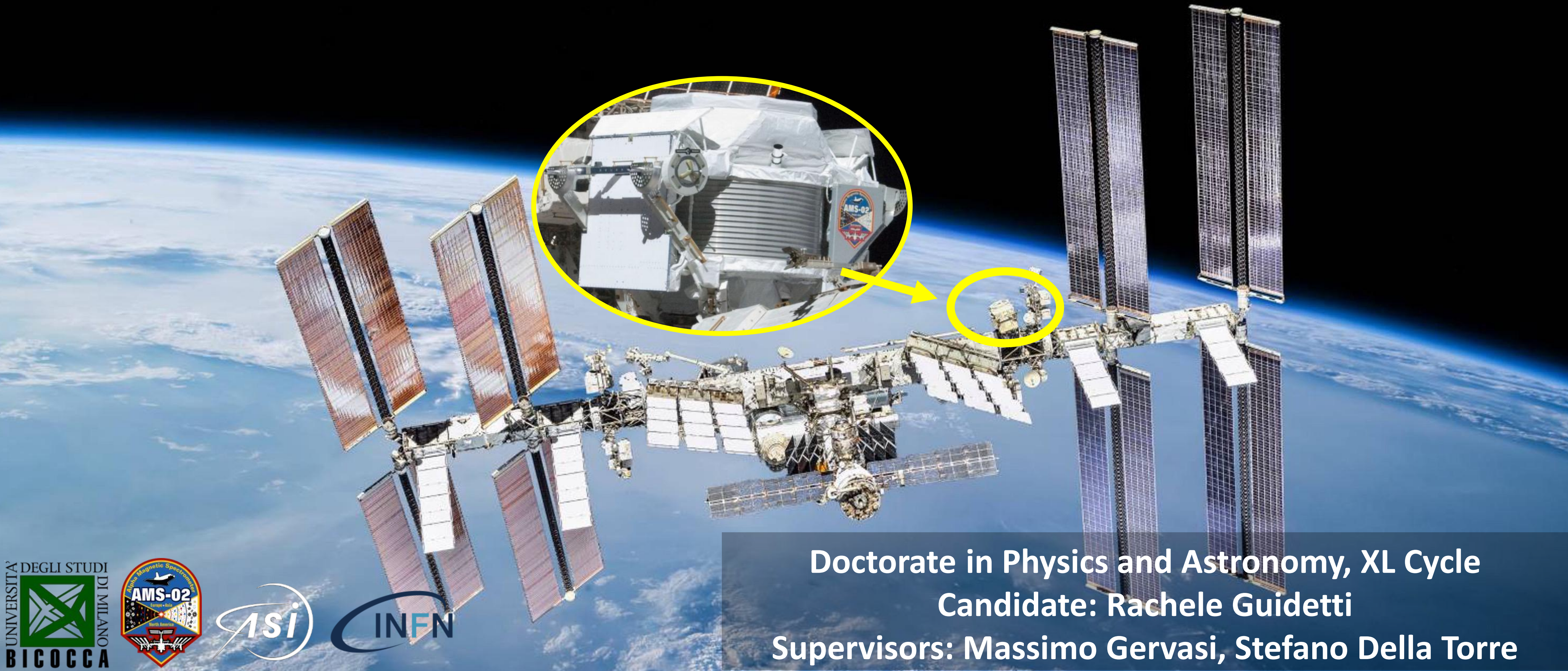
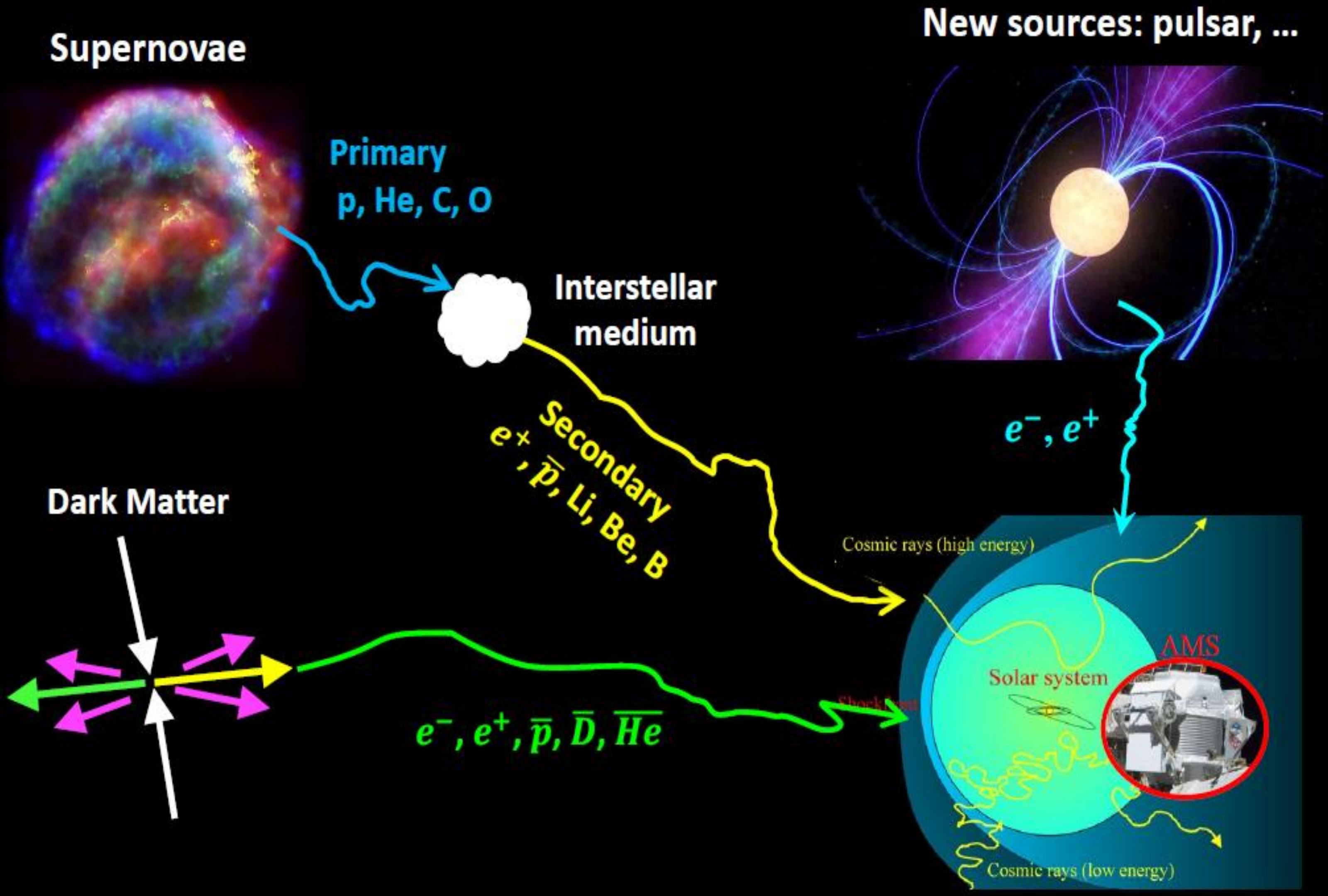
Study of cosmic proton fluxes and Solar energetic particles with the AMS-02 experiment



Doctorate in Physics and Astronomy, XL Cycle
Candidate: Rachele Guidetti
Supervisors: Massimo Gervasi, Stefano Della Torre

Cosmic Rays

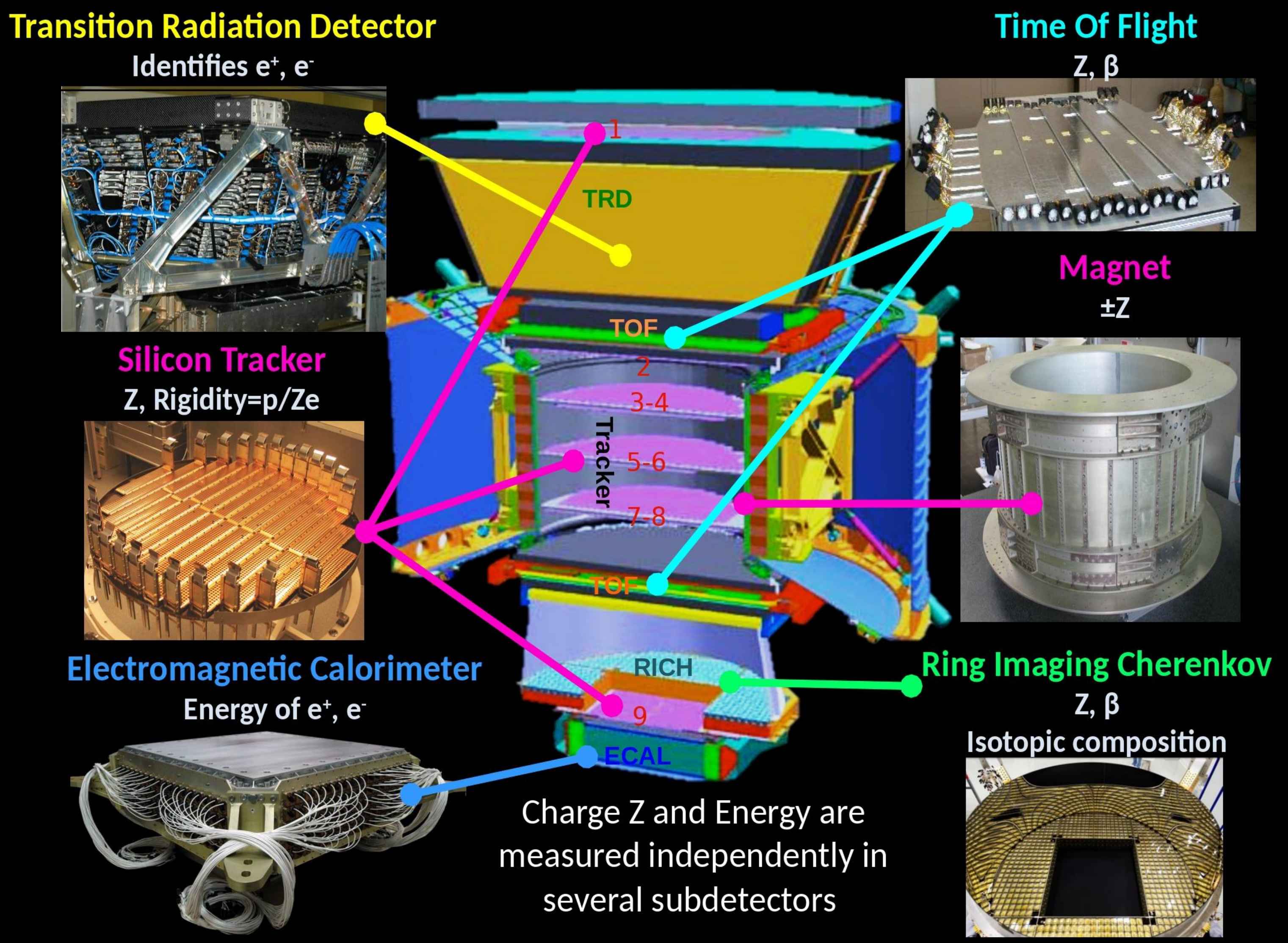
- **Cosmic rays** are **high-energy** particles, travelling in space at **relativistic speed**.
- **Galactic cosmic rays** are thought to be originated from extreme events, like **supernovae**.
- **Galactic cosmic rays** propagate in the solar system (**heliosphere**). Entering the **heliosphere**, they are affected by solar activity



AMS-02

AMS is a space version of a precision detector used in accelerators. It's a **magnetic spectrometer** able to separates particle **species**: p, anti-p, e+,e-, He, nuclei

5m x 4m x 3m, 7.5 tons, installed on the **ISS**



PhD Research Program

Final Goal:

📌 Low-energy proton analysis

Steps:

1st year — Build pipeline for proton flux extraction (1-40 GV)

2nd year — SEP (Solar Energetic Particles)

Extend the analysis to lower energies

Proton Flux

1st year – Proton flux

- Proton count
- Exposure Time
- Acceptance
- Efficiencies

$$\Phi_i(t,R) = \frac{N_{selected,i}(t,R)}{\Delta R_i \cdot T_{exp,i}(t,R) \cdot A(R) \cdot \varepsilon(t,R)}$$

Rigidity Range: 1-40 GV

Time Interval: 2011-2024 → 2025

2nd year

- Extended to 2025
- Comparisons and validation

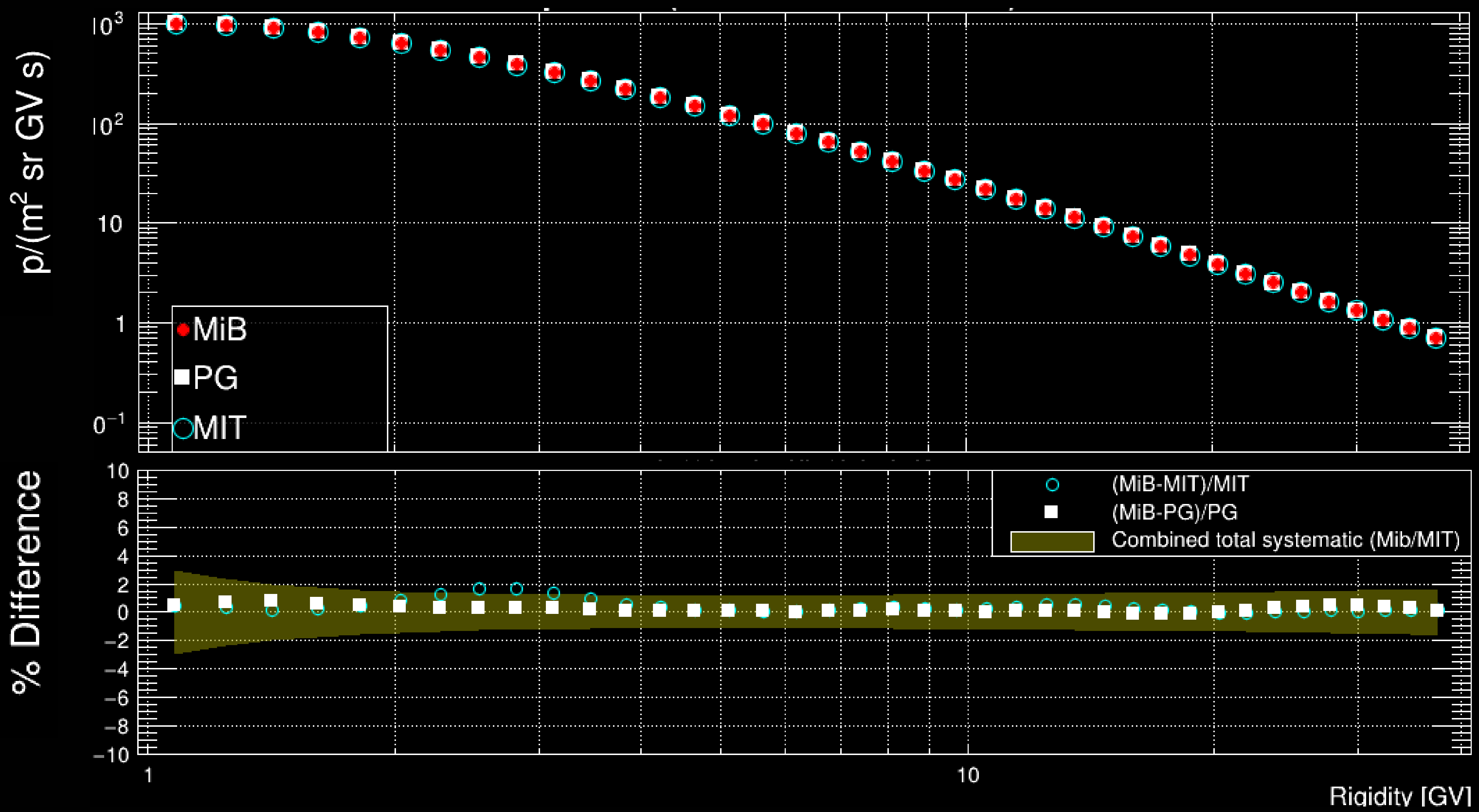
Comparisons and validation

Inside the AMS collaboration, different groups carry on analysis on the same topic independently. When 2-3 groups agree on the findings, the results are published.

