UNIVERSITÉ
DE GENÈVE
FACULTÉ DES SCIENCES
Département de physique
nucléaire et corpusculaire

Recent results on galactic cosmic rays with the DAMPE experiment

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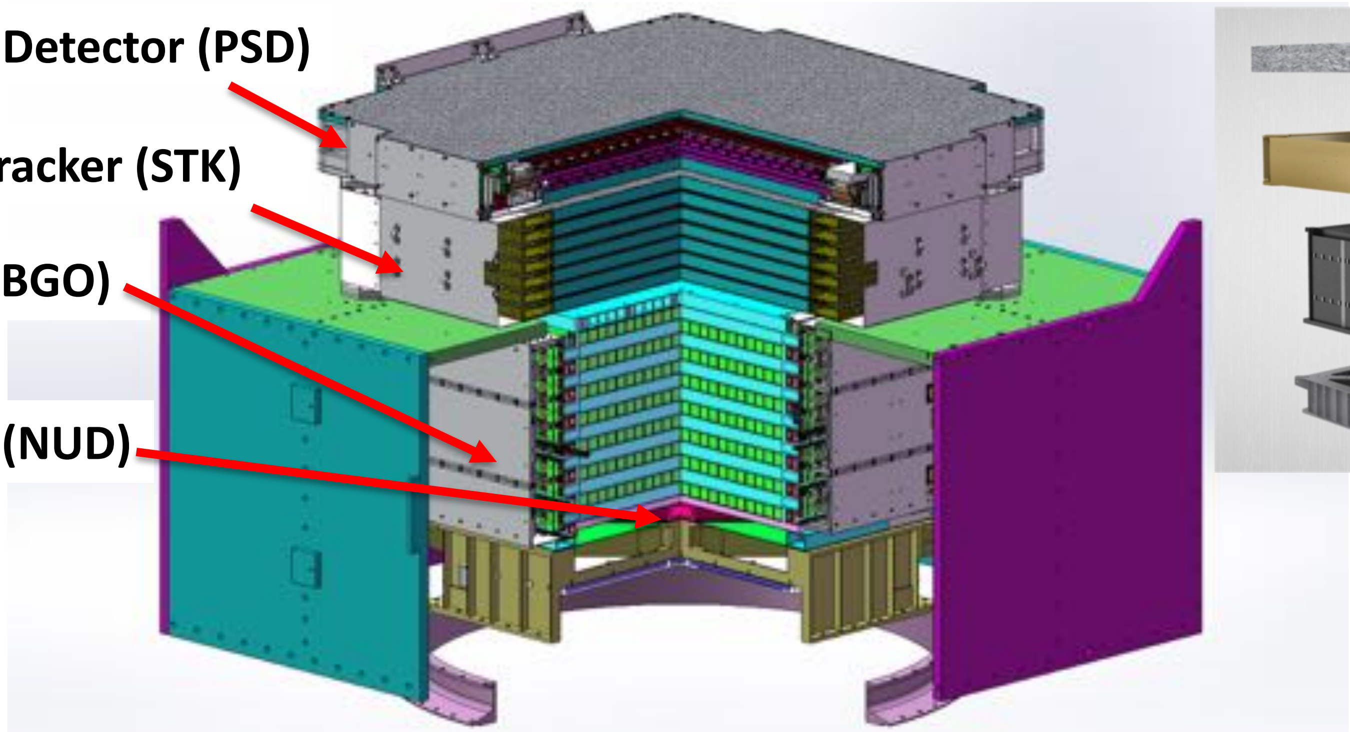
Outline

- Introduction to the DAMPE experiment
- Description and performance of the detector
- Recent cosmic ray results


DAMPE
Launched ~4 years ago (17/12/2015)
High energy particle physics experiment in space

The Detector



- ✓ Charge measurements (PSD and STK)
- ✓ Precise tracking with Si strip detectors (STK)
- ✓ Tungsten photon converters in tracker (STK)
- ✓ Thick imaging calorimeter (BGO of 32 X_0, 1.6 λ)
- ✓ Extra hadron rejection (NUD)

➡ high energy γ-ray, electron and cosmic ray nuclei telescope

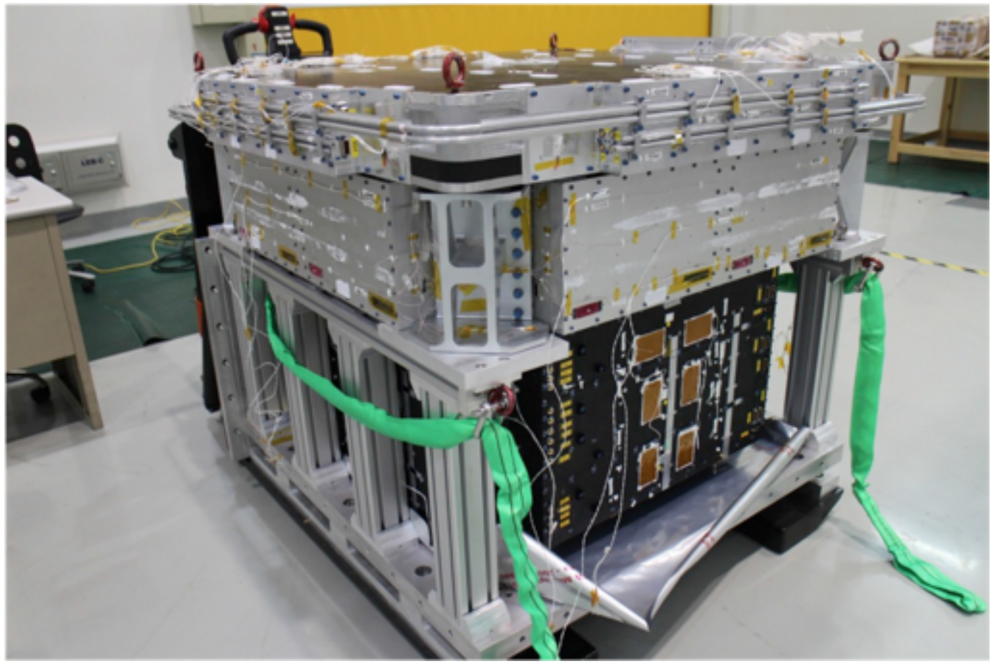
The Collaboration

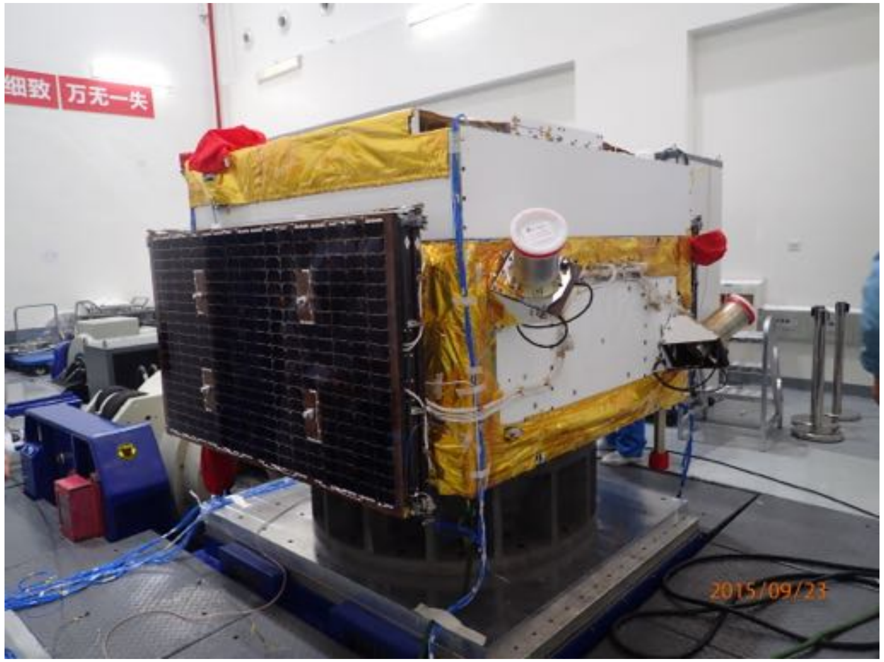
- China
  - Purple Mountain Observatory, CAS, Nanjing
  - Institute of High Energy Physics, CAS, Beijing
  - National Space Science Center, CAS, Beijing
  - University of Science and Technology of China, Hefei
  - Institute of Modern Physics, CAS, Lanzhou

- Switzerland
  - University of Geneva, Switzerland

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

The DAMPE Satellite



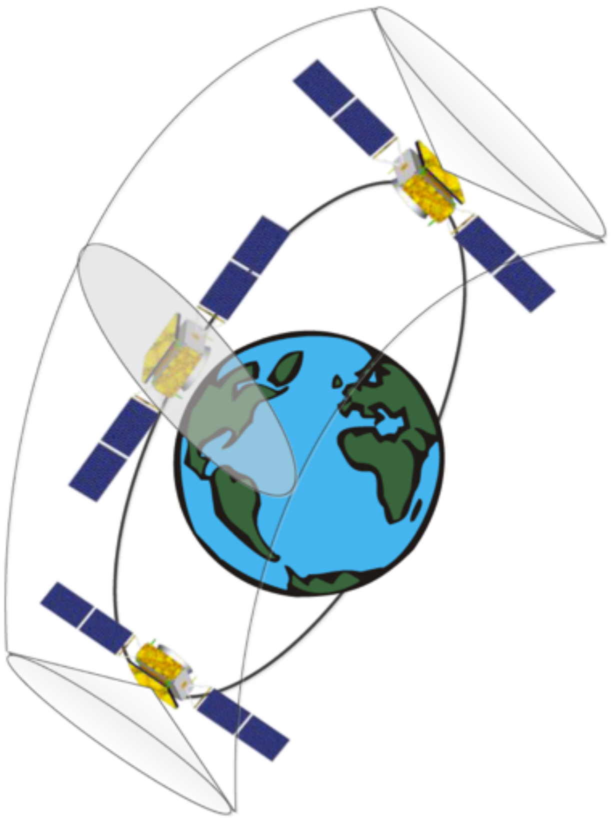


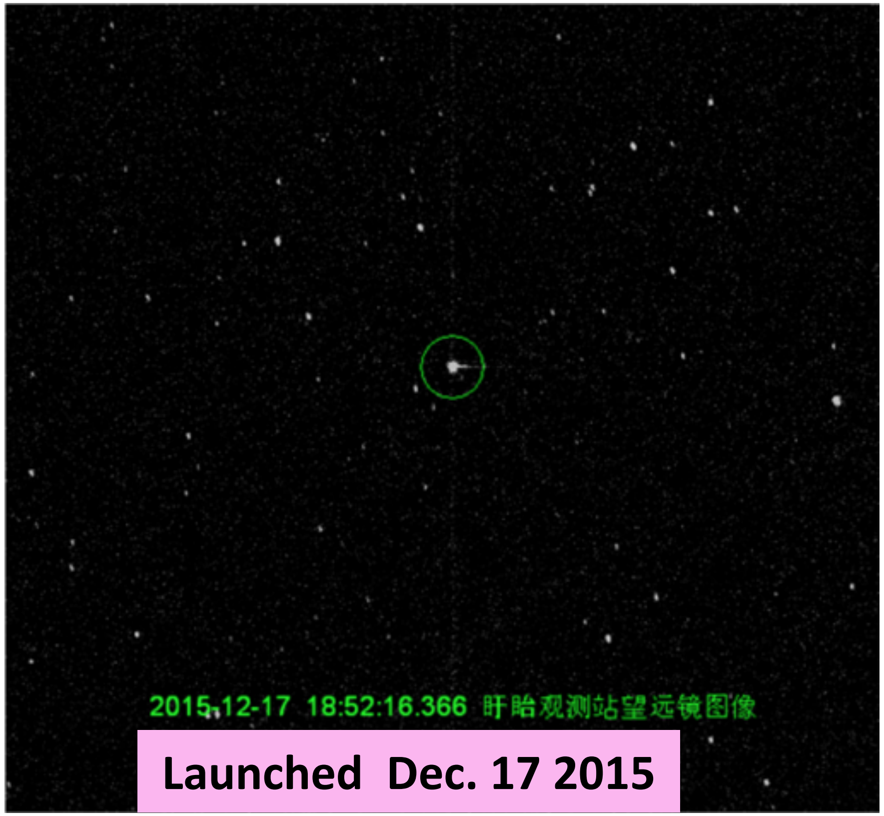
EQM, Oct. 2014, CERN → Integrated satellite, Sept. 2015, Shanghai

Weight : 1450/1850 kg (payload/satellite)
Power: 300/500 W (payload/satellite)
Readout channels: 75,916 (STK 73,728)
Size: 1.2m x 1.2 m x 1.0 m

The Orbit

- Altitude: 500 km
- Inclination: 97.4065°
- Period: 95 minutes
- Orbit: sun-synchronous

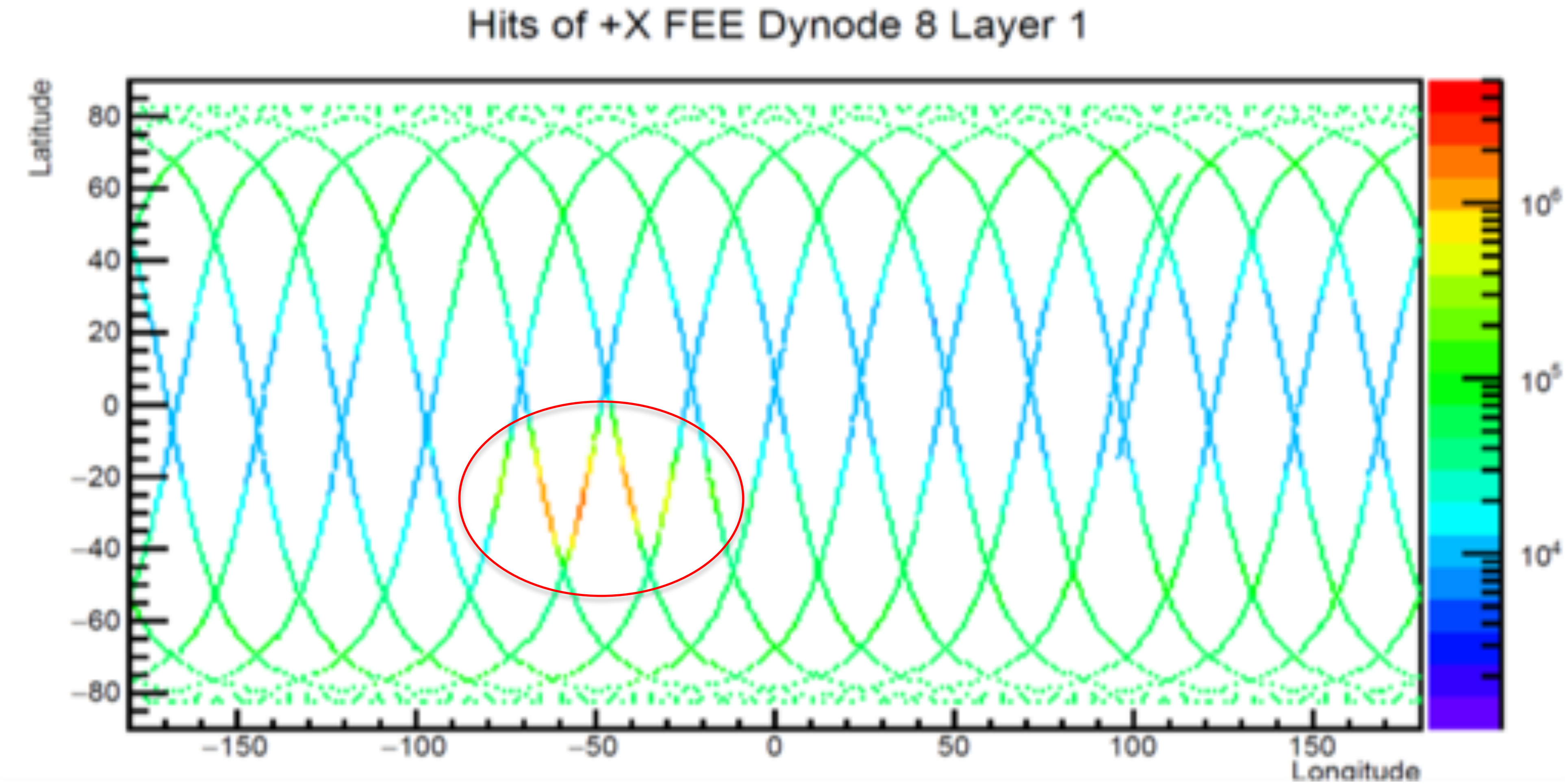




Launched Dec. 17 2015

- Dec. 20: all detectors powered on, except the HV for PMTs
- Dec. 24: HV on!
- Dec. 30: stable trigger condition
- Very smooth operation since!

