Muon Energy Spectrum

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IceCube Collaboration Meeting

Spring 2009

Detector Calibration

High Statistics from atmospheric muons

Distributions near the horizon sensitive to:

- Zenith Angle Resolution
- Misreconstructed Background

High-Energy Events

Systematics discovered in the course of this analysis:
See PB talk in Muon Session

Diffuse Analyses

High-Energy Events

Validity of lepton production models

CR composition effects

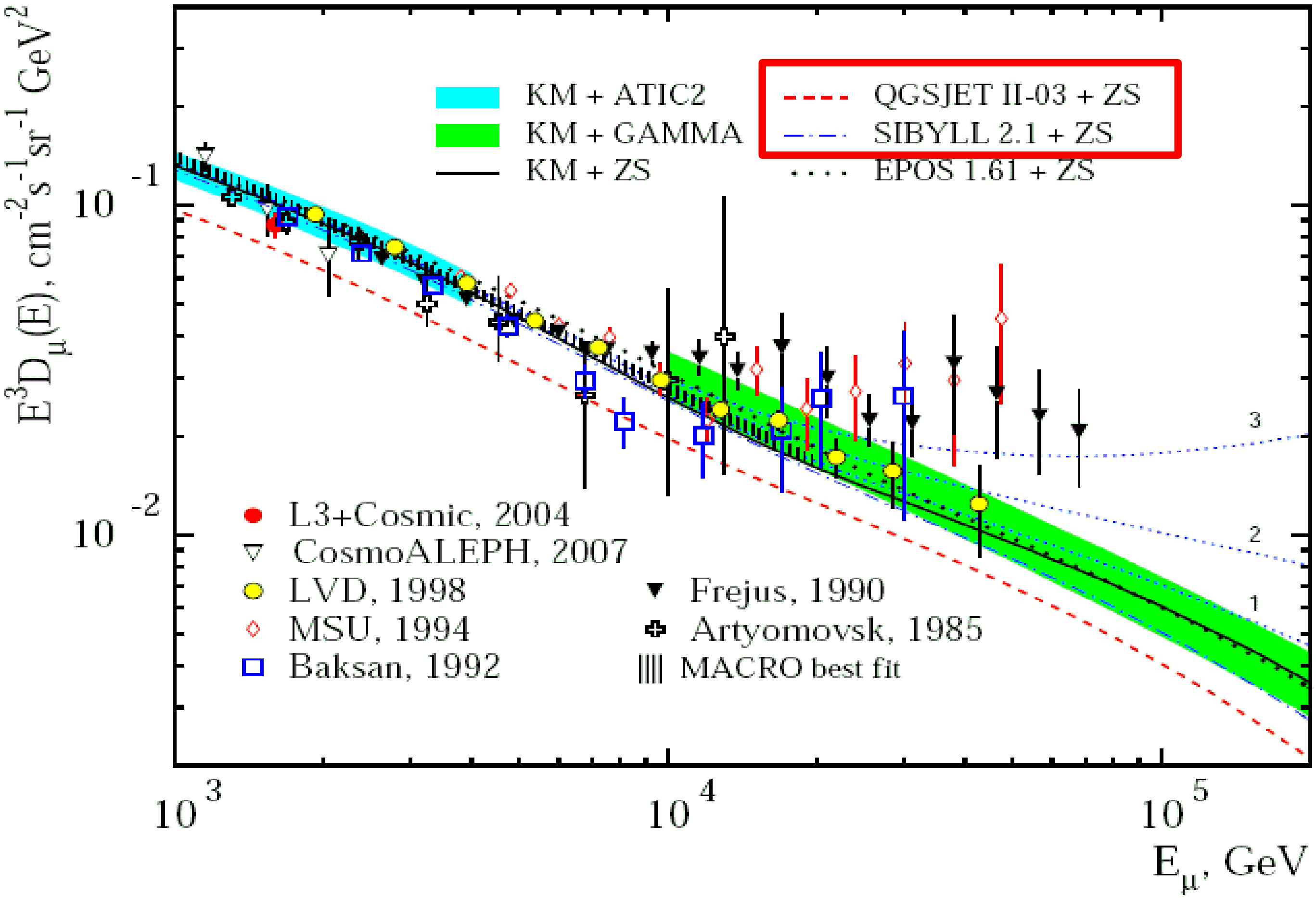
CR Physics

CR composition

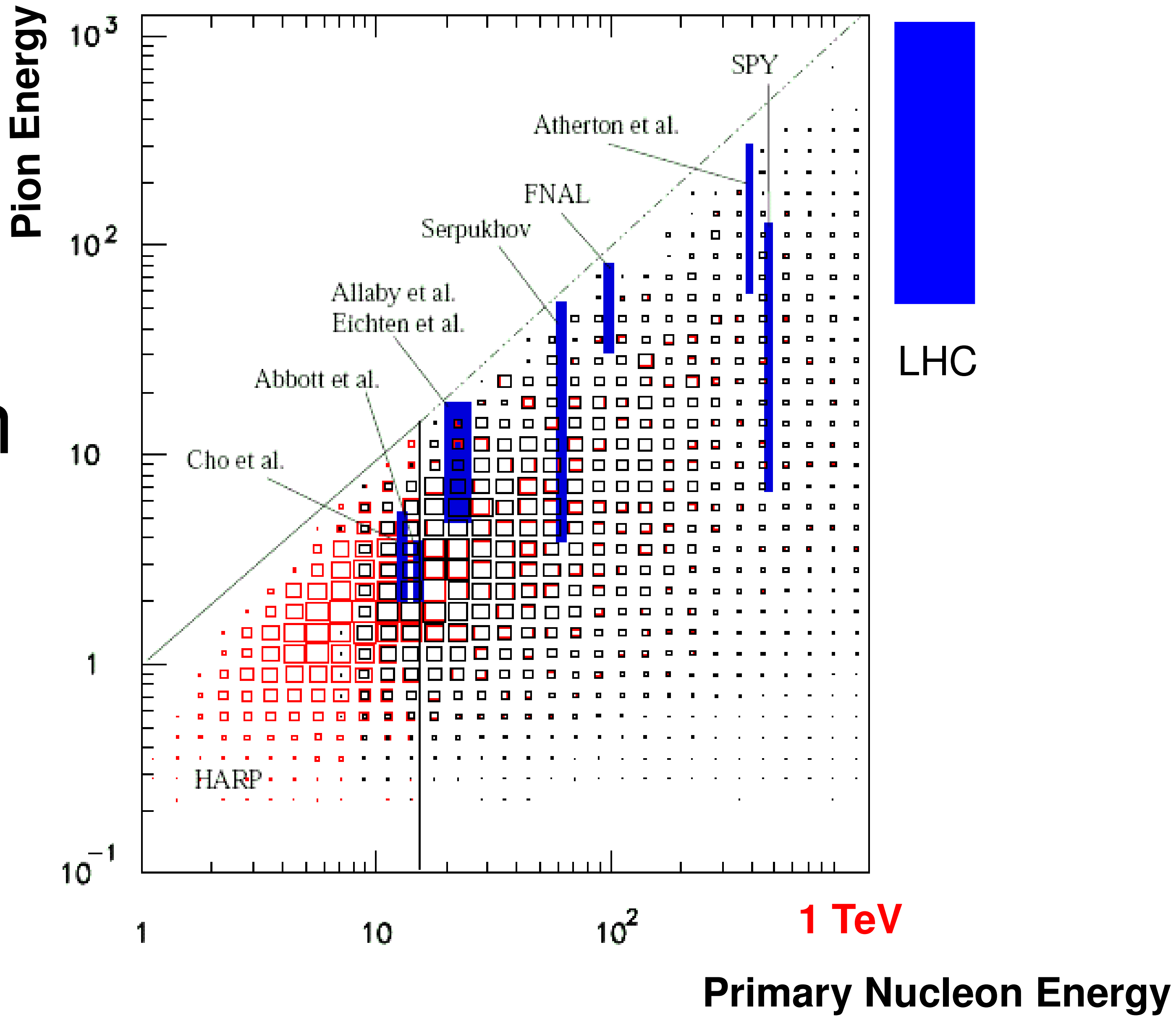
Hadron production in nn interactions

Air Shower Models

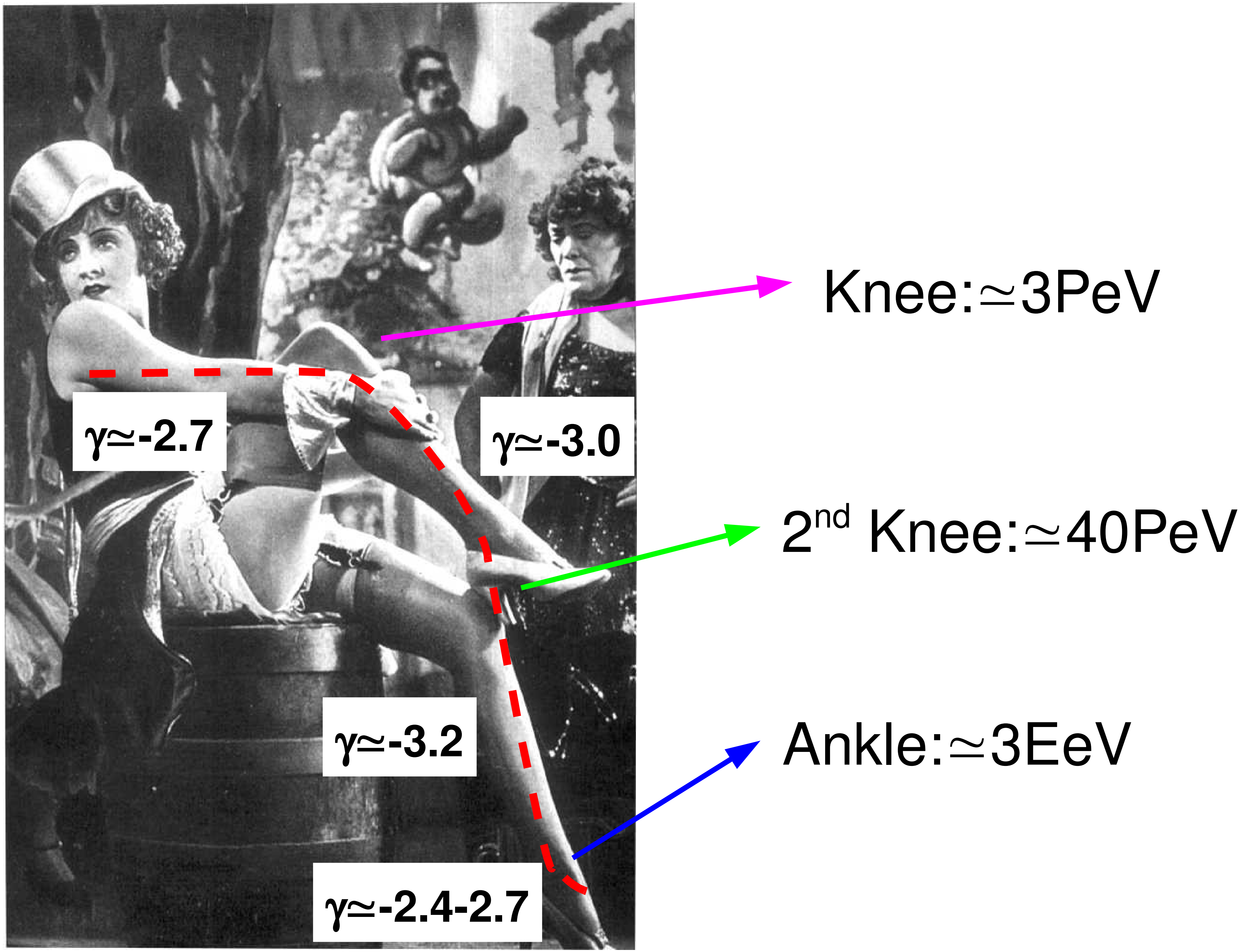
Muon Spectrum



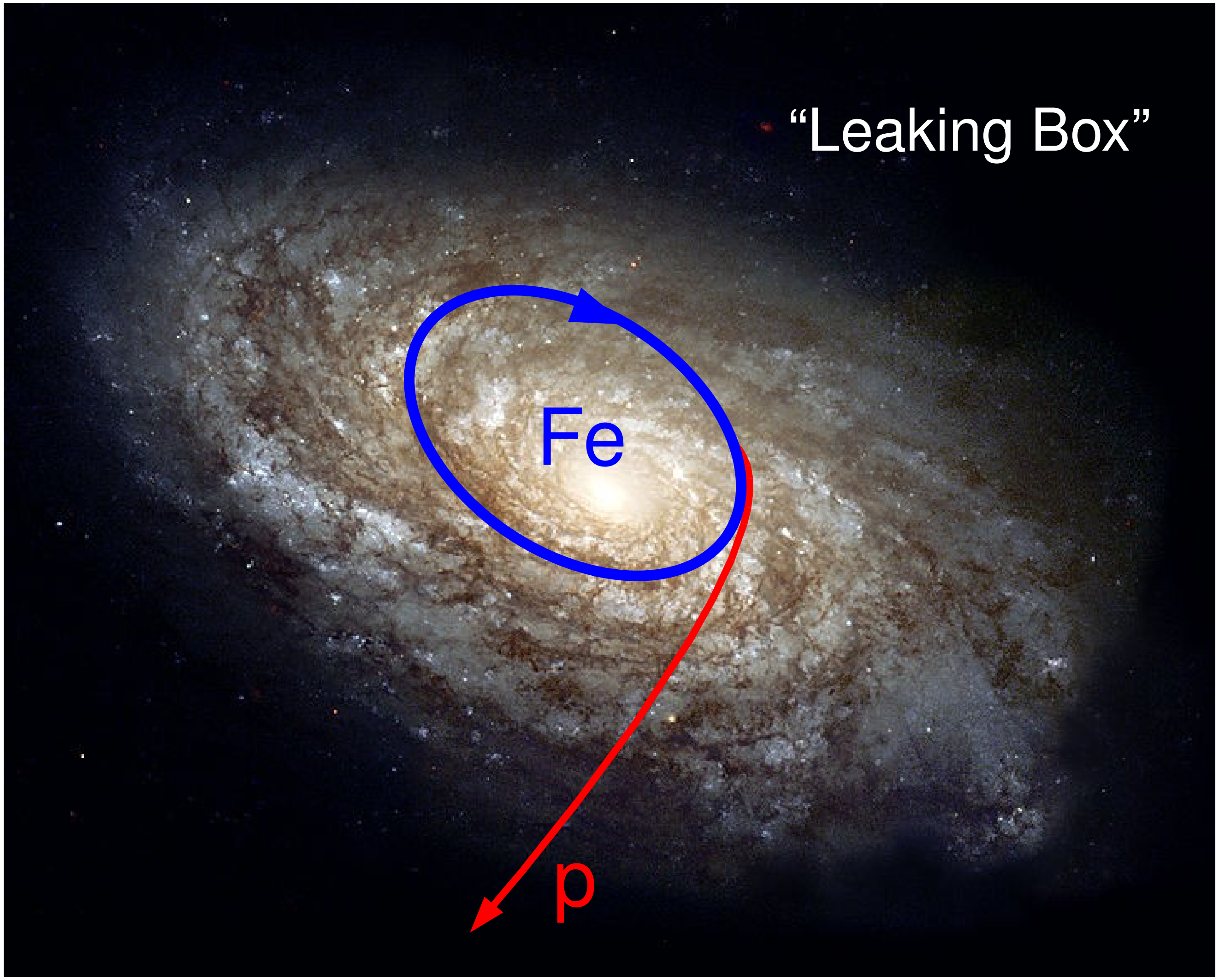
Pion Production



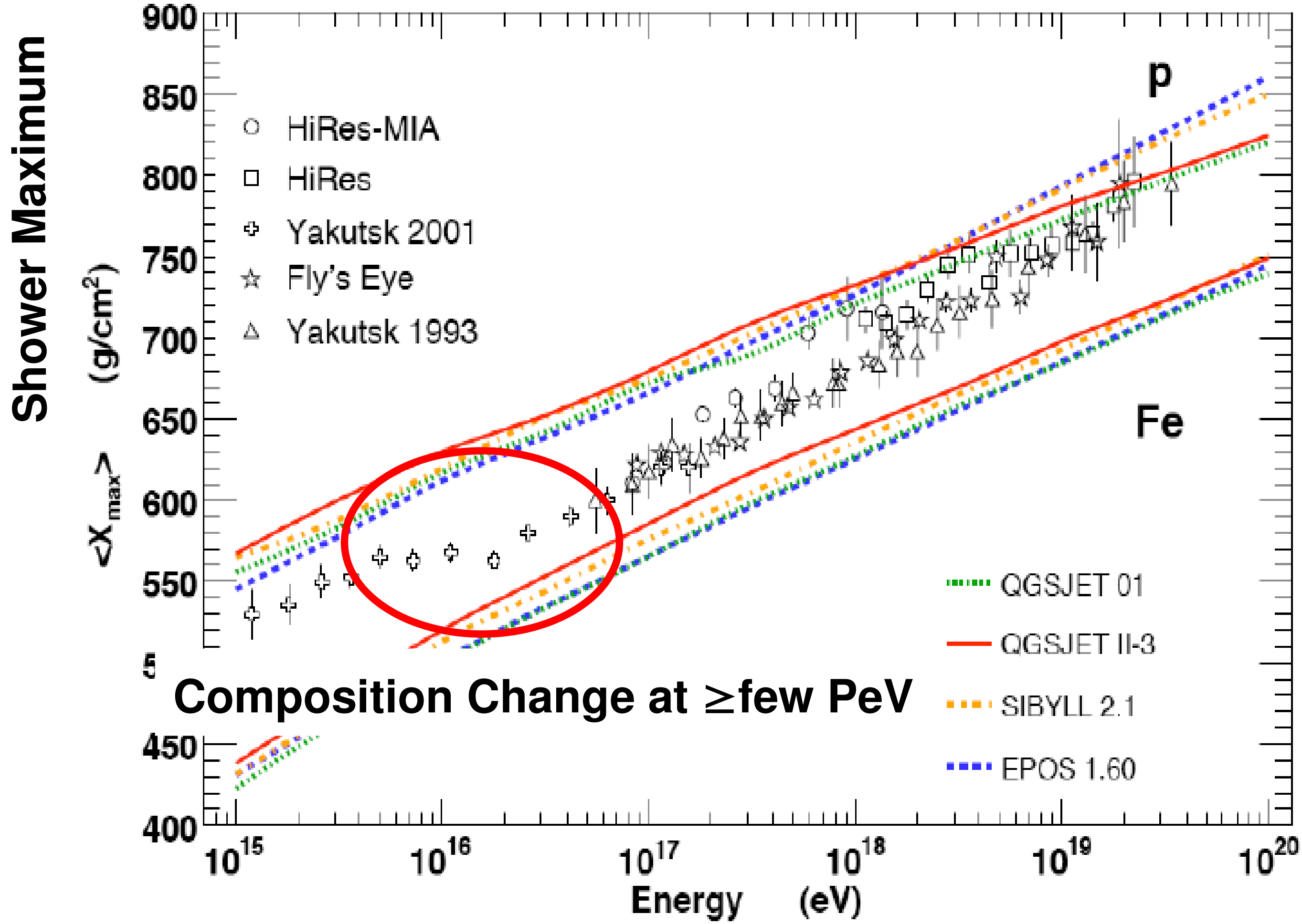
G.D. Barr, T.K. Gaisser, S. Robbins, T. Stanev, astro-ph/0611266


γ≃-2.7
γ≃-3.0
γ≃-3.2
γ≃-2.4-2.7
Knee:≃3PeV
2nd Knee:≃40PeV
Ankle:≃3EeV

Gyroradius: $R = \frac{p}{eZB} \simeq (10pc)\frac{E_{prim}[PeV]}{ZB[\mu G]}$



Extended Air Shower Measurements: Altitude of Shower Maximum



poly-gonato (Hoerandel)

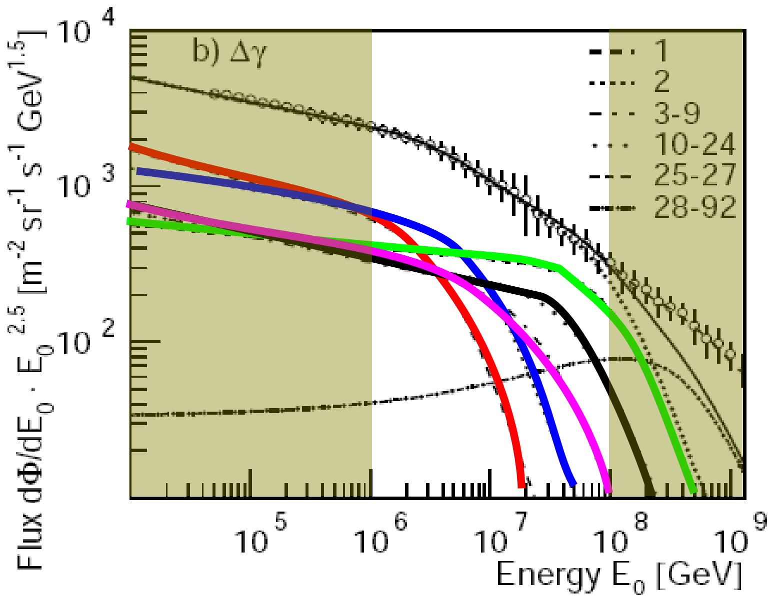
$$\frac{d\Phi_Z}{dE_0} = \Phi_Z^0 \left[1 + \left(\frac{E_0}{E_{trans}}\right)^{\epsilon_c}\right]^{\frac{-\Delta\gamma}{\epsilon_c}}$$

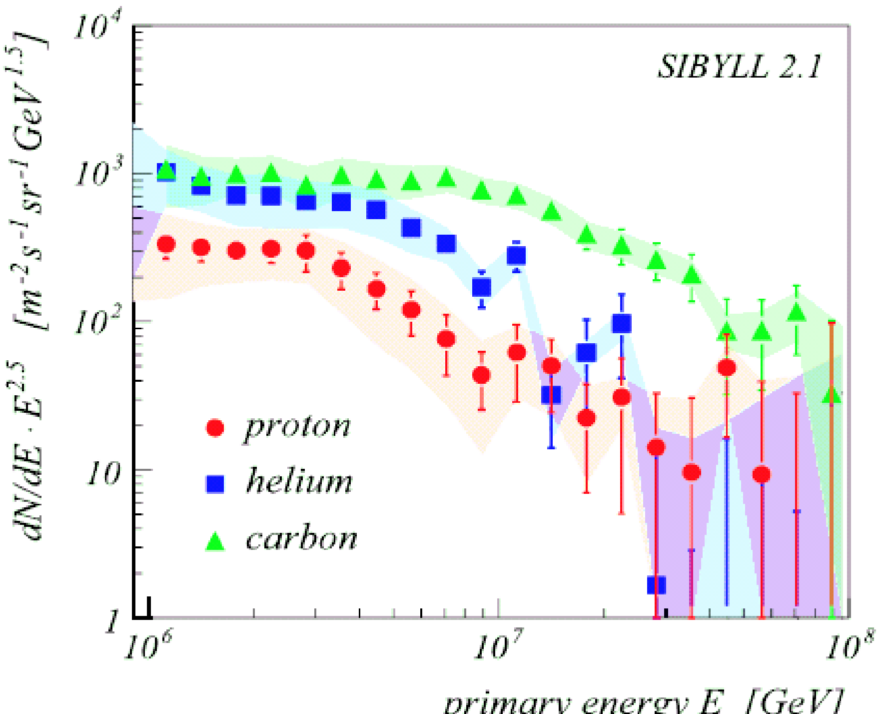
cut–off:	rigidity dependent	mass dependent	constant	
$\hat{E}_Z =$	$\hat{E}_p \cdot Z$	$\hat{E}_p \cdot A$	$\hat{E}_p$	
$\hat{E}_p$ [PeV] =	4.51 ± 0.52	3.66 ± 0.41	3.50 ± 0.38	common γ_c
$\gamma_c =$	-4.68 ± 0.23	-7.82 ± 1.09	-3.06 ± 0.02	
$\epsilon_c =$	1.87 ± 0.18	2.30 ± 0.23	1.94 ± 0.51	
χ^2/d.o.f =	0.116	0.290	0.086	
$\hat{E}_p$ [PeV] =	4.49 ± 0.51	3.81 ± 0.43	3.68 ± 0.39	common $\Delta\gamma$
$\Delta\gamma =$	2.10 ± 0.24	5.70 ± 1.23	0.44 ± 0.02	
$\epsilon_c =$	1.90 ± 0.19	2.32 ± 0.22	1.84 ± 0.45	
χ^2/d.o.f. =	0.113	0.292	0.088	

