Seasonal Variation of Muon Flux in Daya Bay Using the Full Data Set

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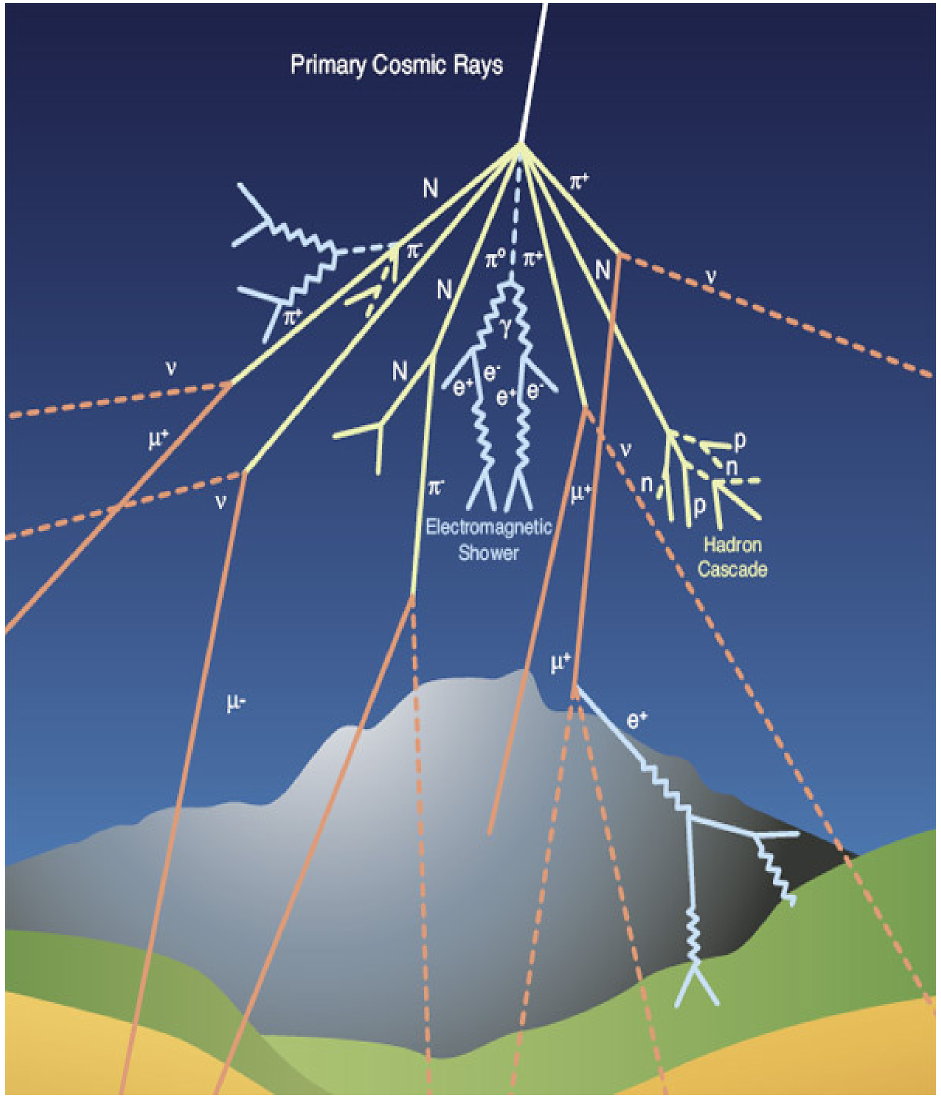
on Behalf of the Daya Bay Collaboration

Introduction



Cosmic Ray Shower Illustration

- Primary cosmic rays interact with atmospheric molecules, initiating hadronic cascades in which mesons are produced.
- These mesons either undergo further interactions or decay into high-energy muons capable of penetrating rock and reaching deep underground detectors.
- An increase in temperature reduces atmospheric density, enhancing the likelihood of meson decays into muons.
- The positive correlation between atmospheric temperature and the intensity of muons reaching the underground detector is[Astroparticle Physics 33 (2010) 140–145]:

$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

- Correlation coefficient α is expected to be dependent on overburden.

Daya Bay Reactor Neutrino Experiment

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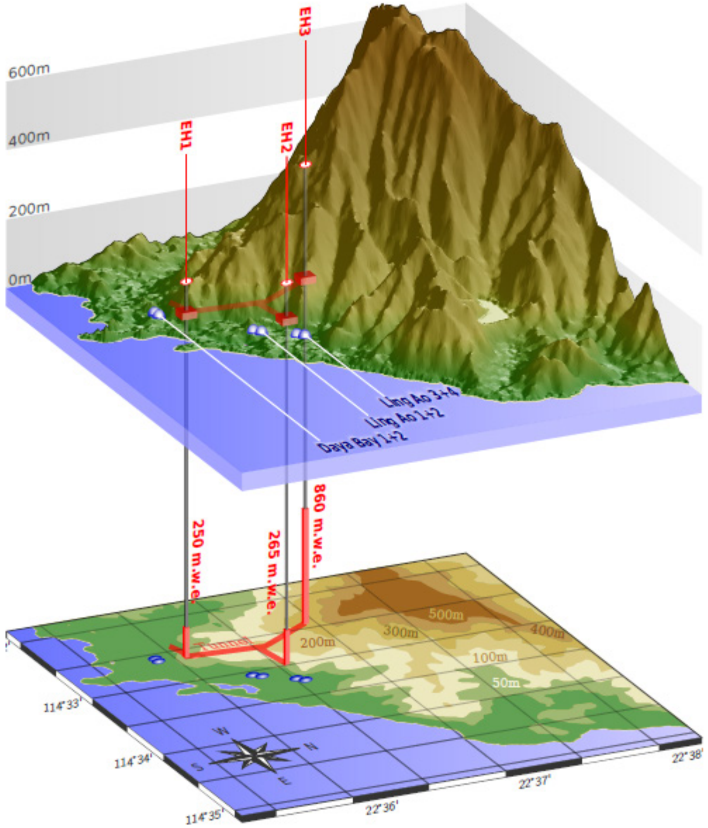

	Overburden		Muon flux
Hall	m	m.w.e.	Hz/m^2
EH1	93	250	1.27
EH2	100	265	0.95
EH3	324	860	0.056

- Daya Bay Experiment features eight identical antineutrino detectors in three underground experimental halls at different depths.
- It provides an ideal setup to study coefficient α using identical detectors at different overburdens.