Particle hit counts vs orbit

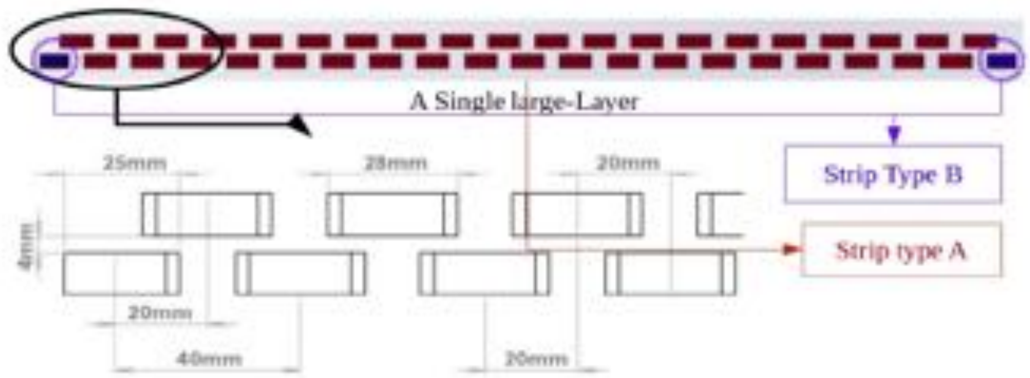


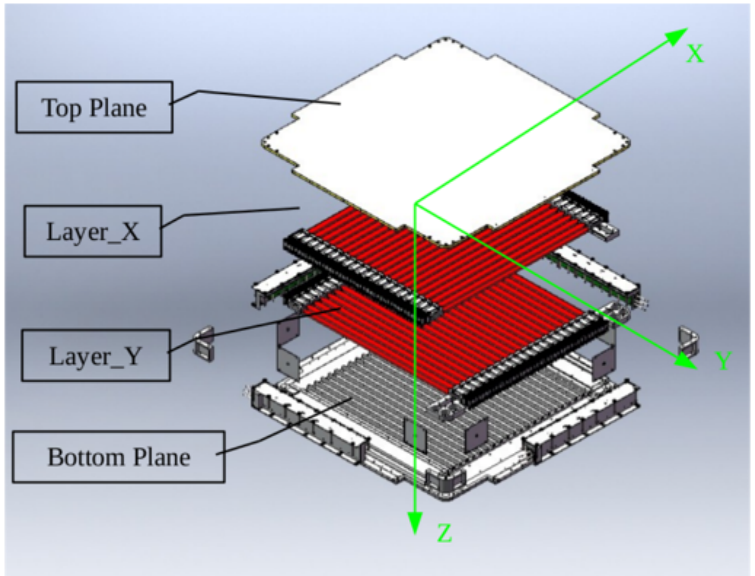
- 15 orbits/day, 96 minutes/orbit
- ~50 Hz average trigger rate, ~5 M events/day
  - Main high energy trigger and prescaled low energy and MIP triggers

Plastic Scintillator Detector (PSD)

2 layers (x, y) of strips 1 cm thick, 2.8 cm wide and 88.4 cm long
Sensitive area 82.5 cm x 82.5 cm, **no dead zone**

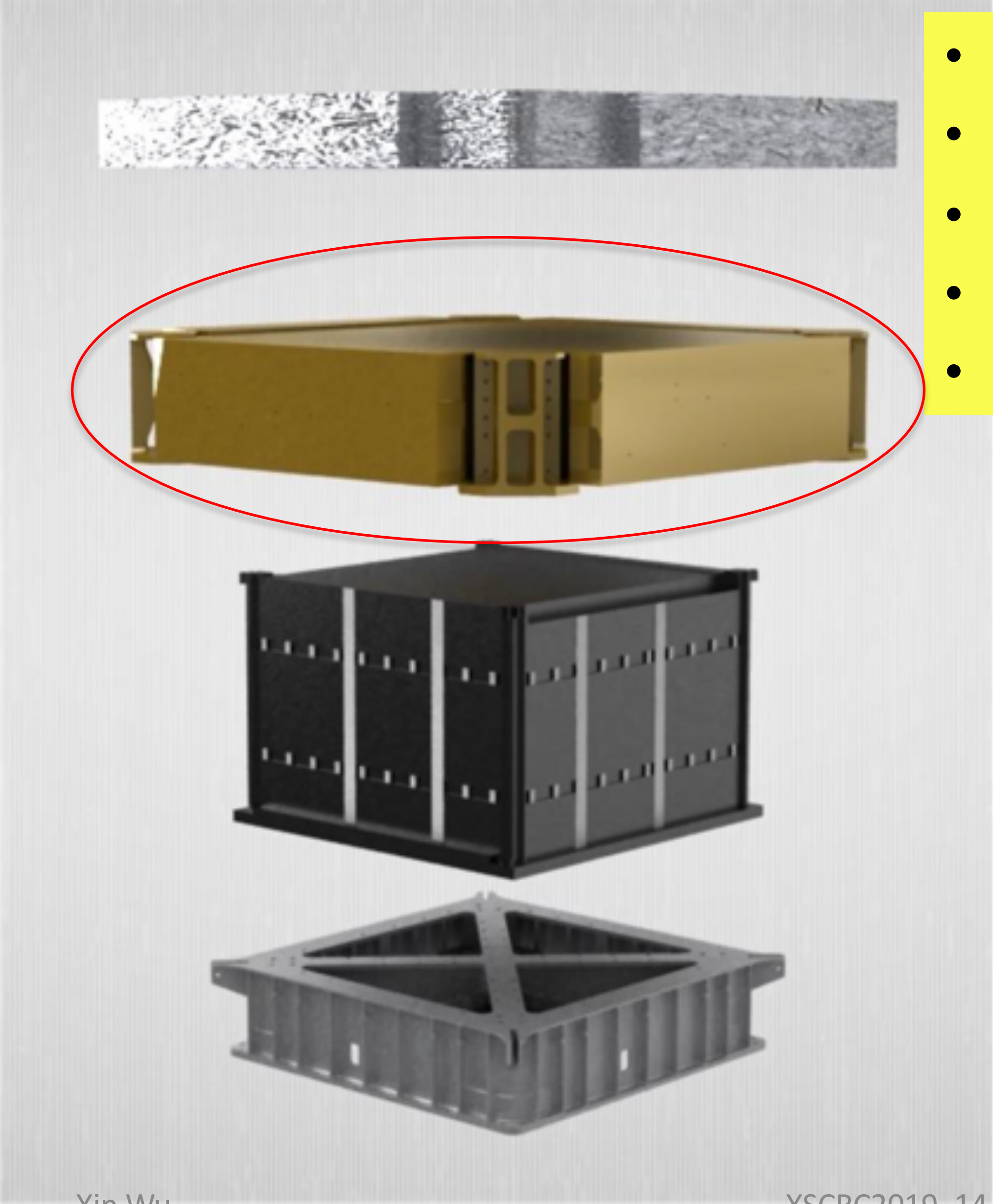
- Strip staggered by 0.8 cm





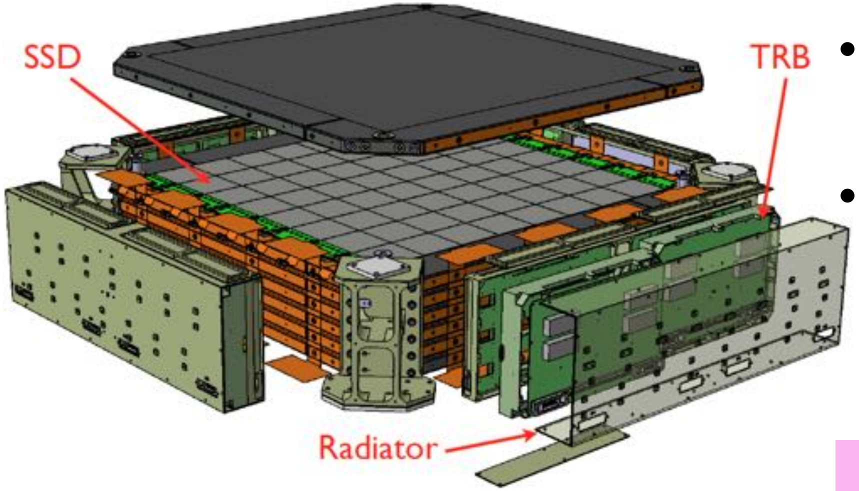
Readout both ends with PMT, each uses 2 dynode signals (factor ~40) to extend the dynamic range to cover Z = 1, 26

Silicon-Tungsten Tracker (STK)

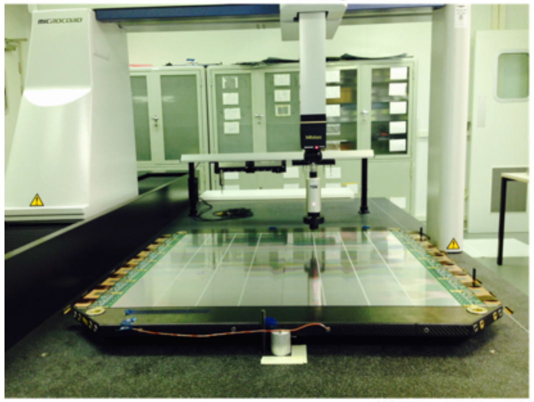


- Outer envelop 1.12m x 1.12m x 25.2 cm
- Detection area 76 x 76 cm^2
- ~7 m^2 of silicon
- Total weight: 154.8 Kg
- Total power consumption: ~85W

The STK structure



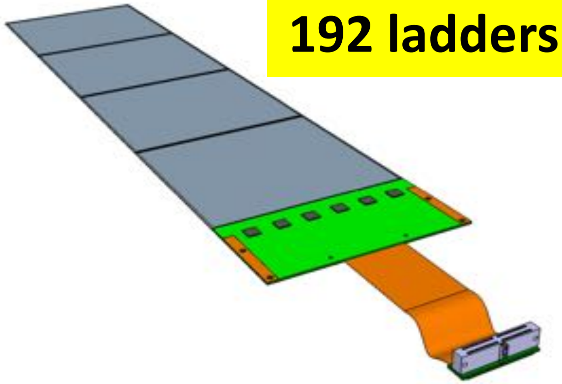
- 12 layers (6x, 6y) of single-sided Si strip detector mounted on **7 support trays**
- **Tungsten plates (1mm thick)** integrated in trays 2, 3, 4 (from the top)
  - Total 0.85 X_0 for photon conversion



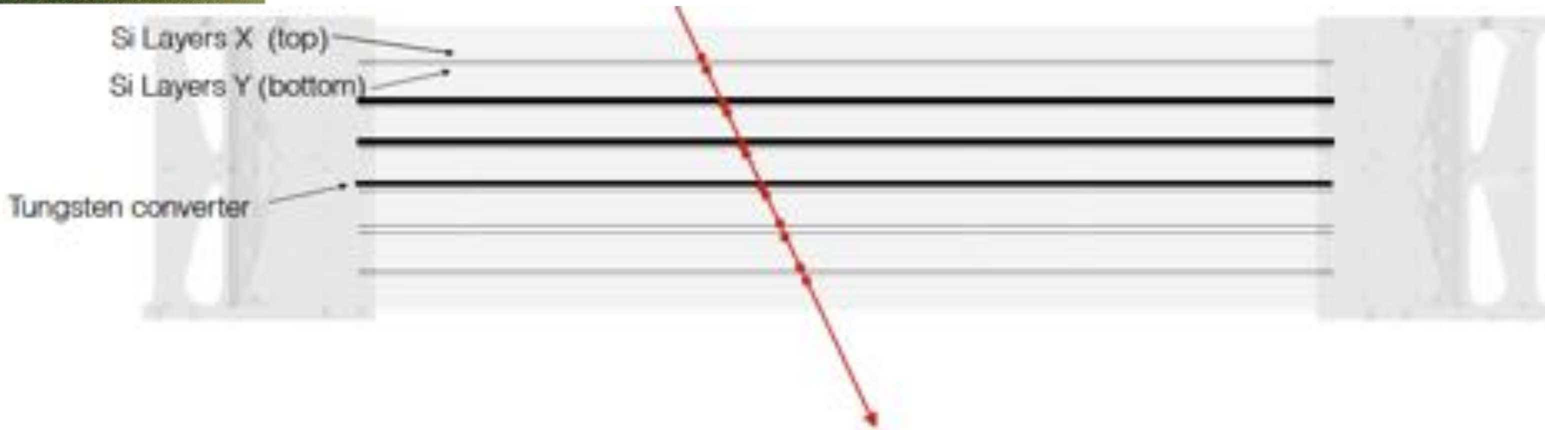
768 silicon sensors
95 x 95 x 0.32 mm^3

1,152 ASICs

73,728 channels



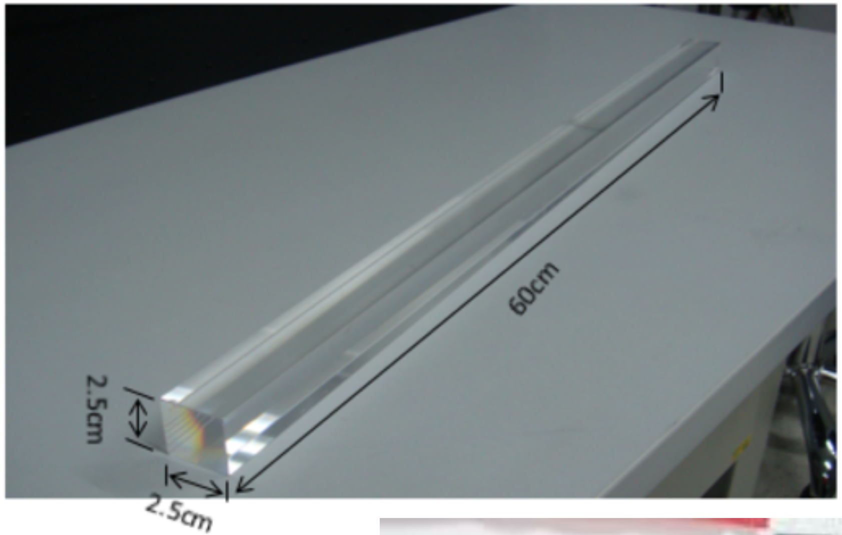
192 ladders

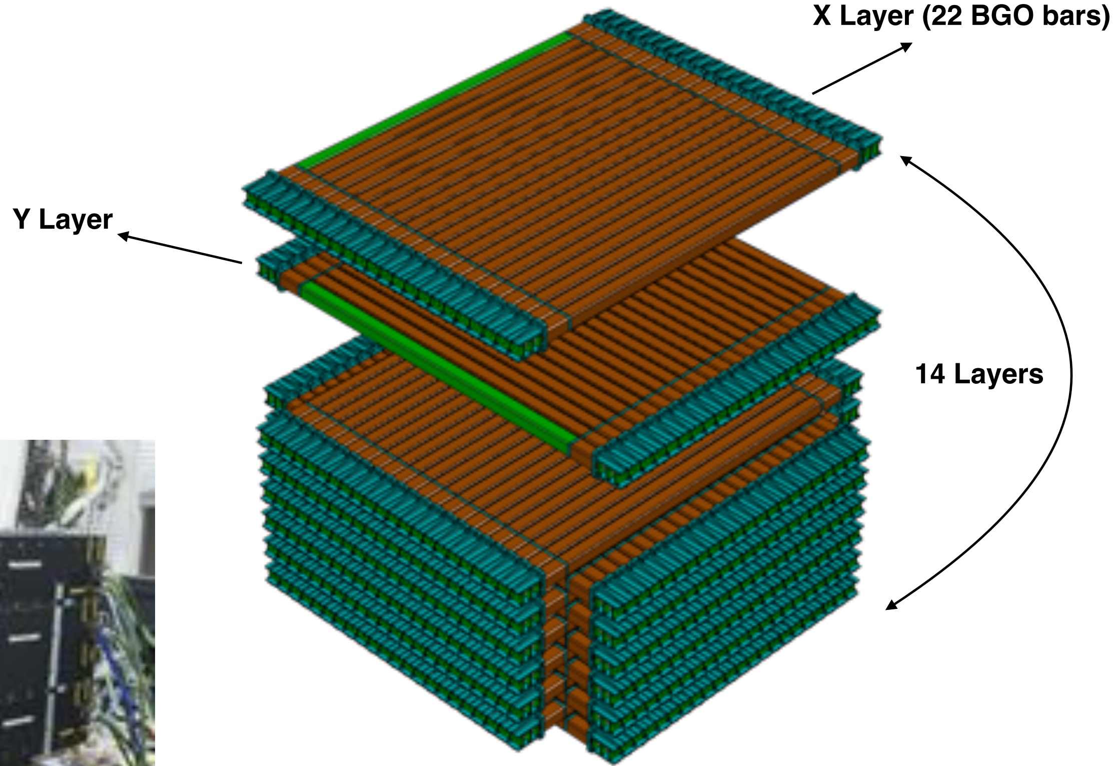


BGO Calorimeter (BGO)

- 14-layer BGO, 7 x-layers + 7 y-layers
  - BGO bar 2.5 cm × 2.5 cm x 60 cm, readout both ends with PMT
    - Use 3 dynode (2, 5, 8) signals to extend the dynamic range
  - Charge readout/Trigger: ASIC with dynamic range up to 12 pC

