Validation of Electromagnetic Showers in CORSIKA 8

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for the CORSIKA 8 Collaboration

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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
  - Mortran 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
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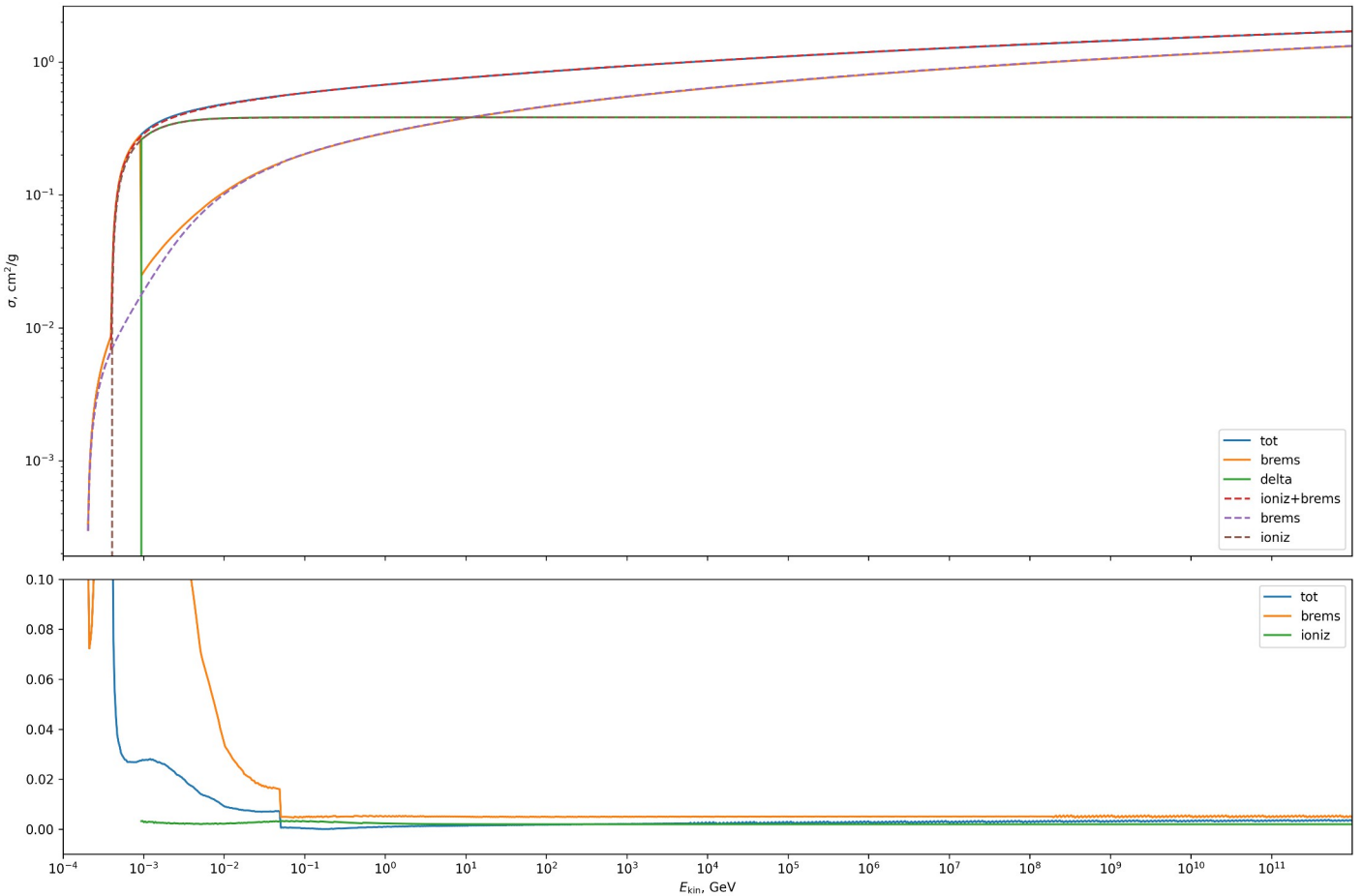
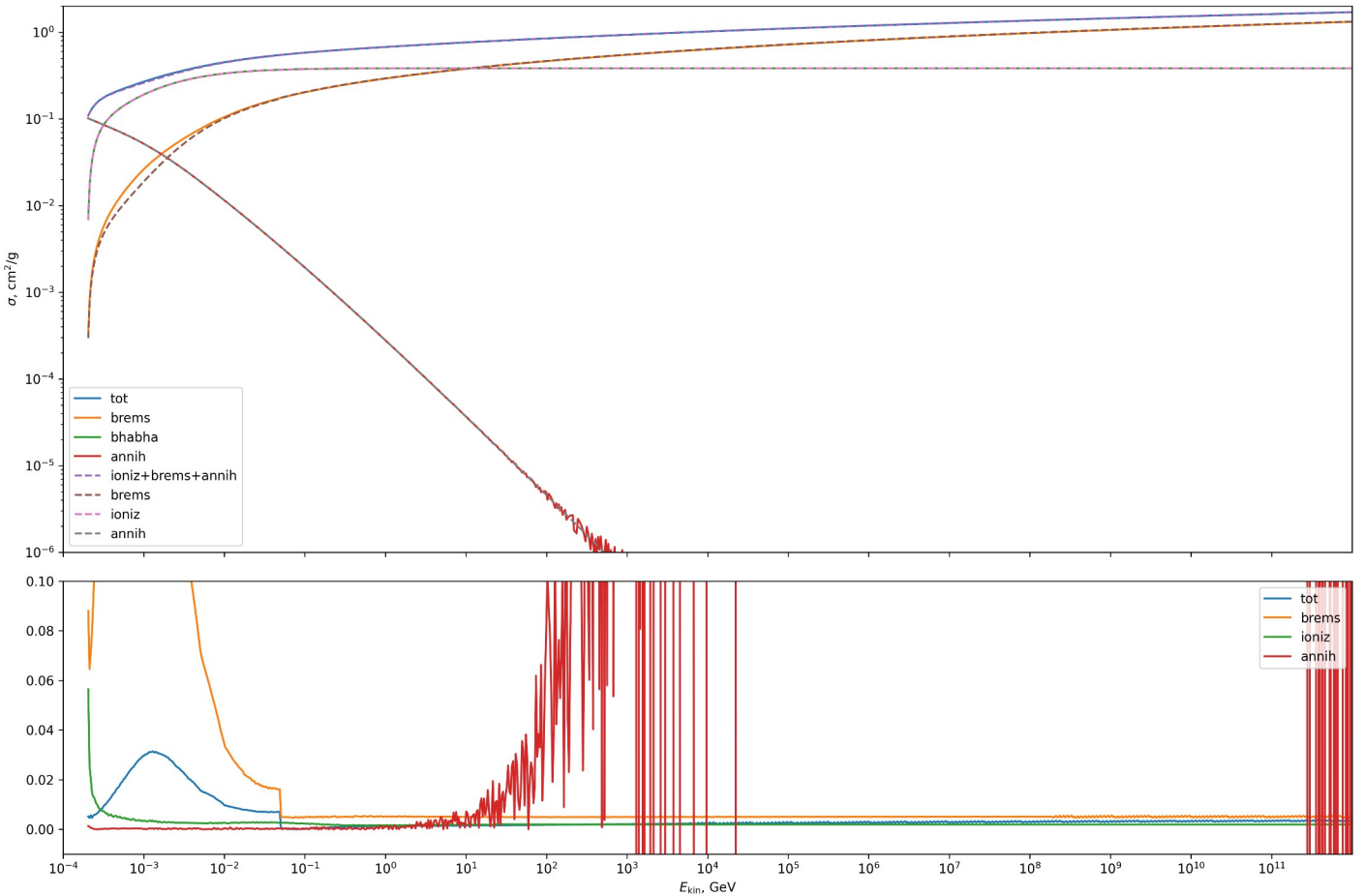
Different parametrizations

