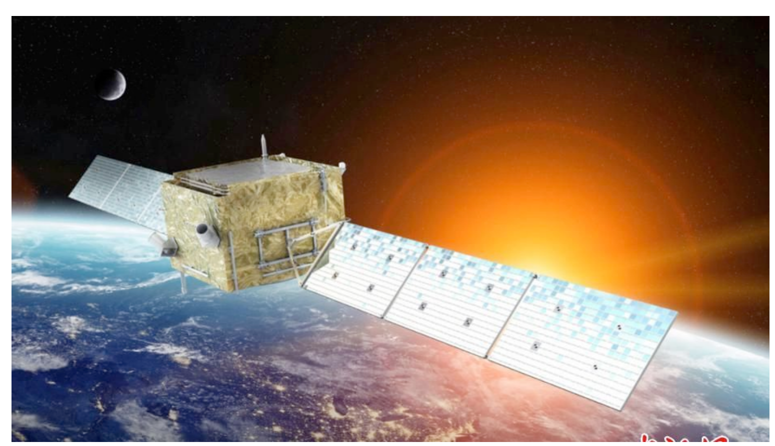
# High-energy simulation experience from DAMPE

Andrii Tykhonov
University of Geneva

UNIVERSITÉ DE GENÈVE

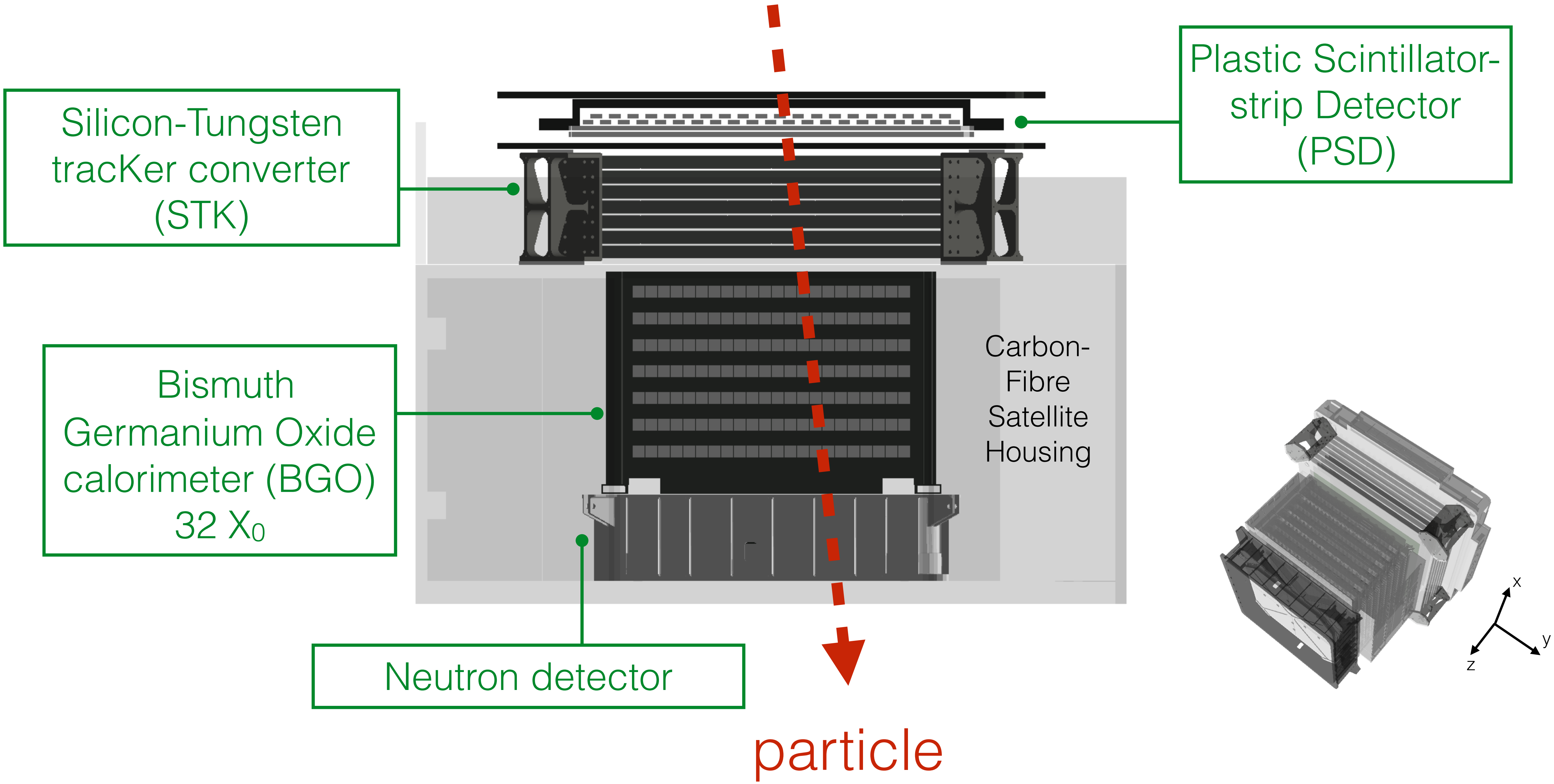


DARK MATTER PARTICLE EXPLORER

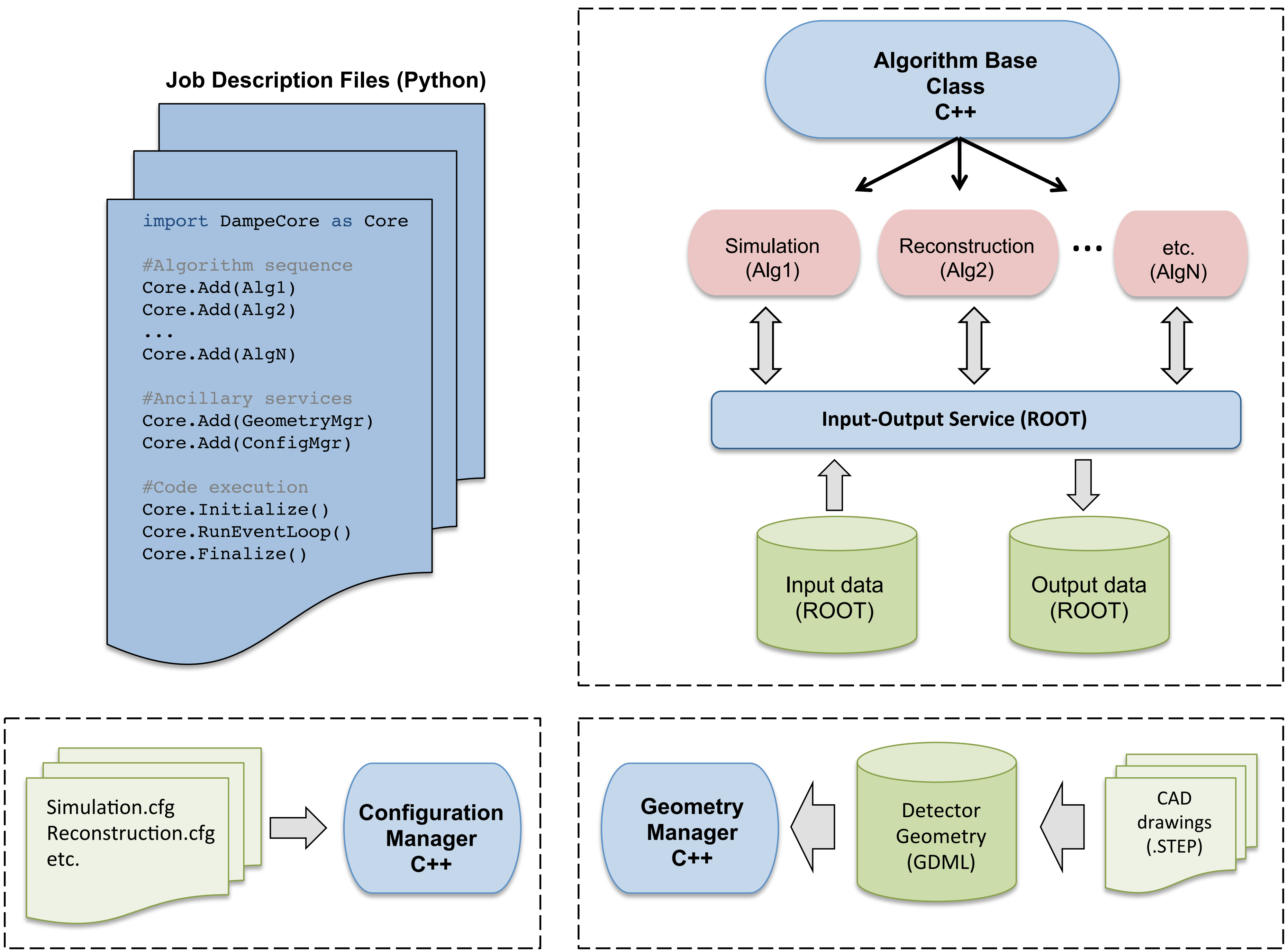
# Outline

- DAMPE & Simulation:
    - Cosmic-Ray (CR) proton/ion analyses
    - High-energies (>100 TeV)
    - Cosmic-Ray (CR) electron analysis

