UMD-SD muon density calibration

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Double Doctoral degree in Astrophysics
DDAp

Goal:

Indirect measurement of the muon content on the surface with the WCD + SSD at the highest energies

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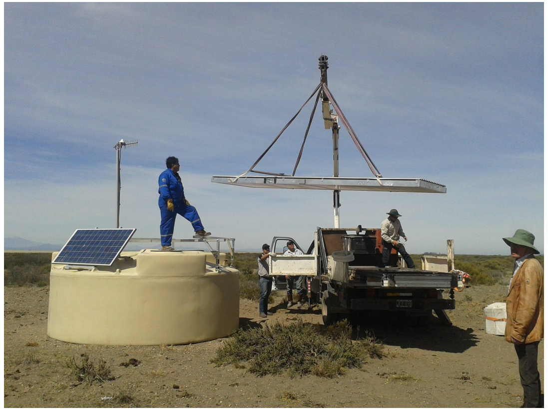
AugerPrime:



Goal:

Indirect measurement of the muon content on the surface with the WCD + SSD at the highest energies

AugerPrime:

- Shower components separation
- Direct muon measurements

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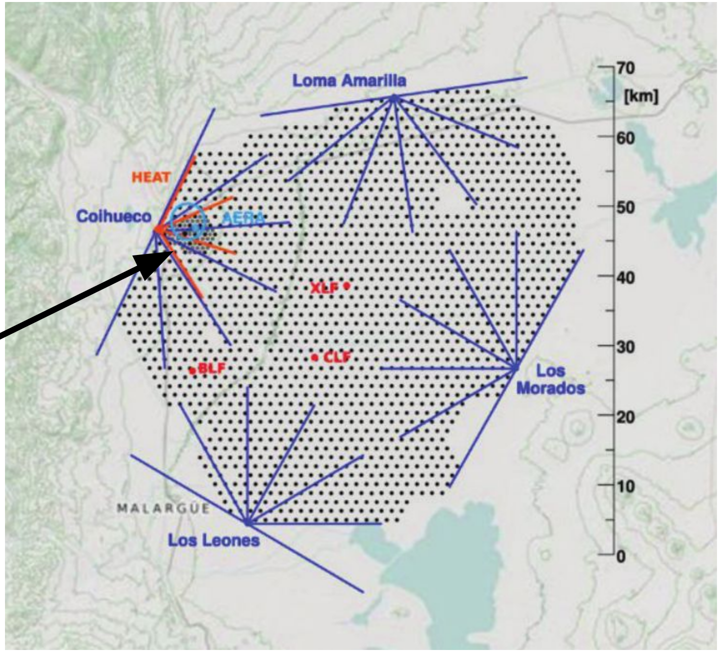
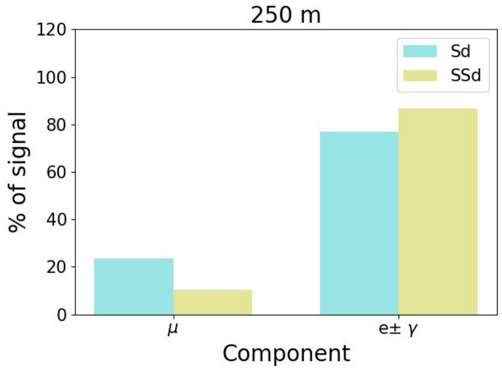


- Shower components separation
- Direct muon measurements

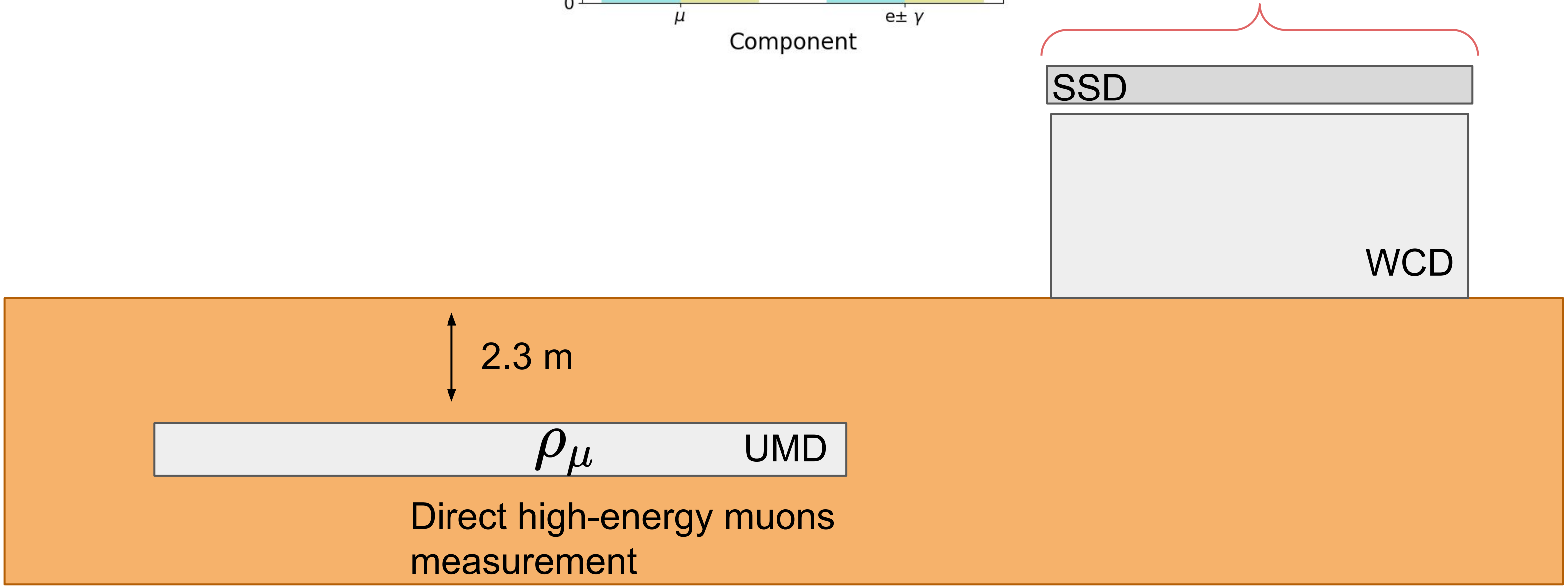
- Nested arrays for lower energies

Method:



Estimation of the muonic signal in the WCD

$$\hat{S}_{\mu}$$



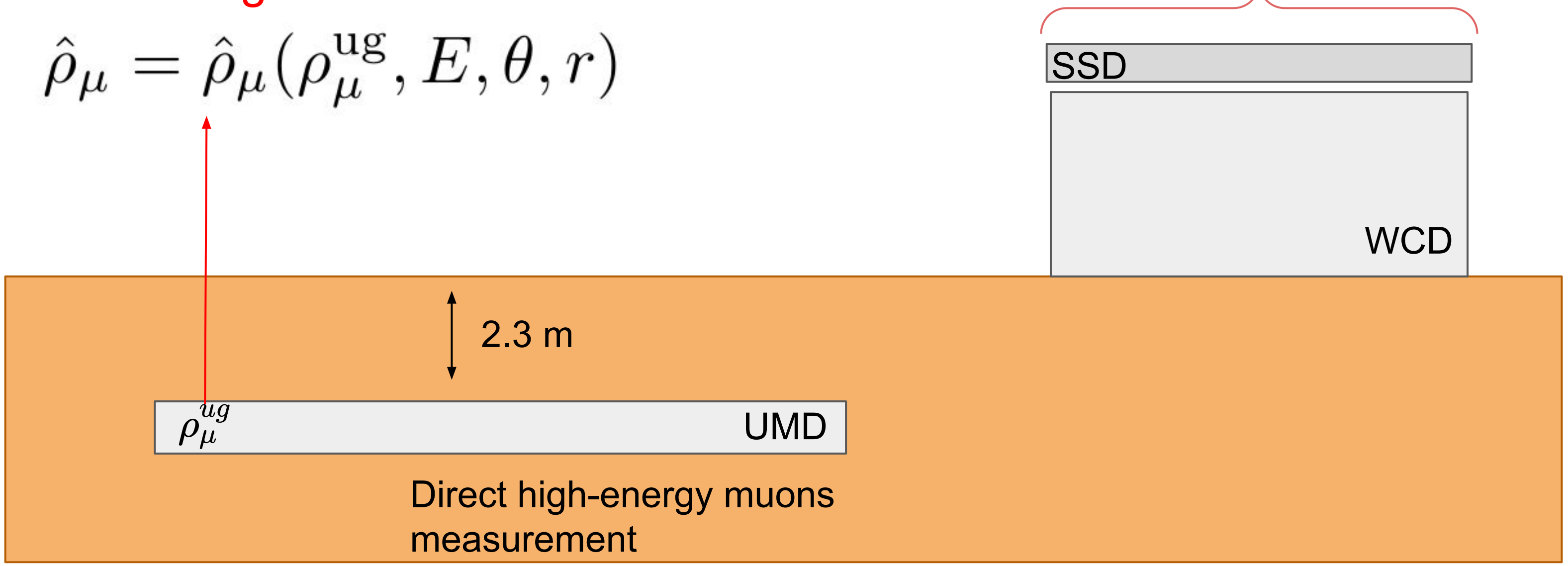
Method:

