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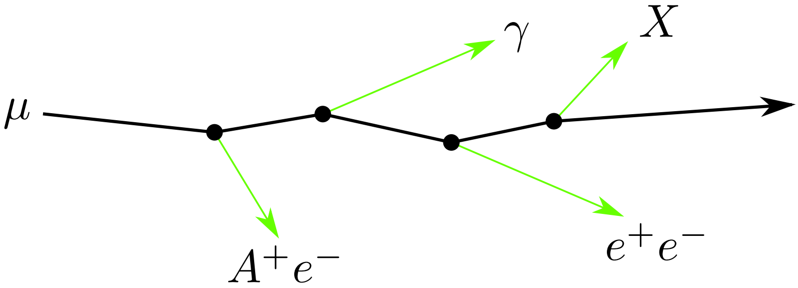


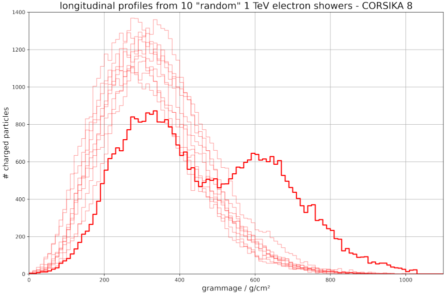
Current status of electromagnetic shower simulations with CORSIKA 8

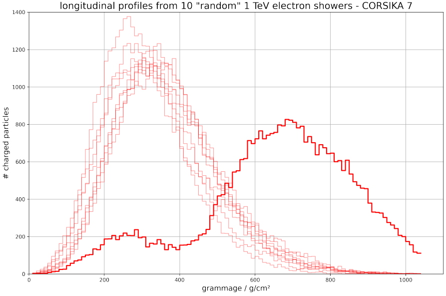
Jean-Marco Alameddine

12.07.2022

CORSIKA 8 Air-Shower Simulation and Development Workshop

Comparing (low-energy) electromagnetic showers is non-trivial and can hold surprises ...





Purpose of this presentation:

- ...show statistically significant comparisons of shower parameters between CORSIKA 7 and CORSIKA 8
- ...highlight current developments and open questions
- ...give input for discussion on the future of CORSIKA 8 (with focus, but not limited, on the EM component)

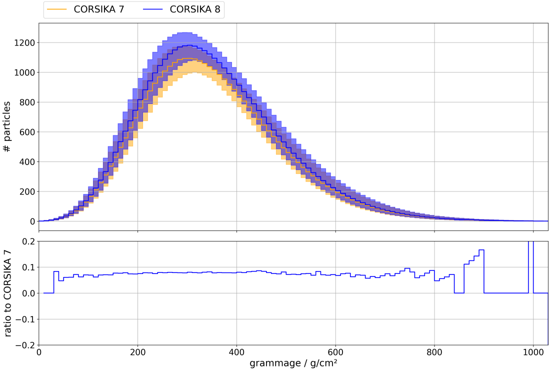
Technical information about the upcoming simulations:

- Simulations using the CORSIKA 8 branch `502-examples-need-some-polishing` (unless stated otherwise)
  - → Simulation script based on `em_shower.cpp`
  - → Electromagnetic component simulated using `PROPOSAL v7.3.1`
- Comparisons to `CORSIKA 7.7500`

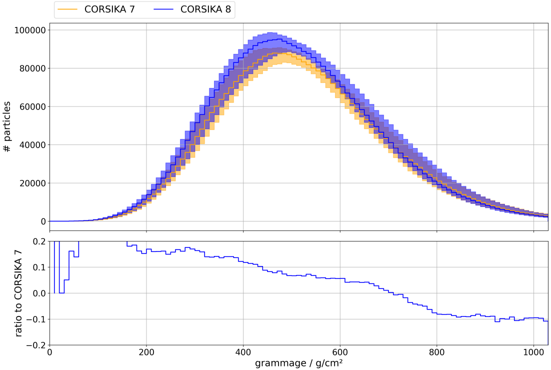
Information about the simulation environment:

- Vertical showers, injected by electrons
- Magnetic field activated, default Karlsruhe values
- Cut values: 2 MeV (both for `energy_resolution` and `ParticleCut`)

Longitudinal distribution of charged particles



1 TeV showers (statistics: 5000)

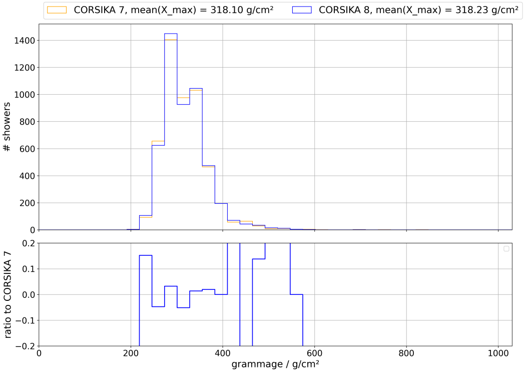


100 TeV showers (statistics: 100)

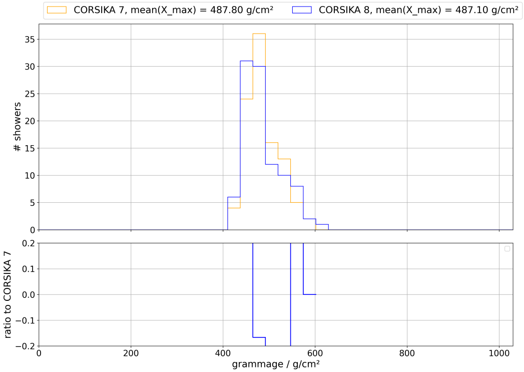
→ More charged particles in CORSIKA 8 (for all energies)

→ For higher energies: CORSIKA 8 showers seem to develop earlier

X_{max} distribution of longitudinal profiles (for charged particles)



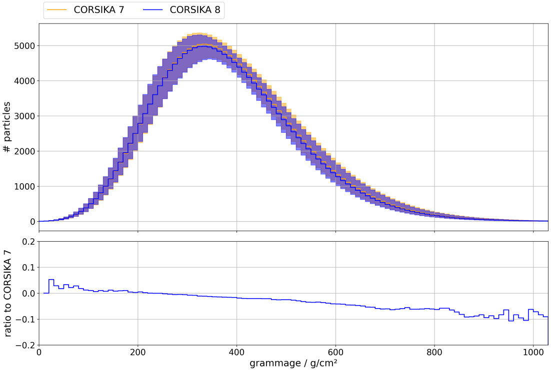
1 TeV showers (statistics: 5000)



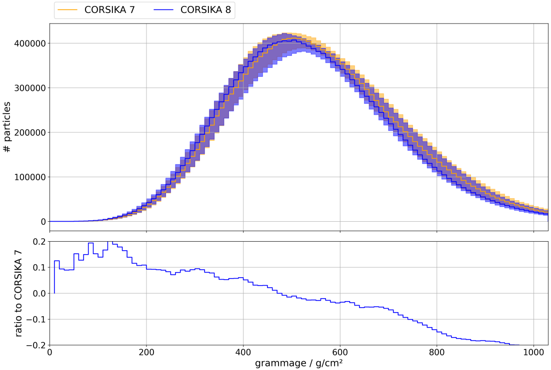
100 TeV showers (statistics: 100)

→ Distributions of X_{max} generally look ok

Longitudinal distribution of photons



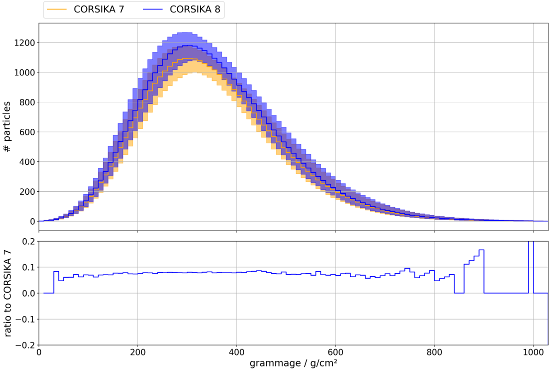
1 TeV showers (statistics: 5000)



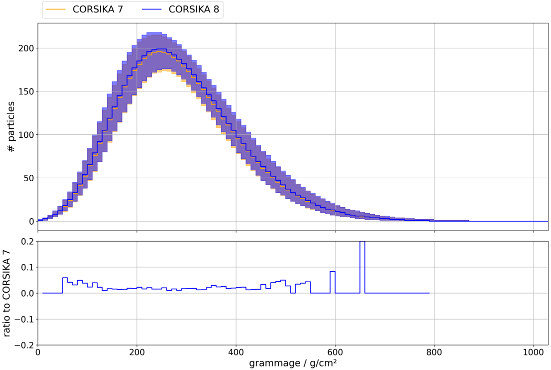
100 TeV showers (statistics: 100)

- → Number of photons in better agreeement
- → Earlier shower development of CORSIKA 8 again visible

Longitudinal distribution of charged particles in 1 TeV showers



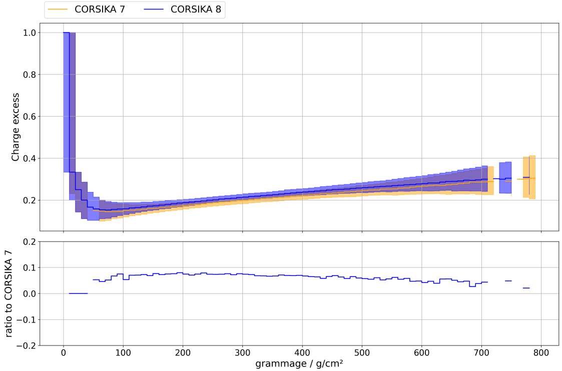
All charged particles above 2 MeV



All charged particles above 200 MeV

→ Agreement in particle number gets better when only looking at high-energy particles

