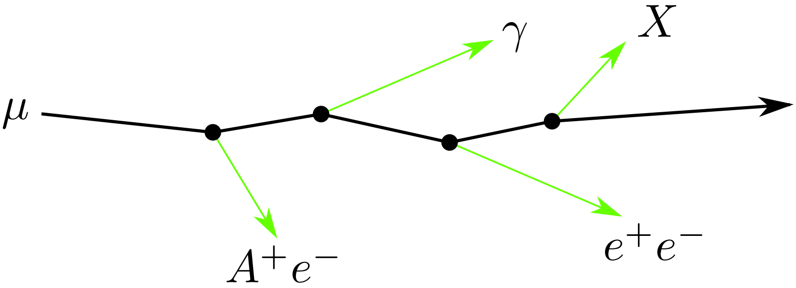


Improvements in the EM cascade

Jean-Marco Alameddine

6/13/2023

CORSIKA 8 Workshop 2023

Motivation

CORSIKA 8 Workshop 2022

→

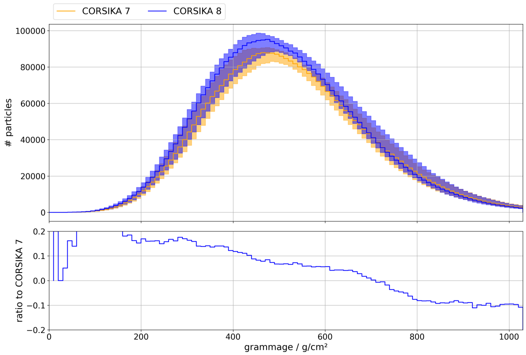
CORSIKA 8 Workshop 2023

- Idea of this talk: Present updates of EM simulations within CORSIKA 8 since the last workshop
  - → However, it is exceptionally hard to present one full year of development in one talk
  - → I'll try to focus on some of the most important updates

Conclusions from the 2022 workshop

Looking back at the 2022 workshop - Which problems within the EM component did we identify?

- **CORSIKA 8 produces too many charged leptons (compared to CORSIKA 7)**
- **CORSIKA 8 showers tend to develop earlier**
- The charge excess within CORSIKA 8 is higher
- Lateral profiles don't agree, CORSIKA 8 particles are shifted towards the shower axis



Longitudinal profile of charged particles in 100 TeV e^- showers, 2022 workshop.

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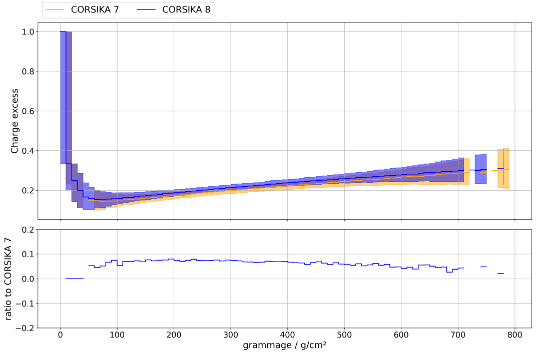

Longitudinal charge excess ($\frac{N_{e^-}-N_{e^+}}{N_{e^-}+N_{e^+}}$) in 1 TeV showers, 2022 workshop.

Looking back at the 2022 workshop - Which problems within the EM component did we identify?

- CORSIKA 8 produces too many charged leptons (compared to CORSIKA 7)
- CORSIKA 8 showers tend to develop earlier
- The charge excess within CORSIKA 8 is higher
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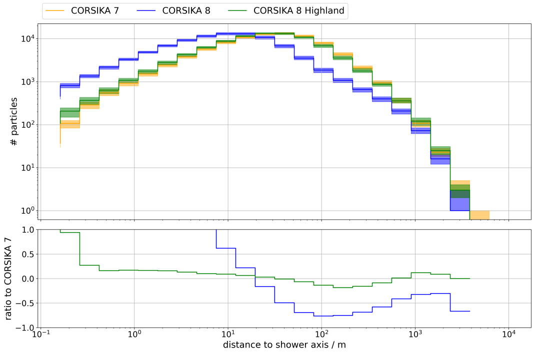


Lateral profiles for 100 TeV showers at X_{max}, 2022 workshop.

