Cosmic Ray Physics with TeV Muons in Large Volume Detectors

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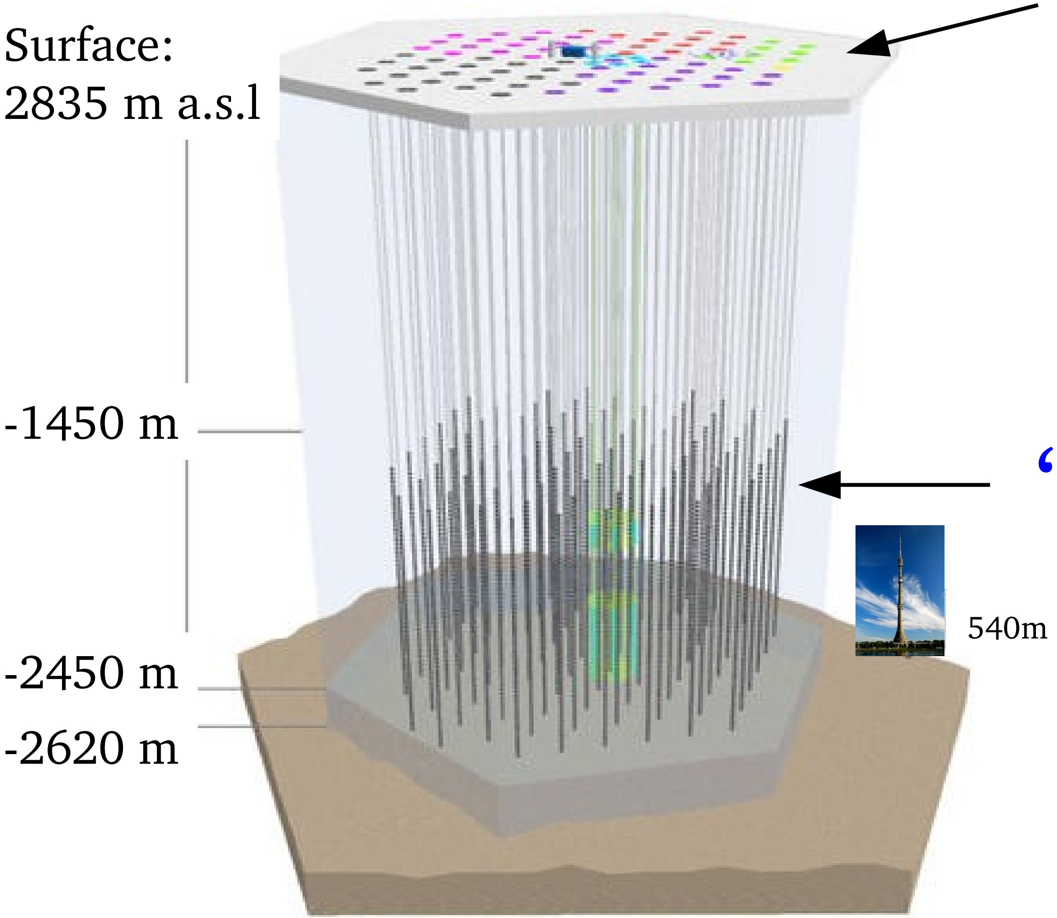
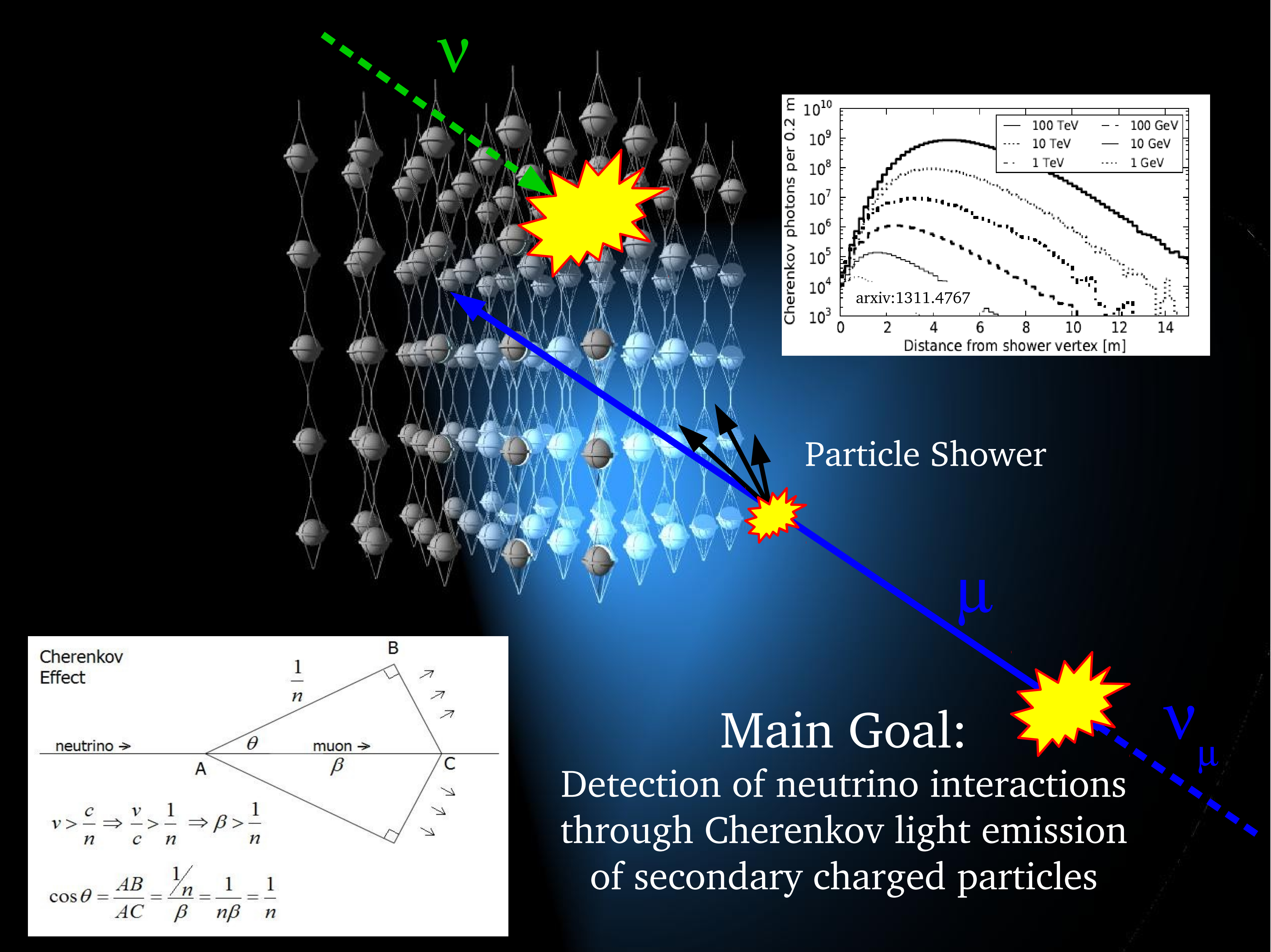
IceCube Components

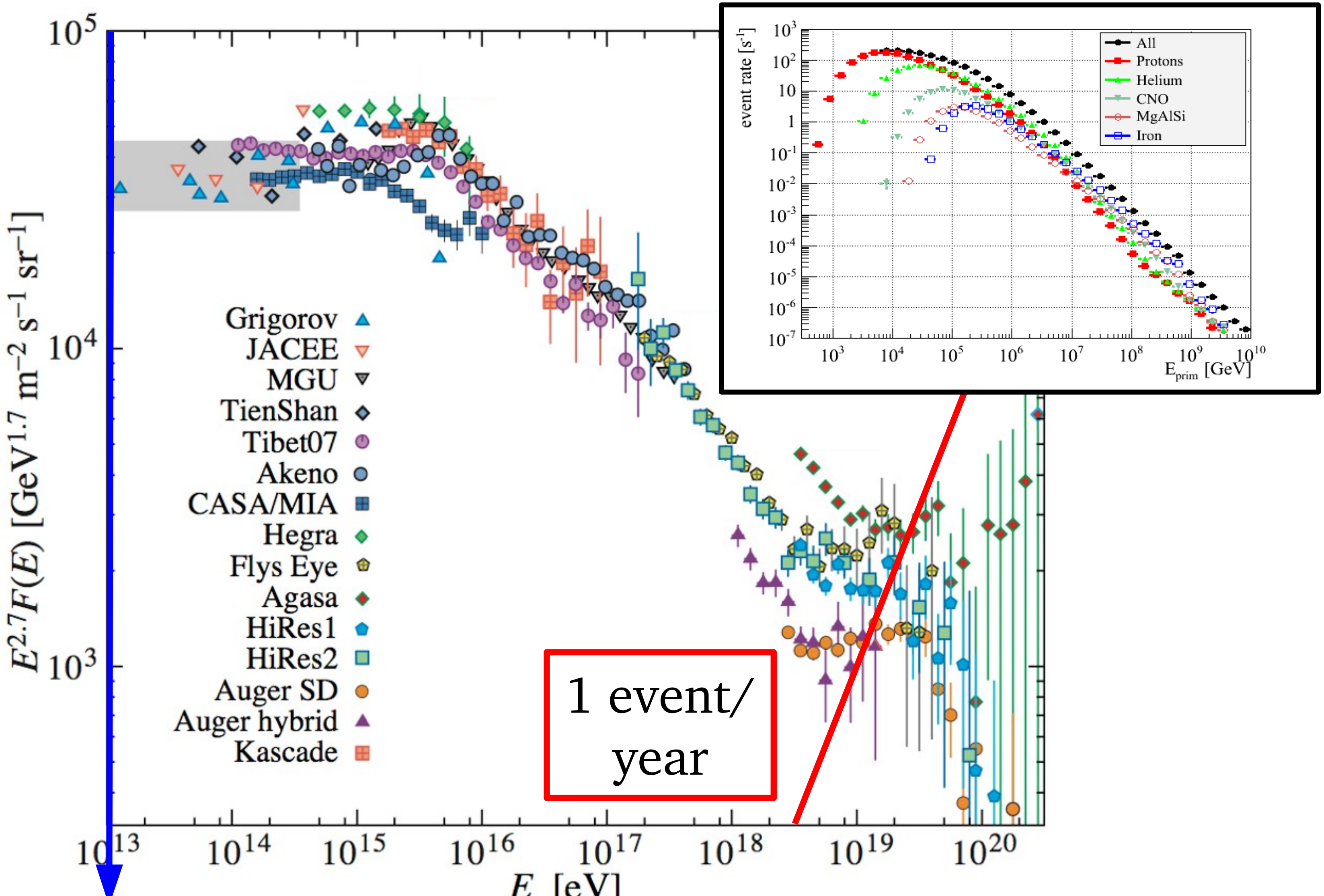


IceTop Surface Array

“InIce” Volume Detector


ν
Particle Shower
μ
ν_μ
Main Goal:
Detection of neutrino interactions through Cherenkov light emission of secondary charged particles
Cherenkov photons per 0.2 m
Distance from shower vertex [m]
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
arxiv:1311.4767
Cherenkov Effect
neutrino →
muon →
A
B
C
$\frac{1}{n}$
θ
β
$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$
$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$

Atmospheric Muons!



Vertical Muon Threshold

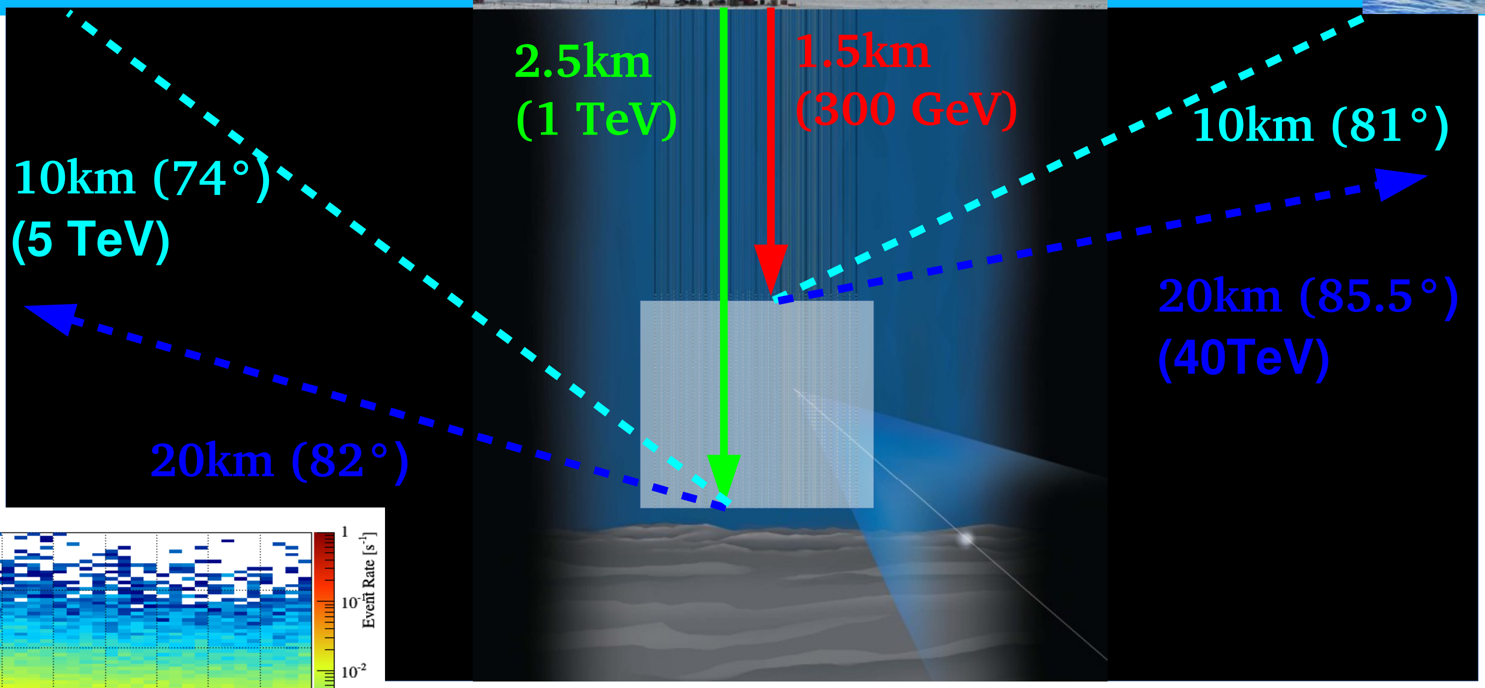
Total event rate: 3000 s^{-1}

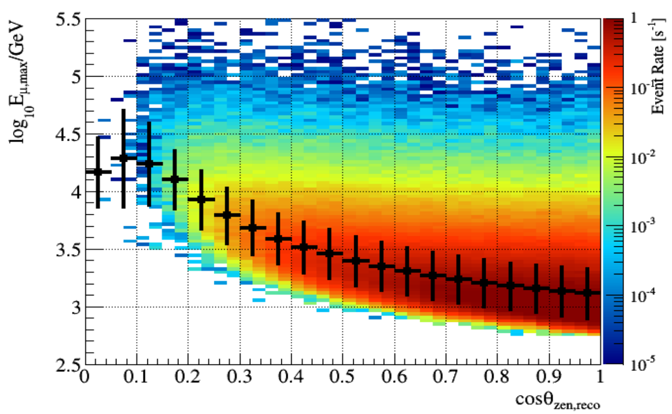
(Neutrinos: $2 \cdot 10^{-3}$ s^{-1})

Propagation through Ice

Slant Depth

(+muon threshold energy)

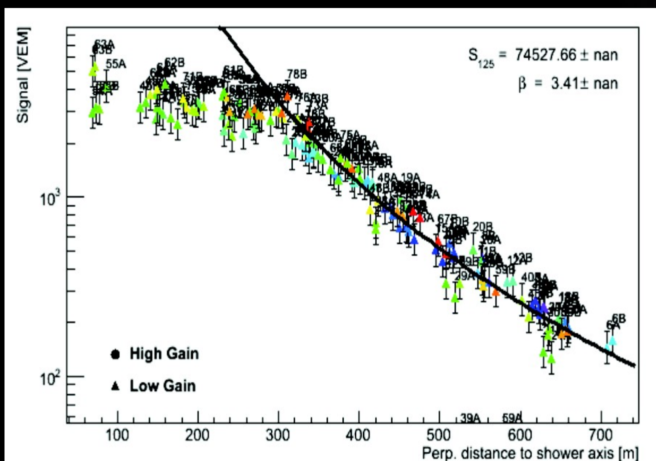




Muon energy threshold increases
as function of angle, approx. as exp(secθ).

Most Energetic Event in IceCube

IceTop (surface)
40 EeV Primary Energy

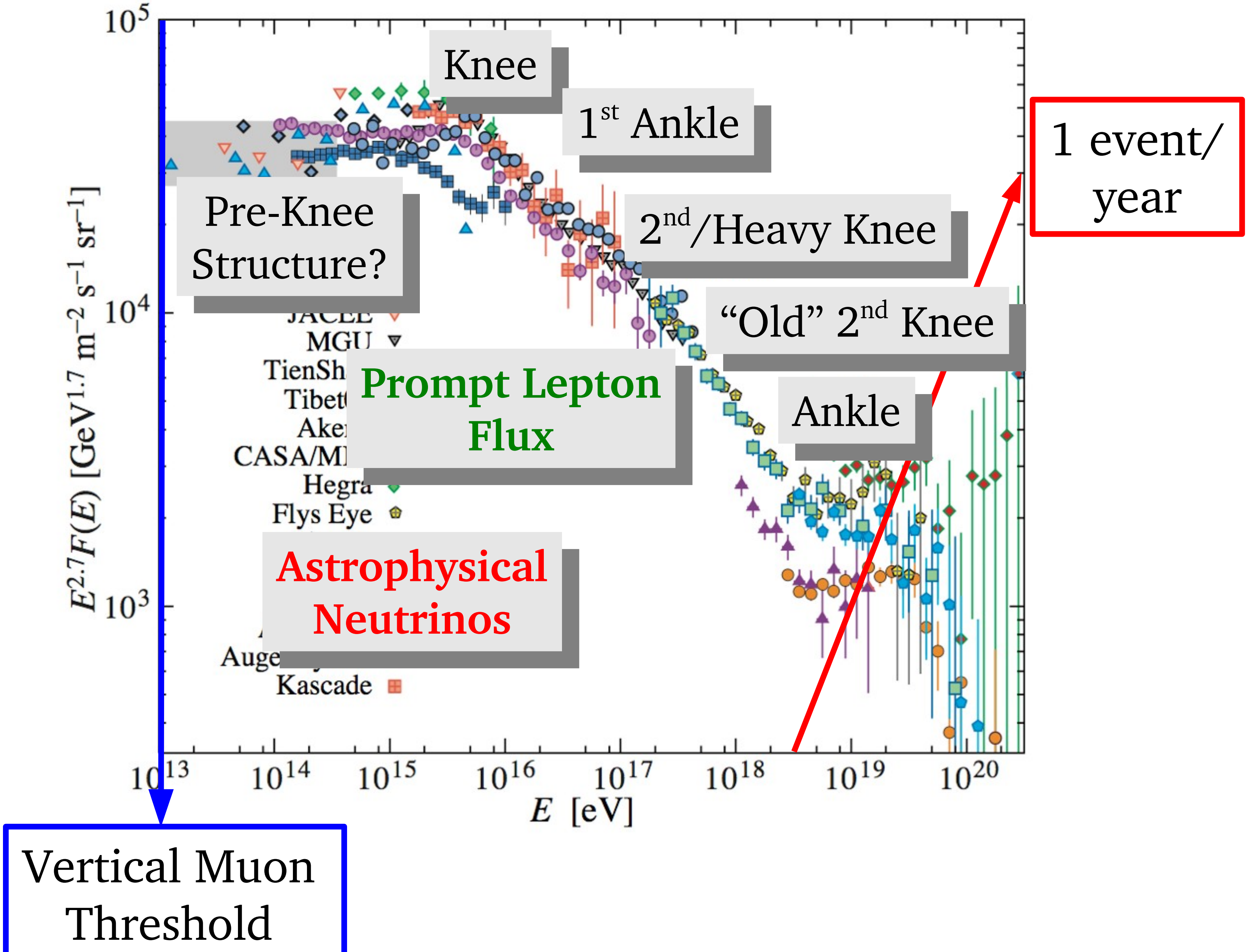


Cosmic Ray Air Shower

"HUMONGOUS"

Energy Estimate from Surface Array Data:
40 EeV (4×10^{19} eV)

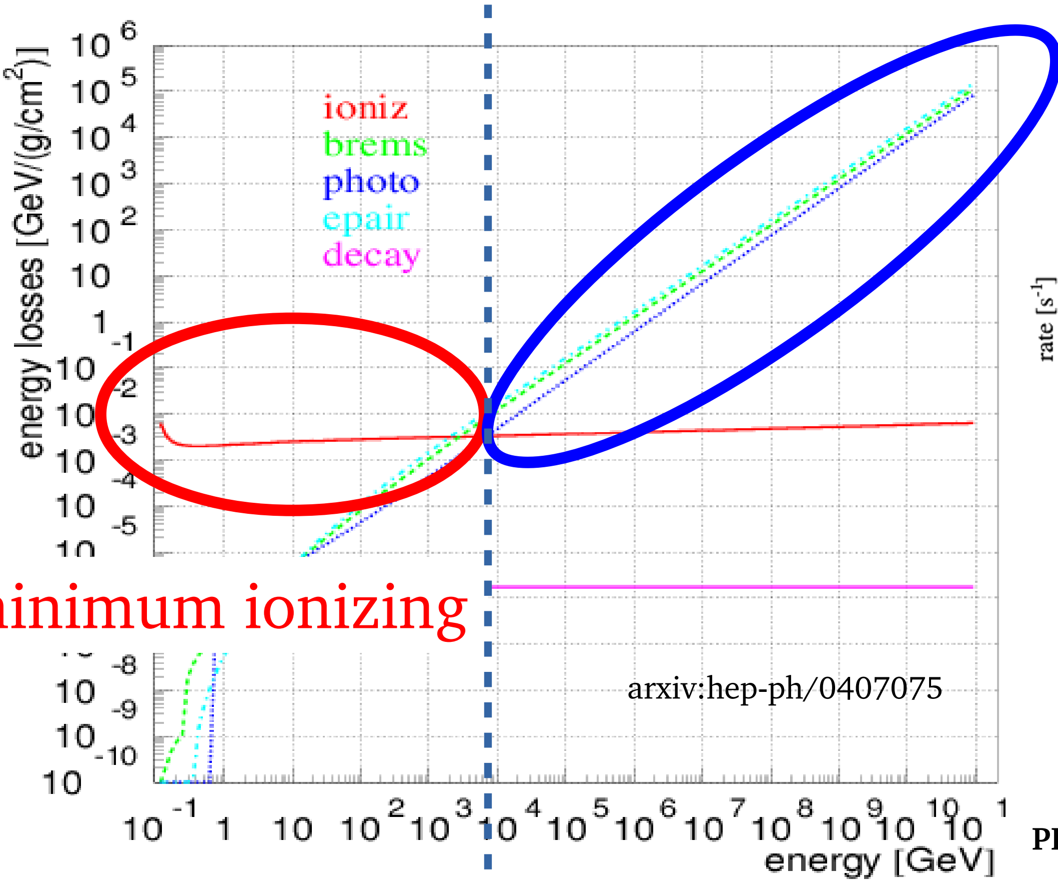
IceCube Muons: Physics



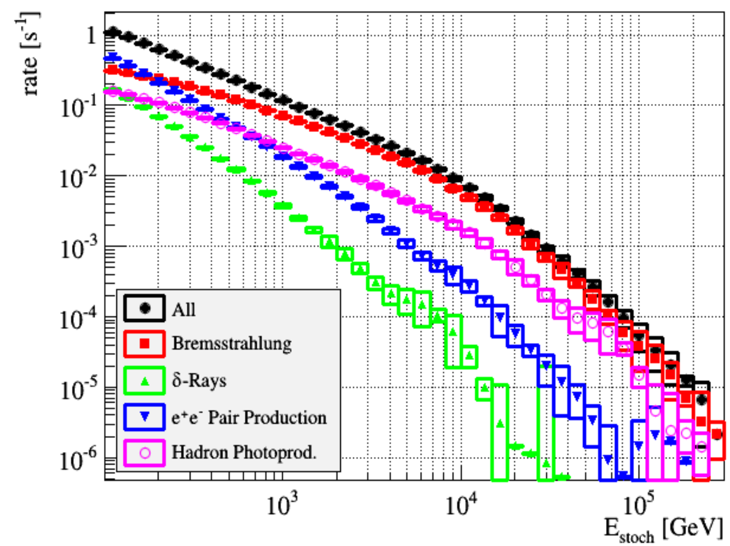
Muon Energy Losses in Matter (Ice)

few TeV

proportional losses



minimum ionizing

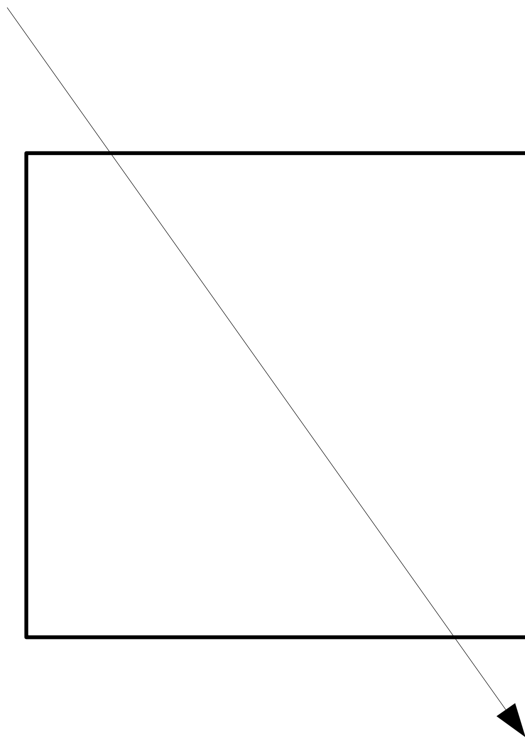


PROPOSAL: A tool for propagation of charged leptons
Comput.Phys.Commun. 184 (2013) 2070-2090

continuous
(smooth)

stochastic
(catastrophic)