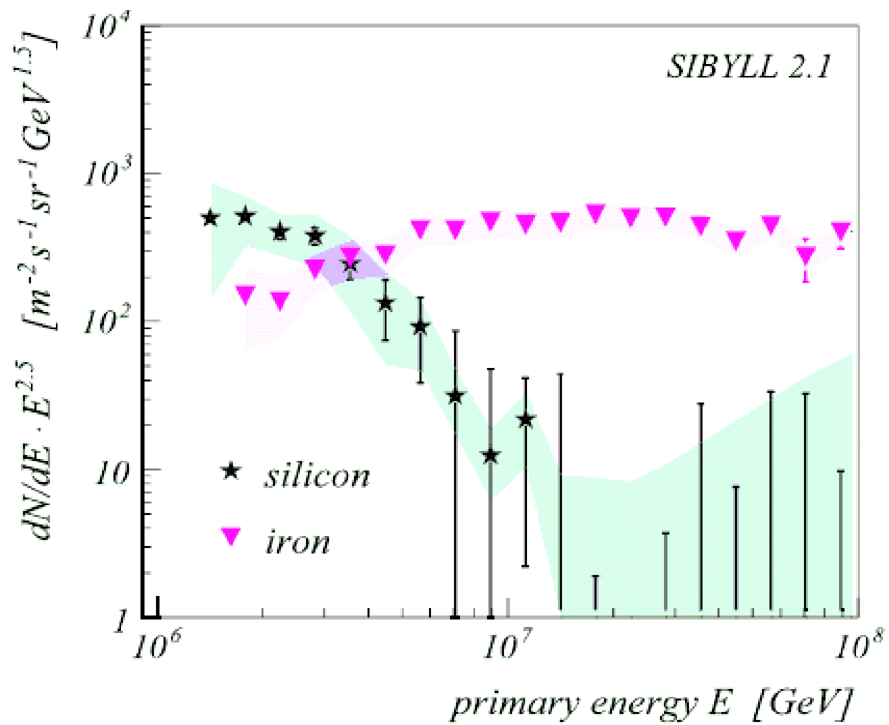
Rigidity Mass Constant

astro-ph/0210453

CASKADE Composition Measurement

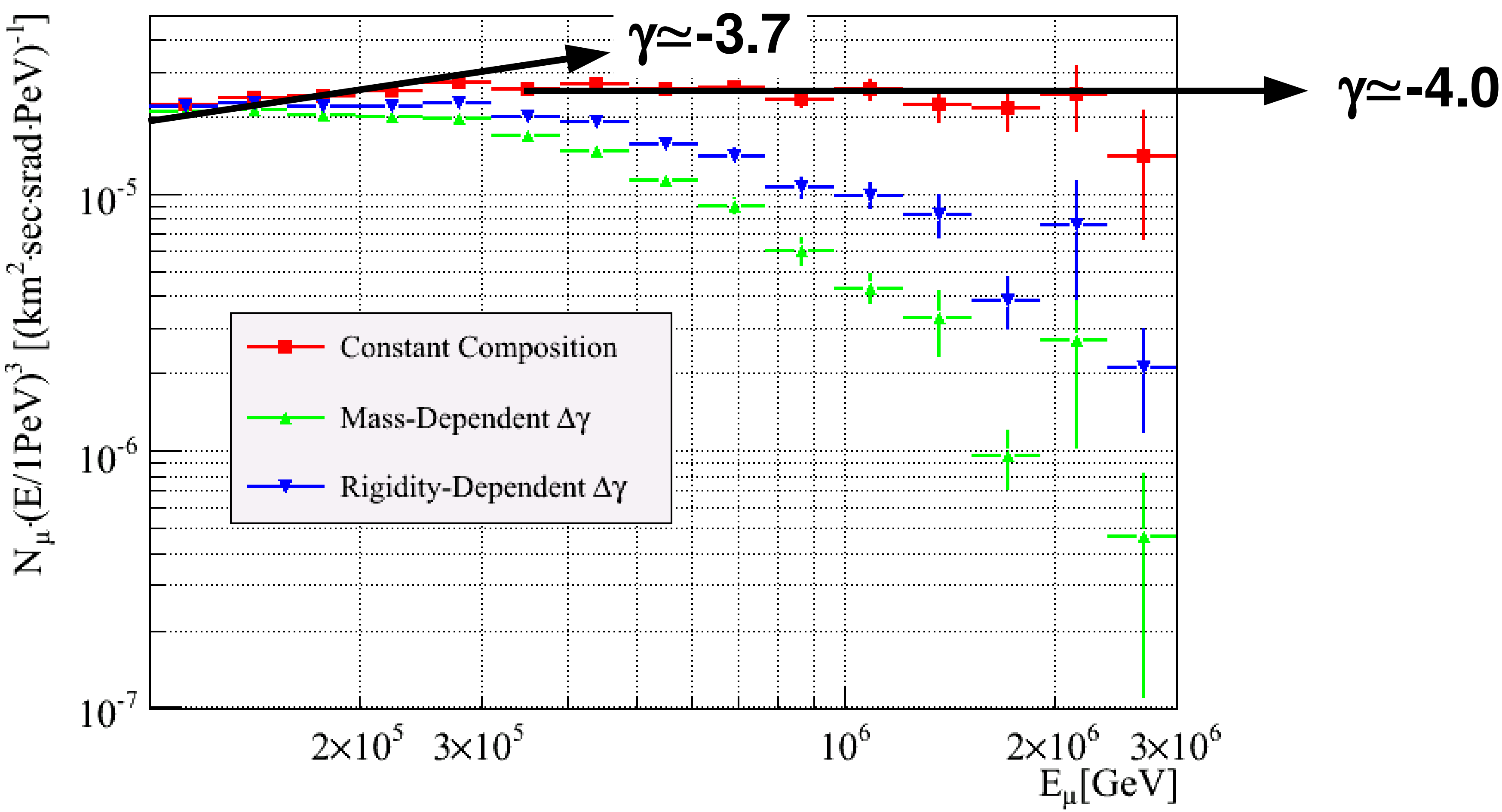




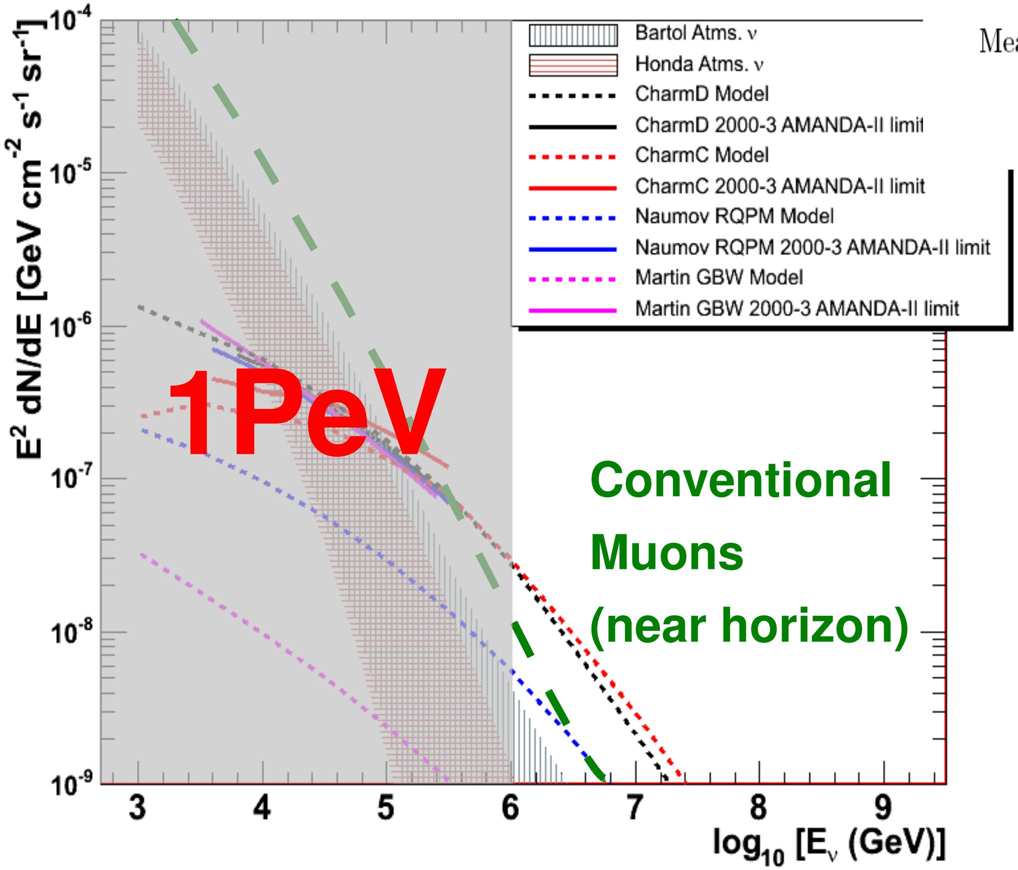


astro-ph/0505413

CR Composition and Muon Energy



Prompt Muons: Out of Reach!



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

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

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

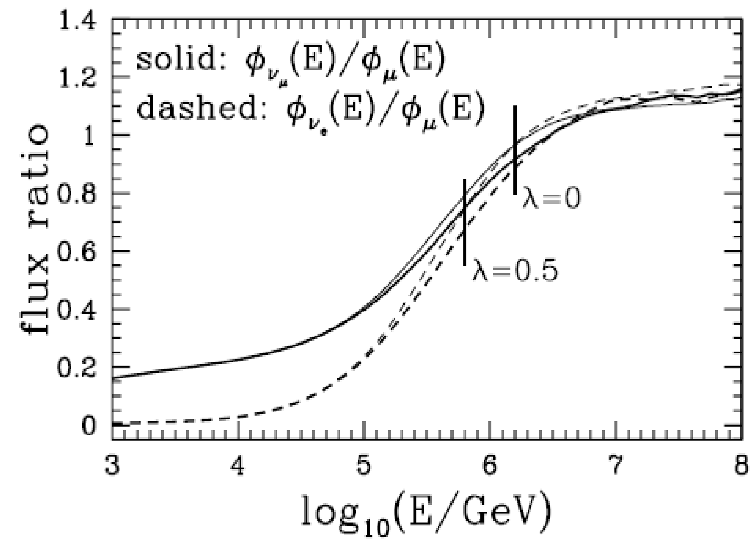
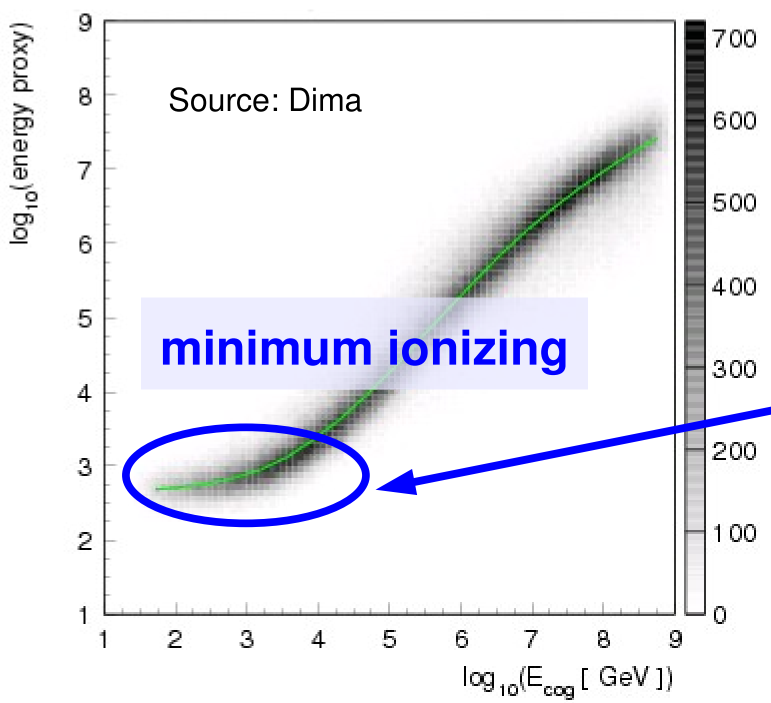
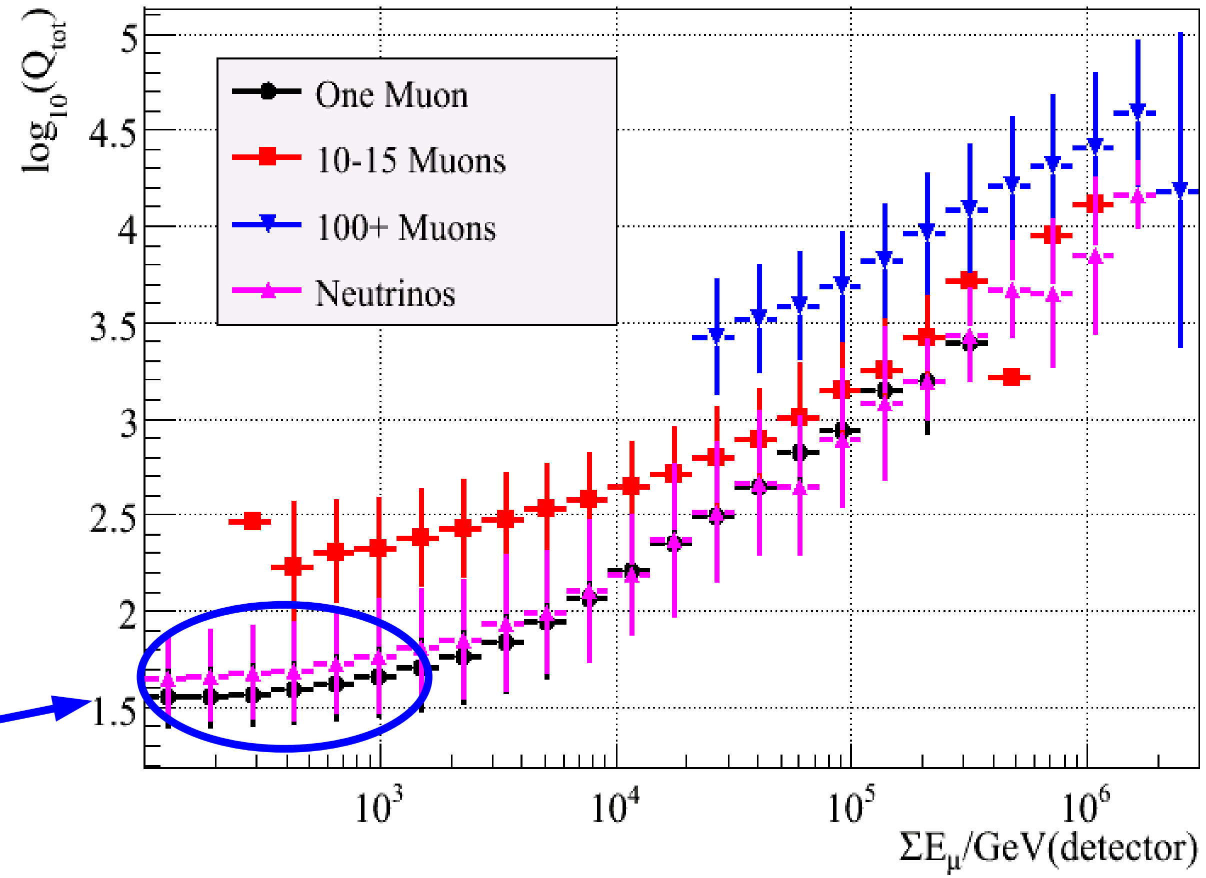


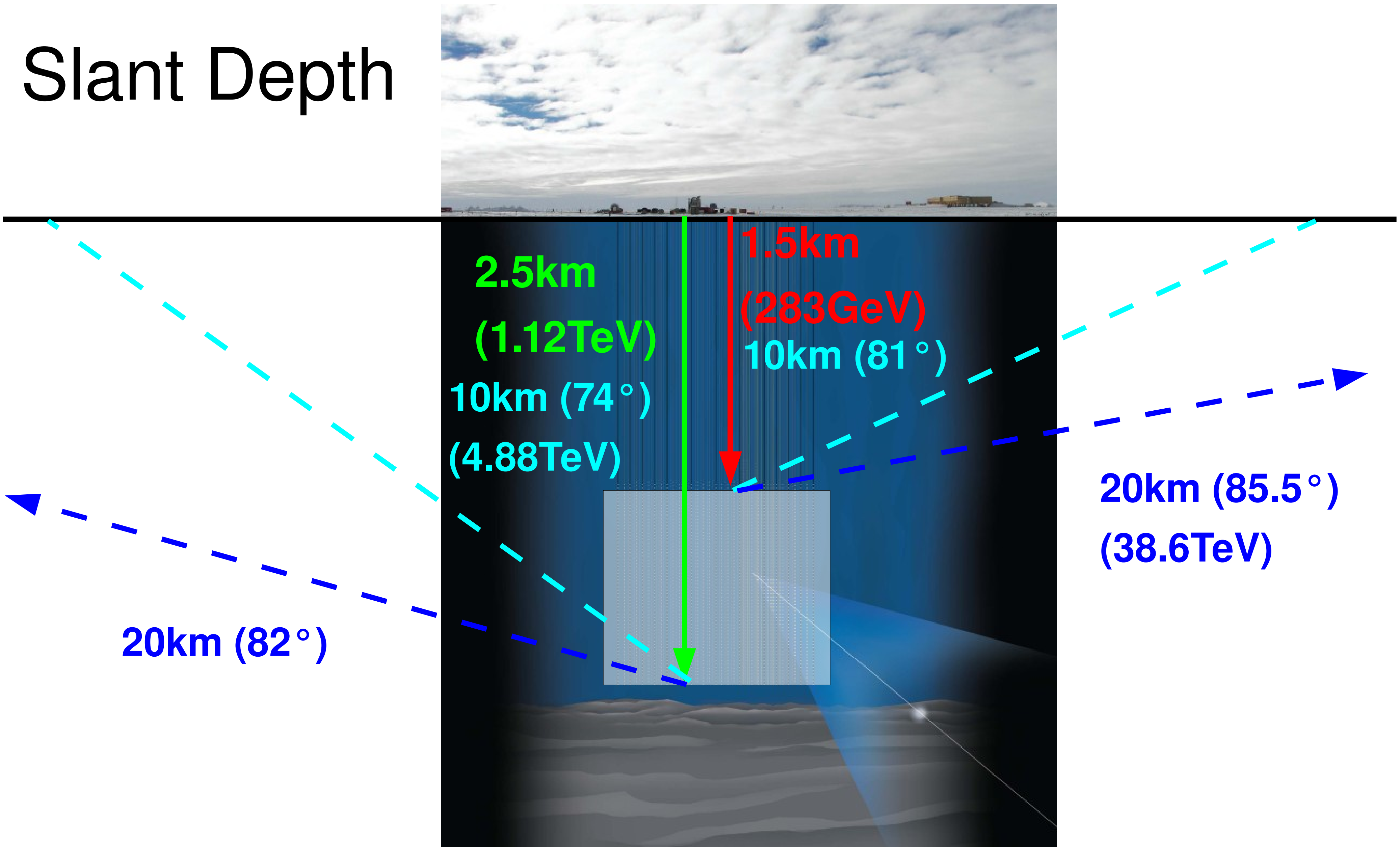
FIG. 4. Total neutrino-over-muon ratio as a function of lepton energy. Vertical marks denote the crossing energy from conventional to prompt muons.

Calorimetric Response for Bundles

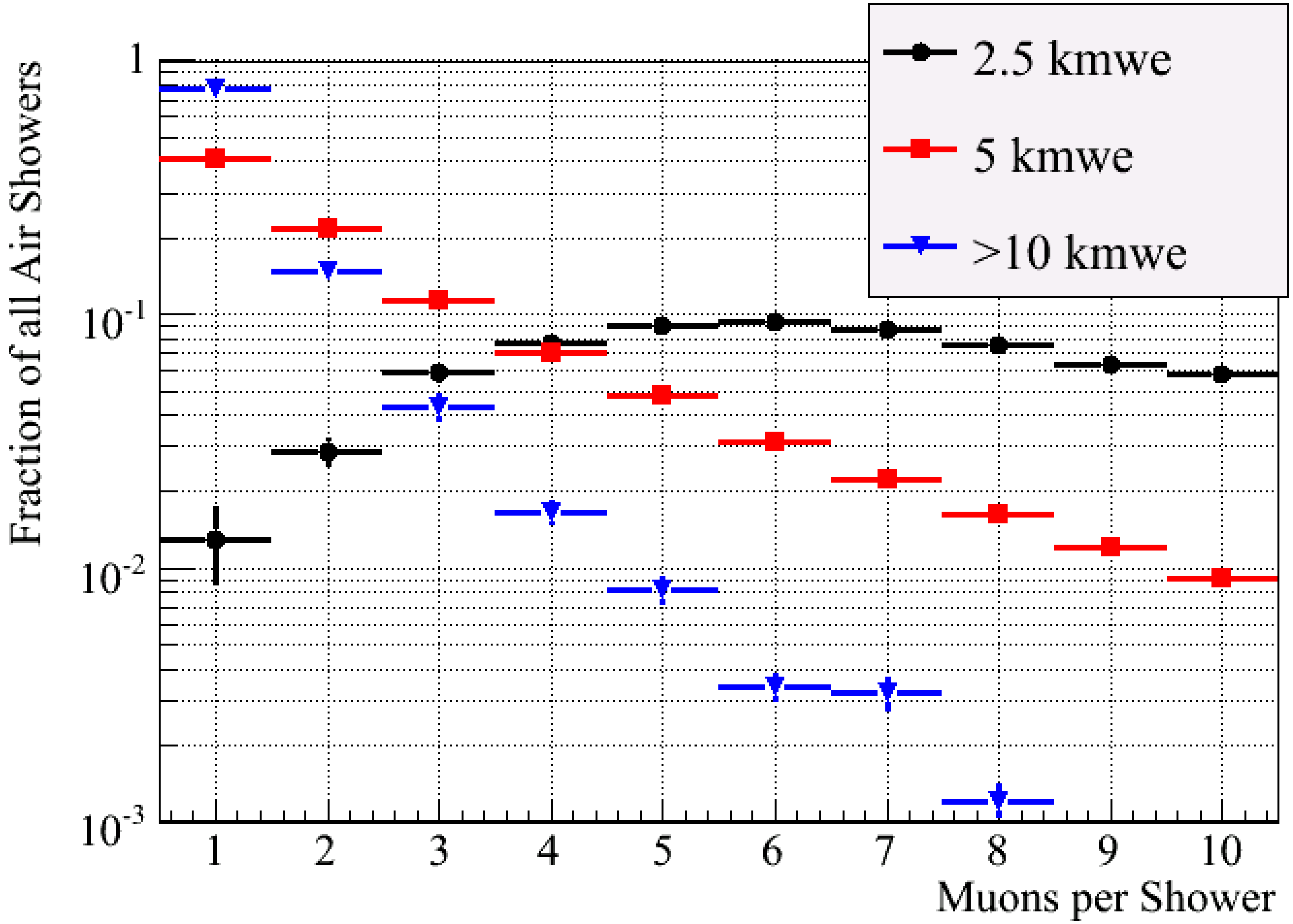




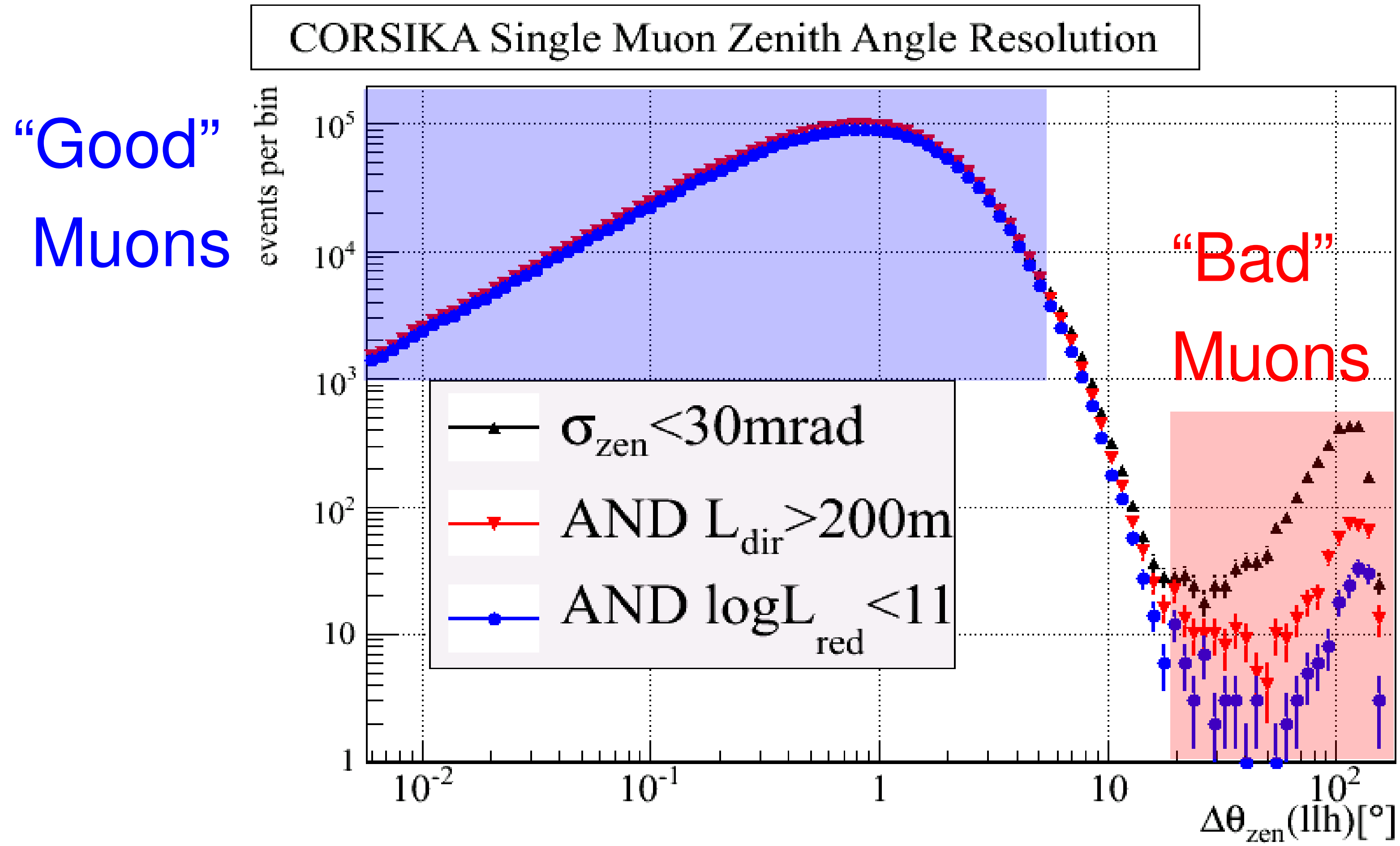
Slant Depth

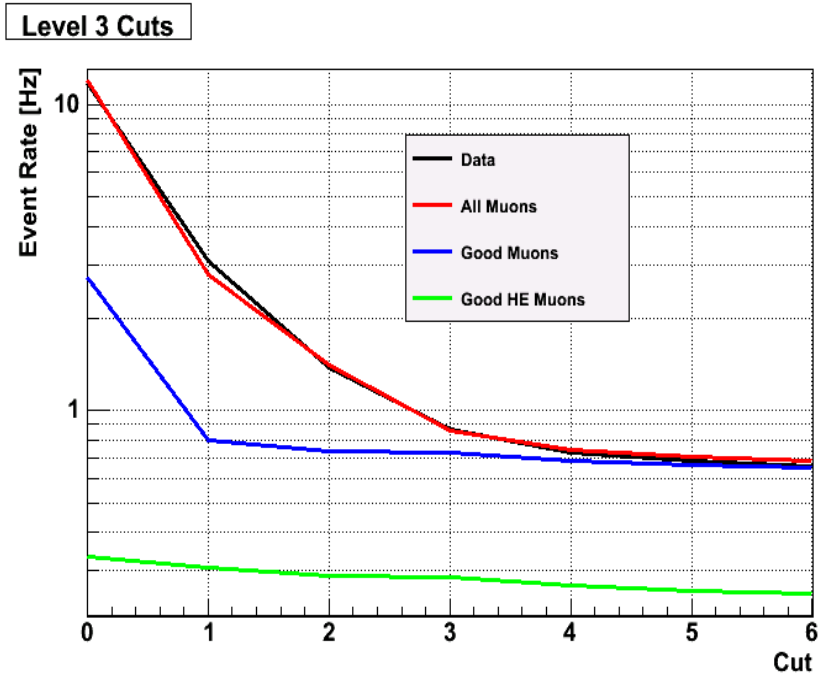

2.5km
(1.12TeV)
1.5km
(283GeV)
10km (81°)
10km (74°)
(4.88TeV)
20km (85.5°)
(38.6TeV)
20km (82°)

