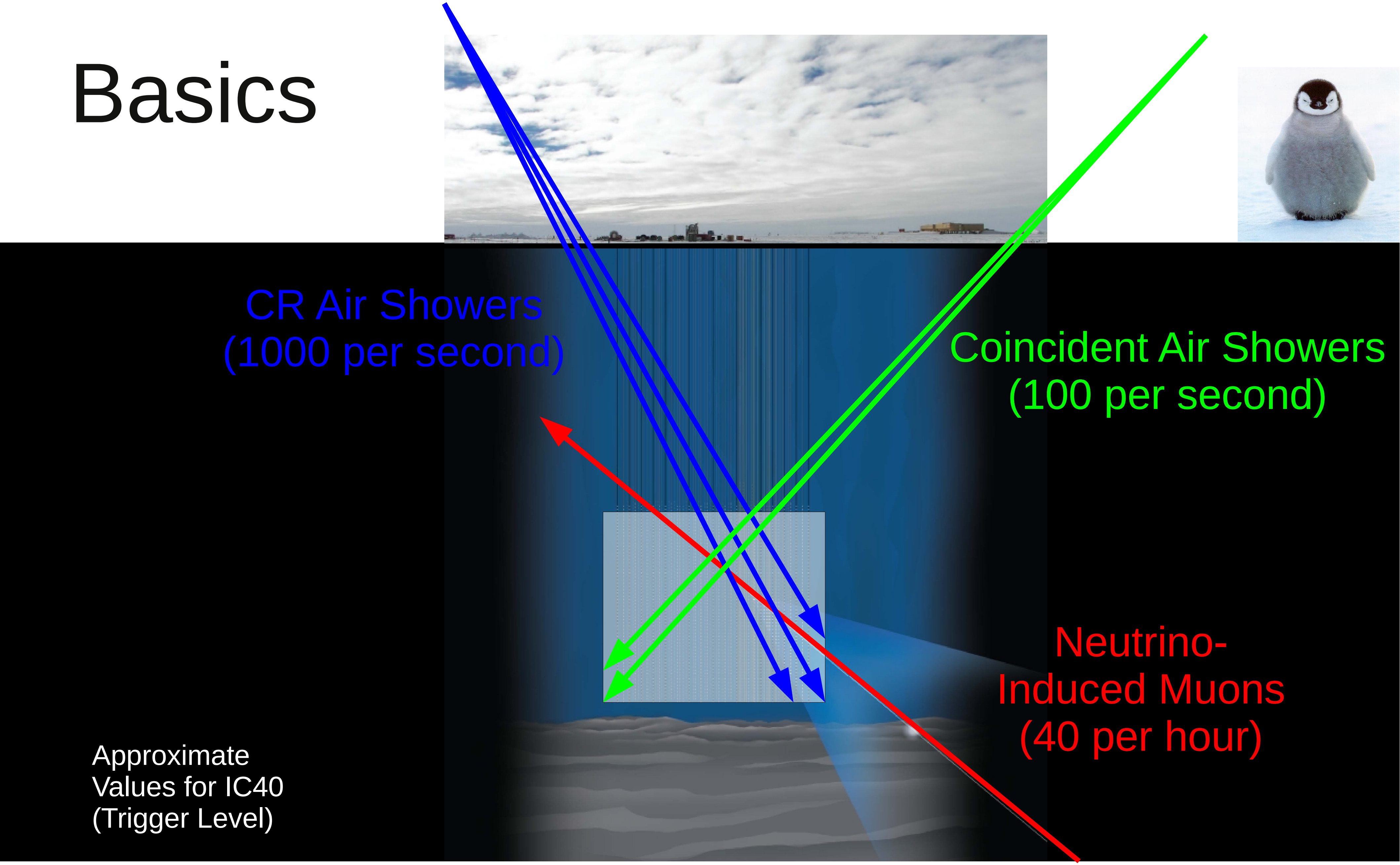
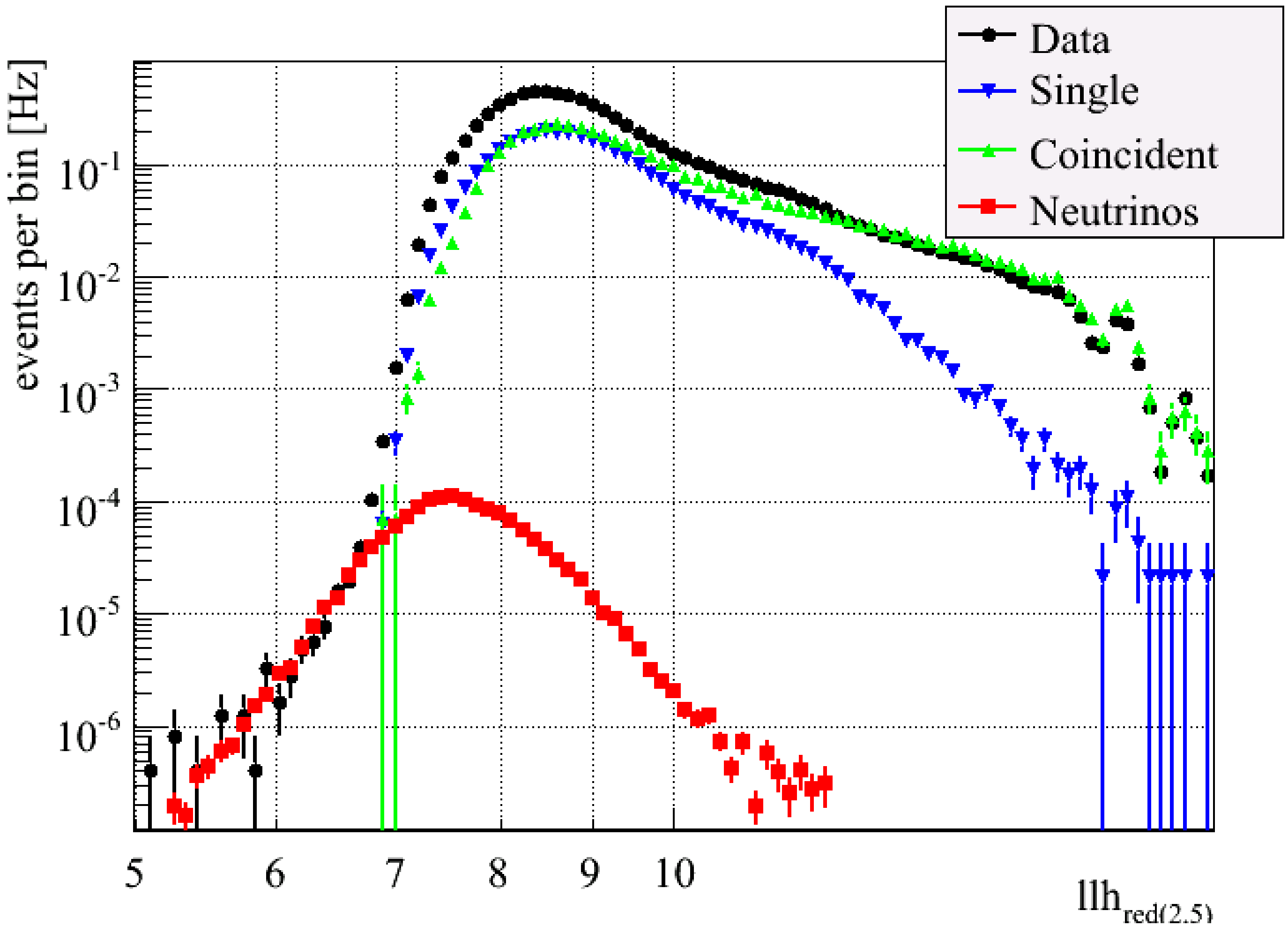
Atmospheric Muons in IceCube

Patrick Berghaus
University of Delaware

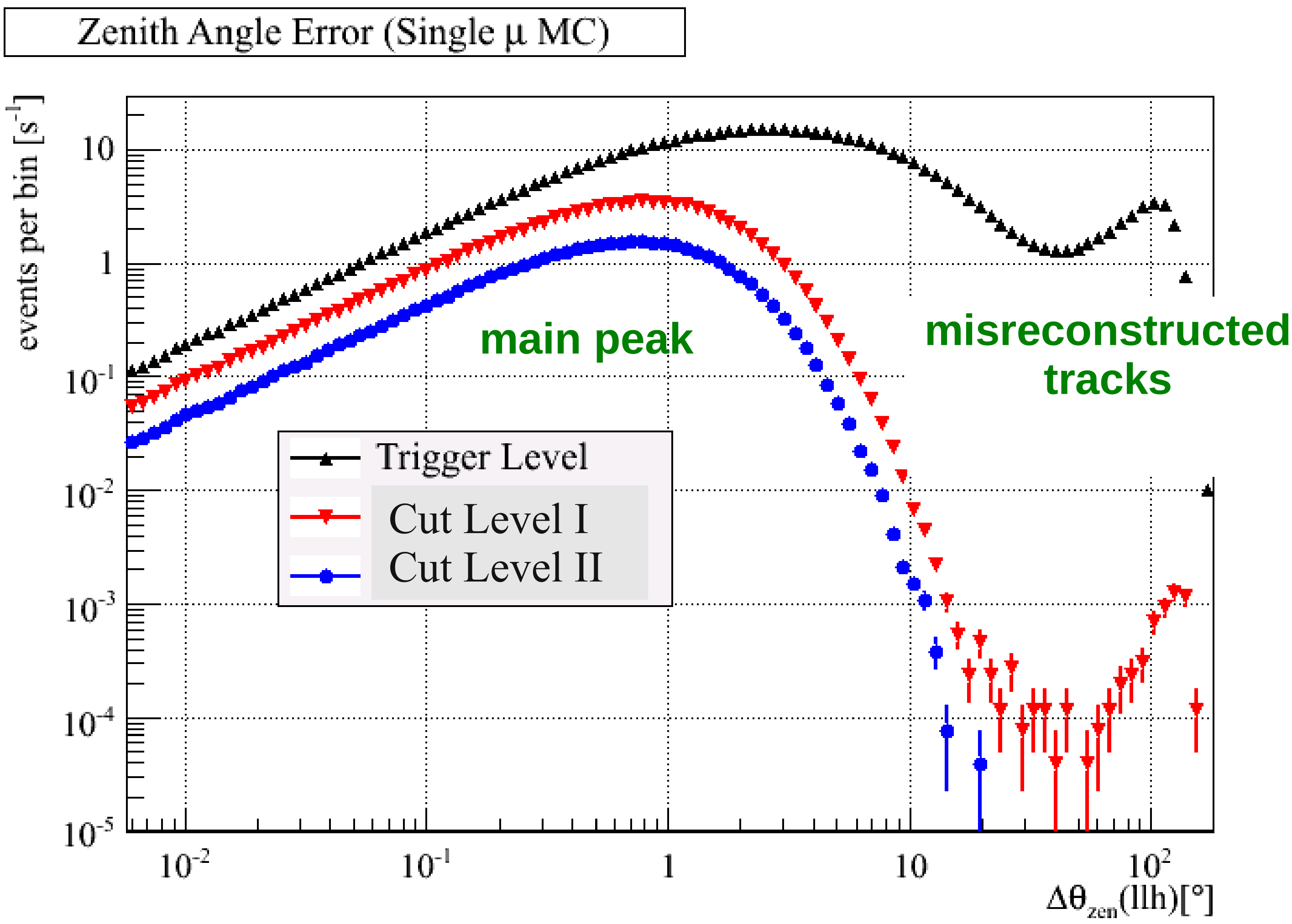
Basics


CR Air Showers
(1000 per second)
Coincident Air Showers
(100 per second)
Neutrino-
Induced Muons
(40 per hour)
Approximate
Values for IC40
(Trigger Level)

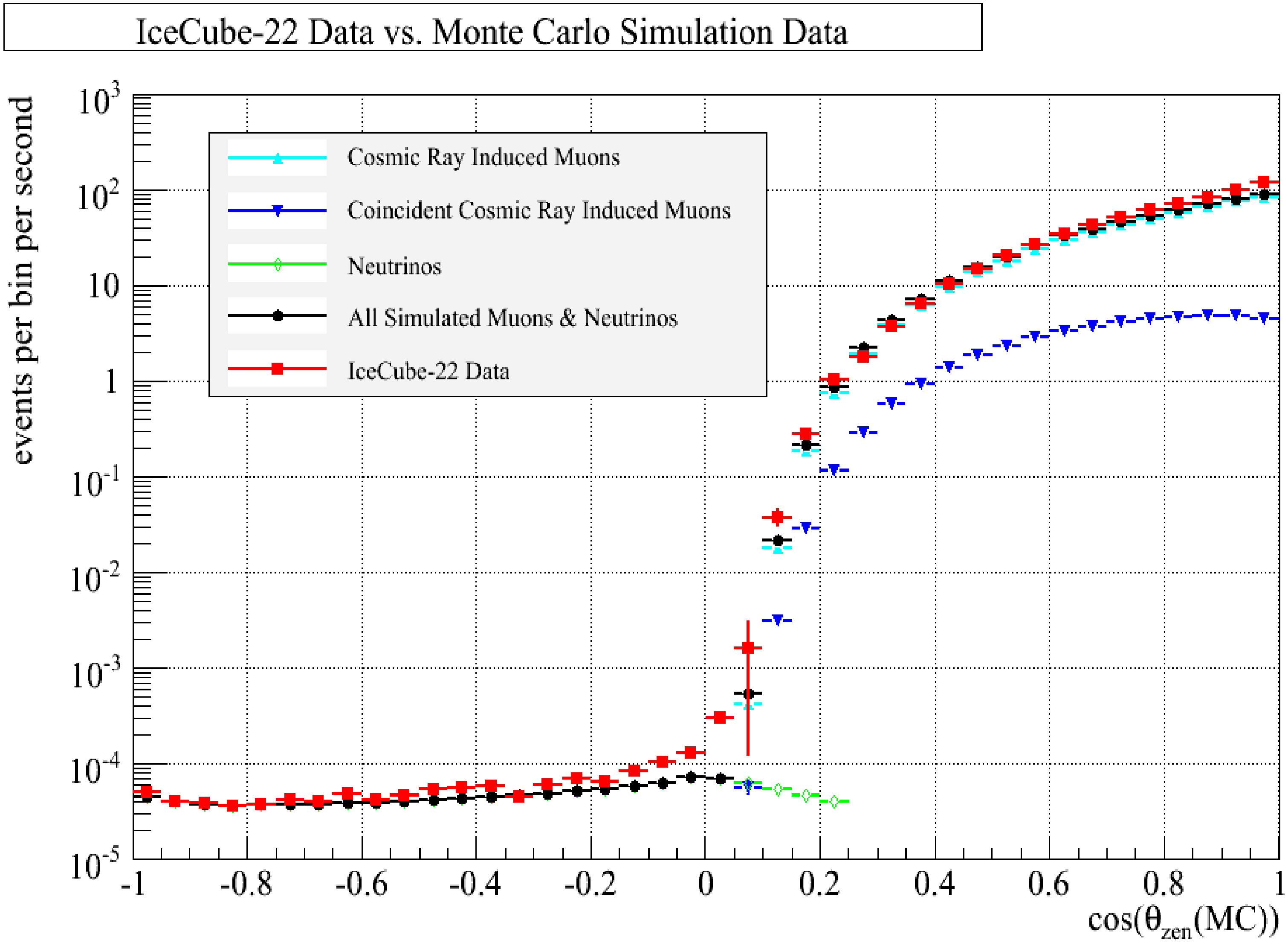
IC22 Trigger Level
Track Reco (SPE llh) below Horizon



All-Sky Analysis: Final Cut Levels



IC22, All Sky (2008)

