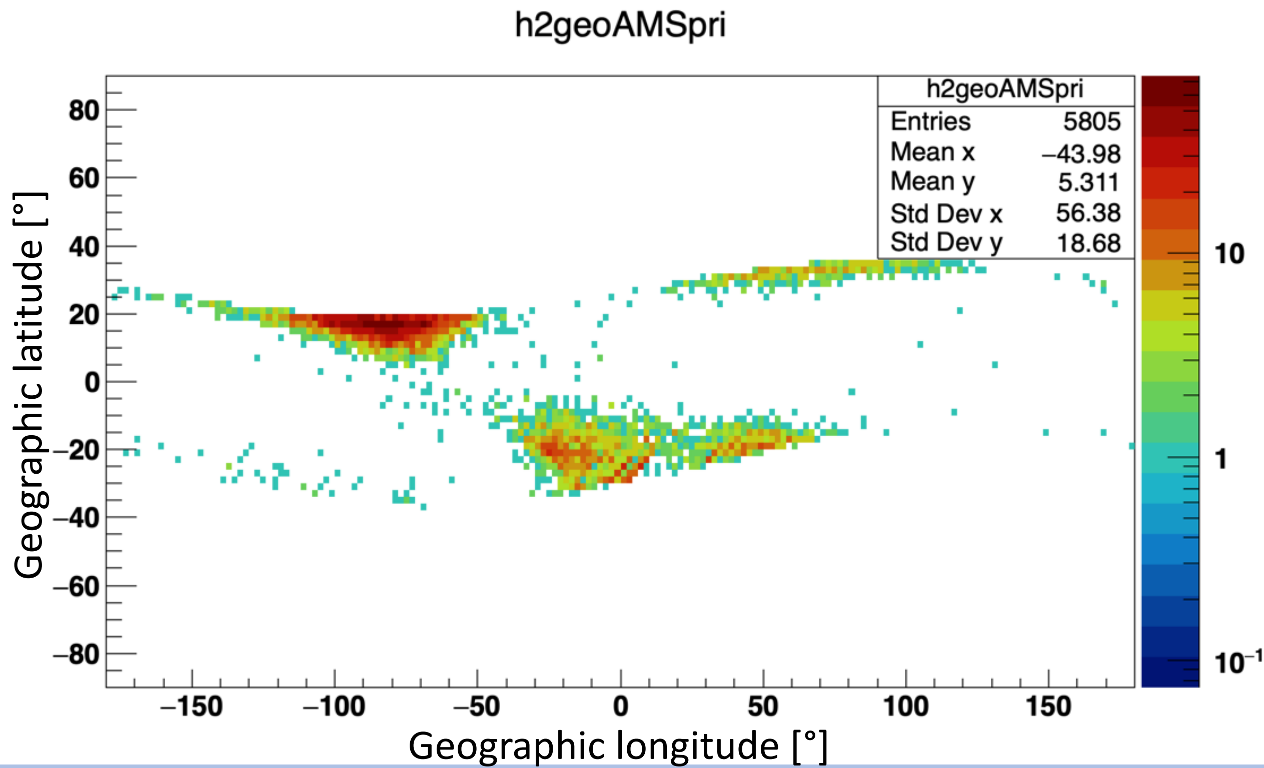
Both IGRF and IGRF+TS05 models were used

