seasonal variations of atmospheric leptons as a probe for charm production

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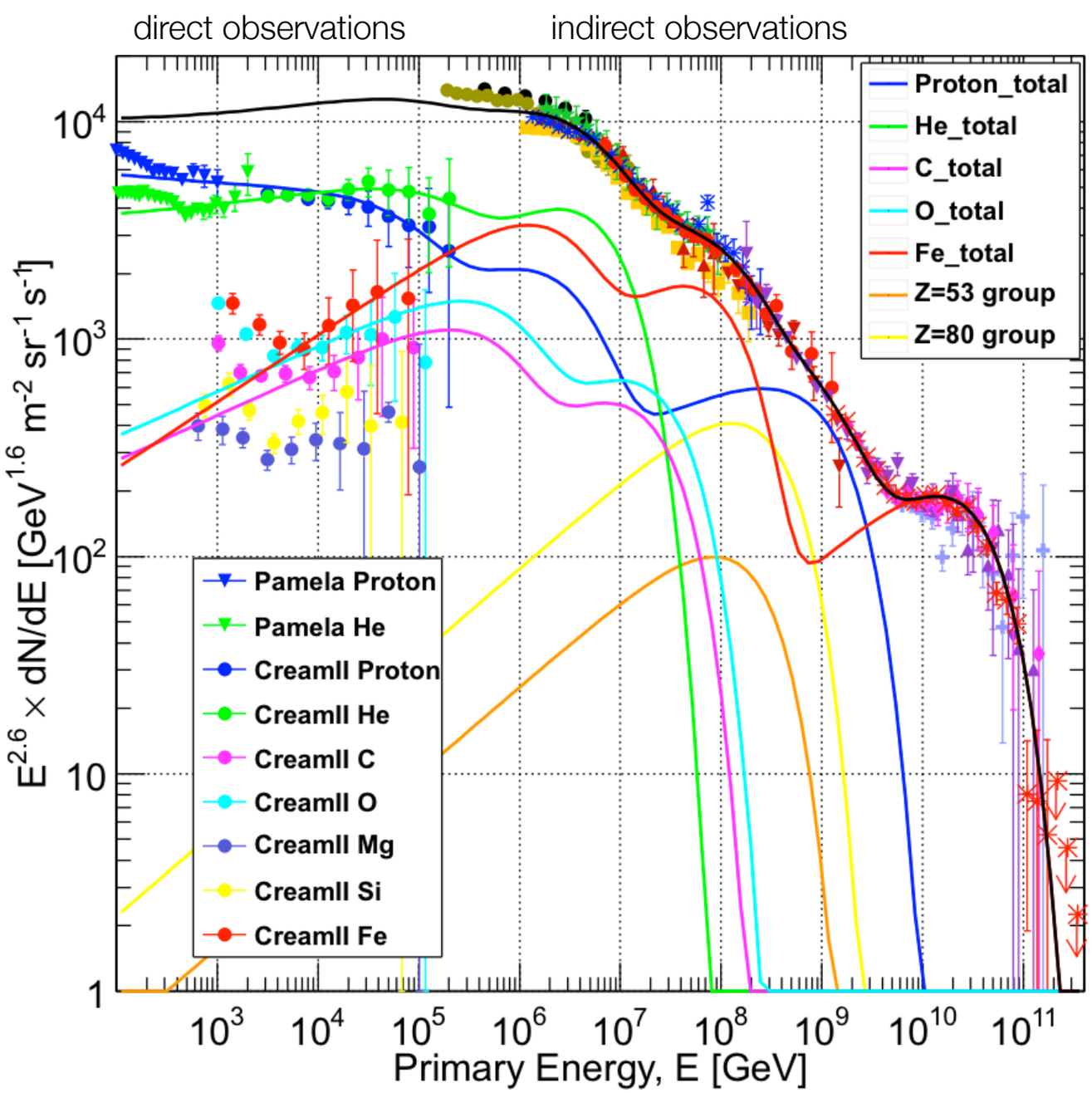
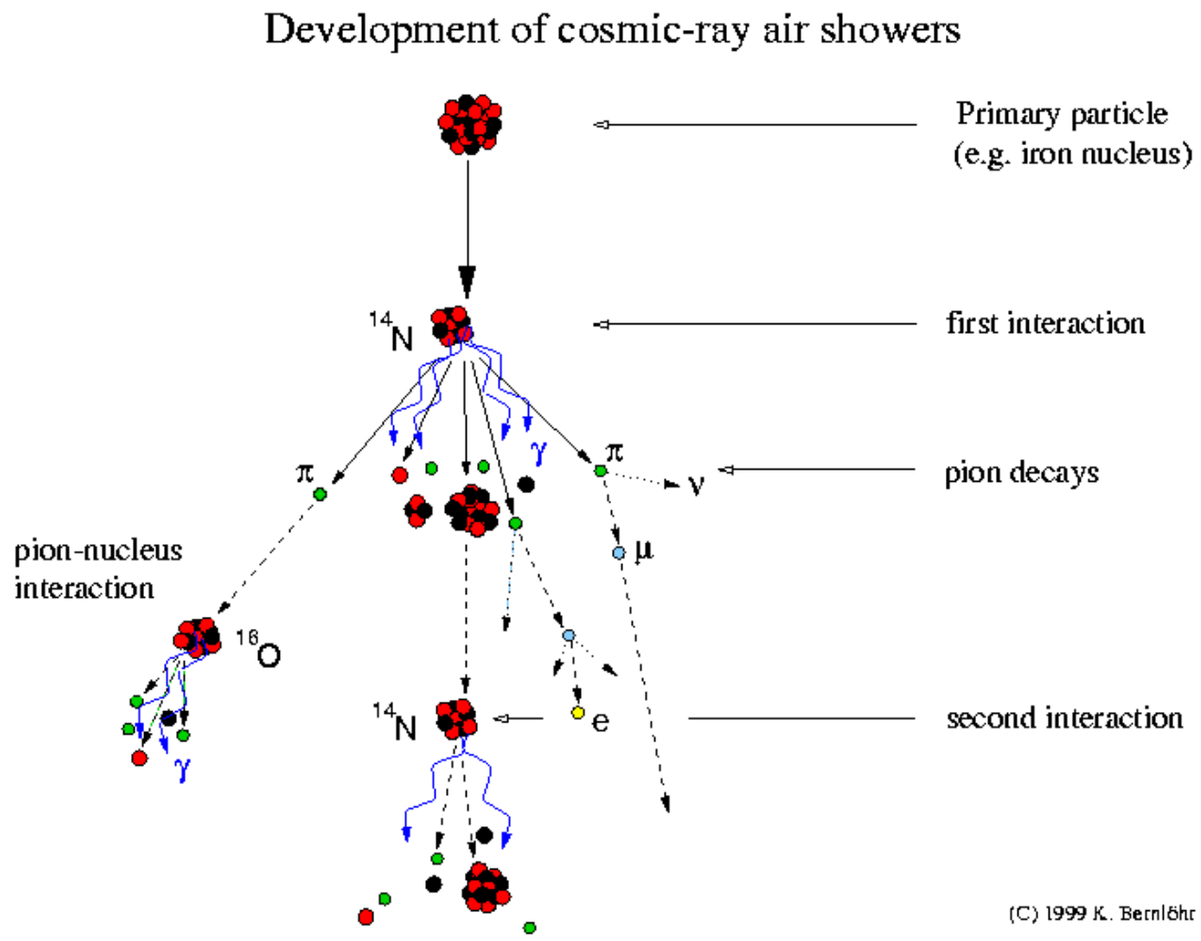
outline

- particle production in extensive air showers
- heavy quark production and window to astrophysical signal
- correlation with Earth’s atmospheric temperature
- probing heavy quark component with seasonal variations

particle production in the atmosphere

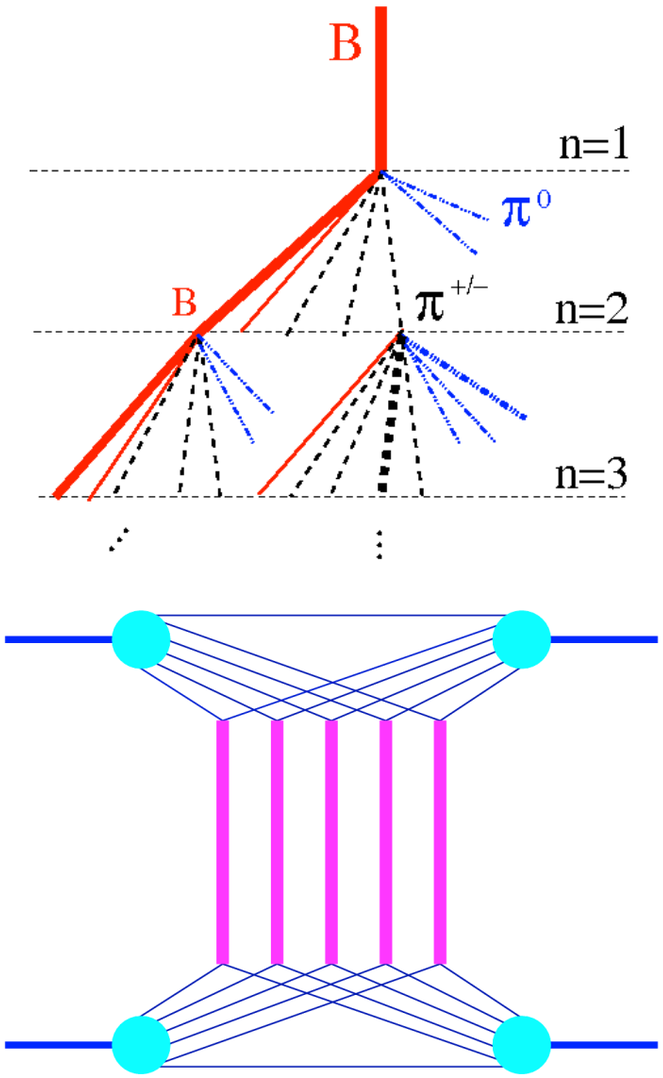
Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565





$$N_{CR} + N_{air} \longrightarrow X \quad + \pi + K + D + \Lambda + \ldots$$

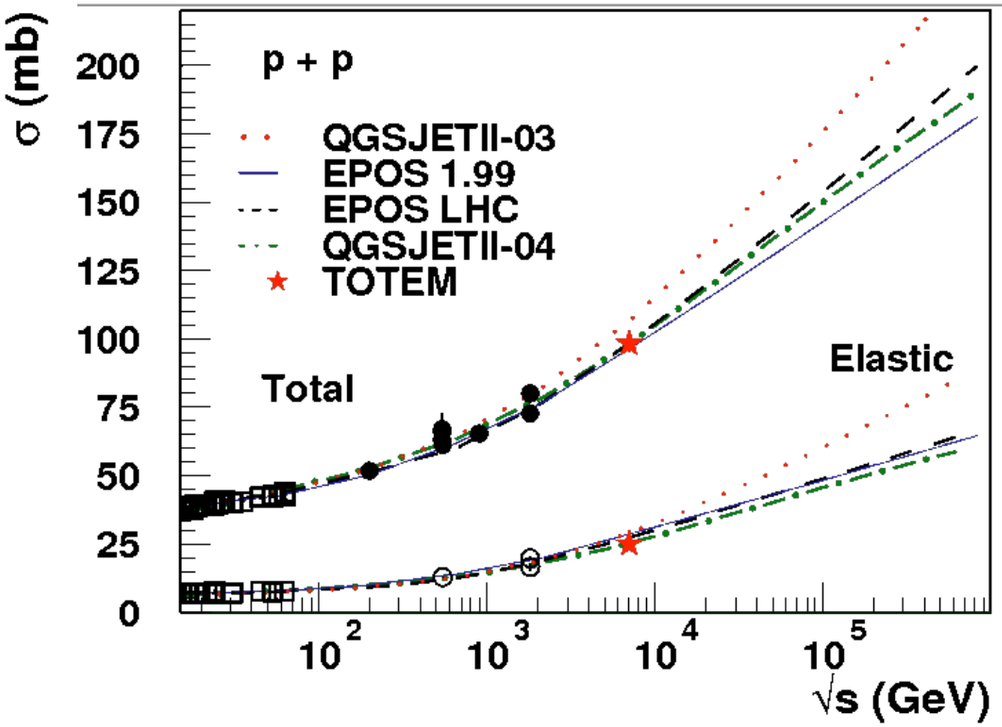
particle production in the atmosphere
hadronic interactions



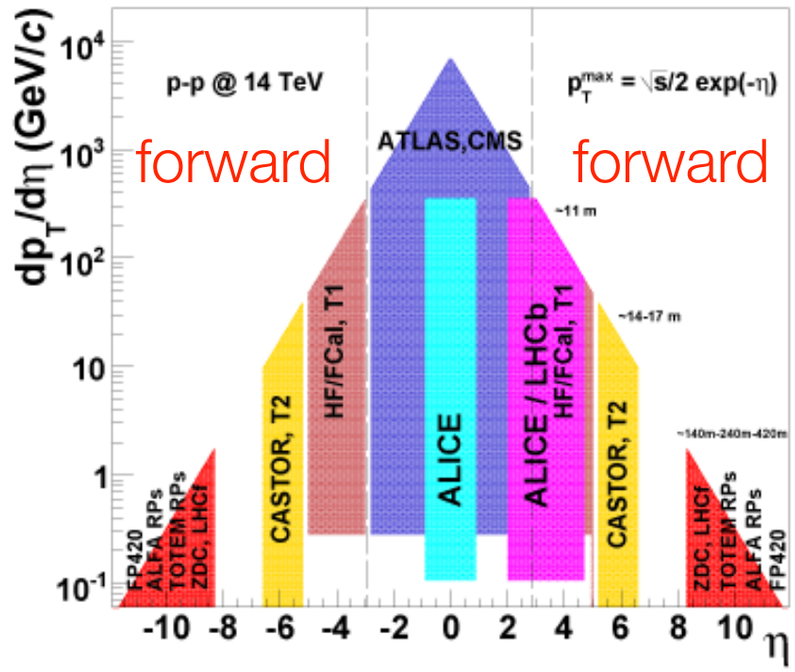
- CR showers dominated by **soft component with small p_T** (*non-perturbative QCD*)
- **hard component with high p_T** with heavy quarks (pQCD)
- **phenomenological** descriptions of hadronic interactions with minijet production for hard component
- **models** to describe soft/hard **interactions** in **forward region** & **extrapolated to high energy**

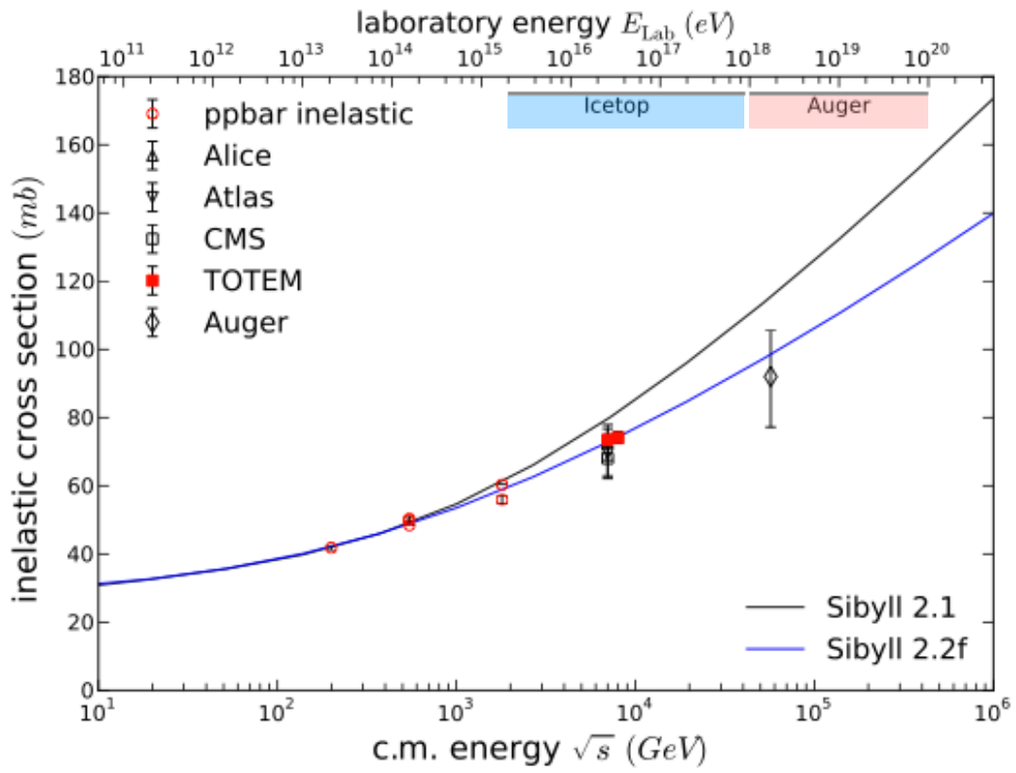
- **interaction models** from accelerators, **extrapolated** to forward region at high energy

particle production in the atmosphere

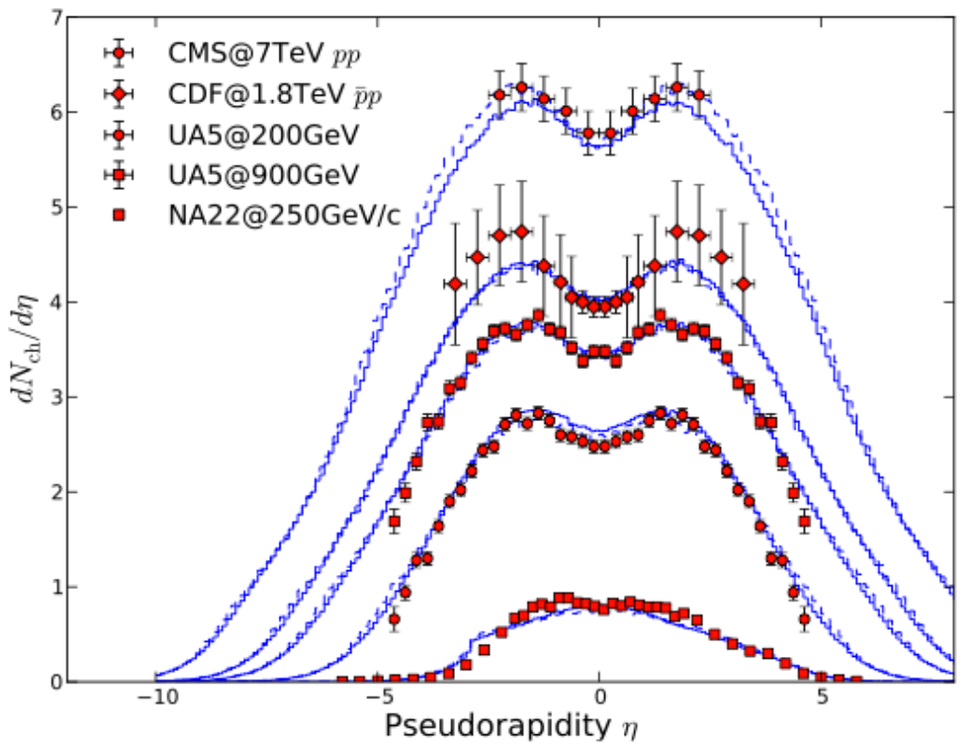


Pierog, Engel



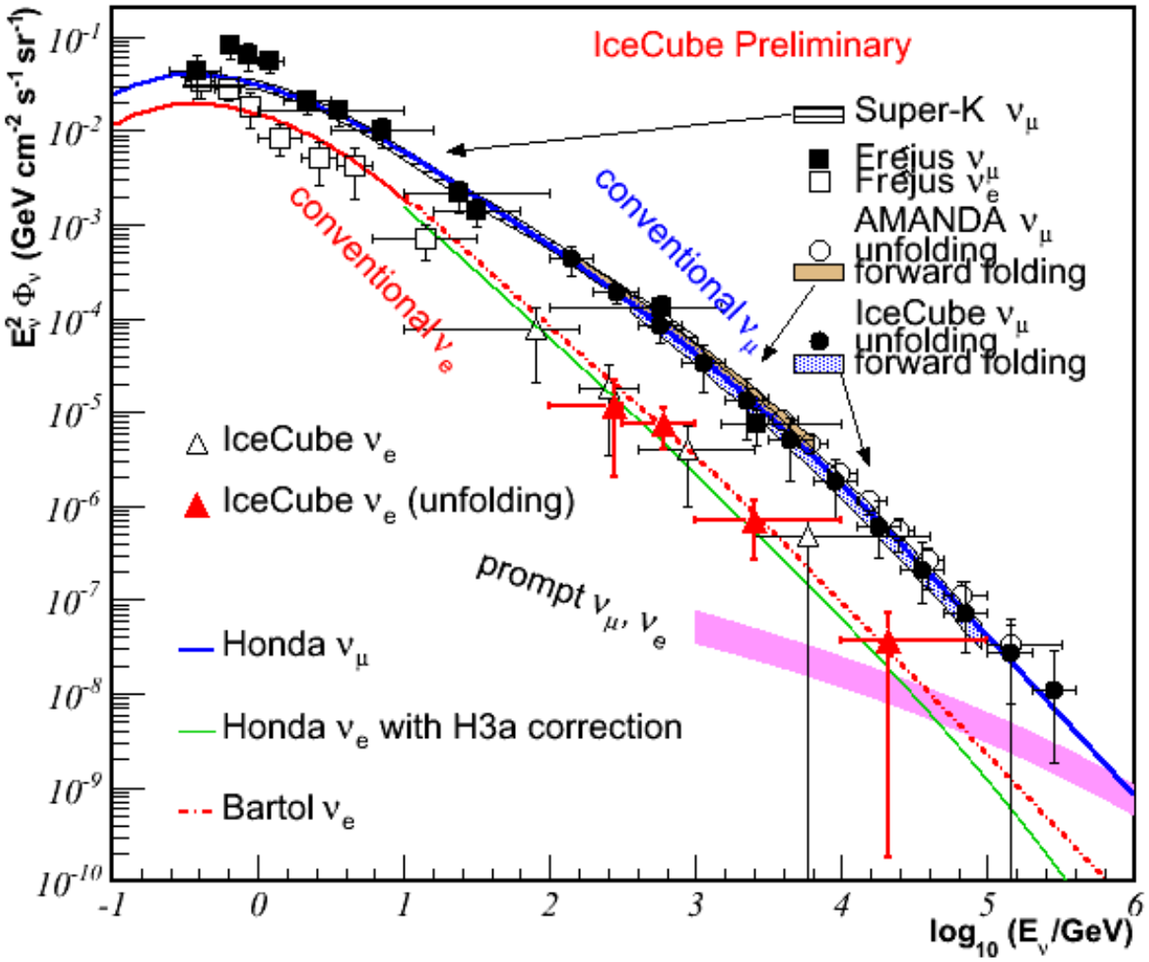


Ahn et al., ICRC 2013



Paolo Desiati

particle production in the atmosphere
atmospheric leptons



$$\phi_\nu(E_\nu) = \phi_N(E_\nu) \times \left\{ \frac{A_{\pi\nu}}{1 + B_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + \frac{A_{K\nu}}{1 + B_{K\nu}\cos\theta\, E_\nu/\epsilon_K} + \frac{A_{\mathrm{charm}\,\nu}}{1 + B_{\mathrm{charm}\,\nu}\cos\theta\, E_\nu/\epsilon_{\mathrm{charm}}} \right\}$$

$$A_{i\nu} = \frac{Z_{Ni} \times BR_{i\nu} \times Z_{i\nu}}{1 - Z_{NN}} \qquad (Z_{NN} = Z_{pp} + Z_{pn})$$