Detection area 60cm × 60cm

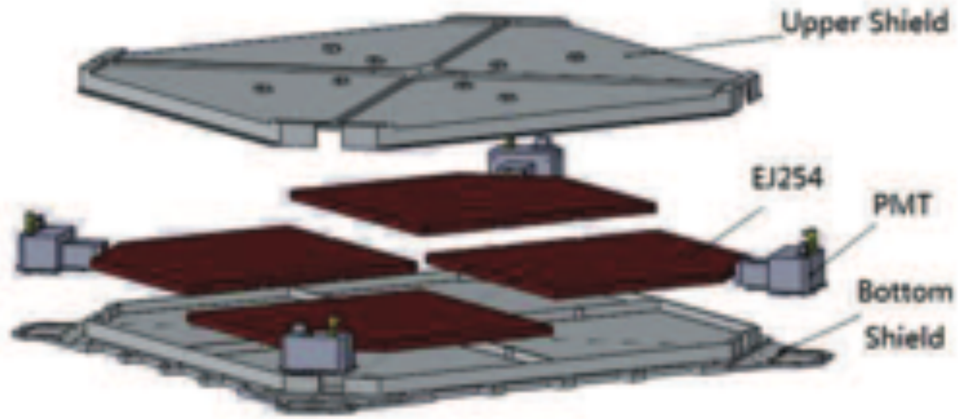




Total thickness 32 X_0/1.6 λ

Neutron Detector (NUD)

- 4 large area boron-doped plastic scintillators (30 cm × 30 cm × 1 cm)
  - Detect the delayed thermal neutron capture signal to help e/h separation
  - Gating circuit to detect delayed signal with a settable delay (0-20μs) after the trigger from the BGO

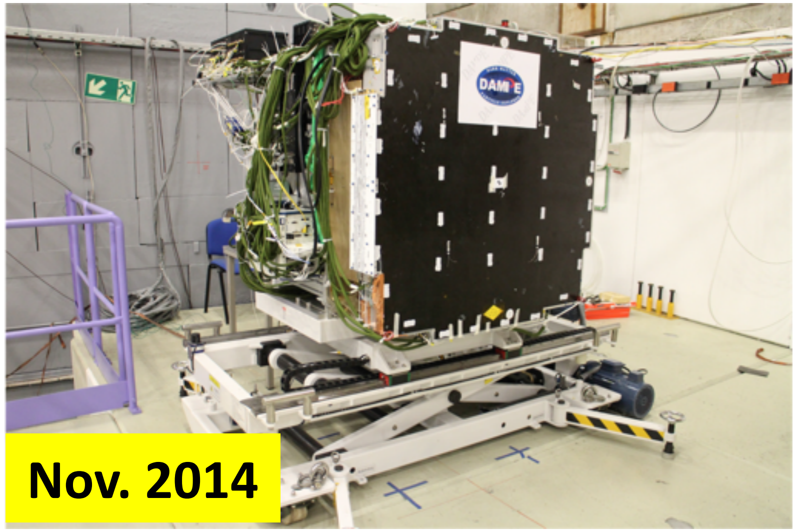


$$n + {}^{10}B \rightarrow \alpha + {}^{7}Li + \gamma$$

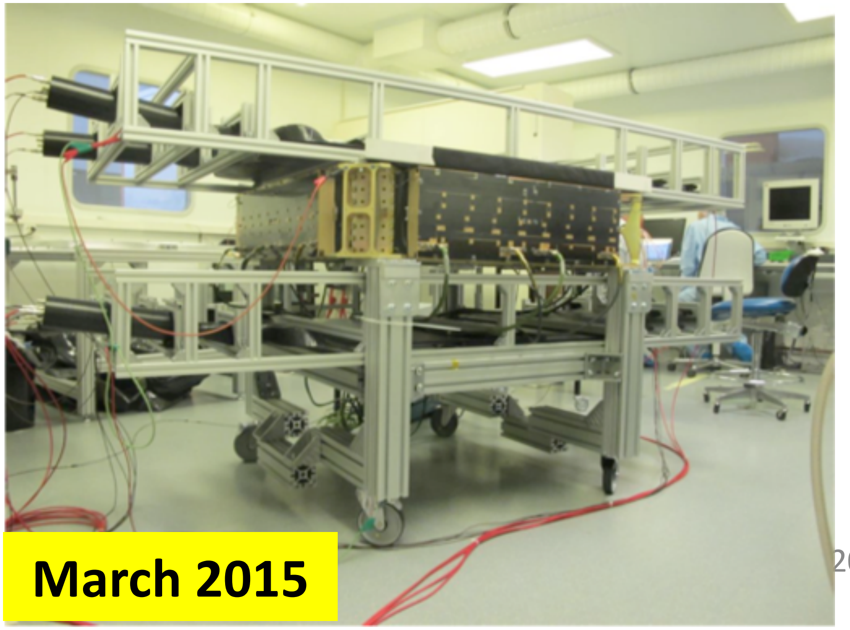
On-ground calibration

- **Several weeks at CERN PS and SPS beams from Oct. 2012 – Nov. 2015 (EQM)**
  - Plus many cosmic muon data (FM)

