ISS Dose Estimates Due to Pions and Electromagnetic Cascade

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Outline

- Extended version of HZETRN with pion and electromagnetic (EM) interactions
  - Motivation
  - Code/model description
- Comparisons to Monte Carlo (Fluka and Geant4)
  - Primary GCR protons
  - Full GCR spectrum
- Validation against Liulin and TEPC measurements on ISS
  - Comparisons performed on a point-by-point basis along trajectory
  - Validation metric
  - Results
- Summary and Conclusions

Motivation

• Contribution to total exposure from pions and decay products was thought to be small for space applications

- HZETRN has generally neglected these particles
  - o Agrees reasonably well with Monte Carlo codes in published benchmarks
  - o Extensively validated against space flight measurements

• At least one targeted study examining pion contribution in GCR environments

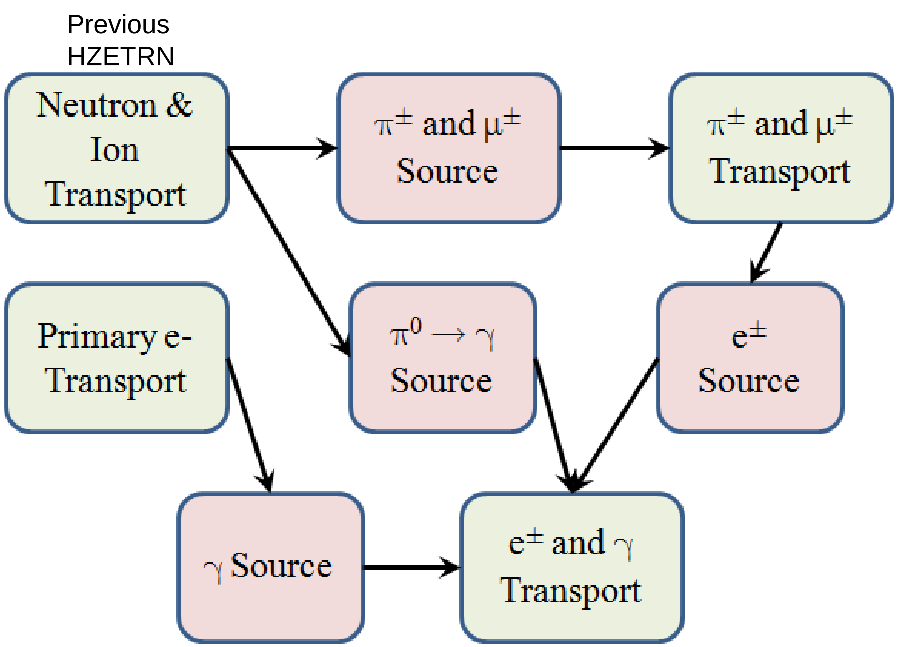
- MCNPX was used to show that ignoring pions reduces dose by 16% behind shielding
- Percent contribution in LEO will be greater due to geomagnetic cutoffs
- Large shielding thicknesses on ISS will also increase pion/EM percent contribution

• Seems to be a conflict in verification and validation results

- Benchmarks against Monte Carlo have been mainly for SPE
  - o Insufficient energy to generate significant pion field
  - o Recent comparisons to FLUKA and HETC focused on ion fragmentation
- Badhwar-O’Neill (BO) 2004 GCR model overestimated fluxes below 5 AGeV
  - o Artificially increased exposures, allowing reasonable agreement against measured doses
  - o Updated model significantly drops overall exposure estimates (20% - 50%)

HZETRN-π/EM

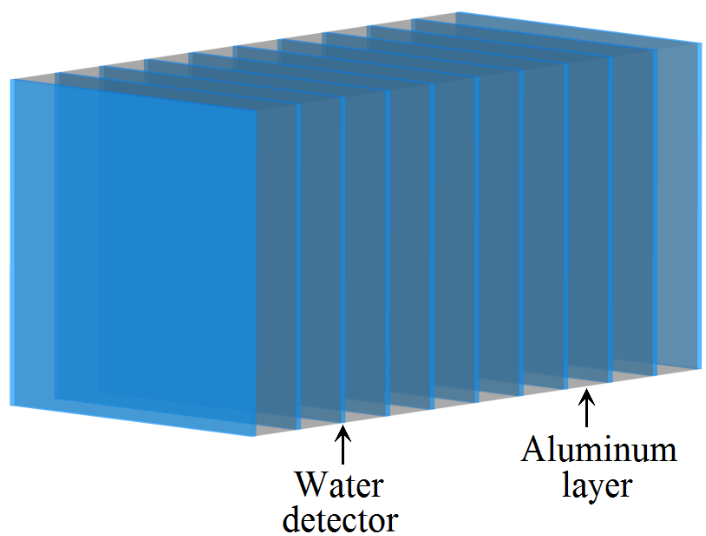
- Extended version of HZETRN includes pion interactions and EM cascade
  - Neutron and ion transport generates source of charged and neutral pions
  - Charged pions decay to muons
    - o Charged mesons and muons explicitly transported
  - Neutral pions decay to two photons and muons decay to like charged leptons
  - Photon and EM sources passed to separate transport algorithm
    - o Fully coupled EM transport solved through Neumann series / iterative source procedure
    - o Based on straight-ahead approximation with corrections for primary electrons



Comparison to Monte Carlo

- Geometry setup consists of either a 10 g/cm^2 or 100 g/cm^2 aluminum slab with thin water detectors (0.1 mm) spaced evenly through the slab
  - Lateral dimensions chosen large relative to slab thickness to avoid lateral leakage
  - Geometry setup chosen to closely simulate deterministic procedure carried out by HZETRN

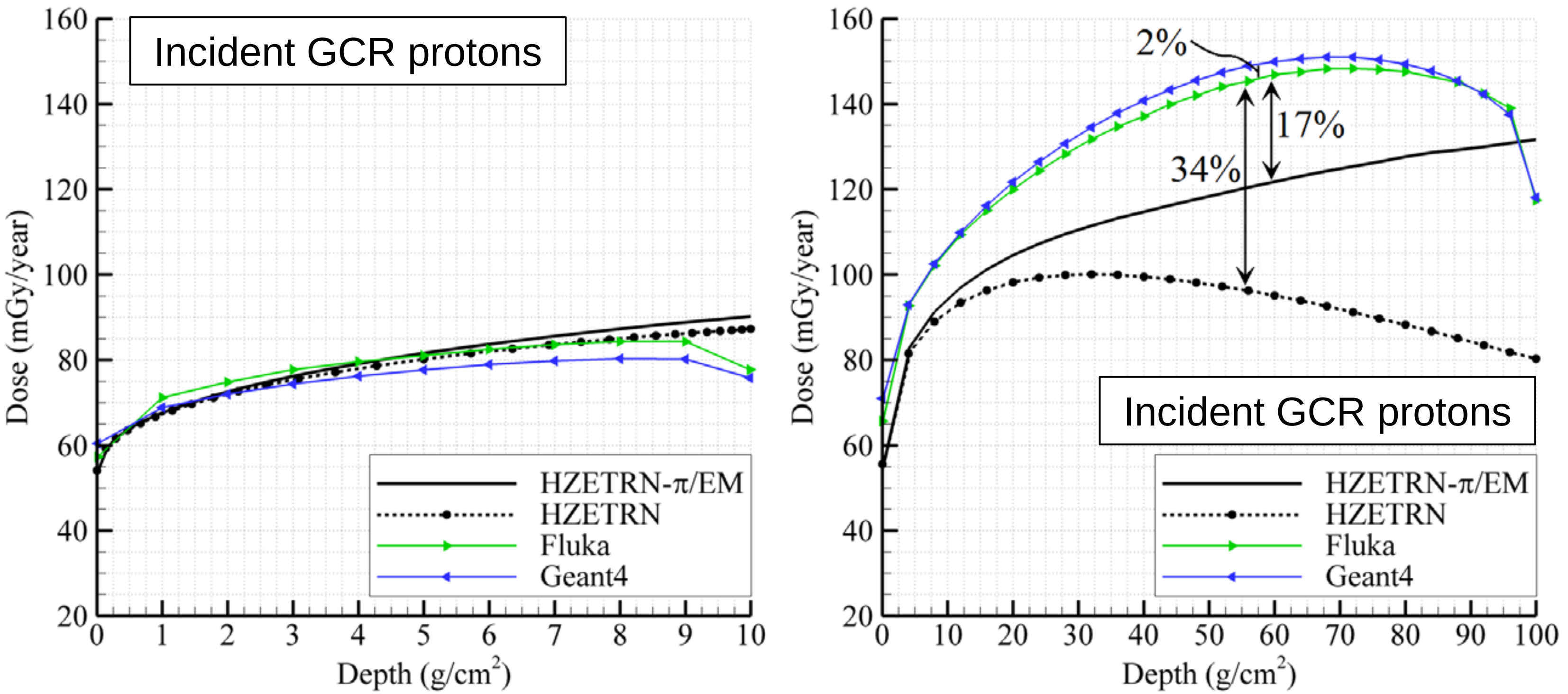
- External boundary condition applied normally to the front of the slab
  - Used GCR spectrum defined by BO2010 model (ϕ = 475 MV) – protons only and full spectrum



Geometry setup for Monte Carlo calculations (not to scale).