Estimation of the muonic signal in the WCD

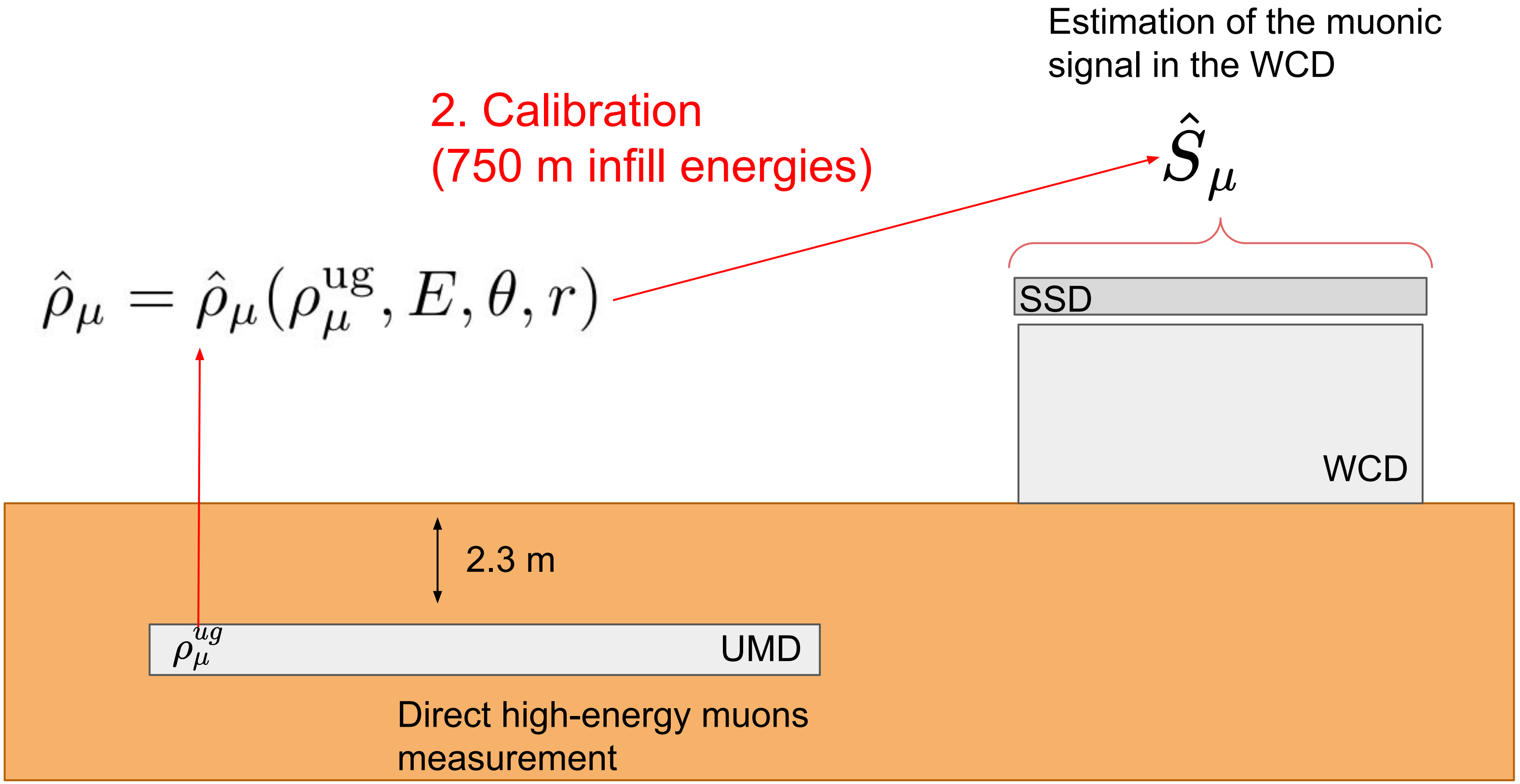
$\hat{S}_{\mu}$

1. Parameterize and convert from muons underground to on-ground

$$\hat{\rho}_{\mu} = \hat{\rho}_{\mu}(\rho_{\mu}^{\mathrm{ug}}, E, \theta, r)$$



Method:



Estimation of the muonic signal in the WCD
$\hat{S}_\mu$
2. Calibration
(750 m infill energies)
$\hat{\rho}_\mu = \hat{\rho}_\mu(\rho_\mu^{\mathrm{ug}}, E, \theta, r)$
SSD
WCD
2.3 m
ρ_μ^{ug}
UMD
Direct high-energy muons measurement

Method:

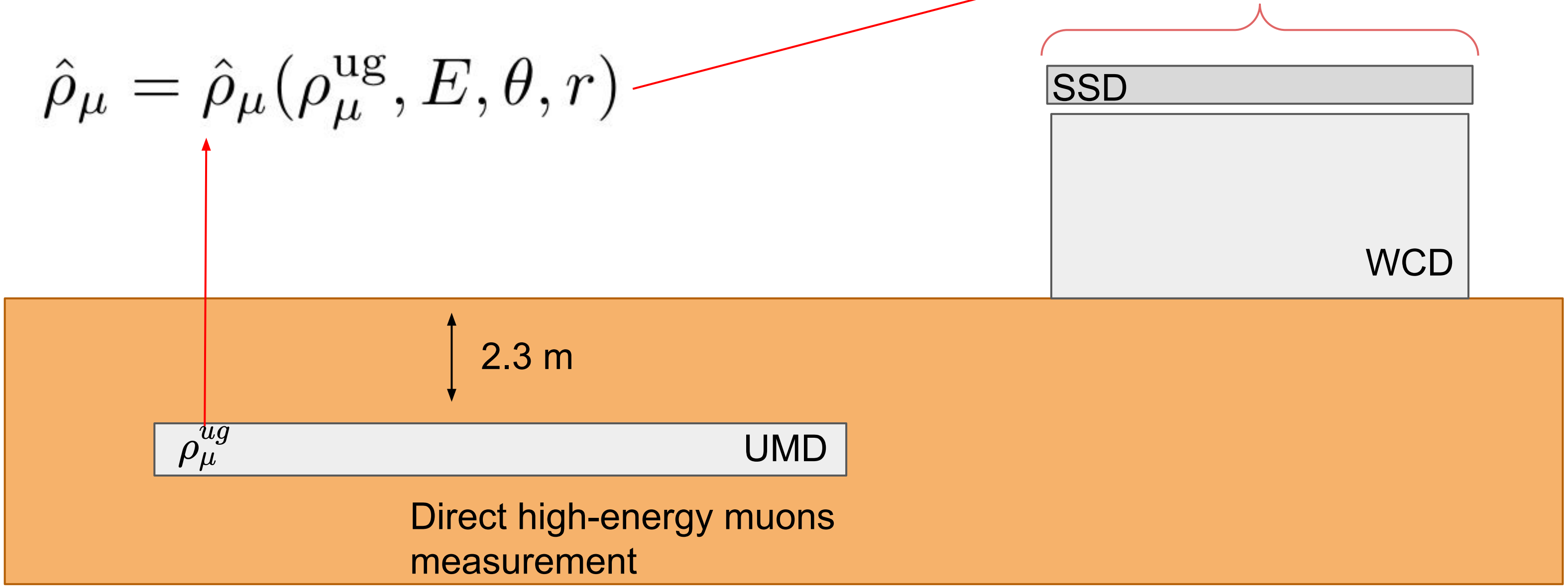
3. Extrapolation to higher energies (1500 array energies)

2. Calibration (750 m infill energies)

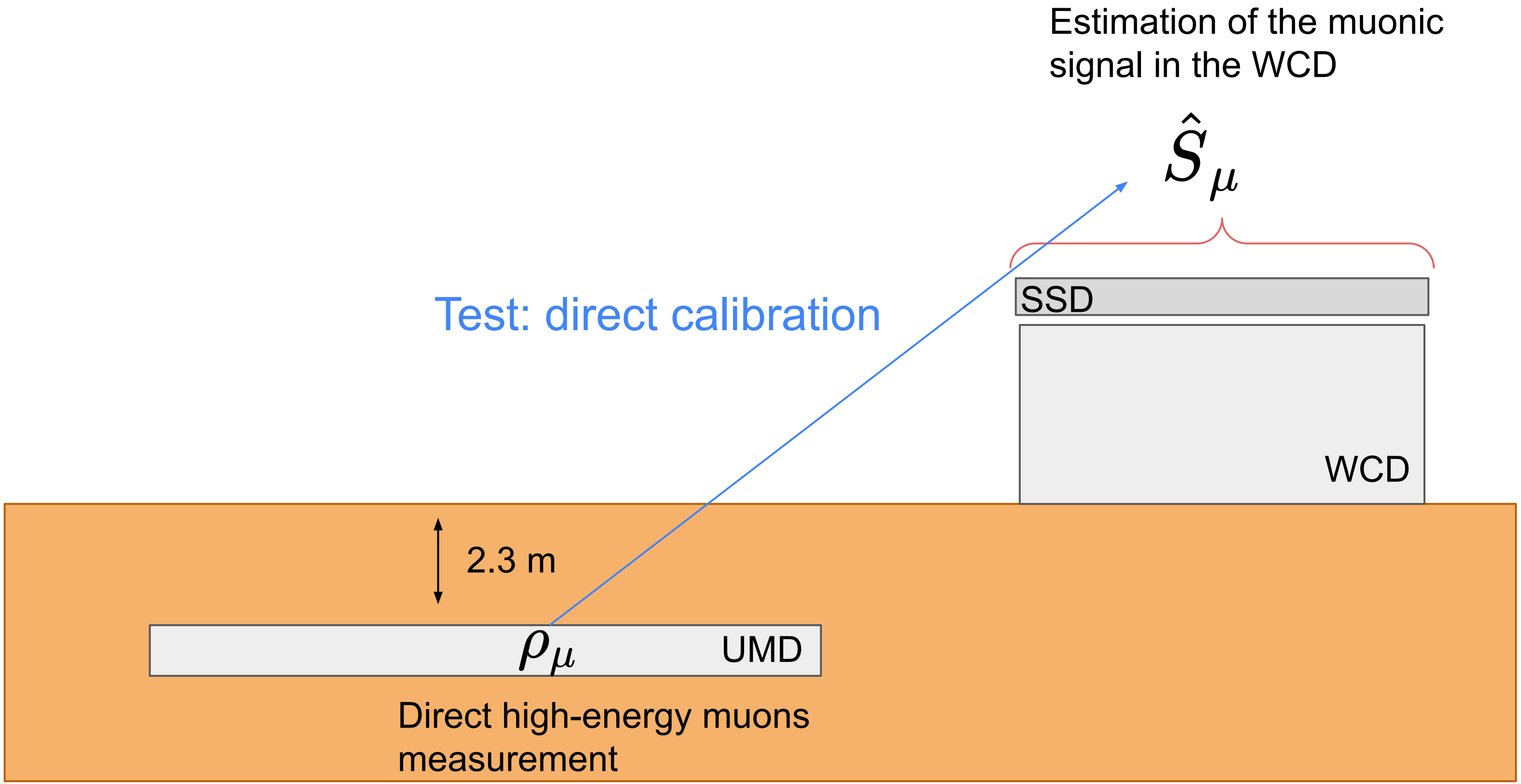
Estimation of the muonic signal in the WCD

