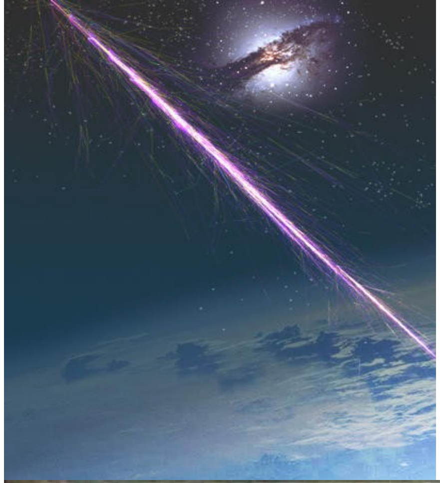
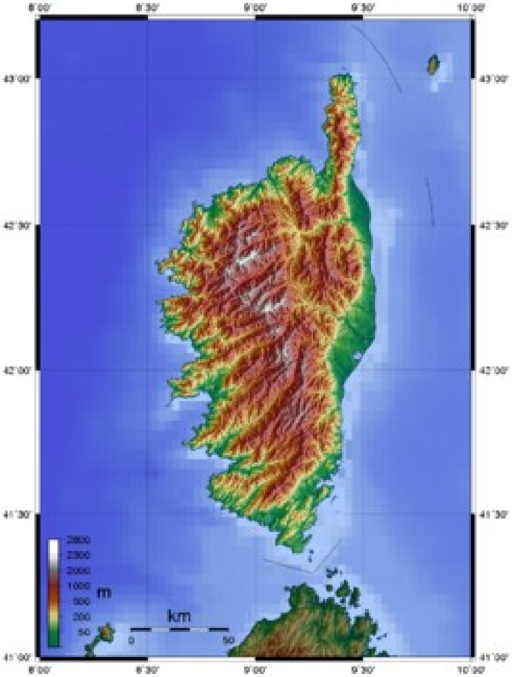
CORSIKA



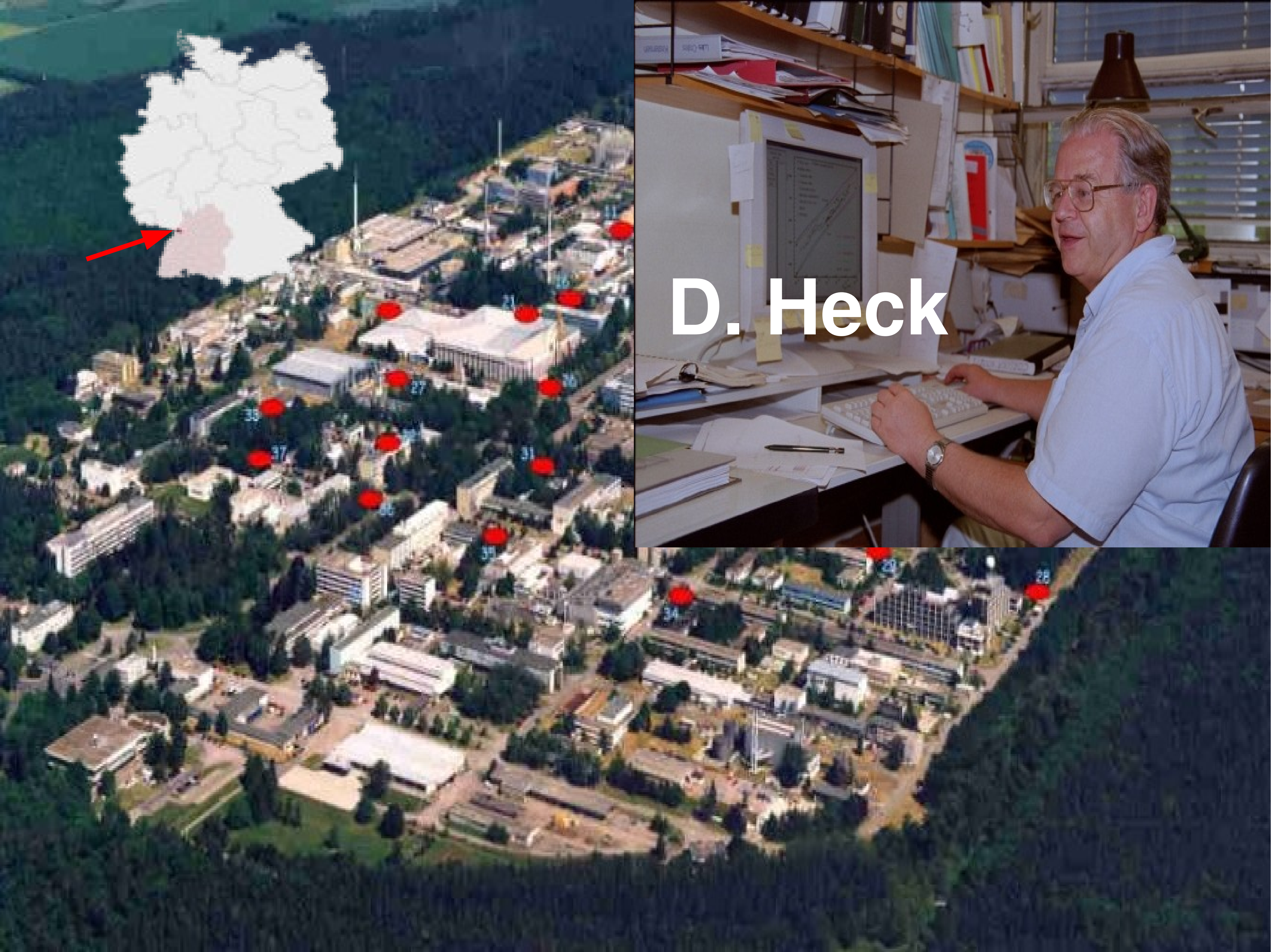
Voilà un rayon cosmique !

(Look, a cosmic ray!)

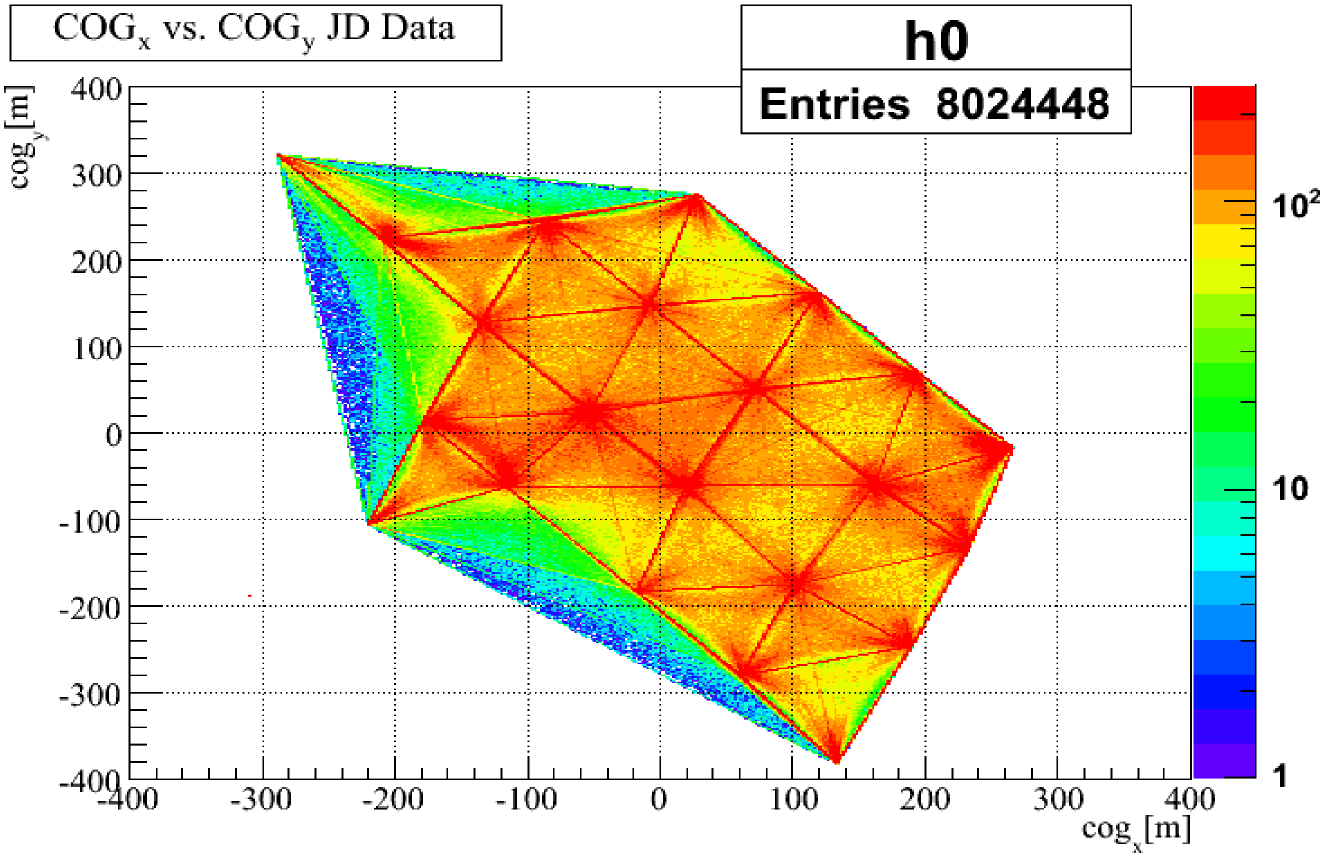


CORSIKA

COsmic **R**ay **SI**mulations for **KA**scade

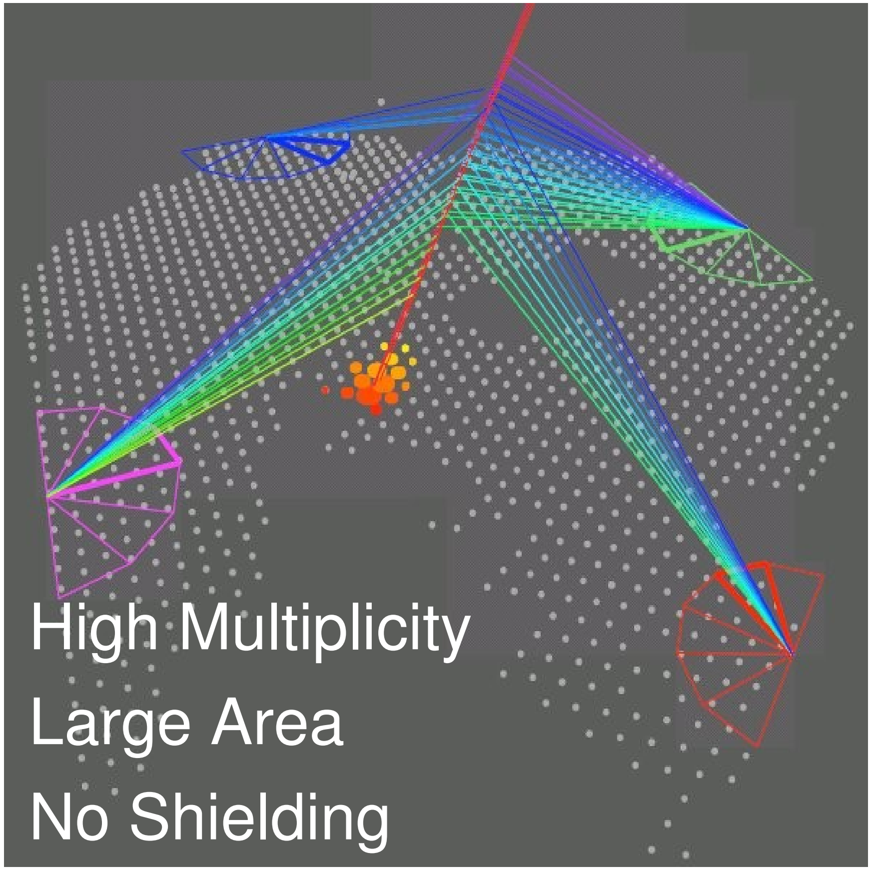

D. Heck

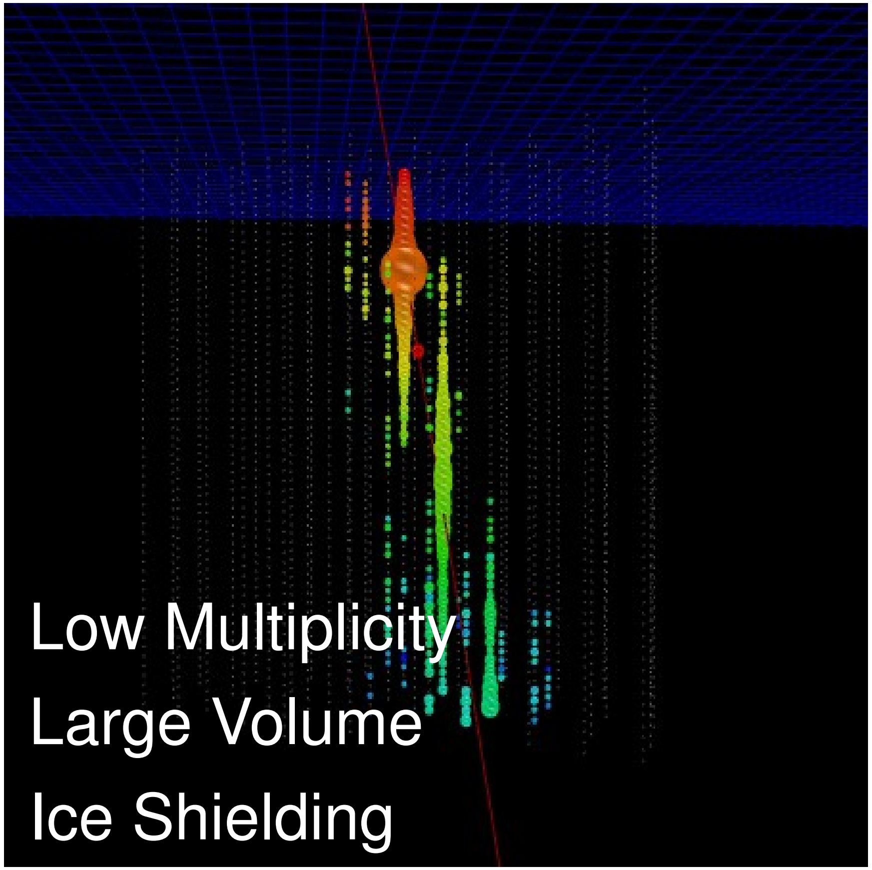
Why do we need Corsika?



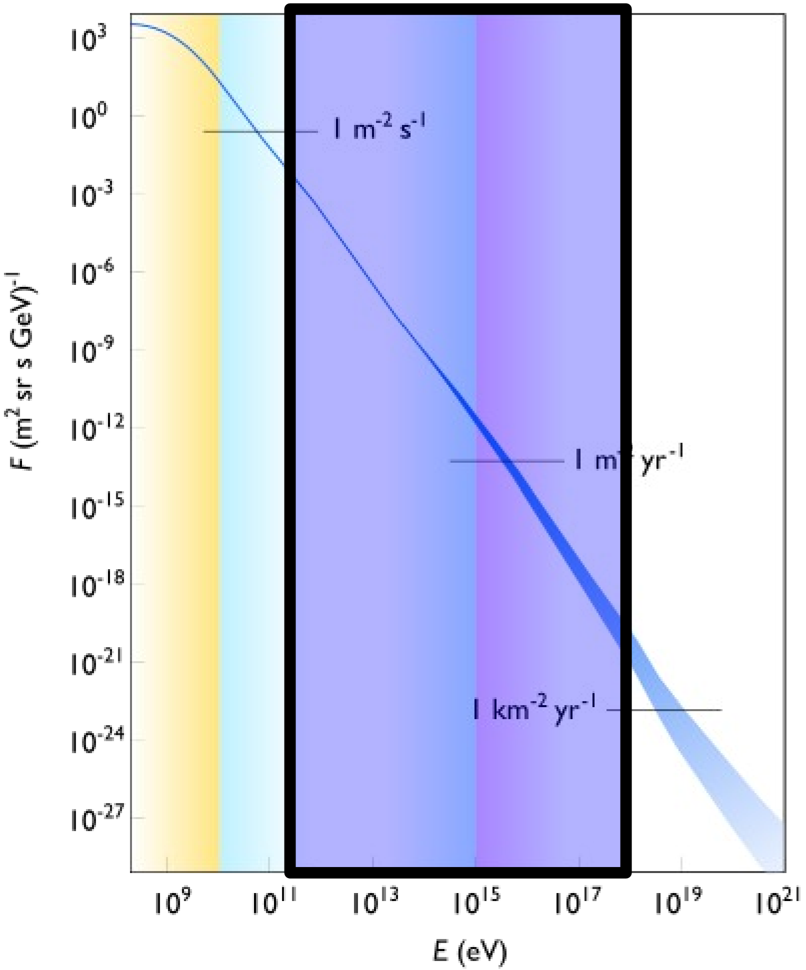
99.999% μ!

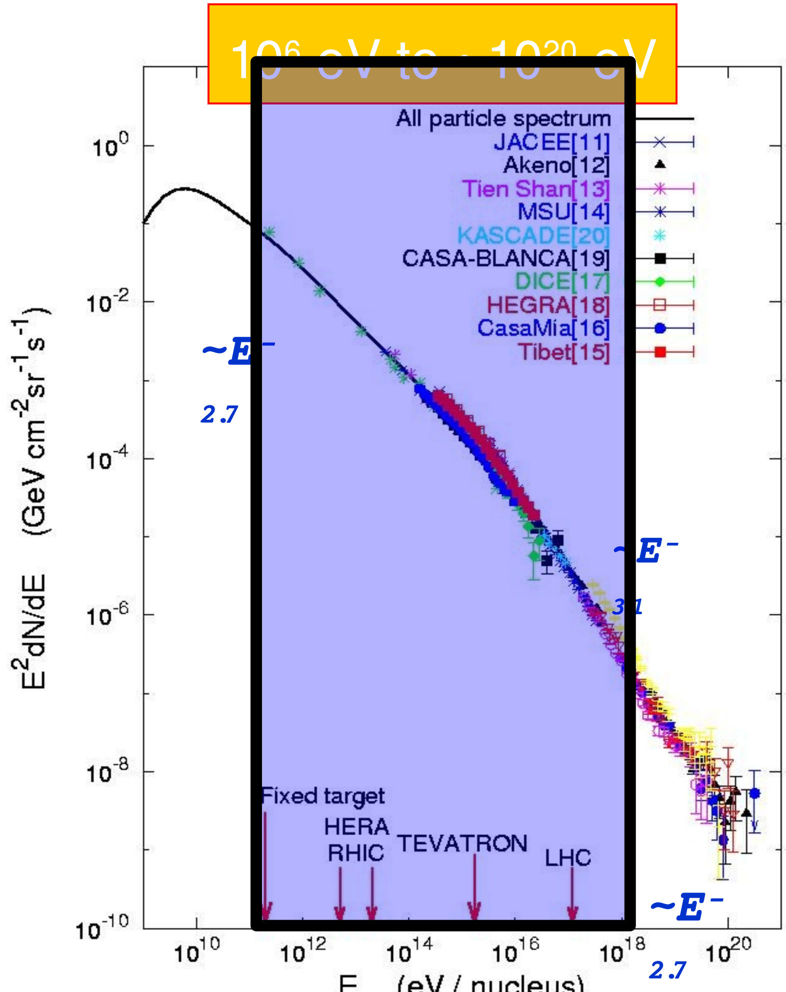
Auger vs. IceCube





CR



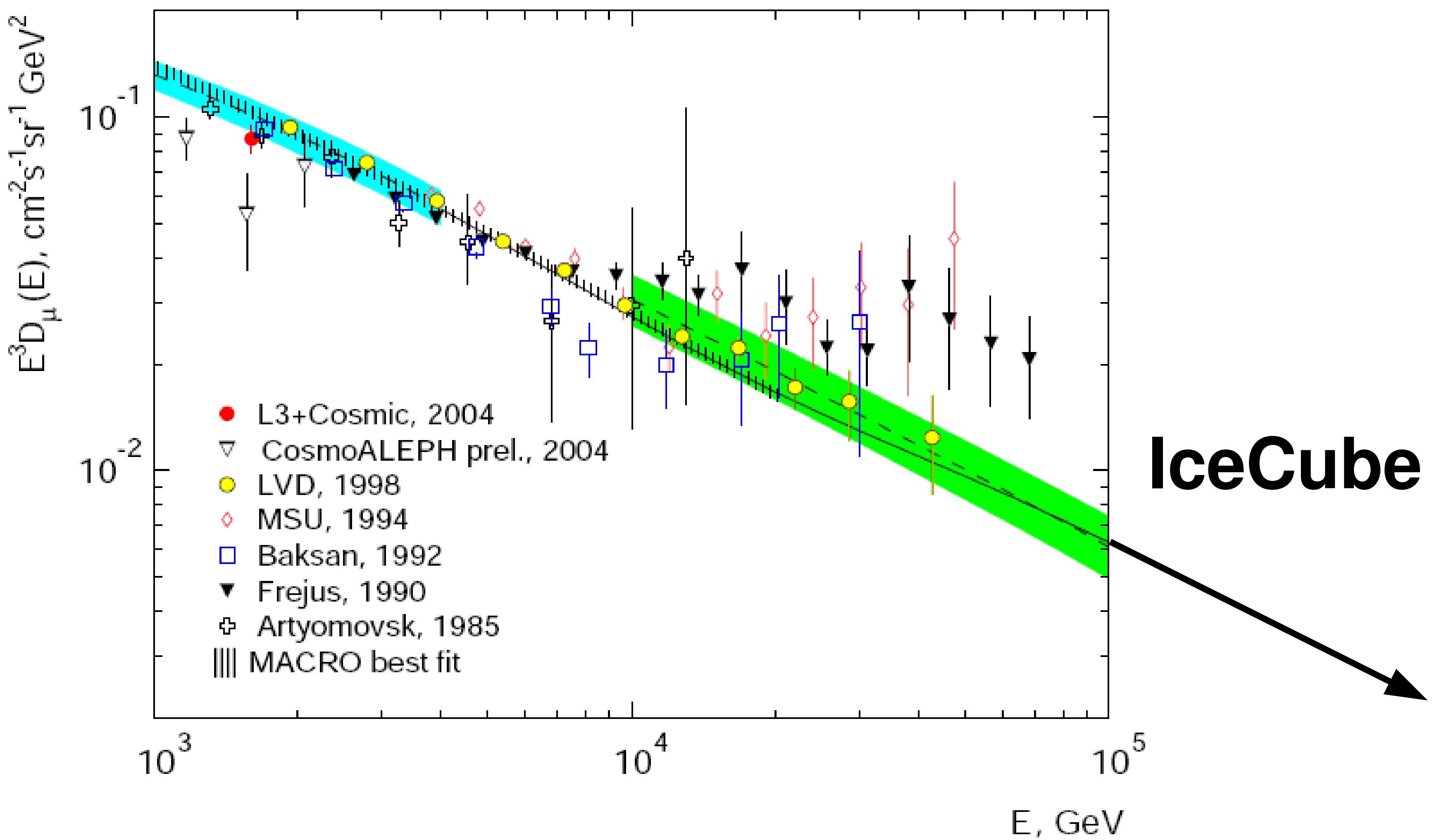


After T. Gaisser, ICHEP02

IceCube

[GeV]

