ATMOSPHERIC NEUTRINO PRODUCTION

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Special thanks to G. Battistoni, A. Ferrari, P. Sala, P. Lipari,T.K. Gaisser, T. Stanev and M. Honda

Les Houches, 18-22 June 2001 - Neutrino Masses and Mixings

Outline

- Atmospheric neutrino results (SK, MACRO, Soudan2) are explained by new physics (oscillations into active or sterile ν, ν decay, FCNC, …)
- Almost model-independent quantities have been singled out:

  flavor ratio and asymmetry

  zenith angular flux shape

- Atmospheric ν study requires investigations on interaction models, primary cosmic rays and other secondary spectra, geomagnetic field and solar modulation
- Warning: not man made ν source ⇨ high precision calculations needed
- Status of current calculations, comparison between models and data, improvements for the future
- All this work aims at answering to "How precisely can we determine Δm^2 ?"

Model independent quantities

Absolute flux normalization still uncertain (20-30%) level but model independent quantities:

- Up/Down symmetry far from geomagnetic effects $E\nu \gtrsim 2$ GeV
- Flavor ratio (μ/e)
- Upgoing Through-going μ $\cos\theta$ distribution and horizontal/vertical (important for $\nu_\mu \to \nu_\tau$ / $\nu_\mu \to \nu_{sterile}$ discrimination)

p, nuclei (He, CNO, Fe, Mg, Fe…)

↓

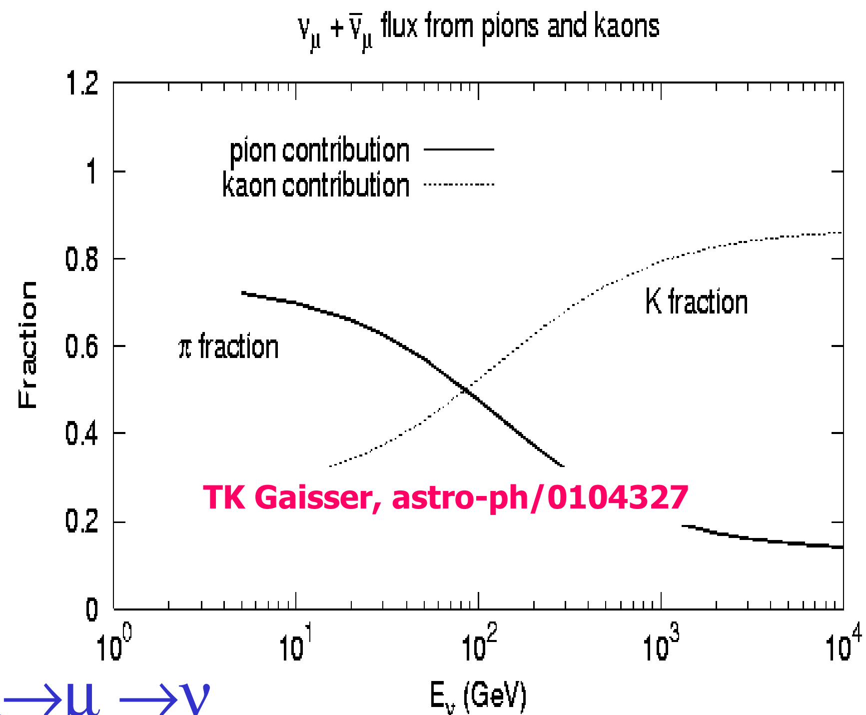
$\pi^\pm$, $K^\pm$, K_L, … → $\pi^\pm e^\pm \overset{(-)}{\nu}_e$ → **only relevant @ high energy**

↓

$\mu^\pm + \overset{(-)}{\nu}_\mu$ (for K 63.5% then $2\pi, 3\pi, \pi\mu\nu$)

→ $e^\pm \overset{(-)}{\nu}_\mu \overset{(-)}{\nu}_e$

μ decay for $E \lesssim 2$ GeV $\quad \overset{(-)}{\nu}_\mu \approx 2\, \overset{(-)}{\nu}_e$



