

# Validation of Electromagnetic Showers in CORSIKA 8

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# CORSIKA

- Air shower simulation code used by many astroparticle physics experiments
- Originally developed for the KASCADE experiment in the 1980s
- Latest version: 7.7500
- Common reference frame for the community

# Limitations of CORSIKA

- Hand-optimized code: excellent performance, but incurs limitations
- Monolithic Fortran code
- Program options heavily intertwined in source code
- Maintenance increasingly difficult
- Parallelization possibilities limited (MPI parallelized, but no multi-threading, no GPU parallelization, ...)

# CORSIKA 8

- Since 2018: rewrite of CORSIKA in modern C++
- Focus on modularity and the needs and possibilities of modern supercomputing
- Coordinated by KIT, strong community integration

# Electromagnetic cascades

- In CORSIKA 7: modified version of EGS 4
  - Morfran code
  - Deeply integrated into CORSIKA source code
  - Added  $\gamma \rightarrow \mu\mu$ ,  $\gamma N \rightarrow X$ , and (optionally) Landau-Pomeranchuk-Migdal (LPM) effect
- In CORSIKA 8: lepton propagator PROPOSAL
  - Modular C++14 library with Python bindings
  - Propagation of electrons, positrons, and photons as well as muons (and taus)
- Recent additions to CORSIKA 8
  - Implementation of LPM effect for inhomogeneous media
  - Photohadronic interaction

# Comparison of implemented cross-sections

- $e^\pm/\gamma$  processes in EGS 4
  - Bremsstrahlung
  - $e^+e^-$  pair production by photons
  - Møller and Bhabha scattering
  - Compton scattering
  - Electron-positron annihilation
  - Photoelectric effect
  - Coherent (Rayleigh) scattering
- Processes added in the customized version for CORSIKA
  - $\mu^+\mu^-$  pair production by photons
  - Photohadronic interaction  $\gamma N \rightarrow X$
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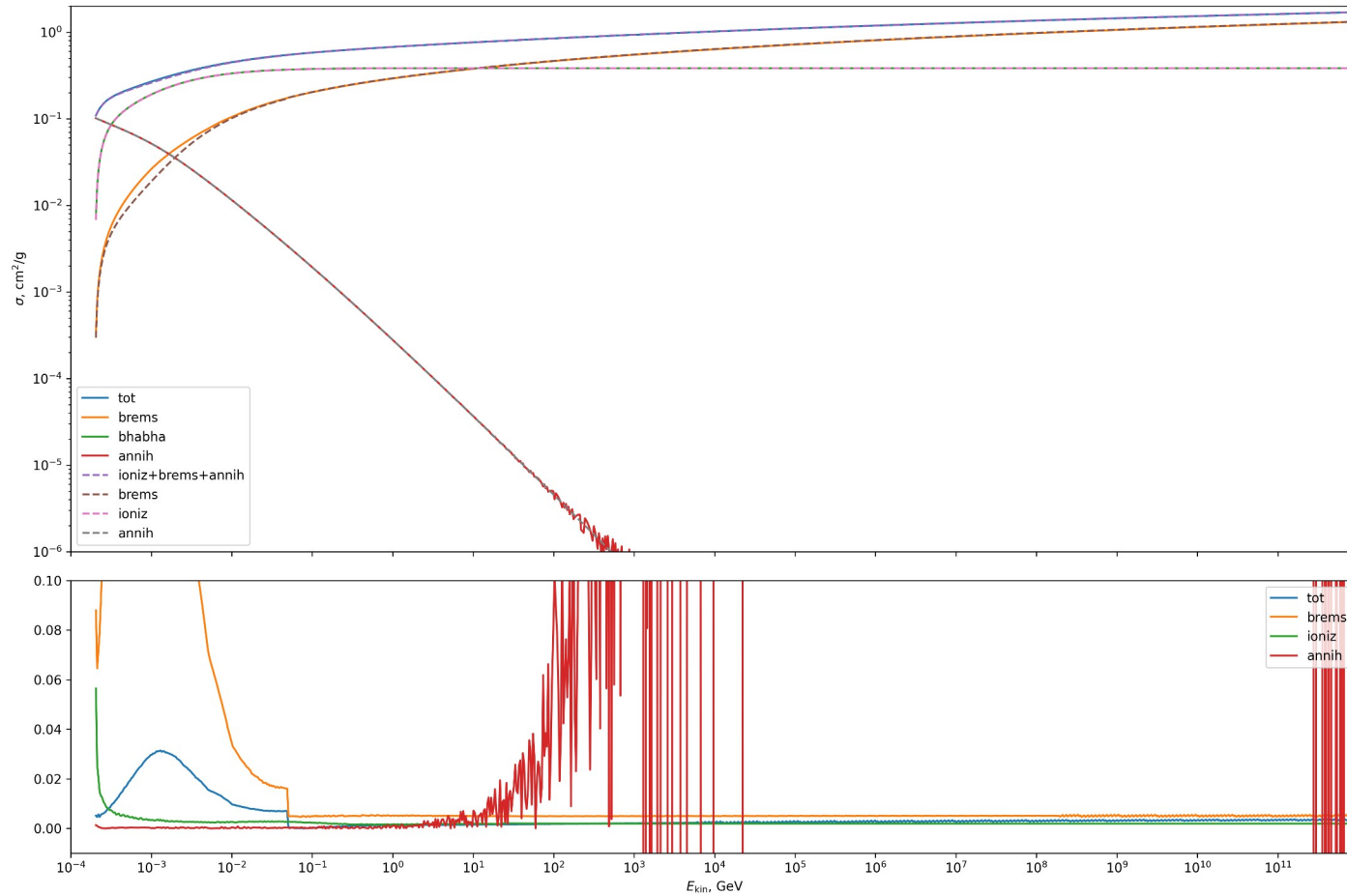
# Different parametrizations

- Photoelectric effect
  - EGS 4: tabulated values, specific for each medium
  - PROPOSAL: analytic parametrization based on Sauter (1931) and empirical correction factors
- Photohadronic interaction
  - EGS 4/C7: secondary particles at low energies produced according to HDPM, at high energies according to high-energy hadronic interaction model
  - PROPOSAL/C8: secondary particles at low energies produced according to SOPHIA, at high energies according to high-energy hadronic interaction model
- Remaining differences are at most at the percent level and appear only at the smallest energies