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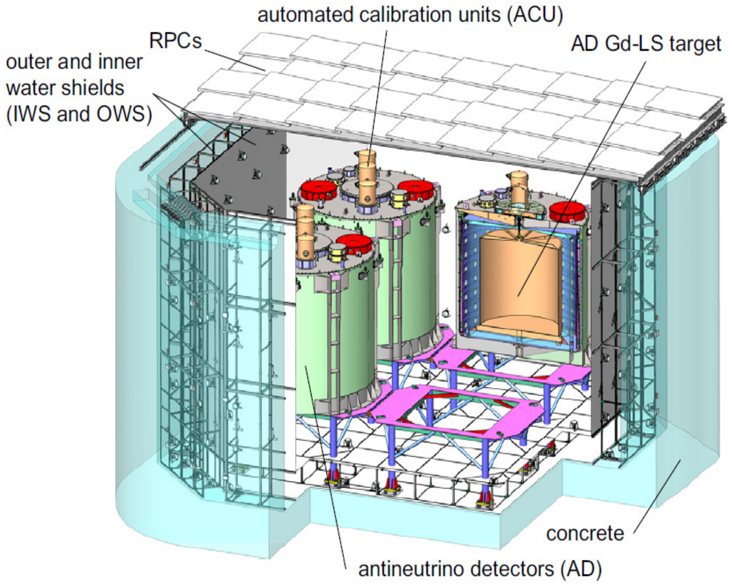
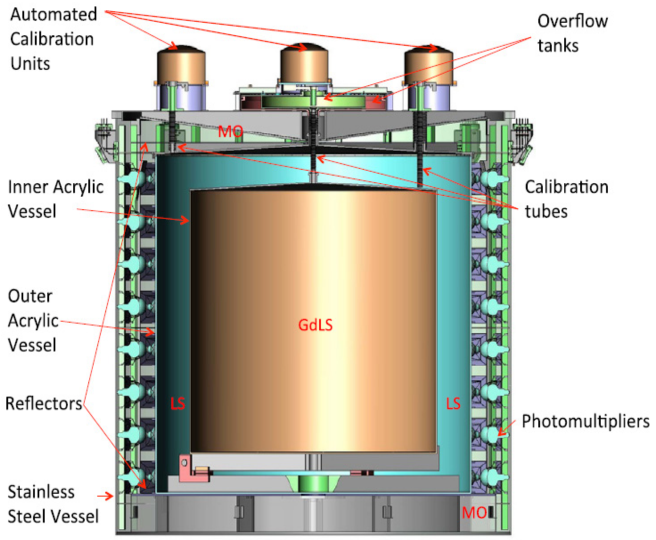
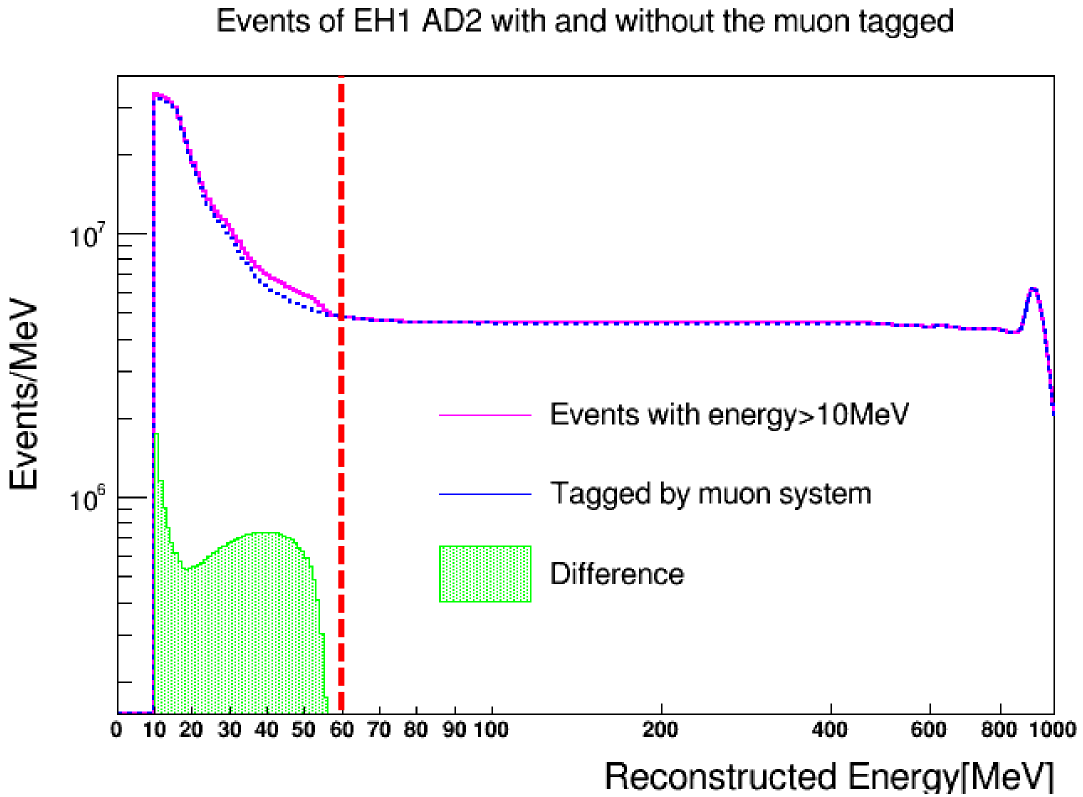
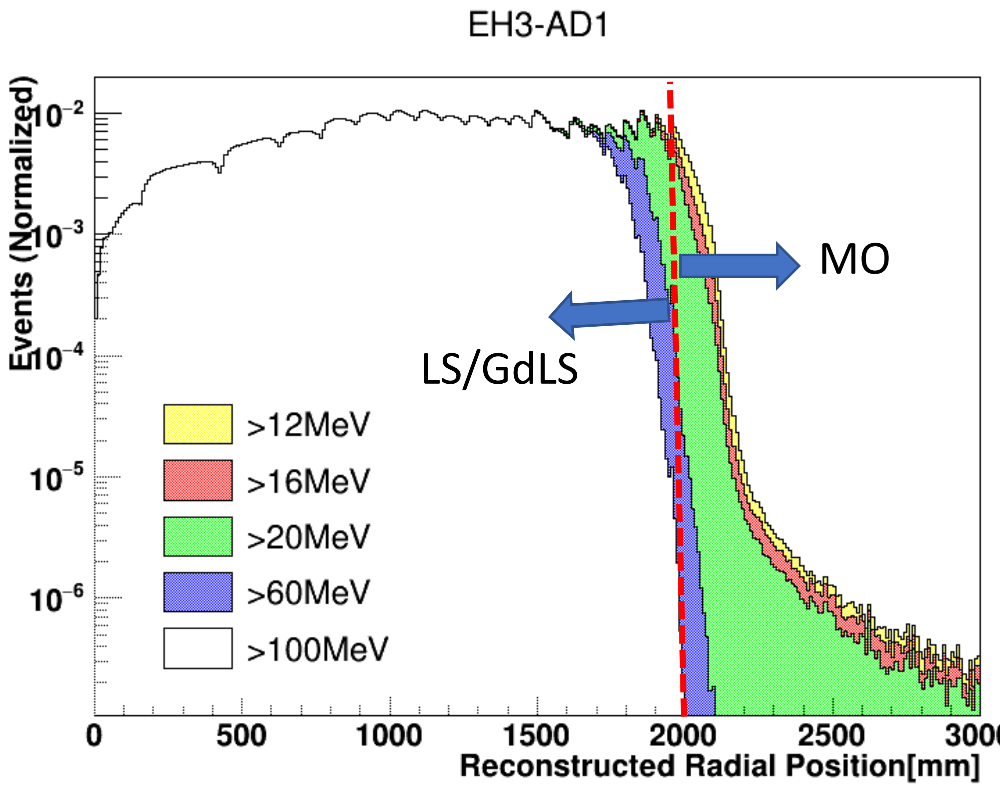




