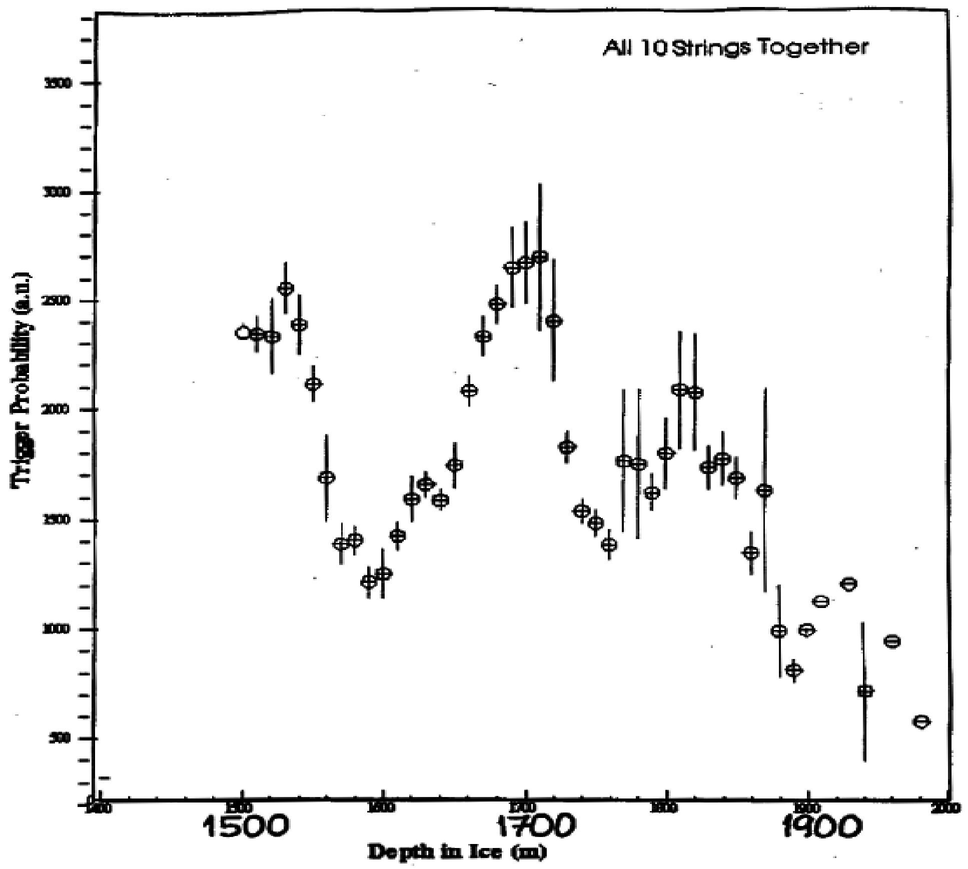
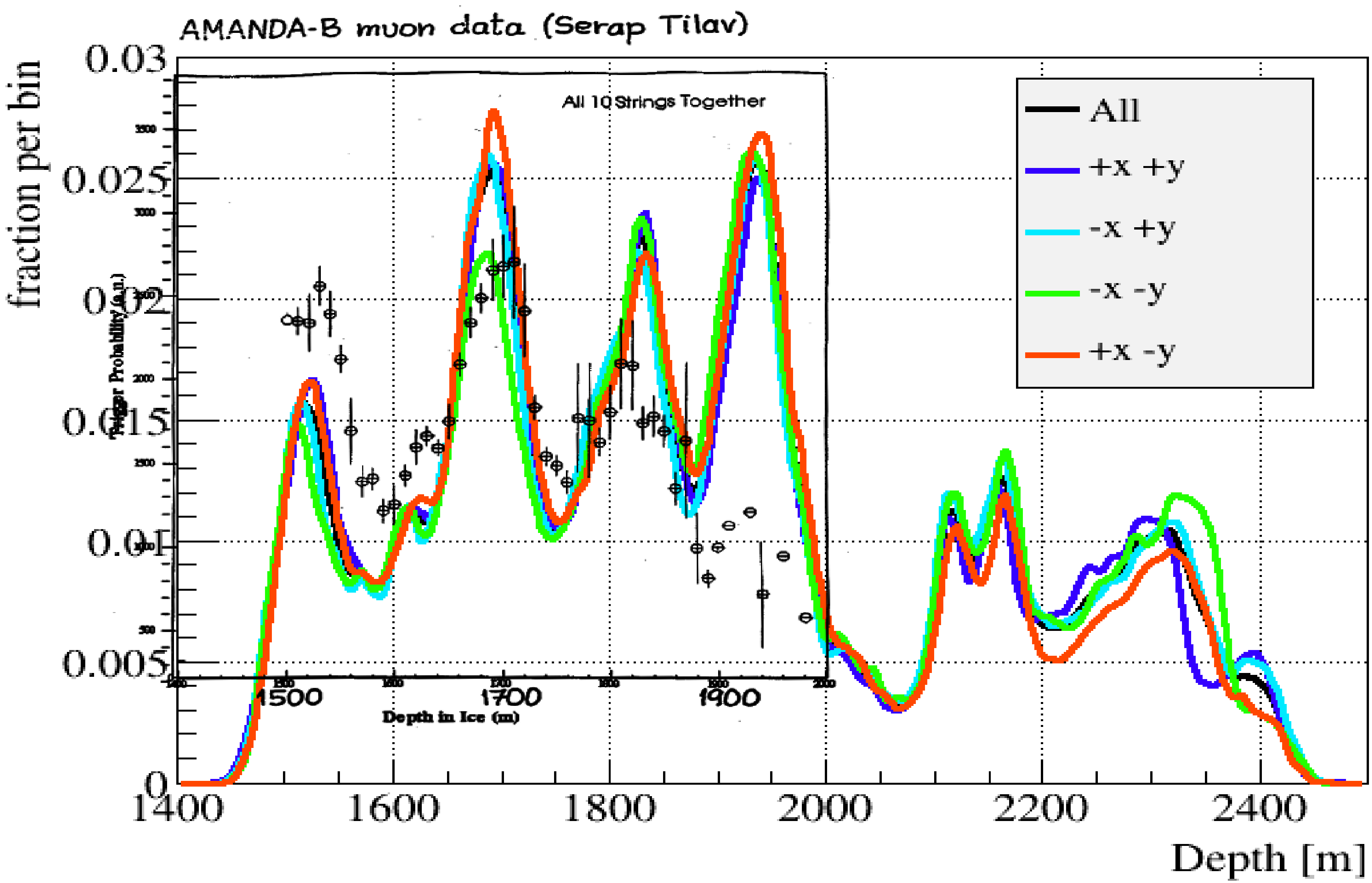
Atmospheric Muons: Systematics

Patrick Berghaus

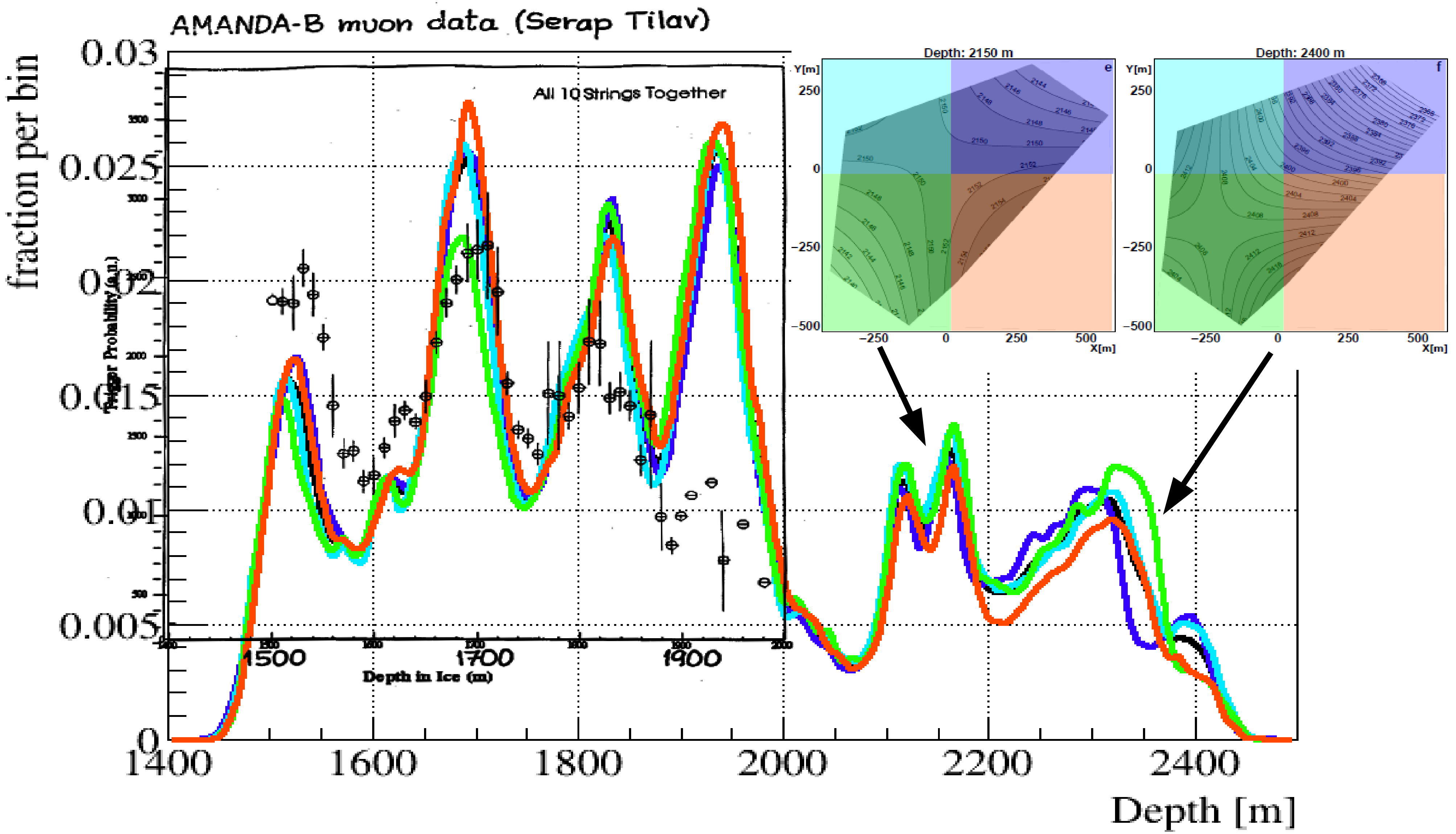
Muon Workshop, Madison 2015

AMANDA-B muon data (Serap Tilav)

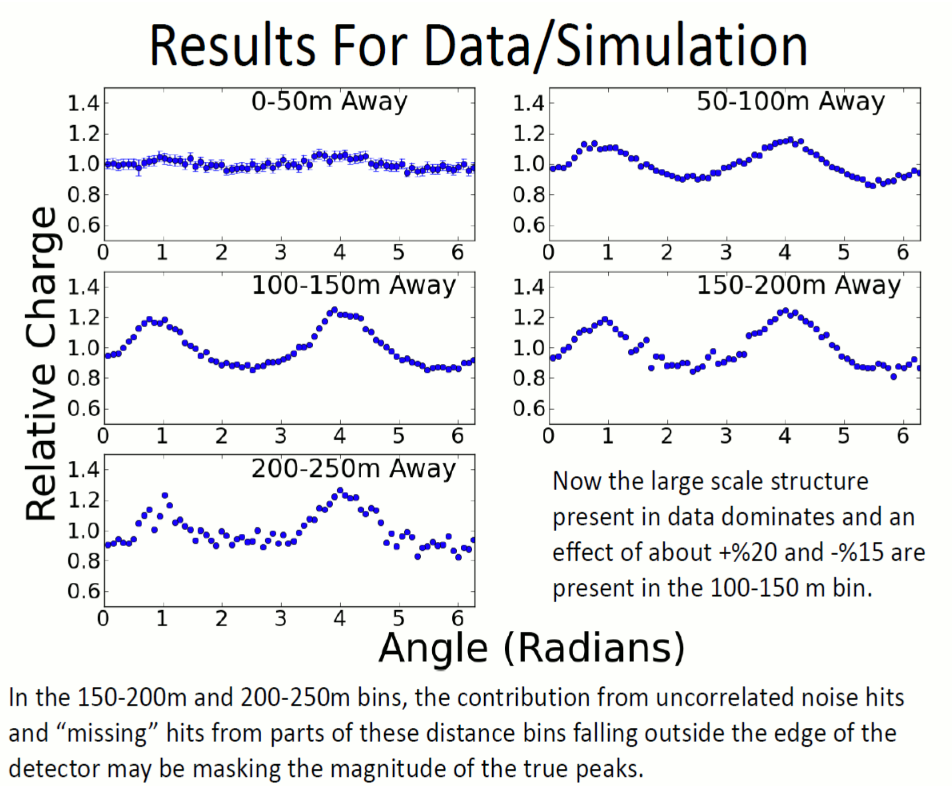


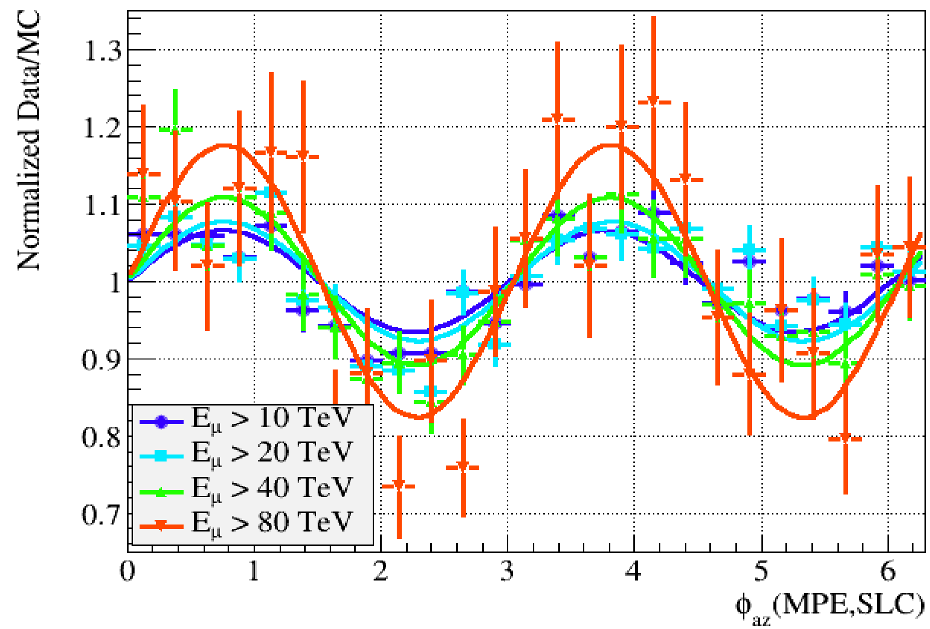

AMANDA-B muon data (Serap Tilav)
All 10 Strings Together
Trigger Probability (a.u.)
Depth in Ice (m)
1500
1700
1900
fraction per bin
0.03
0.025
0.02
0.015
0.01
0.005
0
1400
1600
1800
2000
2200
2400
Depth [m]
All
+x +y
-x +y
-x -y
+x -y

