Neutrino Production in the Atmosphere
and
Accelerator Hadron Yield Measurements

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Cosener's House

19 Feb 2005

Synopsis

Section 1: Production of Neutrinos by Cosmic Rays

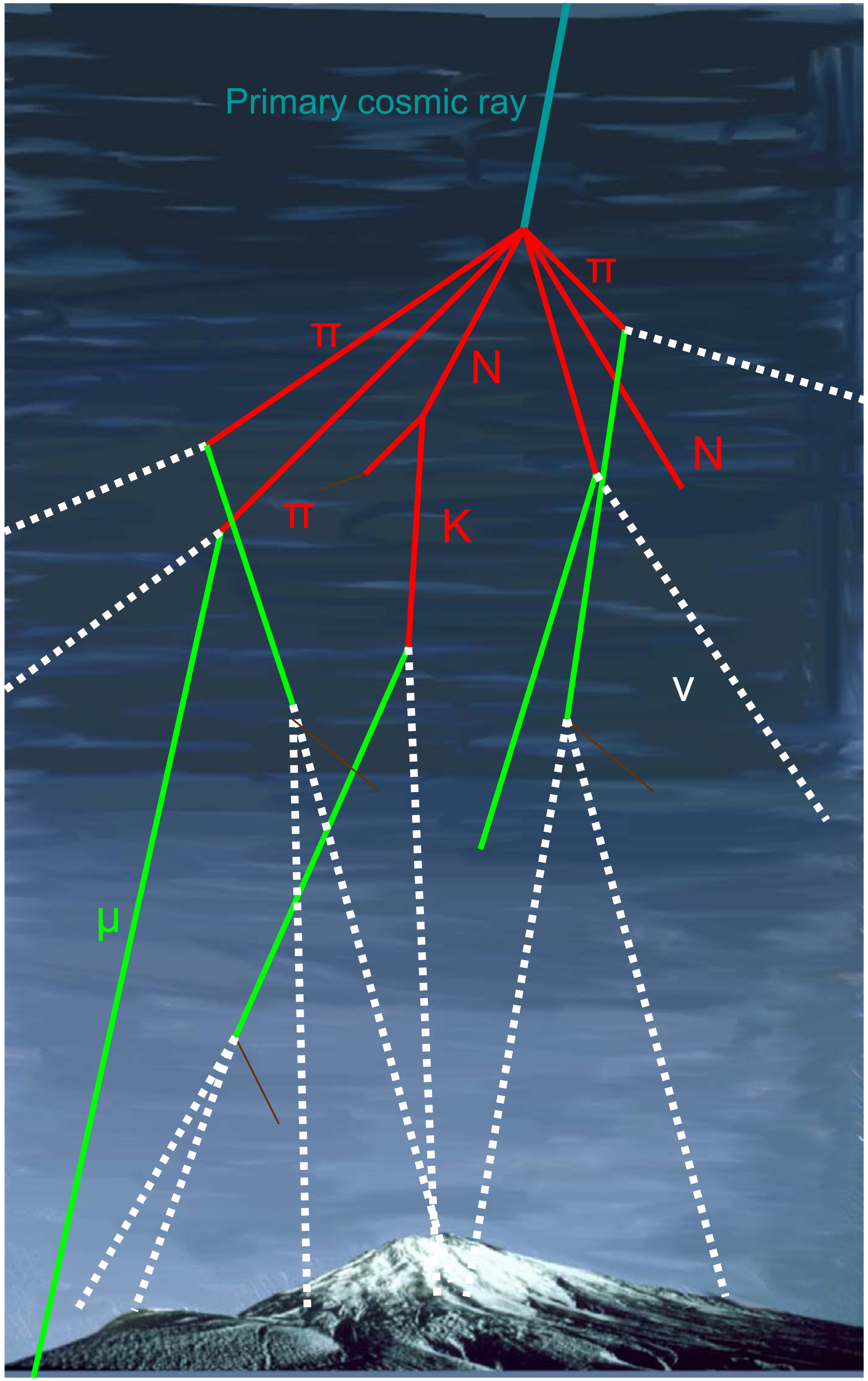
- Neutrino Oscillations (brief)
- Fluxes and their calculations
- Key uncertainties

Section 2: Hadron production

- Experiments: HARP/NA49/MIPP

Section 3: Outlook

- Errors on fluxes
- Further measurement possibilities with atmospheric neutrinos

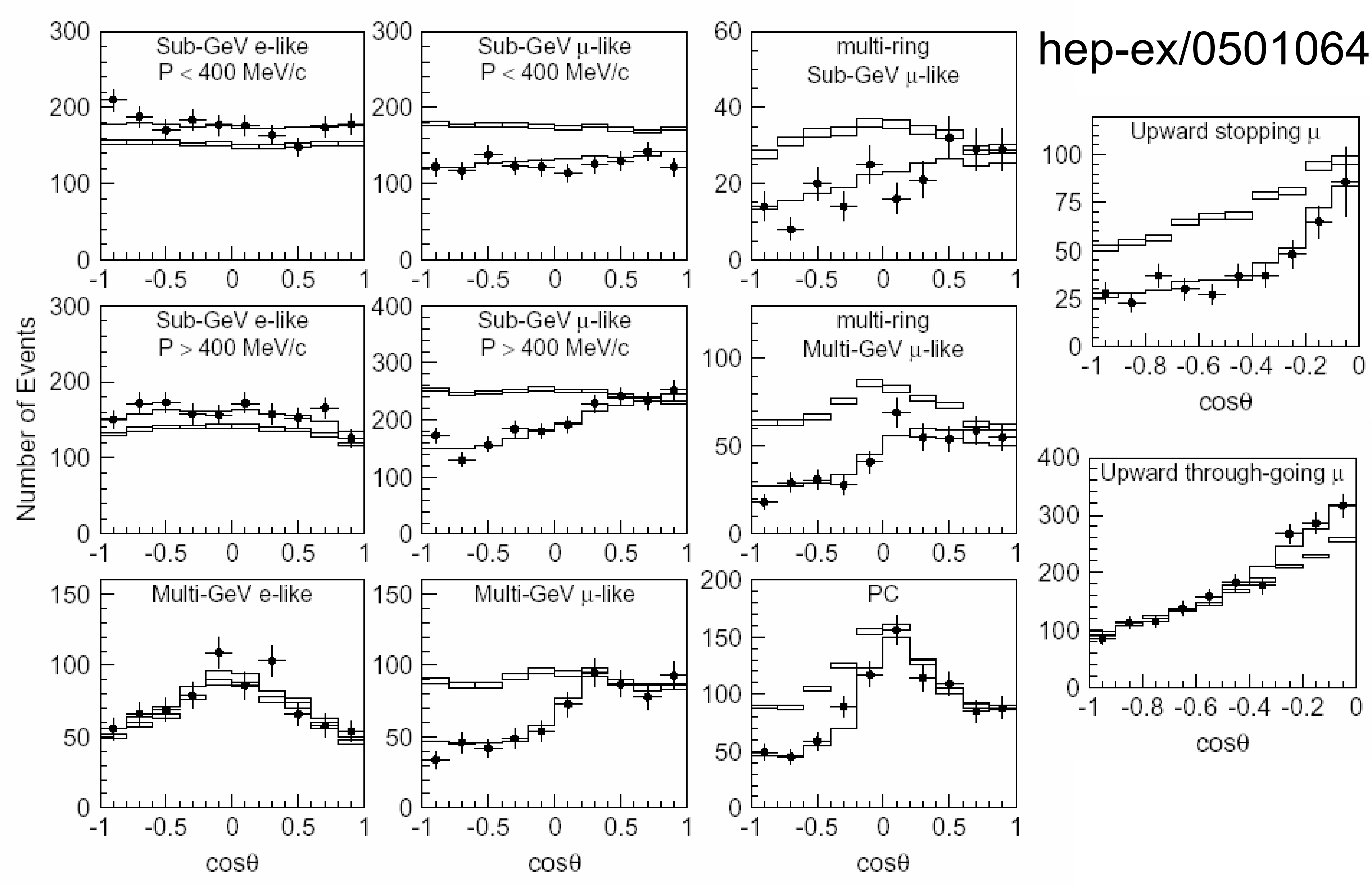


Neutrinos produced from a shower

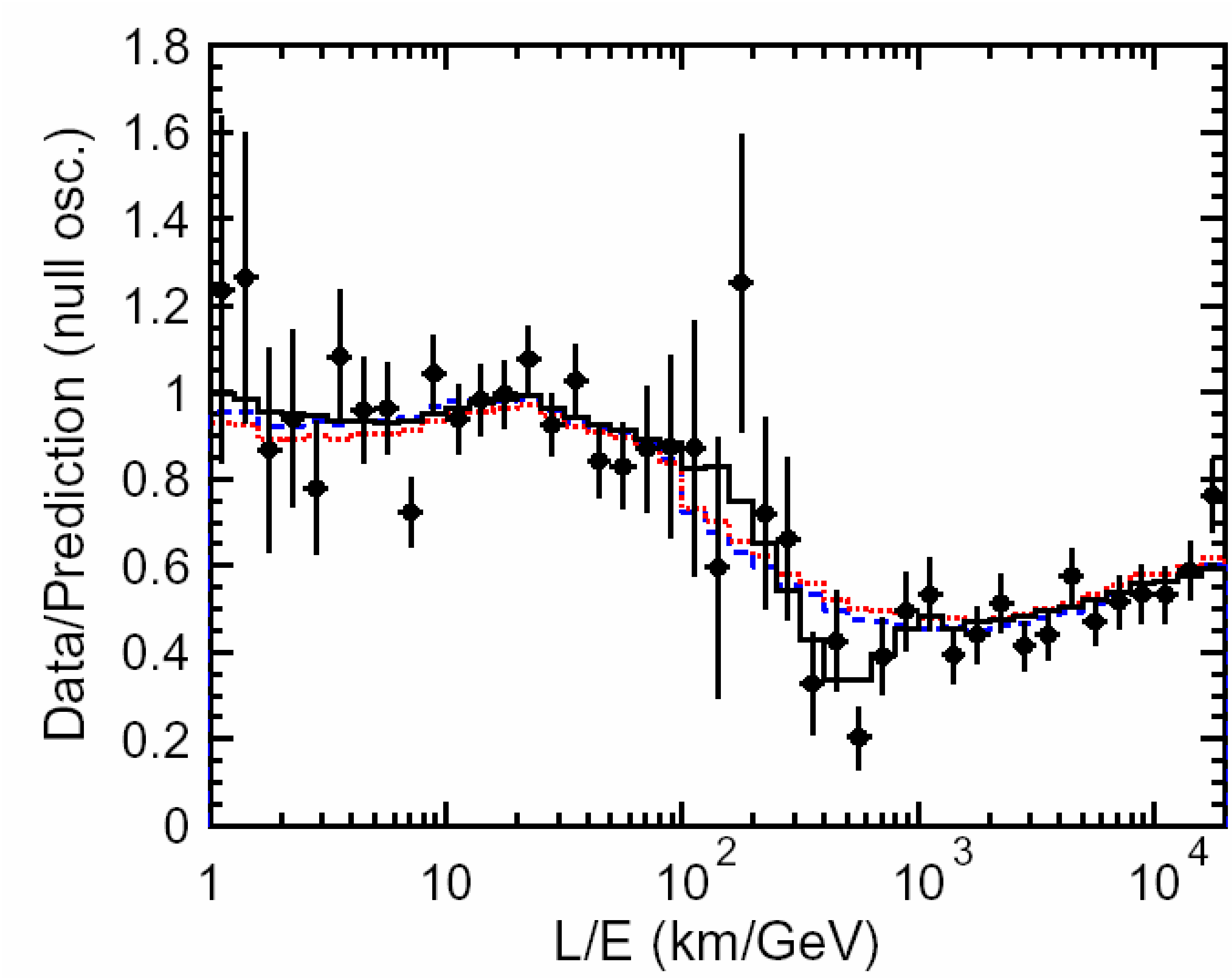
- Primary cosmic ray: proton or heavier nucleus
- Interacts in ~90g/cm^2
- Atmosphere depth 1050 g/cm^2
- Cascade
- Most hadrons don't reach ground.

SuperKamiokande results (1)

hep-ex/0501064

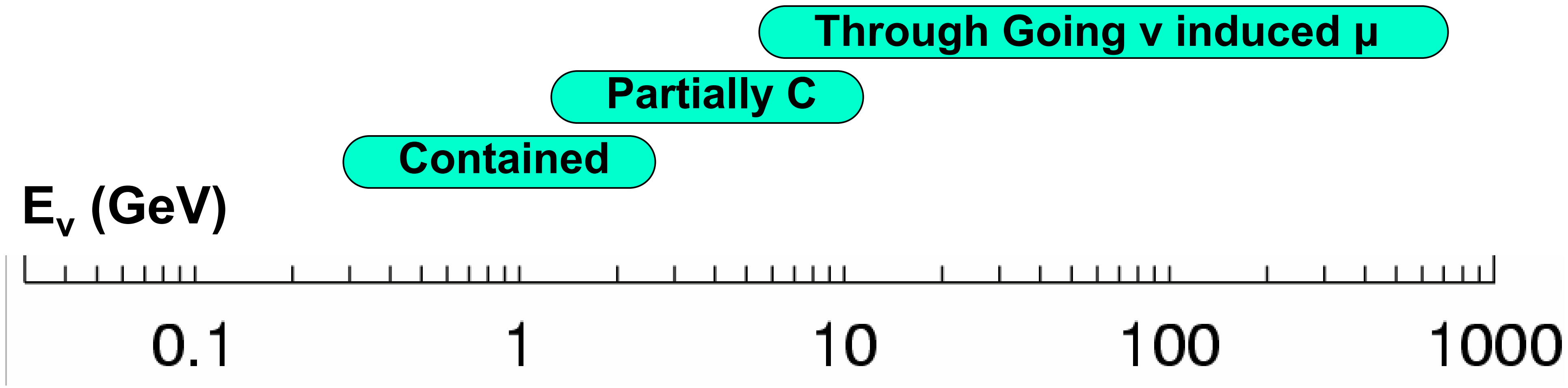


SuperKamiokande results (2)

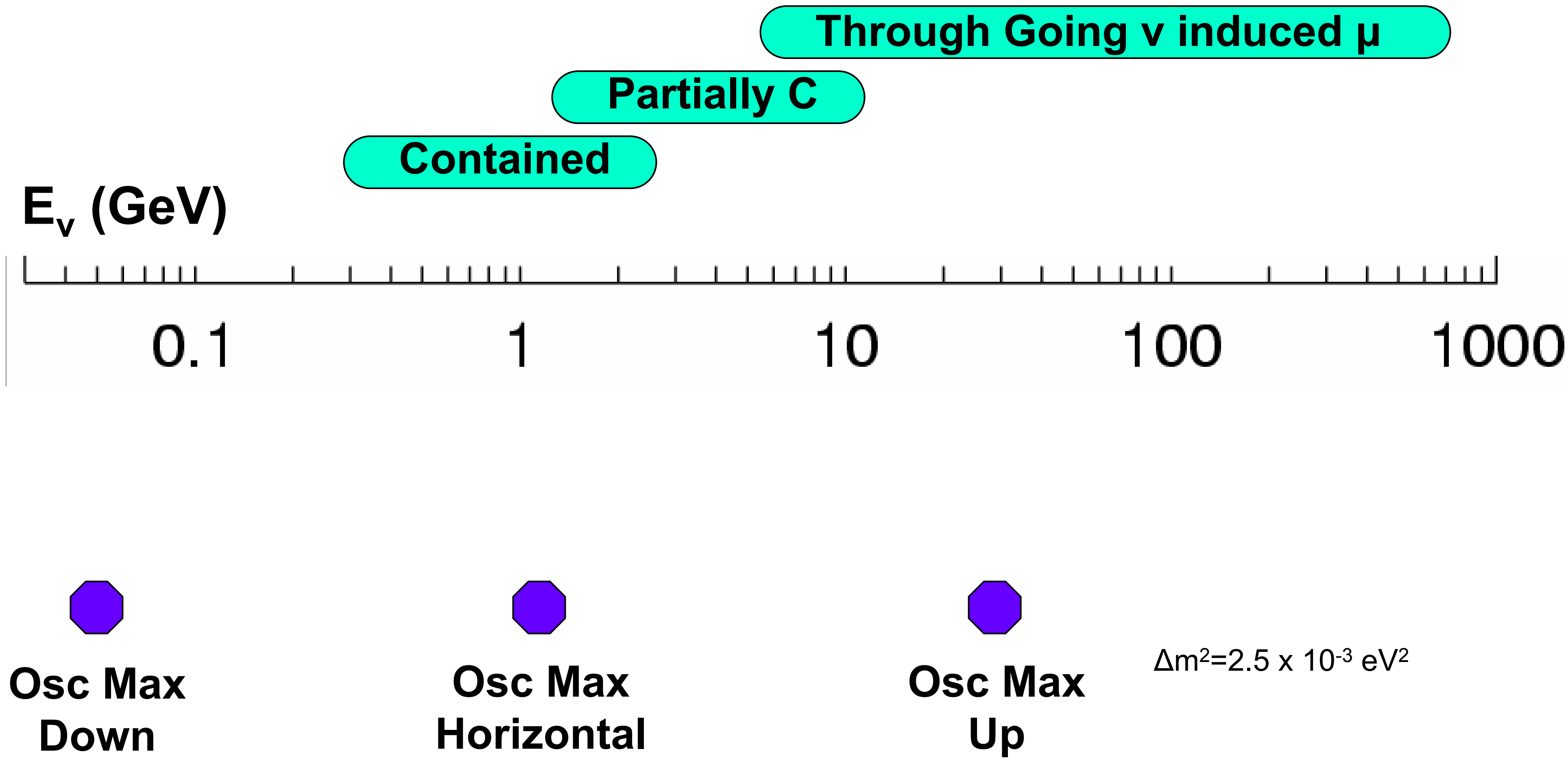


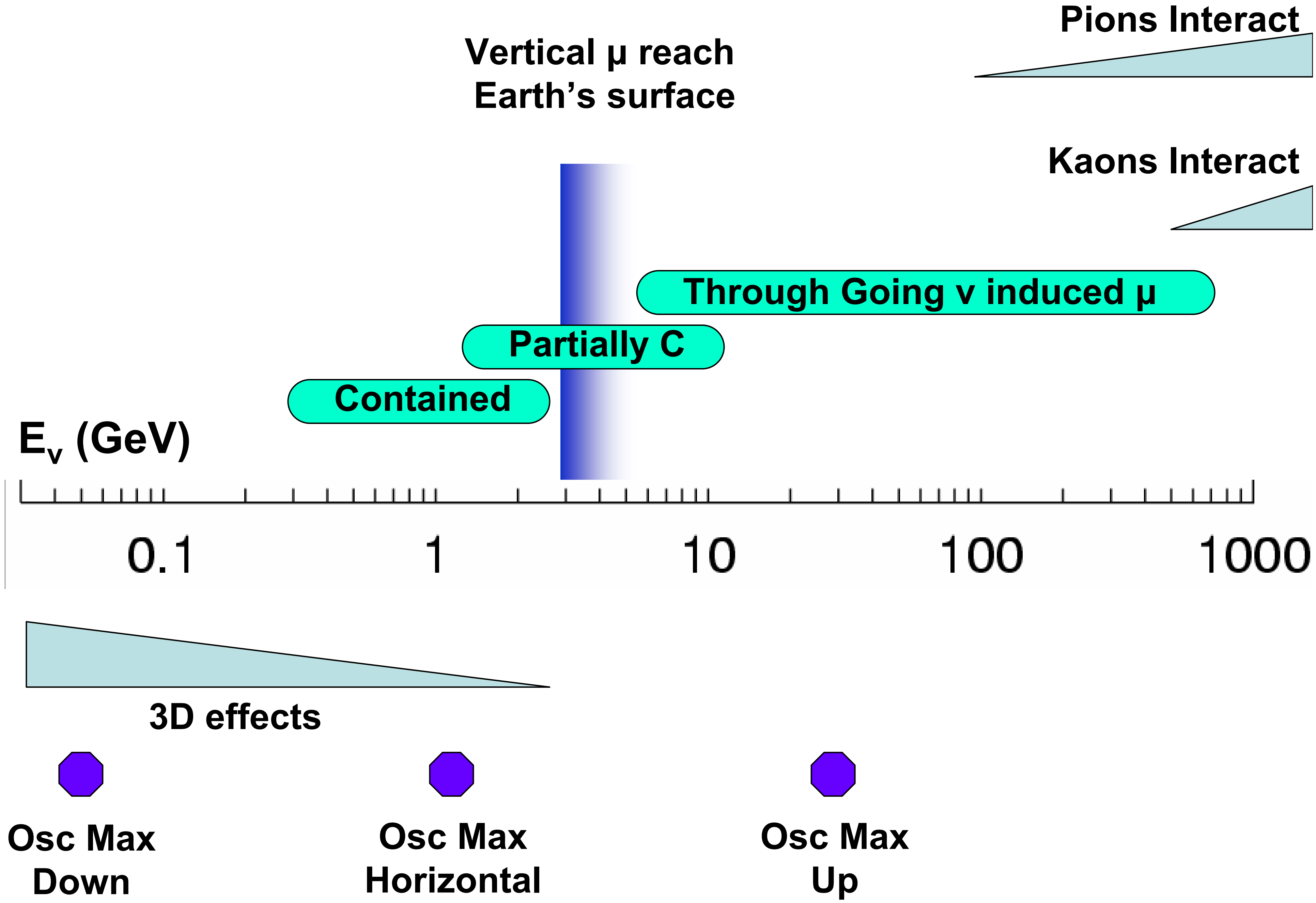
From hep-ex/0404034: PRL 93 (2004) 101801 e