# The DAMPE detector

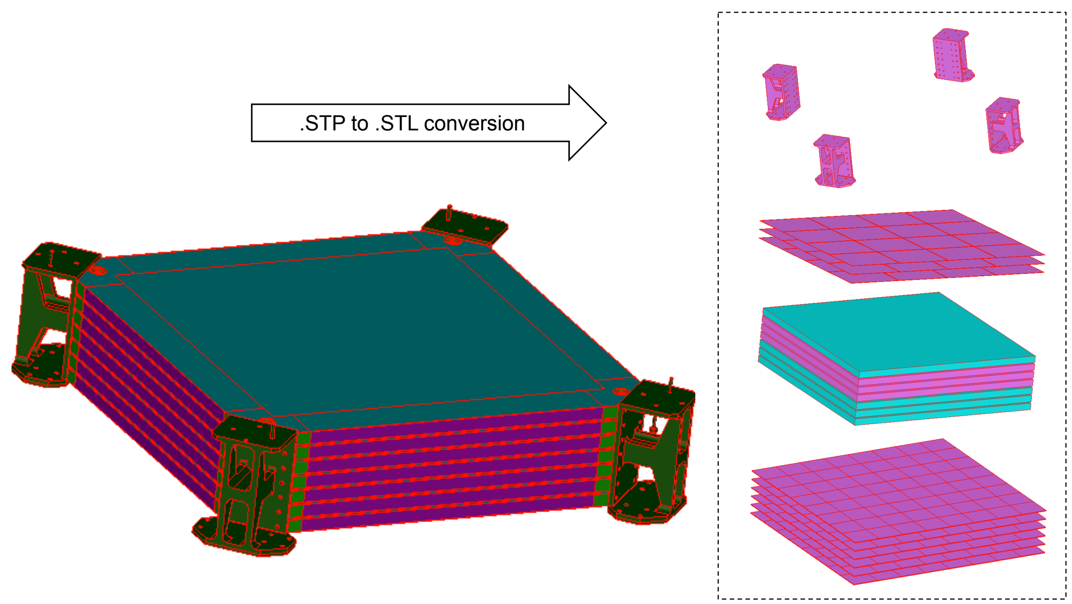


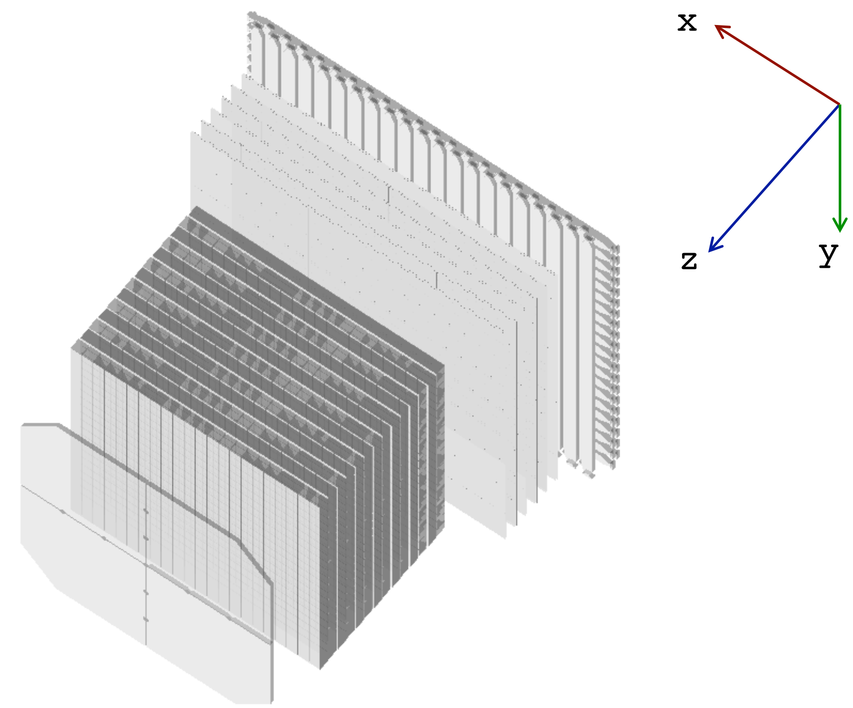
# DAMPE Software framework

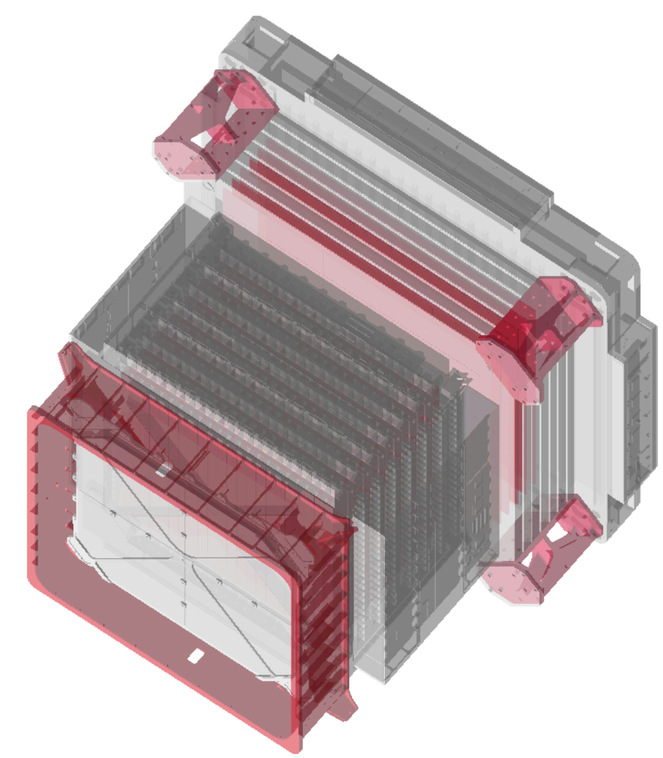


# Geometry

- Geometry model in Geant4 is created from the CAD drawings
  - Each CAD geometry element is saved as a tessellated solid in an STL file
  - STL converted to GDML with material assignment using the conversion tool*



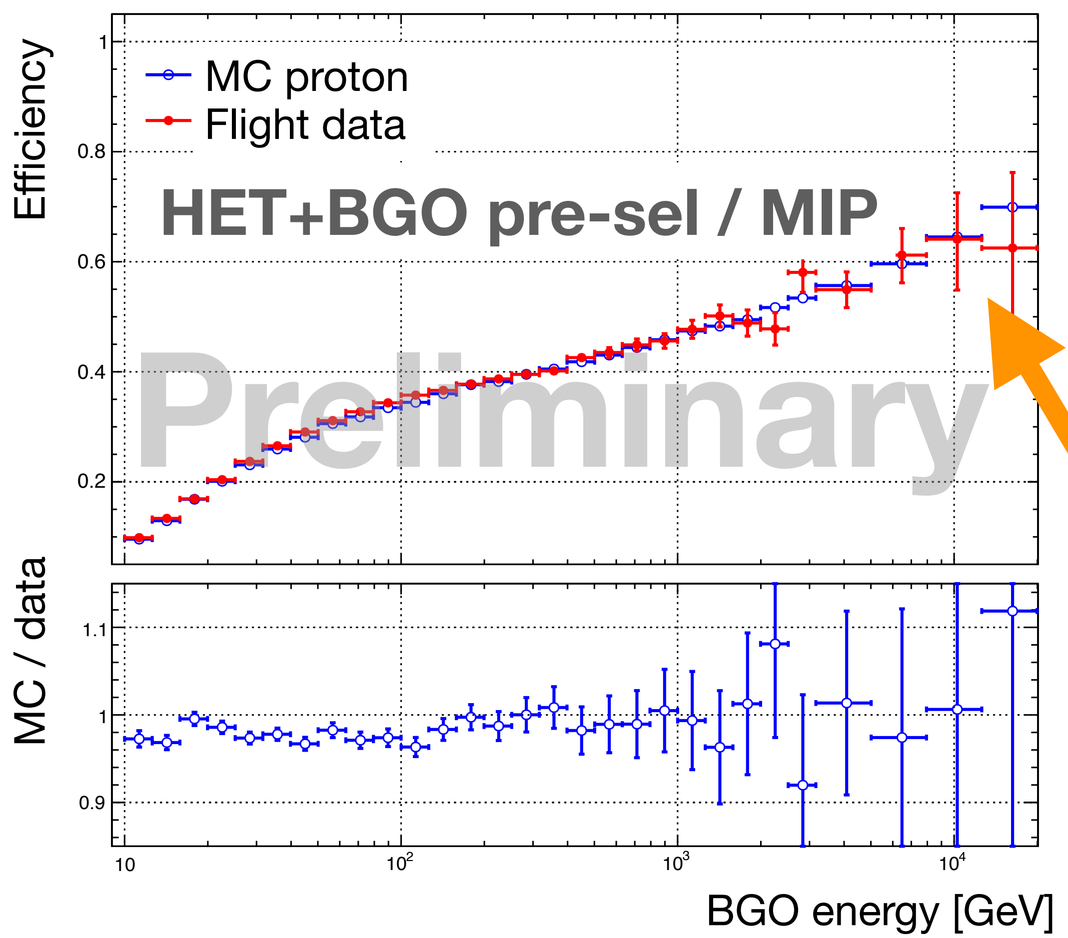
* https://github.com/tihonav/cad-to-geant4-converter

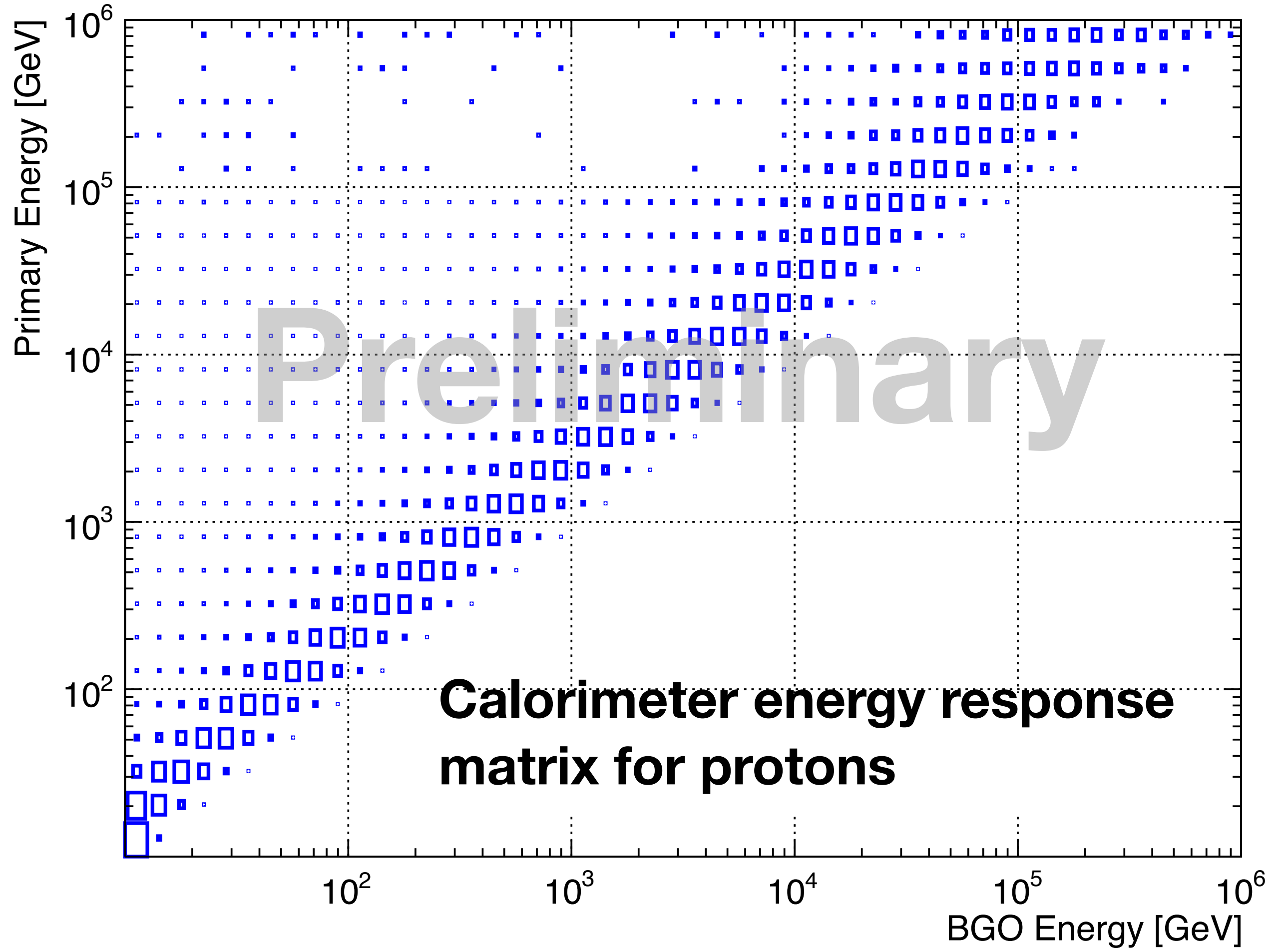
# CR proton/ion analyses

## Simulation challenges

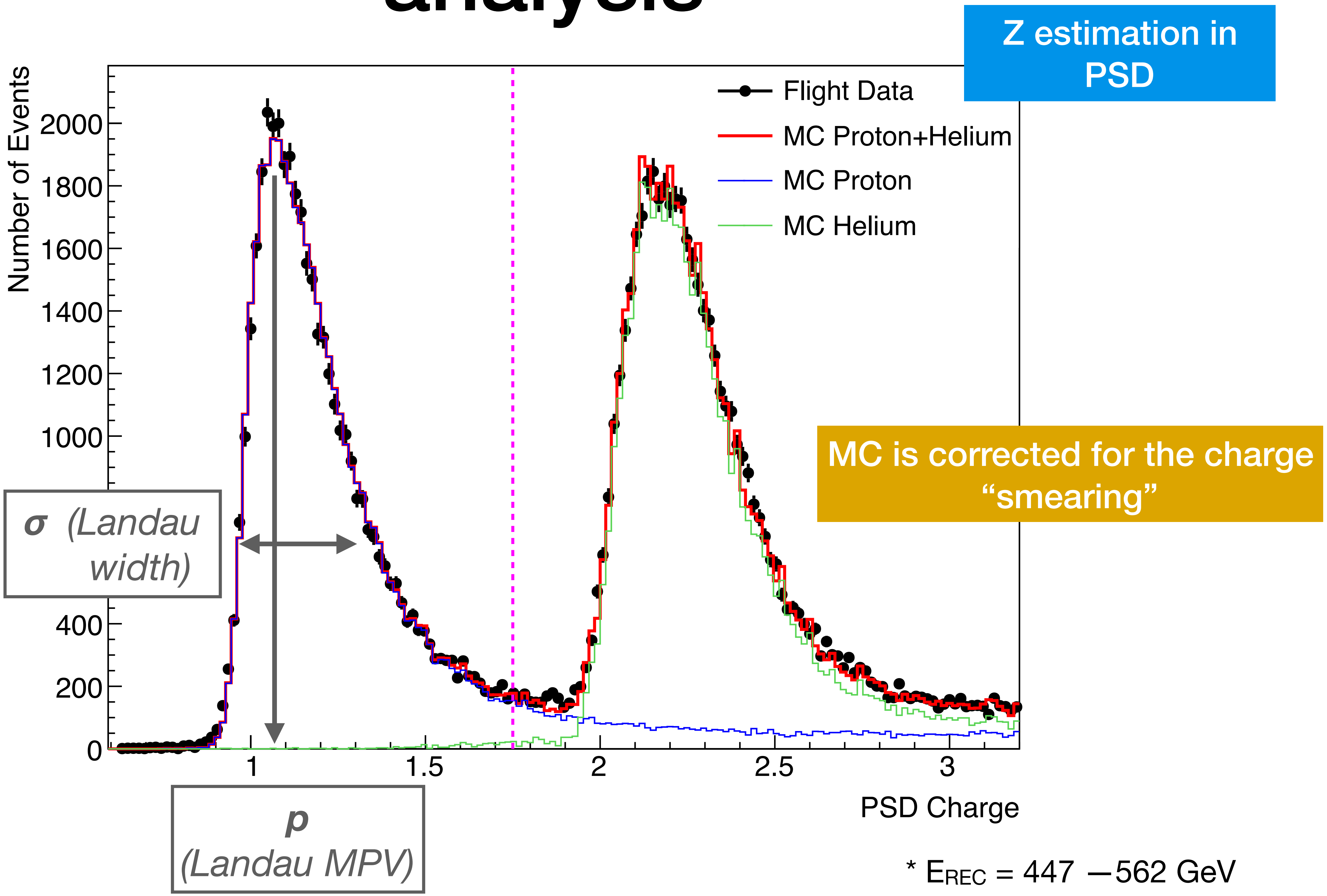
# Simulation challenges in CR analysis

- High-Energy Trigger (HET) — largely determines the proton acceptance
- After the HET selection, average deposited energy fraction for protons ranges from ~50% at 100GeV to ~30% at 100 TeV:
    - **Energy unfolding is needed — relies on MC!**



