Atmospheric Neutrino Fluxes

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NA61/SHINE-2020 workshop

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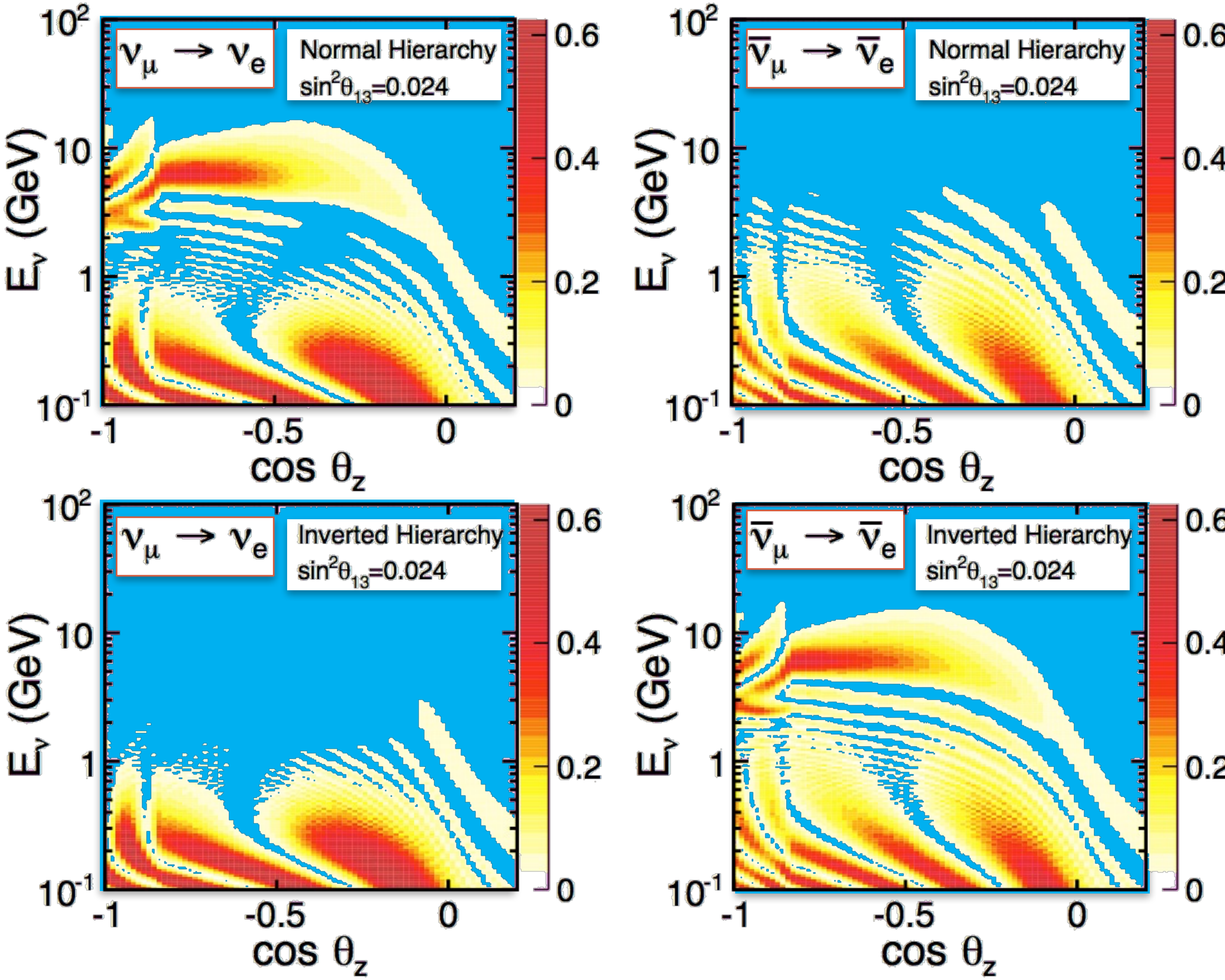
Introduction

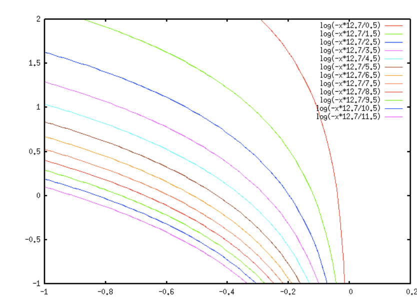
- Objective is to calculate neutrino fluxes underground.
- Simulate cascades in the atmosphere, count the neutrinos resulting from secondary particle decays.
- Negligible probability of seeing more than one neutrino from one cosmic ray shower
  - No need to provide detailed transverse momentum balance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