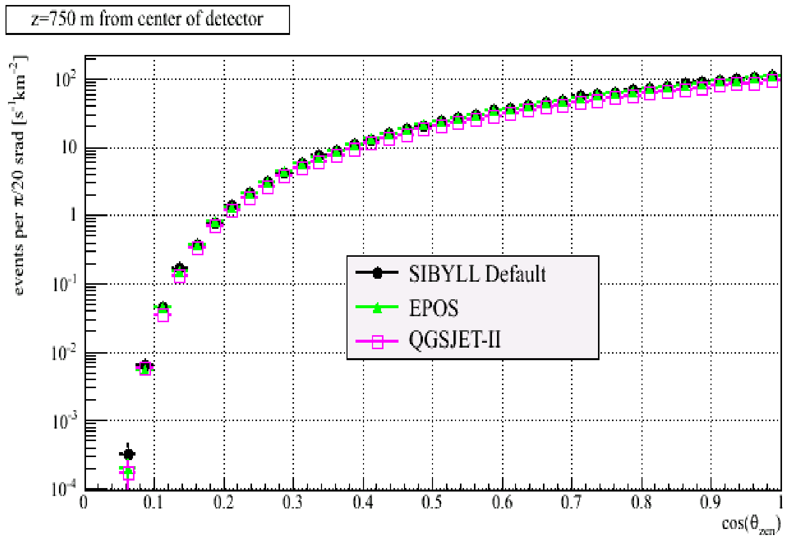


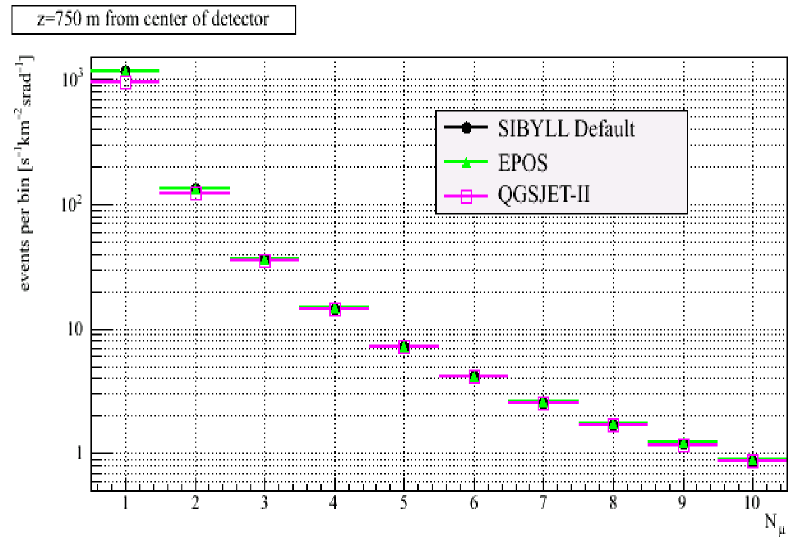
arXiv:0902.0021

CORSIKA: Hadronic Interaction Models

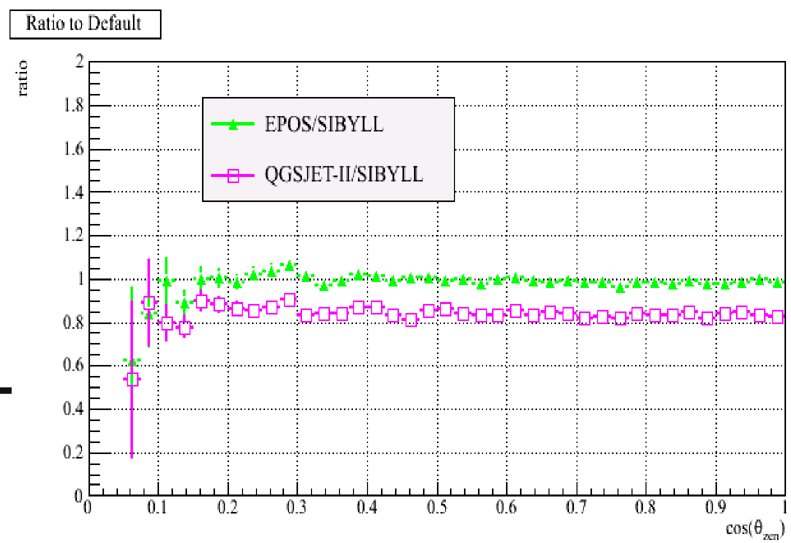
SIBYLL	**IceCube Default**	**40 showers/sec**
QGSJET-II	Common Alternative	3 showers/sec
EPOS 1.9	New in 2009	1 shower/sec

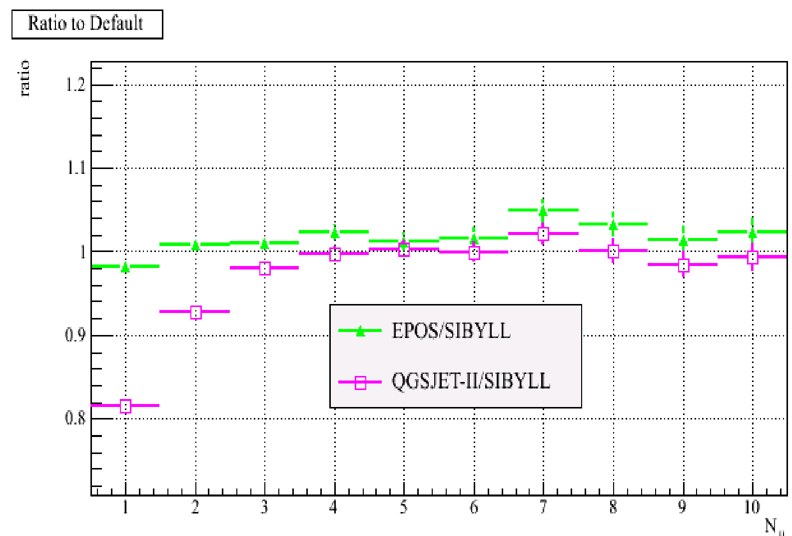
3 Models





Ratio over SIBYLL



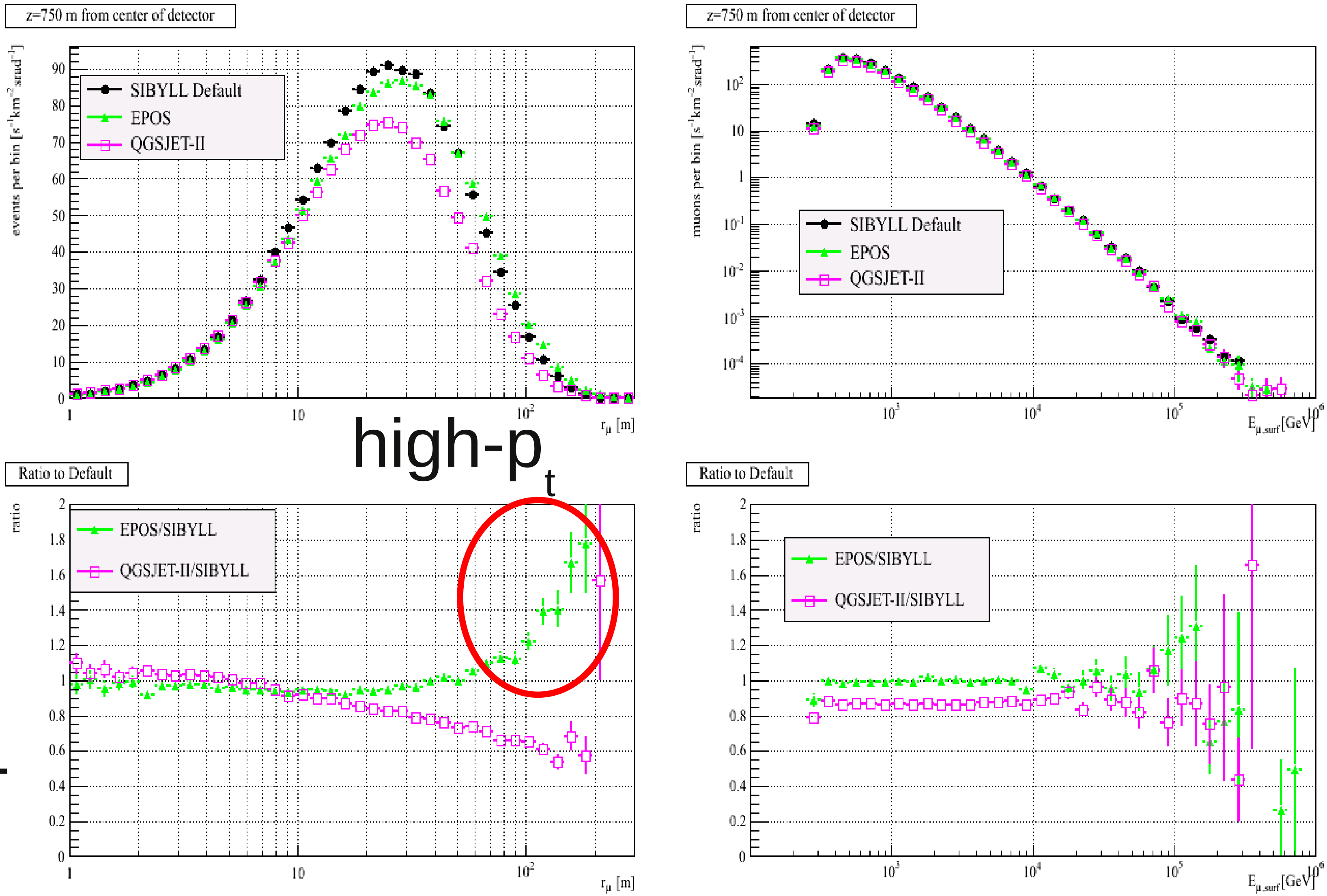


Zenith Angle

Multiplicity

3 Models

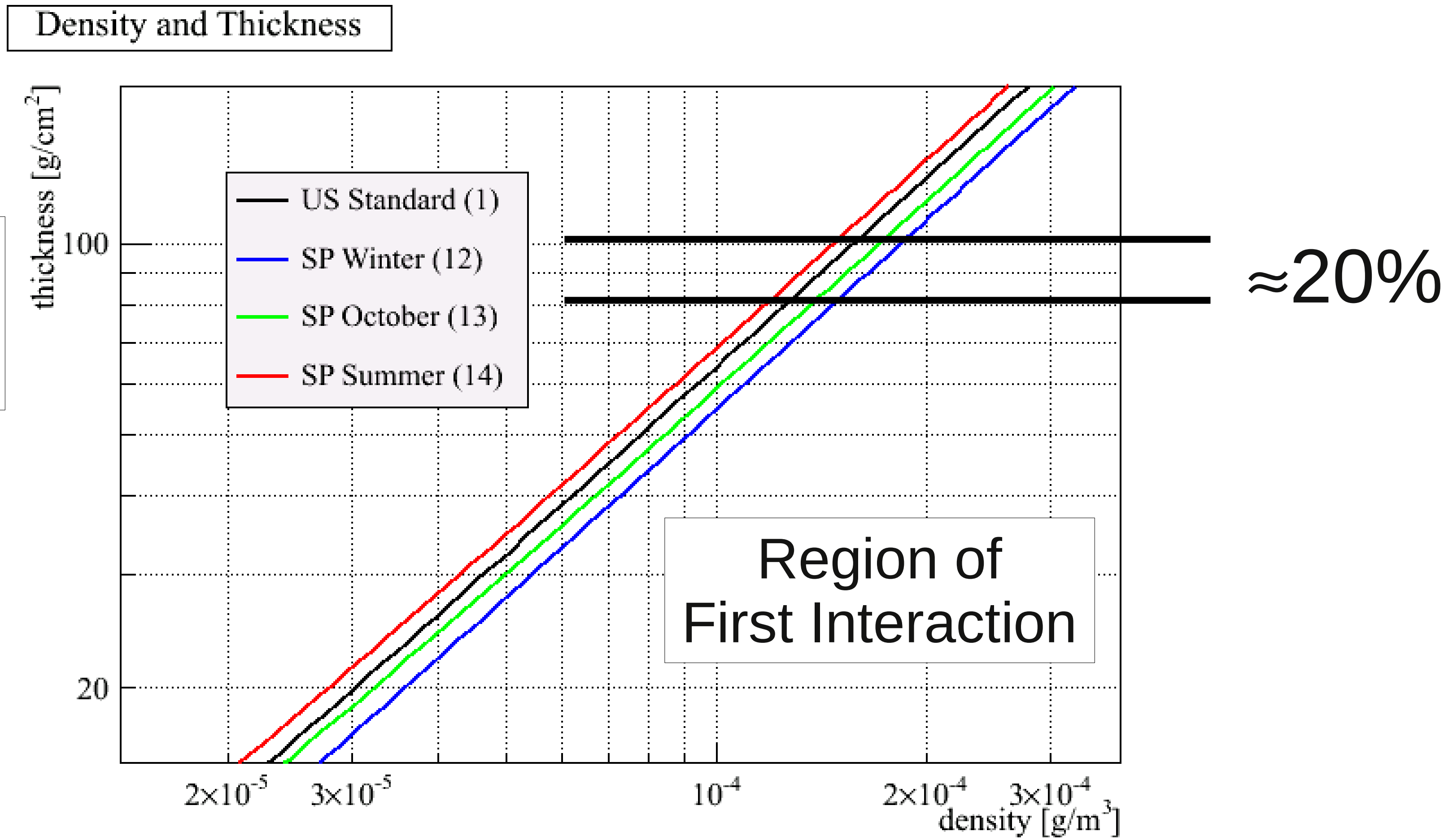
Ratio over SIBYLL



Radius

Muon Energy

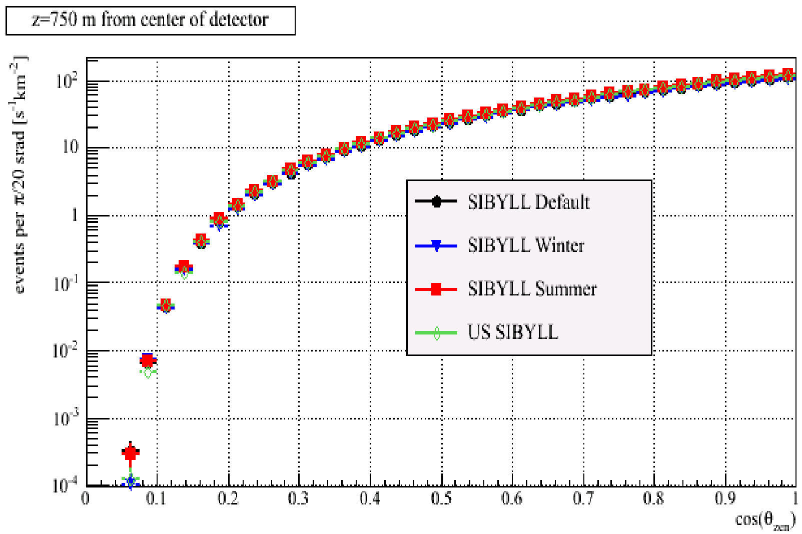
CORSIKA Atmospheres

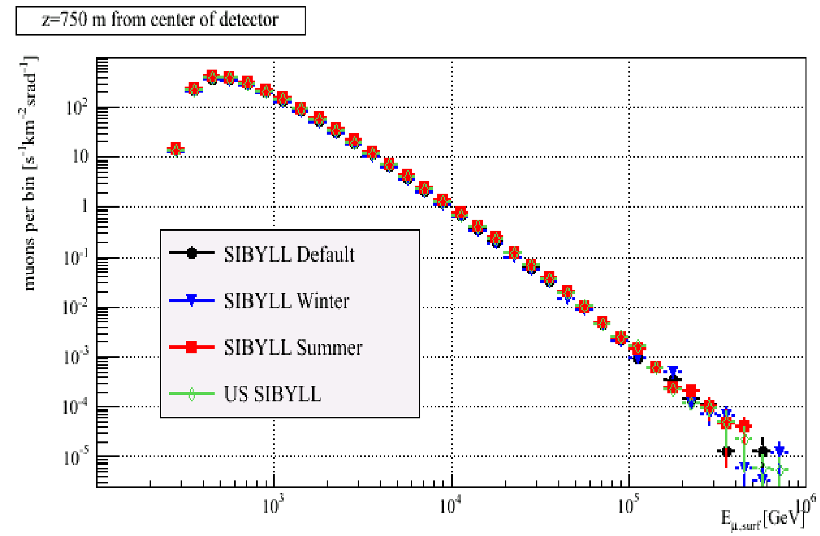


Thickness: Integrated Density (x,∞)

