PDF version, 2 illustrations removed which caused trouble
Greek symbols nu □ mu □ pi □ and Delta □ lost in PDF conversion

Atmospheric Neutrino Fluxes

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Synopsis

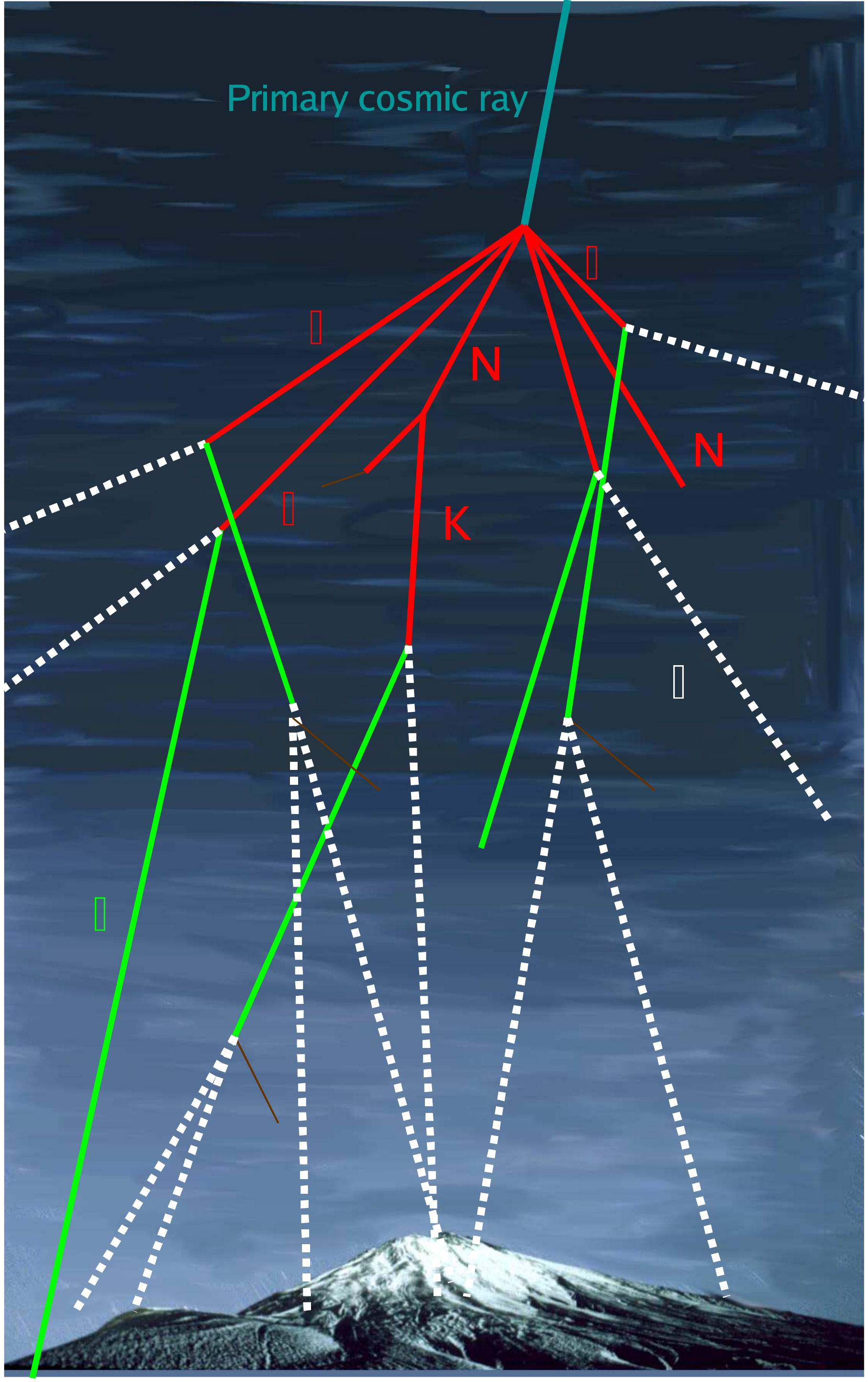
Section 1: Features of atmospheric neutrino fluxes

- Cosmic ray cascades
- 3D effects
- Fluxes, flux ratios

Section 2: Systematics

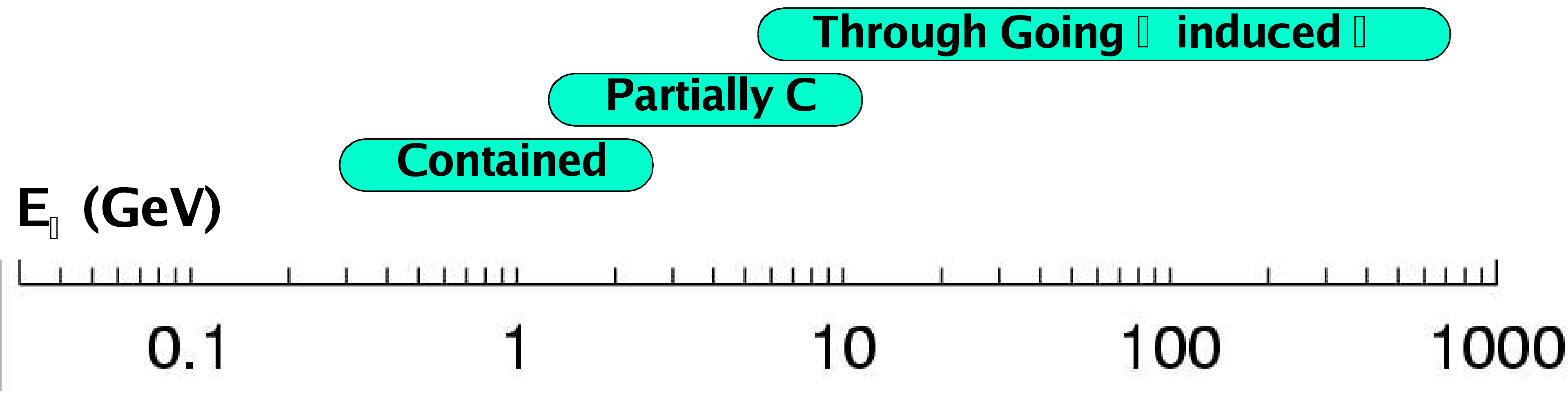
- Primary fluxes
- Hadron production
- Other effects

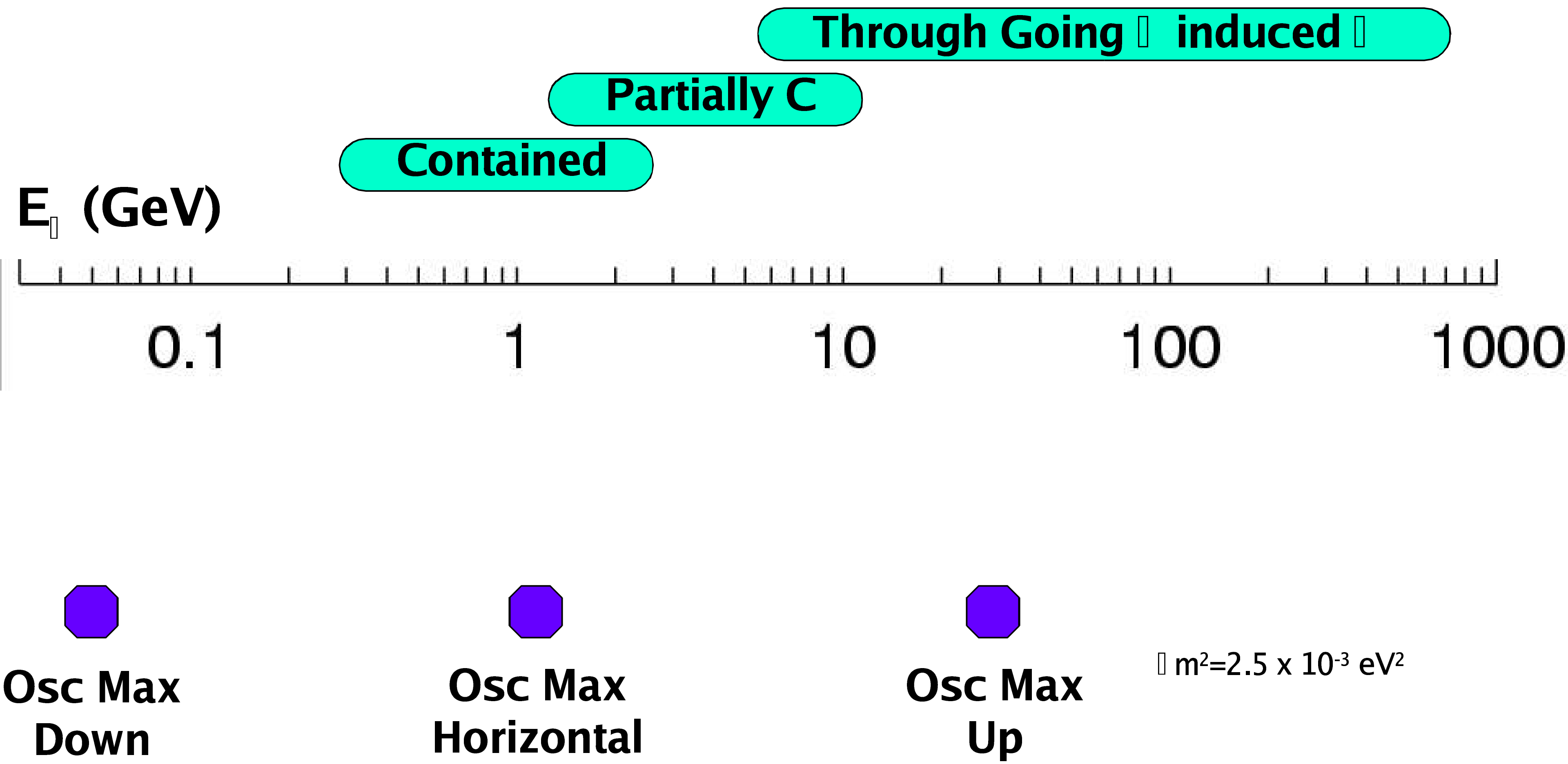
Section 1: Features of Atmospheric neutrino fluxes

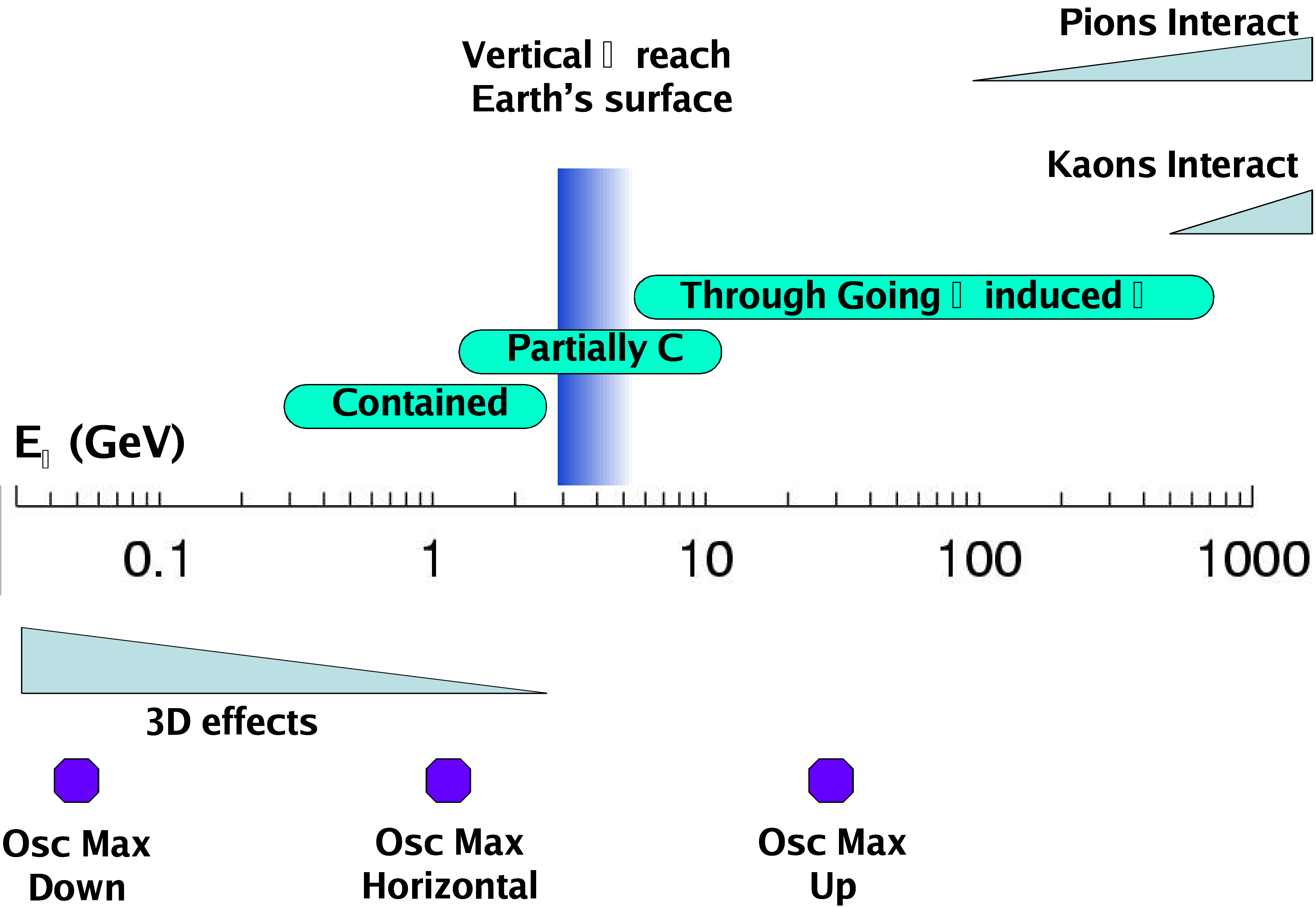


Neutrinos produced from a shower

- Primary cosmic ray: proton or heavier nucleus
- Interacts in ~90g/cm^2
- Atmosphere depth 1050 g/cm^2
- Cascade
- Most hadrons don’t reach ground.