- 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

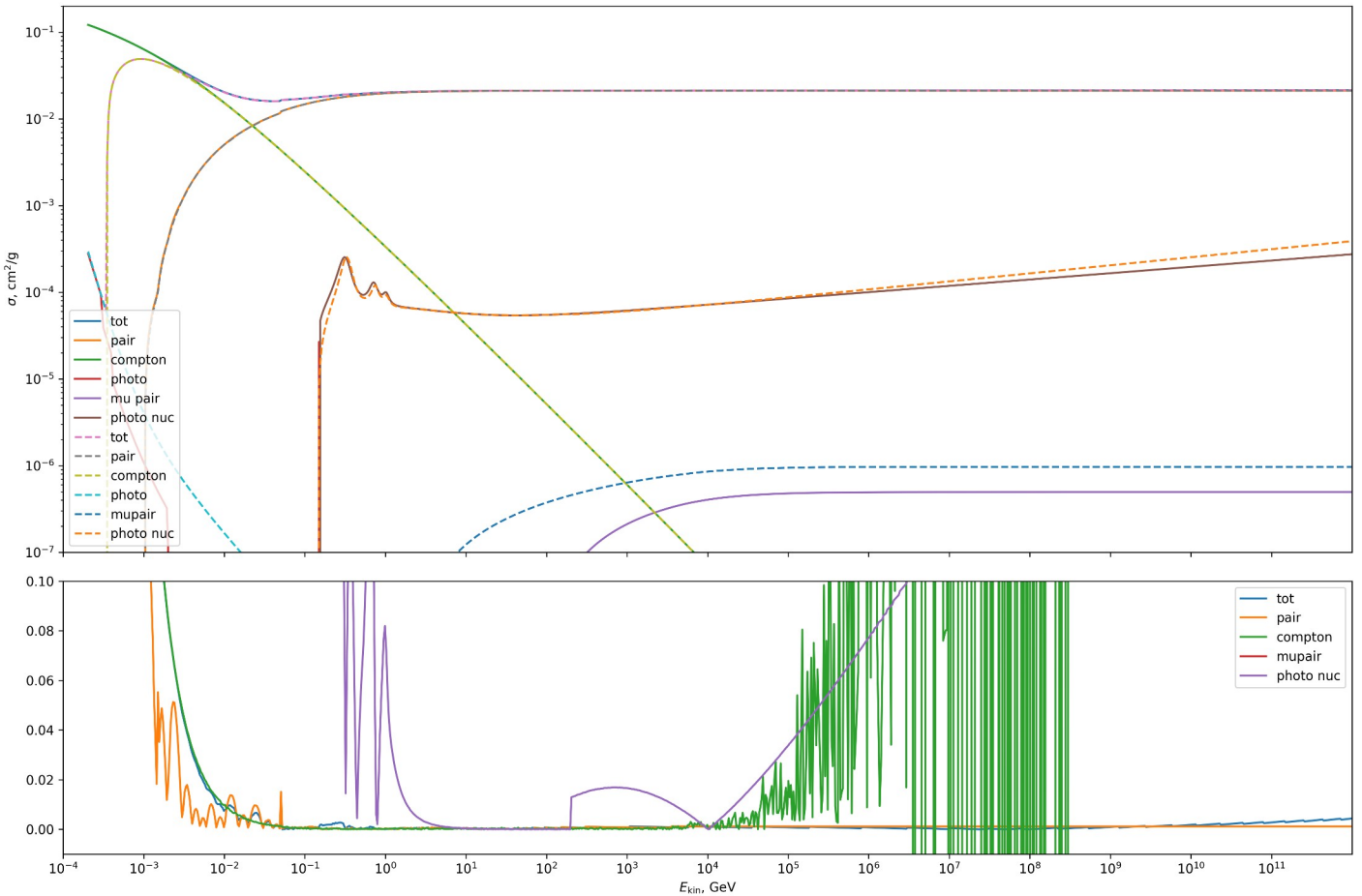
Electron cross sections



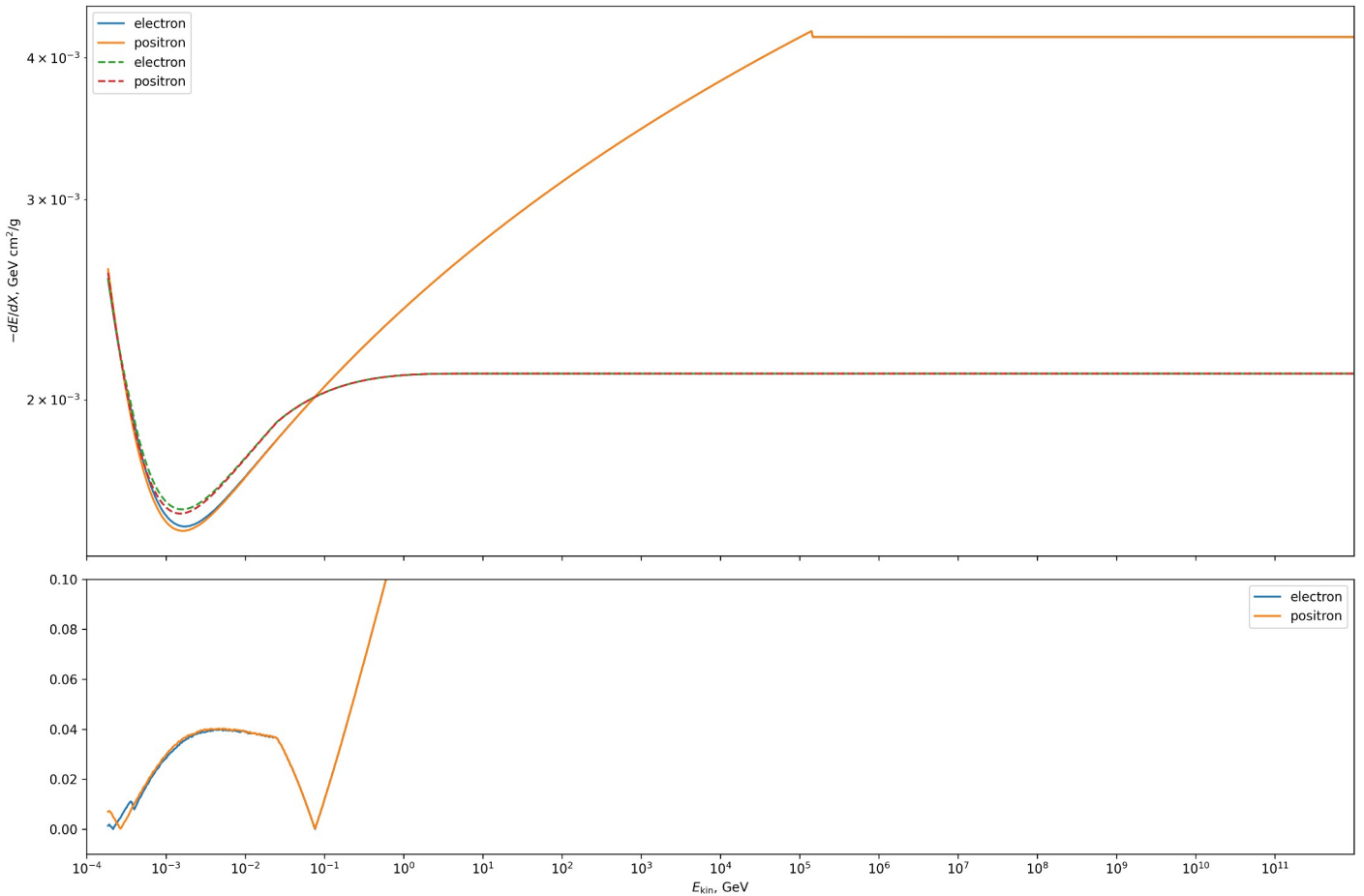
Positron cross sections



Photon cross sections



Continuous energy losses

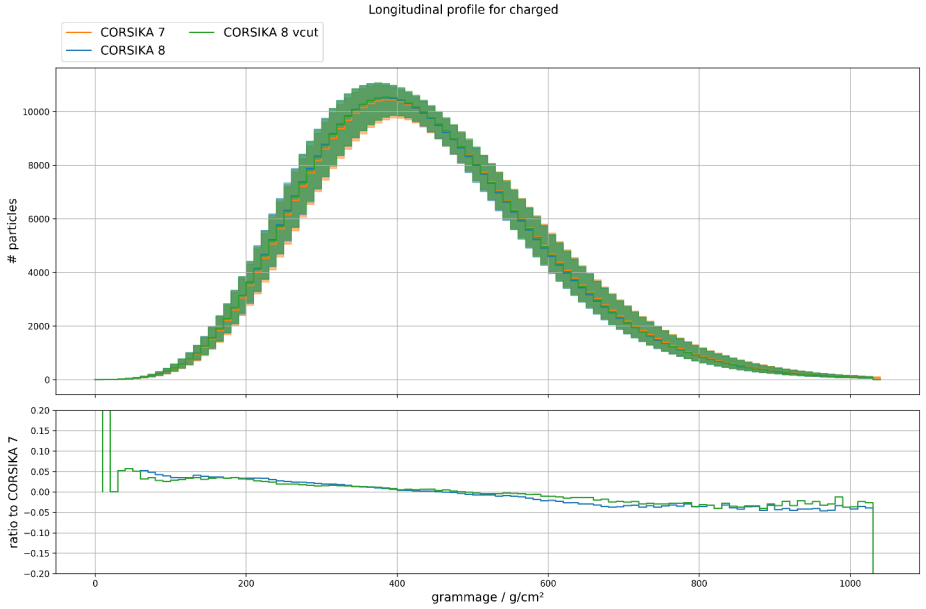


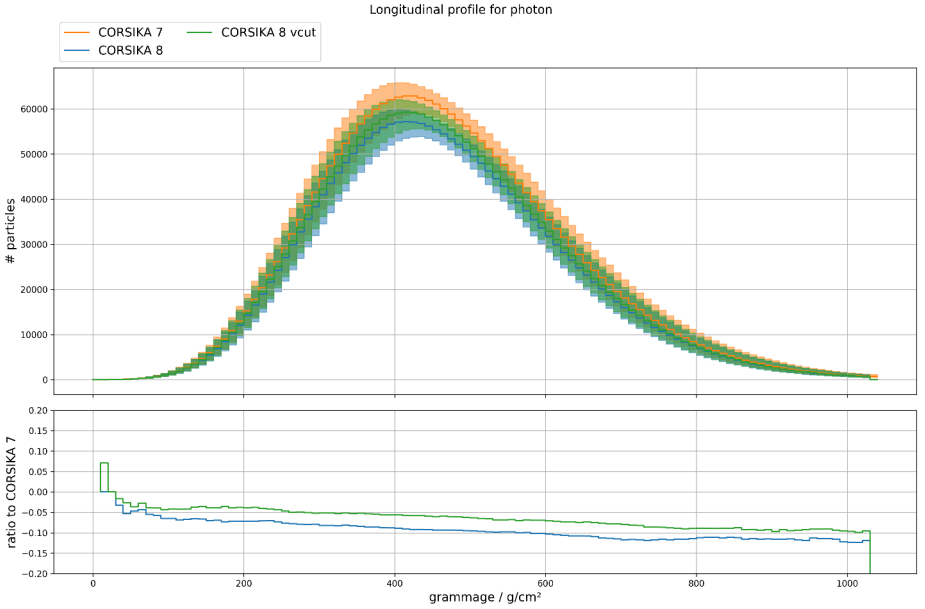
Validation of electromagnetic showers

- Comparison between C7 and C8
  - CORSIKA v7.7500, UrQMD and Sibyll as interaction models
  - CORSIKA 8, current master with above interaction models