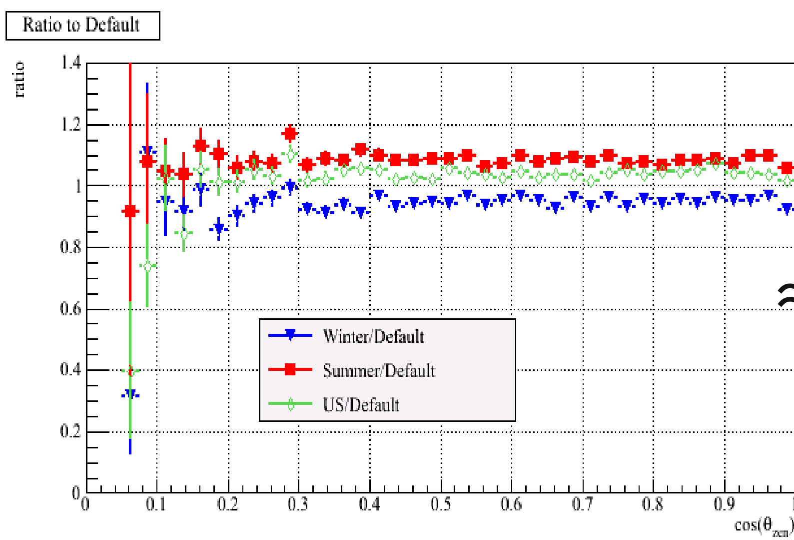
Full Shower Simulation

4 Models

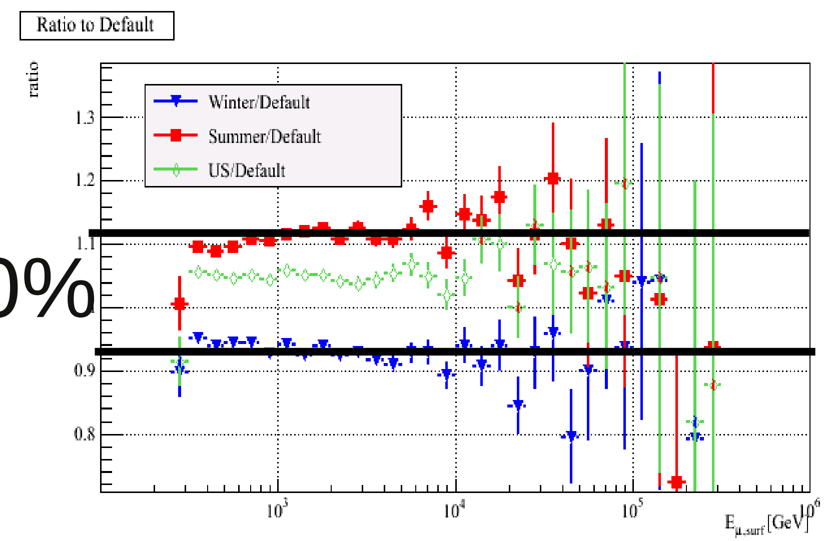




Ratio over SP Oct

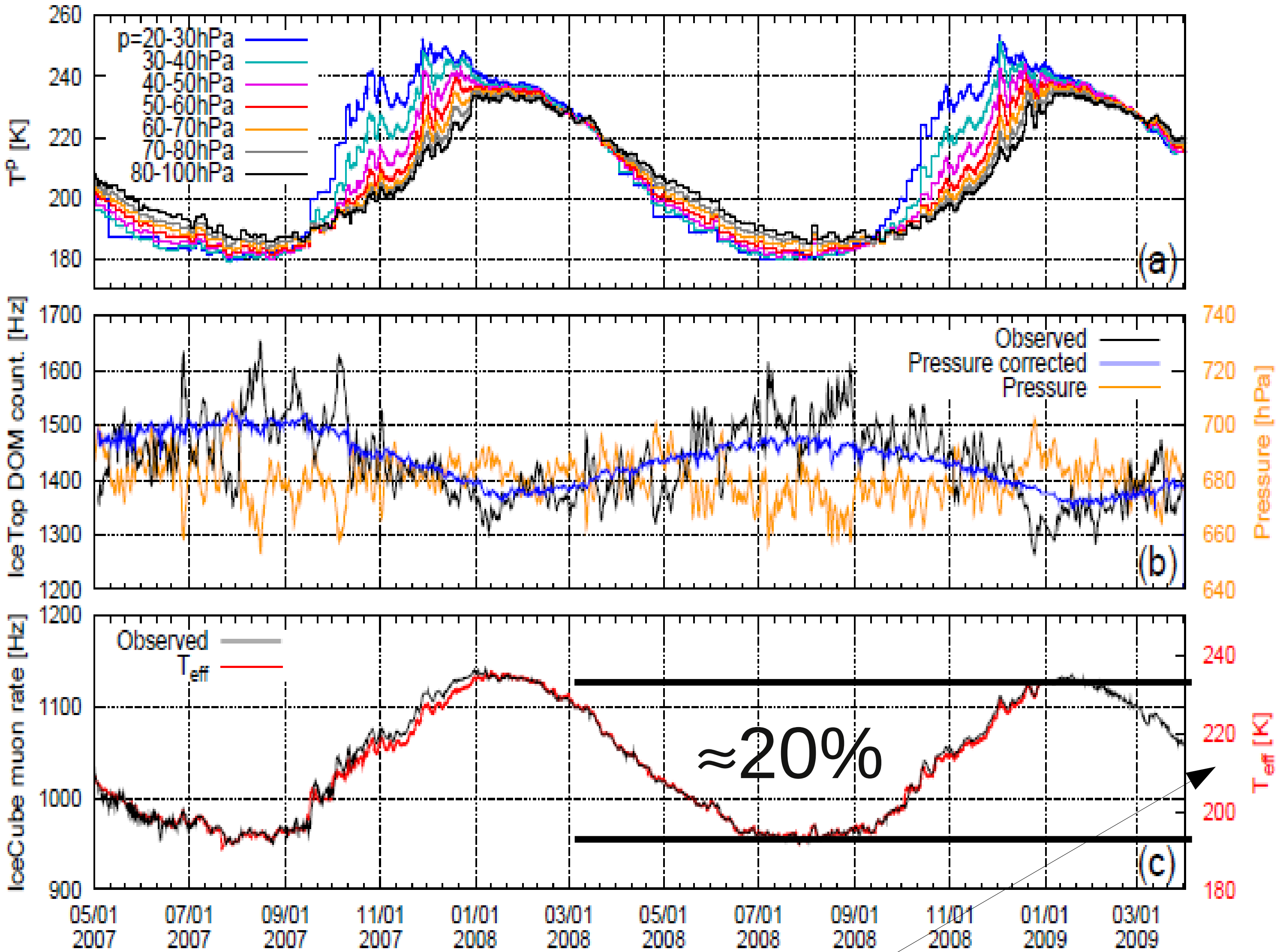


≈20%



Zenith Angle

Muon Energy



Atmospheric Temperature

IceTop (**barometric**)

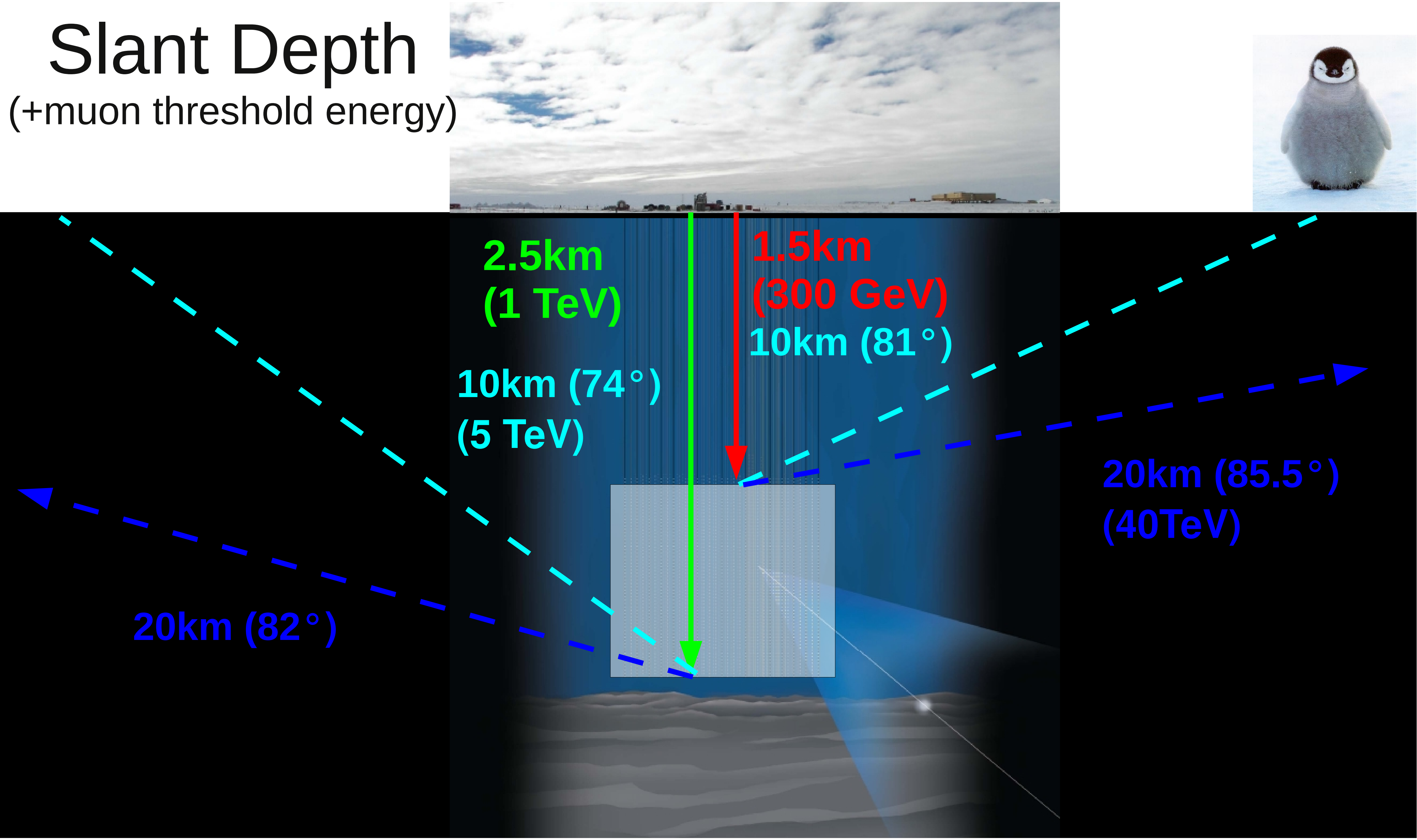
InIce (**temperature**)

T_{eff}: Temperature weighted by muon production probability

$$T_{eff} = \frac{\int_0^\infty \frac{dX}{X} T(X) \left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}{\int_0^\infty \frac{dX}{X} \left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}$$

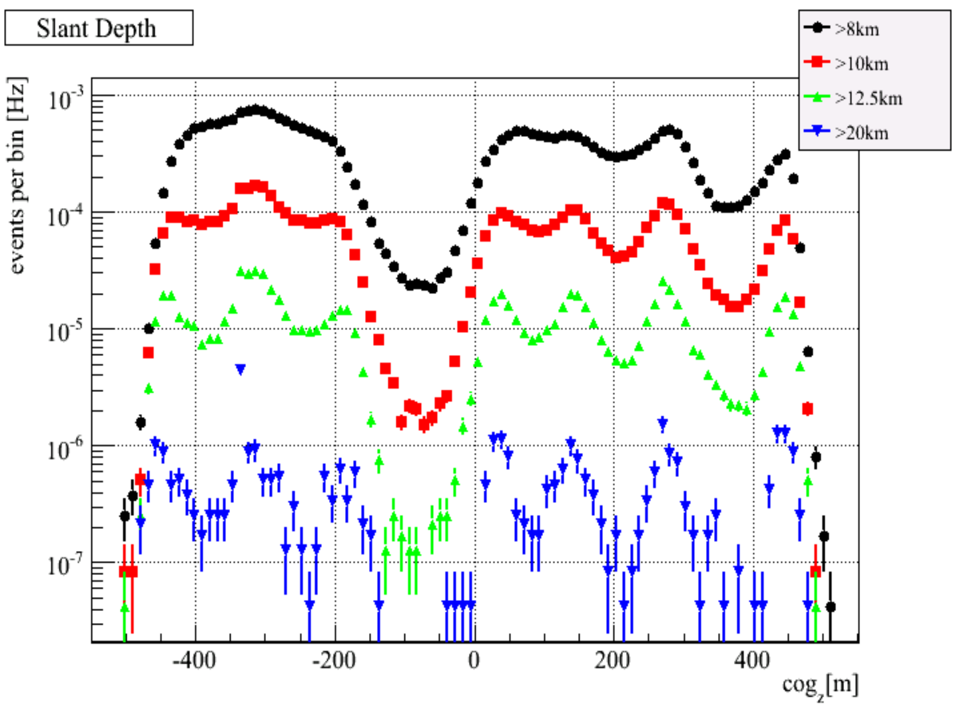
S. Tilav et al., arXiv:1001.0776

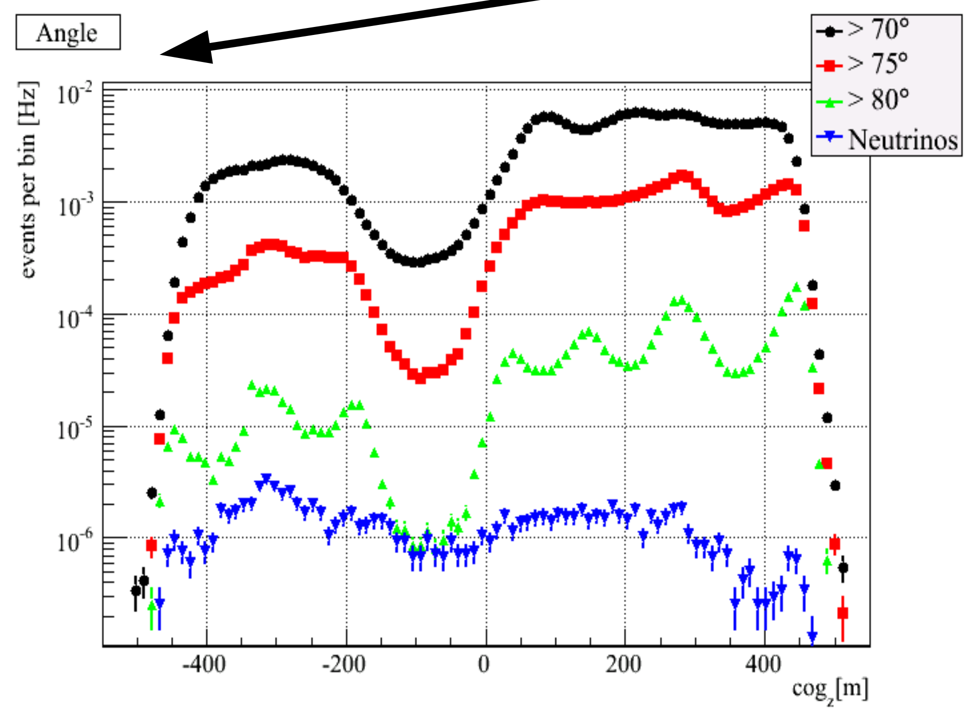
Slant Depth
(+muon threshold energy)



Horizontal Muons

Slope due to absorption in ice



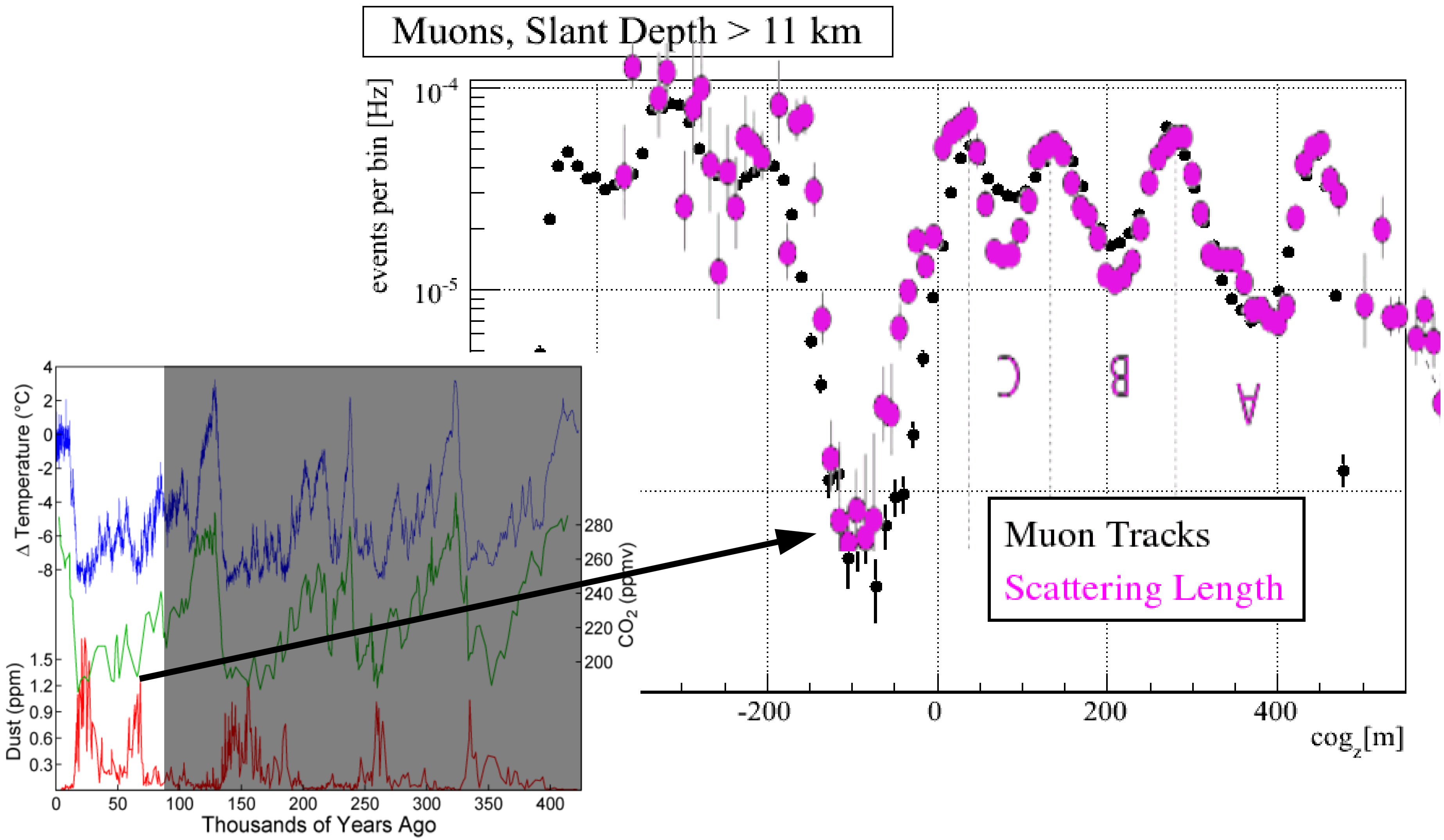


Slant Depth

vertical depth/cos(zenith)