Charge excess (1 TeV showers)



- → Longitudinal distribution of excess of electrons over positrons: $\frac{N_{e^-}-N_{e^+}}{N_{e^-}+N_{e^+}}$
- → Relevant for radio emission in air showers (→ see sessions later today)
- → Higher charge excess in CORSIKA 8 compared to CORSIKA 7

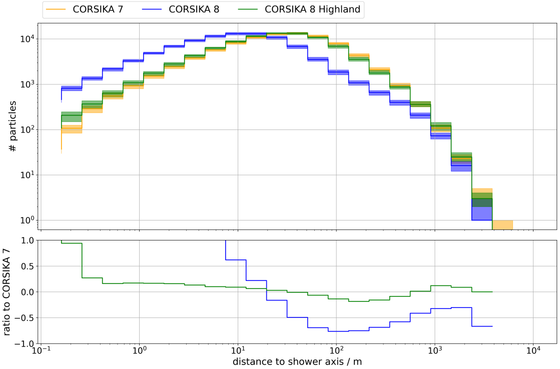
The main differences we've seen so far:

- We produce too many charged leptons, especially for lower energies
- CORSIKA 8 showers tend to develop earlier
- There is a higher charge excess

Possible reasons for this behavior?

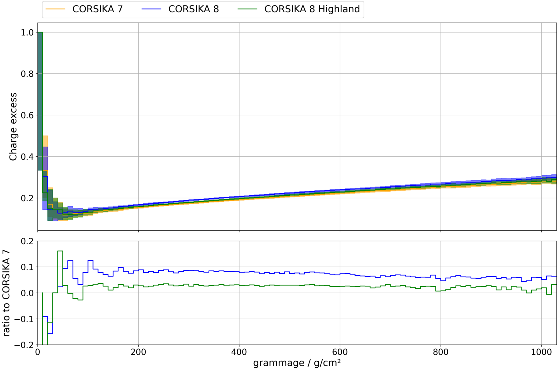
- Differences in cross sections between CORSIKA 8 and CORSIKA 7?
  - → See talk by Alexander S.
  - → Direct comparisons between EGS4 and PROPOSAL necessary
- `Cascade.inl` bug in CORSIKA 8
  - → Cross sections are not always evaluated at correct energies (see issue #482)
  - → Currently, multiple scattering is *not* taken into account (see issue #483)
    - → `Cascade.inl` is currently revised
    - → The fix will introduce a `Step` object for better consistency
    - → New comparisons including these fixes will be necessary. They will influence both lateral and longitudinal profiles.

Lateral profiles of charged particles

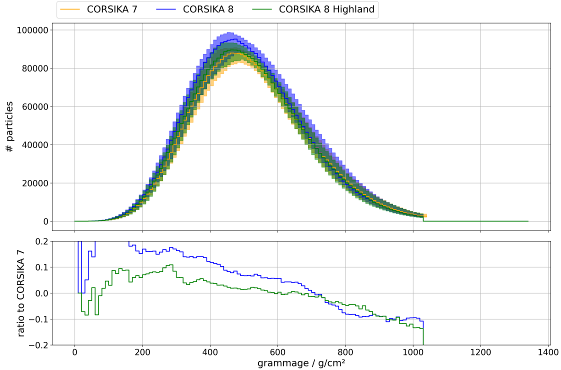


- Lateral profiles for 100 TeV showers at X_{max}
- Without multiple scattering (blue), particles are clearly shifted towards the shower axis
- With multiple scattering (green), profiles are in much better agreement with CORSIKA 7!
  - → However, this result (greeen line) is only preliminary as the fix is still work in progress!

Longitudinal profiles with multiple scattering - Work in progress!



Charge excess for 100 TeV showers



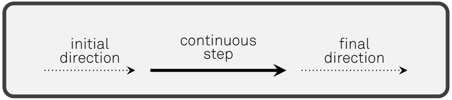
Longitudinal profiles for 100 TeV showers (charged particles)

→ Longitudinal profiles and charge excess also show a better agreement with the upcoming fixes

No multiple scattering:

→ Current version on master branch

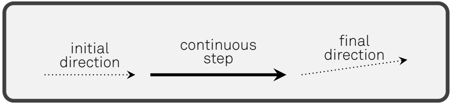
→ Leads to incorrect lateral profiles



Multiple scattering, using change of direction after continuous step:

→ "Trivial" to implement using the new `Step` object

→ However, this description of multiple scattering is incomplete



Multiple scattering, using change of direction after continuous step *and* lateral displacement of the continuous step:

→ This description of multiple scattering would be complete

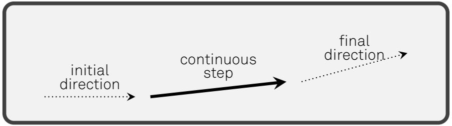
→ However, this treatment of multiple scattering is non-trivial

  → How to combine with magnetic fields?

  → How to work at geometric boundaries?

  → How to work with inhomogeneous density distributions?

→ Discussion in issue #483



Runtimes of EM shower simulations

- There will be a talk dedicated to benchmarking on Wednesday morning
- Note: The exact values depend on the build configuration, optimization levels, used resources, etc.

Energy	CORSIKA 8	CORSIKA 7	$^{C8}/_{C7}$
1 TeV	**45.7** s	**1.1** s	41.5
10 TeV	**305.3** s	**10.7** s	28.5
100 TeV	**2446.9** s	**95.9** s	25.5

Simulation time per shower for electromagnetic showers

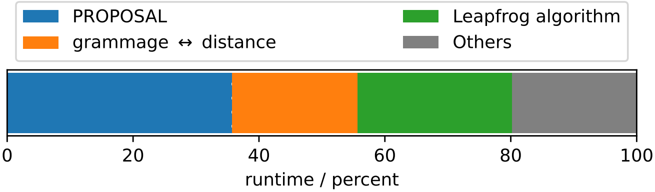
→ In general: CORSIKA 8 is an order of magnitude slower

→ Runtime difference becomes smaller with higher enegries?

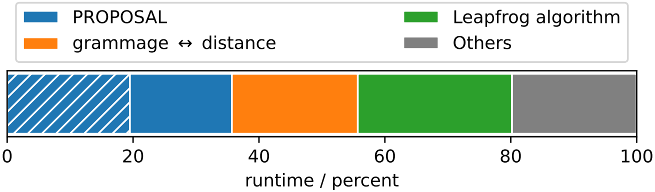
→ Optimizations necessary!

Where is time spent in the simulation of an EM shower in CORSIKA 8?

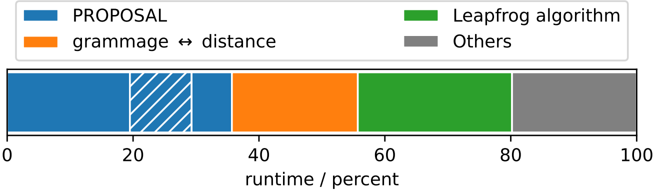
- Approximate values for the simulation of a **10** TeV shower:



- About **35 %** of runtime is spent in PROPOSAL
- About **20 %** of runtime is spent transforming distances to grammge (and vice versa)
- About **25 %** of runtime is spent in the LeapFrog algorithm
  - → There is no single component that individually increases the runtime
  - → Here, we will talk about ways how to **speed up the PROPOSAL** component



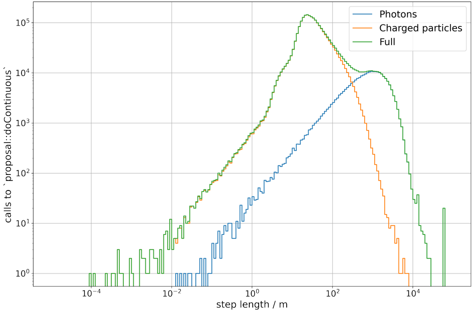
- About **20 %** of the total runtime is spent in the function `PROPOSAL::Interaction::MeanFreePath`
  - → This function is used to calculate the interaction length of a particle
  - → Function is called a lot of times, especially if small steps are made (especially if the possible step length is limited, e.g. due to magnetic fields)
- Currently, for every call of this function, we evaulate multiple 2D interpolation tables (one for each interaction type)
  - → Instead, we can store the interaction lengths in a single 1D interpolation table
  - → This speeds up the function evaluation by a **factor of 30**!



