Bartol
Atmospheric Neutrino Fluxes

presented by Giles Barr,

(including much input from

Thomas K. Gaisser, Todor Stanev)

Hyper-K 7th open meeting

Queen Mary College, London

10 July 2016

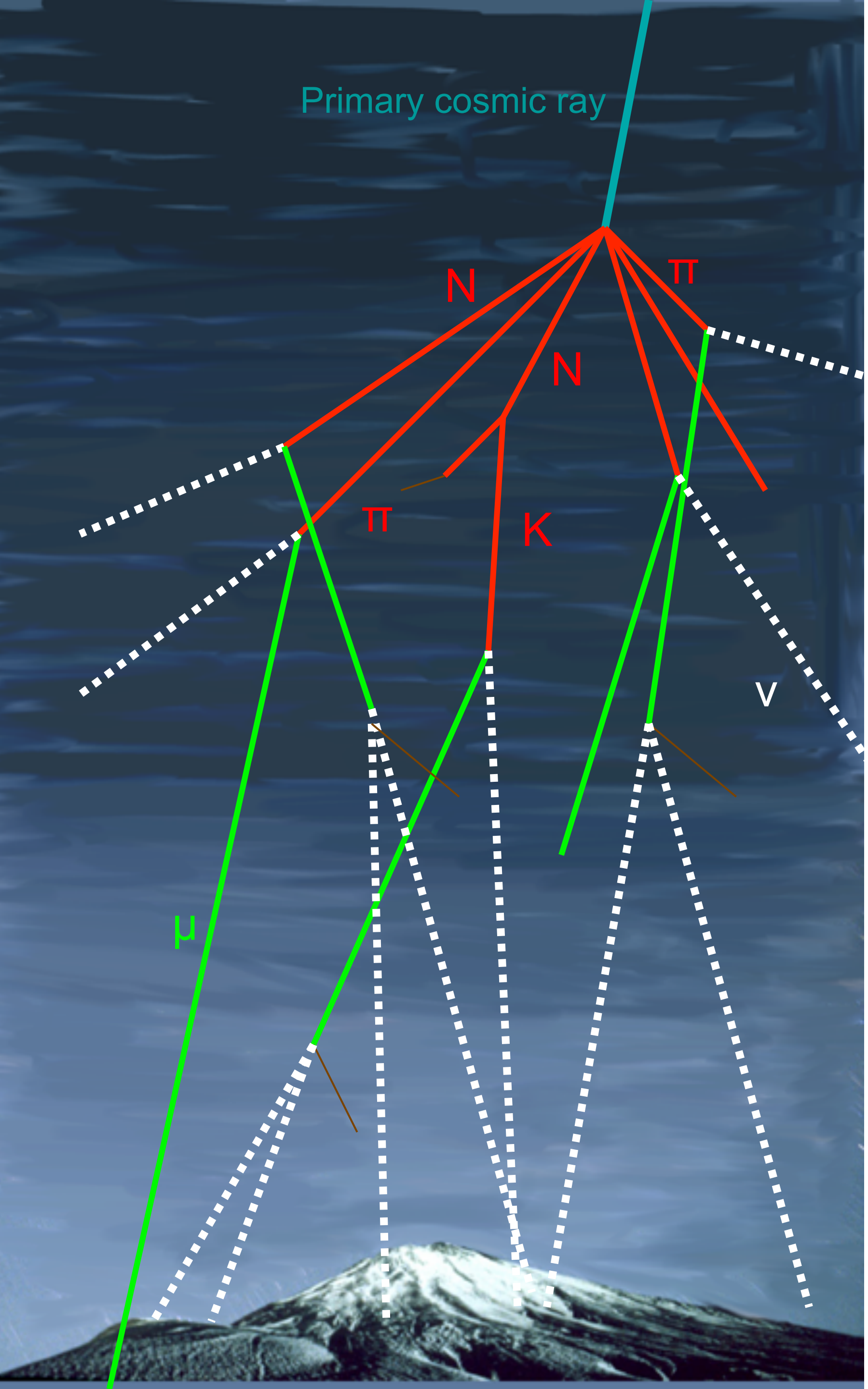
Key points

- We are gearing up to upgrade the calculation at energies in the HK relevant region.
  – It will be slow at first, we have to check the old code still runs properly.
- Much new input data from hadron production cross sections and primary fluxes
- The calculations include hooks for evaluating and propagating uncertainties, and this will be extended.
- The calculations display interesting cancellations of uncertainties when used in the regions of interest for mass hierarchy measurements.

History of the 'Bartol' calculation

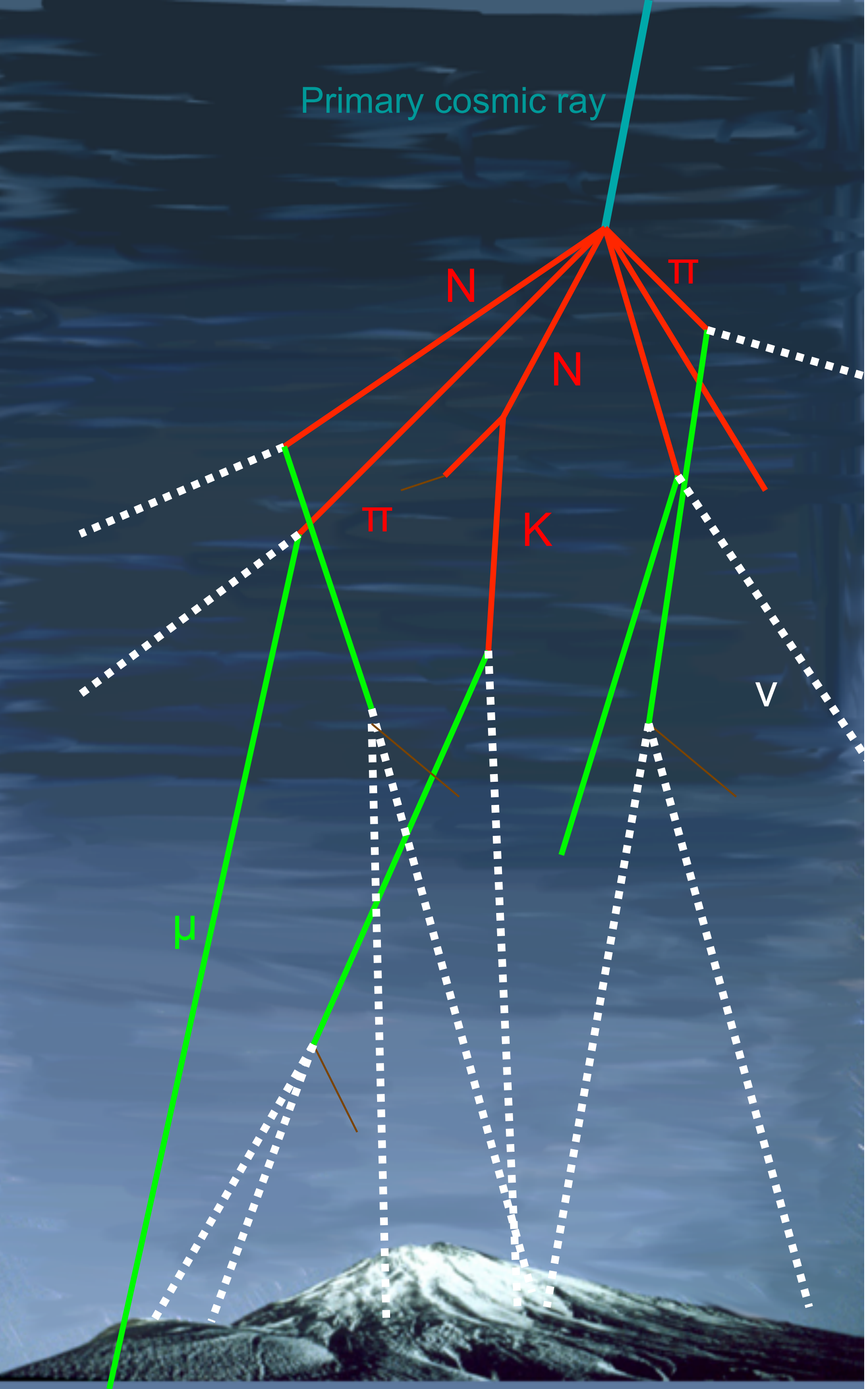
- *Flux of Atmospheric Neutrinos*, T.K. Gaisser, Todor Stanev, S.A. Bludman, H-S Lee, PRL 51 (1983) 223
- *Cosmic Ray Neutrinos in the Atmosphere*, T.K. Gaisser, Todor Stanev, Giles Barr, PR D38 (1988) 85
- *Ratio of ν_e / ν_μ in Atmospheric Neutrinos,* Stephen M. Barr, T.K. Gaisser, Paolo Lipari, Serap Tilav, Phys. Lett. B214 (1988) 147
- *Flux of Atmospheric Neutrinos*, G. Barr, T.K. Gaisser, T. Stanev, PR D39 (1989) 3532
- *Atmospheric neutrino flux above 1 GeV,* Vivek Agrawal, T.K. Gaisser, Paolo Lipari, Todor Stanev, PR D53 (1996) 1314
- *Comparison of atmospheric neutrino flux calculations at low energies,* T.K. Gaisser, M. Honda, K. Kasahara, H-S Lee, S. Midorikawa, Vadim A. Naumov, Todor Stanev, PR D54 (1996) 5578
- *Path length distributions of atmospheric neutrinos,* T.K. Gaisser, Todor Stanev, PR D57 (1998) 1977
- *Geomagnetic effects on atmospheric neutrinos,* Paolo Lipari, Todor Stanev, T.K. Gaisser, PR D58 (1988) 073003
- *Primary spectrum to 1 TeV and beyond,* T.K. Gaisser, M. Honda, P. Llipari, T. Stanev, Proc. 27^{th} ICRC (Hamburg, 2001), vol. 5, p. 1643
- TARGET 2.2, *A hadronic interaction model for inclusive muon and neutrino fluxes* R. Engel, G.D. Barr, T.K. Gaisser, S. Robbins, T. Stanev, Proc, 28^{th} ICRC (Tokyo, 2003) p. 1603
- *A Three-dimensional calculation of atmospheric neutrinos,* G.D. Barr, T.K. Gaisser, P. Lipari, Simon Robbins, T. Stanev, PR D70 (2004) 023006
- *Uncertainties in Atmospheric Neutrino Fluxes,* G.D. Barr, T.K. Gaisser, S. Robbins, Todor Stanev, PR D74 (2006) 094009

Section 1: Bartol atmospheric neutrino calculations



Propagation through the atmosphere

- Start primary high in atmosphere
- Interacts after mean ~90g/cm^2 (atmosphere depth 1050 g/cm^2)
- Interaction generated by TARGET hadron production generator
- Track particles in 3D through atmosphere:
  - Bending in magnetic field
  - Multiple scattering, energy loss
  - Muons do not depolarize
  - Account for Earth curvature
  - Atmospheric density model
  - Decay or re-interact
  - Impact with surface
- Most hadrons don't reach ground.



Propagation through the atmosphere (2)

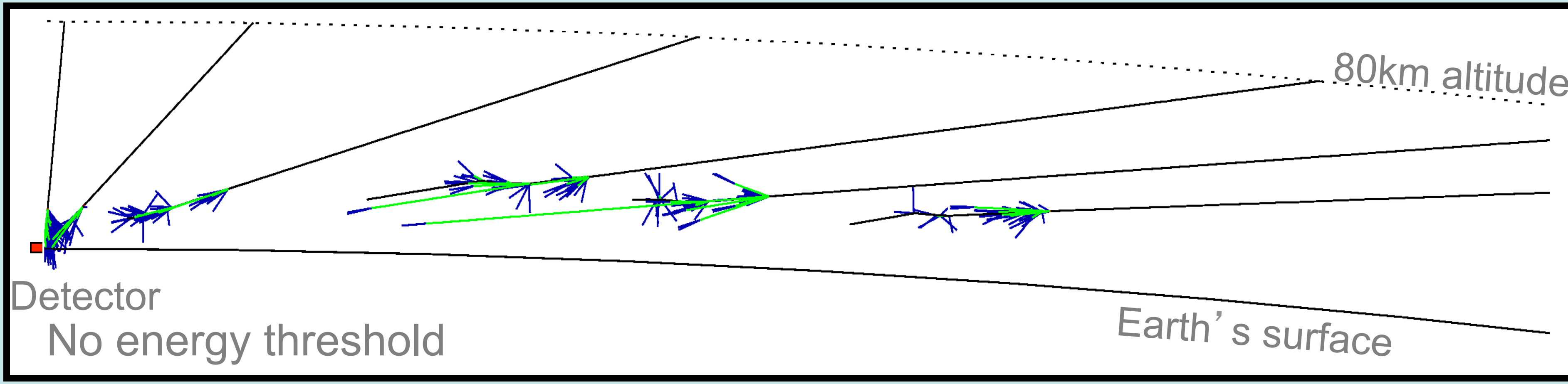
Some flexibility in code modularity: Can 'plug in' various parts of the generation

- Change hadron production generator (different version, or a completely different generator)
- Change atmospheric density model
- Change particle decay routines
- Change cross sections for interaction
- Change between 3D and 1D calculations (see later)

Not done, but would be easy to add:

- Local altitude variation (for where muons hit Earth)

Back-tracing primaries to obtain cutoffs



1. Generate particles isotropically over a sphere of radius R_E+80km.
2. Propagate primary forward in straight line until first interaction
3. Propagate all secondaries with magnetic field turned on
4. Backtrace primary from first interaction point to do cutoff calculation. If backtrace causes trajectory to hit the Earth, it is not allowed and the shower is rejected..
   - There is not always a single value of cutoff
   - To speed up, we have a lookup table defining a band: Below band always reject, above band always accept, inside band do calculation for individual particle.

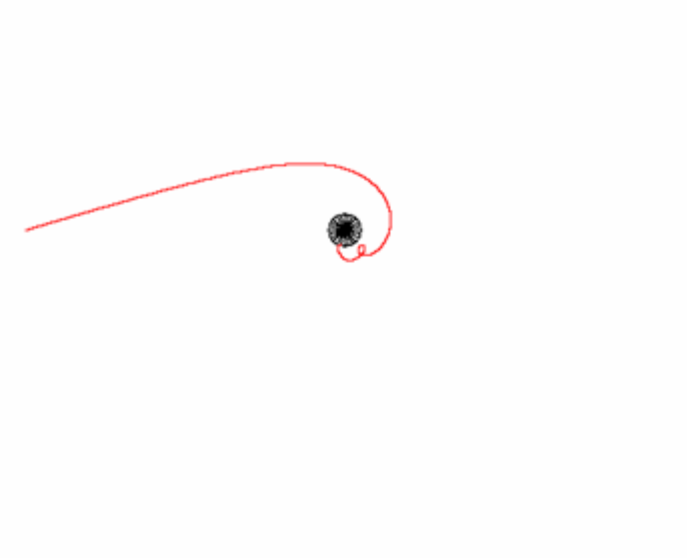
Cutoff calculation

- Cutoff is good approximation to doing forward propagation of cosmic rays. Liouville's theorem is used to justify generating isotropic distribution near surface rather than far away. It breaks down if particles are slowed dissipatively, by scraping the atmosphere. Q: How good is isotropic assumption far away?

See discussion in Favier, Kossakowski and Vialle PRD 68 093006 (2003)

it is important to have far end of trajectory a long way out, we use 30 x R_E

Trajectory of 5 GeV proton with $b=6R_E$ which makes it to Earth.



Compare back tracing vs stepping forward from Favier et al

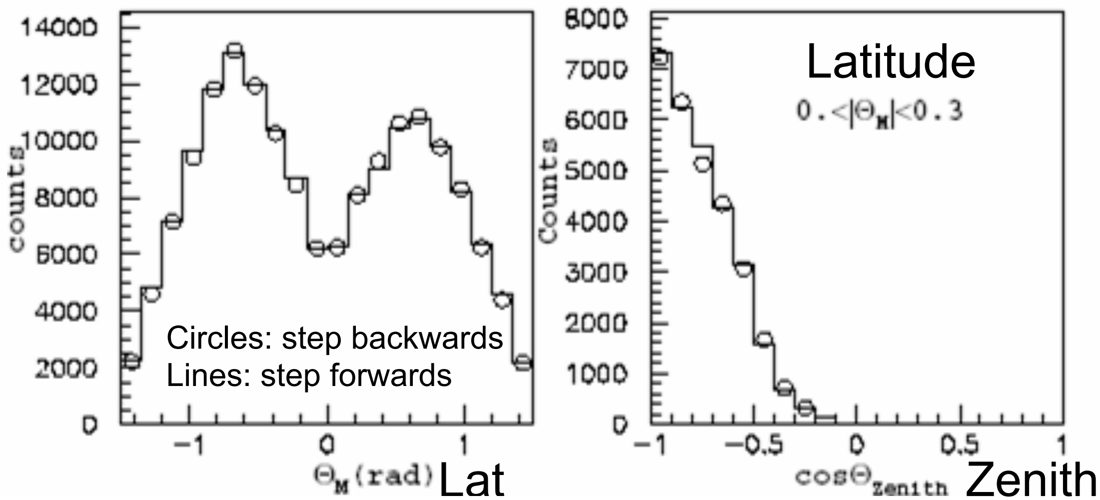
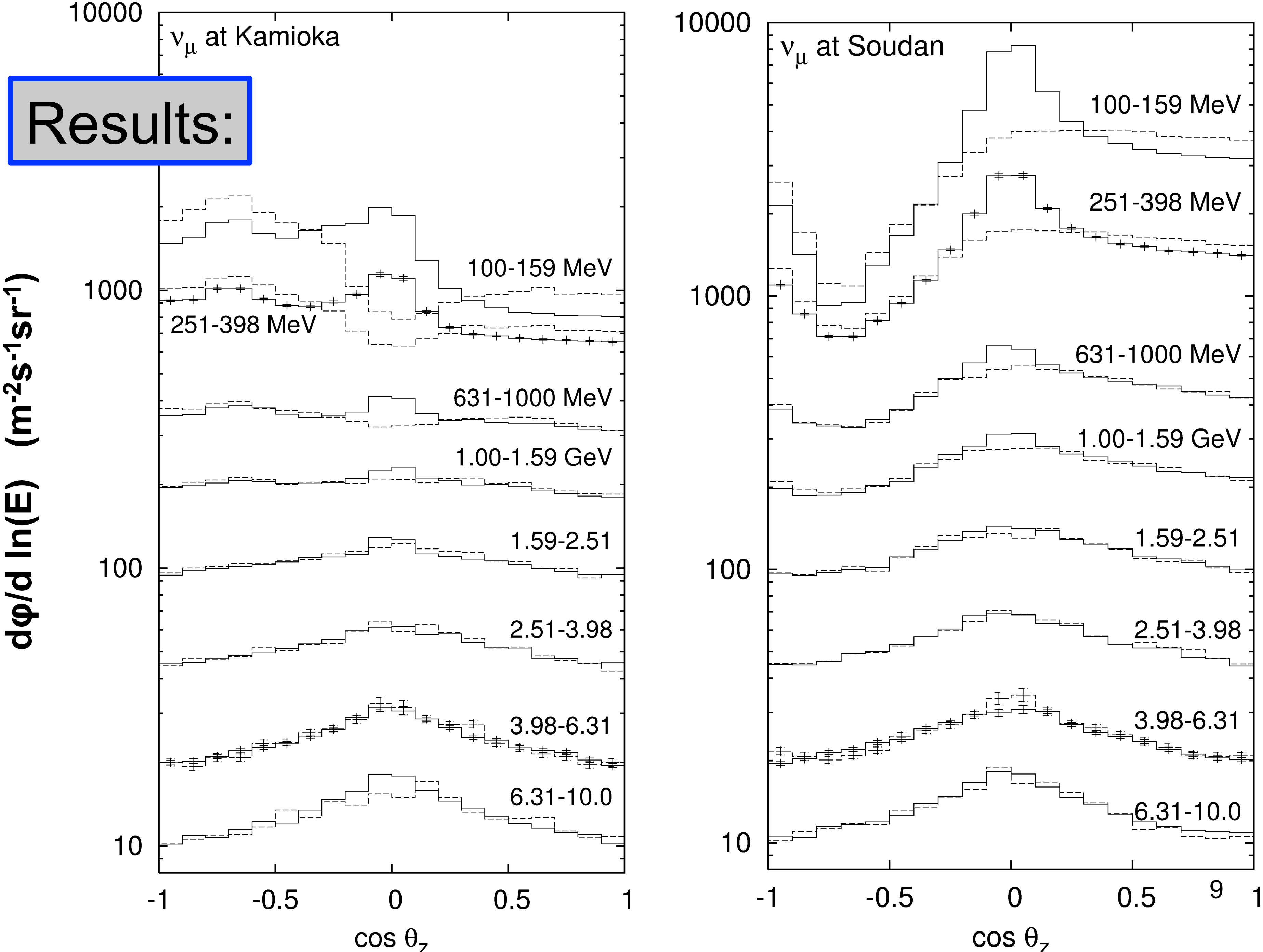


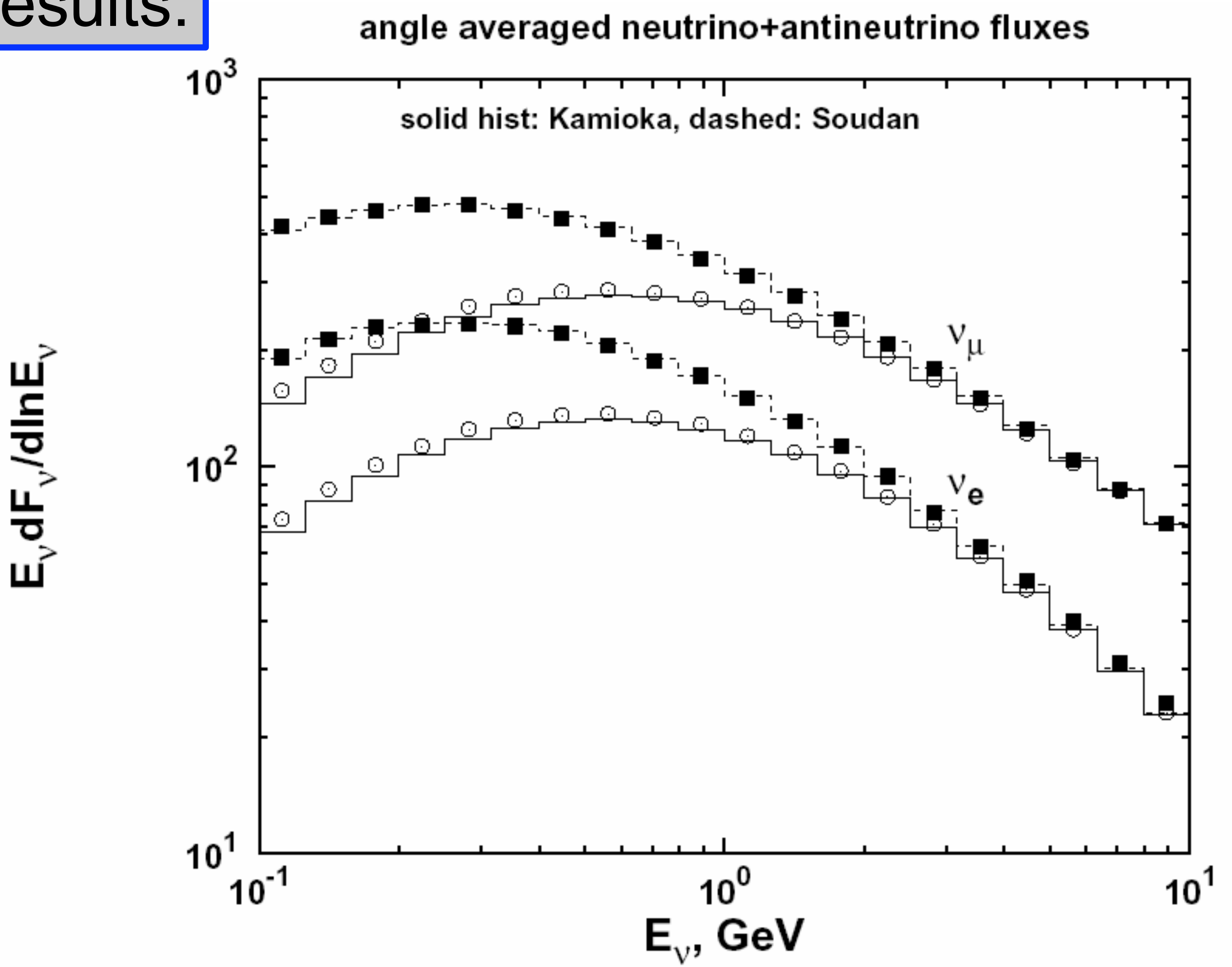
Figure 2: Comparison of generation far from Earth and near Earth (open circles); (a) is the geomagnetic latitude population; the observed distortion of symmetry is a reflection of the difference of a dipole field and the real one which contains also the South-Atlantic anomaly. (b), (c), (d) are distributions of the zenith angle for three geomagnetic latitude bins. Positions and angles are computed at the 380 km altitude and here the proton energy range is 6-30 GeV.

