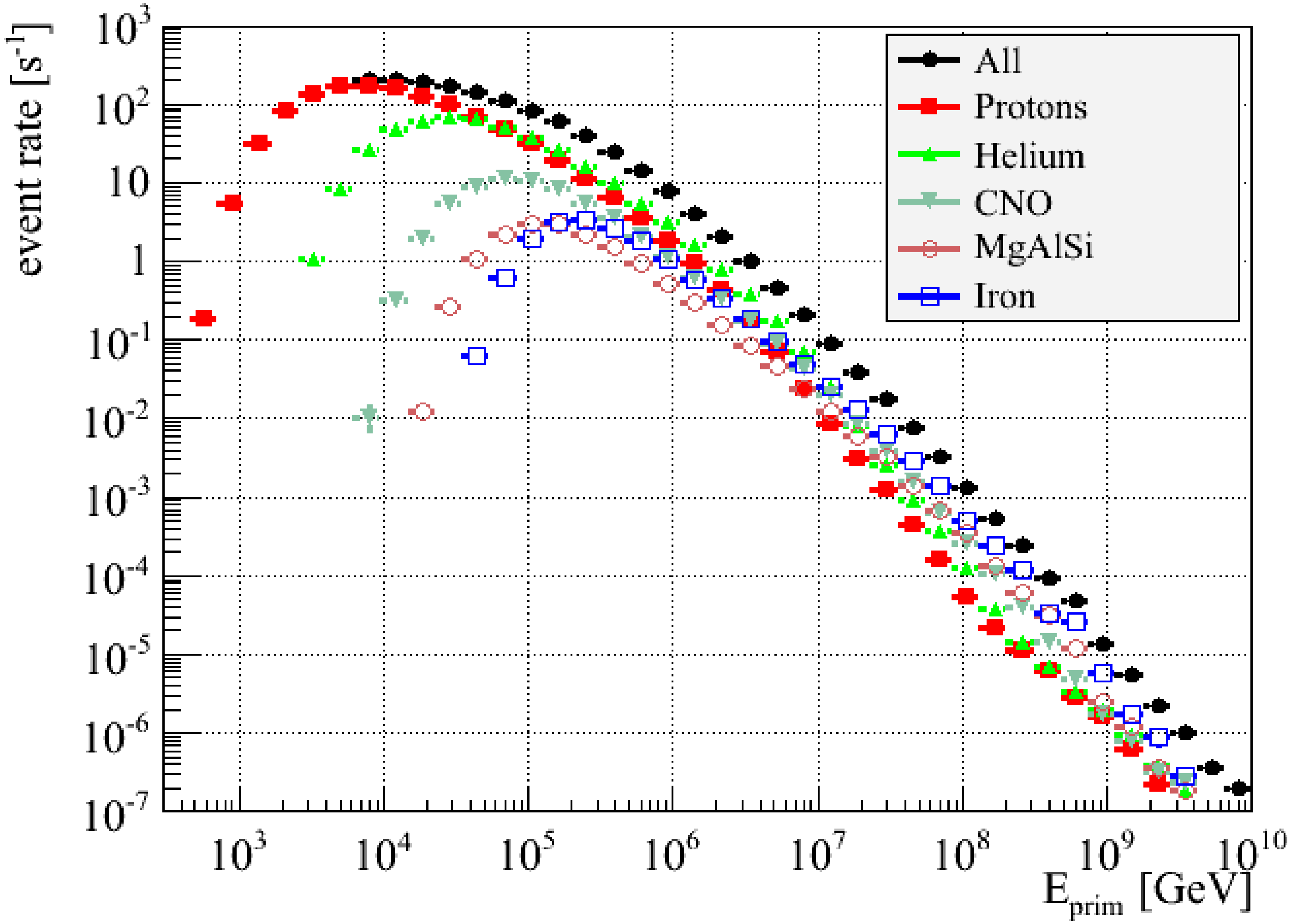
Introduction to Atmospheric Muons in IceCube

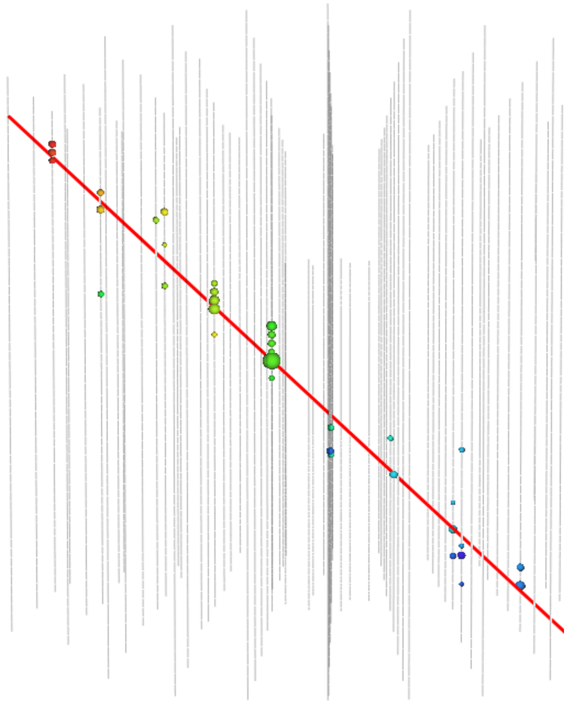
Patrick Berghaus
Muon Workshop, Madison 2015

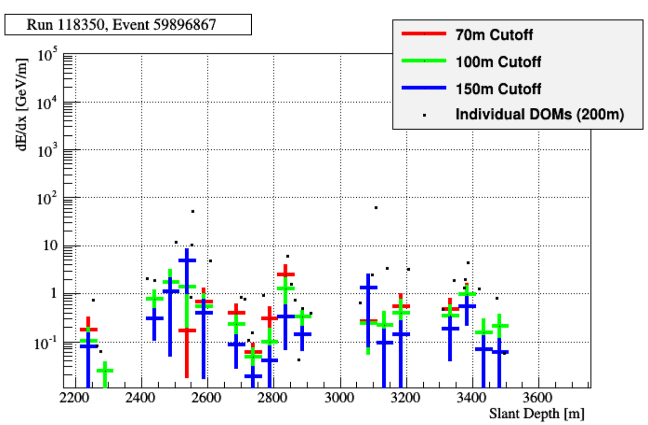
All Muons



event rate [s-1]
10³
10²
10
1
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10³
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
10¹⁰
E_prim [GeV]
All
Protons
Helium
CNO
MgAlSi
Iron

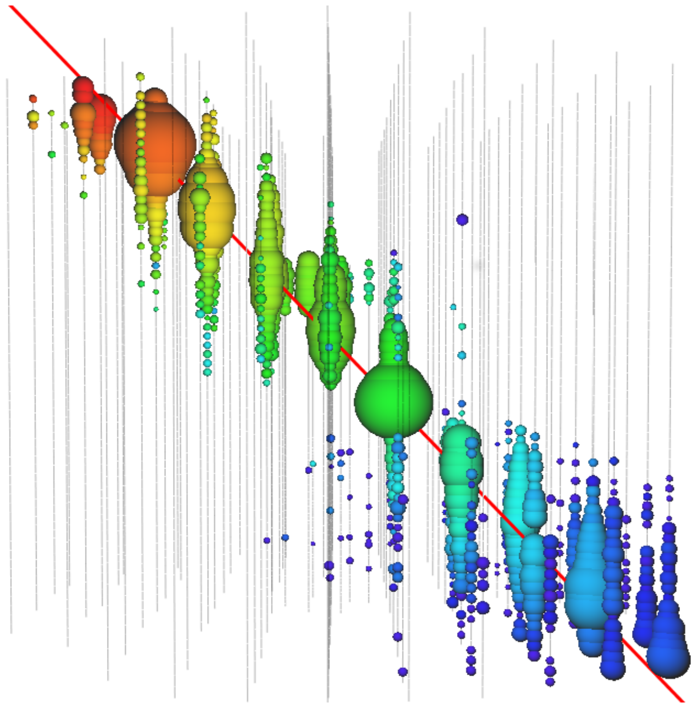
Low-Energy

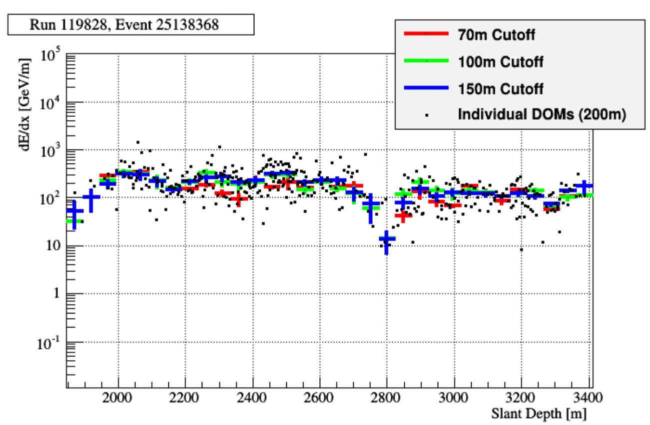




a muon, maybe two

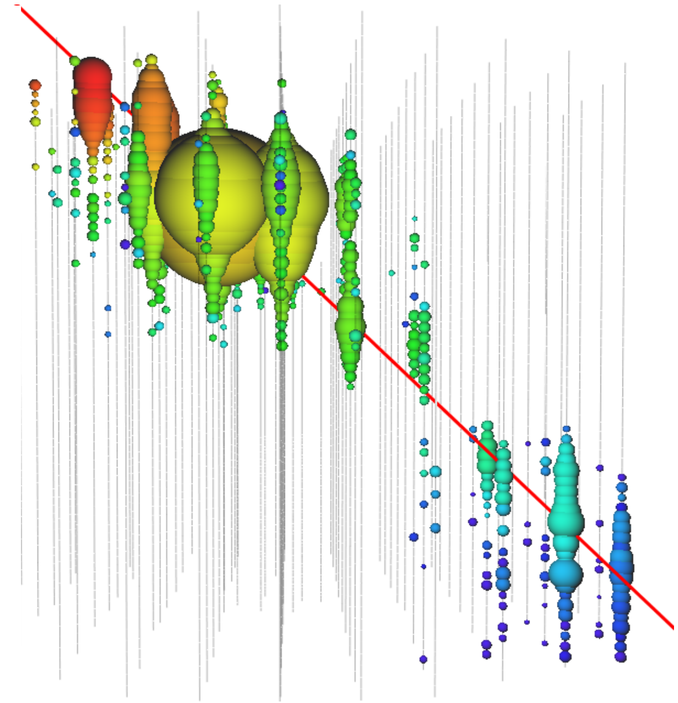
Bundles

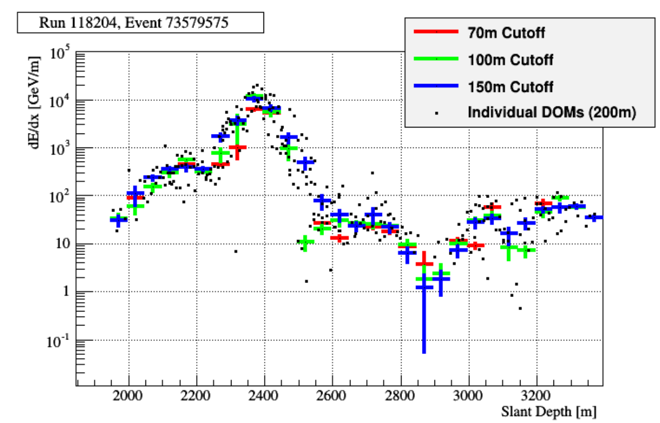




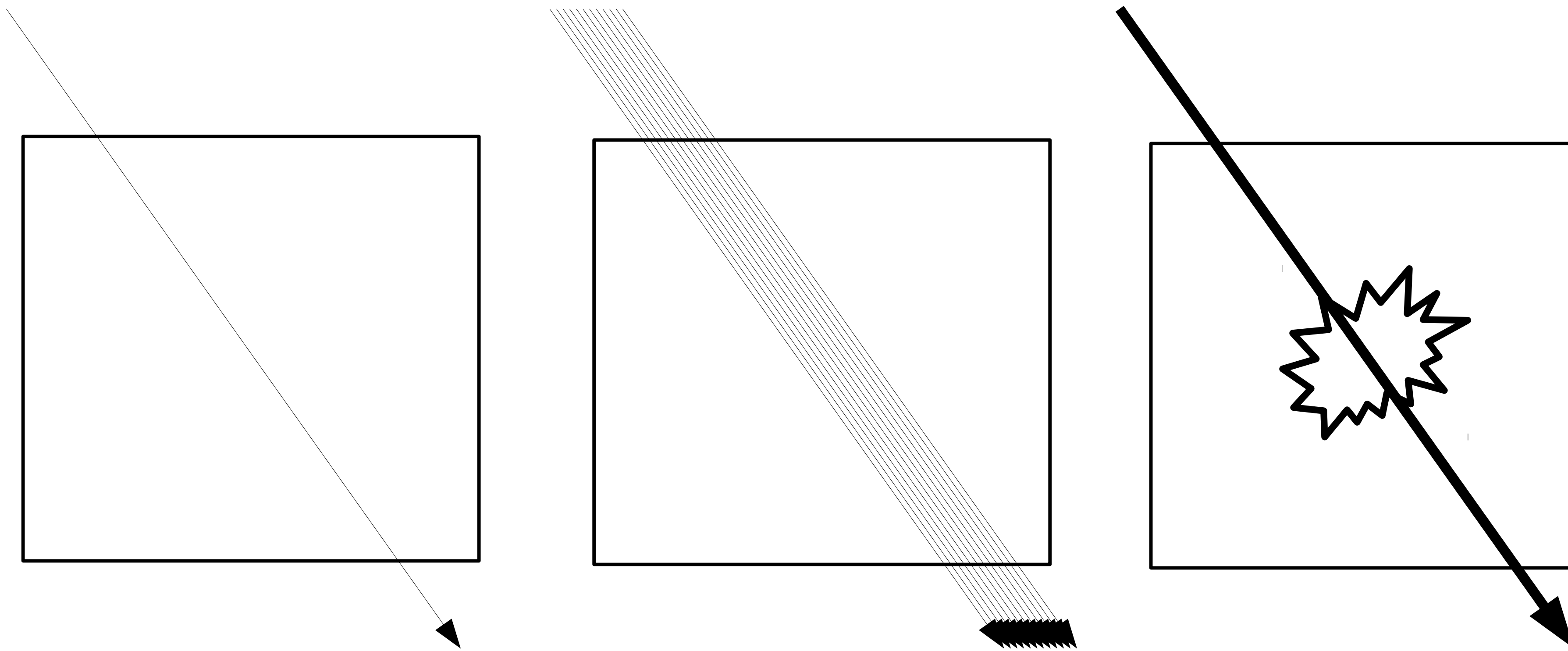
200-310 muons

HE Muons



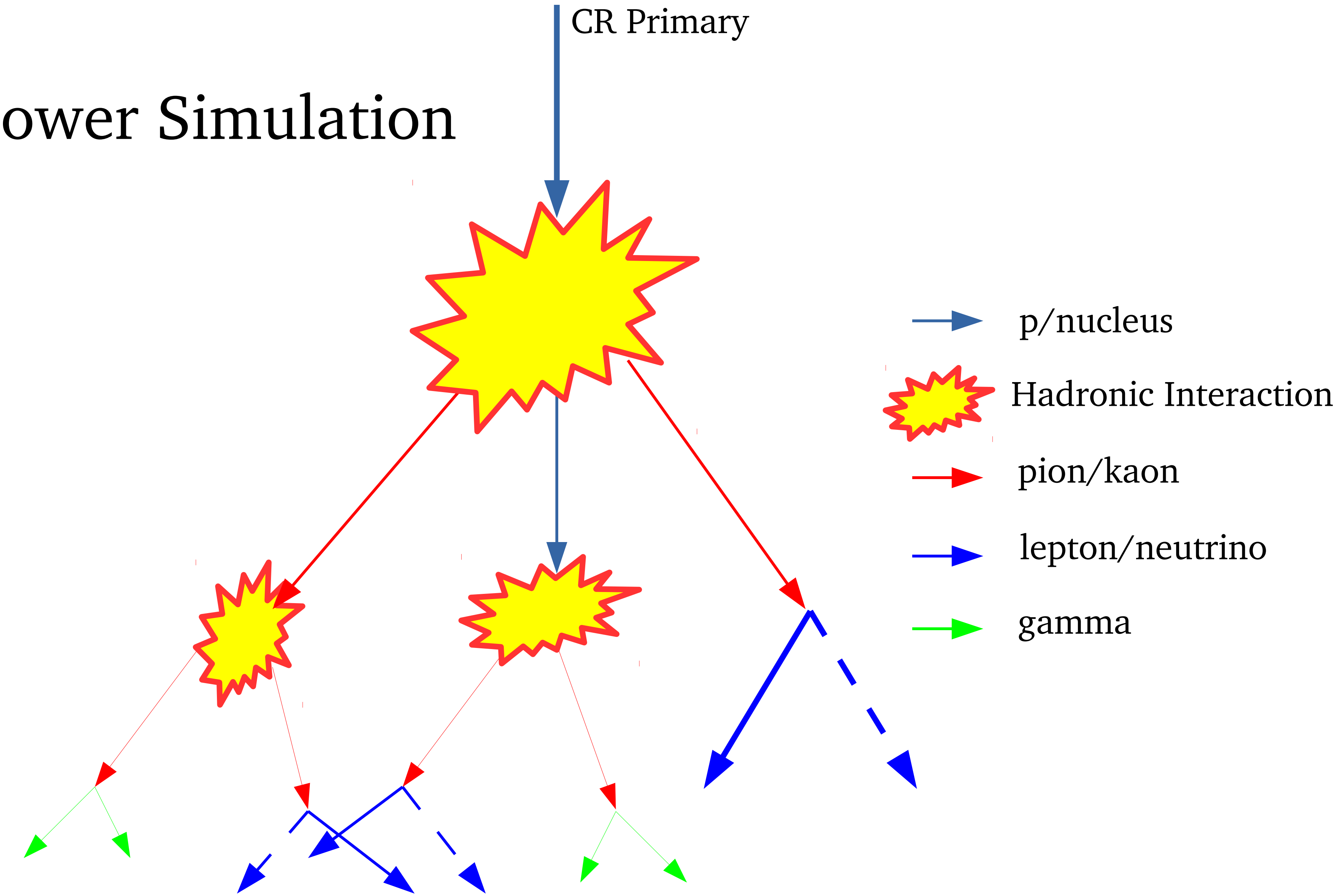


640-1,650 TeV



Low-Energy	Bundles	HE Muons
1,000/second	1/second	0.1/second
Minimum Ionizing	Minimum Ionizing	Stochastic
Single Muons	20-10,000 Muons	1 HE Muon, 10-100 others
10-100 TeV CR	1 PeV-1 EeV CR	100 TeV-10 PeV CR

Air Shower Simulation

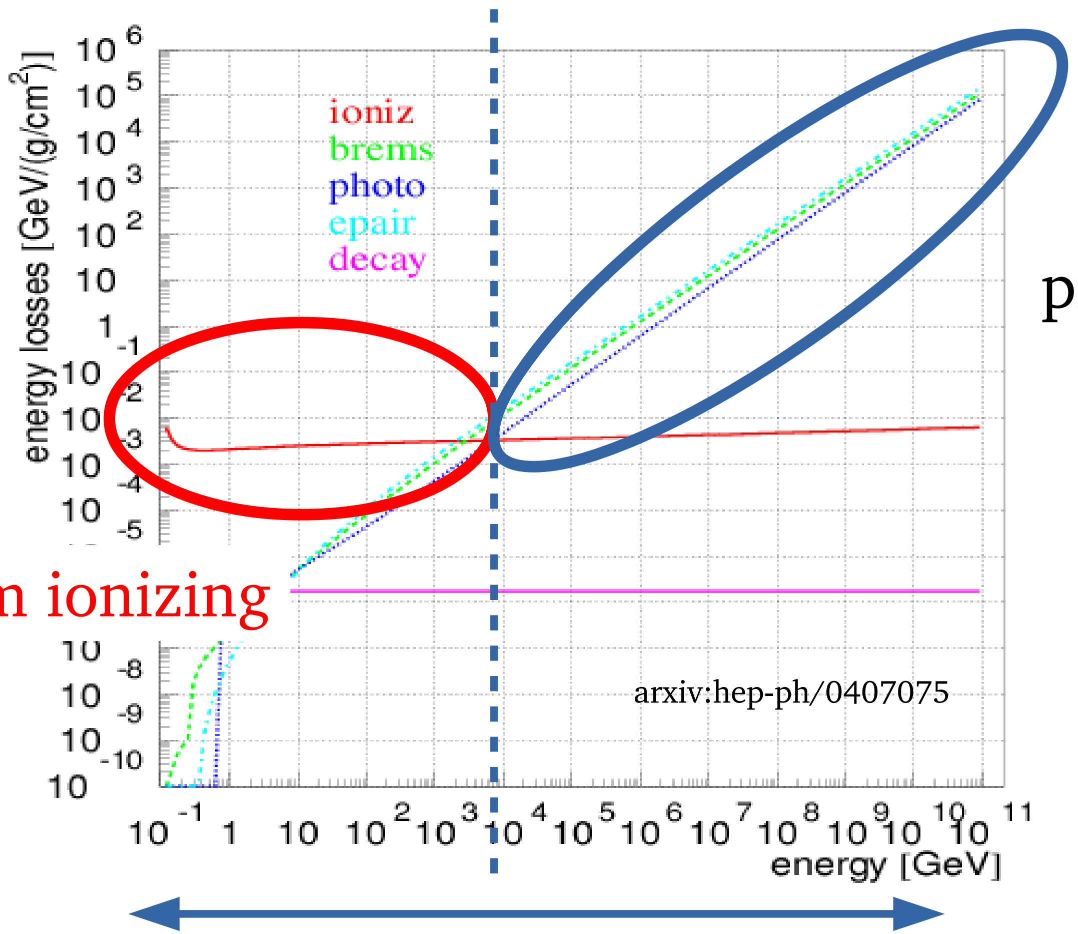


Propagation/Decay is handled by CORSIKA main code

Hadronic Interaction Models provided by external modules (SIBYLL, EPOS, QGSJET...)