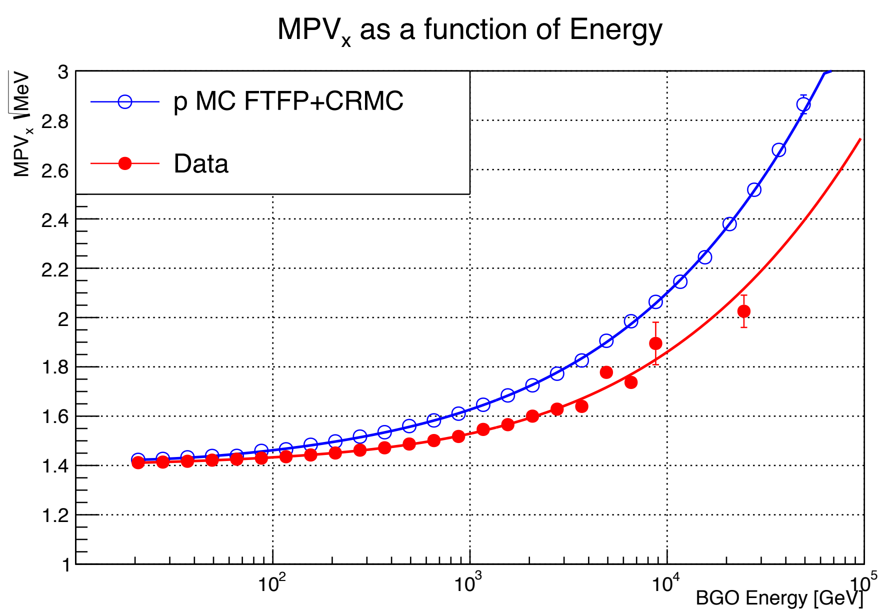
# Simulation challenges in CR analysis

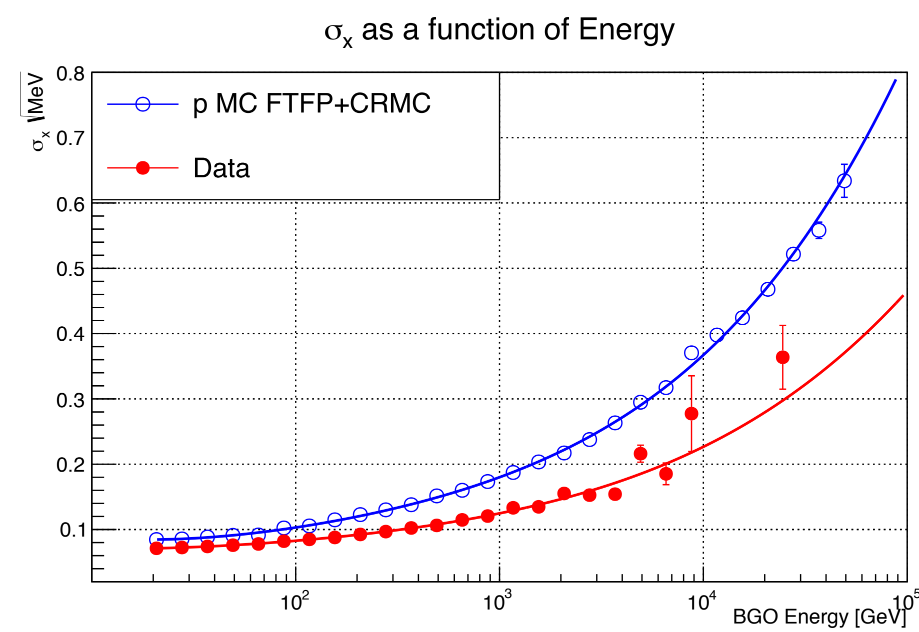



* $E_{REC}$ = 447 —562 GeV

# Simulation challenges in CR analysis

**Charge "smearing" in MC**




**Data**

$$p_0 = f_{\mathrm{MPV\,Data\,x(y)}}(E_{rec})$$

$$s_0 = f_{\sigma\,\mathrm{Data\,x(y)}}(E_{rec})$$

**MC**

$$p_1 = f_{\mathrm{MPV\,pMC\,x(y)}}(E_{rec})$$

$$s_1 = f_{\sigma\,\mathrm{pMC\,x(y)}}(E_{rec})$$

$$\Rightarrow \mathrm{PSD}_{x(y)}(\mathrm{corr}) = (\mathrm{PSD}_{x(y)} - p_1)s_0/s_1 + p_0.$$

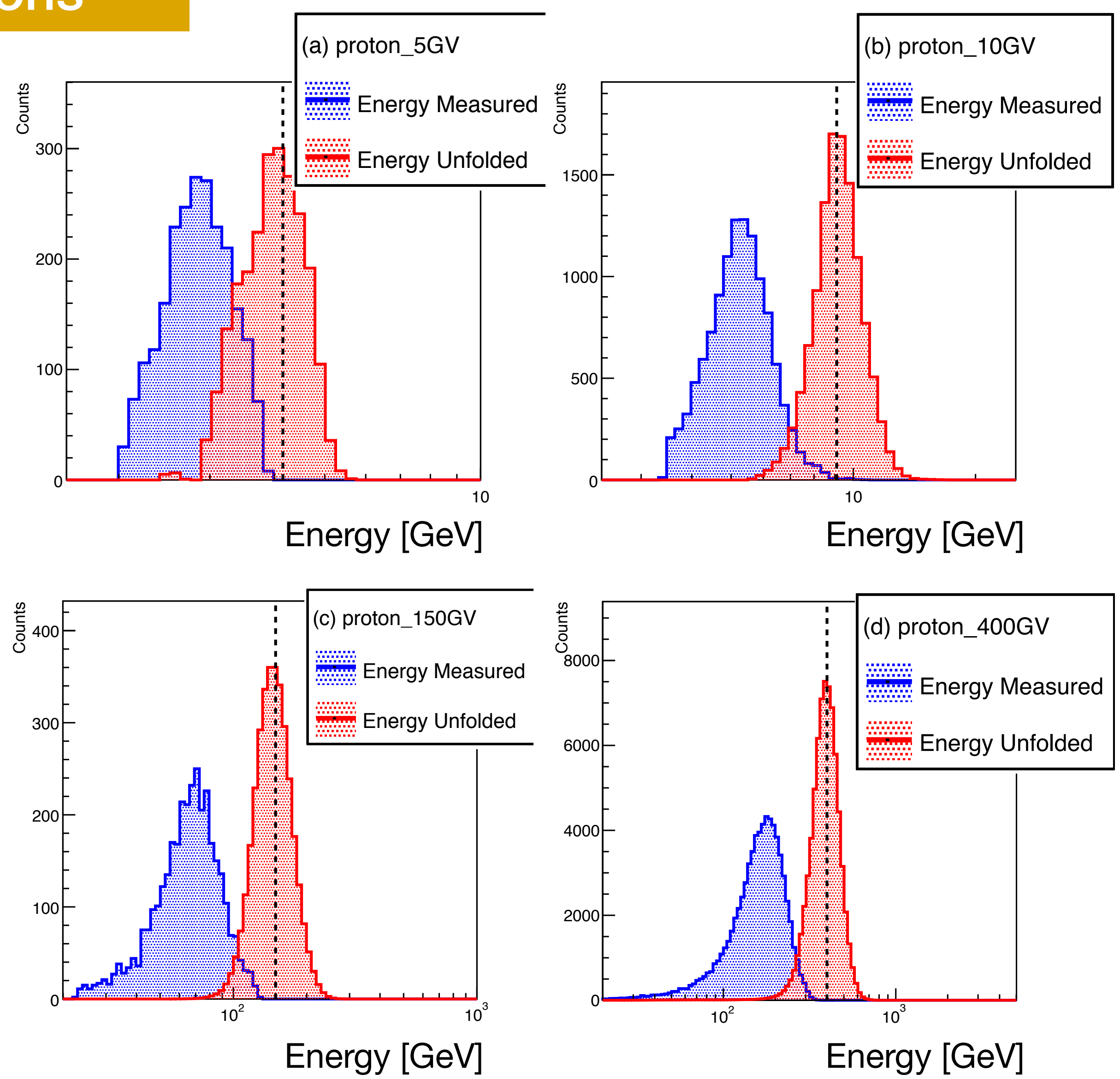
# Simulation

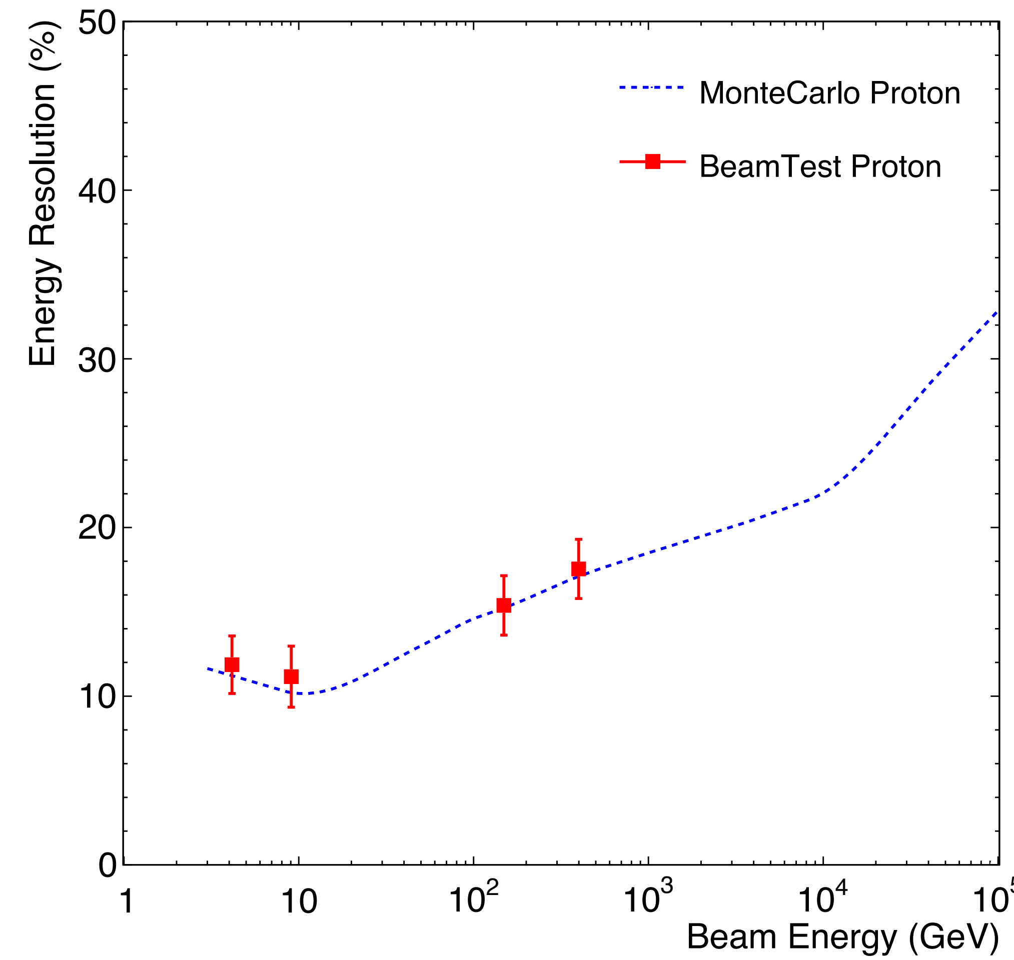
## E > 100 TeV/nucl

# Baseline simulation: Geant4

- Geant4 hadronic simulation shows very good agreement with beam-test data, at PS—SPS energies (up to 400 GeV for protons)