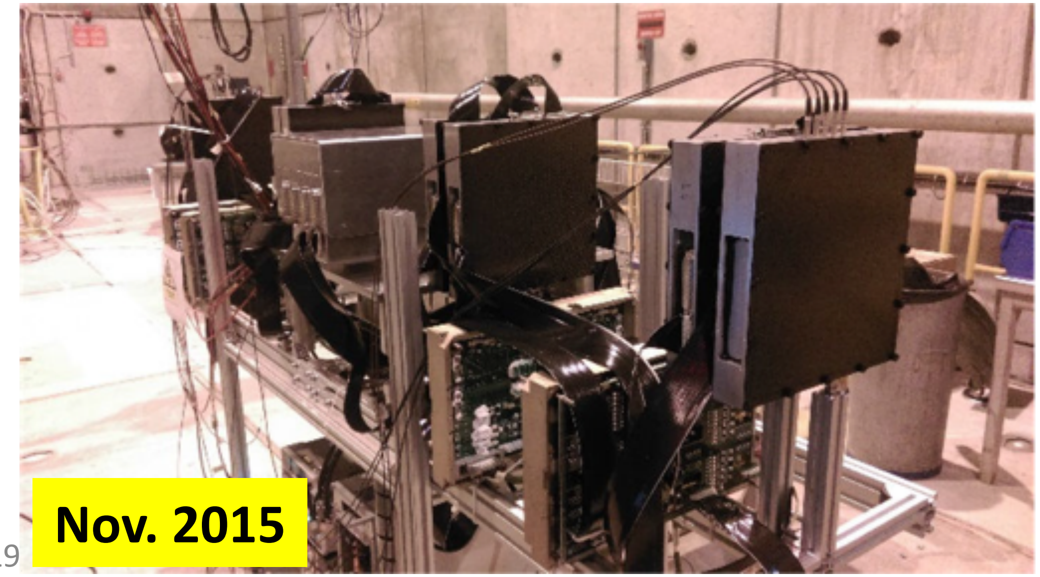
Oct. 2012



Nov. 2014

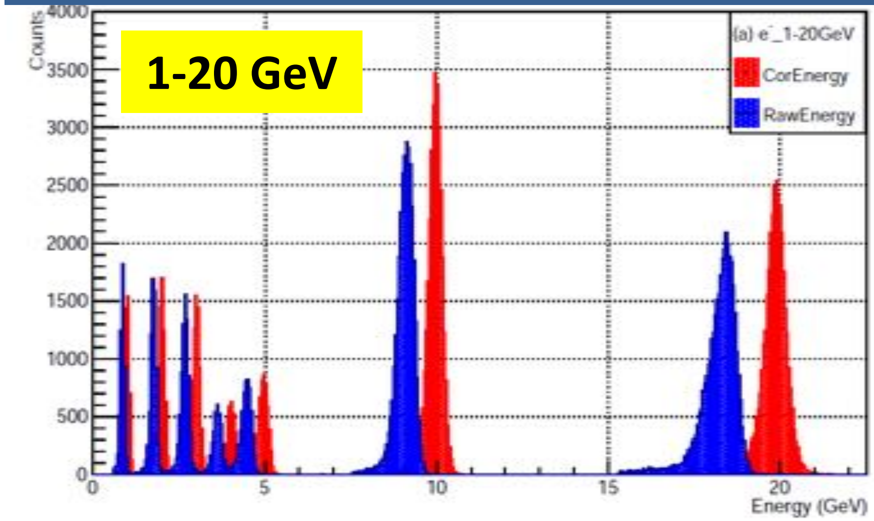


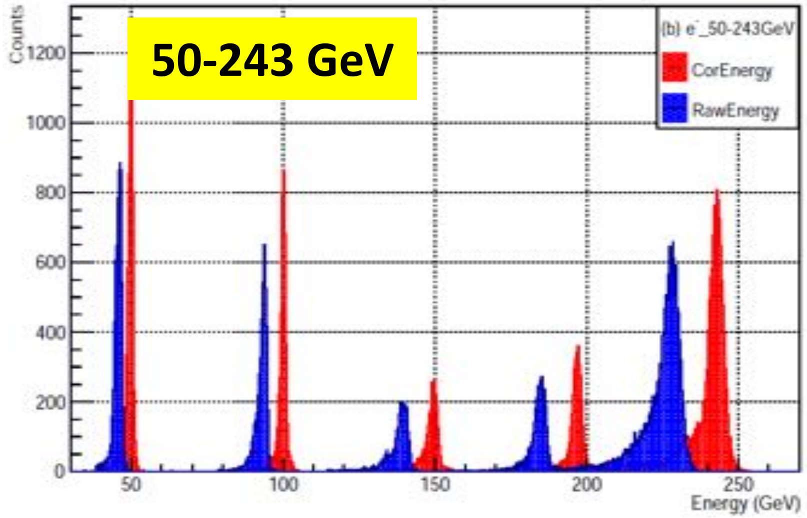
March 2015

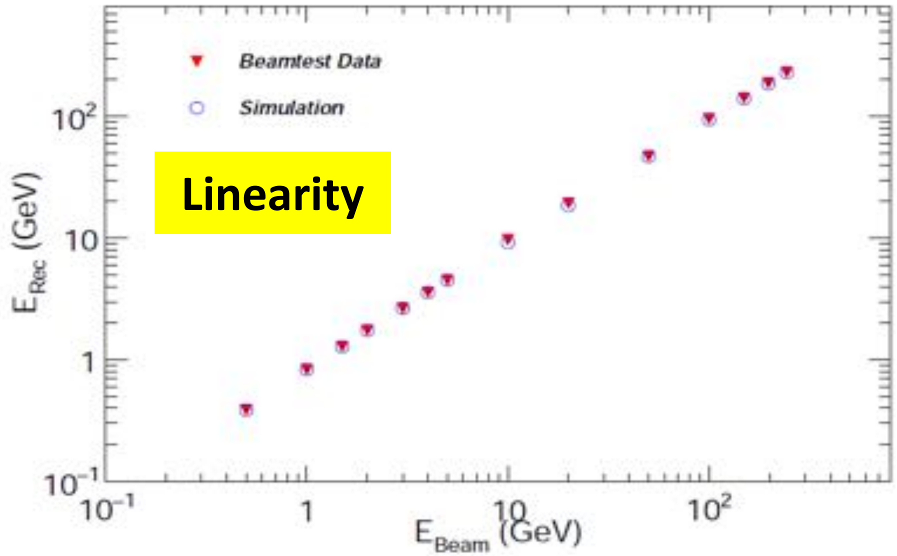


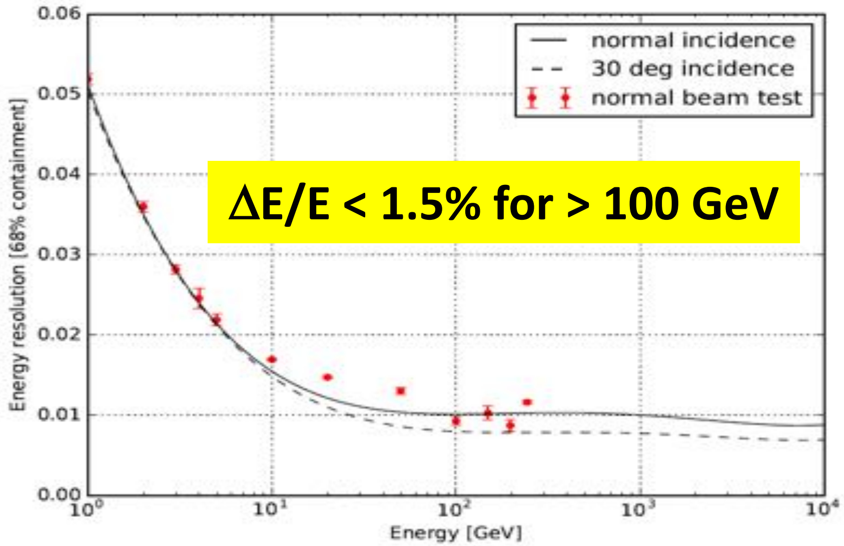
Nov. 2015

Electron energy linearity and resolution





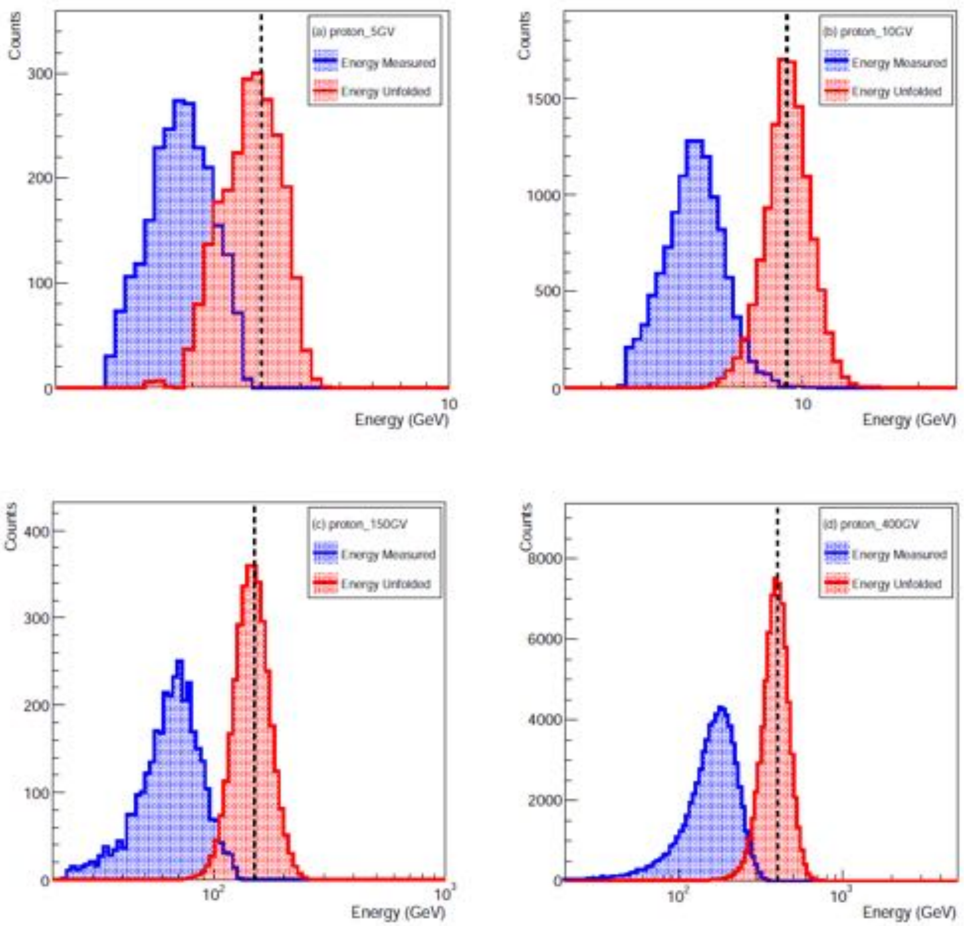


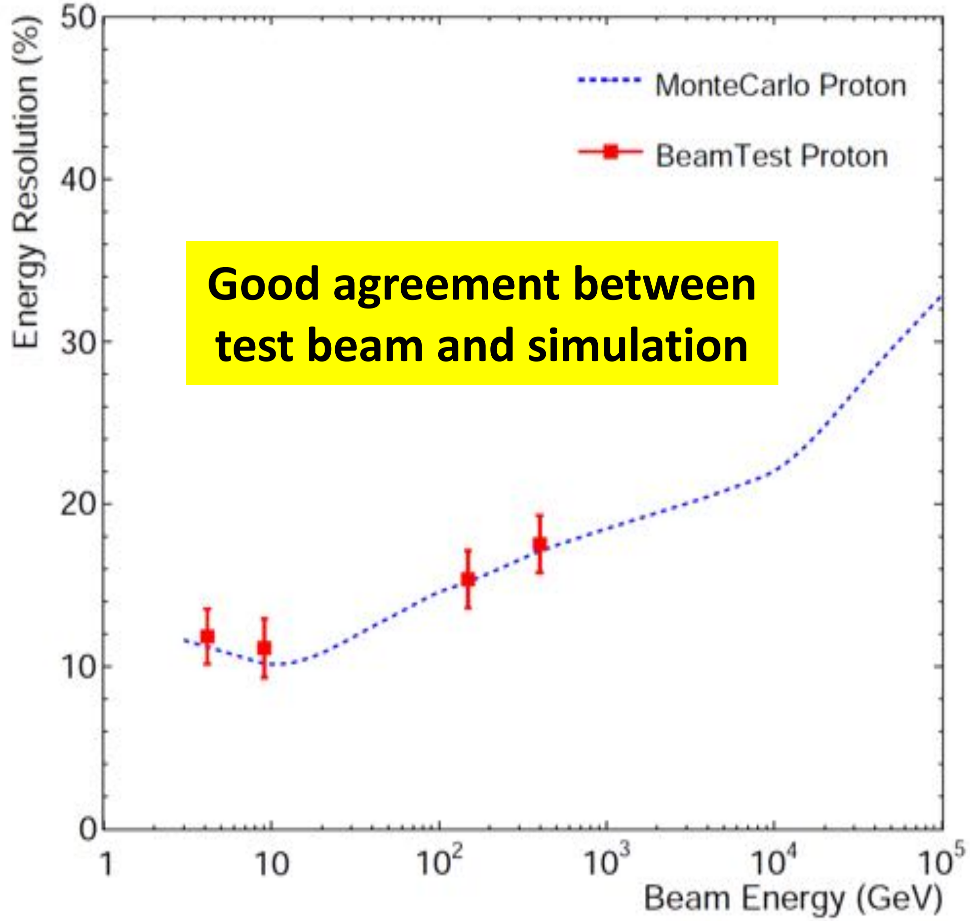


Good linearity and resolution, good agreement between test beam and simulation

Energy correction: ~6-7% for 100 GeV – 1 TeV

Proton energy resolution



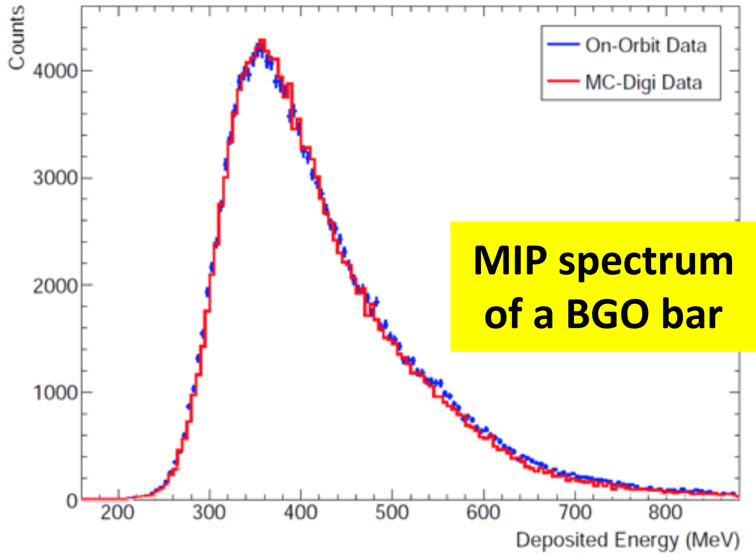


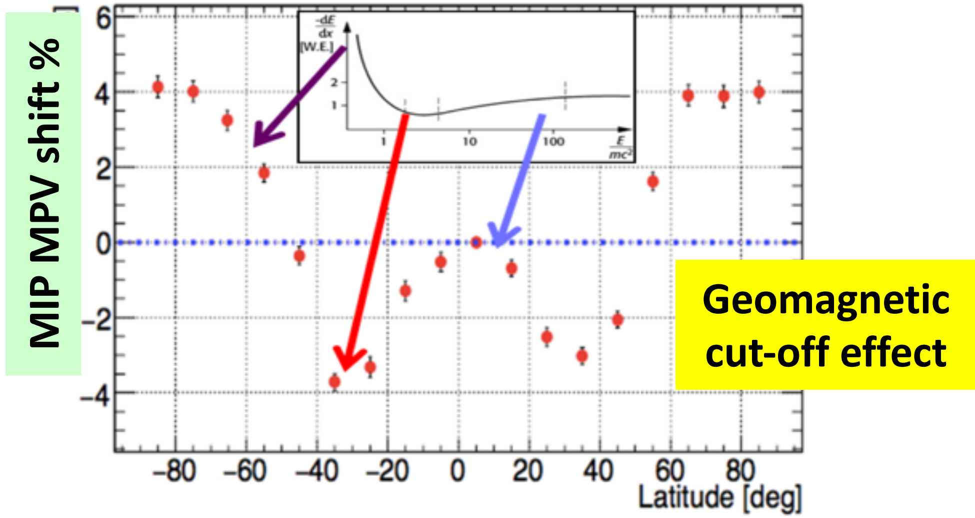
Good agreement between test beam and simulation

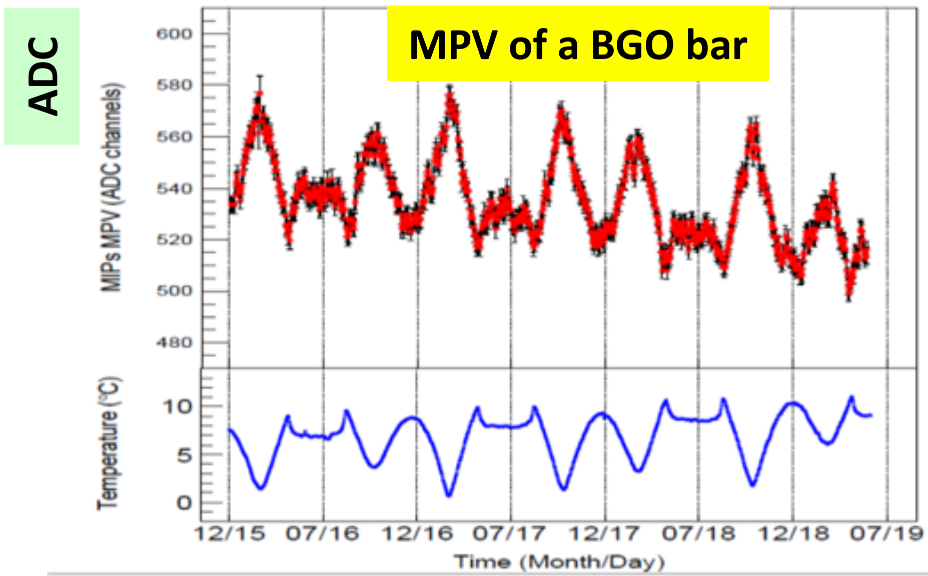
Proton energy cannot be easily corrected. Need unfolding!

BGO in-flight MIP calibration

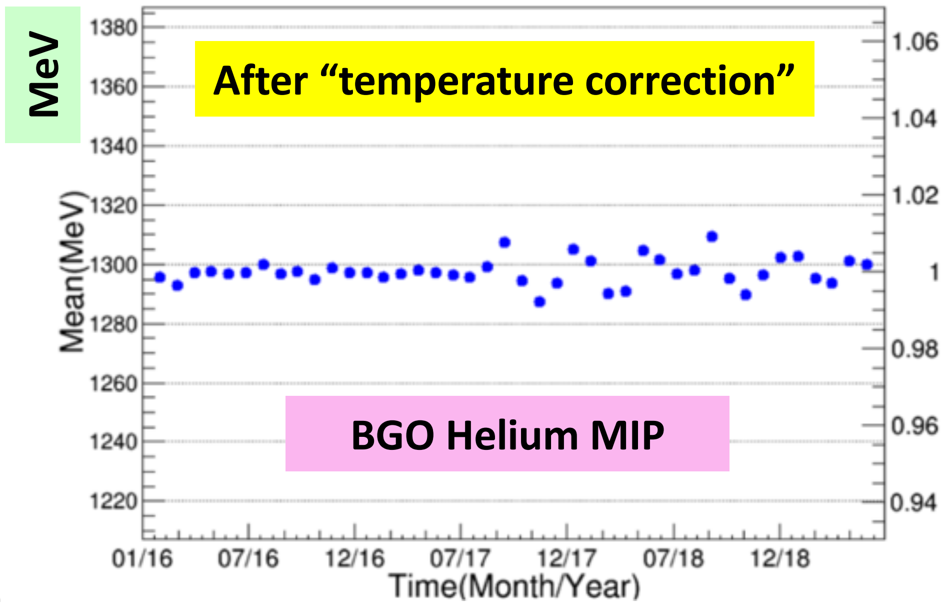
- “MIP” calibration: ADC → MeV and equalization, use events near the equator, ±20°







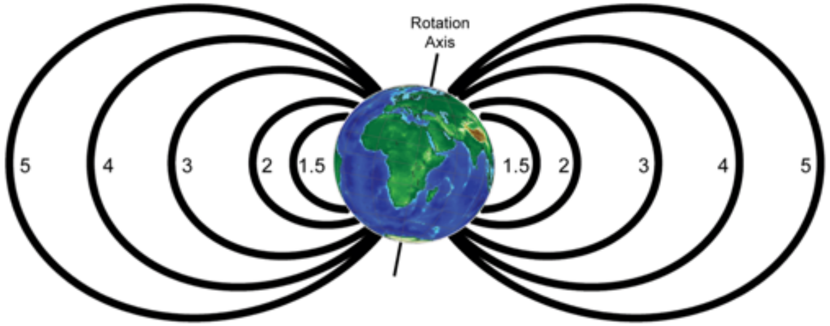
Proton “MIP” MPV vs temperature (time)



Helium “MIP” mean vs time, stable <1%

Absolute energy scale validation

- **Overall energy scale can be checked with geomagnetic cut-off effects**
  - **Charge particles detected in a geomagnetic zone have specific cut-off in the flux (deflection by the magnetic shield)**

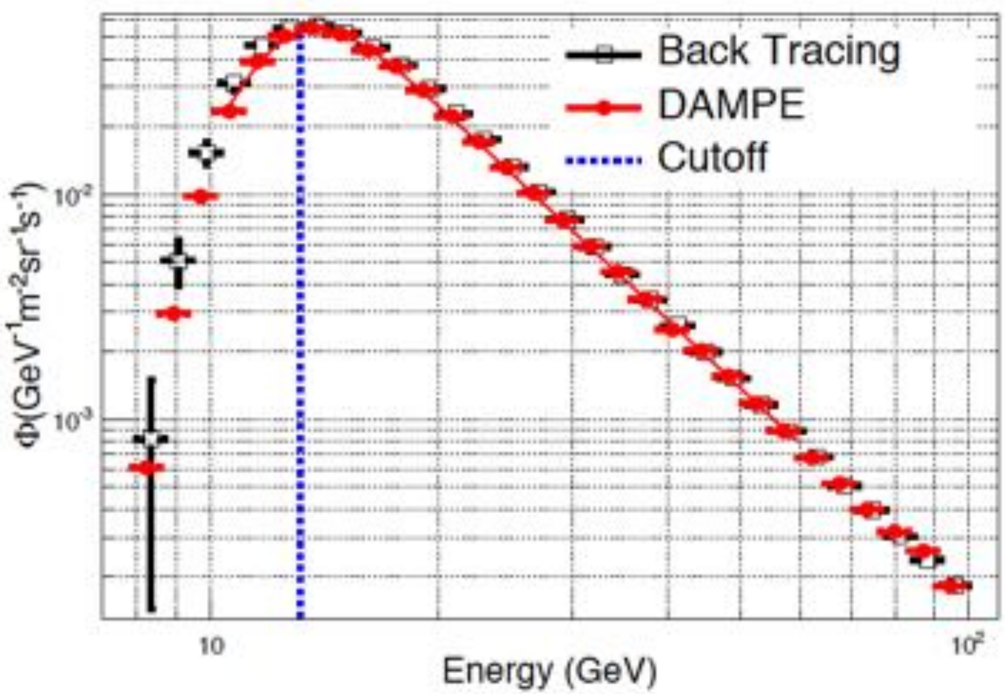


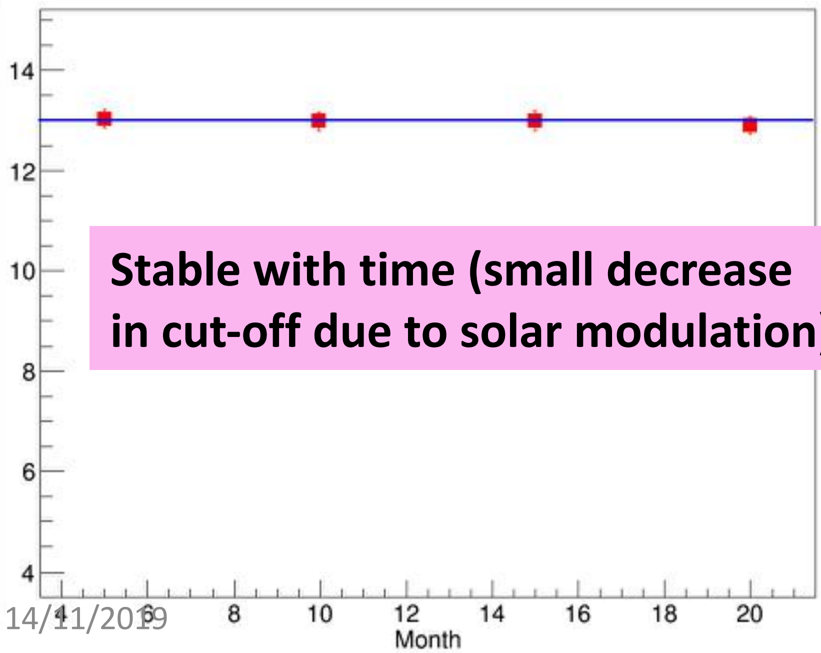
McIlwain L shells

- **Use L in 1 – 1.14, cut-off ~ 13 GeV**
- **Measured cut-off compared to MC simulation with IGRF-12 model and back-tracing code**

C_{data}/C_{pred} **= 1.012±0.017(stat.) ±0.013(sys.)**

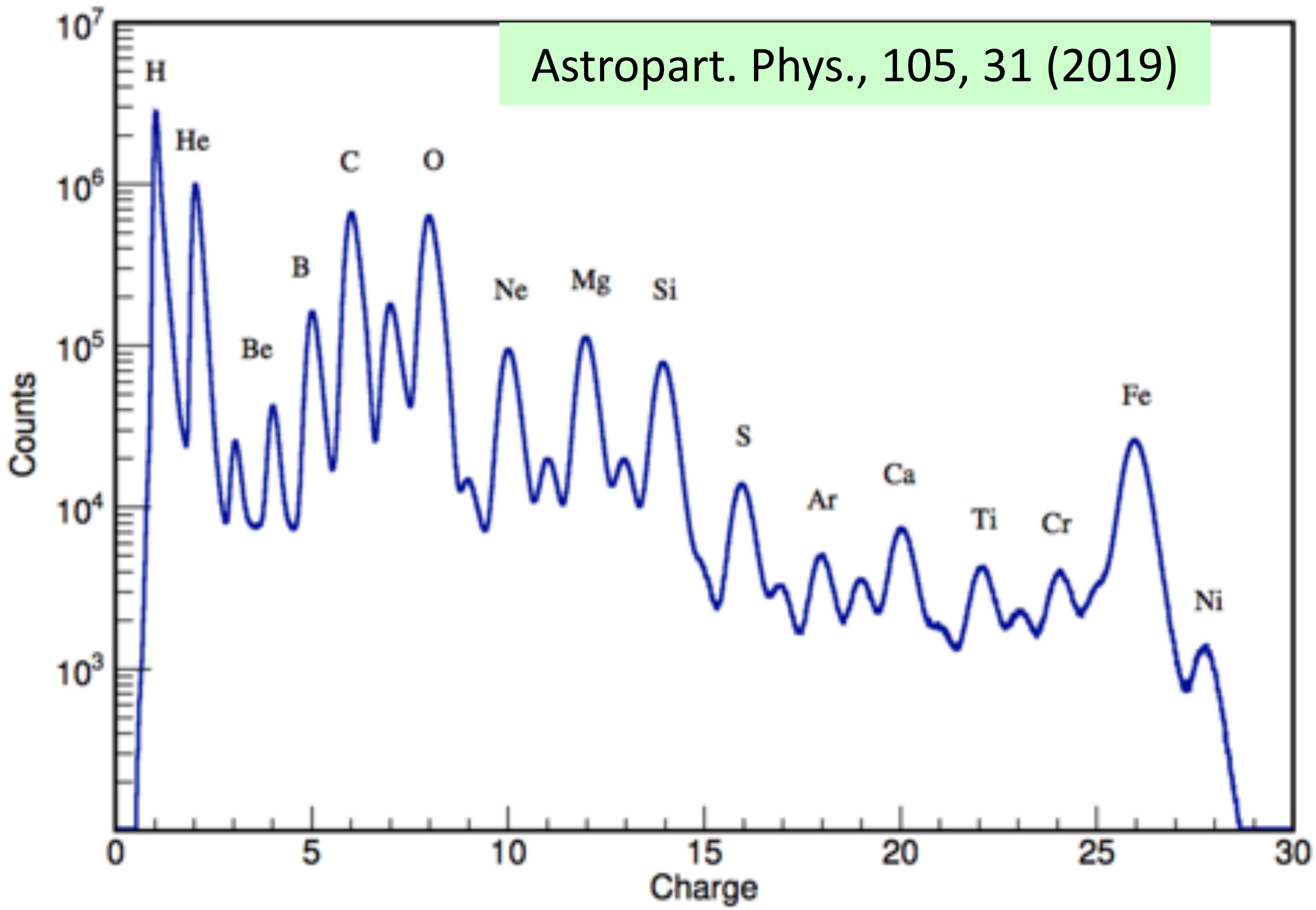
Energy scale agrees with expectation within 2%





Stable with time (small decrease in cut-off due to solar modulation)

