Measurement of

Cosmic-Ray Isotope Fluxes

with the

Alpha Magnetic Spectrometer

on the

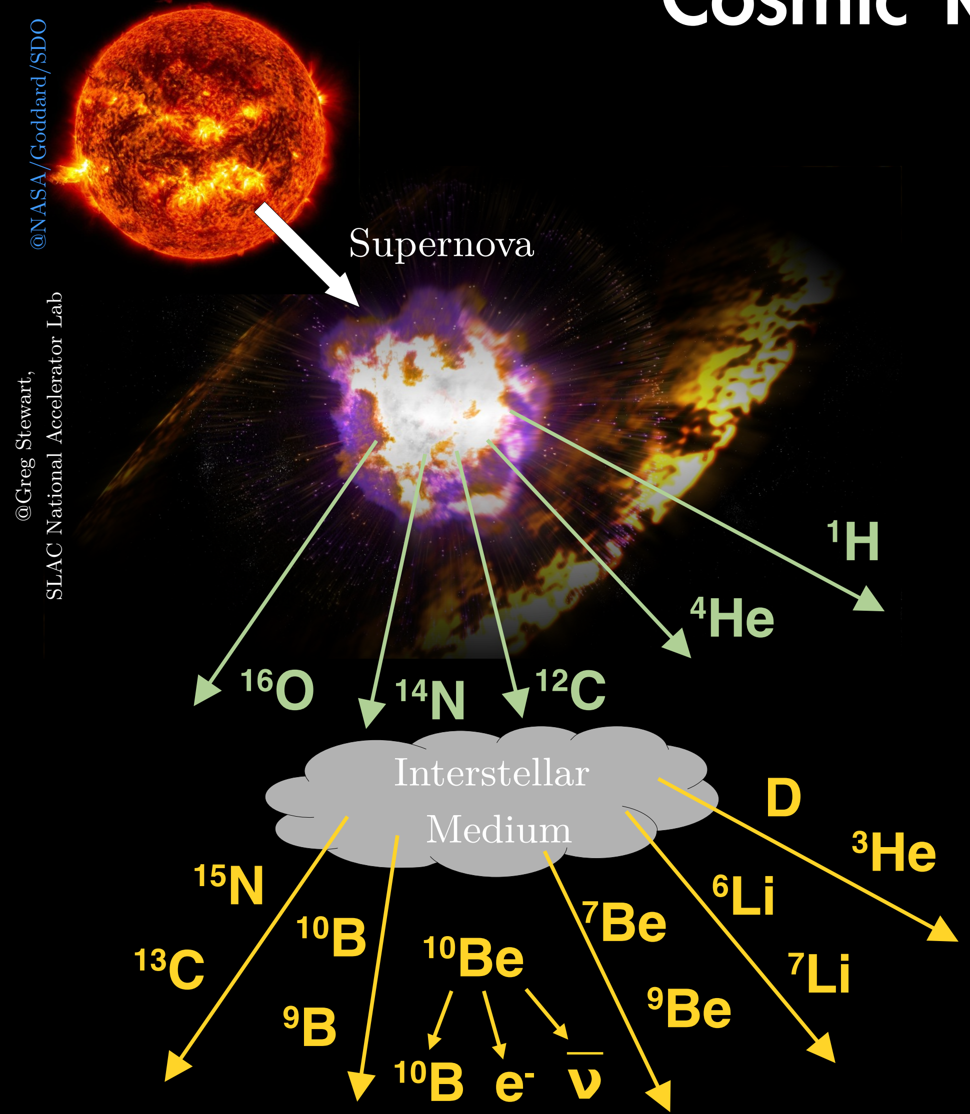
International Space Station

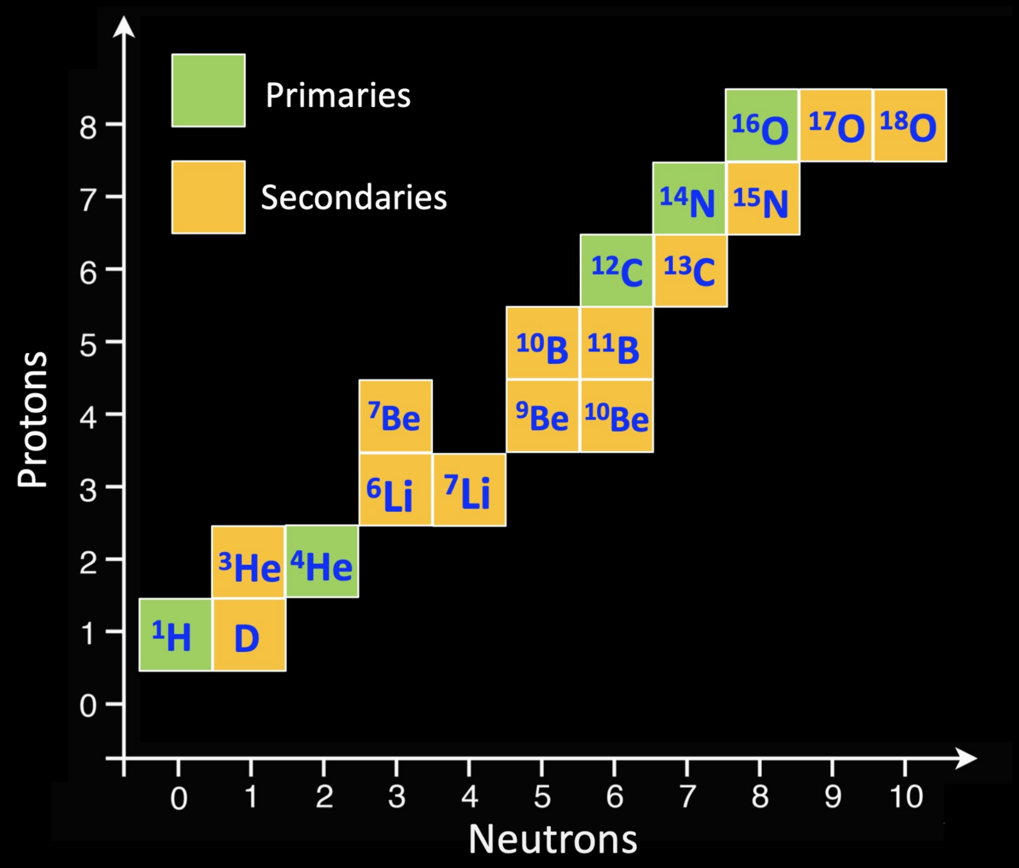
Erwan Robyn

November 27, 2024

INFN BOLOGNA

Cosmic Rays Isotopes



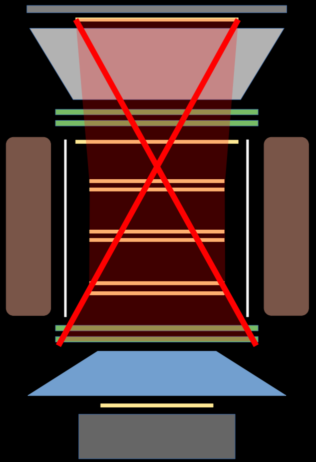


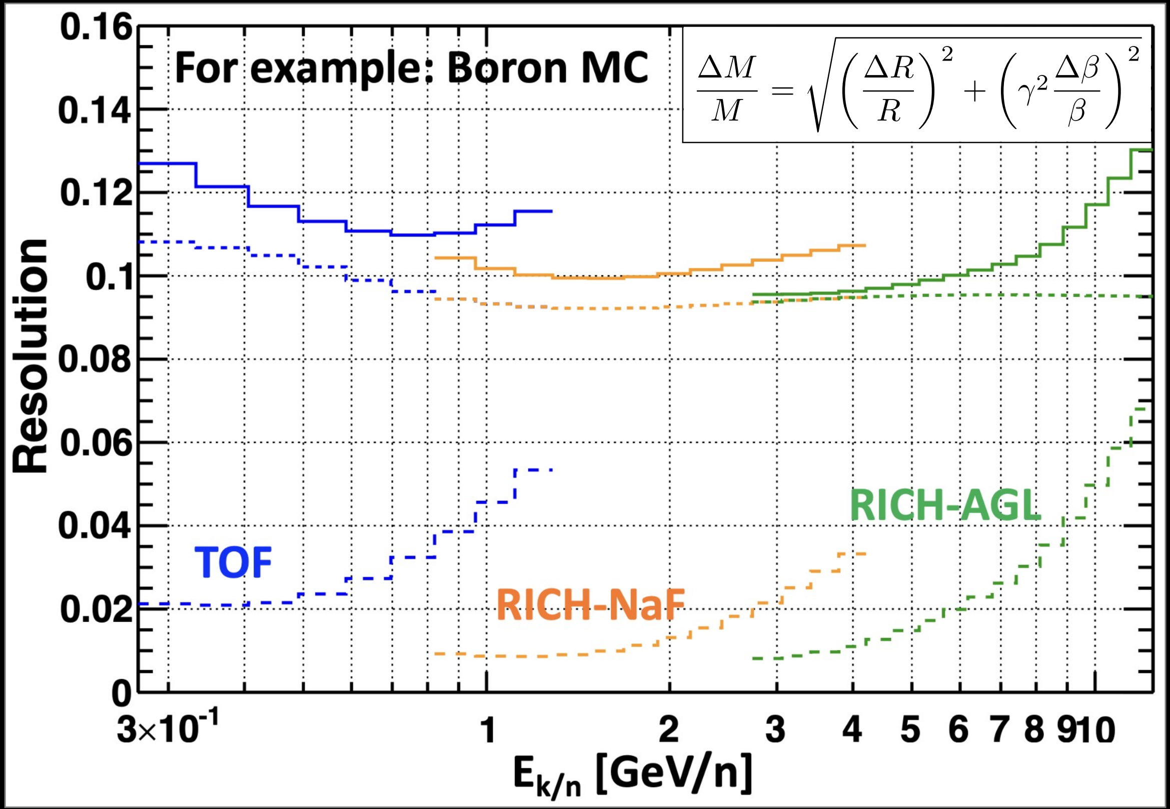
Three Different Geometries

To cover three different beta ranges:

$$M = \frac{ZR}{\beta\gamma}$$

L1Inner + ToF



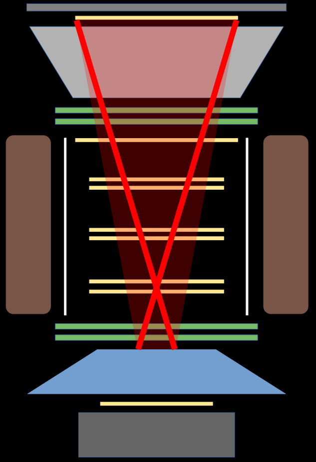


$\frac{\Delta M}{M}$

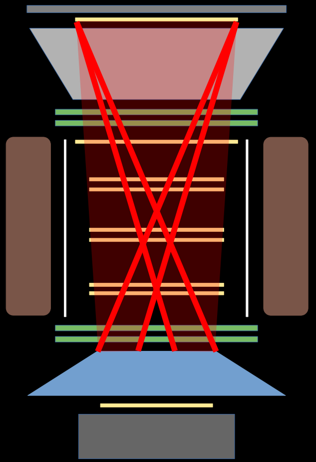
$\frac{\Delta R}{R}$

$\gamma^2 \frac{\Delta \beta}{\beta}$

L1Inner + NaF



L1Inner + Agl



Flux Formula

1st objective : Being able to measure the nuclei fluxes using the different AMS geometries to ensure that we have a good control and understanding of our selections before going to the mass measurement

The nuclei flux ϕ_i in the i^{th} rigidity bin $[R_i, R_i + \Delta R_i]$ is computed as:

$$\phi_i = \frac{N_i - B_{AL1,i} - B_{BL1,i}}{\varepsilon_{L1UQcut,i}} \times \frac{1}{T_i \Delta R_i} \times \frac{1}{A_i \times \Pi_j \varepsilon_{ij,MC} \delta_{ij}} \times \frac{1}{C_{uf}}$$

N_i : event count corrected for

- $B_{AL1,i}$: contamination from nuclei fragmented above the tracker Layer 1
- $B_{BL1,i}$: contamination from nuclei fragmented below the tracker Layer 1
- $\varepsilon_{L1UQcut,i}$: Layer 1 upper charge cut efficiency

T_i : exposure time

ΔR_i : rigidity bin width

A_i : geometric acceptance

$\epsilon_{ij,MC}$: Monte-Carlo detection, reconstruction and selection efficiencies

$\delta_{ij} = \frac{\epsilon_{ij,data}}{\epsilon_{ij,MC}}$: Data/Monte-Carlo efficiencies ratios

C_{uf} : unfolding factor which correct the bin-to-bin migration

Event Selections

Use NAIA v1.1.0: ISS: B1236; MC: ~~B1306~~ $\rightarrow$ B1308

The analysis is performed using a software developed by the Bologna group to measure heavy nuclei fluxes and their time dependence

---

Standard nuclei selections on Inner Tracker track and InnerL1 (L1, UToF, and Inner) charges.

Use L1 hit for charge measurements but the Inner Rigidity!

InnerL1 + ToF :

- Exclude ToF edge paddles
- Coo Chi2 < 5
- Time Chi2 < 10

InnerL1 + RICH :

- Good & clean
- $P_{\text{Kolmogorov}} > 0.01$
- $N_{\text{PMT}} > 2$
- Z-1< Q_{RICH} < Z+2

InnerL1 + RICH NaF :

- NaF geometry
- $N_{\text{pe}}(\text{ring})/N_{\text{pe}}(\text{total}) > 0.45$

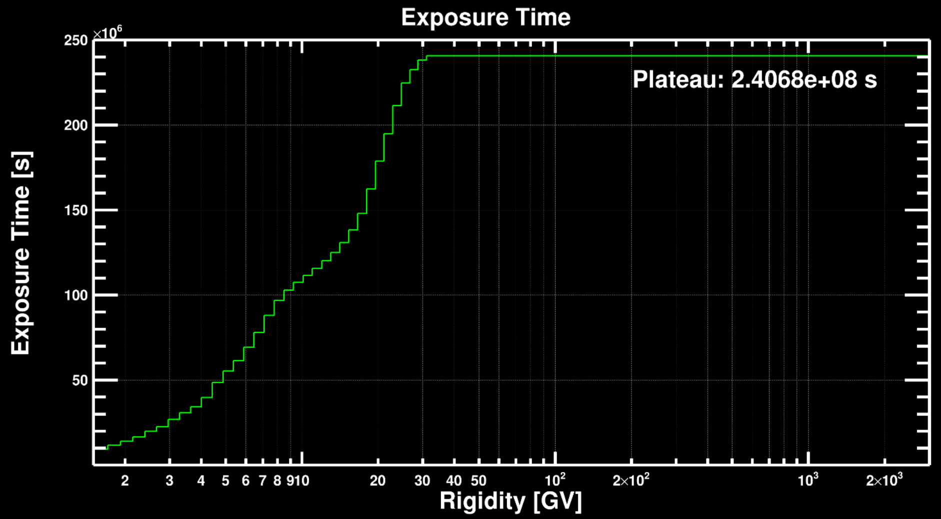
InnerL1 + RICH Agl :

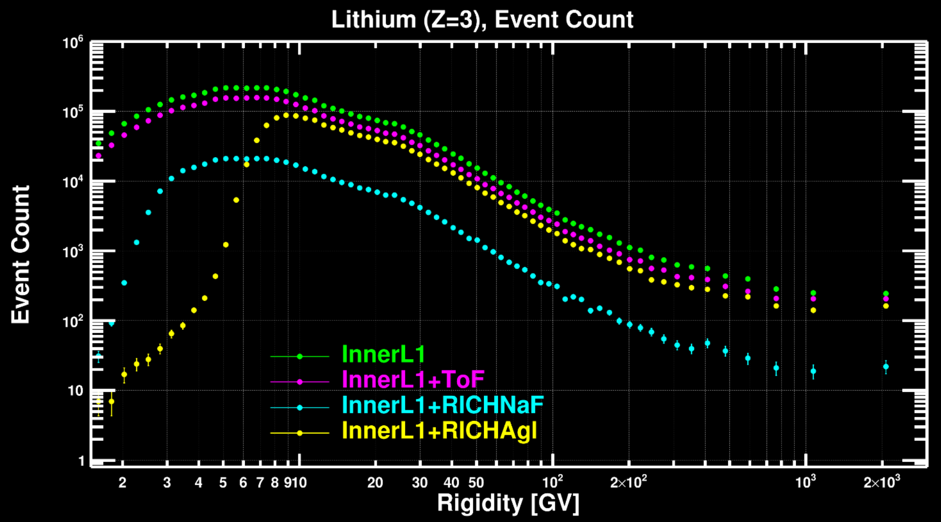
- AGL geometry
- $N_{\text{pe}}(\text{ring})/N_{\text{pe}}(\text{total}) > 0.4$
- Good Rich Tiles

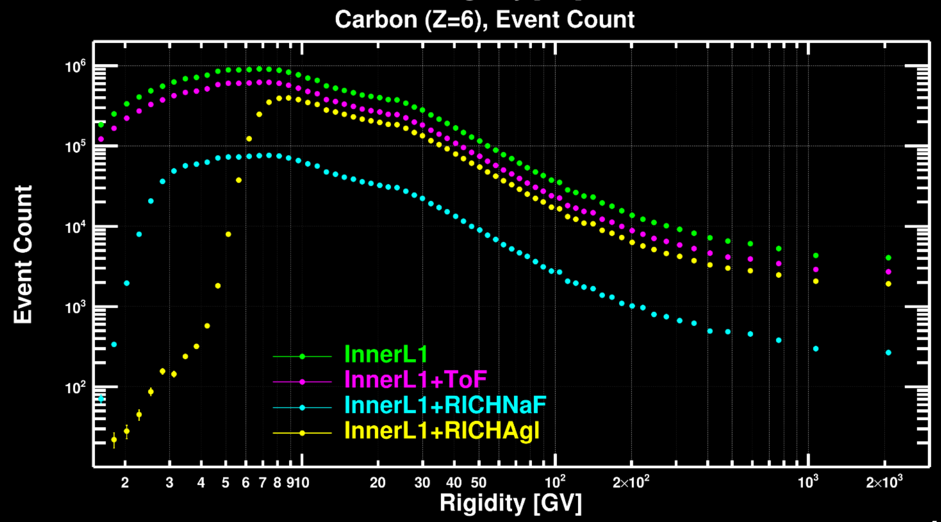
11.5 Years Event Count and Exposure Time

- Event collected during the first 11.5 years of data acquisition
- Photon trigger period discarded

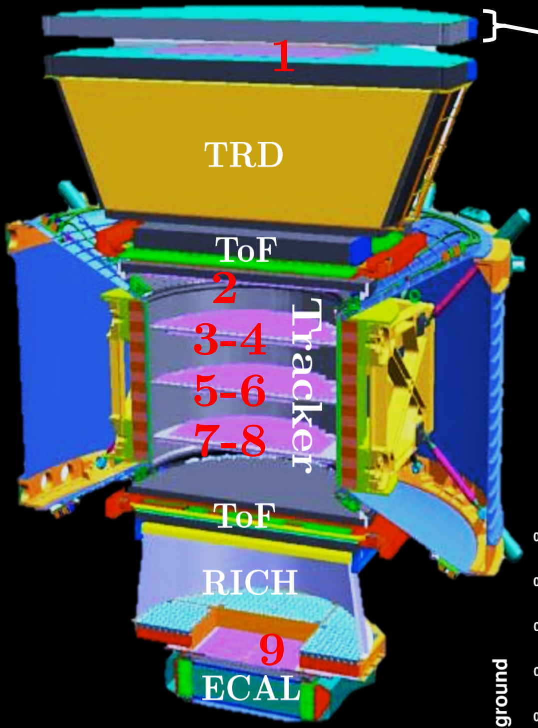
- Flux computation performed on all nuclei from Lithium (Z=3) to Oxygen (Z=8)