**Protons**



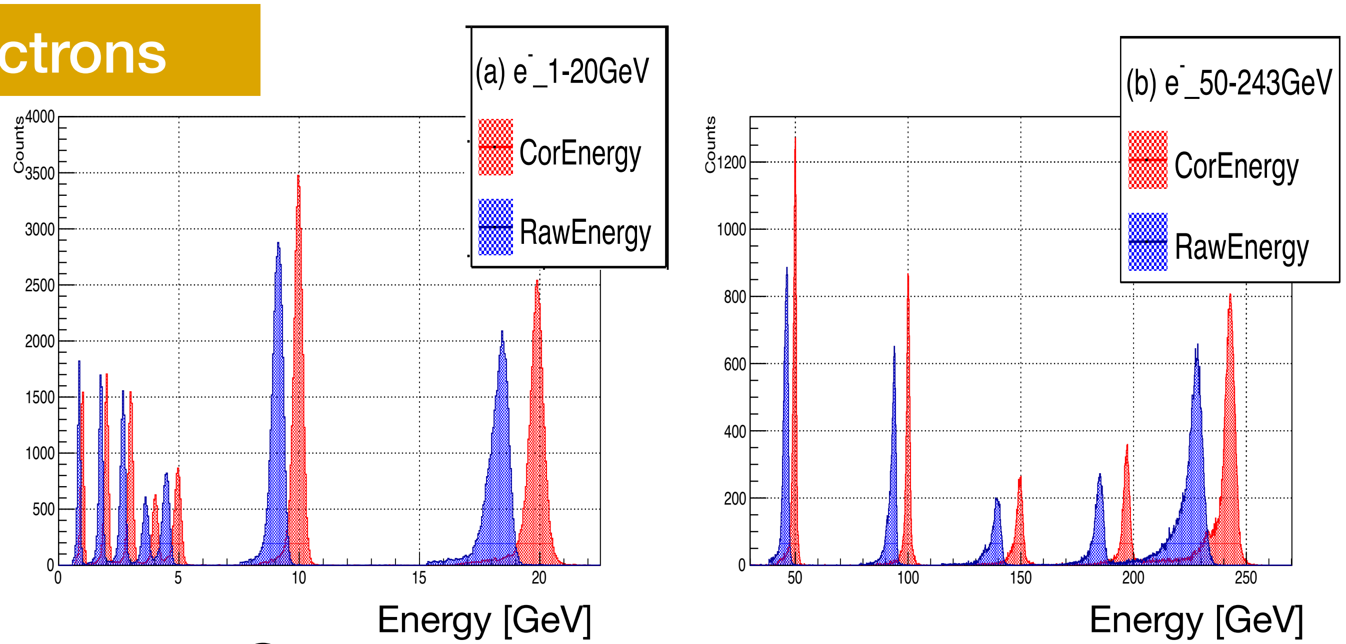



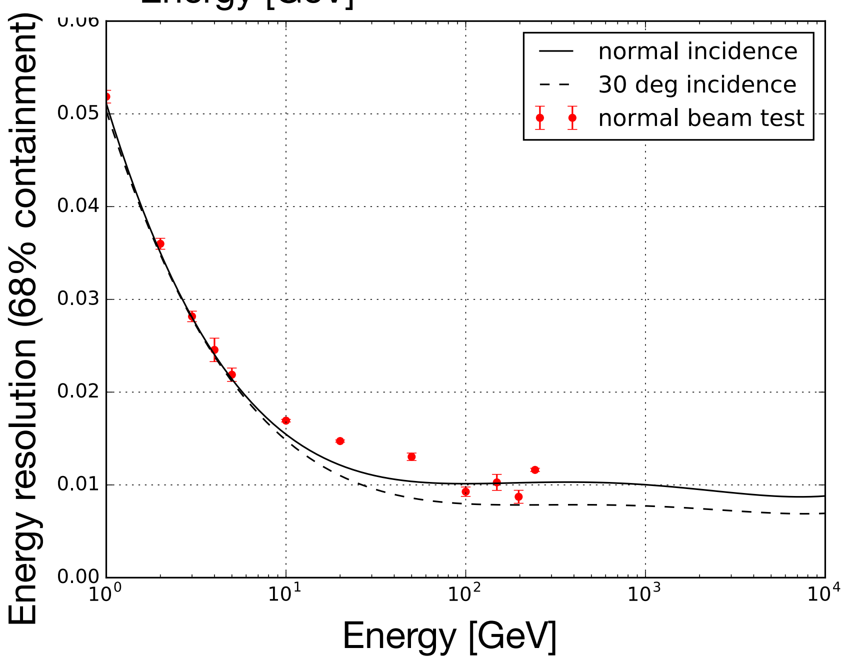

**Geant4 is used as a baseline for DAMPE simulations up to 100 TeV**

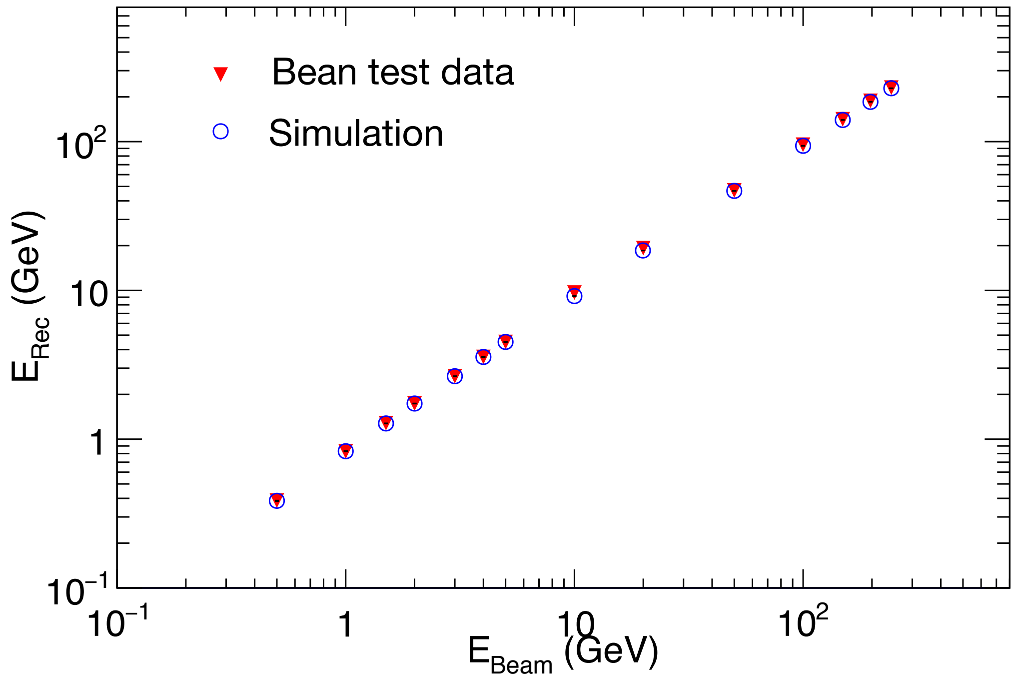
# Baseline simulation: Geant4

- Geant4 hadronic simulation shows very good agreement with beam-test data, at PS—SPS energies (up to 243 GeV for electrons)

**Electrons**



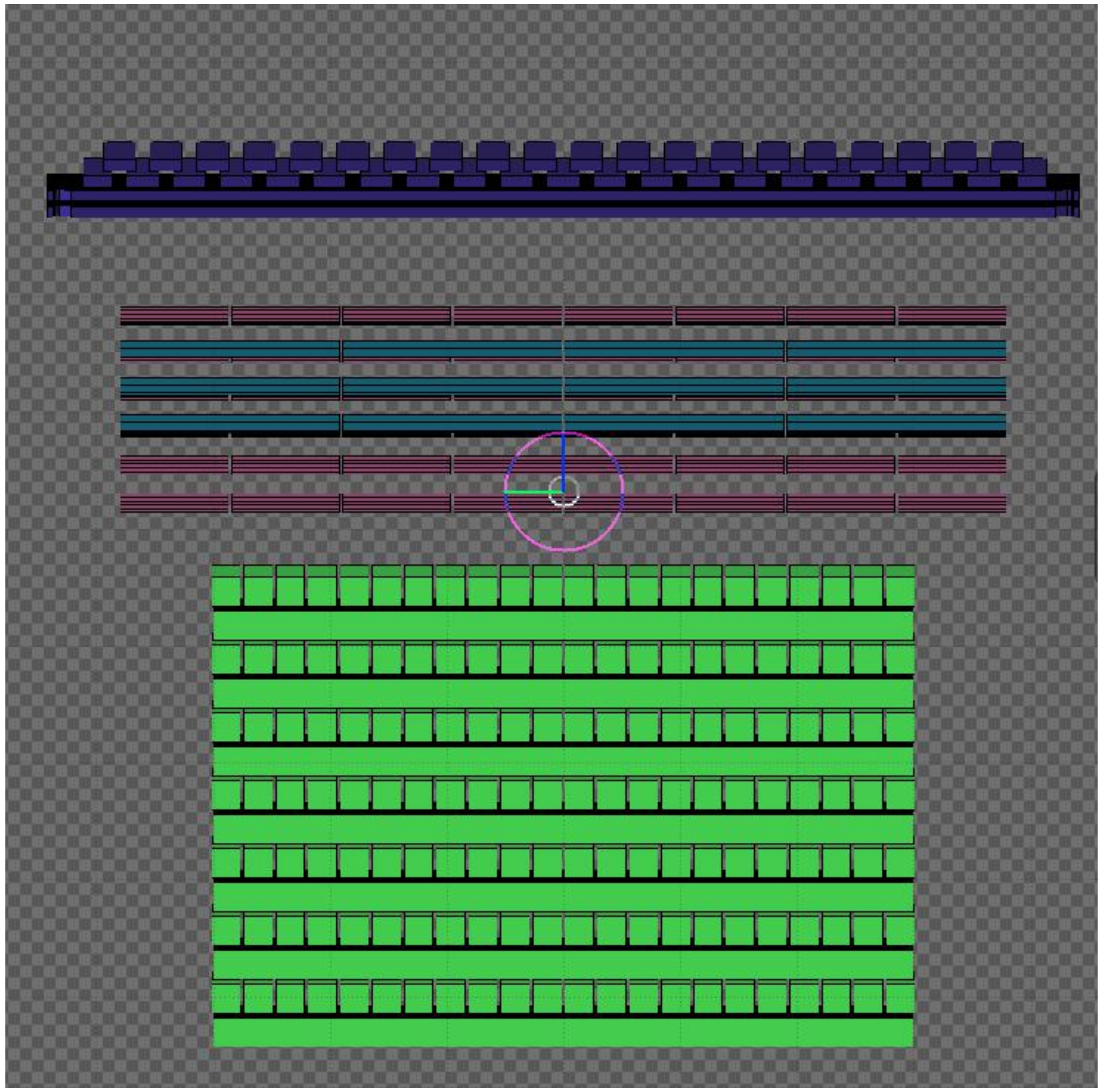




**Geant4 is used as a baseline for DAMPE simulations up to 100 TeV**

# FLUKA

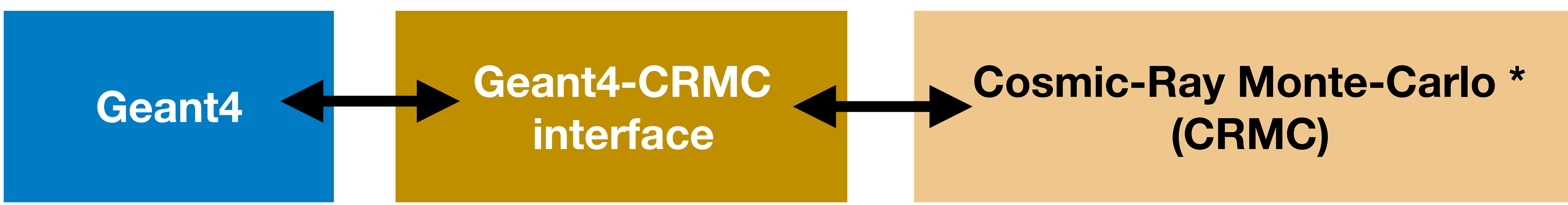
- Alternative FLUKA simulation of DAMPE is implemented in parallel with the baseline Geant4 simulation



# Geant4—CRMC interface

- Running Geant4 simulations at > 100 TeV energies? → CRMC interface:
  - Allows to run simulations with using the DPMJET, EPOS and other models in Geant4:

```
# CRMC & Geant4 combined physics list:
SimAlg.Set("HadronPhysicsList", "DPMJET3_FTFP_BERT")
# ... or
SimAlg.Set("HadronPhysicsList", “EPOS199_FTFP_BERT")

# ... this one is optional:
SimAlg.Set("CrmcEnergyThresholdGeV", “200")
# ... default threshold = 300 GeV
```