Oscillation across the Earth

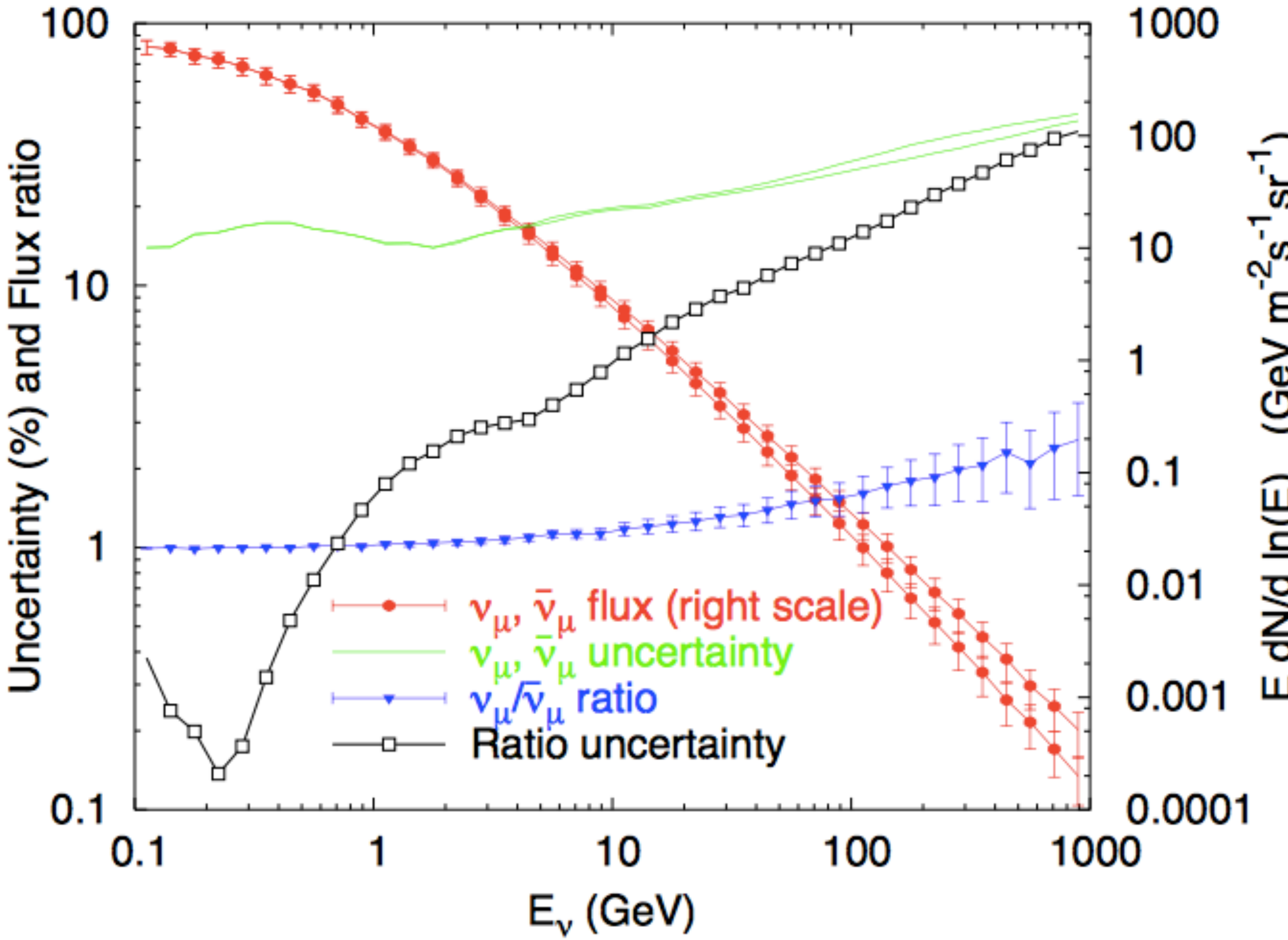
From DUNE arxiv 1307-7335

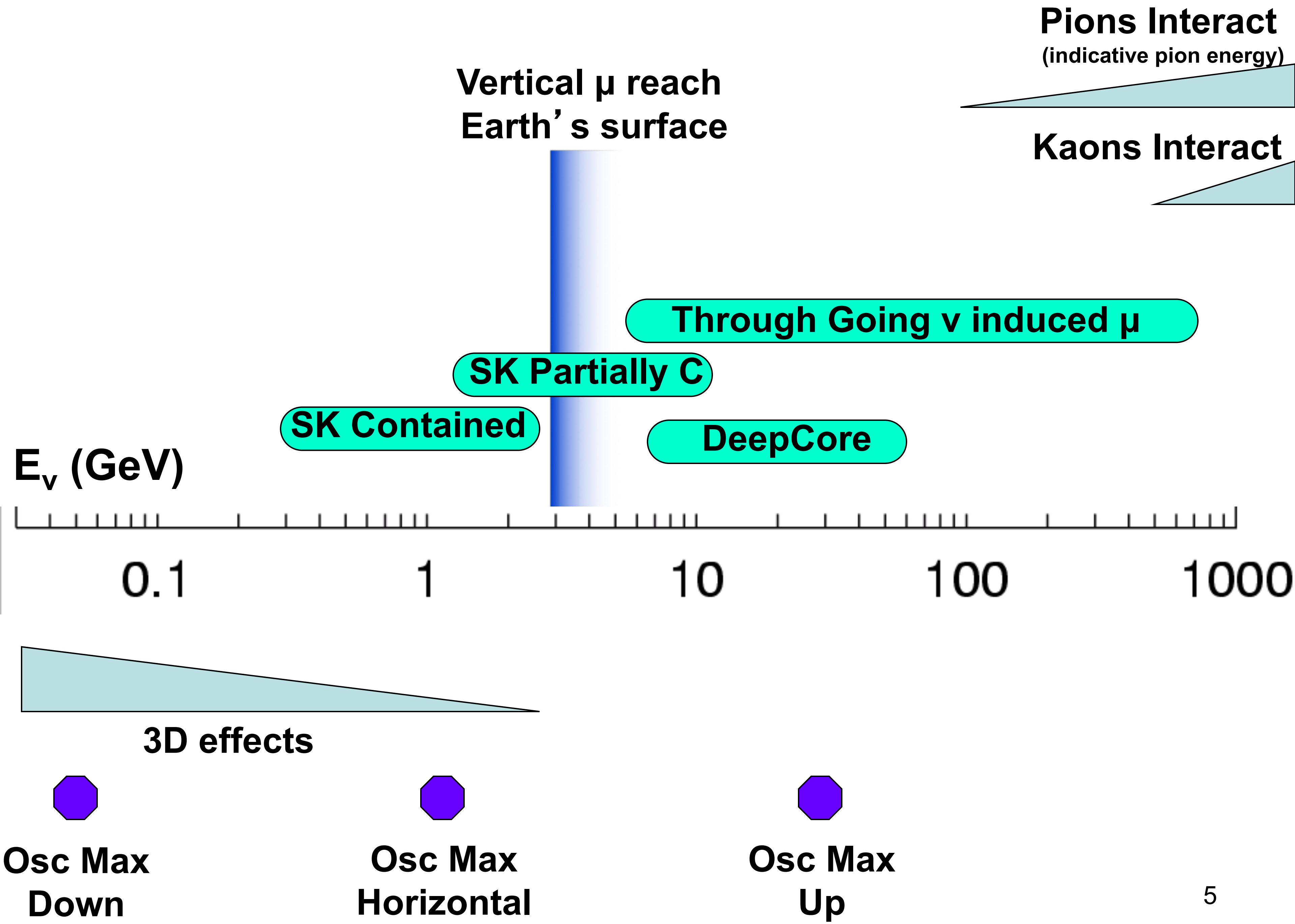


- The resonance effect exists – 3 to 10 GeV. Measurement of mass hierarchy in atmospheric neutrinos.
- SHINE is idea energy range for this hadron production.
- Effects below 1GeV are CP violation. Very interesting, but very hard to resolve. Needs a neutrino beam.



Summary plot, illustration of ratio cancellation effects





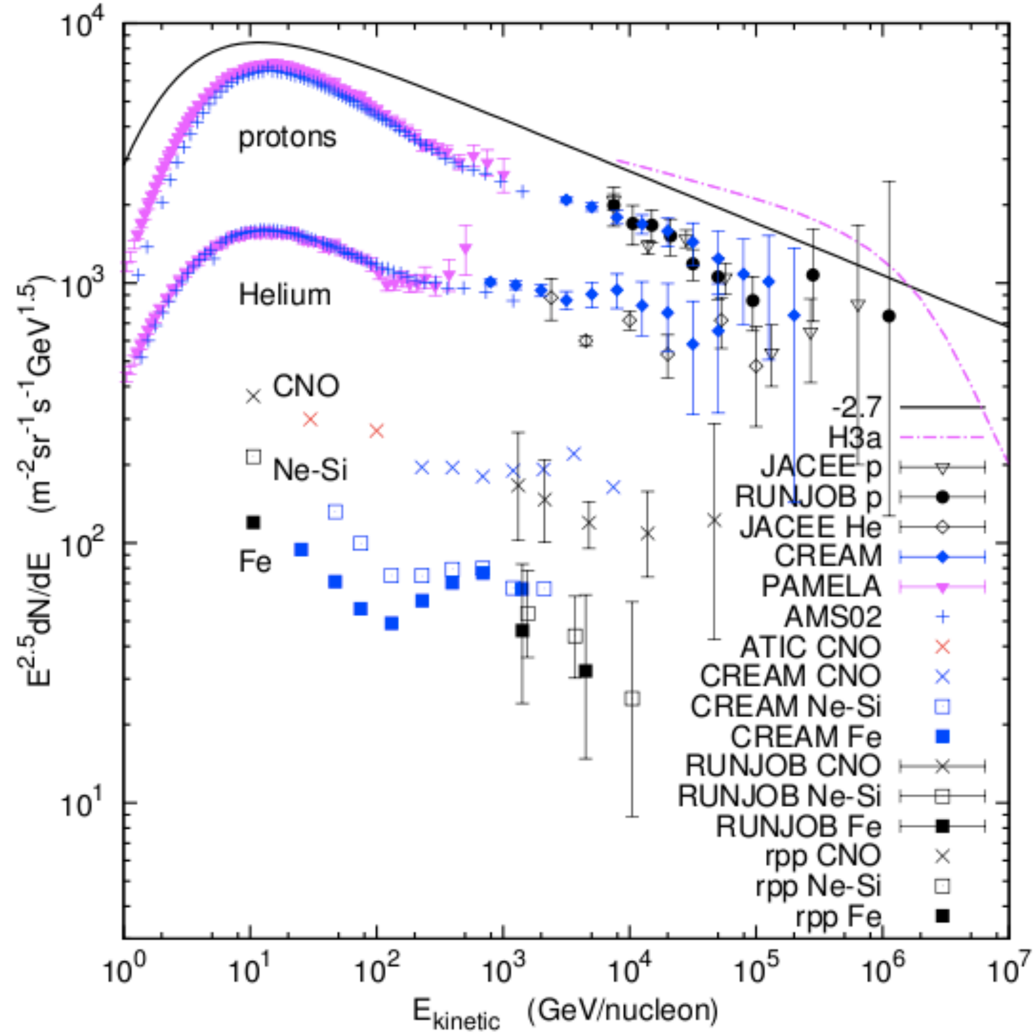
Pions Interact
(indicative pion energy)
Vertical μ reach
Earth's surface
Kaons Interact
Through Going ν induced μ
SK Partially C
SK Contained
DeepCore
Eν (GeV)
0.1
1
10
100
1000
3D effects
Osc Max
Down
Osc Max
Horizontal
Osc Max
Up

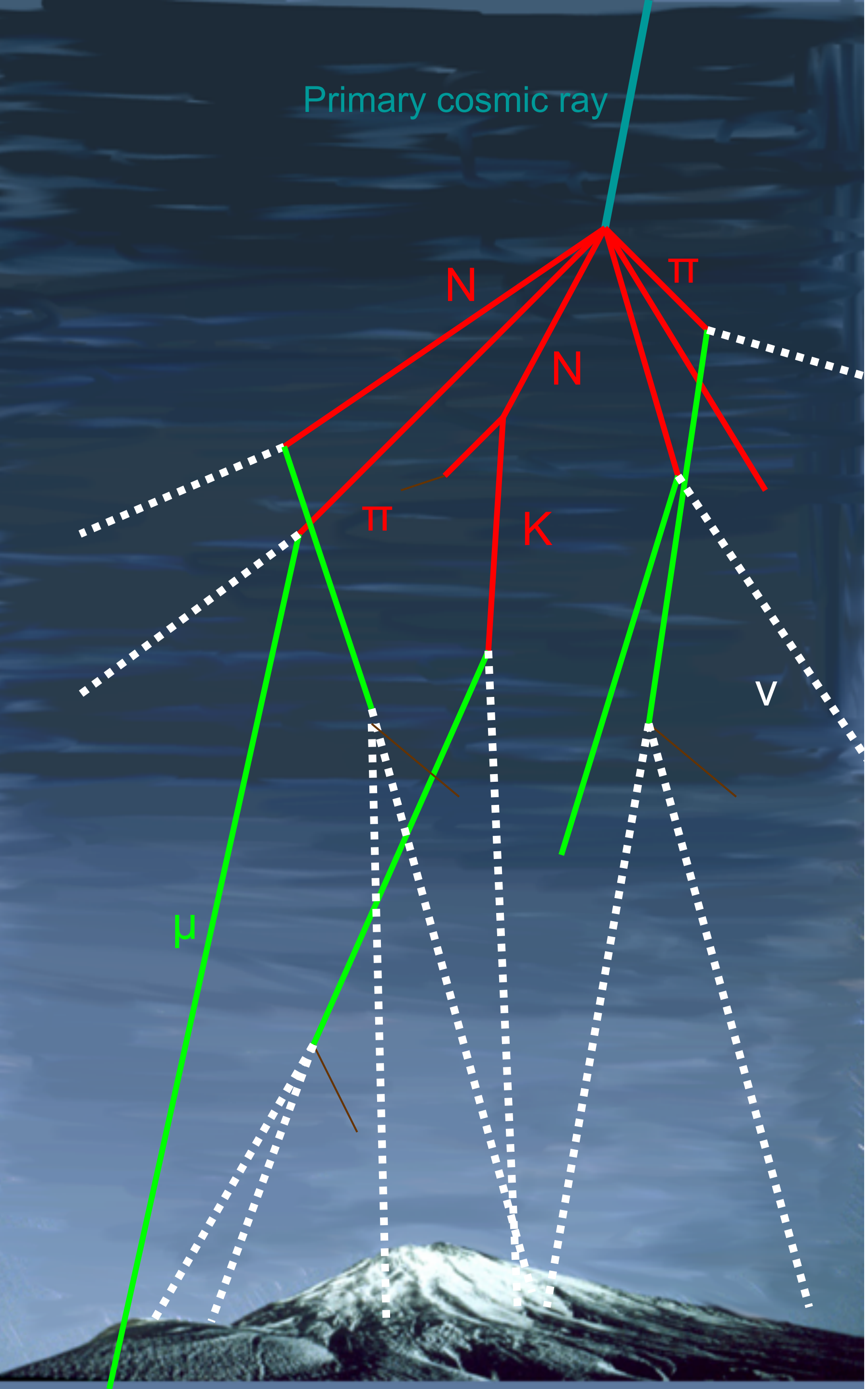
Main feature of cosmic rays...

... is that the flux falls steeply with energy.

[Note: This plot has the y-axis multiplied by $E^{2.5}$].

- Higher energy secondary particles are most interesting.
- Neutrinos from kaons are enhanced
- Forward hadron production measurements very welcome, so gap TPC and FTPCs are a good addition to SHINE for this.