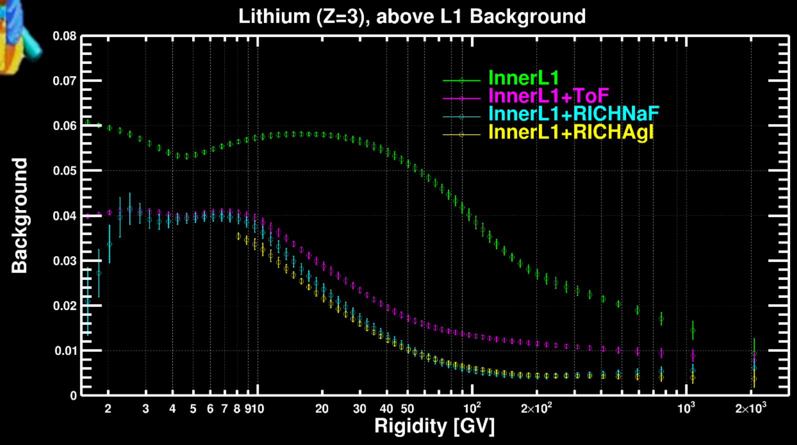


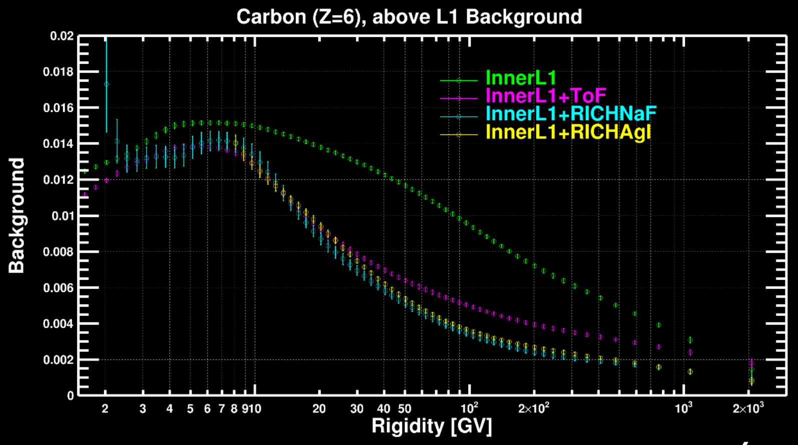
Top-of-Instrument Background



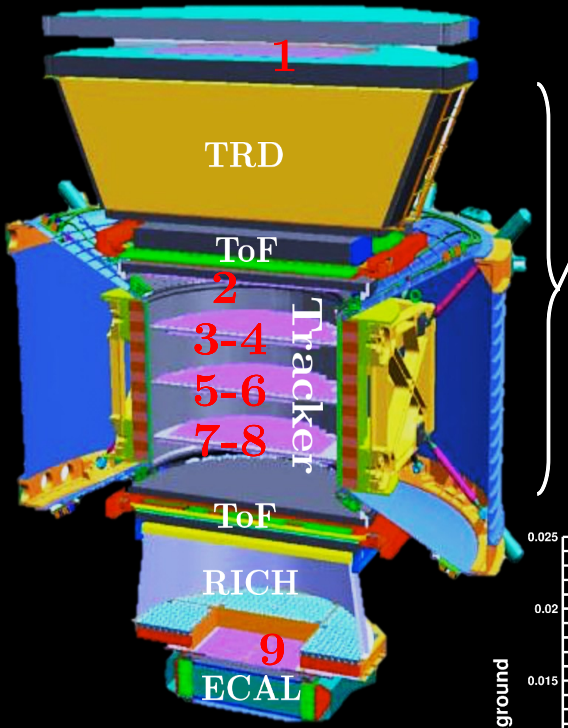
Background arising from fragmentation of heavier nuclei in the AMS material above the tracker L1.

- The background computation is done using the MC simulation
- Each nuclei is reweighted according to the published AMS flux
- Measured using MC nuclei from Lithium (Z=3) to Oxygen (Z=8)





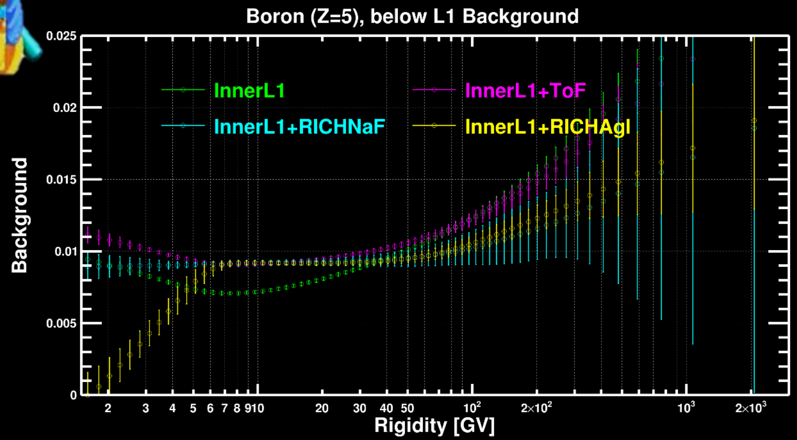
Below Tracker L1 Background

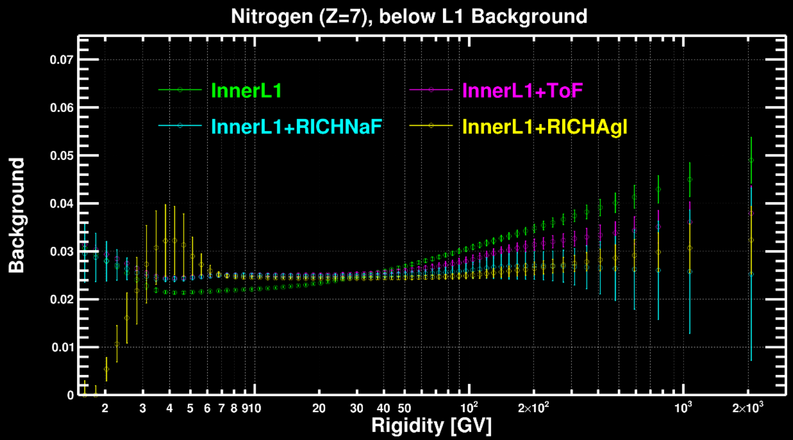


Background arising from charge miss-identification due to finite AMS charge resolution and/or fragmentation of heavier nuclei in the AMS material below the tracker L1.

The background is obtained using L2 charge distribution as charge template.

The background is found to be negligible except for Boron (Z=5) and Nitrogen (Z=7)

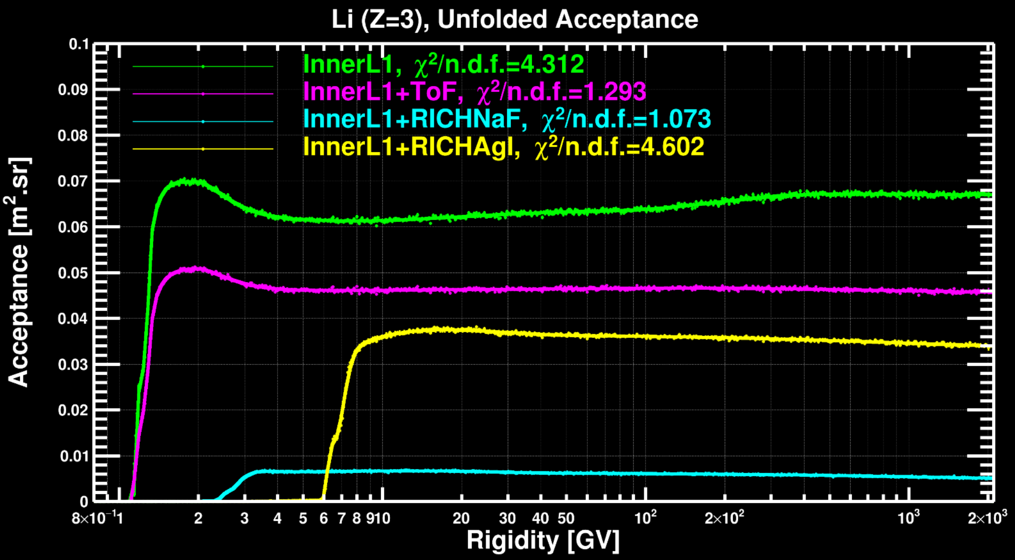


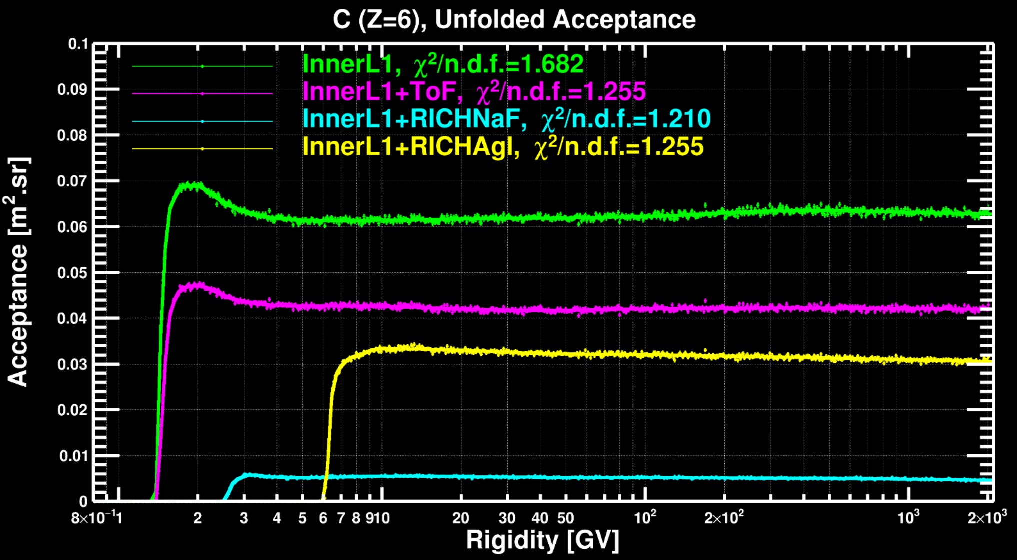


MC Effective Acceptance

MC acceptance computed averaging the isotopic acceptances.

Li		Be		B		C	N		O
^{6}Li	^{7}Li	^{7}Be	^{9}Be	^{10}B	^{11}B	^{12}C	^{14}N	^{15}N	^{16}O
50%	50%	50%	50%	30%	70%	100%	50%	50%	100%





Selections

Denominator:

- Tracker InnerL1 fiducial volume + ToF or RICH
- Physical trigger
- beta > 0.3, NToF Hit >= 3

- 2^{nd} track rigidity < 0.5 GV

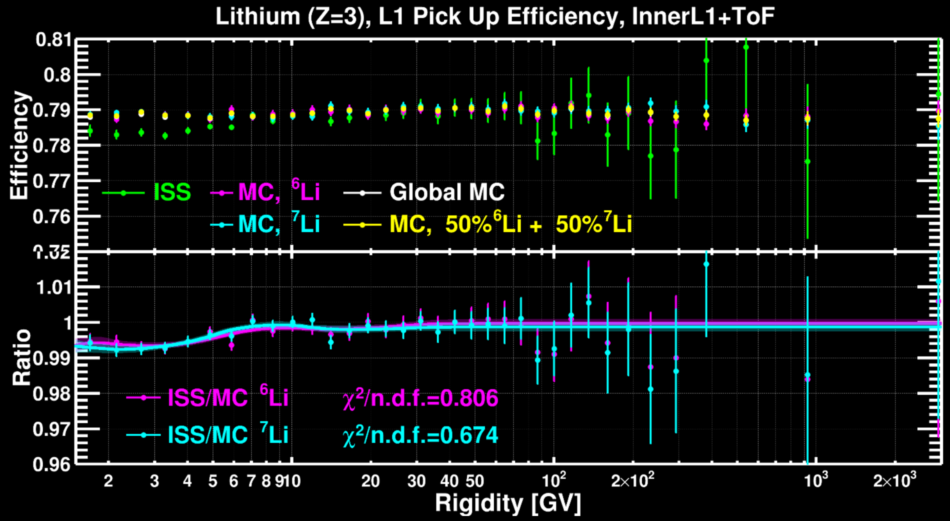
- Charge selections:
  - Z-0.45 < QInner < Z+0.45
  - QInner, RMS < 0.55
  - Z-0.6 < QUToF < Z+1.5

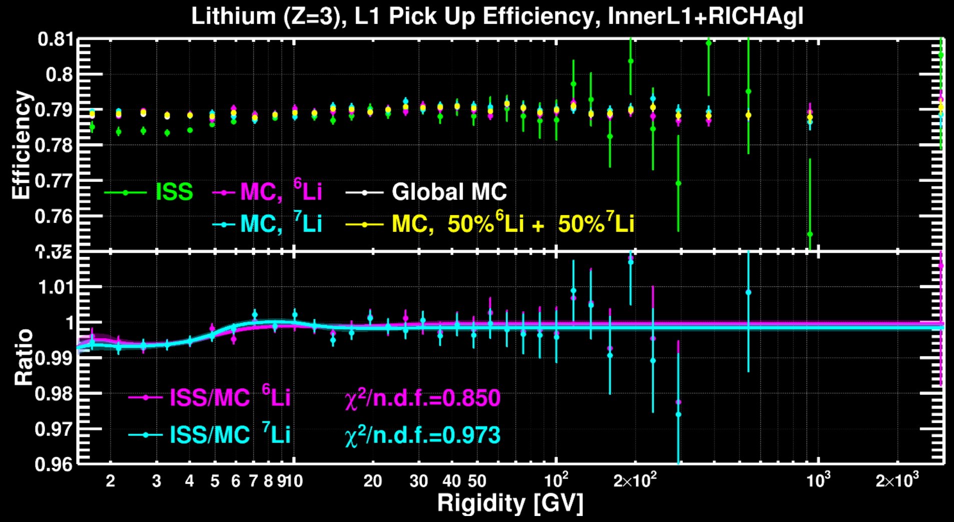
Numerator:

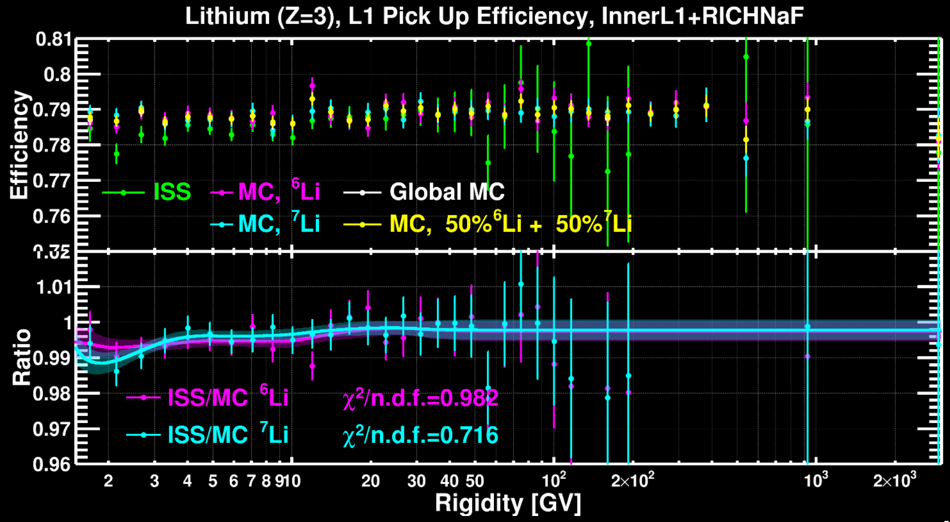
- Charge selections:
  - Z-0.46-0.16(Z-3) < QL1
  - Good L1 charge status

L1 Pick Up Efficiency

The L1 Pick Up efficiency shows no geometry nor mass dependence

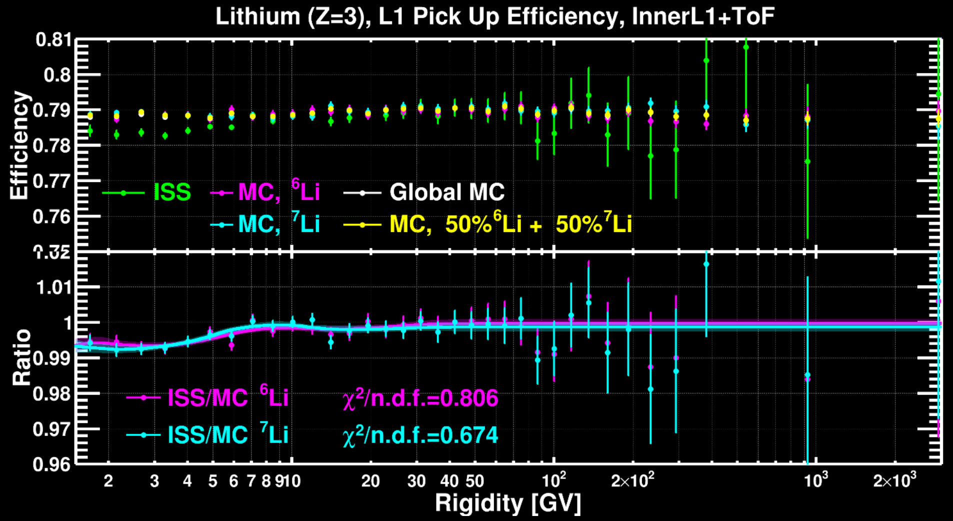


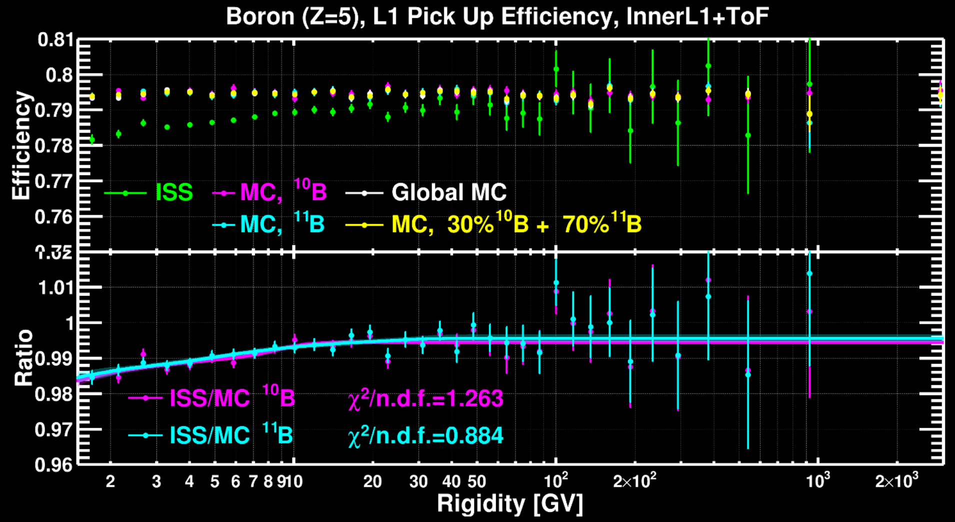


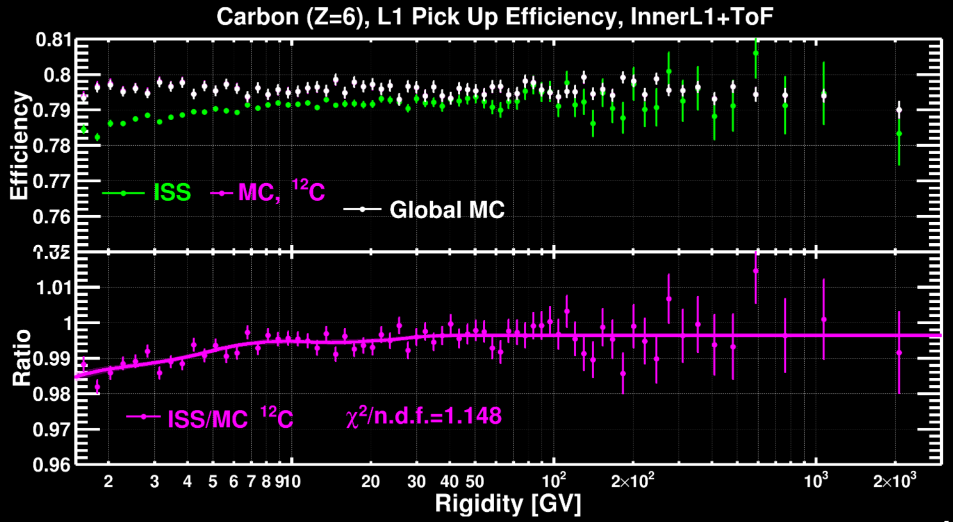


L1 Pick Up Efficiency

Nor charge dependence







Selections

Denominator:

- Tracker InnerL1 fiducial volume ToF or RICH
- Physical trigger
- beta > 0.3, NToF Hit >= 3
- No 2nd Track:
  - 2nd Track Rigidity < 0.5 GV ||
    ntrack==1 ||
    (Inner X Hit < 3 && Inner Y Hit < 5)

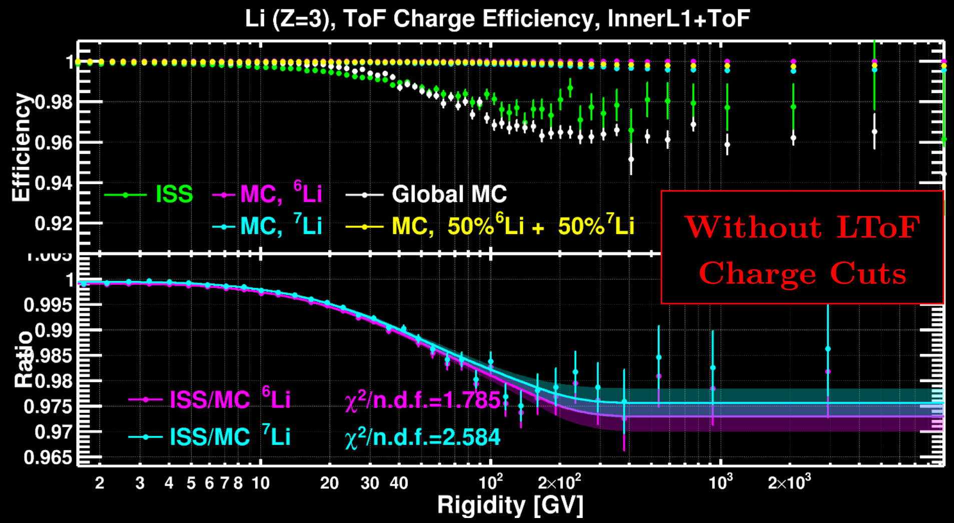
- Track:
  - L1XY Hit
  - InnerNHitY>=5 &&
    L2&(L3|L4)&(L5|L6)&(L7|L8)
  - InnerNormChisY<10

- Charge selections:
  - | QL1 – Z | < Min(0.5, 2σ)
  - | QInner – Z | < Min(0.5, 2σ)
  - | QLToF – Z | < Min(0.5, 2σ)

Numerator:

- Charge selections:
  - Z-0.6 < QUToF < Z+1.5

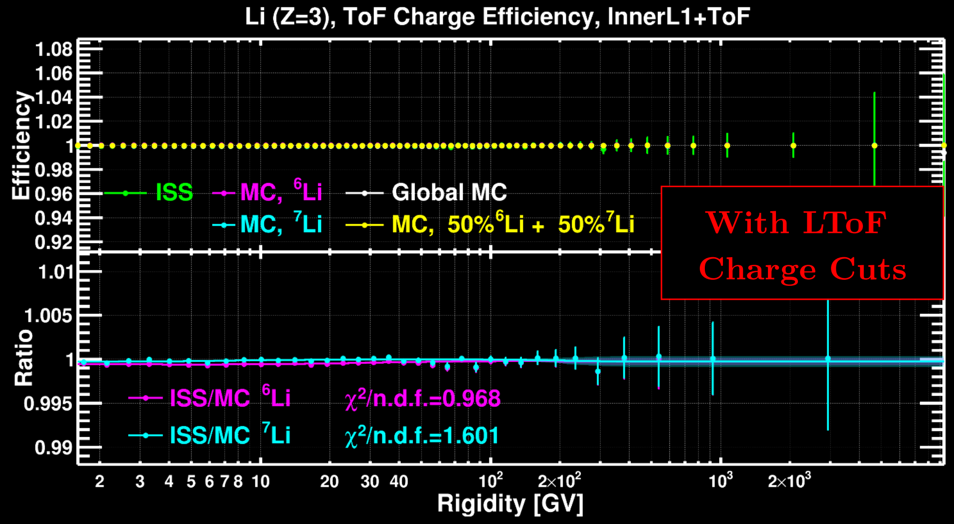
UToF Charge Efficiency

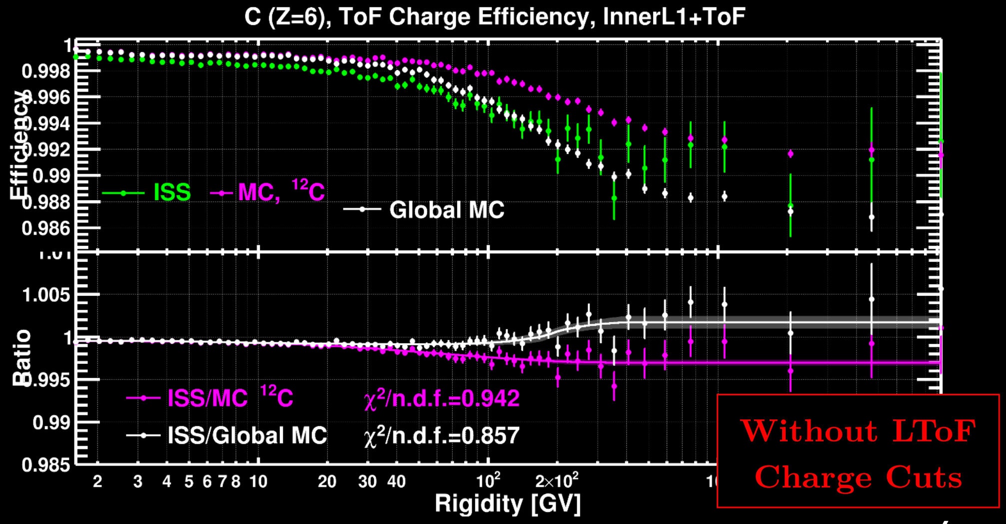


The UToF Charge efficiency is sensitive to contamination

The LToF charge cut helps removing interacting events, but maybe too much?

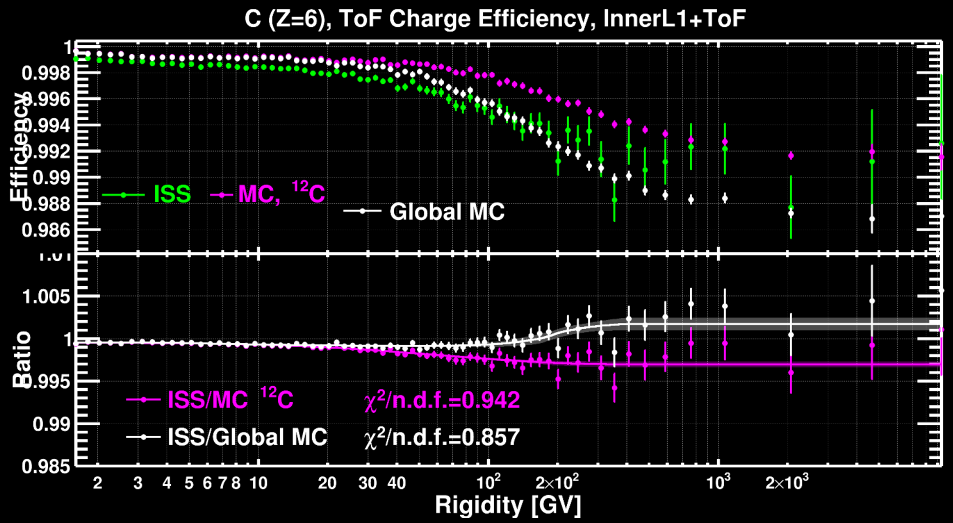
Carbon (~clean) sample shows good agreement between data and MC even with remaining contamination sensitivity.

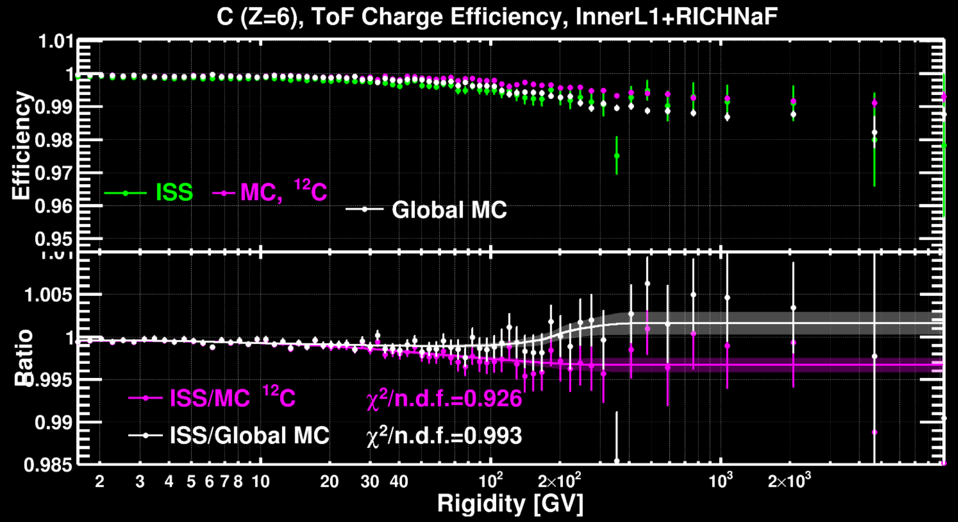


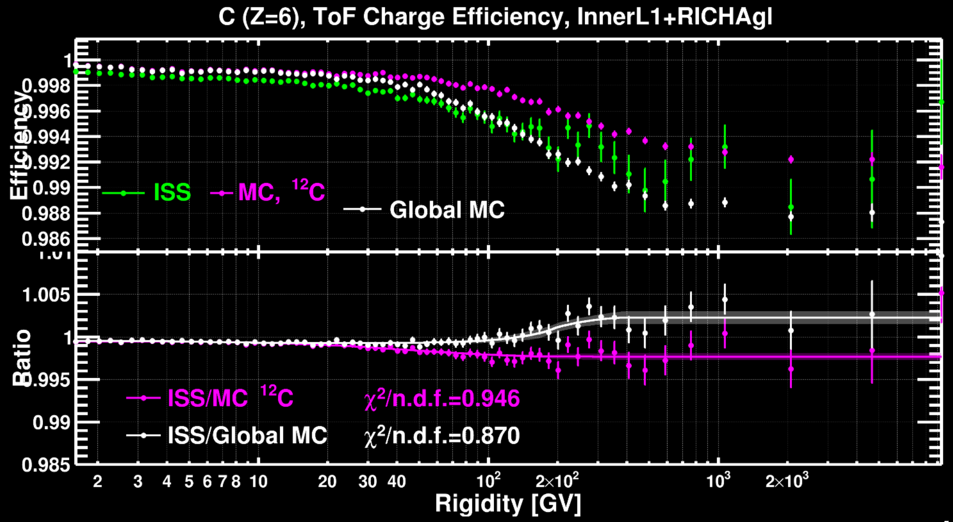


UToF Charge Efficiency

The conclusions are the same for all the geometries







Selections (Only for L1Inner+ToF)

Denominator:

- Tracker InnerL1 fiducial volume ToF
- Physical trigger
- beta > 0.3, NToF Hit >= 3
- No 2nd Track:
  - 2nd Track Rigidity < 0.5 GV ||
    ntrack==1 ||
    (Inner X Hit < 3 && Inner Y Hit < 5)

- Track:
  - L1XY Hit
  - InnerNHitY>=5 &&
    L2&(L3|L4)&(L5|L6)&(L7|L8)
  - InnerNormChisY<10

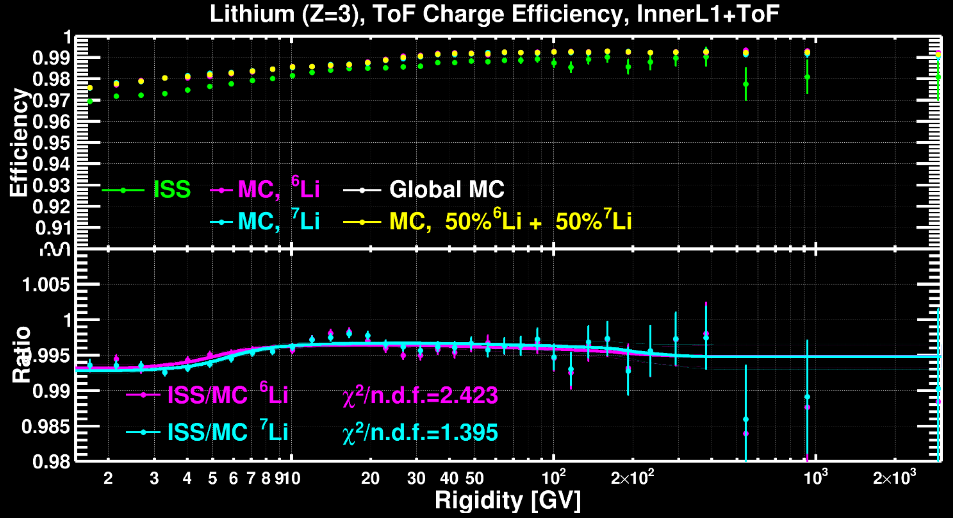
- Charge selections:
  - | QL1 – Z | < Min(0.5, 2σ)
  - | QInner – Z | < Min(0.5, 2σ)
  - | QUToF – Z | < Min(0.5, 2σ)

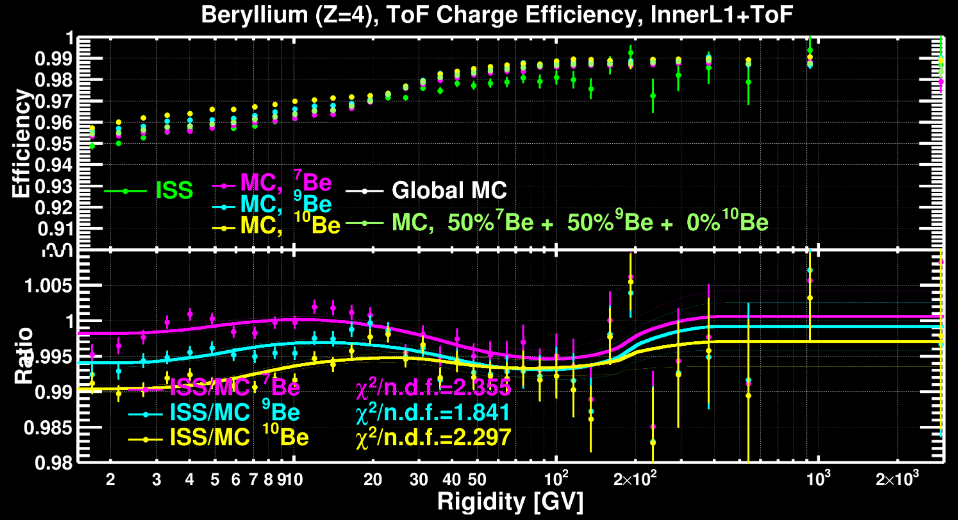
Numerator:

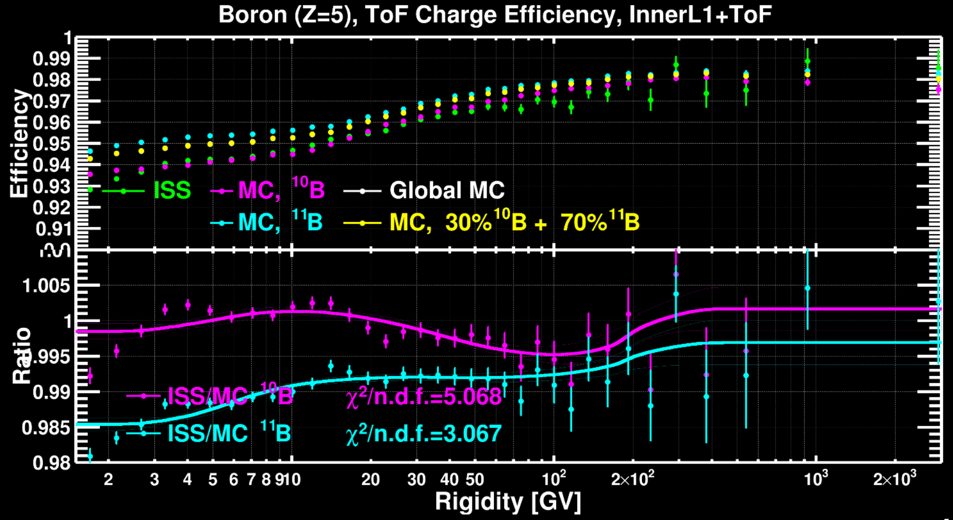
- Charge selections:
  - QLToF > Z-0.6

LToF Charge Efficiency (MC B1308)

The efficiency shows mass dependency for some charges.
These requires further checks...