Bugfixes and improvements

”Cascade bug”

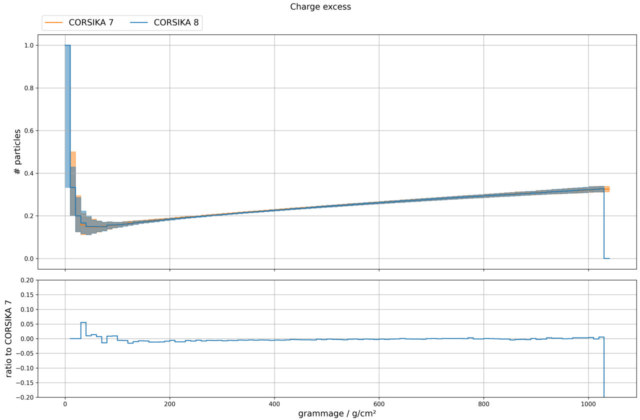
- Prior to the 2022 workshop, we discovered an issue within the basic `Cascade` algorithm of CORSIKA 8
- It was not clear at which position of a continuous step energies are evaluated
  - → Cross sections weren’t evaluated at the correct energies
  - → Multiple scattering was not (correctly) taken into account
- **Huge** effort by Nikos and Maximilian to fix this issue ($\approx$ 6 months of development) 💪
  - → Implementation of a `Step` object, which collects all incremental changes to a particle state from all continuous processes
  - → It is now much clearer what continuous processes are doing

Influence on longitudinal profiles

- The fix of the `Cascade` algorithm means that cross sections are evaluated correctly now
- Furthermore, we have adapted the kinematic limits of the bremsstrahlung cross section
  → Better agreement with EGS4 cross sections, for details see here
- We have fixed a bug where the difference of ionization between e^- and e^+ was treated incorrectly by PROPOSAL

Influence on longitudinal profiles

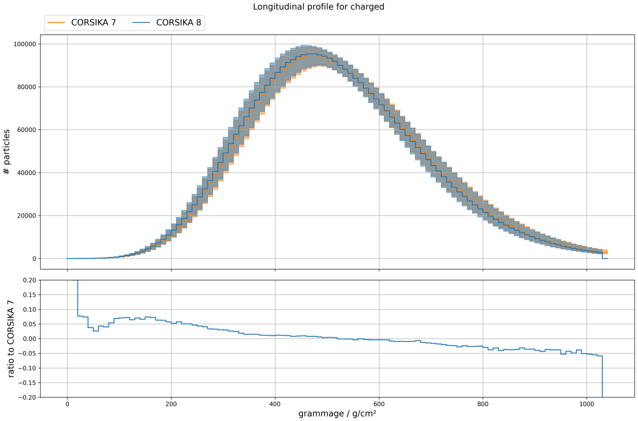
- Charge excess in very good agreement (< 1 %) with CORSIKA 7 now



Longitudinal charge excess ($\frac{N_{e^-}-N_{e^+}}{N_{e^-}+N_{e^+}}$) in 100 TeV showers, current status.

Influence on longitudinal profiles

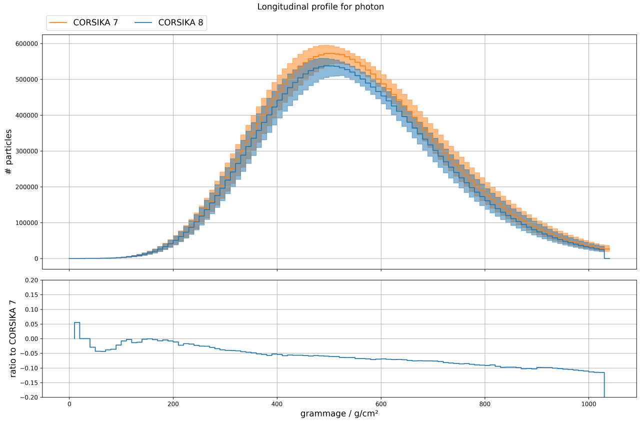
- Better agreement concerning the overall number of charged particles
  → However, CORSIKA 8 showers still develop earlier compared to CORSIKA 7



Longitudinal profile of charged particles in 100 TeV showers, current status.

