

Measurement of the kaon-to-pion ratio for the atmospheric neutrino #217 using the cosmic-ray muon data in Super-Kamiokande

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Determine the atmospheric kaon-to-pion ratio $r_{K/\pi}$ using the cosmic-ray muon and the atmospheric temperature correlation α_T .

1. Introduction

Cosmic-ray muon modulation

- Higher atmospheric temperature \uparrow
- Lower atmospheric density \downarrow
- More meson decays
- More high energy muons
- Higher underground muon rate \uparrow

Expect the positive correlation between muon rate R_μ and atmospheric temperature T variation

$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha_T \frac{\Delta T}{\langle T \rangle}$$

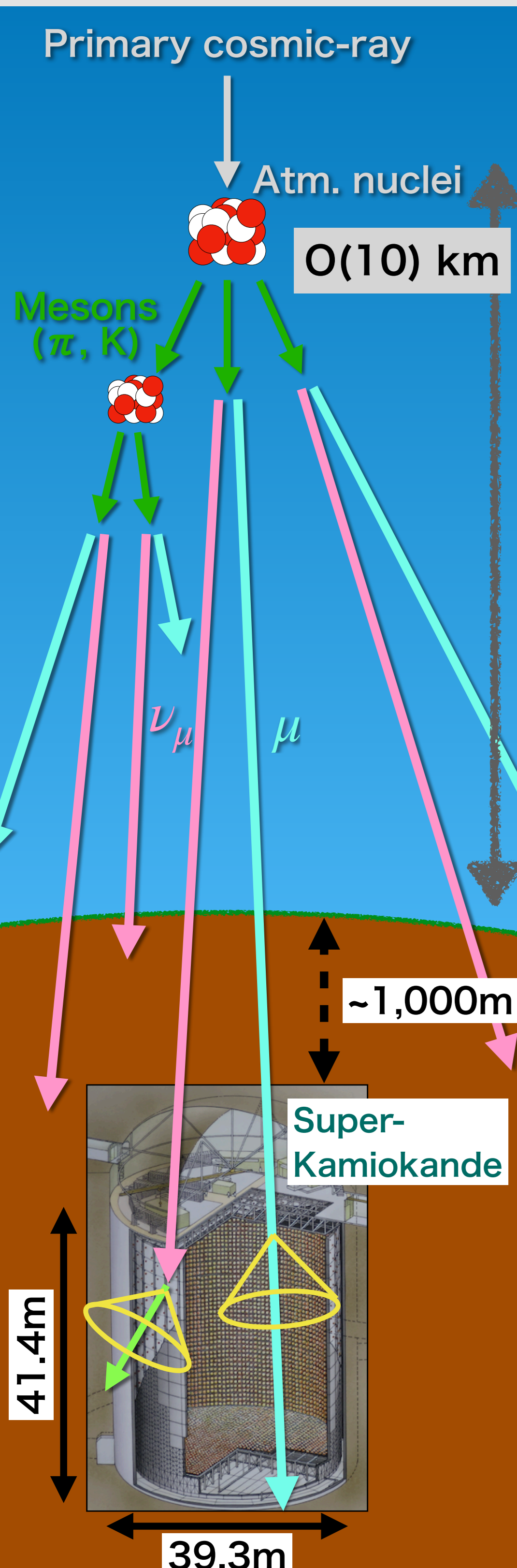
The correlation coefficient α_T [1]

Super-Kamiokande detector [2]

- A water cherenkov detector
- 1,000m underground (2,700 m.w.e, 36.4° N, 137.3° E)
- Detector is separated into ID and OD.
 - OD is used to identify muon event.
- Muon event rate is ~ 2 Hz.
- Muon energy at the surface $> \sim 1$ TeV.

MUBOY (Reconstruction tool) [3]

- Reconstruct Track direction, Entry point, # of track, etc.
- Use T and Q from ID PMT.



The kaon-to-pion production ratio $r_{K/\pi}$

Relative contribution of kaons and pions to the atmospheric muons and neutrinos.

