Particle spectra on the Martian surface – A comparison of models and MSL-RAD measurements

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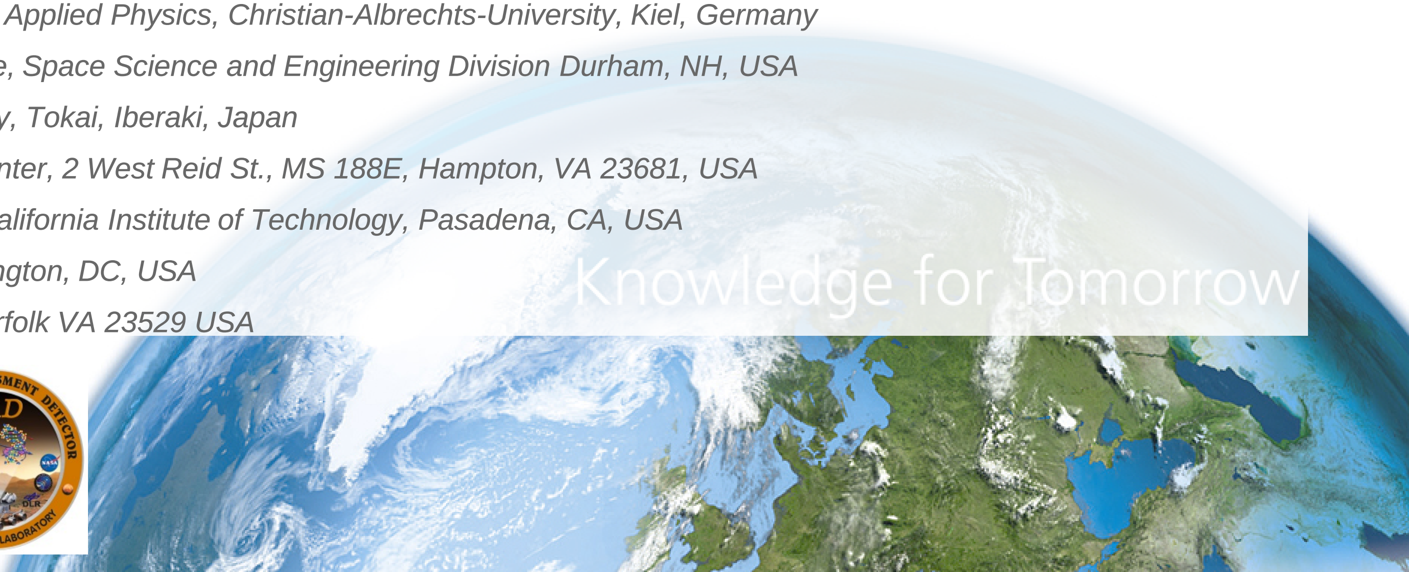


Overview

- Motivation:
  - Numerical models can be used as predictive tools for human exploration
  - Validation of numerical models against experimental data is essential
- Goals:
  - Test of different Galactic Cosmic Radiation (GCR) models
  - Validation of different transport models (GEANT4, PHITS, OLTARIS, HZETRN)
  - Particle flux and dose rates on ground
  - Comparison to RAD results

The setup for the simulations

- **Atmosphere:**
  - 22 g/cm^2
  - Composition (mass %): 95.7% CO_2, 2.7% N,1.6% Ar (Mars-Gram 2001)
- **Soil:** ≥20m, composition from OLTARIS