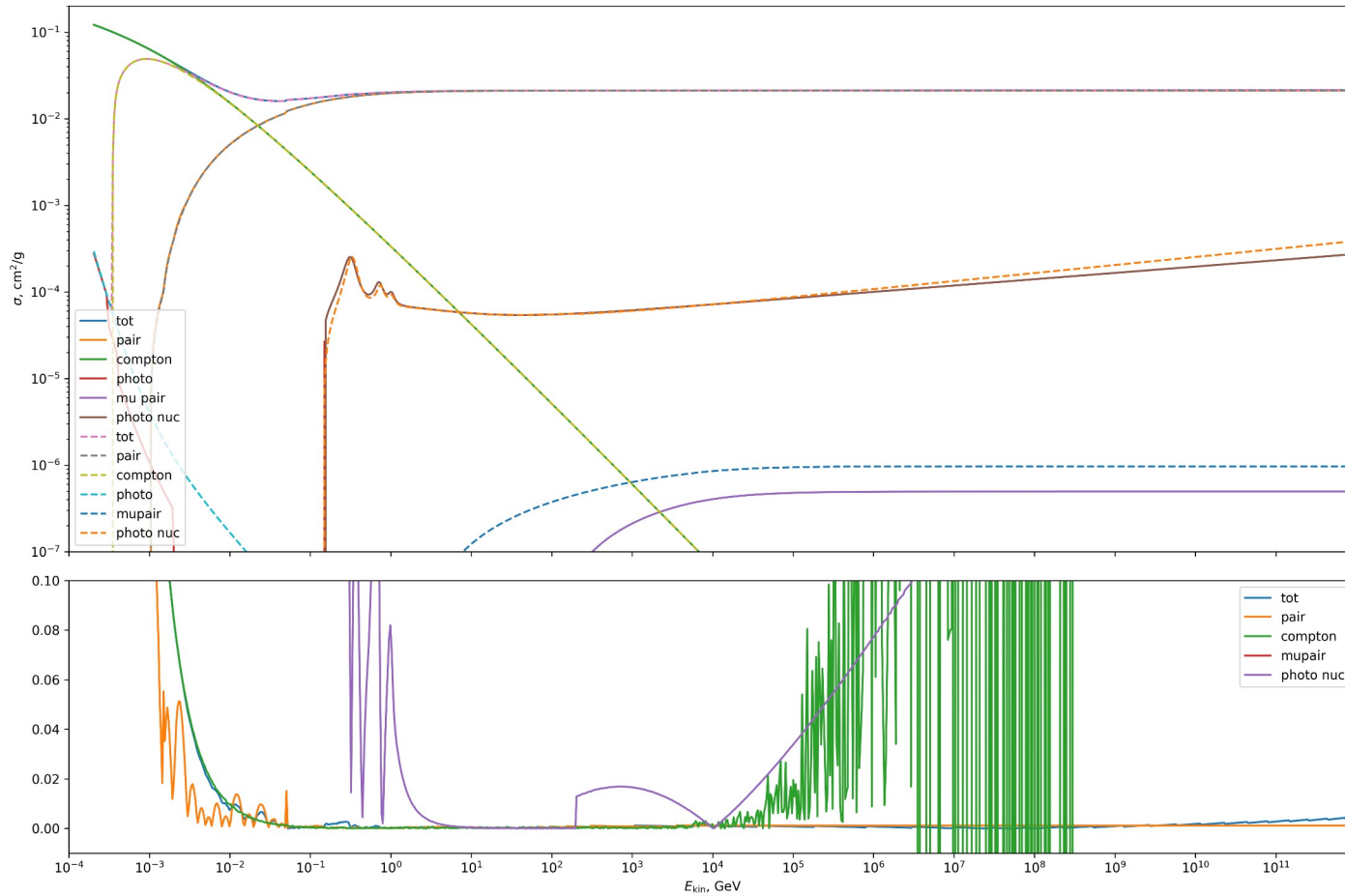




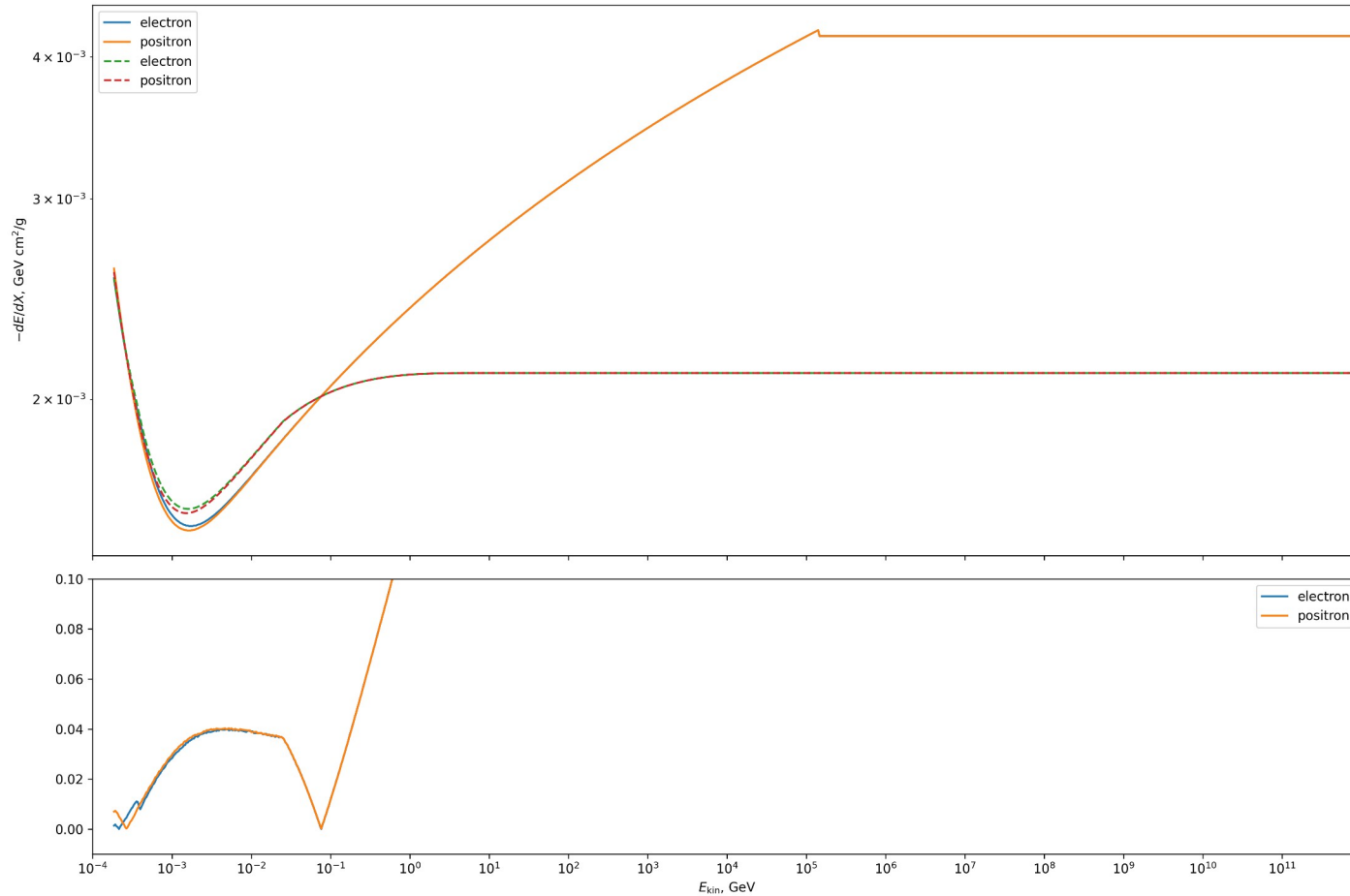
# Positron cross sections



# Photon cross sections



# Continuous energy losses

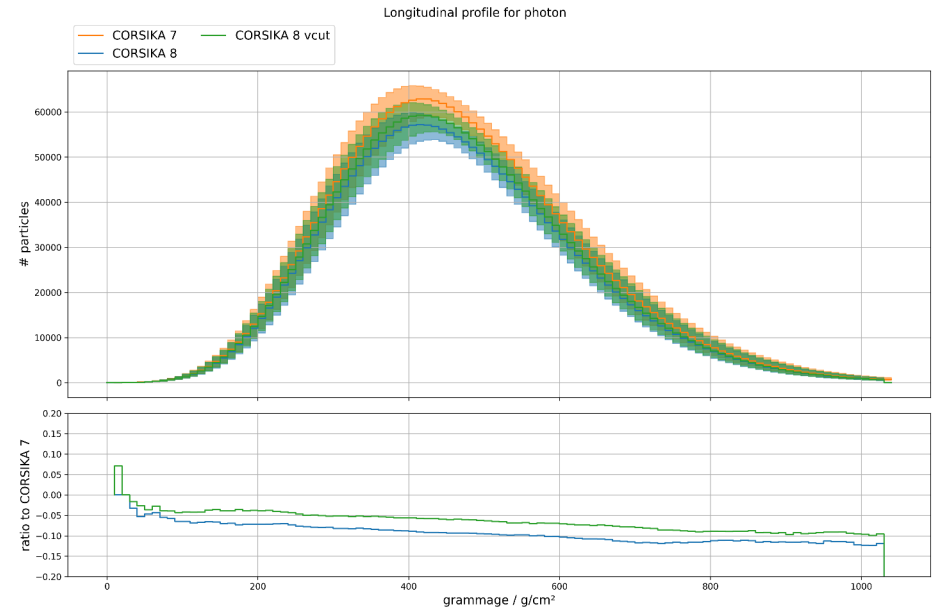
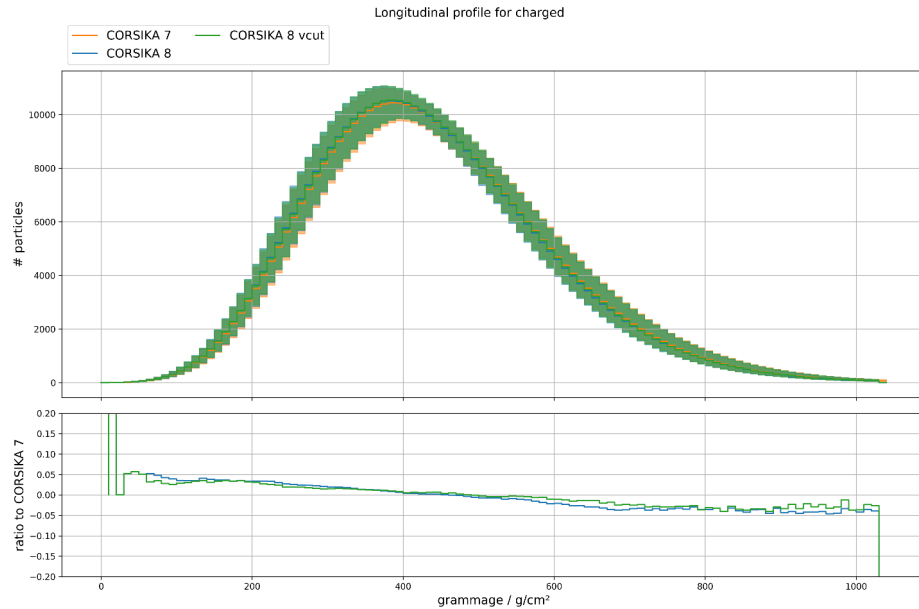


# Validation of electromagnetic showers

- Comparison between C7 and C8
  - CORSIKA v7.7500, UrQMD and Sibyll as interaction models
  - CORSIKA 8, current master with above interaction models, with newest PROPOSAL version
  - CORSIKA 8 with added  $v_{\text{cut}} = 0.01$
- Quantities compared
  - Longitudinal profiles of particle numbers and charge excess
  - Lateral distributions of energy and radius near  $X_{\text{max}}$
- Energies and particle cuts investigated
  - 10 TeV and 100 TeV primary energy with 0.5 MeV and 20 MeV particle cut
  - 10 PeV with 0.5 GeV particle cut
  - 100 EeV with 100 TeV particle cut to compare LPM implementation

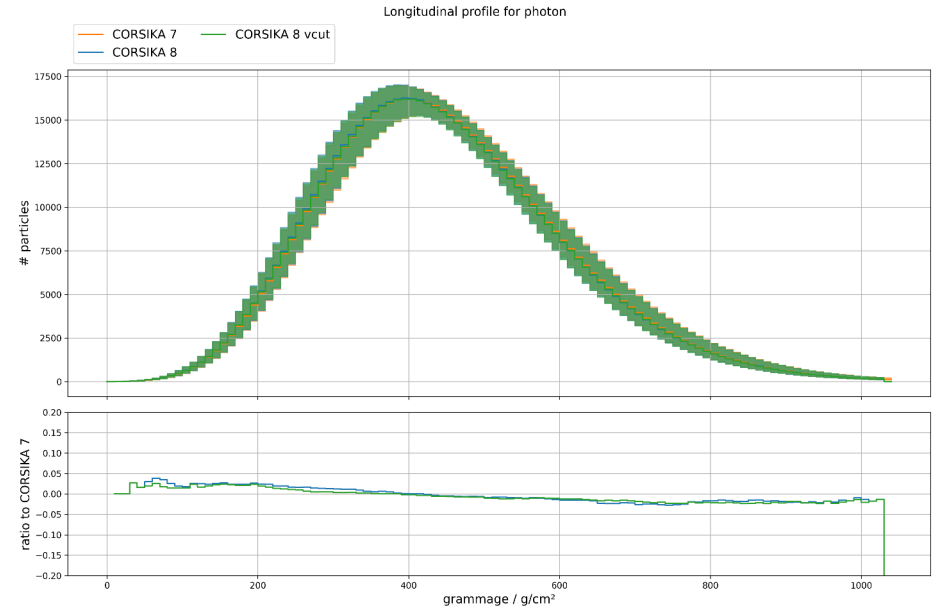
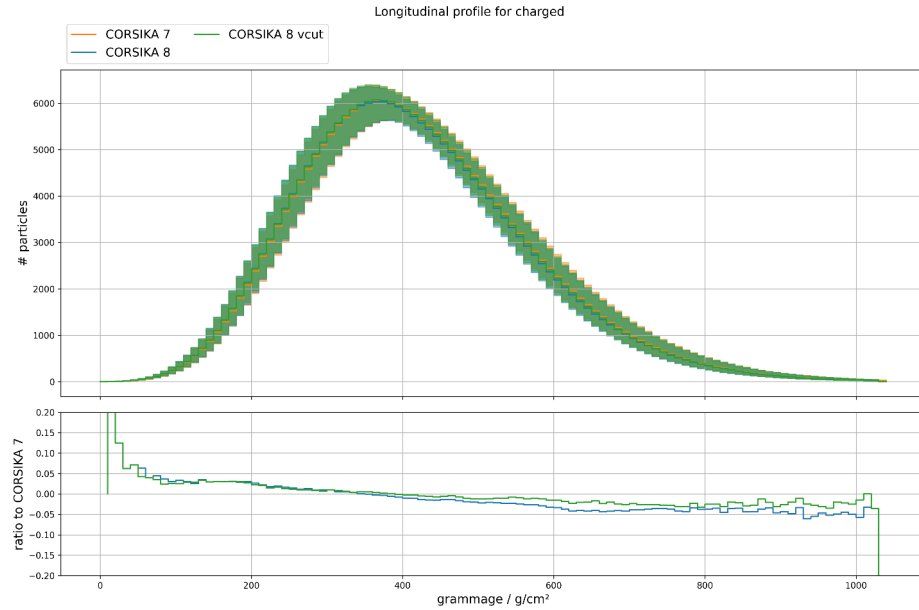
# 10 TeV, 0.5 MeV

