Ultra-High Energy Cosmic Rays with the Pierre Auger Observatory

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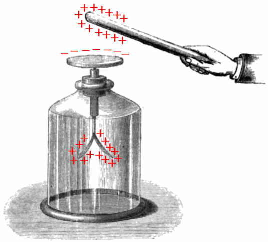
November 27, 2020

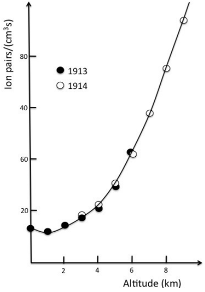
Outline

- Introduction
- The Pierre Auger Observatory
- Recent results
- My work
  - Risetime Studies
  - Machine Learning Studies
  - Differences between Data and Simulations

History of Cosmic Rays

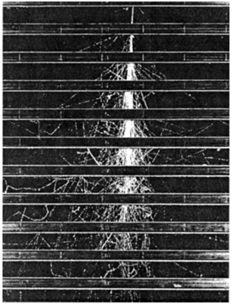
- Search begins motivated by the spontaneous discharge of an electroscope due to external radiation
- Is radiation coming from the Earth or outside?
- First conclusive experiments: balloon flights in 1912 by Victor Hess
- Hess is awarded the Nobel Prize in 1936 for the discovery of cosmic rays



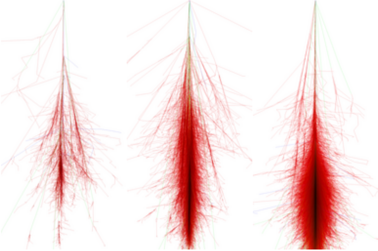


Extensive Air Showers

- When a cosmic ray interacts with an atom or molecule a shower of particles can be produced
- After the first interaction new particles are produced that carry energy and momentum and can interact again or decay
- When the primary has a large energy the shower can extend over several km^2: Extensive Air Shower



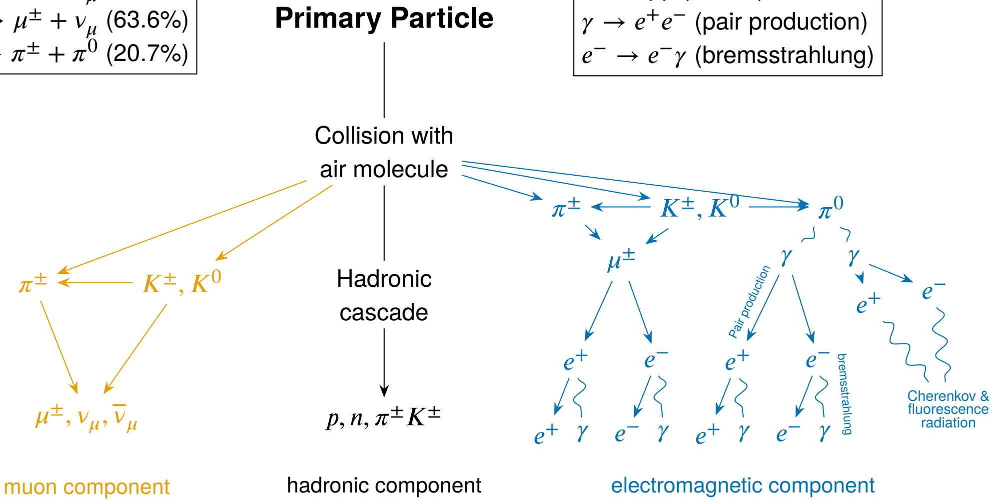
Simulated proton showers



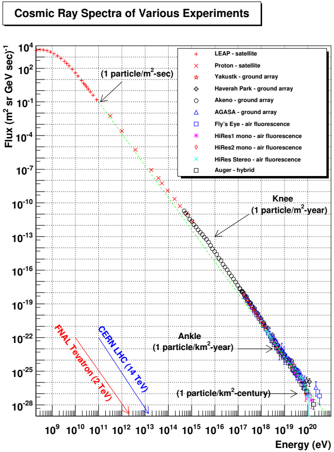
10^{11} eV 10^{12} eV 10^{13} eV

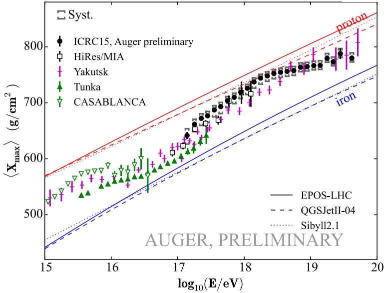
$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ (99.9%)
$K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ (63.6%)
$K^{\pm} \rightarrow \pi^{\pm} + \pi^{0}$ (20.7%)

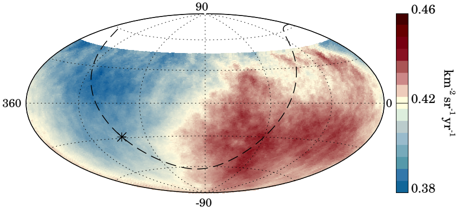
$\pi^{0} \rightarrow \gamma\gamma$ (98.8%)
$\gamma \rightarrow e^{+}e^{-}$ (pair production)
$e^{-} \rightarrow e^{-}\gamma$ (bremsstrahlung)



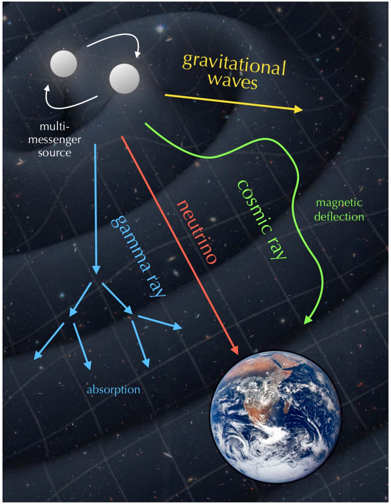
- What is the composition of UHECRs?
  We know they are atomic nuclei
- How are those cosmic rays accelerated to such energies?
- What is their origin?







Multi-Messenger Astronomy



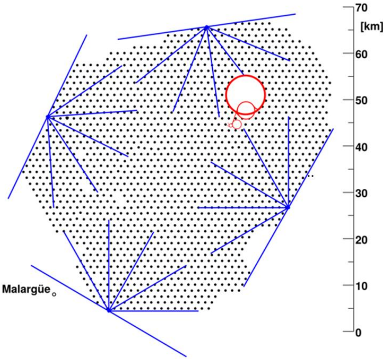
- In your typical picture, cosmic rays are deflected by magnetic fields
- True, but if the cosmic ray has low Z (protons) and very high energy, it needs to travel a very long distance to be significantly deflected
- Proton astronomy?

Outline

The Pierre Auger Observatory

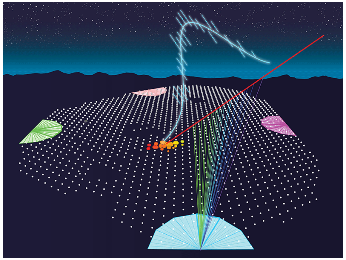
- Founding fathers: Alan Watson and Jim Cronin
- The Pierre Auger Observatory was completed in 2008 and has been running since then
- The Pierre Auger Collaboration has more than 500 people from 17 countries

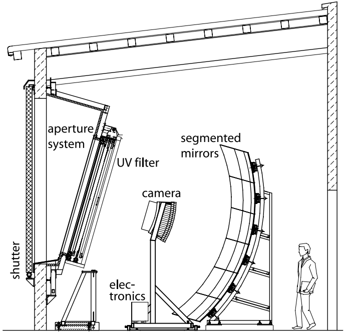
- **Hybrid detector**
- Largest detector of cosmic rays built so far
- 1660 surface detectors located in a triangular array covering 3000 km^2
- The array is overlooked by 24 fluorescence telescopes
- Located near Malargüe, in the province of Mendoza in Argentina

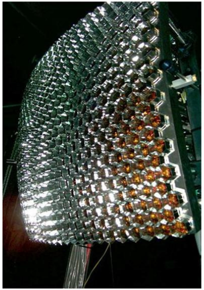


The Fluorescence Detector (FD)

- The FD measures the nitrogen fluorescence caused by the interaction between charged particles in the shower with atmospheric nitrogen
- Duty cycle: $\sim 15\%$ (clear, moonless nights)
- Light is collected in mirrors then focused in the camera



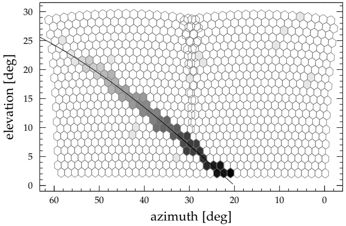


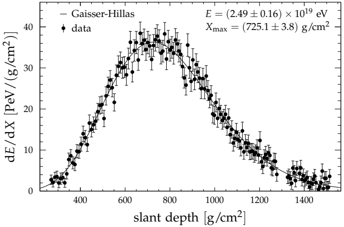


Shower Reconstruction with the FD

- X is the slant depth, measured in g/cm^2

$$X(z) = \int_z^\infty \rho(r(z'))\,\mathrm{d}z'$$





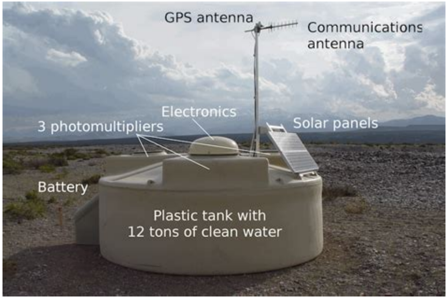
- The plane of the shower is obtained by knowing where the pixels are aiming, need one station at the ground
- The longitudinal profile is fitted with a Gaisser-Hillas function:

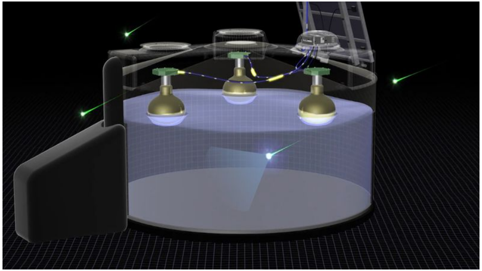
$$f_{\mathrm{GH}} = \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{max}} \left(\frac{X-X_0}{X_{\mathrm{max}}-X_0}\right)^{\frac{X_{\mathrm{max}}-X_0}{\lambda}} e^{\frac{X_{\mathrm{max}}-X}{\lambda}}$$