Muon Selection

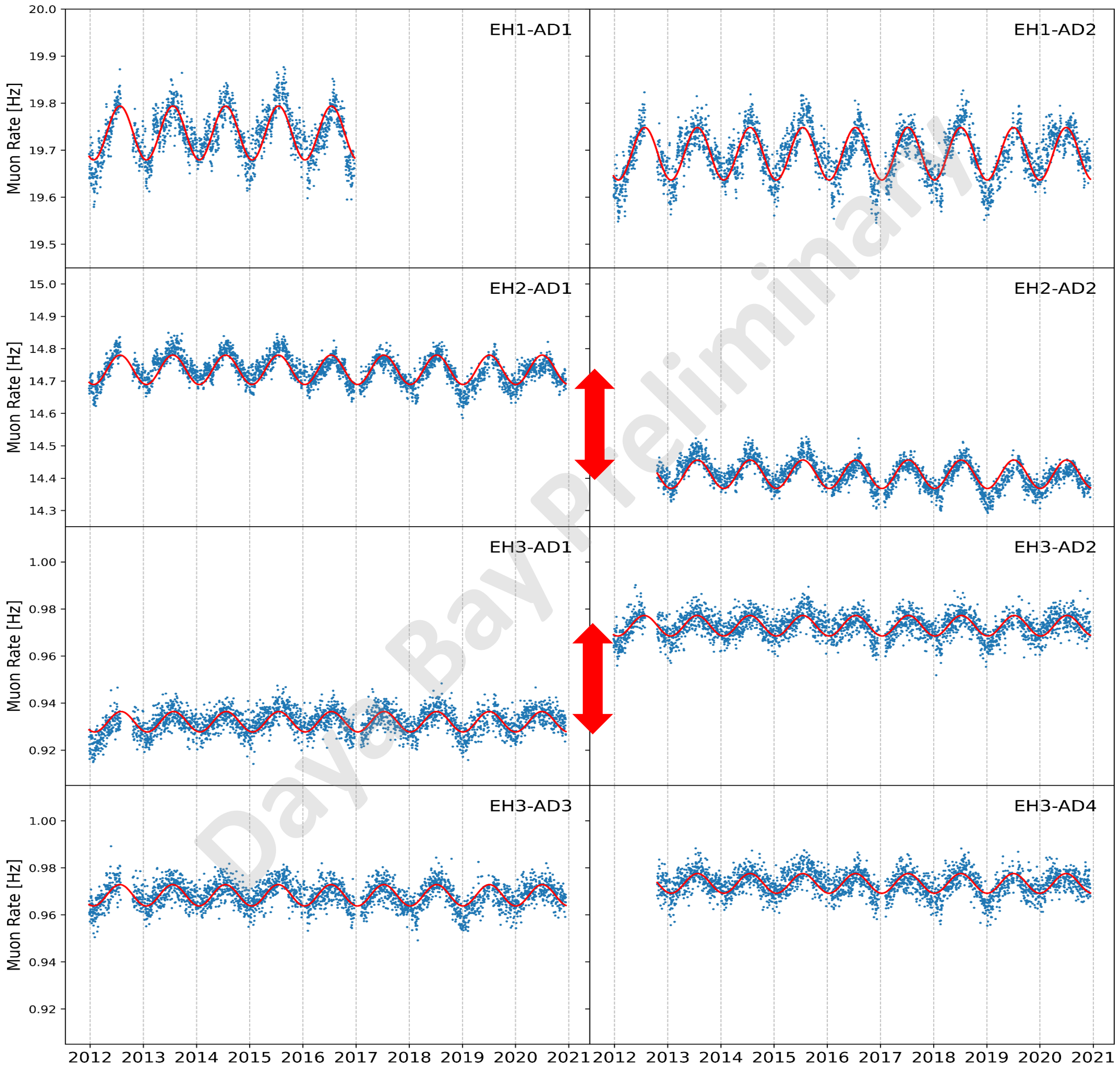
- Muon candidates are defined as events with greater than 60 MeV energy deposition in ADs (antineutrino detectors).
- Events with energies greater than 10 MeV have Michael electron mixed in, and 60 MeV cut can remove them.
- Raising the energy cut of EH3-AD1 to 100 MeV due to the leak of liquid scintillator in summer 2012.





