



UNIVERSITÉ
DE GENÈVE

FACULTÉ DES SCIENCES
Département de physique
nucléaire et corpusculaire

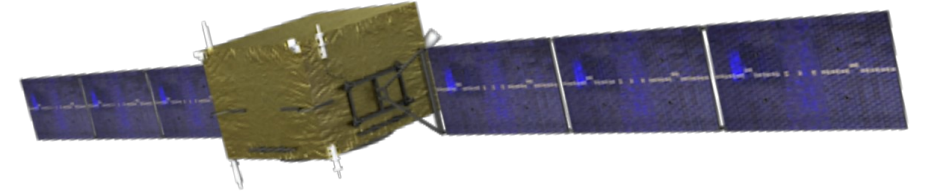
DAMPE: Towards a Decade of Direct Cosmic Ray Measurements in the TeV - PeV Range



Xin Wu, for the DAMPE collaboration
Department of Nuclear and Particle Physics, University of Geneva

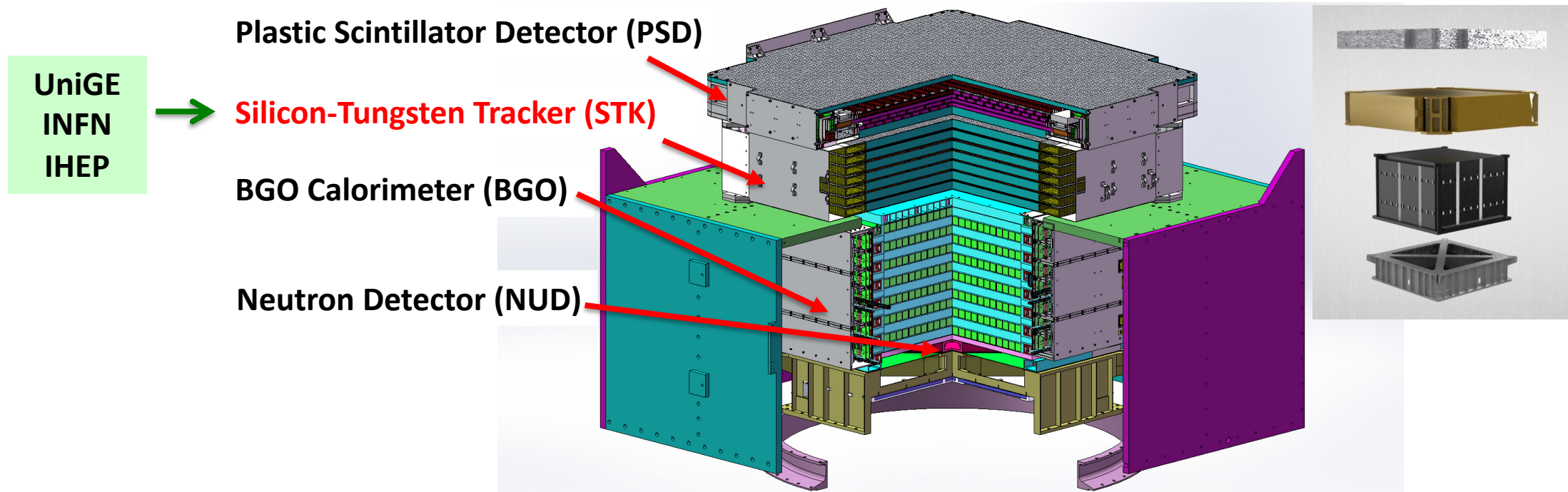
ASAPP 2023, 19-23 June 2023, Perugia

DAMPE: satellite mission launched by the Chinese Academy of Science in Dec. 17, 2015



- International collaboration of Chinese, Swiss, Italian institutes
- CERN Recognized Experiment since March 2014

DAMPE: calorimetric detector for GeV – PeV cosmic ray direct detection

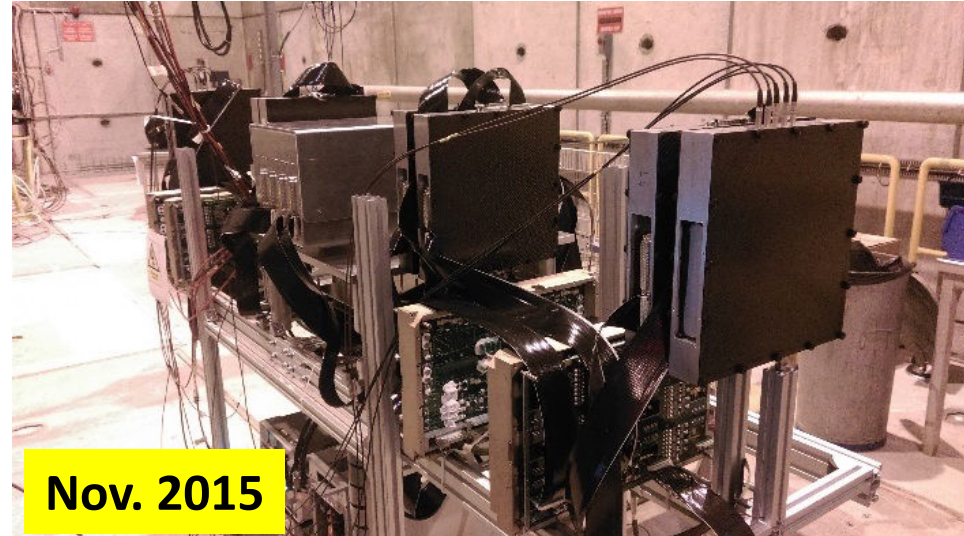
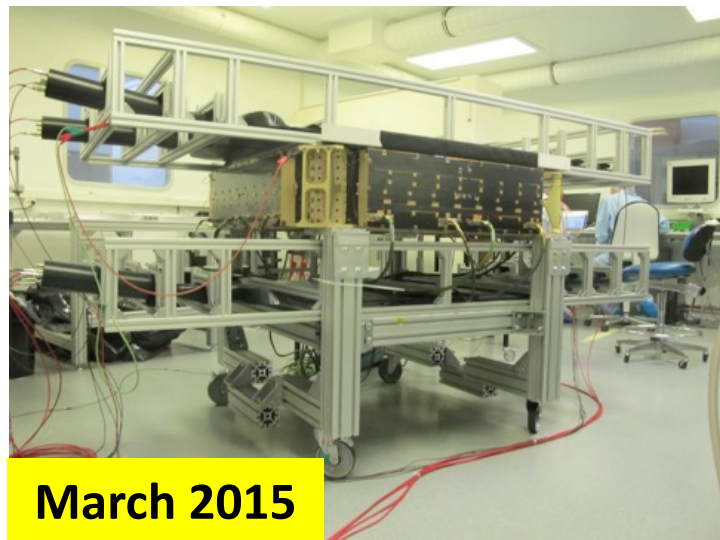
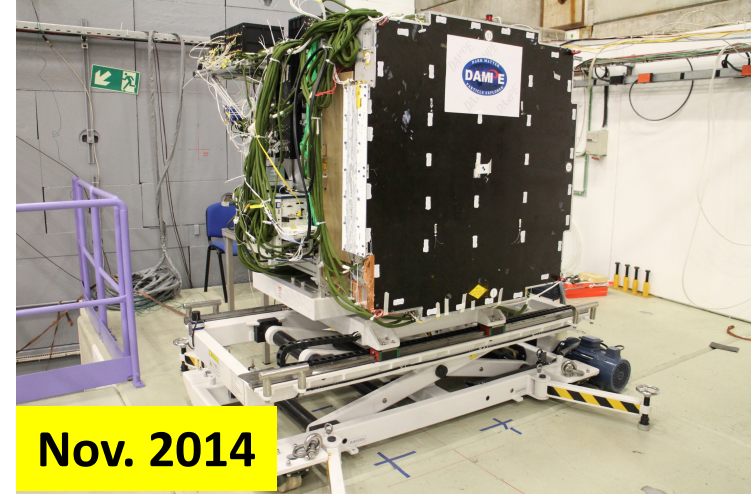


- ✓ Thick imaging calorimeter (BGO of $32 X_0$)
- ✓ Precise tracking with Si strip detectors (STK)
- ✓ Tungsten photon converters in tracker (STK)
- ✓ Charge (Z) measurements (PSD and STK)
- ✓ Extra hadron rejection (NUD)

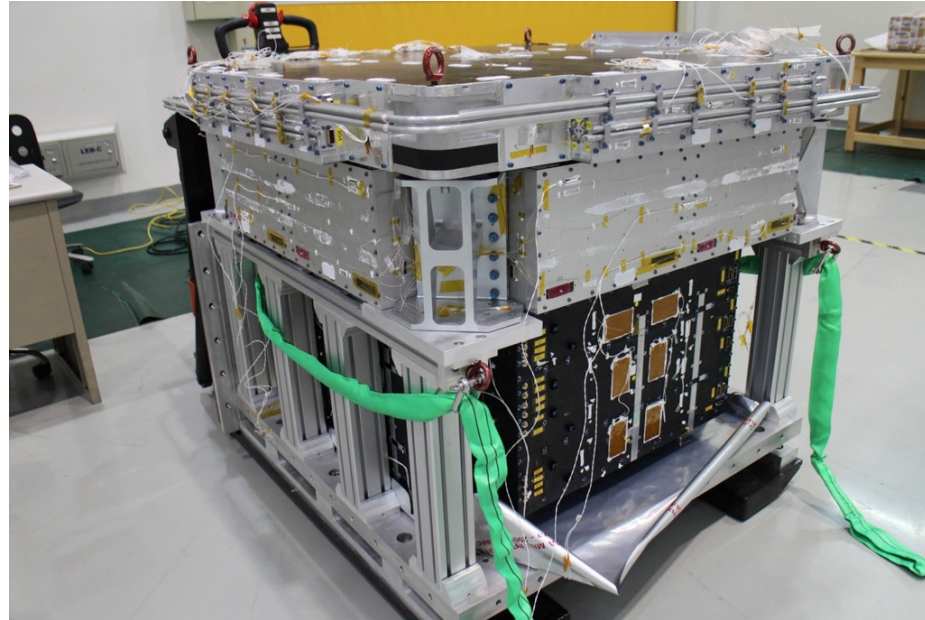
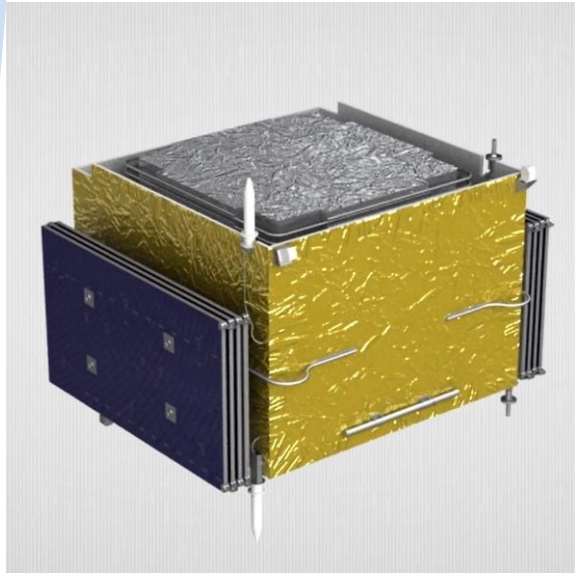
Detection of GeV – 10 TeV e/γ and GeV - PeV nuclei with excellent particle identification, energy resolution and direction reconstruction

DAMPE detector has been fully calibrated at CERN before launch

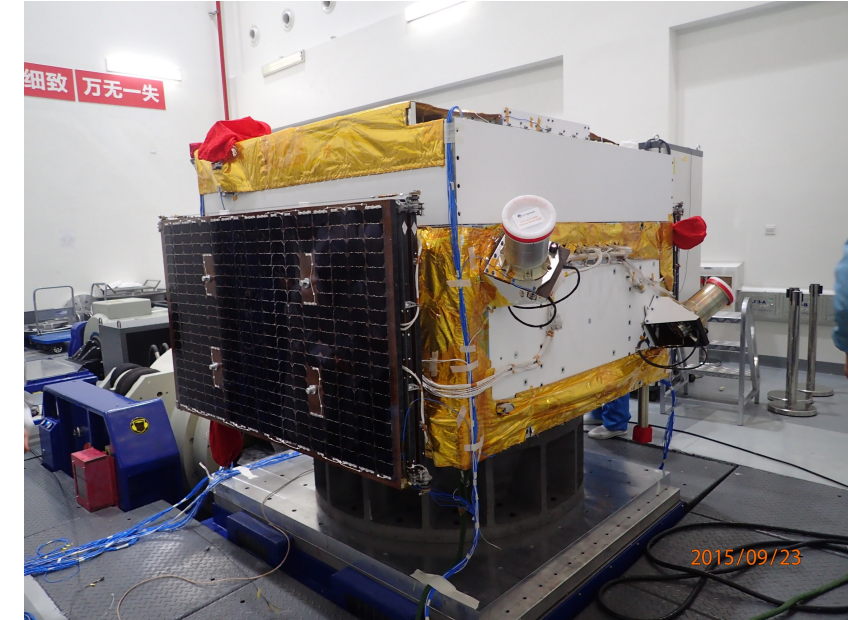
- Several weeks at CERN PS and SPS beams from Oct. 2012 – Nov. 2015 (EQM)
 - **Critical contribution to the (continuing) important science output of the mission!**



