

Atmospheric neutrino flux calculations

Why knowledge of hadron shower
simulation is critical for them

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HSS06, Fermilab, September 8, 2006

This talk is based on two almost complete publications

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Uncertainties in Atmospheric Neutrino Fluxes

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(Dated: 21 June 2006)

An evaluation of the principal uncertainties in the computation of neutrino fluxes produced in cosmic ray showers in the atmosphere is presented. The neutrino flux predictions are needed for comparison with experiment to perform neutrino oscillation studies. The paper concentrates on the main limitations which are due to hadron production uncertainties. It also treats primary cosmic ray flux uncertainties, which are at a lower level. The absolute neutrino fluxes are found to have errors of around 15% in the neutrino energy region important for contained events underground. Large cancellations of these errors occur when ratios of fluxes are considered, in particular, the $\nu_\mu/\bar{\nu}_\mu$ ratio below $E_\nu = 1$ GeV, the $(\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e)$ ratio below $E_\nu = 10$ GeV and the up/down ratios above $E_\nu = 1$ GeV are at the 1% level. A detailed breakdown of the origin of these errors and cancellations is presented.

PACS numbers: 13.85.Tp, 14.60.Pq, 96.40.De, 96.40.Tv

I. INTRODUCTION

The Super-Kamiokande collaboration have published detailed analyses [1, 2] of neutrino oscillation effects based on over 15,000 observed events induced by atmospheric neutrinos. Neutrino oscillations have also been observed in other measurements with atmospheric neutrinos [3–6], accelerator neutrinos [7], solar neutrinos [8, 9] and reactor neutrinos [10]. A crucial part of the study of

π^-). Decay schemes involving kaons also contribute to the higher energy neutrino fluxes. From the main production mechanism, it is easy to see that at low energy where muons decay before hitting the earth, there should be roughly two muon type neutrinos for every electron type neutrino (this is quite a good rule of thumb, because the neutrino from the pion decay is similar in energy to the other neutrinos due to the heavy muon).

In practice, neutrino fluxes are computed using Monte

Inclusive production of charged pions in p+C collisions at 158 GeV/c beam momentum

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(The NA49 Collaboration)

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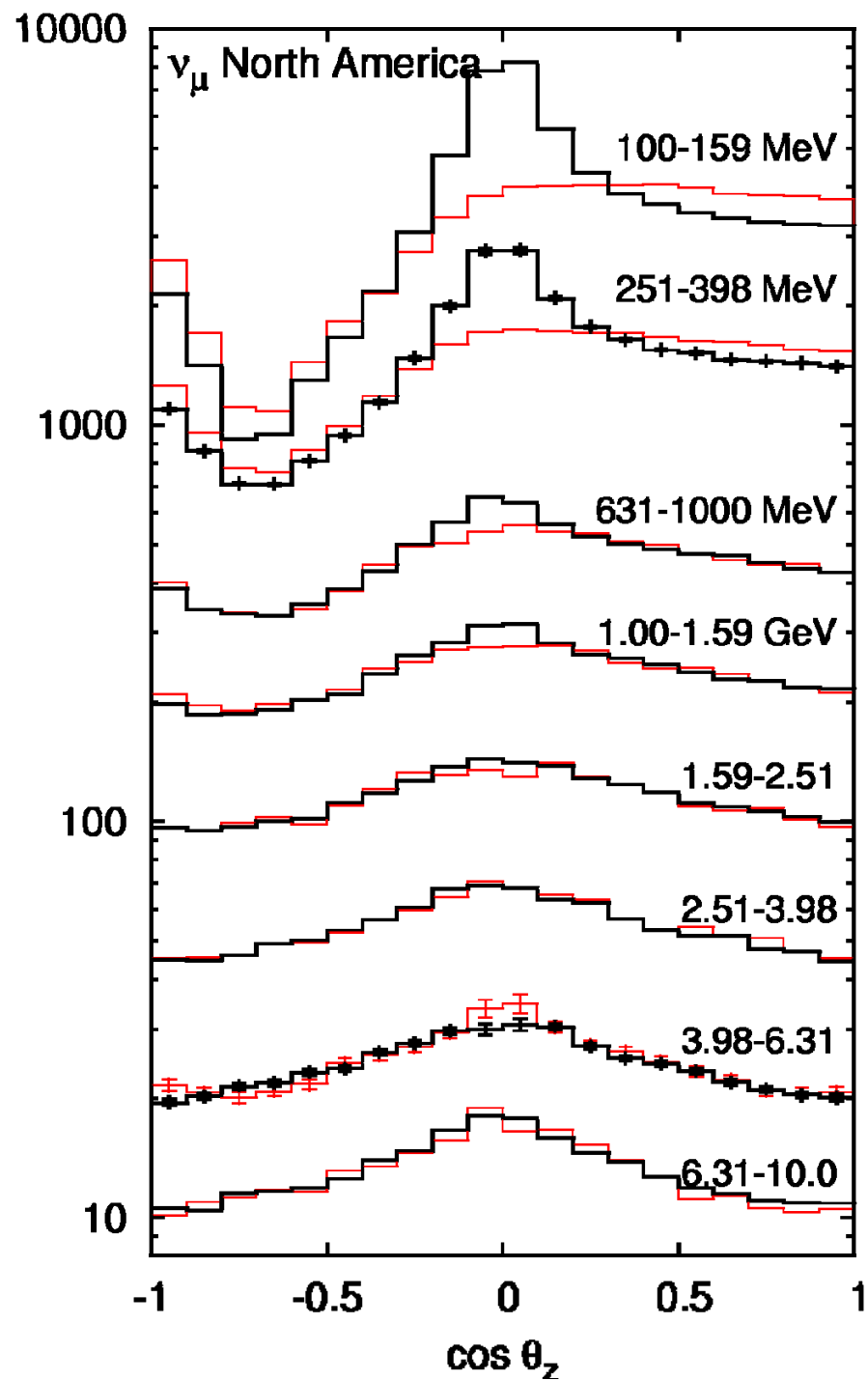
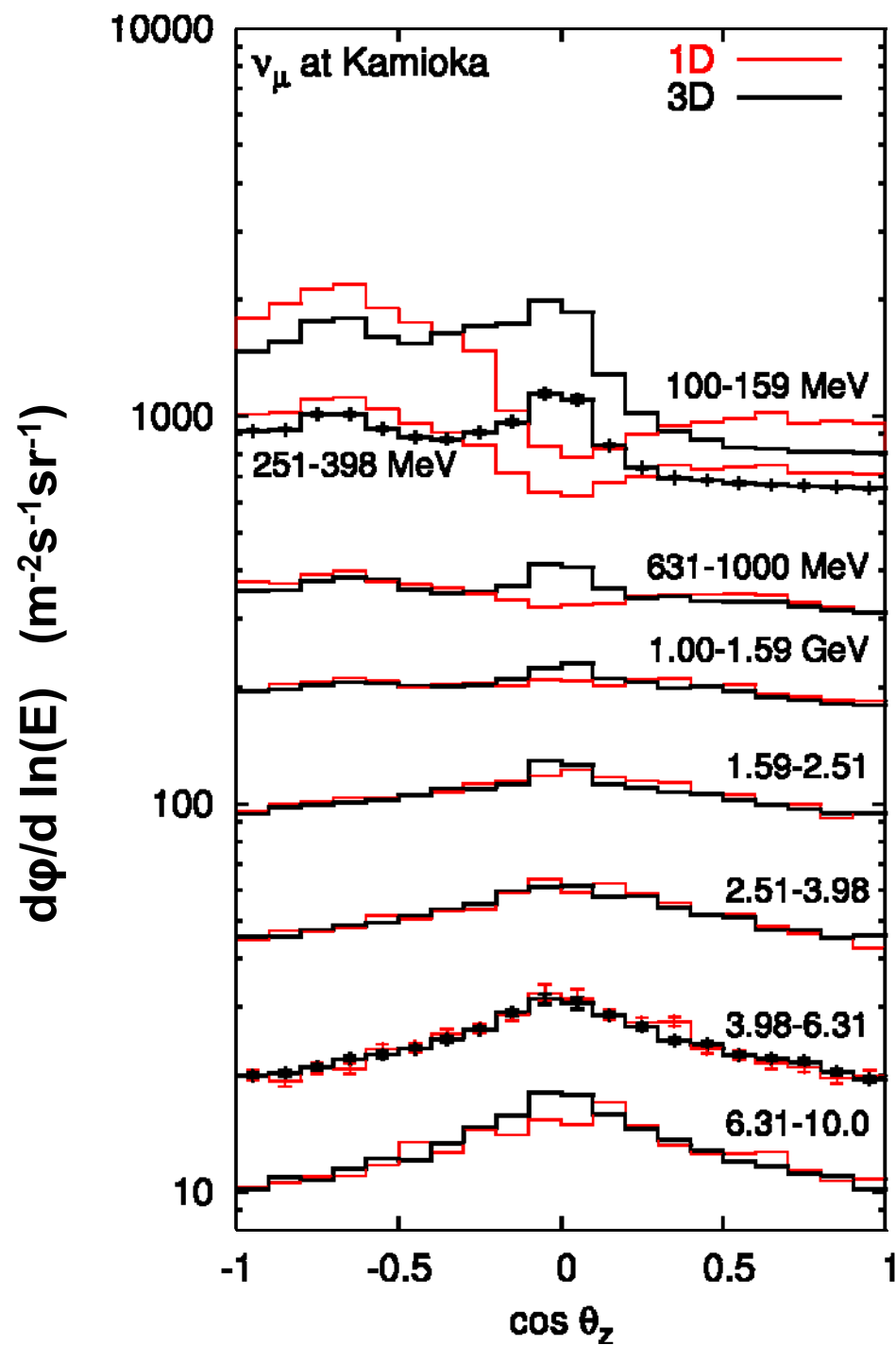
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Abstract