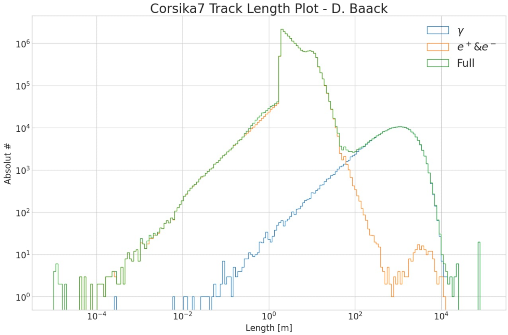
- About **10 %** of the runtime is spend in the function `PROPOSAL::UtilityInterpolant::GetUpperLimit`
  - → This function calculates the continuous energy losses, given a specific grammage
  - → Currently, this is done by solving this integral equation for E_f:

$$X = \int_{E_i}^{E_f} \frac{\mathrm{d}E}{f(E)} \quad \text{with} \quad f(E) = -\frac{\mathrm{d}E}{\mathrm{d}X} \tag{1}$$

  - → Using a simplification, such as $f(E) = f(E_i)$, could make this problem significantly easier to solve
  - → However, this may introduce new limitations, for example on the possible steplength

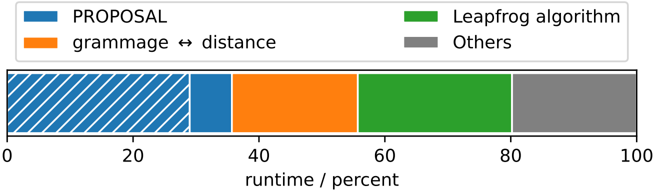


Steplengths in **1** TeV showers in CORSIKA 8
(20 showers, **20** MeV cuts)



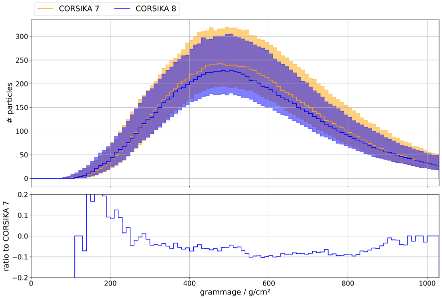
Steplengths in **1** TeV showers in CORSIKA 7
(20 showers, **20** MeV cuts)

- One possible explanation for the generally higher runtimes: Too many simulations steps?
- Perhaps, the number/size of steps in the simulation process in CORSIKA 8 needs to be tweaked?
  - → First comparisons show that the steplengths made in CORSIKA 7 and CORSIKA 8 look similar

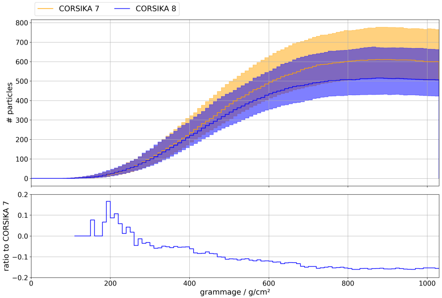


- Using the mentioned improvements, it should be possible to significantly speed up the time spent in PROPOSAL calculations
- Probably, improvements in other areas will still be necessary
  - → See talk dedicated to benchmarking on Wednesday morning!

Hadronic/muonic component in electromagnetic showers



Longitudinal profile of hadrons (≥ **10** GeV) in **10** PeV EM showers



Longitudinal profile of muons (≥ **10** GeV) in **10** PeV EM showers

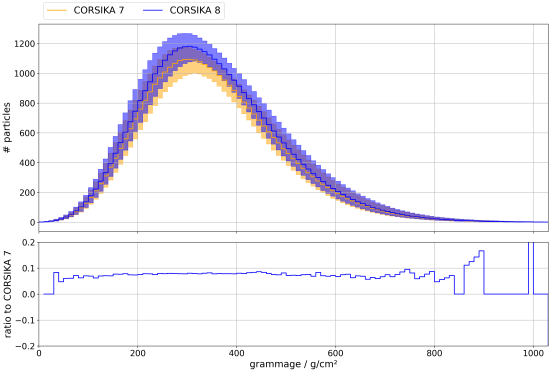
- We wrote an interface between PROPOSAL and SIBYLL to process hadronic interactions in electromagnetic showers
- Currently, this means creating a ρ_0 from hadronic interactions and passing it to SIBYLL
- At the moment, hadronic interactions with Argon or below a threshold energy (≈ **60** GeV) need to be discarded
  - → Might explain why we don't see enough muons/hadrons in CORSIKA 8 yet

Summary

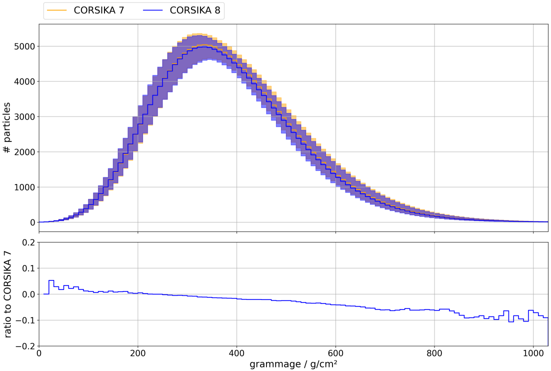
- Electromagnetic showers produced with CORSIKA 8 show reasonable results, however, differences in comparison with CORSIKA 7 are still visible
  - → There is ongoing work which will have a significant impact on the simulation results (`Cascade.inl`)
  - → There are still conceptional questions that need to be answered (multiple scattering, etc.)
- Runtimes of EM shower simulations with CORSIKA 8 are not yet comparable to CORSIKA 7
  - → However: While CORSIKA 7 has been optimized for decades, we are just at the beginning of explicitly improving the runtimes in CORSIKA 8
  - → For the electromagnetic shower component, we have already identified areas where the runtime can be significantly improved
  - → The modular structure of CORSIKA 8 easily allows for the implementation of improvements

Backup slides

1 TeV EM Shower, cut of 2 MeV (statistics: 5000 showers)



Longitudinal profile charged particles



Longitudinal profile photons

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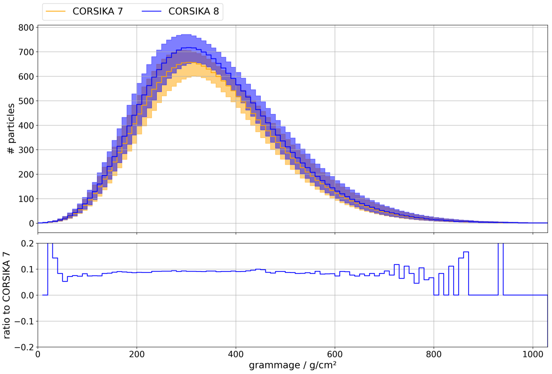
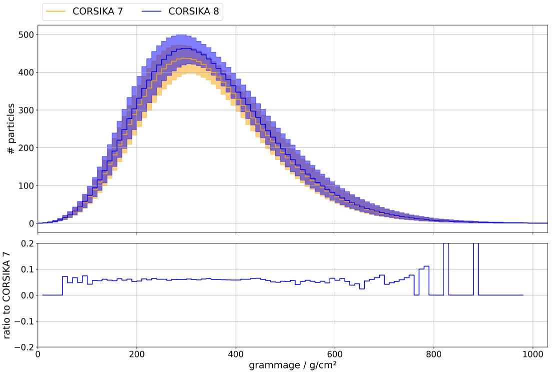
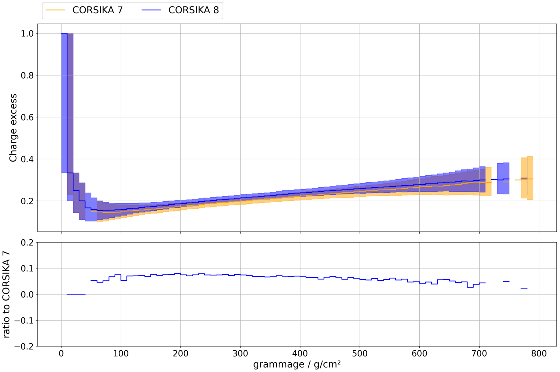