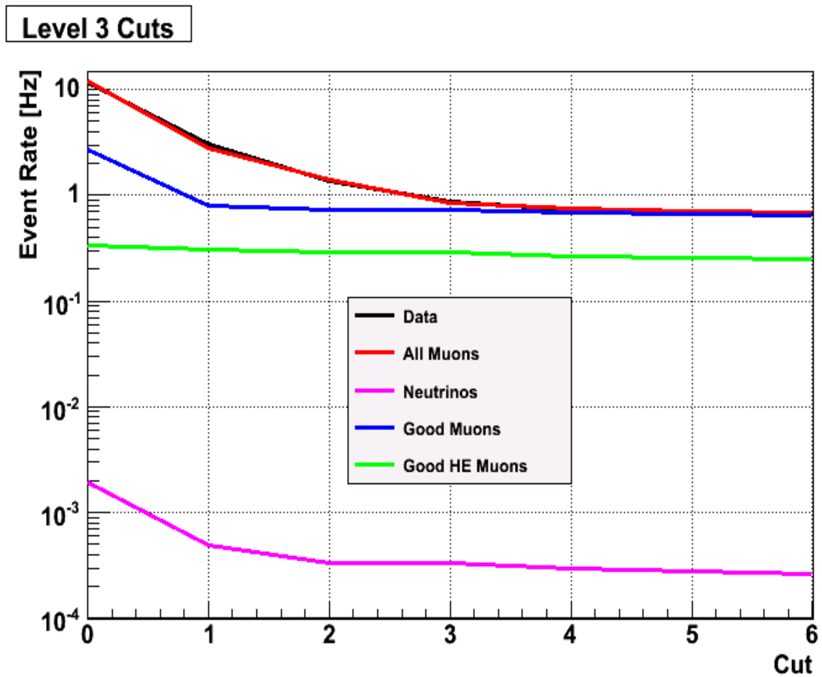
Slant Depth and Bundle Multiplicity



$\Delta\theta_{zen}$







L3 Cuts

0: $\theta_{zen,llh}$>70° && muonfilter

1: N_{chan}>15

2: σ_{parab}<6°

3: $llh_{red}(2.5)$<8

4: $\Psi_{lf,llh}$<0.2rad

5: 100m<L_{dir}(C)<800m

6: 0.15<v_{lf}<0.4 &&

abs(smooth)<0.6

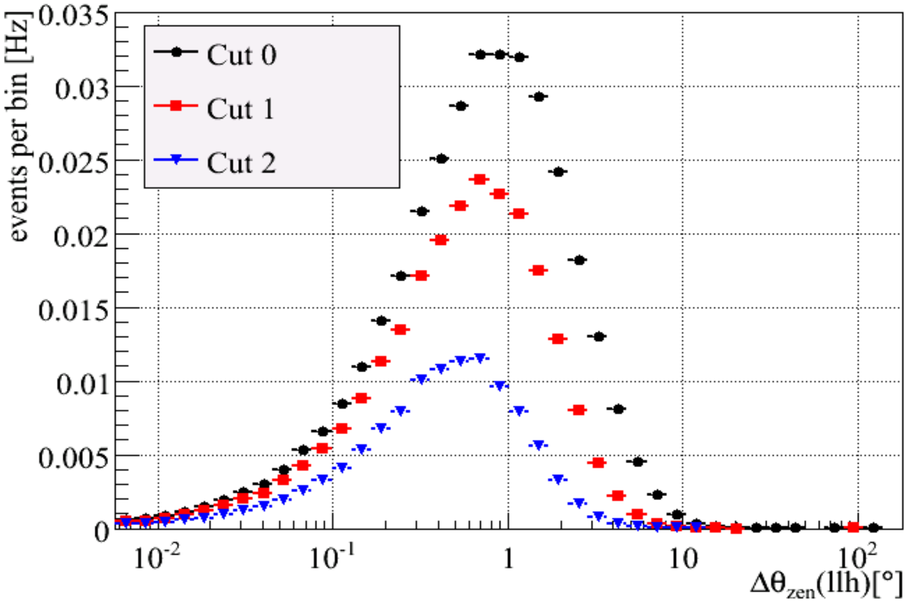
wiki.icecube.wisc.edu/index.php/Muon_Energy_Spectrum/Level_3

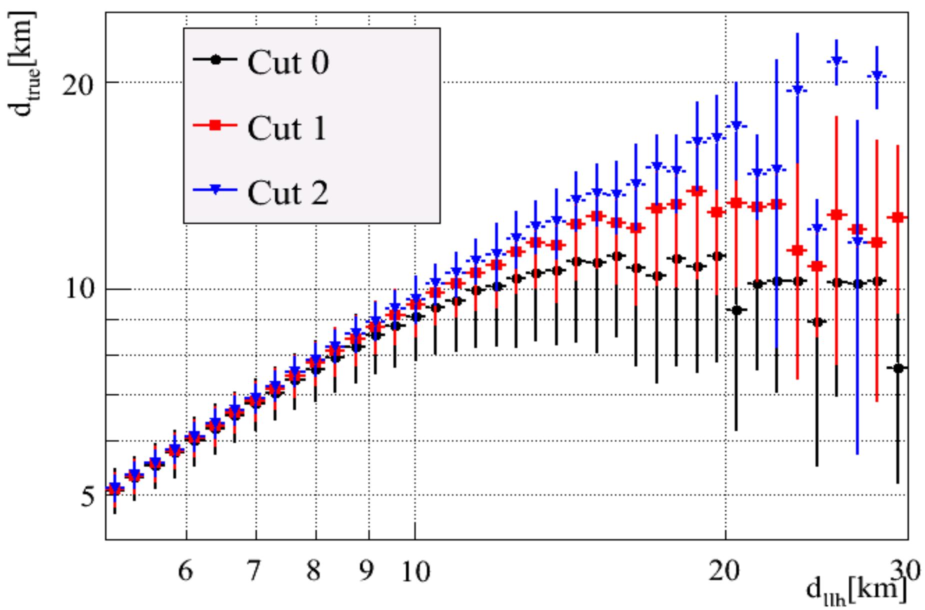
Final Cut Level

Cut 0: $llh_{red}(2.5)<7.25$

Cut 1: $llh_{red}(2.5)<7.1$ $\sigma_{parab,zen}<2°$

Cut 2: $llh_{red}(2.5)<7.0$ $\sigma_{parab,zen}<1.4°$

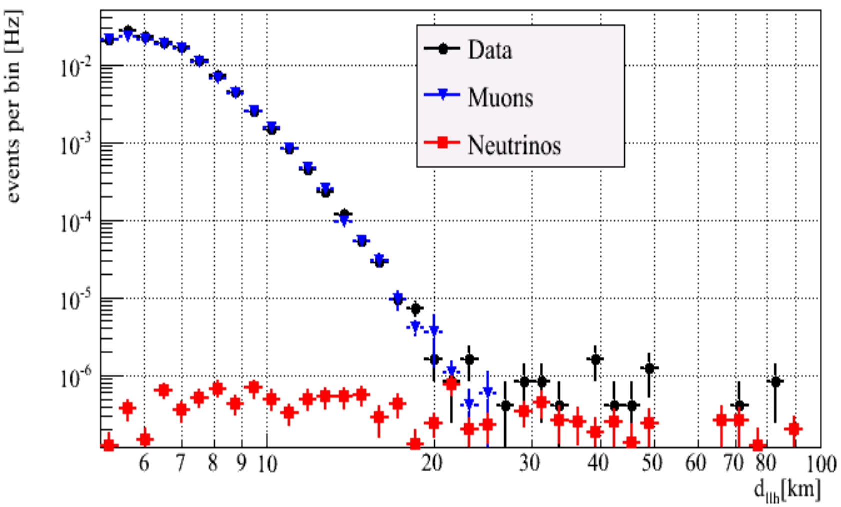


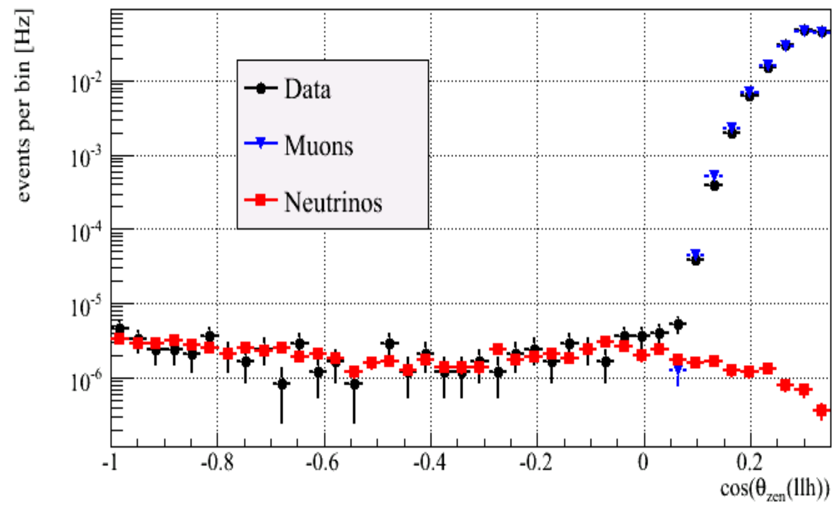


wiki.icecube.wisc.edu/index.php/Muon_Energy_Spectrum/Final_Cuts

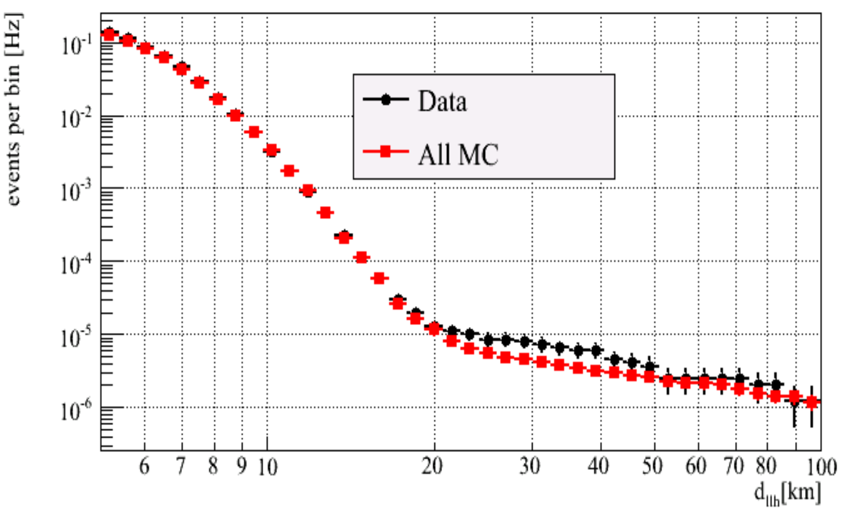
Slant Depth

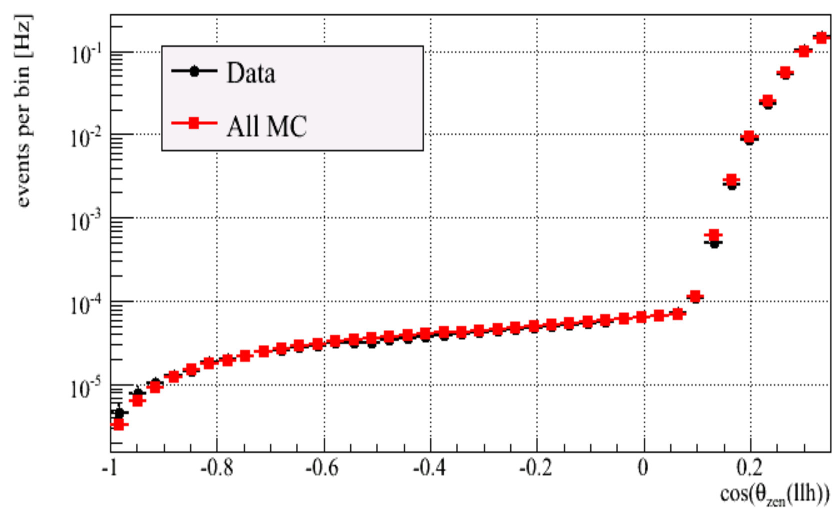
Zenith Angle



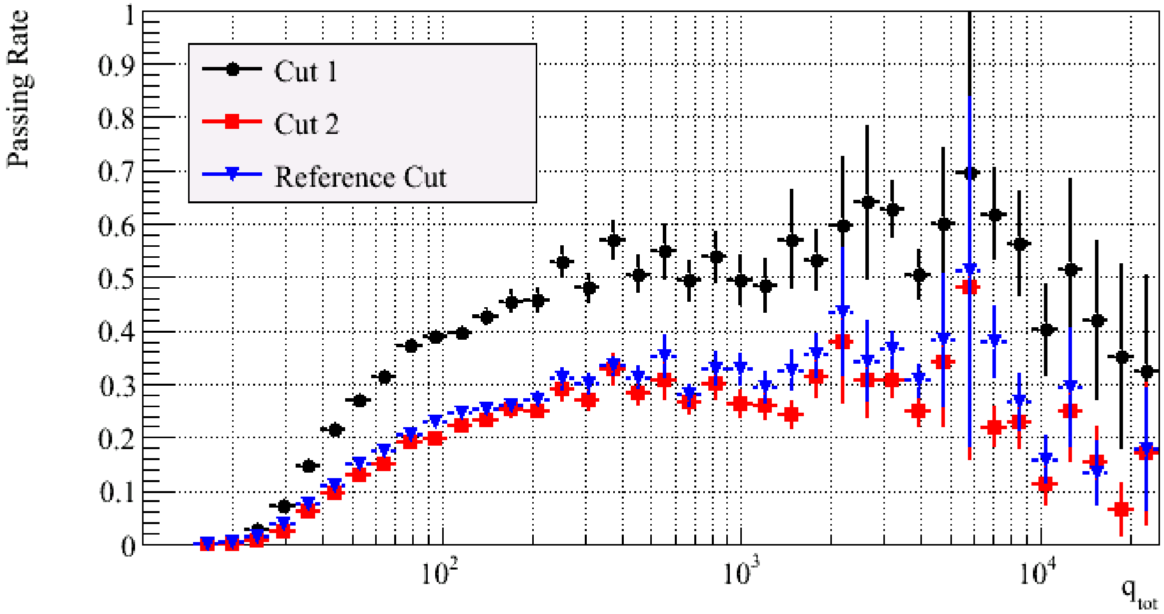


diff





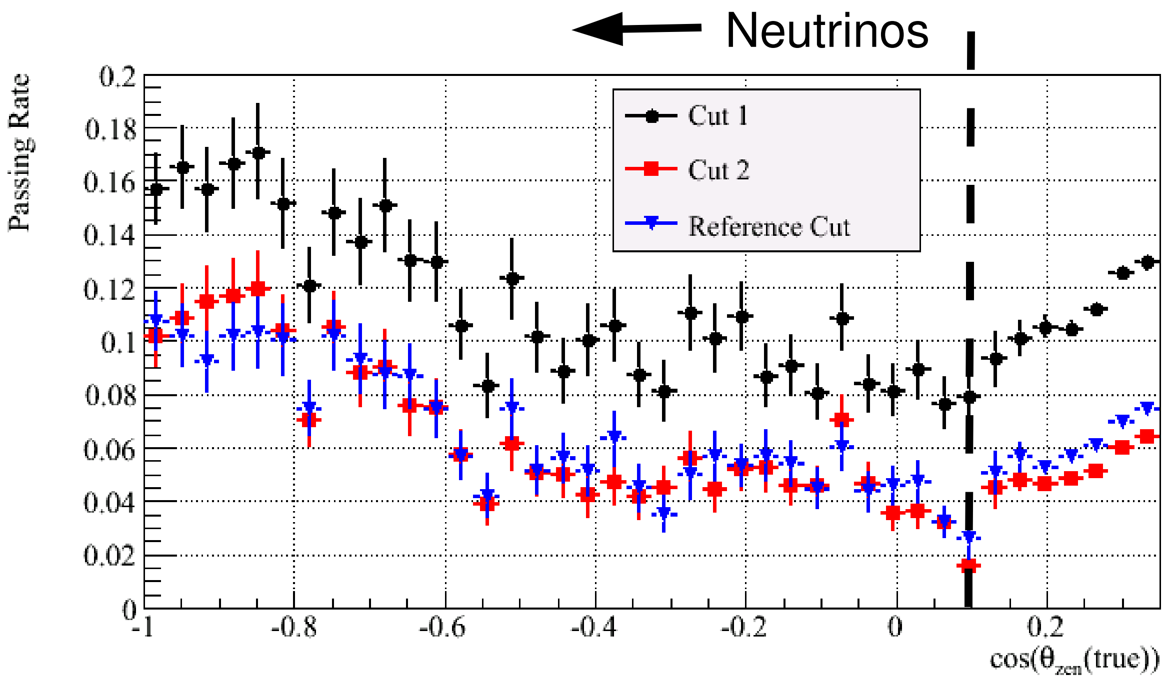
int



Total Charge

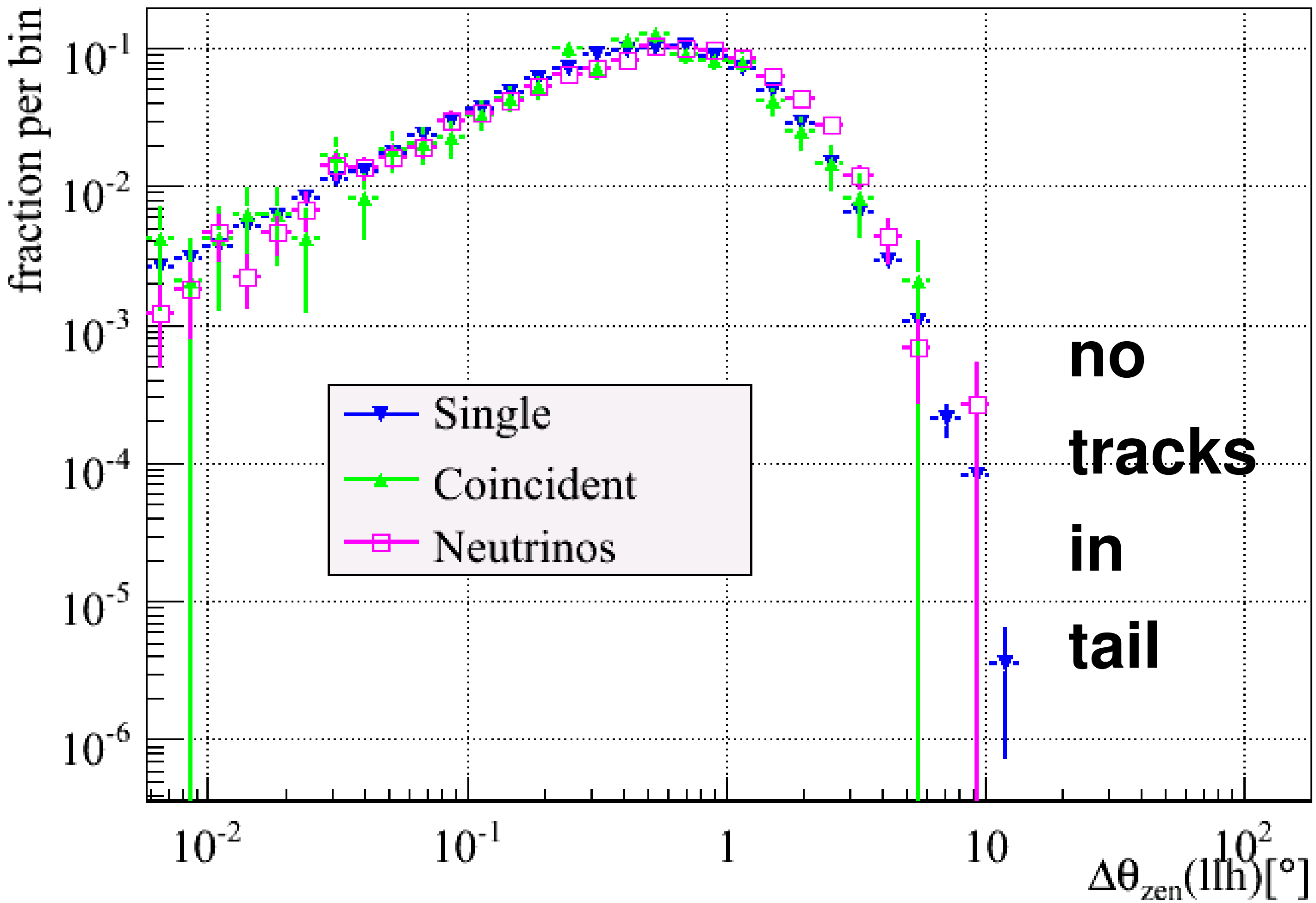
“Reference Cut”:

From All-Sky Analysis

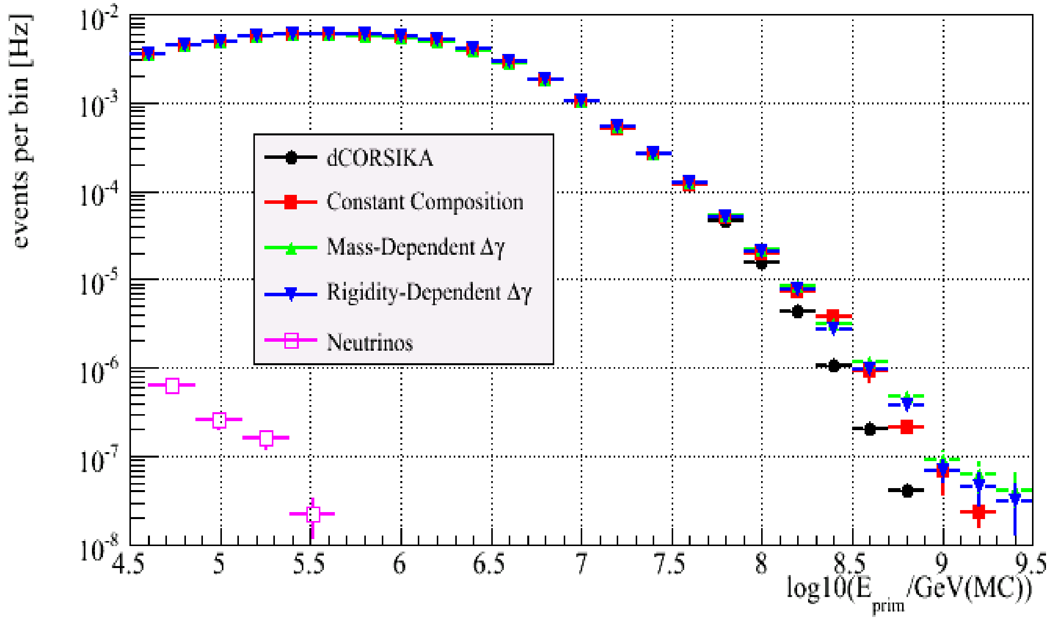


True Zenith

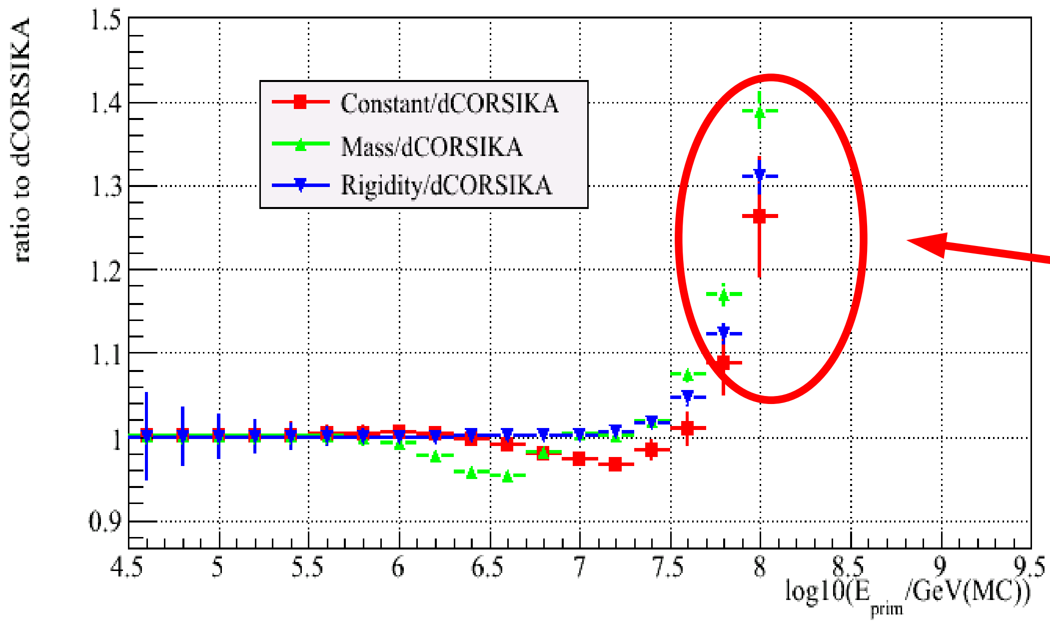
|True Zenith – Reconstructed Zenith|

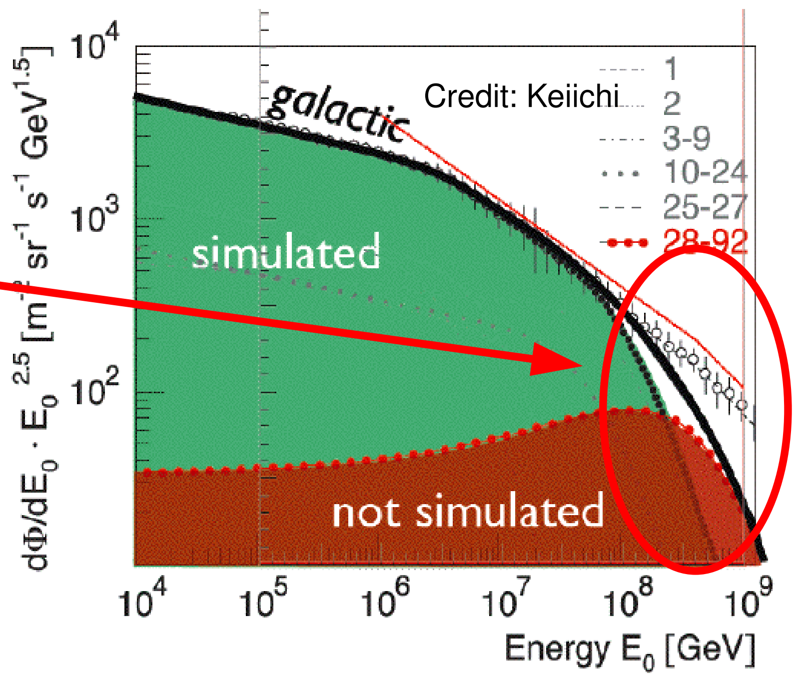


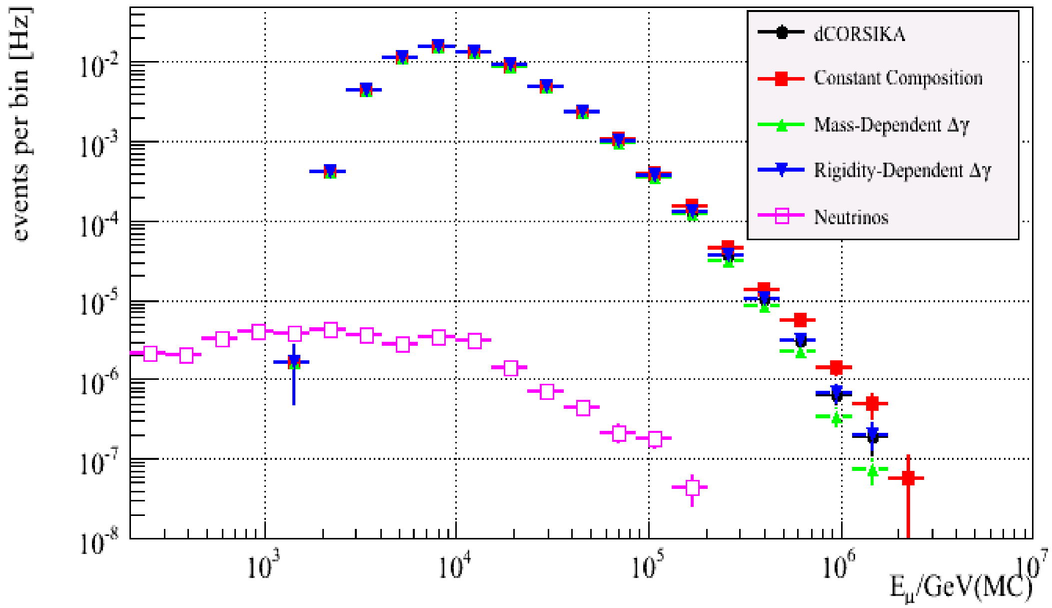
no tracks in tail


events per bin [Hz]
dCORSIKA
Constant Composition
Mass-Dependent Δγ
Rigidity-Dependent Δγ
Neutrinos
log10(E_prim/GeV(MC))