- Kaon contribution increases with muon energy.
- Important parameter for the atmospheric neutrino simulation.
 - The shape of energy spectrum, Flavor ratio
- Pion and Kaons exhibit different sensitivities to the atmospheric temperature variations.
 - Kaon $<$ Pion (due to different mass and critical energy ϵ_π, ϵ_K)

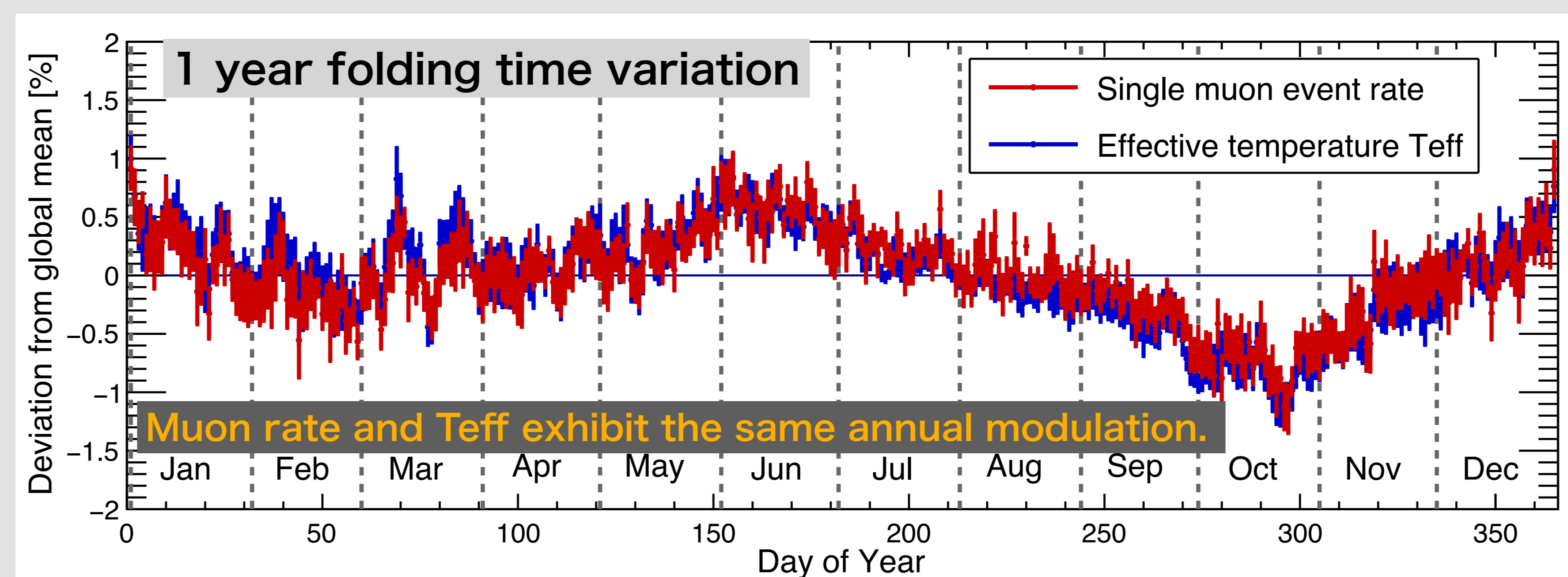
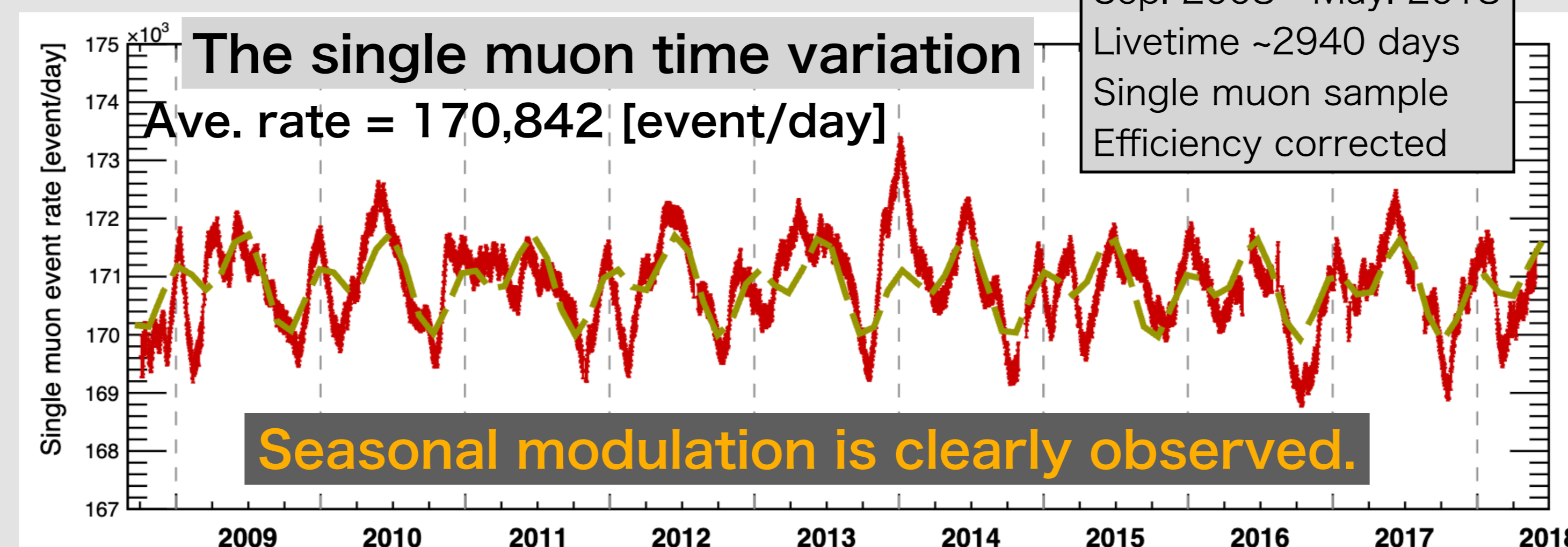
The magnitude of correlation α_T is sensitive to $r_{K/\pi}$.