## Longitudinal profiles for charged particles and photons



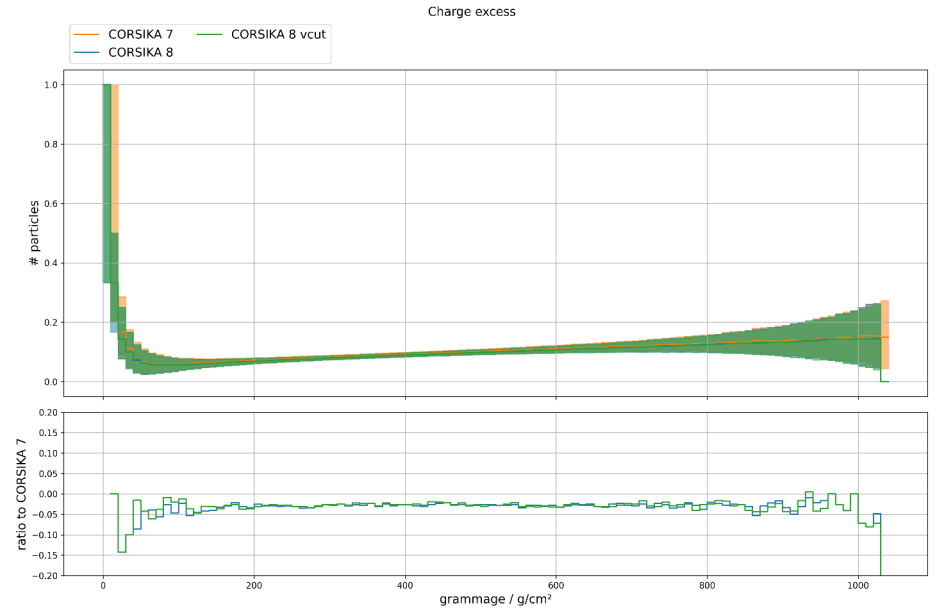
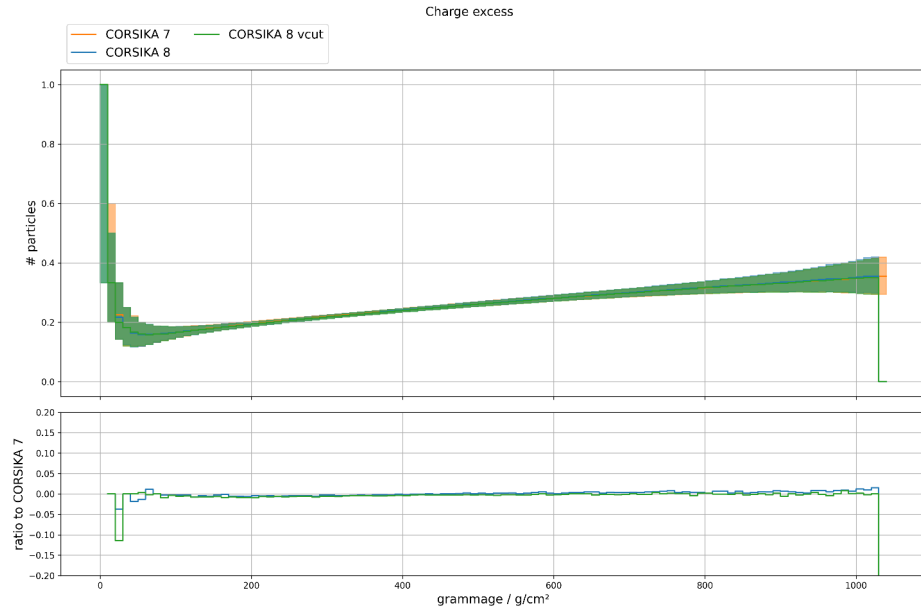
# 10 TeV, 20 MeV

## Longitudinal profiles for charged particles and photons



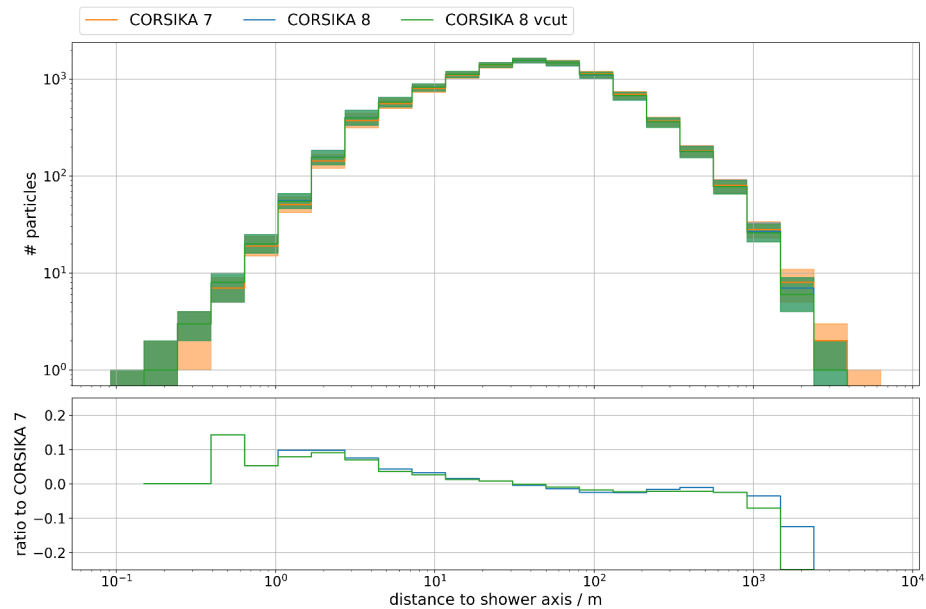
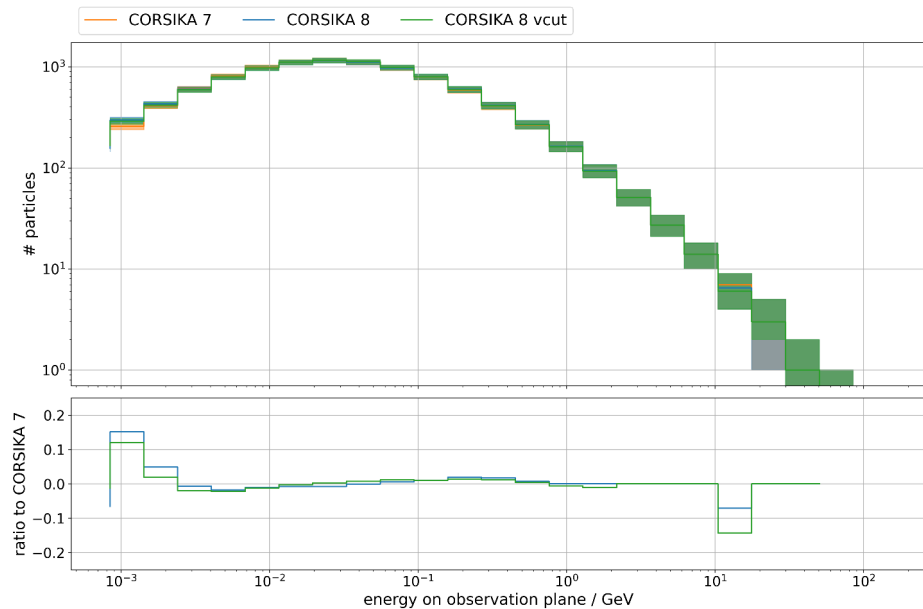
# Charge excess