Through Going induced
Partially C
Contained
E (GeV)
0.1
1
10
100
1000

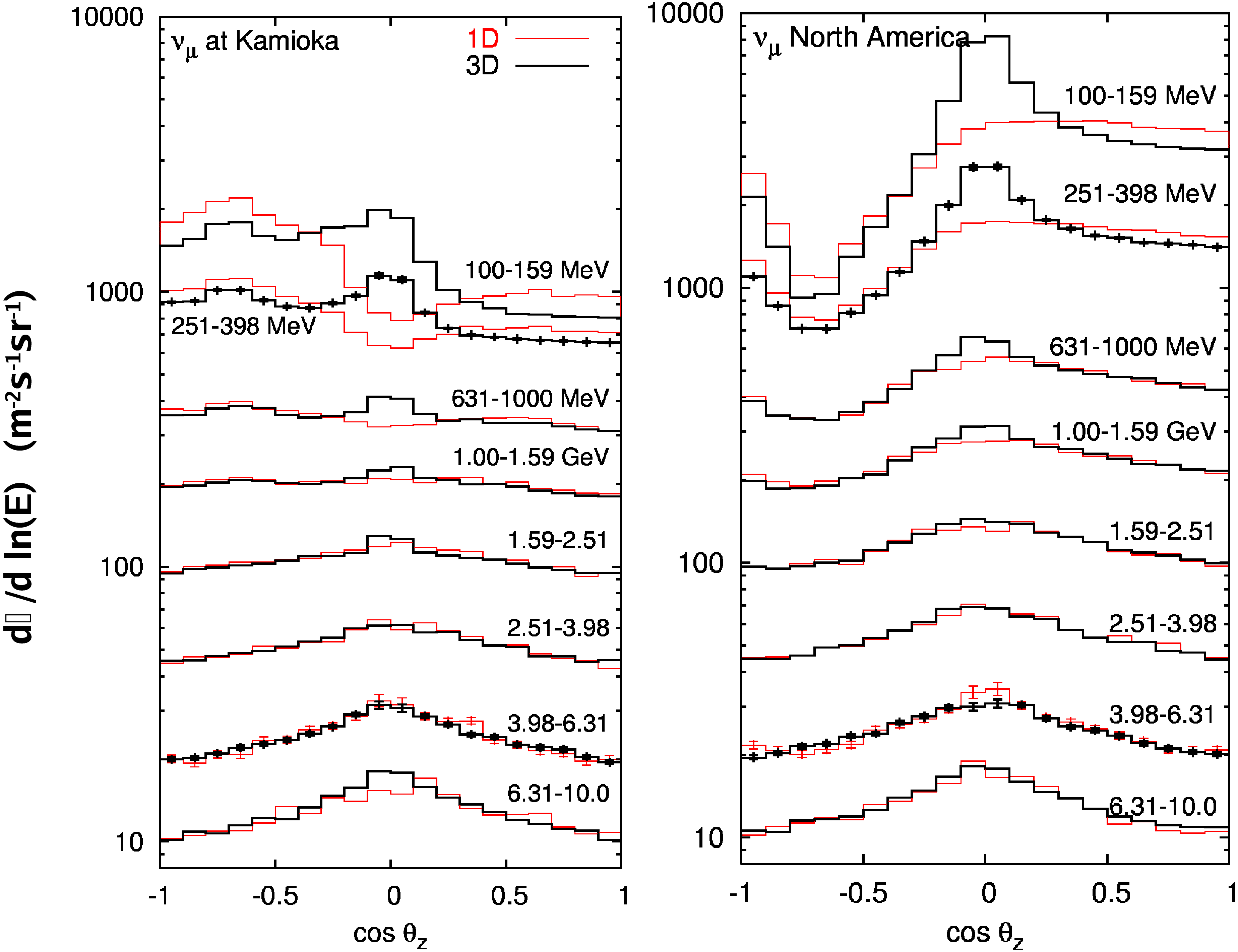

Through Going induced
Partially C
Contained
E (GeV)
0.1
1
10
100
1000
Osc Max Down
Osc Max Horizontal
Osc Max Up
$m^2=2.5 \times 10^{-3}$ eV^2



Pions Interact
Vertical reach
Earth's surface
Kaons Interact
Through Going induced
Partially C
Contained
E (GeV)
0.1
1
10
100
1000
3D effects
Osc Max
Down
Osc Max
Horizontal
Osc Max
Up

Summary of Atmospheric Neutrino Calculations

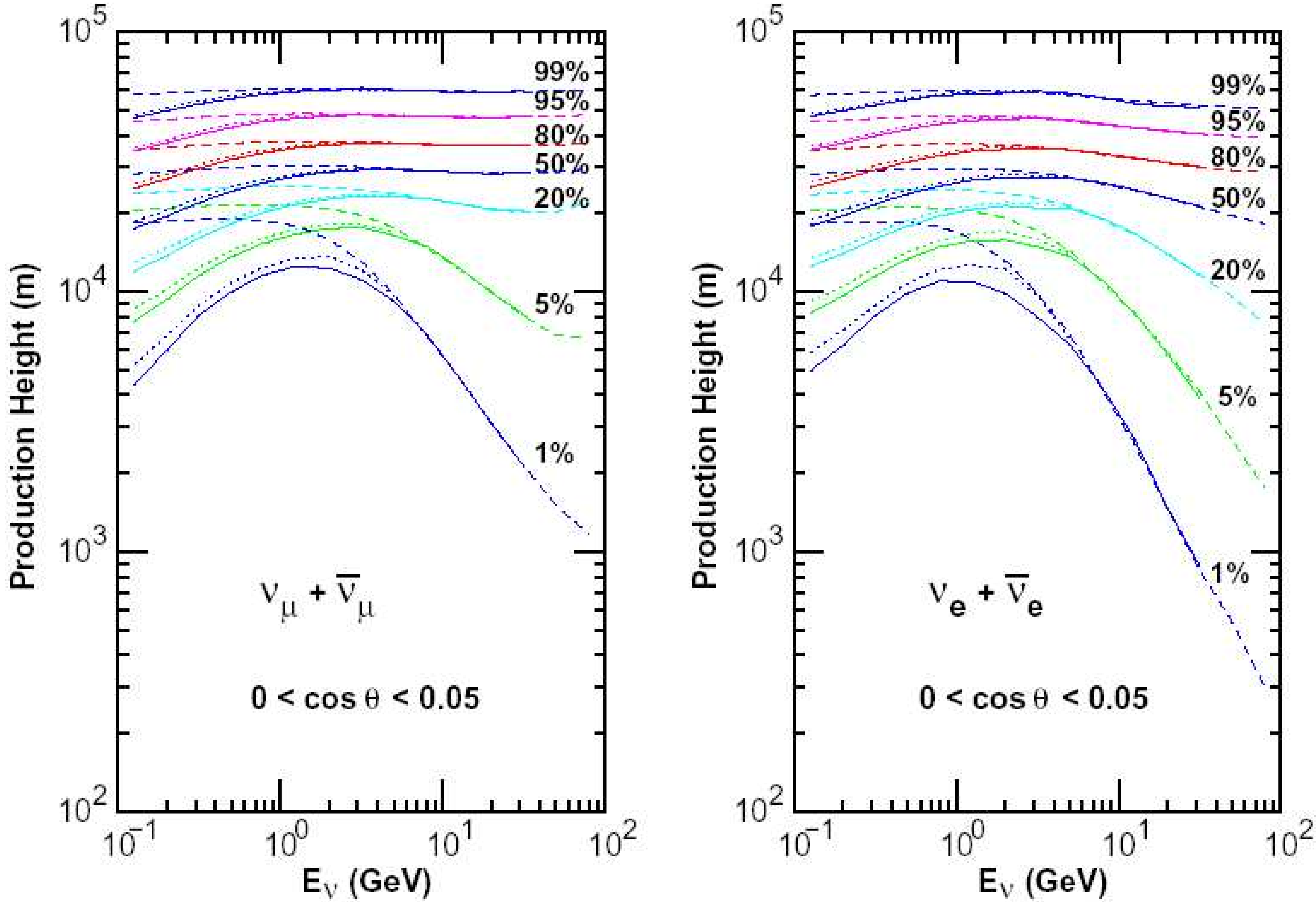
Zatsepin, Kuz'min	SP JETP 14:1294(1961)	1D		
E. V. Bugaev and V. A. Naumov,	PL B232:391 (1989)	1D		
Agrawal, Gaisser, Lipari, Stanev	PRD 53:1314 (1996)	1D		Target
D. Perkins	Asp.Phys. 2:249 (1994)	Mu		
Honda, Kajita, Kasahara, Midorikawa	PRD 52:4985 (1995)	1D		FRITIOF
Battistoni et al	Asp.Phys 12:315 (2000) Asp.Phys 19:269 (2003)	3D		FLUKA
P. Lipari	Asp.Phys 14:171 (2000)	3D		
V. Plyaskin	PL B516:213 (2001) hep-ph/0303146	3D		GHEISHA
Tserkovnyak et al	Asp.Phys 18:449 (2003)	3D		CALOR-FRITIOF GFLUKA/GHEISHA
Wentz et al	PRD 67 073020 (2003)	3D		Corsika: DPMJET VENUS, UrQMD
Liu, Derome, Buénerd	PRD 67 073022 (2003)	3D		
Favier, Kossalsowski, Vialle	PRD 68 093006 (2003)	3D		GFLUKA
Barr, Gaisser, Lipari, Robbins, Stanev	PRD (July 2004)	3D		Target
Honda, Kajita, Kasahara, Midorikawa	PRD 64 053011 (2001) PRD submitted (2004)	3D		DPMJET



νμ at Kamioka
1D
3D
100-159 MeV
251-398 MeV
631-1000 MeV
1.00-1.59 GeV
1.59-2.51
2.51-3.98
3.98-6.31
6.31-10.0
νμ North America
cos θz
dΦ /d ln(E) (m-2s-1sr-1)
10000
1000
100
10
-1
-0.5
0
0.5
1