up-going primaries

IGRF



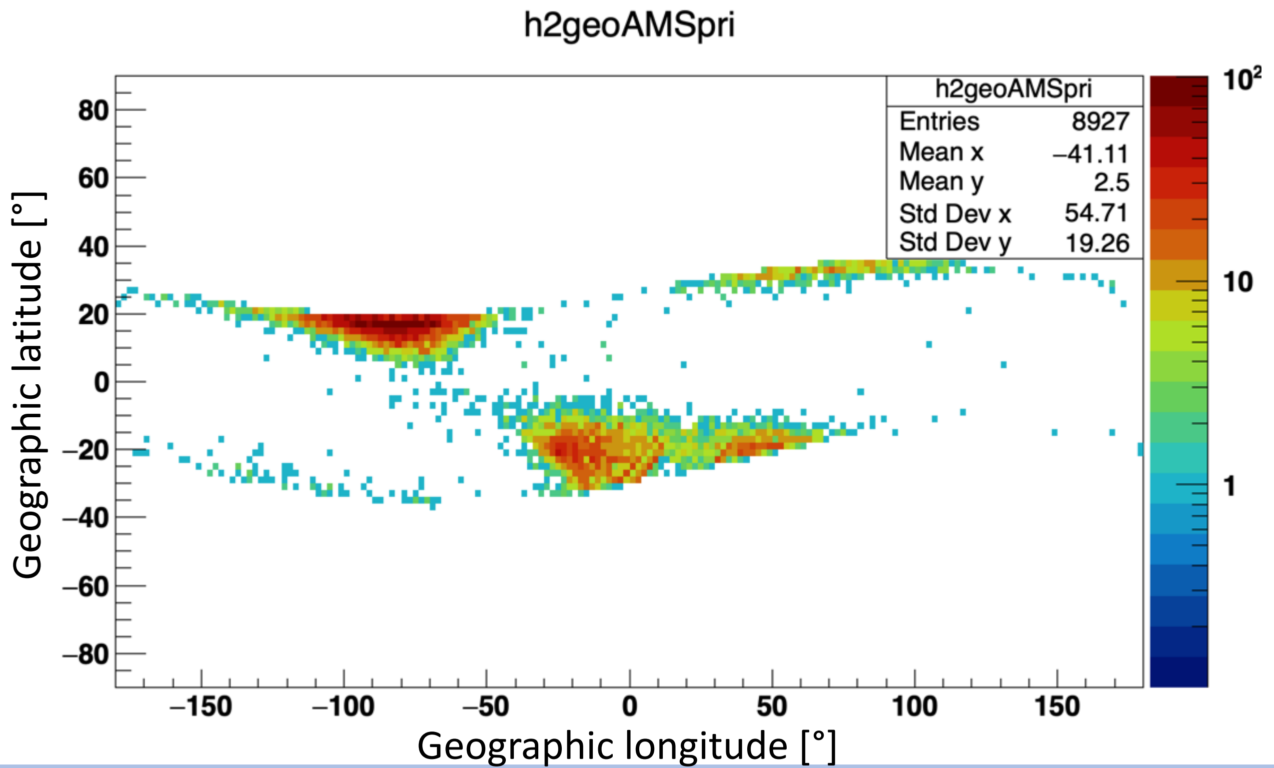
TS05



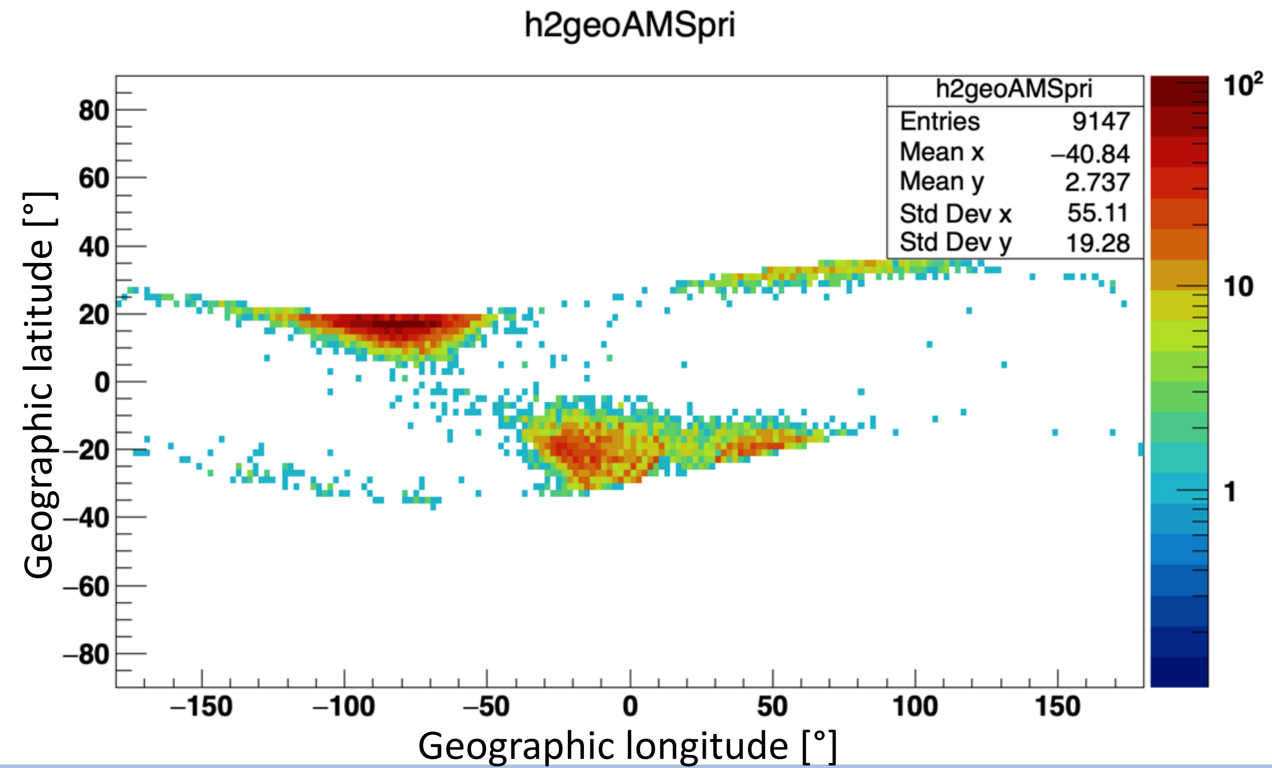
Detection positions

up3-going primaries

IGRF



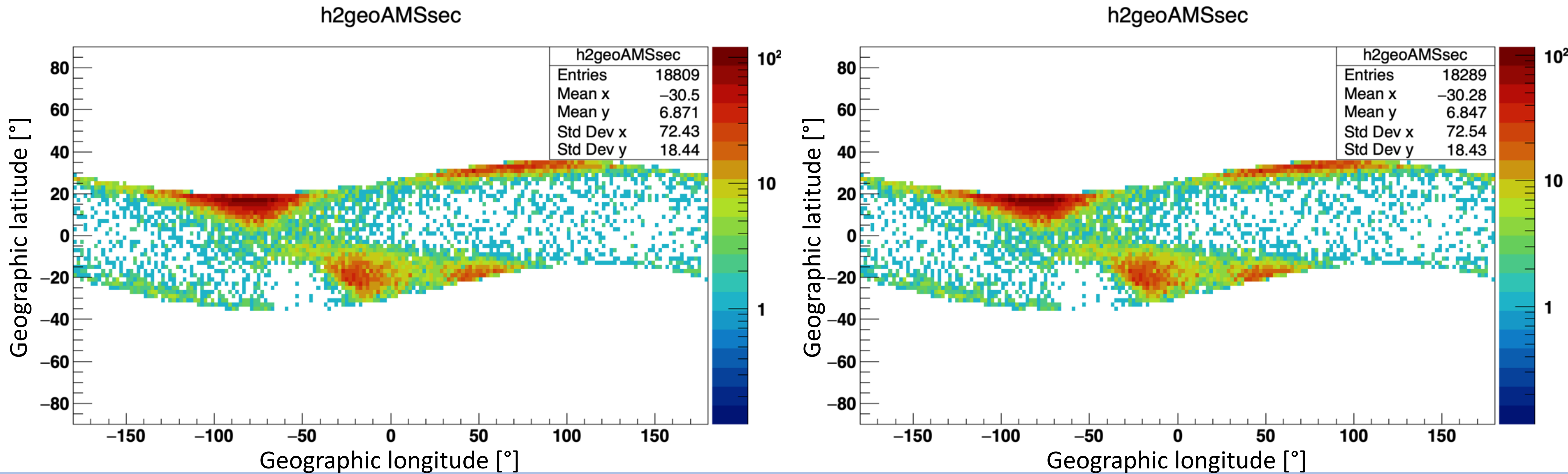
TS05



Detection positions

up-going secondaries

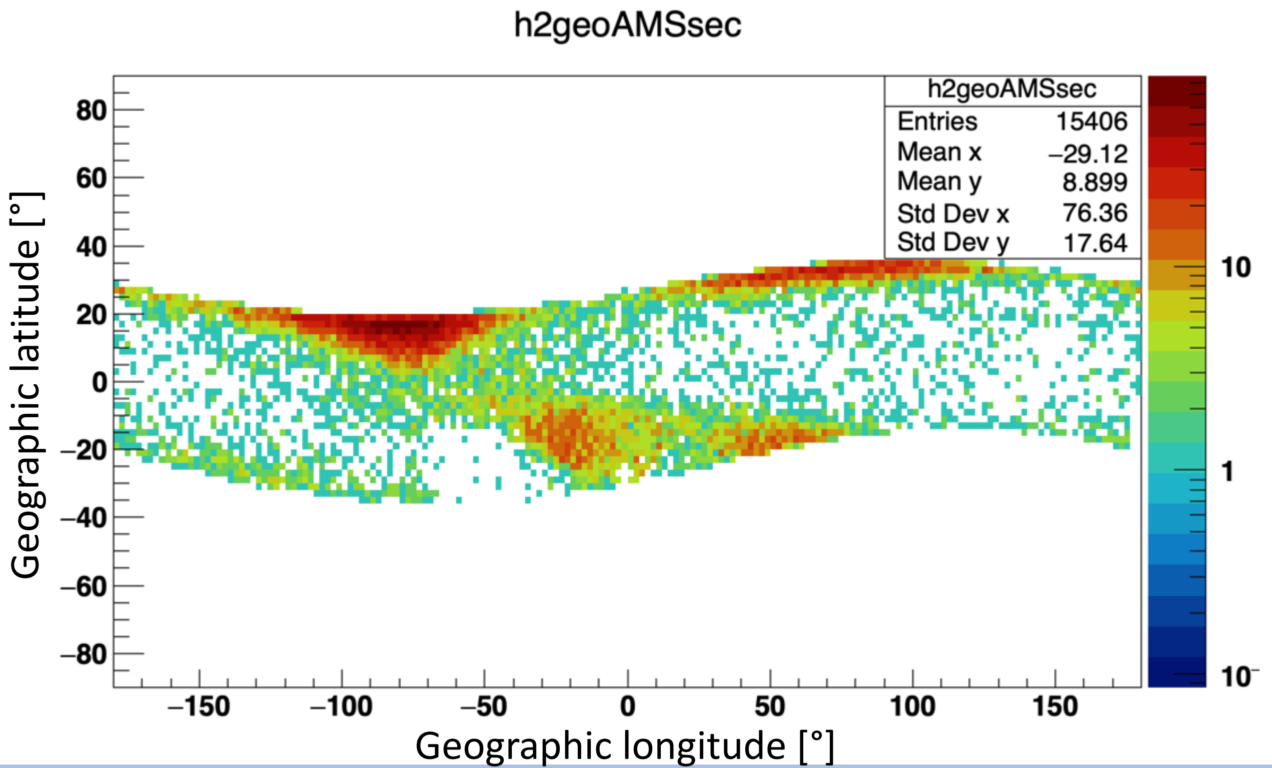
IGRF　　　　　　　　　　TS05



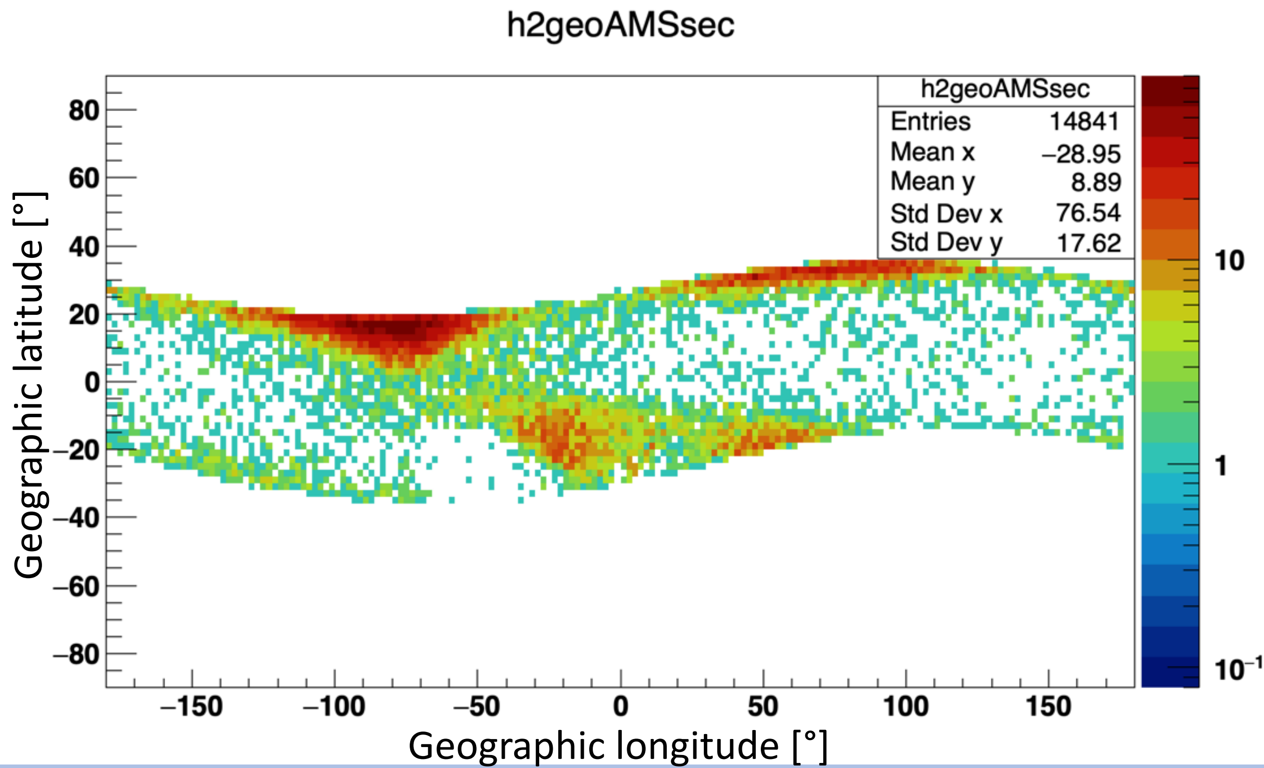
Detection positions

up3-going secondaries

IGRF



TS05

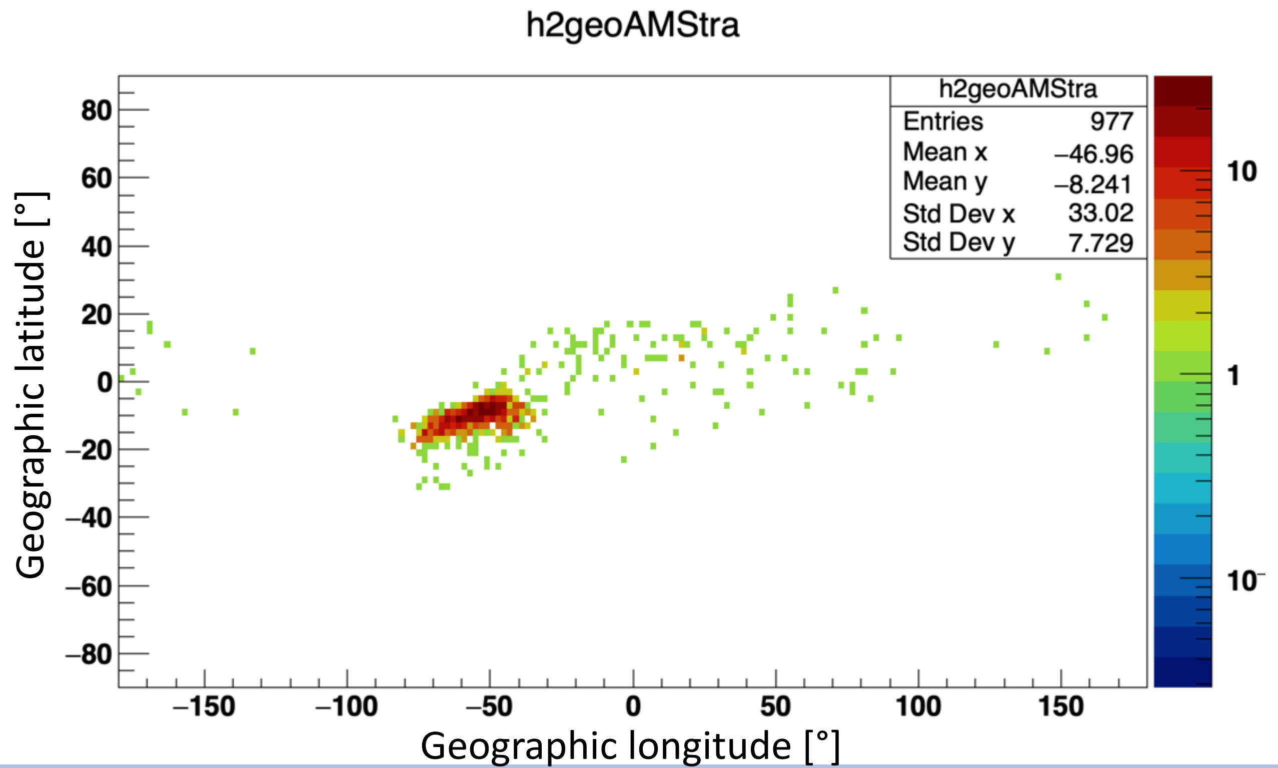


Detection positions

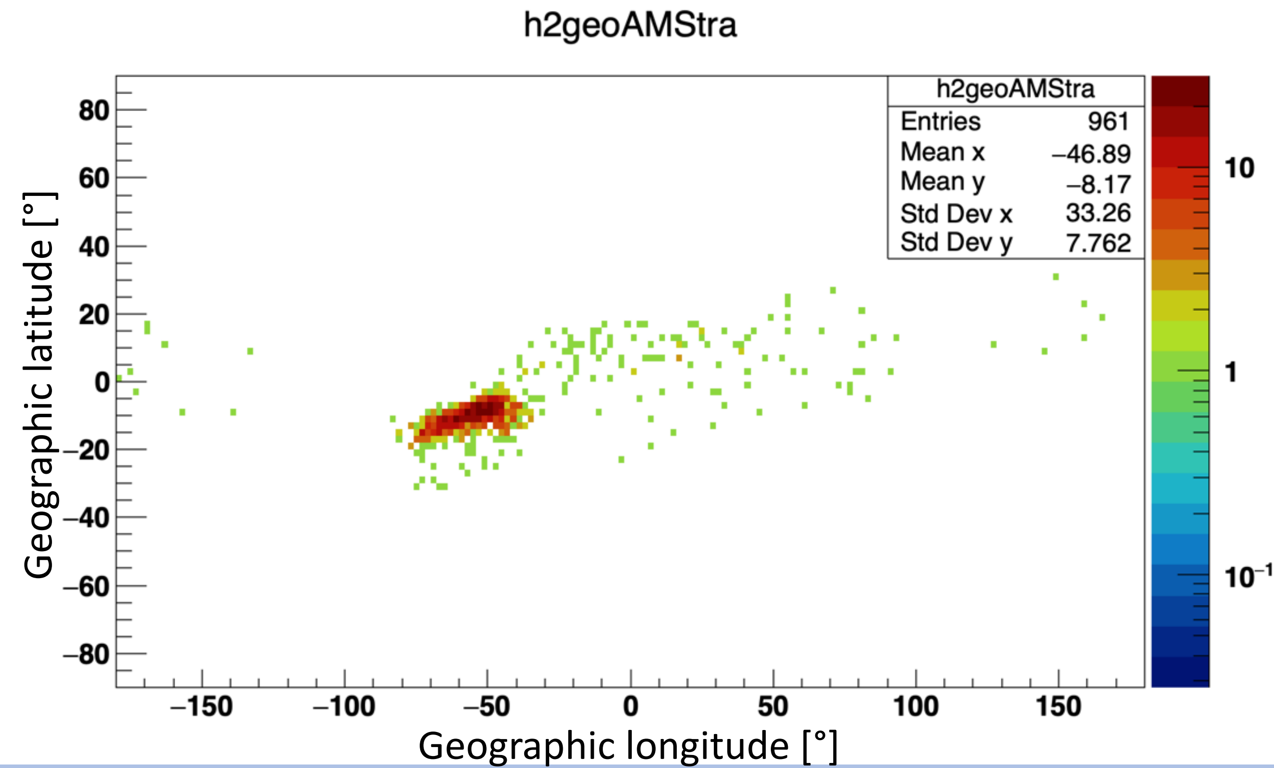
up-going trapped

80% limit acceptance (generate 10 pseudo particles each detected one)

IGRF



TS05



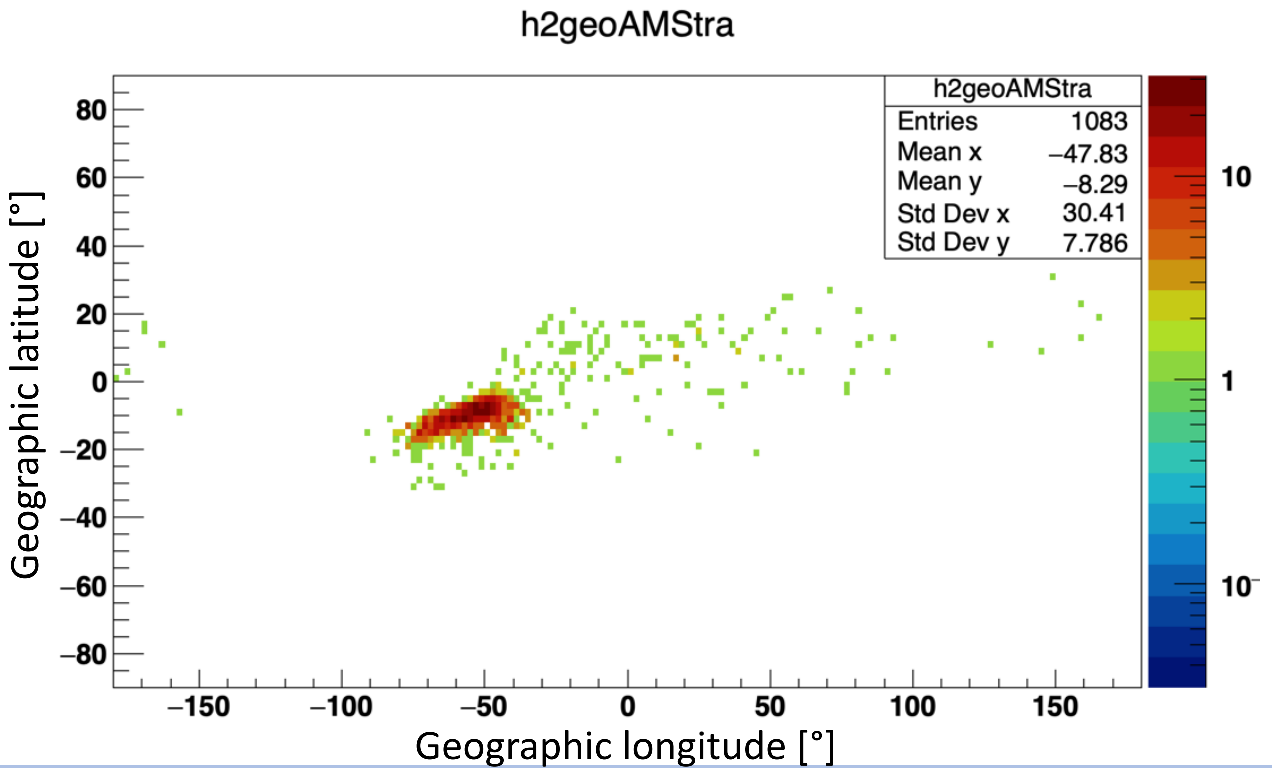
80% of the generated particles are trapped = 966