## 10 TeV with 0.5 MeV resp. 20 MeV

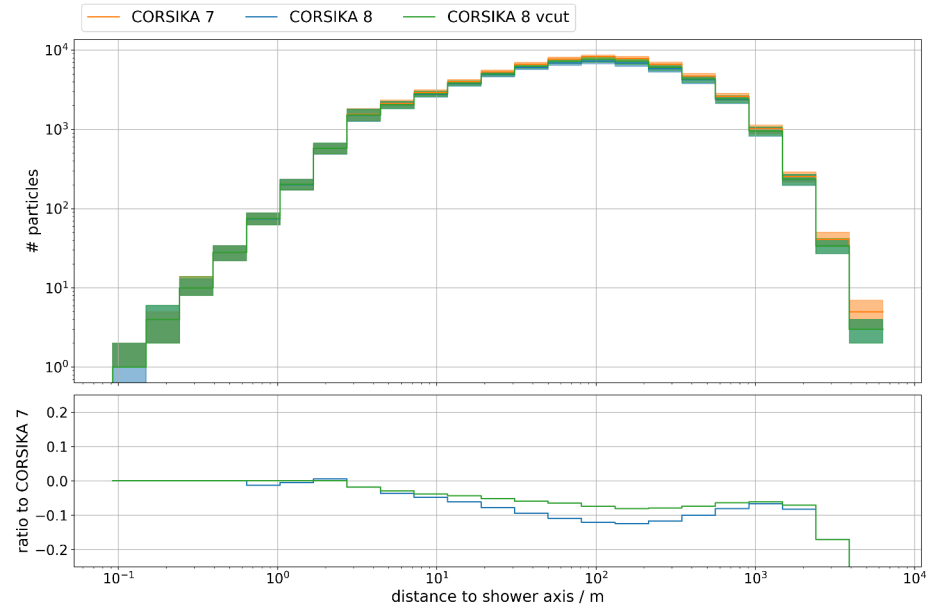
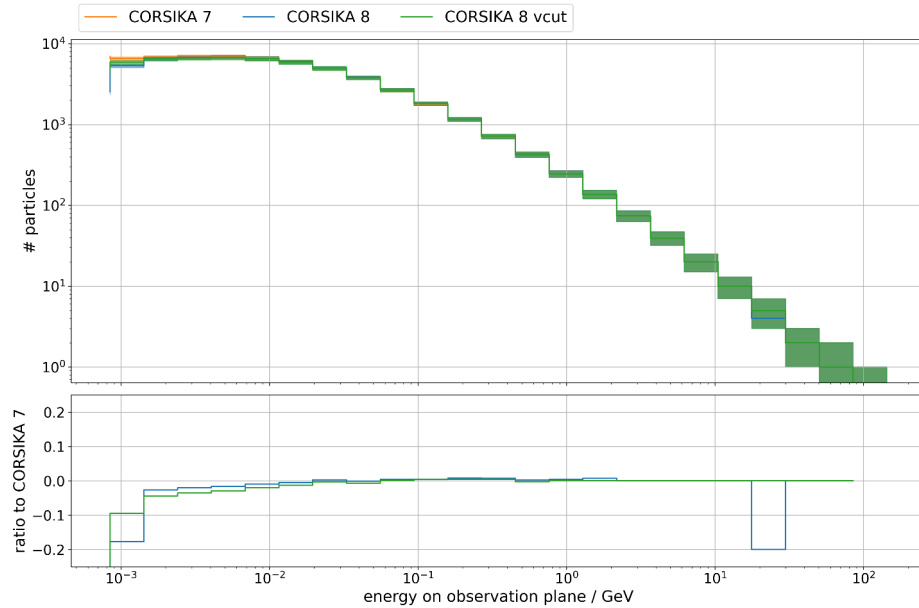




# 10 TeV, Lateral profiles, Charged particles



# 10 TeV, Lateral profiles, Photons

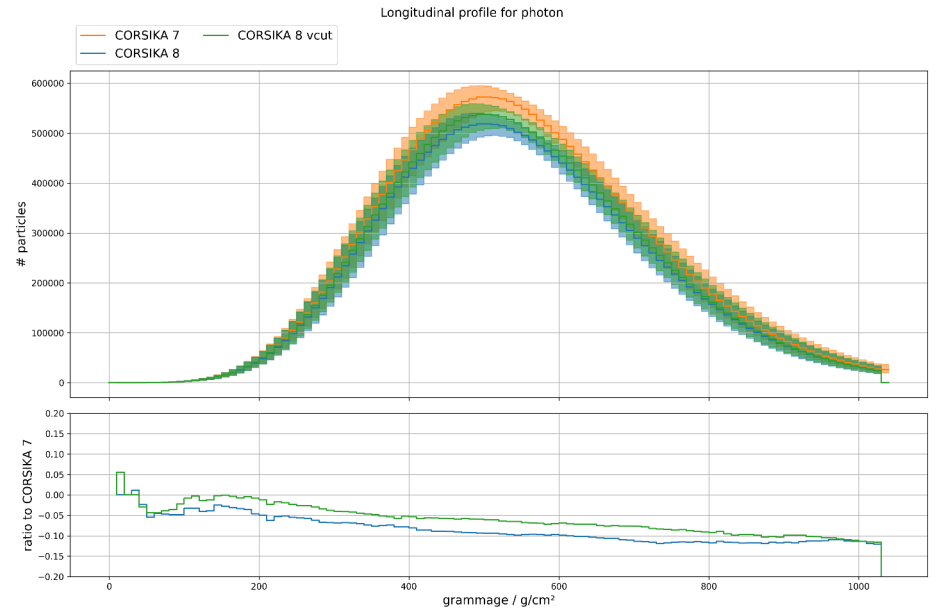
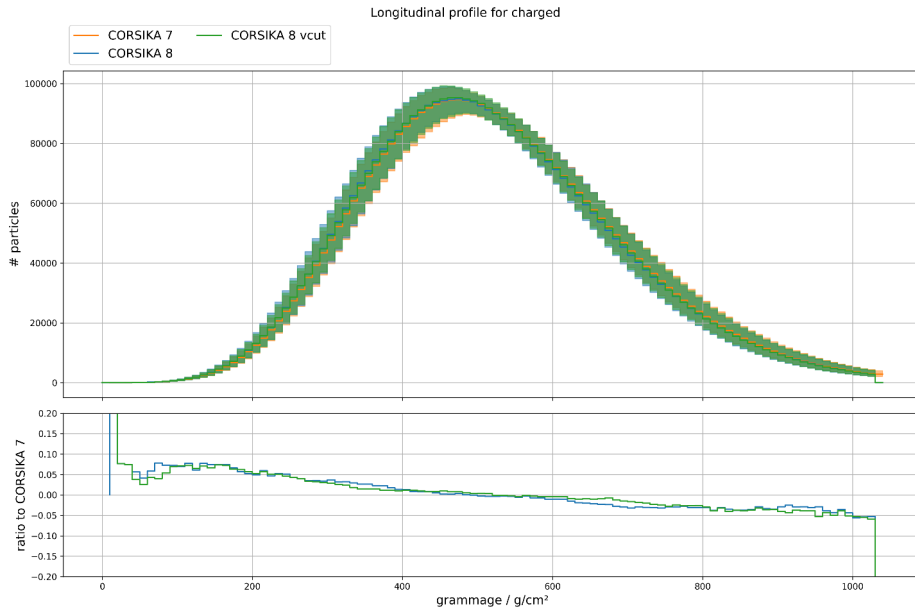


# Conclusions from 10 TeV longitudinal and lateral profiles

- Good agreement of longitudinal profiles for charged particles and charge excess
  - Charge excess systematically too small by a few % for higher particle cut
  - Poorer agreement for photons
  - Different particle cuts show this is due to low-energy photons
- Lateral profiles show generally good agreement, but fewer particles at small radii
- $X_{\max}$  is shifted to slightly earlier depth compared to C7

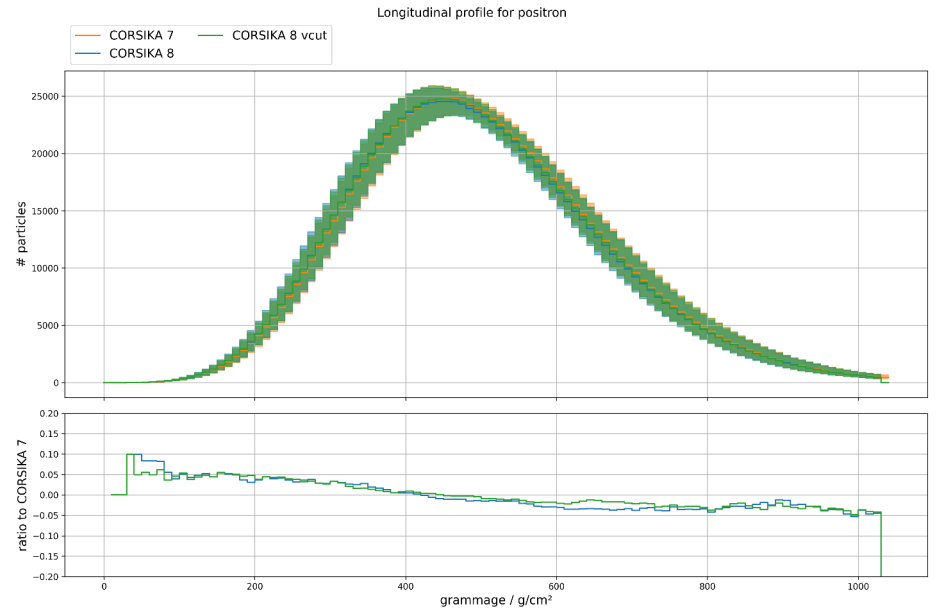
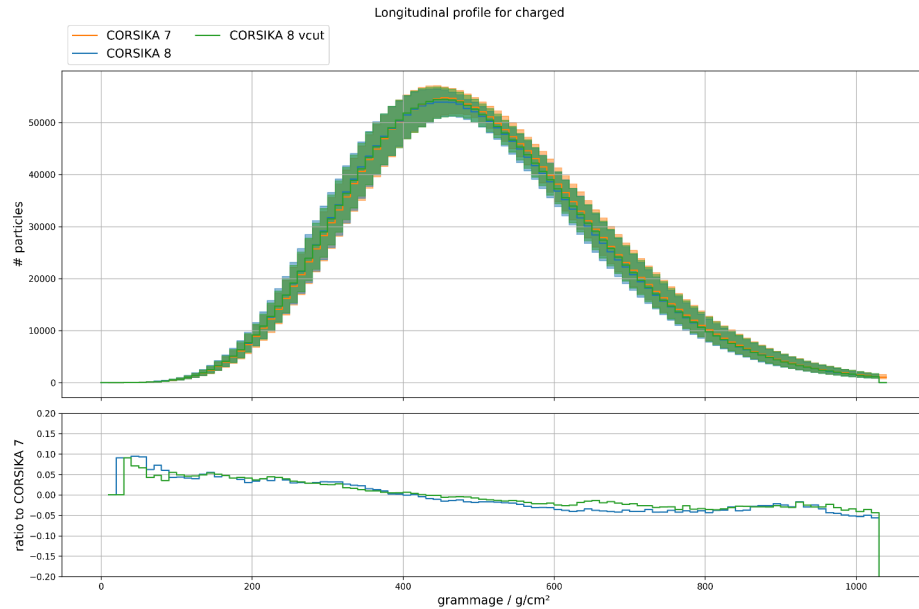
# 100 TeV, 0.5 MeV