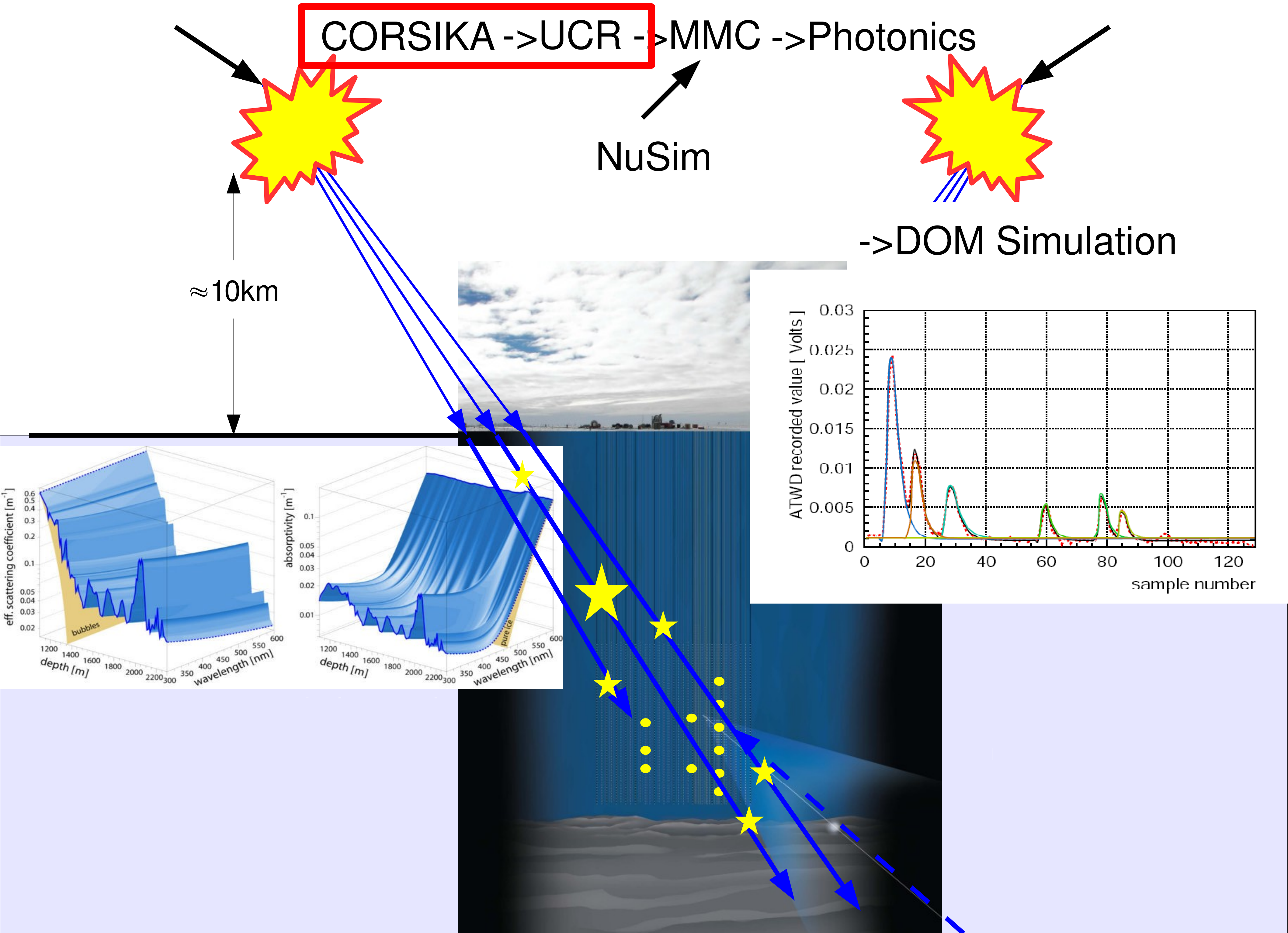
Muons



Calculation of the atmospheric muon flux motivated by the ATIC-2 experiment

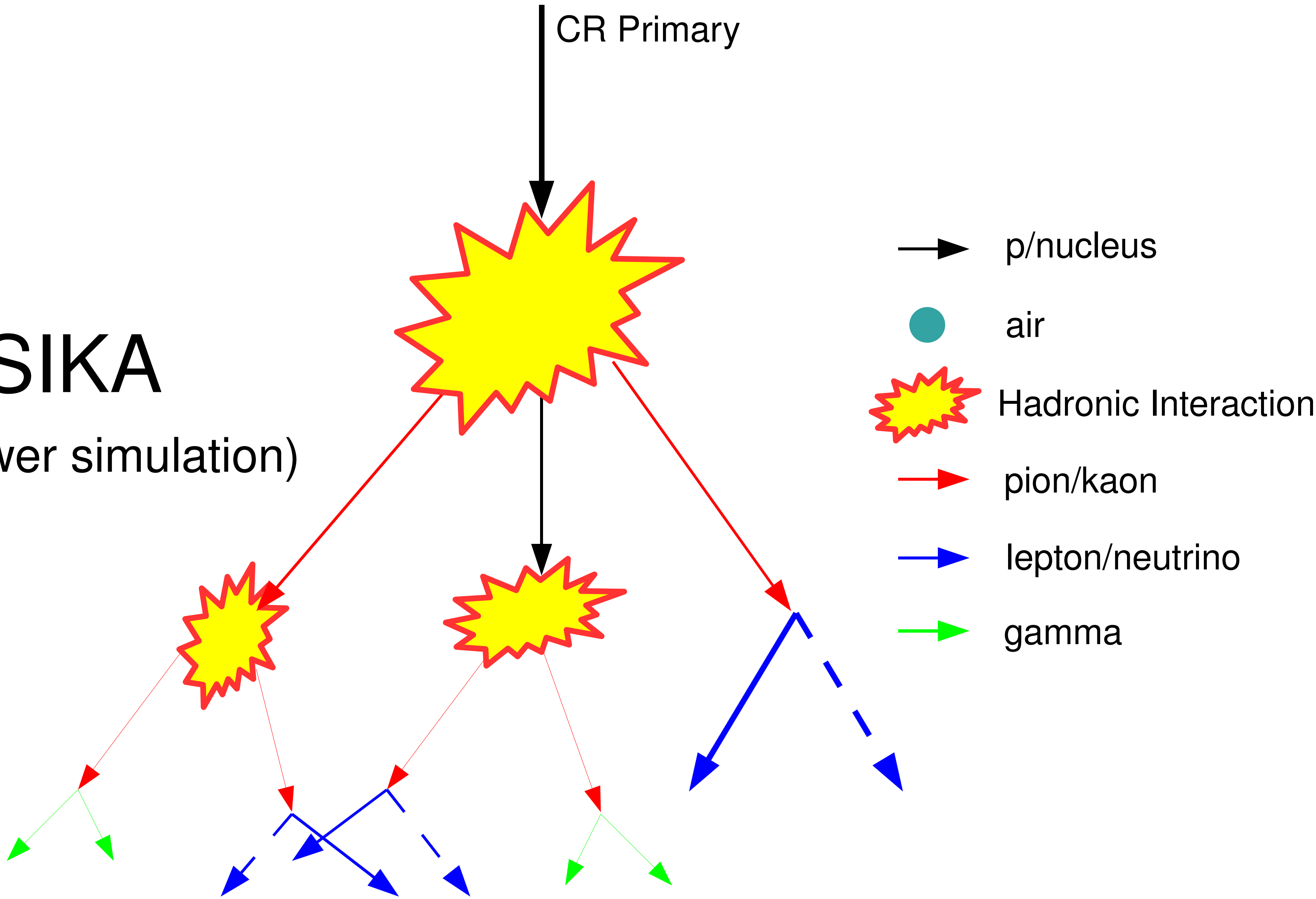
A. A. Kochanov[1], A. D. Panov[2], T. S. Sinegovskaya[1] and S. I. Sinegovsky[1].

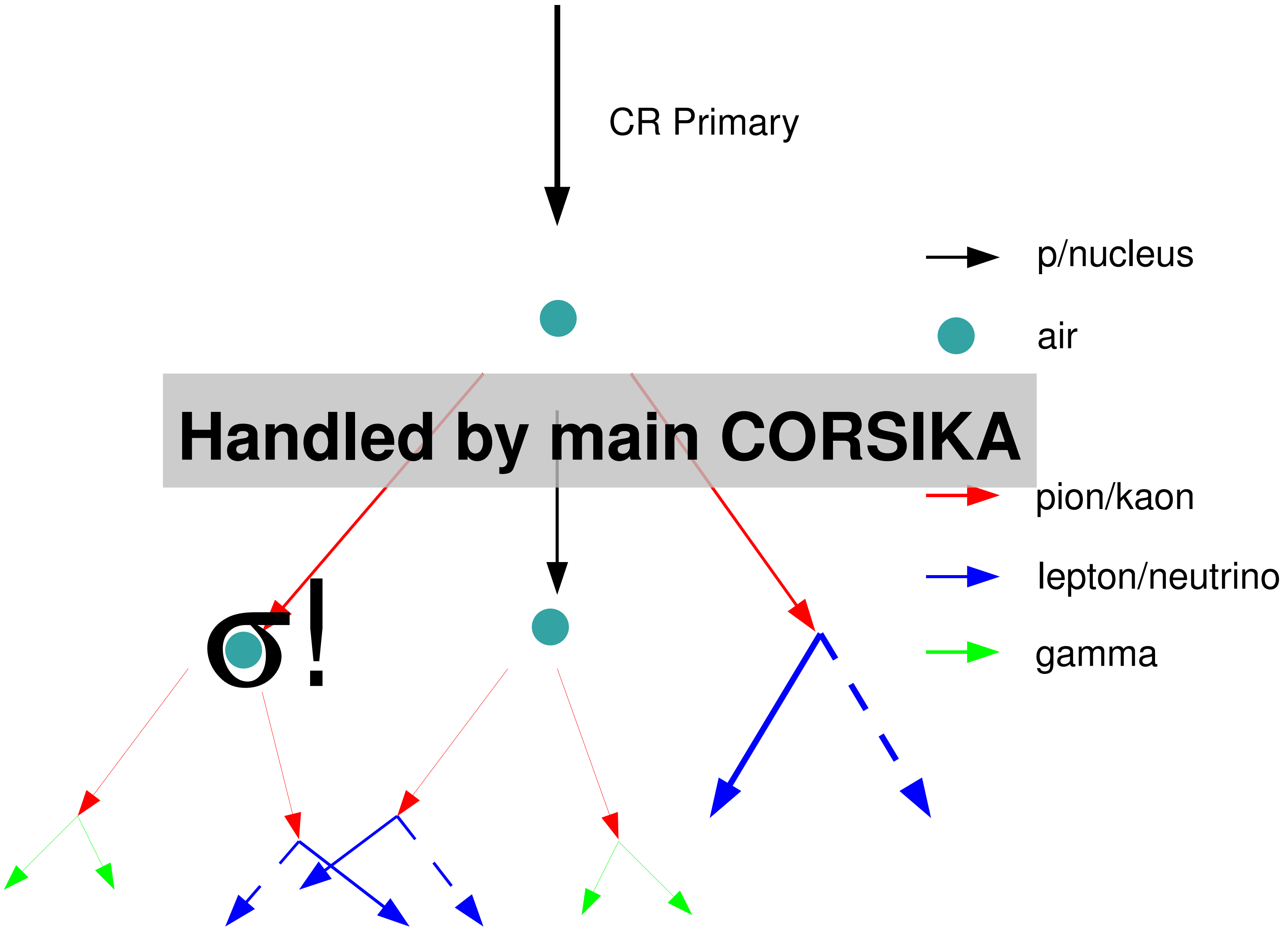
0706.4389


CORSIKA ->UCR ->MMC ->Photonics
NuSim
->DOM Simulation
≈10km
eff. scattering coefficient [m⁻¹]
bubbles
depth [m]
wavelength [nm]
absorptivity [m⁻¹]
pure ice
ATWD recorded value [Volts]
sample number

CORSIKA

(CR shower simulation)

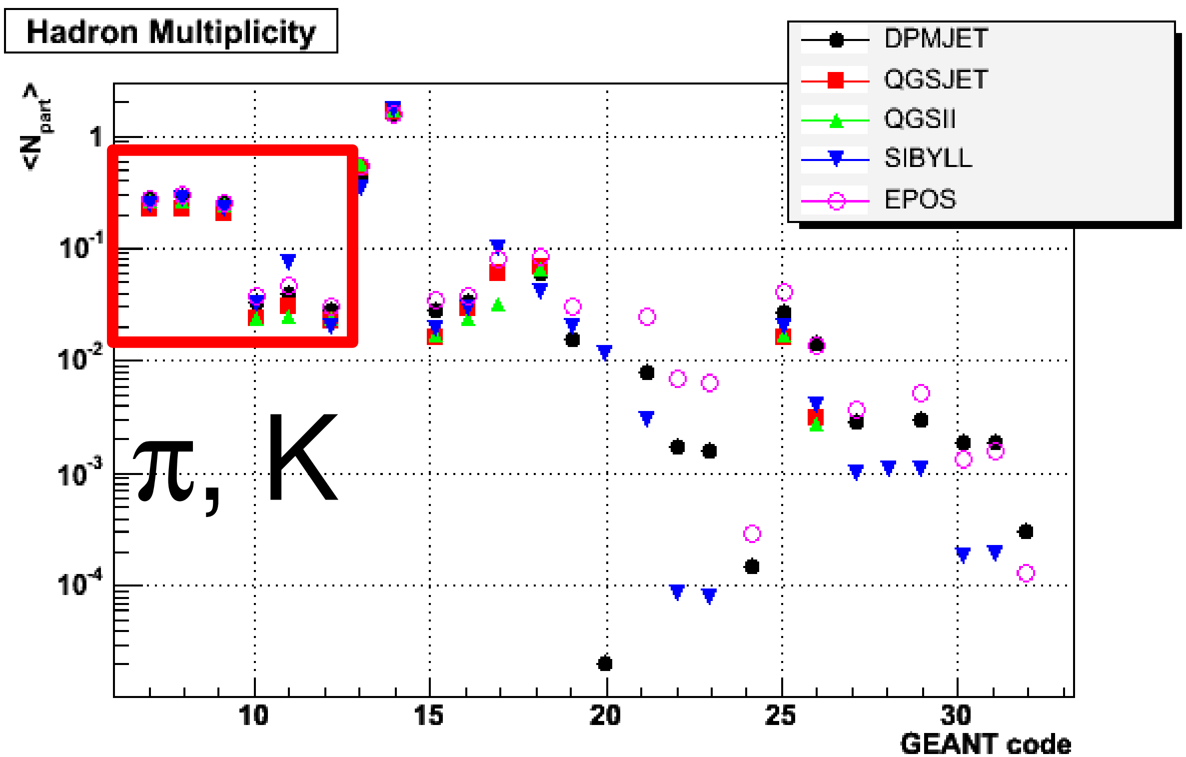




CR Primary
p/nucleus
air
Handled by main CORSIKA
pion/kaon
lepton/neutrino
gamma
σ!