Results:



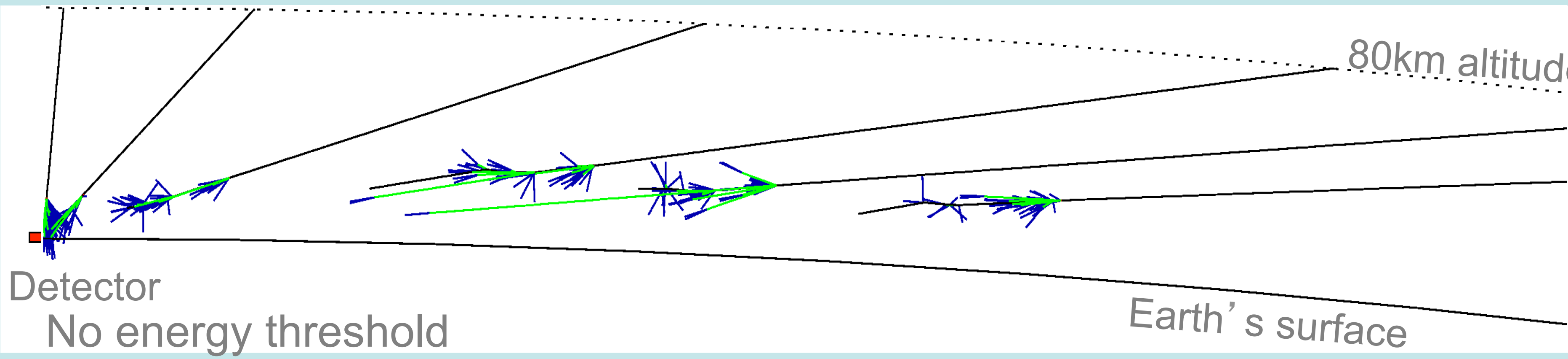
νμ at Kamioka
νμ at Soudan
dφ/d ln(E) (m-2s-1sr-1)
100-159 MeV
251-398 MeV
631-1000 MeV
1.00-1.59 GeV
1.59-2.51
2.51-3.98
3.98-6.31
6.31-10.0
10000
1000
100
10
-1
-0.5
0
0.5
1
cos θz

Results:

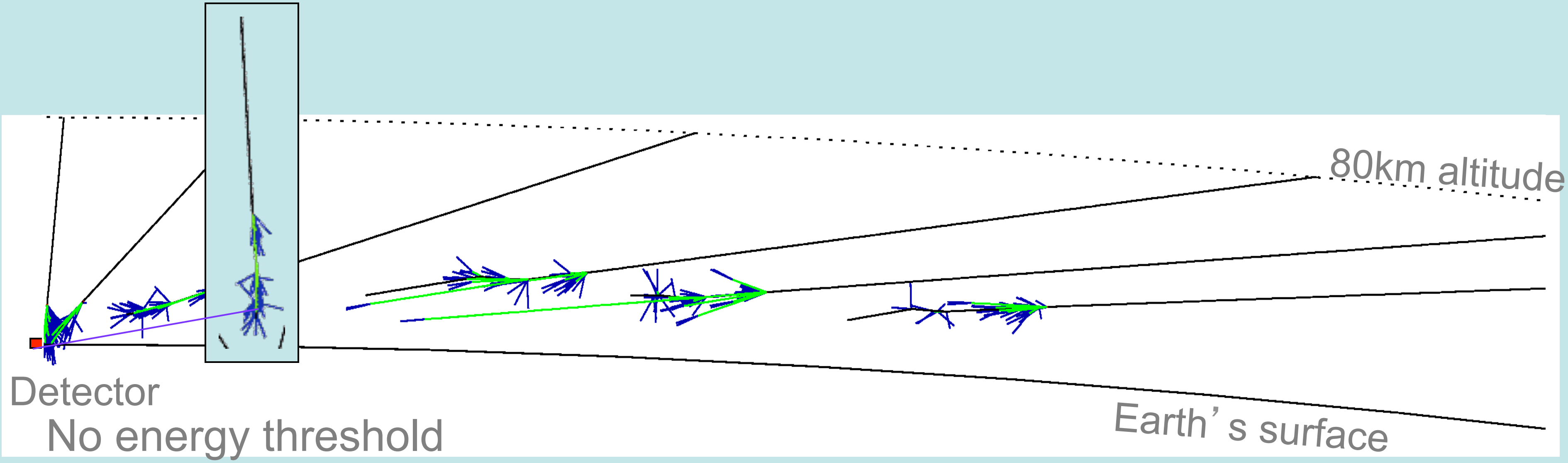


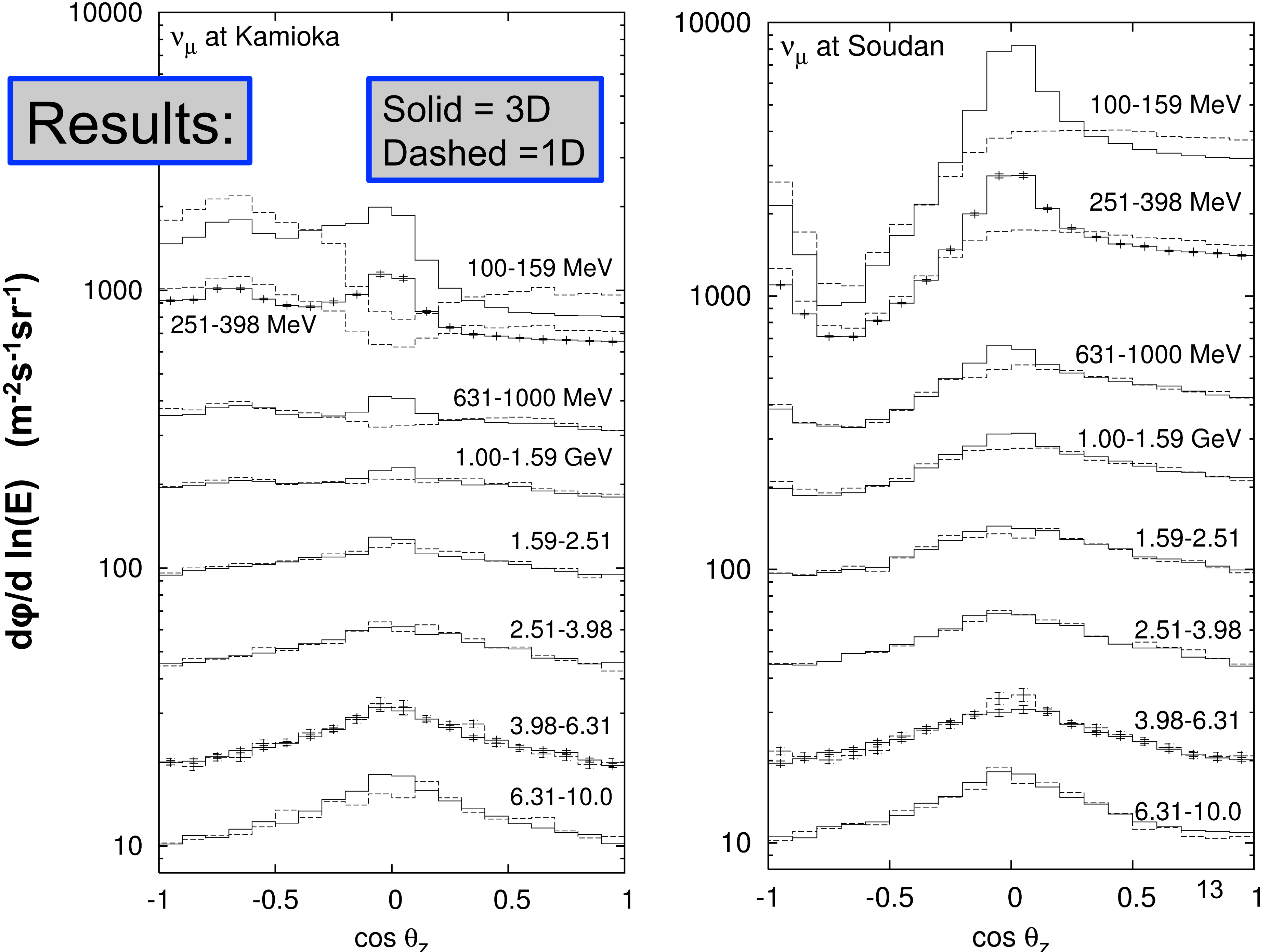
angle averaged neutrino+antineutrino fluxes
solid hist: Kamioka, dashed: Soudan
ν_μ
ν_e
10^3
10^2
10^1
10^{-1}
10^0
10^1
$E_\nu dF_\nu/d\ln E_\nu$
E_ν, GeV

3-Dimensional effect



3-Dimensional effect




Results:
Solid = 3D
Dashed =1D
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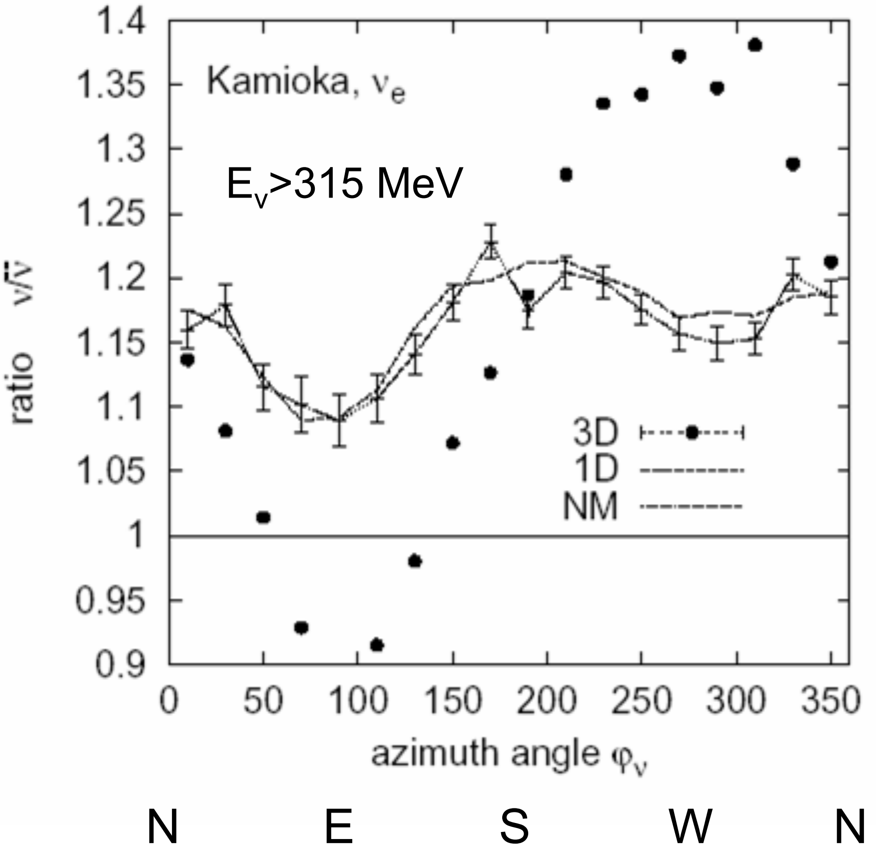
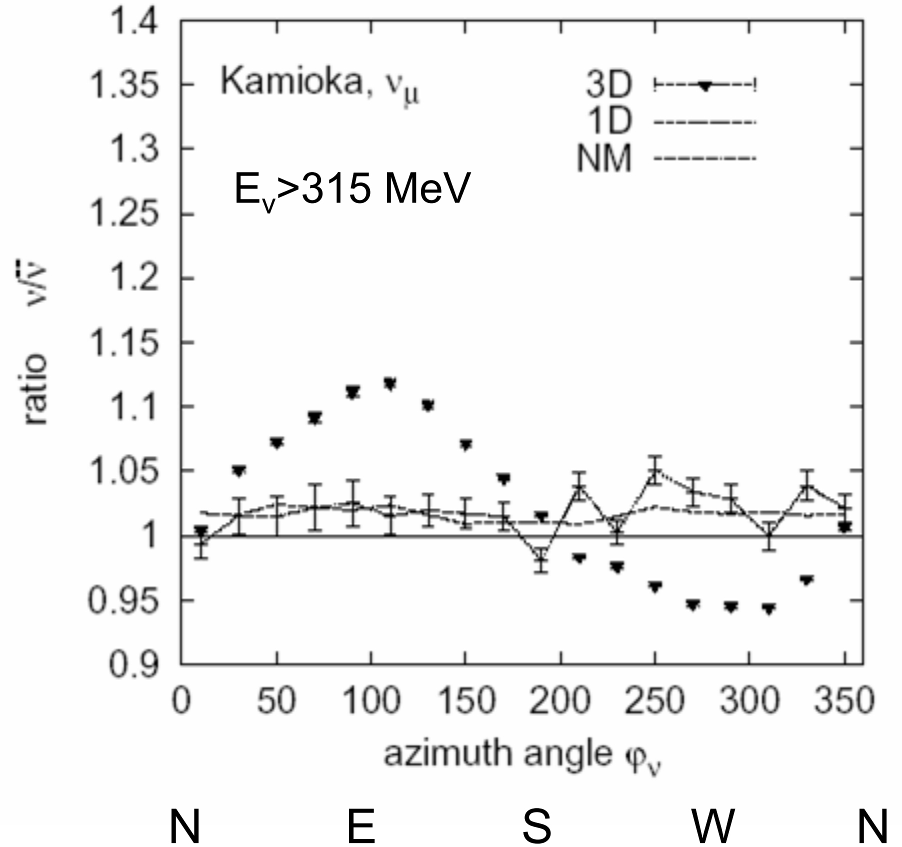
3.98-6.31
6.31-10.0
10000
1000
100
10
-1
-0.5
0
0.5
1
cos θz

Azimuth angle distribution East-West effect





Section 2: Inputs to calculation and their uncertainties

Uncertainties

We have two separate methods of propagating uncertainties in inputs to uncertainties in outputs

1. Variation in z-factors (spectrum weighted moments) and spectral indices
   – well follows the key inputs into calculation
   – can be traced with analytic calculation
   – emphasizes extrapolation uncertainties well

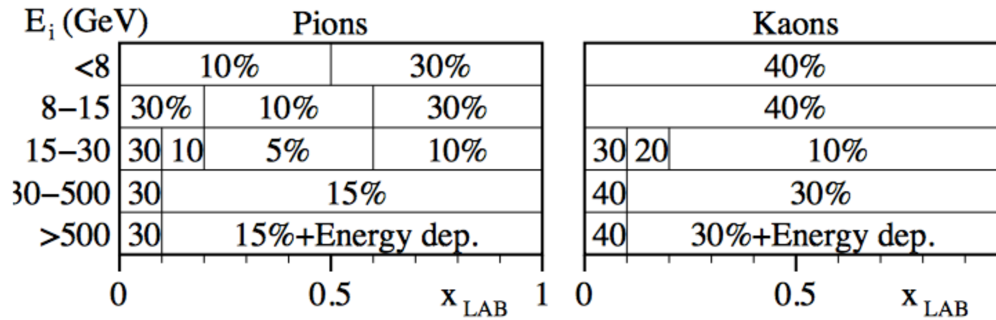
2. Changes in hadron production and flux in ‘zones’. More empirical, related to regions where experiments are good and where they are not.

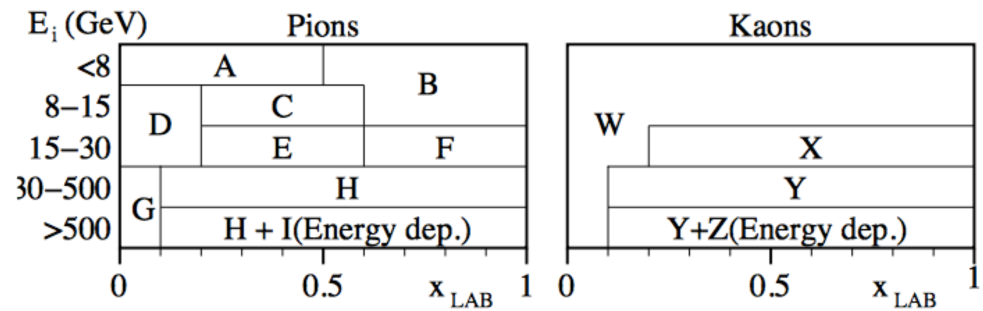
Have avoided comparing different MC for uncertainty estimation attempt

Uncertainty zones

Hadron production

- 9 zones for pions (both charges combined)
- 1 ‘zone’ for π^+/π^-
- 4 zones for K^+
- 4 zones for K^-





- Treat K^+/K^- separately since there was little data on associative production ΛK^+
- Neglect multiple interaction changes, neutrons, π^0, etc.

Fluxes

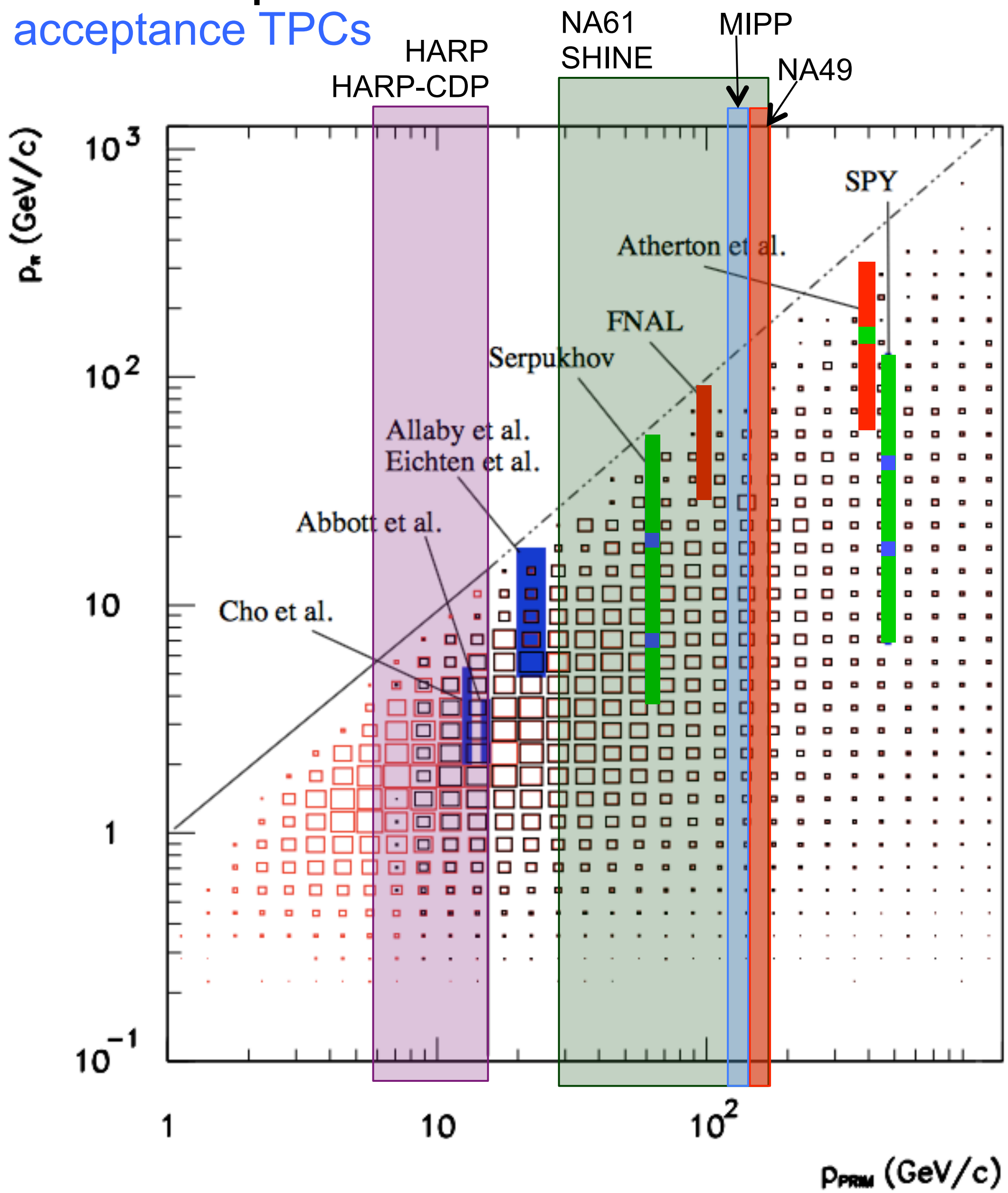
- 4 zones a,b,c,d for protons
- 4 zones a,b,c,d for He

$$\varphi(E_K) = a\left(E_K + b\exp\left[-c\sqrt{E_K}\right]\right)^{-d}$$

Parameter	Proton fluxes	Nuclear fluxes
a (normalization)	1.49 ± 0.10	0.060 ± 0.004
b	2.15 ± 0.025	1.25 ± 0.03
c	-2.21 ± 0.02	-0.14 ± 0.02
d (index) $< 200\text{GeV/n}$	2.74 ± 0.01	2.64 ± 0.02
$> 200\text{GeV/n}$	2.74 ± 0.03	2.64 ± 0.04

Newer Hadron production measurements

Large acceptance TPCs



Population of hadron-production phase-space for $pA \rightarrow \pi X$ interactions.

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

Red/black indicate extremes of magnetic latitude.

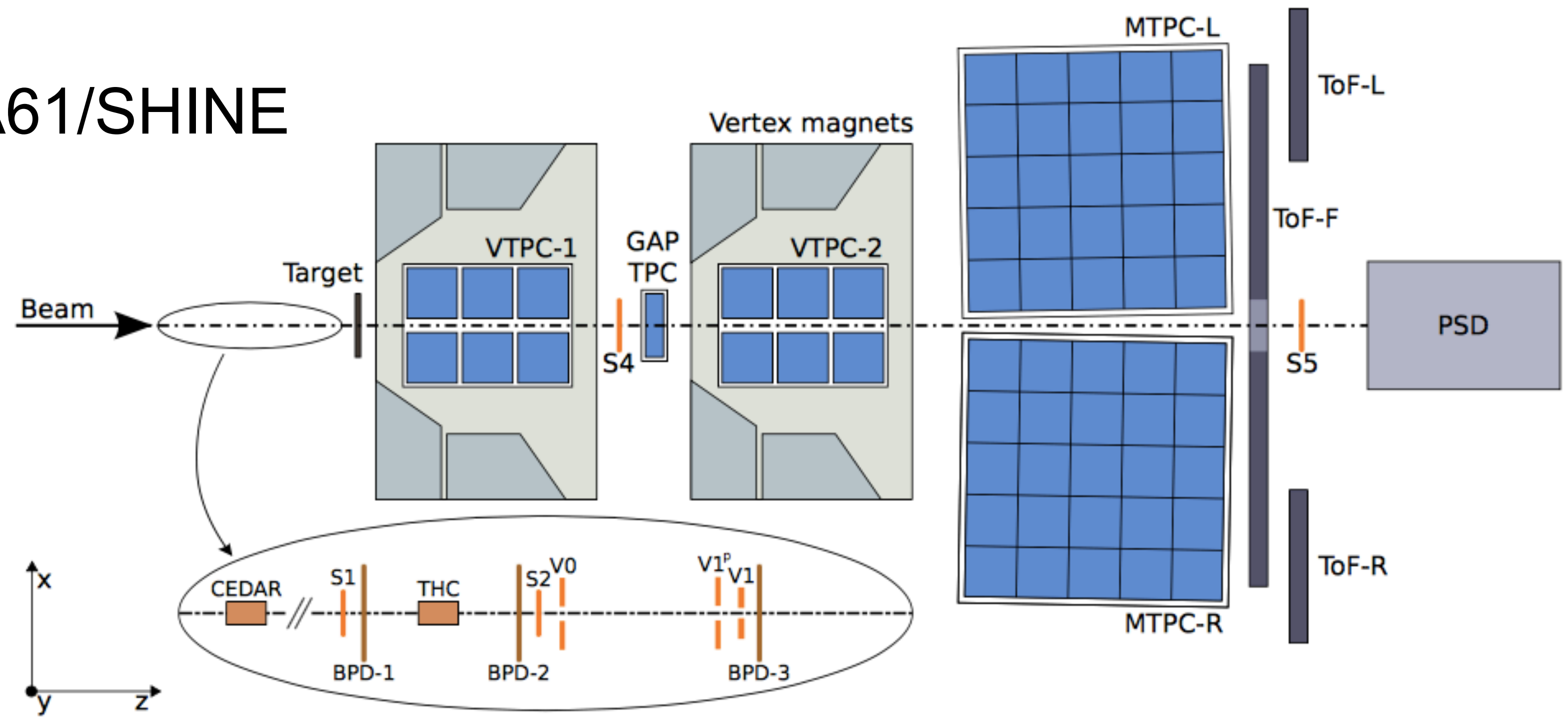
Energies around 1 GeV representing contained events in a SK-sized detector.

Measurements.