Muon Rate History

- Over nine years of operation, the Daya Bay Reactor Neutrino Experiment has accumulated muon data spanning 3,158 days.
- Muon rates in all ADs exhibit seasonal variations over time.
  - Red sinusoidal fits are performed for comparison purpose only.
- Minor variations in muon rates between the two ADs in EH2 are attributed to the structural profile of the mountain above the hall.
- Compared to the other ADs in EH3, the relatively lower average muon rate in EH3-AD1 is a result of its higher energy threshold requirement of 100 MeV, as opposed to the 60 MeV threshold for the other ADs.



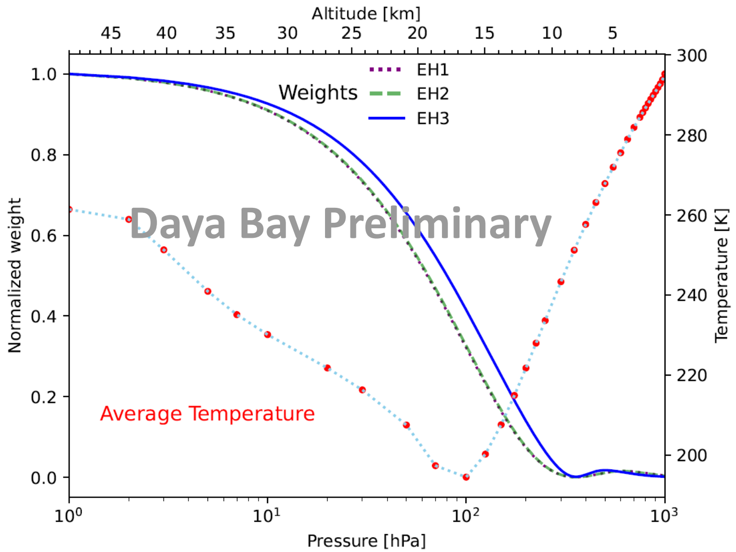
Effective Temperature

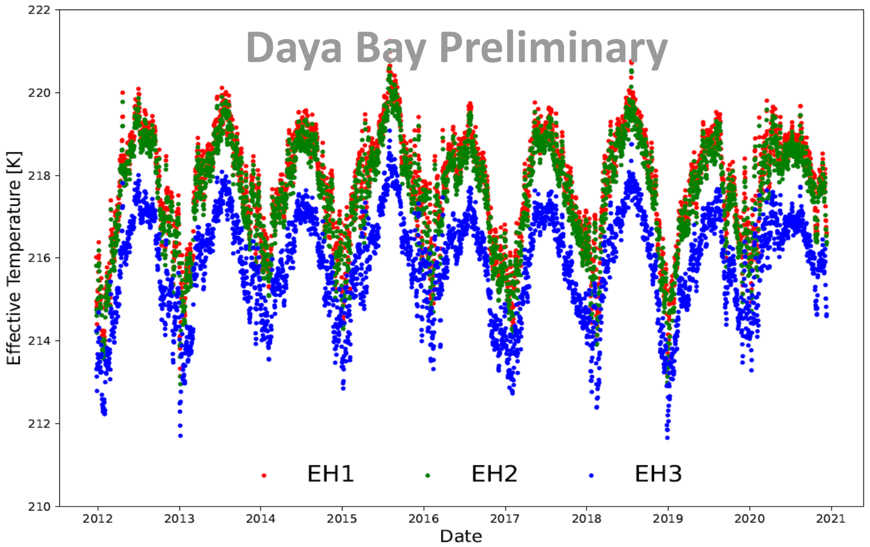
- Atmosphere is treated as an isothermal body with an effective temperature to account for different muon creation heights.
- Effective temperature is computed as a weighted average of temperature T at atmospheric depth X [Astroparticle Physics 33 (2010) 140–145]

$$T_{eff} = \frac{\int_0^\infty dX\, T(X) W(X)}{\int_0^\infty dX\, W(X)} \approx \frac{\sum_i \Delta X_i T(X_i) W(X_i)}{\sum_i \Delta X_i W(X_i)}$$

the weight calculation is in the backup

- The atmospheric temperature data was obtained from ERA5 database provided by ECMWF.
  - Hourly temperature measurements at 37 pressure levels above DayaBay.
  - A cubic spline and interpolated data to accurately determine T_{eff}.

