

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

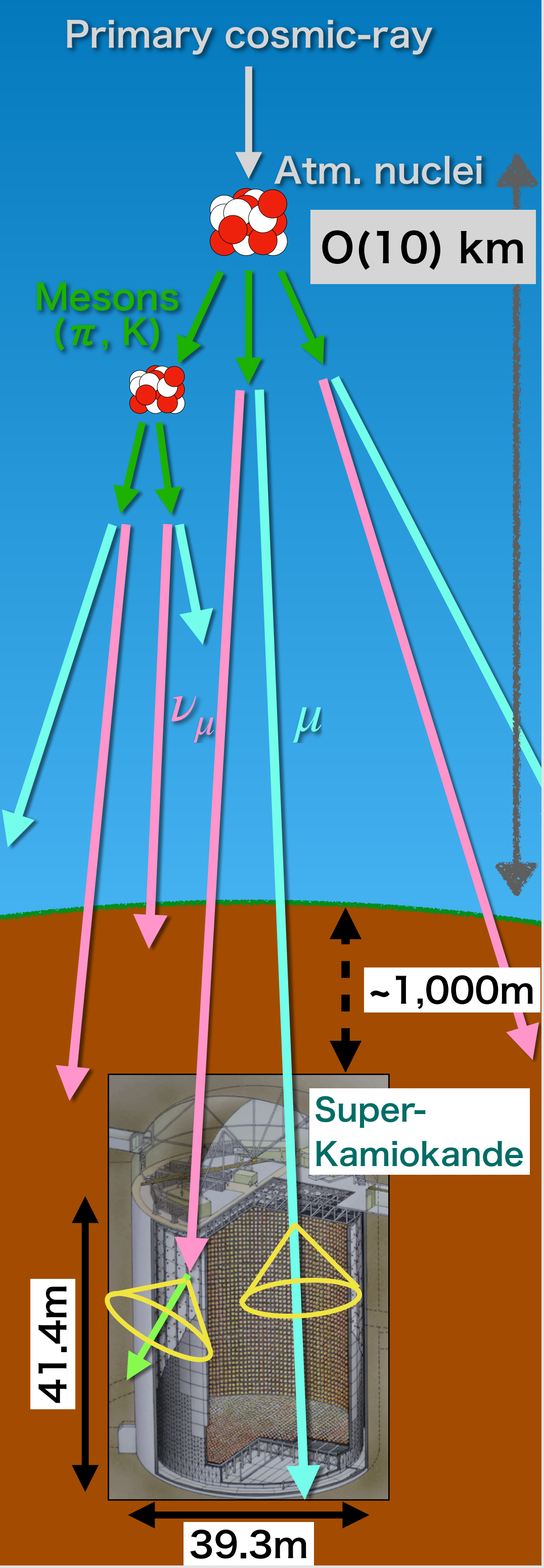
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Determine the atmospheric kaon-to-pion ratio $r_{K/\pi}$ using the cosmic-ray muon and the atmospheric temperature correlation α_T .



1. Introduction

Cosmic-ray muon modulation



1. Higher atmospheric temperature $\uparrow$
2. Lower atmospheric density $\downarrow$
3. More meson decays
4. More high energy muons
5. 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.