Comparison to Monte Carlo

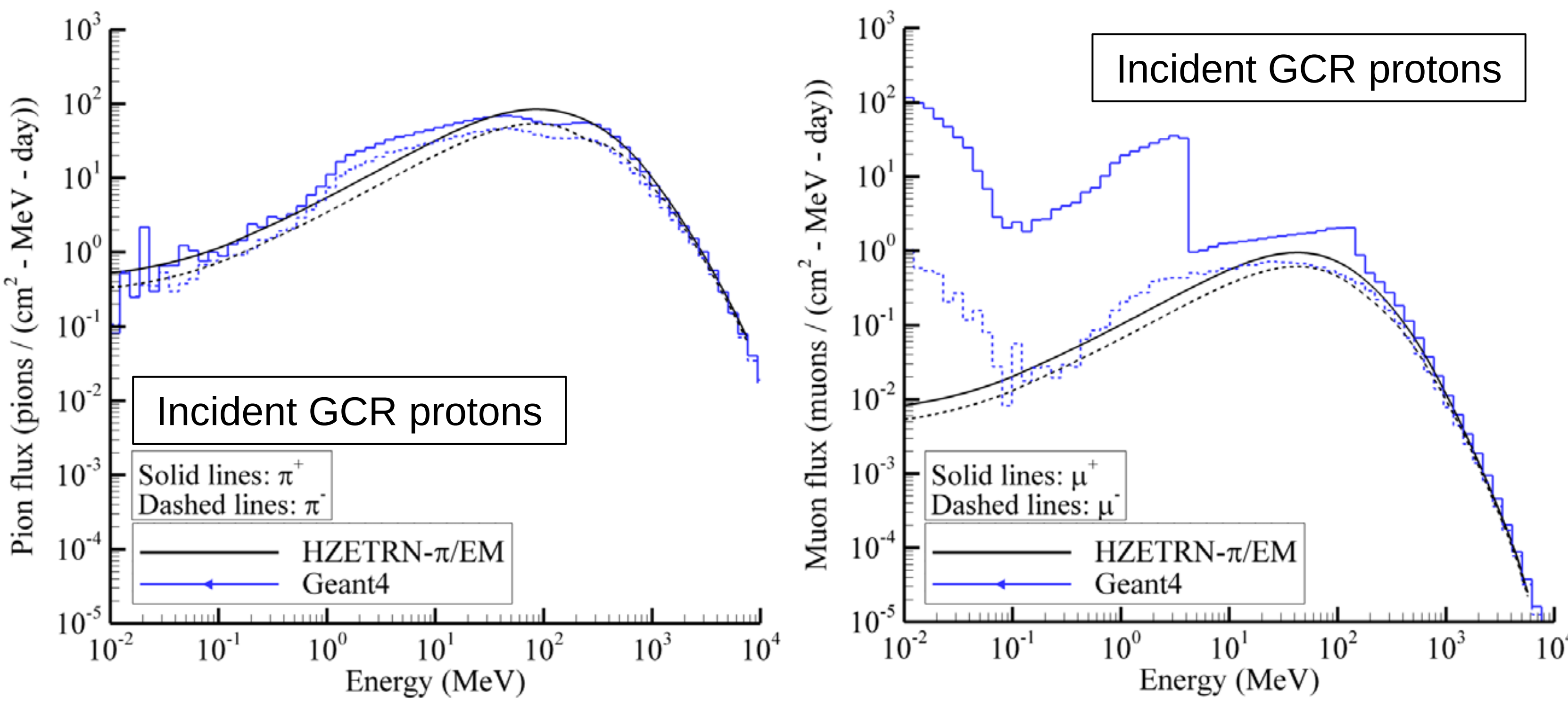
- Reasonable agreement found between code in thinner slab (EM contribution small)
- HZETRN-π/EM within ~20% of Monte Carlo codes in thick slab
  - Remaining error mainly caused by 3D effects in EM transport (electrons and positrons)
  - Significant improvement over previous version of HZETRN



Dose (mGy/year) versus depth in a 10 g/cm^2 aluminum slab (left pane) and a 100 g/cm^2 aluminum slab (right pane) exposed to GCR protons given by the BO2010 model (ϕ = 475 MV).

Comparison to Monte Carlo

- Good agreement between Geant4 and HZETRN-π/EM for charged pion fluxes
- Reasonable agreement between codes for muons above 100 MeV
    - Discrepancy for μ+ below 10 MeV is caused by surface muons (not included yet)
    - Dominates muon dose (small contribution to total)



Pion (left pane) and muon (right pane) flux at 60 g/cm^2 in a 100 g/cm^2 aluminum slab exposed to GCR protons given by the BO2010 model (ϕ = 475 MV).

Comparison to Monte Carlo

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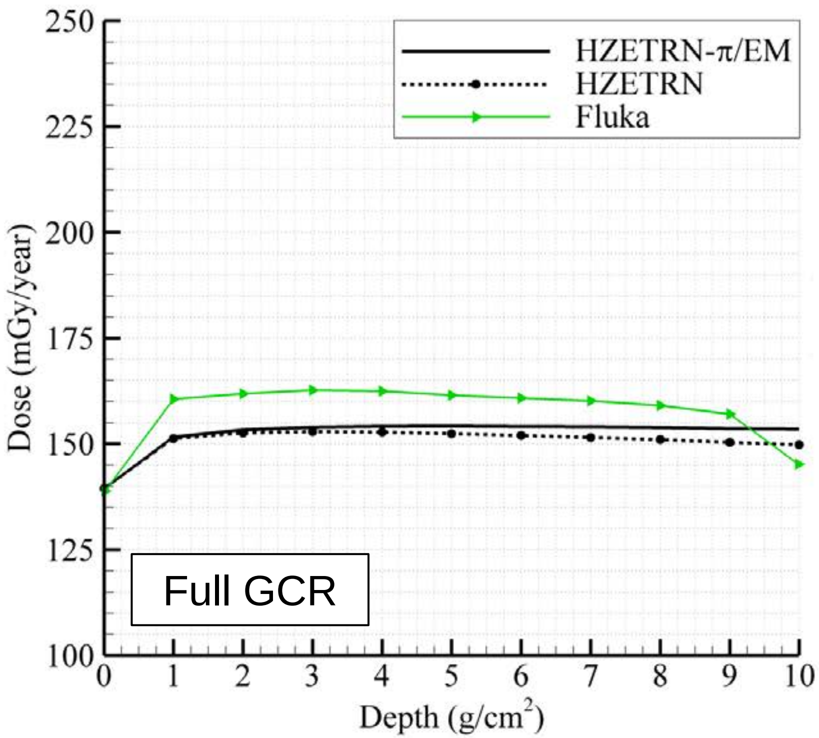
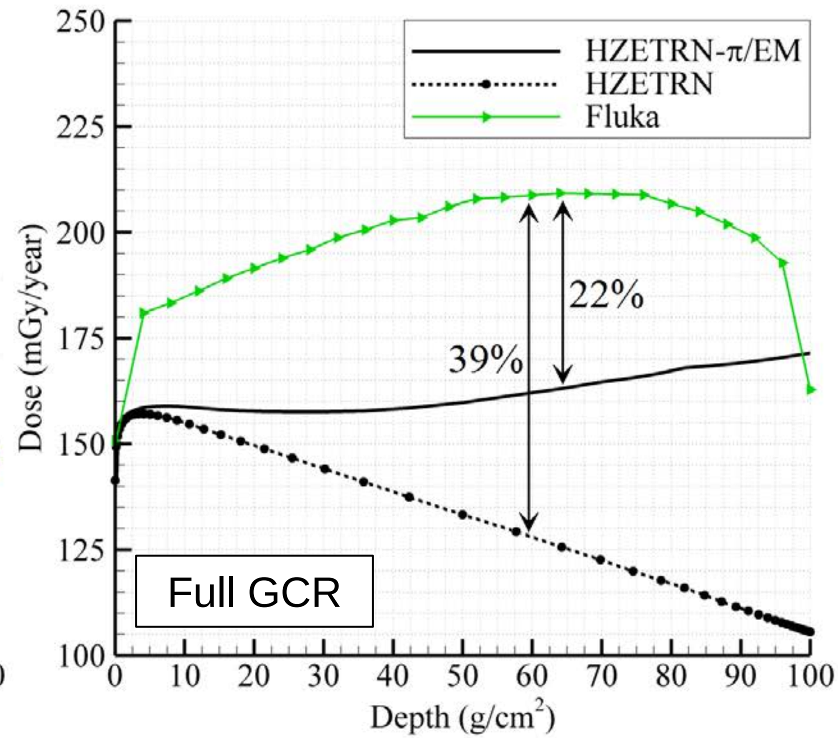
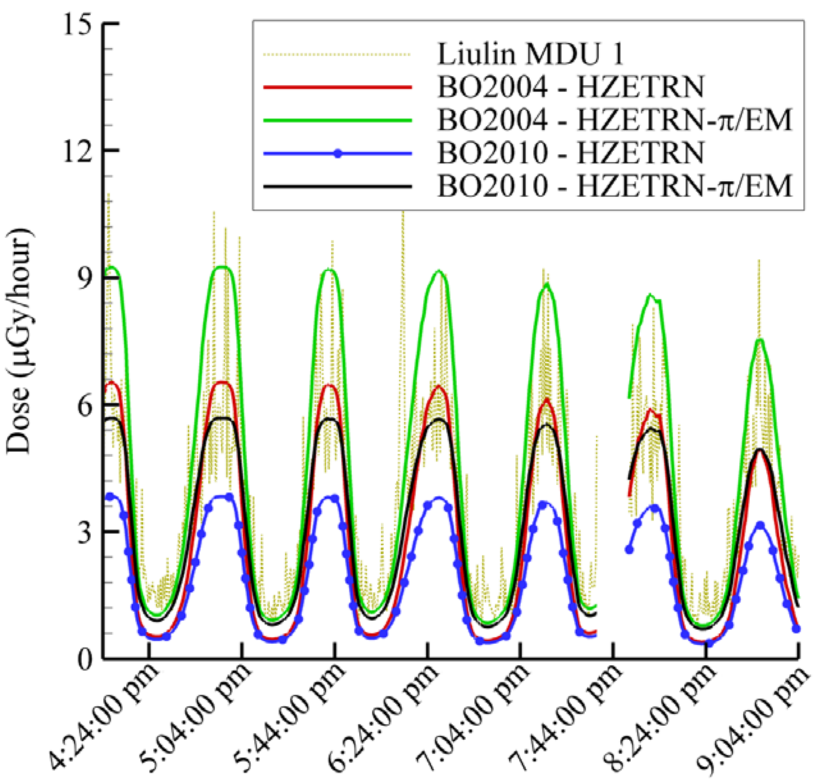