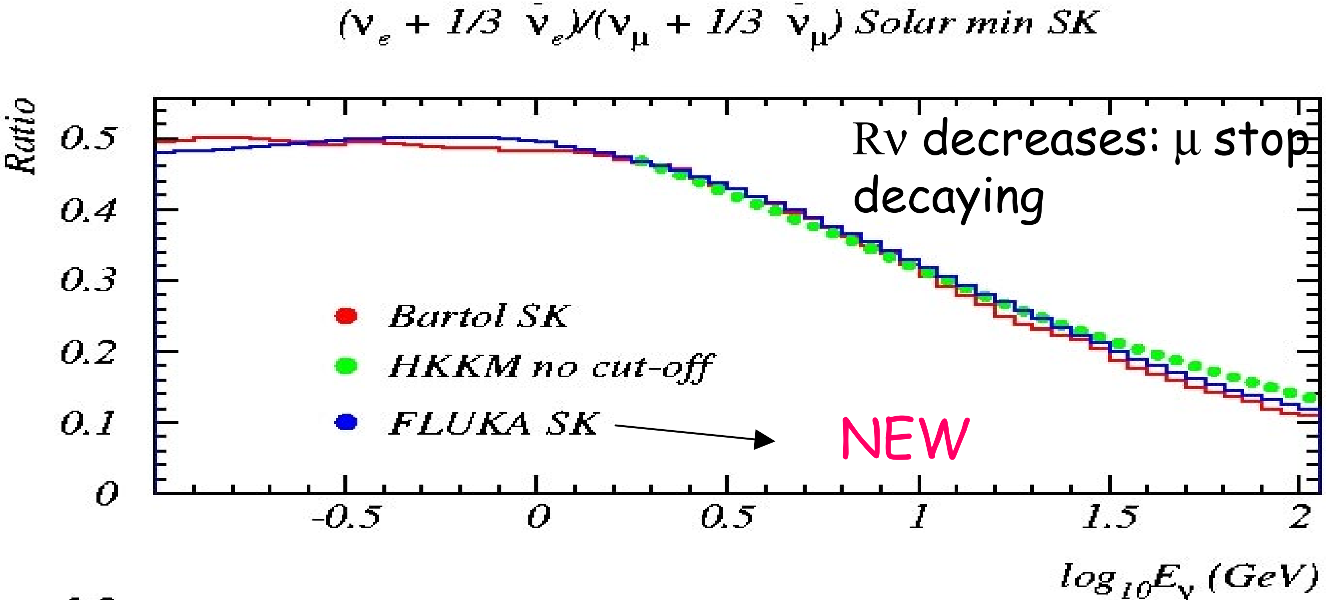
$\pi \to \mu \to \nu$

$$\left\langle \frac{E_\nu}{E_\pi} \right\rangle \approx 0.213\ \nu_\mu, 0.265\ \overline{\nu_\mu}\ 0.257\ \nu_e$$

$K \to \mu \to \nu$

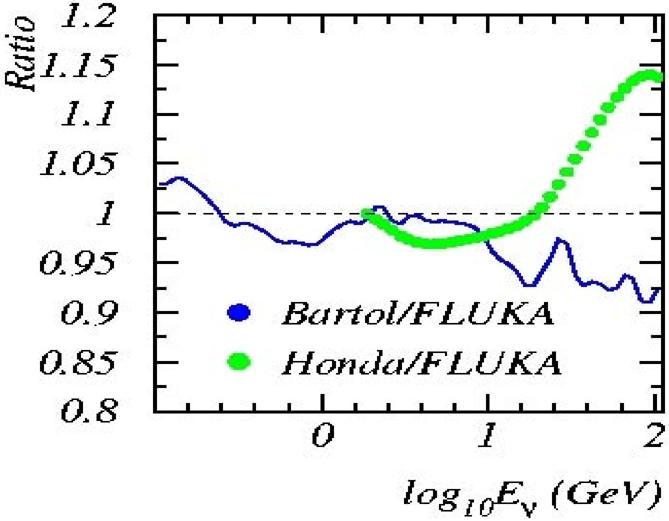
$$\left\langle \frac{E_\nu}{E_K} \right\rangle \approx 0.477\ \nu_\mu, 0.159\ \overline{\nu_\mu}\ 0.205\ \nu_e$$

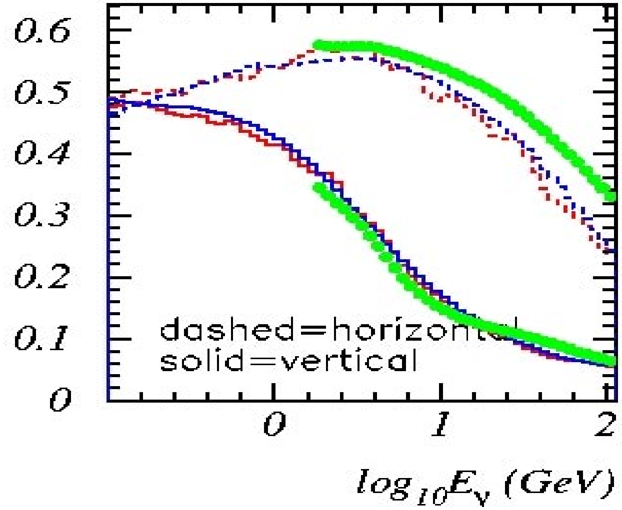
Flavor ratio comparison: νe+1/3anti-νe/νμ+1/3anti-νμ