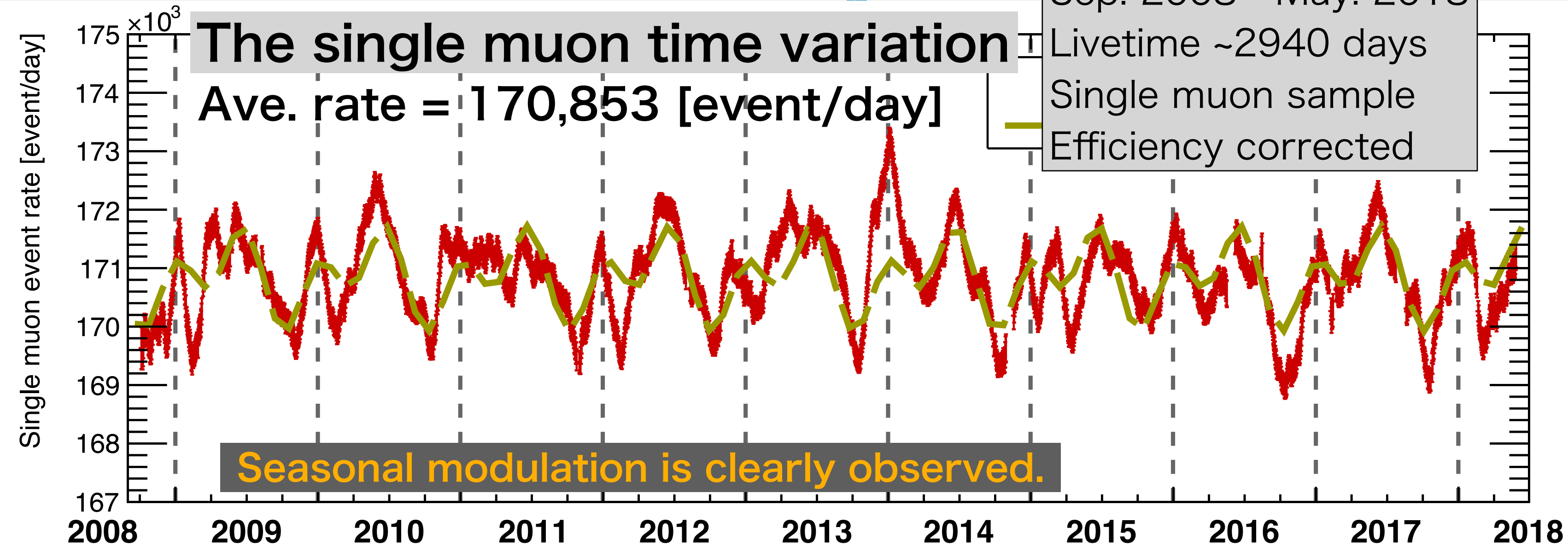
The kaon-to-pion production ratio $r_{K/\pi}$

- **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.**

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

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

2. Muon modulation analysis



Sinusoidal fitting

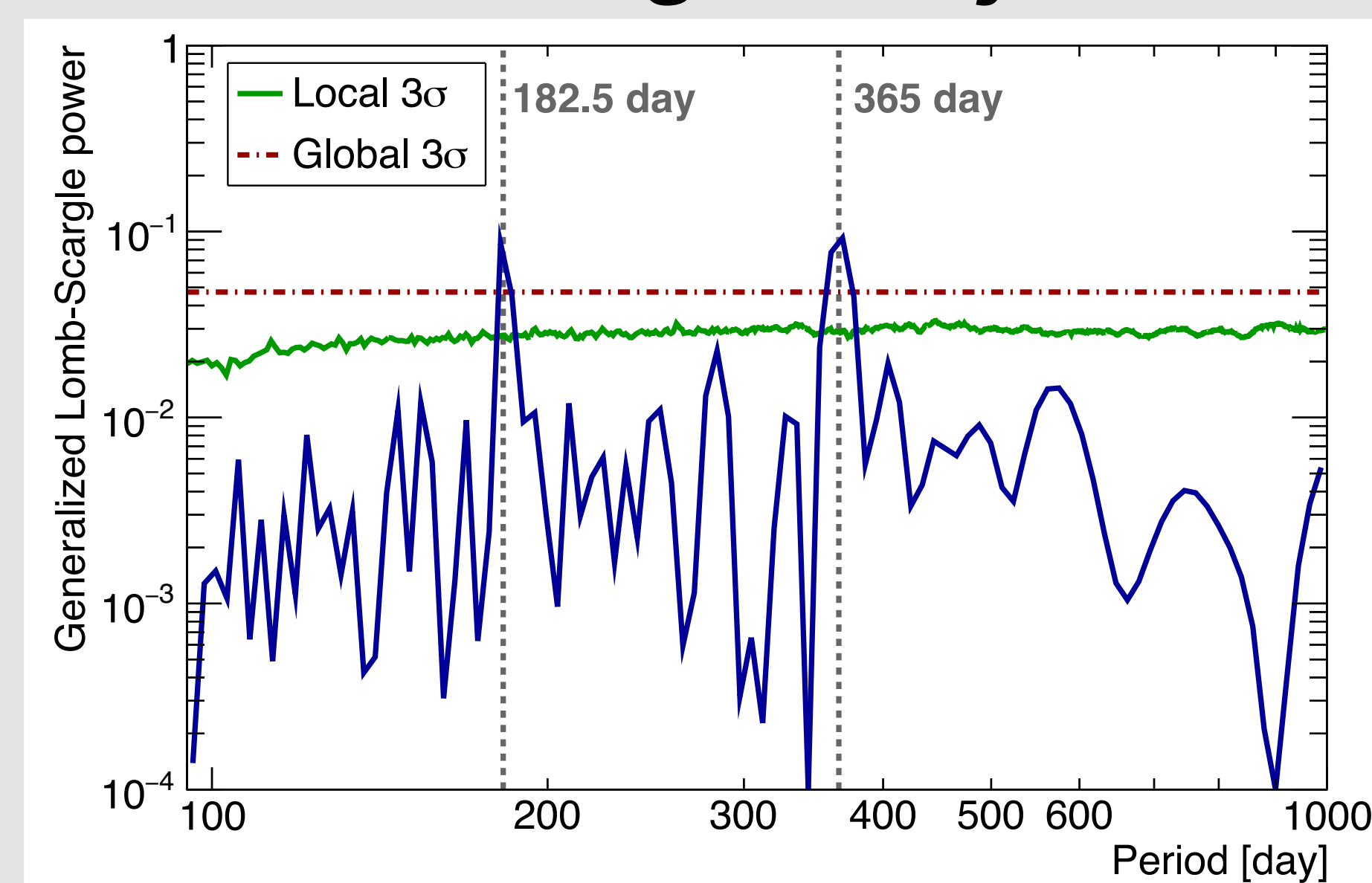
$$I_\mu(t) = \langle I_\mu \rangle + \delta I_\mu^{\text{Year}} \cos\left(2\pi \frac{t - \tau_\mu^{\text{Year}}}{365}\right) + \delta I_\mu^{\text{Half}} \cos\left(2\pi \frac{t - \tau_\mu^{\text{Half}}}{182.5}\right)$$