Influence on longitudinal profiles

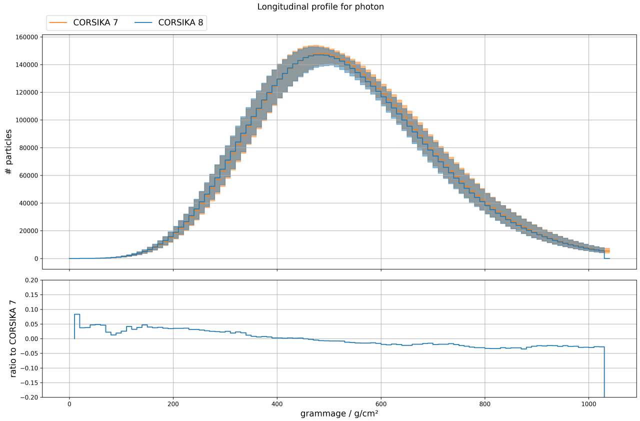
- Looking at the longitudinal profile of photons, we are missing photons compared to CORSIKA 7



Longitudinal profile of photons in 100 TeV showers, current status.

Influence on longitudinal profiles

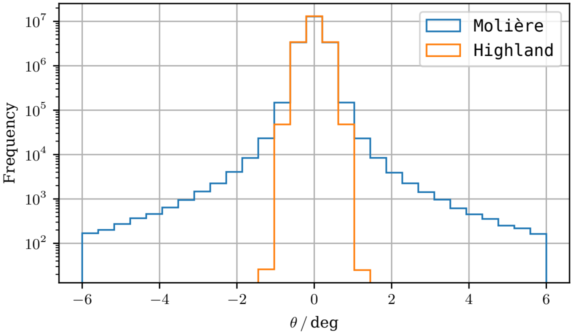
- Looking at the longitudinal profile of photons, we are missing photons compared to CORSIKA 7
  - → If we only look at photons with enegies above **20** MeV, the particle number agrees
  - → This means that low-energy photons are missing



Longitudinal profile **of photons above 20 MeV** in 100 TeV showers, current status.

Influence on lateral profiles

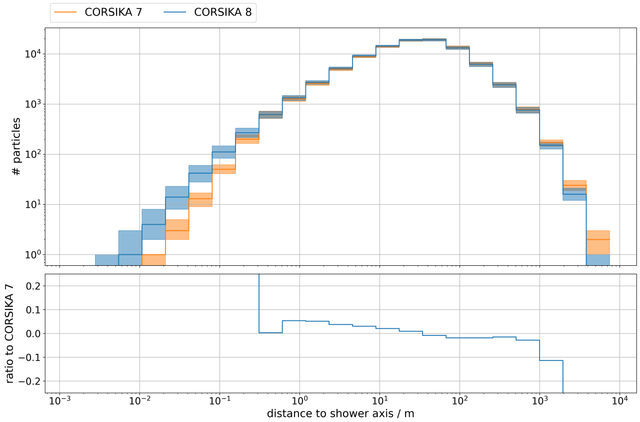
- With the fix of `Cascade`, multiple scattering is now (correctly) taken into account
- So far, we had always used the `Highland` parametrization of multiple scattering
  - → `Highland` is a Gaussian approximation of the complete `Molière` parametrization of multiple scattering
  - → The `Highland` parametrization is faster to evaluate, but neglects outliers
  - → Most recent release of PROPOSAL includes a parametrization of `Molière` scattering with improved performance (`MolièreInterpol`)



Exemplarily: Sampled scattering angles for an electron in air during a continuous step from $E_i = 1$ GeV to $E_f = 0.9$ GeV, corresponding to a grammage of $X \approx 3.5\,\mathrm{g\,cm^{-2}}$.

Influence on lateral profiles

- Lateral profiles with a better agreement (within **5 %** for most bins)
- Remaining discrepancies for bins very close and very far from shower axis



Lateral profile of charged particles for 100 TeV showers at X_{max}, current status.

Looking back at the 2022 workshop - Which problems within the EM component did we identify?

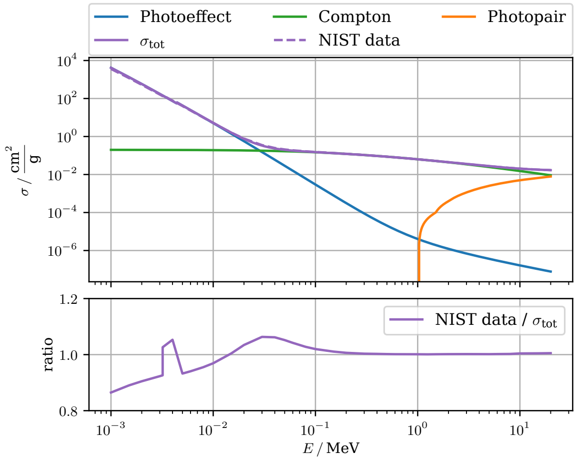
- CORSIKA 8 produce too many charged leptons (compared to CORSIKA 7)
  → (✔️) Fixed, but remaining issue for low-energy photons
- CORSIKA 8 showers tend to develop earlier
  → ❌ Issue still existing
- The charge excess within CORSIKA 8 is higher
  → ✔️ Fixed
- Lateral profiles don't agree, CORSIKA 8 particles are shifted towards the shower axis
  → (✔️) Improved, but still not perfect for outliers

Big steps towards the right direction!