Hadronic Interactions

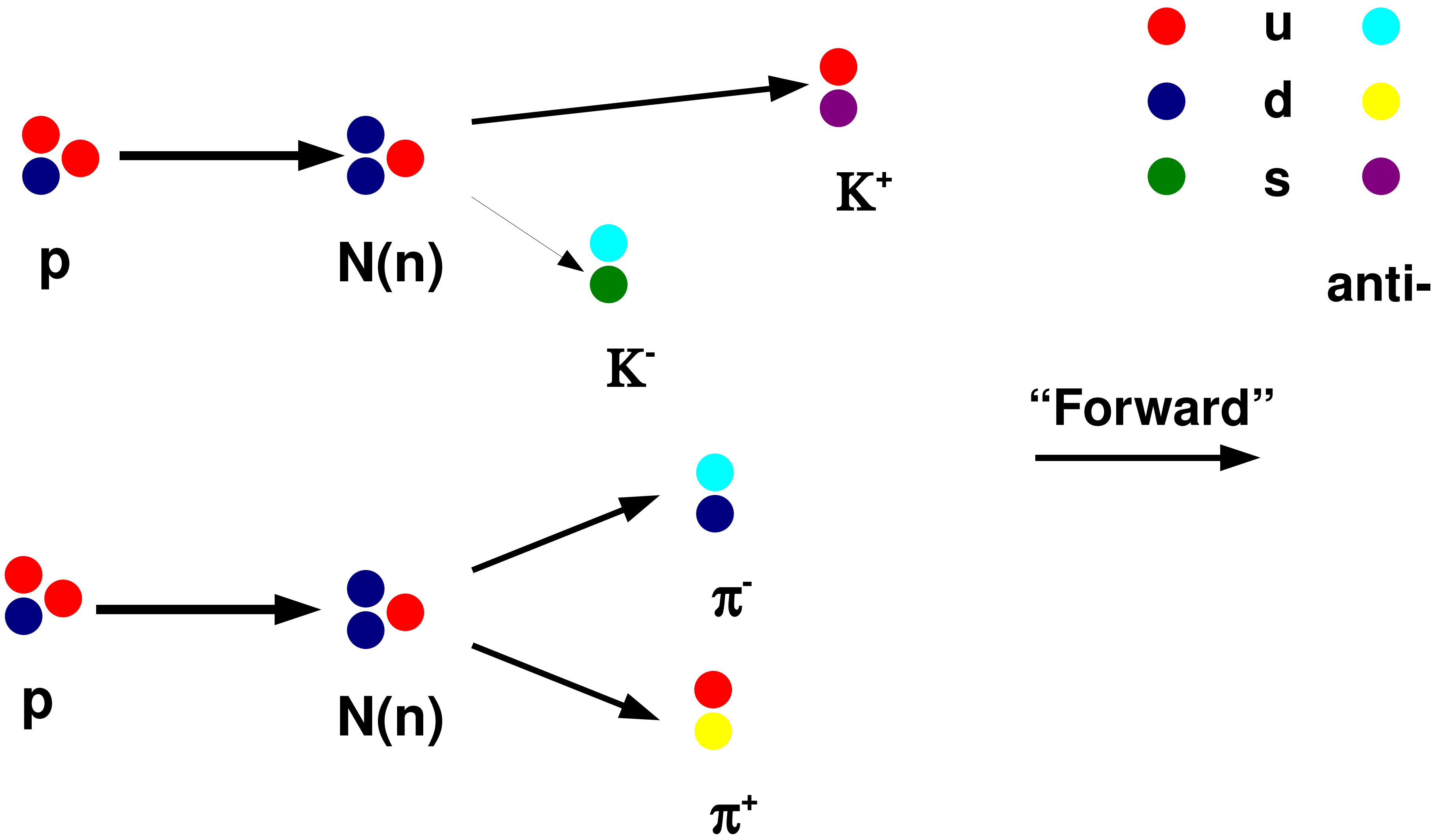
CORSIKA compile options

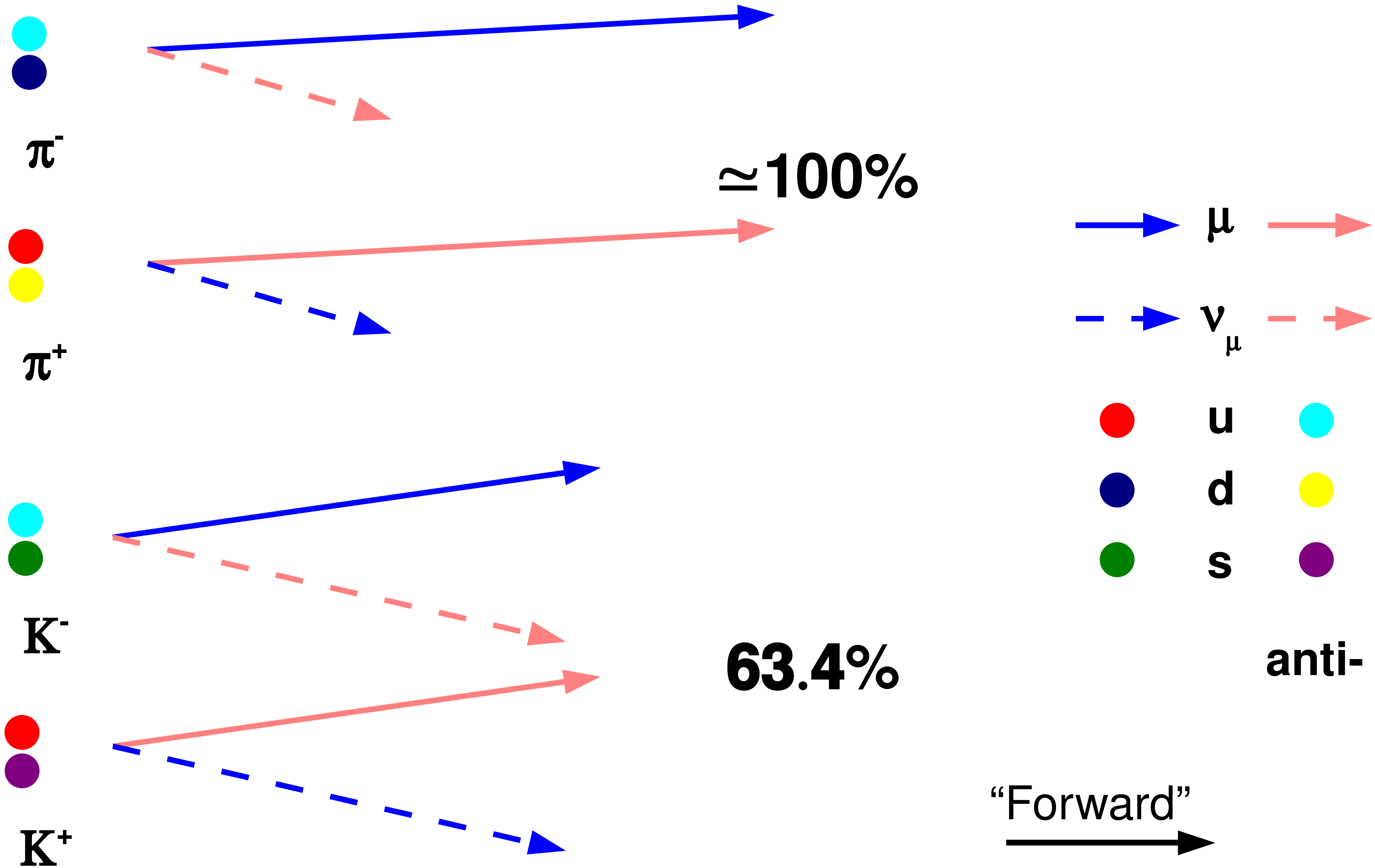


DPMJET
NEXUS
QGSJET
QGSJET II
SIBYLL
VENUS
EPOS

High E →

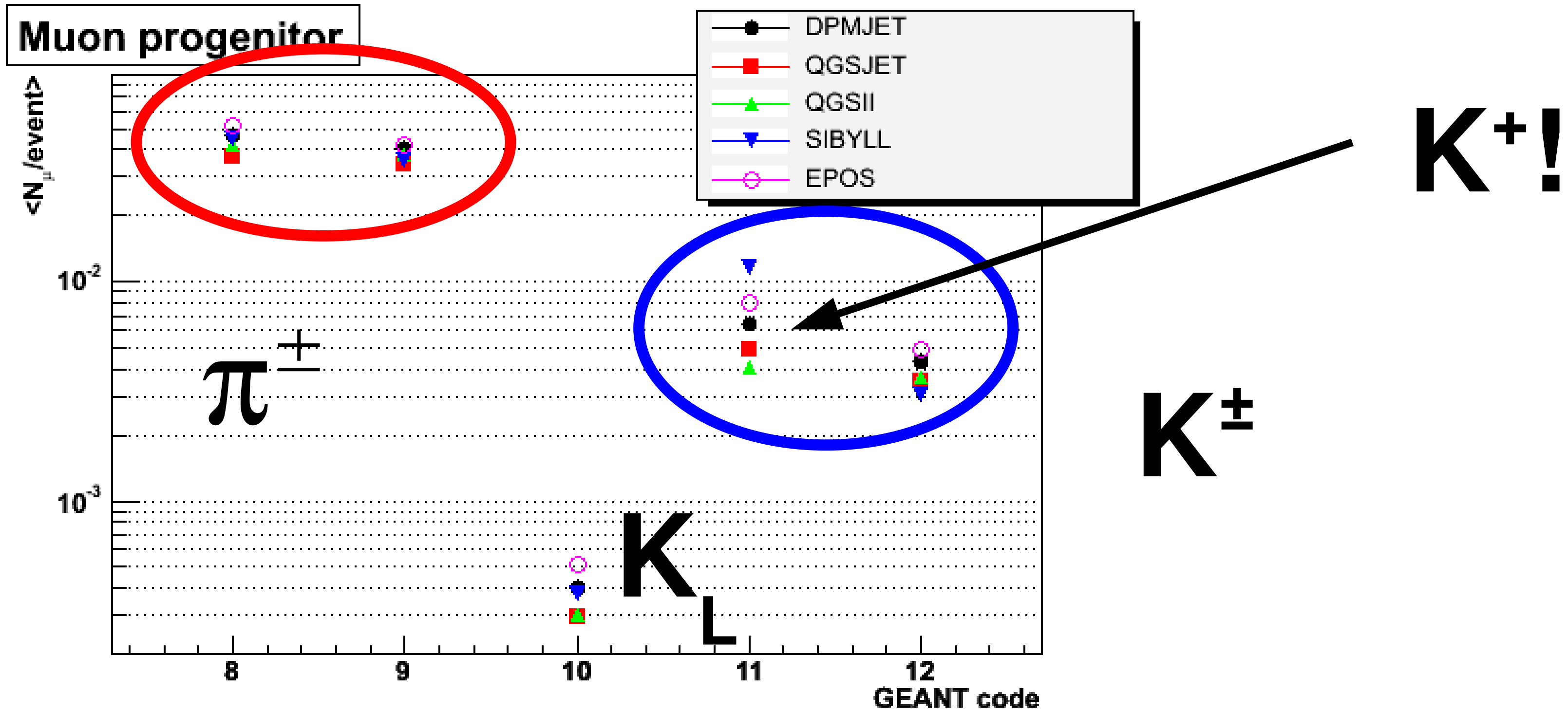
Production Asymmetry





π-
π+
≃100%
K-
K+
63.4%
μ
ν μ
u
d
s
anti-
"Forward"

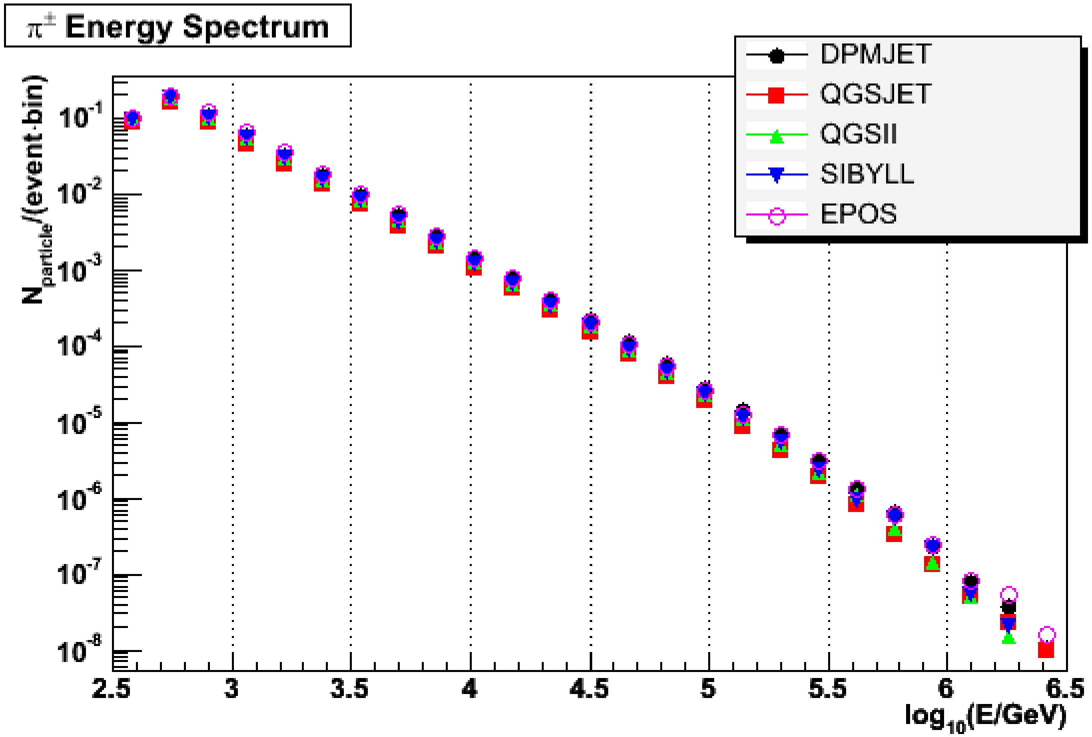
Muon Parents



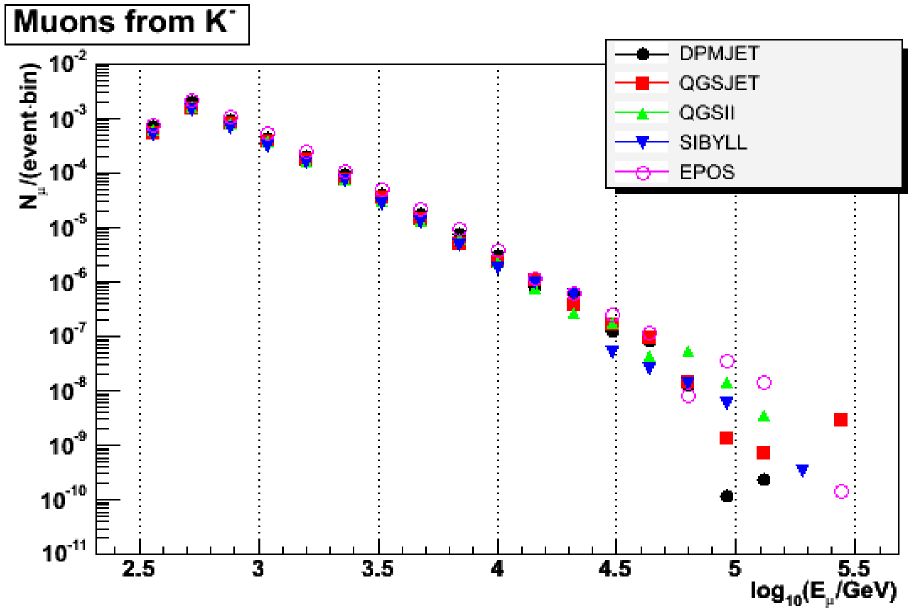
Pions ($u\bar{d}$)

E(μ)>400GeV

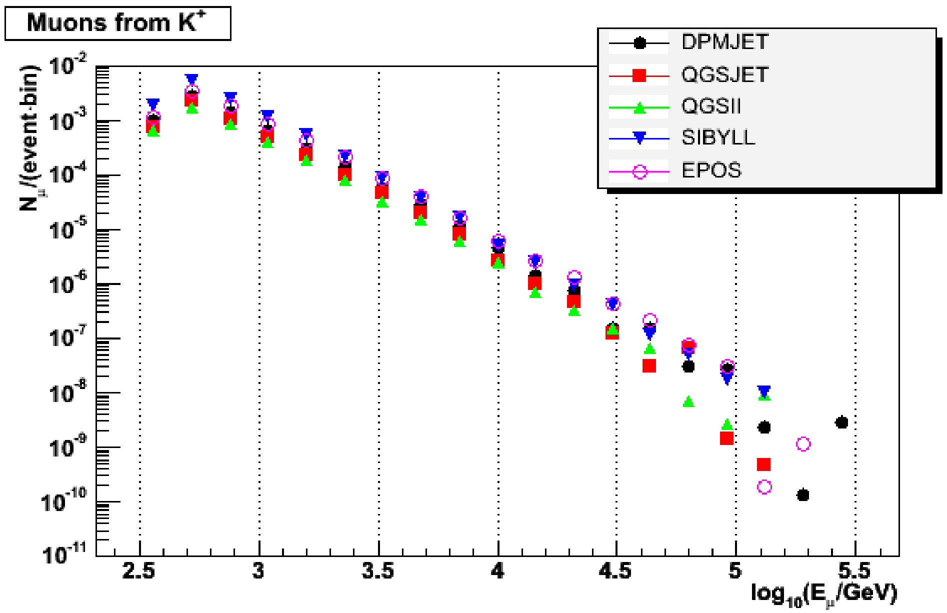
DSLOPE=-1



Kaons ($u\bar{s}$)



Muons from K-
DPMJET
QGSJET
QGSII
SIBYLL
EPOS
N_μ/(event·bin)
log10(E_μ/GeV)



Muons from K+
DPMJET
QGSJET
QGSII
SIBYLL
EPOS
N_μ/(event·bin)
log10(E_μ/GeV)

-

+

Atmospheric Neutrino Fluxes

T. Gaisser, hep-ph/0209195

$$\frac{dN_\nu}{dE_\nu} = \frac{\phi_N(E_\nu)}{(1-Z_{NN})(\gamma+1)}\left\{\left[\frac{Z_{N\pi}(1-r_\pi)^\gamma}{1+B_{\pi\nu}\cos\theta E_\nu/\epsilon_\pi}\right] + 0.635\left[\frac{Z_{NK}(1-r_K)^\gamma}{1+B_{K\nu}\cos\theta E_\nu/\epsilon_K}\right]\right\}, \quad (2)$$

where

$$\phi(E_0) = \frac{dN}{dE_0} = A\times E_0^{-(\gamma+1)} \quad (3)$$

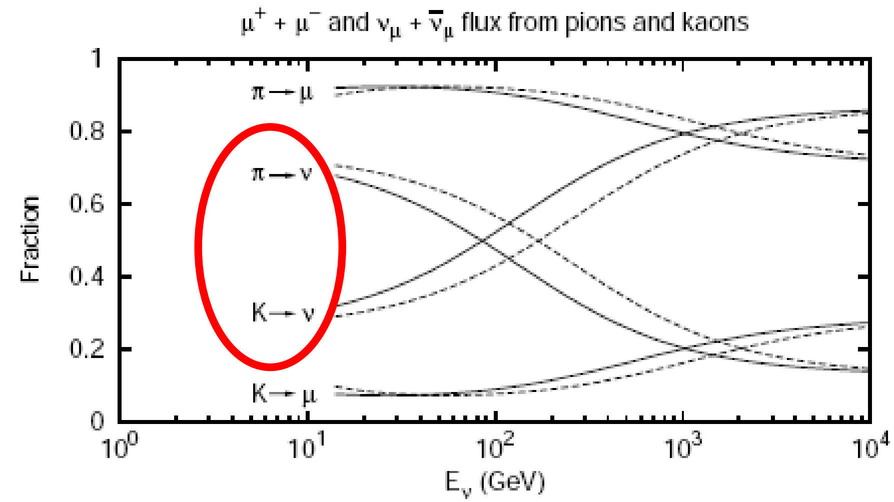
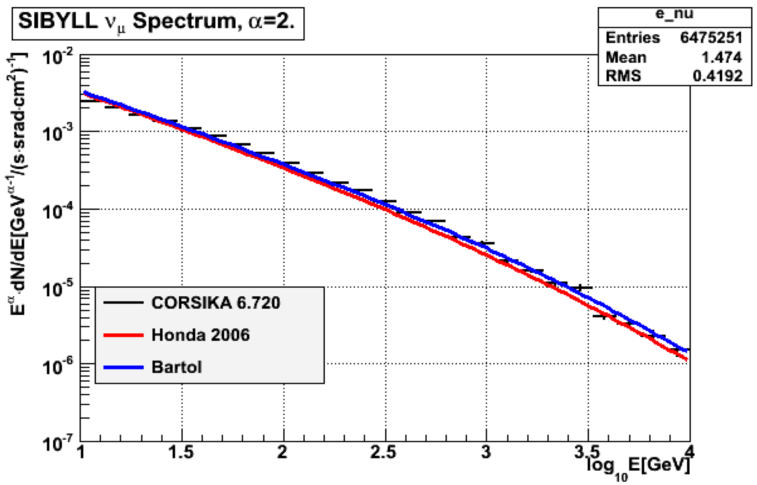
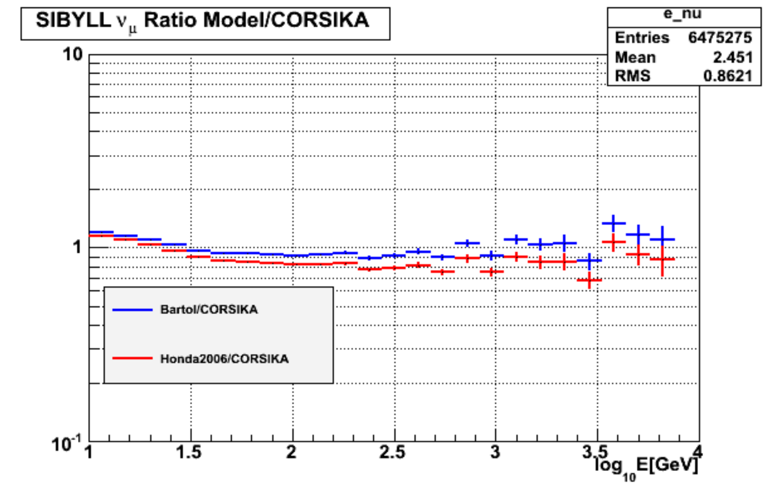


Figure 8. Fraction of atmospheric muons and neutrinos from pions and kaons. Solid: vertical; dashed: 60°.

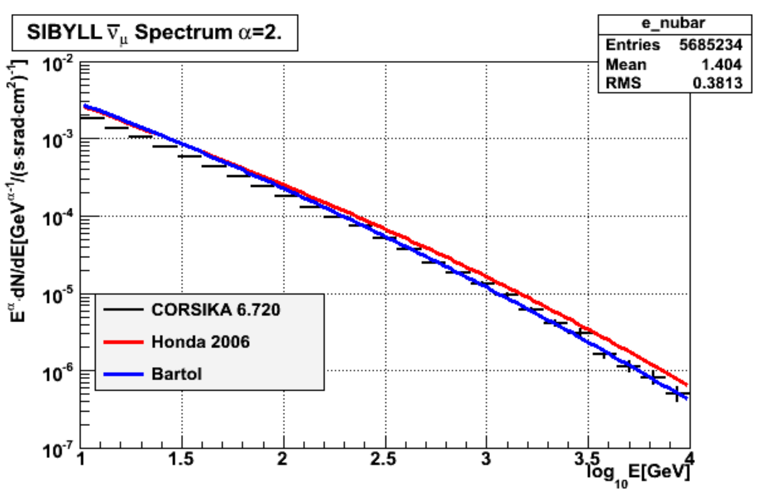
SIBYLL (good)

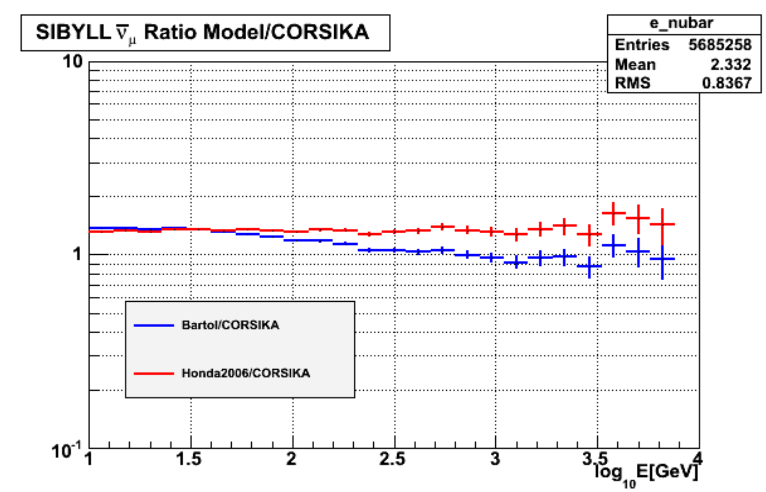
ν_μ





$\bar{\nu}_\mu$



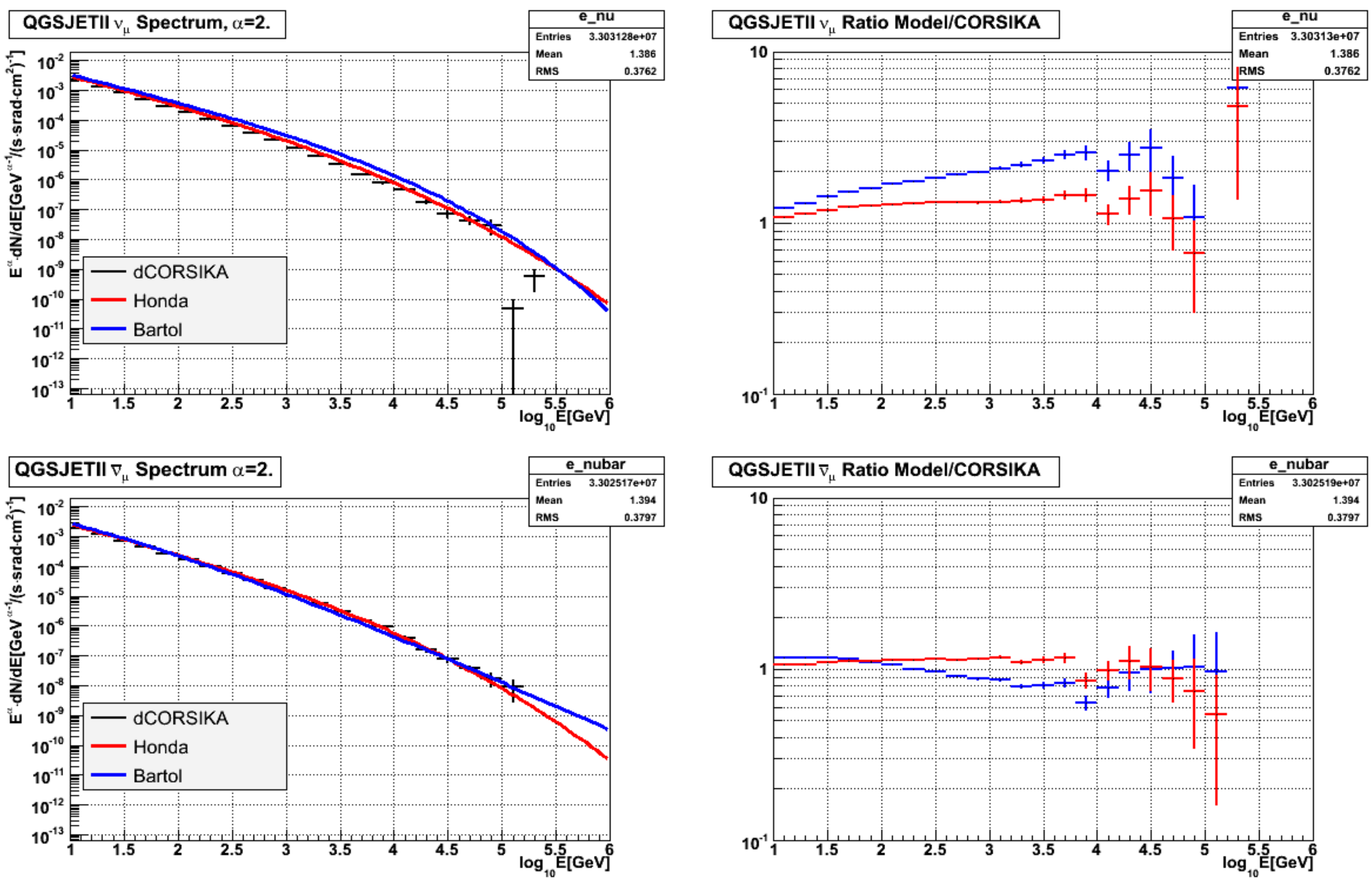


QGSJET (bad)