I compared my analysis:

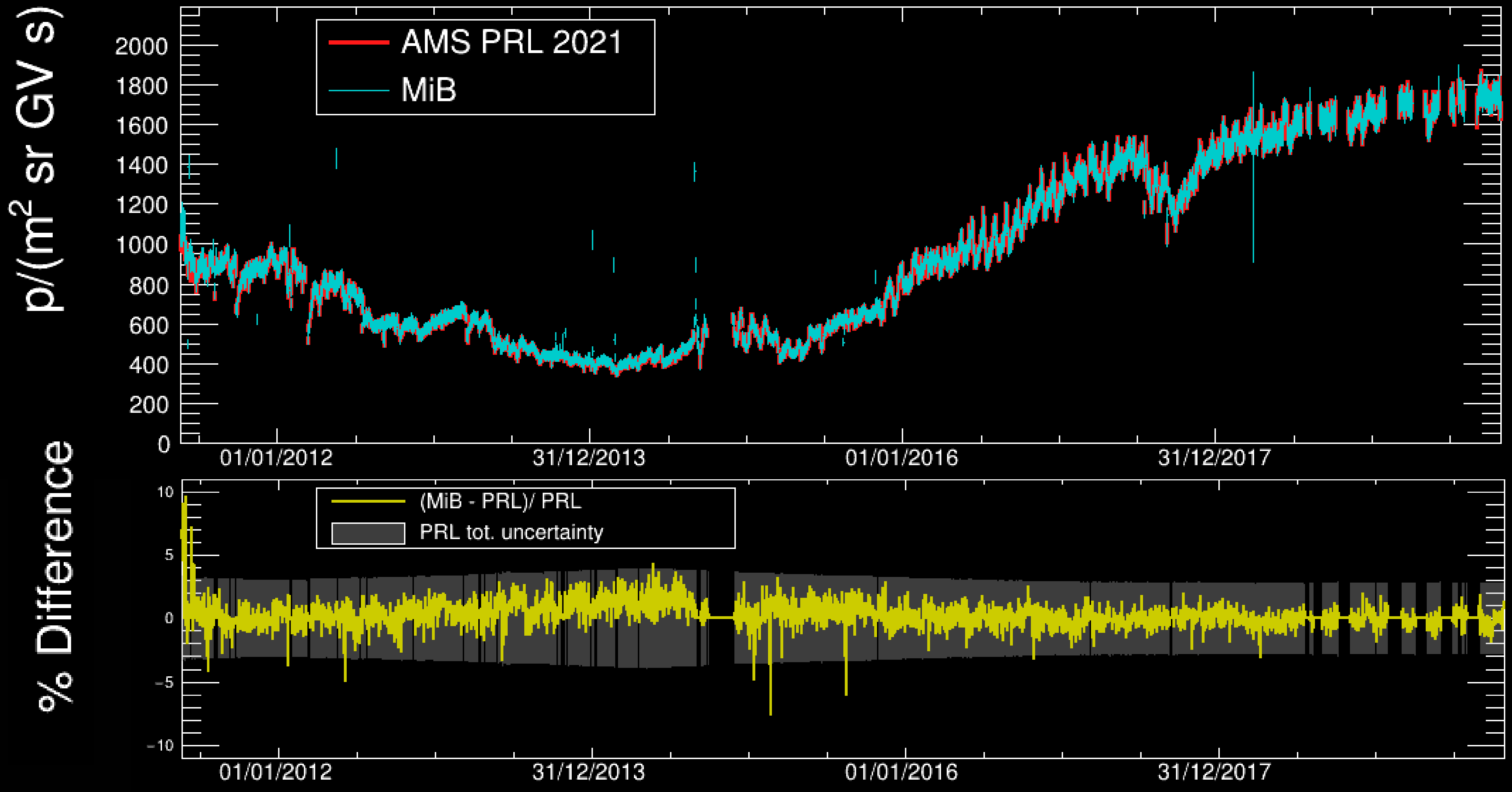
- with two groups from the AMS collaboration working on protons: MIT and Perugia (PG)
- With the published results on protons: https://link.aps.org/doi/10.1103/PhysRevLett.127.271102

Comparison with MIT and PG
(May 20 2011 – Nov 13 2023)



Daily Comparison with AMS PRL 2021

R = [1.00 – 1.16] GV



https://link.aps.org/doi/10.1103/PhysRevLett.127.271102

Daily Comparison with AMS PRL 2021

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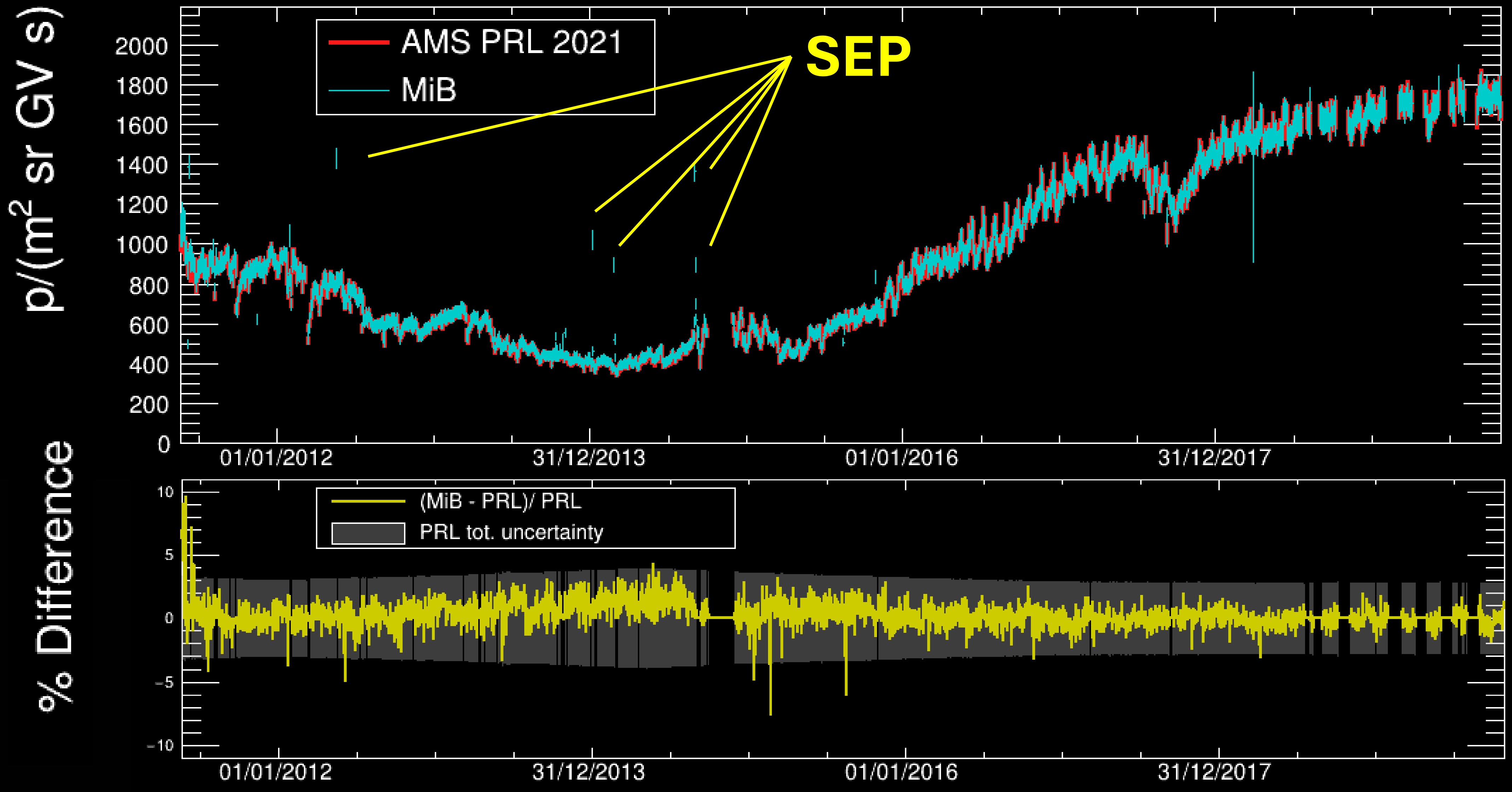
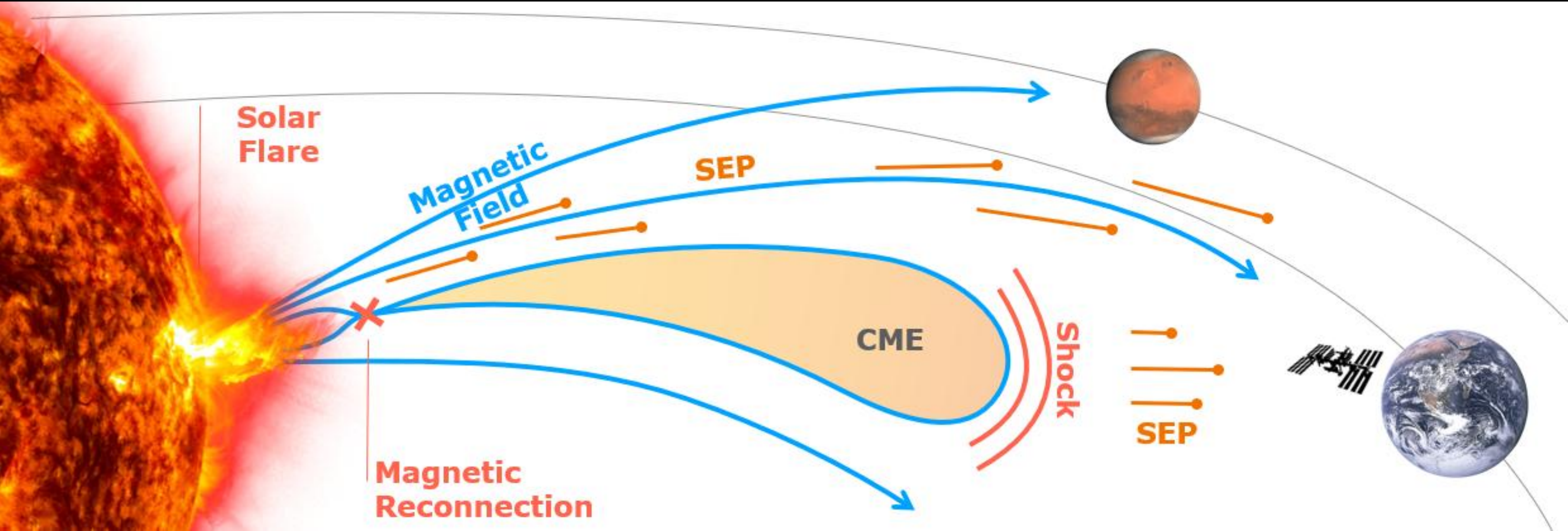


https://link.aps.org/doi/10.1103/PhysRevLett.127.271102

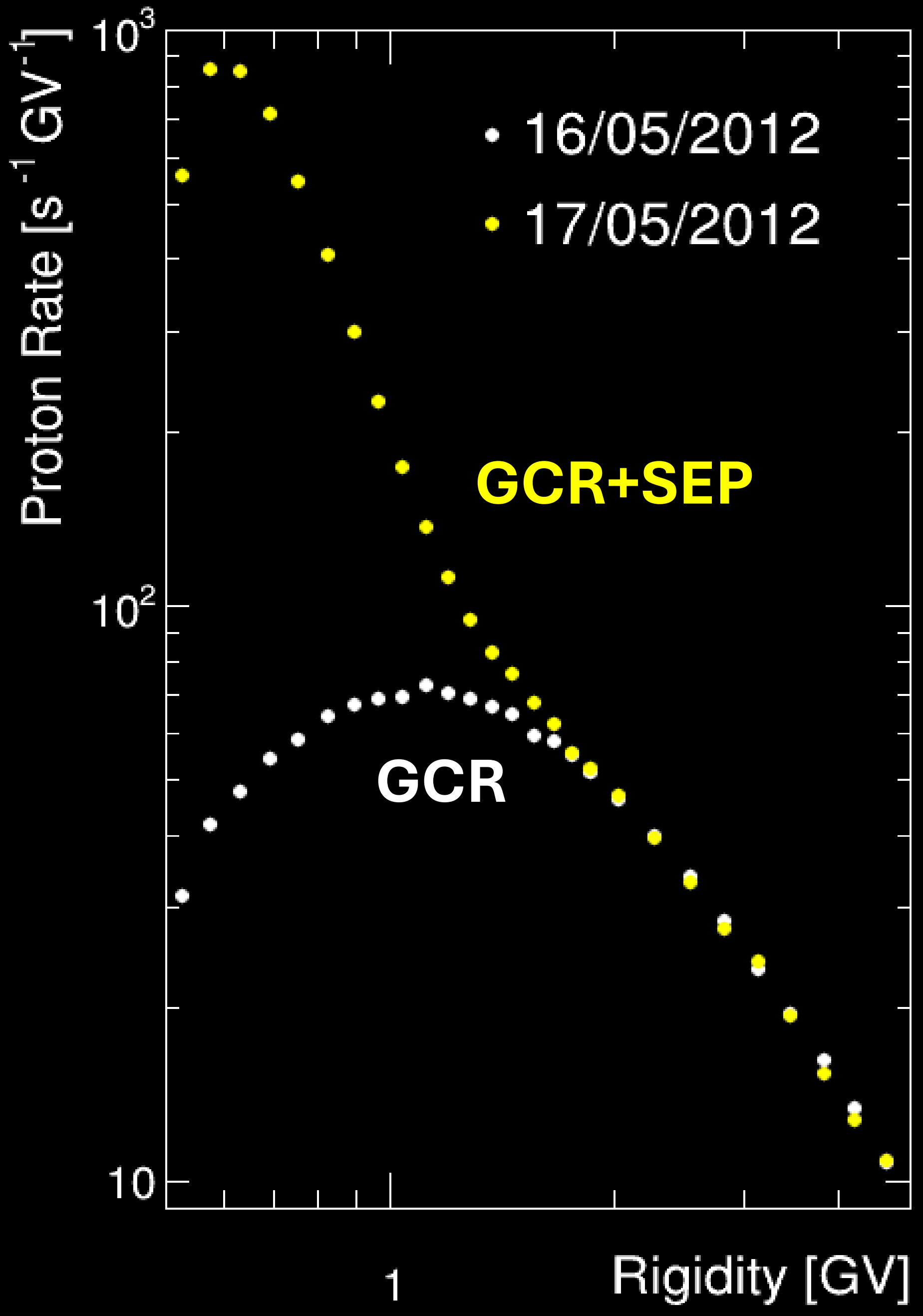
Solar energetic particles

The Sun produces its own cosmic rays: **Solar Energetic Particles (SEP)**. SEP are accelerated by **CME**s and by **magnetic reconnections** in solar flares.



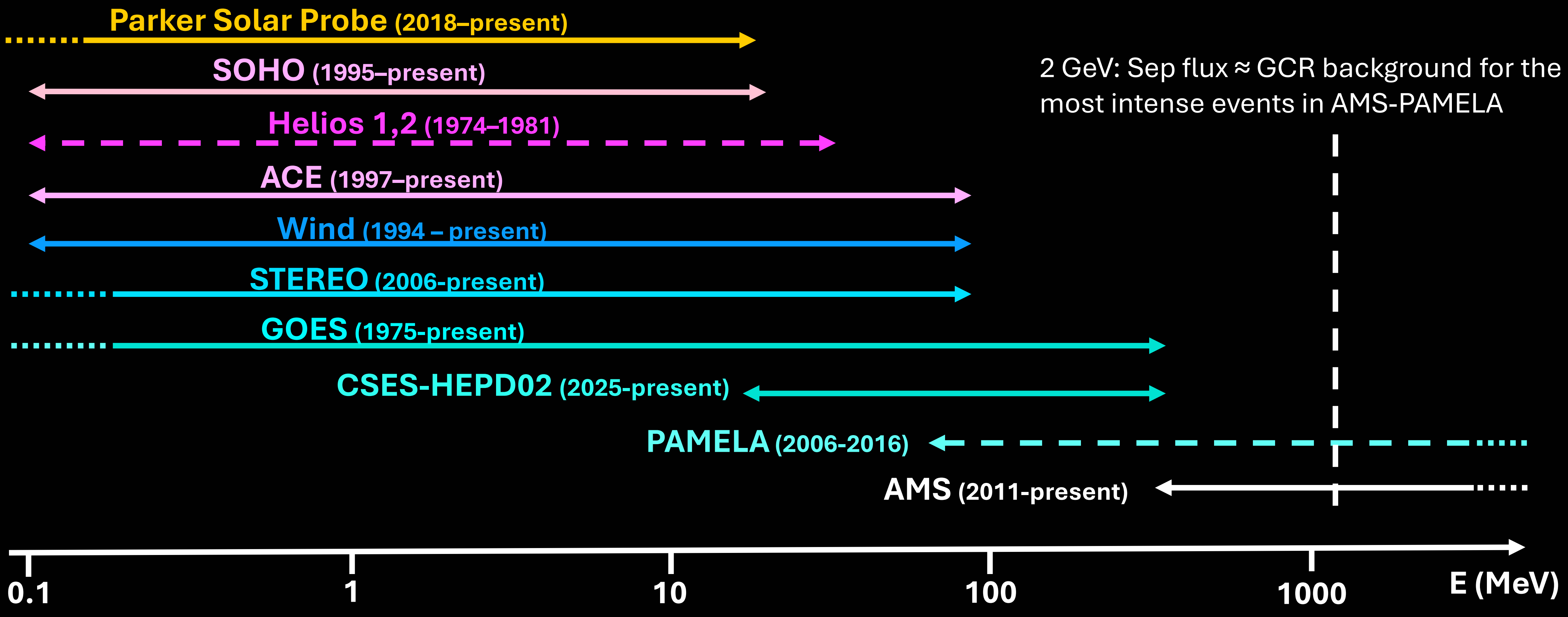
SEP

AMS measures **SEP** as an **excess** of particles above the **GCR** flux. SEP become compatible with the GCR background at **2 GV**.



