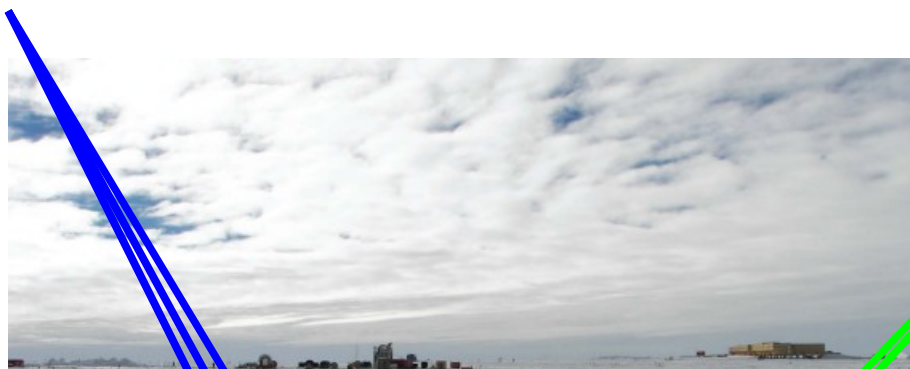# Atmospheric Muons in IceCube
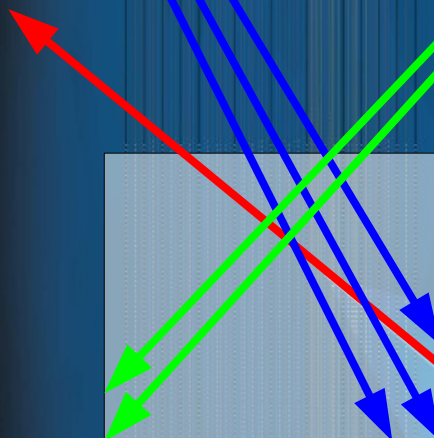
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Basics

CR Air Showers
(1000 per second)
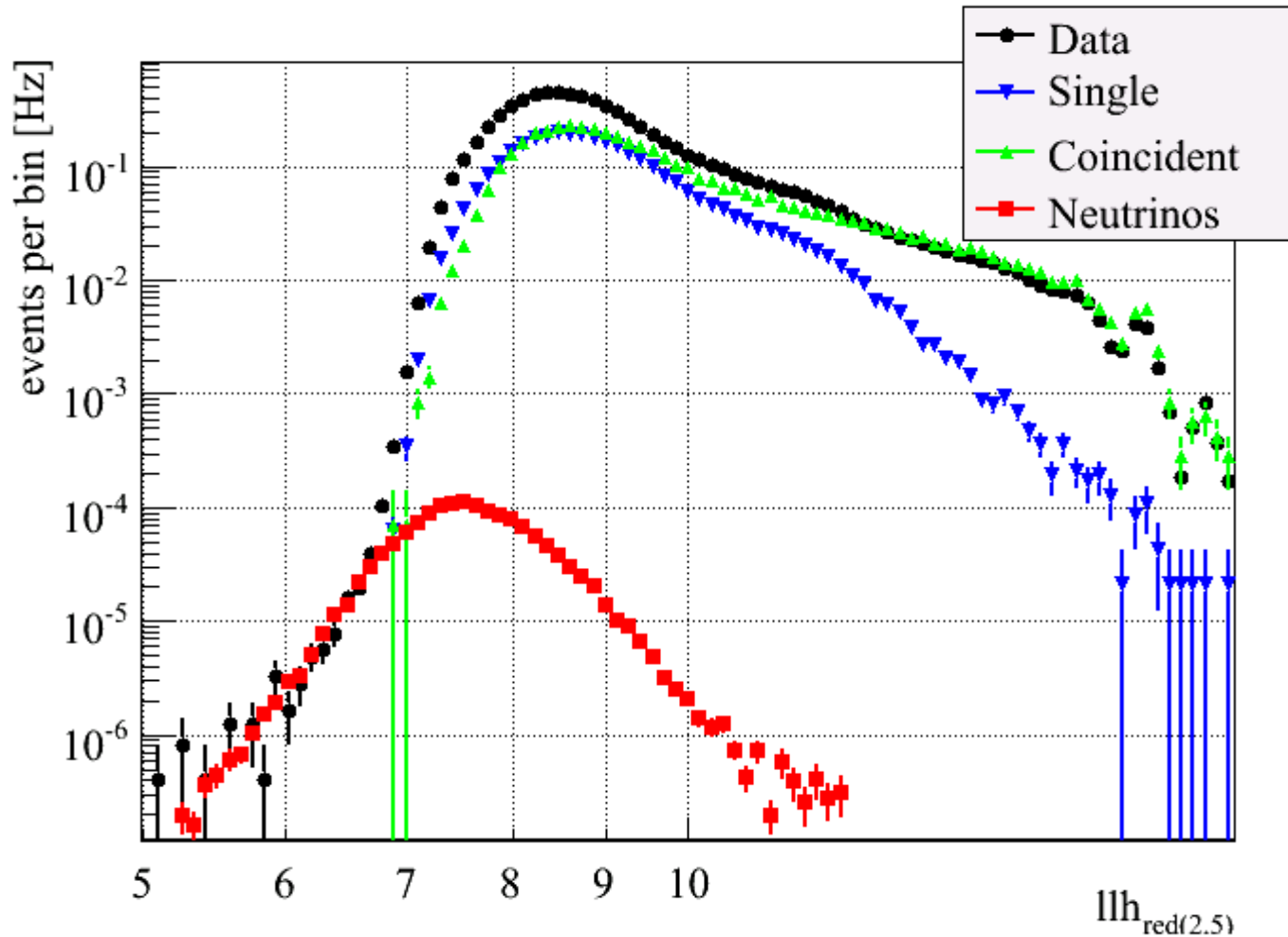
Coincident Air Showers
(100 per second)

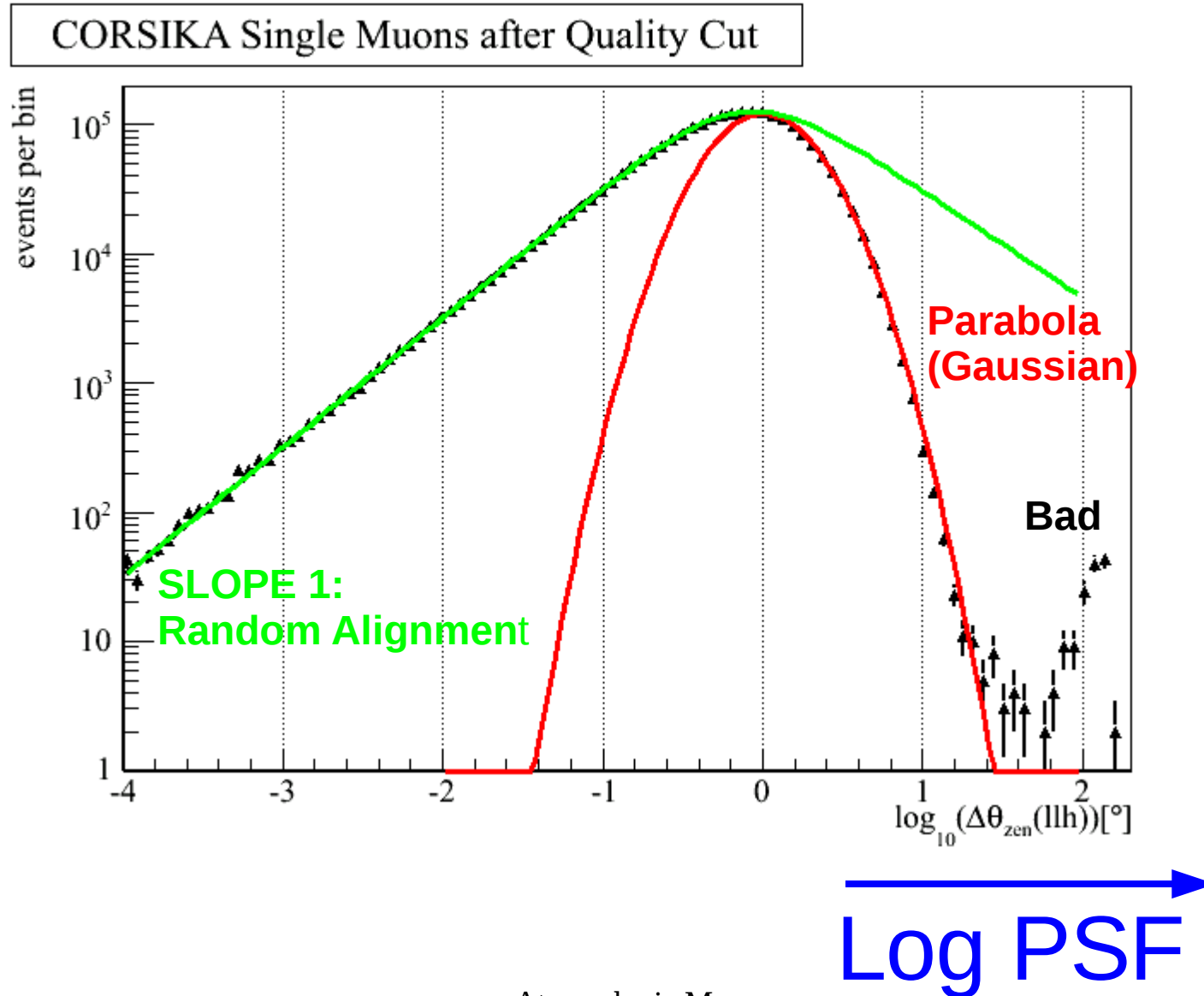Neutrino-
Induced Muons
(40 per hour)
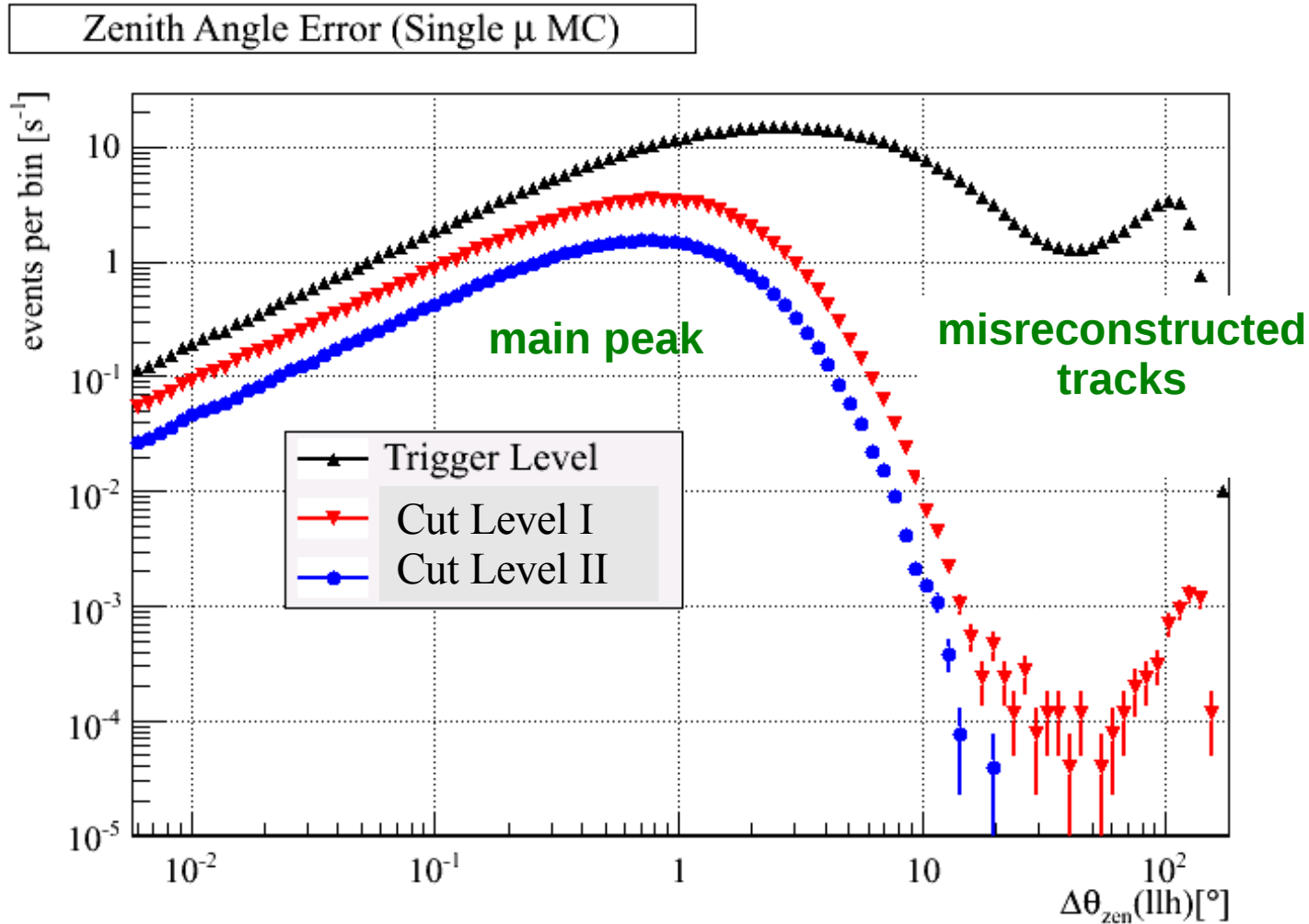
Approximate
Values for IC40
(Trigger Level)

