An estimation of the muon signal in the SD using Deep Neural Networks

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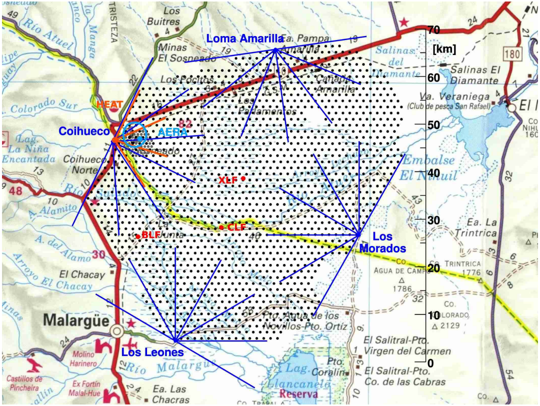
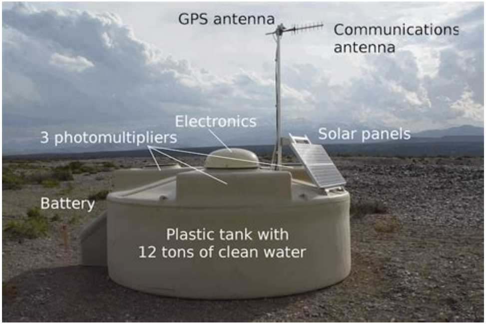
The Pierre Auger Observatory

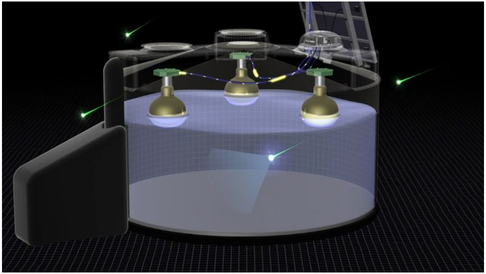
- Largest detector of cosmic rays built so far
- Hybrid detector
- 1660 surface detectors covering a total area of 3000 km^2
- Array is overlooked by 30 fluorescence telescopes
- Located in the province of Mendoza in Argentina



The Surface Detector (SD)

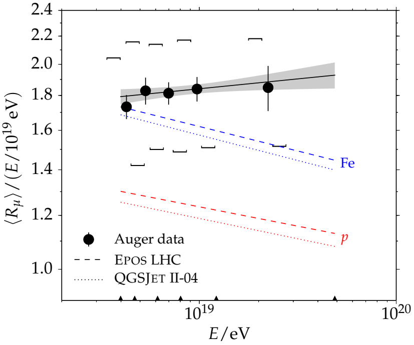
- Measures the arrival time of secondary particles of the shower at the ground
- Particles emit Cherenkov radiation in water that can be measured by the photomultiplier tubes
- Duty cycle ∼ 100%

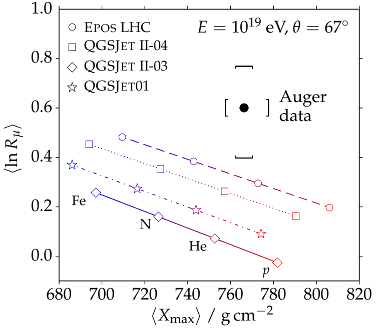




The importance of muons

- The muon signal in the ground depends on the composition of the primary cosmic ray
- Valuable information about hadronic interactions
- Number of muons in data is 30%-80% higher than what models predict





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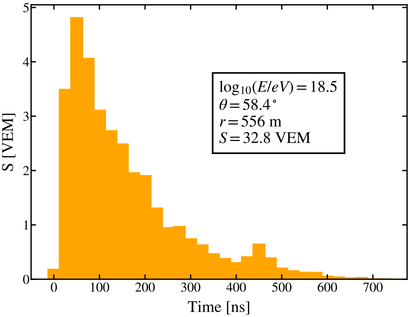
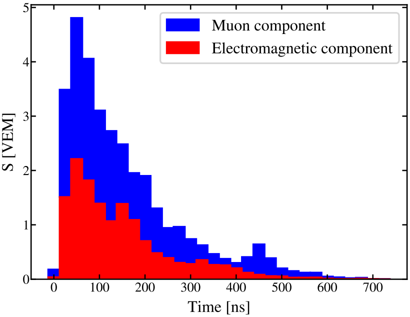
Our problem