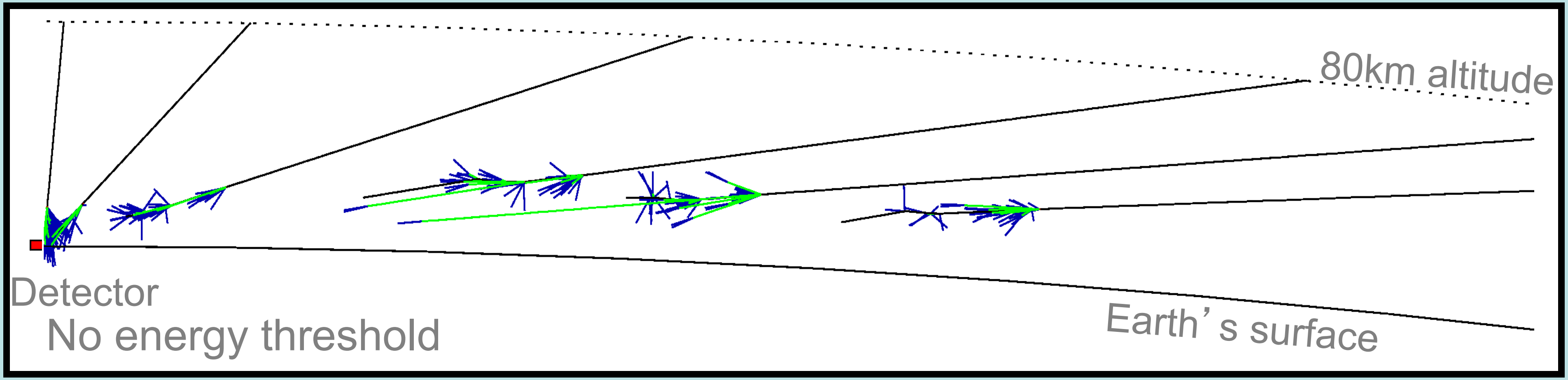




Propagation through the atmosphere

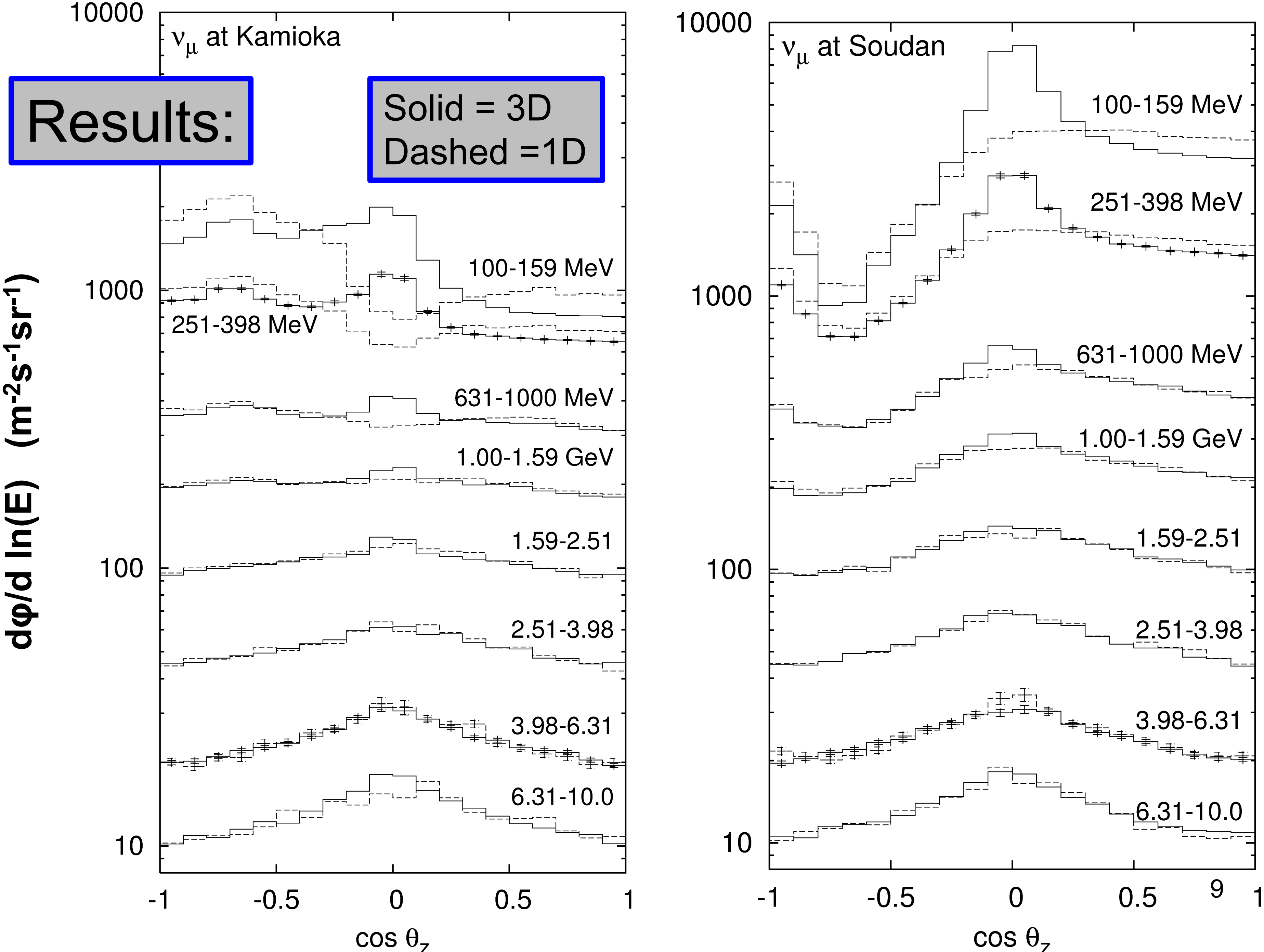
- Start primary high in atmosphere
- Interacts after mean ~90g/cm^2 (atmosphere depth 1050 g/cm^2)
- Interaction generated by hadron production MC generator
- Track particles in 3D through atmosphere:
  - Bending in magnetic field
  - Multiple scattering, energy loss
  - Muons do not depolarize
  - Account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

Back-tracing primaries to obtain cutoffs



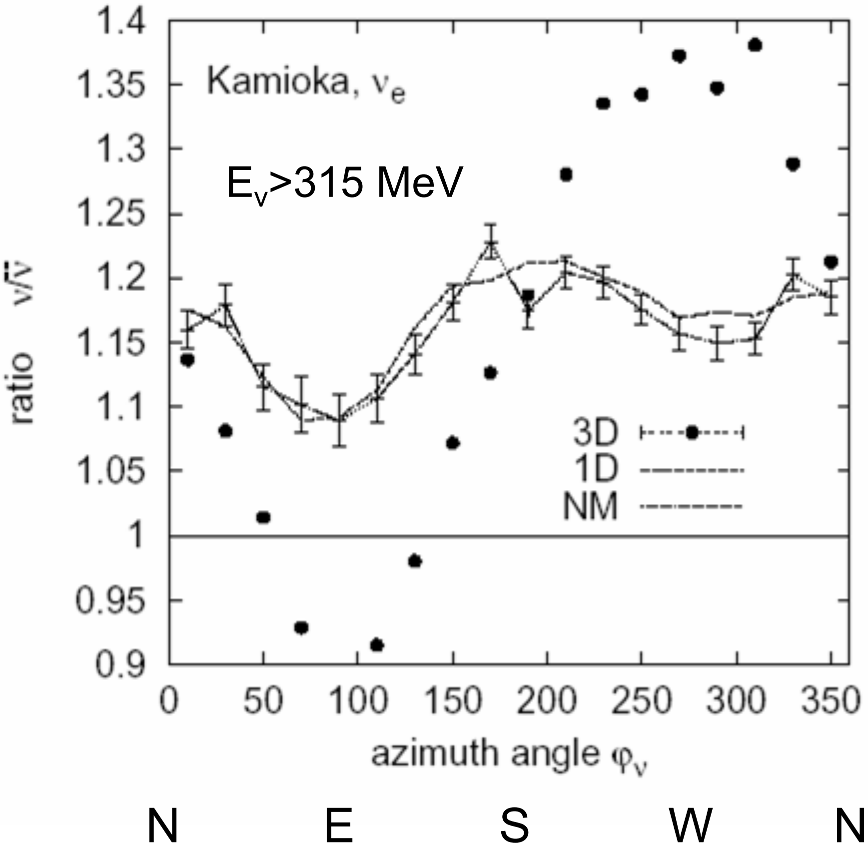
1. Generate particles isotropically over a sphere of radius R_E+80km.
2. Propagate primary forward in straight line until first interraction
3. Propagate all secondaries with magnetic field turned on
4. Backtrace primary from first interaction point to do cutoff calculation. If backtrace causes trajectory 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.

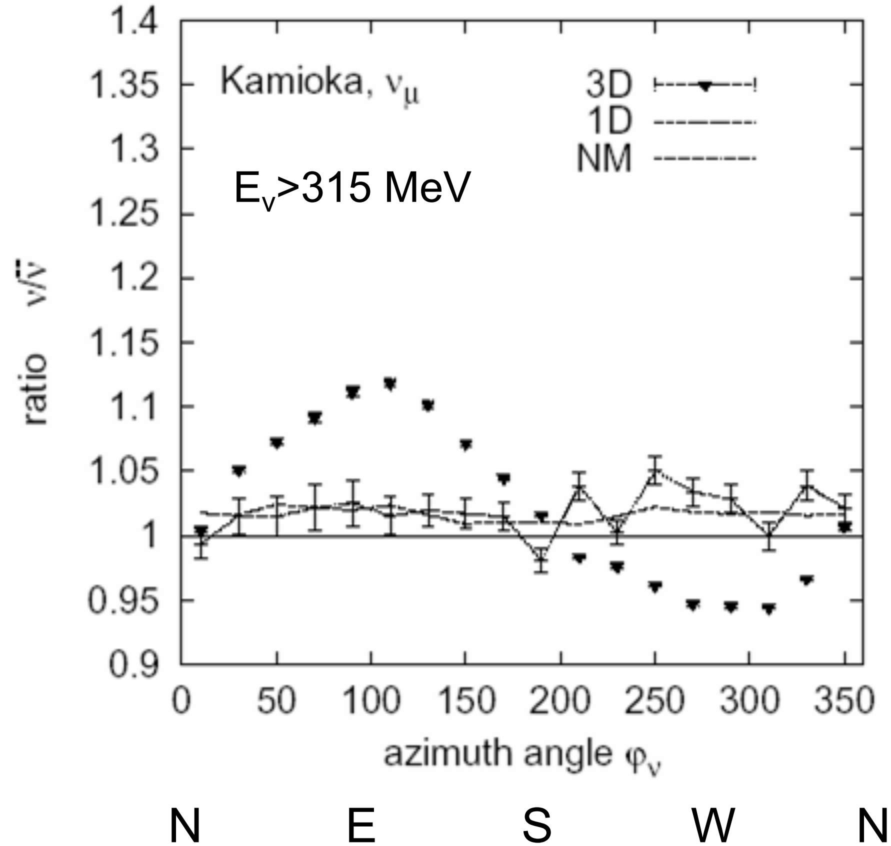
Results:



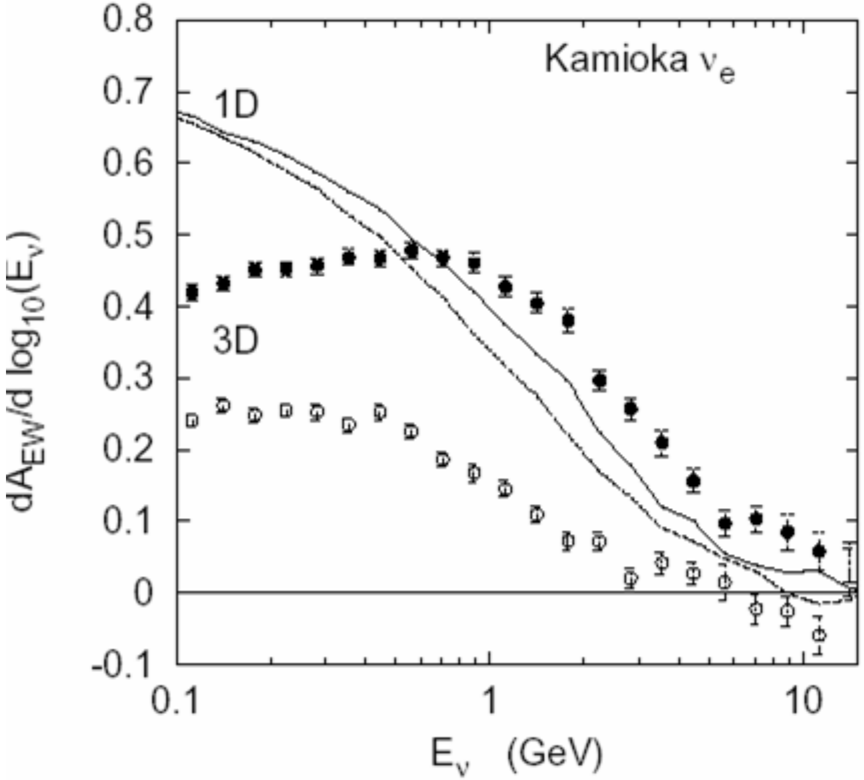
Solid = 3D
Dashed =1D
ν_μ at Kamioka
ν_μ at Soudan
dφ/d ln(E) (m-2s-1sr-1)
100-159 MeV
251-398 MeV
631-1000 MeV
1.00-1.59 GeV
1.59-2.51
2.51-3.98
3.98-6.31
6.31-10.0
10000
1000
100
10
-1
-0.5
0
0.5
1
cos θz

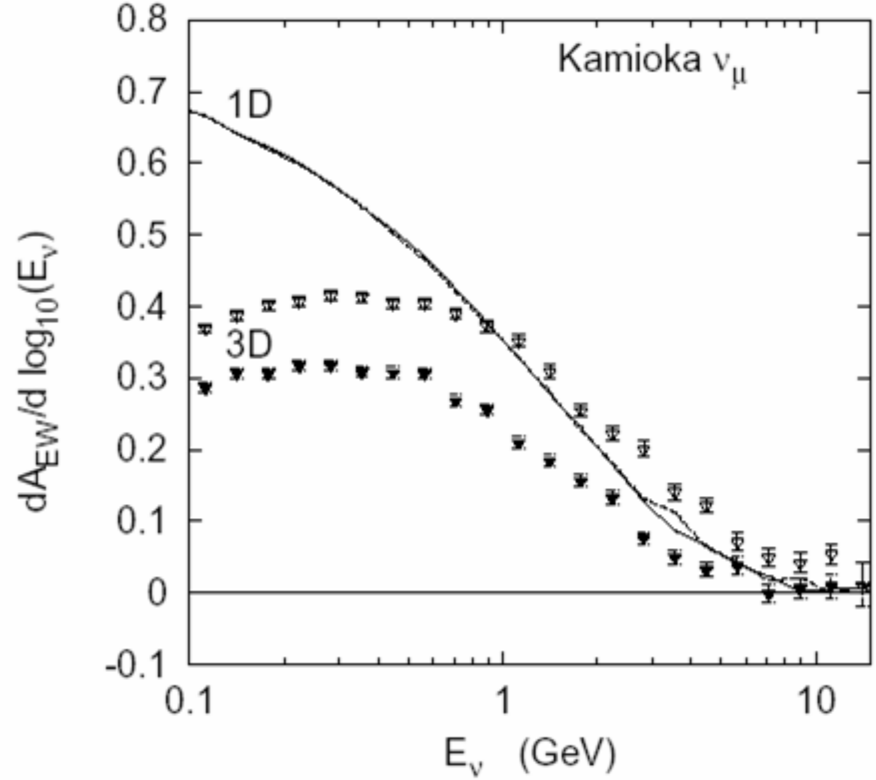
Azimuth angle distribution East-West effect





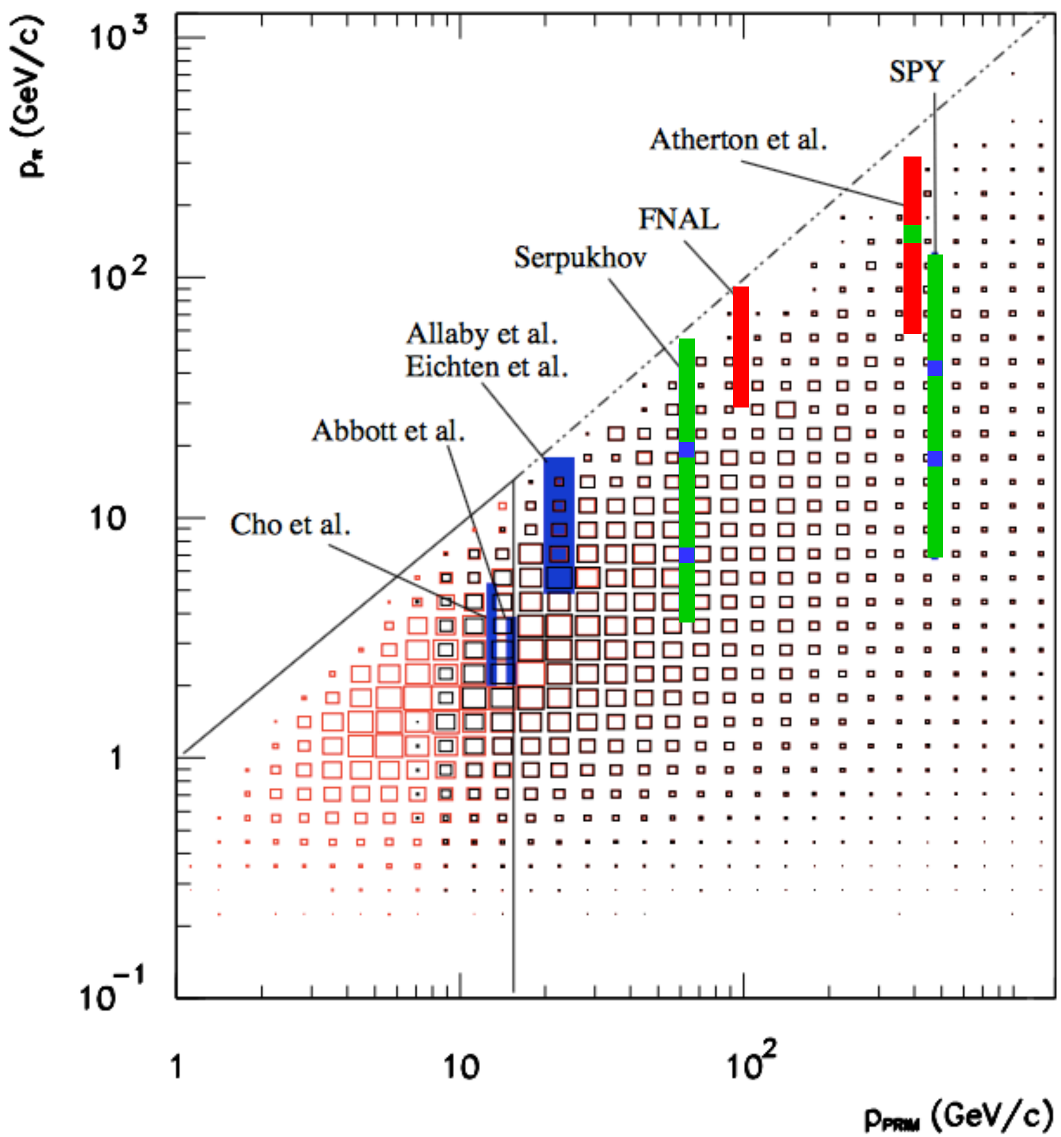
Energy dependence of East-West effect





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.