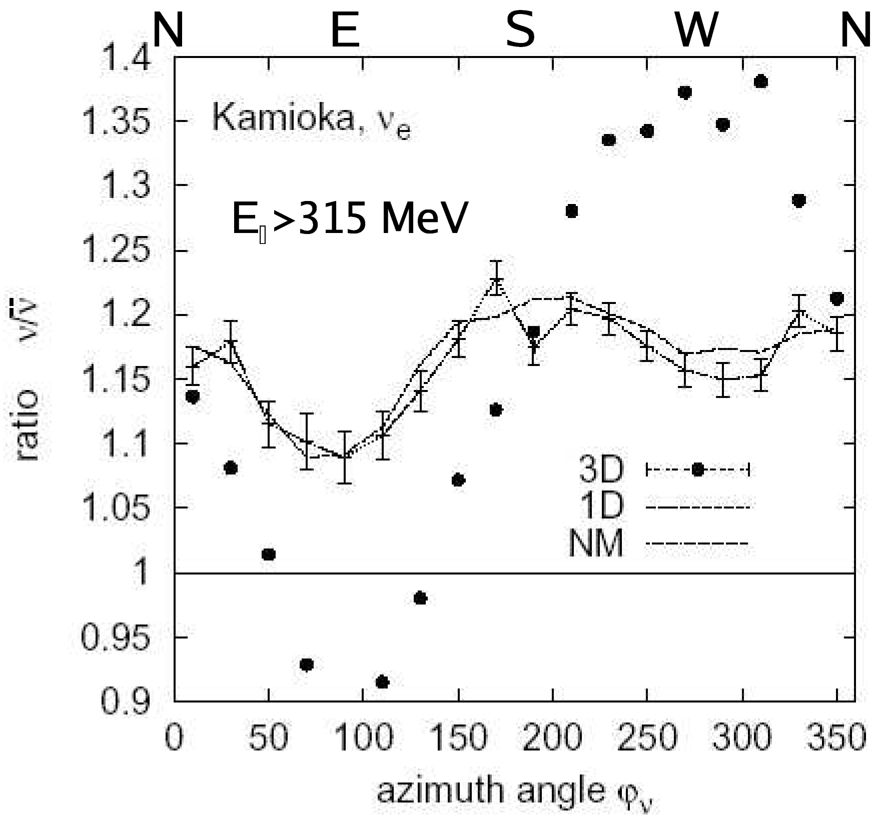
Path length distributions

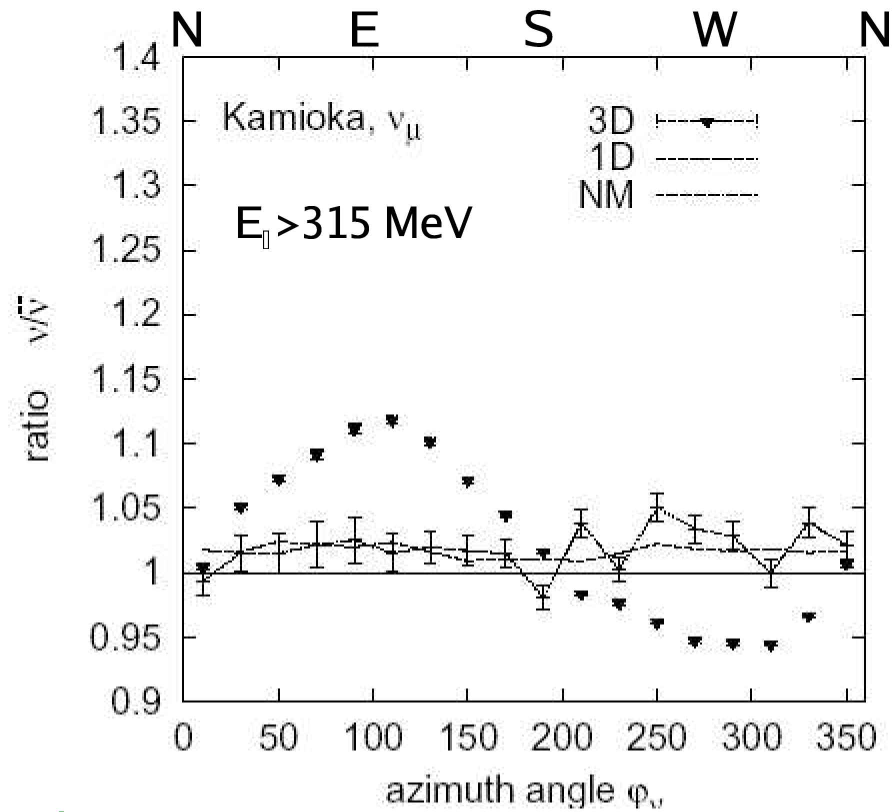
From Honda et. al. astro-ph/040445
Solid 3D at Kamioka, Dashed 1D at Kamioka, Dot 3D at Soudan