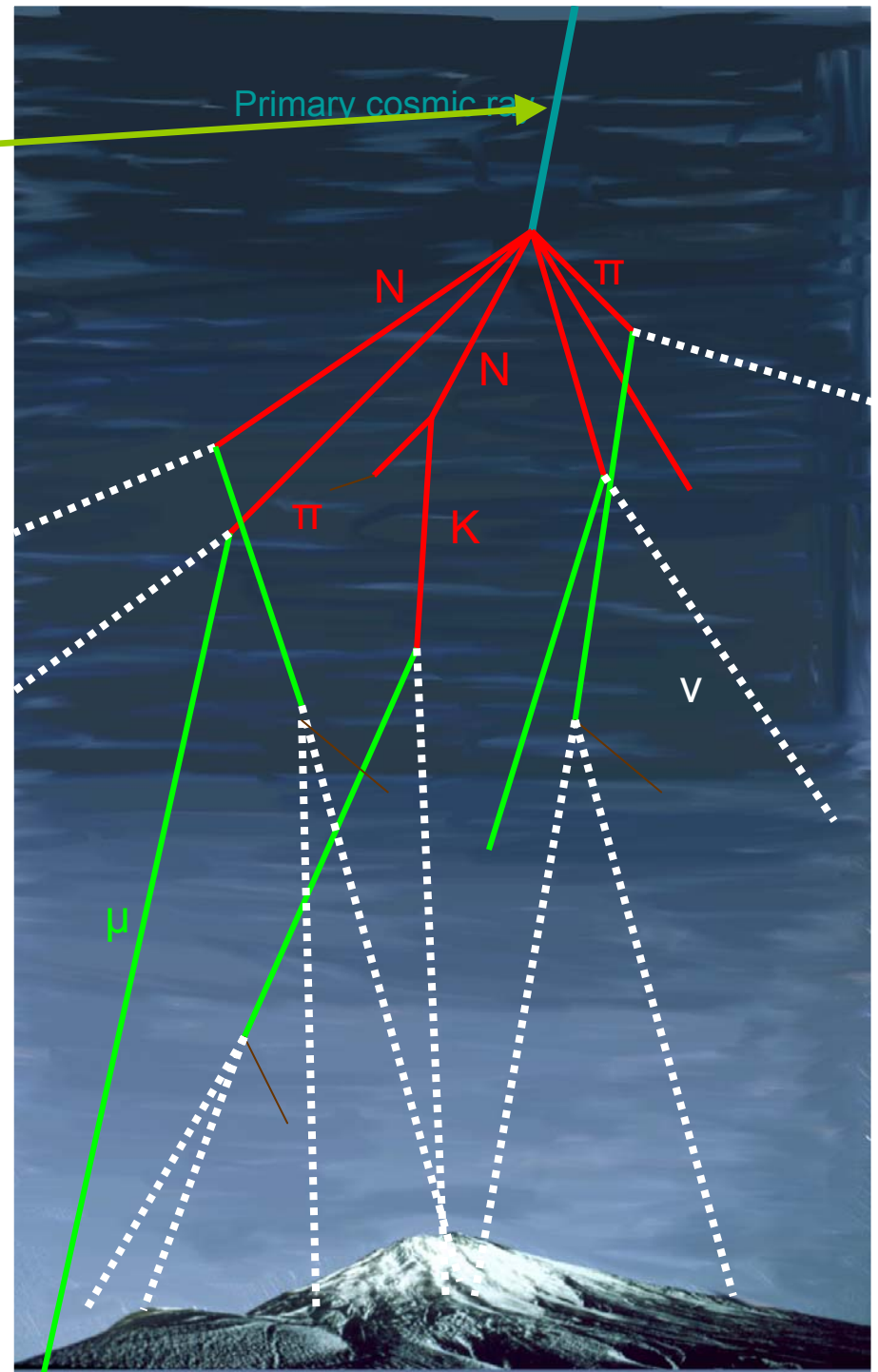
The production of charged pions in minimum bias p+C interactions is studied using a sample of 377 000 inelastic events obtained with the NA49 detector at the CERN SPS at 158 GeV/c beam momentum. The data cover a phase space area ranging from 0 to 1.8 GeV/c in transverse momentum and from -0.1 to 0.5 in Feynman x. Inclusive invariant cross sections are given on a grid of 270 bins per charge thus offering for the first time a dense coverage of the projectile hemisphere and of the cross-over region into the target fragmentation zone.

arXiv:hep-ex/0606028 v1 14 Jun 2006

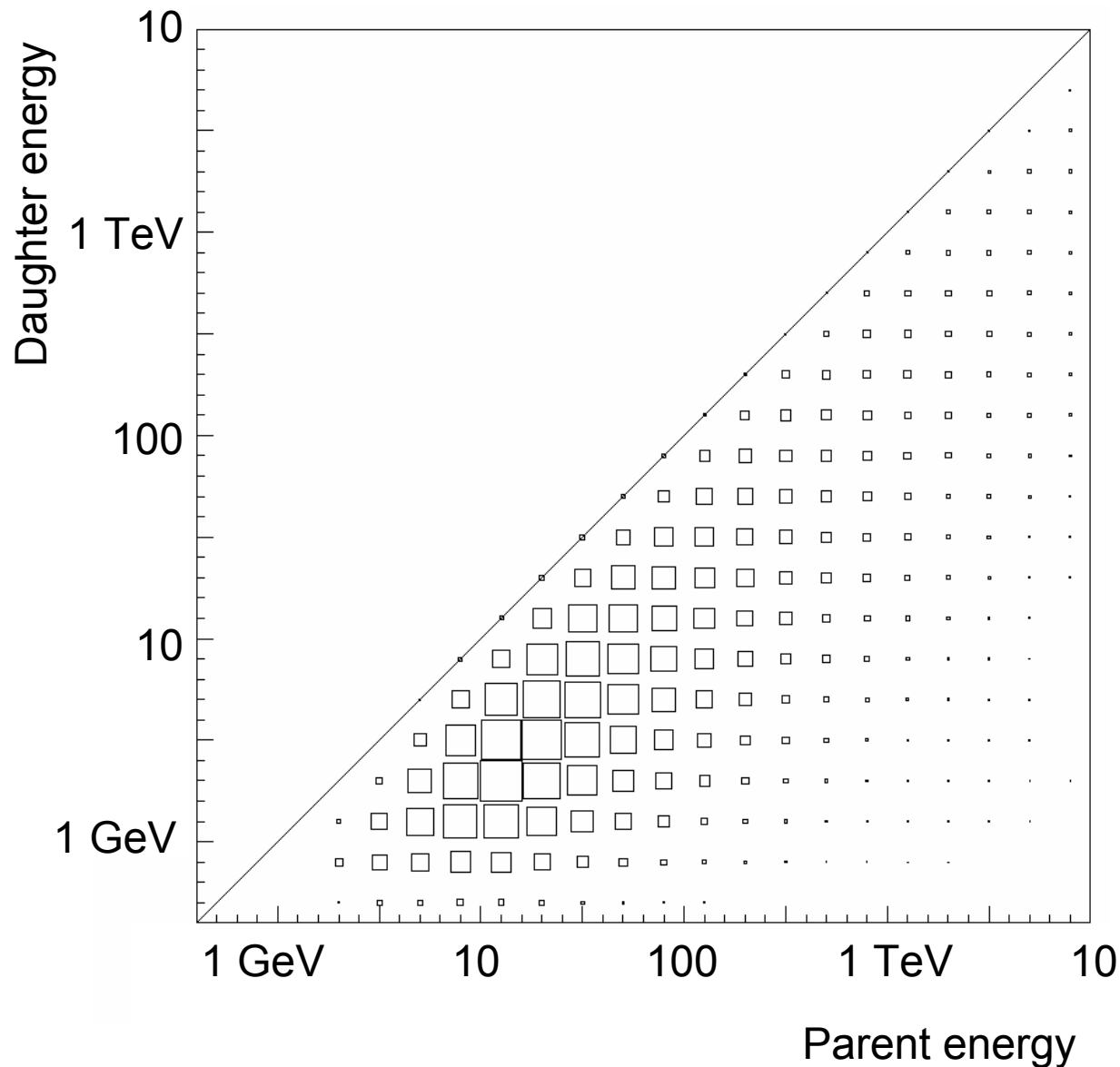


Injection height 80km

- Track forward.
- When first neutrino hits detector, perform cutoff calculation – i.e. track back.
- Forward stepping – equal steps except:
 - smaller near Earth surface or when near end of range.
 - large steps for high energy muons
- Backward stepping – adaptive step sizes depending on the amount of bending and the distance from the earth.



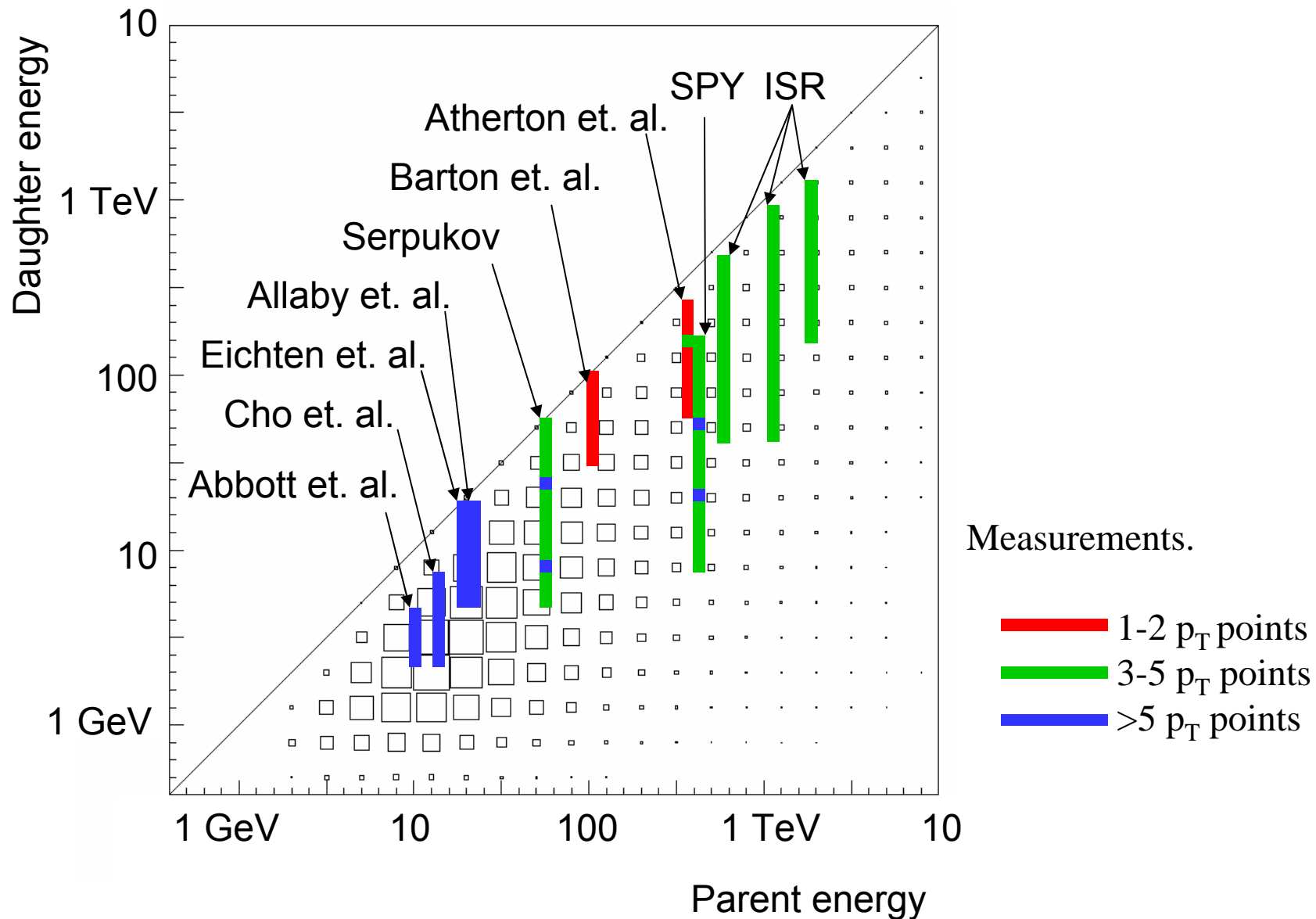
Which bits of phase space are we interested in?