Low energy analysis

With **AMS,** we can observe the **high-energy tail** of **SEP**.
AMS can measure from **120 MeV**, while most instruments studying SEP only reach **100 MeV**.
This region is therefore almost **unexplored**.



Solar Energetic Particle Selection

Standard Proton Selection

RTI Cuts
- Livetime Fraction > 0.05
- Zenith Angle < 25
- Not in SAA
- Good Event Data Acquisition

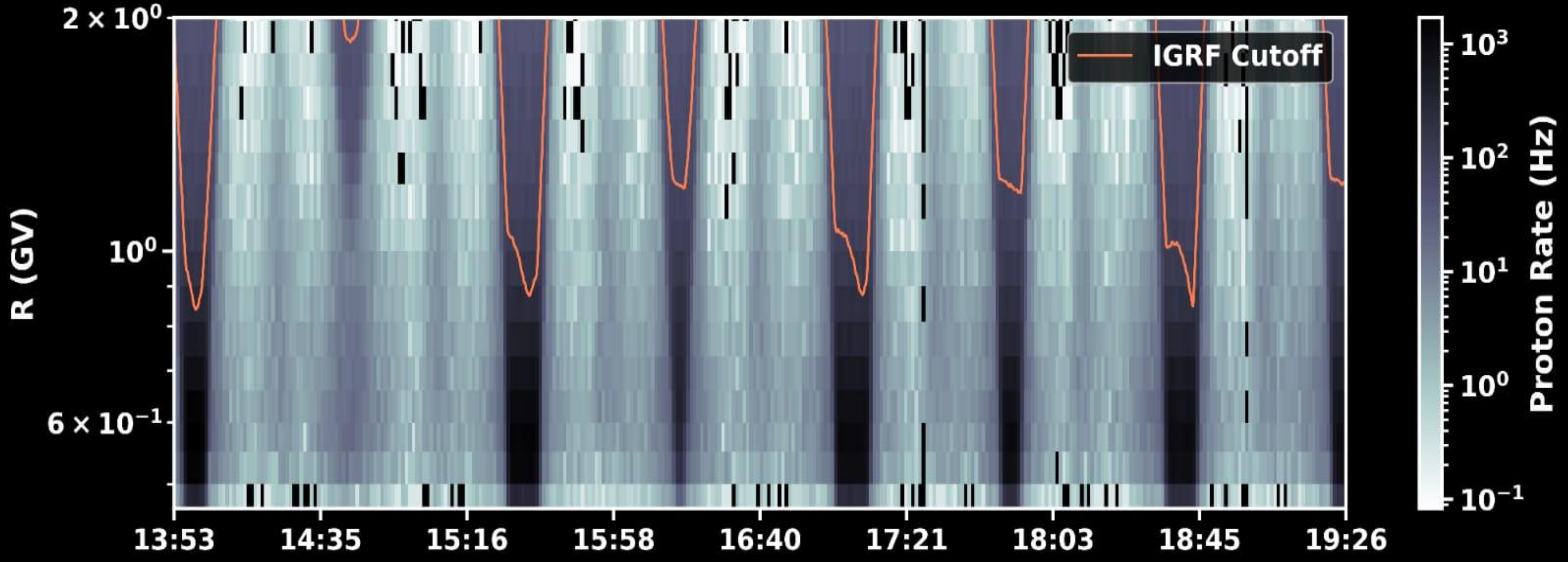
Physical Cuts
- Any Physical trigger
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4
- Chi2Y < 10 (Inner track)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- Inside Inner Fiducial (InnerL1 track)
- 0.6 < L1 Charge < 2
- Chi2Y < 10 (InnerL1 track)
- Inside L1 Fiducial (InnerL1 track)
- L1 Normalized Residual < 10
- Beta > 0.4
- 0.5 < Upper ToF Charge < 2.5
- InnerL1 Rigidity > MAX IGRF Cutoff

IGRF Cutoff

The IGRF (International Geomagnetic Reference Field) cutoff is the minimum rigidity required for a particle to enter the geomagnetic field. It is used to exclude secondary particles.

AMS is exposed to SEP only for a small amount of times, near the magnetic poles (cutoff < 2GV)

The IGRF cutoff models limits our statistics at low rigidities at the poles.



F. Faldi (AMS collaboration)

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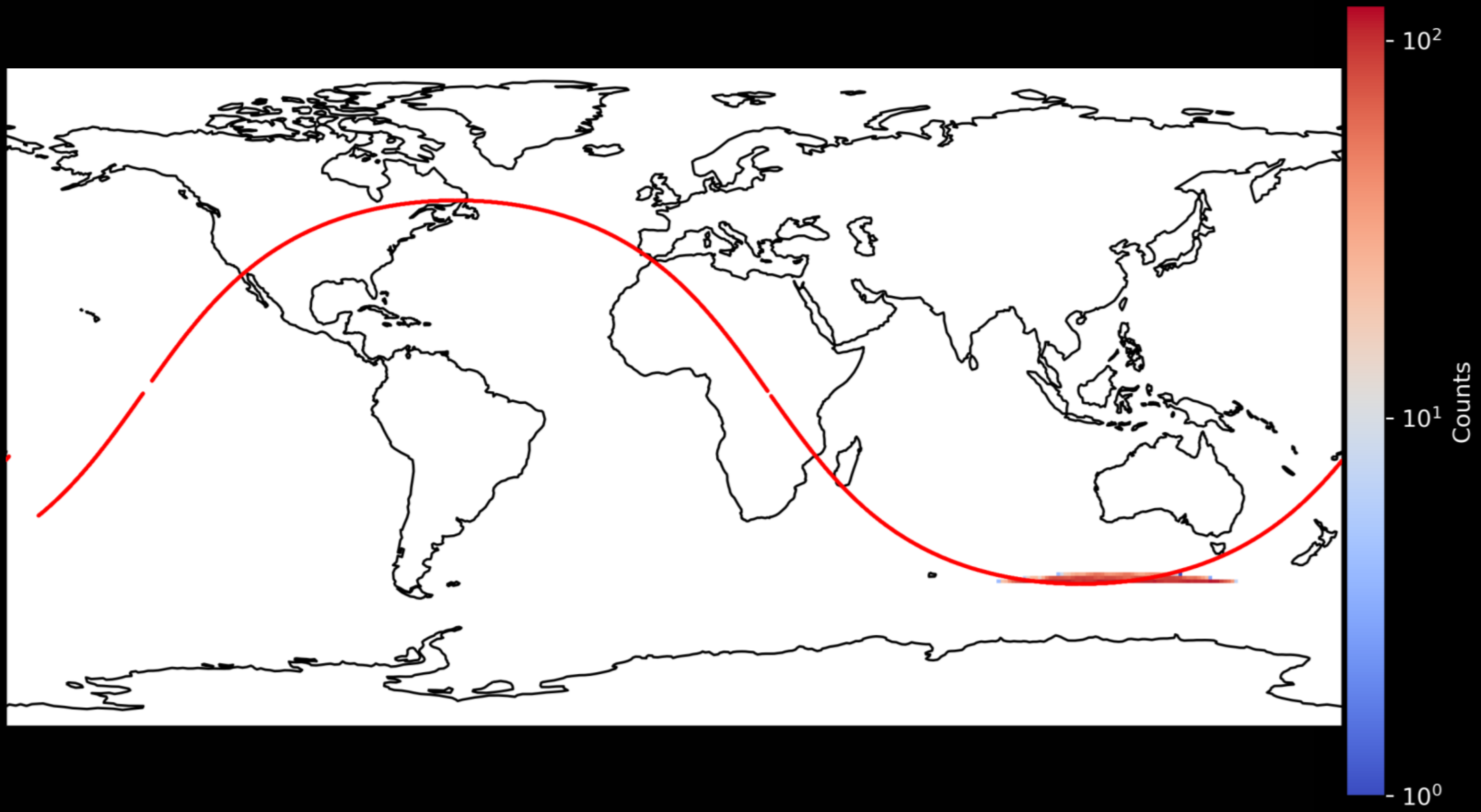
- ~~InnerL1 Rigidity > MAX IGRF Cutoff~~ → Magnetic Latitude > 62°



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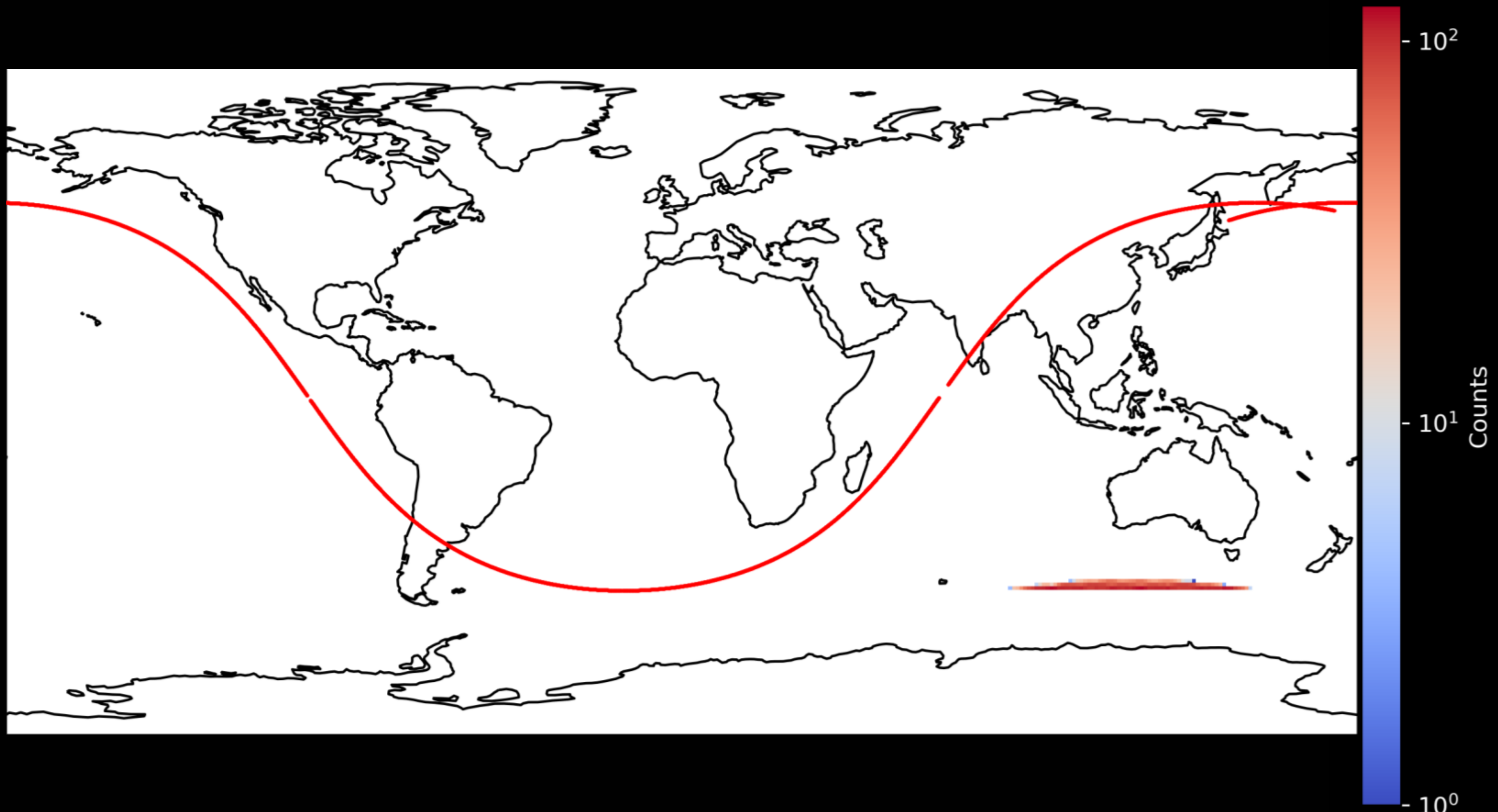
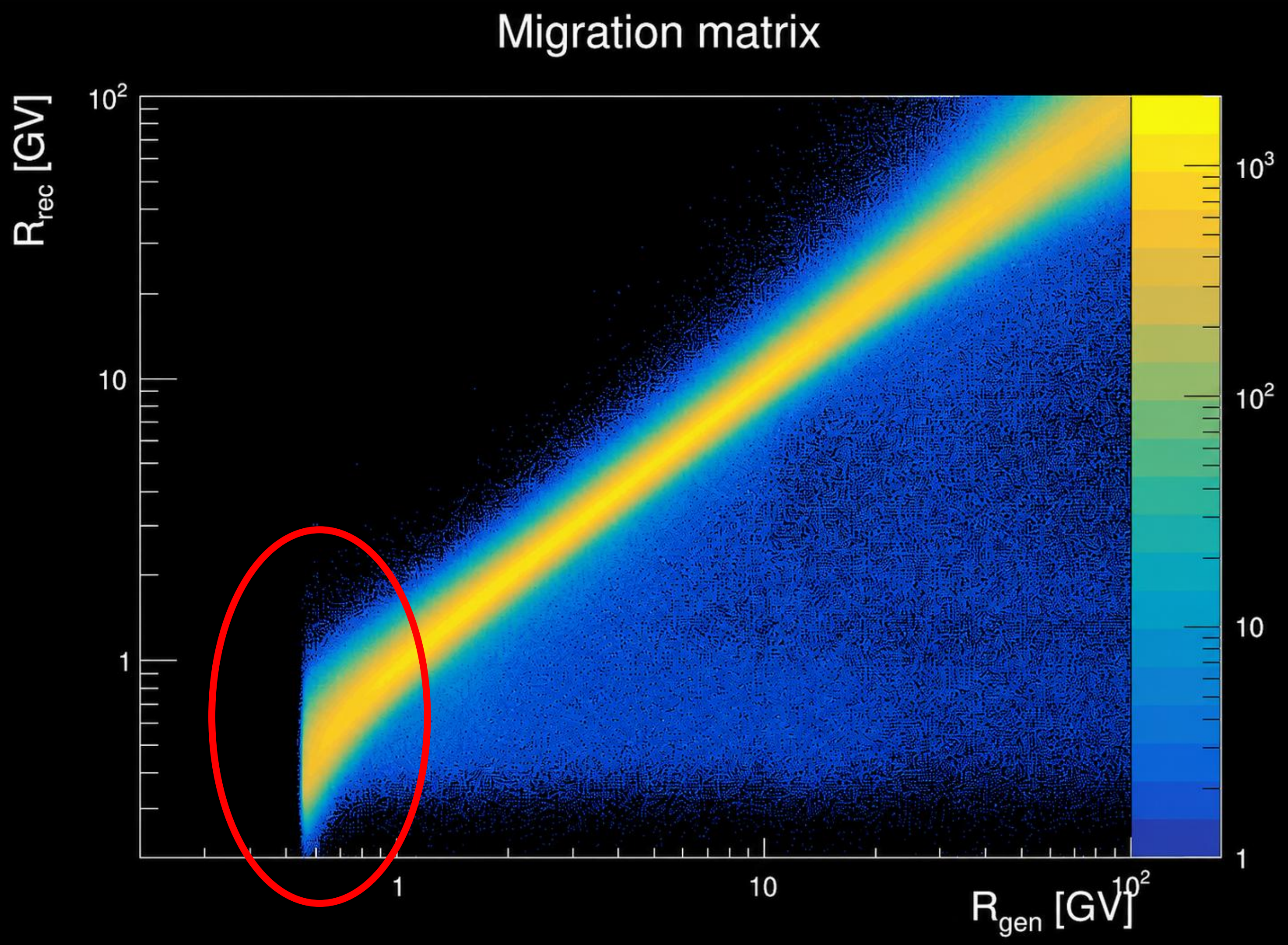


Rigidity correction

The **migration matrix** shows a strong deviation from diagonality due to energy losses by low-energy particles below 1 GV.