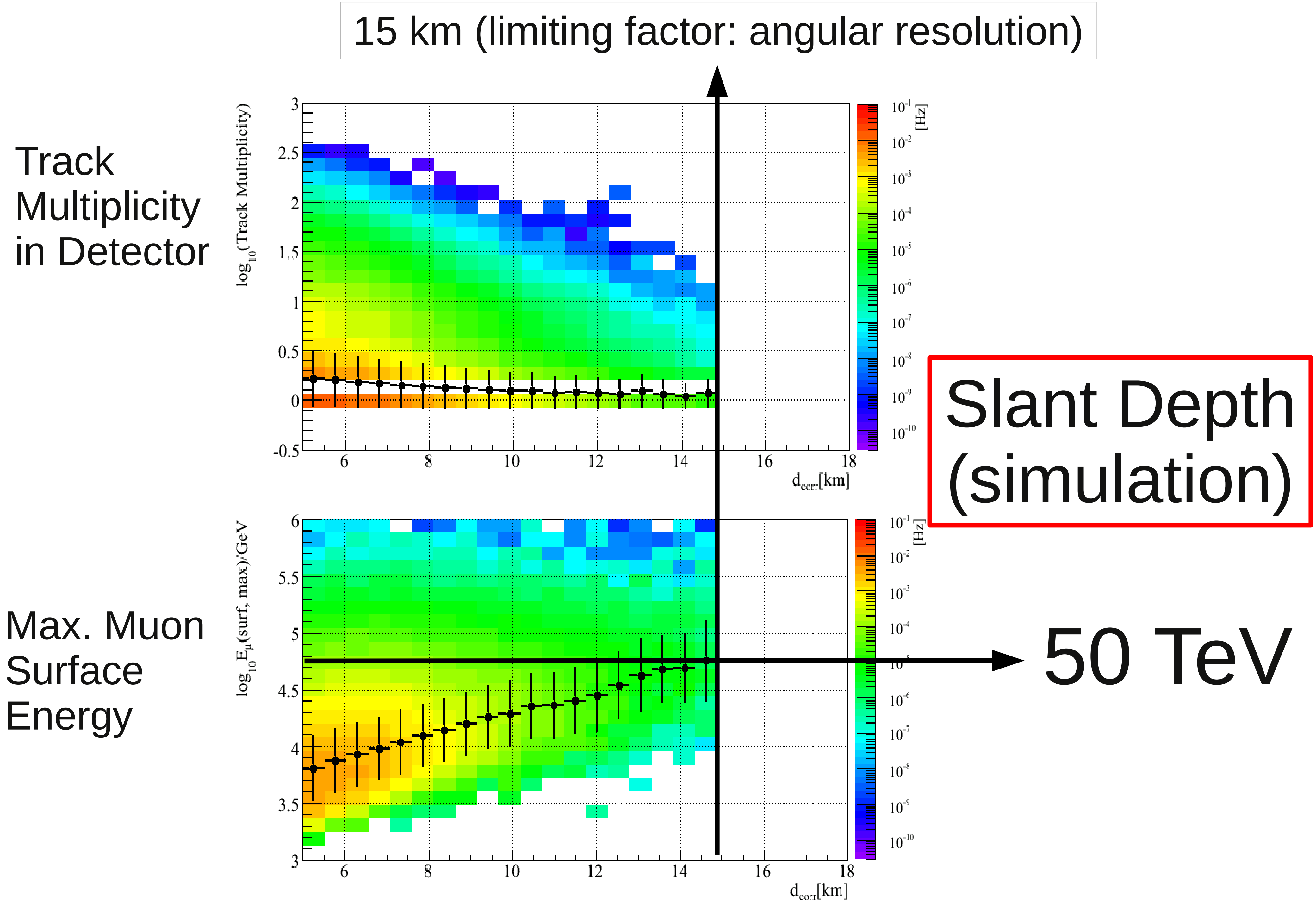
Zenith Angle

Dust Layers



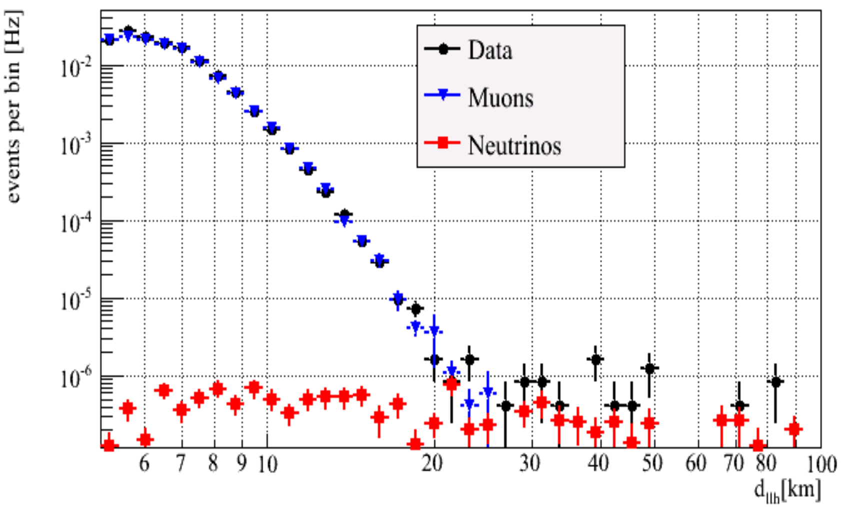
Vostok Ice Core

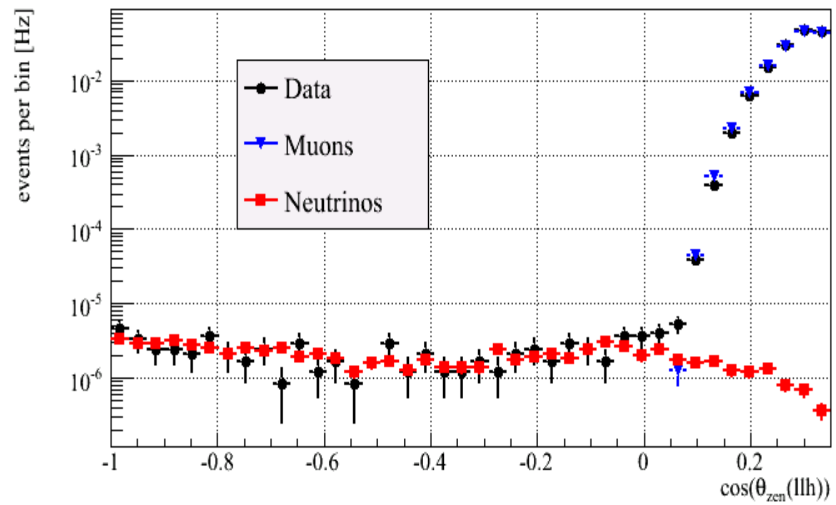
(source: wikipedia)



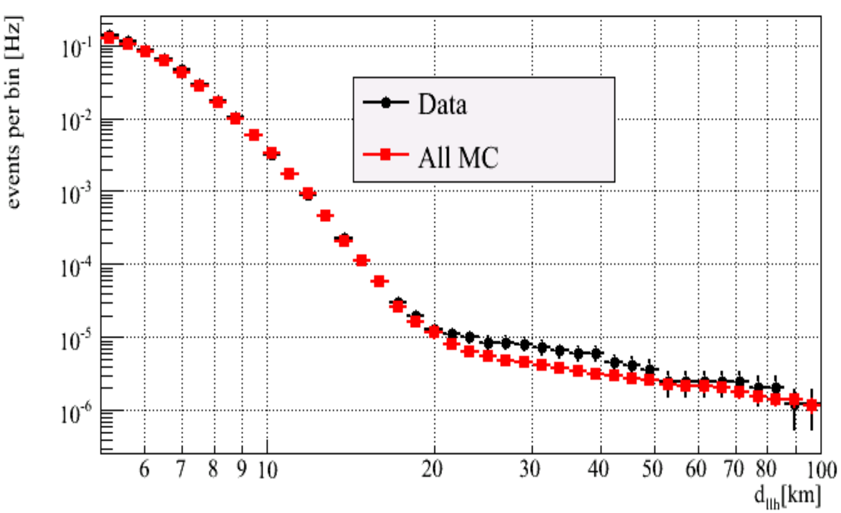
15 km (limiting factor: angular resolution)
Track Multiplicity in Detector
Slant Depth (simulation)
Max. Muon Surface Energy
50 TeV
log10(Track Multiplicity)
log10 Eμ(surf, max)/GeV
dcorr[km]
[Hz]

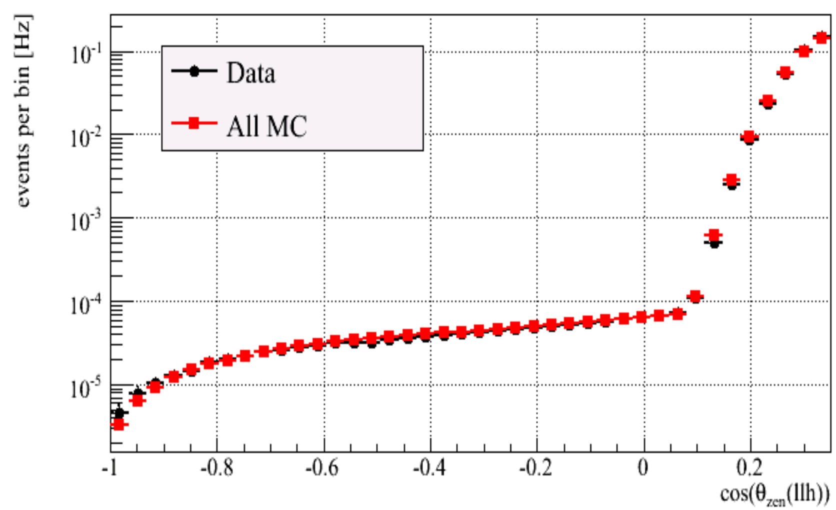
μ-ν Transition: Data and MC





diff





int

Slant Depth

Zenith Angle

Composition Models (poly-gonato)

cut–off:	rigidity dependent	mass dependent	constant	
$\hat{E}_Z =$	$\hat{E}_p \cdot Z$	$\hat{E}_p \cdot A$	$\hat{E}_p$	
$\hat{E}_p$ [PeV] $=$	4.51 ± 0.52	3.66 ± 0.41	3.50 ± 0.38	common γ_c
$\gamma_c =$	-4.68 ± 0.23	-7.82 ± 1.09	-3.06 ± 0.02	
$\epsilon_c =$	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	
$\epsilon_c =$	1.90 ± 0.19	2.32 ± 0.22	1.84 ± 0.45	
χ^2/d.o.f. $=$	0.113	0.292	0.088	