- Integral → Calorimetric energy (resolution of 7 % on E_{FD})
- Position of the Maximum, X_{max} is a very good proxy for mass composition

The Surface Detector (SD)

- Measures the arrival time of secondary particles of the shower at the ground
- These particles emit Cherenkov radiation in water that can be detected by the photomultiplier tubes
- Duty cycle $\sim 100\%$





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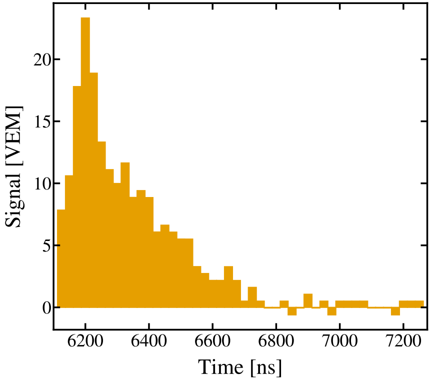
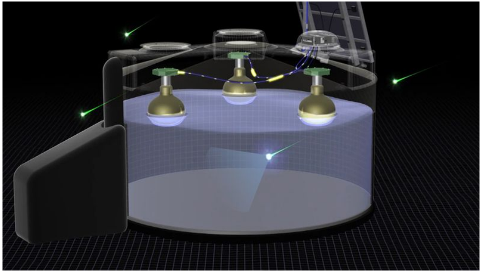
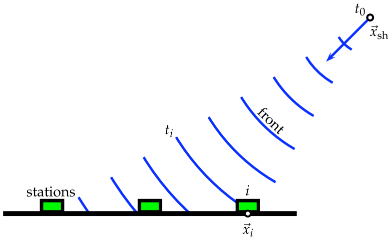




Direction reconstruction

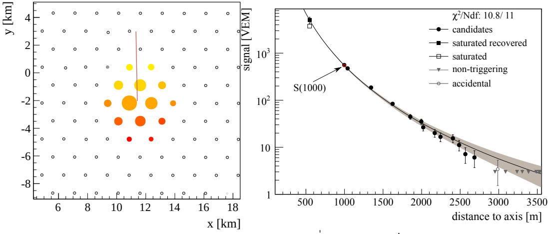
- The direction of the cosmic ray is obtained by fitting a spheric plane to the time of arrival of particles at the stations

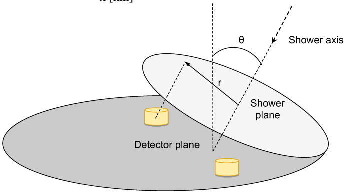


- Resolution better than $1.5°$

Energy reconstruction

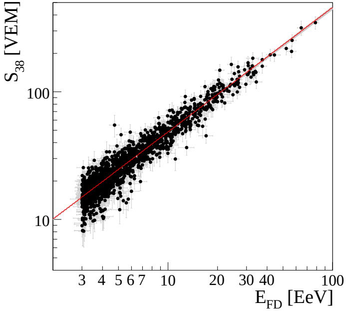
- The energy is obtained from the lateral distribution of particles





Hybrid detector? Calibration of the energy

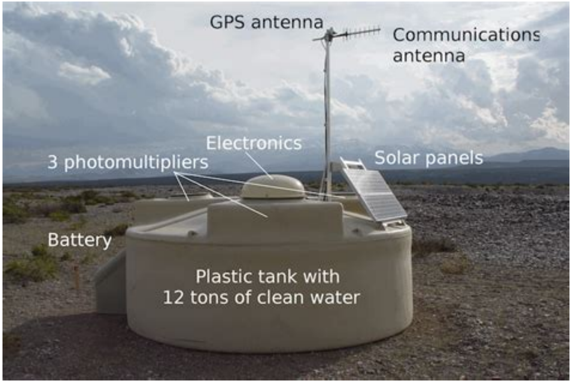
- Why is it called hybrid detector?
- Measurements of the energy by the FD are used to calibrate the measurement of the energy in the SD **without using simulations**
- S(1000) is transformed to its value if the shower had arrived at $38°$, S_{38}
- A calibration is performed



$$E_{\mathrm{SD}} = A(S(1000)/f_{\mathrm{CIC}}(\theta)/\mathrm{VEM})^{B}$$

- Resolution for the SD: 16 to 12 % depending on the energy

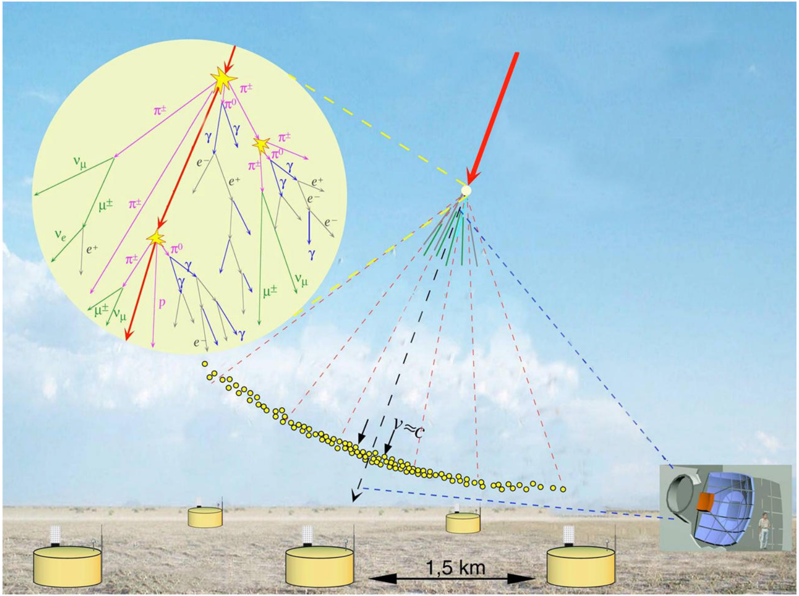
Question: Why are the edges of the detector round?



- Better detector?
- Easier manufacturing?

Well . . .

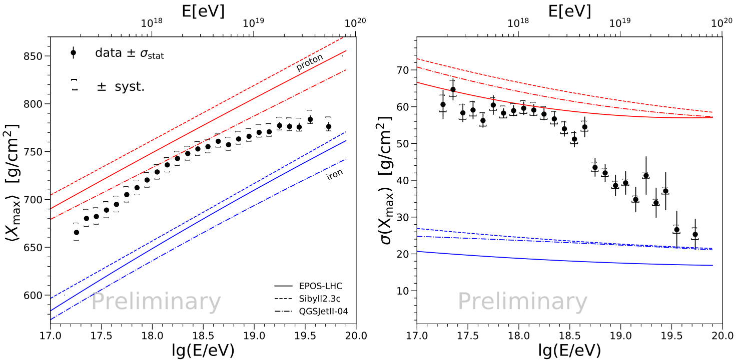

The Sweet Relief of Scratching the Itch
PPYCOW
Made in Canva



π±
π0
γ
νμ
μ±
νe
e+
e−
p
v≈c
1,5 km

Outline

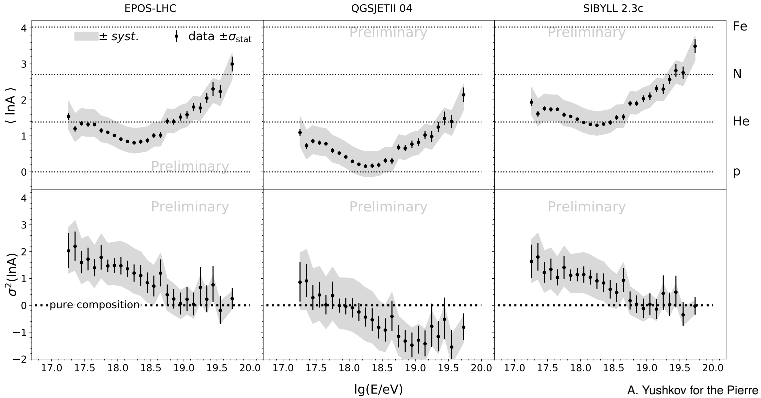
X_{max}: First two moments



A. Yushkov for the Pierre Auger Collaboration
Proc. 36th ICRC (2019)

- For a constant composition $D_{10} = \frac{\mathrm{d}\,X_{max}}{\mathrm{d}\,\lg(E/\mathrm{eV})} = 60$ g/cm^2/decade
- $D_{10} = 77 \pm 2$ g/cm^2/decade between $10^{17.2}$ and $10^{18.32}$ eV
- $D_{10} = 26 \pm 2$ g/cm^2/decade from $10^{18.32}$ eV onwards

X_{max}: First two moments→ $\langle \ln A \rangle$

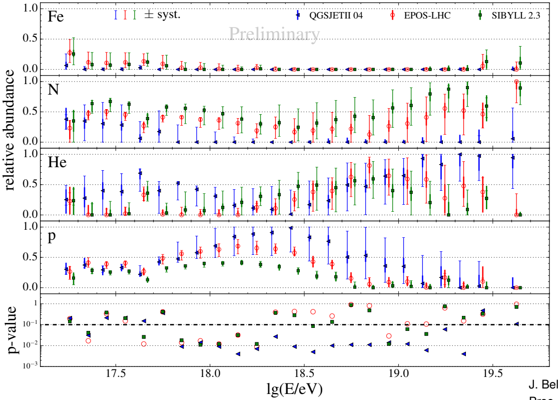


A. Yushkov for the Pierre Auger Collaboration
Proc. 36th ICRC (2019)

- Values $\sigma^2 < 0$ are due to models predicting larger $\sigma(X_{max})$ than the observed
- Similar trend for all the models: ligther mass up to $10^{18.33}$ eV and then heavier mass
- Results depend on the hadronic interaction model