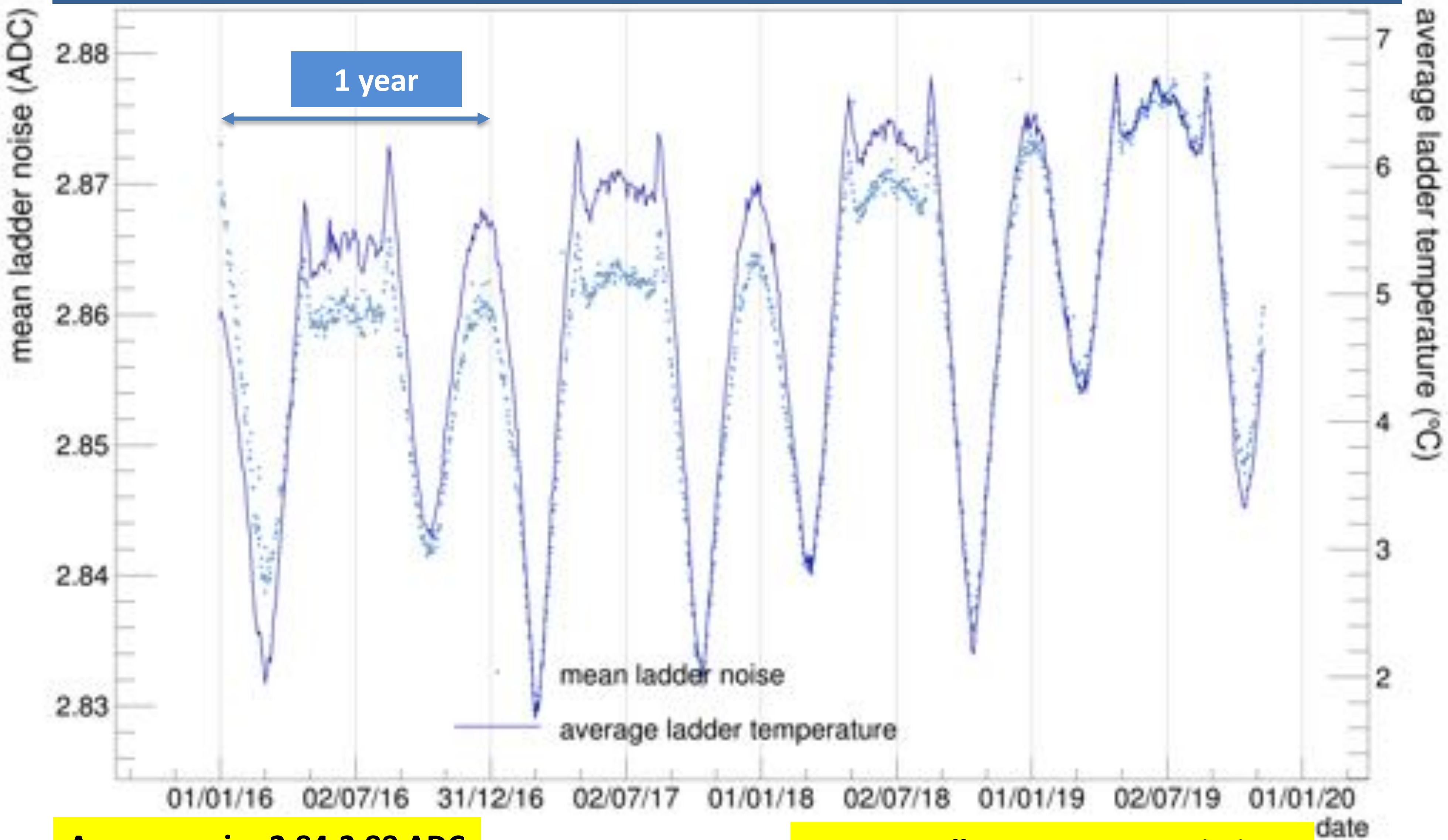
PSD in-orbit charge measurement



Element	σ_Z
H	0.07
He	0.10
Li	0.14
Be	0.21
B	0.17
C	0.18
N	0.21
O	0.20

Excellent for cosmic-ray measurements

STK noise very stable since launch



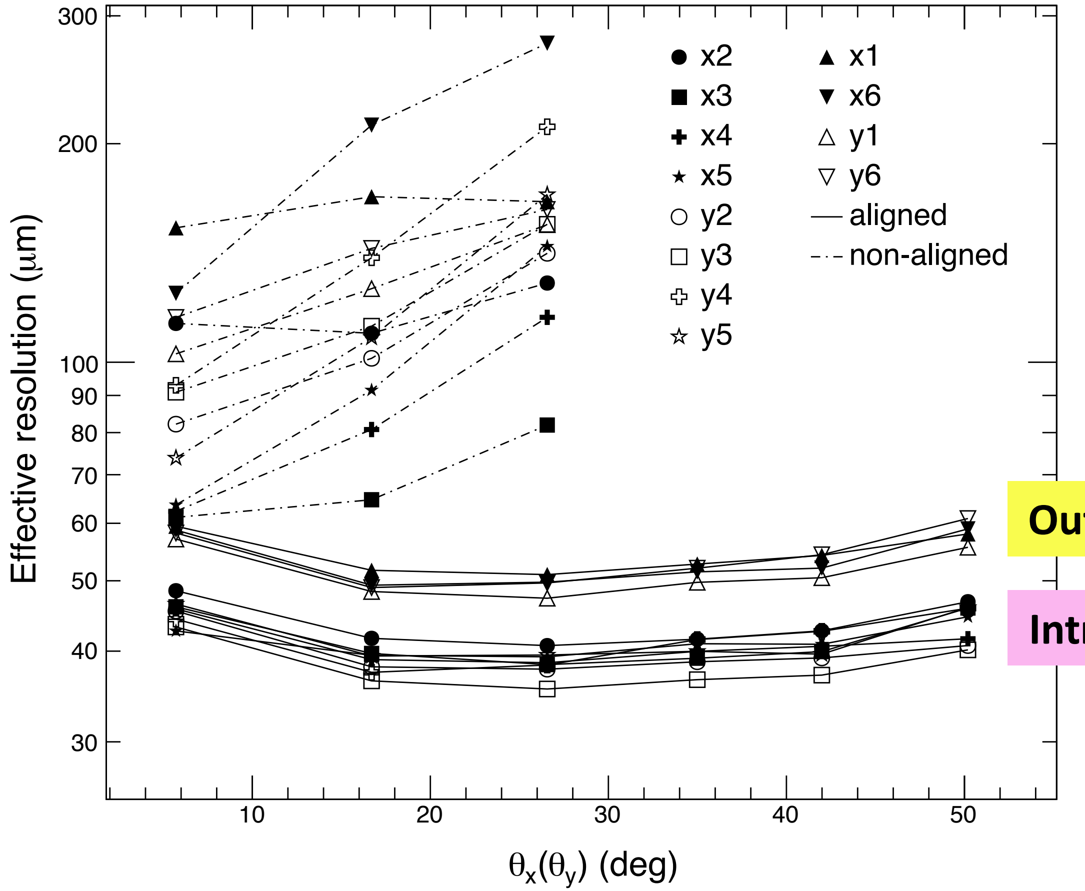
Average noise 2.84-2.88 ADC

Very small temperature variation

~4 year in orbit, >99.5% channels are still working perfectly!

STK in-flight alignment

- Good thermal stability guaranteed a good short term mechanical stability



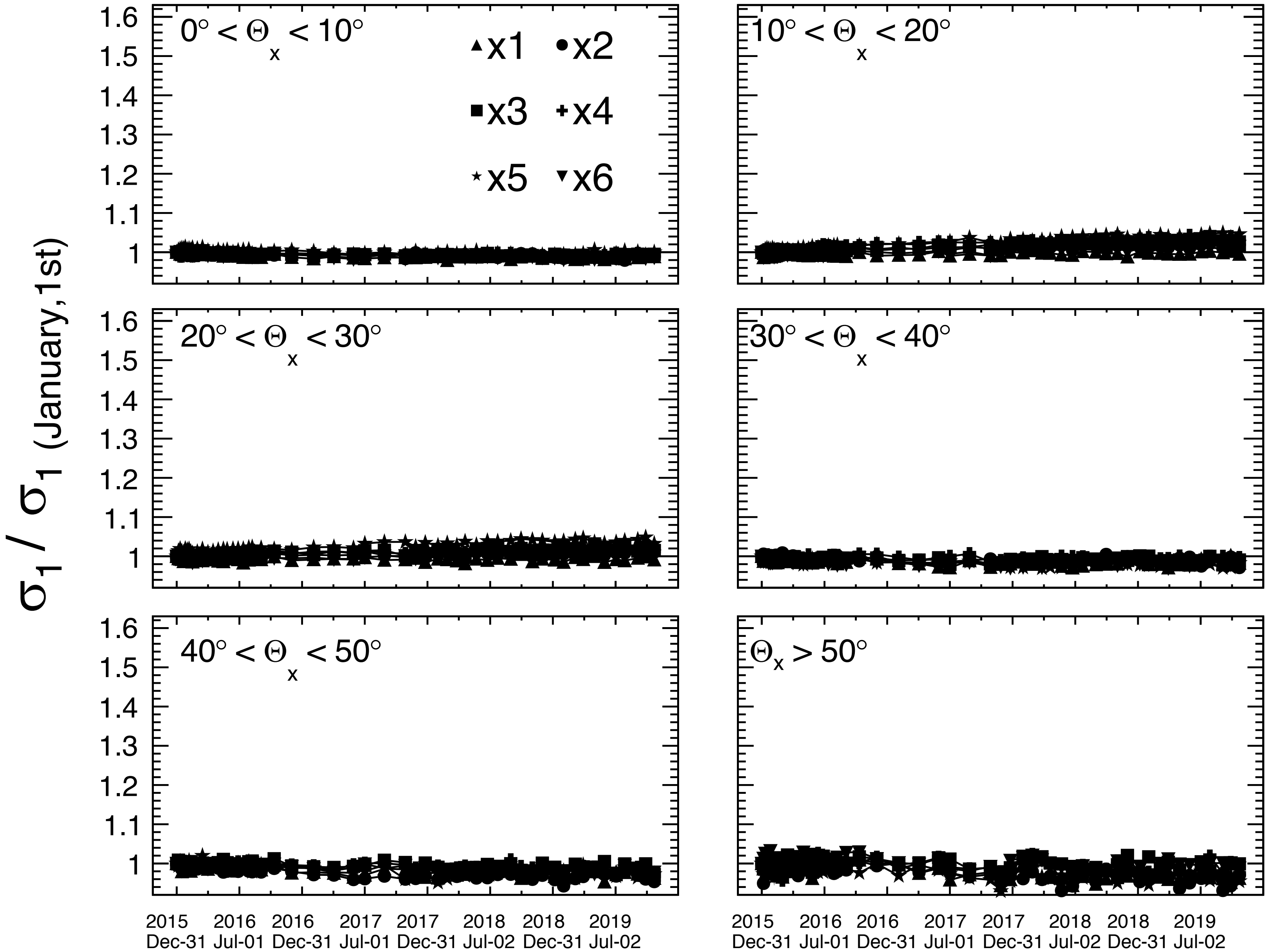
Re-align every 2 weeks to correct for long term shift

Outside layers with larger extrapolation errors

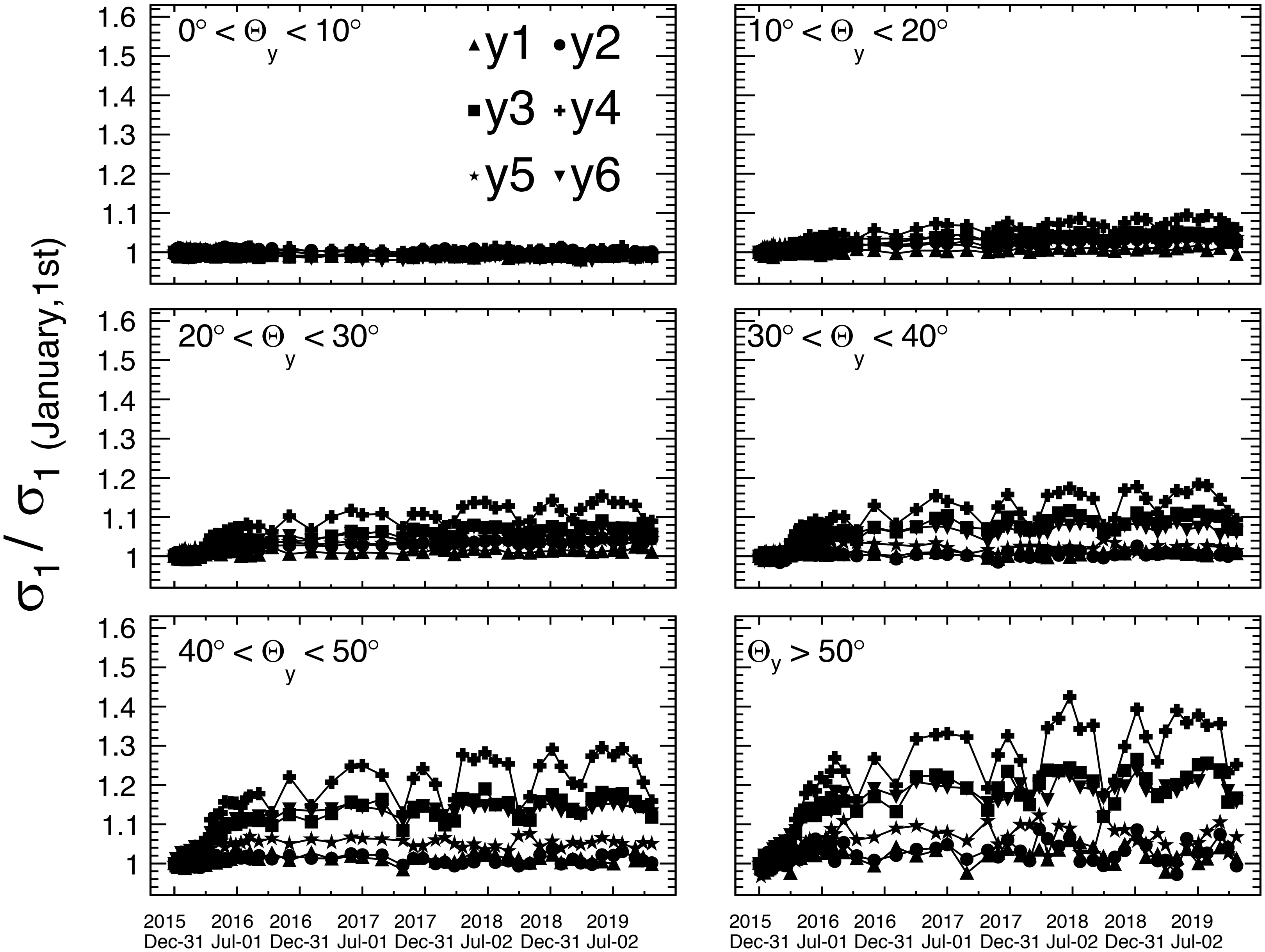
Intrinsic position resolution 40 -50 µm

Unbiased hit residual of 12 layers before/after (re)alignment, as function of incidence angle