Muon Energy Losses in Matter (Ice)

few TeV



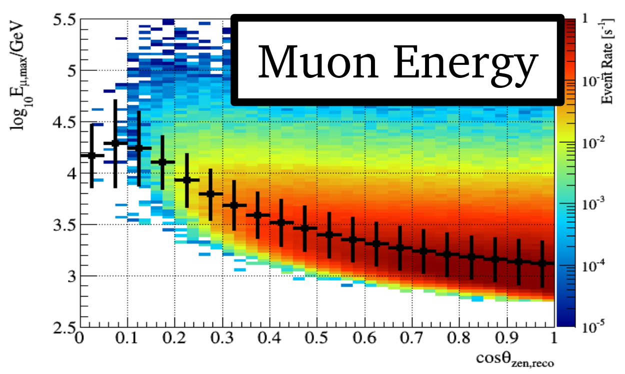
proportional losses

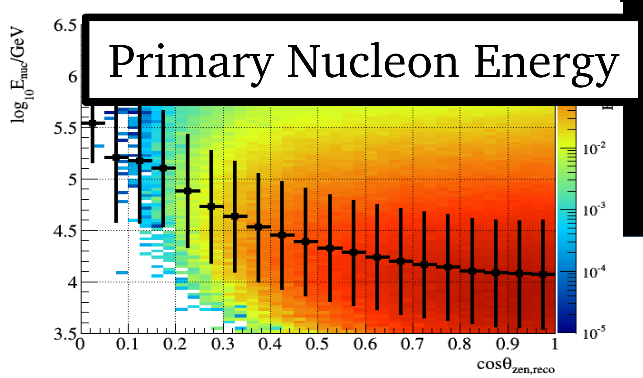
minimum ionizing

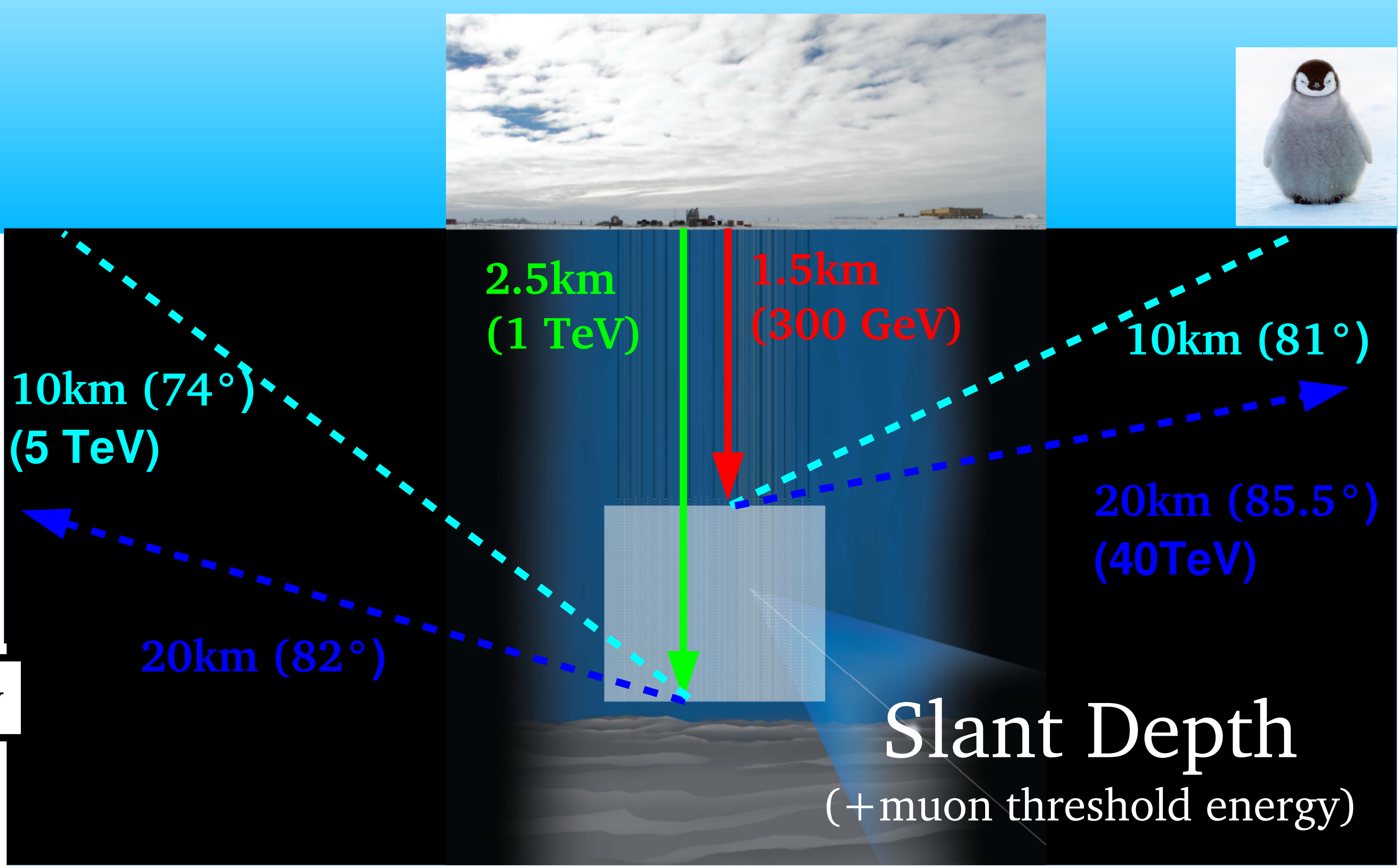
continuous
(smooth)

stochastic
(catastrophic)

Low-Energy Muons: Zenith Angle

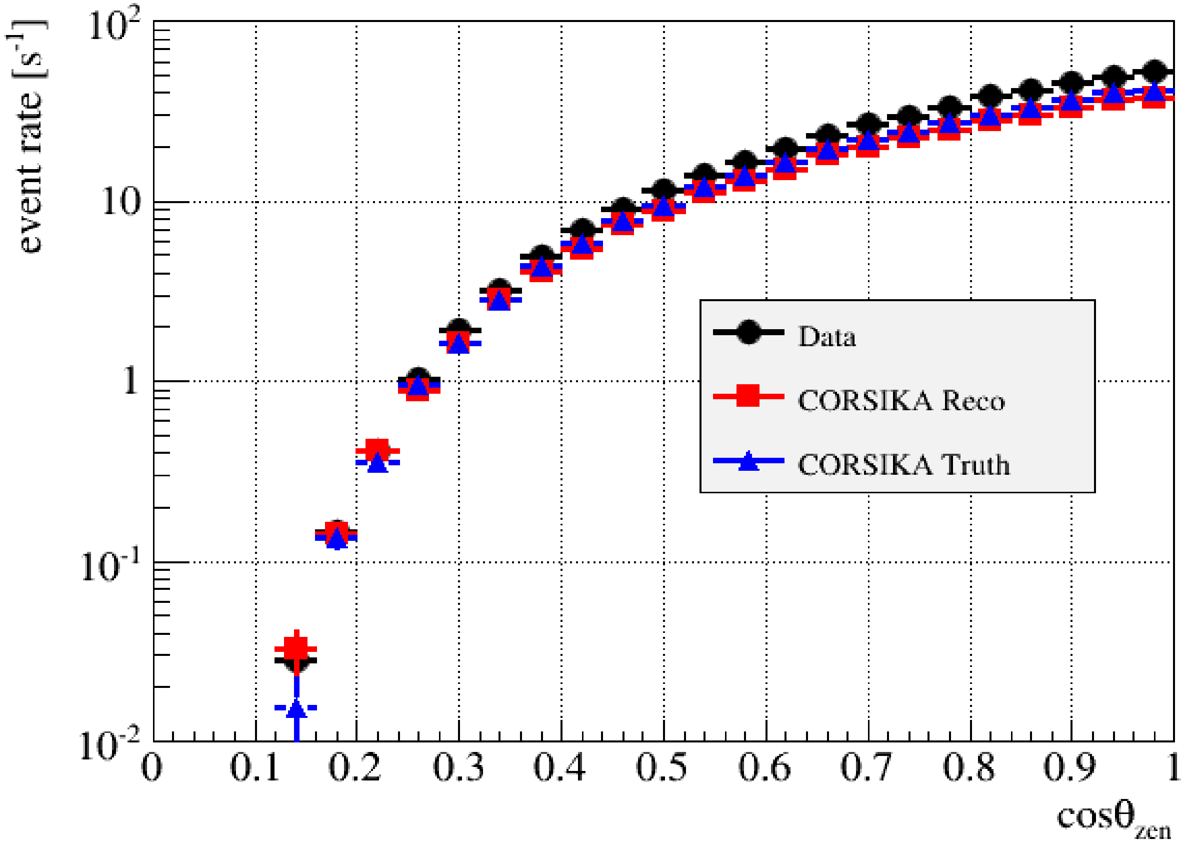


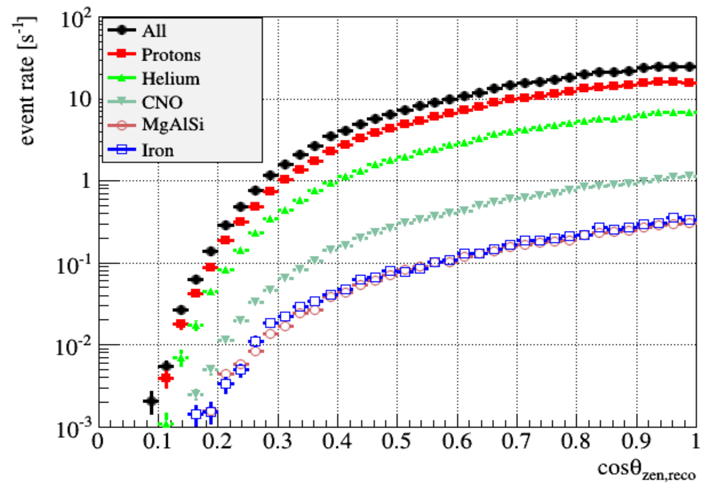




Angular Distribution → Muon Spectrum → Nucleon Spectrum

Zenith Angle





Event sample is at all angles strongly dominated by light elements, especially protons!

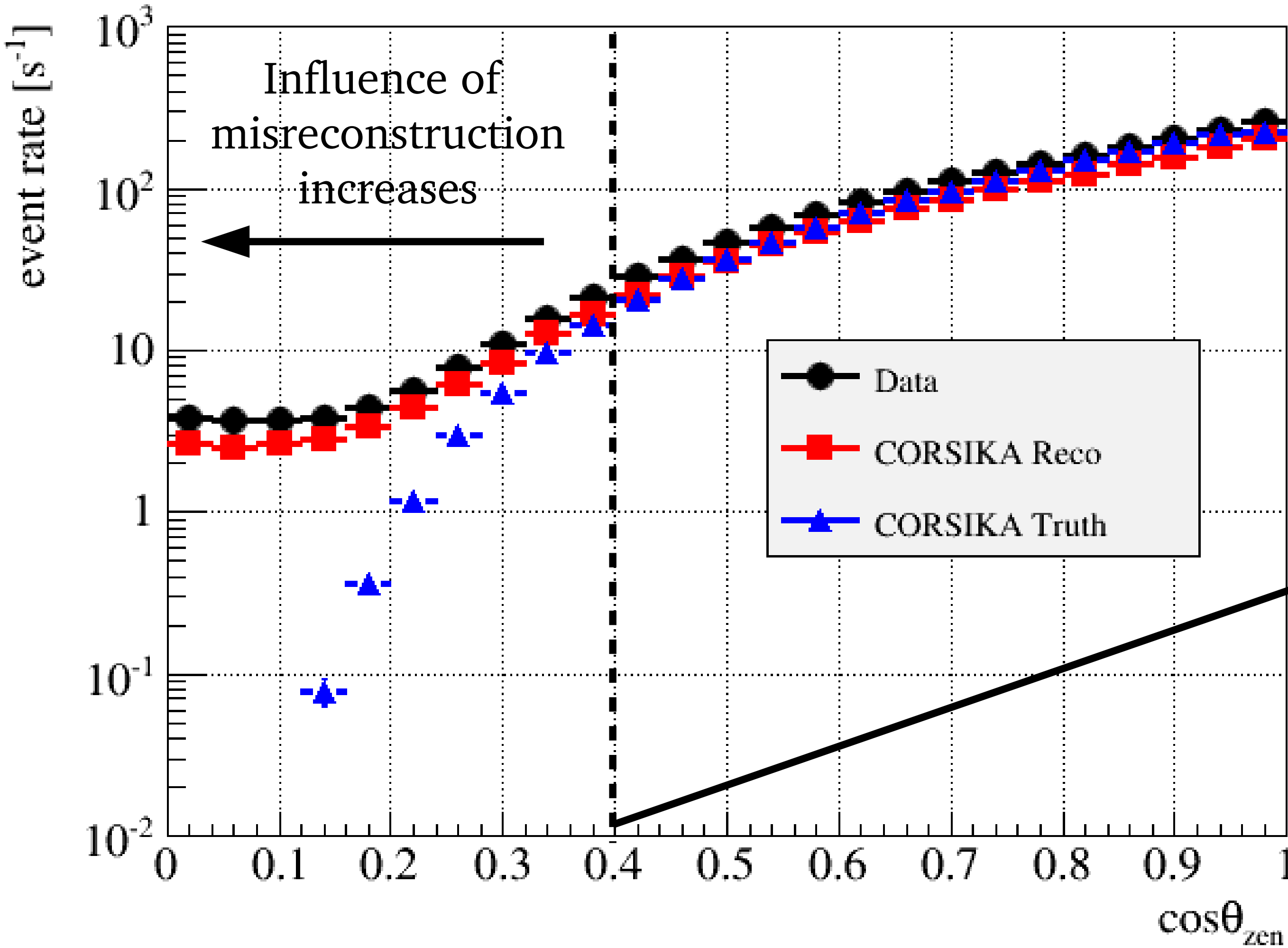
Reason: Threshold depends on **nucleon** energy E_{prim}/A

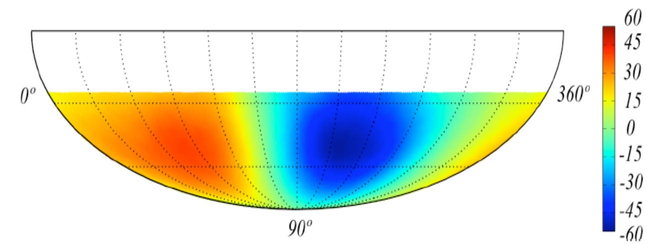
Minimum Bias Data

L_{dir} > 600 m

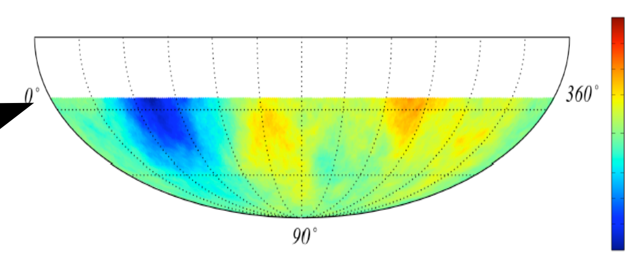
$llh/(N_{ch}-2.5) < 7.5$

Zenith Angle: Trigger Level





(a)

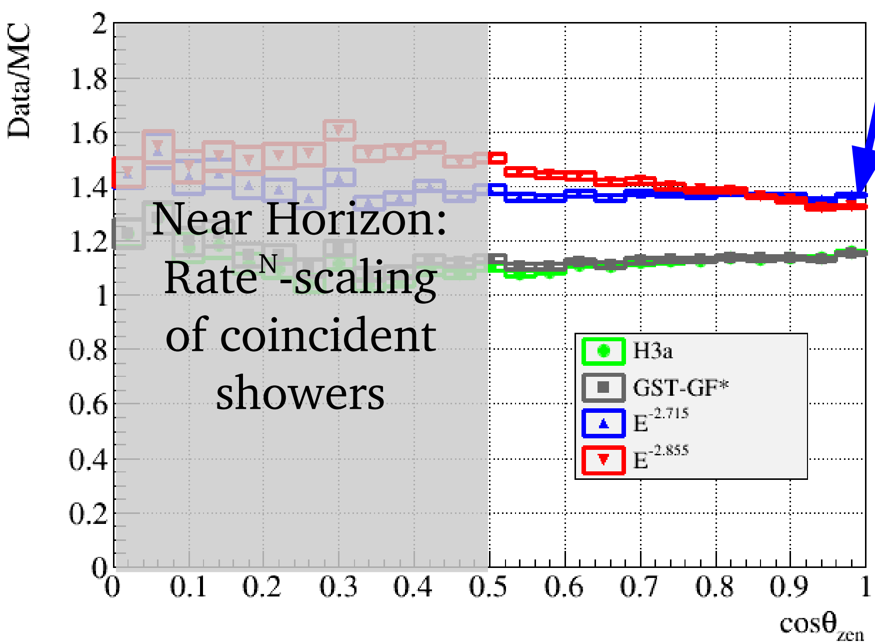


(b)

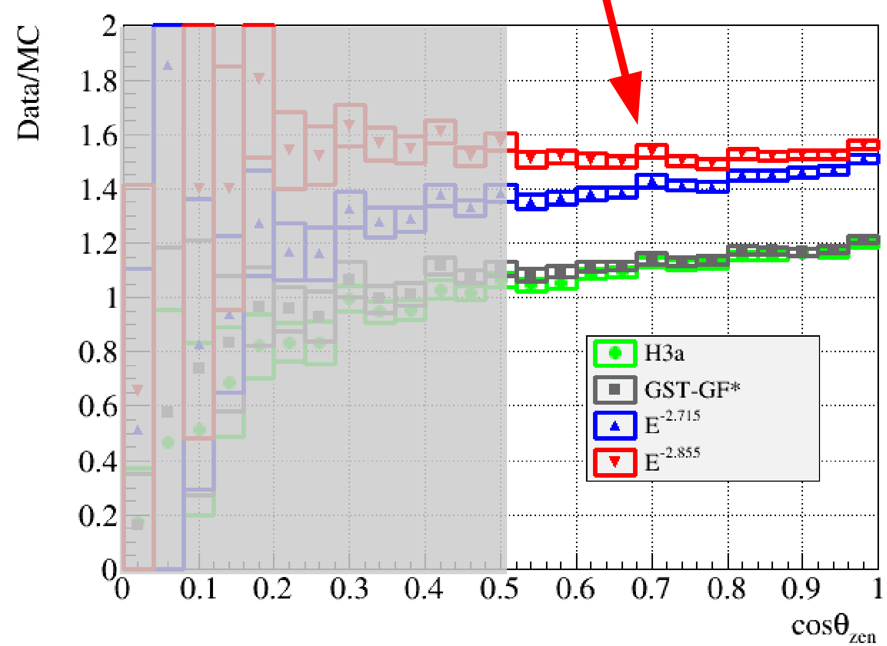
For downgoing tracks, relative level of misreconstructed tracks is low.
Analyses can be done without quality cuts! (Example: Anisotropy)

Nucleon Spectrum Derived from Zenith Angle

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	±10%	± 0.03	± 0.02	± 0.05
Bulk Ice Scattering	±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	±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