Dose (mGy/year) versus depth in a 10 g/cm^2 aluminum slab (left pane) and a 100 g/cm^2 aluminum slab (right pane) exposed to full GCR spectrum given by the BO2010 model (ϕ = 475 MV).

Validation against ISS Data

- Comparison of models to ~77,000 measurements
  - Data from five detectors at ~30 second intervals from July 6-13, 2001
  - Includes Liulin MDU (1-4) and TEPC (ISS 6A configuration)
  - Allows errors to be mapped as a function of meaningful physical quantities
  - Enables extrapolation of LEO errors to free-space conditions

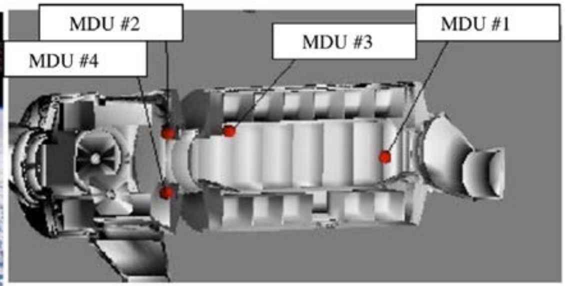


Comparison of models to measured data taken aboard ISS on July 6, 2001

Spikes in measurements are statistical errors due to low count rates

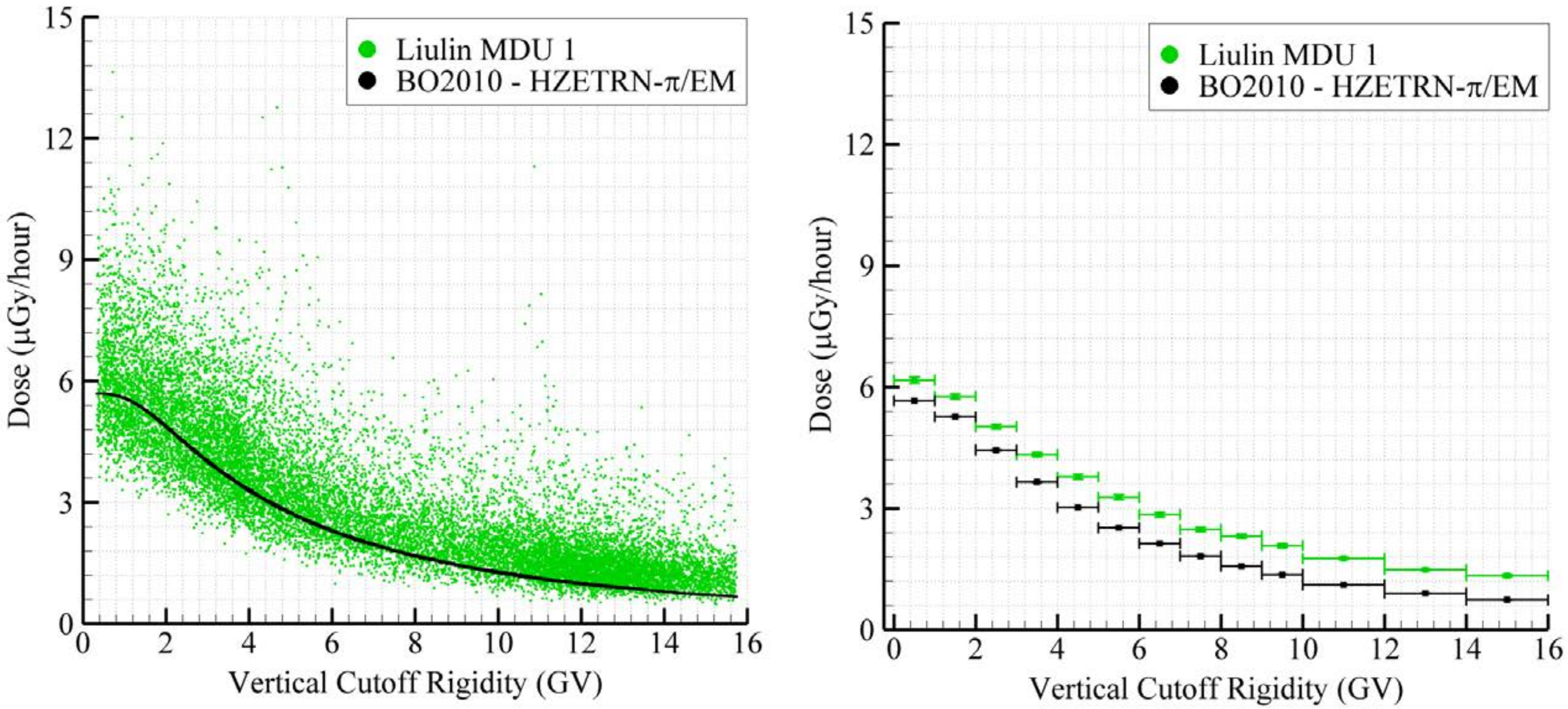
Gap in data near 7:44 is SAA (data removed)

Liulin detectors located in US lab and Node 1 and TEPC was near FRED phantom in US lab



Validation against ISS Data

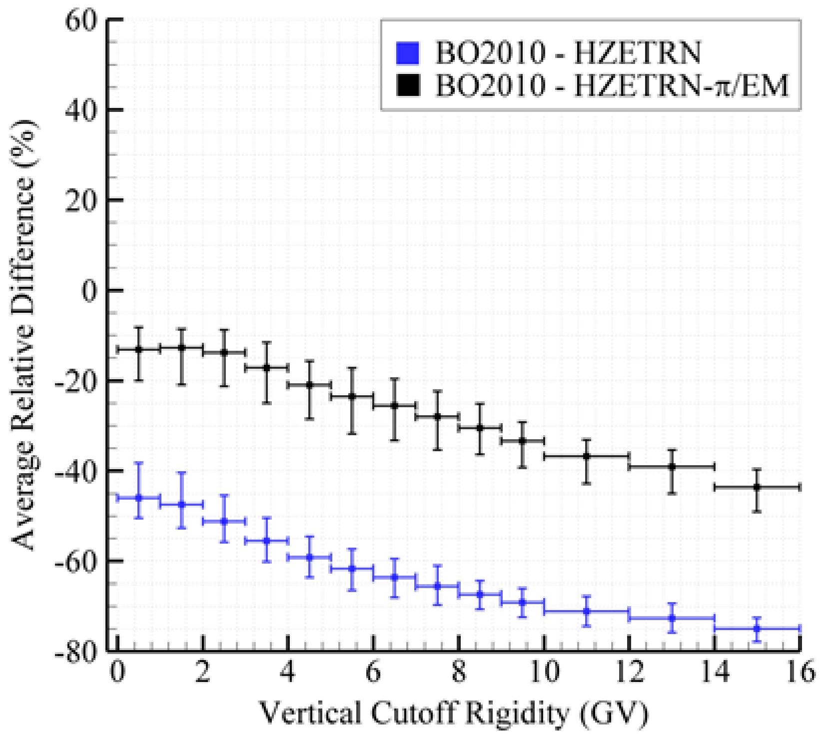
• Model results and measurements are first mapped as a function of vertical cutoff rigidity
  - Allows errors to be studied as a function of geomagnetic field strength
  - Clear extrapolation of errors to free space conditions
  - Enough data in each rigidity bin to do meaningful statistical analysis



BO2010 - HZETRN-π/EM model results and Liulin MDU 1 data plotted as a function of vertical cutoff rigidity over the entire trajectory (left pane). The right pane shows binned data with horizontal error bars representing the bin width and vertical error bars (smaller than symbols) representing 90% confidence level on the bin average value.