μ



Through Going ν induced μ
Partially C
Contained
Eν (GeV)
0.1
1
10
100
1000


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



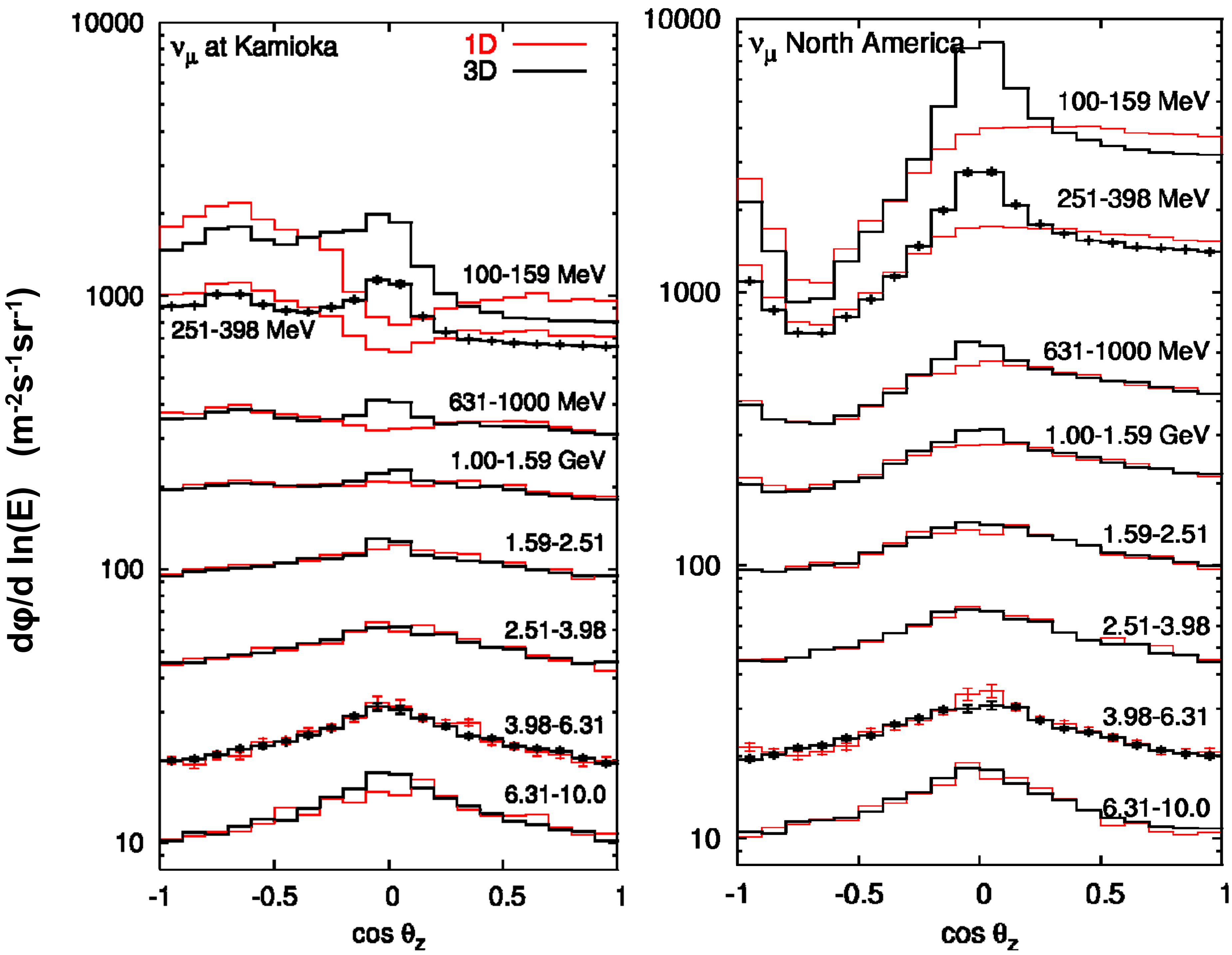
Pions Interact
Vertical μ reach
Earth's surface
Kaons Interact
Through Going ν induced μ
Partially C
Contained
E_ν (GeV)
0.1
1
10
100
1000
3D effects
Osc Max
Down
Osc Max
Horizontal
Osc Max
Up

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

Key uncertainties

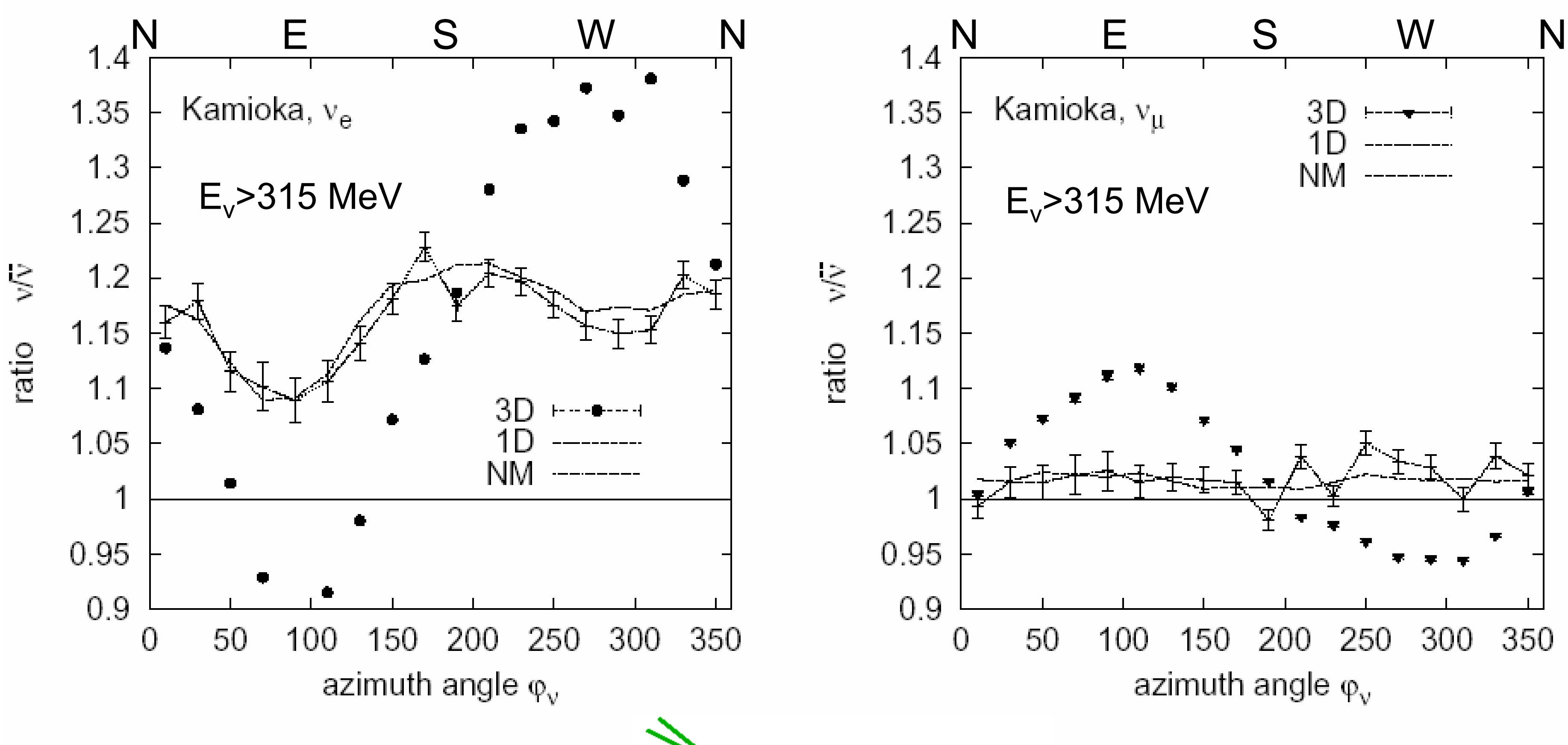
- Hadron production
- Primary Fluxes
- (Geomagnetic Field)
- 3D effects
- Atmosphere

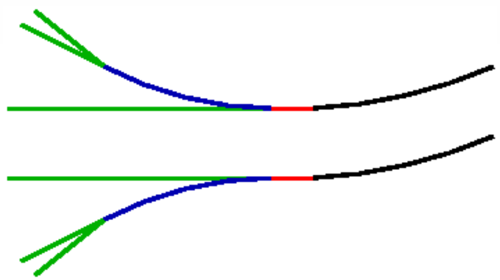


ν_μ at Kamioka
1D
3D
ν_μ North America
100-159 MeV
251-398 MeV
631-1000 MeV
1.00-1.59 GeV
1.59-2.51
2.51-3.98
3.98-6.31
6.31-10.0
10000
1000
100
10
-1
-0.5
0
0.5
1
$d\varphi/d\ ln(E)\ \ (m^{-2}s^{-1}sr^{-1})$
$\cos\theta_z$

Azimuth angle distribution

East-West effect

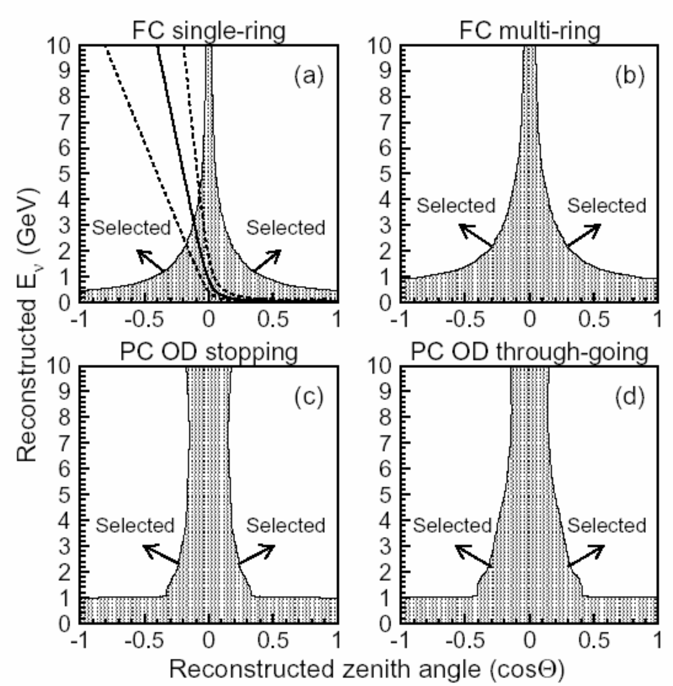




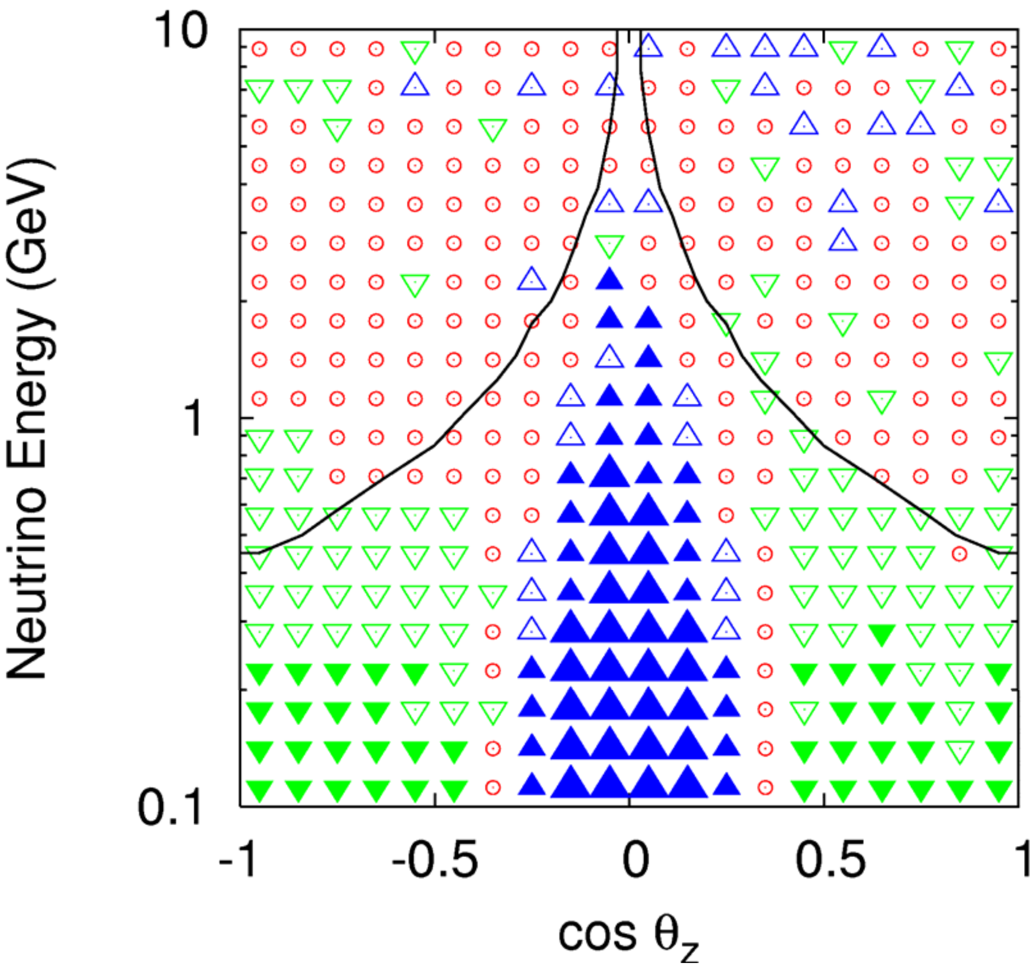
Return to 3D:
Is it important?

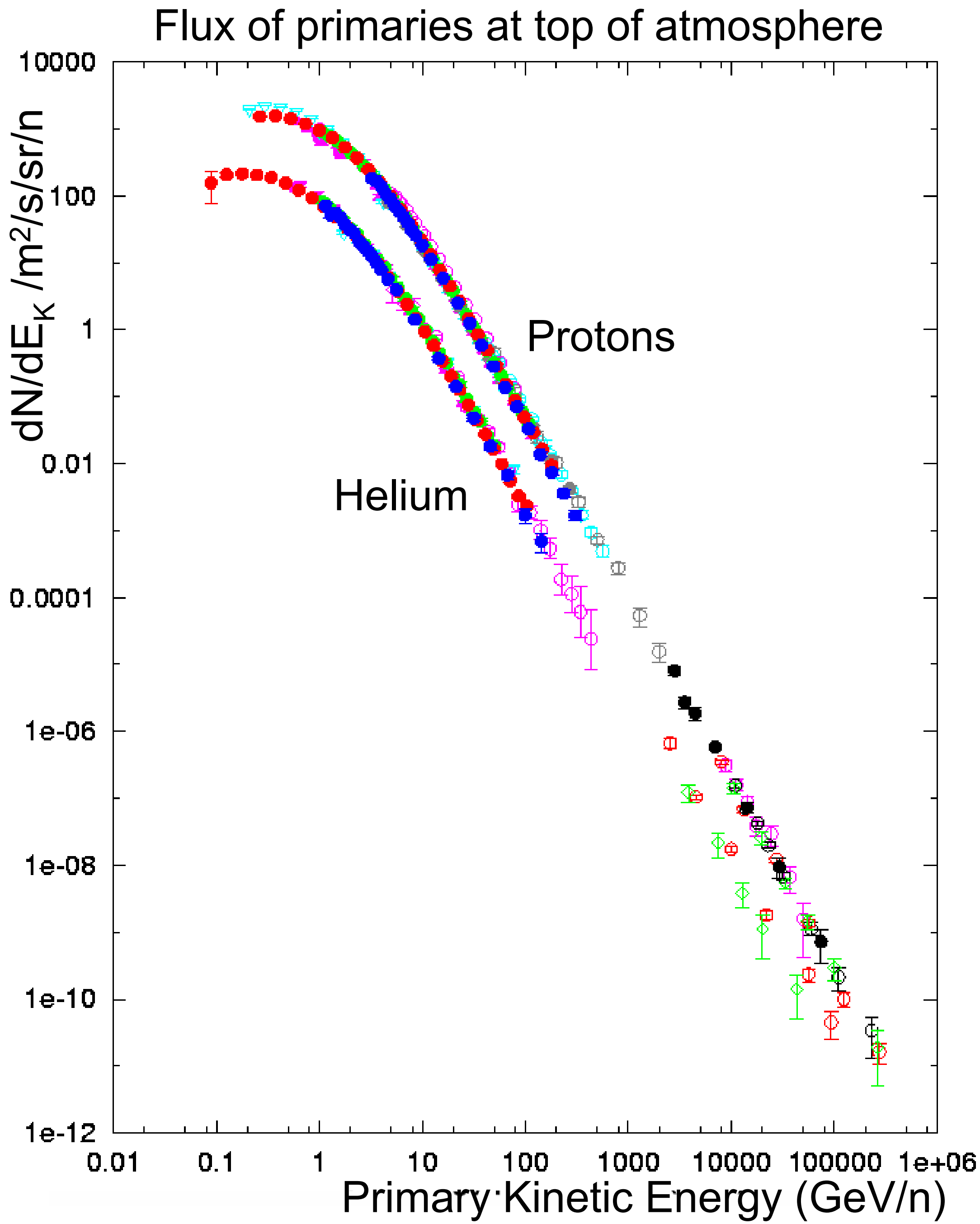
▲	3D bigger	>30%
▲		10%-30%
△		3%-10%
○		<3%
▽	1D bigger	3%-10%
▼		10%-30%

SuperKamiokande Collaboration
hep-ex/0404034



Difference between 3D and 1D calculations





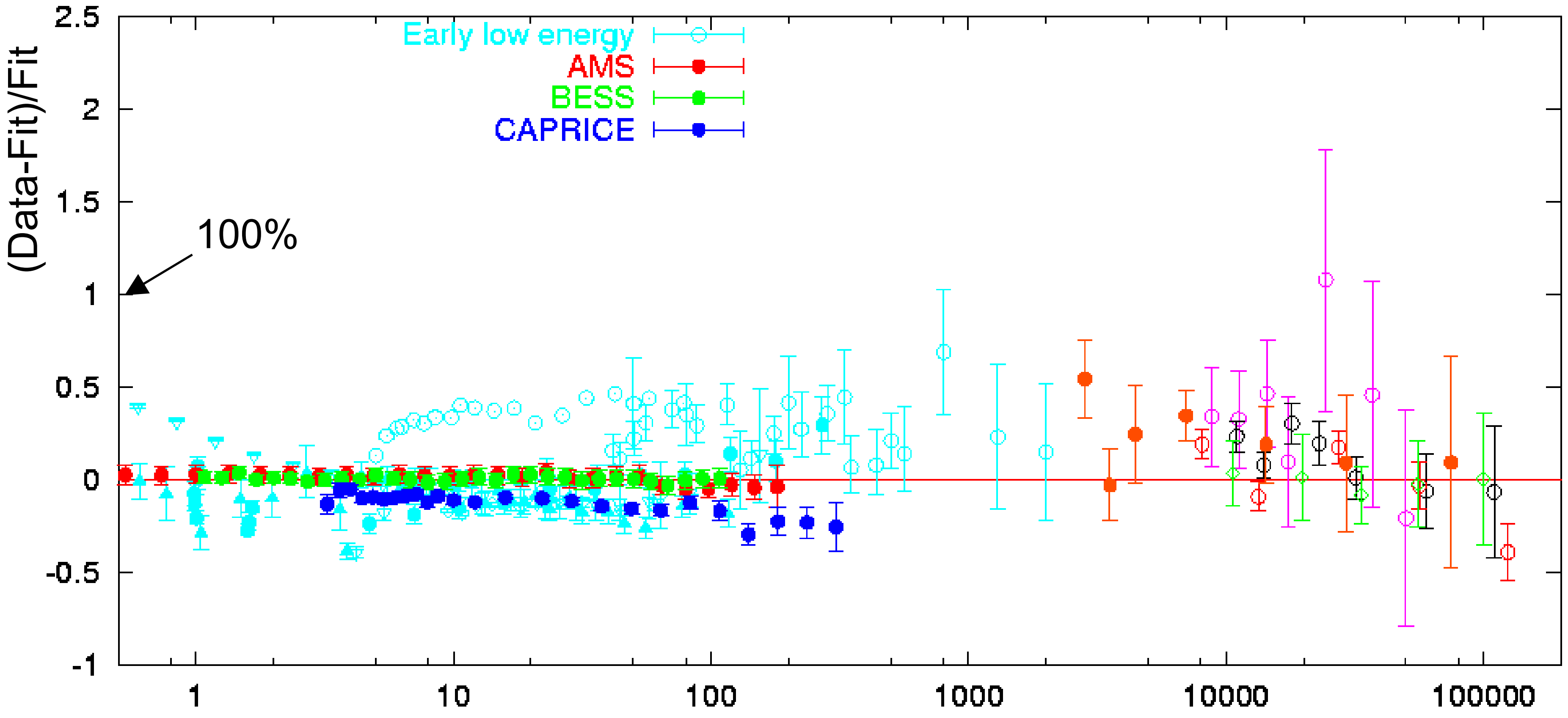
Primary fluxes

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

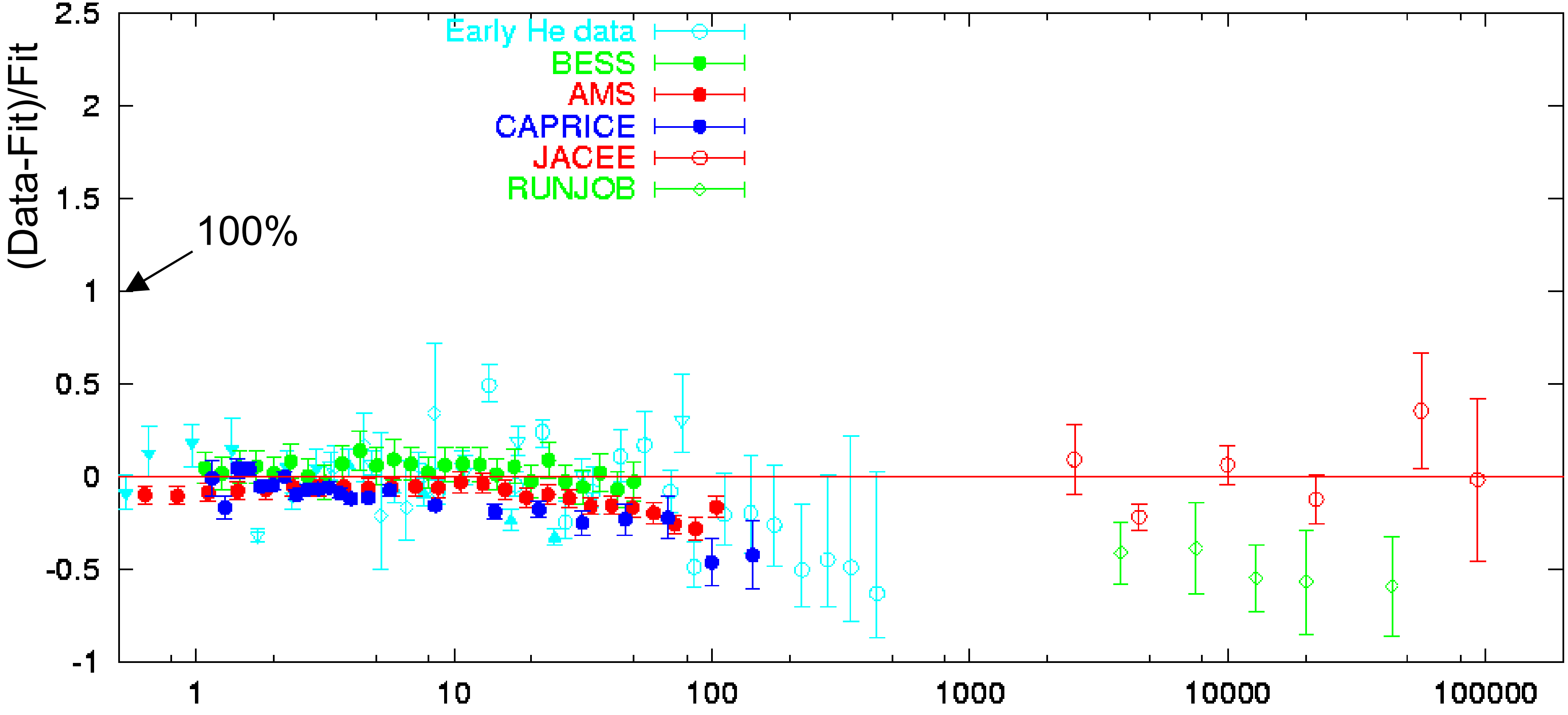
	α	K	b	c
H	2.74	14900	2.15	0.21
He	2.64	600	1.25	0.14
CNO 14	2.70	62.4	1.78	0.02
Ne-Si 24	2.70	21.4	1.78	0.02
Fe(56)	2.70	5.1	1.78	0.02

