Measurements of the boron-to-carbon and boron-to-oxygen flux ratios in cosmic rays with DAMPE

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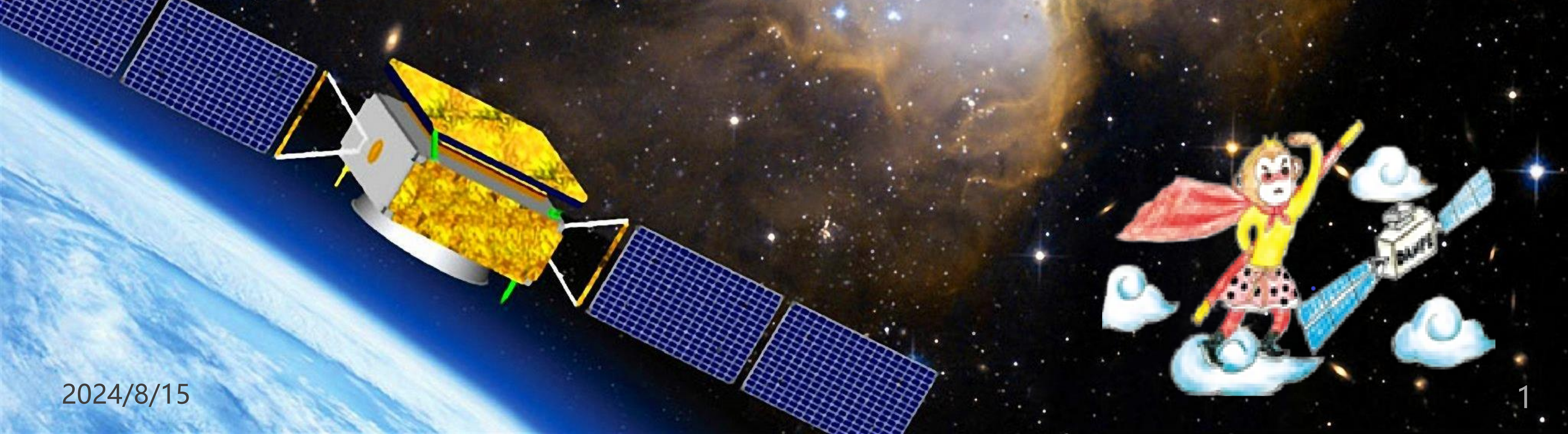
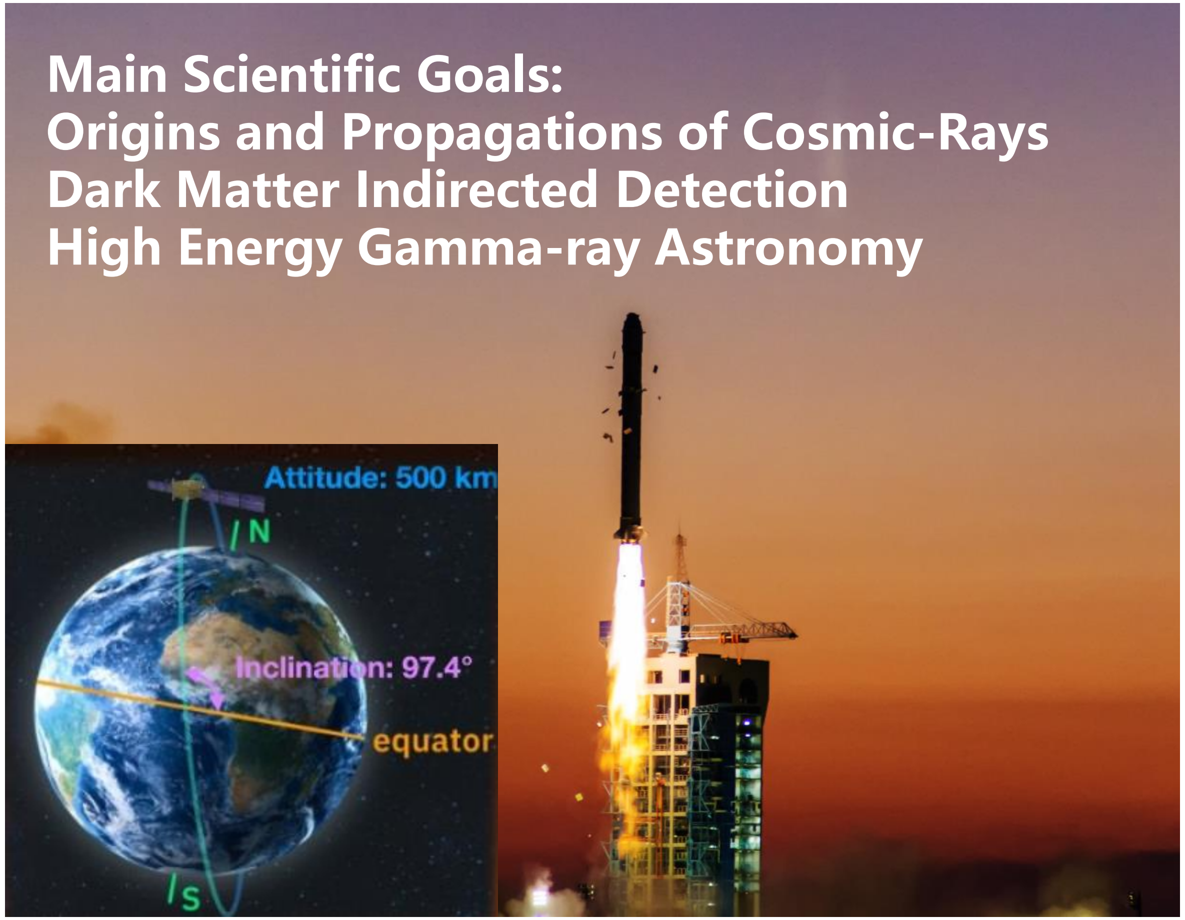
(on behalf of the DAMPE Collaboration)



DAMPE: The Dark Matter Particle Explorer

The mission



DAMPE is a space-borne high energy particle detector launched in Dec. 2015 from the Jiuquan Satellite Launch Center

International collaboration:

China

- Purple Mountain Observatory, CAS
- University of Science and Technology of China
- Institute of High Energy Physics, CAS
- Institute of Modern Physics, CAS

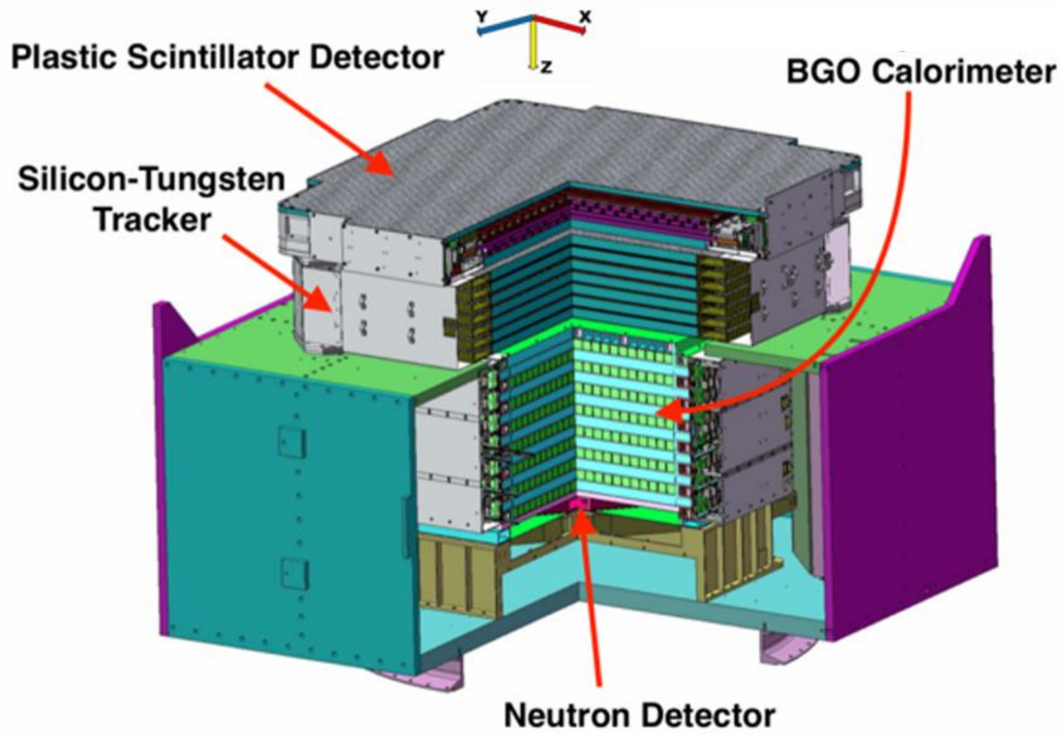
Italy

- INFN Perugia and University of Perugia
- INFN Bari and University of Bari
- INFN-LNGS and Gran Sasso Science Institute
- INFN Lecce and University of Salento

Switzerland

- University of Geneva

DAMPE: Detector system

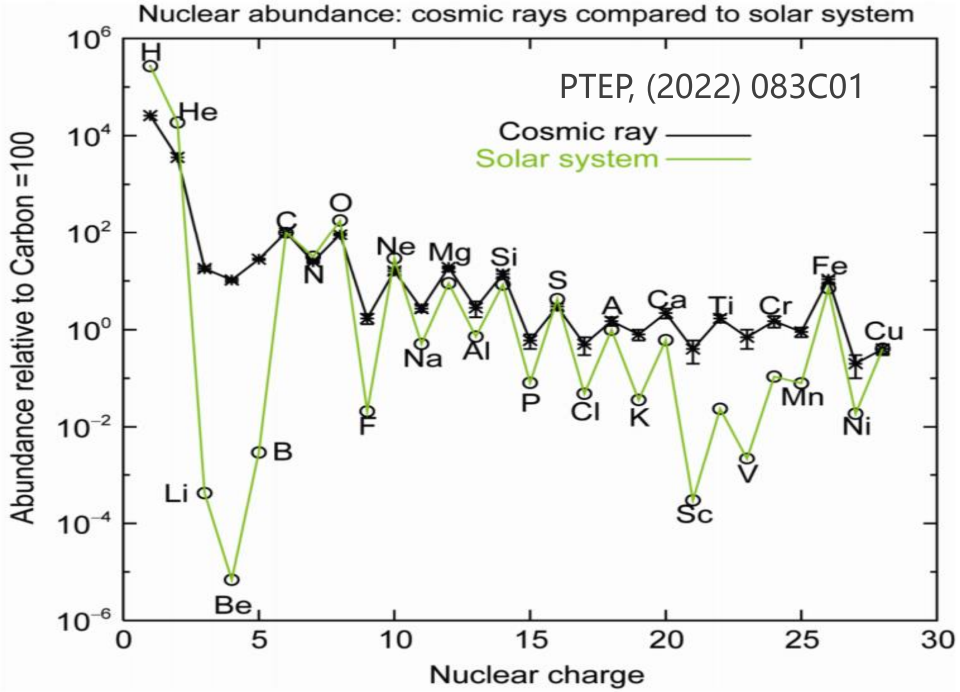


Parameter	Value
Energy range (e/γ)	5 GeV to 10 TeV
Energy resolution (e/γ)	1.5% at 800 GeV
Energy range (p/ion)	50 GeV to 500 TeV
Energy resolution (p)	40% at 800 GeV
Geometric factor (e)	0.3 m^2 sr above 30GeV
Angular resolution (γ)	0.1 degree at 100 GeV
Field of view	1.0 sr