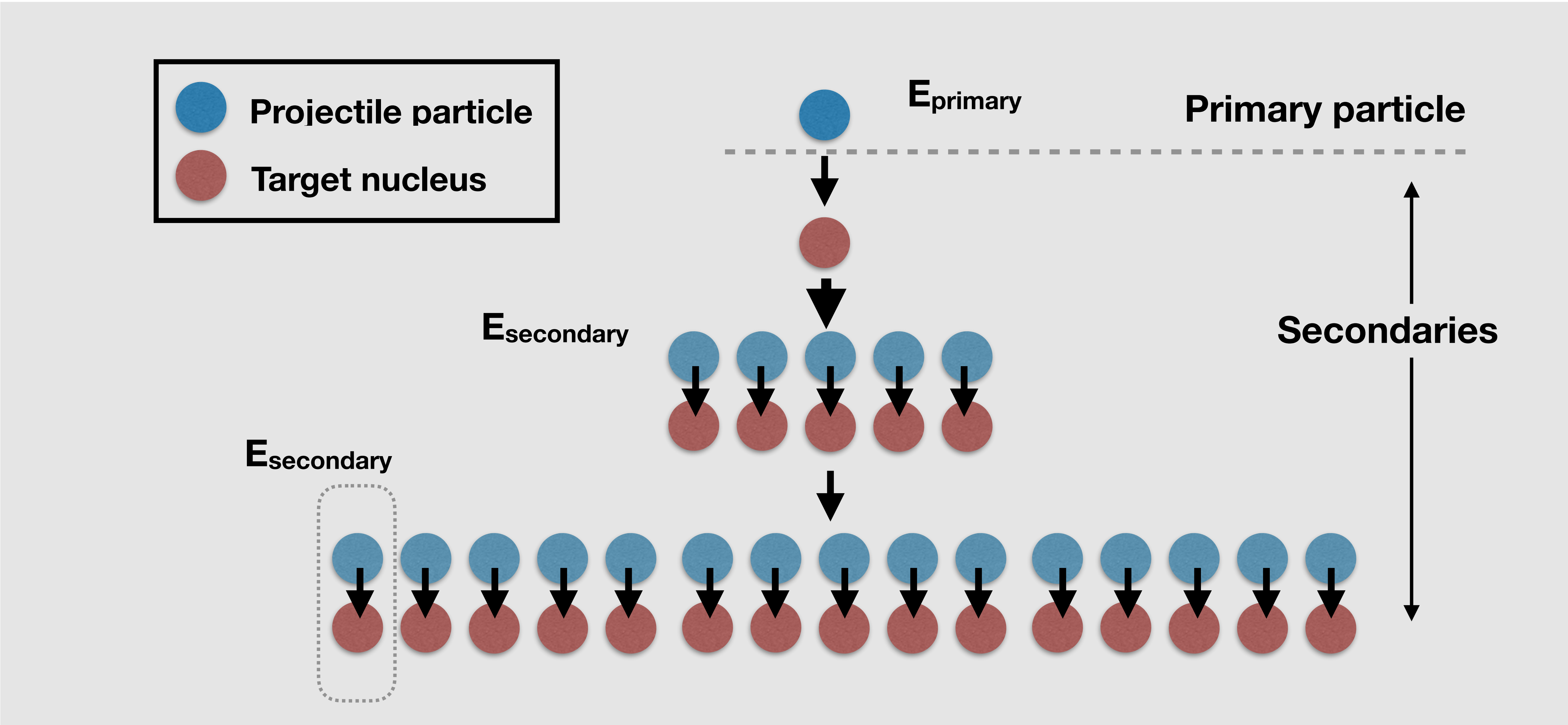



* https://web.ikp.kit.edu/rulrich/crmc.html

**CRMC:**
- **DPMJET**
- **EPOS**
- **SYBILL**

**... other models**

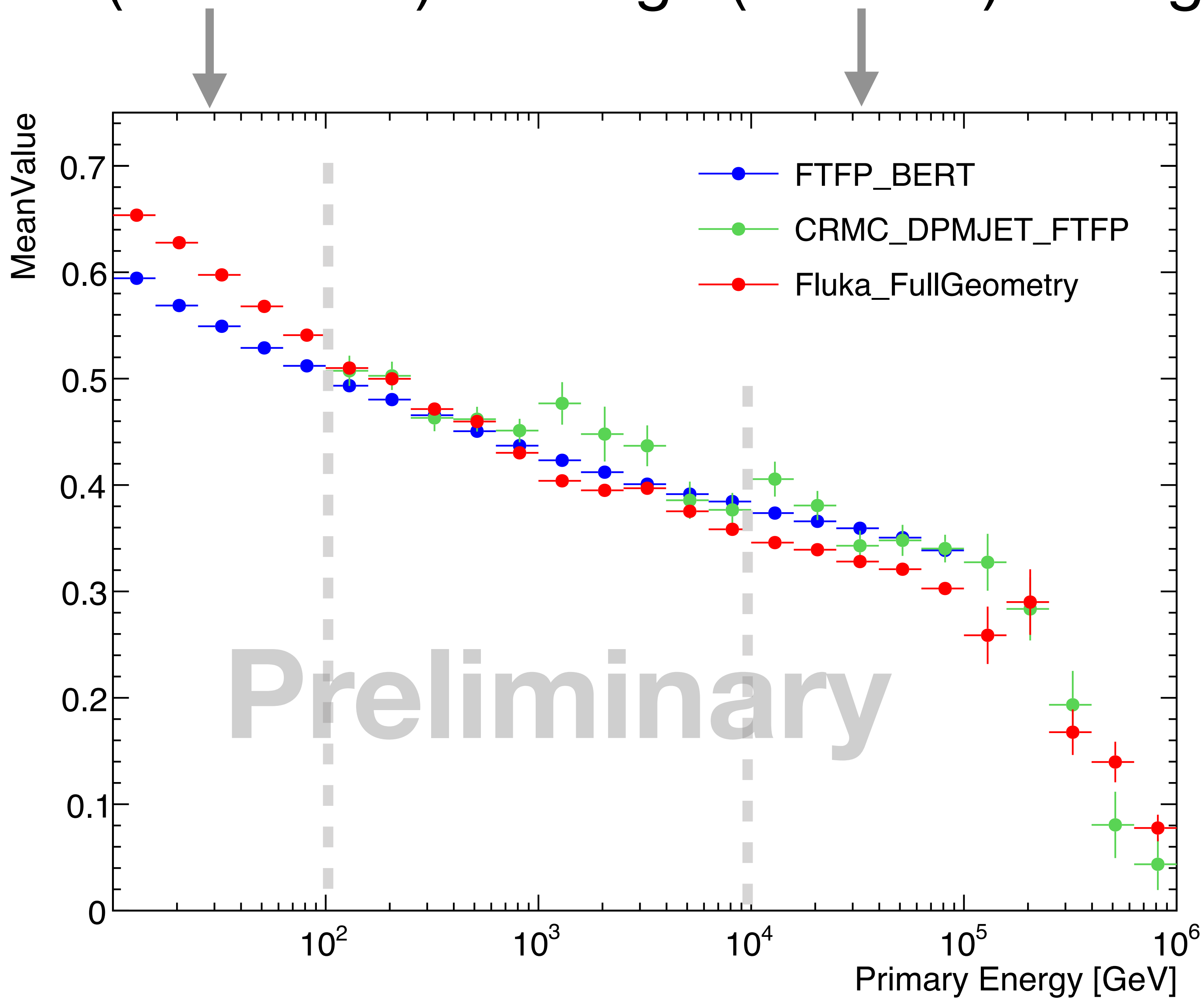
# Geant4—CRMC interface




```
If E < Ether
     use FTFP (GEANT4)
else
     use CRMC (EPOS/DPMJET/..)
```

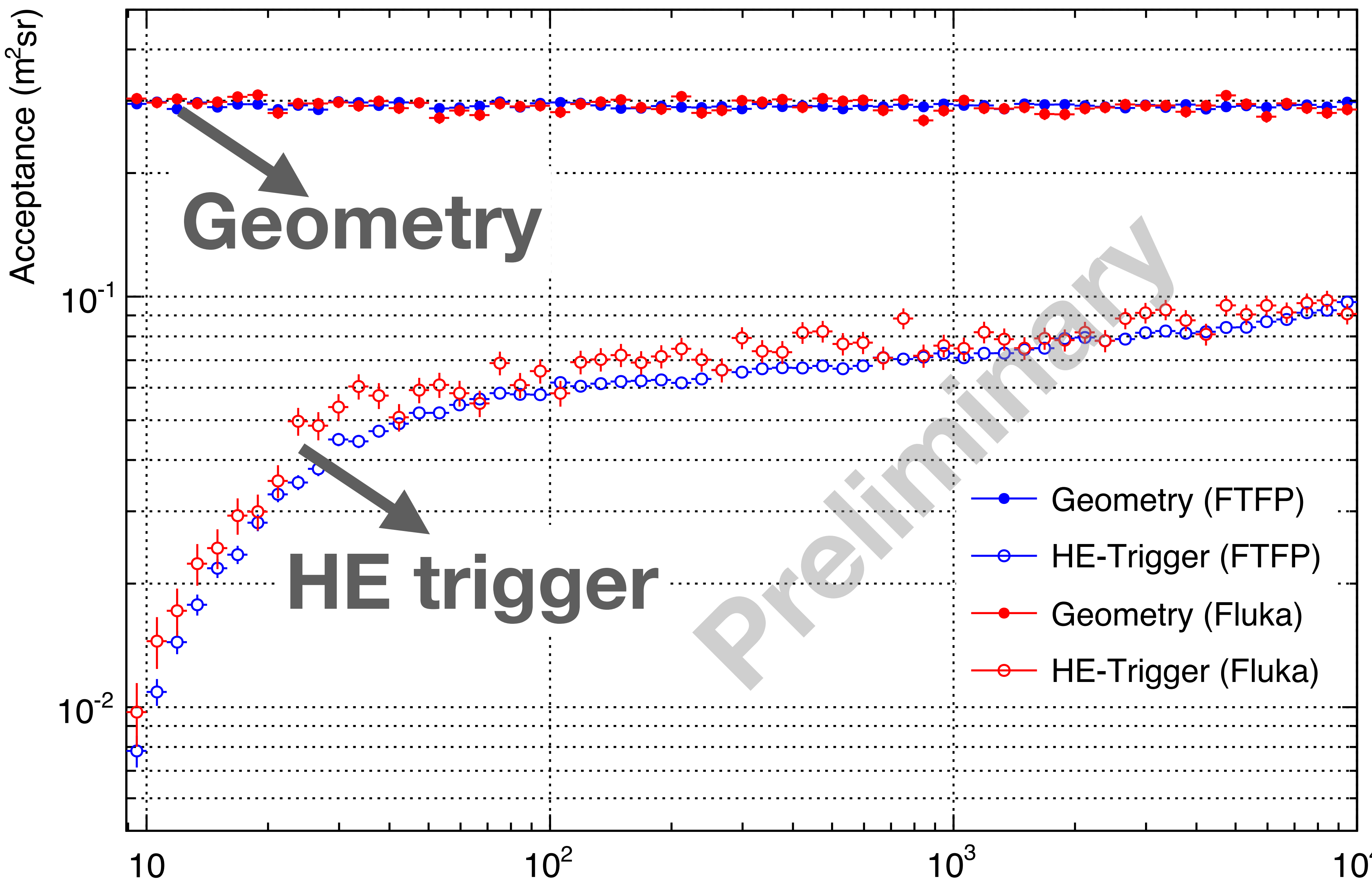
# FLUKA & Geant4—CRMC

- Geant4 and Fluka show discrepancy at low (<100 GeV) and high (>10 TeV) energies