Longitudinal profile electrons

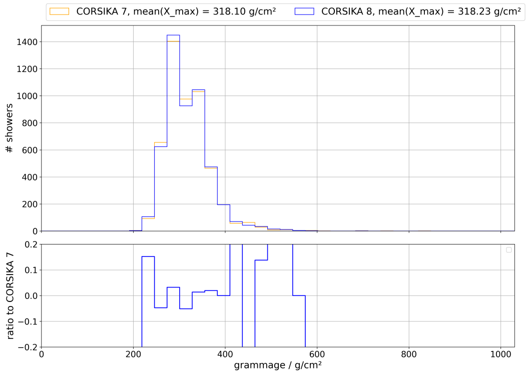


Longitudinal positrons

1 TeV EM Shower, cut of 2 MeV (statistics: 5000 showers)

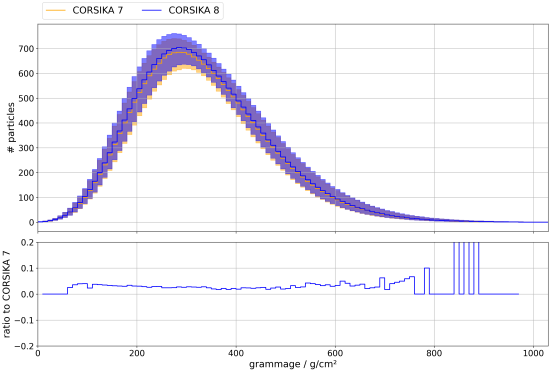


Charge excess $\frac{N_{e^-}-N_{e^+}}{N_{e^-}+N_{e^+}}$

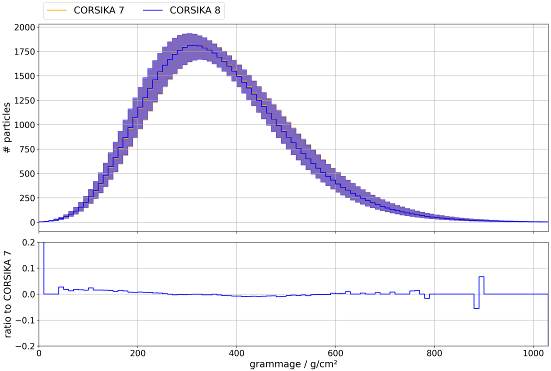


X_{max} distribution of charged particles

1 TeV EM Shower, cut of 20 MeV (statistics: 5000 showers)

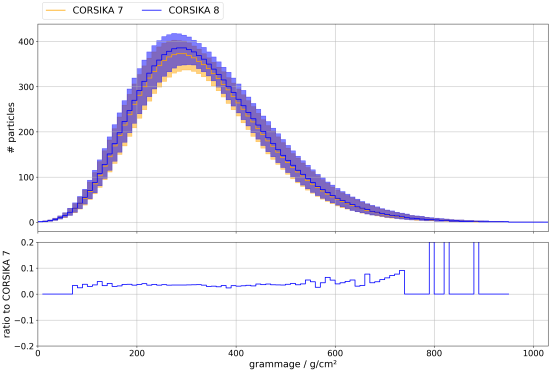


Longitudinal profile charged particles

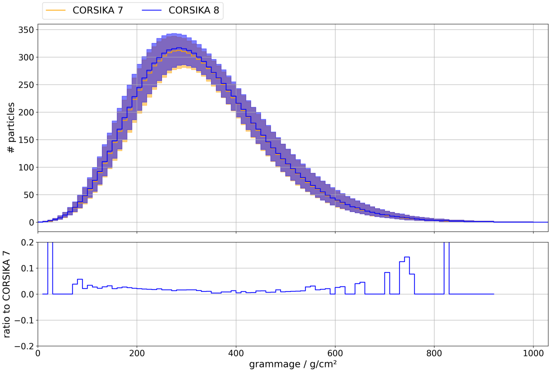


Longitudinal profile photons

1 TeV EM Shower, cut of 20 MeV (statistics: 5000 showers)

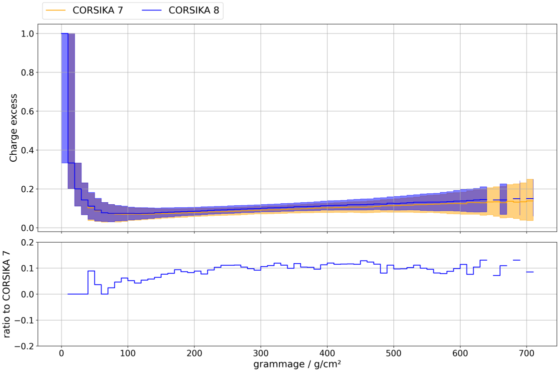


Longitudinal profile electrons

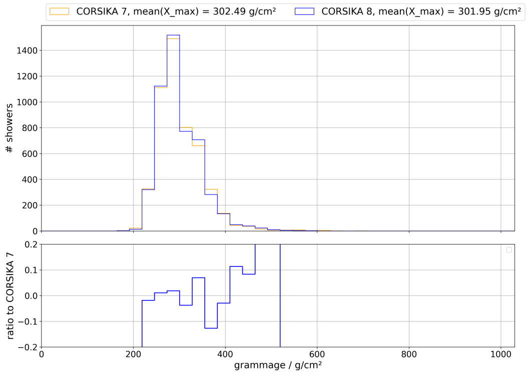


Longitudinal positrons

1 TeV EM Shower, cut of 20 MeV (statistics: 5000 showers)

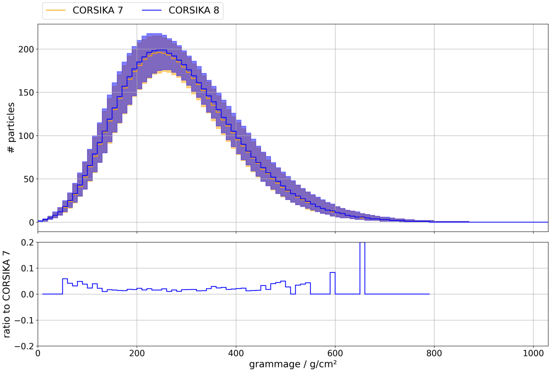


Charge excess $\frac{N_{e^-} - N_{e^+}}{N_{e^-} + N_{e^+}}$

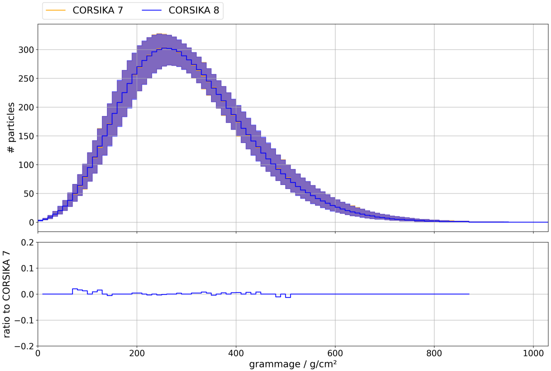


X_{max} distribution of charged particles

1 TeV EM Shower, cut of 200 MeV (statistics: 5000 showers)

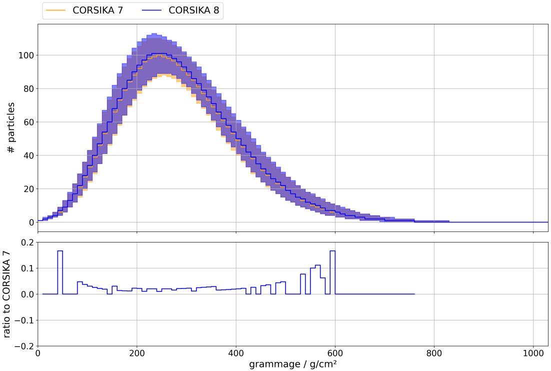


Longitudinal profile charged particles

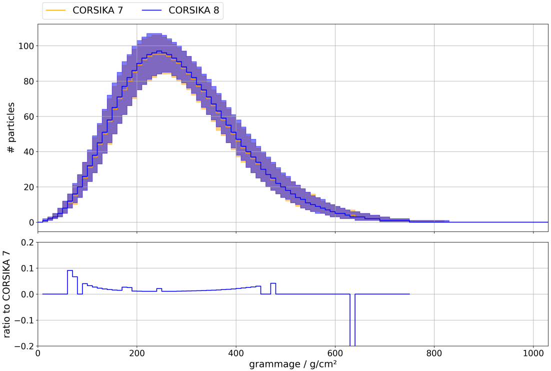


Longitudinal profile photons

1 TeV EM Shower, cut of 200 MeV (statistics: 5000 showers)

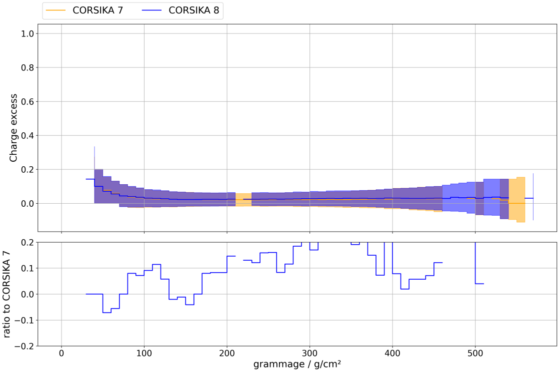


Longitudinal profile electrons

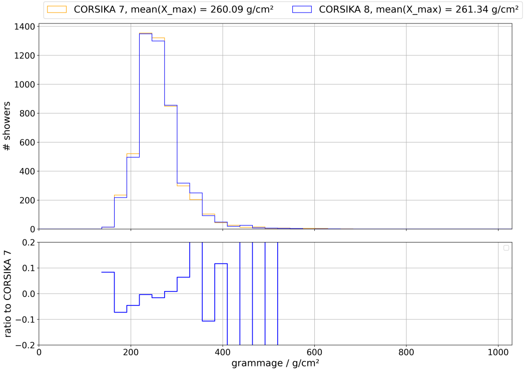


Longitudinal positrons

1 TeV EM Shower, cut of 200 MeV (statistics: 5000 showers)

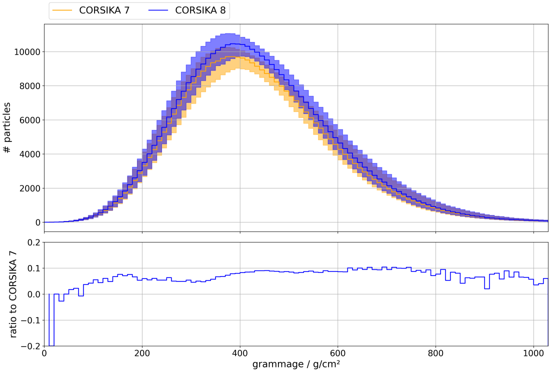


Charge excess $\frac{N_{e^-} - N_{e^+}}{N_{e^-} + N_{e^+}}$

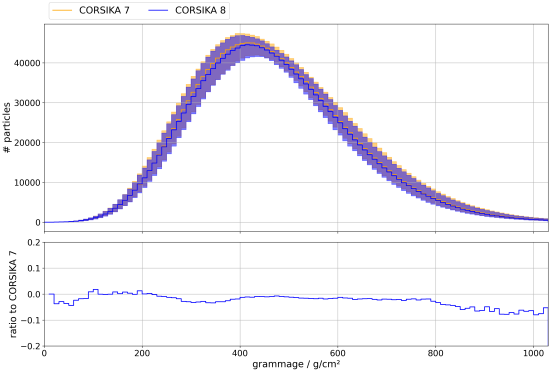


X_{max} distribution of charged particles