Low Energy



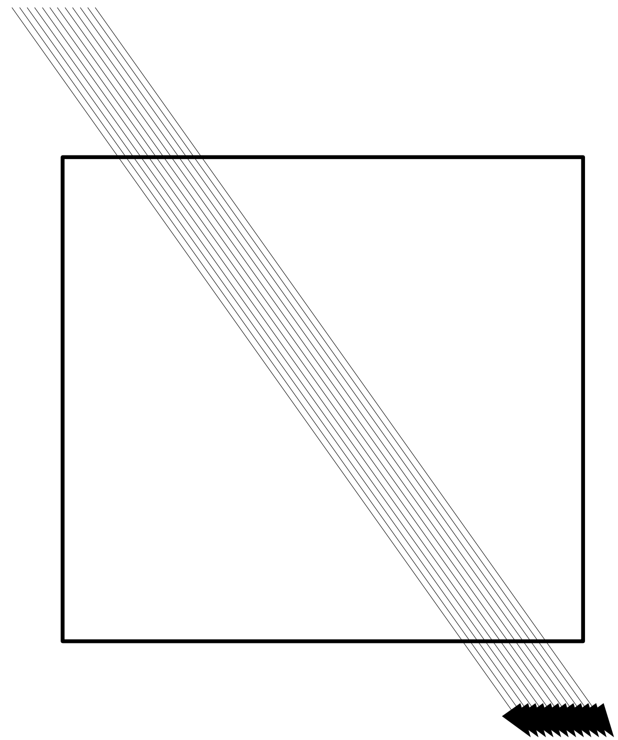
1,000/second

Minimum Ionizing

Single Muons

10-100 TeV CR

Bundles



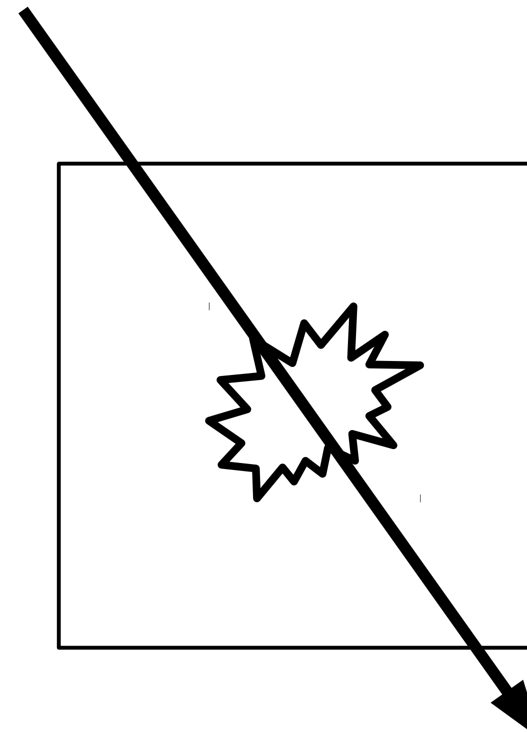
1/second

Minimum Ionizing

20-10,000 Muons

1 PeV-1 EeV CR

HE Muons



0.1/second

Stochastic

1 HE Muon, 10-100 others

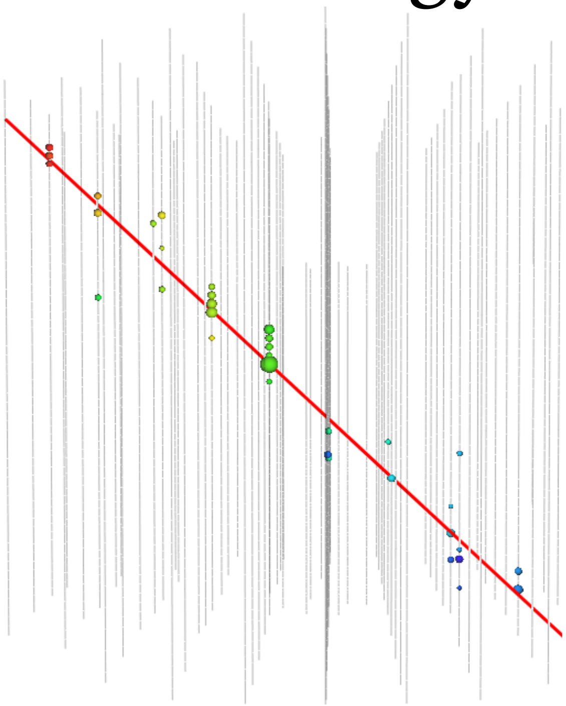
100 TeV-10 PeV CR

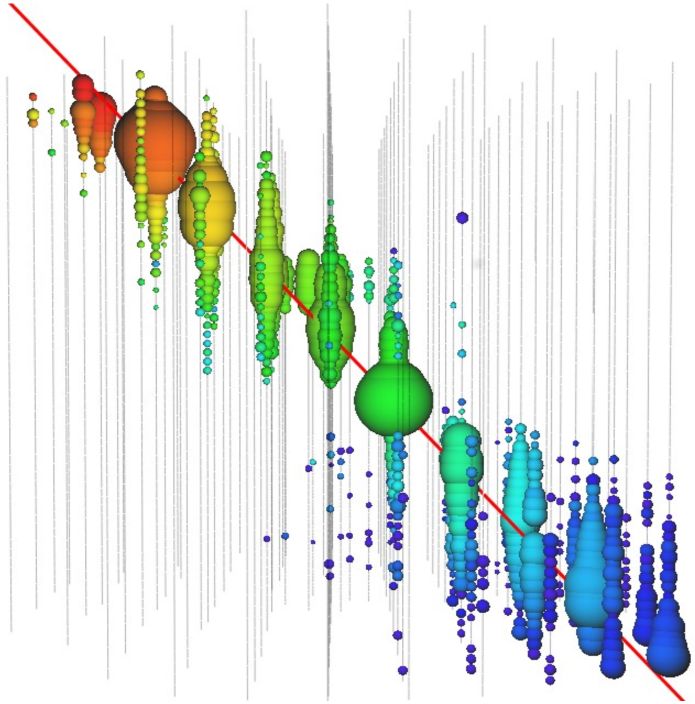
Experimental Data Events

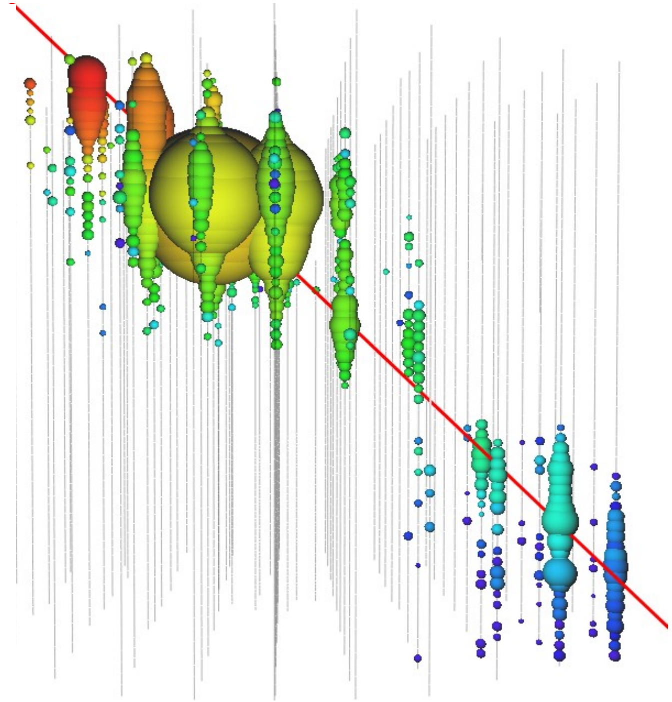
Low-Energy

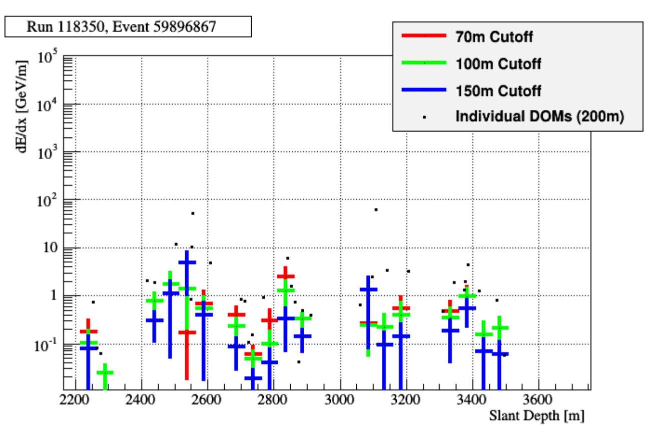
Bundle

HE Muon

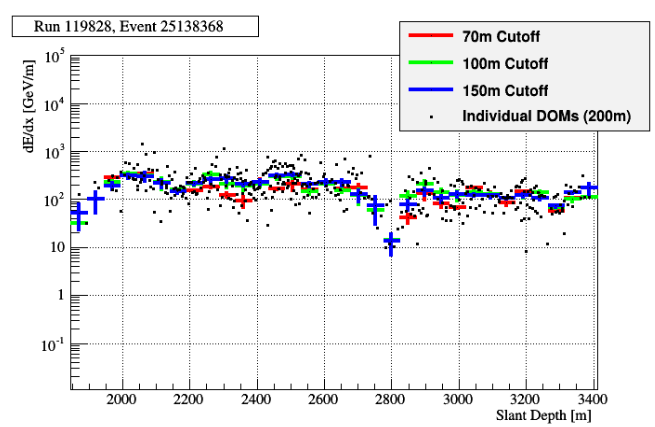




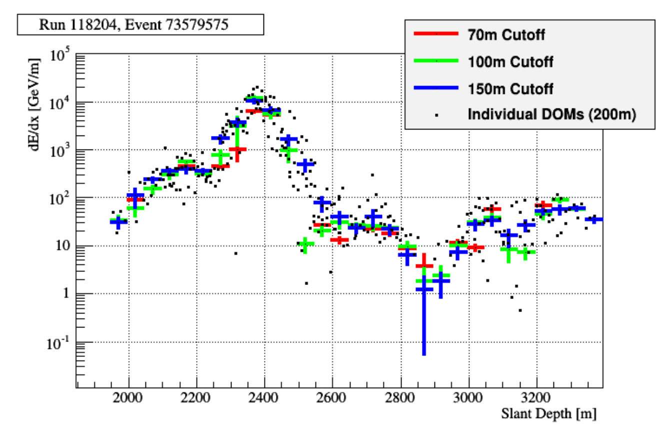




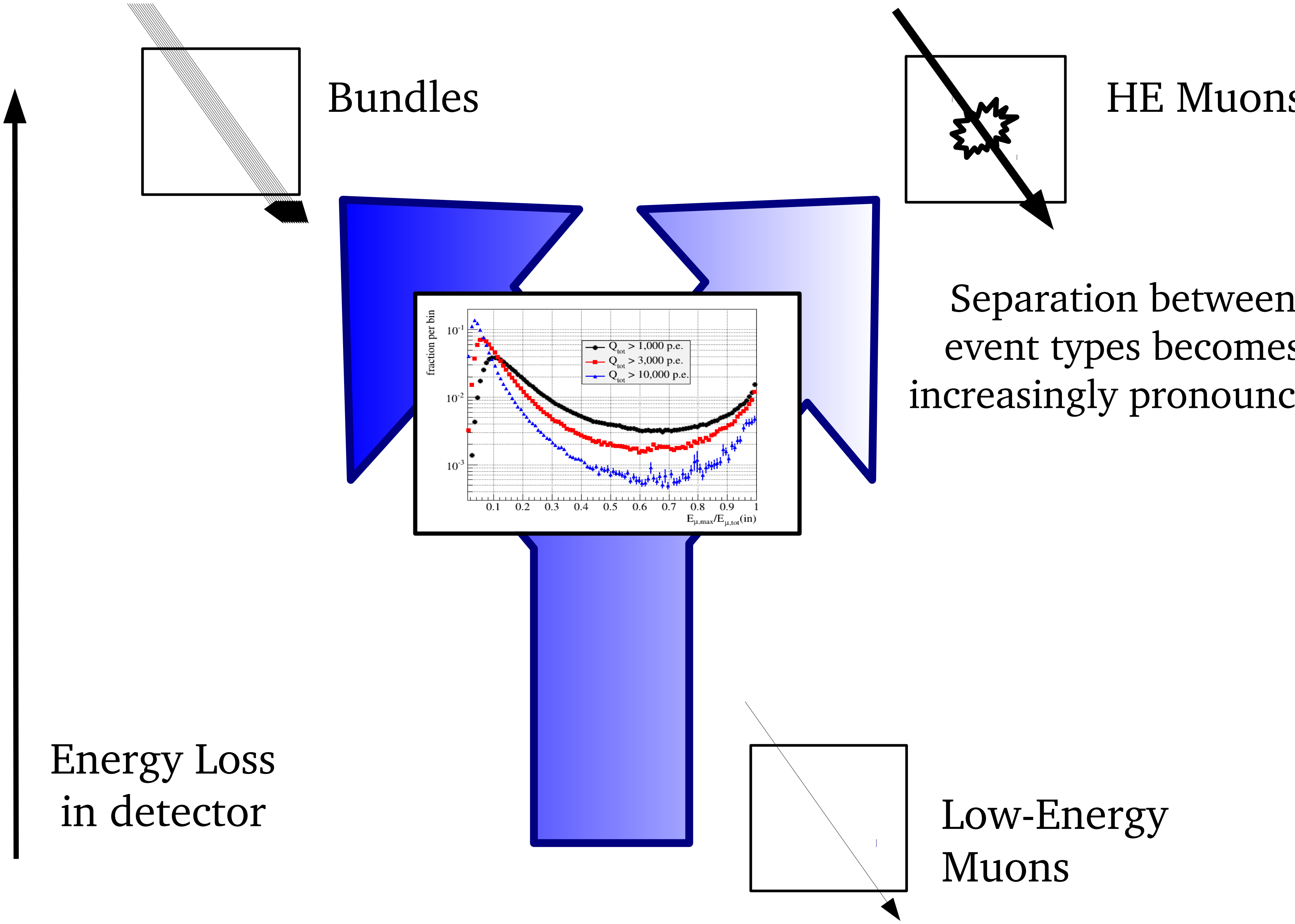
minimum ionizing track



smooth energy loss

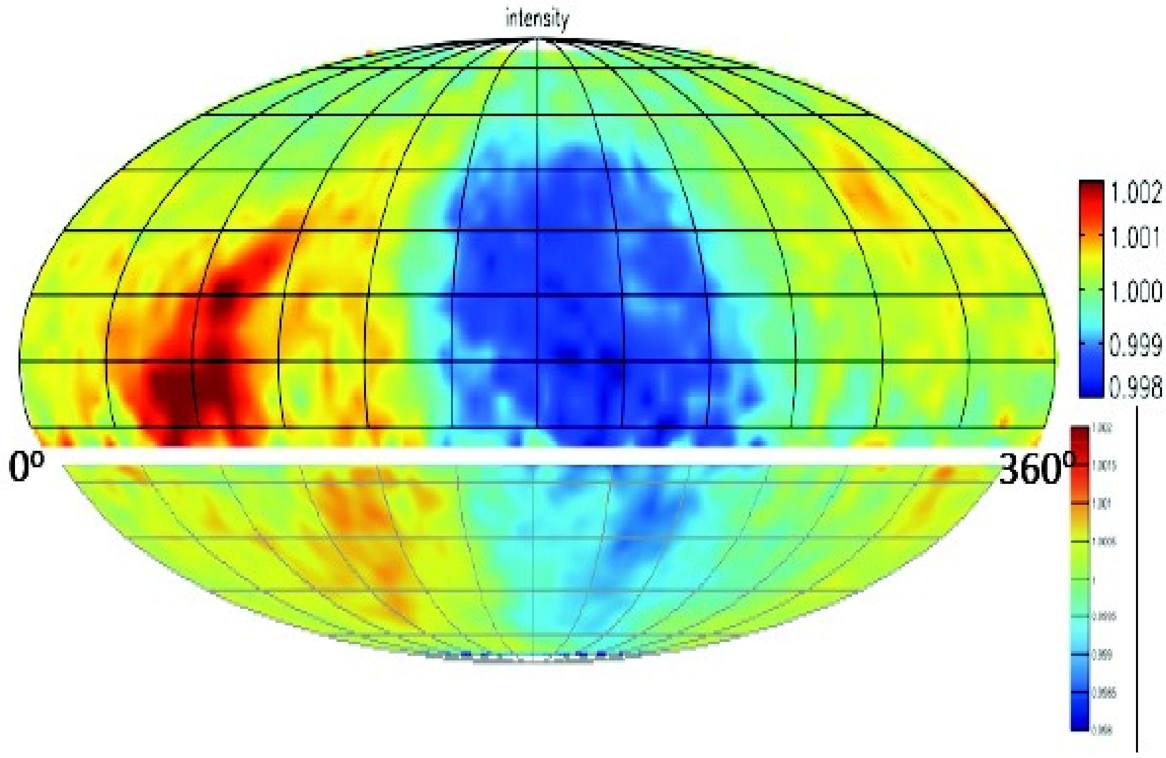


stochastic energy loss



Separation between event types becomes increasingly pronounced

Low Energy: CR Anisotropy



Tibet Array

5TeV

IceCube-59

20 TeV

(predominantly protons)

$$\frac{\Delta I}{\langle I \rangle} = (\gamma + 2)\ \frac{v}{c}\ \cos\vartheta$$

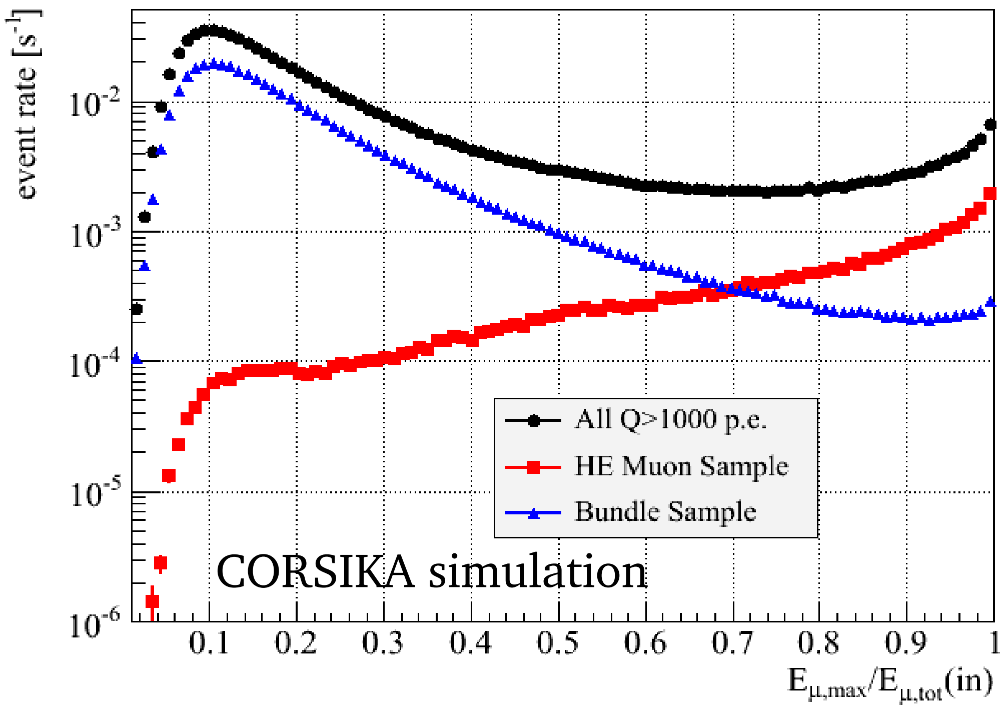
$\gamma = 2.7$ cosmic ray spectral index

$v = 220$ km/s speed

The anisotropy in IceCube data is *not a pure dipole* and does not have the right phase to be explained by the Compton-Getting effect. If the Compton-Getting effect is present in the data, it is overshadowed by a stronger effect.