  - CORSIKA 8 with added $v_{cut} = 0.01$
- Quantities compared
  - Longitudinal profiles of particle numbers and charge excess
  - Lateral distributions of energy and radius near X_{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

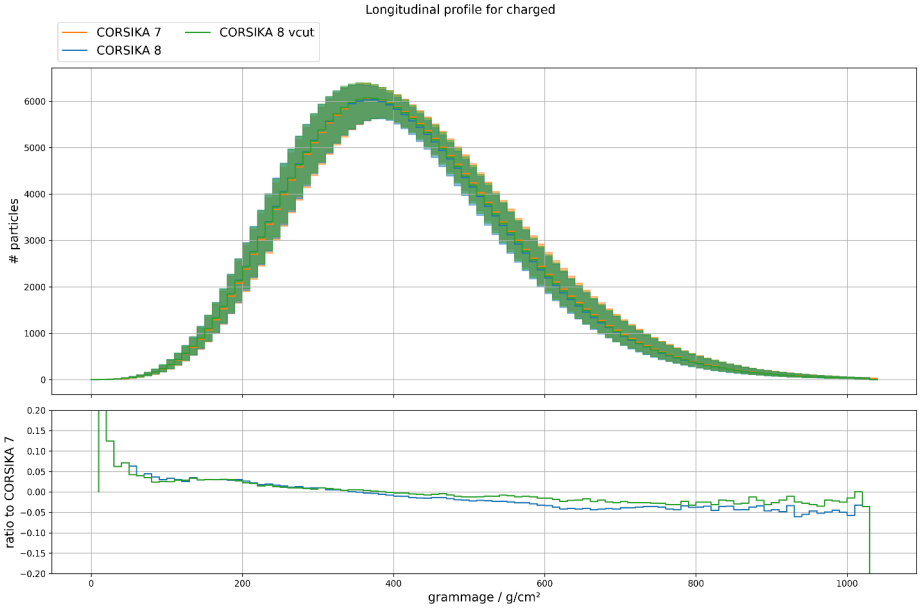
Longitudinal profiles for charged particles and photons

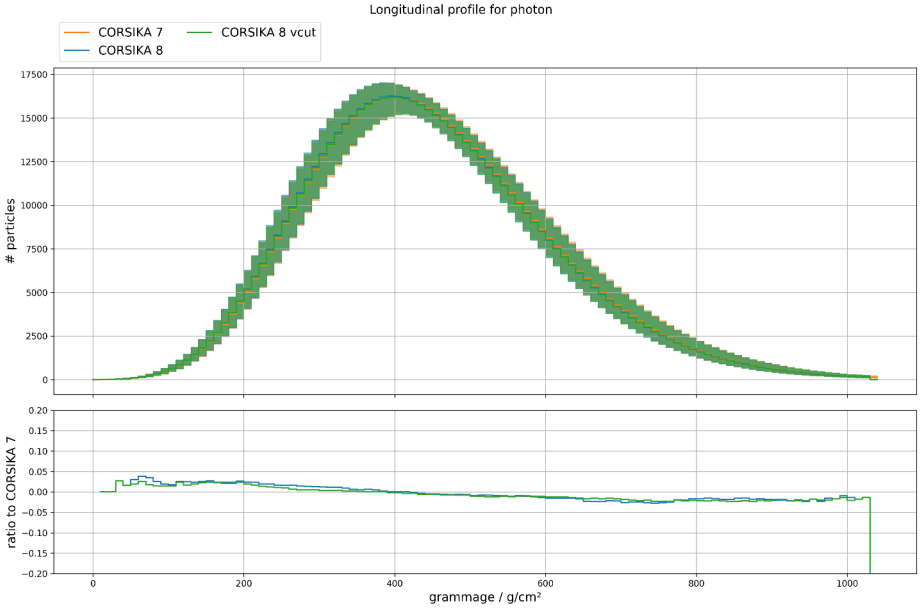




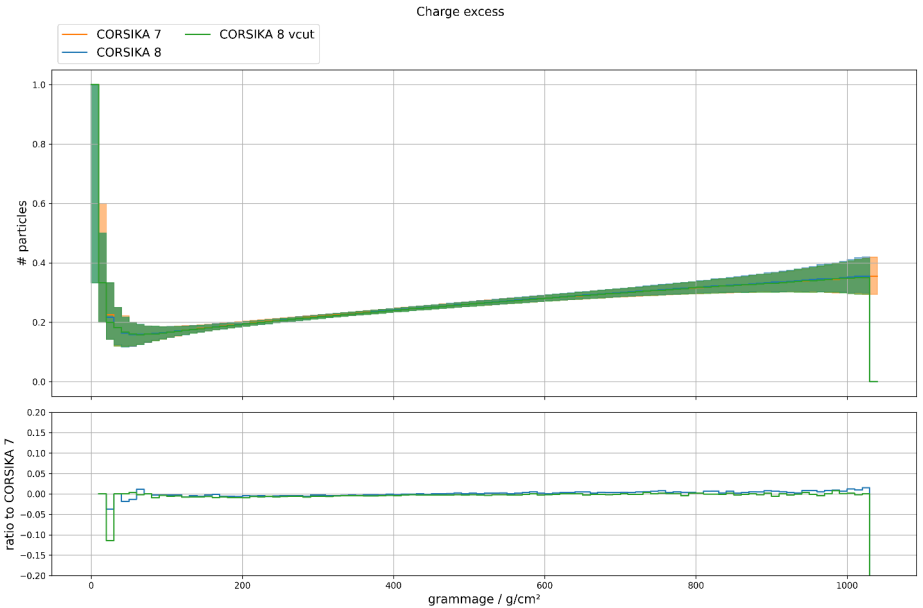
10 TeV, 20 MeV

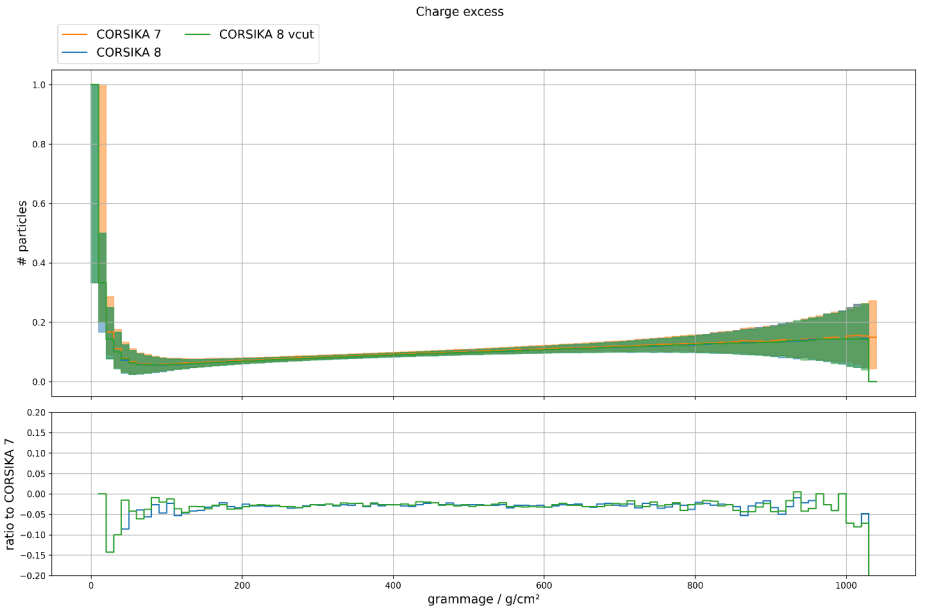
Longitudinal profiles for charged particles and photons