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IC22 Trigger Level
Track Reco (SPE llh) below Horizon

Point Spread Function (MC)

CORSIKA Single Muons after Quality Cut

events per bin

Parabola (Gaussian)

Bad

SLOPE 1: Random Alignment

$\log_{10}(\Delta\theta_{zen}(llh))[\degree]$

Log PSF

All-Sky Analysis: Final Cut Levels

Zenith Angle Error (Single μ MC)

IC22, All Sky (2008)

IceCube-22 Data vs. Monte Carlo Simulation Data

Legend:
- Cosmic Ray Induced Muons
- Coincident Cosmic Ray Induced Muons
- Neutrinos
- All Simulated Muons & Neutrinos
- IceCube-22 Data

y-axis: events per bin per second

x-axis: $\cos(\theta_{zen}(MC))$

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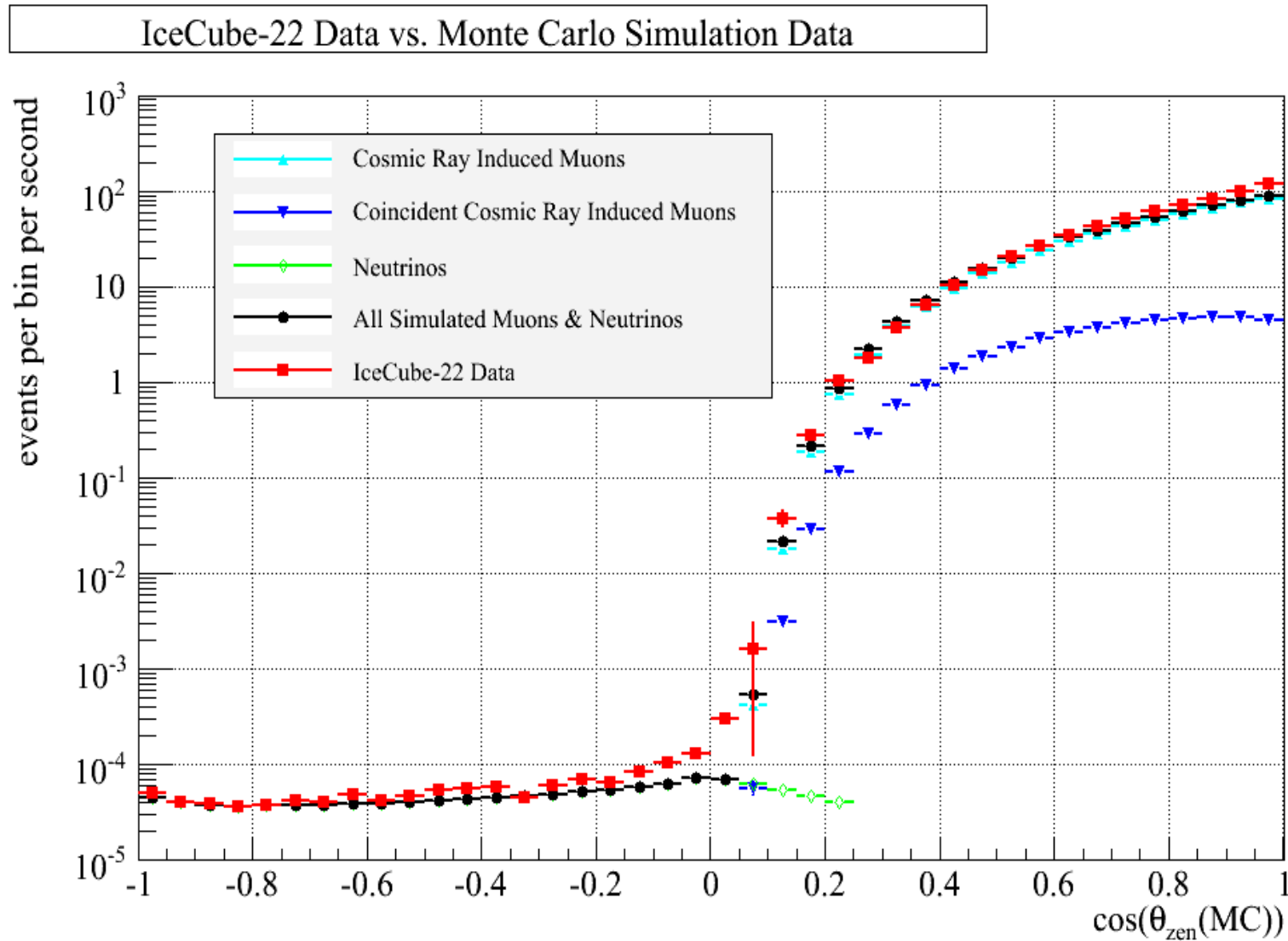
CORSIKA Atmospheres

Density and Thickness
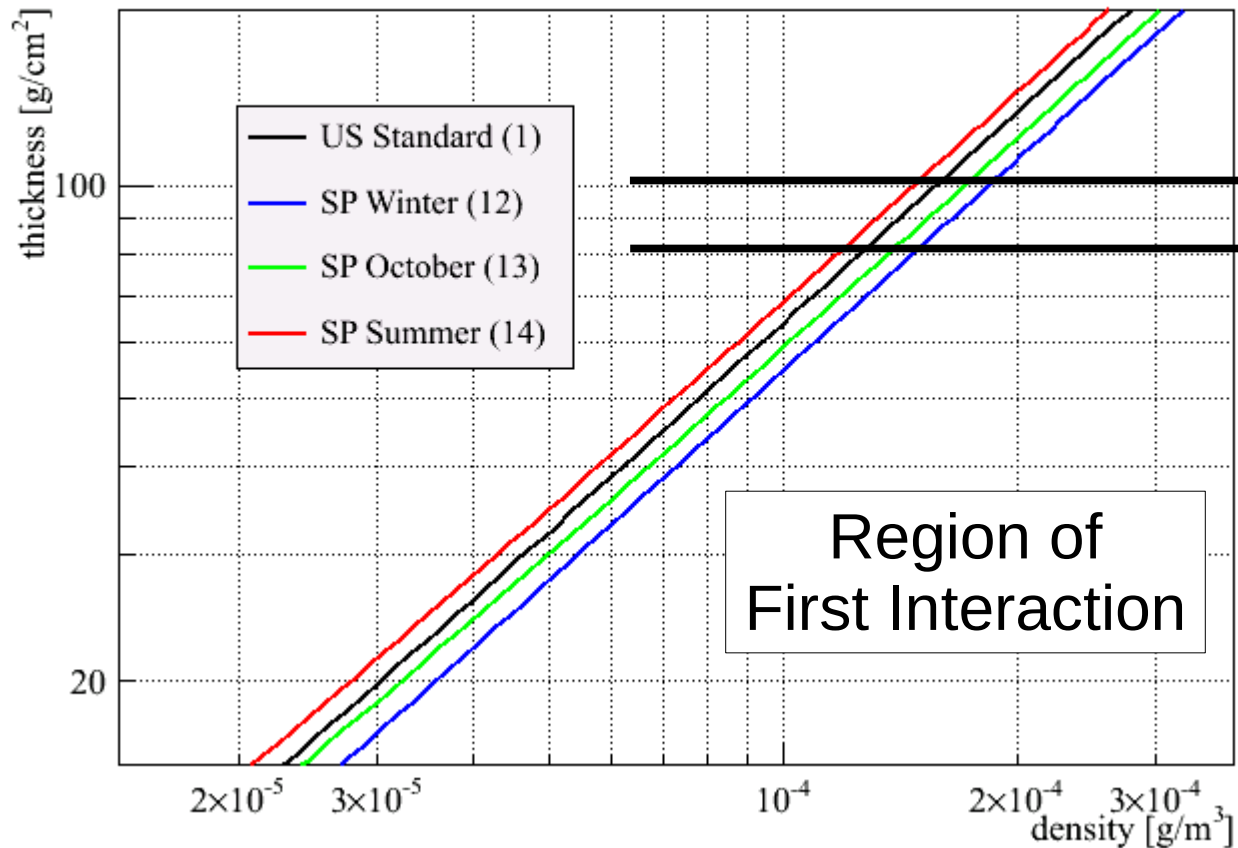
Thickness:
Integrated
Density (x,∞)

US Standard (1)
SP Winter (12)
SP October (13)
SP Summer (14)

≈20%

Region of
First Interaction

thickness [g/cm^2]

100

20

2×10^{-5} 3×10^{-5} 10^{-4} 2×10^{-4} 3×10^{-4}
density [g/m^3]