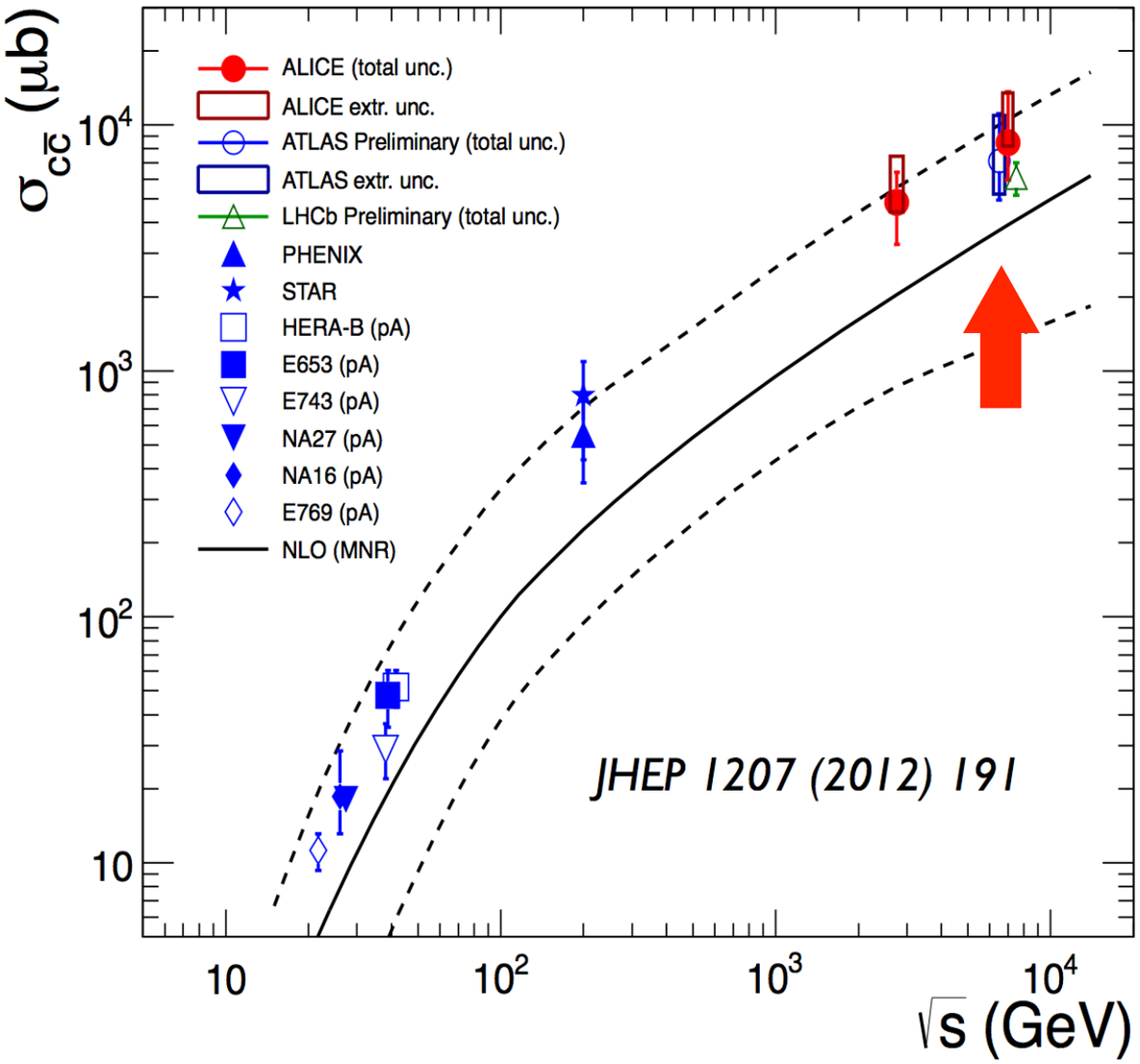
$$Z_{N\pi^\pm}(E) = \int_E^\infty \mathrm{d}E' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{\mathrm{d}n_{\pi^\pm}(E', E)}{\mathrm{d}E}$$

$$\epsilon_i = \frac{kT}{Mg} \frac{m_i c^2}{c\tau_i} \qquad i = \pi, K, charm, ...$$

meson's characteristic energy

Particle (α):	$\pi^\pm$	$K^\pm$	K_L^0	Charm
ϵ_α (GeV):	115	850	205	$\sim 3 \times 10^7$

heavy quark production and astrophysics



- LHC data show agreement of observations within FONLL (wide range of η) - **pQCD**

- **intrinsic charm** production: asymmetry in $c\bar{c}$ baryon production (SELEX 2002)

- $p \rightarrow \Lambda_c^+ + \bar{D}^0$ of order 1% $(m_s/m_c)^2$ compared to associated production $p \rightarrow \Lambda K^+$

- inclusive D-meson spectrum dominated by intrinsic charm at **high pseudo-rapidity** & **p_T**

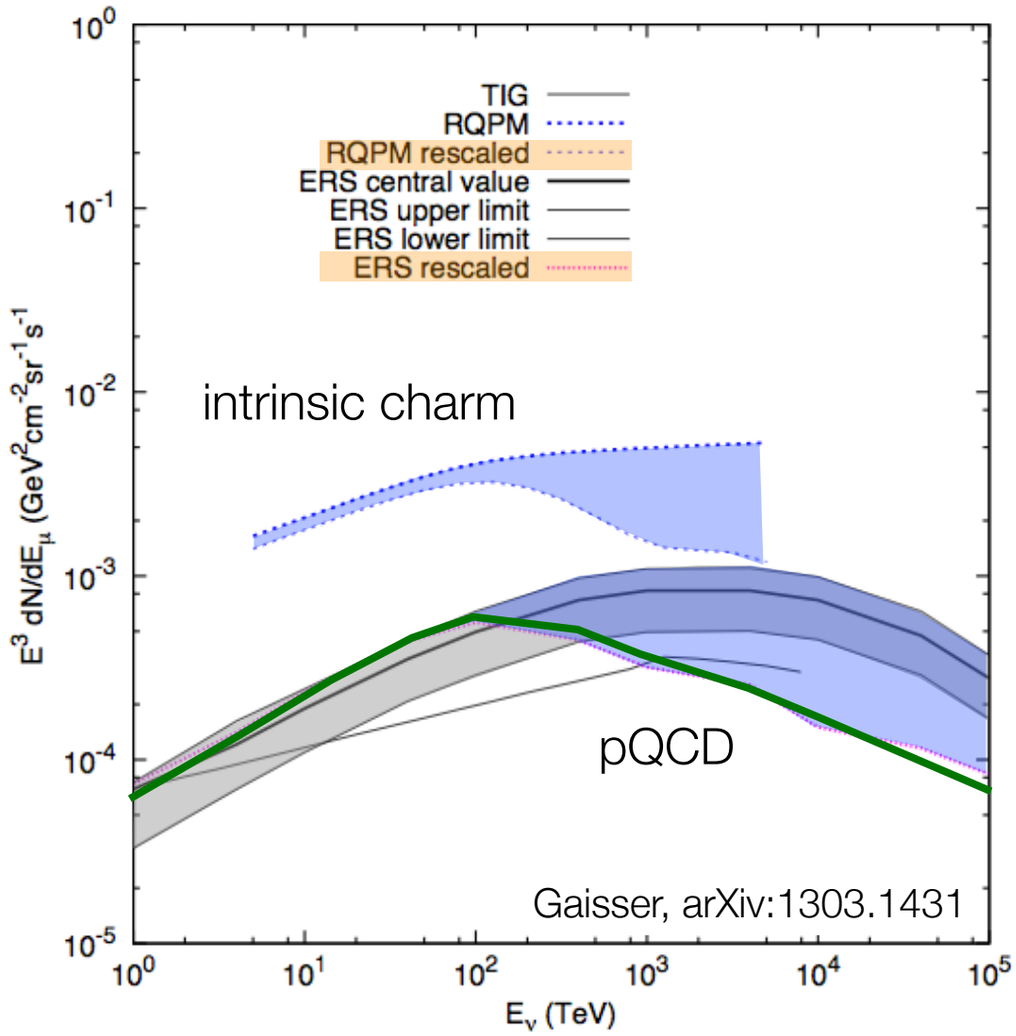
  (Lykasov+ 2012; @LHC: Bednyakov+ 2013)

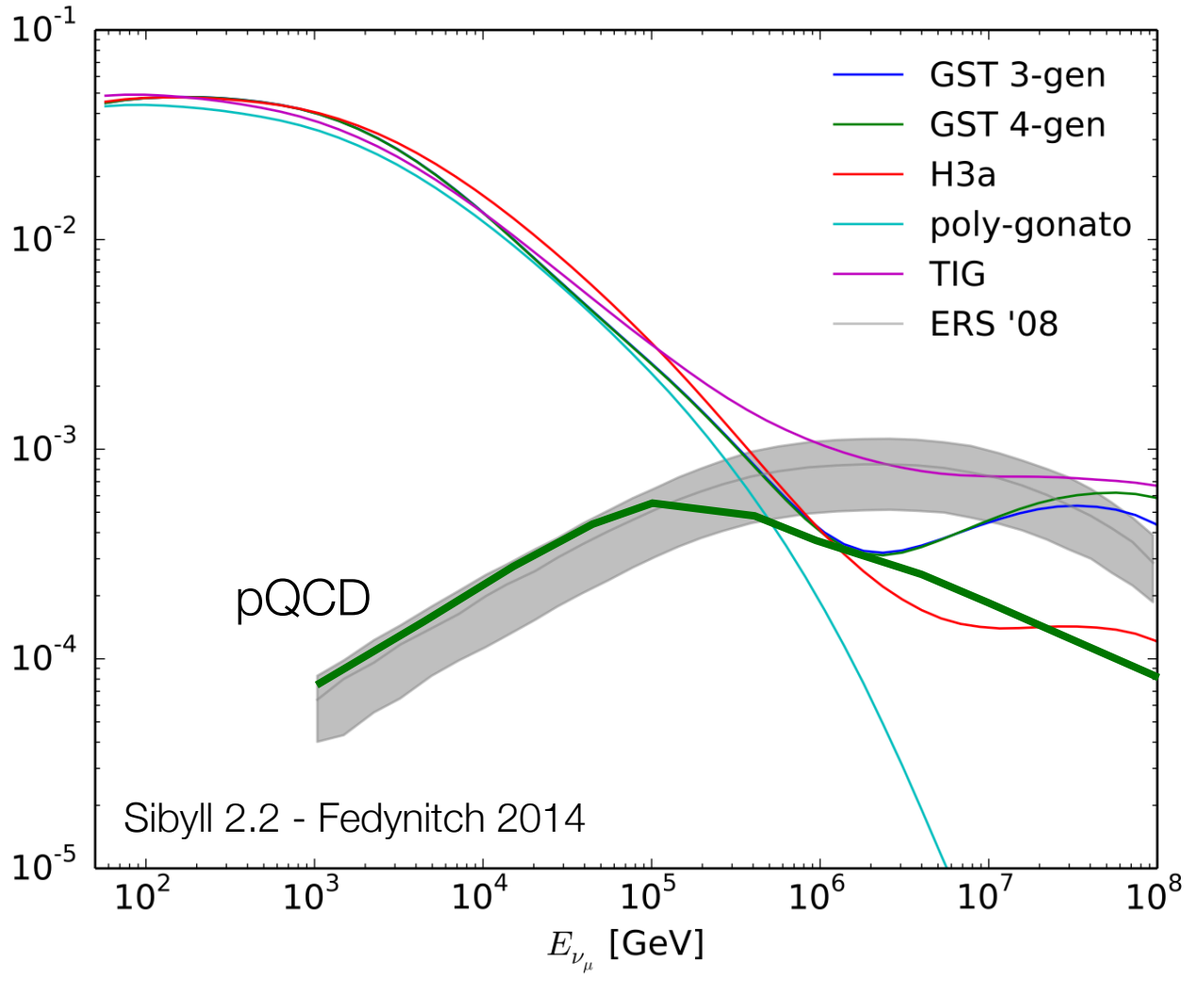
- **non-perturbative QCD**

heavy quark production and astrophysics

- effect of charm production **models**

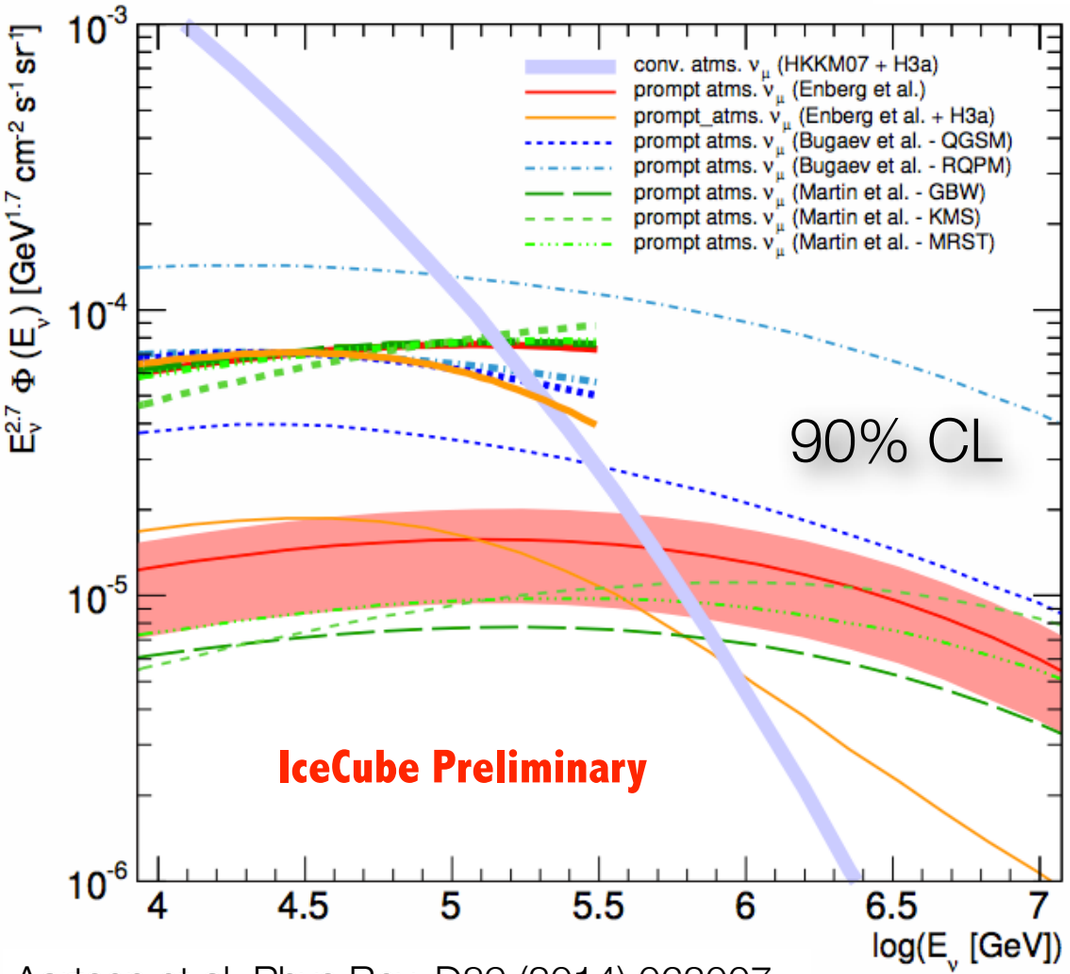
- effect of primary **cosmic ray spectrum**





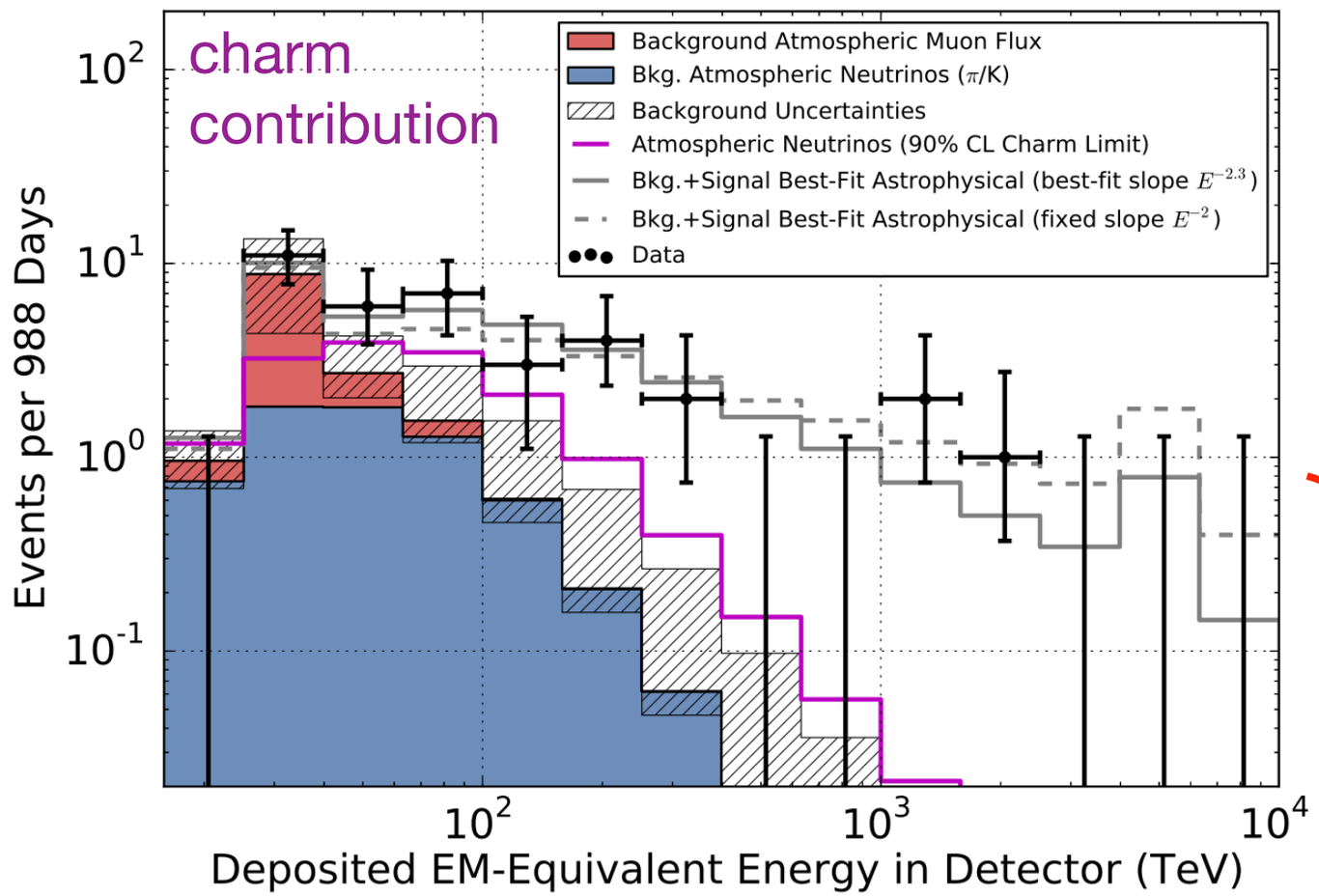
heavy quark production and astrophysics

observed through-going up-ward $\nu_\mu + \bar{\nu}_\mu$



Aartsen et al. Phys.Rev. D89 (2014) 062007

observed starting all-direction **all-flavor**



Aartsen et al. Science 342 (2013) 1242856
Aartsen et al. arXiv:1405.5303

→ can neutrino telescopes measure neutrinos from charm ?

astrophysical neutrinos ?