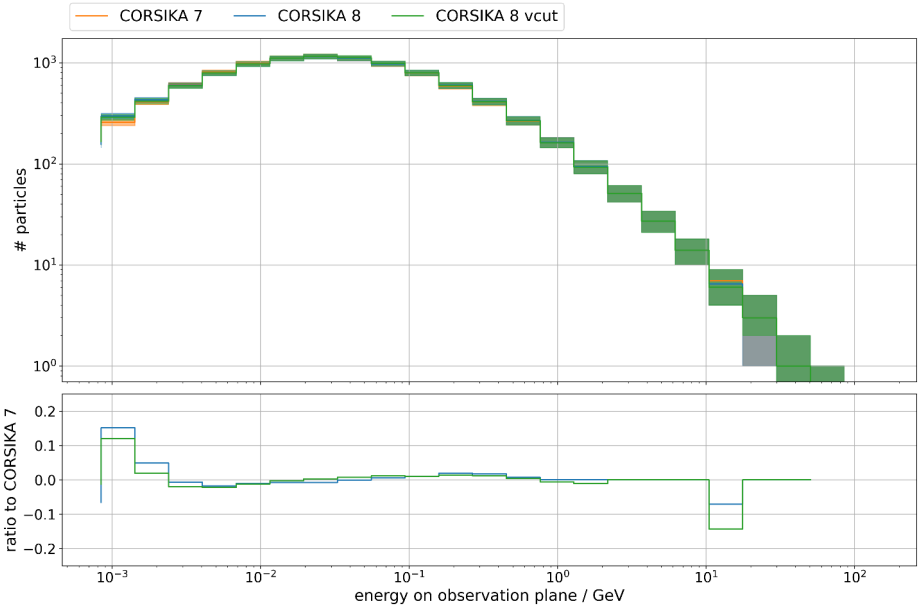


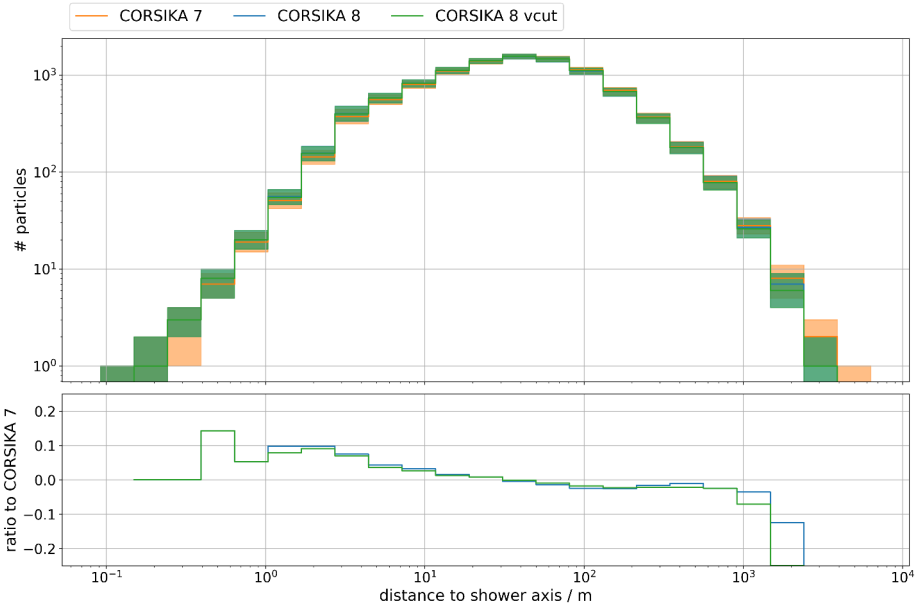
Charge excess
10 TeV with 0.5 MeV resp. 20 MeV



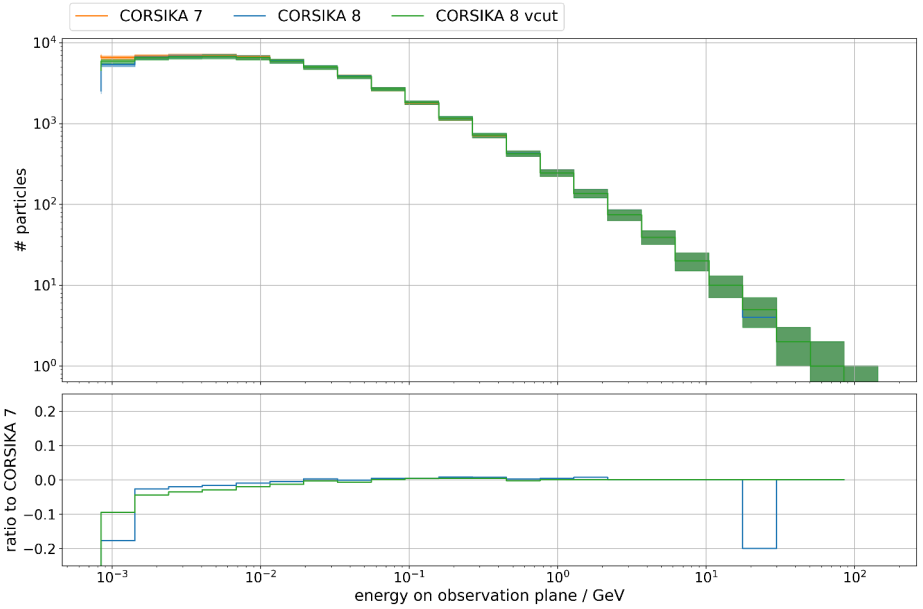


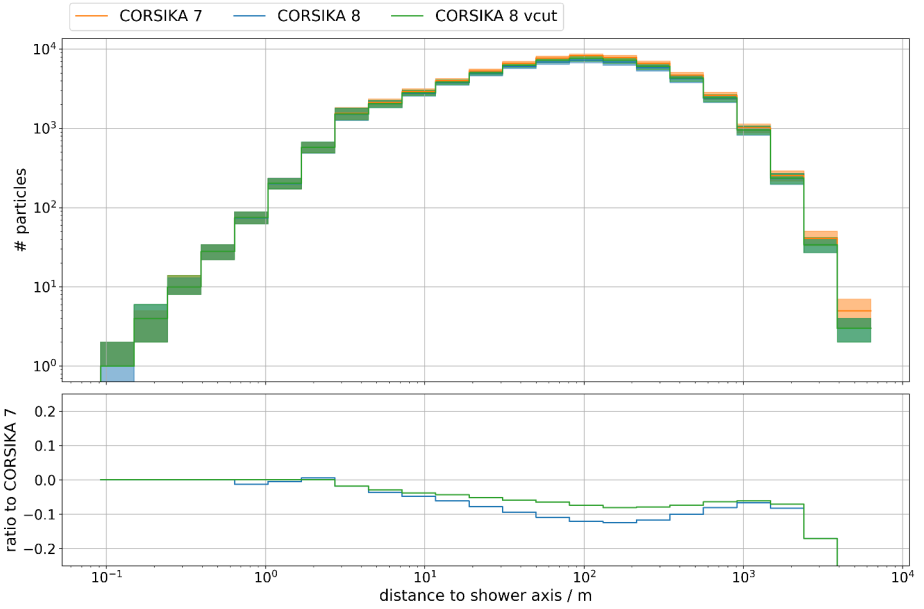
10 TeV, Lateral profiles, Charged particles