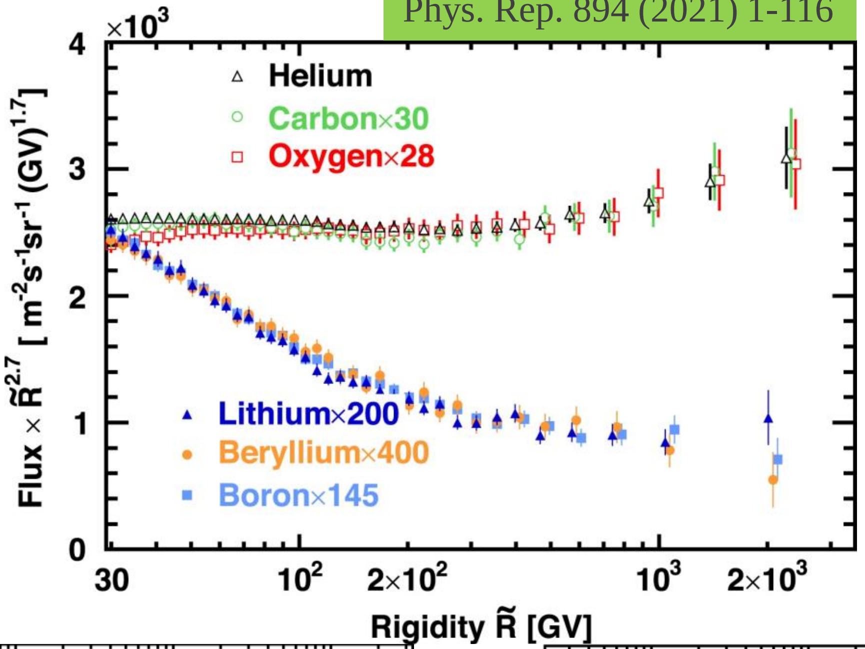
PSD: Anti-coincidence detector for gammas and charges measurement
STK: Particle tracker, photon converter & additional charge measurement
BGO: Energy measurement & particle identification via shower topology
NUD: Further particle ID from electromagnetic & hadronic showers

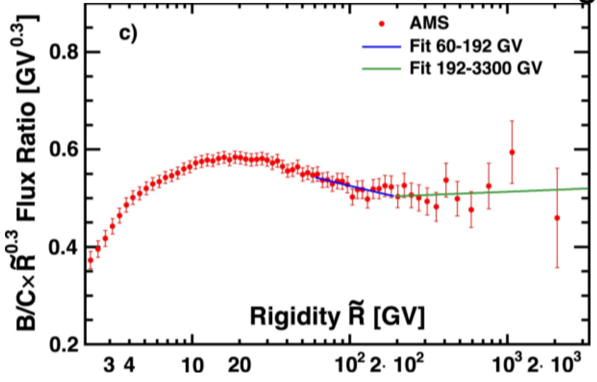
Astropart.Phys 95 (2017) 6–24

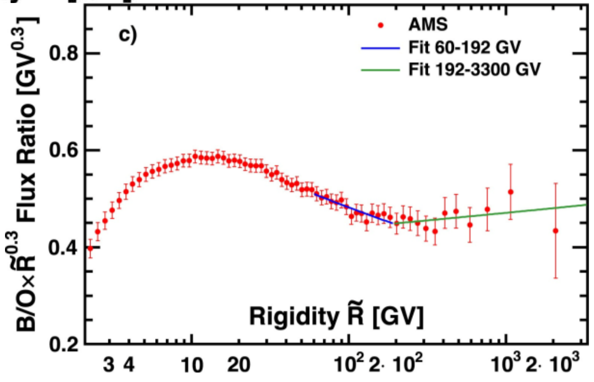
Motivation



Phys. Rep. 894 (2021) 1-116







- Boron nuclei in cosmic rays are mainly produced by **the fragmentation of heavier nuclei**, e.g. C and O
- Precise measurements of the B/C(O) flux ratio are crucial to constrain **the CR propagation process**
- The rigidity/energy dependence of the B/C(O) flux ratio **above TeV/n** remains to be urgently improved

DAMPE data sample

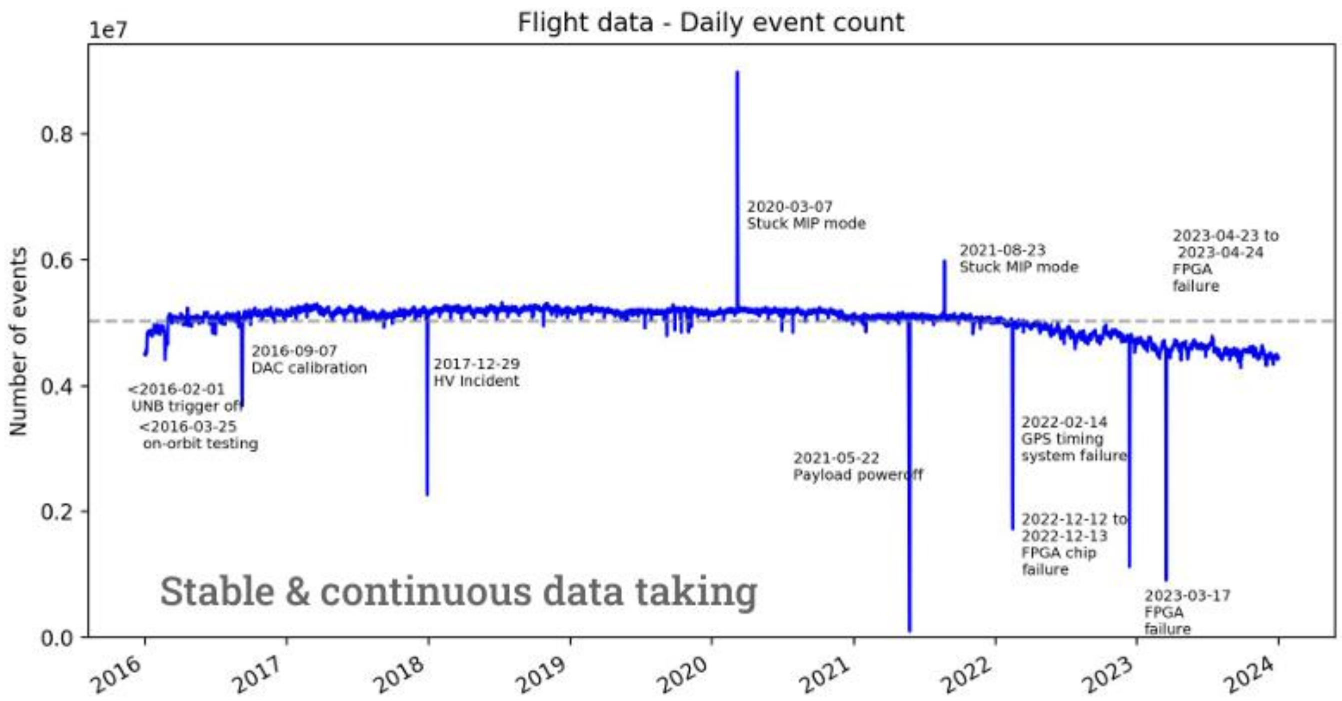
Flight Data:

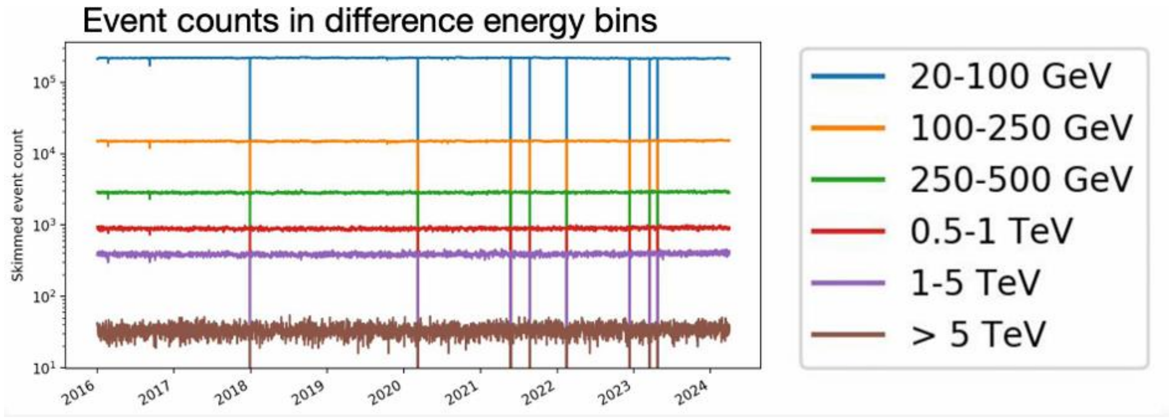
- 72 months
- ~11.4 billion events
- livetime ~1.43×10^8 seconds
- Data in **South Atlantic Anomaly** region are excluded
- Data during Sep.2017 Solar Flare (20170908-20170913) are excluded

Simulation Data:

The MC samples are generated with:

- Geant4 CRMC_FTFP_BERT, version 10.5.1 (EPOSLHC/DPMJET3)
- FLUKA, version 2011.2x.7





Selection Cuts

Analysis Selection

- Energy deposited in BGO: E_{BGO} **> 70 GeV**
- **High Energy Trigger** (HET) activation

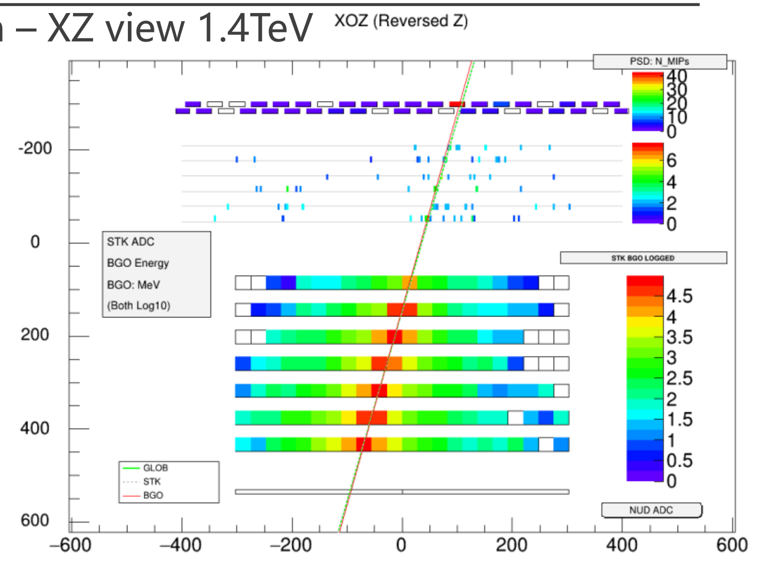
Trajectory Selection

- STK track reconstructed with the **Kalman filter** algorithm
- BGO-STK match: Match the **track and the shower axis in BGO**
- PSD-STK match: Match the **track and the PSD with maximum energy**