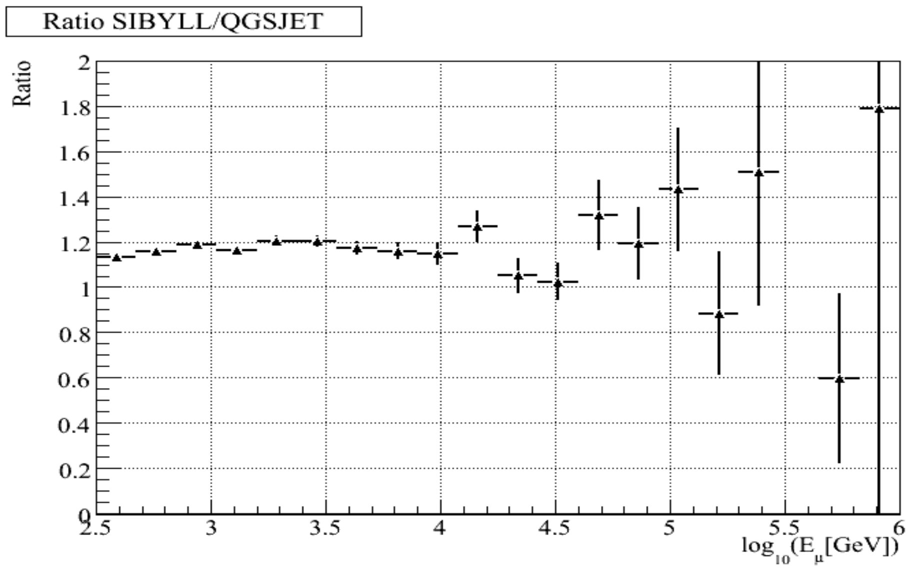
$K^+ \rightarrow \mu^+ \nu_\mu$

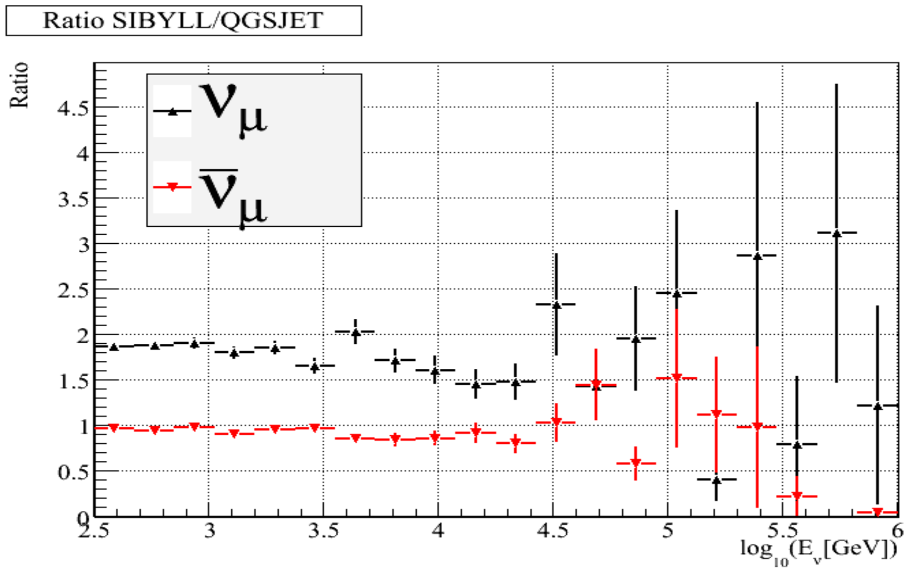
ν_μ

$\bar{\nu}_\mu$



Good / Bad: Energy

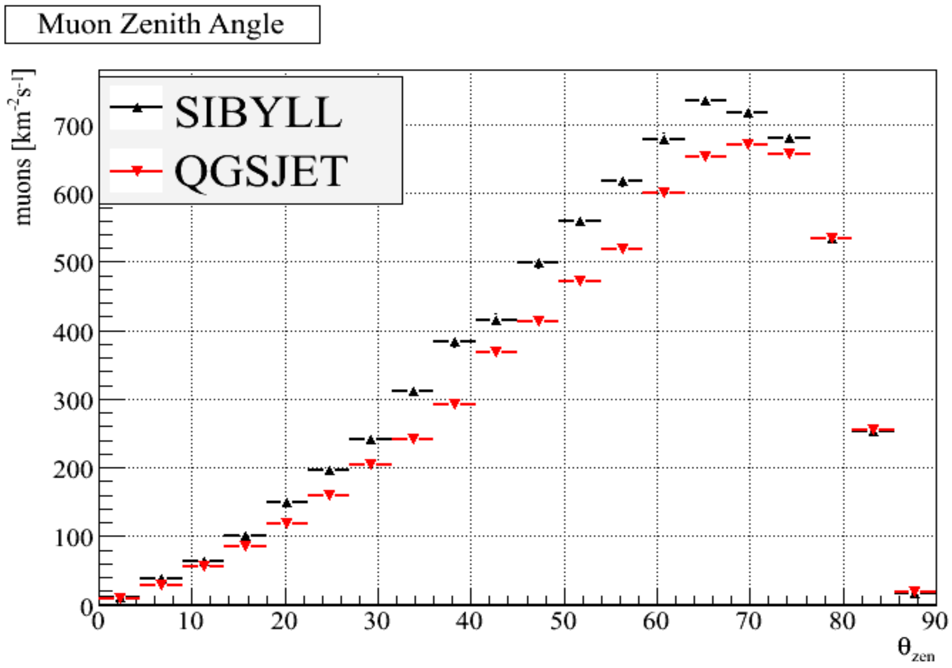


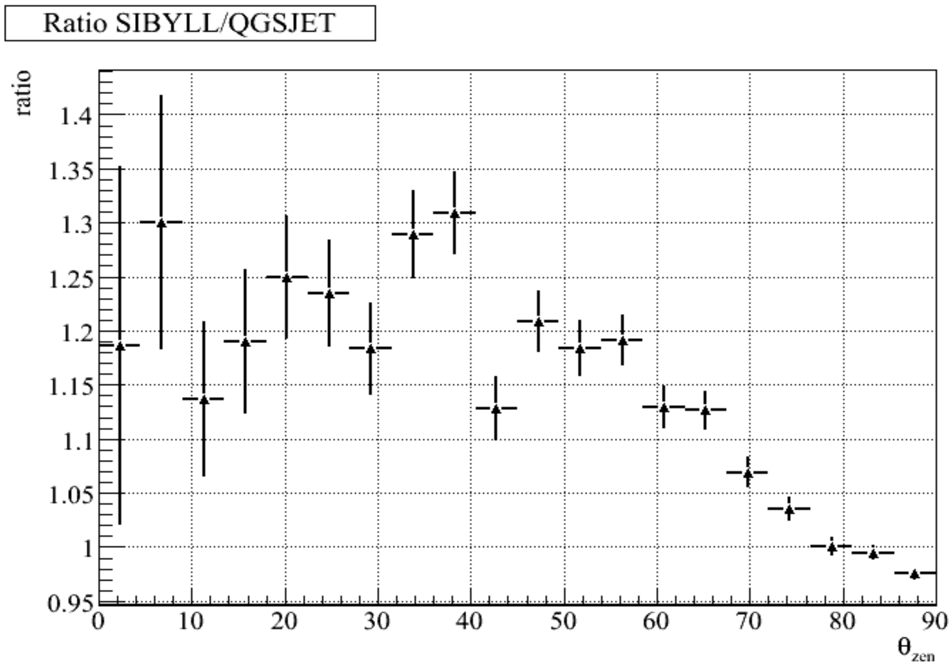


μ

ν

Good / Bad: Zenith Angle





Needs full detector simulation!

MINOS

0705.3815

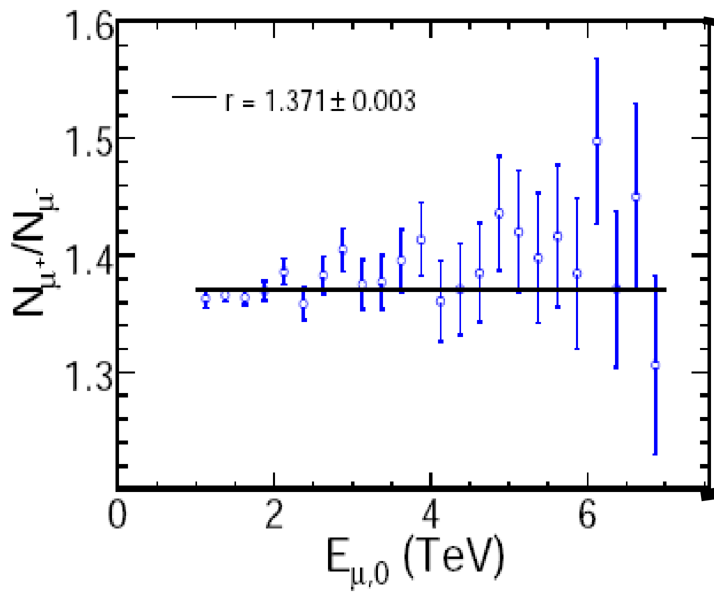
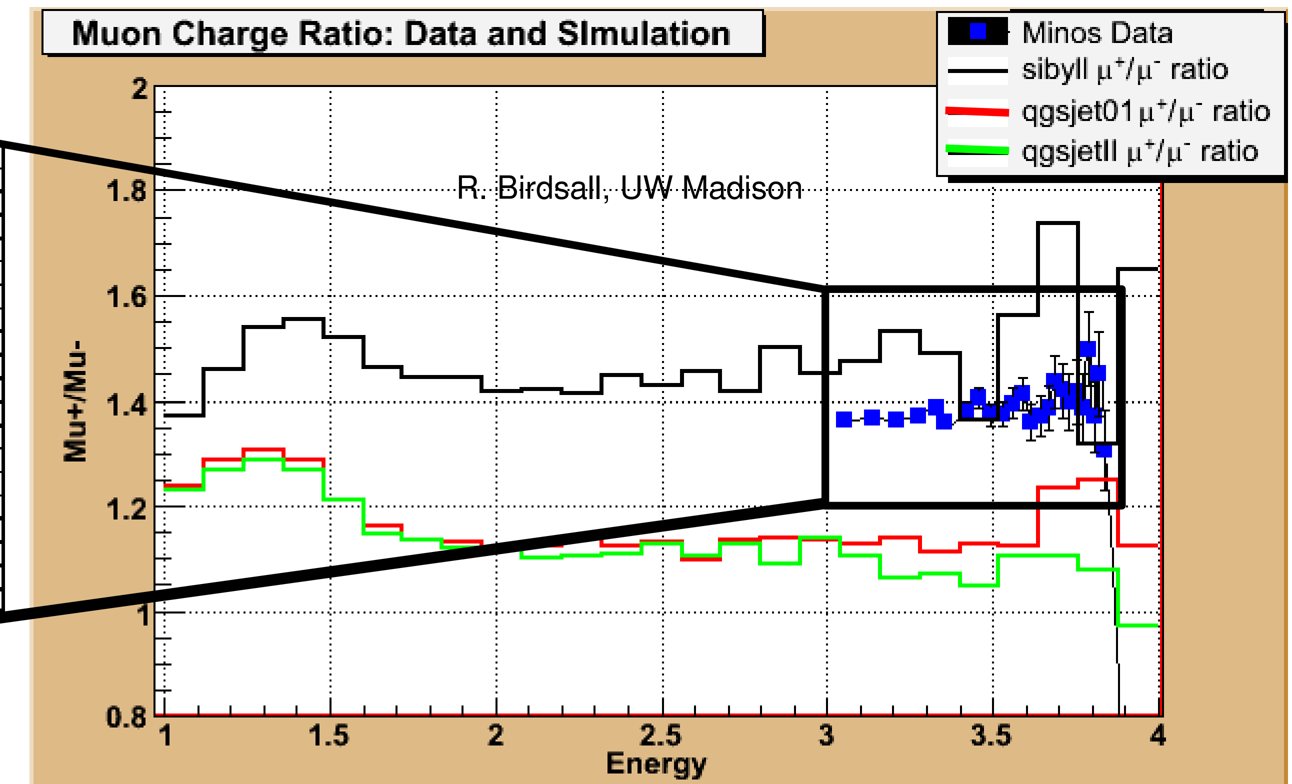


FIG. 15: The muon charge ratio $N_{\mu+}/N_{\mu-}$ at the Earth's surface. The errors shown are statistical.



```
RUNNR    15001                        number of run
EVTNR    1                            number of first shower event
NSHOW    10000000                     number of showers to generate
PRMPAR   14                           particle type of prim. particle
ESLOPE   -2.7                         slope of primary energy spectrum
ERANGE   600   100000000000           energy range of primary particle
THETAP   0   89.999                   range of zenith angle (degree)
PHIP     0.   360.                    range of azimuth angle (degree)
SEED     45003    0    0              seed for 1. random number sequence
SEED     45004    0    0              seed for 2. random number sequence
SEED     45005    0    0              seed for 3. random number sequence
OBSLEV   2834.E2                      observation level (in cm)
ELMFLG   T   F                        em. interaction flags (NKG,EGS)
RADNKG   2.E5                         outer radius for NKG lat.dens.determ.
ARRANG   0.                           rotation of array to north
FIXHEI   0.   0                       first interaction height & target
FIXCHI   0.                           starting altitude (g/cm**2)
MAGNET   16.4  -53.4                  magnetic field south pole
MFDECL   -27.05                       magnetic field declination (+E, -W)
HADFLG   0   1   0   1   0   2        flags hadr.interact. & fragmentation
SIBYLL   T   0                        use sibyll for high energy hadrons
SIBSIG   T                            use sibyll hadronic cross sections
ECUTS    273 273 .003 .003            energy cuts for particles
MUADDI   T                            additional info for muons
MUMULT   T                            muon multiple scattering angle
LONGI    F   20.   F   F              longit.distr. & step size & fit
MAXPRT   0                            max. number of printed events
ECTMAP   100                          cut on gamma factor for printout
STEPFC   1.0                          mult. scattering step length fact.
DEBUG    F   6   F   1000000          debug flag and log.unit for out
DIRECT   ./                           output directory
ATMOD    13                           october atmosphere
DETCFG   1                            detector information (l/d)
F2000    T                            choses F2000 format
LOCUT    T 1.58                       enables skew angle cutoff
RANPRI   2                            random primary
SPRIC    T                            separate primary energy cutoffs
FSEED    F                            enable random generator seed recovery
DSLOPE   0                            slope correction
SCURV    T 6.4E8 1.95E5               curved surf., radius of Earth, depth
EXIT                                  terminates input
```

general

IceCube

Run

```
RUNNR   15001                              number of run
EVTNR   1                                  number of first shower event
NSHOW   10000000                           number of showers to generate
PRMPAR  14                                 particle type of prim. particle
ESLOPE  -2.7                               slope of primary energy spectrum
ERANGE  600  100000000000                  energy range of primary particle
THETAP  0  89.999                          range of zenith angle (degree)
PHIP    0.  360.                           range of azimuth angle (degree)
```

Seed

```
SEED    45003   0   0                      seed for 1. random number sequence
SEED    45004   0   0                      seed for 2. random number sequence
SEED    45005   0   0                      seed for 3. random number sequence
OBSLEV  2834.E2                            observation level (in cm)
ELMFLG  T  F                               em. interaction flags (NKG,EGS)
RADNKG  2.E5                               outer radius for NKG lat.dens.determ.
ARRANG  0.                                 rotation of array to north
FIXHEI  0.  0                              first interaction height & target
FIXCHI  0.                                 starting altitude (g/cm**2)
MAGNET  16.4  -53.4                        magnetic field south pole
MFDECL  -27.05                             magnetic field declination (+E, -W)
HADFLG  0  1  0  1  0  2                   flags hadr.interact. & fragmentation
```

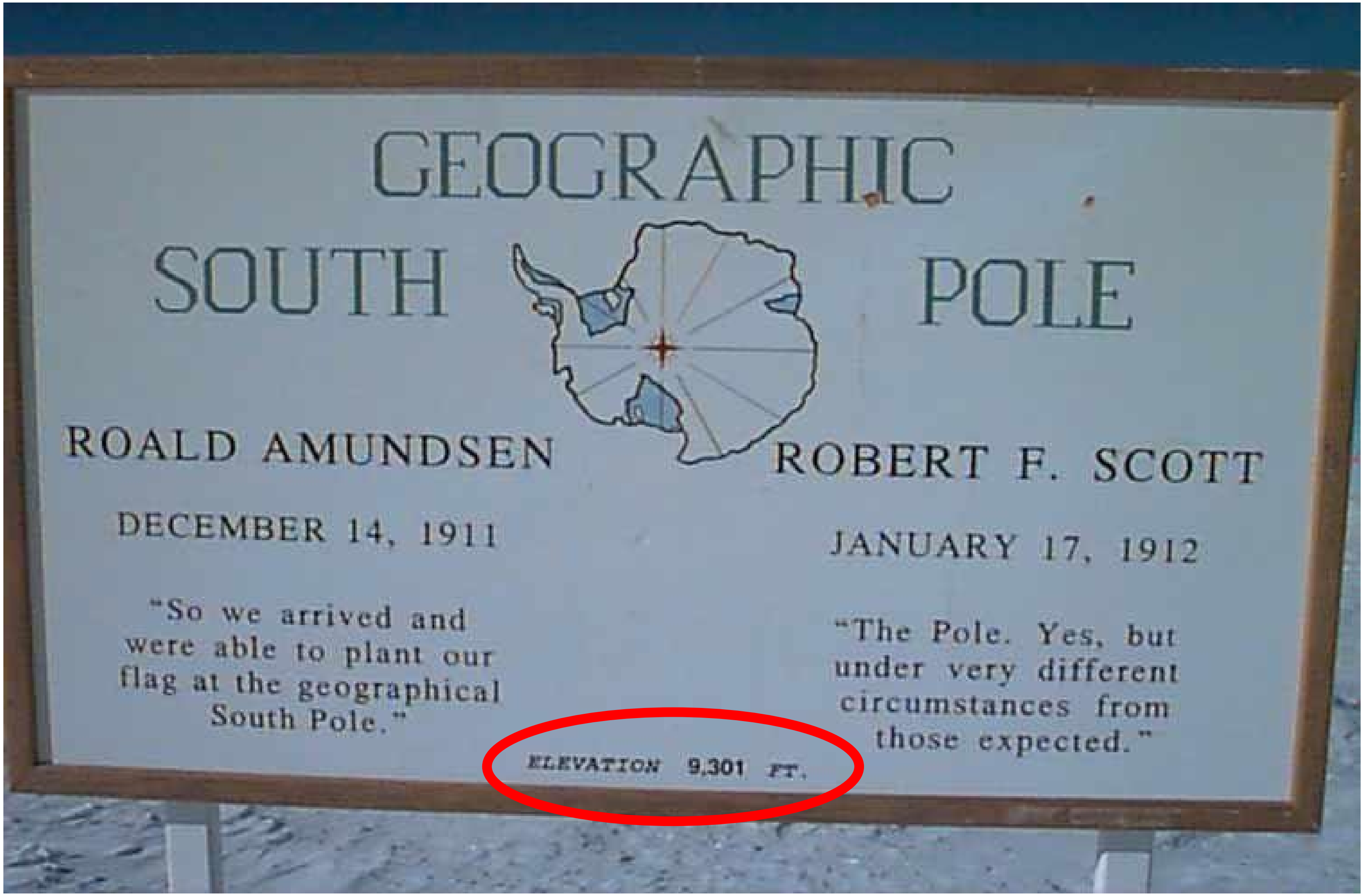
Had. Sim

```
SIBYLL  T  0                               use sibyll for high energy hadrons
SIBSIG  T                                  use sibyll hadronic cross sections
ECUTS   273 273 .003 .003                  energy cuts for particles
MUADDI  T                                  additional info for muons
MUMULT  T                                  muon multiple scattering angle
LONGI   F  20.  F  F                       longit.distr. & step size & fit
MAXPRT  0                                  max. number of printed events
ECTMAP  100                                cut on gamma factor for printout
STEPFC  1.0                                mult. scattering step length fact.
DEBUG   F  6  F  1000000                   debug flag and log.unit for out
```

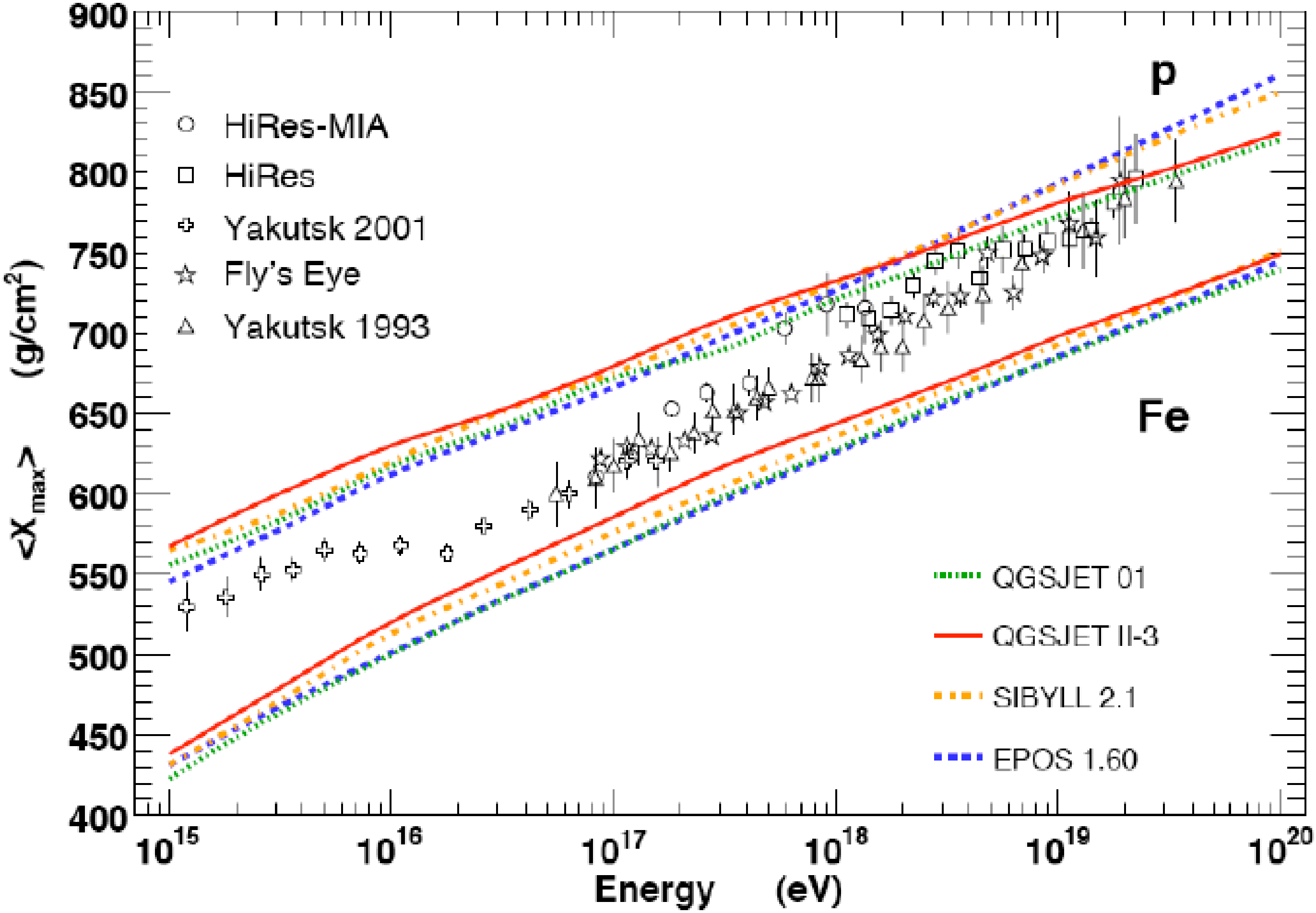
Output

```
DIRECT  ./                                 output directory
ATMOD   13                                 october atmosphere
DETCFG  1                                  detector information (l/d)
F2000   T                                  choses F2000 format
LOCUT   T 1.58                             enables skew angle cutoff
RANPRI  2                                  random primary
SPRIC   T                                  separate primary energy cutoffs
FSEED   F                                  enable random generator seed recovery
DSLOPE  0                                  slope correction
SCURV   T 6.4E8 1.95E5                     curved surf., radius of Earth, depth
EXIT                                       terminates input
```

ATMOD and OBSLEV



CR Composition



On the Knee in the Energy Spectrum of Cosmic Rays

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http://www-ik.fzk.de/~joerg

Preprint arXiv:astro–ph/0210453
Submitted to Astroparticle Physics 15. April 2002; accepted 6. August 2002.