- Typical signal measured in VEM (Vertical Equivalent Muon) (left) is the sum of an electromagnetic and muon component (right)

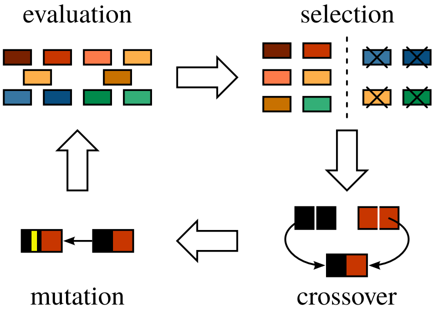


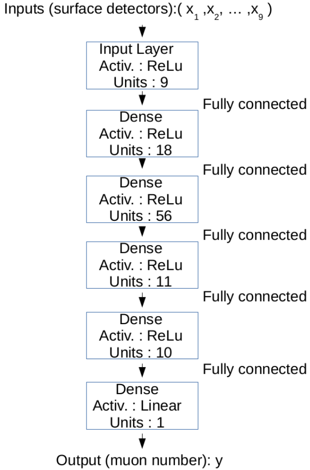


- We decided to use a novel approach: Deep Learning Techniques
- We predict the integral of the muon trace S_μ

Choosing a Neural Network

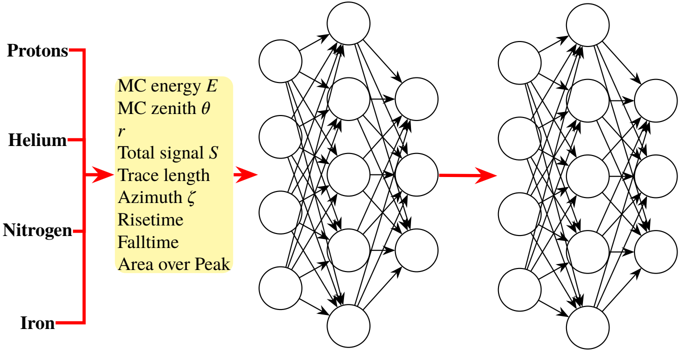
- Several free parameters can be tuned (number of layers of the NN, number of neurons in each layer. . .)
- **Genetic algorithms**





Neural Networks: From input to output

Simulations (Input) → **Neural Network** → **Trained Neural Network** → **Predicted Muon Signal (Output)**



- We use more simulations (that the net has not seen) to test the prediction.

- **One prediction for each station: $S_{\mu}^{\mathbf{pred}}$**

How did we train the NN?

Training
25% Proton, Helium, Nitrogen and Iron (QGSJet)
Roughly 20000 stations of each primary.

Variables used in training:

1. MonteCarlo energy E → $\log_{10}$
2. MonteCarlo zenith θ → $\sec\theta$
3. Distance to the core r → m
4. Total signal S → VEM
5. Trace length
6. Azimuth ζ → radians
7. Risetime → ns
8. Falltime → ns
9. Area over Peak

- These 9 variables are used to predict the total muon signal S_{μ}^{true}, known in simulations

△ Before training, the input is normalized

Number of simulations

- Training, validation and test correspond to distinct sets of detectors

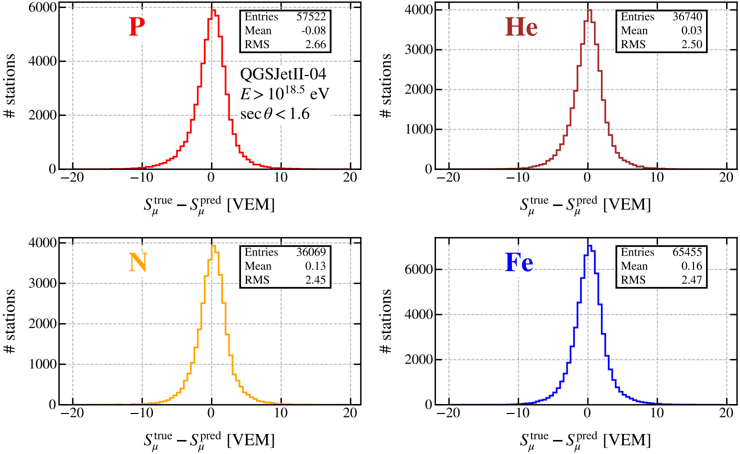
QGSJETII-04				
		Training	Validation	Test
Primary	# of events	# of detectors		
Proton	19362	16088	4022	57522
Helium	12341	15960	3989	36740
Nitrogen	12201	16071	4017	36069
Iron	19478	16076	4018	65455
EPOS-LHC				
		Training	Validation	Test
Primary	# of events	# of detectors		
Proton	18456	–	–	78063
Iron	18779	–	–	86862