$\langle I_\mu \rangle$	170853 ± 16
$\delta I_\mu^{\text{Year}}$	484 ± 22 (0.283 %)
τ_μ^{Year}	132 ± 3 day
$\delta I_\mu^{\text{Half}}$	537 ± 22 (0.314 %)
τ_μ^{Half}	2 ± 1 day
χ^2/ndf	$4231 / 3324 = 1.27$

Temperature data (JRA-55 [5])

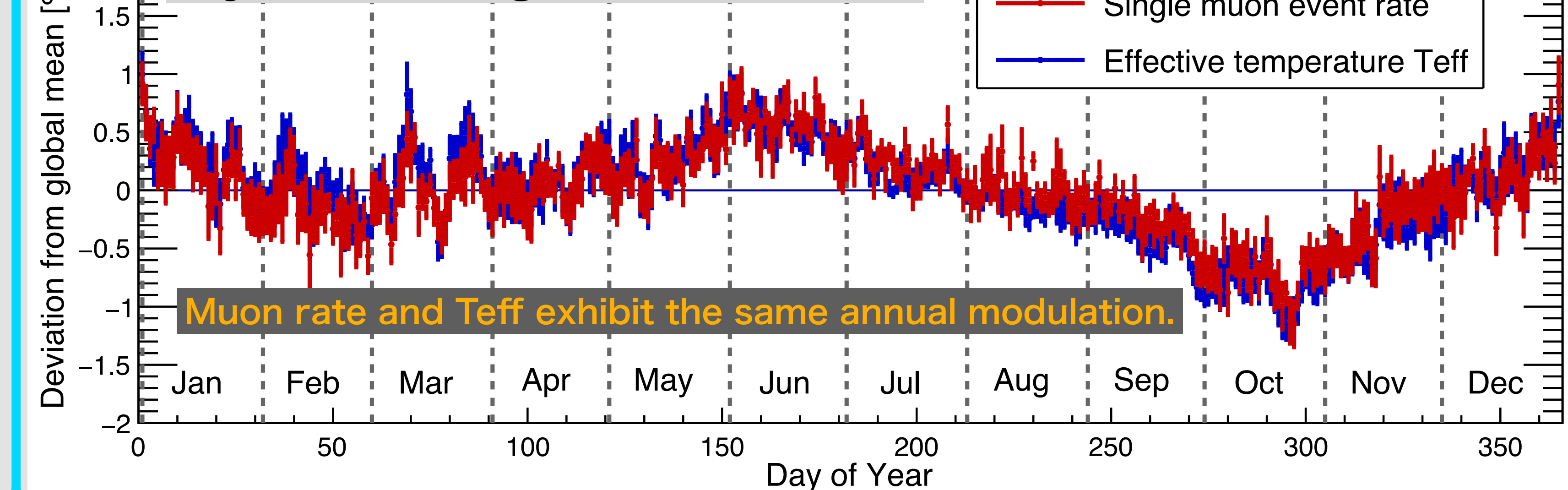
- 37 discrete pressure in 1~1000 hPa.
- 4 times a day (0:00, 6:00, 12:00, 18:00)
- 36.25° N and 137.5° E (Closest of SK)
- The effective atmospheric temperature (T_{eff}) is calculated using this data-set. [1]