Ice Layer Tilt



Ice Anisotropy

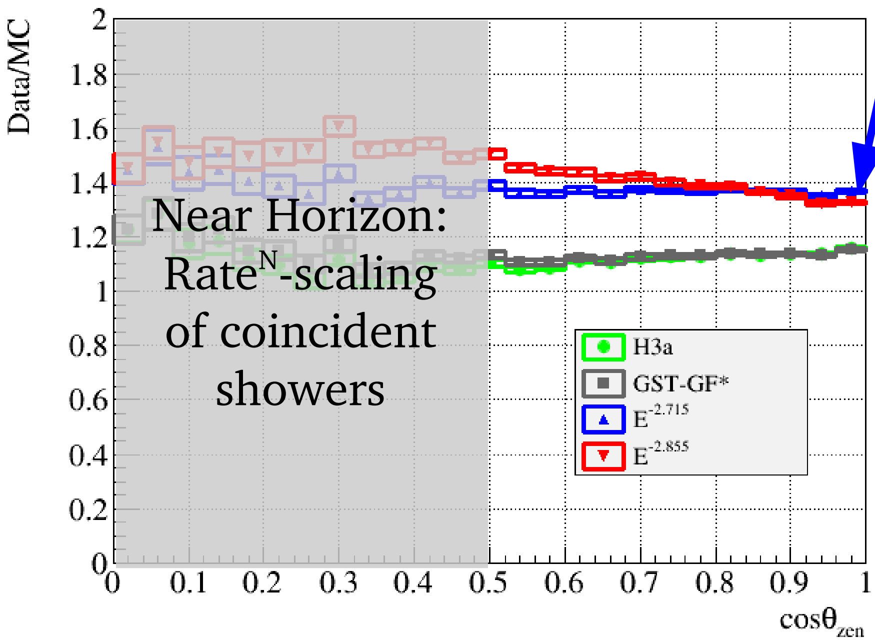




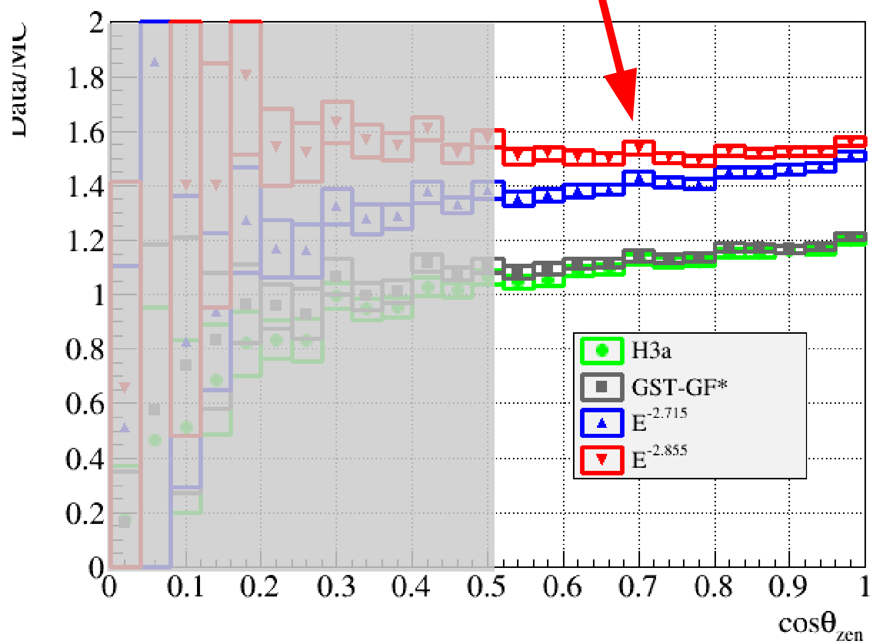
Dima/Kyle J.

HE Muon Analysis

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



Trigger Level



Quality Cuts

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

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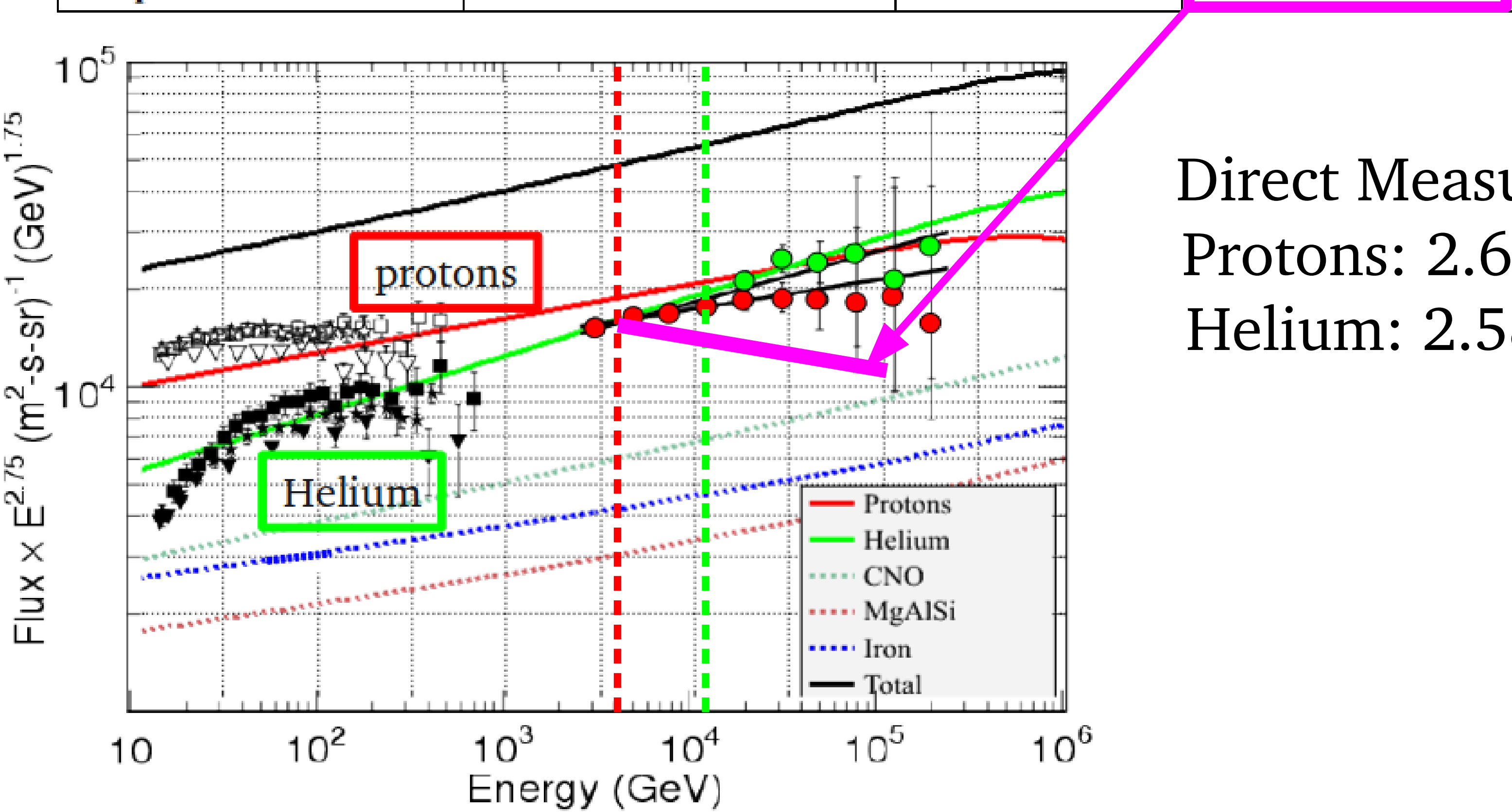
Bulk Ice Scattering	$\pm 10\%$	< 0.01	± 0.01	< 0.015
Primary Composition	p/He	< 0.01	$+0.03/-0.10$	$-0.03/+0.10$
Hadronic Model	QGSJET-II/EPOS 1.99	$+0.02/<0.01$	$+0.03/<0.02$	< 0.02
DOM Efficiency	$\pm 10\%$	< 0.02	$+<0.02/-0.04$	$+0.02/-<0.02$
Experimental Value	Statistical Error	2.715 ± 0.003	2.855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



H3a model overlayed on CREAM Data,
dashed lines are IceCube thresholds

Direct Measurement
Protons: 2.66±0.02
Helium: 2.58±0.02

Type	Variation	$\gamma_{CR,Trigger}$	$\gamma_{CR,High-Q}$	$\Delta\gamma_{CR}$
Hole Ice Scattering	30cm/100cm	±0.03	$+0.03/-0.05$	$+0.01/-0.02$
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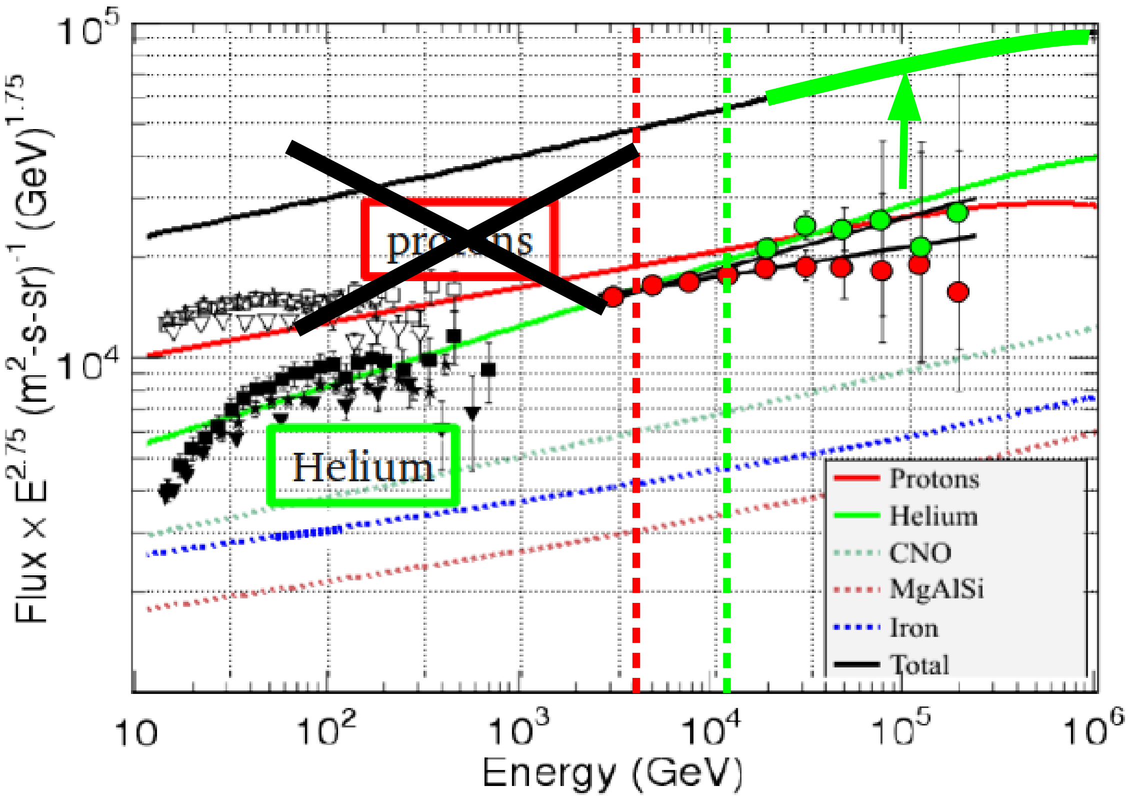
DOM Efficiency	$\pm10\%$	< 0.02	$+ < 0.02/-0.04$	$+0.02/- < 0.02$
Experimental Value	Statistical Error	2.715 ± 0.003	2.855 ± 0.007	0.140 ± 0.008

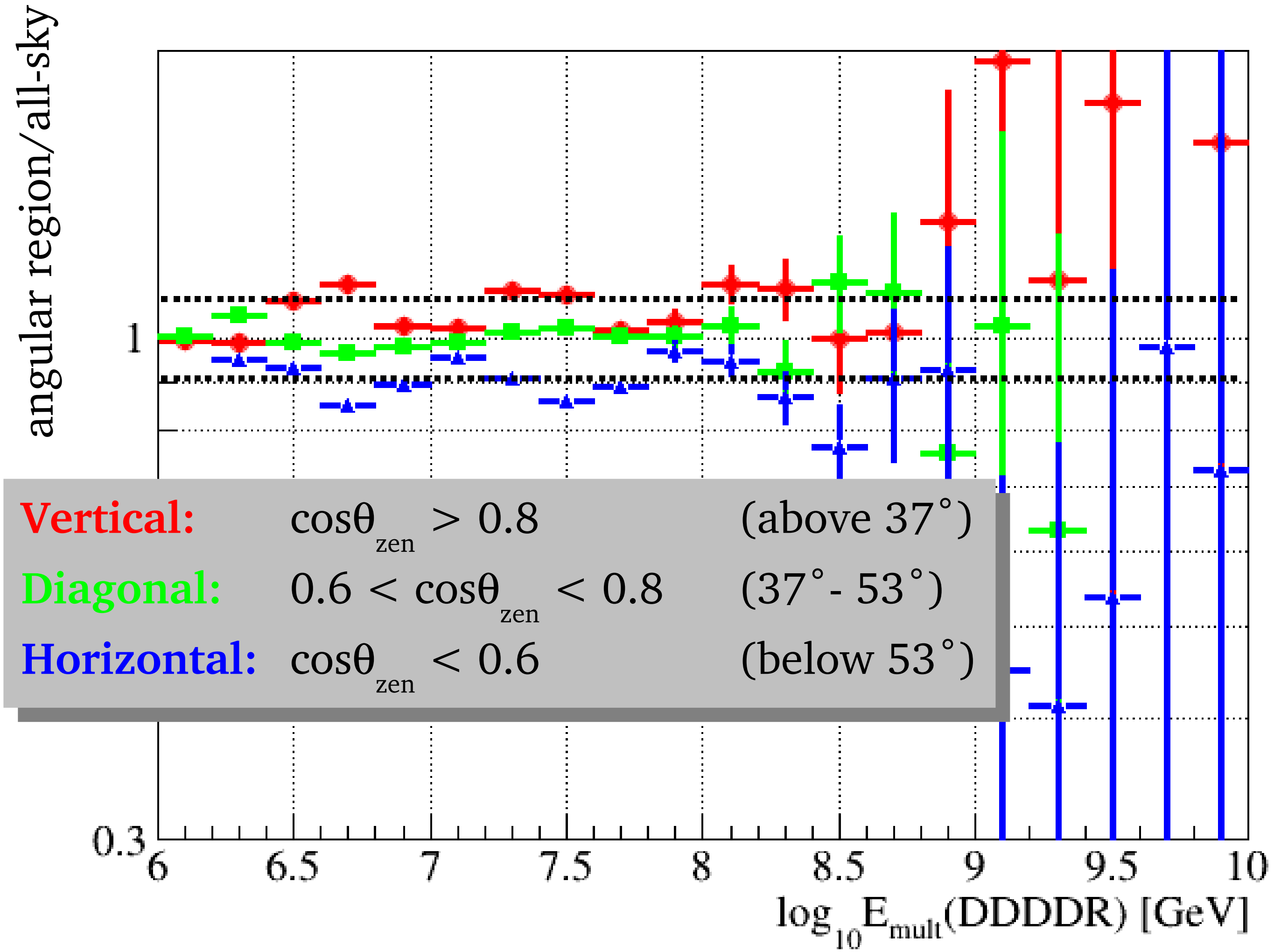


H3a model overlayed on CREAM Data, dashed lines are IceCube thresholds

Composition:
Explanation would require
3 x Helium Flux
No Protons

(energy threshold is per-nucleon, 4 times higher for He)