For Eν<30 GeV agreement~5%

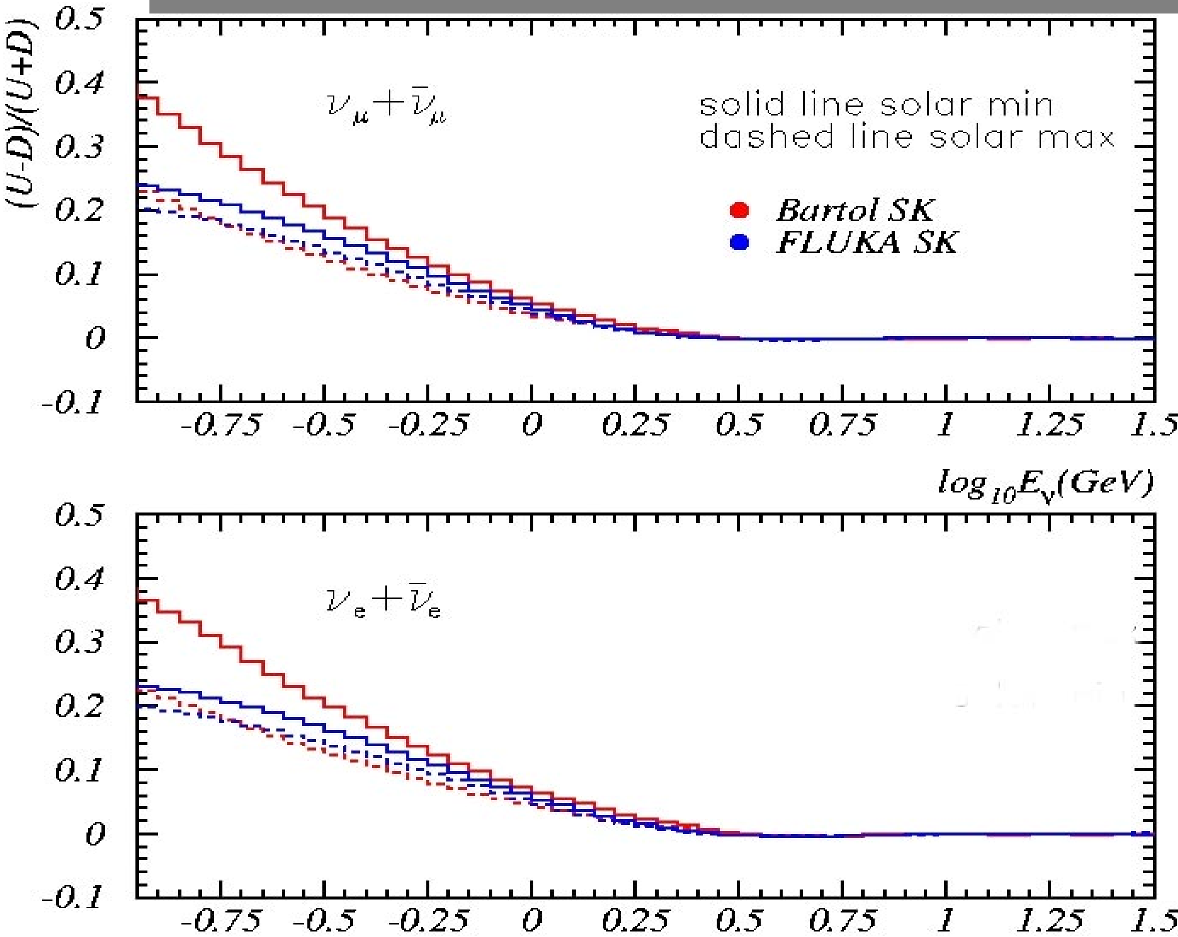
At larger energies larger uncertainties in K physics (must be understood)

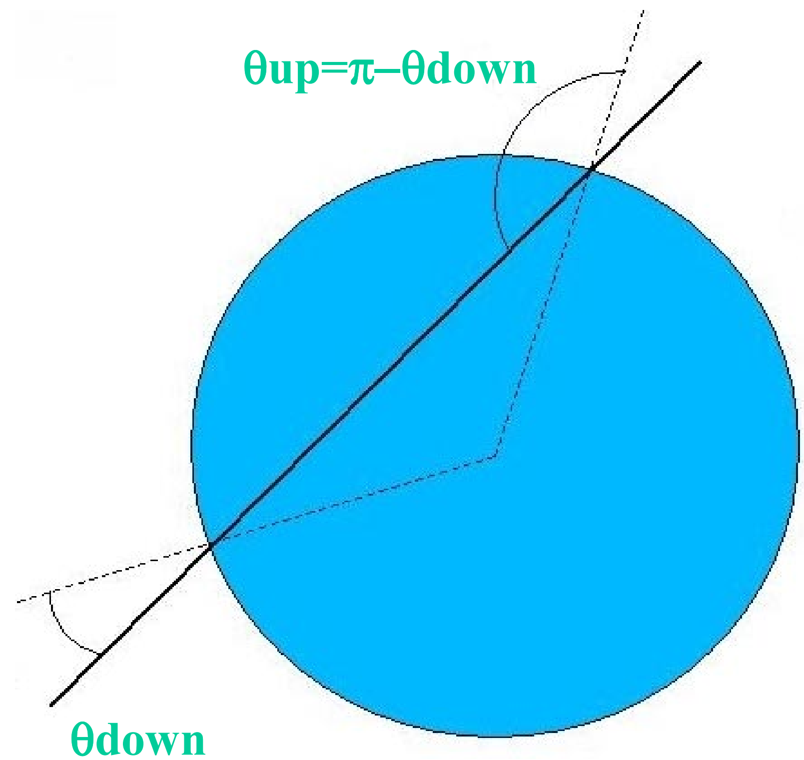




Rν = e/μ decreases more at vertical due to longer path at horizon available for μ decay

Up/Down Asymmetry





Earth spherical symmetry
+CR flux isotropy ⇨
$\Phi(E\nu,\theta) = \Phi(E\nu,\pi-\theta)$

At $E\nu \gtrsim 2$ GeV solar modulation
+geomagnetic effects negligible ⇨
asymmetry is model independent

Shape of the angular distribution

HE events have larger uncertainties due to:

- external upgoing μs ⇨ no electron flavor, lower hemisphere
- flux normalization larger uncertainty than at lower Eν due to primary flux measurements and role of K decay more relevant
- Horizontal/vertical important to discriminate active/sterile oscillations

Uncertainties:

1) δ(V/H)/(V/H)~0.12 δ(K/π)/(K/π)