## Longitudinal profiles for charged particles and photons



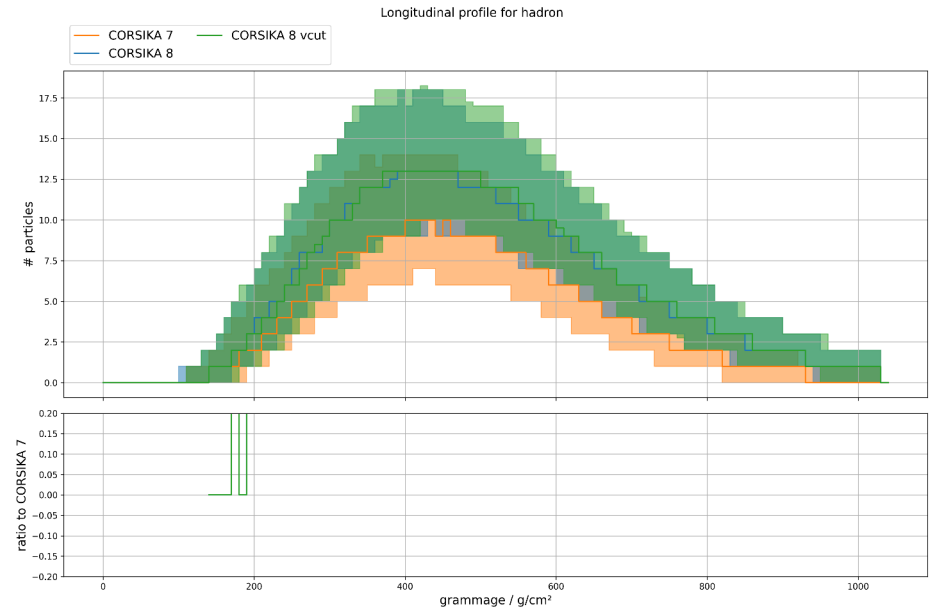
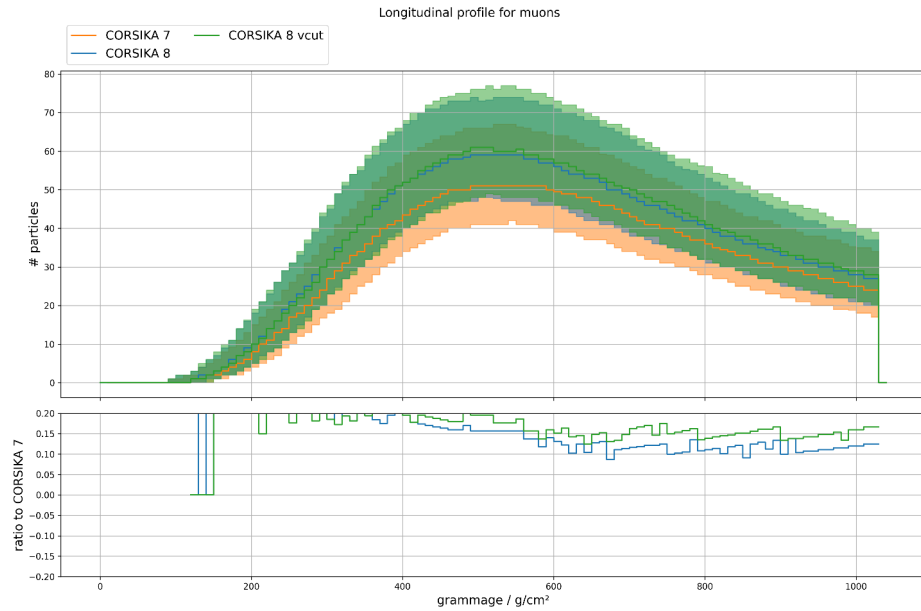
# 100 TeV, 20 MeV

## Longitudinal profiles for charged particles and photons



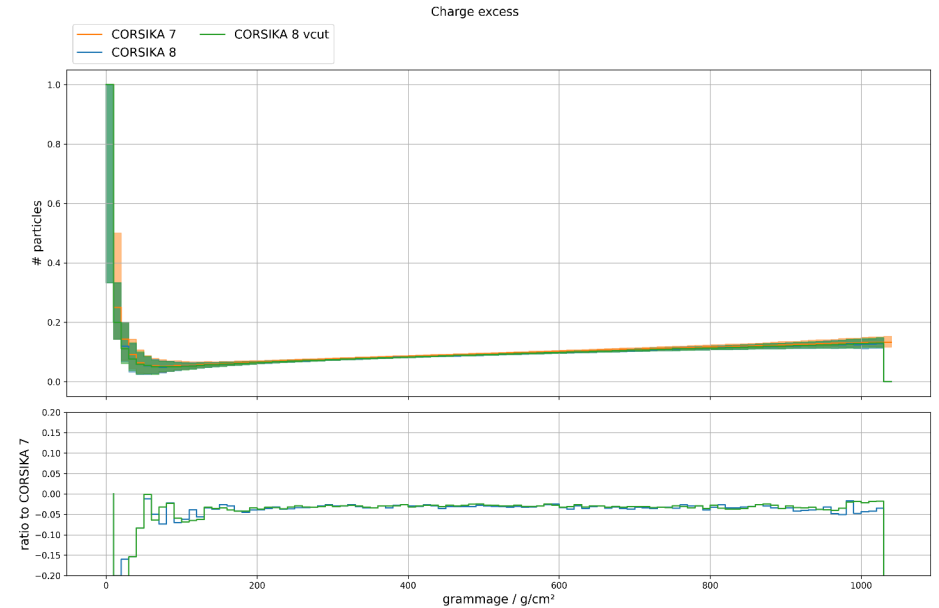
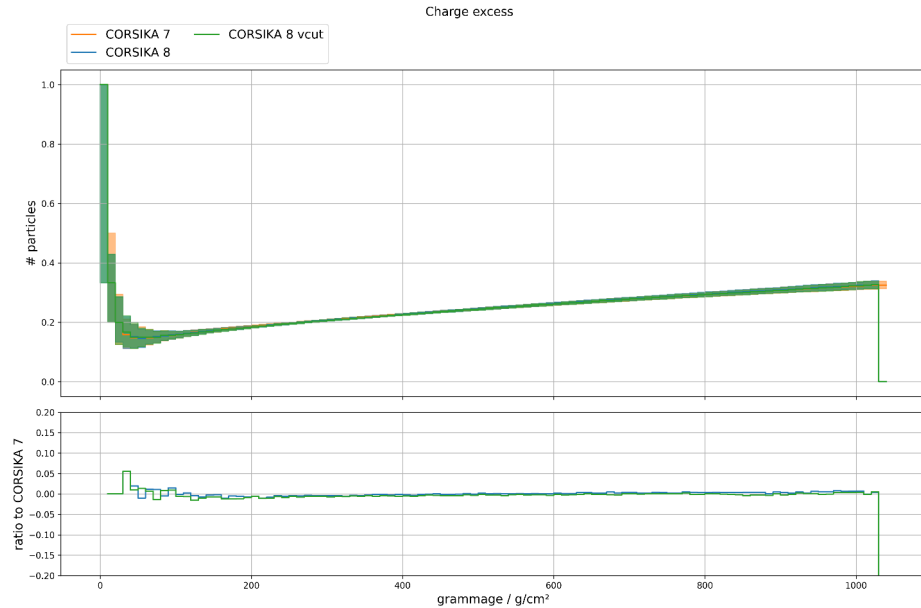
# 100 TeV, 20 MeV

## Longitudinal profiles for muons and hadrons

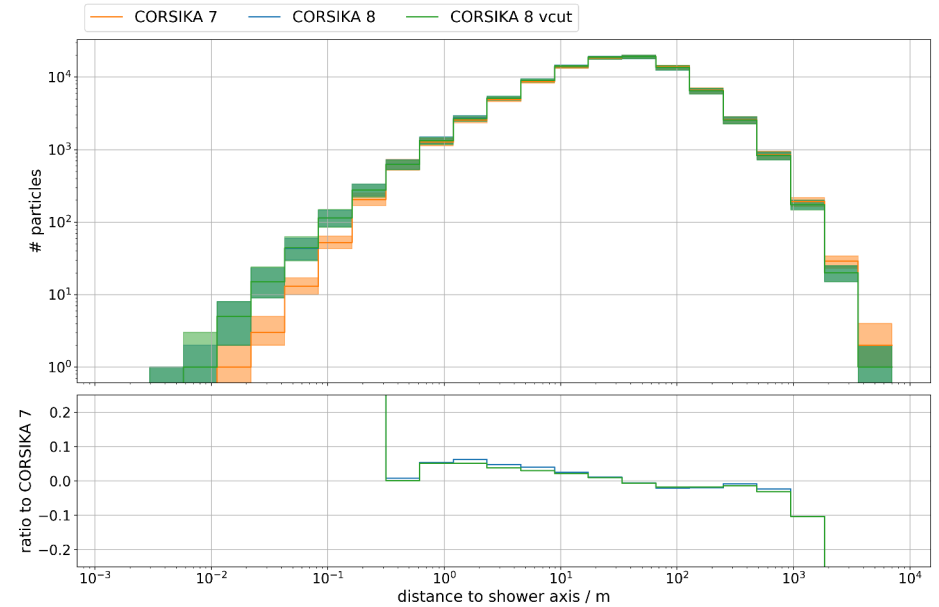
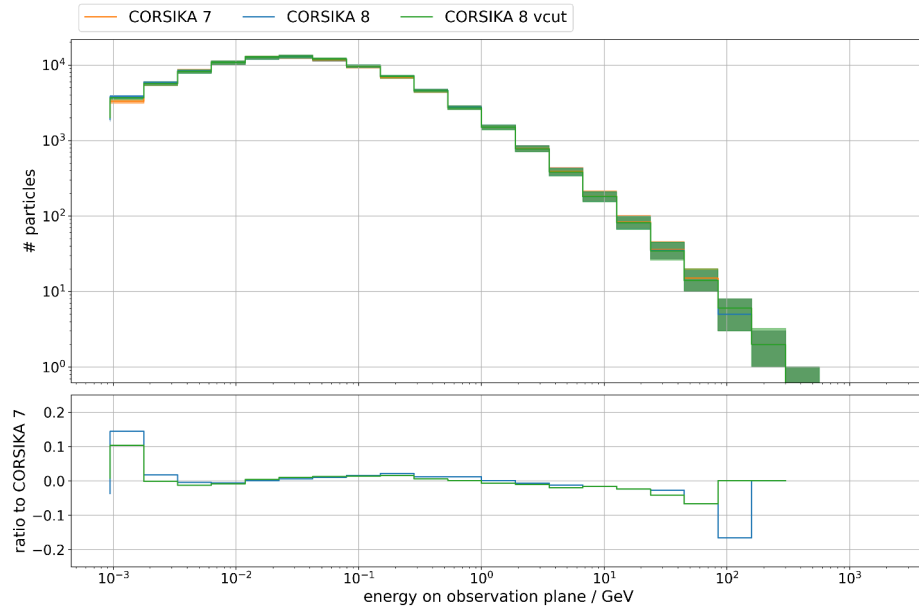