$r_{K/\pi}$ can be used to constraint of the atmospheric neutrino simulation and new input parameter.

$$r_{K/\pi} = 0 \rightarrow \pi \text{ only}$$

$$r_{K/\pi} = \infty \rightarrow K \text{ only}$$

2. Muon modulation analysis



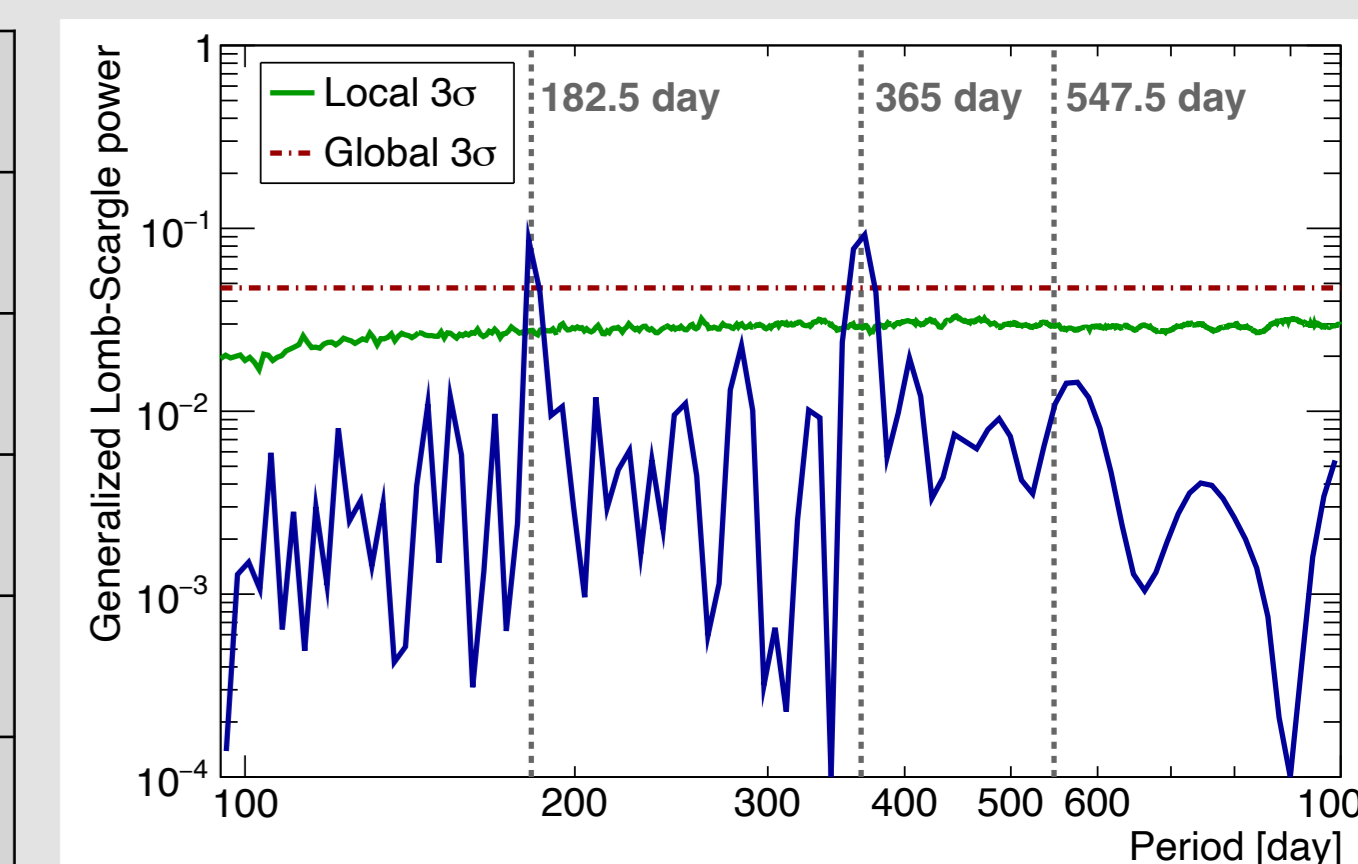
Data-set (10 years)
 Sep. 2008 - May. 2018
 Liveness ~ 2940 days
 Single muon sample
 Efficiency corrected