$L_{dec} \sim$ 0.75 (E(GeV)/100) km (K)

$L_{dec} \sim$ 5.6 (E(GeV)/100) km (π)

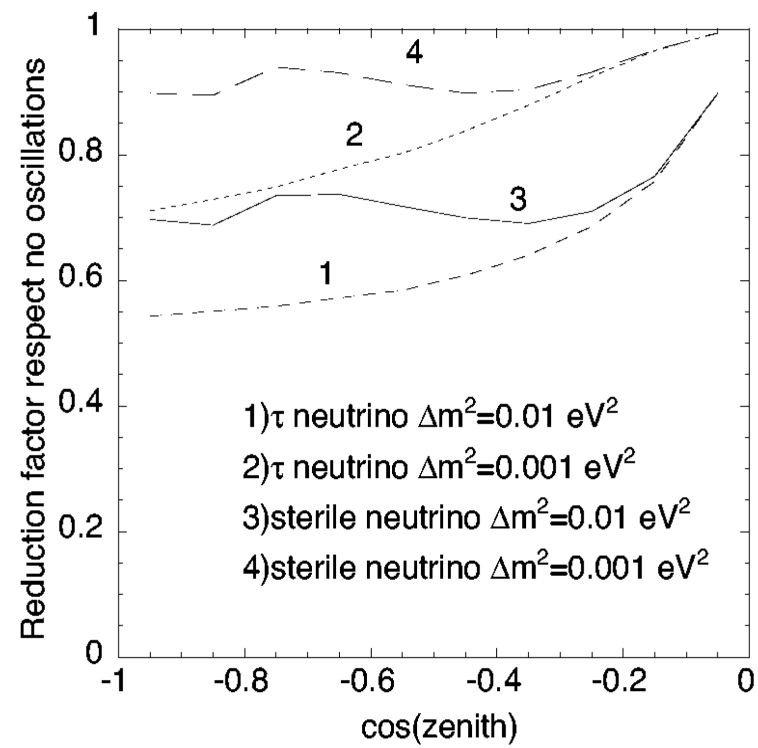
almost all K decay at ~100 GeV ⇨ almost isotropic ν contribution with θ

competition of interaction/decay for $\pi^{\pm}$: decay more easily at horizon for increasing energy ⇨ horizontal > vertical flux