# Charge excess

## 100 TeV with 0.5 MeV resp. 20 MeV

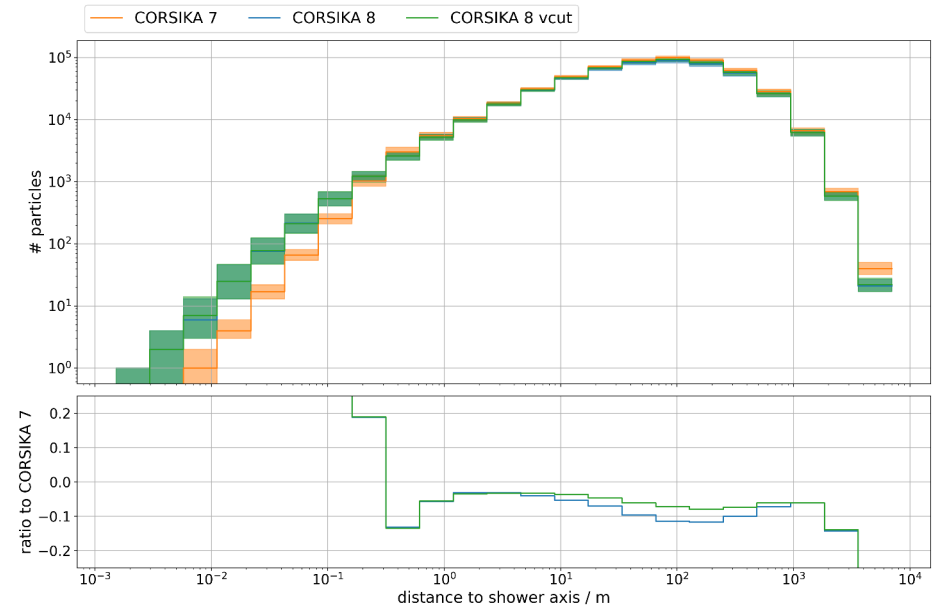
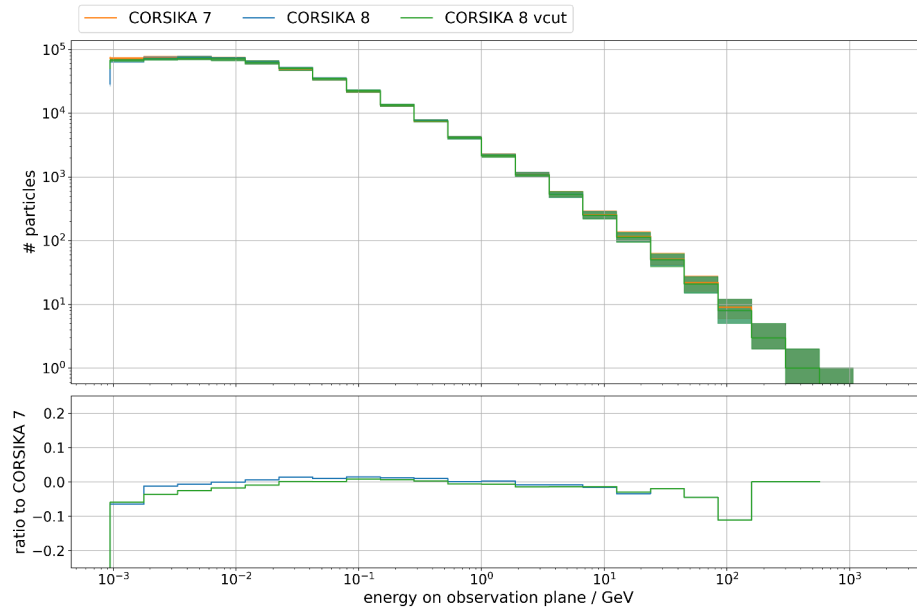


# 100 TeV, Lateral profiles, charged





# 100 TeV, Lateral profiles, Photons

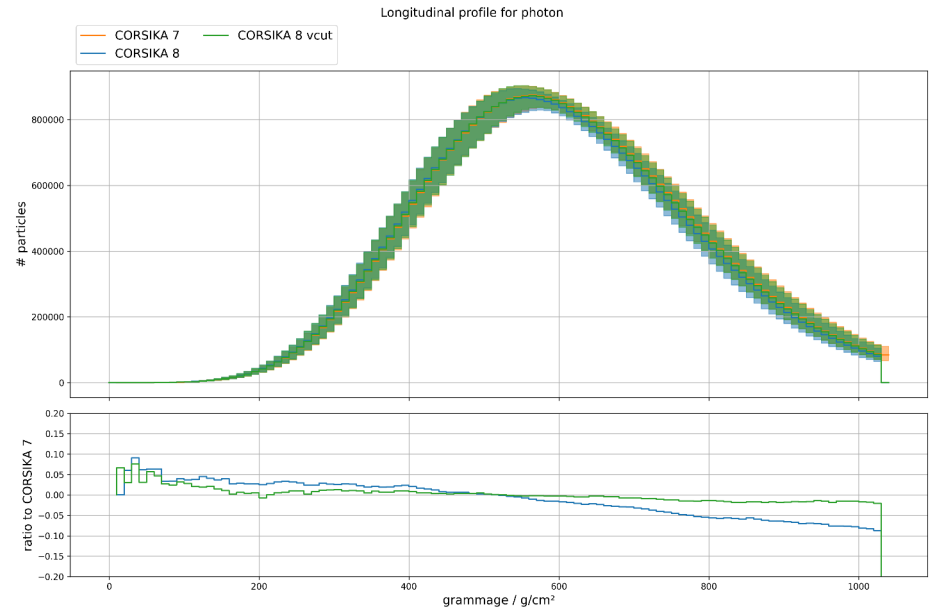
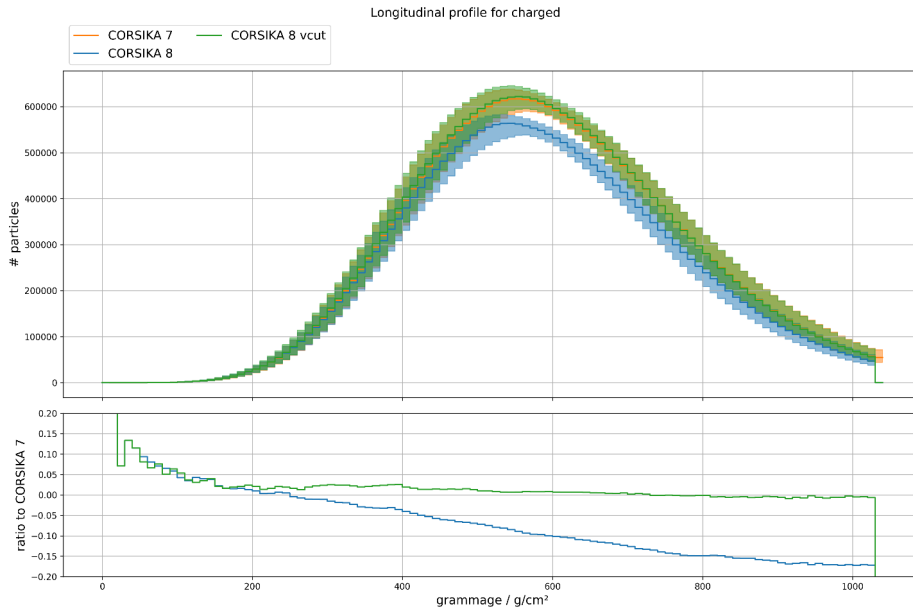


# Conclusions from 100 TeV longitudinal and lateral profiles

- Similar situation to 10 TeV showers
- Trend towards earlier shower maximum is more pronounced
- Muon and hadron profiles show good agreement within uncertainties
  - Muon and hadron numbers are systematically slightly higher in CORSIKA 8