10 TeV EM Shower, cut of 2 MeV (statistics: 500 showers)

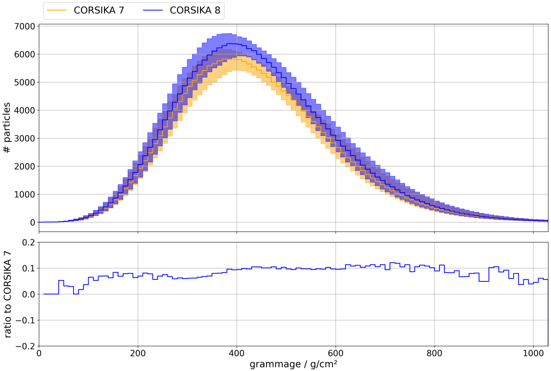


Longitudinal profile charged particles

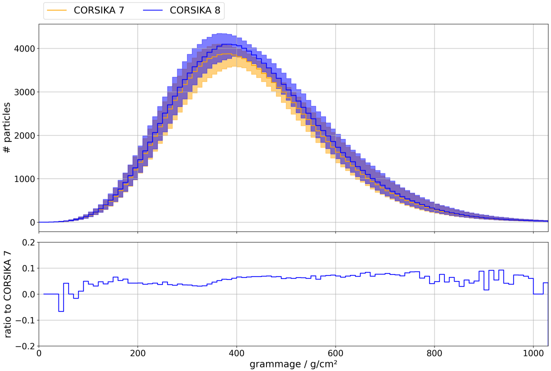


Longitudinal profile photons

10 TeV EM Shower, cut of 2 MeV (statistics: 500 showers)

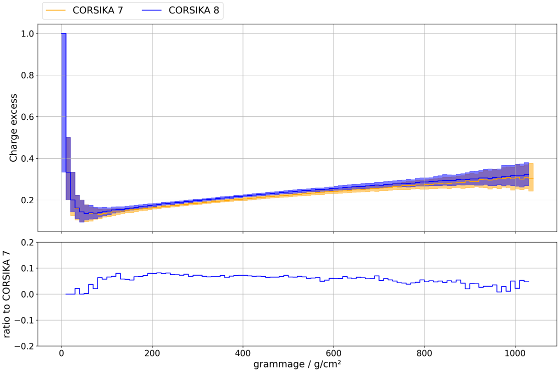


Longitudinal profile electrons

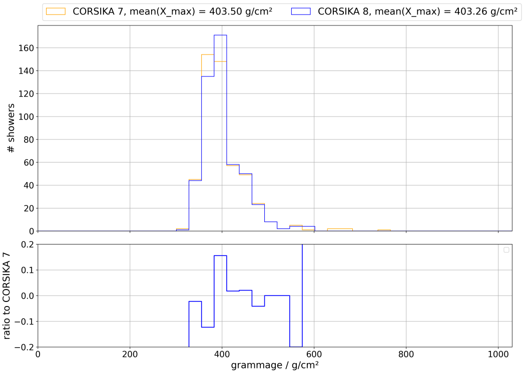


Longitudinal positrons

10 TeV EM Shower, cut of 2 MeV (statistics: 500 showers)

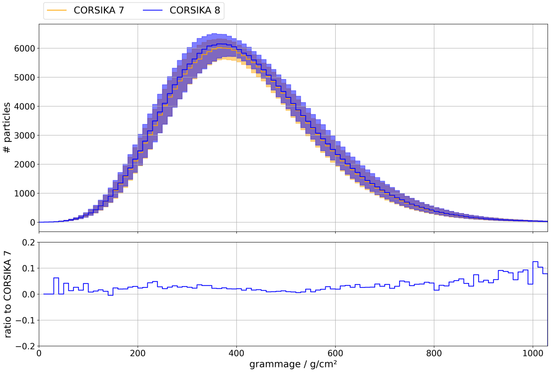


Charge excess $\frac{N_{e^-} - N_{e^+}}{N_{e^-} + N_{e^+}}$

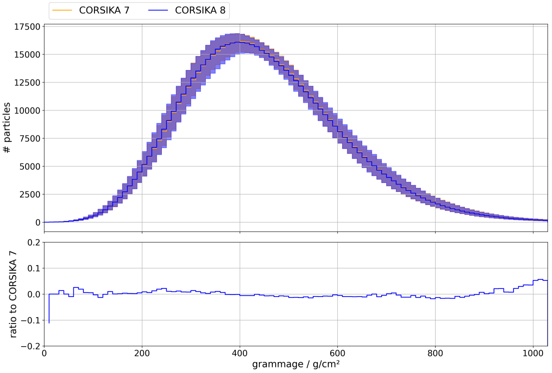


X_{max} distribution of charged particles

10 TeV EM Shower, cut of 20 MeV (statistics: 500 showers)

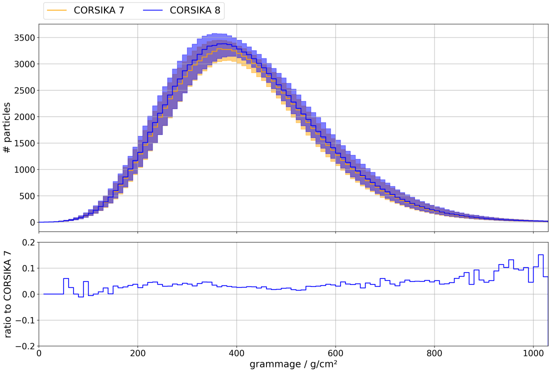


Longitudinal profile charged particles

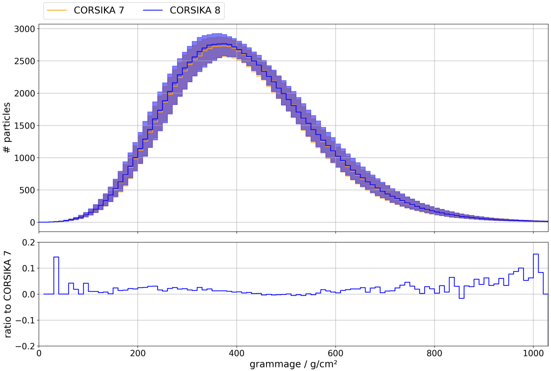


Longitudinal profile photons

10 TeV EM Shower, cut of 20 MeV (statistics: 500 showers)

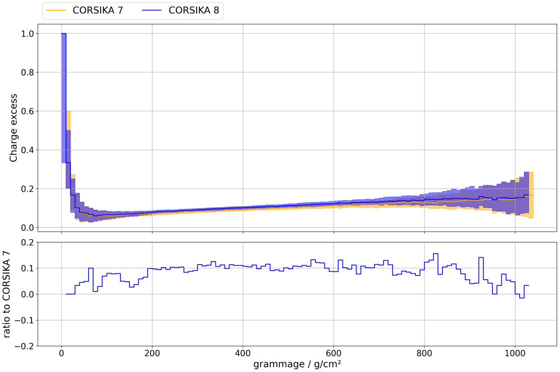


Longitudinal profile electrons

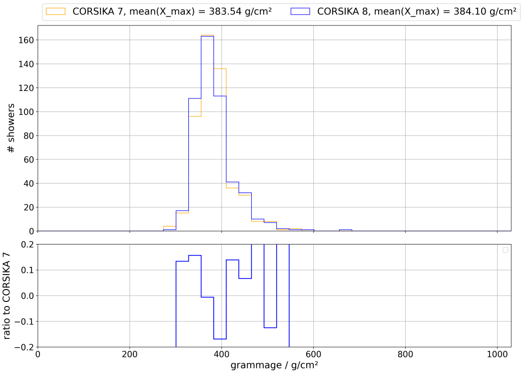


Longitudinal positrons

10 TeV EM Shower, cut of 20 MeV (statistics: 500 showers)

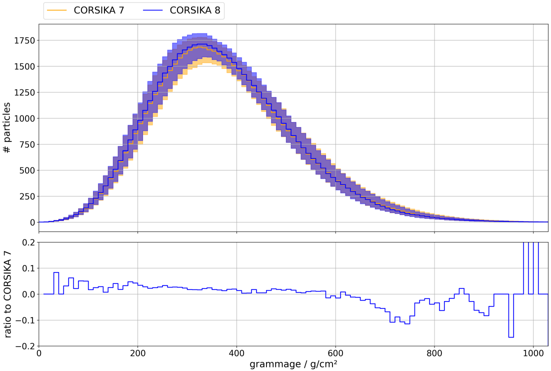


Charge excess $\frac{N_{e^-} - N_{e^+}}{N_{e^-} + N_{e^+}}$

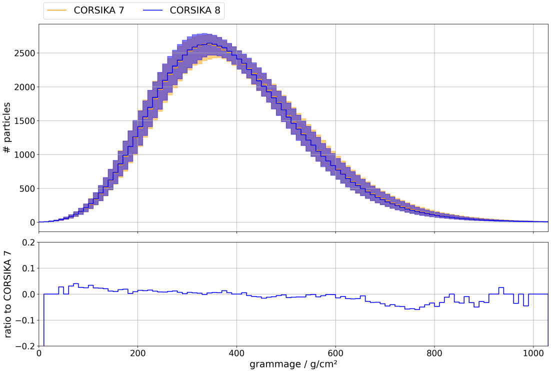


X_{max} distribution of charged particles

10 TeV EM Shower, cut of 200 MeV (statistics: 500 showers)

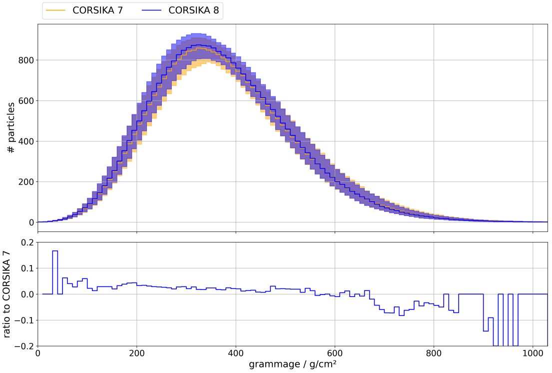


Longitudinal profile charged particles

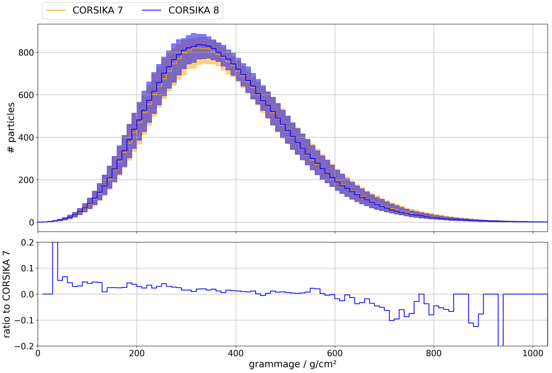


Longitudinal profile photons

10 TeV EM Shower, cut of 200 MeV (statistics: 500 showers)

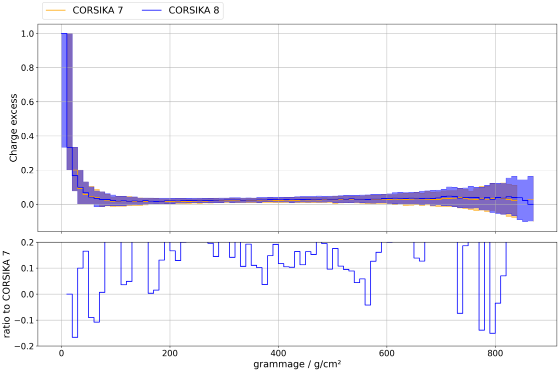


Longitudinal profile electrons