80% of the generated particles are trapped = 950

Detection positions

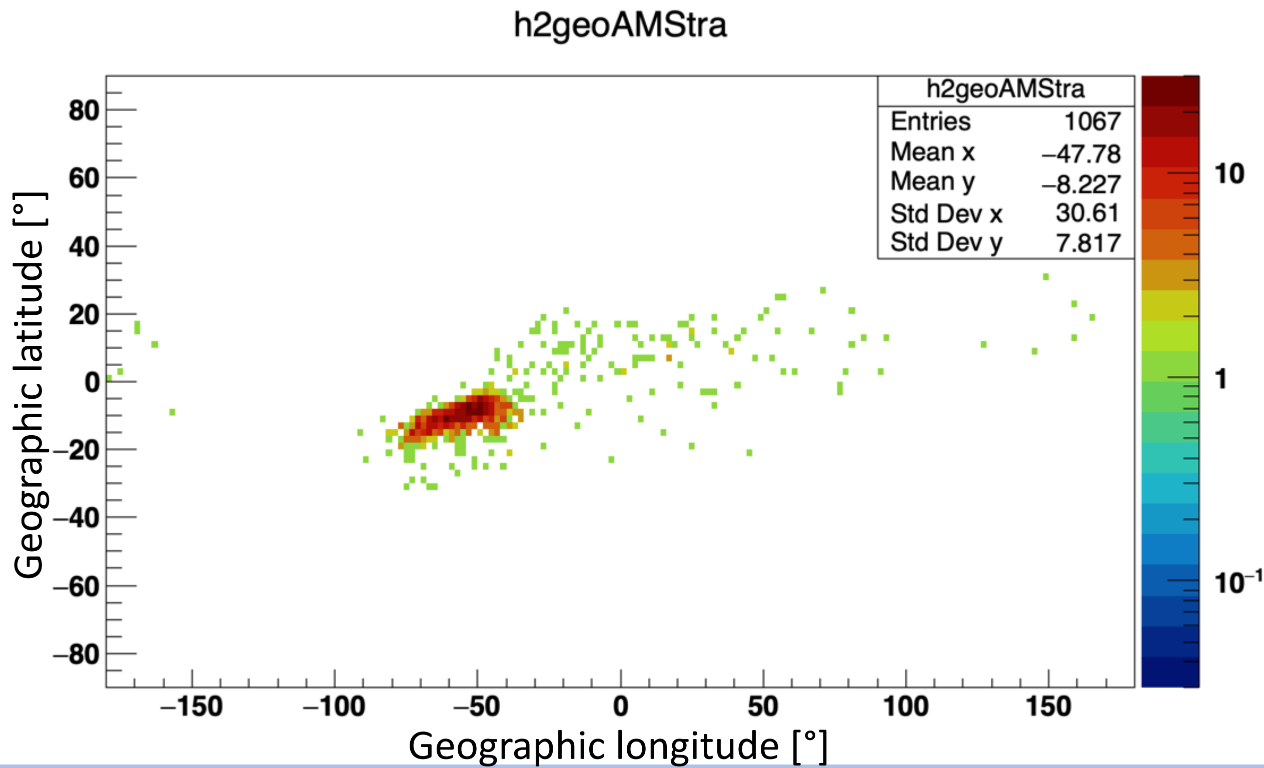
up3-going trapped

IGRF



80% of the generated particles are trapped = 1074

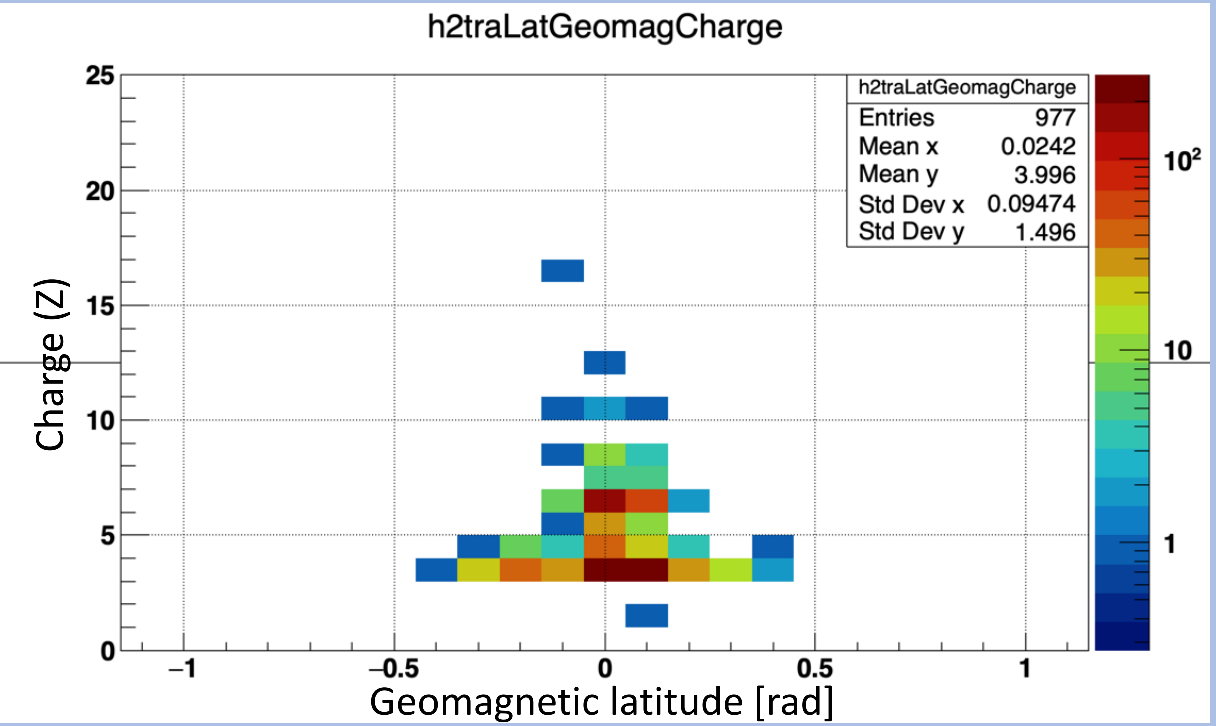
TS05

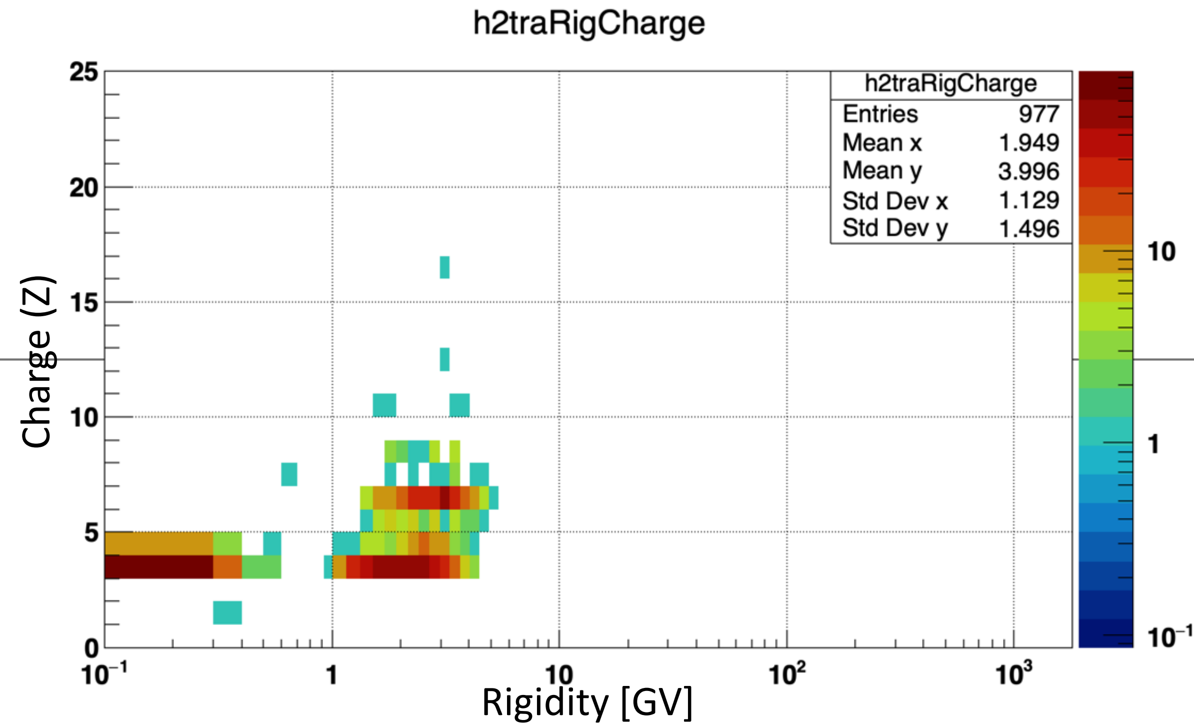


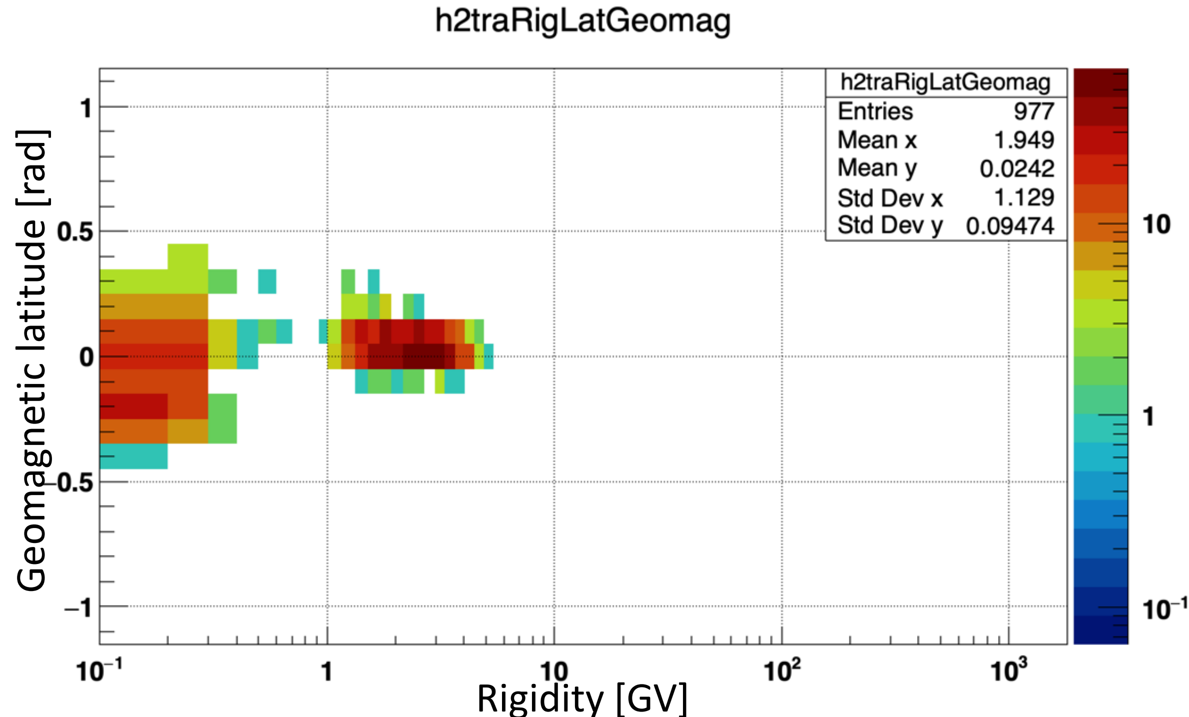
80% of the generated particles are trapped = 1058