CR Energy

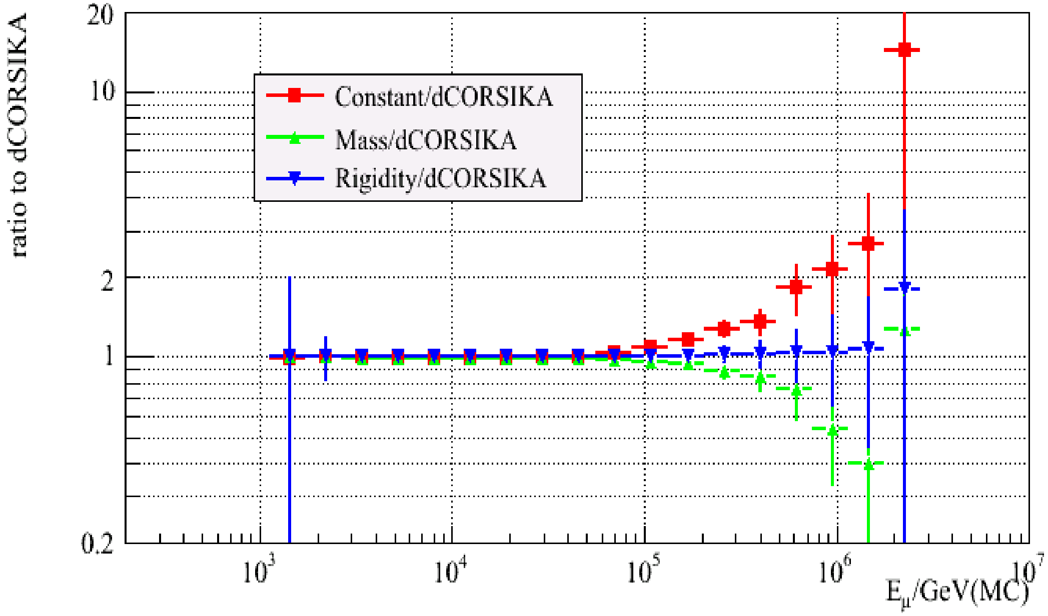

ratio to dCORSIKA
Constant/dCORSIKA
Mass/dCORSIKA
Rigidity/dCORSIKA
log10(E_prim/GeV(MC))

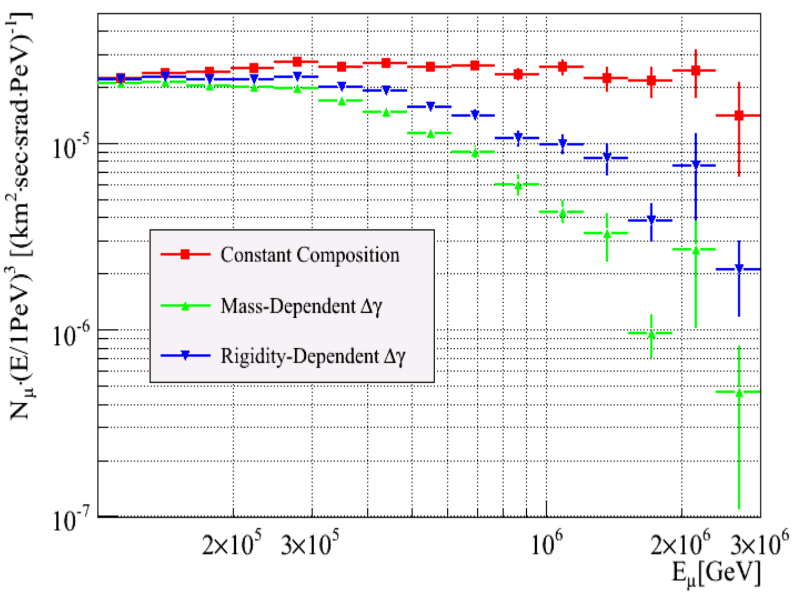

galactic
Credit: Keiichi
1
2
3-9
10-24
25-27
28-92
simulated
not simulated
dΦ/dE0 · E0^2.5 [m^-2 sr^-1 s^-1 GeV^1.5]
Energy E0 [GeV]

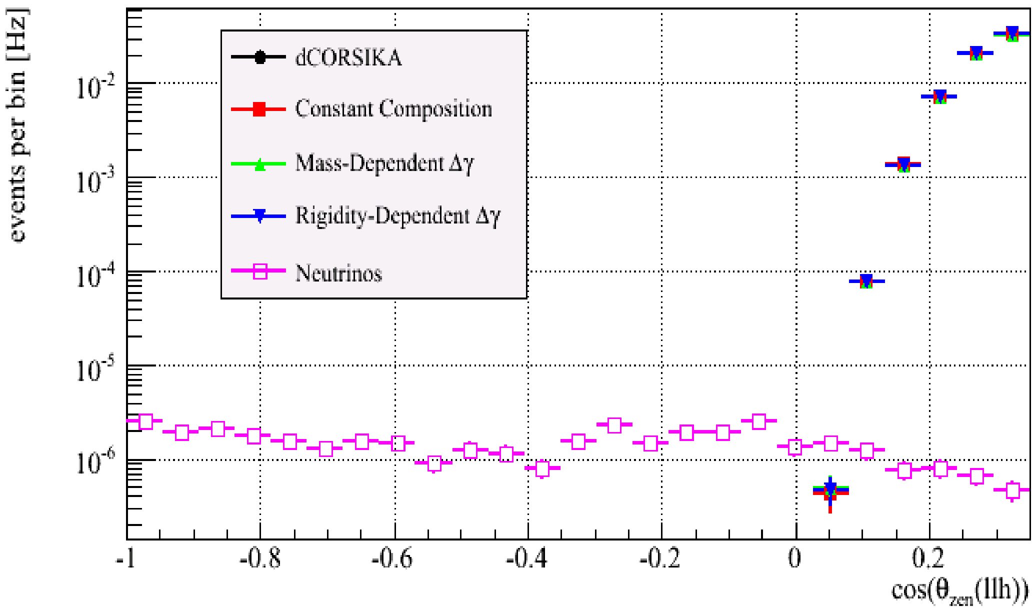


Highest Muon Energy in Shower

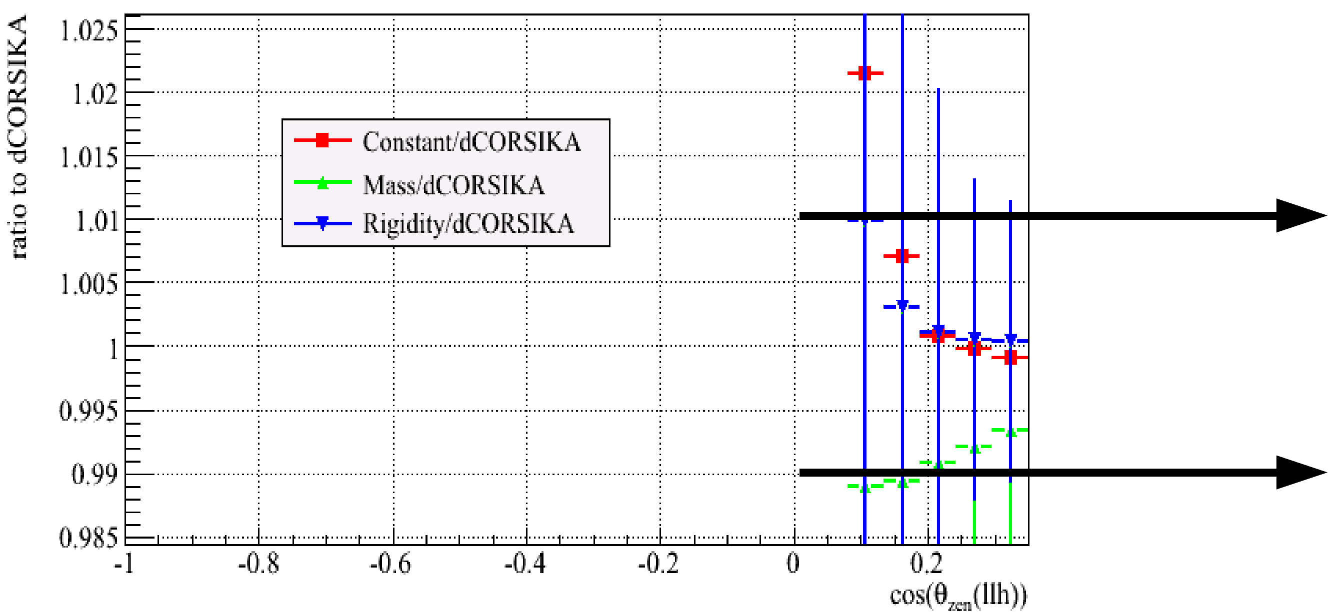
(at surface)



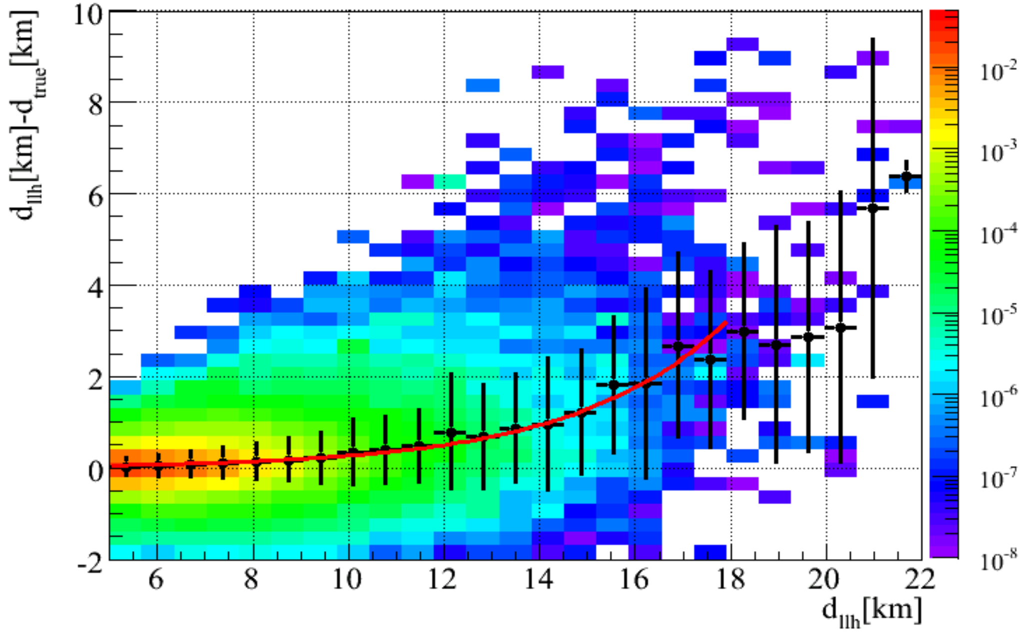


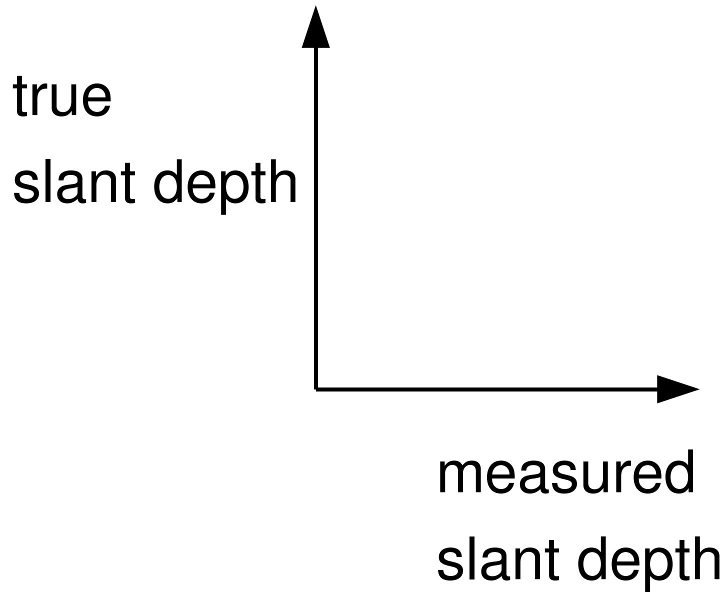


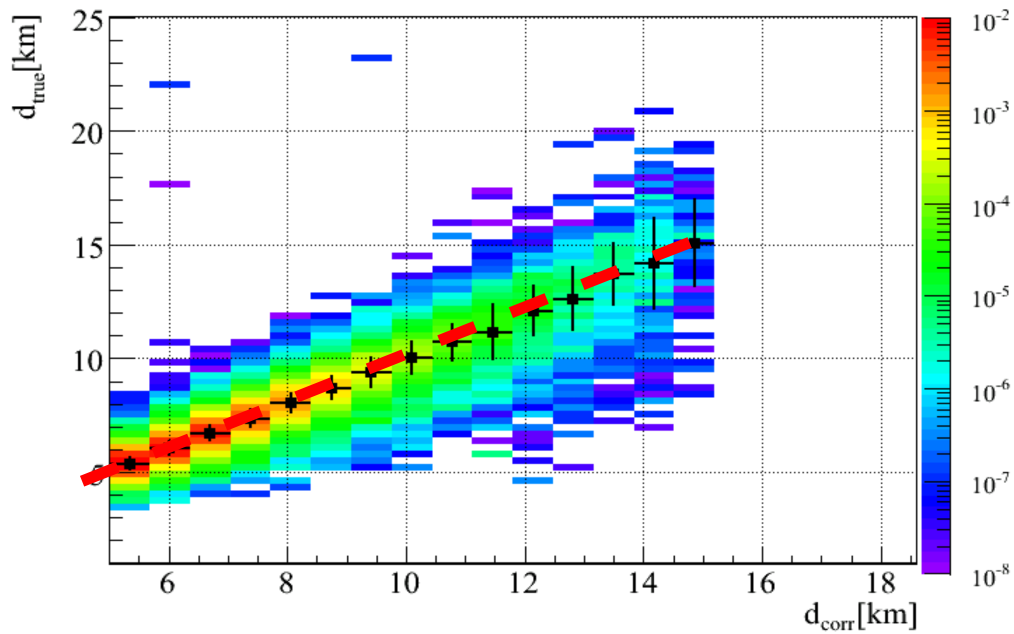
Zenith Angle



±0.1%

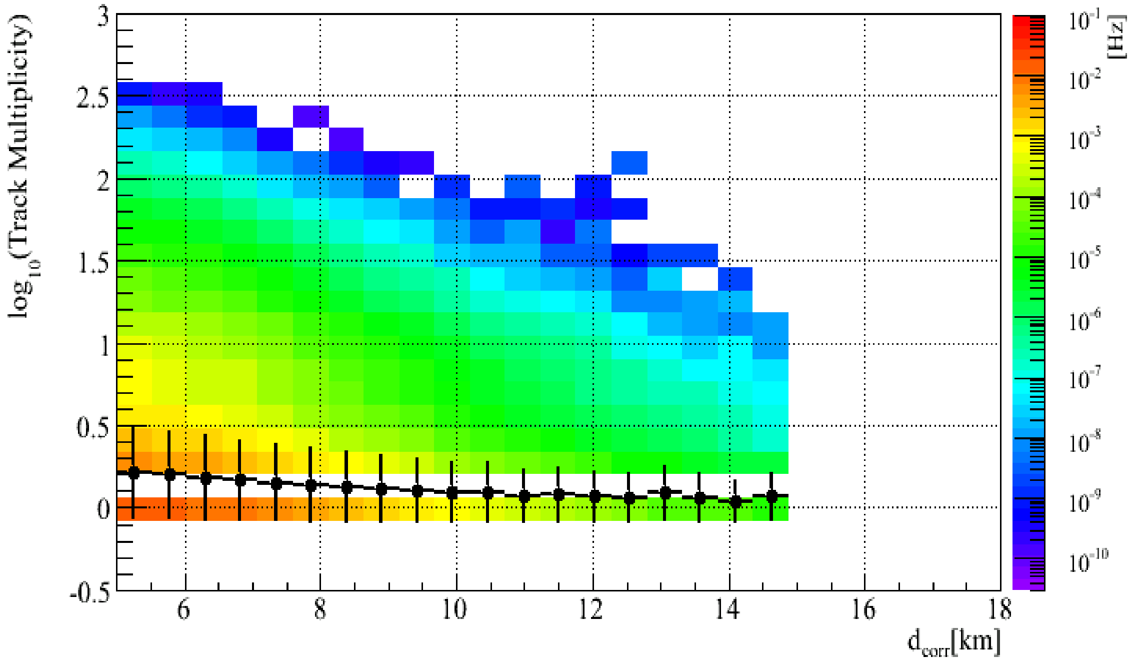






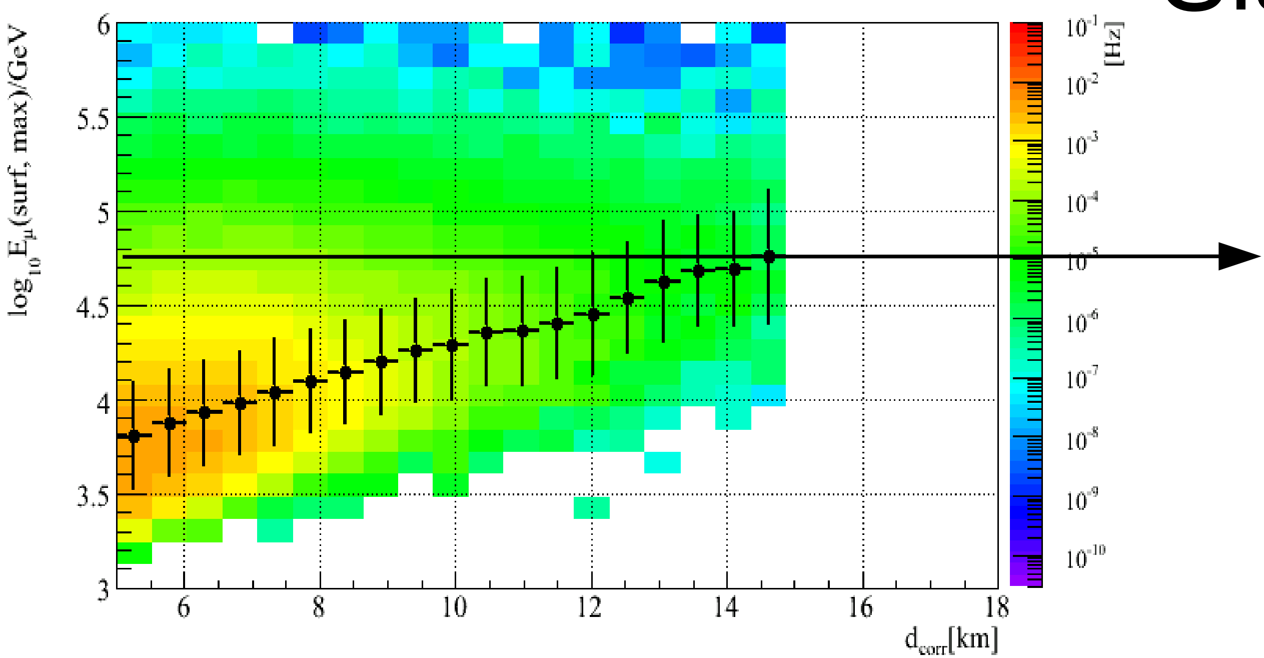
Slant Depth: Correction

Track Multiplicity in Detector



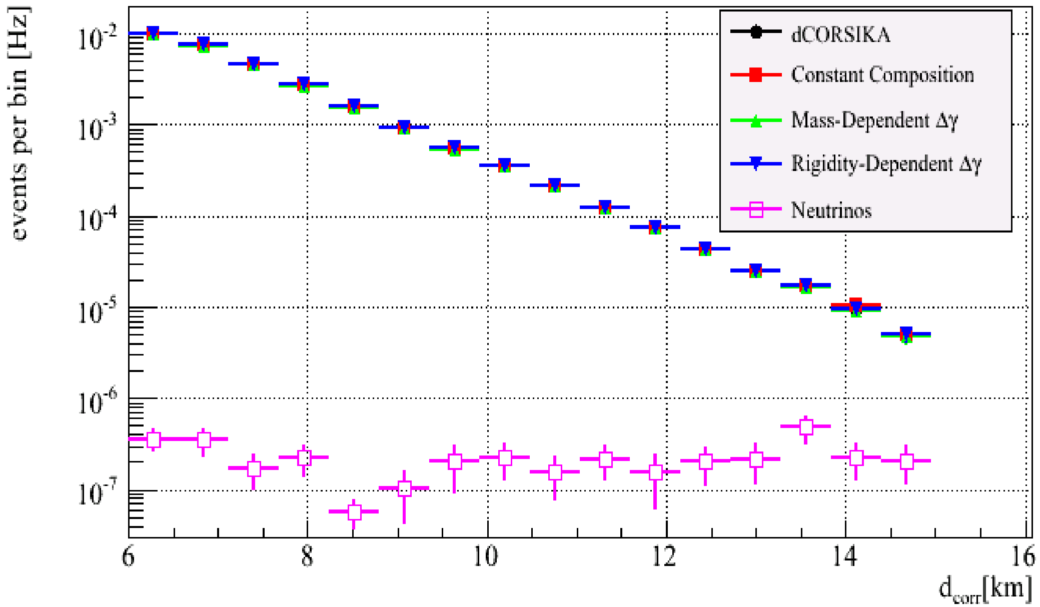
Slant Depth

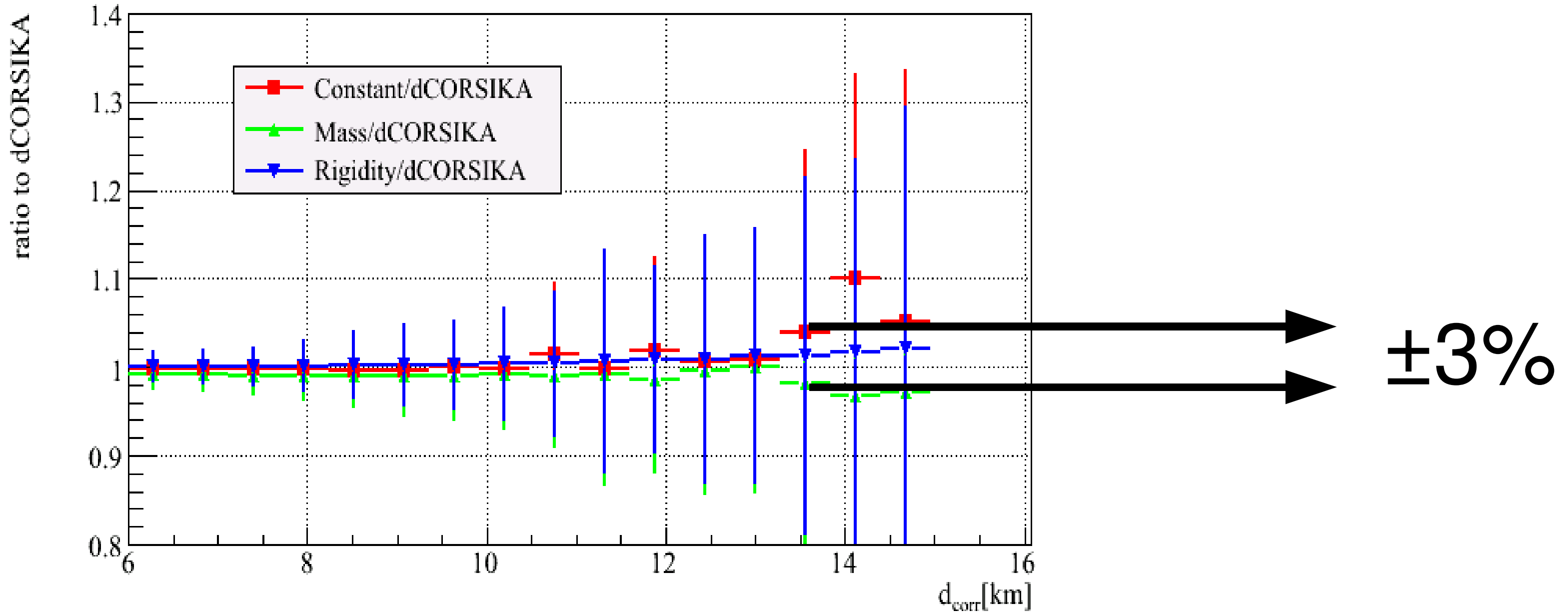
Max. Muon Surface Energy



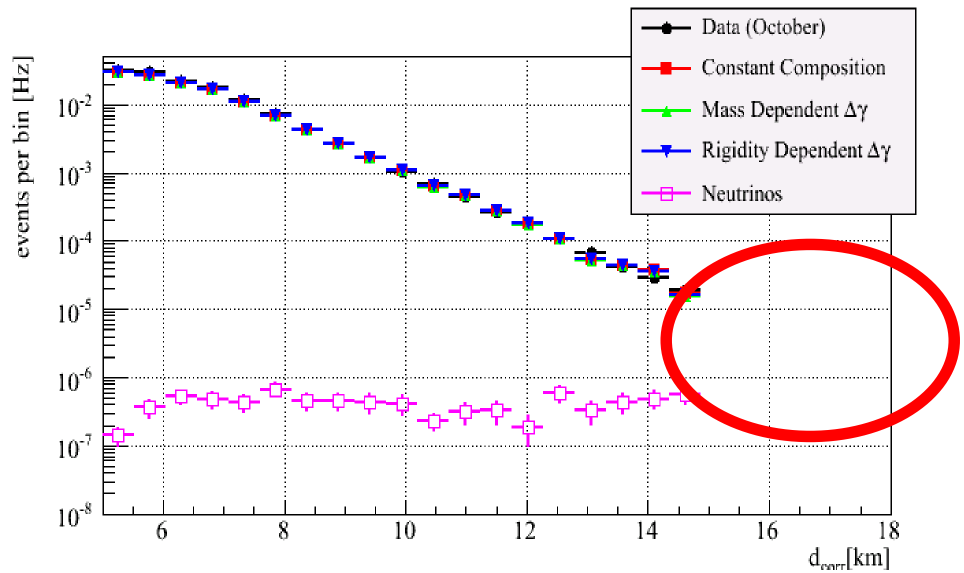
50 TeV

Slant Depth

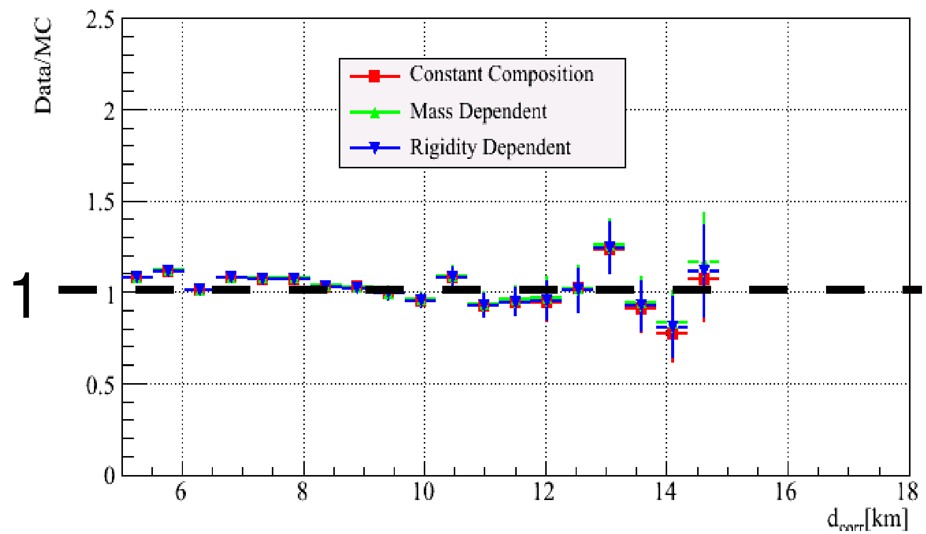

events per bin [Hz]
dCORSIKA
Constant Composition
Mass-Dependent Δγ
Rigidity-Dependent Δγ
Neutrinos
d_corr[km]


ratio to dCORSIKA
Constant/dCORSIKA
Mass/dCORSIKA
Rigidity/dCORSIKA
d_corr[km]
±3%