Table 7: Absolute flux Φ_Z^0 $[(\mathrm{m}^2\ \mathrm{sr\ s\ TeV})^{-1}]$ at E_0 = 1 TeV/nucleus and spectral index γ_Z of cosmic-ray elements.

Z		Φ_Z^0	$-\gamma_Z$	Z		Φ_Z^0	$-\gamma_Z$	Z		Φ_Z^0	$-\gamma_Z$
1[2]	H	$8.73 \cdot 10^{-2}$	2.71	32[4]	Ge	$4.02 \cdot 10^{-6}$	2.54	63[4]	Eu	$1.58 \cdot 10^{-7}$	2.27
2[2]	He	$5.71 \cdot 10^{-2}$	2.64	33[4]	As	$9.99 \cdot 10^{-7}$	2.54	64[4]	Gd	$6.99 \cdot 10^{-7}$	2.25
3[3]	Li	$2.08 \cdot 10^{-3}$	2.54	34[4]	Se	$2.11 \cdot 10^{-6}$	2.53	65[4]	Tb	$1.48 \cdot 10^{-7}$	2.24
4[3]	Be	$4.74 \cdot 10^{-4}$	2.75	35[4]	Br	$1.34 \cdot 10^{-6}$	2.52	66[4]	Dy	$6.27 \cdot 10^{-7}$	2.23
5[3]	B	$8.95 \cdot 10^{-4}$	2.95	36[4]	Kr	$1.30 \cdot 10^{-6}$	2.51	67[4]	Ho	$8.36 \cdot 10^{-8}$	2.22
6[3]	C	$1.06 \cdot 10^{-2}$	2.66	37[4]	Rb	$6.93 \cdot 10^{-7}$	2.51	68[4]	Er	$3.52 \cdot 10^{-7}$	2.21
7[3]	N	$2.35 \cdot 10^{-3}$	2.72	38[4]	Sr	$2.11 \cdot 10^{-6}$	2.50	69[4]	Tm	$1.02 \cdot 10^{-7}$	2.20
8[3]	O	$1.57 \cdot 10^{-2}$	2.68	39[4]	Y	$7.82 \cdot 10^{-7}$	2.49	70[4]	Yb	$4.15 \cdot 10^{-7}$	2.19
9[3]	F	$3.28 \cdot 10^{-4}$	2.69	40[4]	Zr	$8.42 \cdot 10^{-7}$	2.48	71[4]	Lu	$1.72 \cdot 10^{-7}$	2.18
10[3]	Ne	$4.60 \cdot 10^{-3}$	2.64	41[4]	Nb	$5.05 \cdot 10^{-7}$	2.47	72[4]	Hf	$3.57 \cdot 10^{-7}$	2.17
11[3]	Na	$7.54 \cdot 10^{-4}$	2.66	42[4]	Mo	$7.79 \cdot 10^{-7}$	2.46	73[4]	Ta	$2.16 \cdot 10^{-7}$	2.16
12[3]	Mg	$8.01 \cdot 10^{-3}$	2.64	43[4]	Tc	$6.98 \cdot 10^{-8}$	2.46	74[4]	W	$4.16 \cdot 10^{-7}$	2.15
13[3]	Al	$1.15 \cdot 10^{-3}$	2.66	44[4]	Ru	$3.01 \cdot 10^{-7}$	2.45	75[4]	Re	$3.35 \cdot 10^{-7}$	2.13
14[3]	Si	$7.96 \cdot 10^{-3}$	2.75	45[4]	Rh	$3.77 \cdot 10^{-7}$	2.44	76[4]	Os	$6.42 \cdot 10^{-7}$	2.12
15[3]	P	$2.70 \cdot 10^{-4}$	2.69	46[4]	Pd	$5.10 \cdot 10^{-7}$	2.43	77[4]	Ir	$6.63 \cdot 10^{-7}$	2.11
16[3]	S	$2.29 \cdot 10^{-3}$	2.55	47[4]	Ag	$4.54 \cdot 10^{-7}$	2.42	78[4]	Pt	$1.03 \cdot 10^{-6}$	2.10
17[3]	Cl	$2.94 \cdot 10^{-4}$	2.68	48[4]	Cd	$6.30 \cdot 10^{-7}$	2.41	79[4]	Au	$7.70 \cdot 10^{-7}$	2.09
18[3]	Ar	$8.36 \cdot 10^{-4}$	2.64	49[4]	In	$1.61 \cdot 10^{-7}$	2.40	80[4]	Hg	$7.43 \cdot 10^{-7}$	2.08
19[3]	K	$5.36 \cdot 10^{-4}$	2.65	50[4]	Sn	$7.15 \cdot 10^{-7}$	2.39	81[4]	Ti	$4.28 \cdot 10^{-7}$	2.06
20[3]	Ca	$1.47 \cdot 10^{-3}$	2.70	51[4]	Sb	$2.03 \cdot 10^{-7}$	2.38	82[4]	Pb	$8.06 \cdot 10^{-7}$	2.05
21[3]	Sc	$3.04 \cdot 10^{-4}$	2.64	52[4]	Te	$9.10 \cdot 10^{-7}$	2.37	83[4]	Bi	$3.25 \cdot 10^{-7}$	2.04
22[3]	Ti	$1.14 \cdot 10^{-3}$	2.61	53[4]	I	$1.34 \cdot 10^{-7}$	2.37	84[4]	Po	$3.99 \cdot 10^{-7}$	2.03
23[3]	V	$6.31 \cdot 10^{-4}$	2.63	54[4]	Xe	$5.74 \cdot 10^{-7}$	2.36	85[4]	At	$4.08 \cdot 10^{-8}$	2.02
24[3]	Cr	$1.36 \cdot 10^{-3}$	2.67	55[4]	Cs	$2.79 \cdot 10^{-7}$	2.35	86[4]	Rn	$1.74 \cdot 10^{-7}$	2.00
25[3]	Mn	$1.35 \cdot 10^{-3}$	2.46	56[4]	Ba	$1.23 \cdot 10^{-6}$	2.34	87[4]	Fr	$1.78 \cdot 10^{-8}$	1.99
26[2]	Fe	$2.04 \cdot 10^{-2}$	2.59	57[4]	La	$1.23 \cdot 10^{-7}$	2.33	88[4]	Ra	$7.54 \cdot 10^{-8}$	1.98
27[3]	Co	$7.51 \cdot 10^{-5}$	2.72	58[4]	Ce	$5.10 \cdot 10^{-7}$	2.32	89[4]	Ac	$1.97 \cdot 10^{-8}$	1.97
28[3]	Ni	$9.96 \cdot 10^{-4}$	2.51	59[4]	Pr	$9.52 \cdot 10^{-8}$	2.31	90[4]	Th	$8.87 \cdot 10^{-8}$	1.96
29[4]	Cu	$2.18 \cdot 10^{-5}$	2.57	60[4]	Nd	$4.05 \cdot 10^{-7}$	2.30	91[4]	Pa	$1.71 \cdot 10^{-8}$	1.94
30[4]	Zn	$1.66 \cdot 10^{-5}$	2.56	61[4]	Pm	$8.30 \cdot 10^{-8}$	2.29	92[4]	U	$3.54 \cdot 10^{-7}$	1.93
31[4]	Ga	$2.75 \cdot 10^{-6}$	2.55	62[4]	Sm	$3.68 \cdot 10^{-7}$	2.28				

[2] This work, see Figures 2 to 4 and text.
[3] From Wiebel–Sooth et al. [16].
[4] This work, extrapolation for ultra–heavy elements, see text.

RANPRI 2

DSLOPE=-1: 1.71

H	1	FLUX:	0.087300	GAMMA:	2.71
He	2	FLUX:	0.057100	GAMMA:	2.64
Li	3	FLUX:	0.002080	GAMMA:	2.54
Be	4	FLUX:	0.000474	GAMMA:	2.75
B	5	FLUX:	0.000895	GAMMA:	2.95
C	6	FLUX:	0.010600	GAMMA:	2.66
N	7	FLUX:	0.002350	GAMMA:	2.72
O	8	FLUX:	0.015700	GAMMA:	2.68
F	9	FLUX:	0.000328	GAMMA:	2.69
Ne	10	FLUX:	0.004600	GAMMA:	2.64
Na	11	FLUX:	0.000754	GAMMA:	2.66
Mg	12	FLUX:	0.008010	GAMMA:	2.64
Al	13	FLUX:	0.001150	GAMMA:	2.66
Si	14	FLUX:	0.007960	GAMMA:	2.75
P	15	FLUX:	0.000270	GAMMA:	2.69
S	16	FLUX:	0.002290	GAMMA:	2.55
Cl	17	FLUX:	0.000294	GAMMA:	2.68
Ar	18	FLUX:	0.000836	GAMMA:	2.64
K	19	FLUX:	0.000536	GAMMA:	2.65
Ca	20	FLUX:	0.001470	GAMMA:	2.70
Sc	21	FLUX:	0.000304	GAMMA:	2.64
Ti	22	FLUX:	0.001130	GAMMA:	2.61
V	23	FLUX:	0.000631	GAMMA:	2.63
Cr	24	FLUX:	0.001360	GAMMA:	2.67
Mn	25	FLUX:	0.001350	GAMMA:	2.46
Fe	26	FLUX:	0.020400	GAMMA:	2.59

Table 7: Absolute flux Φ_Z^0 [(m^2 sr s TeV)$^{-1}$] at $E_0 = 1$ TeV/nucleus and spectral index γ_Z of cosmic-ray elements.

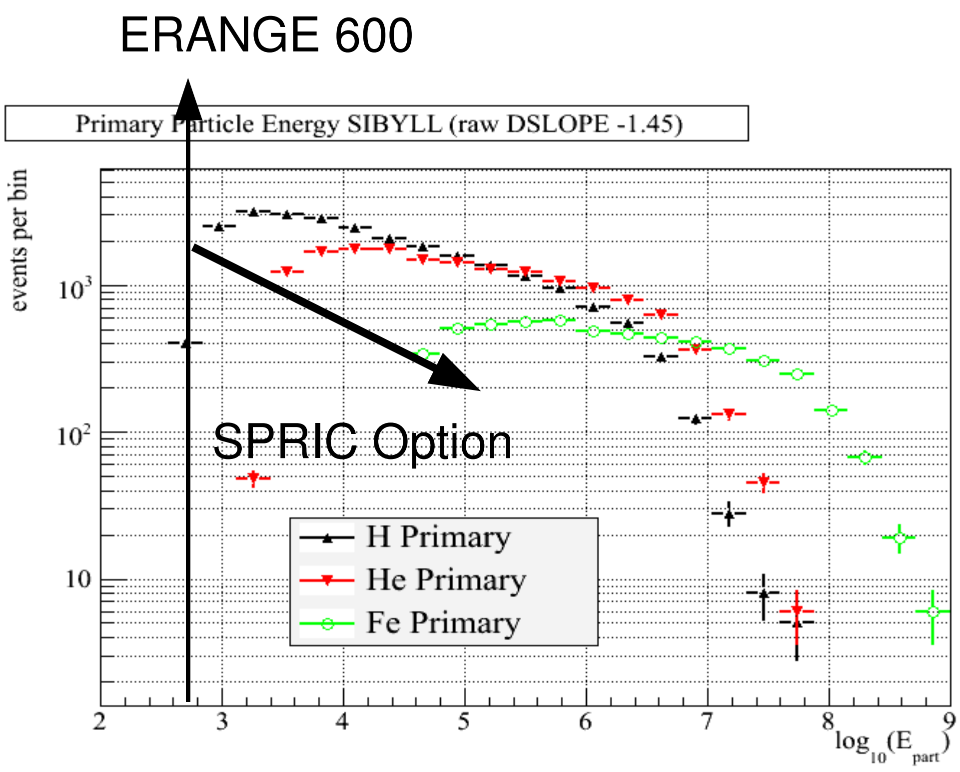
Z		Φ_Z^0	$-\gamma_Z$	Z		Φ_Z^0	$-\gamma_Z$	Z		Φ_Z^0	$-\gamma_Z$
1[2]	H	$8.73 \cdot 10^{-2}$	2.71	32[4]	Ge	$4.02 \cdot 10^{-6}$	2.54	63[4]	Eu	$1.58 \cdot 10^{-7}$	2.27
2[2]	He	$5.71 \cdot 10^{-2}$	2.64	33[4]	As	$9.99 \cdot 10^{-7}$	2.54	64[4]	Gd	$6.99 \cdot 10^{-7}$	2.25
3[3]	Li	$2.08 \cdot 10^{-3}$	2.54	34[4]	Se	$2.11 \cdot 10^{-6}$	2.53	65[4]	Tb	$1.48 \cdot 10^{-7}$	2.24
4[3]	Be	$4.74 \cdot 10^{-4}$	2.75	35[4]	Br	$1.34 \cdot 10^{-6}$	2.52	66[4]	Dy	$6.27 \cdot 10^{-7}$	2.23
5[3]	B	$8.95 \cdot 10^{-4}$	2.95	36[4]	Kr	$1.30 \cdot 10^{-6}$	2.51	67[4]	Ho	$8.36 \cdot 10^{-8}$	2.22
6[3]	C	$1.06 \cdot 10^{-2}$	2.66	37[4]	Rb	$6.93 \cdot 10^{-7}$	2.51	68[4]	Er	$3.52 \cdot 10^{-7}$	2.21
7[3]	N	$2.35 \cdot 10^{-3}$	2.72	38[4]	Sr	$2.11 \cdot 10^{-6}$	2.50	69[4]	Tm	$1.02 \cdot 10^{-7}$	2.20
8[3]	O	$1.57 \cdot 10^{-2}$	2.68	39[4]	Y	$7.82 \cdot 10^{-7}$	2.49	70[4]	Yb	$4.15 \cdot 10^{-7}$	2.19
9[3]	F	$3.28 \cdot 10^{-4}$	2.69	40[4]	Zr	$8.42 \cdot 10^{-7}$	2.48	71[4]	Lu	$1.72 \cdot 10^{-7}$	2.18
10[3]	Ne	$4.60 \cdot 10^{-3}$	2.64	41[4]	Nb	$5.05 \cdot 10^{-7}$	2.47	72[4]	Hf	$3.57 \cdot 10^{-7}$	2.17
11[3]	Na	$7.54 \cdot 10^{-4}$	2.66	42[4]	Mo	$7.79 \cdot 10^{-7}$	2.46	73[4]	Ta	$2.16 \cdot 10^{-7}$	2.16
12[3]	Mg	$8.01 \cdot 10^{-3}$	2.64	43[4]	Tc	$6.98 \cdot 10^{-8}$	2.46	74[4]	W	$4.16 \cdot 10^{-7}$	2.15
13[3]	Al	$1.15 \cdot 10^{-3}$	2.66	44[4]	Ru	$3.01 \cdot 10^{-7}$	2.45	75[4]	Re	$3.35 \cdot 10^{-7}$	2.13
14[3]	Si	$7.96 \cdot 10^{-3}$	2.75	45[4]	Rh	$3.77 \cdot 10^{-7}$	2.44	76[4]	Os	$6.42 \cdot 10^{-7}$	2.12
15[3]	P	$2.70 \cdot 10^{-4}$	2.69	46[4]	Pd	$5.10 \cdot 10^{-7}$	2.43	77[4]	Ir	$6.63 \cdot 10^{-7}$	2.11
16[3]	S	$2.29 \cdot 10^{-3}$	2.55	47[4]	Ag	$4.54 \cdot 10^{-7}$	2.42	78[4]	Pt	$1.03 \cdot 10^{-6}$	2.10
17[3]	Cl	$2.94 \cdot 10^{-4}$	2.68	48[4]	Cd	$6.30 \cdot 10^{-7}$	2.41	79[4]	Au	$7.70 \cdot 10^{-7}$	2.09
18[3]	Ar	$8.36 \cdot 10^{-4}$	2.64	49[4]	In	$1.61 \cdot 10^{-7}$	2.40	80[4]	Hg	$7.43 \cdot 10^{-7}$	2.08
19[3]	K	$5.36 \cdot 10^{-4}$	2.65	50[4]	Sn	$7.15 \cdot 10^{-7}$	2.39	81[4]	Tl	$4.28 \cdot 10^{-7}$	2.06
20[3]	Ca	$1.47 \cdot 10^{-3}$	2.70	51[4]	Sb	$2.03 \cdot 10^{-7}$	2.38	82[4]	Pb	$8.06 \cdot 10^{-7}$	2.05
21[3]	Sc	$3.04 \cdot 10^{-4}$	2.64	52[4]	Te	$9.10 \cdot 10^{-7}$	2.37	83[4]	Bi	$3.25 \cdot 10^{-7}$	2.04
22[3]	Ti	$1.14 \cdot 10^{-3}$	2.61	53[4]	I	$1.34 \cdot 10^{-7}$	2.37	84[4]	Po	$3.99 \cdot 10^{-7}$	2.03
23[3]	V	$6.31 \cdot 10^{-4}$	2.63	54[4]	Xe	$5.74 \cdot 10^{-7}$	2.36	85[4]	At	$4.08 \cdot 10^{-8}$	2.02
24[3]	Cr	$1.36 \cdot 10^{-3}$	2.67	55[4]	Cs	$2.79 \cdot 10^{-7}$	2.35	86[4]	Rn	$1.74 \cdot 10^{-7}$	2.00
25[3]	Mn	$1.35 \cdot 10^{-3}$	2.46	56[4]	Ba	$1.23 \cdot 10^{-6}$	2.34	87[4]	Fr	$1.78 \cdot 10^{-8}$	1.99
26[2]	Fe	$2.04 \cdot 10^{-2}$	2.59	57[4]	La	$1.23 \cdot 10^{-7}$	2.33	88[4]	Ra	$7.54 \cdot 10^{-8}$	1.98
27[3]	Co	$7.51 \cdot 10^{-5}$	2.72	58[4]	Ce	$5.10 \cdot 10^{-7}$	2.32	89[4]	Ac	$1.97 \cdot 10^{-8}$	1.97
28[3]	Ni	$9.96 \cdot 10^{-4}$	2.51	59[4]	Pr	$9.52 \cdot 10^{-8}$	2.31	90[4]	Th	$8.87 \cdot 10^{-8}$	1.96
29[4]	Cu	$2.18 \cdot 10^{-5}$	2.57	60[4]	Nd	$4.05 \cdot 10^{-7}$	2.30	91[4]	Pa	$1.71 \cdot 10^{-8}$	1.94
30[4]	Zn	$1.66 \cdot 10^{-5}$	2.56	61[4]	Pm	$8.30 \cdot 10^{-8}$	2.29	92[4]	U	$3.54 \cdot 10^{-7}$	1.93
31[4]	Ga	$2.75 \cdot 10^{-6}$	2.55	62[4]	Sm	$3.68 \cdot 10^{-7}$	2.28				

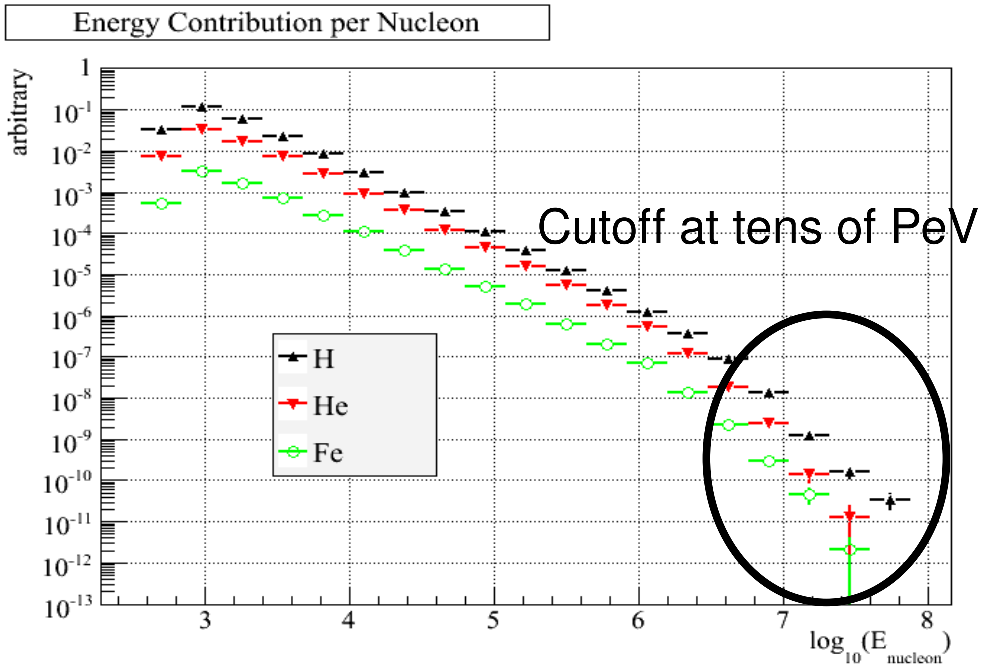
DSLOPE limit! text.