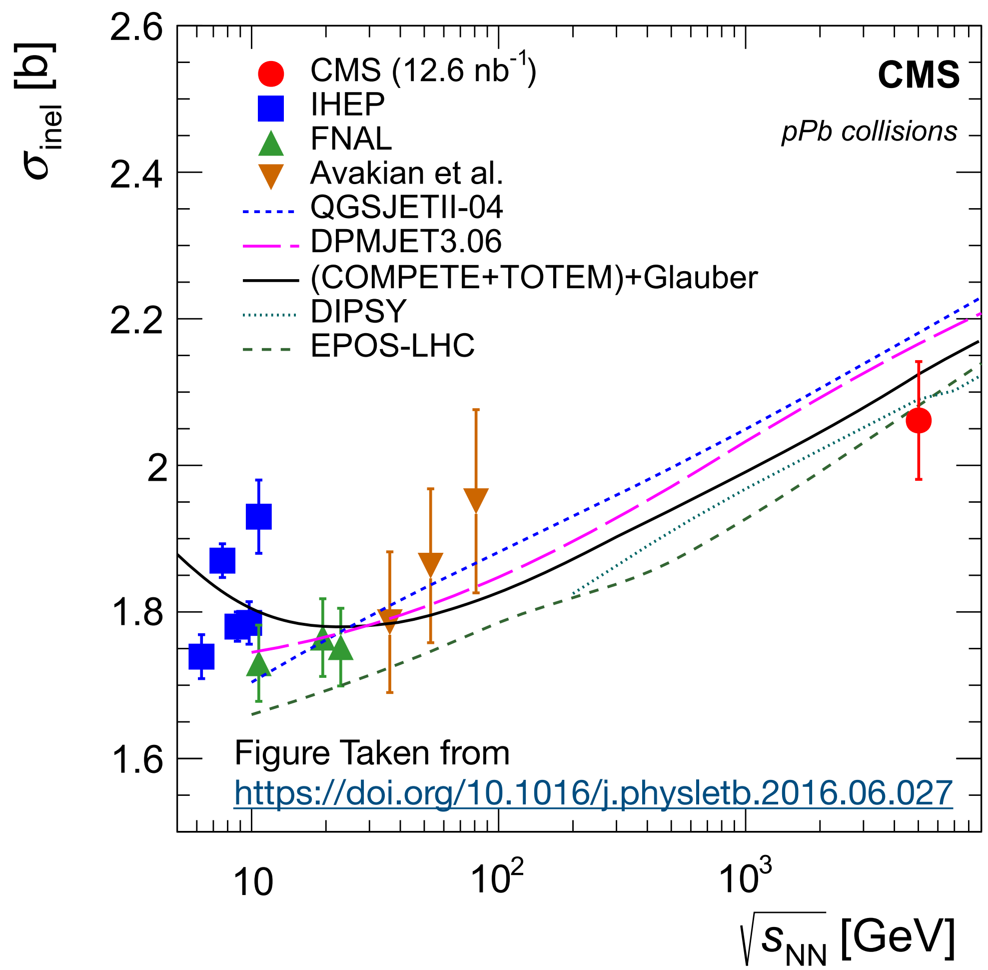


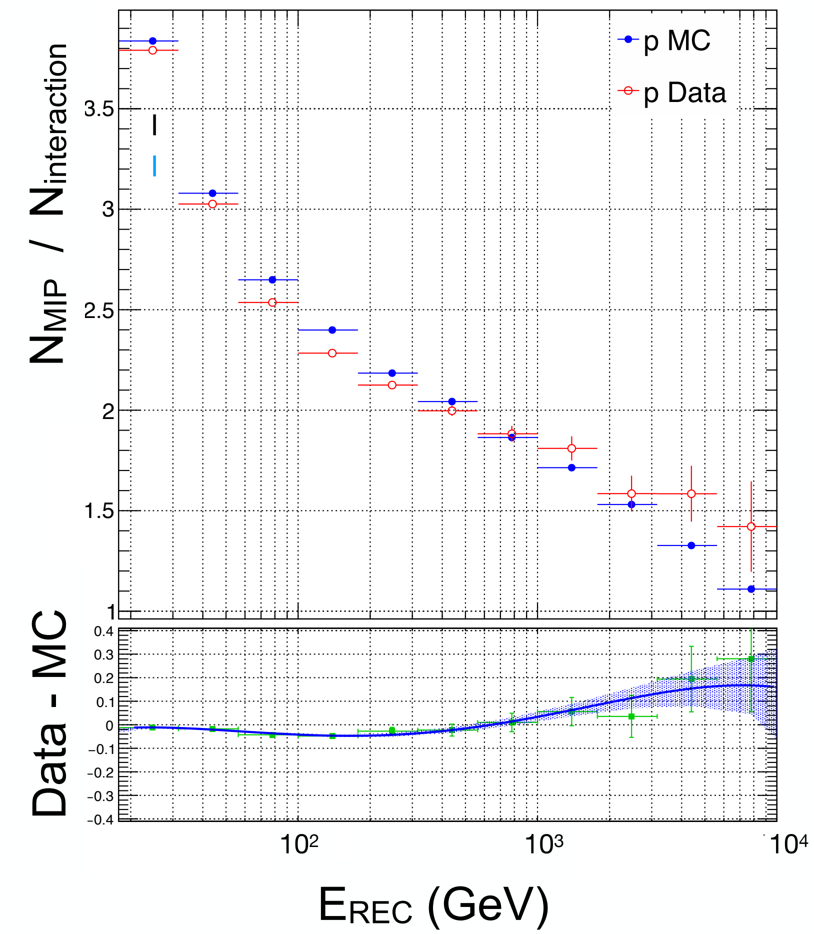
# FLUKA & Geant4—CRMC

- Geometrical acceptance is consistent between FLUKA and G4
- The difference observed for HE trigger efficiency at low energies (<100 GeV)



# Hadronic cross-sections uncertainties




- Uncertainty of hadronic cross-sections in MC simulations → can be tested by varying cross-sections at Geant4 level:

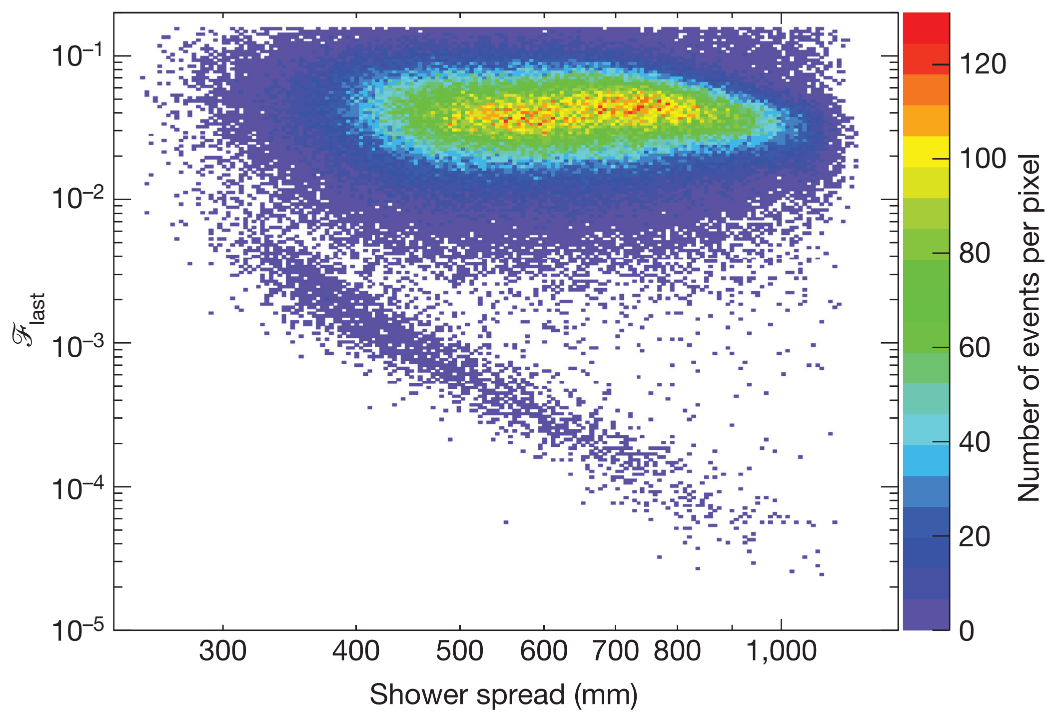
```
# Modify elastic/inelastic cross-section by 10% down
SimAlg.Set("ModifyInelasticCrossSection", "0.9")

# Set minimal particle energy for which the cross-section is modified
SimAlg.Set("ModifyCrossSectionMinTotalEnergyGeV", “0")
```

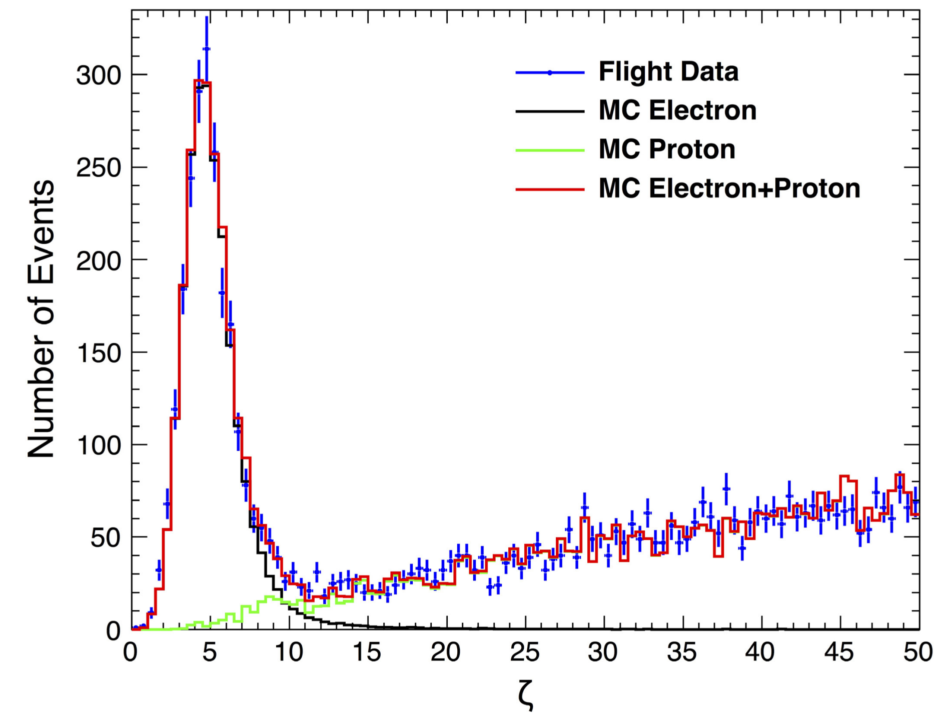
# CR electron analysis

## Simulation challenges

# Discrimination of e/p & Simulation

- Electron/proton discrimination in DAMPE is based on the shoer-shape variables:
  - Sum of shower RMS in all 14 layers of the BGO calorimeter ($RMS_i$)
  - Fraction of energy in the last BGO layer ($\mathcal{F}_{last}$)




$$\mathrm{RMS}_i = \sqrt{\frac{\sum_j (x_{j,i} - x_{c,i})^2 E_{j,i}}{\sum_j E_{j,i}}}$$

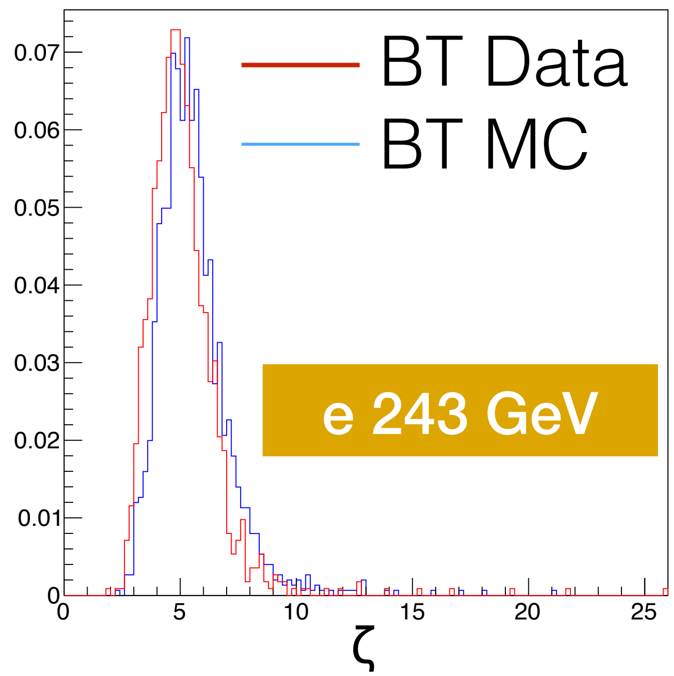
nature
International journal of science

https://doi.org/10.1038/nature24475

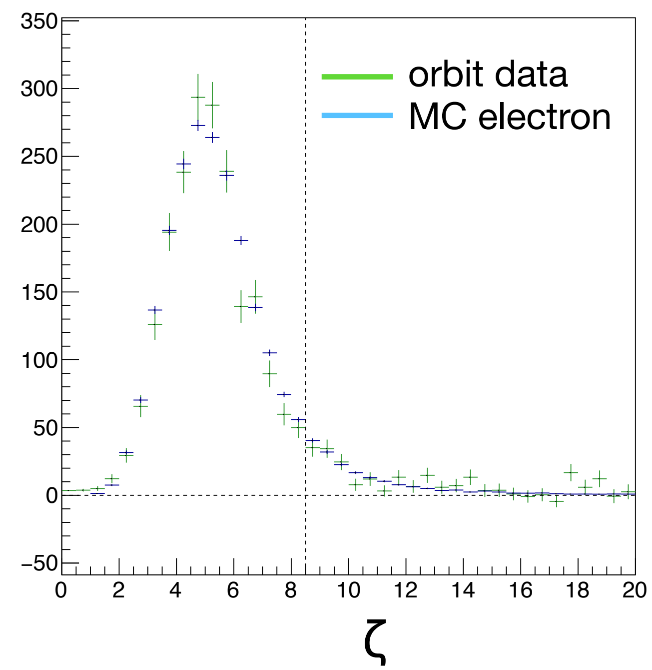
$$\zeta = \mathcal{F}_{\mathrm{last}} \times (\Sigma_i \mathrm{RMS}_i/\mathrm{mm})^4/(8 \times 10^6)$$