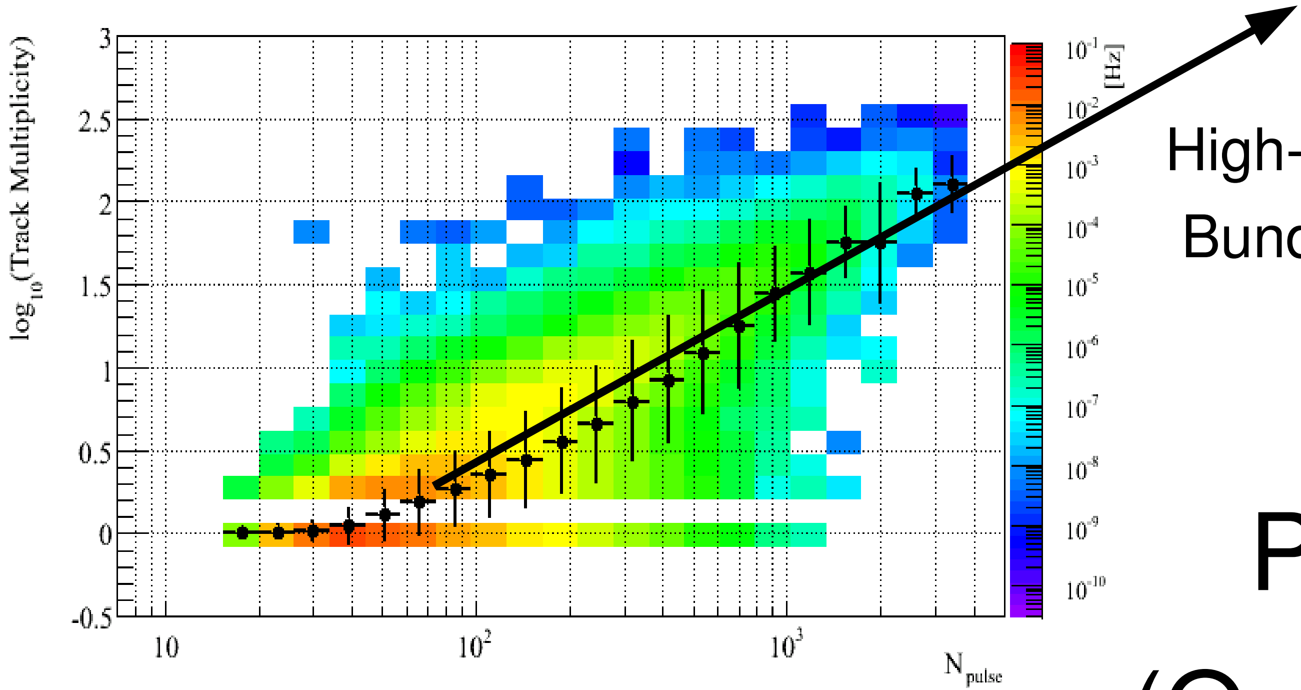
Data/MC: Slant Depth



Angular resolution too low
to go further, better in the future!



Track Multiplicity in Detector

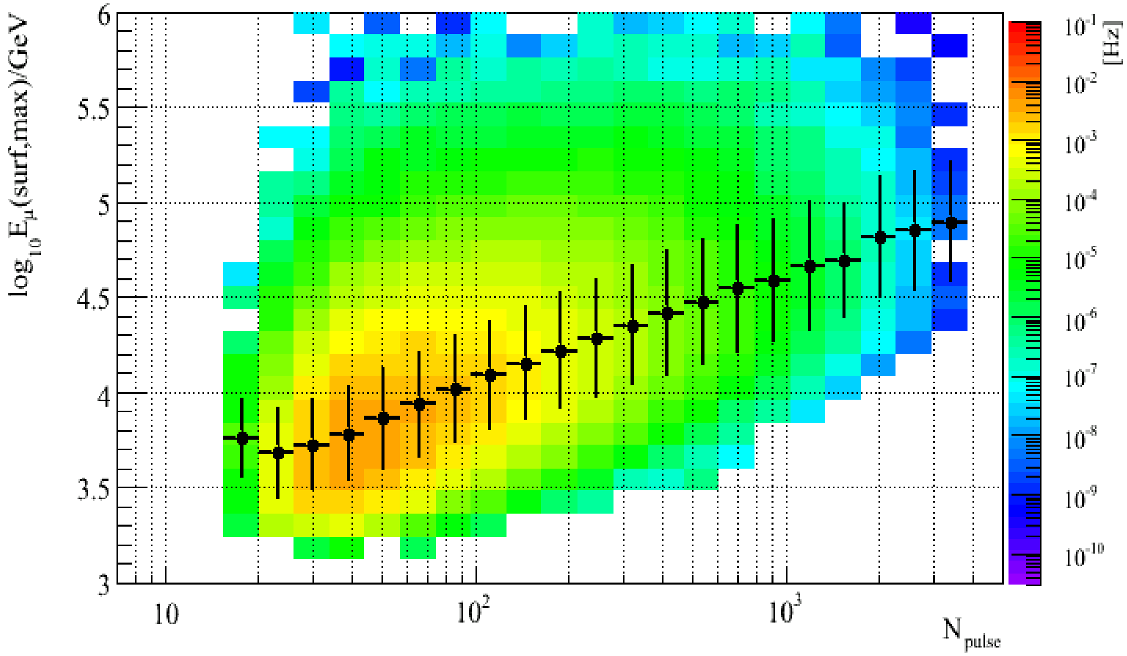


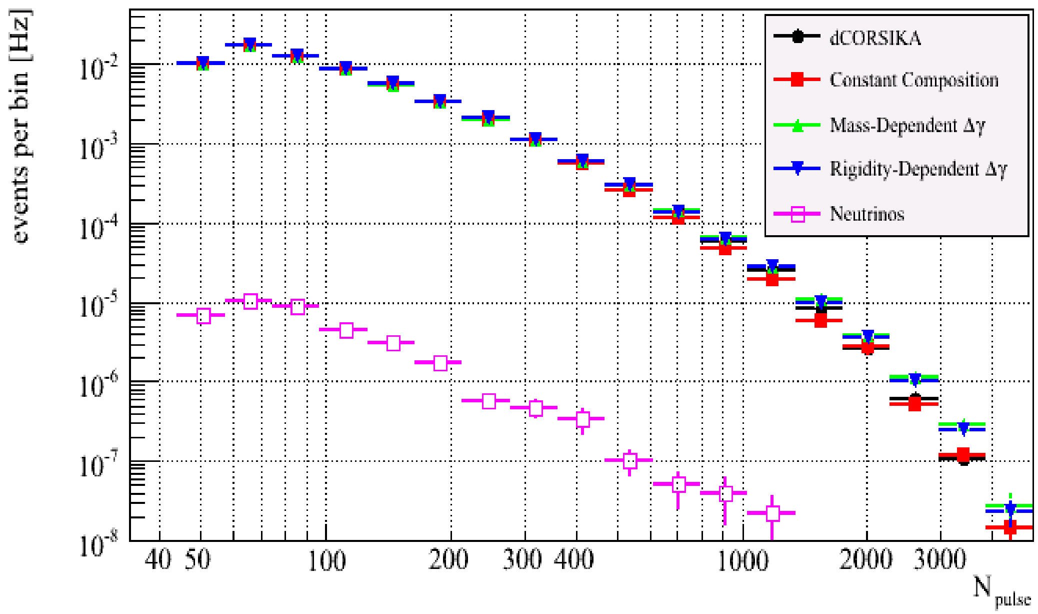
High-Multiplicity Bundles

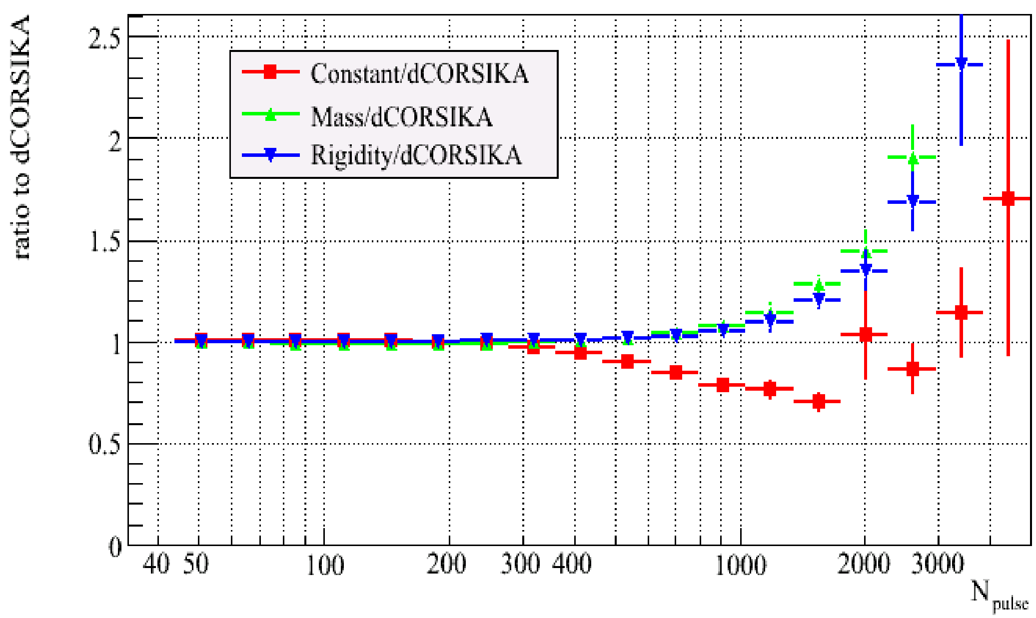
Pulses

(Q_{tot} similar)

Max. Muon Surface Energy







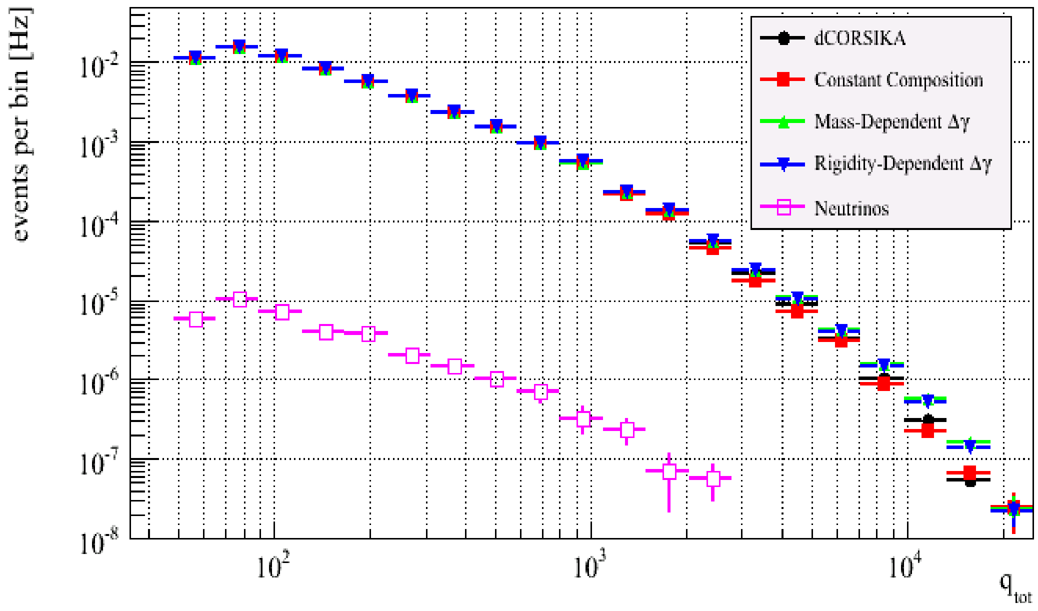
Pulses

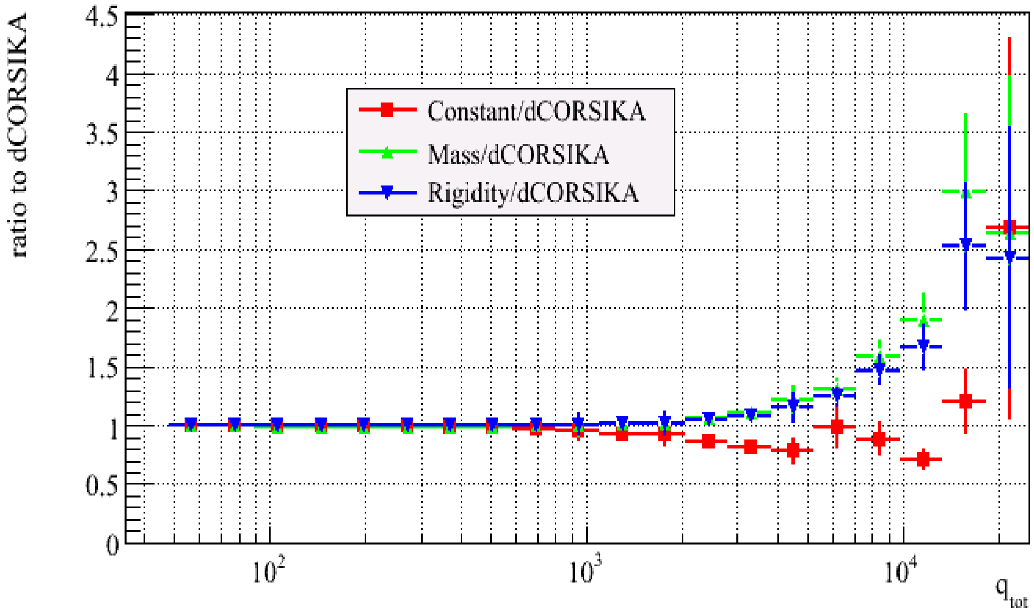
"Elbert-Formula"

$$\bar{N}_\mu \propto \frac{A}{E_\mu \cos\theta}\left(\frac{E_0}{AE_\mu}\right)^\alpha$$

$$\frac{\bar{N}_\mu^1}{\bar{N}_\mu^2} = \left(\frac{A_1}{A_2}\right)^{1-\alpha}$$

2.5-3 times more muons for Fe than p





Total Charge

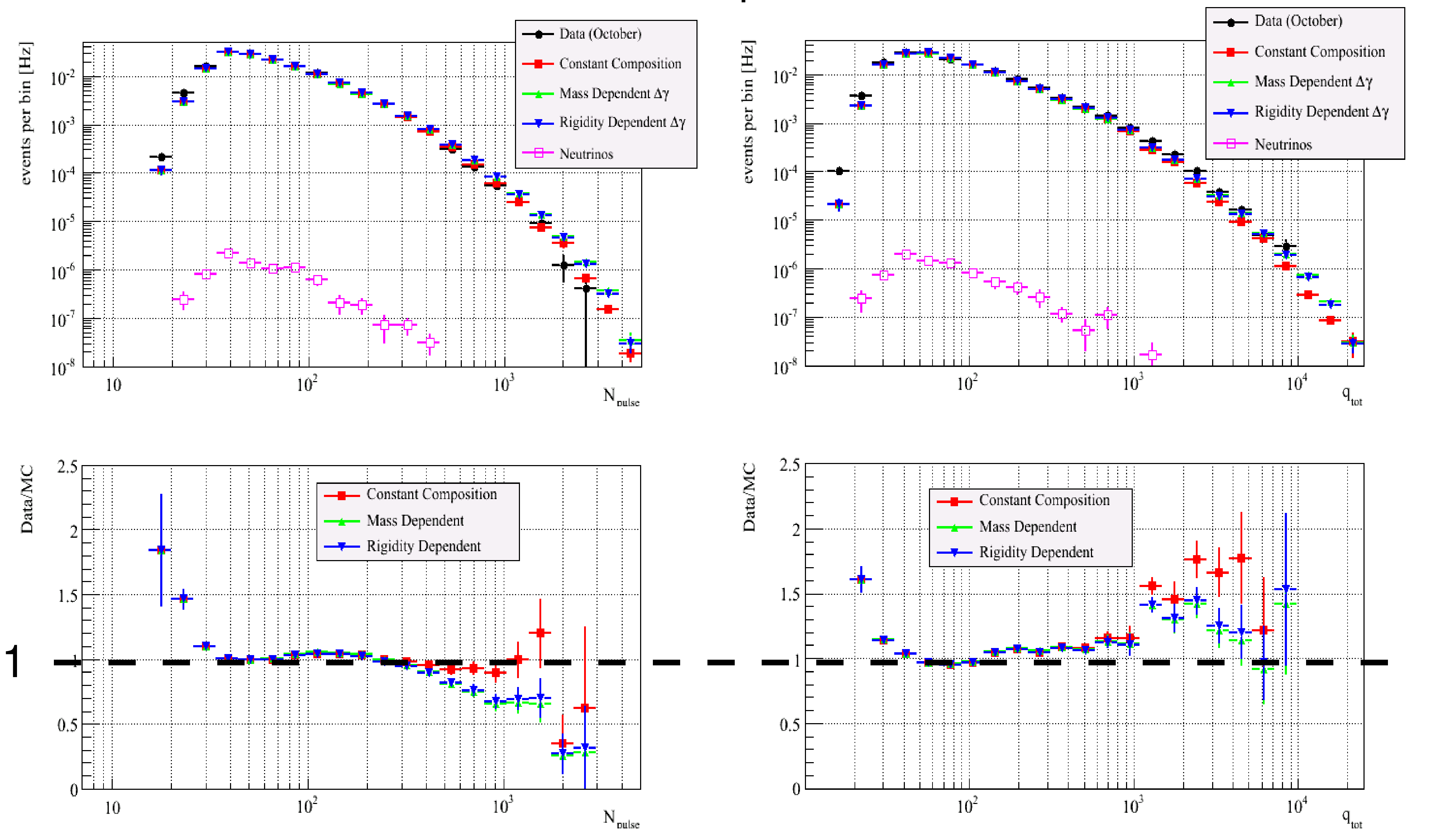
"Elbert-Formula"

$$\bar{N}_\mu \propto \frac{A}{E_\mu \cos\theta}\left(\frac{E_0}{AE_\mu}\right)^\alpha$$

$$\frac{\bar{N}^1_\mu}{\bar{N}^2_\mu} = \left(\frac{A_1}{A_2}\right)^{1-\alpha}$$

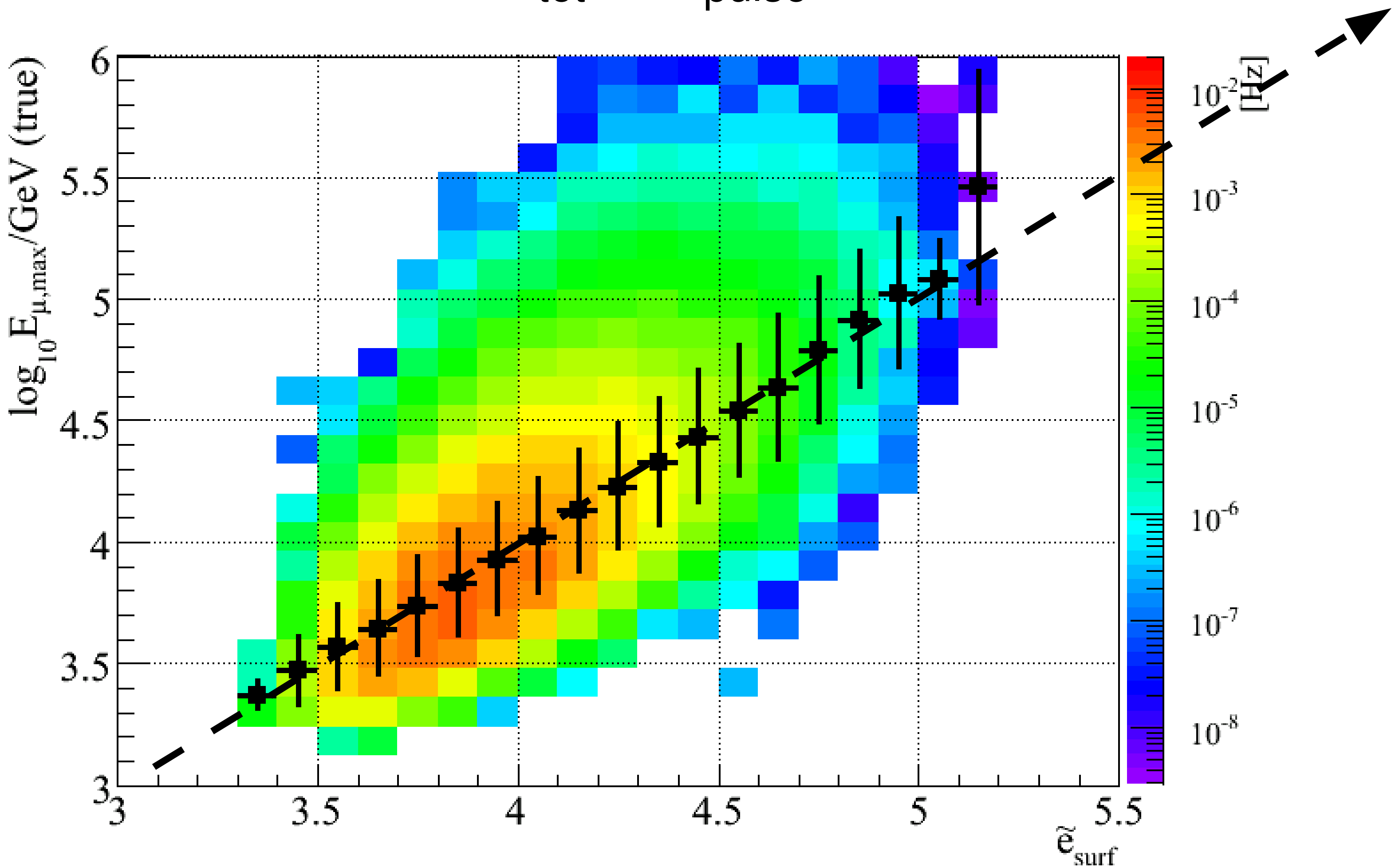
2.5-3 times more muons for Fe than p

Data/MC: N_{pulse} and Q_{tot}

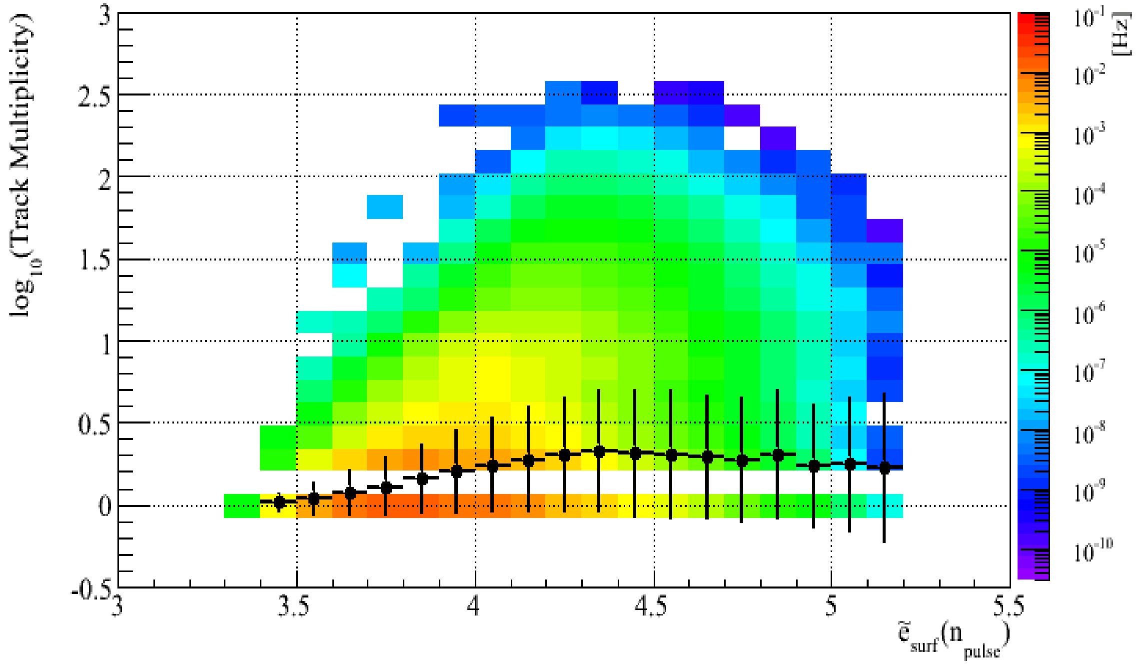


$$\tilde{e}_{surf} \propto \log n_\gamma \cdot d_{slant}$$

(Q_{tot} / N_{pulse})