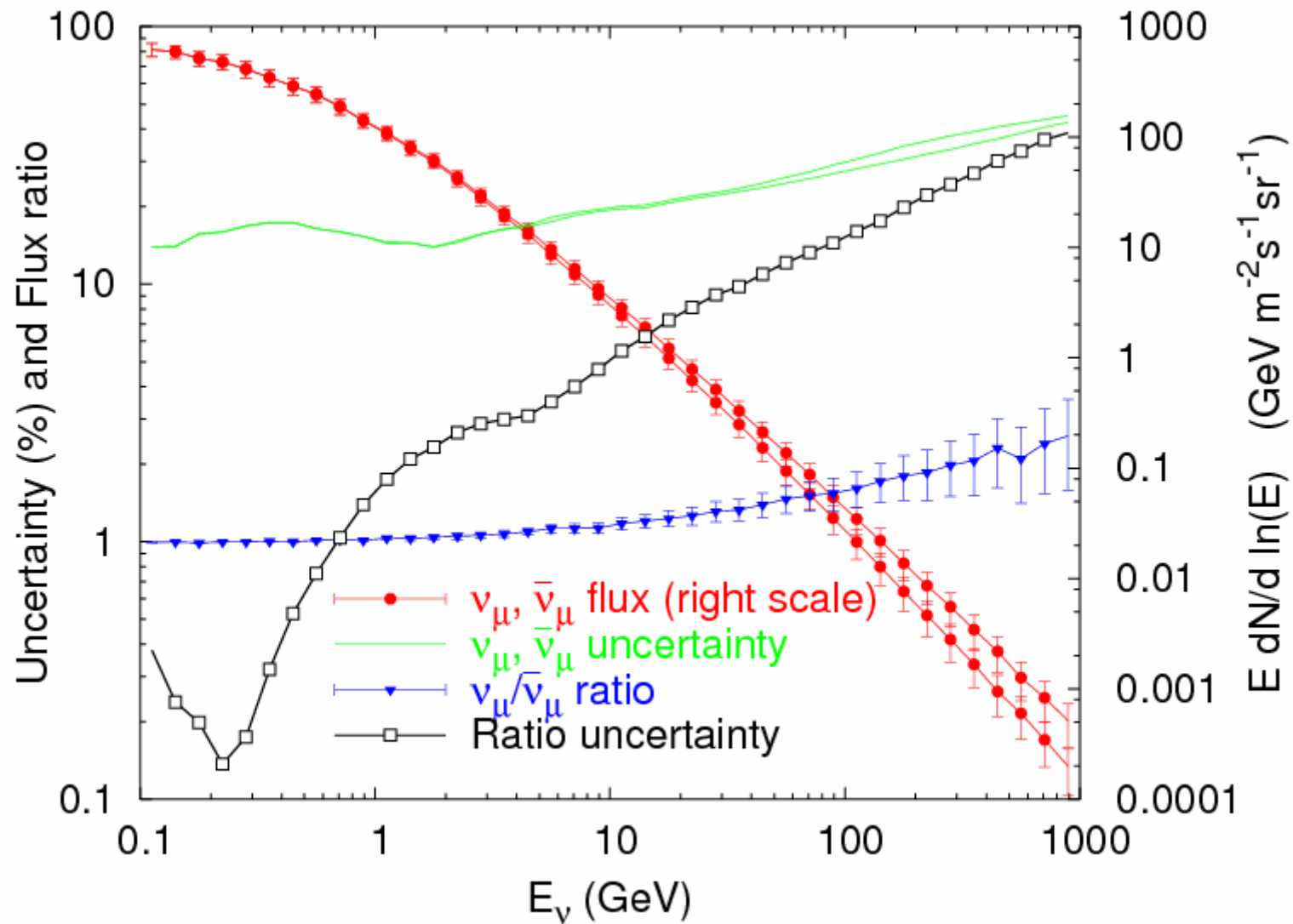
Boxes show importance of phase space region for contained atmospheric neutrino events.

- Very wide phase space requirements (E_i , E_s , part type)
- Target=air (isoscalar)
- p_T doesn't matter.

Phase space covered by pion measurements



Absolute fluxes and ratios



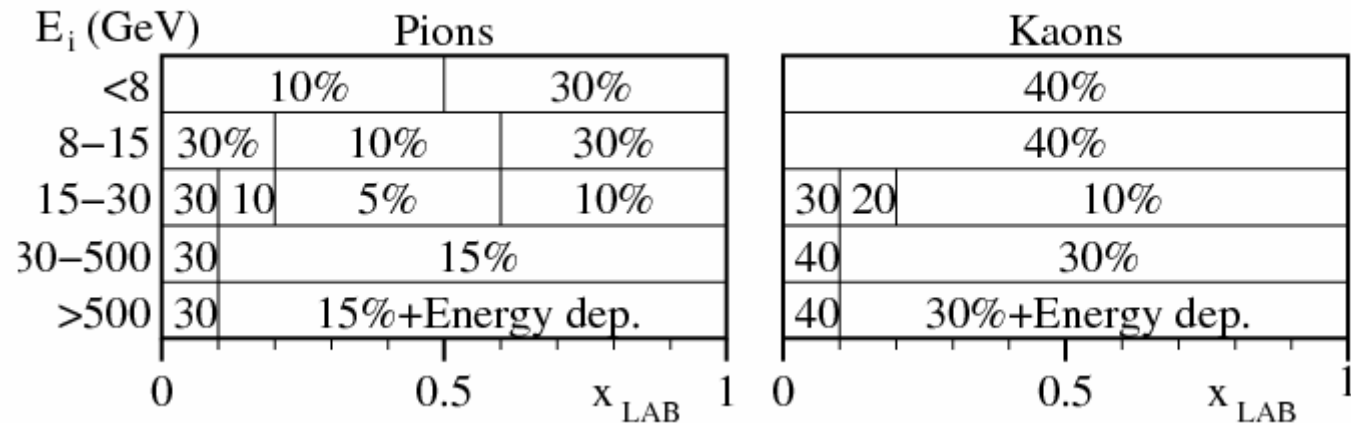
Method for evaluating uncertainties

Level of
uncertainty

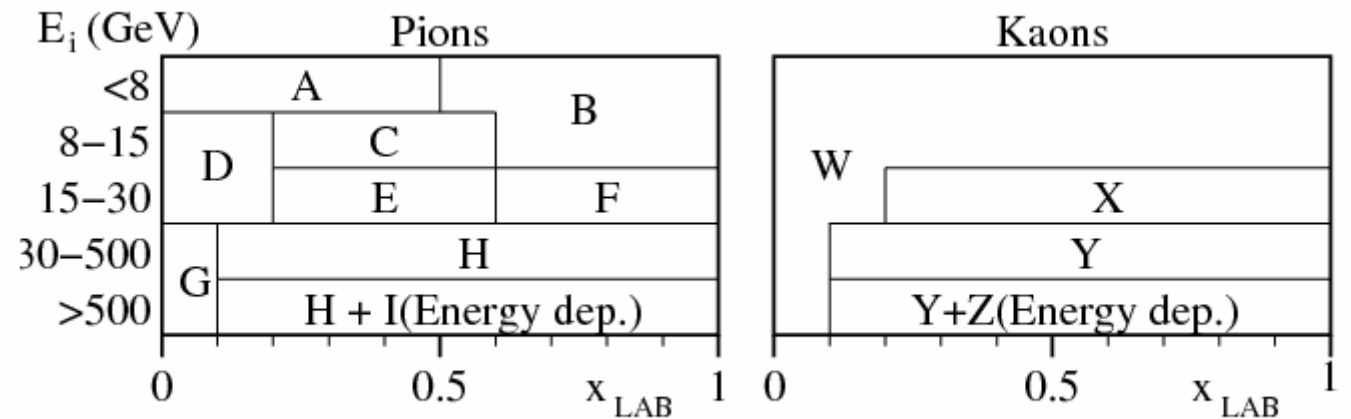
E_i (GeV)	Pions				Kaons					
<8	10%		30%		40%					
8–15	30%	10%		30%	40%					
15–30	30	10	5%		10%	30	20	10%		
30–500	30	15%				40	30%			
>500	30	15%+Energy dep.				40	30%+Energy dep.			
	0	0.5			x_{LAB}	1	0	0.5		