X_{max}: Composition Implications

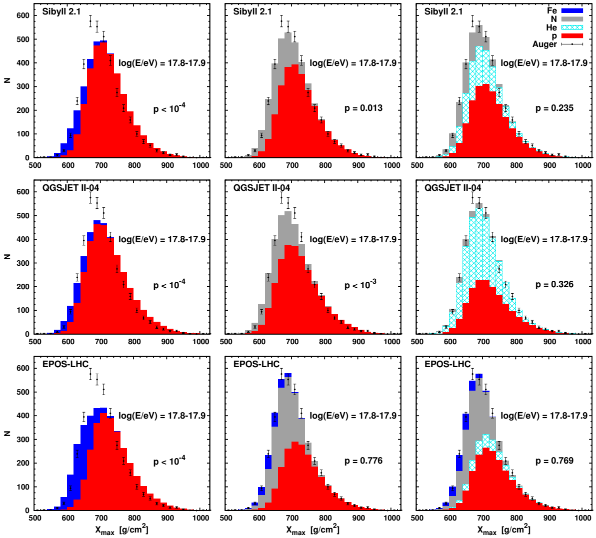
- Composition that best matches the distribution of X_{max} in data:



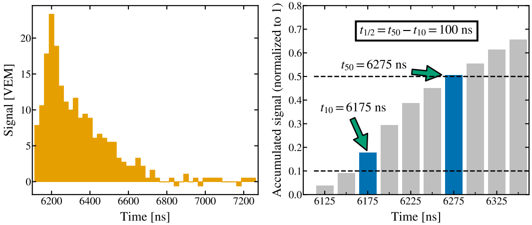
J. Bellido for the Pierre Auger Collaboration
Proc. 35th ICRC (2017)

- Fewer p-values were expected below the 0.1 line (bad fits)
- Models can not find a combination of fractions that can reproduce the details of the distributions of X_{max}

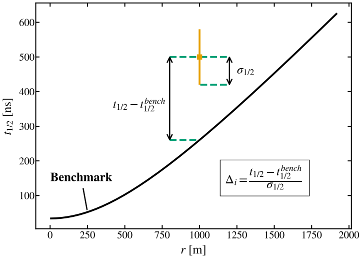
X_{max}: Composition Implications



- Based on the risetime $t_{1/2}$, time for the signal measured by the SD to raise between a 10% and a 50% of the total signal.



- Benchmark: Parameterization of the risetime as a function of the distance to the core

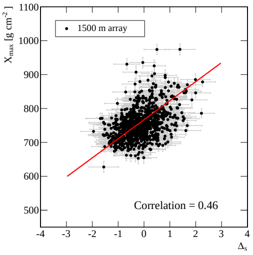


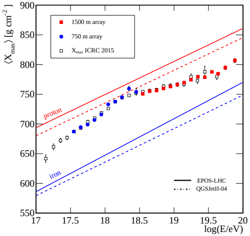
- The final observable is the average over all the stations in each event:

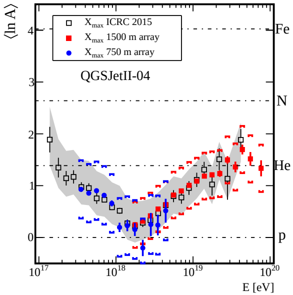
$$\Delta_s = \frac{1}{n}\sum_{i=1}^{n}\Delta_i$$

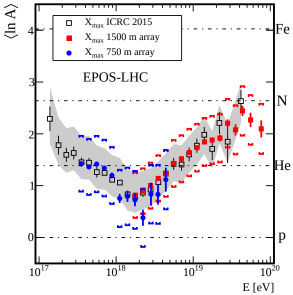
Delta Method: Calibration with X_{max}

- Δ_s can be calibrated with hybrid events that have X_{max}: $X_{max} = a + b\Delta_s + c\log(E/\mathrm{eV})$





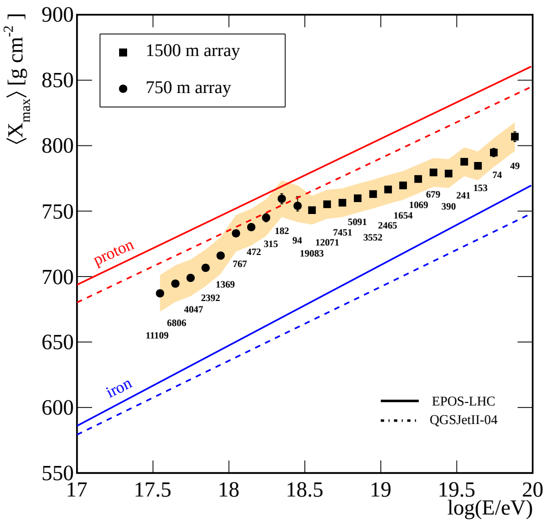




Conclusions

- X_{max} can be measured with the SD up to 100 EeV
- Mass is getting smaller until ~ 2 EeV then rises possibly stopping at the highest energies

Delta Method: Calibration with X_{max}

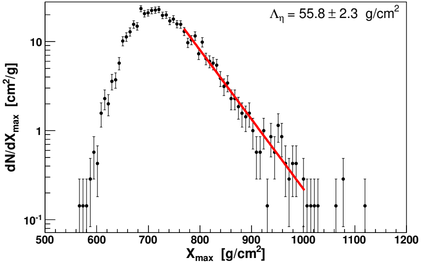


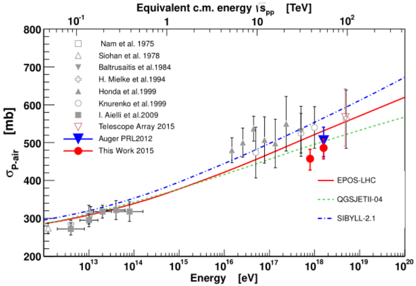
Phys. Rev. D. 96, 122003 (2017)

Proton-Air Cross-Section

- At the tail of the X_{max} distribution: $\frac{dN}{dX_{max}} \propto e^{\frac{-X_{max}}{\Lambda_\eta}}$
- η is the fraction of most deeply penetrating showers used ($\eta = 0.2$)

$$\Lambda_\eta = [55.8 \pm 2.3(\text{stat}) \pm 1.6(\text{sys})]\ \text{g/cm}^2$$





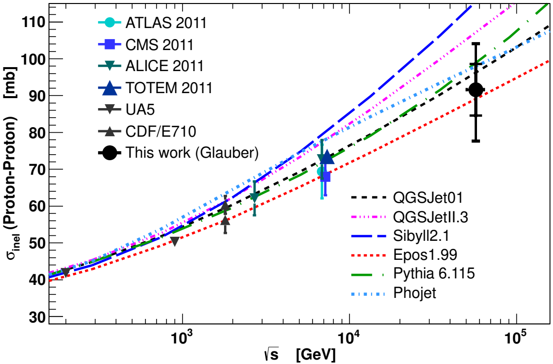
- Cross-sections are modified in simulations to match Λ_η with the following factor

$$F(E,\ f_{19}) = 1 + (f_{19} - 1)\ \frac{\log\left(E/E_{\text{thr}}\right)}{\log\left(10^{19}\ \text{eV}/E_{\text{thr}}\right)}$$

$$\sigma^{\text{prod}}_{p\text{-air}} = \left[505 \pm 22(\text{stat})\ ^{+28}_{-36}(\text{sys})\right]\ \text{mb}$$

R. Ulrich for the Pierre Auger Collaboration
Proc. 34th ICRC (2015)

- Inelastic and total cross-sections are computed using the Glauber model at $\sqrt{s} = 57$ TeV.



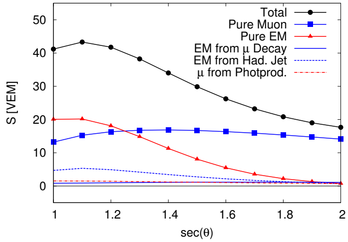
Phys. Rev. Lett. 109, 062002 (2012)

$$\sigma_{pp}^{\text{inel}} = \left[92 \pm 7(\text{stat})\ ^{+9}_{-11}(\text{sys}) \pm 7(\text{Glauber})\right] \text{ mb}$$

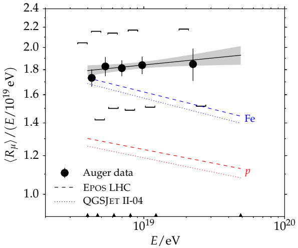
$$\sigma_{pp}^{\text{tot}} = \left[133 \pm 13(\text{stat})\ ^{+17}_{-20}(\text{sys}) \pm 16(\text{Glauber})\right] \text{ mb}$$

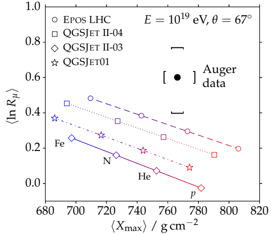
- Muons dominate the signal in inclined events
- The muon density ρ_μ is modeled at the ground point $\vec{r}$ as:

$$\rho_\mu(\vec{r}) = N_{19}\ \rho_{\mu,19}(\vec{r};\theta,\phi),$$



- N_{19} is studied and simulation and corrected by its bias $\rightarrow R_\mu$

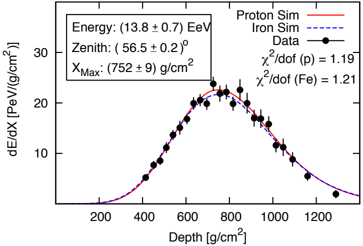




$62° < \theta < 80°$
174 events accepted
$4 \cdot 10^{18}$ eV $< E < 5 \cdot 10^{19}$ eV

Phys. Rev. D 91, 059901 (2015)

- Number of muons 30%-80% higher than what models predict



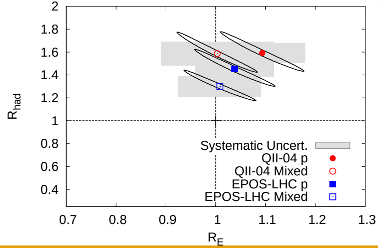
$0^\circ < \theta < 60^\circ$
411 events accepted
6 EeV $< E <$ 16 EeV

- Simulations that match the longitudinal profile of data are produced
- The signal is rescaled to match the signal at the ground in data:

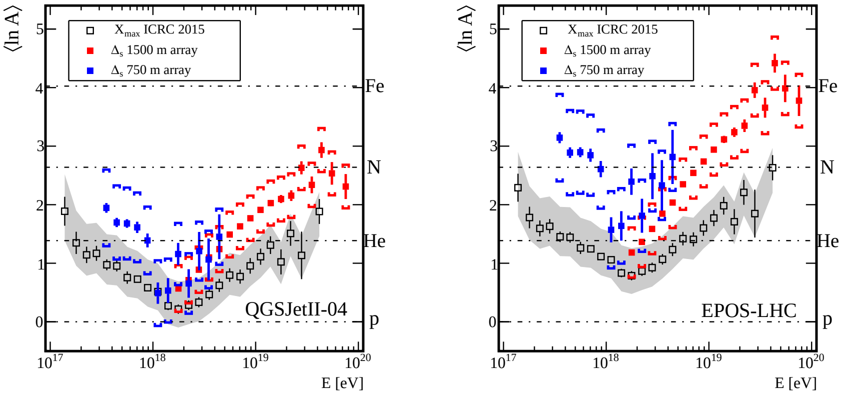
$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E\, S_{EM,i,j} + R_{\text{had}}\, R_E^{\alpha}\, S_{\text{had},i,j}$$

Model	R_E	R_{had}
QII-04 p	$1.09 \pm 0.08 \pm 0.09$	$1.59 \pm 0.17 \pm 0.09$
QII-04 Mixed	$1.00 \pm 0.08 \pm 0.11$	$1.61 \pm 0.18 \pm 0.11$
EPOS p	$1.04 \pm 0.08 \pm 0.08$	$1.45 \pm 0.16 \pm 0.08$
EPOS Mixed	$1.00 \pm 0.07 \pm 0.08$	$1.33 \pm 0.13 \pm 0.09$

Phys. Rev. Lett. 117, 192001 (2016)



- No energy rescaling is needed
- Hadronic signal is significantly larger for data than that predicted by models



- In the risetime (and therefore Δ) there is a mixture of electromagnetic and muonic component
- The values of Δ can not reproduce X_{max}, coming from the electromagnetic cascade

What did I do?

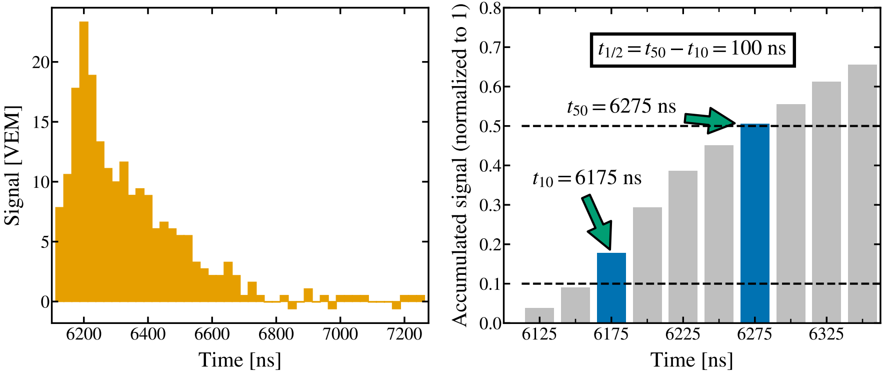

80
Continental

Outline

- Introduction
- The Pierre Auger Observatory
- Recent results
- My work
  - Risetime Studies
  - Machine Learning Studies
  - Differences between Data and Simulations

- Study **mass composition** using:
  - The SD data sample: highest statistics
  - Traditional methods & modern methods

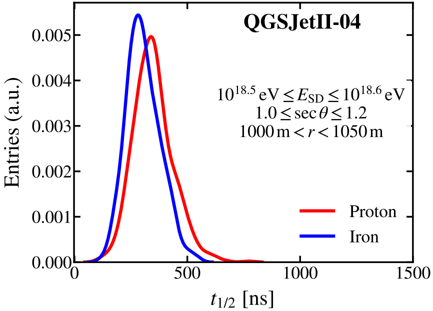
- Time it takes for the signal measured in one photomultiplier (PMT) to rise between 10% and 50% of the total signal

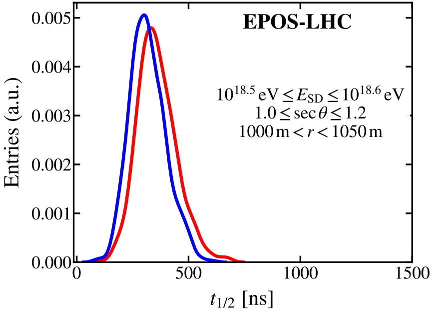


- We average over the operating PMTs to obtain a value for $t_{1/2}$ at each station

Why use the Risetime for Mass Composition?

- Showers initiated by a heavier primary have more muons and develop lower in the atmosphere
- Muons have a shorter risetime
- Showers initiated by a heavier primary have a shorter risetime



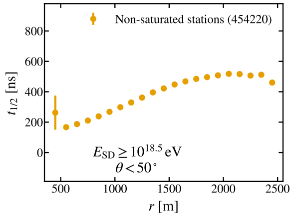


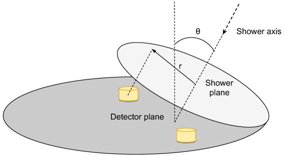
The Time over Distance $\overline{\text{ToD}}$: Definition

- $t_{1/2}$ approximately linear with r for a wide range of distances
- A single value for each event is obtained computing the average:

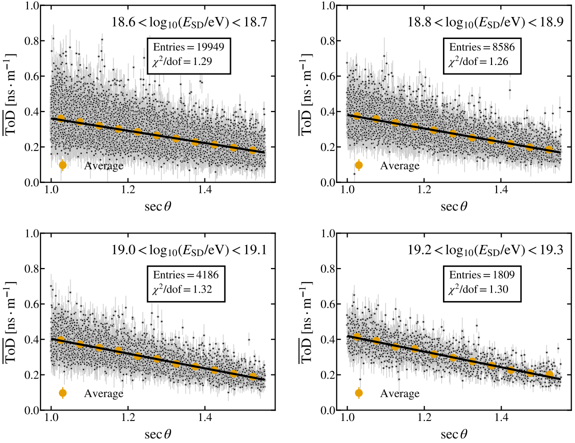
$$\overline{\text{ToD}} = \left\langle \frac{t_{1/2}}{r} \right\rangle = \frac{1}{n} \sum_{i=1}^{n} \frac{t_{1/2_i}}{r_i}$$

- An observable that characterizes each event with a single value
- Does not depend on r

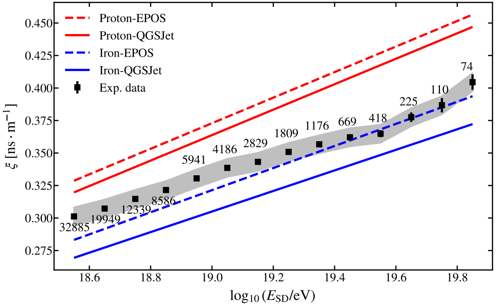




- $\overline{\text{ToD}}$ depends linearly on $\sec\theta$
- A fit is done for each energy bin



- The value at $\theta = 30°$ (ξ) is picked and plotted as a function of the energy

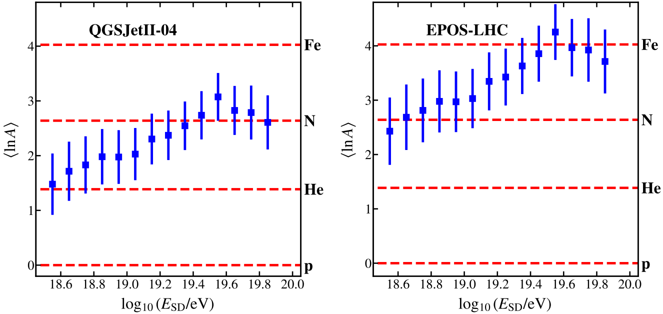


- Mass going to heavier until $10^{19.6}$ eV
- Going to lighter above $10^{19.6}$ eV?

$\langle \ln A \rangle$

- ξ can be transformed to the logarithm of the mass number A
- Linear interpolation between the lines for simulations

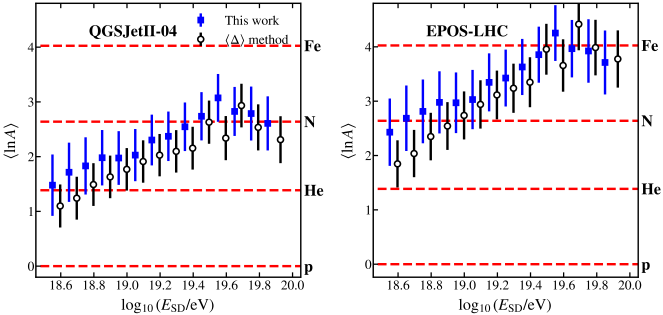
$$\alpha I + (1-\alpha)P = D \longrightarrow \langle \ln A \rangle = \ln 56 \cdot \alpha = \ln 56 \frac{P-D}{P-I} \longleftarrow \begin{cases} P \rightarrow \text{Protons} \\ I \rightarrow \text{Iron} \\ D \rightarrow \text{Data} \end{cases}$$



$\langle \ln A \rangle$: Comparison with the $\langle \Delta \rangle$ Method

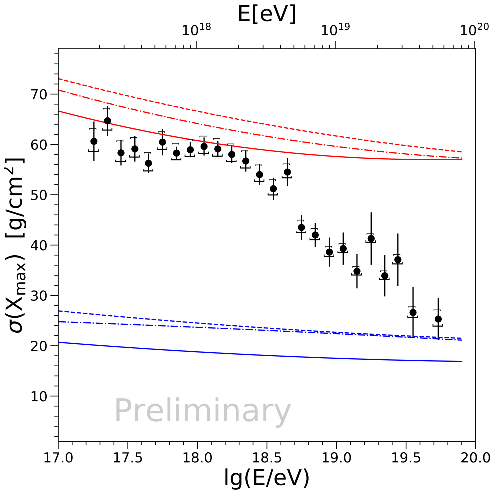
- ξ can be transformed to the logarithm of the mass number A
- Linear interpolation between the lines for simulations

$$\alpha I + (1-\alpha)P = D \longrightarrow \langle \ln A \rangle = \ln 56 \cdot \alpha = \ln 56 \frac{P-D}{P-I} \longleftarrow \begin{cases} P \rightarrow \text{Protons} \\ I \rightarrow \text{Iron} \\ D \rightarrow \text{Data} \end{cases}$$