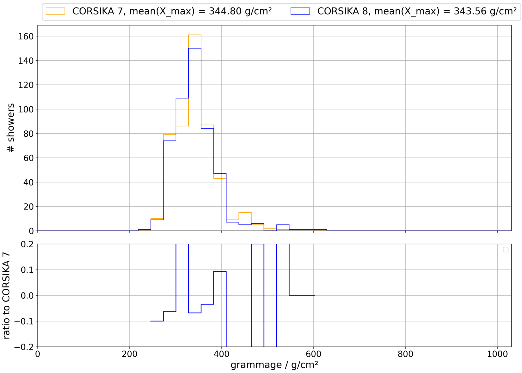


Longitudinal positrons

10 TeV EM Shower, cut of 200 MeV (statistics: 500 showers)

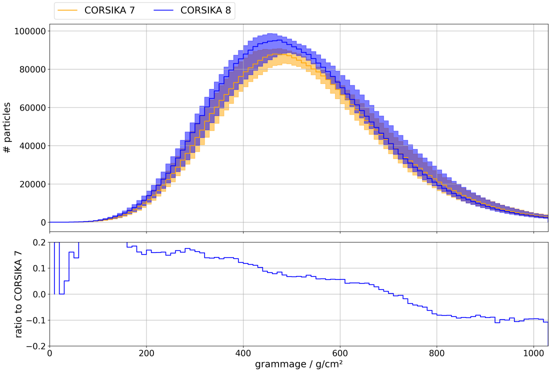


Charge excess $\frac{N_{e^-}-N_{e^+}}{N_{e^-}+N_{e^+}}$

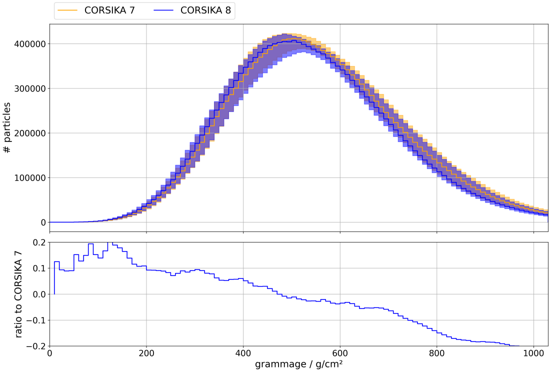


X_{max} distribution of charged particles

100 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

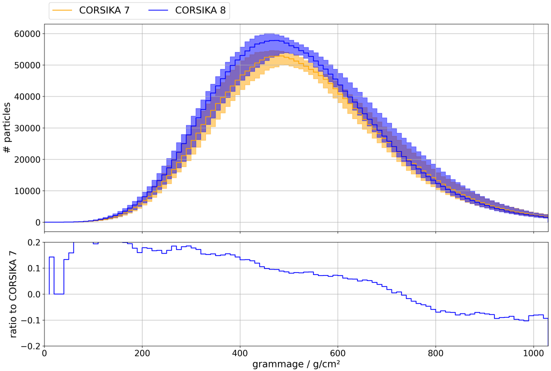


Longitudinal profile charged particles

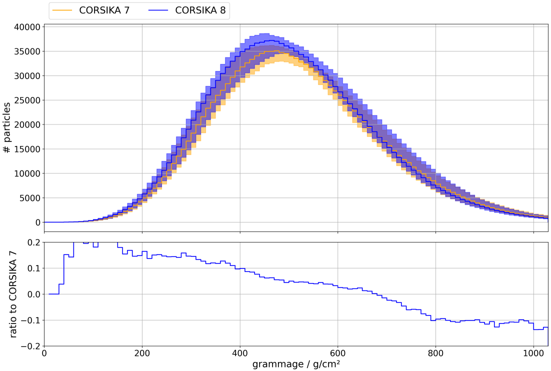


Longitudinal profile photons

100 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

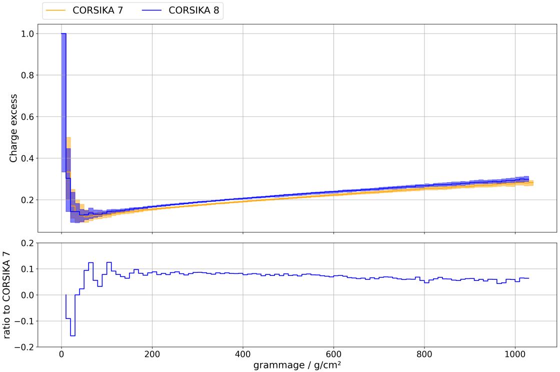


Longitudinal profile electrons

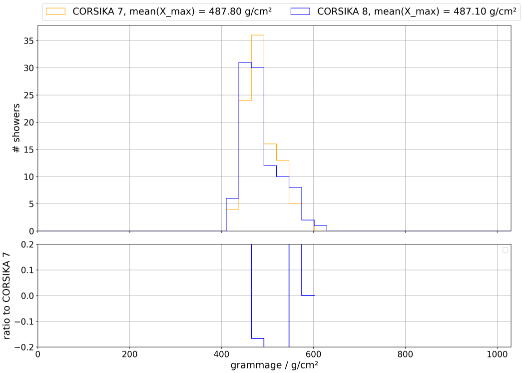


Longitudinal positrons

100 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

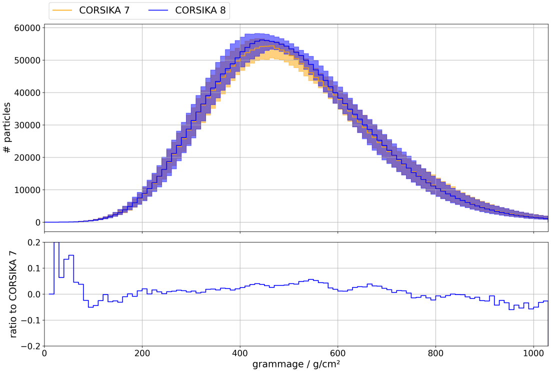


Charge excess $\frac{N_{e^-} - N_{e^+}}{N_{e^-} + N_{e^+}}$

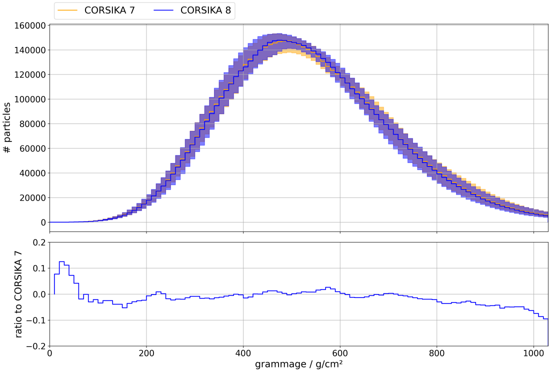


X_{max} distribution of charged particles

100 TeV EM Shower, cut of 20 MeV (statistics: 100 showers)

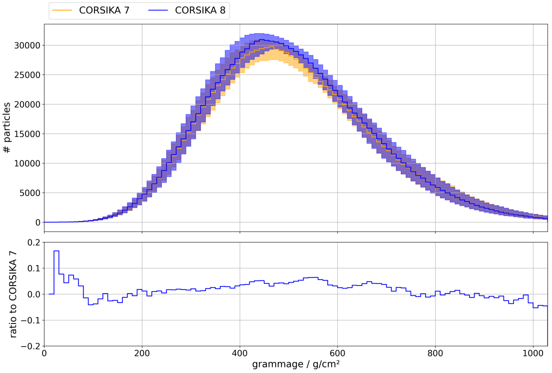


Longitudinal profile charged particles

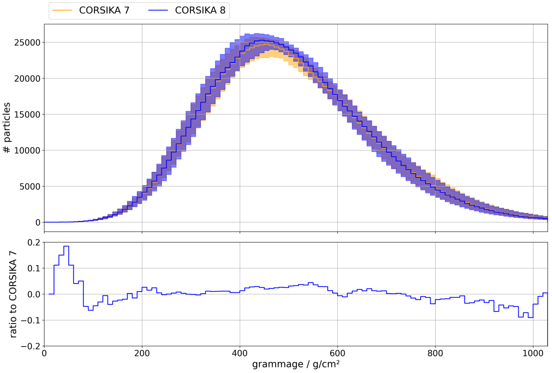


Longitudinal profile photons

100 TeV EM Shower, cut of 20 MeV (statistics: 100 showers)

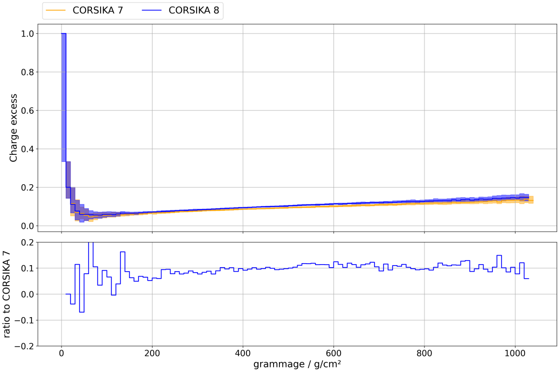


Longitudinal profile electrons

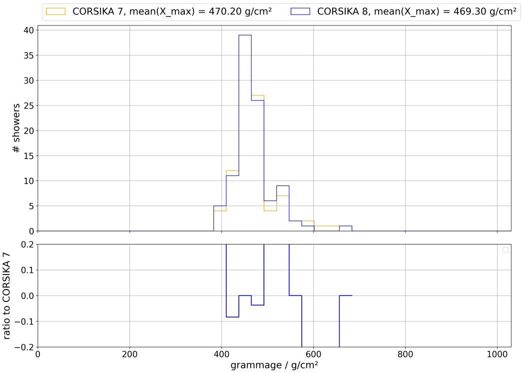


Longitudinal positrons

100 TeV EM Shower, cut of 20 MeV (statistics: 100 showers)

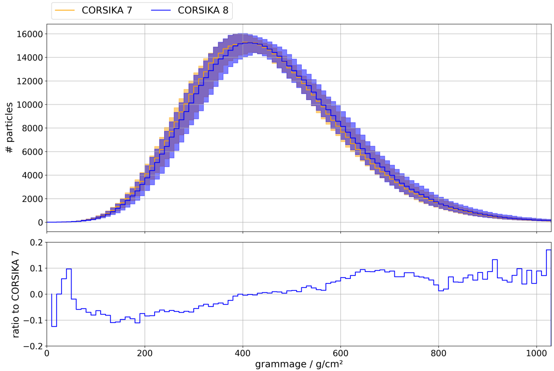


Charge excess $\frac{N_{e^-} - N_{e^+}}{N_{e^-} + N_{e^+}}$

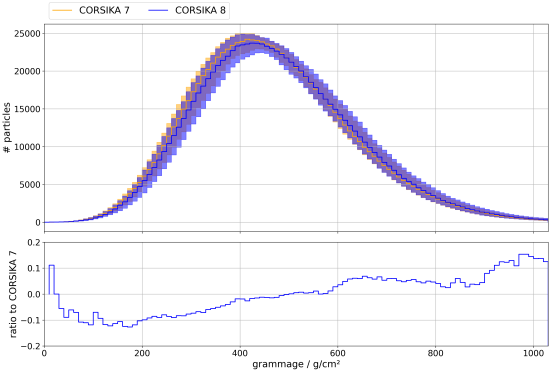


X_{max} distribution of charged particles

100 TeV EM Shower, cut of 200 MeV (statistics: 100 showers)