# Discrimination of e/p & Simulation

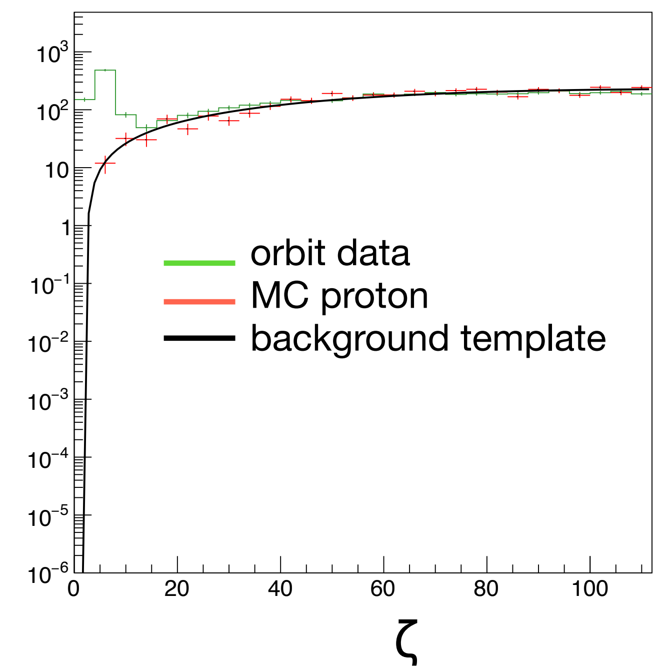
- Very good data-MC agreement of e/p classifier at beam-test energies.
- Good agreement  for flight data, 8% uncertainty at 4 TeV (at ~80% electron selection efficiency)

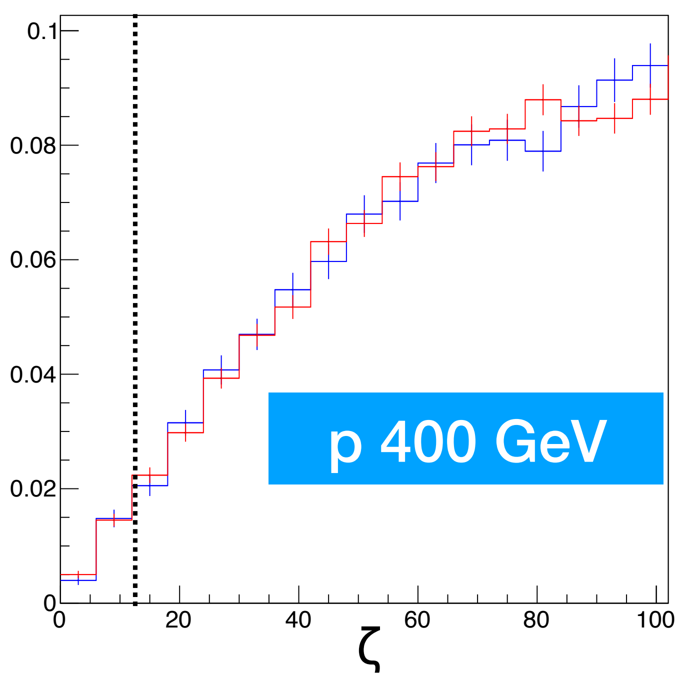



500 GeV — 1 TeV

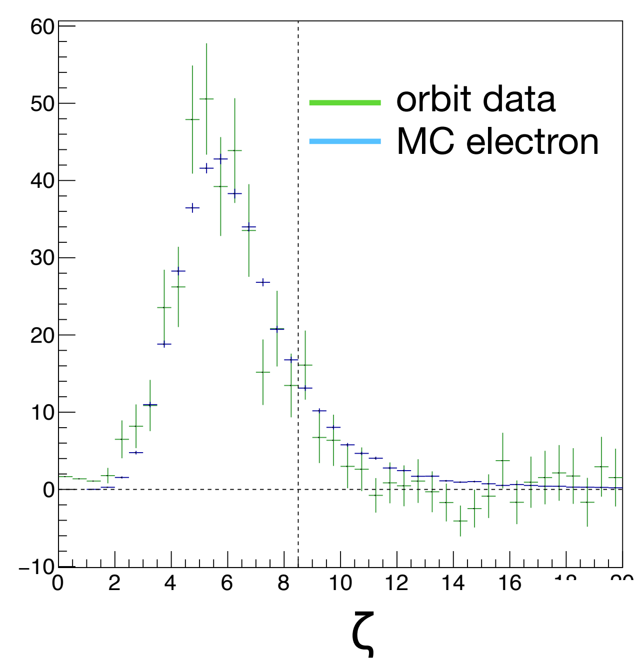



500 GeV — 570 GeV

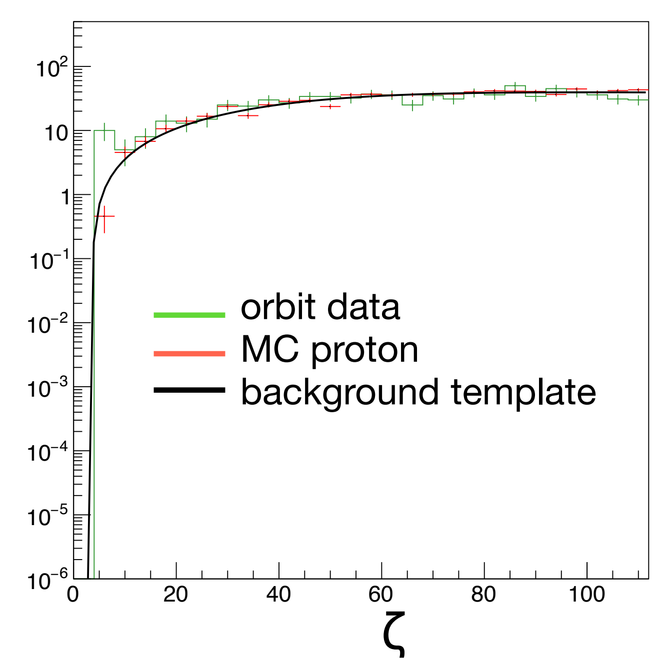



1— 2 TeV

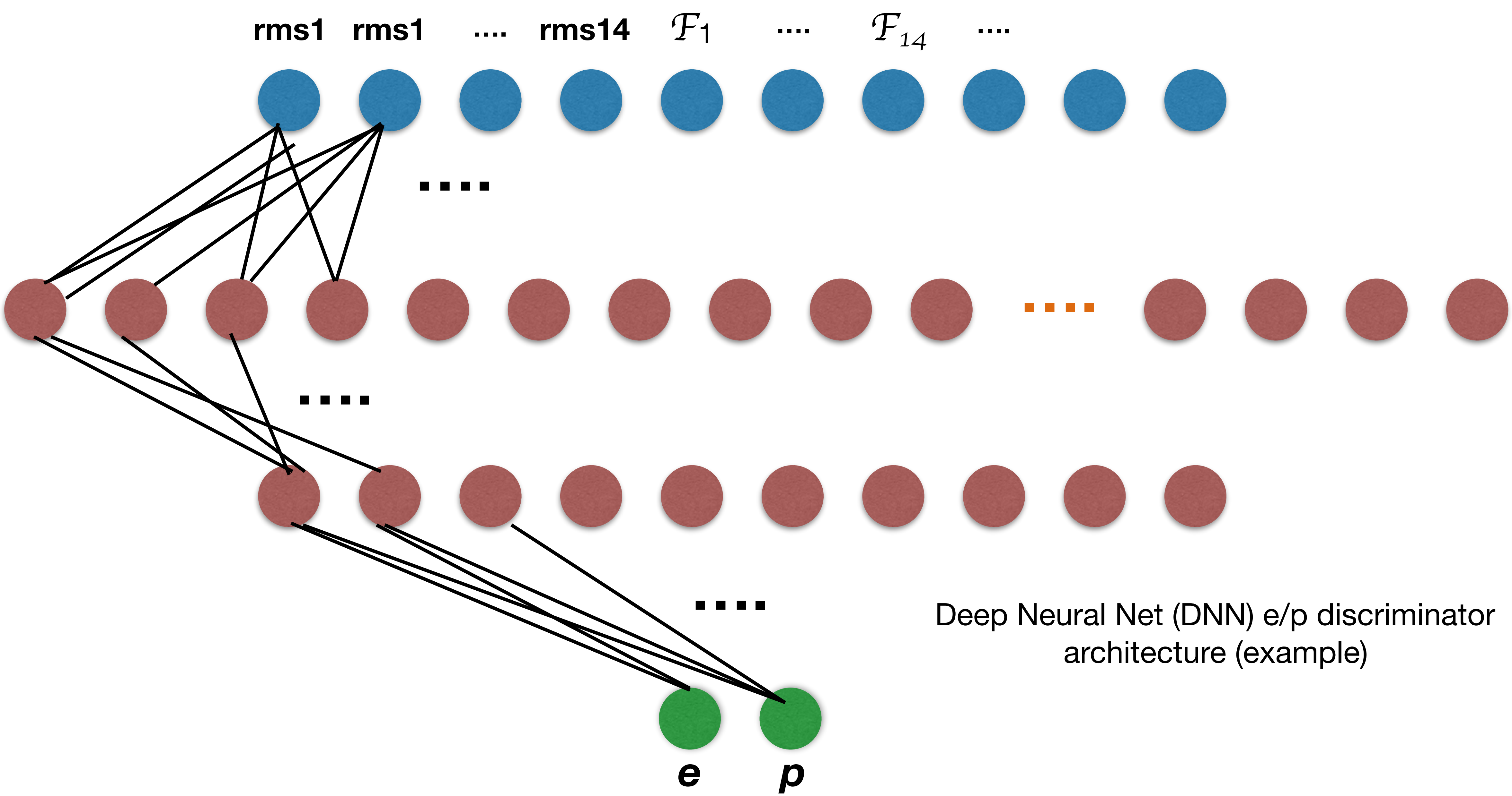



2.2— 2.6 TeV



# Discrimination of e/p & Simulation

- At >5 TeV energies Deep Learning or similar approaches appear promising for e/p discrimination → represents challenge for the simulation.

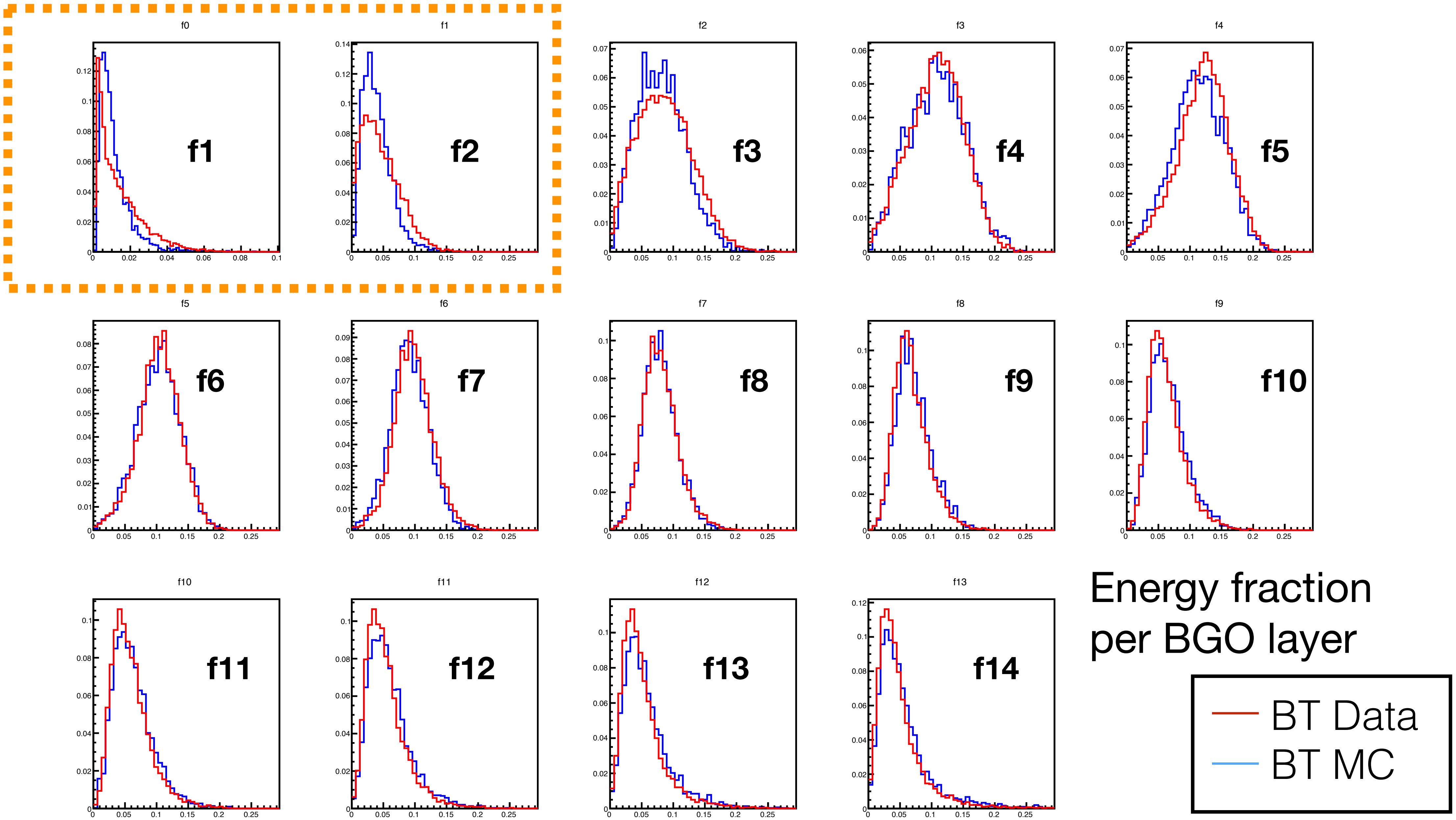



Deep Neural Net (DNN) e/p discriminator architecture (example)

# Discrimination of e/p & Simulation

- e/p classifier optimised with the simulation → relies significantly on the MC precision
- Works well with MC — does it work with the real data? How to estimate background?