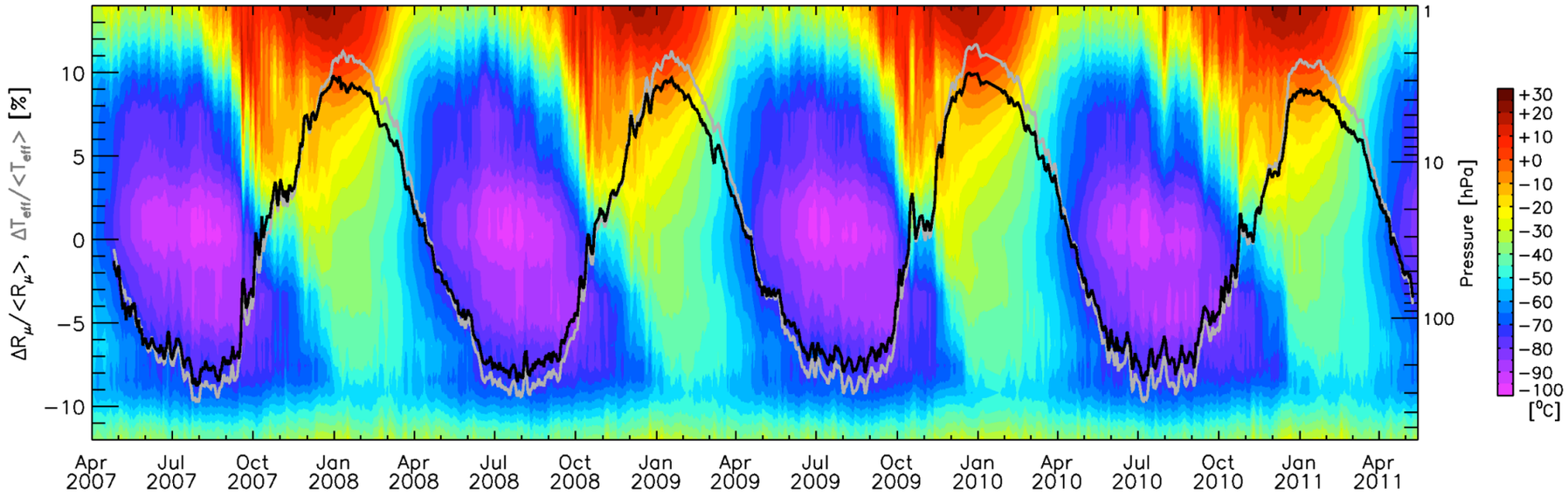
temperature seasonal variations

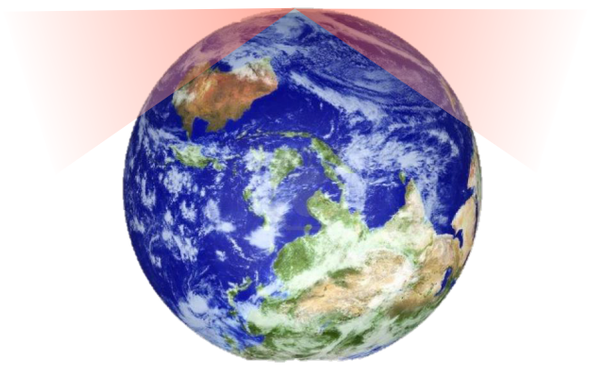
IceCube Preliminary

μ

μ multiplicity - ICRC 2013

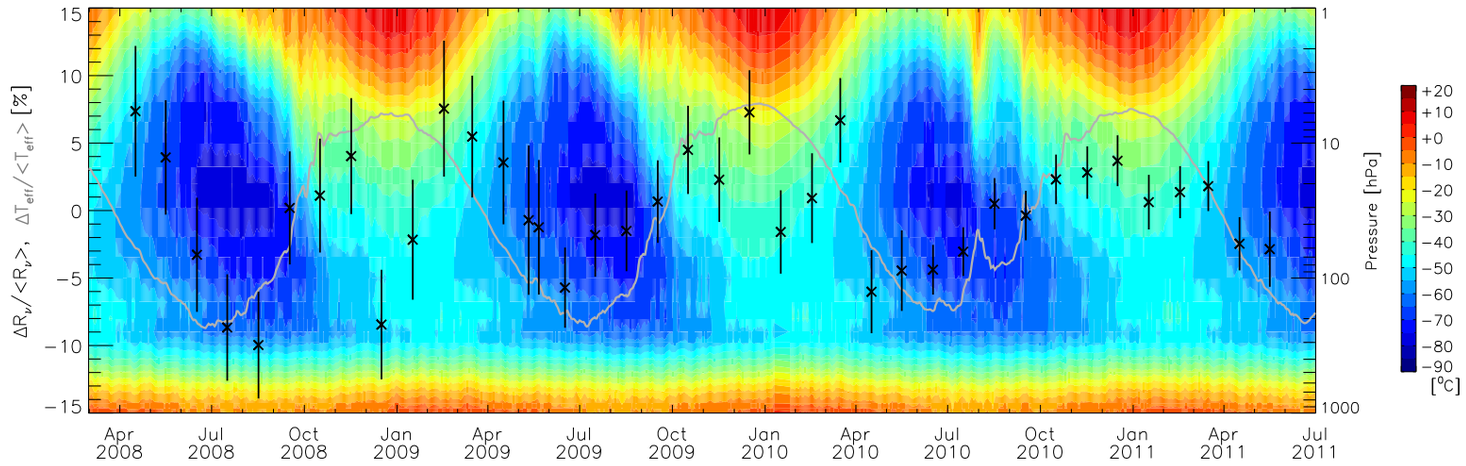
Tilav et al., ICRC 2009
PD et al., ICRC 2011





Vμ

ICRC 2013



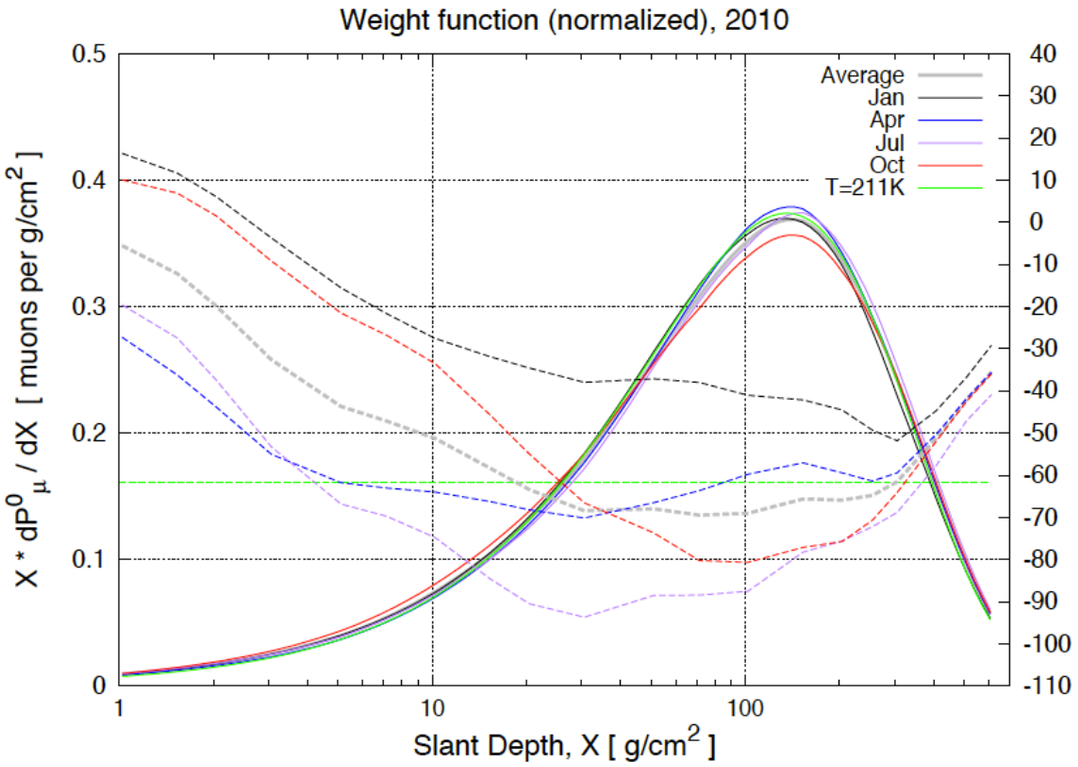
temperature seasonal variations

- muon production spectrum $\mathcal{P}_\mu(E_i, \theta, X)$

- effective temperature

$$T_{eff}(E_i, \theta) = \frac{\int dE_i \int dX\, \epsilon(E_i, \theta)\, \mathcal{P}_\mu(E_i, \theta, X)\, T(\theta, X)}{\int dE_i \int dX\, \epsilon(E_i, \theta)\, \mathcal{P}_\mu(E_i, \theta, X)}$$

temperature data from NASA AIRS instrument on board the Aqua satellite



- temperature dependency of atmosphere density → meson critical energy

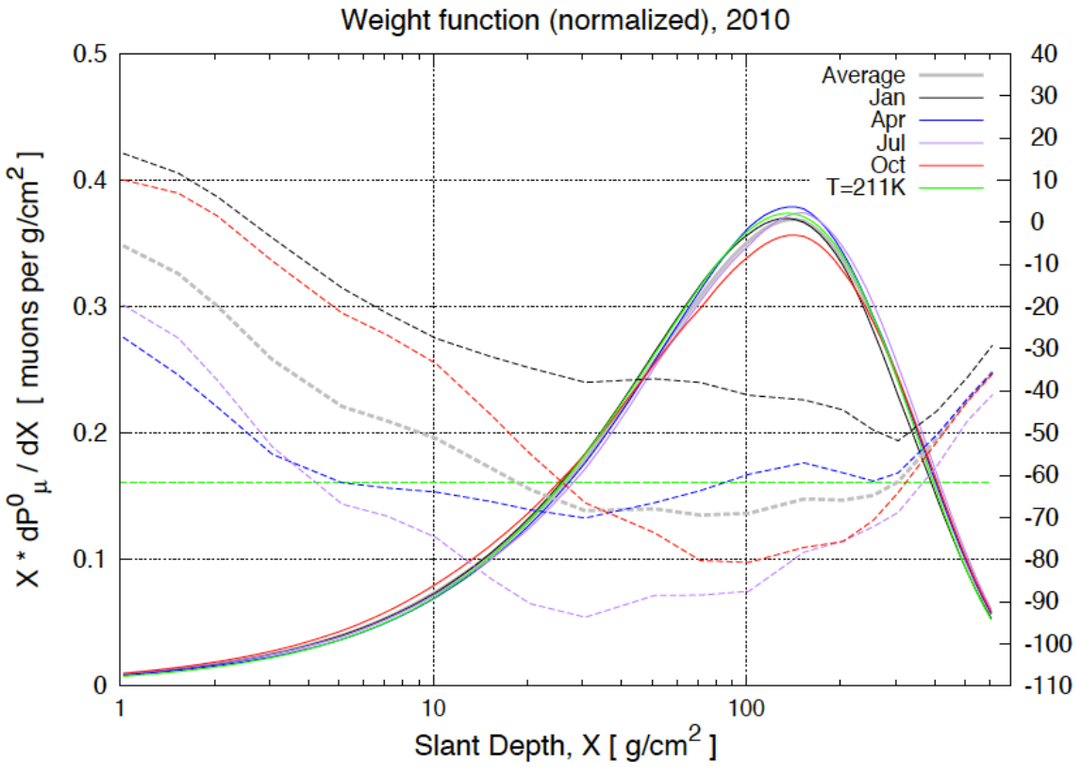
temperature seasonal variations

- temperature coefficient

$$\alpha_T^{th}(\theta) = \frac{T \cdot \frac{\partial}{\partial T} \int dE_i \, \phi_i(E_i, \theta) \, \epsilon(E_i, \theta)}{\int dE_i \, \phi_i(E_i, \theta) \, \epsilon(E_i, \theta)}$$

$$\phi(E_i, \theta) = \int_0^\infty \mathcal{P}_\mu(E_i, \theta) \, dX$$

temperature data from NASA AIRS instrument on board the Aqua satellite



- temperature correlation of lepton intensity

$$\frac{\Delta I_i}{\langle I_i \rangle} = \alpha_T^{th} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle} \qquad vs. \qquad \frac{\Delta R_i}{\langle R_i \rangle} = \alpha_T^{exp} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

$$\alpha_T^{\mu,exp} = 0.860 \pm 0.002(stat.) \pm 0.010(syst.)$$

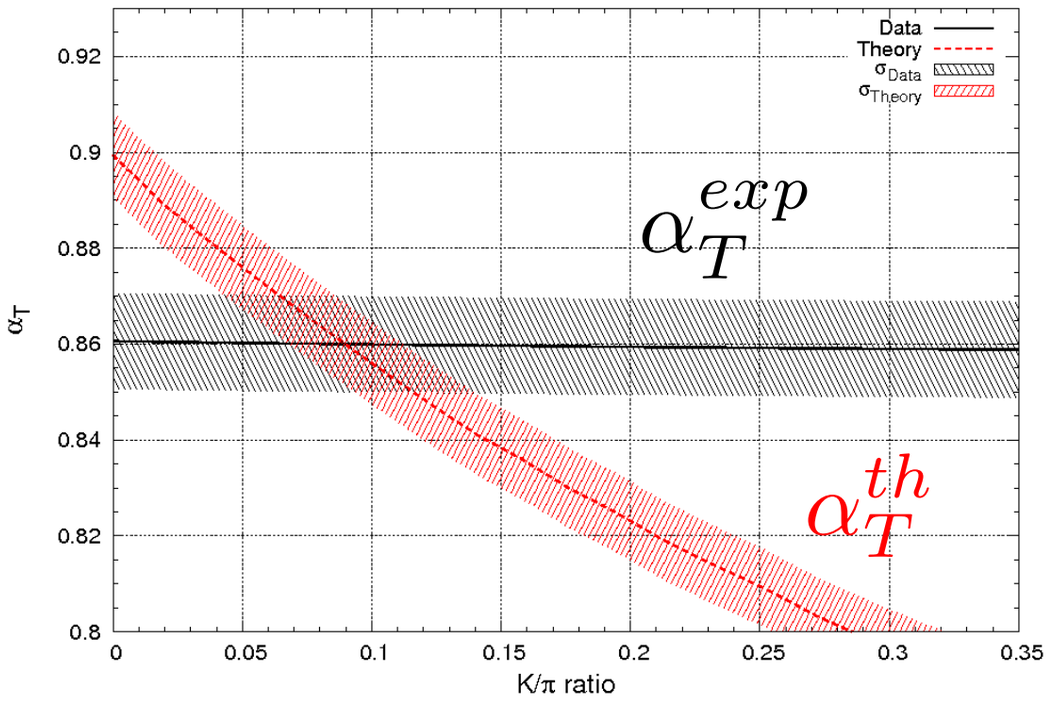
PD et al., ICRC 2011

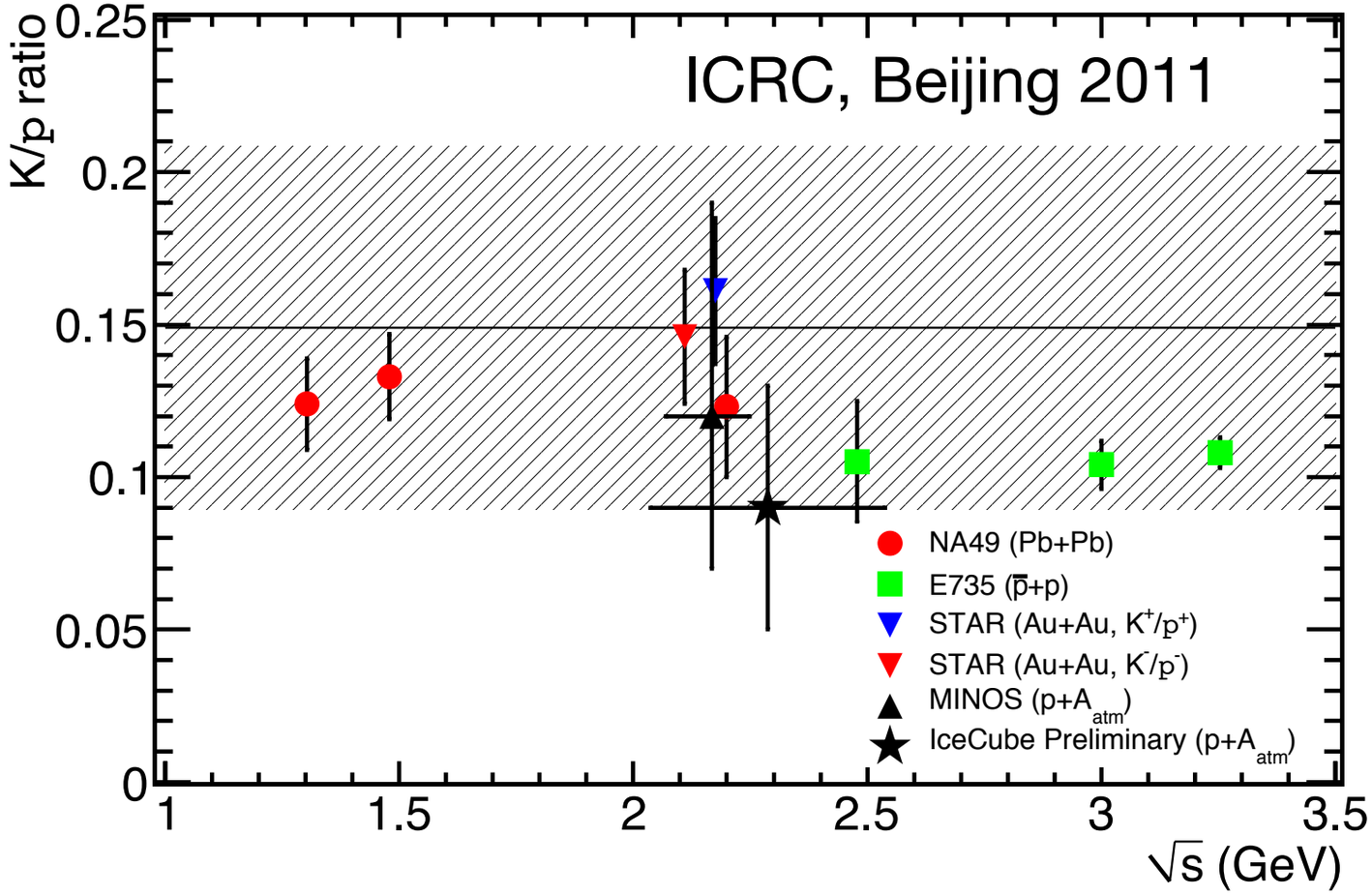
temperature seasonal variations
K/π ratio

$$\phi_\mu(E_\mu,\theta) = \phi_N(E_\mu) \times \left(\frac{1}{1 + B_{\pi\mu}\, cos\theta^\star\, E_\mu/\epsilon_\pi} + \frac{A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu}\, cos\theta^\star\, E_\mu/\epsilon_K} \right) \quad \gamma \approx 1.7$$