2) δ(V/H)/(V/H)~0.25 δα

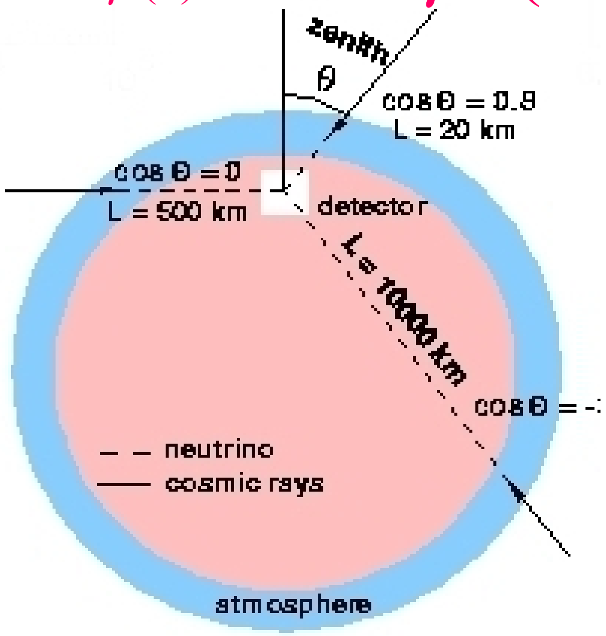
uncertainty in the slope

In quadrature: ~3% error on V/H



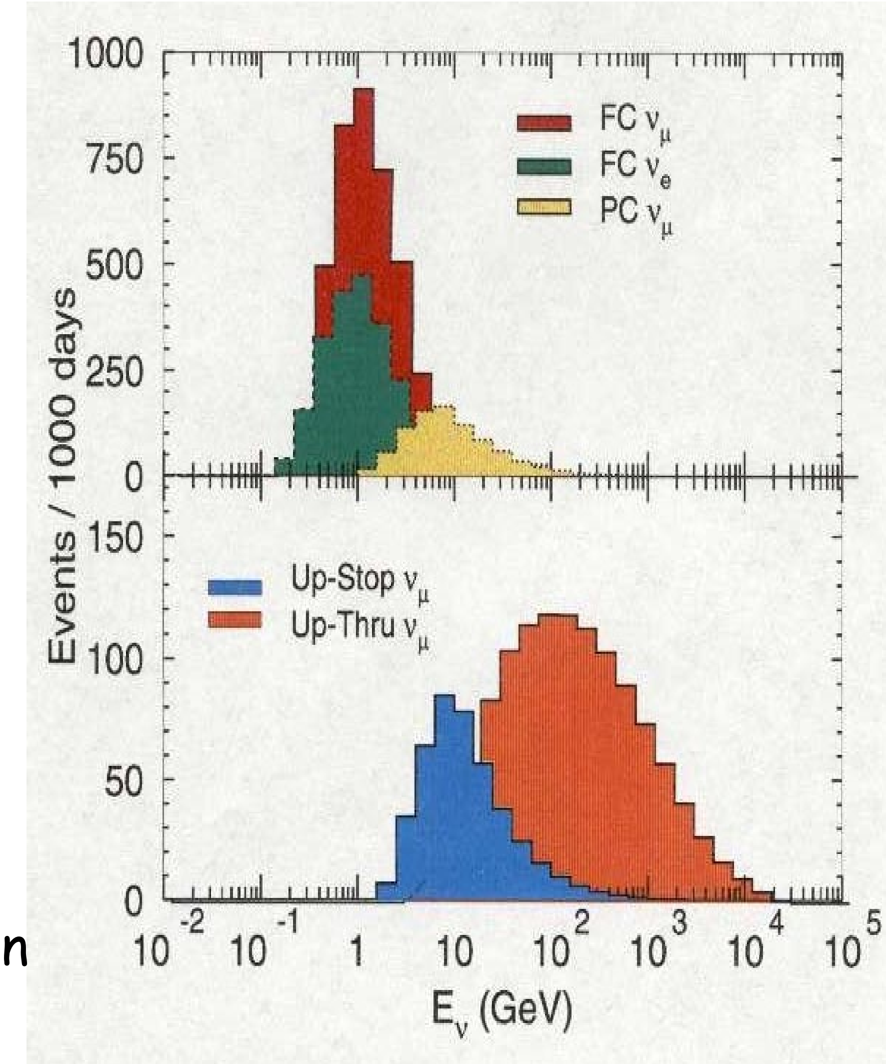
Atmospheric ν events

$$\overset{(-)}{\nu}_{\mu(e)} + N \rightarrow \mu^{\pm}(e^{\pm}) + X$$



Volume events: ν CC int. vertex inside detectors

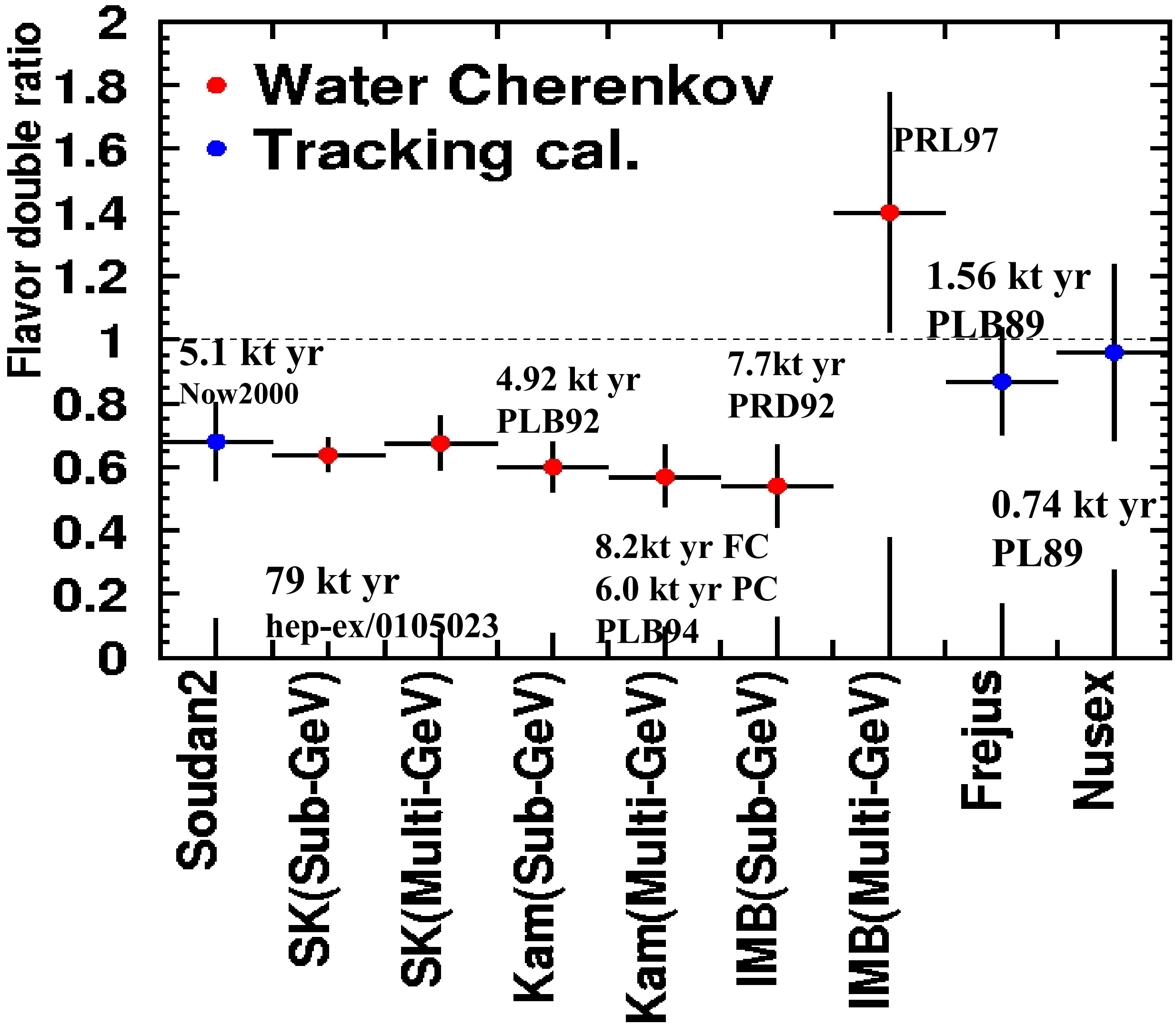
Super-Kamiokande response curves



Surface events: through-going/stopping μs from external interactions

upward versus to discriminate atm μ background; detection region increased by muon range

Do atmospheric νs need a new physics?