New features

Photoeffect

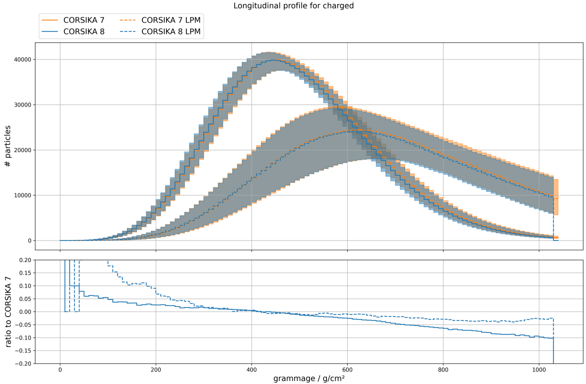
- Implementation of an approximate treatment of the photoeffect
- This allows us to simulate the EM component to energies of **0.5** MeV and lower
  - → Important for radio simulations



Photon cross sections in air, compared to tables from the NIST Standard Reference Database.

LPM effect

- The LPM effect is a suppression of bremsstrahlung and pair production
  - → Relevant for very-high energy air showers (above 10^{18} eV for EM showers, above 10^{20} eV for hadronic showers[1]) or for dense media
- Implemented as a rejection sampling for stochastic interactions
  - → No treatment for the change of continuous energy losses due to LPM implemented yet (discussion about this see here)



Longitudinal profile for 10^{20} eV showers with and without the LPM effect (simulated down to 100 TeV)

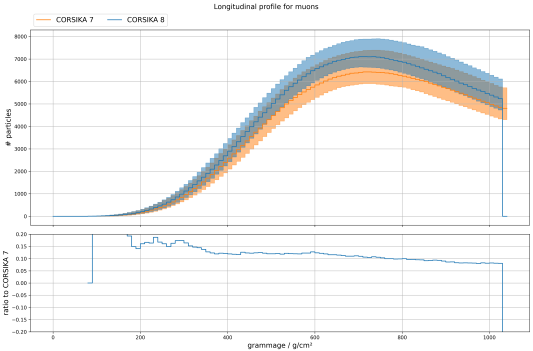
[1] Knapp et al., Astroparticle Physics 19.1 (2003), pp. 77–99

Hadronic interactions in EM showers

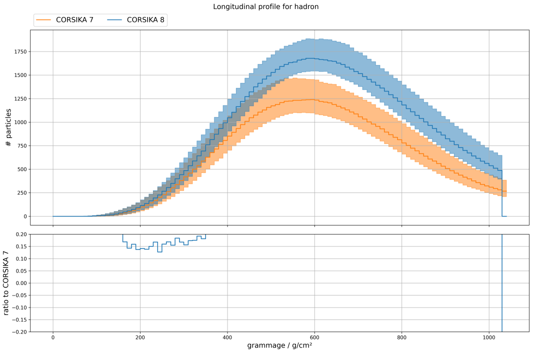
- Photons and charged particles can (in rare cases) interact hadronically
  - → Source of hadrons and muons from the EM component
- We have an interface to SIBYLL (high-energy) and SOPHIA (low-energy) now
  - → We pass the hadronic interaction as a ρ_0 to the hadronic model to produce the secondary particles
- In the 2022 workshop, preliminary results showed that we have less hadrons and muons compared to CORSIKA 7
  - → Back then, we only had the interface to SIBYLL

Hadronic interactions in EM showers

- Now, there are significantly more muons and hadrons within our EM showers
- Since we are using a different approach compared to CORSIKA 7, different results are expected
  - → Requires more investigation



Muon distribution in 10 PeV e^- showers (down to 0.5 GeV)