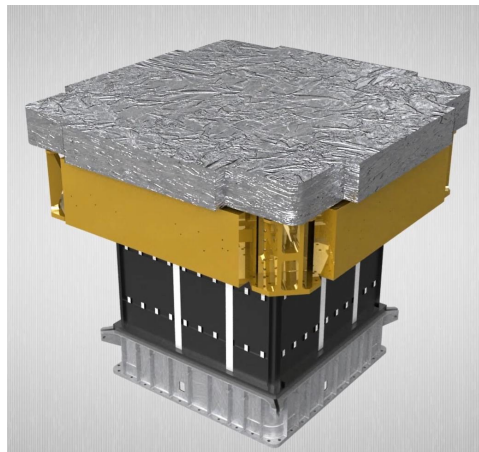
The DAMPE payload and satellite



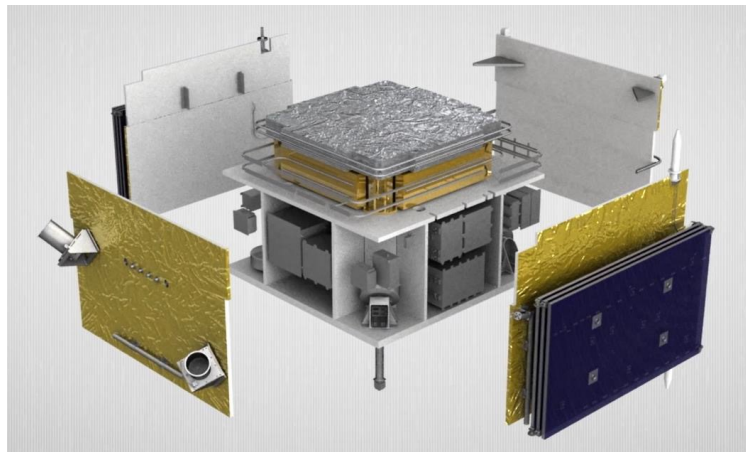
EQM, Oct. 2014, CERN



Integrated satellite, Sept. 2015, Shanghai



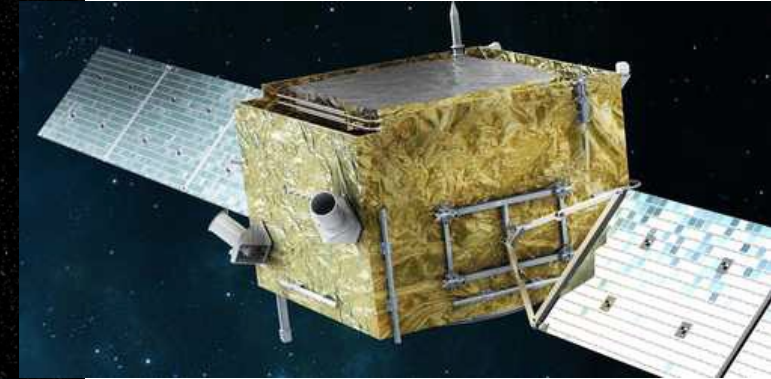
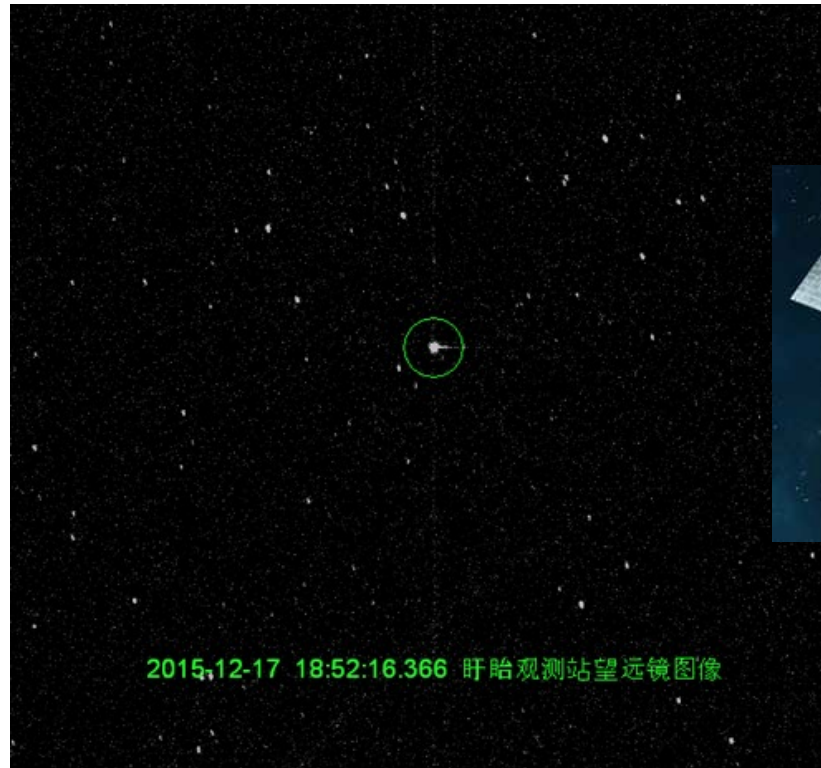
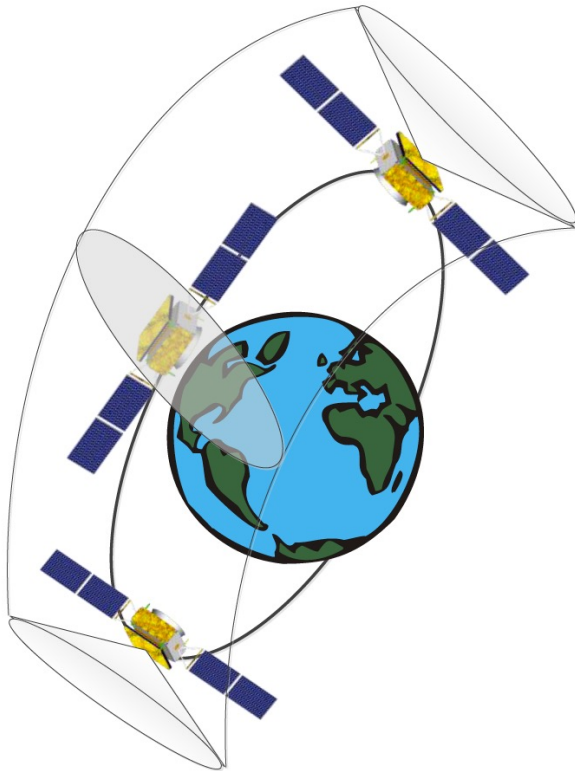
Xin Wu



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

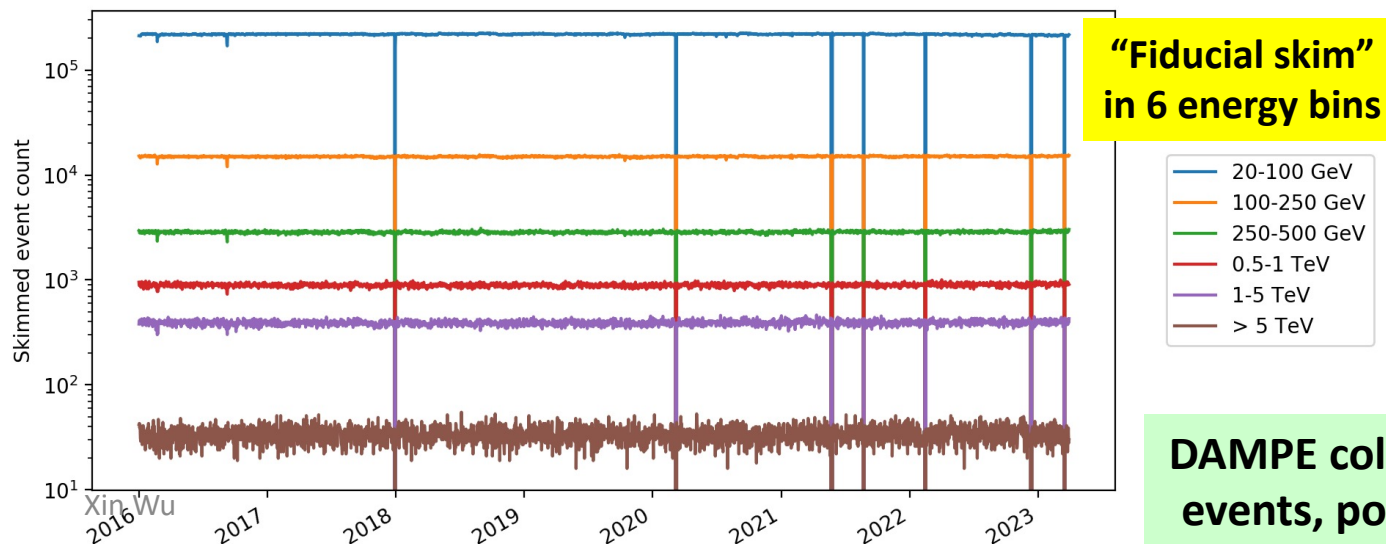
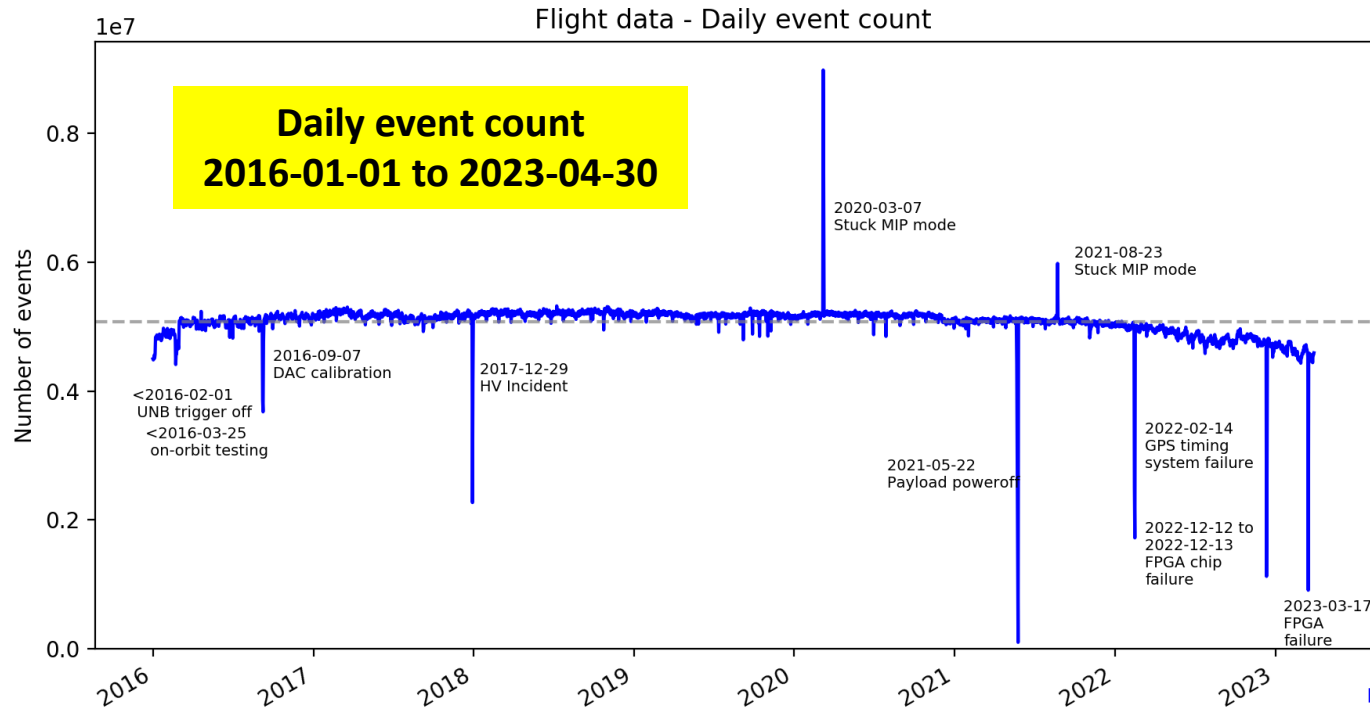
Dec. 17 2015: launched!

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

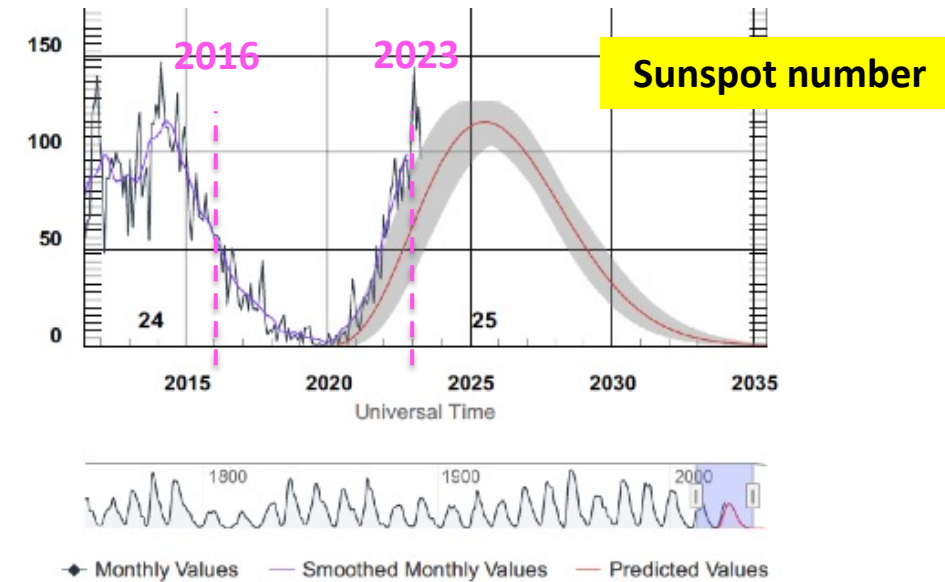


- Dec. 20, 2015: all detectors powered on, except the HV for PMTs
- Dec. 24, 2015 : HV on!
- Dec. 30, 2015: stable trigger condition
- **Stable and continuous data-taking since!**

DAMPE in excellent condition since launch, for more than 7 years!



<https://www.swpc.noaa.gov/products/solar-cycle-progression>

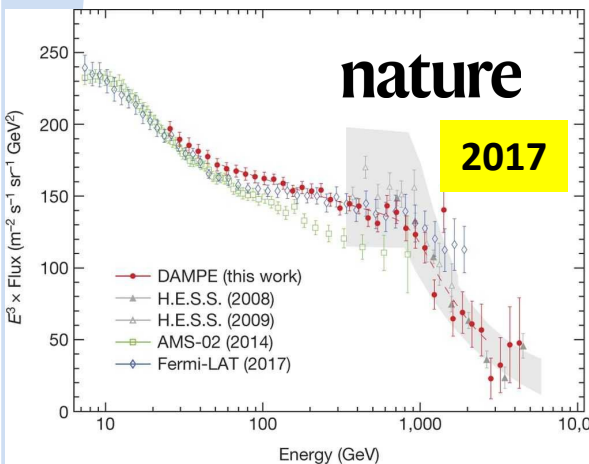


Smooth data-taking besides a few isolated incidents

- Daily: ~5M events, ~30 GB raw data
- Live time ~76%
- >13 billions events collected so far
- Trigger rate dropping since 2021: solar activities affecting only low energy (calibration) triggers
 - >20 GeV event rates are stable

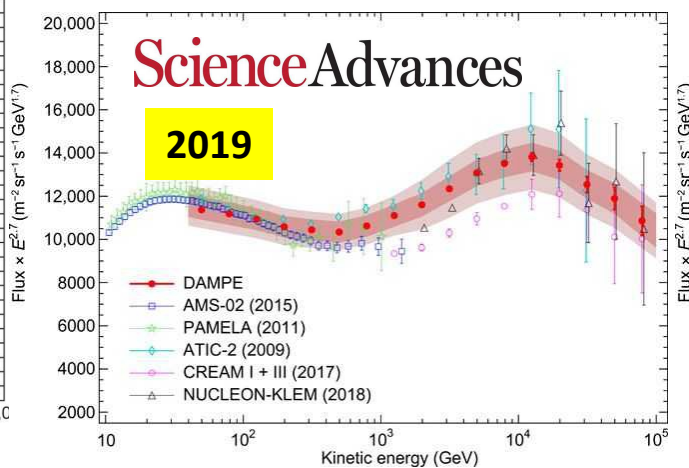
DAMPE collects daily ~400 >1 TeV and ~30 >5 TeV well contained events, possibly the largest sample of >TeV CR direct detection!

Major DAMPE publications: 2017-2022



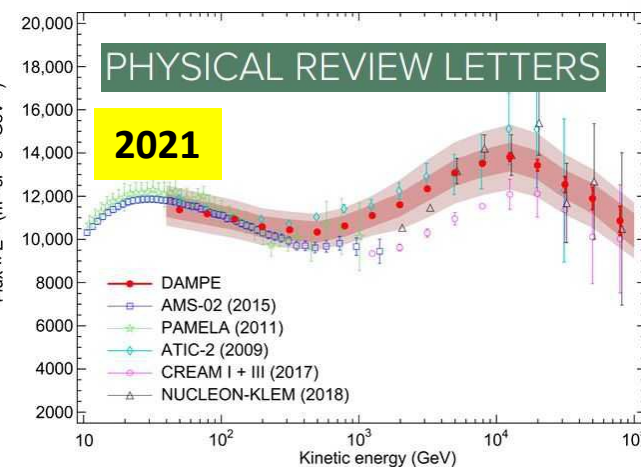
e^+e^- : 25 GeV – 4.6 TeV

1.4 years of data



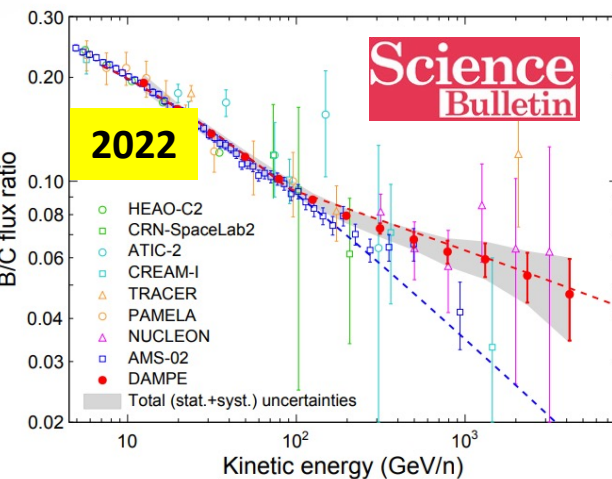
Proton : 40 GeV – 100 TeV

2.5 years of data



Helium: 70 GeV – 80 TeV

4.5 years of data



B/C: 10 GeV/n to 5.6 TeV/n

6 years of data

Spectral break at 1 TeV @ 6.6σ

Softening at 14 TeV @ 4.7σ

Softening at 34 TeV @ 4.3σ

Hardening at 100 GeV/n @ 4.3σ

The breaking of simple power laws observed at multiple places in the 100 GeV – 100 TeV range → rich underlying physics

To come: with > 7 years of data, more elaborated calibration and advanced analysis techniques:

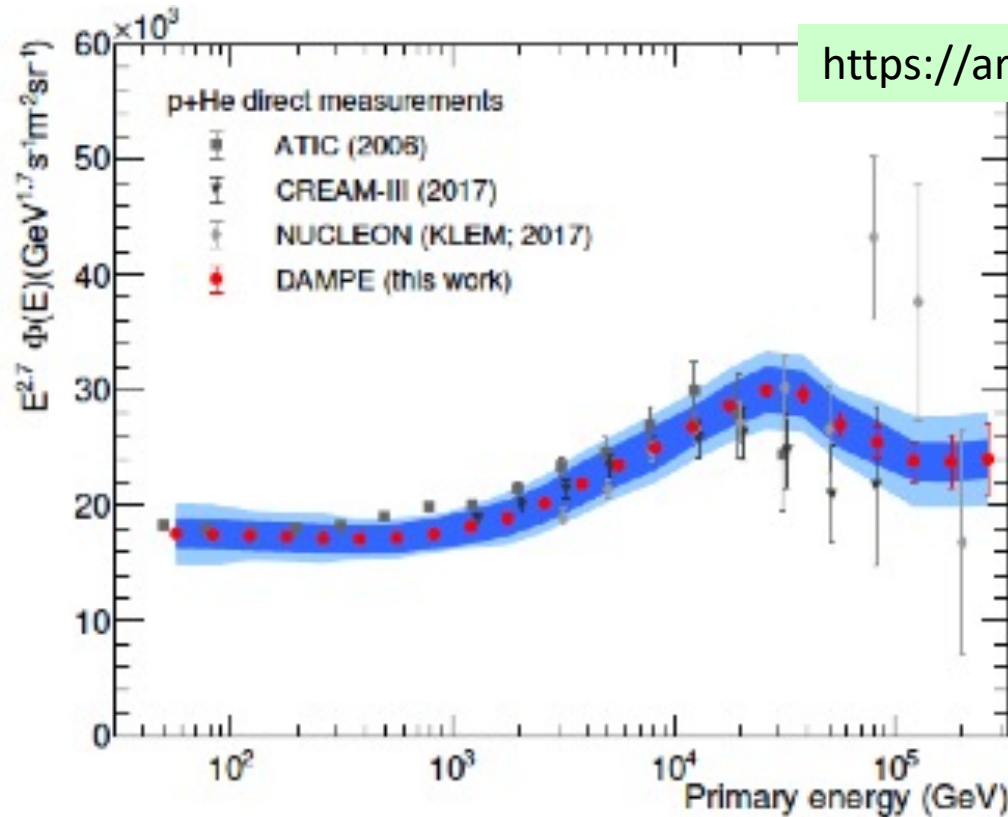
e^+e^- : beyond 10 TeV and look for nearby sources/DM

proton up to 1 PeV, He up to 250 TeV/n with reduced systematics

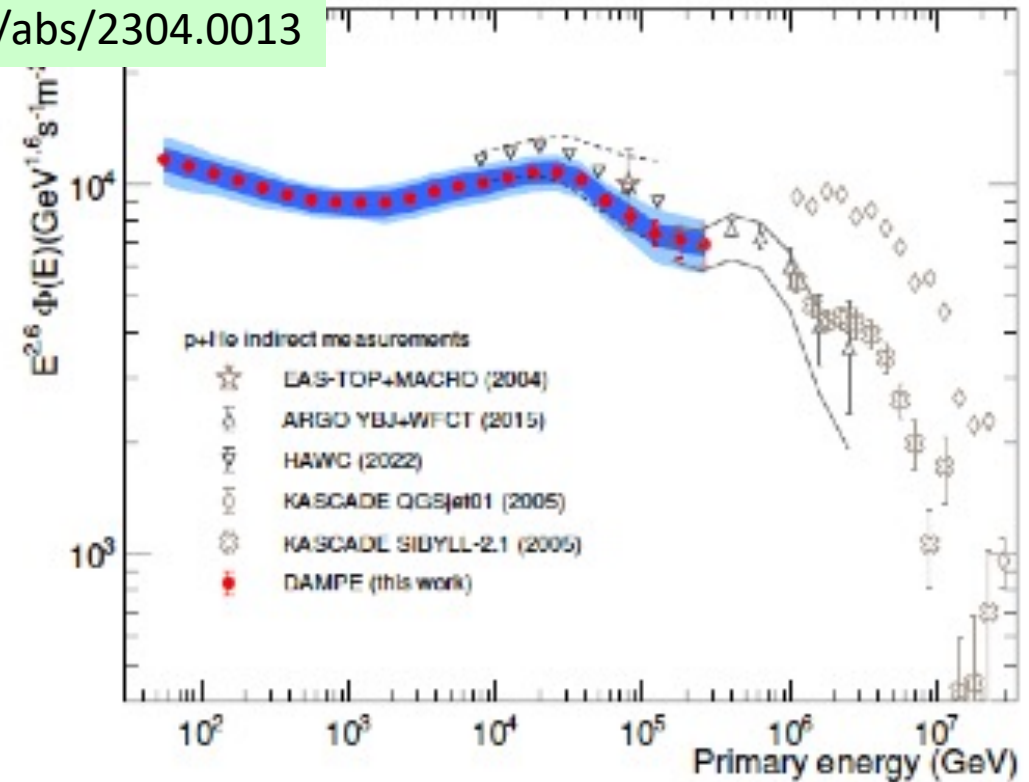
Secondaries: Li, Be, B, ... reaching 10 TeV/n

Primaries: C, O, Si, ... reaching ~10 TeV/n

Very recently submitted to PRL: p+He flux up to 316 TeV with 6 years of data



Comparison with other direct measurements



Comparison with indirect measurements

- Linking the space-based direct measurements to the ground-based indirect experiments
 - Hint of a second hardening at ~ 150 TeV
- Individual fluxes up to 1 PeV in progress
 - Focusing on reducing the dominant systematic error (up to 15%) related to the hadronic model

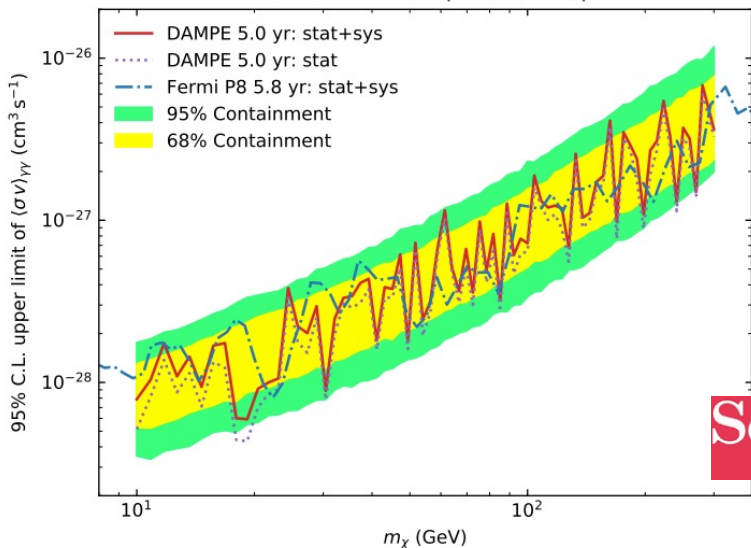
Photon analysis (the idea of an e/γ /CR general-purpose detector works!)

- Thanks to the STK DAMPE is also an excellent high energy gamma-ray imager/spectrometer

DM annihilation and decay: Science Bulletin 67 (2022) 679

>2 GeV γ sources PoS ICRC2021-631

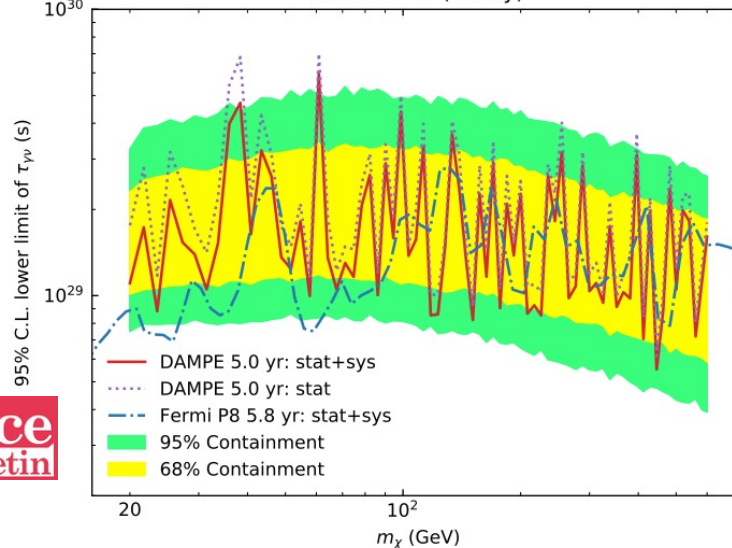
R86: Isothermal (annihilation)



Science Bulletin

95% C.L. upper limits on neutralino annihilation cross section

R150: NFW (decay)

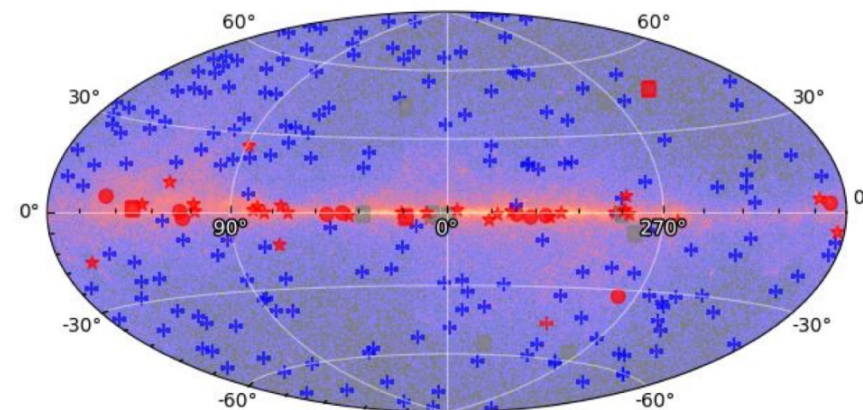
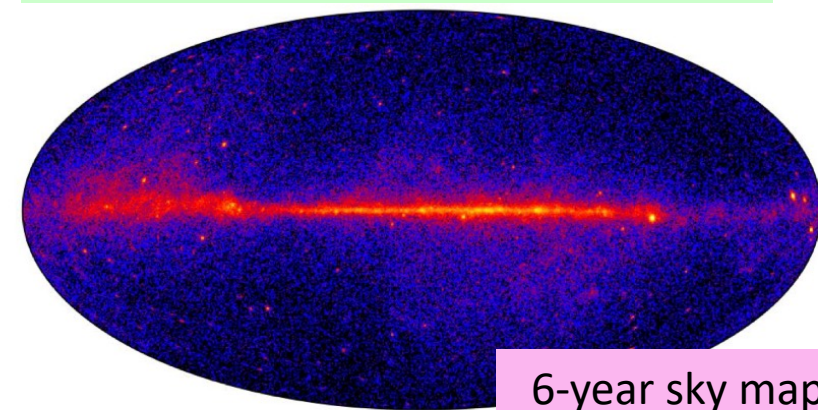


95% C.L. lower limits on graviton decay lifetime

DM limits with 5 years of data similar to Fermi with 5.8 years of data

260 sources of > 2 GeV identified with 6 years data

251 associated with sources in the Fermi-LAT catalog (4FGL)



+ AGN * Pulsar ● SNR/PWN ■ Binary + Global Cluster ■ Unassociated

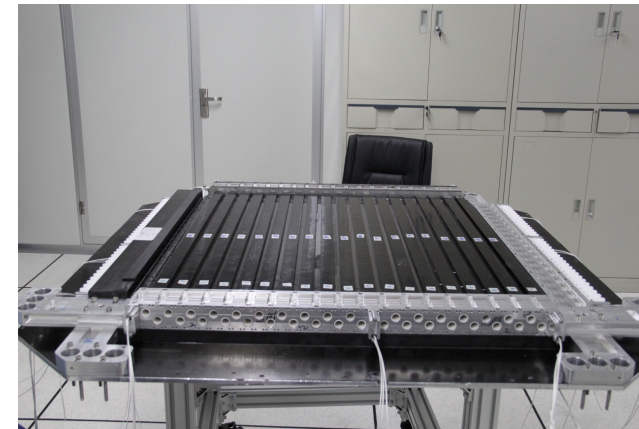
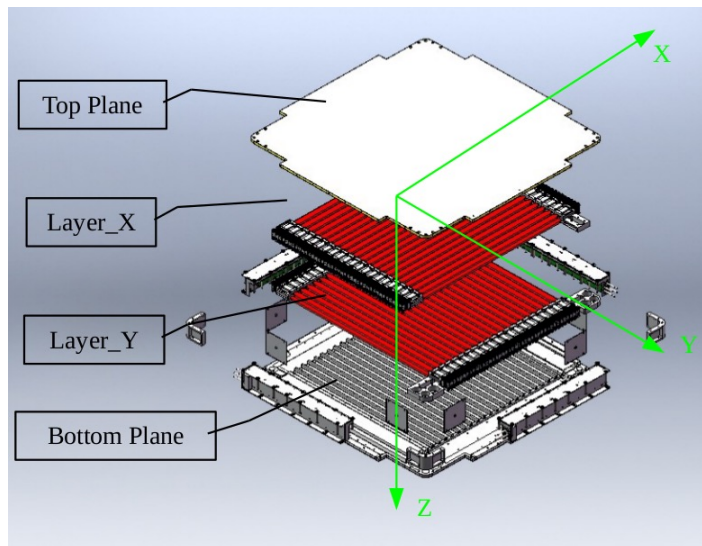
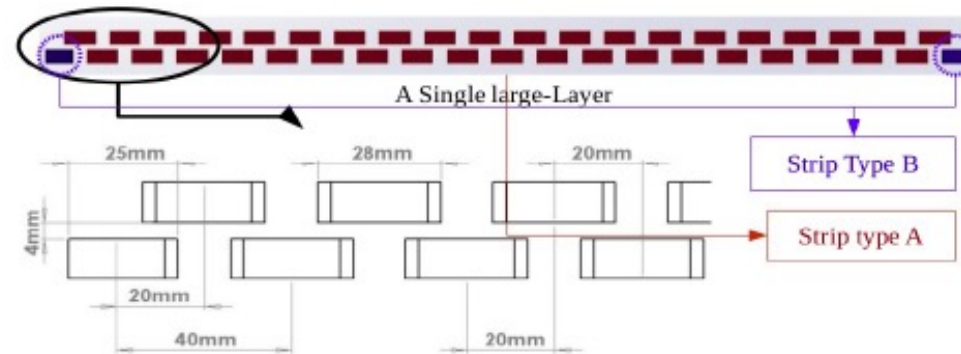
6-year source map

Plastic Scintillator Detector (PSD)



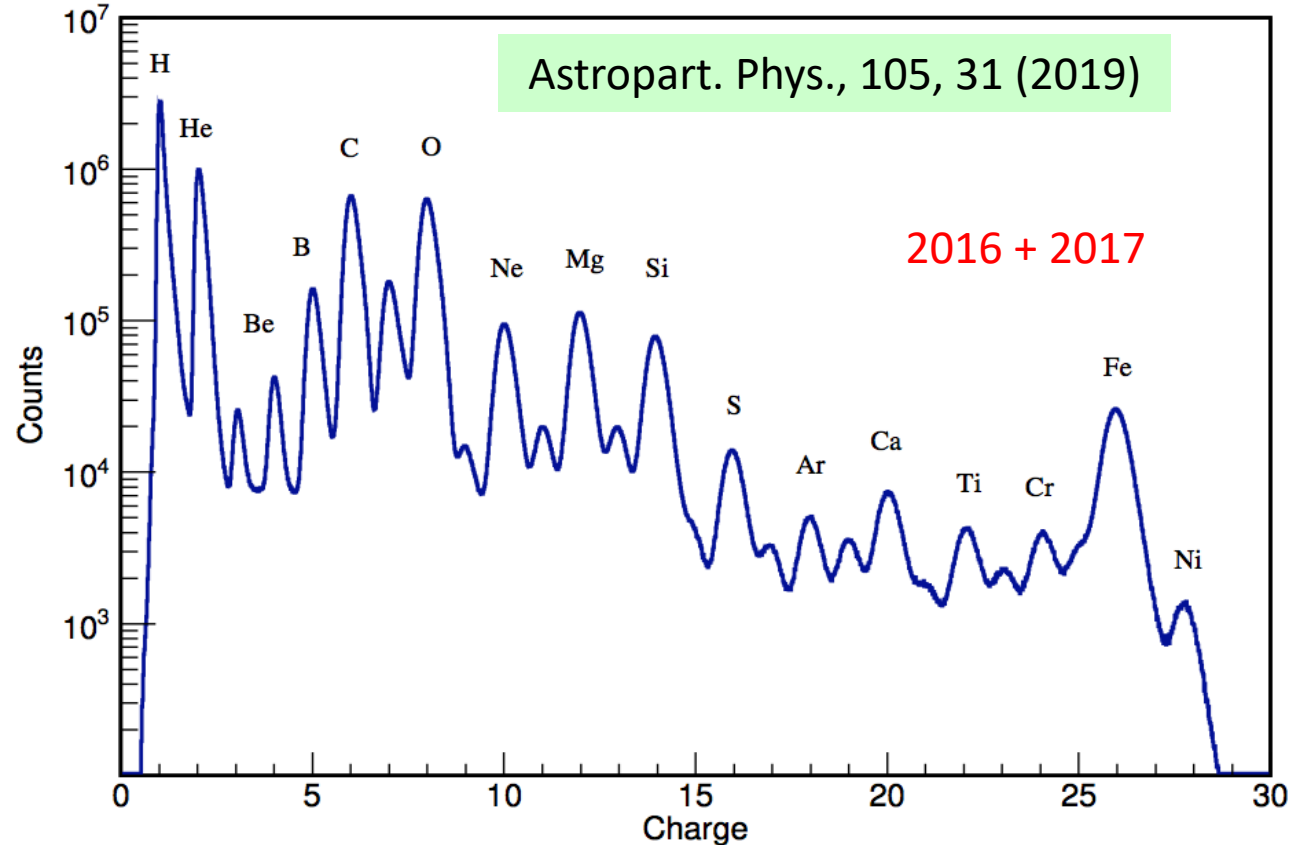
2 layers (x, y) of bars 1 cm thick, 2.8 cm wide and 88.4 cm long
Sensitive area 82.5 cm x 82.5 cm, **no dead zone**