Sinusoidal fitting results

C	170853 ± 16
A_1	484 ± 22 (0.283 %)
τ_1	132 ± 3 day
A_2	537 ± 22 (0.314 %)
τ_2	2 ± 1 day
χ^2/ndf	$4231 / 3324 = 1.27$

$$F(t) = C + A_1 \cos \frac{2\pi(t - \tau_1)}{365} + A_2 \cos \frac{2\pi(t - \tau_2)}{182.5}$$

Lomb-Scargle analysis [4]

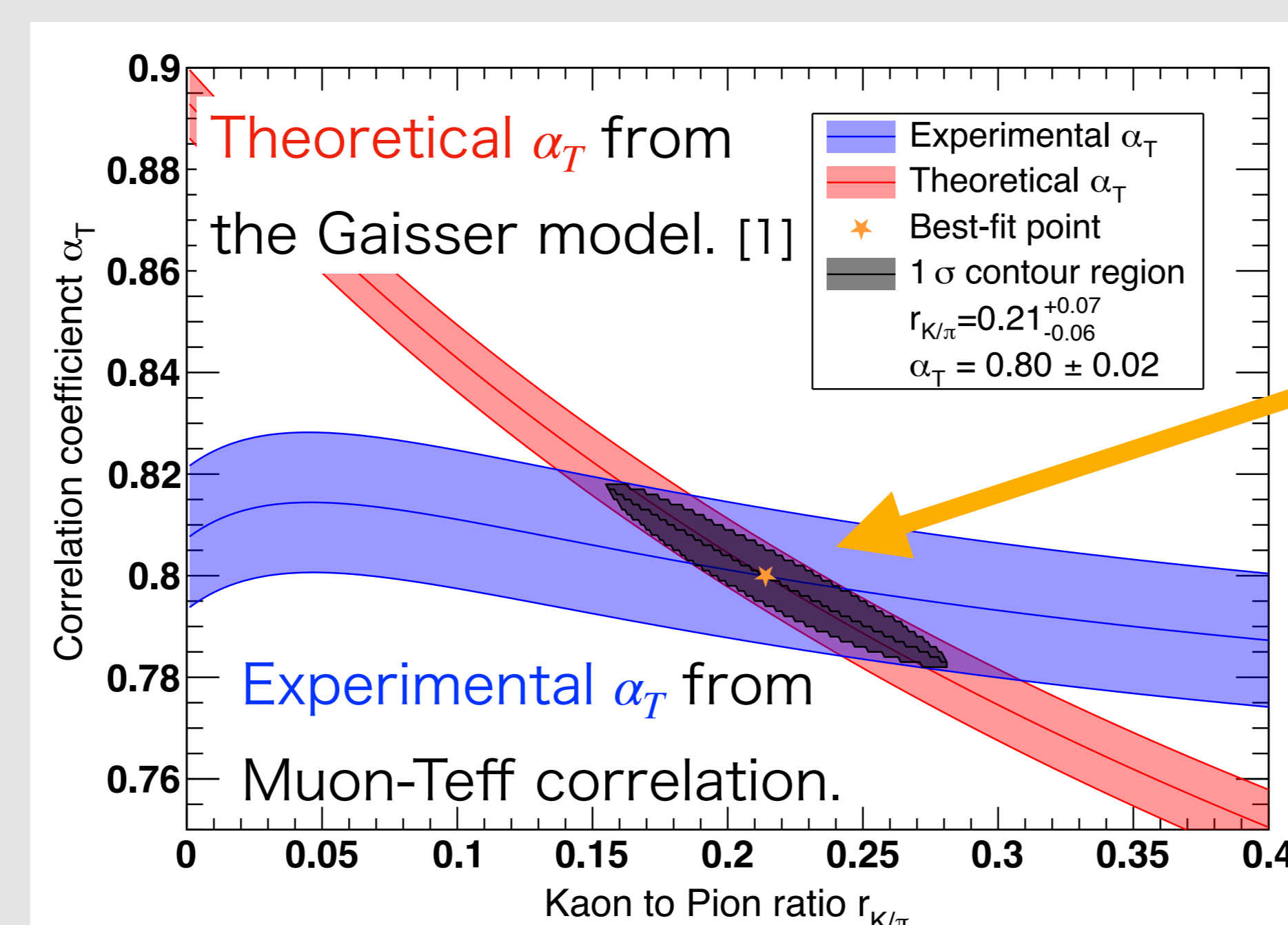


- Lomb-Scargle analysis identified the expected 1 year and half year periodicities.
- Sinusoidal fitting is fixed to 1 year and half year.
- The fit is used to determine the amplitudes and phases of the seasonal modulation.