Full Shower Simulation

4 Models

Ratio over SP Oct

≈20%
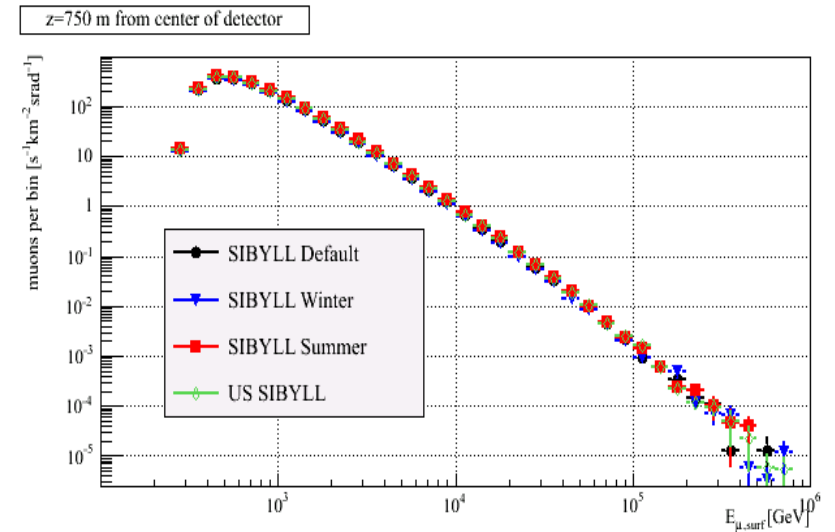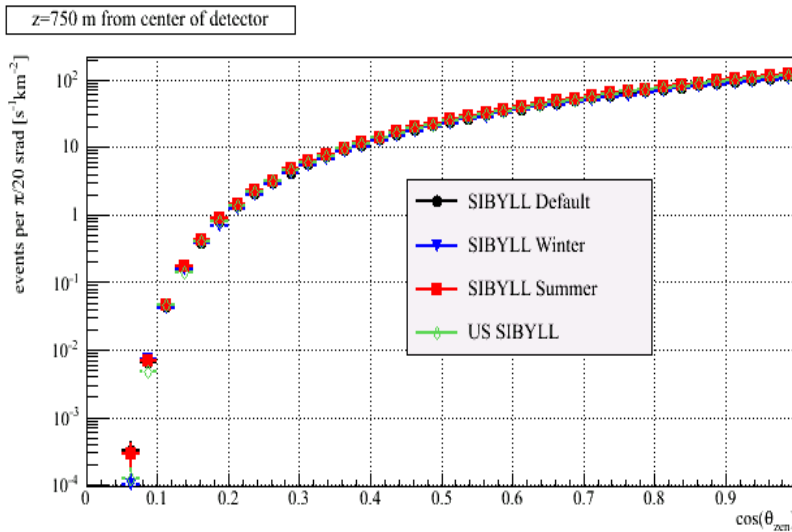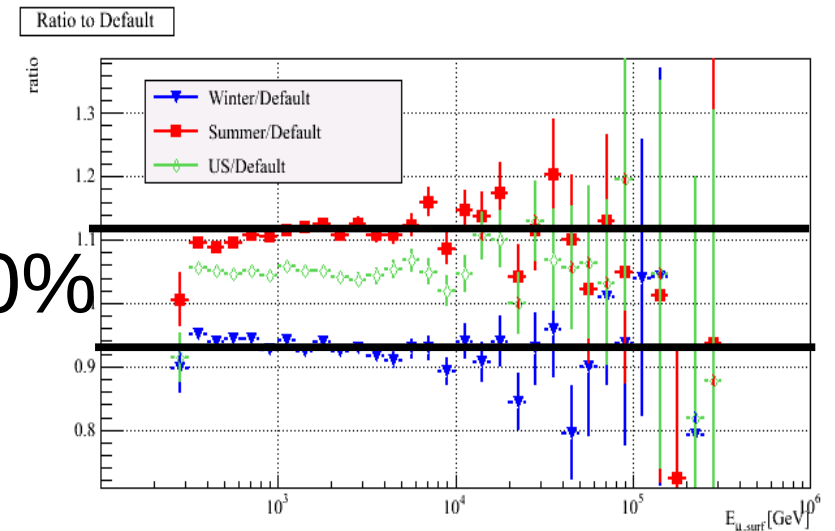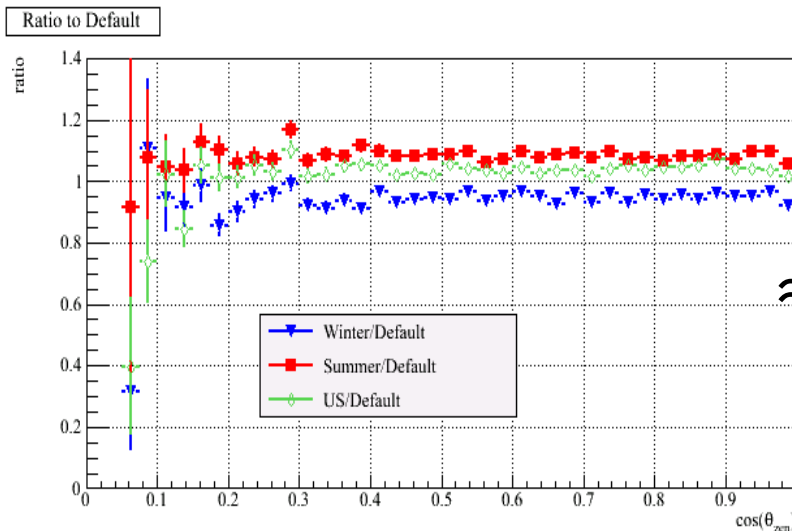
Zenith Angle

Muon Energy

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2008 Data

Relative Muon Rate and T_{eff} vs Days

- **Muon Rate**
- **Effective Temperature T_{eff}**

≈20%

Source: D. Rocco

Days Since 1/1/07
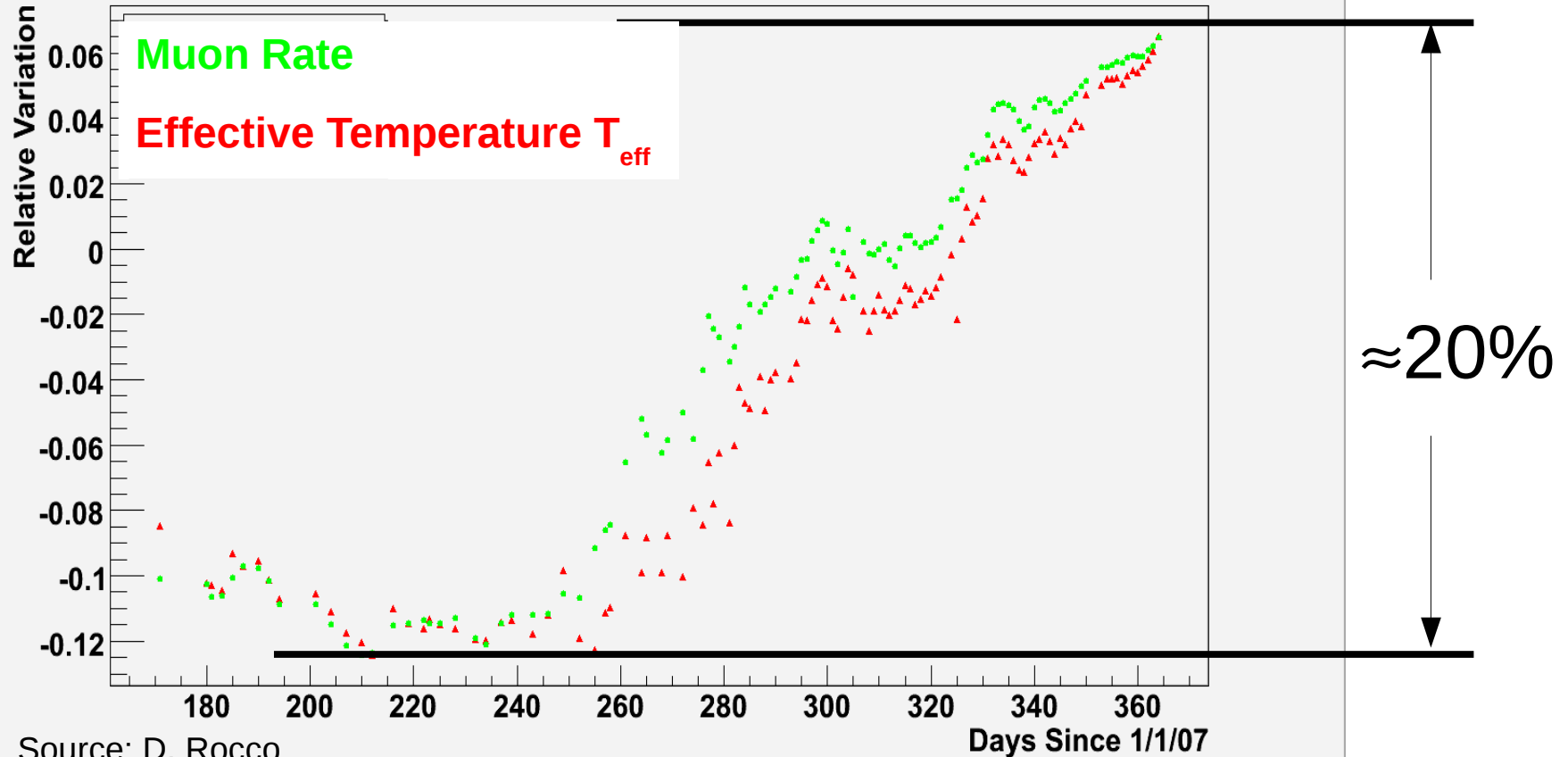
T_{eff}: Temperature weighted by muon production probability
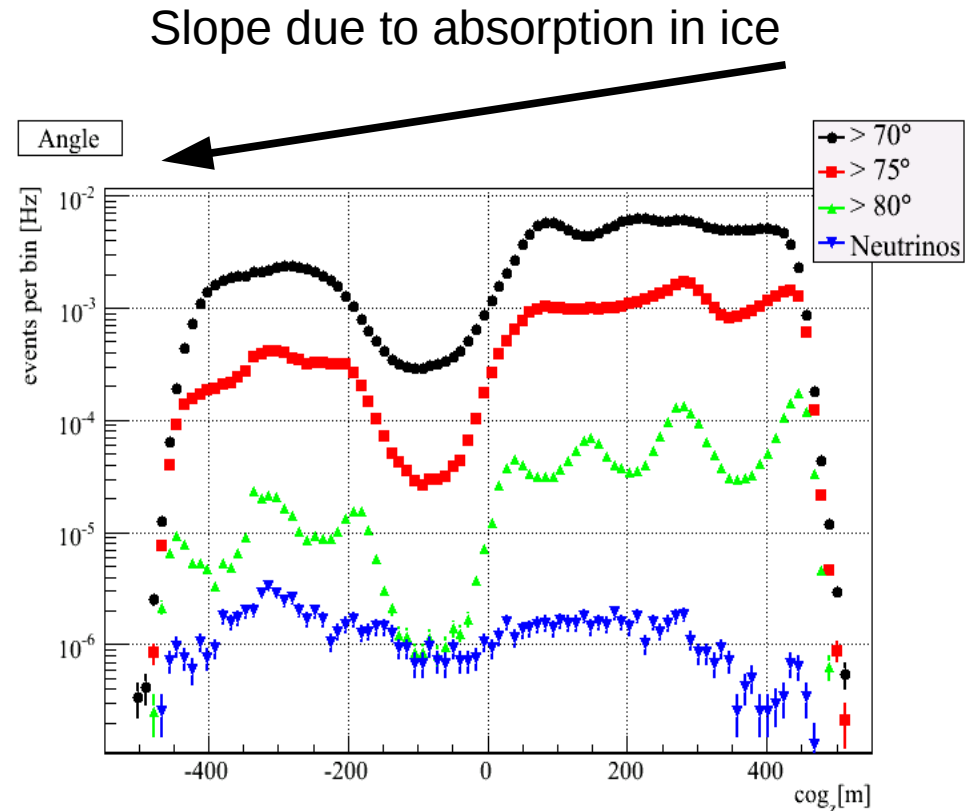
$$T_{eff} = \frac{\int_0^\infty \frac{dX}{X} T(X)(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N})}{\int_0^\infty \frac{dX}{X}(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N})}$$