Detection positions

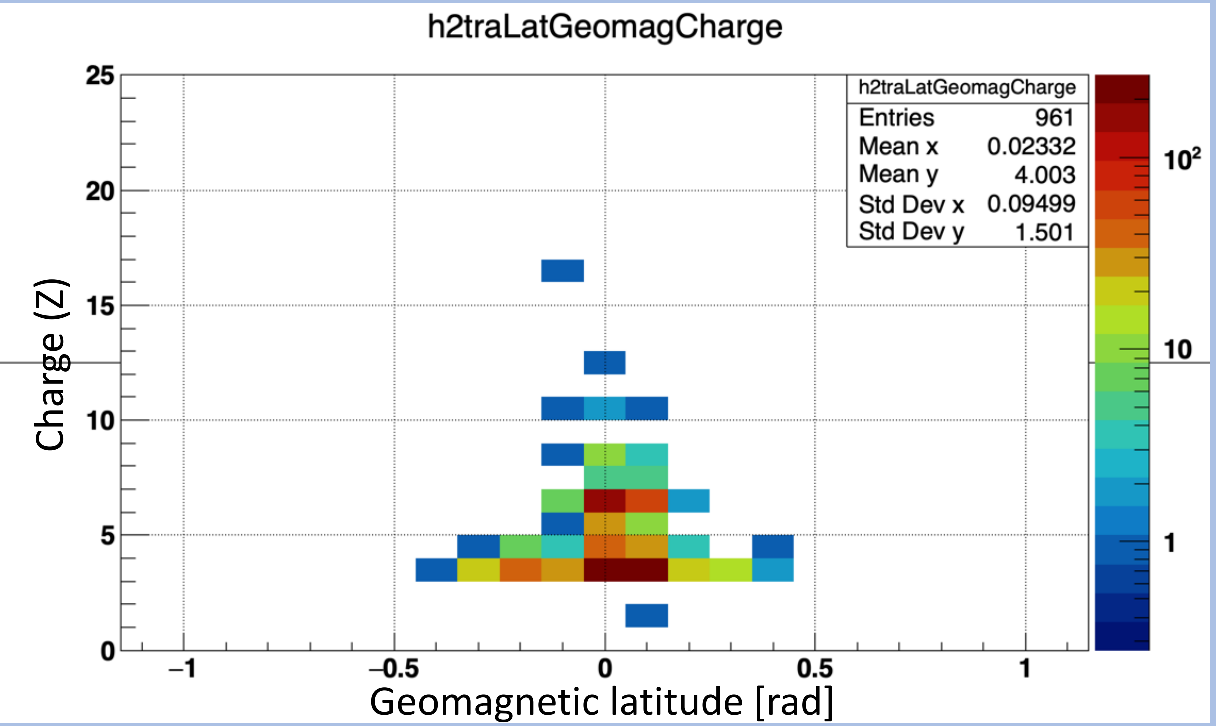
up-going trapped IGRF

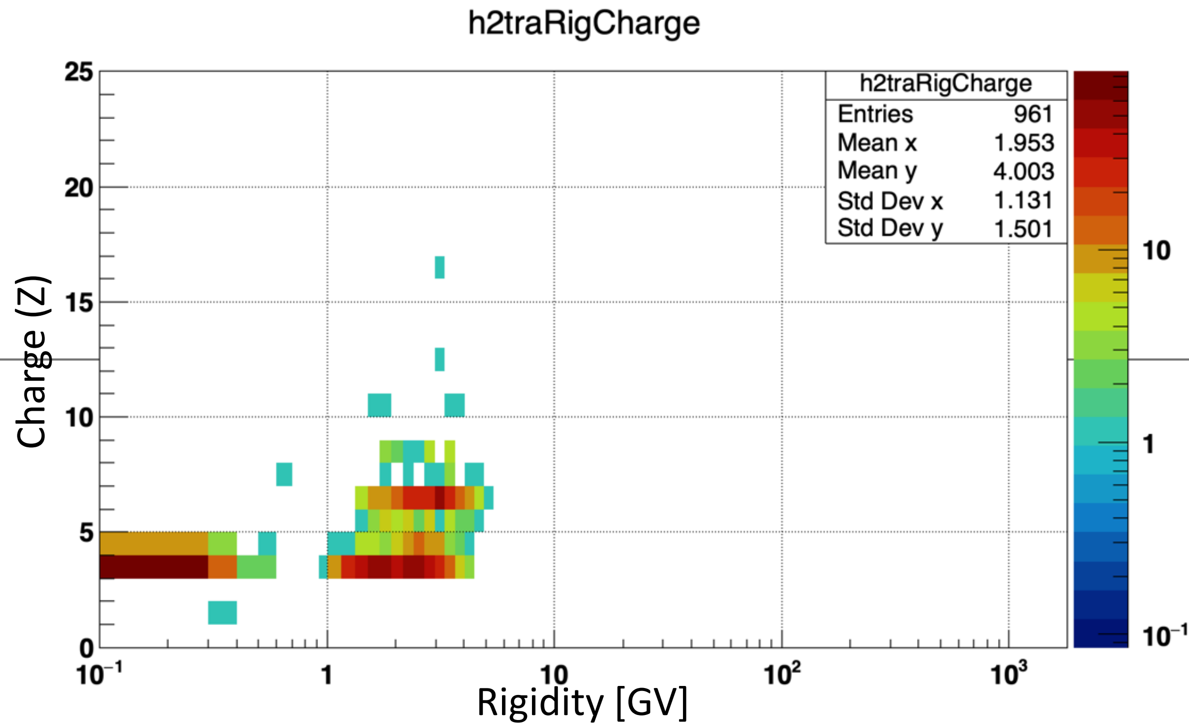


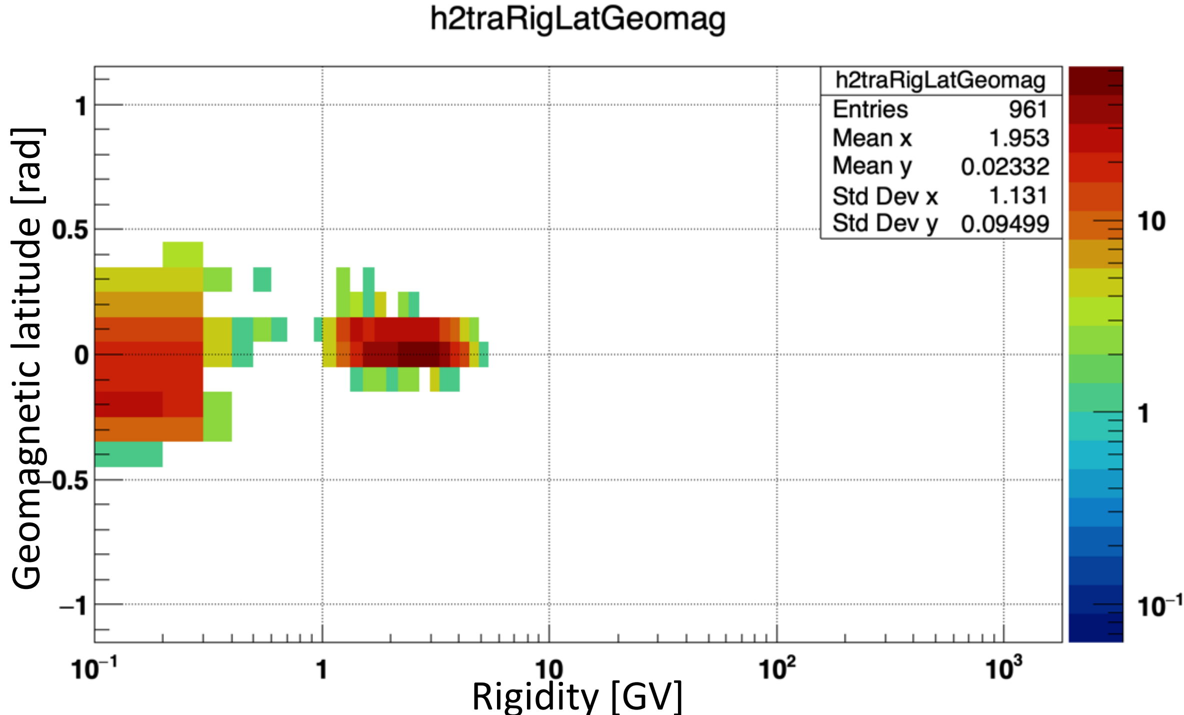




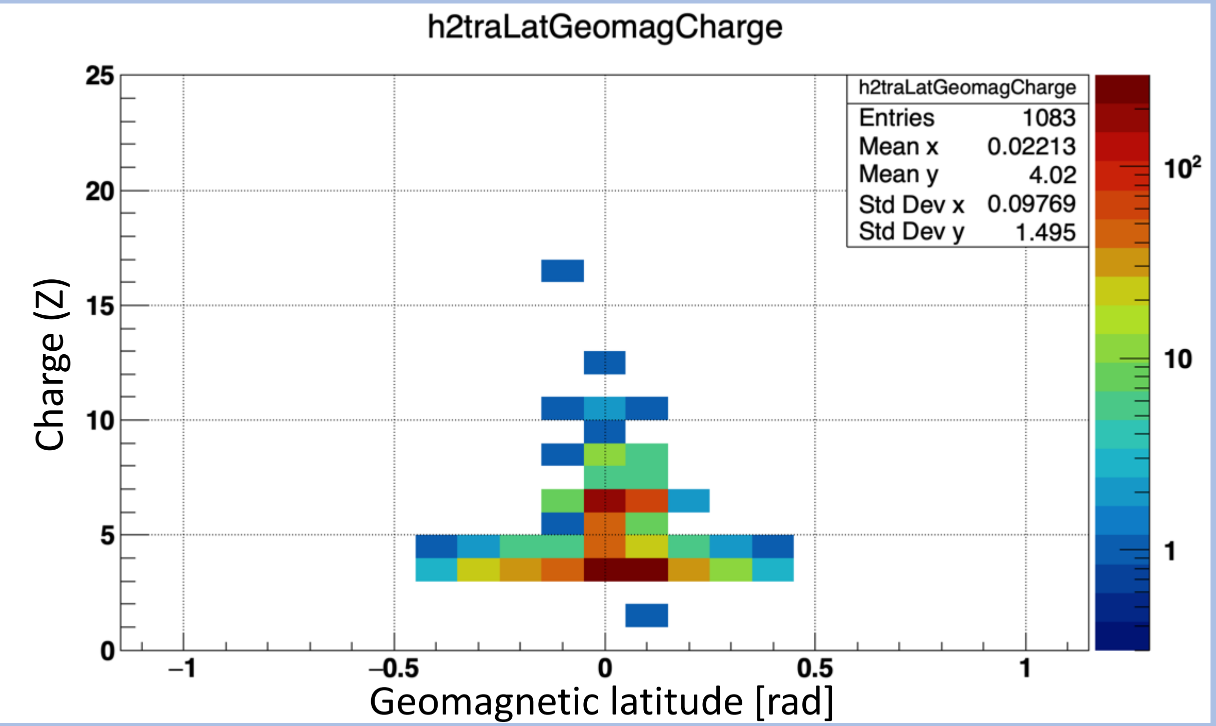
up-going trapped TS05

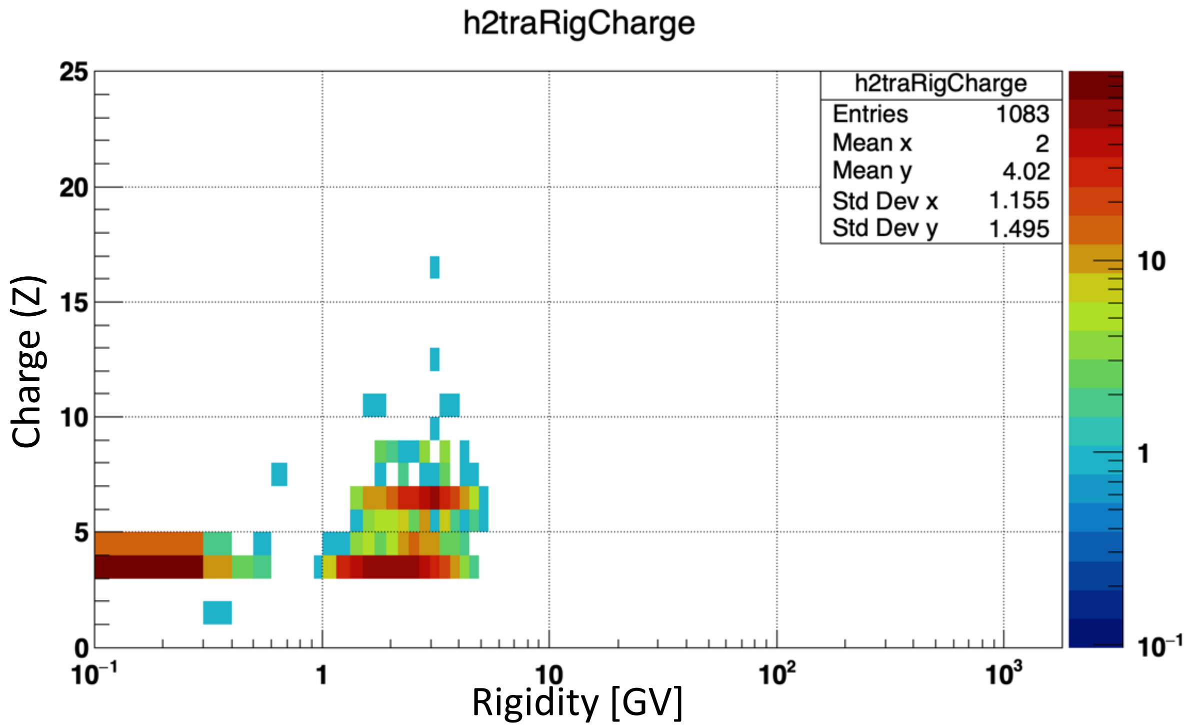


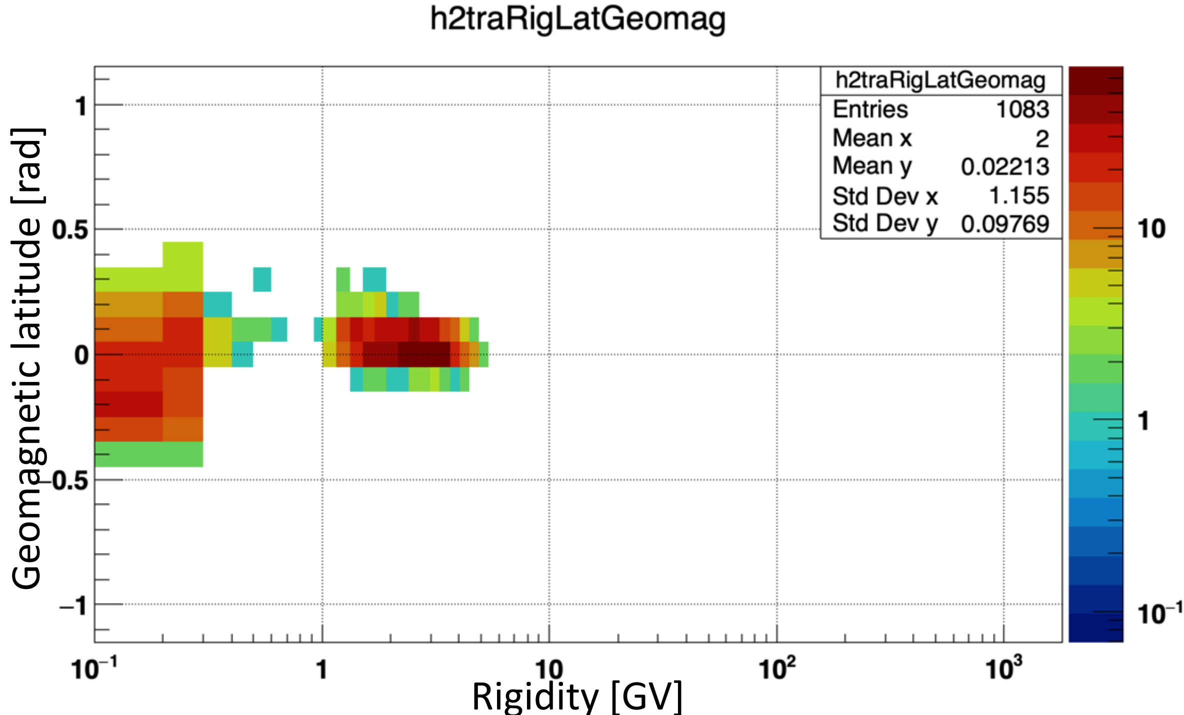




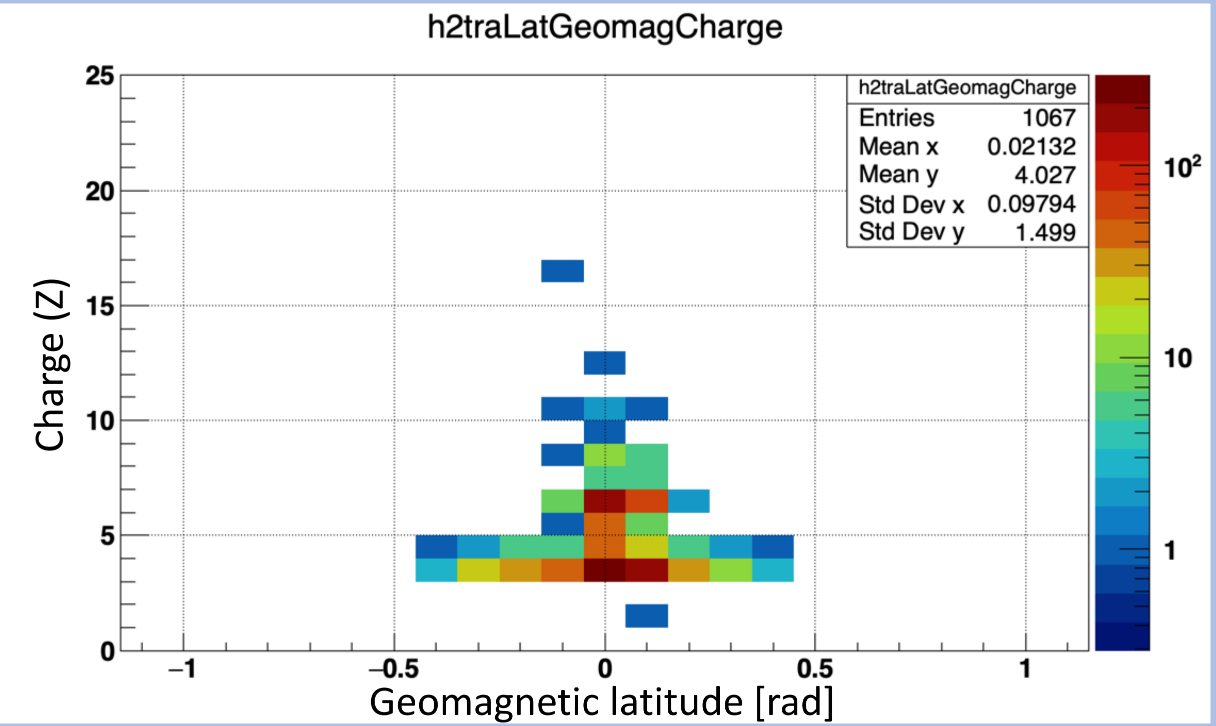
up3-going trapped IGRF

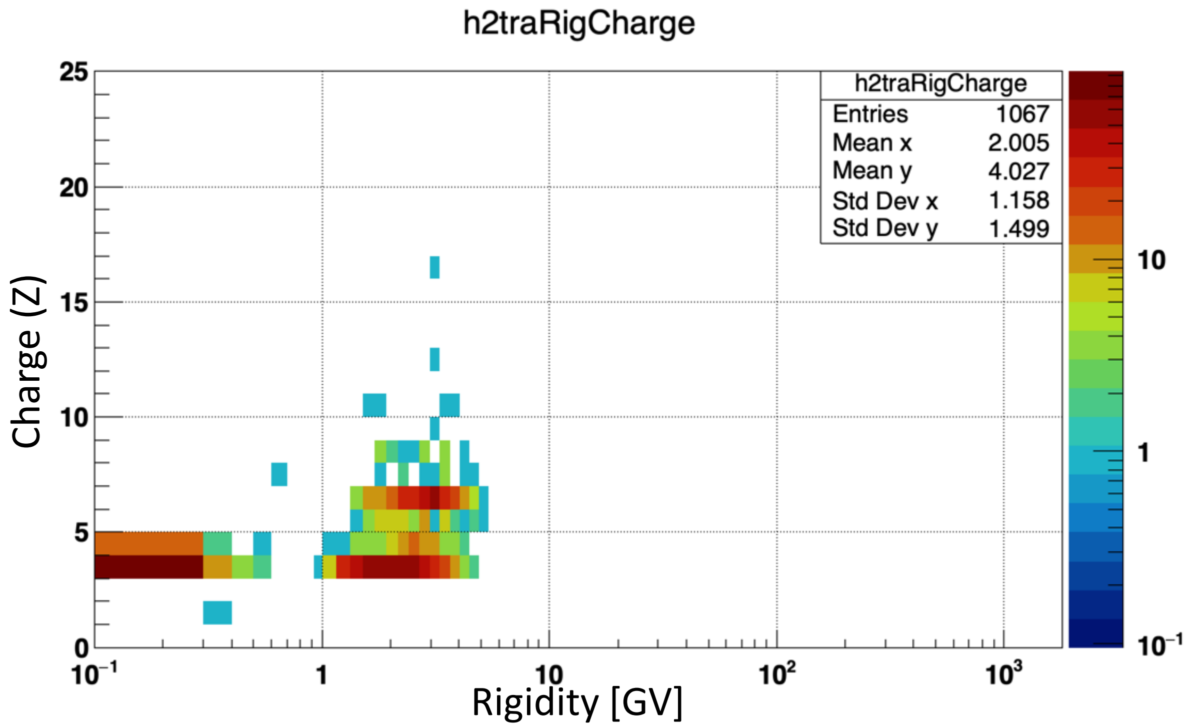


