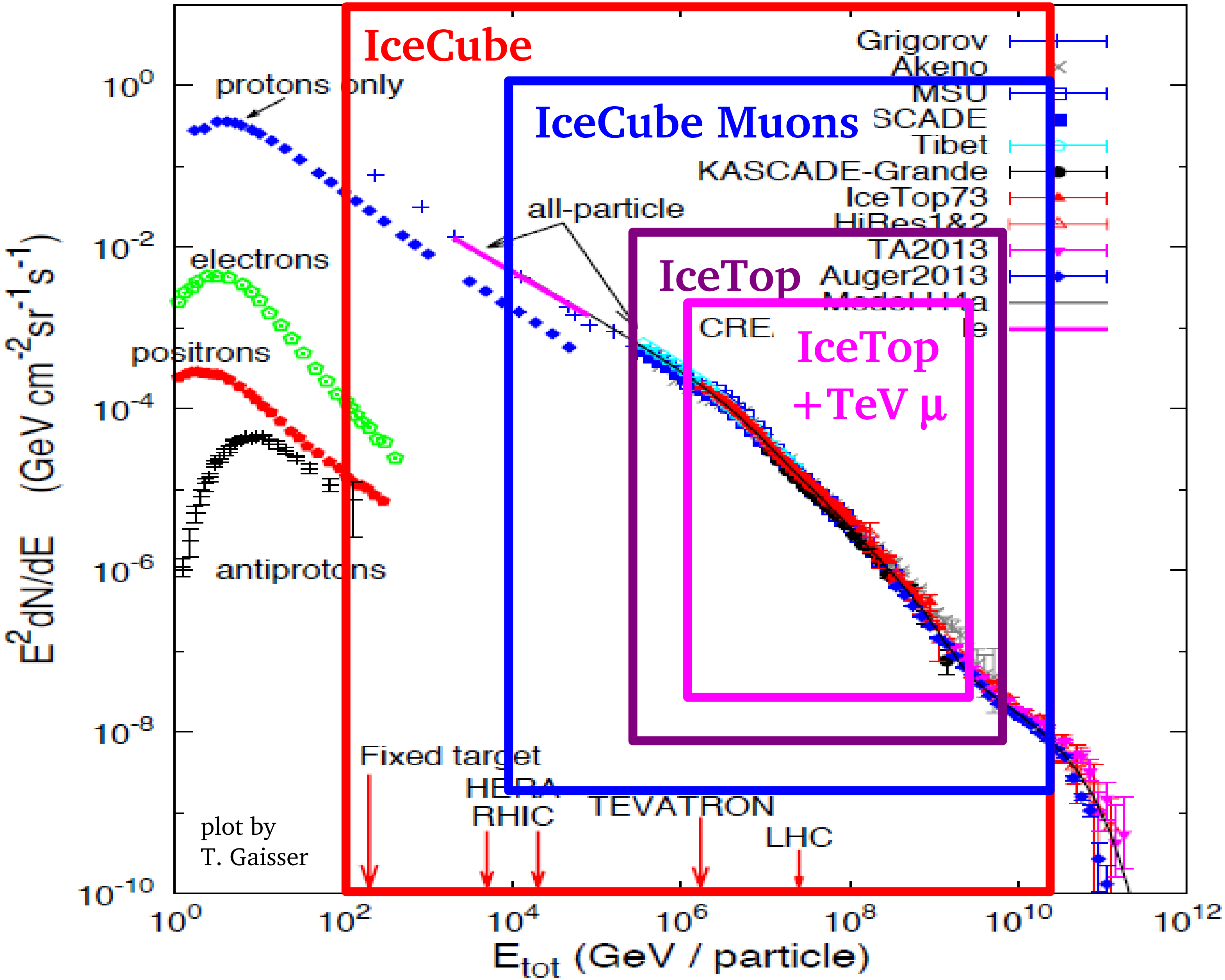
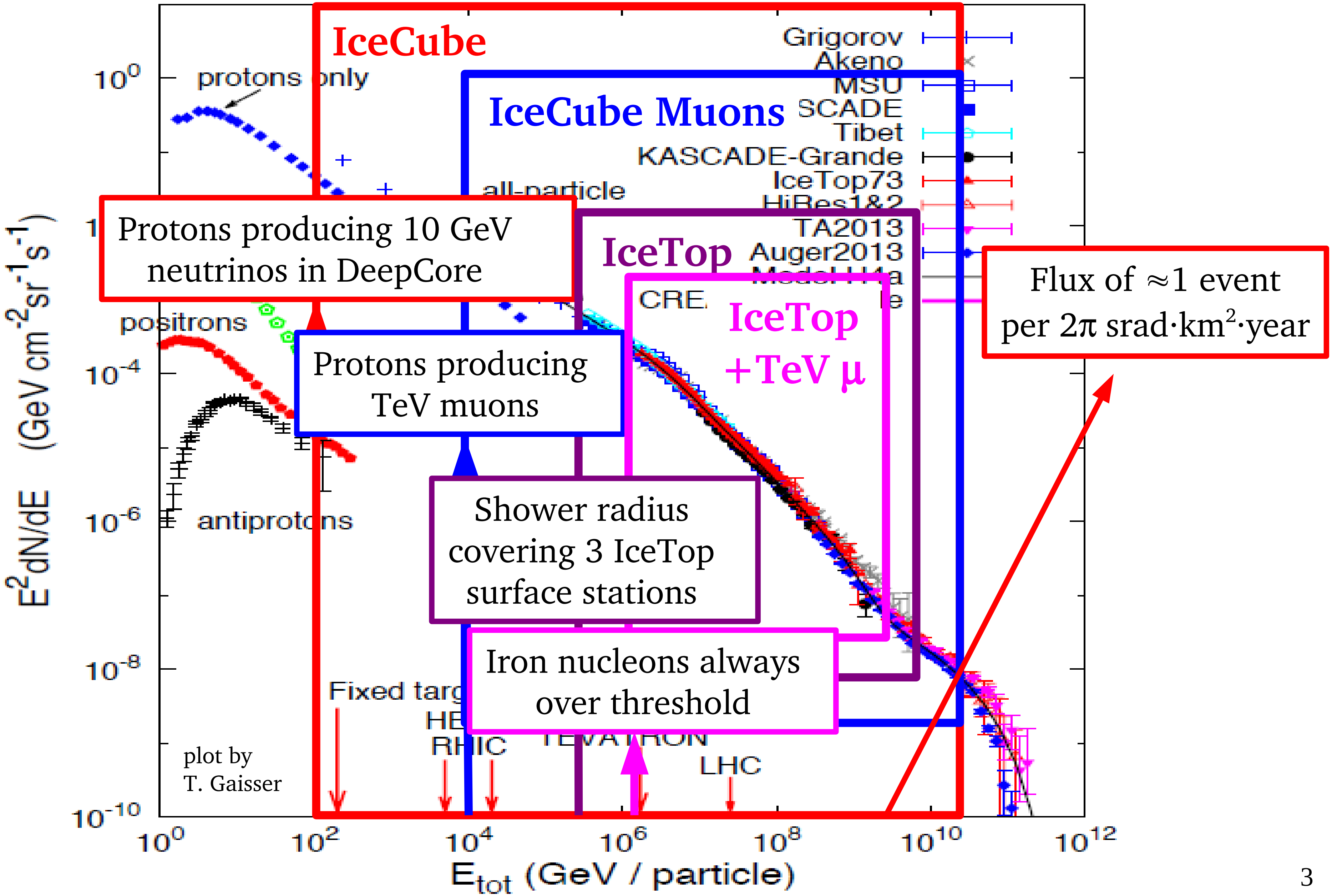
CR Physics with TeV Muons in IceCube