Horizontal Muons

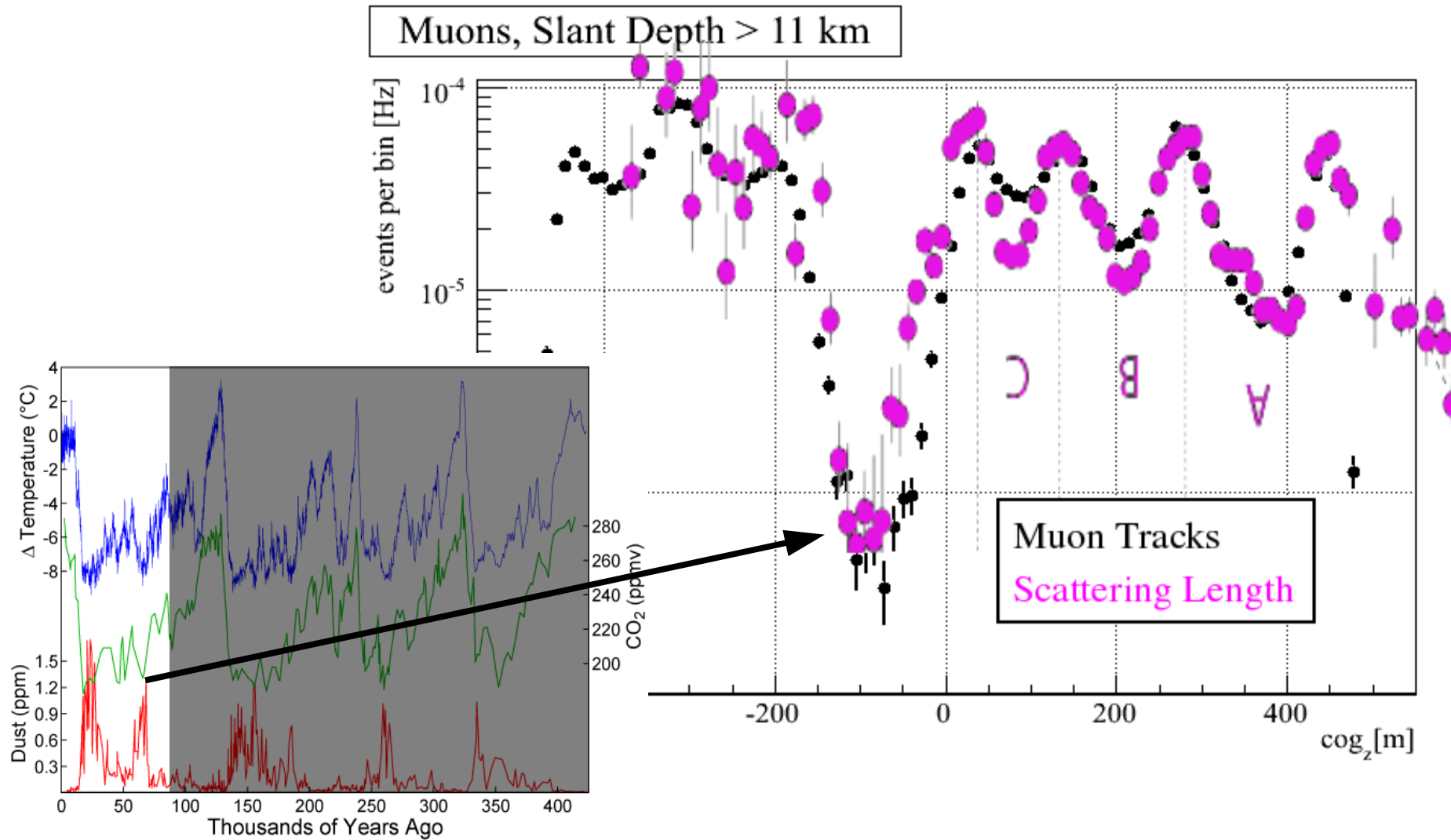Slope due to absorption in ice
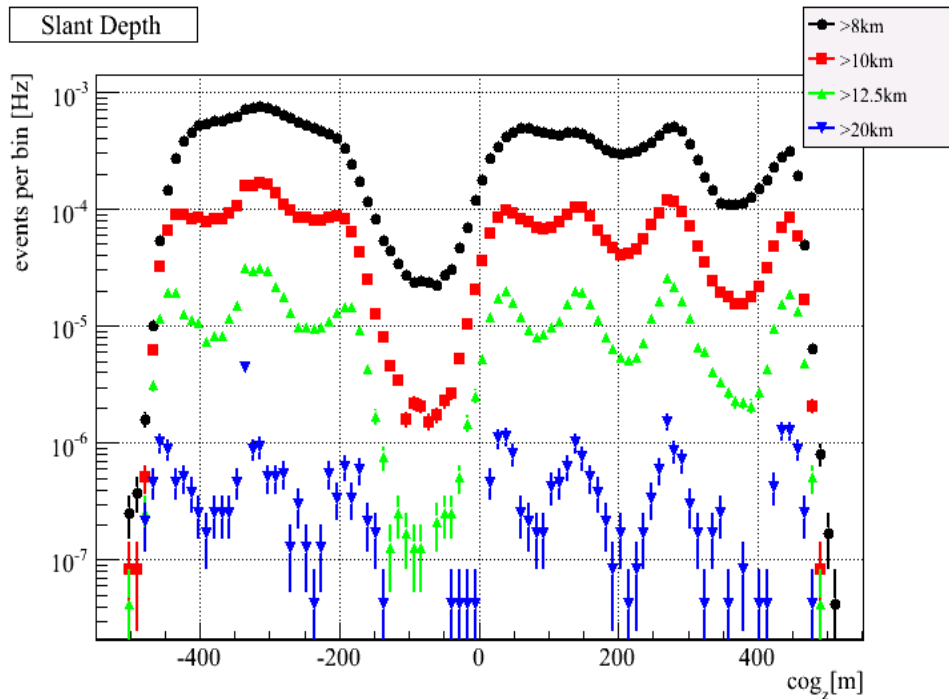
Slant Depth

vertical depth/cos(zenith)
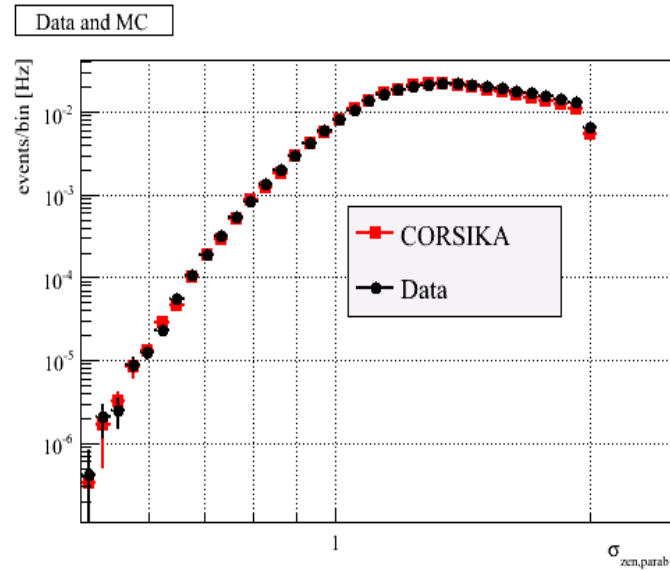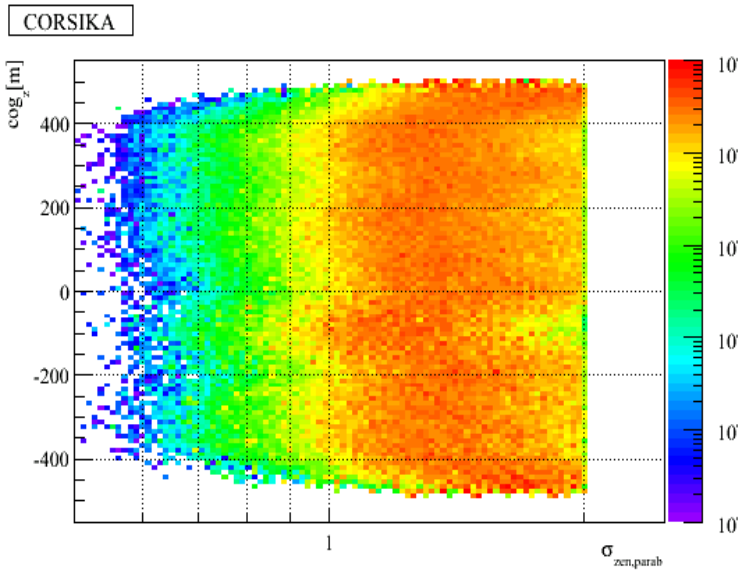
Zenith Angle

Dust Layers

Vostok Ice Core
(source: wikipedia)

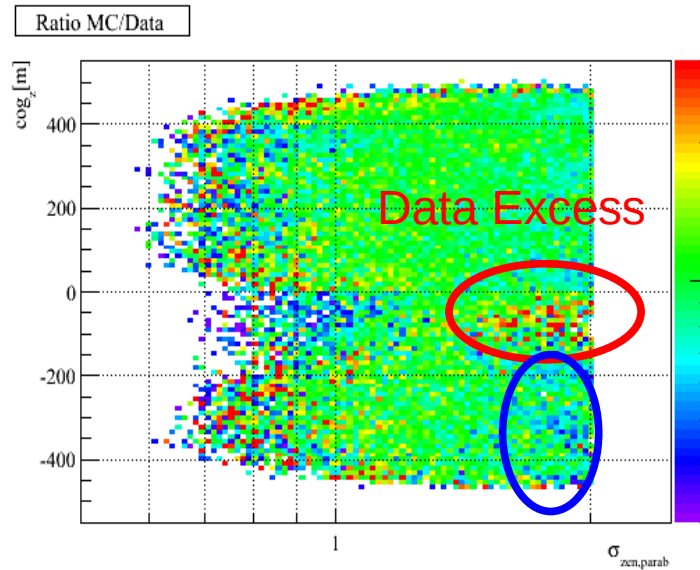# Example: σ_{parab} (Area of Error Ellipse in Likelihood Reconstruction)

$$\text{Example: } \sigma_{parab} \left(\text{Area of Error Ellipse in Likelihood Reconstruction} \right)$$

MC

depth

Data

1-dim

MC/Data

Data Excess

Data Deficit

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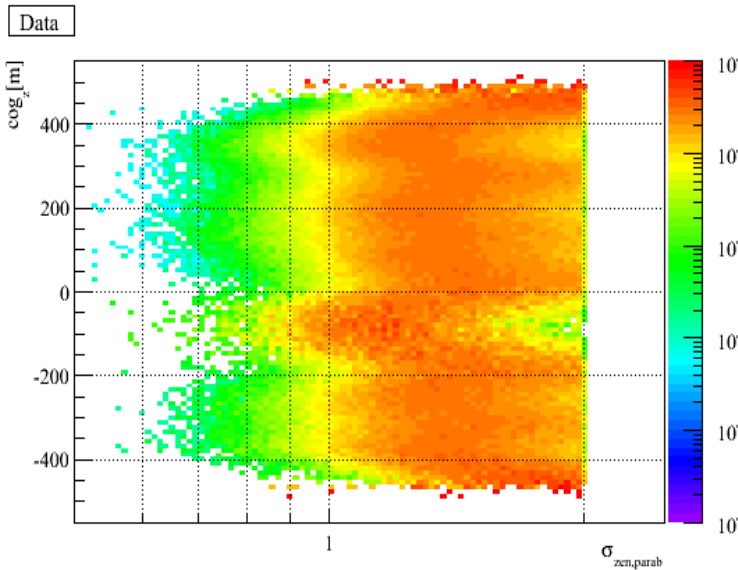
Slant Depth
(+muon threshold energy)

2.5km
(1 TeV)

1.5km
(300 GeV)

10km (81°)

10km (74°)

(5 TeV)

20km (85.5°)

(40TeV)