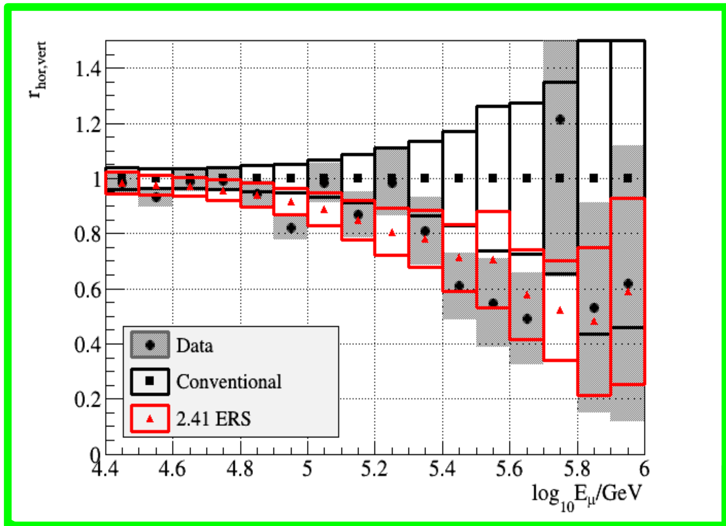
Bundle Spectral Unfolding



IC86 Data
ppc CORSIKA MC

Measured flux decreases towards horizon

(https://wiki.icecube.wisc.edu/index.php/IC79_Atmospheric_Muons/Multiplicity_Result#Angular_Acceptance)



Best Fit (ang. corr.):

Correction: 0.18

Prompt Flux: 2.41 ERS

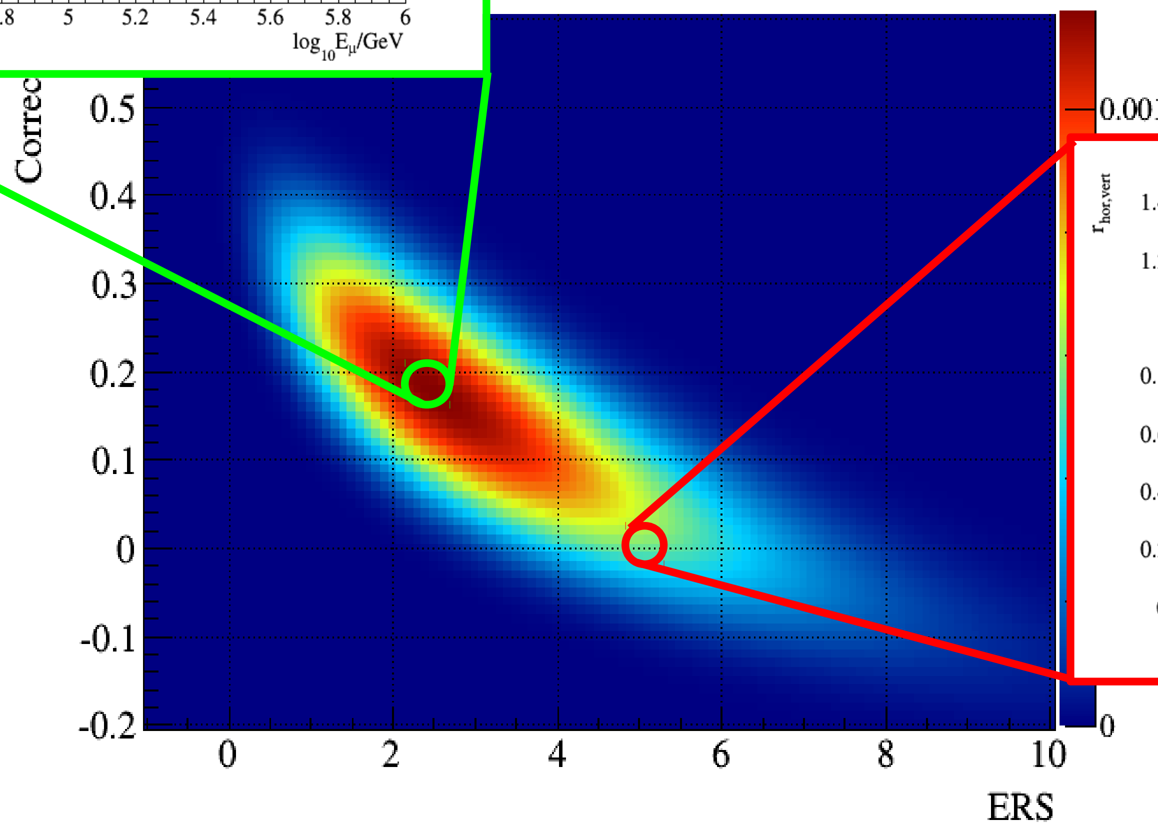
χ^2/dof: 14.9/15

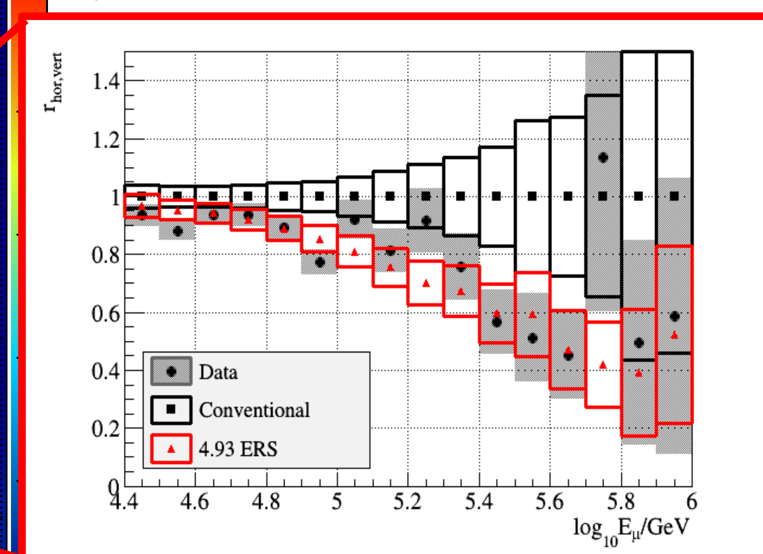
Best Fit (default):

No Correction

Prompt Flux: 4.93 ERS

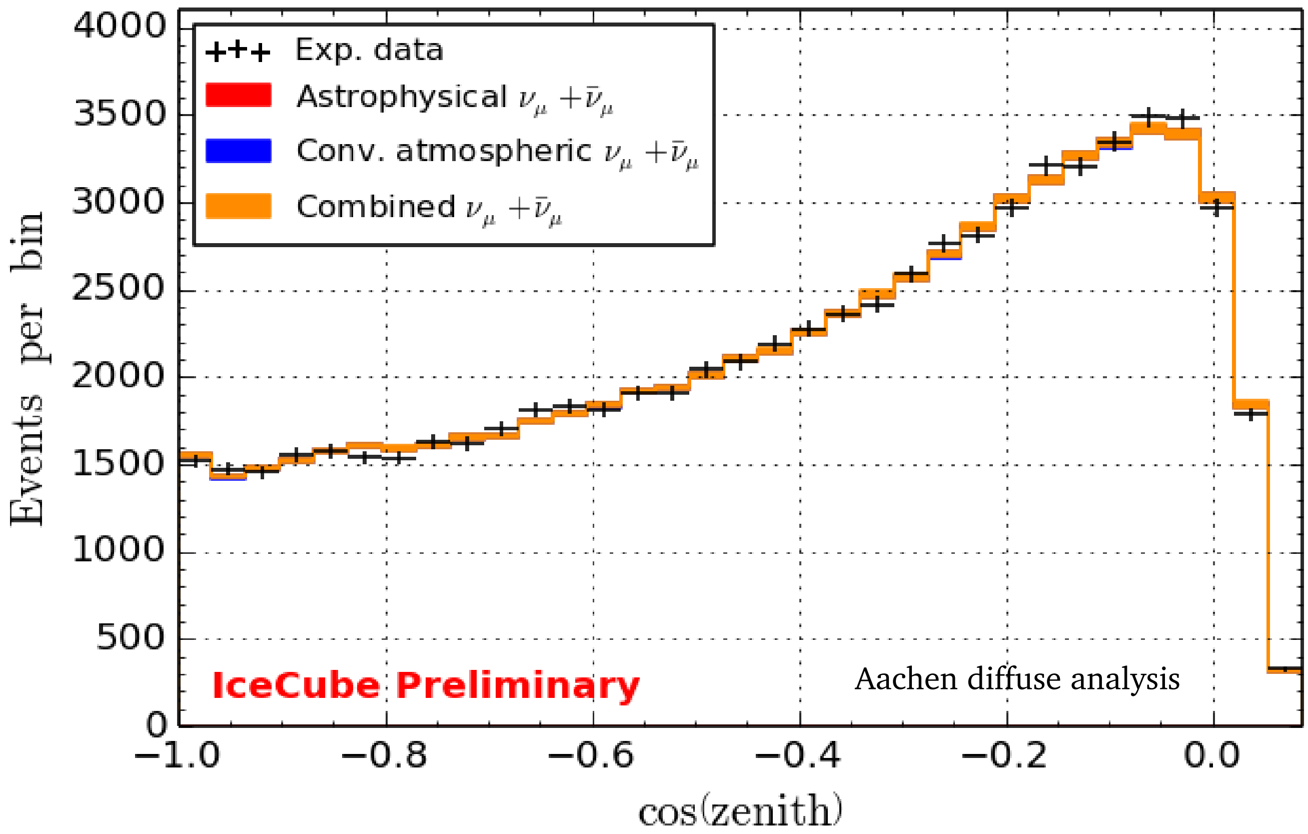
χ^2/dof: 20.0/15



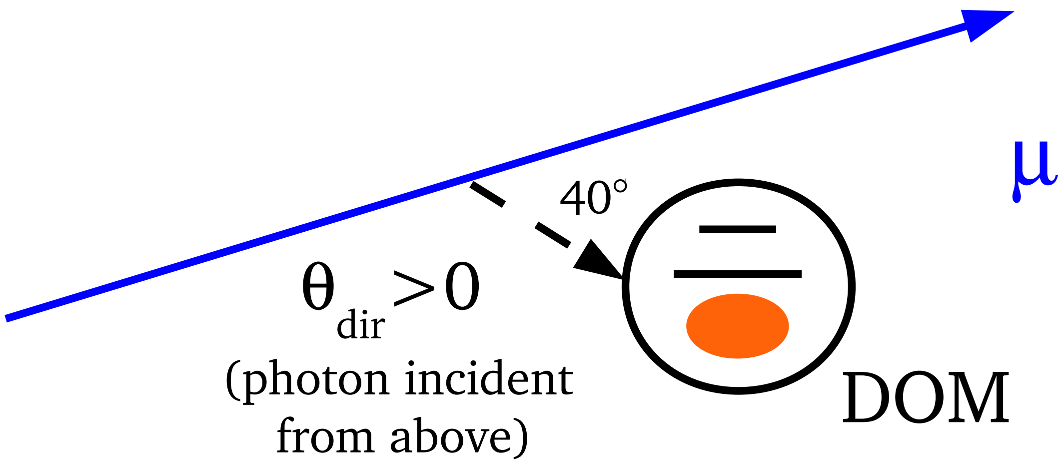


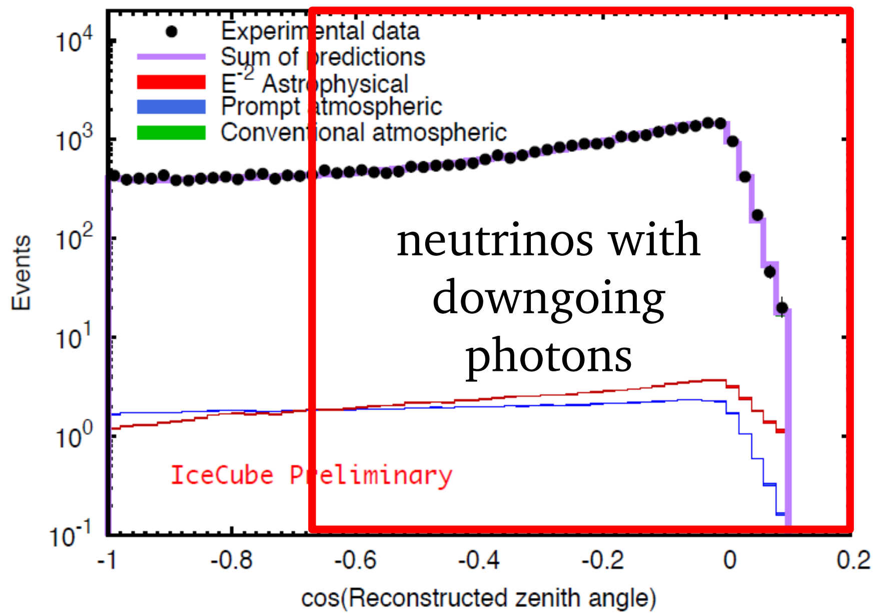
Better fit, more realistic result!

Neutrinos: Good Agreement!



Neutrino-induced tracks have downgoing photons!





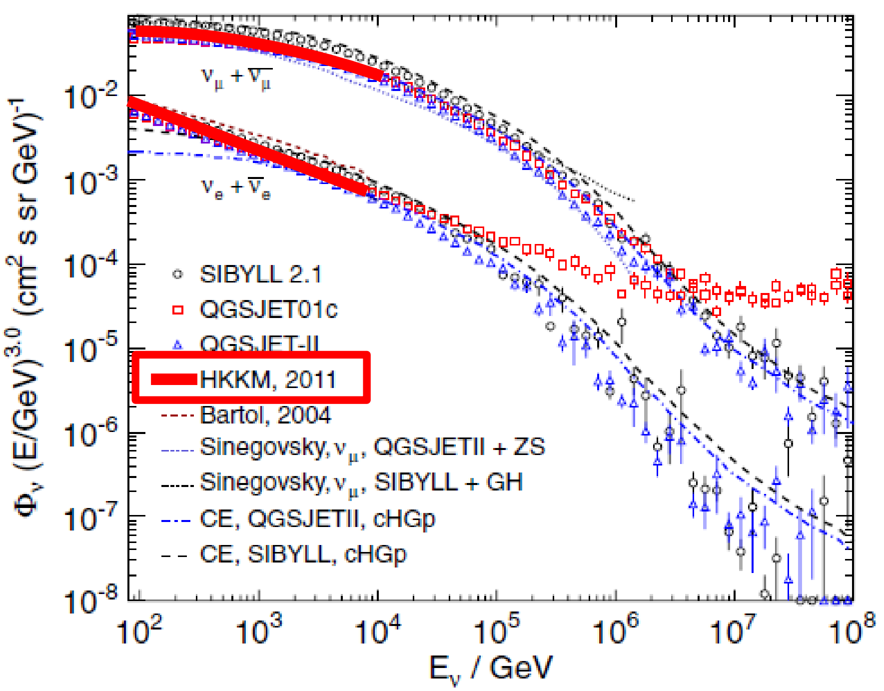
CORSIKA should be better than neutrino models!