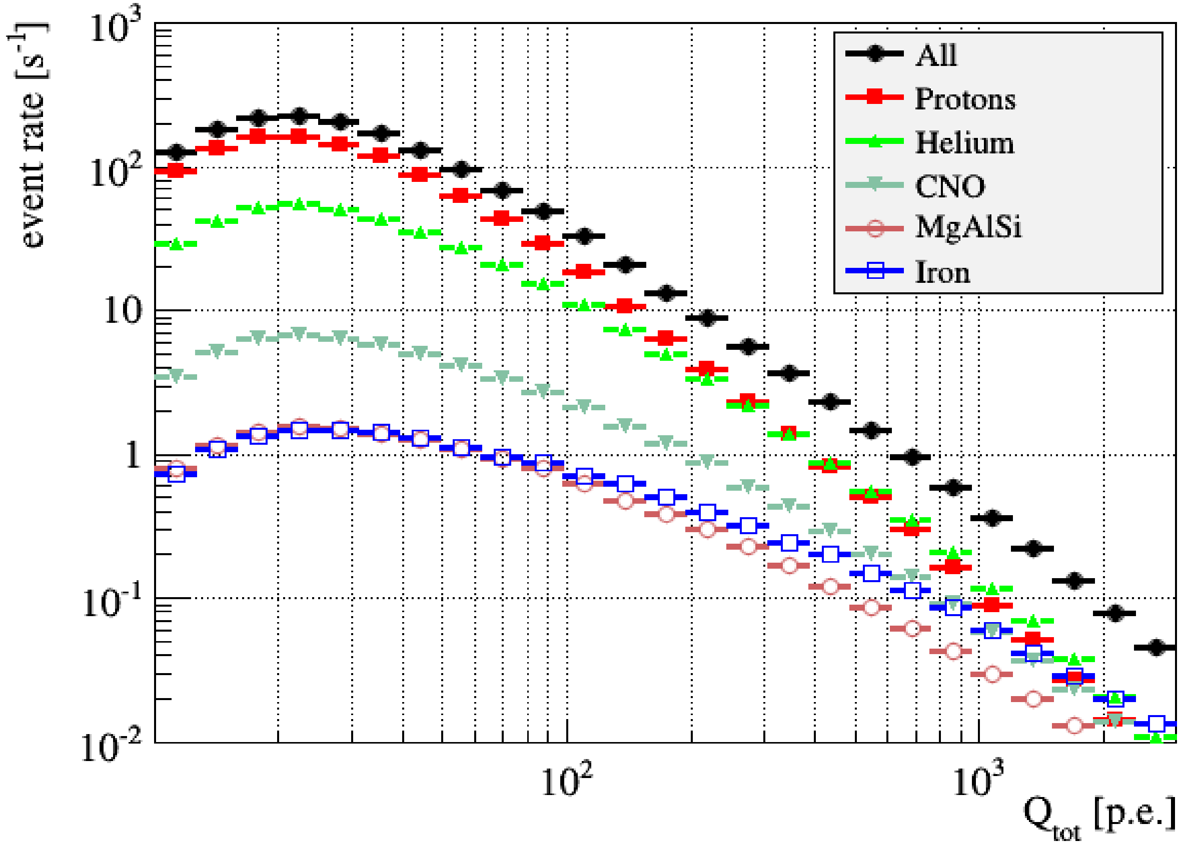
Trigger Level



Quality Cuts

Inconsistency in CR nucleon spectrum measurement between Trigger and High-Q Level

Total Charge

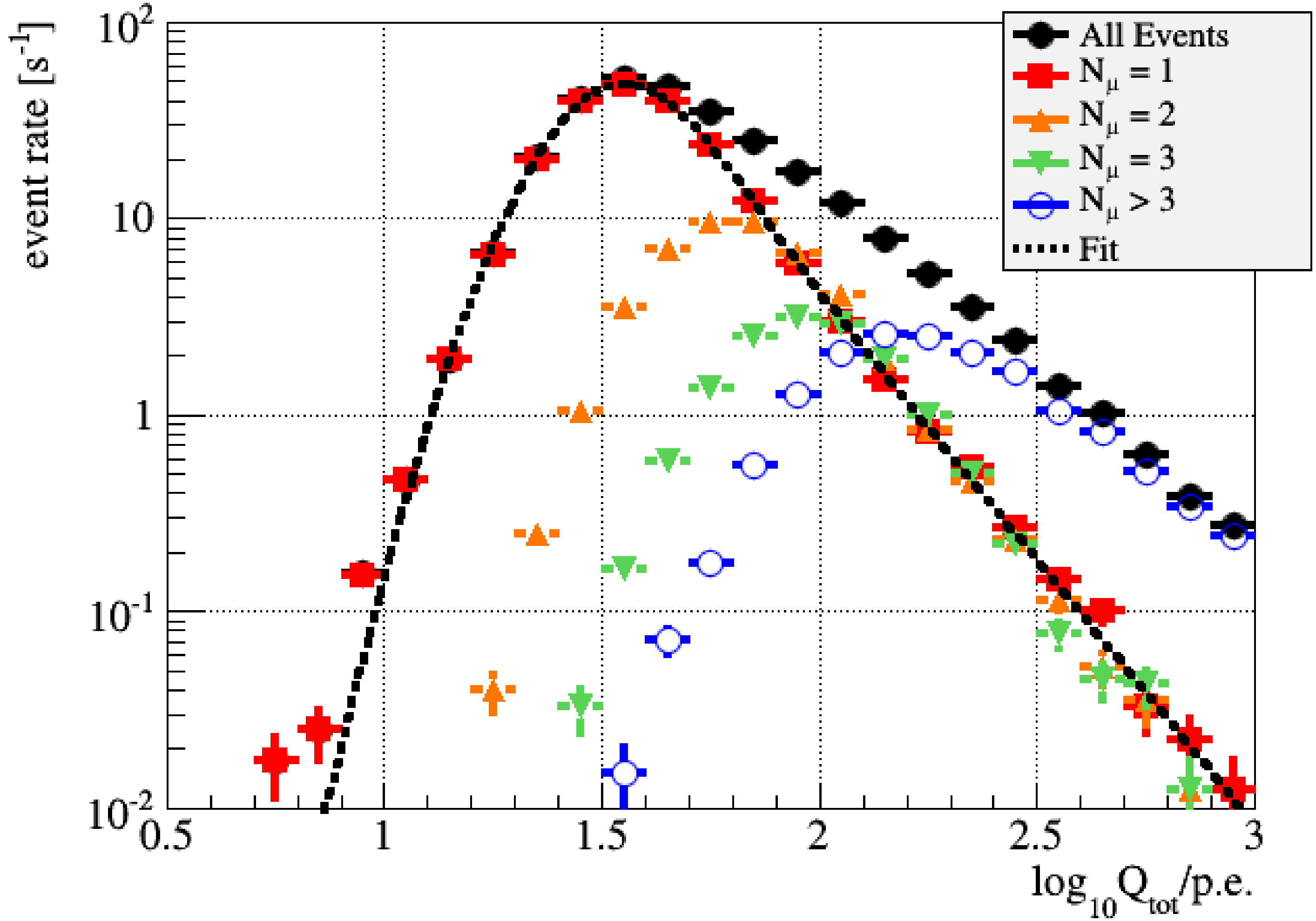


Minimum Bias MC

L_{dir} > 600 m

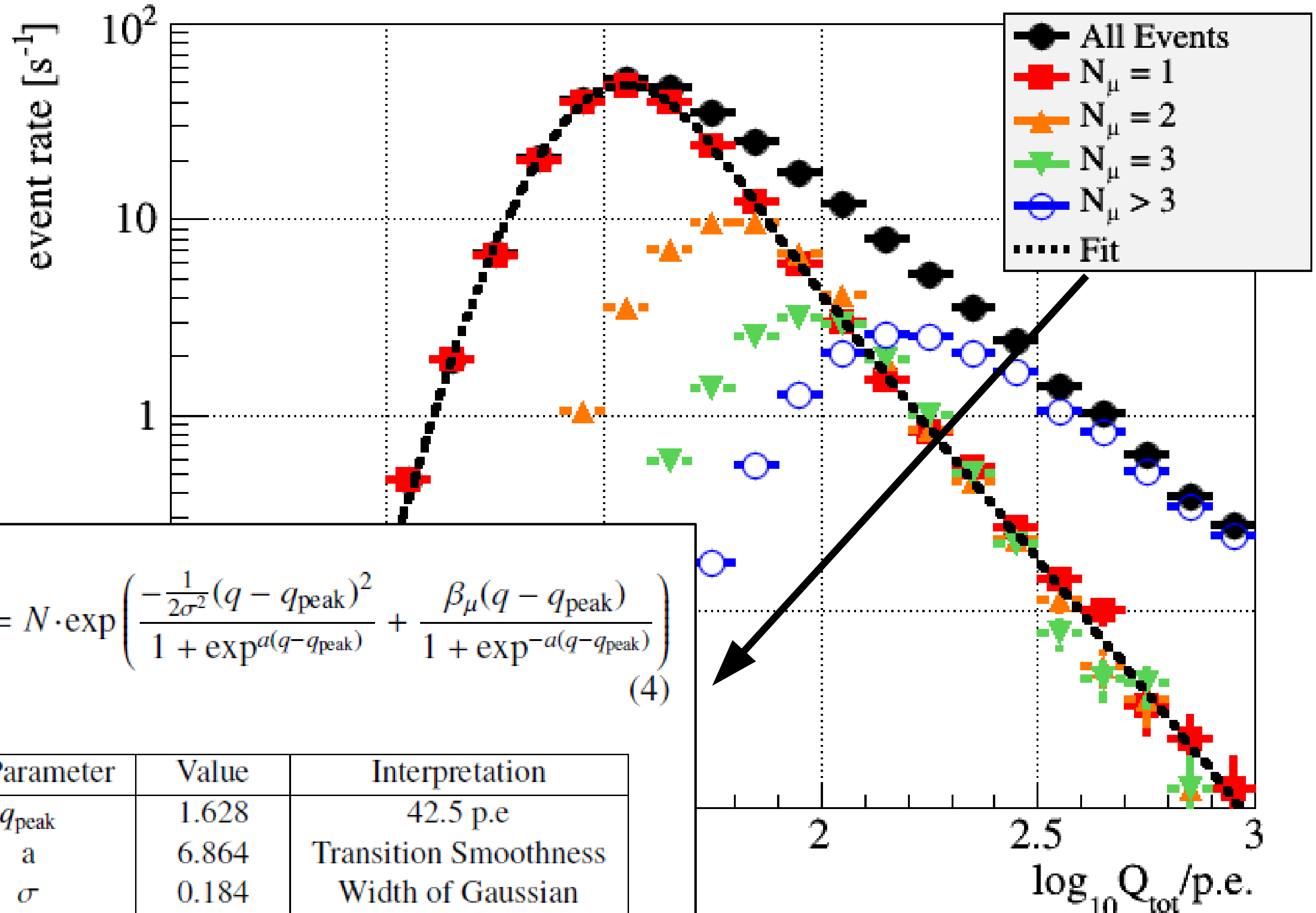
llh/(N_{ch}-2.5) < 7.5

Total Charge



Can be used to “count muons” in CR showers

Total Charge

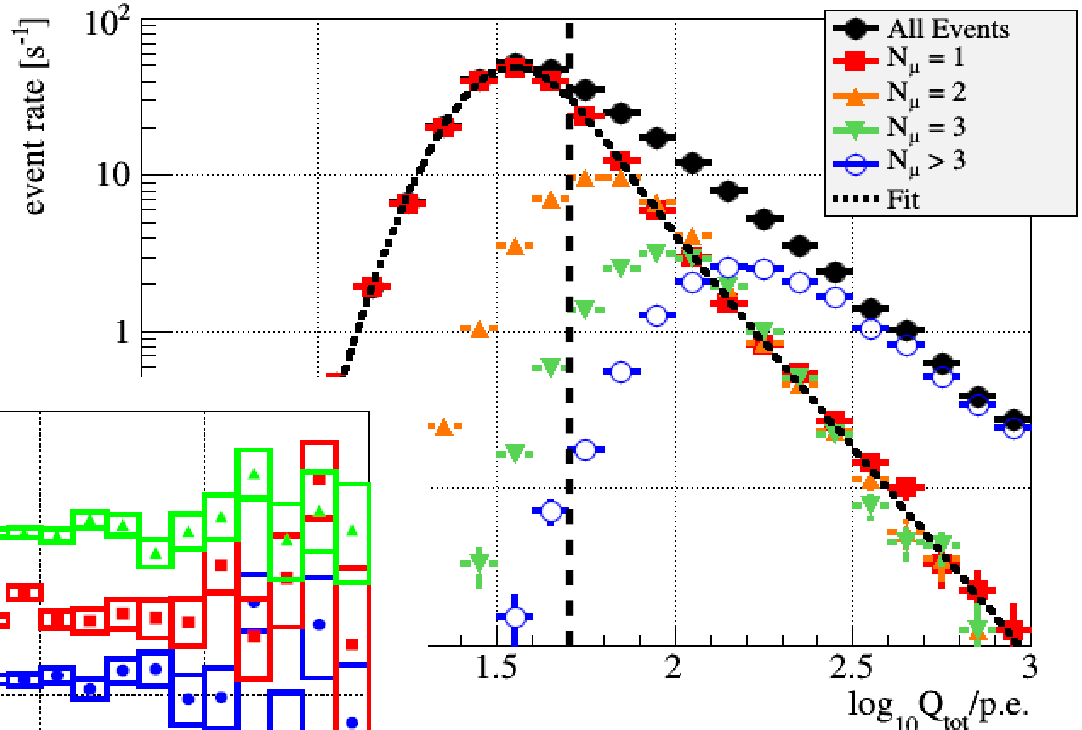


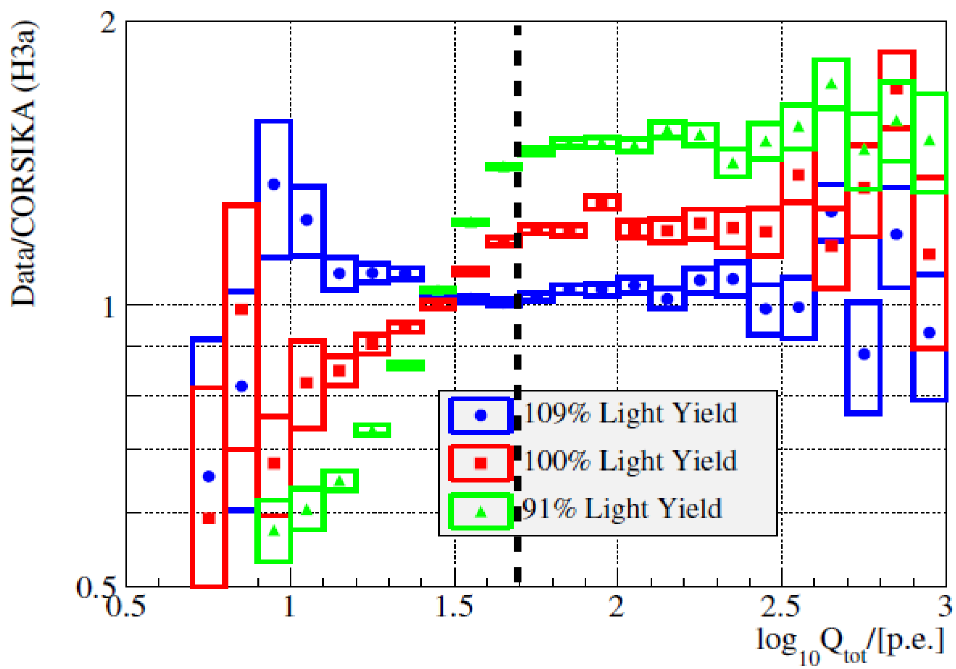
$$\frac{\Delta n_{\text{event}}}{\Delta q} = N \cdot \exp\left(\frac{-\frac{1}{2\sigma^2}(q - q_{\text{peak}})^2}{1 + \exp^{a(q - q_{\text{peak}})}} + \frac{\beta_\mu (q - q_{\text{peak}})}{1 + \exp^{-a(q - q_{\text{peak}})}} \right) \tag{4}$$

Fit Parameter	Value	Interpretation
q_{peak}	1.628	42.5 p.e
a	6.864	Transition Smoothness
σ	0.184	Width of Gaussian
β_μ	-6.245	Power Law Index
N	arbitrary	normalization

Total Charge: Systematics

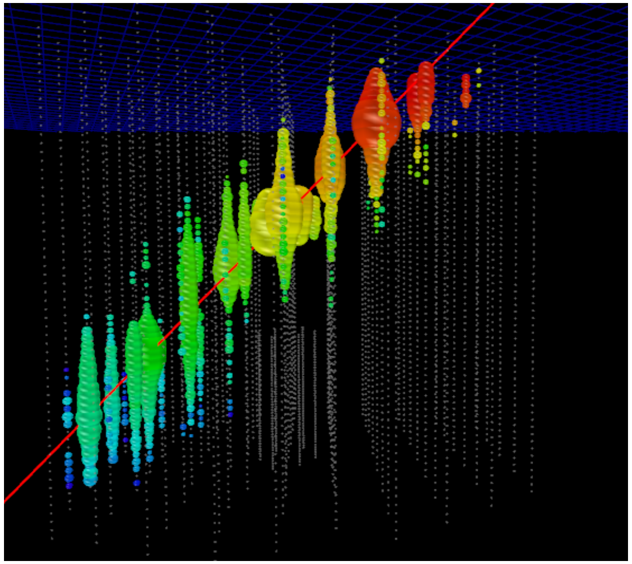
Systematics influence almost exclusively the threshold region, and are usually degenerate with the Light Yield ("DOM Efficiency").

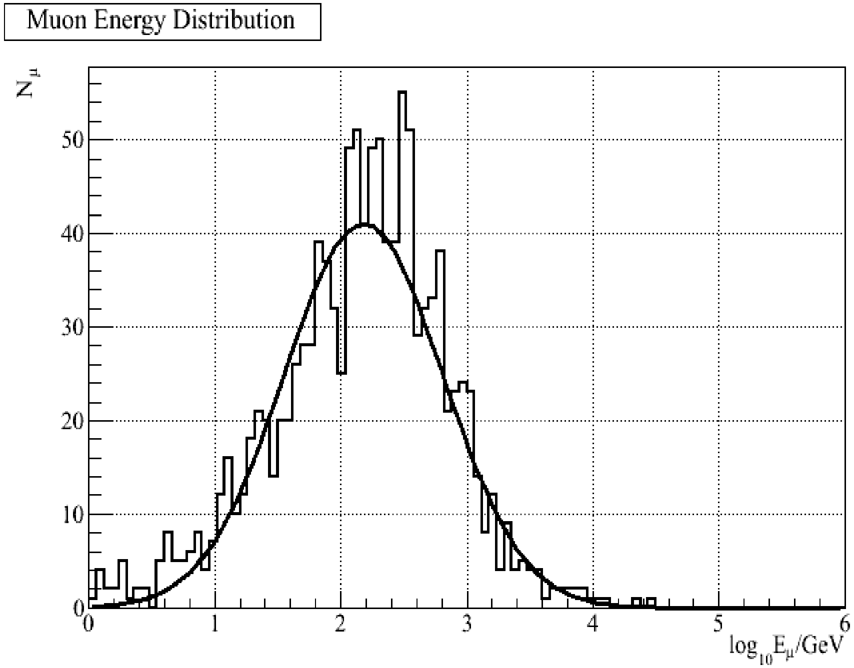




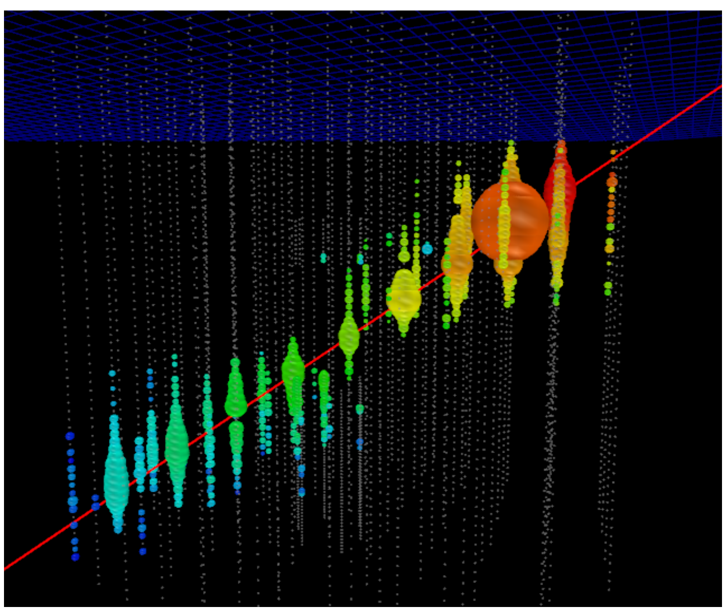
Low-energy charge distribution is consistent with H3a within systematic uncertainty.