Temperature data (JRA-55 [5])

- 37 discrete pressure in 1-1000 hPa.
- 4 times a day (0:00, 6:00, 12:00, 18:00)
- 36.25° N and 137.5° E (Closest of SK)
- The effective atmospheric temperature (Teff) is calculated using this data-set. [1]

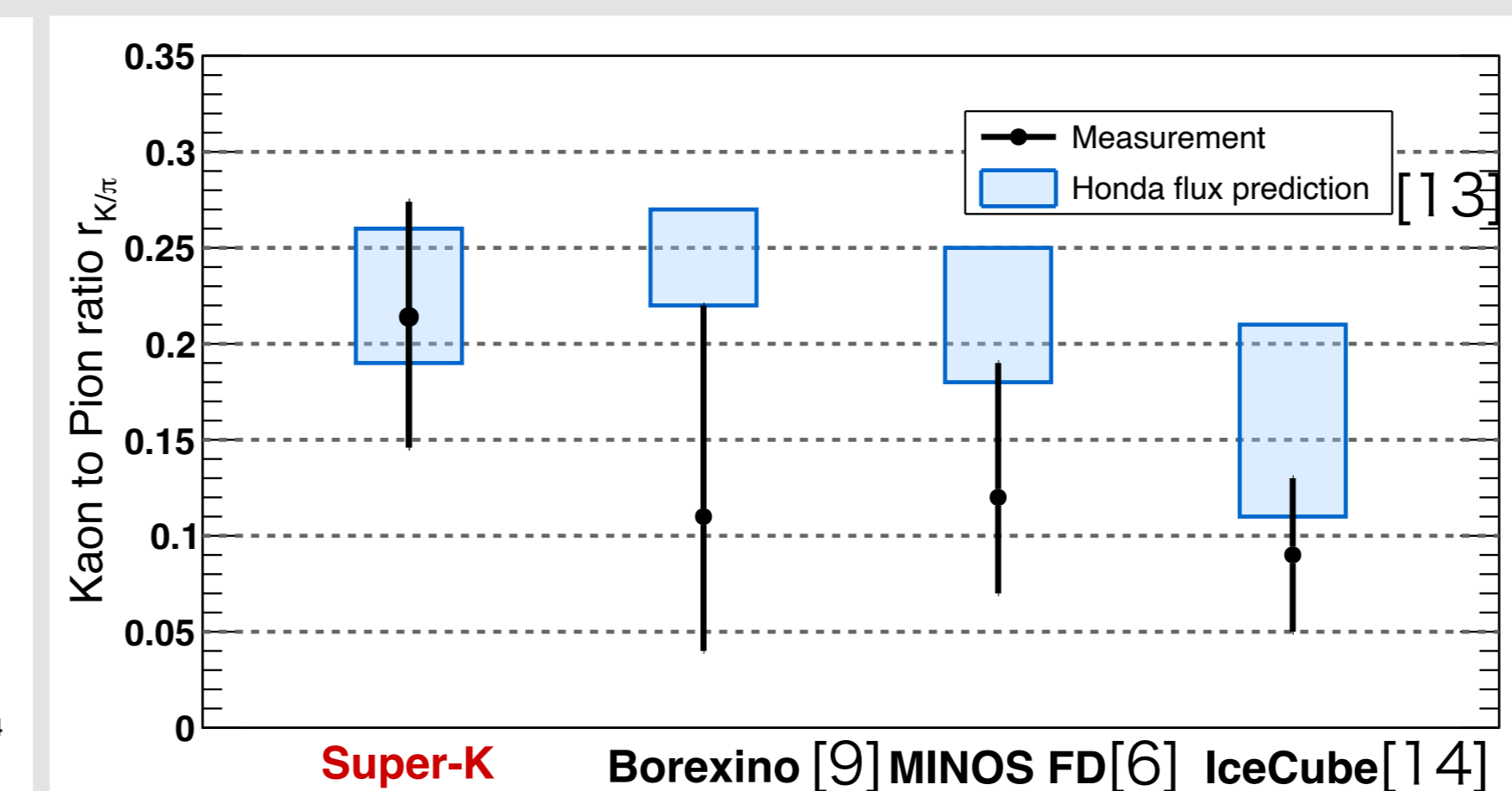
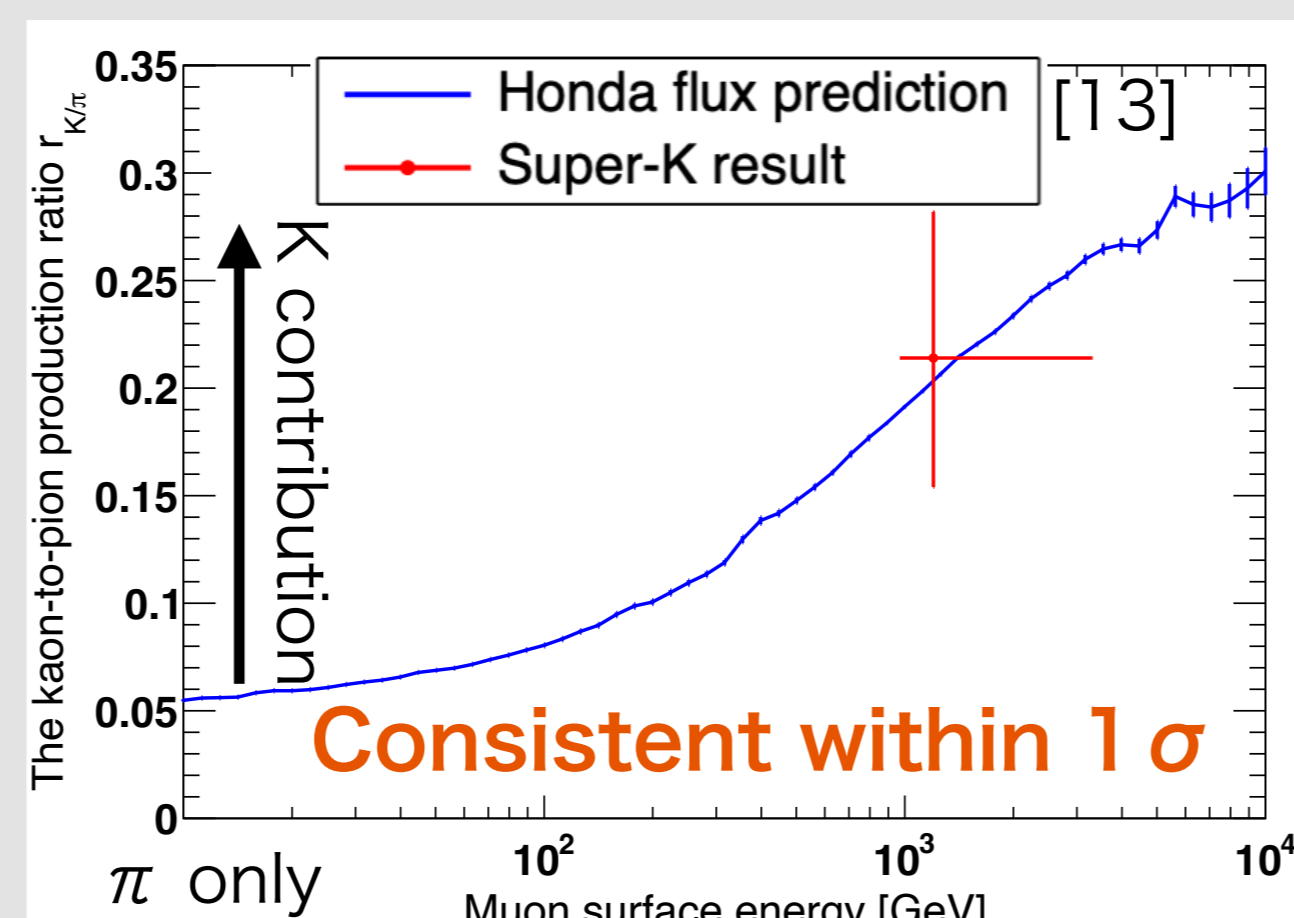