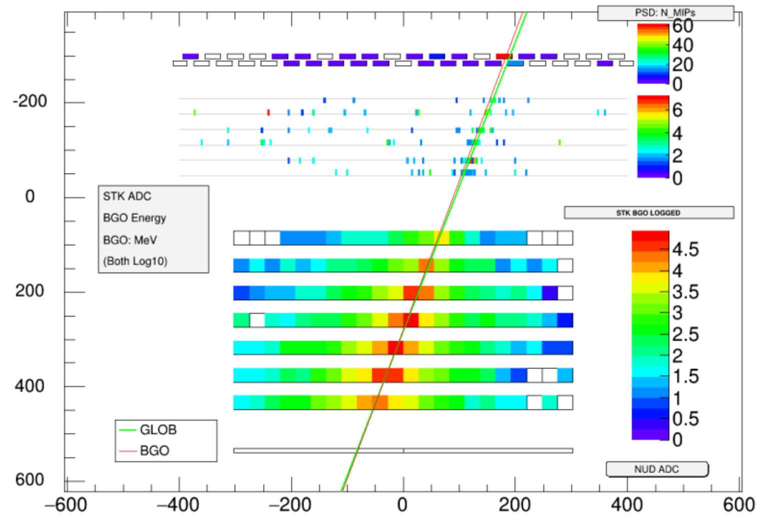
Fiducial Selection

- **Fiducial containment** of track direction in the whole detector

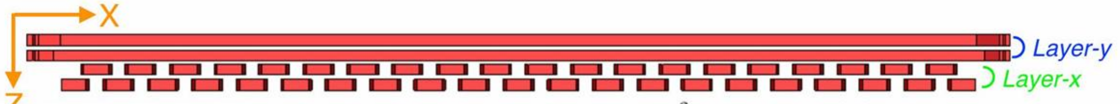
Carbon – XZ view 1.4TeV



Oxygen – XZ view 1.0TeV



Charge selection



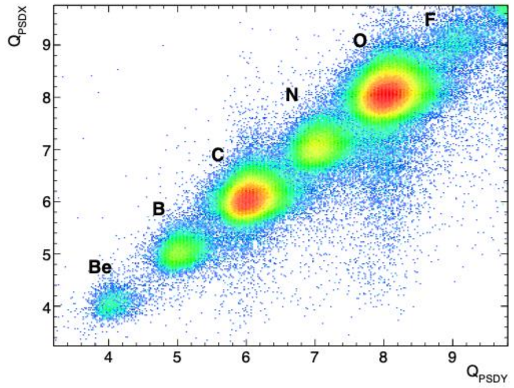
Bethe-Bloch $-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$

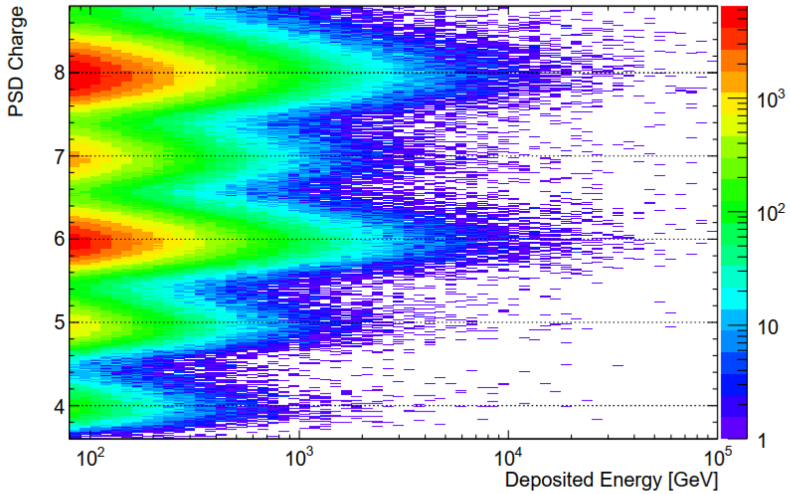
Progressing PSD charge selection:

$$Q^{PSD} = \frac{\sum_i Q_i^{PSD}}{N_{Layers}}$$

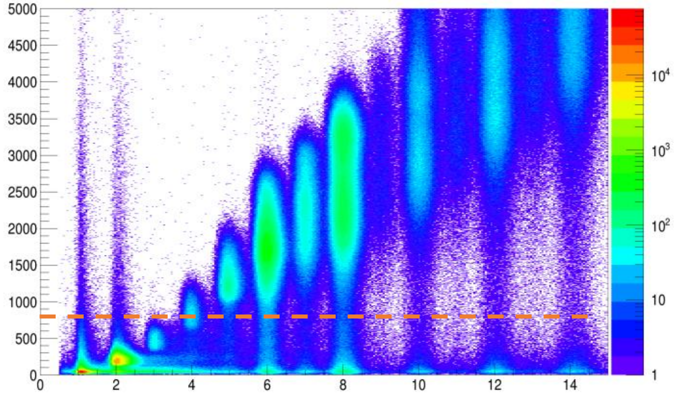
i=index of consecutive layer with charge

$$\left|Q_{i+1}^{PSD} - Q_i^{PSD}\right| < 1e$$

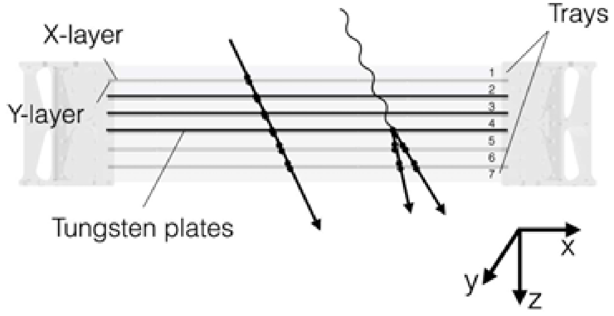




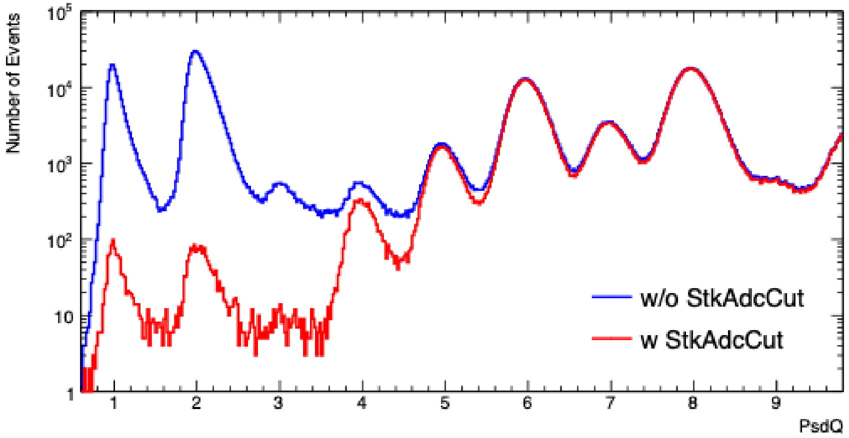
A good energy-independence



STK Charge selection



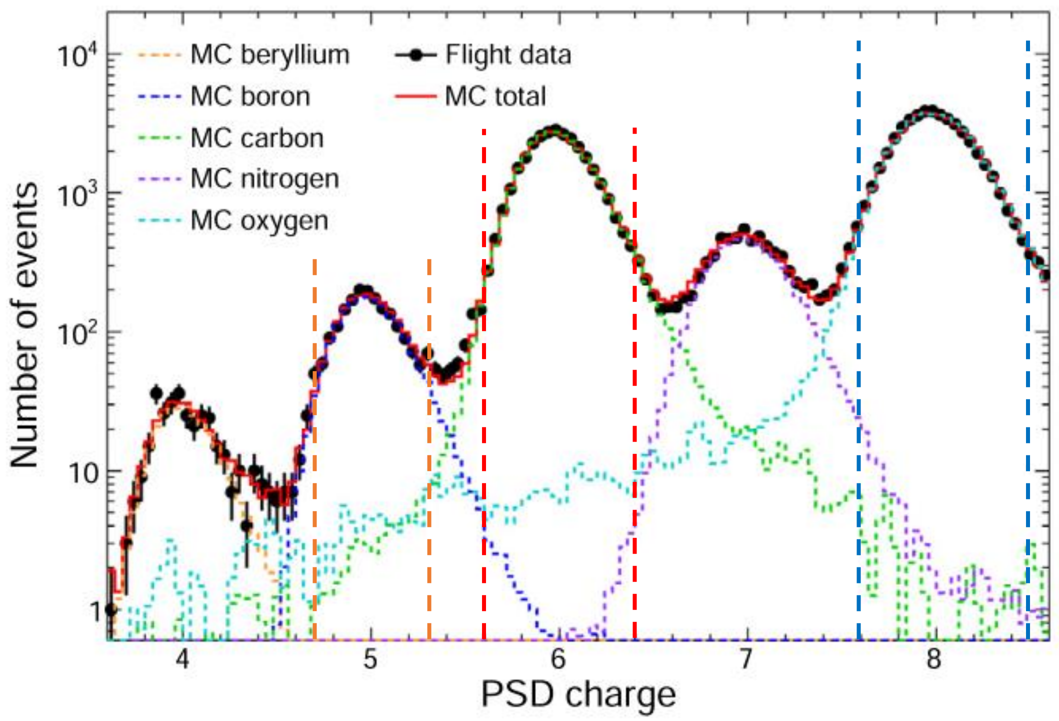
$$\text{StkAdc0} = \frac{Adc_{x0} + Adc_{Y0}}{isX0 + isY0} > 800\ ADC$$



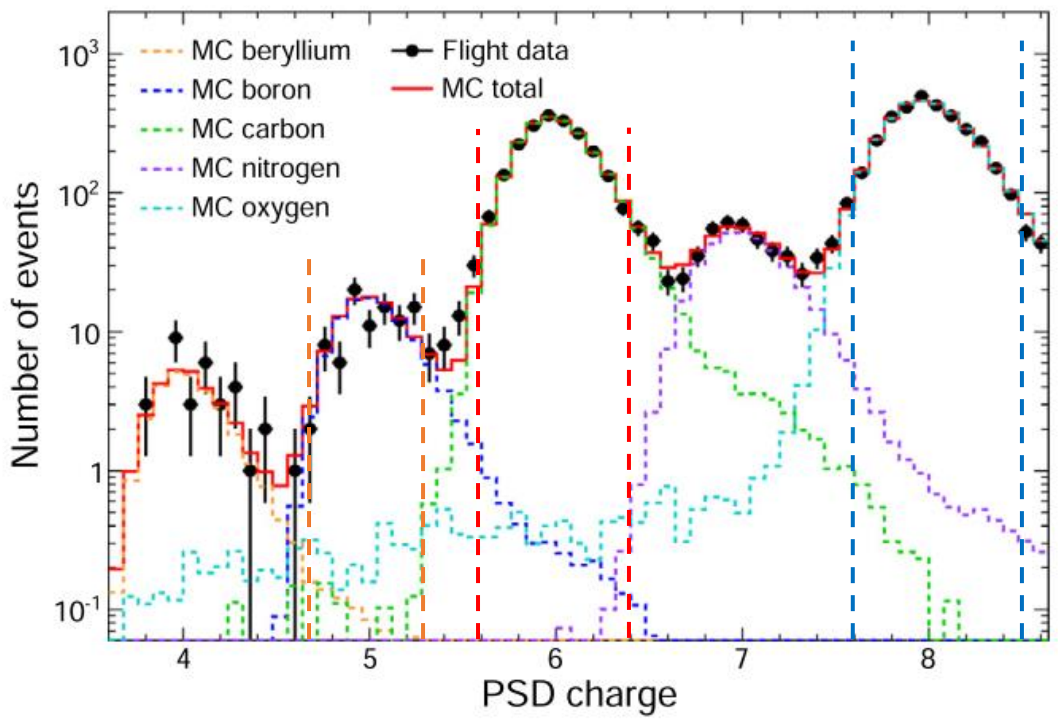
Flight Data: BgoE = [100 GeV,158 GeV]