10 TeV, Lateral profiles, Photons



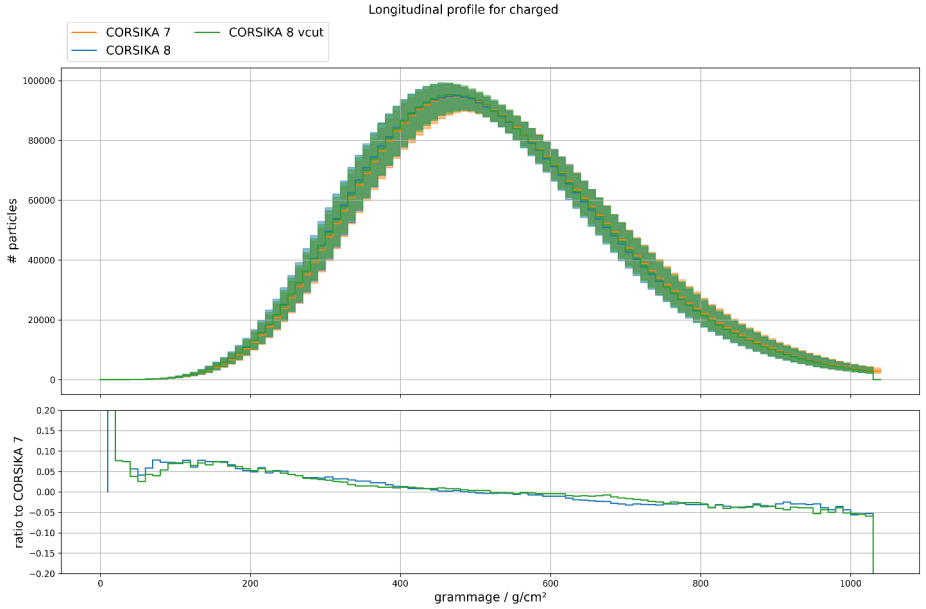


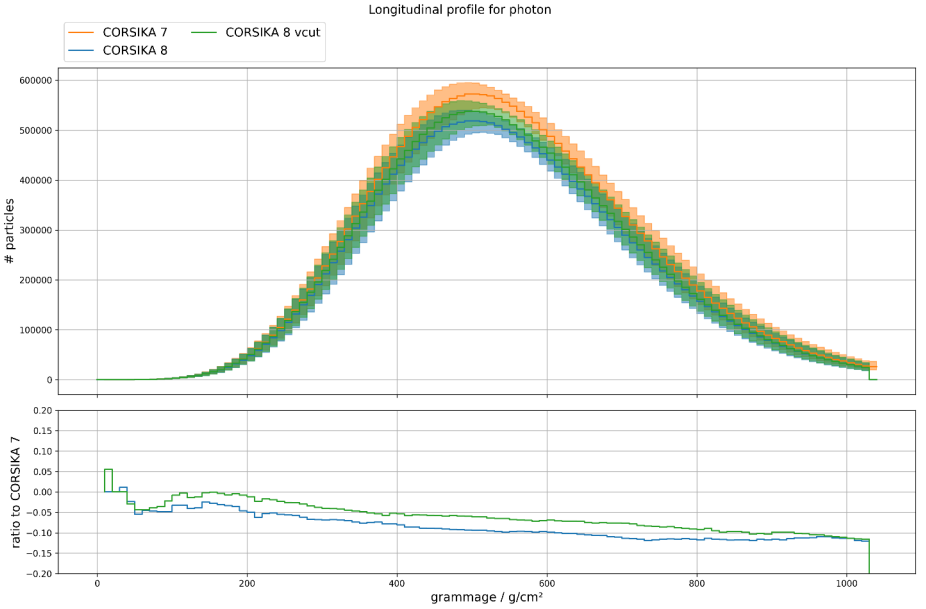
Conclusions from 10 TeV longitudinal and lateral profiles

- 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

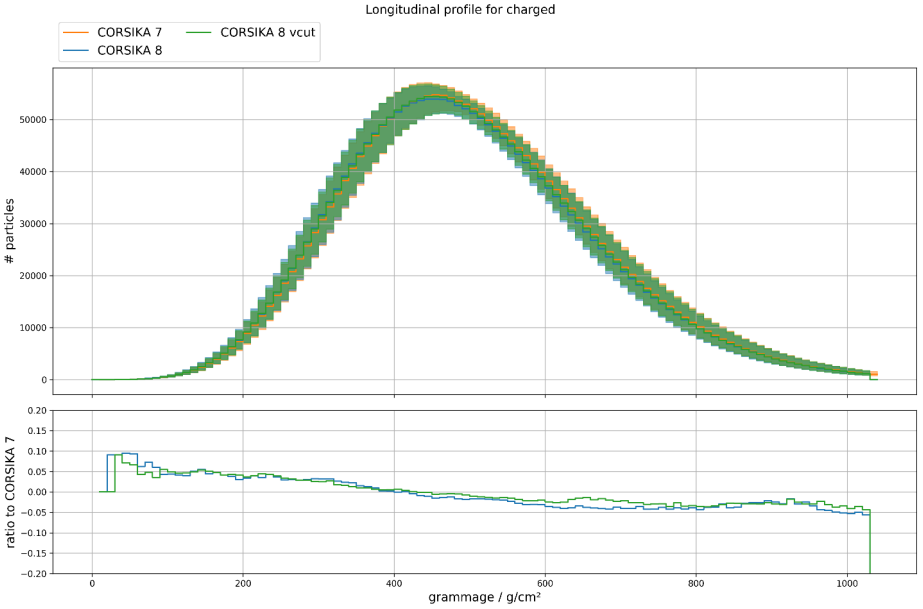
Longitudinal profiles for charged particles and photons

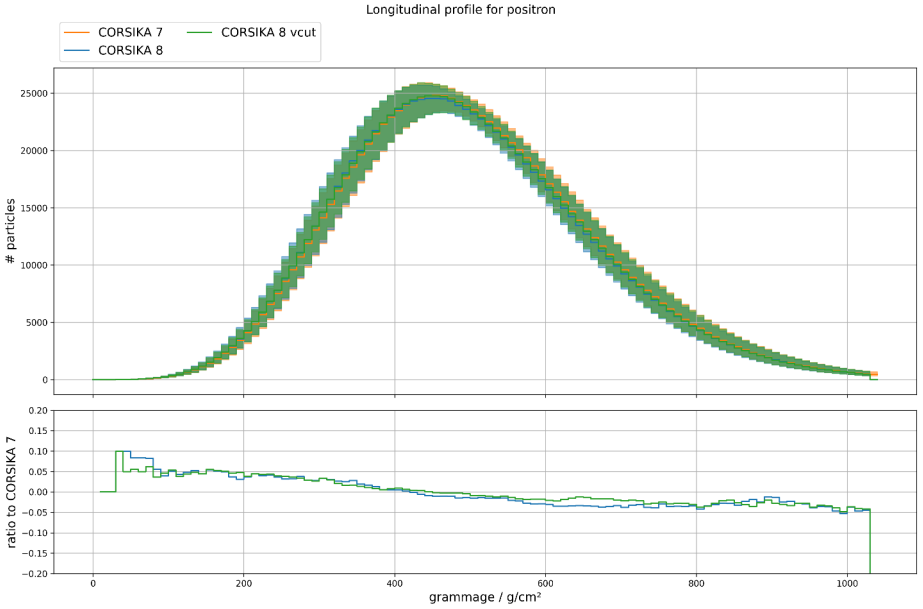




100 TeV, 20 MeV

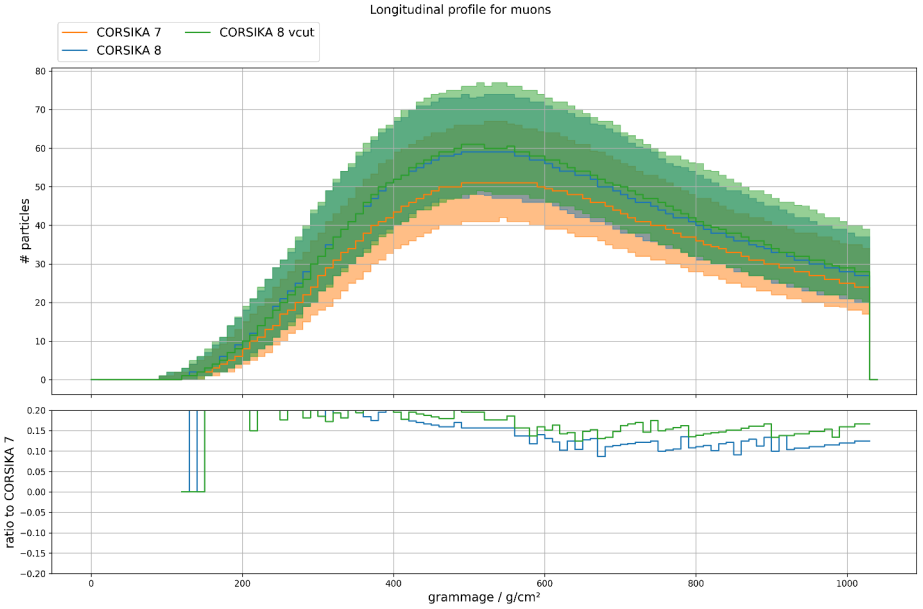
Longitudinal profiles for charged particles and photons