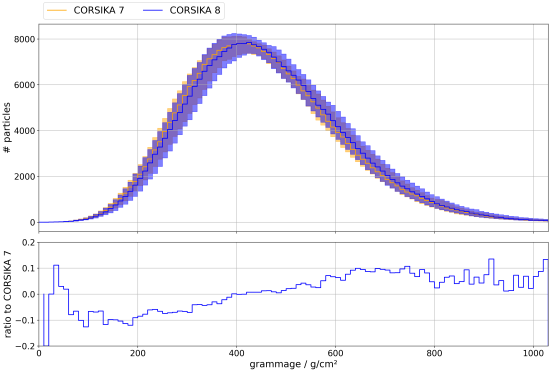


Longitudinal profile charged particles

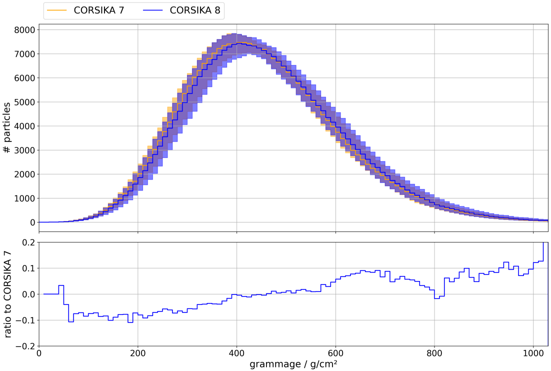


Longitudinal profile photons

100 TeV EM Shower, cut of 200 MeV (statistics: 100 showers)

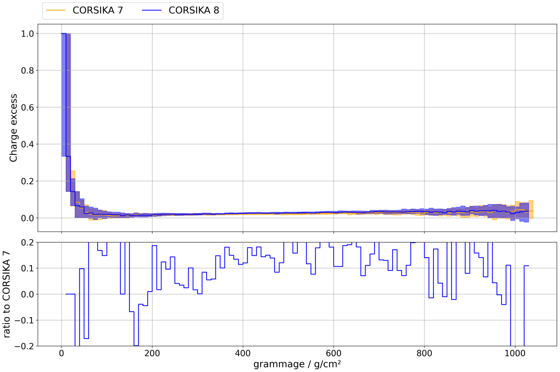


Longitudinal profile electrons

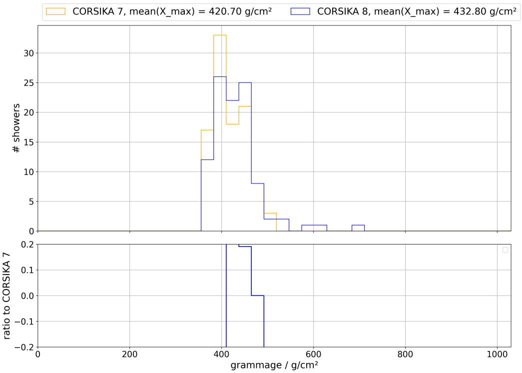


Longitudinal positrons

100 TeV EM Shower, cut of 200 MeV (statistics: 100 showers)

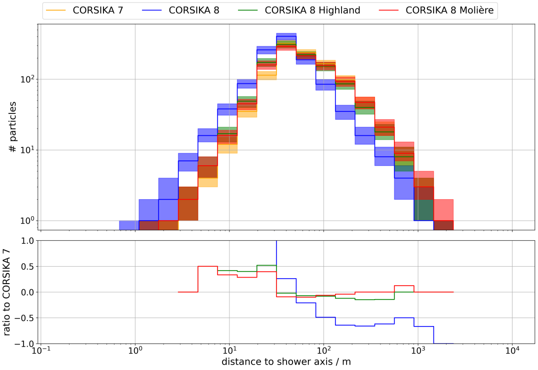


Charge excess $\frac{N_{e^-} - N_{e^+}}{N_{e^-} + N_{e^+}}$

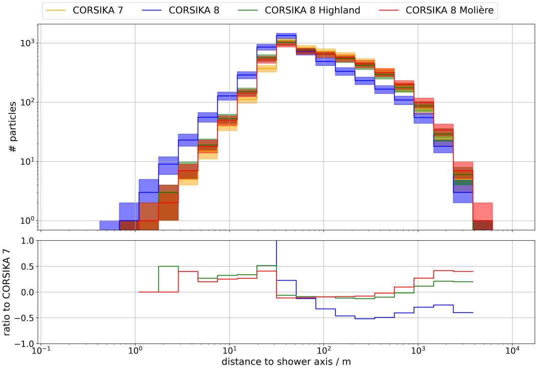


X_{max} distribution of charged particles

1 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

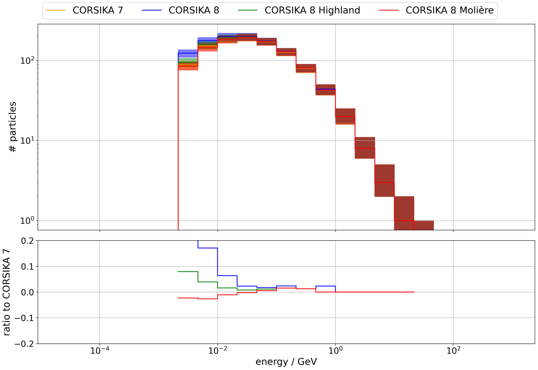


Lateral profile of charged particles at X_{max}

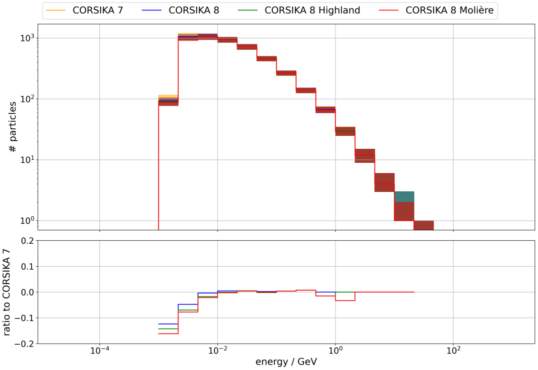


Lateral profile of photons at X_{max}

1 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

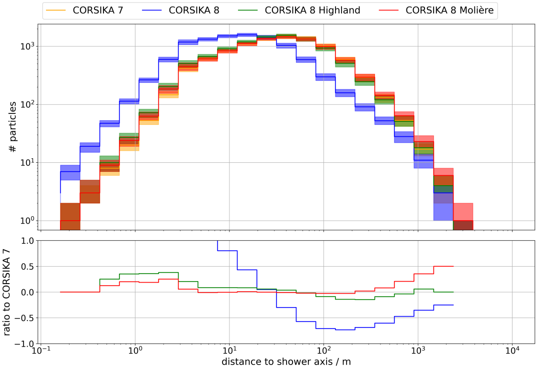


Energy distribution of charged particles at X_{max}

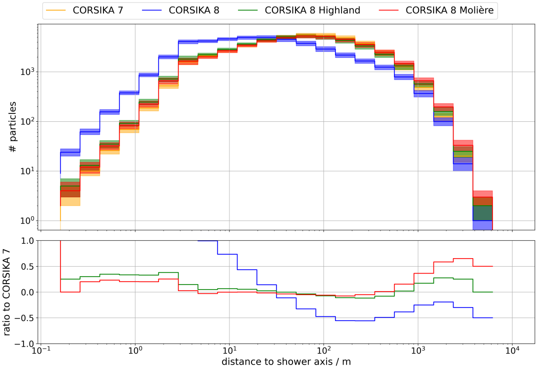


Energy distribution of photons at X_{max}

10 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

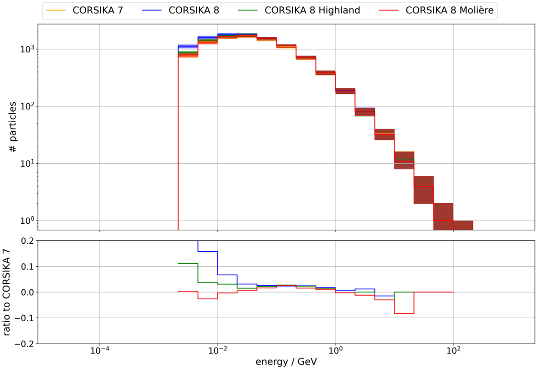


Lateral profile of charged particles at X_{max}

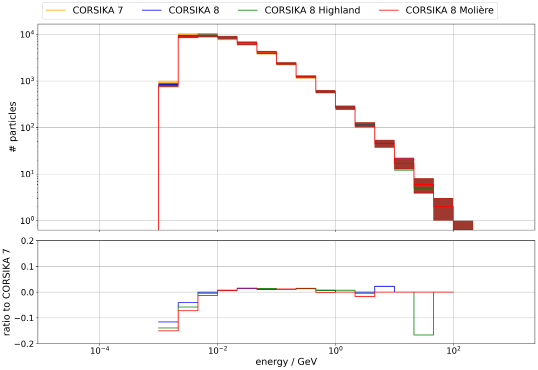


Lateral profile of photons at X_{max}

10 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

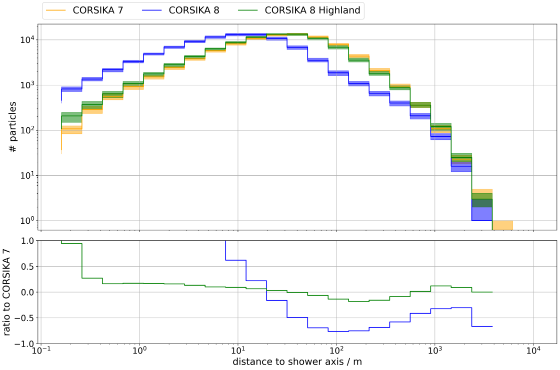


Energy distribution of charged particles at X_{max}

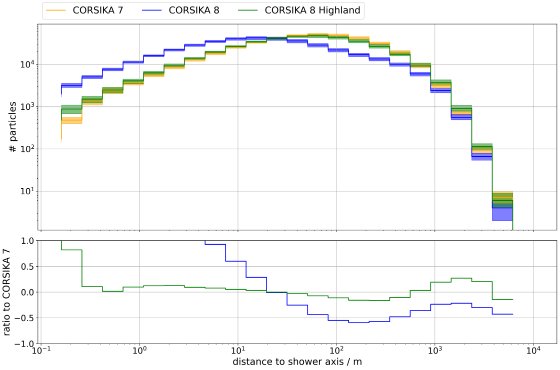


Energy distribution of photons at X_{max}

100 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)

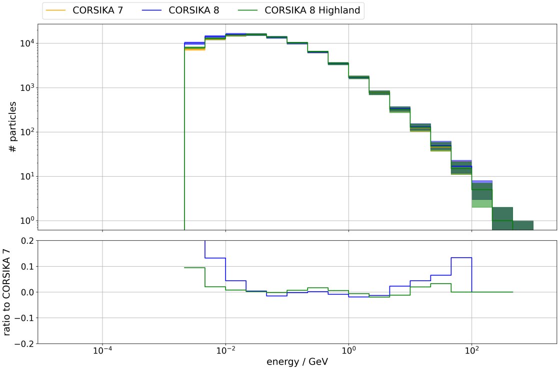