Validation against ISS Data

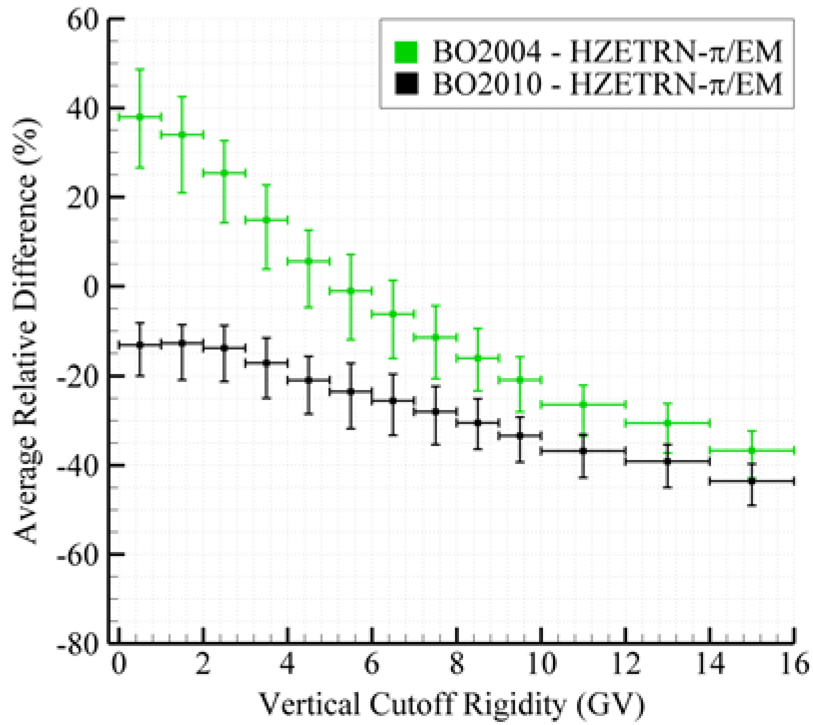
- Impact of π/EM significant across all rigidities
  - ~40% increase in dose across all rigidities (for Liulin detectors) (25% for TEPC)



Average relative difference as a function of vertical cutoff rigidity between model results and Liulin measurements.

Validation against ISS Data

- Impact of π/EM significant across all rigidities
  - ~40% increase in dose across all rigidities (for Liulin detectors) (25% for TEPC)
- Impact of GCR model updates significant at low cutoff rigidities
  - 10% – 60% reduction in dose across all rigidities (for Liulin and TEPC)
  - Important for deep space exposure estimates



Average relative difference as a function of vertical cutoff rigidity between model results and Liulin measurements.

Validation against ISS Data

- Comparing to Liulin data
  - GCR model updates dropped doses by ~35%
  - π/EM interactions increased doses by ~45%

- Comparing to TEPC data
  - GCR model updates dropped dose/doseq by ~40%
  - π/EM interactions increased doses by ~25% and dose eq. by ~8%

- Currently examining more recent TEPC data (3 locations)
  - Angular dependence in environment
  - Material approximations (equivalent aluminum)
  - Effect of neutrons (ray-by-ray transport with bi-directional neutrons)

Average relative difference (%) between model and measurements over the entire trajectory.

Detector	BO2004		BO2010	
	HZETRN	HZETRN-π/EM	HZETRN	HZETRN-π/EM
[a]Liulin Avg.	-40%	8%	-58%	-22%
[b]TEPC D	-50%	-34%	-66%	-54%
[c]TEPC H	-39%	-34%	-56%	-52%

[a] Dose is computed in silicon.
[b] Dose is computed in tissue.
[c] Dose equivalent is computed in tissue using ICRP 60 quality factor.

Summary and Conclusions

- Extended version of HZETRN with π/EM interactions has been developed
  - Utilizes previous HZETRN for neutron/ion transport
  - Separate algorithms for pions/muons and EM portion
  - Computational efficiency maintained despite additional algorithms

- Benchmark comparisons made between HZETRN-π/EM and Monte Carlo codes in slab geometry
  - Good agreement (5%) between codes in thin slabs
  - Extended code is a significant improvement in thick slabs (20%)
    - o Need to improve new transport algorithms

- Validation comparisons made against Liulin and TEPC measurements from ISS
  - Rigorous statistical validation metric developed and applied
  - Recent updates to GCR model (BO2010) significantly reduce exposure estimates (30-40%)
  - π/EM interactions provide some compensation (40% for Liulin dose)
    - oTEPC detector location/response affecting validation results
    - o π/EM interactions showing little impact on dose equivalent

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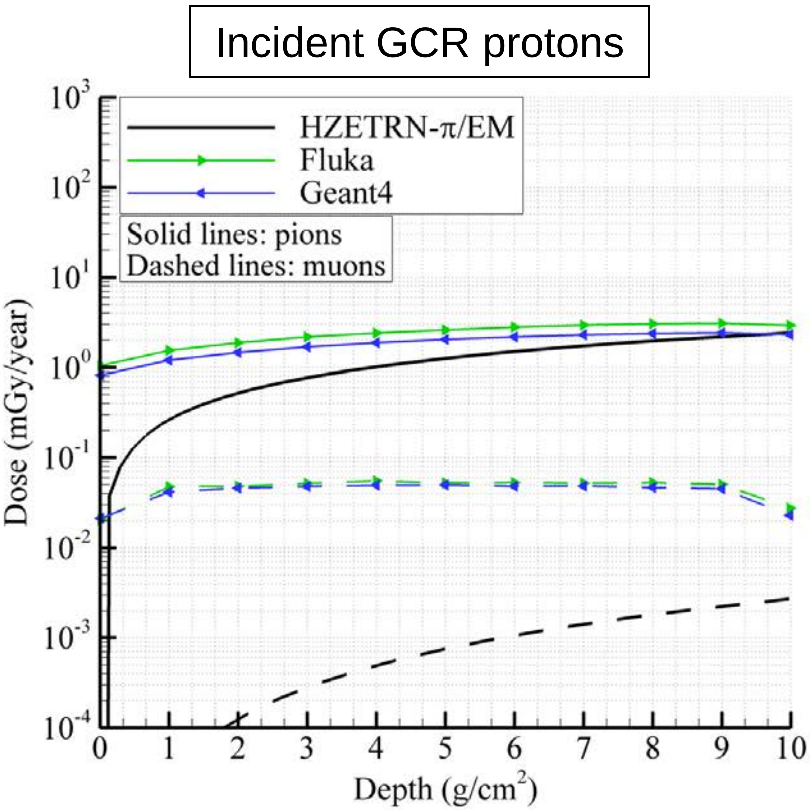
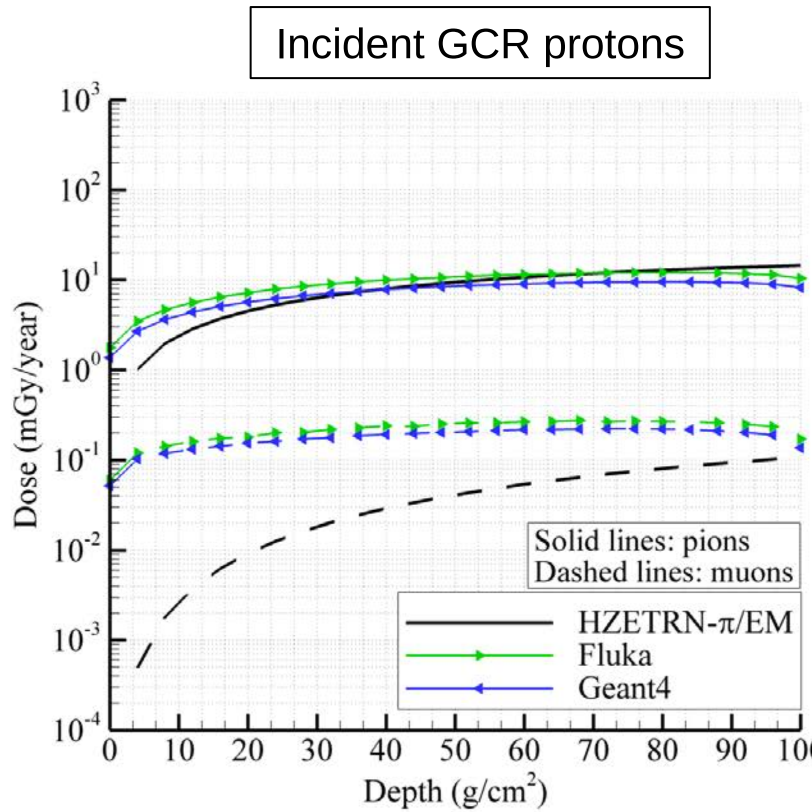
Comparison to Monte Carlo-backup





Dose (mGy/year) versus depth in a 10 g/cm^2 aluminum slab (left pane) and a 100 g/cm^2 aluminum slab (right pane) exposed to GCR protons given by the BO2010 model (ϕ = 475 MV).