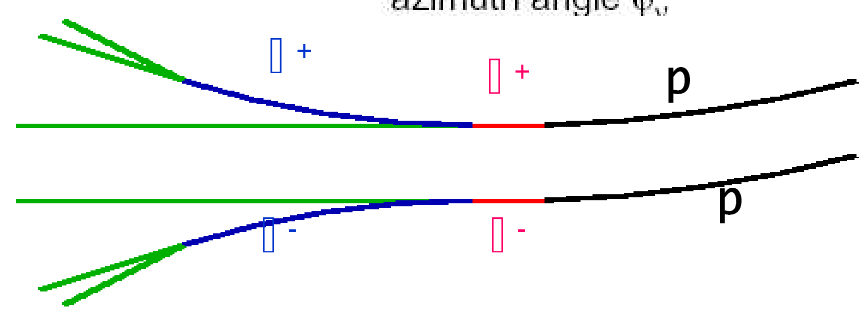


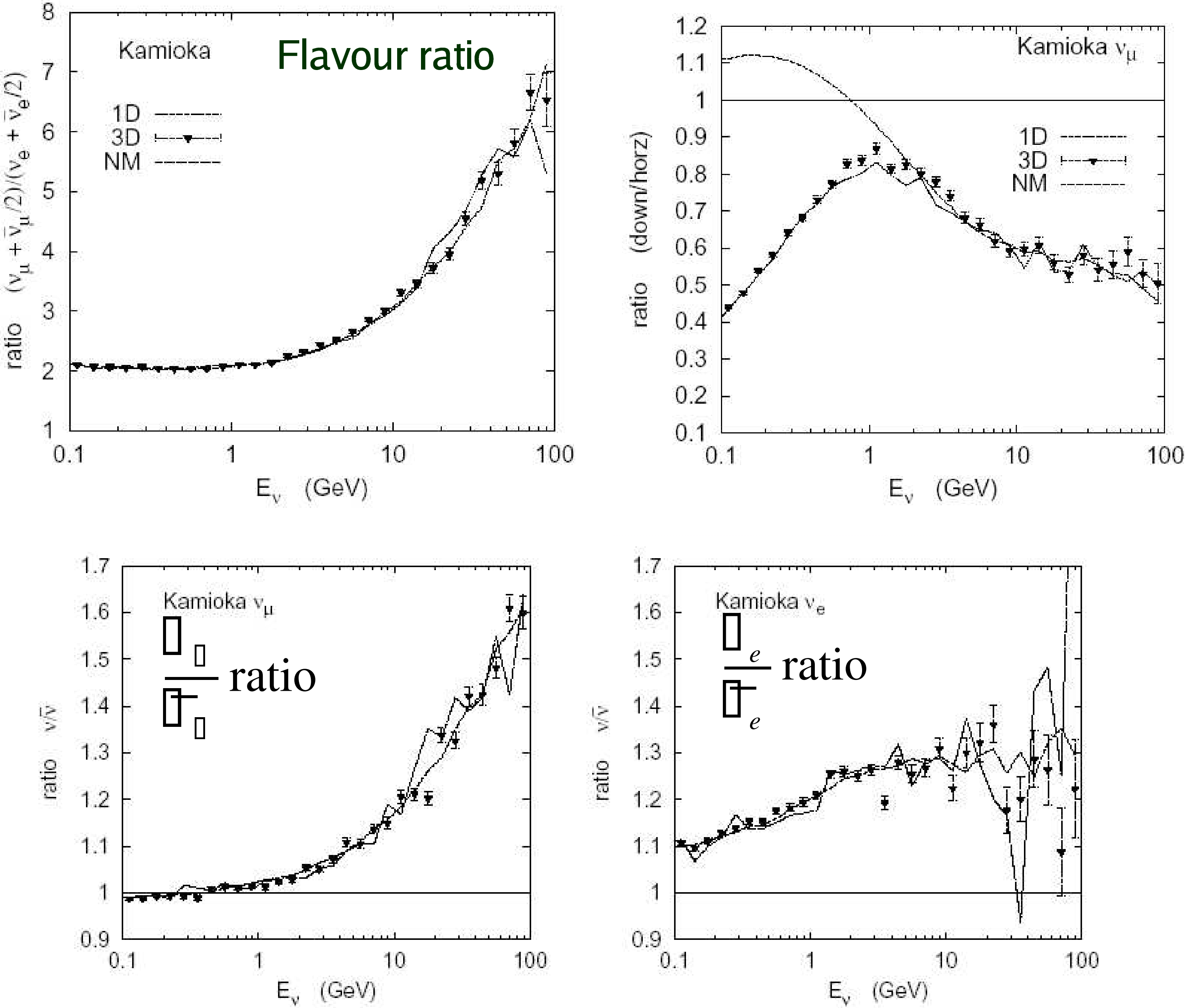
Azimuth angle distribution

East-West effect



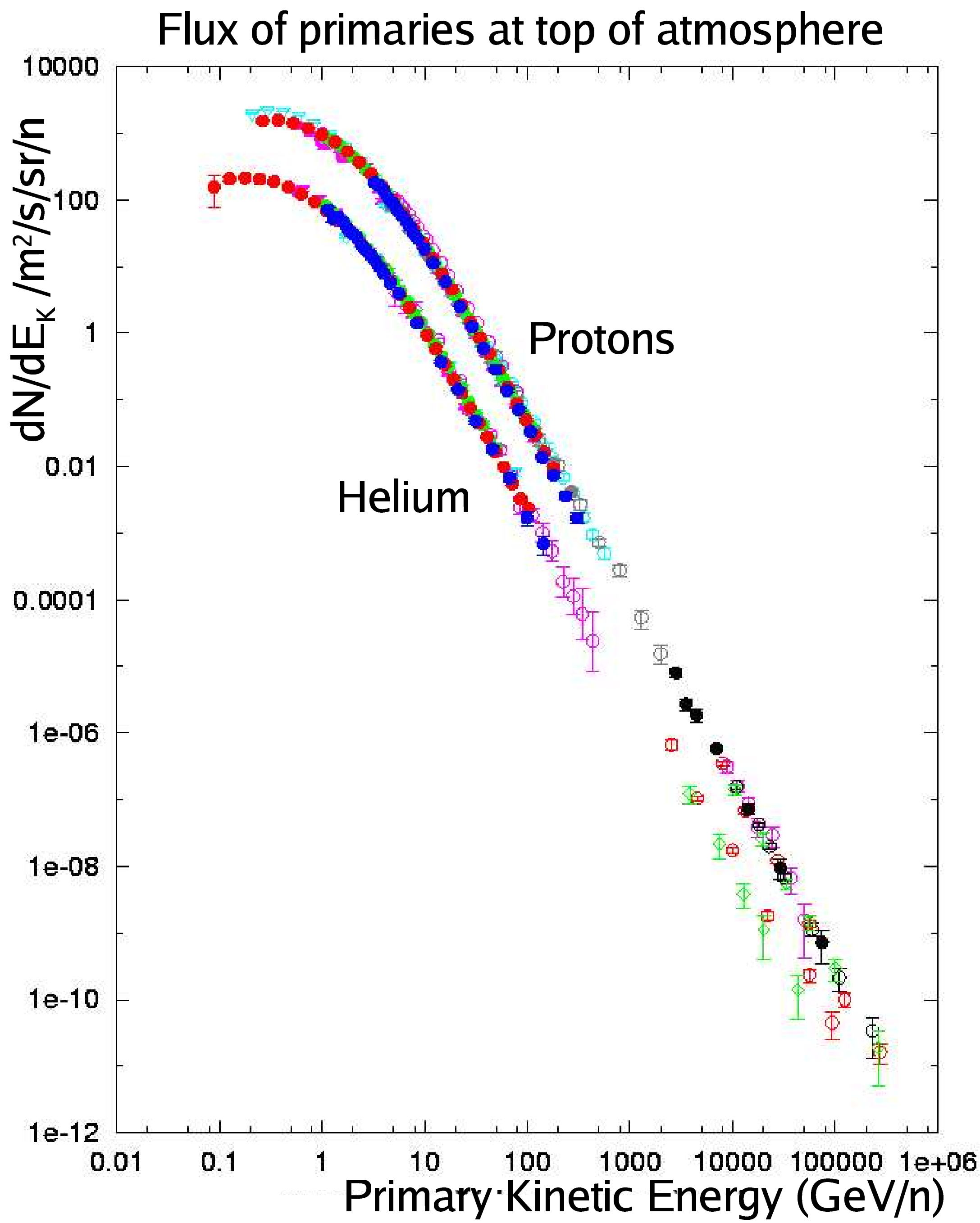






NM=3D with no bending of secondaries in Earth's mag field

Section 2: Systematics



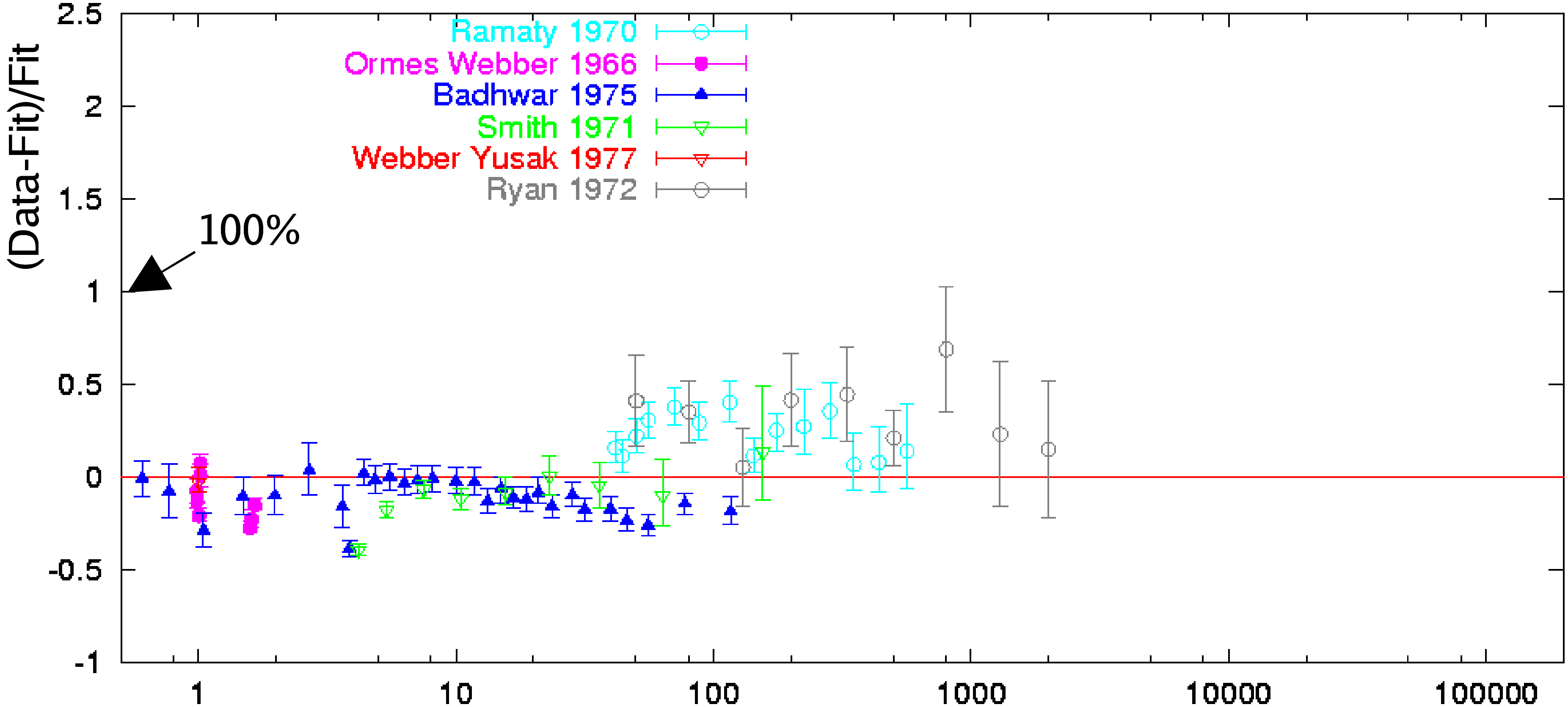
Primary fluxes

$$\phi(E_K) = K\left(E_K + b\exp\left(-c\sqrt{E_K}\right)\right)^{-\alpha}$$

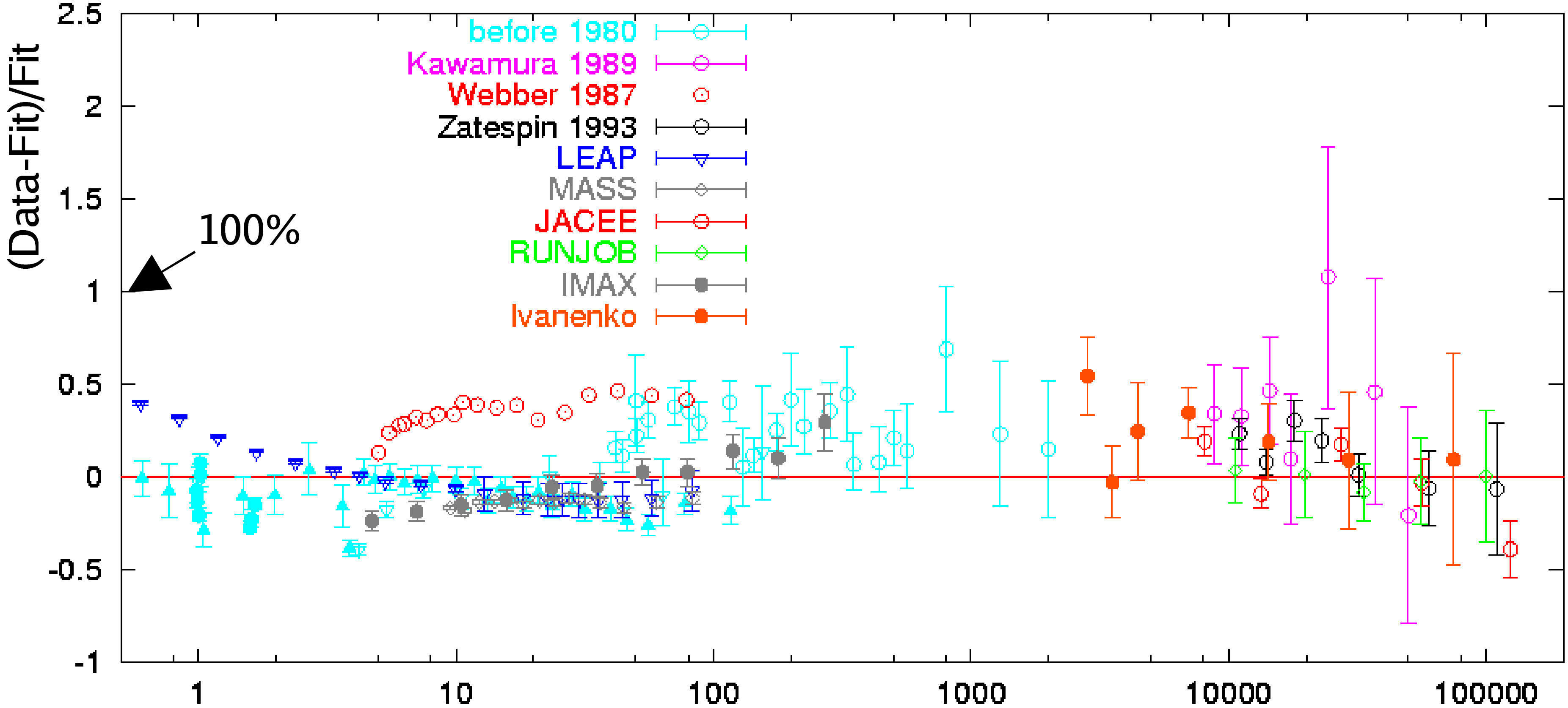
	α	K	b	c
H	2.74	14900	2.15	0.21
He	2.64	600	1.25	0.14
CNO 14	2.70	62.4	1.78	0.02
Ne-Si 24	2.70	21.4	1.78	0.02
Fe(56)	2.70	5.1	1.78	0.02

- Protons = 75% of all nucleon fluxes
- Helium = 15% of all nucleons = 60% of all nuclei.