- For any observable, its fluctuations have two contributions: the detector and physics $\sigma^2_{\text{total}} = \sigma^2_{\text{det}} + \sigma^2_{\text{f}}$
- σ^2_{f} provides information for studies of mass composition, for example fluctuations of X_{max} are larger for proton than for iron
- **Using the $\overline{\textbf{ToD}}$** we measure σ^2_{f} by subtracting the effects of the detector from the total fluctuations

$$\sigma^2_{\text{f}} = \sigma^2_{\text{total}} - \sigma^2_{\text{det}}$$



σ^2_{det} Calculation: The Method of Splitting

- Split the stations of each event into two groups so that we have two independent measurements of the $\overline{\text{ToD}}$ for obtaining σ^2_{det}:

$$\overline{\text{ToD}}_1 = \frac{1}{n_1}\sum_{i=1}^{n_1}\frac{t_{1/2\,i}}{r_i} \quad \text{and} \quad \overline{\text{ToD}}_2 = \frac{1}{n_2}\sum_{j=1}^{n_2}\frac{t_{1/2\,j}}{r_j}$$

Mock example of an event

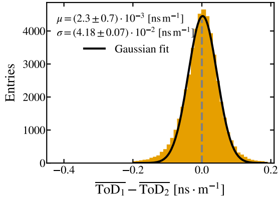
S [VEM]	r [m]	$t_{1/2}$ [ns·m^{-1}]
100	1000	200
50	1300	150
30	1500	300
10	1800	400

$$\overline{\text{ToD}}_1 = \frac{1}{2}\left(\frac{200}{1000}+\frac{300}{1500}\right) = 0.20$$

$$\overline{\text{ToD}}_2 = \frac{1}{2}\left(\frac{150}{1300}+\frac{400}{1800}\right) \simeq 0.17$$

$$\Longrightarrow \overline{\text{ToD}}_1 - \overline{\text{ToD}}_2 \simeq 0.03$$

- Stations are ordered by signal.
- Odd positions belong to the first group
- Even positions belong to the second group
- Results do not depend on this ordering scheme



σ^2_{det} Calculation: Analysis of Variance (ANOVA)

- ANOVA: total variance has two contributions based on arbitrary division of the data in groups

$$\sigma^2_{\text{total}} = \sigma^2_{\text{between groups}} + \sigma^2_{\text{within groups}}$$

- The following equality from ANOVA is general

$$\underbrace{\sum_i \left(x_i - \langle x \rangle\right)^2}_{\text{total}} = \underbrace{\sum_g n_g \Big(\langle x^g \rangle - \langle x \rangle\Big)^2}_{\text{between groups}} + \underbrace{\sum_g \sum_{j \in g} \Big(x^g_j - \langle x^g \rangle\Big)^2}_{\text{within groups}}$$

<u>General definition</u>

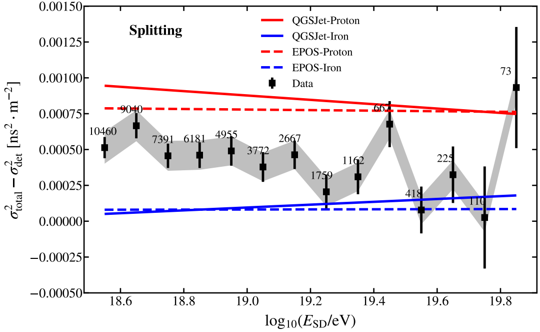
- x is a vector
- $\langle x \rangle$ is the average of x
- Each group g has n_g elements
- $\langle x^g \rangle$ is the average in the group g
- x^g_j is the j-th element of the group g

<u>Our case</u>

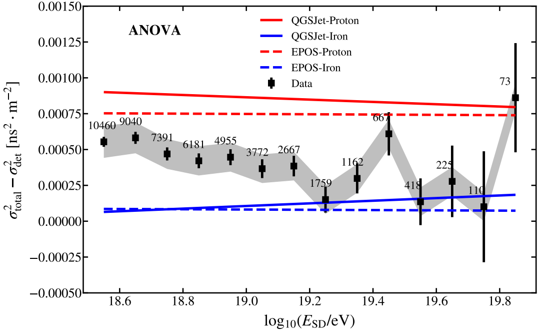
- x is the vector of all values of $t_{1/2}/r$
- $\langle x \rangle$ is the average value of $t_{1/2}/r$
- Each g is an event with $n_g = 4$ stations
- $\langle x^g \rangle = \overline{\text{ToD}}$
- x^g_j is $t_{1/2}/r$ for the station j and the event g

Final Results

Splitting

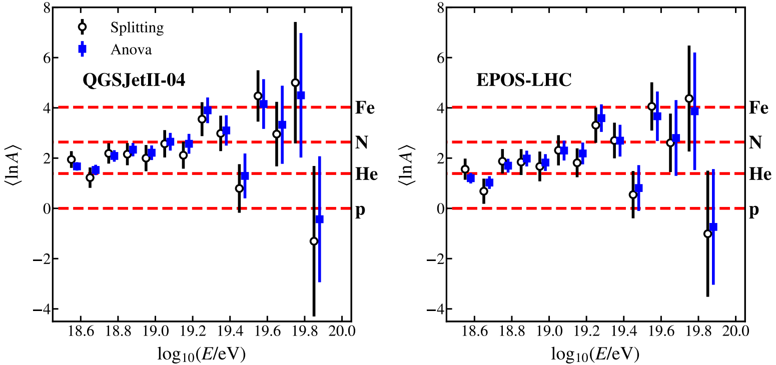


ANOVA



- A dependence of the fluctuations with the energy has been tested making a constant fit and a fit of a straight line to the data points
- A maximum likelihood ratio test gives a 3σ with the splitting method and 5σ with ANOVA

- When plotted together both results are compatible within the uncertainties (values for Anova have been shifted slightly to the right)



Bonus: Uncertainty of the Risetime

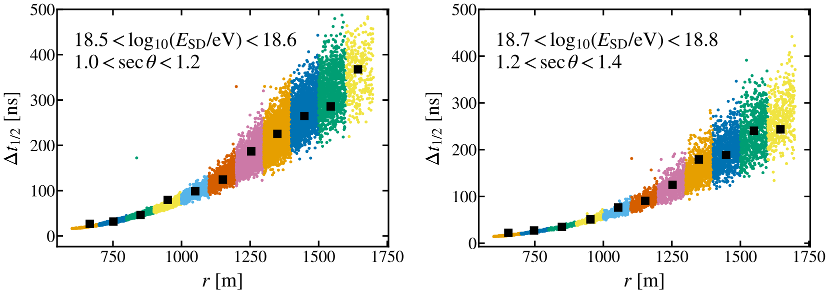
- We compare σ^2_{det} obtained with ANOVA and the parameterization of the uncertainty of the risetime $\sigma_{1/2}$
- Groups are chosen as events with two or more stations in bins of 100 m

Black squares
(One value per bin)

$$\sigma^2_{\text{det}} = \frac{1}{4}\frac{\sum_g \sum_{j\in g}\left(x_j^g - \langle x^g\rangle\right)^2}{N - N_g}$$

Colored circles
(One value per station)

Parameterization of the risetime uncertainty done with twins and pairs of stations

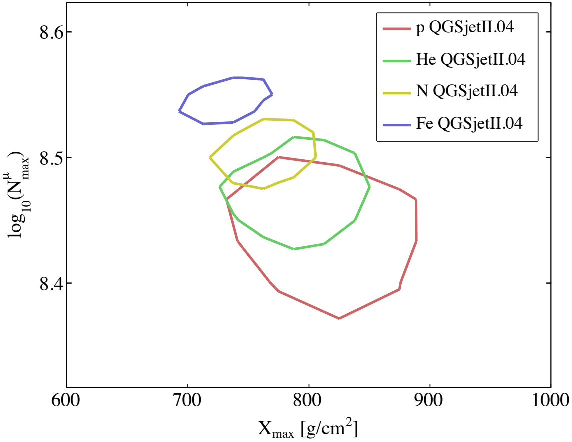


σ^2_{det} is compatible with the values of the parameterization of the uncertainty of the risetime

Outline

Why is Knowledge about Muons Important?

- Infer information about mass composition
- Study hadronic interactions
- Help to understand differences between data and simulations

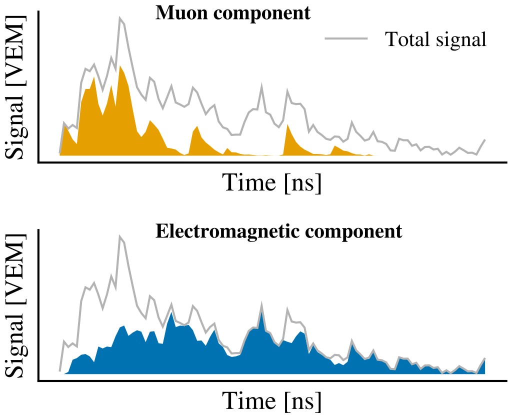


Muon component

- Earlier times
- Usually spiky

Electromagnetic component

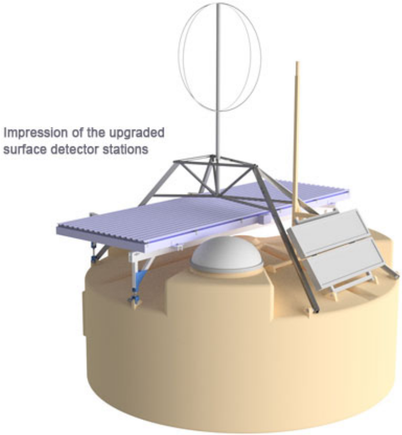
- Later times
- Spread and not very spiky



- This information is **only** known in simulations!