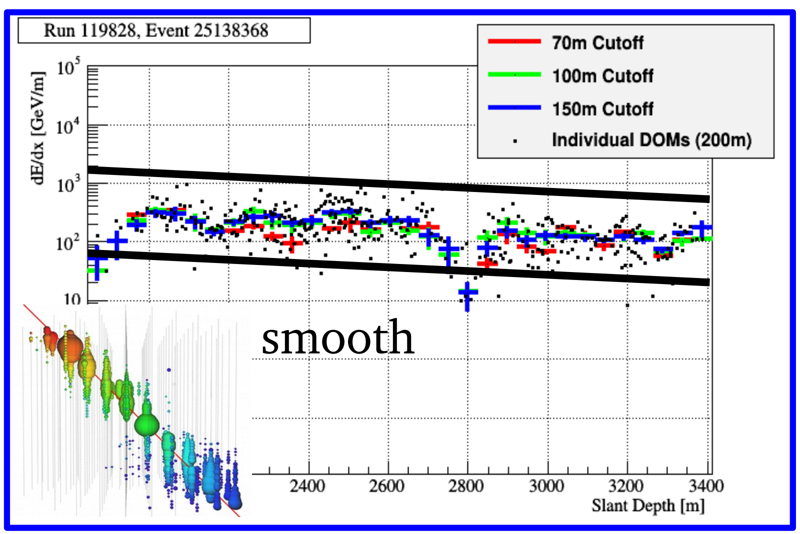
arXiv:1005.2960, 1105.2326, 1109.1017

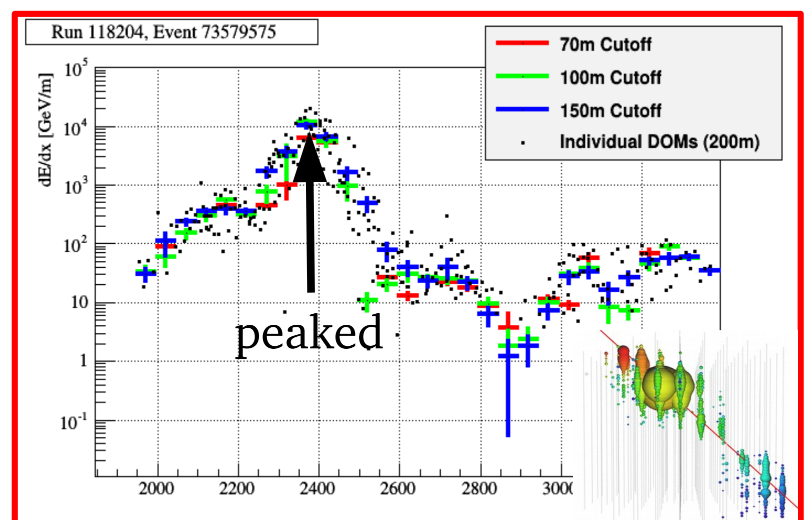
Energy Carried by Leading Muon



Derivation of analysis samples in experimental data

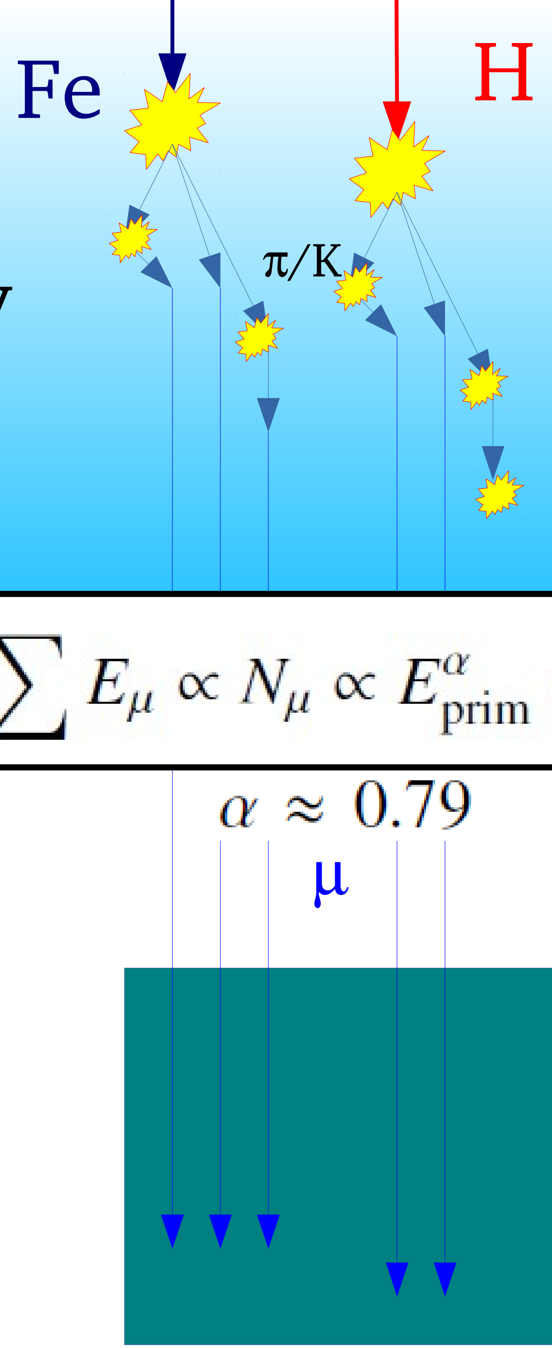
Events are selected based on differential energy loss along track:





Bundles **HE Muons**

High-Multiplicity Muon Bundle

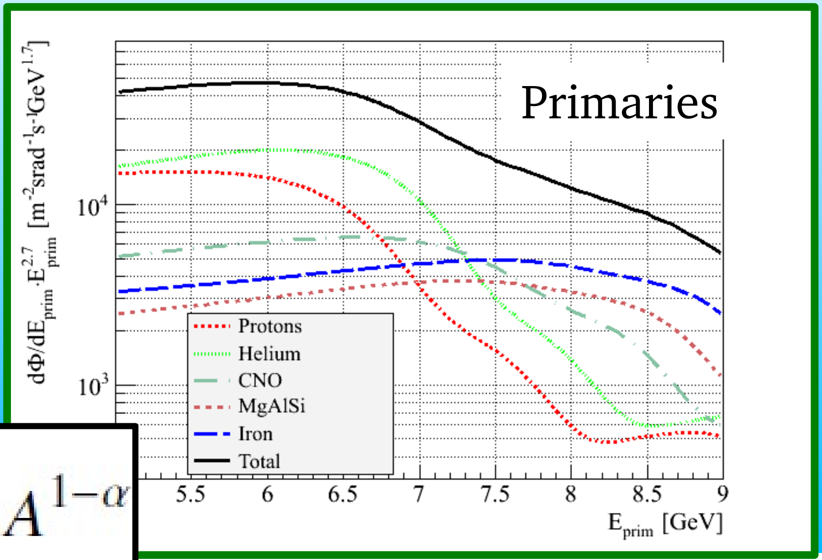


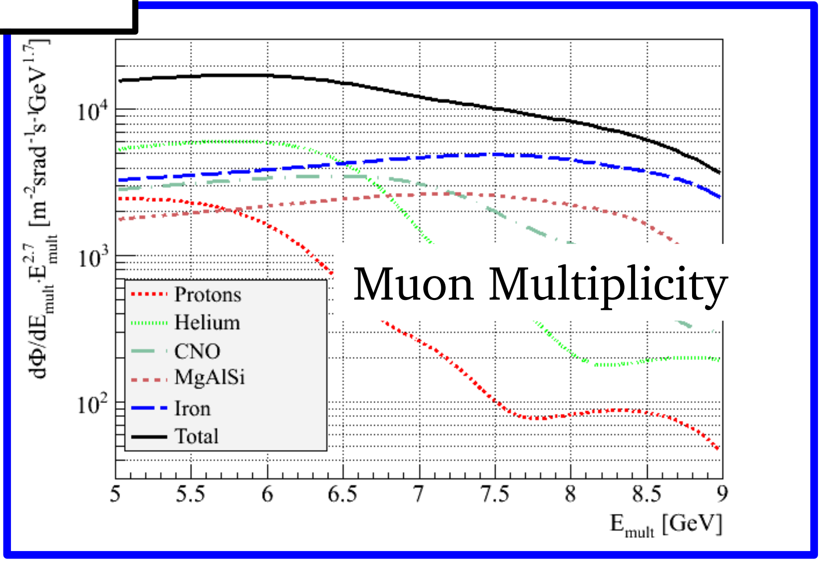
$$\sum E_\mu \propto N_\mu \propto E_{\text{prim}}^{\alpha} \cdot A^{1-\alpha}$$

$$\alpha \approx 0.79$$

Energy Spectrum follows **Nuclei**

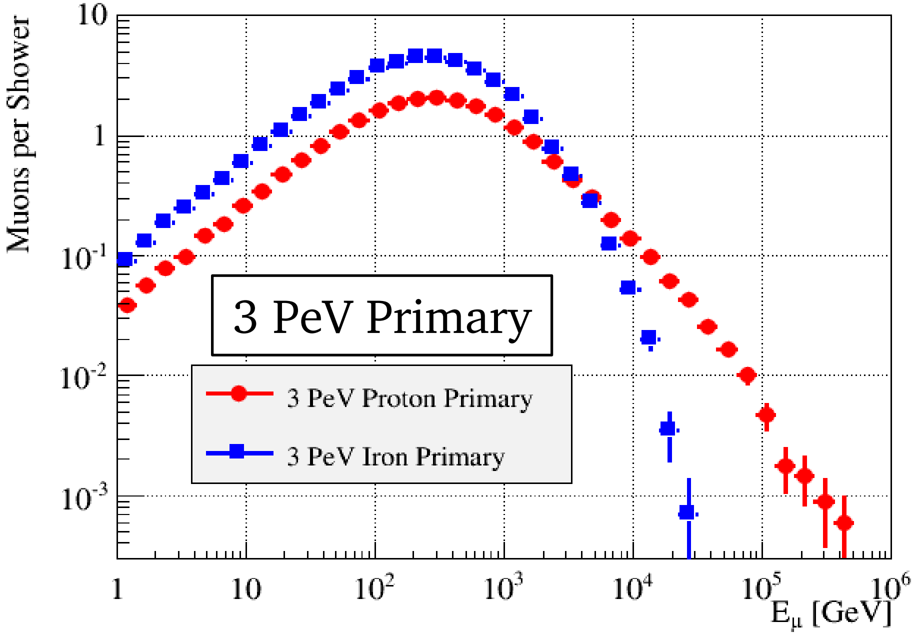
Main contribution from **heavy** primaries

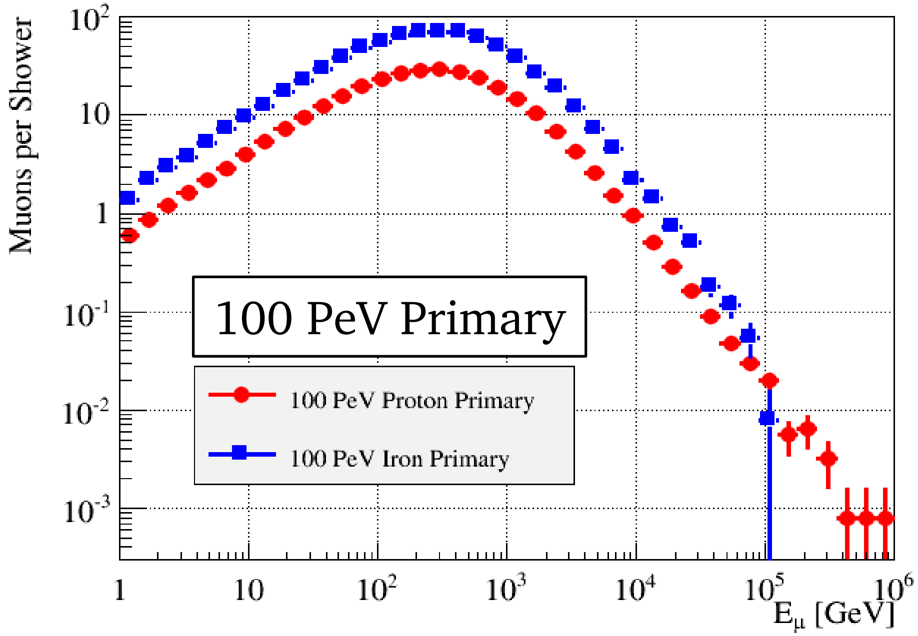




Example: Gaisser H3a Flux Model
arxiv:1303.3565

Muons per Shower in Deep Detector

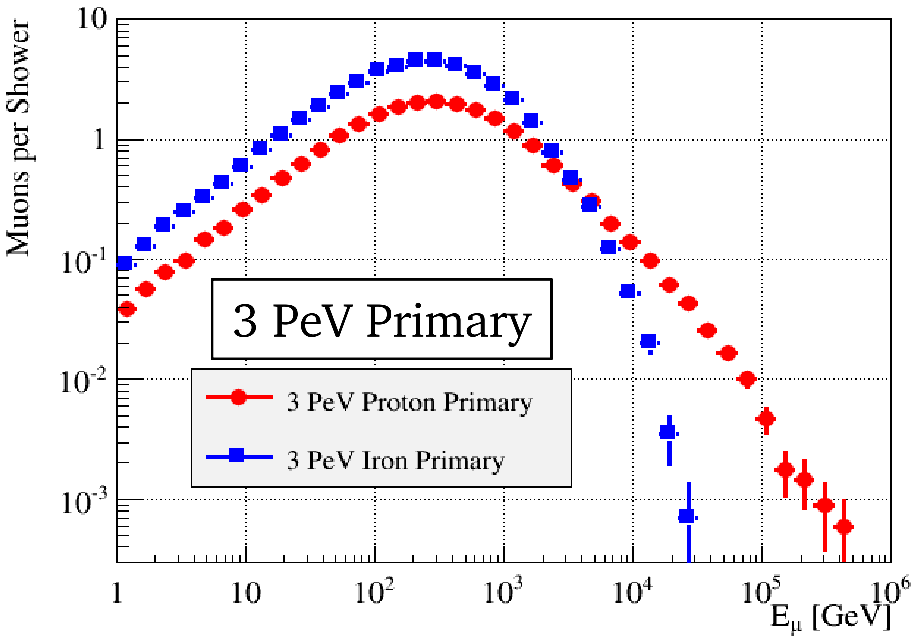


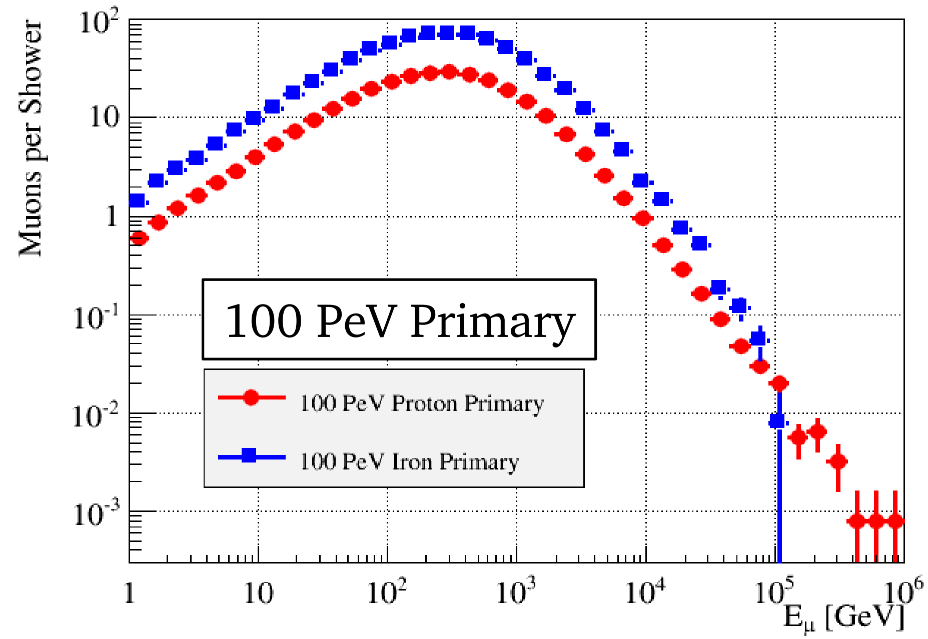


$$N_\mu(E > E_{\mu,\min}) \propto A \cdot \frac{E_0}{E_{\mu,\min} \cos\ \theta} \cdot \left(\frac{E_{\rm prim}}{AE_\mu}\right)^{\alpha \approx 0.79} \cdot \left(1 - \frac{AE_\mu}{E_{\rm prim}}\right)^\beta$$

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

Muons per Shower in Deep Detector

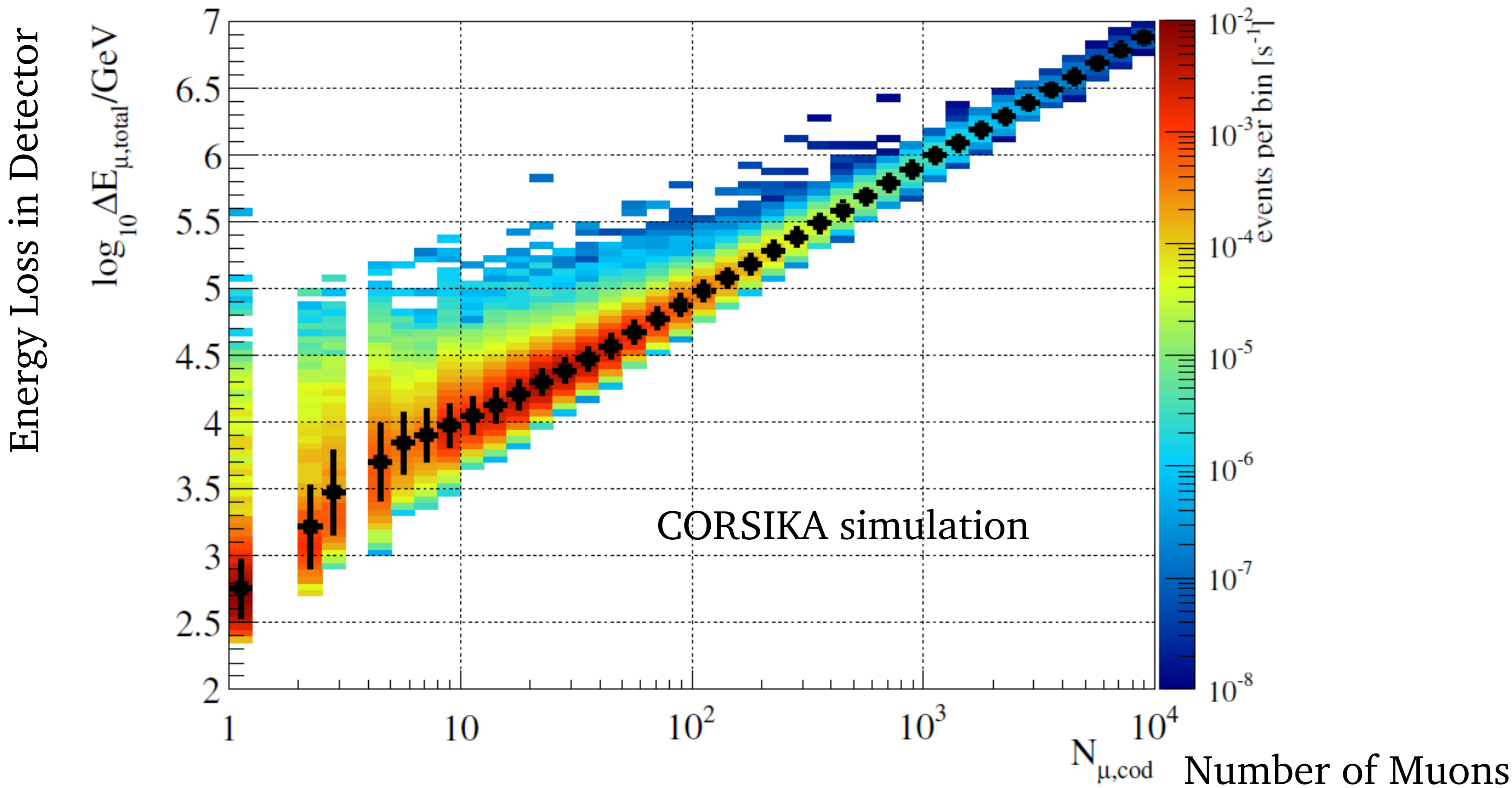




$$N_\mu(E > E_{\mu,\min}) \propto A \cdot \frac{E_0}{E_{\mu,\min}\cos\theta} \cdot \left(\frac{E_{\text{prim}}}{A E_\mu}\right)^{\alpha \approx 0.79} \cdot \left(1 - \frac{A E_\mu}{E_{\text{prim}}}\right)^{\beta}$$

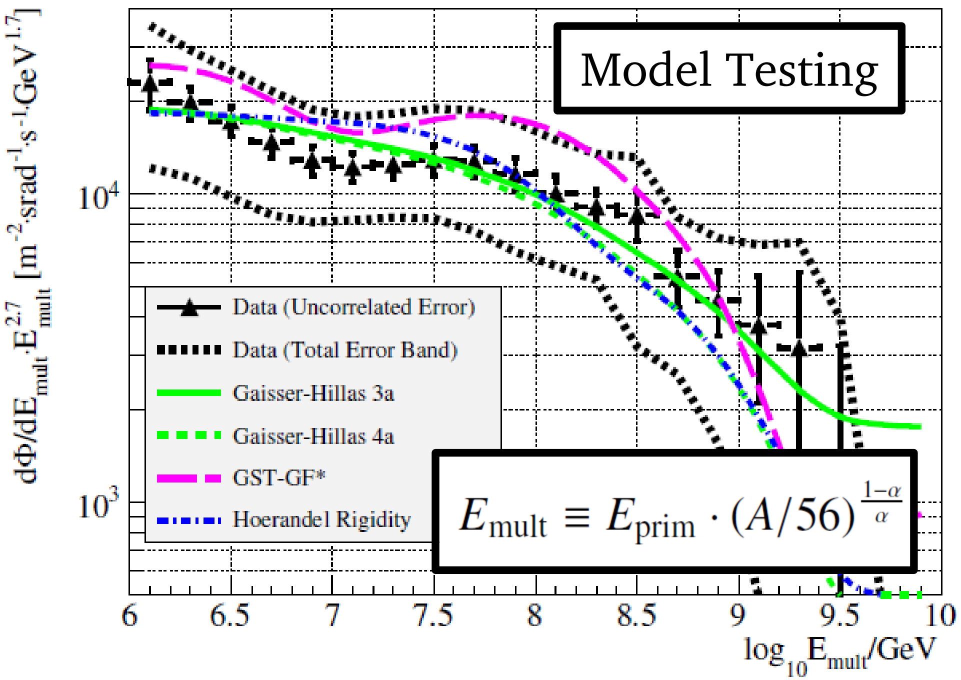
(see e.g. T.K. Gaisser: CR&Part.Phys.)

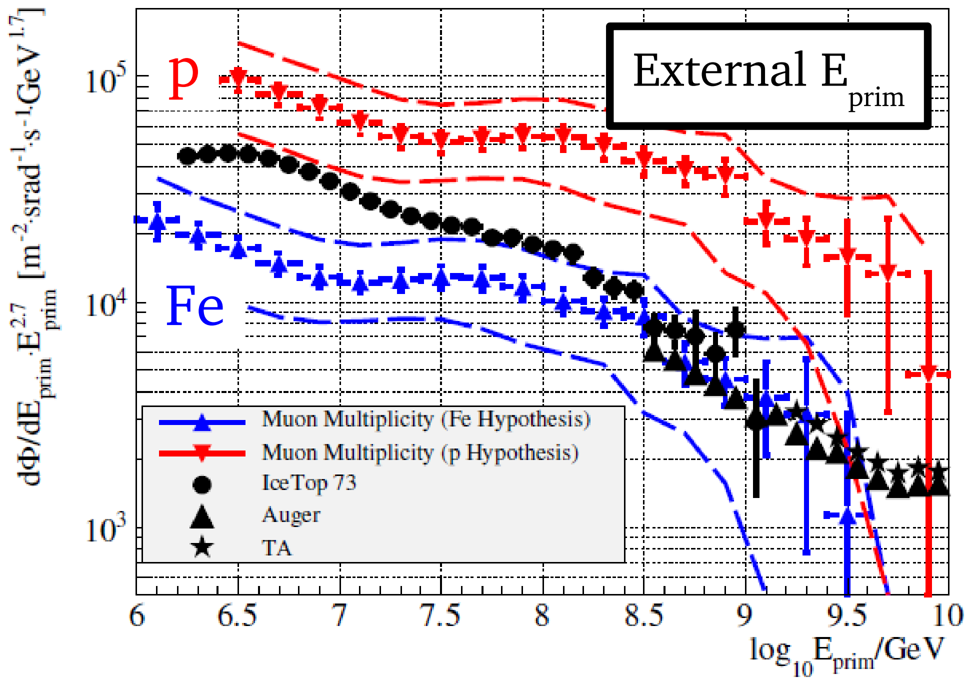
For fixed angle θ and $E_{\text{prim}}/A \gg E_\mu$: $N_\mu \propto A^{1-\alpha} \cdot E_{\text{prim}}^{\alpha}$



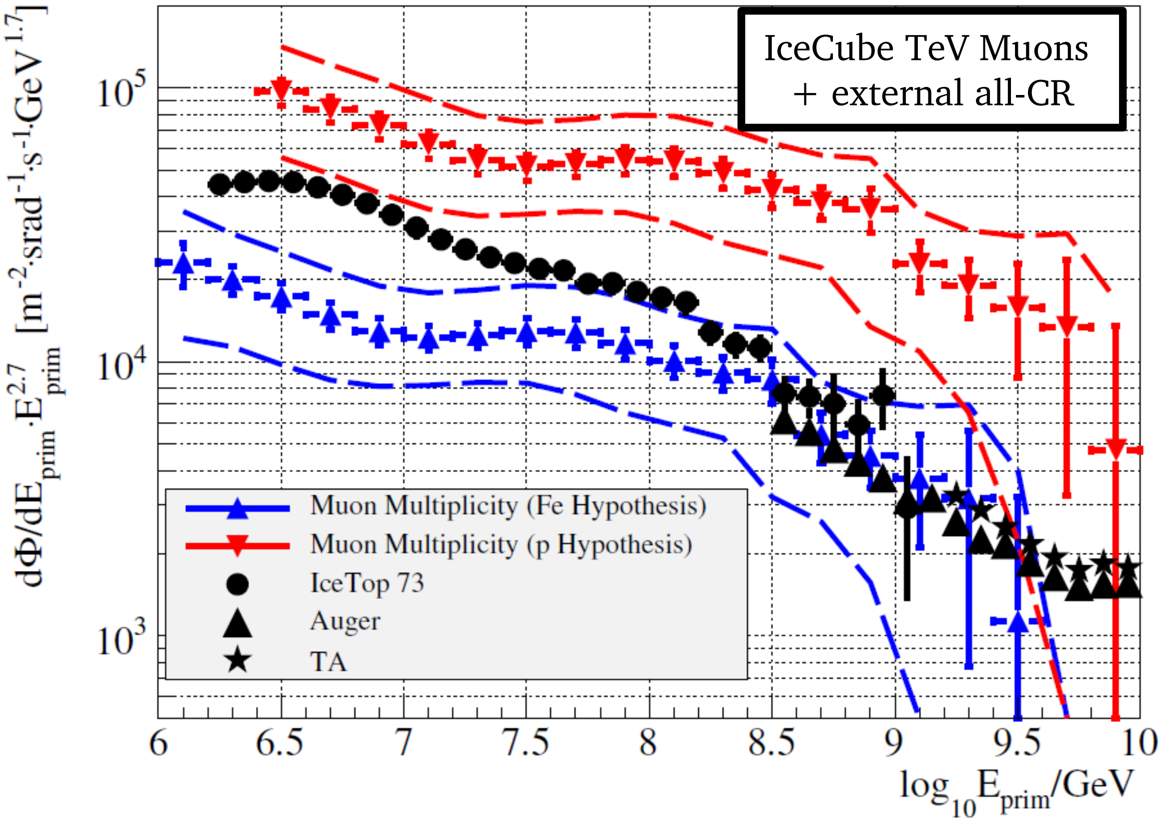
Experimental Measurement of Muon Multiplicity:
At final analysis level, integrated
energy deposition in detector is in good approximation
simply proportional to number of muons.