Before the results

- The trace used is the average of the traces recorded by each of the active PMTs of the station.
- We only use stations with total signal S_{total} above 10 VEM.
- We restrict to energies between $10^{18.5}$ eV and 10^{20} eV and zenith angles between 0 and 45 degrees.

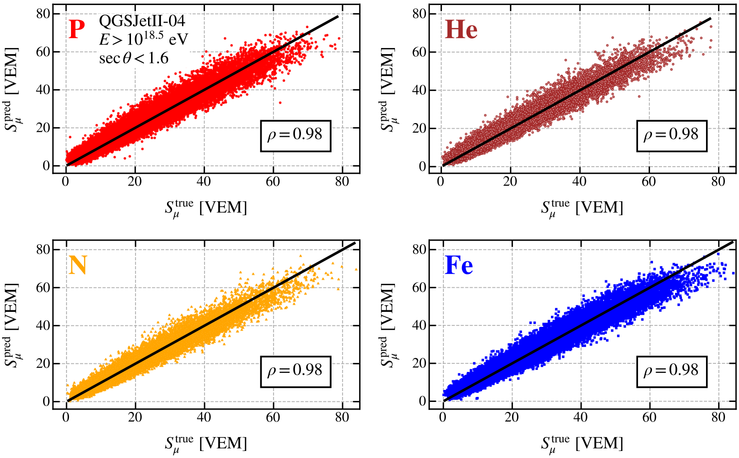
S_μ^{true}-S_μ^{pred} (station level)

- The difference between the real S_μ^{true} and predicted S_μ^{pred} signals is a few VEMs.
- The mean of the distribution is very close to zero, changing slightly as the mass of the primary increases.
- The RMS of the distribution is ~ 2.5 VEM.

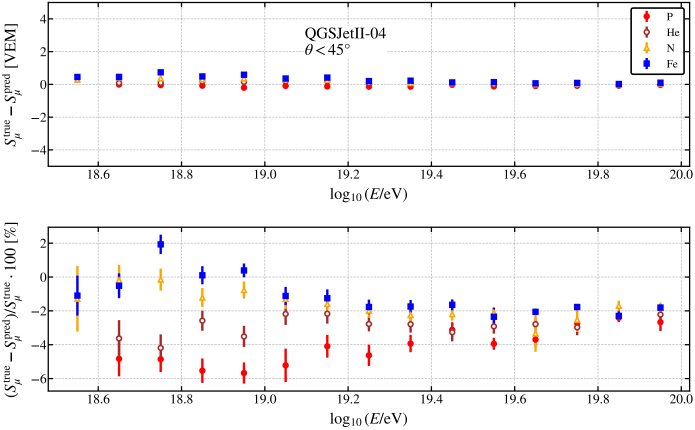


S_μ^{true}-S_μ^{pred} (station level)

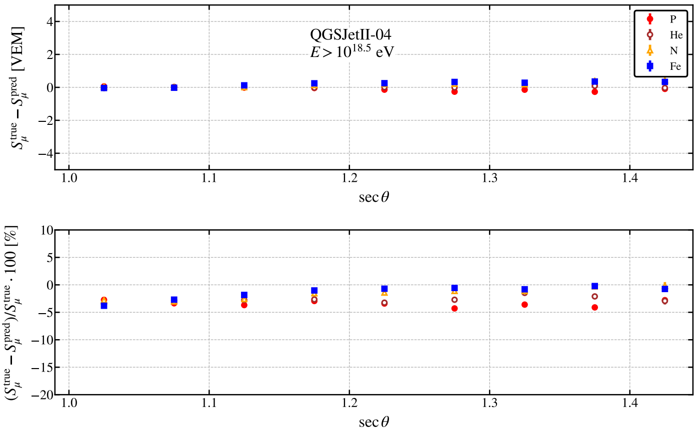
- The correlation between S_μ^{true} and S_μ^{pred} is very high, with a Pearson correlation coefficient $\rho = 0.98$.