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

Residuals: Newest measurements

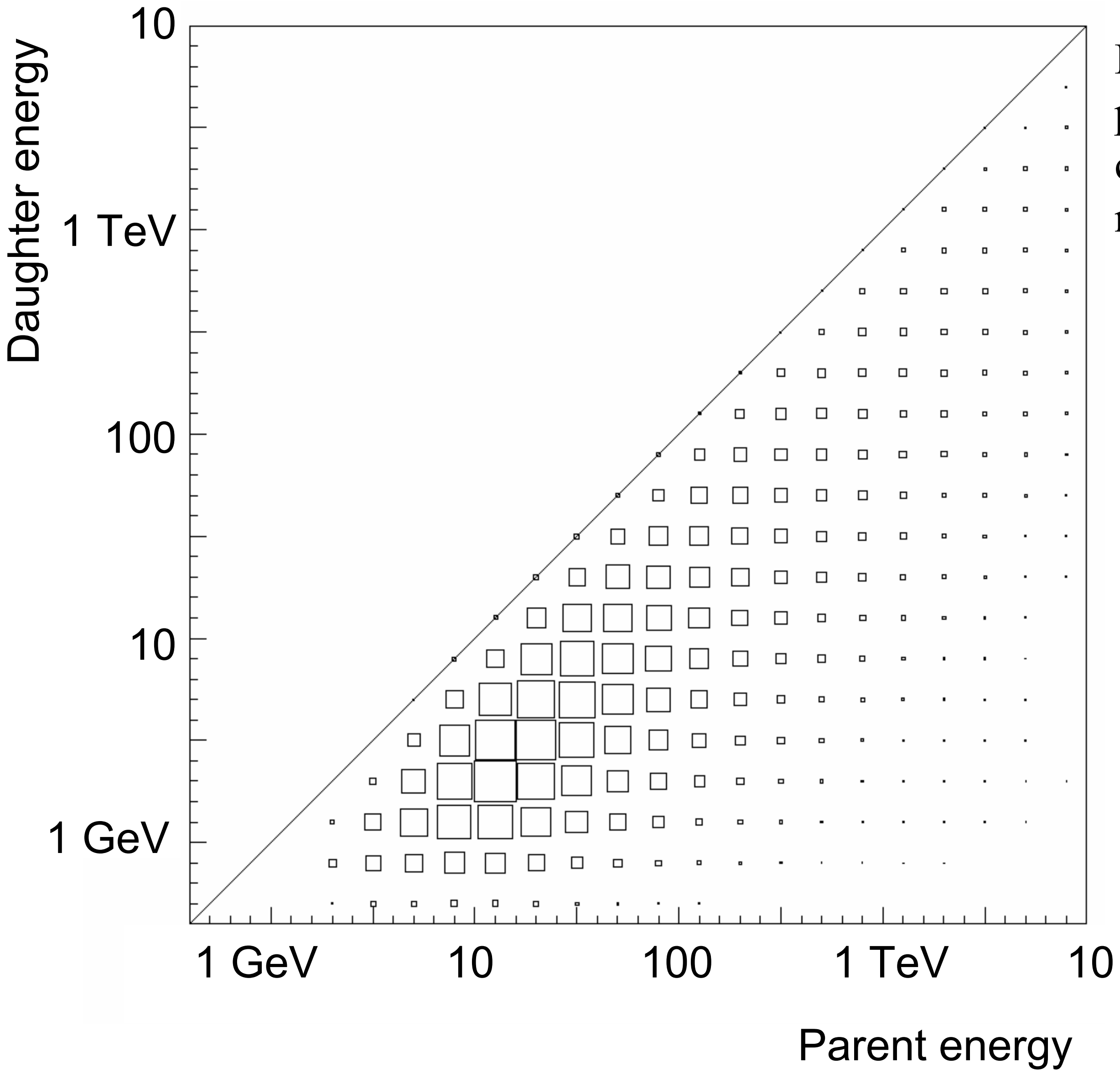


Helium Fluxes



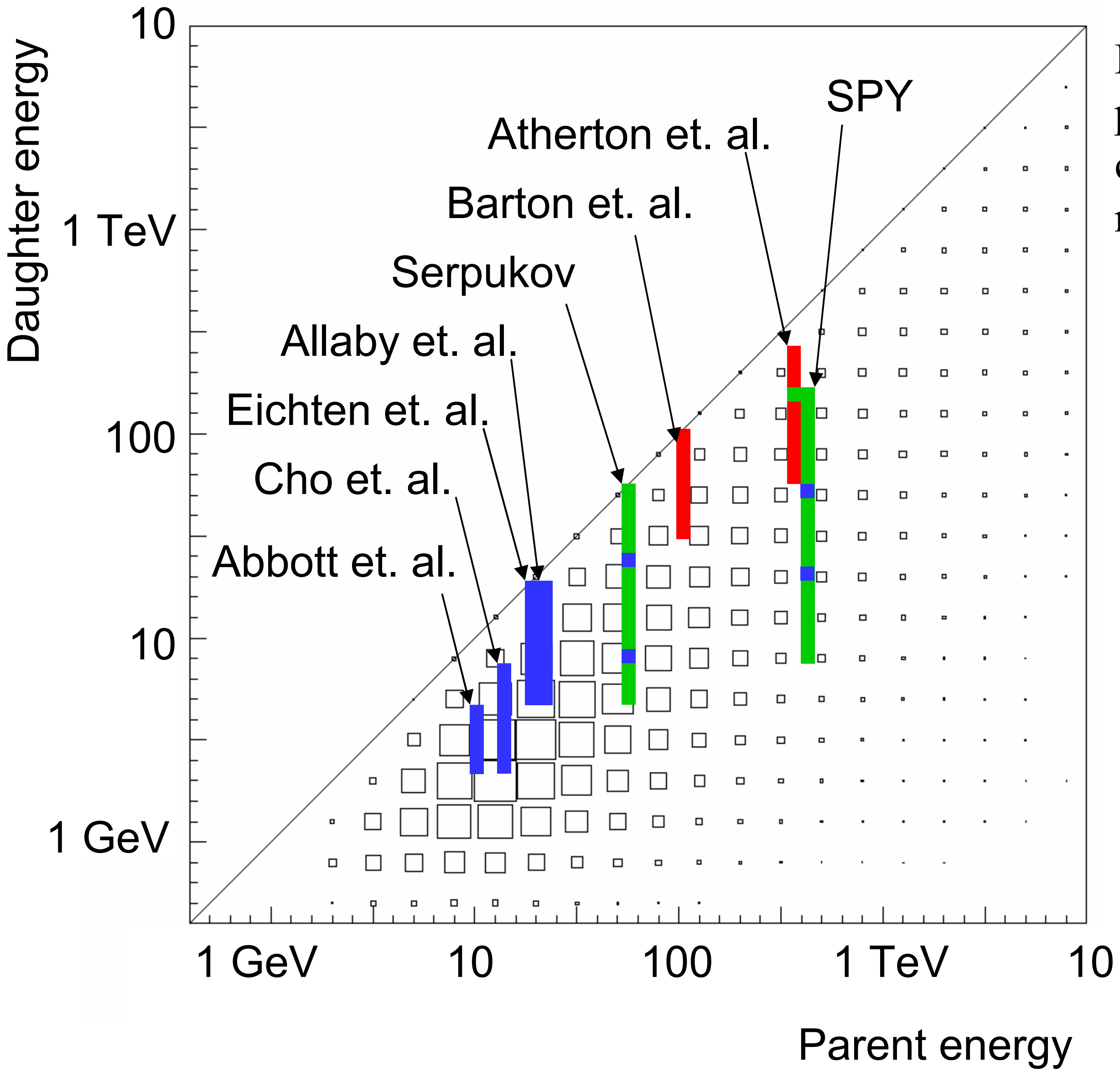
Section 2: Hadron production Measurements at Accelerators

Summary of measurements available



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

P_T range covered

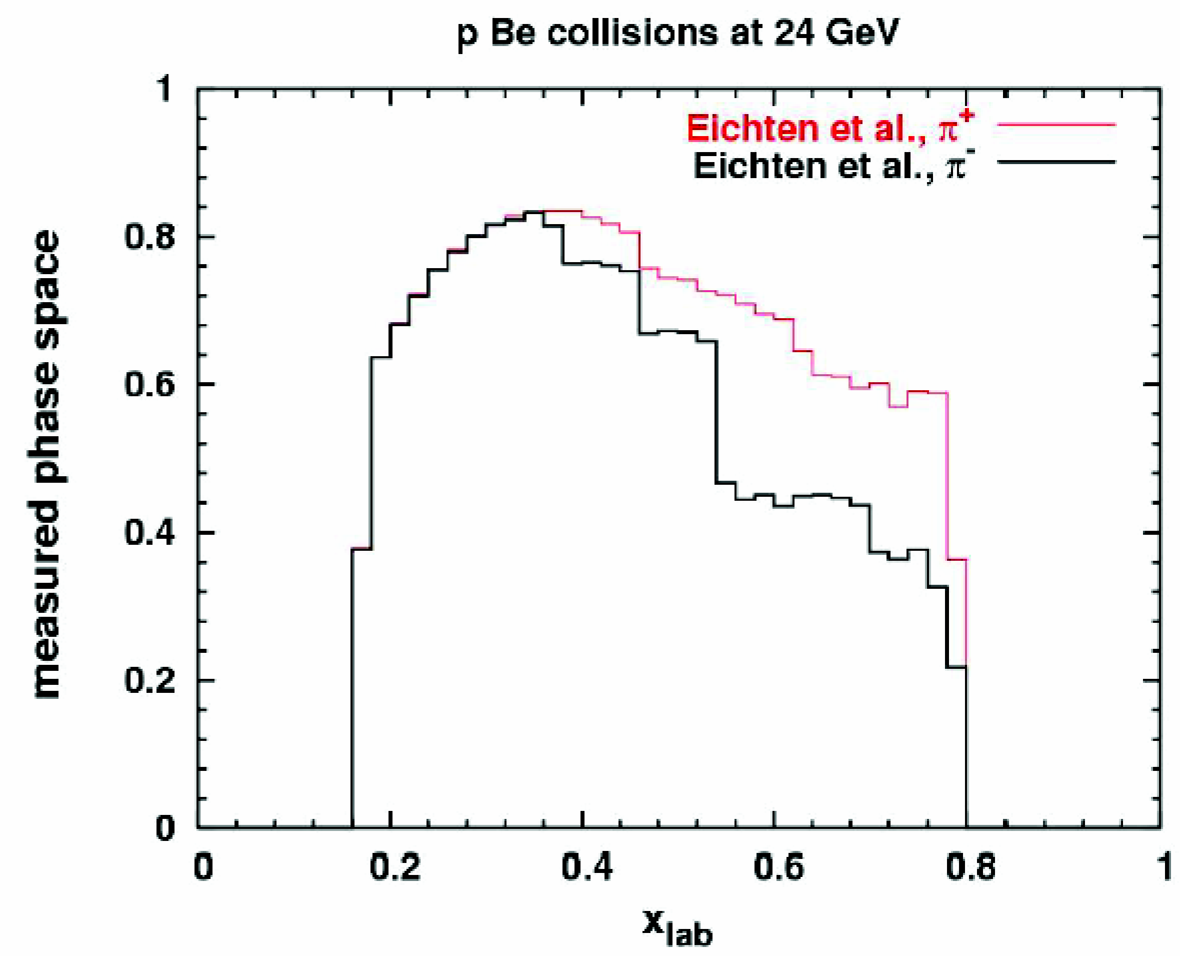


Boxes show importance of phase space region for contained atmospheric neutrino events.

Measurements.

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

pT range coverage

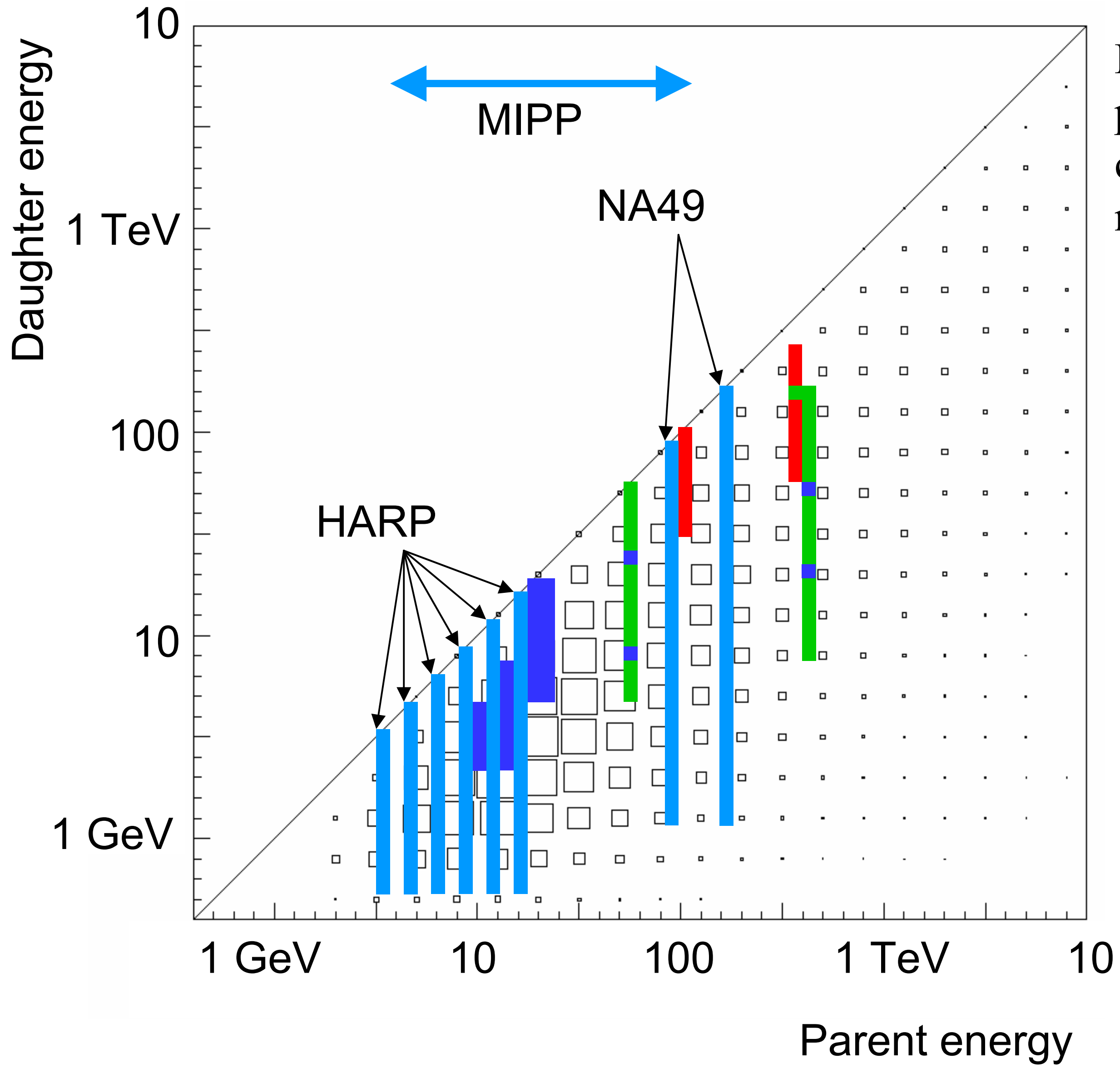


Eichten et al.:
measurement with best phase space coverage

Simulation:
fraction of secondaries in measurement bins or between bins

This energy is best situation

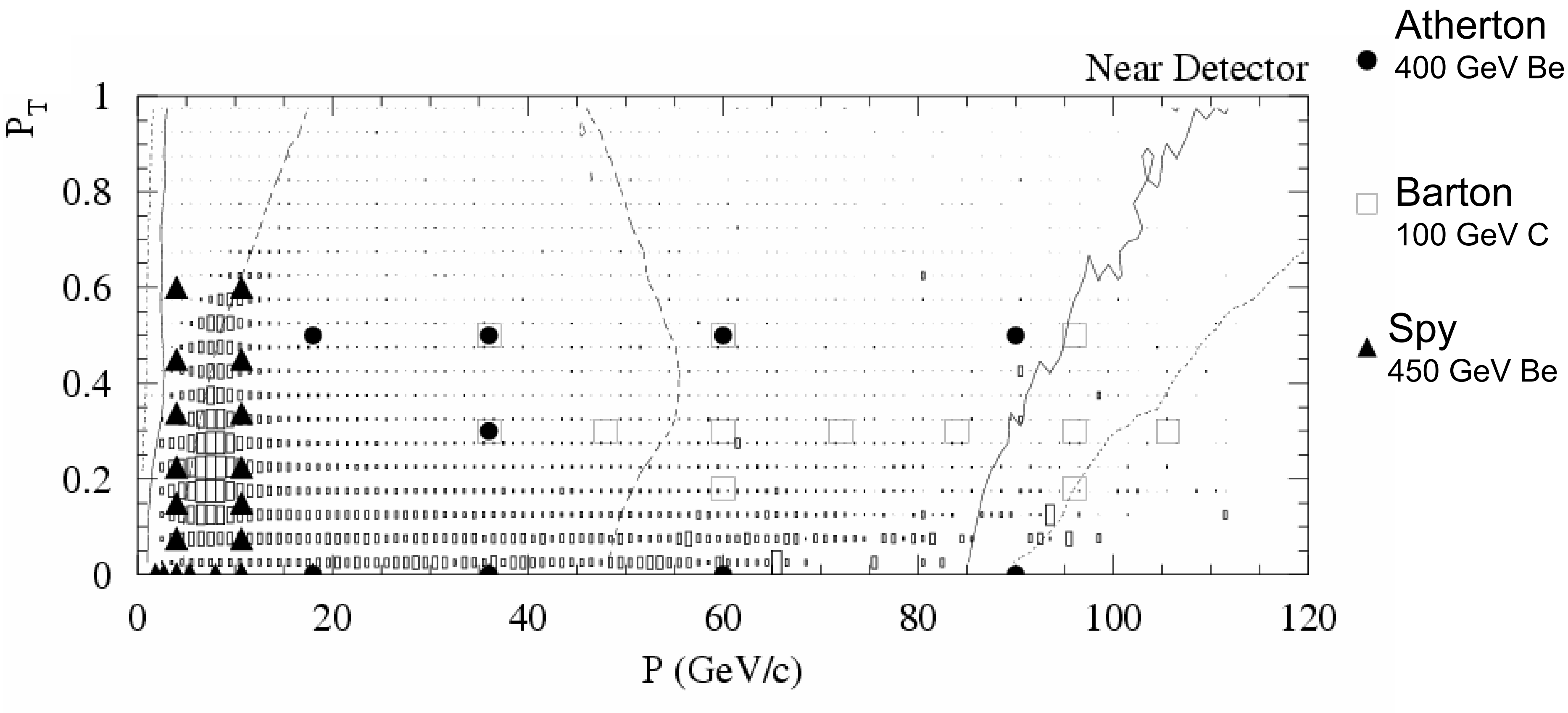
New measurements



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

New measurements.

Another view (MINOS)...