Full Air Shower Simulation

Detailed Primary Flux

Atmosphere

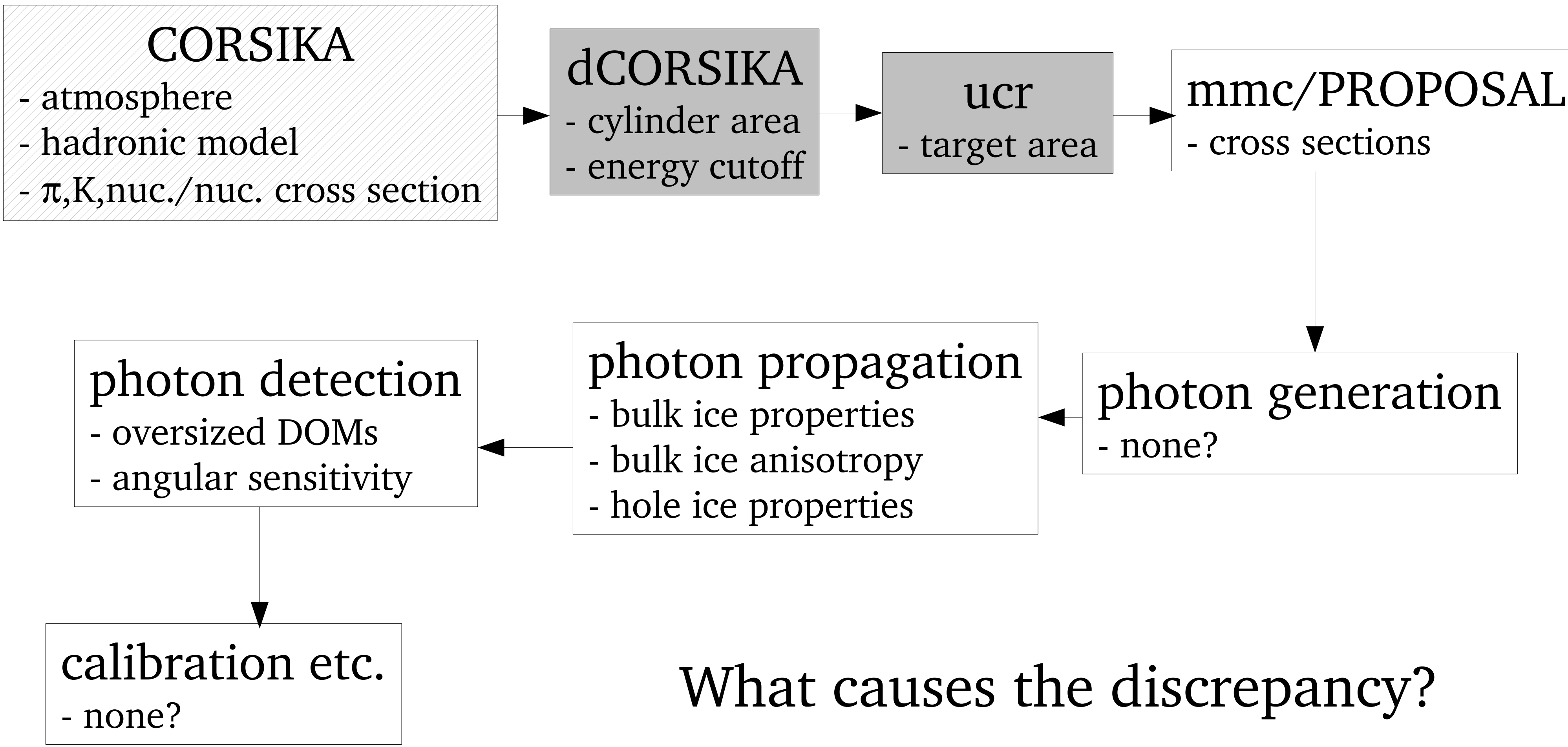
etc...



Fedynitch, Tjus, Desiati:
arXiv:1206.6710

Simulation Chain

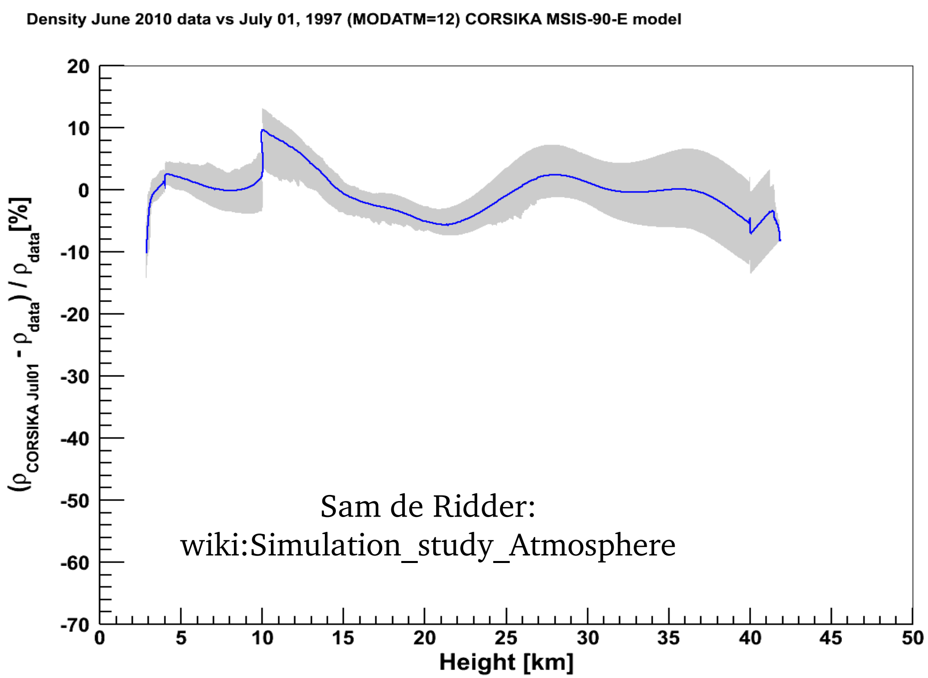
shaded: muon-specific



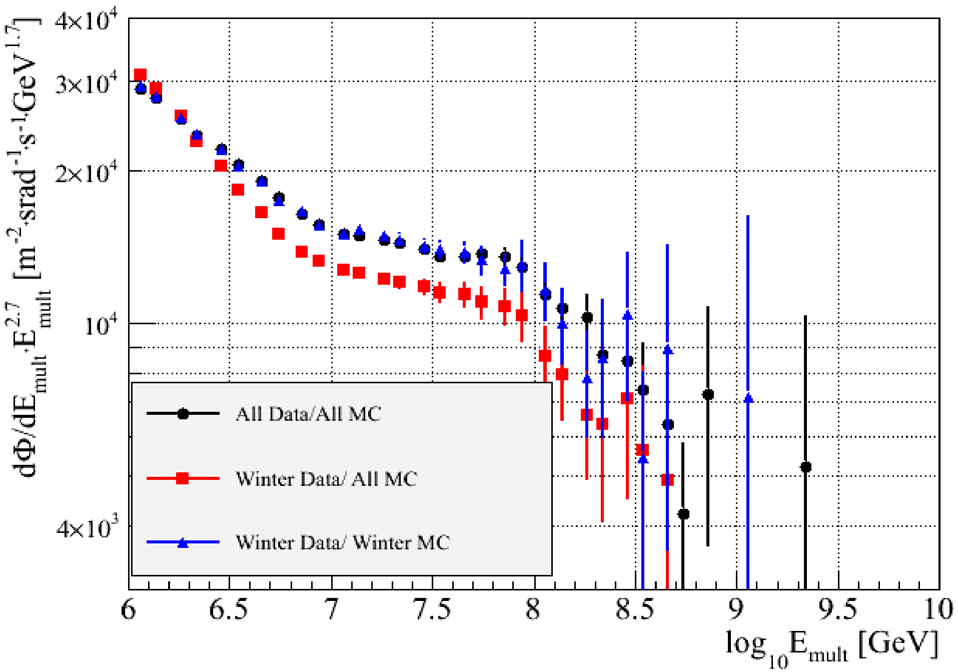
What causes the discrepancy?

CORSIKA
- atmosphere
- hadronic model
- π,K,nuc./nuc. cross section

Comparison CORSIKA atmosphere/ actual measurement

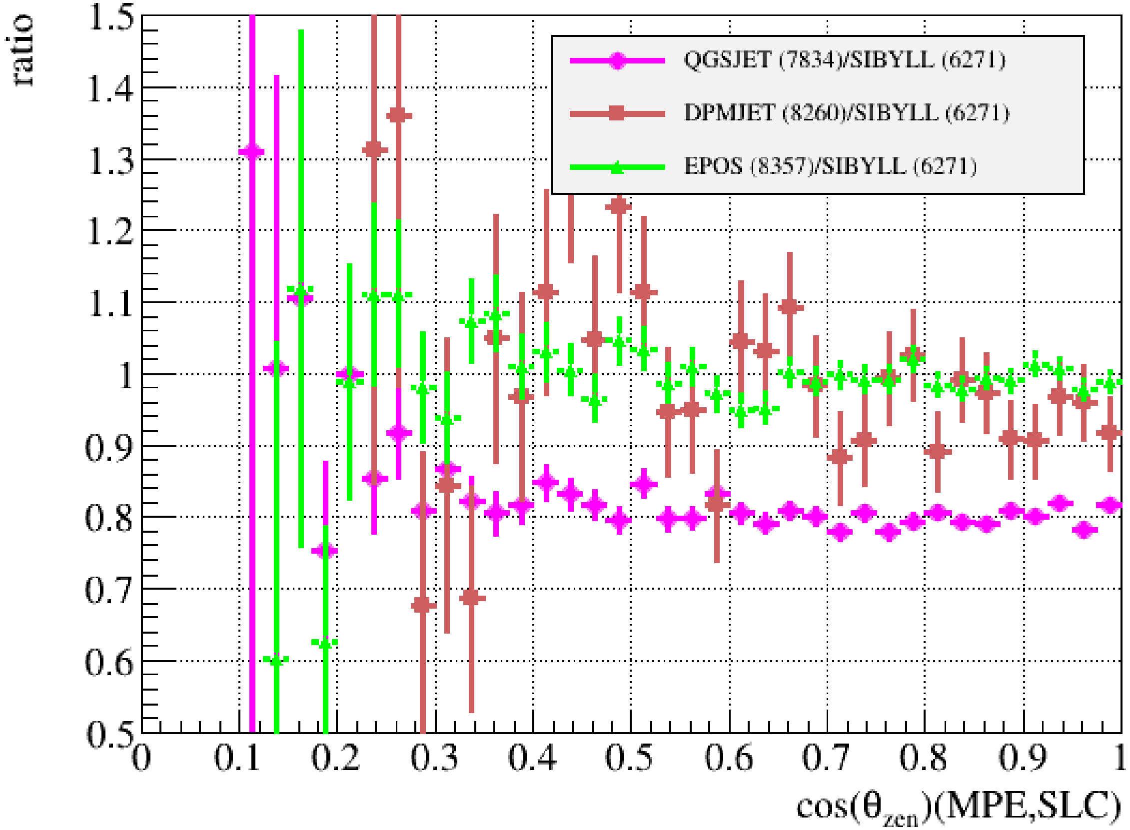


Seasonal variations in Bundle Unfolding



wiki:IC79_Atmospheric_Muons/Multiplicity_Unfolding#Seasonal_Effects

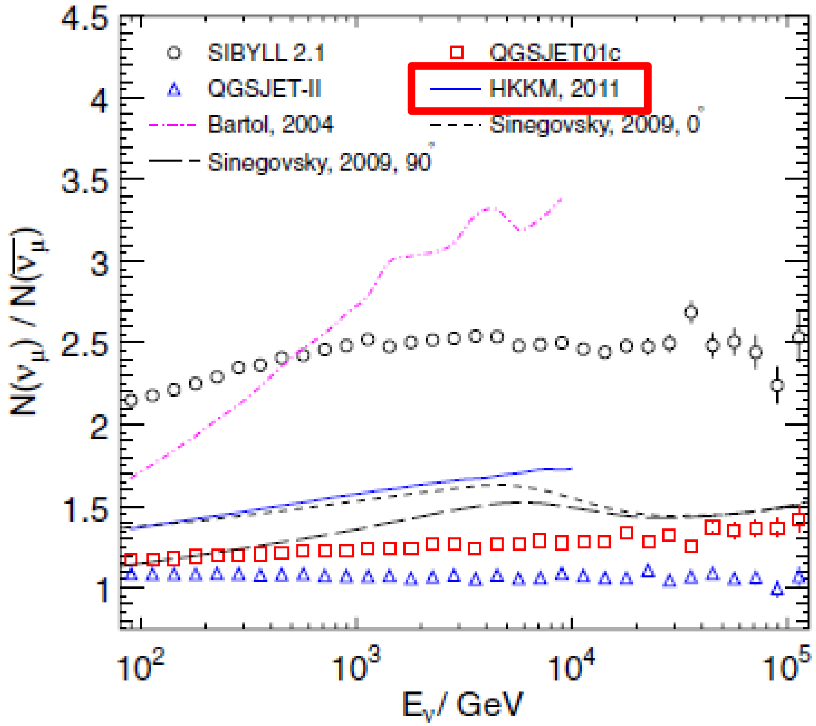
CORSIKA
- atmosphere
- hadronic model ←
- π,K,nuc./nuc. cross section



No variation seen in released models.
What about new LHC data-based versions?

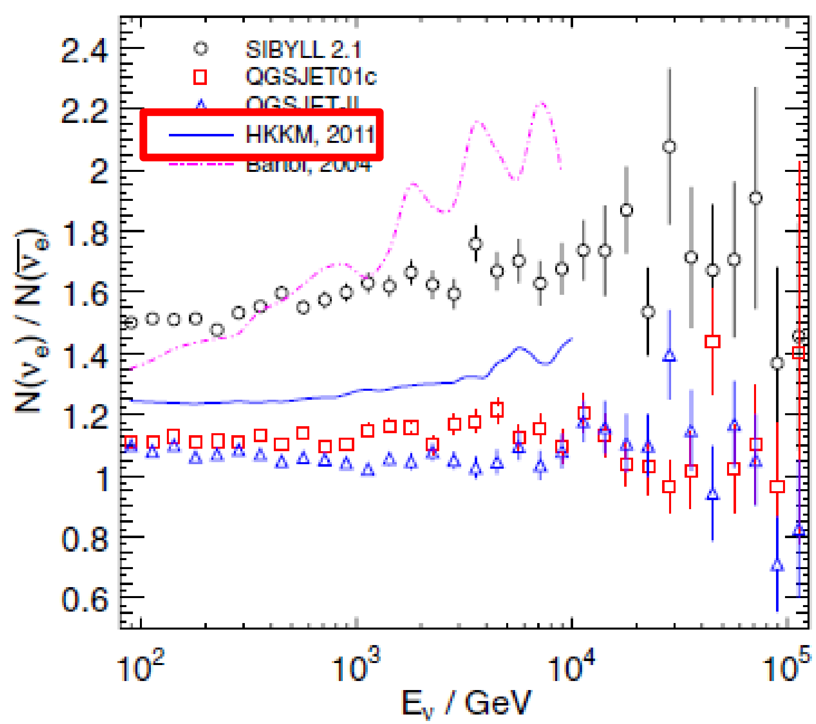
CORSIKA

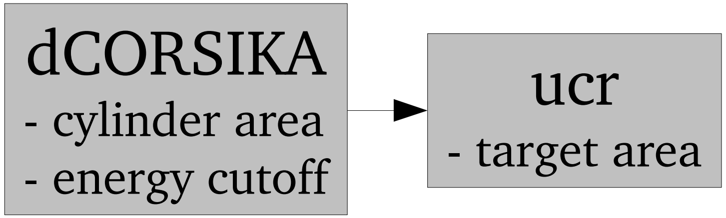
- atmosphere
- hadronic model
- π,K,nuc./nuc. cross section



HKKM: Updated “Honda Model” (DPMJET-based)