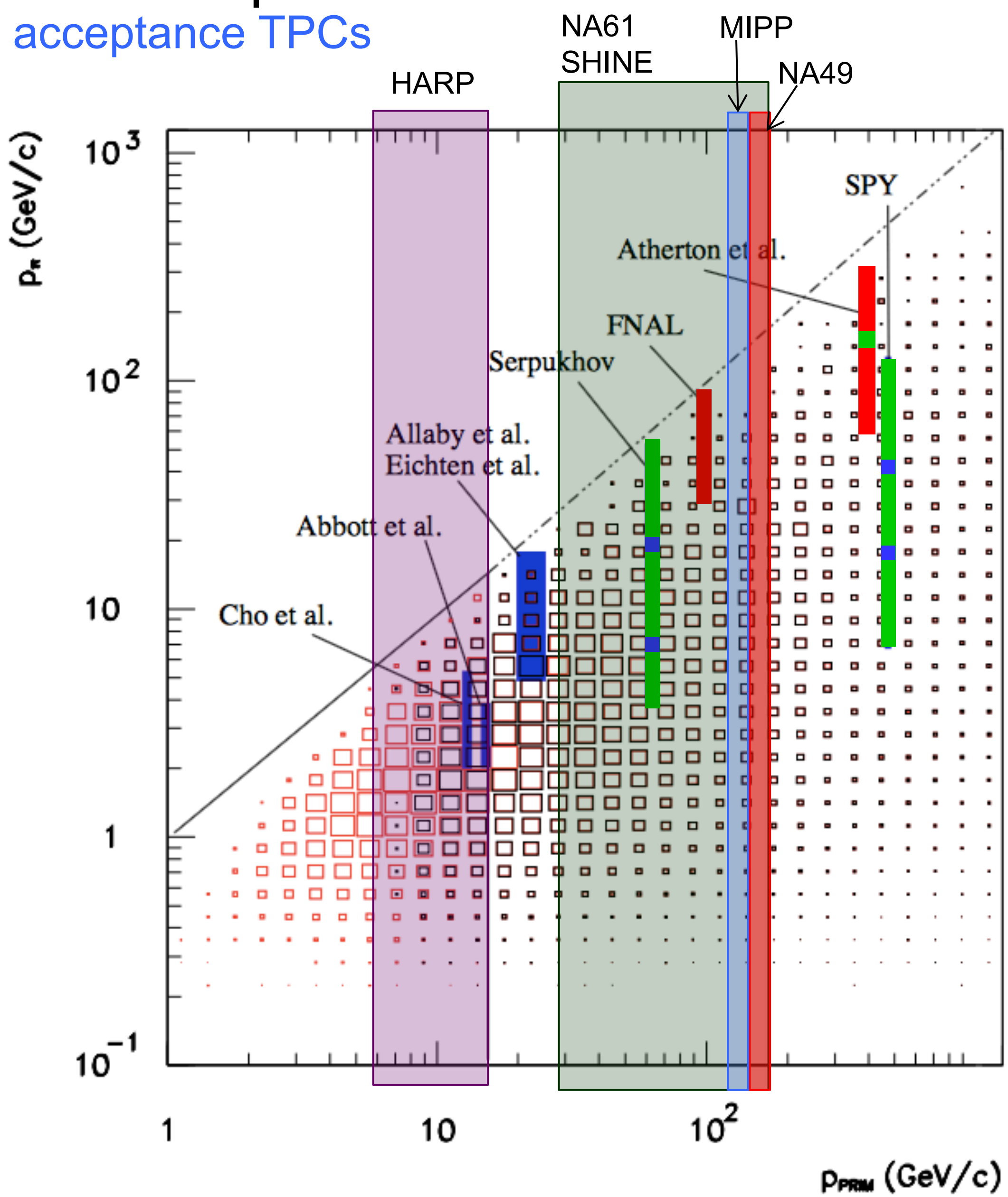
Energies around 1 GeV representing contained events in a SK-sized detector.

Measurements.

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

Newer Hadron production measurements

Large acceptance TPCs



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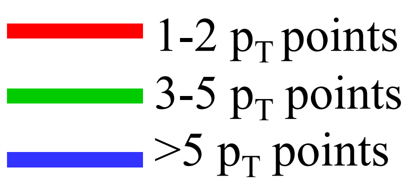
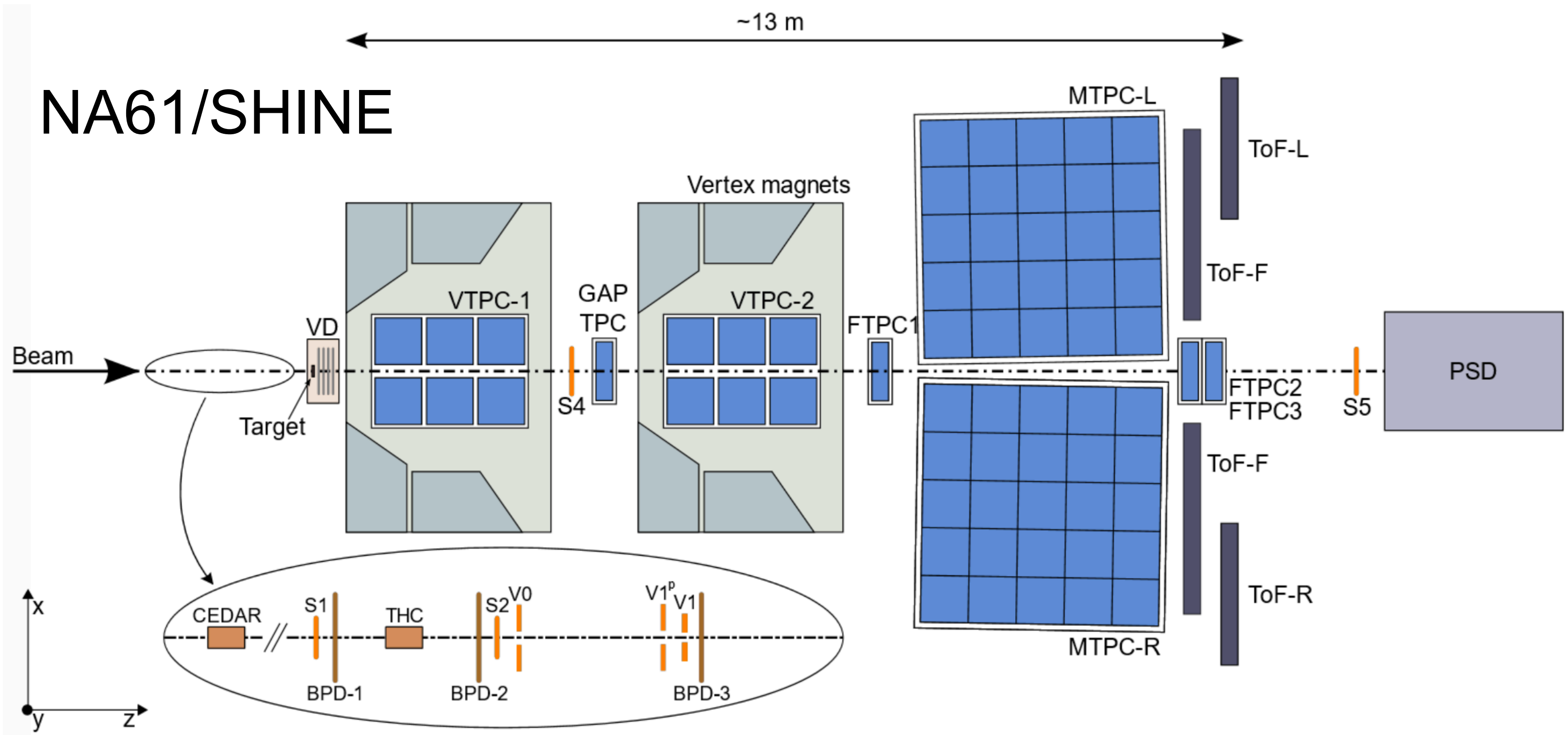
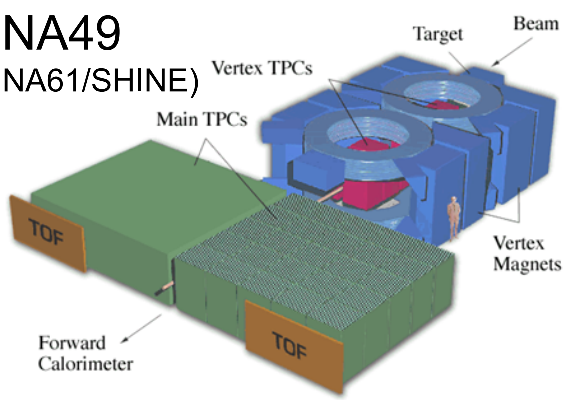


Hadron production experiments

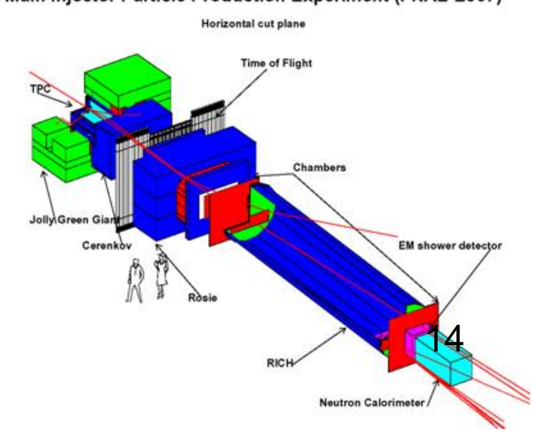


NA49
(now NA61/SHINE)



MIPP

Main Injector Particle Production Experiment (FNAL-E907)



