On the identification of a proton component at ultra-high energy

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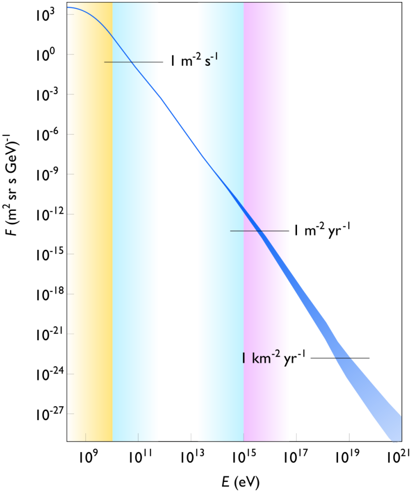
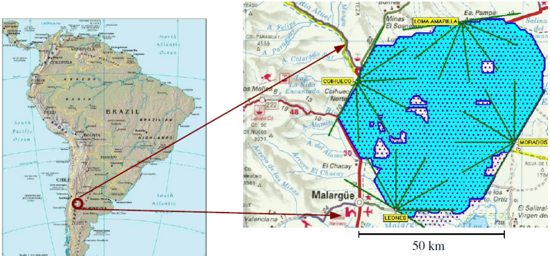
Cosmic rays

- Low energetic cosmic rays: direct measurement possible
- High energetic cosmic rays: direct measurement unuseful
  $\rightarrow$ Indirect detection of cosmic rays (e.g. Pierre Auger Observatory)
- Determination of primary mass difficult



The Pierre Auger Observatory



- SD-Detector: covering $3000\,\mathrm{km}^2$ with 1660 water cherenkov tanks (duty cycle 100%)
- 5 FD stations: 27 Fluorescence telescopes, measurements only in clear and moonless nights (duty cycle ≈ 10%)

- Determination of primary energy and shower maximum
- Huge covered area: good probability to detect ultra-high energetic air showers

Question

- Up to which energy $E_{\mathrm{max}}^{\mathrm{p}}$ can one observe protons in cosmic rays?
- Useful for tests of astrophysical scenarios or of possible violation of Lorentz invariance
- Violation of Lorentz invariance may be caused by new unknown effects at the Planck scale

Approach

- Given: Air shower of energy E_0 and observed maximum with depth $X_{\mathrm{max}}^{\mathrm{obs}}$
- Determine probability $P\left(A_i, E_0\right)$ of a primary of mass A_i inducing a shower with depth of maximum at $X_{\mathrm{max}}^{\mathrm{obs}}$ or higher depth
- Proton candidates: Events with low $P\left(A_i, E_0\right)$ for Helium or heavier
$\rightarrow$ " lighter than Helium " $\Rightarrow$ conservative conclusion: Proton!

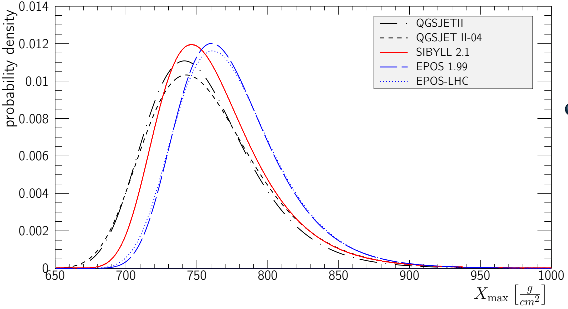
- No attempt to determine overall composition or proton fraction
- Only question: Is there a non-zero proton component in cosmic rays at highest energies?

Parametrization of the $X_{\max}$-distribution

- Model De Domenico et al. (JCAP07(2013)050): stochastic model of the shower maximum's dependence on energy and mass
- Parametrization of $X_{\max}$-distribution via generalized Gumbel function

$$\mathcal{G}(z) = \frac{1}{\sigma} \frac{\lambda^{\lambda}}{\Gamma(\lambda)} \left(e^{-\lambda z - \lambda e^{-z}} \right) \quad \text{with } z = \frac{X_{\max} - \mu}{\sigma}.$$