→ we must implement a correction



Rigidity correction

1. Construct the **resolution matrix**

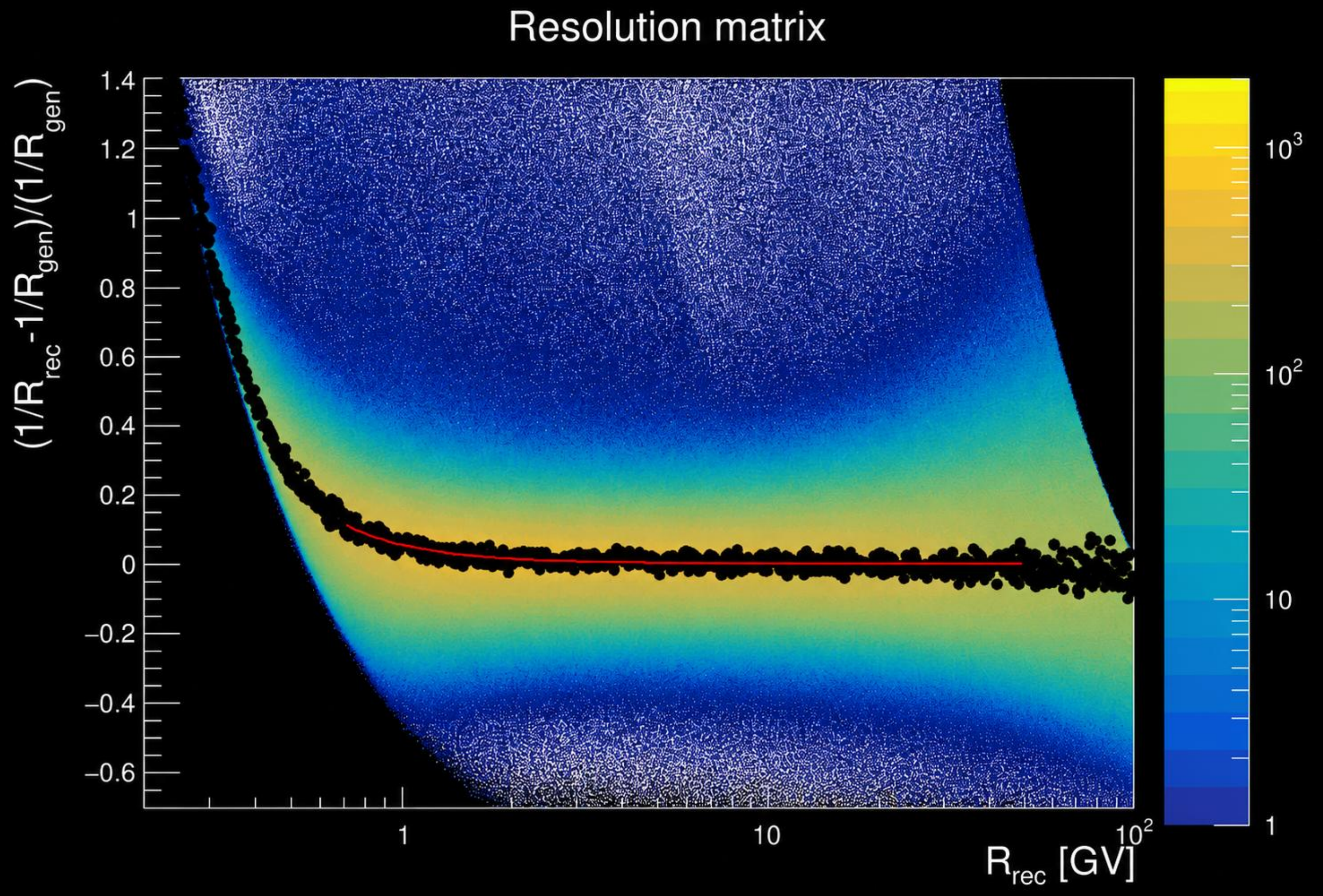
2. For each slice in Rrec find the **maximum value**.

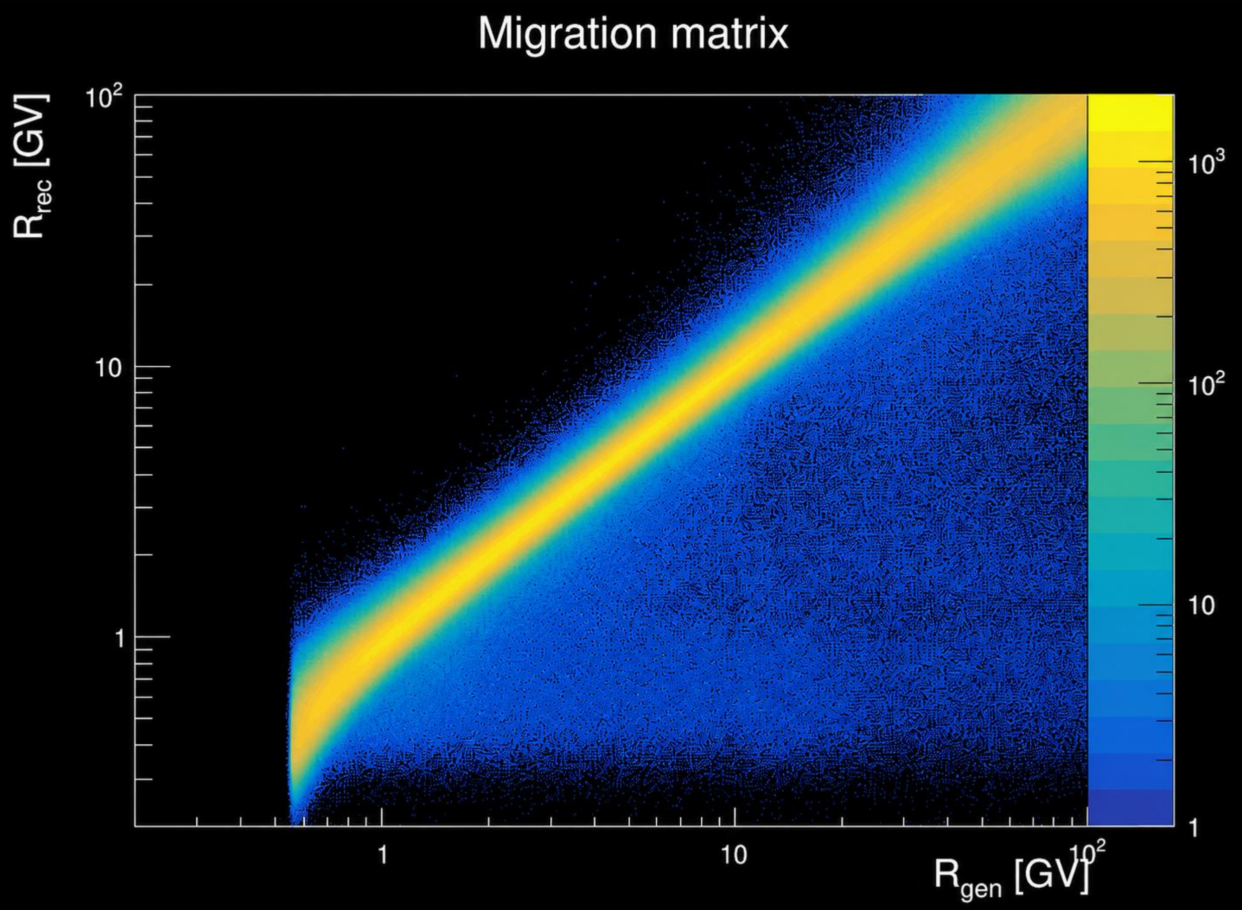
3. **Fit the maximum** with :

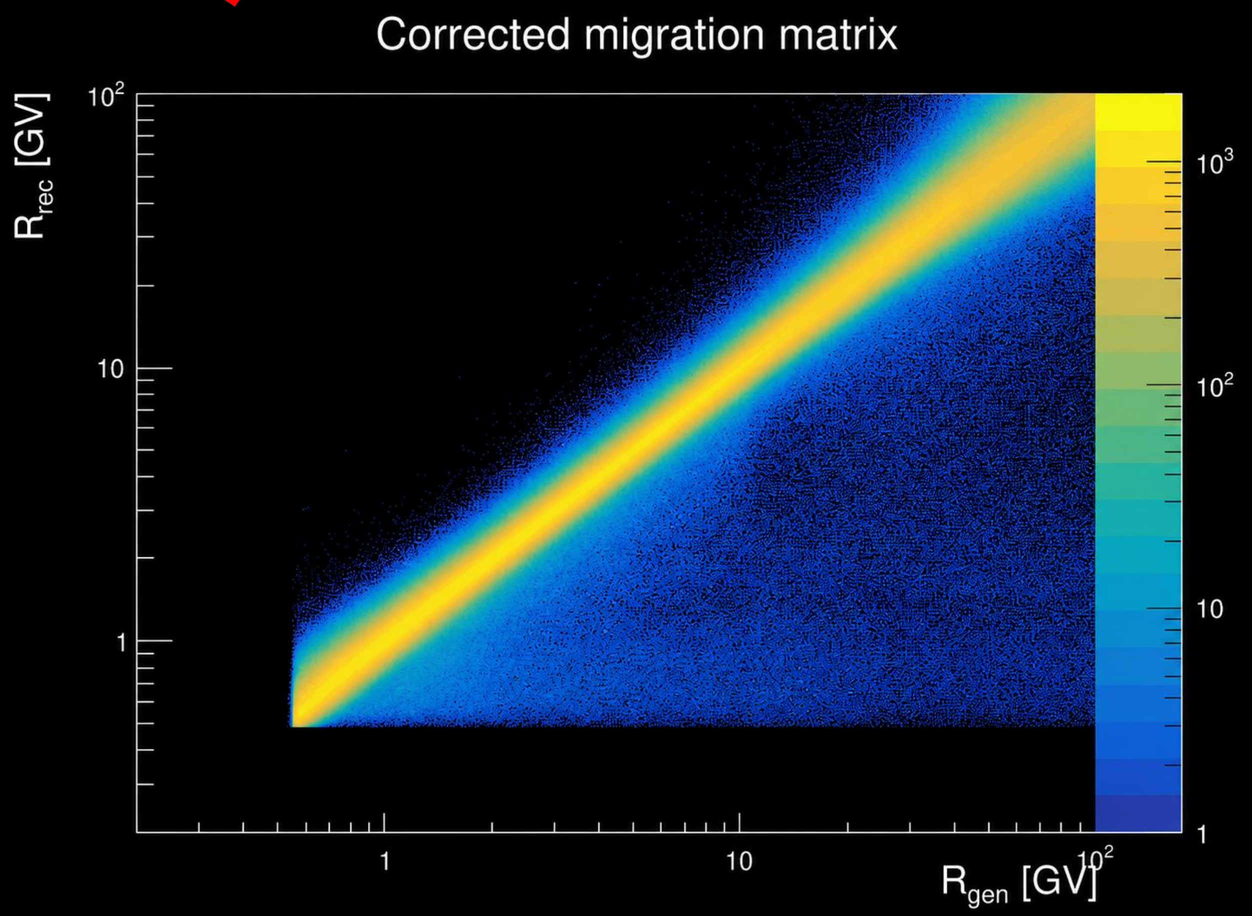
   $f(RGEN) = Ax^{-B}y$

4. **Correct** the rigidities as

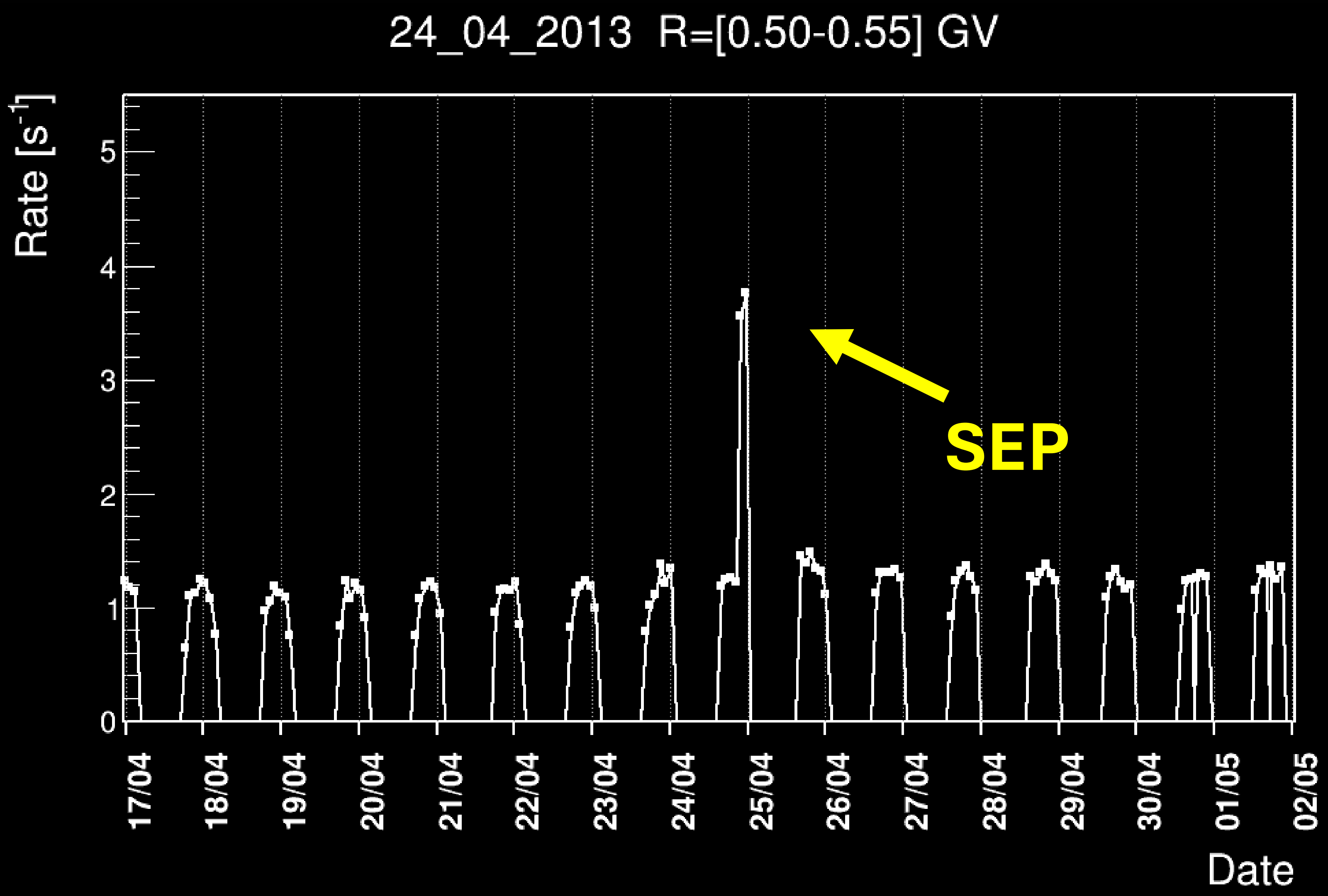
   $Rcorr(R) = R + AR^{(1-B)}$




Migration matrix
R_{rec} [GV]
10^2
10
1
R_{gen} [GV]
1
10
10^2
10^3
10^2
10
1


Corrected migration matrix
R_{rec} [GV]
10^2
10
1
R_{gen} [GV]
1
10
10^2
10^3
10^2
10
1

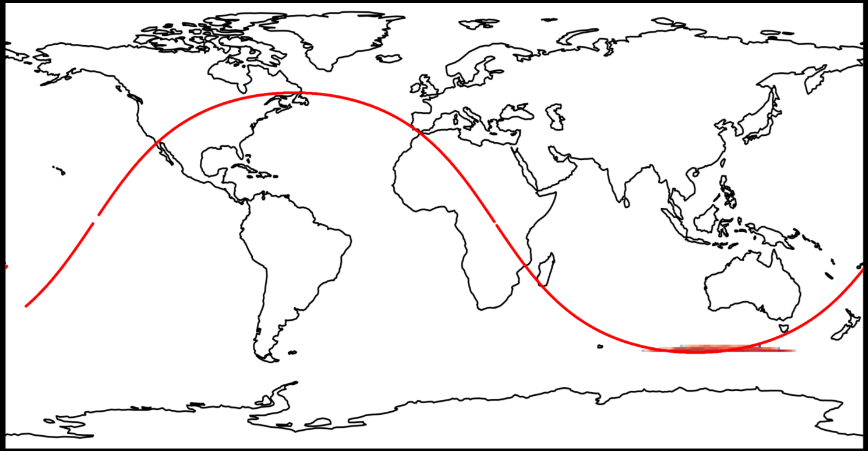
SEP orbital proton rate



$$\mathrm{R}_i(t,R) = \frac{N_{selected,i}(t,R)}{T_{exp,i}(t,R)}$$

$\mathrm{N_{selected}}$ = proton count

$\mathrm{T_{exp}}$ = effective time above the magnetic theta in the AMS FoV



SEP identification algorithm(s)

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3 methods working on **orbital rate** (Φ) at [0.5 – 0.55] GV

SEP identification algorithm(s)

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I tested different rigidity bins, and this one gives the best agreement with already existing AMS SEP catalogues

SEP identification algorithm(s)

3 methods working on **orbital rate** (Φ) at [0.5 – 0.55] GV

1. $\dfrac{\Phi(\text{orbit}) - \Phi(\text{24 prev. hours})}{\Phi(\text{24 prev. hours})} > \text{threshold}$

Thresholds = 37.5 (solar min), 47 (intemediate), 70 (solar max)

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2. $$\frac{\Phi(\text{orbit}) - \Phi(\text{median orbit})}{\Phi(\text{median orbit})} > \text{threshold}$$

   Median over 10 previous days
   Thresholds = 56 (solar min), 83.7 (intemediate), 90 (solar max)

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3. $$\Phi_{(\text{orbit})} > \Phi_{(\text{mean}|\text{11 days})} + N\sigma_{(\text{11 days})}$$