Rigidity

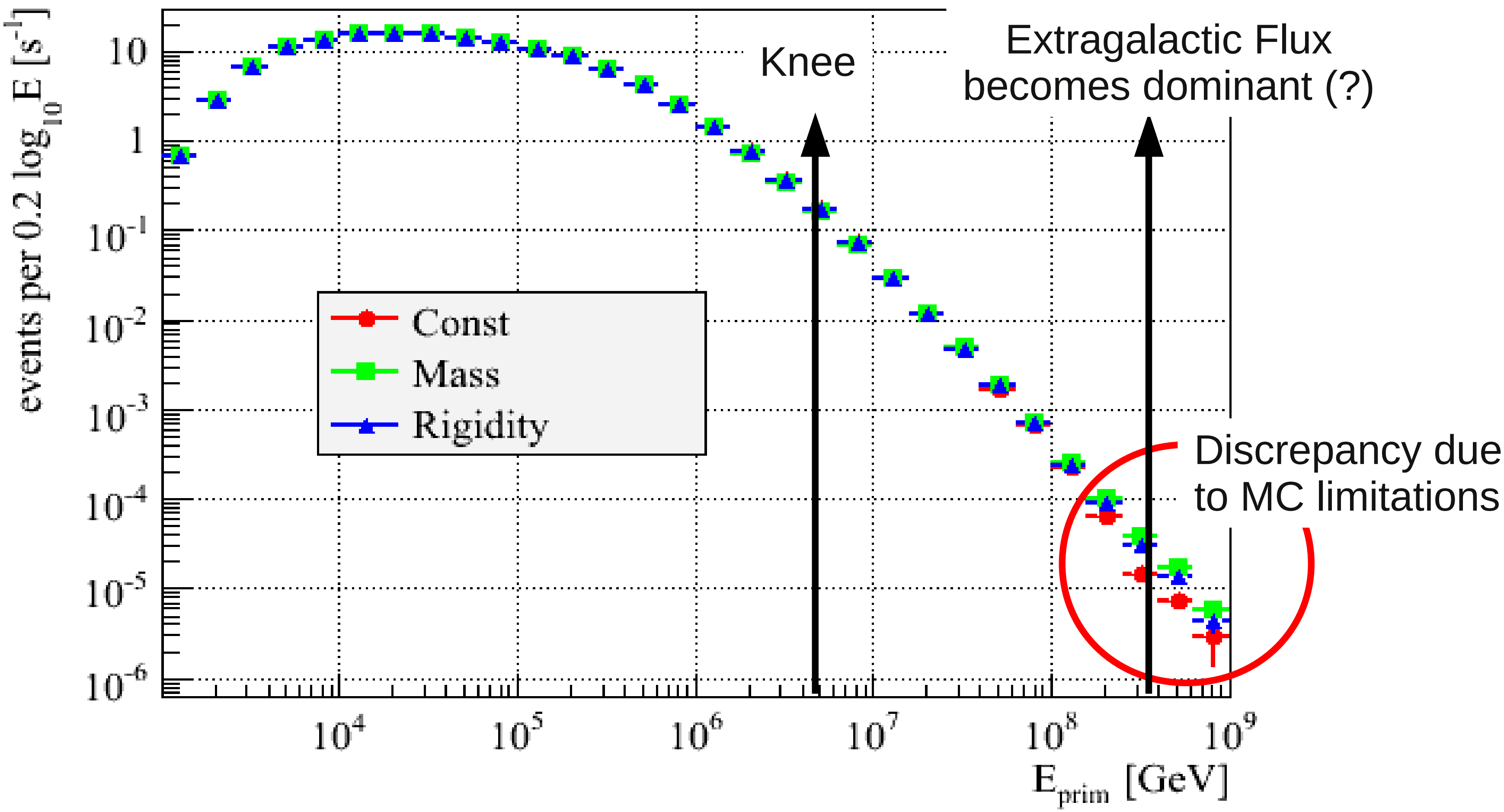
Mass

-Dependent Cutoff

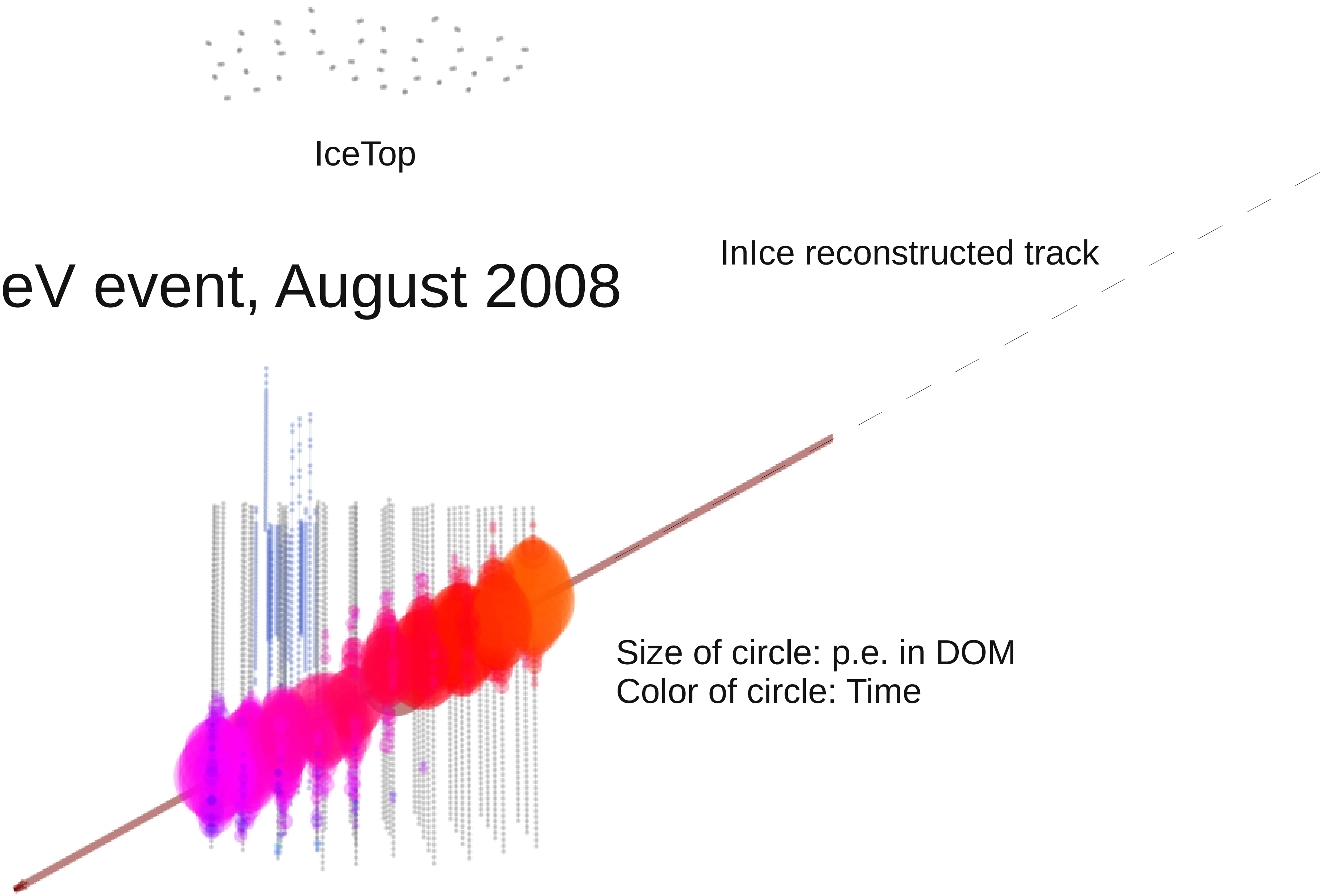
Constant Composition

astro-ph/0210453

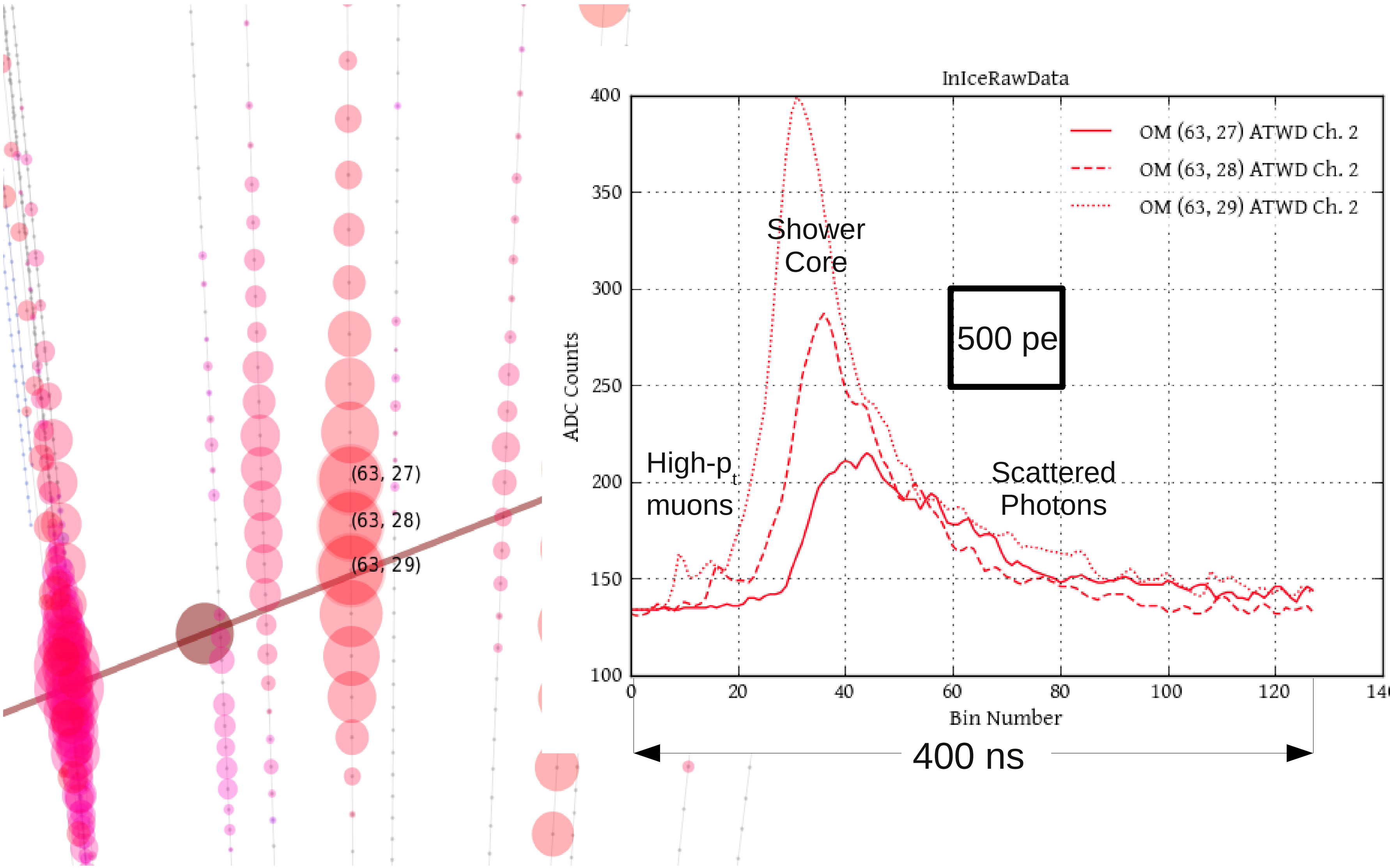
MC Event Rates in IC40 (High-Quality)



≈1EeV event, August 2008



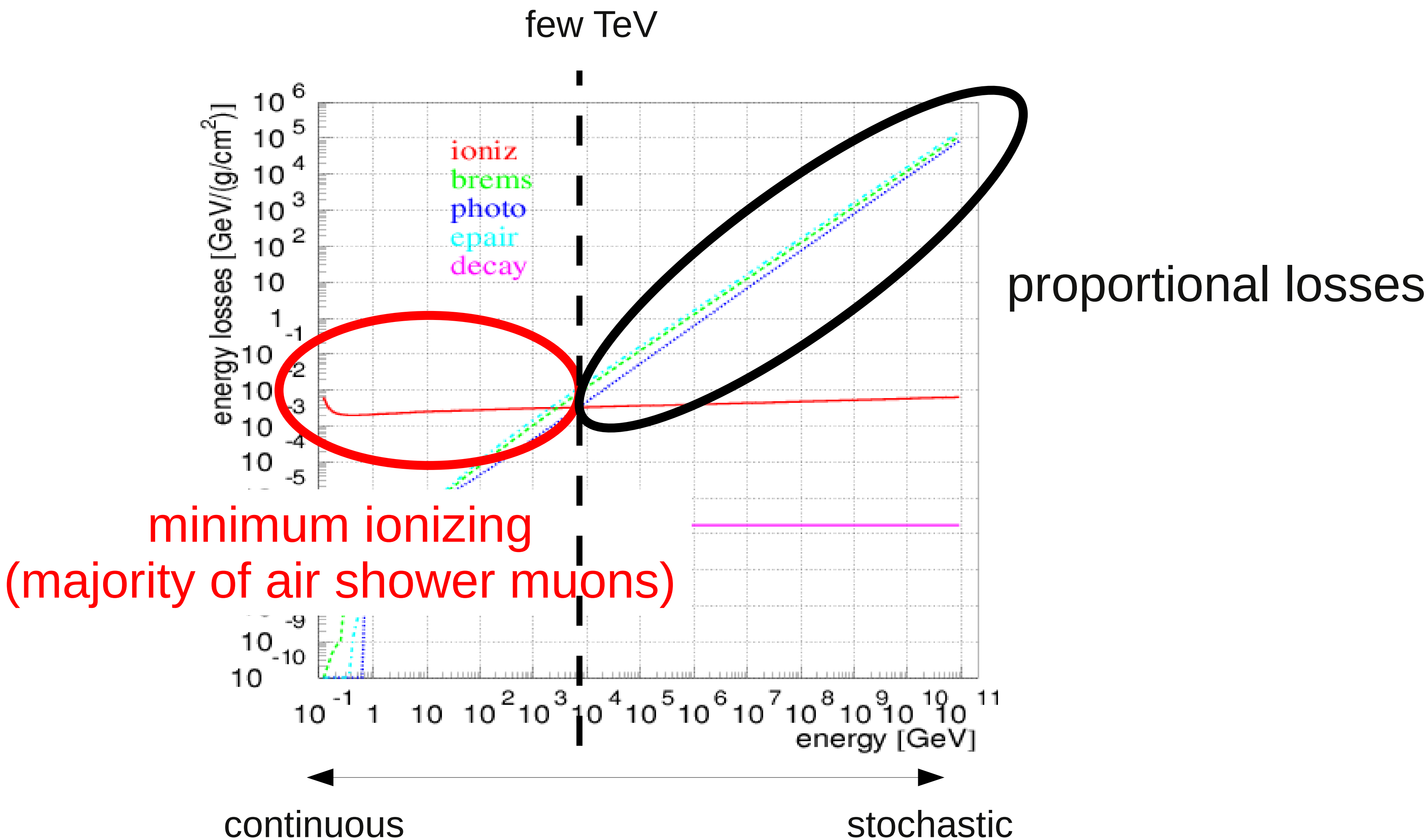
DOM Waveforms

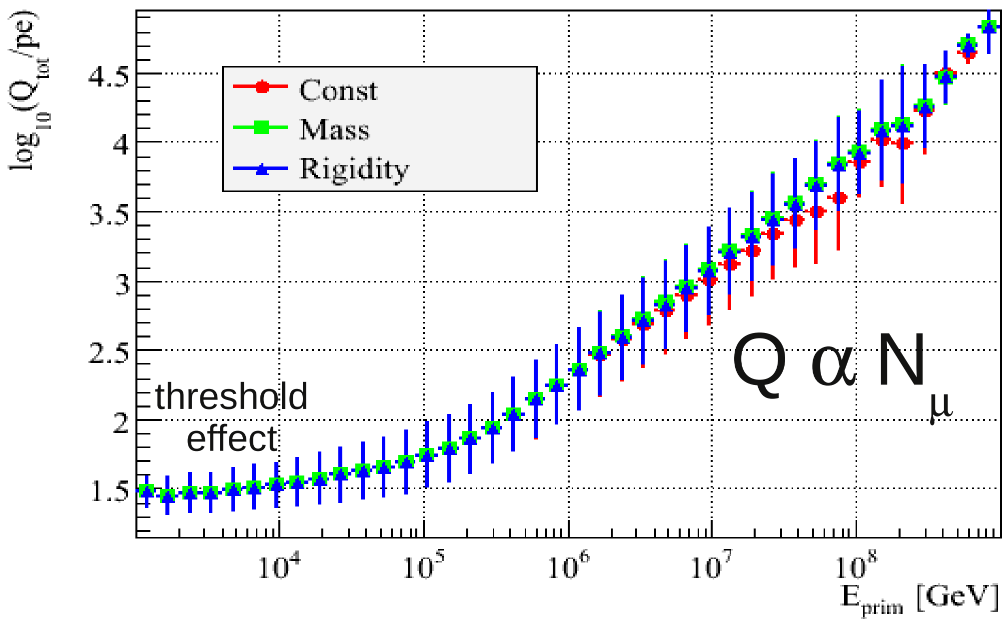


Muon Monte Carlo: a high-precision tool for muon propagation through matter

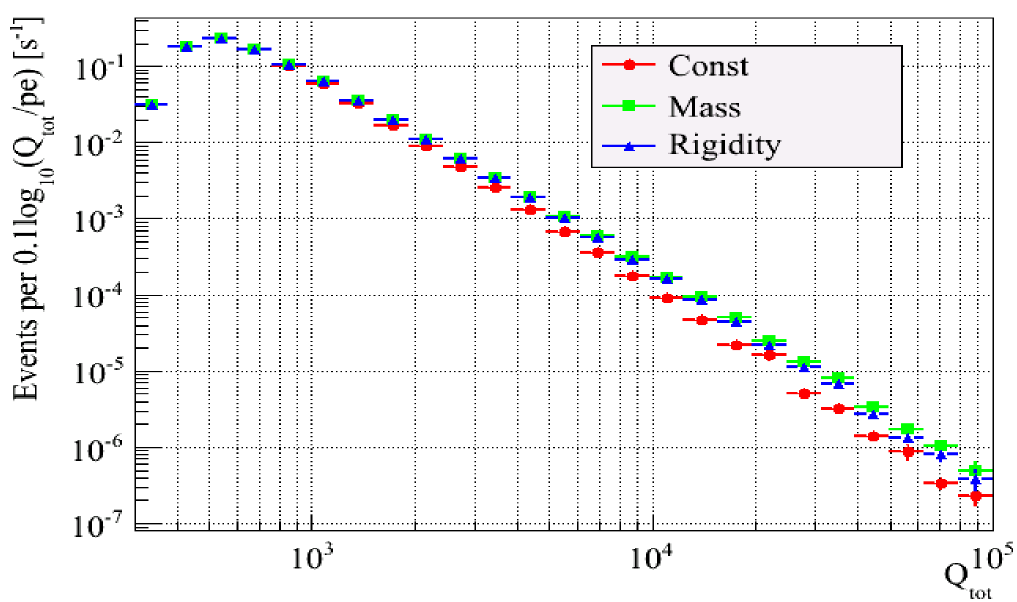
hep-ph/0407075

Dmitry Chirkin[1], Wolfgang Rhode[2]
chirkin@physics.berkeley.edu
rhode@uni-wuppertal.de





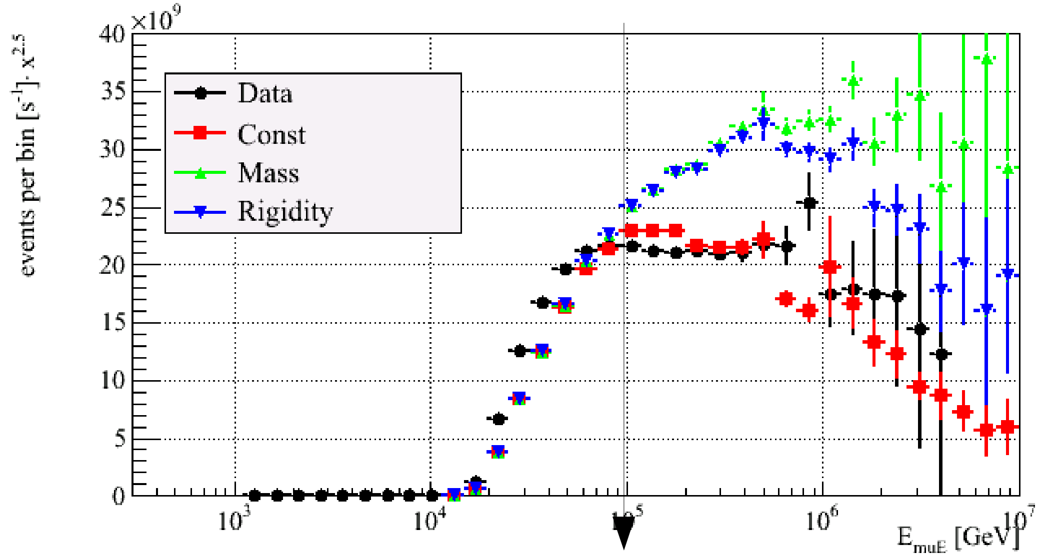
Simulated detector Response to vertical showers (total pe)