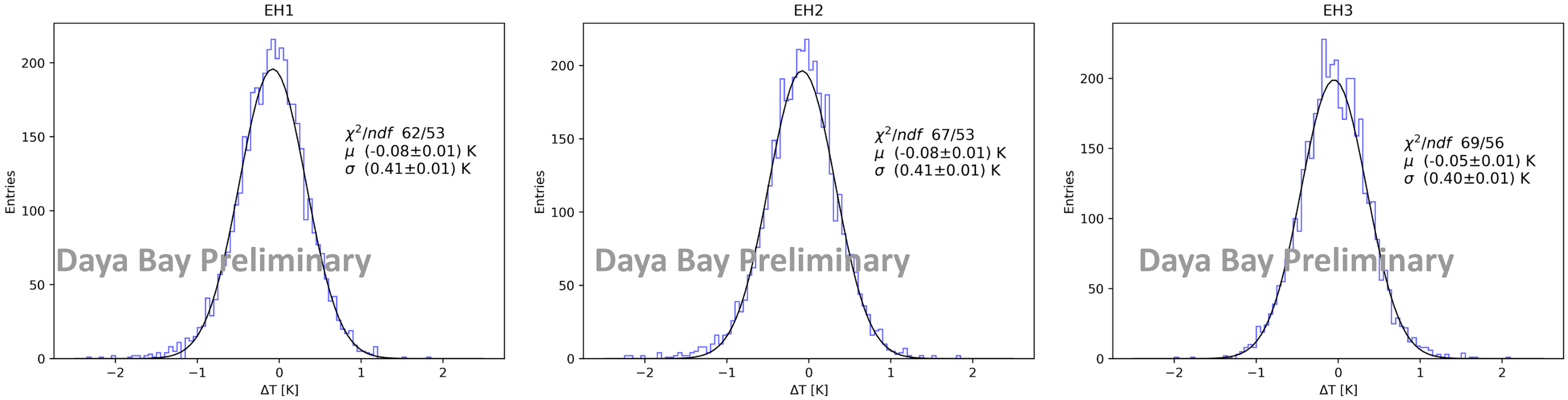




Uncertainty of the Effective Temperature

Two sources: temperature data set uncertainty and weight parameters uncertainty.

1. Compute the difference in Teff using another temperature dataset: IGRA from US national Climatic Data Center.
   - Spread of the difference considered to be an estimate of the uncertainty.
2. Propagate errors of parameters in the weight by varying their values (bootstrap method) .
   - Repeatedly calculate Teff by sampling parameters from normal distribution (mean value and error are derived from the measurements of each parameter).



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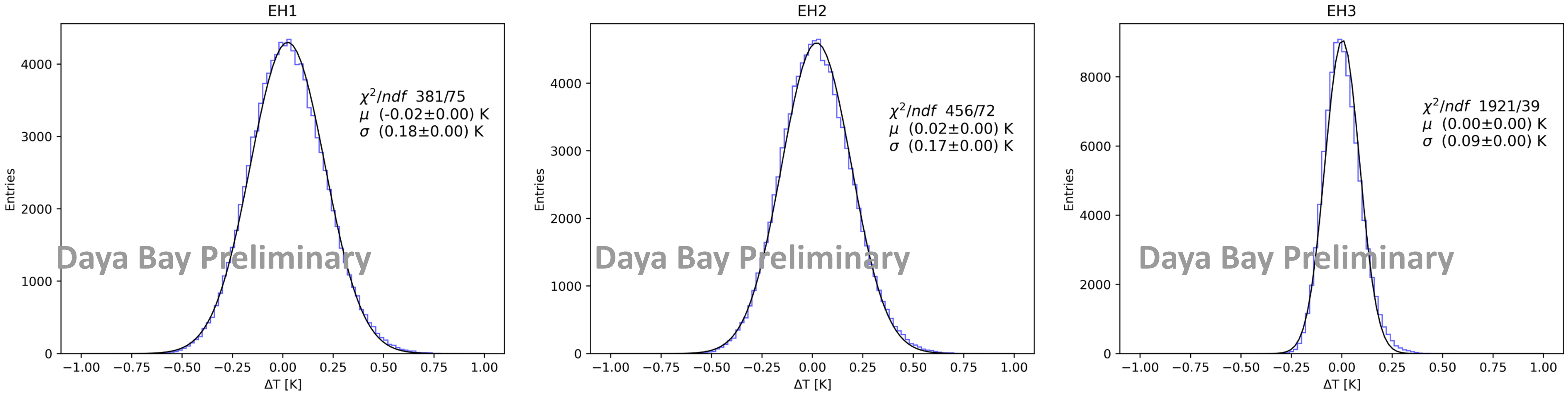
Total uncertainty 0.45 K for EH1, 0.44 K for EH2, and 0.41 K for EH3.