- Strip staggered by 0.8 cm



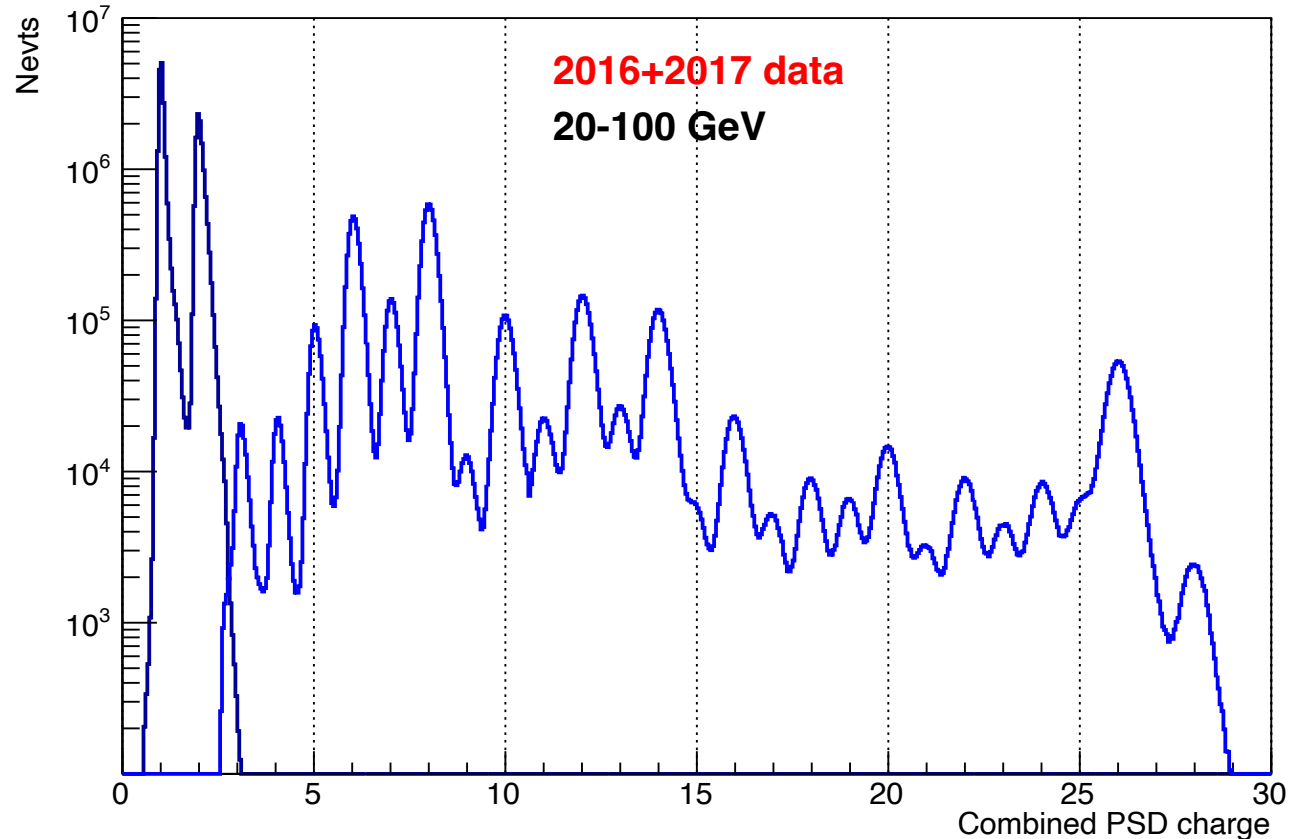
Readout both ends with PMT, each uses 2 dynode signals
(factor ~ 40) to extend the dynamic range to cover $Z = 1, 26$

PSD charge measurement, 2 years of data of 2016-2017, published in 2019

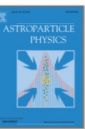


- All the elements in cosmic rays from H to Fe, and Ni can be identified clearly
 - Multiple calibration/correction steps are needed
 - Pedestal calibration, PMT gain calibration, energy (MIP) calibration, alignment of PSD, light attenuation correction, quenching and equalization correction, and track finding
 - A good PSD charge measurement involves both the PSD and the STK
- Xin Wu ■ Need a precise track to find the right PSD bar, in particular at high energy with multiple backplash hits¹²

PSD charge measurement improved with ML tracking, 2 years of data of 2016-2017



- ML tracking improves track precision → improves PSD hit finding and corrections
- Allows to identify particles interacting in the PSD and efficiently remove them
 - Also very useful for hadronic interaction model studies
- ML optimized separately for light (p, He) and heavier ($Z > 2$) ions

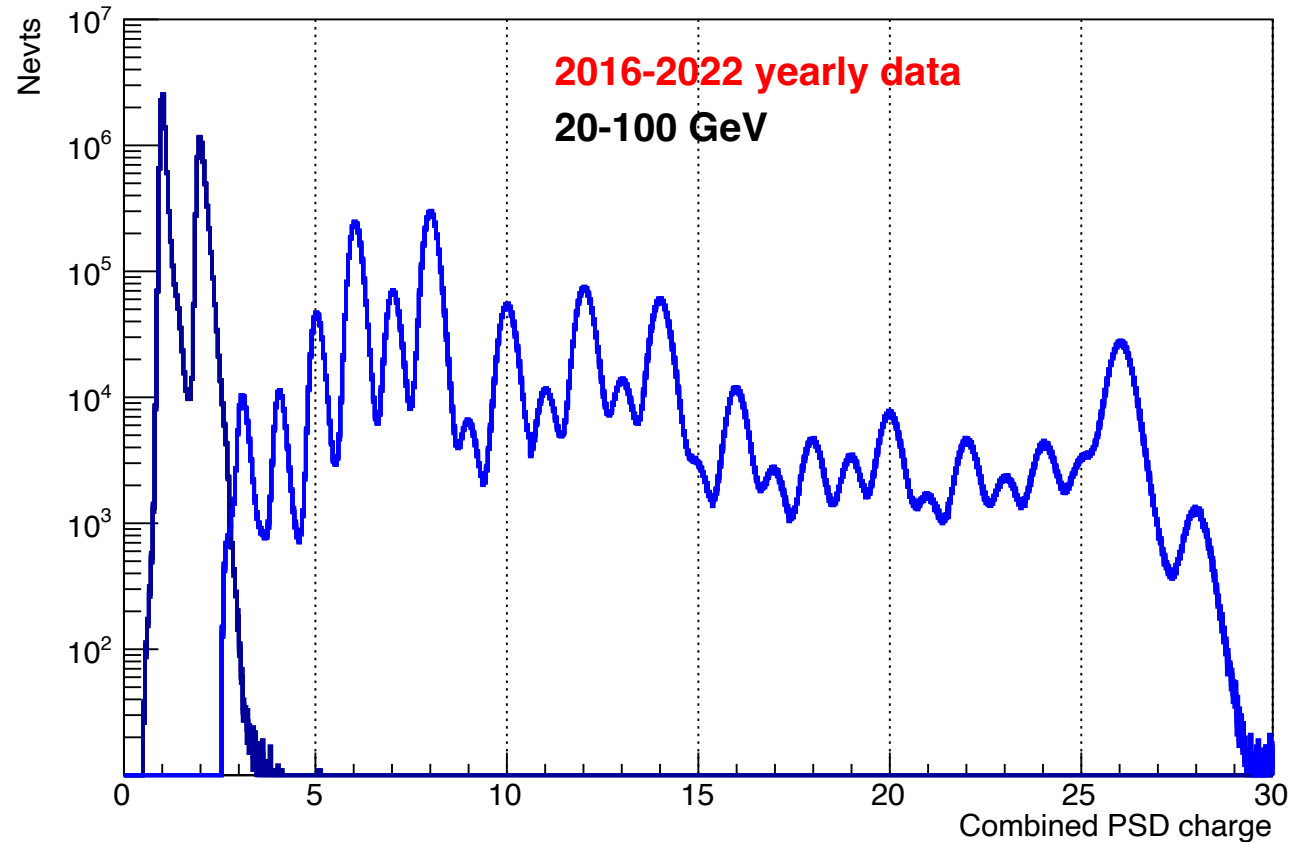


A deep learning method for the trajectory reconstruction of cosmic rays with the DAMPE mission

Andrii Tykhonov ^a ✉, Andrii Kotenko ^a, Paul Coppin ^a, Maksym Deliyergiyev ^a, David Droz ^a, Jennifer Maria Frieden ^b, Chiara Perrina ^b, Enzo Putti-Garcia ^a, Arshia Ruina ^a, Mikhail Stolpovskiy ^a, Xin Wu ^a

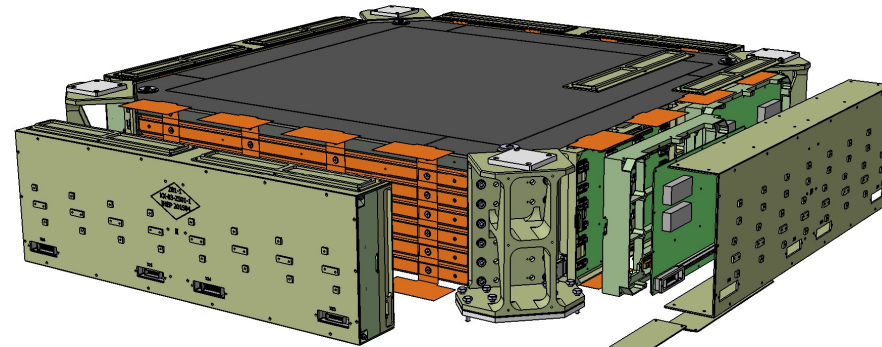
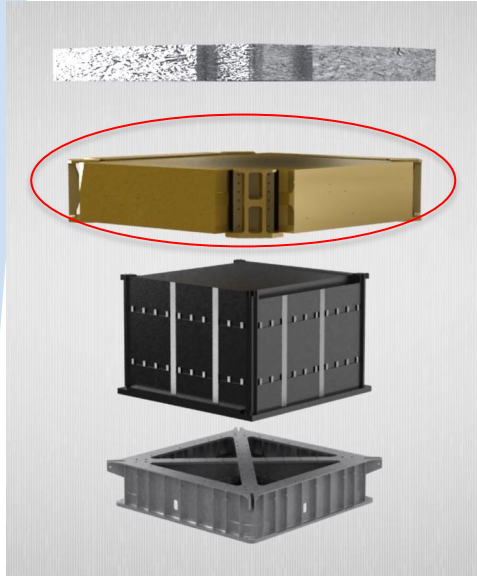
Astropart. Phys., 146, 102795 (2023)

PSD charge measurement stability: 2016 - 2022 yearly data overlayed

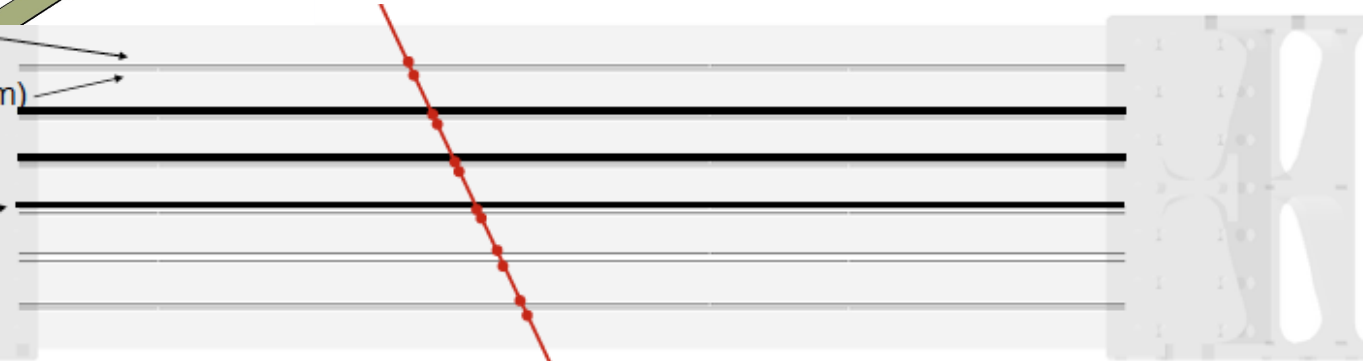


- 7 yearly histograms overlayed, not adjusted for live time!
 - Excellent stability: not only the charge measurements, but also the full chain of mission operation
 - Achieved thanks to the robust PSD calibration and STK alignment procedures running routinely

Silicon Tungsten Tracker Converter (STK)



Si Layers X (top)
Si Layers Y (bottom)
Tungsten converter



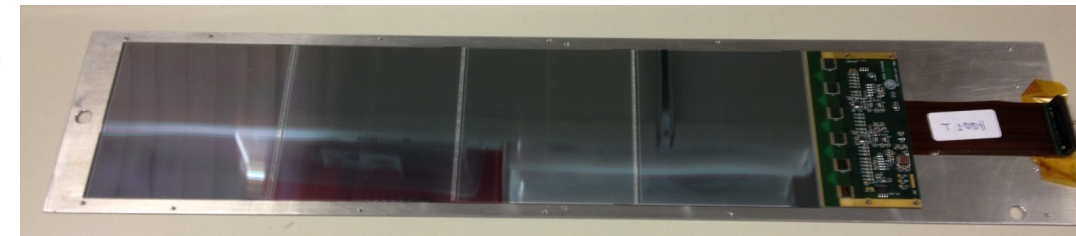
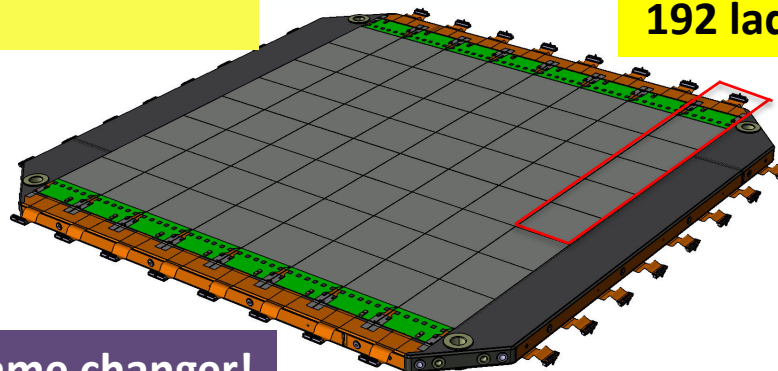
- Outer envelop 1.12m x 1.12m x 25.2cm
- Detection area 76 x 76 cm²
- ~7 m² of silicon**