Plot courtesy of M. Messier

NA20 (Atherton et al.), CERN-SPS (1980)

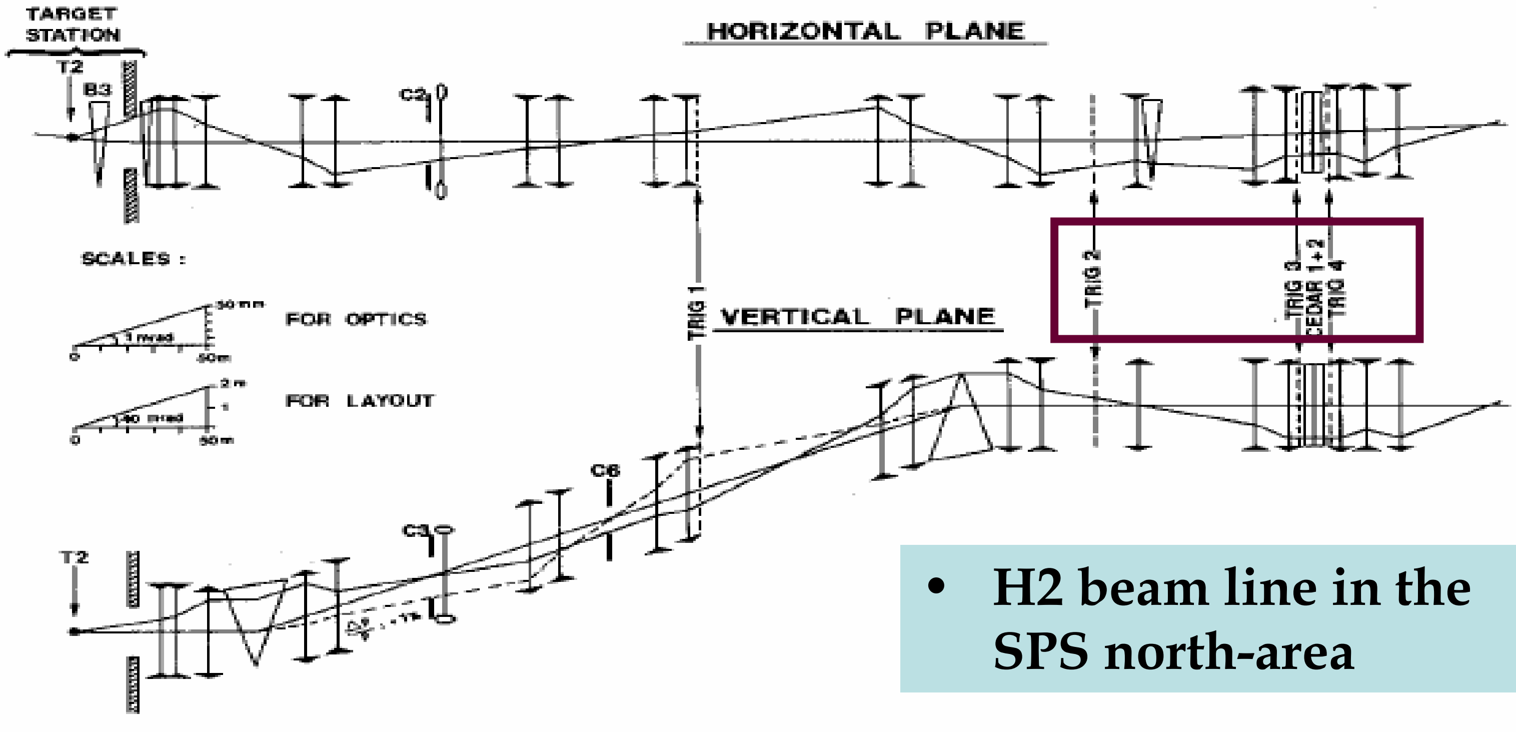


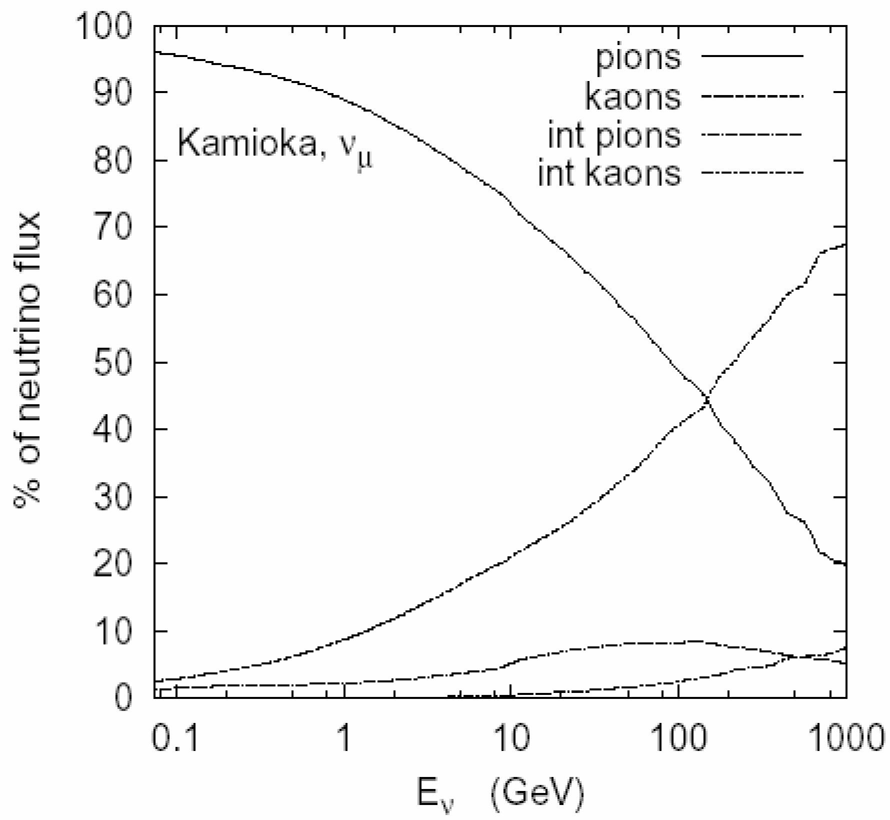
Fig. 1 Layout and optics of H2 beam

- **H2 beam line in the SPS north-area**

- **Secondary energy scan: 60,120,200,300 GeV**

Overall quoted errors
Absolute rates: ~15%
Ratios: ~5%

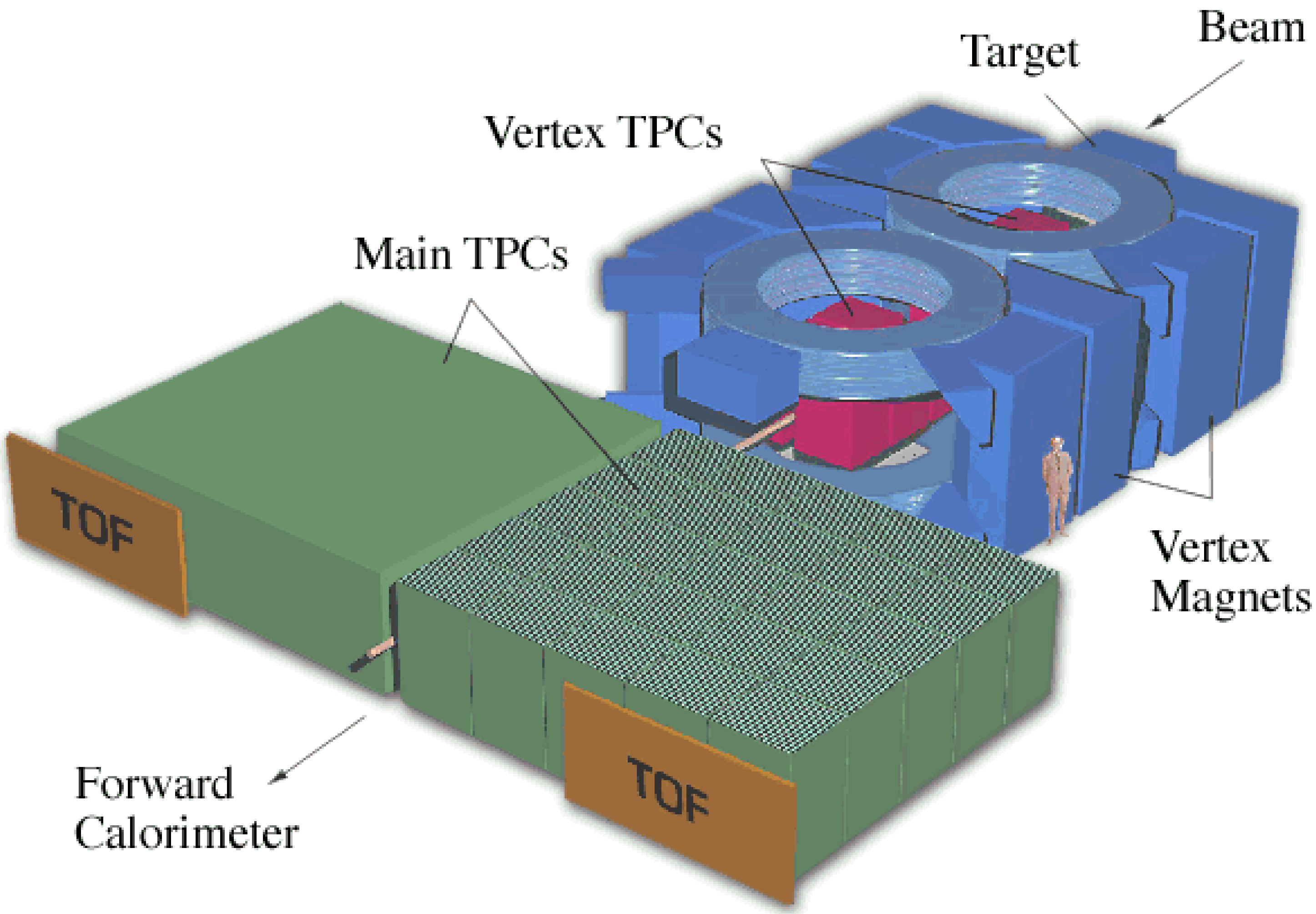
Needs...



Importance of kaons at high energy
(Thanks to S. Robbins for plot)

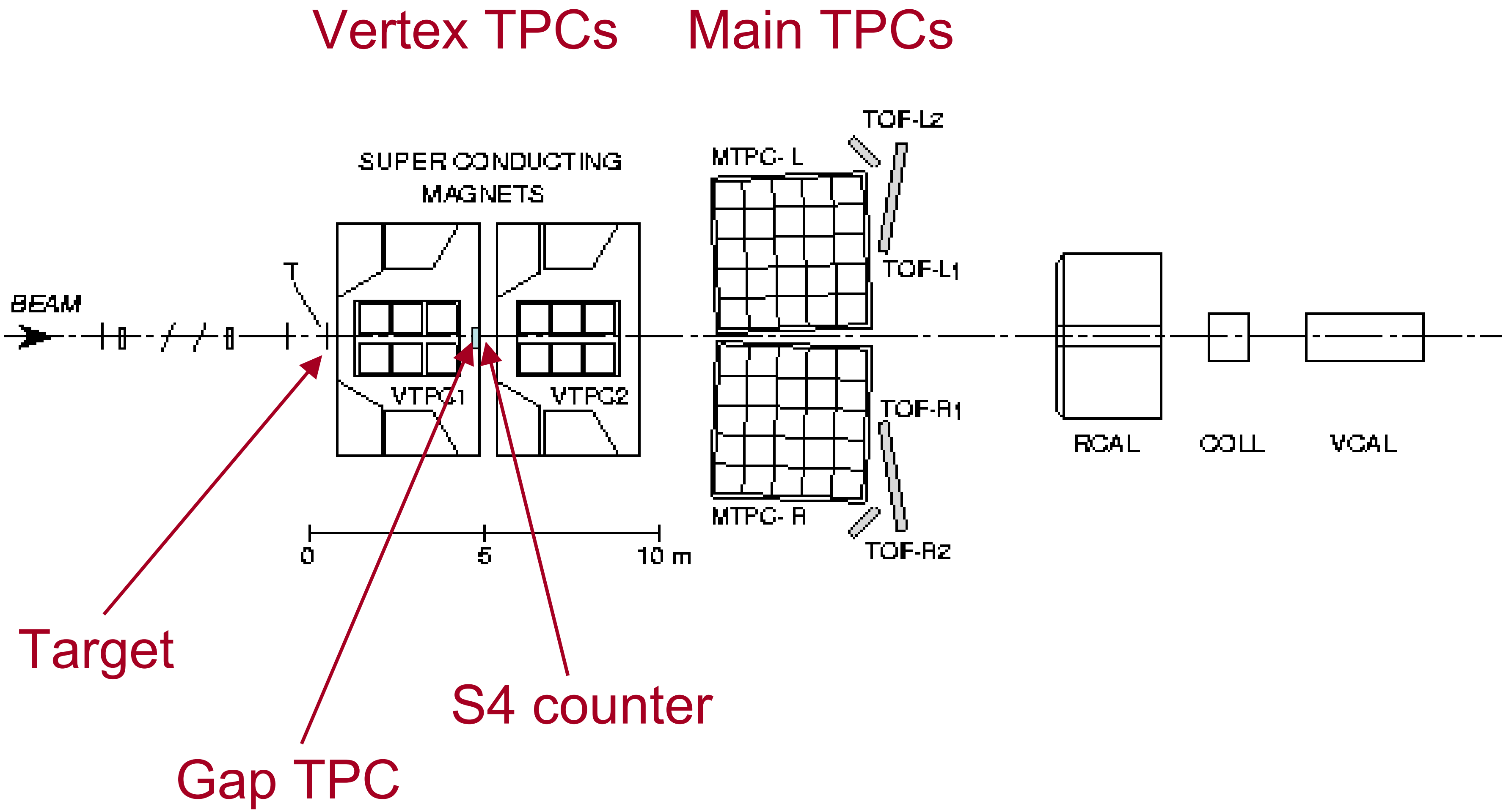
- Pion and kaon production
- Projectile: p, He, π, K etc.
- Very large range of primary energies [2 GeV,>1 TeV]
- Target: Air nuclei (nearby isoscalar nuclei acceptable)
- Full phase space coverage
- p_T distribution not interesting
- Full coverage of p_T important

NA49

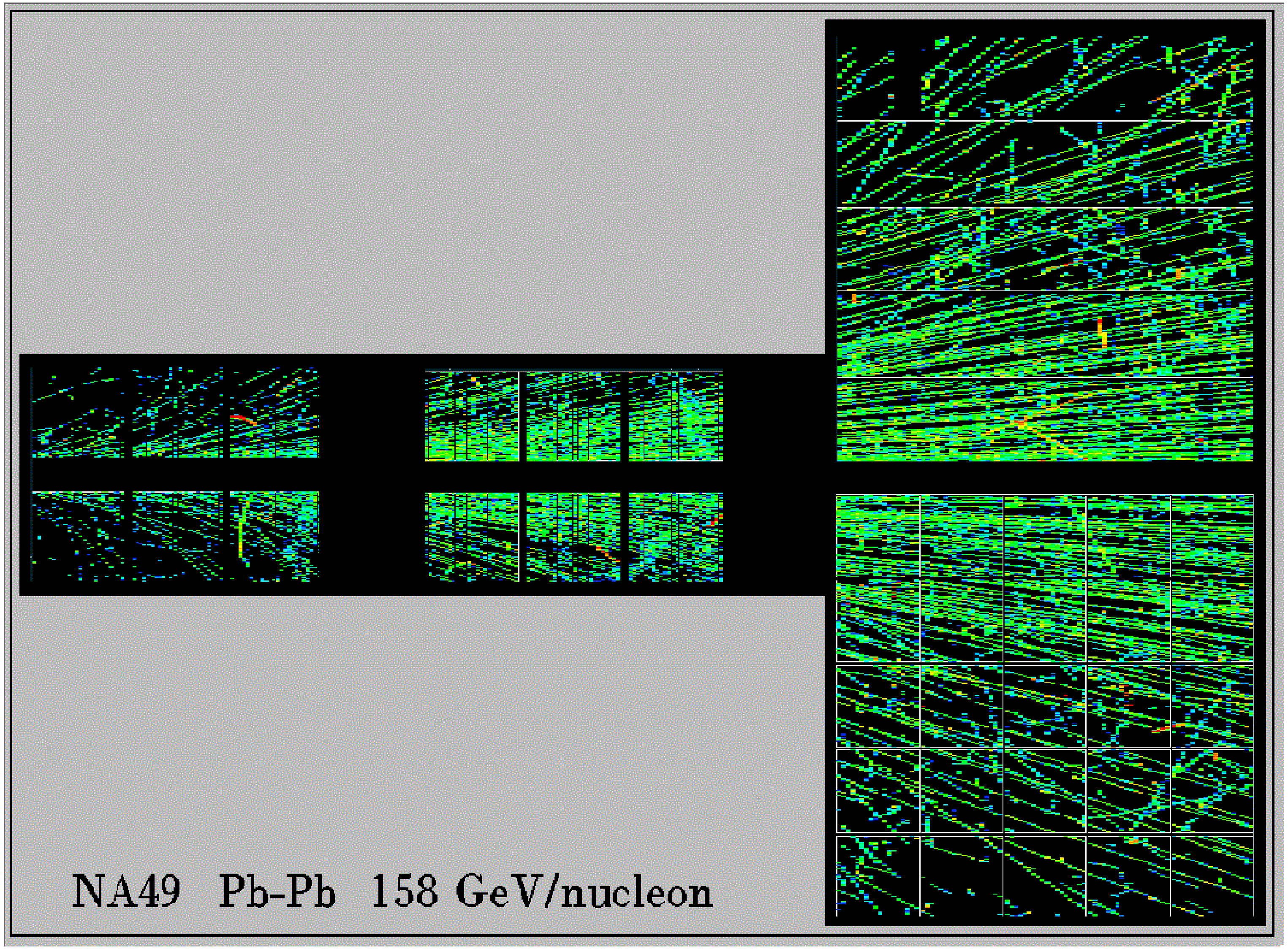


Beam
Target
Vertex TPCs
Main TPCs
TOF
TOF
Vertex
Magnets
Forward
Calorimeter

NA49 experimental layout

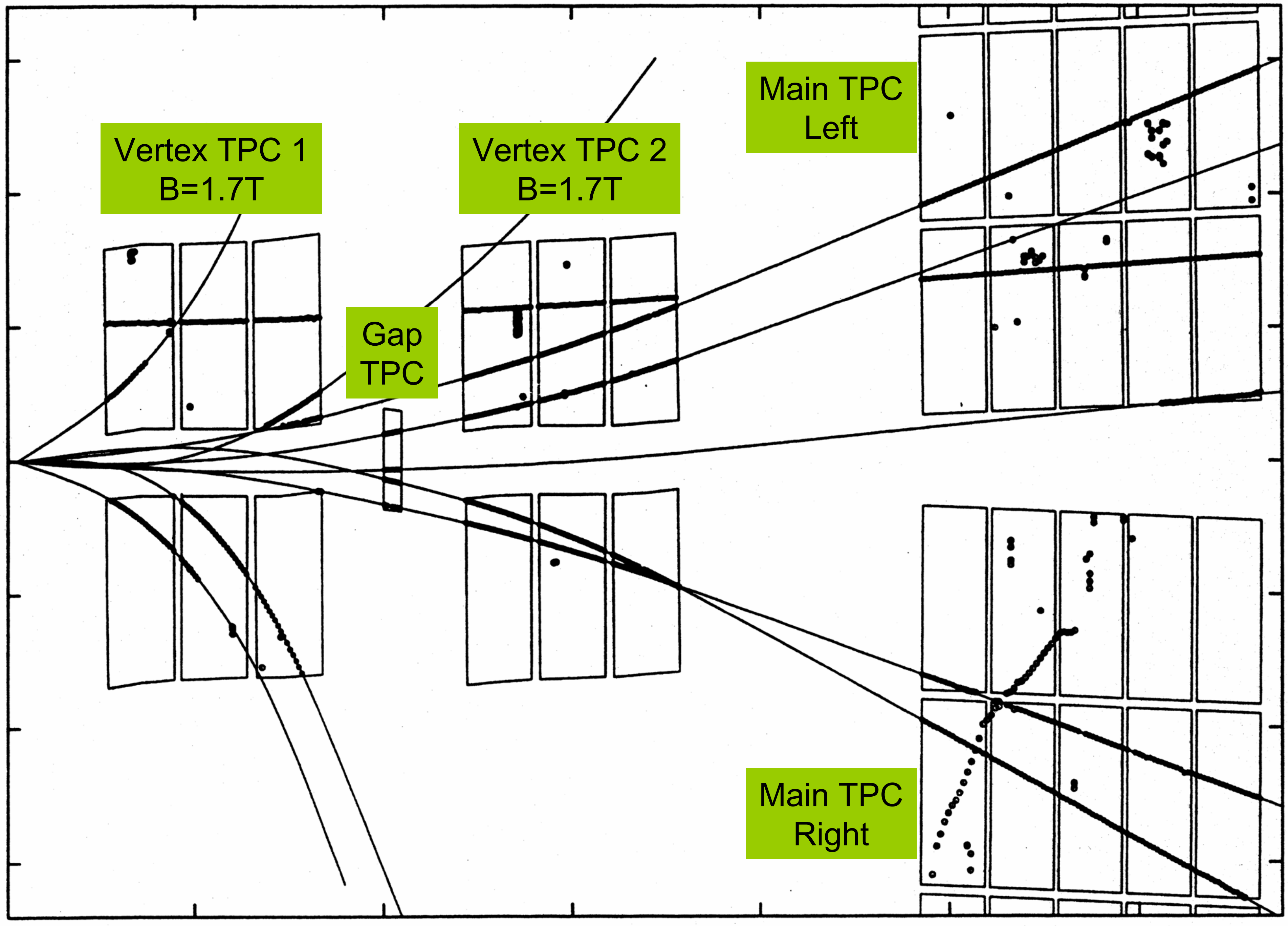


- NA49 originally designed for Lead-Lead collisions.
- Also used for pp and pA collision physics



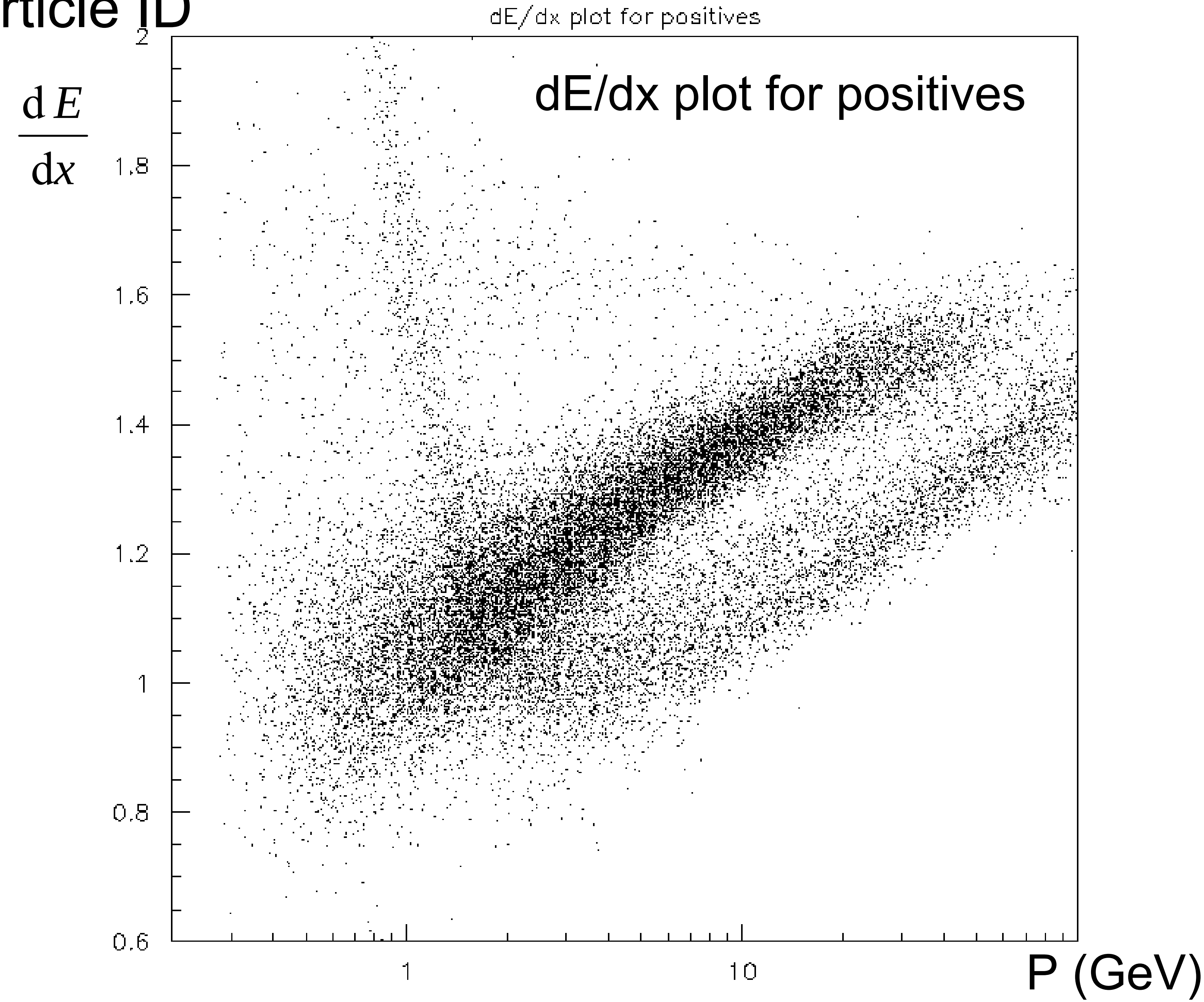
NA49 Proton-Carbon run

- ‘P322 group’ consisting of some atmospheric neutrino flux calculators, HARP experimentalists and MINOS experimentalists formed collaboration with NA49 and proposed a series of measurements.
- Received a 1 week test run with a carbon target.
- It took place in June 2002.
  - 158 GeV run, 500k triggers.
  - 100 GeV run, 160k triggers.
  - 1% interaction length carbon target.
- Immediately preceeding run was an NA49 proton-proton run, using a liquid hydrogen target.