Template fits

BgoEnergy 0.63 – 2 TeV



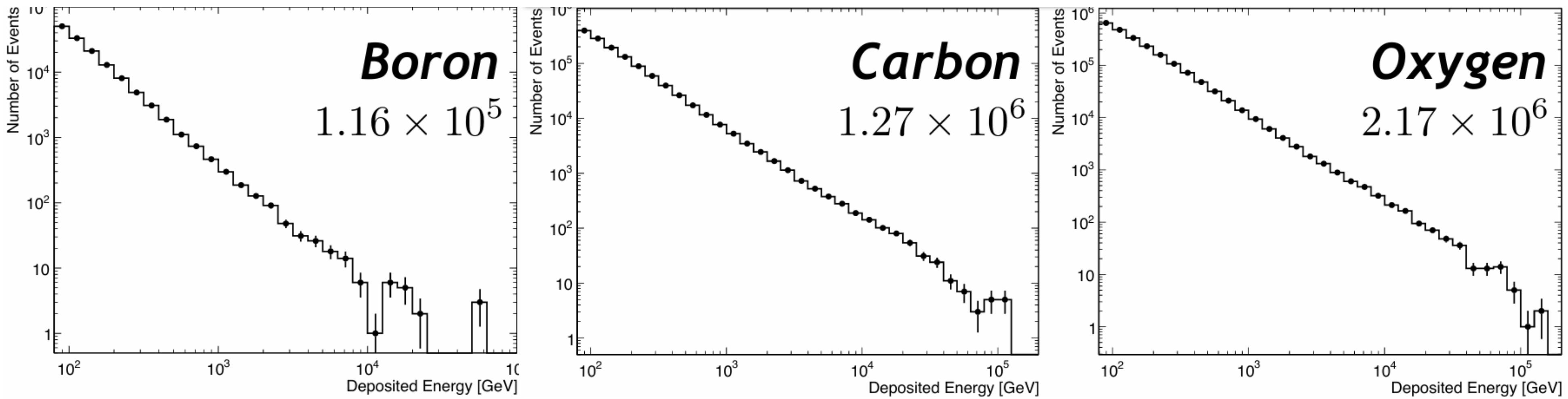
BgoEnergy 3.16 – 10 TeV



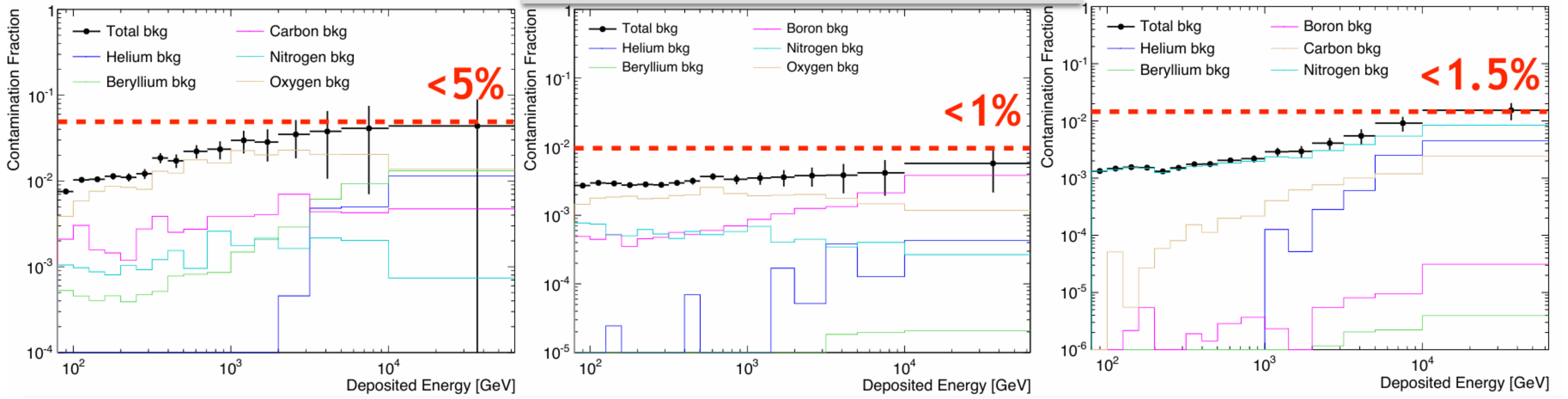
Boron Selection: 4.7-5.3 Carbon Selection: 5.6-6.4 Oxygen Selection: 7.6-8.5

The contamination is estimated based on the template fitting method

Candidate events



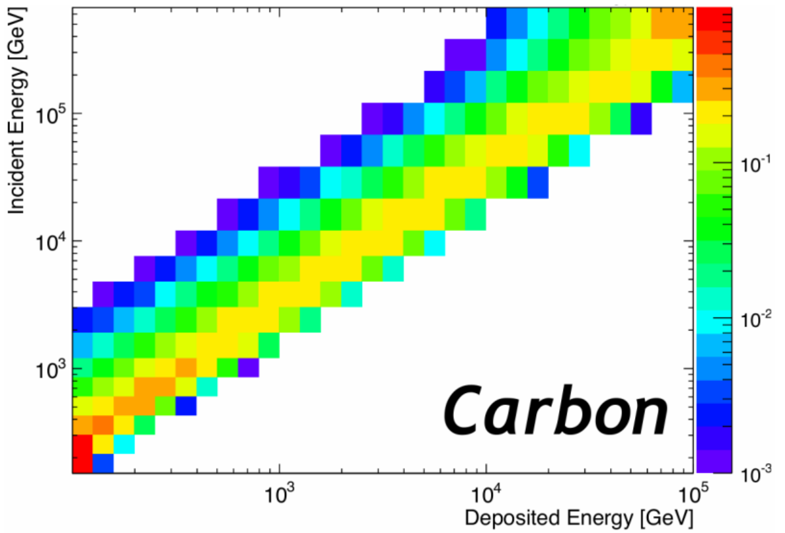
Background estimate



Flux ratio calculation

Bayes' theorem

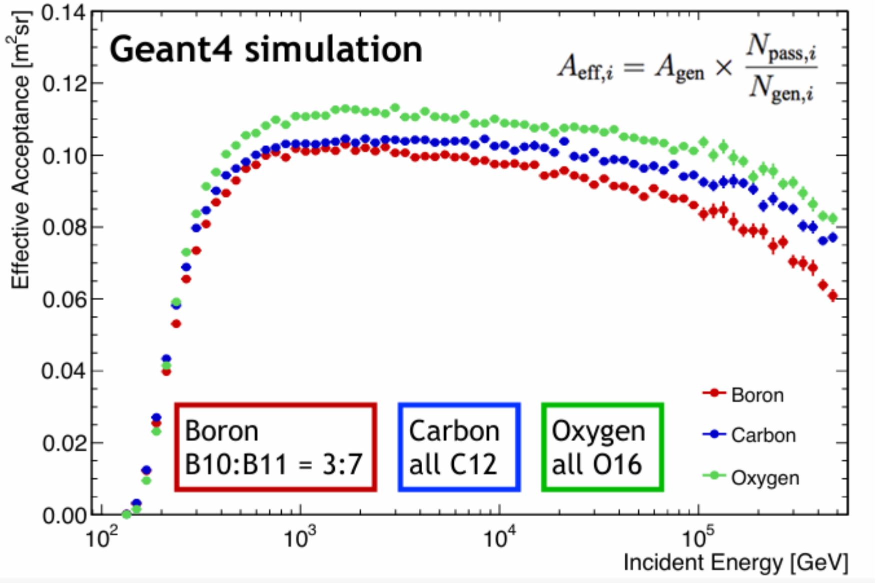
$$P(E_{true,j}|E_{meas,i}) = \frac{P(E_{meas,i}|E_{true,j})P(E_{true,j})}{\sum_k P(E_{meas,i}|E_{true,k})P(E_{true,k})}$$



Flux and ratio in *i*-th incident energy bin:

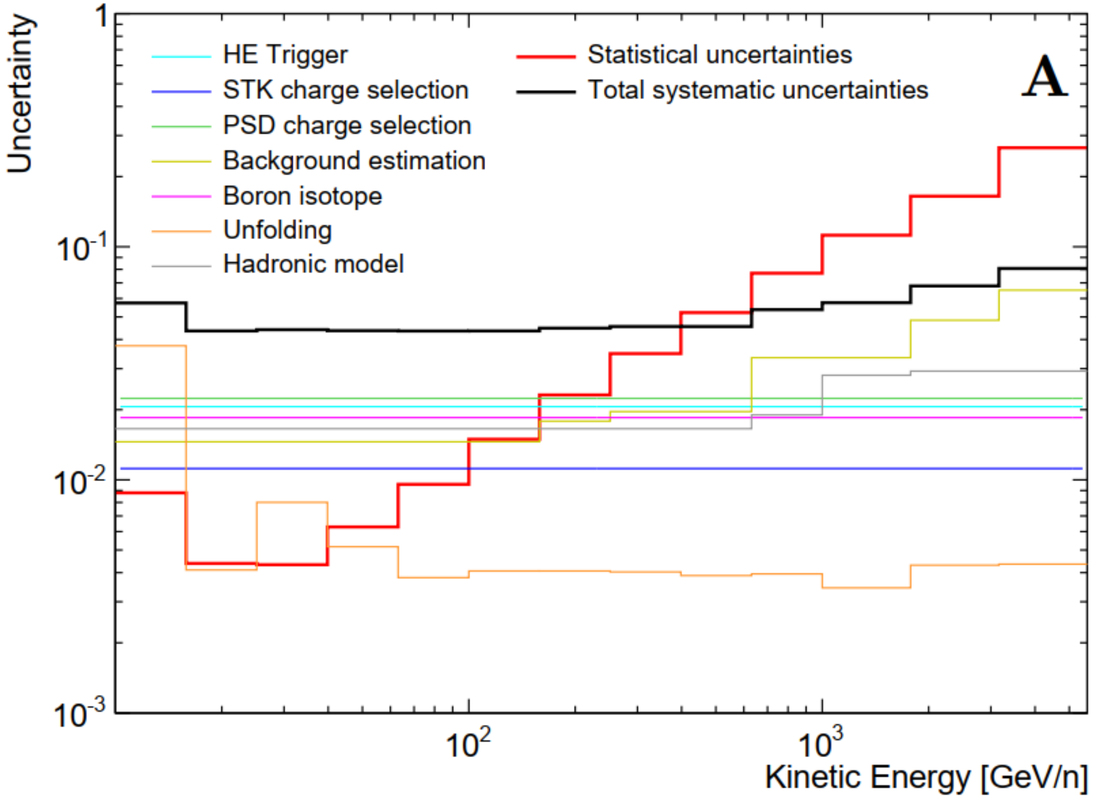
$$\phi(E_i, E_i + \Delta E_i) = \frac{\Delta N_i}{\Delta E_i\, A_{eff,i}\, \Delta T}$$

$$R_i = \frac{\phi_i^B}{\phi_i^{C(O)}} = \frac{N_i^B}{N_i^{C(O)}}\left(\frac{\varepsilon_i^B}{\varepsilon_i^{C(O)}}\right)^{-1}$$