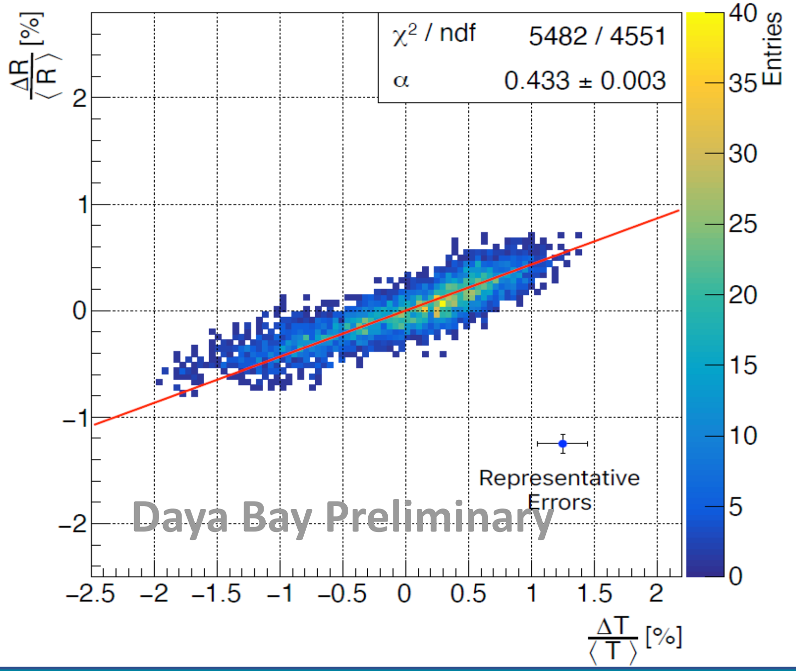
Correlation Coefficients

- The relative muon rate variation versus the relative effective temperature variation was constructed by combining data from the ADs in the same experimental hall.
- A linear regression accounting for errors on both axes is performed to each scatter plot.

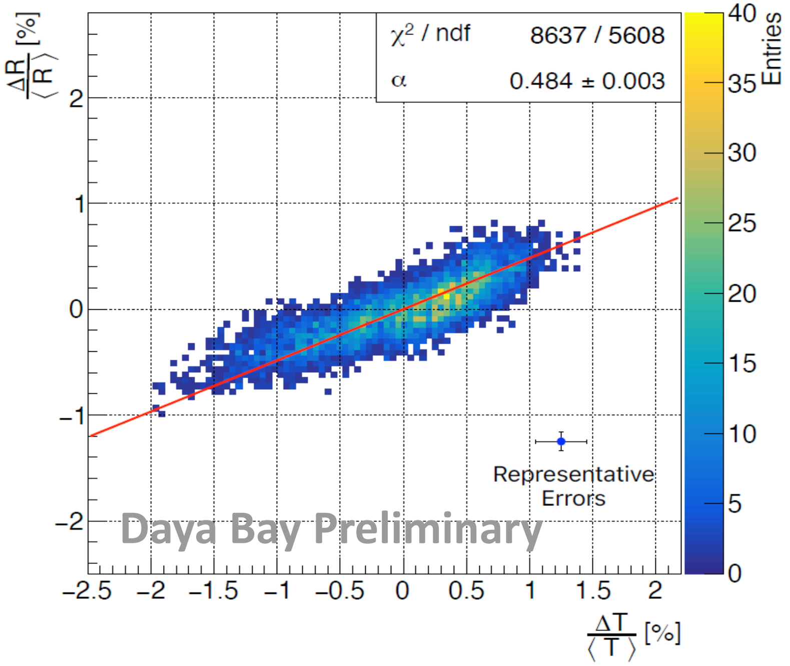
Chi-square definition:

$$\chi^2 = \sum_i \frac{[y_i - \alpha \cdot x_i)]^2}{e_y^2 + \alpha^2 \cdot e_x^2}$$