Patrick Berghaus
DESY Zeuthen/MEPhI Moscow

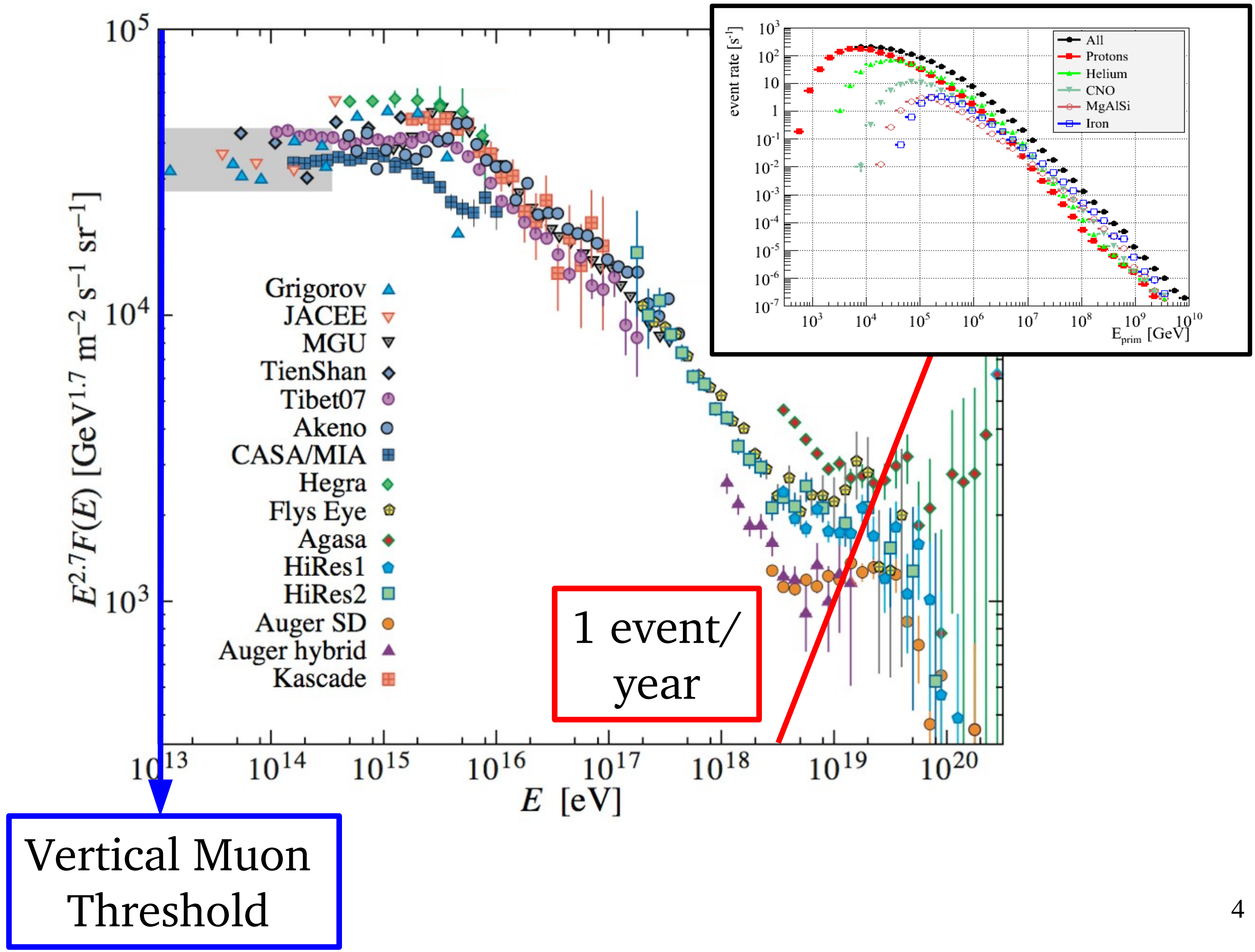
CR Energy Range of IceCube



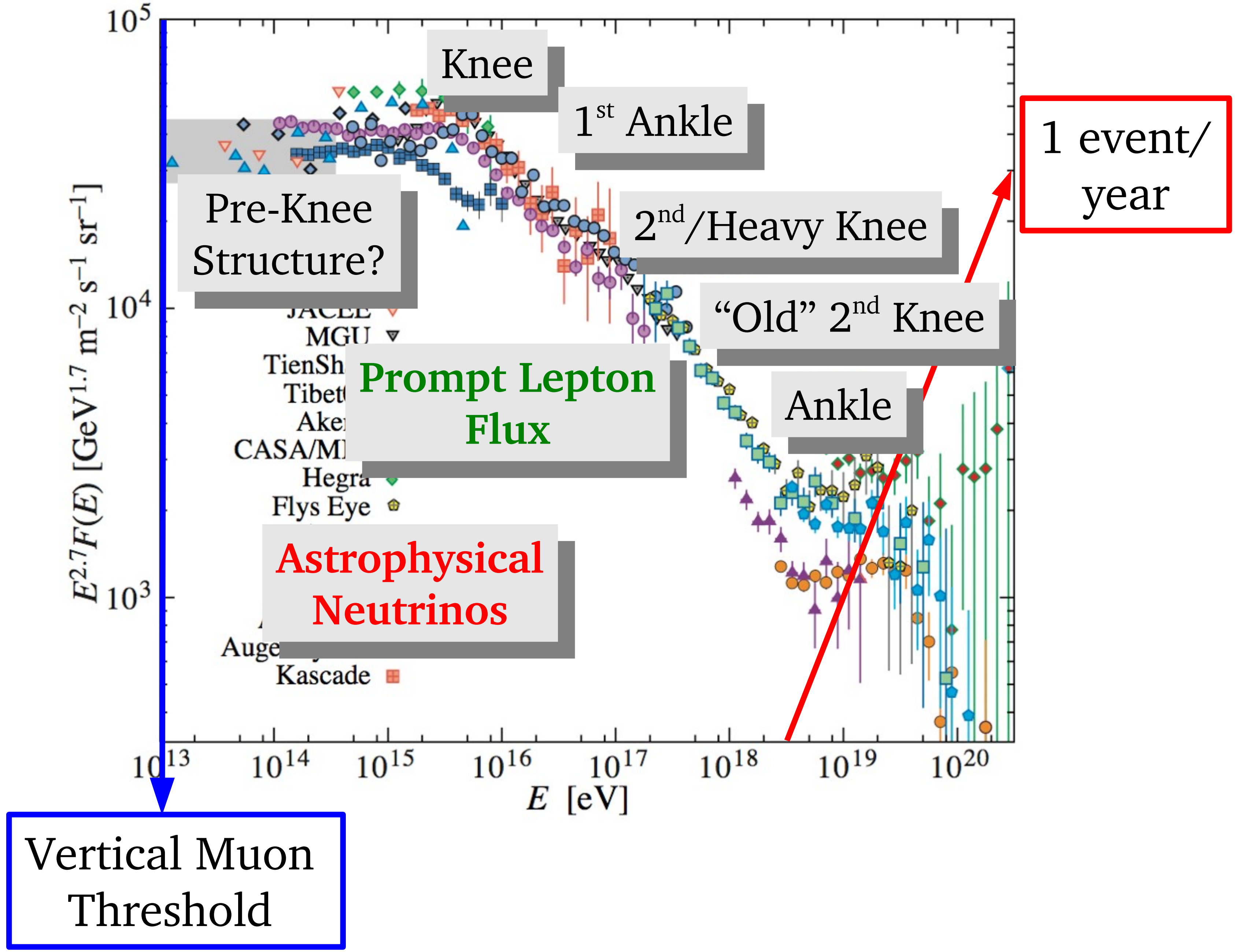
CR Energy Range of IceCube



Muon Energy Range of IceCube

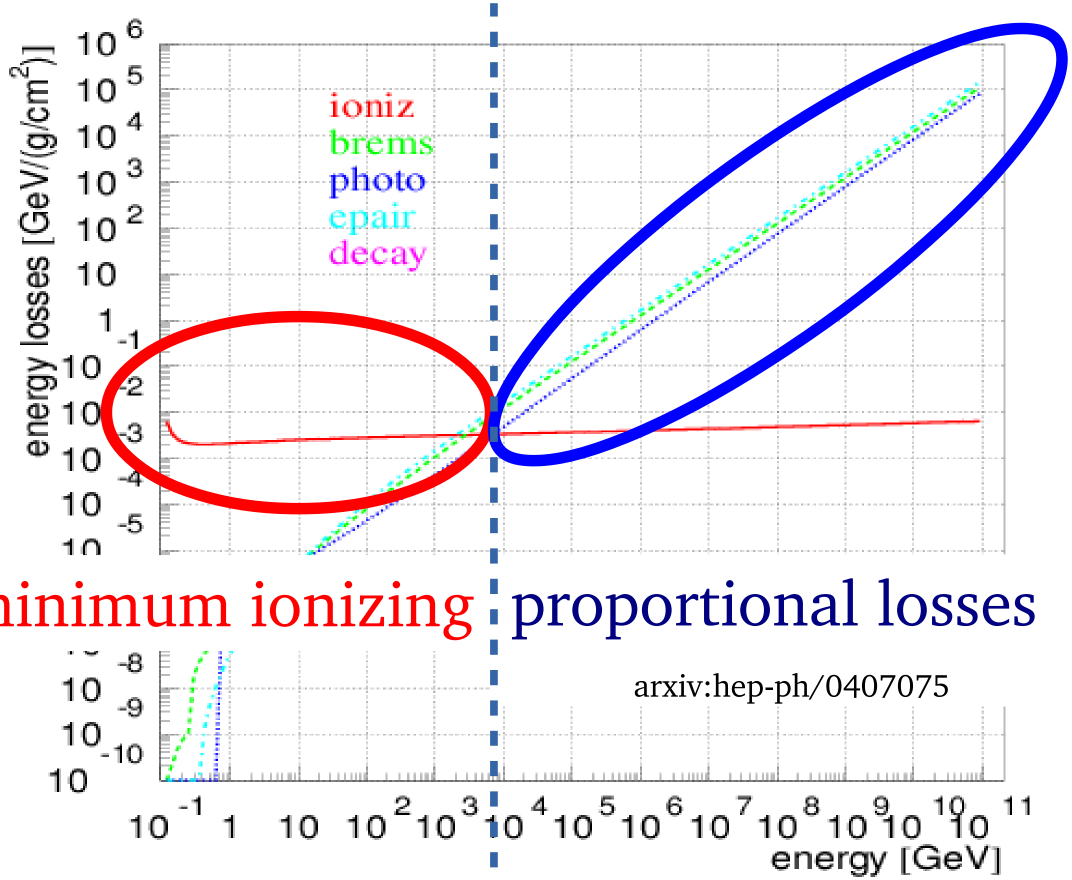


IceCube Muons: Physics



Muon Energy Losses in Matter (Ice)

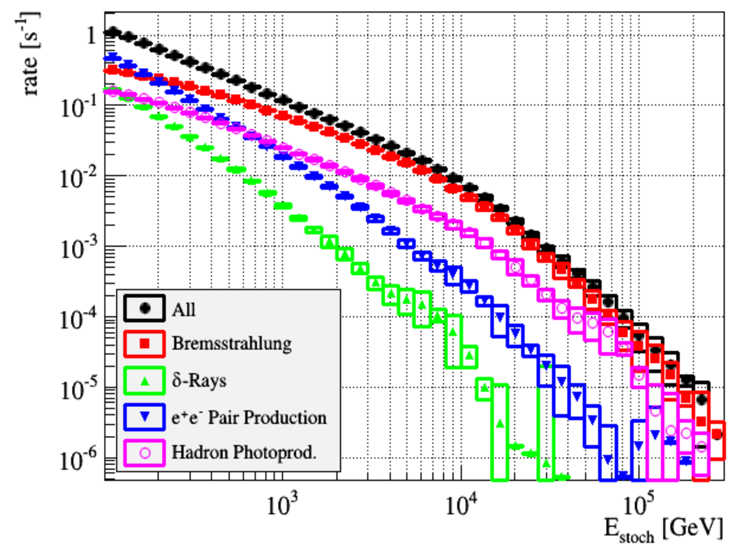
few TeV



minimum ionizing | proportional losses

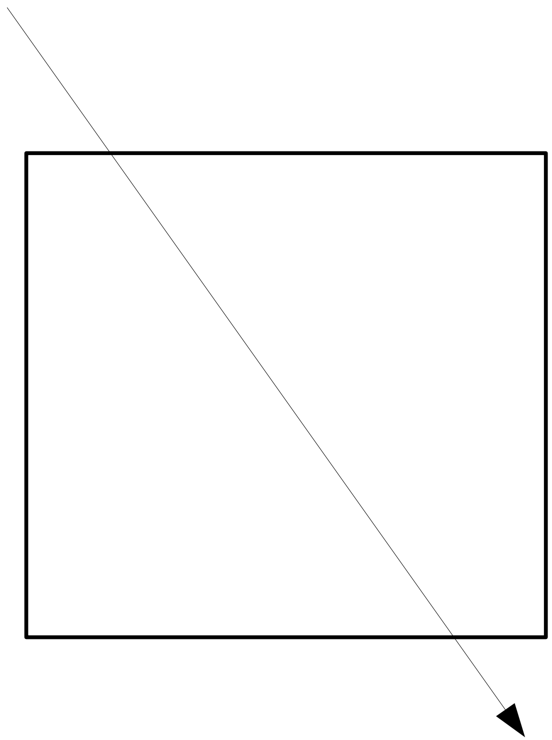
continuous (smooth) ⟷ **stochastic (catastrophic)**

Simulated loss rates along muon tracks in IceCube detector for $E^{-2.7}$ CR Spectrum



PROPOSAL: A tool for propagation of charged leptons
Comput.Phys.Commun. 184 (2013) 2070-2090