X Residual width variation: aligned

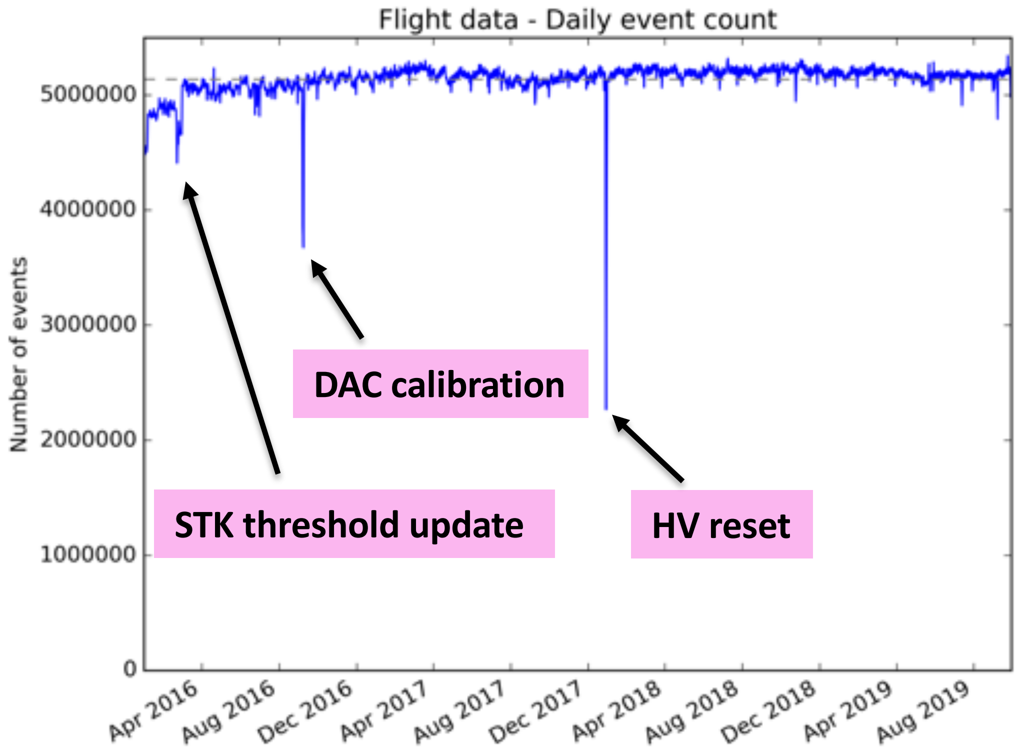


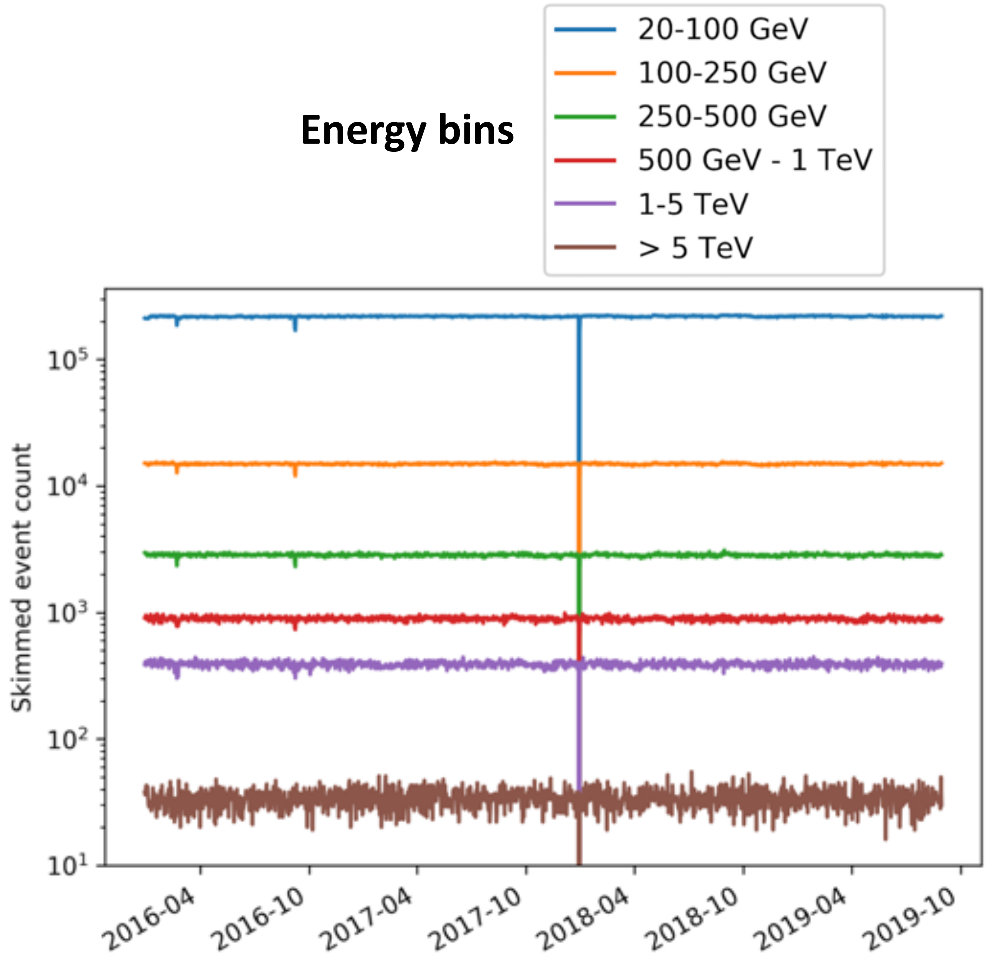
X Residual width variation: not aligned



Very stable operation

- Basically no important down time for 46 months and counting …





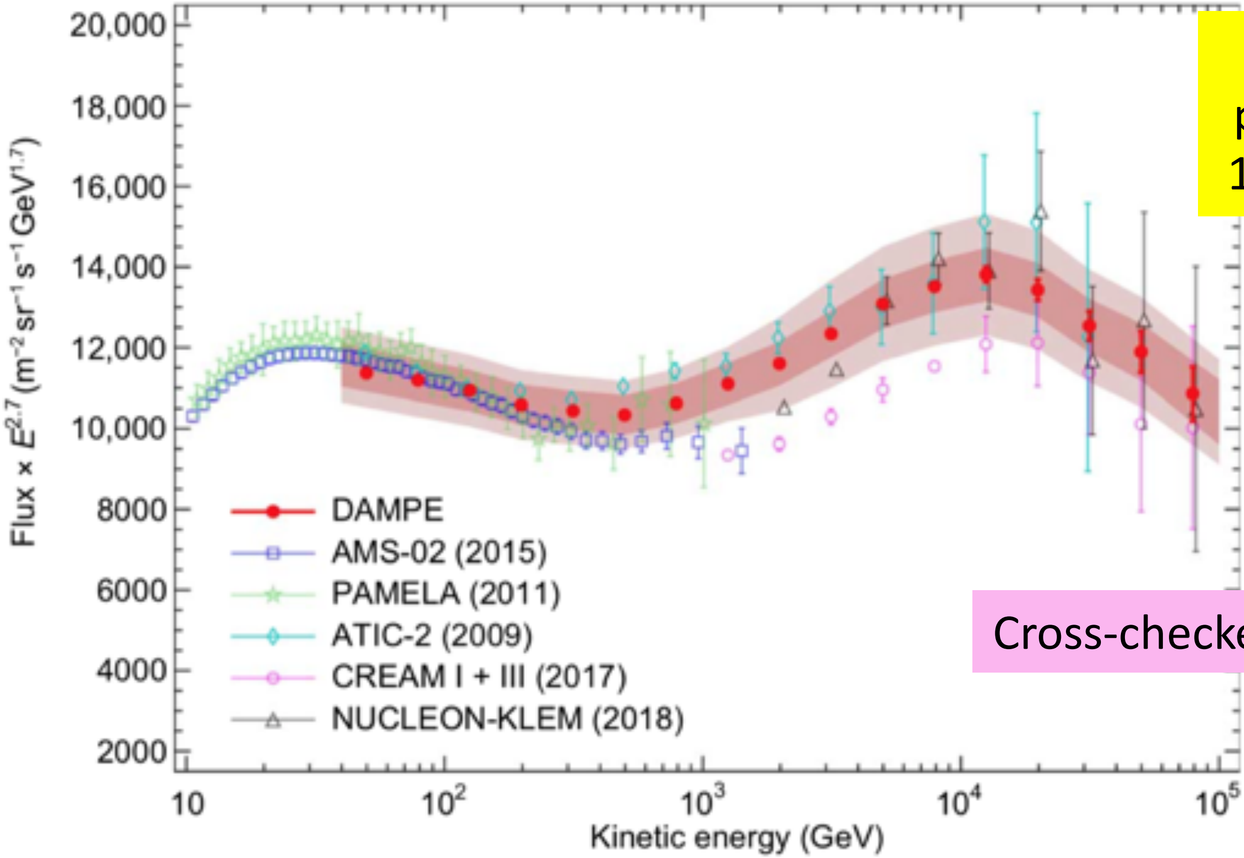
~5.2 M events recoded per day

More than 7 billion events collected

Skimmed datasets: number of events per energy interval very stable

Proton flux

- Published in 17 September 2019 in ***Science Advances (Sci. Adv., 5, 9 (2019))***



Measurement of the cosmic ray proton spectrum from 40 GeV to 100 TeV with the DAMPE satellite

Cross-checked with 3 independent analyses

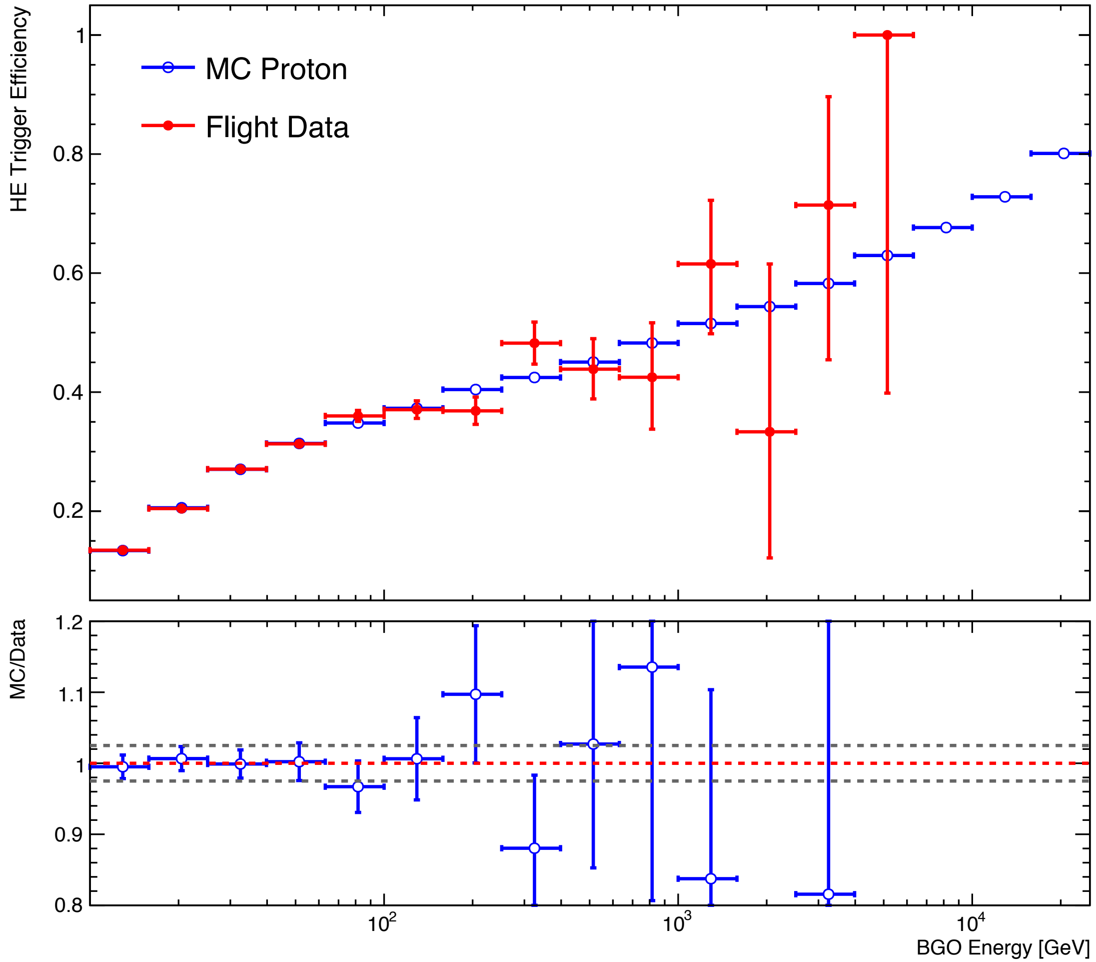
ant component of the cosmic radiation, is necessary to understand the source and acceleration of cosmic rays in the Milky Way. This work reports the measurement of the cosmic ray proton fluxes with kinetic energies from 40 GeV to 100 TeV, with $2^1/_2$ years of data recorded by the DArk Matter Particle Explorer (DAMPE). This is the first time that an experiment directly measures the cosmic ray protons up to ~100 TeV with high statistics. The measured spectrum confirms the spectral hardening at ~300 GeV found by previous experiments and reveals a softening at ~13.6 TeV, with the spectral index changing from ~2.60 to ~2.85. Our result suggests the existence of a new spectral feature of cosmic rays at energies lower than the so-called knee and sheds new light on the origin of Galactic cosmic rays.

Proton flux measurement

- Key steps of the analysis
  - Preselection
    - **High Energy Trigger**
    - **STK track selection**: crucial for linking BGO shower to the correct PSD hit
  - Charge selection
    - **Proton selection based on the charged measured in PSD**
      - STK charge used for validation
    - **Helium background: template fit of the PSD charge**
      - Helium contamination $\lesssim$1% for deposited energies at <10 TeV and up to ~5% around 50 TeV
    - Electron rejected based on BGO shower shape variables, residual < 0.05%
  - Energy unfolding
    - Bayesian unfolding (D'Agostini, NIM A362(1995), 487)
  - Systematic uncertainties
- Three independent analyses gave consistent final proton flux results

Trigger efficiency

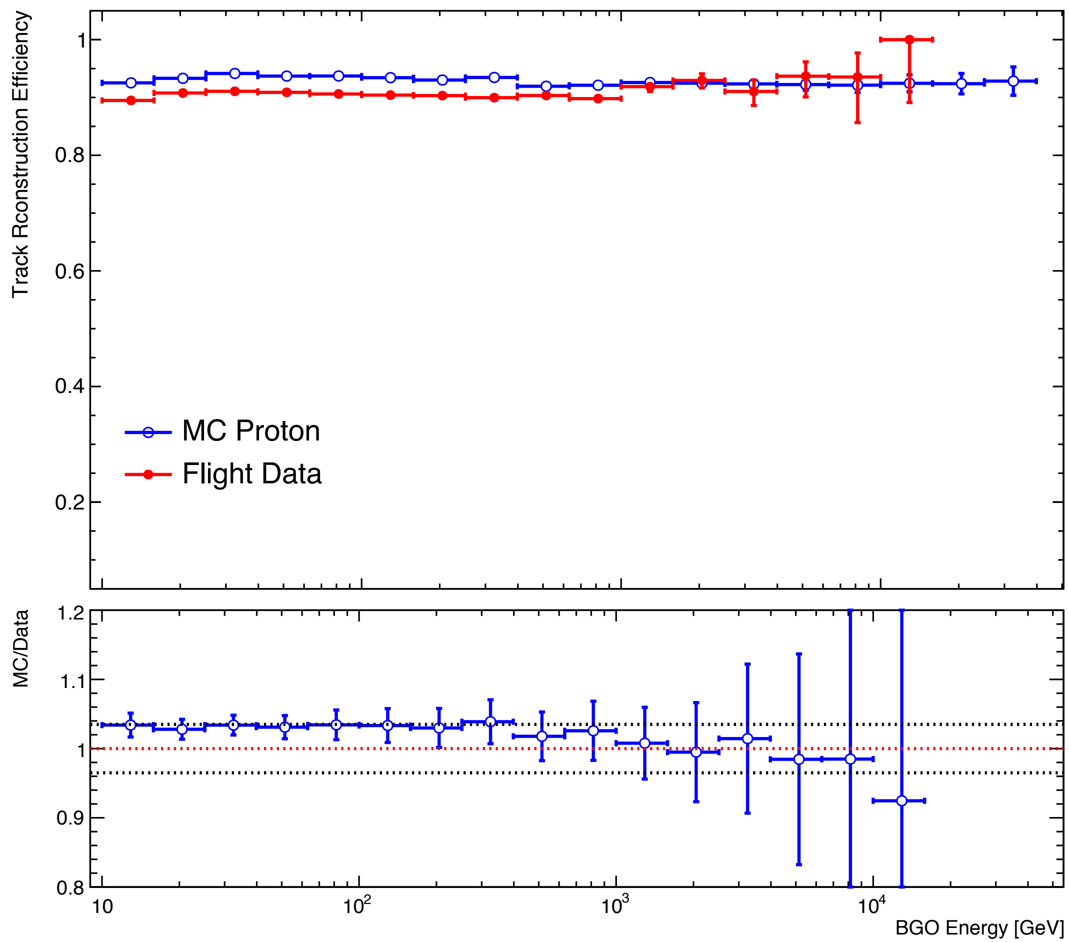
- Trigger efficiency is validated with data using the unbiased trigger



Good data-MC agreement, use 2.5% as systematic error

Tracking efficiency

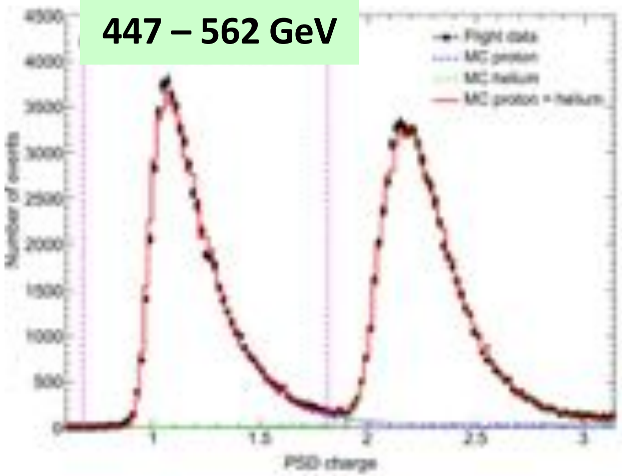
- Trigger efficiency is validated with data with a proton selection using “BGO tracks”

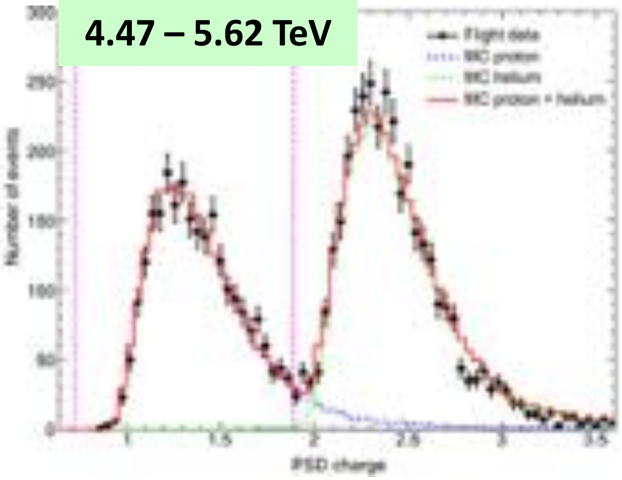


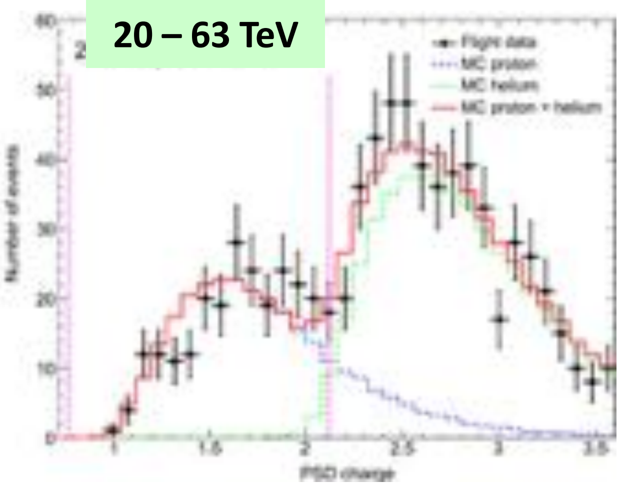
Data-MC consistent within 3.5%, use as systematic error