Flavor ratio:

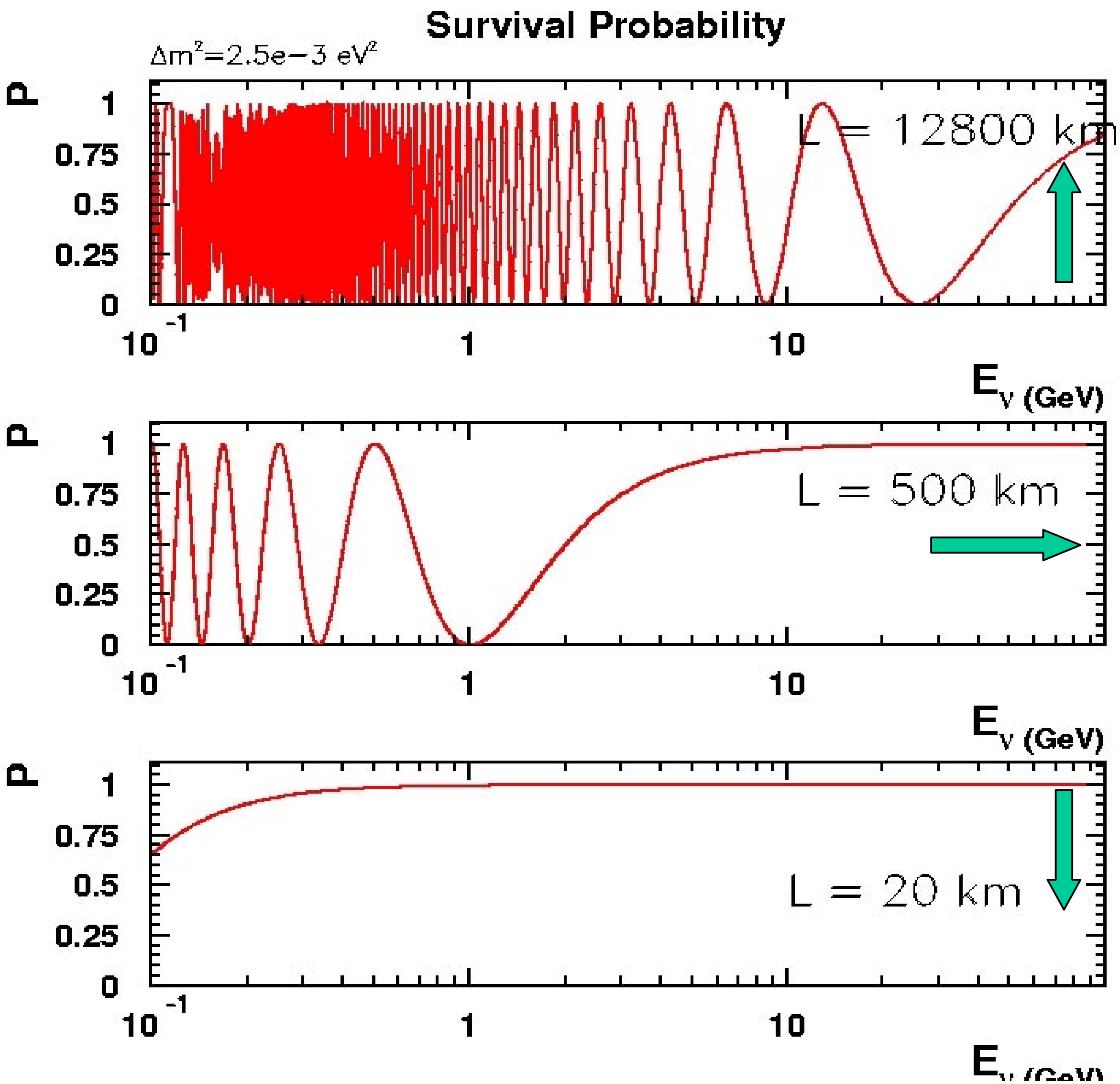
$$R = \frac{\left(\frac{\mu - like}{e - like}\right)_{DATA}}{\left(\frac{\mu - like}{e - like}\right)_{MC}}$$

μ-like (tracks): deficit

e-like (showers): in agreement with expected

Kamiokande Multi-GeV: flavor ratio angular dependence as expected from oscillations

Oscillations in atmospheric νs



100 MeV ≲ Eν ≲ 10 TeV

10 km ≲ L ≲ 10^4 km

Wide range to investigate oscillations!