Low Energy



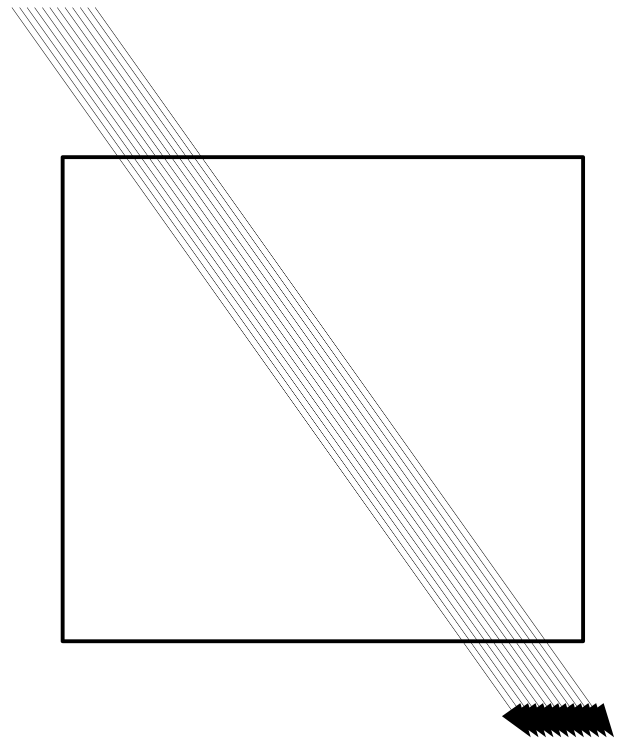
1,000/second

Minimum Ionizing

Single Muons

10-100 TeV CR

Bundles



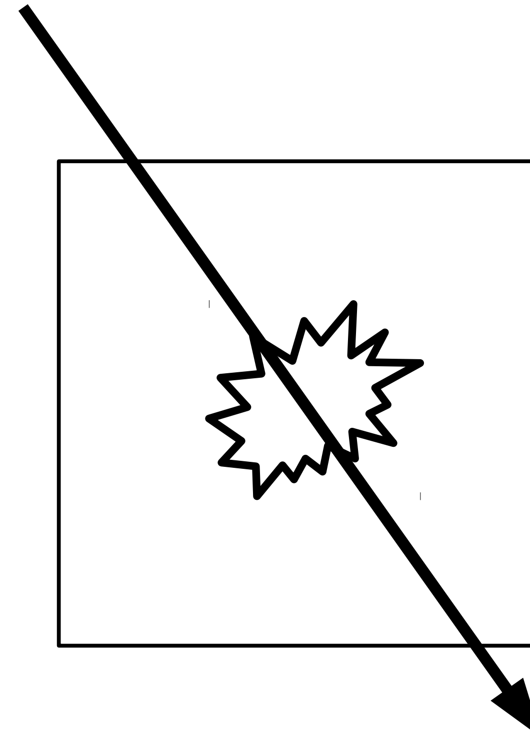
1/second

Minimum Ionizing

20-10,000 Muons

1 PeV-1 EeV CR

HE Muons



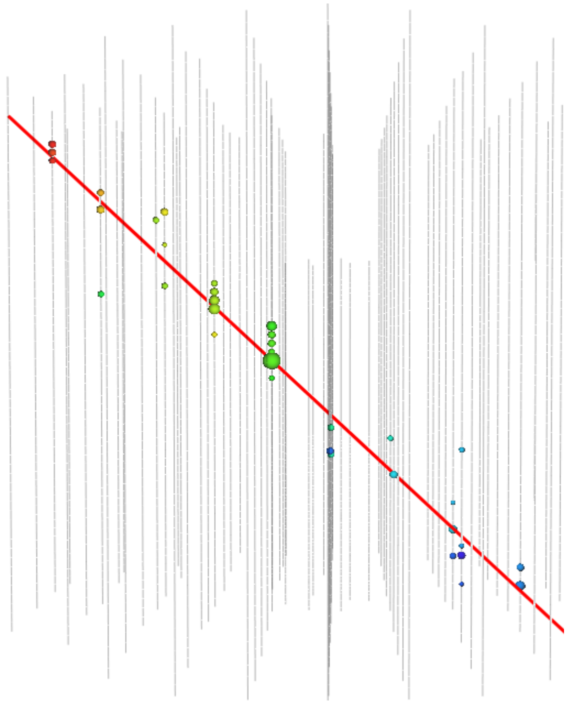
0.1/second

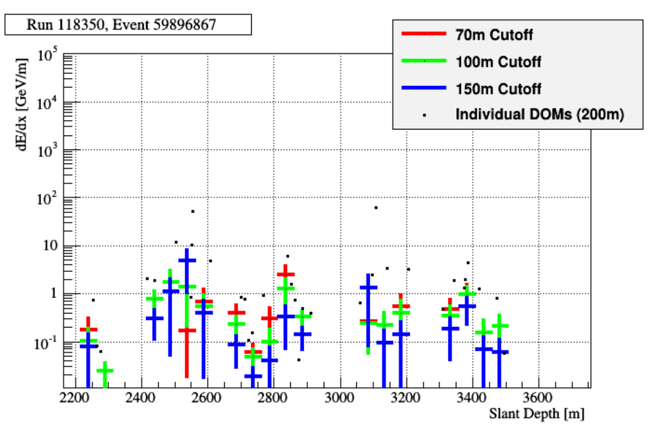
Stochastic

1 HE Muon, 10-100 others

100 TeV-10 PeV CR

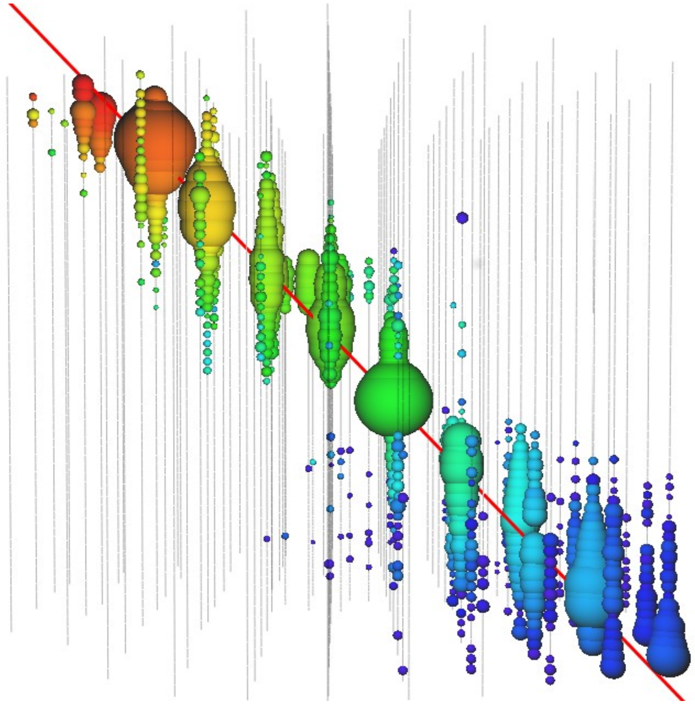
Low-Energy

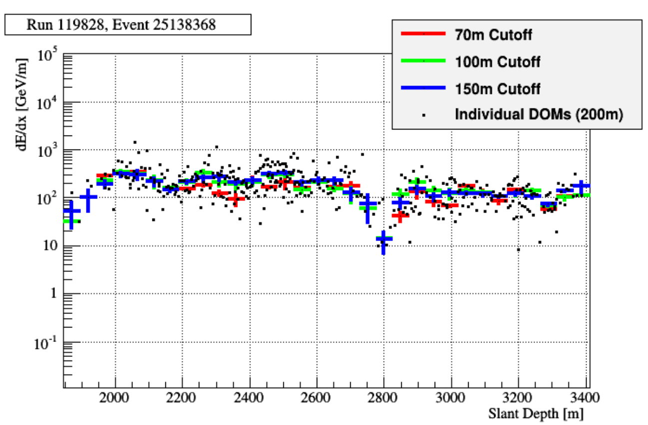




a muon, maybe two

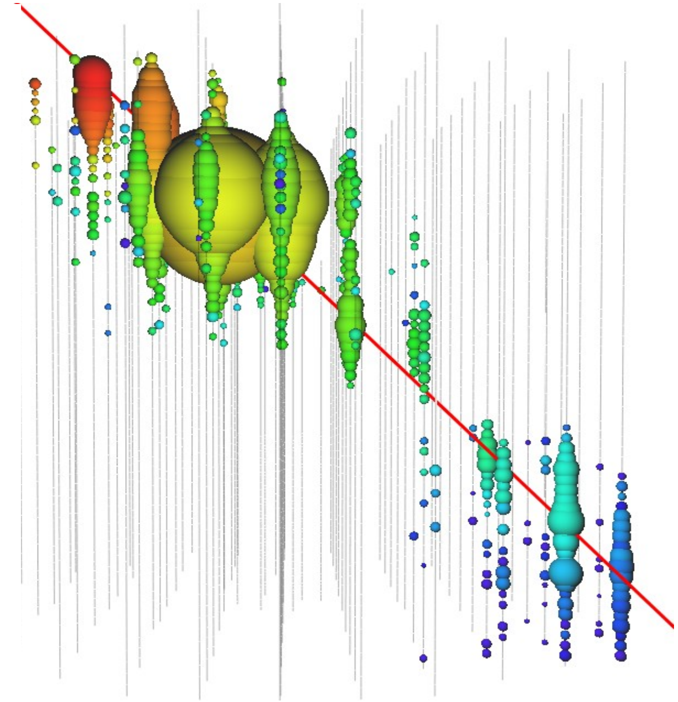
Bundles

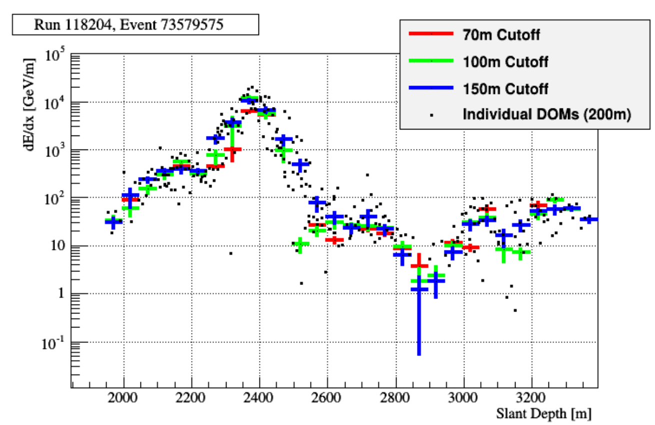




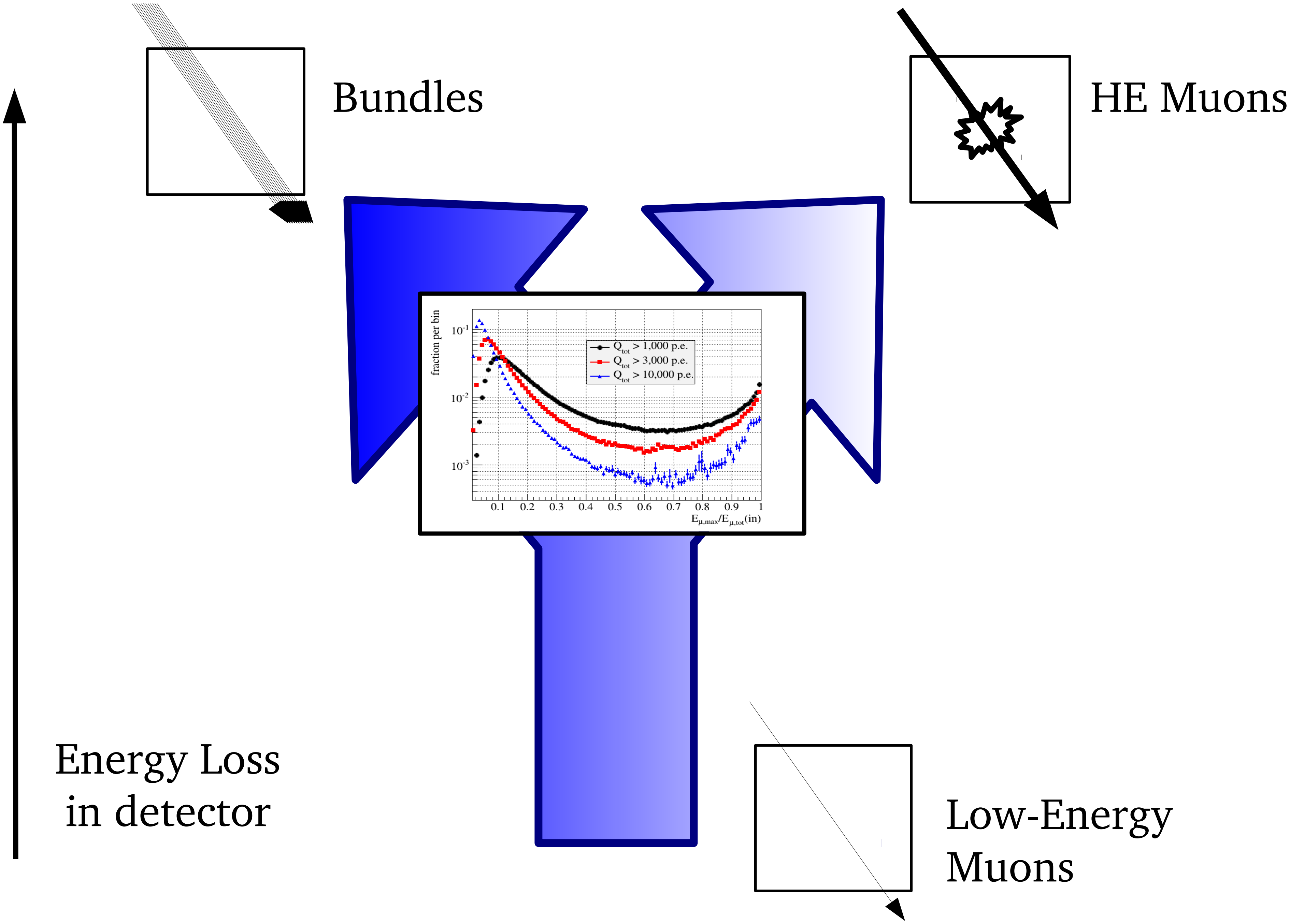
200-310 muons

HE Muons

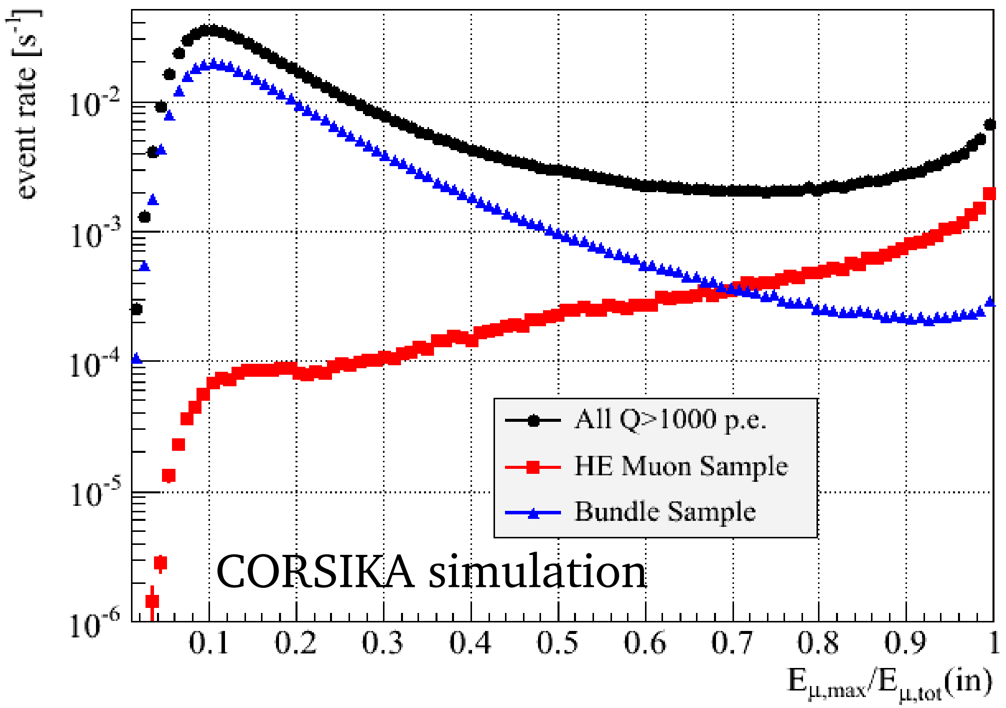




640-1,650 TeV muon,
< 30 others

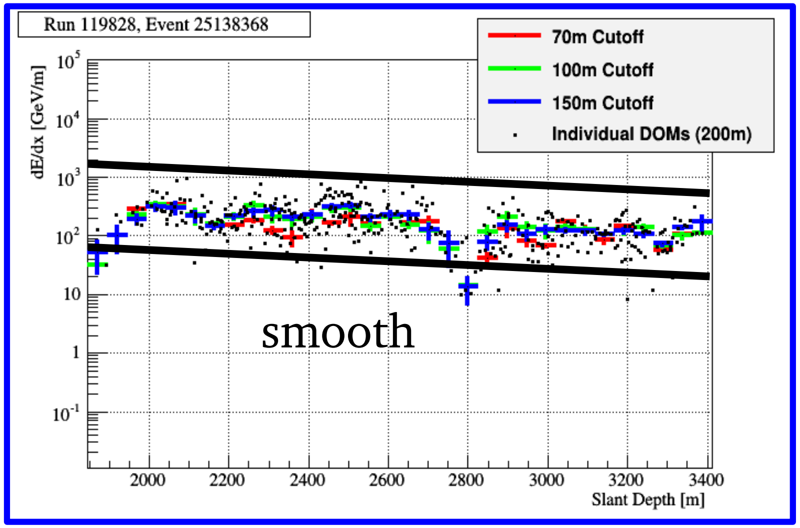

Bundles
HE Muons
Energy Loss
in detector
Low-Energy
Muons
fraction per bin
10^{-1}
10^{-2}
10^{-3}
Q_{tot} > 1,000 p.e.
Q_{tot} > 3,000 p.e.
Q_{tot} > 10,000 p.e.
0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
$E_{\mu,max}/E_{\mu,tot}$(in)