Bundle Spectrum

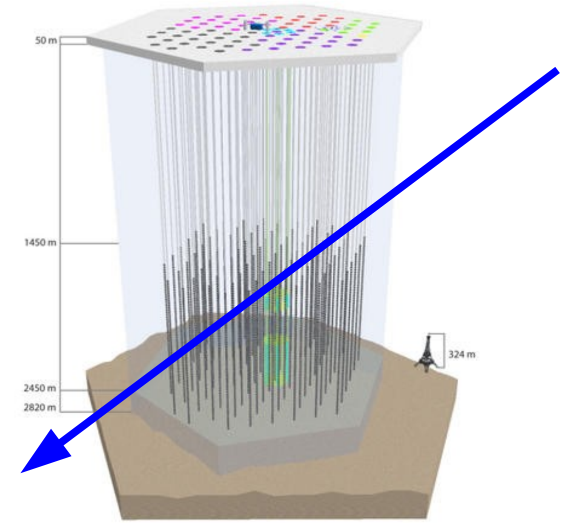


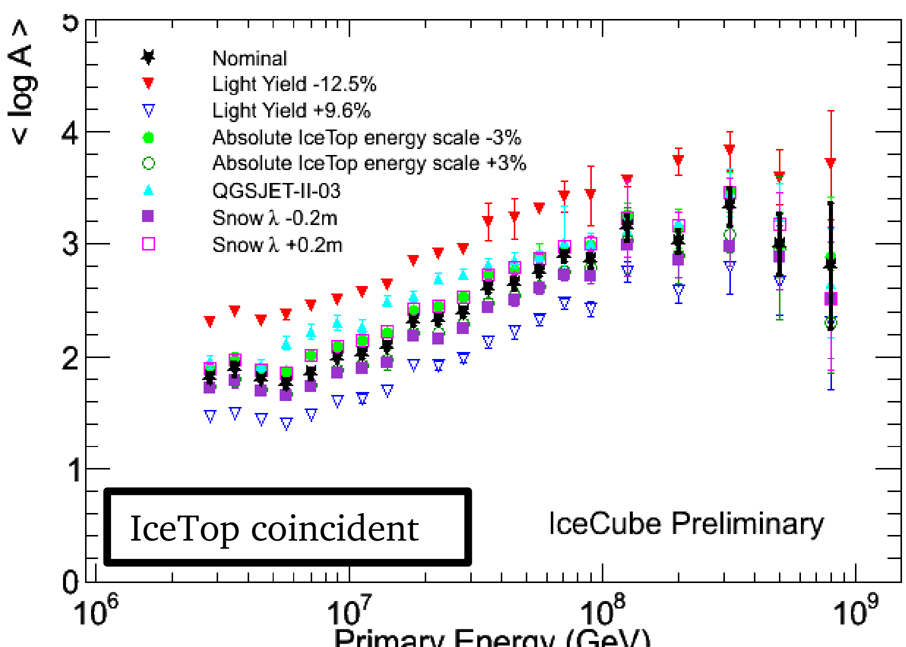


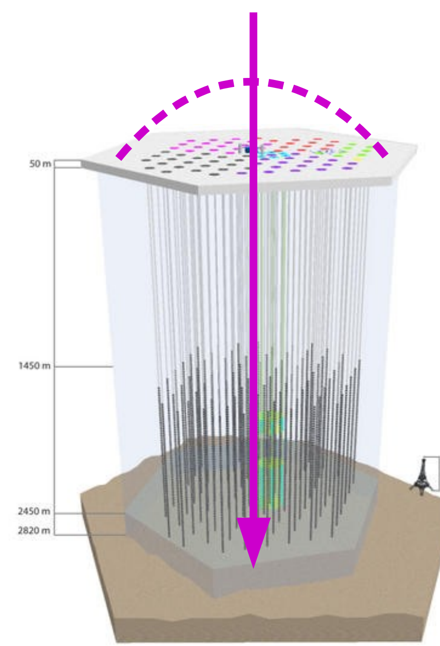
Bundles cover CR energy range from knee to ankle
Lower energy limit determined by threshold of muons produced in Fe-air interactions.



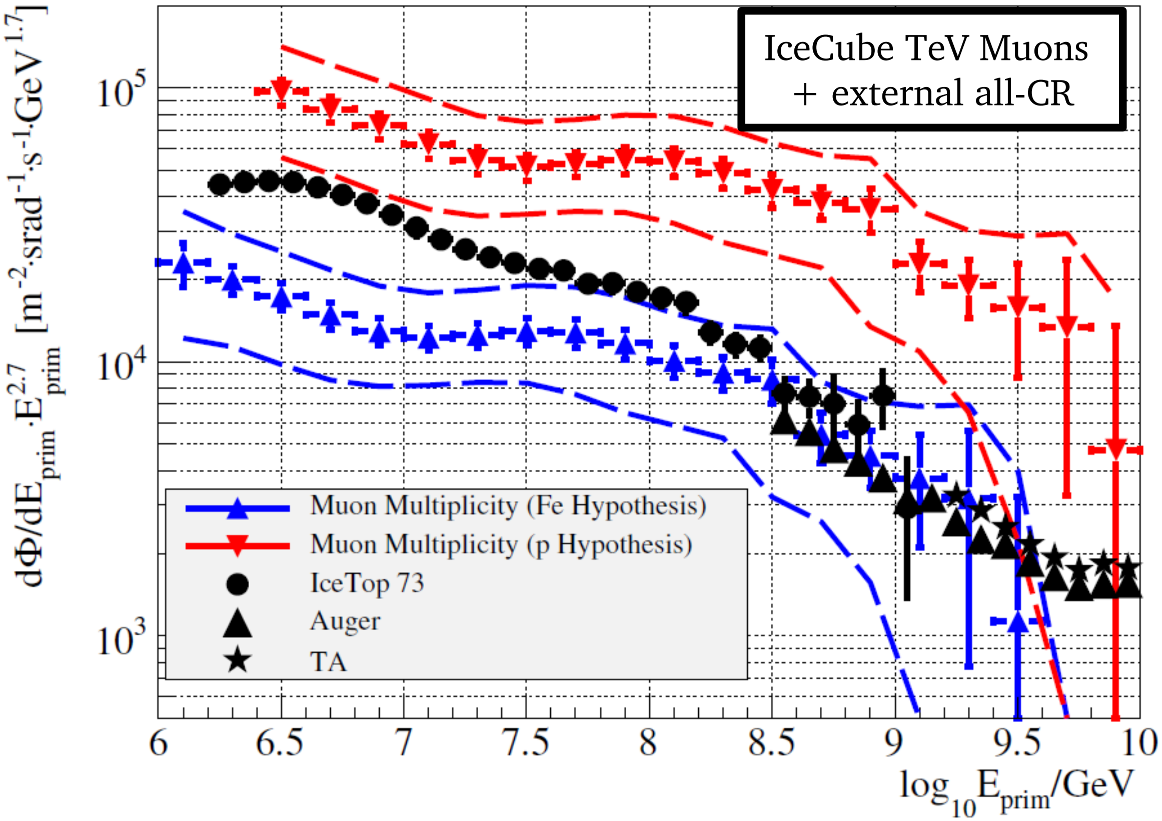
Deep Detector Muons



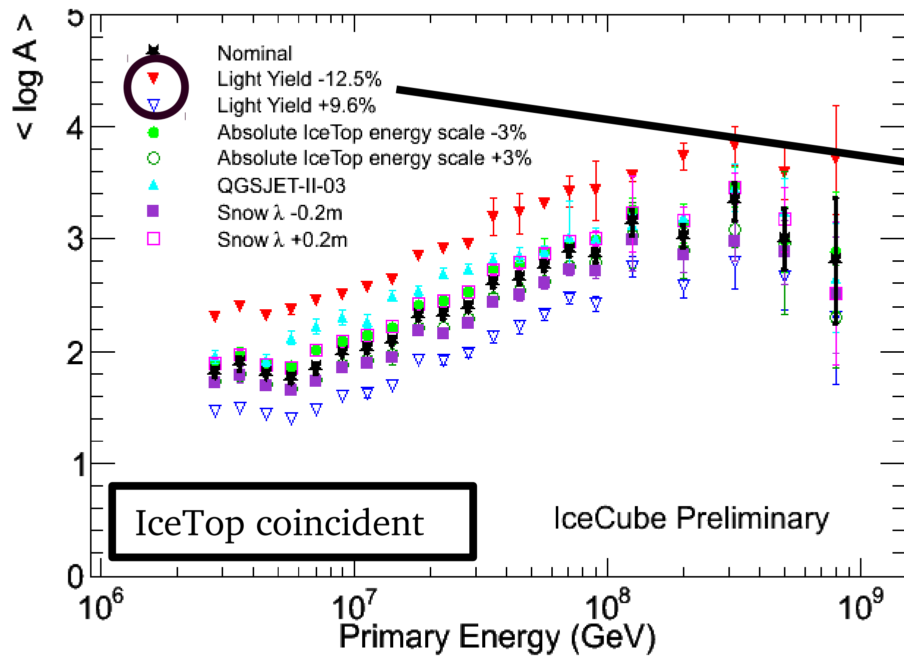




Surface Coincident Showers



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").

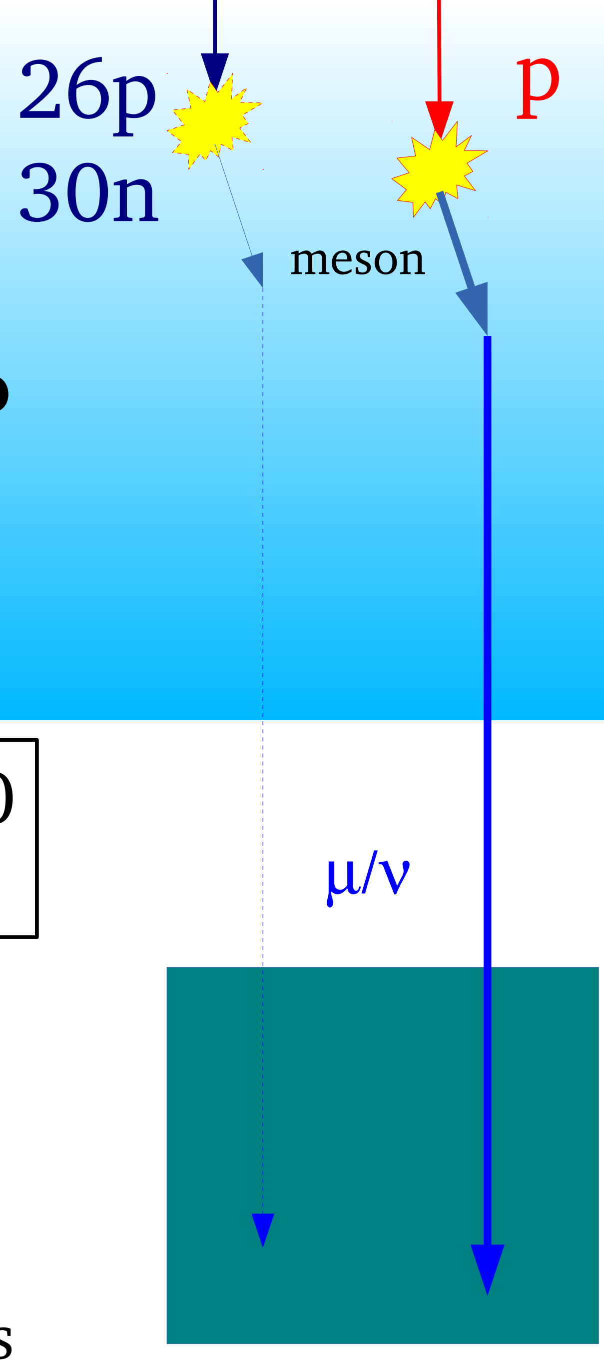
High-Energy Muon/Neutrino

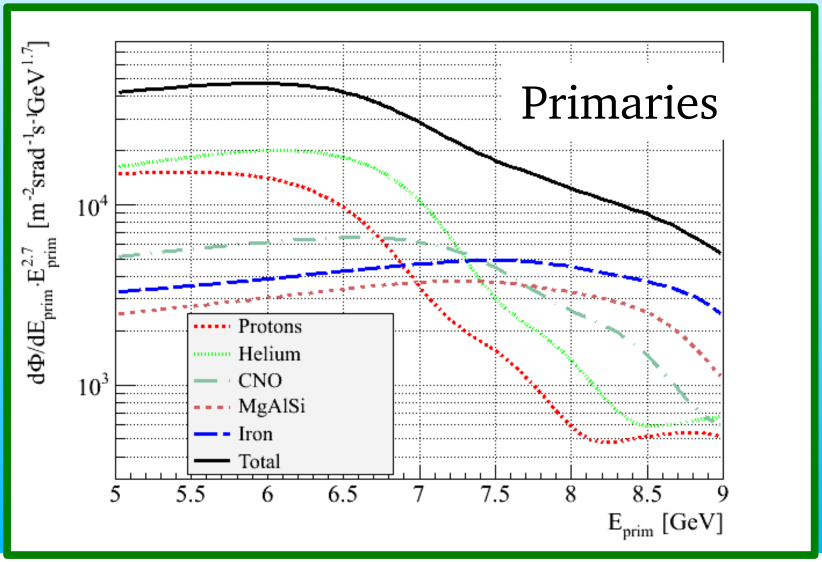
$$E_{nucleon}/E_{lepton} \simeq 10$$

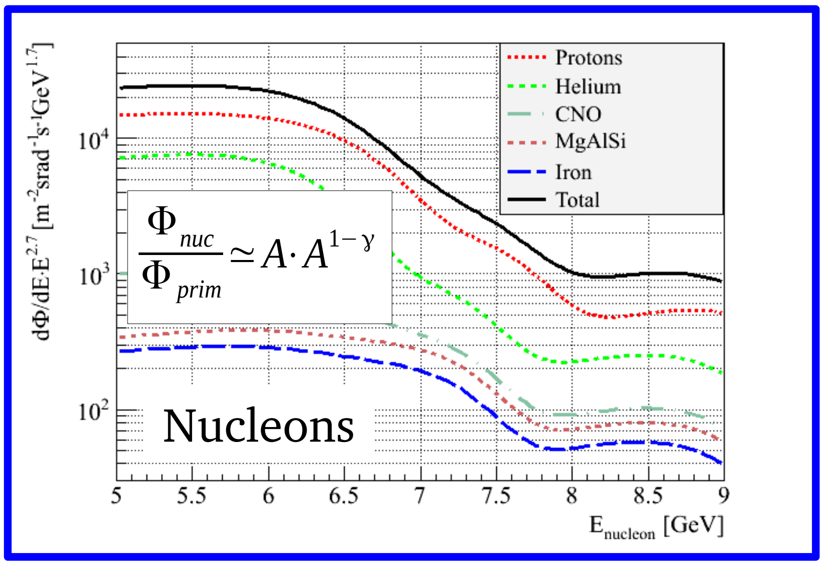
(e.g. T.K. Gaisser: CR&Part.Phys.)

Energy Spectrum follows **Nucleons**

Main contribution from **light** primaries



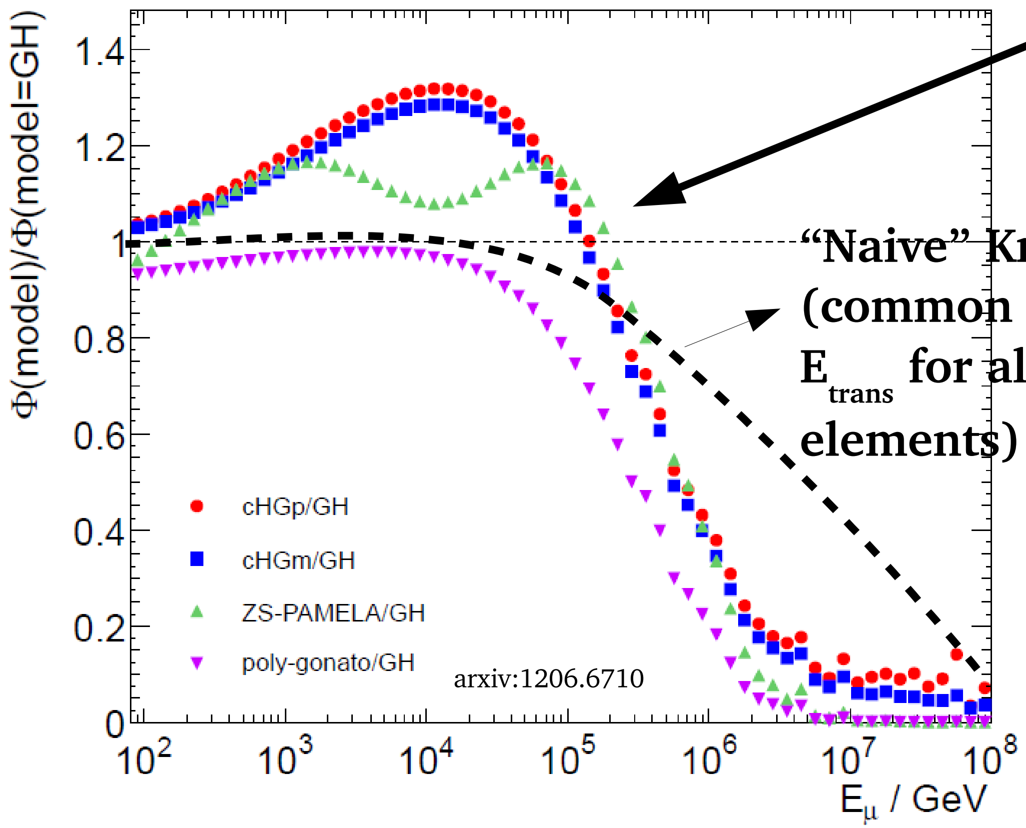




Example: Gaisser H3a

arxiv:1303.3565

CR Knee: Muon Spectrum



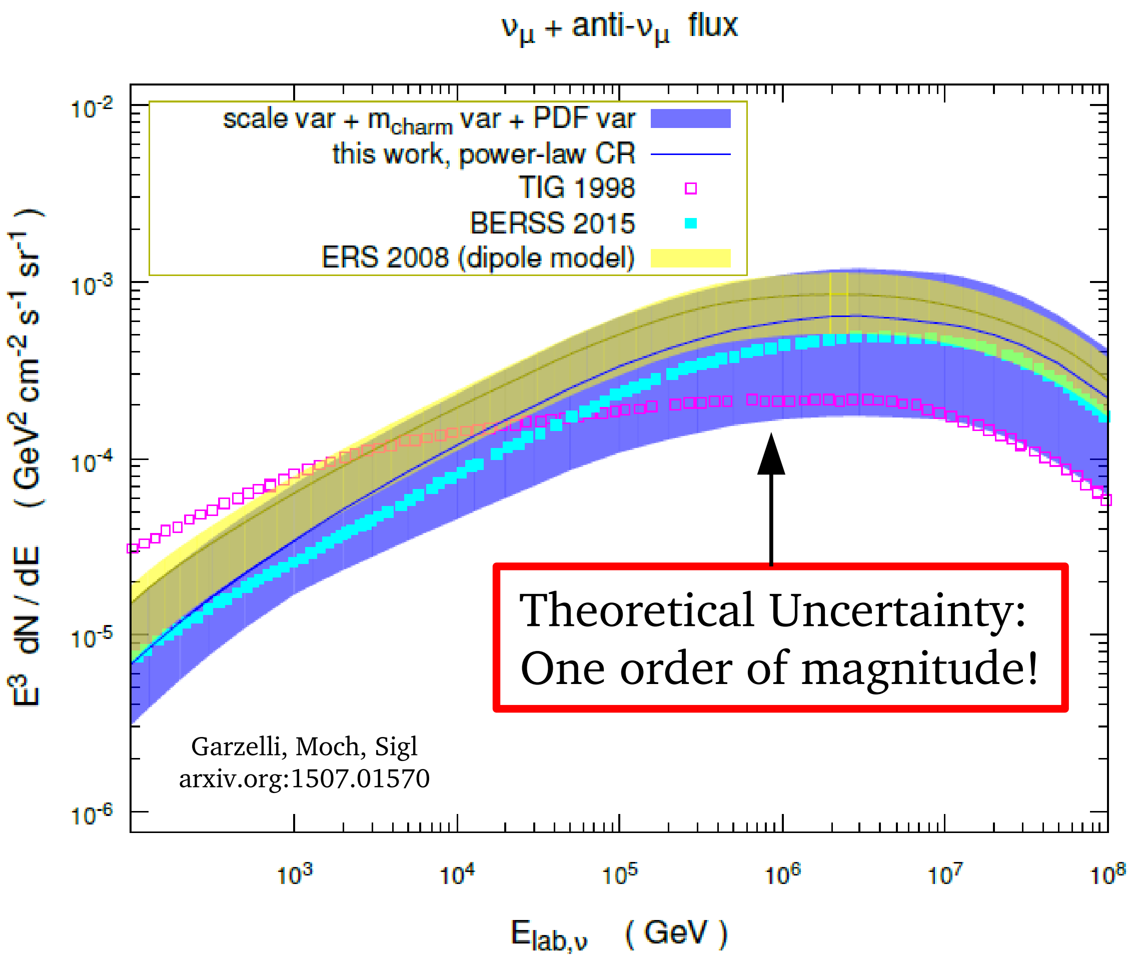
Sharp knee signature due to dependence on **nucleon** spectrum.
Directly related to cutoff!