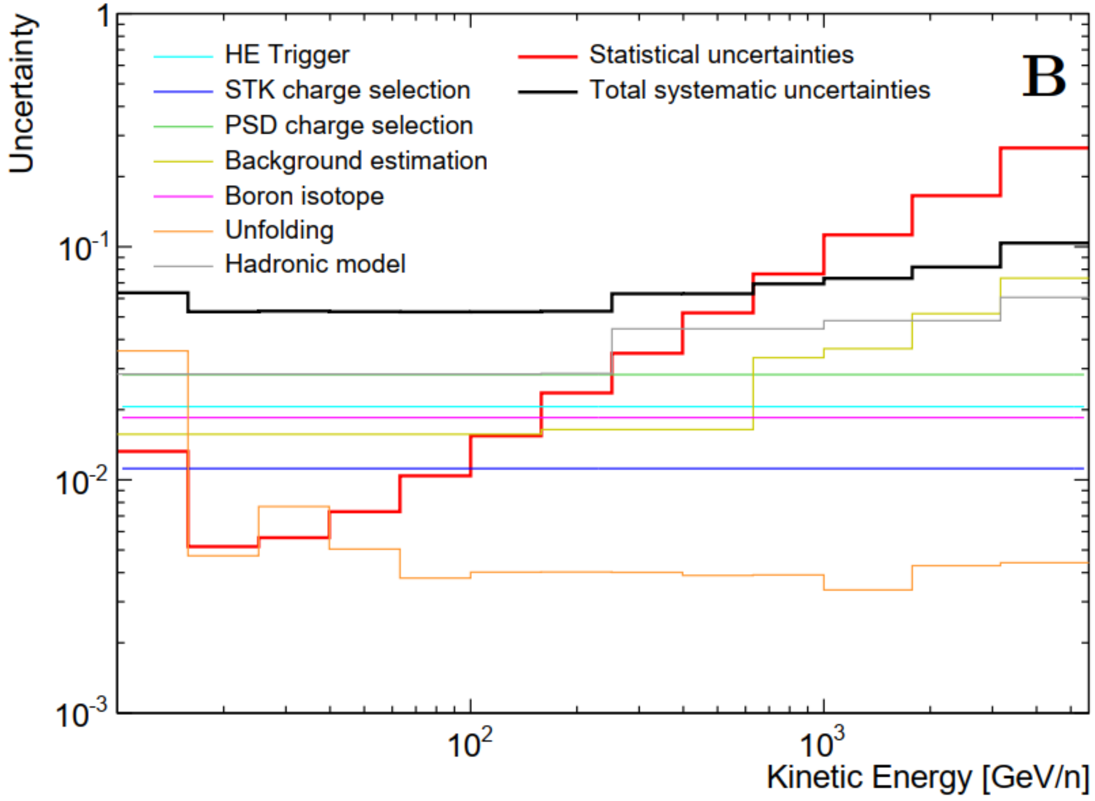


Total uncertainties

Uncertainties for B/C

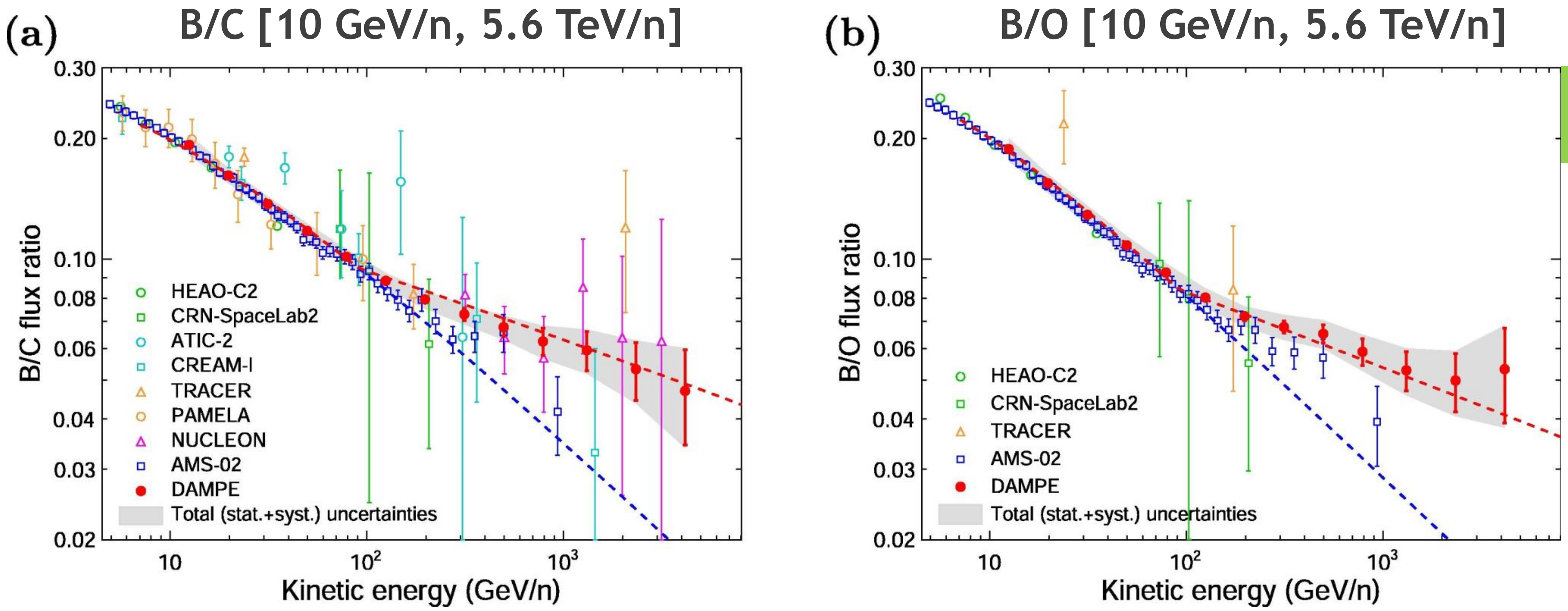


Uncertainties for B/O



The statistical uncertainties dominate over the systematic ones for energies above 1 TeV/n

Cosmic ray B/C and B/O



Science Bulletin 67 (2022) 2162-2166

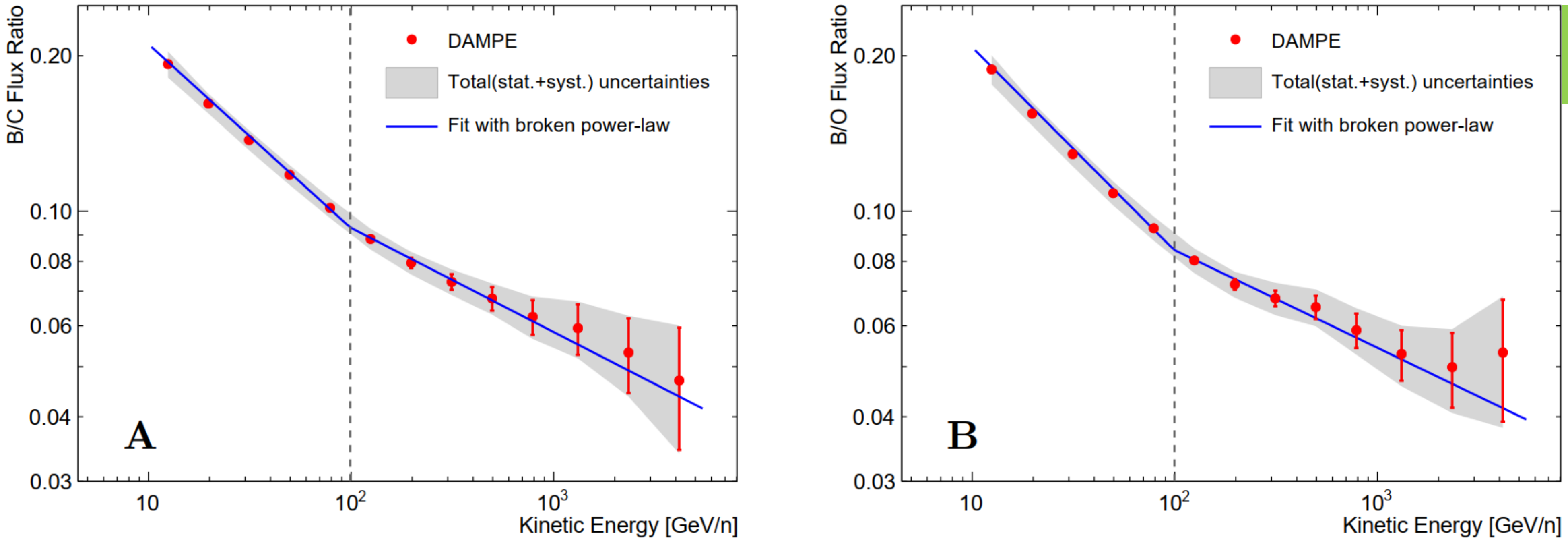
- At energies below a few hundreds of GeVs, the DAMPE measurements are well consistent with other results within uncertainties
- **Measurements clearly reveal a significant hardening feature at ~100 GeV/n for both B/C and B/O**

Spectral fitting

Power-law (PL): $R(E_k) = R_0 \left(\frac{E_k}{\frac{GeV}{n}}\right)^{-\gamma}$

Broken power-law (BPL): $R(E_k) = \begin{cases} R_0 (E_k/E_b)^{-\gamma_1}, E_k \le E_b \\ R_0 (E_k/E_b)^{-\gamma_2}, E_k > E_b \end{cases}$

	B/C	B/O
Nuisance parameters	4	4
R_0	$0.093^{+0.004+0.000}_{-0.004-0.001}$	$0.084^{+0.003+0.000}_{-0.003-0.000}$
γ_1	$0.356^{+0.008+0.000}_{-0.008-0.017}$	$0.394^{+0.010+0.000}_{-0.010-0.026}$
E_b (GeV/n)	$98.9^{+8.9+10.0}_{-8.8-0.0}$	$99.5^{+7.4+7.7}_{-7.1-0.0}$
γ_2	$0.201^{+0.024+0.008}_{-0.024-0.000}$	$0.187^{+0.024+0.000}_{-0.024-0.019}$
χ^2/dof	6.61/5	5.51/5