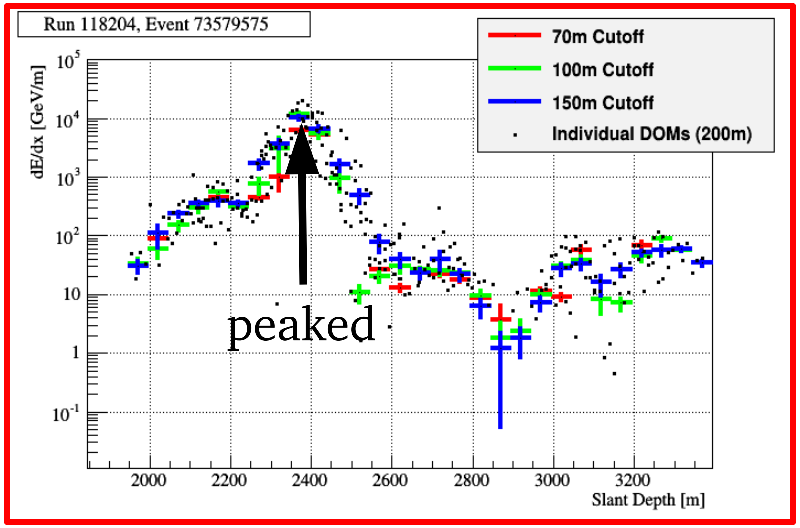
Energy Carried by Leading Muon



High-Level Muon Analyses:
HE Muons
Bundles

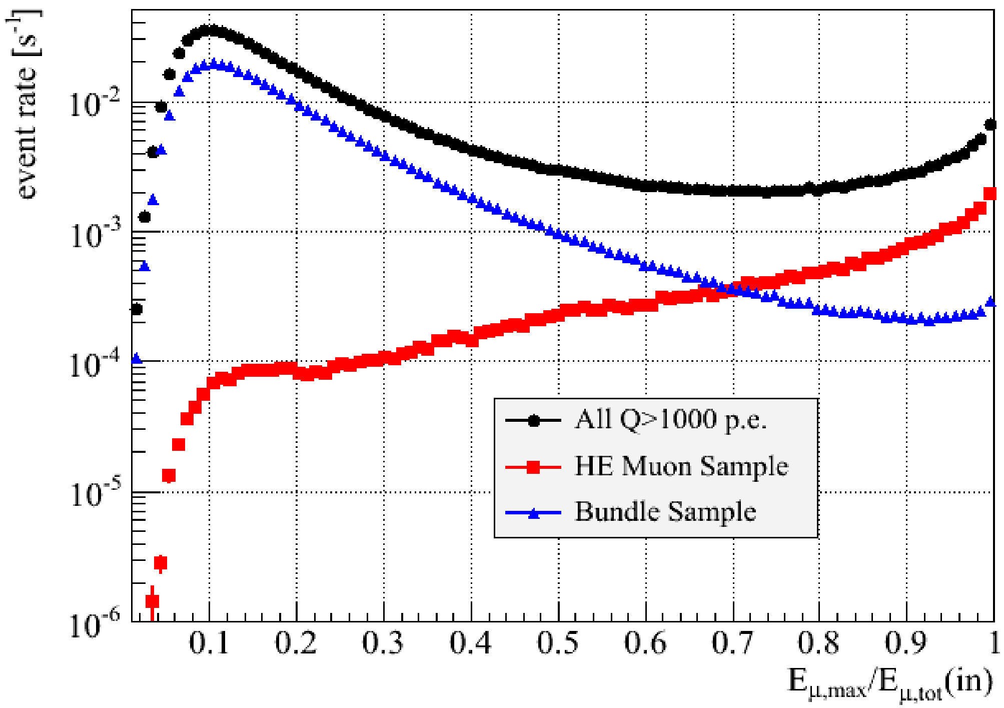
Events are selected based on differential energy loss along track:





Bundles **HE Muons**

Energy Carried by Leading Muon

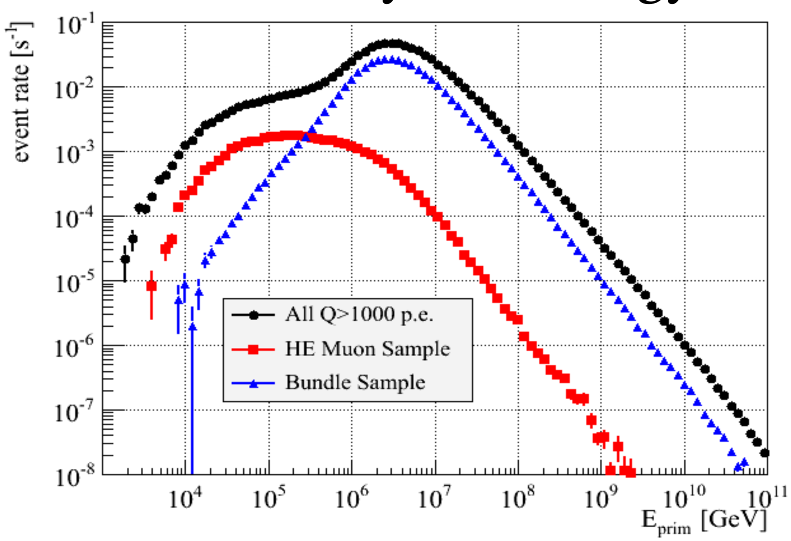


Final Cut Level: True MC Distributions

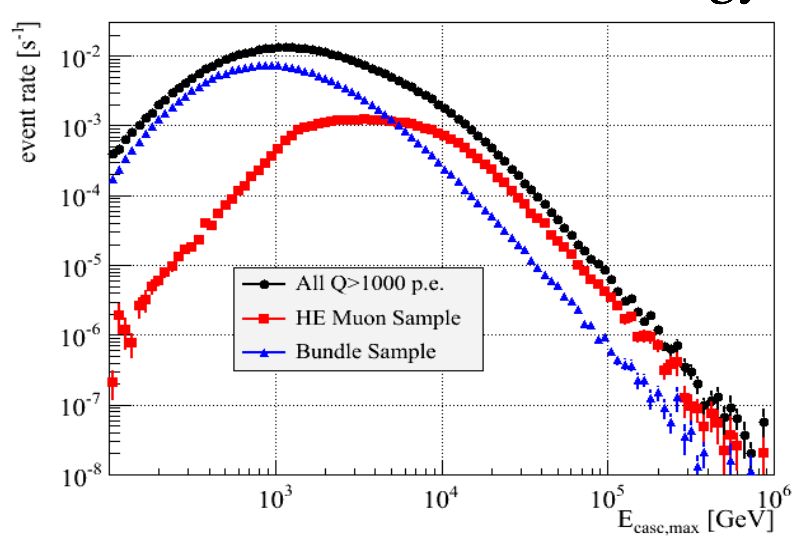
HE Muons

Bundles

Primary CR Energy



Stochastic Cascade Energy



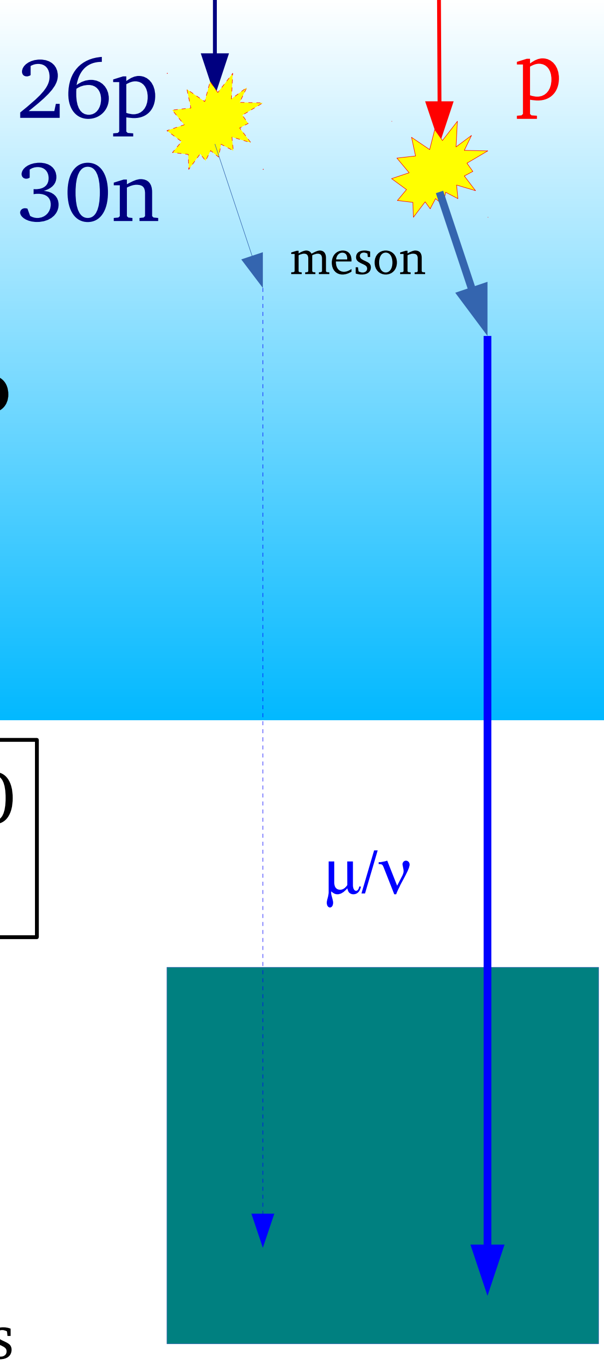
High-Energy Muon/Neutrino

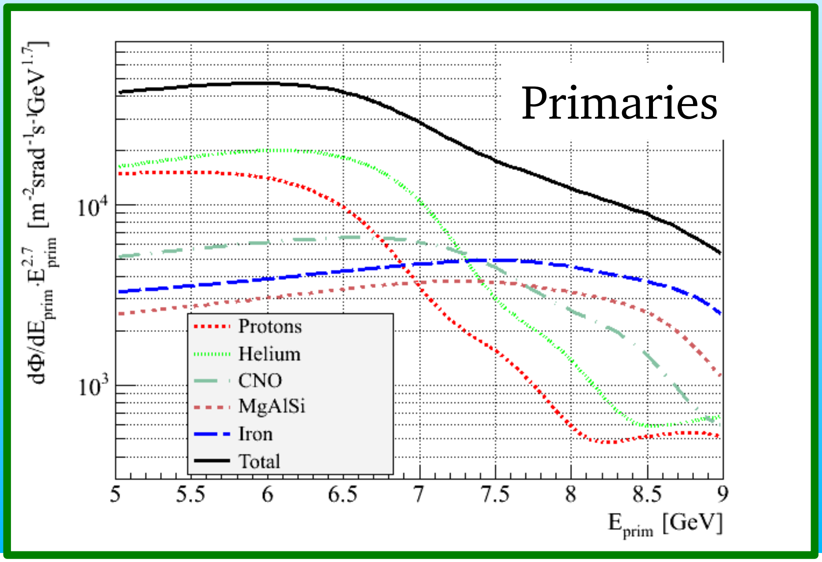
$$E_{nucleon}/E_{lepton} \simeq 10$$

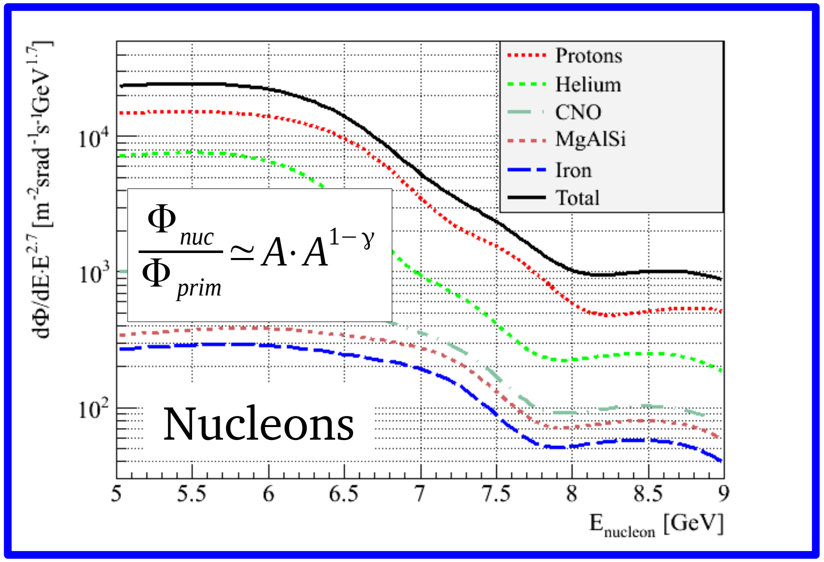
(e.g. T.K. Gaisser: CR&Part.Phys.)