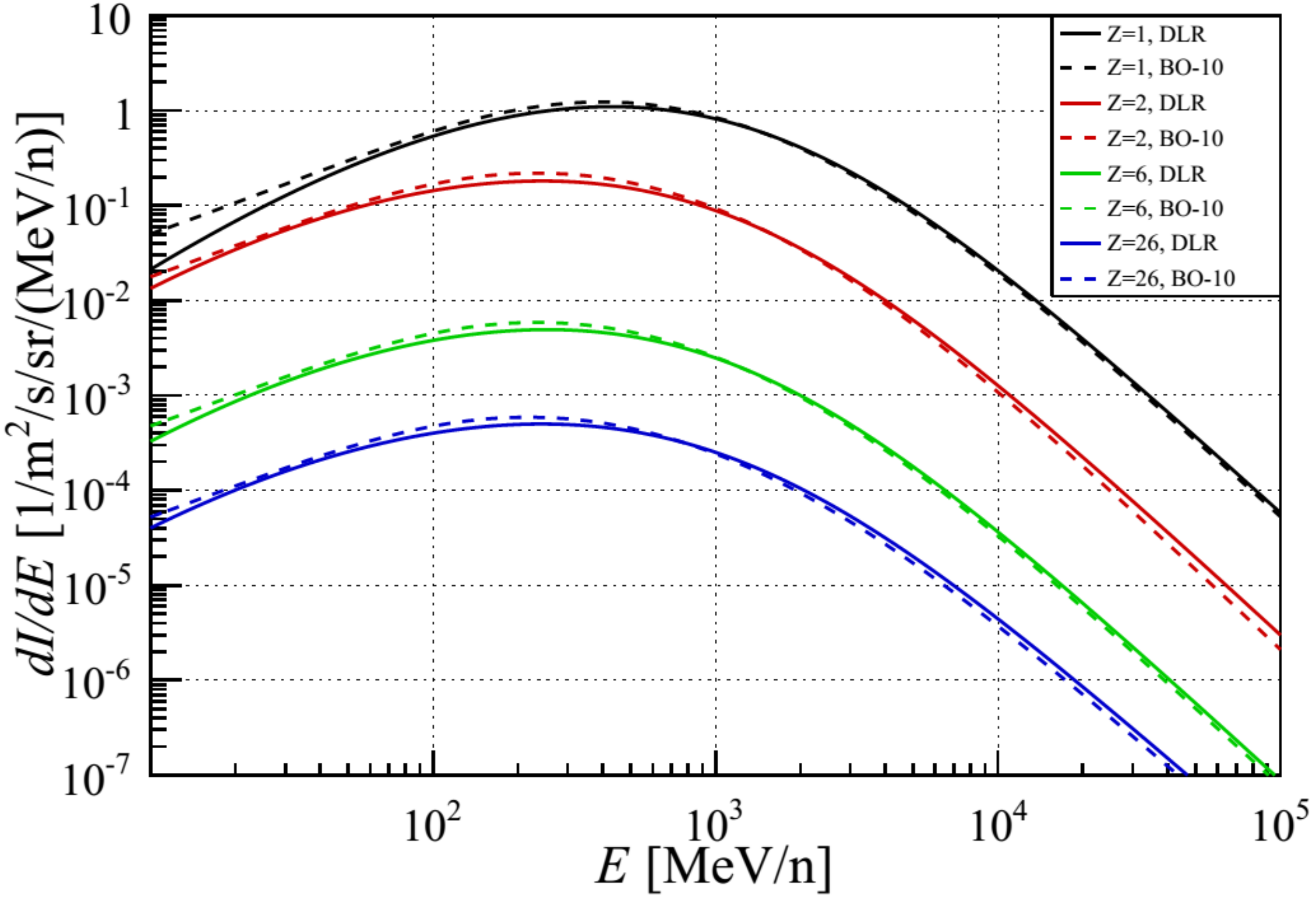
Density: 1.7 g/cm^3

Defined in Terms of Molecular Percentages	
Formula	**Percentage(0 < p <= 100)**
O_2Si	51.2
Fe_2O_3	9.3
$Al_2CaK_2MgNa_2O_7$	32.1
H_2O	7.4
Total	**100.0**

- **GCR-Input:** DLR and Badhwar/O'Neill 2010:
  - 19. Aug. 2012 (doy 232, 2012) until 17. Feb. 2013 (doy 48, 2013), 182 days
- **Particles: neutron** (10^{-8} MeV to 10^4MeV), **proton** (1MeV to 10^5MeV), **gamma** (10^{-3}MeV to 10^4MeV), **e$^{-,+}$** (10^{-3}MeV to 10^4MeV), **deuteron, triton, ^{3}He, ^{4}He, Li/Be/B, C/N/O, Z=9-13, Z≥14** (all 1MeV/n to 10^5MeV/n)
- 4π, zenith angle < 30° (32.3° maximum in RAD)

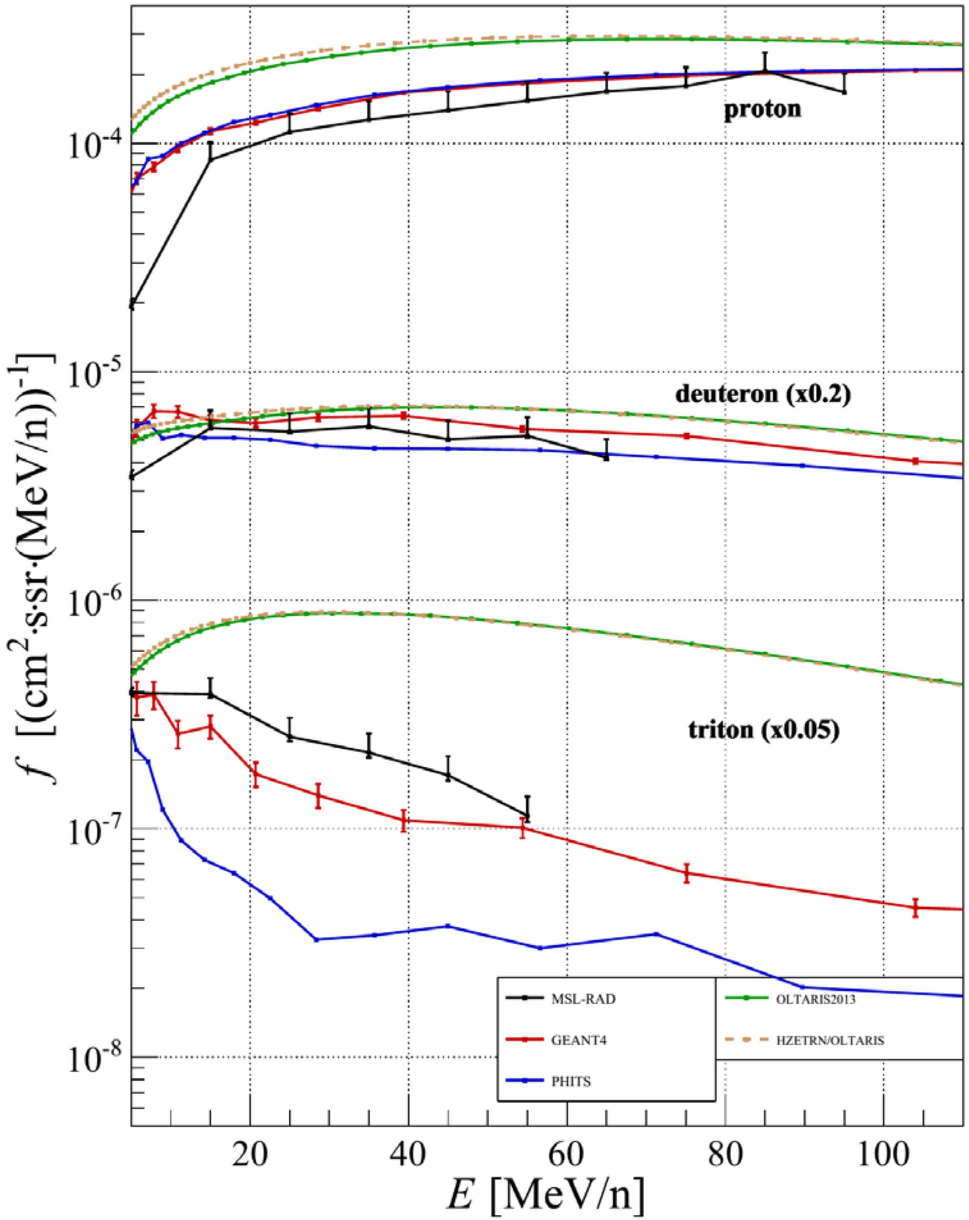
GCR input spectra, DLR and Badhwar/O‘Neill 2010