AugerPrime

- There is an ongoing upgrade of the detector
- One scintillator panel will be put on top of each station



Example Traces

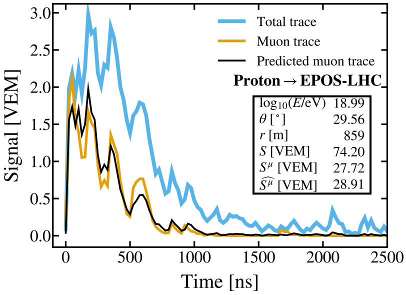
- Objective: Predict the temporal sequence of values in the muon trace
- Predictions follow the shape of the total trace
- Predictions capture the spiky shape of the muon trace

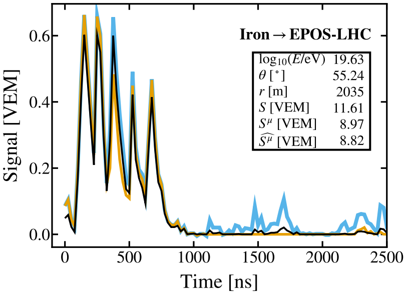
Notation

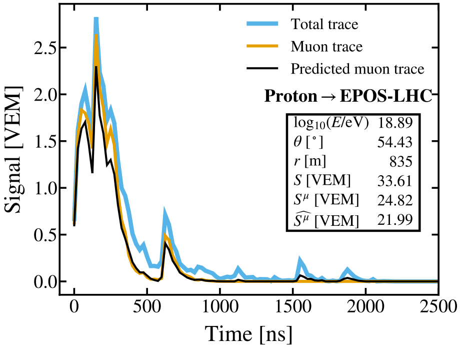
$\hat{}$ for the predicted quantities

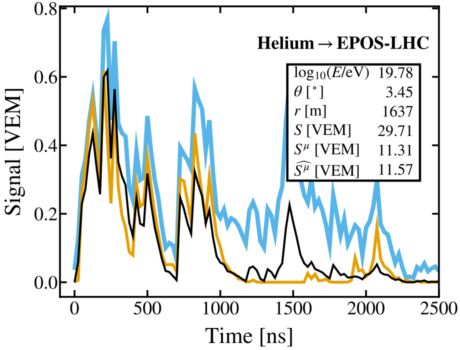
$\widehat{S^{\mu}}$ (integral of the predicted muon trace)

S^{μ} (integral of the true muon trace)

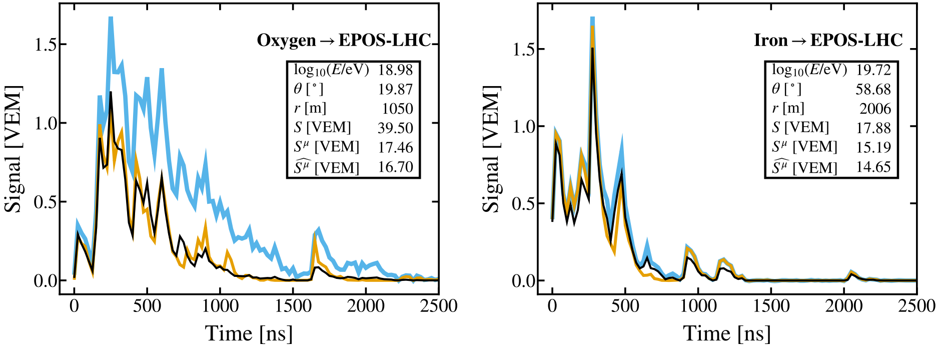




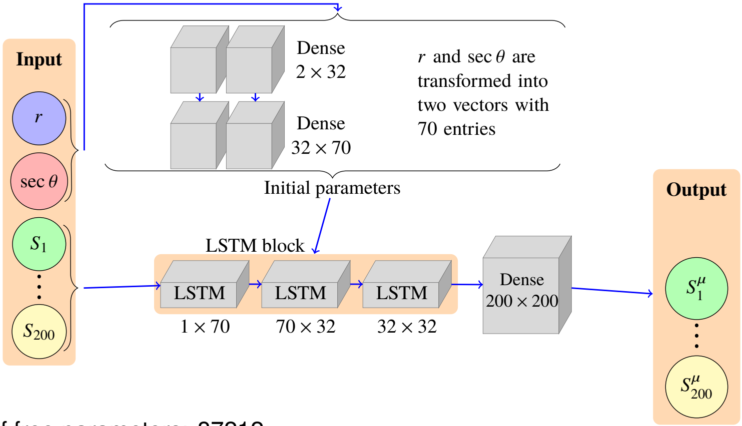

Total trace
Muon trace
Predicted muon trace
Proton → EPOS-LHC
log10(E/eV) 18.89
θ [°] 54.43
r [m] 835
S [VEM] 33.61
S^μ [VEM] 24.82
Ŝ^μ [VEM] 21.99
Signal [VEM]
Time [ns]


Helium → EPOS-LHC
log10(E/eV) 19.78
θ [°] 3.45
r [m] 1637
S [VEM] 29.71
S^μ [VEM] 11.31
Ŝ^μ [VEM] 11.57
Signal [VEM]
Time [ns]

Example Traces II



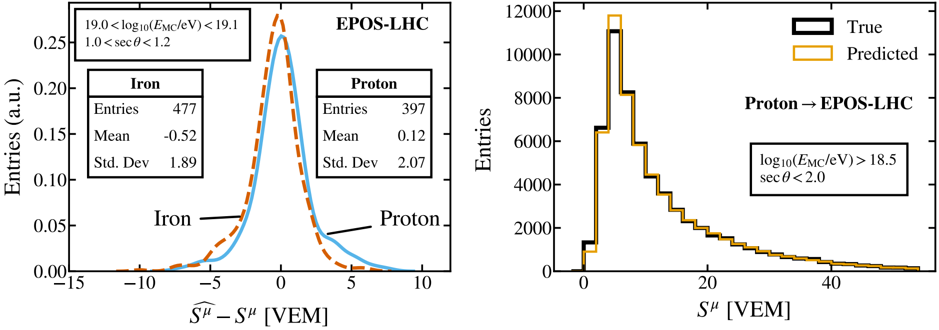
Neural Network



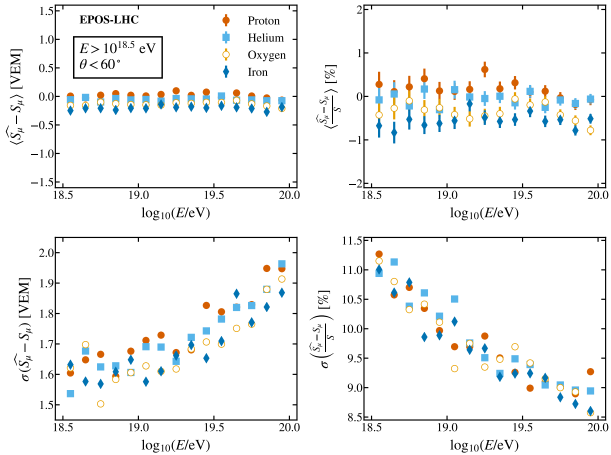
- Total number of free parameters: 87212
- r, $\sec\theta$ and $S_1 \ldots S_{200}$ are normalized to be between 0 and 1
- Train with 25% of P, He, O and Fe (EPOS-LHC): +400 000 showers

Performance Plots: S^μ and $\widehat{S^\mu}$

- We compare the integral of the predicted muon trace $\widehat{S^\mu}$ to the integral of the true muon trace S^μ
- Mean around zero, standard deviation close to 2 VEM (depends heavily on the zenith angle)