- Total weight: 154.8 Kg
- Total power ~85W**

192 ladders

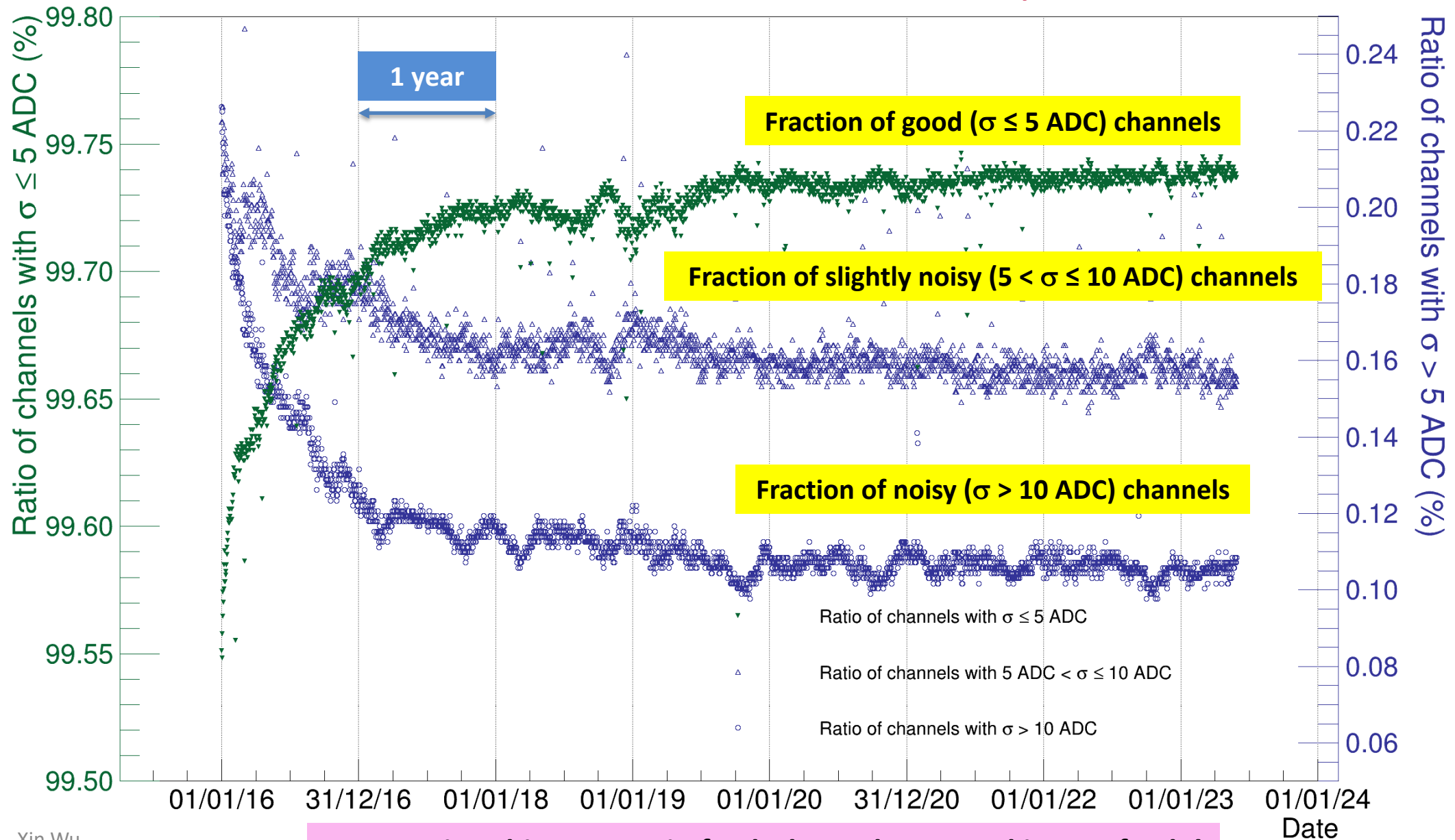
768 silicon sensors
95 x 95 x 0.32 mm³

1,152 ASICs
73,728 channels



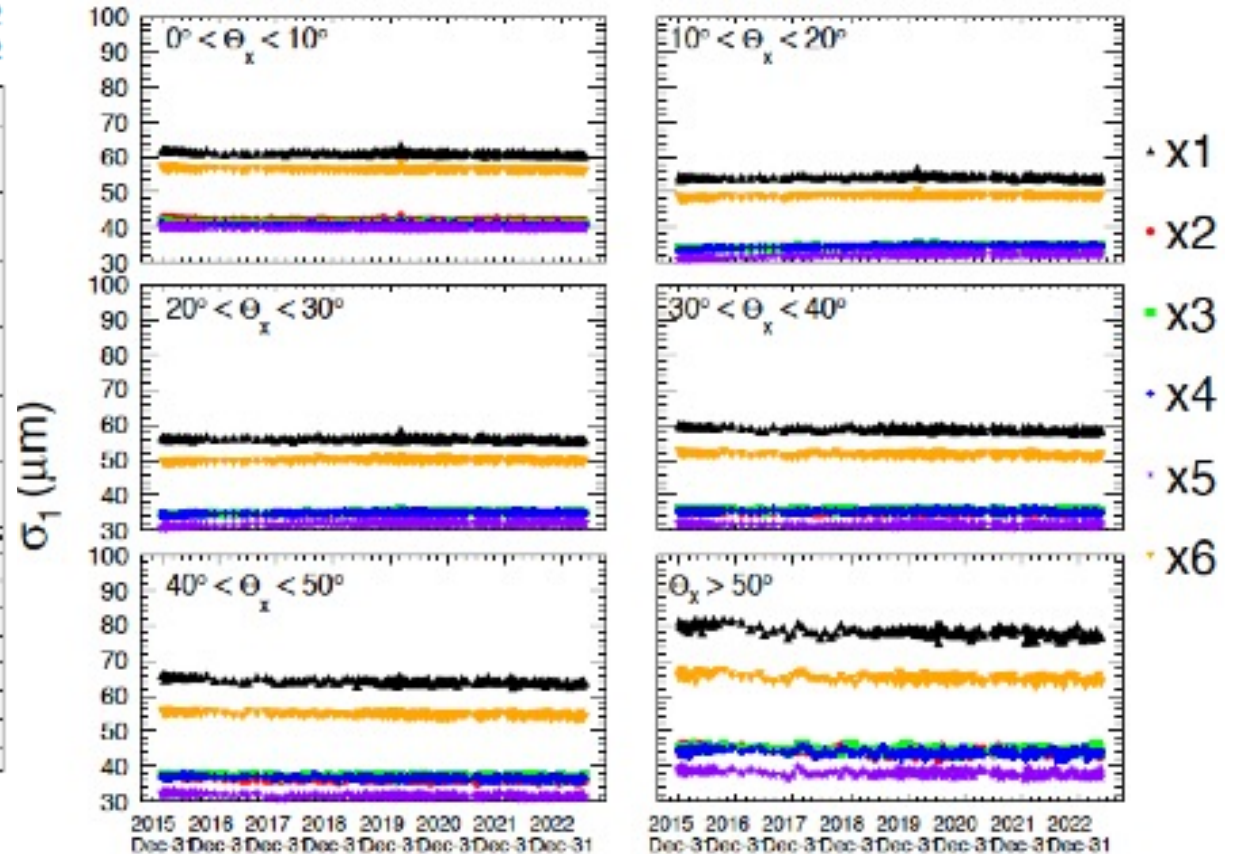
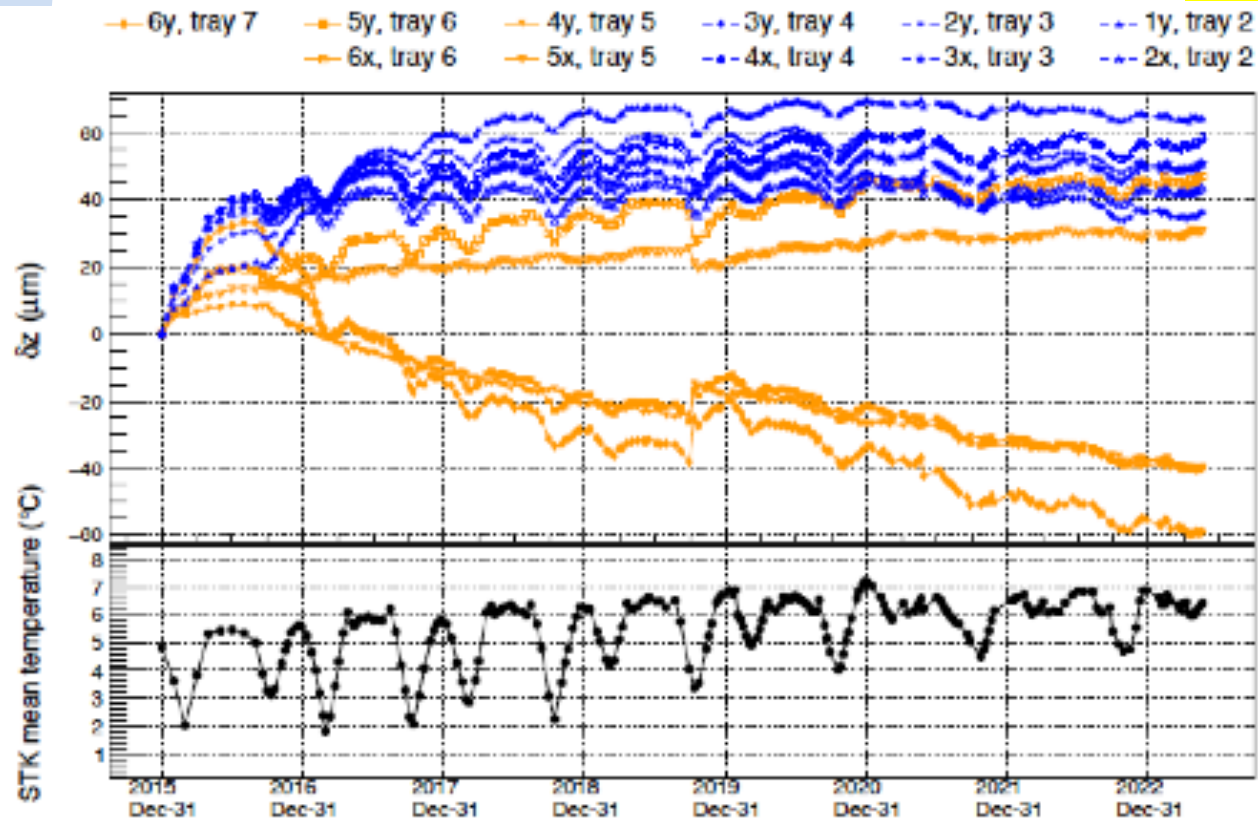
Low power readout ASIC is a game changer!

STK in excellent condition since launch, for more than 7 years!



STK in-flight alignment

up to May 2023



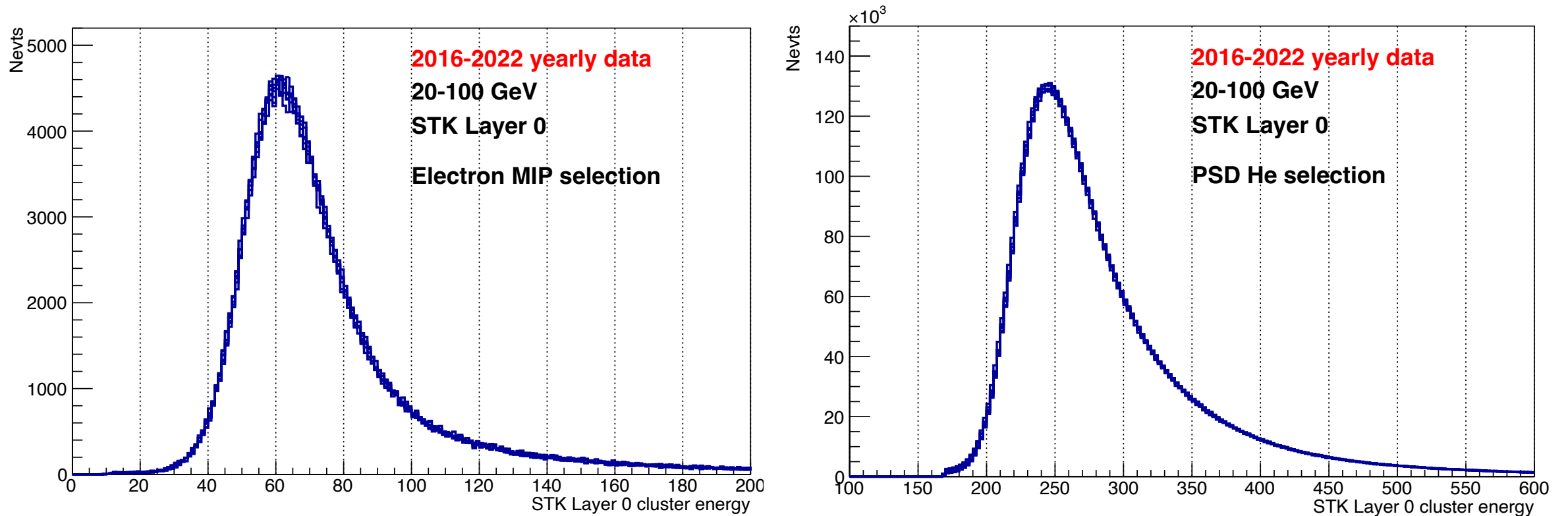
In 7 years detector position shifts in z are within $100\ \mu\text{m}$,
< 1% of the support tray thickness

Re-align every 2 weeks to track long term shift

Intrinsic position resolution 30 -40 μm , better than 70-100 μm required

- STK is the “backbone” of experiment allowing to link precisely all the sub-detectors for alignment, calibration, particle identification, event classification, ...

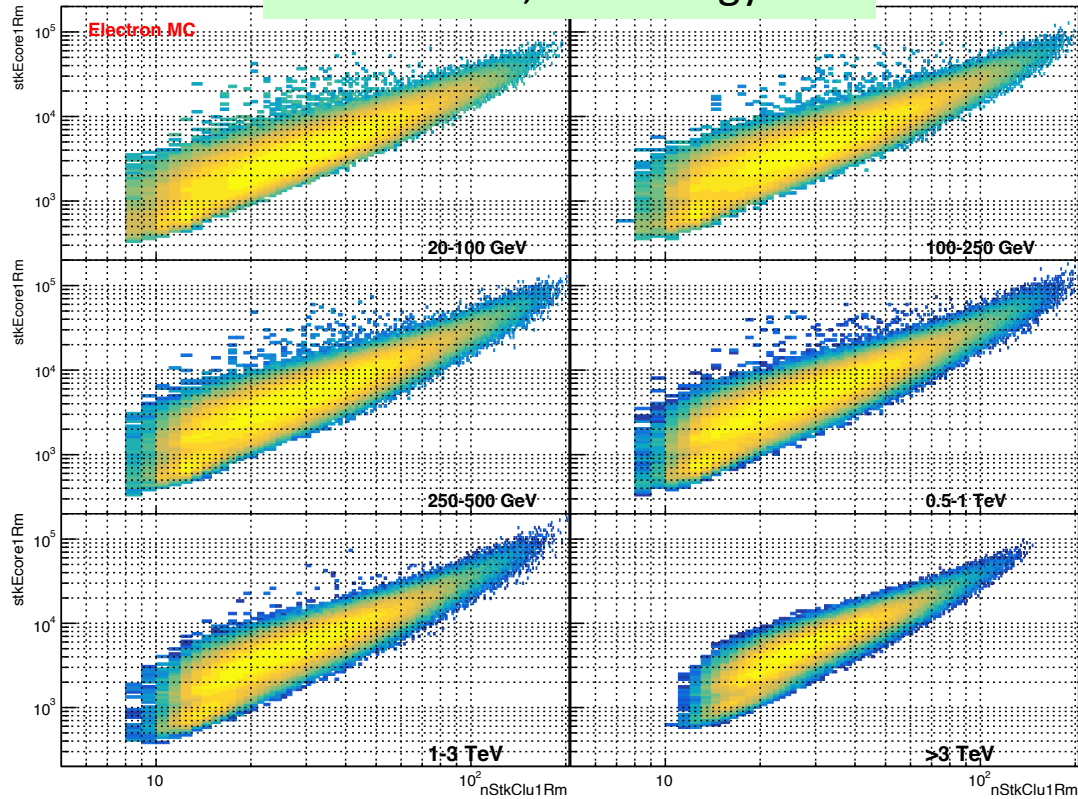
STK p/He MIP measurement stability: 2016 - 2022 yearly data overlayed