**Mismodelling of input variables may throw off the data—MC agreement**



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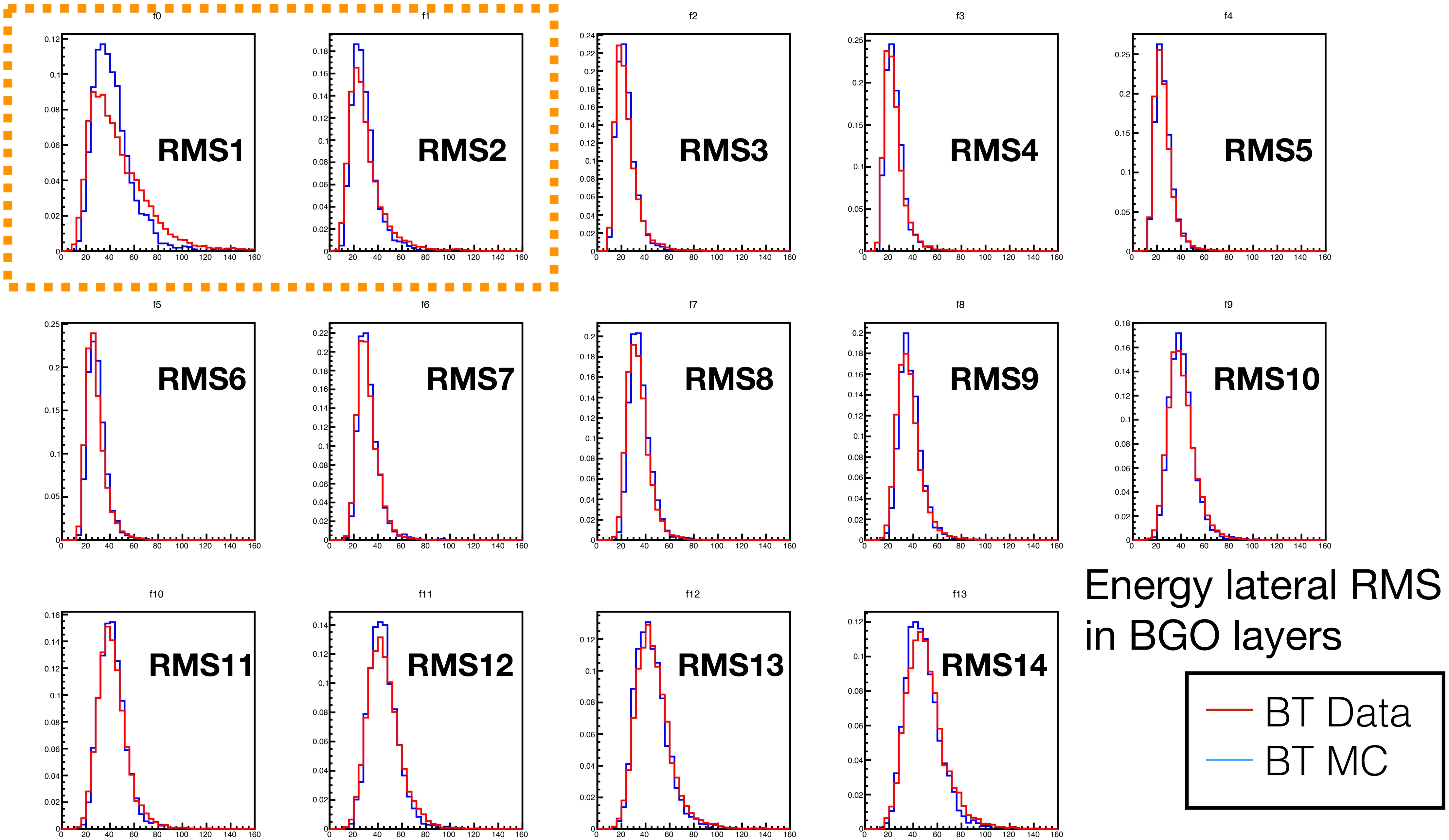
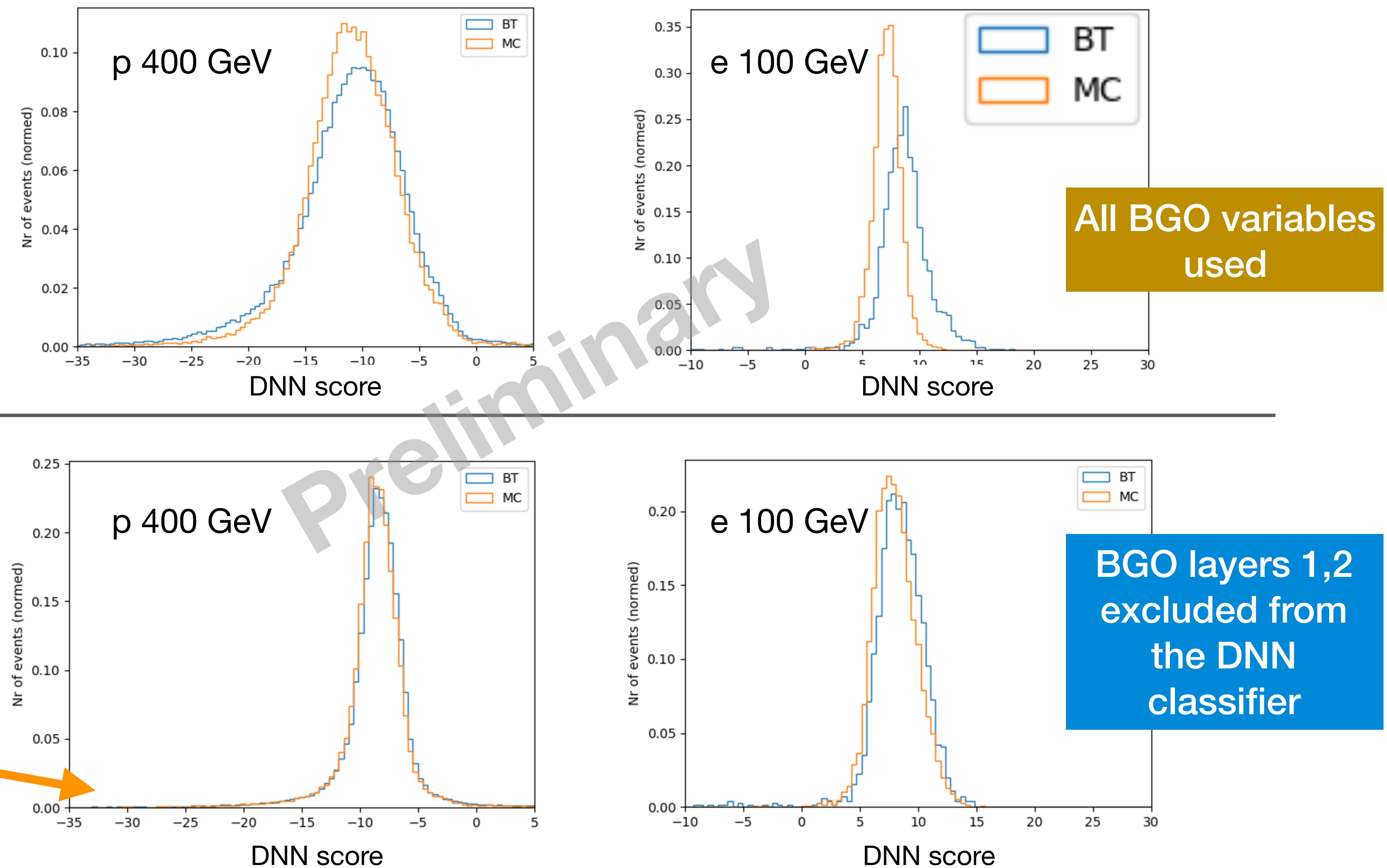



Energy lateral RMS in BGO layers

# Discrimination of e/p & Simulation

- Excluding some non well-modelled variables from DNN allowed to maintain good data-MC agreement of the classifier score, while keeping (almost) the same DNN performance.




**Good data —MC agreement of classifier score**

# Conclusions

- Geant4 DAMPE simulation proven to work well: good agreement with beam-test and orbit data.
- Solutions for performing simulations above 100 TeV:
  - FLUKA
  - GEANT4 + CRMC
- Simulation in CR proton/ion analysis:
  - Energy unfolding
  - Trigger efficiency
  - Charge simulation
  - Hadronic cross-sections
- Good quality of simulation  is important for CR electron analysis and e/p discrimination optimisation.

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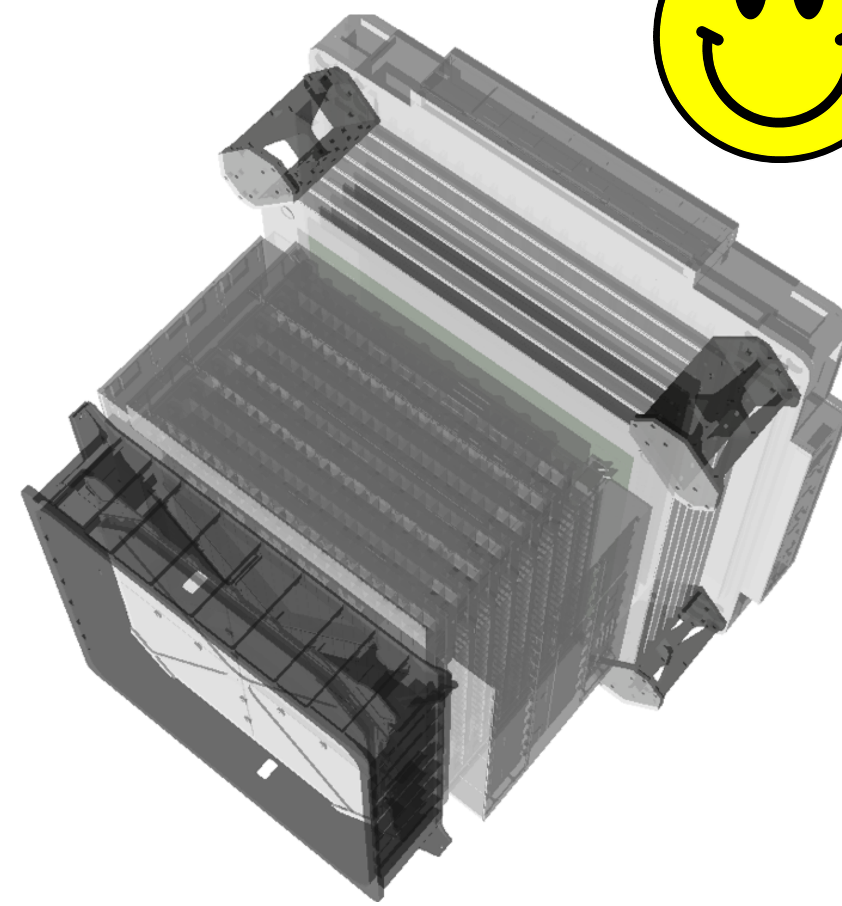

**Thank you!**