20km (82°)
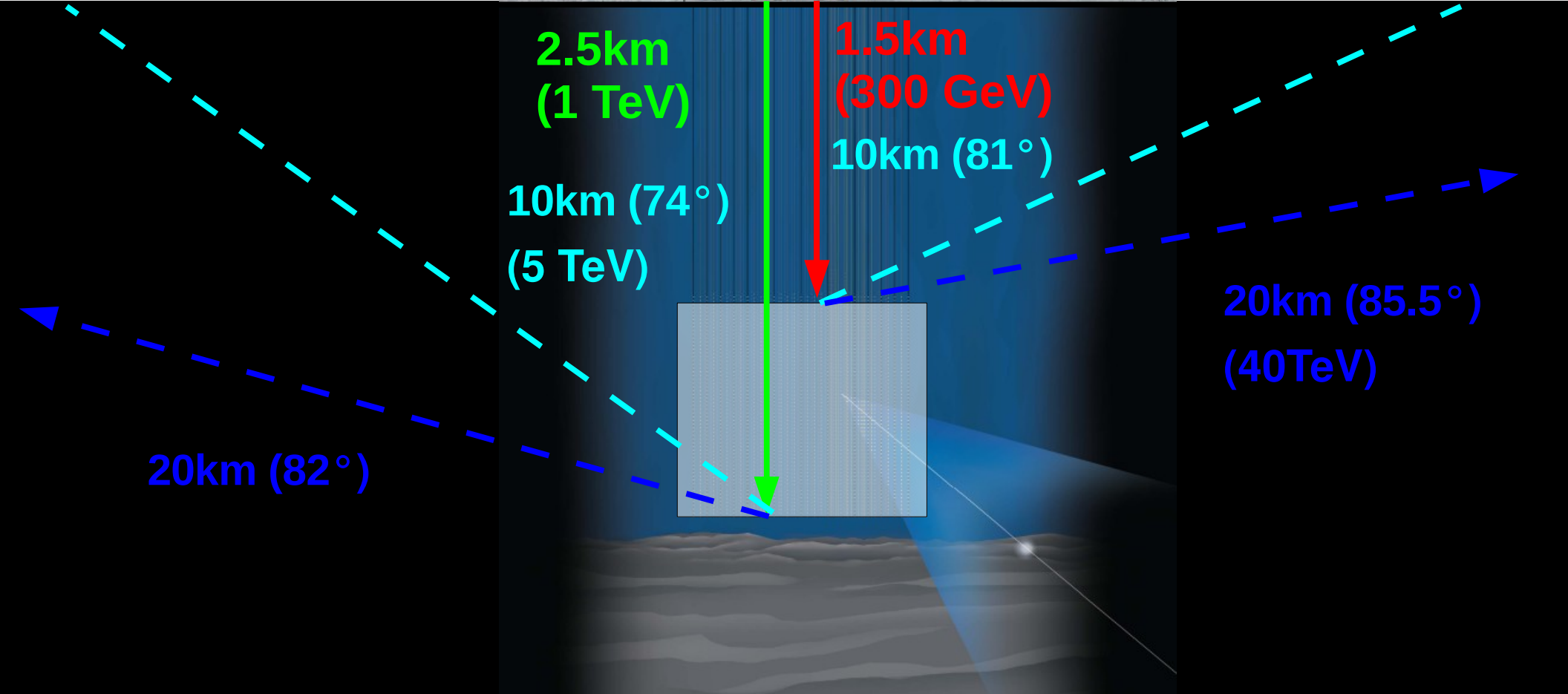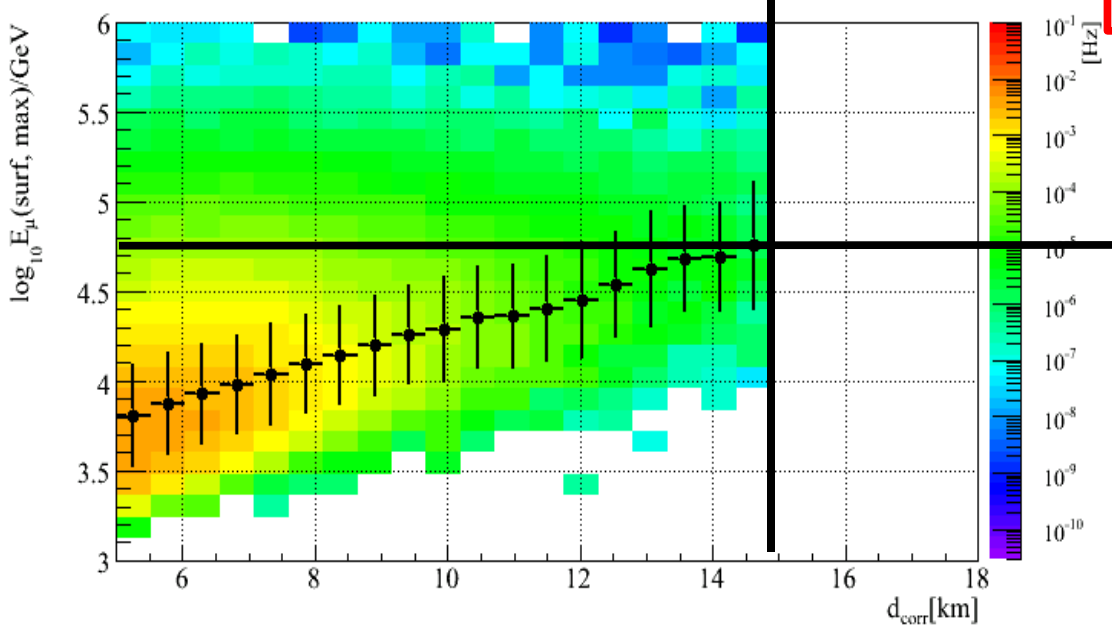
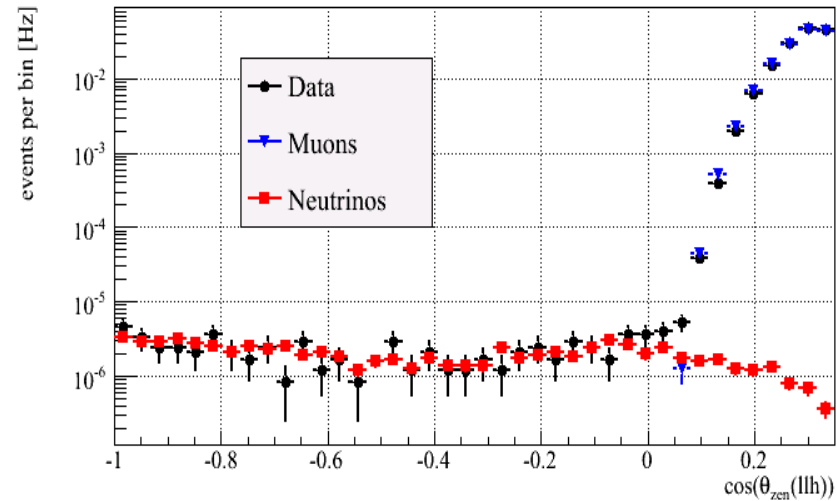15 km (limiting factor: angular resolution)

Track
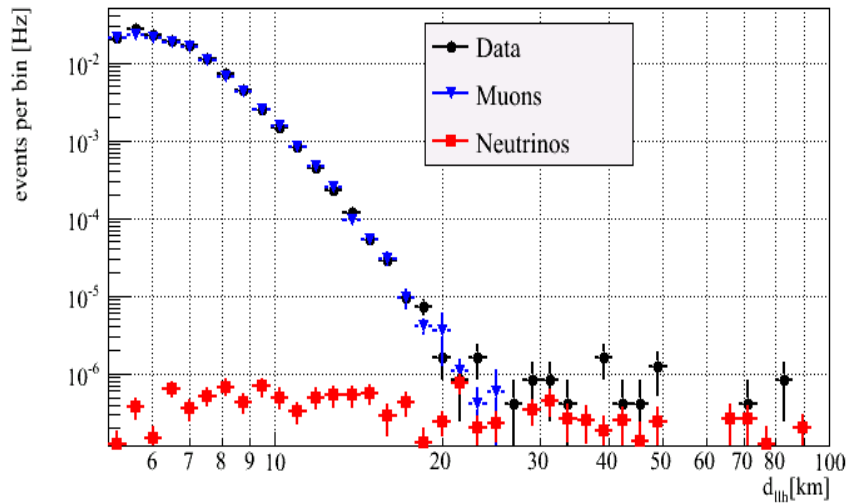Multiplicity
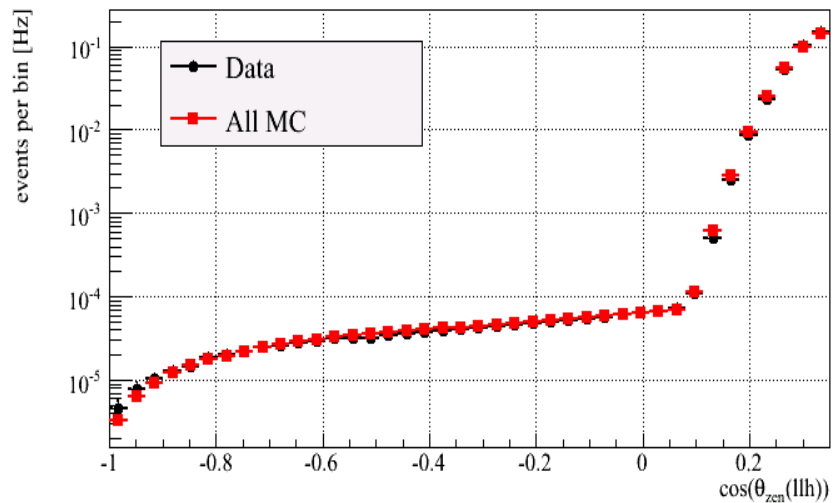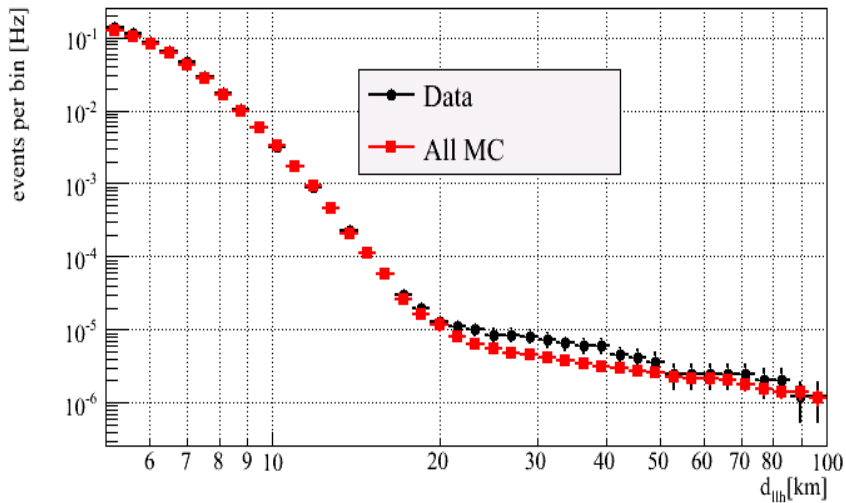in Detector
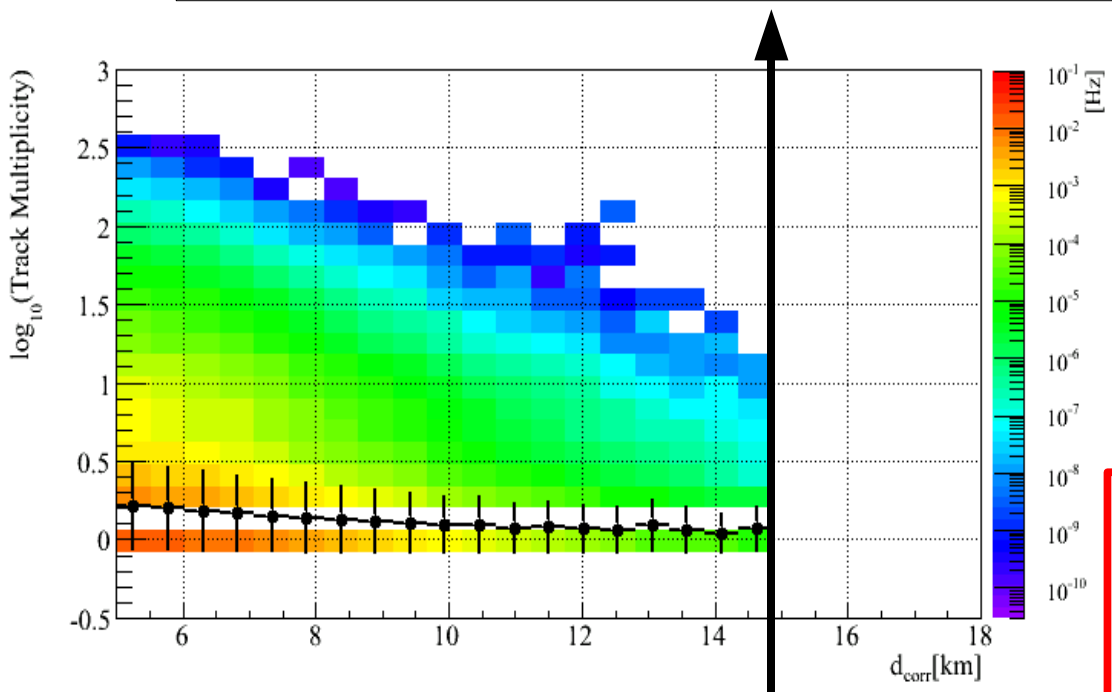
Slant Depth
(simulation)