$$\hat{S}_\mu$$

$$\hat{\rho}_\mu = \hat{\rho}_\mu(\rho_\mu^{\mathrm{ug}}, E, \theta, r)$$



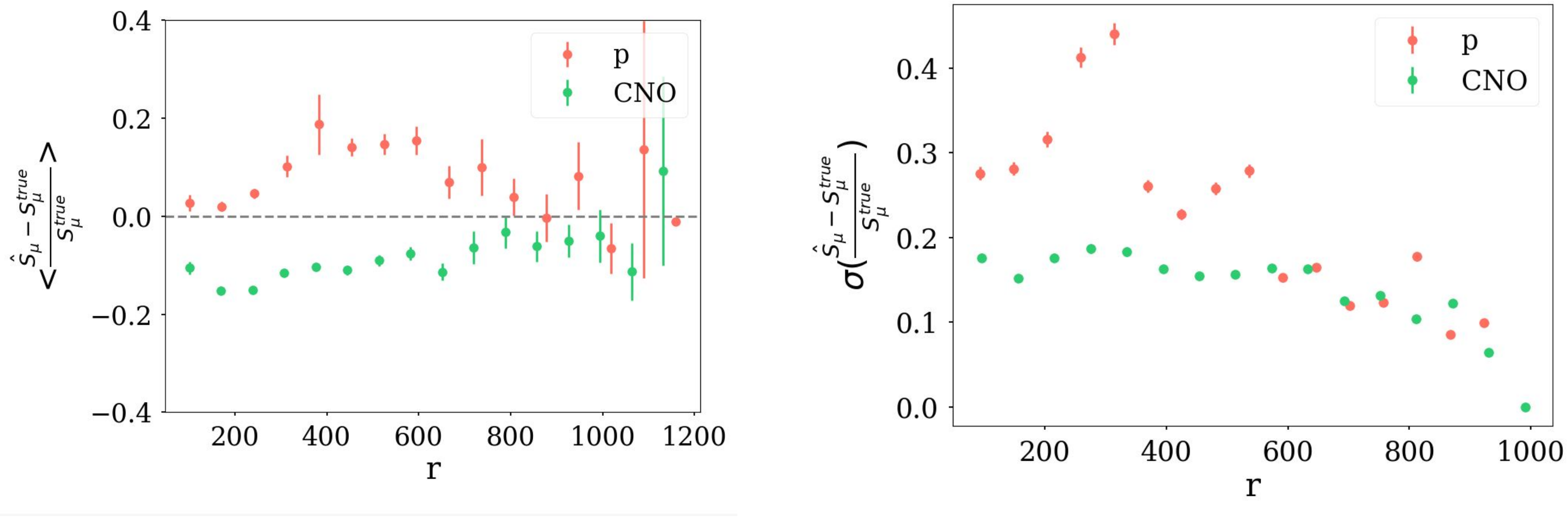
Method:



Estimation of the muonic signal in the WCD
$\hat{S}_\mu$
Test: direct calibration
SSD
WCD
2.3 m
ρ_μ
UMD
Direct high-energy muons measurement

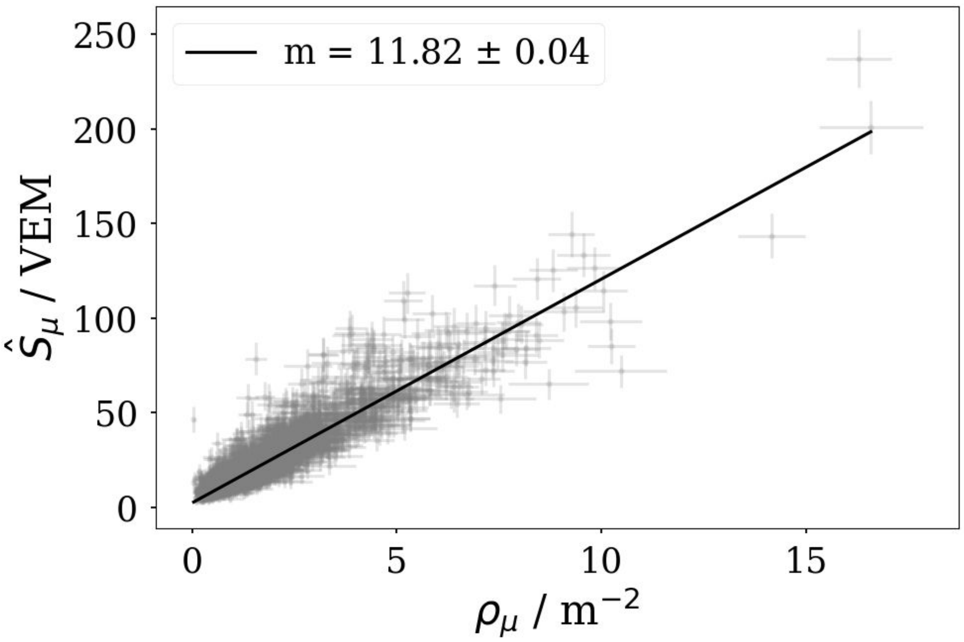
S_μ estimation

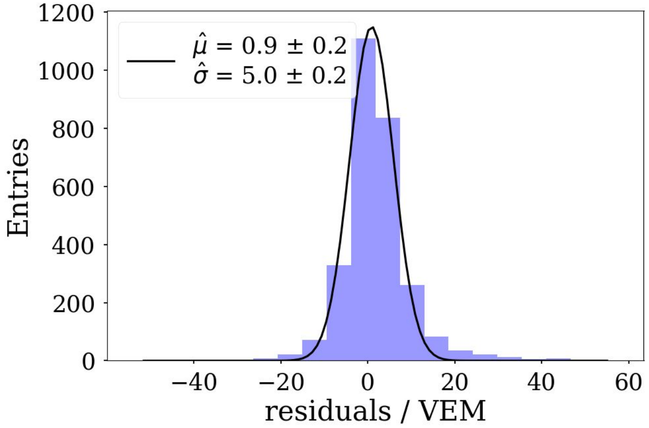
$$\hat{S}_\mu = m\, S_{\mathrm{tot}}^{\mathrm{SSD}} + n\, S_{\mathrm{tot}}^{\mathrm{WCD}}$$

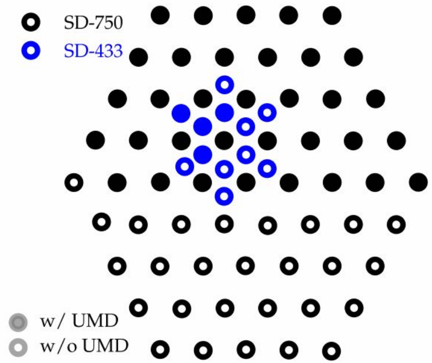


- m, n depending on E, zenith and r according to A. Payeras, Malargue meeting, Nov. 2022.
- The muonic signal in the WCD is estimated
- Bias depends on composition