Energy Spectrum follows **Nucleons**

Main contribution from **light** primaries



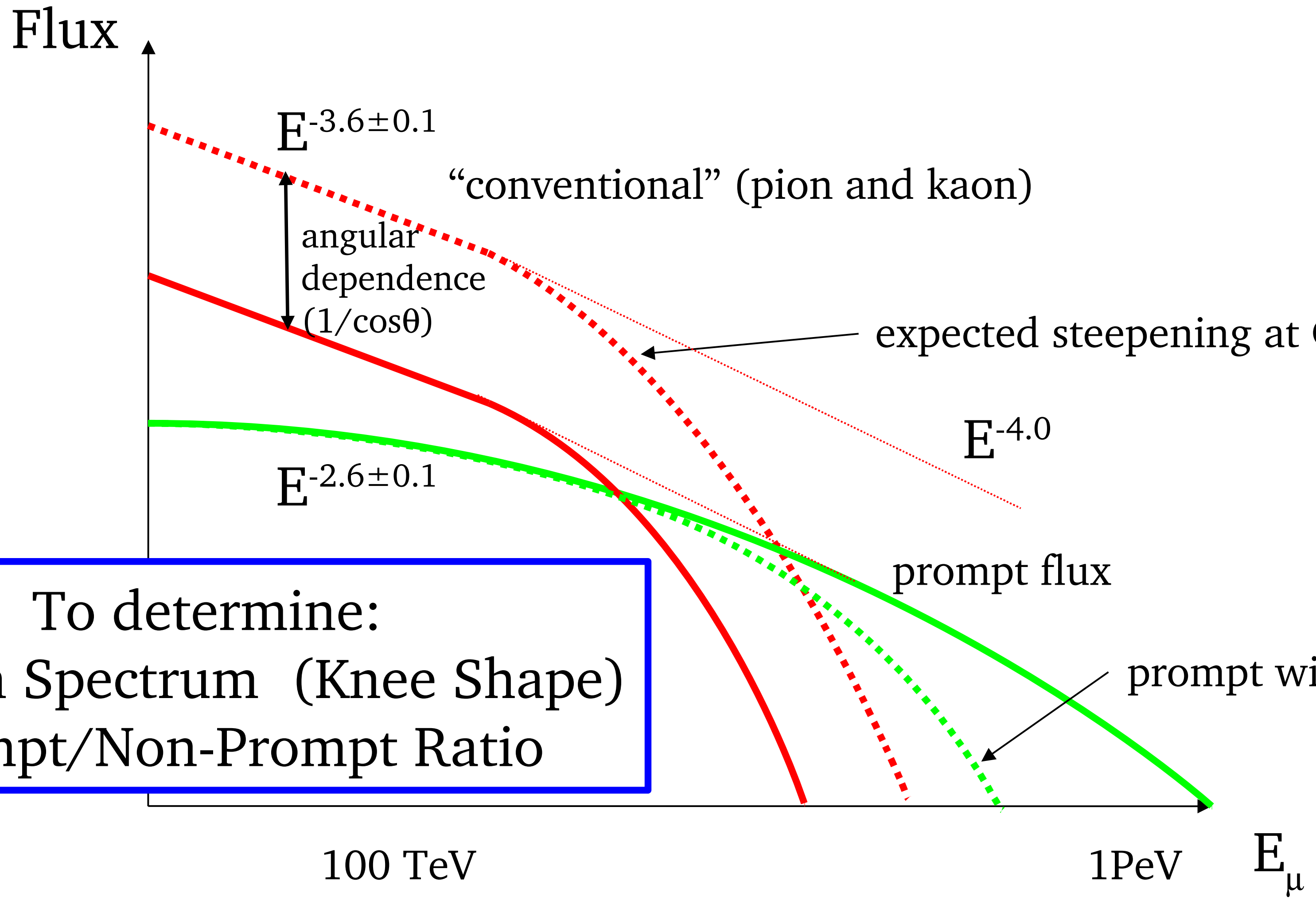




Example: Gaisser H3a

arxiv:1303.3565

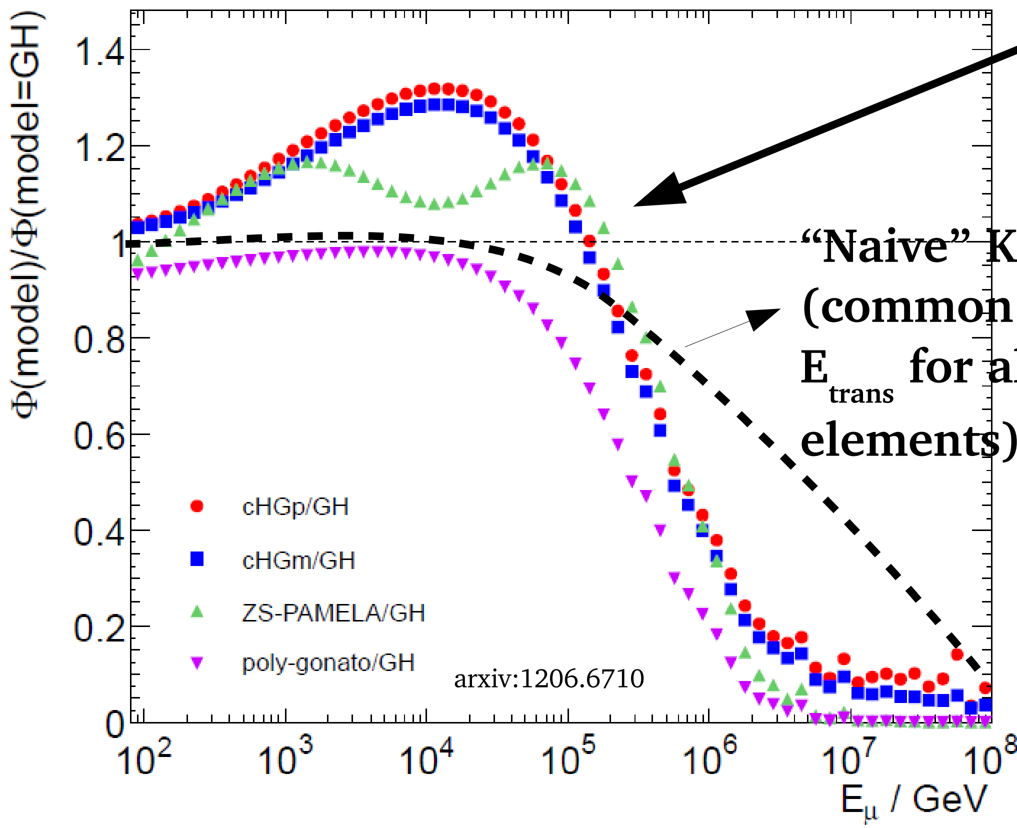
Muon Spectrum (Qualitative)



To determine:
Nucleon Spectrum (Knee Shape)
Prompt/Non-Prompt Ratio

Knee: Muon Spectrum

Sharp knee signature due to dependence on **nucleon** spectrum.
Directly related to cutoff!



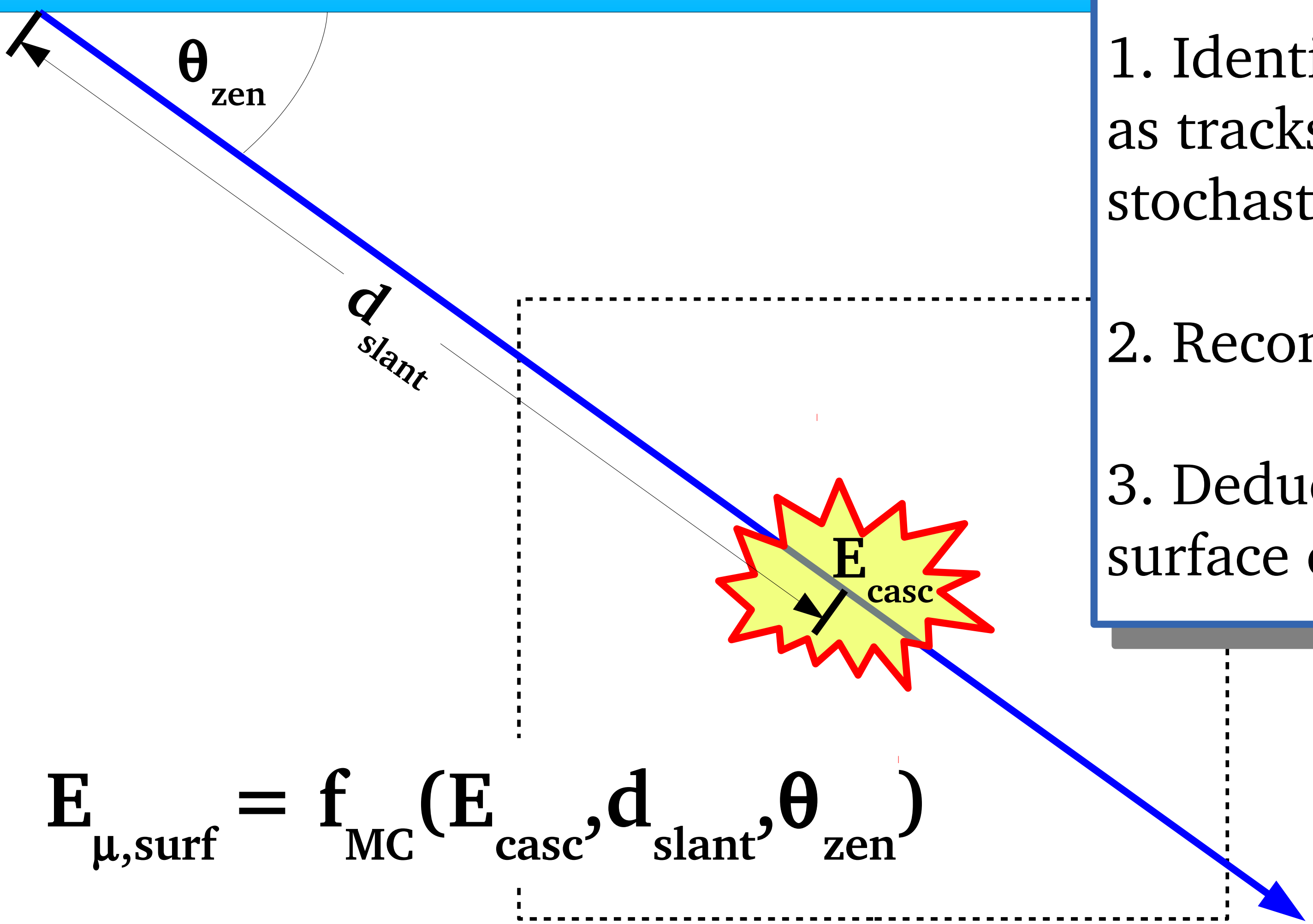
"Naive" Knee (common $\Delta\gamma$, E_{trans} for all elements)

H3a
H4a
Zatsepin-Sokolskaya
Poly-Gonato(Hoerandel)

Influence of primary CR model on (conventional) muon and neutrino flux:

Ratio to straight power-law ("kneeless") assumption.