Max. Muon
Surface
Energy

50 TeV

μ-ν Transition: Data and MC

diff

int

Slant Depth   Zenith Angle
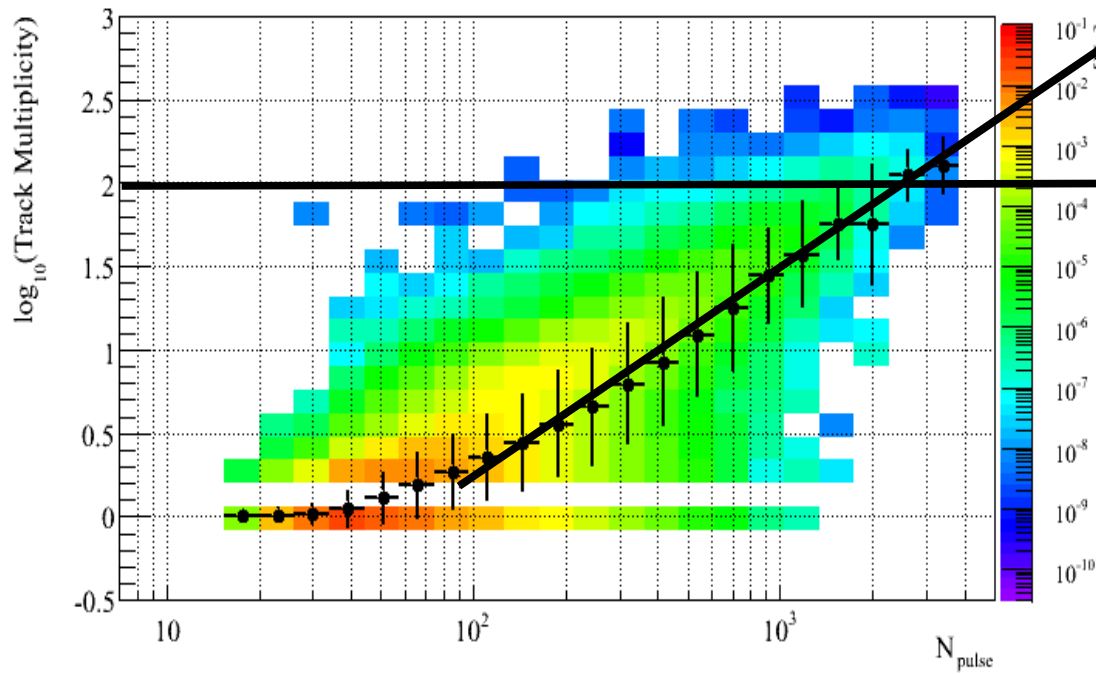
High-Multiplicity Bundles

100

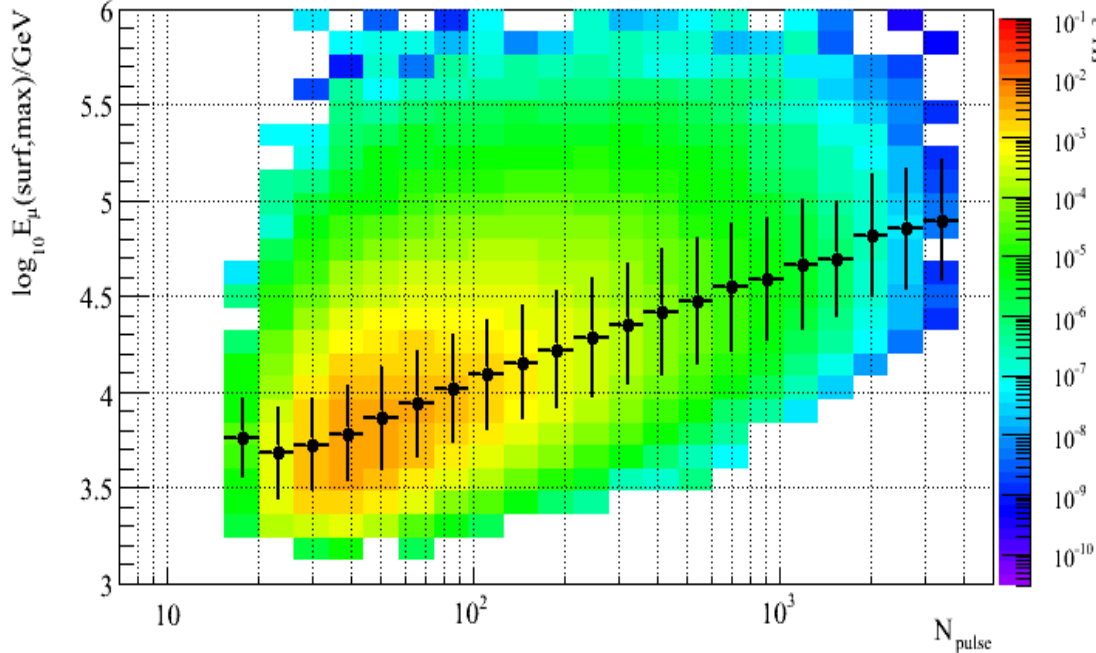Track Multiplicity in Detector

Number of p.e. in Event (simulation)

Max. Muon Surface Energy

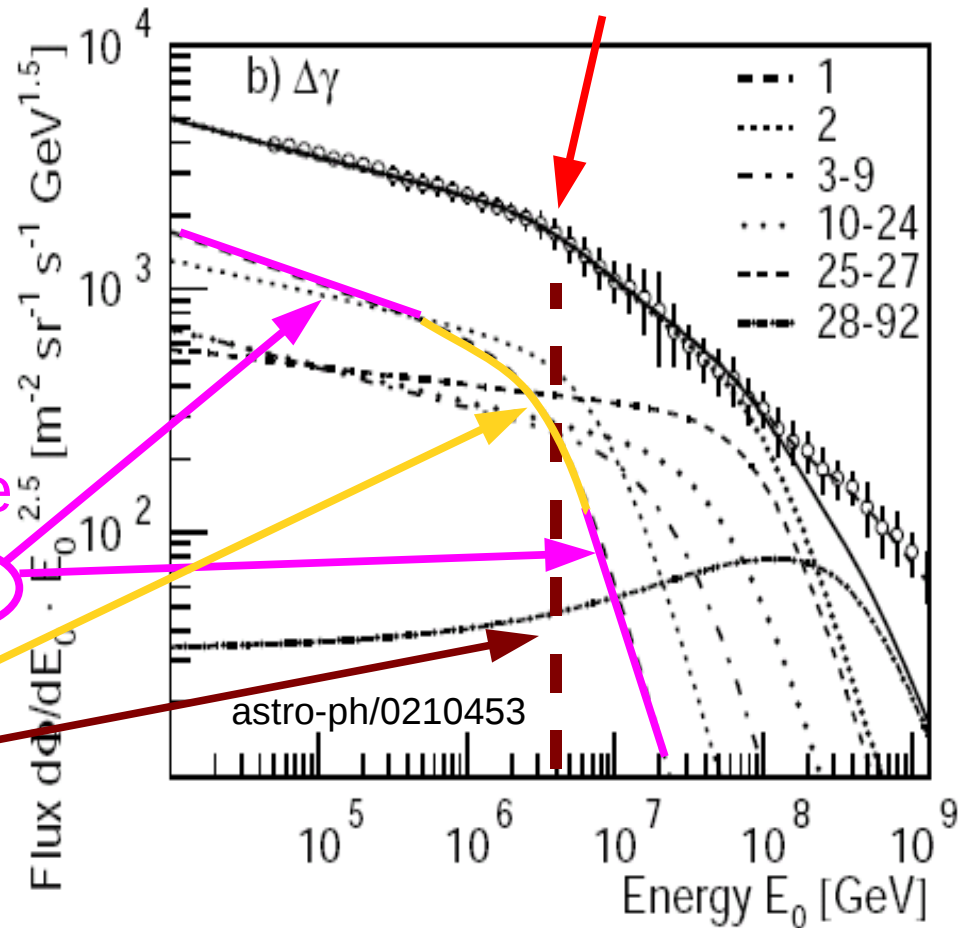All Tracks below 70° (IceCube Muon Filter)

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poly-gonato (Hoerandel) Model

CR-Knee

Slope Change

Smoothness of Transition

$$\frac{d\Phi_z}{dE_0} = \Phi_Z^0 \left[1 + \left(\frac{E_0}{E_{trans}} \right)^{\epsilon_c} \right]^{\frac{-\Delta\gamma}{\epsilon_c}}$$

Transition Energy

astro-ph/0210453

Primary composition becomes heavier

Composition Models

cut–off:	rigidity dependent $\hat{E}_Z = \hat{E}_p \cdot Z$	mass dependent $\hat{E}_p \cdot A$	constant $\hat{E}_p$	
E_p [PeV] =	4.51 ± 0.52	3.66 ± 0.41	3.50 ± 0.38	common γ
γ =	−4.68 ± 0.23	−7.82 ± 1.09	−3.06 ± 0.02	
ϵ_c =	1.87 ± 0.18	2.30 ± 0.23	1.94 ± 0.51	
χ^2/d.o.f =	0.116	0.290	0.086	
$\hat{E}_p$ [PeV] =	4.49 ± 0.51	3.81 ± 0.43	3.68 ± 0.39	common $\Delta\gamma$
$\Delta\gamma$ =	2.10 ± 0.24	5.70 ± 1.23	0.44 ± 0.02	
ϵ_c =	1.90 ± 0.19	2.32 ± 0.22	1.84 ± 0.45	
χ^2/d.o.f. =	0.113	0.292	0.088	