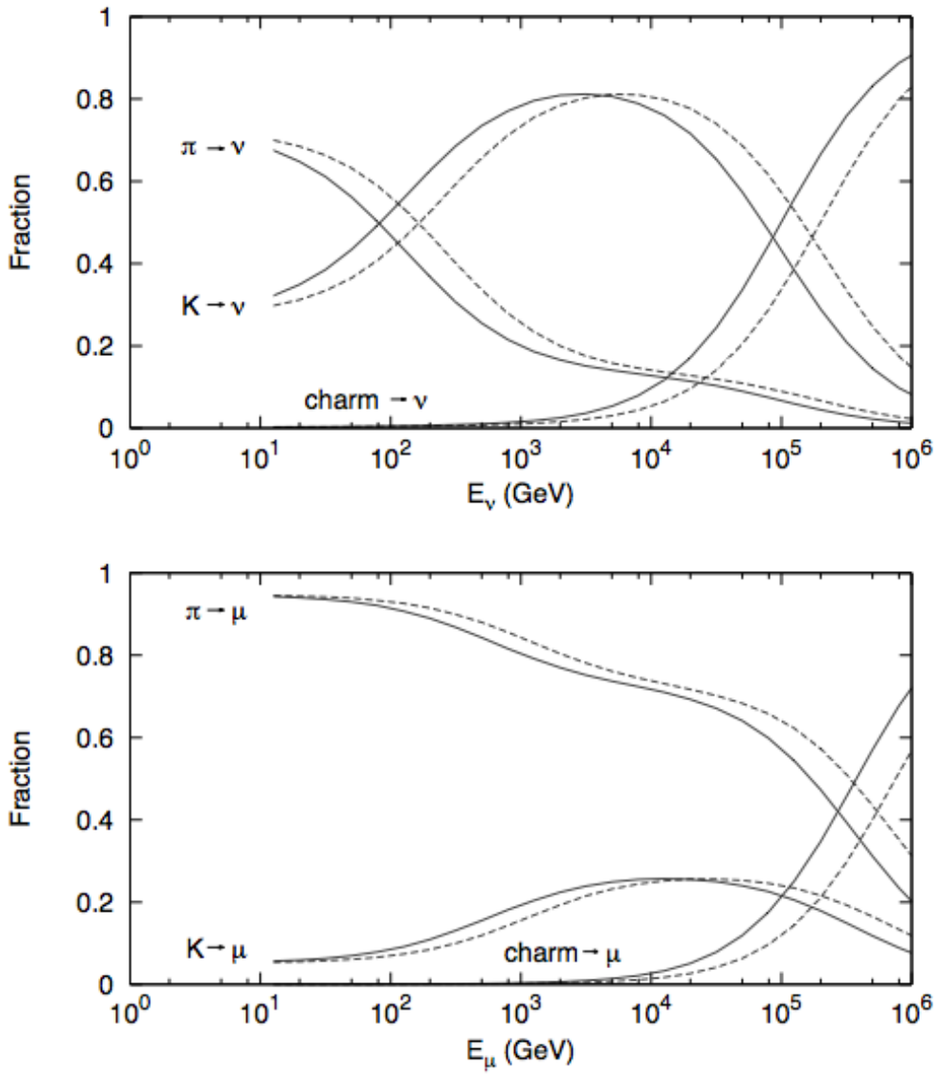
$$A_{K\,\mu}/A_{\pi\,\mu} = \left(\frac{BR_{K\,\mu}}{BR_{\pi\,\mu}}\right)\left(\frac{Z_{K\,\mu}}{Z_{\pi,\mu}}\right)\left(\frac{Z_{N\,K}}{Z_{N\,\pi}}\right)$$

kaon/pion ratio $R(K/\pi) = \dfrac{Z_{N\,K}}{Z_{N\,\pi}}$



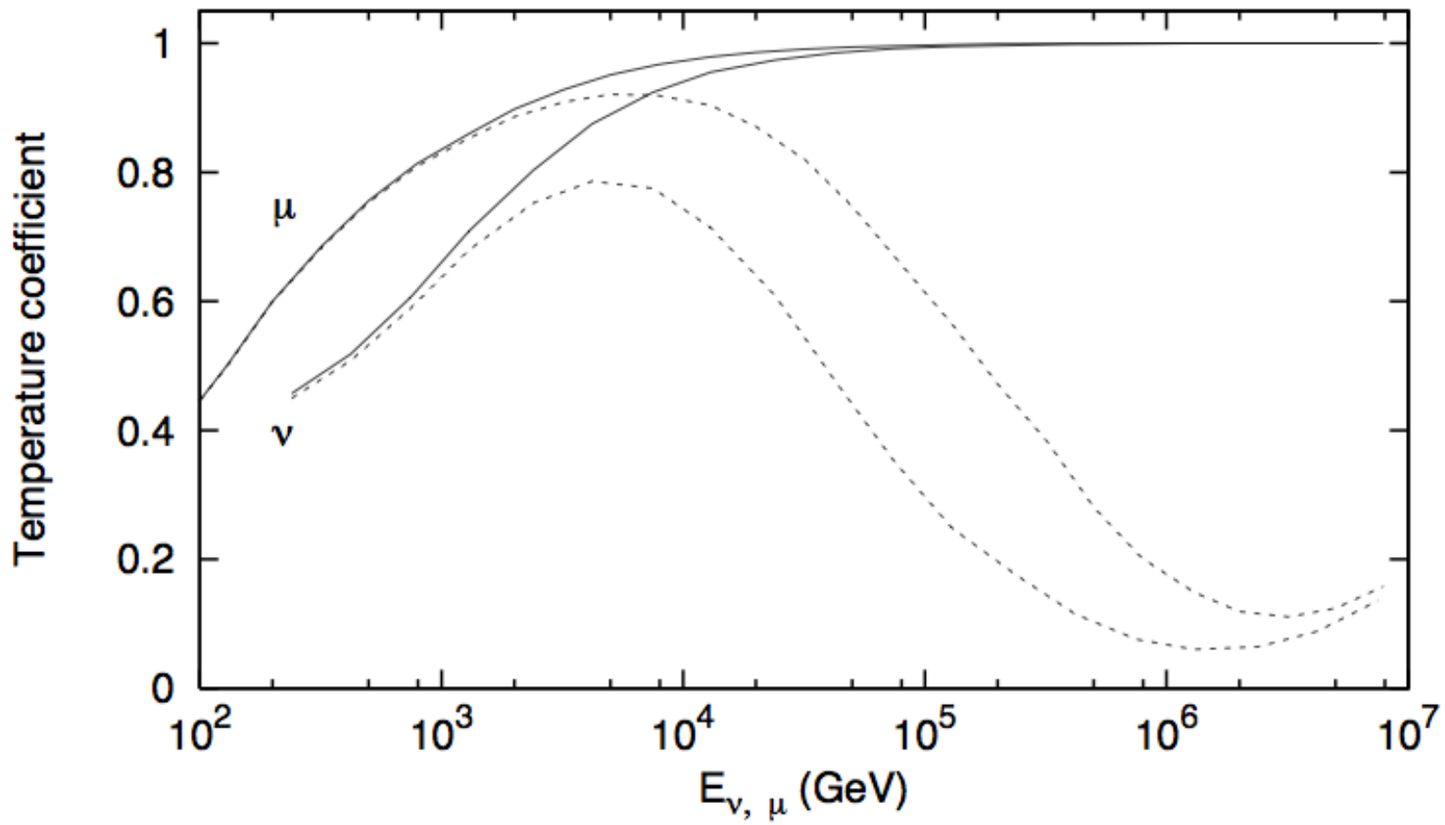


temperature seasonal variations
charm component



PD, Gaisser 2010

charm contribution from RQPM model (Bugaev et al. 1998)

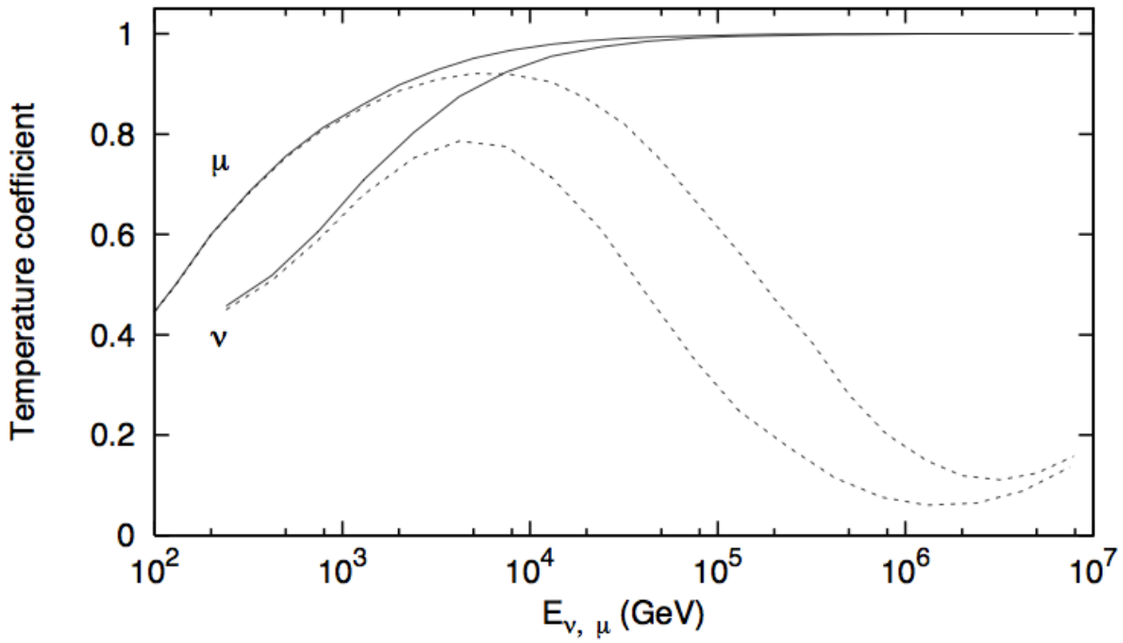


temperature correlation increases as meson interaction probability increases with energy

measurable effect as relative importance of prompt component increases

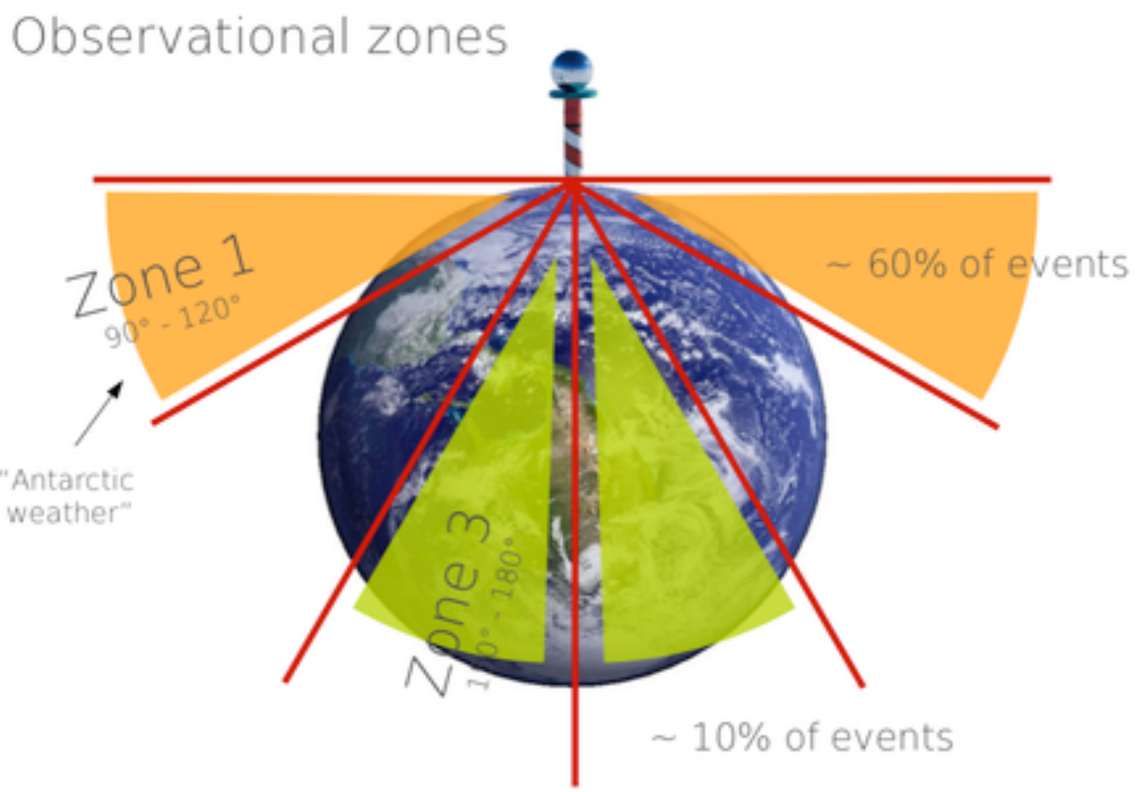
temperature seasonal variations
charm component

PD, Gaisser 2010



$E_{\mu,\min}$	no charm		RQPM charm		ERS charm		int. charm	
	α	Rate	α	Rate	α	Rate	α	Rate
0.5	0.83	2050	0.82	2070	0.82	2050	0.82	2060
10	0.98	1.26	0.89	1.40	0.97	1.26	0.94	1.34
100	1.0	0.0025	0.53	0.0049	0.91	0.0028	0.71	0.0036

TABLE I: Correlation coefficients for muons with ($\theta \leq 30^\circ$) for three levels of charm (energy in TeV; rate in Hz/km^2).

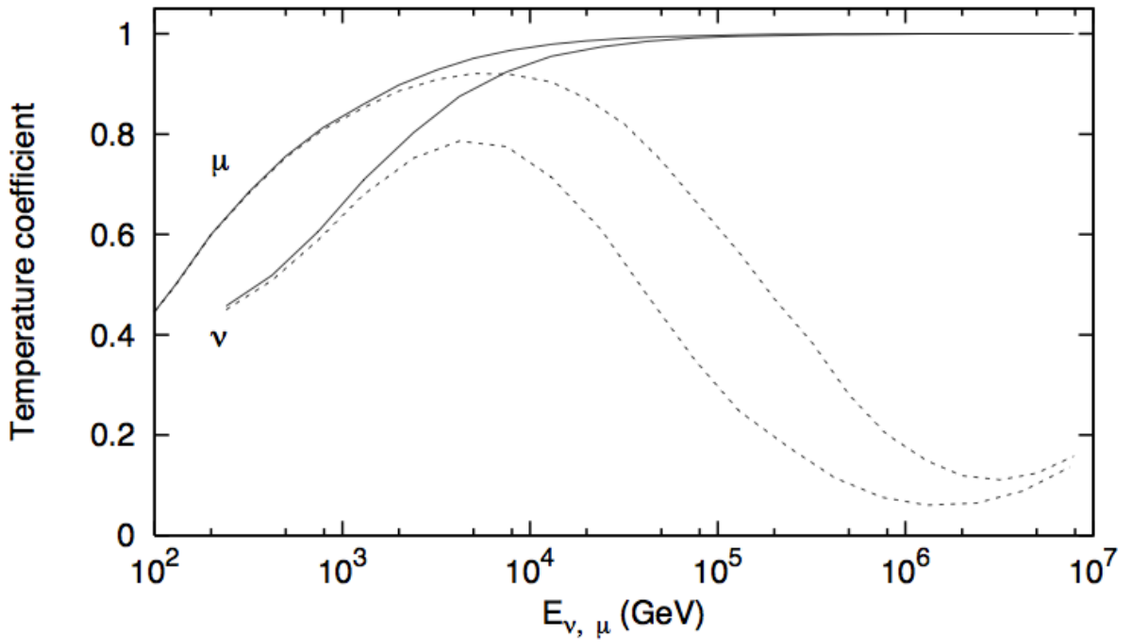


IC40×2

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 1	α	Events/yr	α	Events/yr
all	0.54	16000	0.52	17000
3	0.70	5900	0.62	6300
30	0.94	350	0.72	450

temperature seasonal variations
charm component

PD, Gaisser 2010



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muon multiplicity modifies temperature correlation (ICRC 2013)

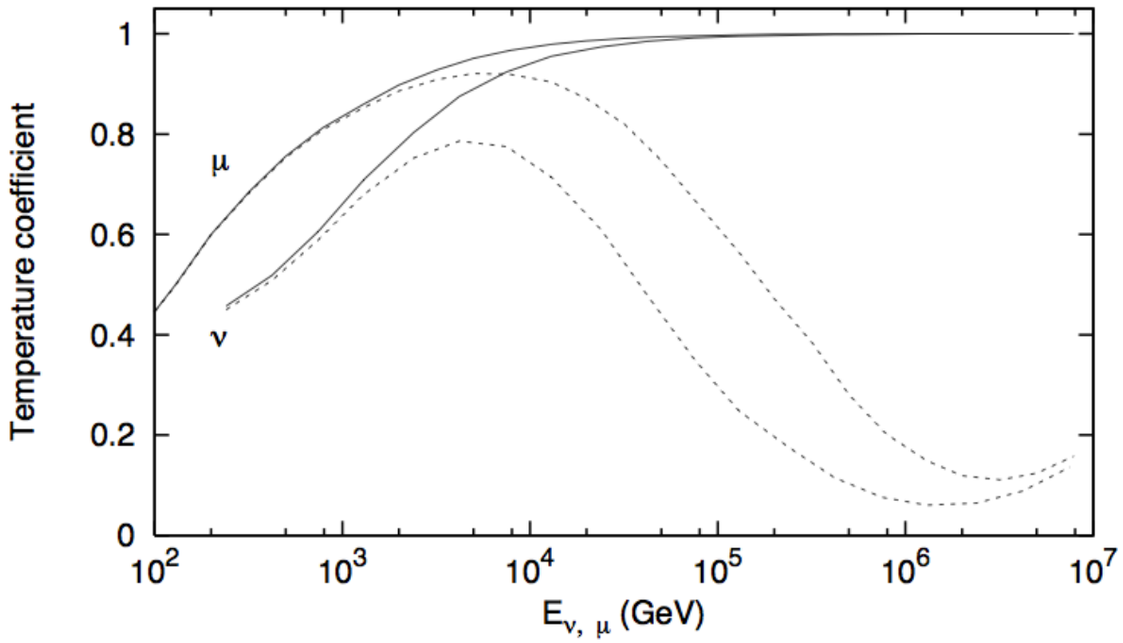
need to evaluate the energy of individual muons in the bundle

→ *single muons*

- 2×10^8 μ/day → 220-430 μ/day
- α_T^{th} decreases 10-30% for $E_\mu > 100$ TeV
- **10 years of HE muon data**

temperature seasonal variations
charm component

PD, Gaisser 2010



- 100 v/day → 2-3 v/day
- α_T^{th} decreases 20% for E_ν > 30 TeV
- long time to accumulate enough statistics

astrophysical neutrinos do not correlate with atmospheric temperature

neutrinos produced in larger portion of Earth's atmosphere

small event statistics

IC40×2 → **IC86** ~ 4.8×IC40

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 1	α	Events/yr	α	Events/yr
all	0.54	38400	0.52	40800
3	0.70	14160	0.62	15120
30	0.94	840	0.72	1080

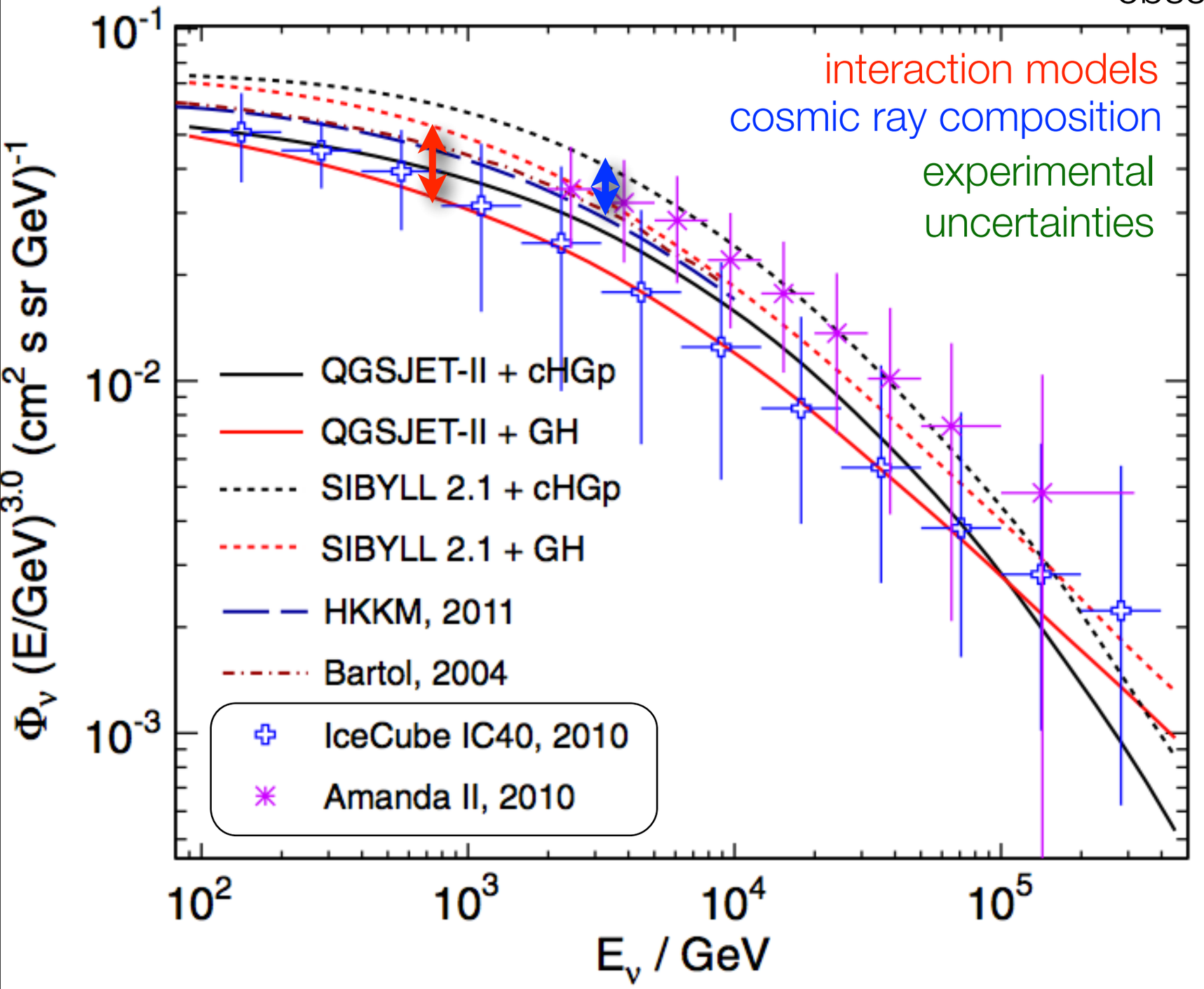
conclusions

- *single / low multiplicity* **muons** useful tool to probe **charm production** in the atmosphere
  - in association to lower **stratospheric temperature** variations in Antarctica
  - measuring **laterally separated muons** @ high energy (Soldin's talk)
  - measuring **spectrum** of *single/low multiplicity (horizontal)* **muons**
- **hadronic models** for heavy quark production & μ/ν correlation
- charm production described with pQCD: **intrinsic charm** & **forward physics**