Method for evaluating uncertainties

Level of
uncertainty

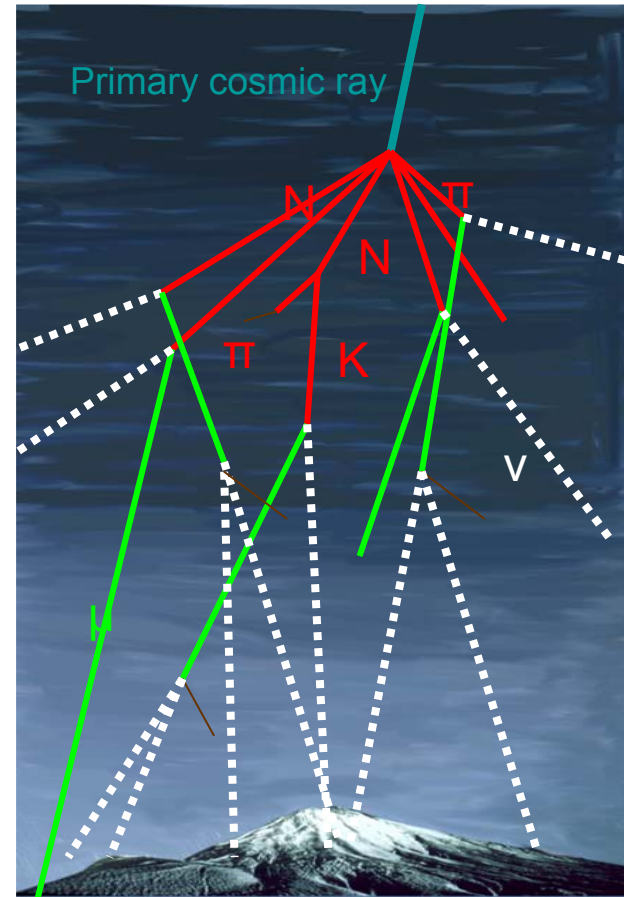


Correlation of
uncertainty

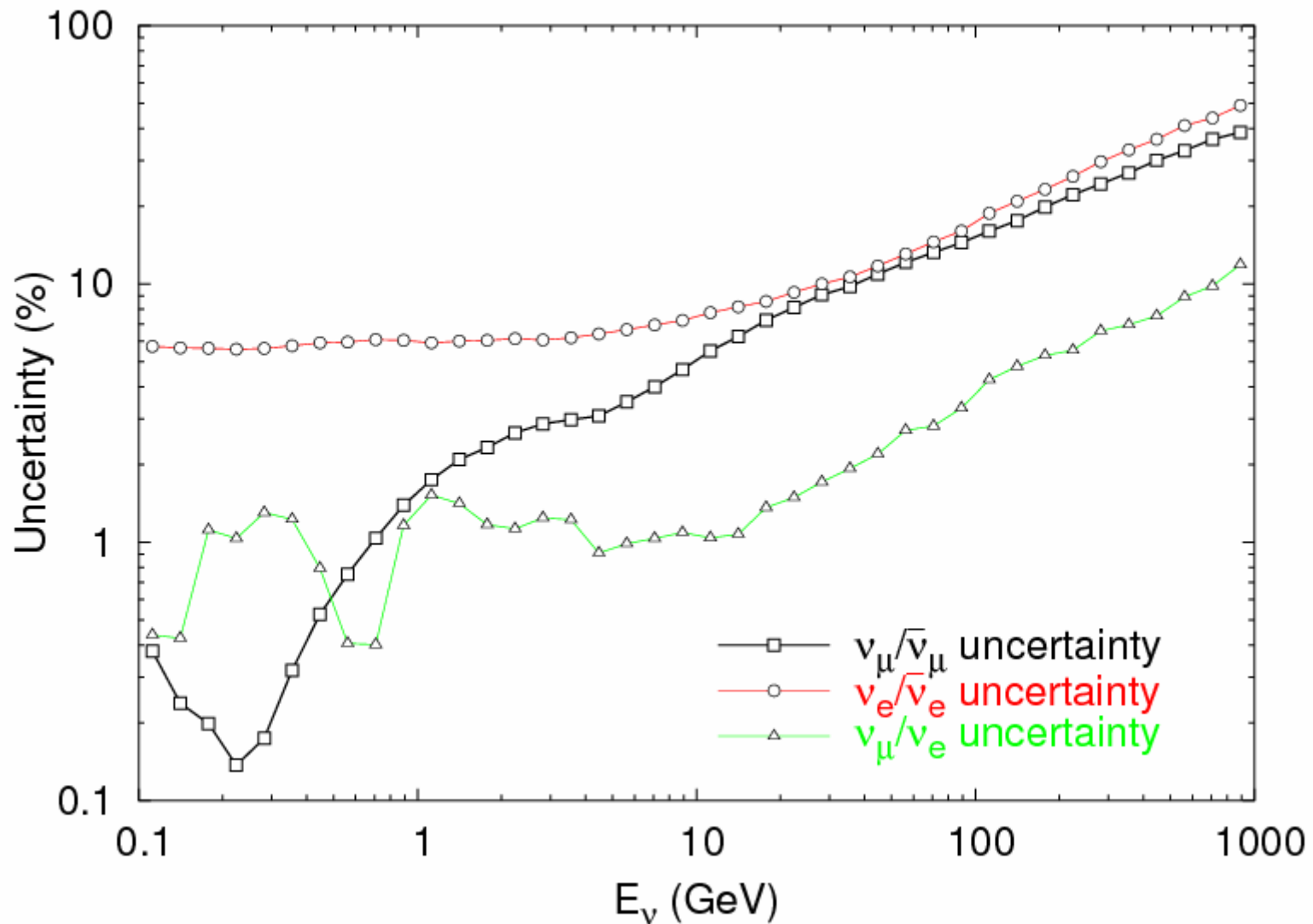


Method for evaluating uncertainties

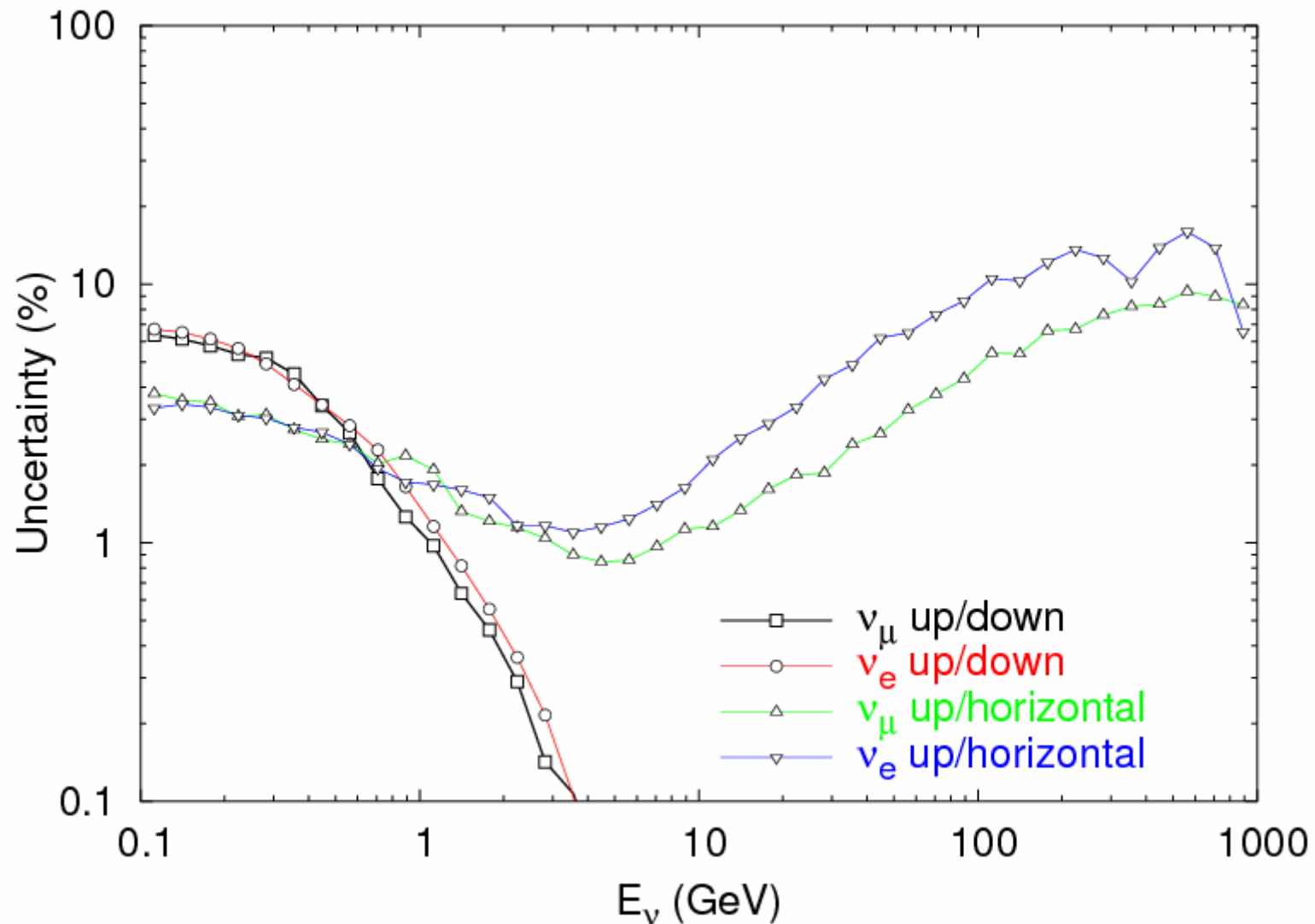
- 1st meson
- Weight events by 1σ in each uncertainty region.
- Include primary flux uncertainties similarly.
- Neutrons (discuss)
- Energy conservation (discuss)
- Measured muon fluxes not used in this evaluation.
- Intention is a data driven uncertainty estimate NOT comparing Monte-Carlos with each other.



Flavour ratio uncertainties



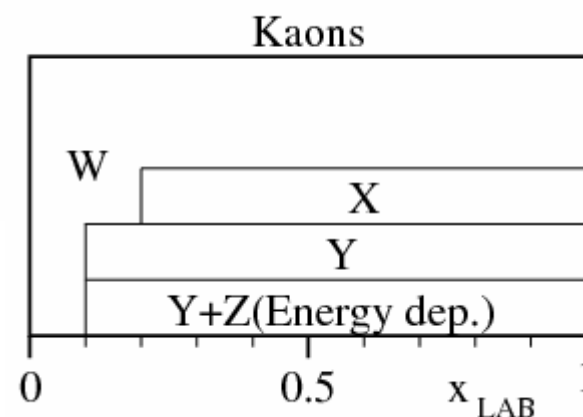
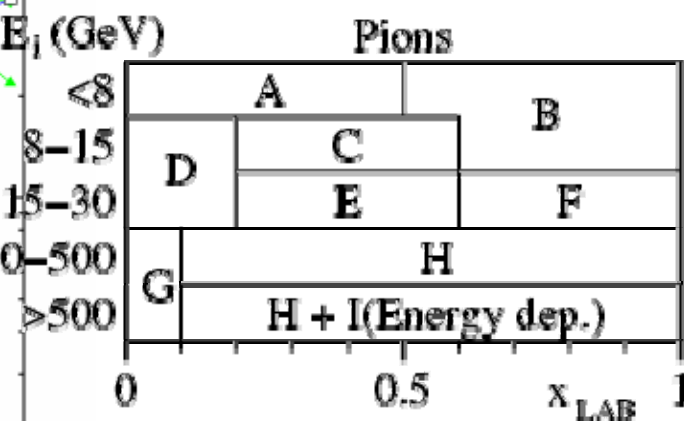
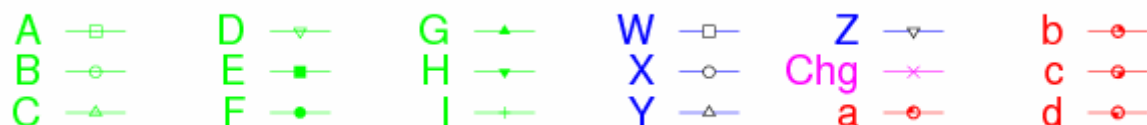
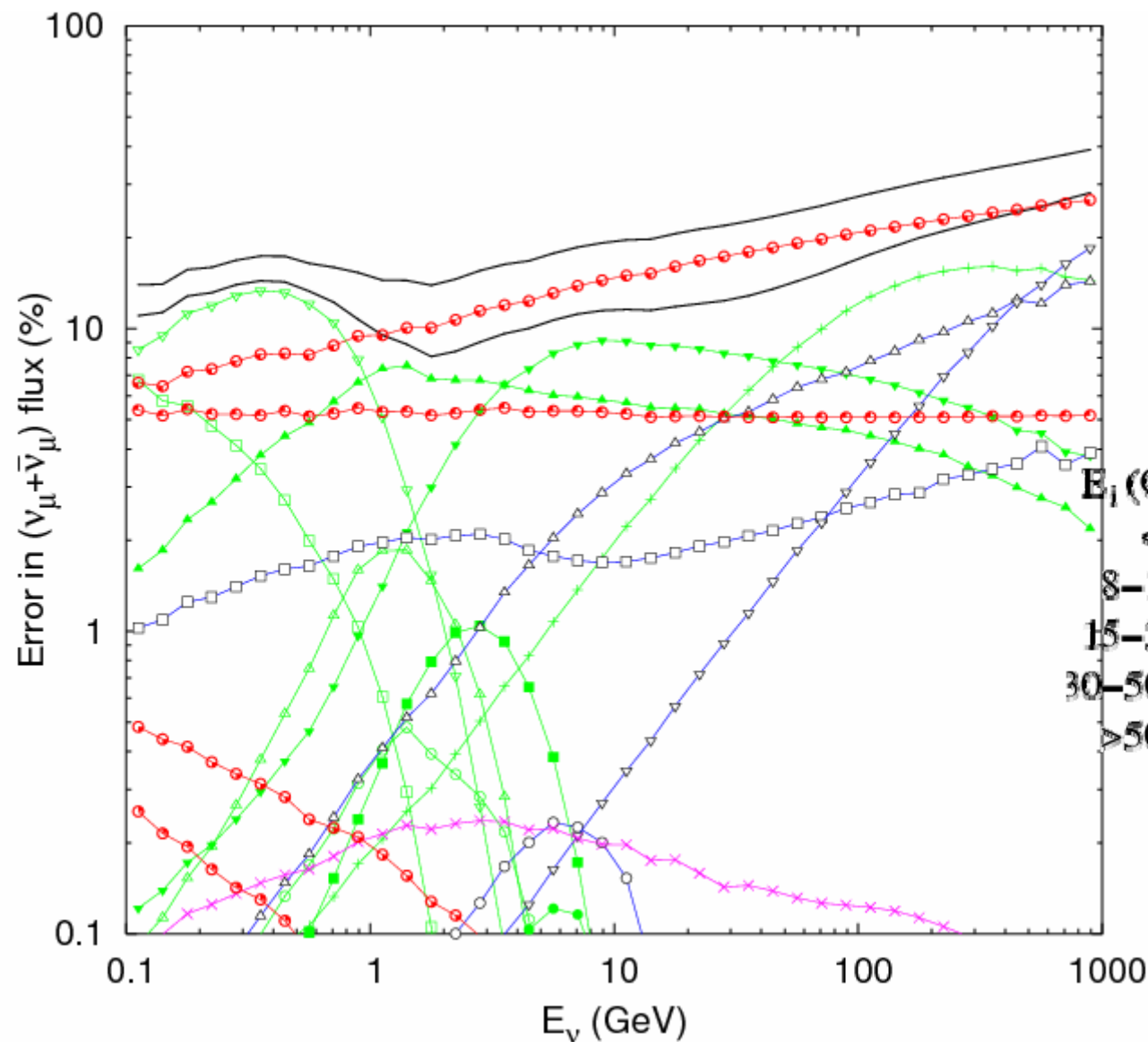
Up/Down/Horizontal Cancellation