CORSIKA

"Poly-Gonato"

Protons, Helium and Iron





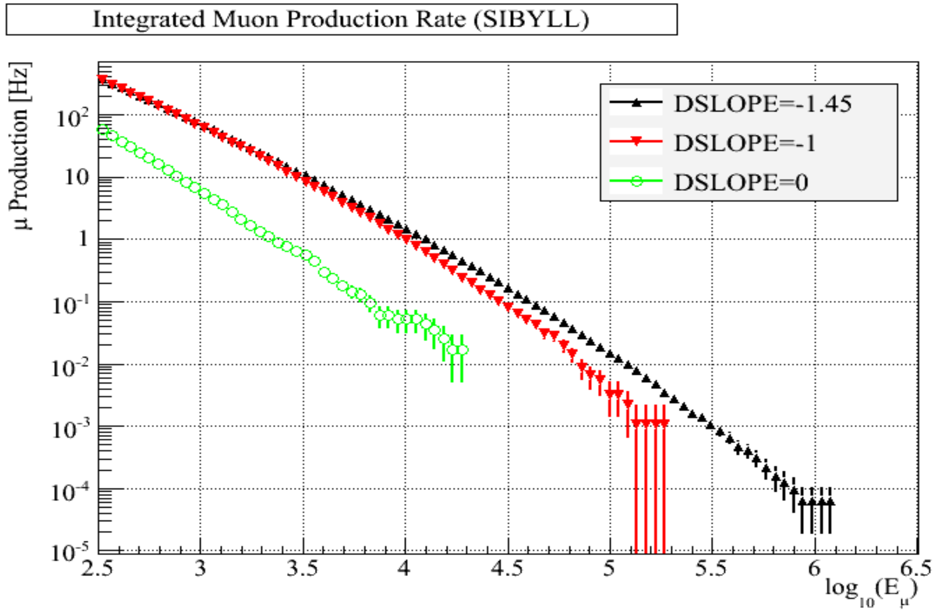
Speed

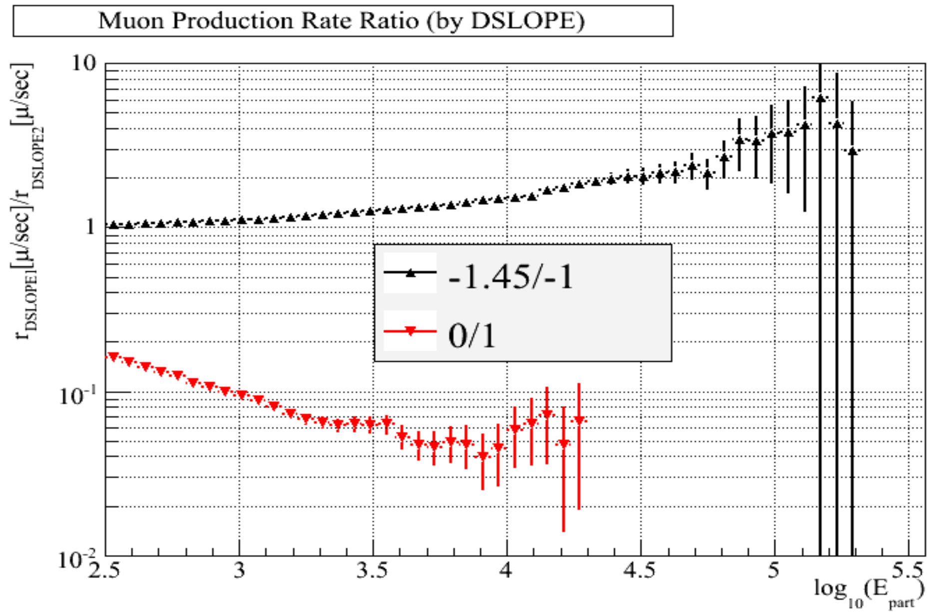
here: DSLOPE=-1.45, E_{prim}>600GeV, E_{μ}>273GeV

SIBYLL	3.128Hz
QGSJET	3.025Hz

DPMJET	0.102Hz
QGSJET-II	0.093Hz
EPOS	0.042Hz

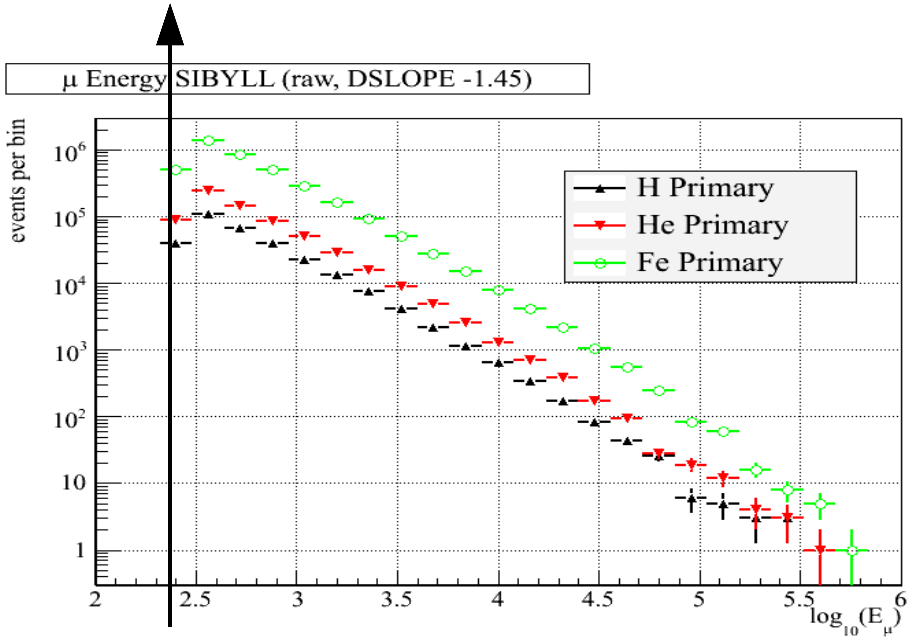
DSLOPE=0: Most Events DSLOPE=-1.45(max): Best Spectrum

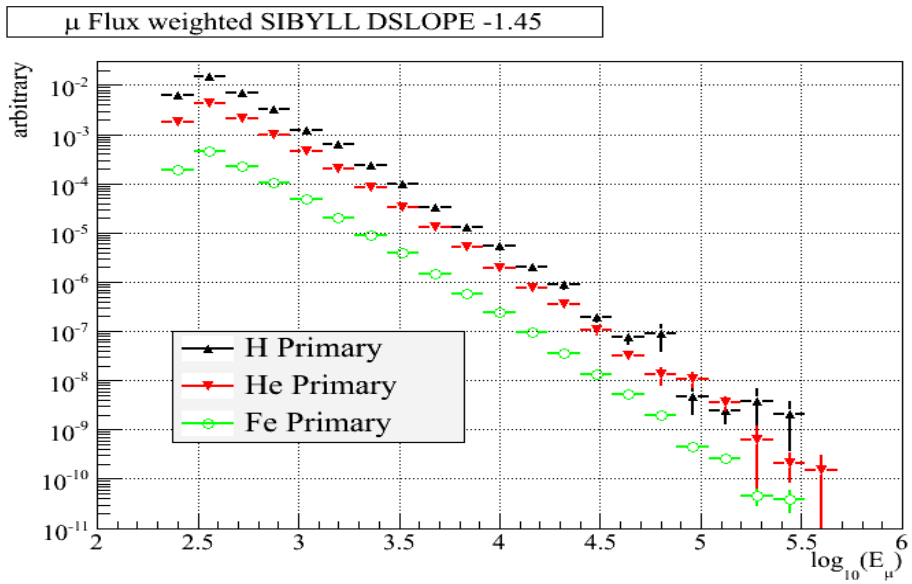




DSLOPE= -1.45

ECUTS 273.





Most Muons from Iron

Inverted after weighting!

Composition/High-E Studies

One Primary Type	RANPRI 0
Specified PL Index	ESLOPE -2.72
Primary Type (here:p)	PRIMPAR 14

Add them together separately

Work in Progress

Normalization

Primary Particle Flux: `FLUXSUM =  1.05042094 per meter2 second sr`

Depends on: $[E_{min}, E_{max}]$
DSLOPE
Composition

NSHOW*N_{files}

$$w_{ev} = E_{prim}^{DSLOPE} * F * 10^{-3*DSLOPE} * 10^{-4} / N_{prim}$$

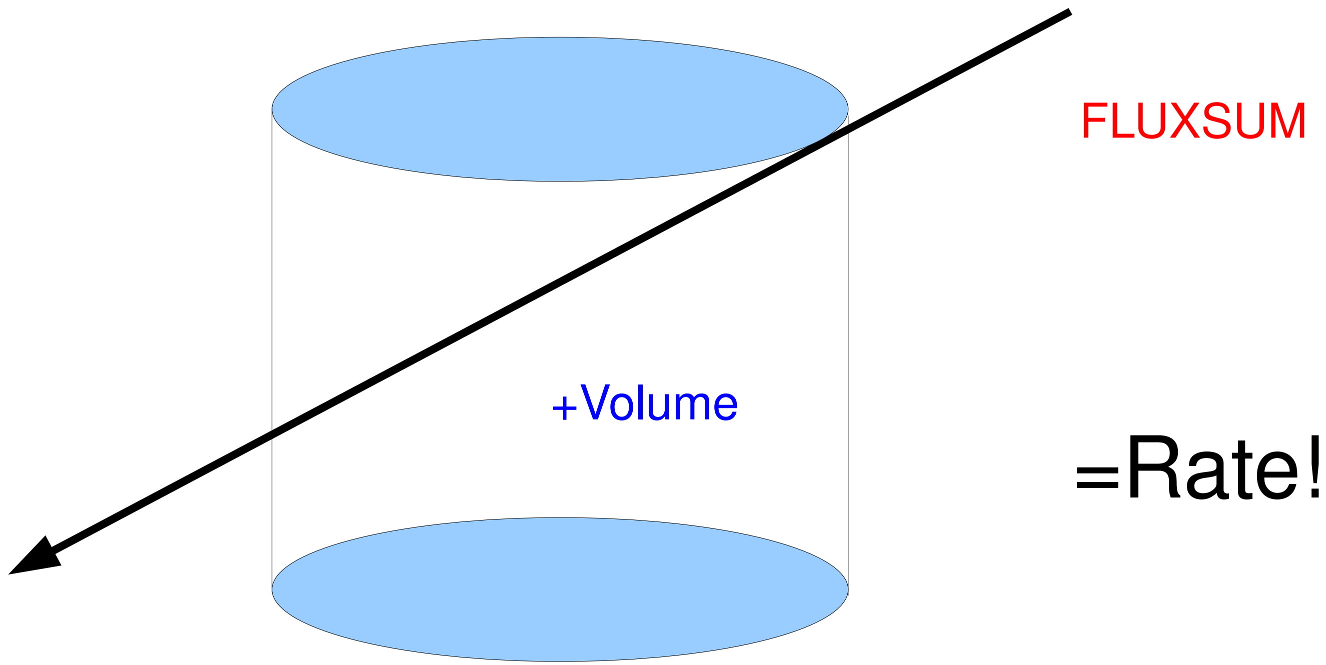
Individual event

TeV->GeV

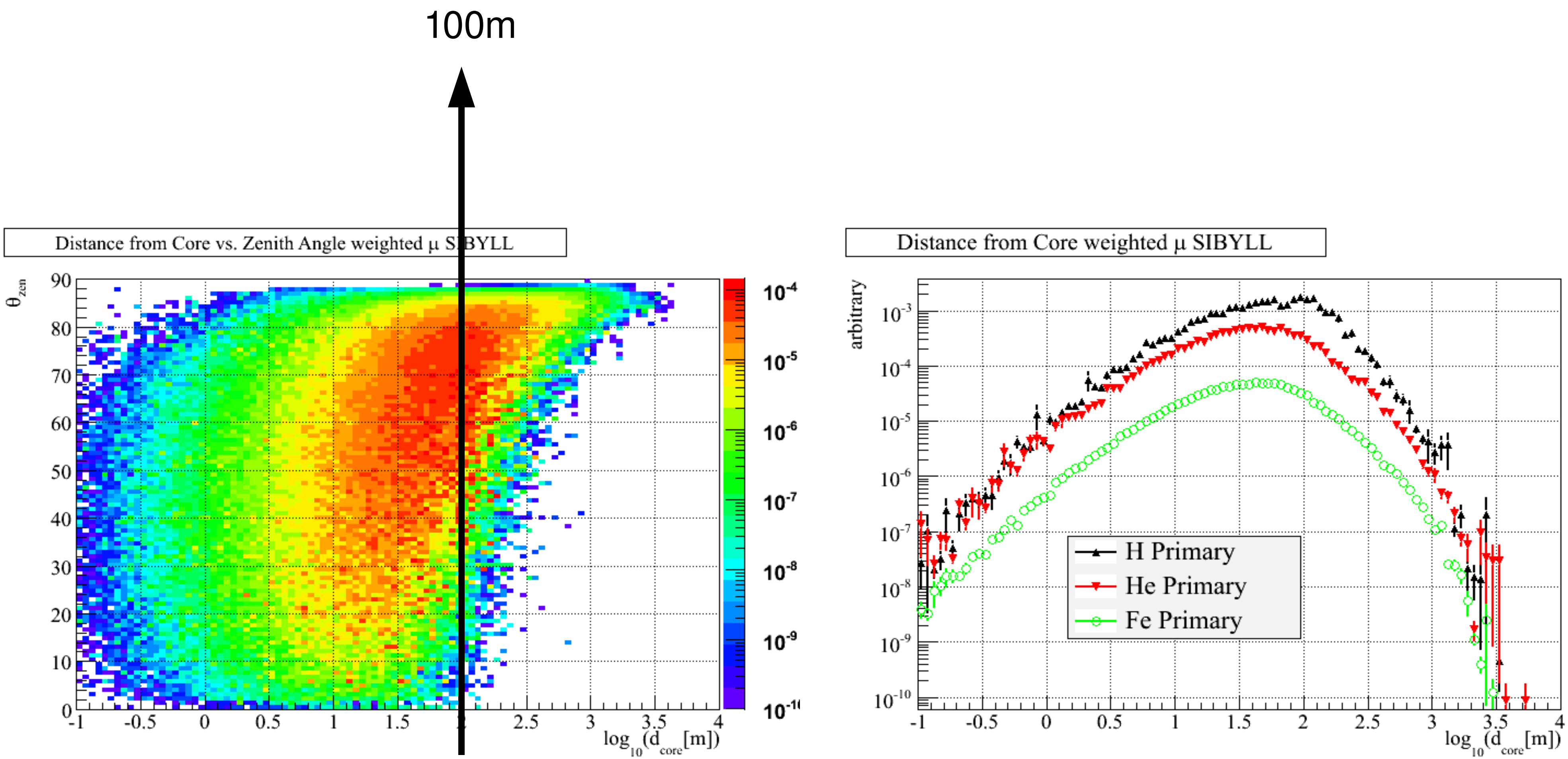
m^2->cm^2

IceSim

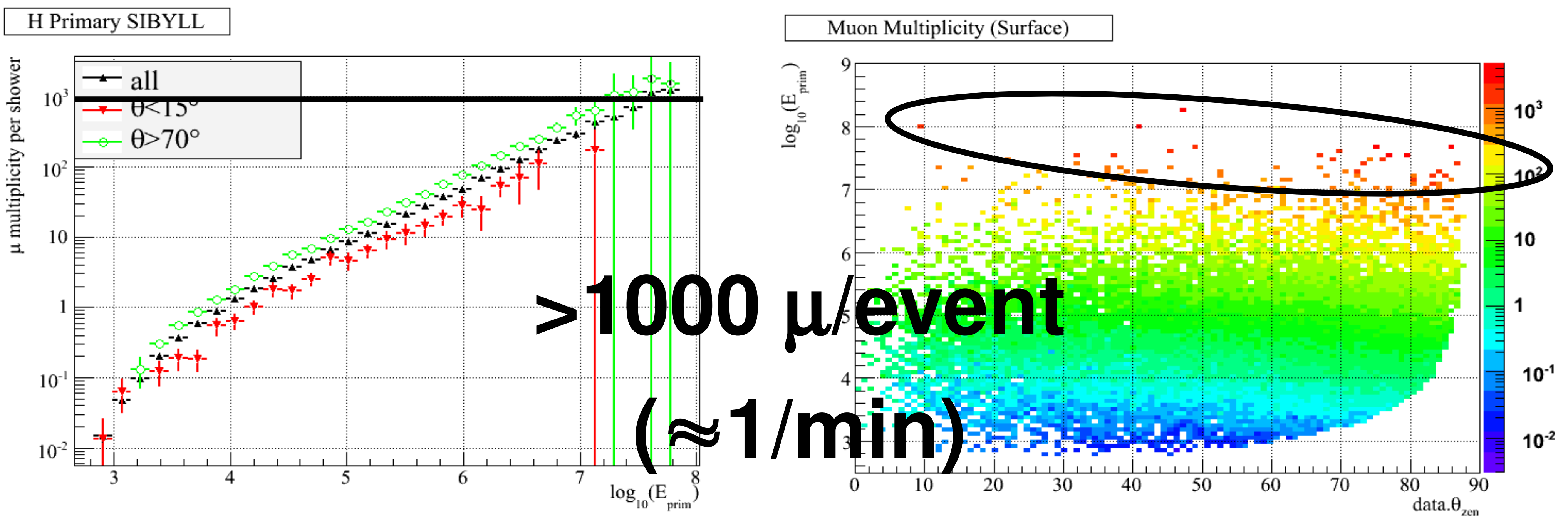
```
tray.AddModule("I3CorsikaWeightModule","corsikaweight")(
   ("nevents",10000000),                         # number of showers generated in CORSIKA
   ("spectrumtype",2),                           # the RANPRI parameter in CORSIKA steering file (Hoerandel spectrum)
   ("cylinderlength",1400*I3Units.meter),        # the generation cylinder length as in -LENGTH=1400 above
   ("cylinderradius",700*I3Units.meter),         # the generation cylinder radius as in -RADIUS=700 above
   ("fluxsum",0.131475115),                      # the energy-integrated spectrum calculated by CORSIKA
   ("energyprimarymin",600.*I3Units.GeV),        # the minimum energy as from ERANGE in CORSIKA steering file
   ("energyprimarymax",100000000000.*I3Units.GeV), # the maximum energy as from ERANGE in CORSIKA steering
file
 )
```



Shower Size


100m
Distance from Core vs. Zenith Angle weighted μ SIBYLL
θzen
log10(dcore[m])
Distance from Core weighted μ SIBYLL
arbitrary
H Primary
He Primary
Fe Primary
log10(dcore[m])

Multiplicity



>1000 μ/event (≈1/min)

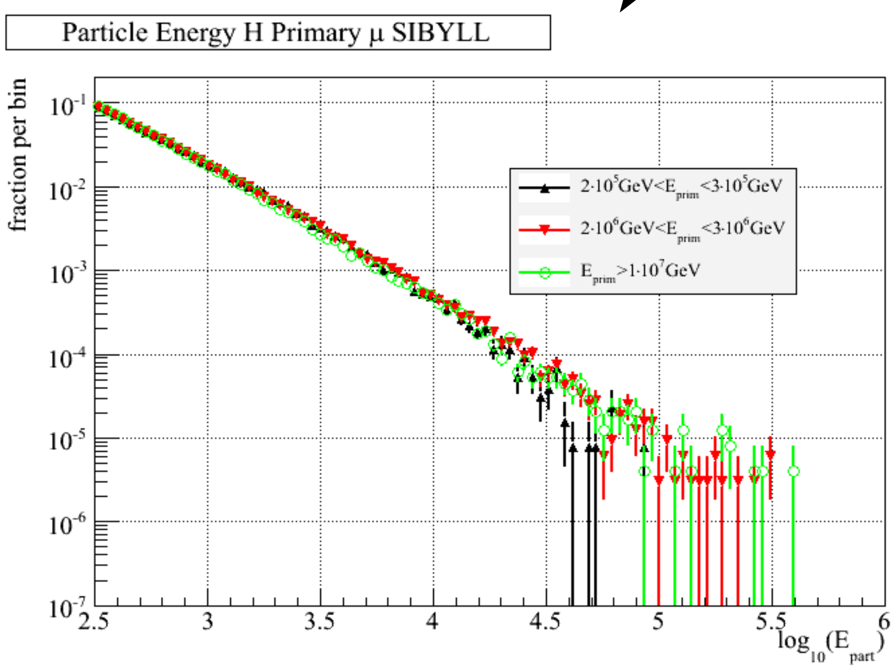
Energy Spectrum

-2.6 +.8 -2.7

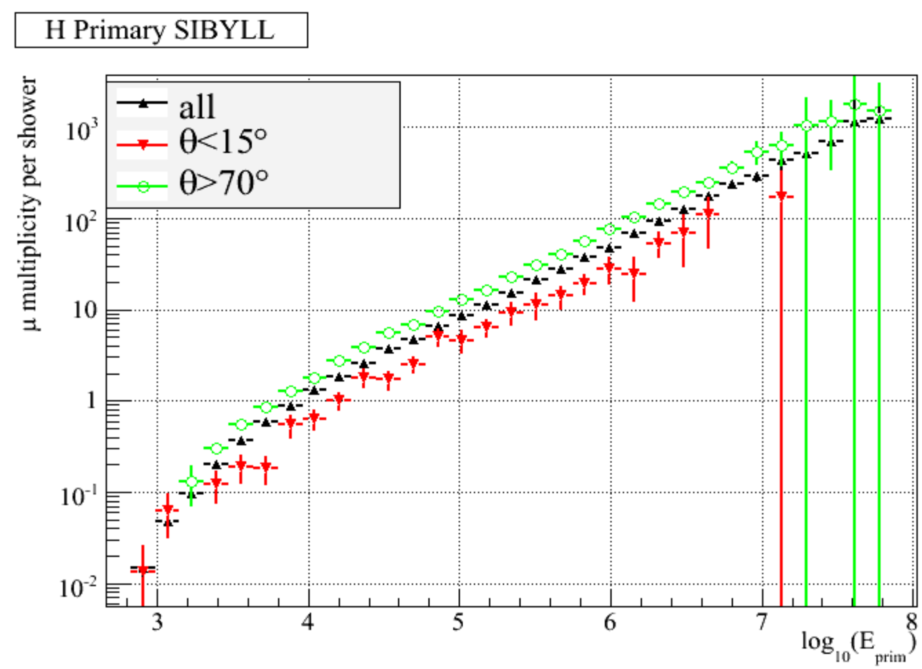
$$\gamma_\mu = \gamma_{\mu 0} + \gamma_{mult} + \gamma_{CR} + 1 = -3.5$$

$$dN_\mu/dE_\mu = (dN_\mu/dE_\mu)_0 * dN_\mu/dE_{CR} * \int (dN_{CR}/dE_{CR})\, dE_{CR}$$