Charge selection efficiency

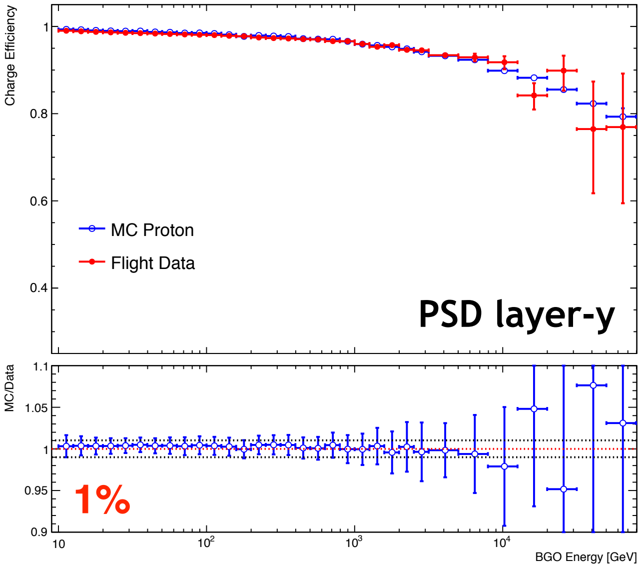
- PSD charge templates from proton and Helium MC (corrected for back scattering)

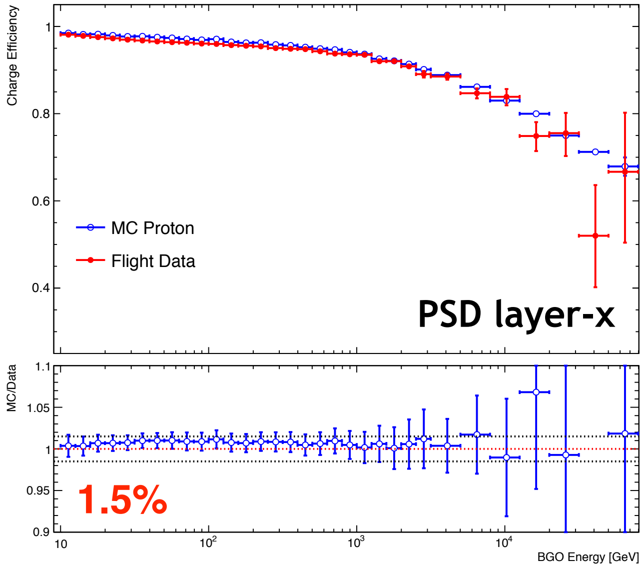






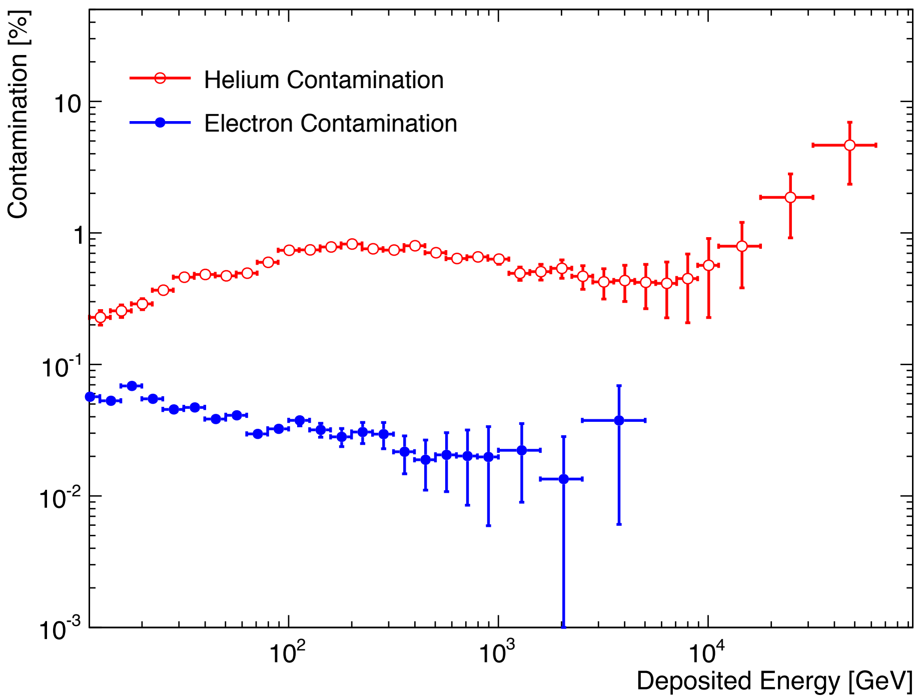
- Cut: $0.6 + 0.05 \cdot \log(E_{\mathrm{dep}}/10\ \mathrm{GeV}) \leq Z_{\mathrm{PSD}} \leq 1.8 + 0.002 \cdot \log^4(E_{\mathrm{dep}}/10\ \mathrm{GeV})$
- Efficiency validated by data using first layer of STK

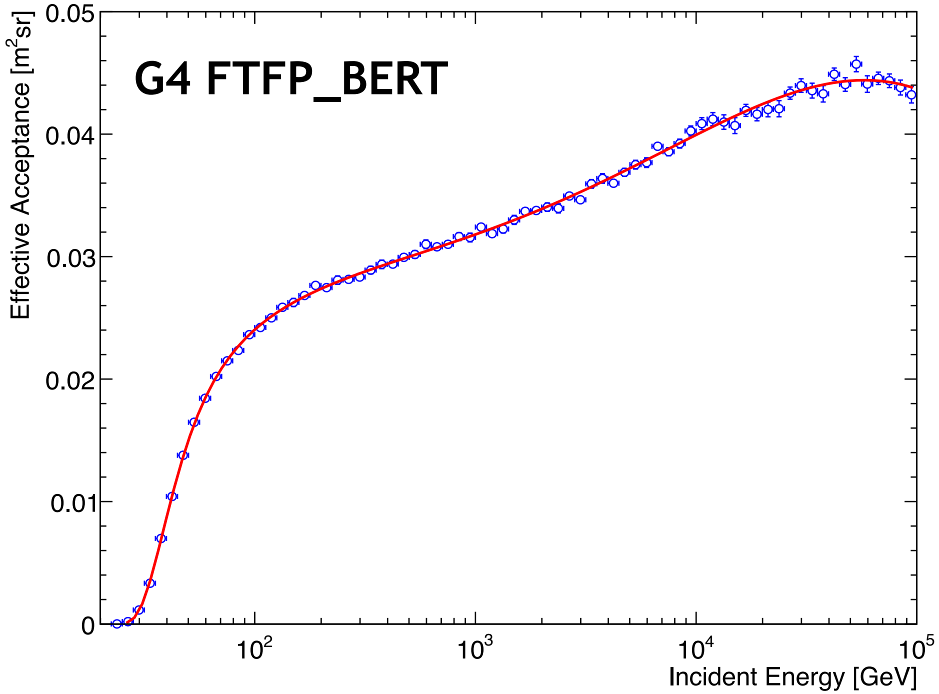




Good data-MC agreement, 1.8% systematic error

Background fraction and effective acceptance

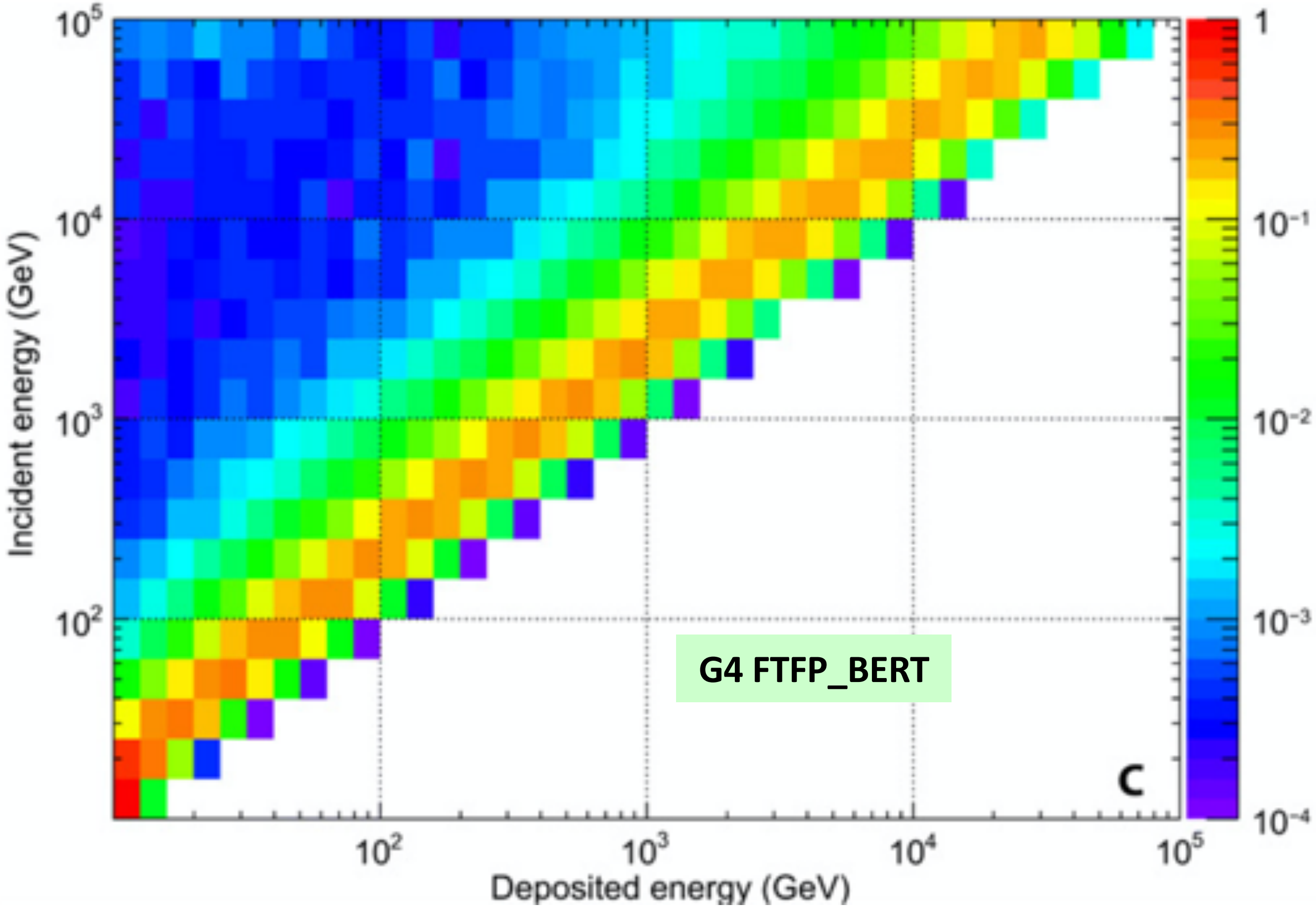




- Helium background varies between ≲1% for <10 TeV to ~5% around 50 TeV
  – Electron negligible
- Effective Acceptance (GF x Eff) evaluated with G4 with the FTFP_BERT physics list

Energy unfolding

- With a homogenous detector, the energy resolution is relatively good.
- Unfolding performed with the Bayesian method (D'Agostini, NIM A362(1995), 487)



Systematic Uncertainties

- Selection efficiency: 4.7%

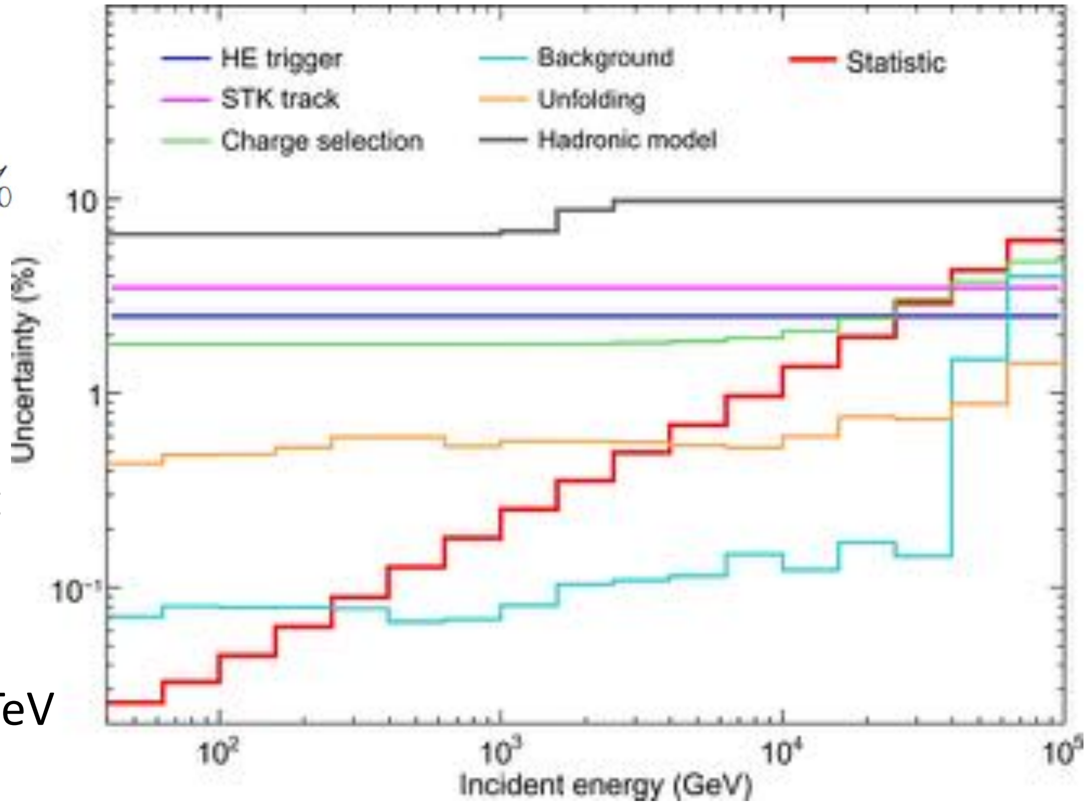
$$\sigma_{\text{sel}} = \sqrt{\sigma^2_{\text{trigger}} + \sigma^2_{\text{track}} + \sigma^2_{\text{charge}}} \approx 4.7\%$$

  - Charge selection became important above 50 TeV

- Background only relevant at highest energy: 1-4% from 40 -100 TeV

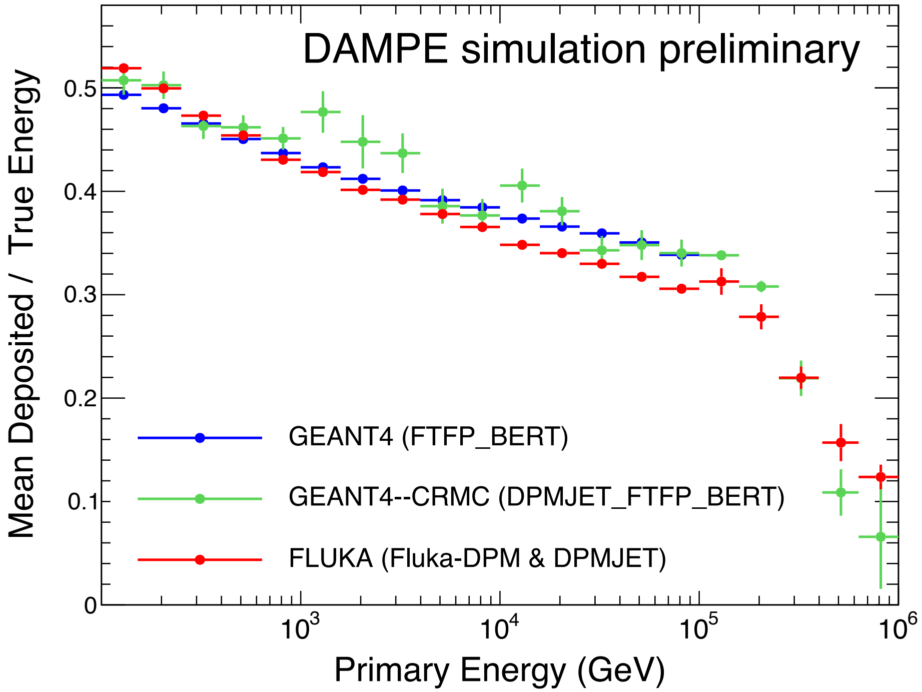
- Statistical error 2-6% from 10 -100 TeV