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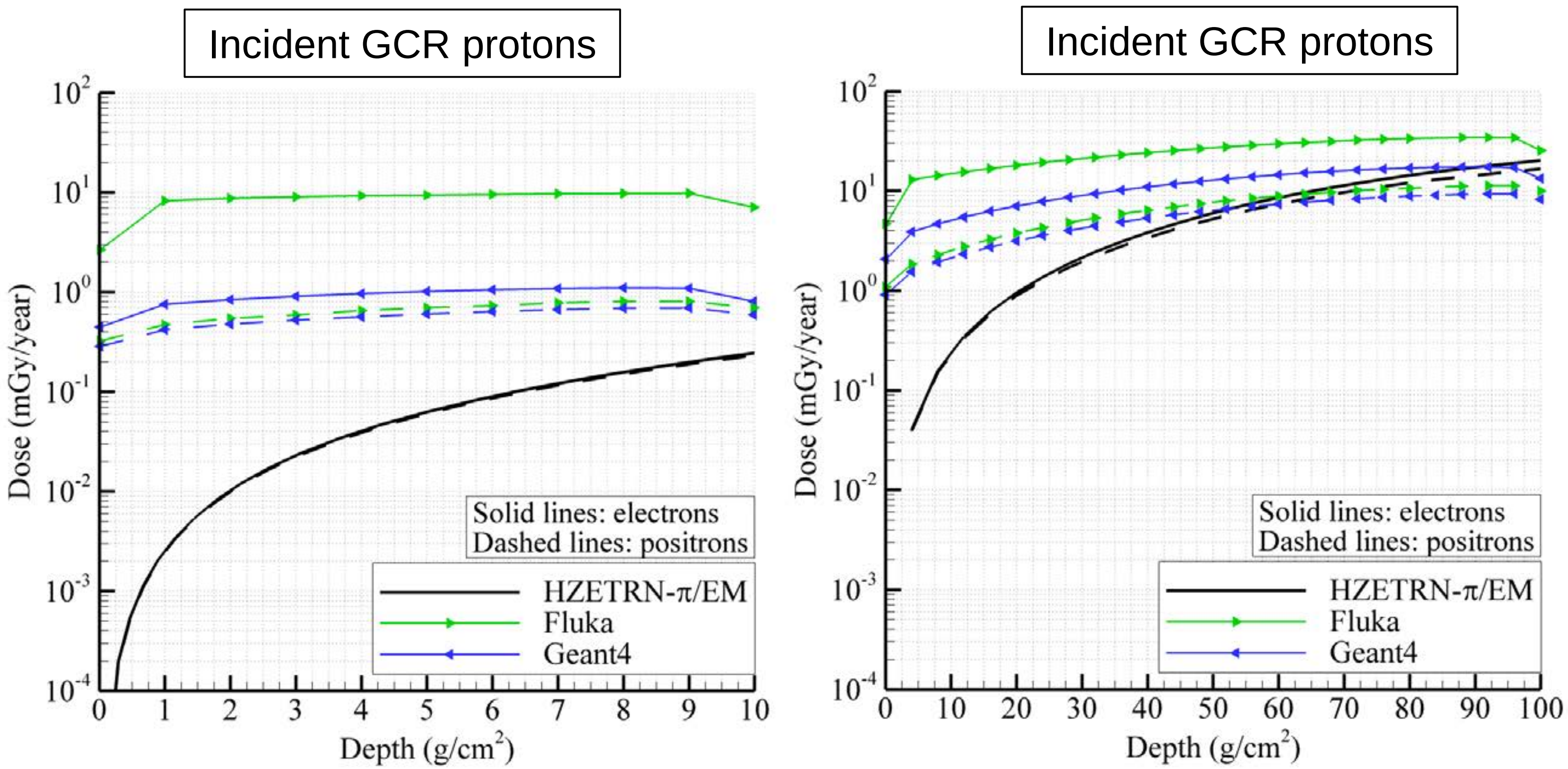

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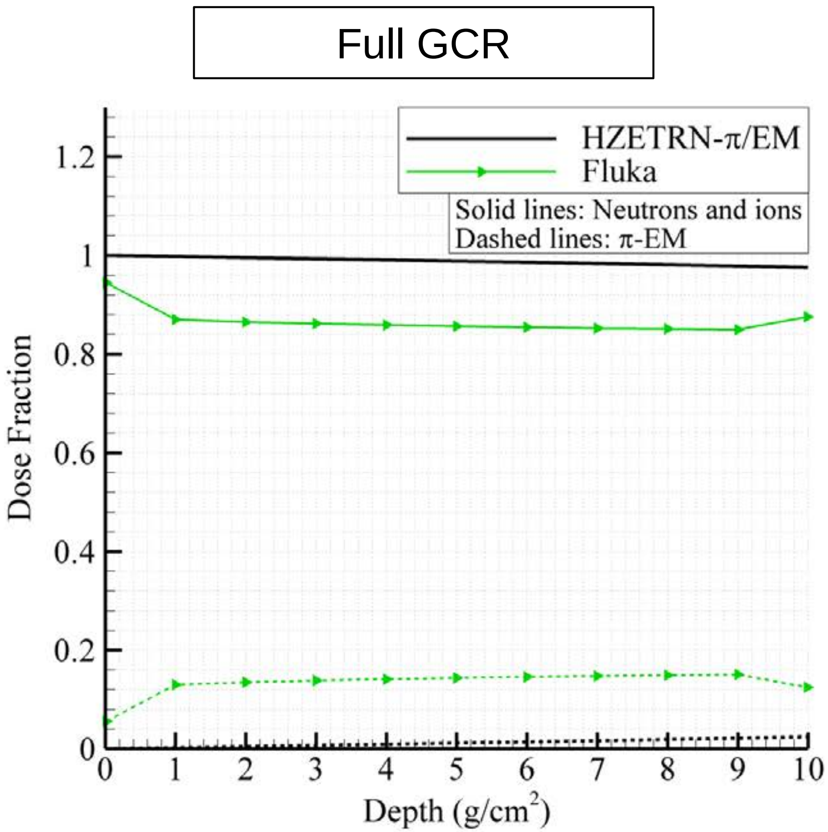

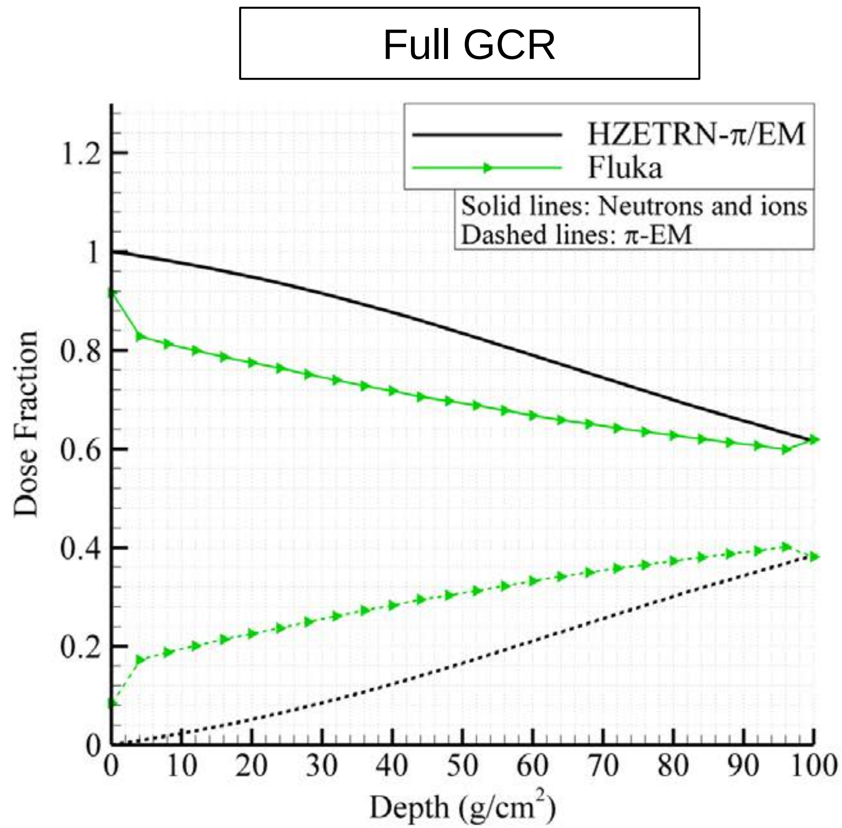

Dose fraction versus depth in a 10 g/cm^2 aluminum slab (left pane) and a 100 g/cm^2 aluminum slab (right pane) exposed to full GCR spectrum given by the BO2010 model (ϕ = 475 MV).