H3a
H4a
Zatsepin-Sokolskaya
Poly-Gonato(Hoerandel)

Influence of primary CR model on muon and neutrino flux:

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

Prompt Lepton Flux

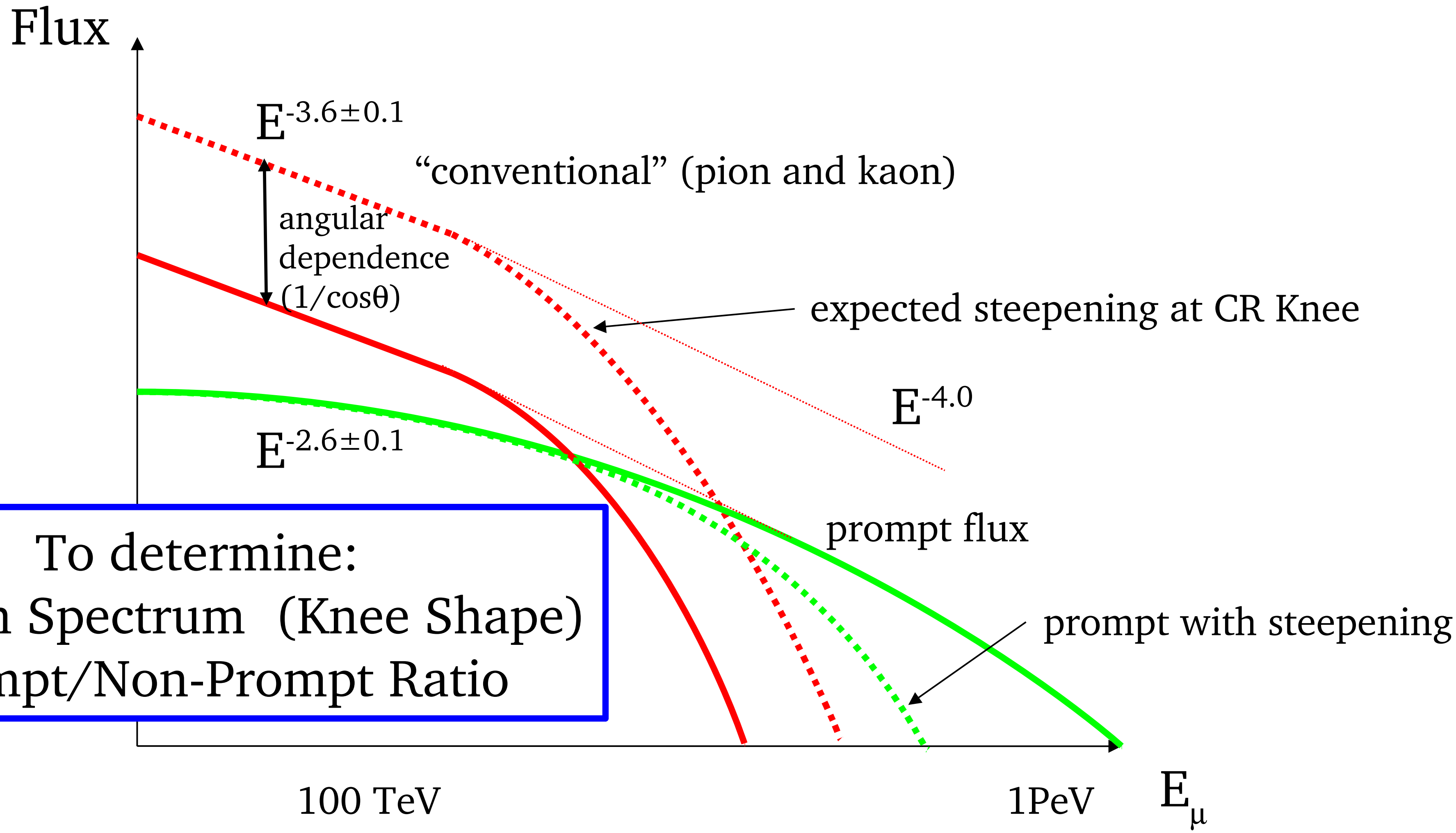


No attenuation due to re-interactions, therefore harder spectrum than “conventional” (π,K) component.

Neutrinos: Main contribution from charmed hadrons.
Muons: Additional flux from ϕ, ρ, $\eta \rightarrow \mu^+\mu^-$.

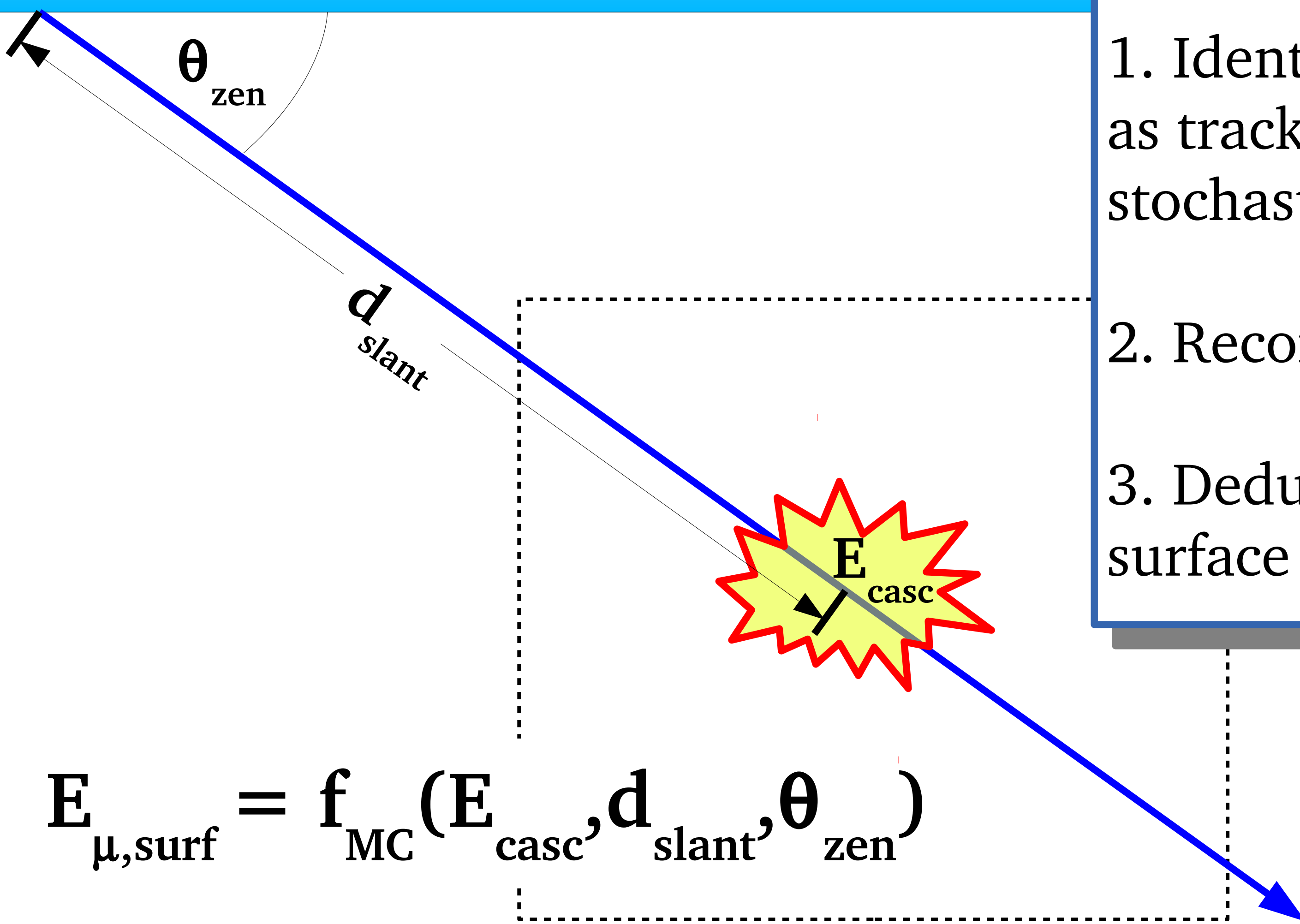
Forward production difficult to probe in colliders.

Muon Spectrum (Qualitative)



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

Analysis Strategy



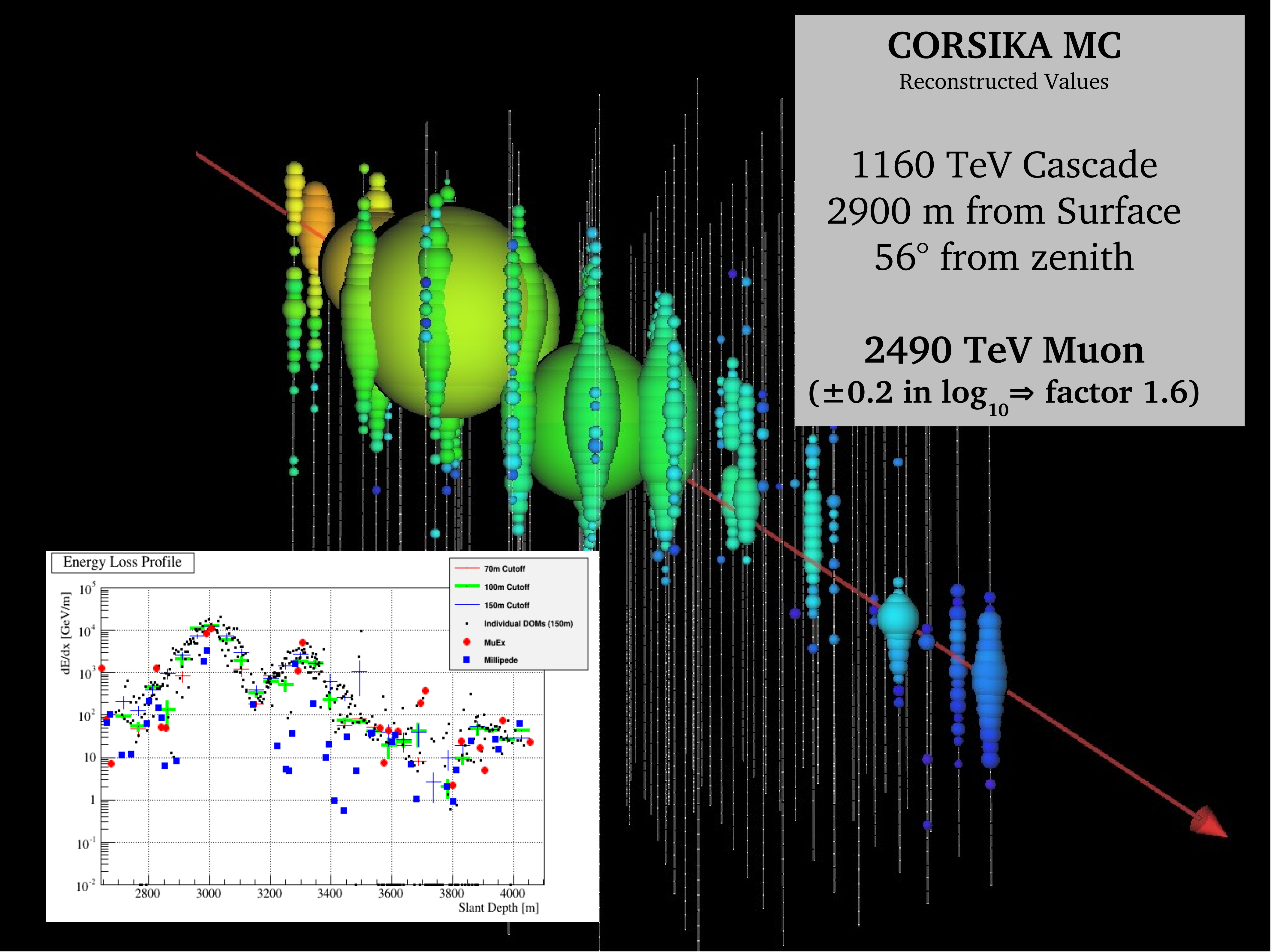
1. Identify HE muons as tracks with exceptional stochastic losses

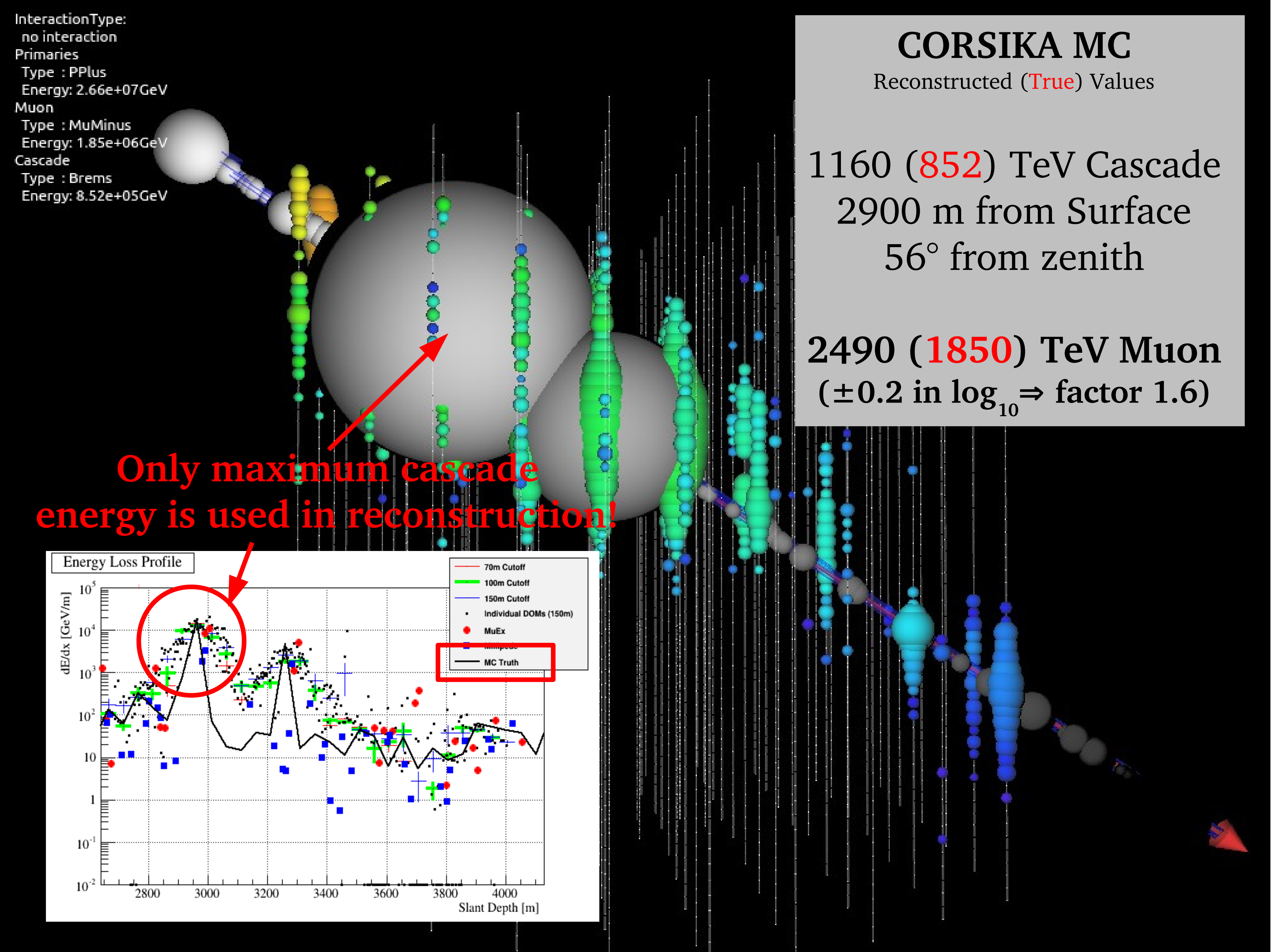
2. Reconstruct cascade energy

3. Deduce most likely muon surface energy from simulation

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

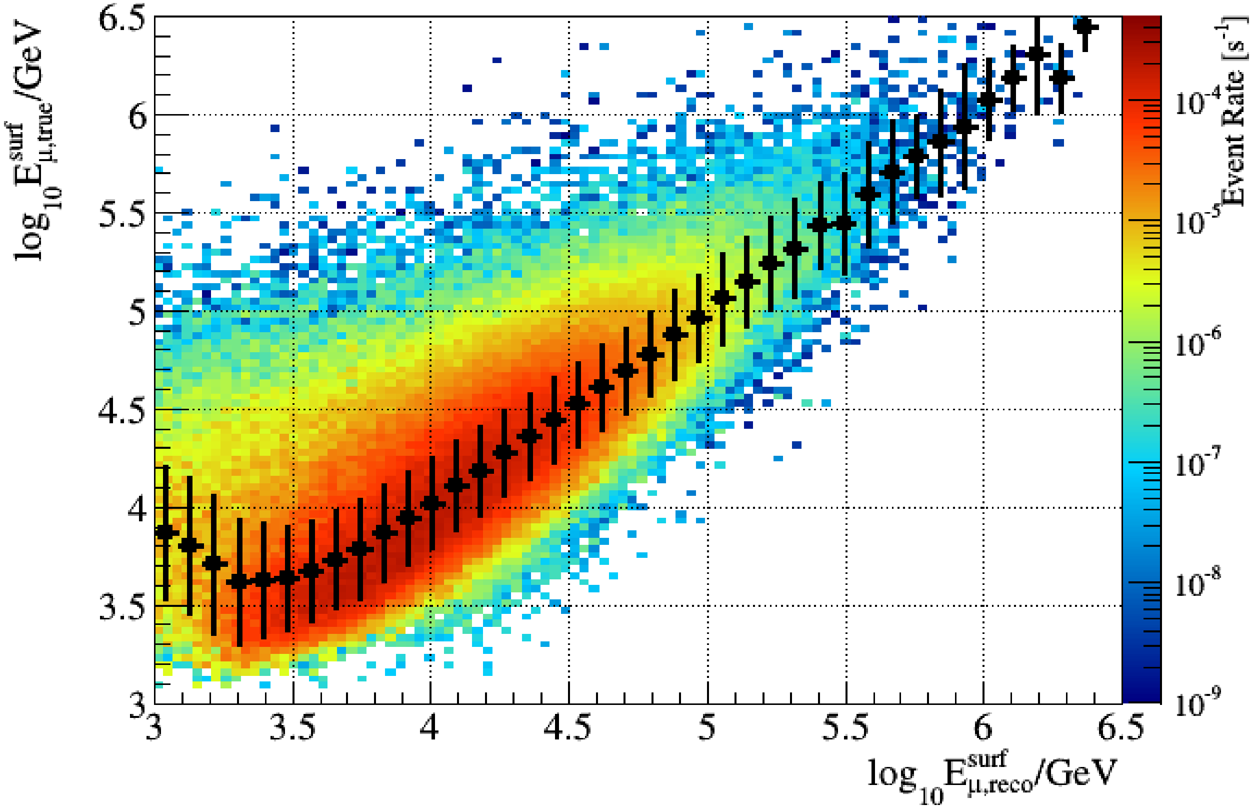
HE Cascade requires HE Muon


CORSIKA MC
Reconstructed Values
1160 TeV Cascade
2900 m from Surface
56° from zenith
2490 TeV Muon
(±0.2 in $\log_{10}$ ⇒ factor 1.6)
Energy Loss Profile
70m Cutoff
100m Cutoff
150m Cutoff
Individual DOMs (150m)
MuEx
Millipede
dE/dx [GeV/m]
Slant Depth [m]
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
2800
3000
3200
3400
3600
3800
4000

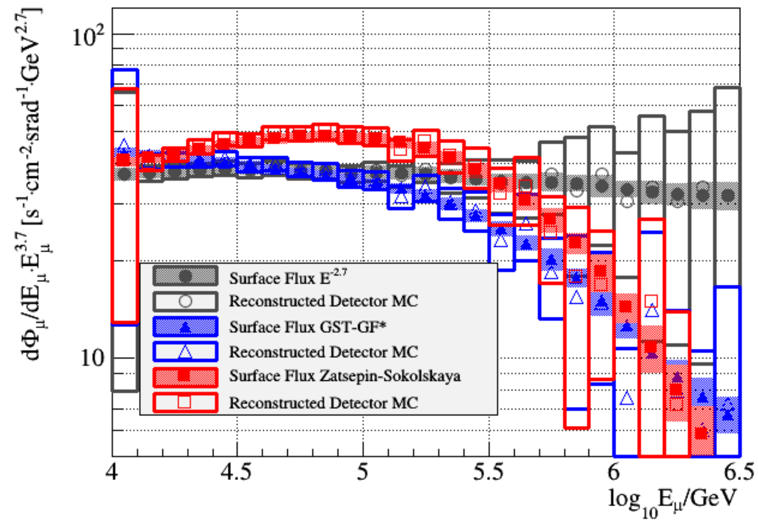


InteractionType:
no interaction
Primaries
Type : PPlus
Energy: 2.66e+07GeV
Muon
Type : MuMinus
Energy: 1.85e+06GeV
Cascade
Type : Brems
Energy: 8.52e+05GeV
CORSIKA MC
Reconstructed (True) Values
1160 (852) TeV Cascade
2900 m from Surface
56° from zenith
2490 (1850) TeV Muon
(±0.2 in log10 ⇒ factor 1.6)
Only maximum cascade
energy is used in reconstruction!
Energy Loss Profile
70m Cutoff
100m Cutoff
150m Cutoff
Individual DOMs (150m)
MuEx
MC Truth
dE/dx [GeV/m]
Slant Depth [m]

Surface Spectrum Reconstruction

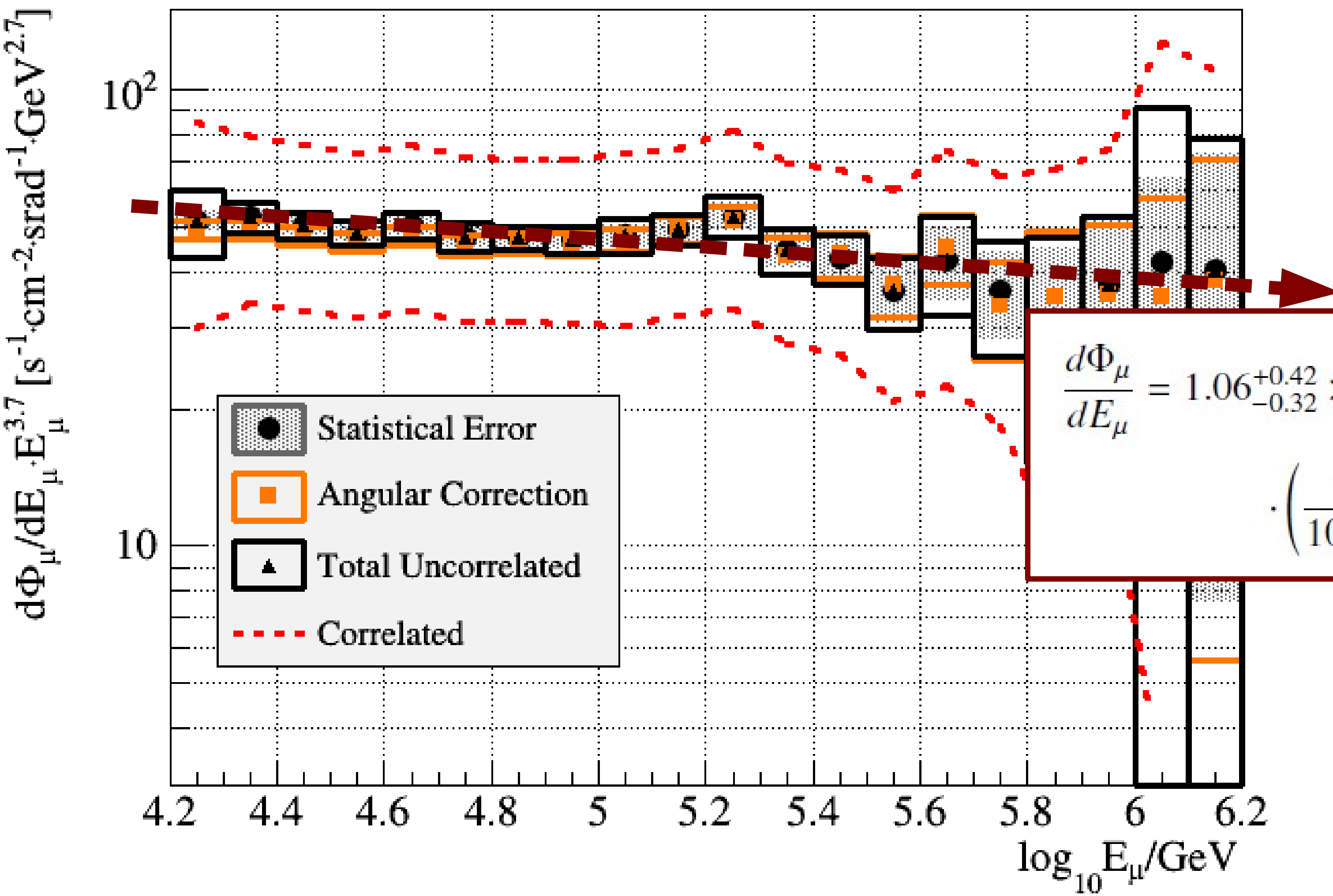


Muon Surface Energy:
Fully parameterized observable vs. True MC value
(Simulation weighted to $E^{-2.7}$ primary spectrum)