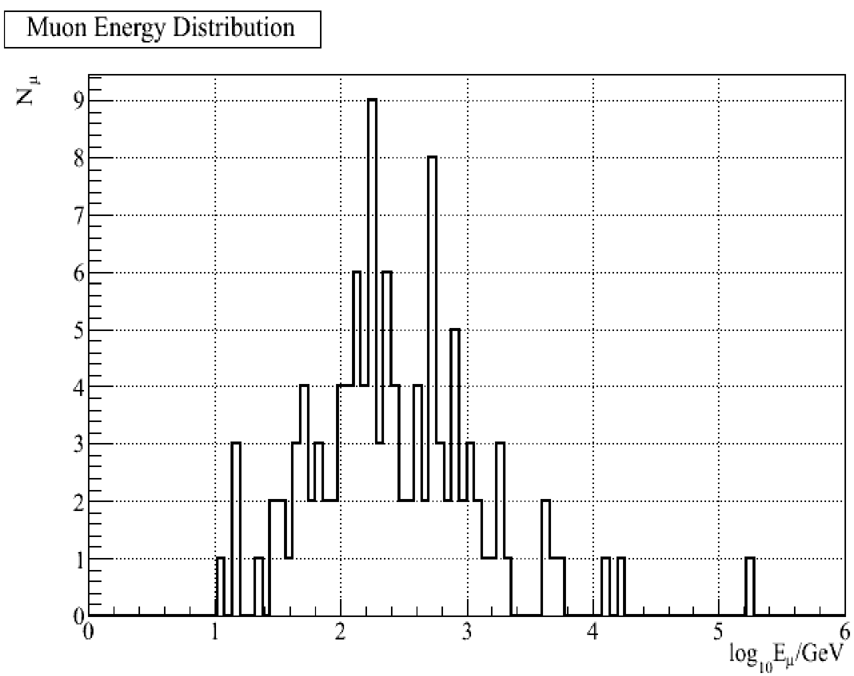
20,000 Photo-Electron Events (**CORSIKA**)





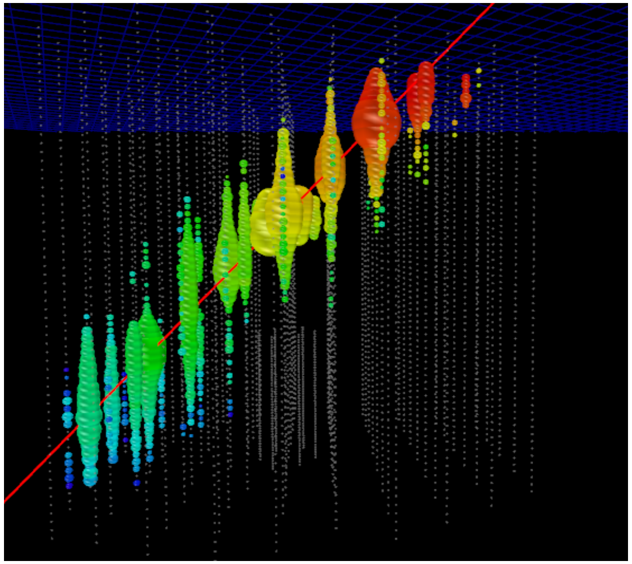
1,000 Muons

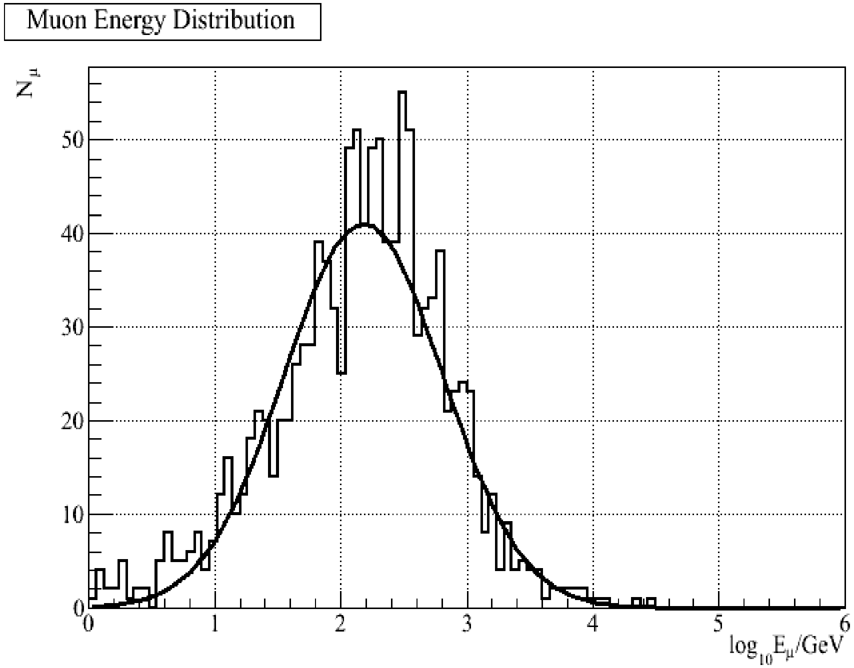




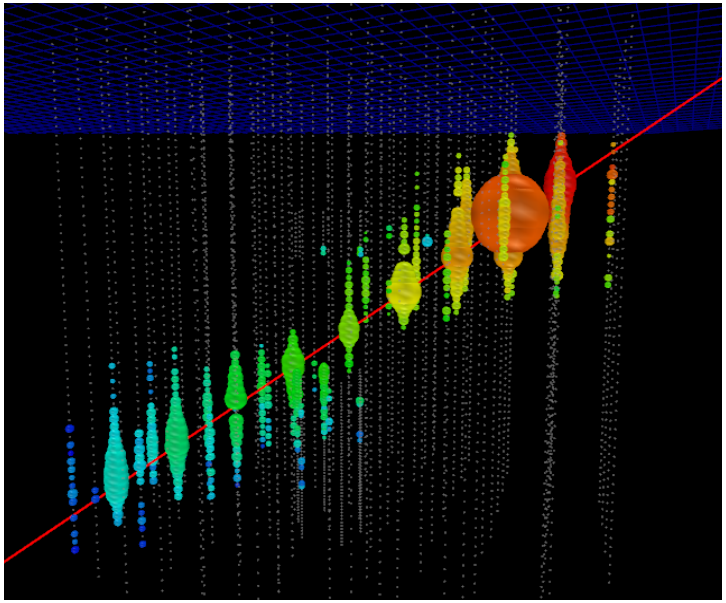
100 Muons

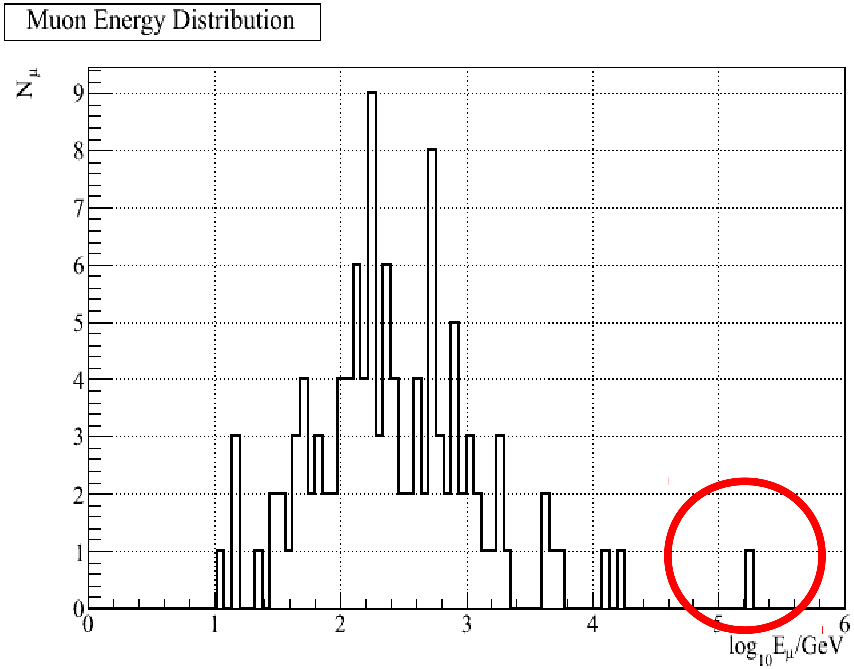
20,000 Photo-Electron Events (**CORSIKA**)





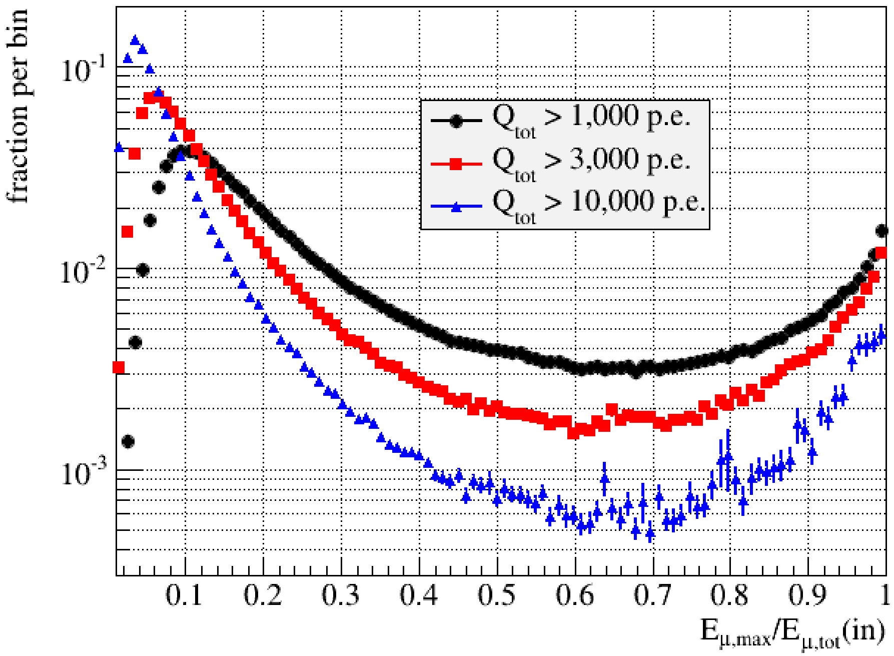
1,000 Muons



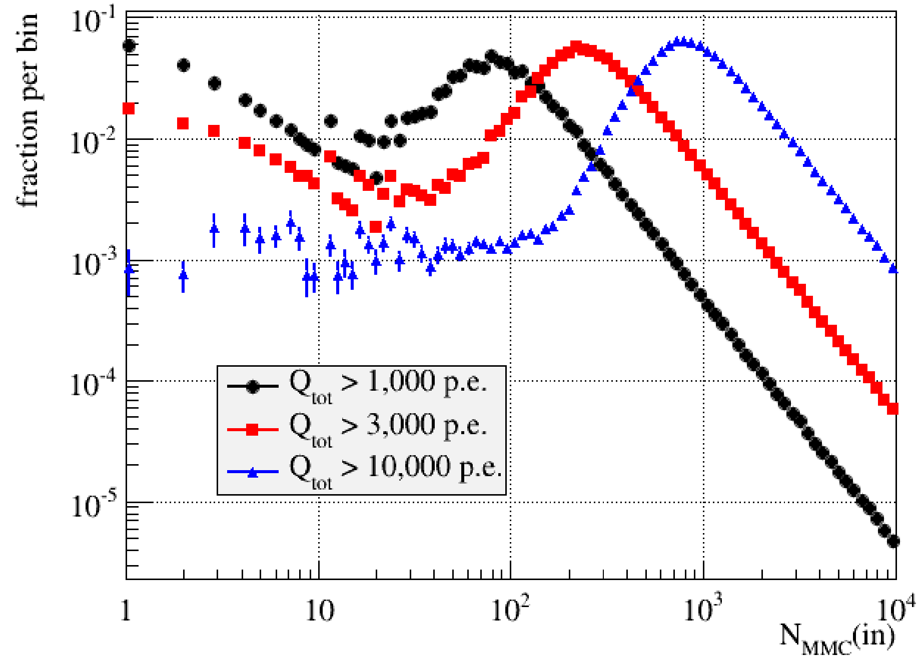


100 Muons

True MC Parameters



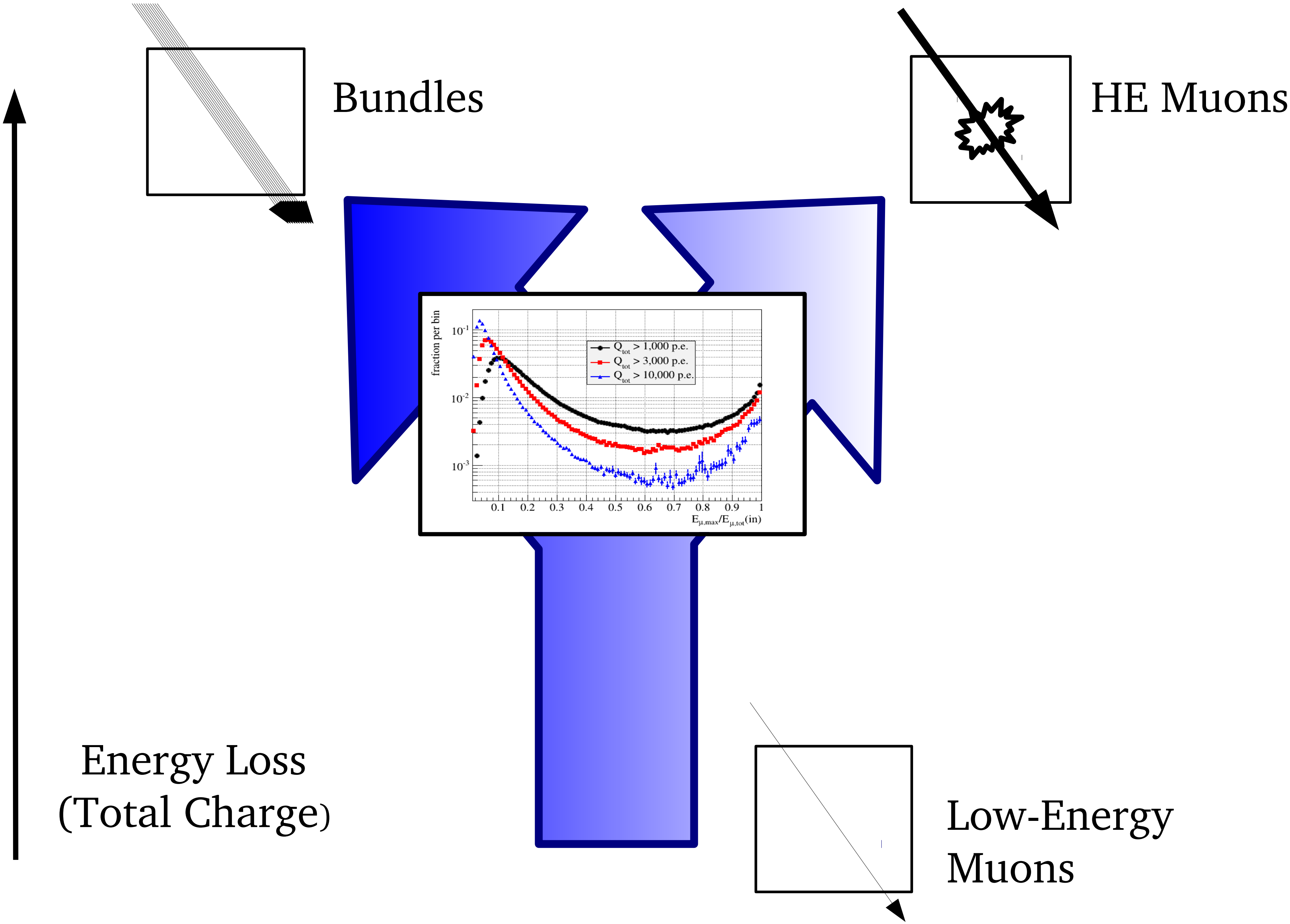
Energy Carried by Leading Muon



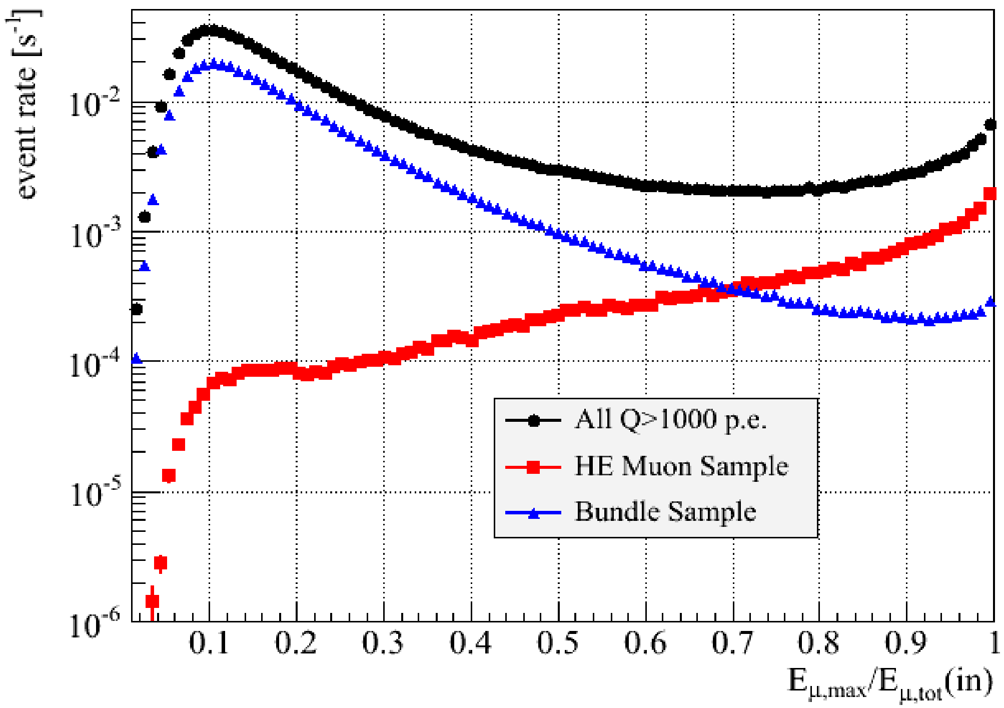
Number of Muons in Detector

Bi-Modal (Bundles/HE Muons)!

HE Muons become rarer (spectrum)


Bundles
HE Muons
Energy Loss
(Total Charge)
Low-Energy
Muons
fraction per bin
Q_tot > 1,000 p.e.
Q_tot > 3,000 p.e.
Q_tot > 10,000 p.e.
E_μ,max/E_μ,tot(in)

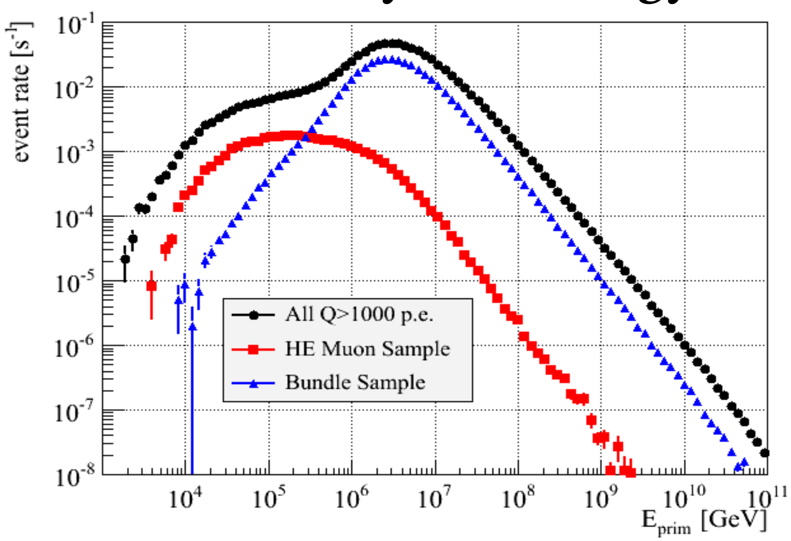
Energy Carried by Leading Muon



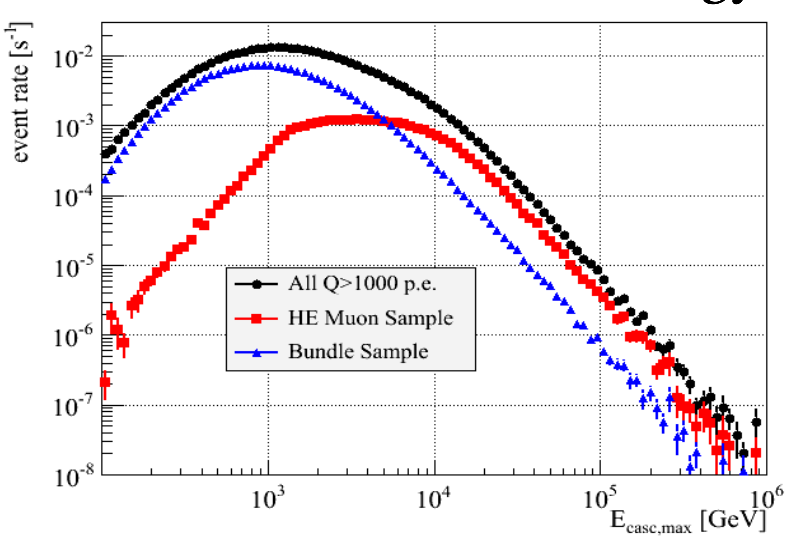
Final Cut Level: True MC Distributions

HE Muon Sample in red

Primary CR Energy



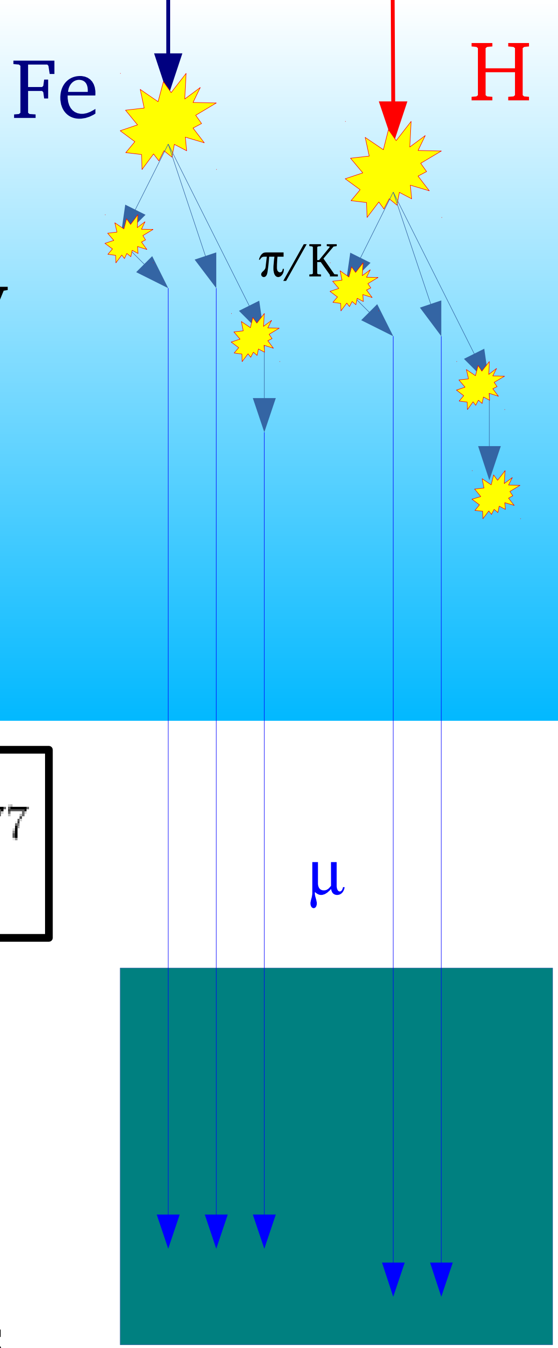
Stochastic Cascade Energy



High-Multiplicity Muon Bundle

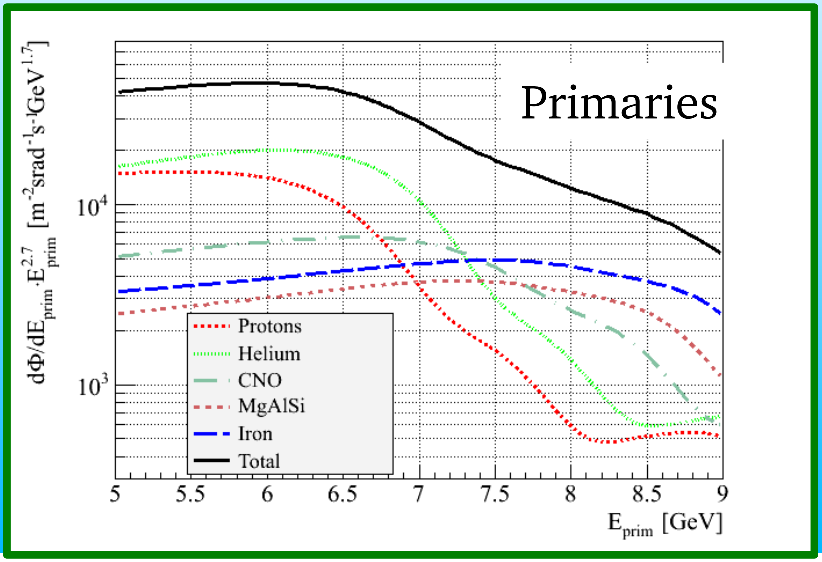
$$< N_\mu > \propto A^{1-\alpha} \cdot E_{prim}^{\alpha} \qquad \alpha \approx 0.77$$