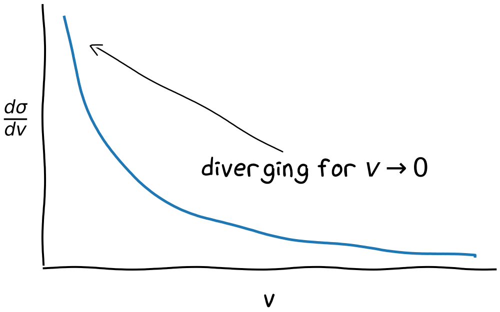


Hadron distribution in 10 PeV e^- showers (down to 0.5 GeV)

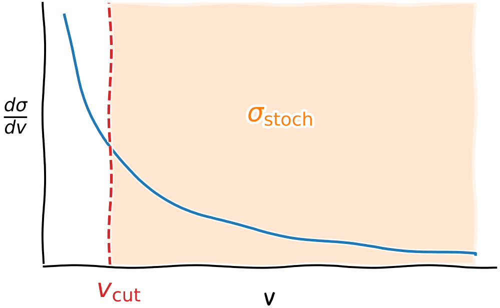
Open issues, questions, and future developments

Short interlude: Concept of PROPOSAL

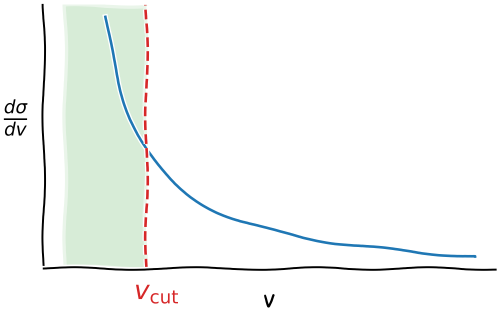
- How to calculate the mean free path $\lambda \propto \sigma^{-1}$ of a particle?
- Naive idea: Take total cross section $\sigma = \int_{v_{min}}^{v_{max}} \frac{d\sigma}{dv} dv$, where v is the relative energy loss of a particle in a single interaction
  - → First problem: Differential cross section diverges for $v \to 0$. Therefore, λ approaches 0 ⚡
  - → Second issue: Inefficient, because this would mean we would have to sample every single interaction individually (no matter how small v is!). Or in other words: We get very small steps.



- Approach: When sampling λ, only take into account energy losses with $v > v_{\text{cut}}$
  - → $\sigma_{\text{stoch}} = \int_{v_{\text{cut}}}^{v_{\text{max}}} \frac{d\sigma}{dv} \, dv$
- This gives us a finite value for σ_{stoch} and λ_{stoch}
- Note: This v_{cut} can either be a relative value (e.g. **1 %**) or an absolute value (e.g. **5** MeV)



- What about the interactions with $v \leq v_{\text{cut}}$?
- We calculate an effective energy loss per distance:
  → $\frac{\mathrm{d}E}{\mathrm{d}x} \propto E \int_{v_{\text{min}}}^{v_{\text{cut}}} v \frac{\mathrm{d}\sigma}{\mathrm{d}v} \, \mathrm{d}v$
- Apply these continuous energy losses to propagated distance between stochastic interactions
- Now, all energies losses are correctly taken into account! 🎉
- Important question: Which value to choose for v_{cut}?

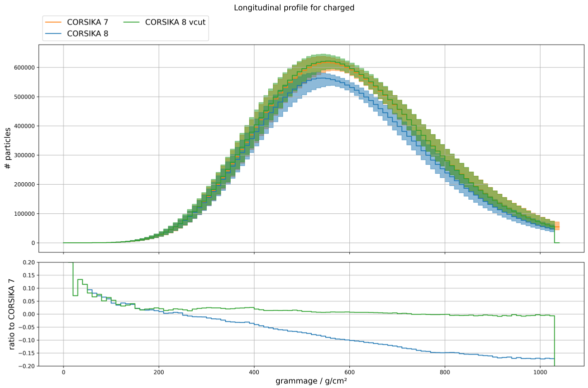


Usage of ParticleCut and ProductionThreshold

- Within CORSIKA 8, there are two energy settings relevant for the EM component
  - → `ParticleCut`: Particles below this (total) energy are removed from the Stack
  - → `ProductionThreshold`: Only energy losses above this energy are treated stochastically. Individual energy losses below this energy are treated continuously. This is what I have just introduced as a v_{cut}.
- So far, both settings have been set to an identical total energy
  - → Motivation: We don't need to individually simulate an energy loss if the produced secondary particles would be directly removed from the stack
- However, recent simulations showed that there is a significant difference if one sets the `ProductionThreshold` below the `ParticleCut`
  - → This means we individually sample energy losses although we know that these particles will be directly removed from the stack
  - → However, this might be necessary for an accurate simulation of the shower development, since the approximation as a continuous energy loss might be inaccurate.