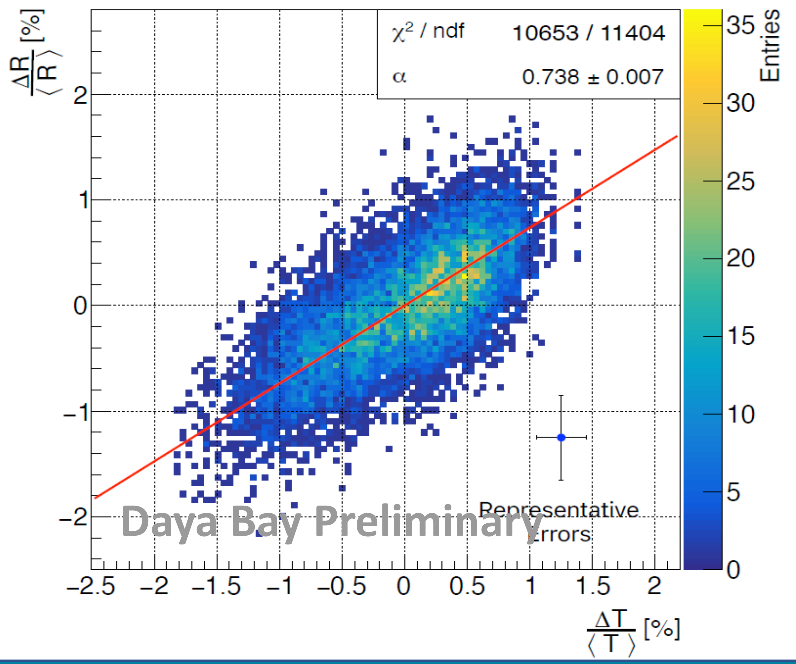
EH1



EH2

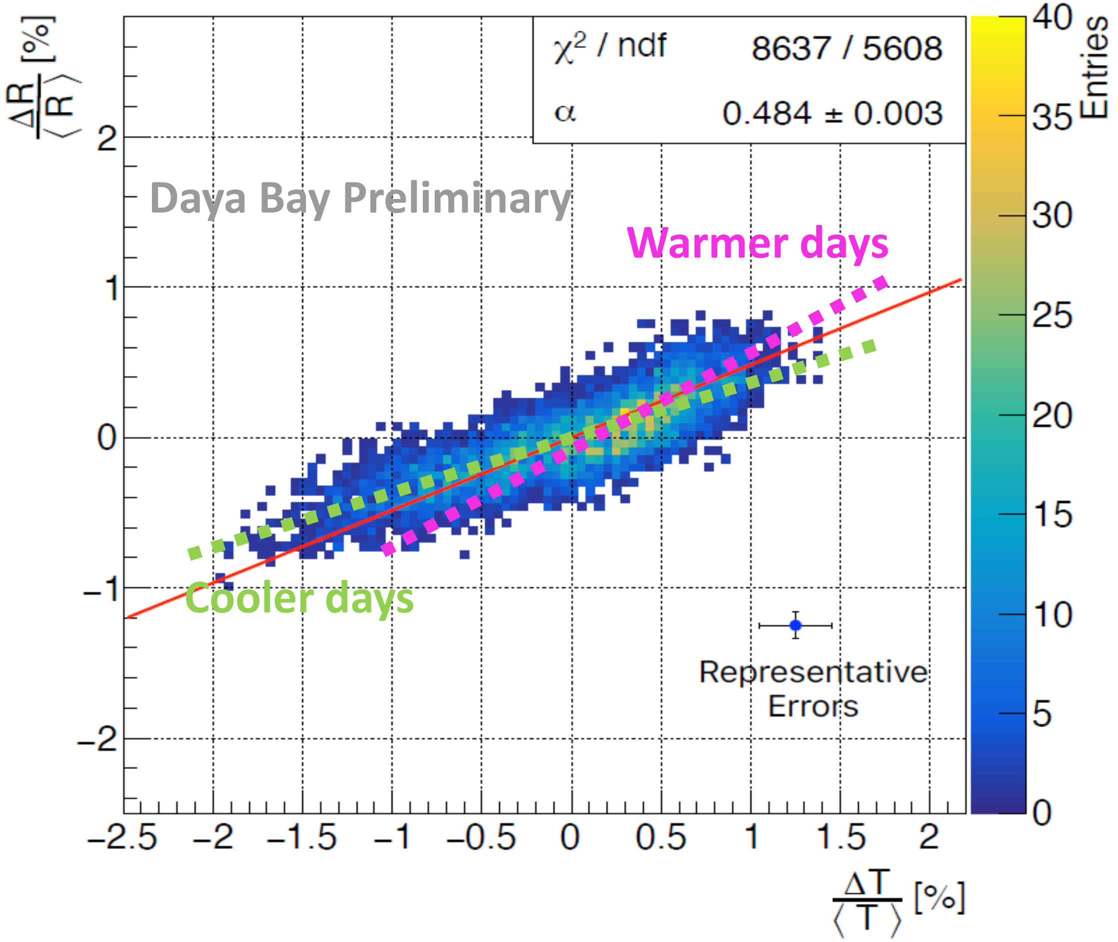


EH3



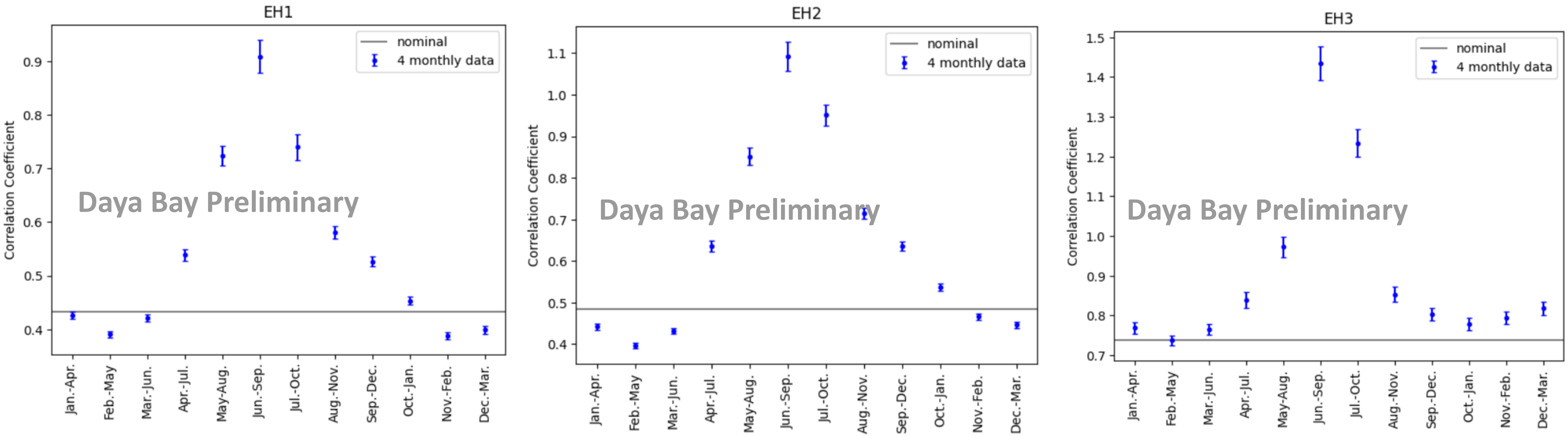
Difference between Warmer and Cooler days

- We have observed a slight deviation from the expected linear relationship.
- The correlation coefficient of warmer days(May-Oct.) is greater than that of cooler days(Nov.-Apr.).
- Dashed lines are included to guide the eye and facilitate comparison.
- Further investigation is being performed:
  - Preliminary simulations using CORSIKA exhibit a similar phenomenon.



Dependence on the Time of Year

- The correlation coefficient of the four-month sliding window was calculated.
- The strength of the correlation varies across different four-month sliding windows.
  - Each 4-month sliding window is characterized by a unique average temperature.



Summary

- A study on seasonal variations in muon rates was conducted using the full dataset from the Daya Bay experiment.
- The high-statistics data reveals deviations from an ideal linear relationship between temperature and muon rate:
  - Alpha dependence on different subset of data of different time of year.
- Further study is underway.
- Stay tuned!