Validation – Backup

Average dose (□Gy/hour) and dose equivalent (□Sv/hour) rate.

Detector	Meas.	BO2004		BO2010	
		HZETRN	HZETRN-π/EM	HZETRN	HZETRN-π/EM
[a]MDU 1	[3.13, 3.23]	2.18	3.55	1.50	2.54
[a]MDU 2	[3.82, 3.92]	2.08	3.77	1.45	2.74
[a]MDU 3	[3.46, 3.56]	2.14	4.01	1.49	2.90
[a]MDU 4	[3.46, 3.55]	2.04	3.79	1.43	2.76
Liulin Avg.	[3.47, 3.57]	2.11	3.78	1.47	2.74
[b]TEPC D	[5.08, 5.27]	2.58	3.41	1.77	2.39
[c]TEPC H	[16.7, 17.9]	10.5	11.4	7.63	8.27

[a] Dose is computed in silicon.
[b] Dose is computed in tissue.
[c] Dose equivalent is computed in tissue using ICRP 60 quality factor.

Average relative difference (%) between model and measurements over the entire trajectory.

Detector	BO2004		BO2010	
	HZETRN	HZETRN-π/EM	HZETRN	HZETRN-π/EM
[a]MDU 1	-32	12	-53	-20
[a]MDU 2	-46	-3	-62	-29
[a]MDU 3	-39	14	-58	-17
[a]MDU 4	-42	8	-59	-21
Liulin Avg.	-40	8	-58	-22
[b]TEPC D	-50	-34	-66	-54
[c]TEPC H	-39	-34	-56	-52

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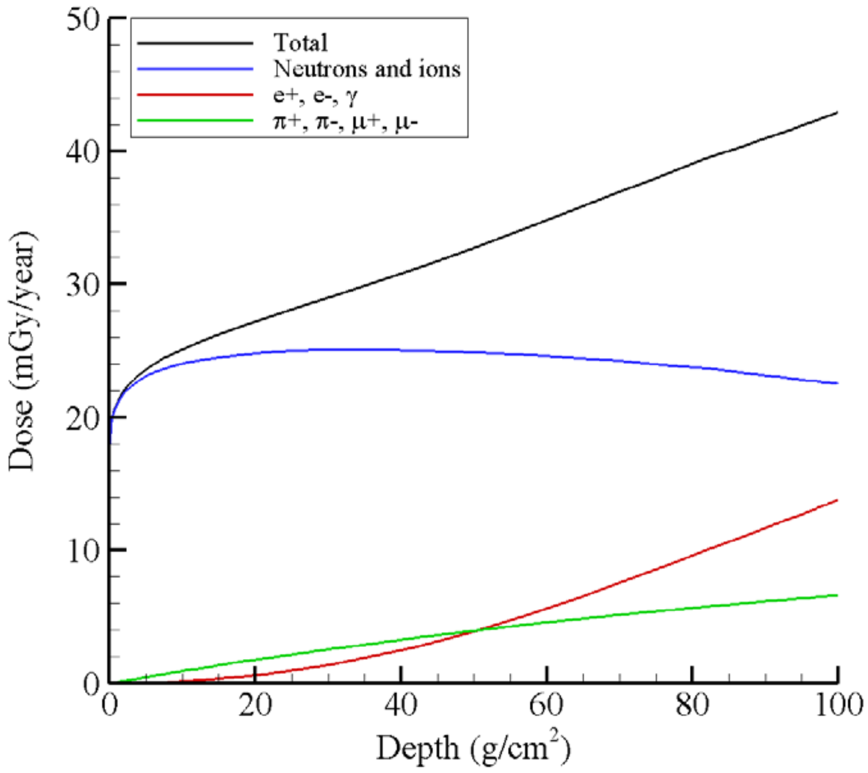
Exposure vs Depth – Backup

Dose versus depth in aluminum for LEO (400 km, 51.6 degree circular oribt). The BO 2010 model was used with a PHI value of 475 MV.



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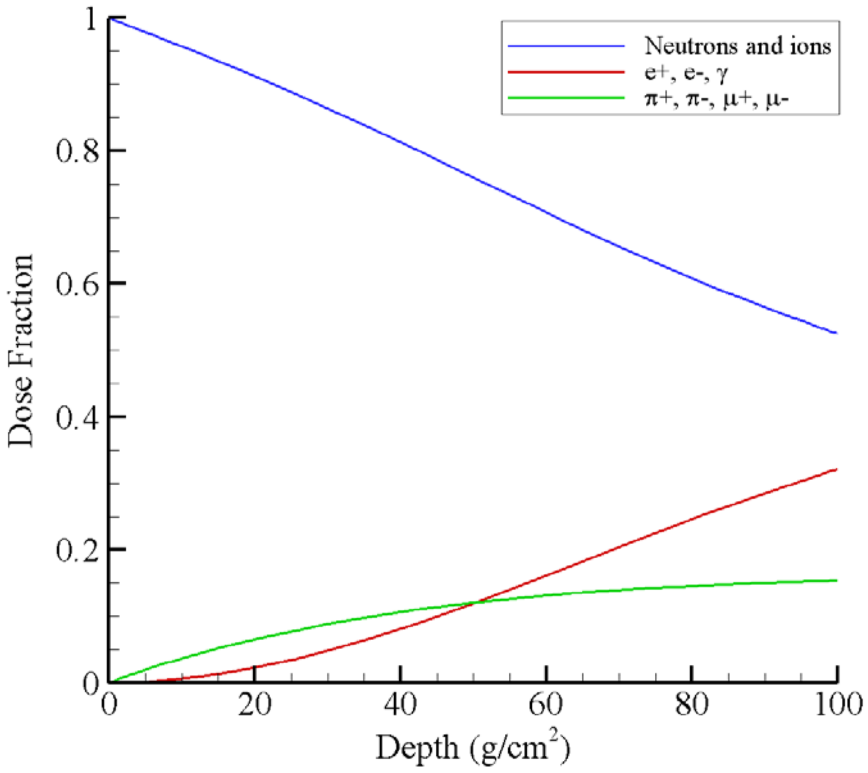

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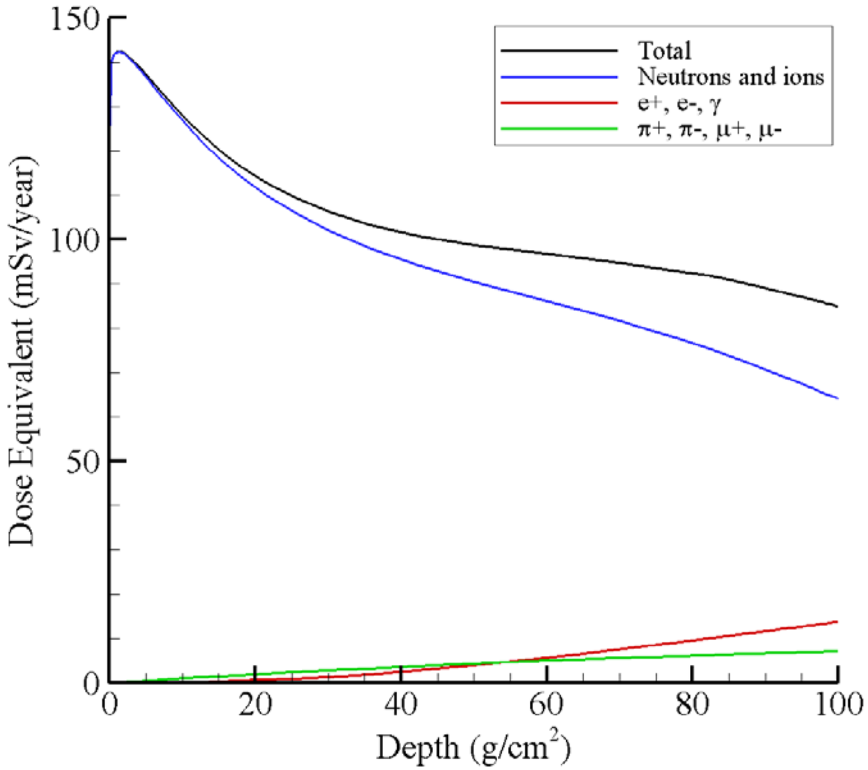