19. Aug. 2012 (doy 232, 2012) until 17. Feb. 2013 (doy 48, 2013), 182 days



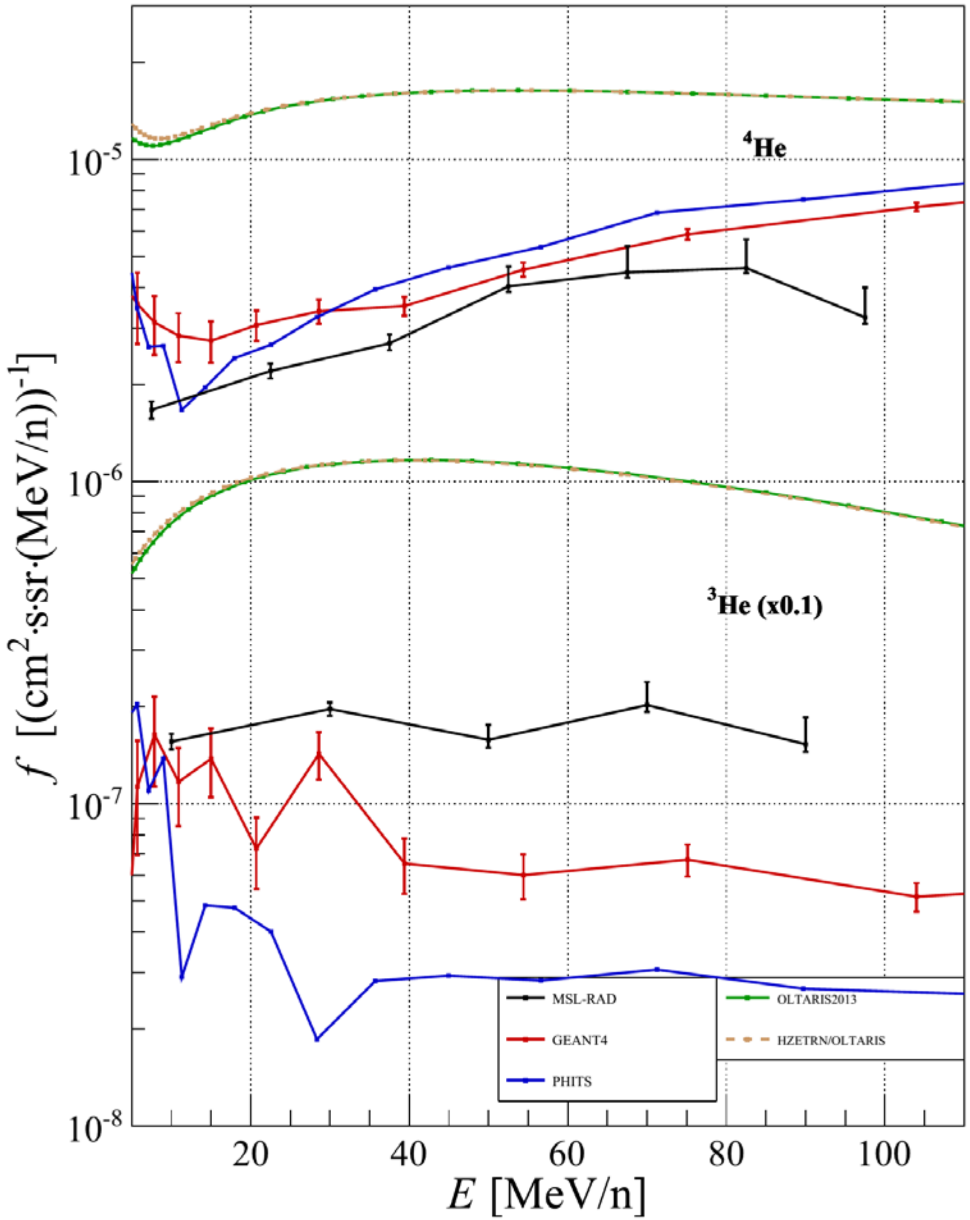
Proton, deuteron, triton

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- **proton:** G4/PHITS best agreement, HZETRN and OLTARIS2013 overestimate
- **deuteron:** all reasonable
- **triton**: G4 good, PHITS underestimates, HZETRN and OLTARIS2013 overestimates
- HZETRN and OLTARIS2013 identical (OLTARIS2013 provided only downward flux)