Selections

Denominator:

- Standalone Tracker InnerL1 fiducial volume + ToF or RICH
- Physical trigger

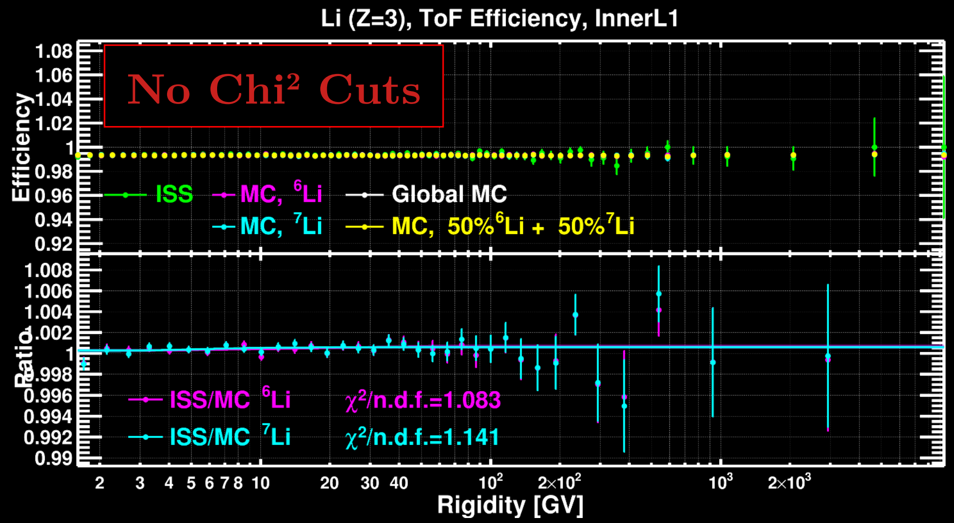
- Track:
  - Standalone InnerNHitY>=5 && L2&(L3|L4)&(L5|L6)&(L7|L8)
  - Standalone InnerNormChisY<10

- Charge selections:
  - | Standalone QL1 – Z | < Min(0.5, 2σ)
  - | Standalone QInner – Z | < Min(0.5, 2σ)
  - | QLToF – Z | < Min(0.5, 2σ)

Numerator:

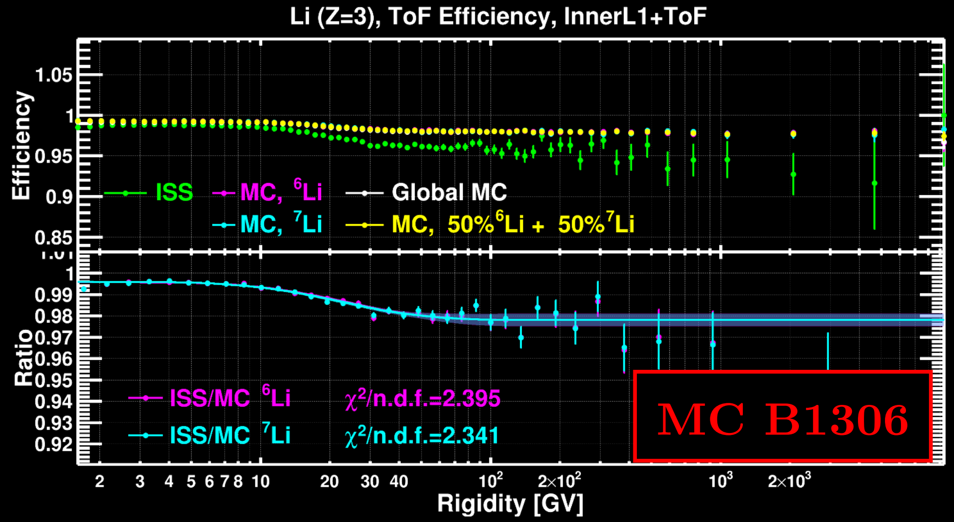
- beta > 0.3, NToF Hit >= 3
- Coo Chi2 < 5
- Time Chi2 < 10

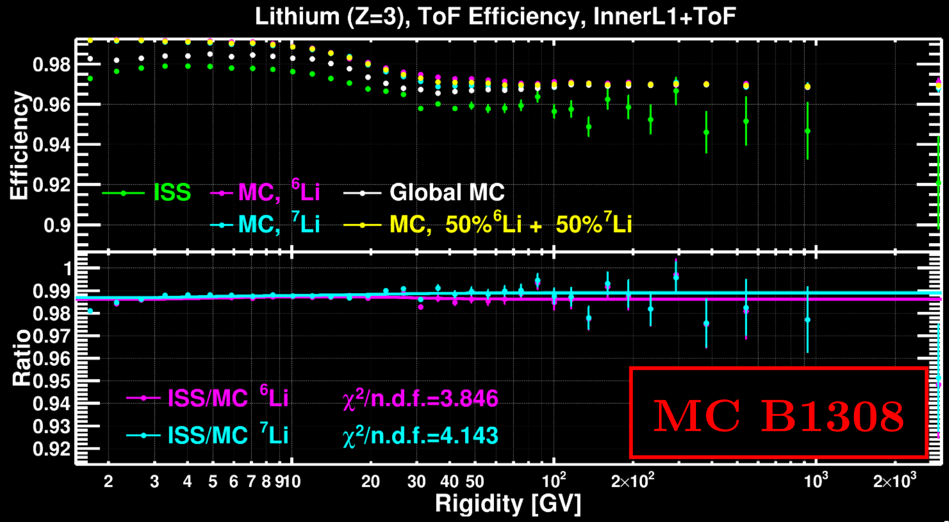
ToF Beta Efficiency



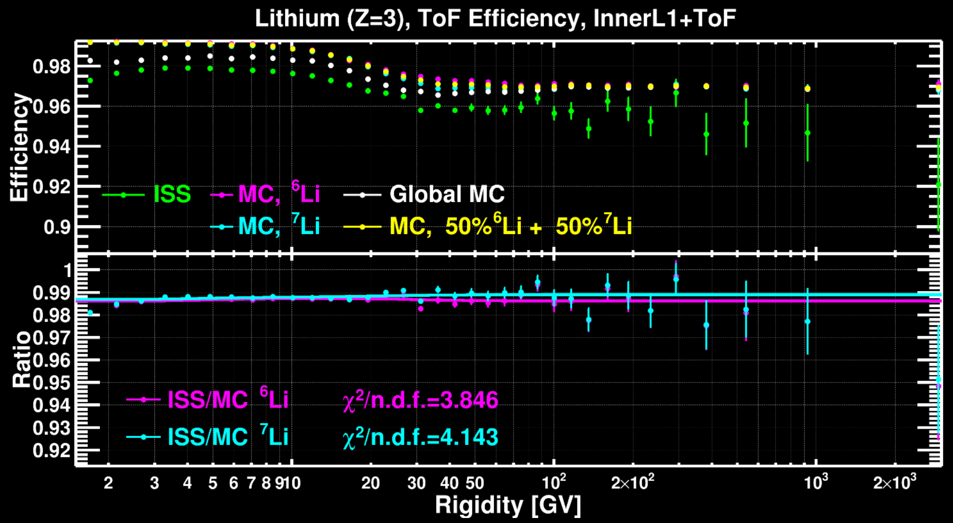
The ToF Chi² cuts introduce a discrepancy between data and MC efficiencies

The discrepancy is reduced in the new MC version (B1308) and its rigidity dependence as disappeared

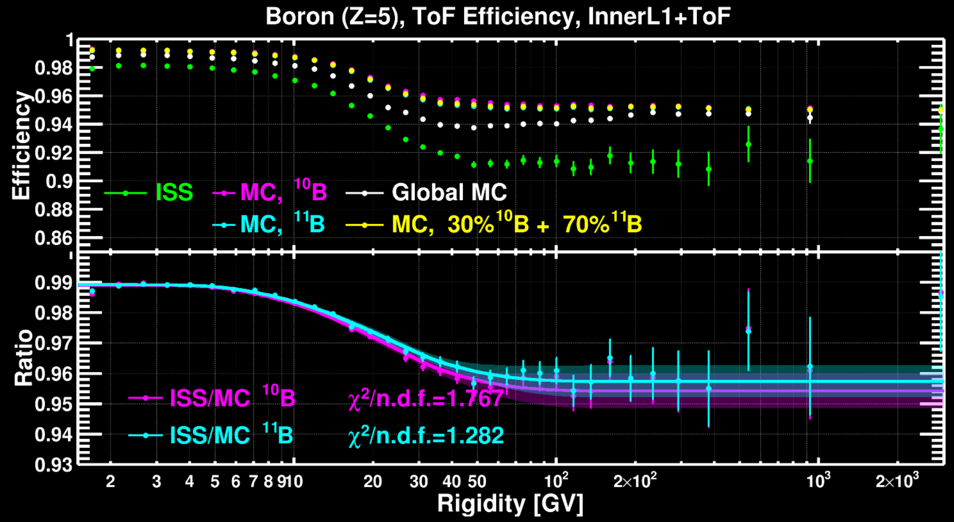


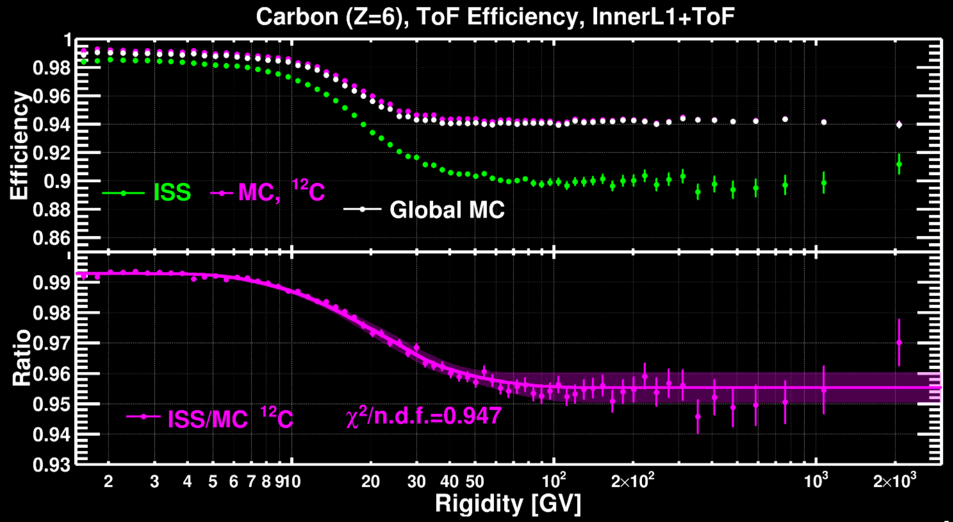


ToF Beta Efficiency



B1308 is better but only for Lithium ??





Selections

Denominator:

Common:

- Standalone Tracker InnerL1 fiducial volume + ToF or RICH
- Physical trigger

- Track:
  - Standalone InnerNHitY>=5 && L2&(L3|L4)&(L5|L6)&(L7|L8)
  - Standalone InnerNormChisY<10

- Charge selections:
  - | Standalone QL1 – Z | < Min(0.5, 2σ)
  - | QUToF – Z | < Min(0.5, 2σ)
  - | QLToF – Z | < Min(0.5, 2σ)

InnerL1 + ToF :

- | Standalone QL9 – Z | < Min(0.5, 2σ)

RICH :

- Good & clean
- $P_{Kolmogorov} > 0.01$
- $Z\text{-}1 < Q_{RICH} < Z+2$

InnerL1 + RICH NaF :

- NaF geometry
- $N_{PMT} > 10$
- $N_{pe}(\text{ring})/N_{pe}(\text{total}) > 0.45$

InnerL1 + RICH Agl :

- AGL geometry
- $N_{PMT} > 2$
- $N_{pe}(\text{ring})/N_{pe}(\text{total}) > 0.4$
- Good RICH Tiles

Numerator:

- Track:
  - InnerNHitY>=5 && L2&(L3|L4)&(L5|L6)&(L7|L8)
  - L1XY Hit
  - InnerNormChisY<10

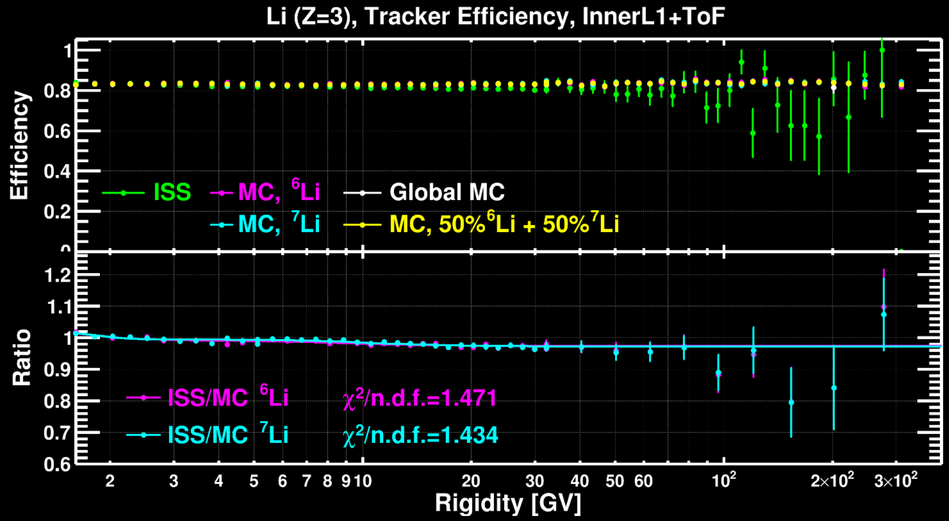
- Charge selections:
  - Z-0.45 < QInner < Z+0.45
  - QInner, RMS<0.55

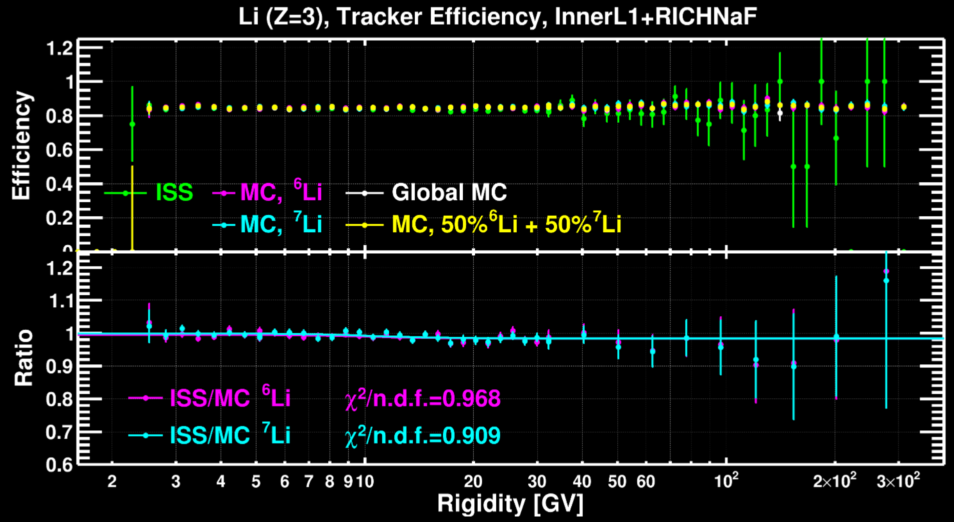
Rigidity Estimator:

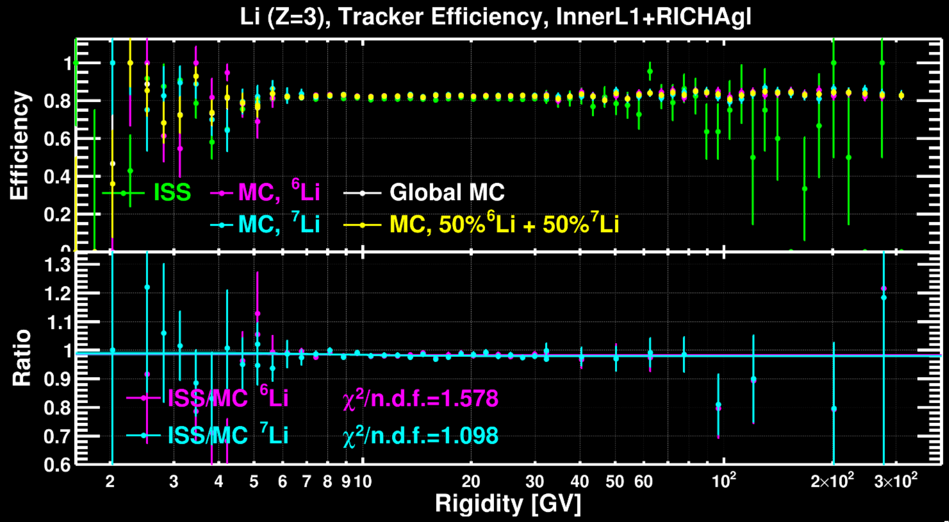
- Geomagnetic Cutoff:
- ToF Beta
- ECAL energy

Tracker Efficiency

The efficiency shows no geometry nor mass dependency

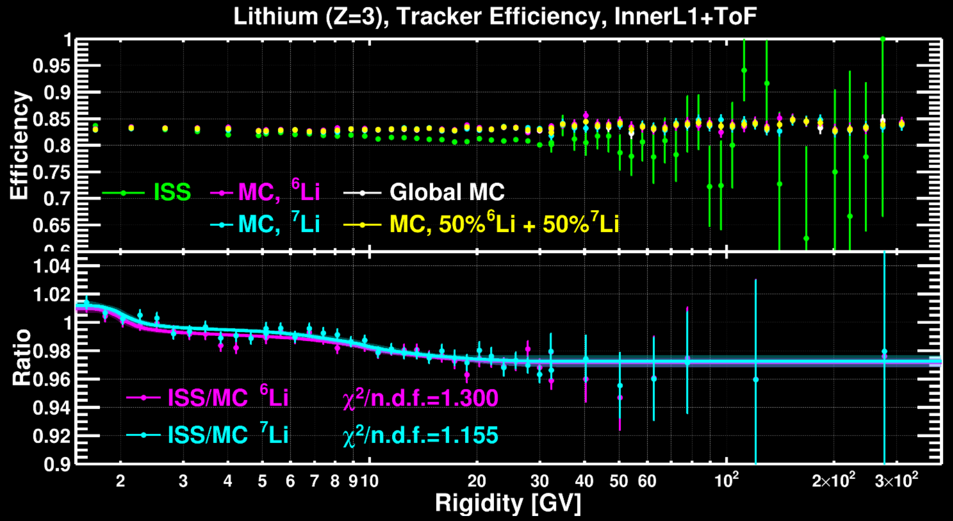


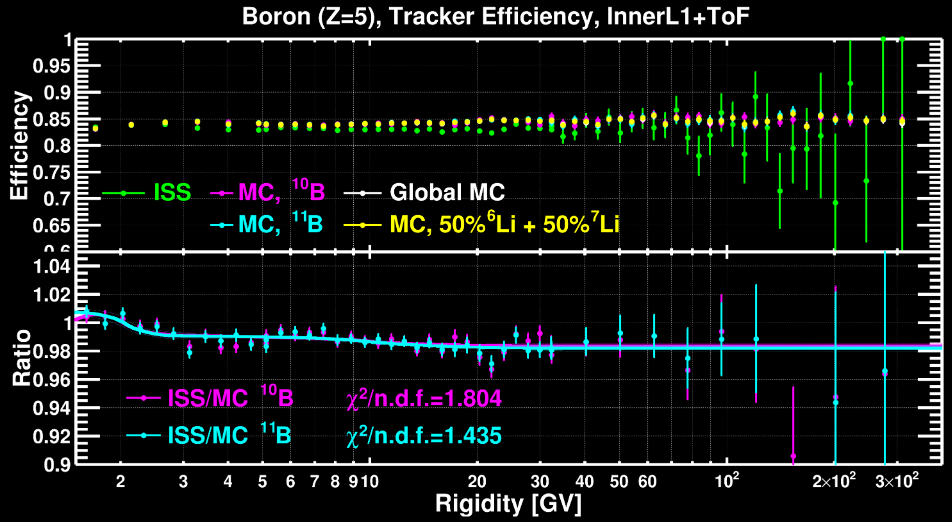


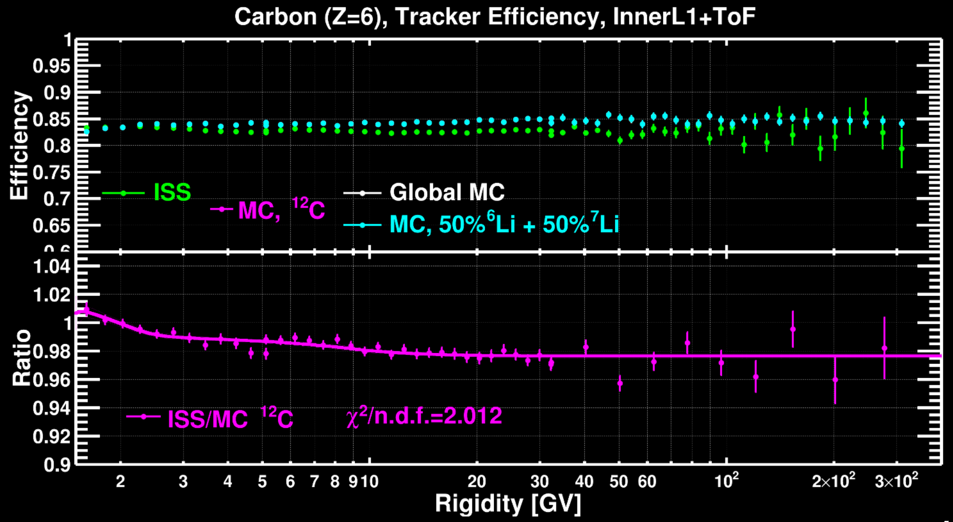


Tracker Efficiency

And small charge dependency







Selections

Denominator :

- Tracker InnerL1 fiducial volume
- Physical trigger
- beta > 0.3, NToF Hit >= 3
- R > 1.2 x Geom Cutoff

- No 2nd Track
  - 2nd Track Rigidity < 0.5GV ||
    ntrack==1 ||
    (Inner X Hit < 3 &&
    Inner Y Hit < 5)

- Track:
  - InnerNHitY>=5 &&
    L2&(L3|L4)&(L5|L6)&(L7|L8)
  - L1XY Hit
  - InnerNormChisY<10