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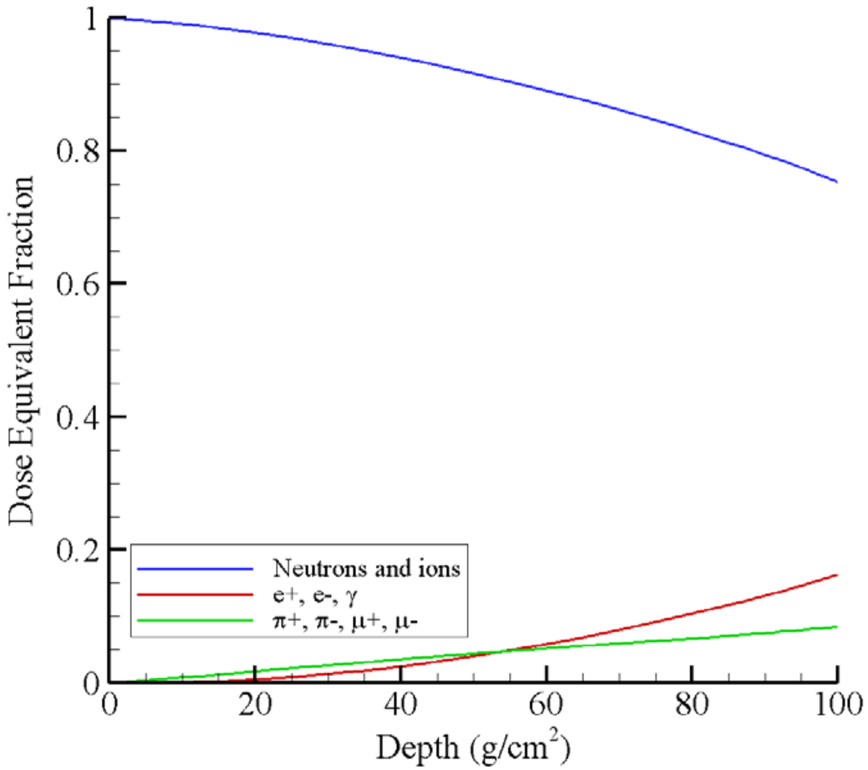

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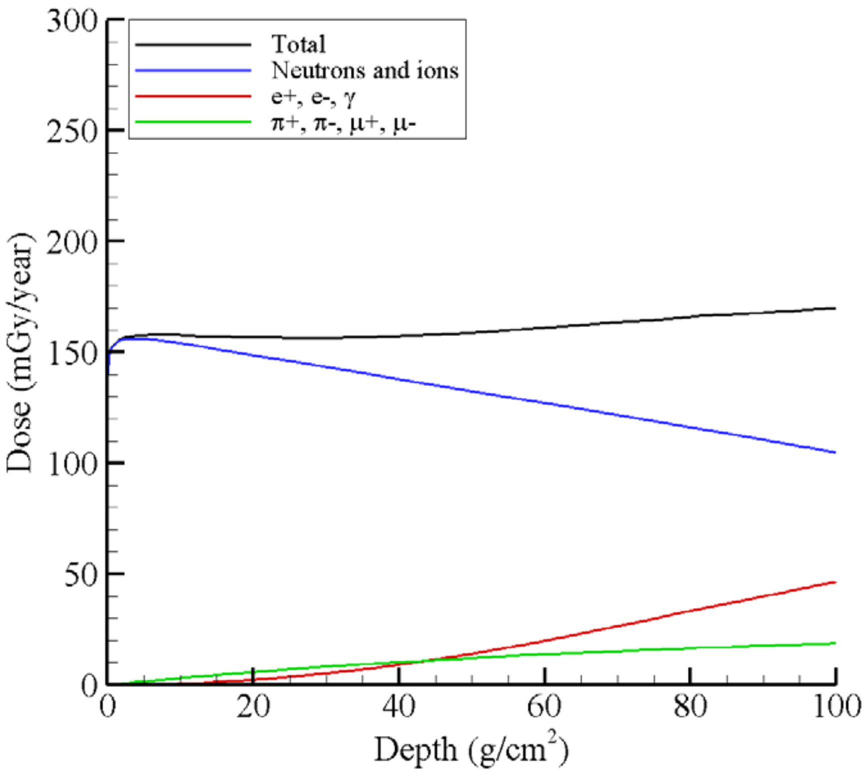
Dose versus depth in aluminum for free-space. The BO 2010 model was used with a PHI value of 475 MV.



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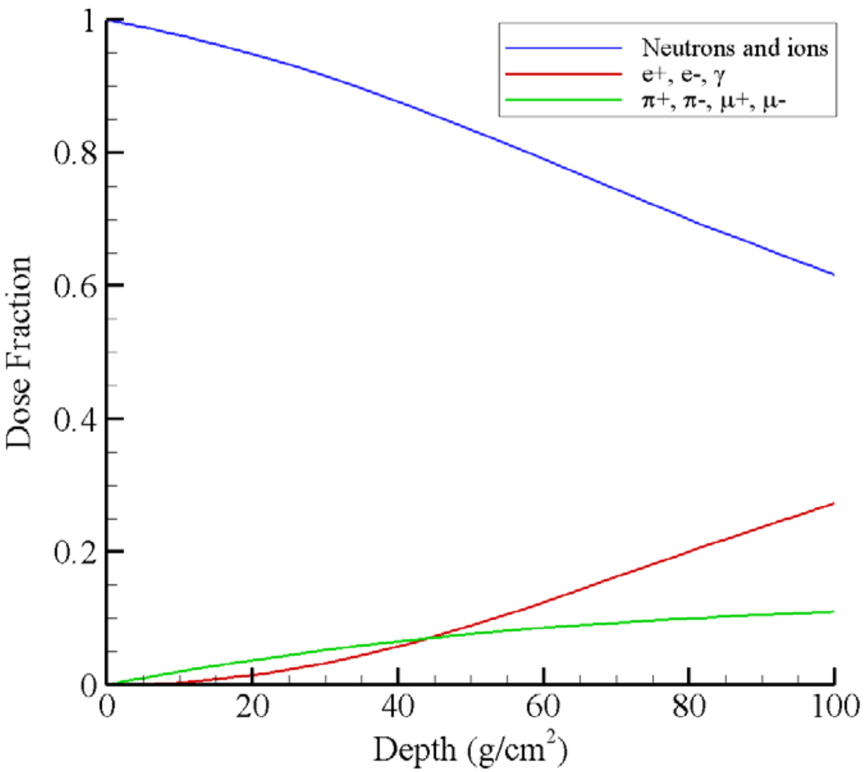

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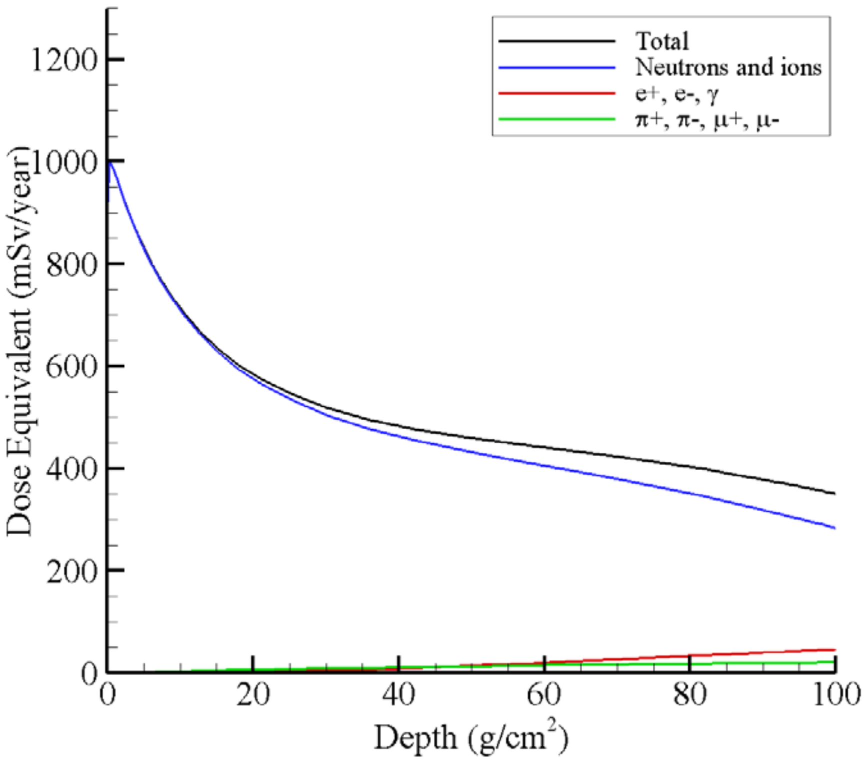