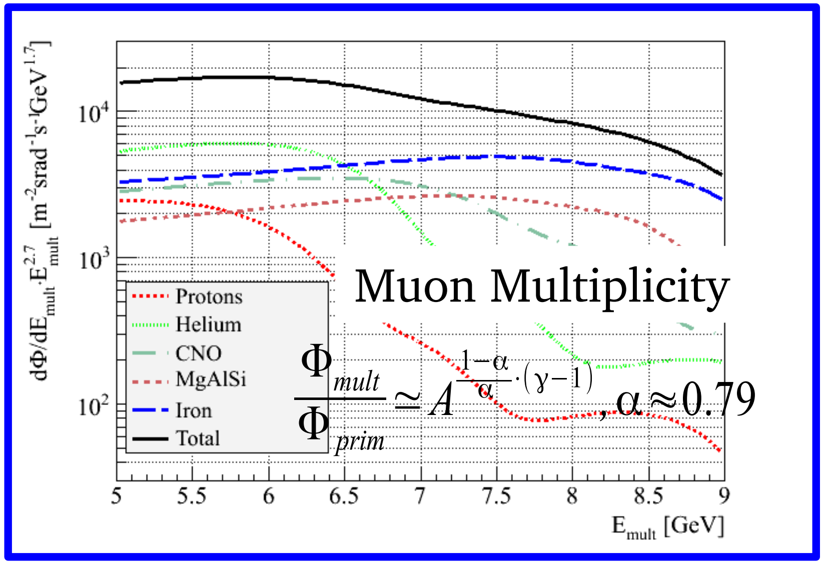
(e.g. T.K. Gaisser: CR&Part.Phys.)



Energy Spectrum follows **Nuclei**

Main contribution from **heavy** primaries

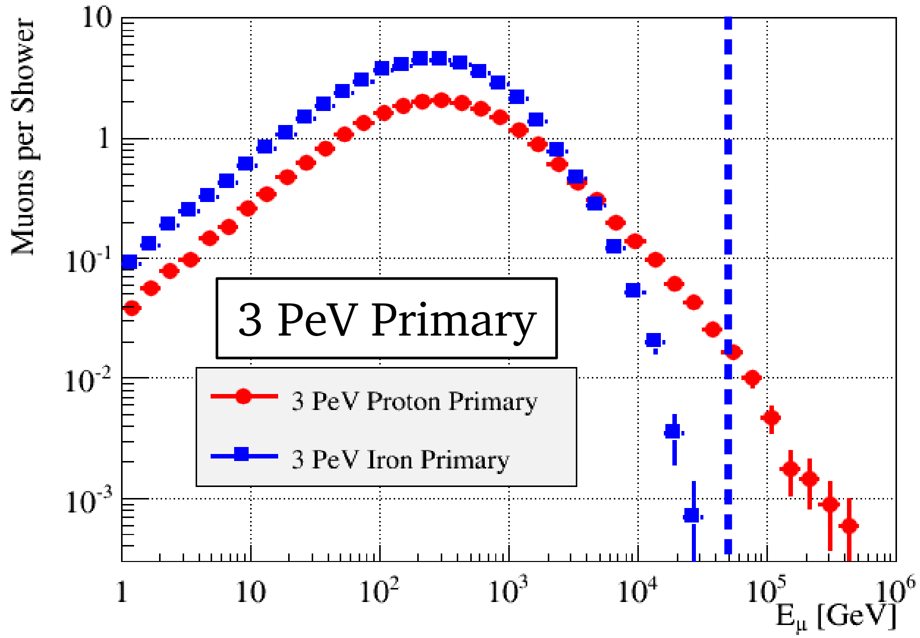


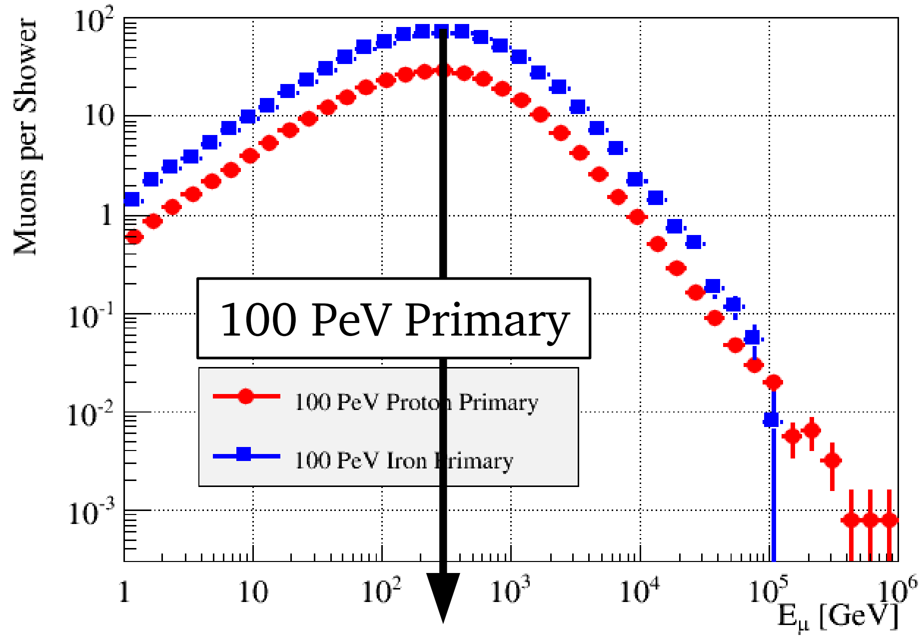


Example: Gaisser H3a

Muon Energy Distribution in Bundles

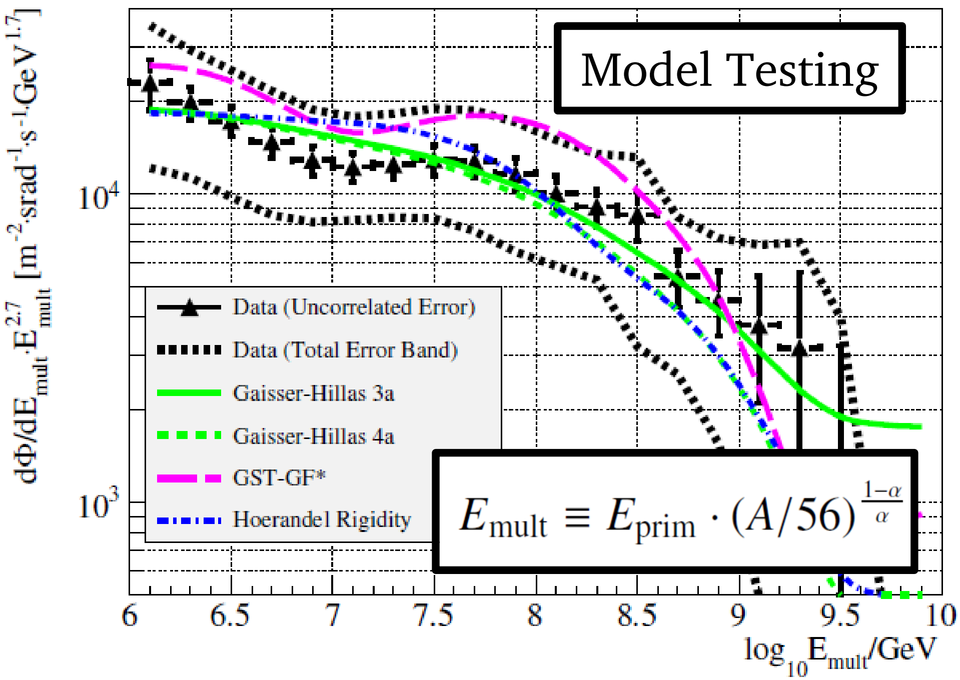
Fe threshold: 3 PeV/56 nucleons

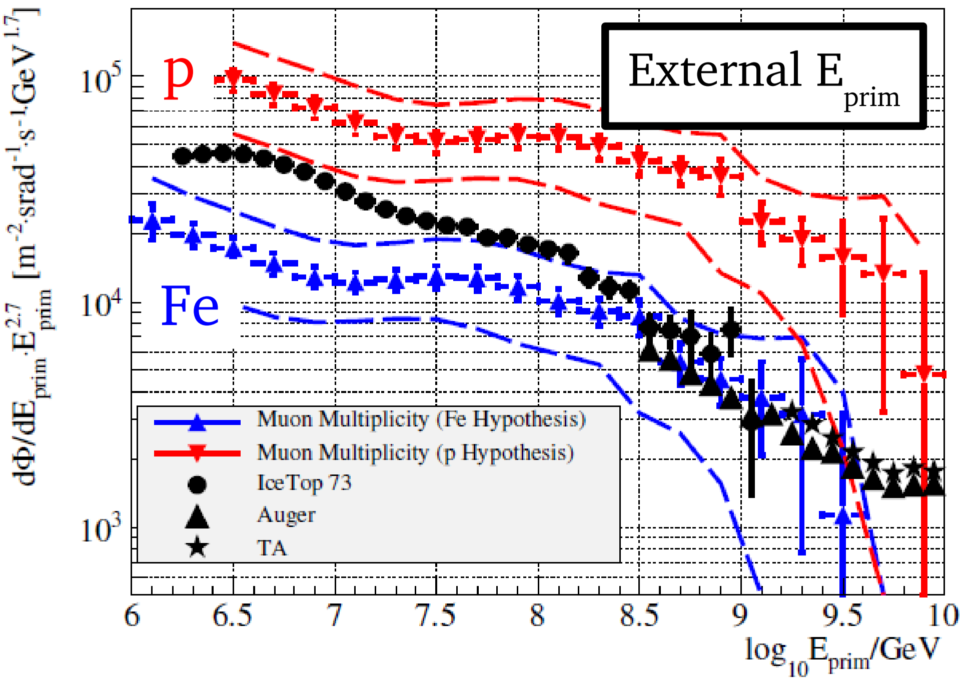




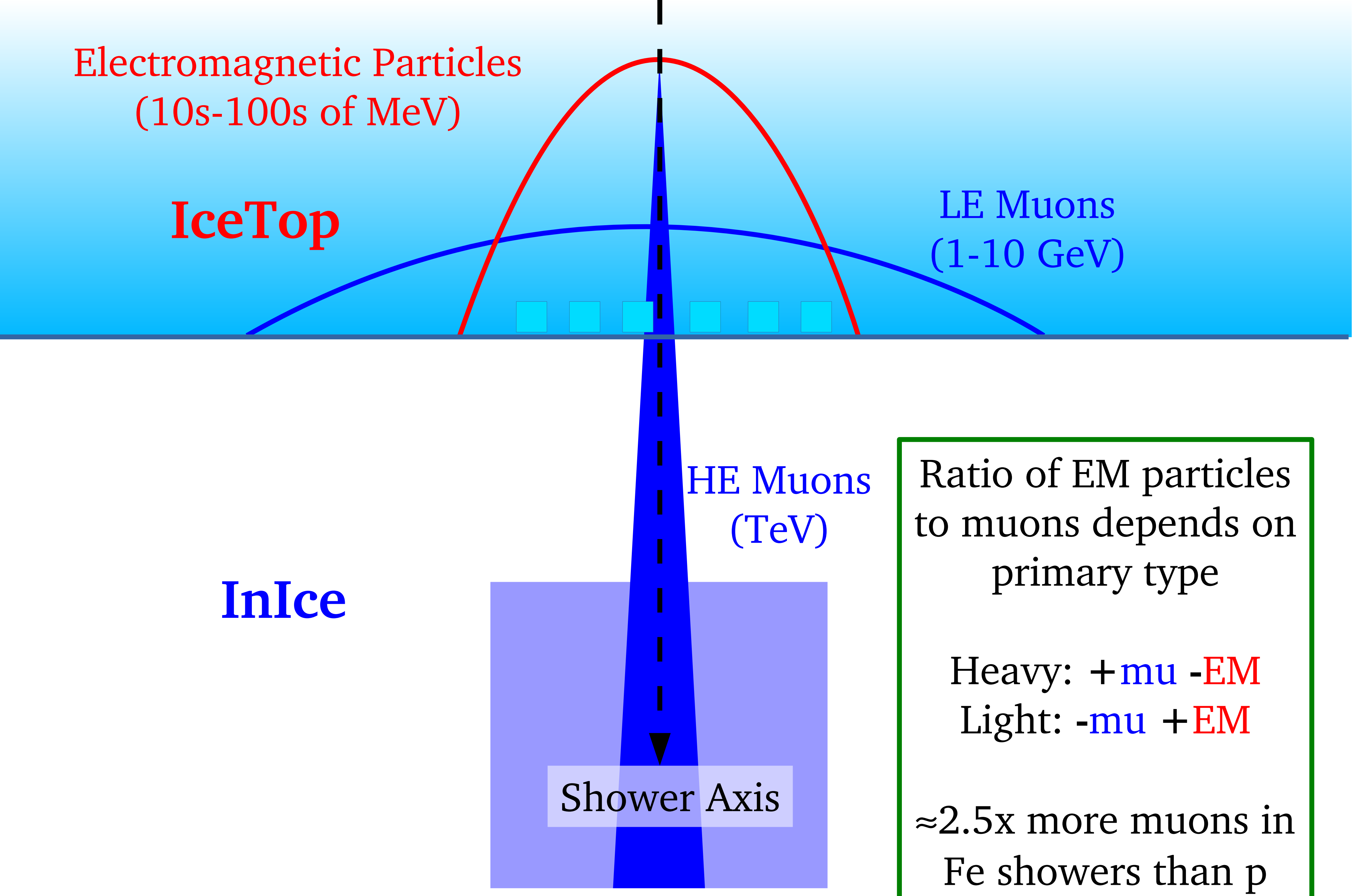
Median Energy in detector:
about 300 GeV
(exact value depending on angle)

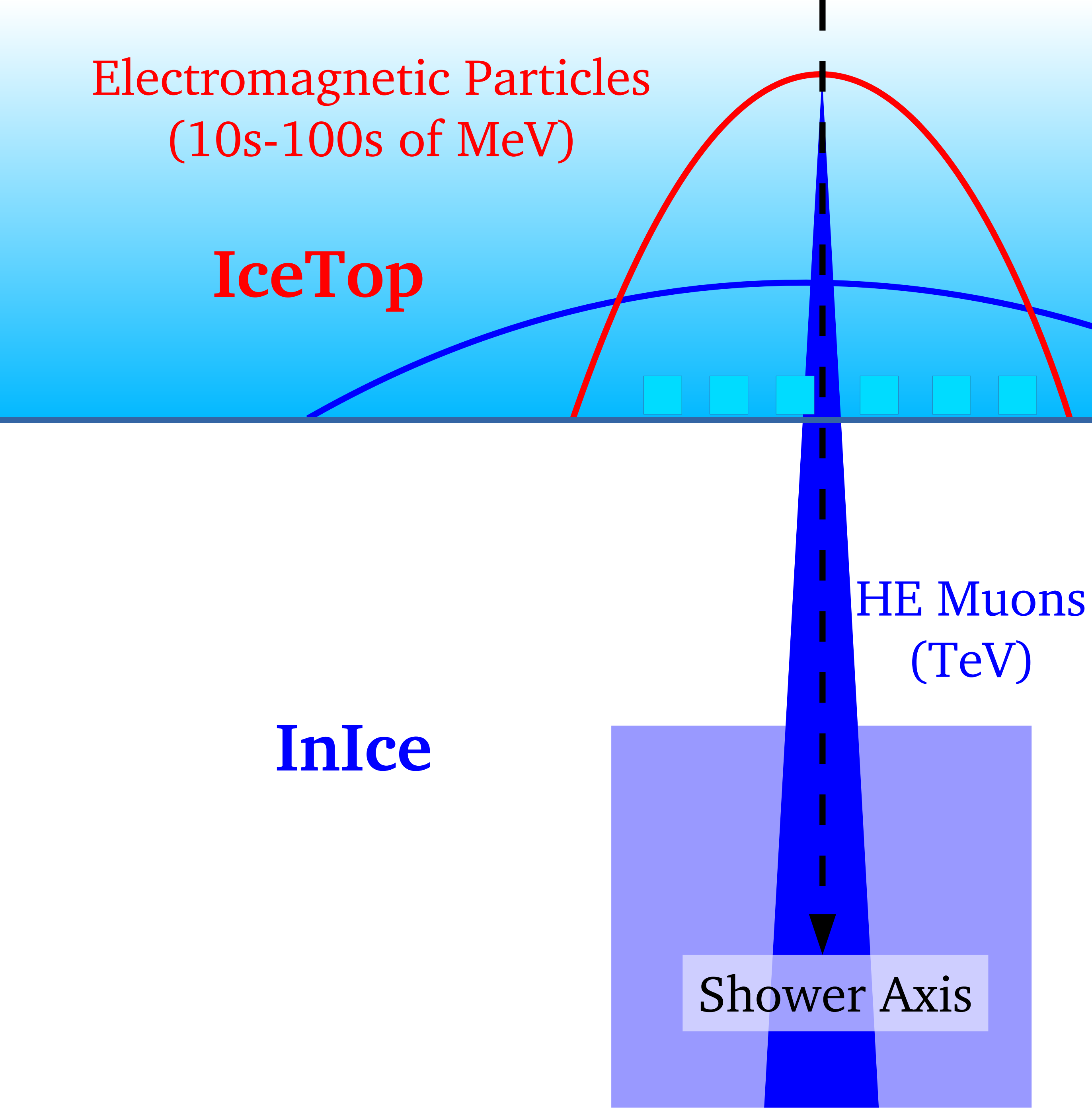
Bundle Spectrum





Bundles cover CR energy range from knee to ankle
Lower energy limit due to Fe threshold


Electromagnetic Particles
(10s-100s of MeV)
IceTop
LE Muons
(1-10 GeV)
HE Muons
(TeV)
InIce
Shower Axis
Ratio of EM particles to muons depends on primary type
Heavy: +mu -EM
Light: -mu +EM
≈2.5x more muons in Fe showers than p