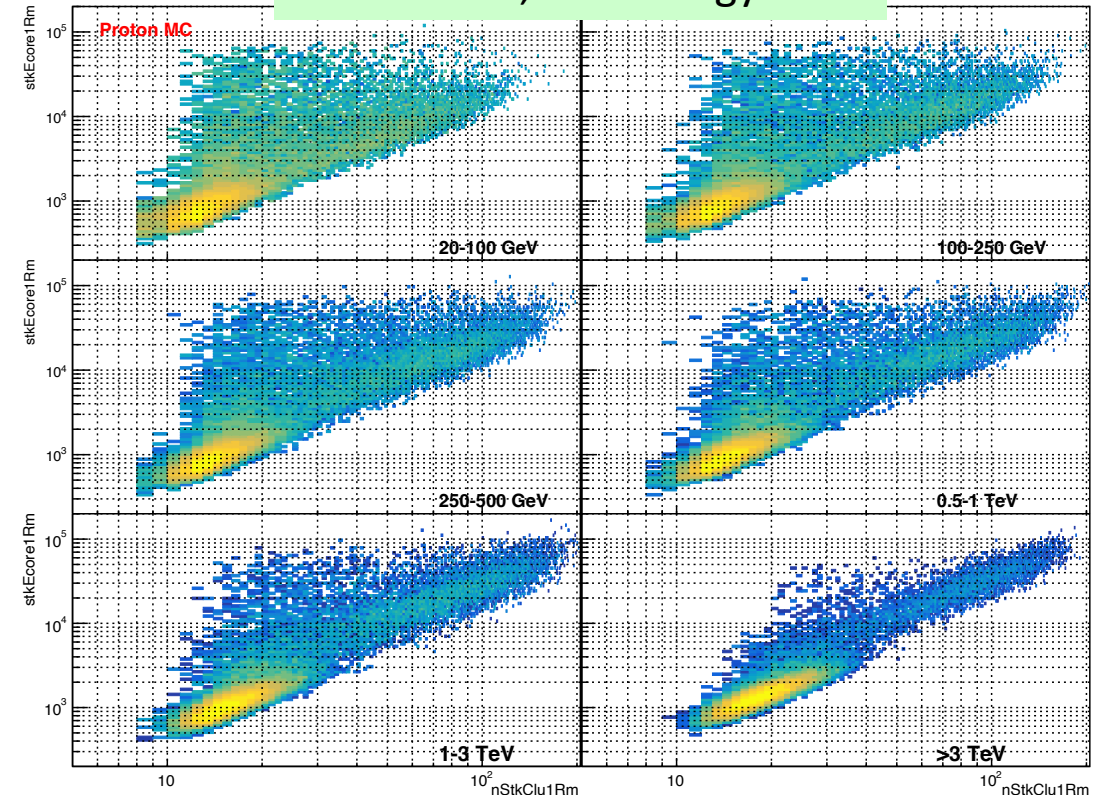
- 7 yearly histograms overlayed, not adjusted for live time!
 - Excellent stability: not only the charge measurements, but also the full chain of mission operation
 - Achieved also thanks to the robust STK calibration and alignment procedures running routinely
- Higher charge calibration in progress
 - More challenging due to readout ASIC nonlinearity and saturation

STK is also a pre-shower detector → contribution to electron identification

Electron MC, in 6 energy bins

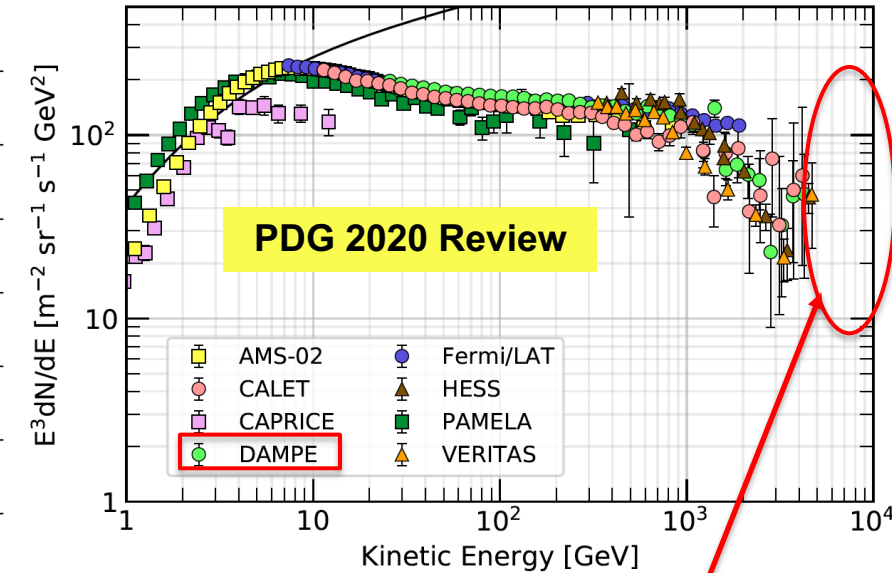
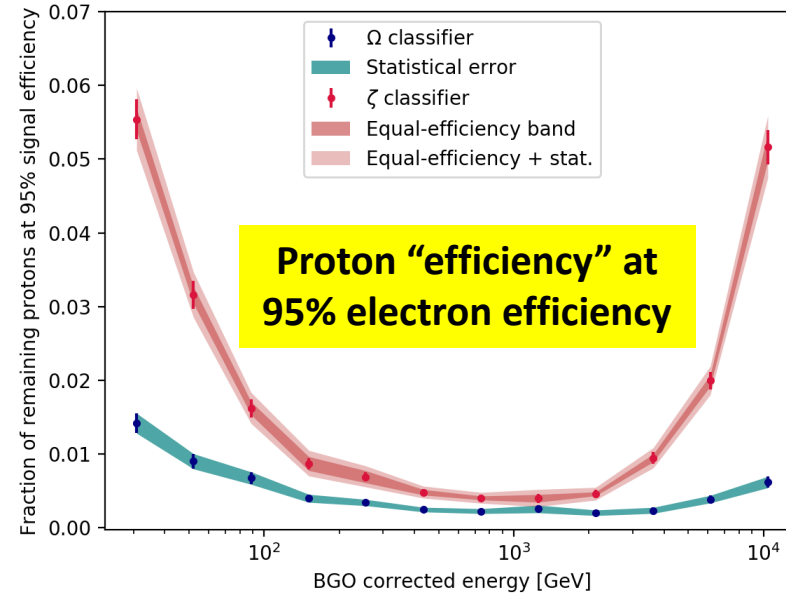
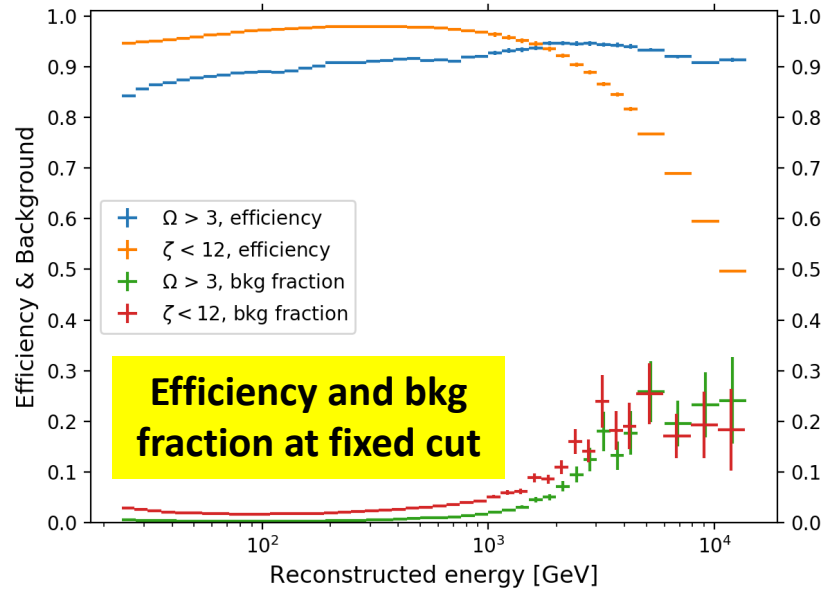


Proton MC, in 6 energy bins



- Number of clusters and cluster energies within 1 Molière Radius of the particle direction have discrimination power between electrons and protons
 - Used in a DNN classifier in addition to calorimeter shower shape variables
 - DNN classifier (Ω) performs much better than the previous analytical classifier (ζ) based only on shower shape variables

Towards a CRE flux beyond 10 TeV



D. Droz et al 2021 JINST 16 P07036, PoS(EPS-HEP2021)045

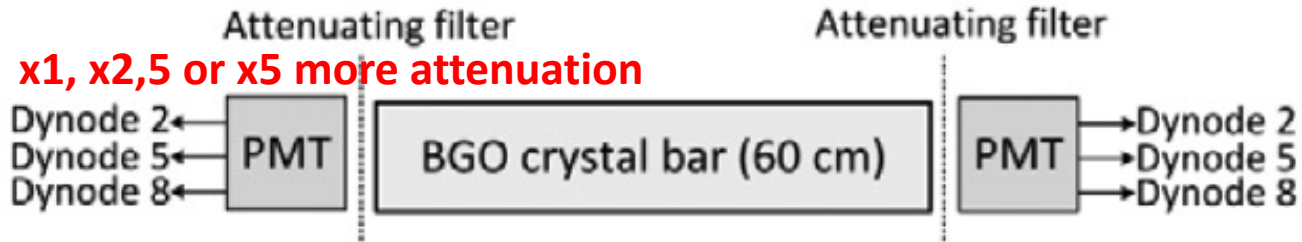
Stay tuned

- With the continuously increasing data sample and better performing classifier, as well as a possible increase of acceptance ($\sim 60\%$) by adding larger angle events ("top fiducial") with ML tracking, we are extending the electron flux measurement towards ~ 20 TeV

>9 million full fiducial electrons >20 GeV has already been collected

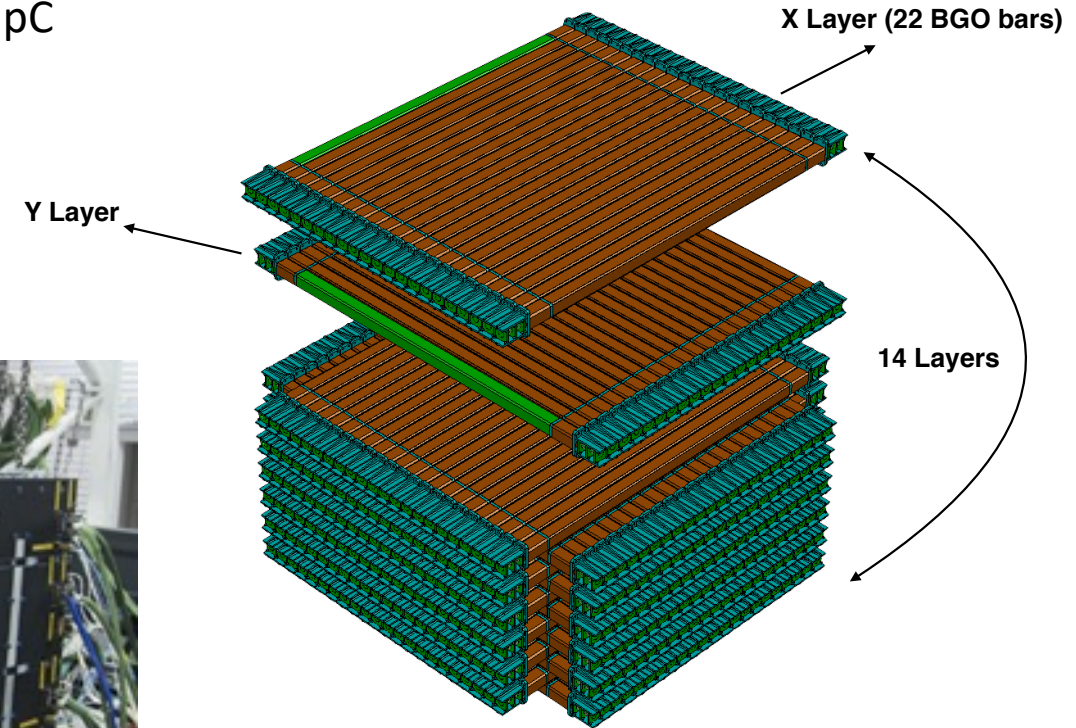
BGO Calorimeter

- 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
 - Optical filters: x1 (L0, L13), x2.5 (L1, L12) and x5 (L3-L11) more attenuation on one end (negative end)
 - Charge readout/Trigger: ASIC with dynamic range up to 12 pC

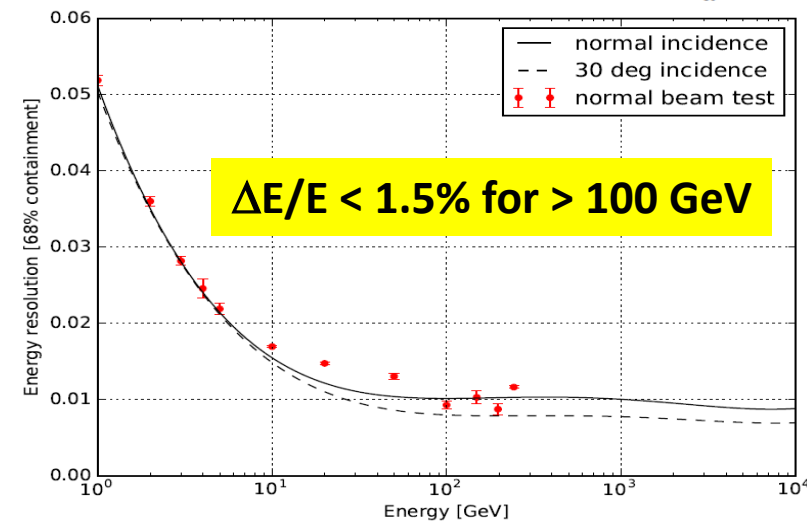
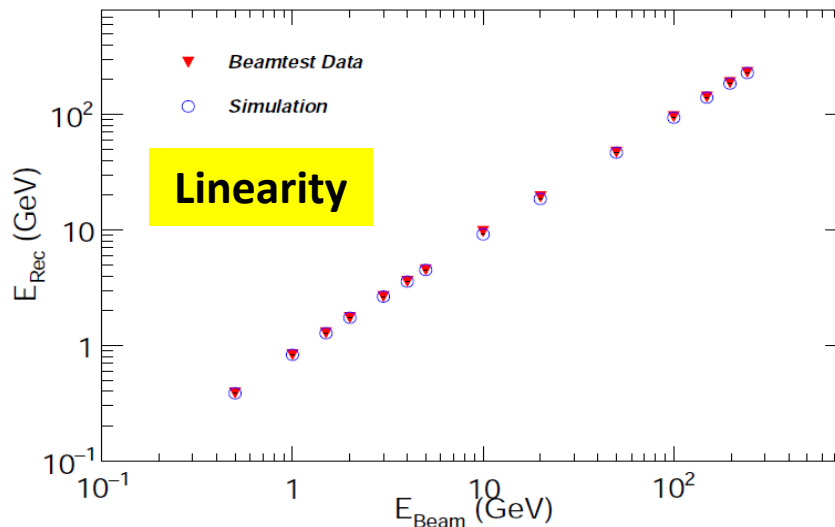
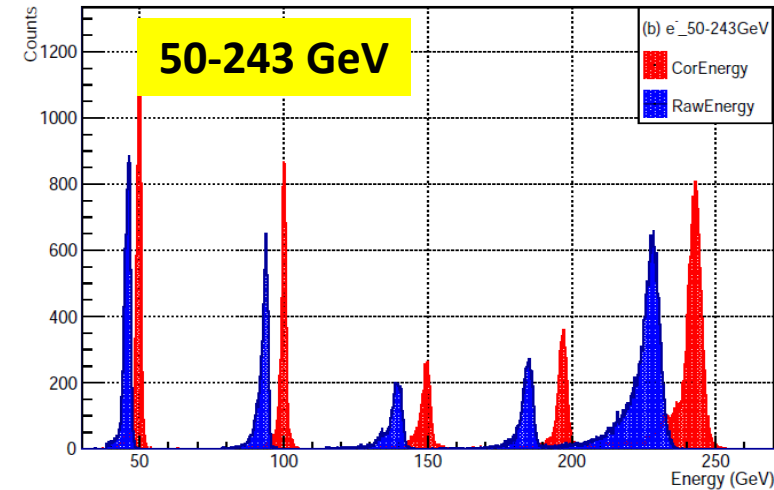
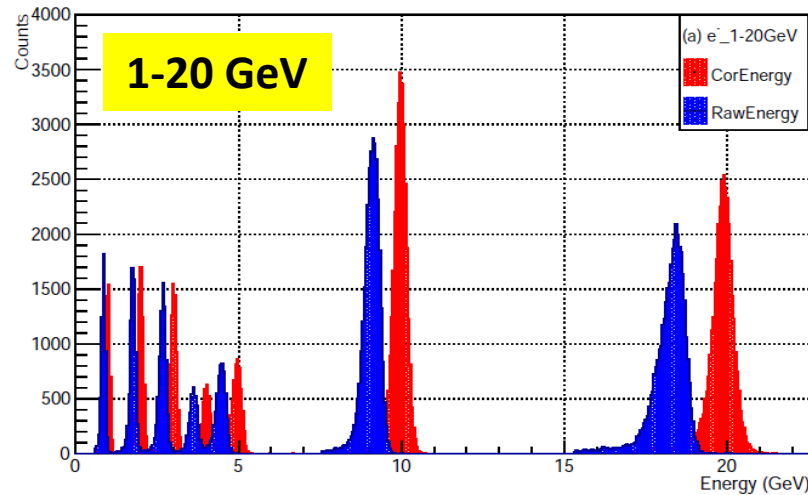