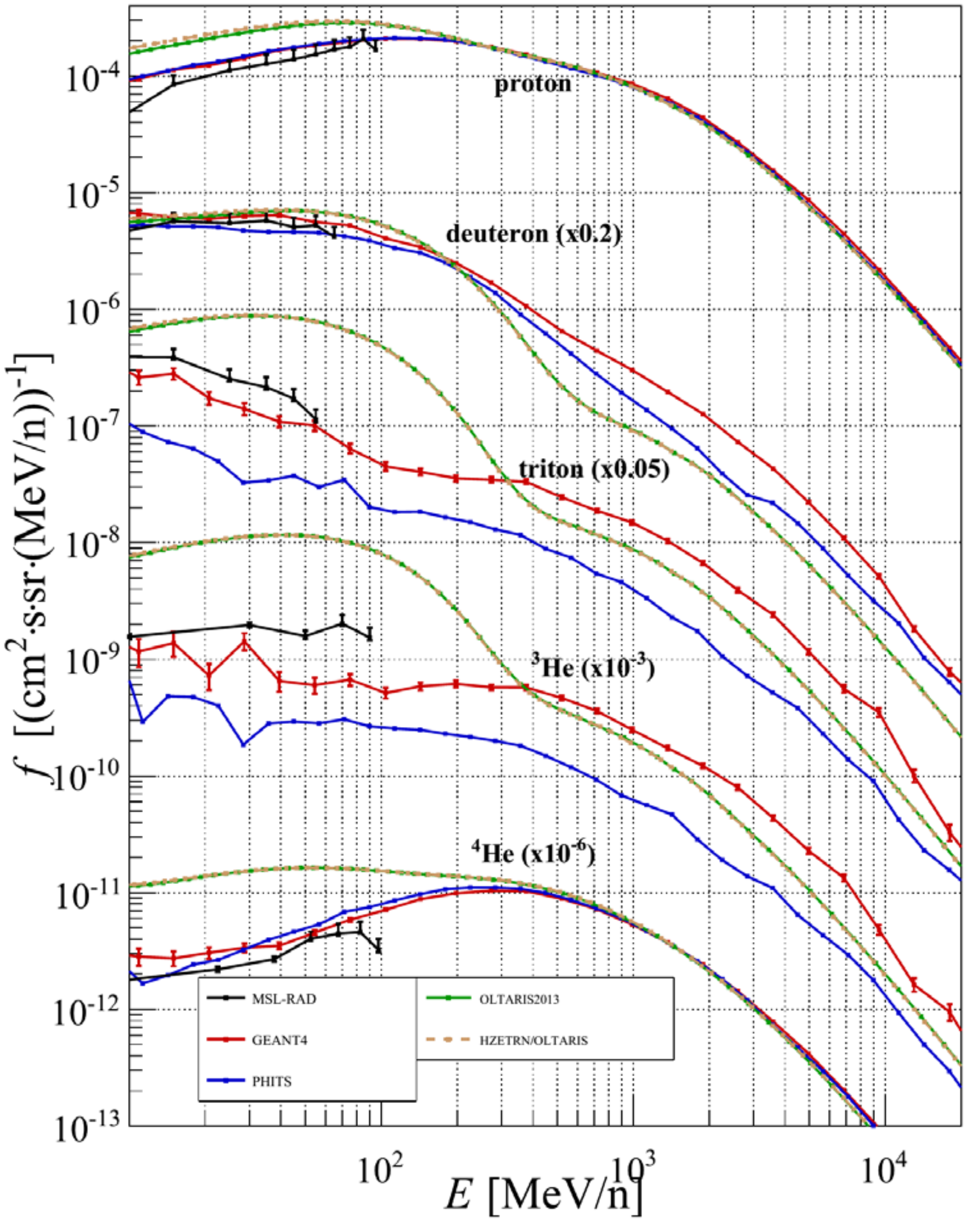
^{3}He, ^{4}He (alpha)

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- **^{3}He**: G4/PHITS underestimate; HZETRN and OLTARIS2013 overestimate
- **^{4}He**: G4 good, PHITS slightly overestimates; HZETRN and OLTARIS2013 overestimate



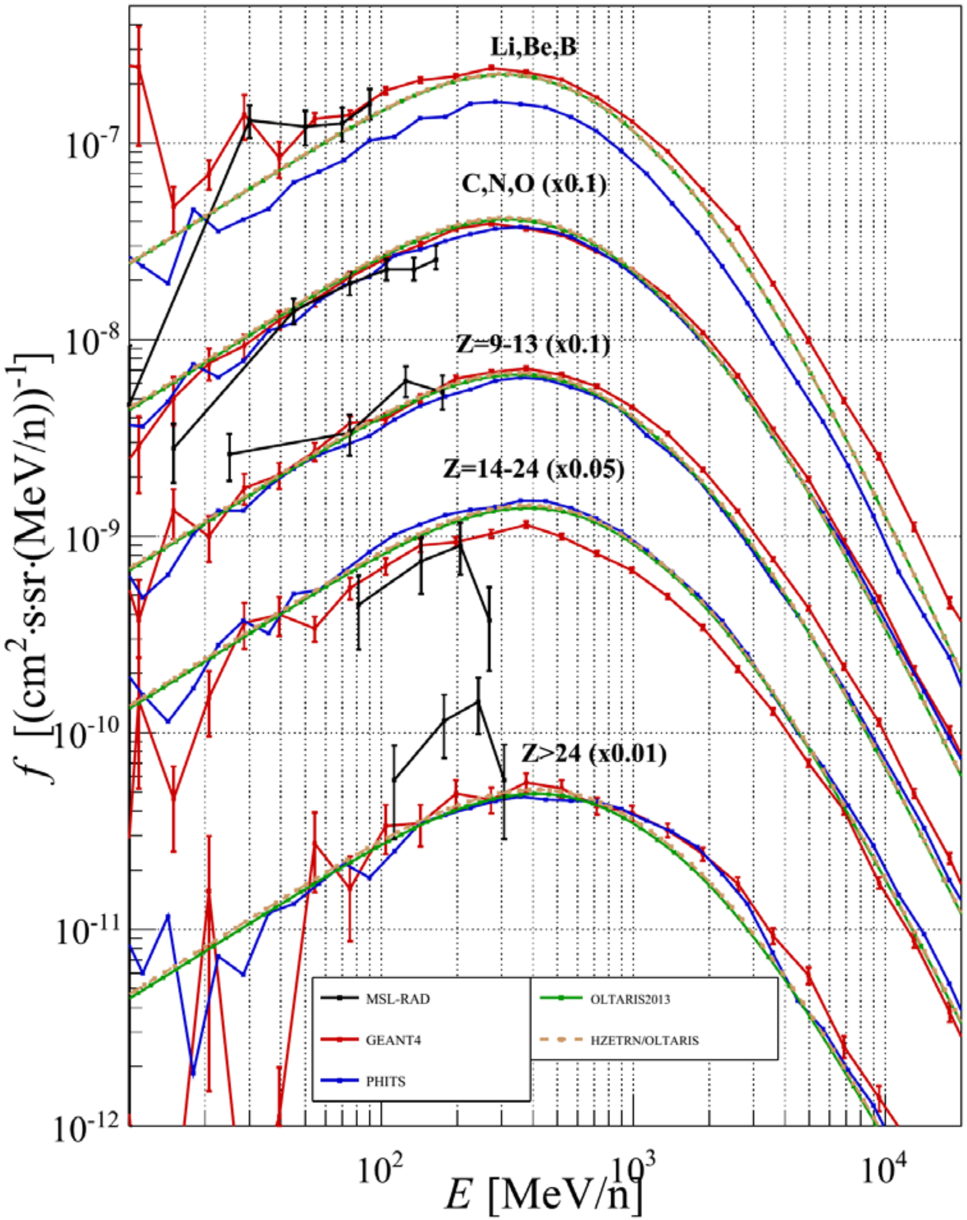
Proton, deuteron, trition, ^{3}He, ^{4}He (alpha)