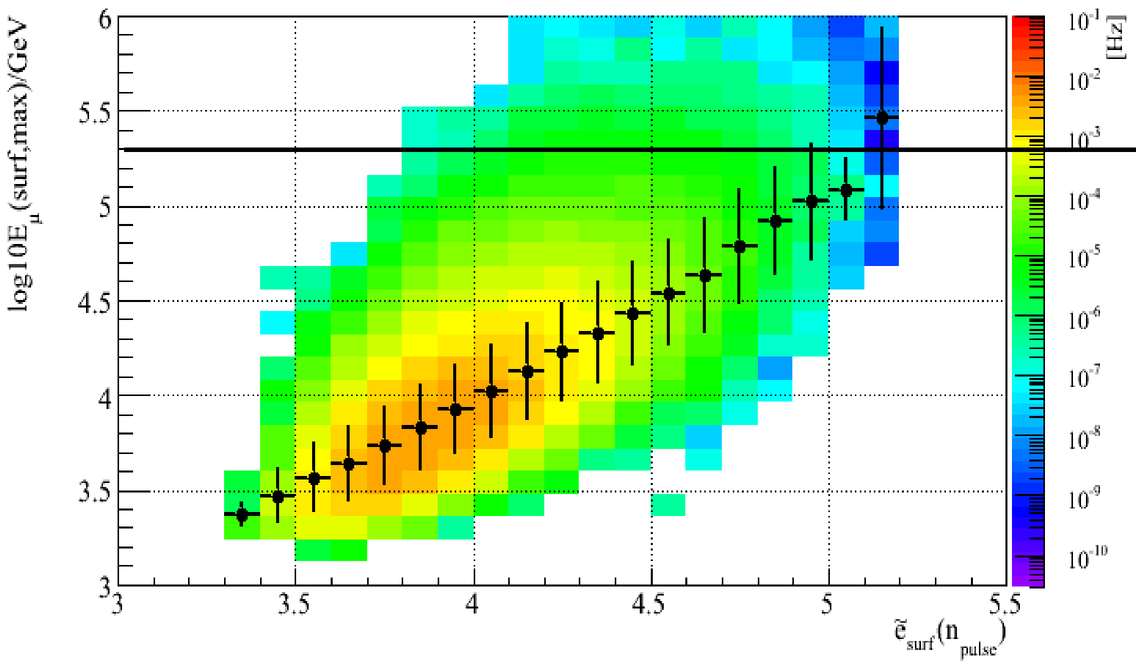


Track Multiplicity in Detector



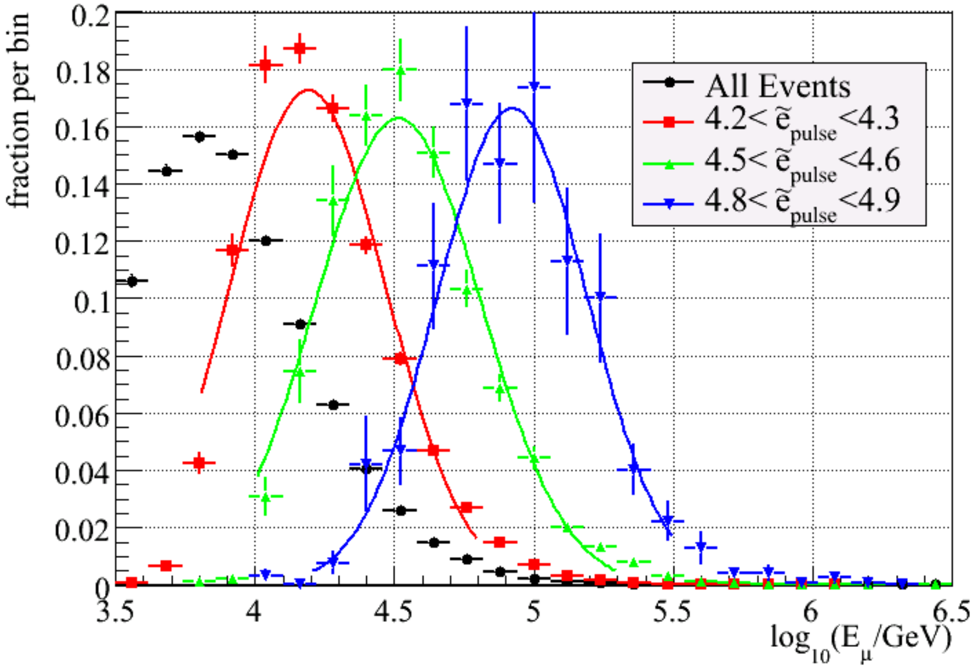
Surface Energy Estimator

Max. Muon Surface Energy



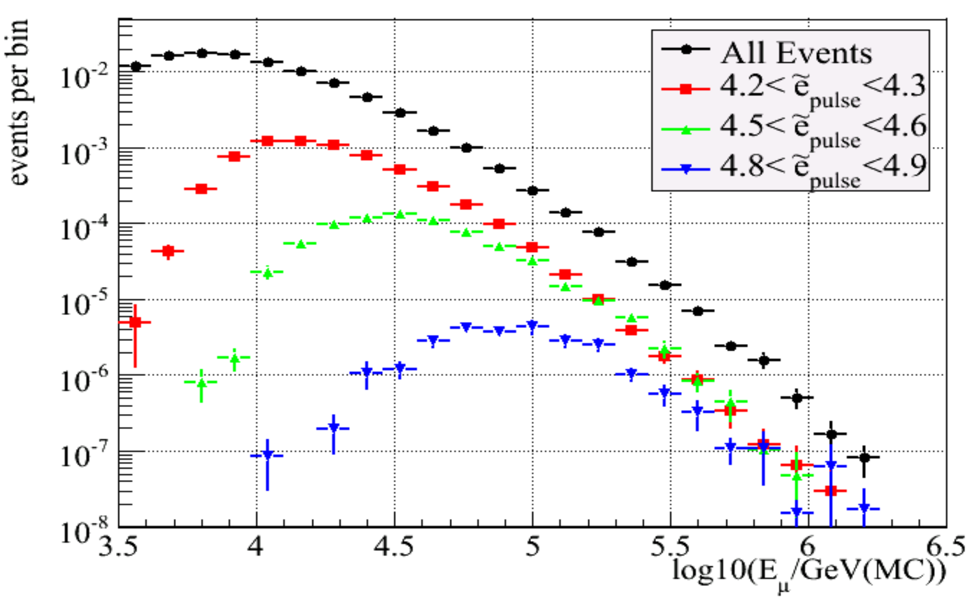
200 TeV

Energy of most energetic muon in shower by ẽ-bin



unit area

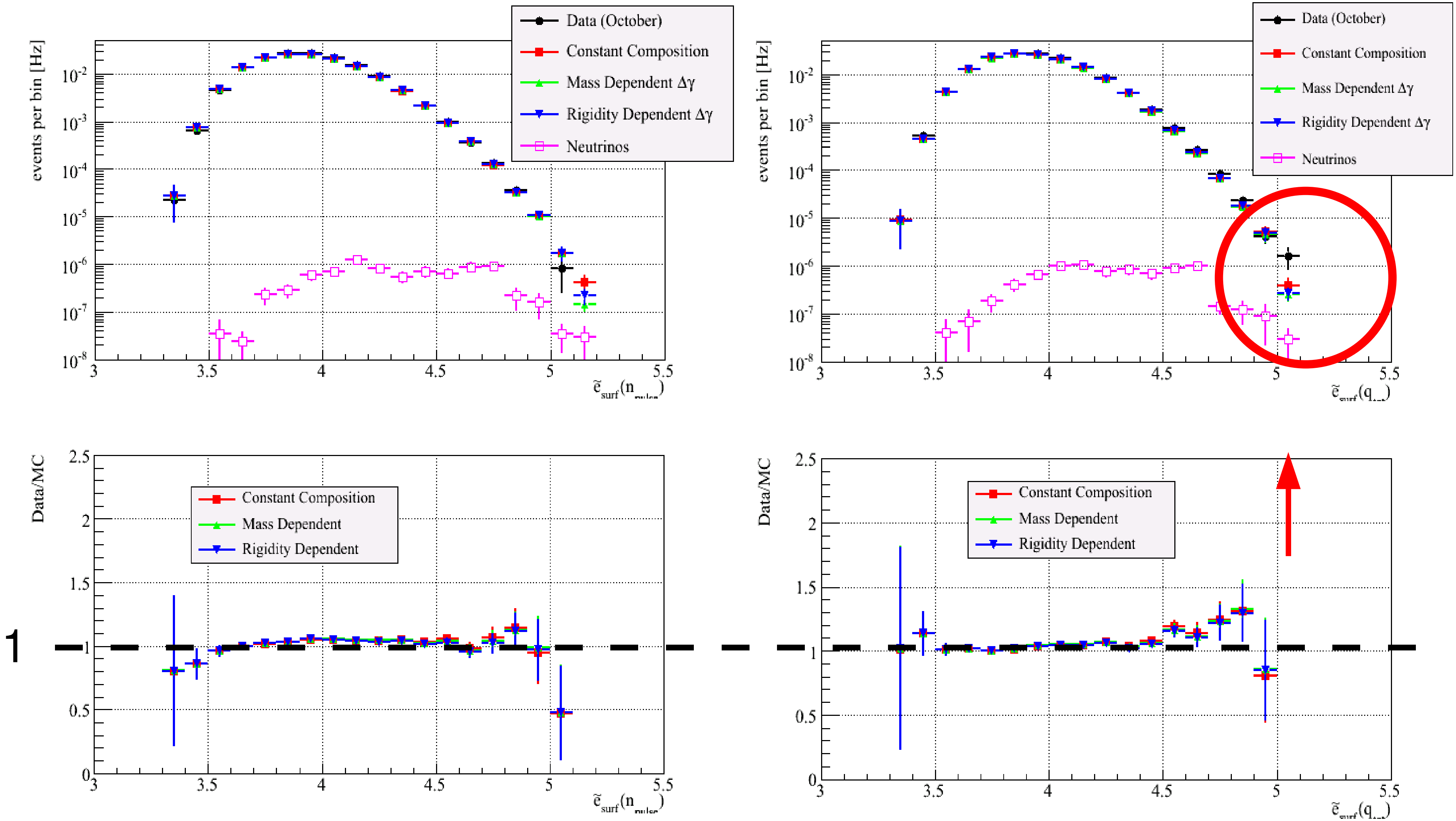
linear scale

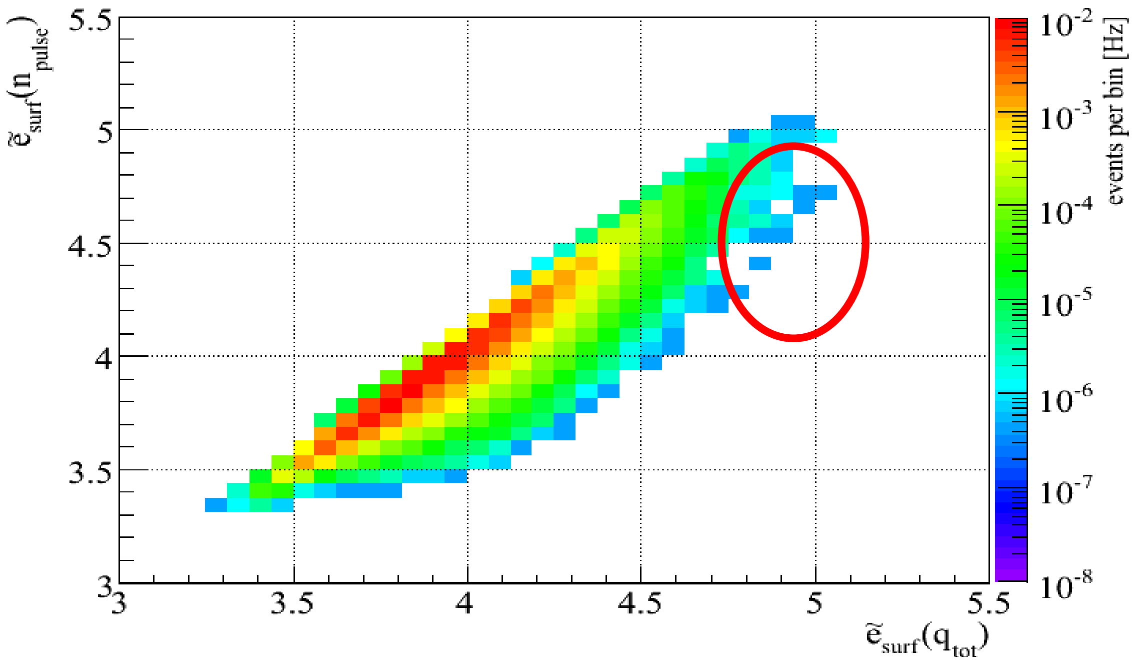


events per second

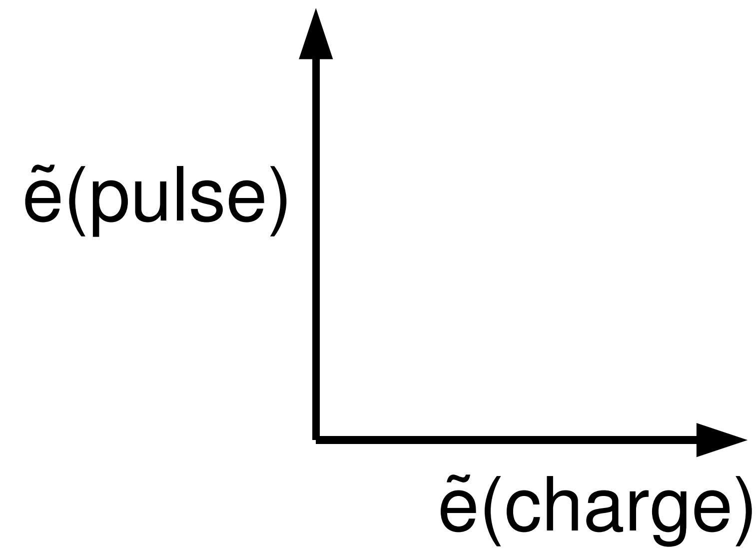
logarithmic scale

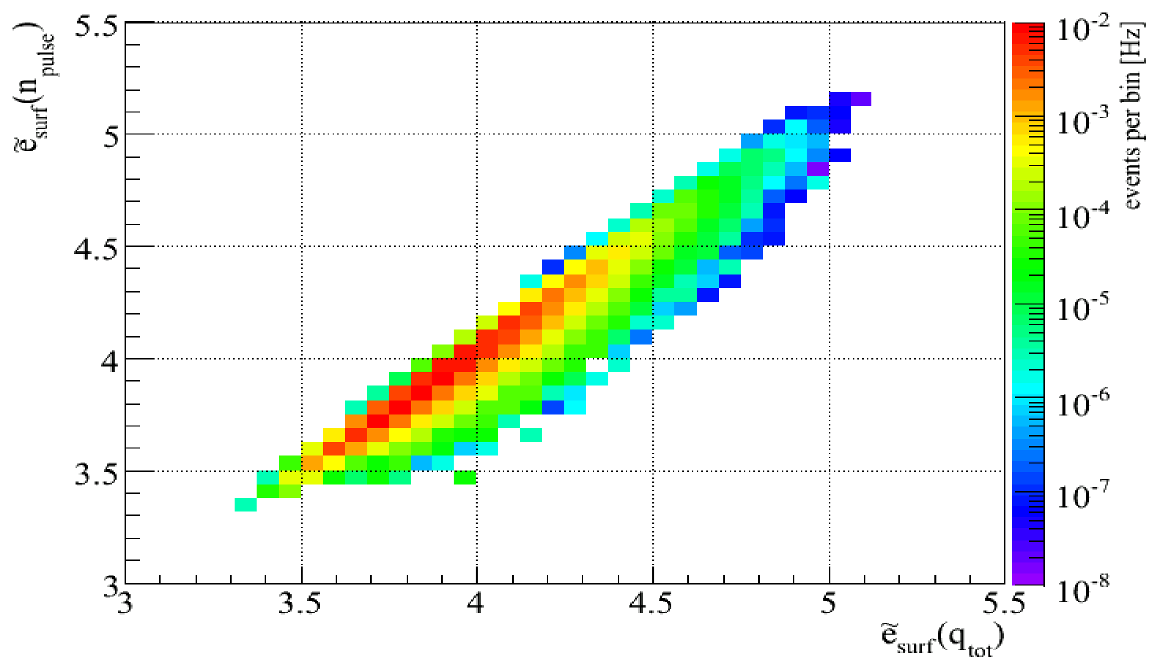
Data/MC: ẽ(N_{pulse}) and ẽ(Q_{tot})





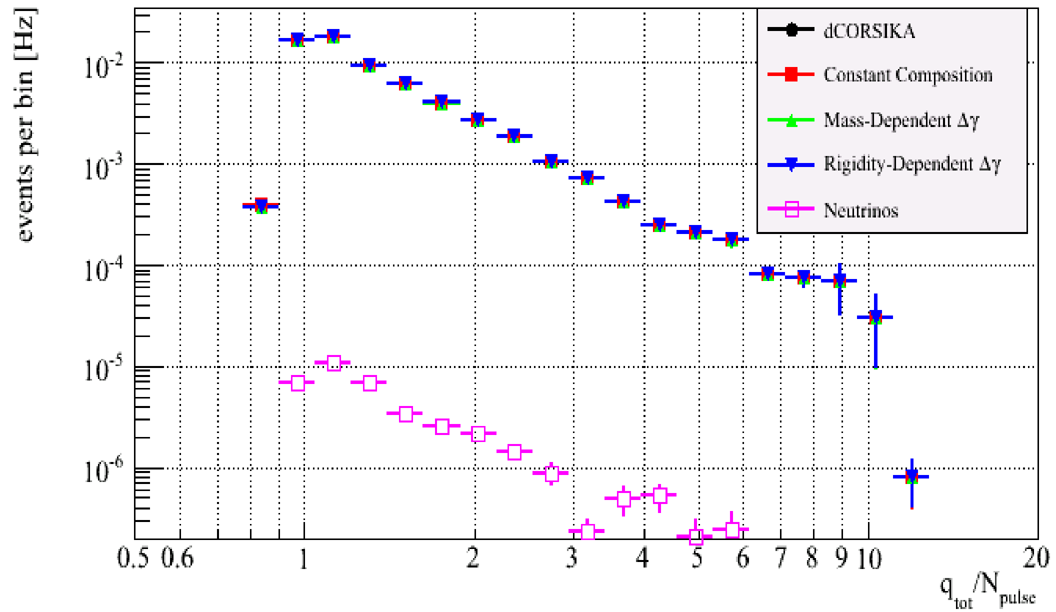
Data



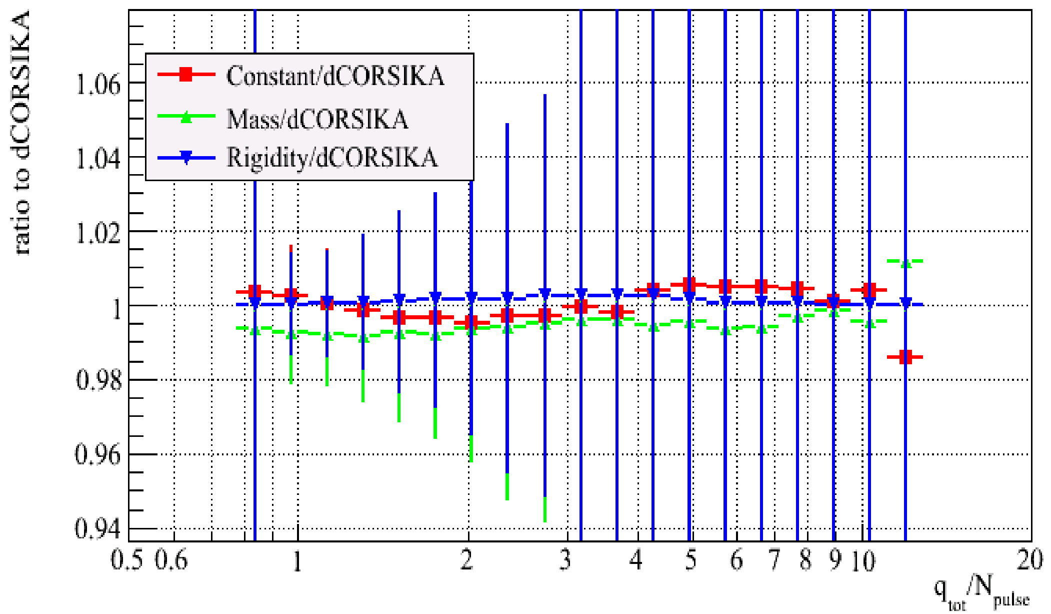


MC

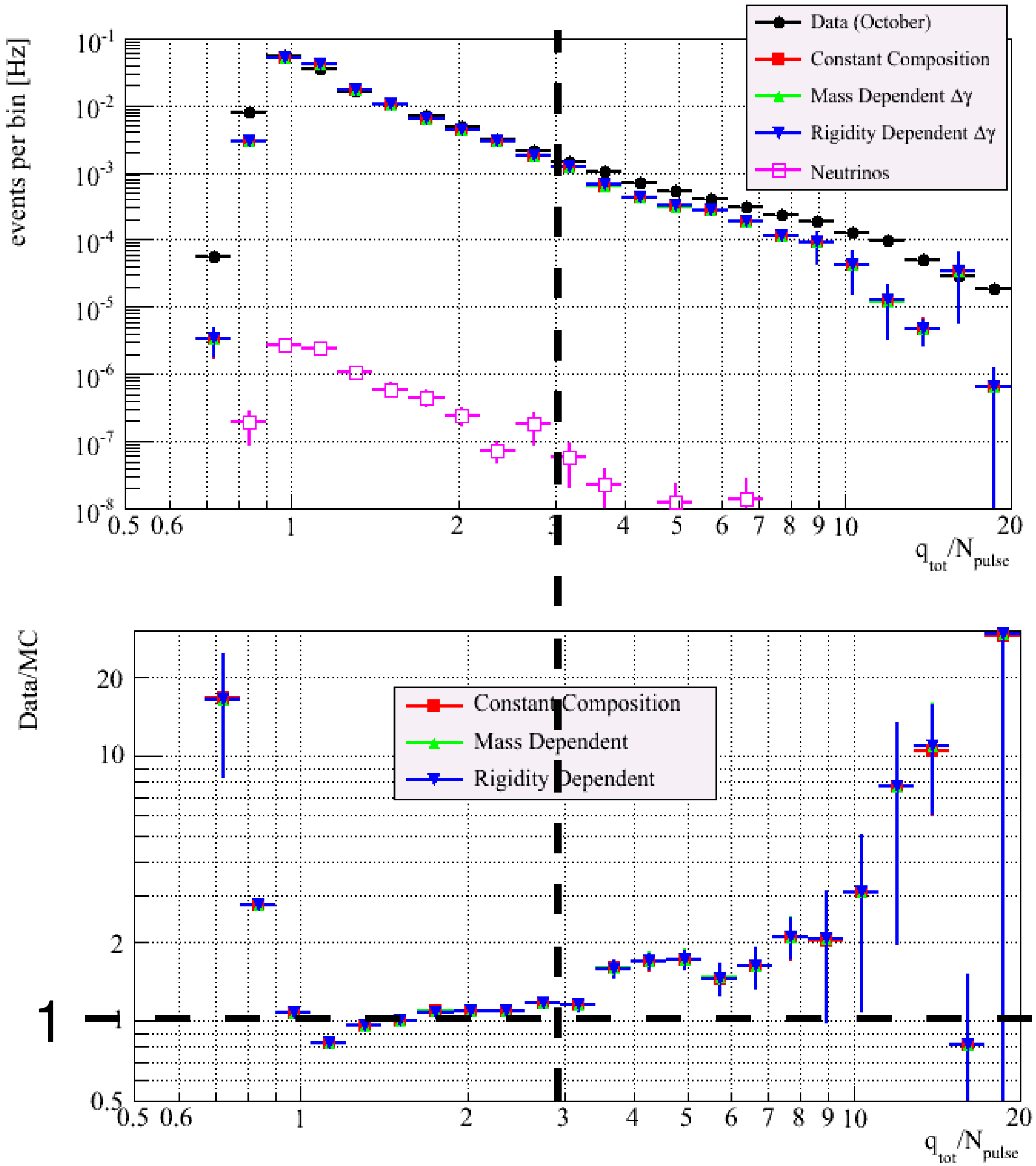
Patrick Berghaus



Average Charge per Pulse



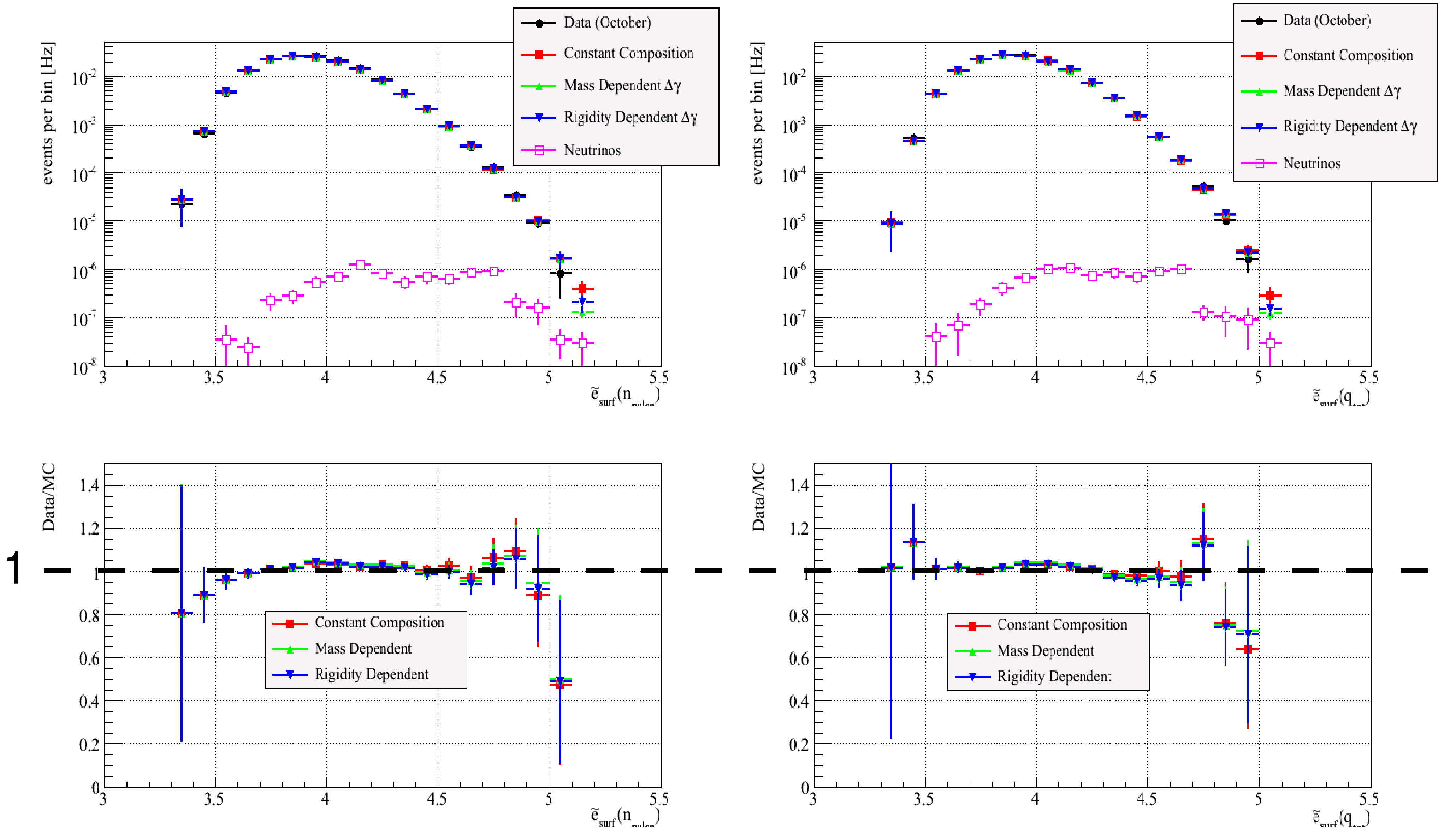
Invariant!