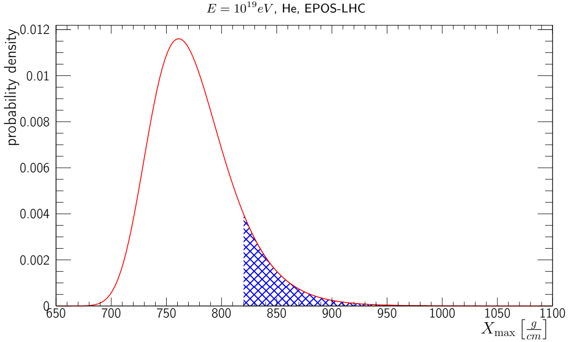
$E = 10^{19}$ eV, He



- Gumbel functions were fitted to CONEX simulations with different interaction models

He-probability from Gumbel distribution

- Calculate $P\left(X_{\max} \geq X_{\max}^{\text{obs}}\right)$



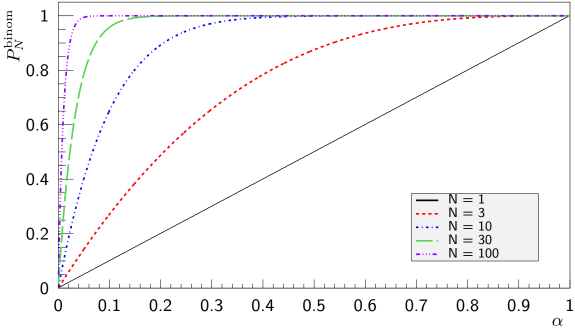
- Example: $E = 10^{19}\,\text{eV}$, $X_{\max}^{\text{obs}} = 820\,\frac{\text{g}}{\text{cm}^2}$
  $\Rightarrow$ EPOS-LHC: $P(He) \simeq 11.9\,\%$,$P(Li) \simeq 6.0\,\%$
- Example: $E = 10^{19}\,\text{eV}$, $X_{\max}^{\text{obs}} = 1050\,\frac{\text{g}}{\text{cm}^2}$
  $\Rightarrow$ EPOS-LHC: $P(He) \simeq 0.0018\,\%$,$P(Li) \simeq 0.000095\,\%$

Data set related probability (1)

- To this point: proability P_{He} of a single event, introducing now a data set related probability $\mathcal{P}$
- Given $P_{\mathrm{He}}\left(X_{\max} \geq X_{\max}^{\mathrm{obs}}\right) = \alpha$, the probability for N events producing k air showers with $X_{\max} \geq X_{\max}^{\mathrm{obs}}$ follows a binominal distribution:

$$P^{\mathrm{binom}} = \begin{pmatrix} N \\ k \end{pmatrix} (1-\alpha)^{N-k} \alpha^k$$

- Assuming $\forall X_{\max} < X_{\max}^{\mathrm{obs}}$ $(k = 0)$:



Data set related probability (2)

- Approach: $N_{\text{obs}}^{\text{tot}}$ observed events in an energy bin
  How many events N_{exp} do one expect following the Gumbel distribution with a depth of maximum at $X_{\text{max}}^{\text{cut}}$ or deeper?
- The number of expected events is given by

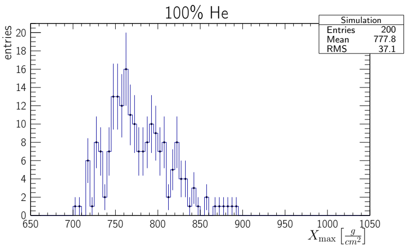
$$N_{\text{exp}}\left(X_{\text{max}} \geq X_{\text{max}}^{\text{cut}}\right) = N_{\text{obs}}^{\text{tot}} \cdot P_{\text{He}}^{\text{Gumbel}}\left(X_{\text{max}} \geq X_{\text{max}}^{\text{cut}}\right)$$

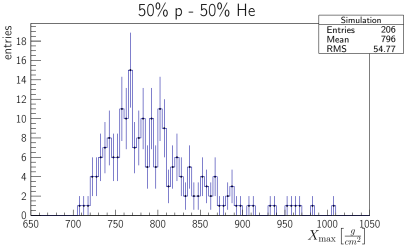
- Poisson probability of observing N_{obs} events with N_{exp} expected events:

$$\mathcal{P}_{\text{He}}^{\text{Poiss}} = \sum_{k=N_{\text{obs}}}^{\infty} \frac{\left(N_{\text{exp}}\right)^k}{k!} e^{-N_{\text{exp}}}$$