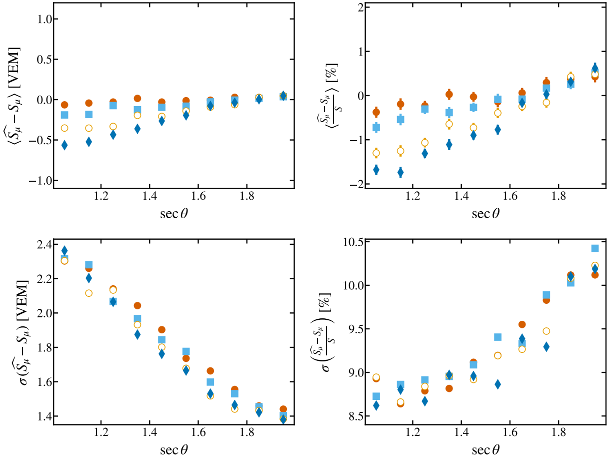


- Unbiased predictions
- Resulution better than 11%



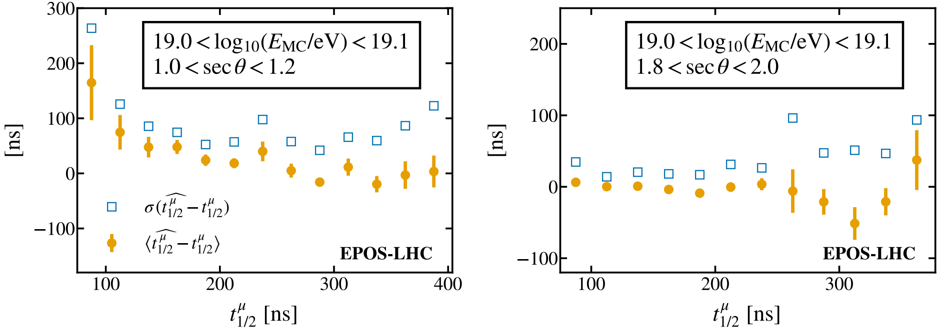
Performance Plots: $\sec\theta$

- Unbiased predictions
- Resulution better than 11%

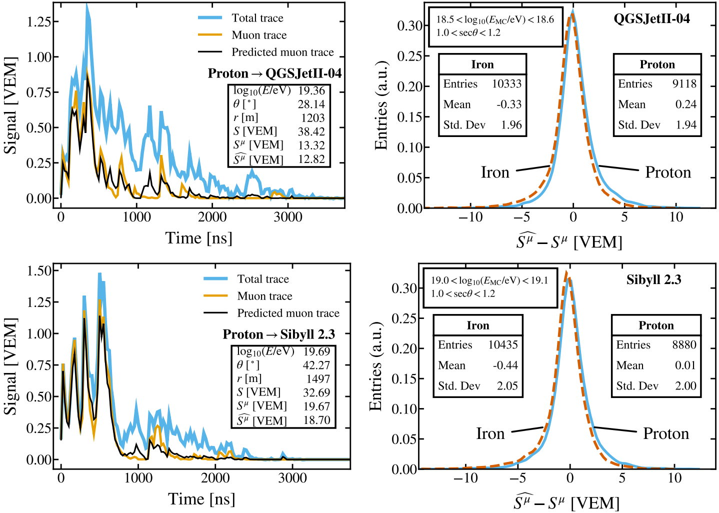


Performance Plots: Muon Risetime

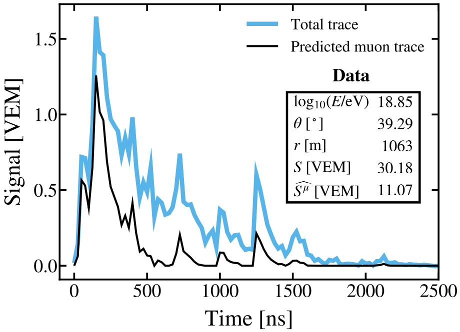
- We compare the risetime of the predicted muon trace $\widehat{t^{\mu}_{1/2}}$ with the risetime of the true muon trace $t^{\mu}_{1/2}$
- Mean close to 0, standard deviation less than 100 ns
- A single muon has a risetime of 15 ns and a decay constant of 60 ns

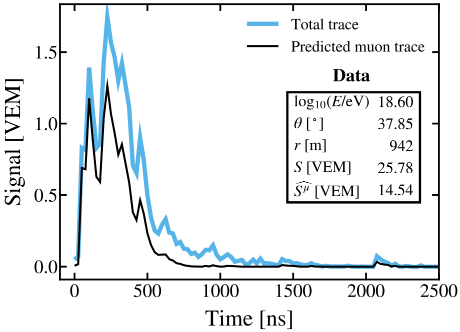


- The predictions are as good when predicting for simulations done with a different hadronic model



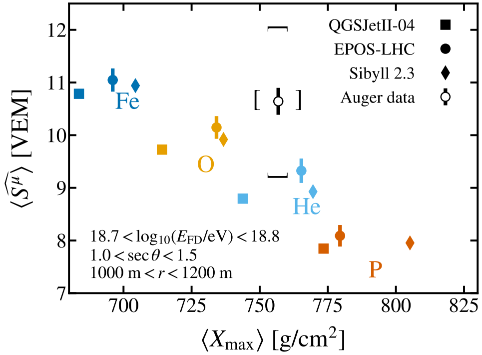
- Two examples of traces for two stations from two different events recorded by the SD





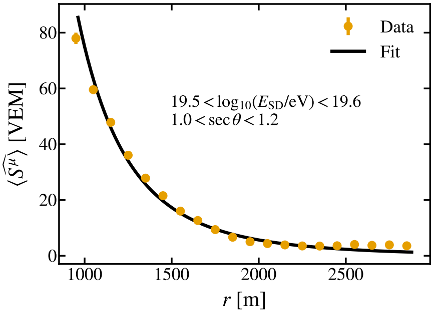
Comparing Data and Simulations: Muon Deficit

- We compare predicted muon signals (at $\sim$ 1000 m, by only picking stations with $1000\,\mathrm{m} < r < 1200\,\mathrm{m}$) in simulations and hybrid data
- We obtain a muon deficit in simulations for **vertical events** for the first time
- We compare predicted muon signals in simulations and hybrid data



- We fit our data with parameterizations obtained from other experiments, keeping the values of the original parameters

Akeno: J. Phys. G. Nucl. Part. Phys 21 1101 (1995)

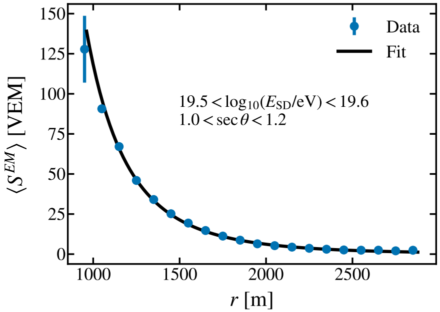


$$\rho_{\mu}(r) = N_{\mu}(C_{\mu}/R_0^2)R^{-\alpha}(1+R)^{-\beta}[1+(r/800\text{m})^3]^{-\delta}$$

Comparing to Data from Other Experiments

- We fit our data with parameterizations obtained from other experiments, keeping the values of the original parameters
- The electromagnetic signal is obtained as follows $S^{EM} = S - S^{\mu}$

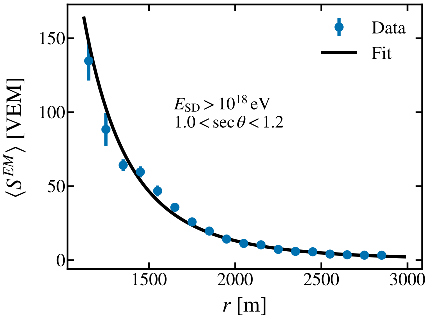
Akeno: J. Phys. G. Nucl. Part. Phys 18 423 (1992)



$$\rho_e = N_e C_e R^{-\alpha}(1+R)^{-\eta+\alpha}\left(1+\frac{r}{2000}\right)^{-0.5}$$

- We fit our data with parameterizations obtained from other experiments, keeping the values of the original parameters
- The electromagnetic signal is obtained as follows $S^{EM} = S - S^{\mu}$

Volcano Ranch: Phys. Rev. Lett. 10 146 (1963)



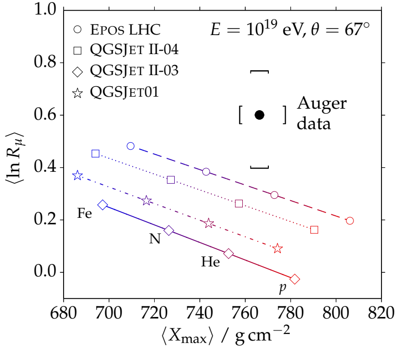
$$VR(\alpha, \eta) = \frac{N}{R_0^2} C(\alpha, \eta) \left(\frac{R}{R_0}\right)^{-\alpha} \left(1 + \frac{R}{R_0}\right)^{-\eta+\alpha}$$

Outline

Differences between Data and Simulations: Previous Studies

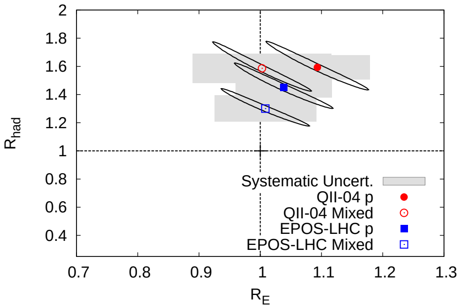
- Previous results point to a deficit of muons in simulations

Muons in inclined events



- Only studies the muon signal

$$S_{\text{resc}}(R_E, R_{\text{had}})_{i,j} \equiv R_E\ S_{EM,i,j} + R_{\text{had}}\ R_E^{\alpha}\ S_{\text{had},i,j}$$

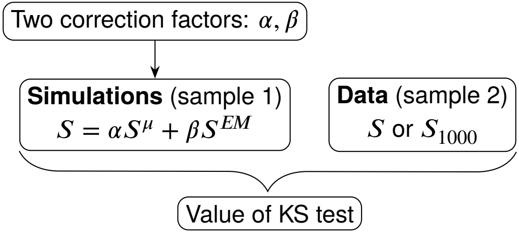


- Studies data and simulations with the same longitudinal profile

- We study differences without restricting to only the muon signal

Comparing Data and Simulations

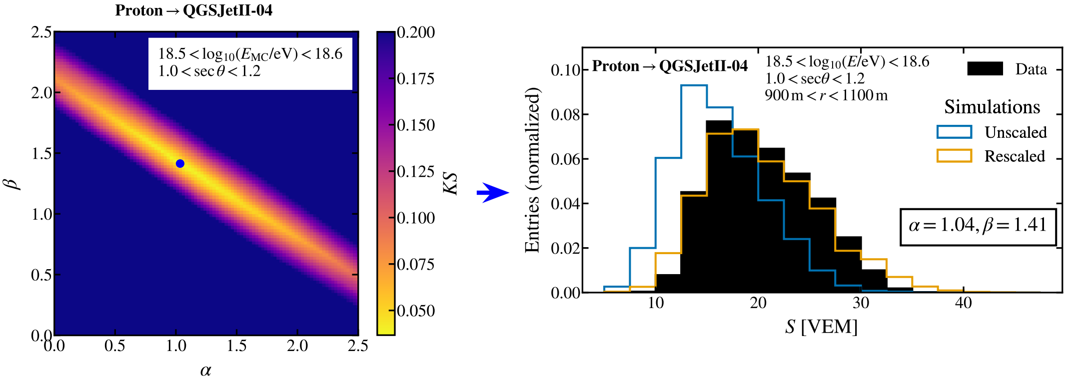
- We use the Kolmogorov-Smirnov test (KS) to compare the distributions of data and **rescaled** signal in simulations
- KS tells us if two samples belong to the same distribution
- Truth: $S = S^{\mu} + S^{EM}$



- Find value of α and β that minimize the KS test (data and simulations match)