Thank You for Your Attention

Backup

Backup: Seasonal Variation of Muon Flux in DayaBay

- Correlation coefficients were extracted with 707 Days (2011.12-2013.11)
- This work :
  - Dataset: 3,158 Days (2011.12- 2020.12)
  - Muon Selection Updates
  - Improved calculation of effective tempreture
  - Minimun DAQ time 6 hours
  - Temperature Database changed from ERA-Interim to ERA5

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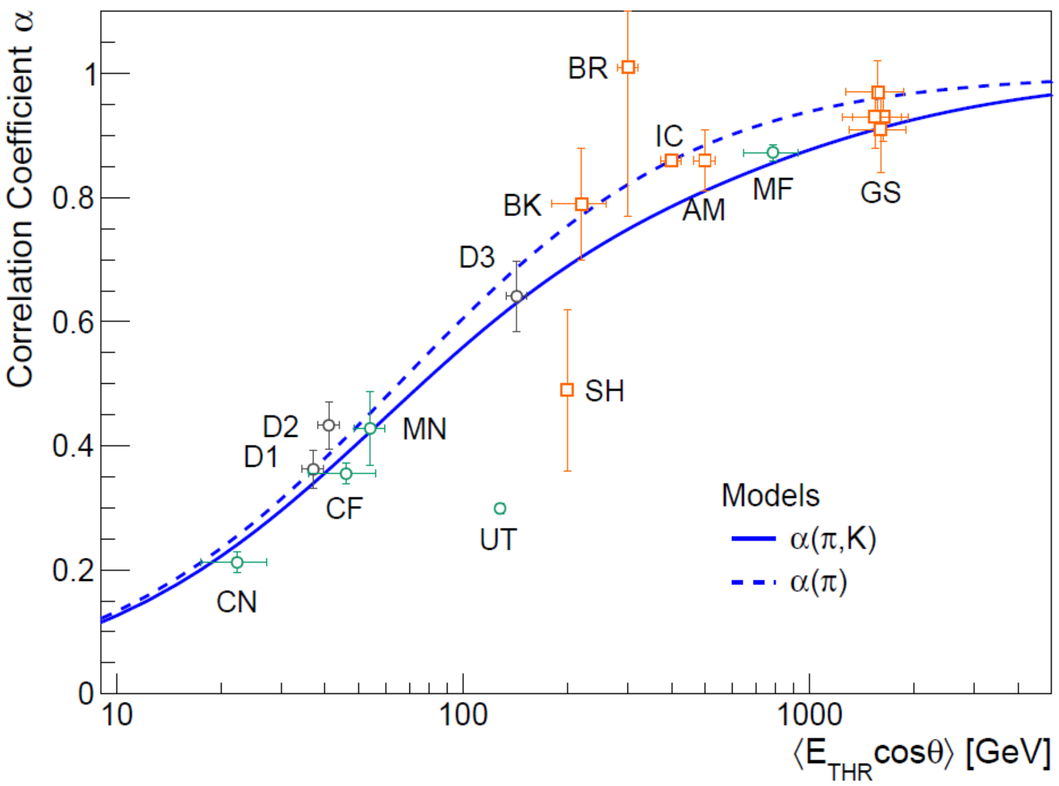

Backup: Effective Temperature Weight

- Effective temperature is computed as a weighted average of temperature T at atmospheric depth X, where the weight is

$$W^{\pi(K)} \simeq \frac{\left(1-\frac{X}{\lambda_{\pi(K)}}\right)^2 e^{-\frac{X}{\Lambda_{\pi(K)}}} A_{\pi(K)}}{\gamma+(\gamma+1)B_{\pi(K)}K(X)\left(\frac{\langle E_{\rm thr}\cos\theta\rangle}{\epsilon_{\pi(K)}}\right)^2},$$

$$K(X) \equiv \frac{X\left(1-\frac{X}{\lambda_{\pi(K)}}\right)^2}{\left(1-e^{-\frac{X}{\lambda_{\pi(K)}}}\right)\lambda_{\pi(K)}},$$

$$\frac{1}{\lambda_{\pi(K)}} = \frac{1}{\Lambda_N} - \frac{1}{\Lambda_{\pi(K)}}.$$

The parameter values used in the weight calculation:

Parameter	Value
A_π	1
A_K	$0.38 \cdot r_{K/\pi}$
$r_{K/\pi}$	0.15 ± 0.06
B_π	1.460 ± 0.007
B_K	1.740 ± 0.028
Λ_N	$120\ \mathrm{g/cm^2}$
Λ_π	$180\ \mathrm{g/cm^2}$
Λ_K	$160\ \mathrm{g/cm^2}$
$\langle \mathrm{E_{thr}}\cos\theta\rangle_{\mathrm{EH1}}$	(37 ± 3) GeV
$\langle \mathrm{E_{thr}}\cos\theta\rangle_{\mathrm{EH2}}$	(41 ± 3) GeV
$\langle \mathrm{E_{thr}}\cos\theta\rangle_{\mathrm{EH3}}$	(143 ± 10) GeV
γ	1.7 ± 0.1
ϵ_π	(114 ± 3) GeV
ϵ_K	(851 ± 14) GeV

Backup: Systematic Uncertainties

Systematic uncertainties affecting the correlation coefficients can be divided into muon-related and time-related

1. Muon-related:
   ① AD-dependent correction of the energy drift (below 1%) over time:
   - We conservatively adjusted the muon selection energy thresholds by $\pm$1%. The maximum deviation of the correlation coefficient from the nominal value as the systematic uncertainty

   ② Tighter energy cut for EH3-AD1:
   - We raise the energy cut from 60 MeV to 100 MeV in the EH1 and EH2 ADs and we look at variation in the α values
2. Time-related:
   ③ Potential bias from uneven data collection across all seasons
   - Quantified by evening DAQ across months

Systematic	Variation Considered	Impact on the Coefficients Scatter Plot Method	Applicability
Energy Drift	1% change in muon energy cut	1%	Applied to all ADs
Energy Cut	100 MeV energy cut for all ADs	3%	Applied only to EH3-AD1
Time Period	Even amount of days per month	5%	Applied to all ADs