For Sub-GeV and Multi-GeV

$$P(\nu_\ell \to \nu_\ell) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

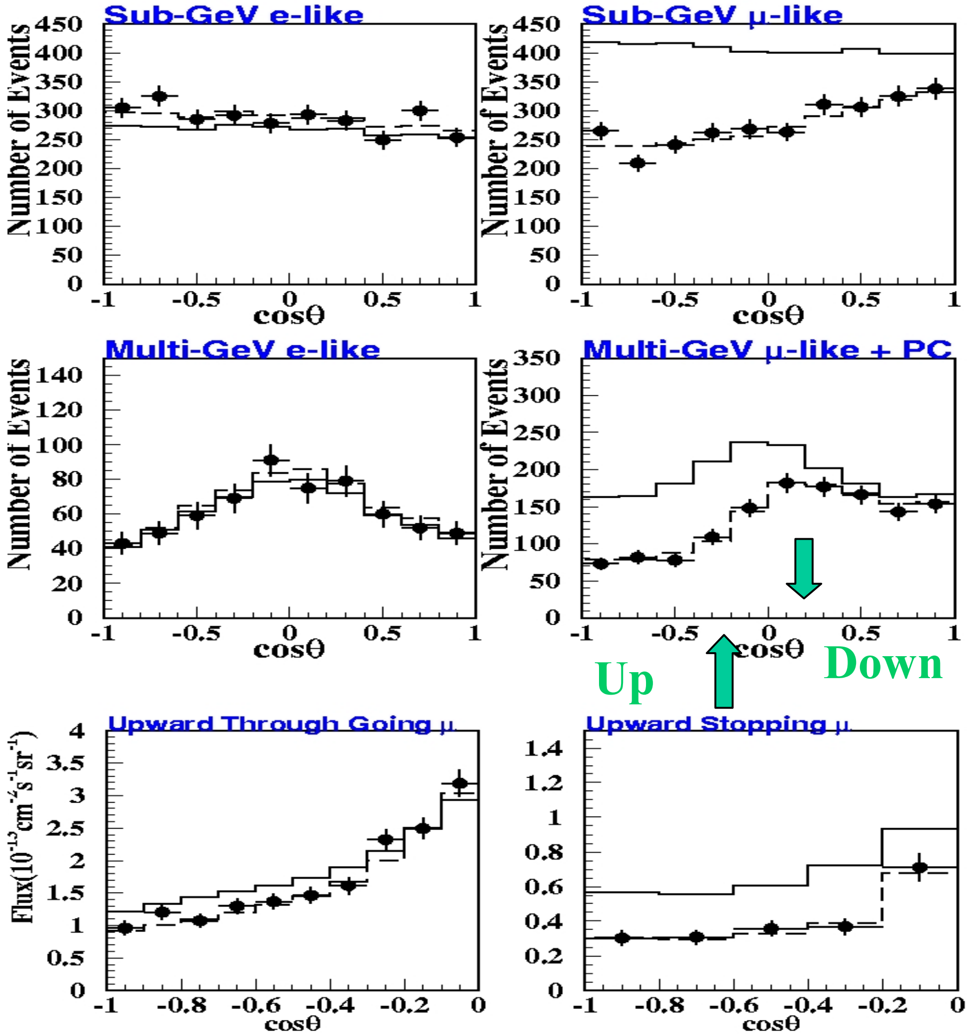
$$\langle P(L \leq 100\ km)\rangle \to 1$$

$$\langle P(L \geq 2000\ km)\rangle \to 1 - \frac{\sin^2 2\theta}{2} \Rightarrow \frac{1}{2}$$

Horizontal events in transition region L ~500 km are important to determine Δm^2

Super-Kamiokande evidences

Super-Kamiokande data (Y. Totsuka talk) explained by $\nu\mu \rightarrow \nu\tau$ oscillations



$\nu\mu \rightarrow \nu$sterile disfavoured 99%cl

Muon deficit is energy dependent

Best fit: $\Delta m^2 = 0.0025$ eV^2

$\sin^2 2\theta = 1$, χ^2/dof = 142/152

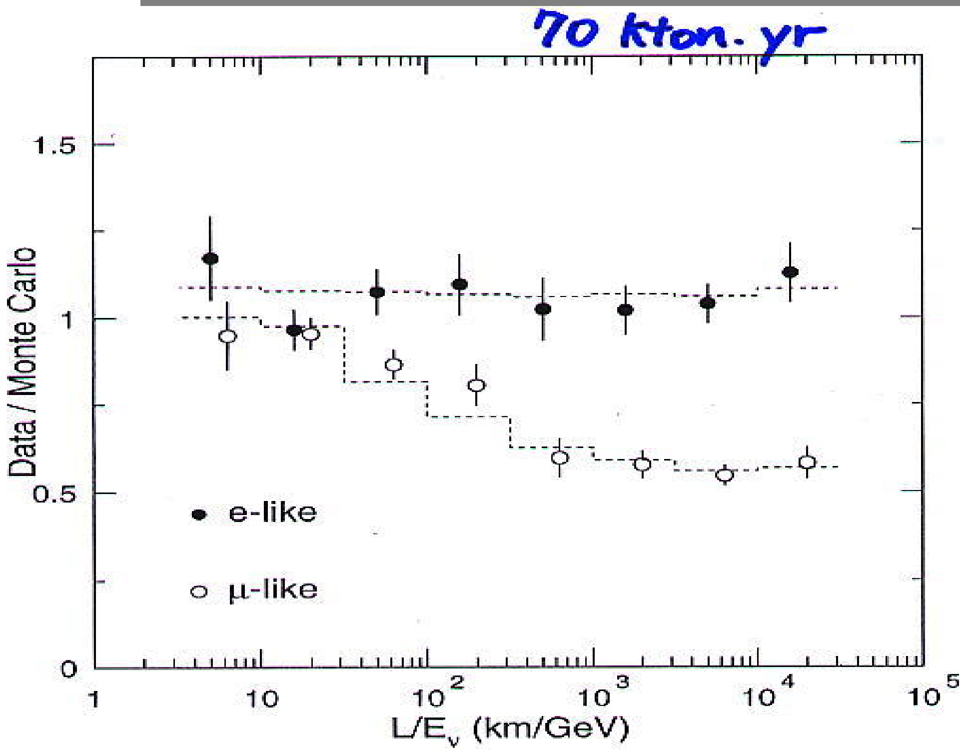
Smoking gun:

asymmetry UP/Down μ-like (70kt yr)