S_μ^{true}-S_μ^{pred} as a function of the energy

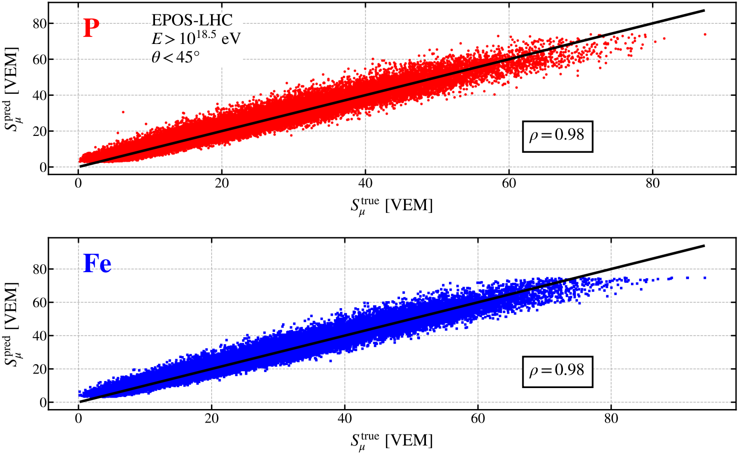


S_μ^{true}-S_μ^{pred} as a function of $\sec\theta$



S_μ^{true}-S_μ^{pred} for EPOS (station level)

- The neural network has not seen any simulations done with EPOS during training
- The correlation between S_μ^{true} and S_μ^{pred} is very high, with a Pearson correlation coefficient $\rho = 0.98$.

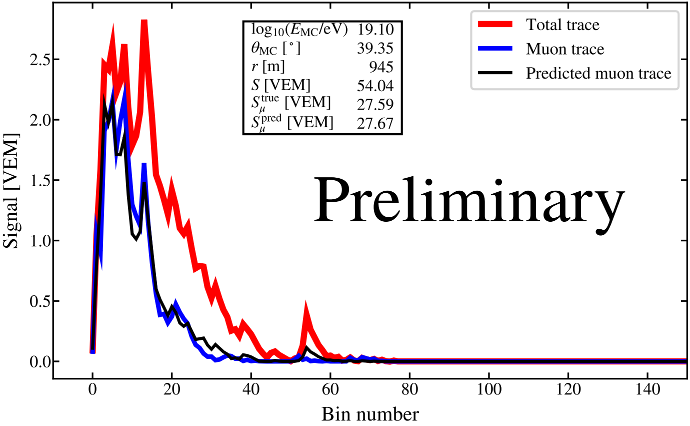


Remarks

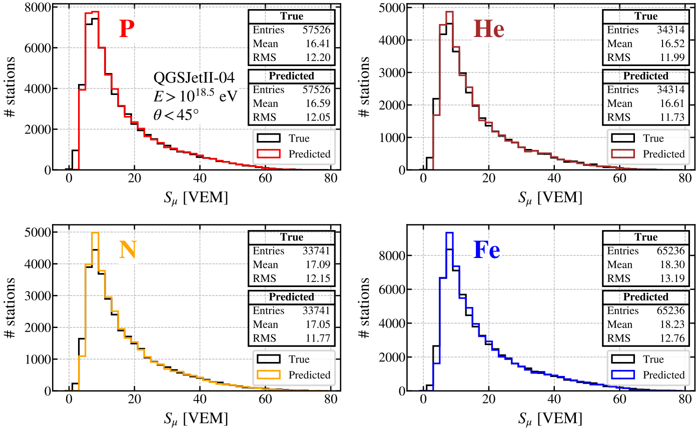
- We have proved that using Neural Networks, one can predict the muon signal with very high precision.
- The muon signal can be consistently predicted across a large range of energies and zenith angles, within 2 VEMs of the true value in each station.
- The estimation shows a very small bias with the distance to the core r, energy E, zenith angle $\sec\theta$ and hadronic model used.