   N = 2.3

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→ A SEP is identified if at least 2 of 3 methods detect it

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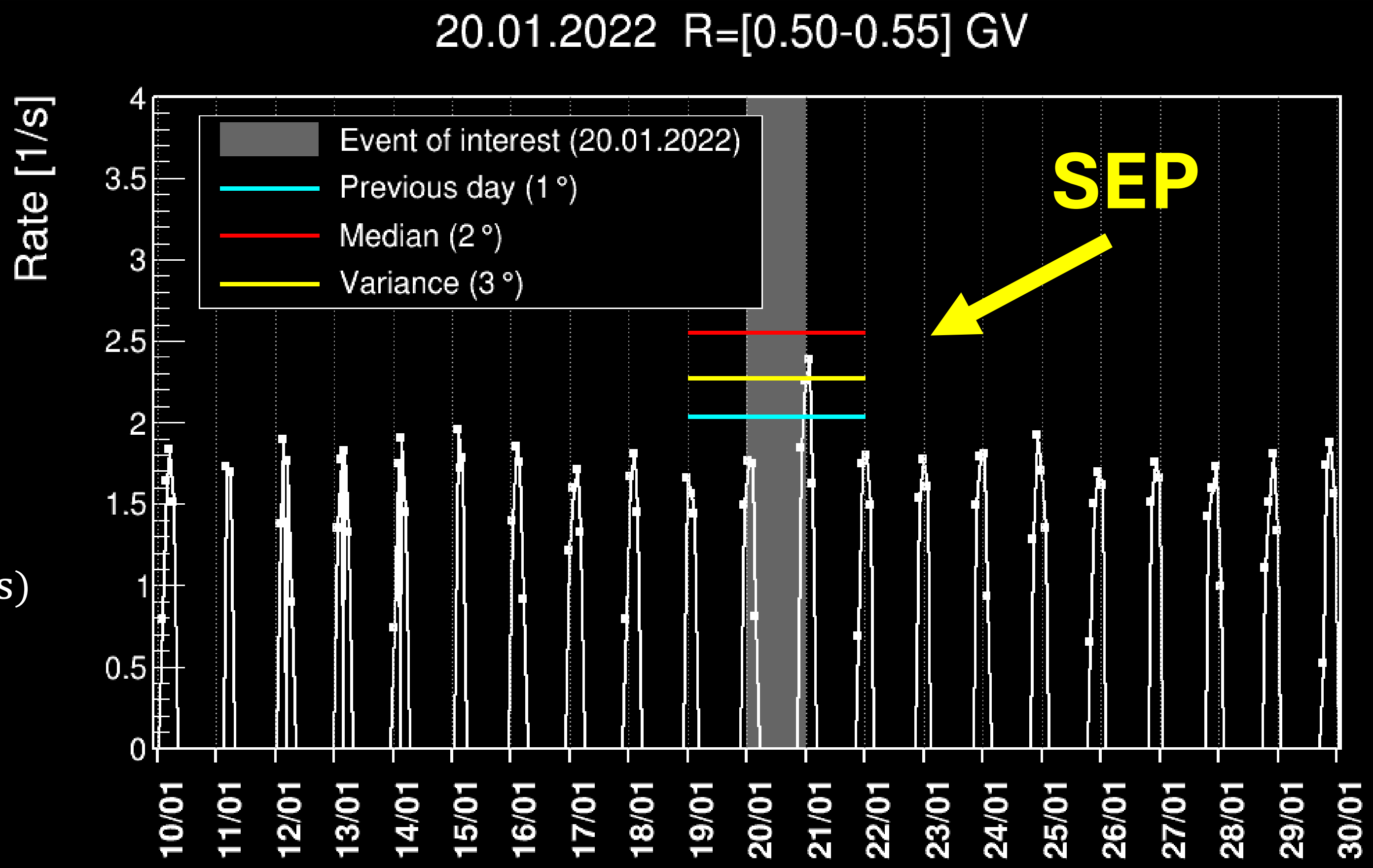


SEP List

69 events from 2011 to 2025

→ Comparison with AMS joint SEP lists (from the union of 3 independent lists)

07/06/2011	28/09/2012	25/02/2014	18/07/2023	23/07/2024
04/08/2011	08/11/2012	18/04/2014	25/07/2023	05/08/2024
09/08/2011	06/03/2012	02/09/2014	28/07/2023	04/09/2024
07/09/2011	11/04/2013	11/09/2014	01/09/2023	14/09/2024
23/09/2011	24/04/2013	25/09/2014	29/01/2024	03/10/2024
04/11/2011	23/05/2013	29/10/2015	09/02/2024	09/10/2024
23/01/2012	30/09/2013	06/09/2017	11/02/2024	27/10/2024
28/01/2012	11/10/2013	11/09/2017	14/02/2024	03/10/2024
07/03/2012	12/10/2013	21/01/2022	16/02/2024	09/10/2024
13/03/2012	29/10/2013	16/02/2022	23/03/2024	27/10/2024
17/05/2012	02/11/2013	28/03/2022	11/05/2024	05/01/2025
07/07/2012	28/12/2013	30/03/2022	20/05/2024	31/05/2025
19/07/2012	06/01/2014	02/04/2022	08/06/2024	22/10/2025
23/07/2012	08/01/2014	13/03/2023	12/06/2024	

SEP List

67 common SEP events (MiB: 69 events, AMS: 72 events)

→ Agreement = 93%

AMS JOINT LIST ONLY
6/9/2011
6/3/2013
25/10/2013
6/9/2024
11/9/2024

07/06/2011	28/09/2012	25/02/2014	18/07/2023	23/07/2024
04/08/2011	08/11/2012	18/04/2014	25/07/2023	05/08/2024
09/08/2011	06/03/2012	02/09/2014	28/07/2023	04/09/2024
07/09/2011	11/04/2013	11/09/2014	01/09/2023	14/09/2024
23/09/2011	24/04/2013	25/09/2014	29/01/2024	03/10/2024
04/11/2011	23/05/2013	29/10/2015	09/02/2024	09/10/2024
23/01/2012	30/09/2013	06/09/2017	11/02/2024	27/10/2024
28/01/2012	11/10/2013	11/09/2017	14/02/2024	03/10/2024
07/03/2012	12/10/2013	21/01/2022	16/02/2024	09/10/2024
13/03/2012	29/10/2013	16/02/2022	23/03/2024	27/10/2024
17/05/2012	02/11/2013	28/03/2022	11/05/2024	05/01/2025
07/07/2012	28/12/2013	30/03/2022	20/05/2024	31/05/2025
19/07/2012	06/01/2014	02/04/2022	08/06/2024	22/10/2025
23/07/2012	08/01/2014	13/03/2023	12/06/2024	

Conclusions

Proton Flux

- Integrated proton flux (2011-2025) in agreement with MIT and PG
- Daily flux in agreement with AMS PRL 2021

Solar energetic particles

- SEP proton selection
- SEP identification algorithm and SEP list in agreement with AMS catalogues ~93%

Current Progress & Next Steps

Final Goal:

Low-energy proton analysis

Steps:

Build pipeline for proton flux extraction

SEP flux and Background removal

Extend the analysis to lower energies

Next Steps

SEP flux and background subtraction

Thank you for your attention!

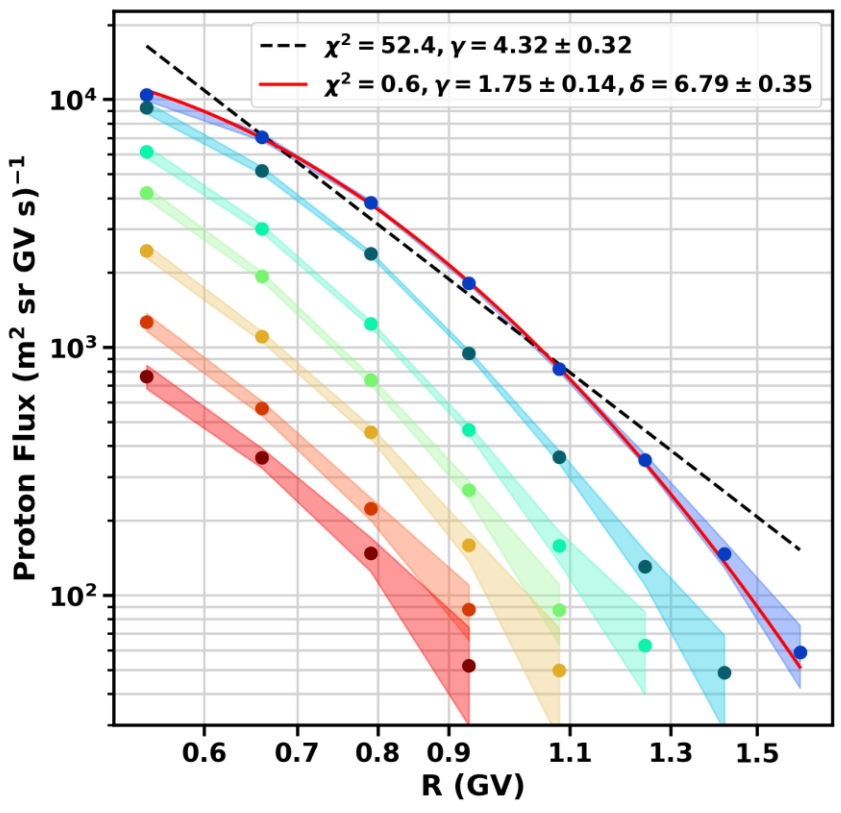
BACKUP

Spectral Fits with AMS at Peak Intensity

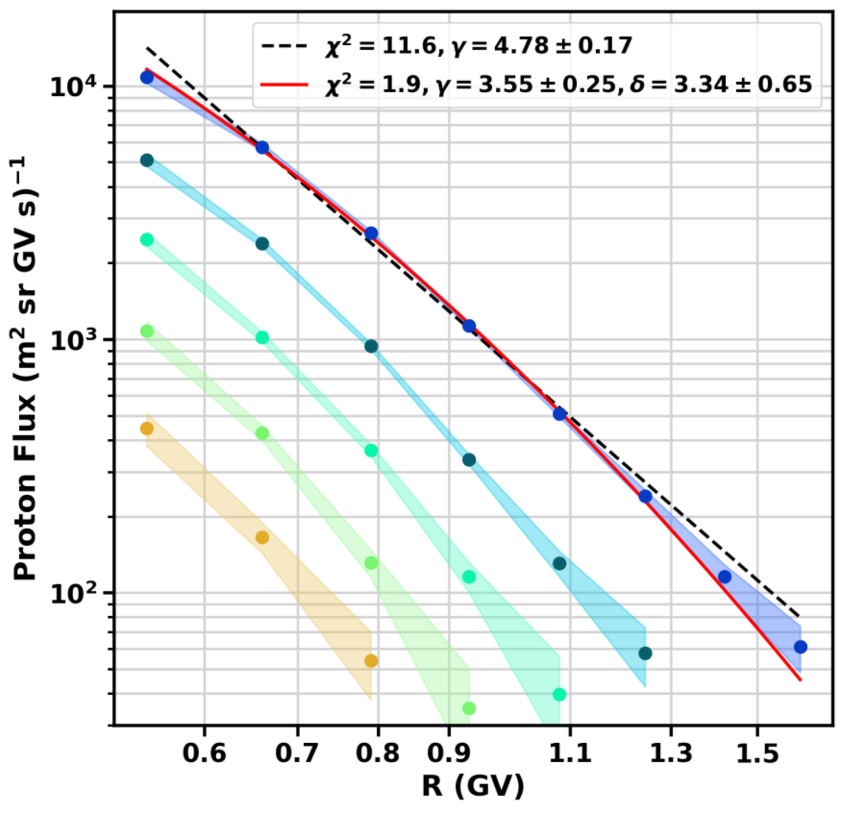
courtesy of F. Faldi (AMS general meeting, 2025)

Background-subtracted **SEP spectra**, at peak intensity, are **fitted** with a single power-law (dashed) and the Modified Power-Law (red) models.

Back-side event: low spectral index (γ = 1.8 ± 0.1), pronounced rollover (δ = 6.8 ± 0.4).



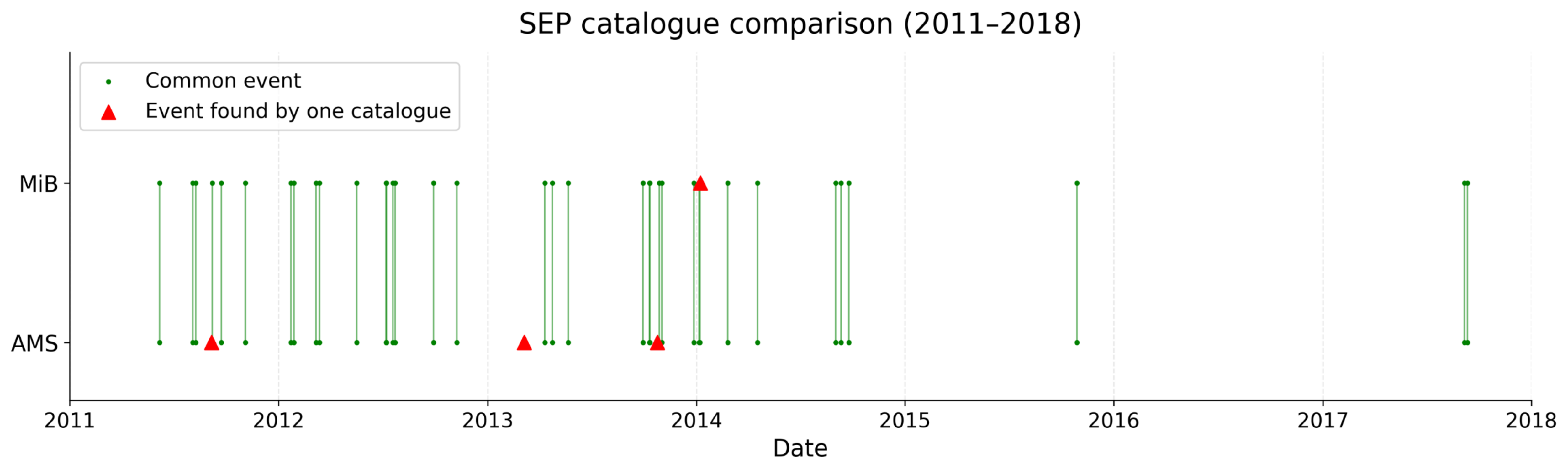
Eastern-side event: higher spectral index (γ = 3.6 ± 0.3), slighter rollover (δ = 3.3 ± 0.7).