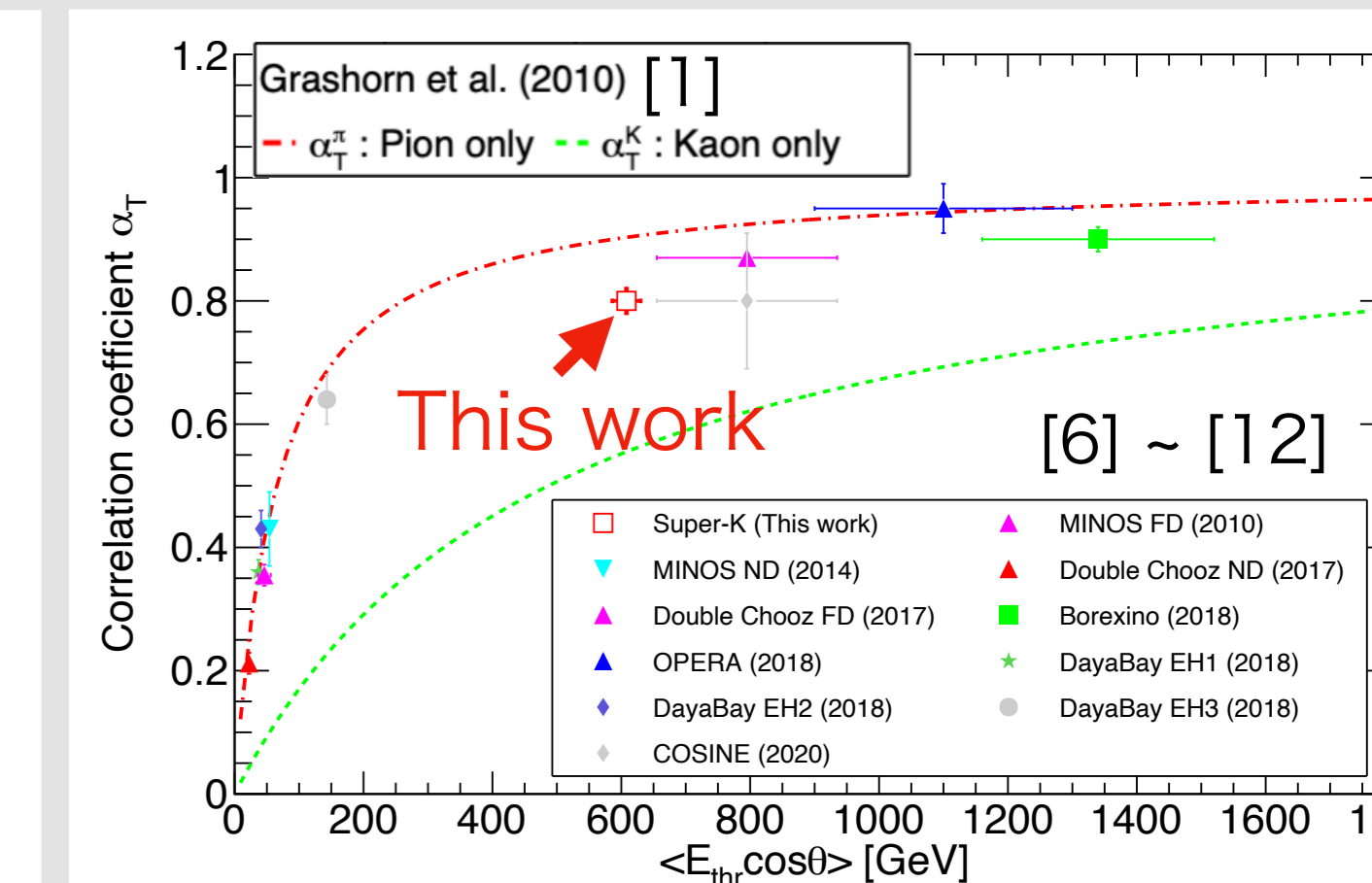
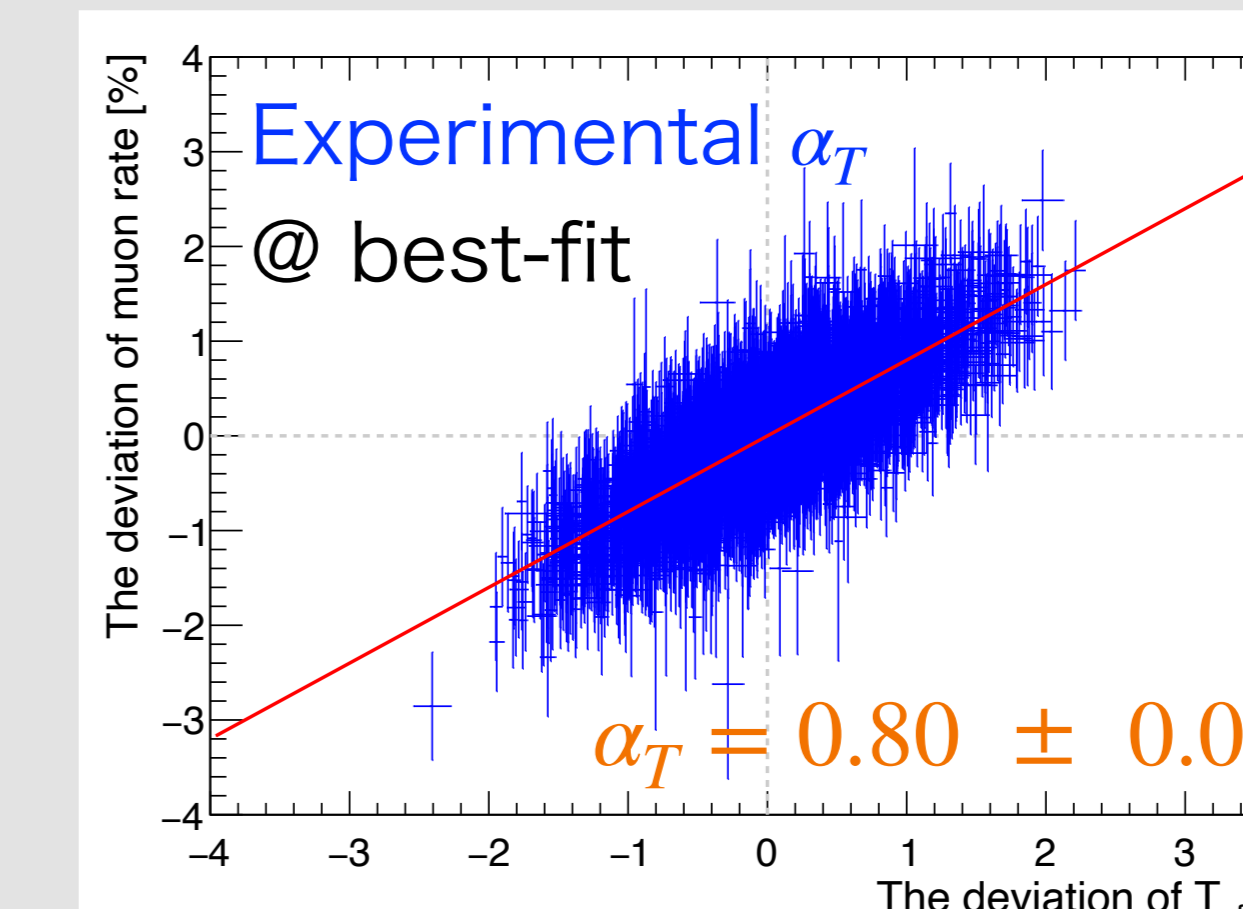
3. The correlation and the kaon-to-pion ratio