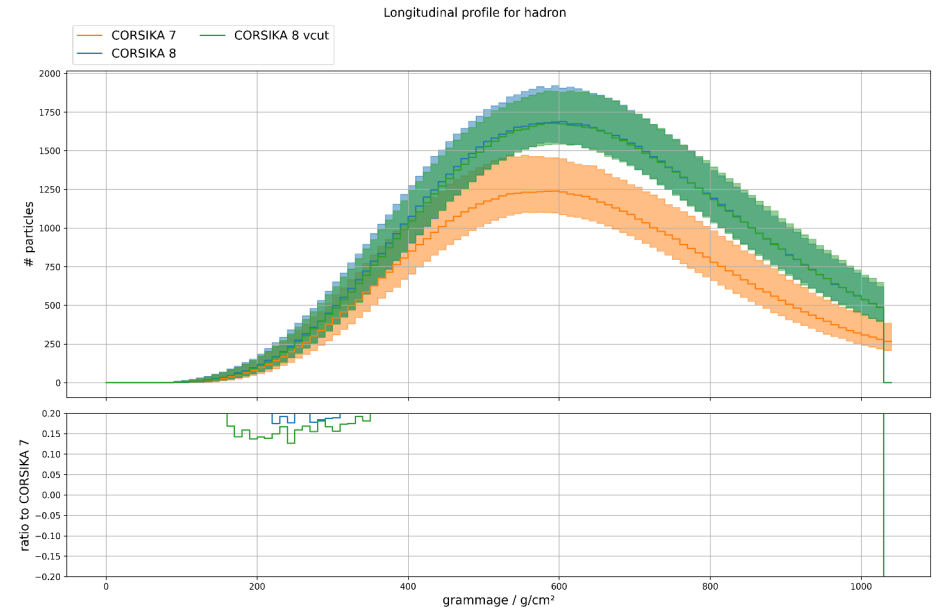
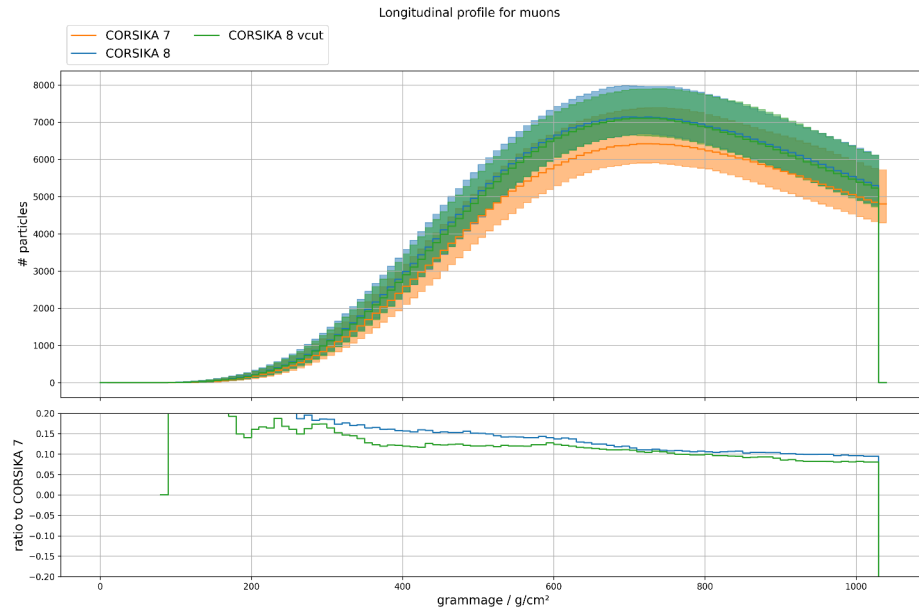
# 10 PeV, 0.5 GeV

## Longitudinal profiles for charged particles and photons



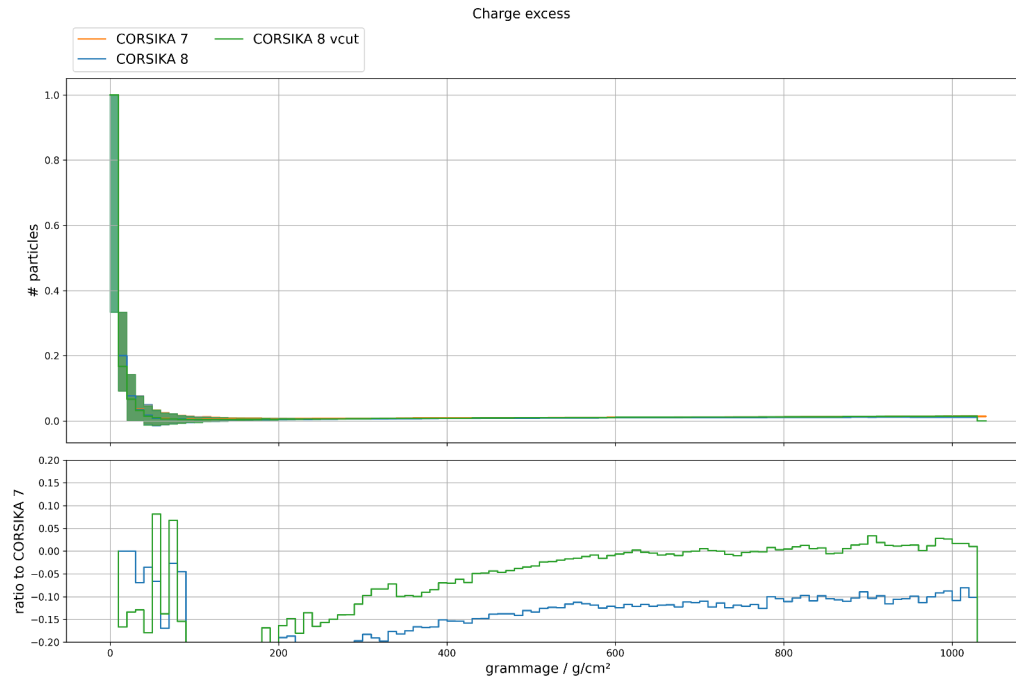
# 10 PeV, 0.5 GeV

## Longitudinal profiles for muons and hadrons



# Charge excess

## 10 PeV with 0.5 GeV



# Conclusions from 10 PeV longitudinal profiles

- Trends from lower energies continue
  - Earlier shower maximum
  - More muons and hadrons in C8 (10–15%)
- Agreement between C7 and C8 is substantially improved by introducing an additional cut on the secondary energy fraction  $v_{\text{cut}}$  → see Jean-Marco's talk for more details

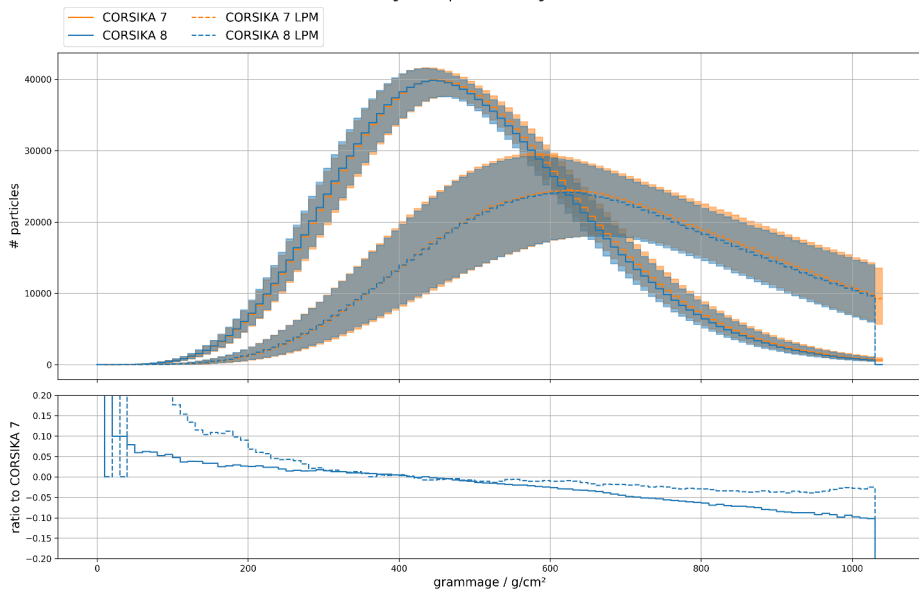
# LPM implementation validation

- Neumann rejection method based on LPM and BH cross-sections → details in Jean-Marco's presentation
- To keep runtimes bearable, extremely high particle cut
  - Primary energy: 100 EeV
  - Particle cut: 100 TeV

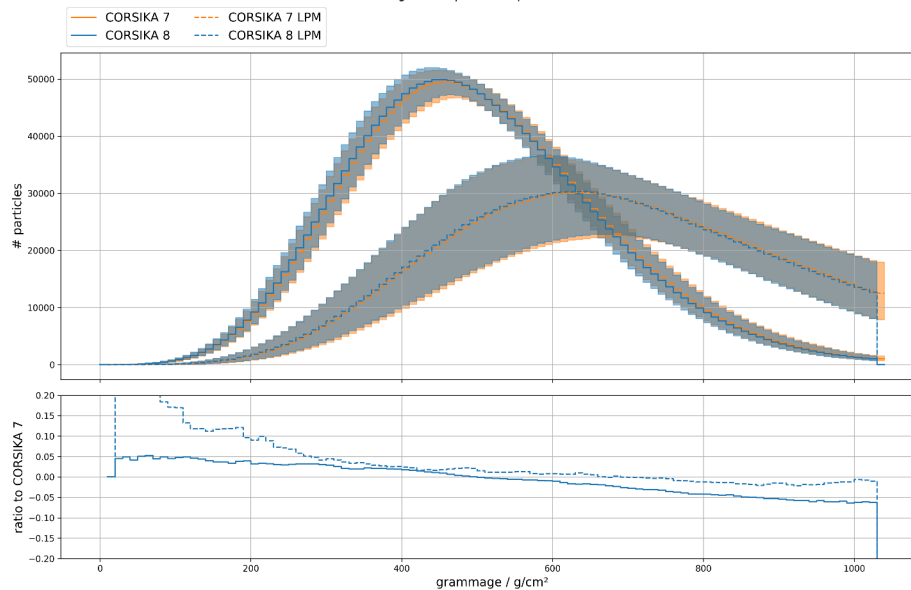
# 100 EeV with 100 TeV cut

## Longitudinal profiles for charged particles and photons

Longitudinal profile for charged



Longitudinal profile for photon





# Conclusions from 100 EeV profiles

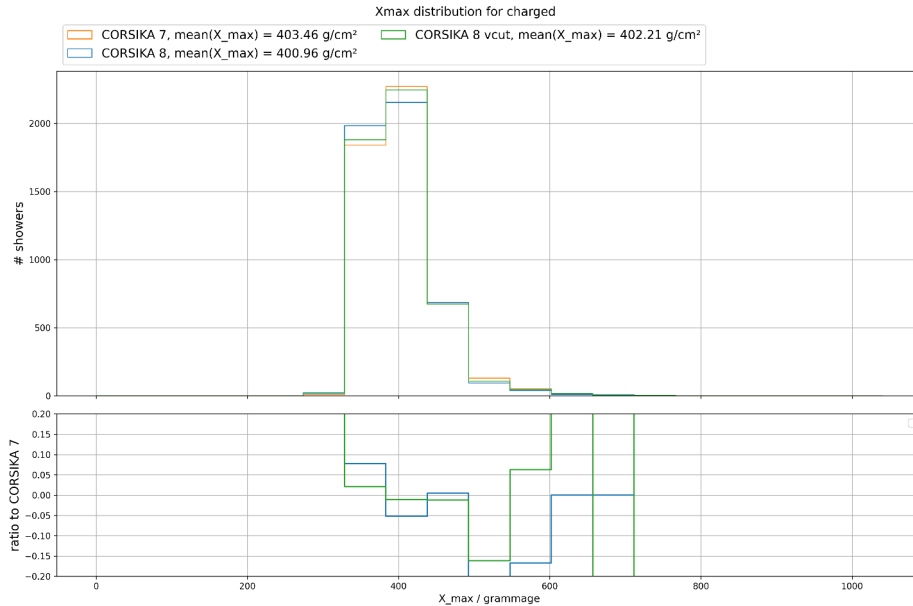
- Agreement within 5–10% between C7 and C8
- LPM effect shows expected behaviour
  - Suppression of bremsstrahlung and pair production
  - Shower develops later and slower
- Muon and hadron numbers too low at these extreme cuts to draw conclusions