Stations with $r \simeq 1000$ m

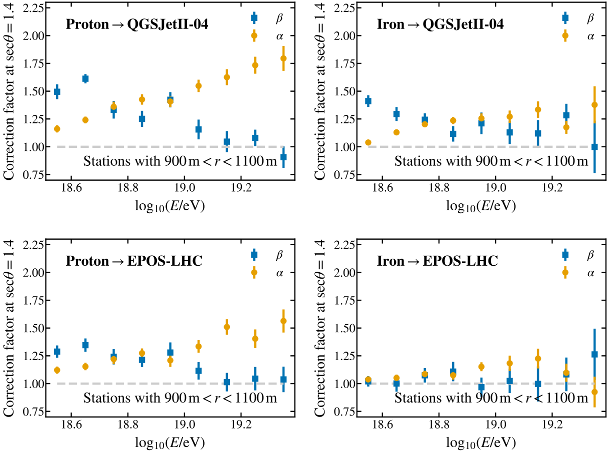
- For each station with $r \in [900, 1100]$ m, the new signal in simulations is $S = \alpha S^{\mu} + \beta S^{EM}$ (S^{μ} and S^{EM} are the Monte Carlo muon and e.m. signal)
- α and β are given values and the best matching is found
- The values of α and β are strongly correlated



Results with $r \simeq 1000$ m

- The rescaling needed is almost always greater than 1
- Signals in EPOS-LHC are slightly larger, less correction needed

$S = \alpha S^{\mu} + \beta S^{EM}$



Summary

- Cosmic rays is a fascinating field with a lot to do
- We measure these cosmic rays indirectly with air showers
- On mass composition: mass going to heavier from $10^{18.3}$ eV onwards
- On hadronic interactions: There are problems with the hadronic models, tuned at the energies of the LHC, more muons in data than in simulations
- Circular problem: To know the mass composition I need good simulations (hadronic models) but to constrain hadronic models I need the composition
- Ongoing upgrade of the Pierre Auger Observatory to solve this

Backup

Heitler-Matthews toy model

- Electromagnetic showers
  - Pair production: A photon produces a pair of an electron and positron
  - Bremsstrahlung: A charged particle emits photons
- Hadronic showers
  - Neutral pions decay to photons and feed the electromagnetic component
  - Charged pions produced more pions (charged and uncharged)

../Images/Heitler.pdf
../Images/Heitler.pdf

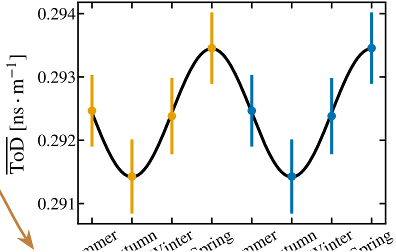
Signal Saturation

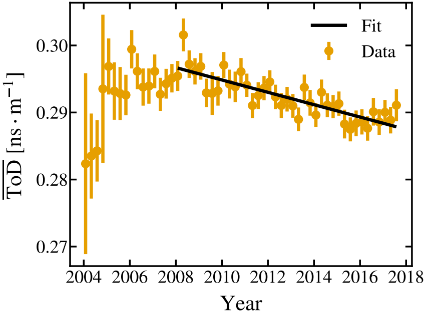
- Signals from PMTs come from the high-gain channel and low-gain channel
- Signals big enough will saturate the high-gain channel first and then the low-gain channel

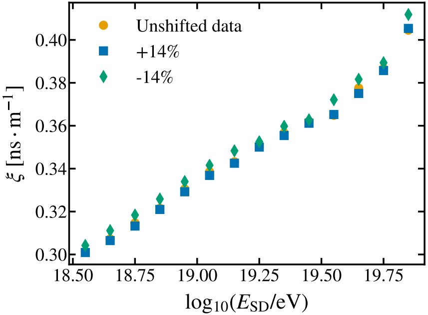
../Saturated-signal/saturated.pdf

Systematic Uncertainties

Ageing of the detectors	$\pm 0.005\ \mathrm{ns \cdot m^{-1}}$
Seasonal effect	$\pm 0.001\ \mathrm{ns \cdot m^{-1}}$
Energy uncertainty	$\pm 0.005\ \mathrm{ns \cdot m^{-1}}$
Total systematic uncertainty	$\pm 0.007\ \mathrm{ns \cdot m^{-1}}$

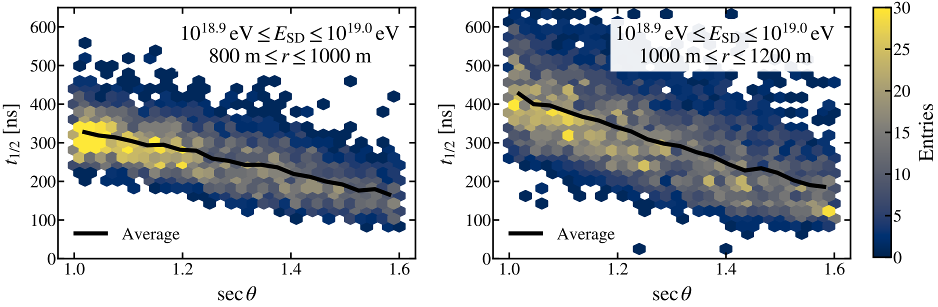




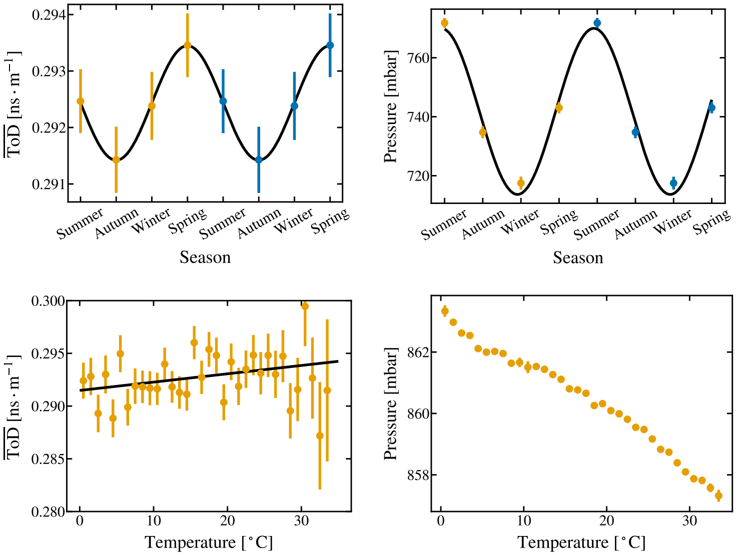


Risetime: Dependence with $\sec\theta$

- As $\sec\theta$ increases the electromagnetic component is attenuated and $t_{1/2}$ decreases



$\overline{\text{ToD}}$: Systematic Uncertainties and Atmospheric Conditions



Differences with The $\langle\Delta\rangle$ Method

- Old slide with the results obtained using the same simulations and a more similar cut on S
- Results match very well

./Images/page.pdf

Energy Differences

- For data the energy from the SD (E_{SD}) is obtained from the calibration curve given by the FD
- We can not use E_{SD} in simulations to compare to data
- We use E_{MC} instead as a proxy for E_{FD}
- For simulations there is a bias that depends on the composition between the energy from the SD and FD

Simulations → MC energy
Data → Energy from the SD

LSTM Layer

- Output obtained from previous hidden state h_{t-1}
- The forget gate selects from the previous cell state C_{t-1}
- Hidden state obtained from the current cell state C_t
- The input gate selects from the candidate cell $\tilde{C}_t$
- The forget vector f_t is built
- The input vector i_t is built
- The candidate cell state $\tilde{C}_t$ is built

../Images/lstm-4.png

../Images/lstm-3.png

../Images/lstm-2.png

../Images/lstm-1.png

../Images/lstm-notation.png

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o)$$

$$h_t = o_t * \tanh(C_t)$$

$$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t$$

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i)$$

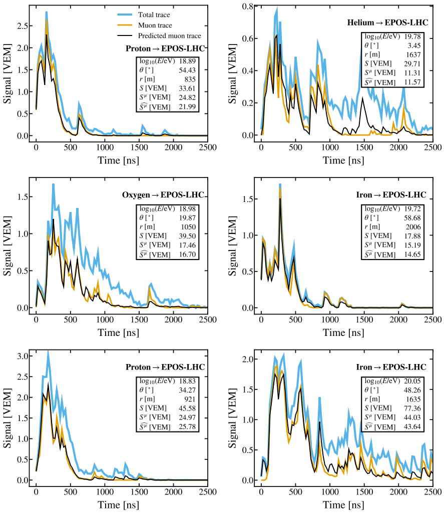
$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, x_t] + b_C)$$

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f)$$

Training: Loss and Other Metrics

../Images/loss-and-diff.pdf

More Examples of Traces



Performance Plots: Mean

../Images/hex-energy-dif-mean.pdf

Performance Plots: Std

../Images/hex-energy-dif-std.pdf

Performance Plots: Correlation

../Images/cor.pdf

Performance: as a function of S^{μ}

- Mean close to 0
- Performance improved for larger zenith angles

- The average muon risetime also points towards a heavier composition than iron

../Images/muon-deficit-and-risetime-data.pdf

Energy equivalence between cosmic rays and accelerators

Lab. frame

$p_1 = (E, E) \qquad p_2 = (m, 0)$

C.M. frame

$p_3 = (E', p) \qquad p_4 = (E', -p)$

Invariance of the norm tells us that $(p_1 + p_2)^2 = (p_3 + p_4)^2$ so

$$(E + m)^2 - E^2 = 4(E')^2 \Rightarrow 2mE + m^2 = 4(E')^2$$

$$2E' = \sqrt{2mE}$$

$$\text{if} \begin{cases} m \sim 10^9 \text{ eV} \\ E \sim 10^{19} \text{ eV} \end{cases} \Rightarrow \begin{aligned} 2E' = \sqrt{s} &\sim \sqrt{2 \cdot 10^{28}} \text{ eV} \\ &\sim \sqrt{2} \cdot 10^{14} \text{ eV} \\ &\sim 140 \text{ TeV} \end{aligned}$$

Saturated stations

Trace used in the computation → Images/vem1.pdf

High gain channel → Images/hg1.pdf

Recent Results: Spectrum

./Images/J_PRL.pdf

$$J(E) = J_0 \left(\frac{E}{10^{18.5}\ \text{eV}} \right)^{-\gamma_1} \prod_{i=1}^{3} \left[1 + \left(\frac{E}{E_{ij}} \right)^{\frac{1}{\omega_{ij}}} \right]^{(\gamma_i - \gamma_j)\omega_{ij}}$$