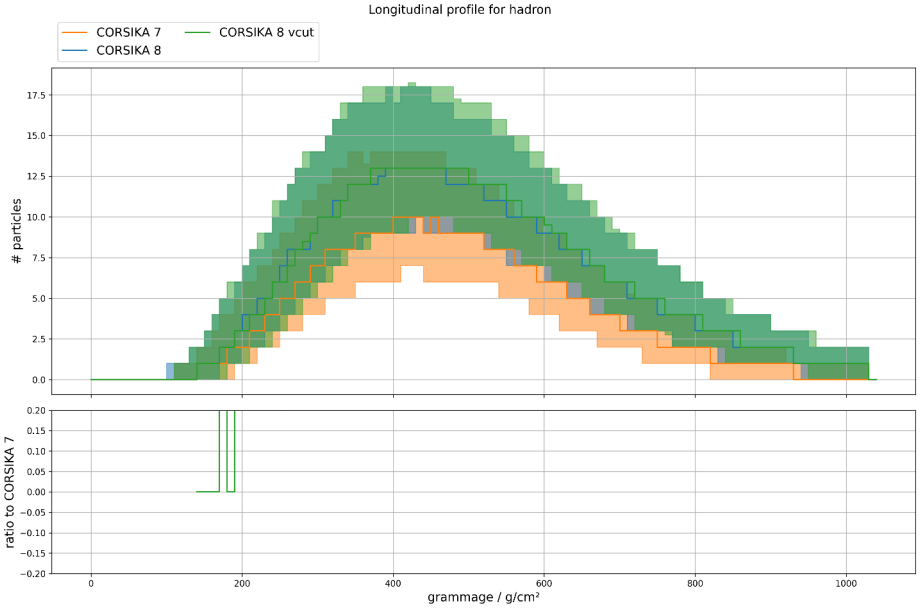




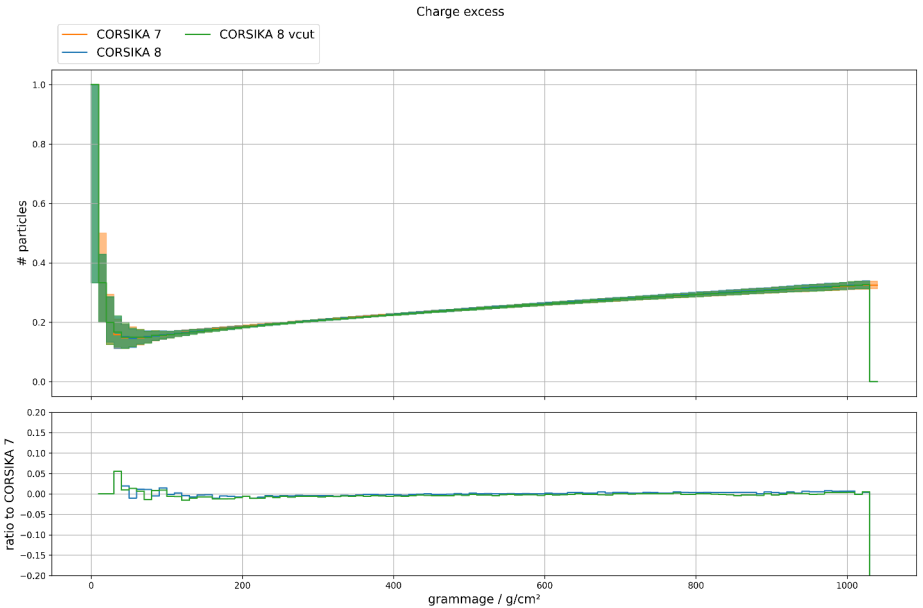
100 TeV, 20 MeV

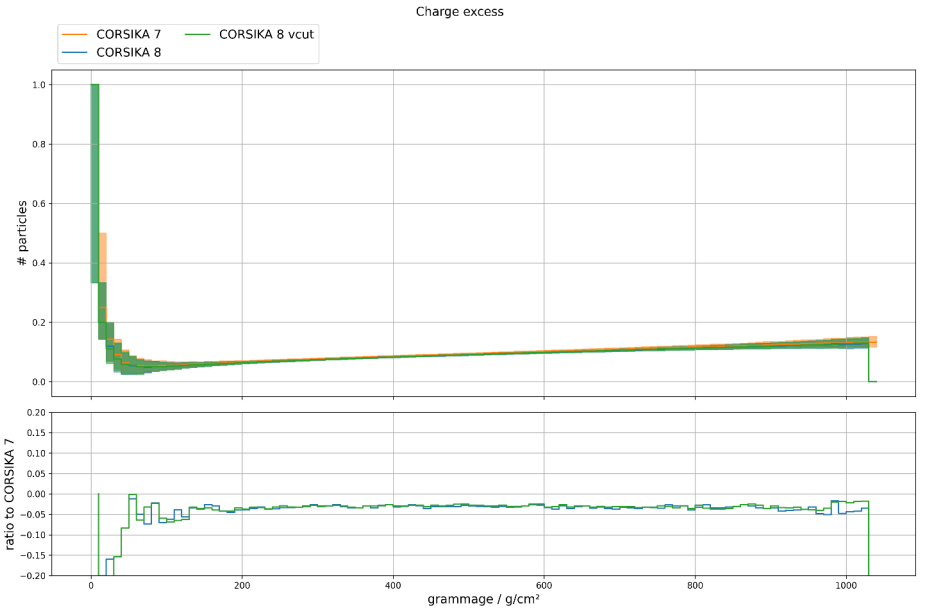
Longitudinal profiles for muons and hadrons



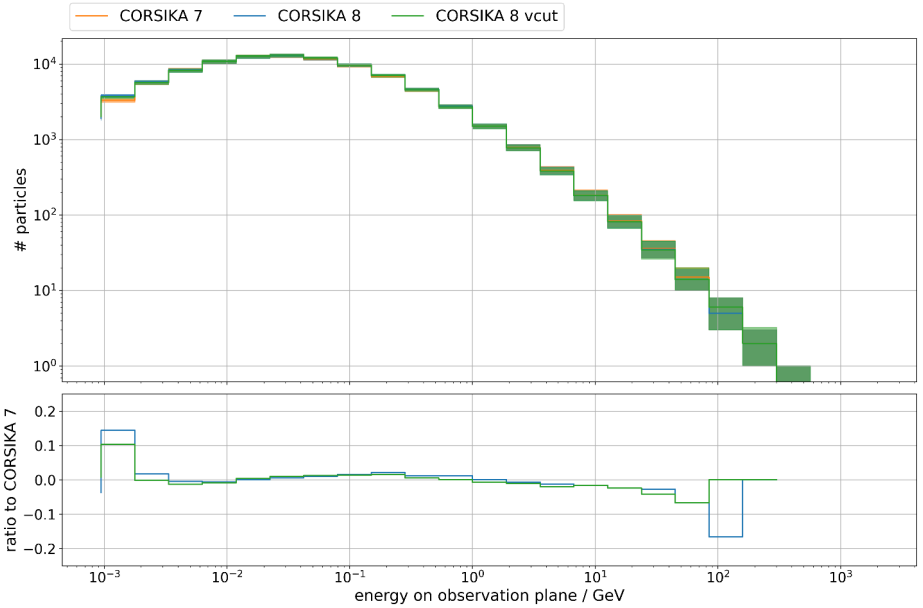


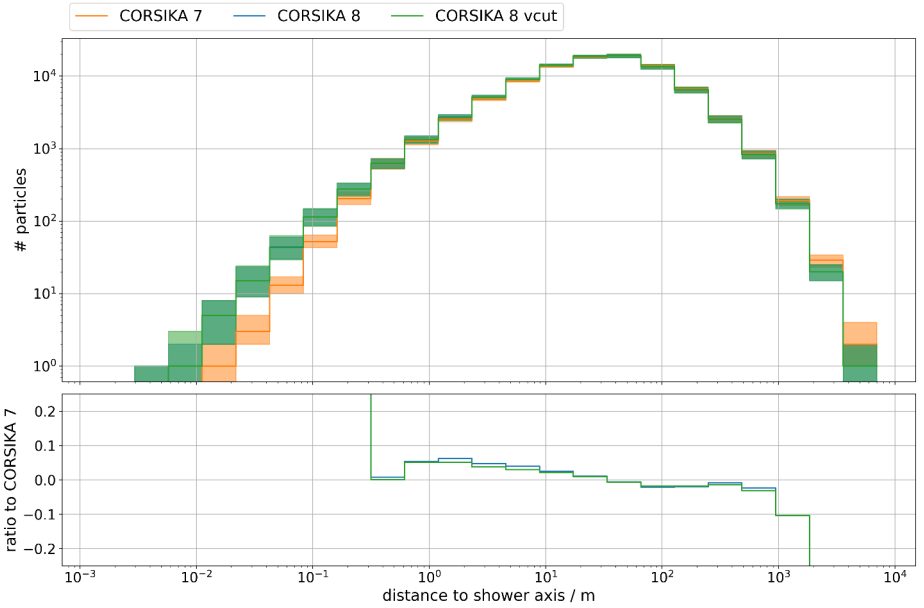
Charge excess
100 TeV with 0.5 MeV resp. 20 MeV