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

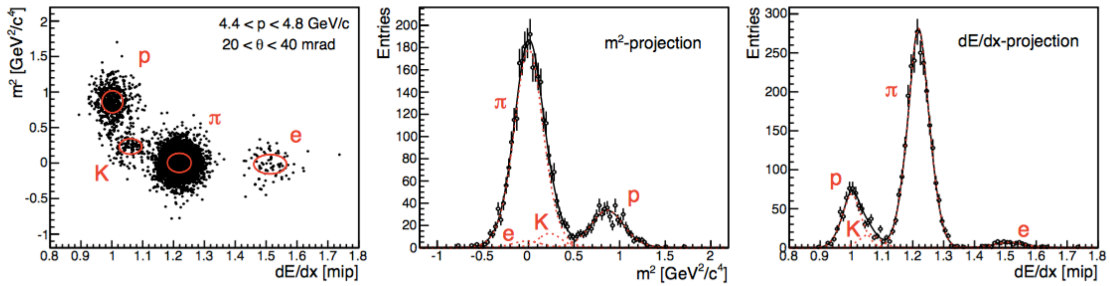
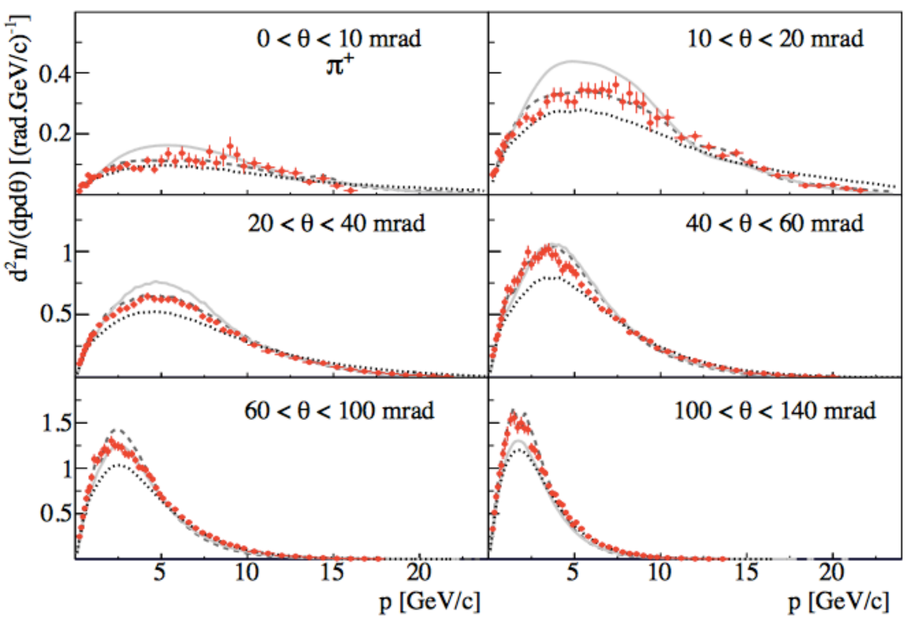
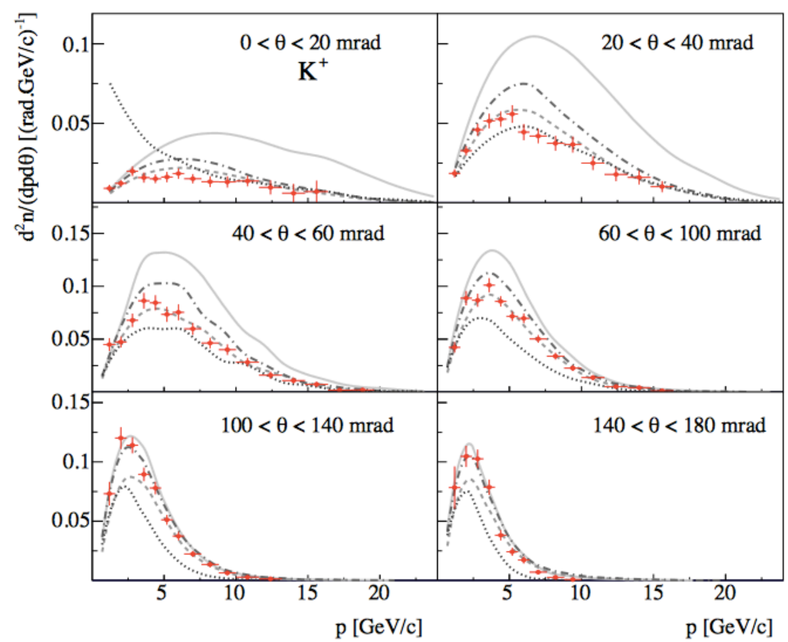


Fig. 13: (Colour online) Example of a two-dimensional fit to the $m^2 - dE/dx$ distribution of positively charged particles (*left*). The m^2 (*middle*) and dE/dx (*right*) projections are superimposed with the results of the fitted functions. Distributions correspond to the $\{p, \theta\}$ bin: $4.4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

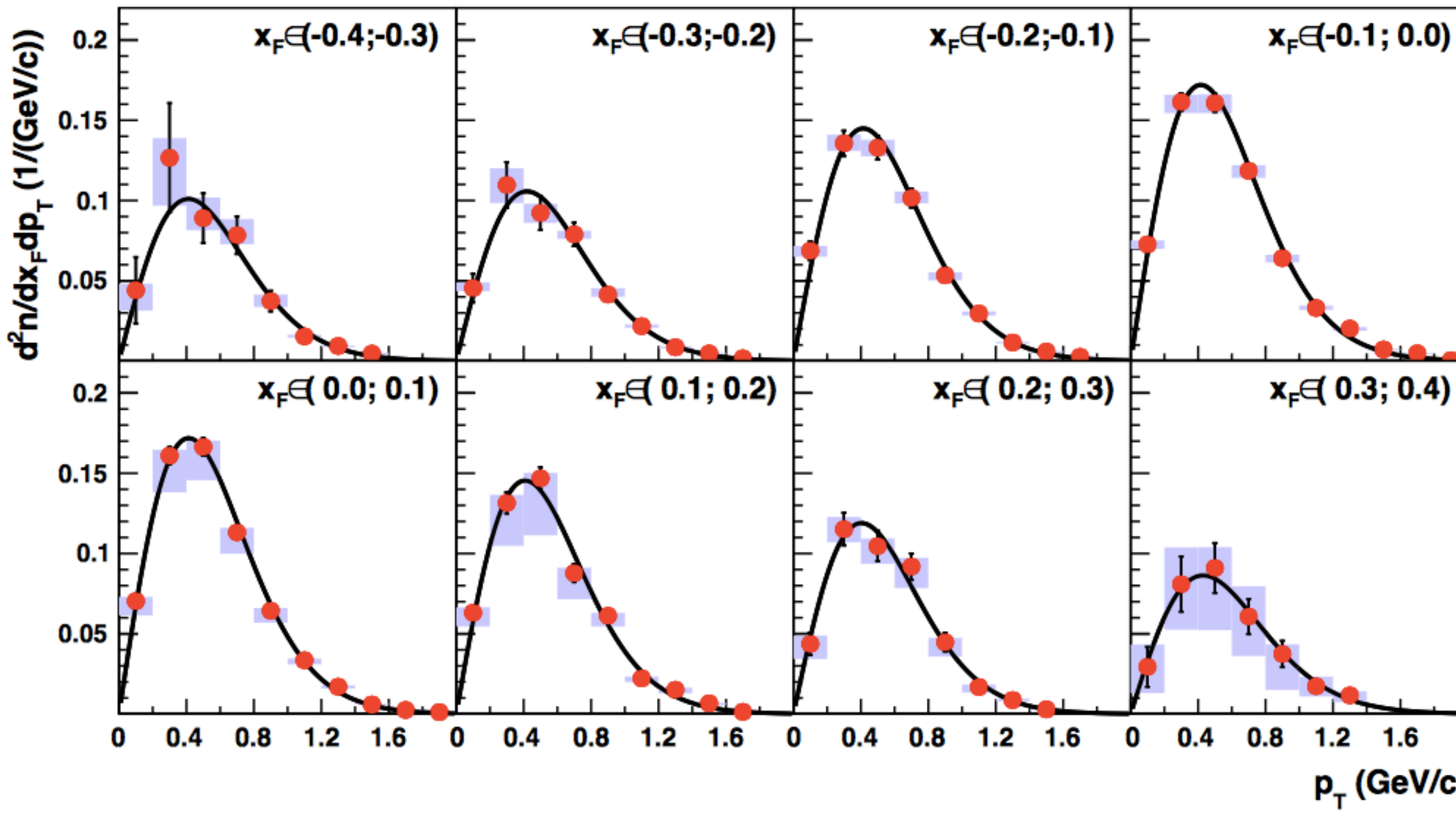


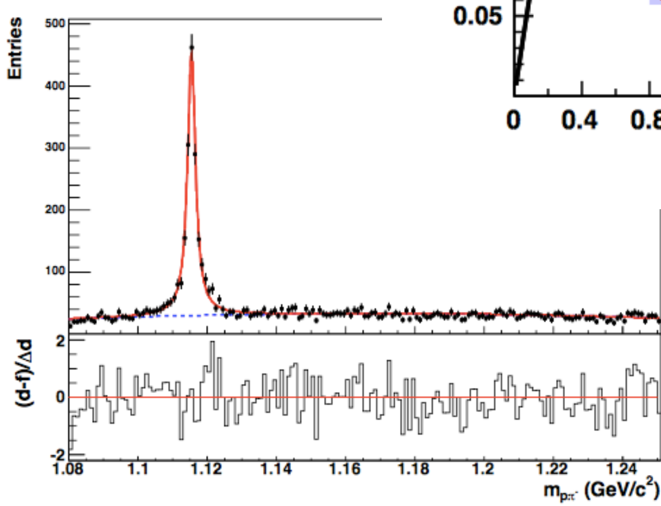


NA61/SHINE Λ strangeness production

arXiv 1510:03720 CERN PH-EP 2015-274

158 GeV/c
p+p





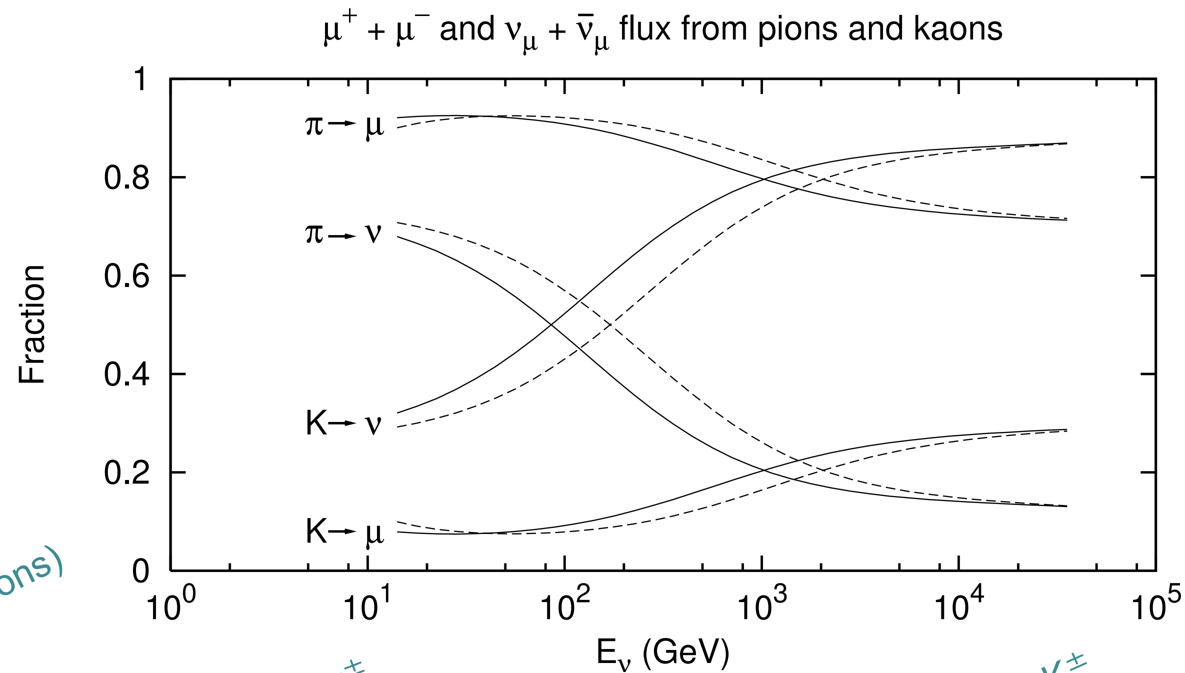
For $E \gg \epsilon / \cos\theta$ mesons preferentially interact, rather than decay