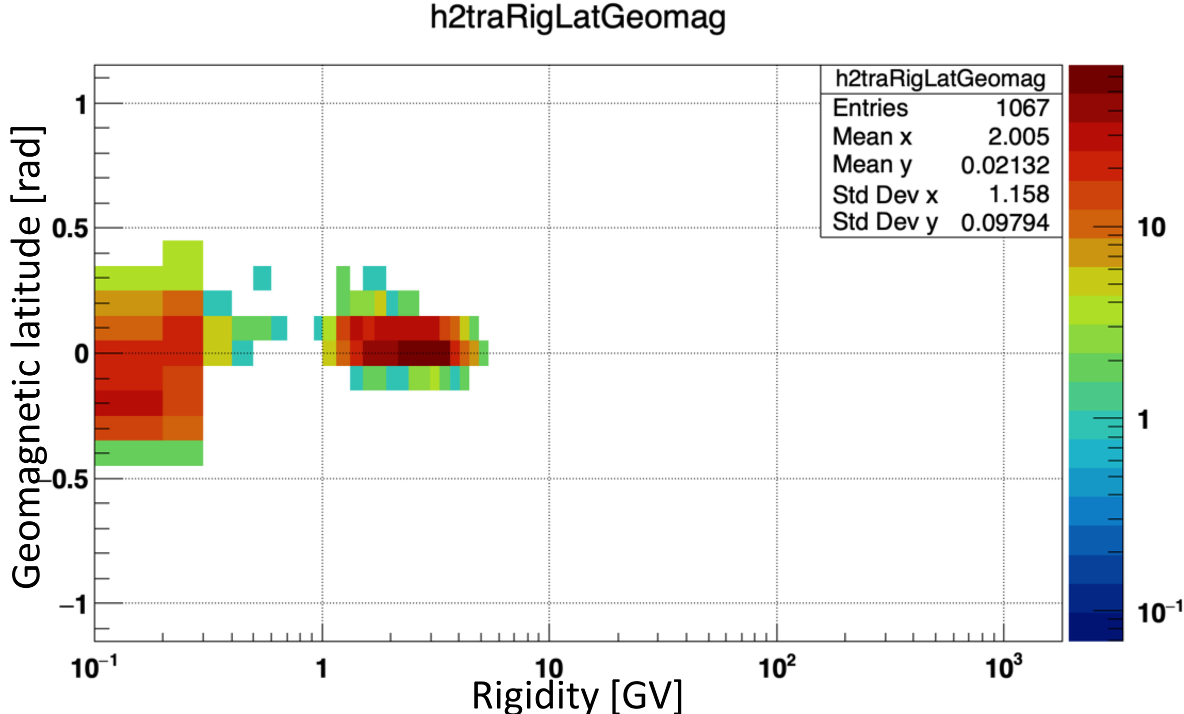




up3-going trapped TS05

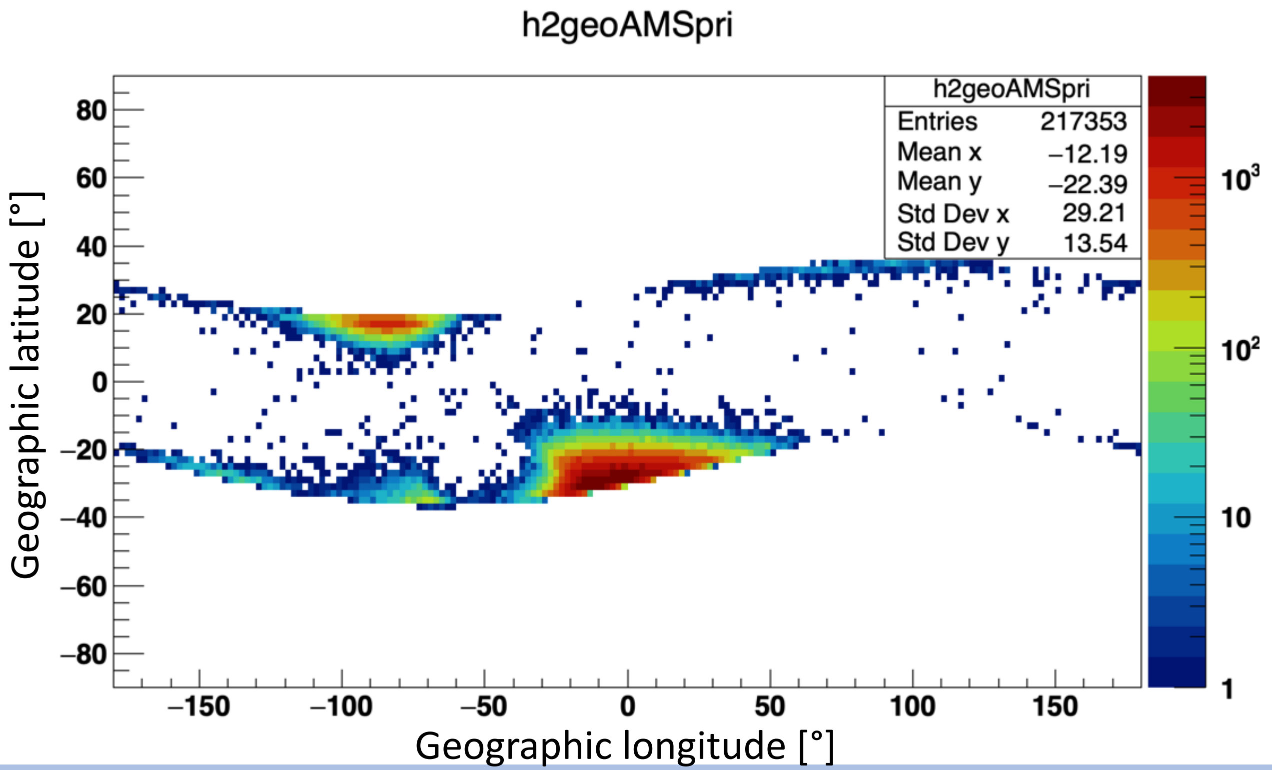




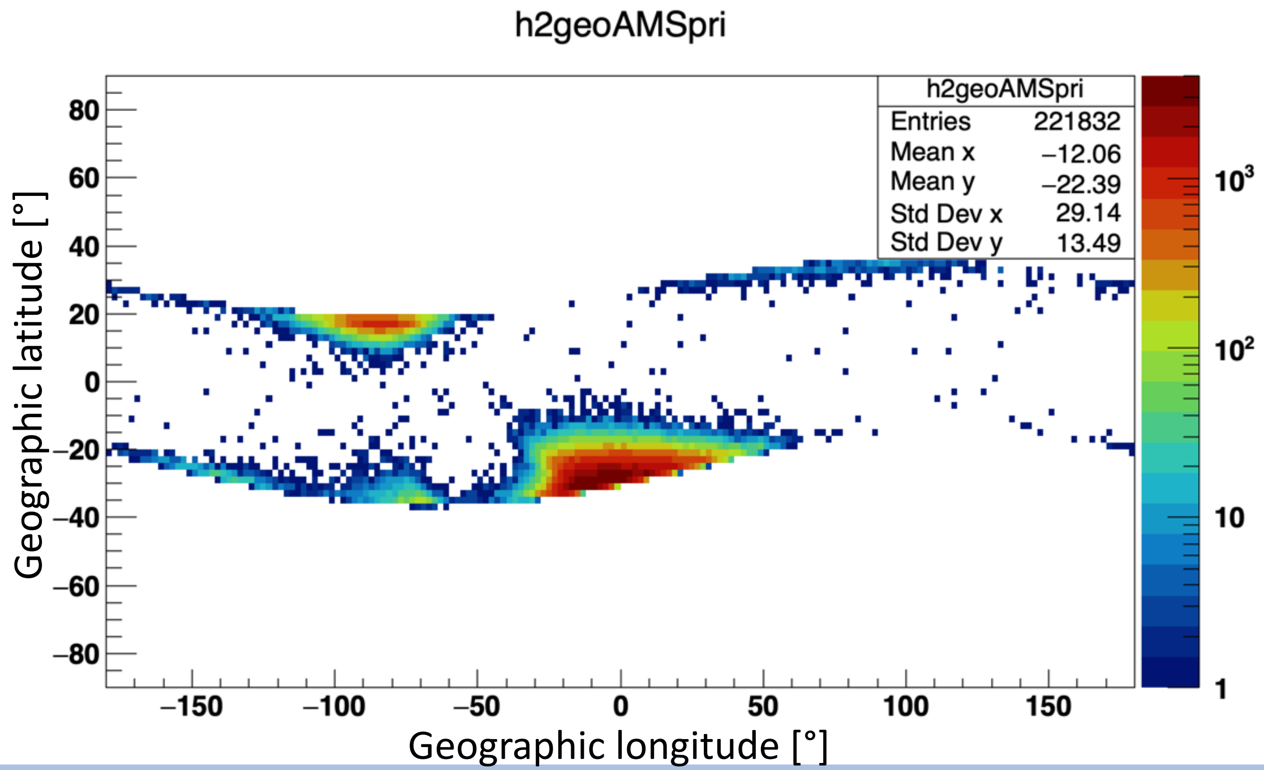


down-going primaries

IGRF



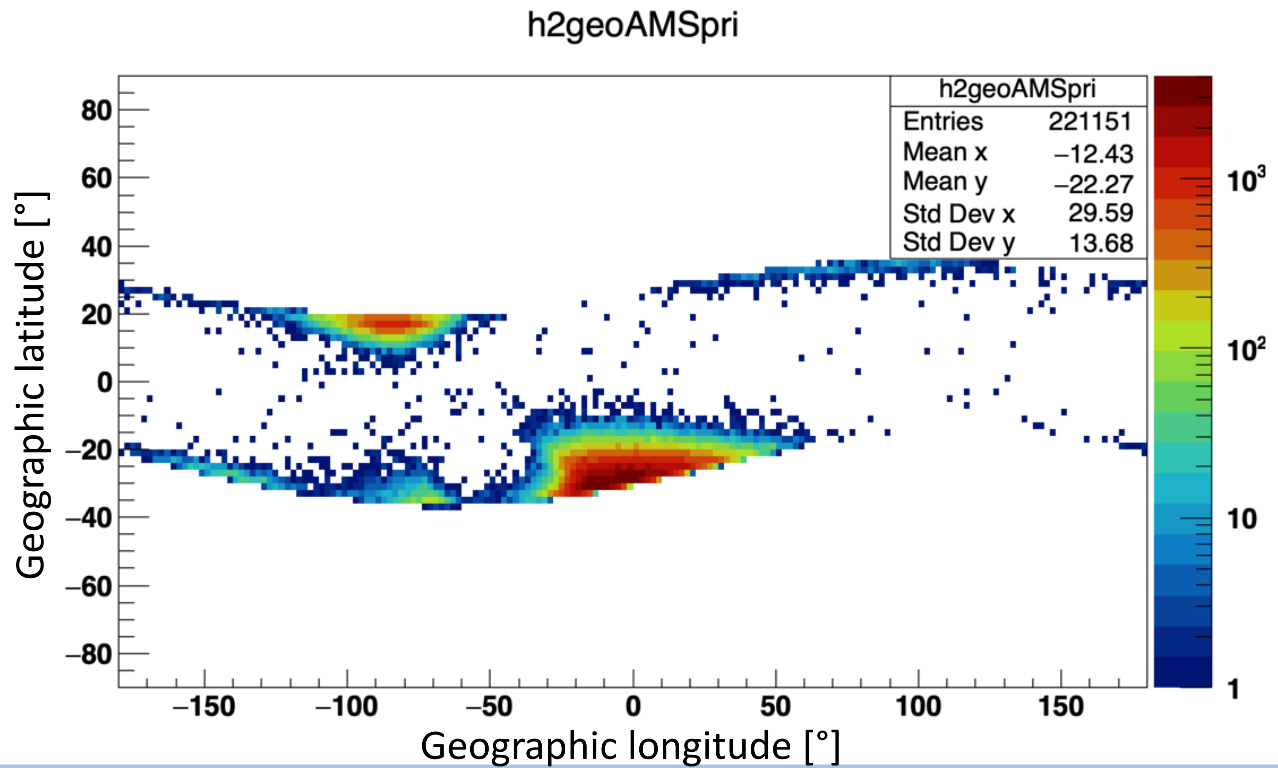
TS05



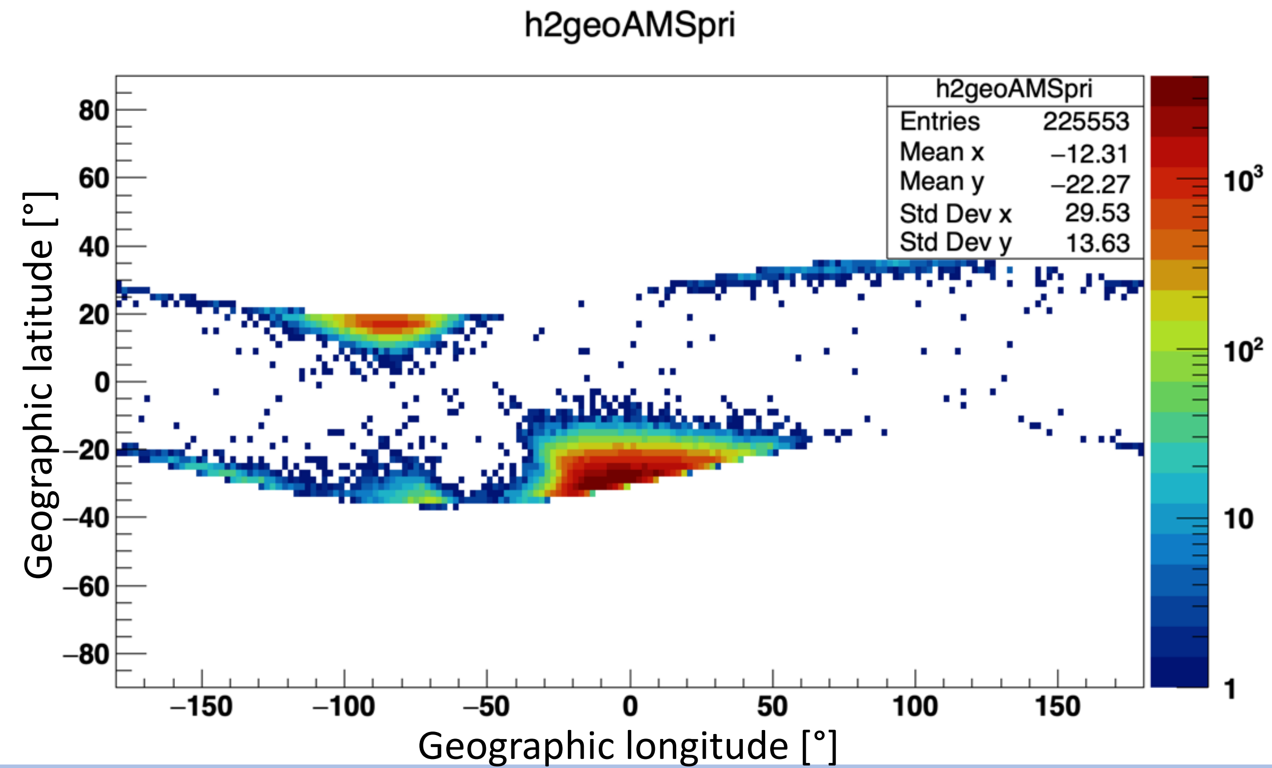
Detection positions

down3-going primaries

IGRF



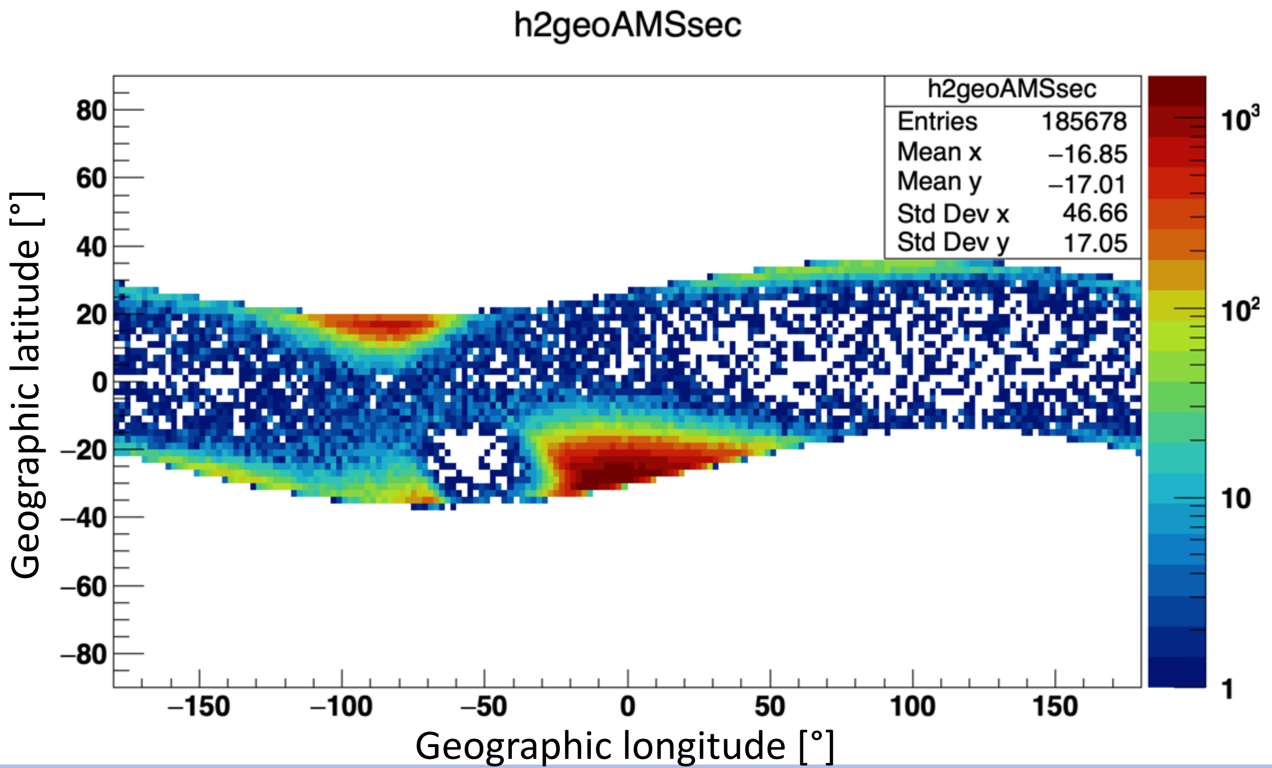
TS05



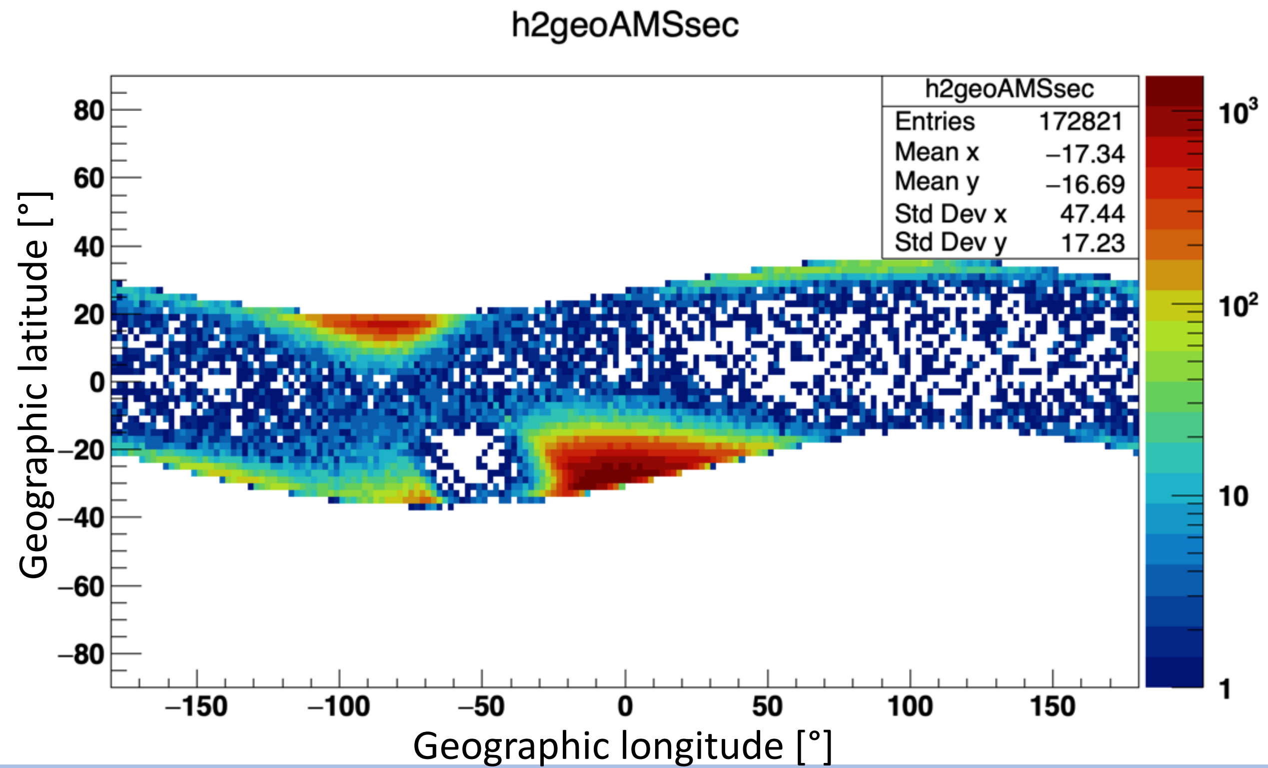