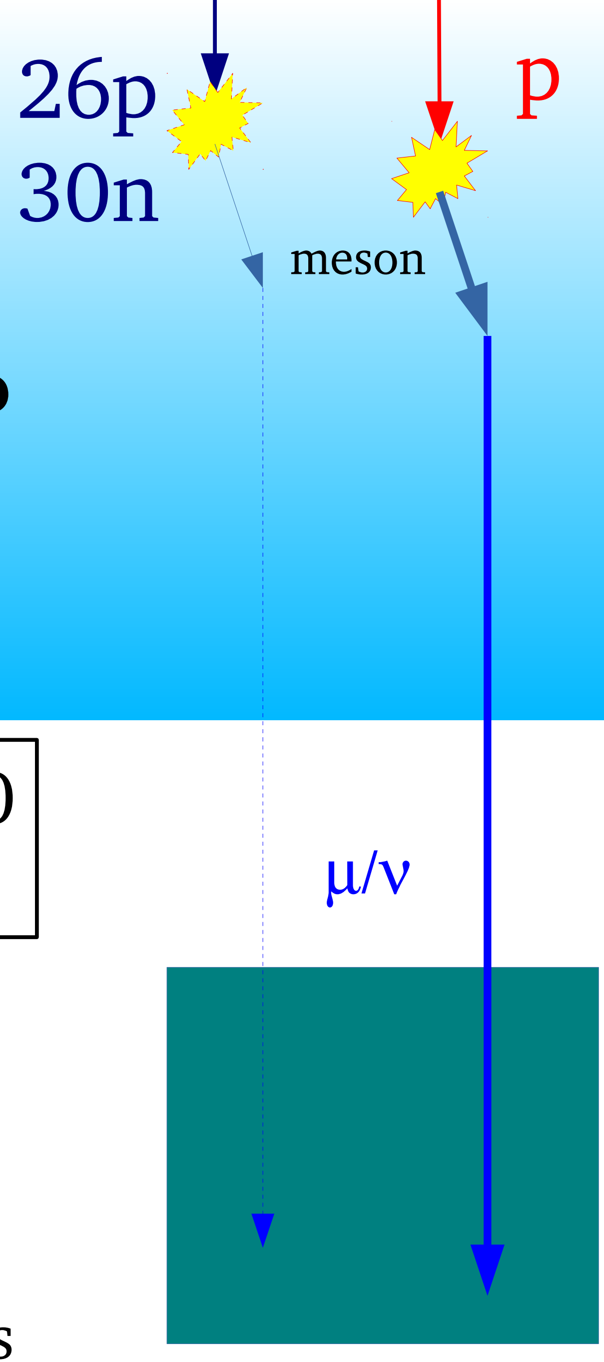


Ratio of EM particles to muons depends on primary type

Heavy: +mu -EM
Light: -mu +EM

≈2.5x more muons in Fe showers than p

High-Energy Muon/Neutrino

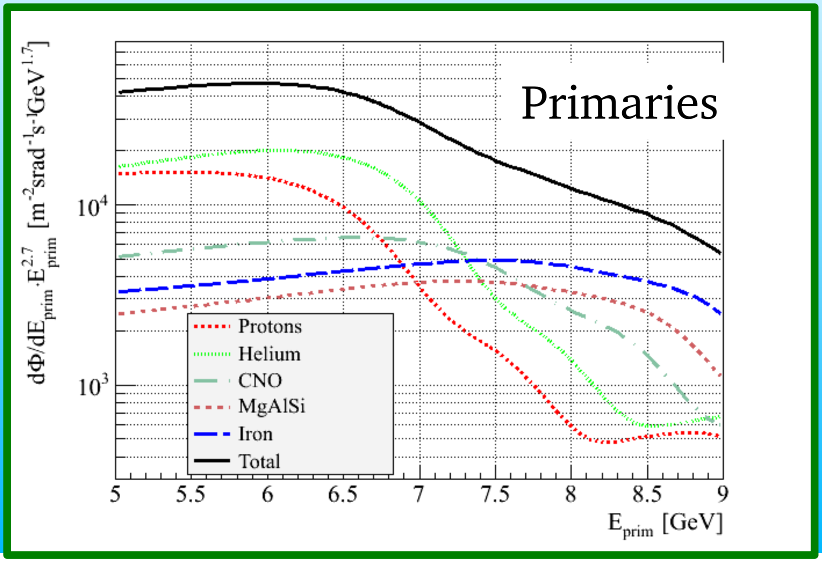


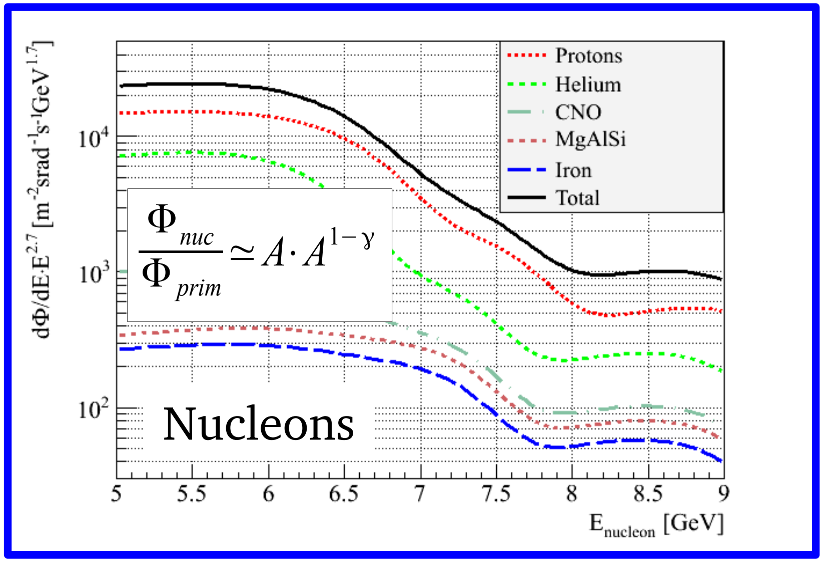
$$E_{\text{nucleon}}/E_{\text{lepton}} \simeq 10$$

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

Energy Spectrum follows **Nucleons**

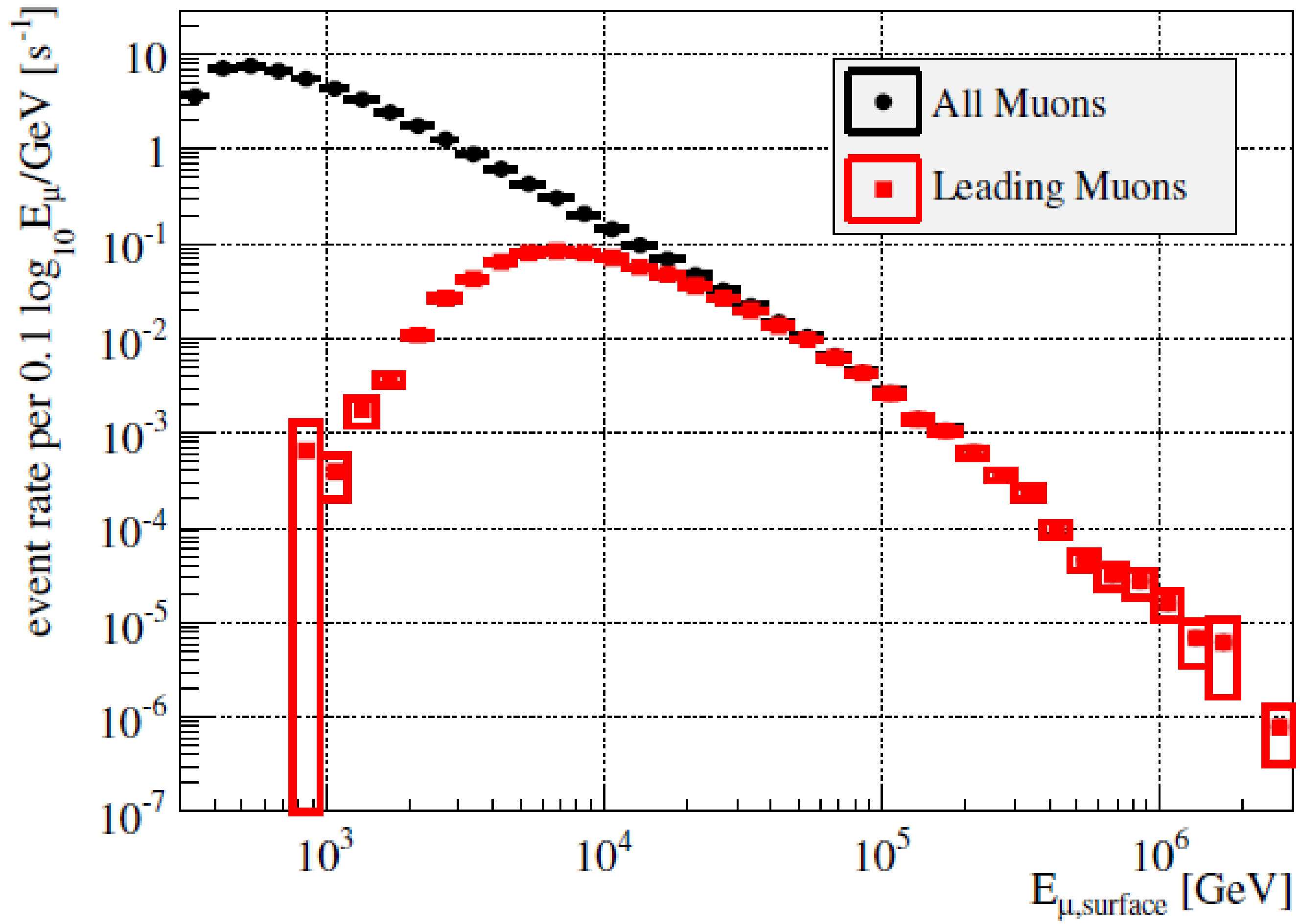
Main contribution from **light** primaries





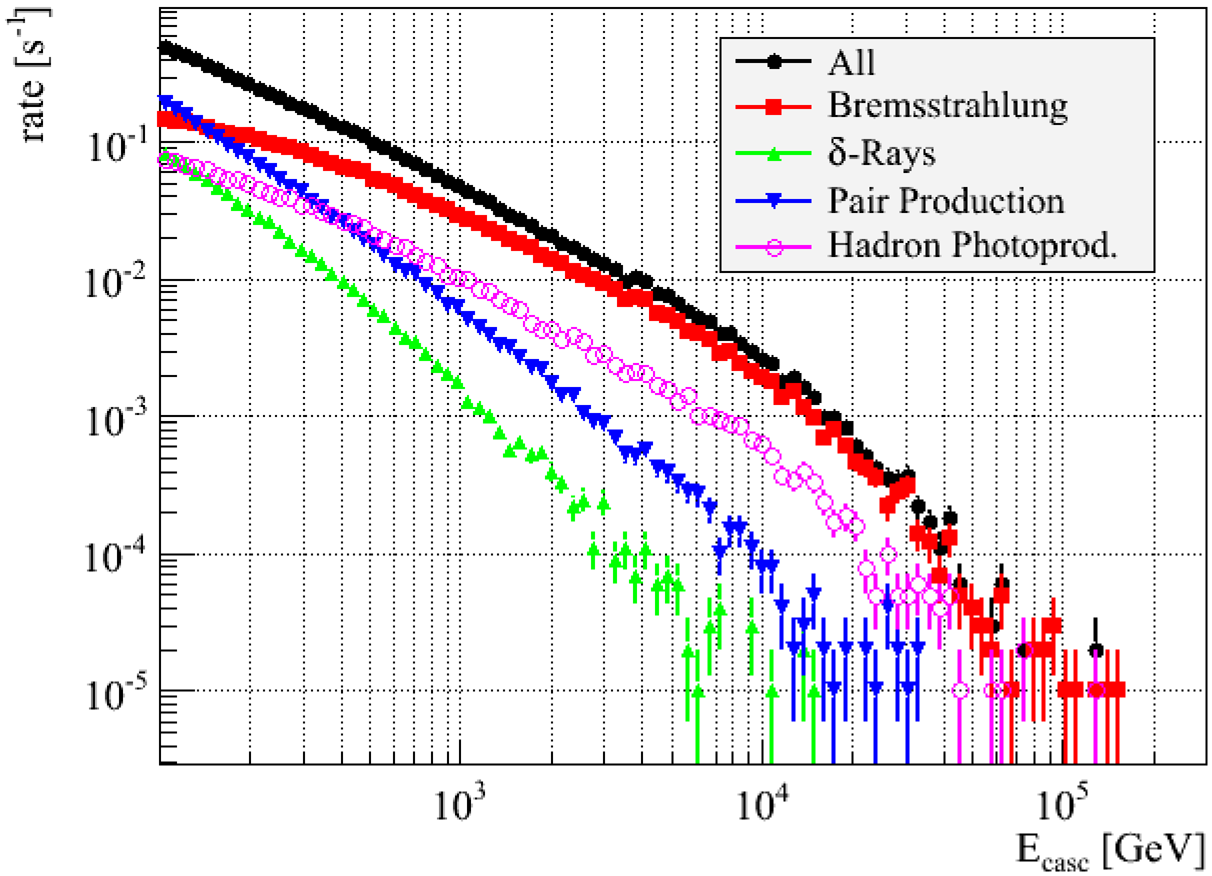
Example: Gaisser H3a

Leading Muons

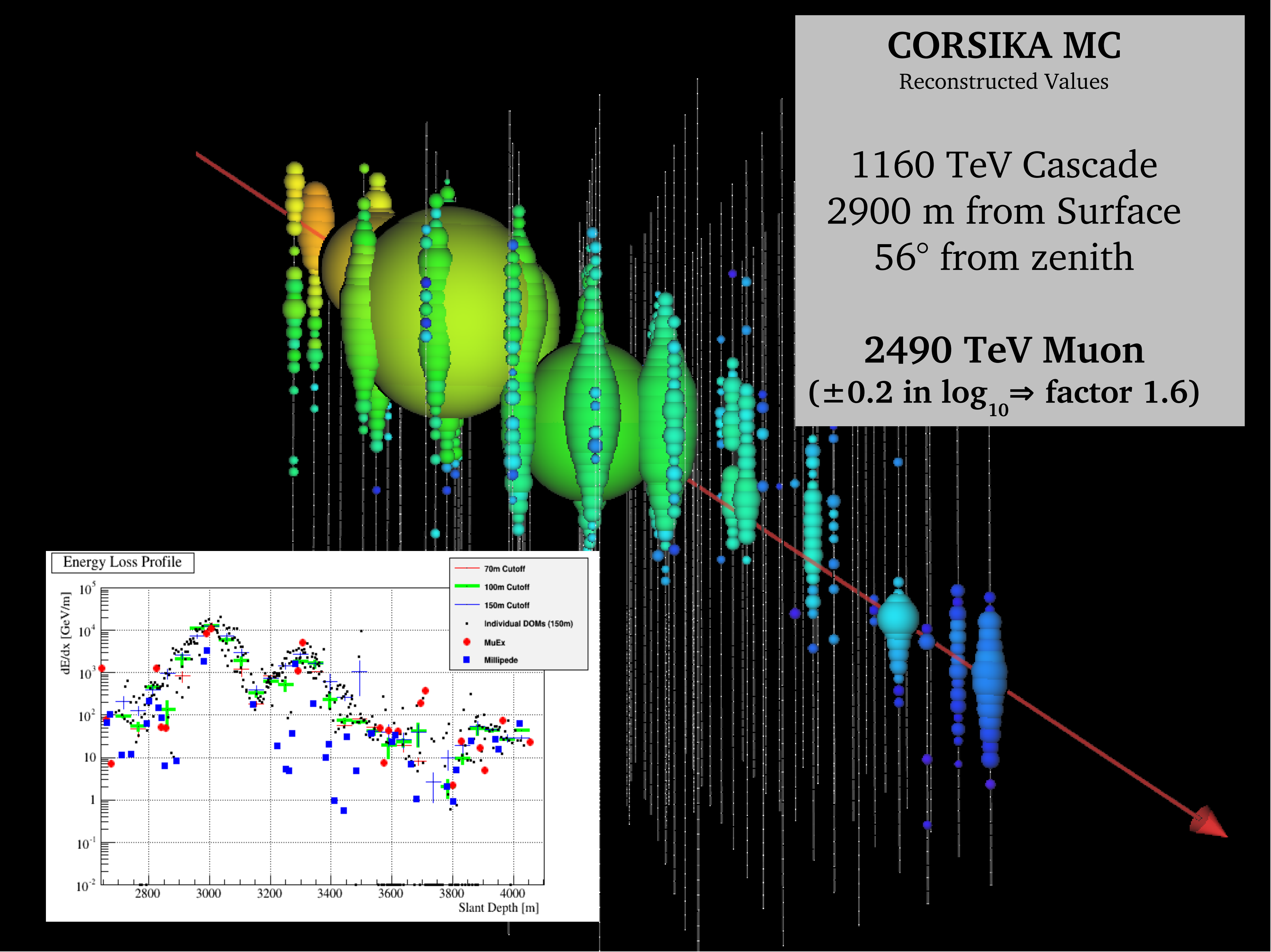


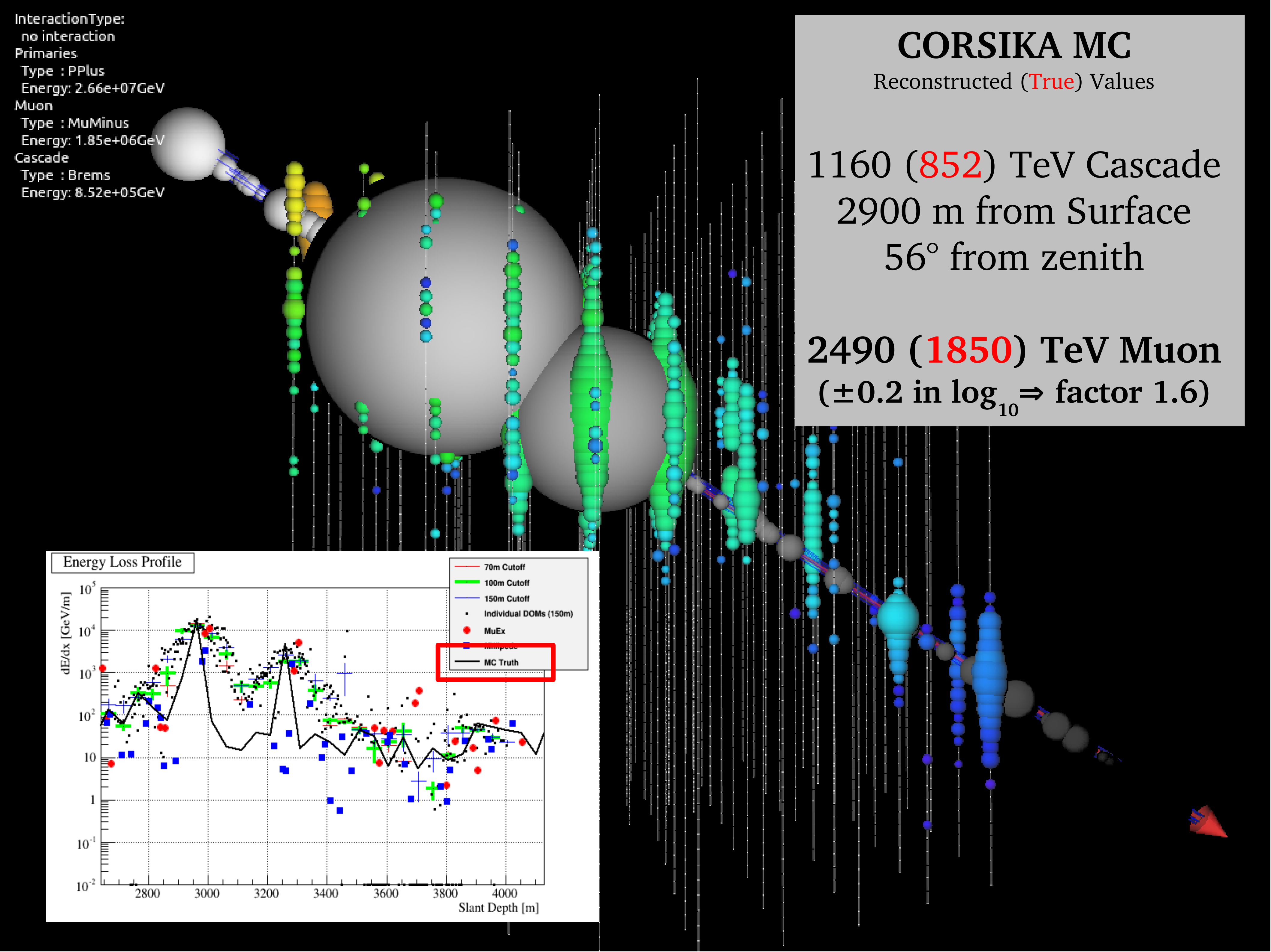
Muons with energies of 20 TeV and above at the surface will be almost always be the leading particle.