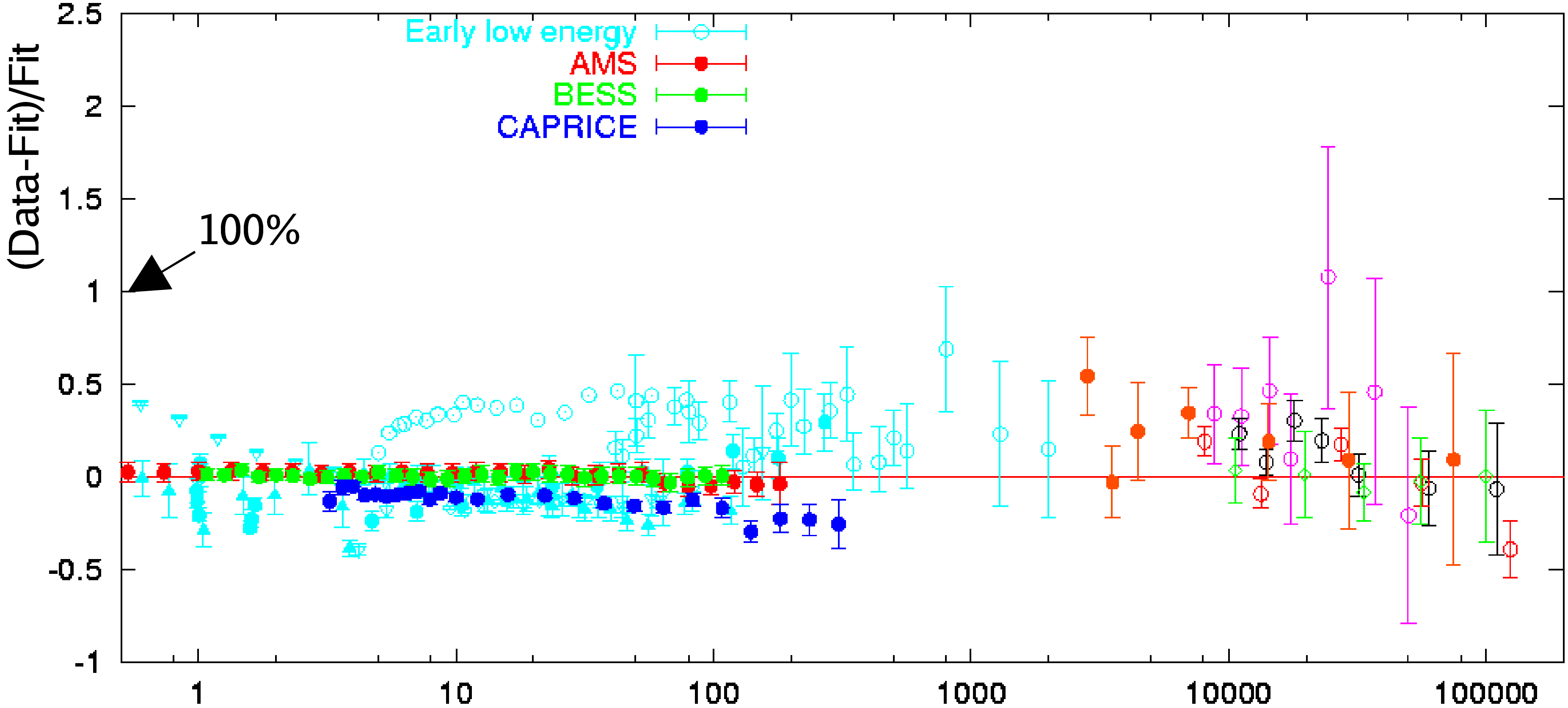
Residuals: Oldest measurements



Residuals: Newer measurements

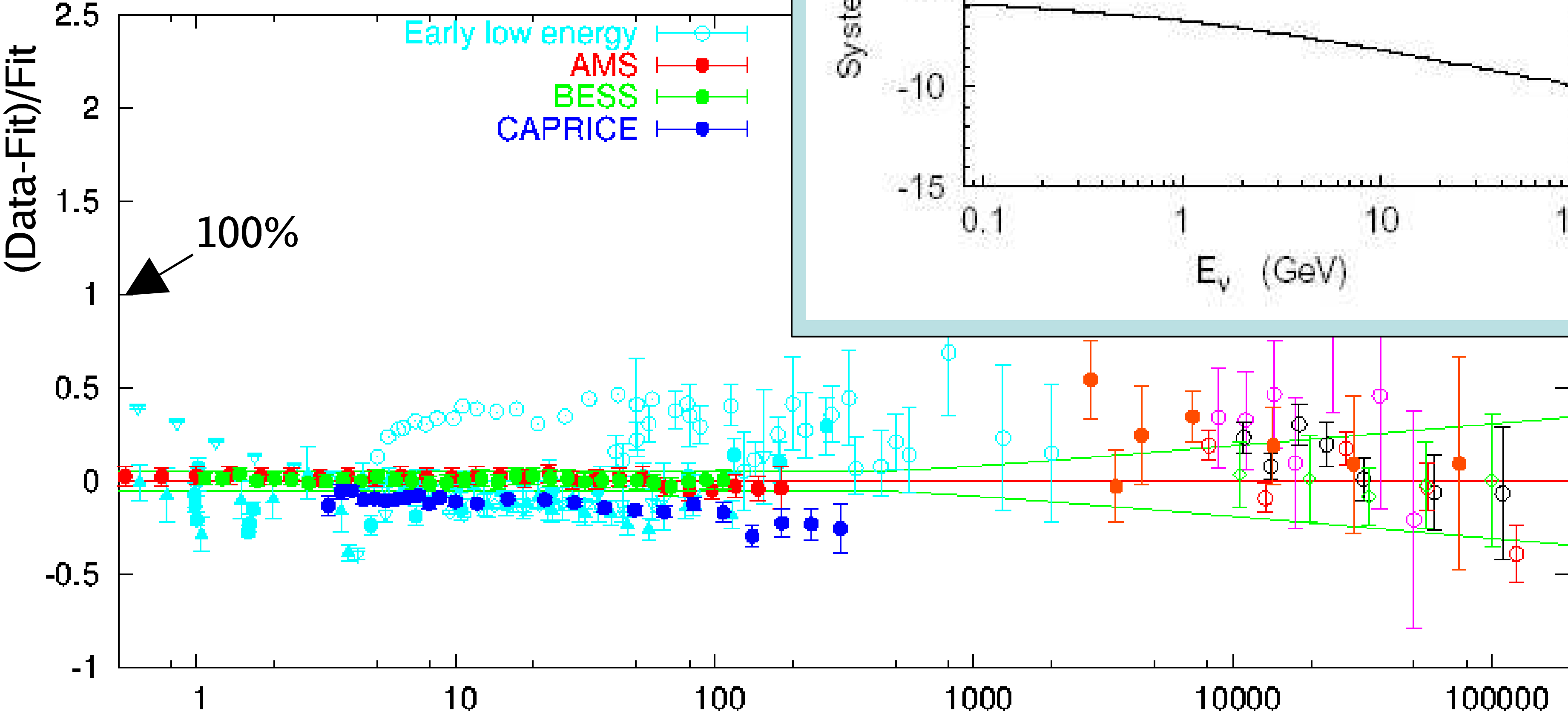


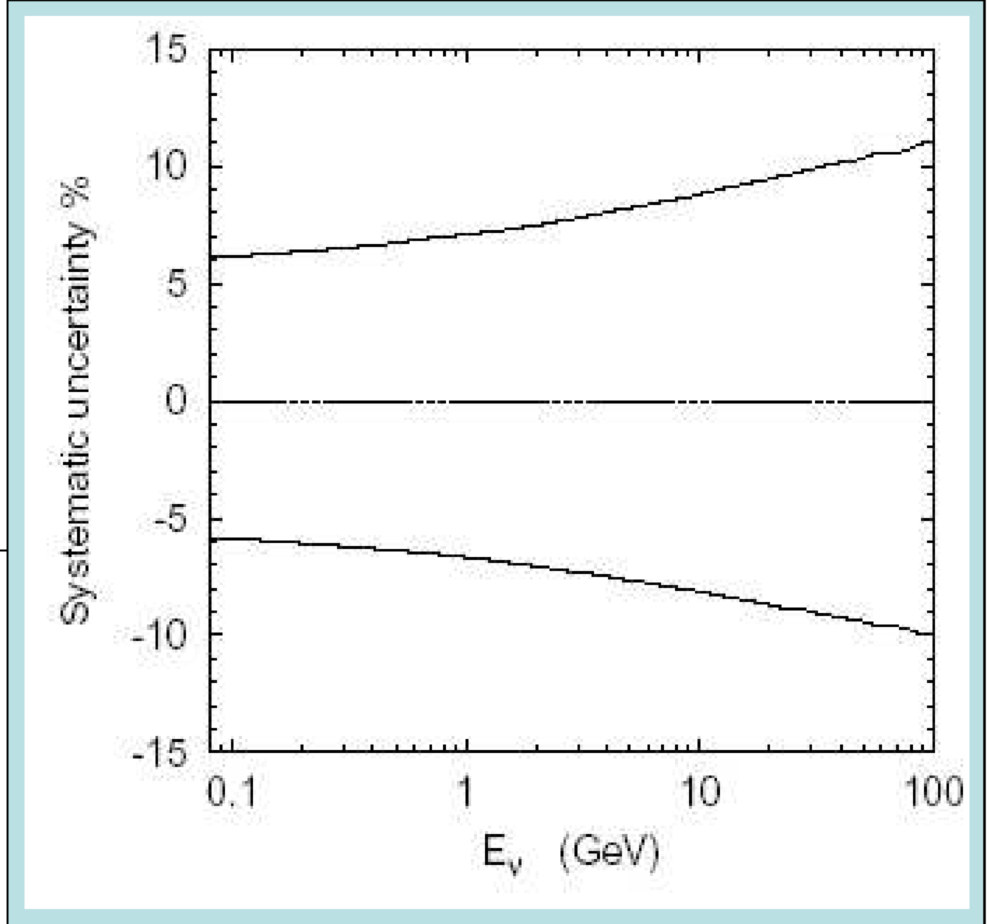
Residuals: Newest measurements



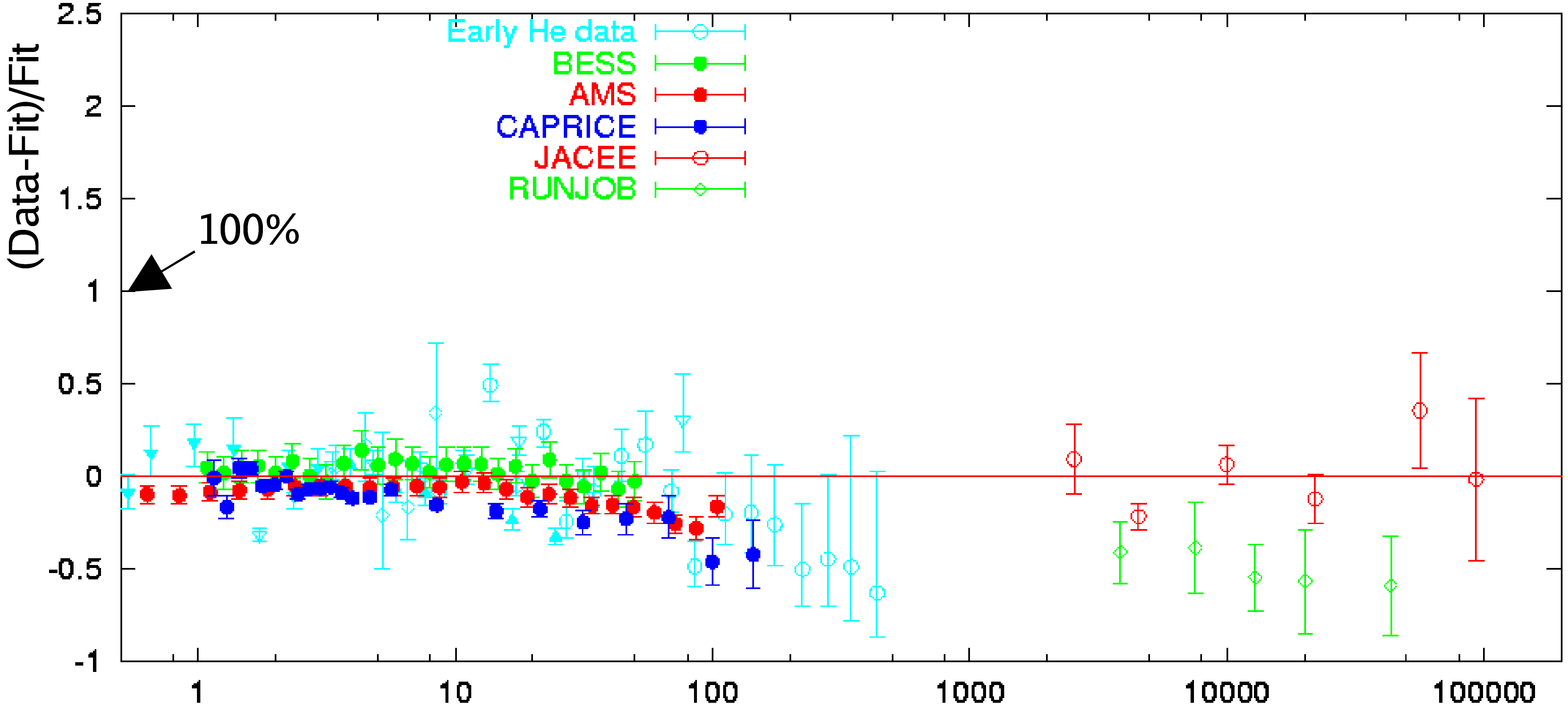
Effect on neutrino fluxes

This includes helium uncertainty shown on next slide

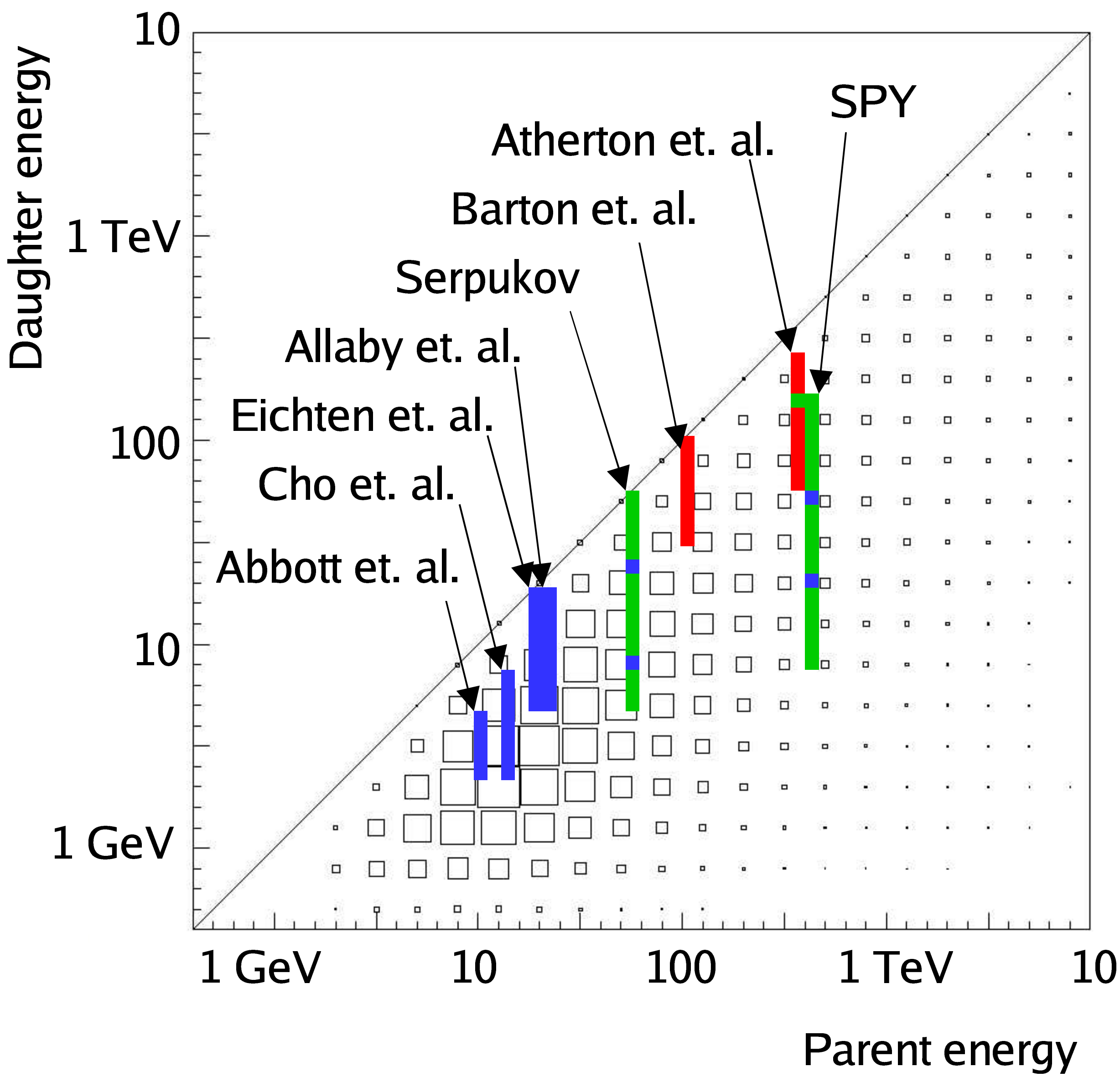




Helium Fluxes



Hadron production measurements



Population of hadron-production phase-space for pA X interactions.