Calibration with infill data

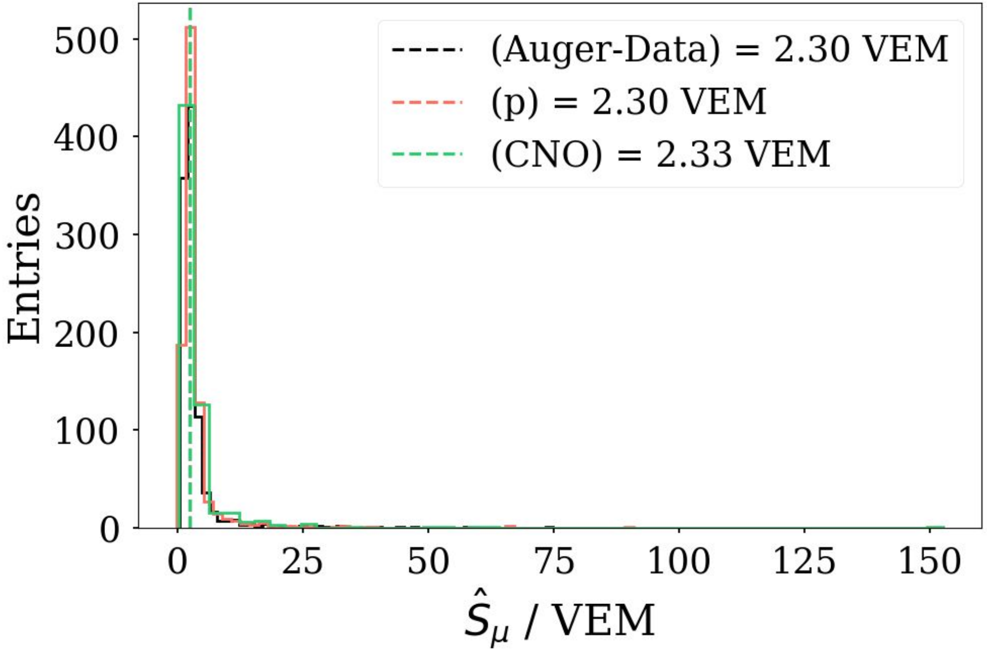






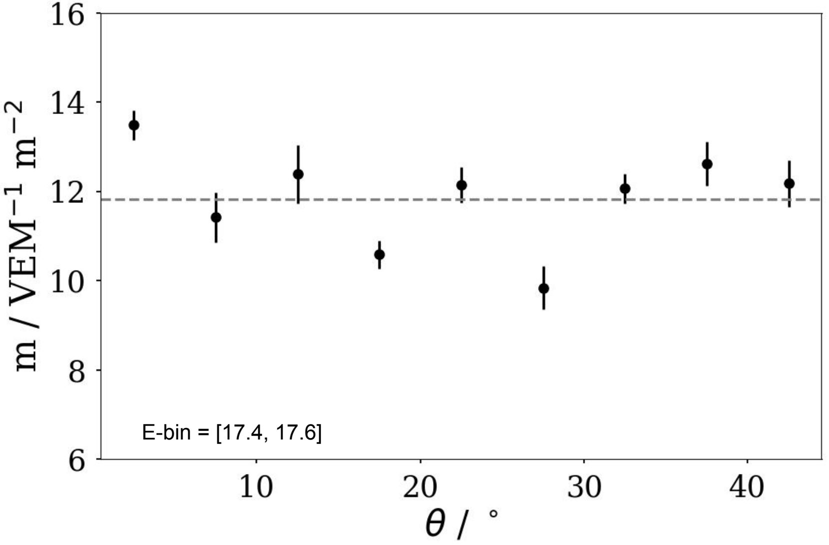
- The slope is estimated with a fix offset

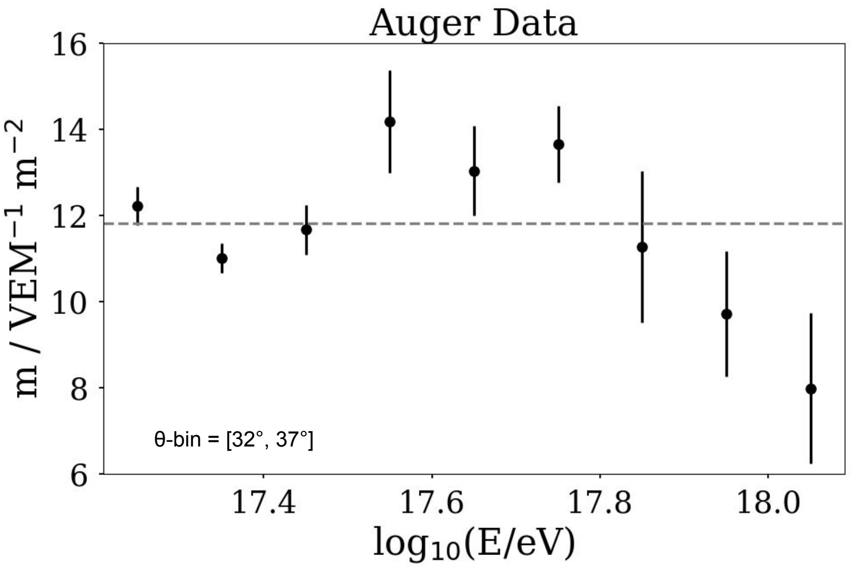
Offset



- Stations with no UMD signal
- Offset is fixed (for now) in 2.3 VEM

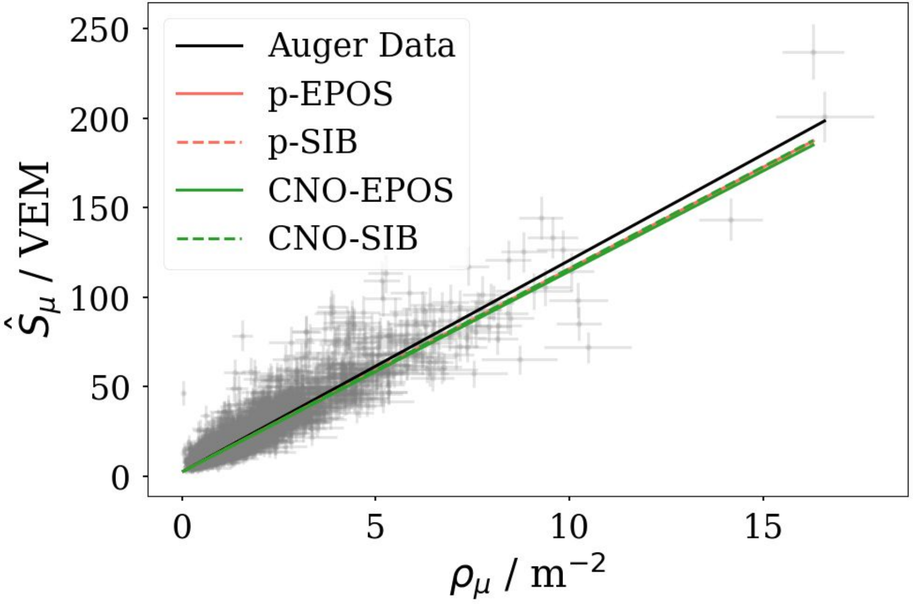
Energy and zenith dependencies





- Slope is zenith-independent
- Energy independent below $10^{17.8}$ eV

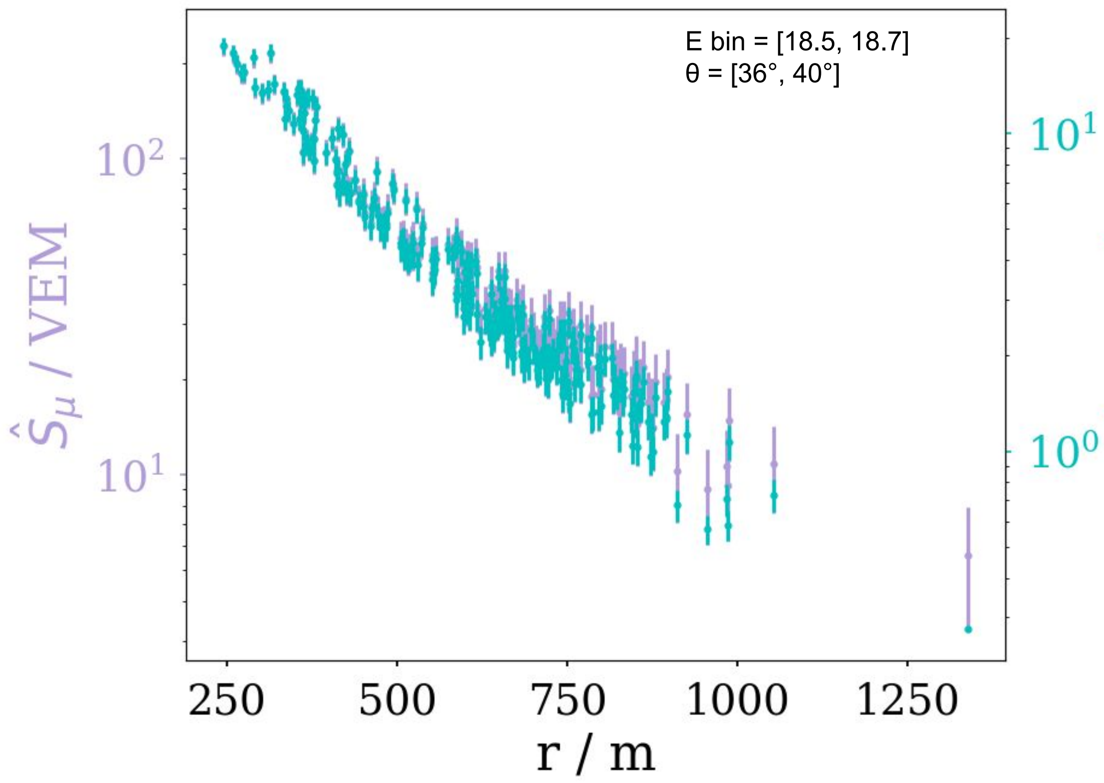
Comparing with simulations



Composition - Model	m
Auger	11.82±0.04
p-EPOS	11.35±0.04
p-SIBYLL	11.31±0.06
CNO-EPOS	11.21±0.05
CNO-SYBILL	11.36±0.04

- Slope of data is over simulations

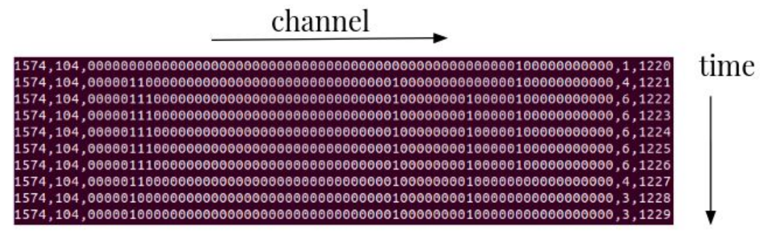
Final goal: ρ_μ estimation for the Main Array on-ground