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Summary

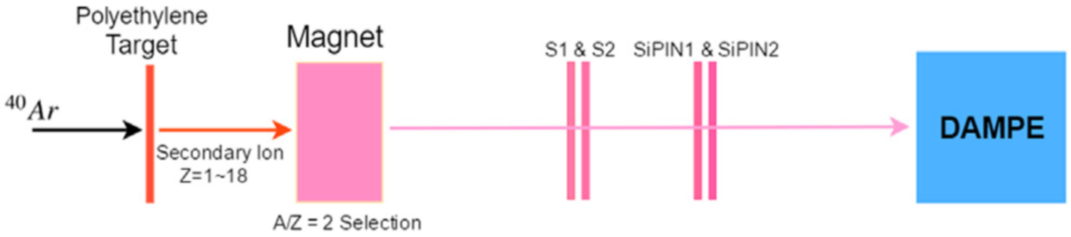
- Based on six years' flight data of DAMPE, the B/C and B/O flux ratios from 10 GeV/n to 5.6 TeV/n are presented
- The B/C and B/O flux ratios of DAMPE show a significant hardening structure at ~100 GeV/n, which sheds a new light on the understanding of CR propagation process
- The statistical uncertainties dominate over the systematic ones for energy above 1 TeV/n
- DAMPE measurements will be extended to ~10 TeV/n in the future

魏逸丰, Latest results of the DArk Matter Particle Explorer, Oral report,中微子物理、粒子天体物理与宇宙学
陈占方, Spectral Analysis of Lithium, Beryllium and Boron Nuclides with DAMPE, Poster,中微子物理、粒子天体物理与宇宙学
马鹏雄, Carbon, Oxygen and CNO combined spectra measurement with DAMPE, Poster,中微子物理、粒子天体物理与宇宙学

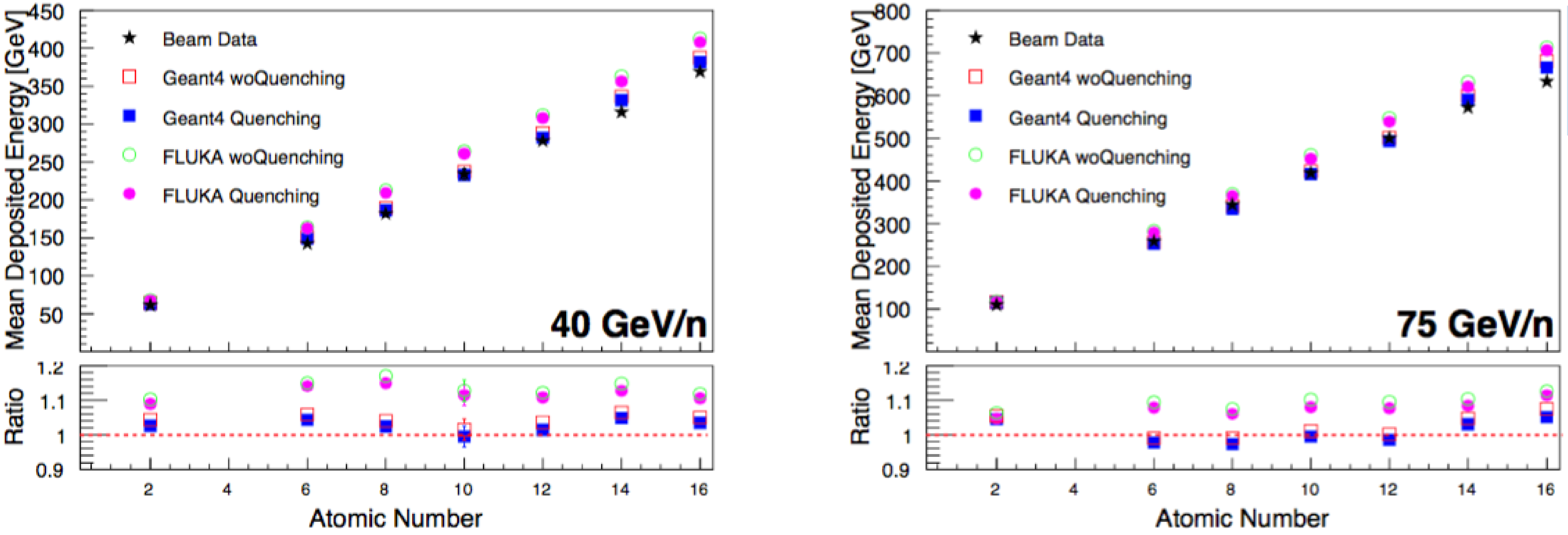
Backup

Hadronic model (G4 vs FLUKA)

Ion Beam Test @ CERN



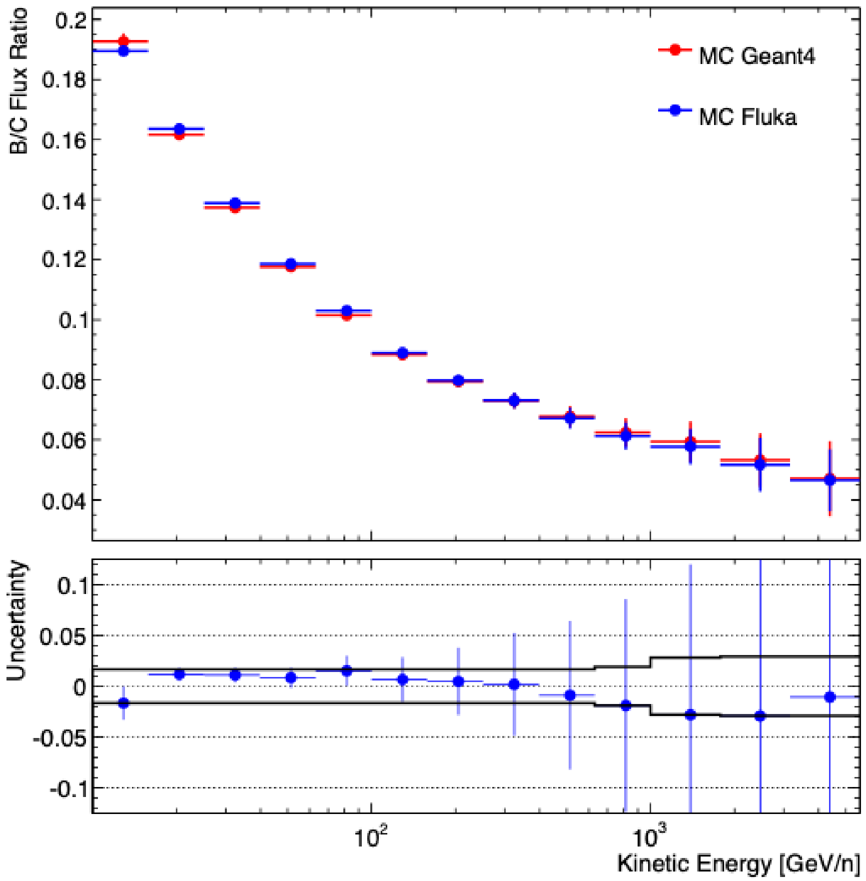
The energy responses of Geant4 show better agreements with beam data



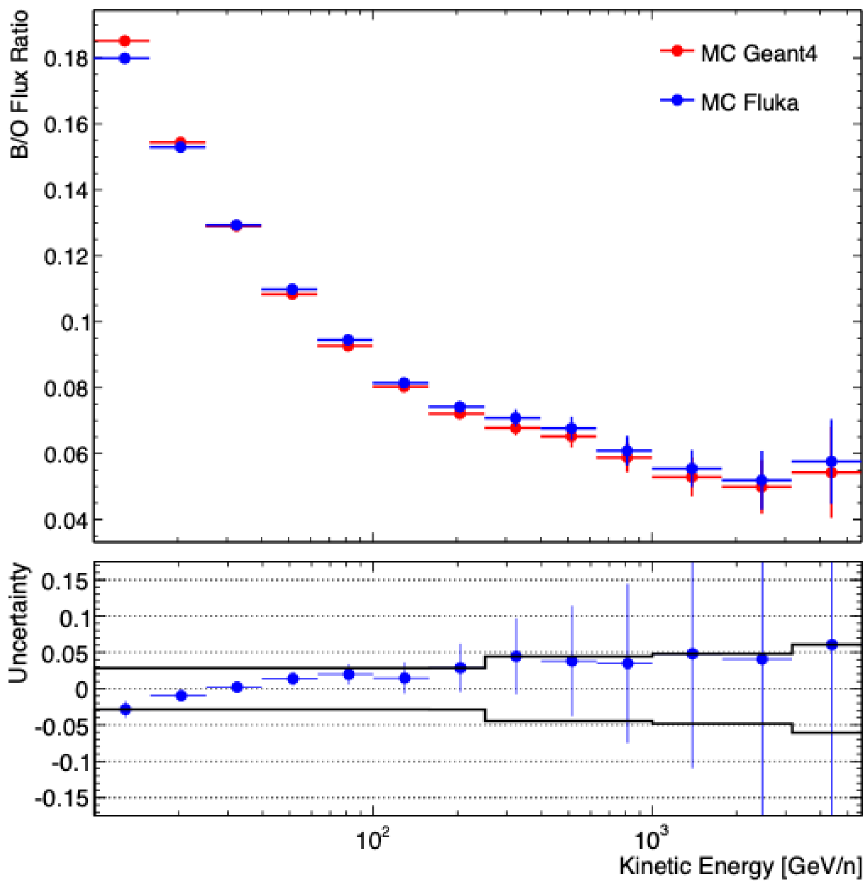
Z.F. Chen et al., NIMA, in press

Hadronic model (G4 vs FLUKA)

B/C flux ratio



B/O flux ratio



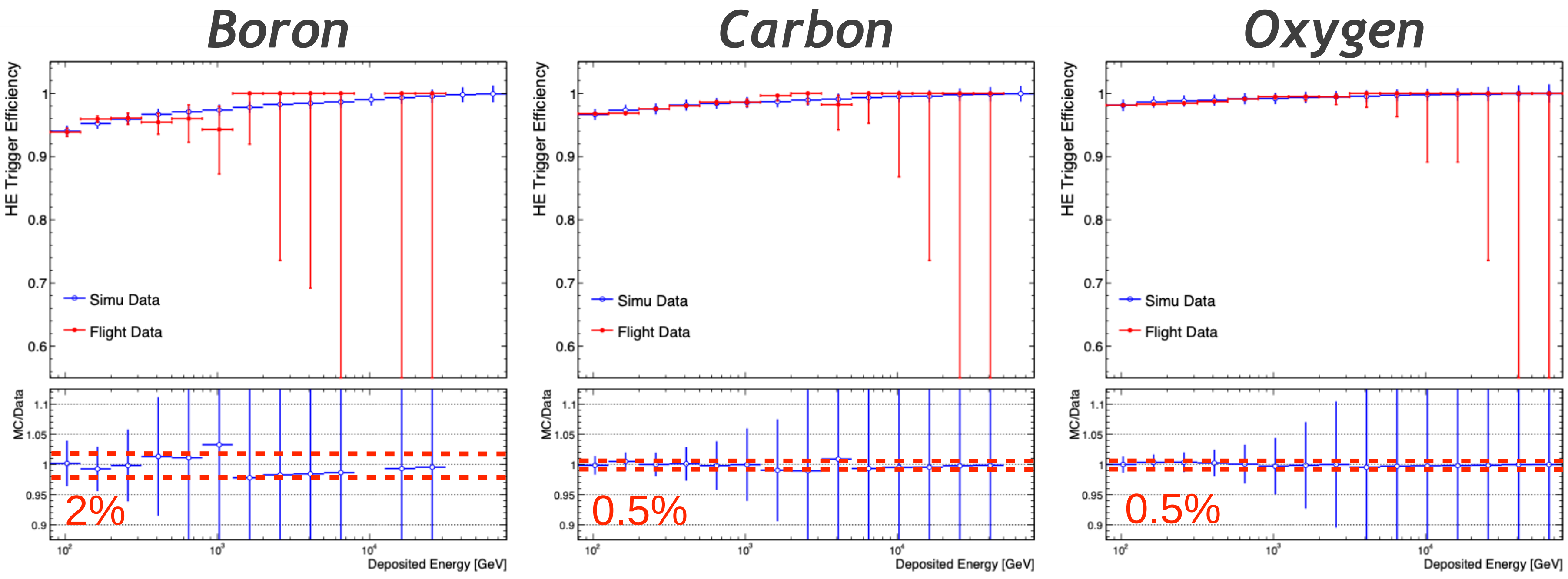
For B/C and B/O flux ratios, the differences between Geant4 and FLUKA are taken as **the uncertainty from hadronic interaction**