- Hadronic model: **7-10%**



Hadronic model uncertainty

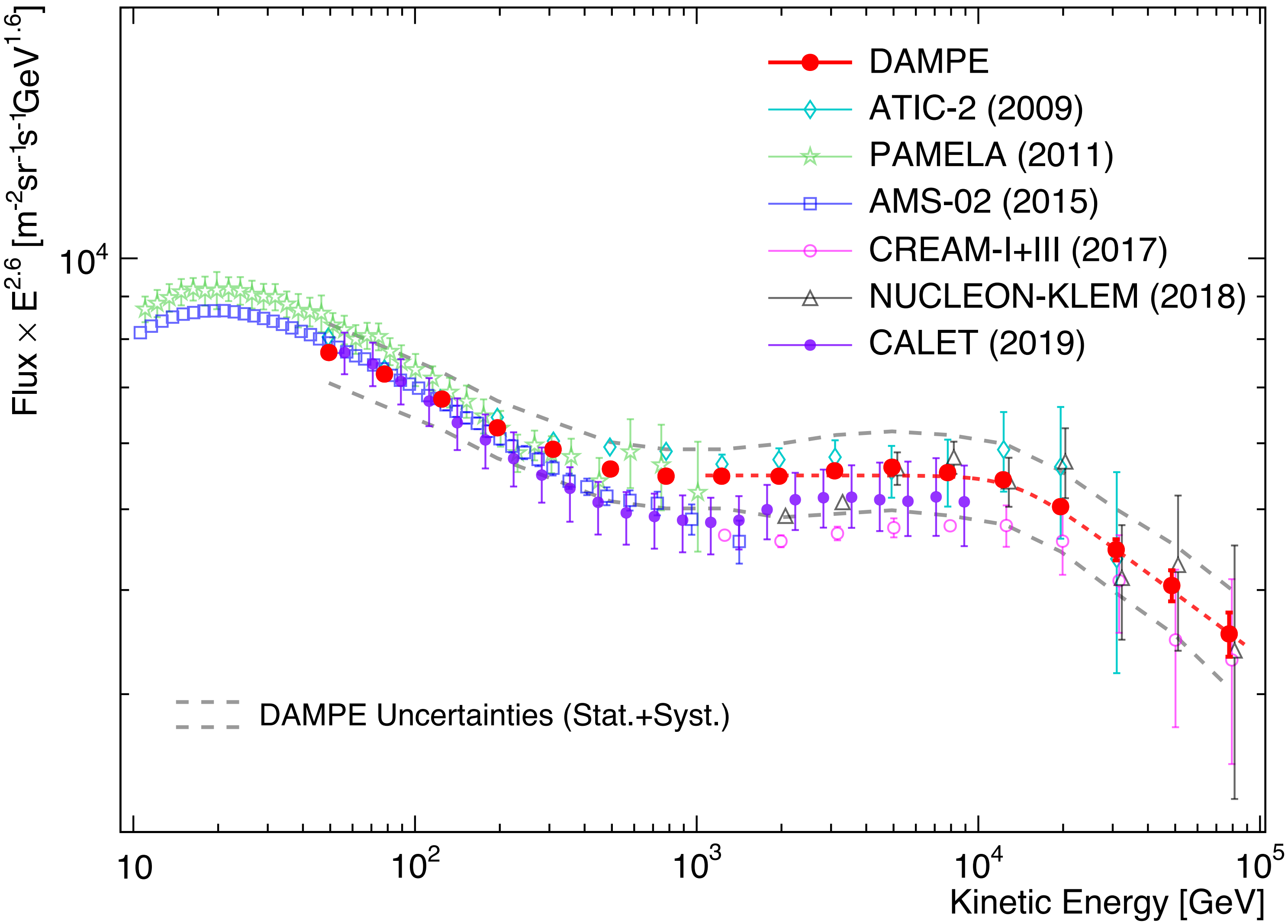
- The largest systematic uncertainty is the hadronic model
  - Low energy (<1 TeV): ~7% by comparing 400 GeV test beam data and GEANT4 FTFP_BERT (baseline model for <100 TeV) simulation.
  - High energy (>1 TeV): 7-10% by comparing FTFP_BERT and FLUKA
    - FLUKA is baseline model for >100 TeV, used only for unfolding
  - Further check with comparing FLUKA and CRMC



- **G4-CRMC interface implemented (A. Tykhonov)**
  - CRMC (DPMJET) and GEANT4 (FTFP_BERT) has good agreement
  - No significant differences between DPMJET and EPOS in CRMC
  - FLUKA energy deposited softer than G4-CRMC
    - Likely due to low-energy hadronic models
    - Also the geometry implementations of G4 and FLUKA is different

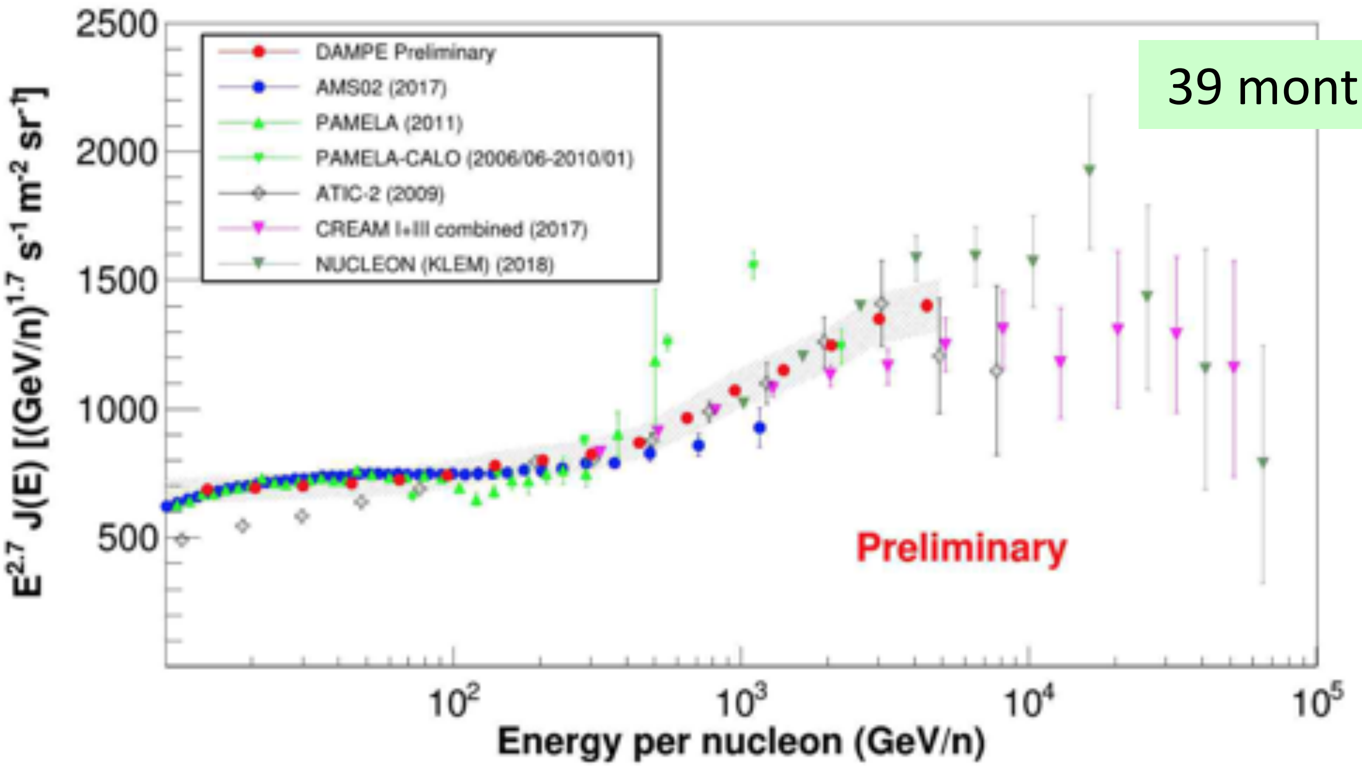
A. Tykhonov et. al. ICRC2019, https://pos.sissa.it/358/122/

Comparison of proton flux measurements



Preliminary Helium flux

- Analysis in progress, final result will extend to higher energy (~25-50 TeV/n)

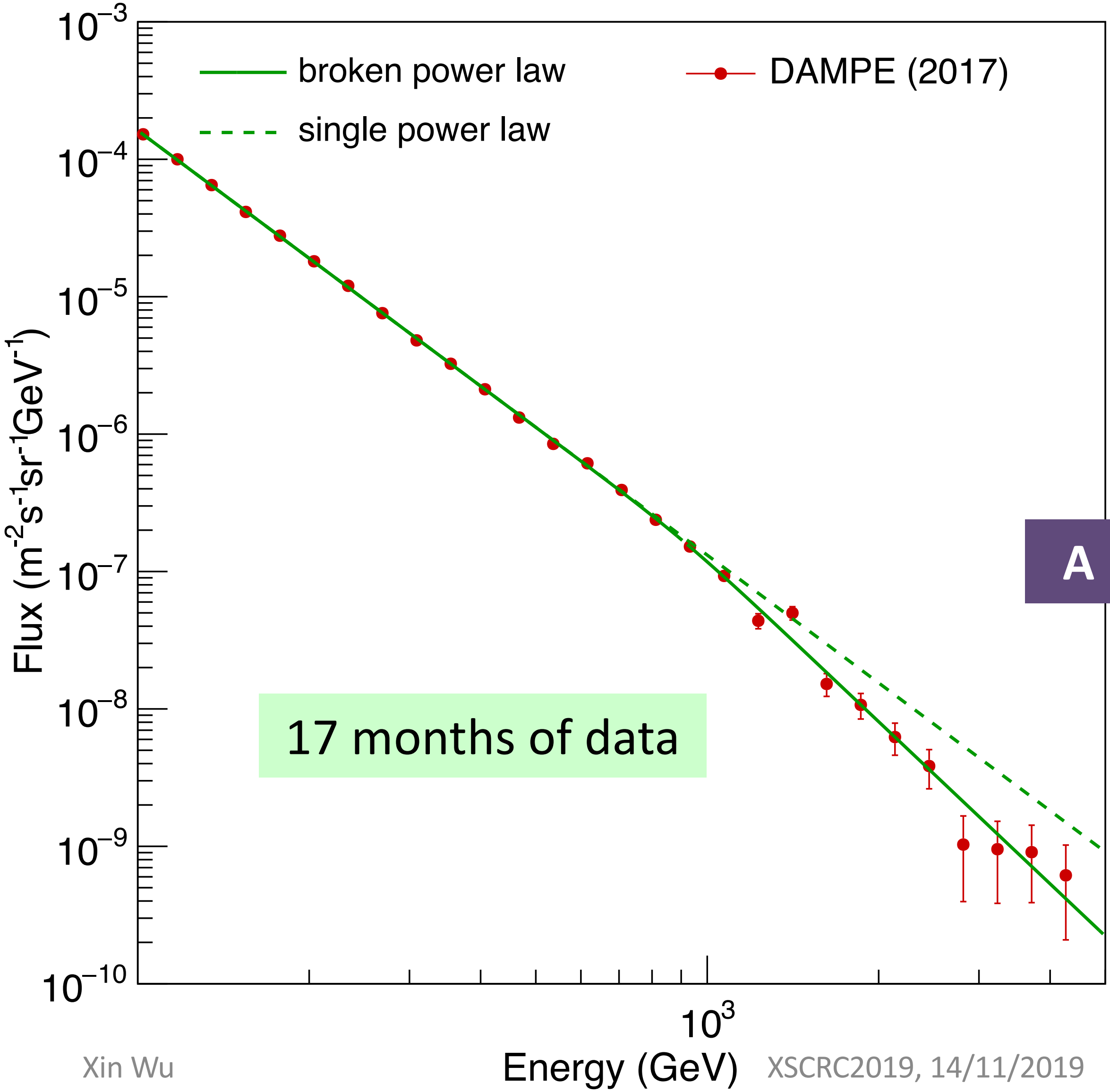


39 months of data

M. Di Santo et. al. ICRC2019, https://pos.sissa.it/358/058/

Electron + positron flux

- Published in 29 November 2017 in ***Nature, 552, 63 (2017)***

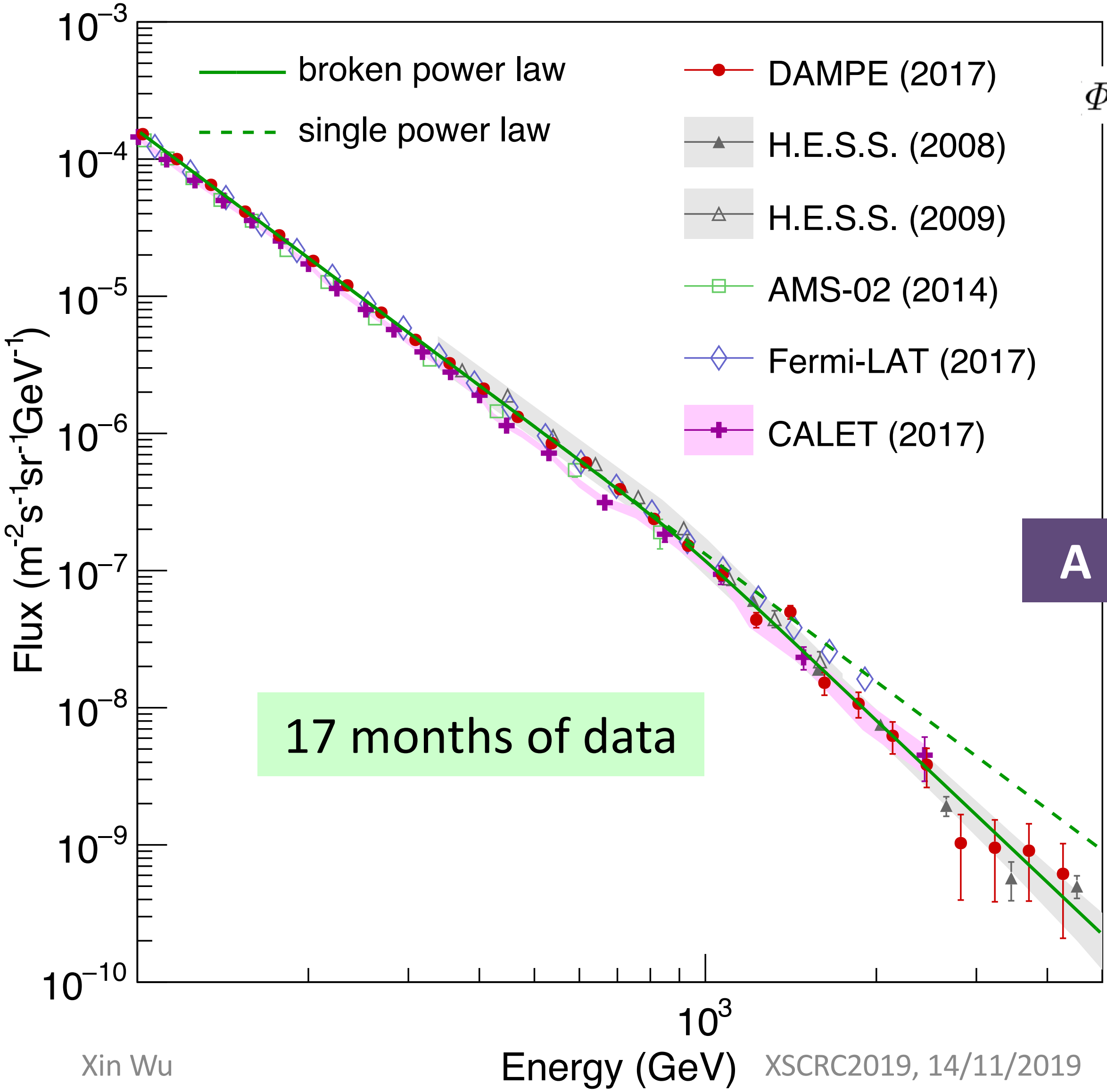


A break at ~0.9 TeV is observed

To be updated soon with more than 2 times data

Electron + positron flux

- Published in 29 November 2017 in ***Nature, 552, 63 (2017)***



$$\Phi = \Phi_0 (E/100\ \mathrm{GeV})^{-\gamma_1}[1 + (E/E_\mathrm{b})^{-(\gamma_1-\gamma_2)/\Delta}]^{-\Delta}$$

γ_1=3.09±0.01
γ_2=3.92±0.20
E_b=914±98 GeV
Φ_0 = (1.64±0.01) x 10-4 m^{-2}s^{-1}sr^{-1}GeV^{-1}
Δ = 0.1
χ2/NdF = 23.3/18 (6.6σ preference over PL)

A break at ~0.9 TeV is observed

To be updated soon with more than 2 times data

Conclusions

- DAMPE is working extremely well since its launch about 4 years ago
  - A precise electron + positron flux in the TeV region has been measured
    - A clear spectral break has been observed at ~ 0.9 TeV
    - Update with more data, extend the measurement to 10 TeV soon
  - Direct high statistics proton flux up to 100 TeV has been published
    - A spectral softening at ~13.6 TeV is observed
  - Direct high statistics Helium flux up to at least 25 TeV/n is coming soon
- DAMPE has provided several new pieces of puzzle to understand many mysteries in cosmic ray physics
- Direct detection of TeV – PeV cosmic rays is entering a precision era
  - Validation of hadronic interaction models in the TeV – PeV range will be key to reduce systematic errors

Thank You!