Lomb-Scargle analysis [4]

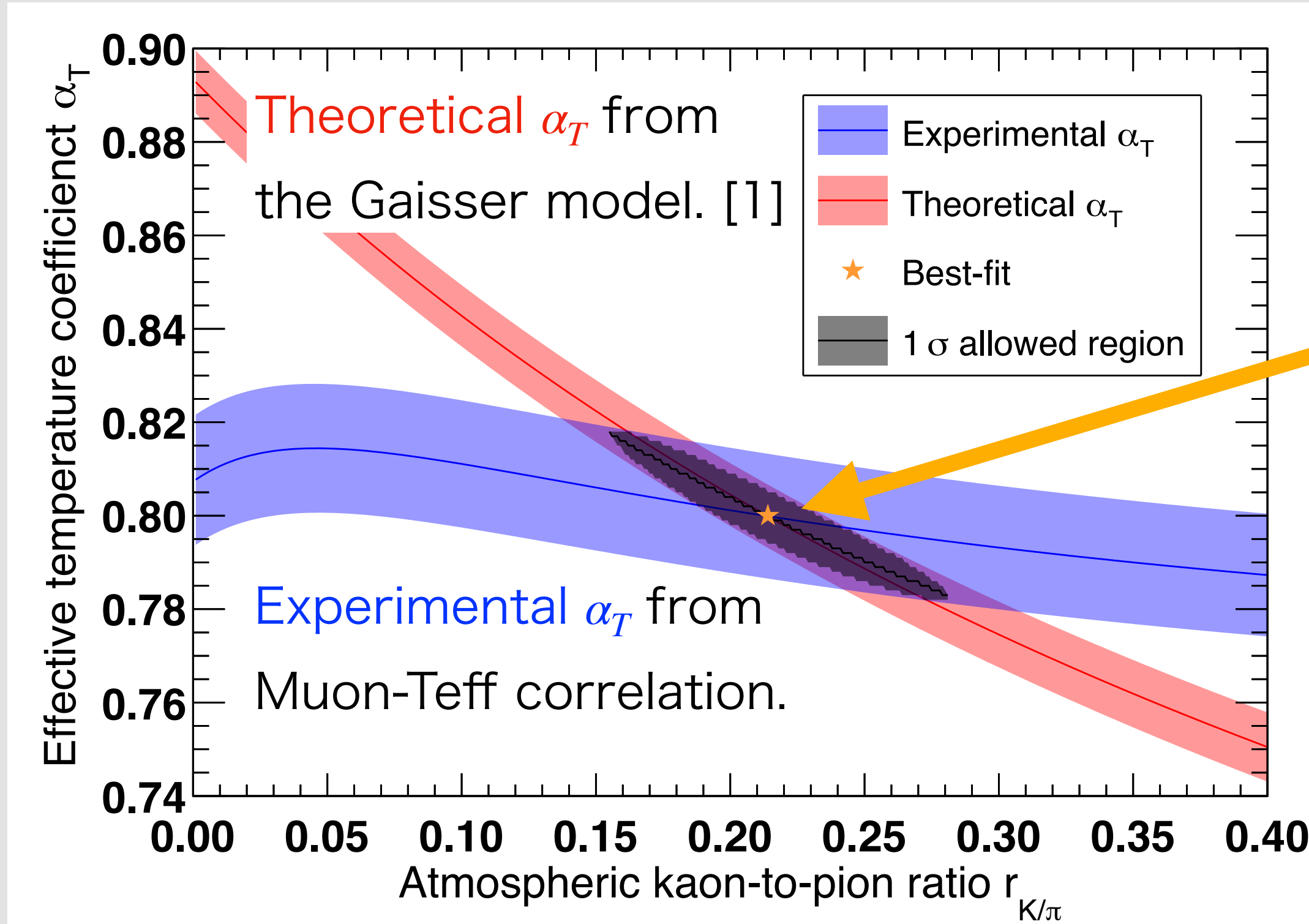


- **Lomb-Scargle analysis identified the expected 1 year and half year periodicities.**
- Sinusoidal fitting is fixed to 1 year and half year.
- The fit is used to determine the amplitudes and phases of the seasonal modulation.