Analysis Strategy



1. Identify HE muons as tracks with exceptional stochastics losses

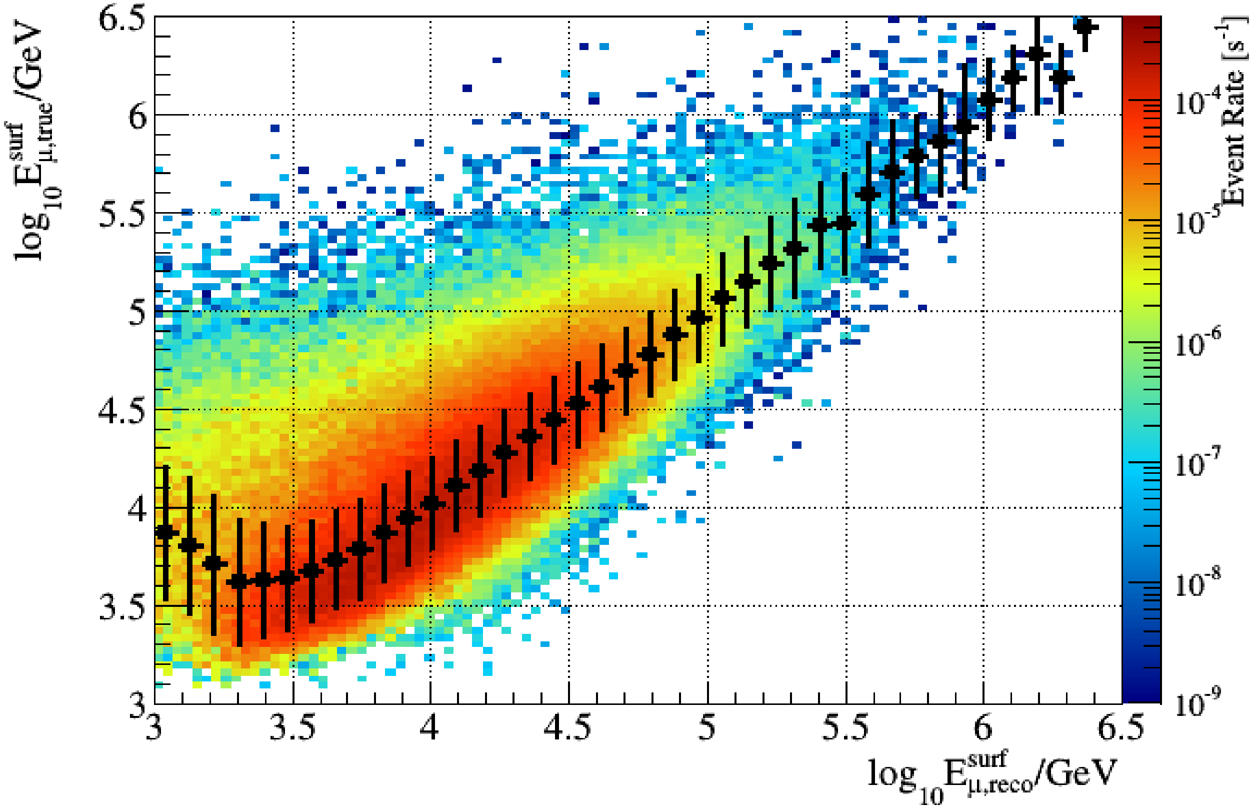
2. Reconstruct cascade energy

3. Deduce most likely muon surface energy from simulation

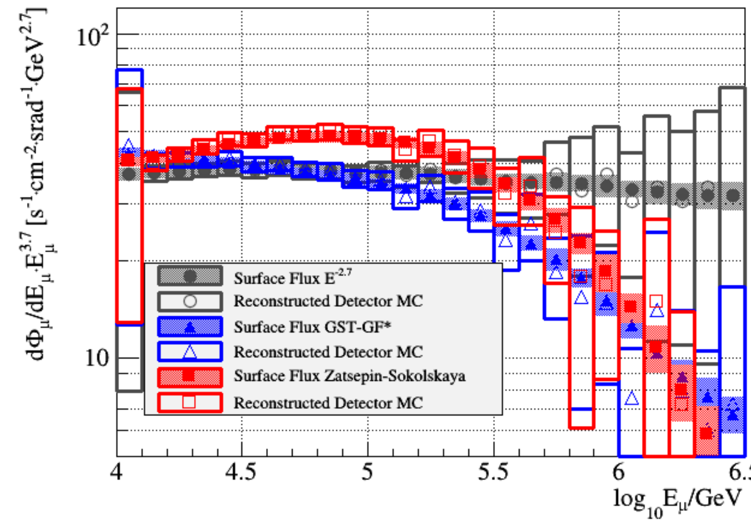
$$E_{\mu,surf} = f_{MC}(E_{casc}, d_{slant}, \theta_{zen})$$

HE Cascade requires HE Muon

Surface Spectrum Reconstruction

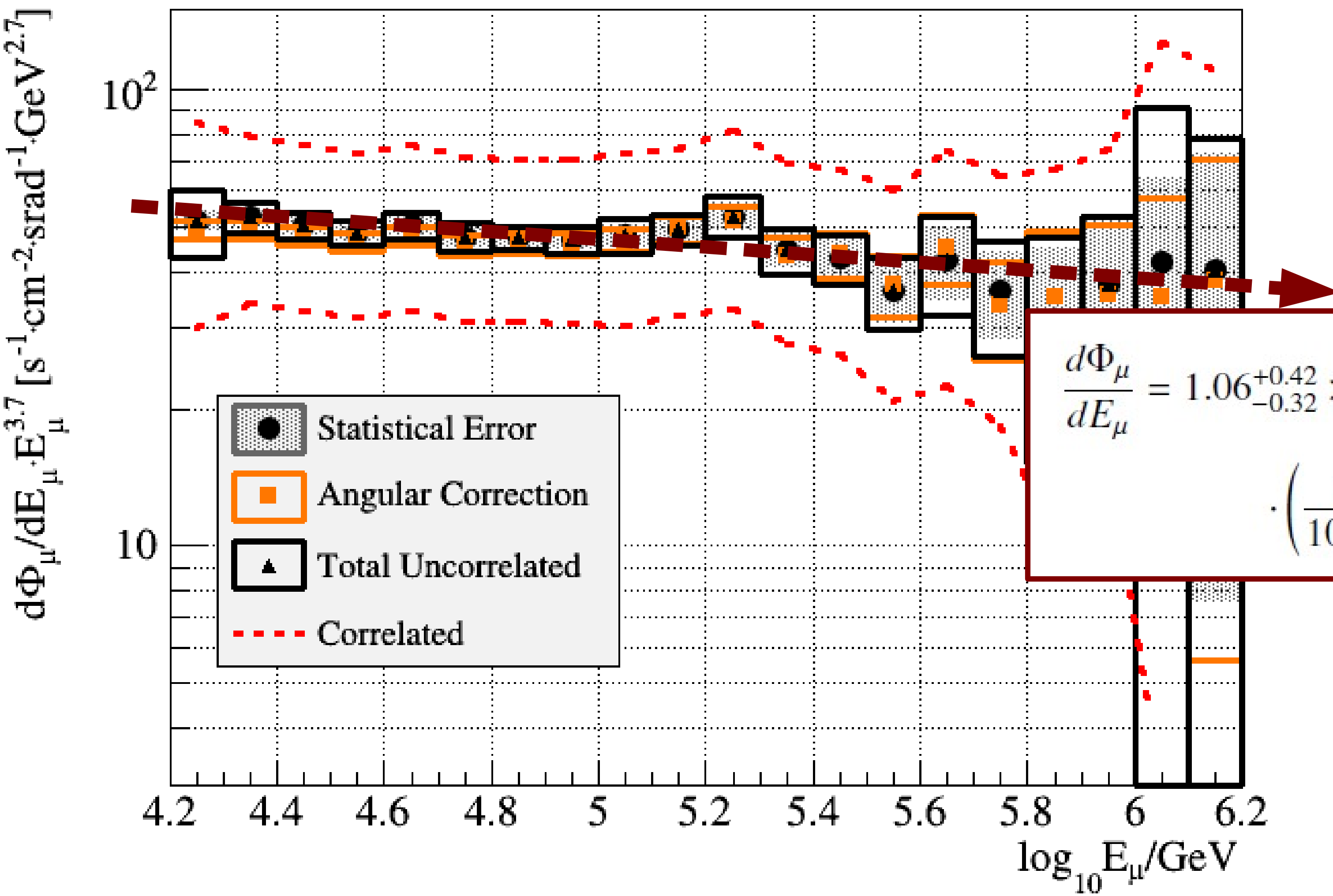


Muon Surface Energy:
Fully parameterized observable vs. True MC value
(Simulation weighted to $E^{-2.7}$ primary spectrum)



Full Circle Test:
Compare result from detector MC to independent surface MC

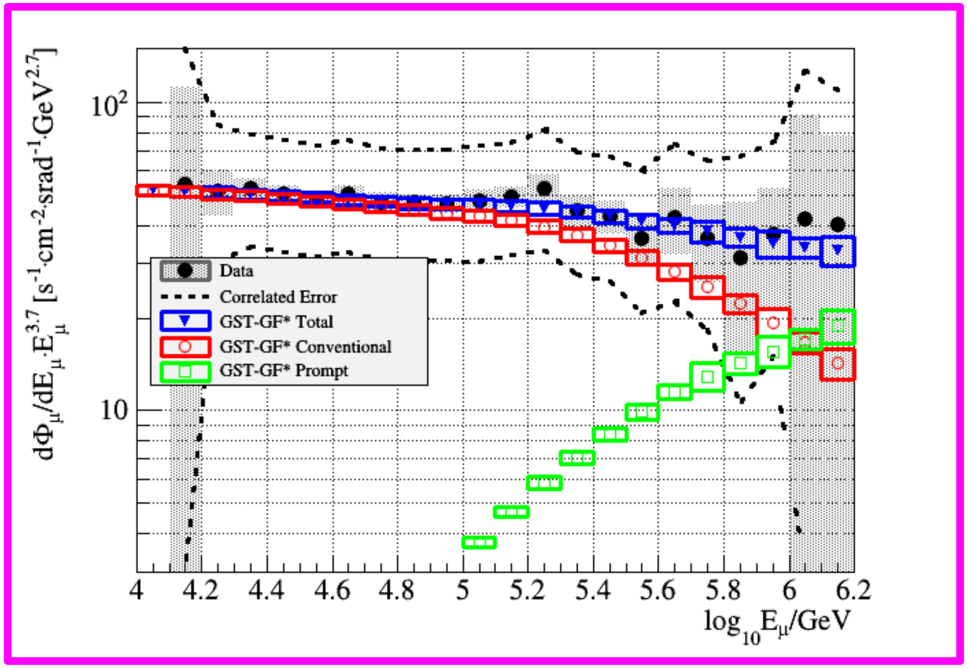
All-Sky Muon Energy Spectrum

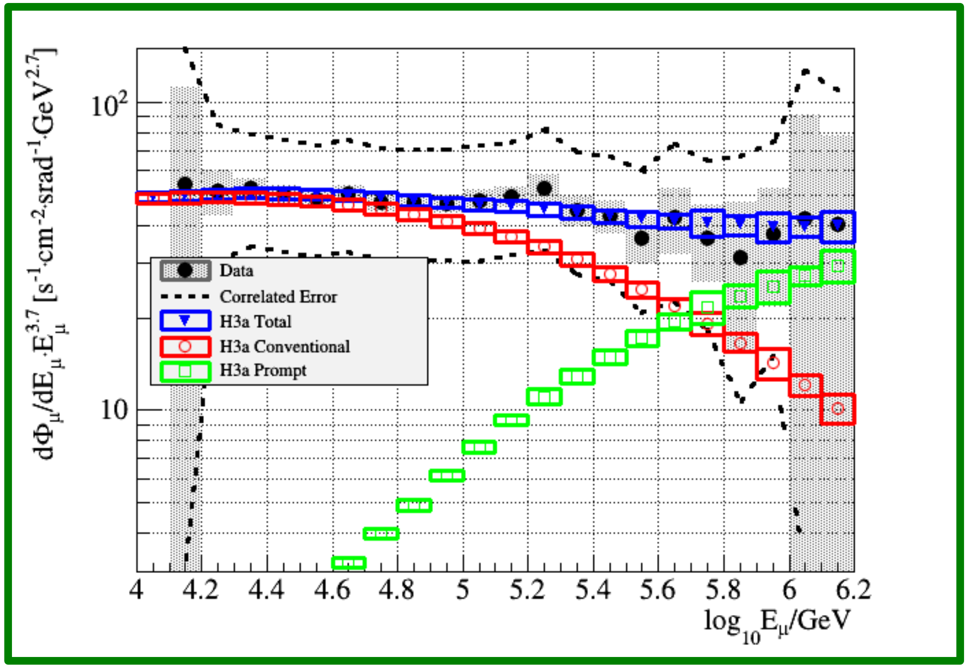


$$\frac{d\Phi_\mu}{dE_\mu} = 1.06^{+0.42}_{-0.32} \times 10^{-10} s^{-1} cm^{-2} srad^{-1} TeV^{-1} \cdot \left(\frac{E_\mu}{10\ \text{TeV}}\right)^{-3.78 \pm 0.02(stat.) \pm 0.03(syst.)}$$