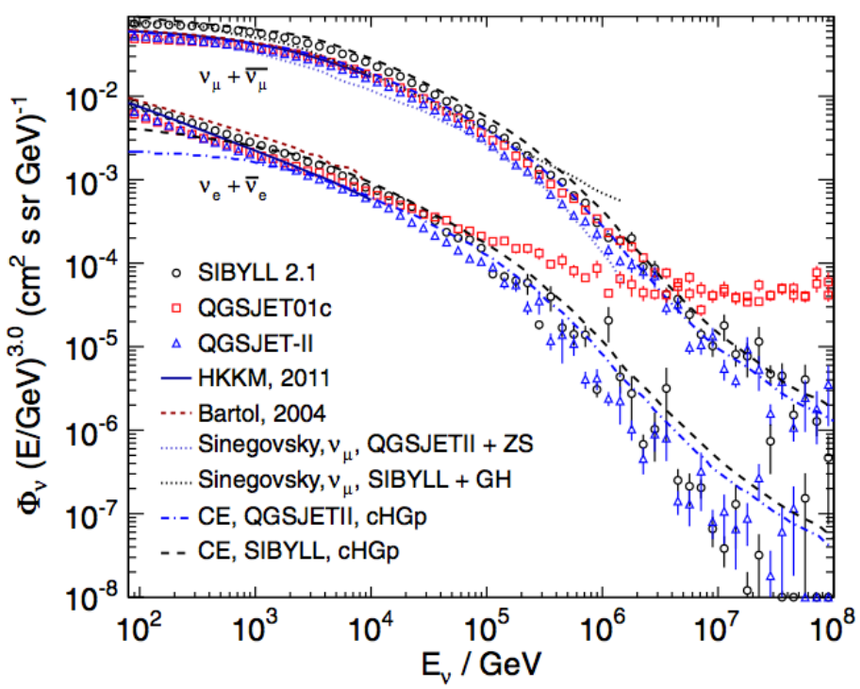
backup slides

particle production in the atmosphere
atmospheric leptons

observed through-going $\nu_\mu + \bar{\nu}_\mu$

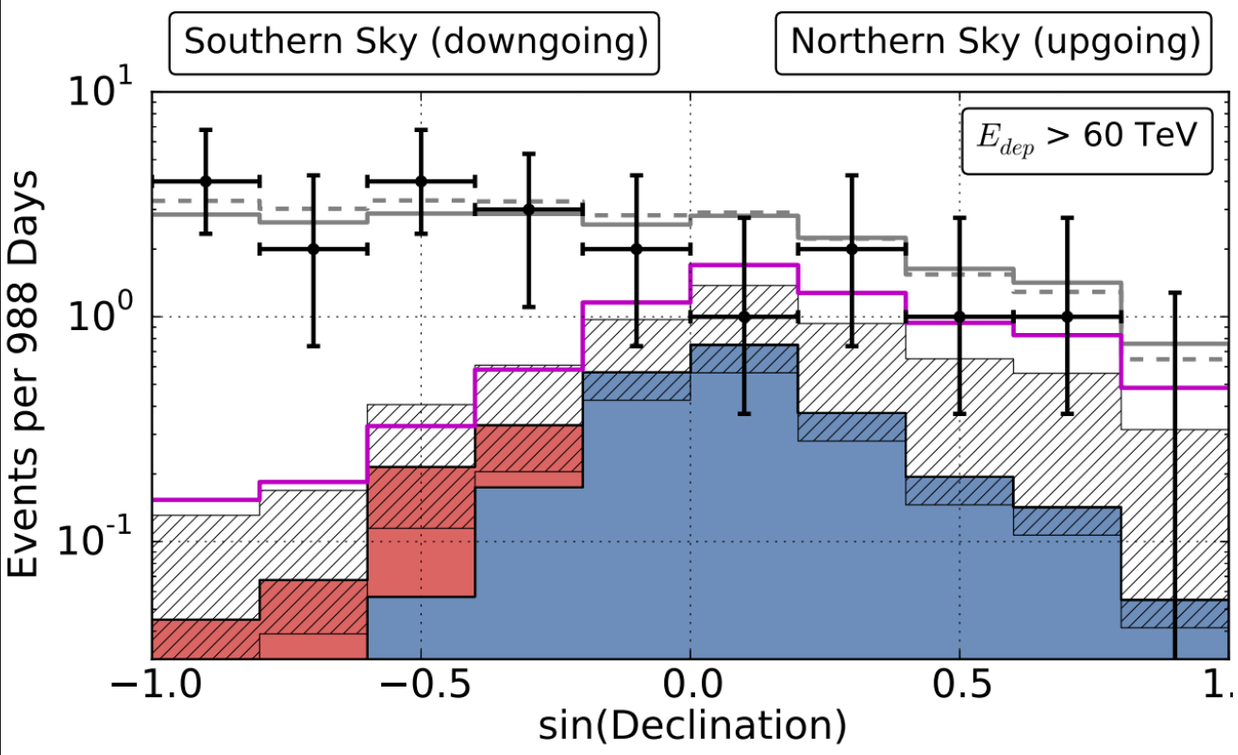


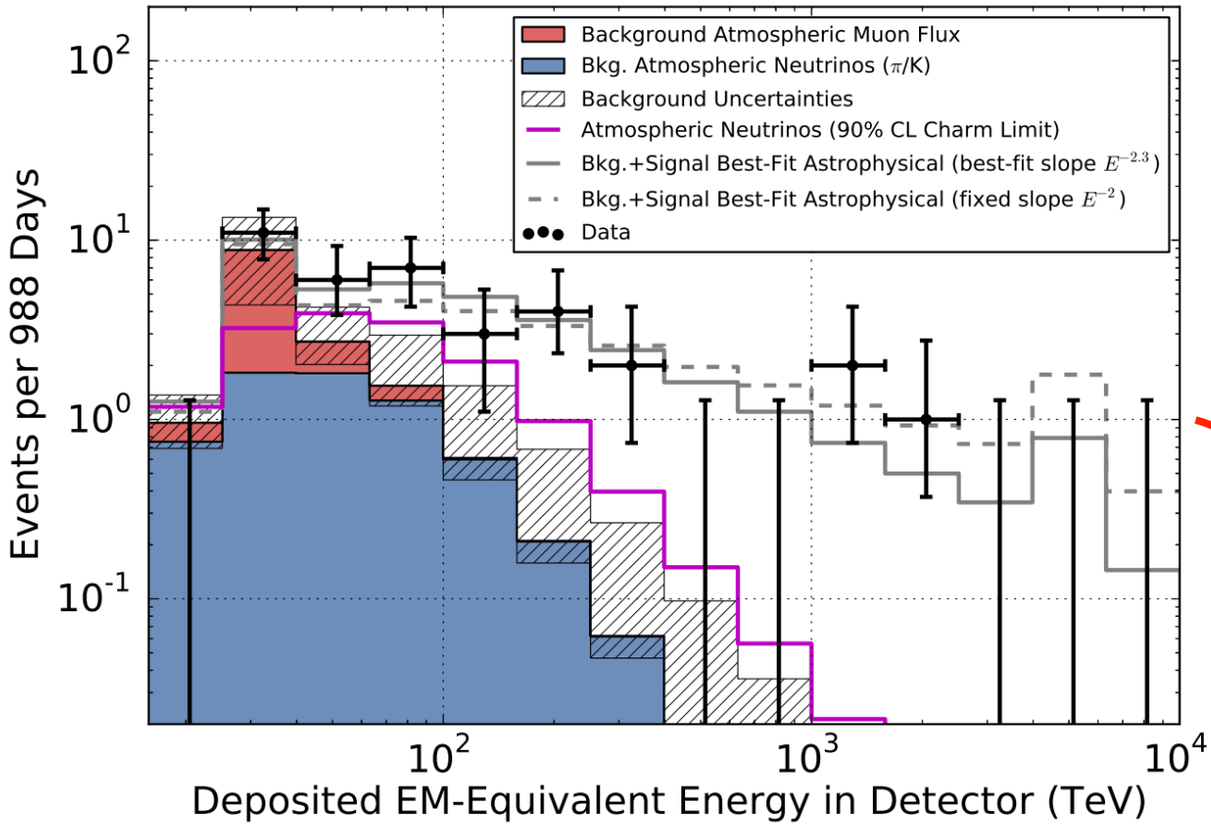
Fedynitch, Becker Tjus, PD 2012



heavy quark production and astrophysics

observed starting all-direction **all-flavor**





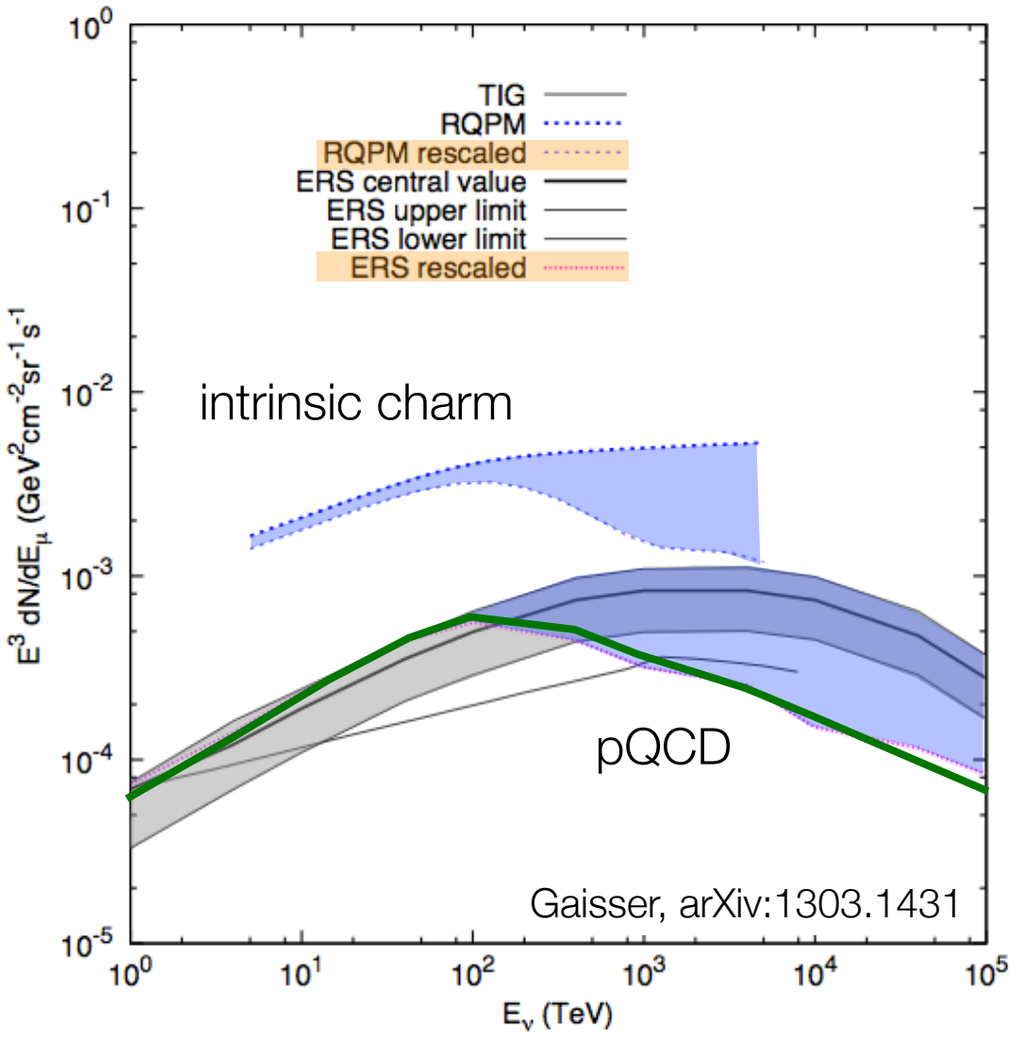
Aartsen et al. Science 342 (2013) 1242856
Aartsen et al. arXiv:1405.5303

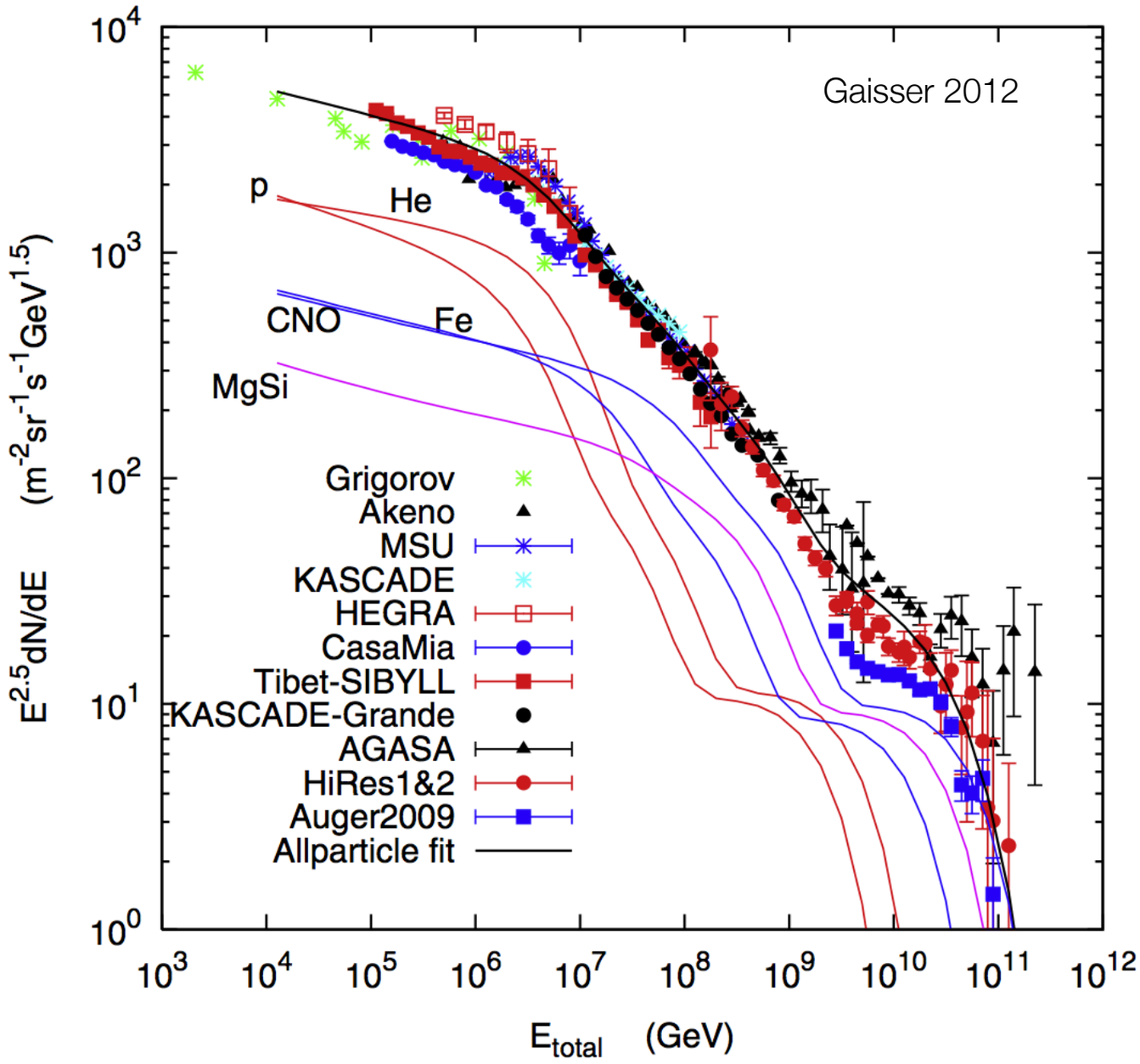
→ can neutrino telescope measure neutrinos from charm ?

astrophysical neutrinos ?

heavy quark production and astrophysics

- effect of charm production **models**
- effect of primary **cosmic ray spectrum**