HE Trigger efficiency

- ☐ Unbias Trigger (G0)
- ☐ MIPs Trigger (G1&G2)
- ☑ High Energy Trigger (G3)
- ☐ Low Energy Trigger (G4)

HE Trigger Efficiency:

$$\varepsilon_{trigger} = \frac{N_{he|le}}{N_{le}}$$

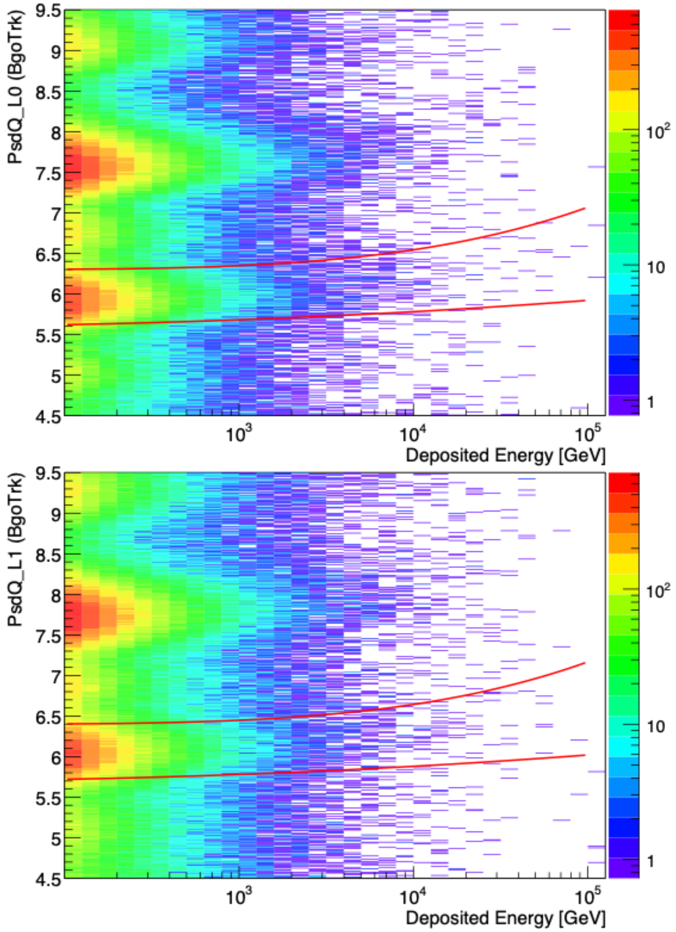


*The uncertainty to HE trigger efficiency is ~2.1% for both the B/C and B/O

STK track efficieny

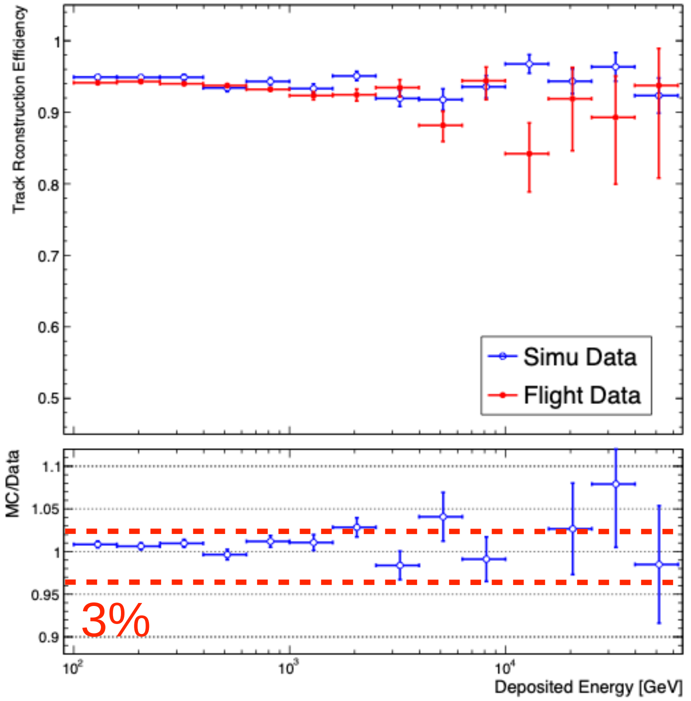
Selecting"pure" Carbon events with BGO-track based PSD charge

Search range for Psd hits: ±50mm around the track



Stk track Efficiency:

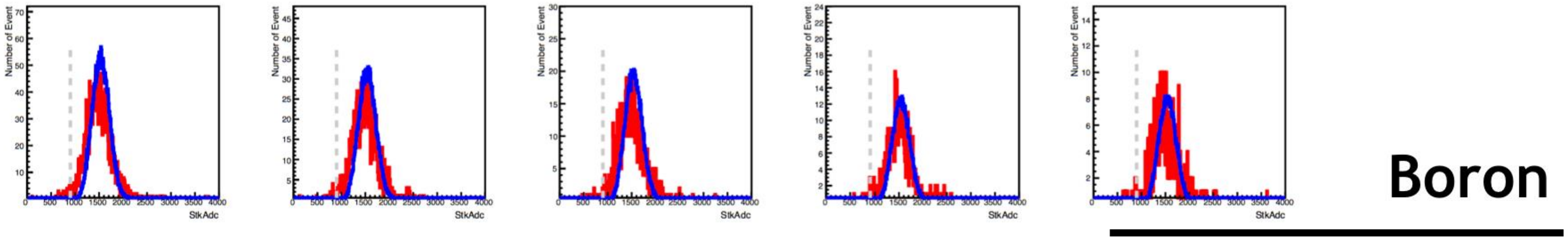
$$\varepsilon_{track} = \frac{N_{track|BGOtrack}}{N_{BGOtrack}}$$

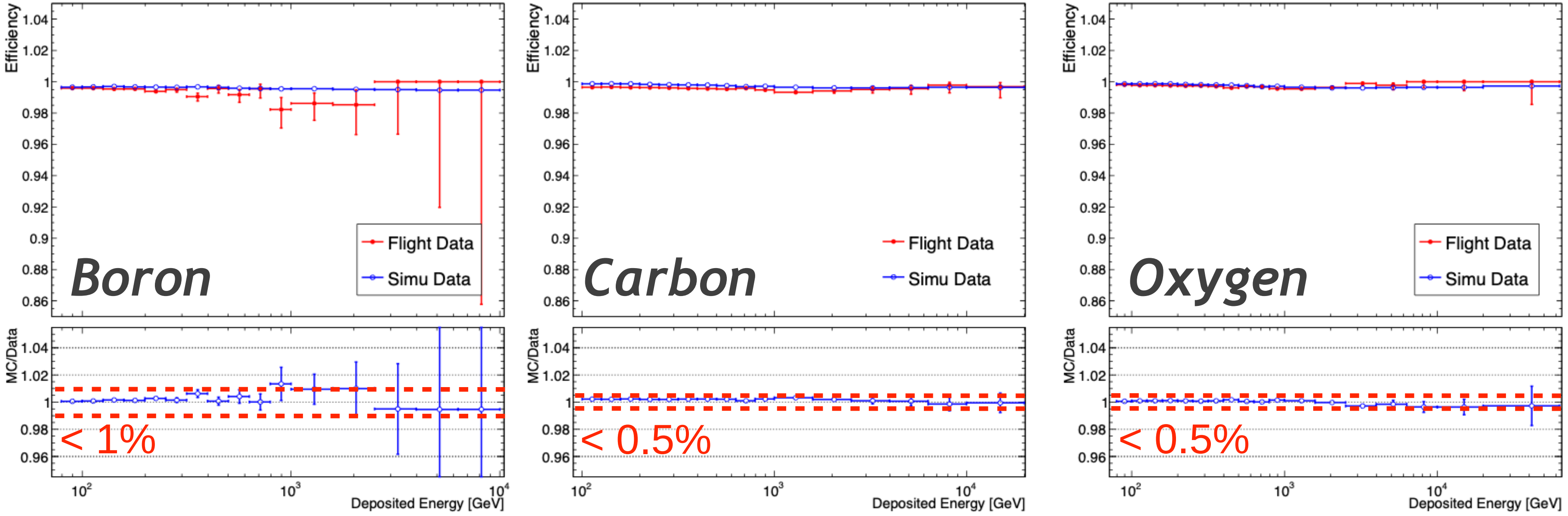


*For B/C and B/O, the uncertainty due to Stk track is negligible as same track selection is applied.