Muon Stochastic Losses in IceCube



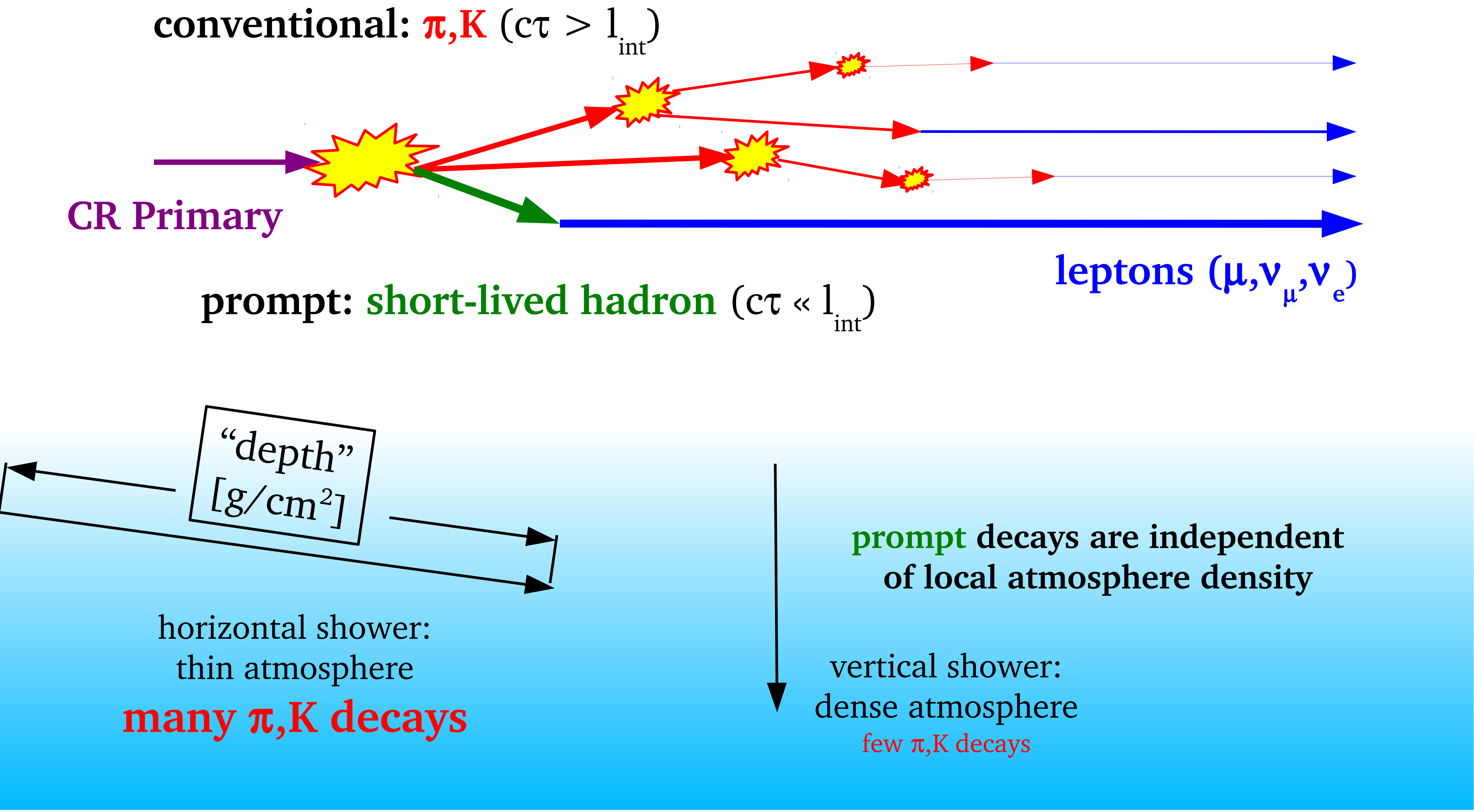
MMC Simulation Output
Rigidity-Dependent poly-gonato


CORSIKA MC
Reconstructed Values
1160 TeV Cascade
2900 m from Surface
56° from zenith
2490 TeV Muon
(±0.2 in log10⇒ factor 1.6)
Energy Loss Profile
70m Cutoff
100m Cutoff
150m Cutoff
Individual DOMs (150m)
MuEx
Millipede
dE/dx [GeV/m]
Slant Depth [m]
2800
3000
3200
3400
3600
3800
4000

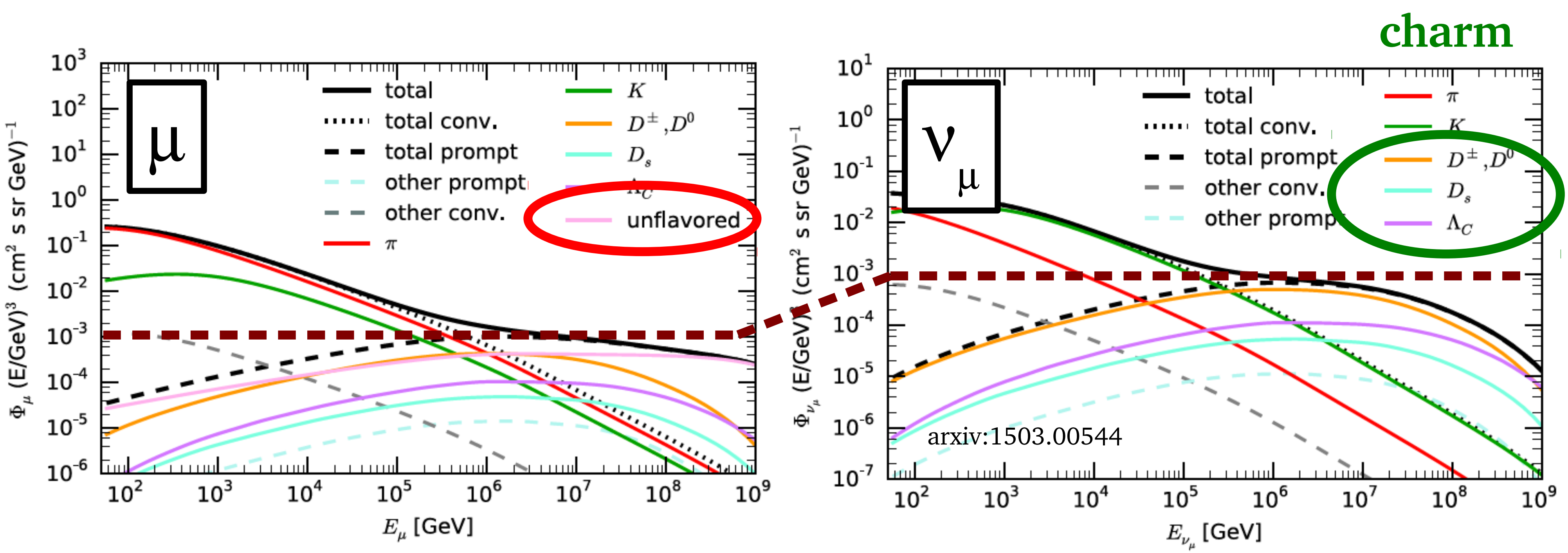


InteractionType:
no interaction
Primaries
Type : PPlus
Energy: 2.66e+07GeV
Muon
Type : MuMinus
Energy: 1.85e+06GeV
Cascade
Type : Brems
Energy: 8.52e+05GeV
CORSIKA MC
Reconstructed (True) Values
1160 (852) TeV Cascade
2900 m from Surface
56° from zenith
2490 (1850) TeV Muon
(±0.2 in log10 ⇒ factor 1.6)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

"Prompt": Decay without Re-Interaction



Prompt ≠ Charm



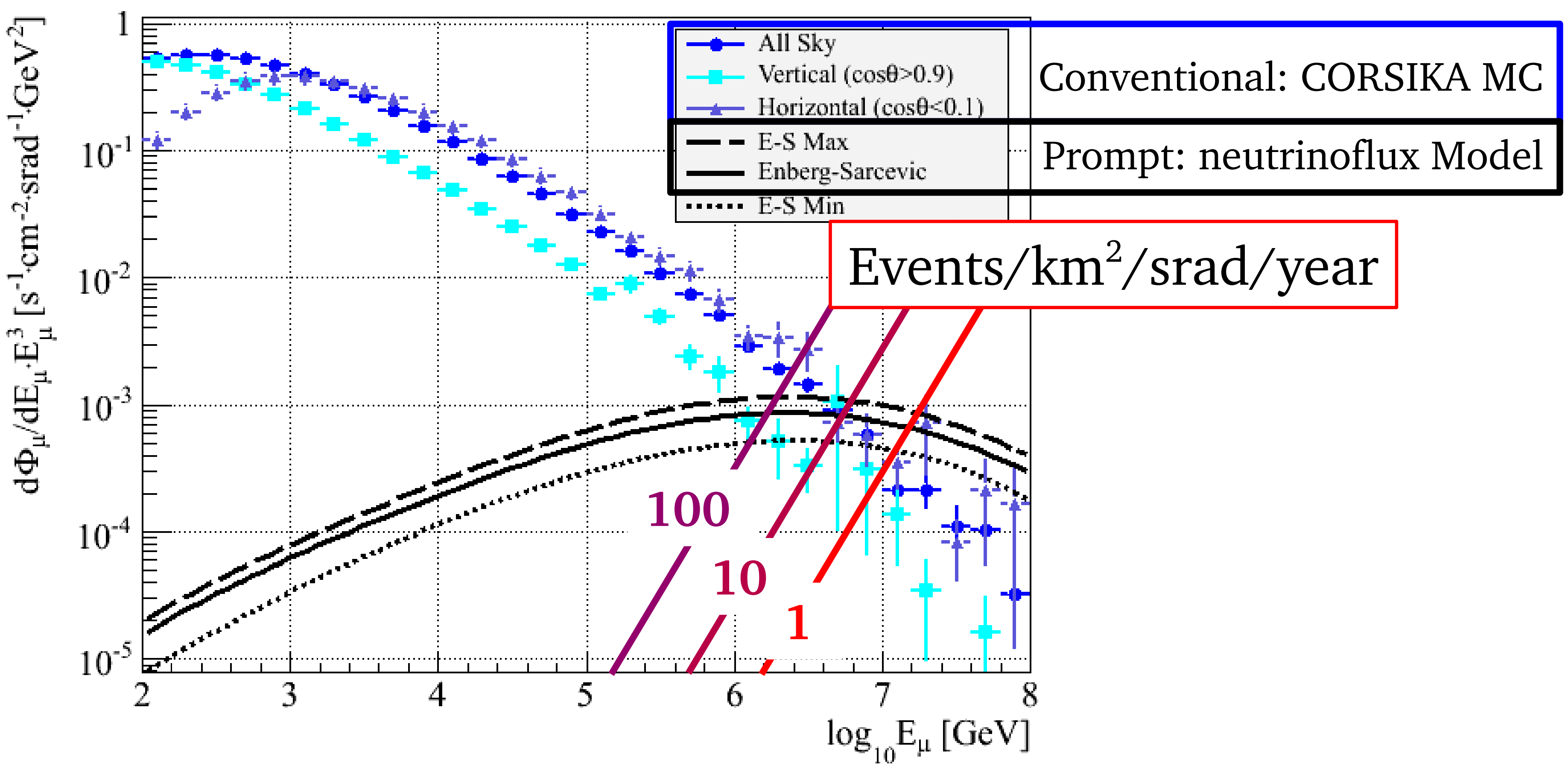
Muons can be produced in e-m decays of short-lived vector mesons

SIBYLL 2.3RC (shown above): charm ≃ ERS charm ≃ unflavored

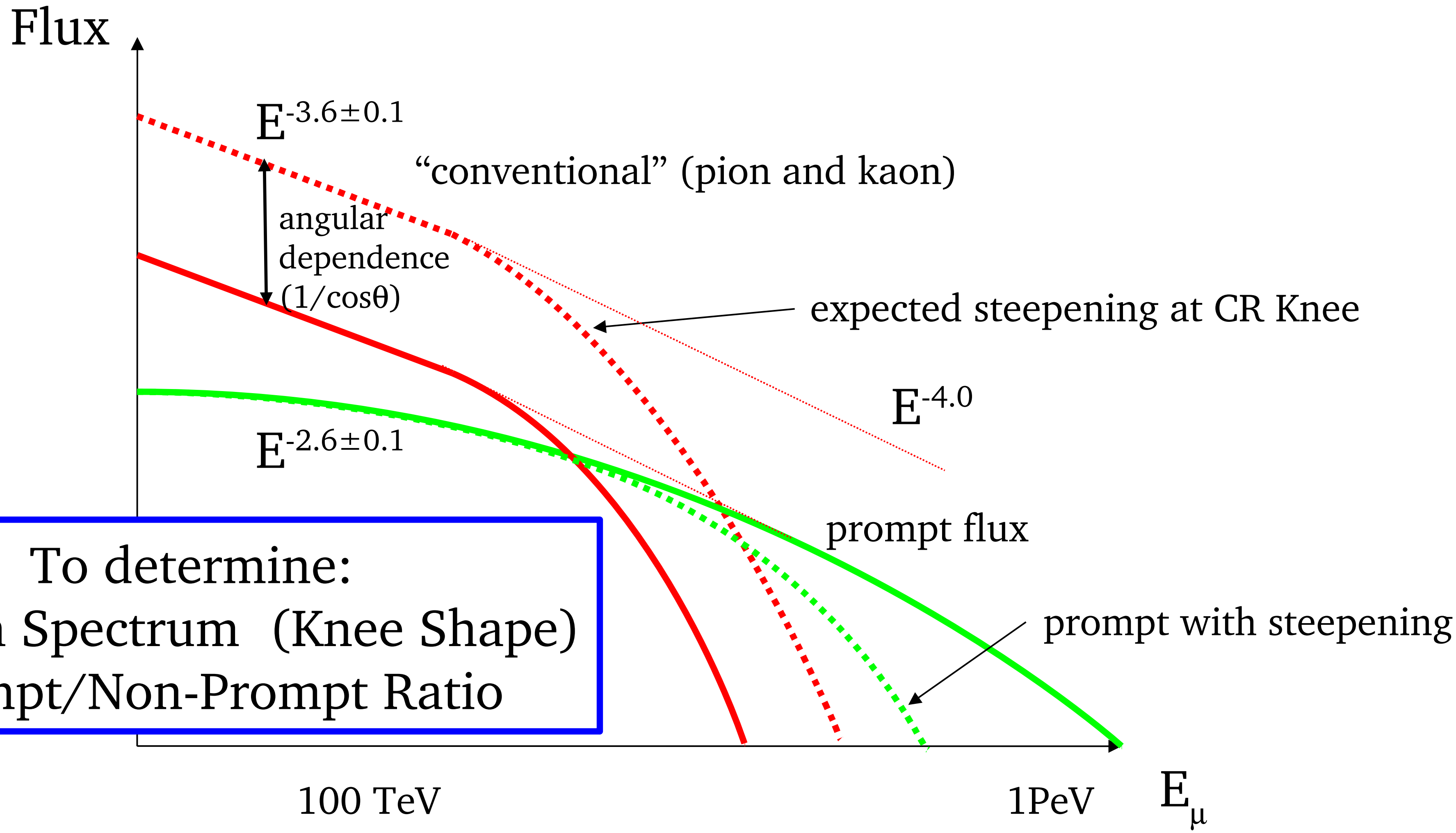
New “BERSS” model (arxiv:1502.01076): charm ≃ ERS charm/2!

Muon Prompt Flux might be predominantly unflavored

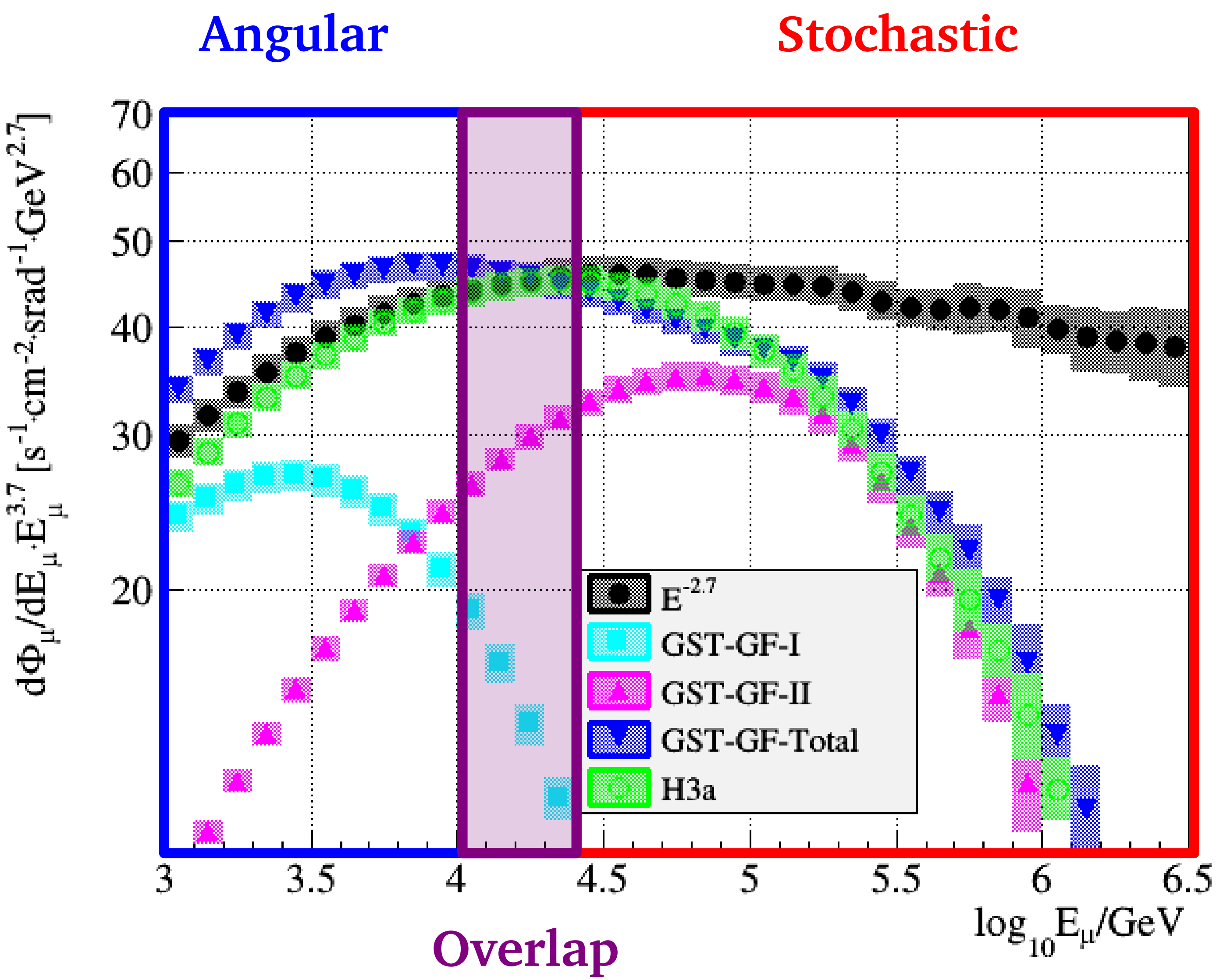
HE Muon Event Rate



Muon Spectrum (Qualitative)