1 year folding time variation



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



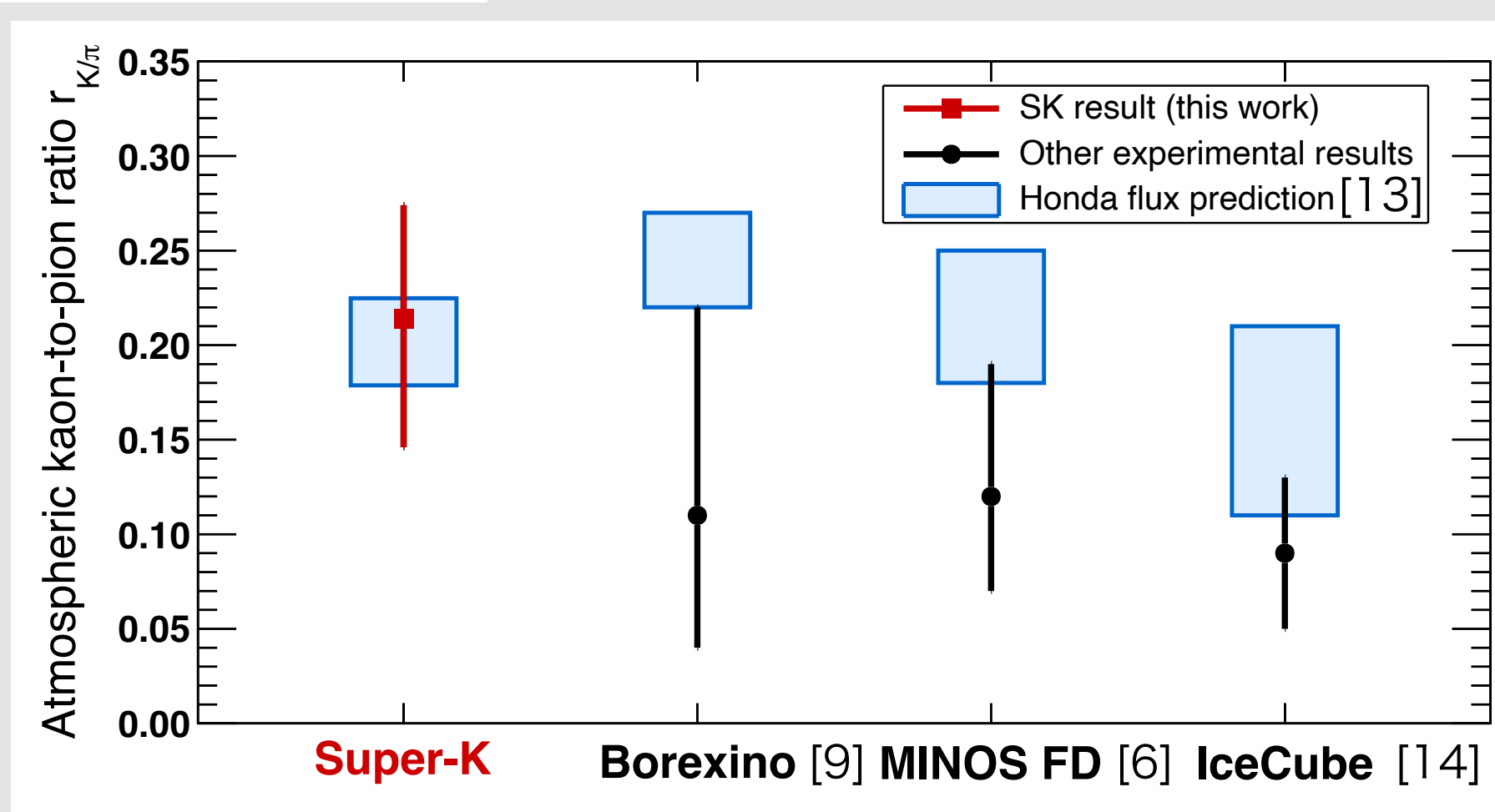
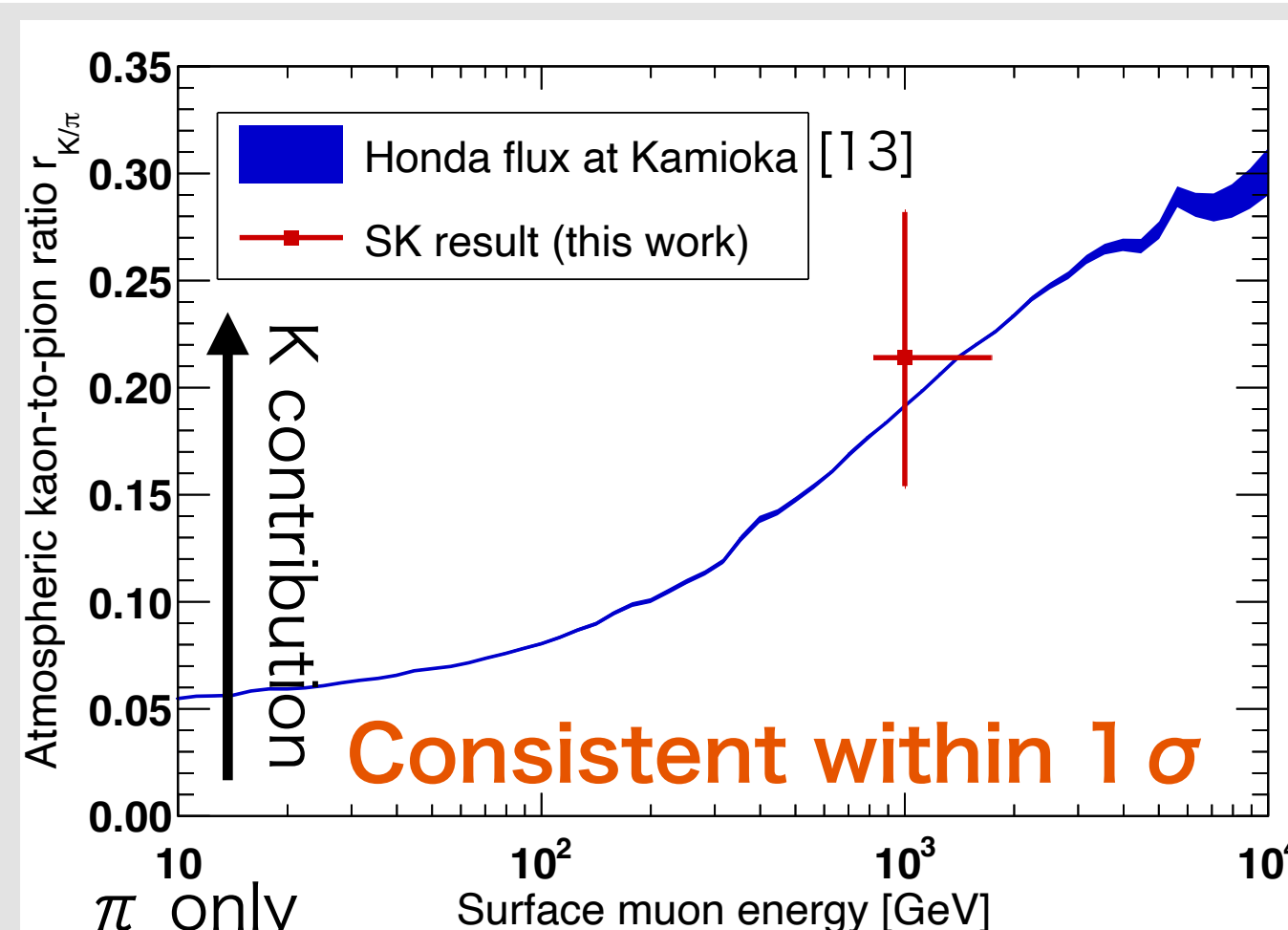
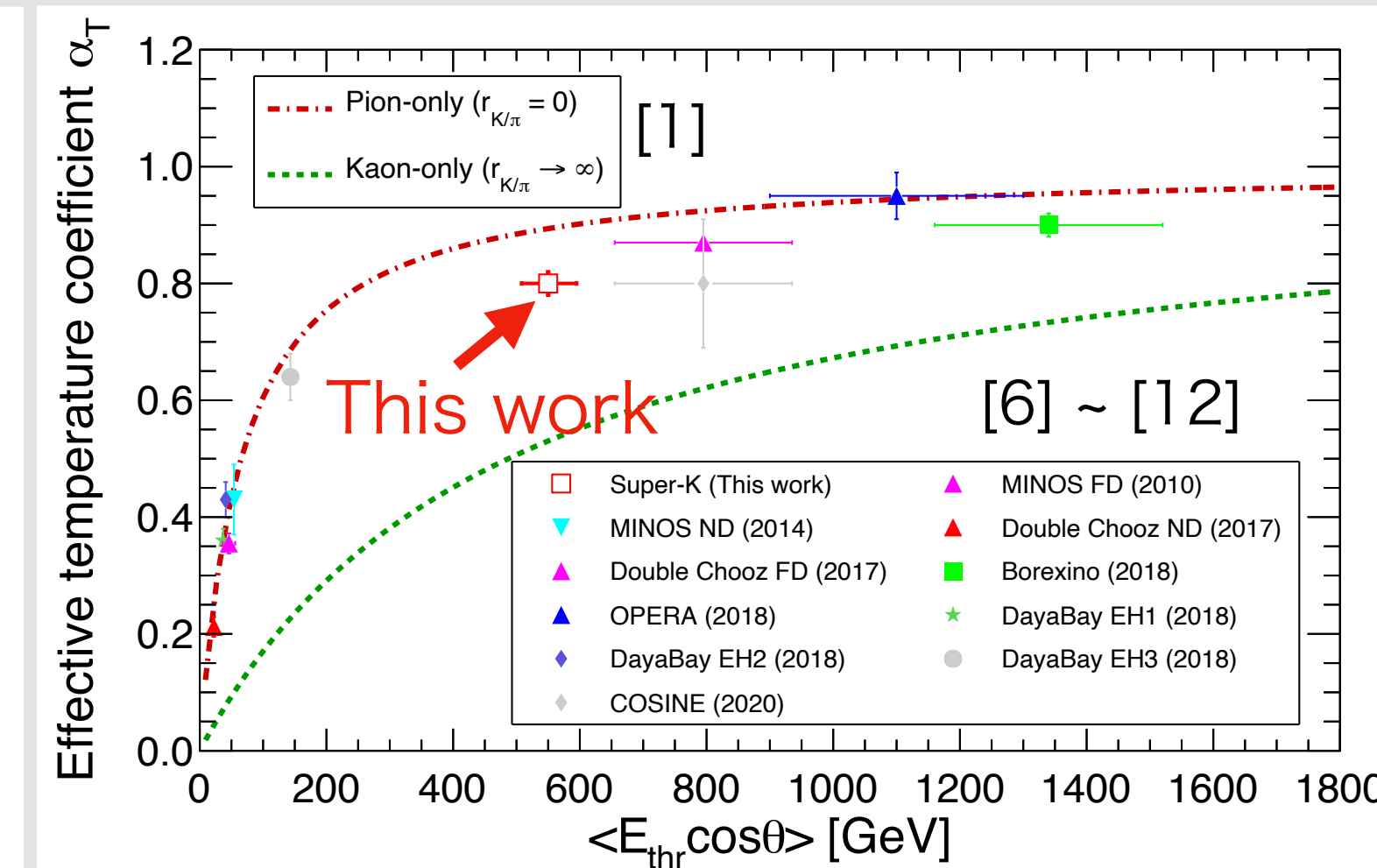