Detection positions

down-going secondaries

IGRF



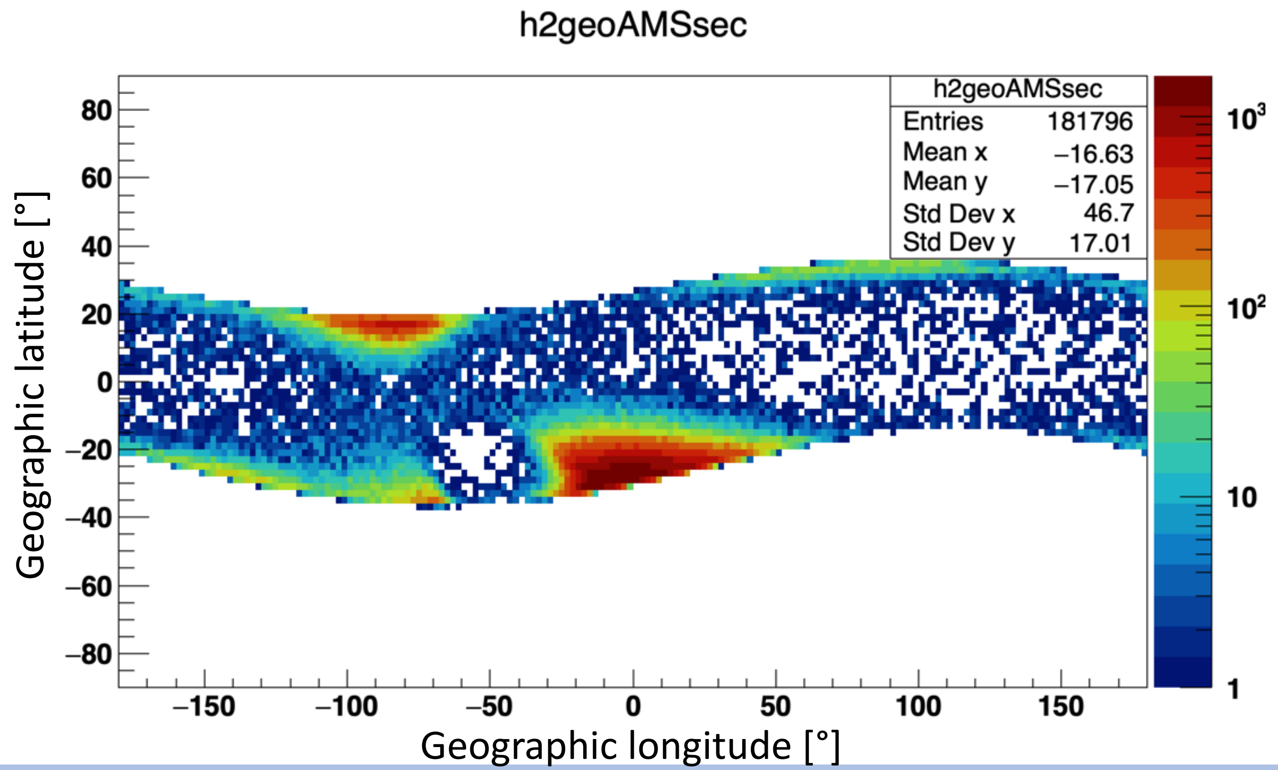
TS05



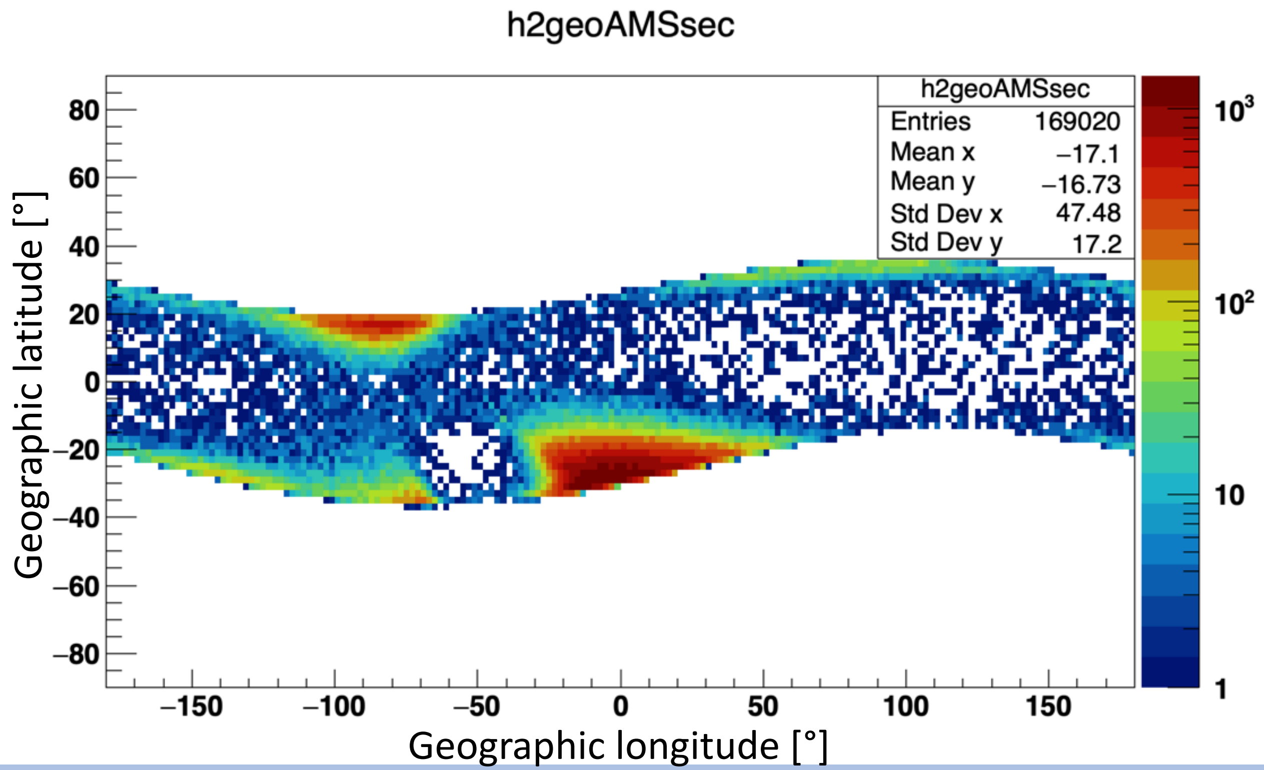
Detection positions

down3-going secondaries

IGRF



TS05

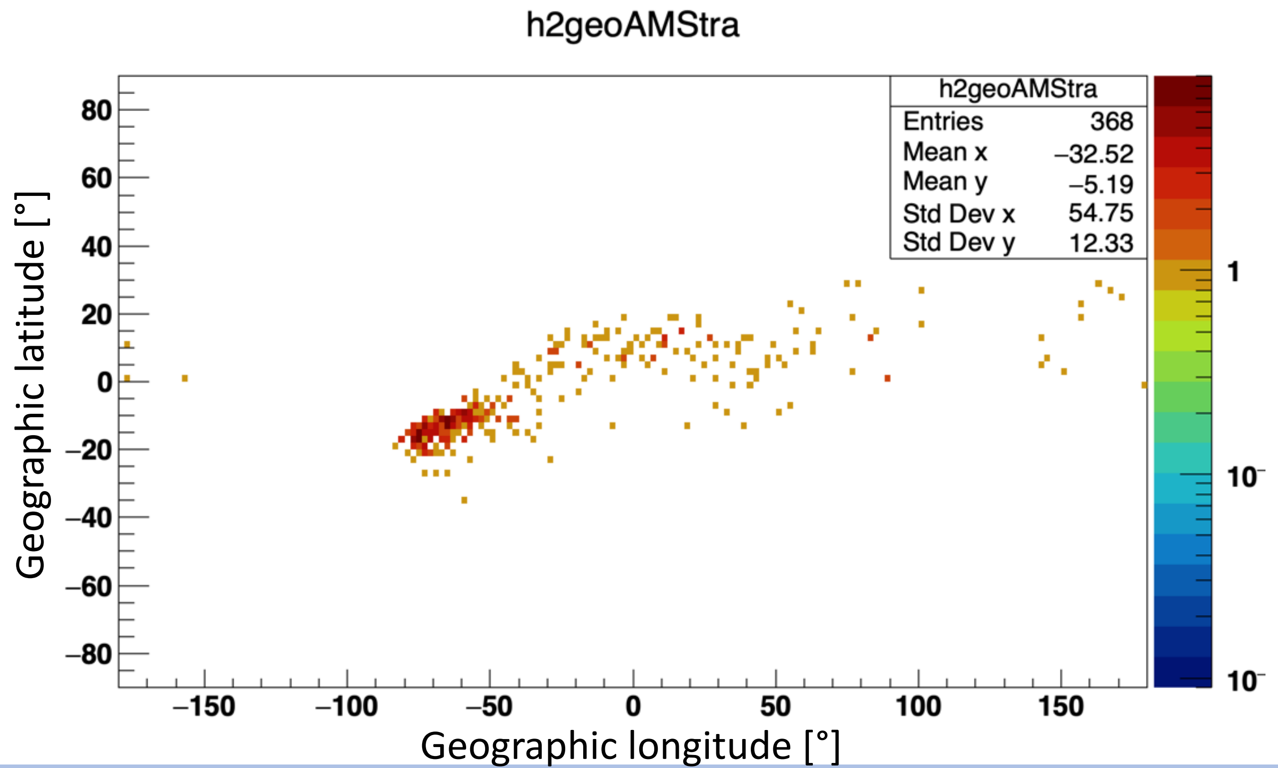


Detection positions

down-going trapped

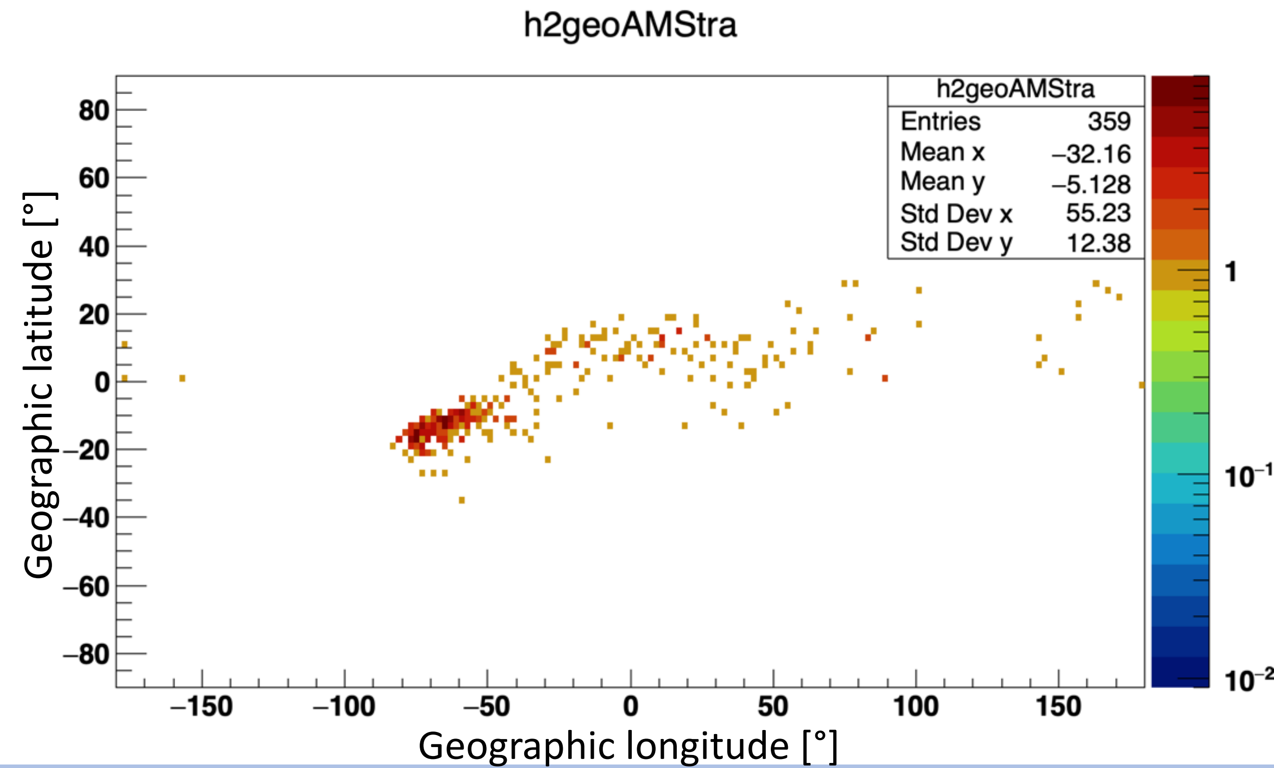
80% limit acceptance (generate 10 pseudo particles each detected one)