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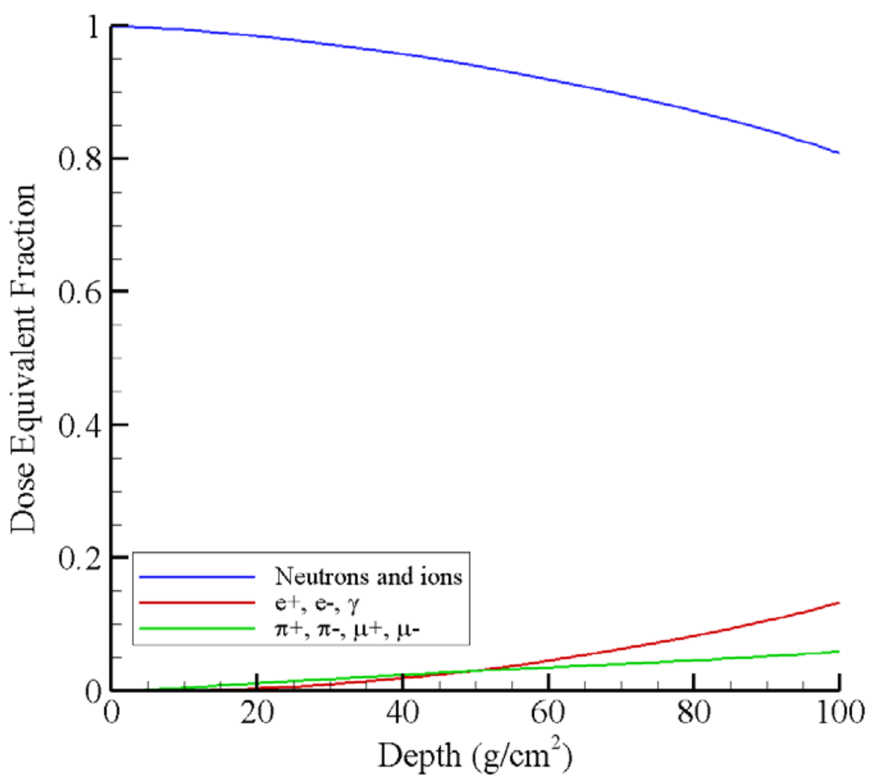

Validation against ISS Data

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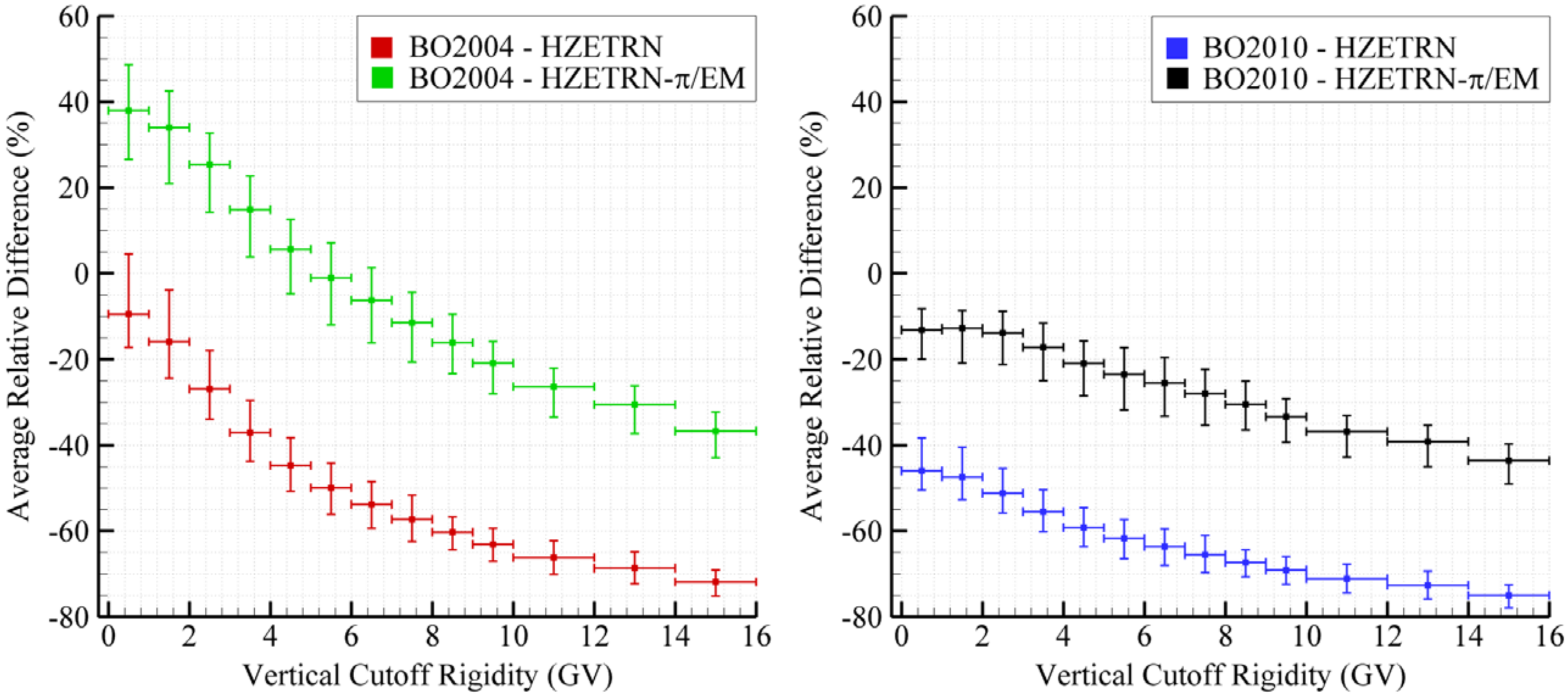
  - ~40% increase in dose across all rigidities (for Liulin detectors) (25% for TEPC)



Average relative difference as a function of vertical cutoff rigidity between model results and Liulin measurements.

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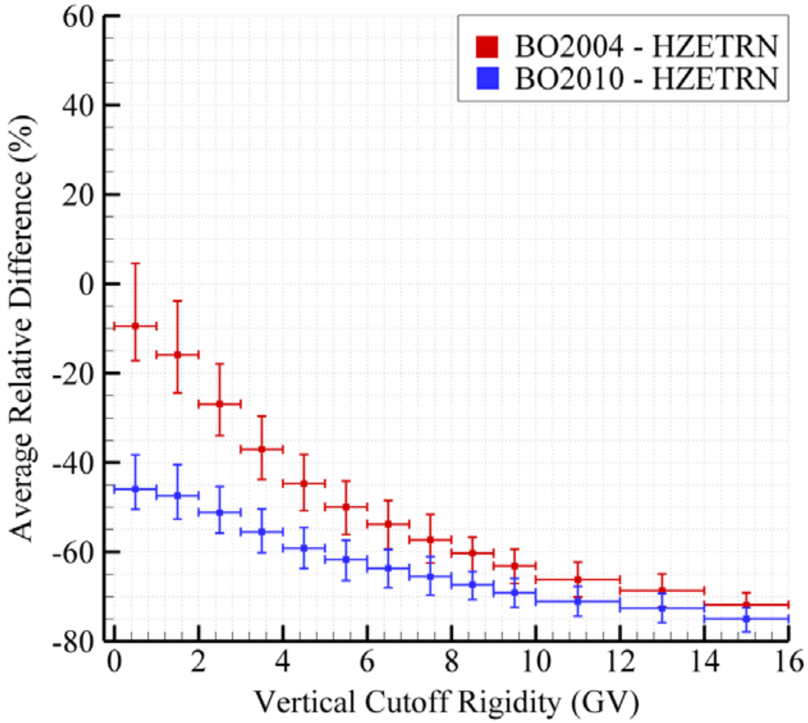

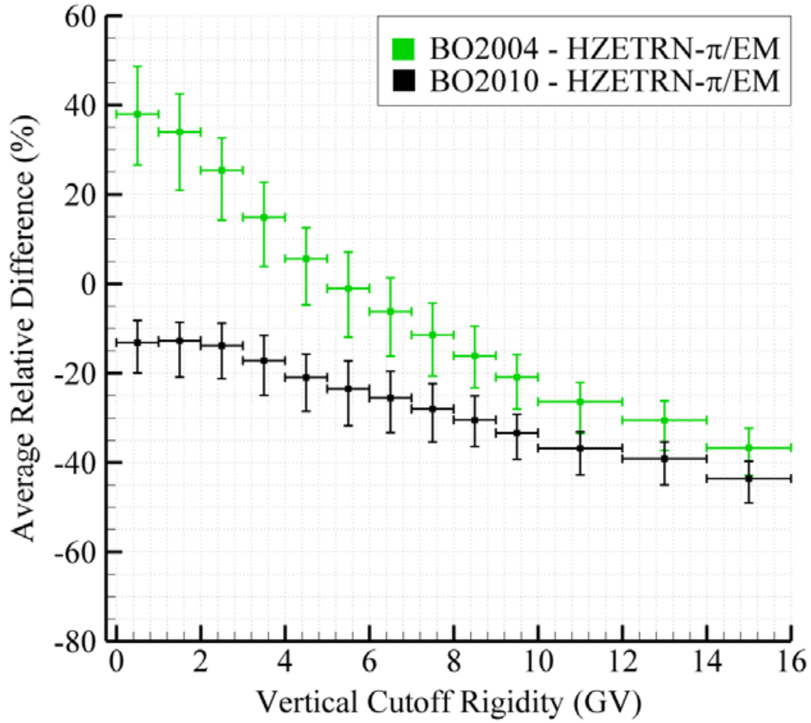

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