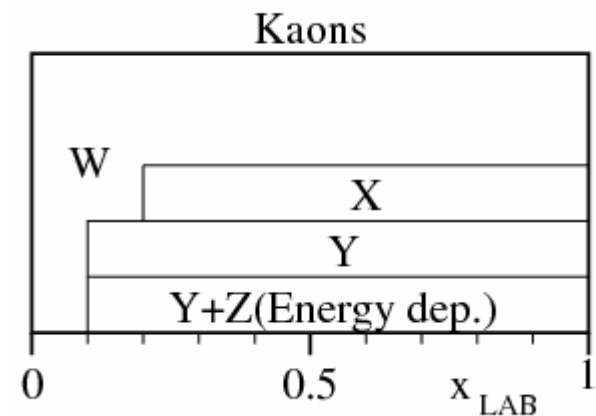
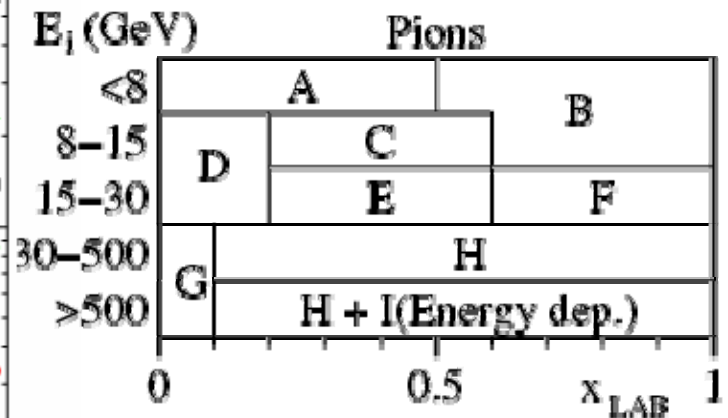
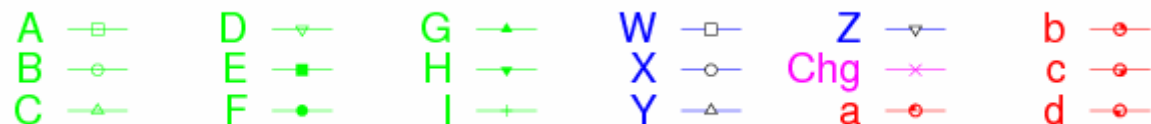
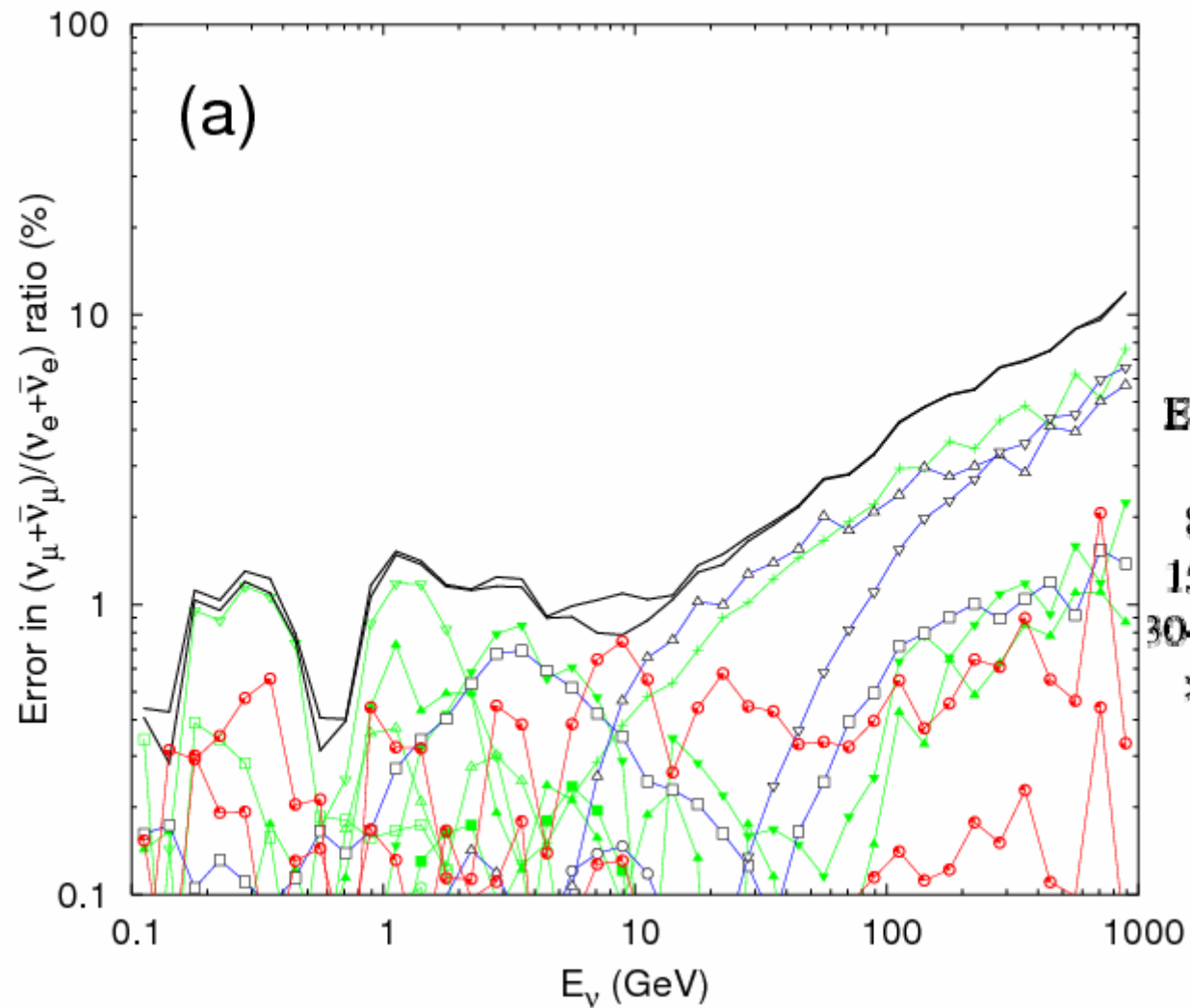
Check of cancellation mechanism: switch off geomagnetic field

Error

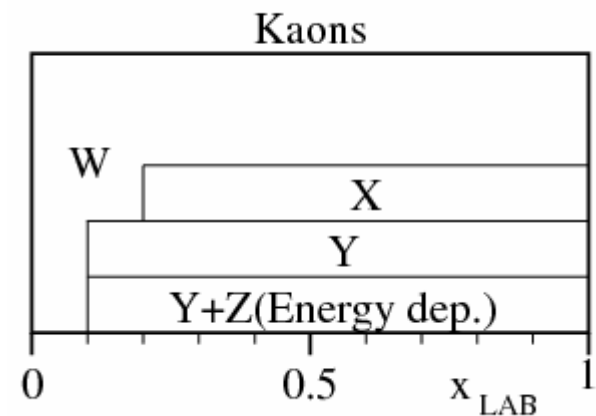
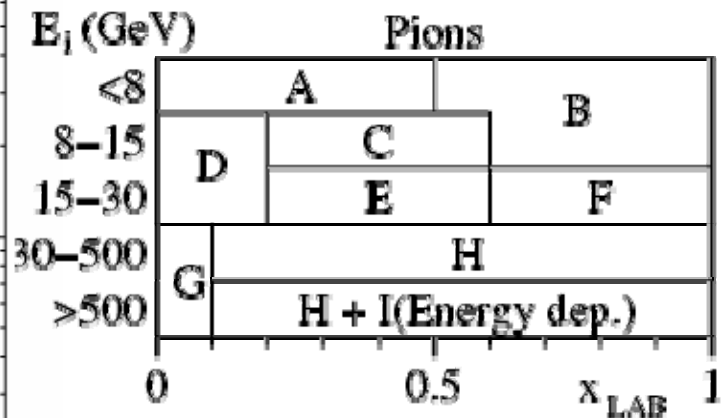
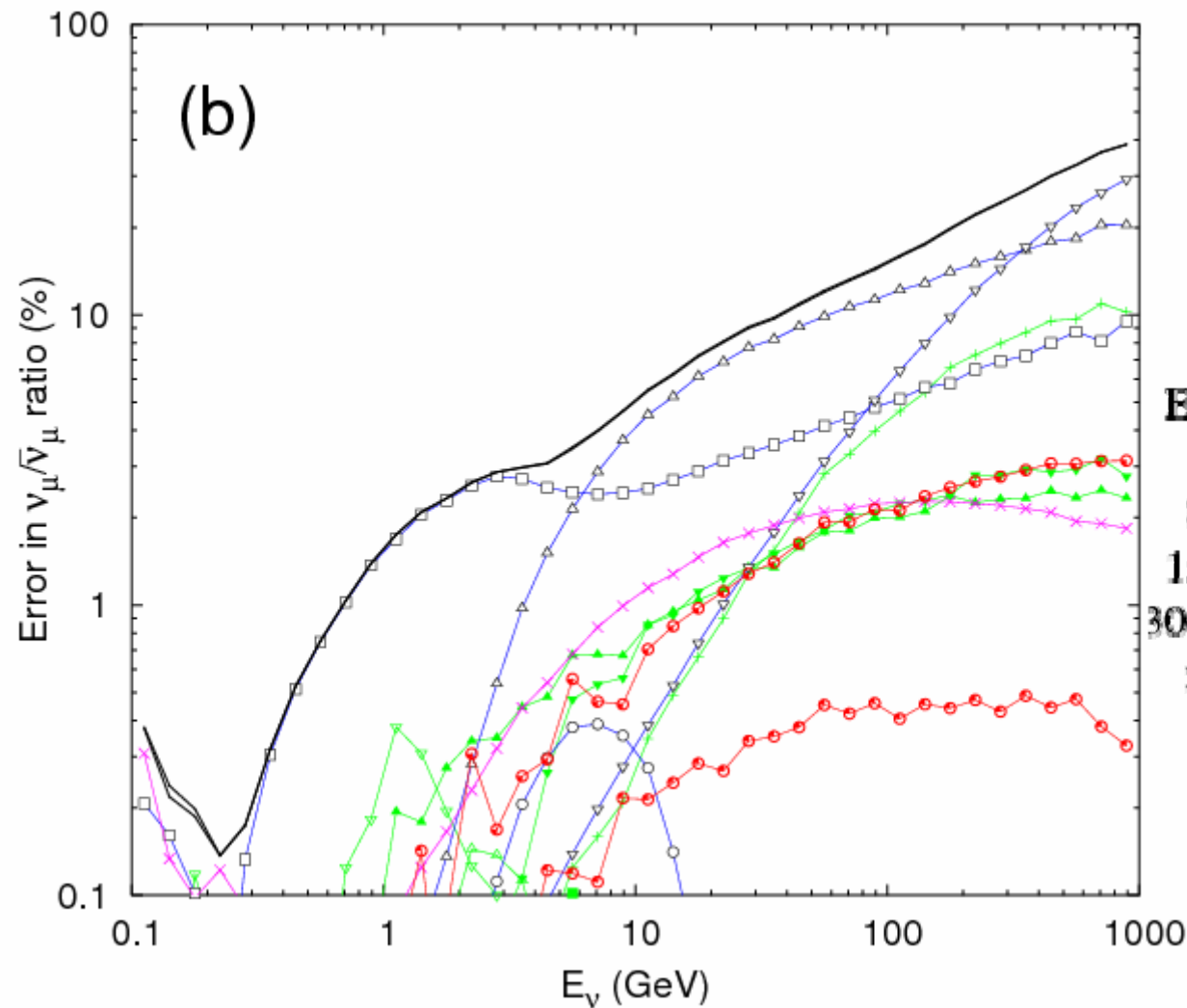
breakdown of
absolute fluxes