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS



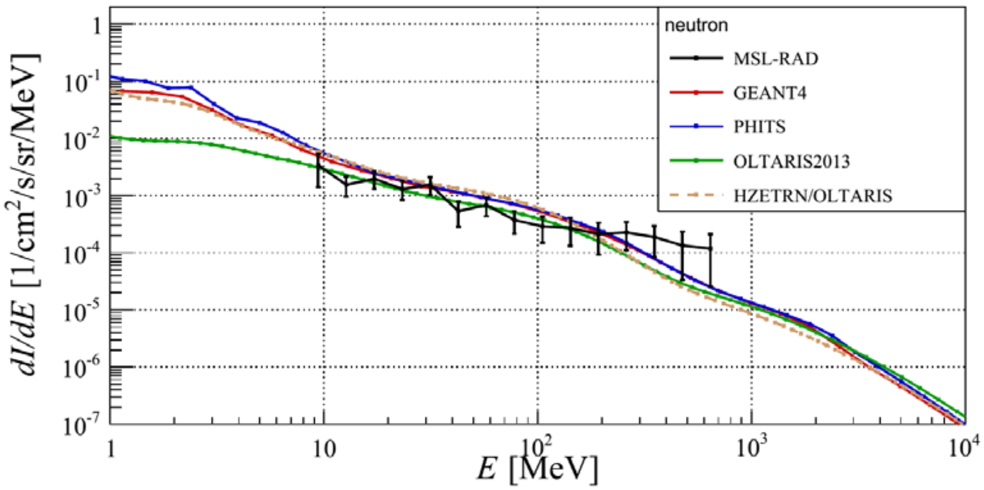
Li/Be/B, C/N/O, Z=9-13, Z=14-24, Z≥25

- Zenith angle ≤30°
- MSL-RAD data: *Ehresmann et al. 2014*
- GEANT4, PHITS, OLTARIS2013, HZETRN/OLTARIS
- **Li/Be/B:** PHITS underestimates
- **C/N/O, Z=9-13:** agreement reasonable
- **Z=14-24**: G4 good, PHITS, HZETRN and OLTARIS2013 overestimate
- **Z>24**: all underestimate

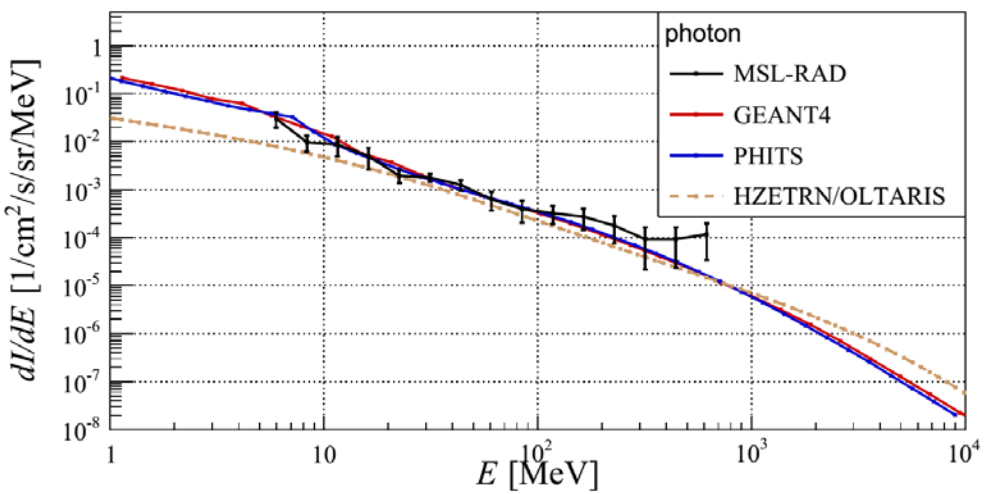


Neutron and photon

- MSL-RAD data: *Köhler et al. 2014*
- Neutrons (GEANT4, PHITS, HZETRN, OLTARIS2013)
  - Good agreement above 1GeV
  - Lower neutron fluxes from OLTARIS2013 below 1GeV (upward fluxes are missing)