heavy quark production and astrophysics

transverse momentum p_T
vs
pseudo-rapidity

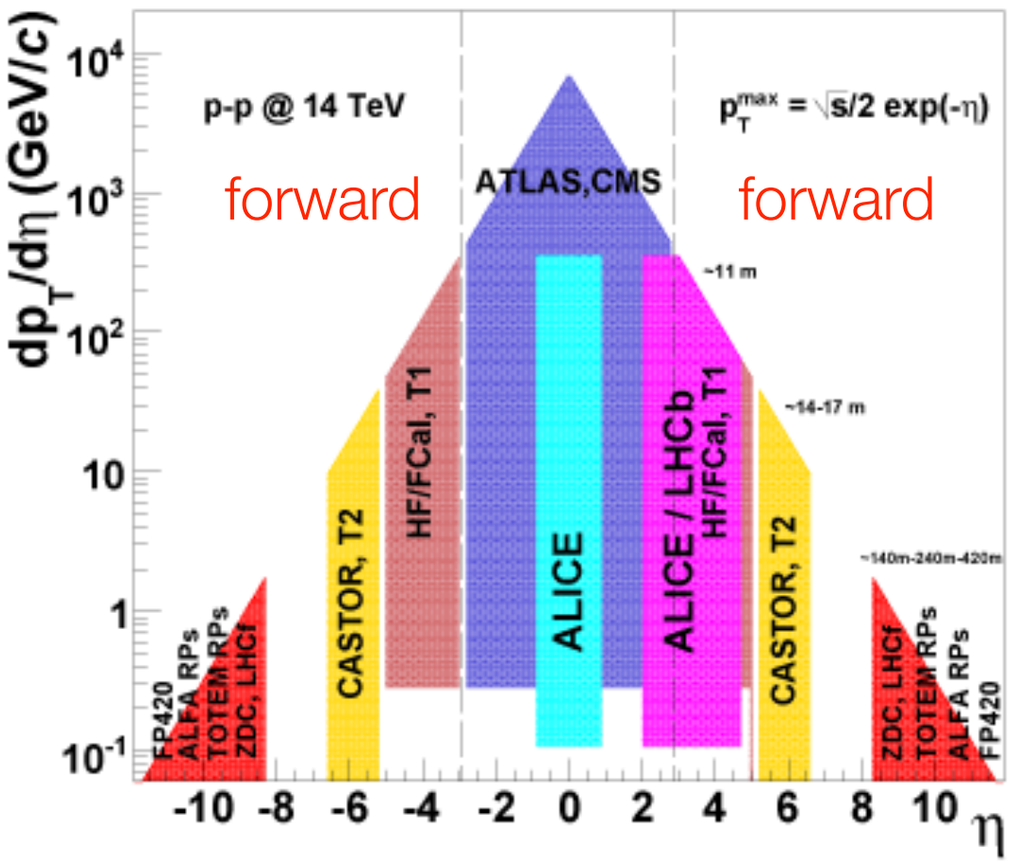
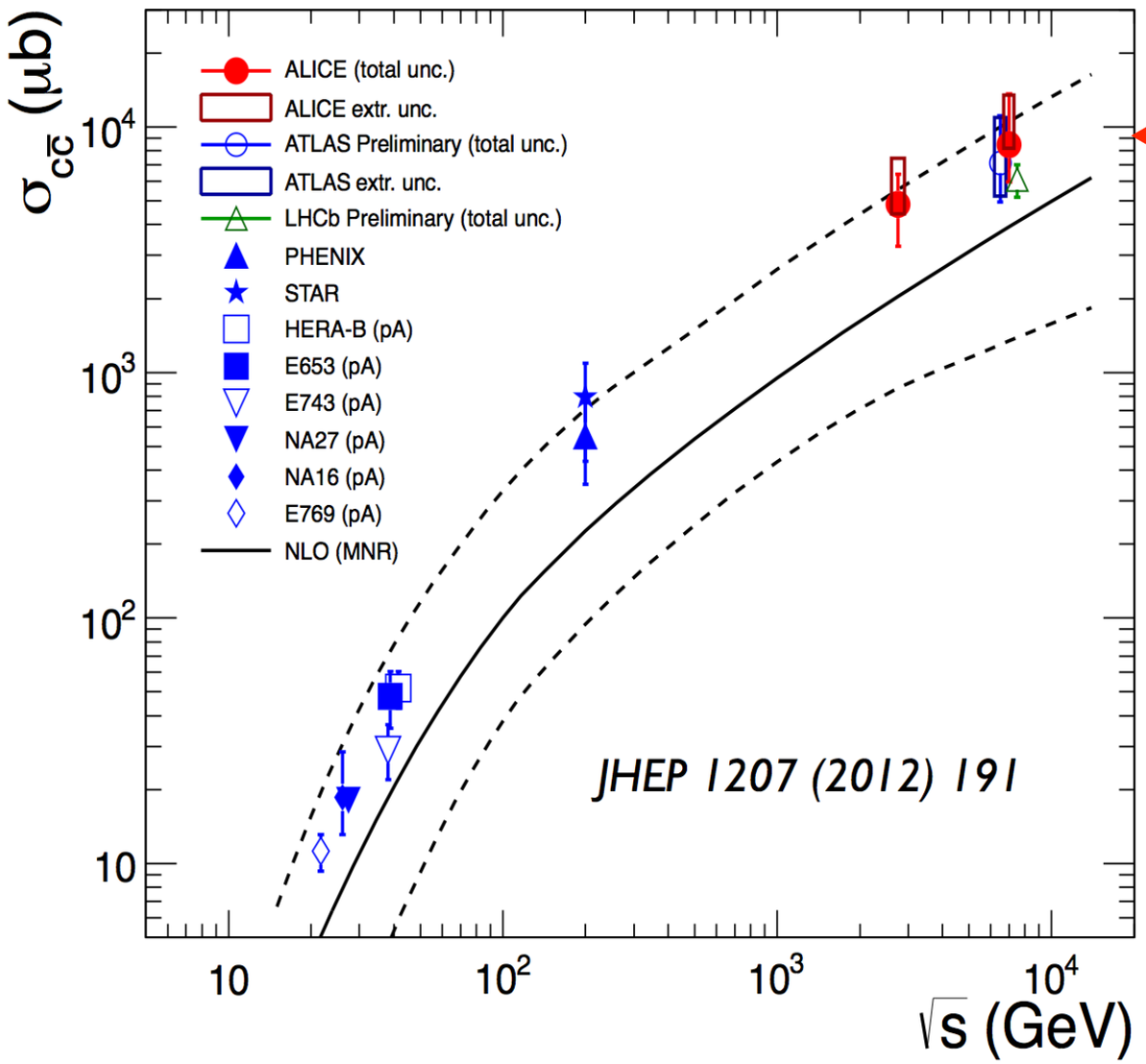


FIG. 3: Approximate p_T-η coverage of current (and proposed) detectors at the LHC (adapted from [2]).



data in available range of η agrees with models

extrapolation to full phase space (FONLL)

heavy quark production and astrophysics

- due to large quark mass, **perturbative QCD** can be used (hard component). However
  - significant charm production observed at $\sqrt{s}$ = 20 GeV
  - asymmetry in charm / anti-charm baryons (Selex Coll. 2002) → **intrinsic production**

- $|p\rangle = \alpha|uud\rangle + \beta|uudc\bar{c}\rangle + \ldots$: the **c-pair** produced in projectile fragmentation can recombine with valence quarks and with sea-quarks to **produce charmed hadrons**.

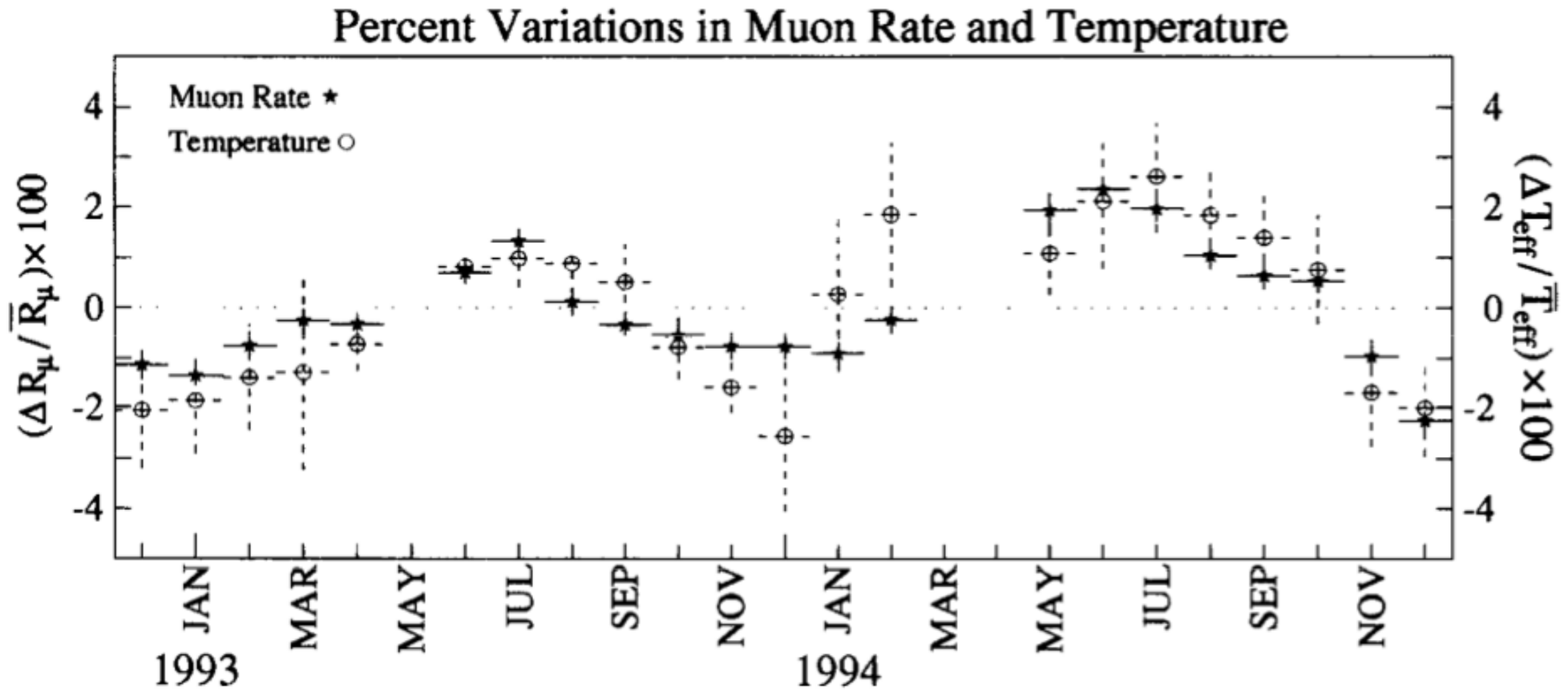
$p \rightarrow \Lambda_c^+ + \bar{D}^0$ ~ order $(m_s/m_c)^2$ (~1%) compared to $p \rightarrow \Lambda K^+$

- inclusive D-meson spectrum dominated by intrinsic charm at high pseudo-rapidity & p_T

  Lykasov+ 2012

- steep cosmic ray spectrum might **enhance the effect of intrinsic production** of charm

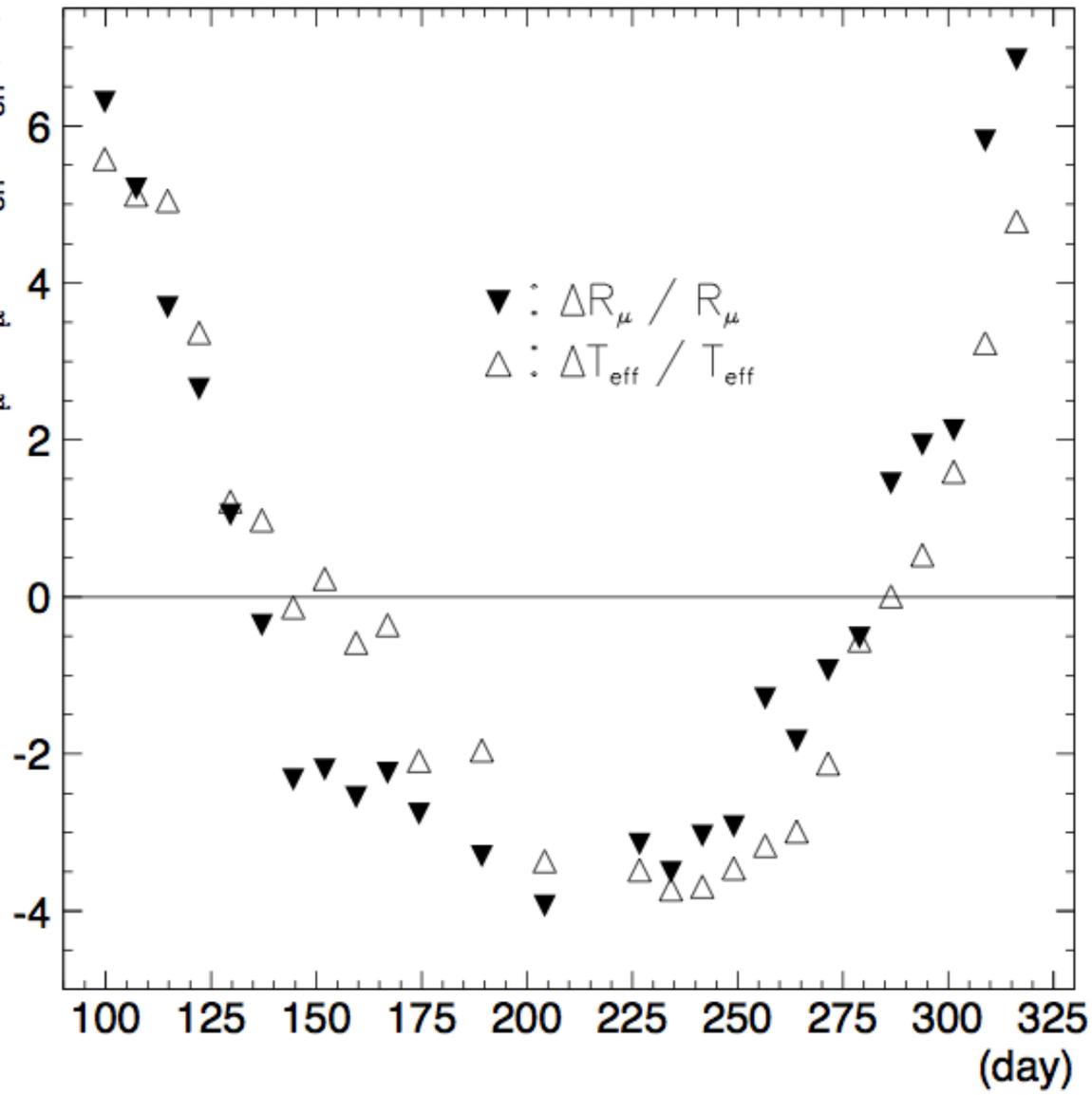
temperature seasonal variations



MACRO

Ambrosio et al. 1997

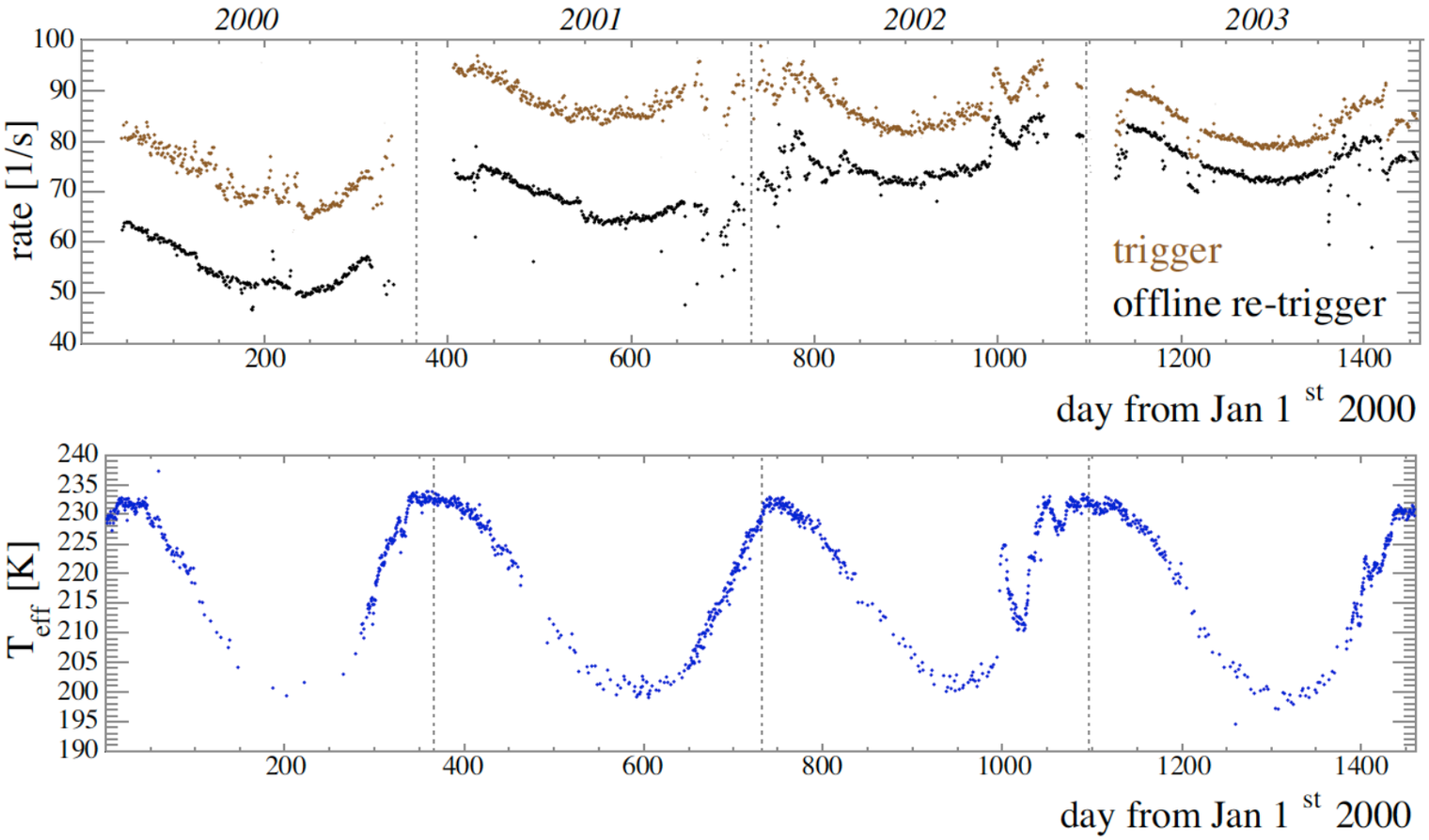
temperature seasonal variations



AMANDA

Bouchta et al. 1999

temperature seasonal variations



AMANDA

Wissing, 2004

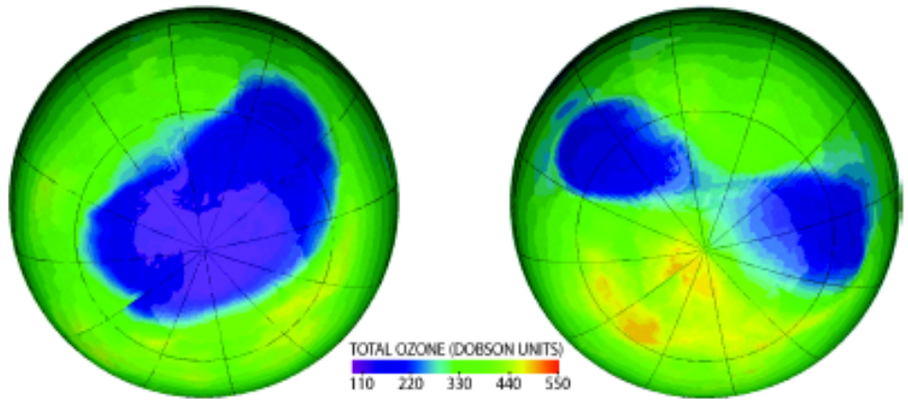
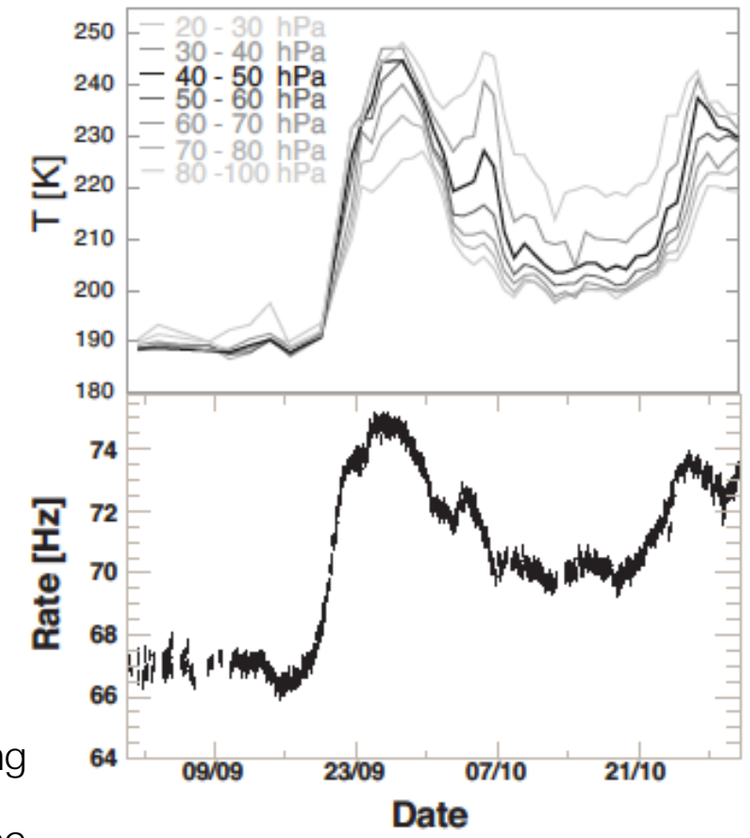


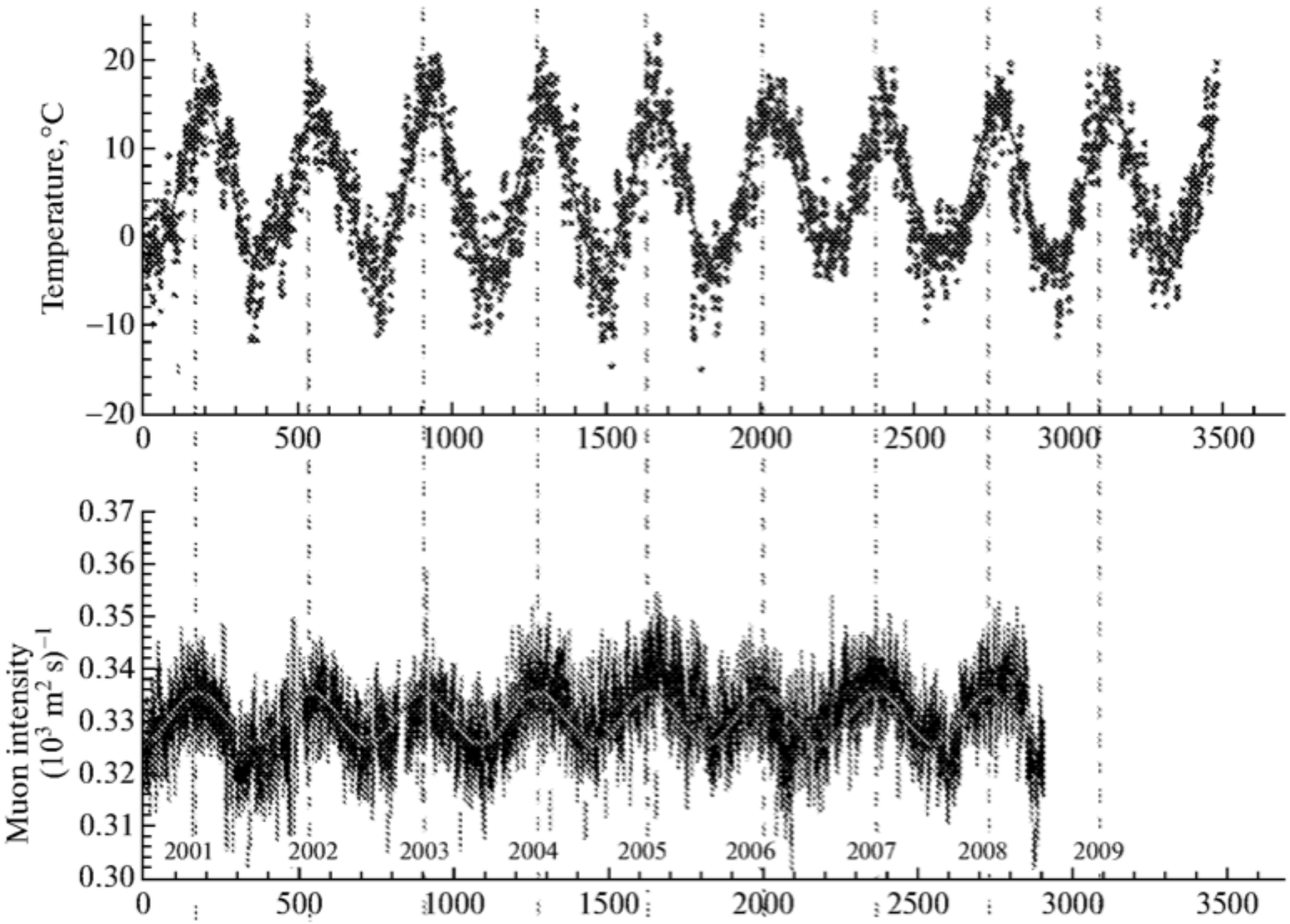
Fig. 3. Ozone concentration over the southern hemisphere on September 20th 2002 (left) and September 25th 2002 (right) [10].