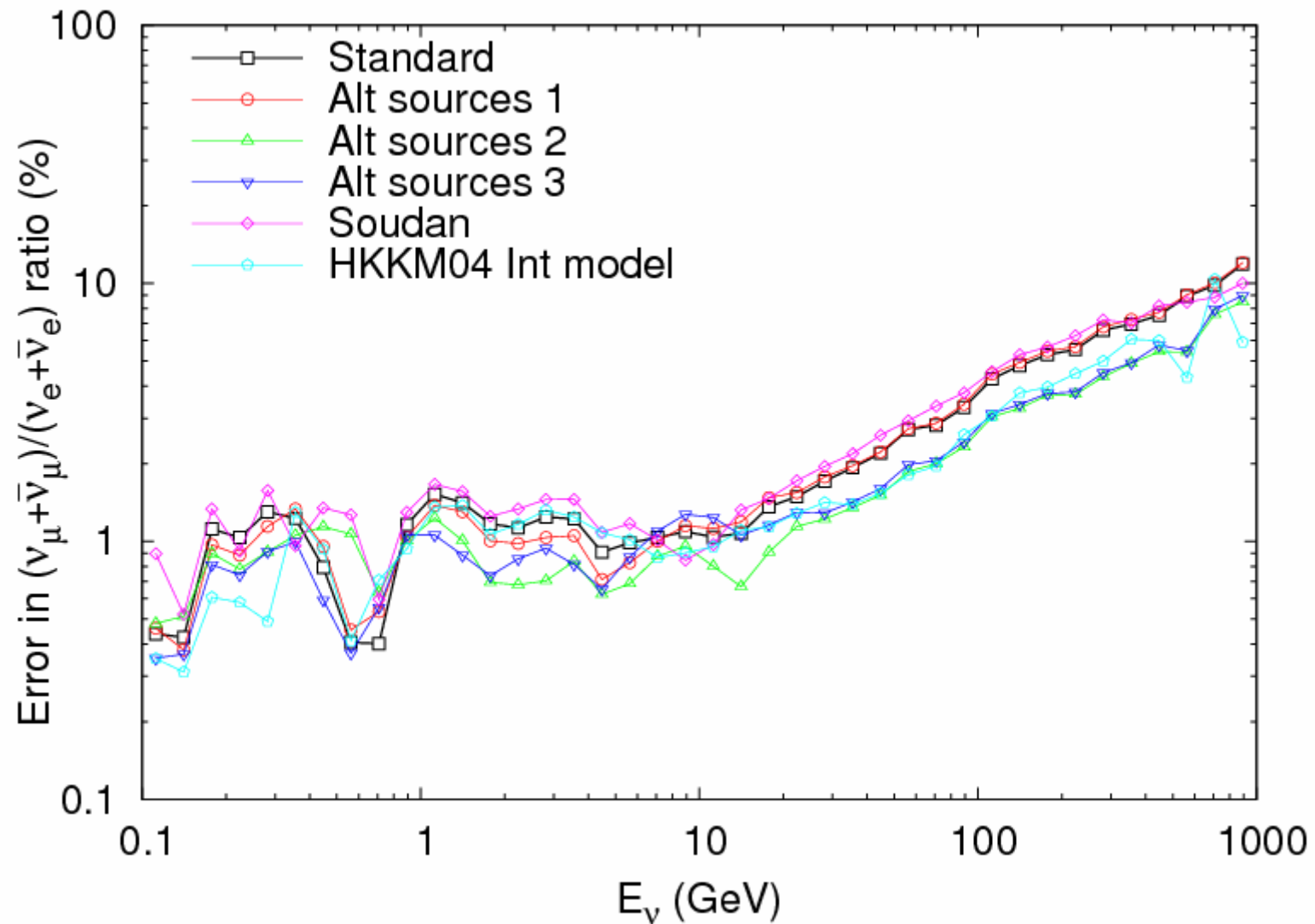
Error breakdown of flavour ratio



Error breakdown of muon neutrino- antineutrino ratio



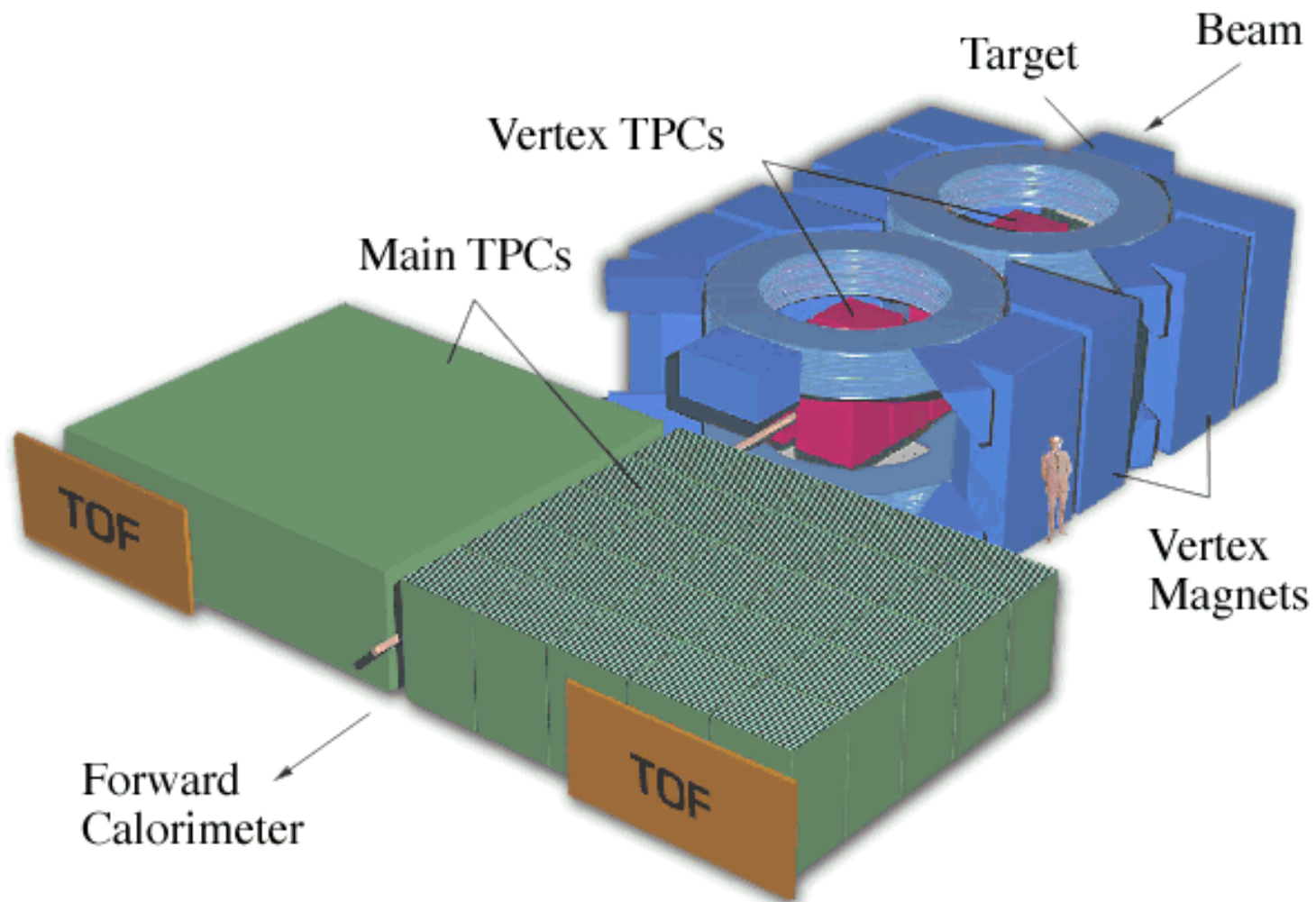
Cross checks...