SEP List- Comparison with the joint AMS SEP Catalogue

67 common SEP events (69 events by MiB and 72 events by AMS)

→ Agreement = 93%



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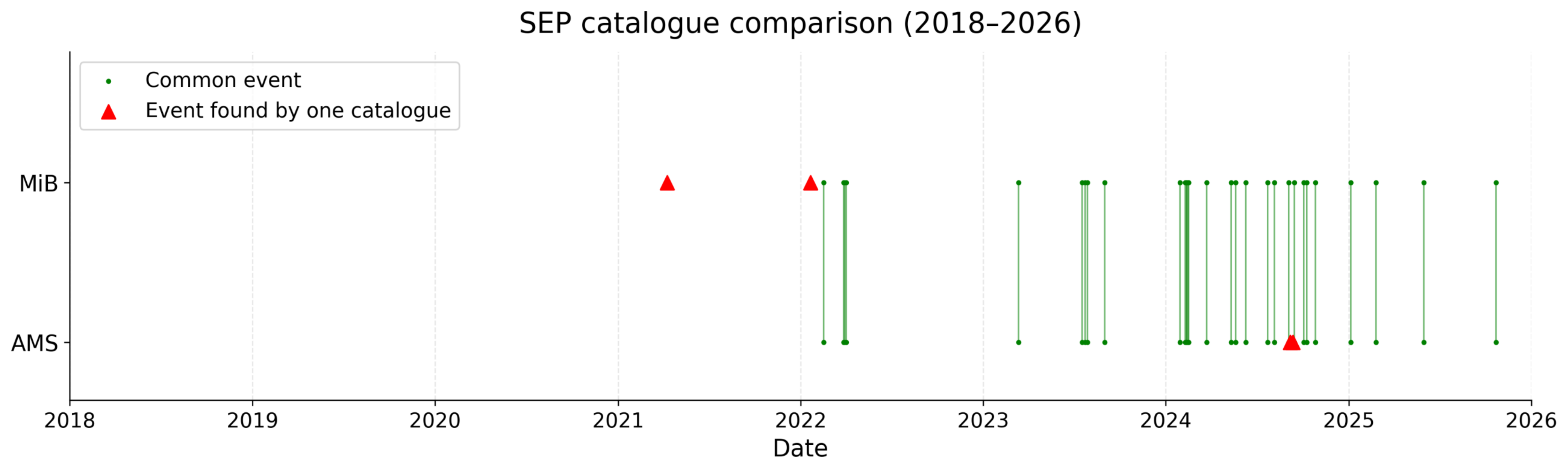
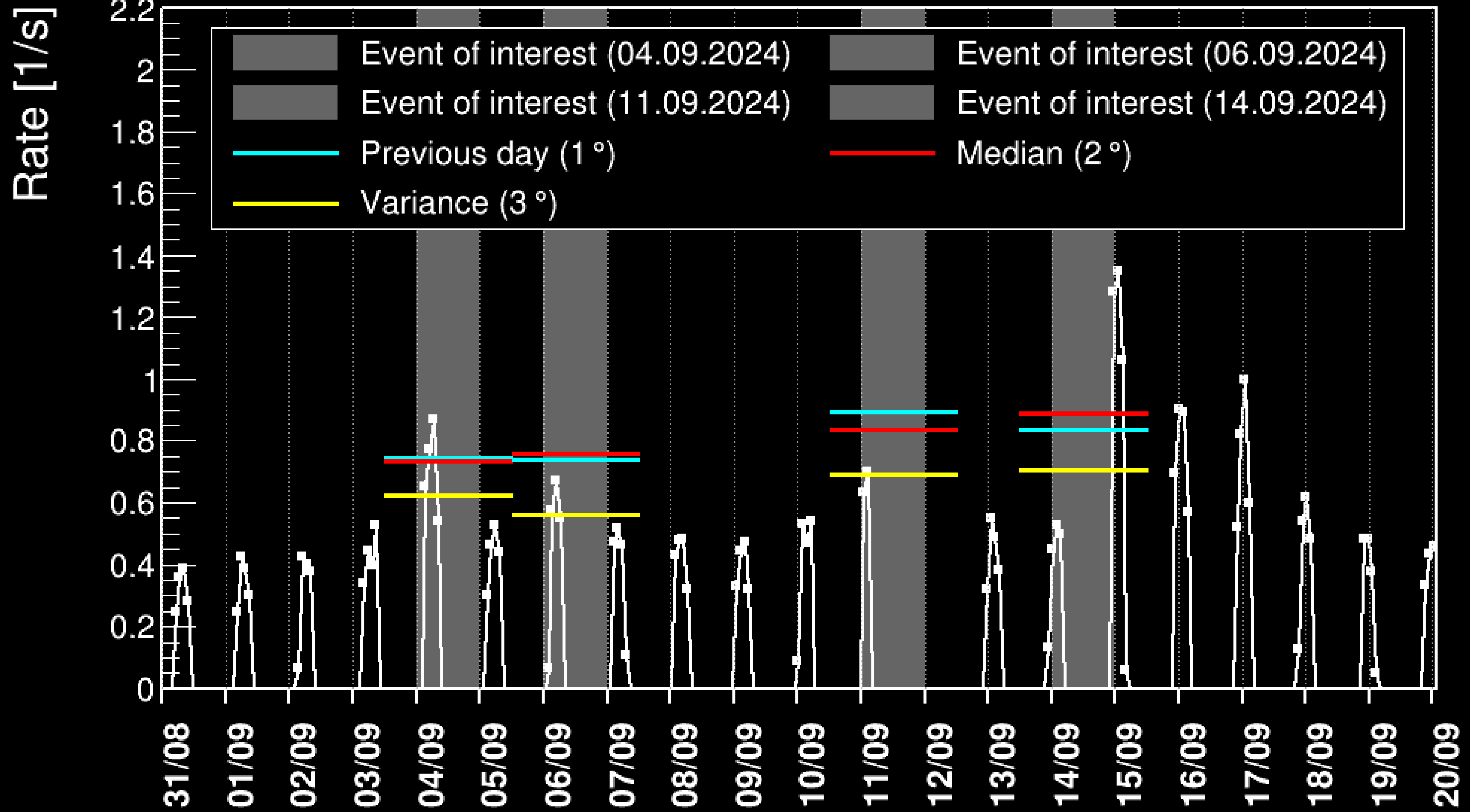
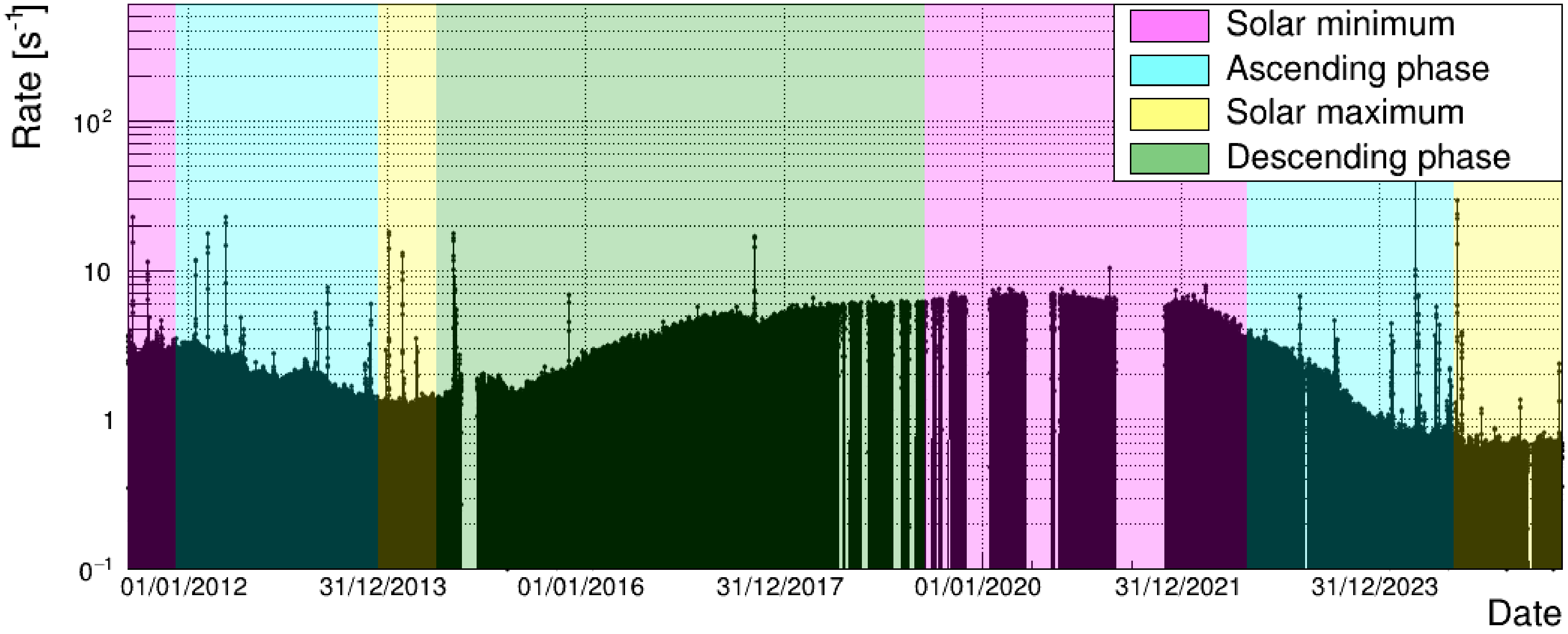


3-6-11-14/09/2024

	AMS	MiB
03/09/2024	yes	yes
06/09/2024	yes	no
11/09/2024	yes	no
14/09/2024	yes	yes



Thresholds and solar periods



Solar minimum 1 = 24.05.2011 - 16.11.2011

Ascending phase 1 = 16.11.2011 - 01.12.2013

Solar maximum 1 = 01.12.2013 - 01.07.2014

Descending phase 1 = 01.07.2014 - 01.06.2019

Solar minimum 2 = 01.06.2019 - 31.08.2022

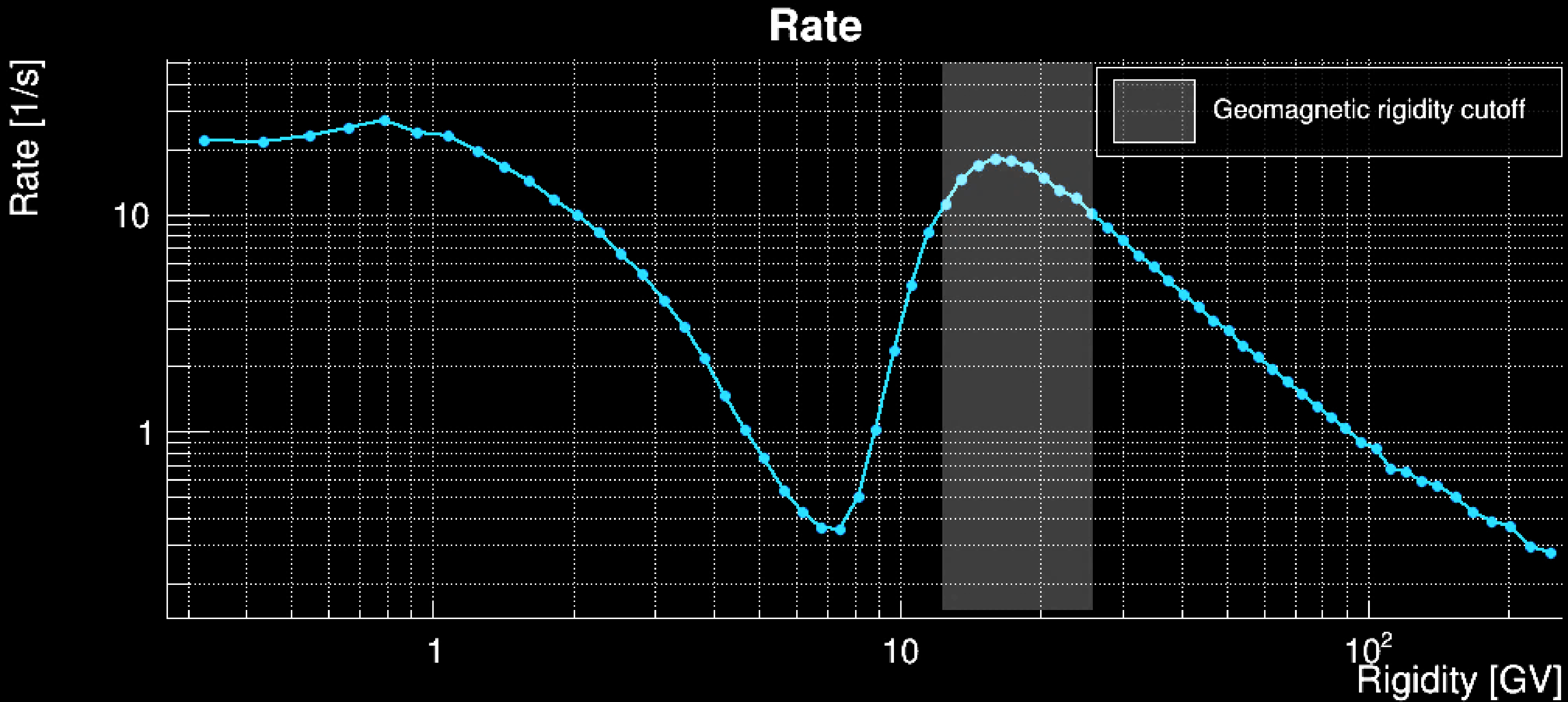
Ascending phase 2 = 31.08.2022 - 01.10.2024

Solar maximum 2 = 01.10.2024 - 31.10.2025

Geomagnetic Rigidity Cutoff

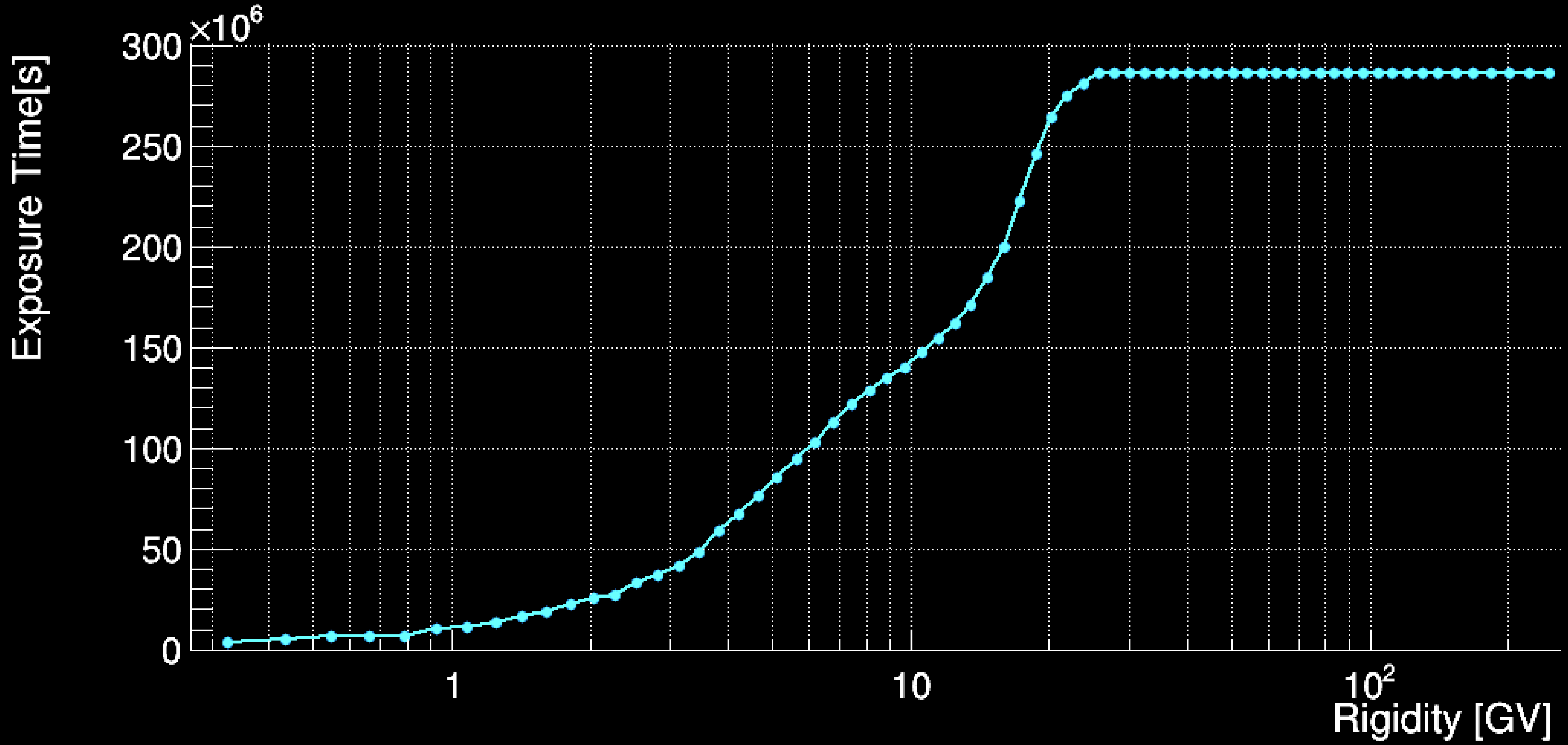
Minimum rigidity required to reach Earth.

The geomagnetic rigidity cutoff is a **function** that depends on position and, at a given location, on direction and charge of incoming particles.



Exposure Time

Effective time (excluding detector dead time) above the maximum geomagnetic cutoff in the AMS FoV (for each rigidity bin).