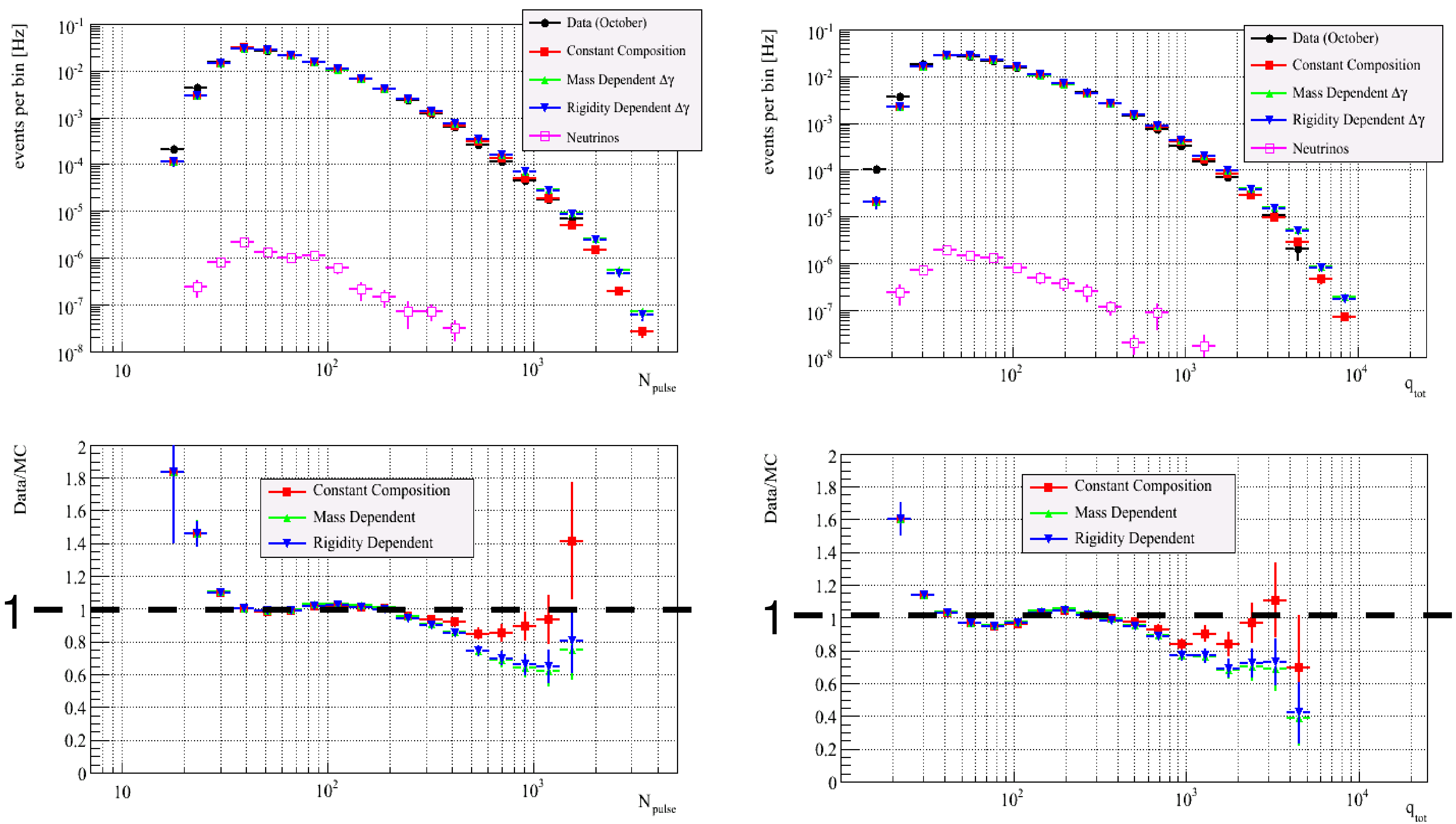
"Balloon"/Droop Correction

Additional Cut:
Average Charge per Pulse
< 3

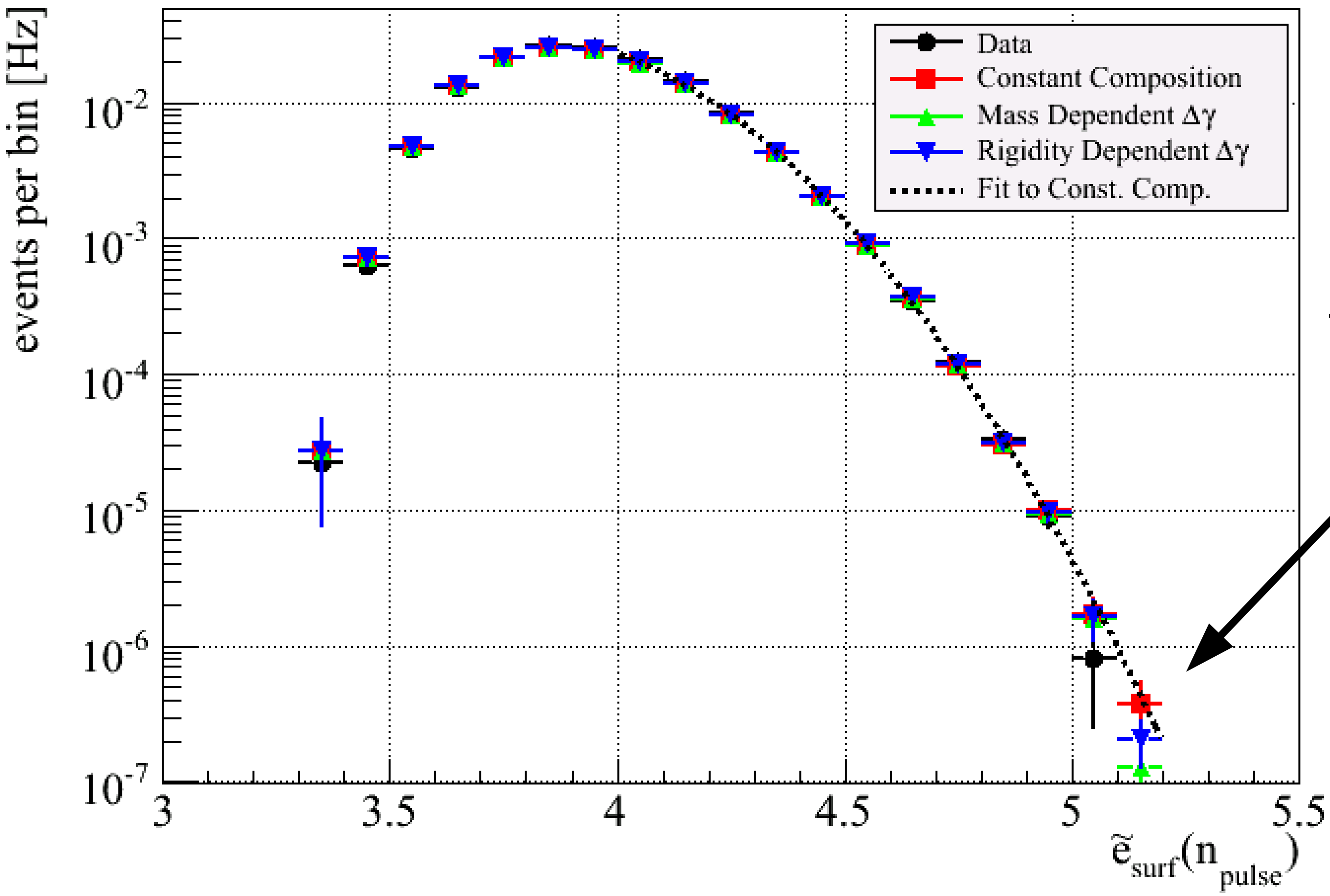
Data/MC: $\tilde{e}(N_{pulse})$ and $\tilde{e}(Q_{tot})$



Data/MC: N_{pulse} and Q_{tot}

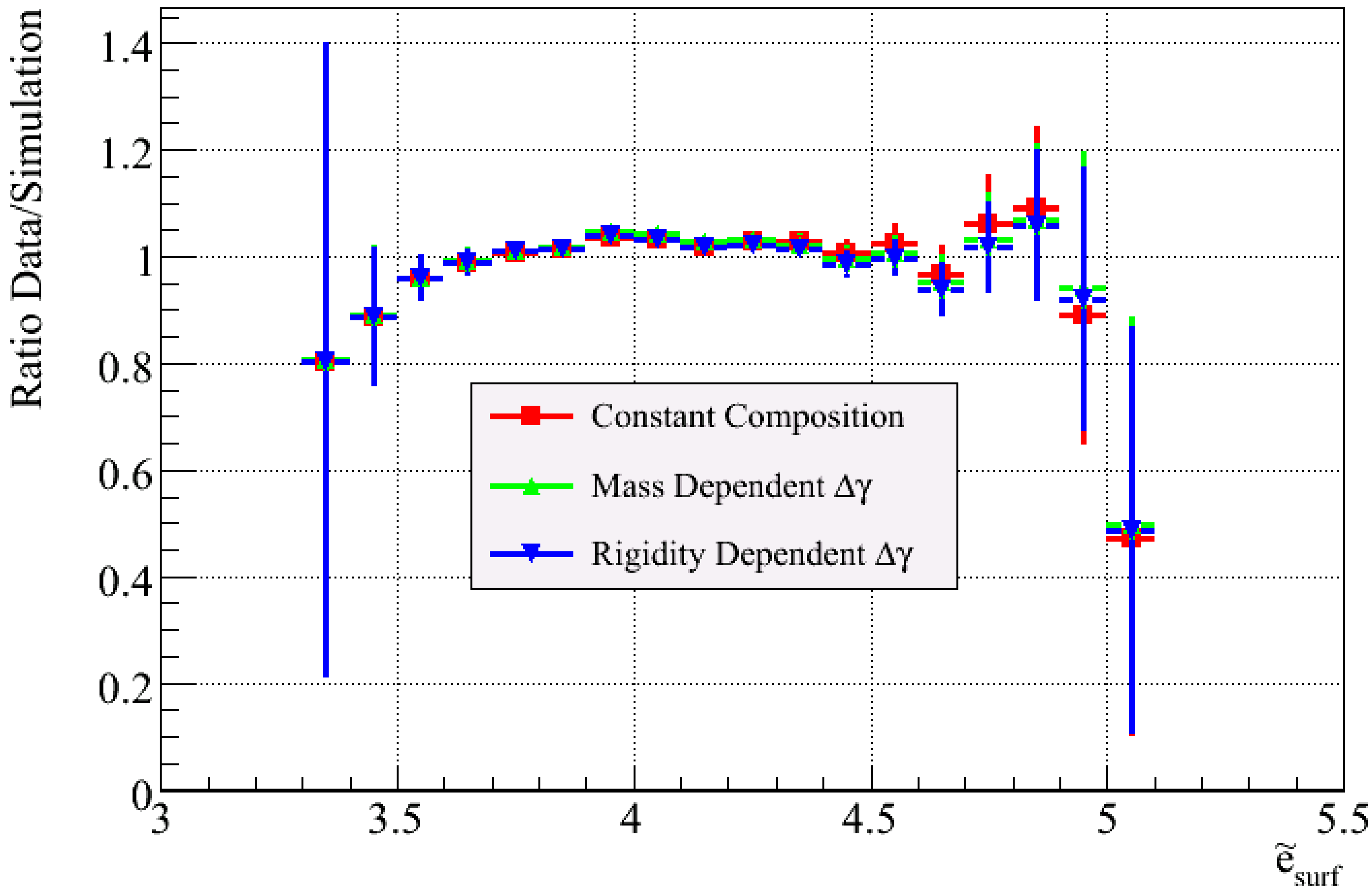


Final Distribution (1 month IC22)

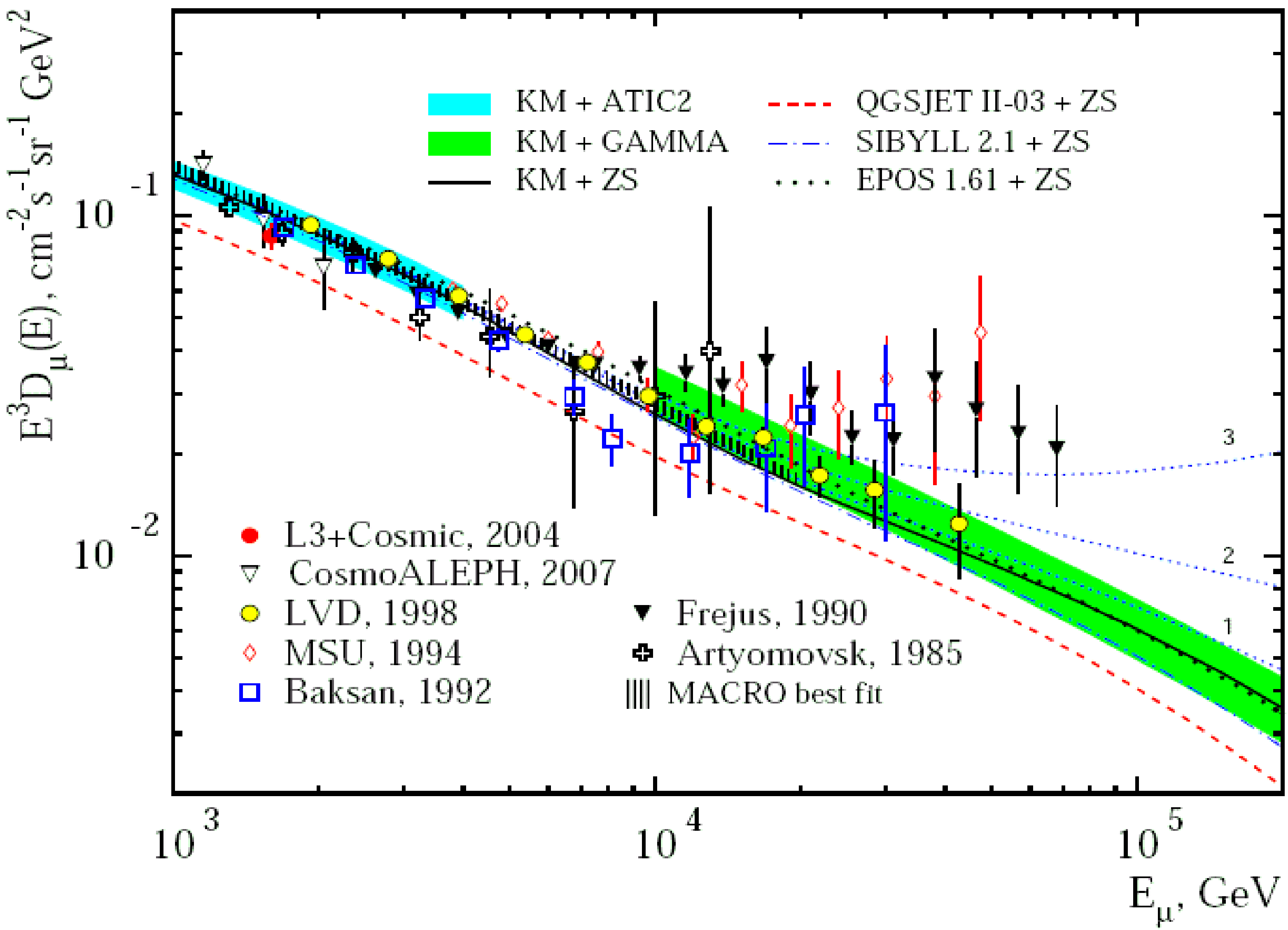


Expect
10 events
in IC22
for const.comp.

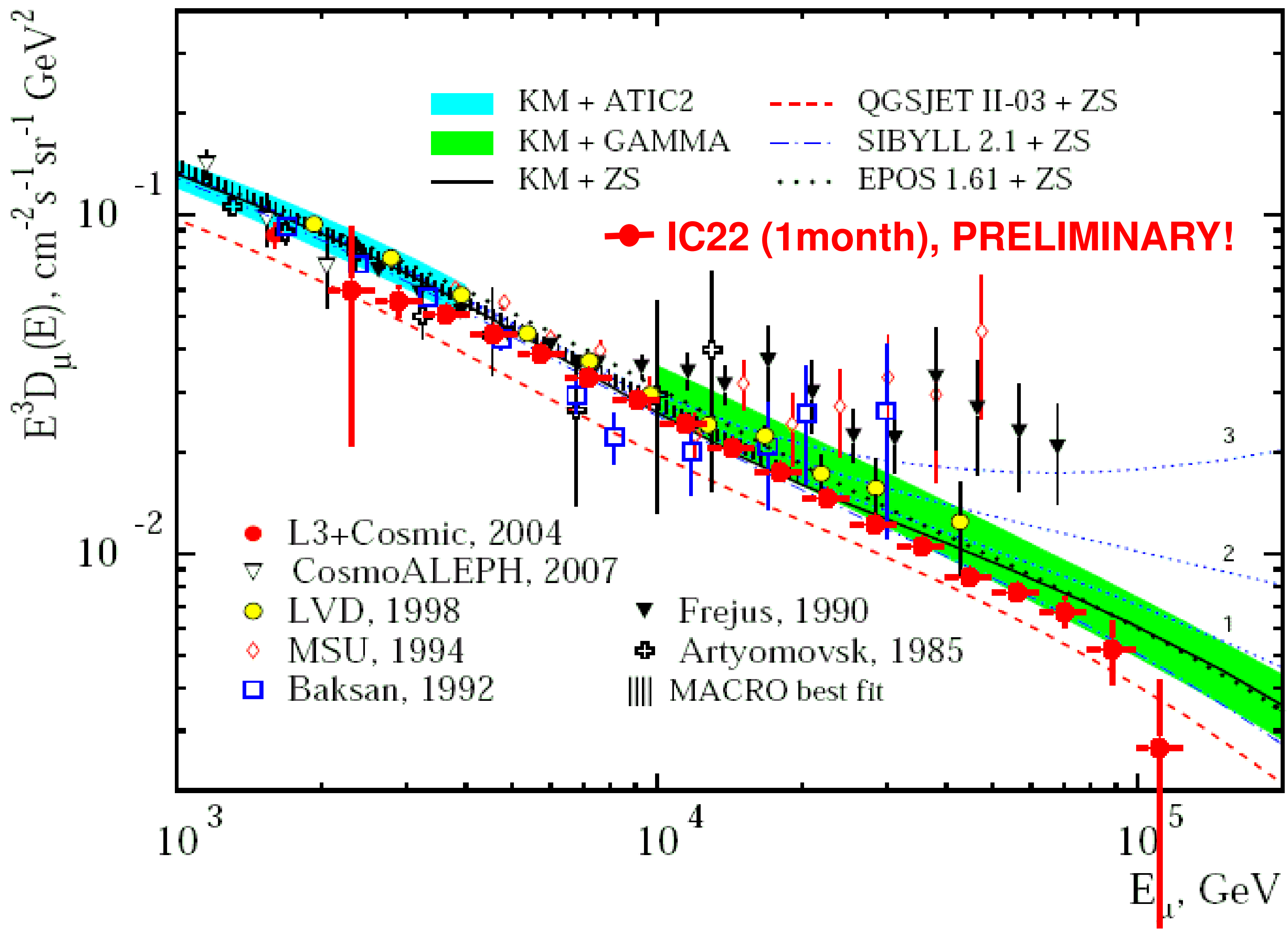
Ratio Data/MC (1 month IC22)



Muon Spectrum



Muon Spectrum



Conclusion

Atmospheric muons are indispensable for investigation of detector systematics

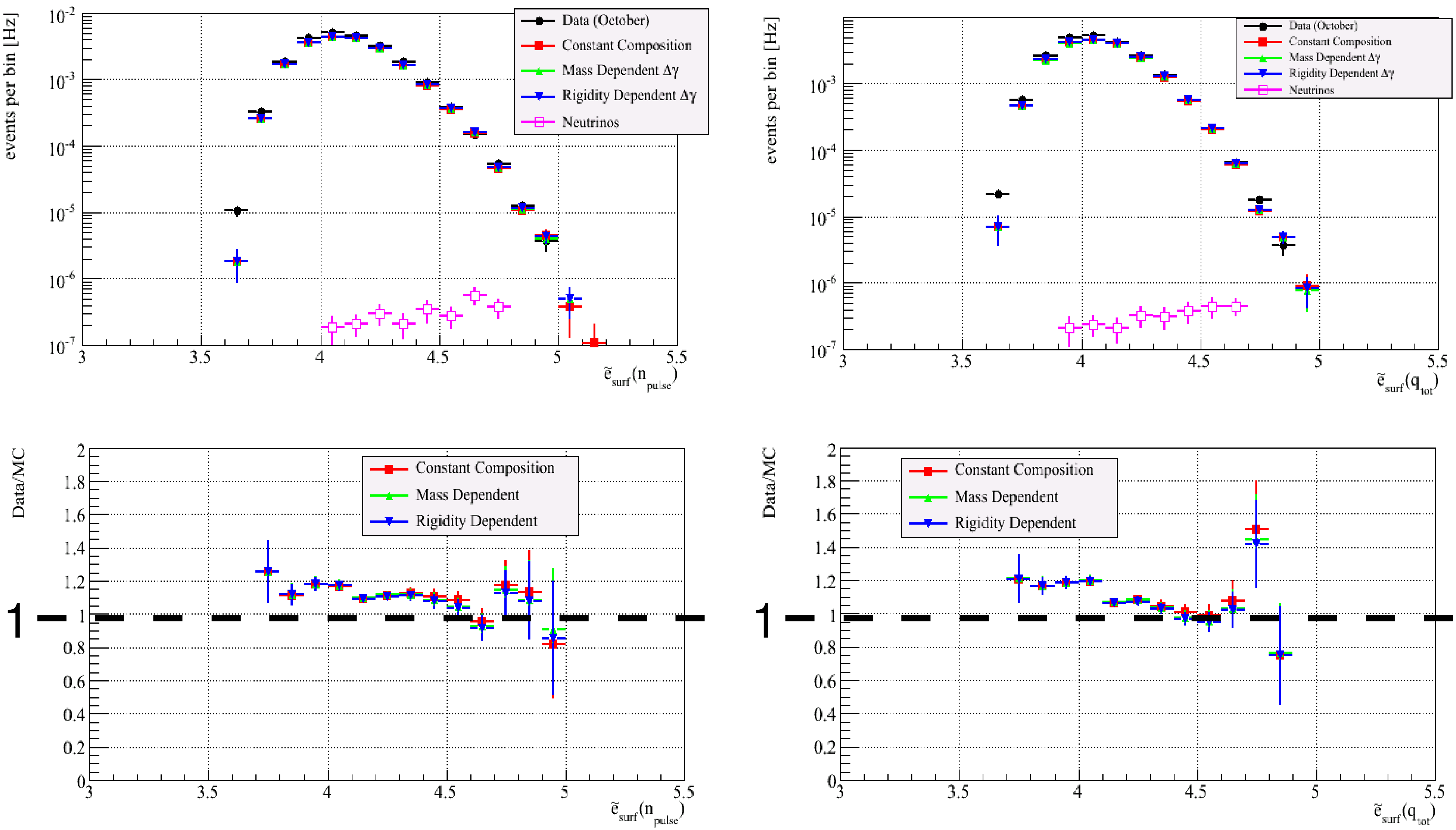
Diffuse analysis is very difficult without understanding HE muons