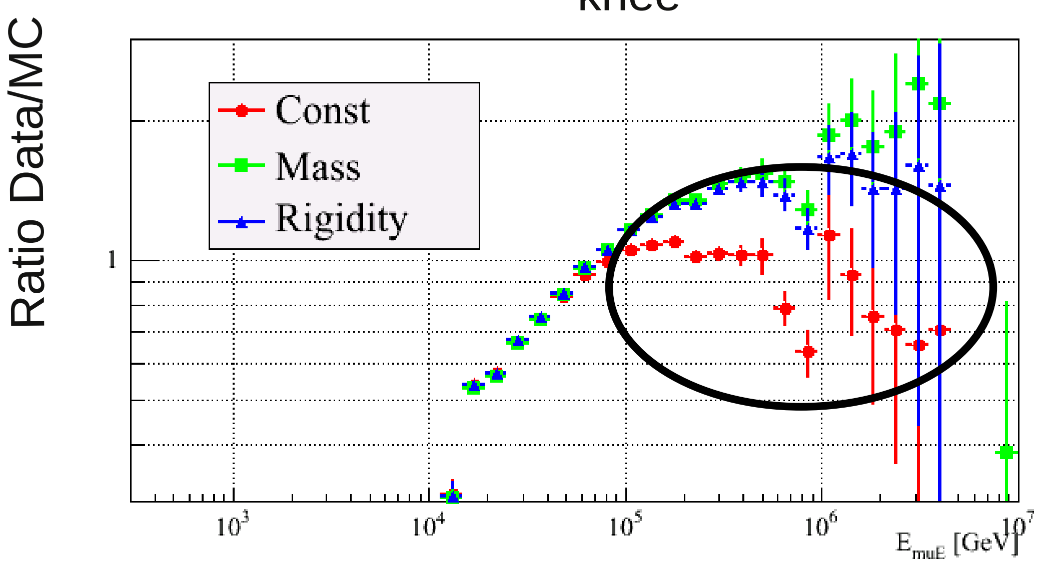
MC Event Rates

Data/MC: p.e. in Event

E$^{2.5}$-weighted



knee



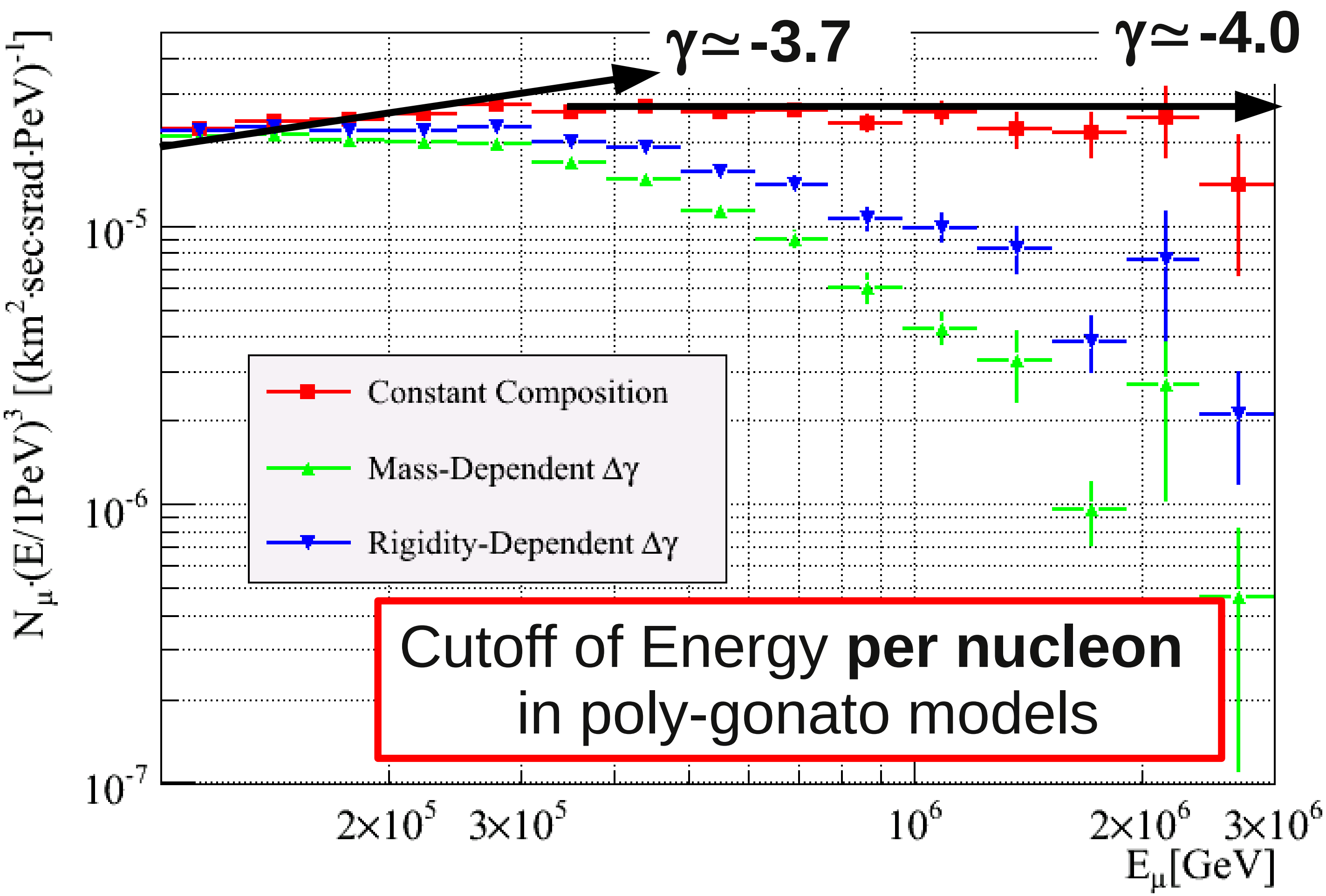
Lighter Primaries

⇒Lower Multiplicity

($N_\mu \propto A^{0.25}$)

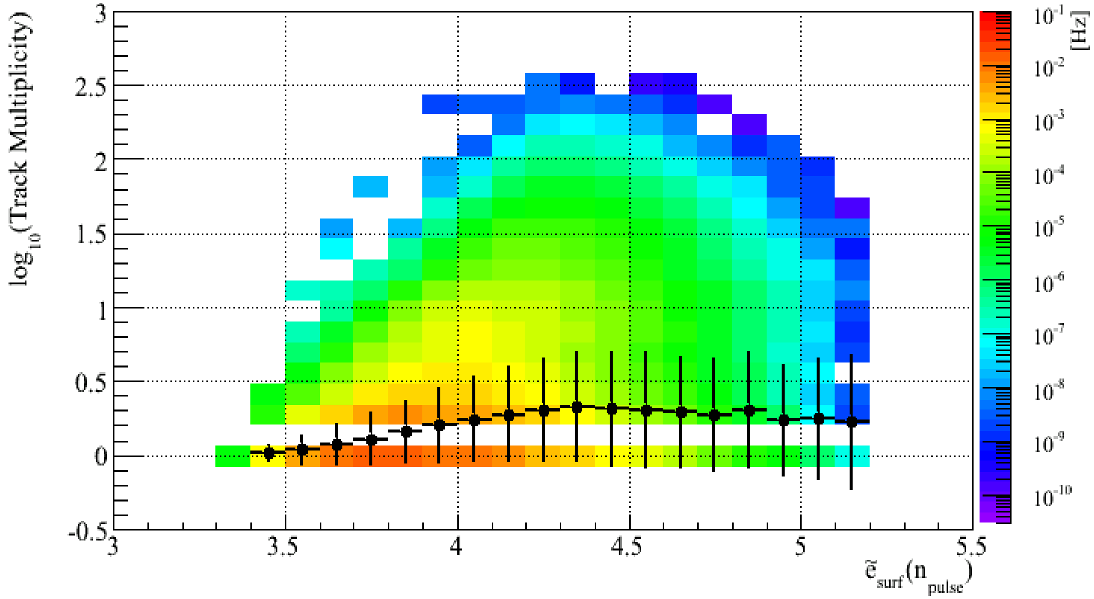
Problem with high-E waveforms?

Single Muon Energy

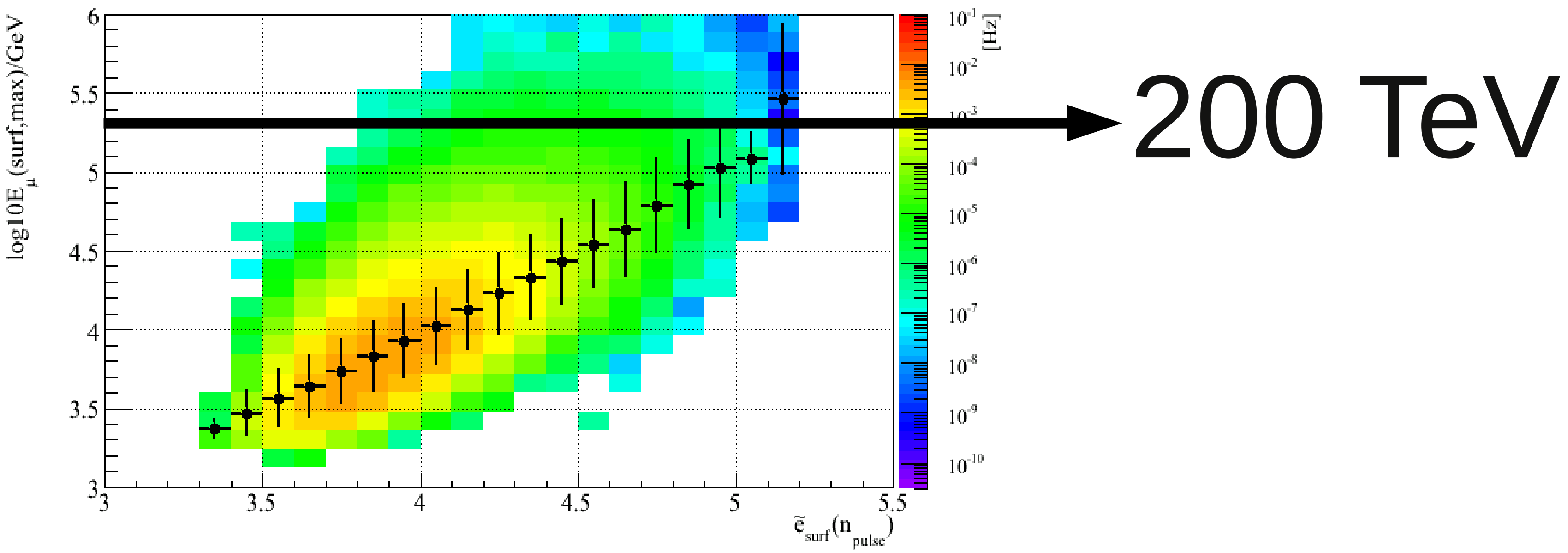


$\tilde{e}_{surf} \propto \log n_\gamma \cdot d_{slant}$ (simulation)