Data set related probability (3)

- Two simulated data sets, only take deepest event into account:



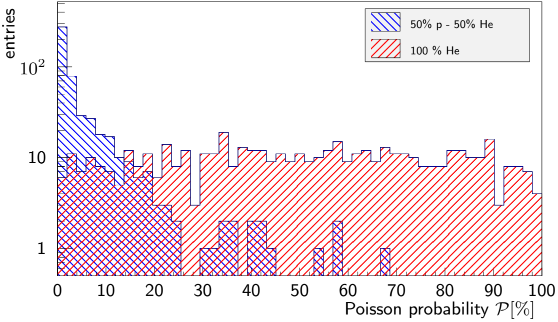


- $X_{\max} = 892.71\ \frac{\mathrm{g}}{\mathrm{cm}^2}$
- $P_{\mathrm{He}}^{\mathrm{Gumbel}} = 8.30 \cdot 10^{-3}$
- $N_{\mathrm{exp}} = 1.66$
- $\mathcal{P}_{\mathrm{He}}^{\mathrm{Poiss}} = 0.81$

- $X_{\max} = 1006.15\ \frac{\mathrm{g}}{\mathrm{cm}^2}$
- $P_{\mathrm{He}}^{\mathrm{Gumbel}} = 9.91 \cdot 10^{-5}$
- $N_{\mathrm{exp}} = 0.02$
- $\mathcal{P}_{\mathrm{He}}^{\mathrm{Poiss}} = 0.02$

Simulation study

- Shown method was applied to 1000 simulated samples (500 pure He, 500 p+He) with 200 events each



- Different distribution of probabilities implies that most of the deepest events in the mixed sample were induced by protons
- More than half of the mixed deepest events leads to Poisson probability $< 2\,\%$

Summary & next steps

Summary

- Difficulties with determination of the absolute composition
- For some analysis the knowledge of the precise composition is not necessary
  - Search for directional anisotropies
  - Test on Lorentz invariance violation
- Here: Only interested in general existence of protons at a certain energy
- Proton candidates are events with small $\mathcal{P}_{\mathrm{He}}$

Next steps

- Taking measurement uncertainties into account
- Taking model uncertainties into account
- Application to Auger data

Backups

Modified Maxwell theory

- The action of a Lorentz-violating modified Maxwell theory is given by [Klinkhamer and Risse, 2008]

$$\mathcal{S}_{\mathrm{modM}} = \int_{\mathbb{R}^4} \mathrm{d}^4x \left(-\frac{1}{4} \left(\eta^{\mu\rho}\eta^{\nu\sigma} + \kappa^{\mu\nu\rho\sigma} \right) F_{\mu\nu}(x) F_{\rho\sigma}(x) \right)$$

  where $F_{\mu\nu}$ is the standard Maxwell field strength tensor over a flat Minkowski spacetime $\eta_{\mu\nu}$.
- So the major difference to standard Maxwell theory is the tensor $\kappa^{\mu\nu\rho\sigma}$, which corresponds to a constant background tensor, with the same symmetries as the Riemann curvature tensor and a double trace condition $\kappa^{\mu\nu}{}_{\mu\nu} = 0$, so it has 19 independent parameters.
- To ensure energy positivity all components of the κ-tensor are assumed to be very small:

$$|\kappa^{\mu\nu\rho\sigma}| \ll 1$$

Parameter set of modified Maxwell theory

- 10 of the 19 independent parameters of this modified Maxwell theory lead to birefringence and are bounded at the 10^{-32} level or better from astrophysics [Kostelecky and Mewes, 2002].
- The 9 non-birefringent parameters were bound to the level of 10^{-19} or worse from UHECR [Klinkhamer and Risse, 2008].
- These 9 parameters can be written as the components of a symmetric and traceless matrix $\tilde{\kappa}^{\mu\nu}$ and parametrized following

$$(\tilde{\kappa}^{\mu\nu}) = \bar{\kappa}^{00} \cdot \mathrm{diag}\left(1, \frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right) + (\delta\tilde{\kappa}^{\mu\nu}), \quad \delta\tilde{\kappa}^{00} = 0.$$