Lateral profile of charged particles at X_{max}

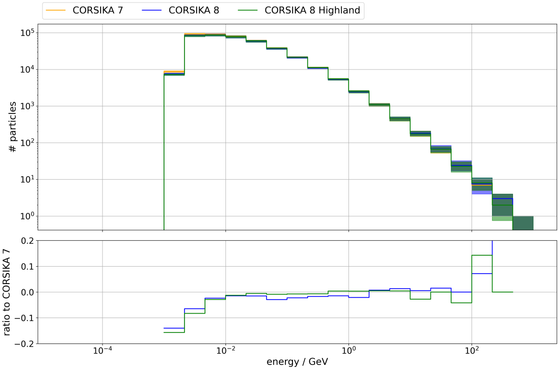


Lateral profile of photons at X_{max}

100 TeV EM Shower, cut of 2 MeV (statistics: 100 showers)



Energy distribution of charged particles at X_{max}

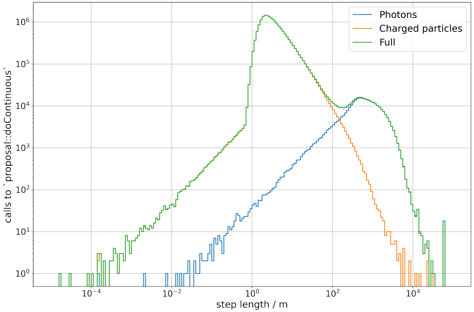


Energy distribution of photons at X_{max}

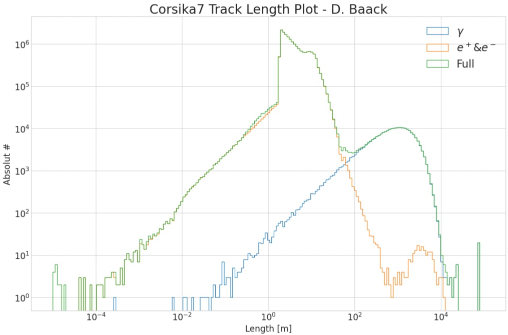
	Function name	runtime (% of total)
1.	`proposal::ContinuousProcess::doContinuous`	25.4 %
	→ `PROPOSAL::UtilityInterpolant::GetUpperLimit`	→ 9.8 % ?
	→ `SlidingPlanarExponential::getIntegratedGrammage`	→ 6.6 %
	→ `LeapFrogTrajectory::getPosition`	→ 4.6 %
	→ `PROPOSAL::multiple_scattering`	→ 2.5 %
2.	`PROPOSAL::Interaction::MeanFreePath`	19.5 %
	→ `cubic_splines::BicubicSplines::evaluate`	→ 5.9 %
	→ `PROPOSAL::CrossSectionDNDX::GetIntegrationLimits`	→ 8.1 % !
3.	`SlidingPlanarExponential::getArclengthFromGrammage`	13.4 %
	→ `LeapFrogTrajectory::getPosition`	→ 9.1 %
	→ `LeapFrogTrajectory::getDirection`	→ 2.3 %
4.	`tracking_leapfrog_curved::Tracking::getTrack`	11.1 %
	→ `Intersect::nextIntersect`	→ 8.4 %
5.	`LeapFrogTrajectory::getPosition`	6.7 %
6.	`proposal::InteractionModel::doInteraction`	3.9 %
7.	`ParticleCut::checkCutParticle`	3.7 %
8.	`tracking_leapfrog_curved::Tracking::intersect`	2.1 %

- Runtime profiling of a single **10** TeV shower
- Using `perf 5.4.0` with a sampling frequency of 1000 samples per second
  - → Count how much time is spent in which function
- Magnetic field is enabled

Steplength comparisons for a 99 % steplength limitation in CORSIKA 8



Steplengths in **1** TeV showers in CORSIKA 8 (**20** MeV cuts)



Steplengths in **1** TeV showers in CORSIKA 7 (**20** MeV cuts)