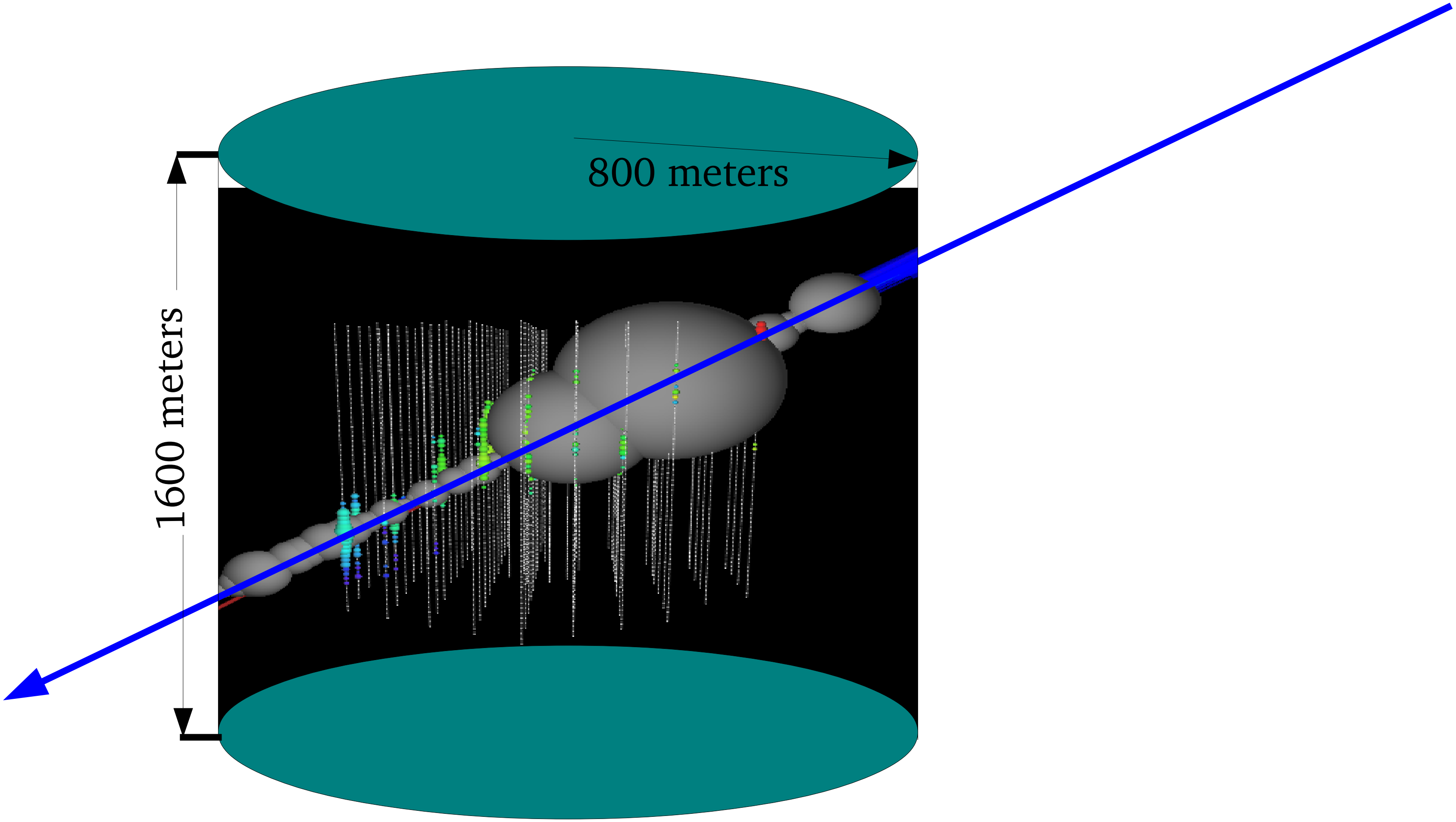
Bartol: “Bartol Model” (using proto-SIBYLL)





$$I \propto (d/2)^2 \cdot \pi \cdot sin\theta \cdot (cos\theta + 4/\pi \cdot l/d \cdot sin\theta)$$

Switch sin and cos – get 20% difference!
Would have been too easy...



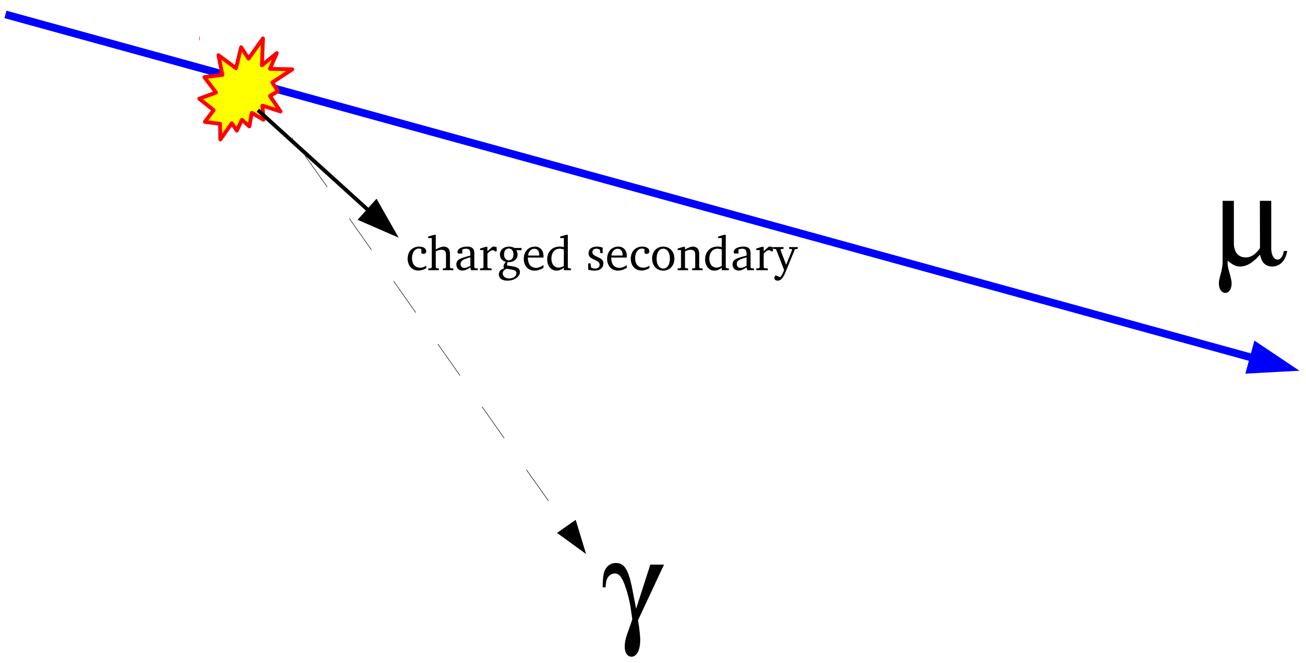
mmc/PROPOSAL
- cross sections

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

Class	Source of uncertainty	E^{-2}	E^{-3}	Atm.
1	Optical module timing resolution	$\pm 2\%$	$\pm 2\%$	$\pm 2\%$
	Optical module sensitivity	$^{+2}_{-9}\%$	$^{+5}_{-17}\%$	$^{+6}_{-19}\%$
2	Neutrino cross section and rock density	$\pm 8\%$	$\pm 3\%$	$\pm 3\%$
	Muon energy loss	$\pm 1\%$	$\pm 1\%$	$\pm 1\%$
3	Photon propagation in ice	$\pm 5\%$	$\pm 5\%$	$\pm 5\%$
	Reconstruction bias	$^{+0}_{-7}\%$	$^{+0}_{-8}\%$	$^{+0}_{-9}\%$
	Neutrino-muon scattering angle	$^{+0}_{-1}\%$	$^{+0}_{-8}\%$	$^{+0}_{-13}\%$
	Sum	$^{+10}_{-15}\%$	$^{+6}_{-21}\%$	$^{+7}_{-25}\%$

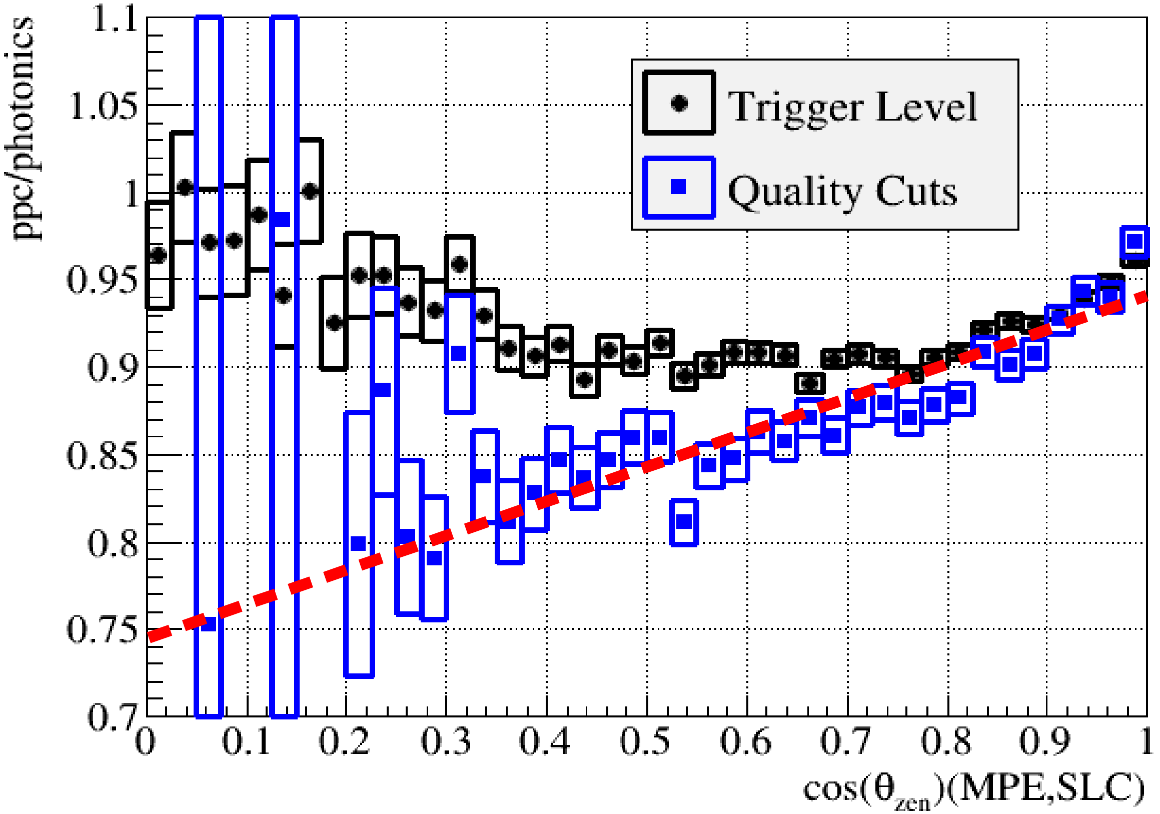
TABLE III: Summary of the systematic error in the measured rate of high energy muon neutrinos due to the three classes of systematic uncertainties, for different assumption on the energy spectrum.

photon generation
- none?



Could something go wrong here?

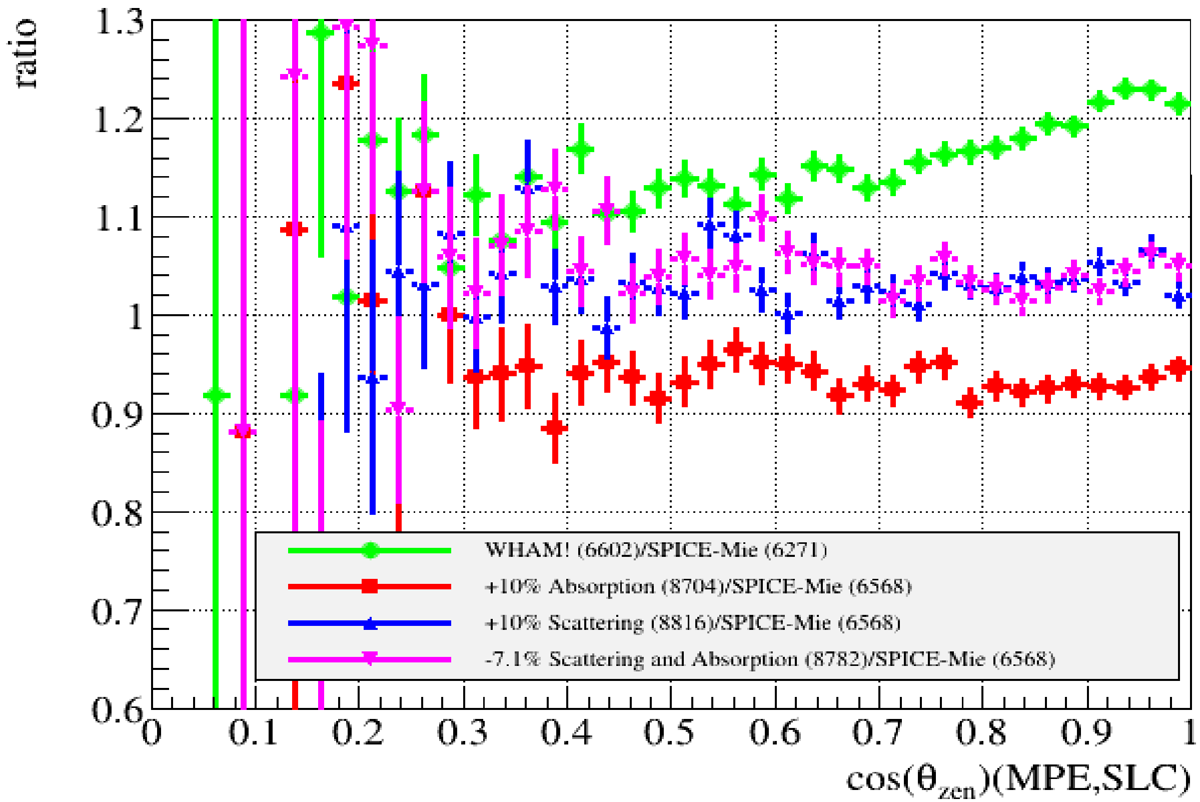
photon propagation
- bulk ice properties
- bulk ice anisotropy
- hole ice properties



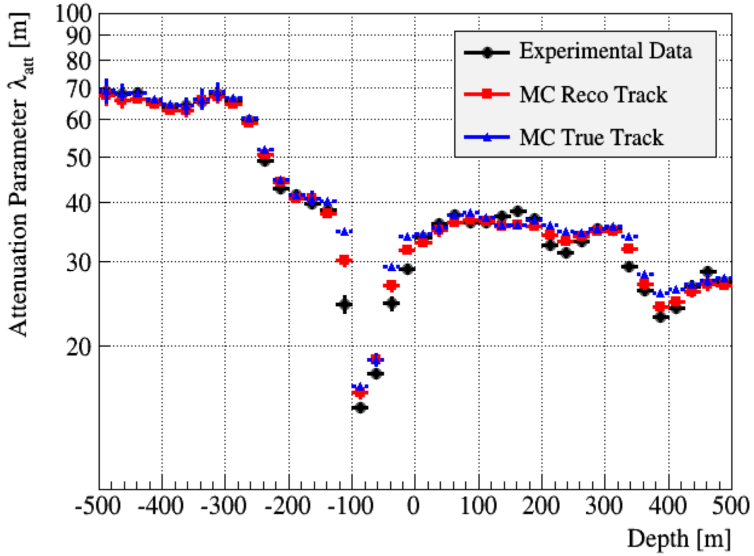
Photonics:

Only major influence on zenith angle ever seen in MC.