Rigidity   **Mass**   **Constant Composition**

-Dependent Cutoff

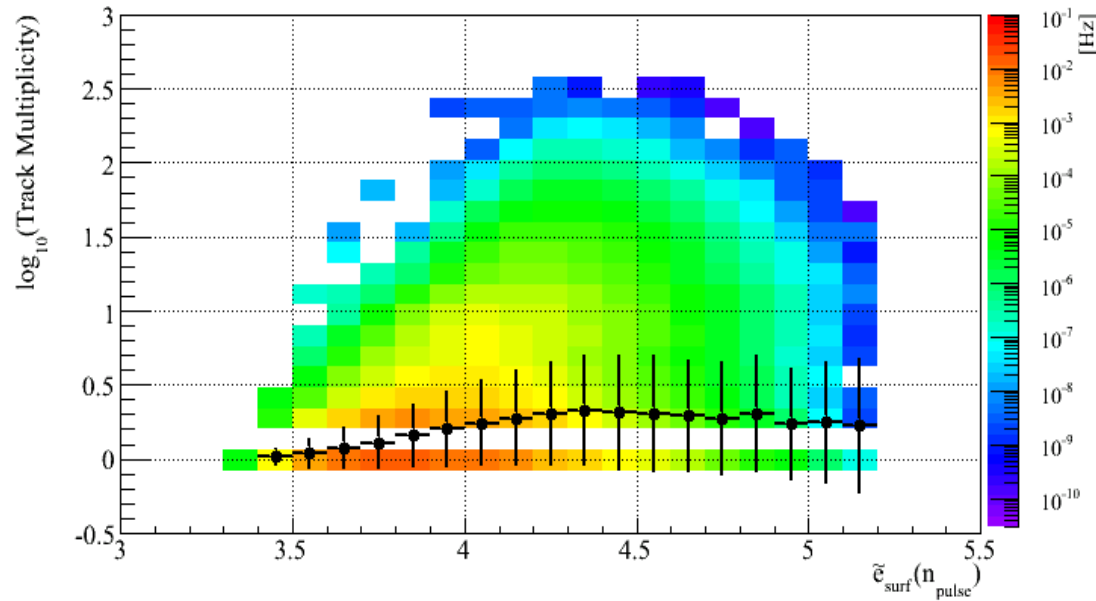# Data/MC: p.e. in Event
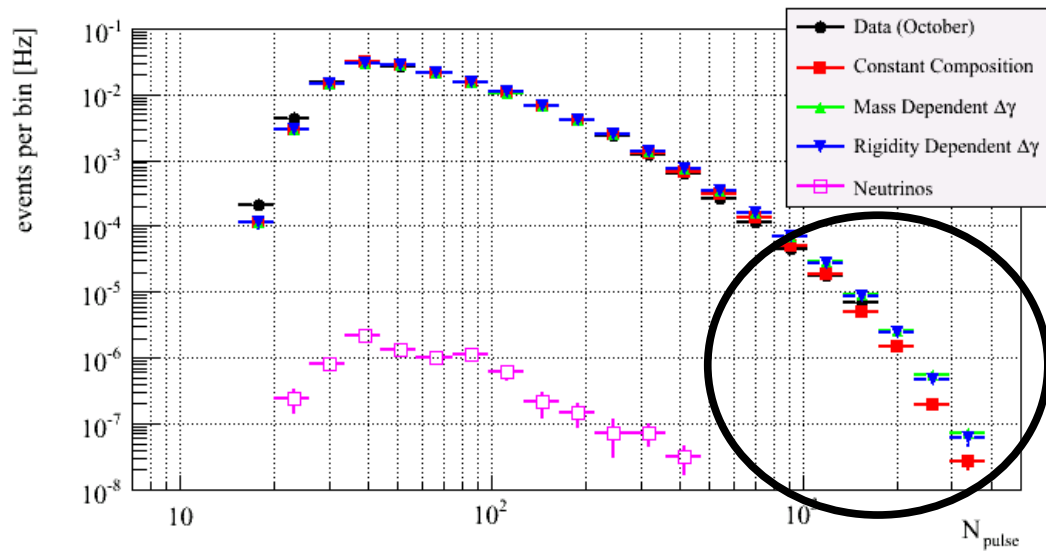
Lighter Primaries
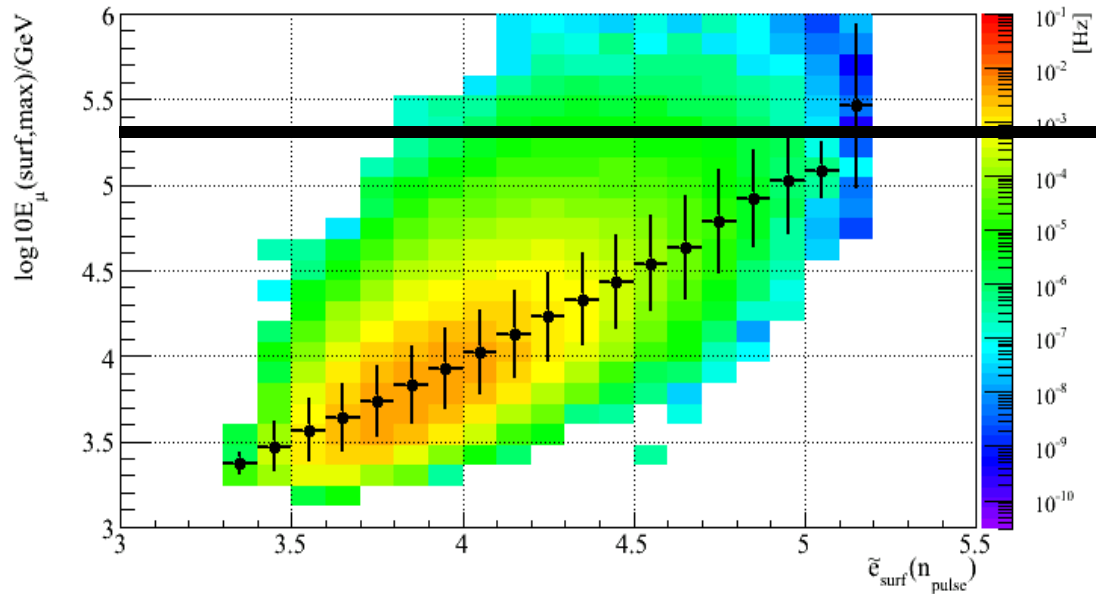
$\Rightarrow$Lower Multiplicity

$$(N_\mu \propto A^{0.25})$$
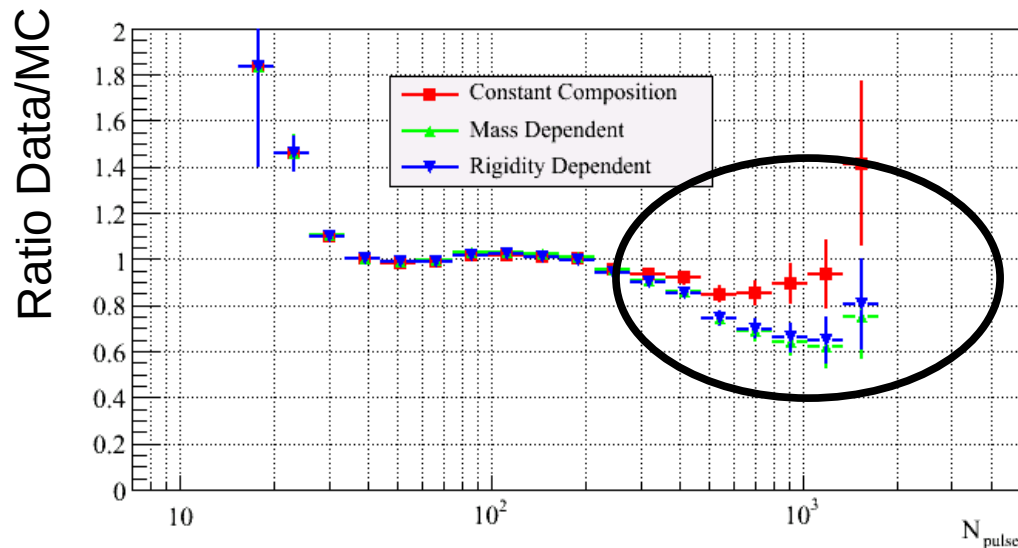
Problem with high-E

events in IC22

$$\tilde{e}_{surf} \propto \log n_{\gamma} \cdot d_{slant}$$ (simulation)
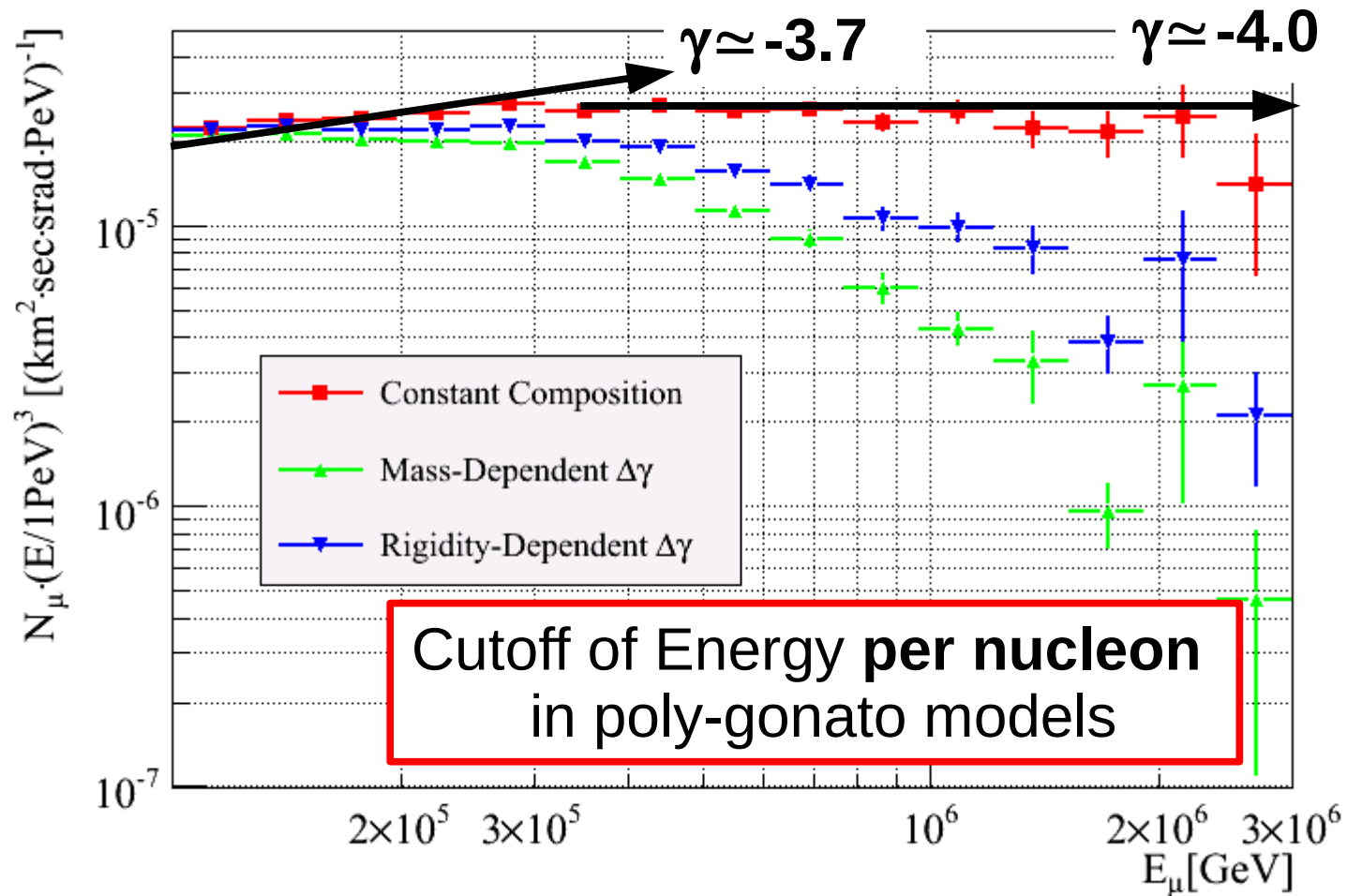
Track Multiplicity in Detector

Max. Muon Surface Energy
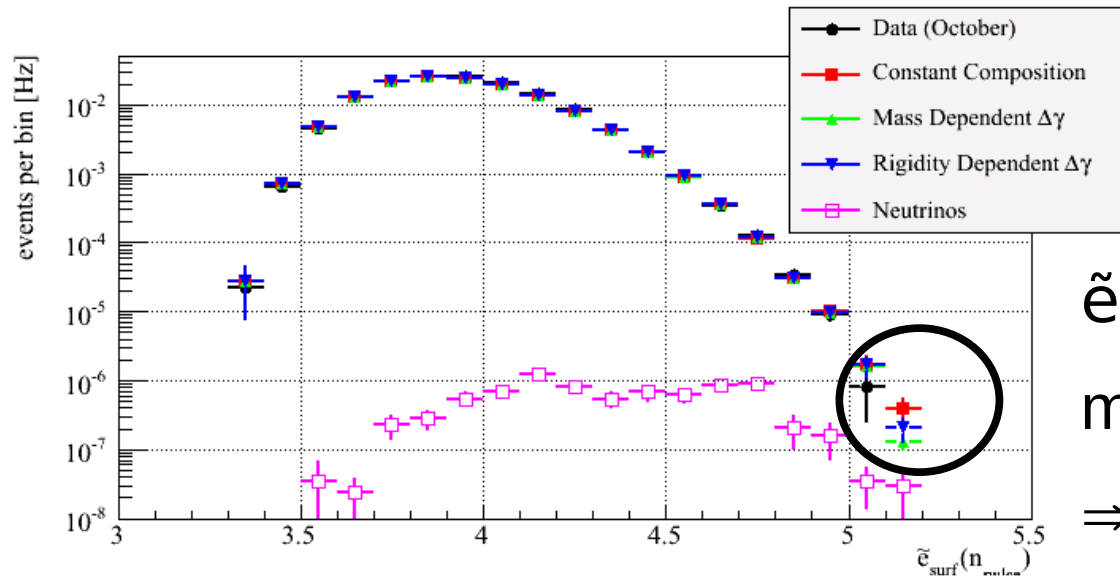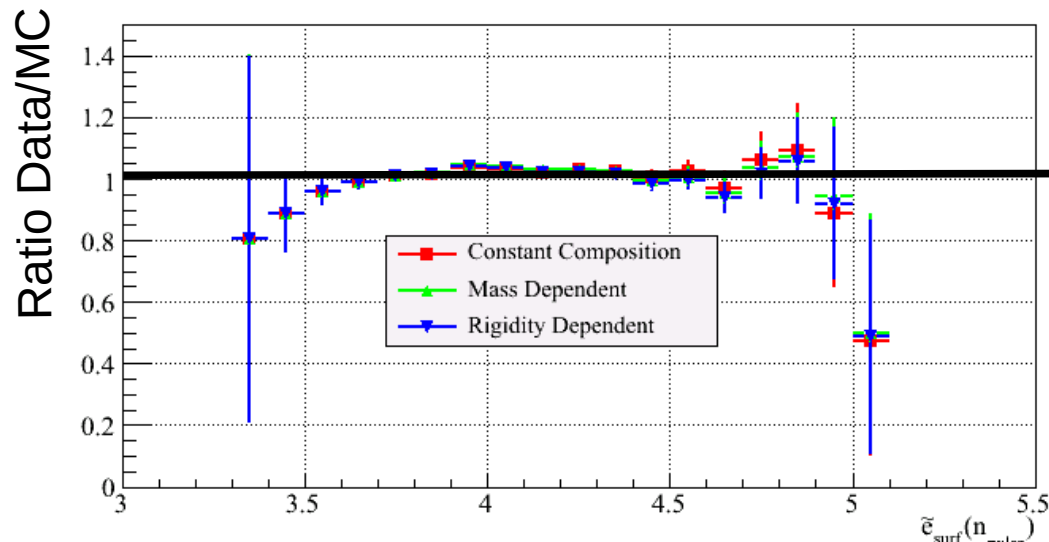