# Overall conclusion

- Electromagnetic cascades show good agreement between C7 and C8
  - Longitudinal profiles of charged particles agree within better than 5% with  $v_{\text{cut}}$
  - Longitudinal profiles of photons show deficit compared to C7
  - Longitudinal profiles of muons and hadrons show ~10% excess compared to C7
  - Shower maximum slightly earlier
  - Charge excess agrees within better than 3%
- Agreement better for higher particle cuts → some remaining issues at low energies
- LPM effect implementation shows good agreement with C7

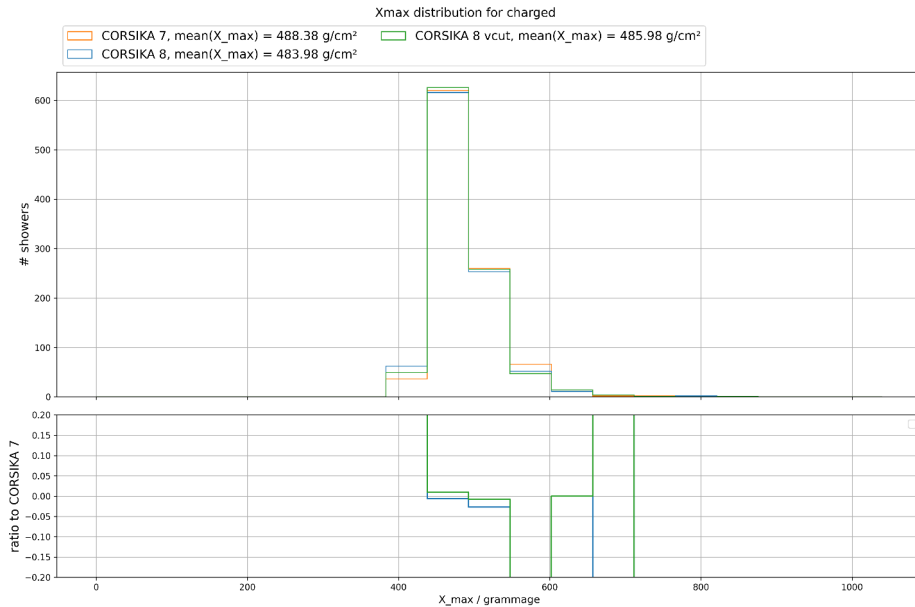
Backup

# Distribution of $X_{\max}$ for 10 TeV



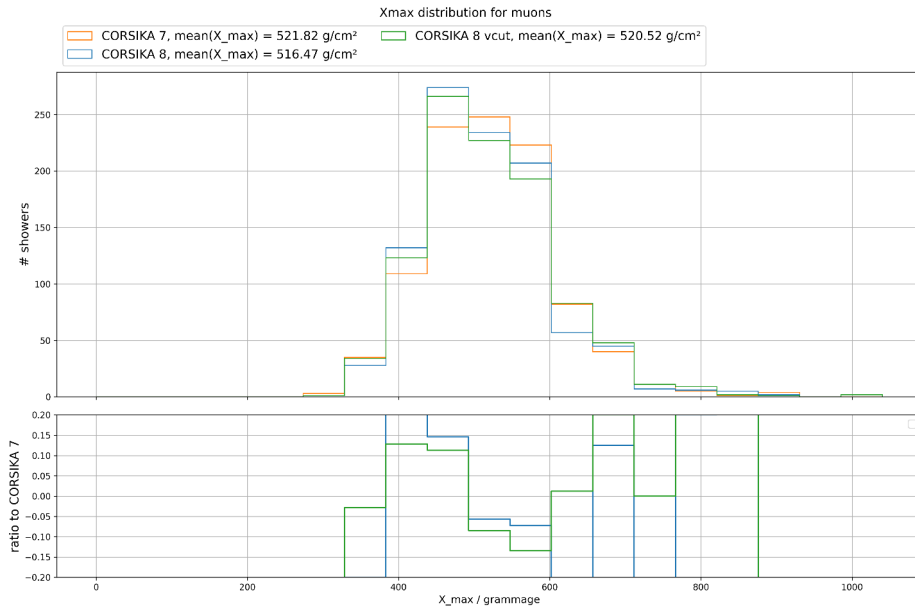
- Depth of bin with highest charged particle number
  - C7: 404 g/cm<sup>2</sup>
  - C8: 401 g/cm<sup>2</sup>
  - C8,  $v_{\text{cut}}$ : 402 g/cm
- Shift of 2–3 g/cm<sup>2</sup>

# Distribution of $X_{\max}$ for 100 TeV



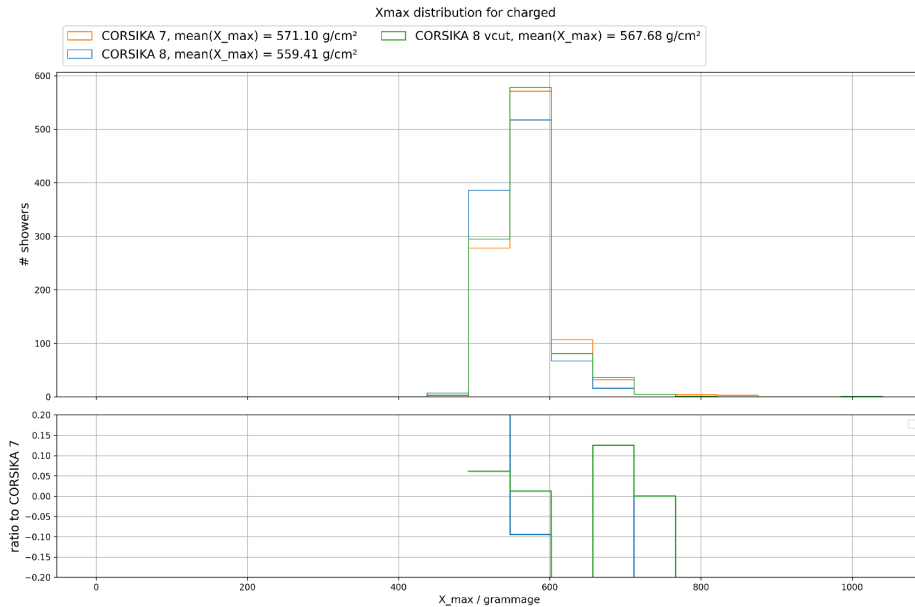
- Depth of bin with highest charged particle number
  - C7: 488 g/cm<sup>2</sup>
  - C8: 484 g/cm<sup>2</sup>
  - C8,  $v_{\text{cut}}$ : 486 g/cm
- Shift of 2–4 g/cm<sup>2</sup>

# Distribution of $X_{\max, \mu}$ for 100 TeV



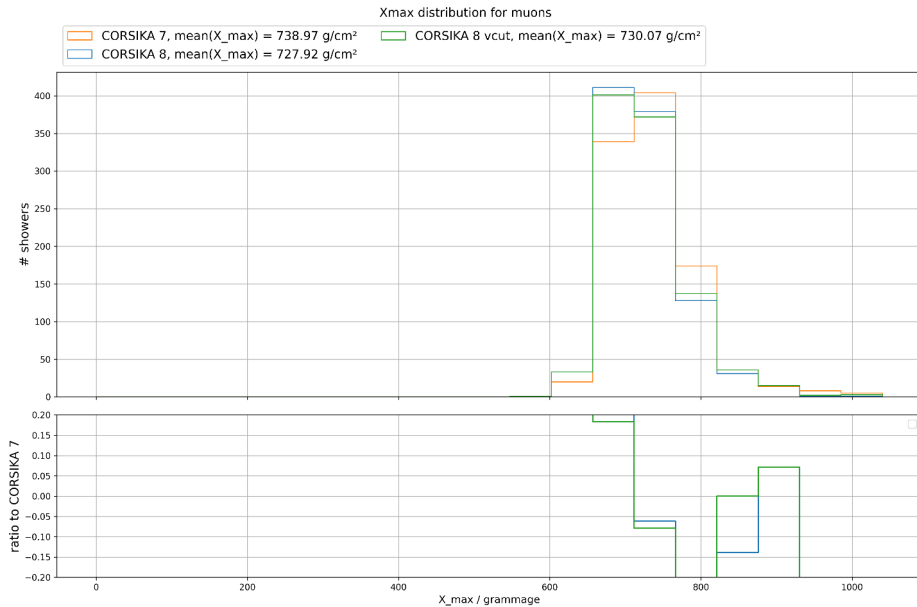
- Depth of bin with highest muon number
  - C7: 522 g/cm<sup>2</sup>
  - C8: 516 g/cm<sup>2</sup>
  - C8,  $v_{\text{cut}}$ : 520 g/cm
- Shift of 2–4 g/cm<sup>2</sup>

# Distribution of $X_{\max}$ for 10 PeV



- Depth of bin with highest charged particle number
  - C7: 571 g/cm<sup>2</sup>
  - C8: 559 g/cm<sup>2</sup>
  - C8,  $v_{\text{cut}}$ : 568 g/cm
- Shift of 3–12 g/cm<sup>2</sup>

# Distribution of $X_{\max, \mu}$ for 10 PeV



- Depth of bin with highest muon number
  - C7: 739 g/cm<sup>2</sup>
  - C8: 728 g/cm<sup>2</sup>
  - C8,  $v_{\text{cut}}$ : 730 g/cm
- Shift of 9–11 g/cm<sup>2</sup>