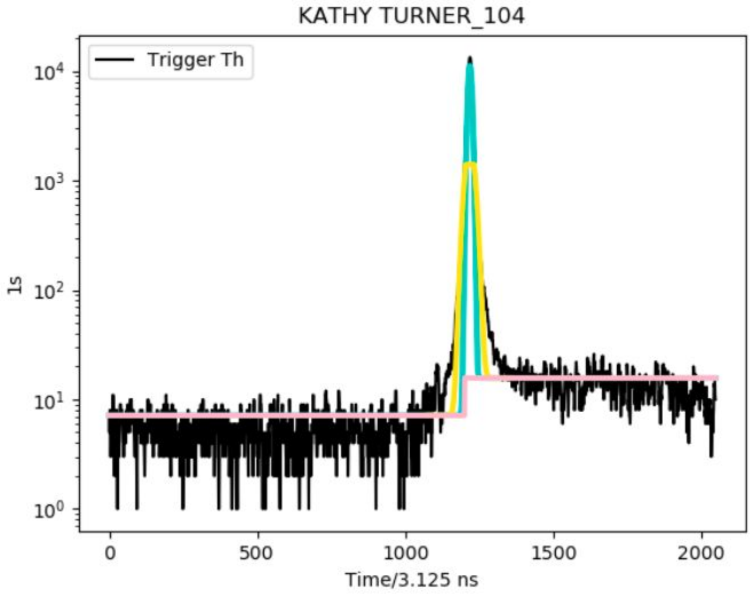
- The estimation is extrapolated to higher energies
- An LDF fit will be done to estimate ρ_{38}

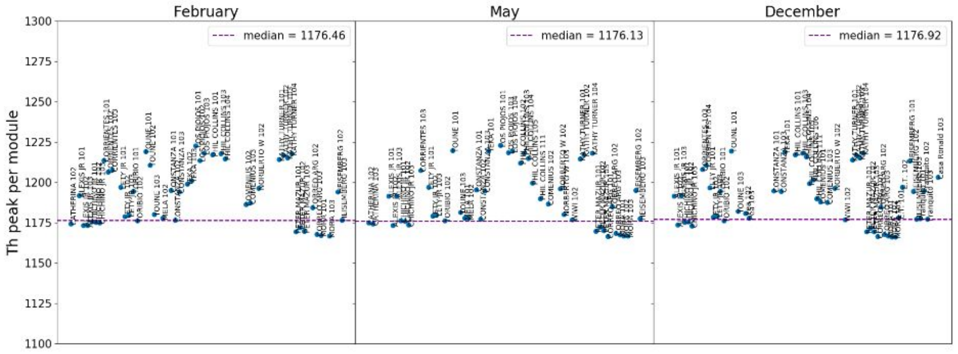
Still underground

UMD signal characterization and Monitoring



- Raw binary traces analysis
- Long term performance
- Monitoring





Th peak

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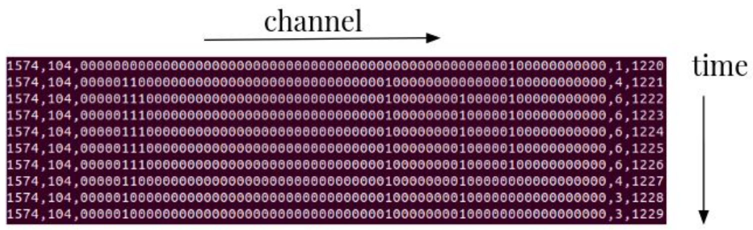
UMD signal characterization and Monitoring



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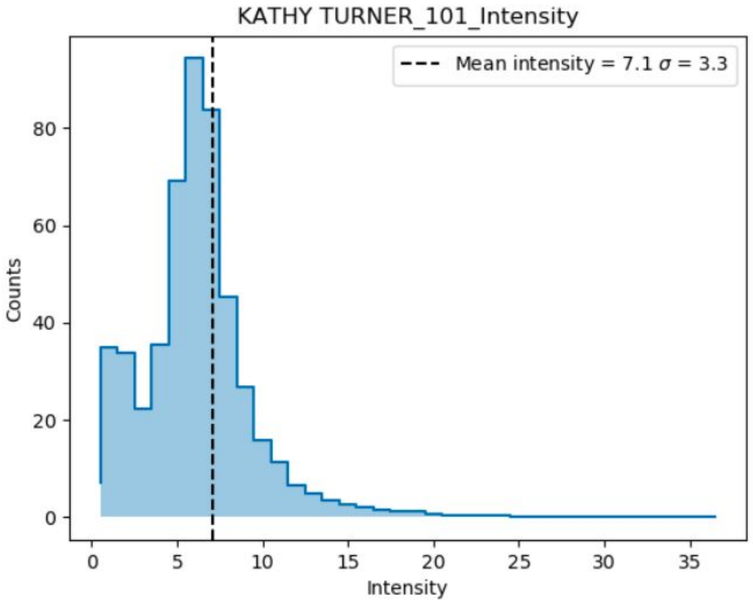
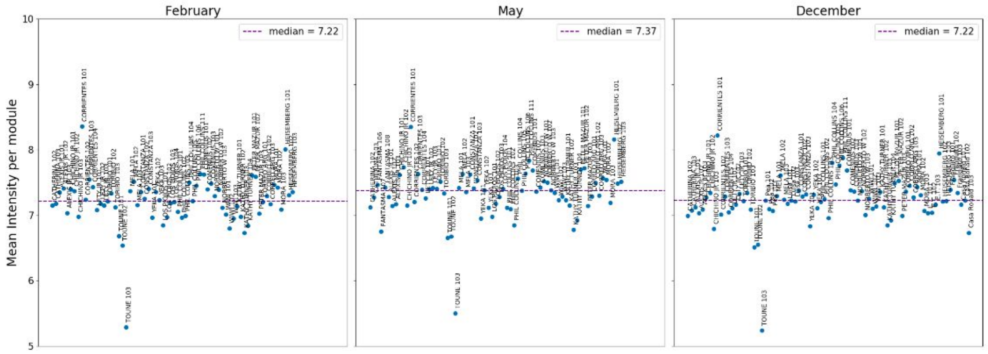




Intensity

GAP2022_043

Stopping Power

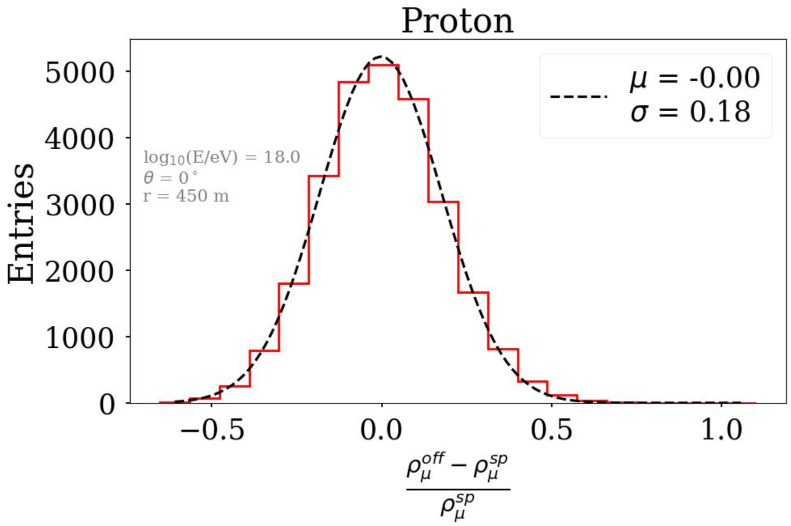
Energy losses of charged particles in a medium described by the Bethe-Block equation

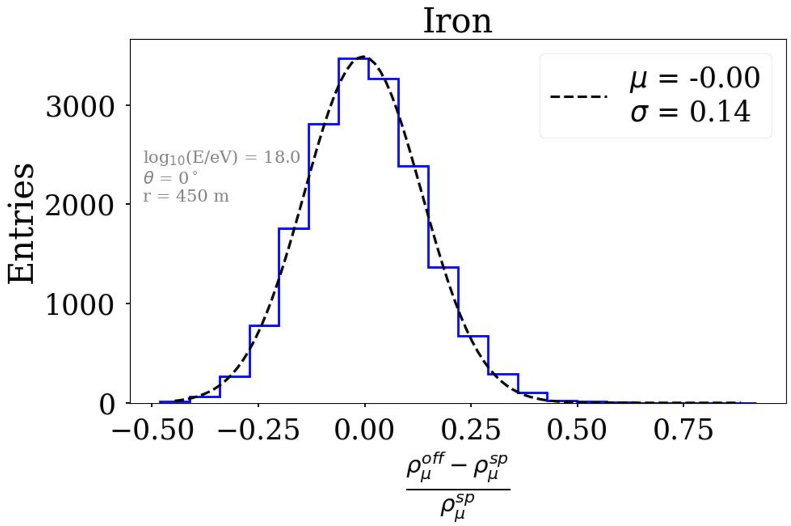
```
Index =  245:  silicon dioxide (fused quartz) (SiO\sub{2})
     Absorber with <Z/A> =  0.49930, density = 2.200 (revised)
Sternheimer coef:  a     k=m_s   x_0    x_1    I[eV]   Cbar  delta0
                0.0841  3.5064  0.1500  3.0140  139.2  4.0560 0.00
(Restricted energy loss for Tcut = 0.05 MeV
Table written with (1X, 1P9E10.3,0PF8.4,f8.5,1pE10.3)          post-Born included in pair prod
*** Results below 10 MeV are not dependable ***
```