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

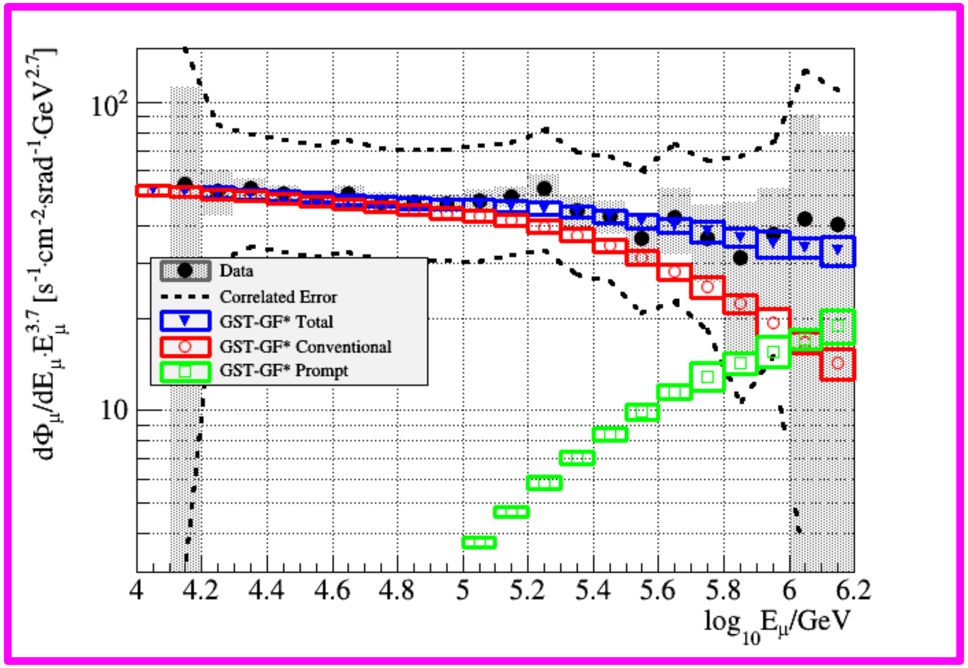
All-Sky Muon Energy Spectrum

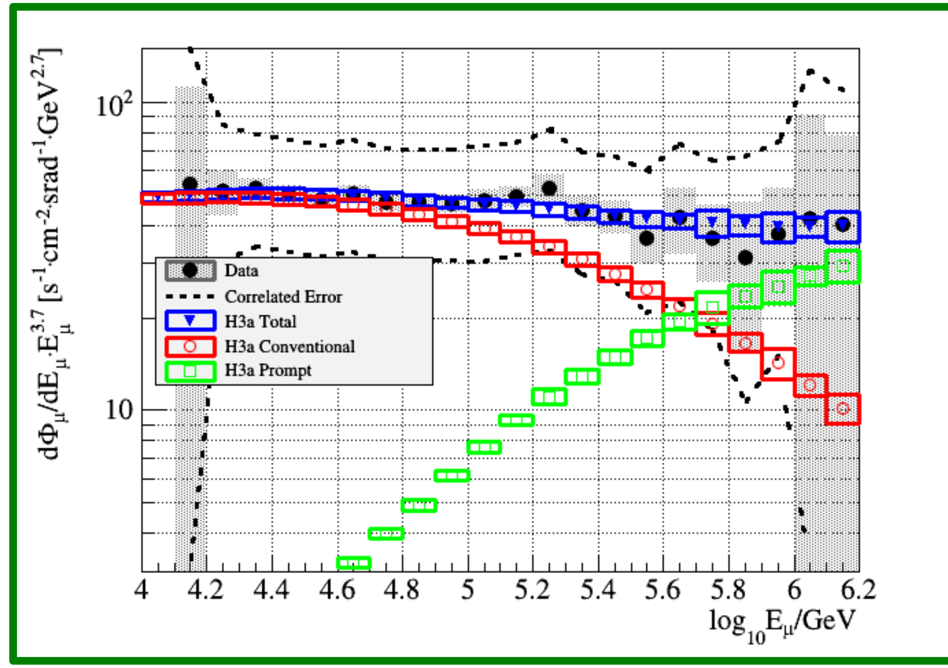


$$\frac{d\Phi_\mu}{dE_\mu} = 1.06^{+0.42}_{-0.32} \times 10^{-10} \mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{srad}^{-1}\mathrm{TeV}^{-1} \cdot \left(\frac{E_\mu}{10\ \mathrm{TeV}}\right)^{-3.78 \pm 0.02(stat.) \pm 0.03(syst.)}$$

Approximately power law with index -3.78

All-Sky Energy Spectrum: Prompt

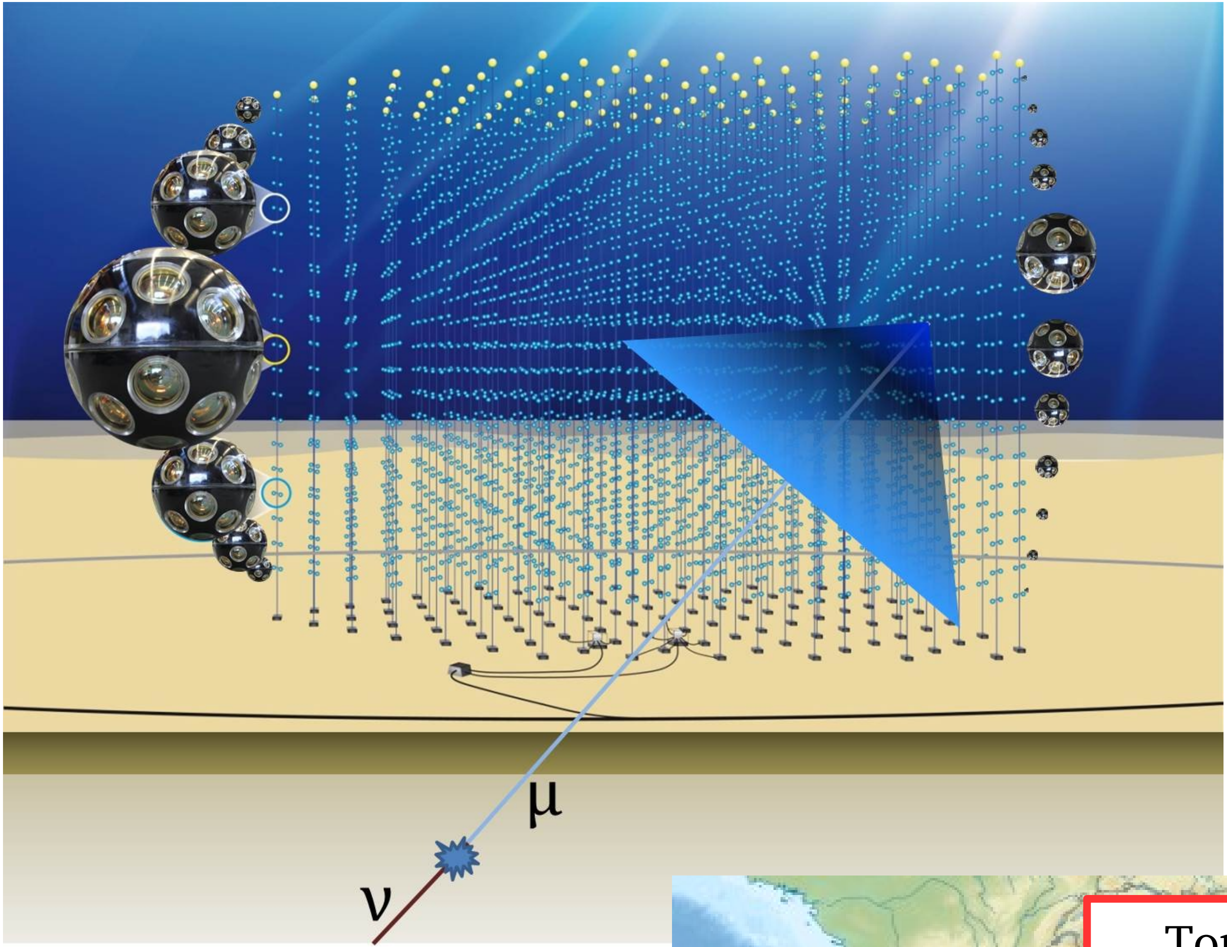




CR Model	Best Fit (ERS)	1σ Interval (90% CL)	Pull ($\Delta\gamma$)	$\sigma(\Phi_{Prompt} > 0)$
GST-Global Fit [11]	2.14	1.27 - 3.35 (0.77 - 4.30)	0.01	2.64
H3a [11]	4.75	3.17 - 7.16 (2.33 - 9.34)	-0.03	3.97

[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.

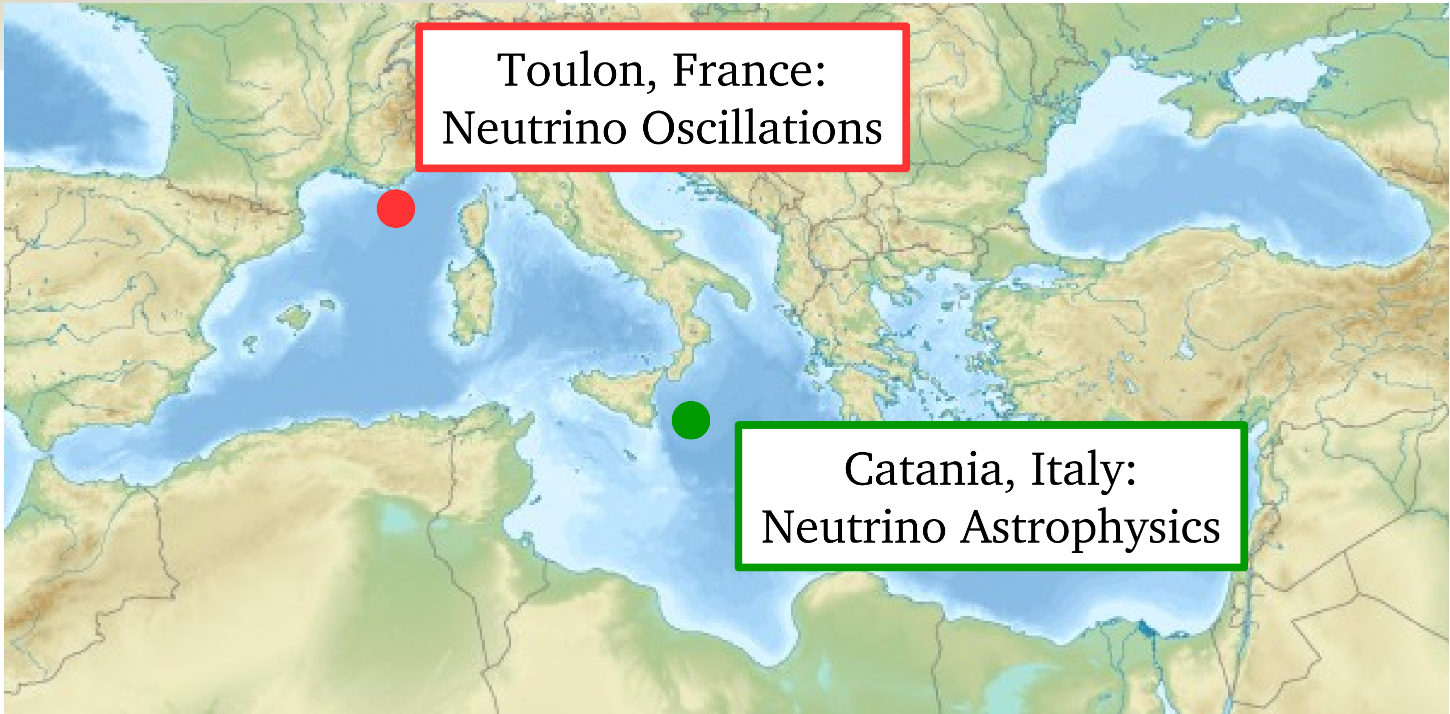


KM3NeT

(Under Construction)

Water-based: Less Light Scattering, homogeneous medium

"Multi-PMTs": 4π acceptance



Very good perspectives for CR Physics!

Summary:

Large-Volume Detectors present new opportunity for CR Physics

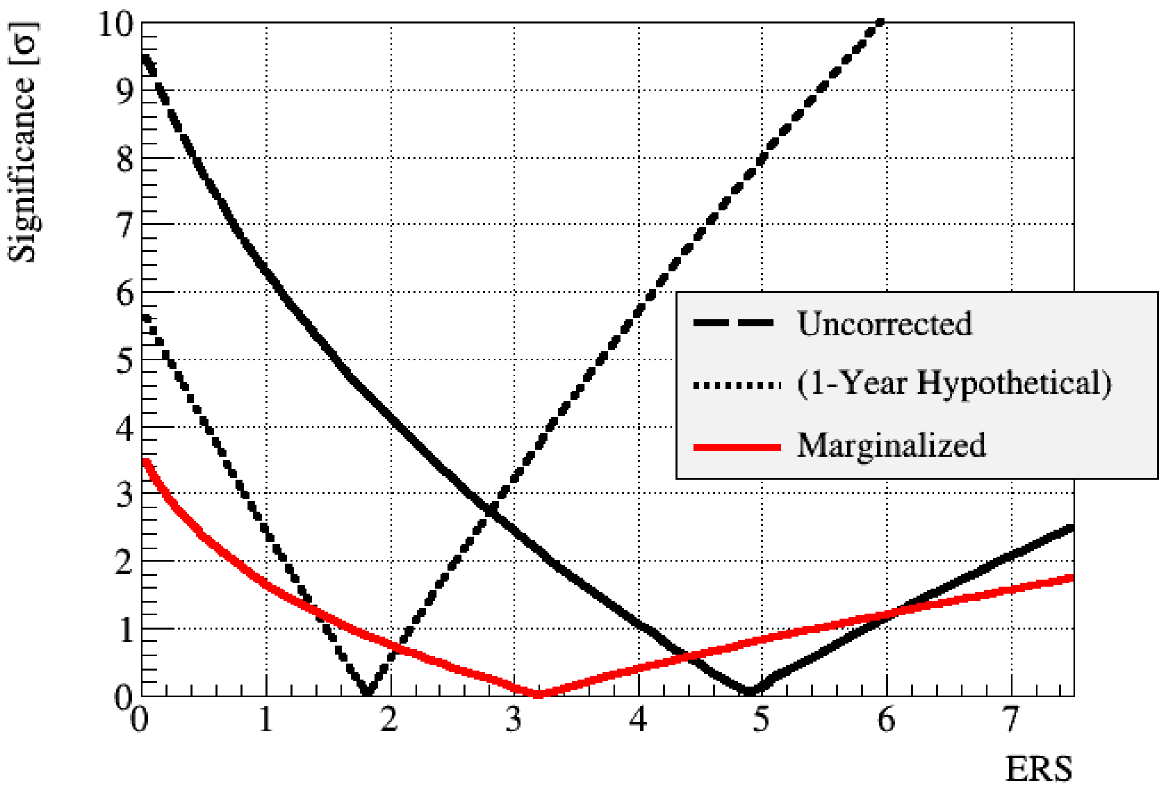
Composition investigations possible without surface array

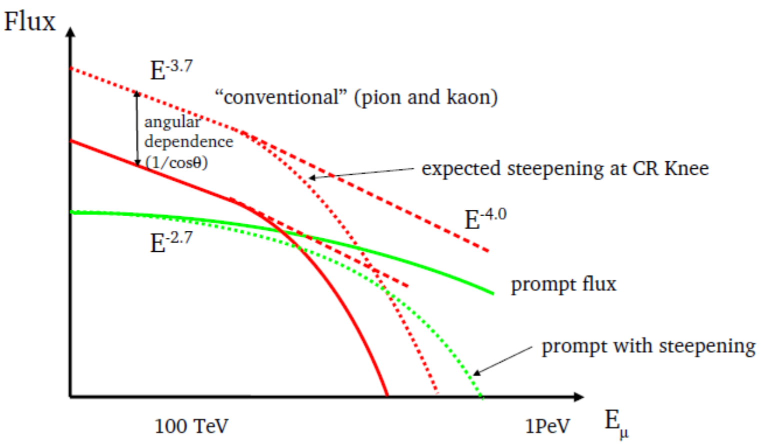
IceCube results cover knee, region between “heavy knee” and ankle

Additional implications for particle physics

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

Angular Dependence: Prompt

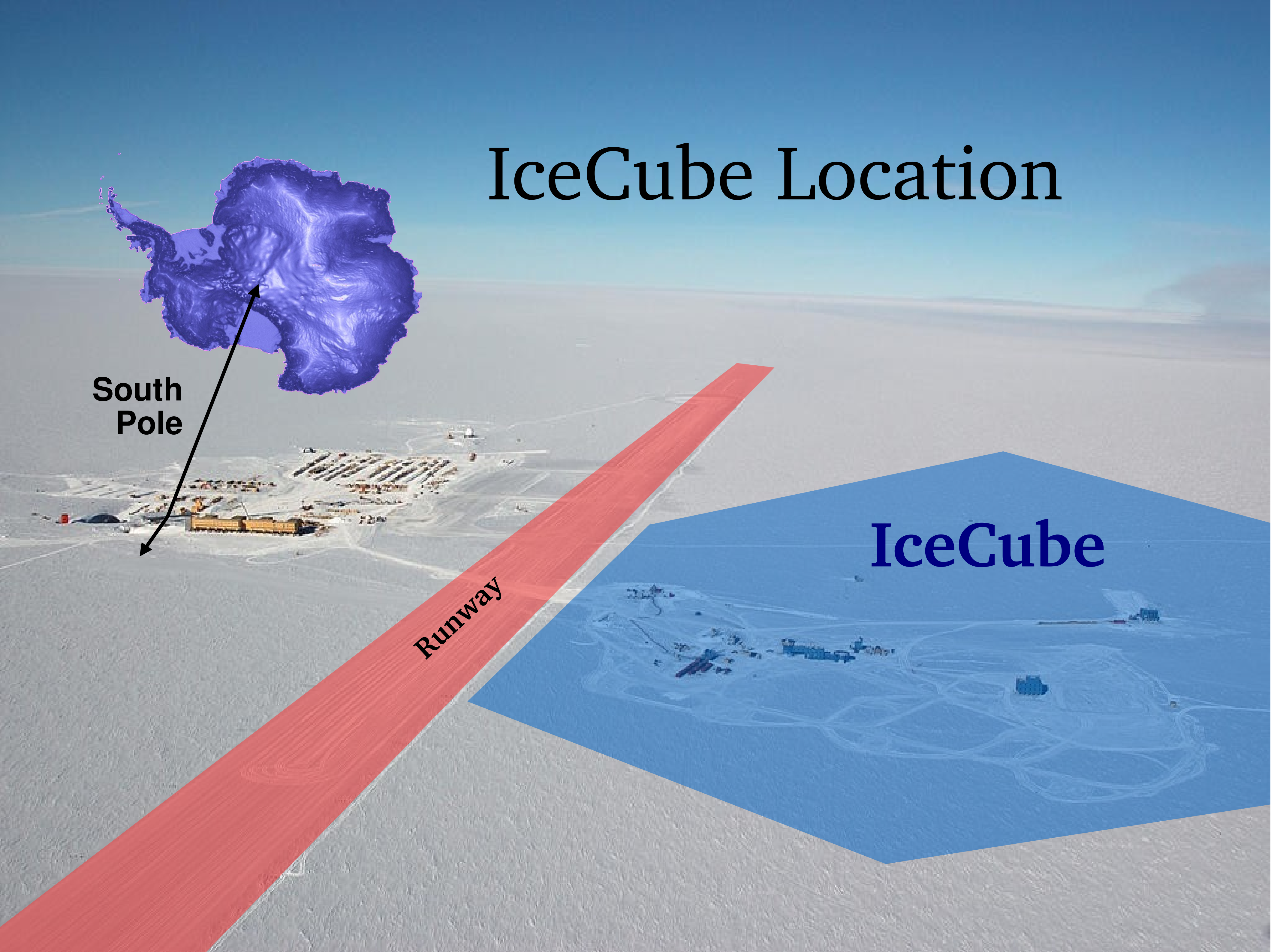




Model-independent measurement of prompt flux using angular distribution requires accounting for systematic uncertainties using statistical technique ("**marginalization**").

Prompt flux measurement, CR flux constraint are (currently) limited by detector systematics!