photon propagation
- bulk ice properties ←
- bulk ice anisotropy
- hole ice properties

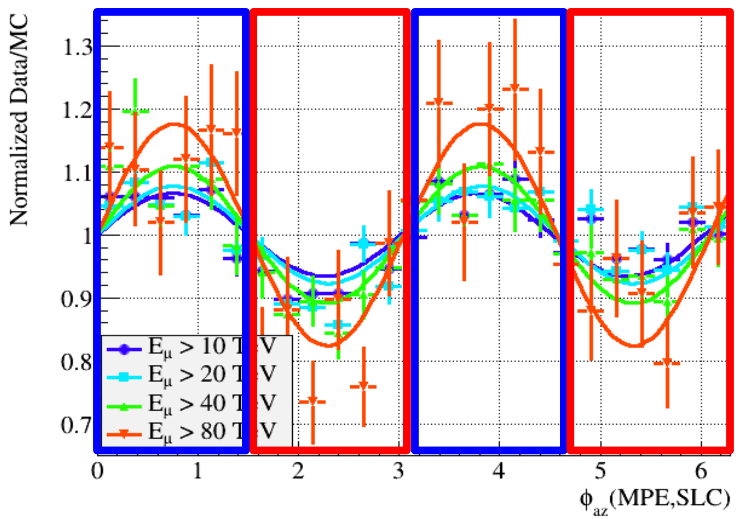


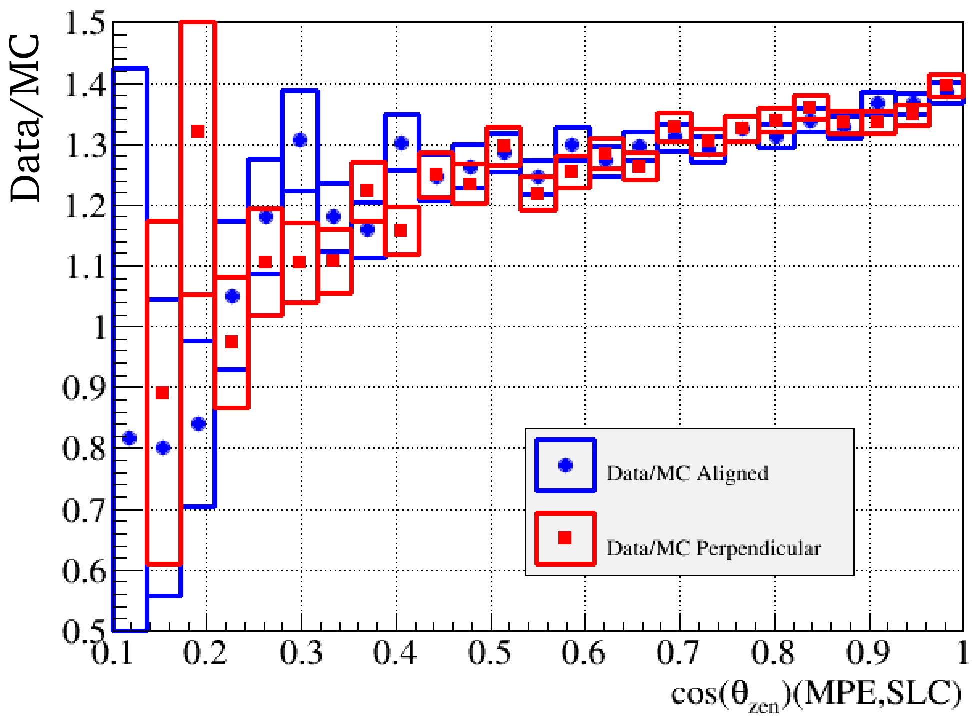
Some effect seen for large, non-uniform variation (WHAM!)



Lateral light attenuation fit (DDDDR)
MC: Spice Mie

photon propagation
- bulk ice properties
- bulk ice anisotropy
- hole ice properties



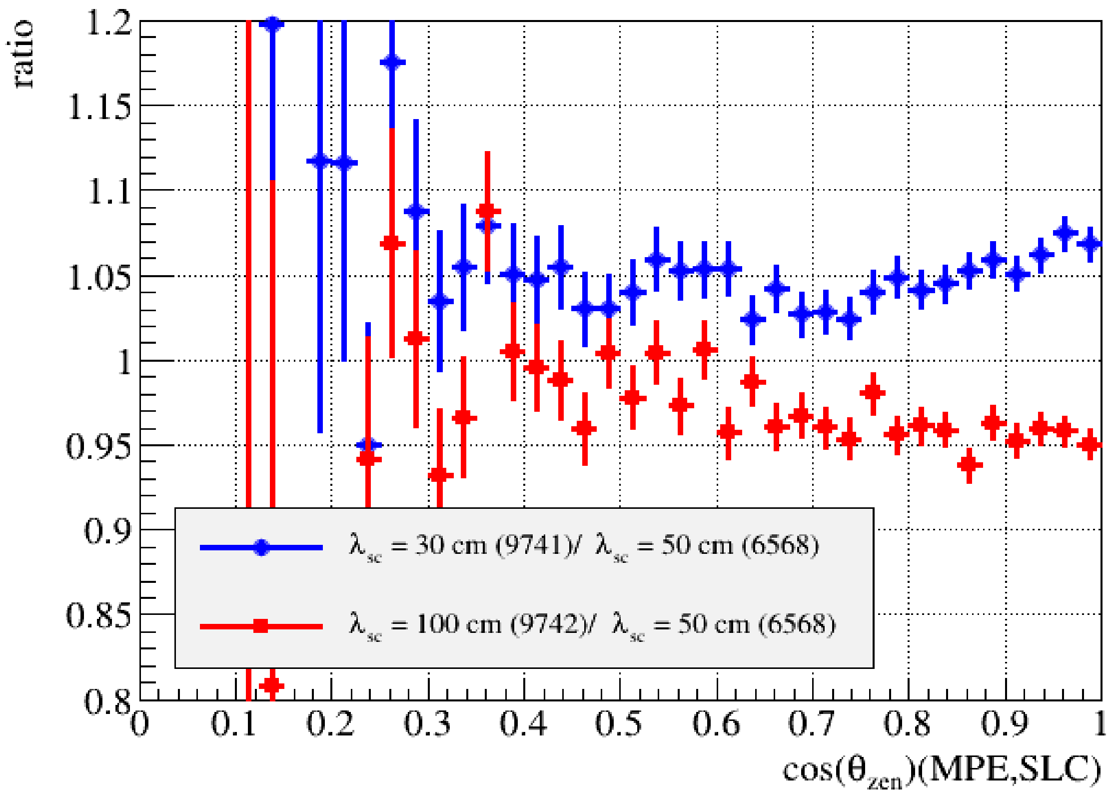


Anisotropy:
Small influence near horizon?
Should cancel out!

photon propagation

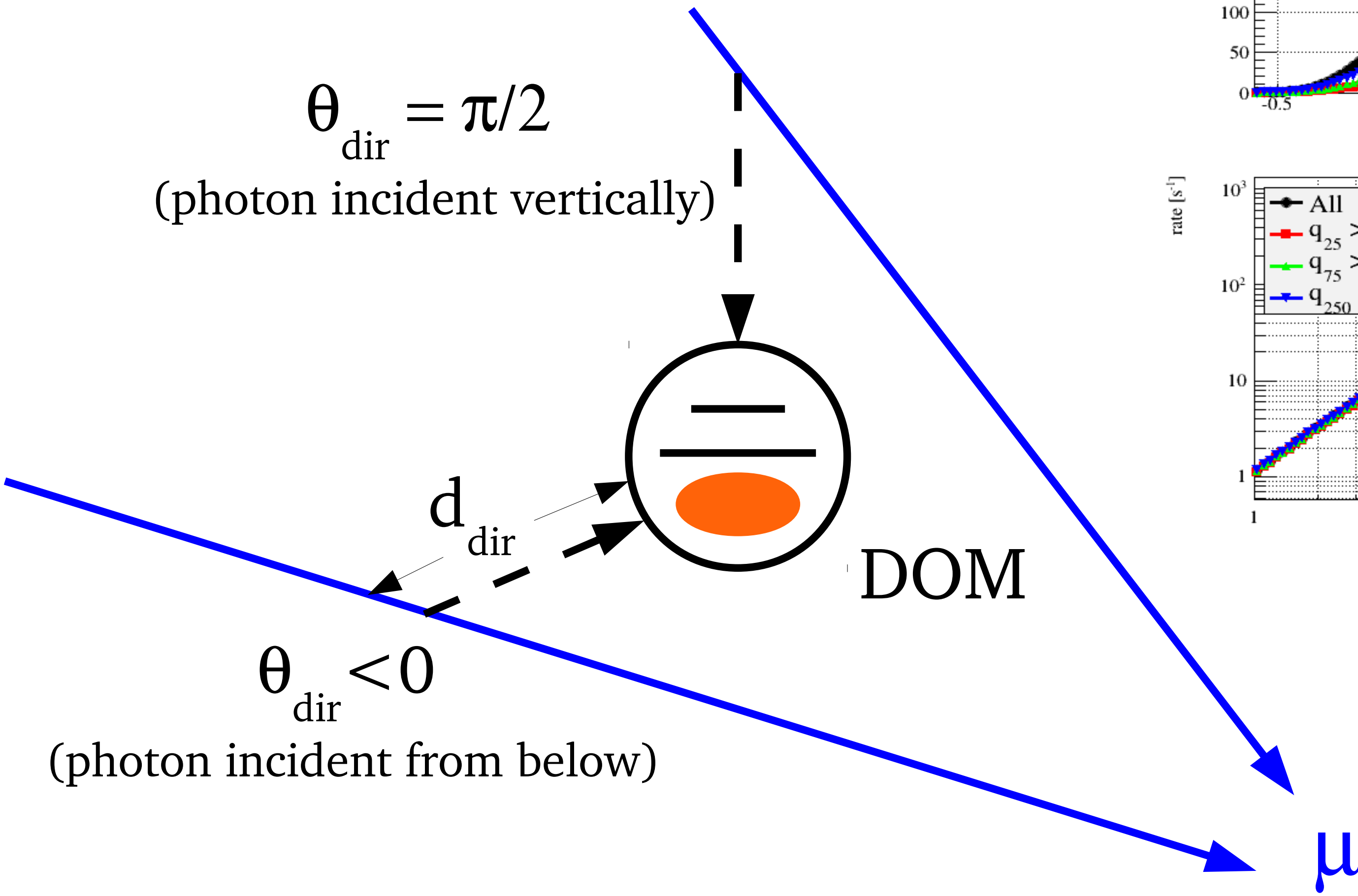
- bulk ice properties
- bulk ice anisotropy
- hole ice properties

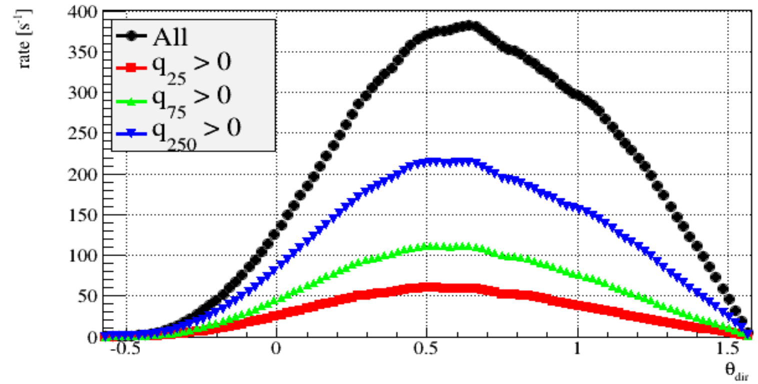
Hole ice scattering length variation (30cm/100cm)

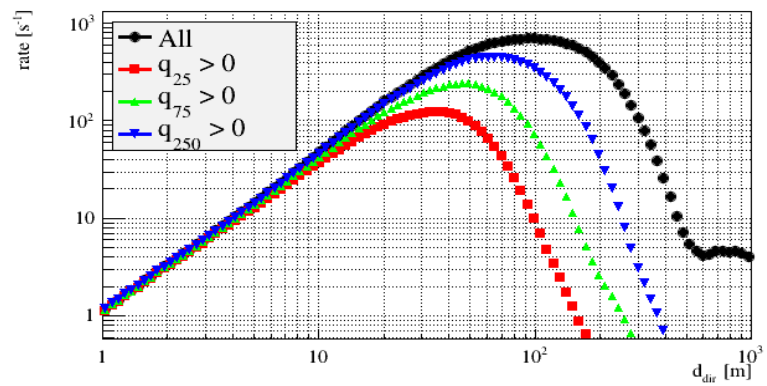


More detail in Dawn W.'s talk this afternoon!

Direct Hit Study







Time Windows:

-15 to +25 ns

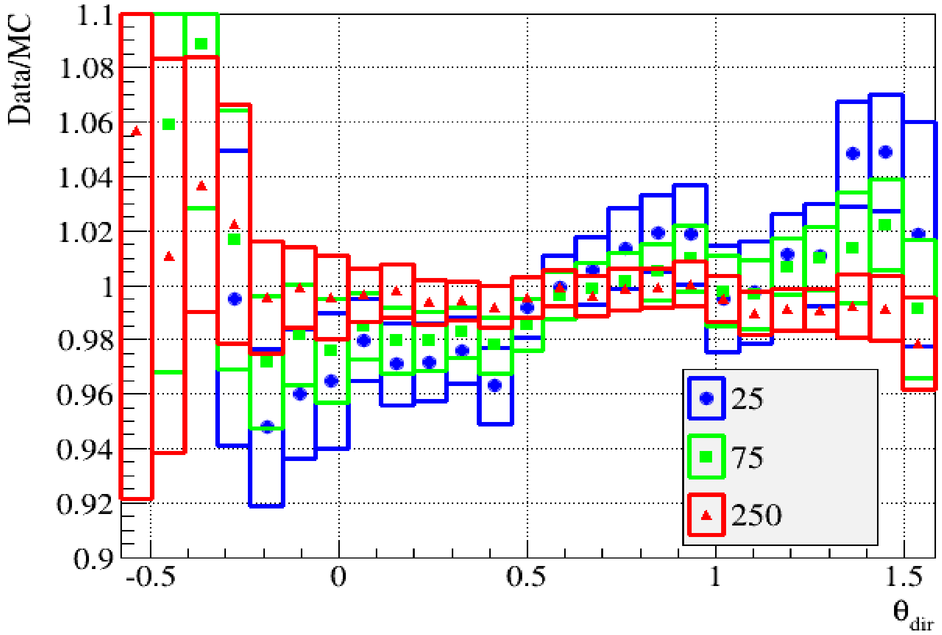
-15 to +75 ns

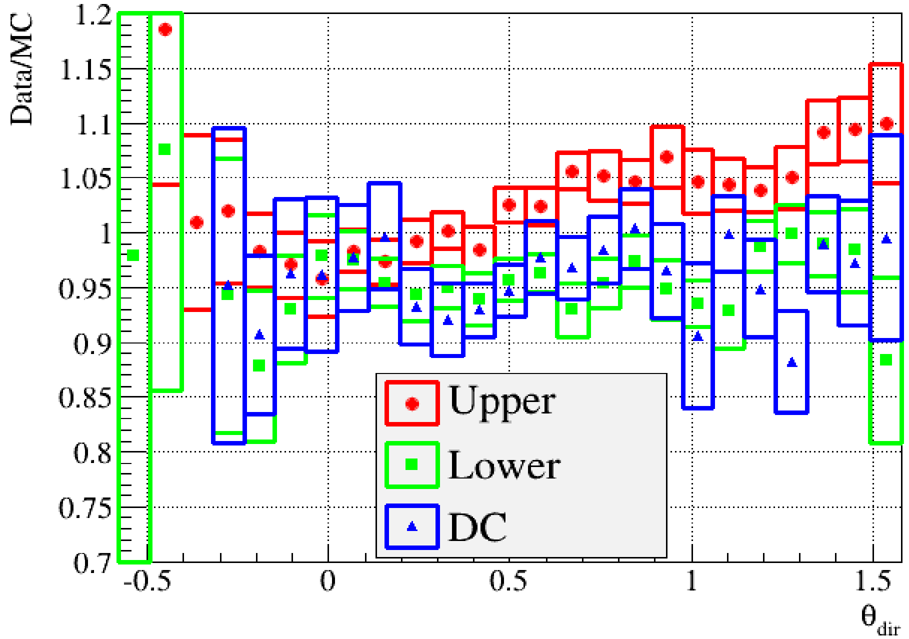
-15 to +250 ns

Investigate direct hits in dependence of photon incidence angle θ_{dir}

Goal: Probe angular-dependent DOM acceptance

https://docushare.icecube.wisc.edu/dsweb/Get/Document-69347/angular_mucall_033114.pdf