200 TeV

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Single Muon Energy

Data/MC: ẽ_{surf}

ẽ measures **single**

muon energy

⇒model order inverted

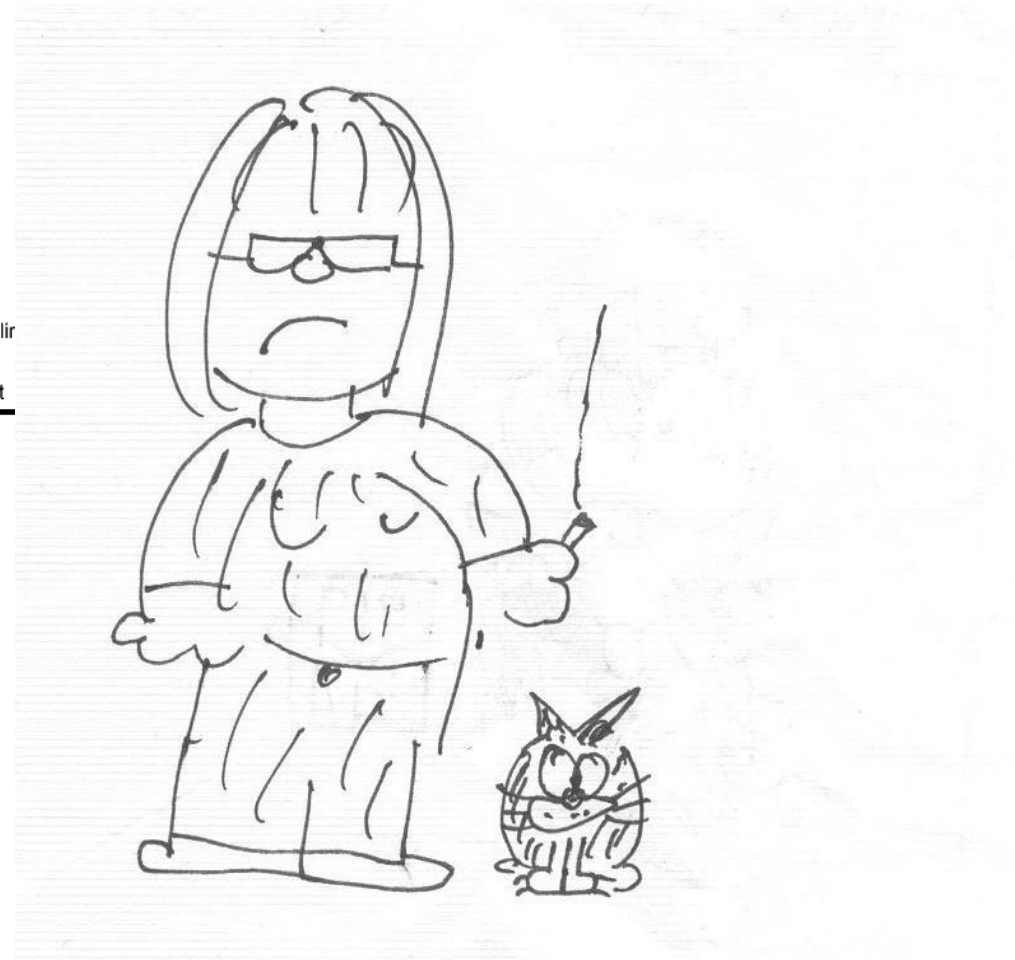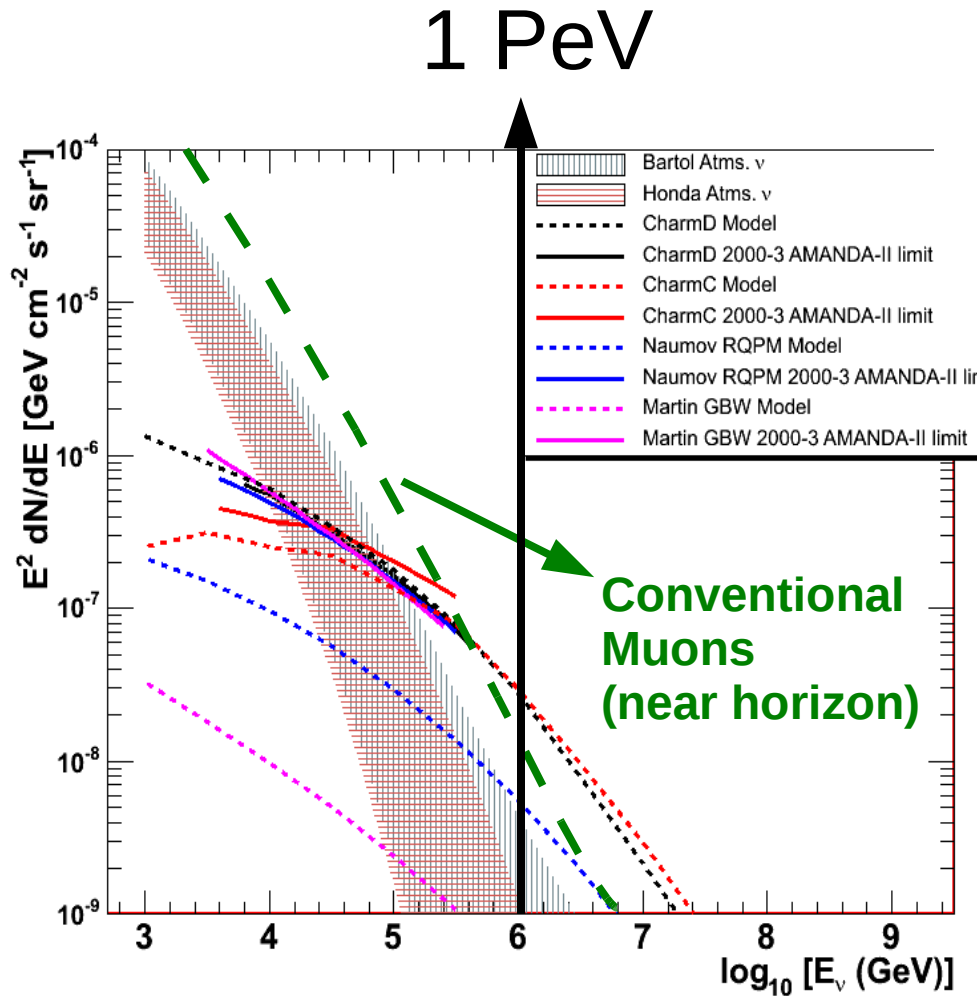MC/Data close to 1

Composition in IC 40

Muon Spectrum

astro-ph:0803.2943
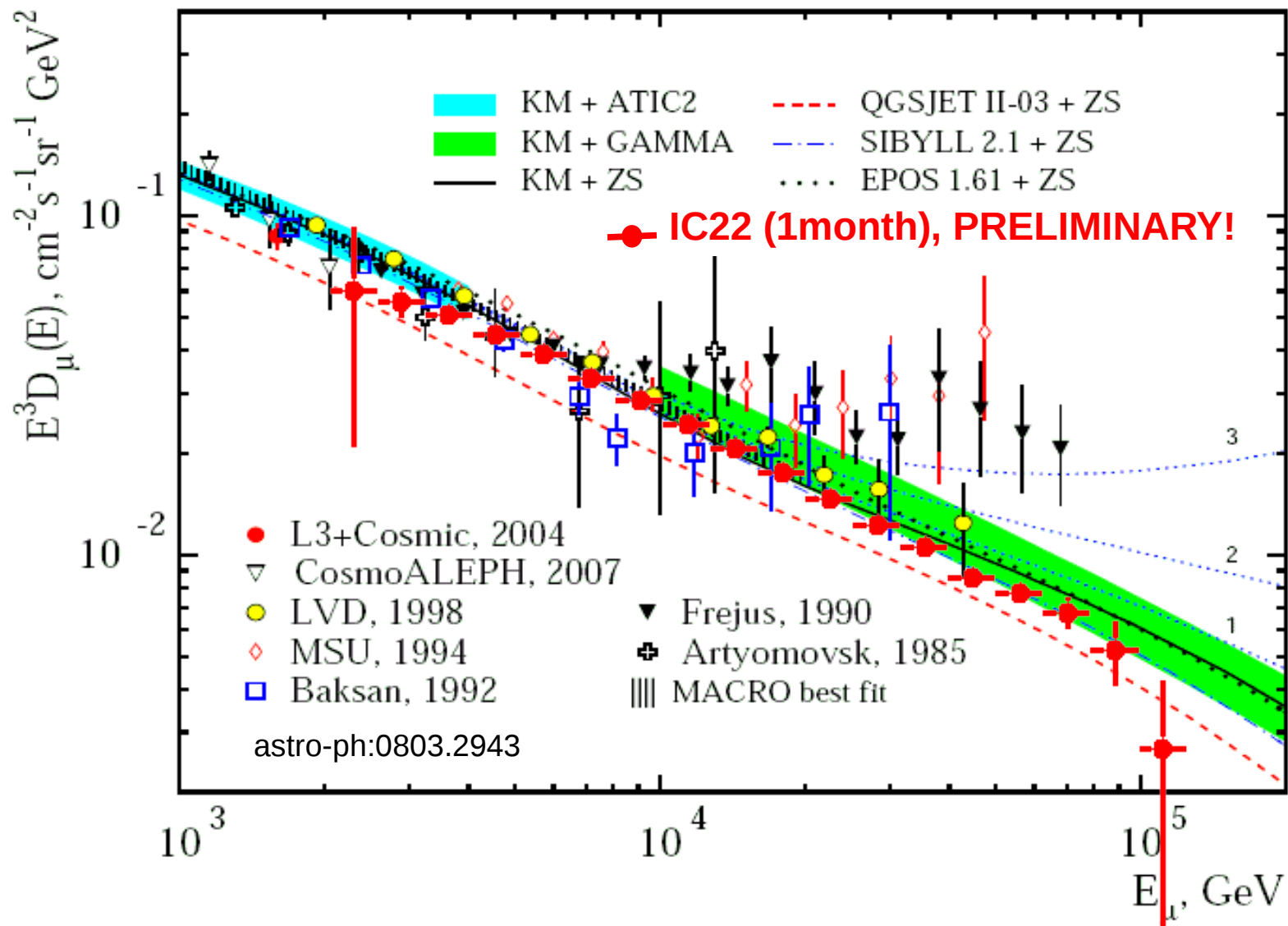
Good!

More:

Moon Shadow (L. Gladstone)

IceTop (T. Gaisser)

Backup Slides

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Prompt Muons: Out of Reach!

1 PeV

Slant Depth and Bundle Multiplicity