Monoenergetic Primary

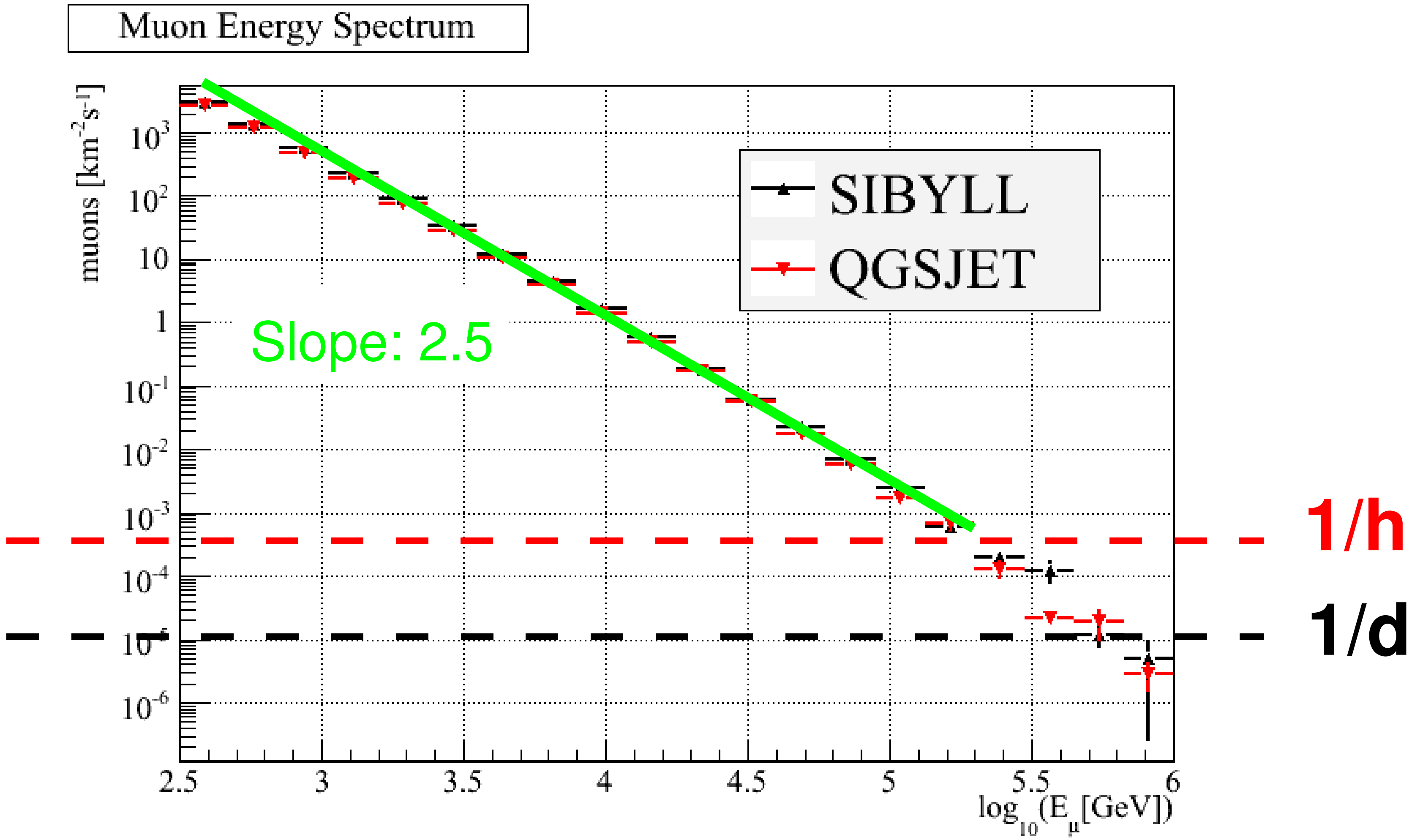


Multiplicity



Power Law: cx^γ

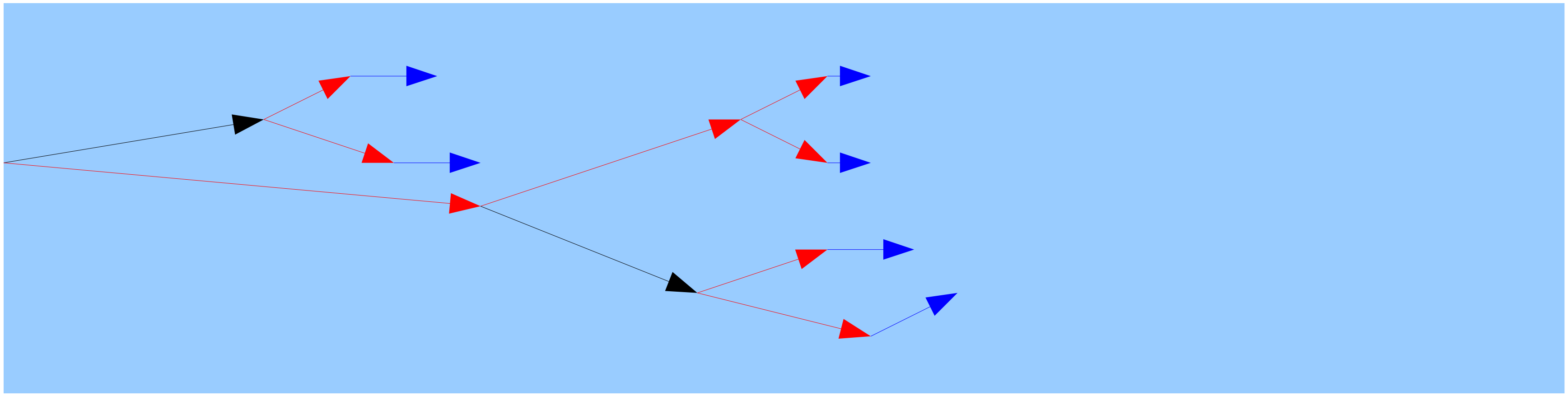
QED



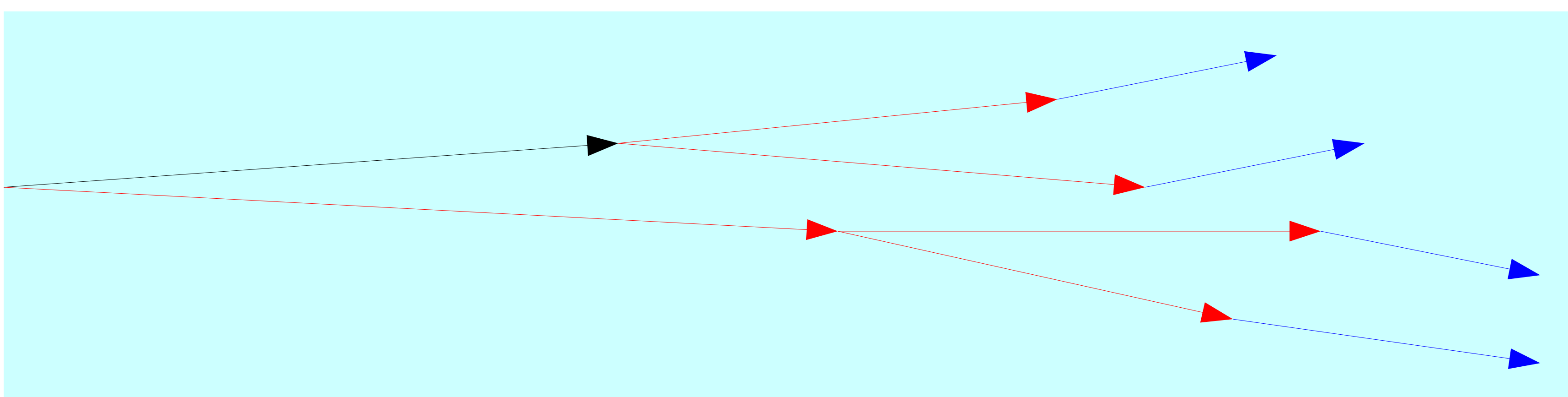
Muon Energy Spectrum
muons [km⁻²s⁻¹]
10³
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
2.5
3
3.5
4
4.5
5
5.5
6
log10(Eμ[GeV])
SIBYLL
QGSJET
Slope: 2.5
1/h
1/d

Spectral Variations

Dense air (vertical, summer): short mean free path, more reinteractions, less energetic muons



Thin air (horizontal, winter): long mean free path, fewer reinteractions, more energetic muons



F2K

Header: Muon Event # 17, Run 100

```
EM 17 100 ? ? 0.000000000 0
TR 1 ? p+ 0 0 2834 12.4081 61.8448 -1 1496.46 0
TR 1 1 mu- 5.24948 8.50714 2834 12.4241 61.8717 16706.6 278.978 -7.0625
EE
```

Primary: 1496GeV Proton, 12.4°

Secondary: 279GeV μ^-

End Event

UCR in IceSim

$I3_SRC/examples-simulation/resources/examples/UCRGenerator.py

module: ucr-icetray

```
tray.AddModule("I3GeneratorUCR","generator")(
    ("EventsToIssue",nevents),
    ("UCROpts",ucropts))
```

executable

F2K file

UCROpts = /home/berghaus/offline/build/bin/ucr-icetray-ucr
/net/local/icecube/i3tools/RHEL4-x86_64/test-data/icesim-corsika/F2K010001.gz
-oms -over=1 -SHOWERS=10000000 -FLUXSUM=0.131475115 -LENGTH=1200 -RADIUS=600
-DEPTH=1945 -HEIGHT=2834 -EARTHR=6.4e6 -DCORR=35 -cutfe=400. -curved=4 -cutth=85 -tr=2

UCR

```
-out=[NAME]  change output file to NAME
-tr=[NUM]  output only events with # of tracks >= NUM
```
-over=[..] oversample by this number, default is 1
```
-r = -randomize randomize shower core xy locations
-c = -curved same for curved Earth's surface
-curved=[1-4] different curved surface treatment:
1: only downgoing primaries (th from 0 to 90 deg.)
2: only upgoing primaries (th from 90 to 180 deg.)
3: decide at random, either goes up or down
4: oversample x2 each event with th > cutth
-phi = -rphi    also randomize azimuth angle
-cutth=[degrees]    value used for -curved=4
-EARTHR=[radius]    of the Earth             [m]
-LENGTH=[length]    of the detector          [m]
-RADIUS=[radius]    of the detector          [m]
-DEPTH=[depth]      of the detector center   [m]
-HEIGHT=[altitude]  of the ice surface       [m]
-DCORR=[correction] depth correction (35 m) [m]
-trigw=[time in ms] assign event times and combine events that are within trigw ms of each other
-rmpri  remove primaries
-rmusr  remove user blocks
```
-oms   output only muons
```
-ohm    leave only muon with highest energy per event
-msn    leave only muon and neutrinos, delete others
-cmt=[file]    append comments contained in the file
-run=[number]  set the run number
-FLUXSUM=[CORSIKA's value]   per meter2 second sr
-SHOWERS=[number] of showers generated by CORSIKA
-rr     remove possible previous xy randomization
-rr=[DEPTH]    and set the previous value of DEPTH
-test [num] [theta] [phi]   test xy randomization
```
-cutfe=[GeV] angle-dependent cutoff energy for muons
```
-corr   enforce f2k compliance
```

Options: ucr-icetray-ucr -h

Threshold Energy

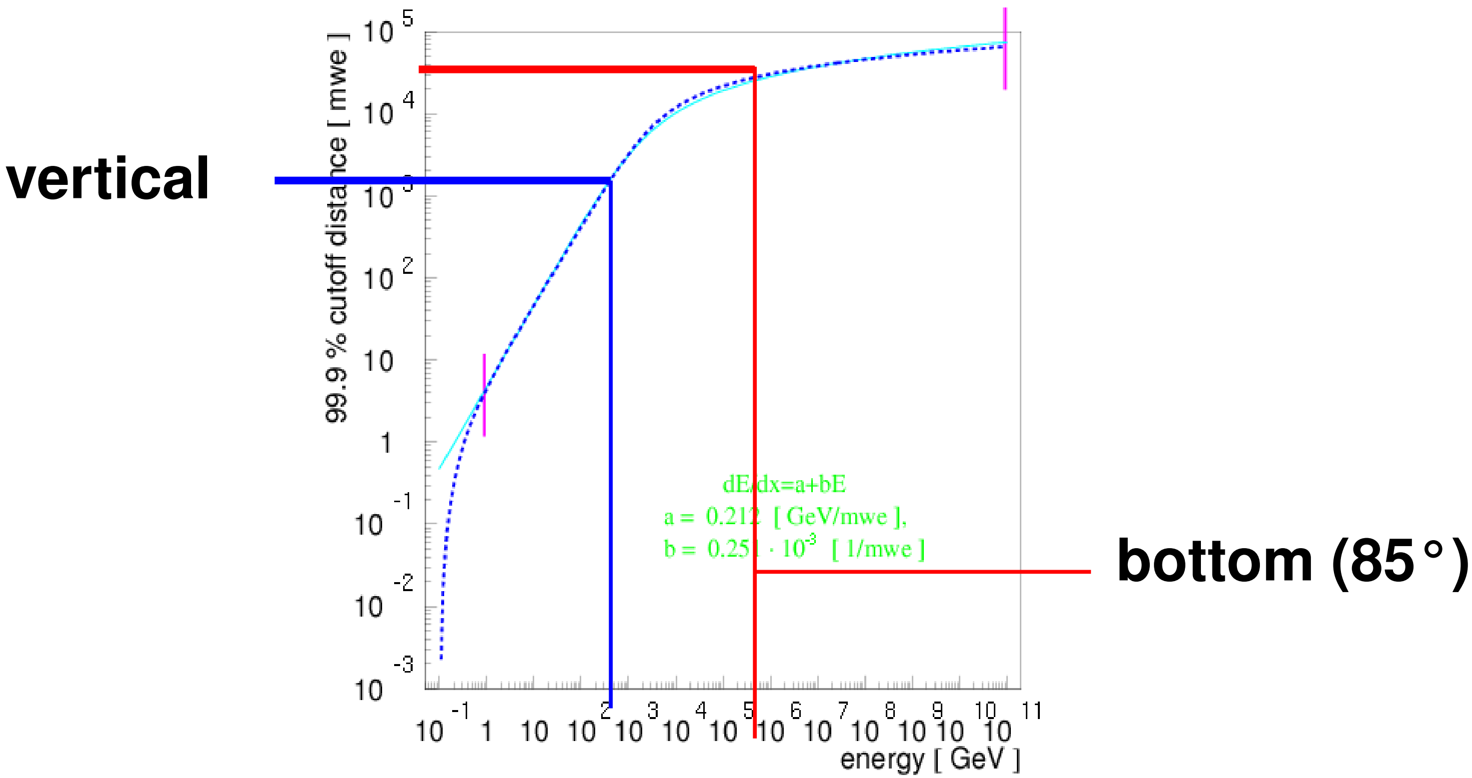
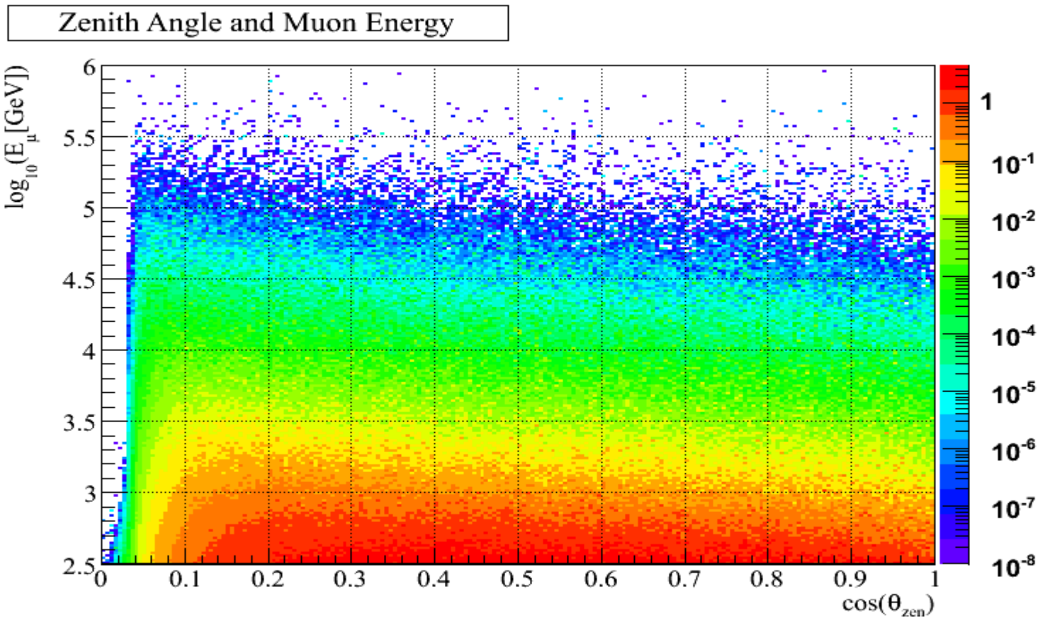