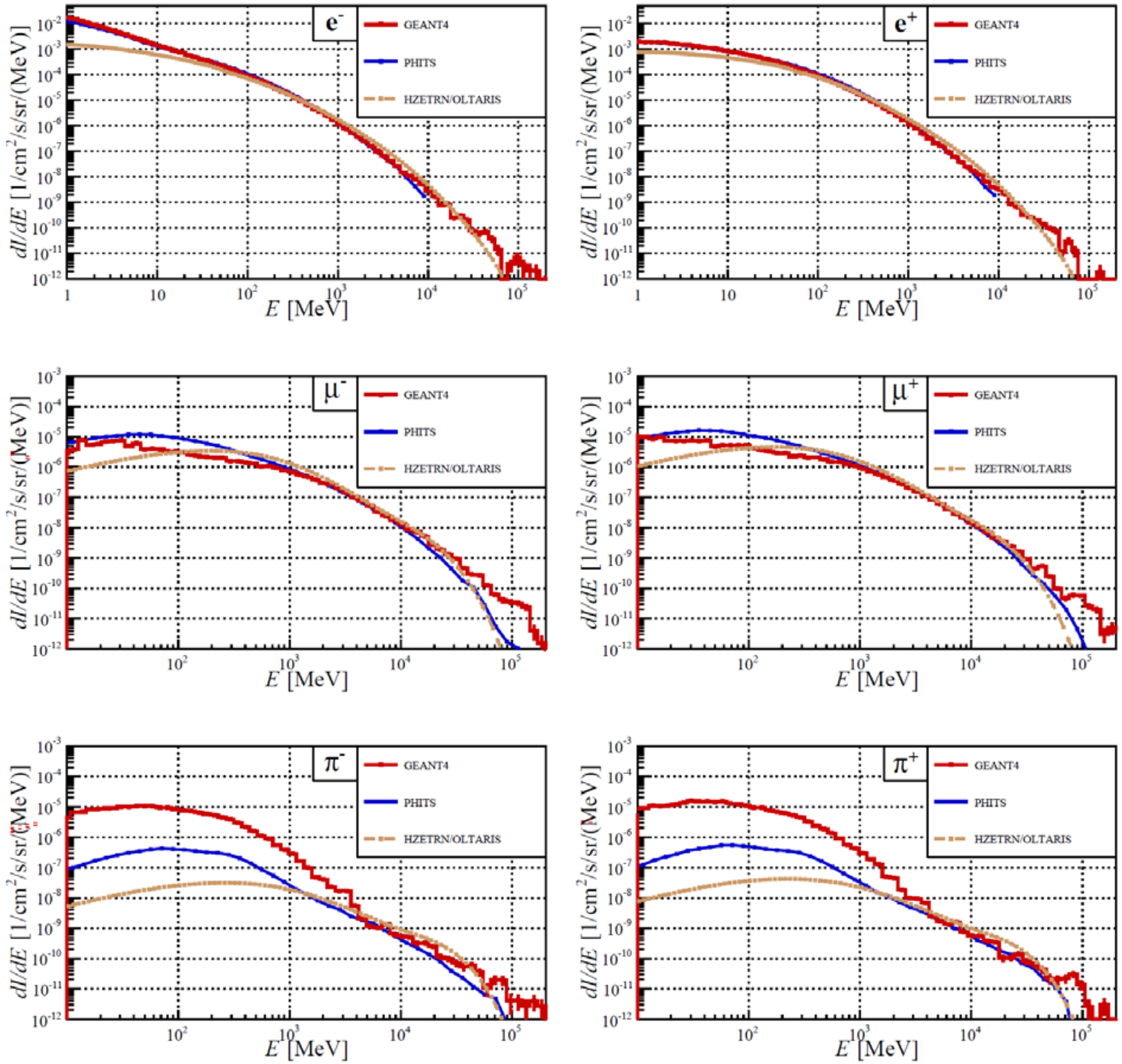


- Photons:
  - Good agreement G4/PHITS
  - HZETRN significantly lower (higher) at energies < 10MeV (>1GeV)



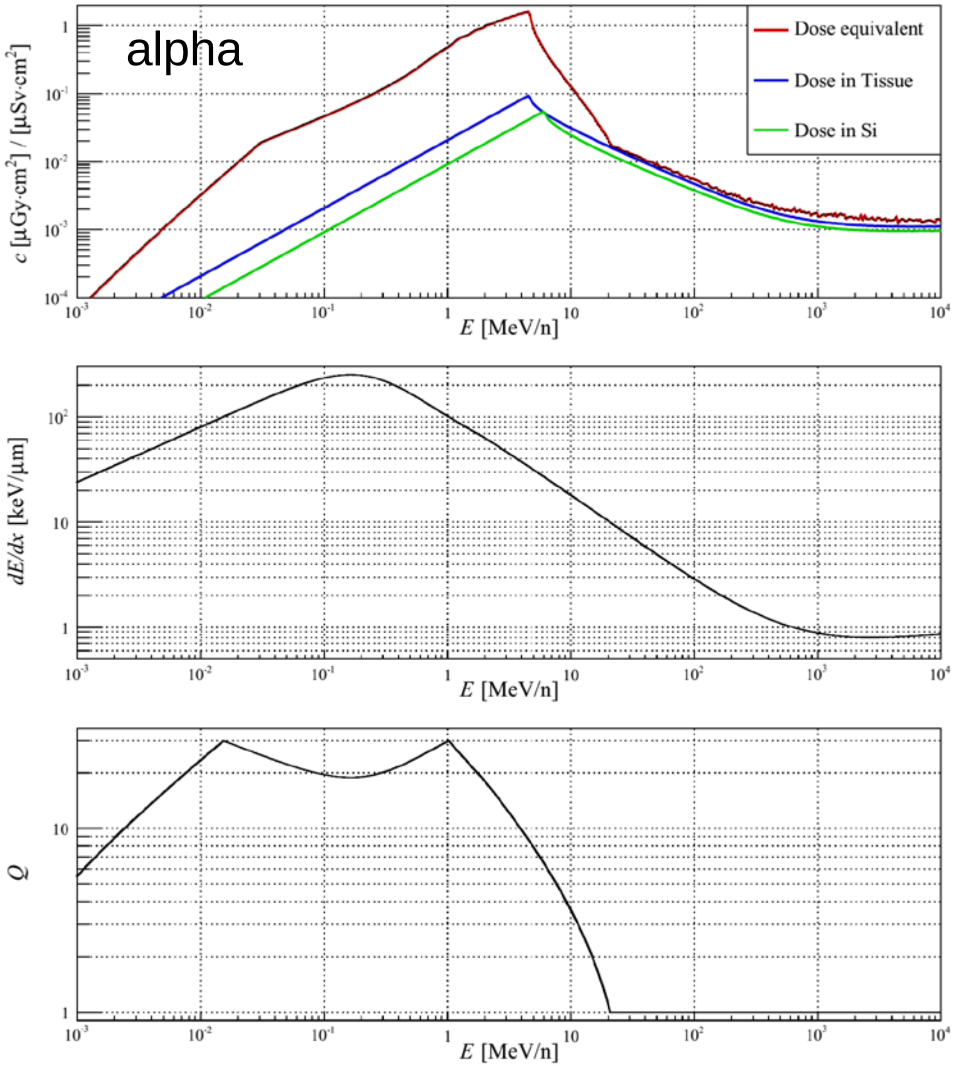
Electron, muon, pion

- No experimental data
- $e^{-/+}$: G4/PHITS agree, HZETRN lower
- $\mu^{-/+}$: differences below 100 MeV
- $\pi^{-/+}$: differences of several orders of magnitude