Total thickness $32 X_0 / 1.6 \lambda$

Detection area 60cm × 60cm

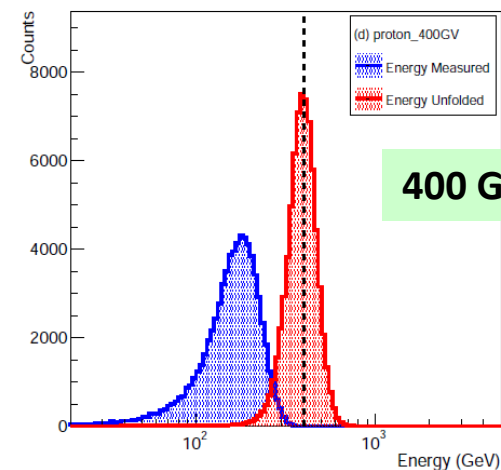
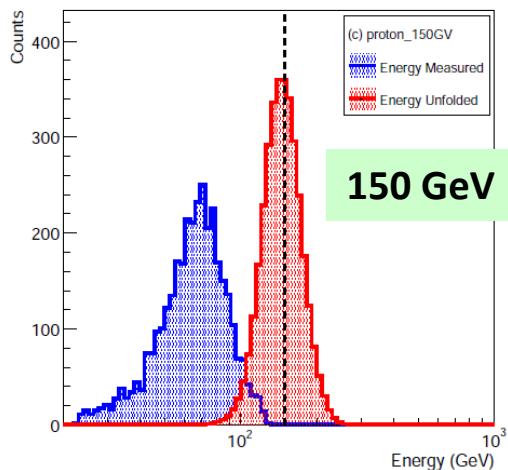
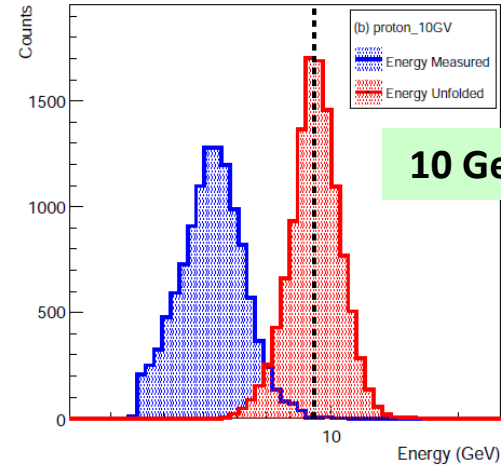
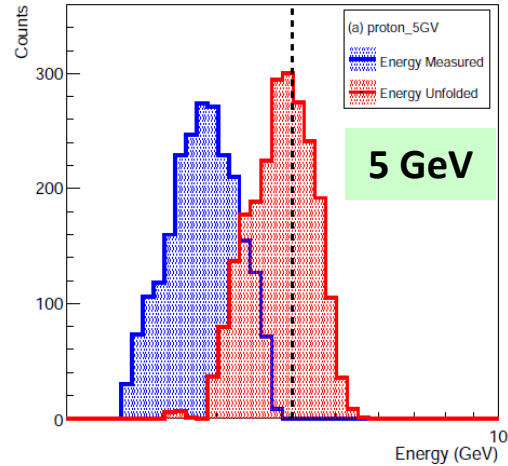


Electron energy linearity and resolution with test beam at CERN

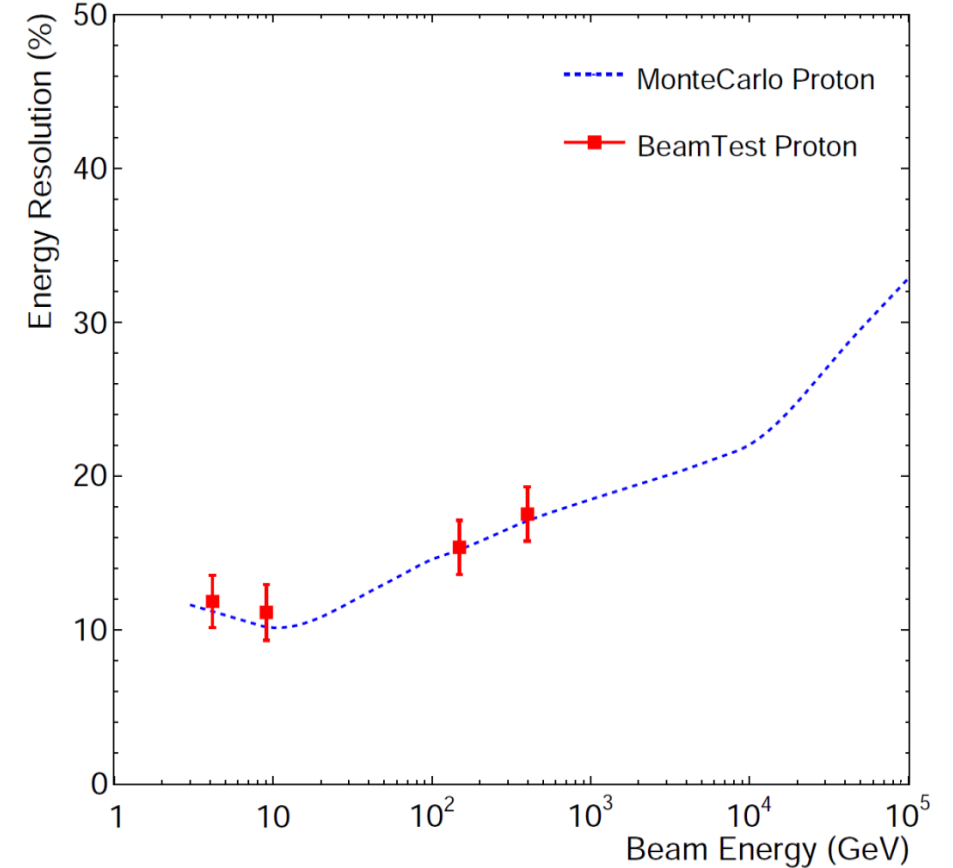


Good linearity and resolution, good agreement between test beam and simulation

Proton energy resolution from test beam at CERN



Before and after unfolding

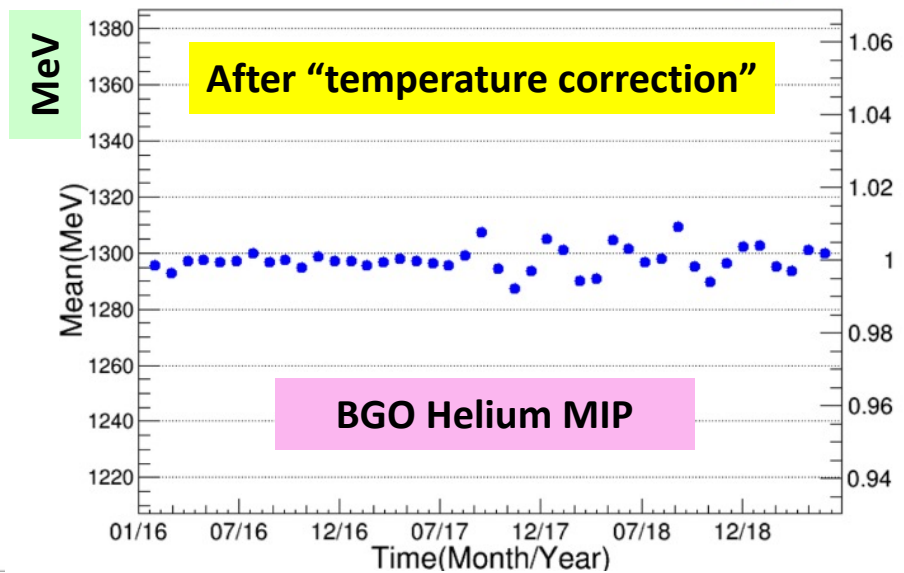
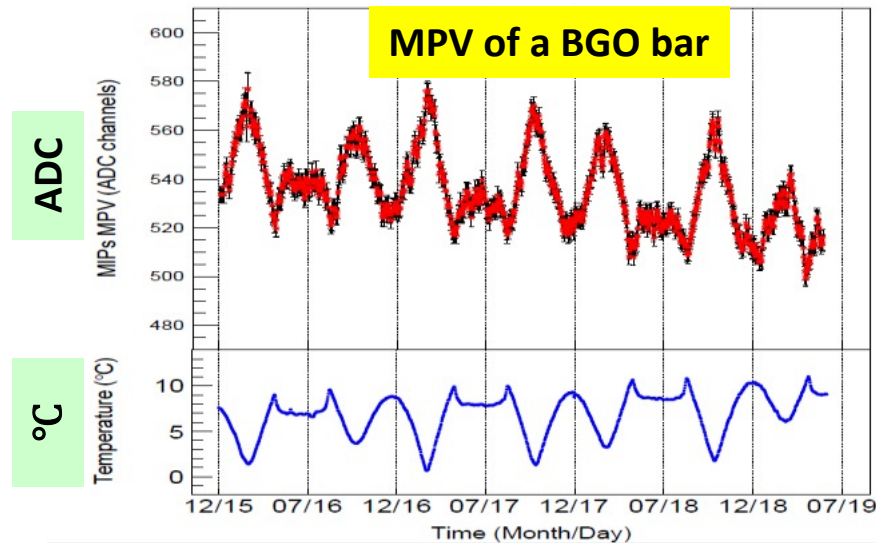
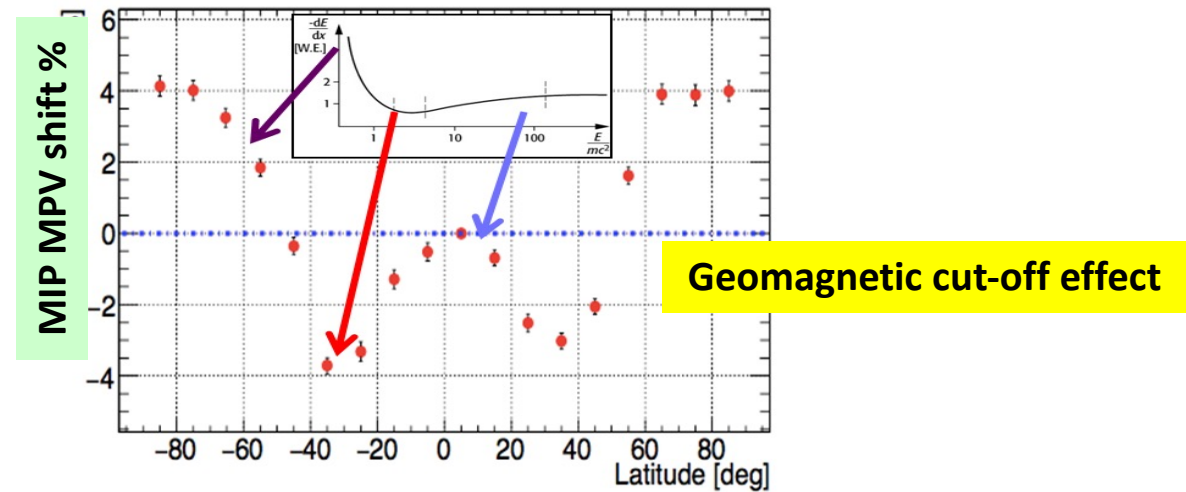
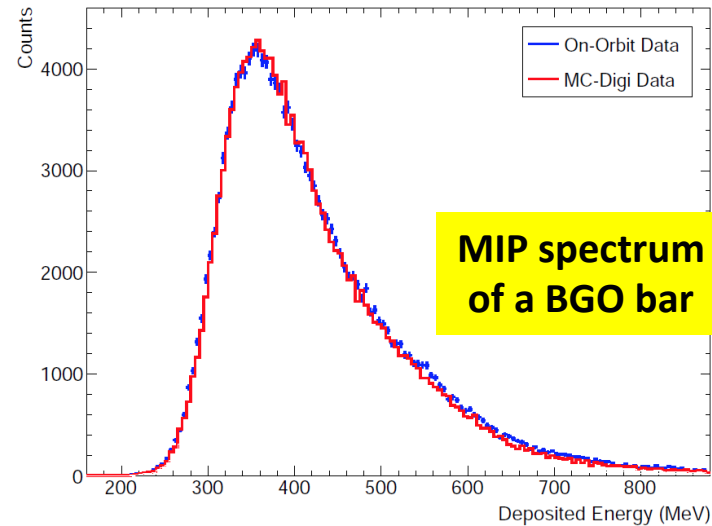


**Resolution: good agreement
between test beam and simulation**

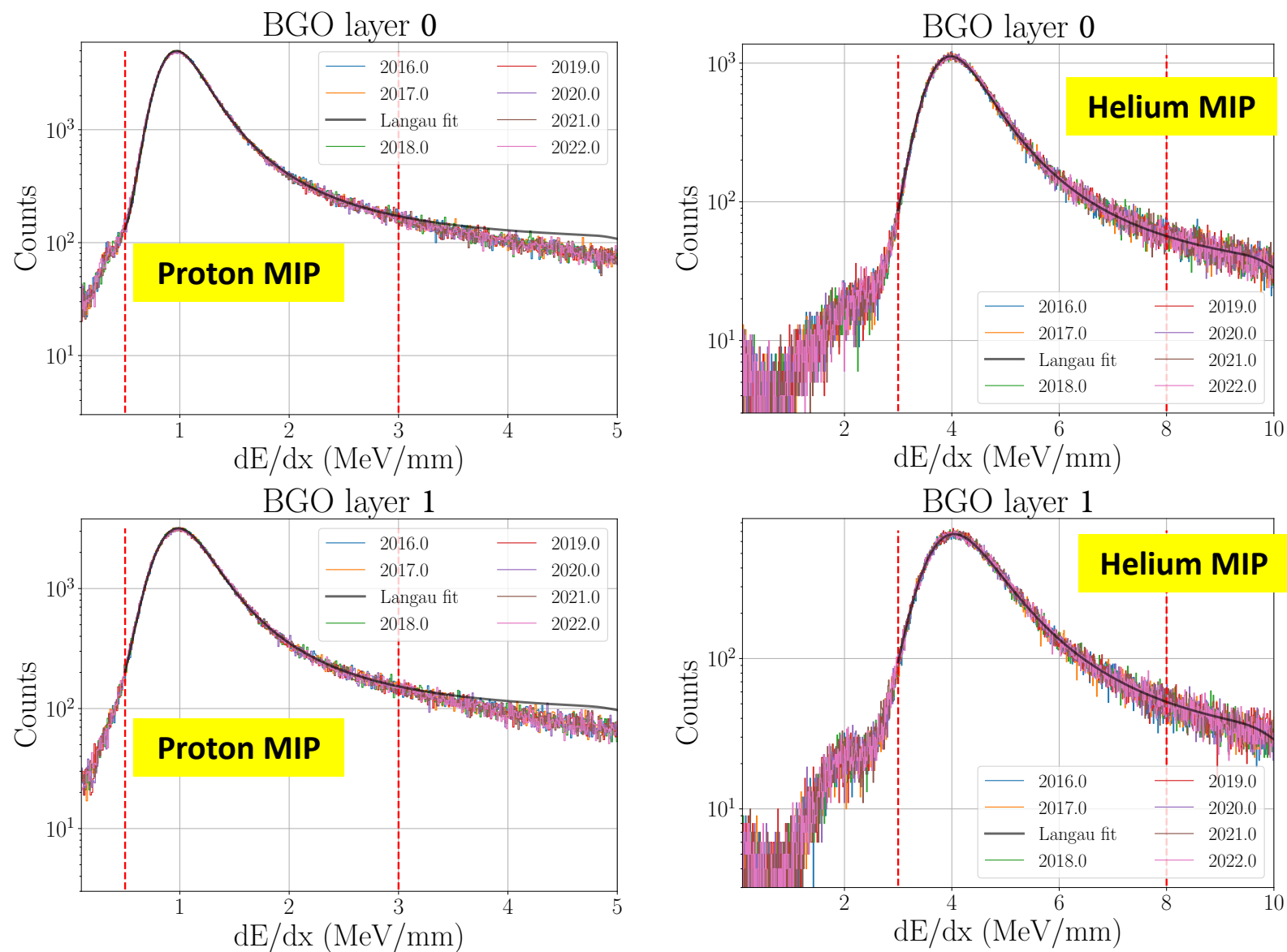
Proton energy cannot be easily corrected. Need unfolding!