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

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

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

$$\epsilon_\pi = \frac{RT}{Mg}\frac{m_\pi c^2}{c\tau_\pi}$$



Primary spectrum (nucleons)

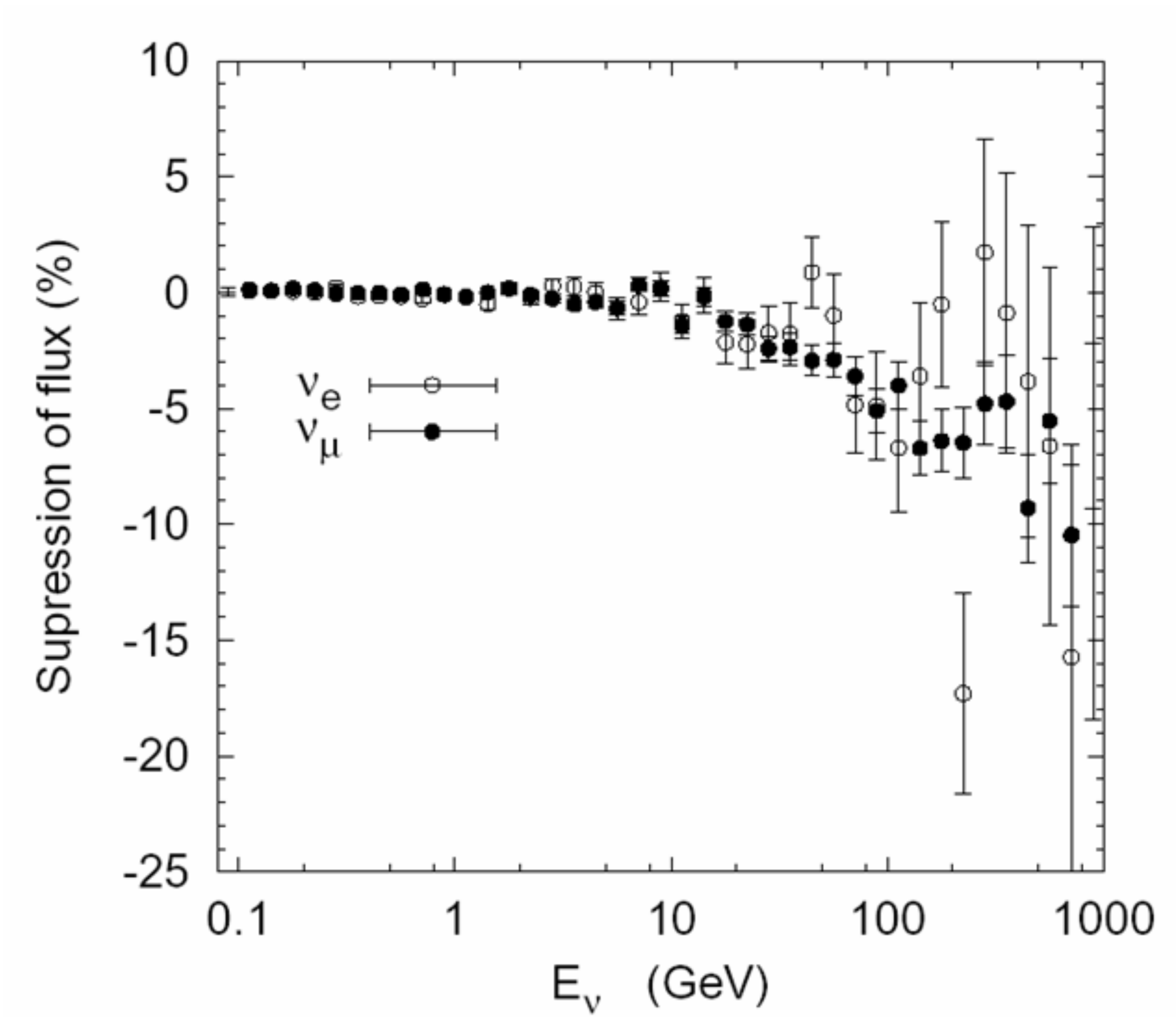
Neutrinos from $\pi^\pm$

Neutrinos from $K^\pm$

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

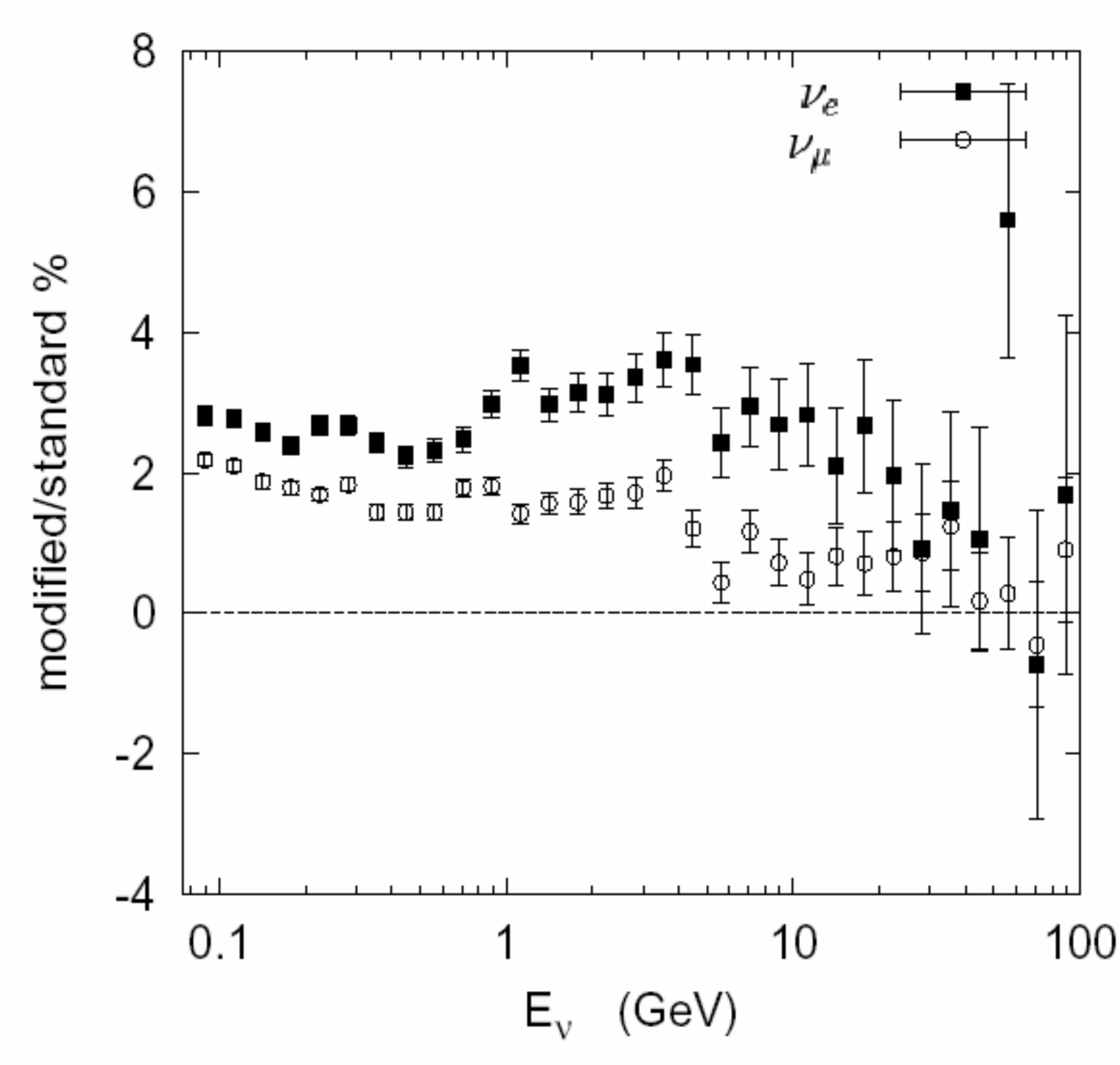
$1-Z_{NN}$: re-interaction of nucleons

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%

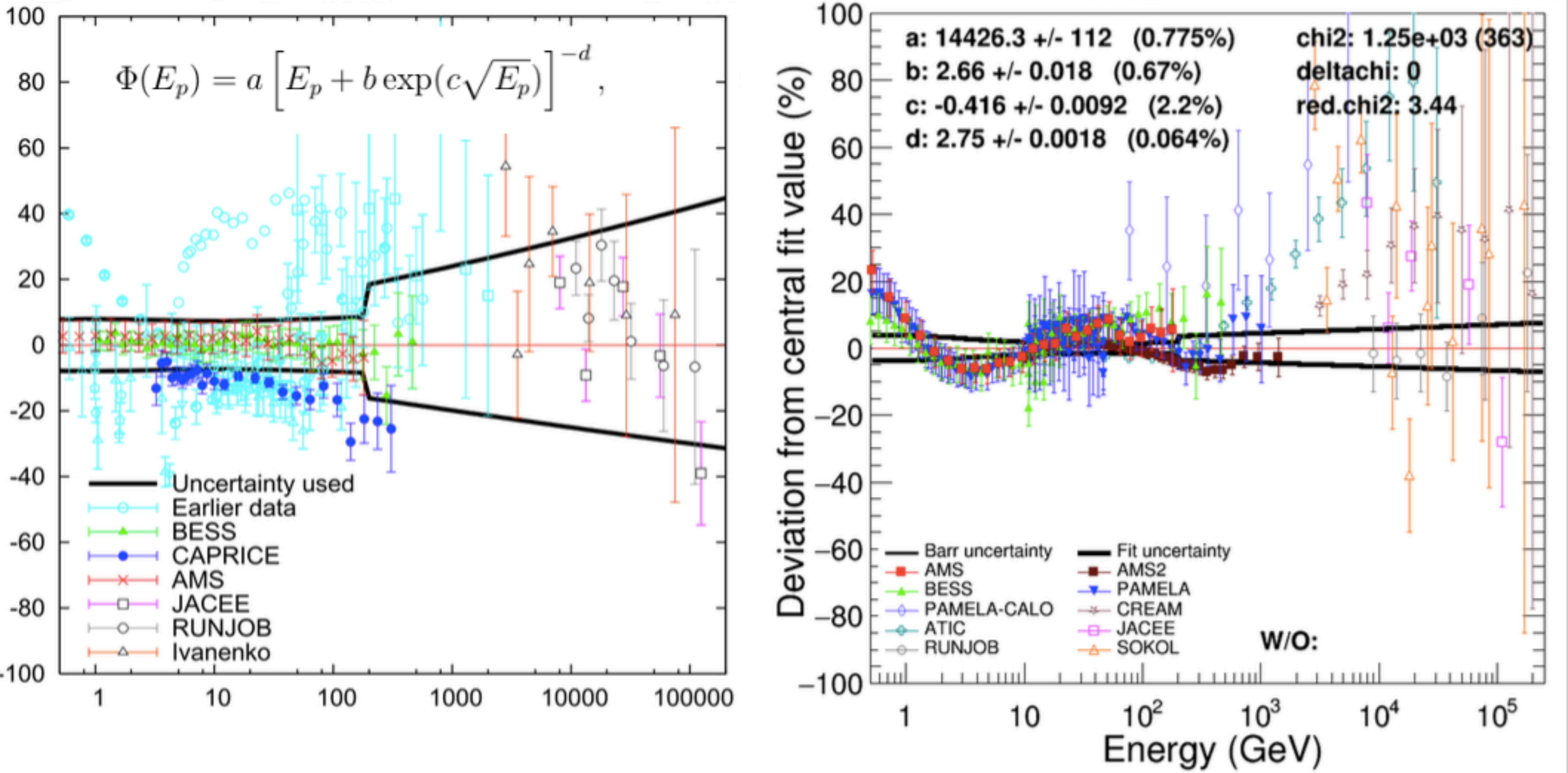
- Effect is small, essentially it just adjusts the altitude of the top of the shower

Salvatore Davide Porzio & Justin Evans
Manchester University

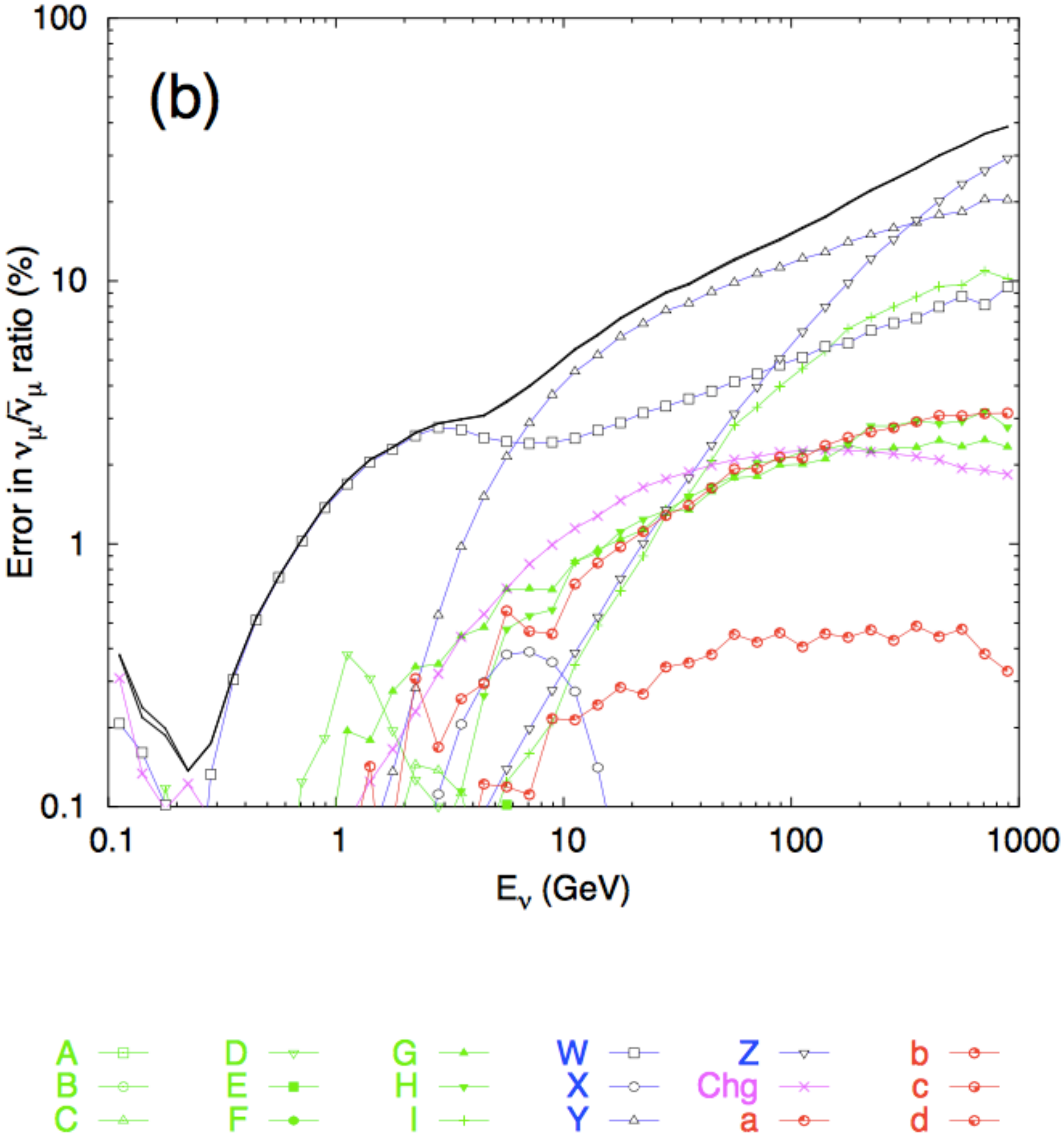
ADDITIONAL COSMIC RAY DATA

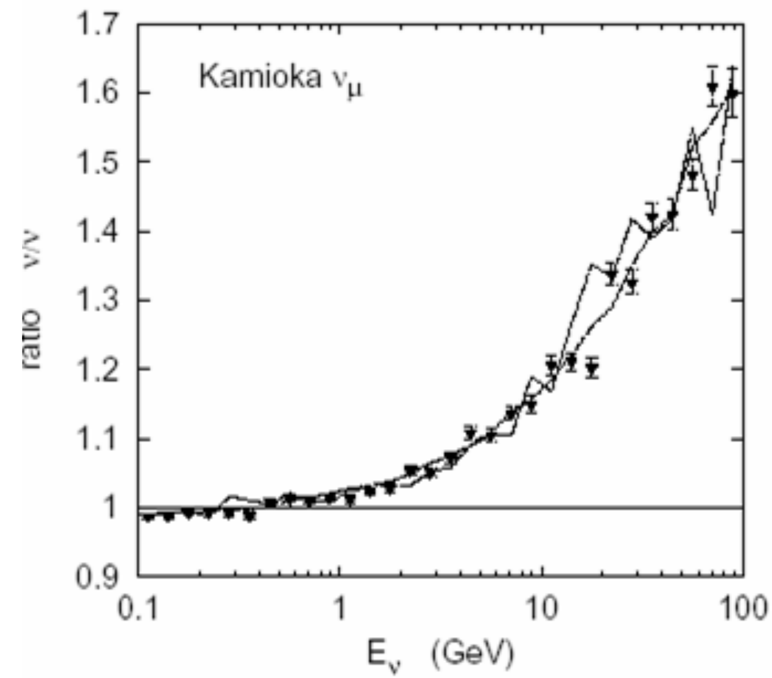
- Data from calorimeter experiments (>200 GeV) show a large spread. Also, data from AMS2 shows an interesting change in spectral index at higher energies which severely affects the values of the fit parameters.

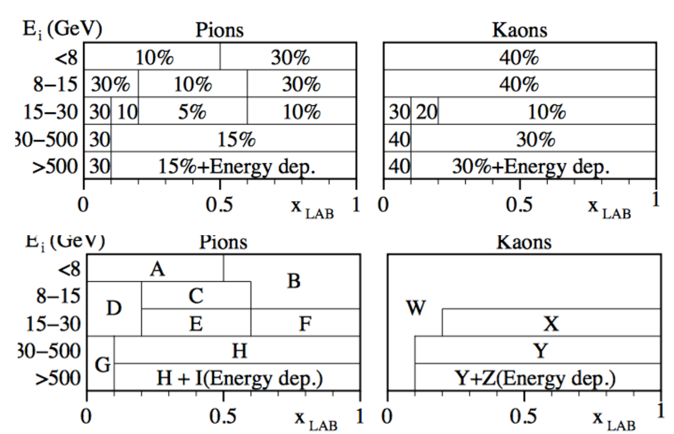
- A global fit to all experimental data seems to underestimate the uncertainties associated with the parameters.



nu-mu/nu-mubar ratio & uncertainty







Idea

- Currently there is data with thin (few % ƛ) targets and 'replica' long but narrow targets for neutrino experiments.
- For atmospheric neutrinos, at lowish energies, pion and kaons often decay before interaction, so thin target data most relevant.
- What about secondary neutrons? They do interact in atmosphere.
- Perhaps data of protons on a thick but wide target would be useful, e.g. carbon 20cm long by 20cm diameter?
  - This is ~ 50% ƛ
- Then use unfolding with thin and wide targets with existing models and cross sections of existing pion measurements to determine contribution from secondary neutron re-interaction.
  - Wide instead of 'replica', so we can ignore p_T effects (they are irrelevant in atmospheric-nu except in low-energy '3D' region) and beam steering corrections.

Conclusions

- NA61/SHINE measurements very welcome indeed. The more the better.
- The BARTOL team of atmospheric flux calculators is back in action – we are using SHINE data to tune hadron production models and assess new error propagation.
- For the mass-hierarchy resonance measurement, hadron-production in the SHINE range is particularly relevant, including extensions to lower and higher energies.
- Kaons get an enhanced importance, Charm production also, so measurements of these secondaries very good.
- As the above becomes better, the next difficulty is neutron secondaries – possible idea with 'wide' target.