IceCube Location

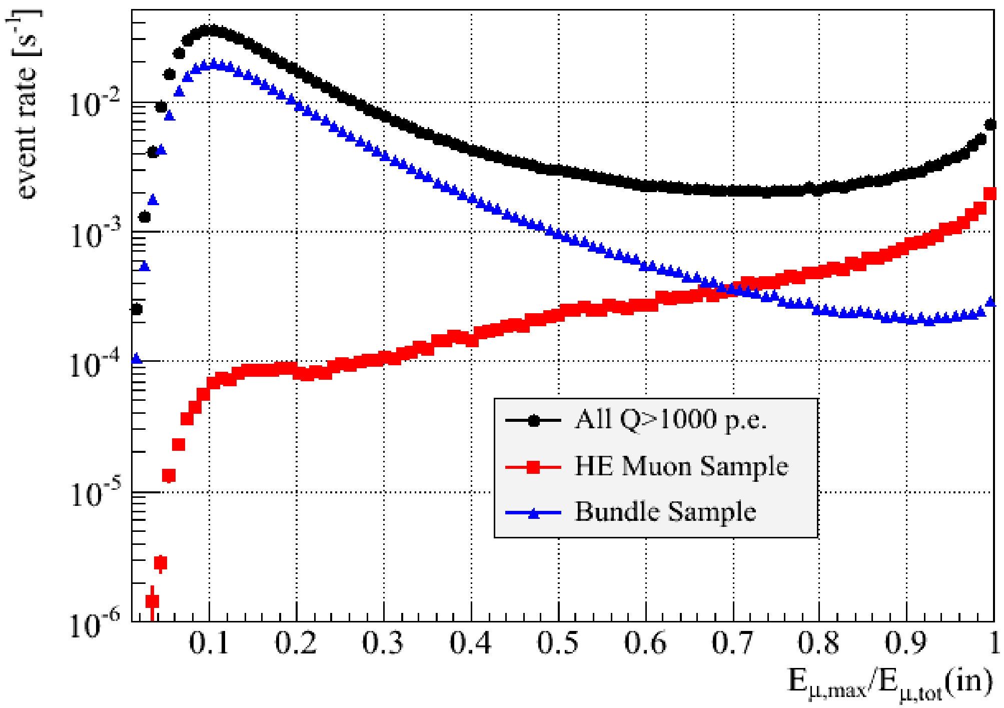


The IceCube Collaboration

Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Energy Carried by Leading Muon

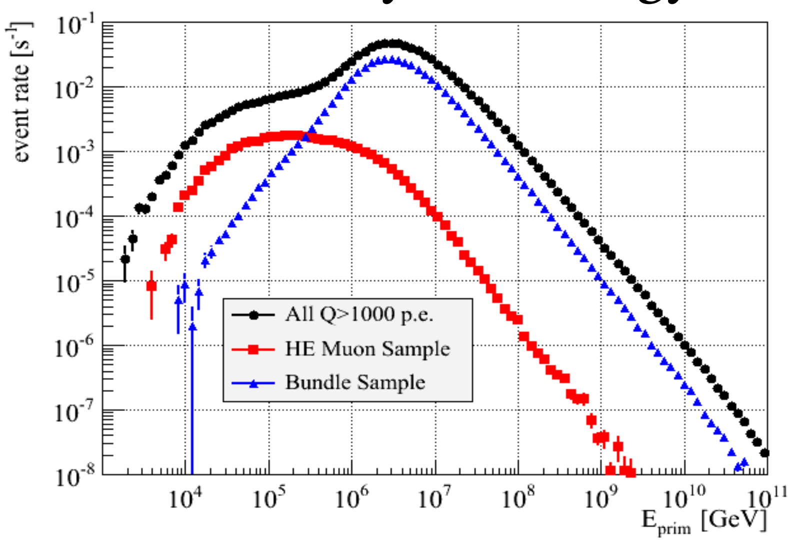


Final Cut Level: True MC Distributions

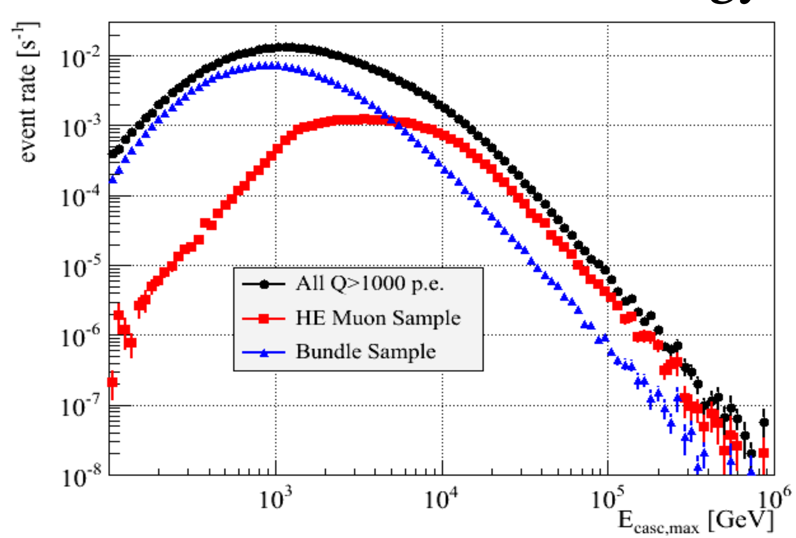
HE Muons

Bundles

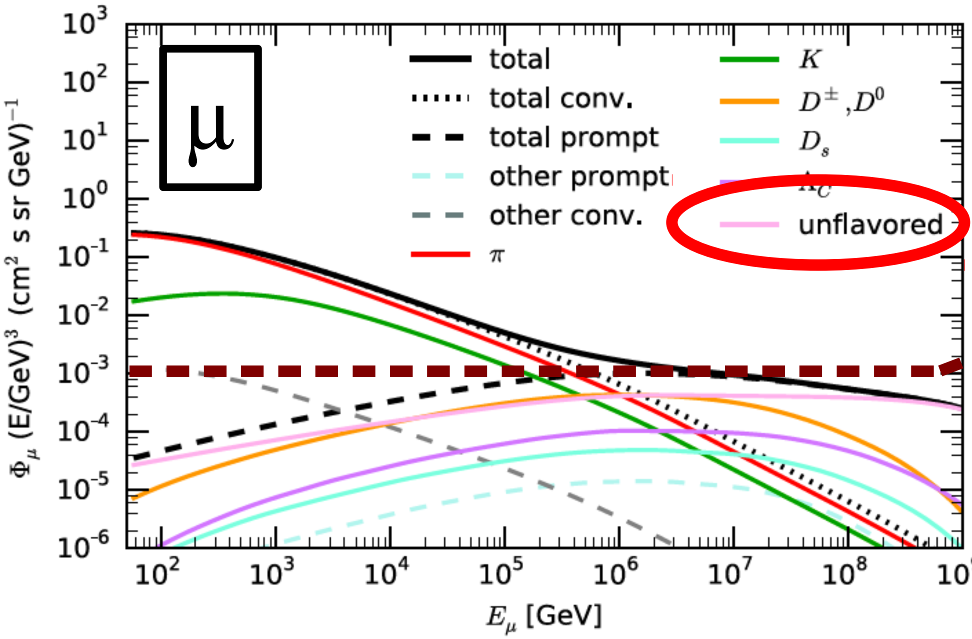
Primary CR Energy

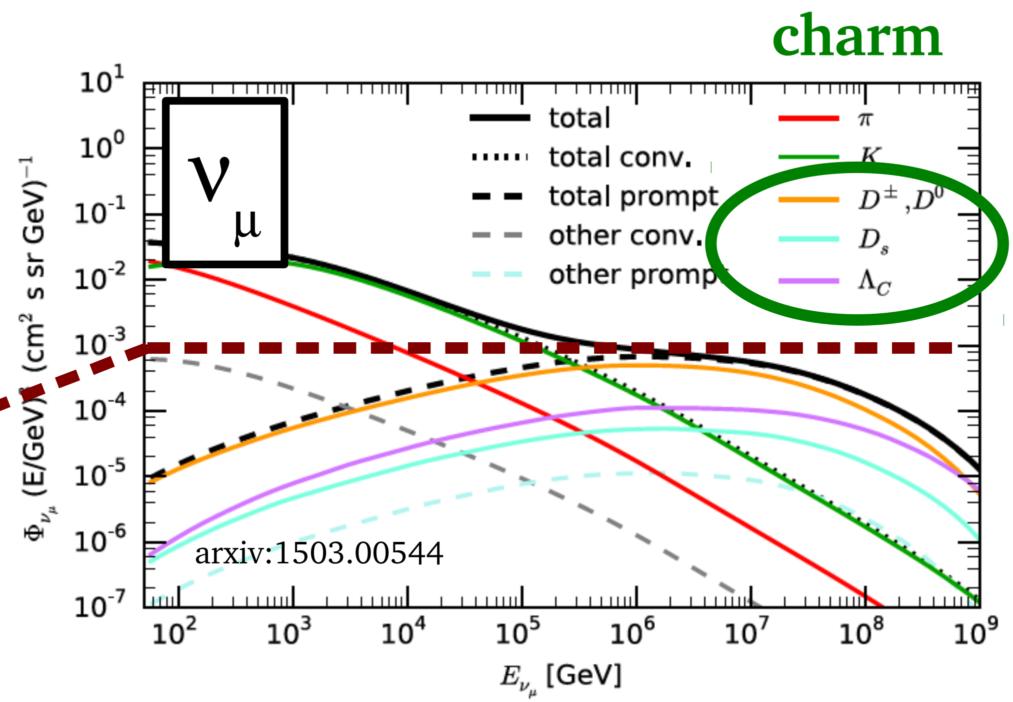


Stochastic Cascade Energy



Prompt Leptons





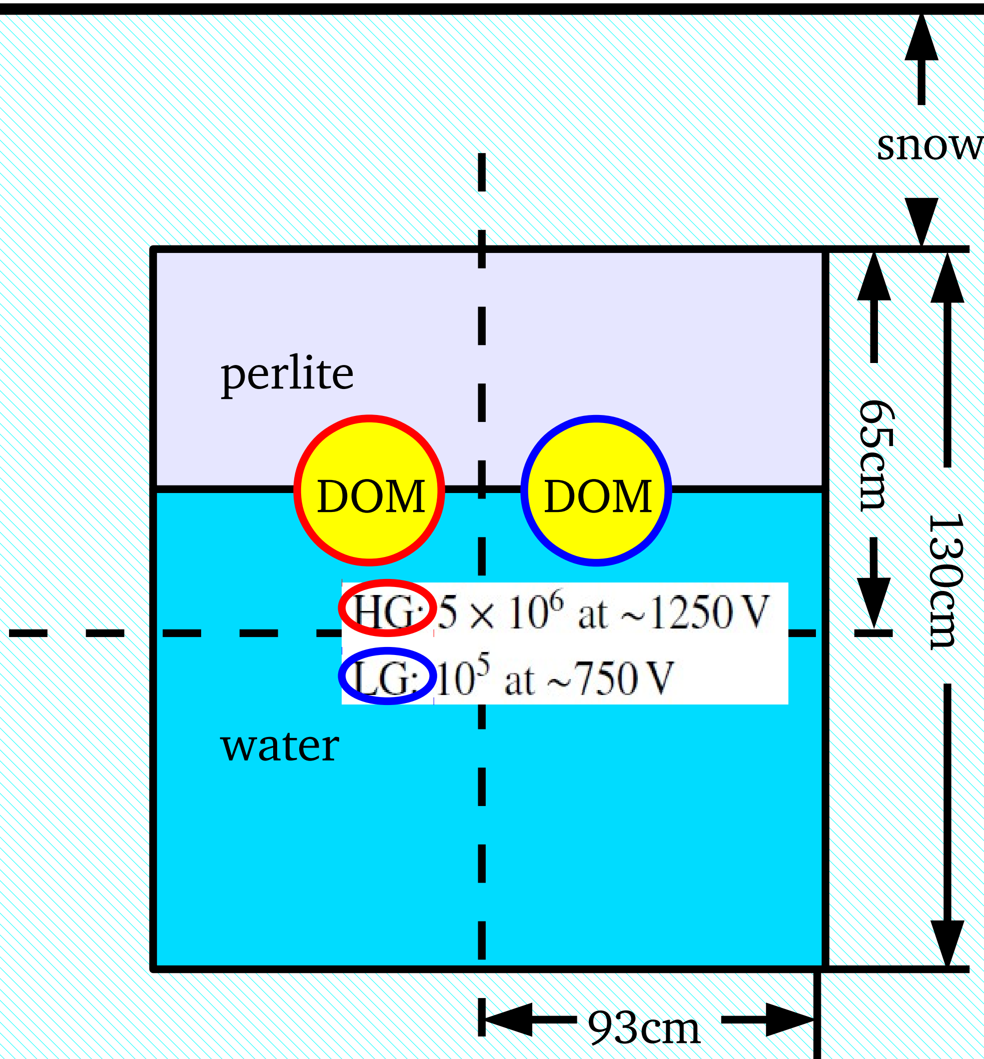
Muons can be produced in decays of light vector mesons (η,η′,ρ,ω,ϕ)

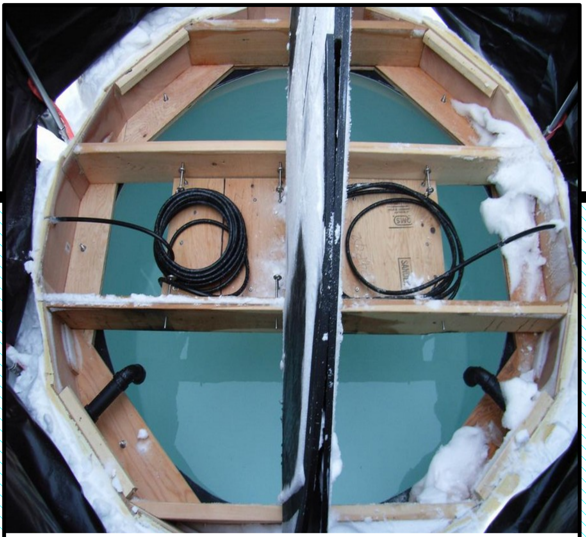
Newest charm prediction is lower than shown above (arxiv:1502.01076)

Muon Prompt Flux might be predominantly unflavored


Temporary Cover
2 Tanks per Station
Freezing Unit
IceTop

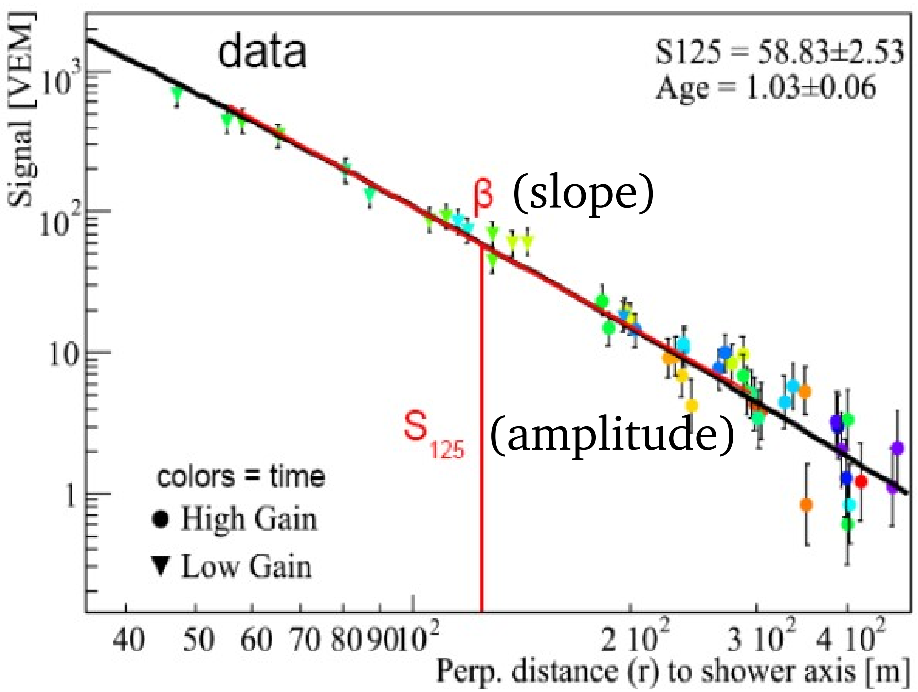
IceTop Tank




view from above, unfrozen

x2 x81

IceTop Shower Reconstruction



Lateral shower profile at 125m

$$S(r) = S_{125}\left(\frac{r}{125m}\right)^{-\beta-\kappa\log_{10}\left(\frac{r}{125m}\right)}$$