Approximately power law with index -3.78

All-Sky Energy Spectrum: Prompt



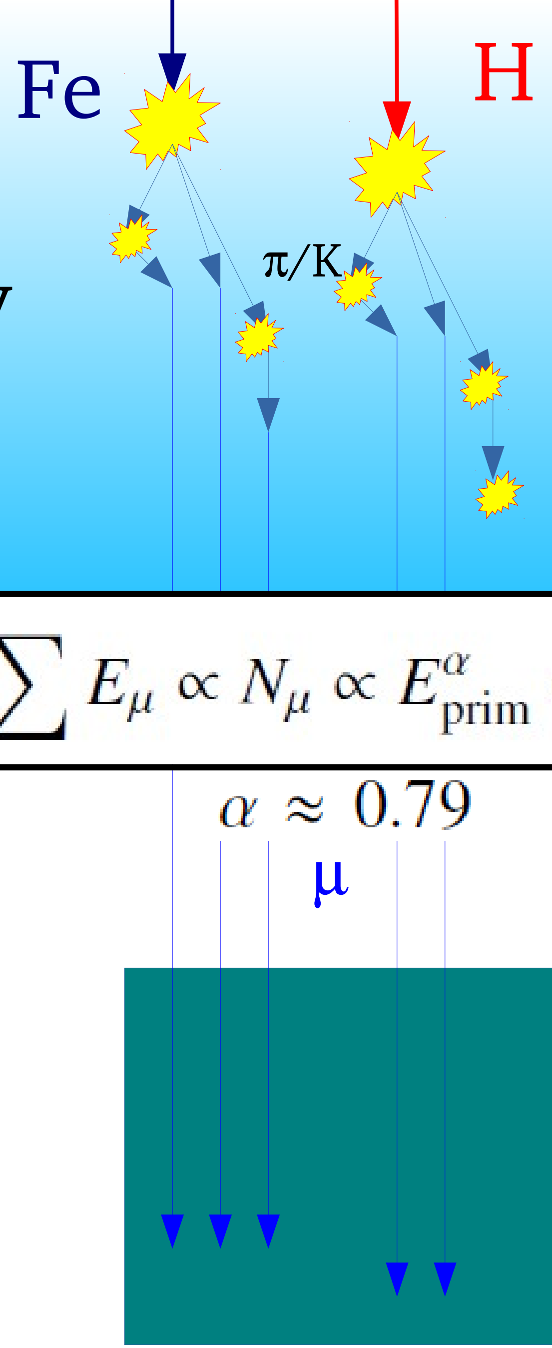


CR Model	Best Fit (ERS)	1σ Interval (90% CL)	Pull ($\Delta\gamma$)	$\sigma(\Phi_{Prompt} > 0)$
GST-Global Fit [11]	2.14	1.27 - 3.35 (0.77 - 4.30)	0.01	2.64
H3a [11]	4.75	3.17 - 7.16 (2.33 - 9.34)	-0.03	3.97

[11] T. K. Gaisser, T. Stanev and S. Tilav, Front. Phys. China 8 (2013) 748 [arXiv:1303.3565 [astro-ph.HE]].

Total flux is sum of light meson (π, K) and poorly constrained prompt (heavy quark, ϕ, ρ, η) components. Relative contributions depend on exact shape of nucleon flux around the knee.

High-Multiplicity Muon Bundle

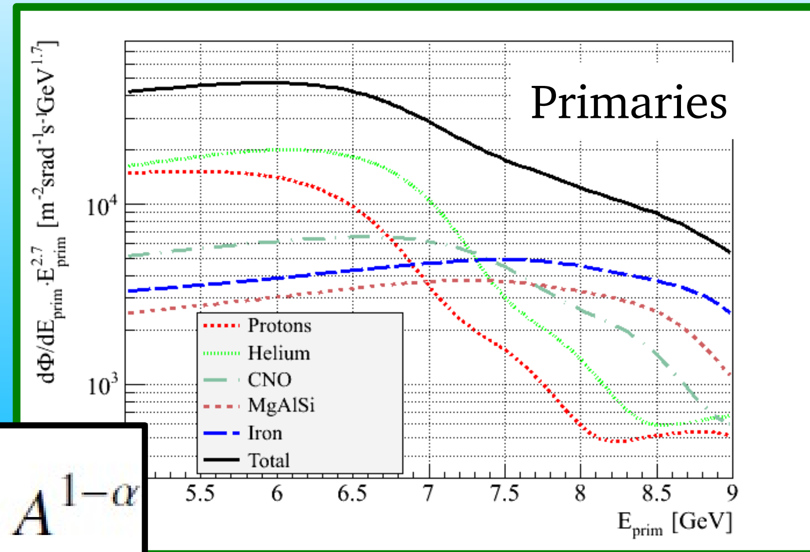


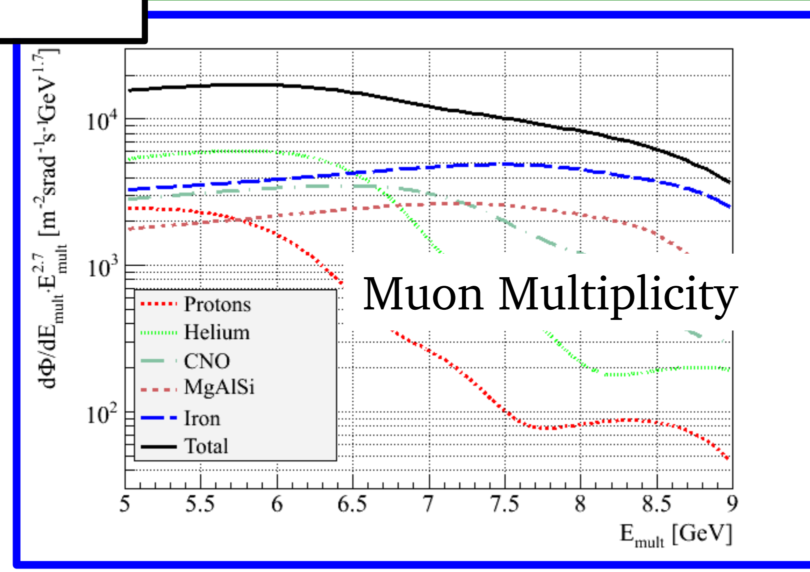
$$\sum E_\mu \propto N_\mu \propto E_{\text{prim}}^{\alpha} \cdot A^{1-\alpha}$$