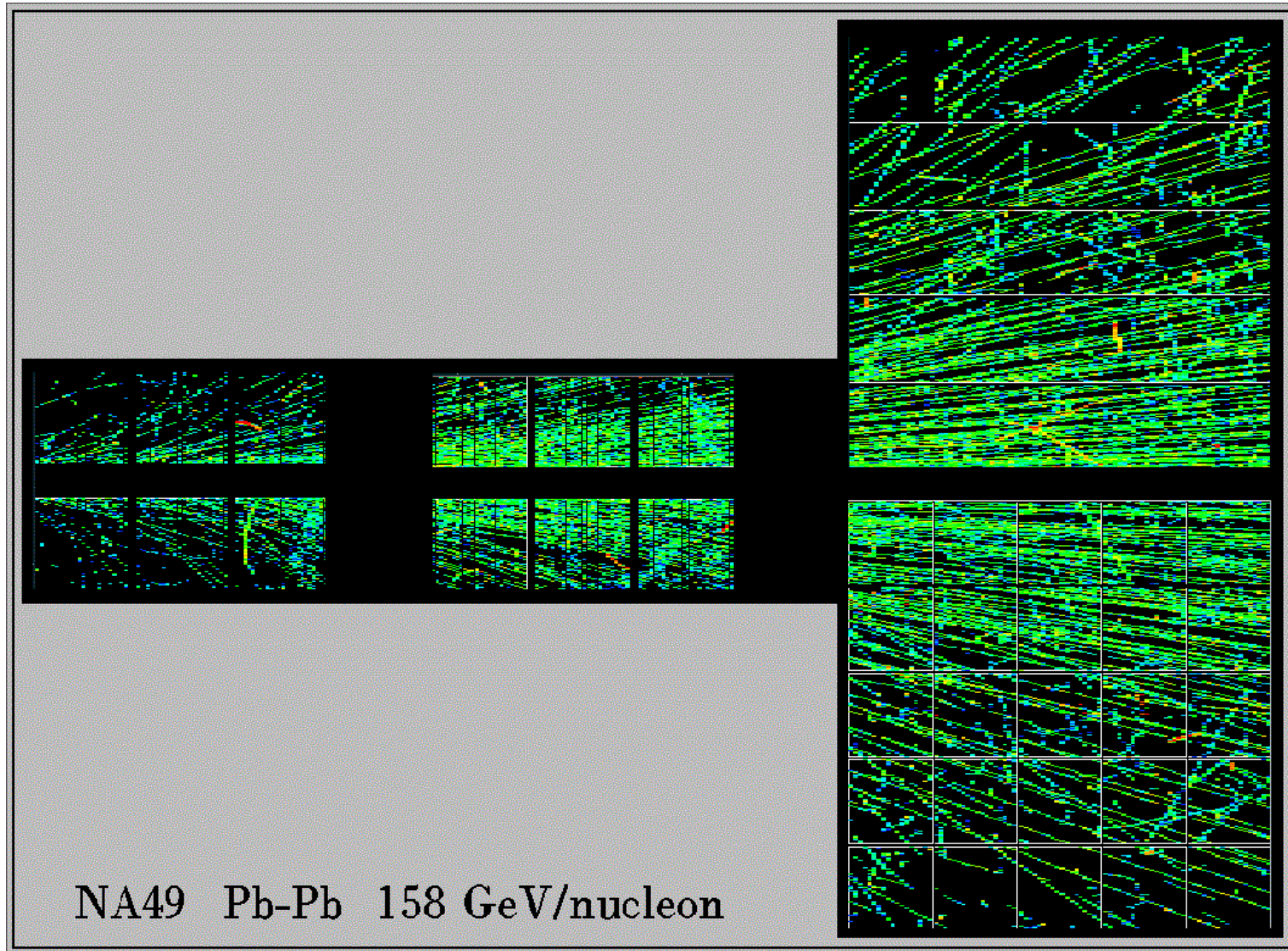
NA49

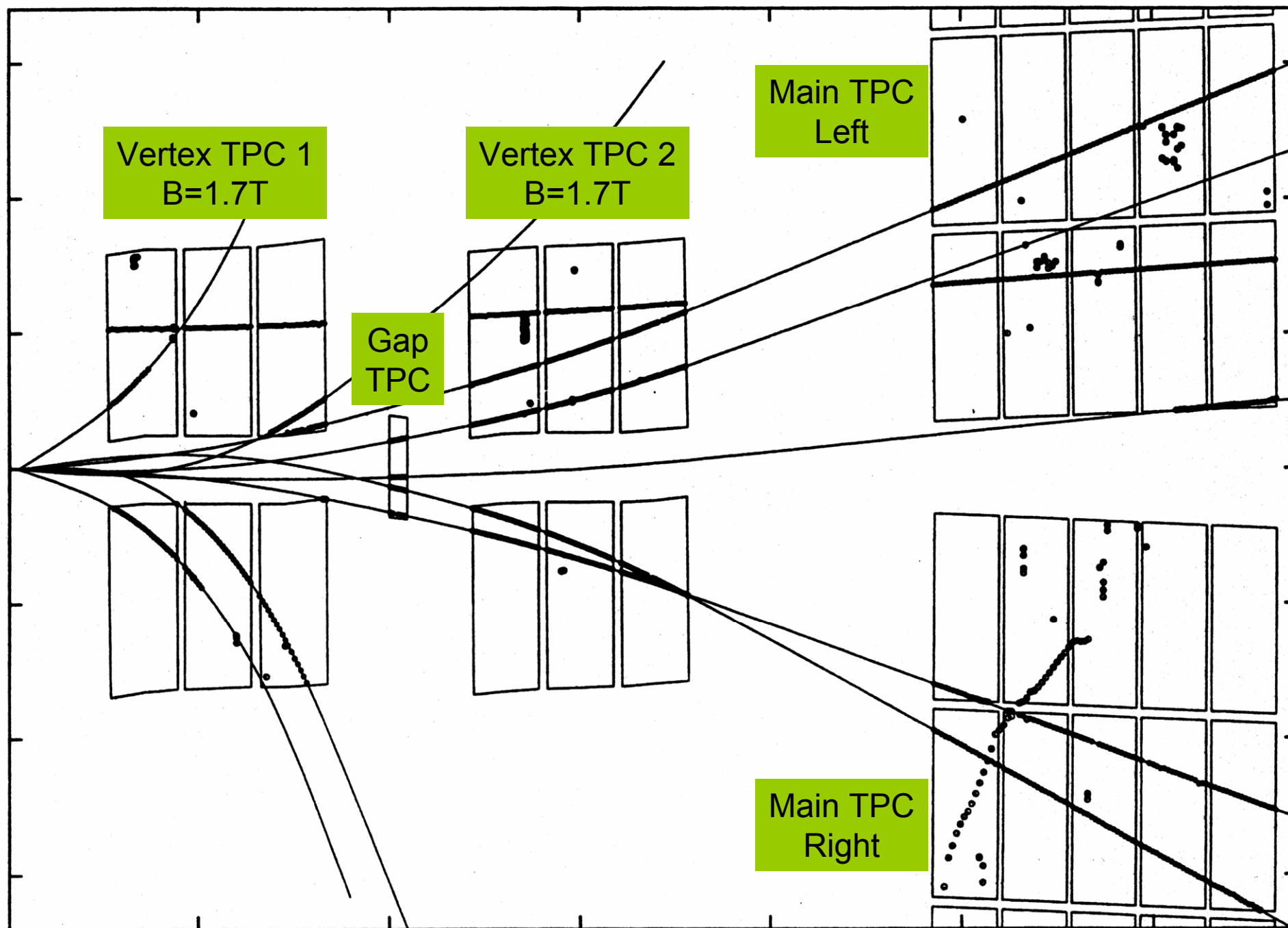
158 GeV protons on thin carbon target

NA49



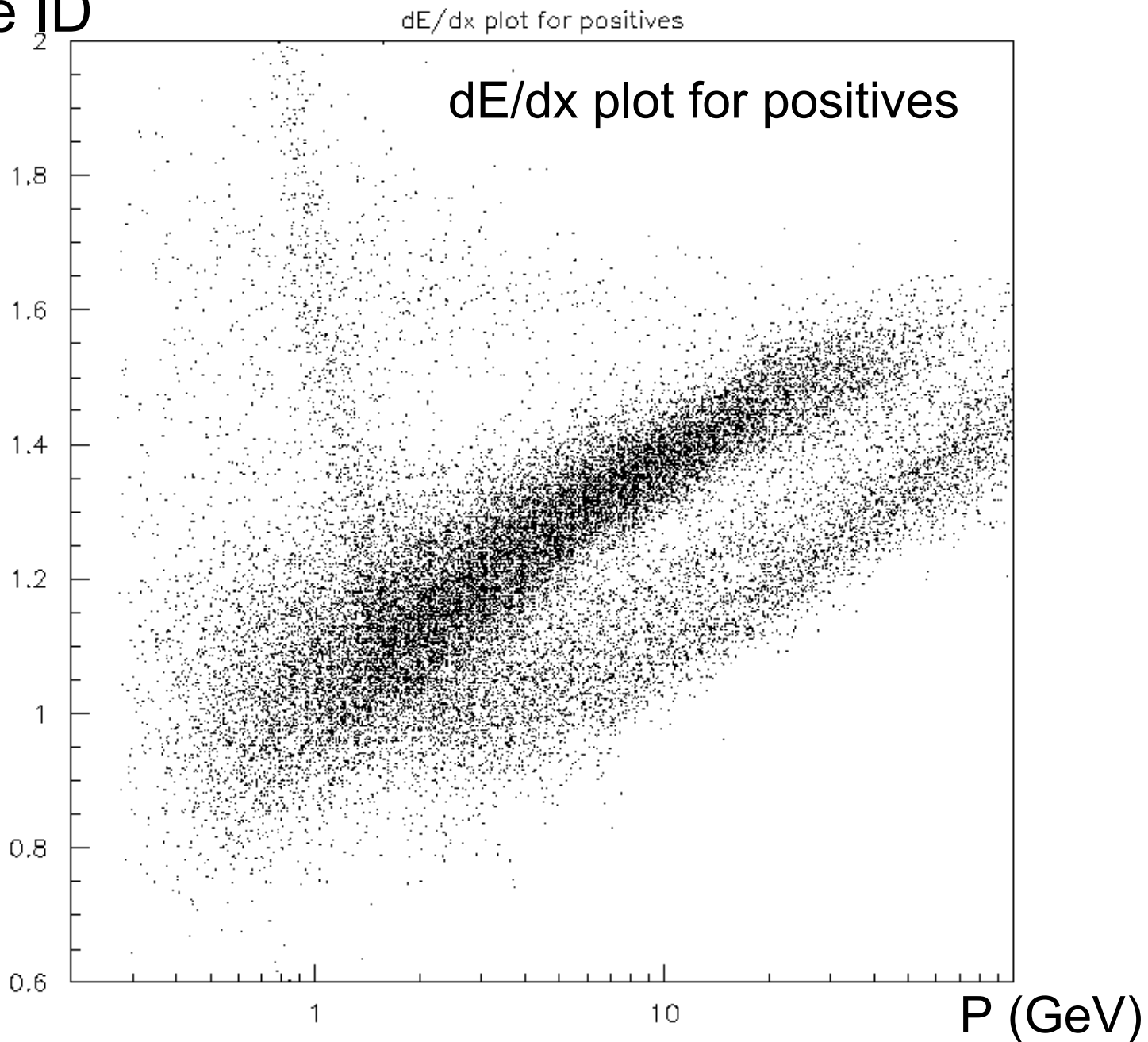
- NA49 originally designed for Lead-Lead collisions.
- Also used for pp and pA collision physics