S_{125} : signal at r = 125m

β : slope at r = 125m

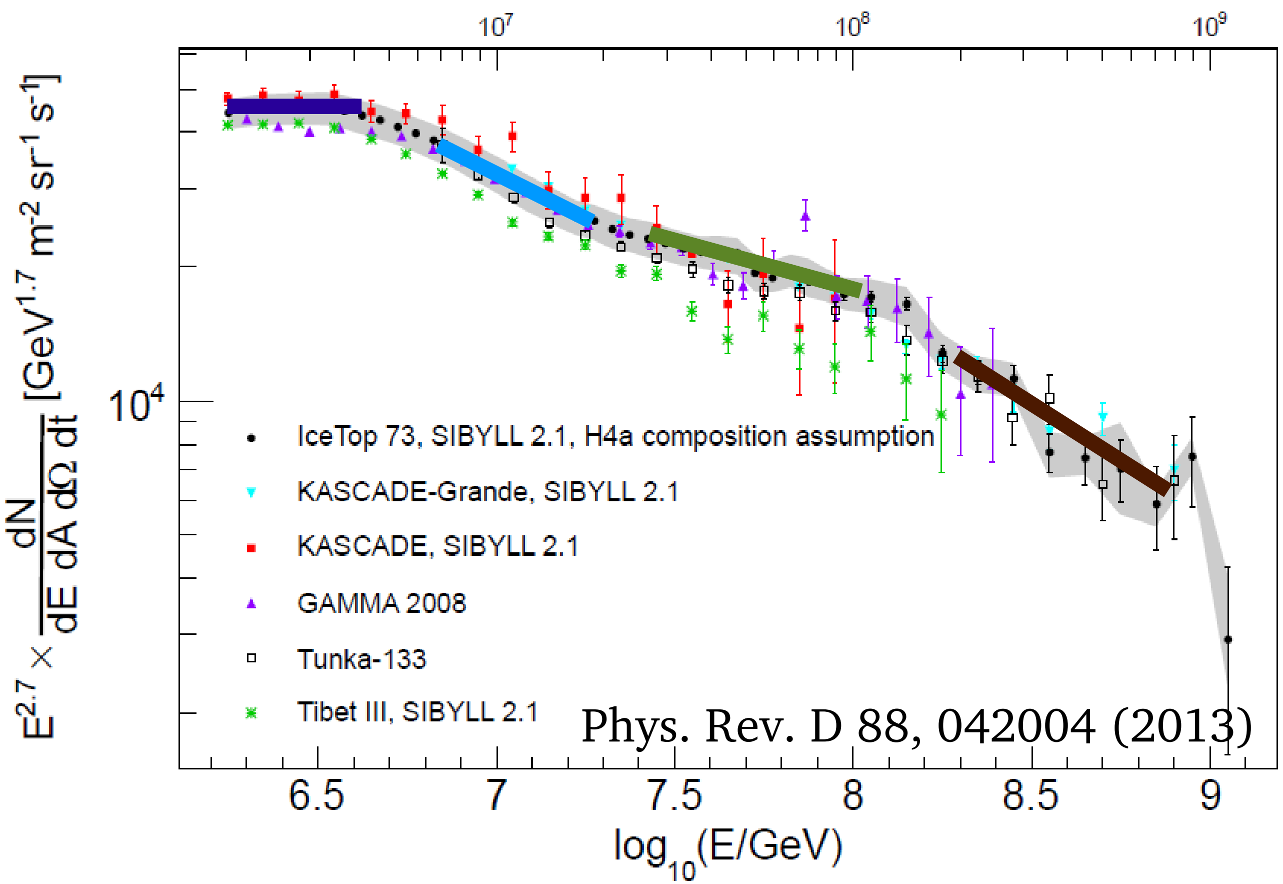
κ = 0.303 fixed

arXiv: 0711.0353

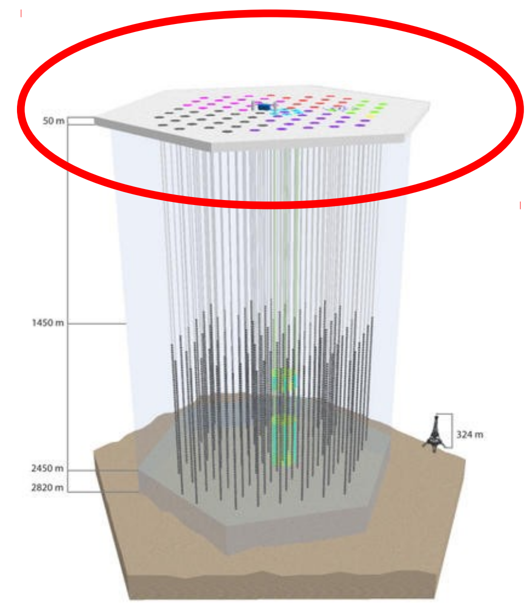
$E_{prim} = f(S_{125}, \theta_{zen})$

“Double-Logarithmic Parabola”:
Simulation-derived empirical description

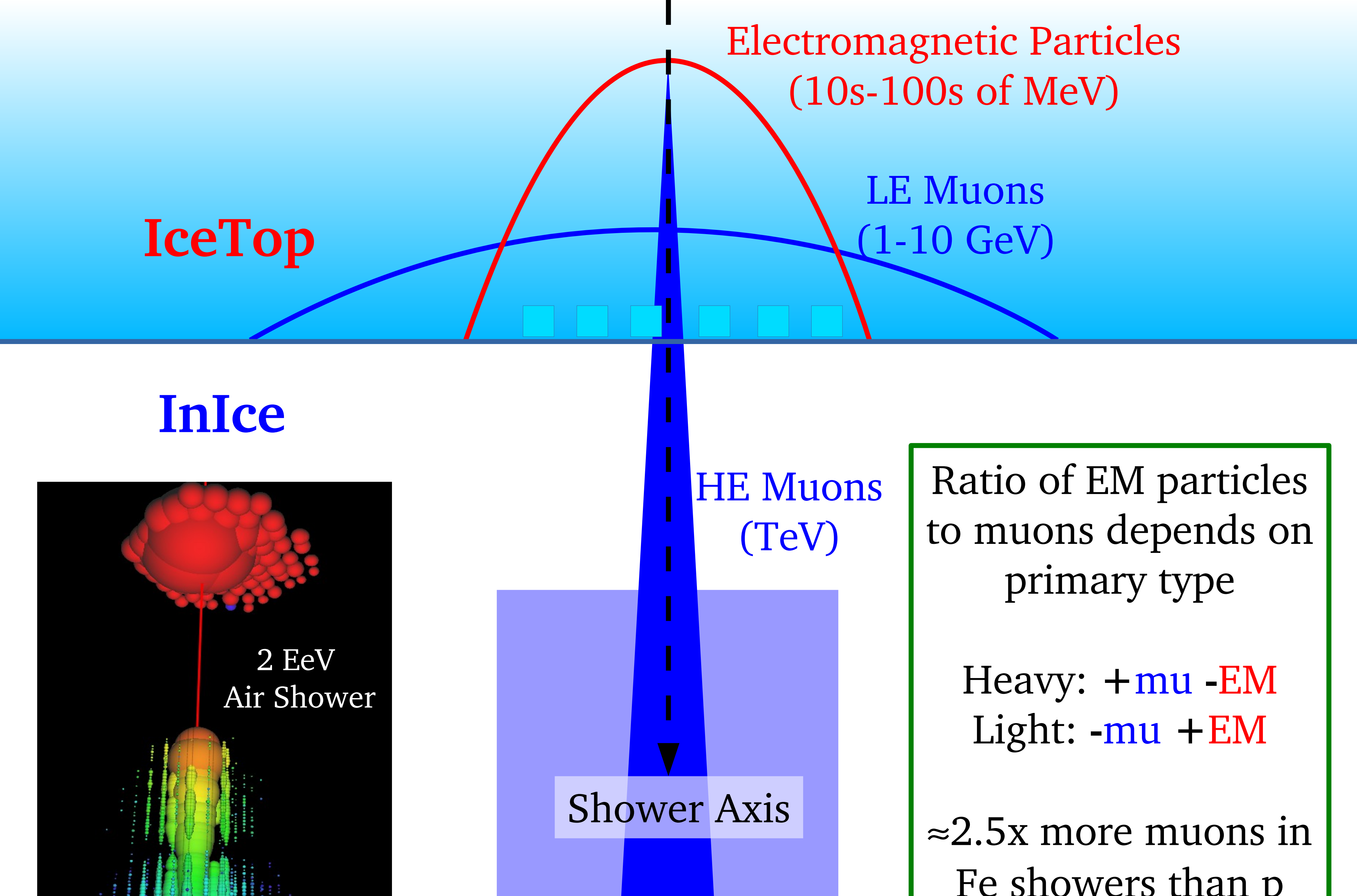
IceTop Data



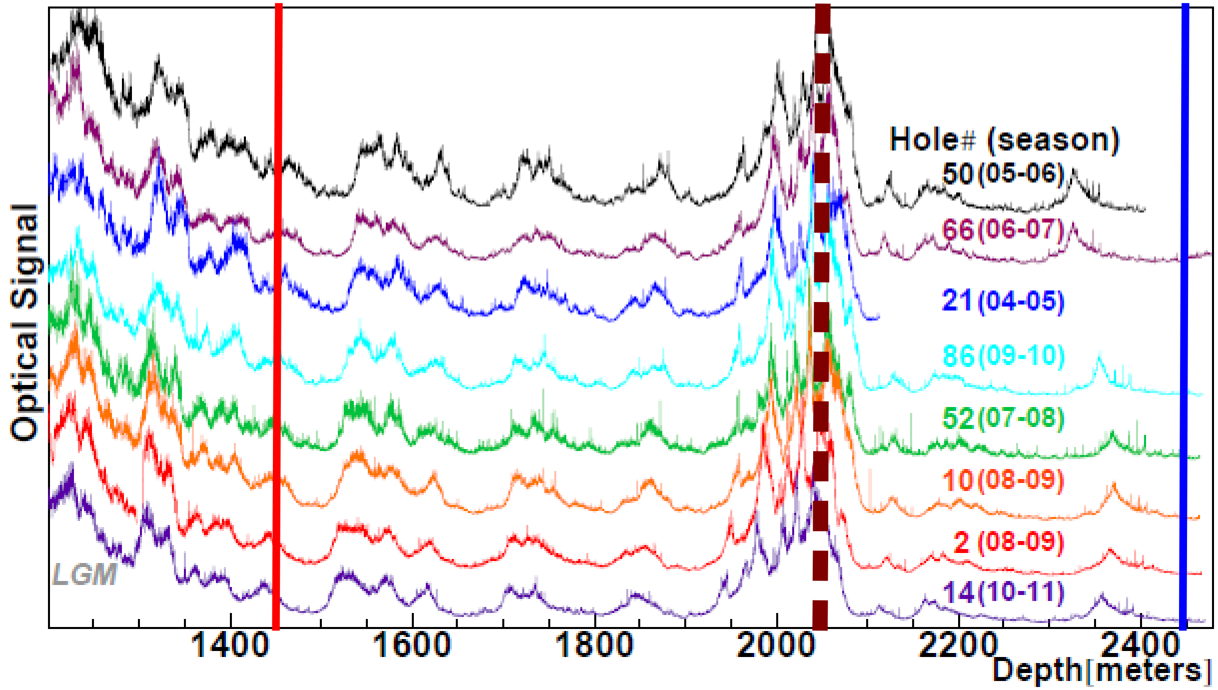
IceTop Only

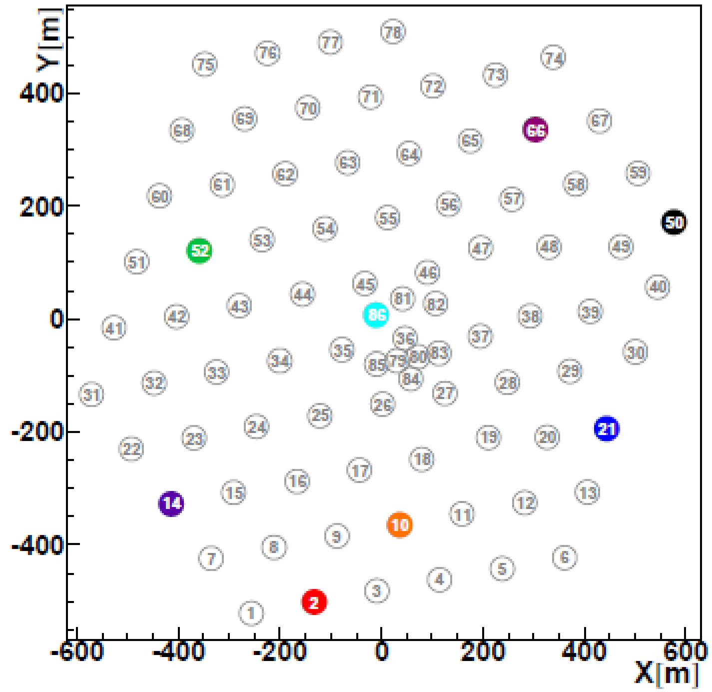


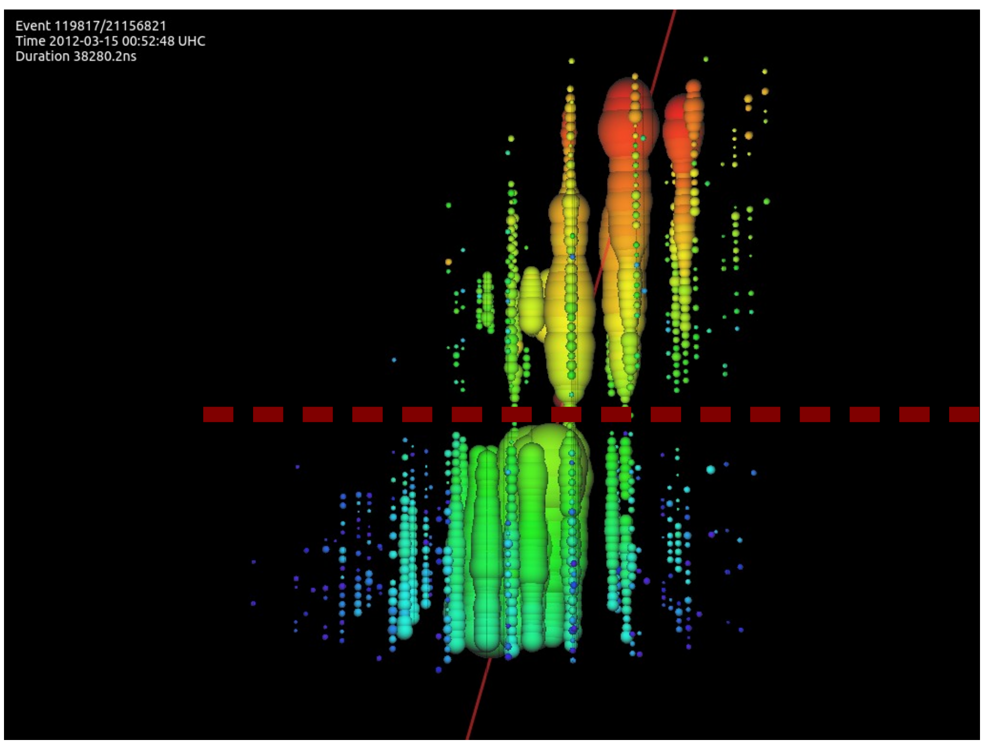
E range	$\mathbf{I_0} \pm$ stat.	$\gamma \pm$ stat. $\pm$ sys.	χ^2/ndf
6.20–6.55	$(2.107 \pm 0.06) \times 10^4$	$2.648 \pm 0.002 \pm 0.06$	206/2
6.80–7.20	$(3.739 \pm 0.34) \times 10^7$	$3.138 \pm 0.006 \pm 0.03$	14/6
7.30–8.00	$(7.494 \pm 1.29) \times 10^5$	$2.903 \pm 0.010 \pm 0.03$	19/12
8.15–8.90	$(4.952 \pm 1.65) \times 10^9$	$3.374 \pm 0.069 \pm 0.08$	8/6



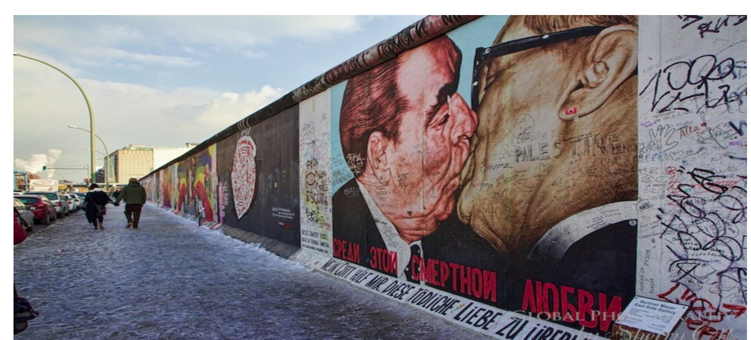
$$N_\mu \propto A^{1-\alpha} \cdot E_{\mathrm{prim}}^{\alpha}$$



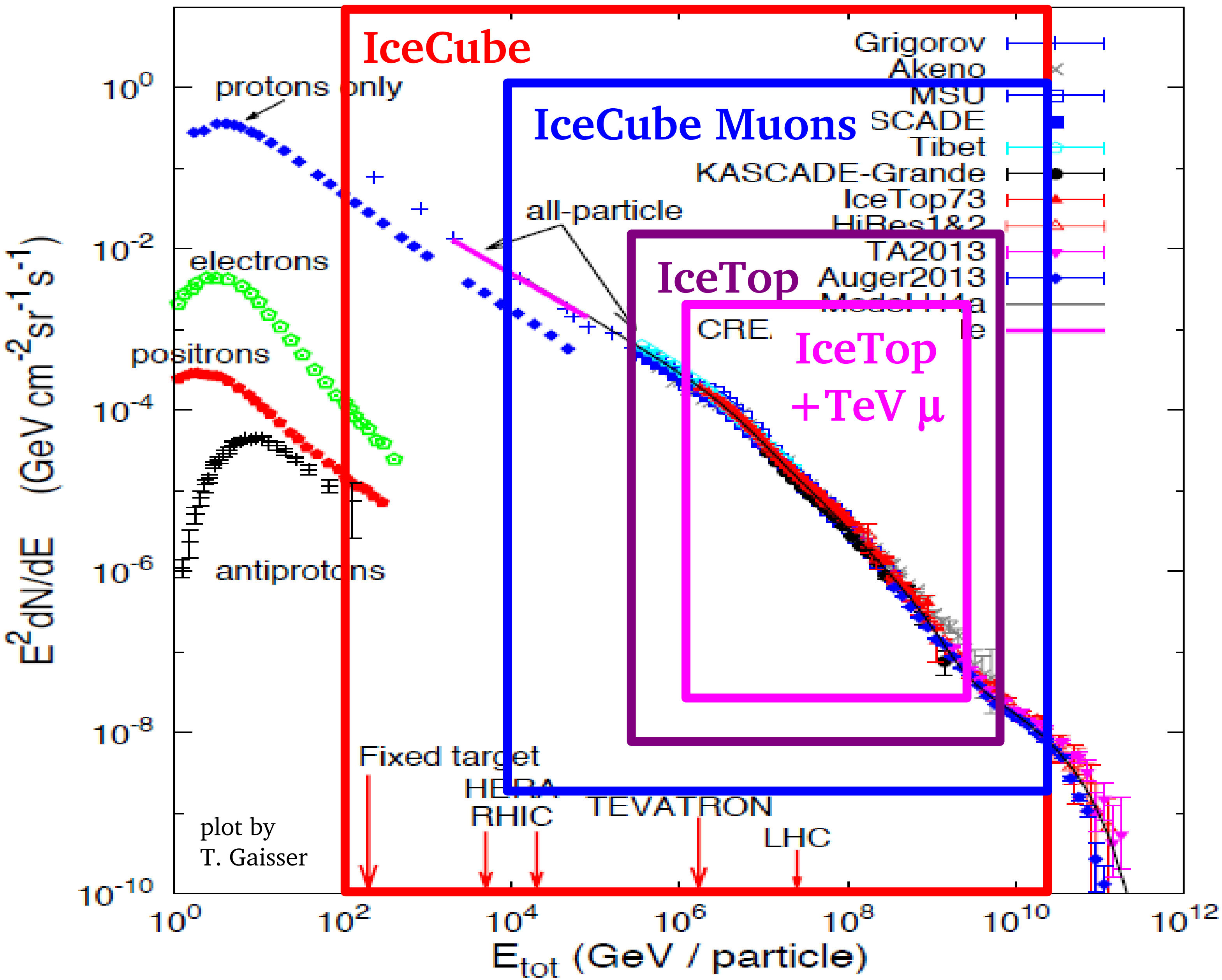




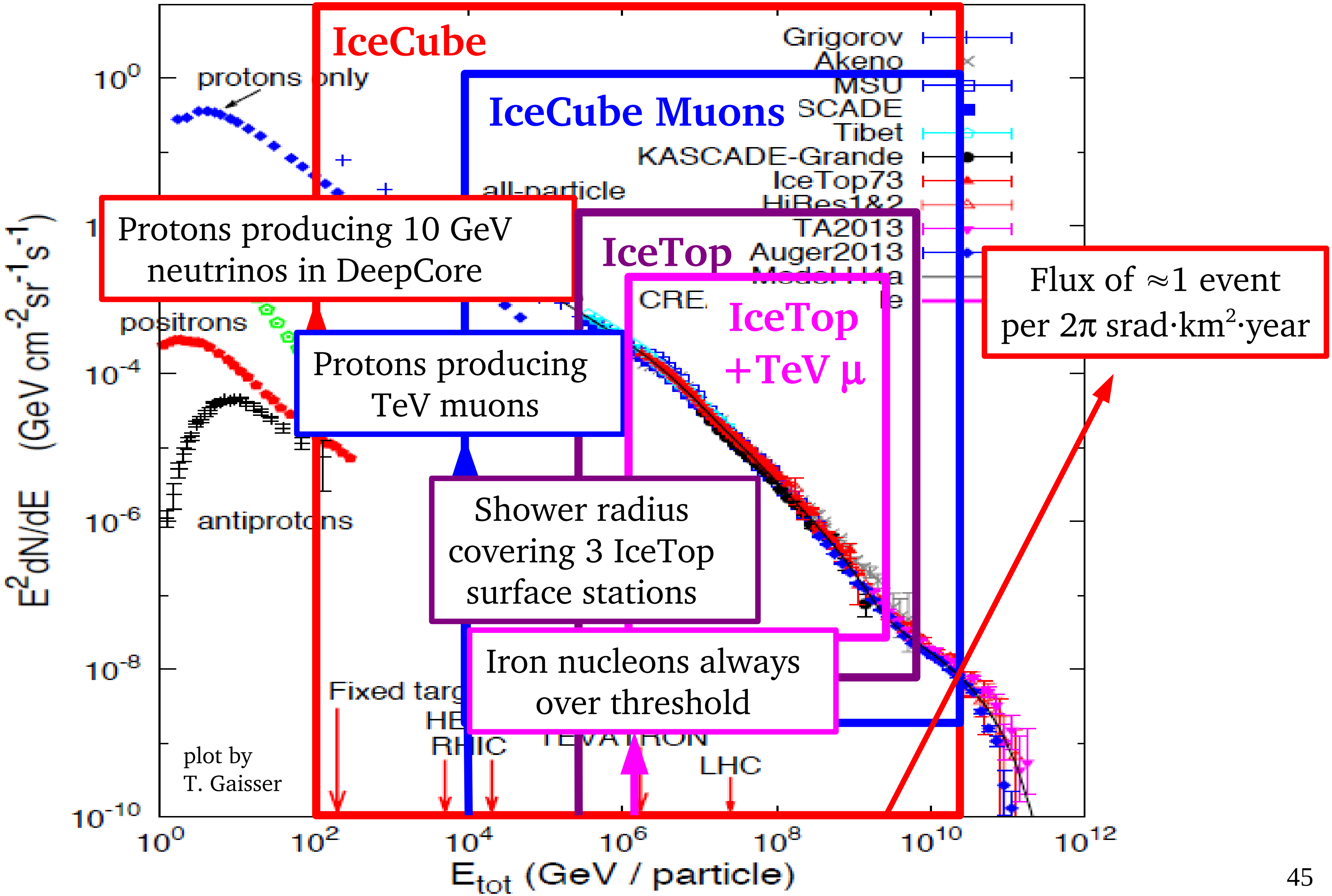
“Dust Layer”:
Impenetrable wall dividing
detector into two parts!

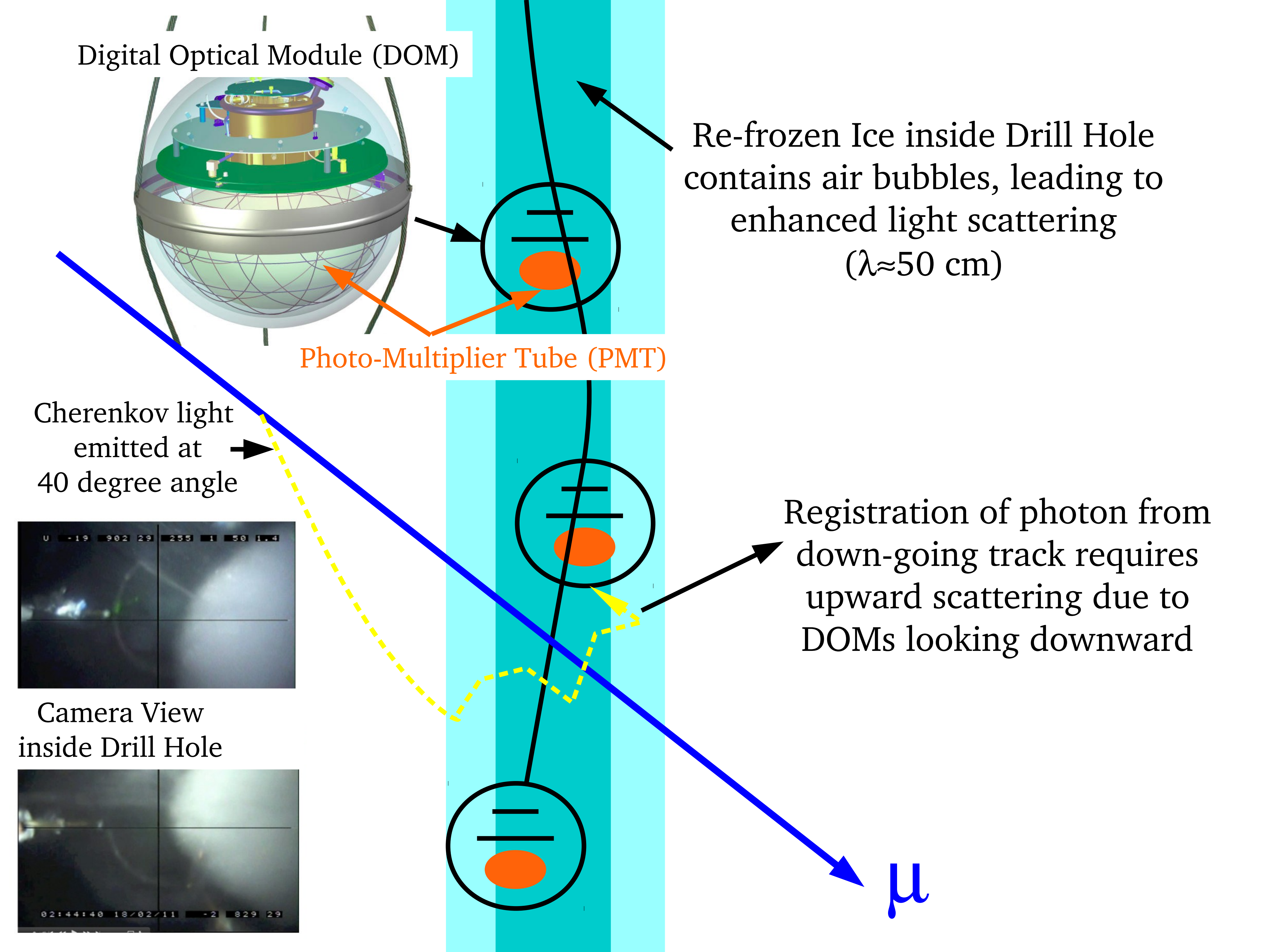


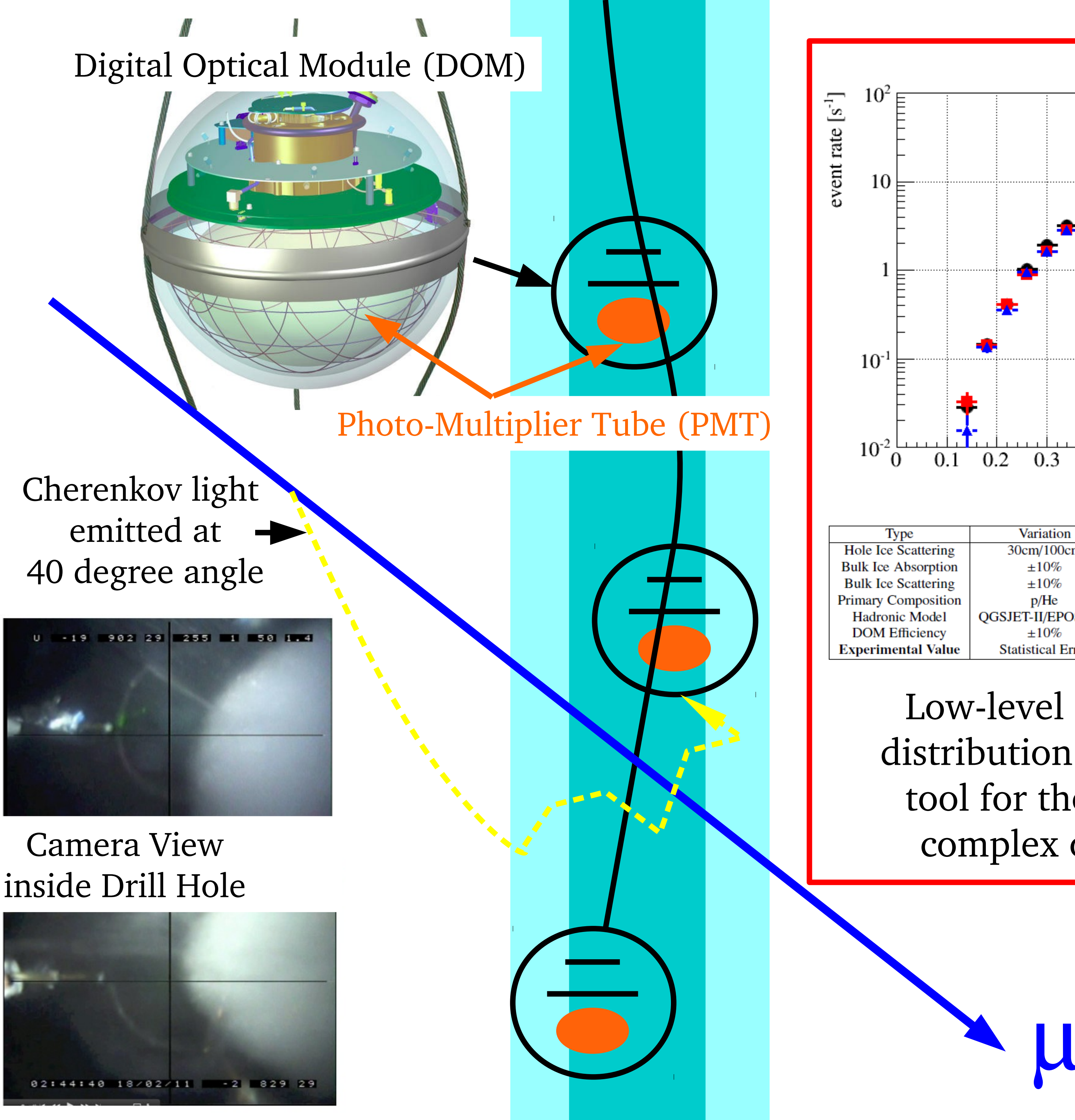
CR Energy Range of IceCube

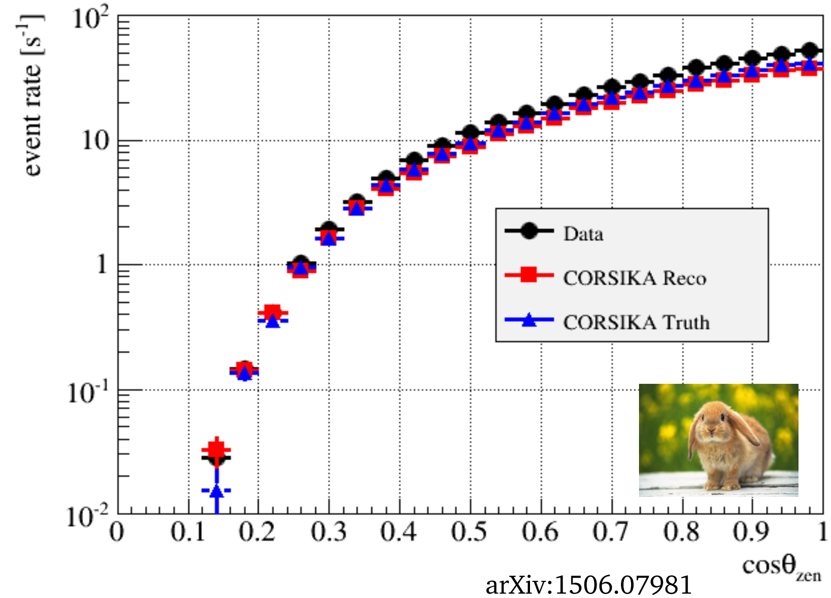


CR Energy Range of IceCube




Digital Optical Module (DOM)
Re-frozen Ice inside Drill Hole
contains air bubbles, leading to
enhanced light scattering
(λ≈50 cm)
Photo-Multiplier Tube (PMT)
Cherenkov light
emitted at
40 degree angle
Registration of photon from
down-going track requires
upward scattering due to
DOMs looking downward
Camera View
inside Drill Hole
μ





arXiv:1506.07981

Type	Variation	$\gamma_{CR,Trigger}$	$\gamma_{CR,High-Q}$	$\Delta\gamma_{CR}$
Hole Ice Scattering	30cm/100cm	± 0.03	$+0.03/-0.05$	$+0.01/-0.02$
Bulk Ice Absorption	$\pm 10\%$	± 0.03	± 0.02	± 0.05
Bulk Ice Scattering	$\pm 10\%$	< 0.01	± 0.01	< 0.015
Primary Composition	p/He	< 0.01	$+0.03/-0.10$	$-0.03/+0.10$
Hadronic Model	QGSJET-II/EPOS 1.99	$+0.02/<0.01$	$+0.03/<0.02$	< 0.02
DOM Efficiency	$\pm 10\%$	< 0.02	$+<0.02/-0.04$	$+0.02/-<0.02$
Experimental Value	Statistical Error	2.715 ± 0.003	2.855 ± 0.007	0.140 ± 0.008

Low-level muon zenith angle distribution serves as diagnostic tool for the understanding of complex optical properties .