Usage of ParticleCut and ProductionThreshold

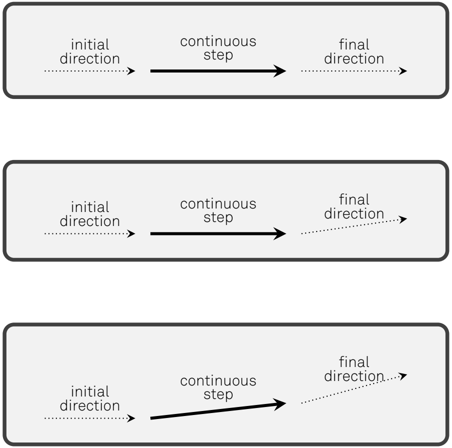
- Possible solutions:
  1. Set the **`ProductionThreshold`** to a fraction of the **`ParticleCut`** (e.g. **1 %**)
  2. Introduce a relative **`ProductionThreshold`** in addition to the absolute one. This is intrinsically possible with PROPOSAL (called v_{cut}).
- Plot on the right shows the comparison to a simulation where the v_{cut} has been included
  → Much better agreement with CORSIKA 7.
- Maybe a point of discussion for the working sessions



Longitudinal profile of charged particles in 10 PeV e^- showers (down to 0.5 GeV)

Lateral particle development

- Multiple scattering is working much better now
- However, a complete treatment of multiple scattering should include the change of direction after a continuous step and the lateral displacement of the particle
    - → Treatment is highly non-trivial, see discussion and slides of last workshop.
    - → More advanced algorithmic treatment of continuous step like *RandomHinge* or *numerical particle propagation* as presented by Maximilian at the last workshop
- Still not included, but important: Path length correction due to multiple scattering



Some other aspects...

Open pull requests

- ~~LPM effect implementation~~ → Merged on monday!
- Stochastic photon propagation
  → No continuous losses for photons anymore. Numerically more stable, less warnings, no endless loops.
- Update to PROPOSAL 7.6.1
  → Includes some vital bugfixes, e.g. for ionization losses
  → `MolièreInterpol`, significant speed-up of multiple scattering
  → Improved sampling methods for pairproduction (θ) and tripet production (ρ)

Points of discussion

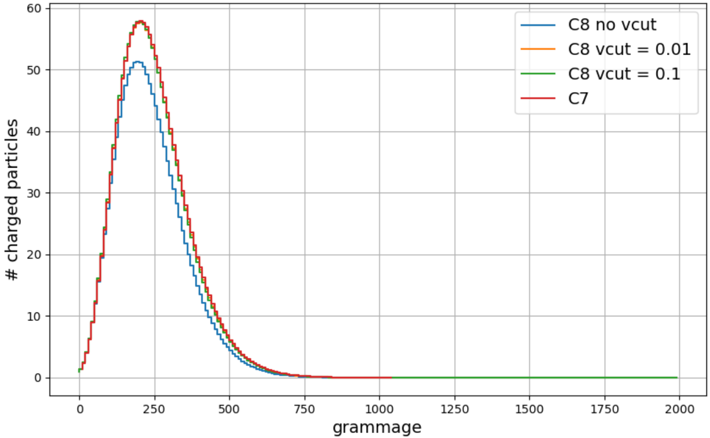
- Steering of the options provided by PROPOSAL
  → PROPOSAL has a flexible structure, allowing users to adapt/change physics parametrizations
  → How to combine these features with steering of CORSIKA 8?
- Table creation
  → Current solution not optimal for users
  → Already had some discussions yesterday after Alexanders talk, in the coffee break, and on the train