ToF:
- Coo $Chi^2 < 5$
- Time $Chi^2 < 10$

- Charge selections:
  - Z-0.46-0.16(Z-3) < QL1 < Z+0.65
  - Good L1 charge status
  - Z-0.6 < QUToF < Z+1.5
  - Z-0.45 < QInner < Z+0.45
  - QInner, RMS<0.55

RICH :

- QLToF > Z-0.6
- Good & clean
- $P_{Kolmogorov} > 0.01$
- $Z-1 < Q_{RICH} < Z+2$
- $N_{PMT} > 2$

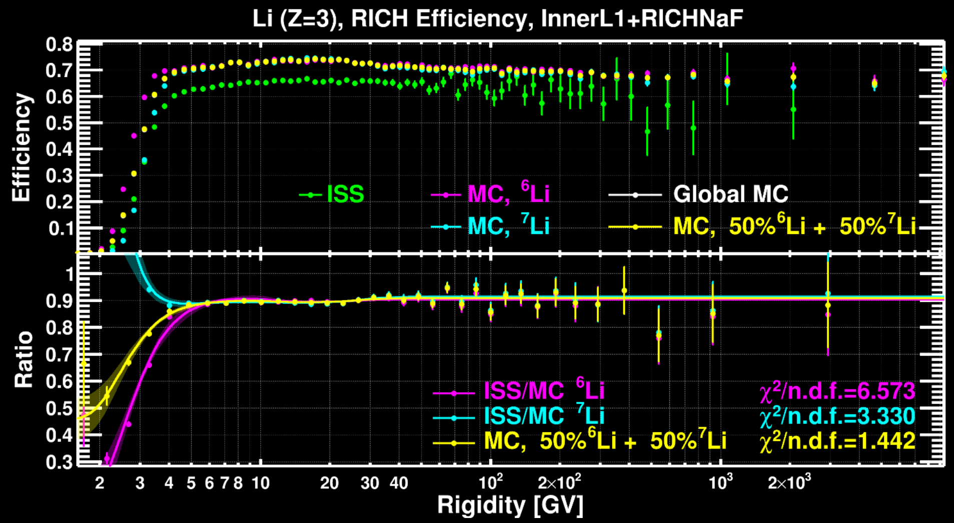
InnerL1 + RICH NaF :

- NaF geometry
- $N_{pe}(ring)/N_{pe}(total) > 0.45$

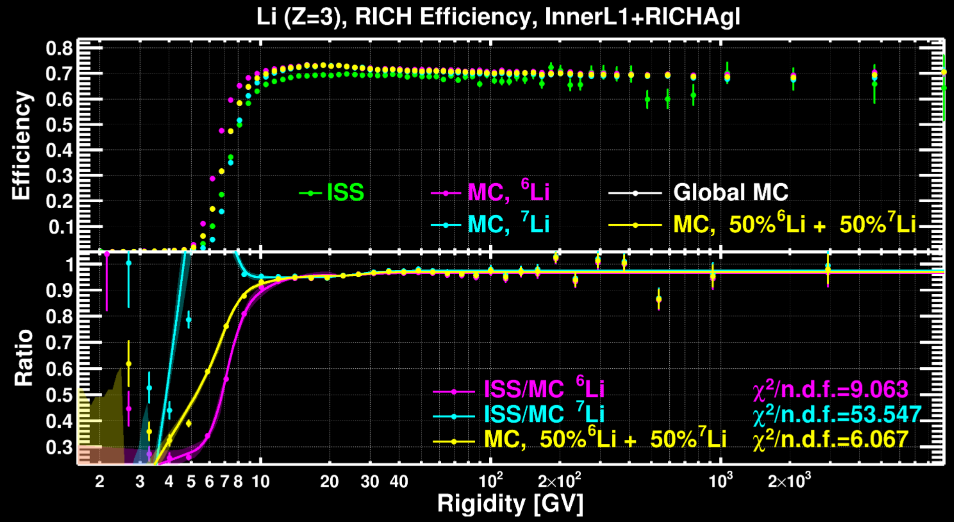
InnerL1 + RICH Agl :

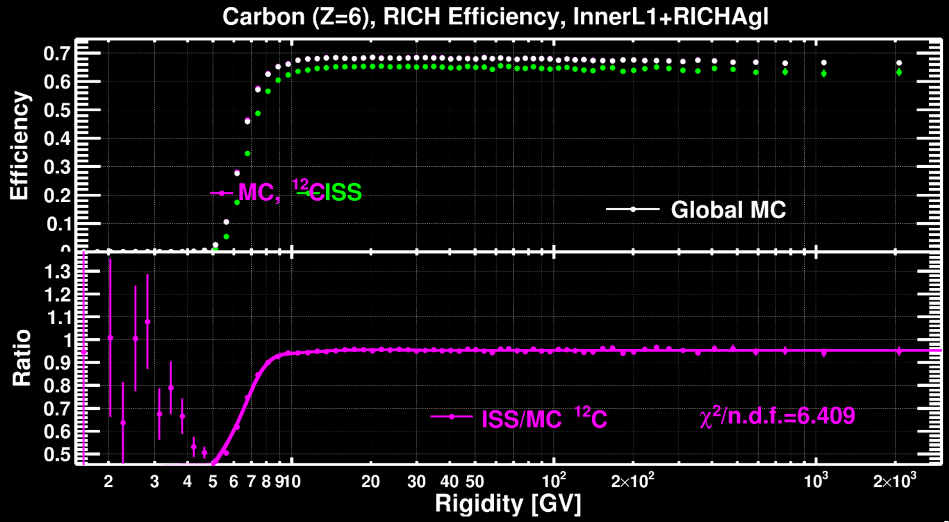
- AGL geometry
- $N_{pe}(ring)/N_{pe}(total) > 0.4$
- Good RICH Tiles

RICH + LToF efficiency



Efficiency depends on the mass at low rigidity due the Cherenkov beta threshold and is, for the same reason depends on the geometry

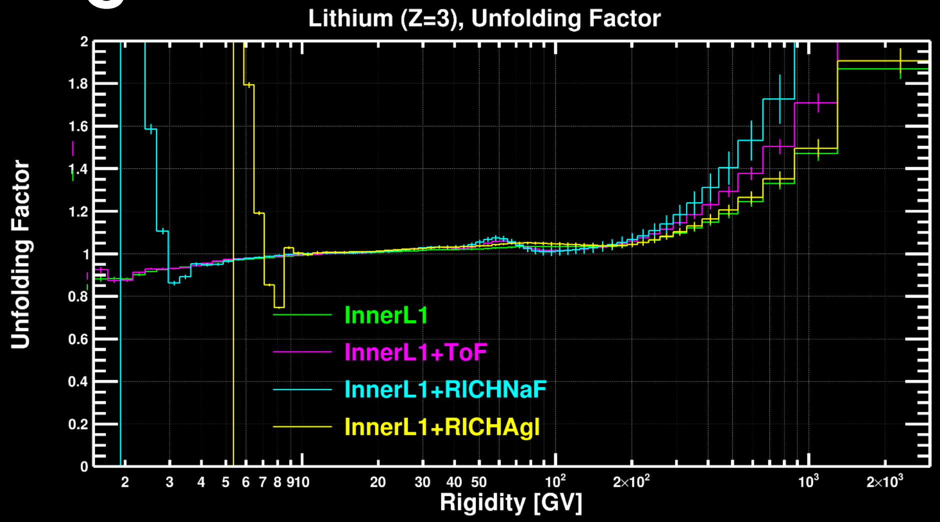


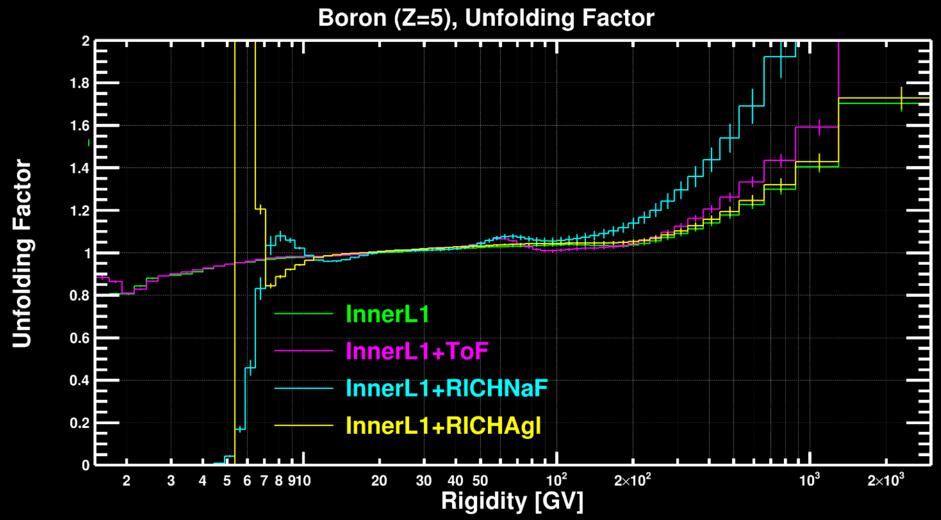


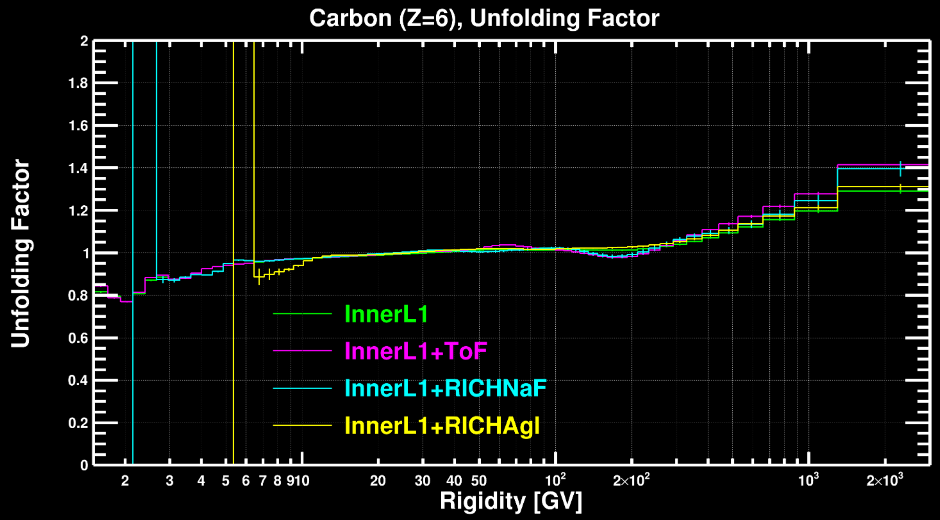
Unfolding

The unfolding is still unstable as function of the rigidity

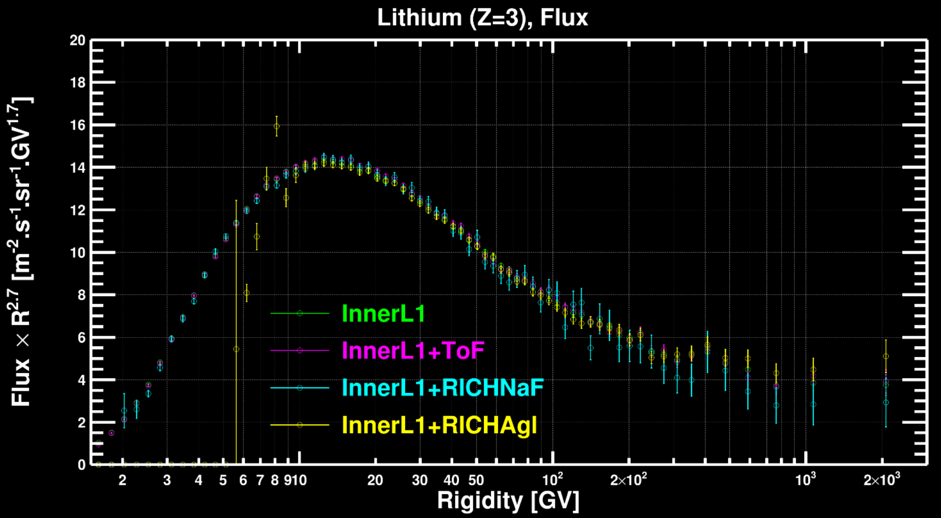
We want to perform a bi-dimensional (rigidity and beta) unfolding to perform the isotope fluxes measurement so the unfolding will be deeply reworked



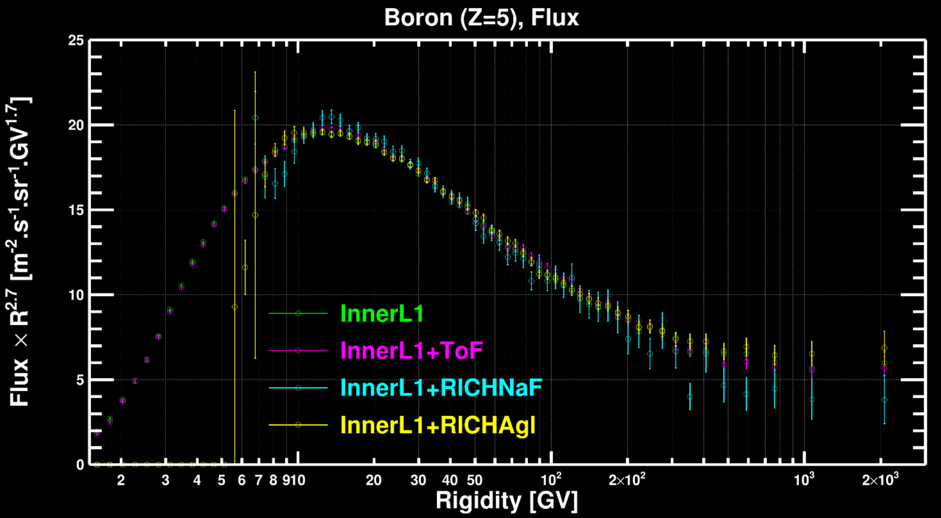




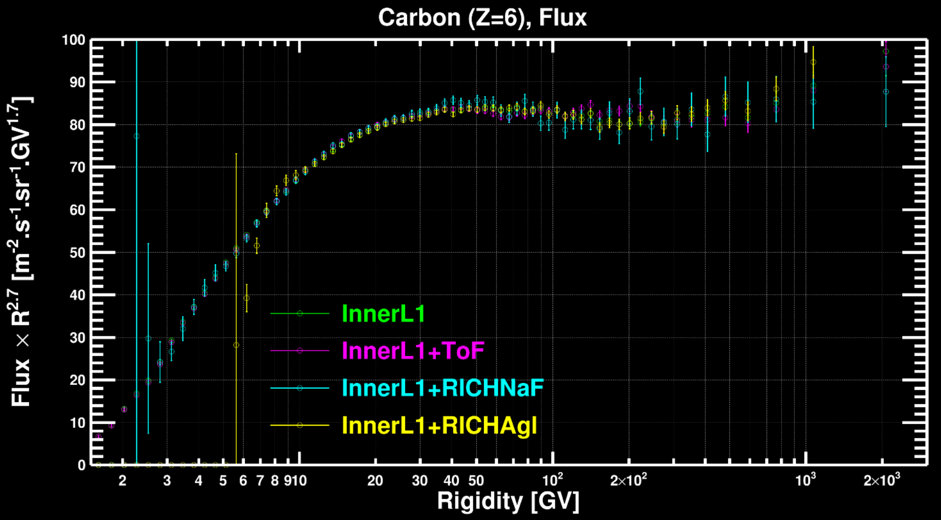
Fluxes



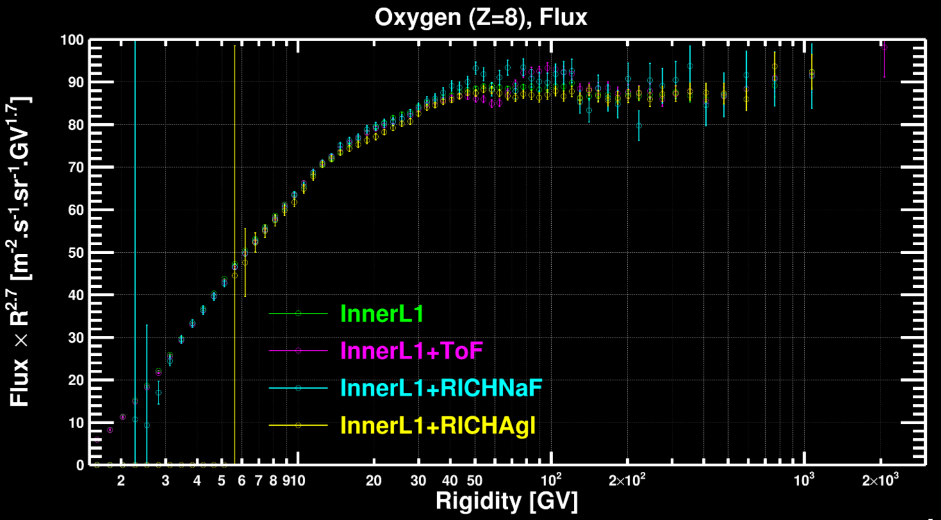
Lithium (Z=3), Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl



Boron (Z=5), Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl



Carbon (Z=6), Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl

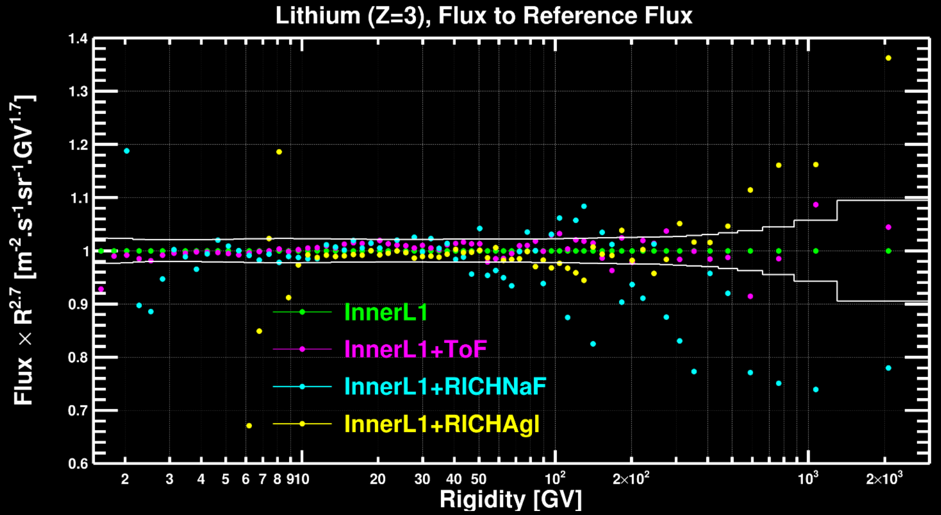


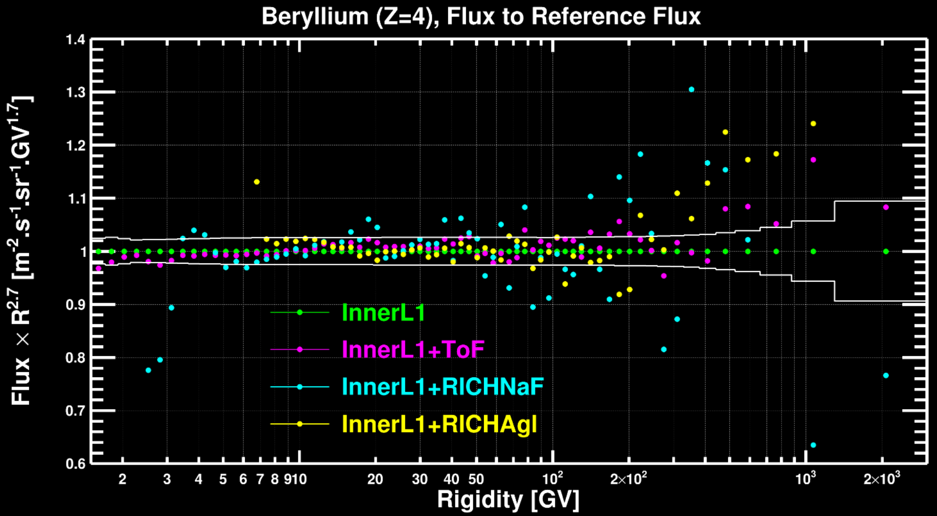
Oxygen (Z=8), Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl

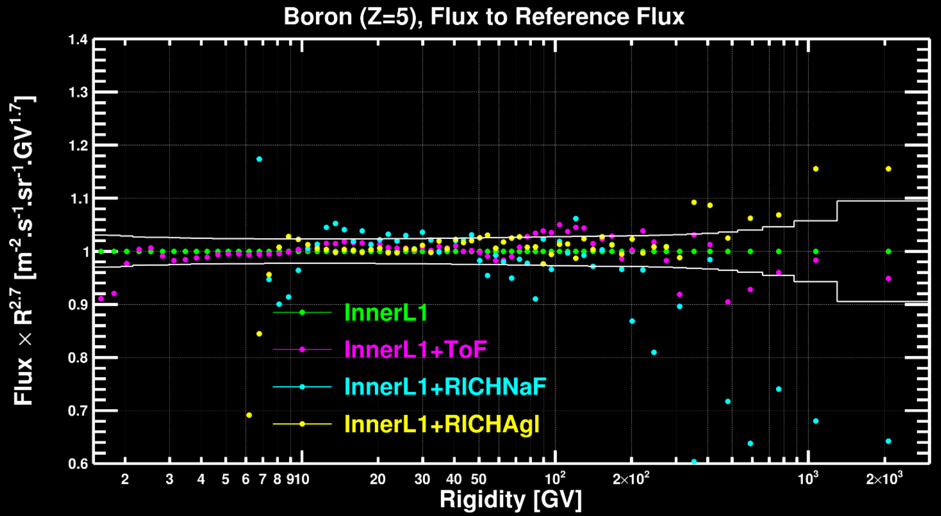
Fluxes to Inner L1 Flux

Wiggles and high rigidity discrepancies are due to instability in the rigidity resolution model fit and unfolding.