Acceptance

The **acceptance** is a function that describes the **angular** and **spatial efficiency** of particle detection

AMS **MC simulations**:

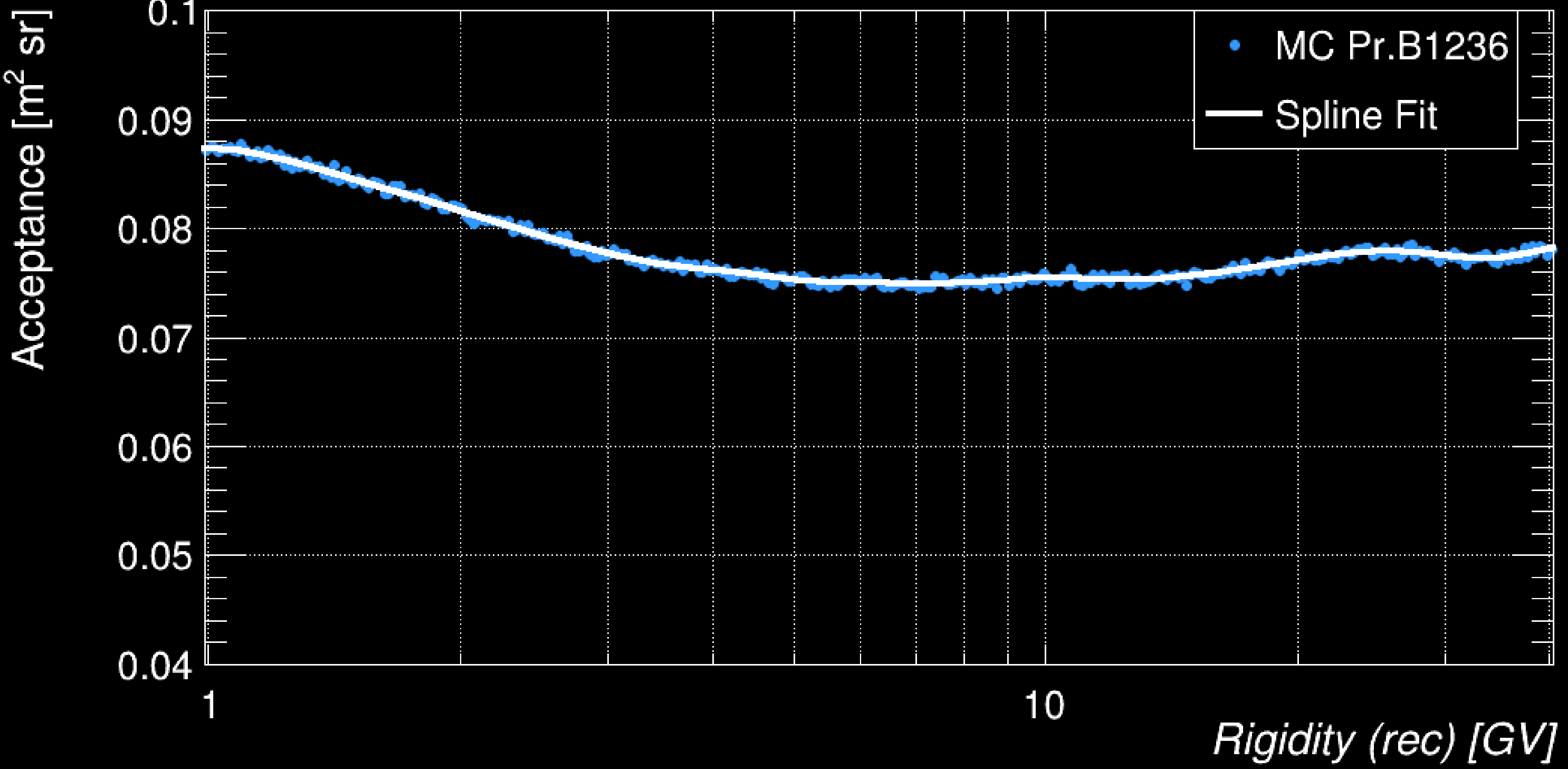
- AMS is too complex for an analytical description
- Model the detector geometry and its efficiency in correctly identifying particles

$$Acc(R) = \frac{N_{sel}(R)}{N_{gen}(R)}\ 3.9^2\pi$$

Acceptance

The **acceptance** is a function that describes the **angular** and **spatial efficiency** of particle detection

$$Acc(R) = \frac{N_{sel}(R)}{N_{gen}(R)}\, 3.9^2\pi$$



Efficiency

The **acceptance** is computed on the MC simulations:
it is a good description of the reality?

↓

We need to correct the acceptance using real data

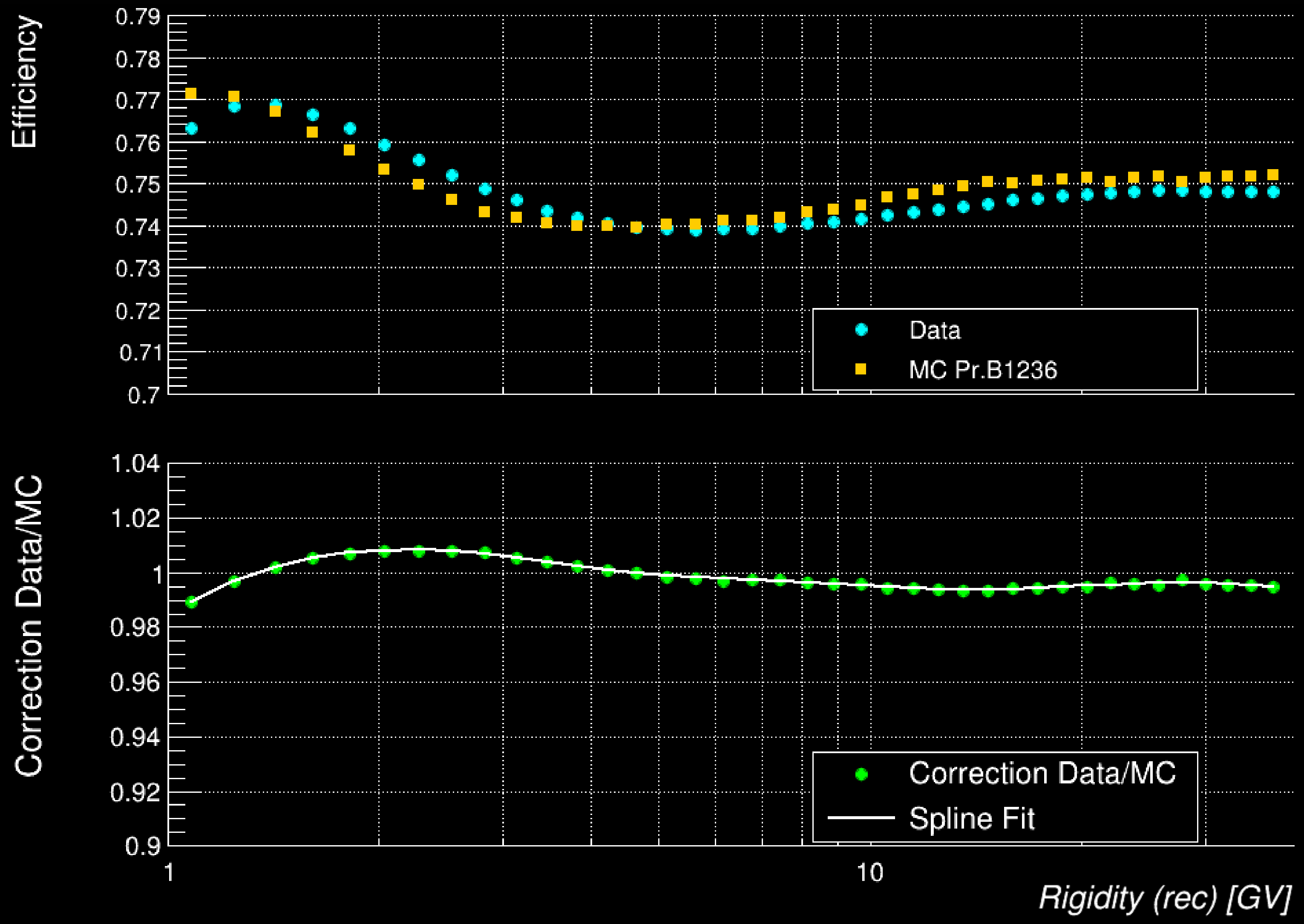
↓

$\frac{DATA}{MC}$ total efficiency correction on 4 sub-detectors of AMS

$$\frac{N\ (\text{events passing reference selection + detector cuts})}{N\ (\text{events passing reference selection})}$$

Layer 1

Probability of getting a **good Layer 1 hit** and a **charge** compatible with a proton, given that we registered a **good proton**.



Denominator

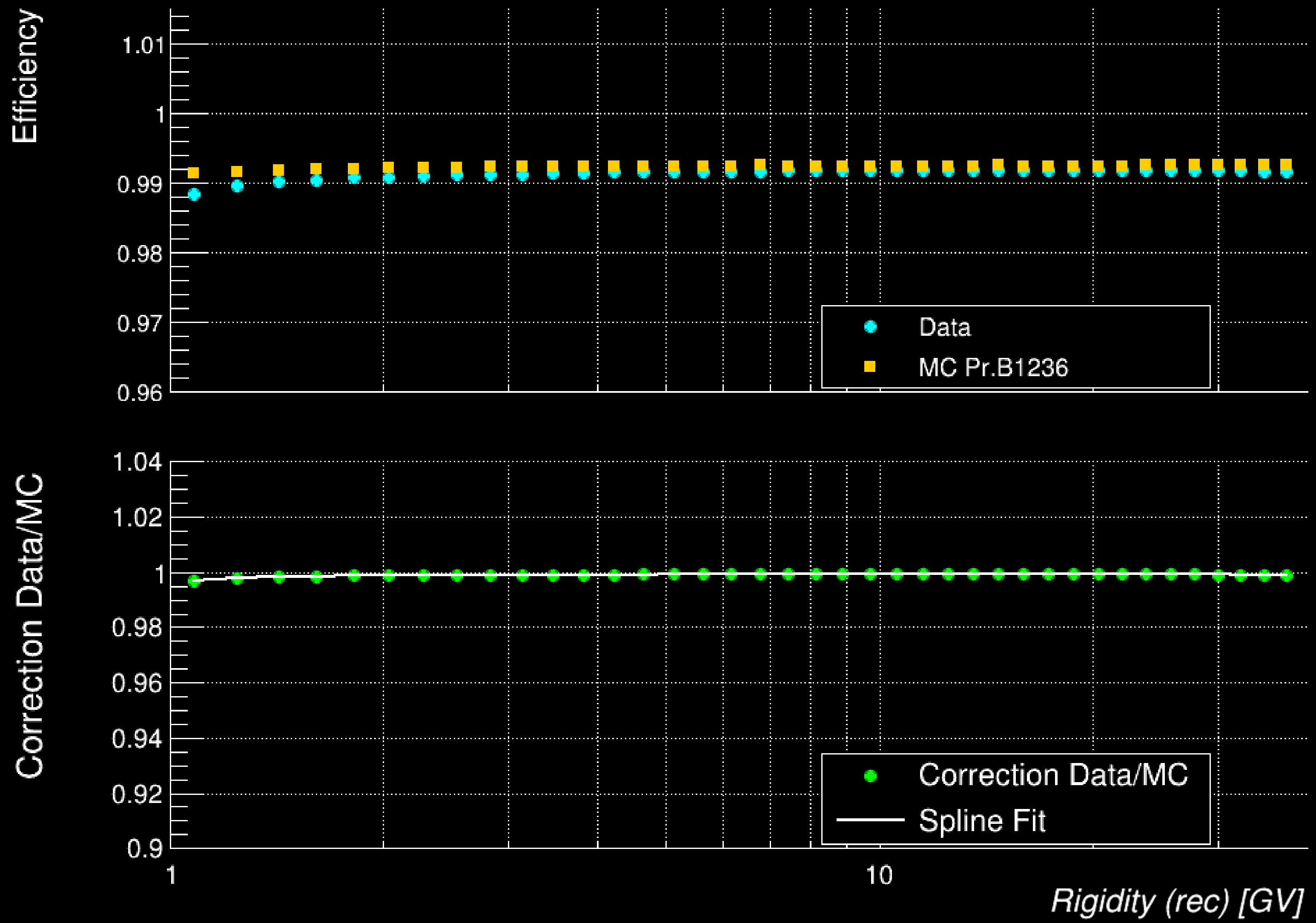
- RTI cuts (see event selection
- Any Physical trigger
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4
- Beta > 0.4
- 0.5 < Upper ToF Charge < 1.7
- Mass Cut (Inner rigidity)
- 0.5 < Lower ToF Charge < 1.7
- Less than 5 ToF Clusters
- ToF Chi2 Coo < 2
- Only one inner track
- No ACC fired
- Inner Rigidity > IGRF Cutof

Numerator

- Denominator
- Chi2Y < 10 (InnerL1 rigidity)
- 0.6 < L1 Charge < 2
- Inside Inner Fiducial (InnerL1 rigidity)
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10

ToF Efficiency

Probability of getting **β** and a **charge** compatible with a proton, given that we registered a **good proton**.



Denominator

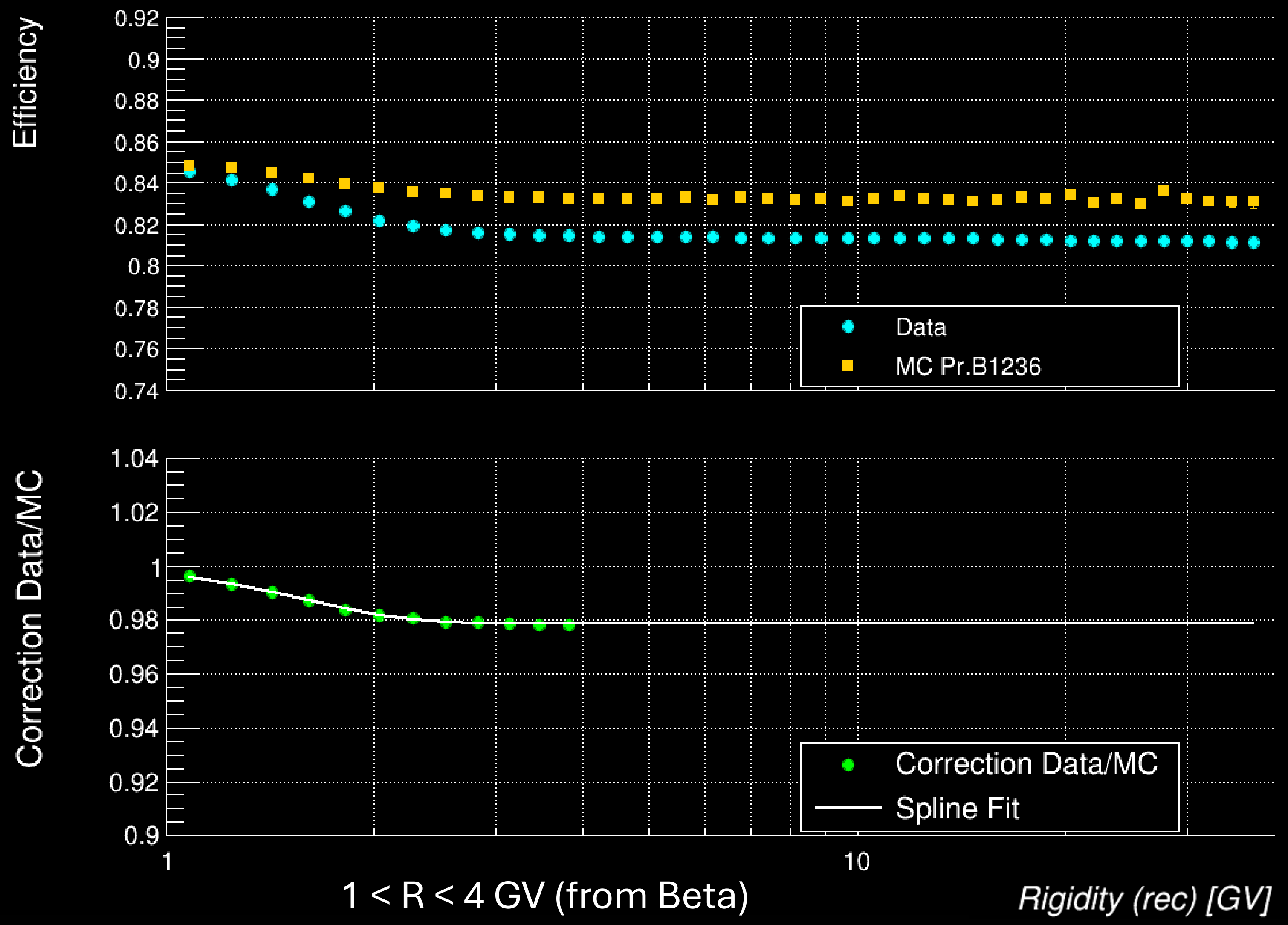
- RTI cuts (see event selection)
- Any Physical trigger
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- Chi2Y < 10 (InnerL1 rigidity)
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4
- 0.6 < L1 Charge < 2
- Inside Inner Fiducial (InnerL1 rigidity)
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10
- InnerL1 Rigidity > IGRF Cutof

Numerator

- Denominator
- Beta > 0.4
- 0.5 < Upper ToF Charge < 2.5

Inner Tracker Efficiency

Probability of getting a **track** and a **charge** compatible with a proton, given that we registered a **good proton with only information from ToF and Layer1.**



Denominator

- RTI cuts (see event selection)
- Any Physical trigger
- 0.6 < L1 Charge < 2
- Beta > 0.4
- 0.5 < Upper ToF Charge < 1.5
- Lower ToF Charge > 0.5
- ToF Chi2 Coo < 2
- ToF Chi2 Time < 2
- ToF Track Inside Inner Fiducial
- ToF Track Inside L1 Fiducial
- TRD Track Inside L1 Fiducial
- Less than 5 ToF Clusters
- Rigidity from Beta > IGRF Cutof