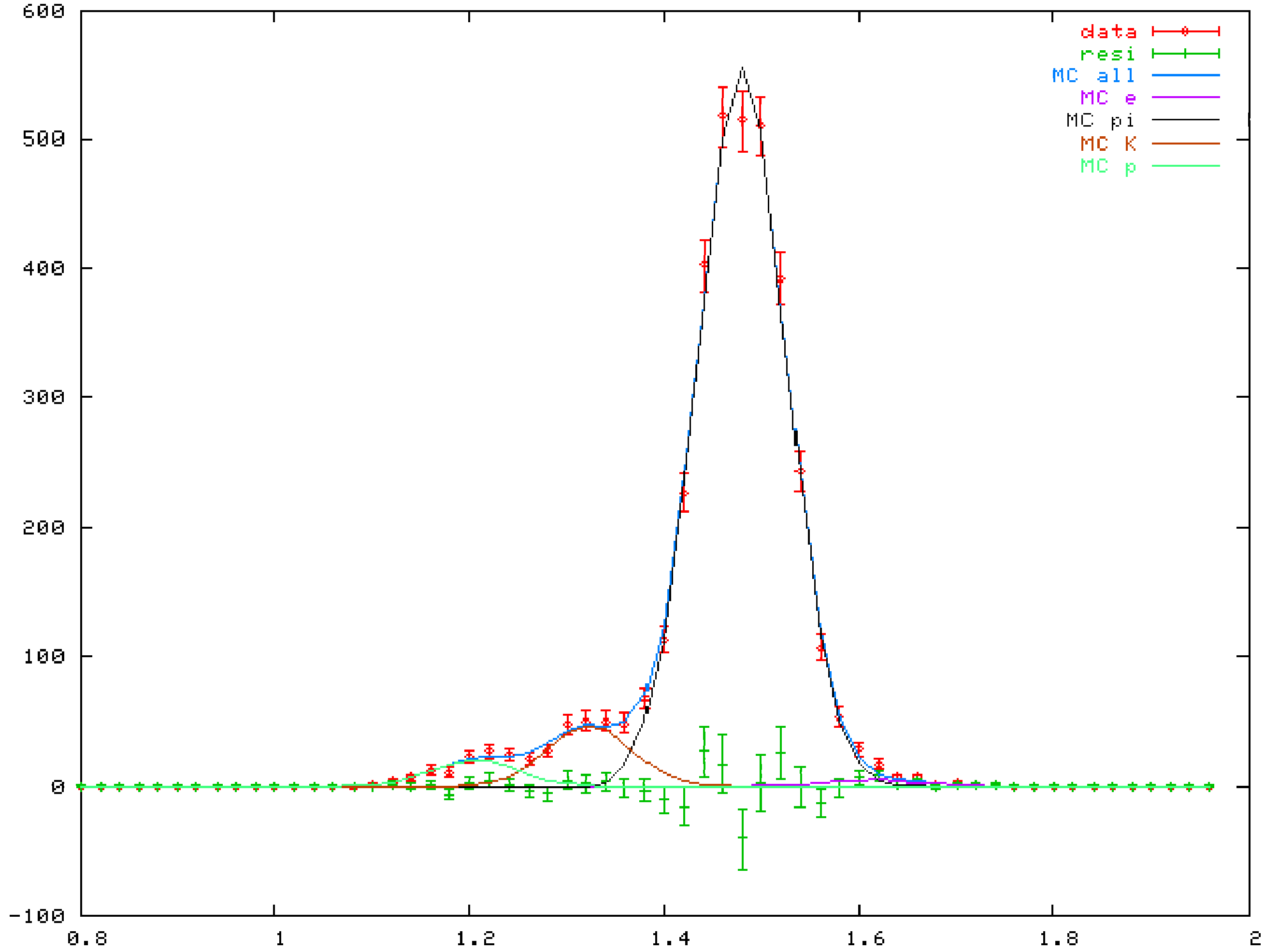
Vertex TPC 1
B=1.7T
Vertex TPC 2
B=1.7T
Main TPC
Left
Gap
TPC
Main TPC
Right

Particle ID



dE/dx plot for positives
$\frac{dE}{dx}$
dE/dx plot for positives
2
1.8
1.6
1.4
1.2
1
0.8
0.6
1
10
P (GeV)

Particle ID



$$\frac{\mathrm{d}E}{\mathrm{d}x}$$

Bins

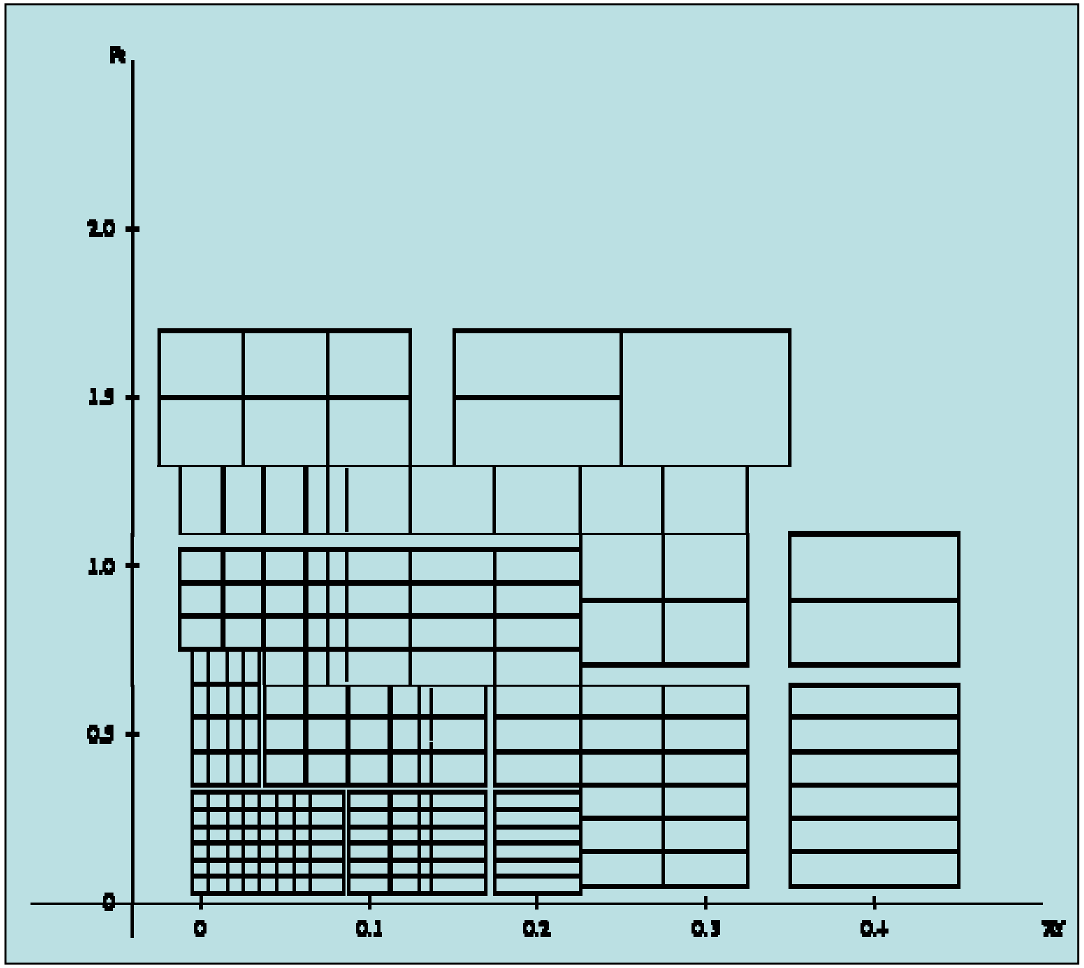
Technique:

Follow closely the analysis of p-p data

x_F and p_T bins

Some corrections are identical

Pion analysis



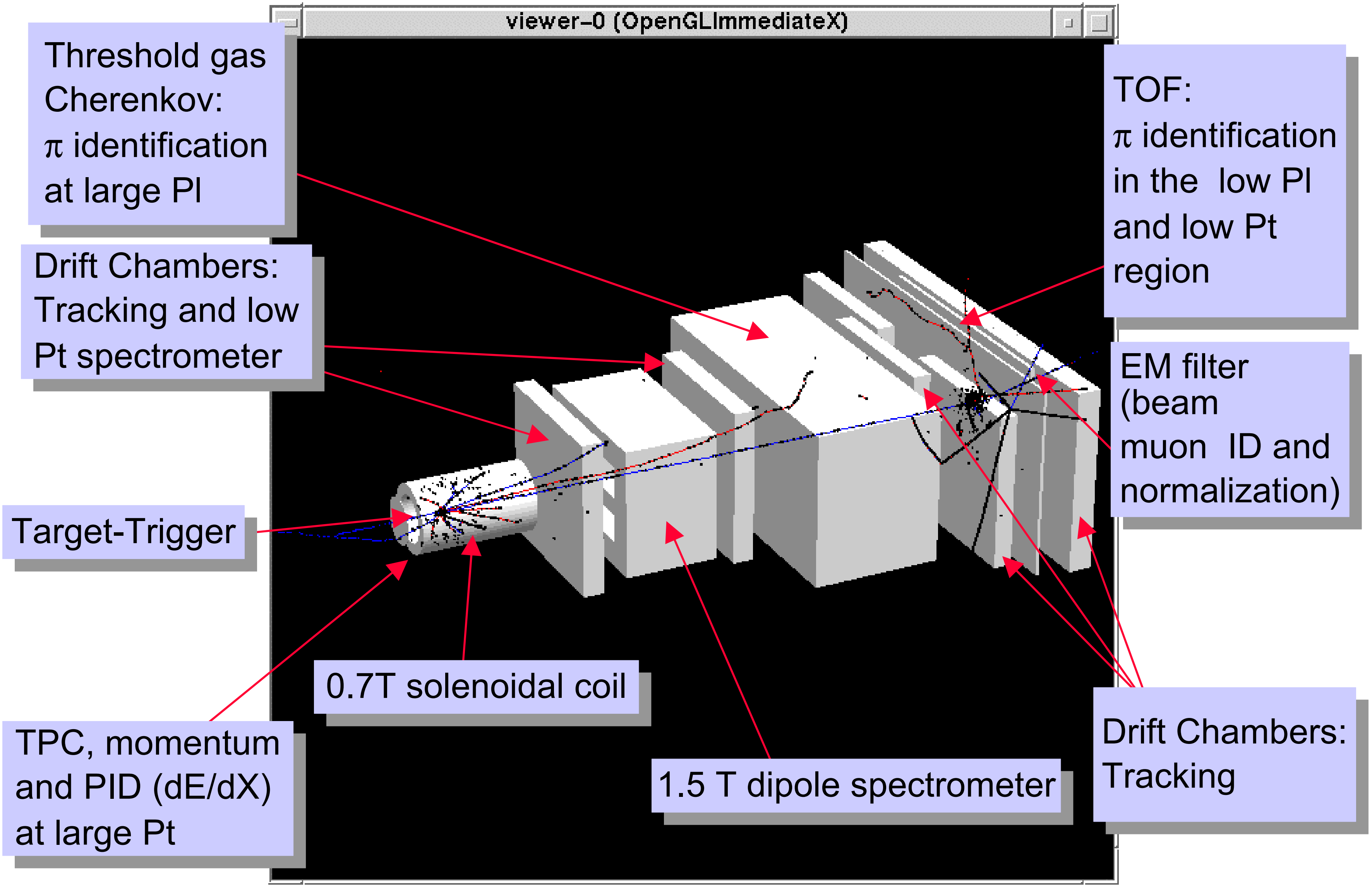
- Analysis:
  1. Get pion yields for proton-proton,
  2. followed by pion yields for proton-carbon
  3. Later, do kaons, antiprotons.
- Pion extraction straightforward
  – shifts and resolution easy to determine
  – Above $x_F = 0.5$, dE/dx information not available near gap. We do have the track distributions.
  – Particular region at low x_F where π and p dE/dx curves overlap. Use reflection in p-p.
  – Almost no information at negative x_F

Corrections and errors on pion yields

Binning correction	~1%
Target re-interaction	<1%
Detector material interaction	<1%→few %
S4 trigger correction	5-15%
Feed down correction K^0, Λ^0, Σ decays	In progress
Pion→Muon decay	small
K→pion decay	small

HARP

The Harp detector: Large Acceptance, PID Capabilities , Redundancy



HARP Experiment

- **Beam 3-15 GeV secondaries from CERN PS**
- Collected data 2001, 2002

- **Close to full acceptance**

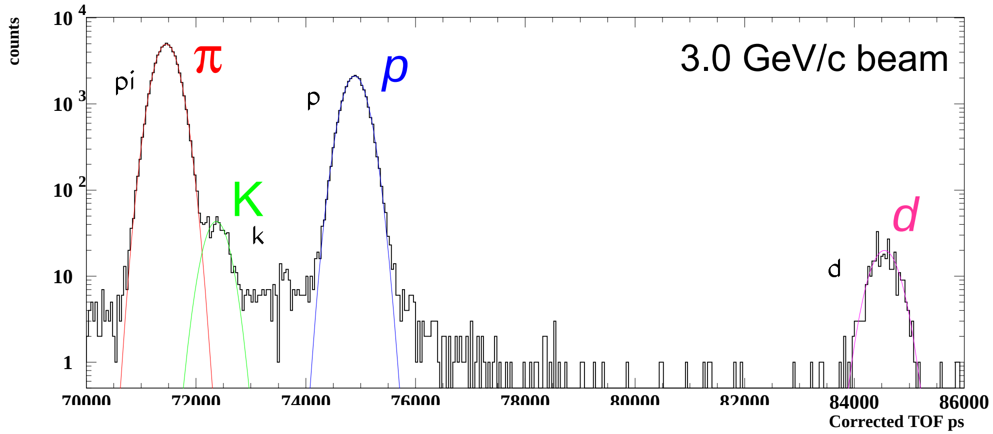
- Targets:

LH_2, LD_2, LO_2 LN_2

Be, C, Al, Cu, Tn, Sn, Pb

- **O(10^6) events per setting**

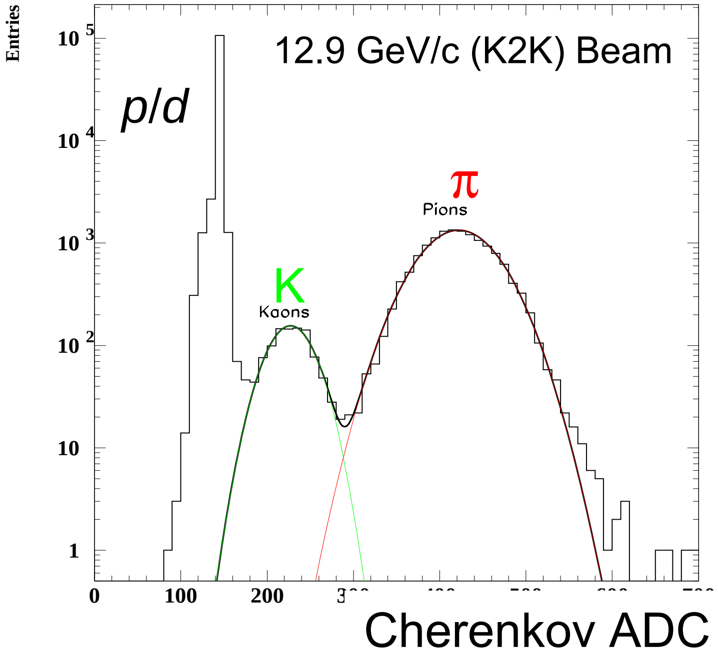
Beam Particle Identification



Beam Time Of Flight (TOF):

separate π/K/p at low energy over 21m flight distance

- time resolution 170 ps after TDC and ADC equalization
- proton selection purity >98.7%

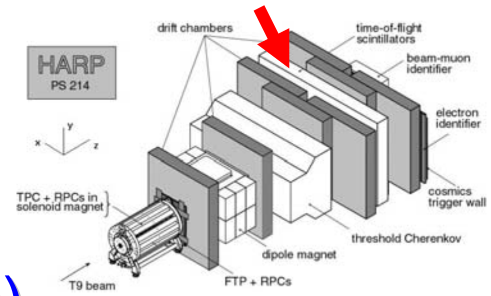


Beam Cherenkov:

Identify electrons at low energy, π at high energy, K above 12 GeV

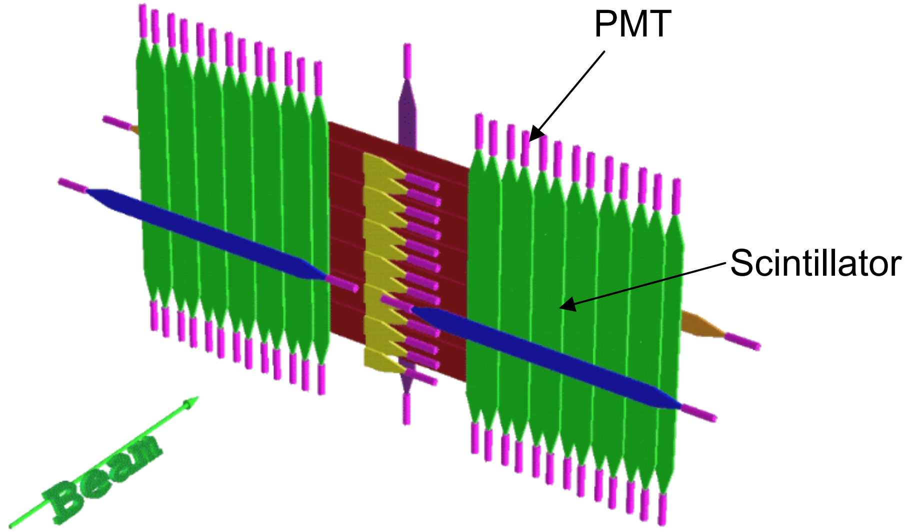
- ~100% eff. in e-π tagging

Forward PID: TOF Wall

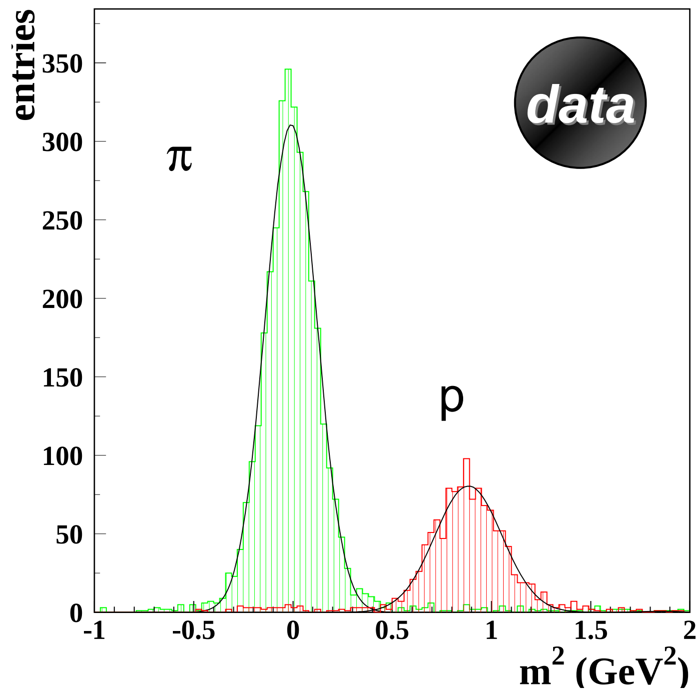


Separate π/p (K/π) at low momenta (0–4.5 GeV/c)