T	p	Ionization	brems	pair	photonuc	Radloss	dE/dx	CSDA Range	delta	beta	dE/dx_R
[MeV]	[MeV/c]	--------------------	[MeV cm^2/g]	--------------------				[g/cm^2]			[MeV cm^2/g]
1.000E+00	1.457E+01	2.660E+00	0.000E+00	0.000E+00	4.793E-05	4.793E-05	5.321E+00	2.327E-03	0.0000	0.13661	4.038E+01
1.200E+00	1.597E+01	3.498E+01	0.000E+00	0.000E+00	4.802E-05	4.802E-05	3.498E+01	7.665E-03	0.0000	0.14944	3.498E+01
1.400E+00	1.726E+01	3.096E+01	0.000E+00	0.000E+00	4.811E-05	4.811E-05	3.096E+01	1.376E-02	0.0000	0.16119	3.096E+01
1.700E+00	1.903E+01	2.653E+01	0.000E+00	0.000E+00	4.824E-05	4.824E-05	2.653E+01	2.426E-02	0.0000	0.17725	2.653E+01
2.000E+00	2.066E+01	2.331E+01	0.000E+00	0.000E+00	4.838E-05	4.838E-05	2.331E+01	3.635E-02	0.0000	0.19186	2.331E+01
2.500E+00	2.312E+01	1.950E+01	0.000E+00	0.000E+00	4.860E-05	4.860E-05	1.950E+01	5.991E-02	0.0000	0.21376	1.950E+01
3.000E+00	2.536E+01	1.686E+01	0.000E+00	0.000E+00	4.883E-05	4.883E-05	1.686E+01	8.758E-02	0.0000	0.23336	1.665E+01
3.500E+00	2.742E+01	1.491E+01	0.000E+00	0.000E+00	4.905E-05	4.905E-05	1.491E+01	1.192E-01	0.0000	0.25120	1.455E+01
4.000E+00	2.935E+01	1.341E+01	0.000E+00	0.000E+00	4.928E-05	4.928E-05	1.341E+01	1.546E-01	0.0000	0.26763	1.296E+01

https://pdg.lbl.gov/2019/AtomicNuclearProperties/

Bias





- Bias is 0 and mass independent

GAP note in progress

Summary

- The estimation of S_μ shows limitations regarding bias and resolution -> a calibration with the UMD is needed
- A first calibration with data was performed: The slope obtained with data is higher than in p and CNO simulations
- Good-performance observables monitored in UMD shifts
- No bias between Offline and Stopping Power

Outlook

- Improve statistics: reconstruct more events
- Convert muons from underground to on-ground
- Study uncertainties and quality cuts of the method
- Include Auger-Mix simulations for comparison

Composition of the soil in the UMD site

“The total of the components analyzed represents ~ 99.8% of the total weight of the samples, and these three elements ~ 81.4%, with the following averages: (64.4 ± 1.6)% for SiO_2, (12.1 ± 0.8)% for Al_2O_3 and (4.9 ± 0.8)% for CaO.”

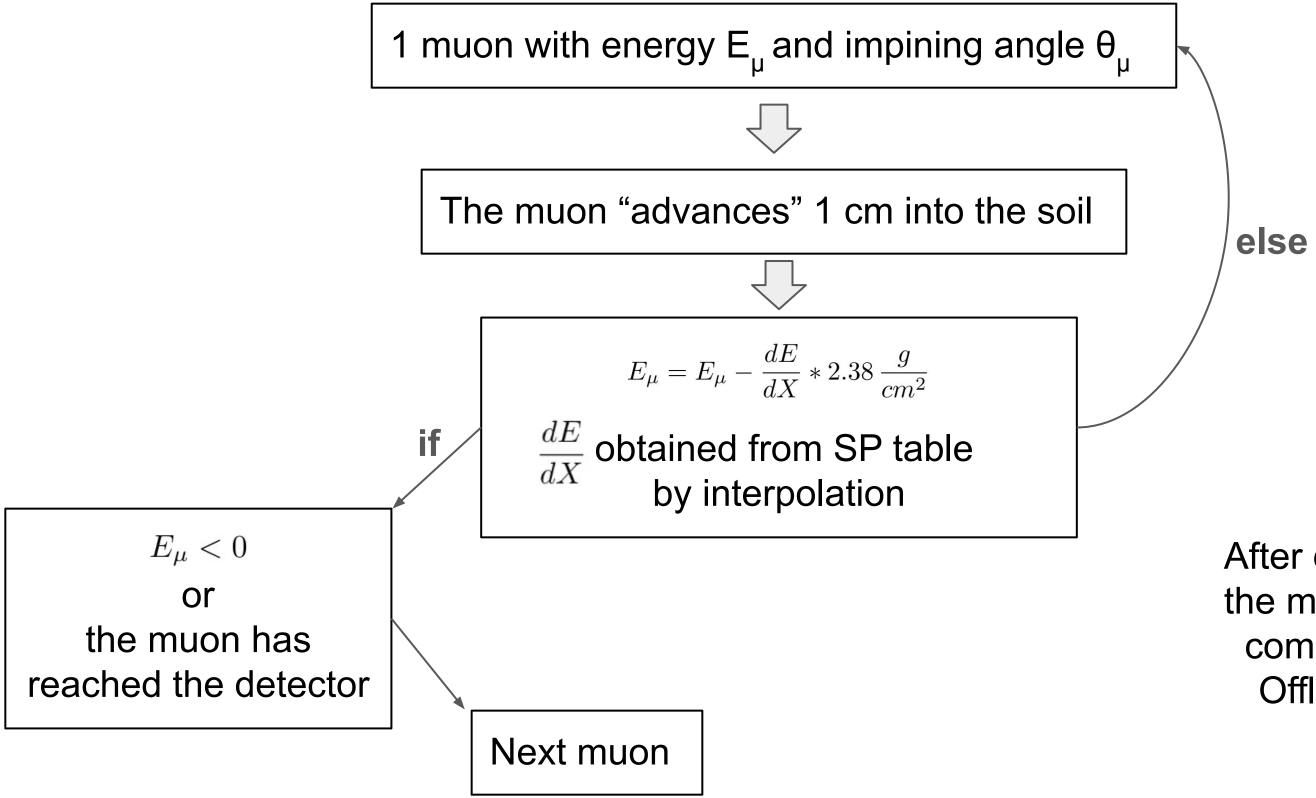
ρ = 2.38 g/cm^3 (soil mean density)

Compuesto [g/100 g]	SiO_2	Al_2O_3	CaO
Tierra del Fuego - 1,0 m	64,51	11,48	5,60
Tierra del Fuego - 2,0 m	66,90	12,64	3,71
Tierra del Fuego - 3,0 m	65,64	12,25	4,50
Lety - 1,0 m	61,80	12,71	5,00
Lety - 2,0 m	63,13	10,78	5,92
Lety - 3,0 m	64,27	12,50	4,75

B. Wundheiler, Doctoral Thesis, 2013

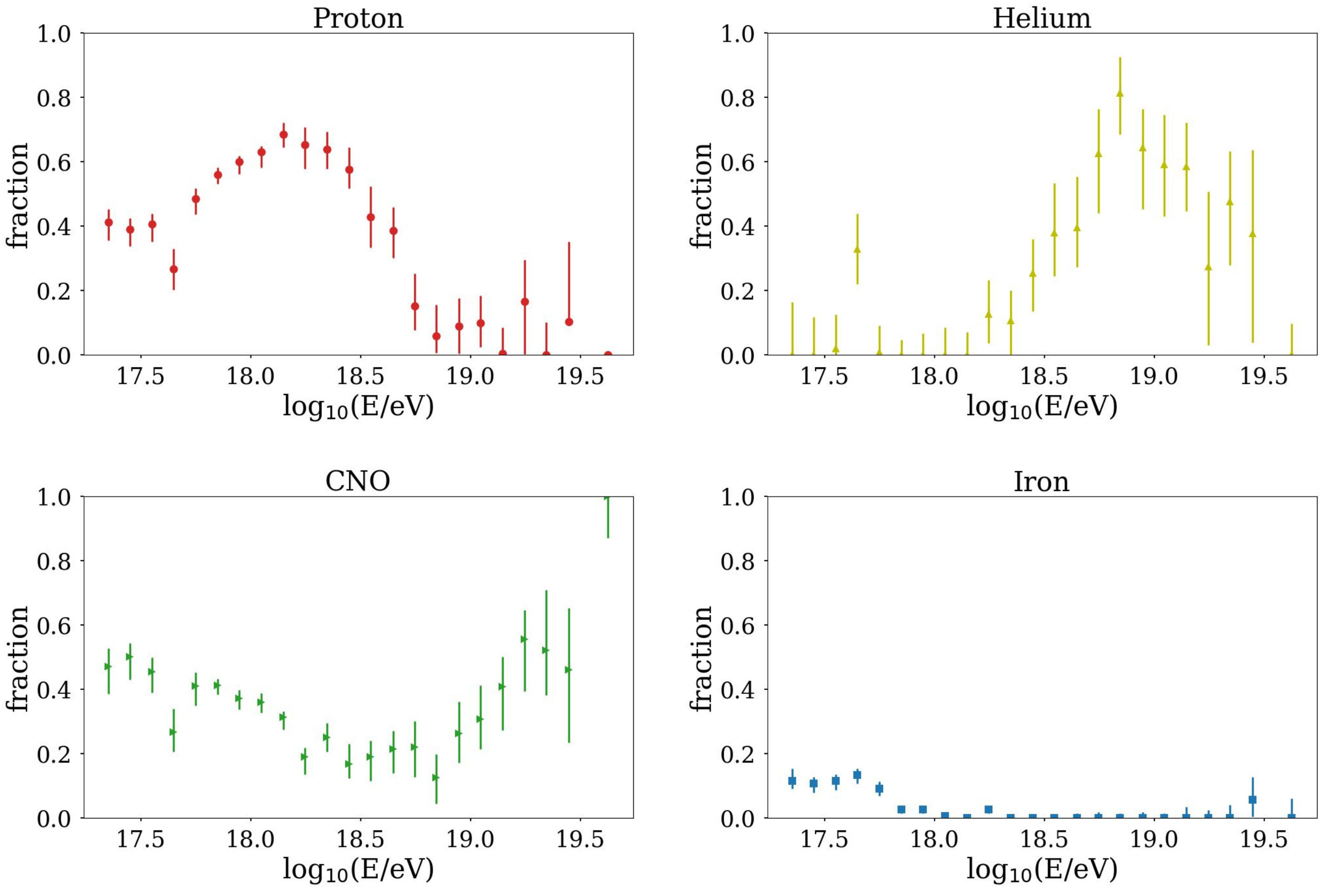
Flux diagram

- From the Corsika shower make a list of all muons arriving inside a surface ring in the shower plane around 450 m.