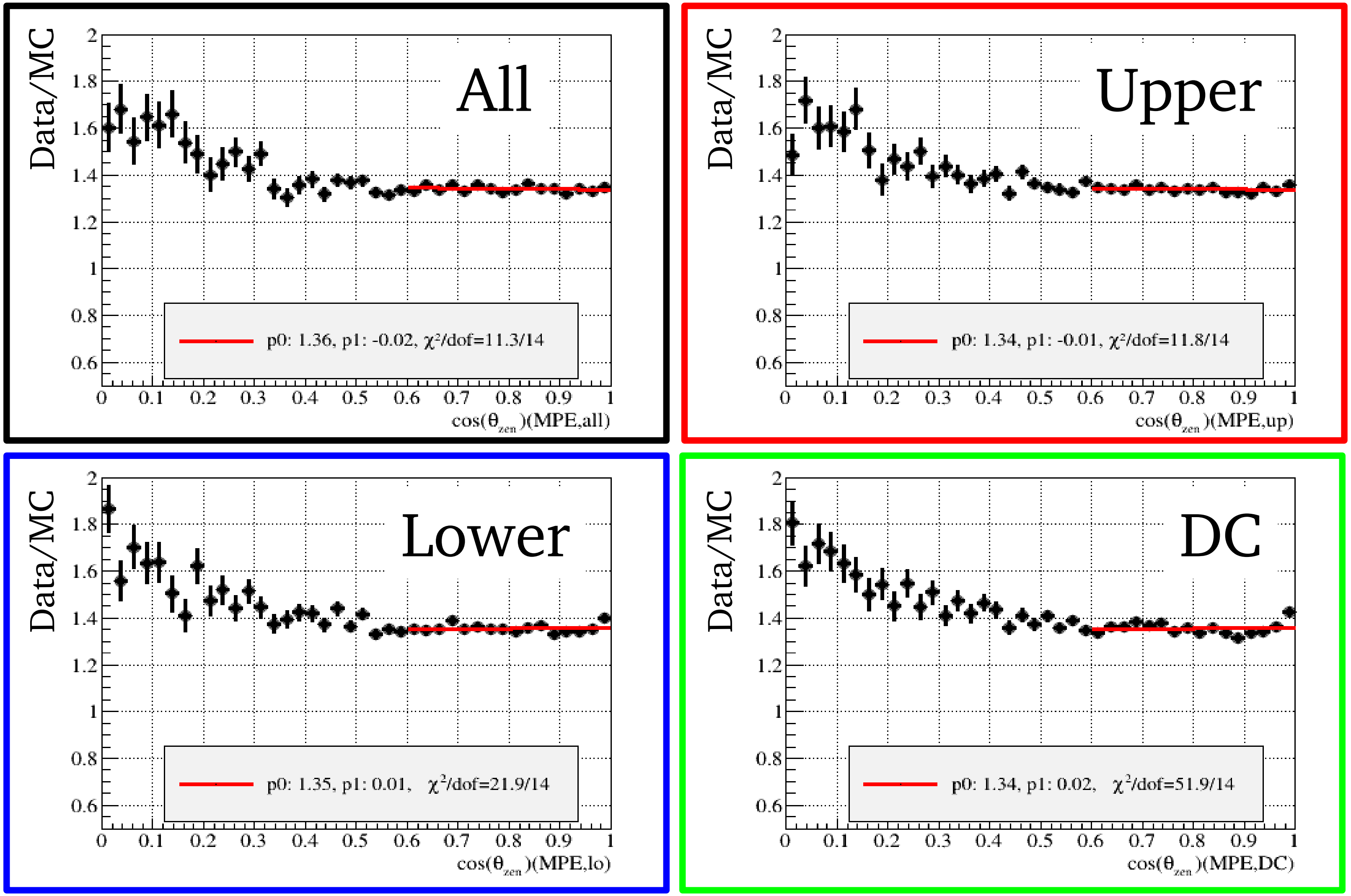


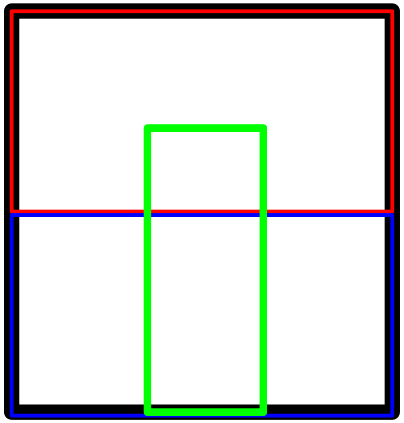
Direct Charge Fraction Data/MC

$(q_{dir,data}/q_{total,data})/(q_{dir,MC}/q_{total,MC})$

Data consistent with expectation for 250ns time window
Angular effect appears for unscattered hits
Stronger above dust layer

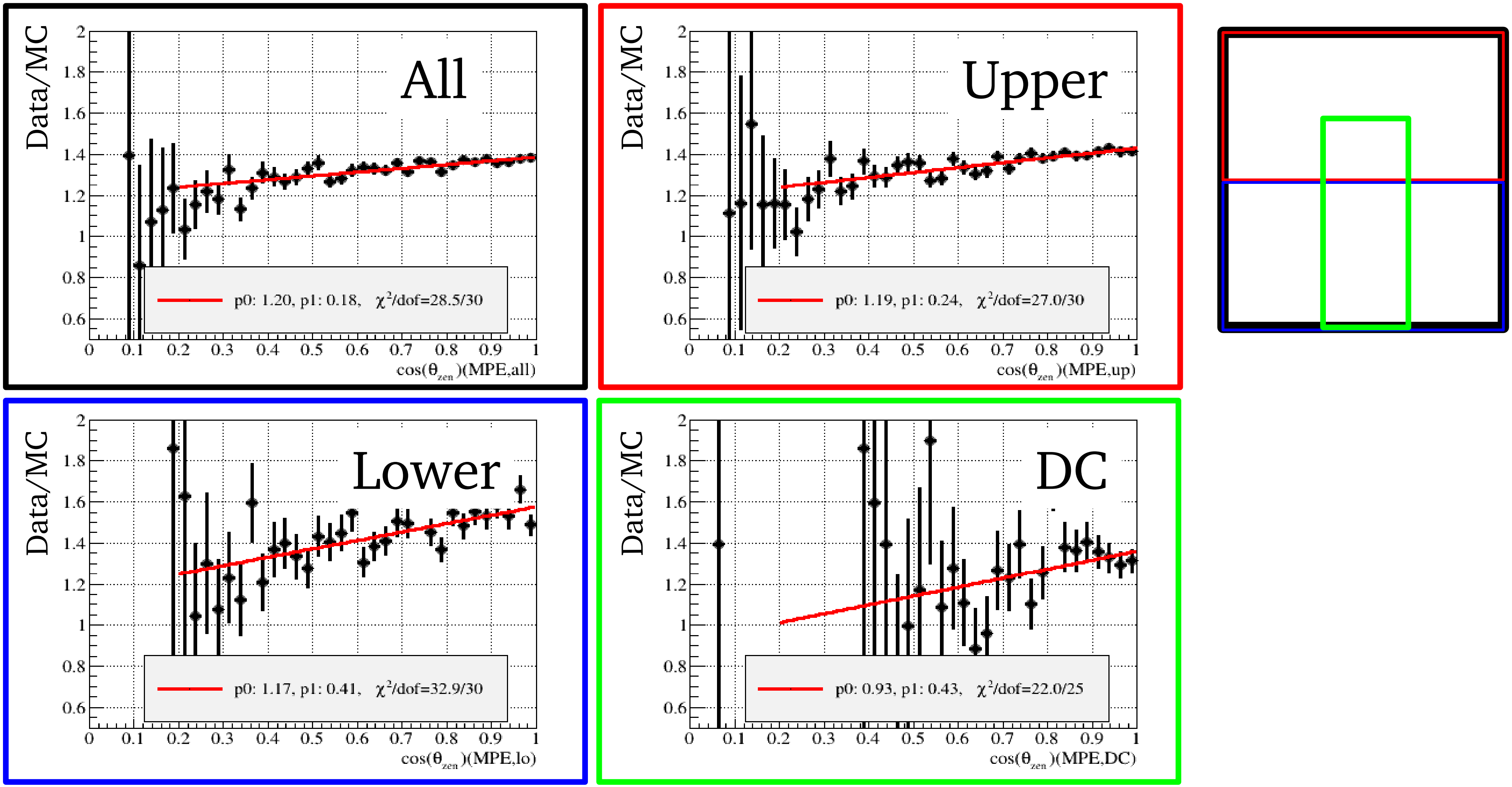
DOM Subset Reco: Trigger Level





Angular Distribution consistent with spectrum assumption (here:poly-gonato)
Excess near horizon due to rate^{Nprim}-scaling of coincident events

DOM Subset Reco: Quality Cuts



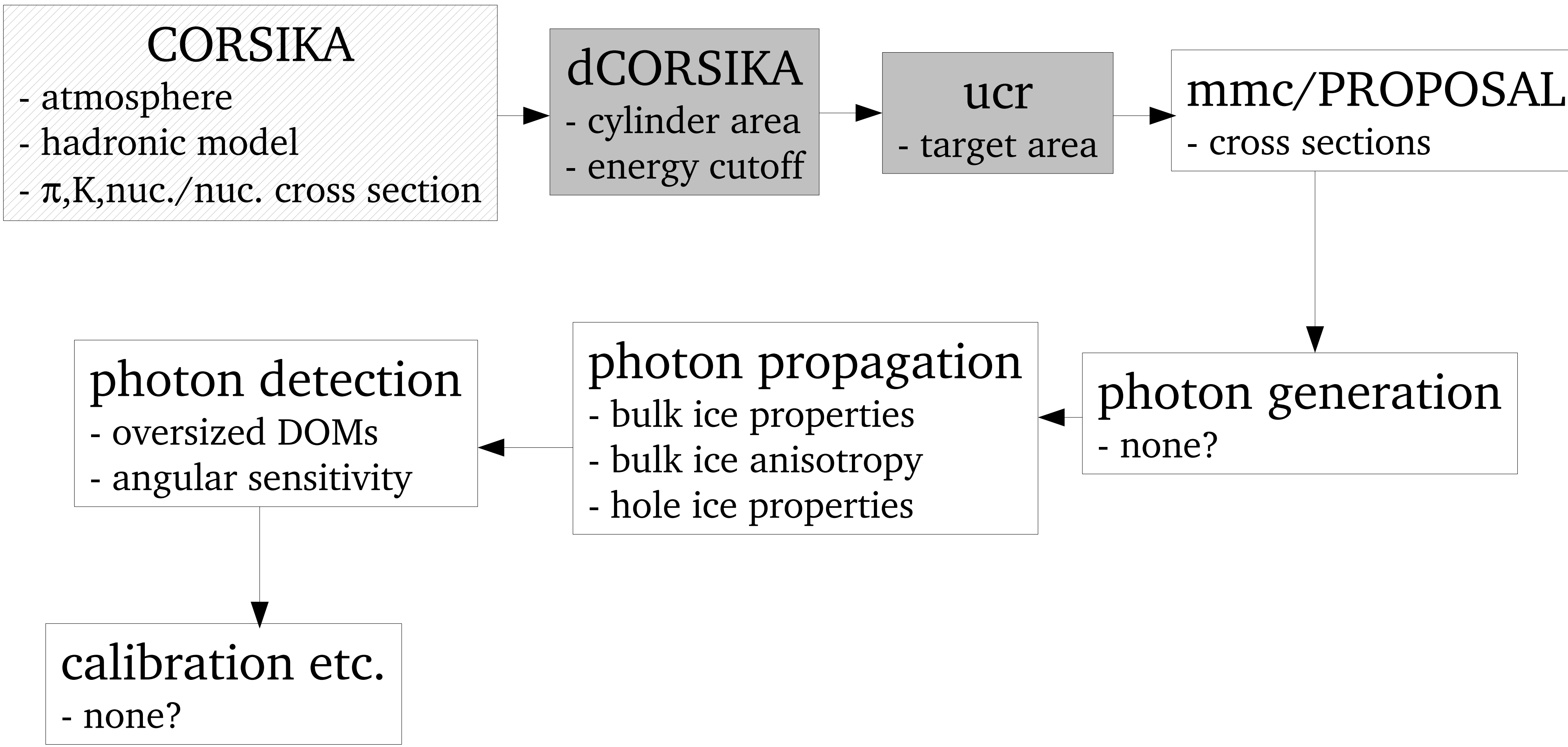
Quality cuts *always* lead to data/MC mismatch (checked: L_{dir}, rlogl, $\Psi_{LF,llh}$)