- For later use we define

$$\vec{\alpha} = \begin{pmatrix} \alpha^0 \\ \alpha^1 \\ \alpha^2 \\ \alpha^3 \\ \alpha^4 \\ \alpha^5 \\ \alpha^6 \\ \alpha^7 \\ \alpha^8 \end{pmatrix} = \begin{pmatrix} \tilde{\alpha}^{00} \\ \tilde{\alpha}^{01} \\ \tilde{\alpha}^{02} \\ \tilde{\alpha}^{03} \\ \tilde{\alpha}^{11} \\ \tilde{\alpha}^{12} \\ \tilde{\alpha}^{13} \\ \tilde{\alpha}^{22} \\ \tilde{\alpha}^{23} \end{pmatrix} = \begin{pmatrix} \frac{4}{3}\bar{\kappa}^{00} \\ 2\delta\tilde{\kappa}^{01} \\ 2\delta\tilde{\kappa}^{02} \\ 2\delta\tilde{\kappa}^{03} \\ \delta\tilde{\kappa}^{11} \\ \delta\tilde{\kappa}^{12} \\ \delta\tilde{\kappa}^{13} \\ \delta\tilde{\kappa}^{22} \\ \delta\tilde{\kappa}^{33} \end{pmatrix}.$$

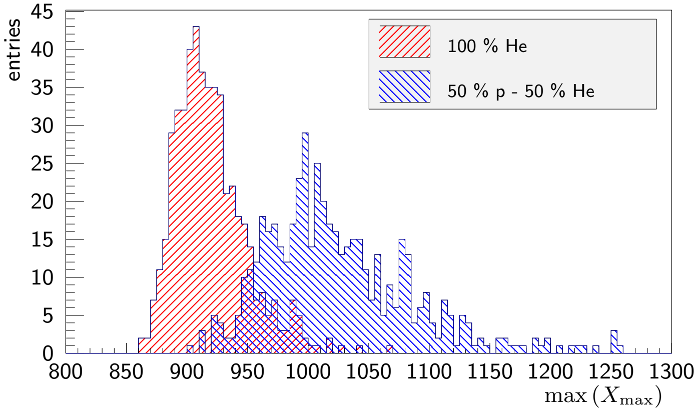
Parameter set of modified Maxwell theory

- The modified Maxwell theory is supposed to produce vacuum Cherenkov radiation by UHE charged particles.
- The threshold energy of vacuum Cherenkov radiation depends on the particle's mass and a scale $\tilde{\kappa}$ obtained from the parameters α^i.
- With the condition that the energy of a UHE particle reaching the earth must be smaller or equal to the threshold energy of vacuum Cherenkov radiation one yields for the Lorentz violatong parameters:

$$R\left(\alpha^0 + \alpha^j \hat{\mathbf{q}}^j_{\mathrm{prim}} + \tilde{\alpha}^{jk} \hat{\mathbf{q}}^j_{\mathrm{prim}} \hat{\mathbf{q}}^k_{\mathrm{prim}}\right) \leq \left(\frac{M_{\mathrm{prim}} c^2}{E_{\mathrm{prim}}}\right)^2$$

with the ramp function $R(x) = \frac{x+|x|}{2}$ and the normalized arrival direction of the primary $\hat{\mathbf{q}}_{\mathrm{prim}}$.

Backups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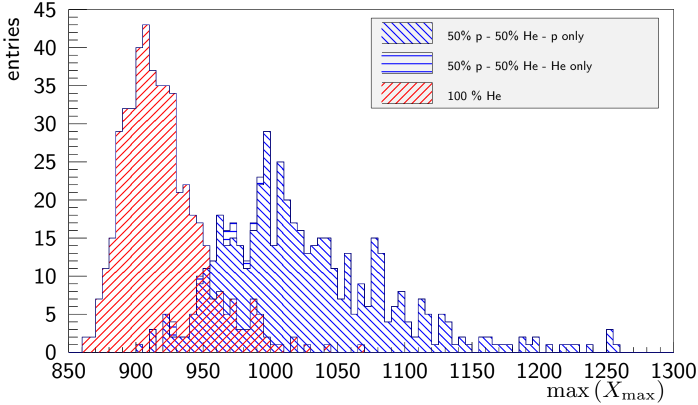
$\max(X_{\max})$
100 % He
50 % p - 50 % He

Backups



entries
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$\max(X_{\max})$
50% p - 50% He - p only
50% p - 50% He - He only
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