BGO in-flight MIP calibration

- “MIP” calibration: ADC \rightarrow MeV and equalization: use events near the equator, $\pm 20^\circ$

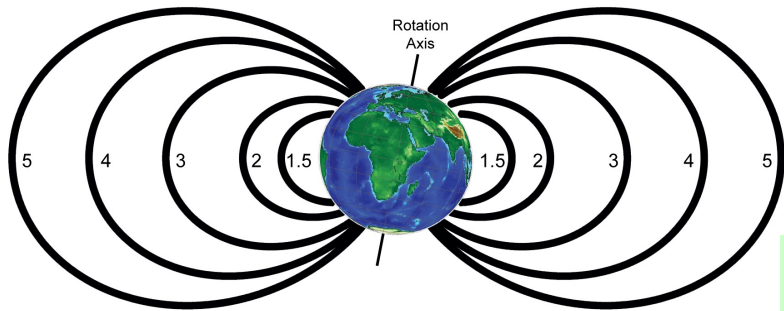


BGO overall calibration stability over 7 years



Absolute energy scale calibration

- 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 due to magnetic shielding

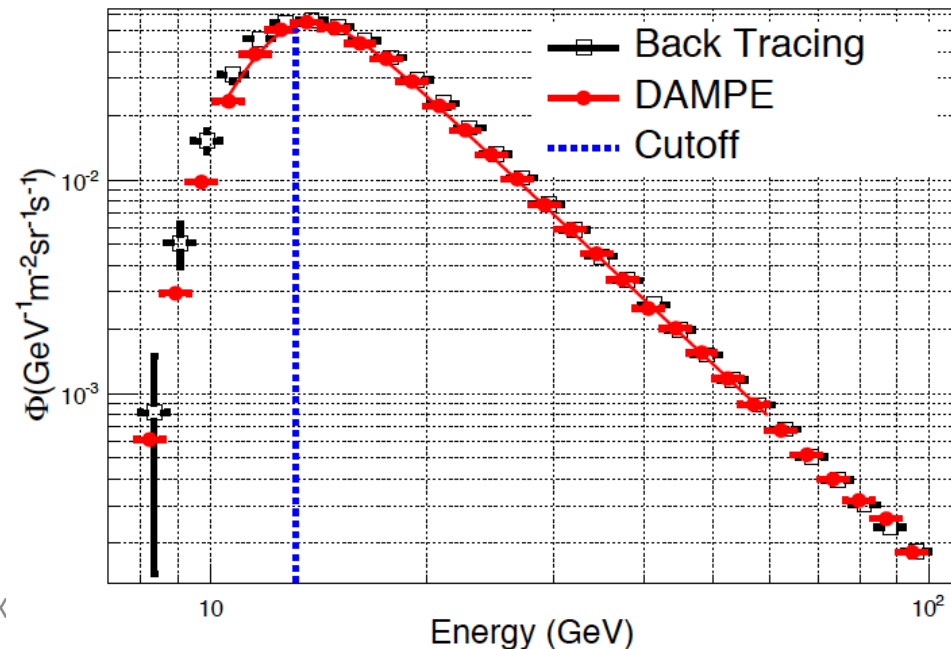


McIlwain L shells

- 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

$$C_{\text{data}}/C_{\text{pred}} = 1.012 \pm 0.017(\text{stat.}) \pm 0.013(\text{sys.})$$

~1.2 years of **electron** data
(ICRC2017-197)



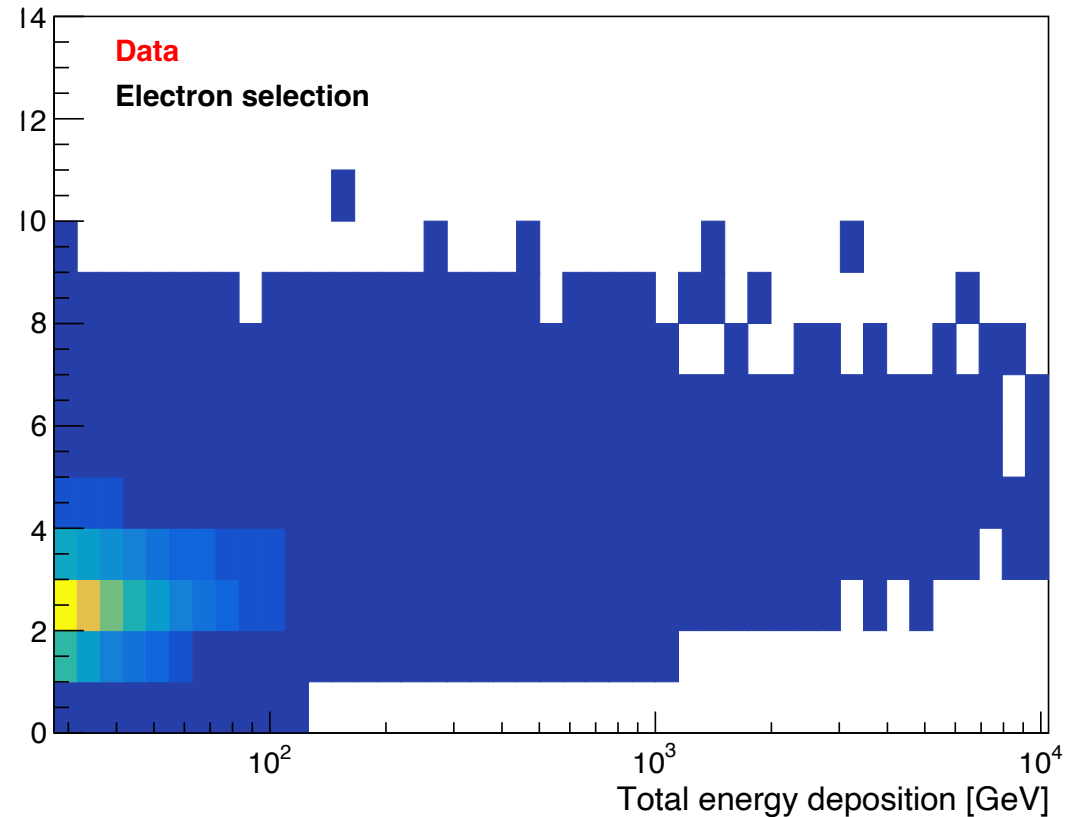
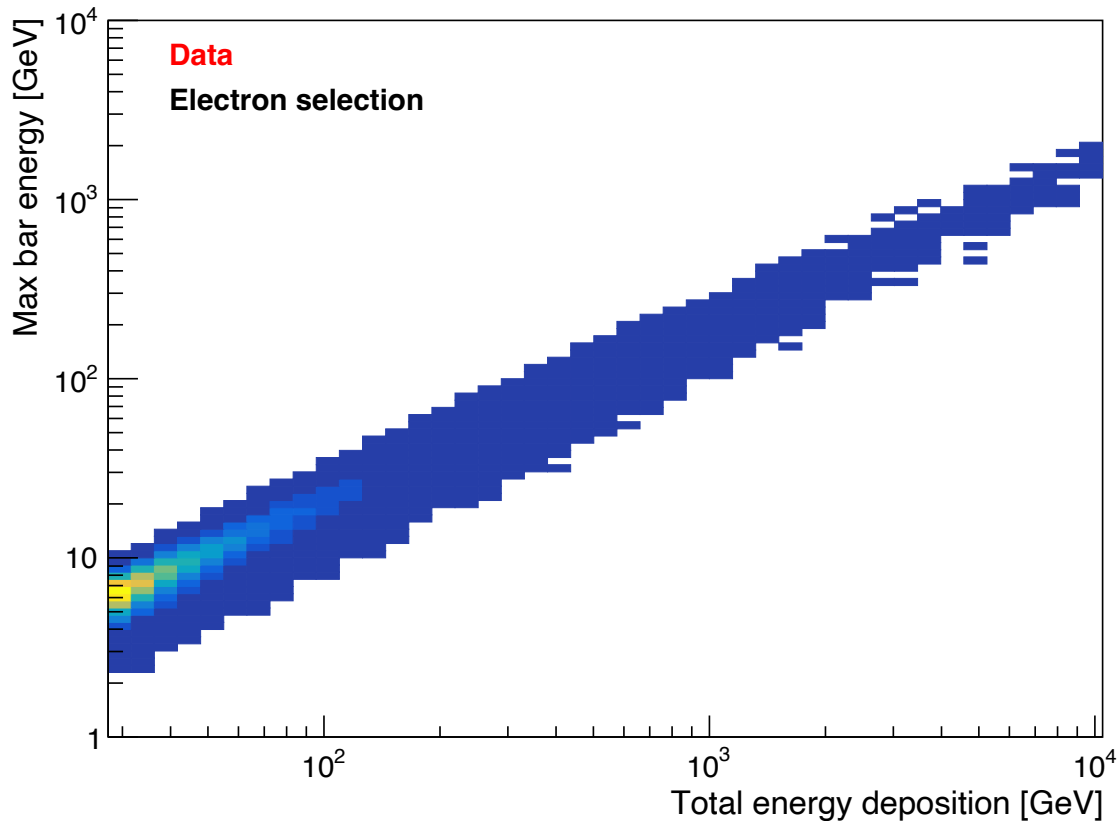
Energy scale agrees with expectation within 2%

- Consistent results obtained with ~7 years of electron data
 - Will be presented at the upcoming ICRC2023
- Consistent results also obtained by measuring the flux cut-offs of carbon, neon, silicon, and iron with ~1.4 years of data
 - Iron cut-off is ~200 GeV

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Energy linearity

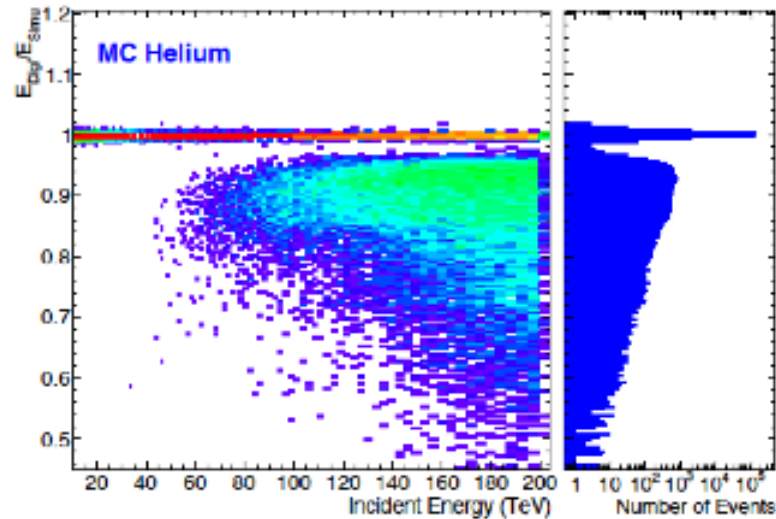
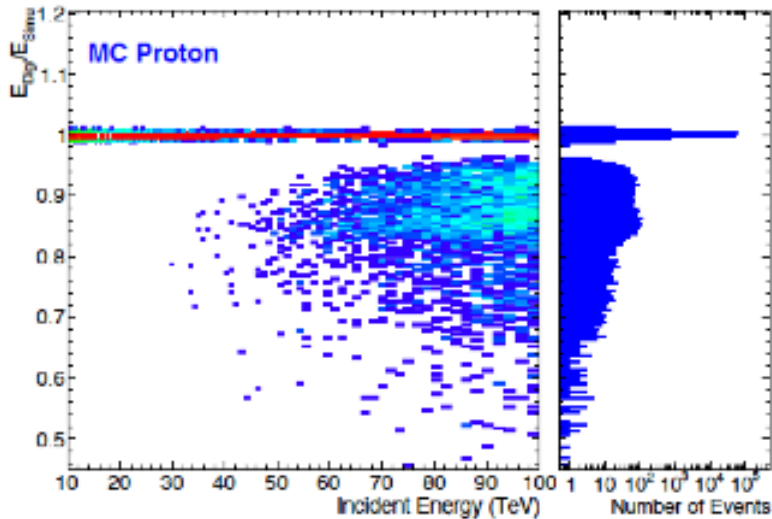
- BGO bar energy linearity can be checked with electron data (EM shower energy well measured)
 - On average ~20% of the total energy is deposited in the “hottest” BGO bar



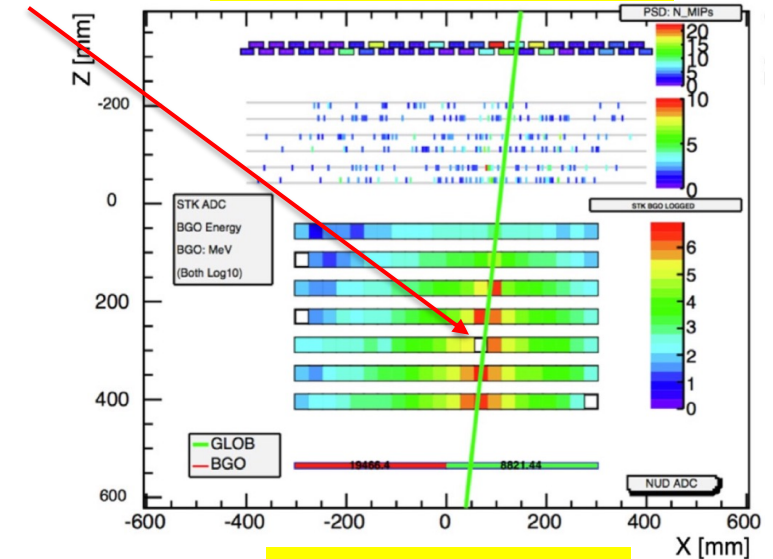
- Good linearity for EM showers up to >10 TeV
 - No fluorescence saturation observed: **ultimate limit is the readout saturation at ~4 TeV/bar → ~20 TeV CRE**
 - Shower max is well contained in the calorimeter for electron up to ~10 TeV

BGO readout saturation correction: towards PeV flux

- Electronics readout saturation starts to happen even with the low gain high attenuation channel with $>\sim 40$ TeV p/He
 - From simulation: $\sim 1.5\%$ / 1.2% of proton/He have saturated bars @100 TeV
 - In data: ADC value set to 0 when the saturation limit of a channel is reached



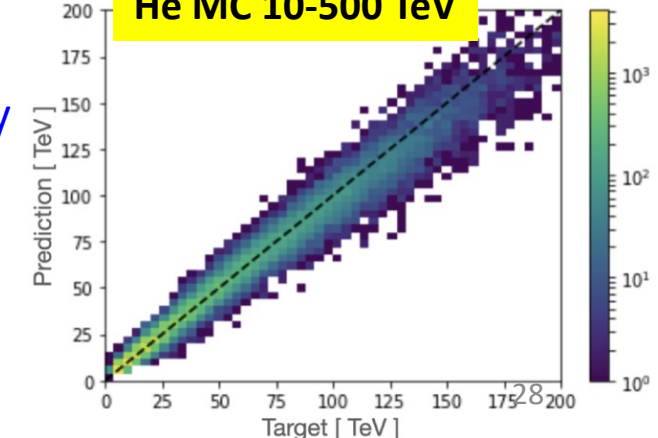
Data: He with 49.4 TeV deposited energy



Analytical and ML algorithms have been developed for readout saturation corrections

- Analytical (NIM A 984 (2020) 164645): using surrounding bars to predicts missing energy
 - not optimal for heavily saturated (multiple saturated bars) events
- ML (2021 JINST 16 P07036): use CNN to process the entire image of BGO
 - Provides an estimate of the total missing energy
 - Can handle multiple saturated bars, less bias than analytical

He MC 10-500 TeV



Conclusions

- DAMPE is working extremely well: has been collecting a unique sample of directly detected TeV - PeV CRs and has produced ground breaking measurements
 - Detector still in excellent condition after 7 years in space
 - Mission has rolling approvals to continue operation, with no plan to stop!
 - In the next 5-10 years DAMPE likely to dominate the CR precision spectroscopy in the TeV - PeV range
- Some (obvious) observations with respect to detector design
 - Dynamic range management is very important for charge and (calorimetric) energy measurement
 - A high precision tracker is indispensable (**it really helps to know where the particle is hitting!**) for robust calibrations/corrections of all subsystems and for “full event” reconstruction (particle ID)
 - Detector optimization is challenging because of multiple species, large energy range and TeV - PeV particle interactions (backsplash)
- Some (obvious) observations with respect to data analysis
 - Detector performance can be continuously improved with better calibrations/corrections
 - ML methods are typically more powerful than “conventional” methods but need long periods of development (**trial and error**) and careful validations (**data/MC agreement**)
 - Modelling of TeV - PeV hadronic interaction is often the biggest source of systematic uncertainties

Thank you very much for your attention!