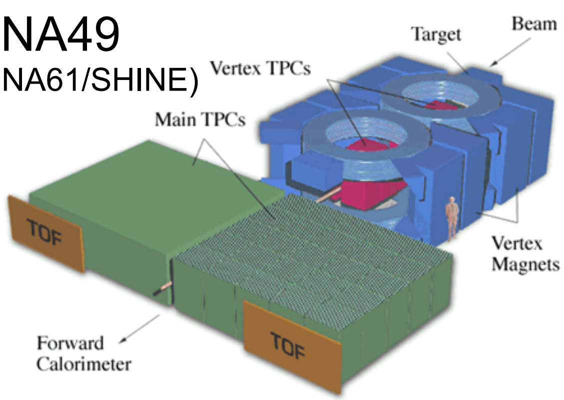
- 1-2 p_T points (red)
- 3-5 p_T points (green)
- >5 p_T points (blue)

Hadron production experiments

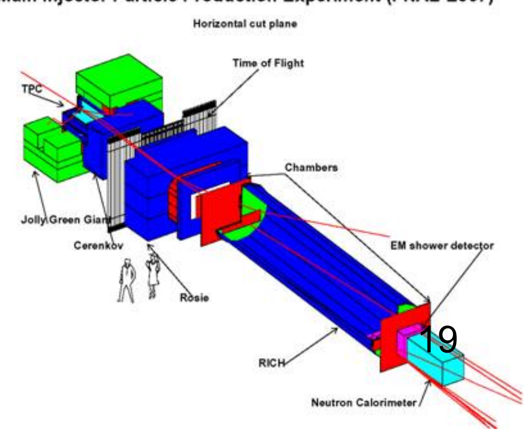
NA61/SHINE



NA49
(now NA61/SHINE)



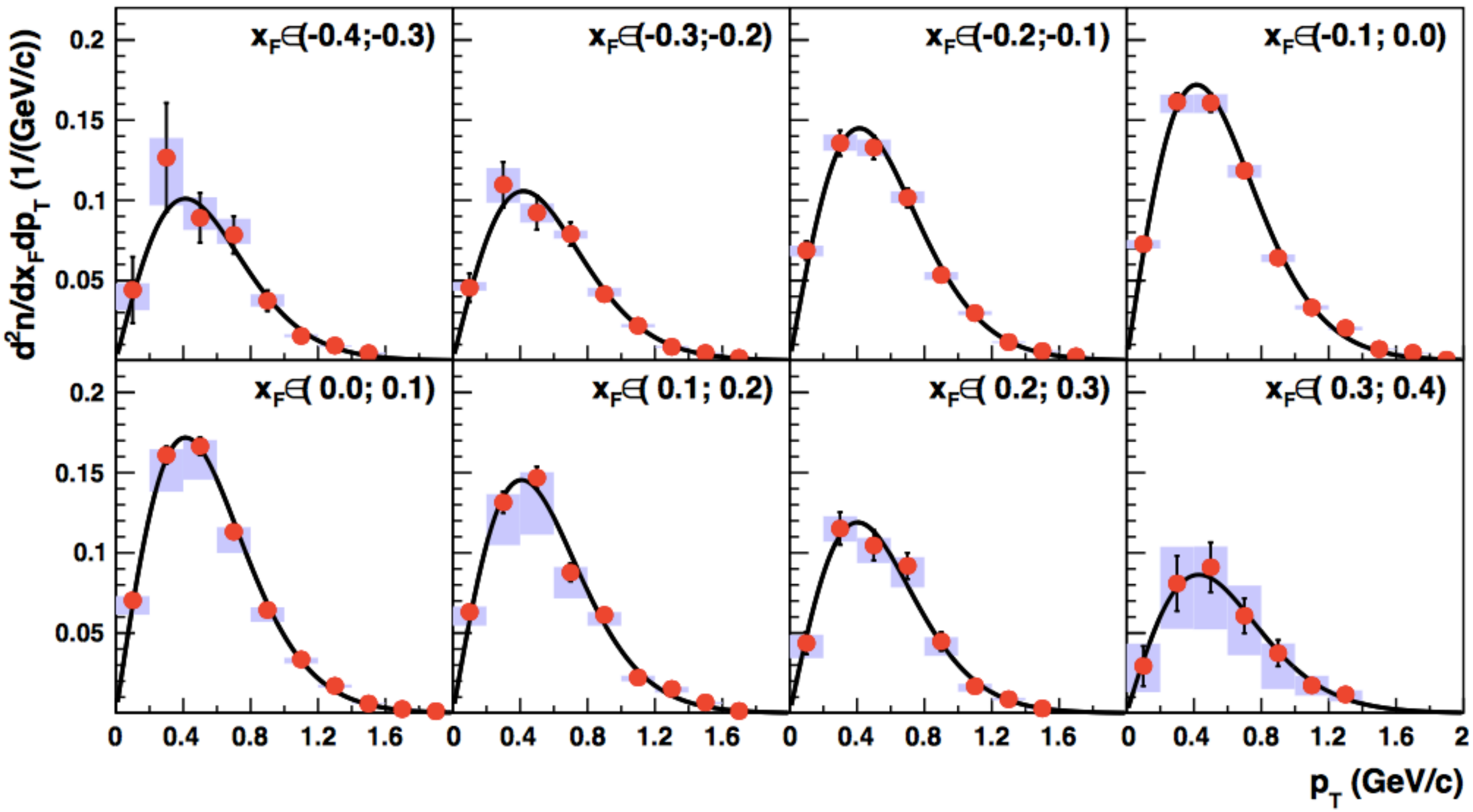
MIPP
Main Injector Particle Production Experiment (FNAL-E907)

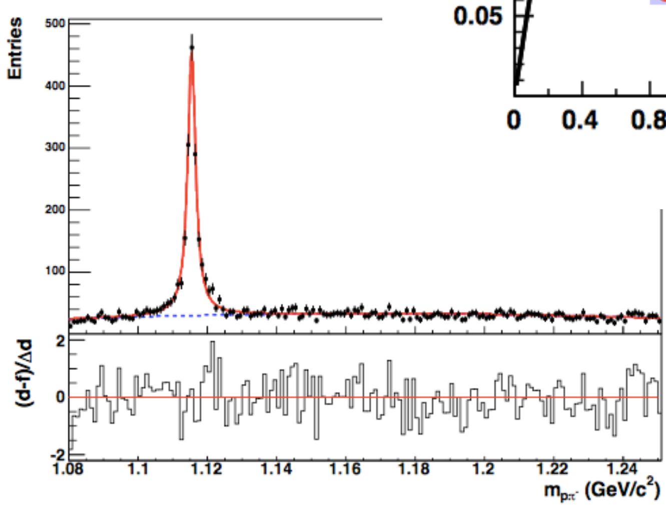


NA61/SHINE Λ strangeness production

arXiv 1510:03720 CERN PH-EP 2015-274

158 GeV/c
p+p

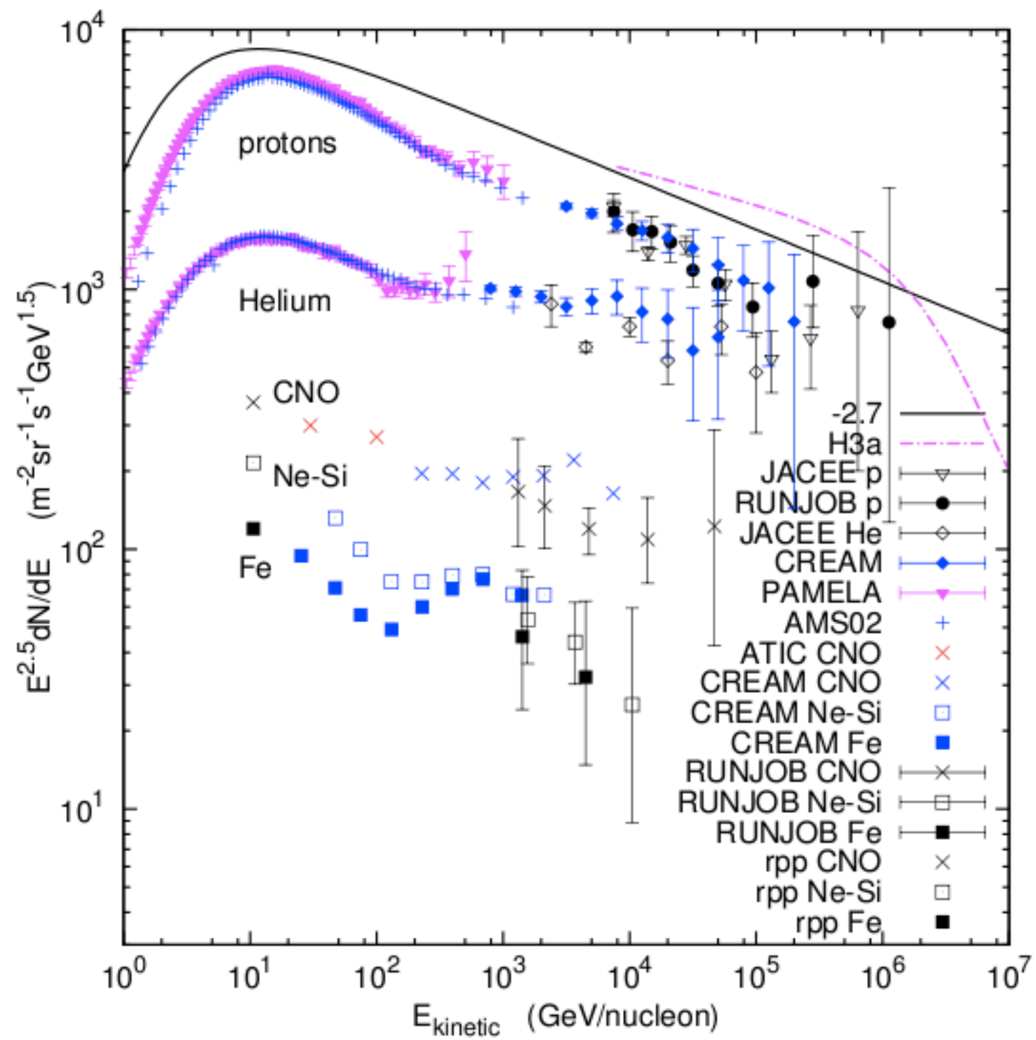




Primary spectrum

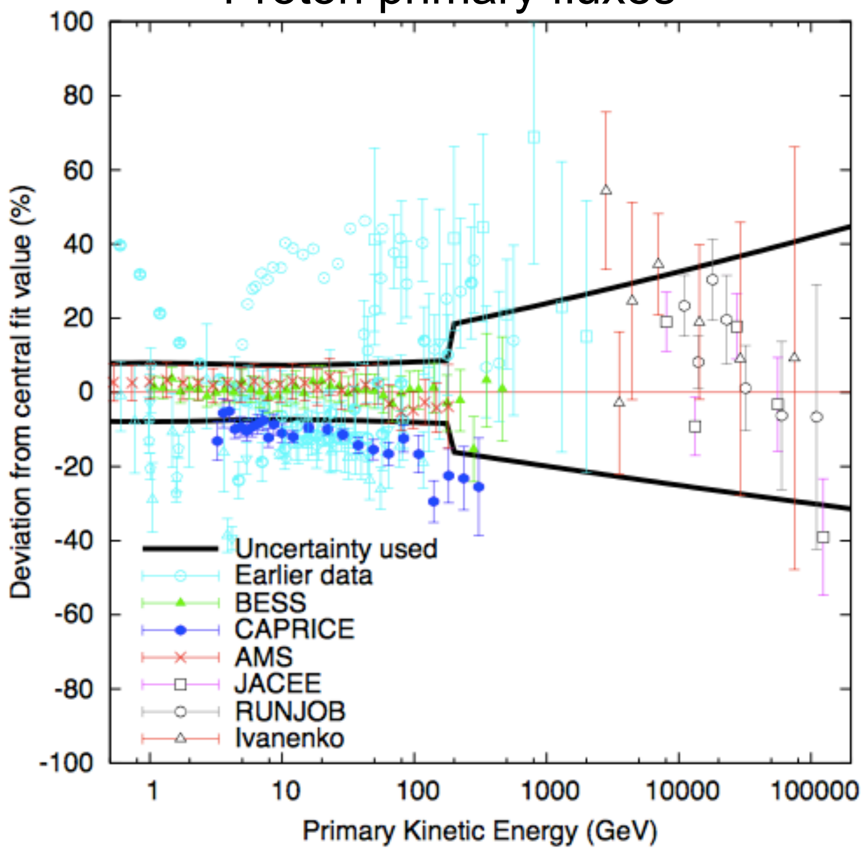
- Atmospheric leptons
  - Superposition approx:
    - Inject primary spectrum (nucleons per GeV/A)
    - For μ^+/μ^- and $\nu/\bar{\nu}$
    - track p and n by δ_0

$$\delta_0 = \frac{p-n}{p+n} \approx \frac{\text{H}}{\text{all nucleons}}$$

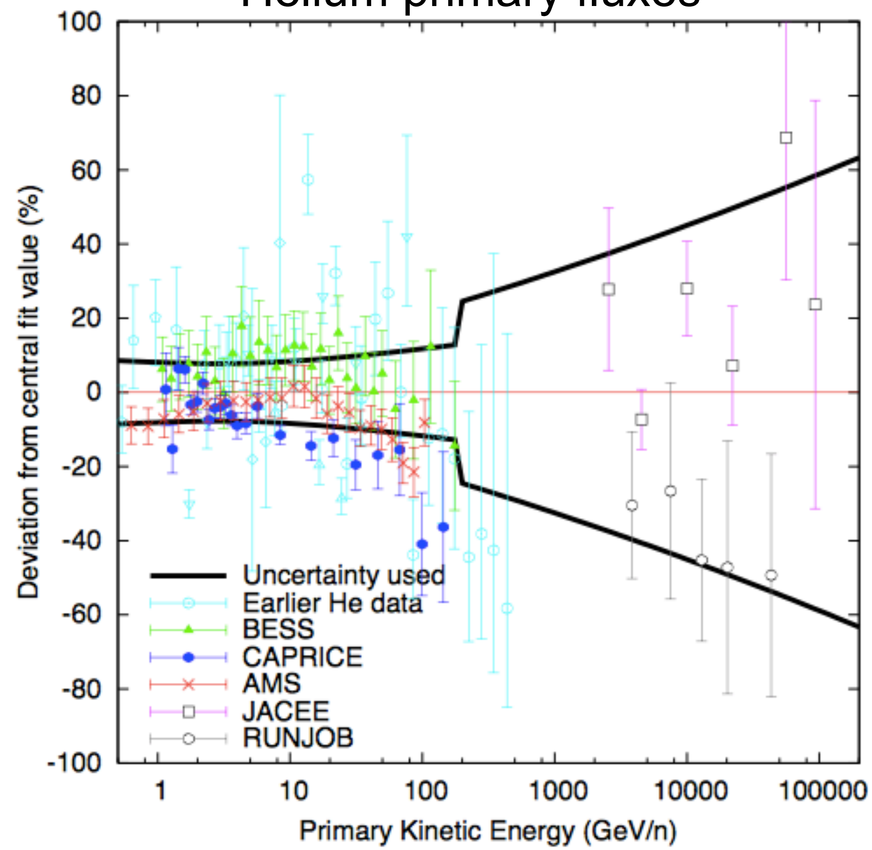


Flux uncertainty at 2004
Input into our uncertainty estimates

Proton primary fluxes



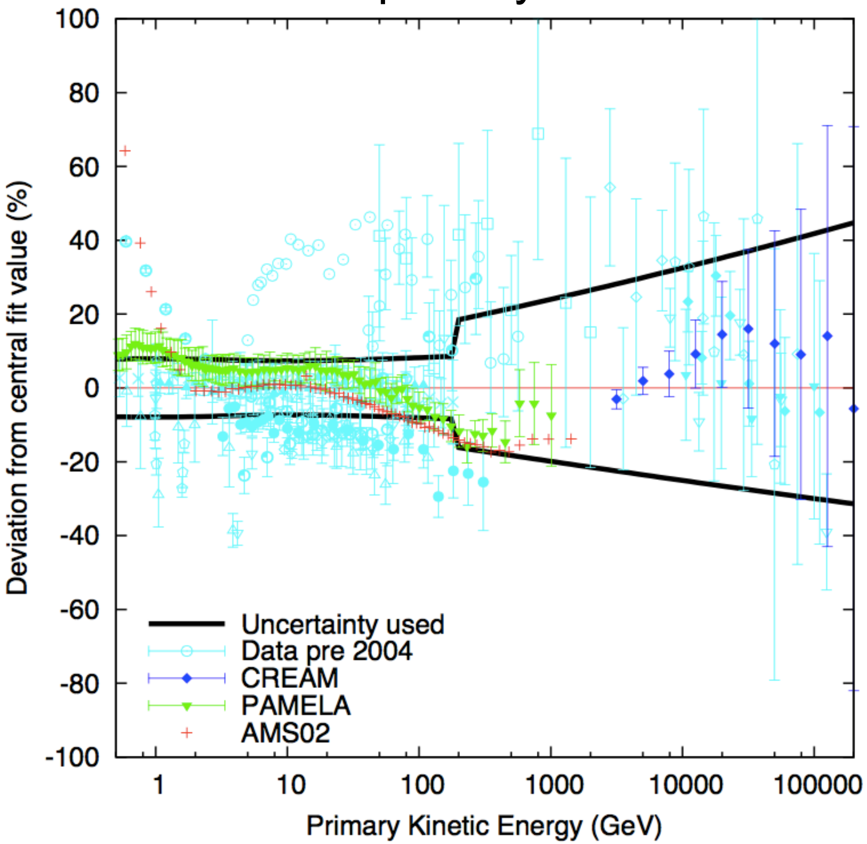
Helium primary fluxes



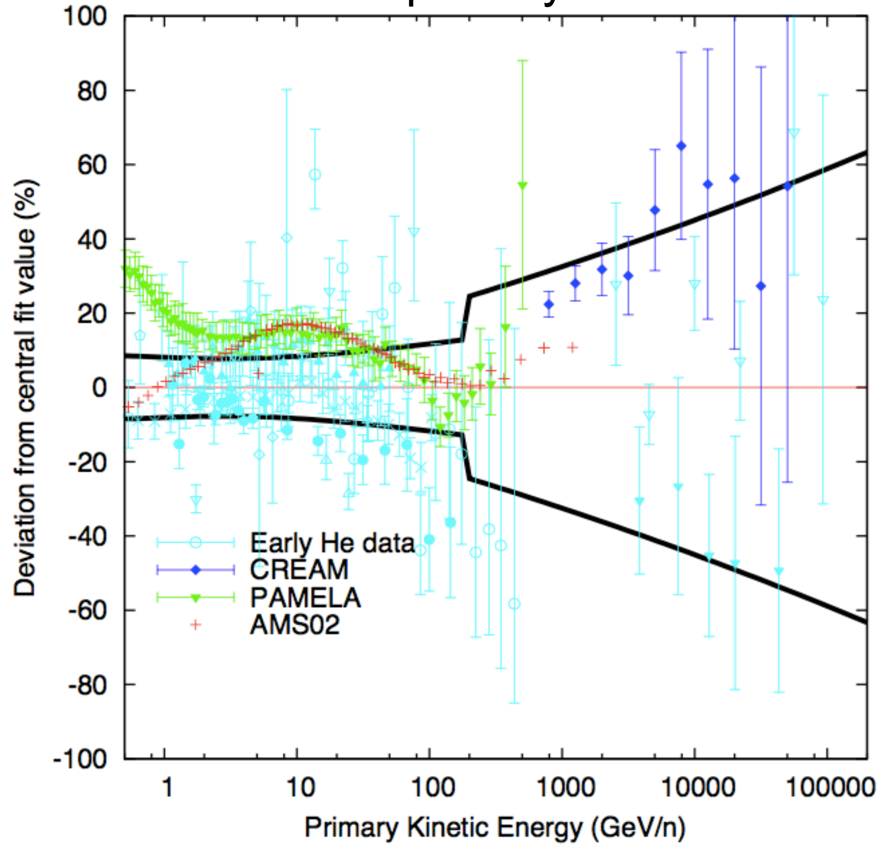
Flux uncertainty at 2004
How it looks with new data

Very preliminary 2016 look by us: Must check for bugs
Note: We have not added the error bars to the AMS02 data points yet