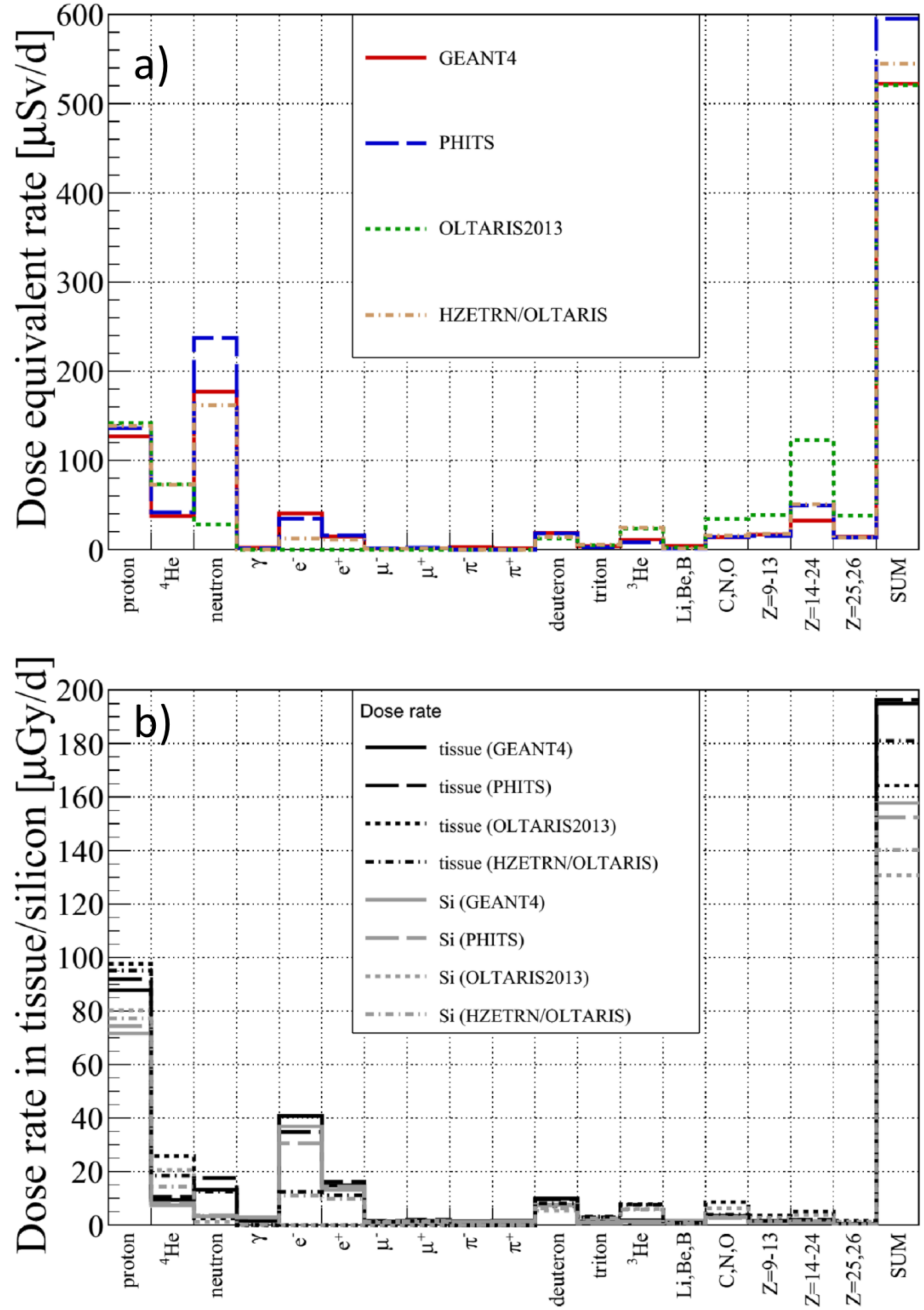
Fluence to dose conversion

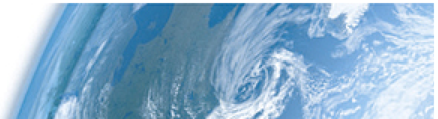
- Pre-calculated fluence-to-dose-conversion factors *c*
- 0.5 mm slab of
  - Tissue
  - Water
  - Si
- $\dot{D} = \int dE \cdot c_D \cdot f$
- $\dot{H} = \int dE \cdot c_H \cdot f$



Contribution of different particles to the dose rate

- Very low neutron dose in OLTARIS2013 (no upward flux)
- High neutron dose in PHITS
- Higher dose from high-Z particles in OLTARIS2013
- Agreement of total dose within 10-20%
- MSL-RAD (*Hassler et al. 2014*)
  - 0.21±0.04 mGy/d
  - 0.64±0.12 mSv/d





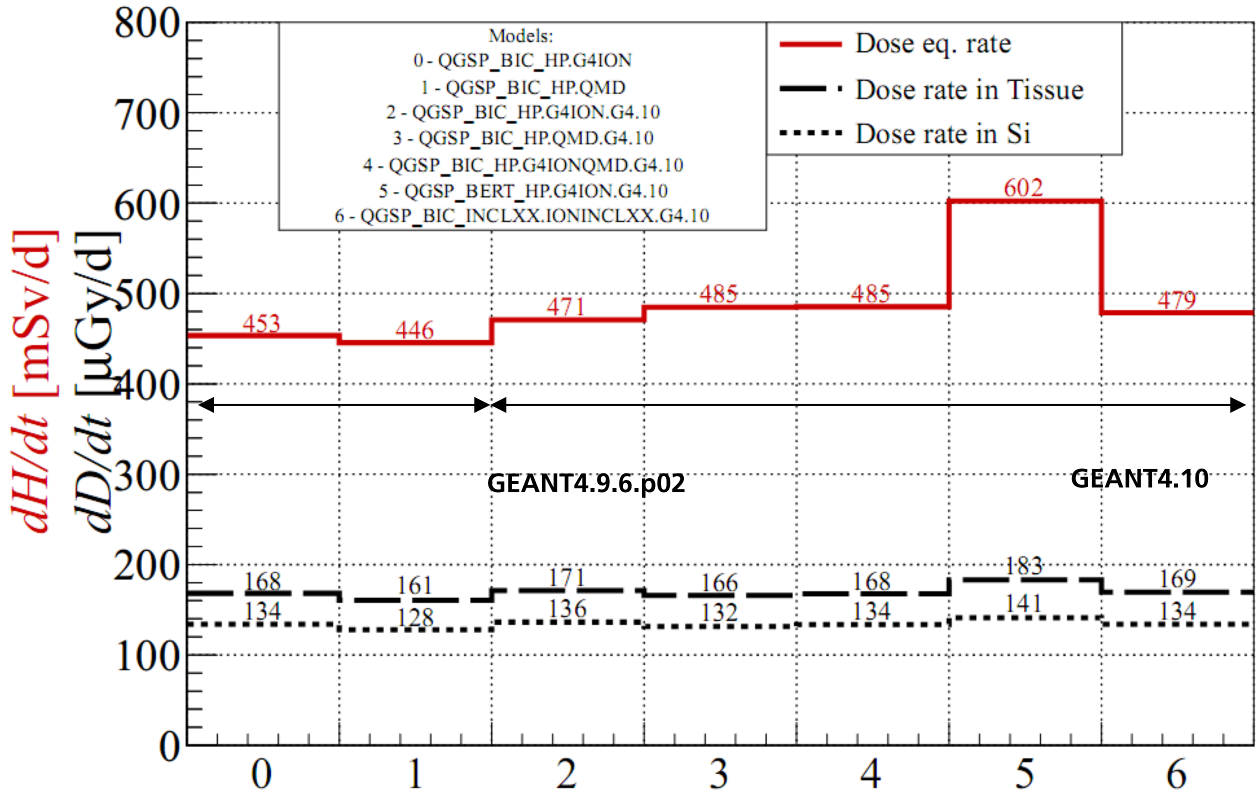
Comparison of calculated and measured dose rates