- 42 slabs of fast scintillator read at both ends by PMTs



3 GeV beam particles



$$m^2 = p^2 \cdot \left[\left(\frac{t_{wall} - t_0}{L} \right)^2 - 1 \right]$$

TOF time resolution ~160 ps

3σ separation: π/p up to 4.5 GeV/c

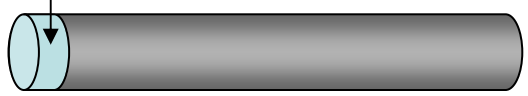
K/π up to 2.4 GeV/c

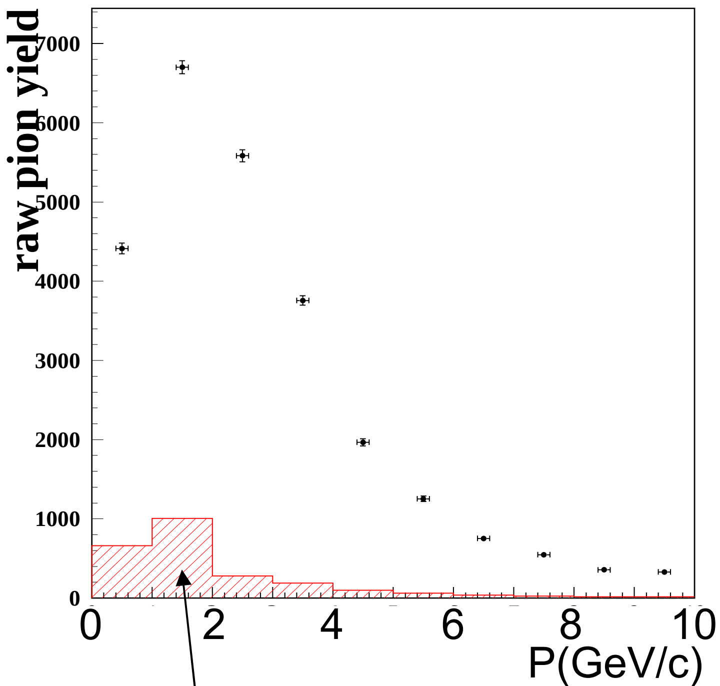
→ 7σ separation of π/p at 3 GeV/c

Pion yield: K2K thin target

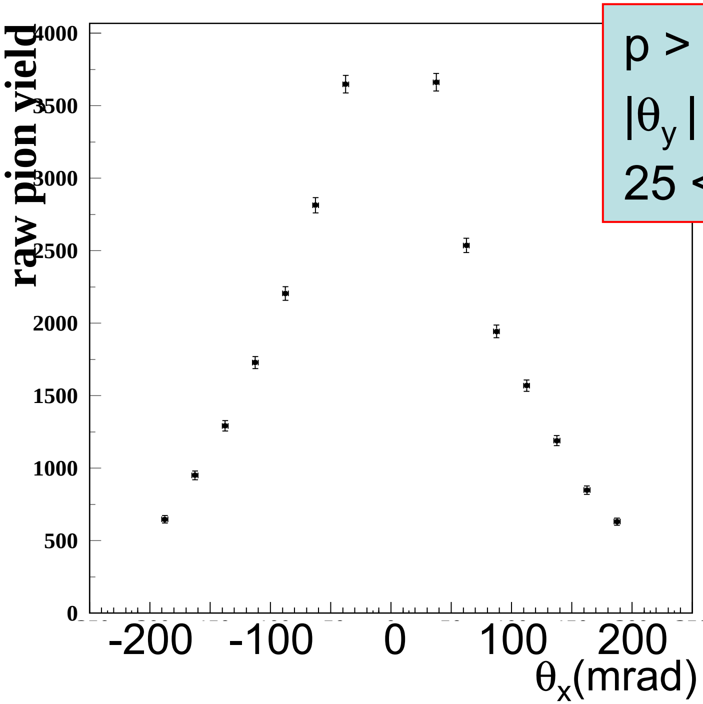
Use K2K thin target (5%λ)

- To study primary *p*-Al interaction
- To avoid absorption / secondary interactions





p-e/π misidentification background

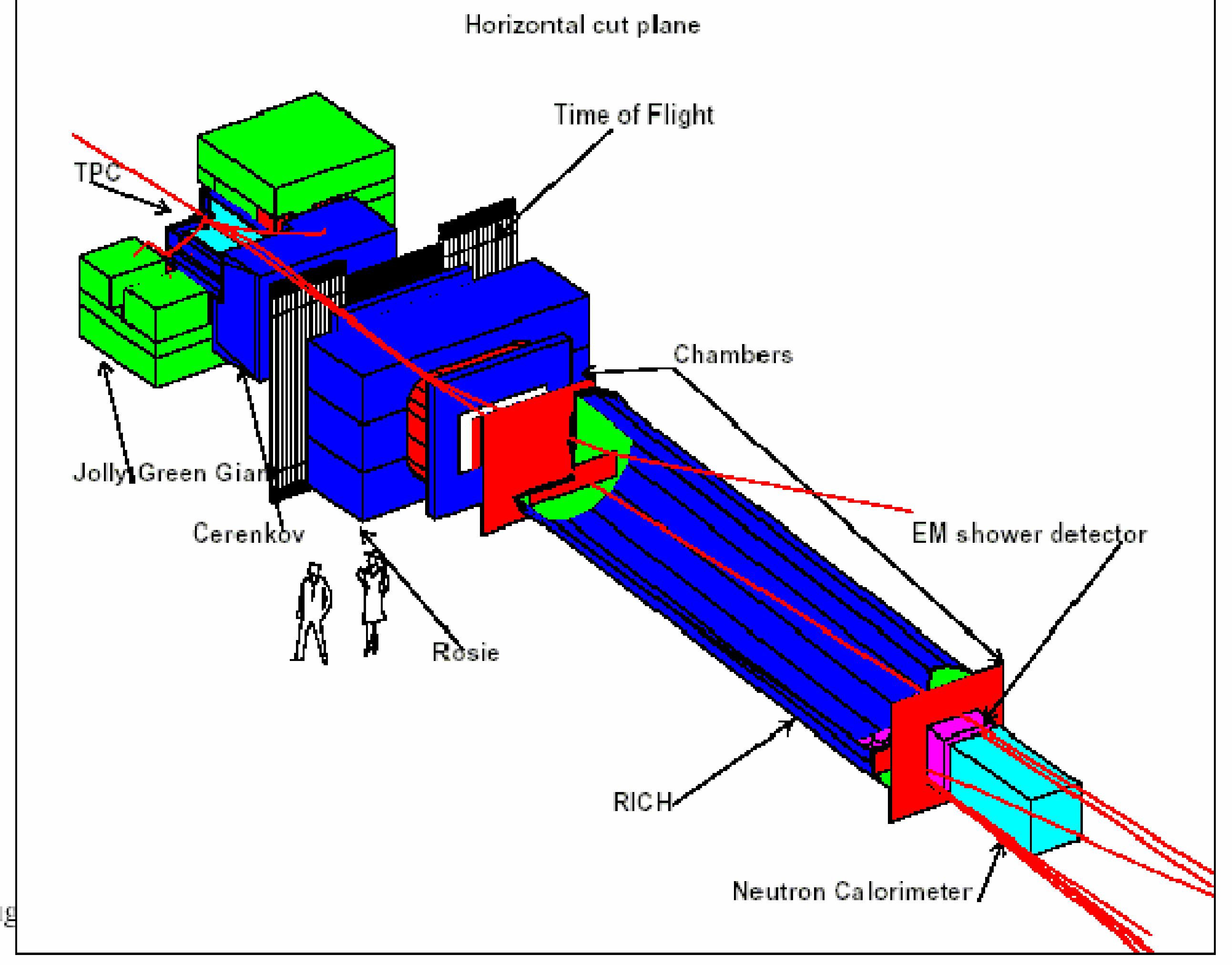


$p > 0.2$ GeV/*c*
$|\theta_y| < 50$ mrad
$25 < |\theta_x| < 200$ mrad

Raw data

MIPP

Main Injector Particle Production Experiment (FNAL-E907)



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R. Winston
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Elmhurst College and EFI
W.Baker,D.Carey,J.Hylen, C.Johnstone,M.Kostin,
H.Meyer, N.Mokhov, A.Para, R.Raja,S. Striganov
Fermi National Accelerator Laboratory
G. Feldman, A.Lebedev, S.Seun
Harvard University
P.Hanlet, O.Kamaev,D.Kaplan, H.Rubin,N.Solomey,
C.White
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D.Rajaram
University of Michigan
A.Bujak, L.Gutay,D.E.Miller
Purdue University
T.Bergfeld,A.Godley,S.R.Mishra,C.Rosenfeld,K.Wu
University of South Carolina
C.Dukes,
H.Lane,L.C.Lu,C.Maternick,K.Nelson,A.Norman
University of Virginia

~50 people, 11 graduates students, 11 postdocs.

MIPP :Physics Program

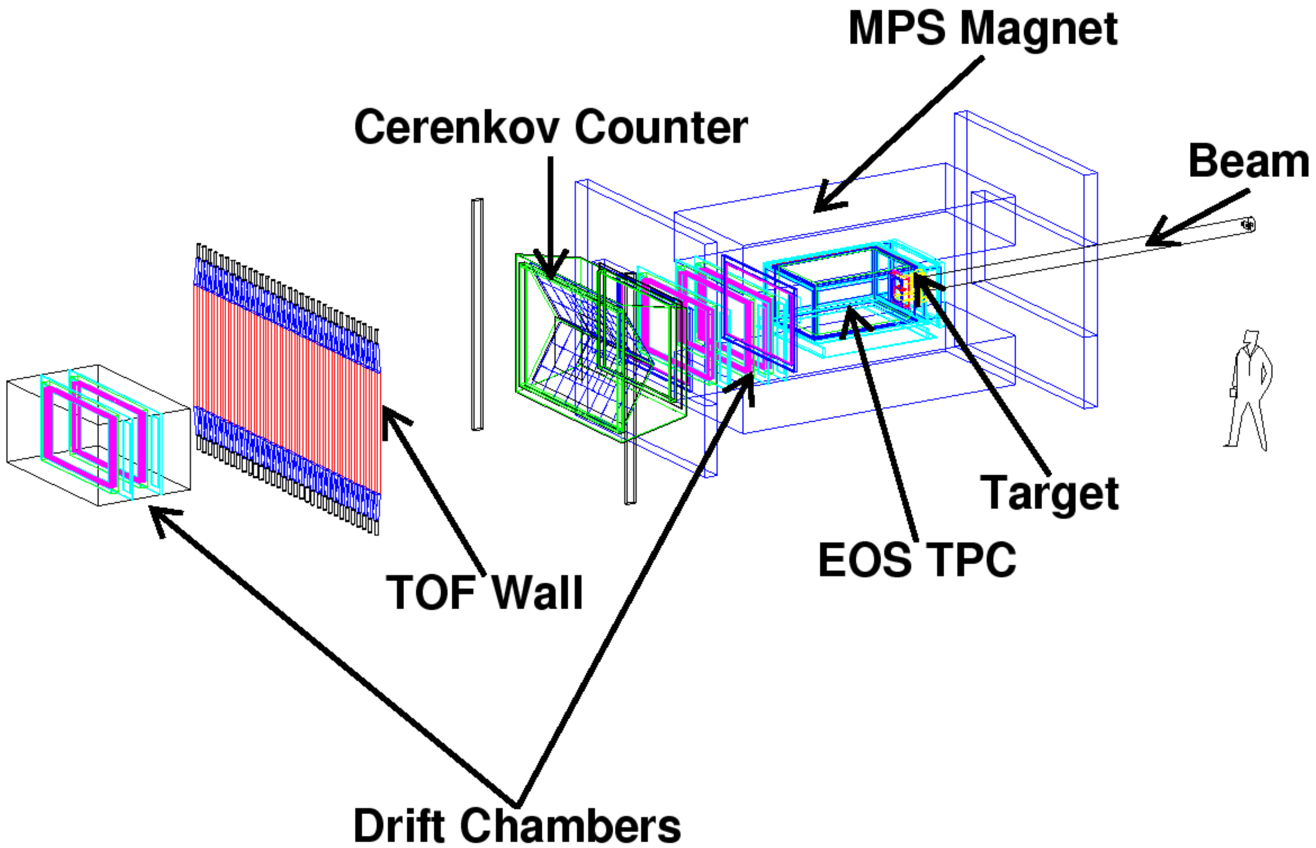
- Particle Physics-To acquire unbiased high statistics data with complete particle id coverage for hadron interactions.
  - Study non-perturbative QCD hadron dynamics, scaling laws of particle production
  - Investigate light meson spectroscopy, pentaquarks, glueballs
- Nuclear Physics
  - Investigate strangeness production in nuclei- RHIC connection
  - Nuclear scaling

Target	Physics	Data Points	Primary proton Average Intensity/spill	Total number of Primary Protons
Numi 1	MINOS	3.3	125000	2.06E+10
NUMI 2	MINOS	3.3	125000	2.06E+10
H2	Scaling	6	9.76E+09	2.93E+15
N2	Atmospheric ν	4	9.76E+09	1.95E+15
Be	pA	2	9.76E+09	9.76E+14
Be	Survey	1	9.76E+09	4.88E+14
C	Survey	1	9.76E+09	4.88E+14
Cu	pA	2	9.76E+09	9.76E+14
Cu	Survey	1	9.76E+09	4.88E+14
Pb	pA	2	9.76E+09	9.76E+14
Pb	Survey	1	9.76E+09	4.88E+14
Total		26.6		9.76E+15

- **Netrinos related Measurements**
  - Atmospheric neutrinos – Cross sections of protons and pions on Nitrogen from 5 GeV- 120 GeV (5,15,25,5070,90) GeV
  - Improve shower models in MARS, Geant4
  - Make measurements of production of pions for neutrino factory/muon collider targets
  - MINOS target measurements – pion production measurements to control the near/far systematics
- **Complementary with HARP at CERN**

Brookhaven Experiment 910

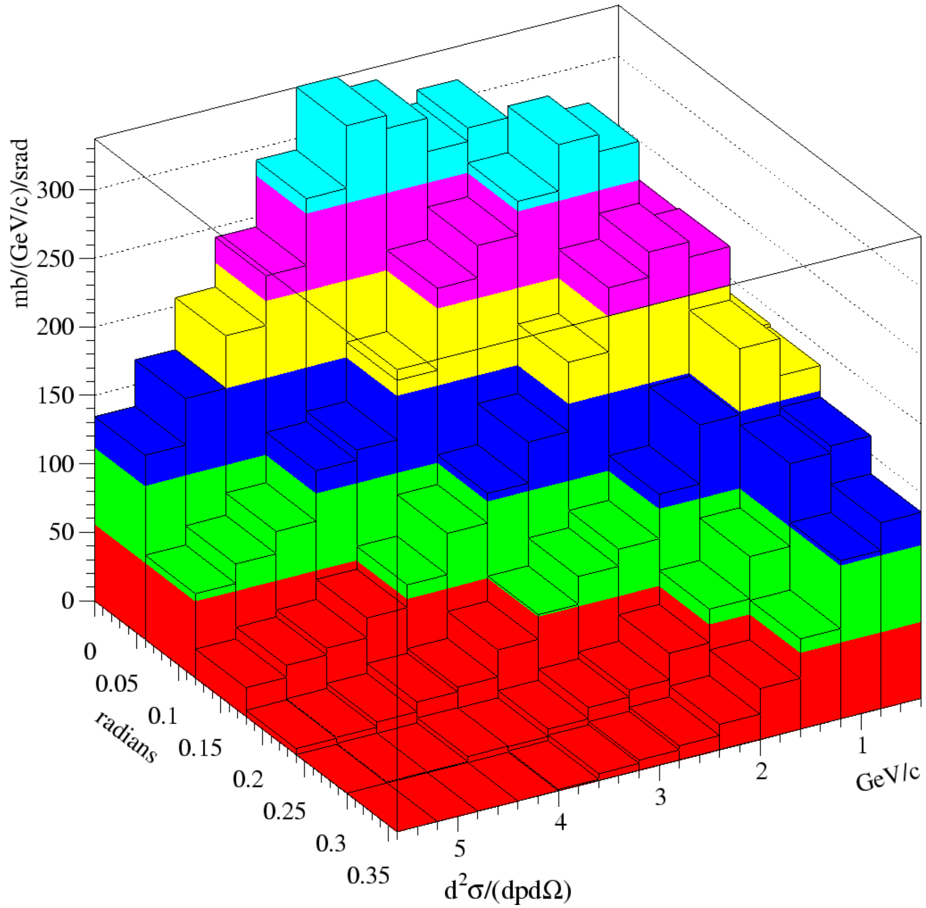
E910 used a spectrometer with good acceptance and particle ID over the momentum and angular range of interest to MiniBooNE.

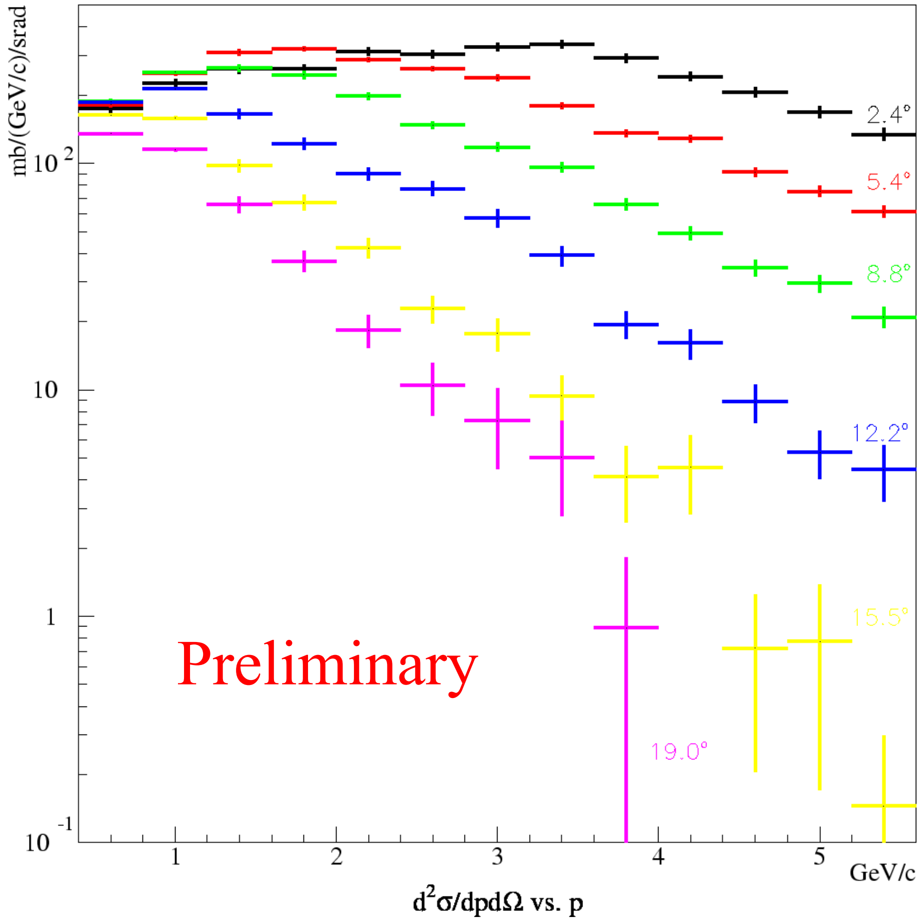


Particle ID from dE/dx in the TPC, threshold Čerenkov, and Time of Flight.

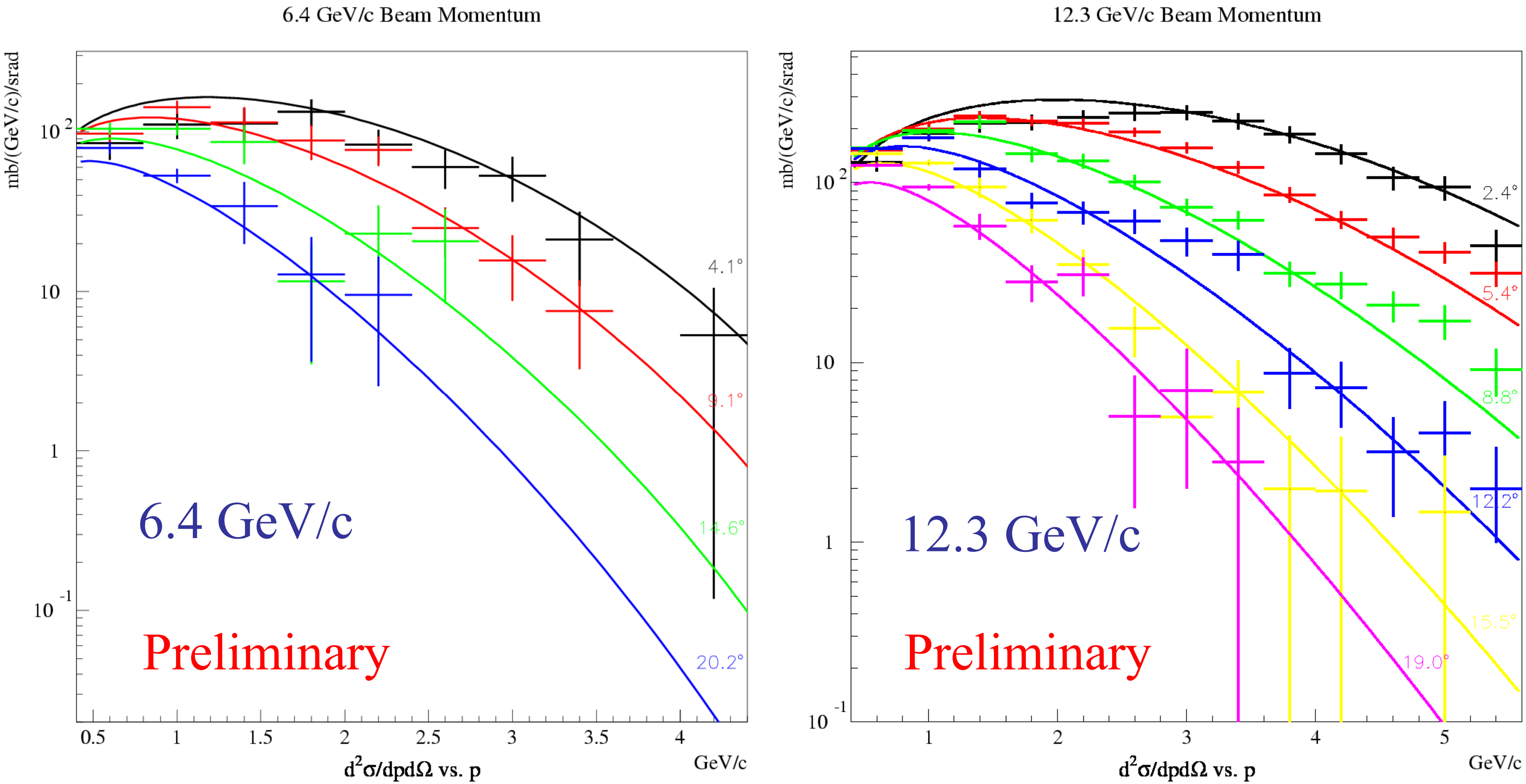
The Results

The π^+ production cross section for a beam momentum of 17.6 GeV/c.