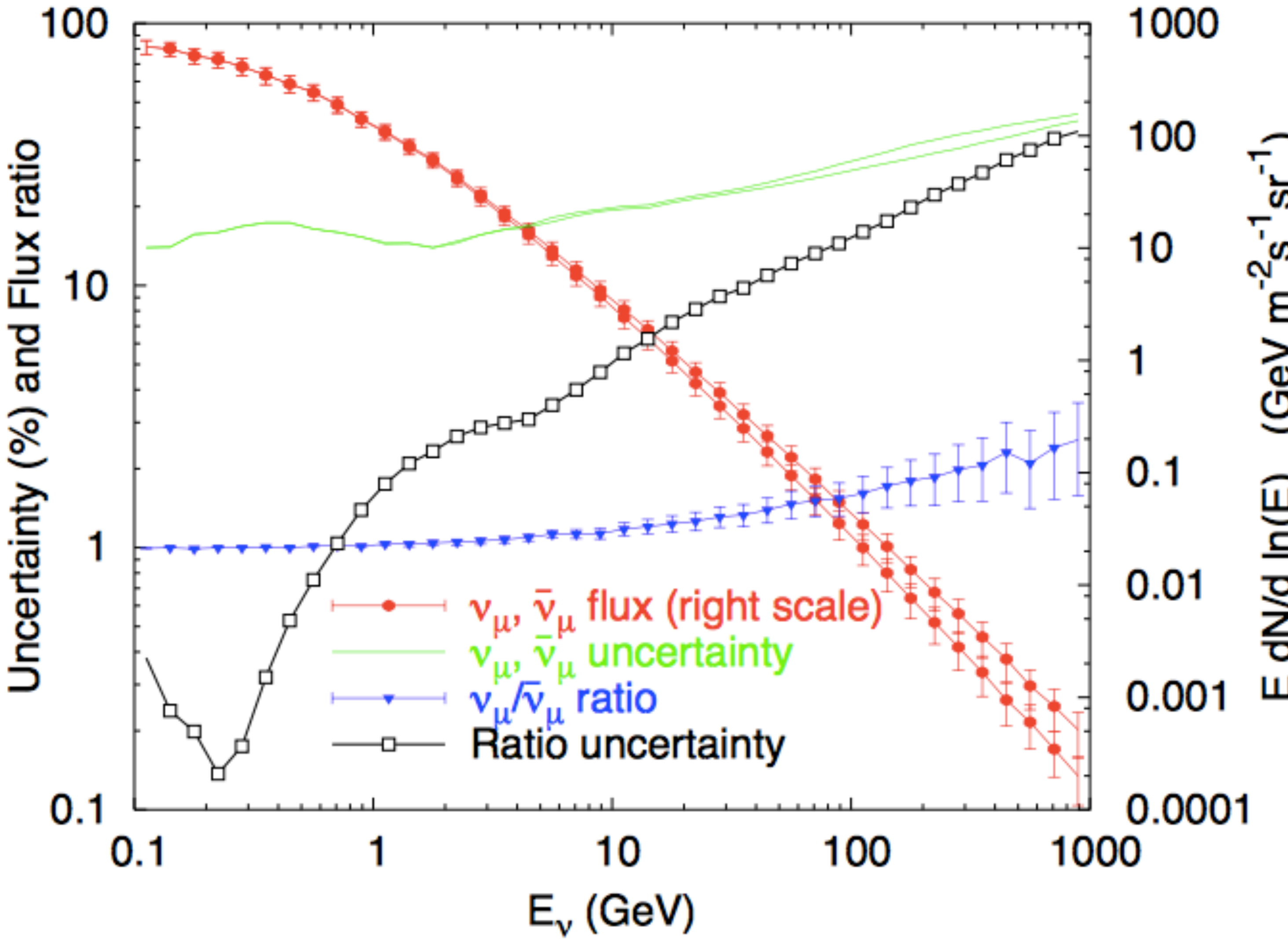
Proton primary fluxes



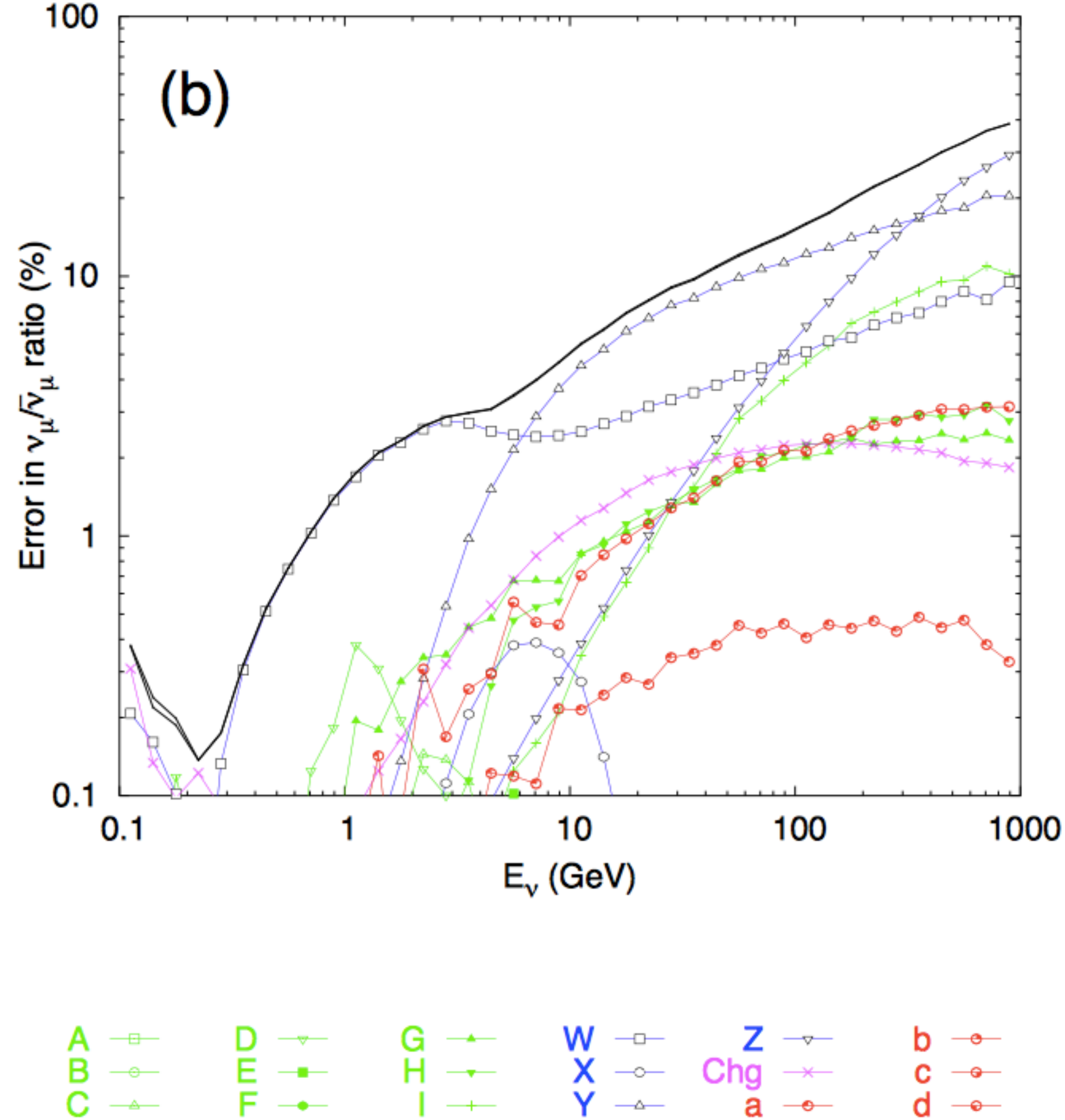
Helium primary fluxes

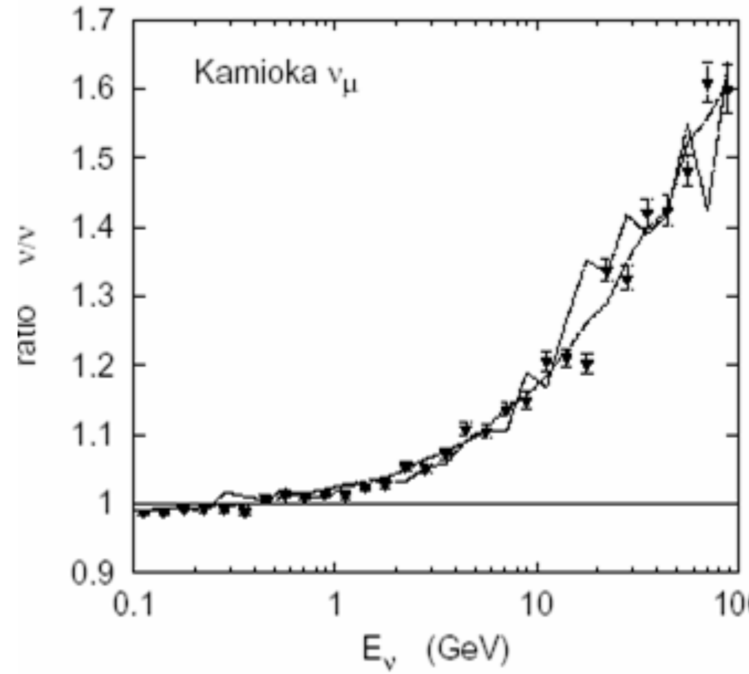


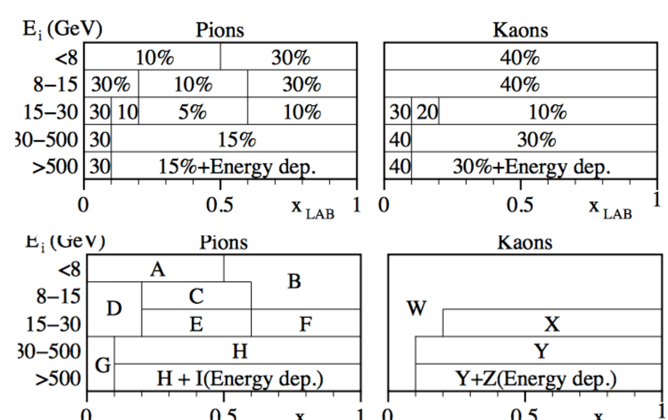
Summary plot, illustration of ratio cancellation effects



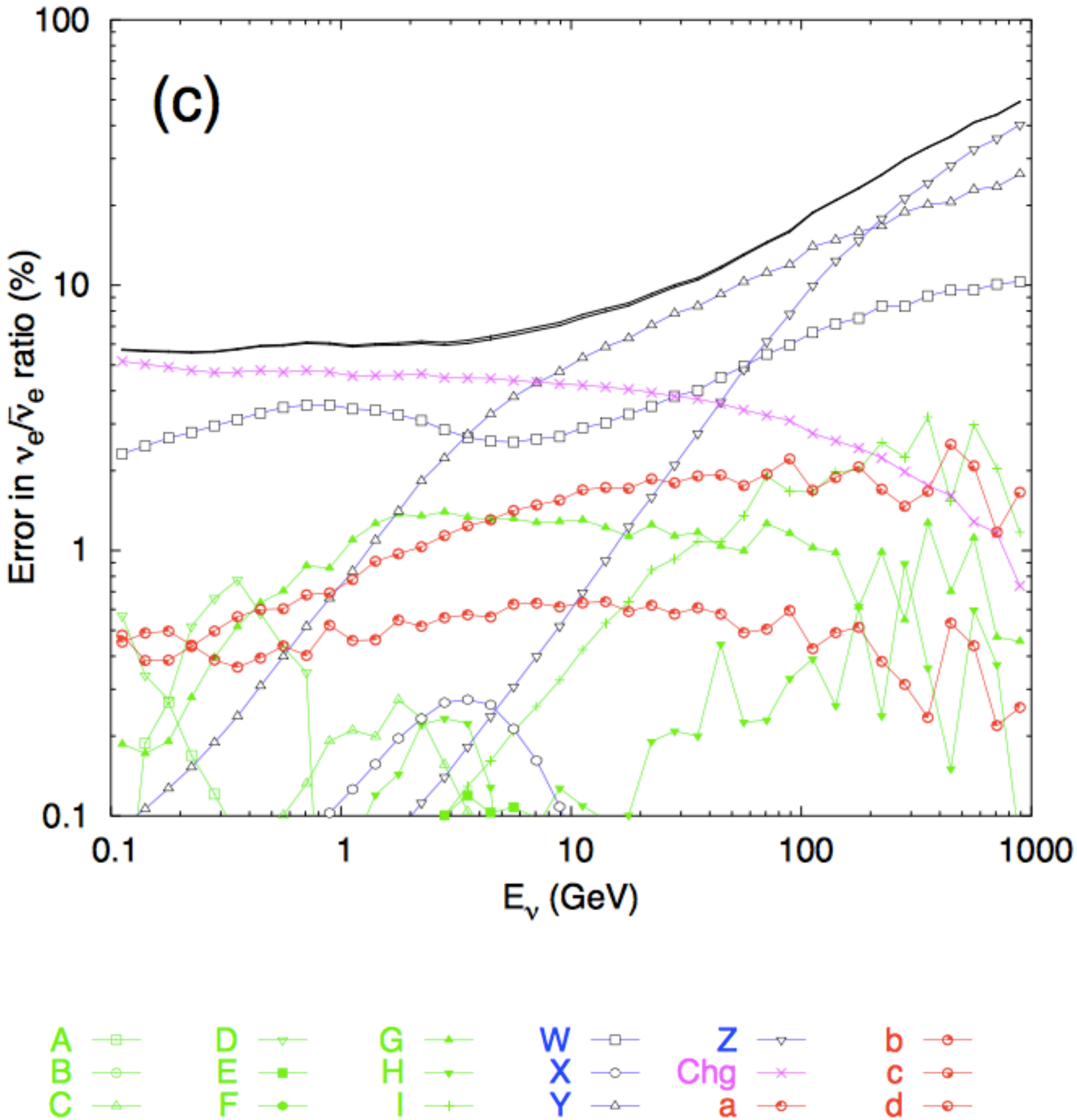
nu-mu/nu-mubar ratio & uncertainty

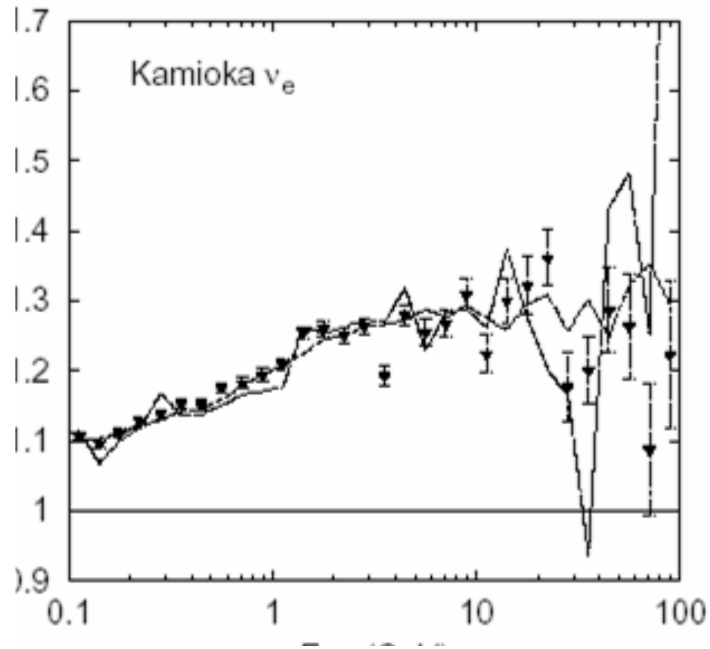


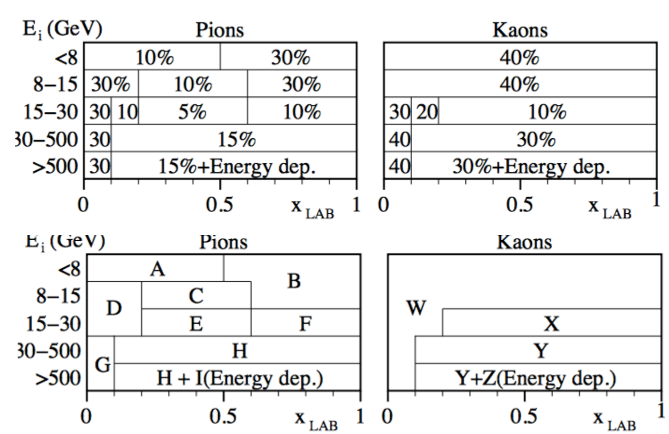




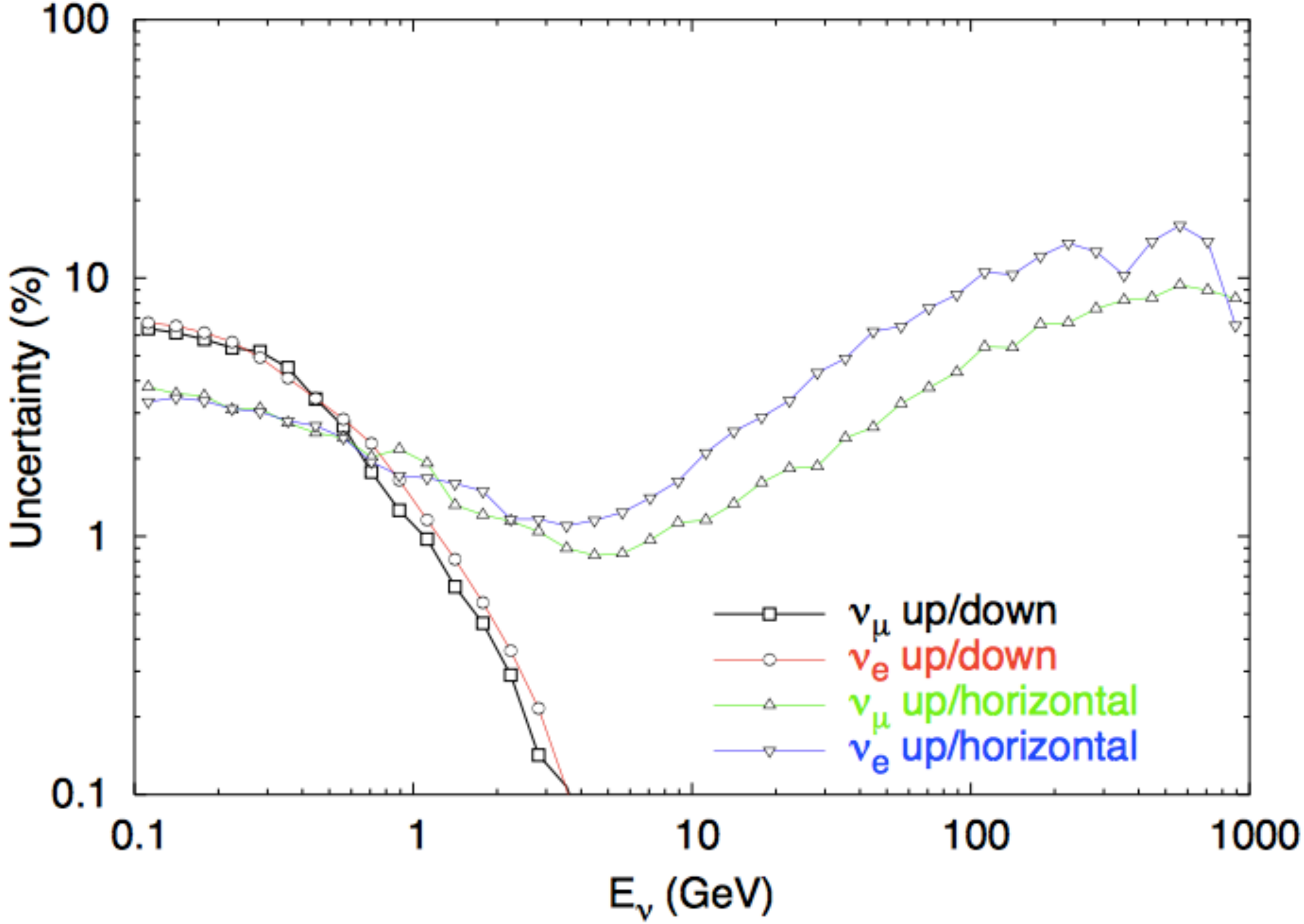
nu-e/nu-e bar ratio & uncertainty



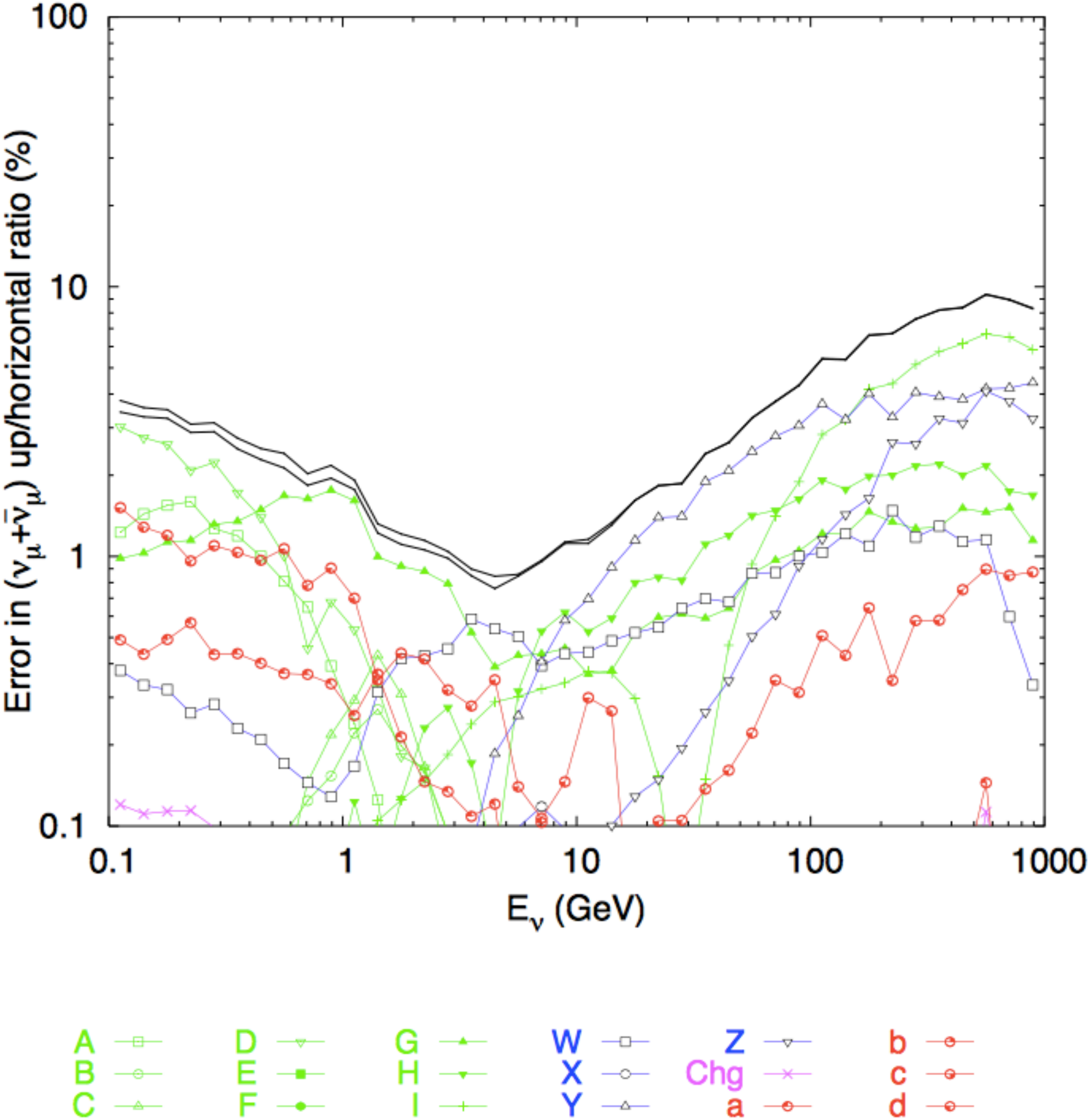




Direction ratio uncertainties



Up/Horizontal - More details



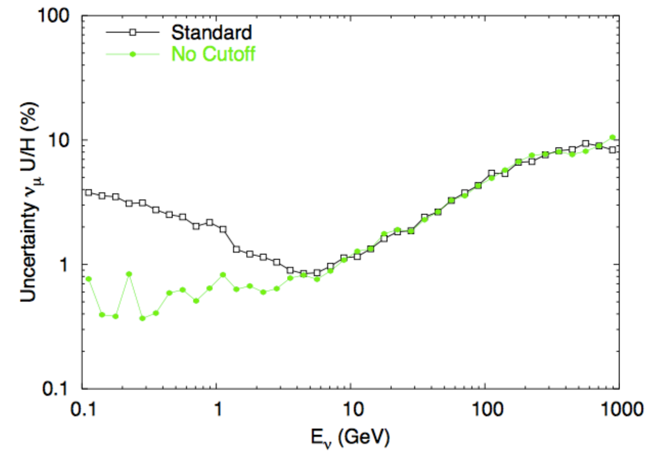
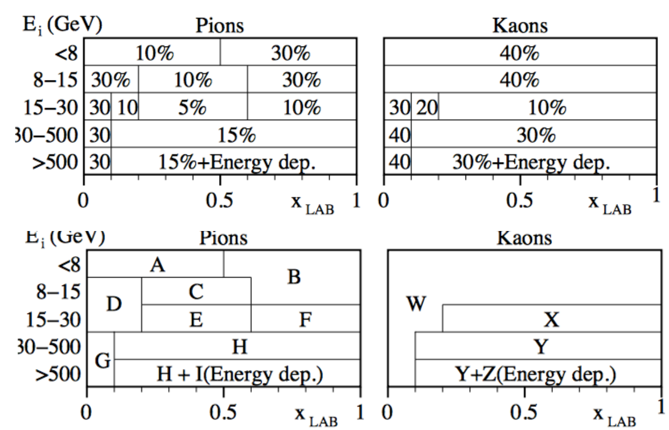
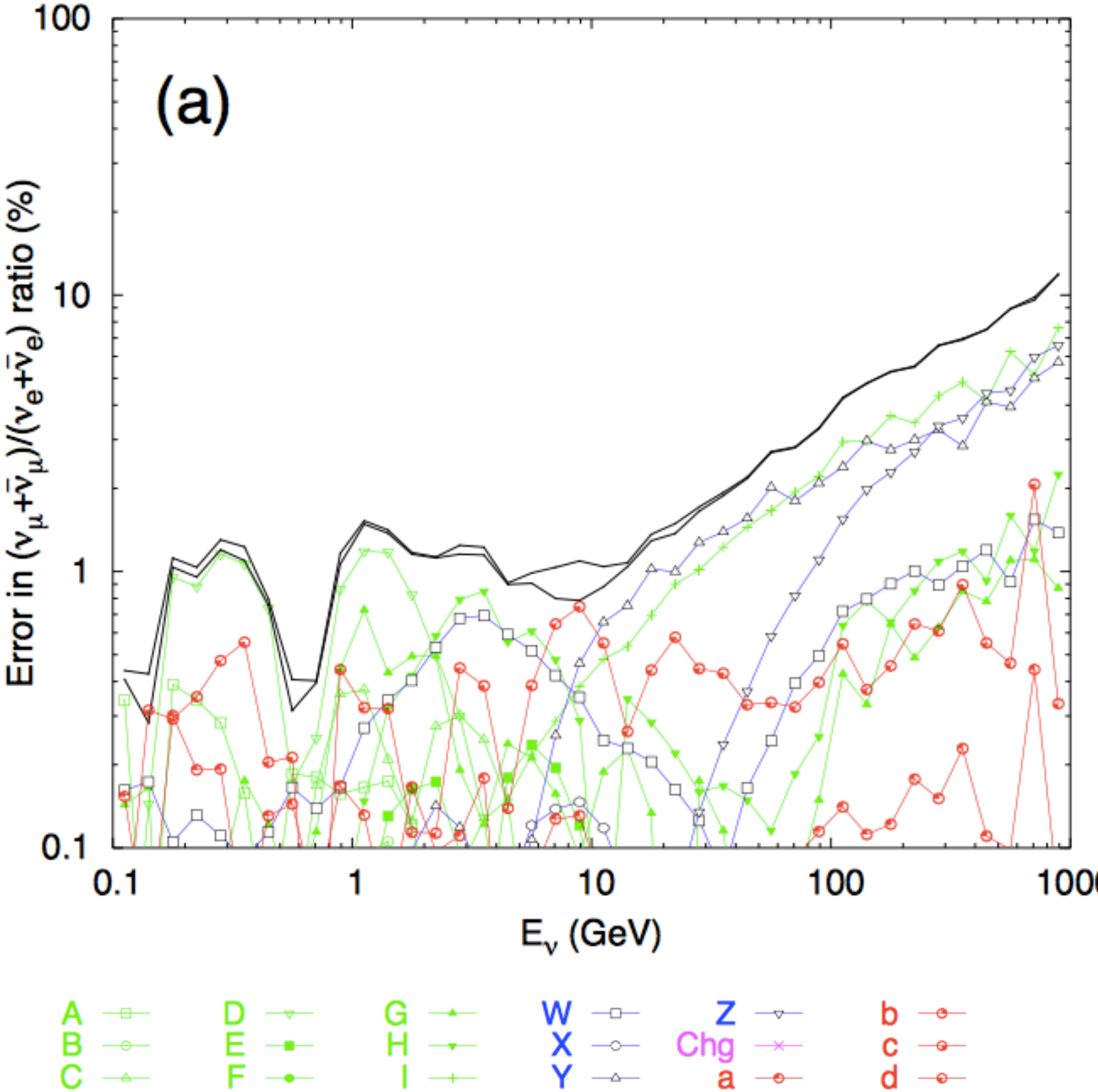
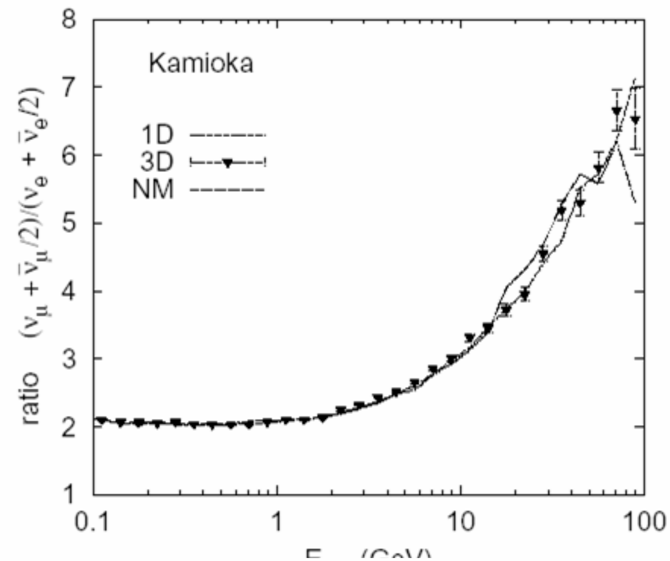


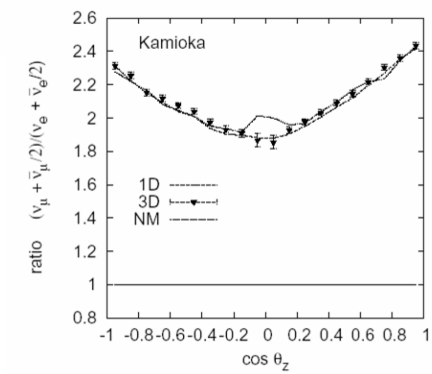
FIG. 18: (color online) Line with open squares shows the standard uncertainty in the up/horizontal ν_μ flux ratio and line with closed circles the uncertainty with the effect of the Earth's magnetic field removed.