Values in parenthesis are the derived quality factors for a restricted zenith angle θ<30°.

	MSL-RAD [Hassler et al., 2014]	GEANT 4.10.p02	PHITS	OLTARIS2013	HZETRN/ OLTARIS
dose rate in tissue [mGy/d]	0.21±0.04	0.19	0.20	0.16	0.18
dose equivalent rate [mSv/d]	0.64±0.12	0.52	0.60	0.52	0.54
Quality factor	**3.05±0.26**	**2.7 (3.0)**	**3.0 (3.4)**	**3.2**	**3.0 (3.2)**

Comparison of calculated dose rate at Martian surface (20 g/cm² atmospheric shielding) from different G4 versions and G4 models:

Dose from Z=1,2,26



- Differences below 5%-10% for absorbed dose rate
- High neutron production in the Bertini model (BERT)
- → 25% higher dose equivalent rate

Summary

- Output of DLR and BO-10 model very similar; differences in dose rates ≤ 5%
- Reasonable agreement between different transport models for many particles but severe differences for others
- Calculated total dose rates are compatible with measurements, but in some cases large discrepancies in the contribution of individual particle types
- Discrepancies in the high energy regime of some particles unresolved

Overview of calculated dose rates at Martian surface

	MSL-RAD [Hassler et al., 2014]	GEANT 4.10.p02					PHITS	OLTARIS 2013	HZETRN /OLTARIS
		[1]	[2] QGSP_BIC, INCL	[3] QGSP_BIC_HP, G4Ion	[4] QGSP_BIC_HP, QMD	[5] QGSP_BERT_HP, G4INCL			
dose rate in Silicon [mGy/d]		0.16 (0.017)	0.15 (0.17)	0.15 (0.017)	0.15 (0.016)	0.16 (0.017)	0.15 (0.019)	0.13	0.14 (0.019)
dose rate in tissue [mGy/d]	0.21±0.04	0.19 (0.021)	0.19 (0.021)	0.19 (0.020)	0.18 (0.020)	0.20 (0.021)	0.20 (0.024)	0.16	0.18 (0.024)
dose equivalent rate [mSv/d]	0.64±0.12	0.52 (0.063)	0.51 (0.063)	0.51 (0.067)	0.51 (0.069)	0.61 (0.068)	0.60 (0.081)	0.52	0.54 (0.076)
Quality factor	3.05±0.26	2.7 (3.0)	2.7 (3.1)	2.7 (3.3)	2.8 (3.5)	3.0 (3.2)	3.0 (3.4)	3.2	3.0 (3.2)

	MSL-RAD [Hassler et al., 2014]	GEANT 4.10.p02	PHITS	OLTARIS 2013	HZETRN /OLTARIS
GEANT4 physics list setups					
[1]	Physics Lists: emstandard_opt3, G4HadronPhysicsINCLXX, G4IonINCLXX Models: Ions: INCL v5.1.14.2 (0 eV < E < 54 GeV); FTFP (53.9 GeV < E < 1 TeV) Neutrons/Protons: PRECO (0 eV < E < 2 MeV); INCL v5.1.14.2 (1 MeV < E < 3 GeV); Bertini (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[2]	Physics Lists: emstandard_opt3, user defined Models: Ions: INCL v5.1.14.2 (0 eV < E < 48 GeV); FTFP (47.999 GeV < E < 1 TeV) Protons: PRECO (0 eV < E < 2 MeV); INCL v5.1.14.2 (1 MeV < E < 3 GeV); Binary Cascade (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); INCL v5.1.14.2 (19.9 MeV < E < 3 GeV); Binary Cascade (2.9 GeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[3]	Lists: emstandard_opt3, G4HadronPhysicsQGSP_BIC_HP, G4IonPhysics Models: Ions: Binary Light Ion Cascade (0 eV < E < 4 GeV); FTFP (2 GeV < E < 100 TeV) Protons: Binary Cascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); Binary Cascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[4]	Physics Lists: emstandard_opt3, G4HadronPhysicsQGSP_BIC_HP, G4IonQMDPhysics Models: Ions: QMDModel (0 eV < E < 10 TeV) Protons: Binary Cascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); Binary Cascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				
[5]	Physics Lists: emstandard_opt3, G4HadronPhysicsQGSP_BERT_HP, G4IonINCLXX Models: Ions: INCL v5.1.14.2 (0 eV < E < 54 GeV); FTFP (53.9 GeV < E < 1 TeV) Protons: BertiniCascade (0 eV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV) Neutrons: NeutronHPInelastic (0 eV < E < 20 MeV); BertiniCascade (19.9 MeV < E < 9.9 GeV); QGSP (12 GeV < E < 100 TeV); FTFP (9.5 GeV < E < 25 GeV)				