The reported systematic error range is the InnerL1 one.



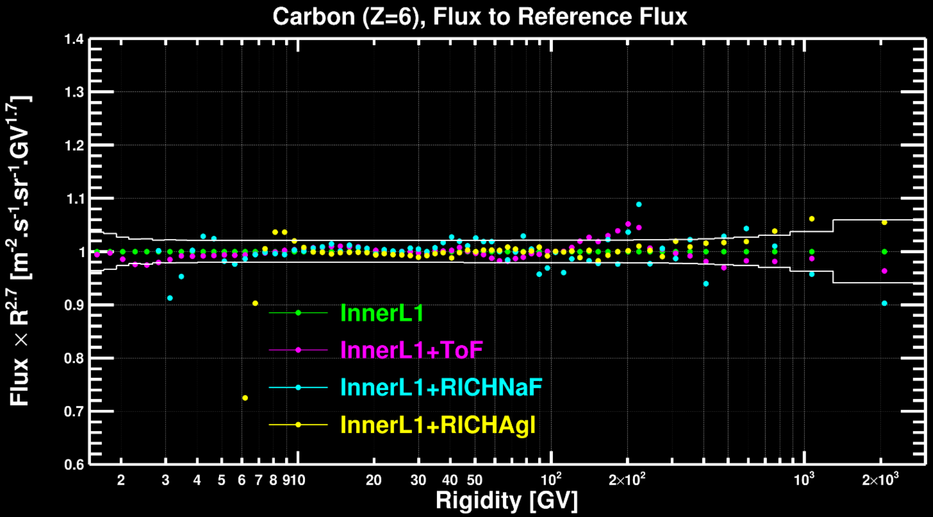


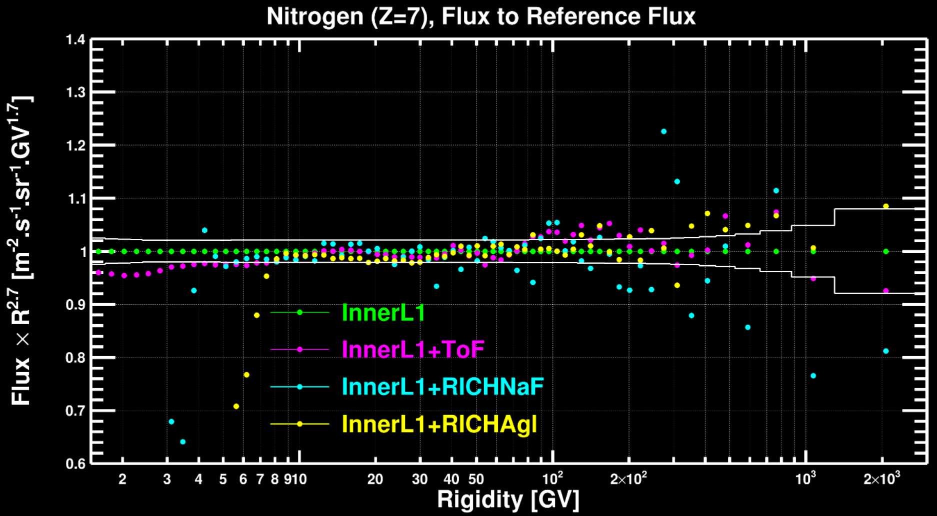


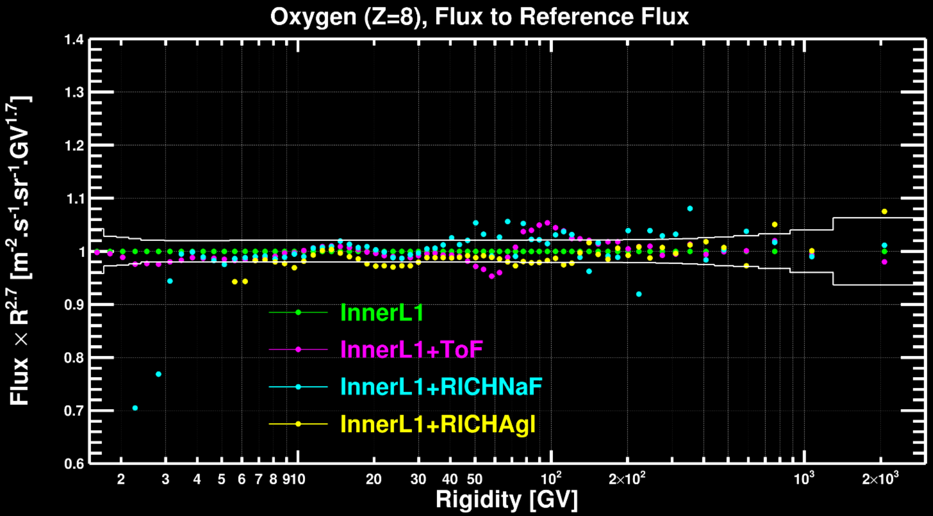
Fluxes to Inner L1 Flux

Wiggles and high rigidity discrepancies are due to instability in the rigidity resolution model fit and unfolding.

The reported systematic error range is the InnerL1 one.







Conclusion

- **Summary:**
  - Nuclei fluxes from Lithium (Z=3) to Oxygen (Z=8) have been computed in three different geometries (InnerL1 + ToF, InnerL1 + Rich NaF and InnerL1 + Rich Agl)
  - The fluxes are found to be in agreement (modulo remaining issue with the unfolding)

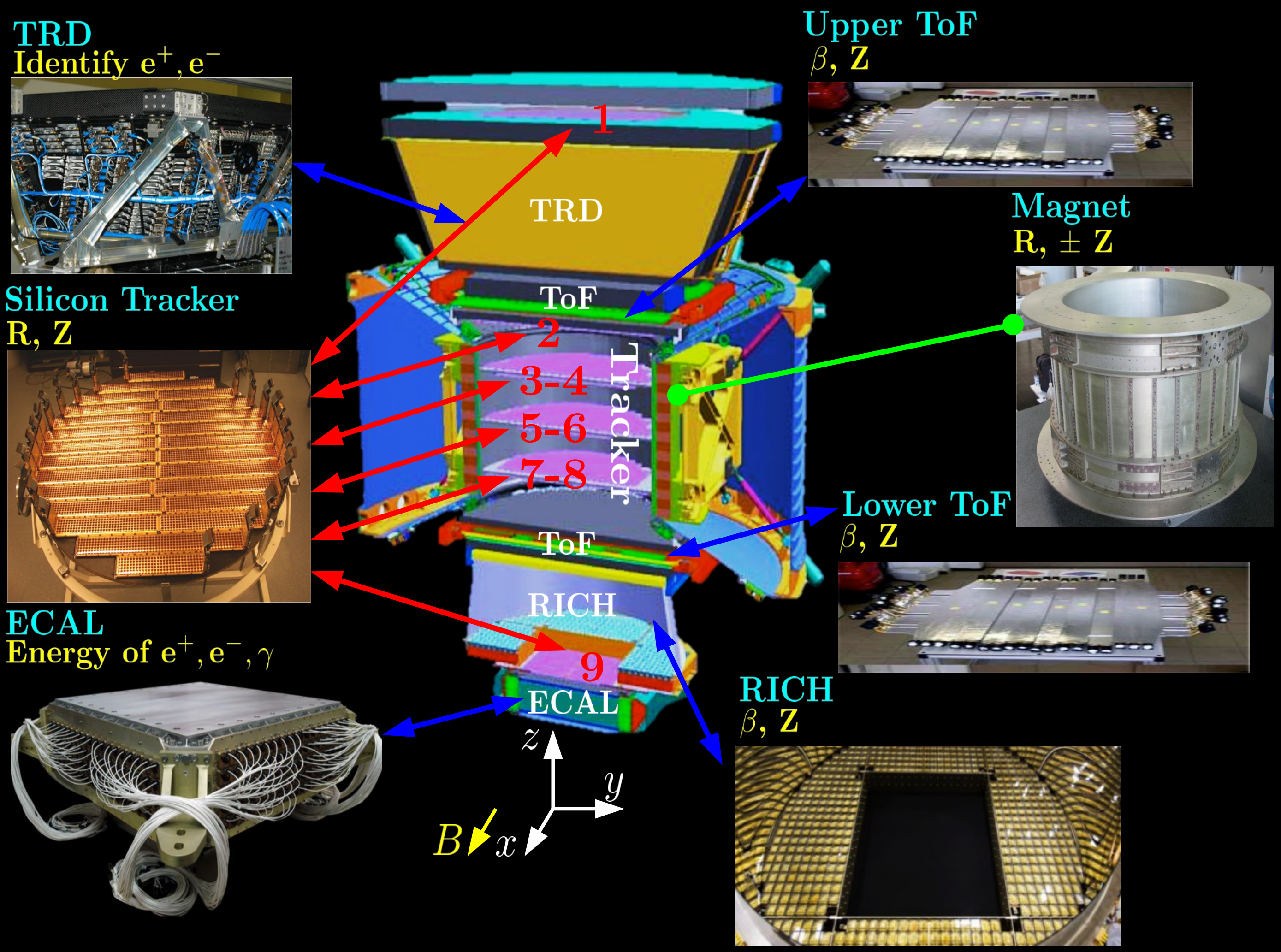
- **Ongoing:**
  - Check of the beta resolution and its correlation with the rigidity resolution

$$\mathrm{Res}\left(\mathrm{R}, \beta, p_0\right) \stackrel{?}{\simeq} \mathrm{Res}\left(\mathrm{R}, p_0\right) \times \mathrm{Res}\left(\beta, p_0\right)$$

- **Next Steps:**
  - Build a new unfolding procedure to extract the isotopic composition of nuclei fluxes

Back Up

Alpha Magnetic Spectrometer-02



Magnetic Spectrometer:

$$R = \frac{p}{Z}$$

– R : Magnetic rigidity

– p : particle momentum

– Z : particle charge

Three different selections

Common :

- Tracker InnerL1 fiducial volume
- Physical trigger
- beta > 0.4, NToF Hit >= 3
- No 2nd Track
  - 2nd Track Rigidity < 0.5GV or ntrack==1 or (Inner X Hit < 3 && Inner Y Hit < 5)

- Track:
  - InnerNHitY>=5 && L2&(L3|L4)&(L5|L6)&(L7|L8)
  - L1XY Hit
  - InnerNormChisY<10

- Charge selections:
  - $Z-0.45 < Q_{Inner} < Z+0.45$
  - $Q_{Inner, RMS}<0.55$
  - $Z-0.6 < Q_{UToF} < Z+1.5$
  - $Z-0.46-0.16(Z-3) < Q_{L1} < Z+0.65$
  - Good L1 charge status
  - $Q_{LToF} > Z-0.6$

Use L1 hit for charge but the Inner Rigidity

InnerL1 + ToF :

- Exclude ToF edge paddles
- Coo Chi2< 5 (data), <10 (MC)
- Time Chi2< 10 (data), < 20 (MC)

InnerL1 + RICH :

- Good & clean
- $P_{Kolmogorov} > 0.01$
- $N_{PMT} > 2$
- $Z-1< Q_{RICH} < Z+2$

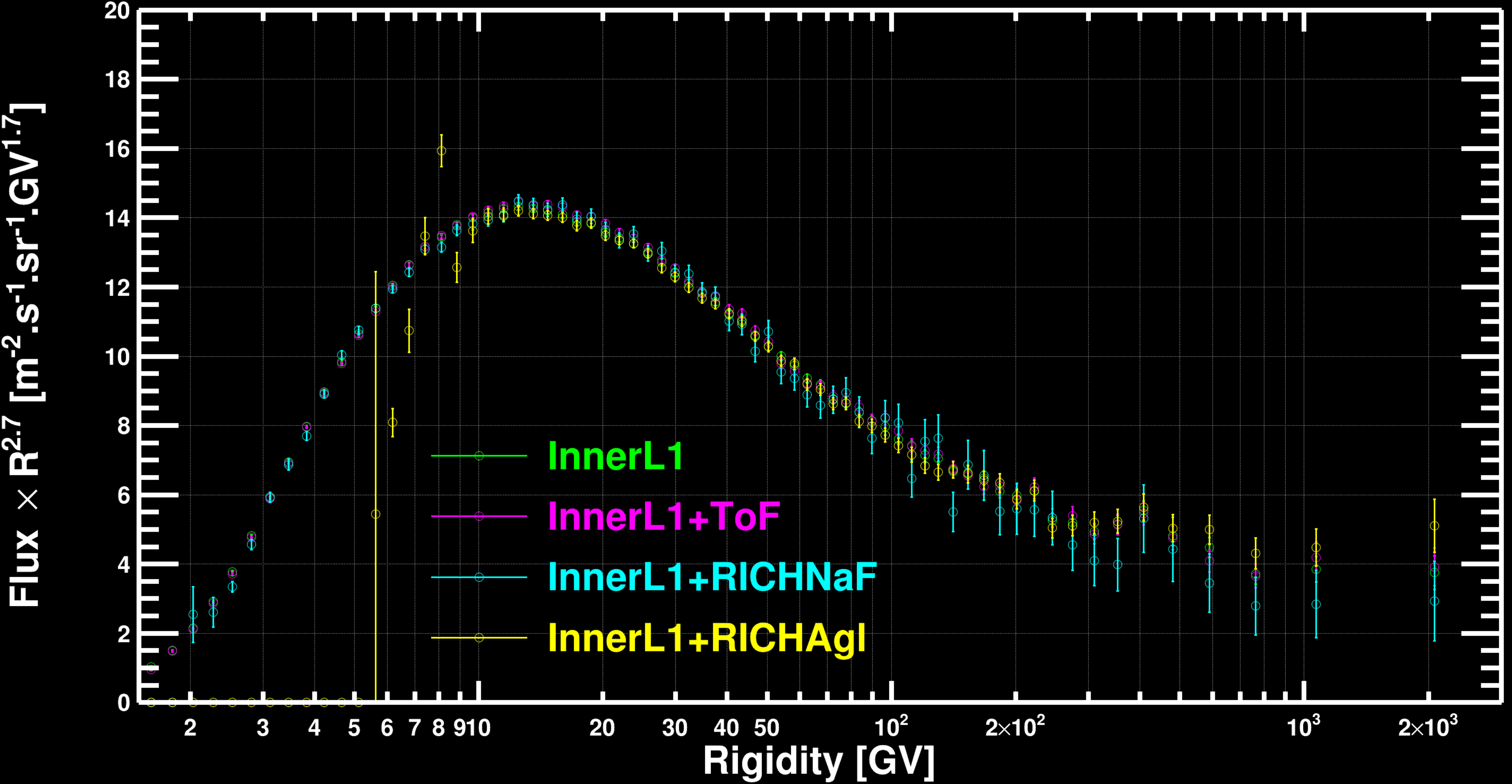
InnerL1 + RICH NaF :

- NaF geometry
- $N_{pe}(ring)/N_{pe}(total) > 0.45$

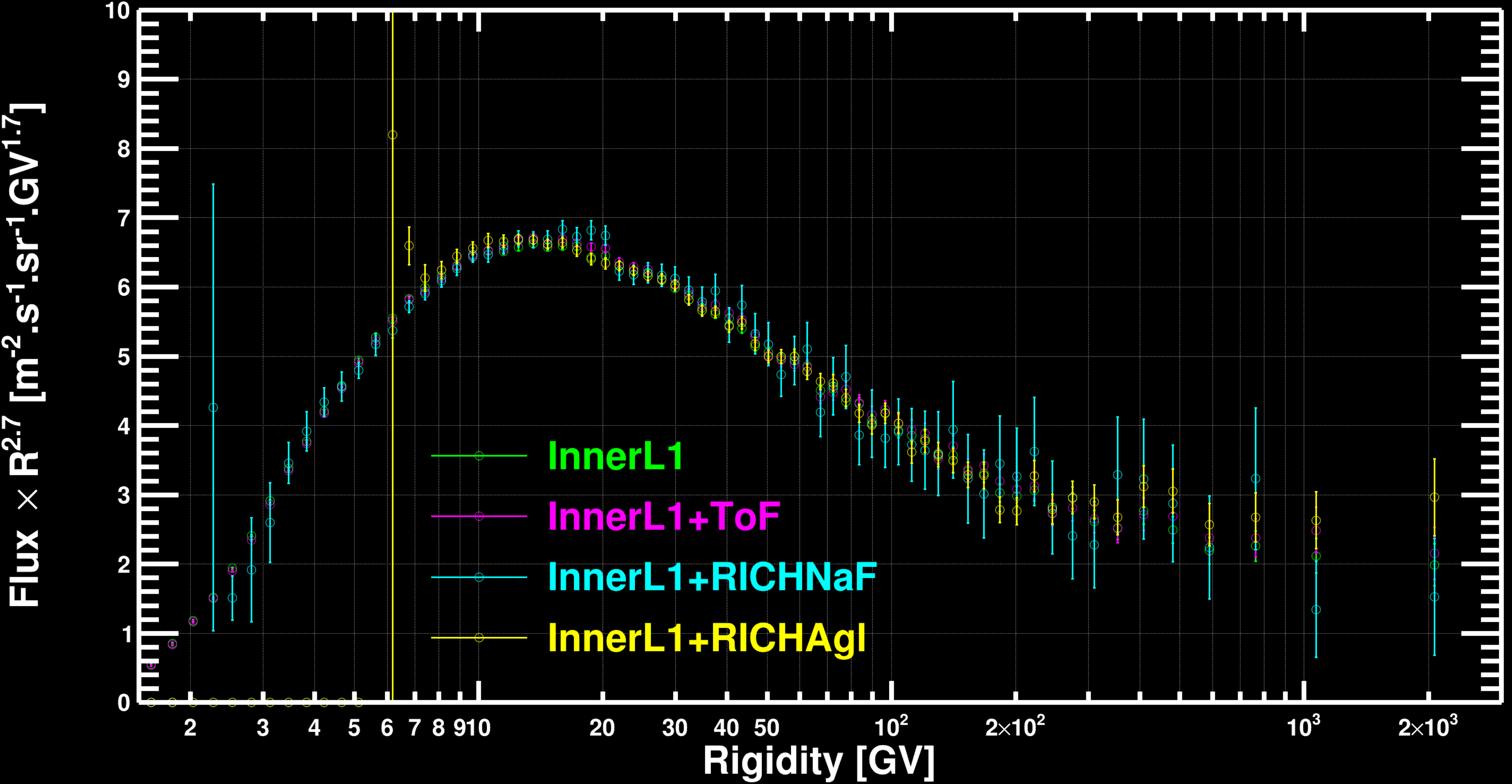
InnerL1 + RICH Agl :