Summary

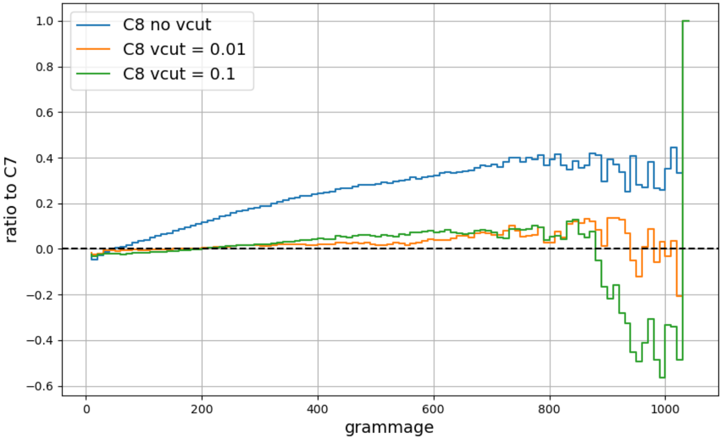
- A lot of issues have been fixed since the last workshop
- What has not been mentioned: A large amount of smaller and larger bugfixes that helped improved the stability of CORSIKA 8
  - → Less crashes and warnings due to the EM component 🤞
- All relevant physics processes are included by now
- Some improvements and investigations are still necessary
  - → Lateral shower development
  - → Hadronic interactions in EM showers
  - → Low-energy photons
- Elephant in the room not mentioned in this talk: Need for runtime optimization 🐘

Backup

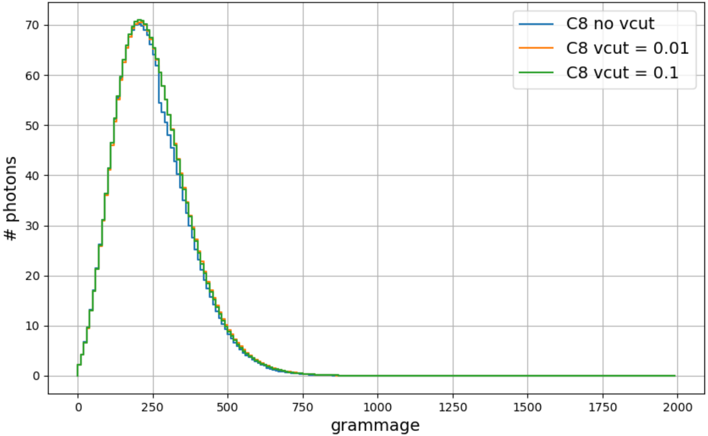
Studies of $\boldsymbol{v}_{\mathrm{cut}}$ settings



Longitudinal profile of charged particles in 100 PeV e^- showers, using different (or none) v_{cut} settings.

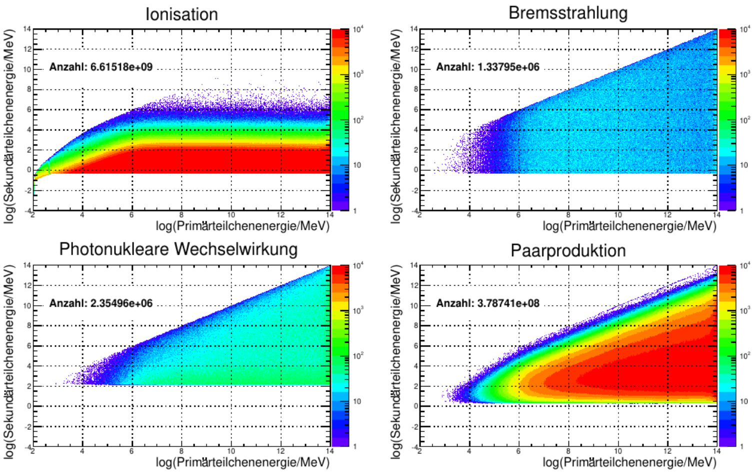


Longitudinal profile of charged particles in 100 PeV e^- showers, using different (or none) v_{cut} settings.



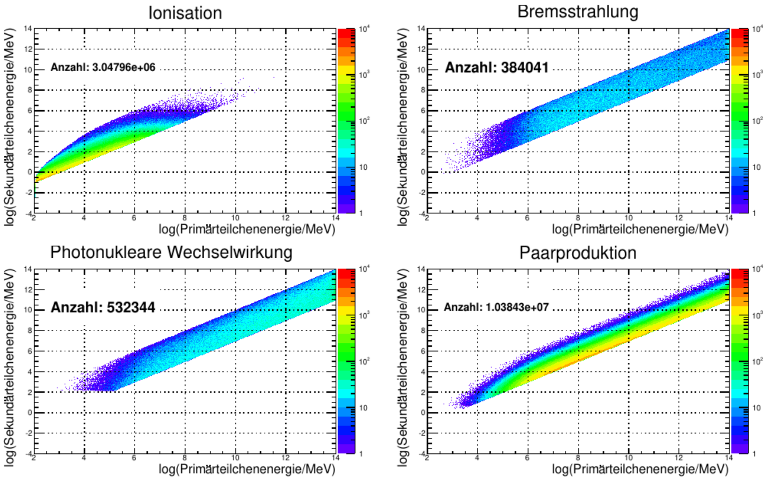
Longitudinal profile of photons in 100 PeV e^- showers, using different (or none) v_{cut} settings.