Sanford-Wang Fit Results

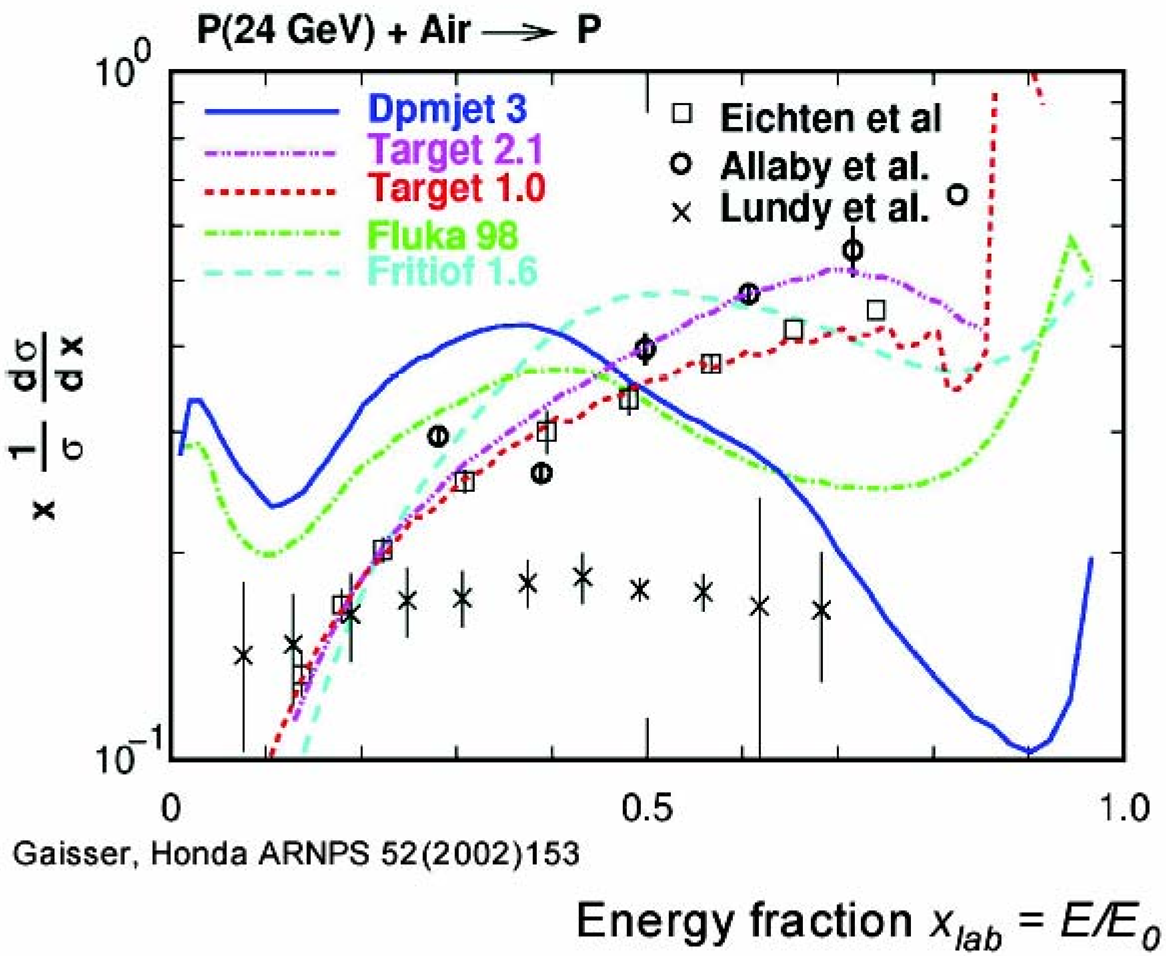


Section 3: Outlook

Estimating impact of Hadron production

New measurements with atmospheric neutrinos.

Estimating Hadron production errors on Cosmic Ray fluxes



Gaisser, Honda ARNPS 52(2002)153

Example:
Proton distribution

Large differences between data sets

Large differences between models

π production at 20 GeV

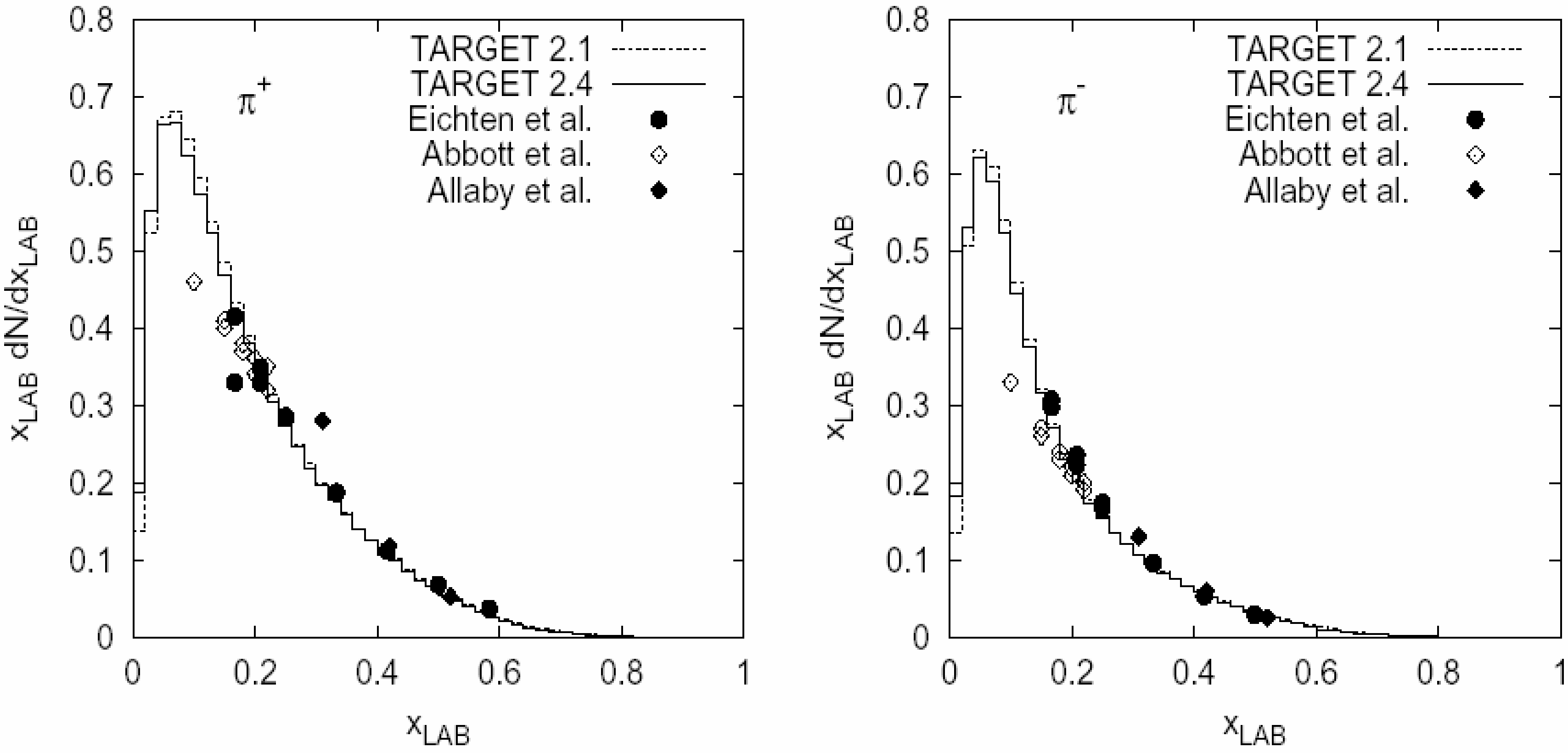


Figure 4.6: Comparison of the TARGET event generator and experimental data at around $24\ GeV$, $pBe \rightarrow \pi^+ X$ (left) and $pBe \rightarrow \pi^- X$ (right).

Lower energy

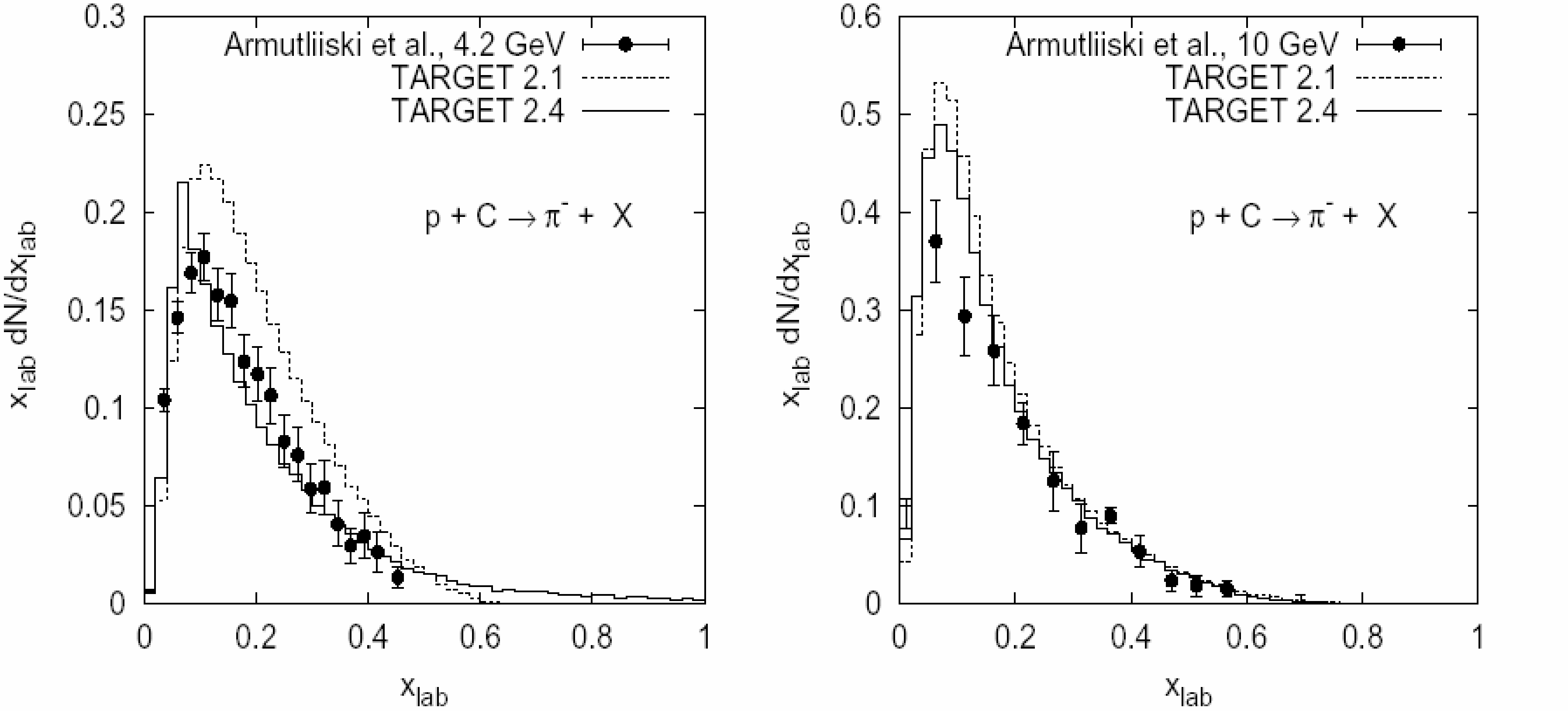


Figure 4.8: Comparison of the TARGET event generator and experimental data at $4.2\ GeV$ (left) and $10\ GeV$ (right), $pC \to \pi^- X$.

Proposed total errors

	Pions										Kaons									
x_{LAB} (low edge)	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
<8 GeV	10%					30%					40%									
8-15 GeV	30%		10%				30%				40%									
15-30 GeV	30	10	5%				10%				30	20	10%							
30-500 GeV	30	15%									40	30%								
>500 GeV	30	15%+Energy dep.									40	30%+Energy dep.								

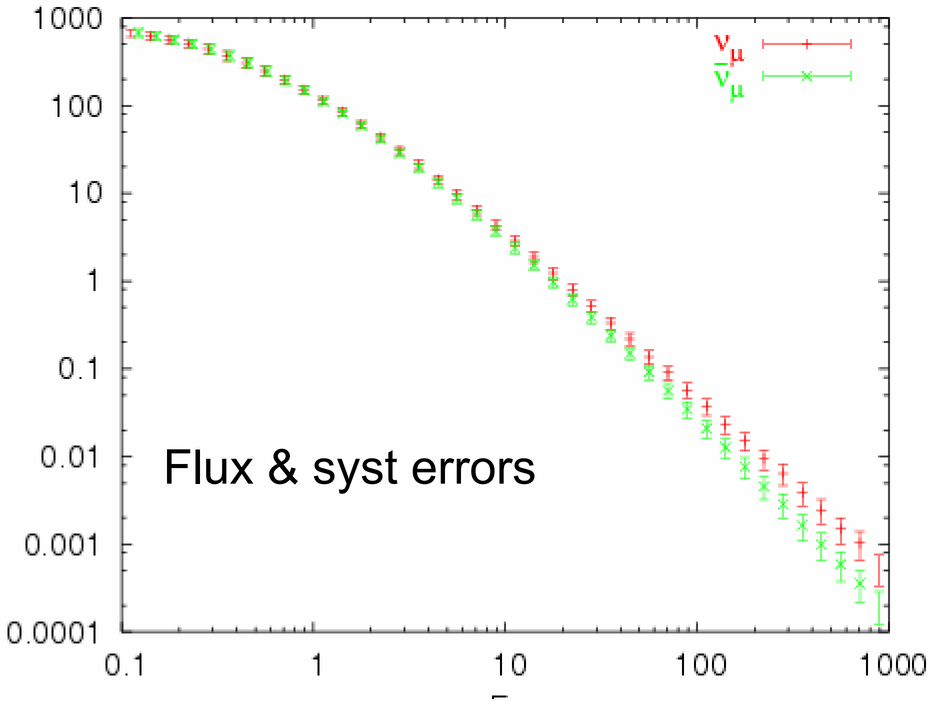
More sophisticated combination

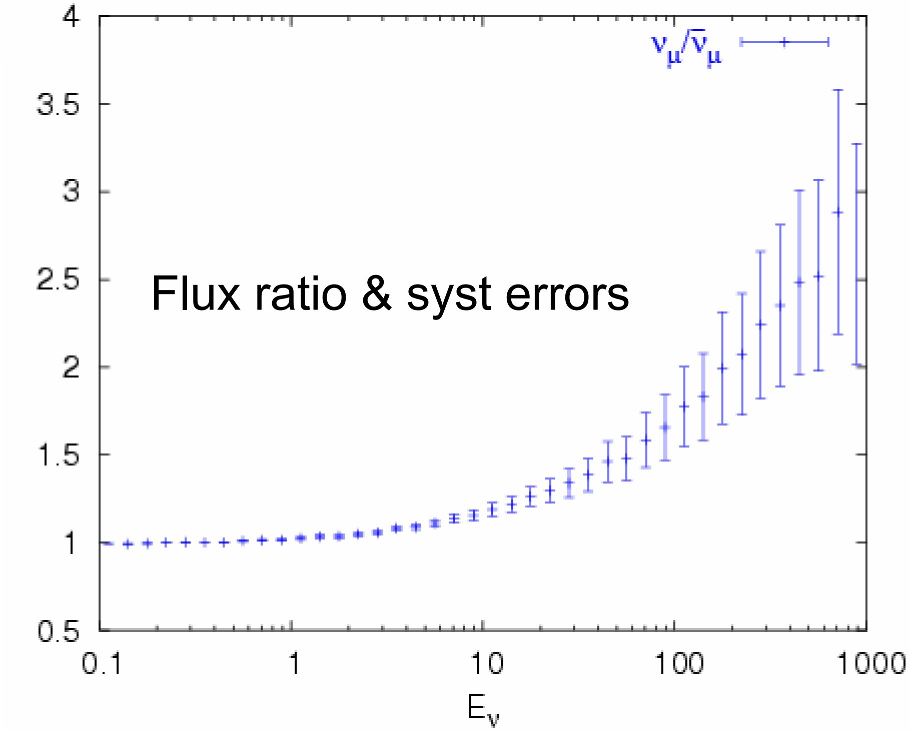
(1)	Pions										Kaons									
x_{LAB} (low edge)	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
<8 GeV	10%										40%									
8-15 GeV	10%										40%									
15-30 GeV	5%										10%									
30-500 GeV	15%										30%									
>500 GeV	15%										30%									

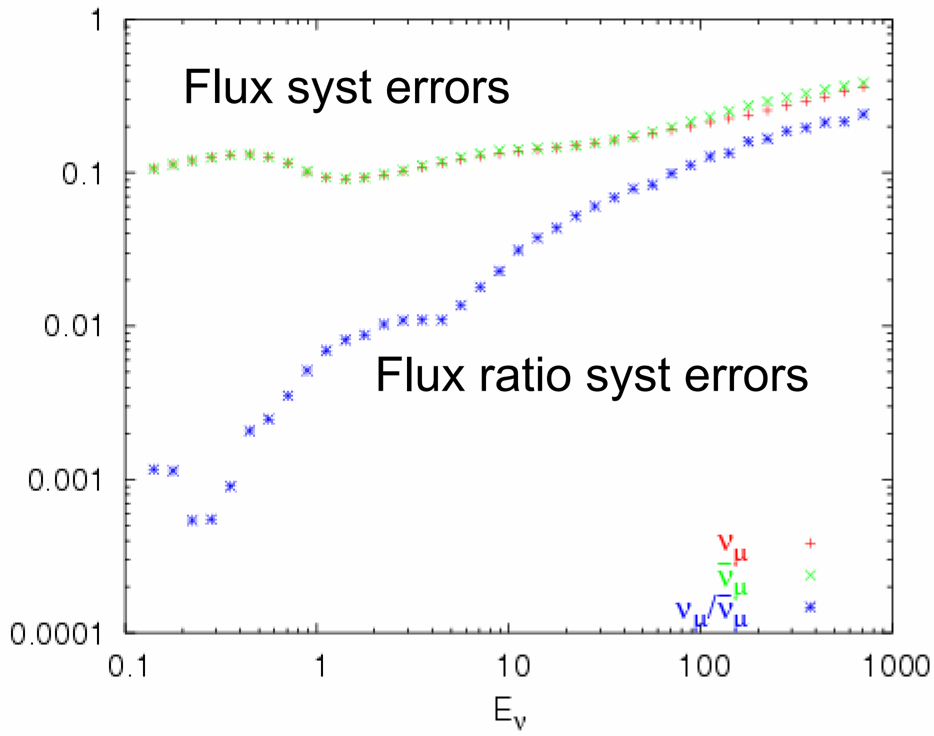
	Pions										Kaons									
x_{LAB} (low edge)	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
<8 GeV	10%					30%					40%									
8-15 GeV	30%		10%				30%				40%									
15-30 GeV	30	10	5%				10%				30	20	10%							
30-500 GeV	30	15%									40	30%								
>500 GeV	30	15%+Energy dep.									40	30%+Energy dep.								