IGRF



80% of the generated particles are trapped = 361

TS05

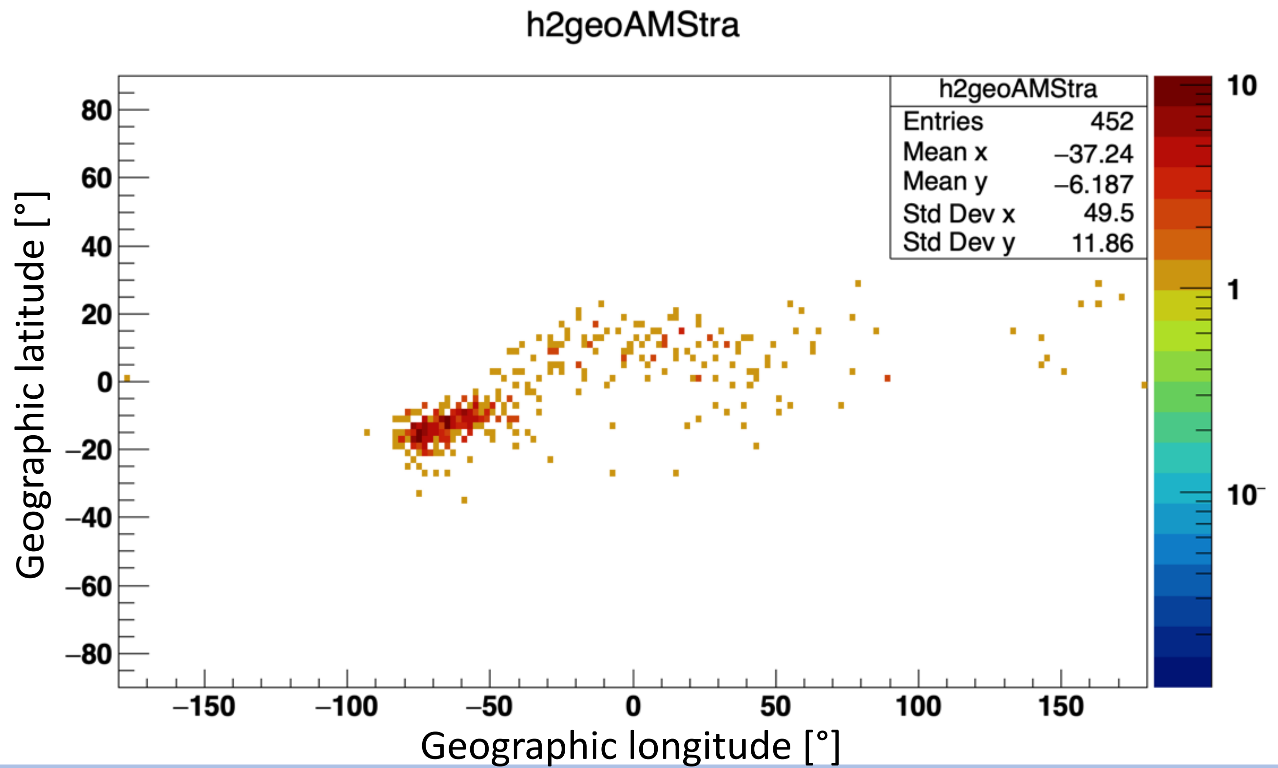


80% of the generated particles are trapped = 352

Detection positions

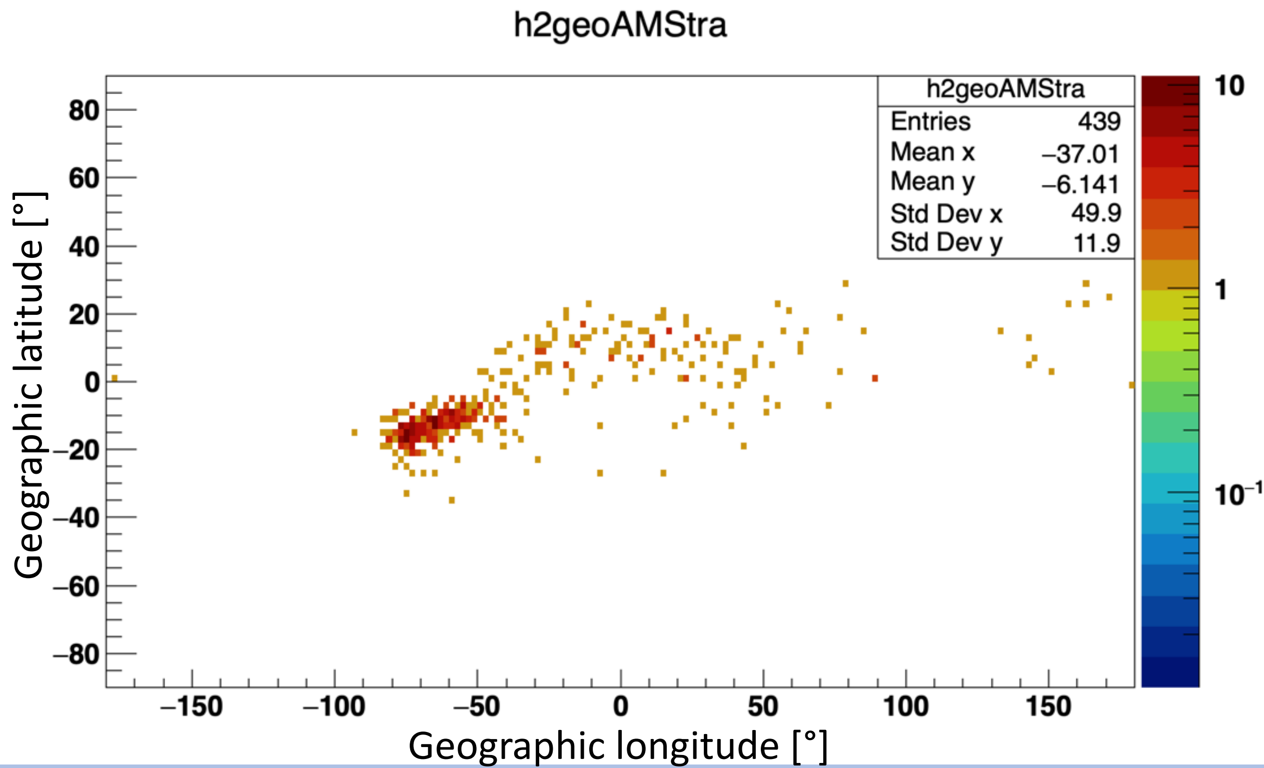
down3-going trapped

IGRF



80% of the generated particles are trapped = 450

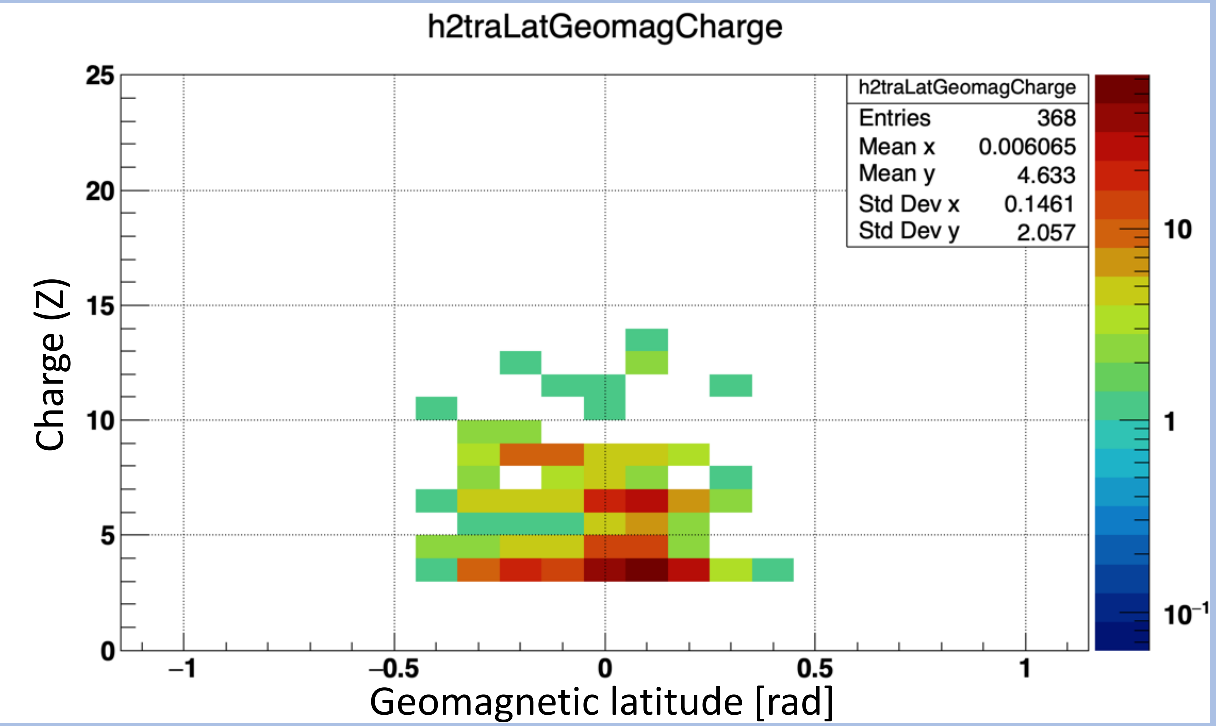
TS05

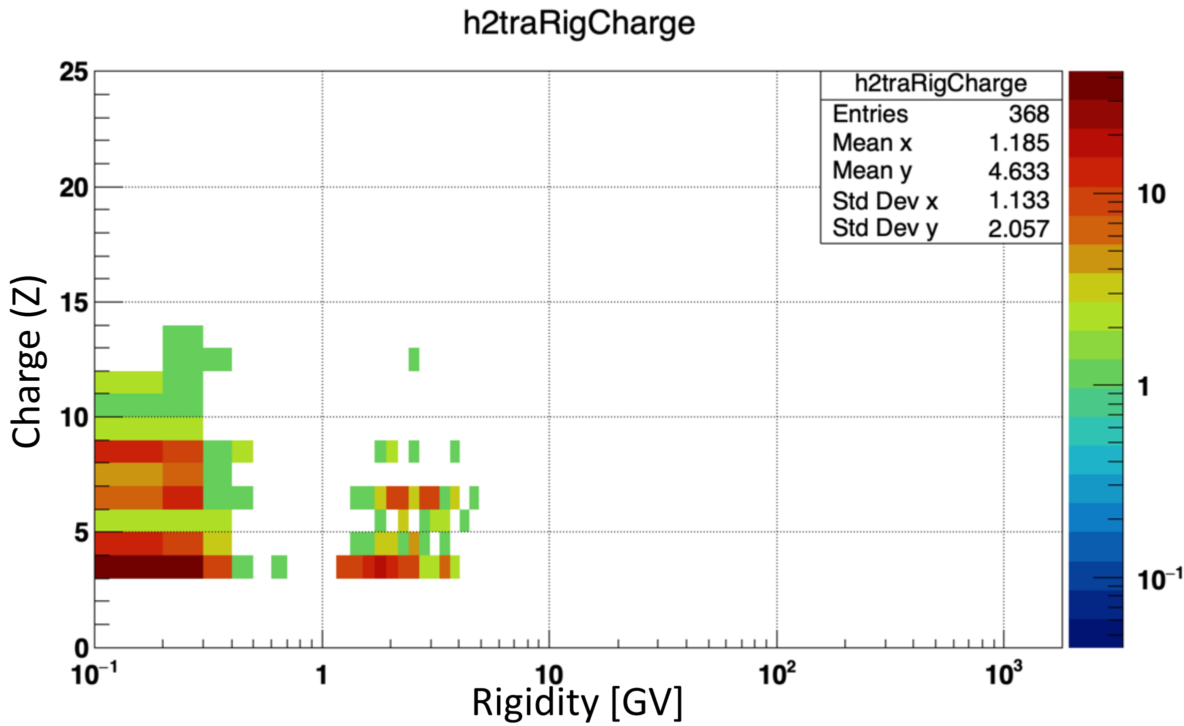


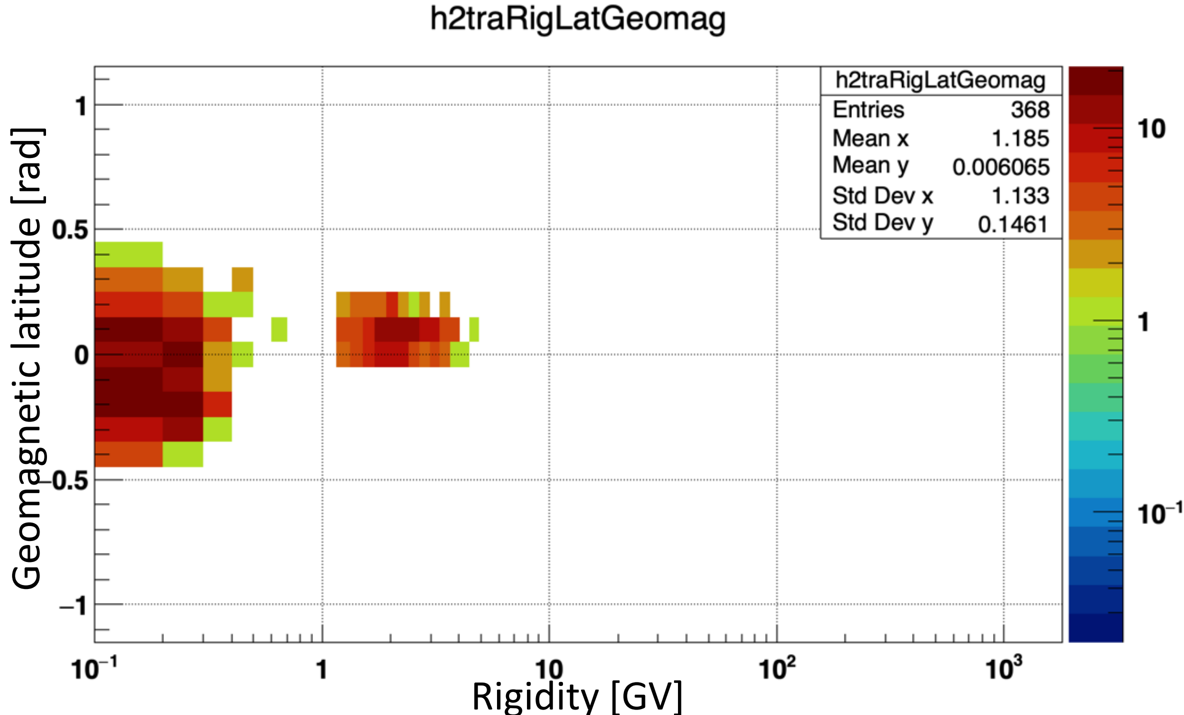
80% of the generated particles are trapped = 437