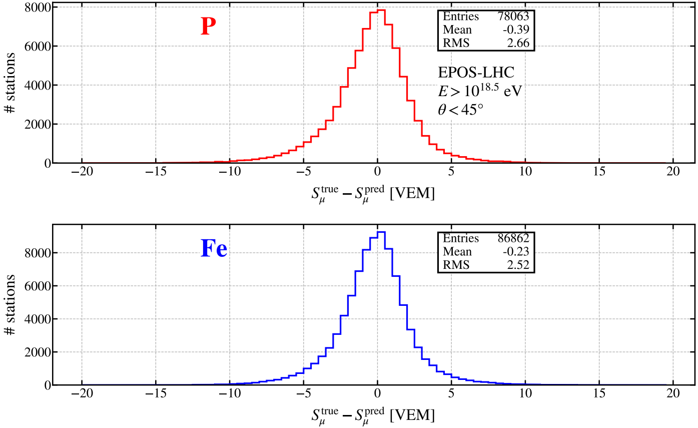
New approach

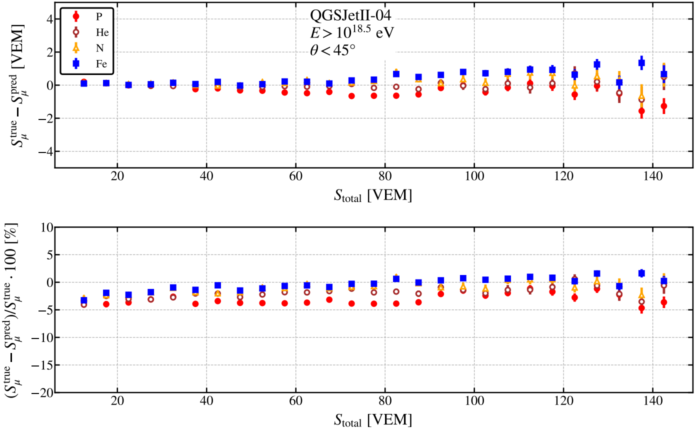
- Predict the complete muon trace
- Recurrent neural networks
- Encouraging results but preliminary

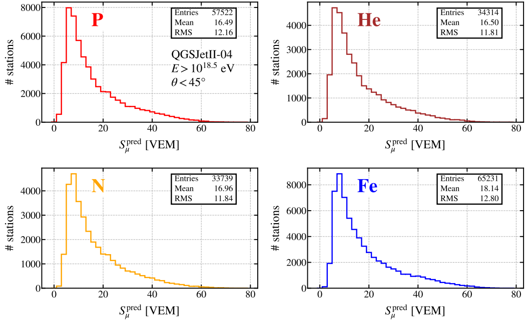


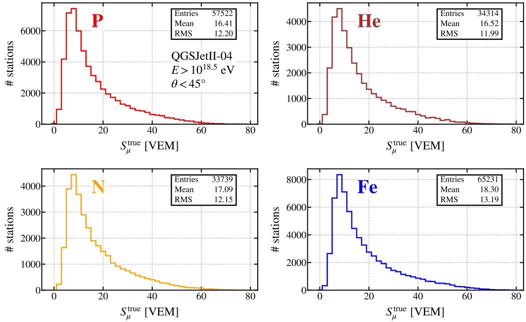
Backup

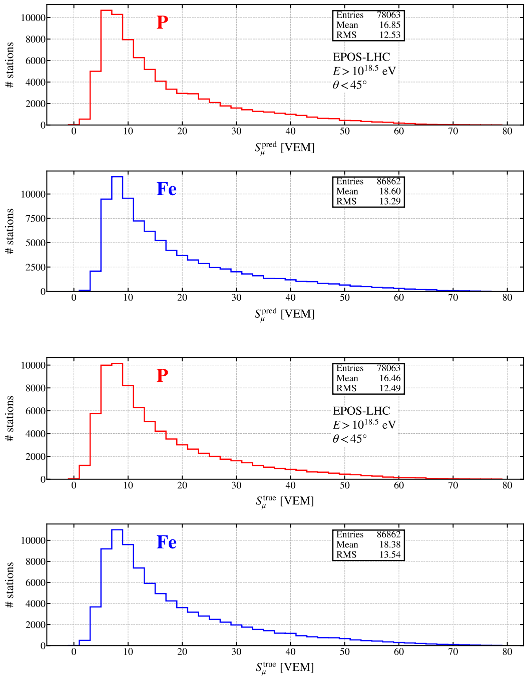

P
QGSJetII-04
E > 10^18.5 eV
θ < 45°
True
Entries 57526
Mean 16.41
RMS 12.20
Predicted
Entries 57526
Mean 16.59
RMS 12.05
He
True
Entries 34314
Mean 16.52
RMS 11.99
Predicted
Entries 34314
Mean 16.61
RMS 11.73
N
True
Entries 33741
Mean 17.09
RMS 12.15
Predicted
Entries 33741
Mean 17.05
RMS 11.77
Fe
True
Entries 65236
Mean 18.30
RMS 13.19
Predicted
Entries 65236
Mean 18.23
RMS 12.76
stations
Sμ [VEM]