Measure $r_{K/\pi}$ and α_T by fitting simultaneously.

Best-fit result
 $r_{K/\pi} = 0.21^{+0.07}_{-0.06}$
 $\alpha_T = 0.80 \pm 0.02$

- Best-fit α_T is in good agreement with other results and theoretical model [1].
- Best-fit $r_{K/\pi}$ is consistent with Honda flux expectation. [13]
 - \rightarrow The " π -only scenario" is disfavored at 3.6σ (most significant exclusion).
 - \rightarrow The world-leading result and the most strongest constraint from cosmic-ray muon modulation analysis.



The π -only scenario exclusion significance: 3.6σ , 1.6σ , 2.4σ , 2.3σ

4. Summary

- Single muon variation exhibit 1 year and half year modulation.
- Best-fit results: $r_{K/\pi} = 0.21^{+0.07}_{-0.06}$, $\alpha_T = 0.80 \pm 0.02$
- α_T is consistent with other results and theoretical model.
- $r_{K/\pi}$ is consistent with Honda flux expectation.
- The " π -only scenario" is excluded at 3.6σ .

[1] Astropart. Phys. **33**, 140 (2010). [2] Nucl. Inst. Meth. A **501**, 418 (2003). [3] Z. Conner, PhD thesis, Univ. of Maryland (1997). [4] Astron. Astrophys. **496**, 577-584 (2009). [5] J. Meteor. Soc. Japan, **94**, 269-302 (2016). [6] Phys. Rev. D **81**, 012001 (2010). [7] Phys. Rev. D **90**, 012010 (2014). [8] JCAP. **02**, 017 (2017). [9] JCAP. **02**, 046 (2019). [10] JCAP. **10**, 003 (2019). [11] JCAP. **01**, 001 (2018). [12] JCAP. **02**, 013 (2021). [13] Phys. Rev. D **92**, 023004 (2015). [14] PoS(ICRC2019)894 (2020).