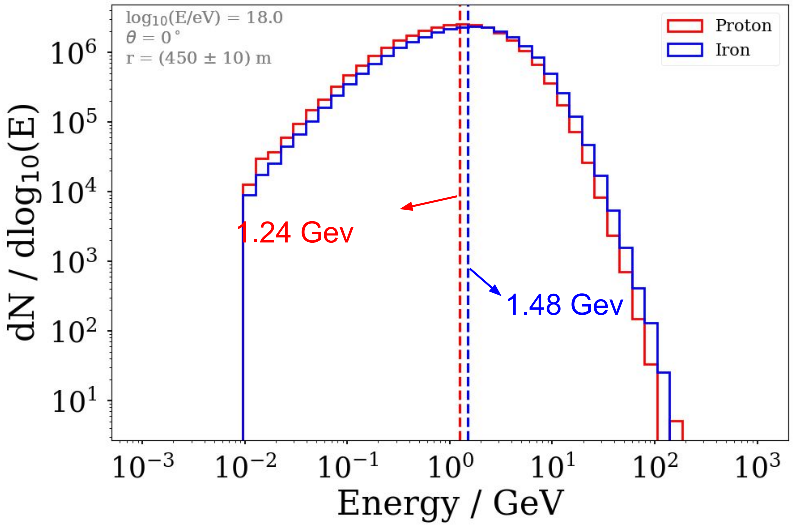
After doing this with all the muons in the list, a comparison with the Offline simulations is done

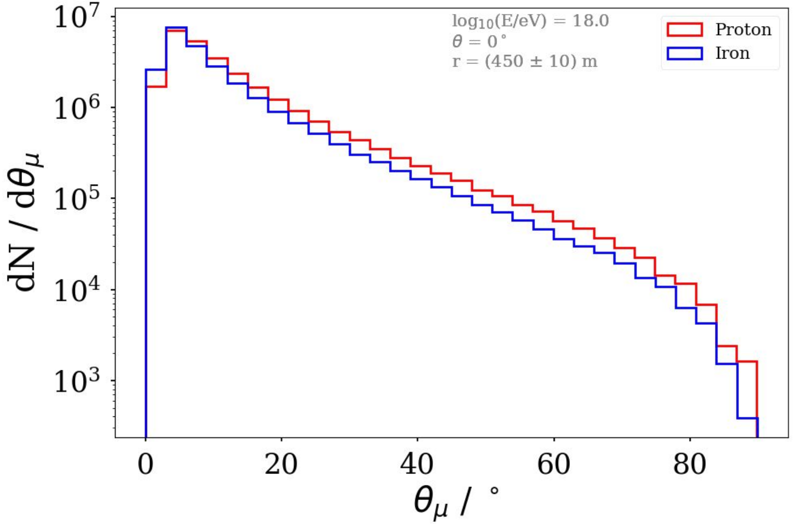
Auger-Composition ICRC2017



- proton and CNO with higher fractions at the infill energy range

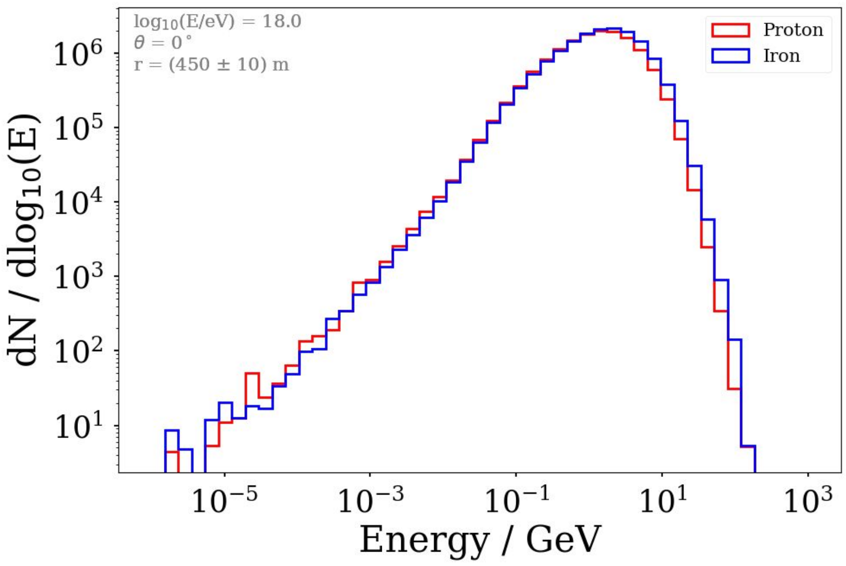
Energy and zenith distributions on ground

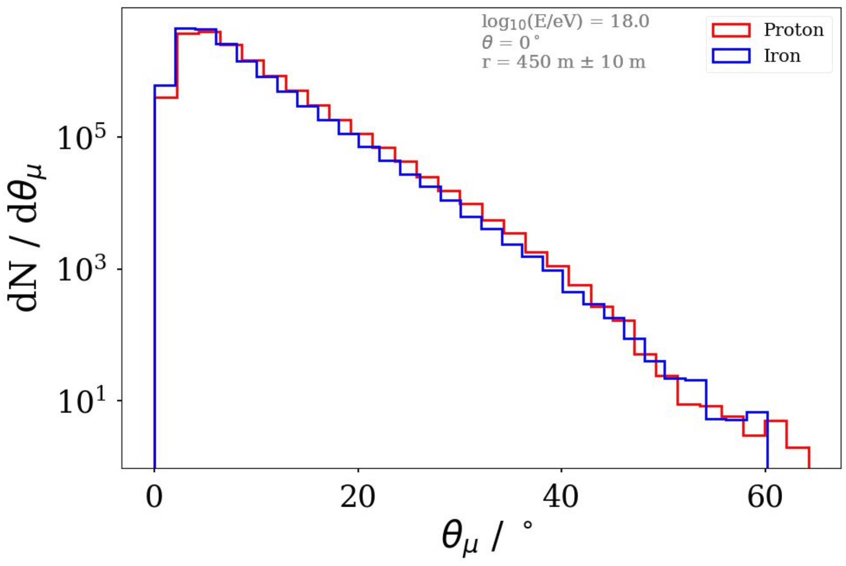




- The median energy is ~6% higher for Fe muons than p
- In the zenith distribution can be seen that muons from Fe have slightly less deflection than the ones from p

Distributions underground



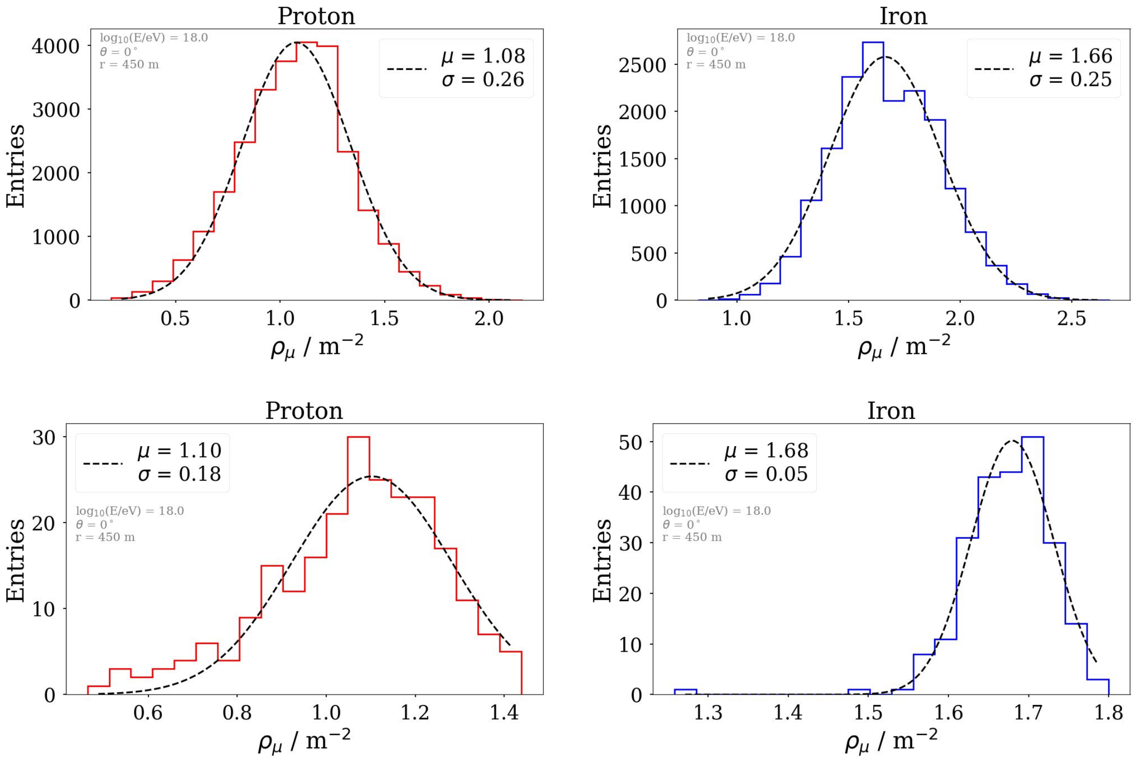


- The energy spectrum is extended to lower energies due to energy loss of muons in the soil
- It can be observed that muons that reach the depth of the UMD have more vertical zenith angles since they’re track into the soil is shorter