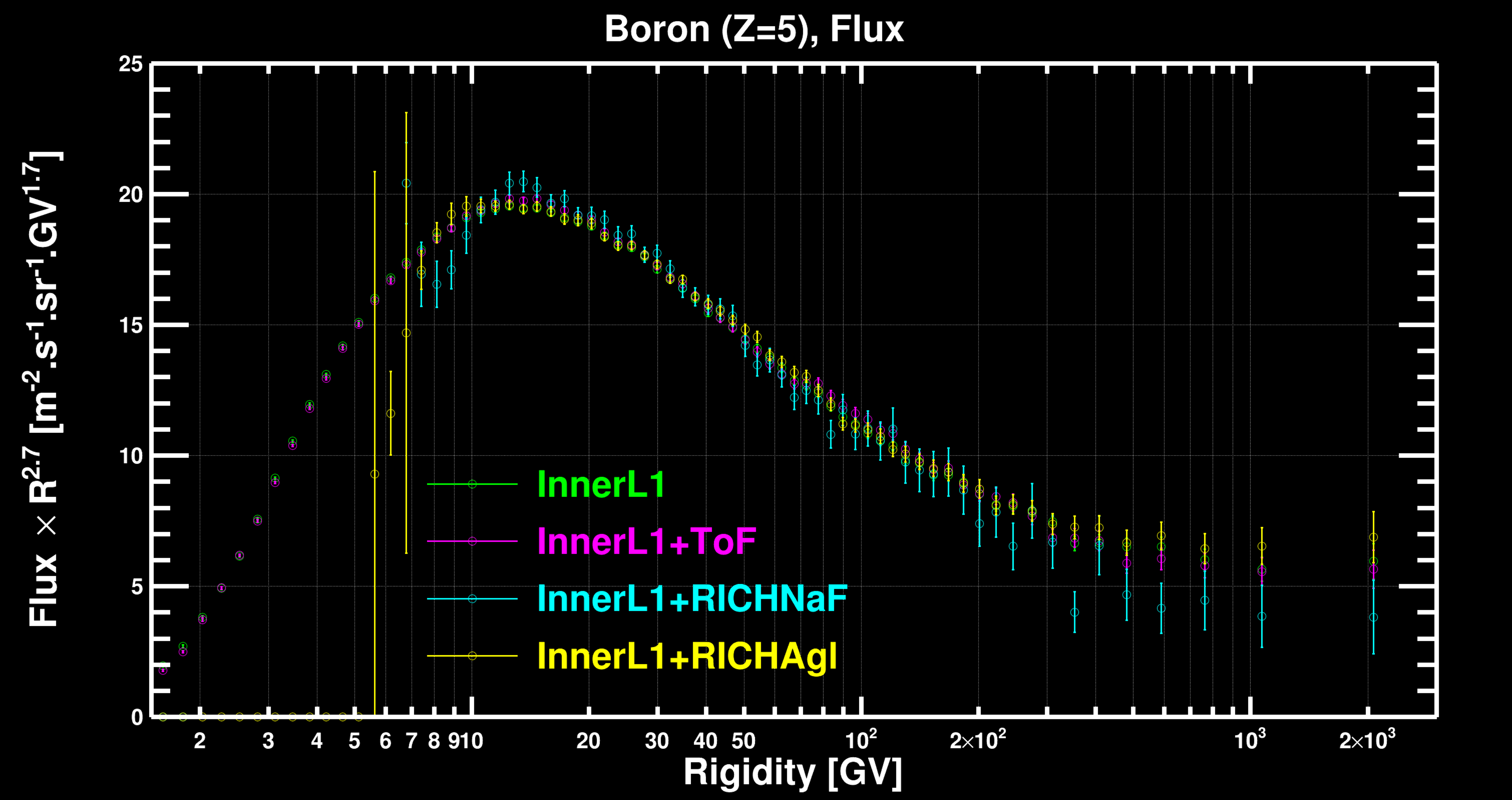
- AGL geometry
- $N_{pe}(ring)/N_{pe}(total) > 0.4$
- Good Rich Tiles

Lithium (Z=3), Flux

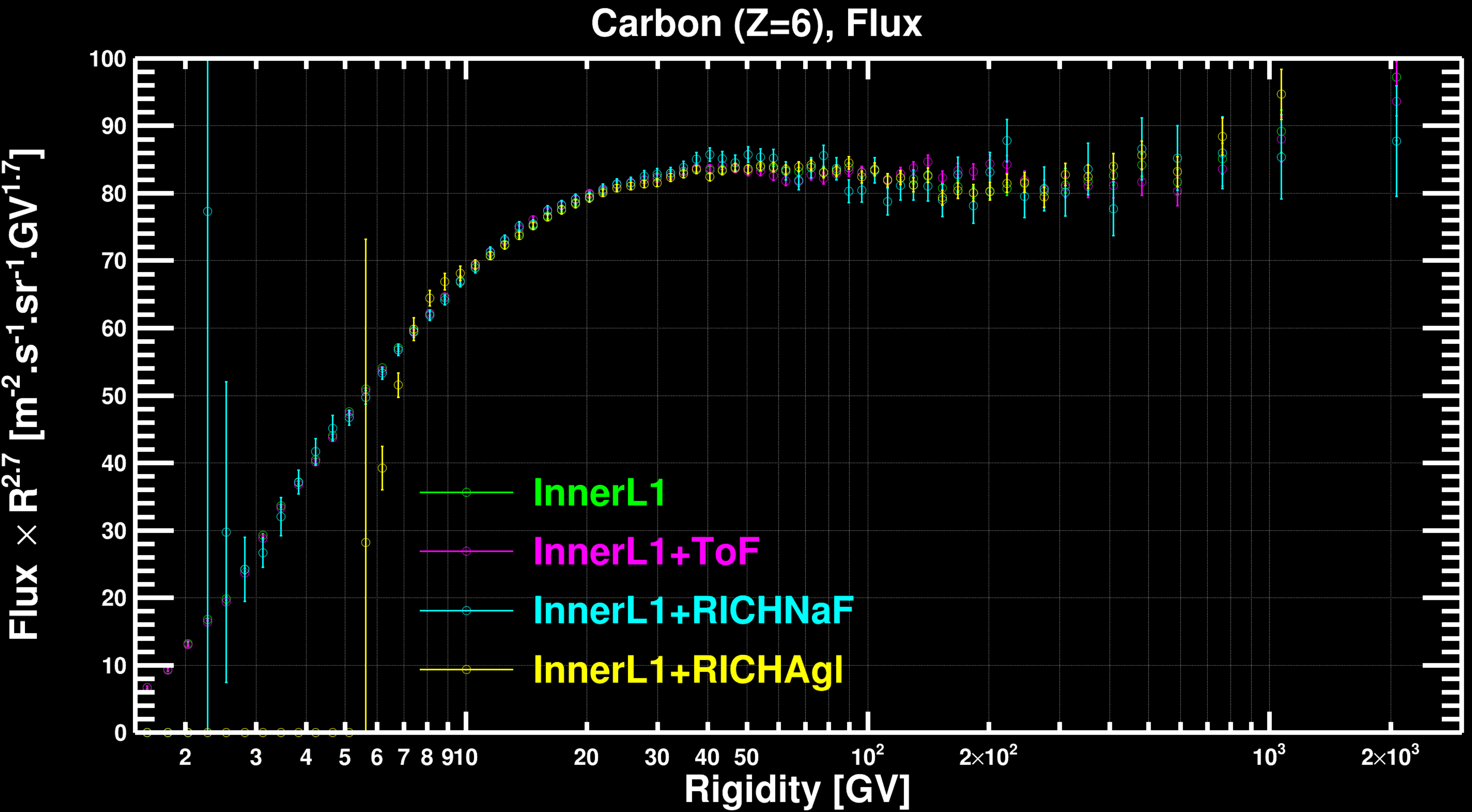


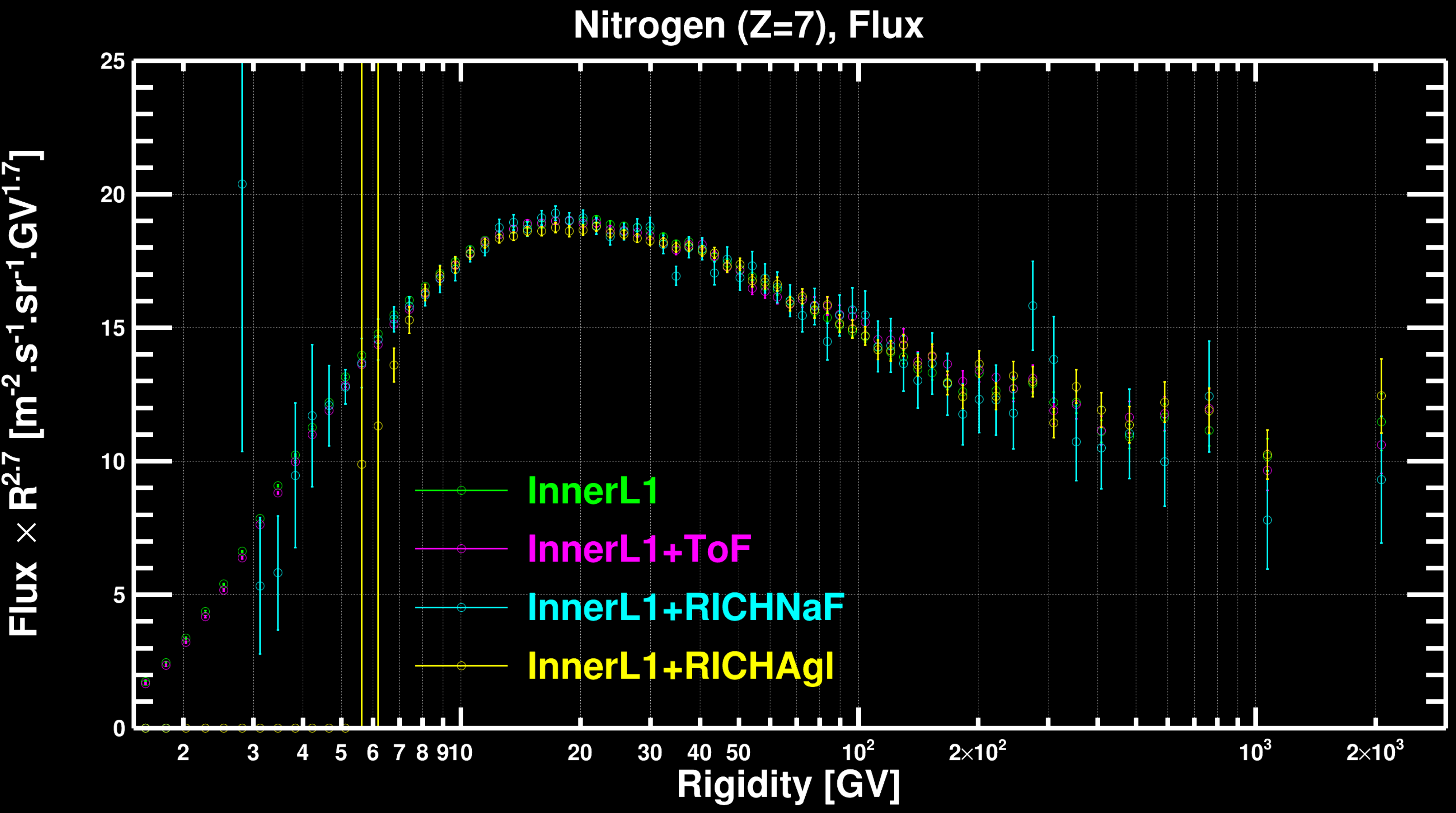
Beryllium (Z=4), Flux



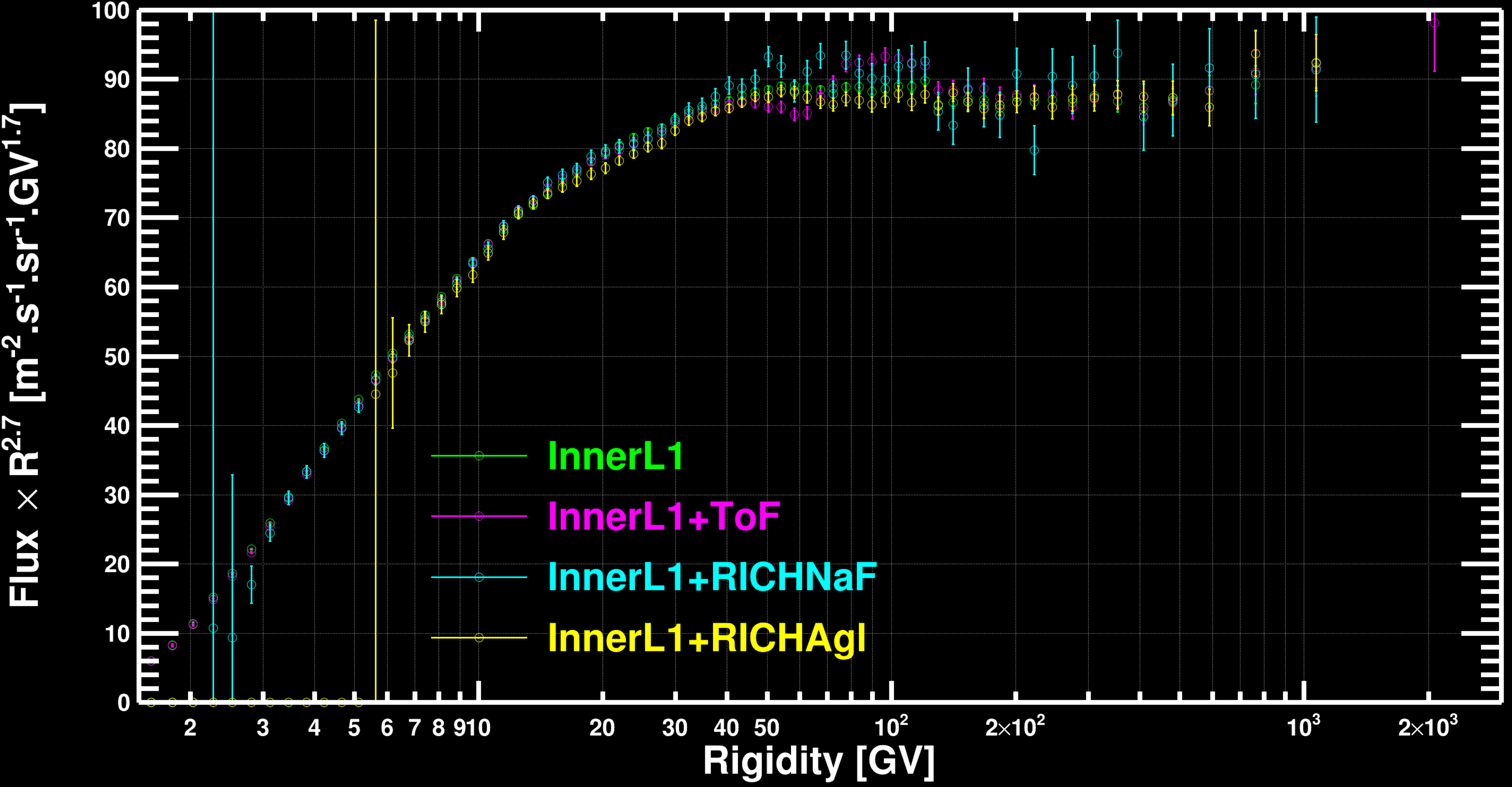


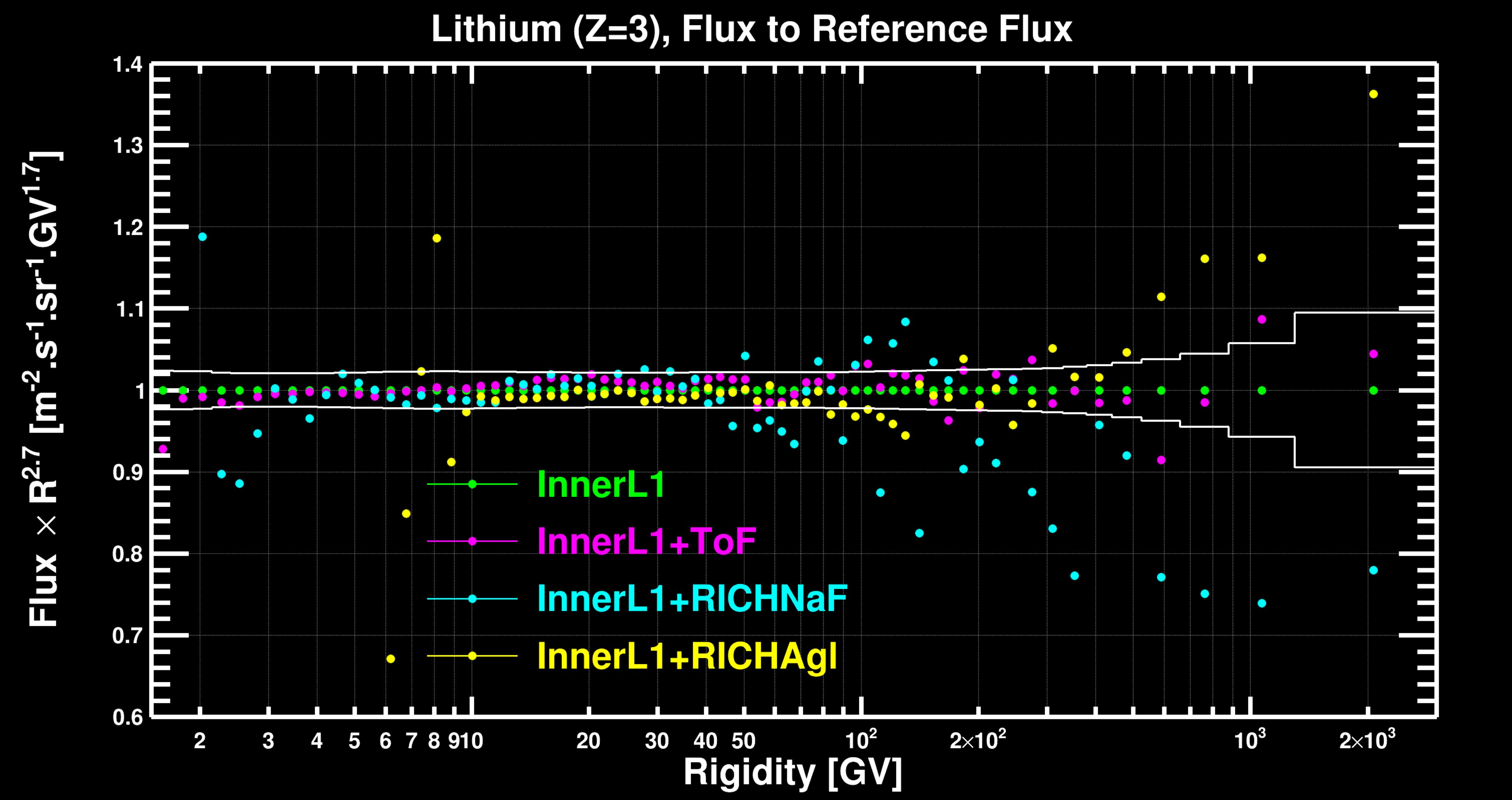
Boron (Z=5), Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
0
5
10
15
20
25
2
3
4
5
6
7
8
9
10
20
30
40
50
10^2
2×10^2
10^3
2×10^3
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl

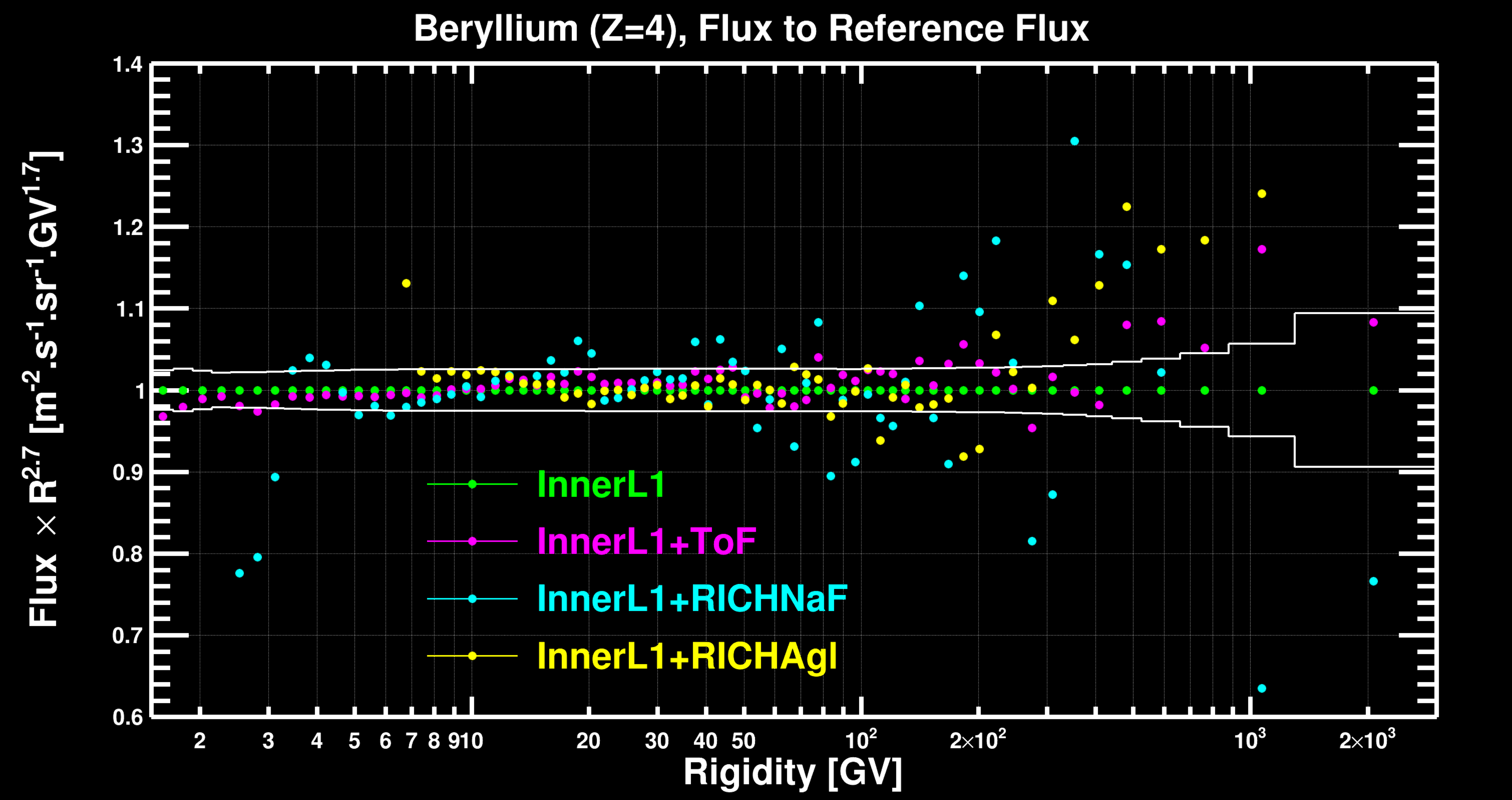

Carbon (Z=6), Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
0
10
20
30
40
50
60
70
80
90
100
2
3
4
5
6
7
8
9
10
20
30
40
50
10^2
2×10^2
10^3
2×10^3
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl


Nitrogen (Z=7), Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl
0
5
10
15
20
25
2
3
4
5
6
7
8
9
10
20
30
40
50
10^2
2×10^2
10^3
2×10^3

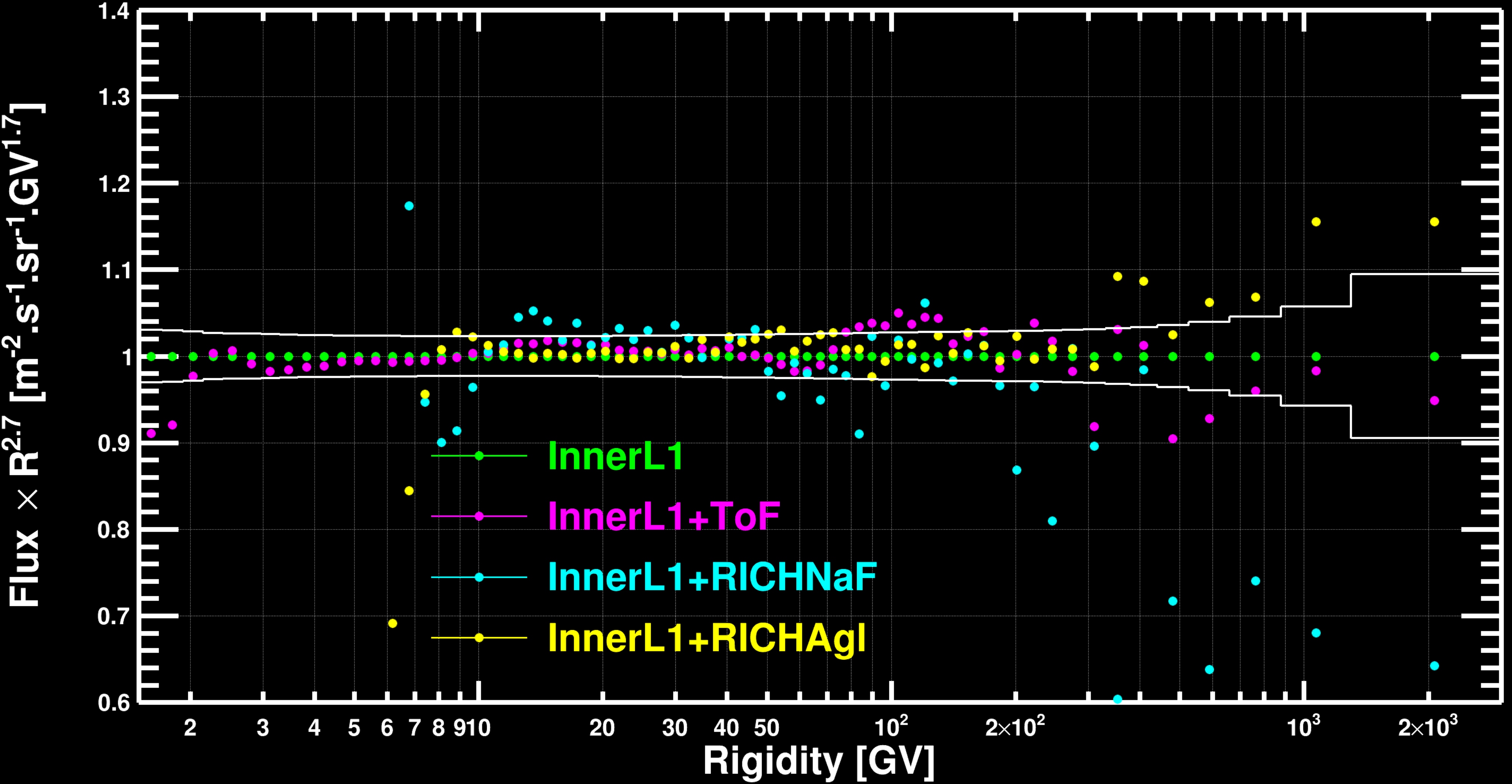
Oxygen (Z=8), Flux

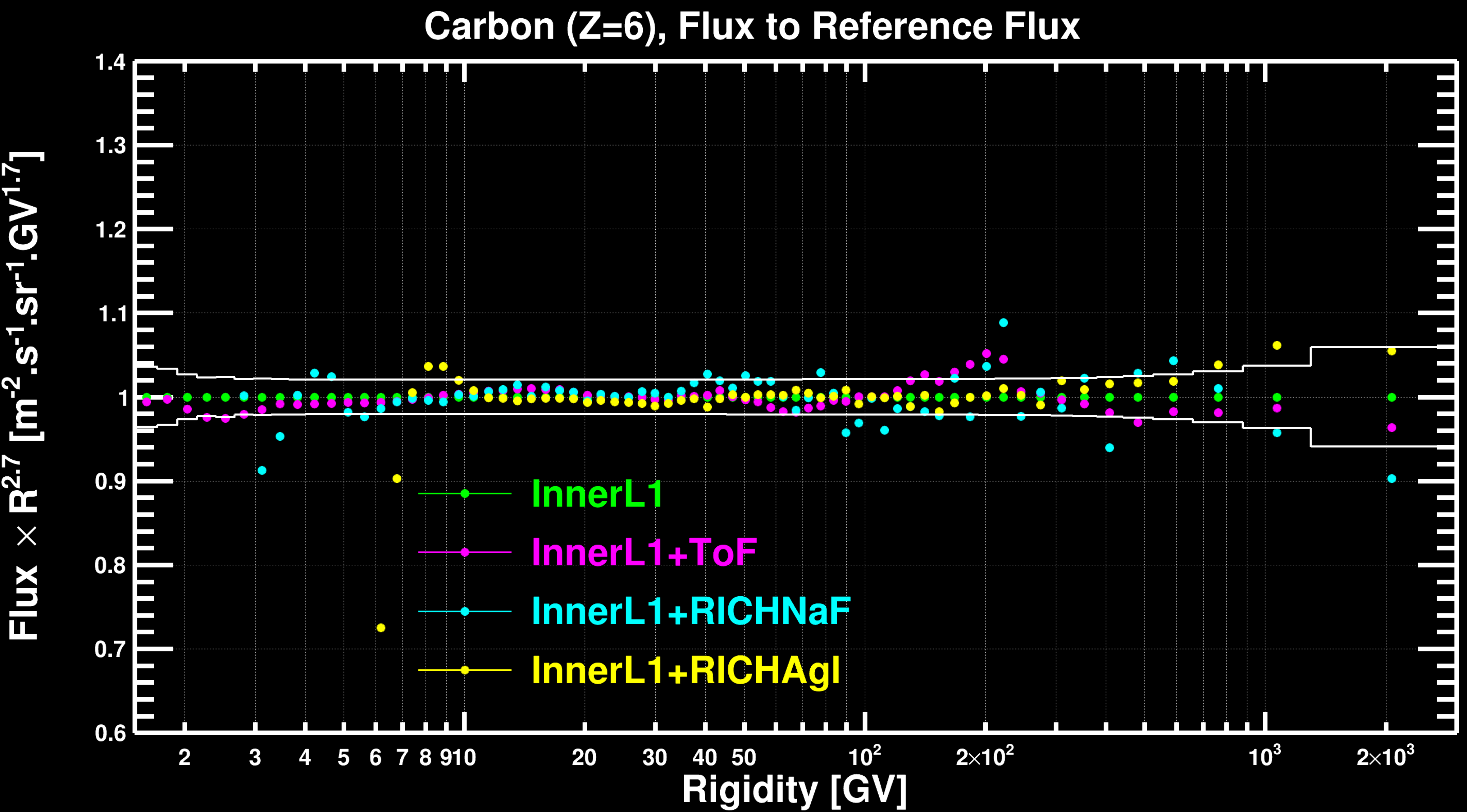



Lithium (Z=3), Flux to Reference Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
2
3
4
5
6
7
8
910
20
30
40
50
10^2
2×10^2
10^3
2×10^3


Beryllium (Z=4), Flux to Reference Flux
Flux × $R^{2.7}$ [$m^{-2}.s^{-1}.sr^{-1}.GV^{1.7}$]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl

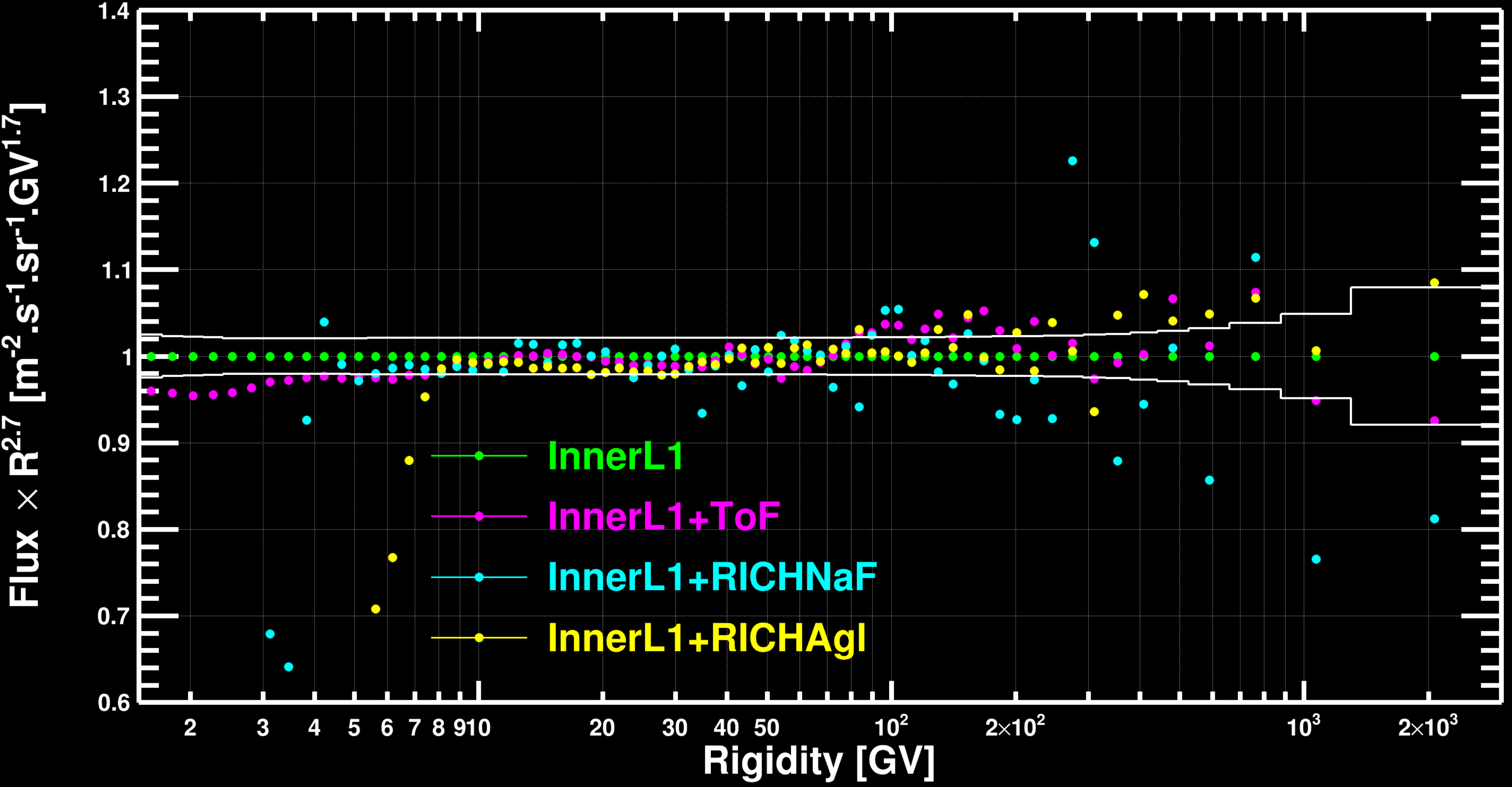
Boron (Z=5), Flux to Reference Flux

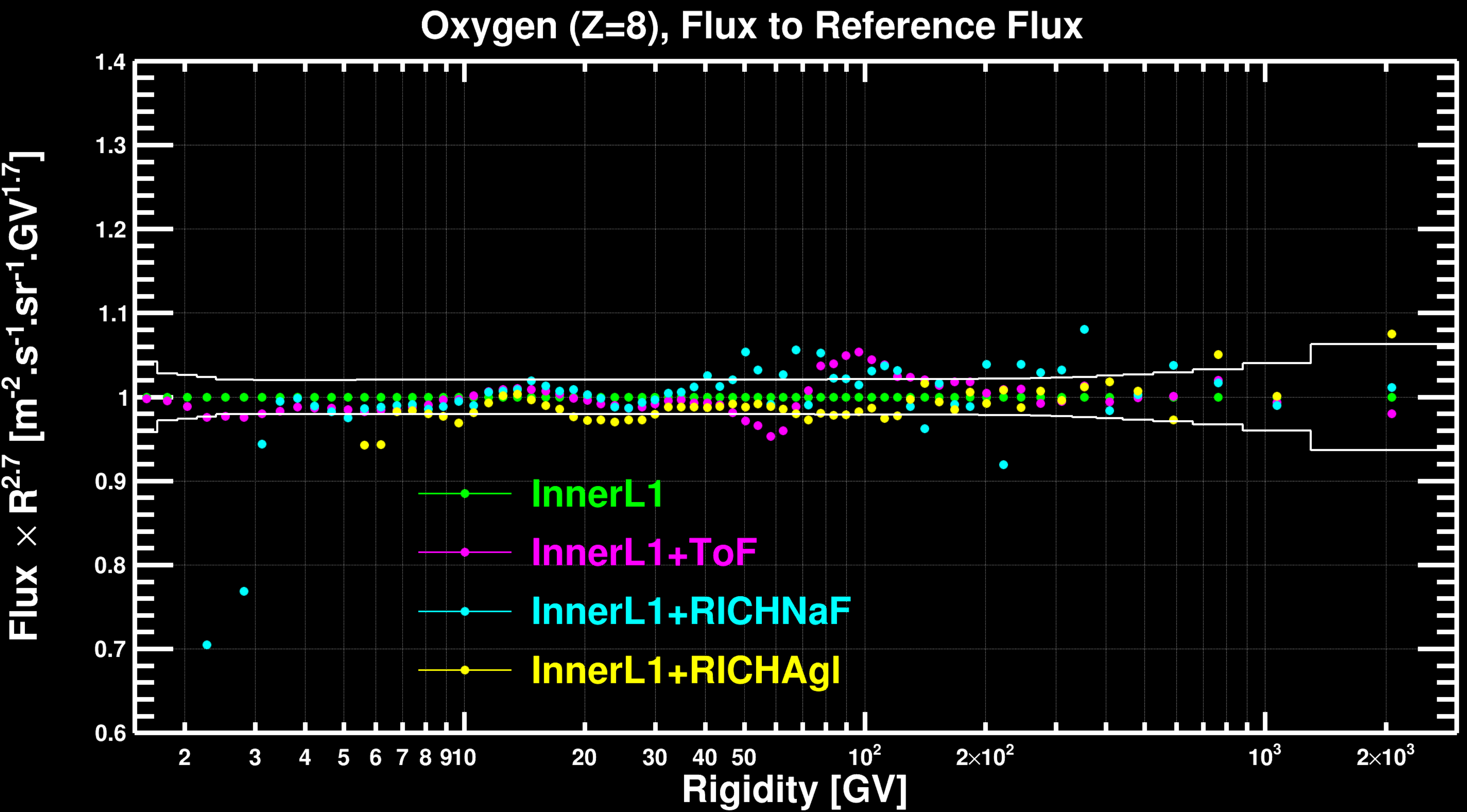




Carbon (Z=6), Flux to Reference Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl

Nitrogen (Z=7), Flux to Reference Flux





Oxygen (Z=8), Flux to Reference Flux
Flux × R^2.7 [m^-2.s^-1.sr^-1.GV^1.7]
Rigidity [GV]
InnerL1
InnerL1+ToF
InnerL1+RICHNaF
InnerL1+RICHAgl