STK charge efficieny

STK charge distribution



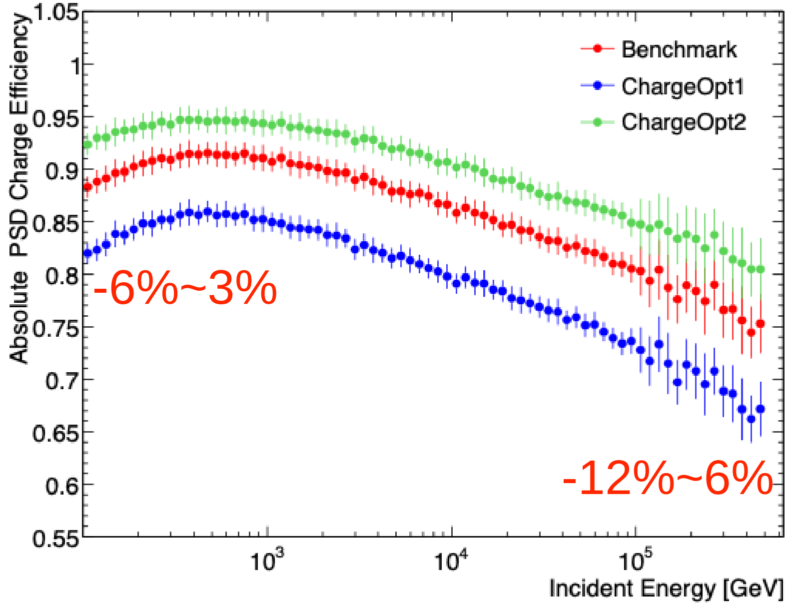


*The uncertainty due to STK charge selection is ~1.1% for both the B/C and B/O

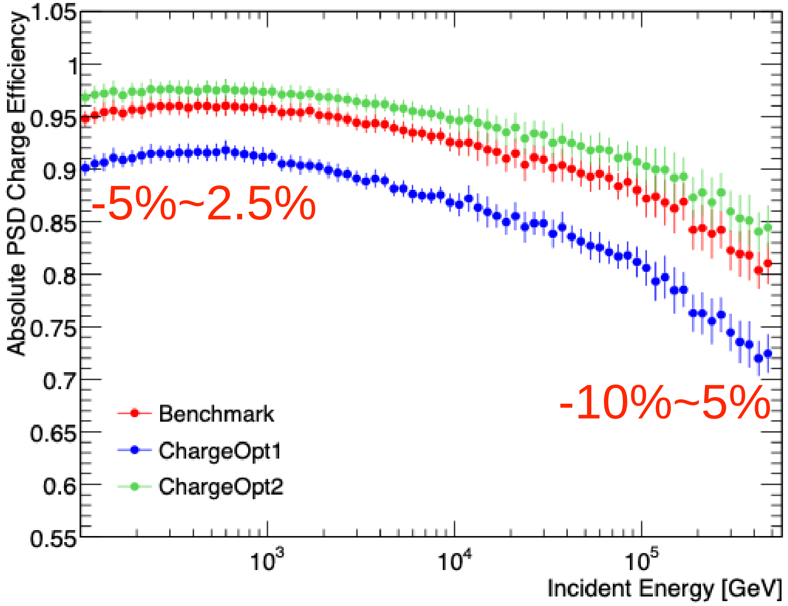
PSD charge efficieny

	Boron	Carbon	Oxygen
Benchmark:	4.7 - 5.3	5.6 - 6.4	7.6 - 8.5
ChargeOpt1:	4.75 - 5.25	5.7 - 6.35	7.7 - 8.45
ChargeOpt2:	4.65 - 5.35	5.5 - 6.45	7.5 - 8.55

Boron



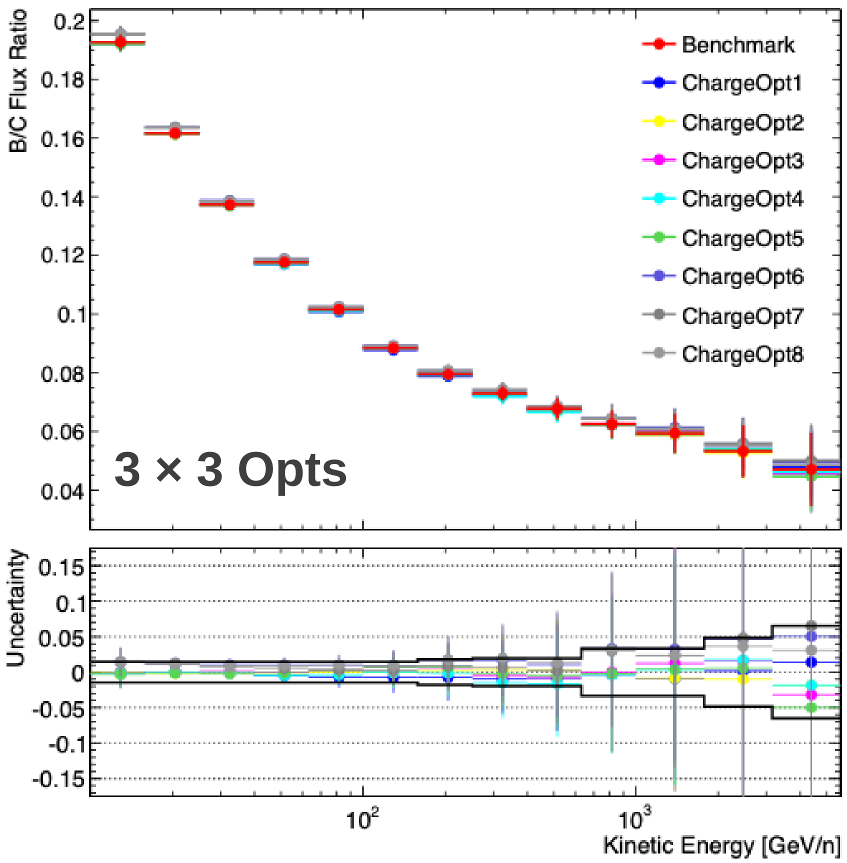
Carbon



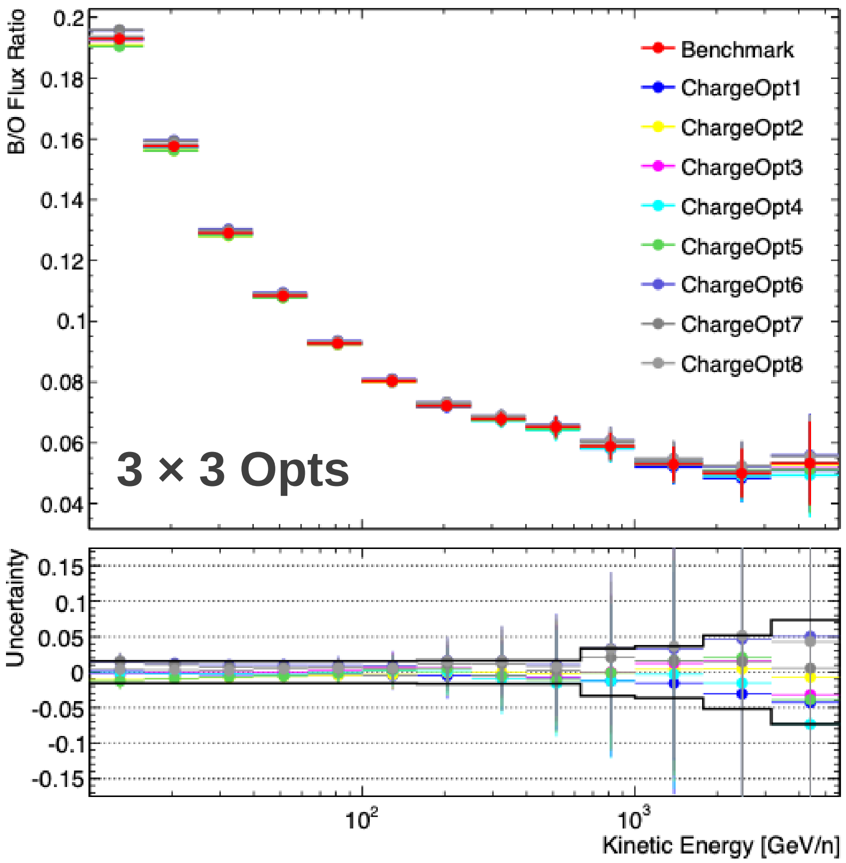
Different charge efficiencies <==> different backgrounds <==> different flux ratios

PSD charge efficieny

B/C



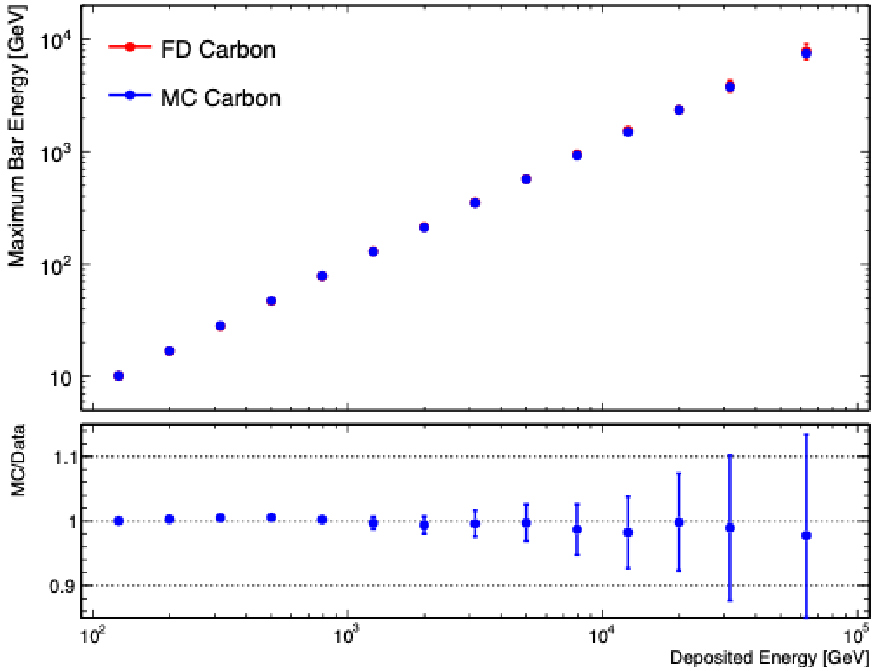
B/O



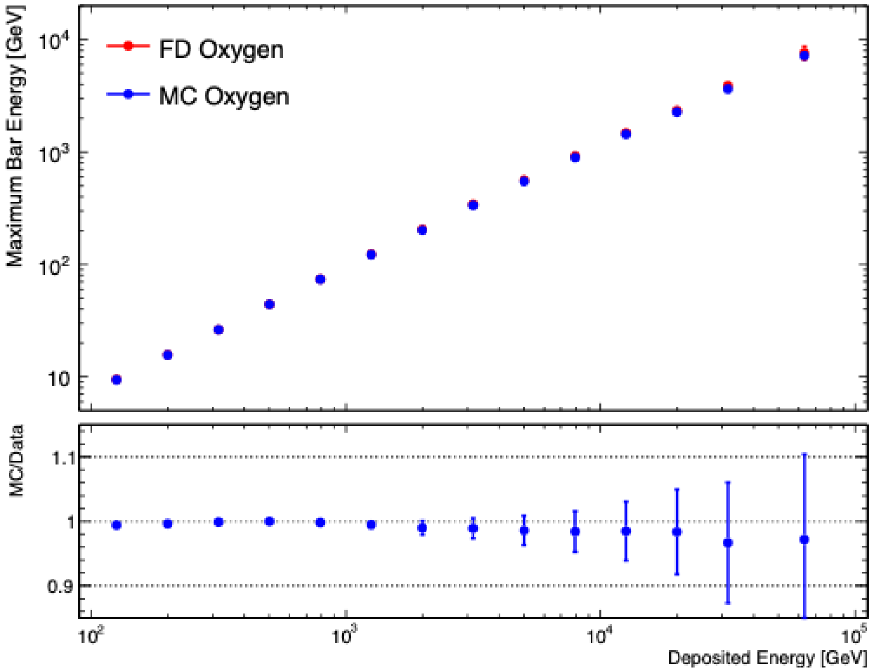
Different charge efficiencies <==> different backgrounds <==> different flux ratios

Energy linearity

Carbon



Oxygen



No significant nonlinearity is found up to the deposited energy of ~100 TeV