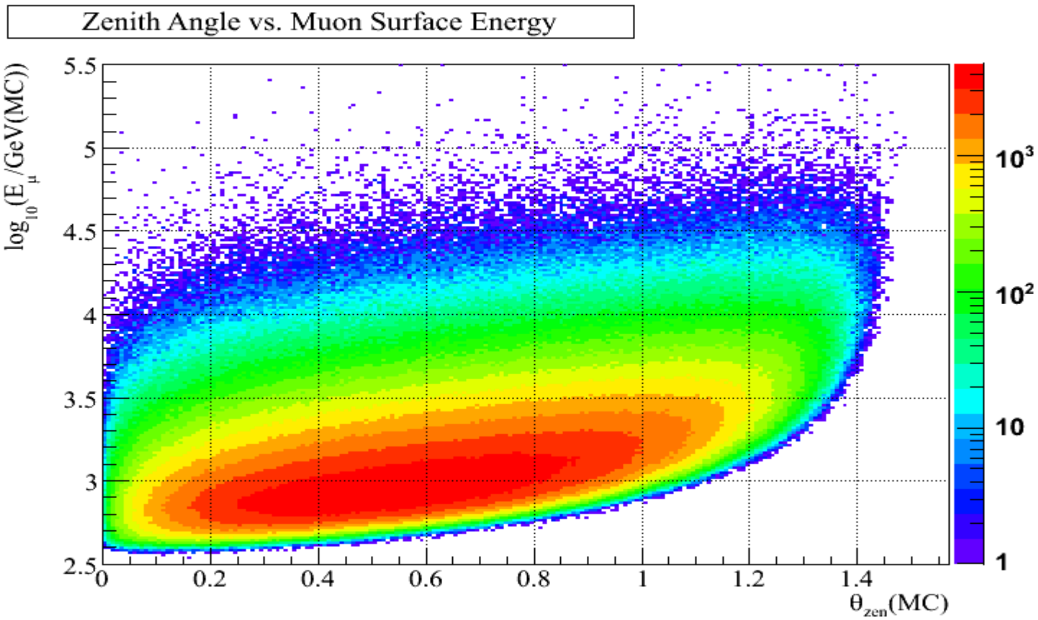
Fig. 29. Fit to the $E_{cut}(x)$

Angle-dependent Energy Cutoff

before ucr



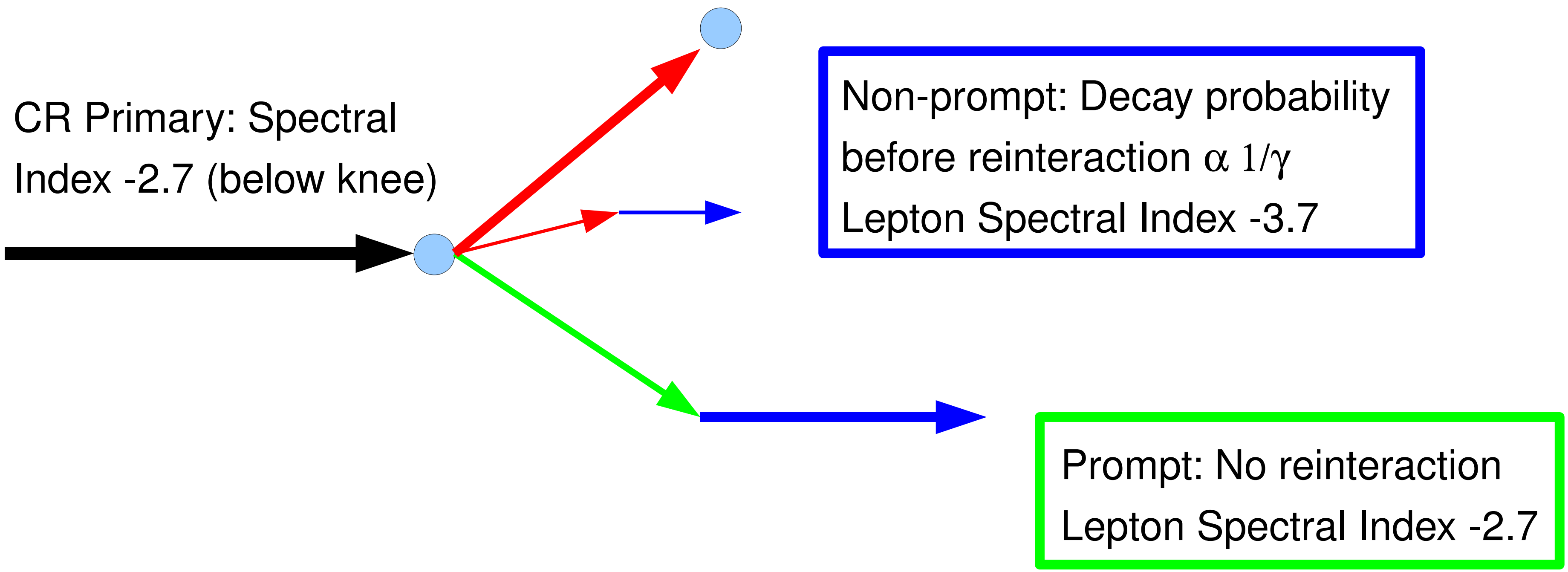
after ucr

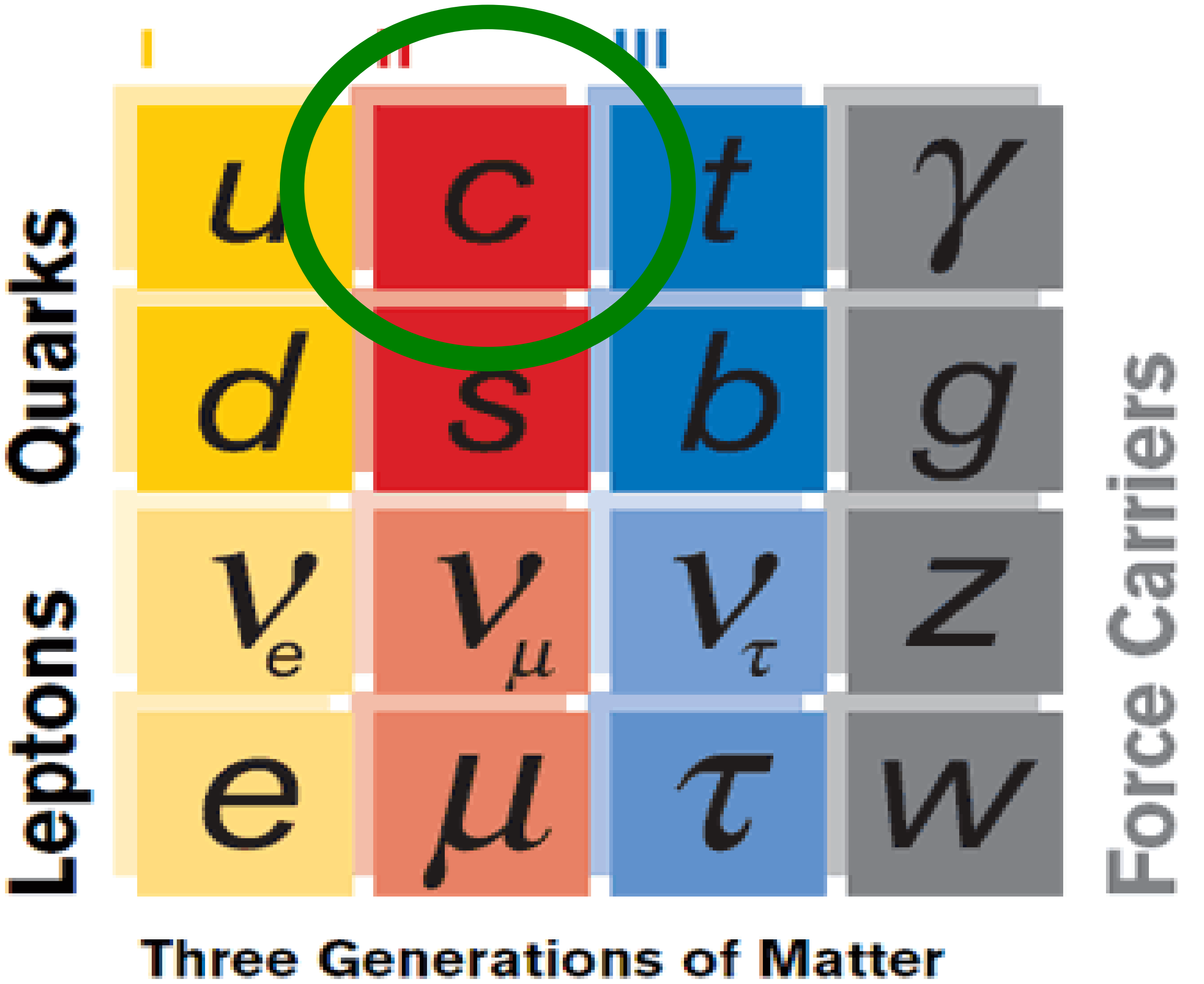


horizon

horizon

Prompt

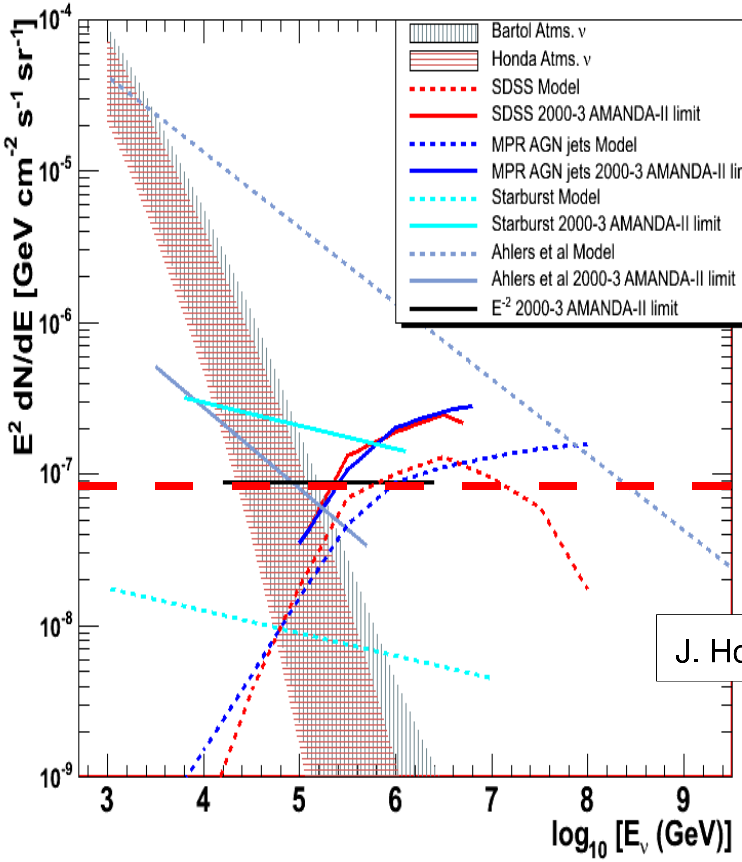

CR Primary: Spectral
Index -2.7 (below knee)
Non-prompt: Decay probability
before reinteraction α 1/γ
Lepton Spectral Index -3.7
Prompt: No reinteraction
Lepton Spectral Index -2.7



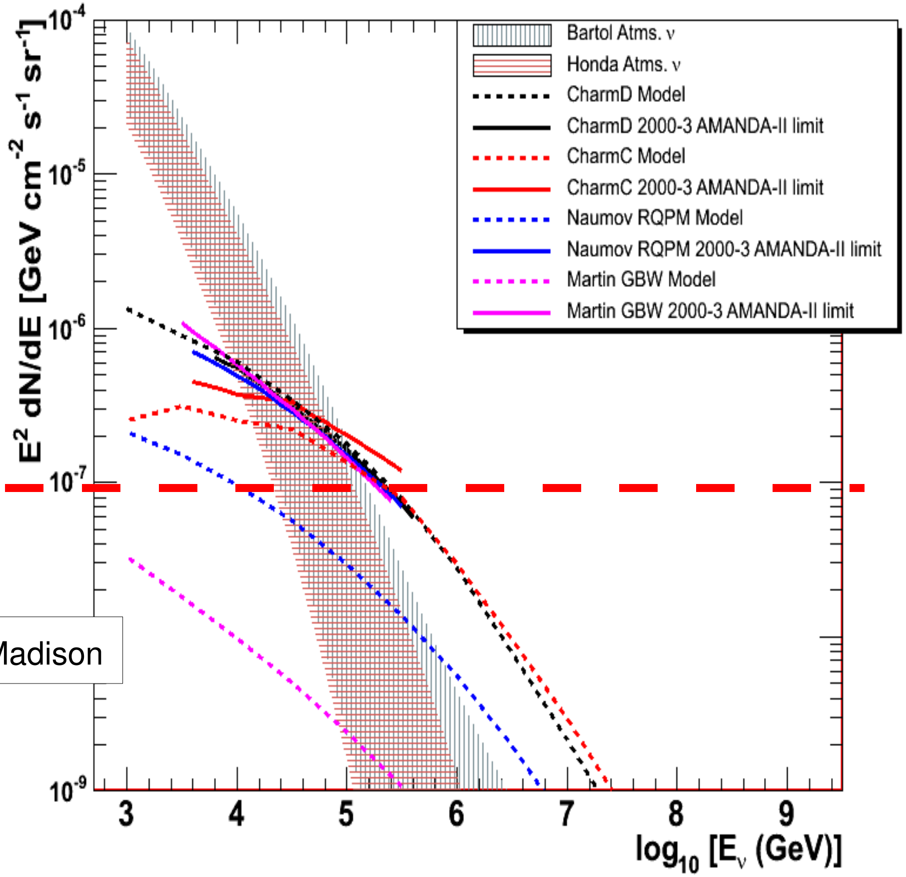
I
II
III
u
c
t
γ
d
s
b
g
ν_e
ν_μ
ν_τ
Z
e
μ
τ
W
Quarks
Leptons
Force Carriers
Three Generations of Matter

Motivation

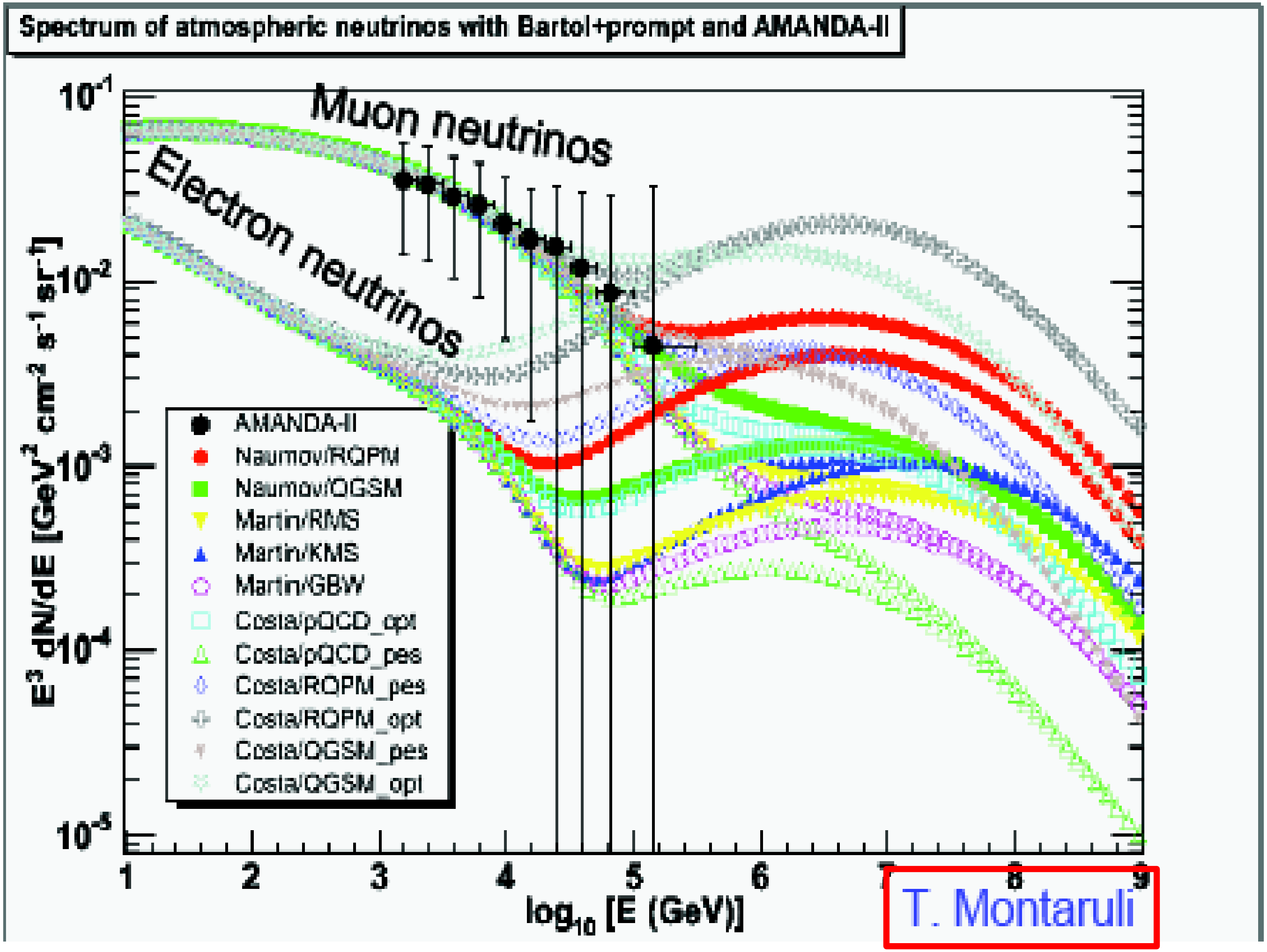
Diffuse Flux



Atmospheric Flux



J. Hodges, UW Madison


Spectrum of atmospheric neutrinos with Bartol+prompt and AMANDA-II
Muon neutrinos
Electron neutrinos
AMANDA-II
Naumov/RQPM
Naumov/QGSM
Martin/RMS
Martin/KMS
Martin/GBW
Costa/pQCD_opt
Costa/pQCD_pes
Costa/RQPM_pes
Costa/RQPM_opt
Costa/QGSM_pes
Costa/QGSM_opt
E^3 dN/dE [GeV^2 cm^-2 s^-1 sr^-1]
log10 [E (GeV)]
T. Montaruli

Hadronic Interactions

Charm?

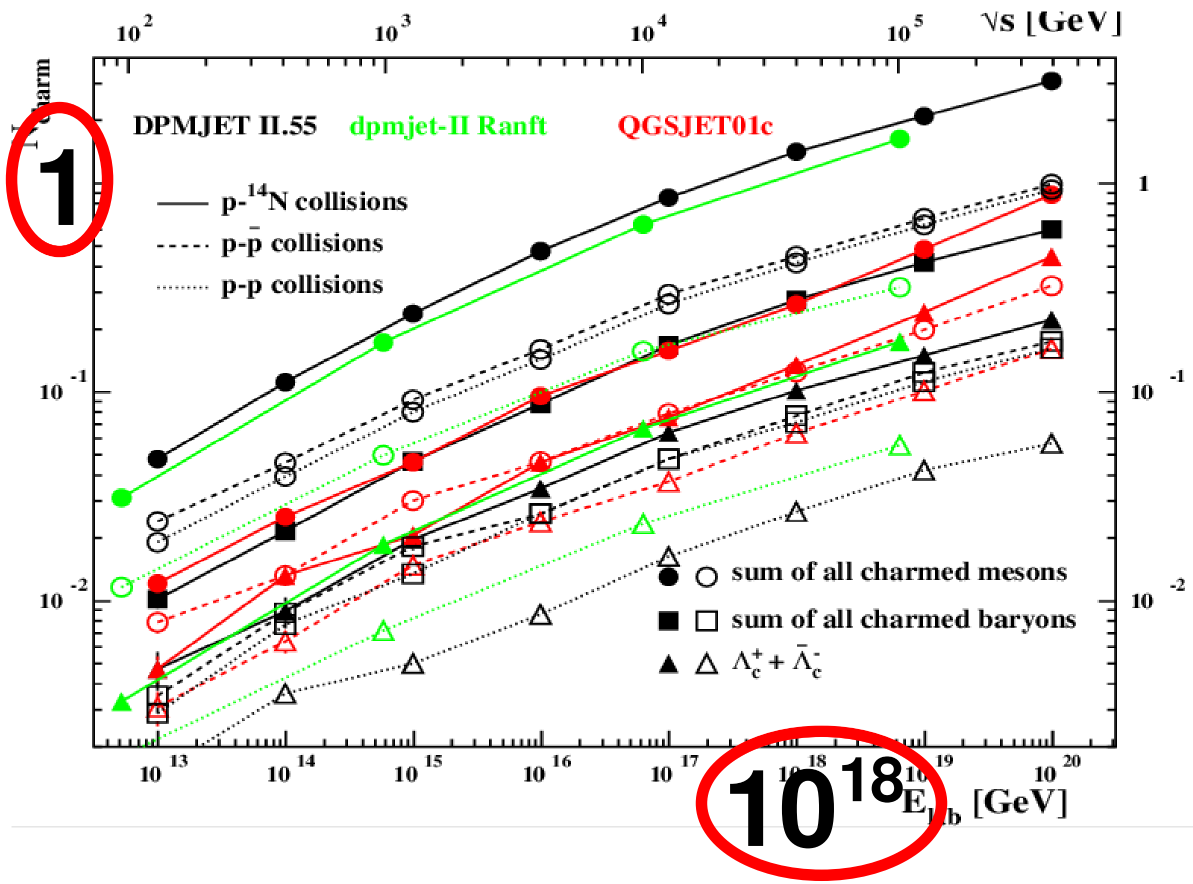
"80GeV"

FLUKA
GHEISHA
QMD

DMPJET

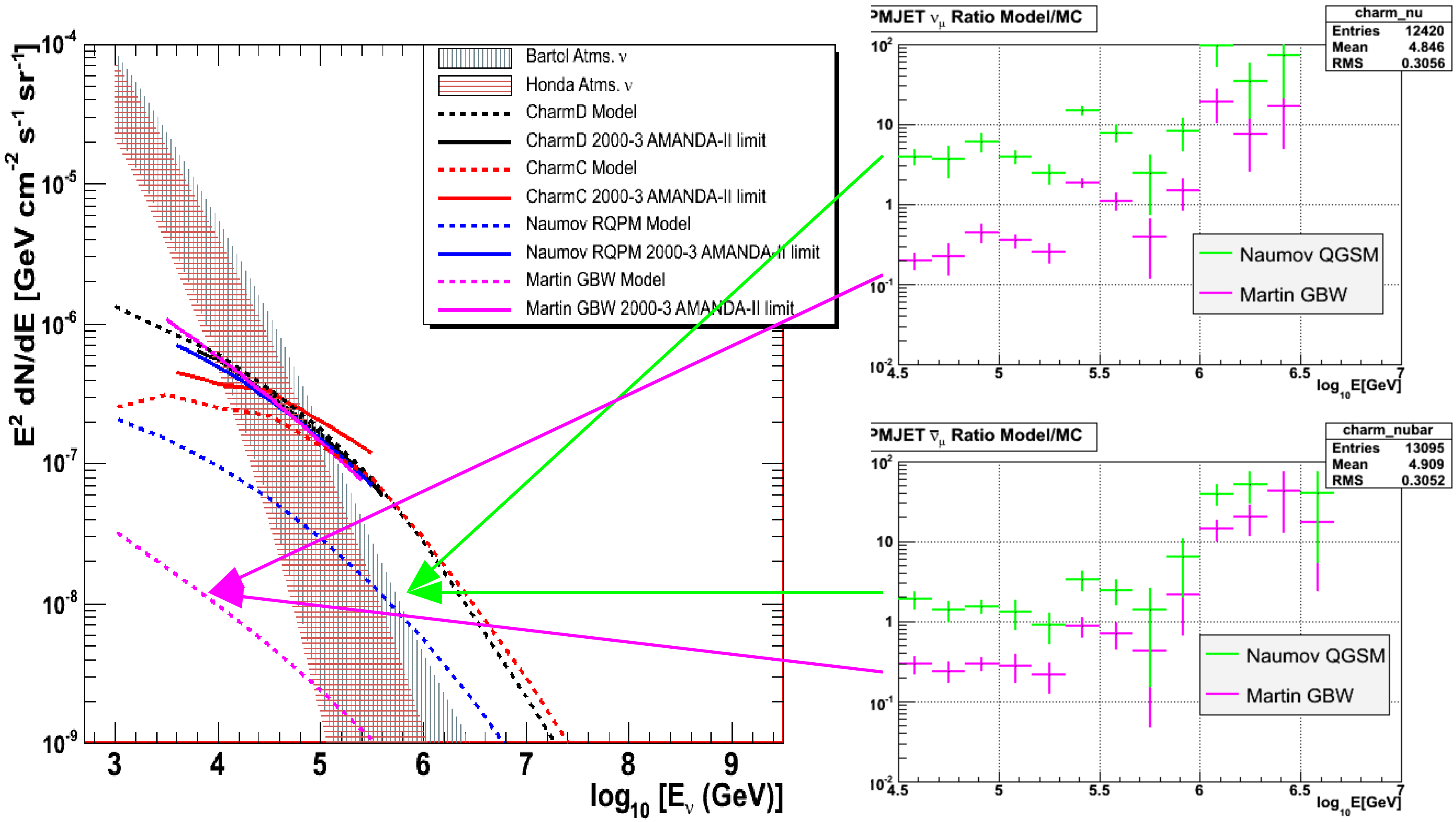
Low E | High E

New DPMJET in CORSIKA



Multiplicity!

Prompt Neutrinos



Good Luck