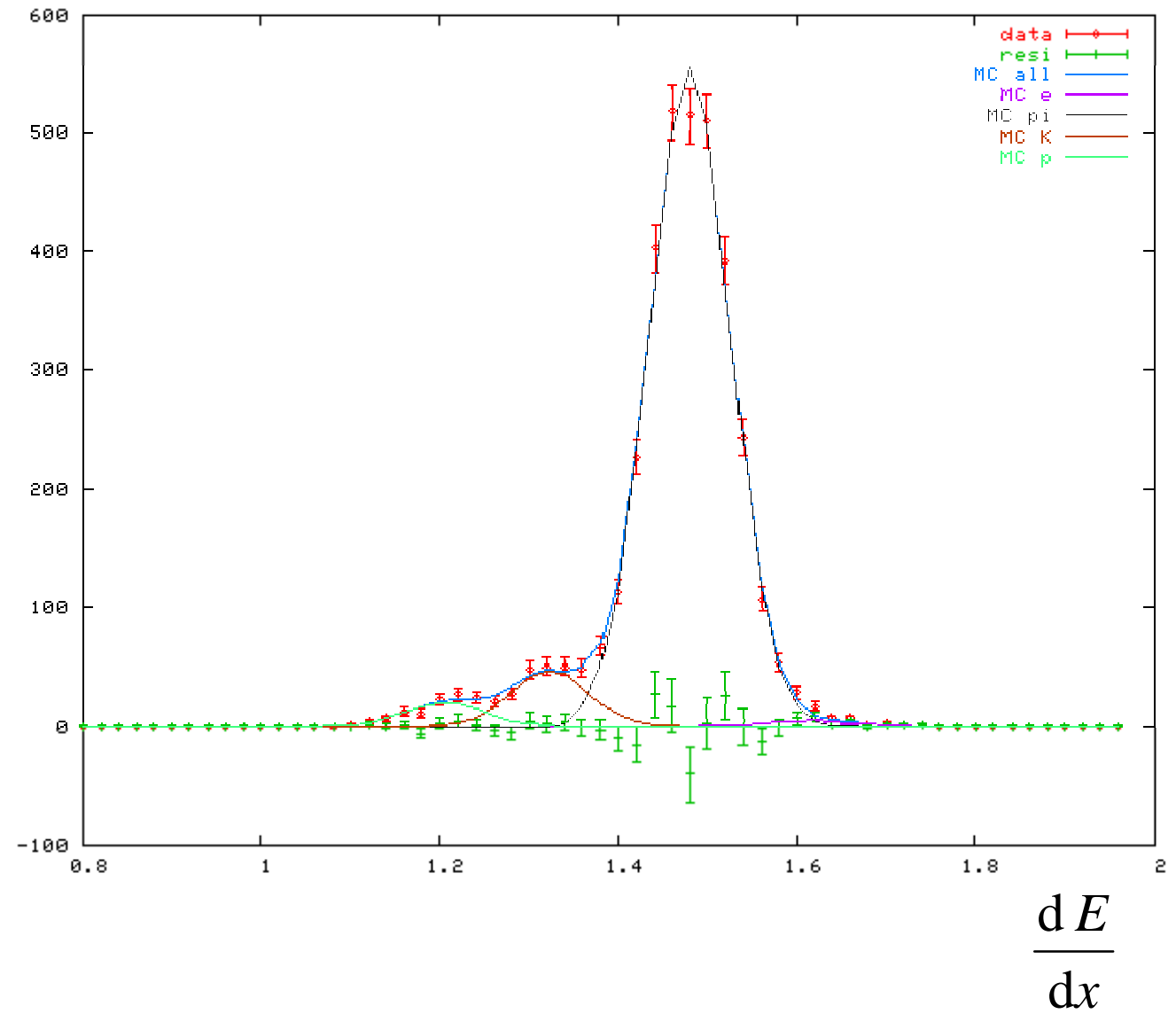


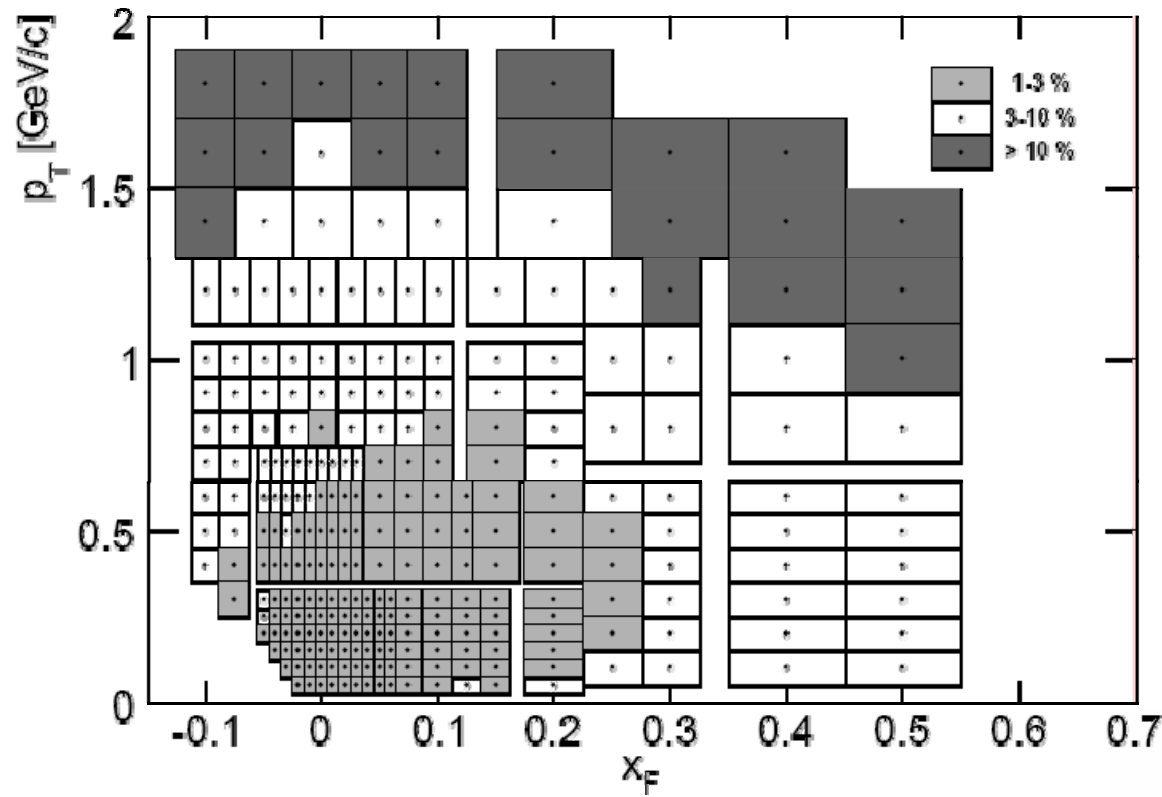
Particle ID

$$\frac{dE}{dx}$$



Particle ID



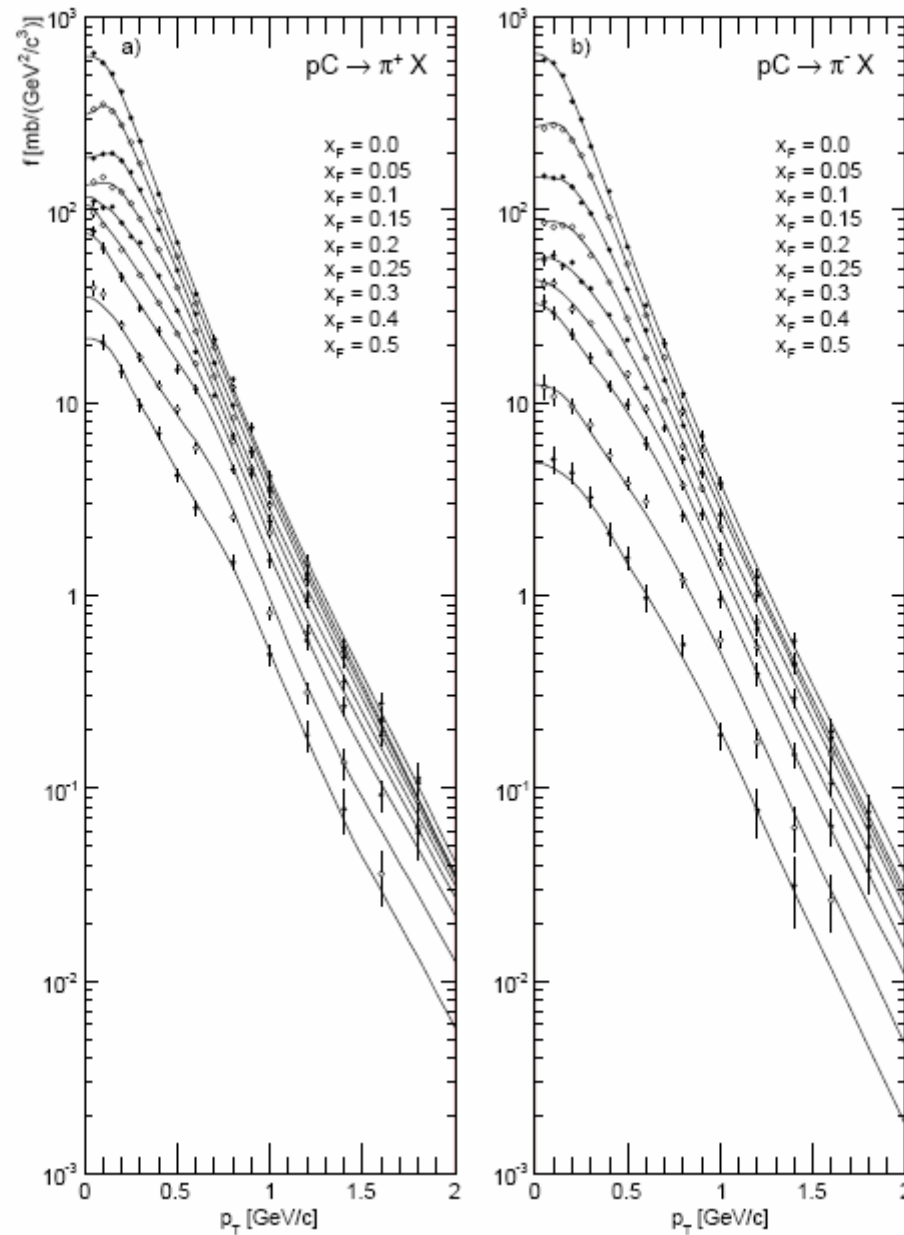


Binning, statistical
and systematic
errors

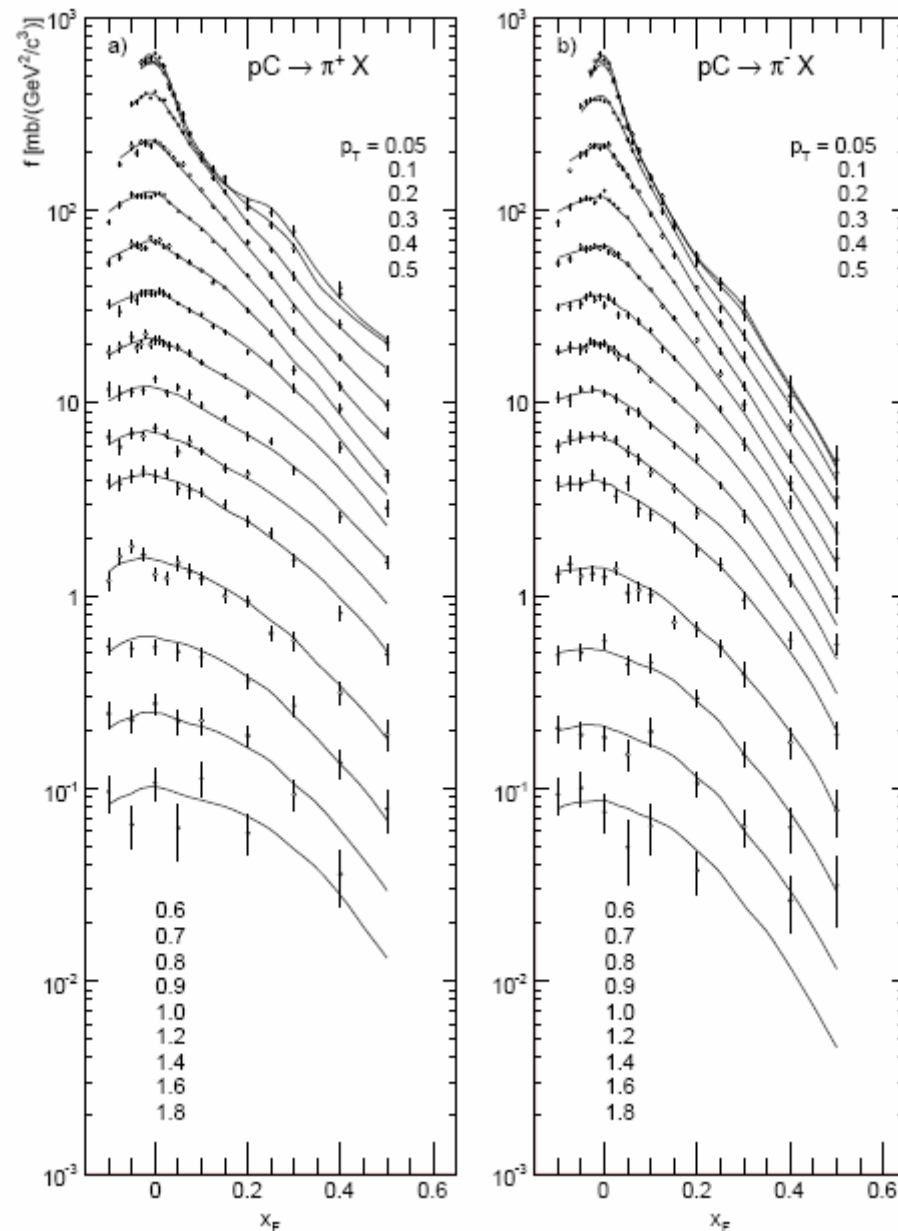
Normalization	2.5%
Tracking efficiency	0.5%
Trigger bias	1%
Feed-down	1-2.5%
Detector absorption	0.5%
Pion decay $\pi \rightarrow \mu + \nu_\mu$	
Re-interaction in the target	
Binning	0.5%
Total(upper limit)	7.5%
Total(quadratic sum)	3.8%

Table 3: Summary of systematic errors

Transverse momentum distributions



Feynman-x distributions



More details of this measurement in
hep-ex/0606028 and
hep-ex/0606029

Summary

- Impressive how much information about neutrino oscillation has been obtained from cosmic rays despite the non-precision status of the hadronic shower simulation.
- Hadron production is definitely the most serious uncertainty in atmospheric neutrino calculations.
- Could get more on sub-dominant neutrino oscillation effects with improved knowledge of hadron production.
- Demonstrated cancellation in ratios has been made. Estimate is not complete: e.g. neutrons.
- New data from NA49 – and others too.