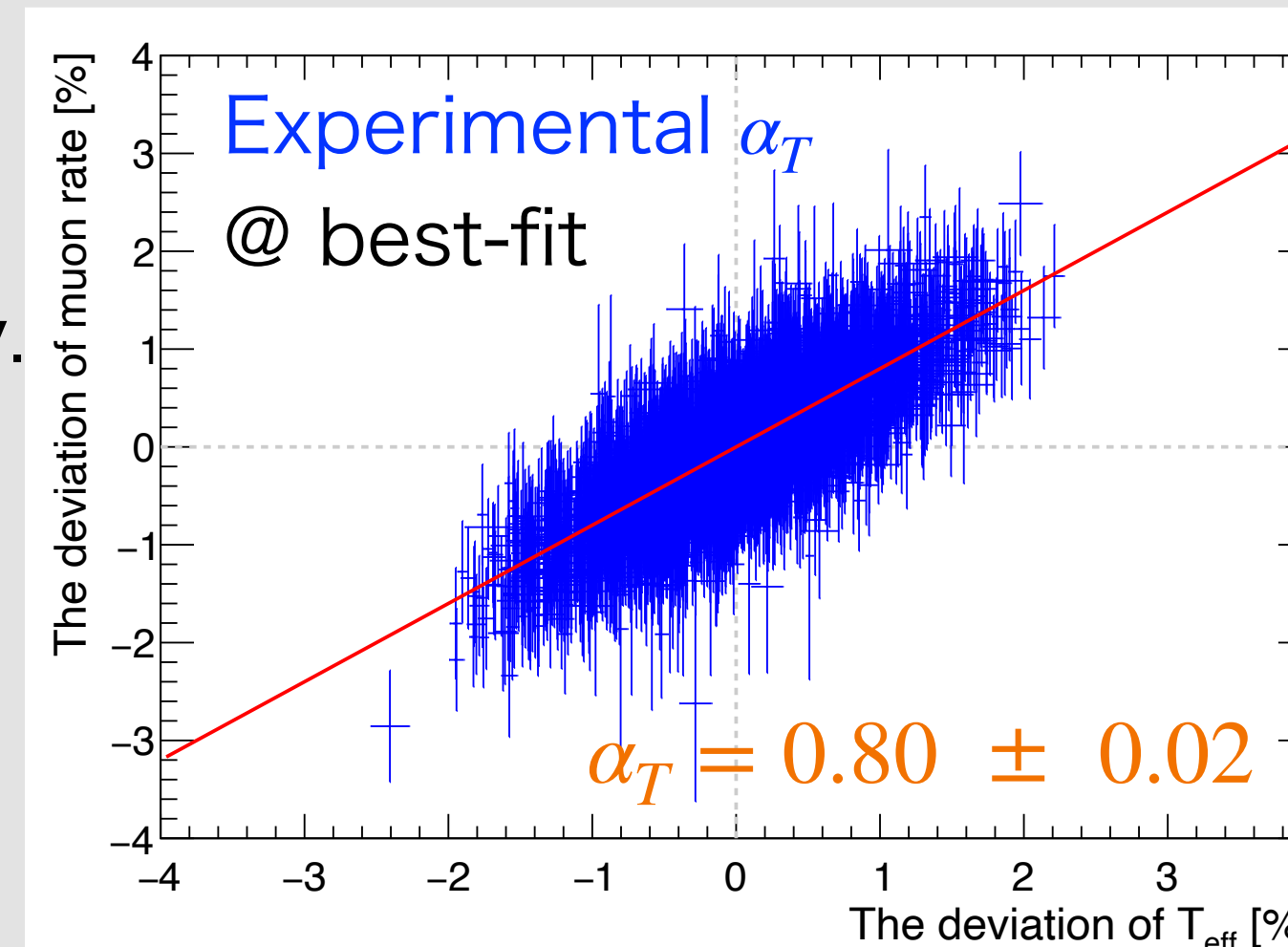
- Measure $r_{K/\pi}$ and α_T by fitting simultaneously.

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]**
 - The " **π -only scenario**" is disfavored at **3.6 σ** (most significant exclusion).
 - The **world-leading result and the most strongest constraint from cosmic-ray muon modulation analysis.**



The π -only scenario exclusion significance

3.6 σ 1.6 σ 2.4 σ 2.3 σ

4. Summary

- Single muon variation exhibit 1 year and half year modulation.
- **Best-fit result $r_{K/\pi} = 0.21^{+0.07}_{-0.06}$ $\alpha_T = 0.80 \pm 0.02$**
- 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 3.6 σ .**

[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).