Flavour ratio – details







E_i (GeV)	Pions	Kaons
<8	10% | 30%	40%
8–15	30% | 10% | 30%	40%
15–30	30 | 10 | 5% | 10%	30 | 20 | 10%
30–500	30 | 15%	40 | 30%
>500	30 | 15%+Energy dep.	40 | 30%+Energy dep.

x_{LAB}: 0 – 0.5 – 1 (Pions); 0 – 0.5 – 1 (Kaons)

E_i (GeV)	Pions	Kaons
<8	A | B	W
8–15	D | C | B	W
15–30	D | E | F	W | X
30–500	G | H	Y
>500	G | H + I(Energy dep.)	Y+Z(Energy dep.)

x_{LAB}: 0 – 0.5 – 1 (Pions); 0 – 0.5 – 1 (Kaons)

Left: Cross checks on uncertainty estimate with

- rearranged uncertainty zones (called 'sources' in plot),
- cutoffs
- hadron generator

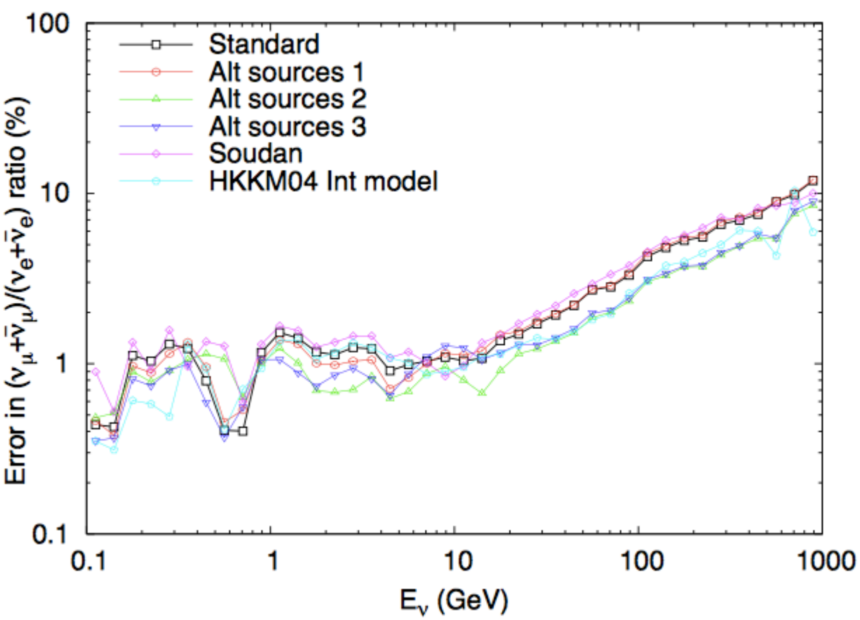


FIG. 14: (color online) Stability of the uncertainty estimates as a function of different choices of uncertainty sources ((1), (2), (3)), detector location (Soudan) and base hadron production generator.

Right: Reduction in cancellation at different parts of solar cycle

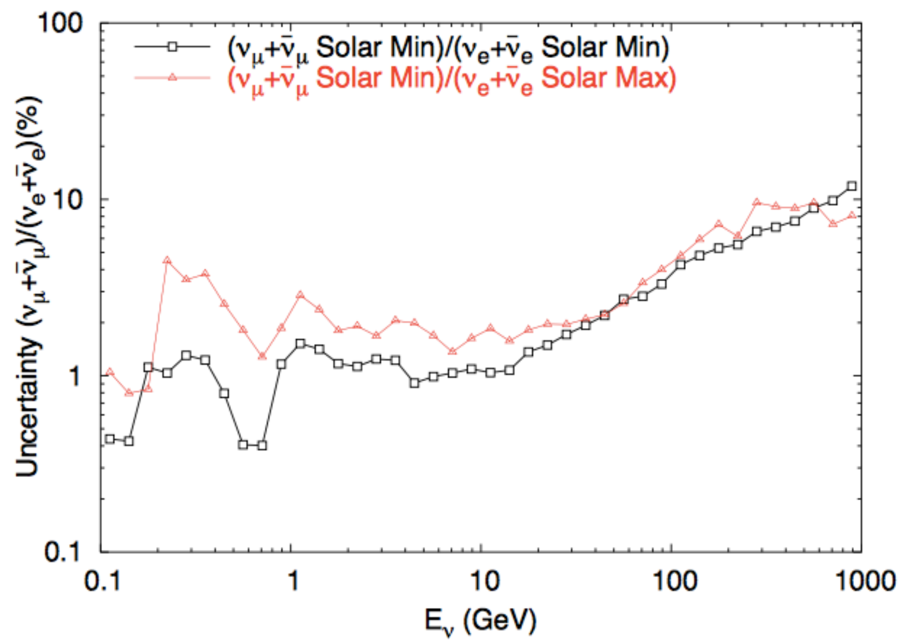
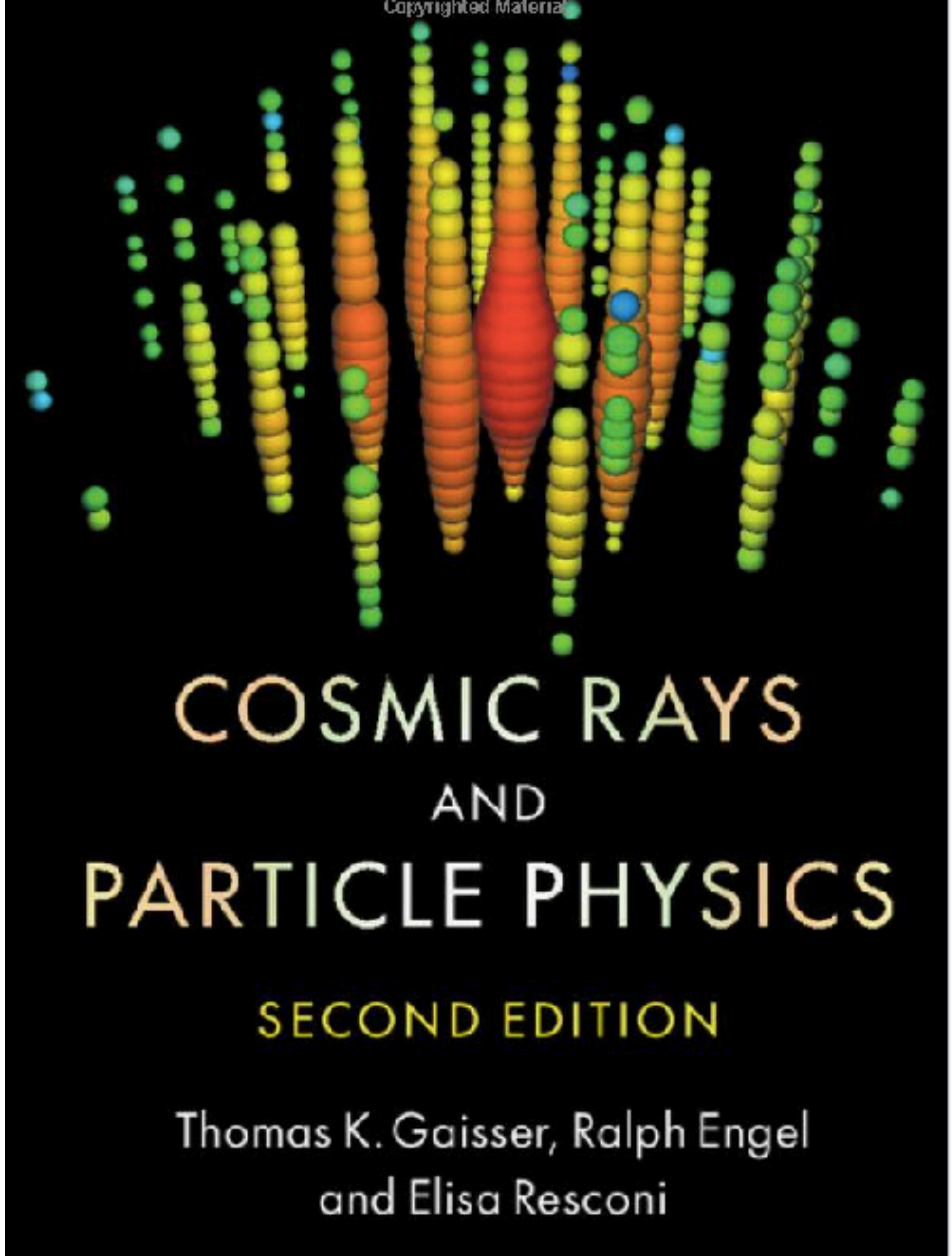


FIG. 17: (color online) Increase in muon neutrino to electron neutrino flux uncertainty when comparing fluxes from different parts of the solar cycle at Soudan.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PARTICLE PHYSICS
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Thomas K. Gaisser, Ralph Engel
and Elisa Resconi

Key points

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  - It will be slow at first, we have to check the old code still runs properly.

- Much new input data from hadron production cross sections and primary fluxes

- The calculations include hooks for evaluating and propagating uncertainties, and this will be extended.

- The calculations display interesting cancellations of uncertainties when used in the regions of interest for mass hierarchy measurements.

END OF TALK
The following slides are spares

Overview

Section 1: Bartol atmospheric neutrino fluxes

- Introduction
- Components of calculation technique
  - Propagation through atmosphere…
  - Back tracing primaries to get cutoffs
- Results

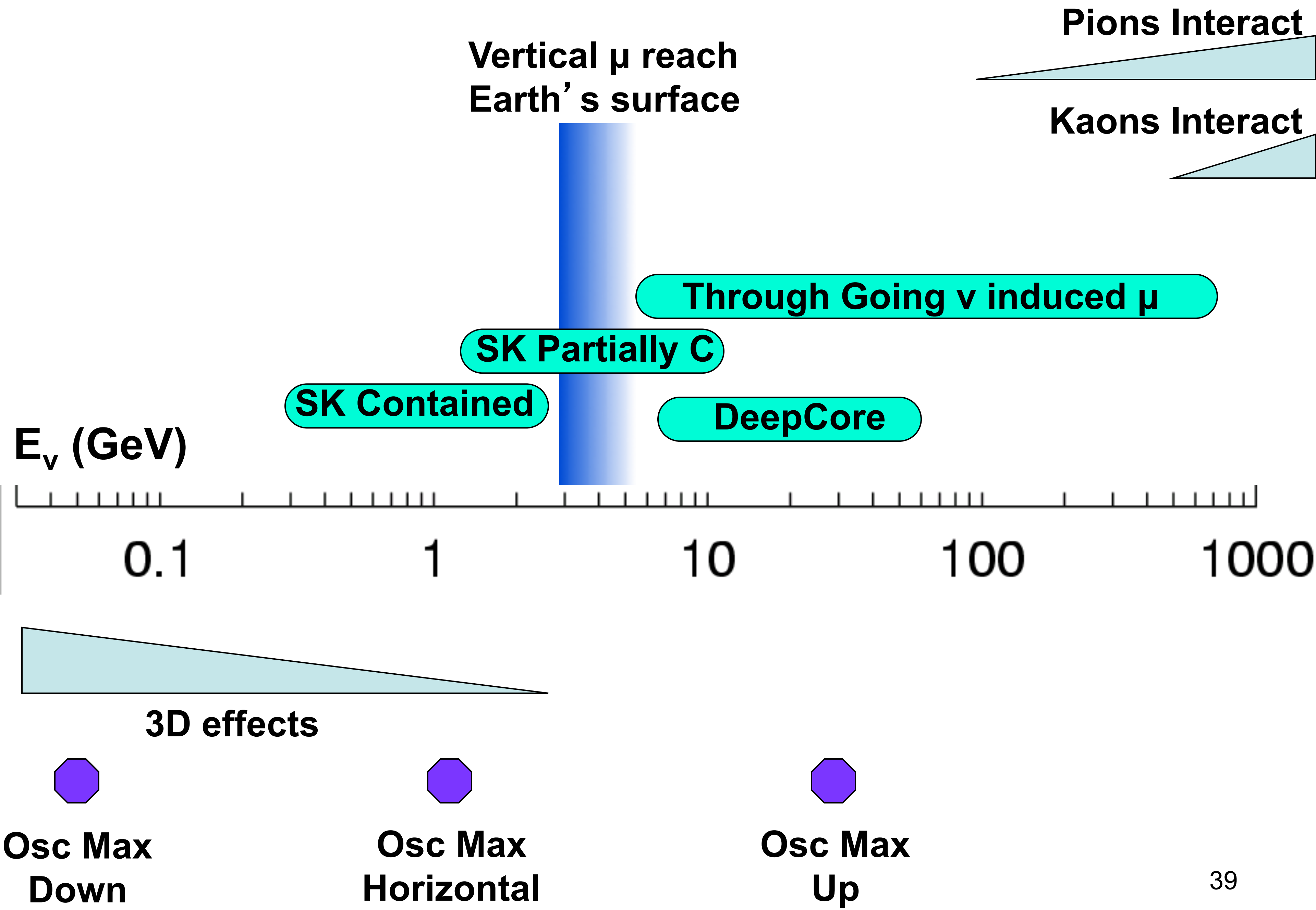
Section 2: Inputs and their uncertainties

- Methodology
- Hadron production
- Primary fluxes
- Uncertainty estimation results

Section 3: Outlook

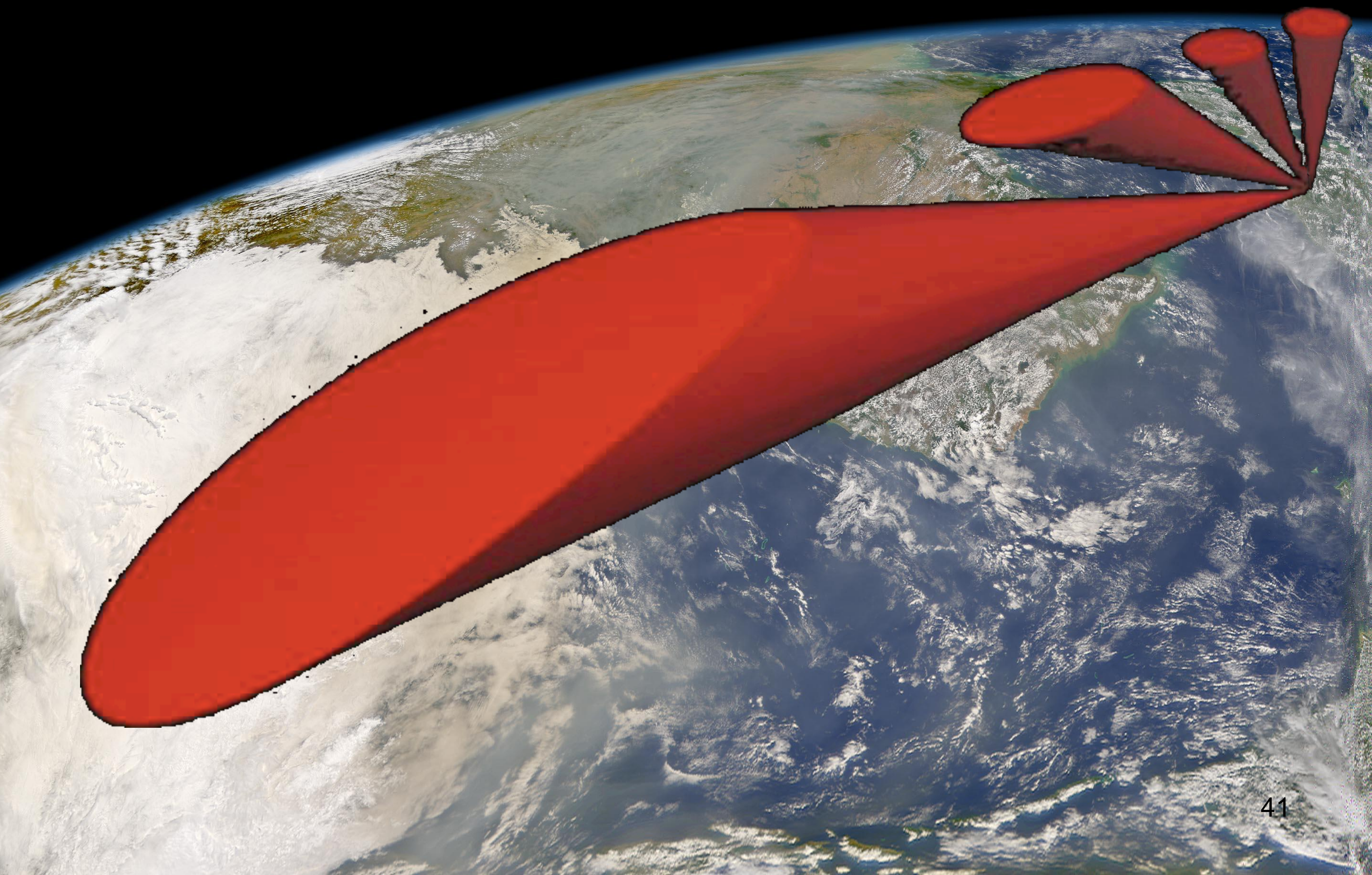
Introduction

- Objective is to calculate neutrino fluxes underground.
- Simulate cascades in the atmosphere, count the neutrinos resulting from secondary particle decays.
- Negligible probability of seeing more than one neutrino from one cosmic ray shower
  - No need to provide detailed transverse momentum balance for each interaction.
  - Superposition technique for dealing with nuclei primaries (i.e. heavier than protons). Treat as individual nucleons.


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

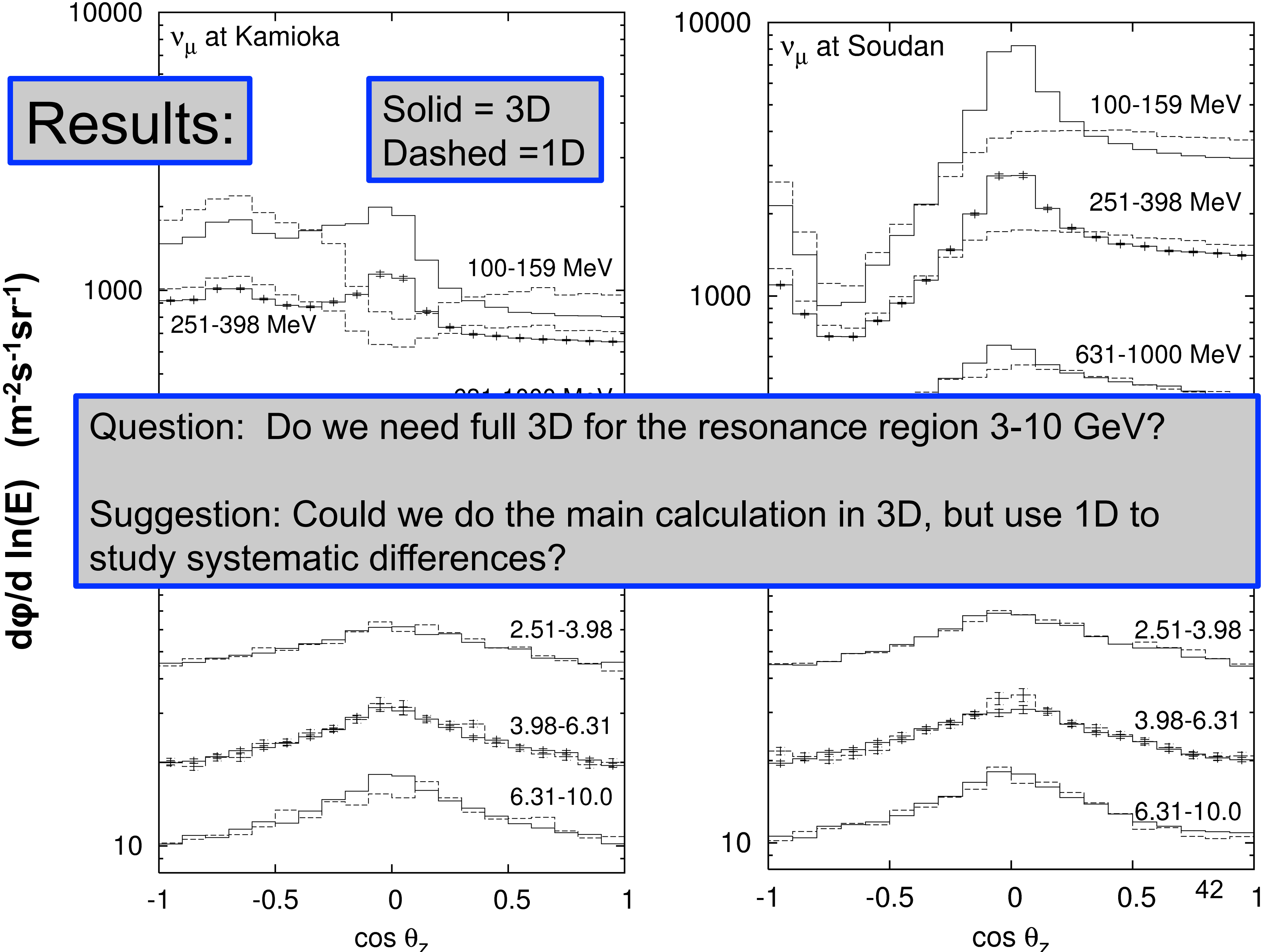
3-Dimensional effect

3-Dimensional effect



Results:

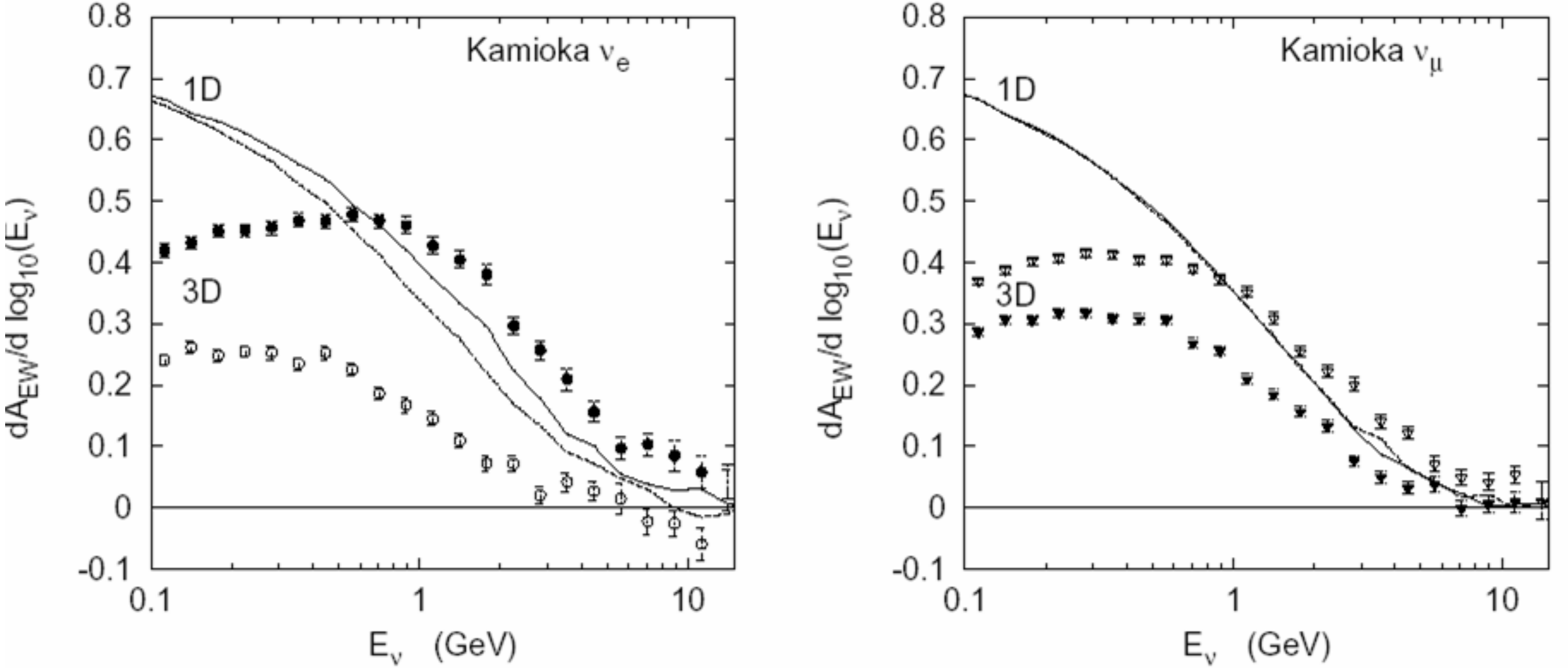
Solid = 3D
Dashed =1D



Question: Do we need full 3D for the resonance region 3-10 GeV?