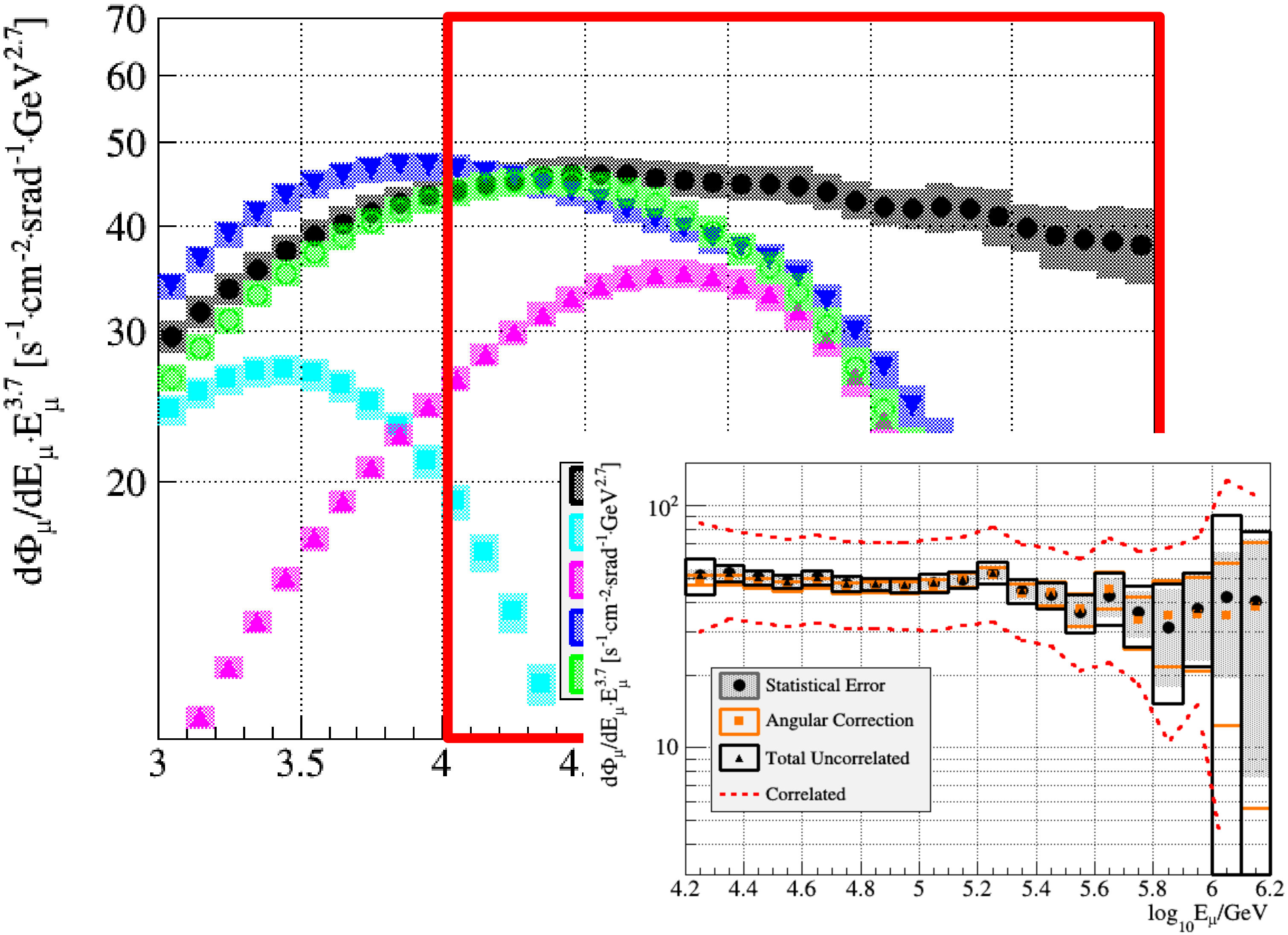


To determine:
Nucleon Spectrum (Knee Shape)
Prompt/Non-Prompt Ratio



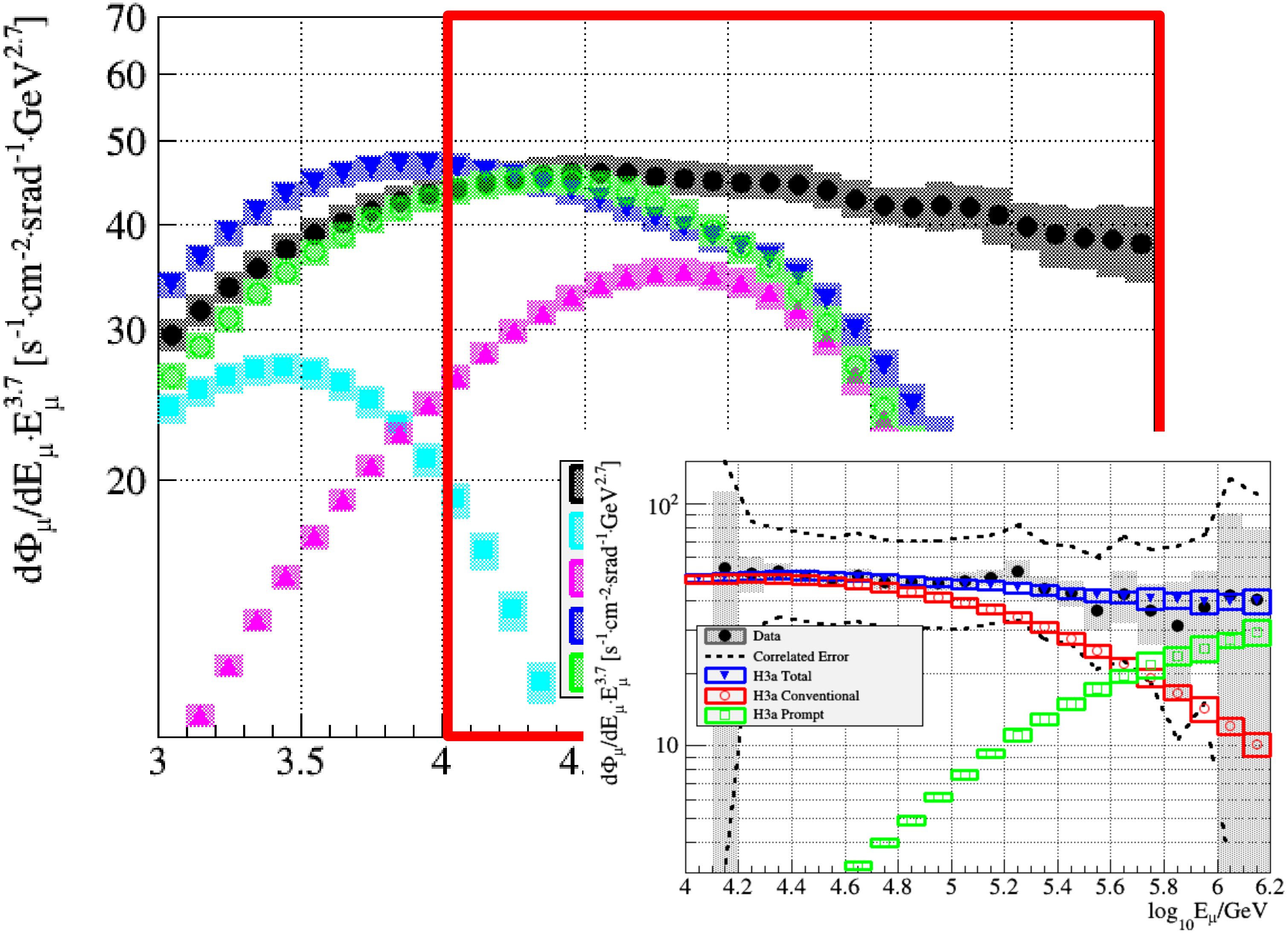
IceCube Muon Energy Range

Stochastic



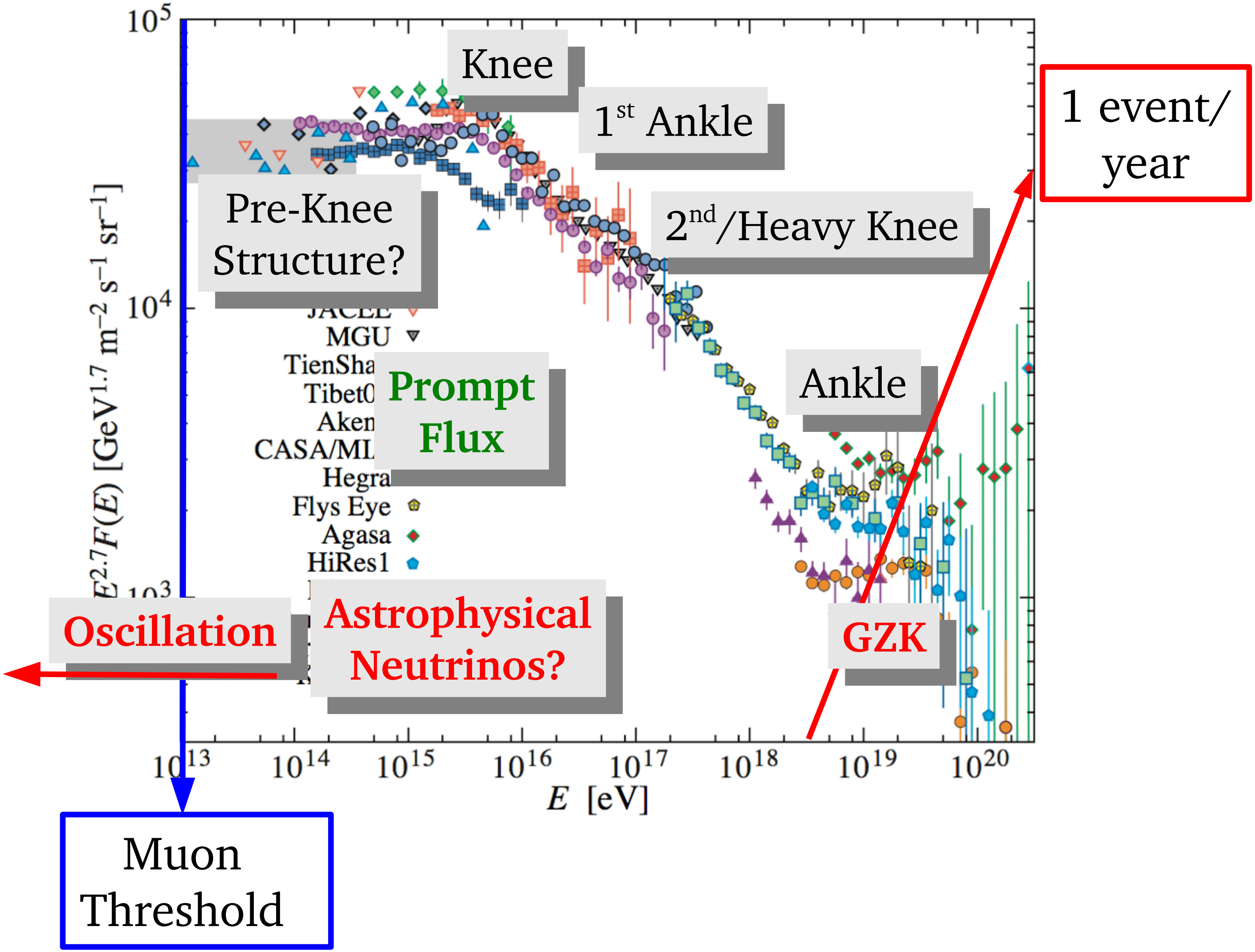
$d\Phi_\mu/dE_\mu \cdot E_\mu^{3.7}$ [$s^{-1} \cdot cm^{-2} \cdot srad^{-1} \cdot GeV^{2.7}$]
70
60
50
40
30
20
3
3.5
4
Statistical Error
Angular Correction
Total Uncorrelated
Correlated
10^2
10
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2
$\log_{10} E_\mu$/GeV

Stochastic

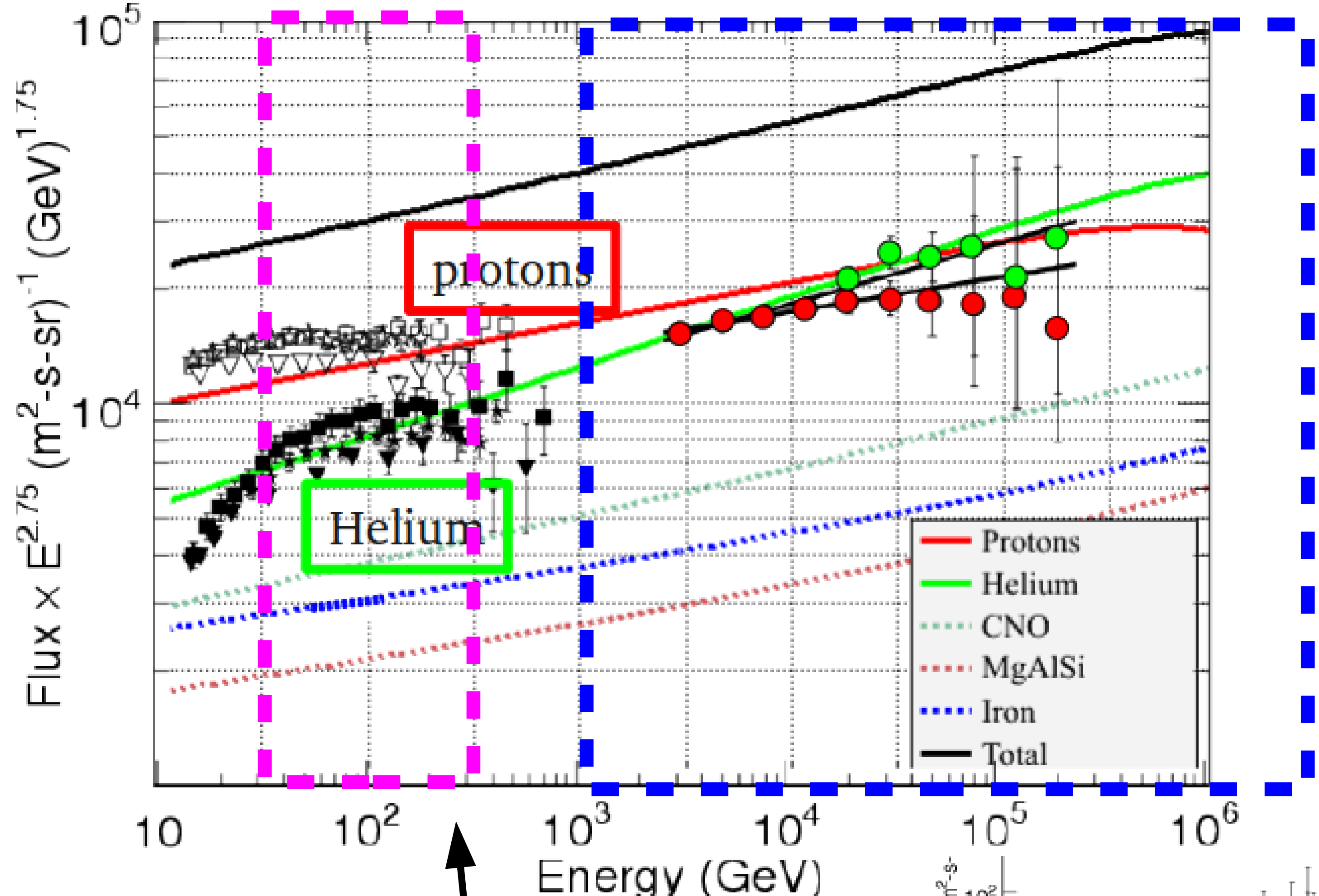


70
60
50
40
30
20
3
3.5
4
$d\Phi_\mu/dE_\mu \cdot E_\mu^{3.7}$ [$s^{-1} \cdot cm^{-2} \cdot srad^{-1} \cdot GeV^{2.7}$]
10^2
10
Data
Correlated Error
H3a Total
H3a Conventional
H3a Prompt
4
4.2
4.4
4.6
4.8
5
5.2
5.4
5.6
5.8
6
6.2
$\log_{10} E_\mu$/GeV

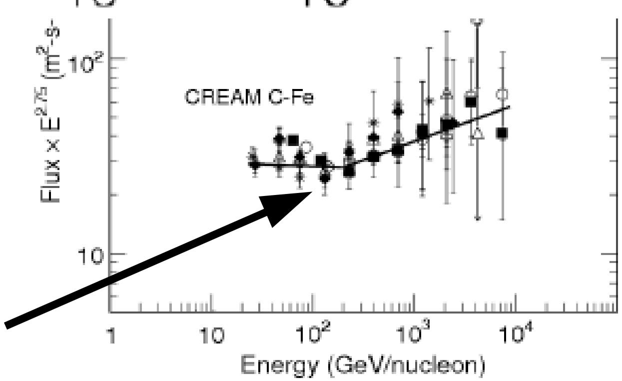
CR Energy Range of IceCube

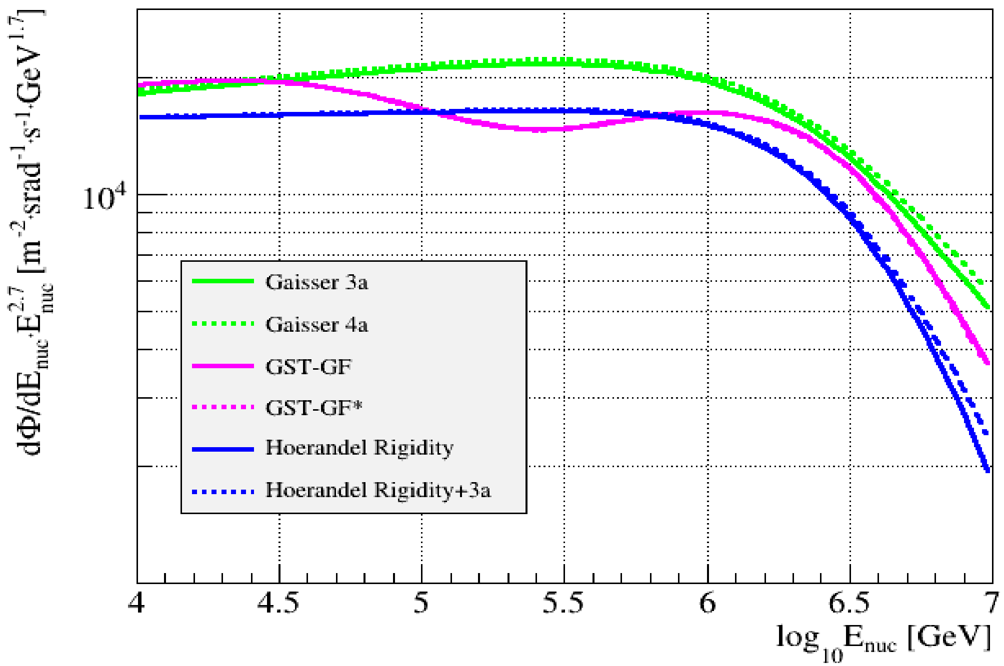


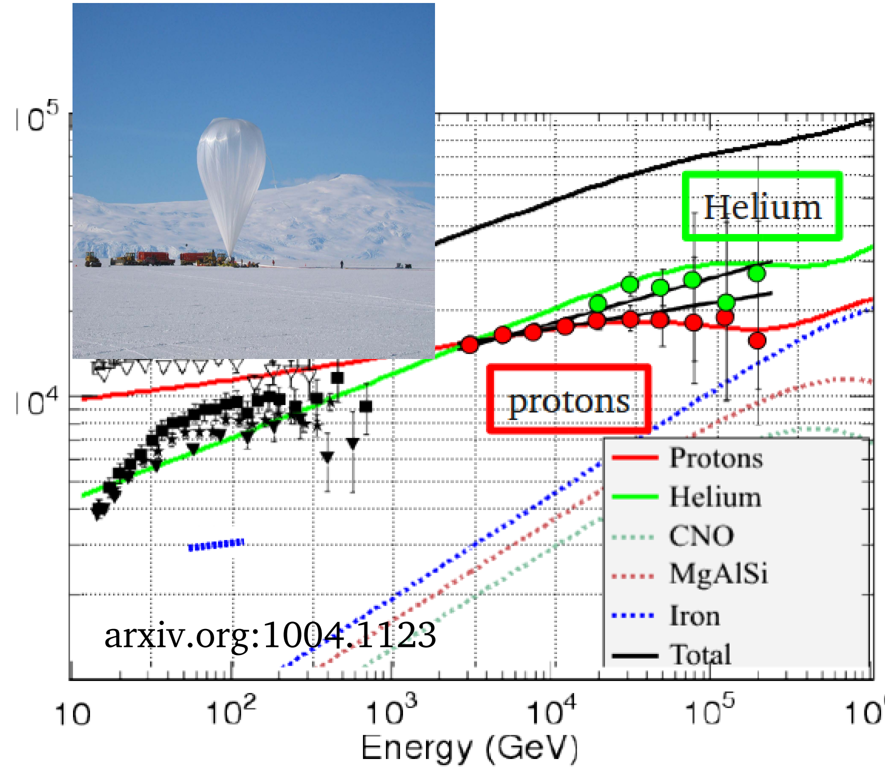
LE Oscillations **Main IceCube Energy Region**

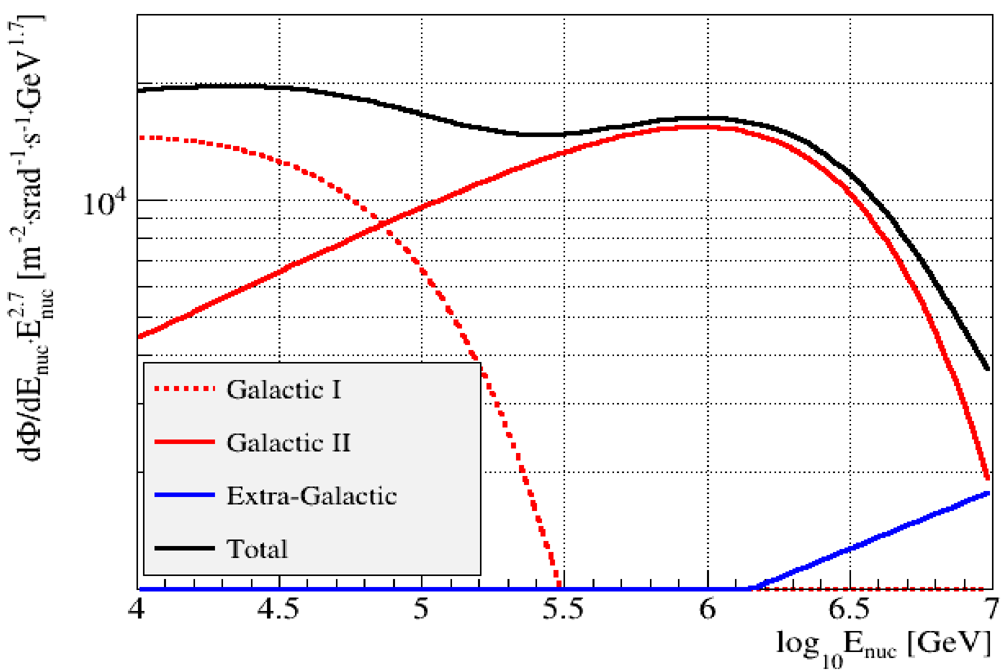


In particular, recent observations by CREAM [15,16] show an overall harder helium spectrum as compared to protons and, mainly, a flattening of their spectral index at about 230 GeV/nucleon.









"Global Fit" (Gaisser/Stanev/**Tilav**): Additional Population with Cutoff at 120 TeV/Z