Comparing Offline with Stopping Power (underground)

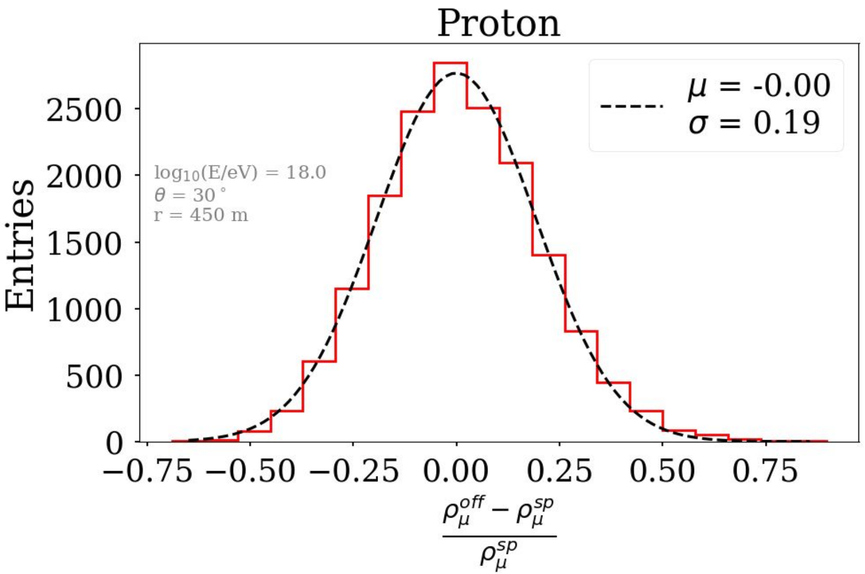
Offline

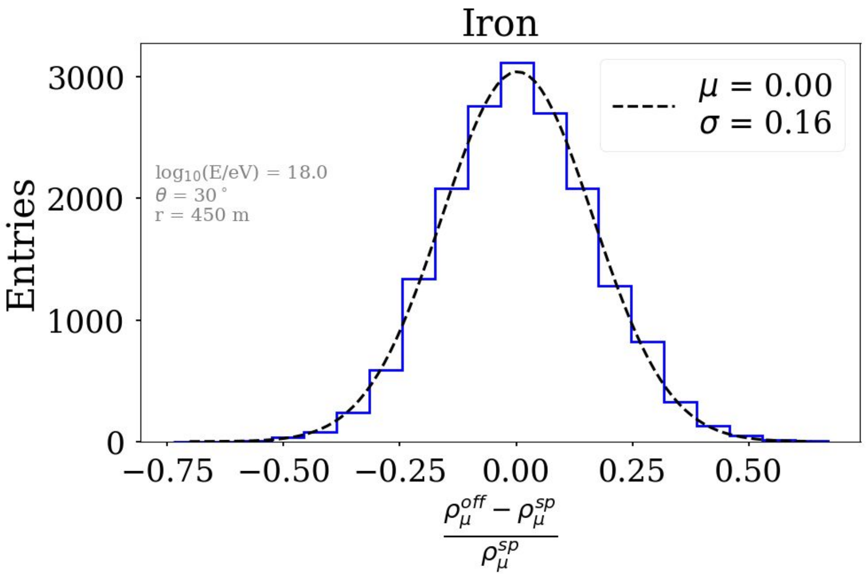
Stopping Power



- A difference of ~2% can be observed between injected density in the UMD and the one from Stopping Power

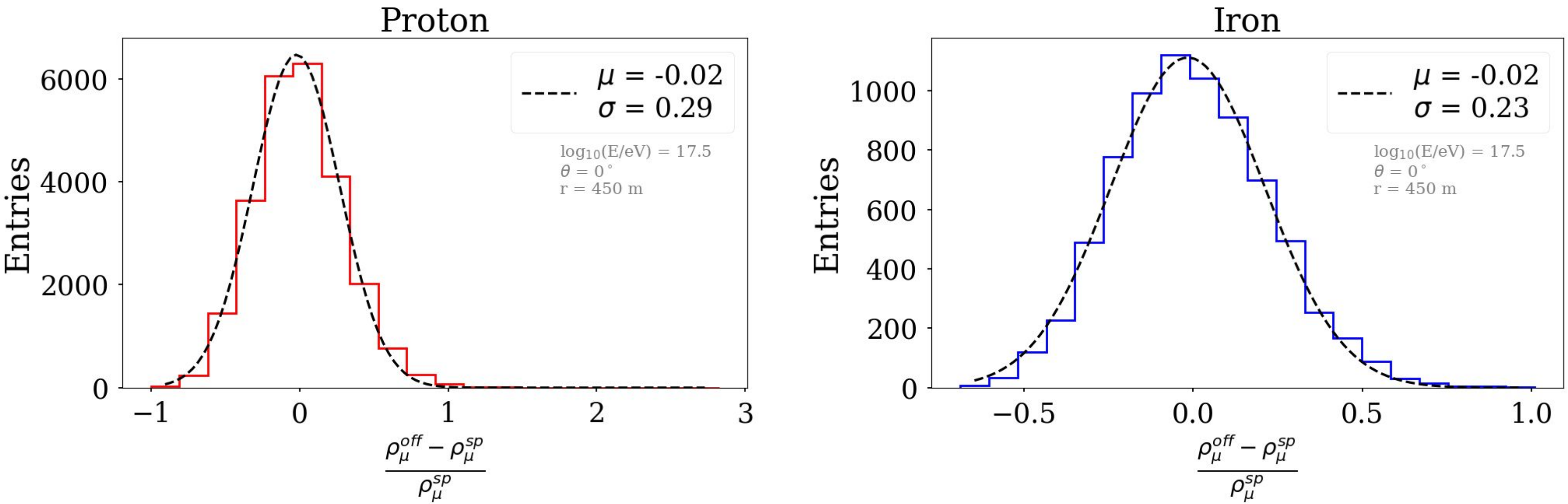
Bias at 30°





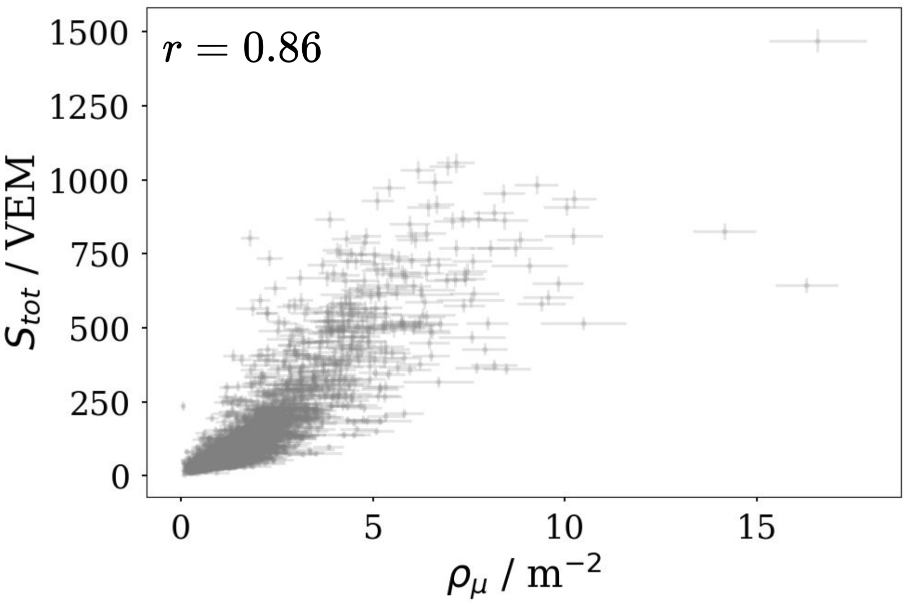
- Bias is 0 and mass independent

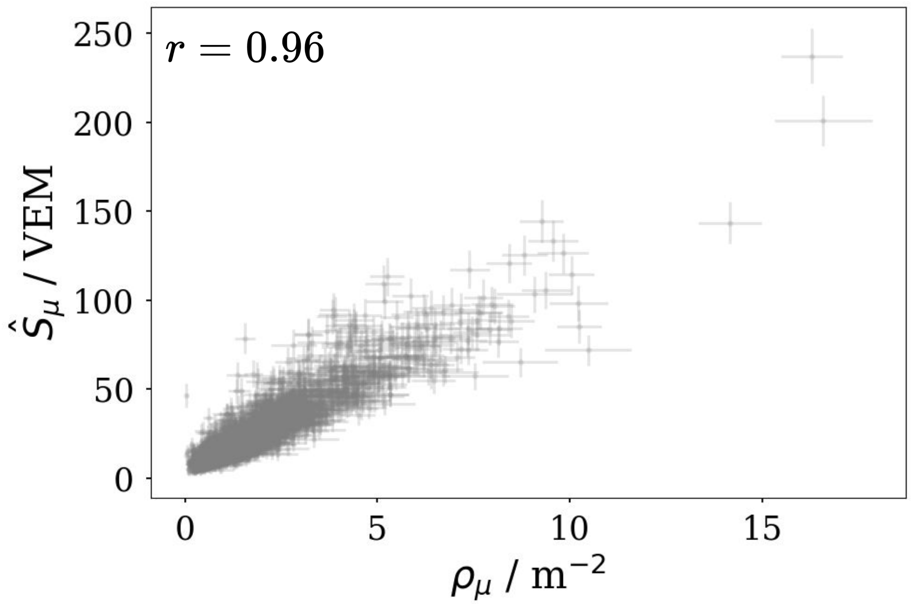
Bias at lower energies



- Bias is 0 and mass independent

Why estimating S_μ?





- Correlation with the estimated S_μ is an 10 % better