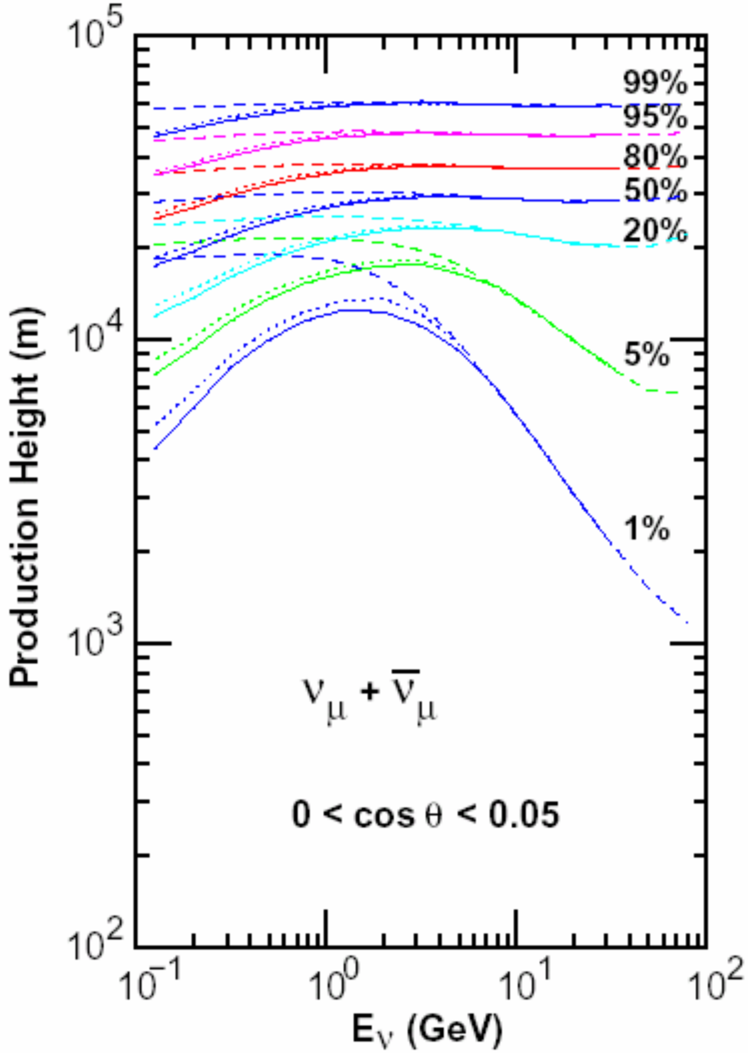
Suggestion: Could we do the main calculation in 3D, but use 1D to study systematic differences?

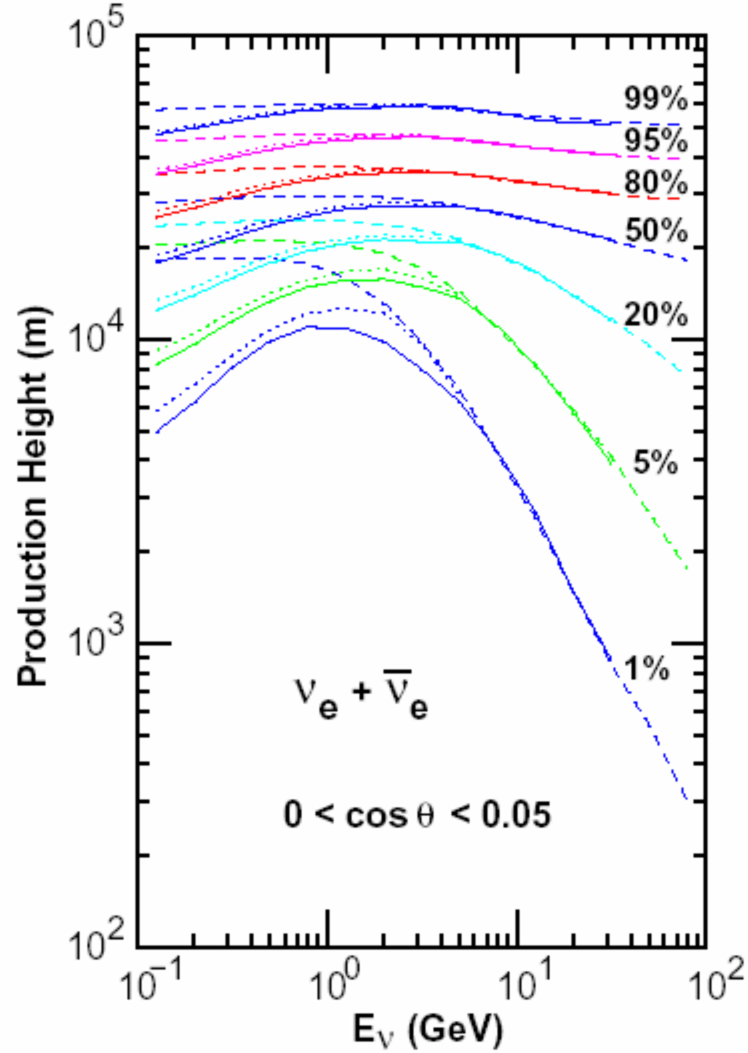
Energy dependence of East-West effect



Path length distributions

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





Primary spectrum (nucleons)

Neutrinos from $\pi^{\pm}$

Neutrinos from $K^{\pm}$

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \simeq \frac{N_0(E_\nu)}{1-Z_{NN}} \left\{ \frac{\mathcal{A}_{\pi\nu}}{1+\mathcal{B}_{\pi\nu}\cos\theta\, E_\nu/\epsilon_\pi} + 0.635\, \frac{\mathcal{A}_{K\nu}}{1+\mathcal{B}_{K\nu}\cos\theta\, E_\nu/\epsilon_K} \right\}$$

$1-Z_{NN}$: re-interaction of nucleons

$$\mathcal{A}_{\pi\nu} \equiv Z_{N\pi} \frac{(1-r_\pi)^{\gamma+1}}{(1-r_\pi)(\gamma+1)} = Z_{N\pi} Z_{\pi\nu} \qquad r_\pi = \frac{m_\mu^2}{m_\pi^2} \approx 0.573$$

$$\gamma \sim 1.7$$

$$\mathcal{A}_{K\nu} \equiv Z_{NK} \frac{(1-r_K)^{\gamma+1}}{(1-r_K)(\gamma+1)} \qquad r_K = \frac{m_\mu^2}{m_K^2} \approx 0.0458$$

The formula for the flux of muons is the same except for the 2-body decay factor (and an overall pre-factor for the muon survival probability)

$$\mathcal{A}_{\pi\mu} \equiv Z_{N\pi} \frac{(1-r_\pi^{\gamma+1})}{(1-r_\pi)(\gamma+1))}$$

Z-factors

A way to weight the phase space of secondary hadrons by the relative importance of parent nucleons in the steep primary spectrum; for example:

$$Z_{p\pi} = \frac{1}{\sigma_{p,air}} \int_0^1 (x_L)^\gamma \frac{\mathrm{d}\sigma_{p\pi}(x_L)}{\mathrm{d}x_L} \mathrm{d}x_L$$

$$\text{where} \quad x_L = \frac{E_\pi}{E_p}$$

$$Z_{p\pi^+} \approx 0.040\,; \quad Z_{p\pi^-} \approx 0.026$$

$$Z_{pK^+} \approx 0.0083\,; \quad Z_{pK^-} \approx 0.0026$$

This subset of Z-factors is of special interest for the ratios μ^+ / μ^- and neutrino / anti-neutrino

Table 5.2 *Spectrum-weighted moments at 1 TeV*

Index	$\gamma = 1$	$\gamma = 1.7$	$\gamma = 2.0$	$\gamma = 1.7$
p-air	Ref. [199]			Ref. [200]
$\pi^0(+\eta)$	0.206	0.0459	0.0279	0.039
π^+	0.206	0.0489	0.0302	0.046
π^-	0.156	0.0324	0.0191	0.033
K^+	0.030	0.0071	0.0044	0.0090
K^-	0.018	0.0036	0.0021	0.0028
$K_L + K_S$	0.043	0.0092	0.0054	–
$p + \bar{p}$	0.217	0.126	0.107	0.263
$n + \bar{n}$	0.114	0.052	0.040	0.035

Index	$\gamma = 1.7$			
Sibyll 2.3 [155]	p-p	p-air	π^+-air	K^+-air
$\pi^0(+\eta)$	0.035	0.039	0.054	0.042
π^+	0.041	0.040	0.206	0.058
π^-	0.25	0.026	0.043	0.033
K^+	0.0088	0.0083	0.012	0.135
K^-	0.0024	0.0026	0.0061	0.0055
$K_L + K_S$	0.0087	0.0088	0.0018	0.064
$p + \bar{p}$	0.253	0.185	0.0096	0.011
$n + \bar{n}$	0.089	0.077	0.011	0.0084

199 = Sanuki, et al., PRD75 (2007) 043005 (thanks to M. Honda)
200 = Cosmic Rays and Particle Physics (1990)
155 = F. Riehn et al., ICRC 2015

Transition to high energy

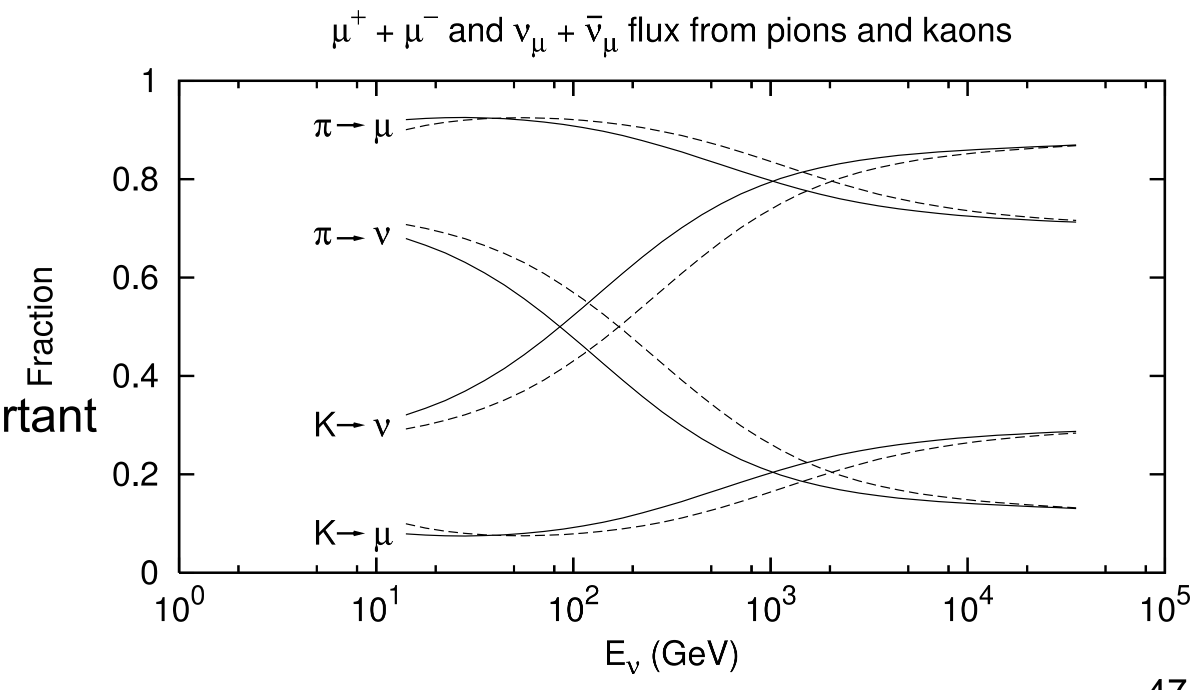
$\text{For } E \gg \epsilon / \cos\theta$ mesons preferentially interact, rather than decay

Then the production spectrum of leptons becomes one power steeper than the primary spectrum of nucleons, and $Z_{\pi\pi}$, Z_{KK} come into play

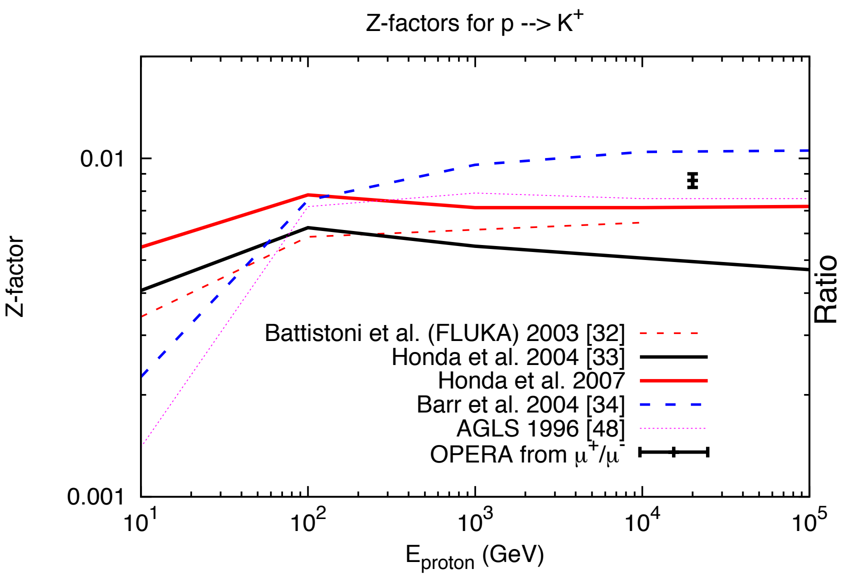
$$\epsilon_{\pi^\pm} \approx 115 \text{ GeV}$$

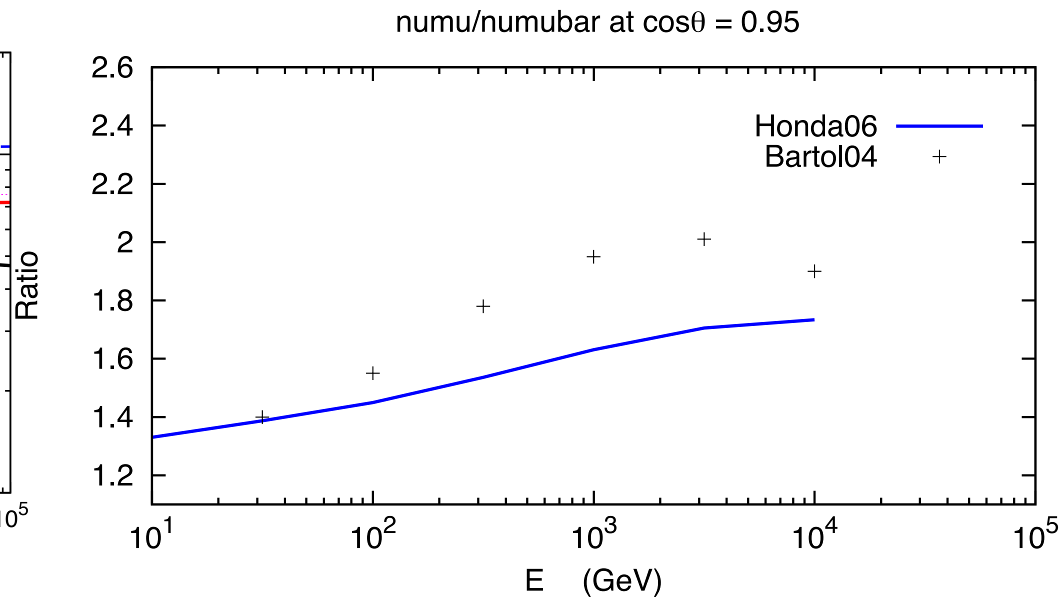
$$\epsilon_{K^\pm} \approx 850 \text{ GeV}$$

ε contains cτ, affected by interaction versus decay. This makes the kaons important above pion critical energy.



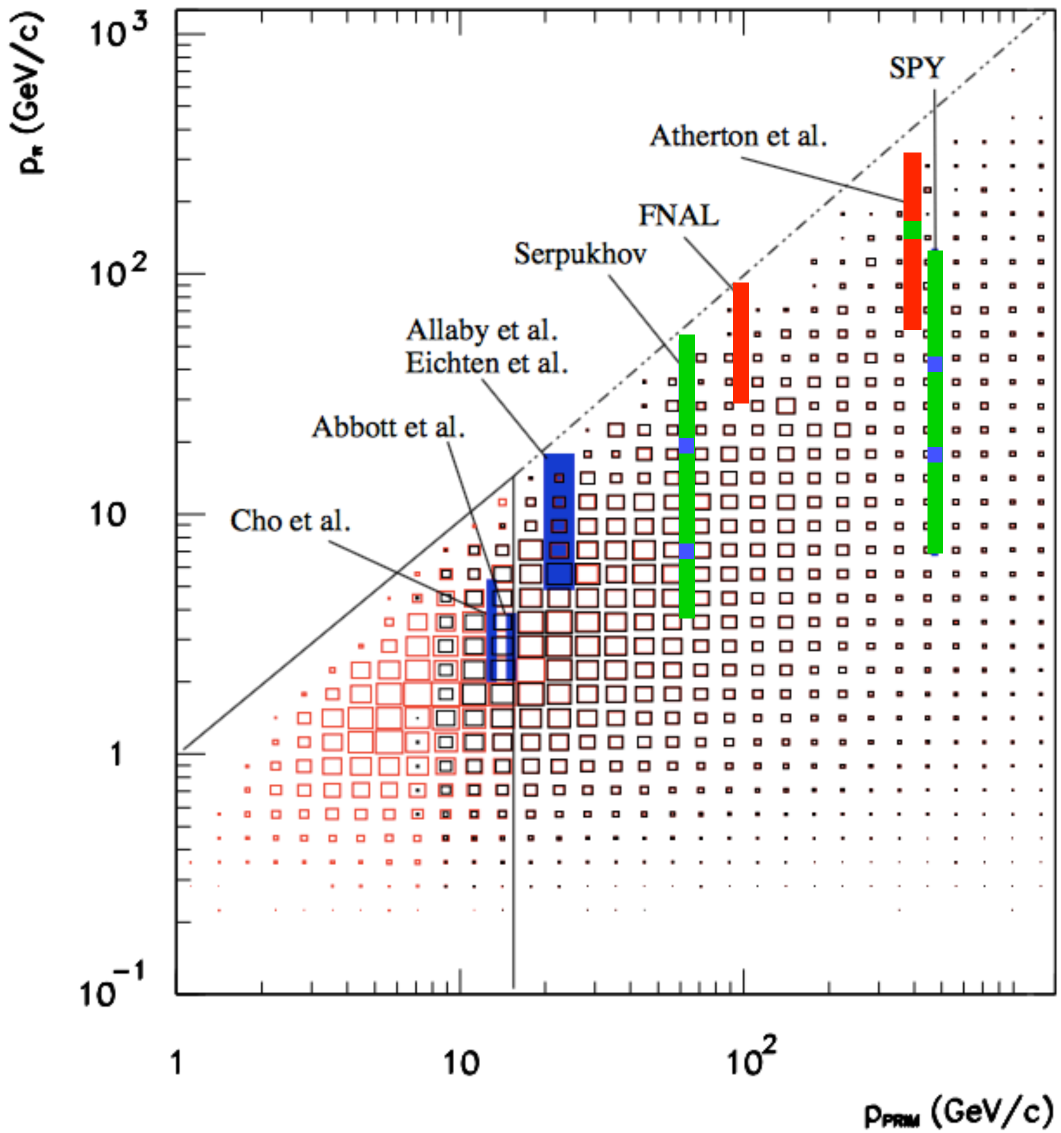
Z-factors as a tool for evaluating uncertainties in atmospheric spectra





Older Hadron production measurements

Small acceptance spectrometers



Population of hadron-production phase-space for $pA \rightarrow \pi X$ interactions.

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

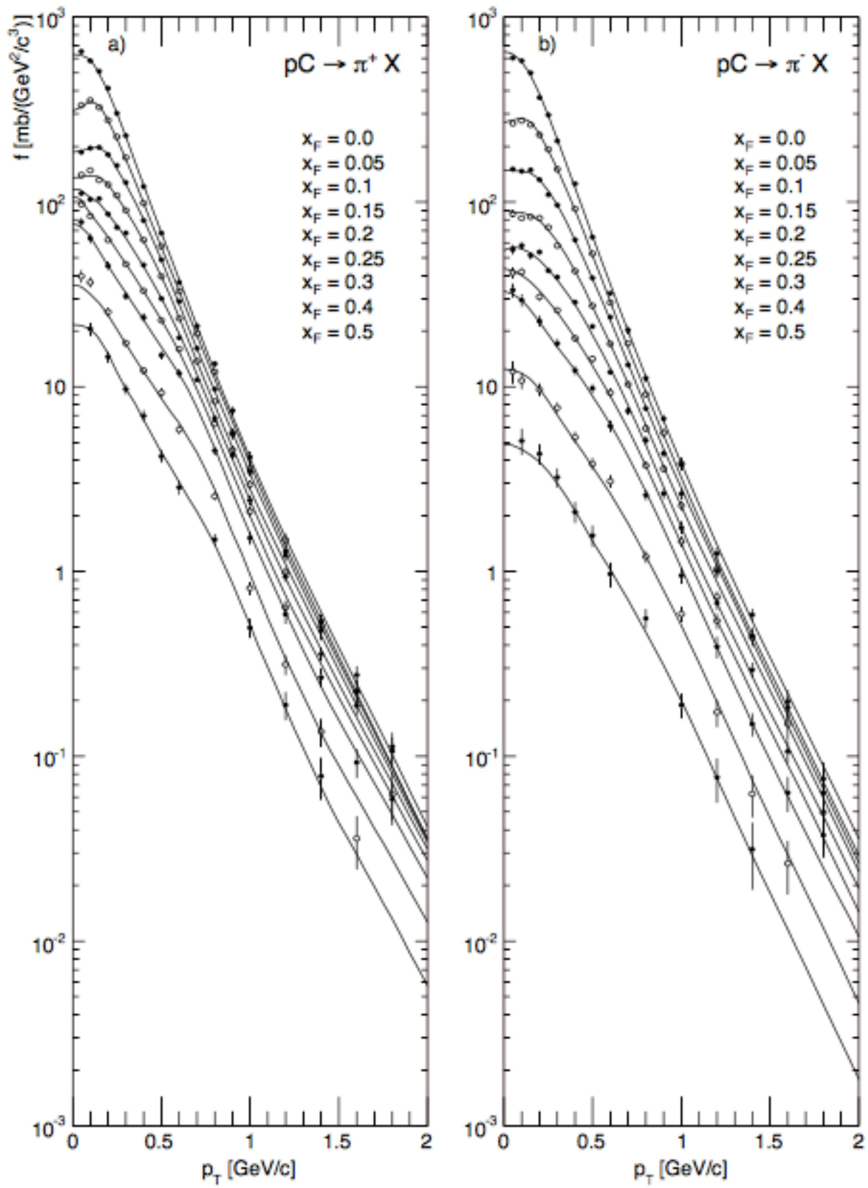
Red/black indicate extremes of magnetic latitude.

Energies around 1 GeV representing contained events in a SK-sized detector.

Measurements.