Effects of $\boldsymbol{e}_{\text{cut}}$ and $\boldsymbol{v}_{\text{cut}}$

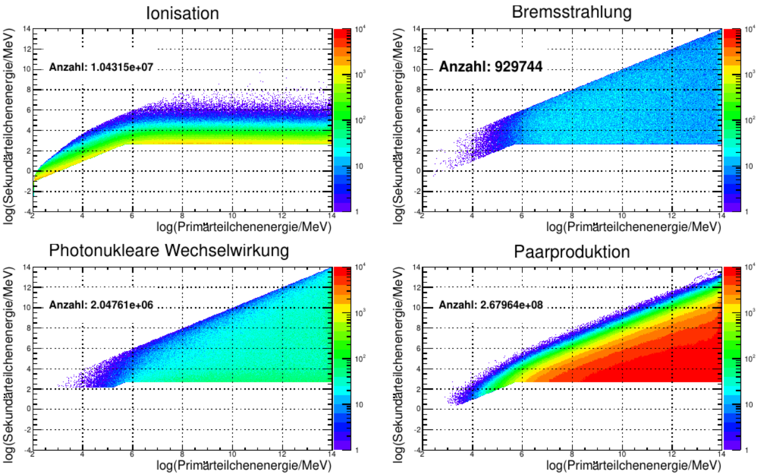


Muon energy losses for different interaction types, using $\boldsymbol{e}_{\text{cut}}$ = 0.5 MeV and $\boldsymbol{v}_{\text{cut}} = 10^{-3}$.

From "Der Leptonpropagator PROPOSAL", Jan-Hendrik Köhne, PhD thesis 2013



Muon energy losses for different interaction types, using no e_{cut} and $v_{cut} = 10^{-3}$.
From "Der Leptonpropagator PROPOSAL", Jan-Hendrik Köhne, PhD thesis 2013



Muon energy losses for different interaction types, using $\boldsymbol{e}_{\mathrm{cut}}$ = 500 MeV and $\boldsymbol{v}_{\mathrm{cut}} = 10^{-3}$.
From "Der Leptonpropagator PROPOSAL", Jan-Hendrik Köhne, PhD thesis 2013

Additional material: LPM effect

LPM effect in air showers

- In the LPM regime, therefore, pair production events are predominantly asymmetric and more rare, and bremsstrahlung losses are predominantly large.
- At LPM energies, we expect photon-induced air showers to develop in two sub-showers
  - The initial photon produces a very asymmetric e^+e^- pair.
  - The low-energy lepton produces a normal (Bethe-Heitler) shower after the first interaction.
  - The high-energy lepton travels farther through the atmosphere because of the suppressed bremsstrahlung loss and produces a second shower deeper in the atmosphere.
- Overall, LPM showers develop more slowly than BH showers and with larger fluctuations (Konishi et al. 1991; Misaki 2019).

Simulation of the LPM effect

- In homogeneous media, PROPOSAL calculates the cross sections taking into account the LPM and TM effect according to Polityko et al. 2002; Stanev et al. 1982. In inhomogeneous media, this approach is not applicable, because the changing density changes the LPM suppression, avoiding its inclusion into the interpolation tables.
- In CORSIKA 7, based on the routines in AIRES (and before that in MOCCA), the LPM effect is taken into account via a variant of Neumann's rejection algorithm:
  - Bremsstrahlung and pair production are sampled according to the BH crosssections.
  - Before writing the secondaries to the stack, the LPM routine checks, whether to discard the interaction: the ratio ξ of the BH and the LPM crosssections is calculated, a uniform random number x between 0 and 1 is determined, and the interaction is discarded if $\xi > x$.

Simulation of the LPM effect

- The rejection procedure correctly takes into account the LPM effect on stochastic interactions. However, when LPM suppression is large, this procedure is inefficient. Also, this approach neglects the LPM effect on the continuous losses. It is therefore most likely not accurate enough for dense media.
- In EmCa (Meighen-Berger et al. 2019), the crosssections are rescaled with a correction factor; as the differential crosssections show, this is not appropriate for strong suppression..