Numerator

- Denominator
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4

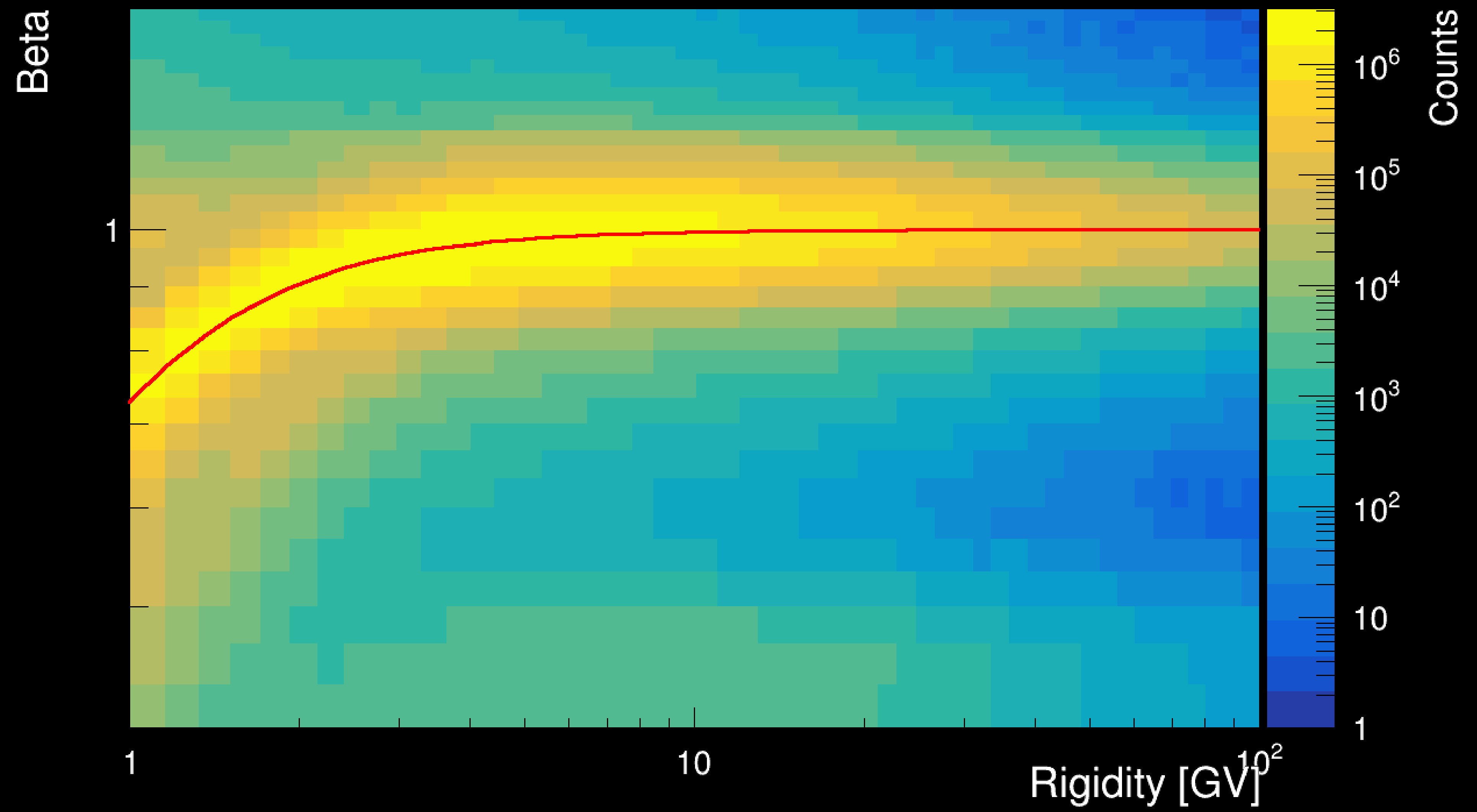
Beta

21/03/2023 – 12/07/2023

$$\beta = \frac{v}{c}$$

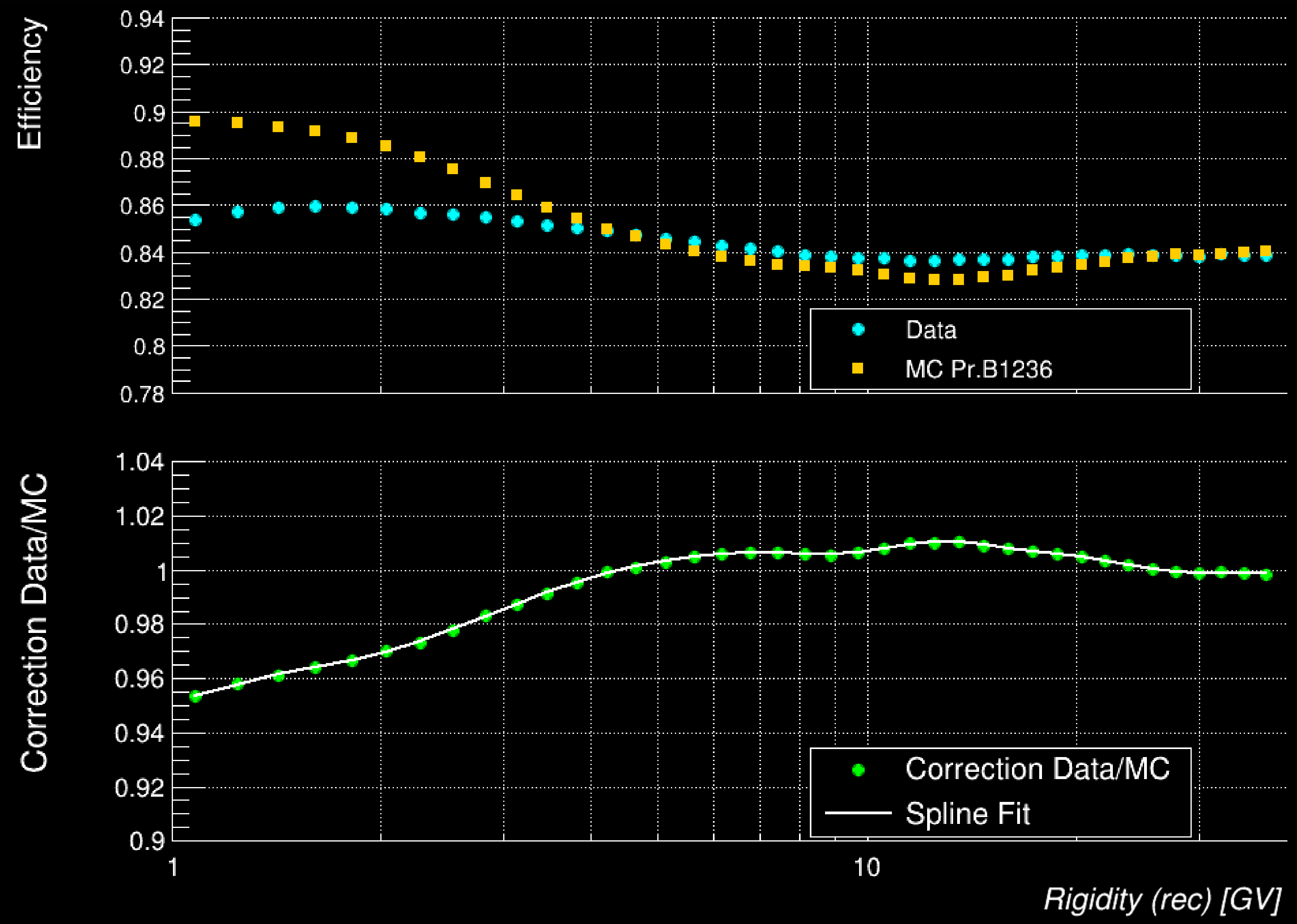
$$R = \frac{pc}{Ze}$$

$$R = \frac{m_p \beta}{\sqrt{1 - \beta^2}}$$



Trigger Efficiency

$$\varepsilon_{tri} = \frac{N_{UNB\,\&\,PHY}}{\propto N_{UNB\,\&\,\overline{PHY}} + N_{UNB\,\&\,PHY}}$$



Denominator

- RTI cuts (see event selection)
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- Chi2Y < 10 (InnerL1 rigidity)
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4
- 0.6 < L1 Charge < 2
- Inside Inner Fiducial (InnerL1 rigidity)
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10
- Beta > 0.4
- 0.5 < Upper ToF Charge < 2.5
- Mass Cut
- InnerL1 Rigidity > IGRF Cutoff
- Unbiased Trigger (PhysBPatt & 01000001)

Numerator

- Denominator
- Any Physical trigger

Trigger Efficiency

Trigger Bitmask	
Bit	**Description**
1	Unbiased Charged (prescale: 1/100)
2	Single Charge
3	Normal Ion
4	Slow Ion
5	Electron
6	Photon
7	Unbiased EM (prescale: 1/1000)

Denominator

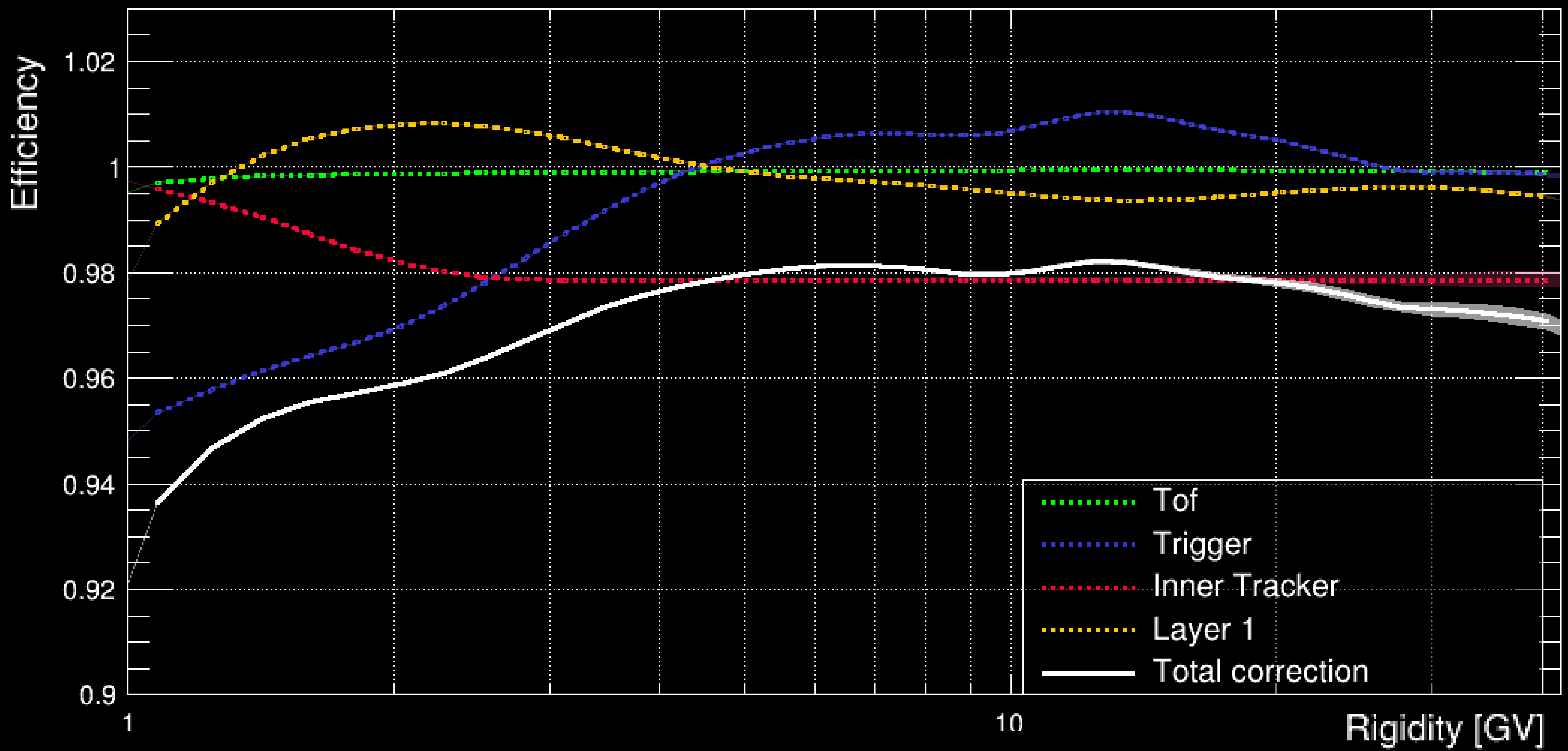
- RTI cuts (see event selection)
- Chi2Y < 10 (Inner rigidity)
- Hits on: L2 & (L3|L4) & (L5|L6) & (L7|L8)
- At least 5 Hits in Inner Tracker
- Chi2Y < 10 (InnerL1 rigidity)
- 0.7 < Inner Charge < 1.5
- Inner Charge / Inner Charge RMS < 0.4
- 0.6 < L1 Charge < 2
- Inside Inner Fiducial (InnerL1 rigidity)
- Inside L1 Fiducial (InnerL1 rigidity)
- L1 Normalized Residual < 10
- Beta > 0.4
- 0.5 < Upper ToF Charge < 2.5
- Mass Cut
- InnerL1 Rigidity > IGRF Cutoff
- Unbiased Trigger (PhysBPatt & 01000001)

Numerator

- Denominator
- Any Physical trigger

Total Efficiency Correction

$$\varepsilon_{\mathrm{TOT}} = \varepsilon_{\mathrm{ToF}}\ \varepsilon_{\mathrm{Trig}}\ \varepsilon_{\mathrm{InnTrack}}\ \varepsilon_{\mathrm{L1}}$$

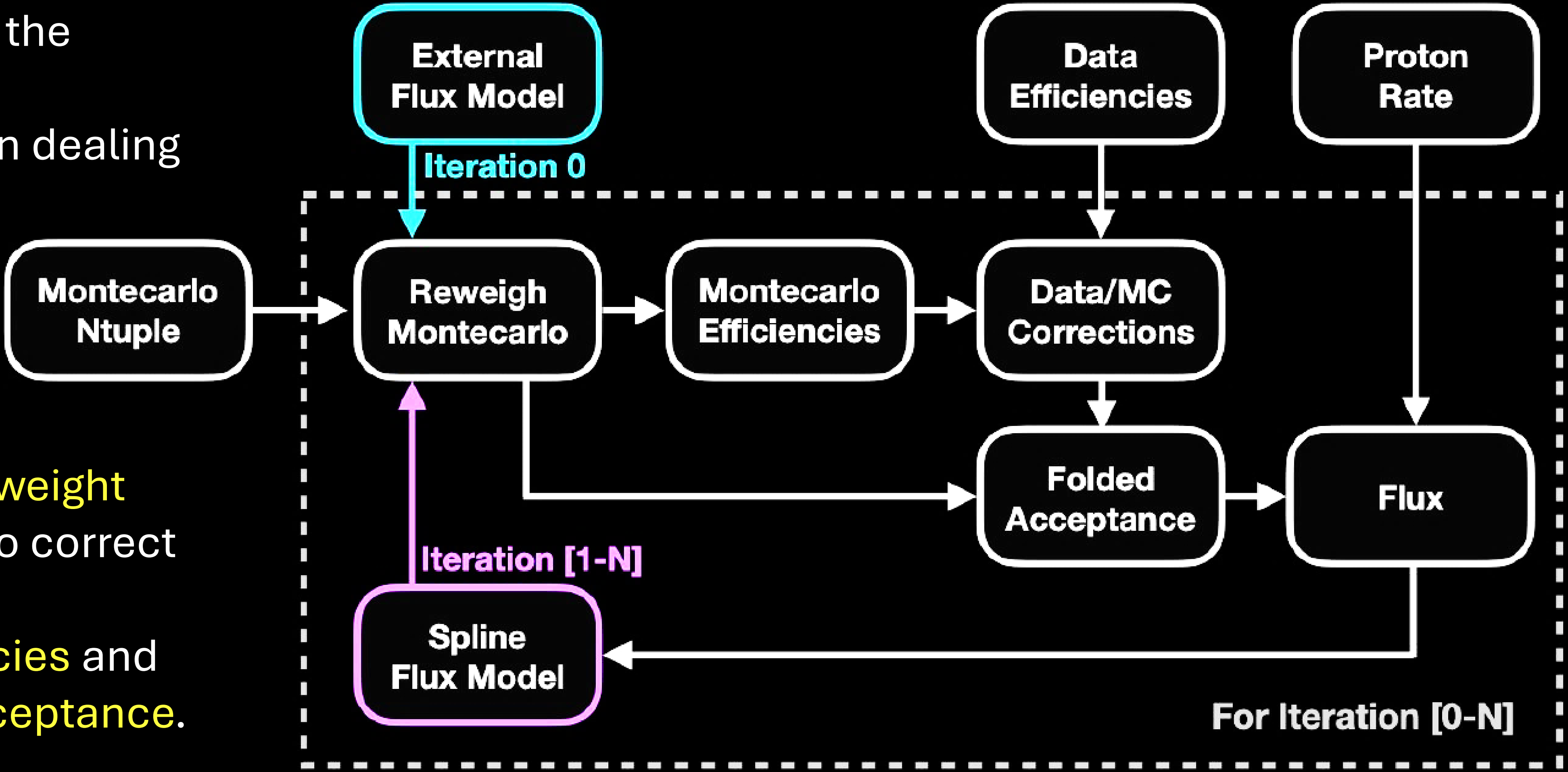


Flux and Unfolding

$$\text{Weight} = \text{gen} * \text{flux(gen)} * \text{norm}$$

$$\text{Norm} = \ln\,(100/0.5)\ /\ \int_{0.5}^{100} \text{flux(R) dR}$$

Unfolding is a procedure meant to correct for the effects of detector measurements when dealing with binned data.



Iterative process: reweight Montecarlo events to correct at each iteration the Montecarlo Efficiencies and the Geometrical Acceptance.