sudden stratospheric warming

Tilav et al., ICRC 2009

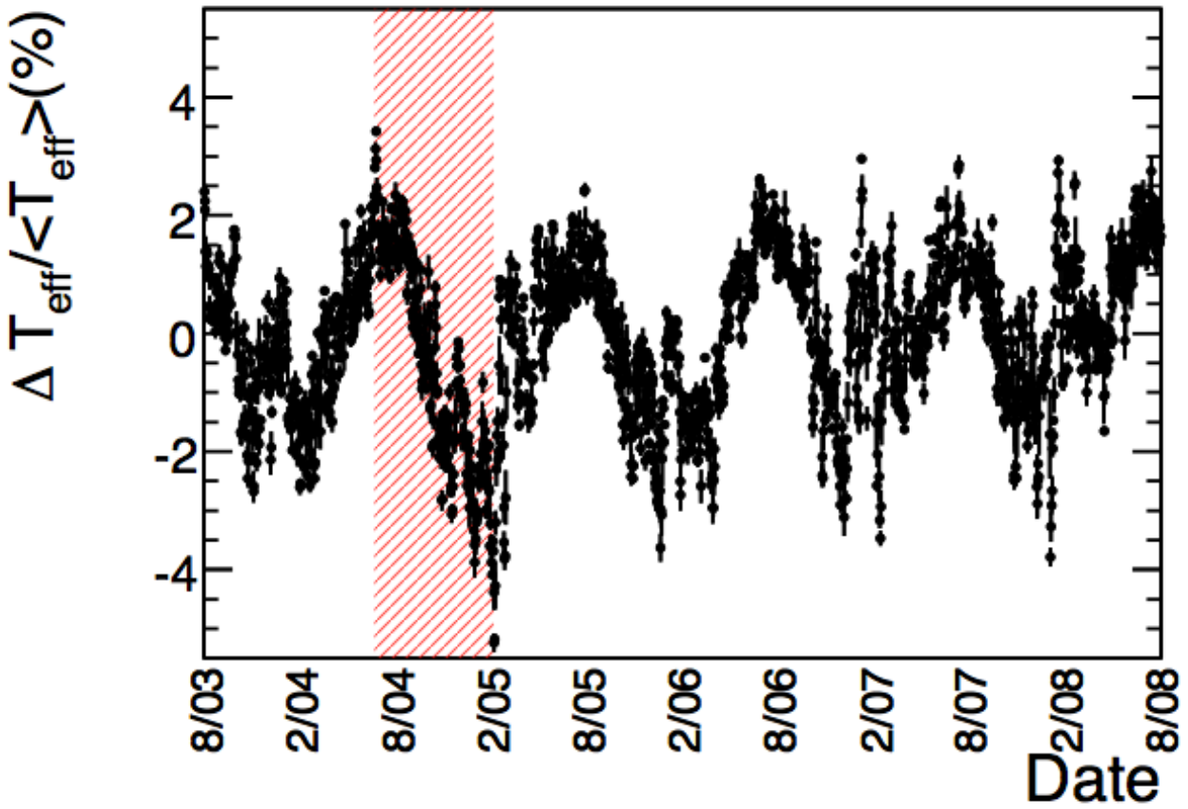
temperature seasonal variations

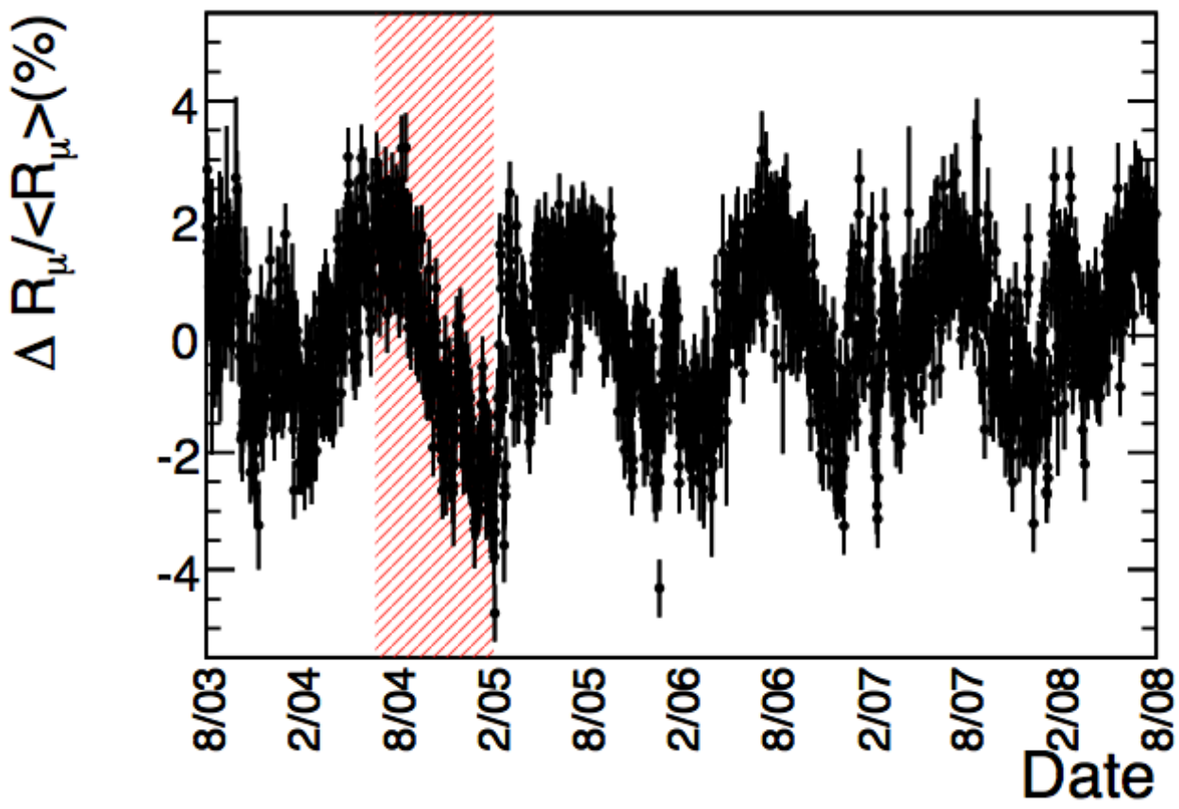


LVD

Selvi et al. 2009
Agafanova et al 2011

temperature seasonal variations

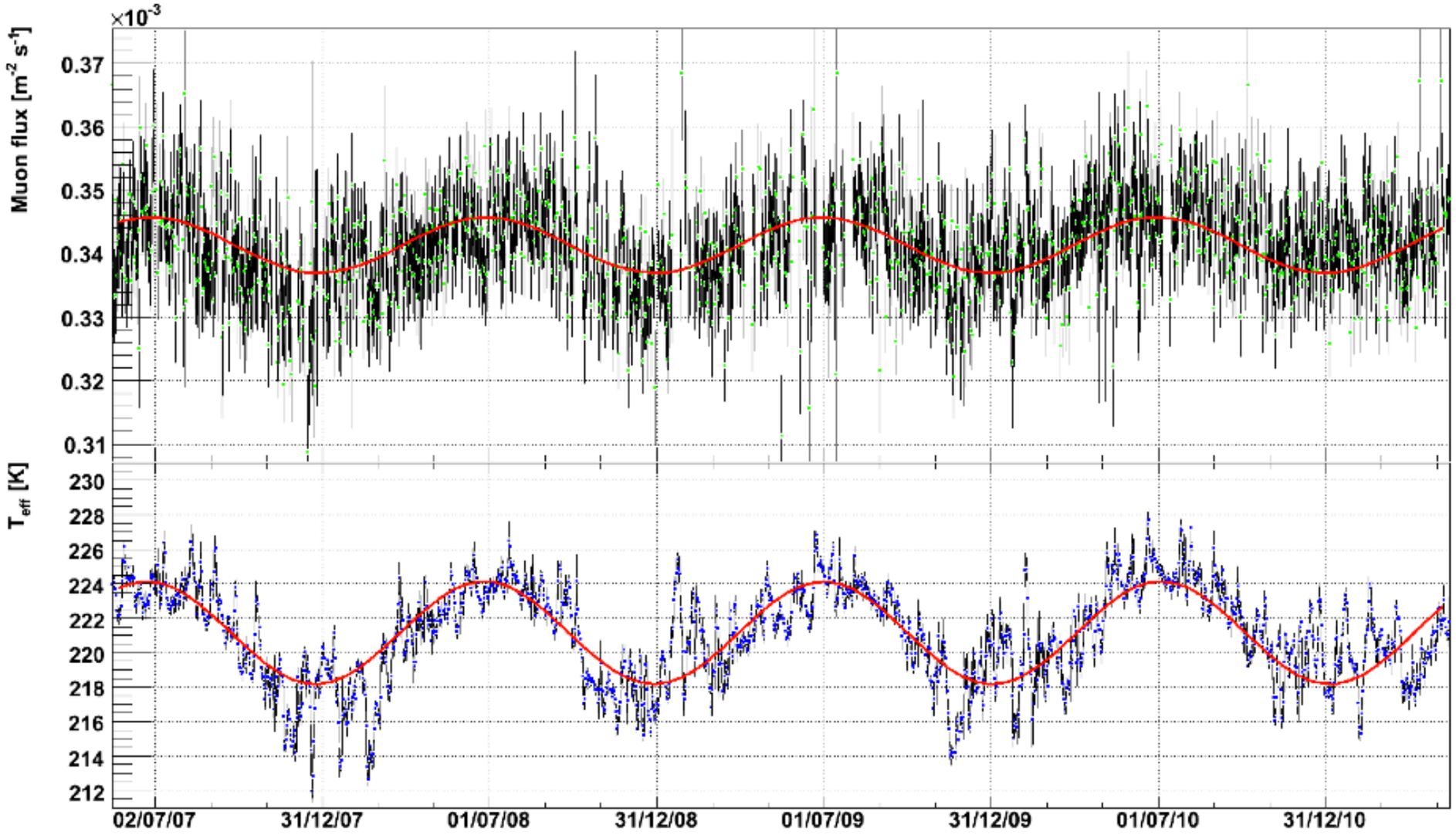




MINOS

de Jong, Grashorn et al. 2009
Adamson et al. 2010

temperature seasonal variations

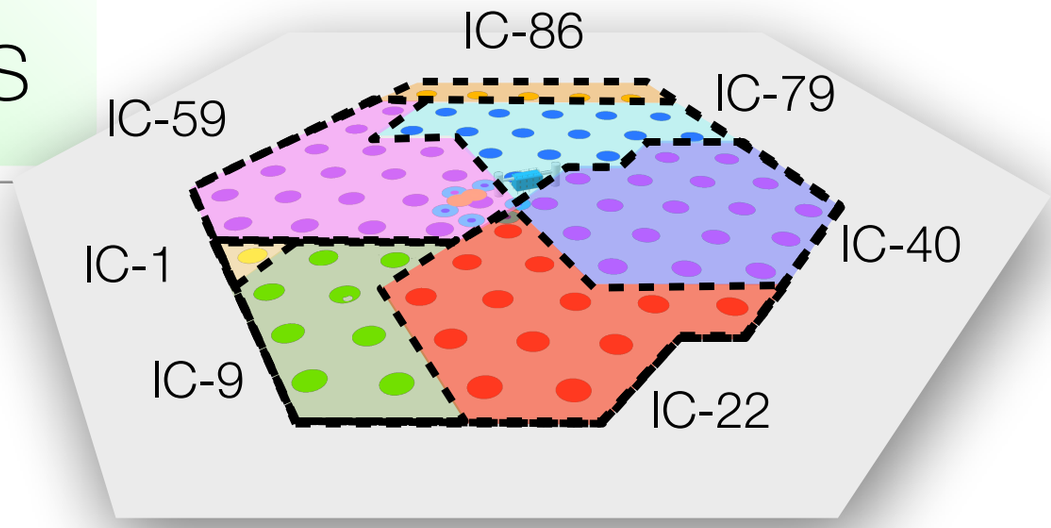


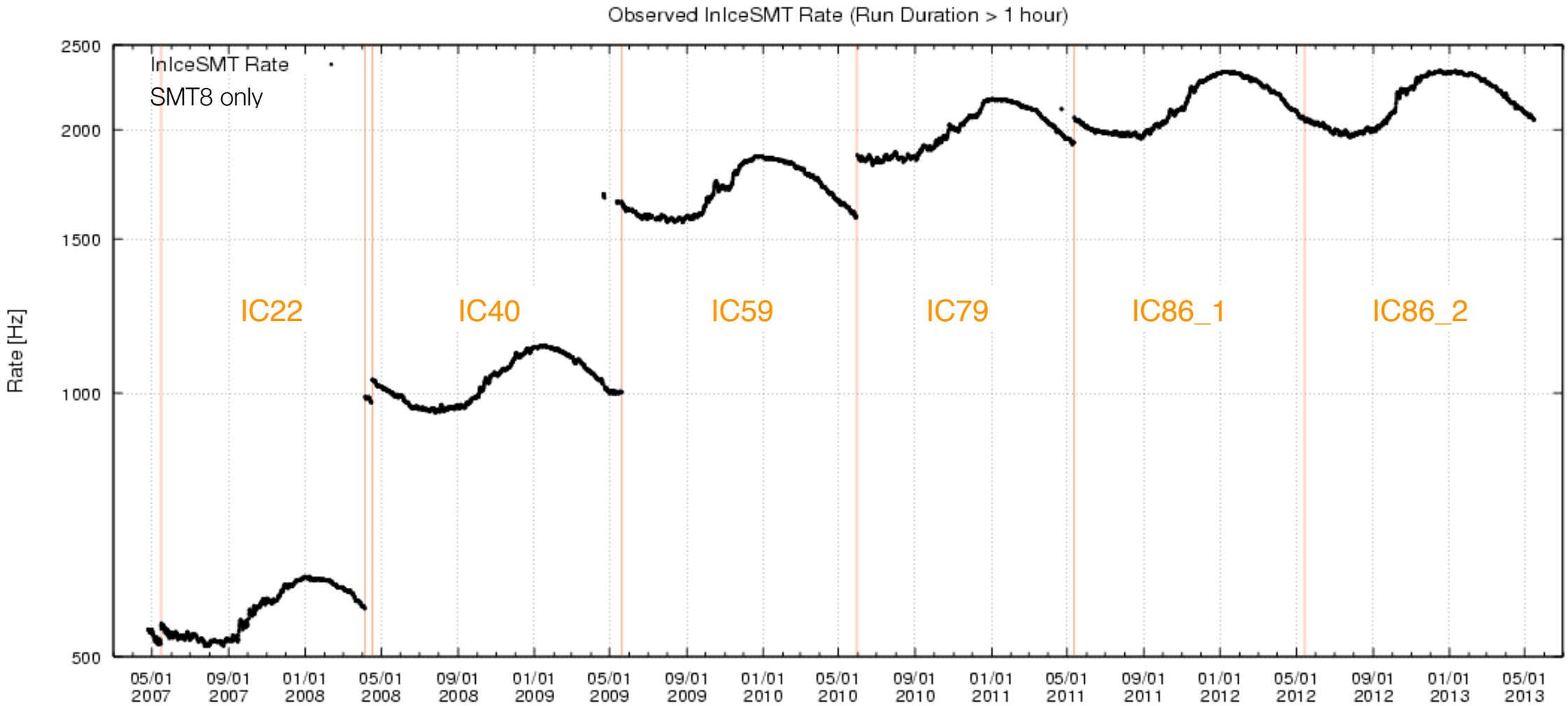
Borexino

Adamson et al. 2010

temperature seasonal variations

Year	μ rate (SMT8)	CR shower rate (STA3)
2007	500 Hz	13 Hz
2008	1100 Hz	15 Hz
2009	1700 Hz	25 Hz
2010	2000 Hz	30 Hz
2011+	2200 Hz	35 Hz

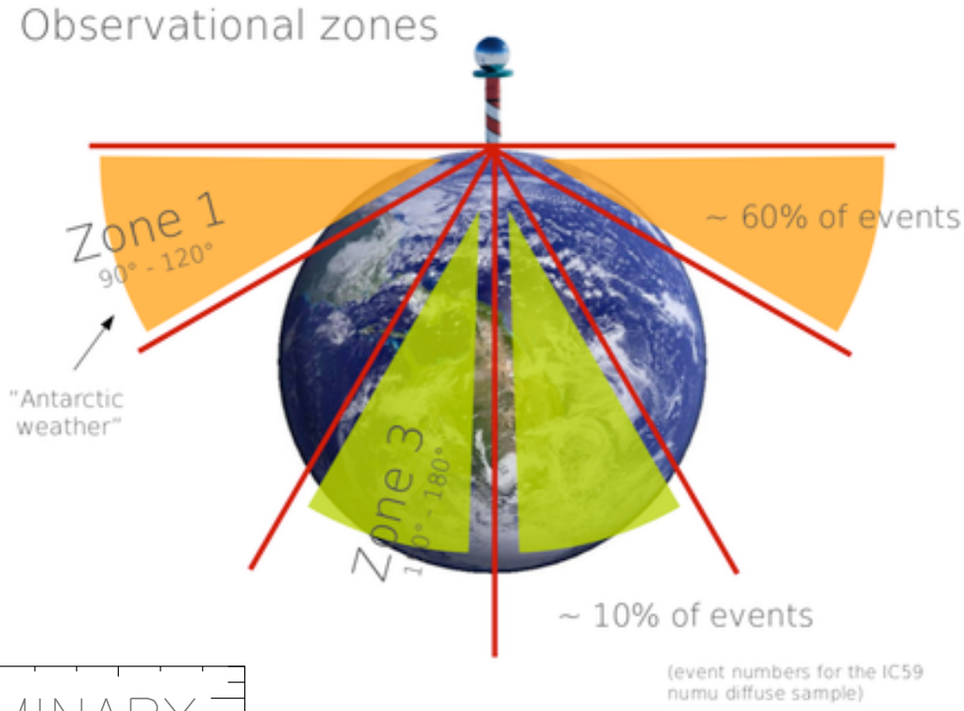




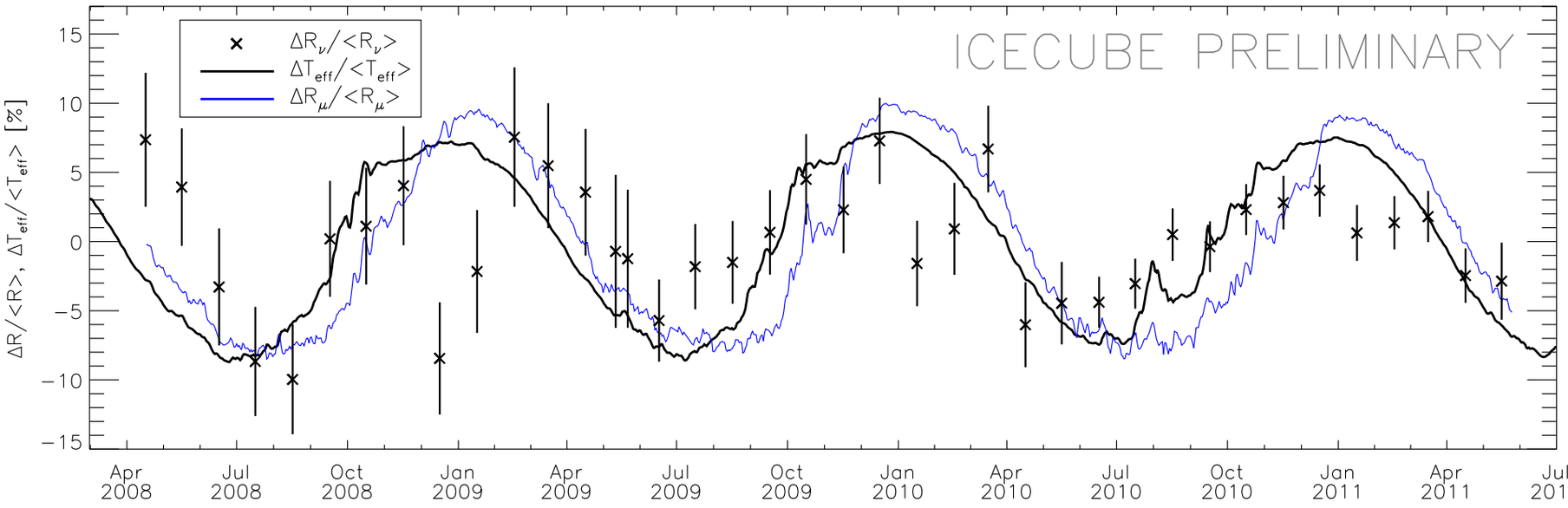
temperature seasonal variations

effective temperature

$$T_{eff}(\theta) = \frac{\int dE_\nu \int dX \; A_{eff}(E_\nu,\theta) P(E_\nu,\theta,X) T(\theta,X)}{\int dE_\nu \int dX \; A_{eff}(E_\nu,\theta) P(E_\nu,\theta,X)}$$