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

NA49 results



NA49 pion production
at 158 GeV/c
C. Alt (+GB) et al
Eur.Phys.J. C49 (2007) 897

Also data on production of protons, antiprotons, neutrons, deuterons and tritium

NA61/SHINE results

1510:02703 CERN PH-EP 2015-278

Extensive results (this is small selection; more angular bins, π^+ π^-, K^+, K^- K_S, p, Λ

4% λ carbon target

31 GeV/c

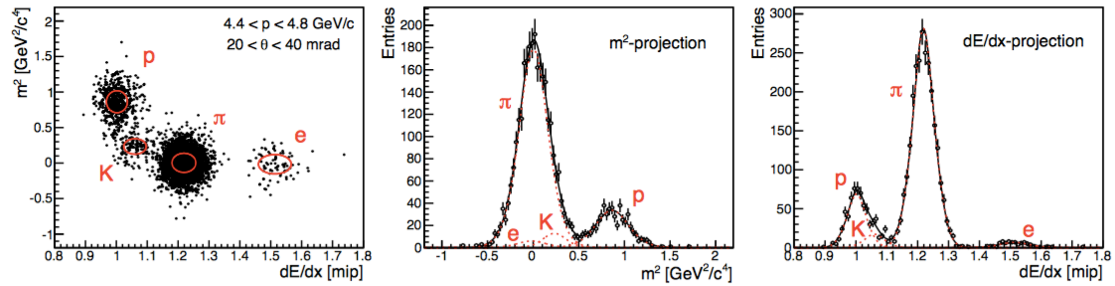
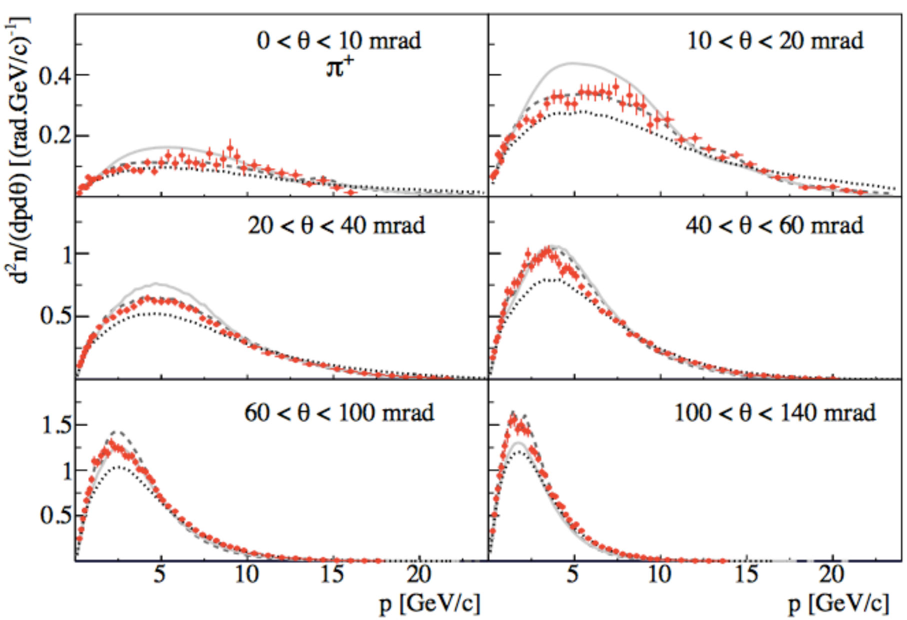
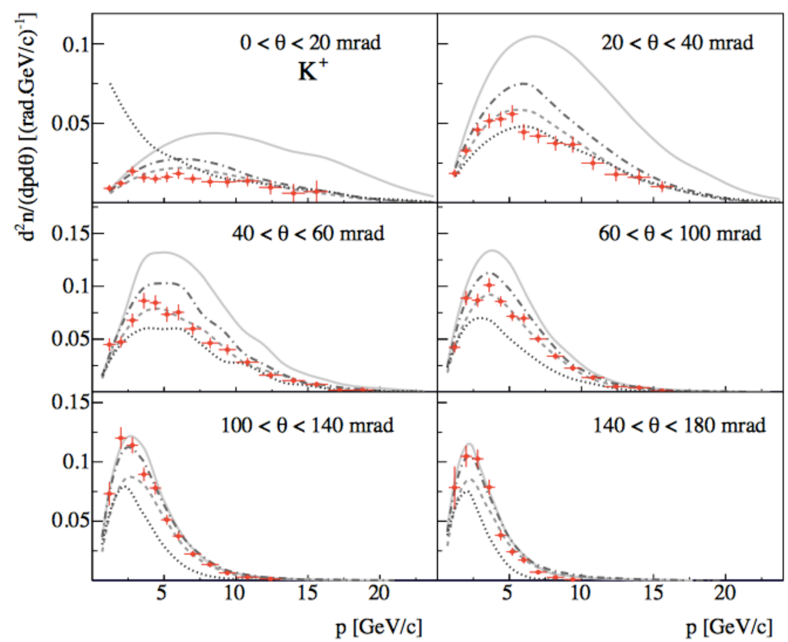


Fig. 13: (Colour online) Example of a two-dimensional fit to the $m^2 - dE/dx$ distribution of positively charged particles (*left*). The m^2 (*middle*) and dE/dx (*right*) projections are superimposed with the results of the fitted functions. Distributions correspond to the $\{p, \theta\}$ bin: $4.4 < p < 4.8$ GeV/c and $20 < \theta < 40$ mrad.



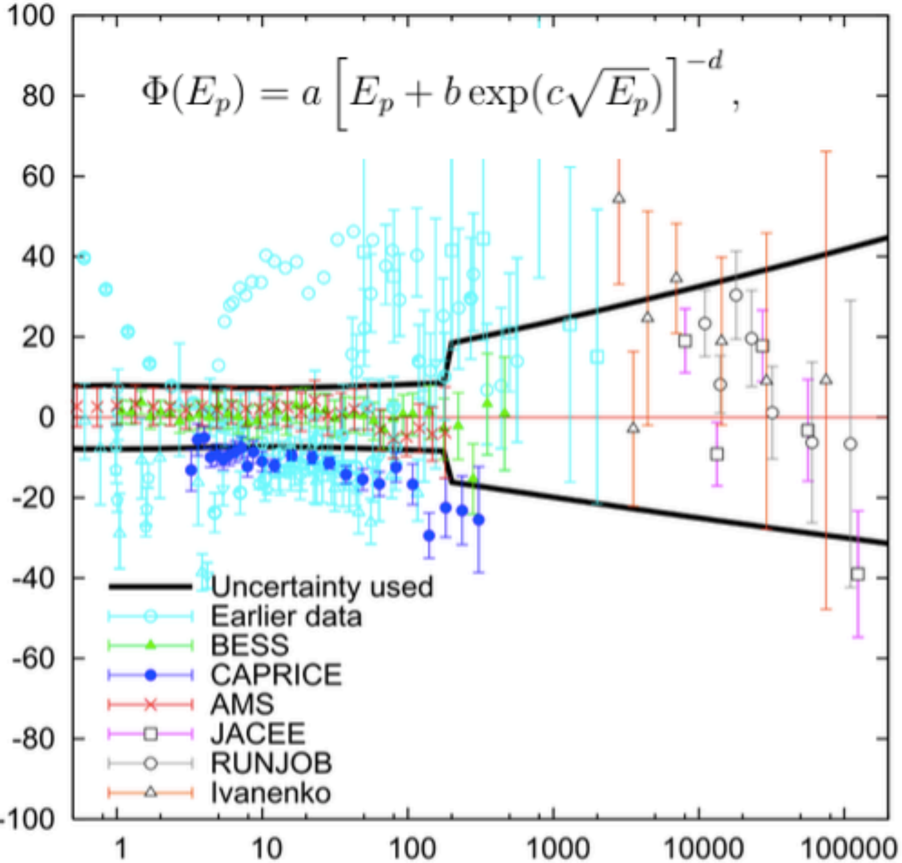


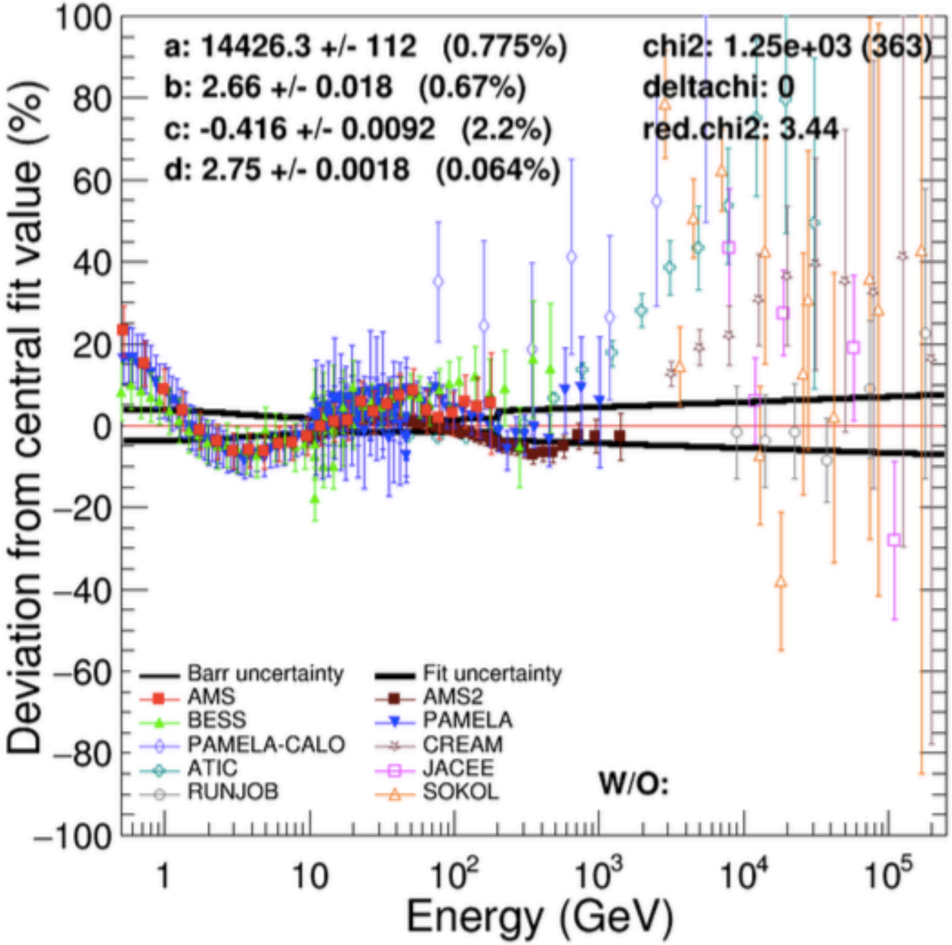
ADDITIONAL COSMIC RAY DATA

Salvatore Davide Porzio & Justin Evans
Manchester University

- Data from calorimeter experiments (>200 GeV) show a large spread. Also, data from AMS2 shows an interesting change in spectral index at higher energies which severely affects the values of the fit parameters.

- A global fit to all experimental data seems to underestimate the uncertainties associated with the parameters.

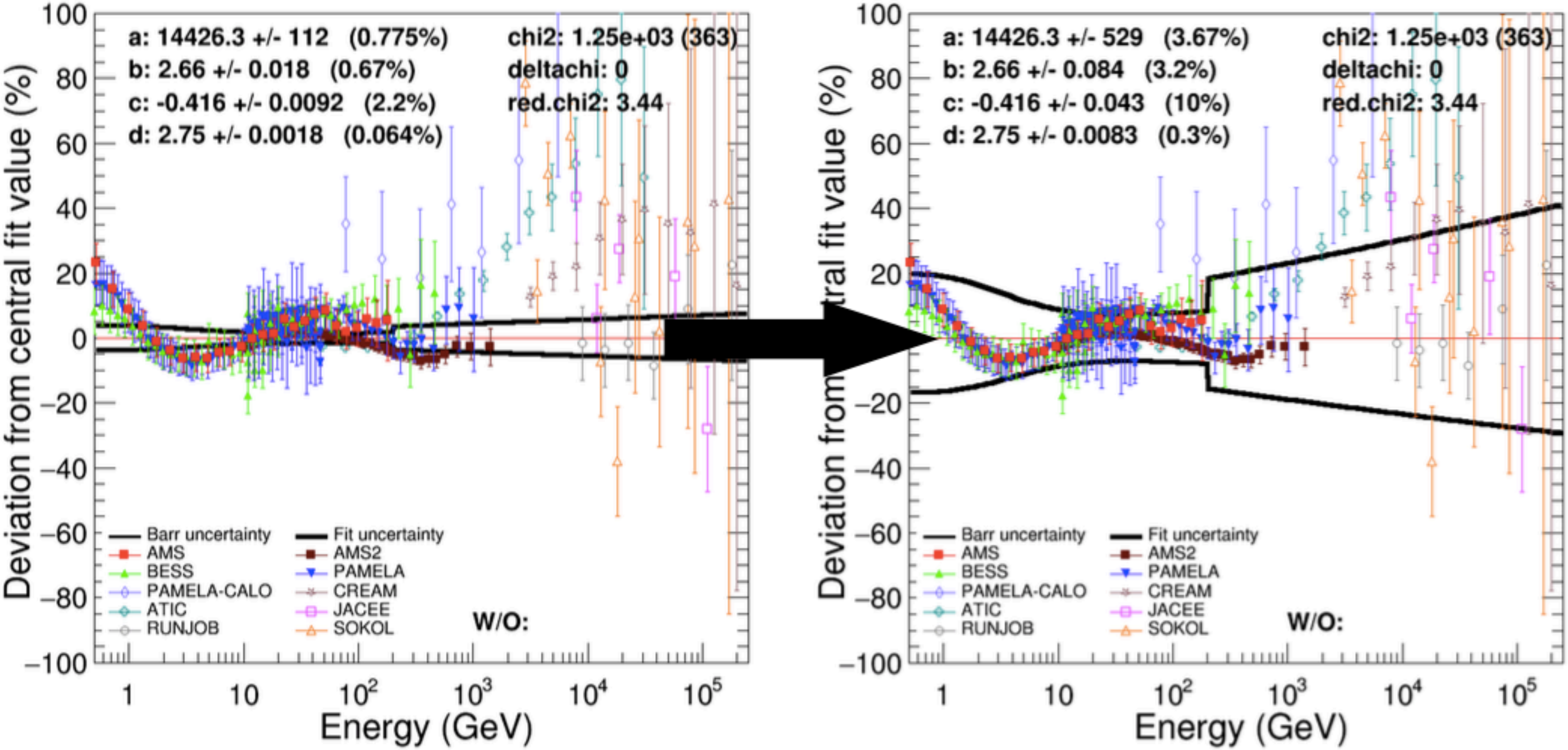




Salvatore Davide Porzio & Justin Evans
Manchester University

DETERMINING TOLERANCE

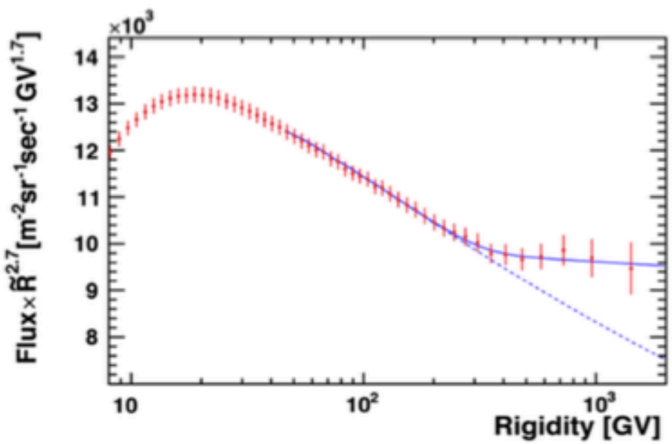
- Based on the paper of Stamp *et al.* (QCD global fit) [http://arxiv.org/abs/hep-ph/0101032], for global fit to different experiments a new tolerance ($\Delta\chi^2$ used to determine the 1σ contours in parameter space) must be determined, based on criteria of acceptability and mutual compatibility between experimental datasets.
- Preliminary analysis shows a sensibly larger uncertainties associated with the parameters.
- Still working on determining the precise value of tolerance (different methods involved).



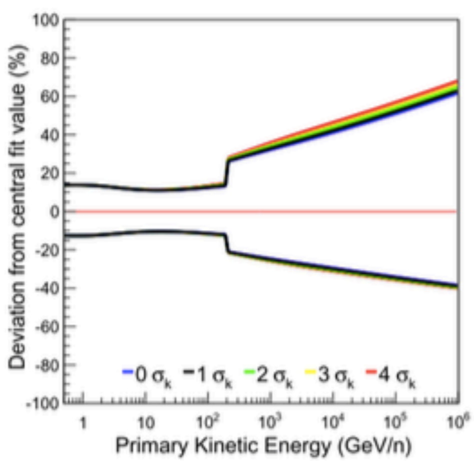
ALTERNATIVE PARAMETRIZATION

Salvatore Davide Porzio & Justin Evans
Manchester University

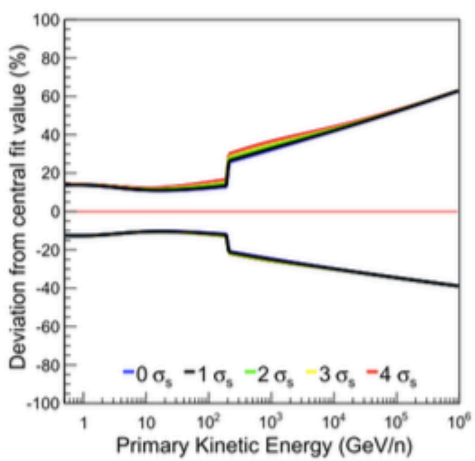
- Based on the interesting features of the proton and helium energy spectrum measured by AMS2 [Phys.Rev.Lett. 115 (2015) no.21, 211101], alternative forms of the GSHL formula including a multiple spectral index are being explored.
- The impact of the uncertainties on the extra non-spectral parameters has been found negligible, so that the scaling method can be successfully used with the alternative parametrization.



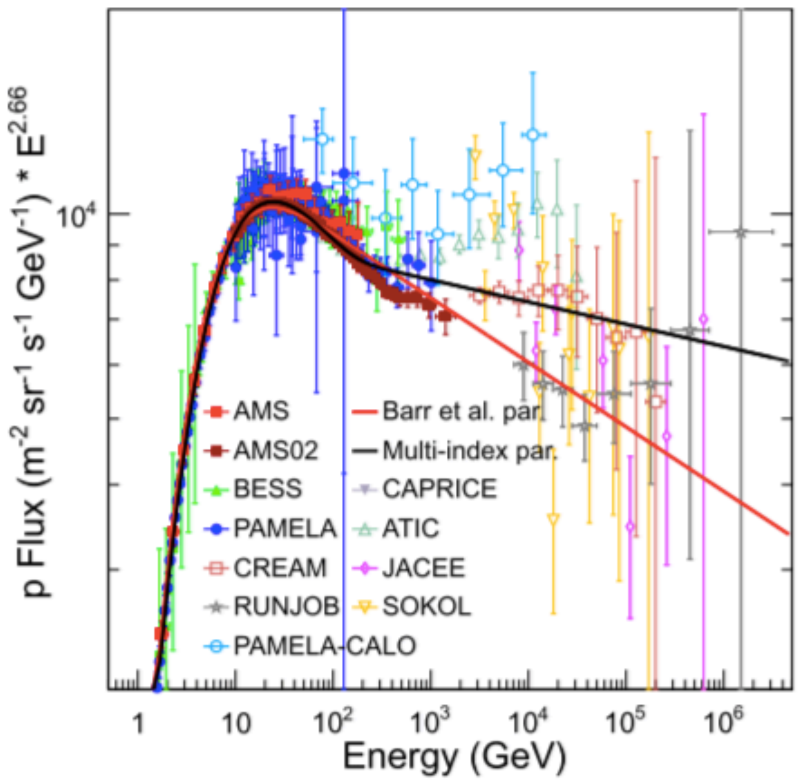
$$\Phi(E_p) = \underbrace{a\left[E_p + b\exp(c\sqrt{E_p})\right]^{-d}}_{\text{GSHL}} \times \underbrace{\left[1+\left(\frac{E_p}{k}\right)^{s}\right]^{\frac{d-e}{s}}}_{\text{Spectral index change}},$$



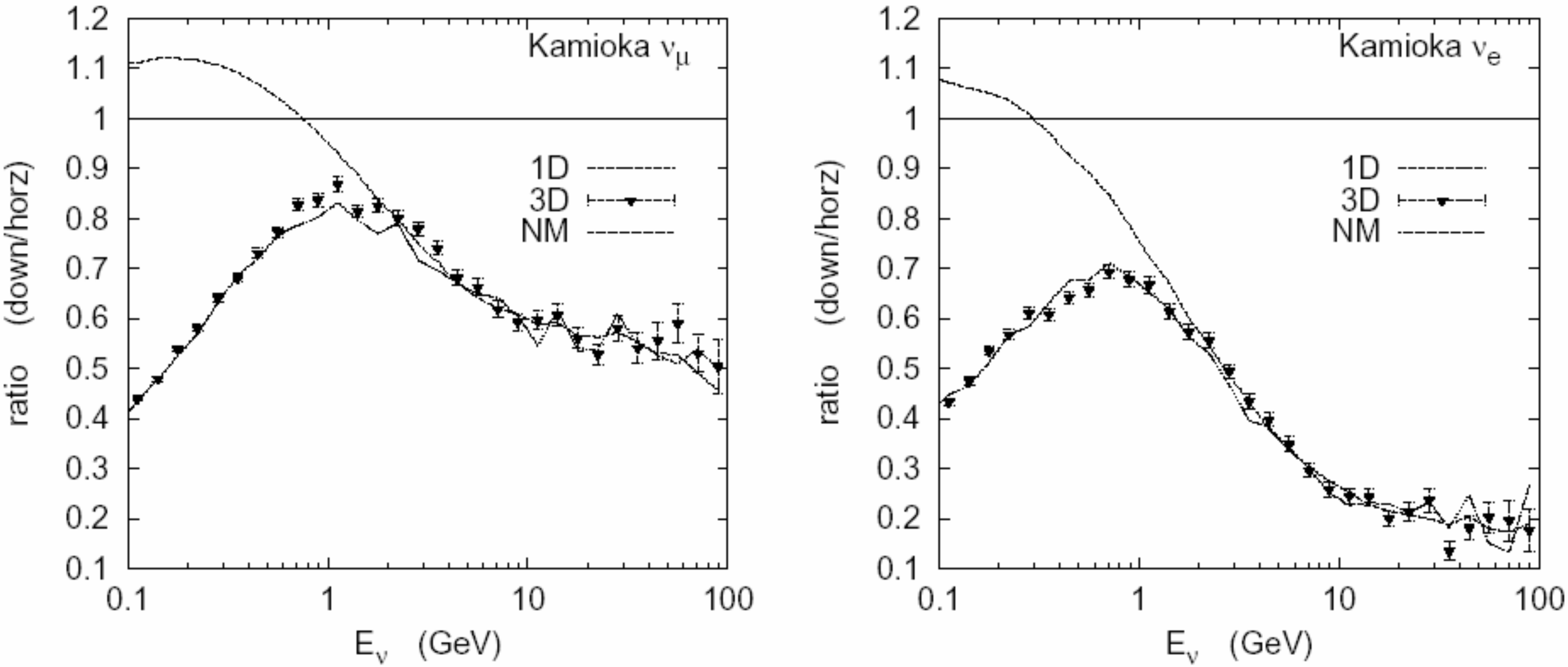
(a) Parameter k.



(b) Parameter s.