$$\alpha \approx 0.79$$

Energy Spectrum follows **Nuclei**

Main contribution from **heavy** primaries

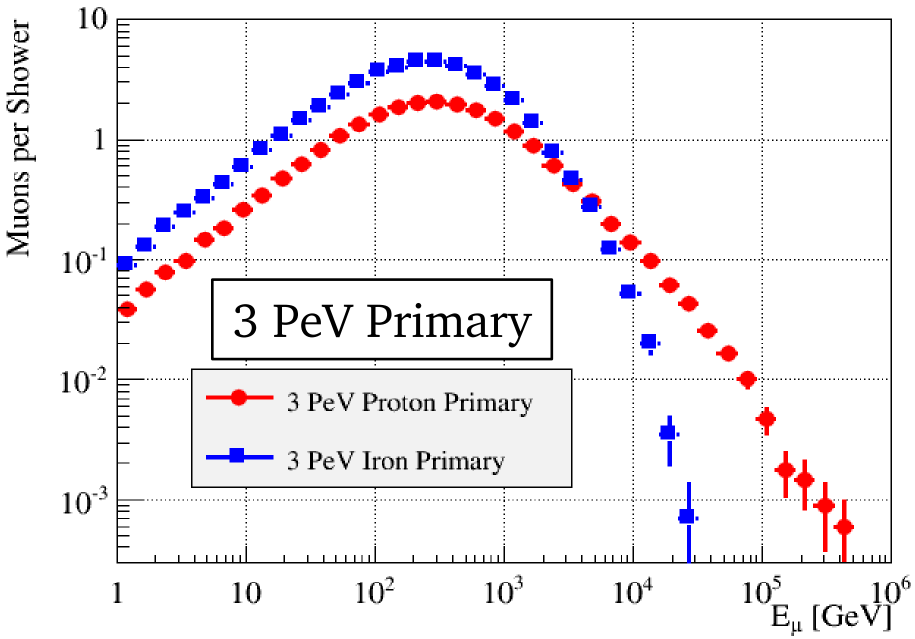


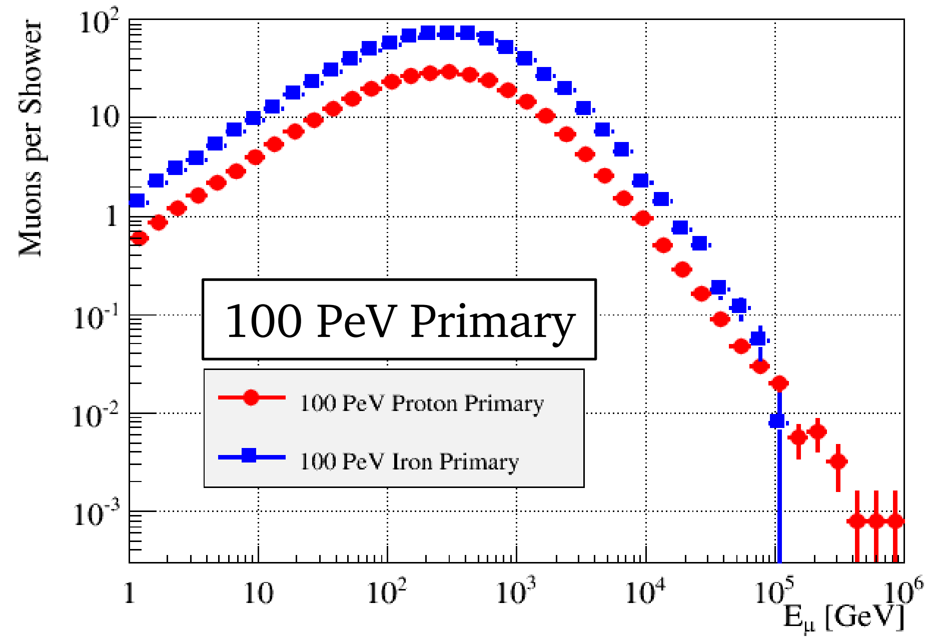


Example: Gaisser H3a

arxiv:1303.3565

Muons per Shower in Deep Detector



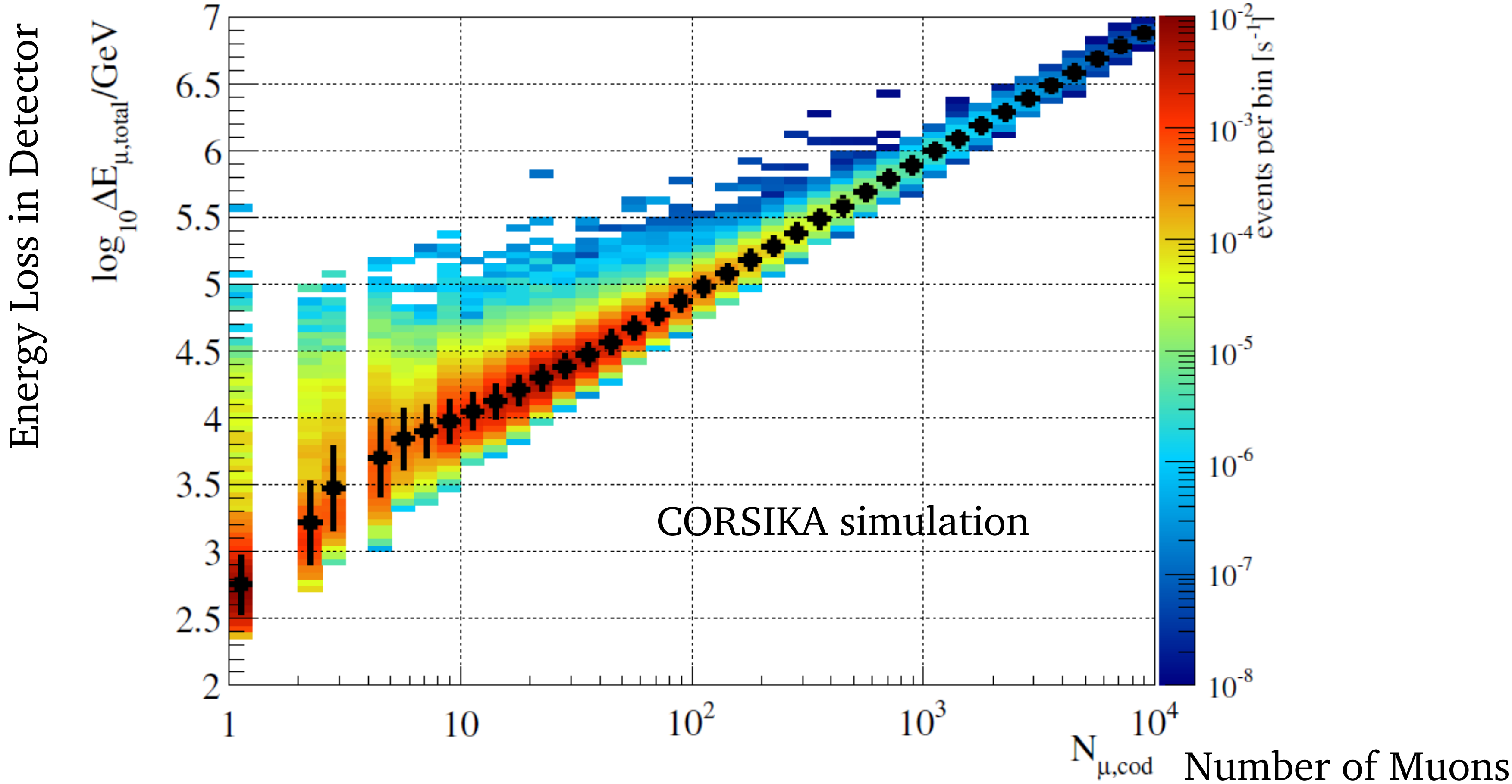


$$N_\mu(E > E_{\mu,\min}) \propto A \cdot \frac{E_0}{E_{\mu,\min}\cos\,\theta} \cdot \left(\frac{E_{\rm prim}}{AE_\mu}\right)^{\alpha \approx 0.79} \cdot \left(1 - \frac{AE_\mu}{E_{\rm prim}}\right)^{\beta}$$

(see e.g. T.K. Gaisser: CR&Part.Phys.)

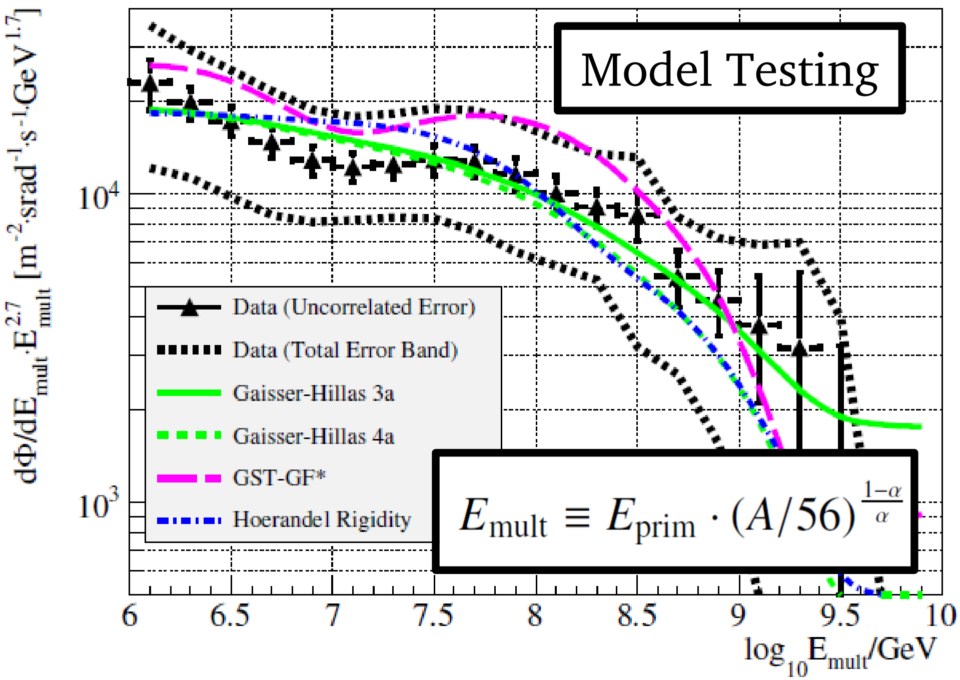
For fixed angle θ and $E_{\rm prim}/A \gg E_\mu$:

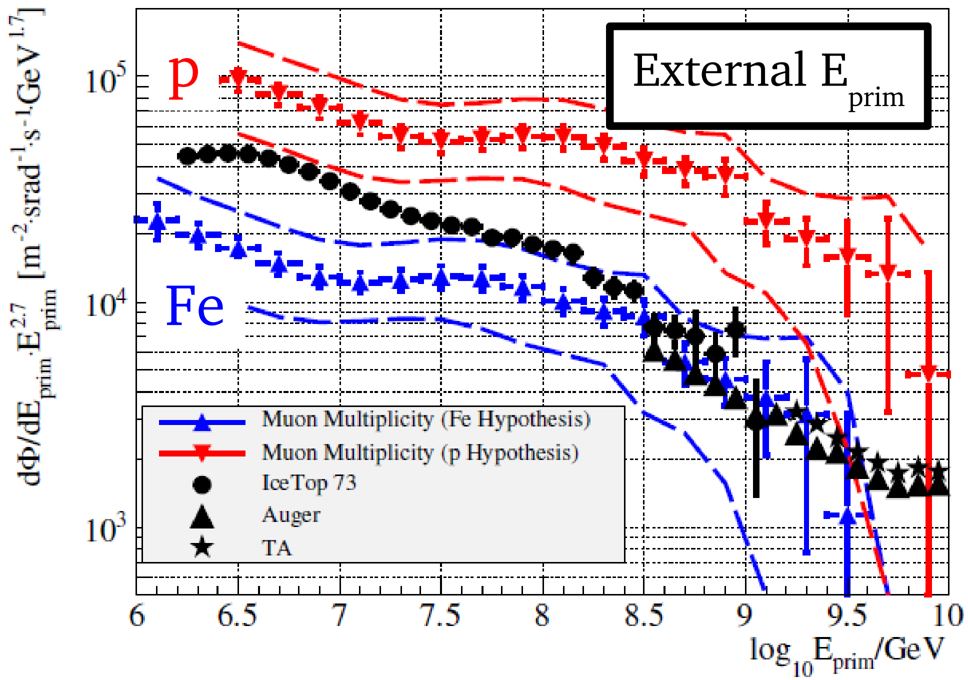
$$N_\mu \propto A^{1-\alpha} \cdot E_{\rm prim}^{\alpha}$$



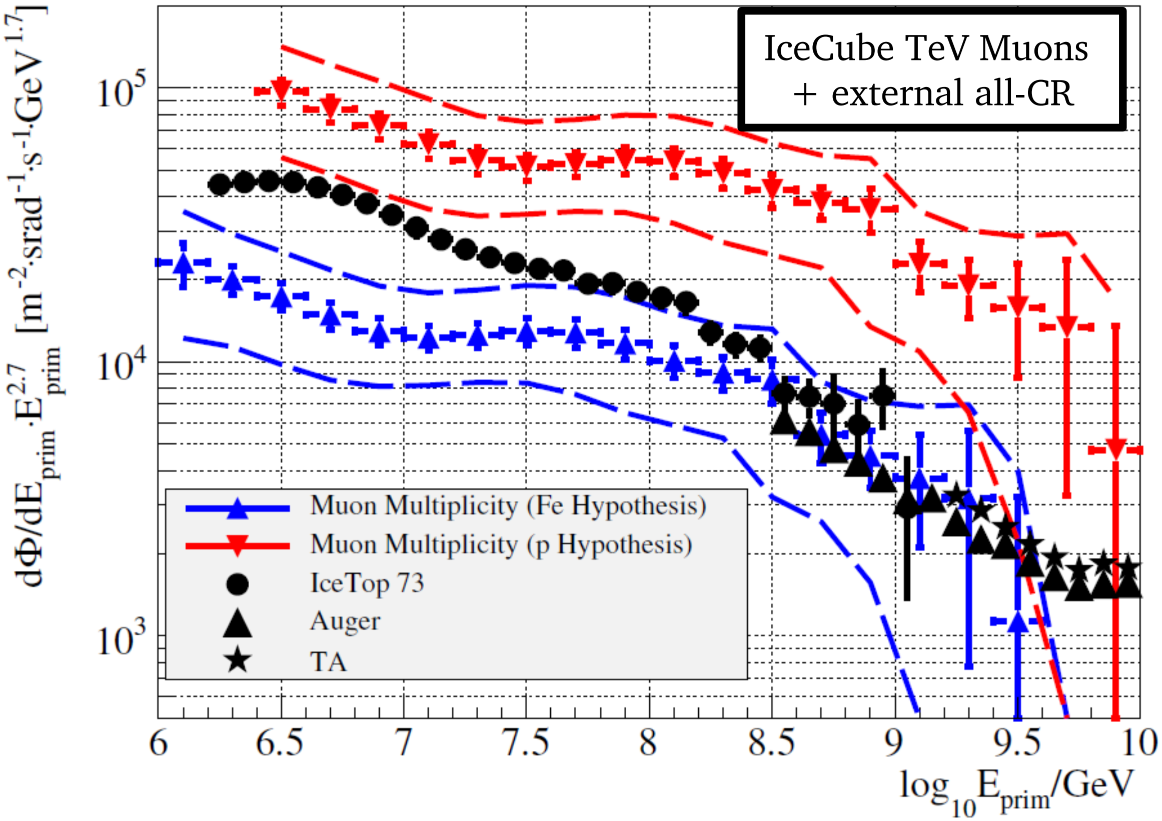
Experimental Aspect: After selection cuts, measurable energy deposition in detector is very closely related to number of muons.

Bundle Spectrum

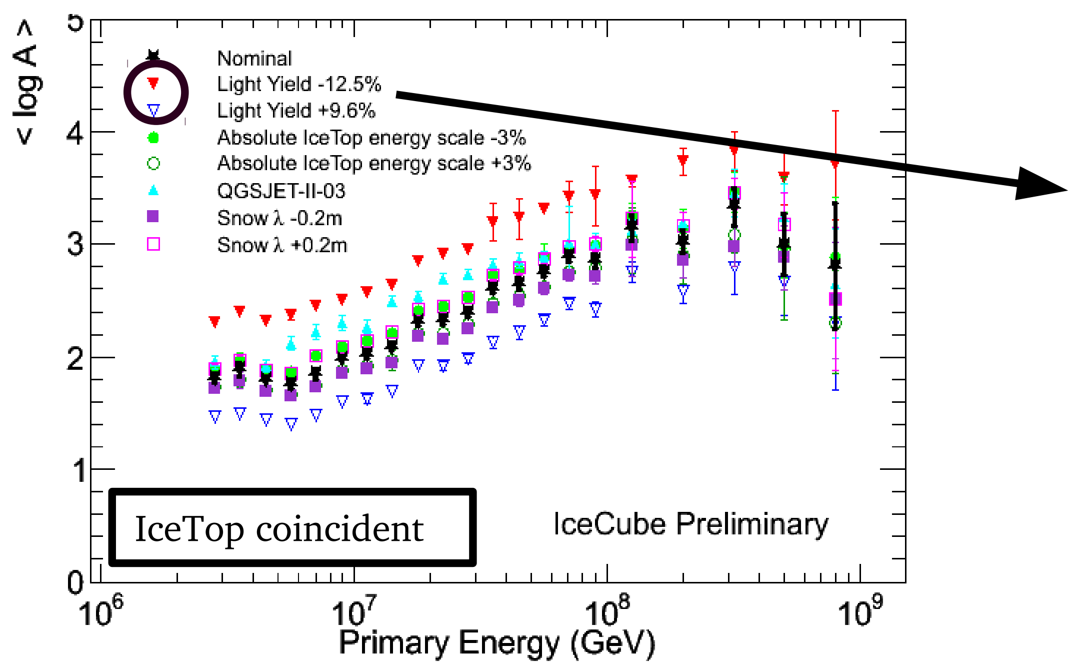




Bundles cover CR energy range from knee to ankle
Lower energy limit determined by threshold of muons produced in Fe-air interactions.



Consistent picture:
Average mass increases up to $3 \cdot 10^{17}$ eV, stays at same level until the ankle.



In IceTop coincident events, systematic uncertainty is dominated by deep detector effects ("Light Yield").

Summary

Large-Volume Detectors present new opportunity for CR Physics

Composition investigations possible without surface array

IceCube results cover knee, region between “heavy knee” and ankle

Paper submitted to Astropart. Ph. (arXiv:1506.07981)