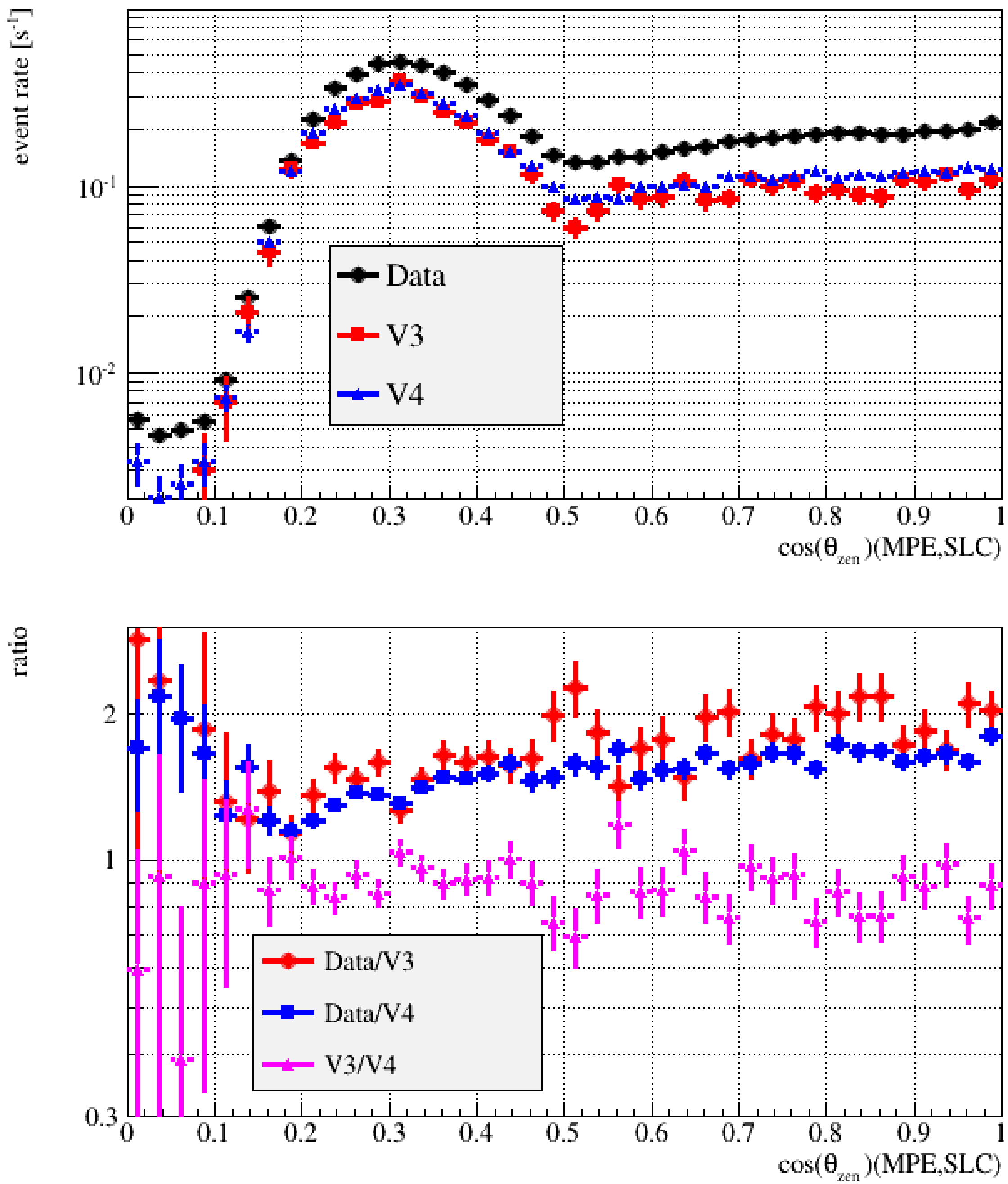
Size of effect depends on cut strength – no trivial comparison between subsets

photon detection
- oversized DOMs
- angular sensitivity

shaded:
muon-specific

Simulation Chain

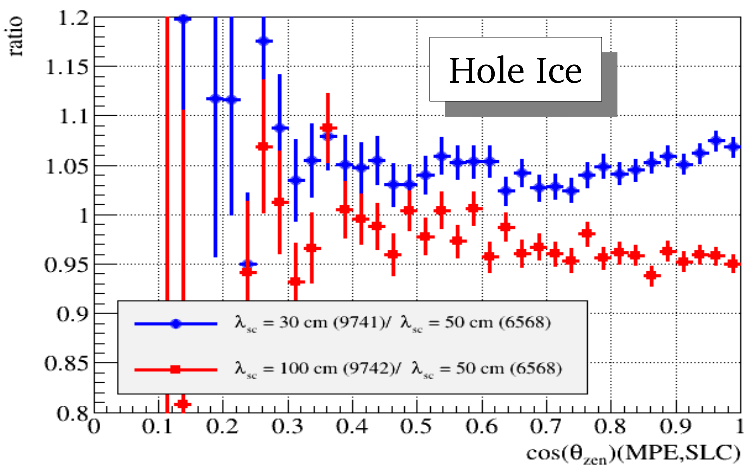


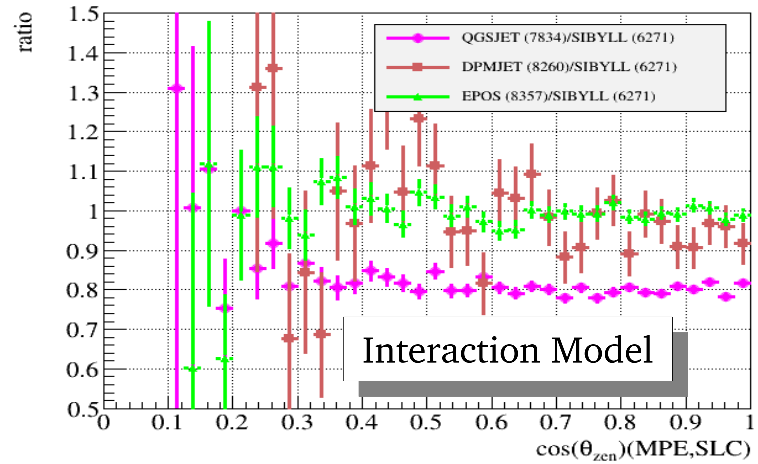


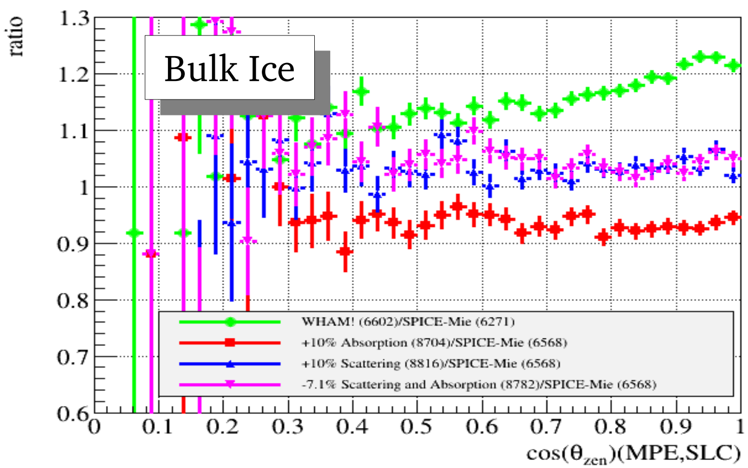
event rate [s^-1]
10^-1
10^-2
Data
V3
V4
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
cos(θ_zen)(MPE,SLC)
ratio
2
1
0.3
Data/V3
Data/V4
V3/V4
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
cos(θ_zen)(MPE,SLC)

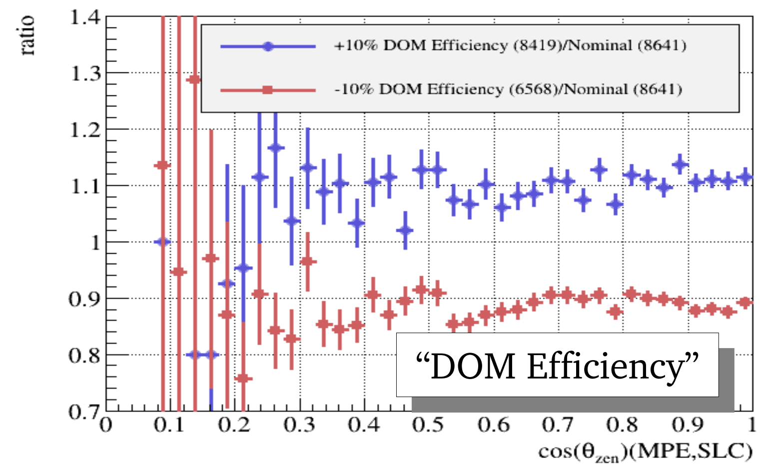
v3 vs. v4

MinBias Angular Distribution Systematics





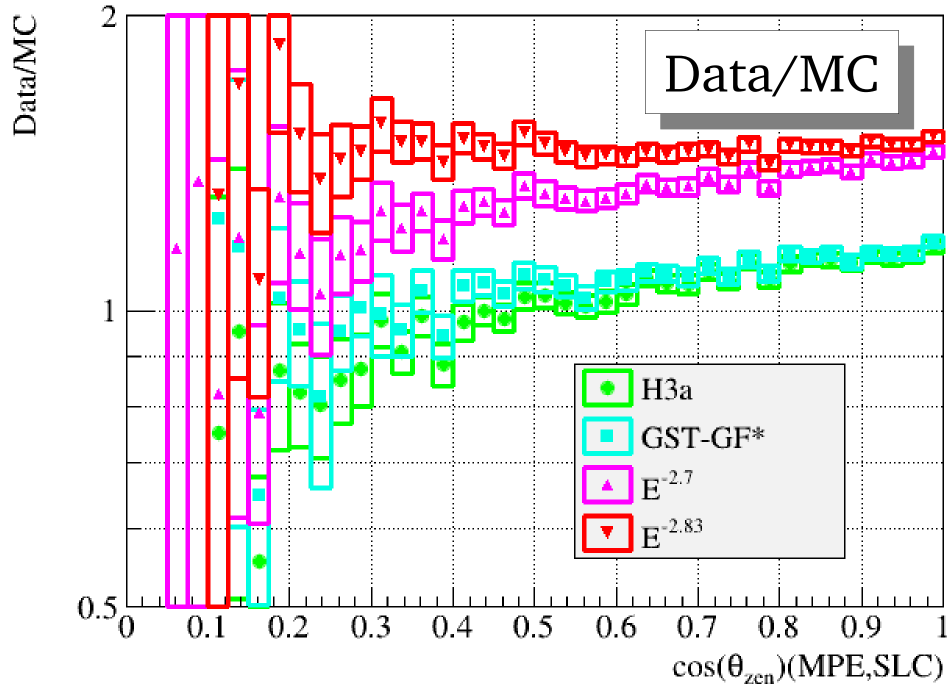


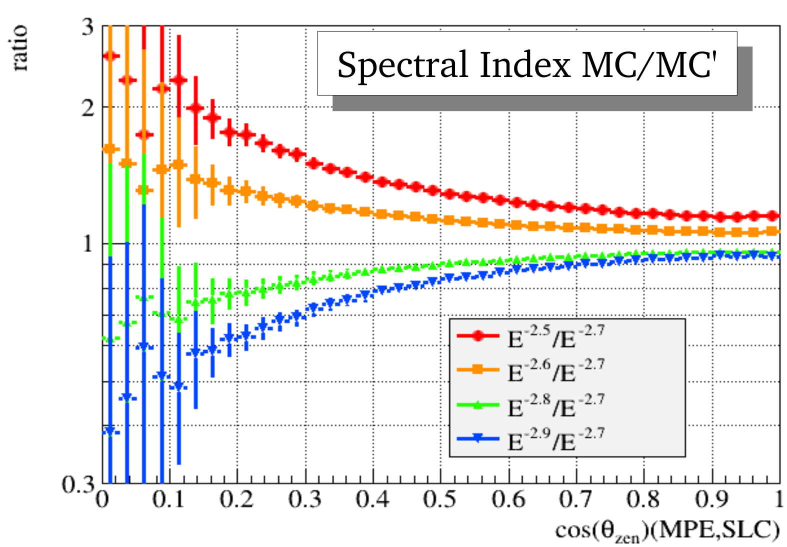


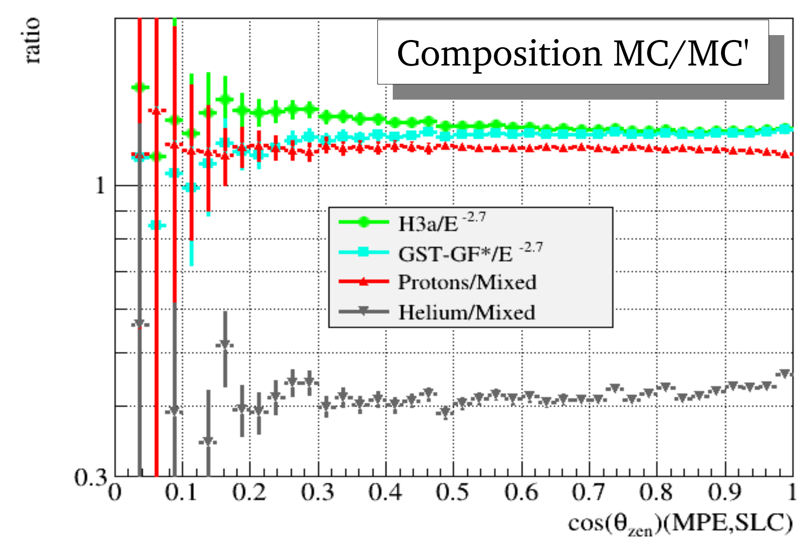
Slope of ratio is (almost) unaffected by systematics

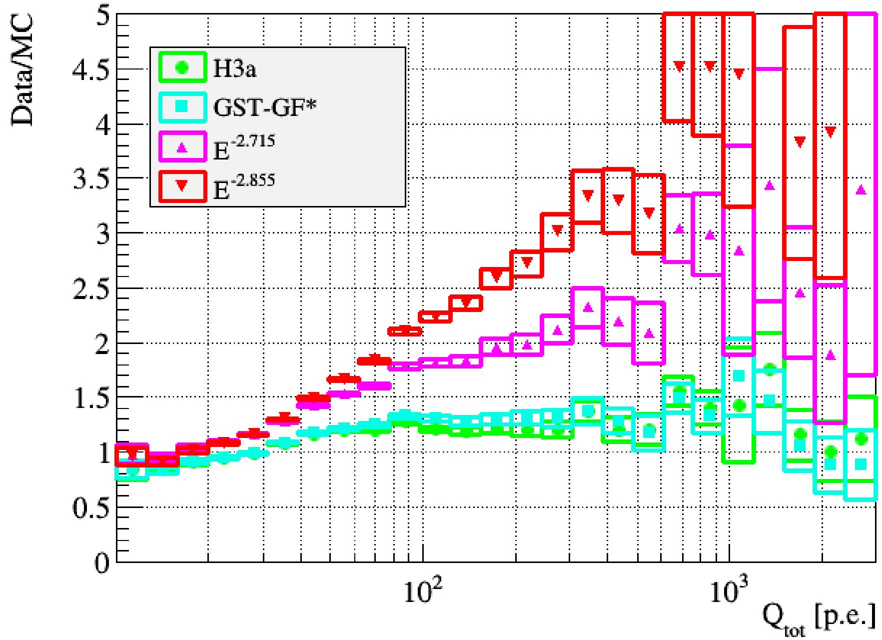
All Ratios are MC/MC'

Zenith Angle Distribution corresponds to $E^{-2.83}$ primary spectrum.



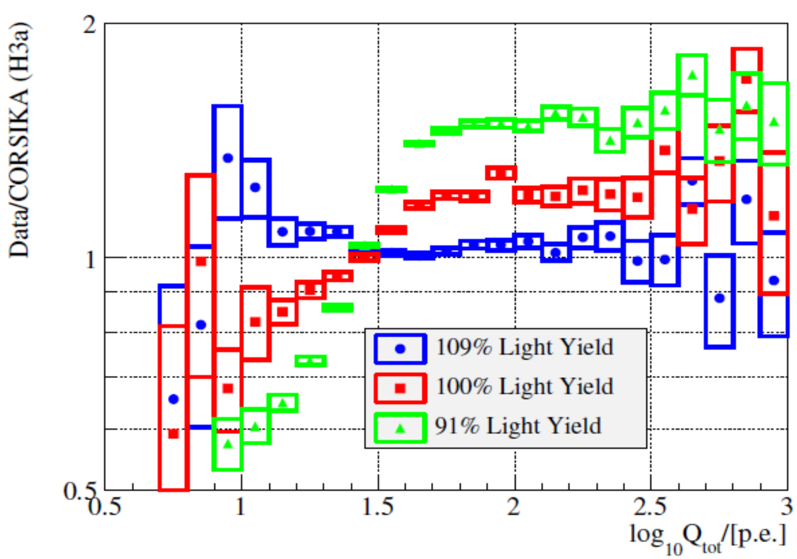






$E^{-2.855}$ Primary Flux strongly disagrees with data:

Zenith angle and charge distributions are not reconcilable!



Light Yield ("Optical Efficiency"):
Consistent with numu diffuse fit!
(here: IC86 = 100%)