Flaws: No difference pi+pi-, or K+K-

ν_μ/anti-ν_μ

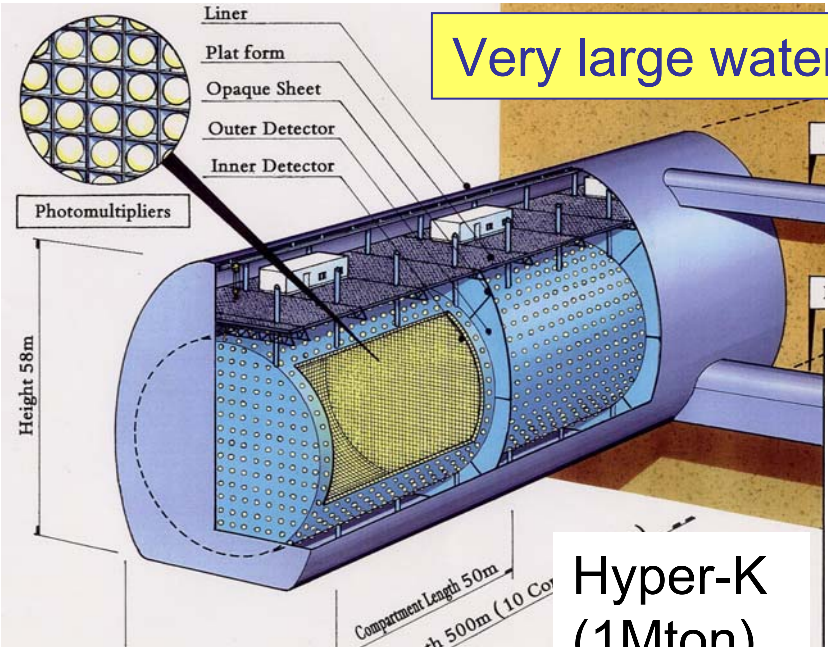






Possible future atmospheric ν detectors

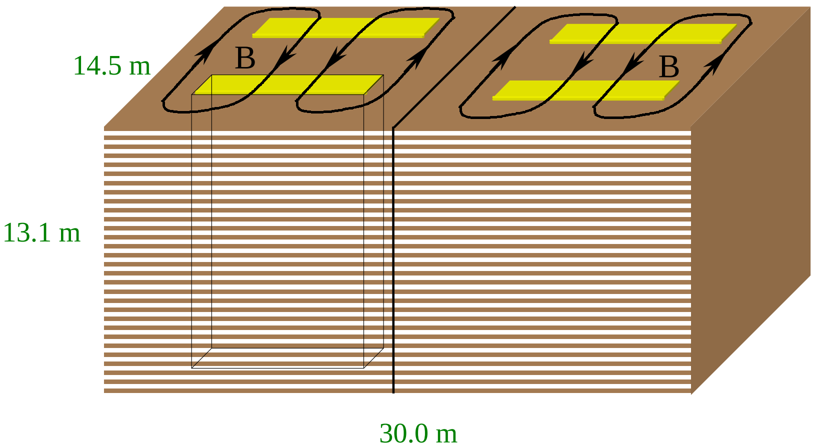
Very large water Cherenkov detector

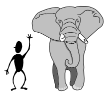


Hyper-K
(1Mton)

UNO

Mton class
detector at Frejus





Magnetized large tracking detector

MONOLITH,

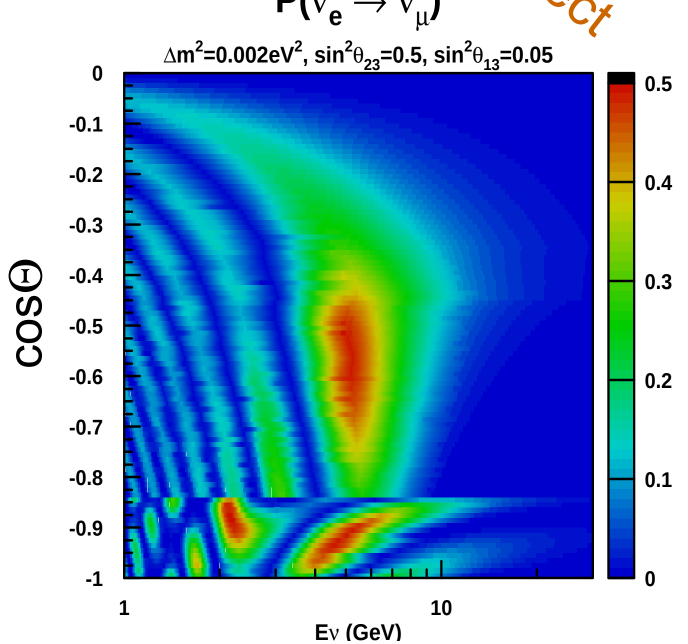
INO (India-based Neutrino Observatory, …

Search for non-zero θ_{13}

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \cdot \sin^2\theta_{13} \cdot \sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E}\right)$$ (Δm_{12}^2=0 assumed)

Matter effect

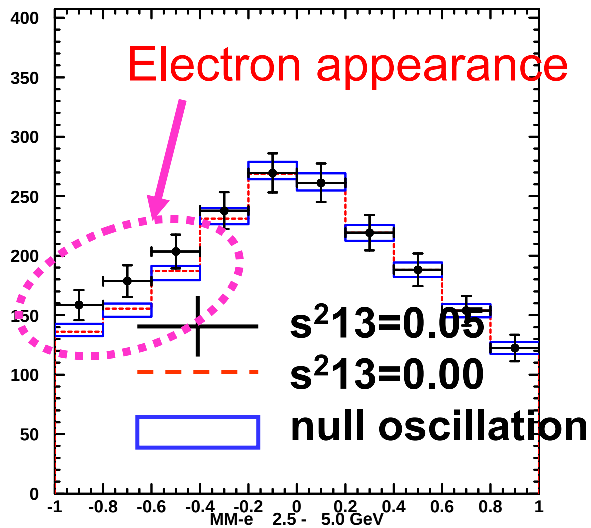
$P(\nu_\mu \to \nu_e)$



Eν(GeV)

MC, SK 20yrs

1+multi-ring, e-like,
2.5 - 5 GeV



cosΘ

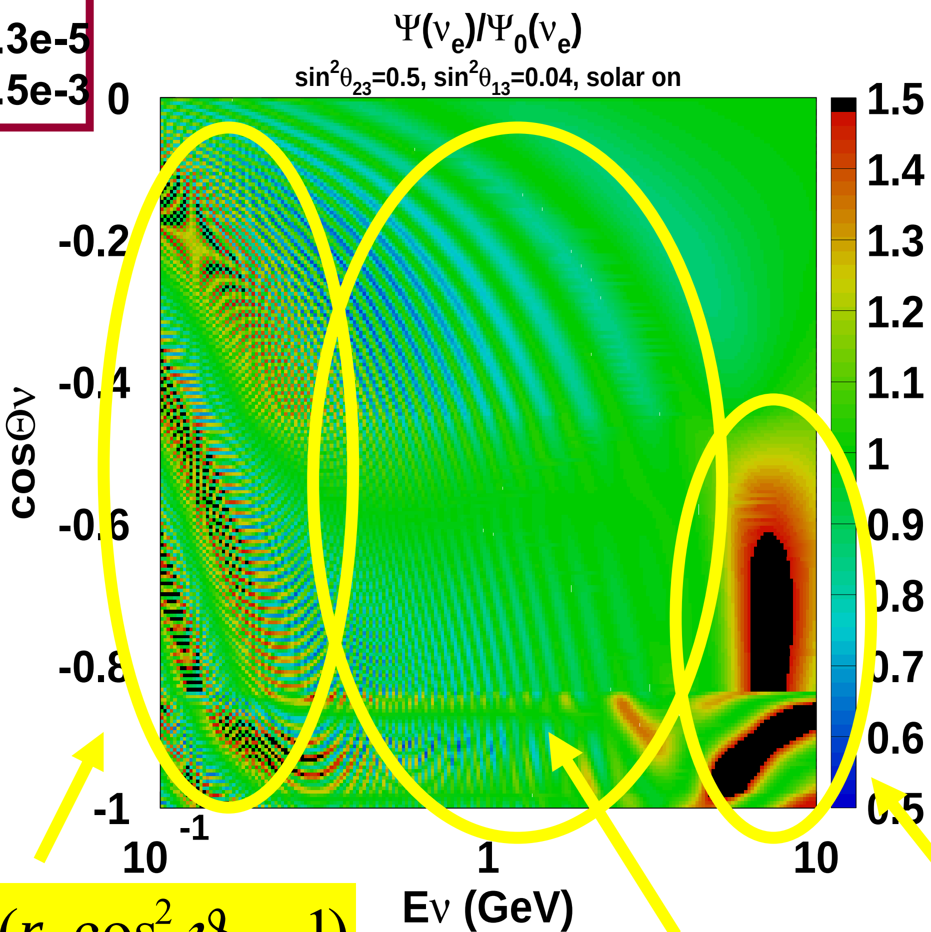
Electron appearance in the 5 – 10GeV upward going events.

From: Talk by T. Kajita, NuFact 04 (Osaka U. Aug 2004)

Quick glance of oscillation effects

$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.4
$s^2\theta_{13}$=0.04
δcp=45°
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

$\Psi(\nu e)/\Psi_0(\nu e)$



$\mathrm{LMA} \propto (r \cdot \cos^2 \vartheta_{23} - 1)$

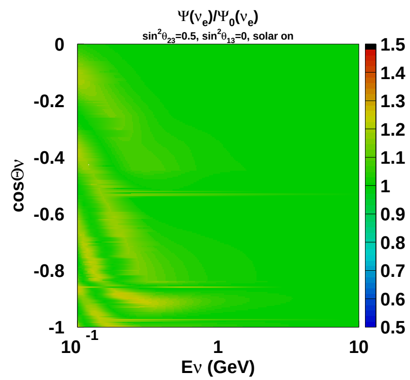
interference

ϑ_{13} resonance

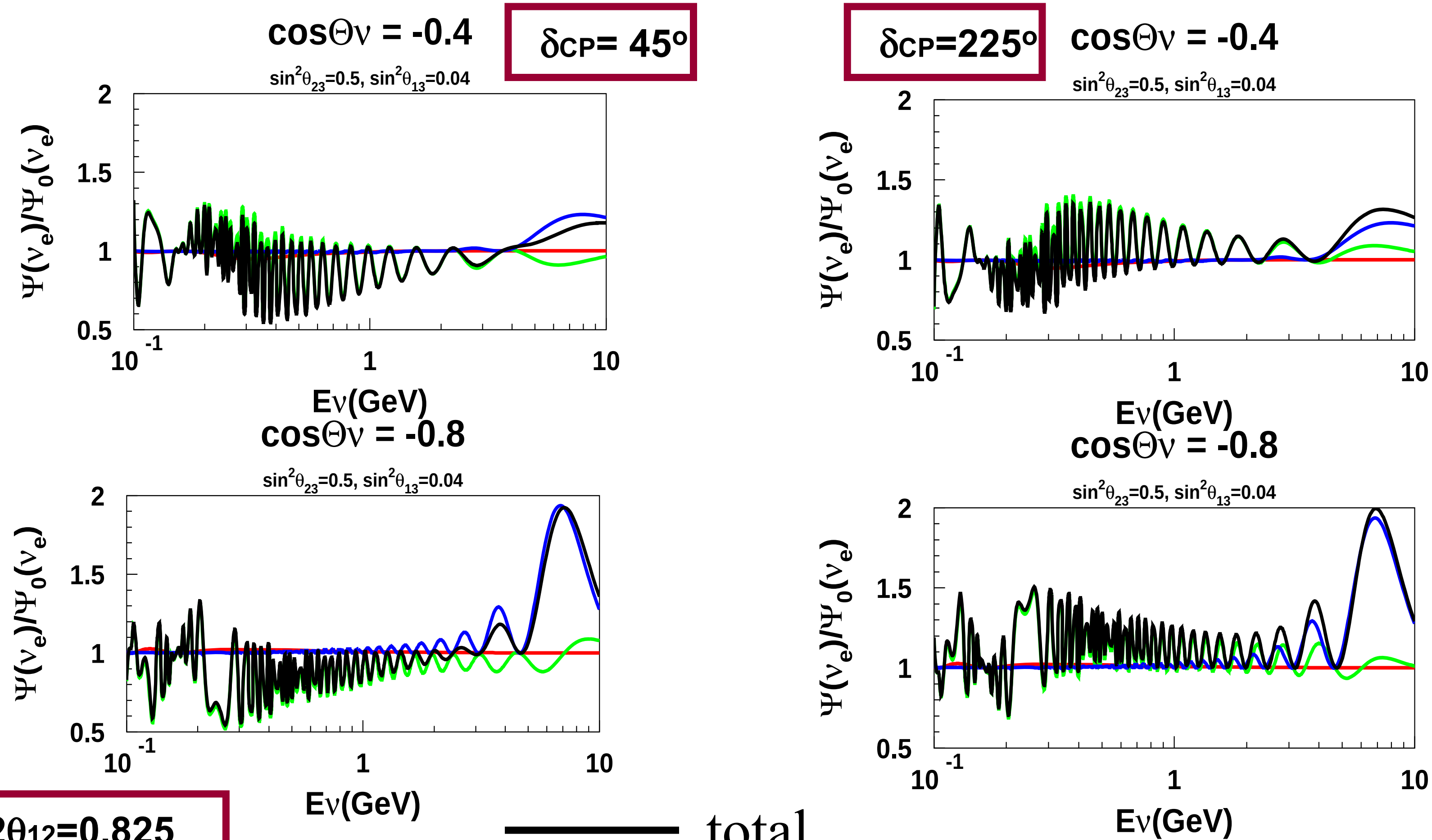
$\propto \sin^2 \vartheta^m_{13} (r \cdot \sin^2 \vartheta_{23} - 1)$

From: Talk by M. Shiozawa
Workshop on Sub Dominant Oscillation Effects, Kashiwa
Dec 2004

$s^2\theta_{13}$=0.0



effect of δ_{CP}



$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.5
$s^2\theta_{13}$=0.04
δcp=45° or 225°
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

total

$\text{LMA} \propto (R\cos^2\vartheta_{23} - 1)$

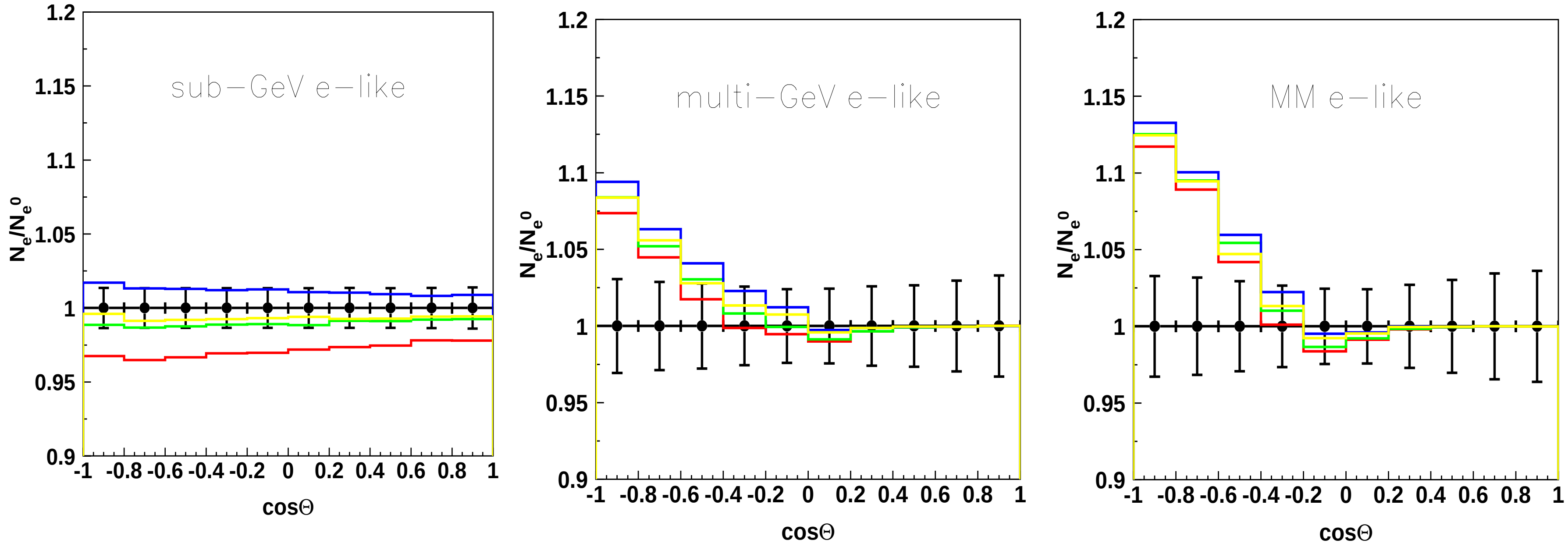
interference

ϑ_{13} resonance $\propto \sin^2\vartheta_{13}^m(R\sin^2\vartheta_{23} - 1)$

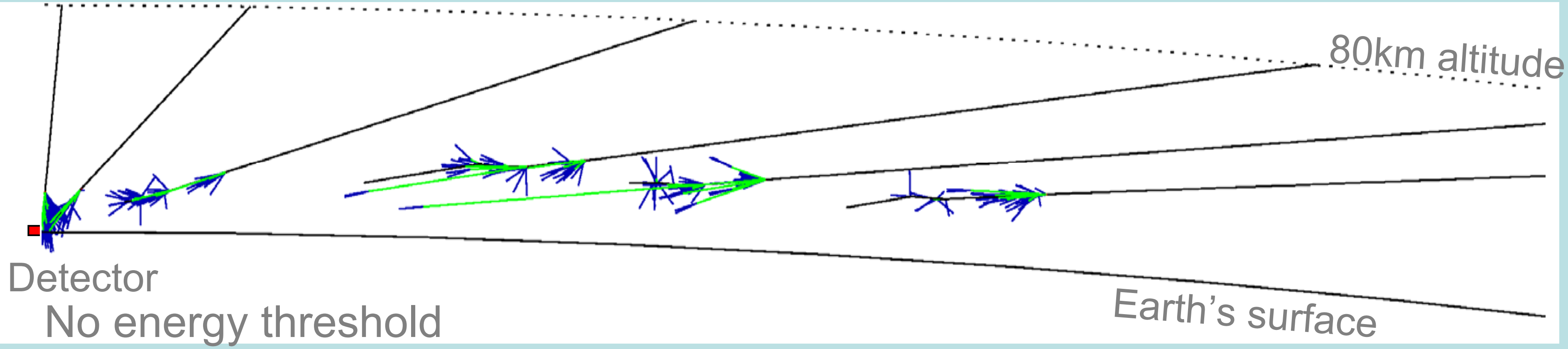
effect of δ_{CP} after ν interactions

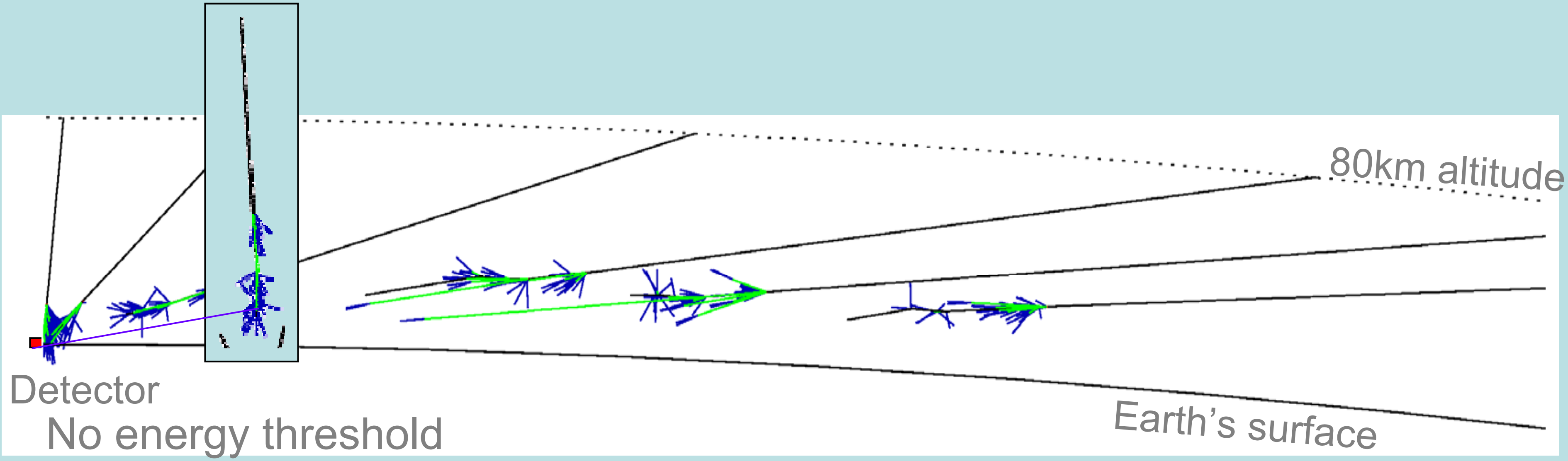
$s^2 2\theta_{12}$=0.825
$s^2\theta_{23}$=0.5
$s^2\theta_{13}$=0.04
δ_{cp}=0°~360°
Δm^2_{12}=8.3e-5
Δm^2_{23}=2.5e-3

no osc. with 80yrs stat.error
δ_{CP}= 45°
135°
225°
315°

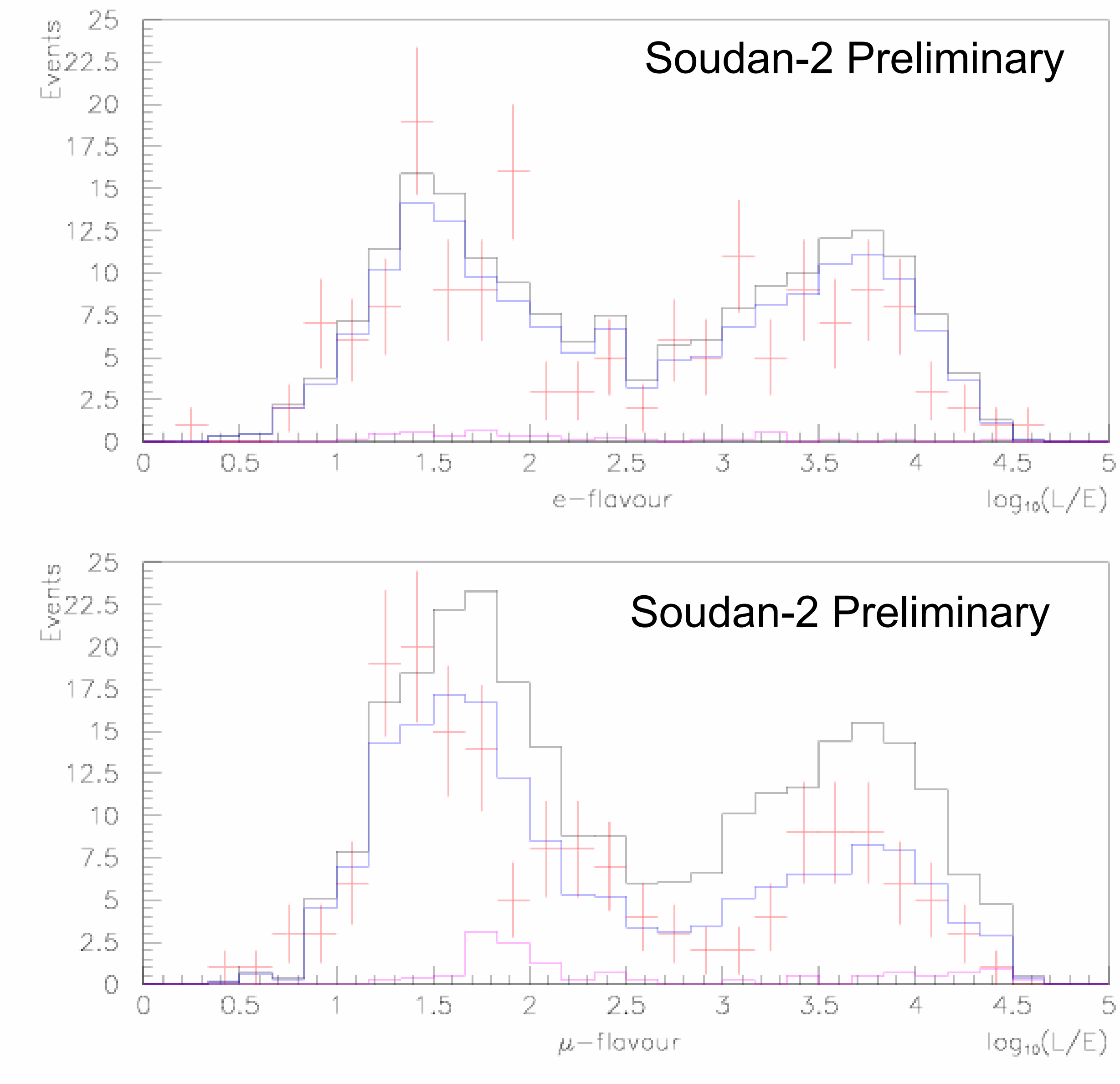


slightly enhance the effect by taking ratio of Ne/Nμ (not shown here)


80km altitude
Detector
No energy threshold
Earth's surface


80km altitude
Detector
No energy threshold
Earth's surface

Also, other detectors: Soudan/Macro



The main effect happens near horizon, just where the L changes *VERY* rapidly with energy.