ν_μ flux (represented by boxes) as a function of the parent and daughter energies.

Measurements.

- 1-2 p_T points
- 3-5 p_T points
- >5 p_T points

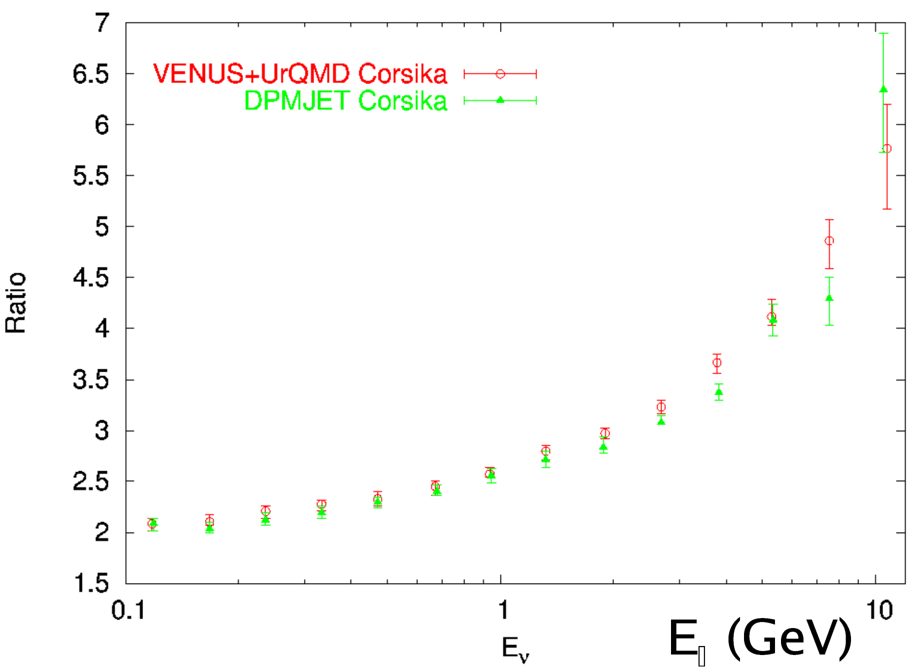
Can attempt fit all the data simultaneously.

Antiproton example: Duperray, Huang, Protasov, Buénerd astro-ph/0305274

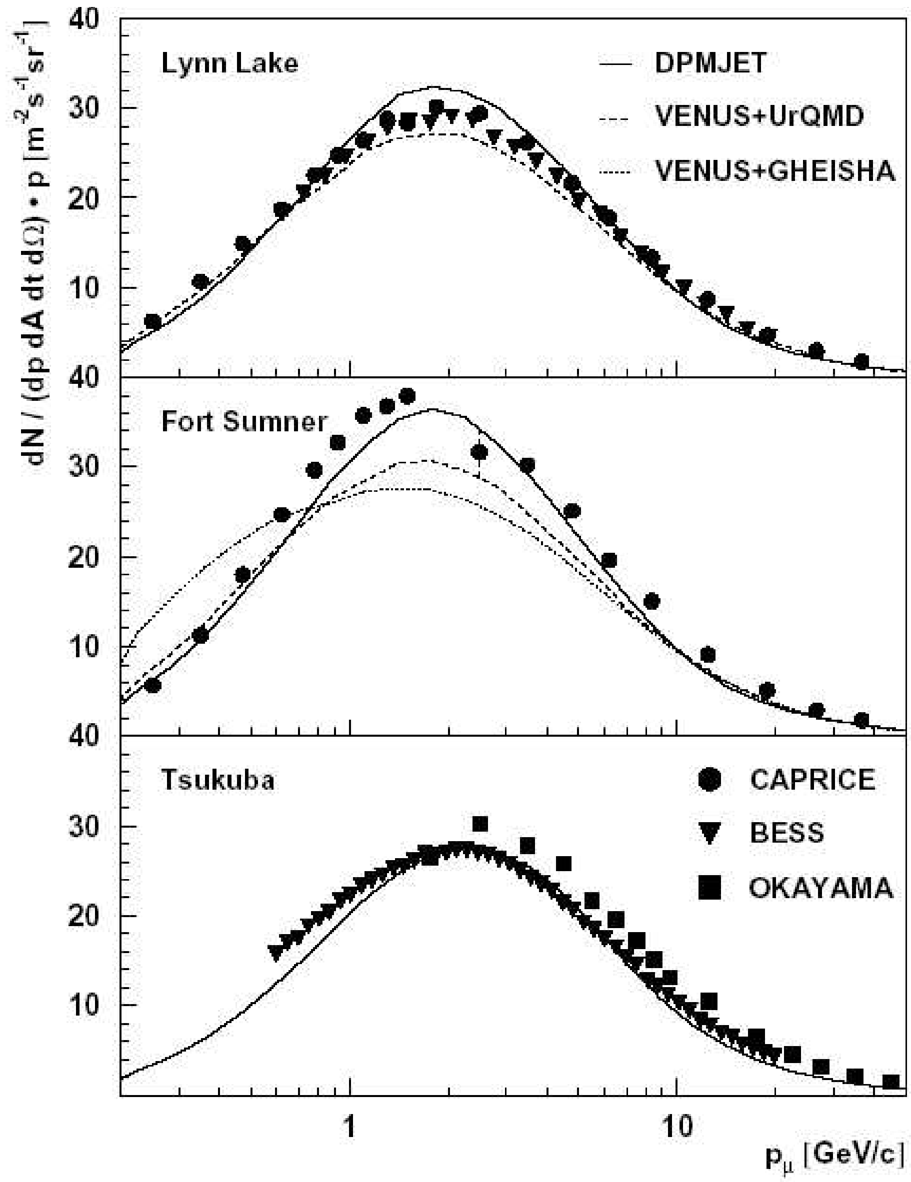
Hadron production: MC comparison Muon fluxes

From: Wentz et al
PRD 67 073020 (2003)

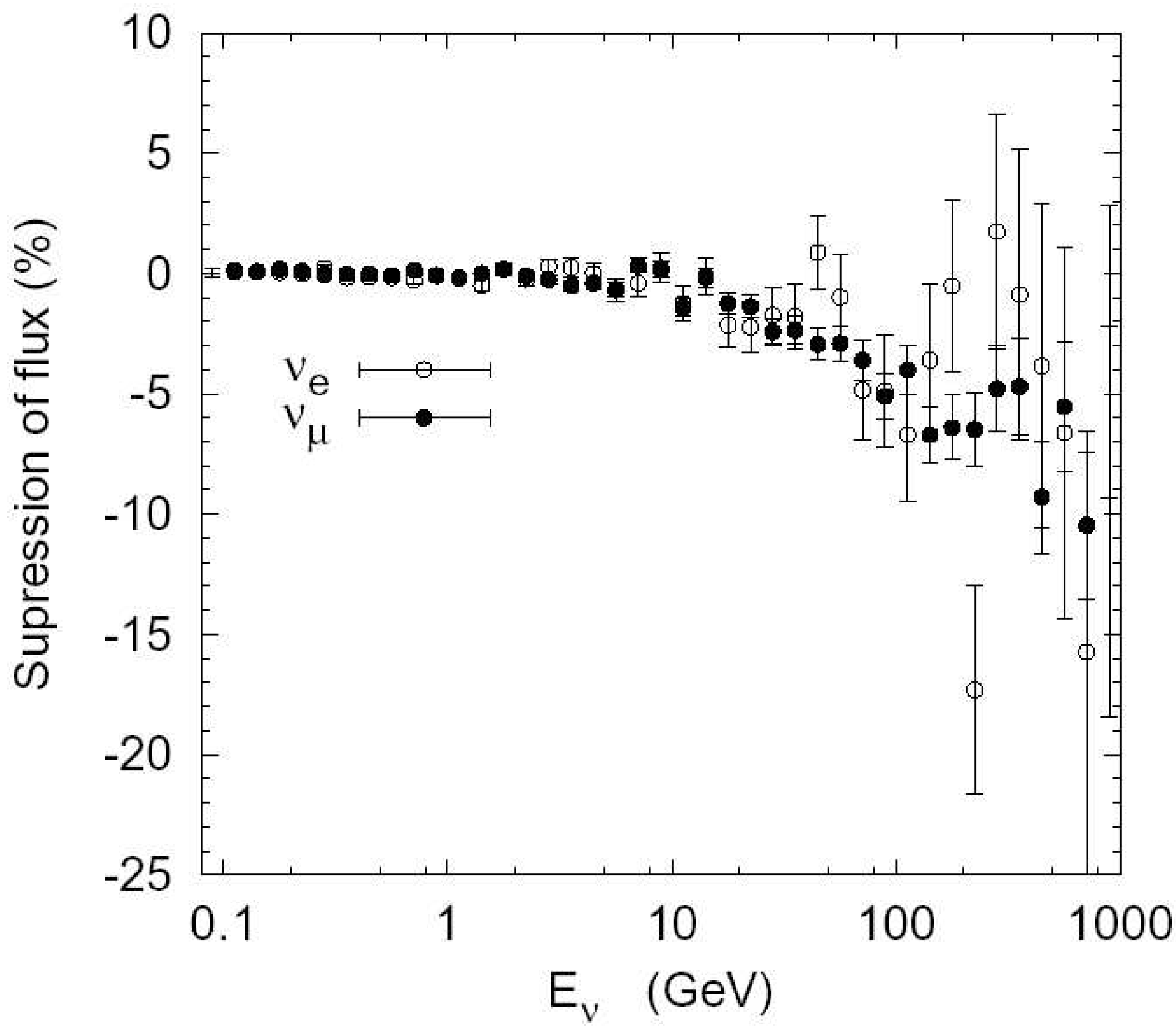
Ratio (□□ □□□)/(□e □□e)