IceCube has huge potential for CR physics

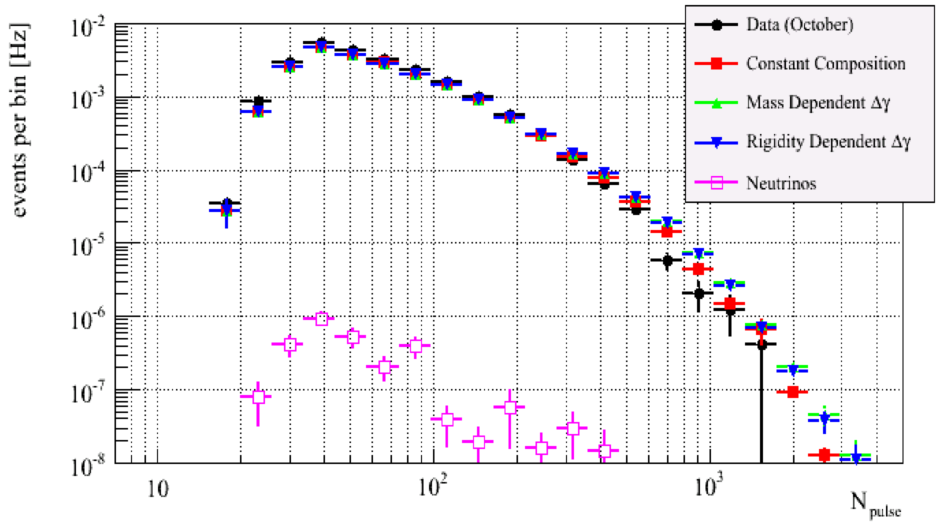
More information:
wiki.icecube.wisc.edu/index.php/Muon_Energy_Spectrum

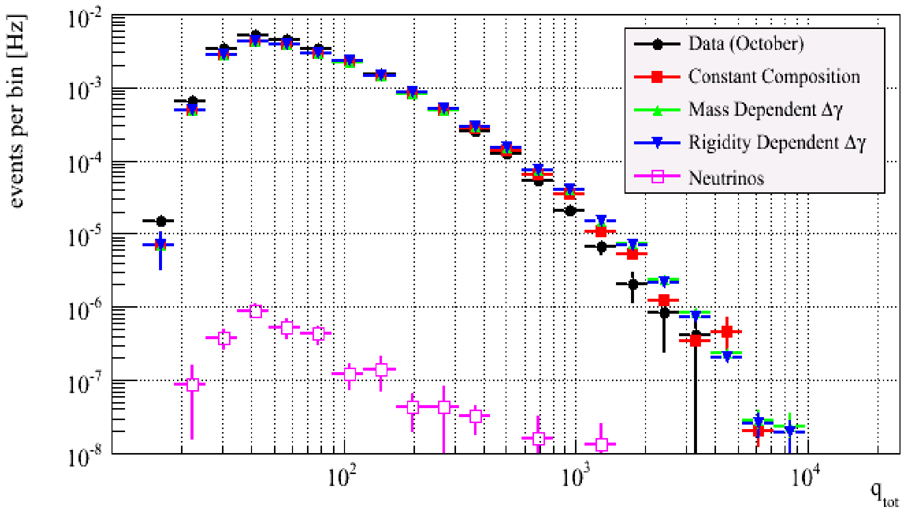
Backup Slides

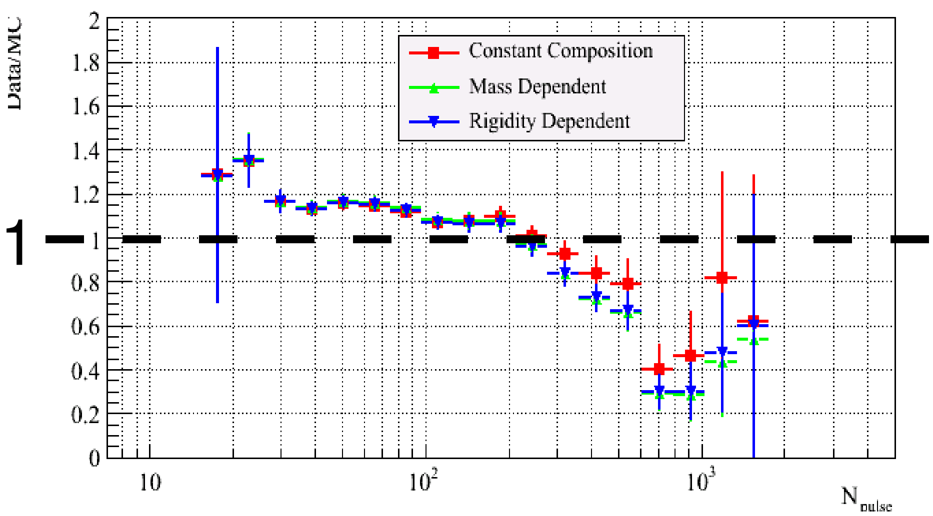
cog_z<-100m: $\tilde{e}(N_{pulse})$ and $\tilde{e}(Q_{tot})$

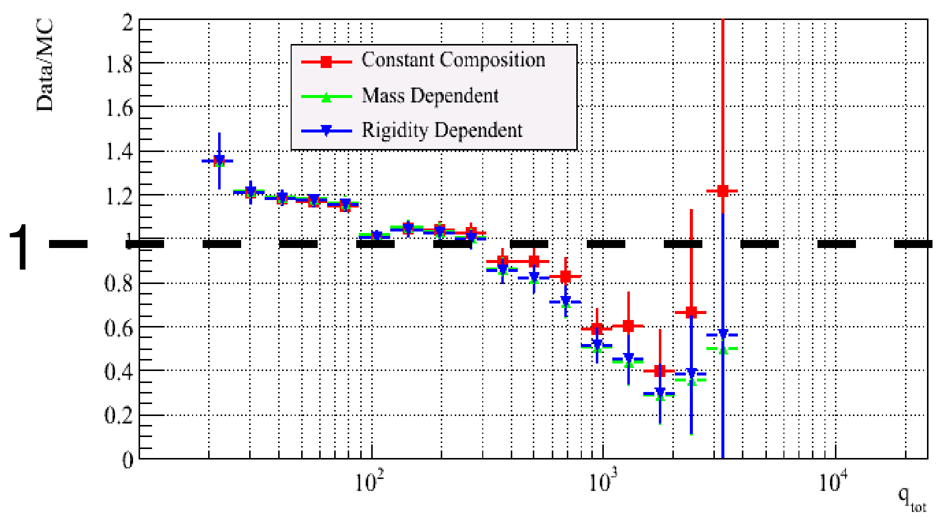


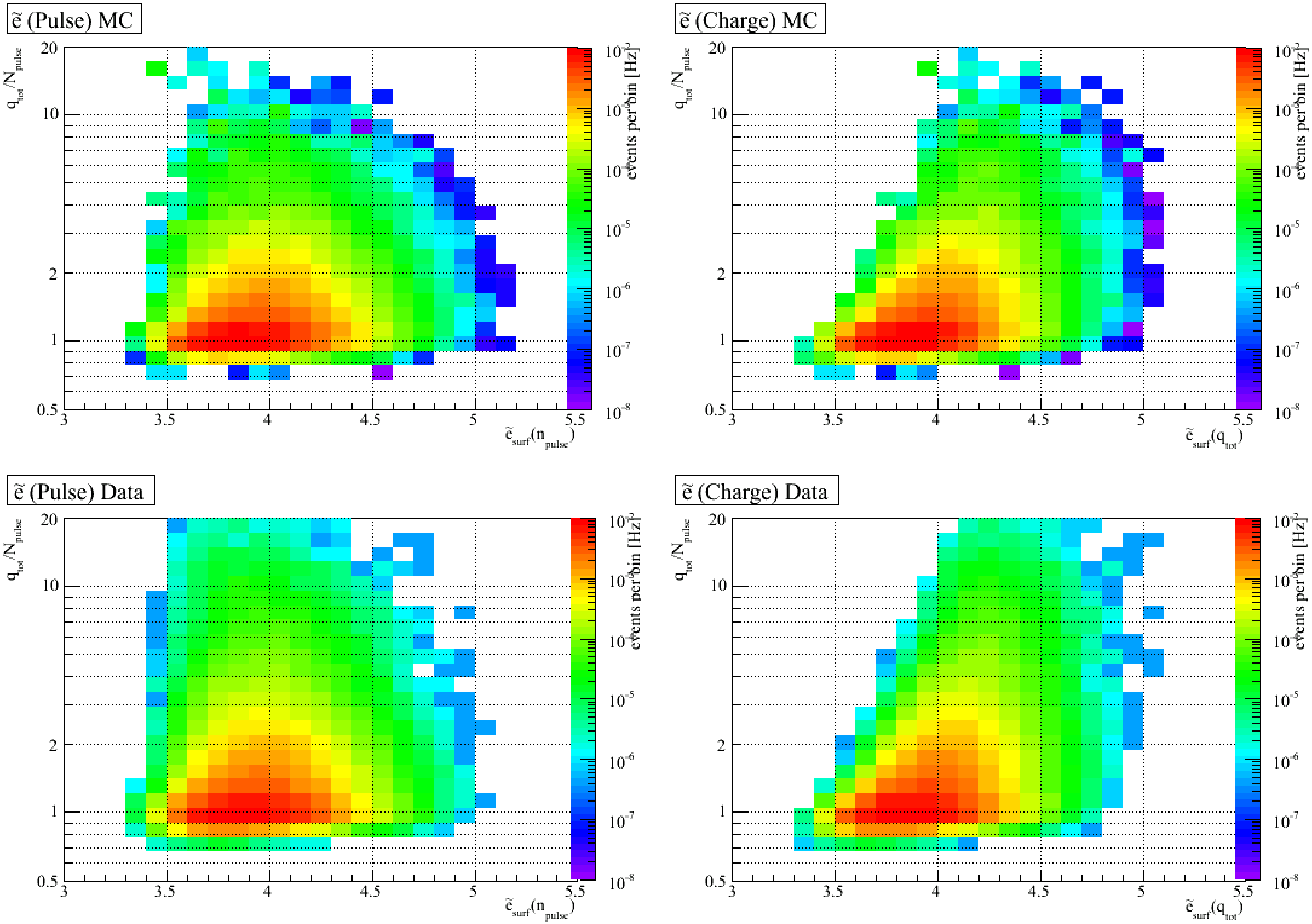
cog_z<-100m: N_{pulse} and Q_{tot}



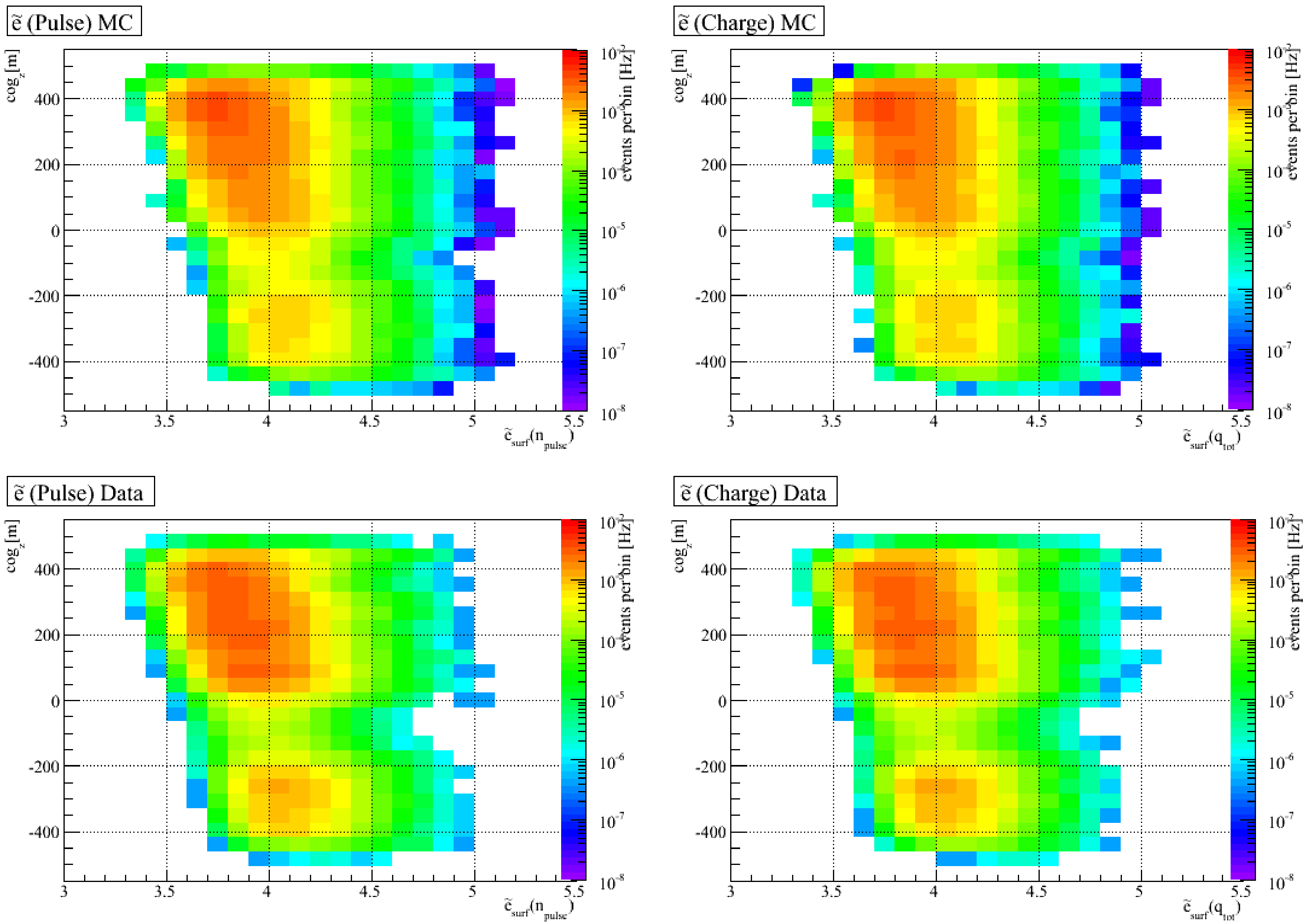


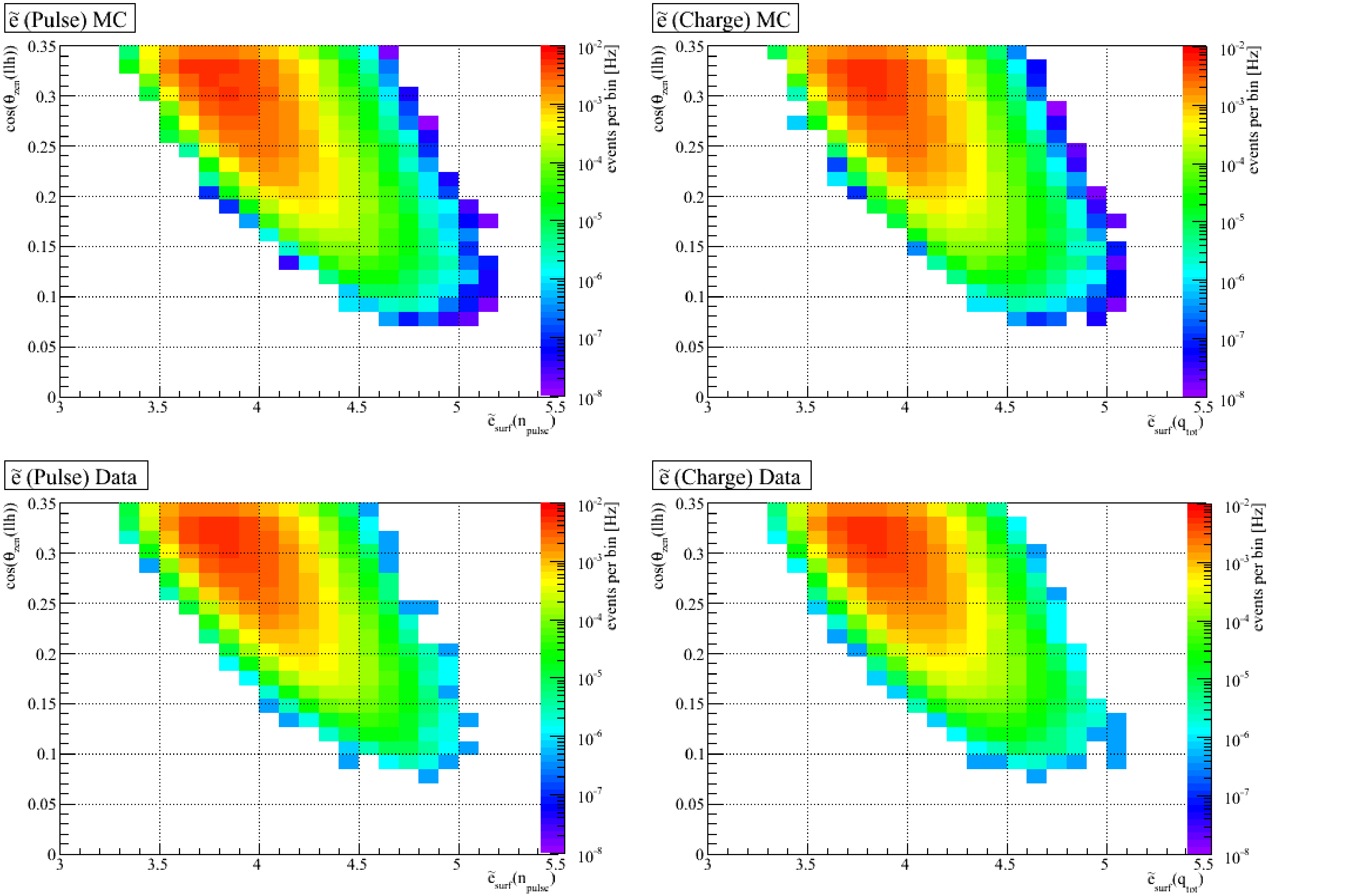




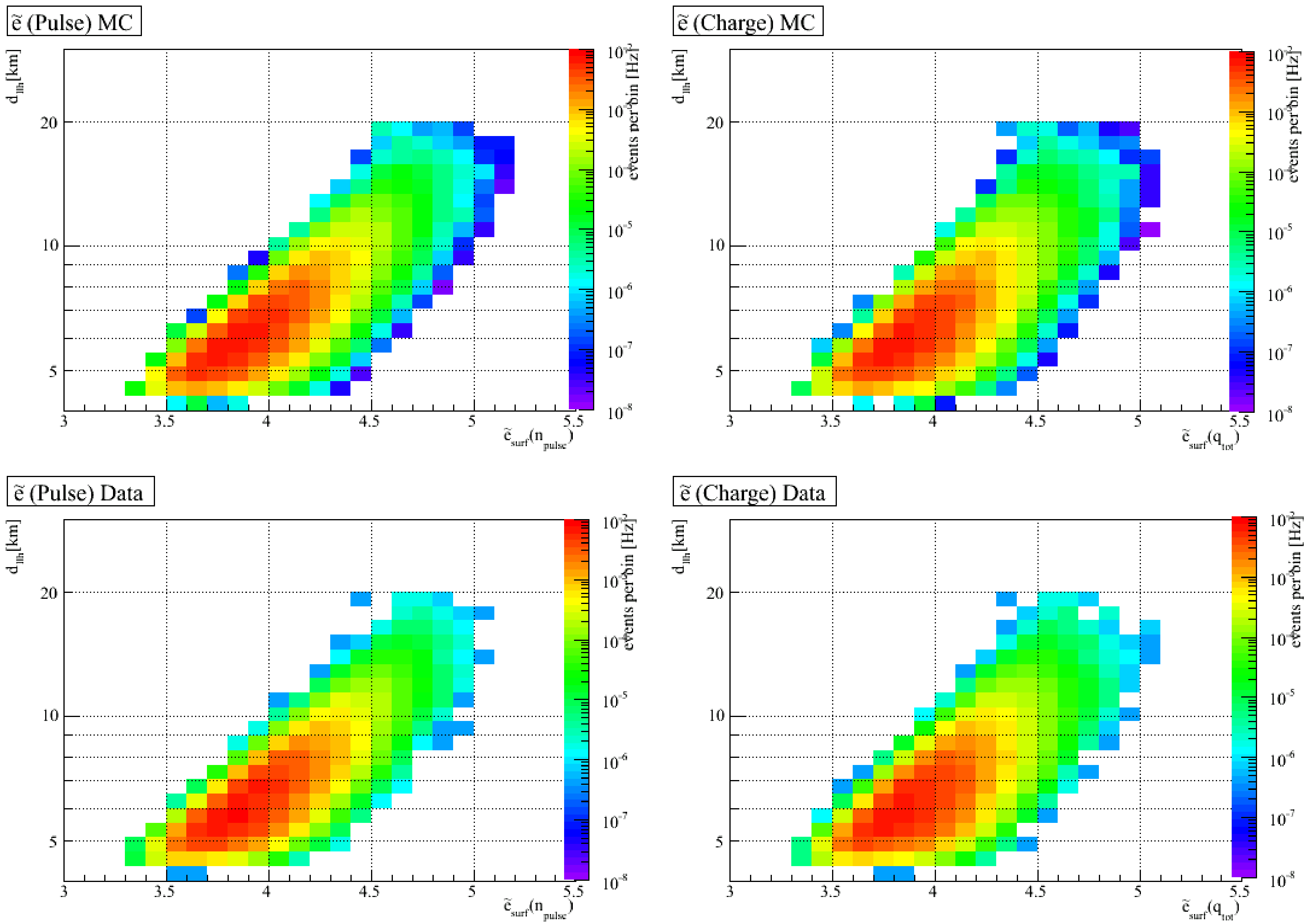


ẽ (Pulse) MC
ẽ (Charge) MC
ẽ (Pulse) Data
ẽ (Charge) Data
q_{tot}/N_{pulse}
events per bin [Hz]
$\tilde{e}_{surf}(n_{pulse})$
$\tilde{e}_{surf}(q_{tot})$

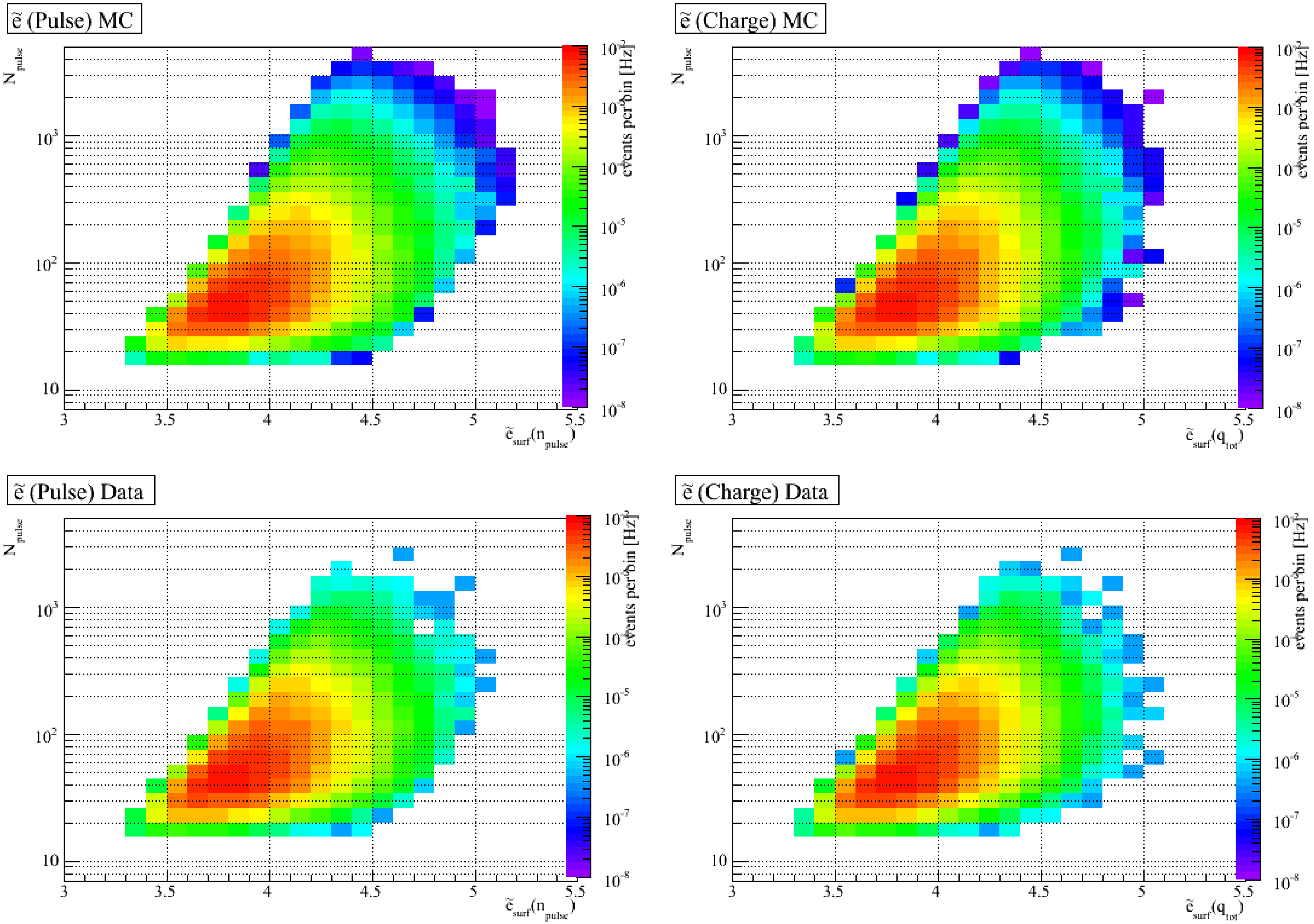

ẽ (Pulse) MC
ẽ (Charge) MC
ẽ (Pulse) Data
ẽ (Charge) Data
cog_z [m]
events per bin [Hz]
ẽ_surf(n_pulse)
ẽ_surf(q_tot)
400
200
0
-200
-400
3
3.5
4
4.5
5
5.5
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8



ẽ (Pulse) MC
ẽ (Charge) MC
ẽ (Pulse) Data
ẽ (Charge) Data
cos(θzen(llh))
events per bin [Hz]
ẽsurf(npulse)
ẽsurf(qtot)



ẽ (Pulse) MC
ẽ (Charge) MC
ẽ (Pulse) Data
ẽ (Charge) Data
d_llh [km]
events per bin [Hz]
ẽ_surf(n_pulse)
ẽ_surf(q_tot)
3
3.5
4
4.5
5
5.5
5
10
20
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8



ẽ (Pulse) MC
ẽ (Charge) MC
ẽ (Pulse) Data
ẽ (Charge) Data
N_pulse
events per bin [Hz]
ẽ_surf(n_pulse)
ẽ_surf(q_tot)