Tilav et al., ICRC 2009
PD et al., ICRC 2011
PD et al., ICRC 2013

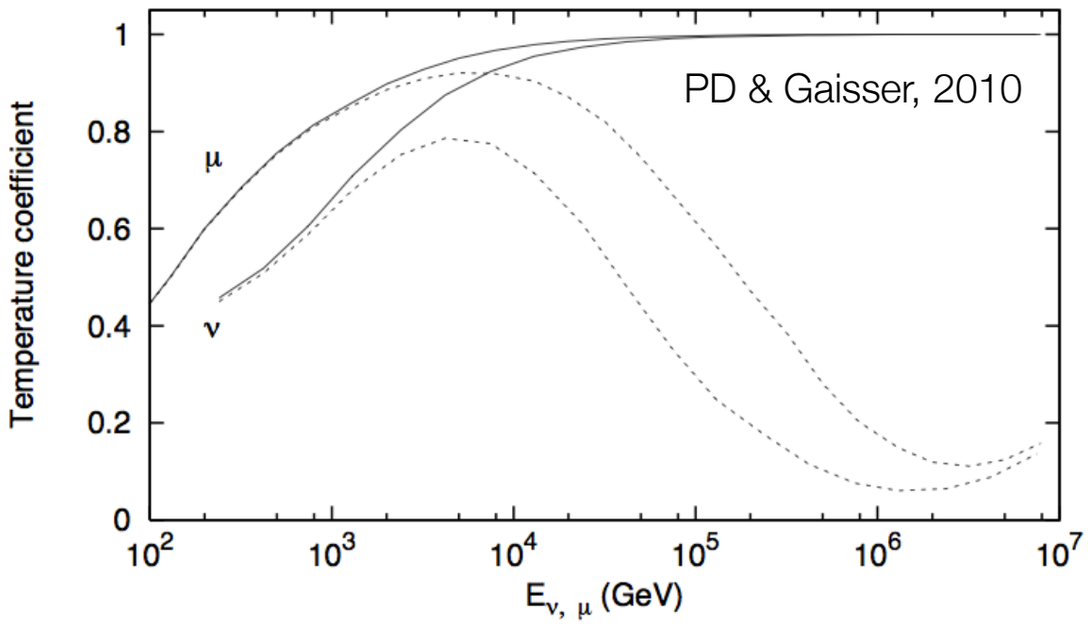


seasonal variations decrease with prompt component

temperature coefficient

$$\alpha_T^{th}(\theta) = \frac{T \cdot \frac{\partial}{\partial T} \int dE_\nu \, \phi_\nu(E_\nu,\theta) A_{\rm eff}(E_\nu,\theta)}{\int dE_\nu \, \phi_\nu(E_\nu,\theta) A_{\rm eff}(E_\nu,\theta)}$$

$$\frac{\Delta R_\nu}{\langle R_\nu \rangle} = \alpha_T^{exp} \frac{\Delta T_{\rm eff}}{\langle T_{\rm eff} \rangle}$$



History

- Cornell — P.H. Barret et al., Refs. Mod. Phys. 24 133 (1952)
- MACRO — M. Ambrosio et al., Astropart. Phys. 7 109 (1997)
- AMANDA — A. Bouchta, Proc. 26th ICRC (1999)
- LVD — M. Selvi, Proc. 31st ICRC (2009)
- IceCube — S. Tilav et al., Proc 31st ICRC (2009)
- MINOS — P. Adamson et al., Phys. Rev. D81 012001 (2010)
- LVD — N.Y. Agafonova et al., Bull. Rus. Acad. Sci. Phys. 75-3 427 (2011)
- Borexino — G. Bellini et al., arXiv:1202.6403

temperature seasonal variations

$$\phi_\mu(E_\mu,\theta) = \phi_N(E_\mu) \times \left(\frac{1}{1 + B_{\pi\mu}\, cos\theta^\star\, E_\mu/\epsilon_\pi} + \frac{A_{K\mu}/A_{\pi\mu}}{1 + B_{K\mu}\, cos\theta^\star\, E_\mu/\epsilon_K} \right)$$

$$A_{K\,\mu}/A_{\pi\,\mu} = \left(\frac{BR_{K\,\mu}}{BR_{\pi\,\mu}}\right)\left(\frac{Z_{K\,\mu}}{Z_{\pi,\mu}}\right)\left(\frac{Z_{N\,K}}{Z_{N\,\pi}}\right)$$

$$Z_{N\pi^\pm}(E) = \int_E^\infty \mathrm{d}E' \frac{\phi_N(E')}{\phi_N(E)} \frac{\lambda_N(E)}{\lambda_N(E')} \frac{\mathrm{d}n_{\pi^\pm}(E',E)}{\mathrm{d}E}$$

spectrum weighted moment of the cross section for a nucleon N to produce a secondary meson from a target nucleus in the atmosphere

kaon/pion ratio $R(K/\pi) = \frac{Z_{N\,K}}{Z_{N\,\pi}}$

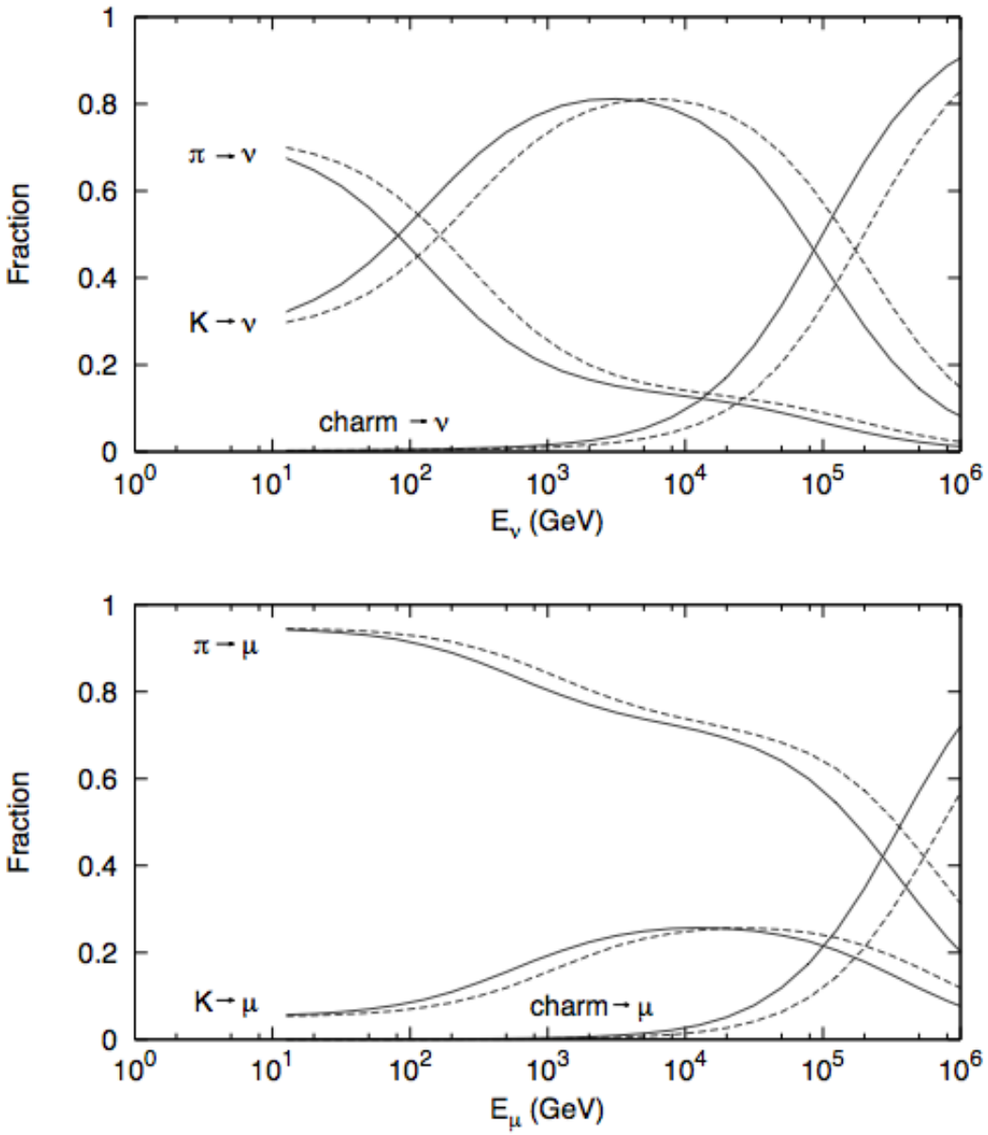
$$\epsilon_{\pi,K} = \frac{kT}{Mg} \frac{m_{\pi,K}\, c^2}{c\,\tau_{\pi,K}}$$

critical energy regulates competition between meson interaction & decay

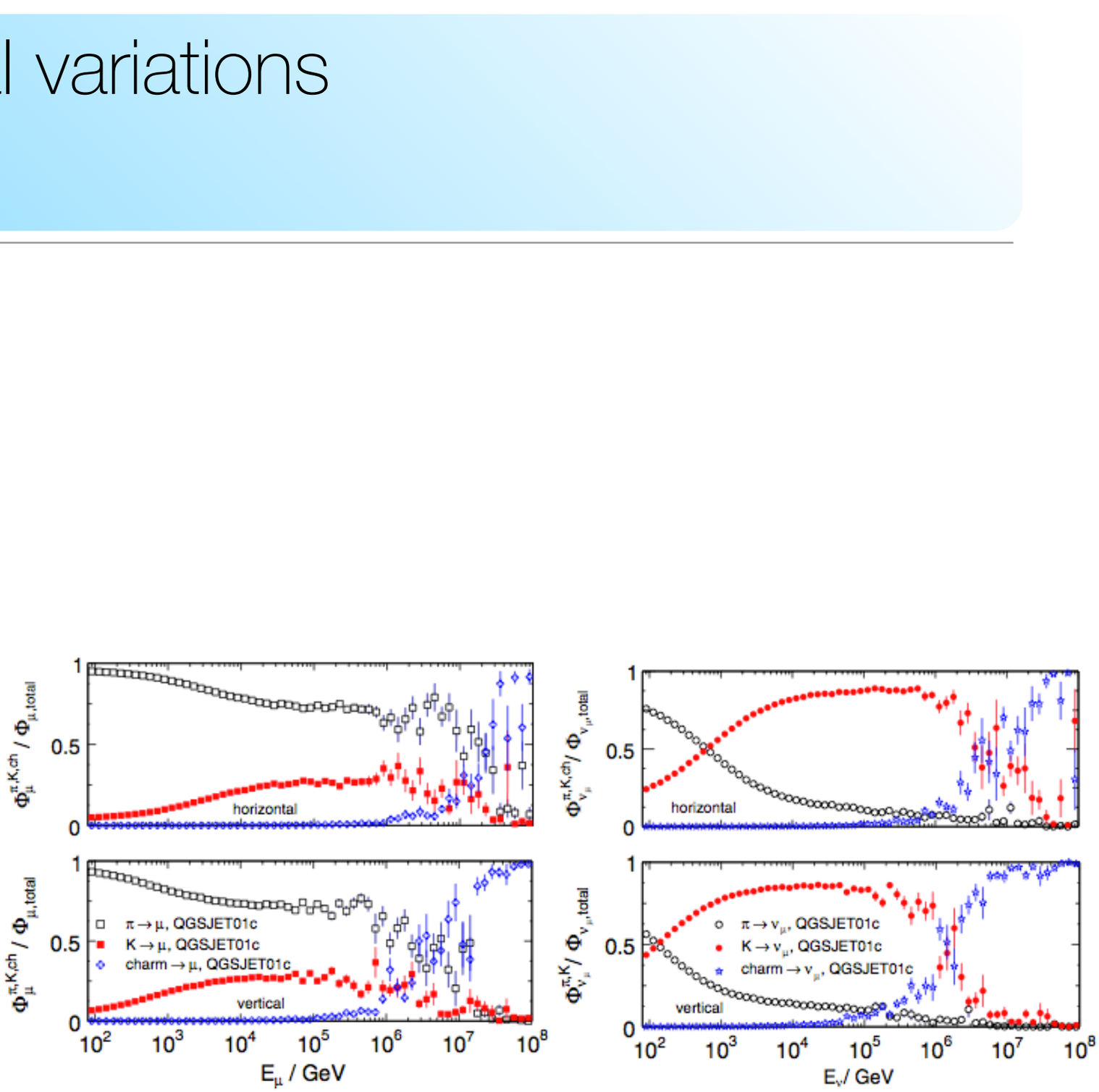
$$\phi_\mu(E_\mu,\theta) = \int_0^\infty \mathcal{P}_\mu(E_\mu,\theta,X)\, dX$$

Muon Flux

temperature seasonal variations
charm component



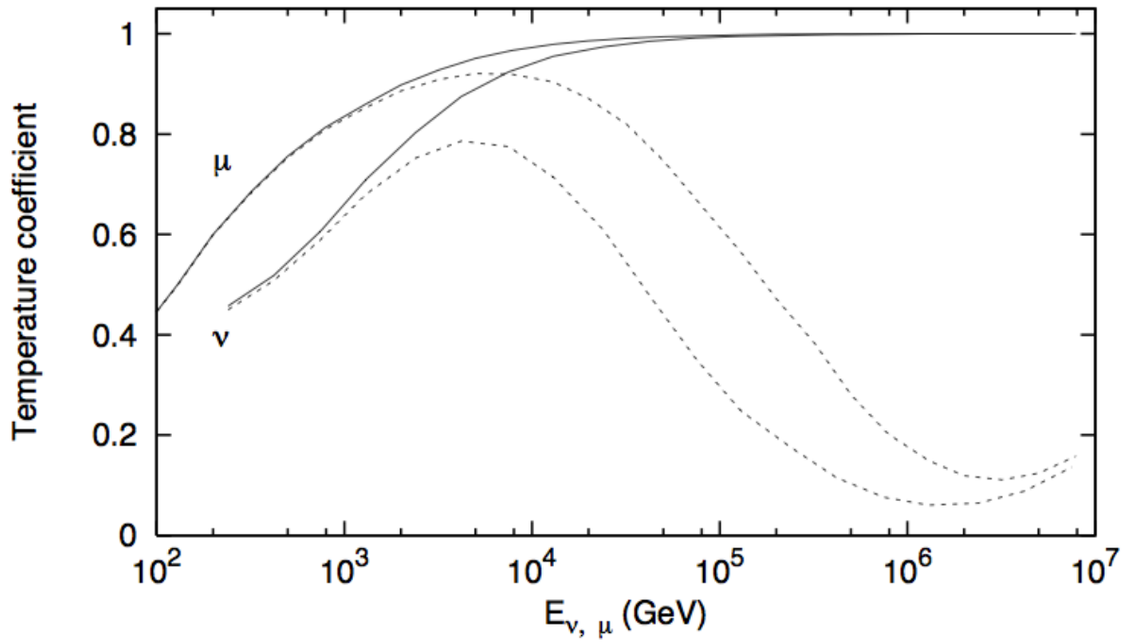
PD, Gaisser 2010

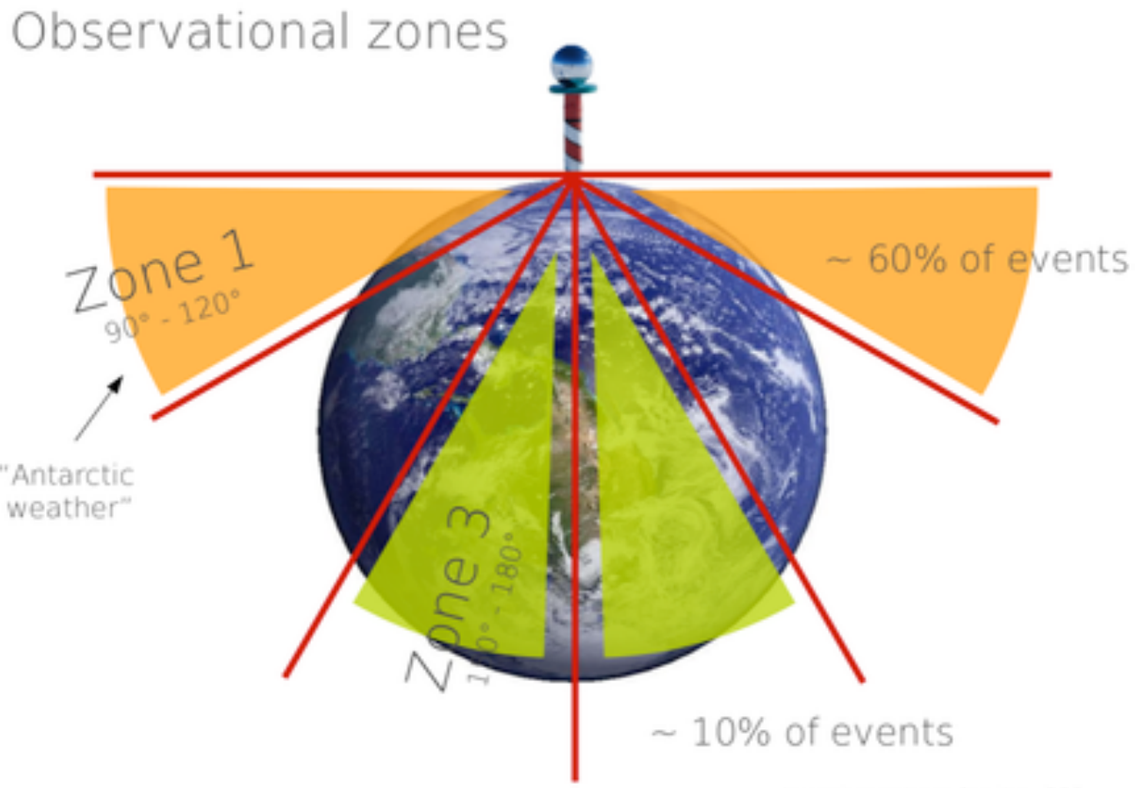


Fedynitch, Becker Tjus, PD 2012

temperature seasonal variations
charm component

PD, Gaisser 2010





$E_{\mu,\min}$	no charm		RQPM charm		ERS charm		int. charm	
	α	Rate	α	Rate	α	Rate	α	Rate
0.5	0.83	2050	0.82	2070	0.82	2050	0.82	2060
10	0.98	1.26	0.89	1.40	0.97	1.26	0.94	1.34
100	1.0	0.0025	0.53	0.0049	0.91	0.0028	0.71	0.0036

TABLE I: Correlation coefficients for muons with ($\theta \leq 30^\circ$) for three levels of charm (energy in TeV; rate in Hz/km^2).

IC40×2

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 1	α	Events/yr	α	Events/yr
all	0.54	16000	0.52	17000
3	0.70	5900	0.62	6300
30	0.94	350	0.72	450

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 2	α	Events/yr	α	Events/yr
all	0.66	6000	0.62	6400
3	0.88	1230	0.75	1450
30	0.98	37	0.46	80

$E_{\nu,\min}$(TeV)	no charm		RQPM charm	
Zone 3	α	Events/yr	α	Events/yr
all	0.68	1650	0.64	1750
3	0.91	260	0.75	320
30	0.99	5.2	0.41	13

TABLE II: Correlation coefficients with and without charm for neutrinos in three zones of the atmosphere (see text).