(Sea level muon fluxes) x p

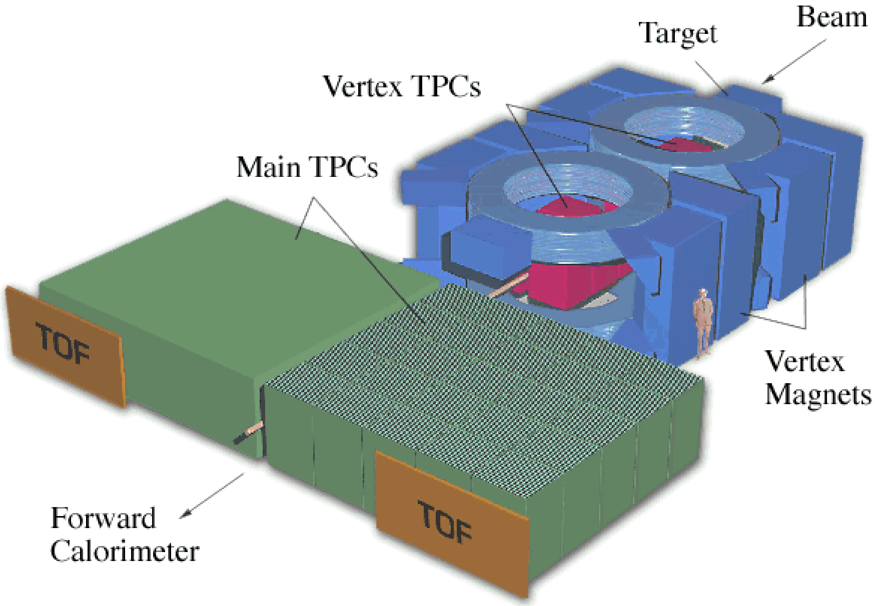


Associative production



- Effect of a 15% reduction in K+ production

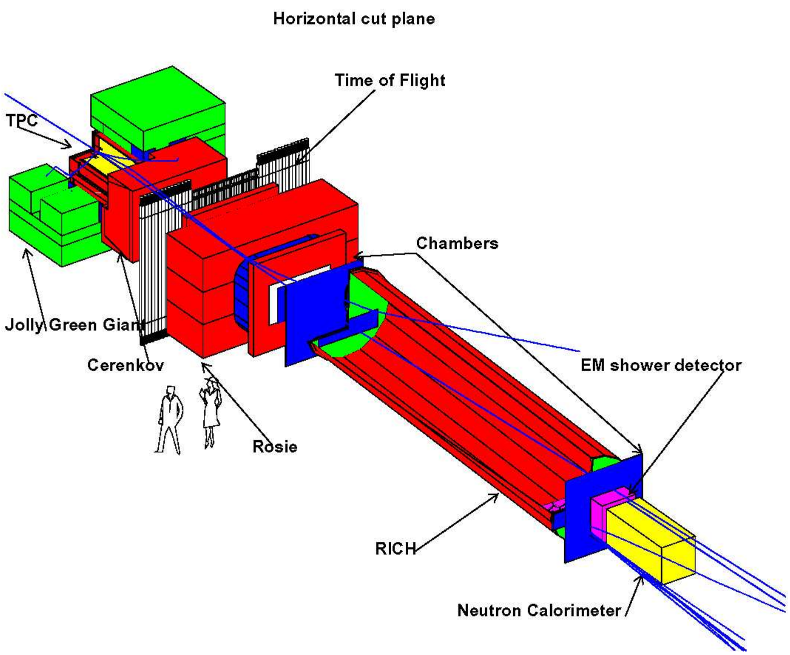
Future hadron-production results



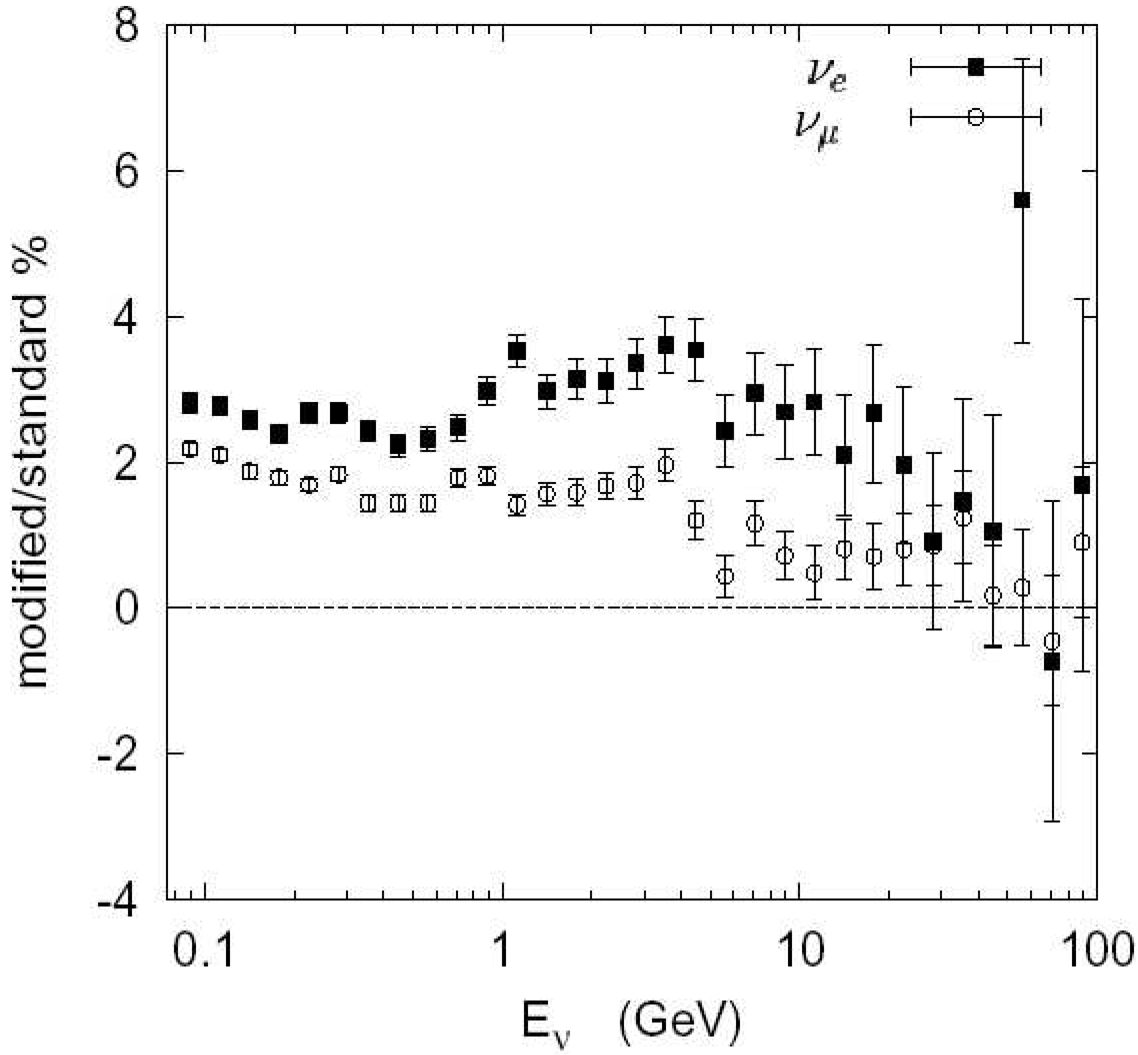
HARP 3-15 GeV at CERN PS
MIPP 5-120 GeV at FNAL MI
NA49 100,160 GeV at SPS

MIPP

Main Injector Particle Production Experiment (FNAL-E907)

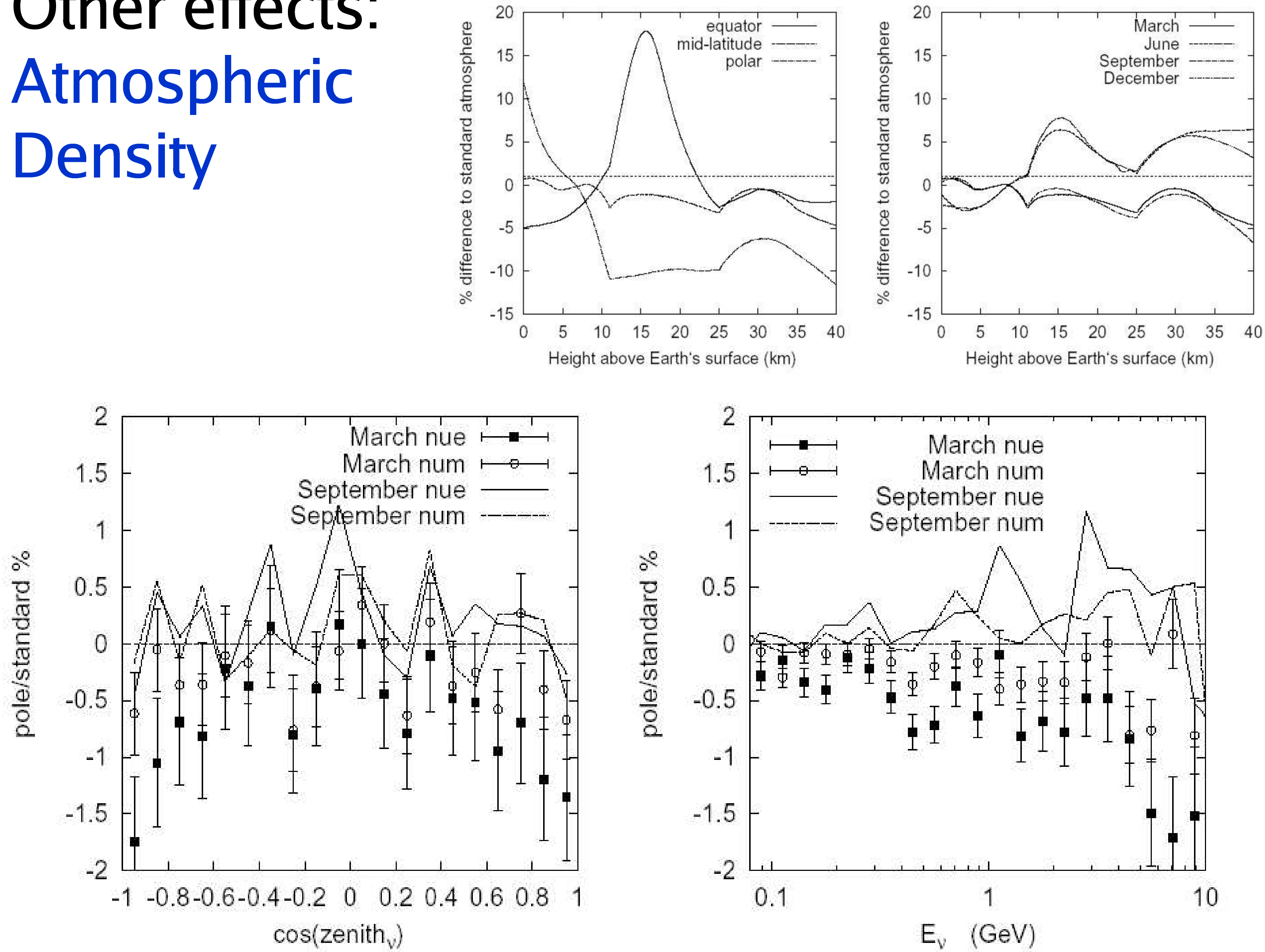


Cross section change

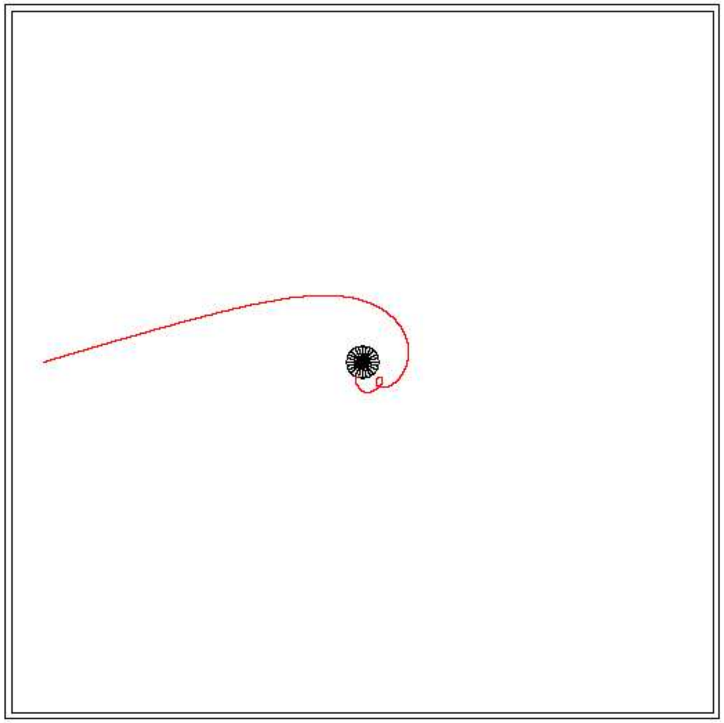


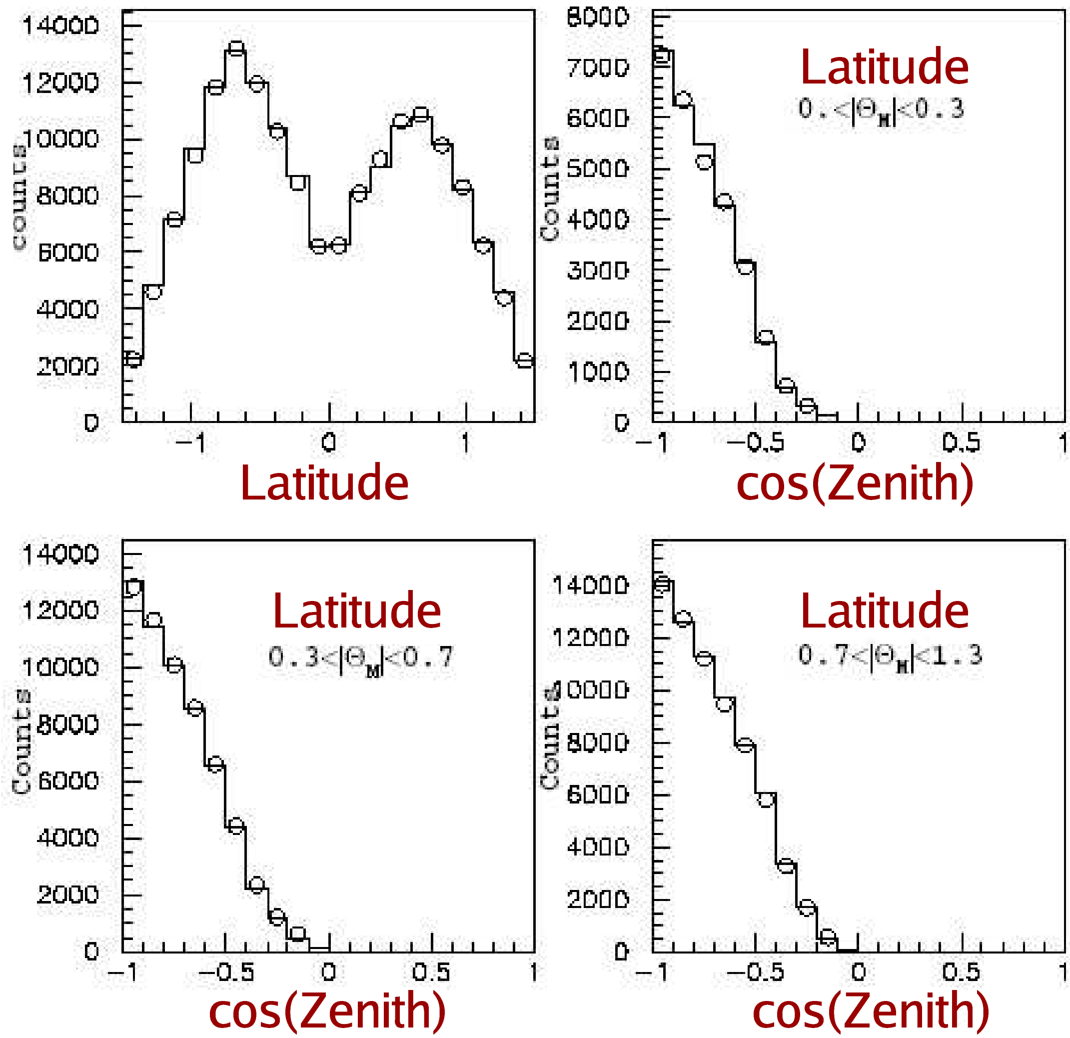
Effect of artificial increase in total cross section of 15%