Detection positions

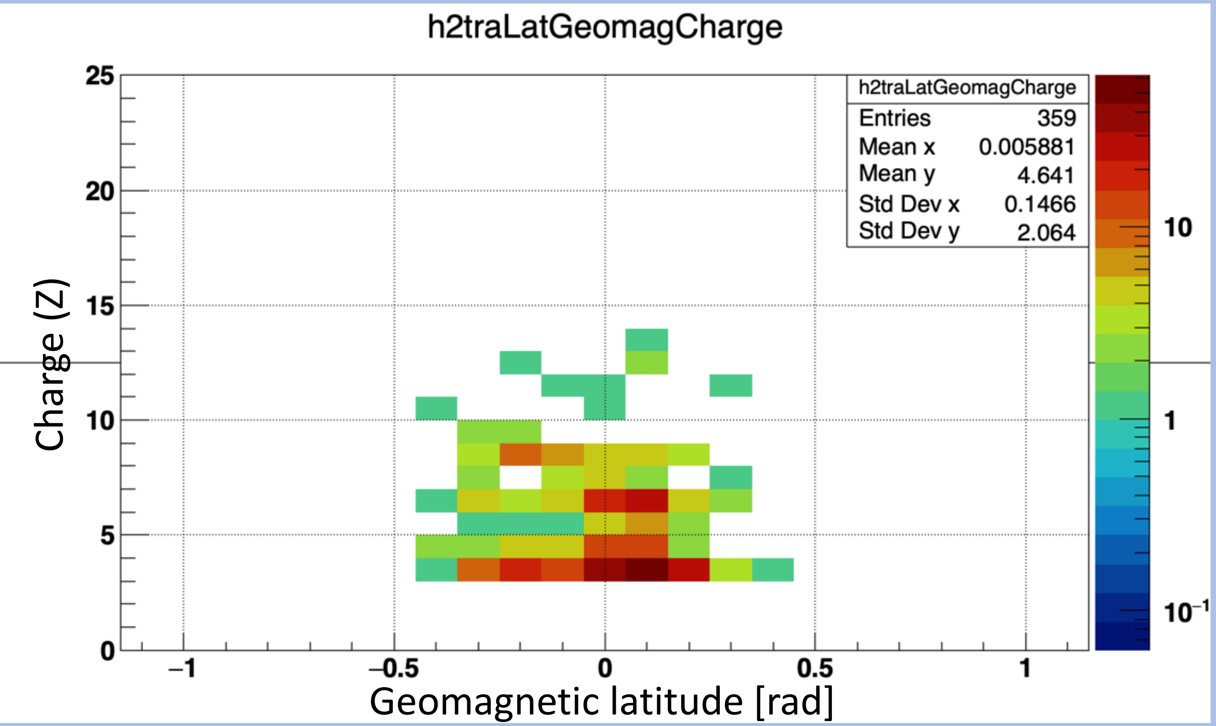
down-going trapped IGRF

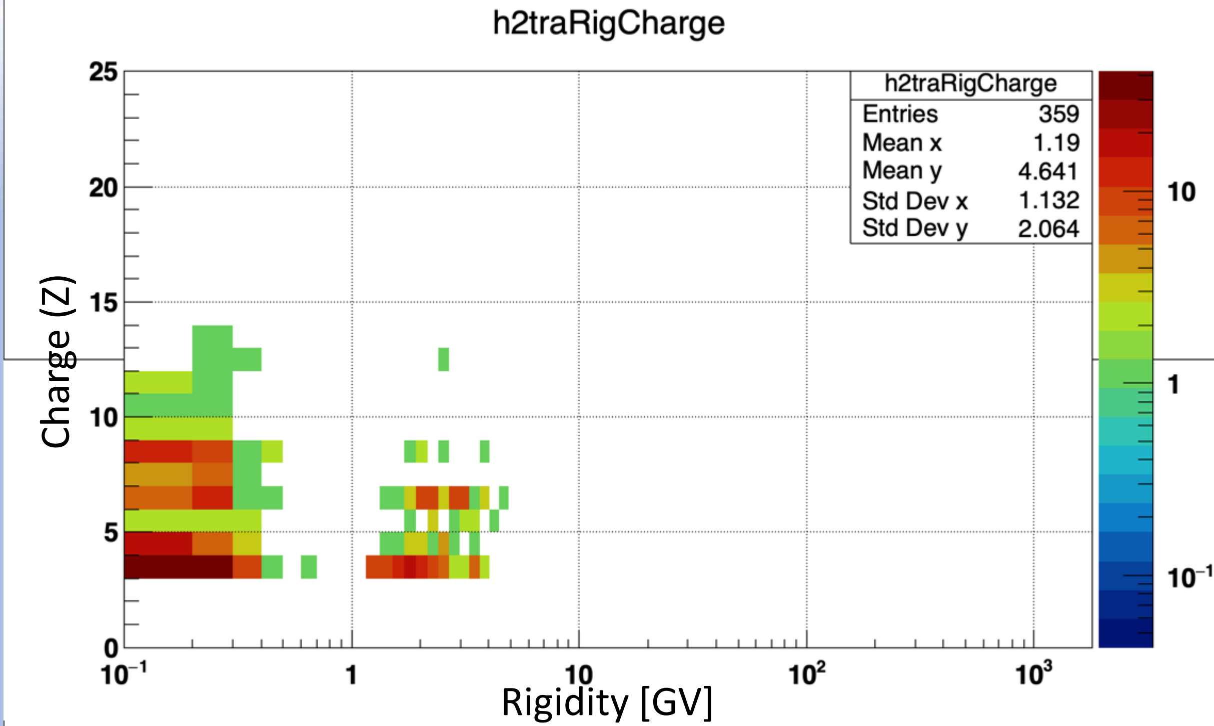


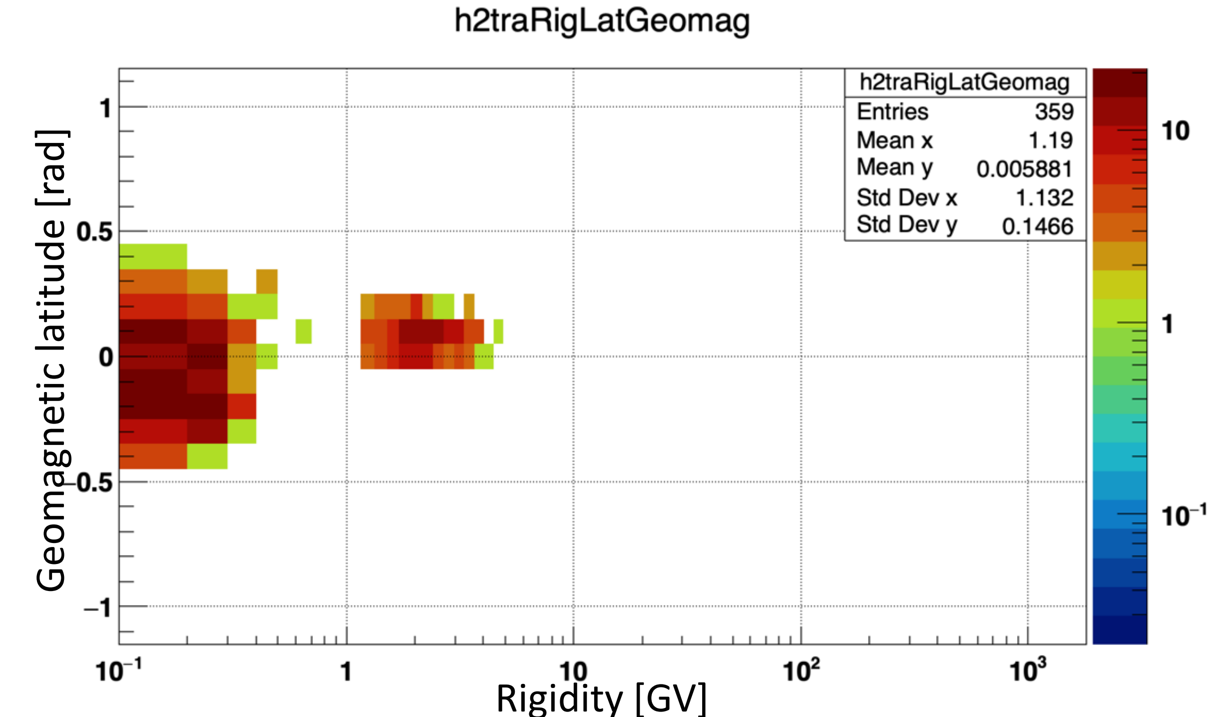




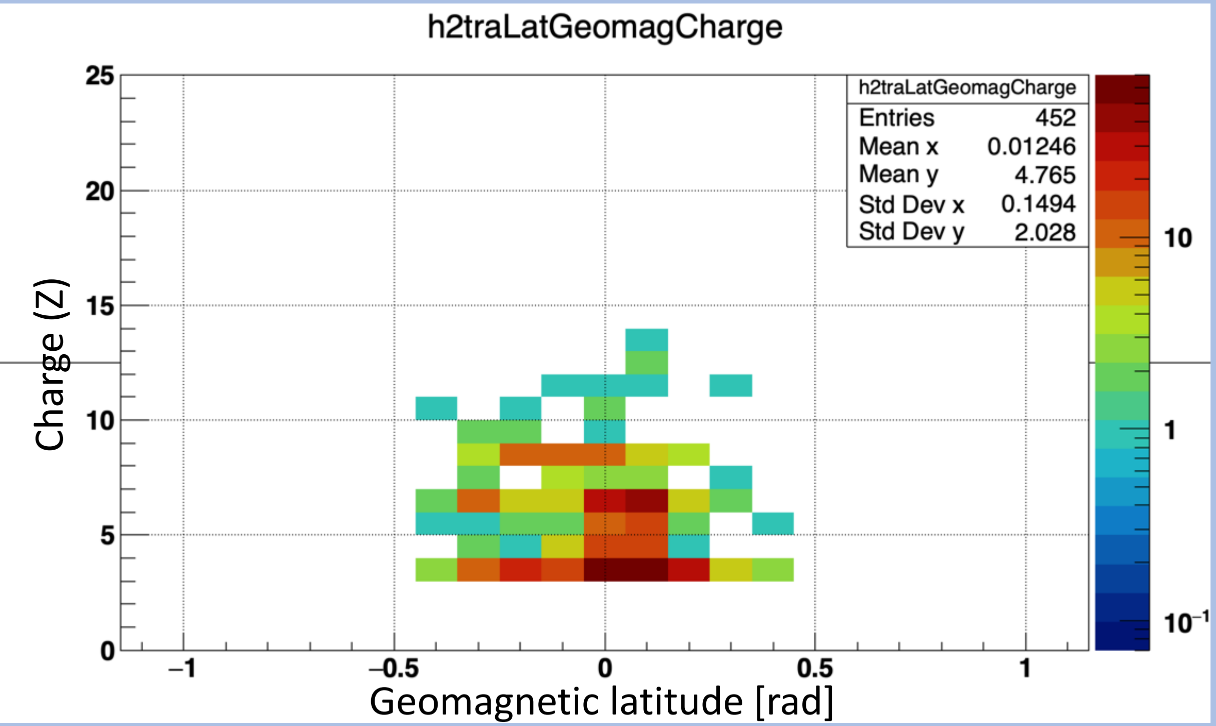
down-going trapped TS05

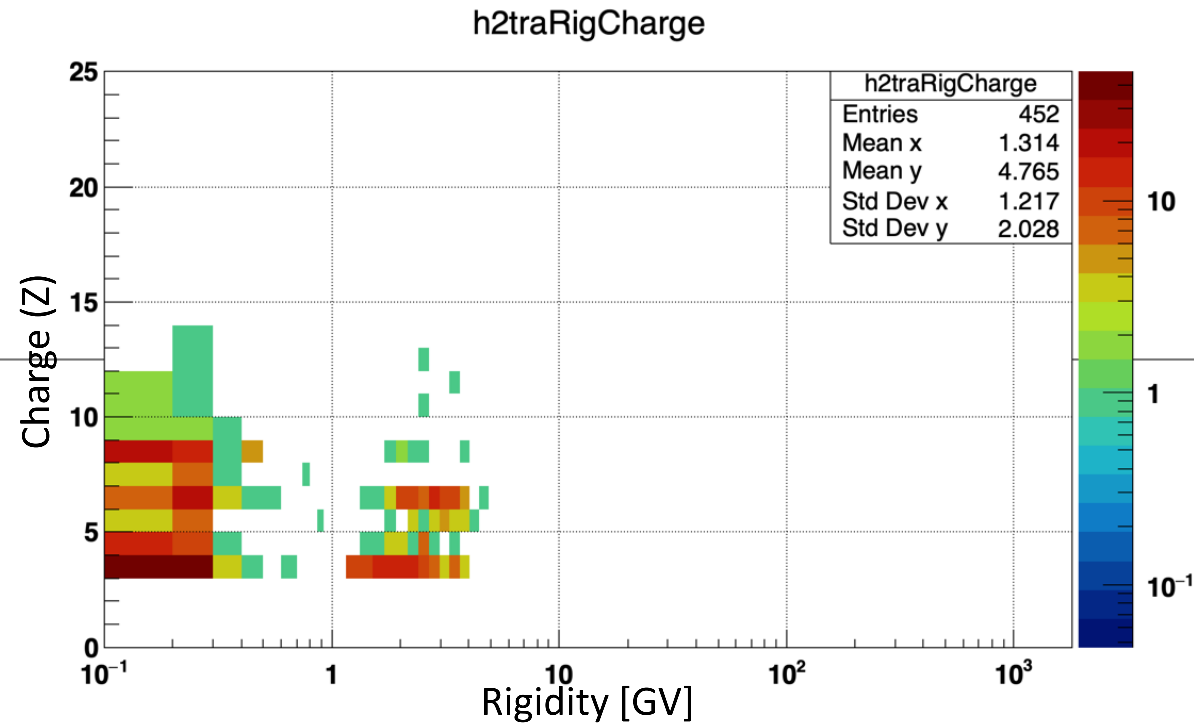


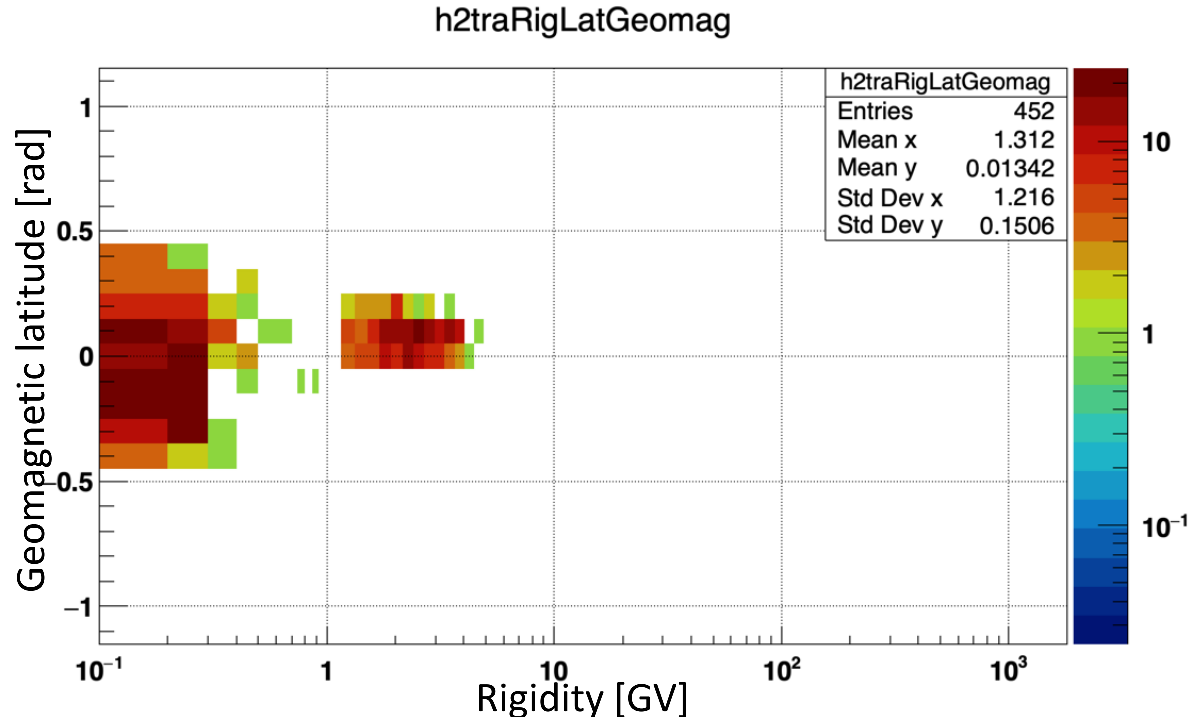




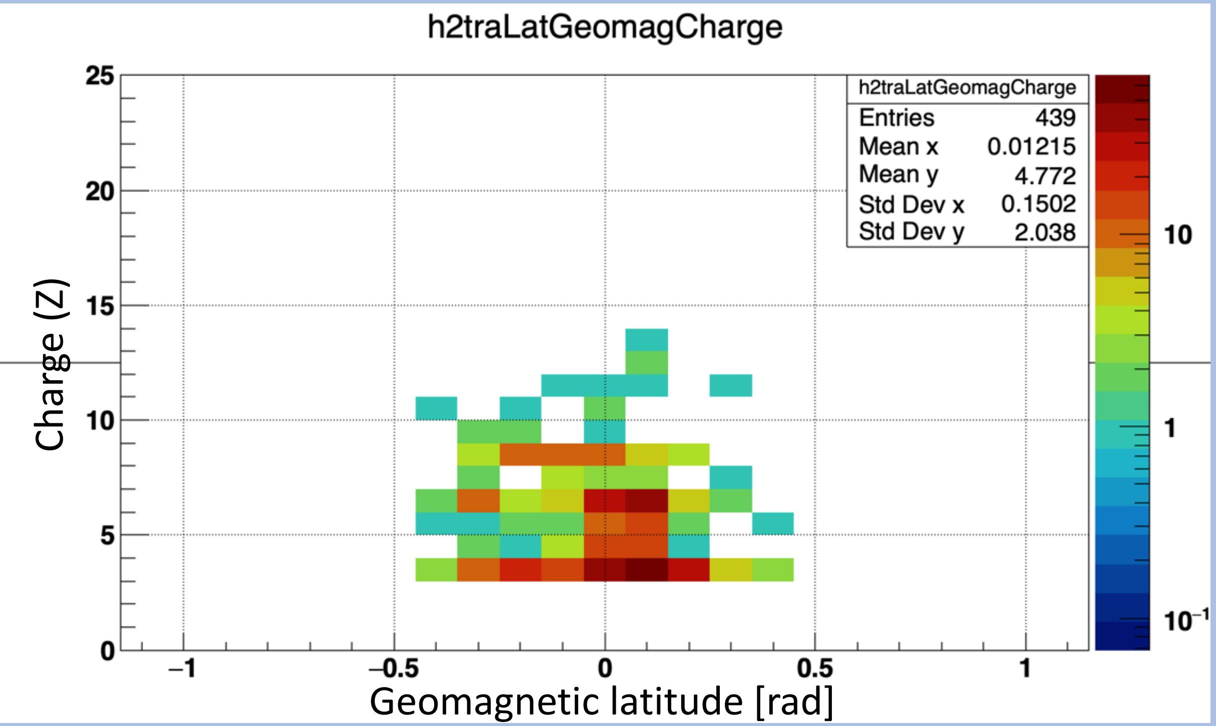
down3-going trapped IGRF

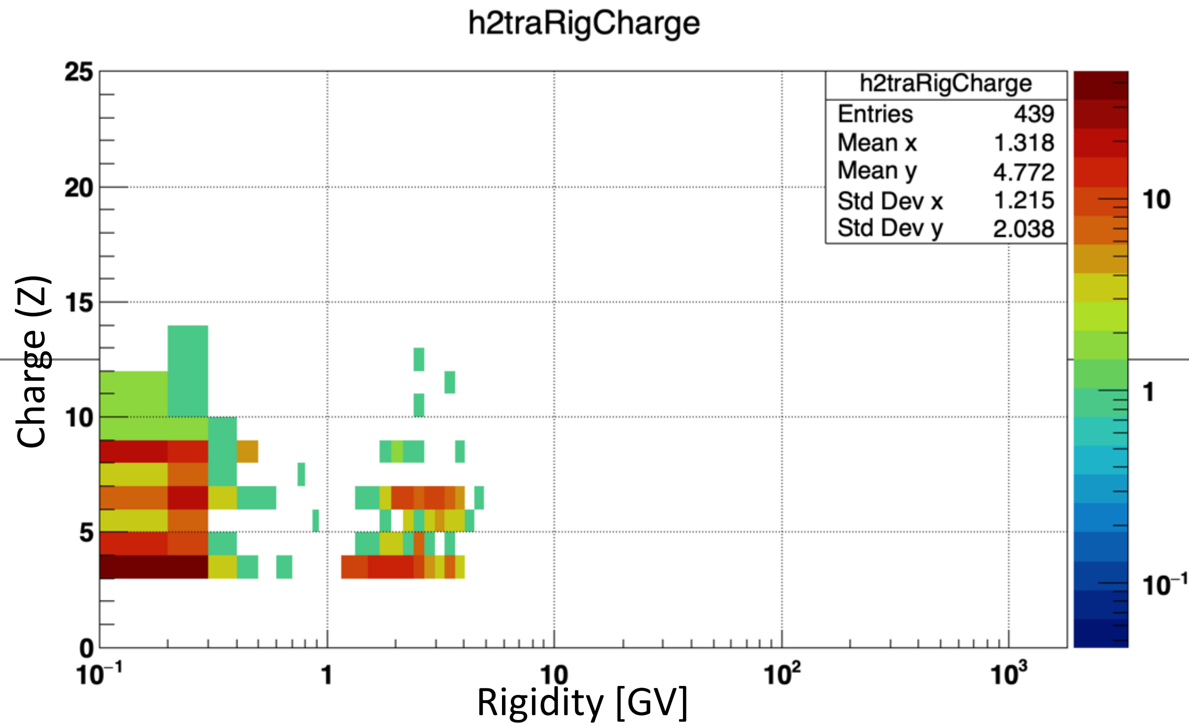


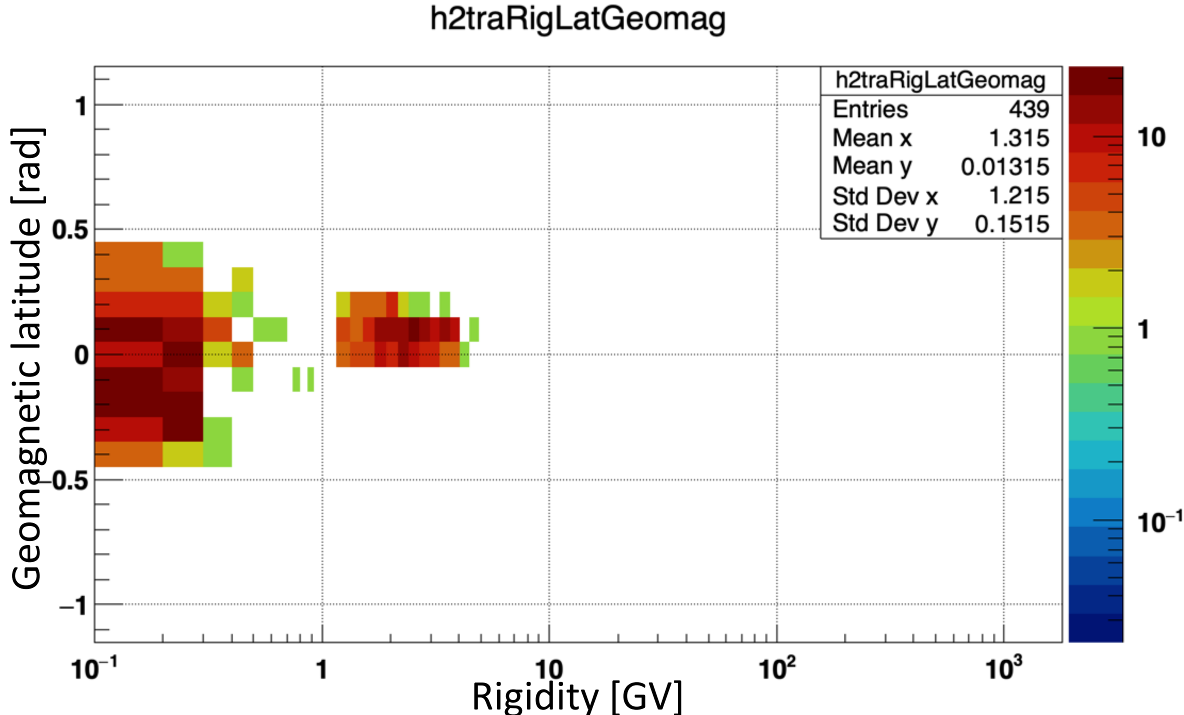




down3-going trapped   TS05







Preliminary Conclusions:

- Primary CR with TS05 are higher than IGRF of about 2-3%
- Secondary CR with TS05 are lower than IGRF of about 3-7%
- Trapped CR with TS05 are lower than IGRF of about 1-3%

- Trapped CR are recognised as trapped inside 1% generating other 10 particles with different direction and requiring 80% of them reconstructed as trapped

- We have two different population with R < 1GV and R > 1GV

FUTURE DEVELOPMENTS (?)

- Select Solar Flares periods during all AMS-02 so 11 year mission
- Select protons in NAIA
- Backtracing of protons with Geomagsphere and TS05
- Both inside and outside SAA
- Extract informations about trapped and primary CR
- Trapped – to be checked with IONS (A. Oliva)
- Primary (low energy) – to be checked with Hawaii (C. Consolandi)
- Eventually possible to study the anisotropy during Solar Flares