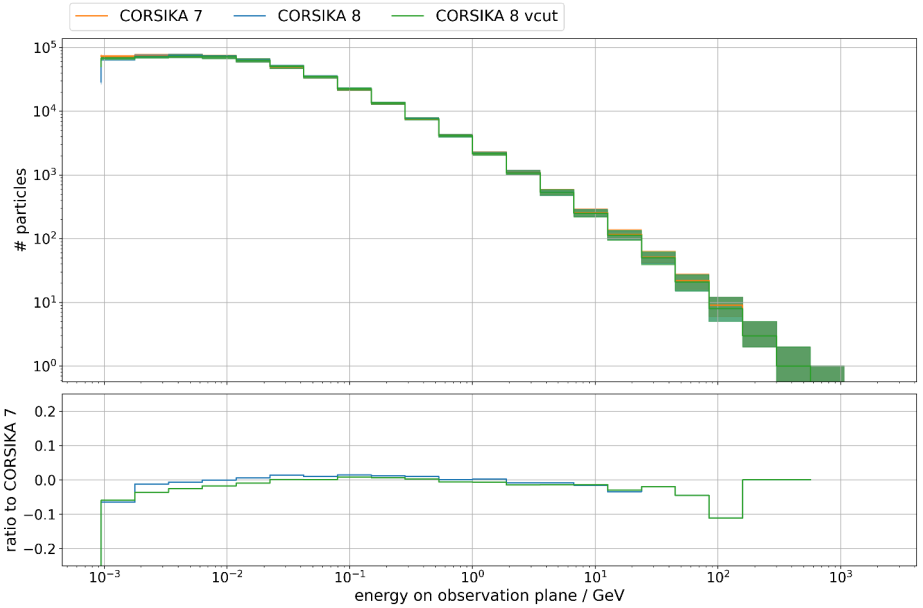


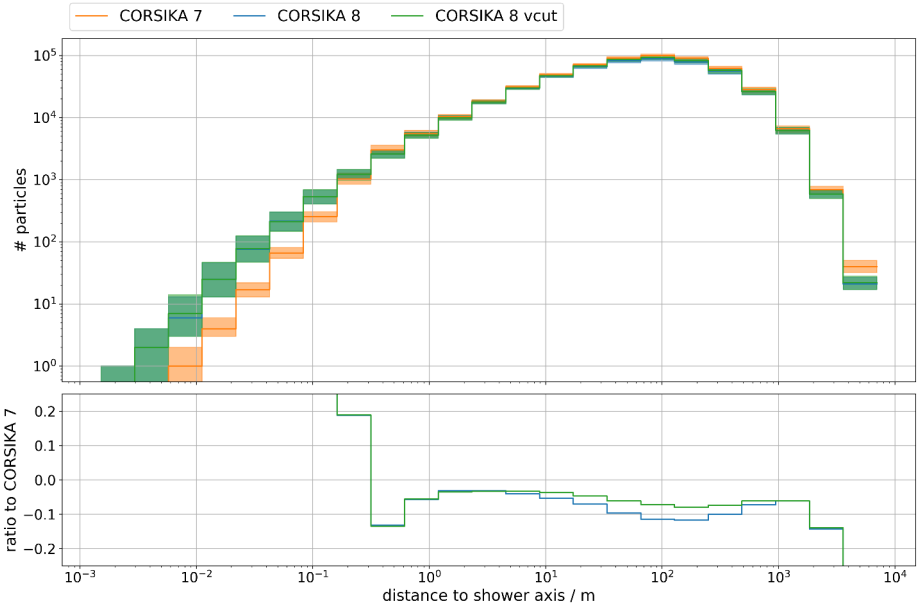
100 TeV, Lateral profiles, charged





100 TeV, Lateral profiles, Photons



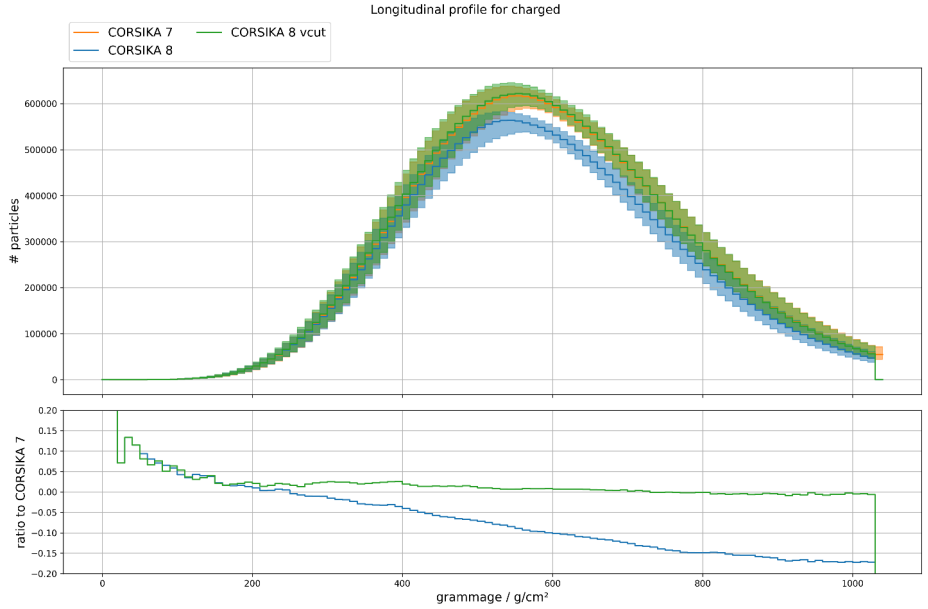


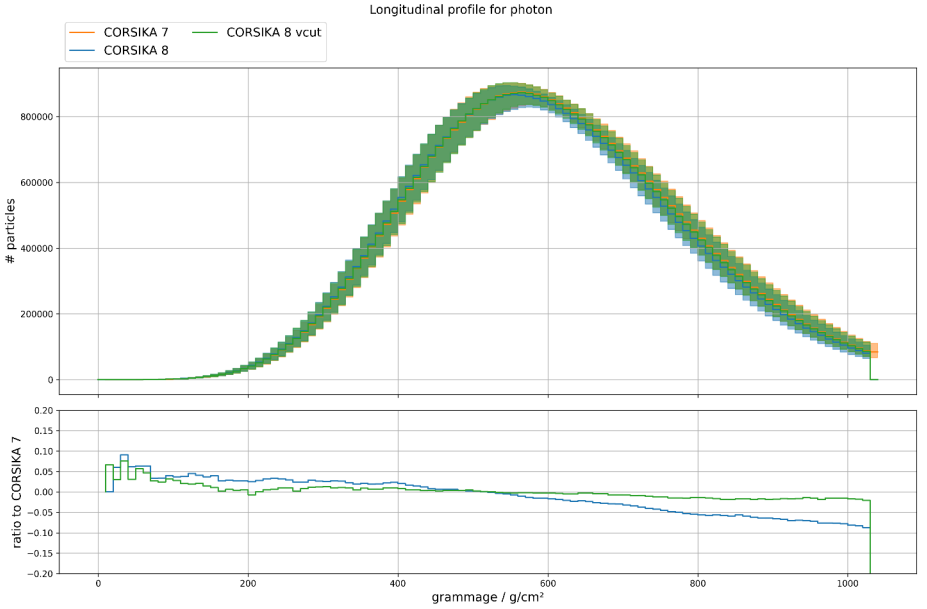
Conclusions from 100 TeV longitudinal and lateral profiles

- 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

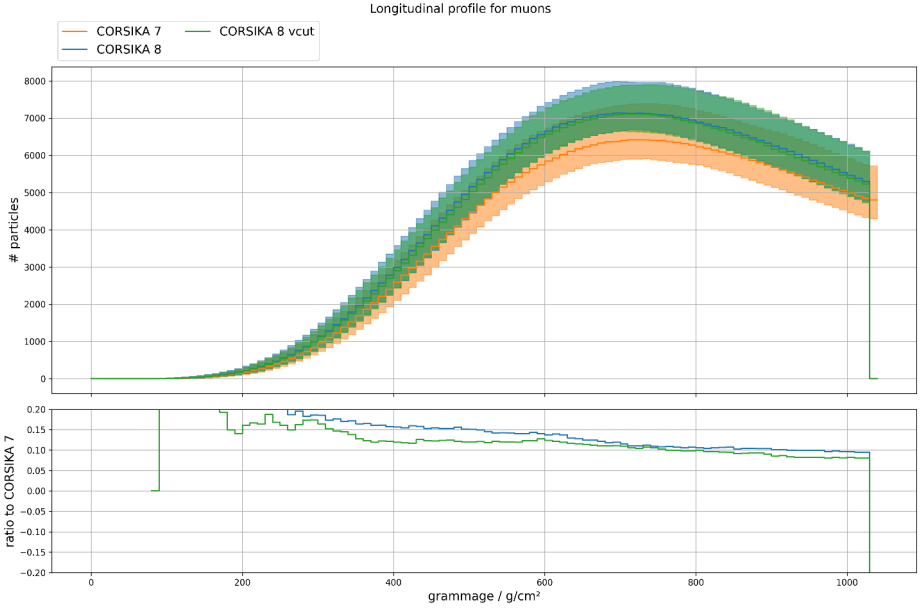
Longitudinal profiles for charged particles and photons