Other effects: Atmospheric Density



Other effects:
Magnetic field





From: Favier, Kossakowski and Vialle. PRD 68 093006 (2003)

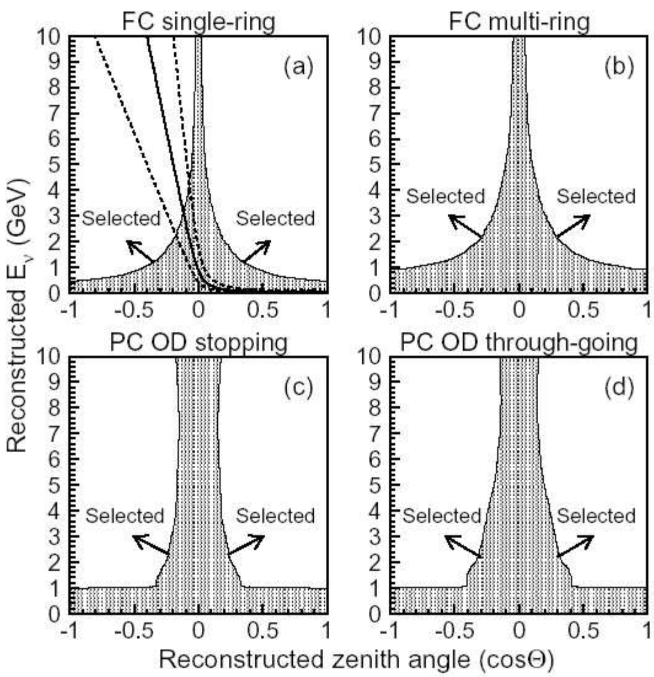
Method A: Generate far from Earth Earth, propagate in (Circles)

Method B: Generate near earth and propagate charge-reversed out.

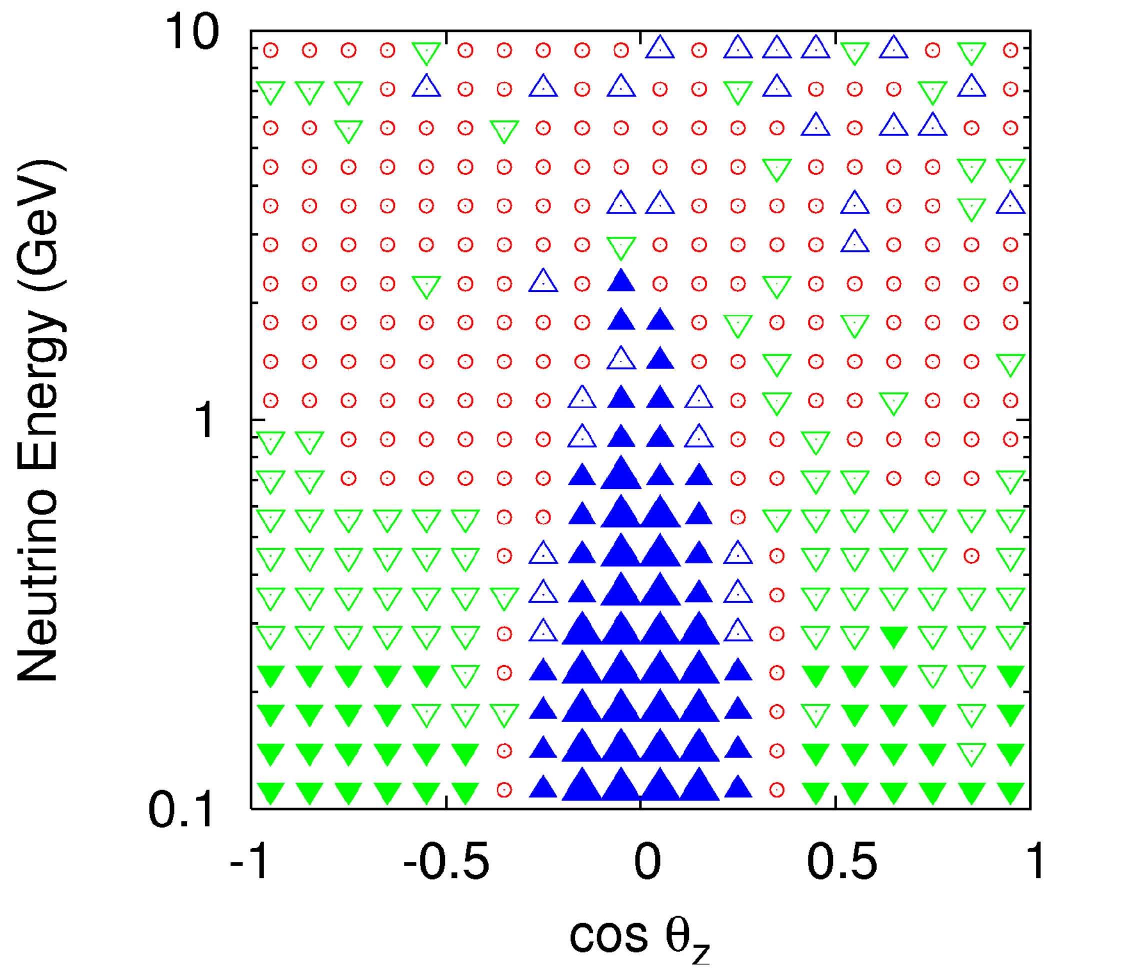
Return to 3D:
Is it important?

▲	3D bigger	>30%
▲		10%-30%
△		3%-10%
○		<3%
▽	1D bigger	3%-10%
▼		10%-30%

SuperKamiokande Collaboration
hep-ex/0404034



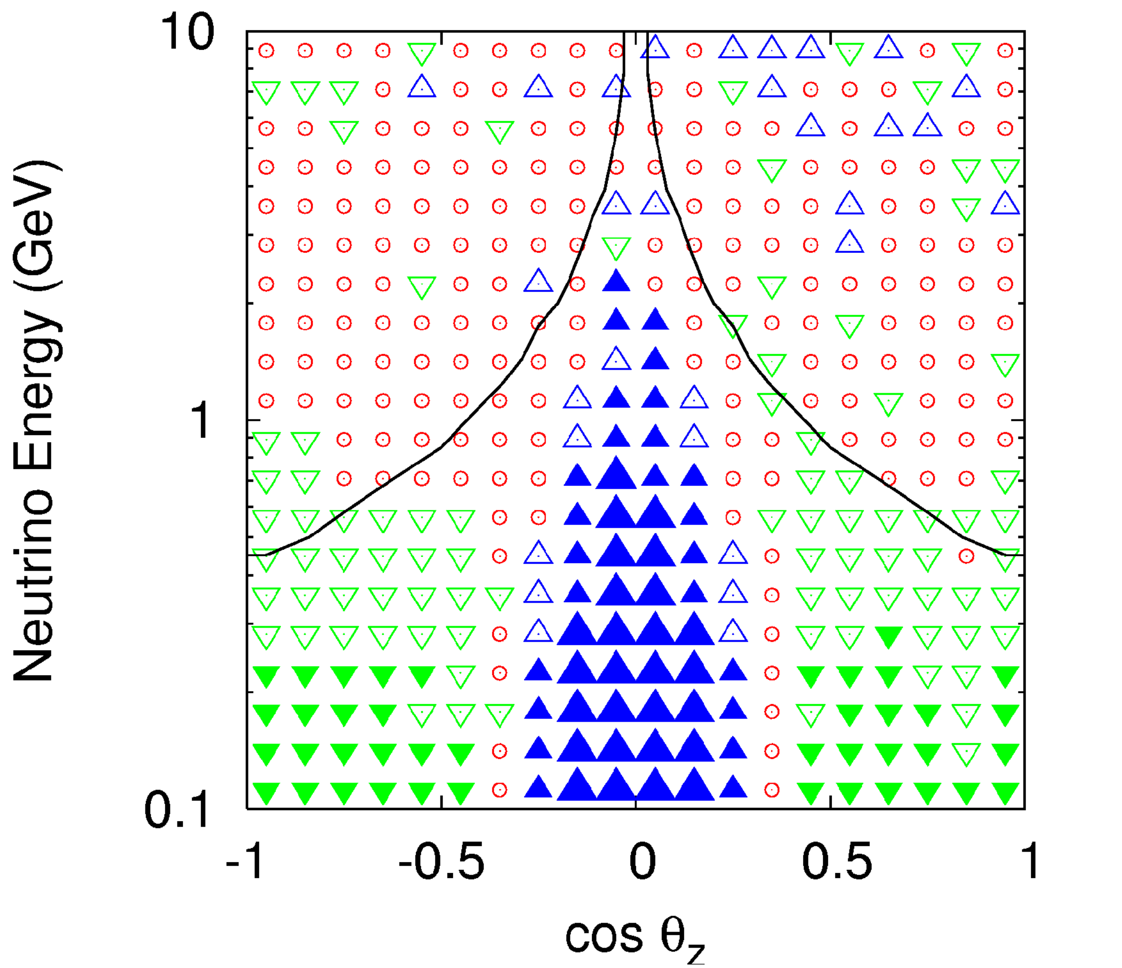
Difference between 3D and 1D calculations



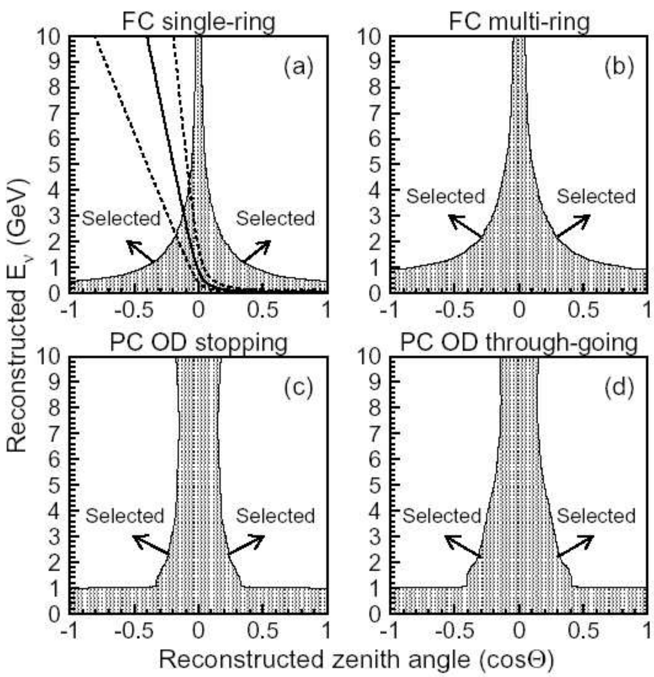
Return to 3D:
Is it important?

▲ (large)	3D bigger	>30%
▲		10%-30%
△		3%-10%
○		<3%
▽	1D bigger	3%-10%
▼		10%-30%

Difference between 3D and 1D calculations



SuperKamiokande Collaboration
hep-ex/0404034



Conclusions

- Since early days of nucleon decay expts and the atmospheric neutrino ‘anomaly’:
  - Large increase in calculation sophistication
  - Much improved primary fluxes
  - Hadron production data still needed

- 3D effects now well understood.