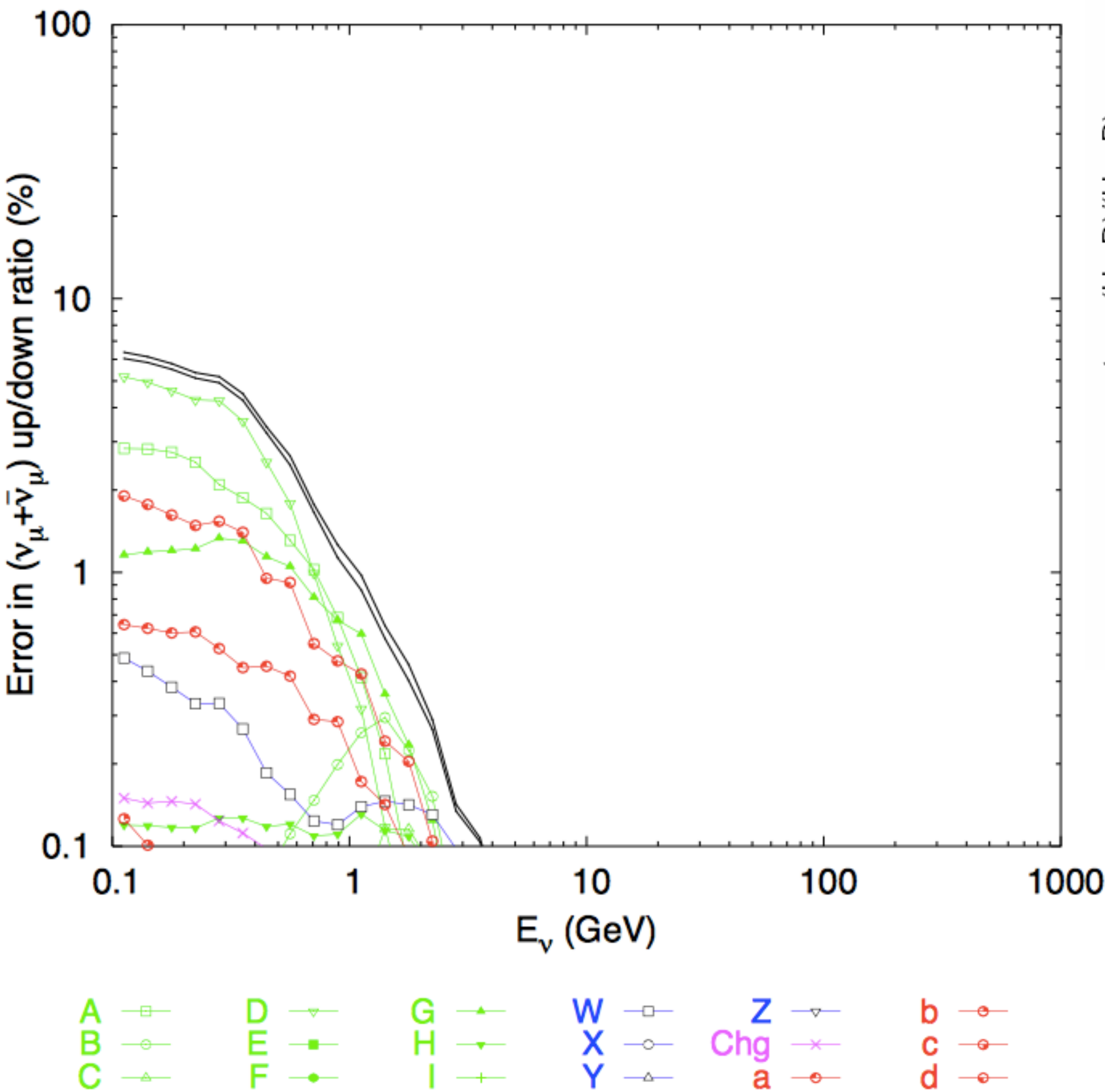


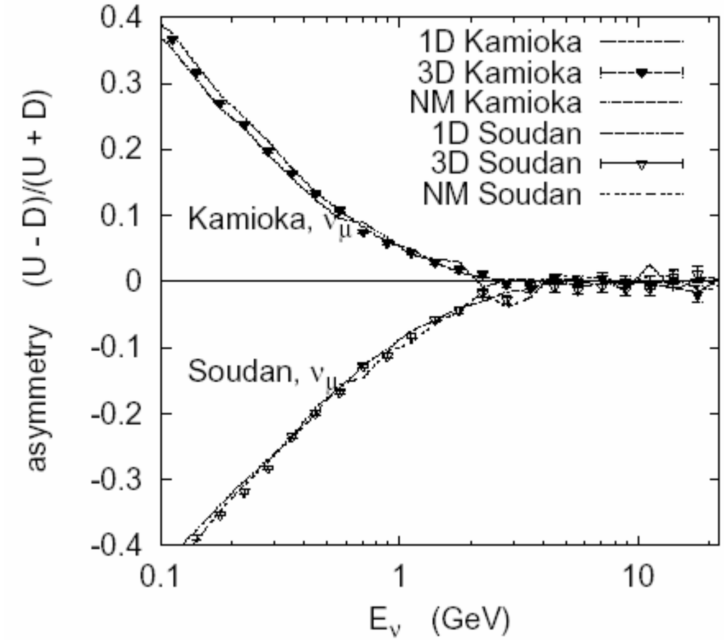
Down/Horizontal Ratios

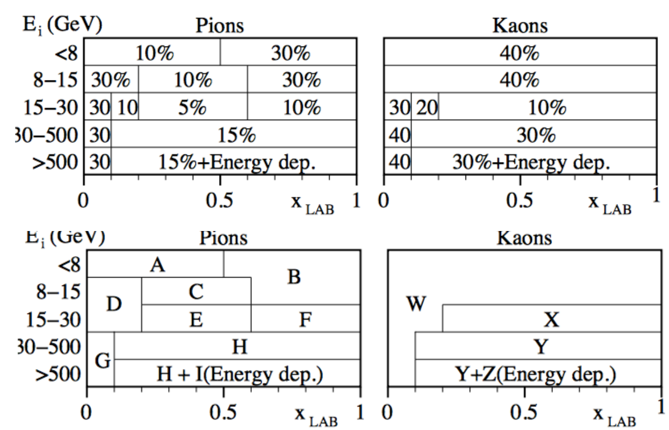


Values of down/horizontal ratios show big 3D/1D effect

Up/Down – more details







Uncertainty estimates - comments

- Techniques of z-factors and uncertainty zones are complementary
- Improvements:
  - Could carve up uncertainty zones in different ways – choice for users.
  - May try a combination of z-factor and zone-uncertainties
- Compared with 2006 uncertainty calculation. Zones W, Y and Chg are the most important
  - Perhaps divide W up – suggestions?
- There is a balance in number of zones to pick, danger of underestimation
  - Too few zones, and the uncertainties represent only a normalization change, which cancels in ratios
  - Too many zones, the individual zones fluctuate, uncertainty averages and again cancels in ratio – need correlation matrix?
- Suggestions welcome

Conclusions

- Results of calculations have been used to contribute to several extremely interesting measurements over the years

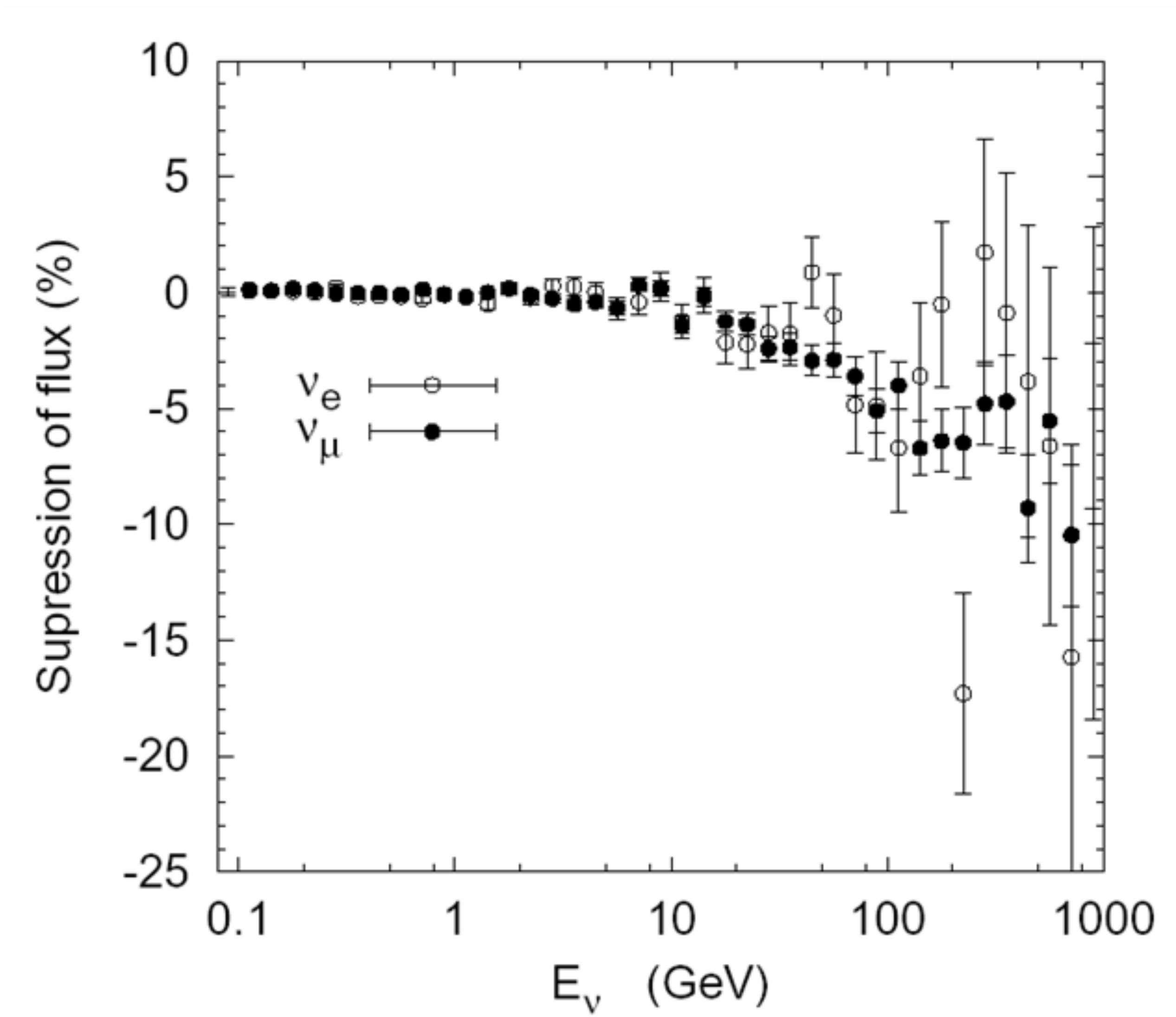
- High interest in better calculations
  - Particularly in ‘resonance region’ 3-10GeV upward. [PINGU, INO, MINOS …]
  - Also at <1GeV ‘CP-region’ [SK, HK, DUNE …]

- Extensive new data: especially NA61/SHINE and primary fluxes
  - We have not got it wrong, but must tune with this modern data

- This workshop is very welcome, can provide input to improve rapidly
  - Resonance region: Do we need 3D everywhere? We intend to try to use 1D for some uncertainty calculations.
  - Primary fluxes very well measured. What are small uncertainties we must now not neglect? – solar wind? isotropy far away?
  - Optimum method for uncertainties
    - which zones
    - how to output them

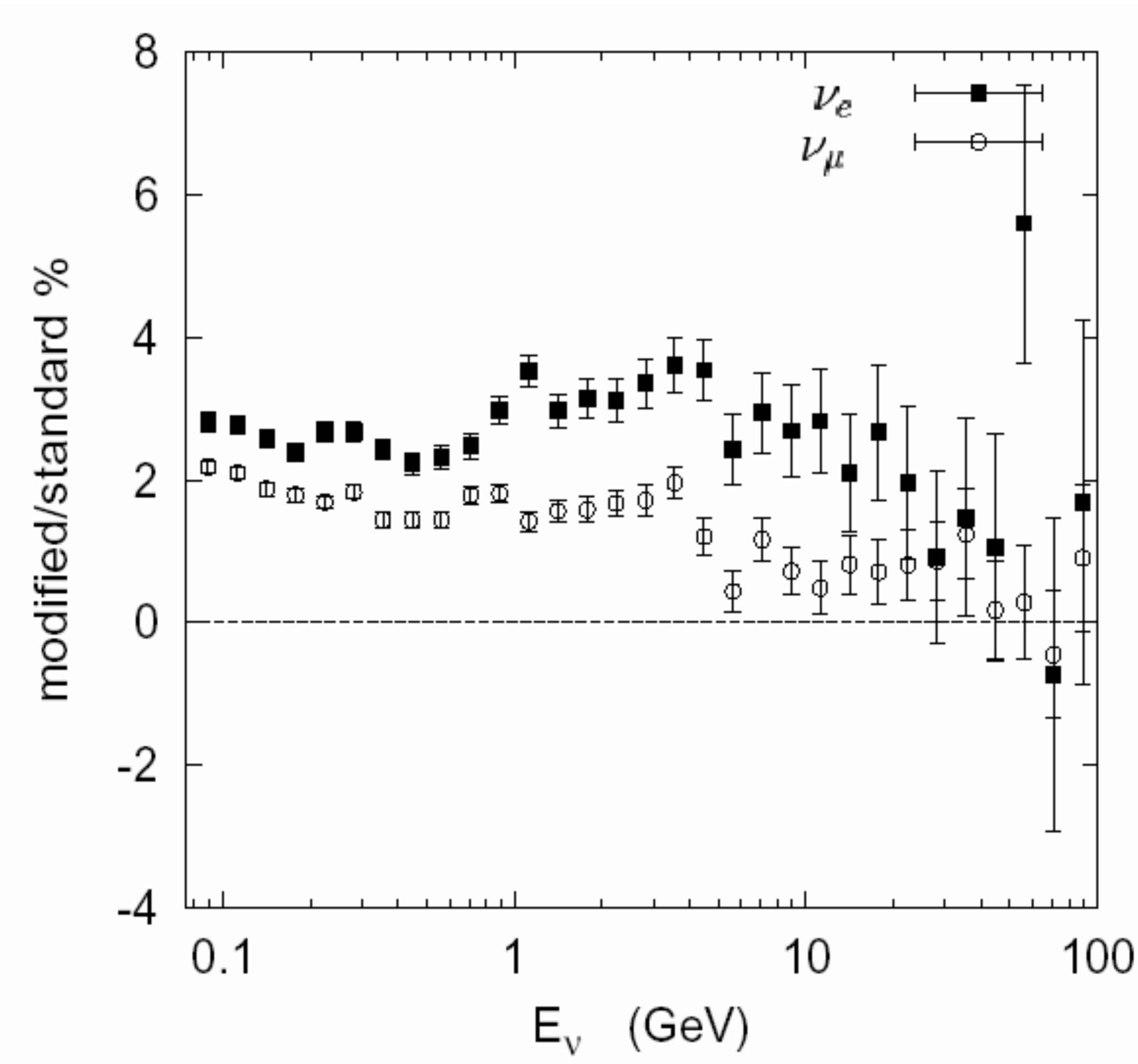
- We have a lot of work to do – ideally would like to rewrite parts of code

Associative production



- Effect of a 15% reduction in ΛK^+ production

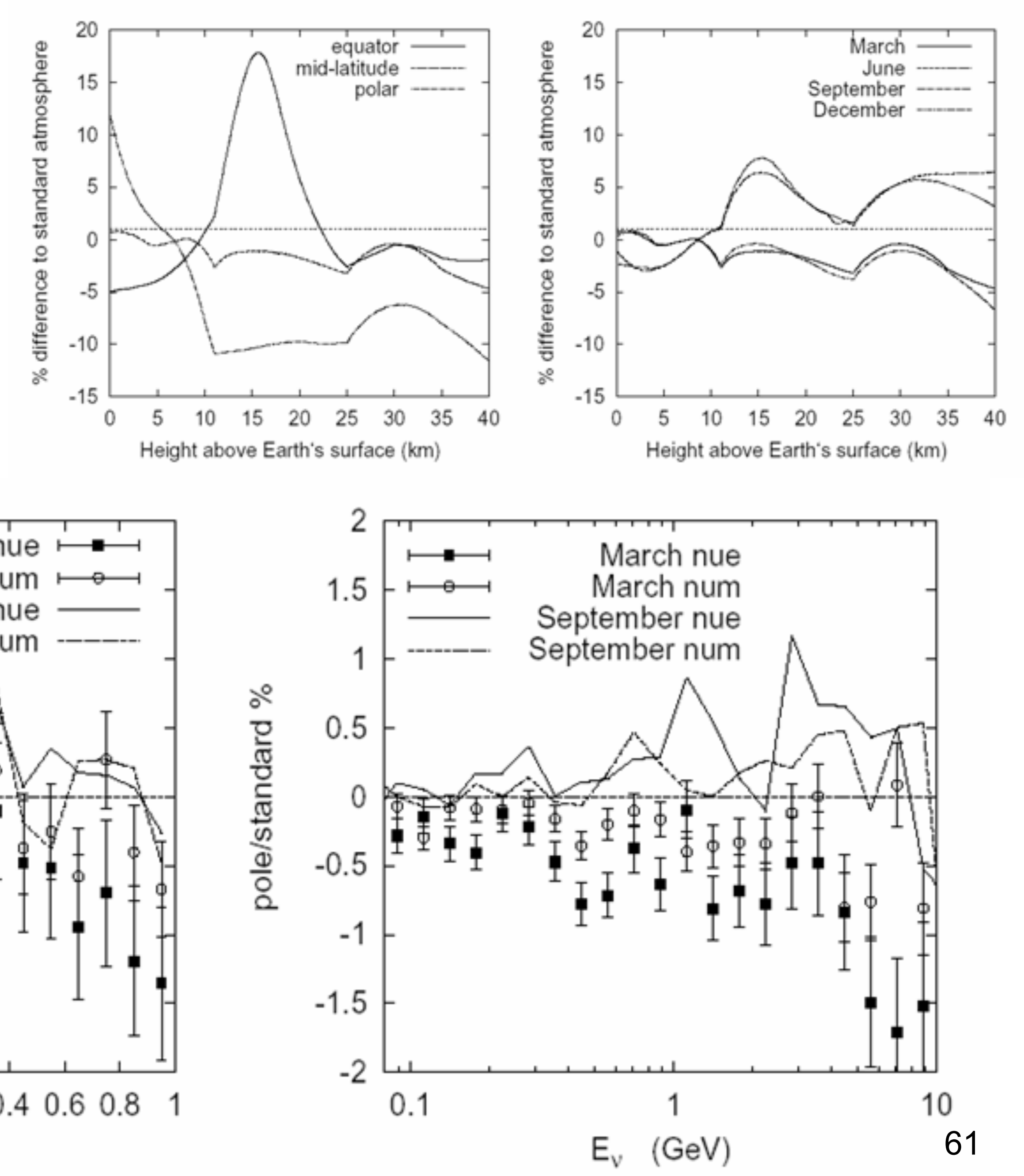
Cross section change



Effect of artificial increase in total cross section of protons of 15%

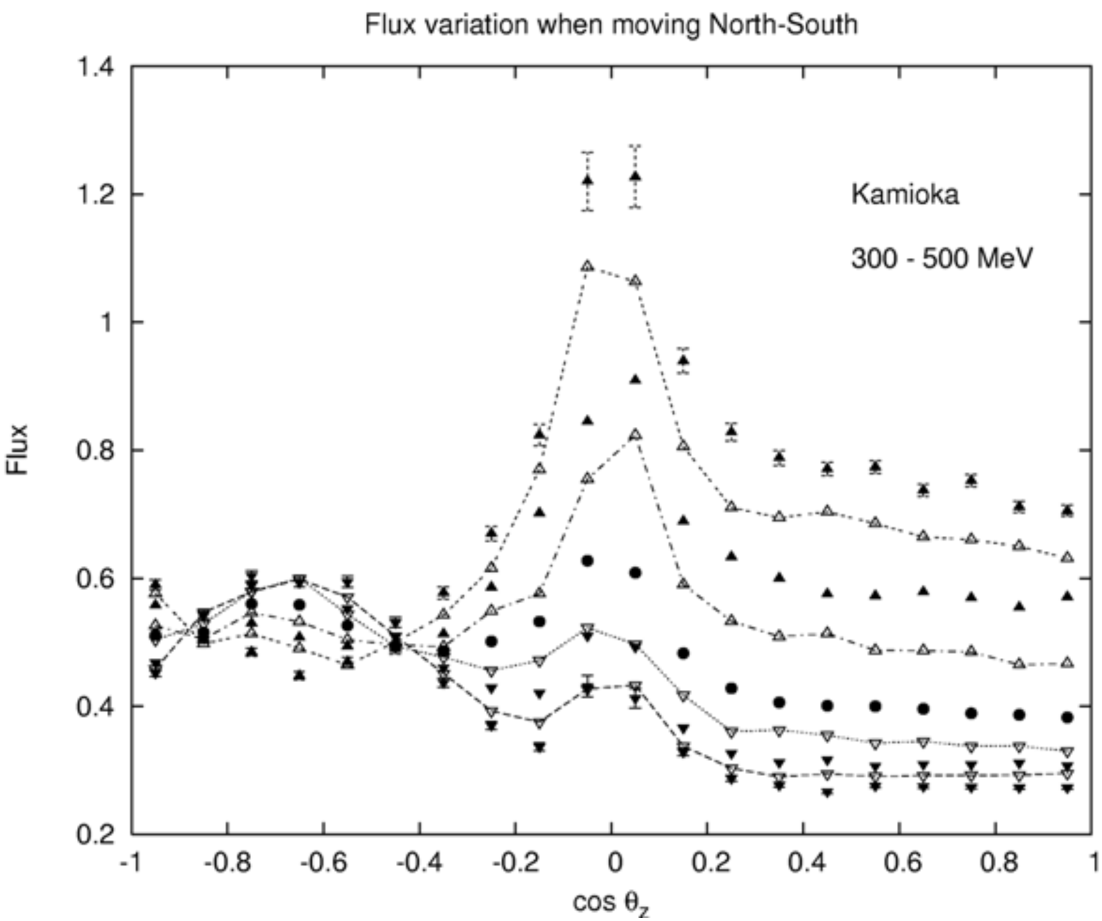
- Effect is small, essentially it just adjusts the altitude of the top of the shower

Atmospheric Density

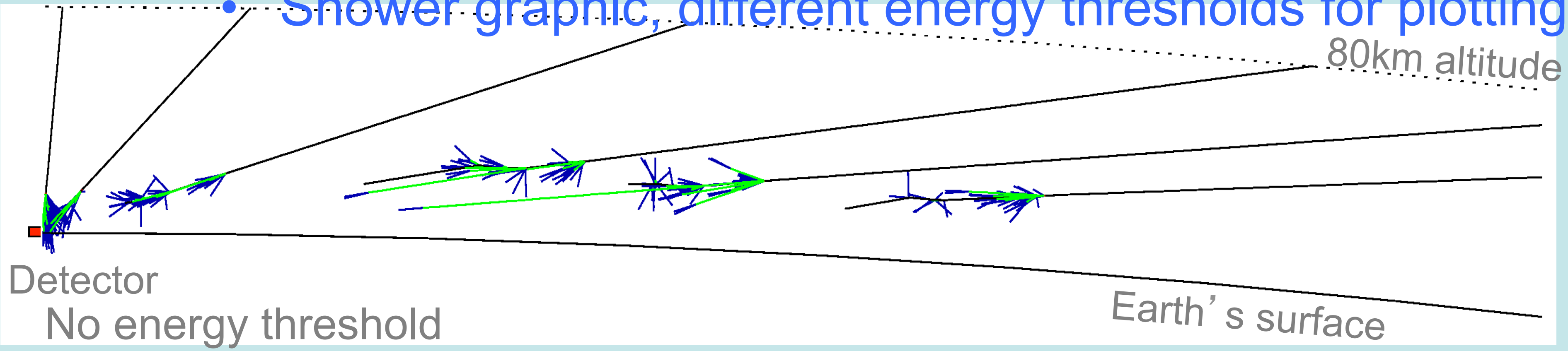


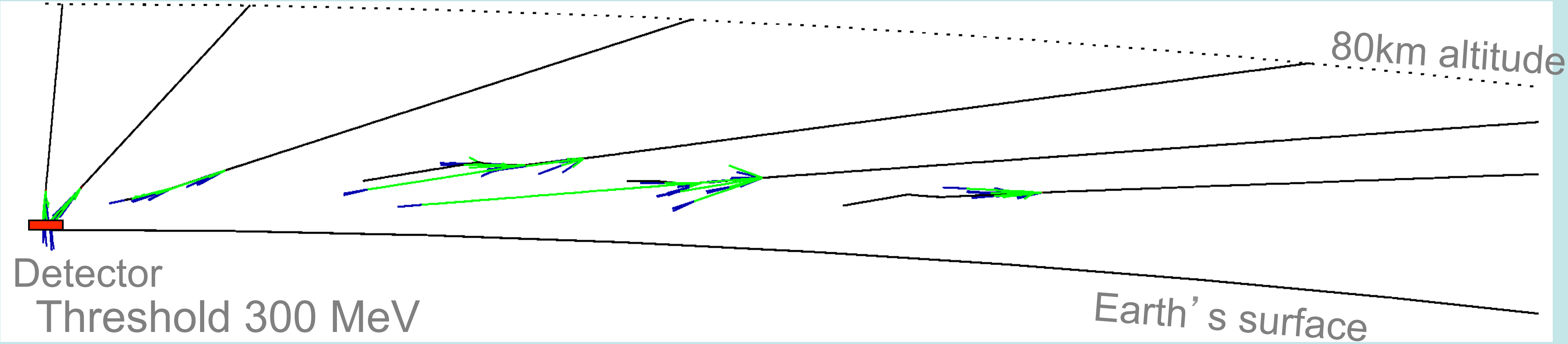
What size detector is appropriate ?

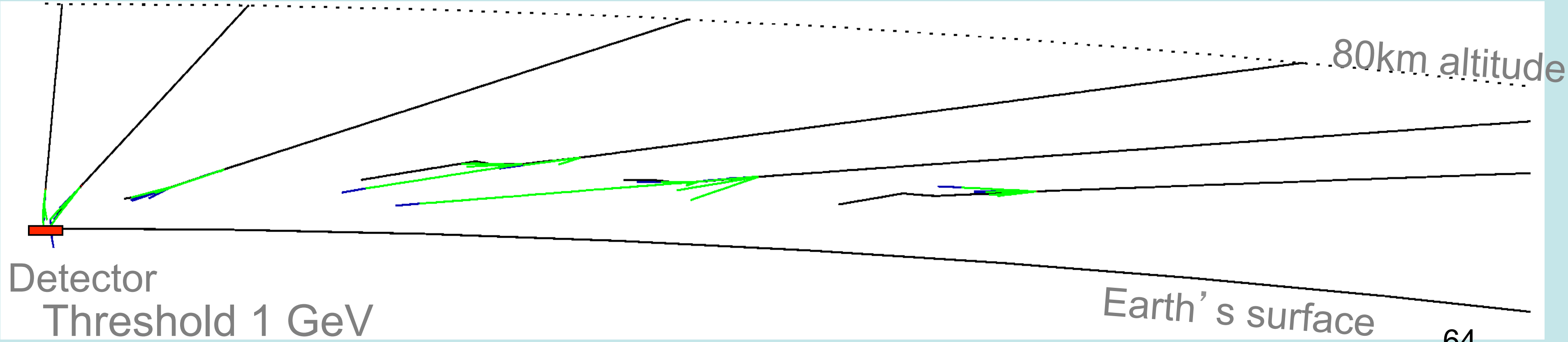
- Repeat the 3D calculation at various locations stepping North and South from the nominal detector location.
- See large variations
- Variations are not completely linear, so this does not just average out.



- Shower graphic, different energy thresholds for plotting







Solar Wind

- Affects primary fluxes below ~20 GeV on an 11 year cycle. The model we use has one degree of freedom.