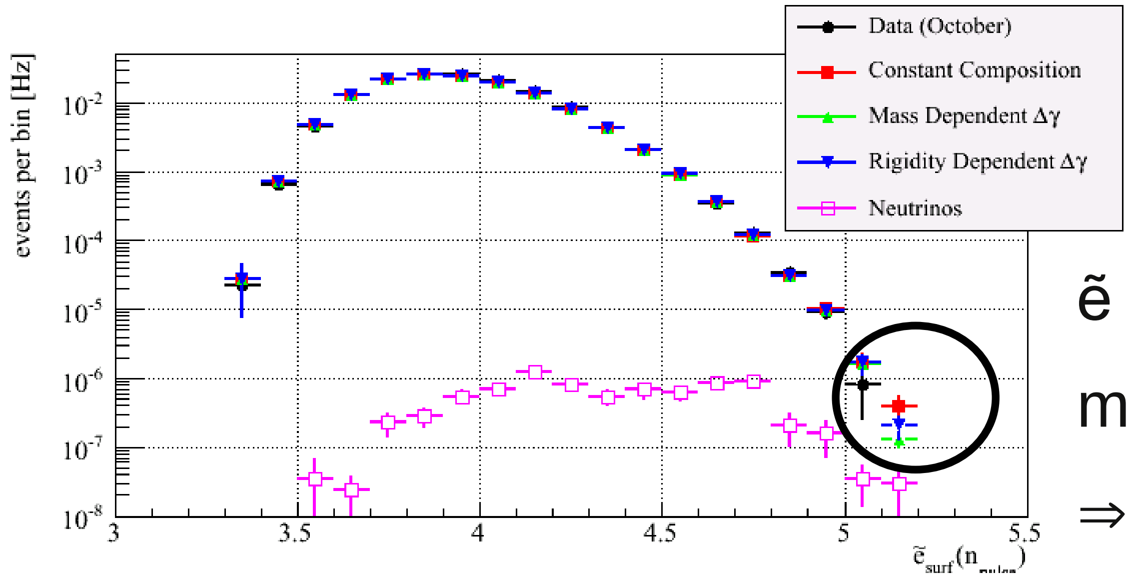
Track Multiplicity in Detector



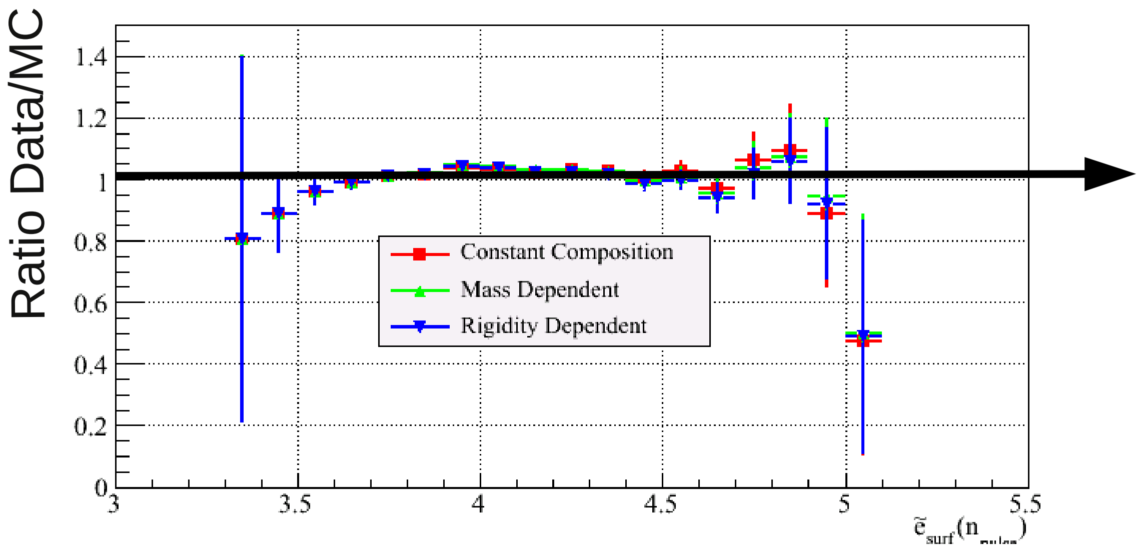
Max. Muon Surface Energy



Data/MC: $\tilde{e}_{surf}$

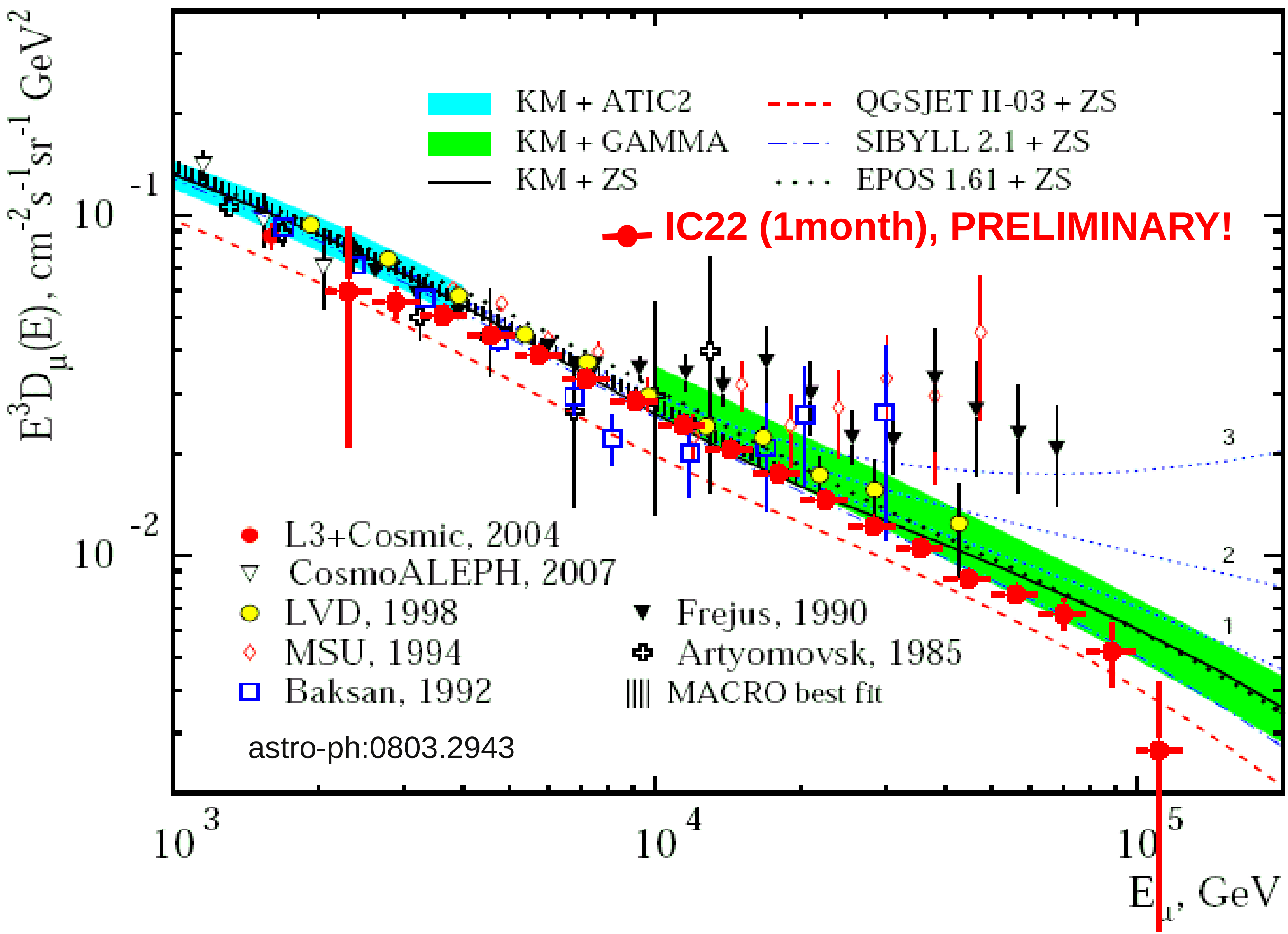


ẽ measures **single** muon energy
⇒model order inverted



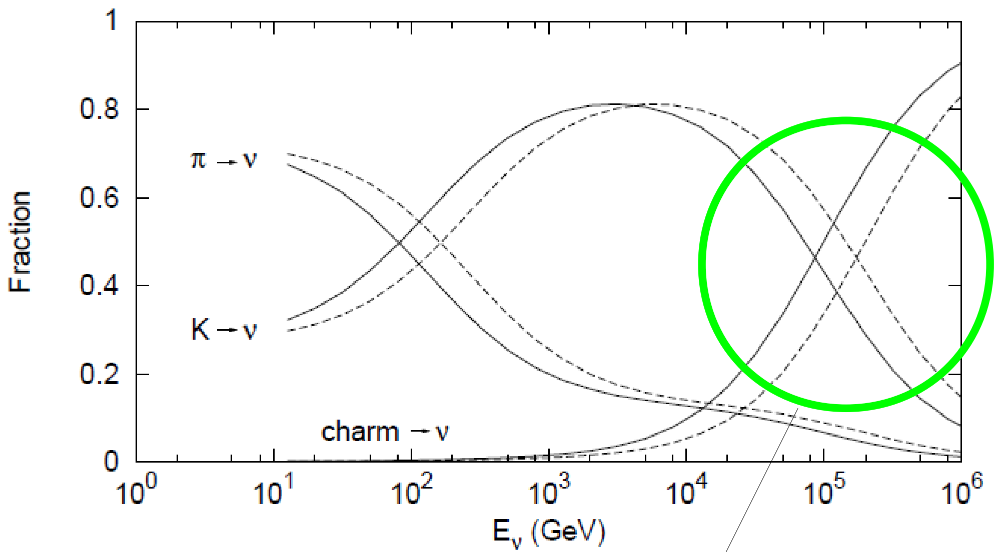
MC/Data close to 1
Composition in IC59

Muon Spectrum



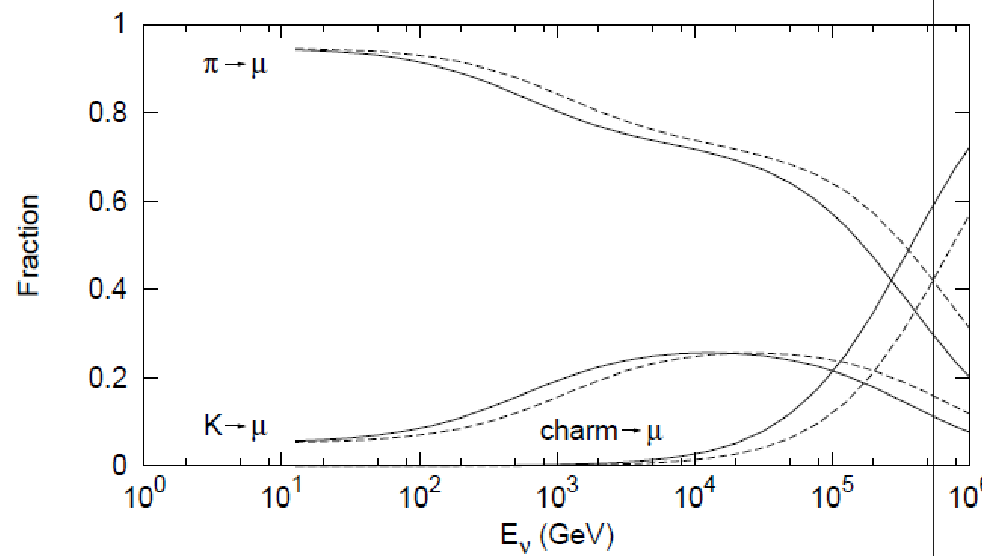
Charm

ν



Source: T. Gaisser

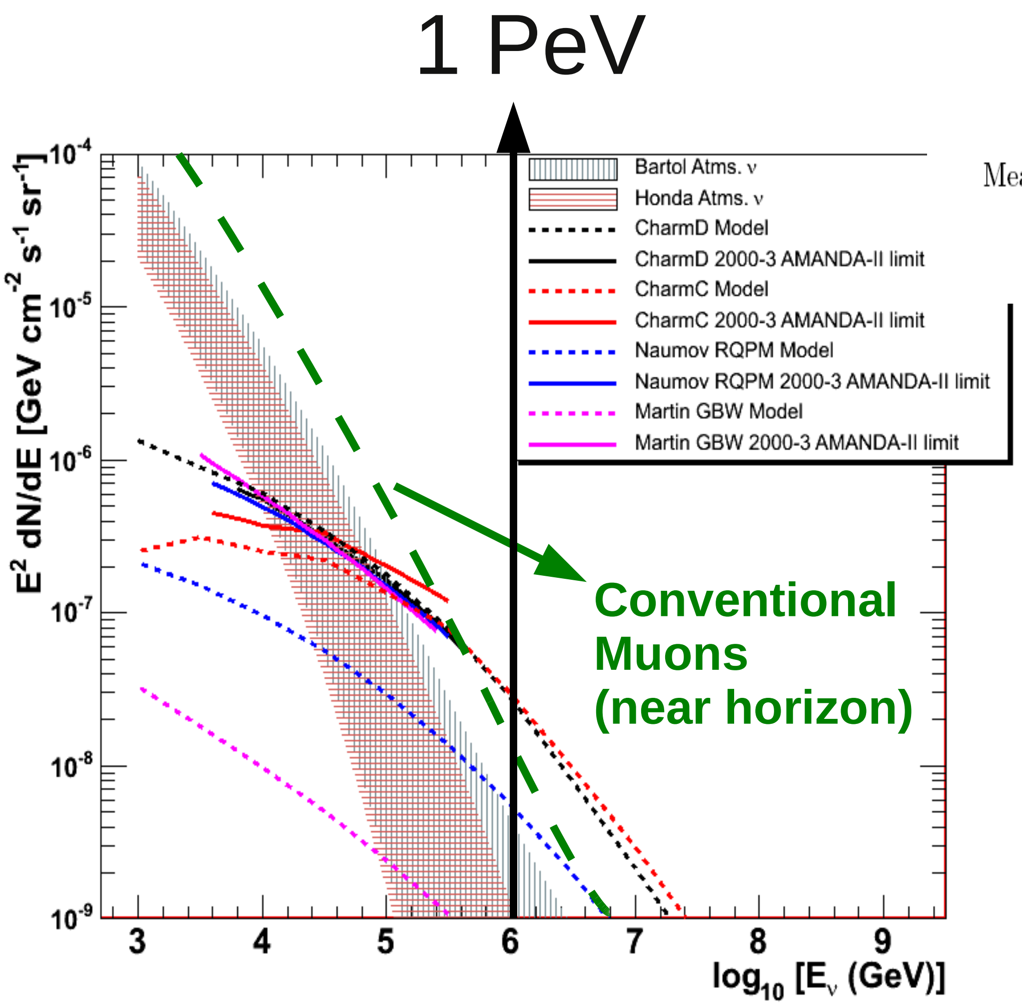
μ



Charm represents major systematic uncertainty for neutrinos above 100 TeV

For muons at 60°, charm Component becomes dominant only at ≈500TeV

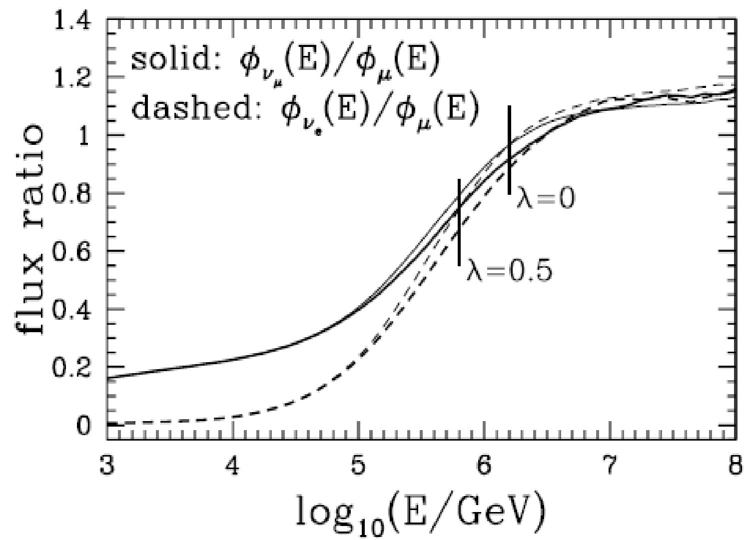
Prompt Muons: Out of Reach?



UCLA/02/TEP/23, CWRU-P13-02, NSF-ITP-02-97

Measuring the prompt atmospheric neutrino flux with down-going muons in neutrino telescopes

Graciela Gelmini[1], Paolo Gondolo[2], and Gabriele Varieschi[3]



Ratio ν/μ

CR Composition Sensitivity of IceCube

IceTop Standalone:

Angular Dependence of Energy Spectrum

IceTop/InIce Coincidence:

Relation between total (EM) shower energy and high-E muon multiplicity

InIce High-E tracks:

Multiplicity (energy loss) spectrum of muon bundles

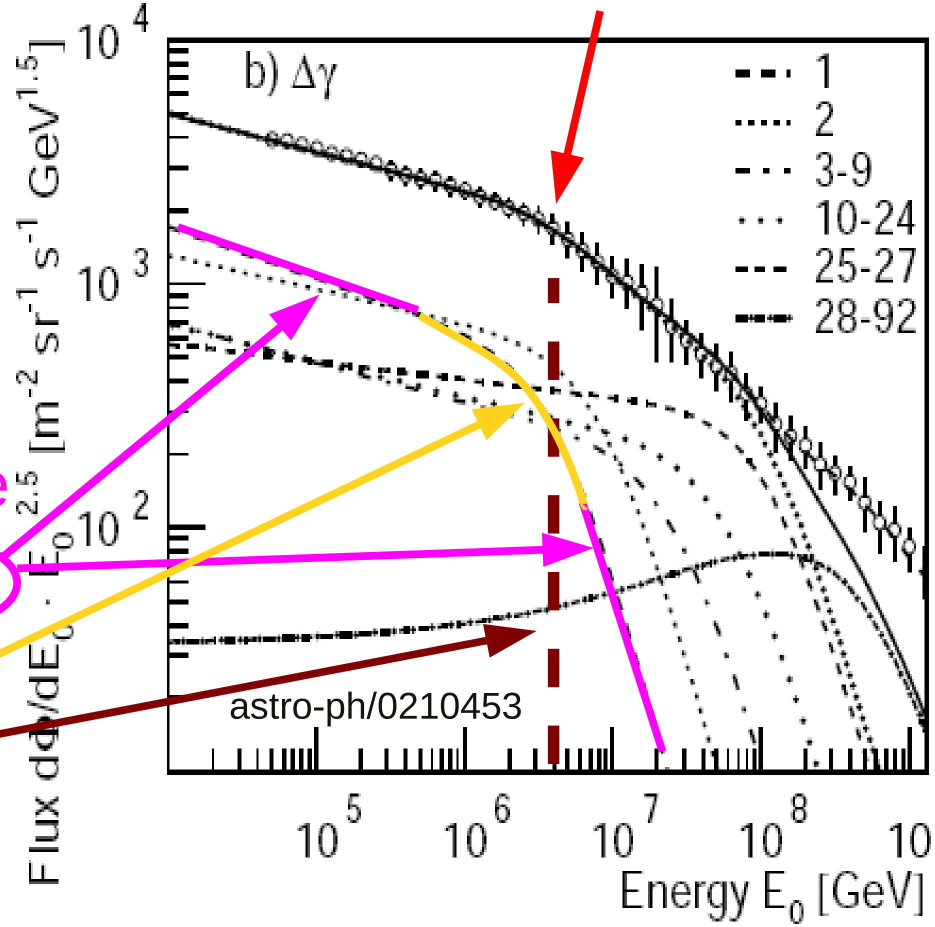
InIce near-horizontal tracks:

Muon energy spectrum cutoff for poly-gonato-like composition

Backup Slides

poly-gonato (Hoerandel) Model

CR-Knee



Slope Change

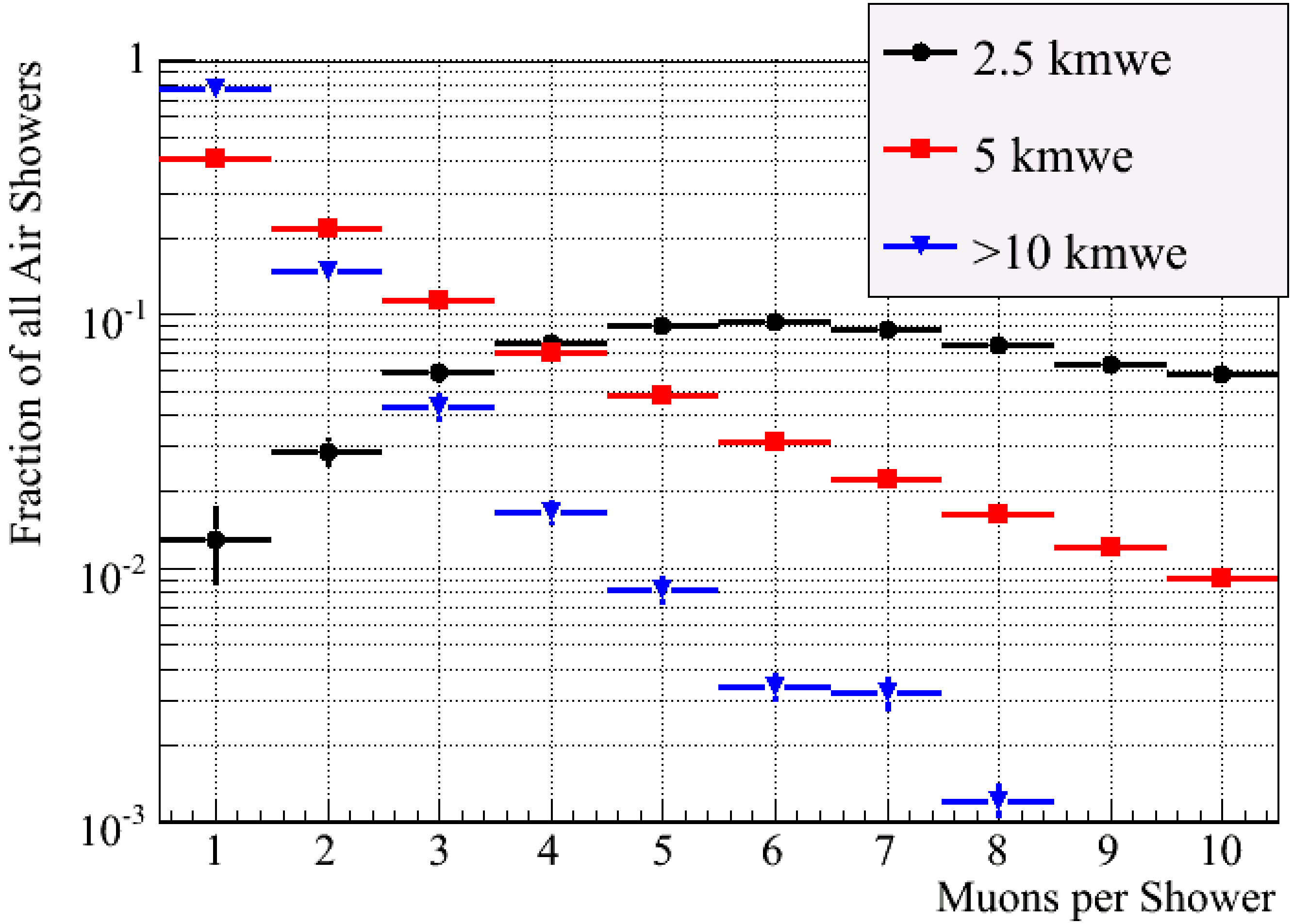
Smoothness of Transition

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

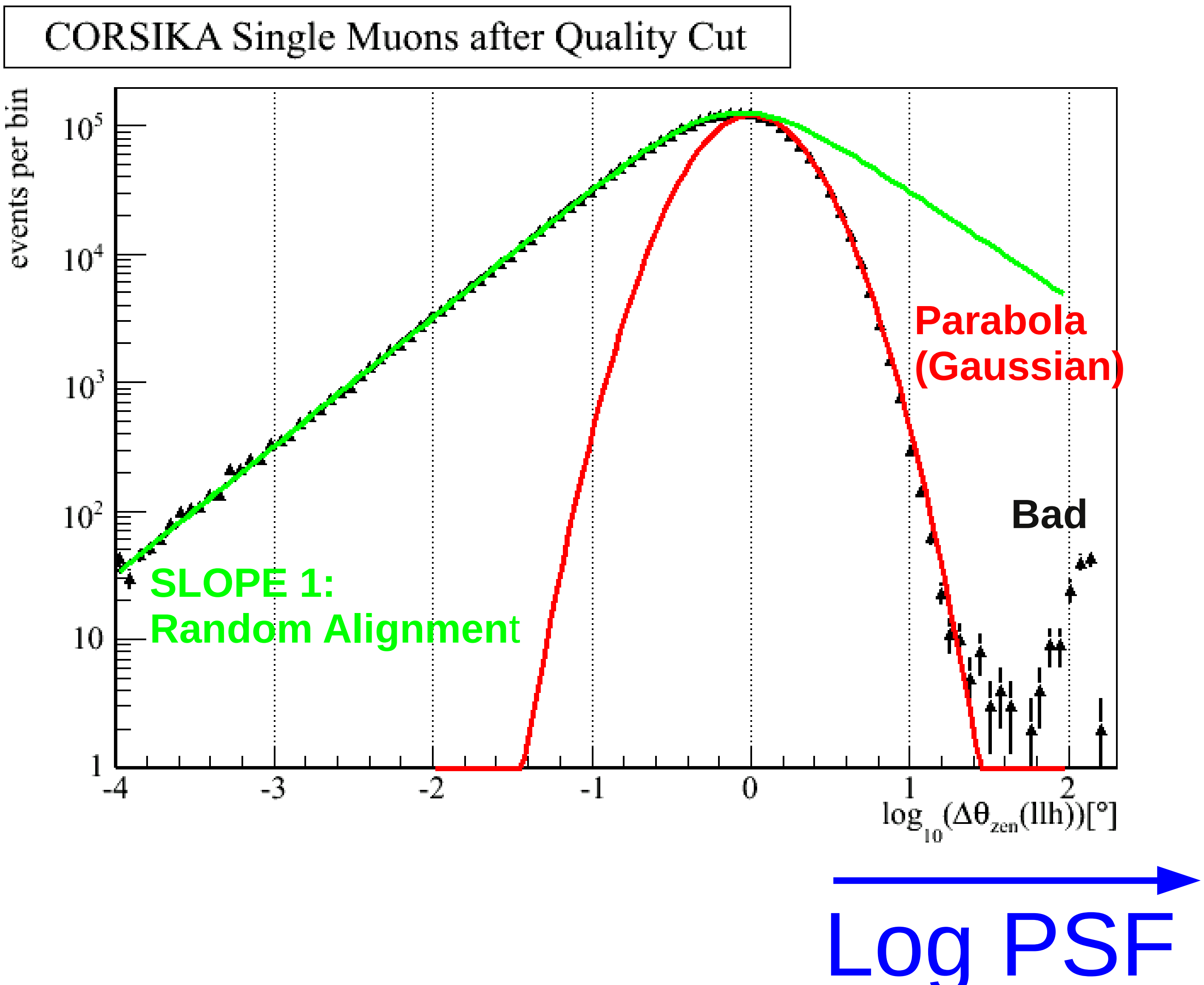
Transition Energy

Primary composition becomes heavier

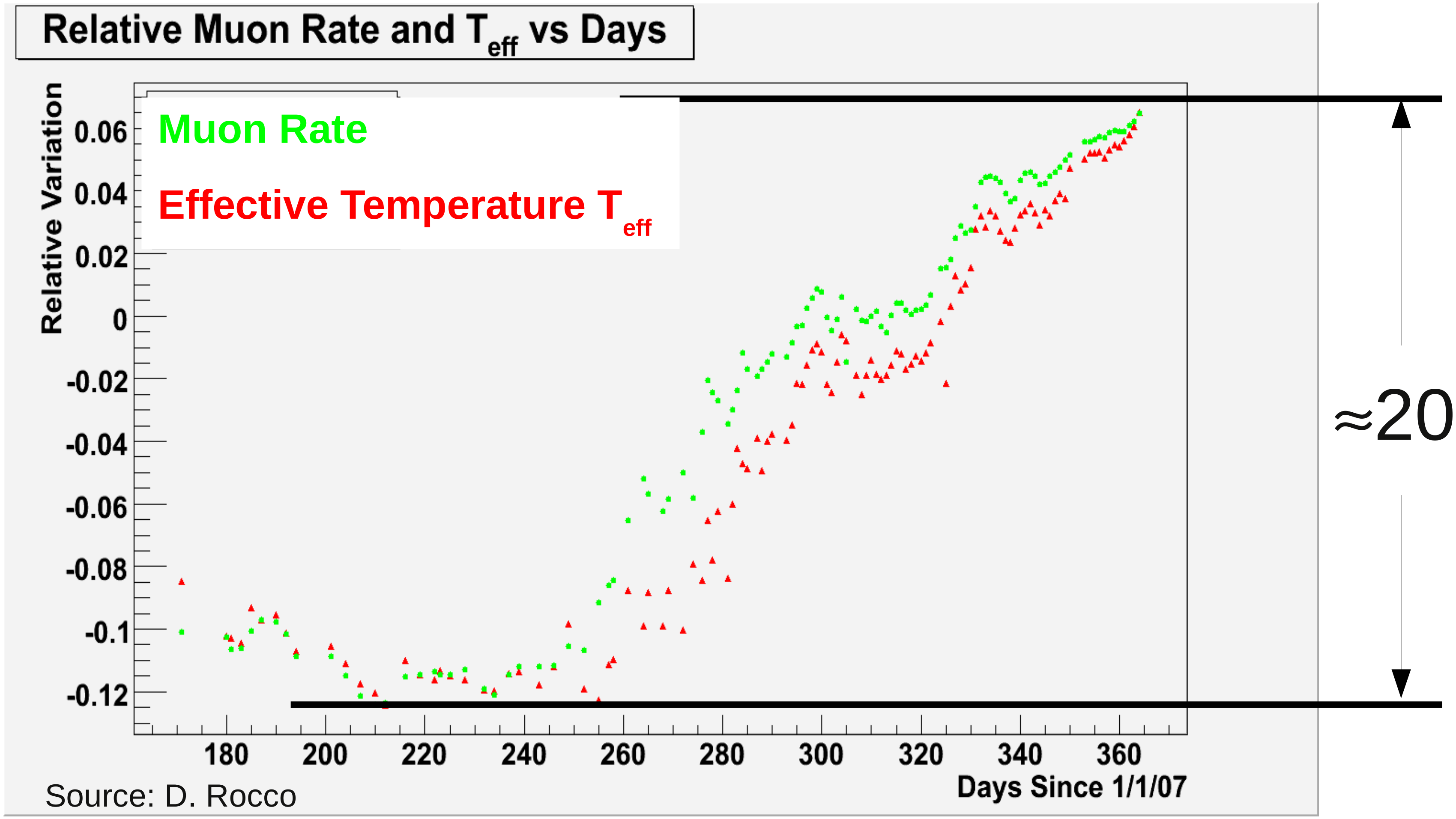
Slant Depth and Bundle Multiplicity



Point Spread Function (MC)



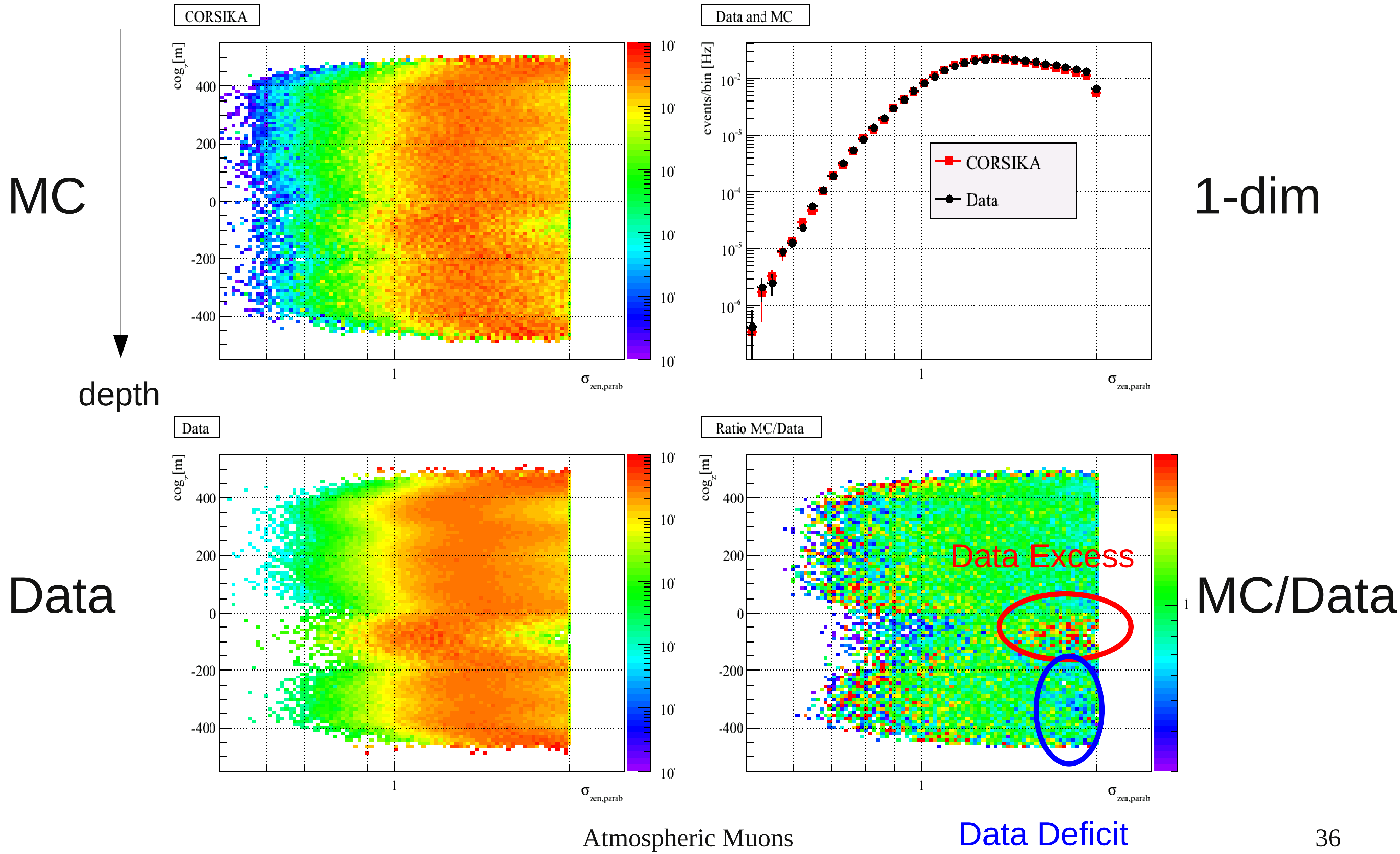
2008 Data



T_{eff}: Temperature weighted by muon production probability

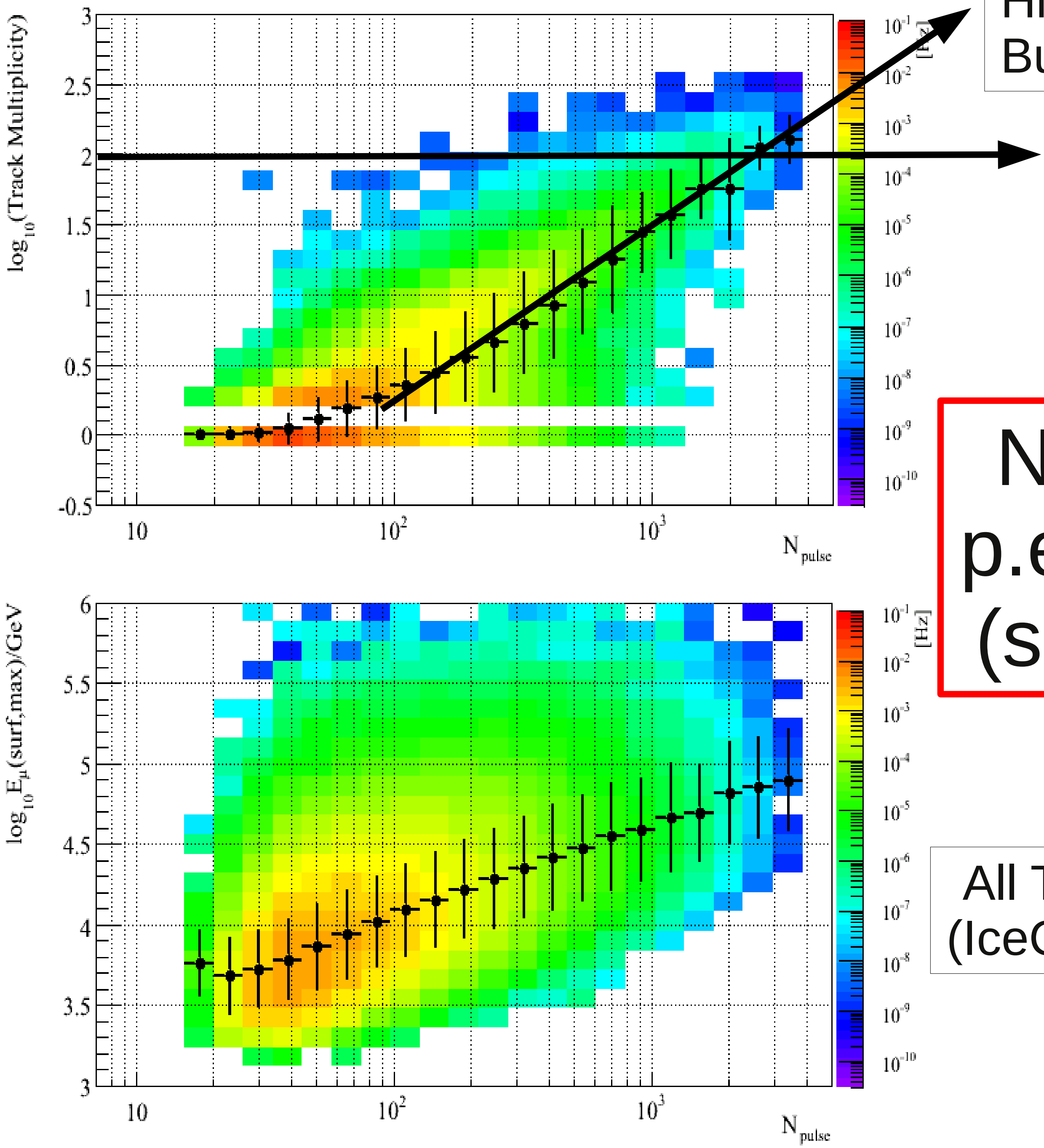
$$T_{eff} = \frac{\int_0^\infty \frac{dX}{X} T(X)\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}{\int_0^\infty \frac{dX}{X}\left(e^{-X/\Lambda_\pi} - e^{-X/\Lambda_N}\right)}$$

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



Track Multiplicity in Detector

Max. Muon Surface Energy



High-Multiplicity Bundles

Number of p.e. in Event (simulation)

All Tracks below 70°
(IceCube Muon Filter)