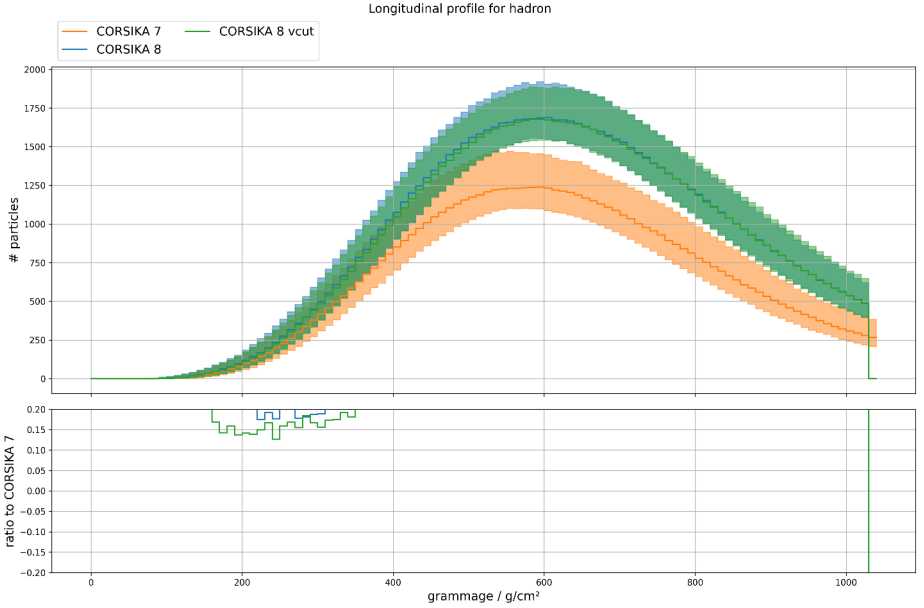




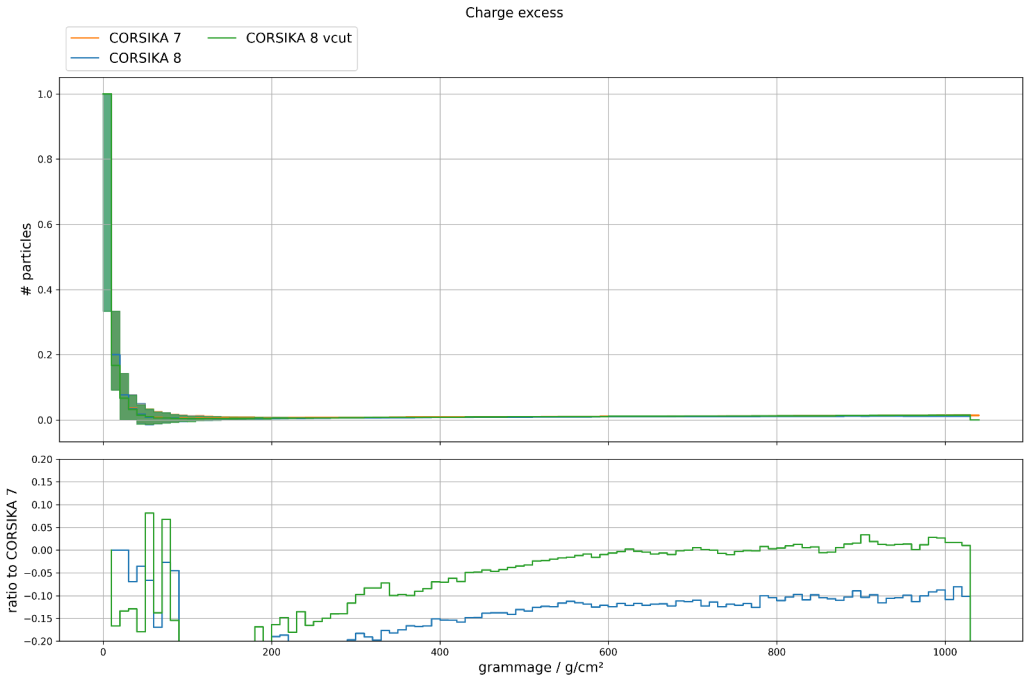
10 PeV, 0.5 GeV

Longitudinal profiles for muons and hadrons





Charge excess
10 PeV with 0.5 GeV



Conclusions from 10 PeV longitudinal profiles

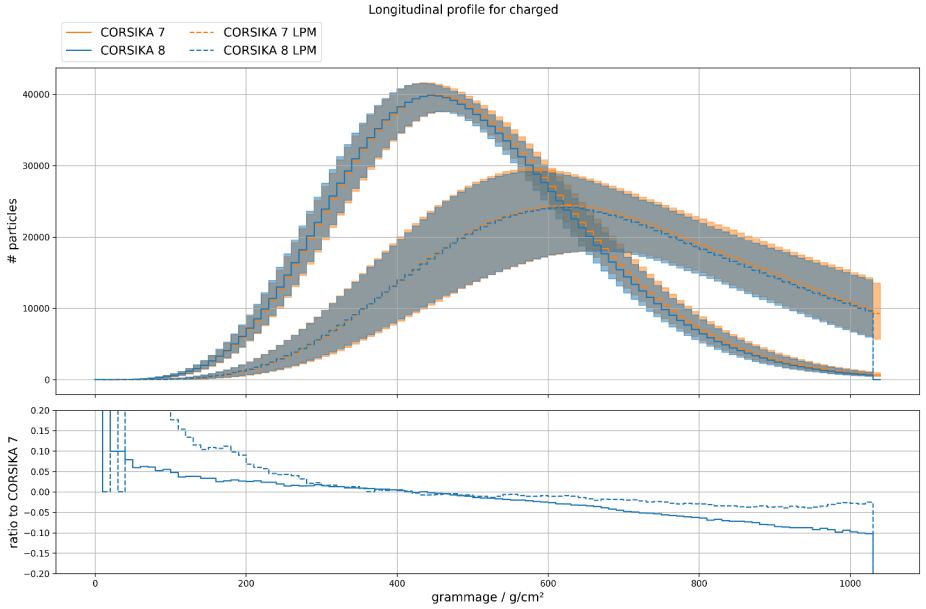
- Trends from lower energies continue
  - Earlier shower maximum
  - More muons and hadrons in C8 (10–15%)
- Agreement between C7 and C8 is substantially improved by introducing an additional cut on the secondary energy fraction v_{cut} → see Jean-Marco's talk for more details

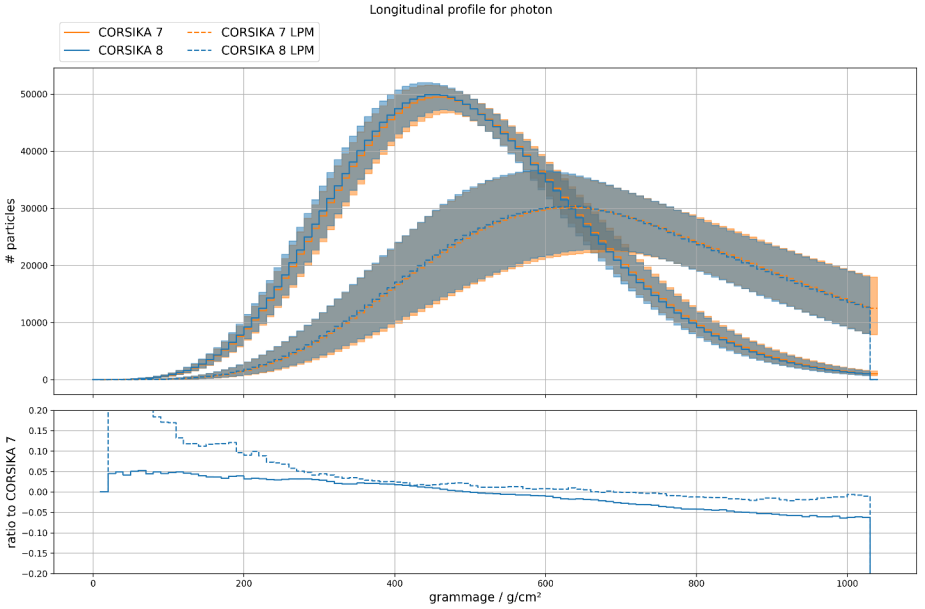
LPM implementation validation

- 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





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_{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