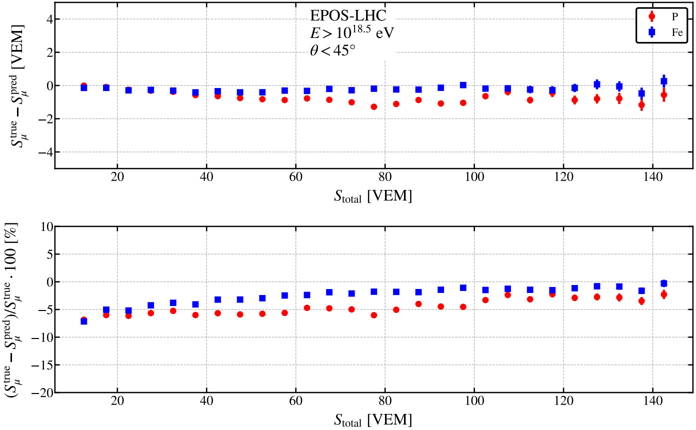

P
Entries 78063
Mean -0.39
RMS 2.66
EPOS-LHC
$E > 10^{18.5}$ eV
$\theta < 45°$
stations
$S_\mu^{true} - S_\mu^{pred}$ [VEM]
Fe
Entries 86862
Mean -0.23
RMS 2.52
stations
$S_\mu^{true} - S_\mu^{pred}$ [VEM]


QGSJetII-04
$E > 10^{18.5}$ eV
$\theta < 45°$
P
He
N
Fe
$S_\mu^{\rm true} - S_\mu^{\rm pred}$ [VEM]
$S_{\rm total}$ [VEM]
$(S_\mu^{\rm true} - S_\mu^{\rm pred})/S_\mu^{\rm true} \cdot 100$ [%]
$S_{\rm total}$ [VEM]


P
Entries 57522
Mean 16.49
RMS 12.16
QGSJetII-04
$E > 10^{18.5}$ eV
$\theta < 45°$
He
Entries 34314
Mean 16.50
RMS 11.81
N
Entries 33739
Mean 16.96
RMS 11.84
Fe
Entries 65231
Mean 18.14
RMS 12.80
stations
$S_\mu^{\rm pred}$ [VEM]


P
Entries 57522
Mean 16.41
RMS 12.20
QGSJetII-04
$E > 10^{18.5}$ eV
$\theta < 45°$
He
Entries 34314
Mean 16.52
RMS 11.99
N
Entries 33739
Mean 17.09
RMS 12.15
Fe
Entries 65231
Mean 18.30
RMS 13.19
stations
$S_\mu^{\rm true}$ [VEM]


P
Entries 78063
Mean 16.85
RMS 12.53
EPOS-LHC
$E > 10^{18.5}$ eV
$\theta < 45°$
stations
S_μ^{pred} [VEM]
Fe
Entries 86862
Mean 18.60
RMS 13.29
stations
S_μ^{pred} [VEM]
P
Entries 78063
Mean 16.46
RMS 12.49
EPOS-LHC
$E > 10^{18.5}$ eV
$\theta < 45°$
stations
S_μ^{true} [VEM]
Fe
Entries 86862
Mean 18.38
RMS 13.54
stations
S_μ^{true} [VEM]


EPOS-LHC
$E > 10^{18.5}$ eV
$\theta < 45°$
P
Fe
$S_\mu^{\mathrm{true}} - S_\mu^{\mathrm{pred}}$ [VEM]
S_{total} [VEM]
$(S_\mu^{\mathrm{true}} - S_\mu^{\mathrm{pred}})/S_\mu^{\mathrm{true}} \cdot 100$ [%]
S_{total} [VEM]