$0.54 \pm 0.04 \pm 0.01$ (9σ)

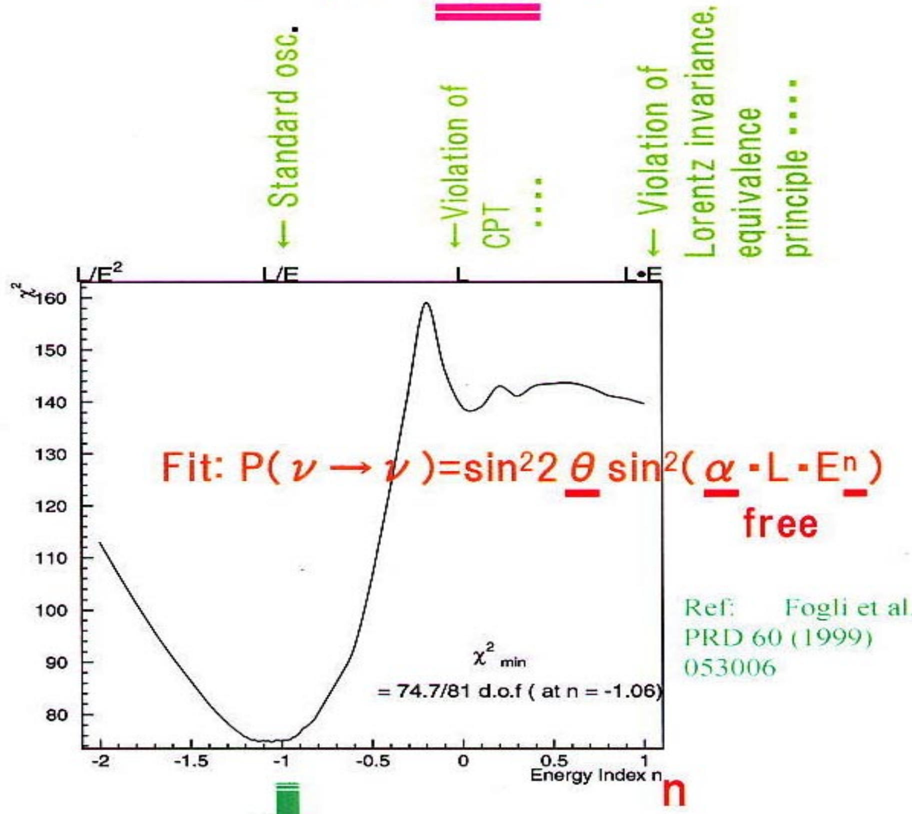
79 kt yr
(1289 d)

Super-Kamiokande: L/E dependence



Warning: oscillation pattern in L/E remains unobserved!

Oscillations are proportional to $\sin^2(\alpha \cdot L/E)$?



Fit: $P(\nu \to \nu) = \sin^2 2\theta \sin^2(\alpha \cdot L \cdot E^n)$

free

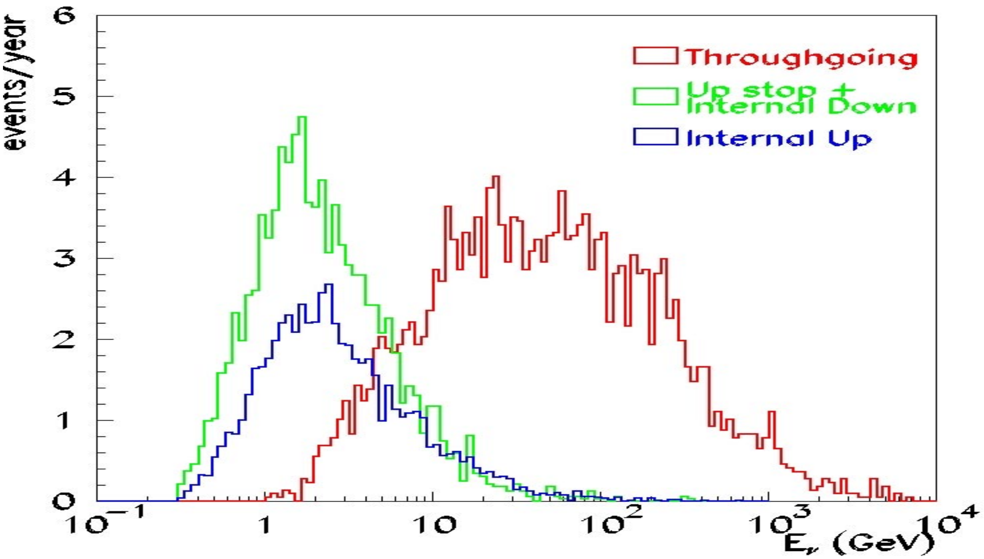
Ref: Fogli et al., PRD 60 (1999) 053006

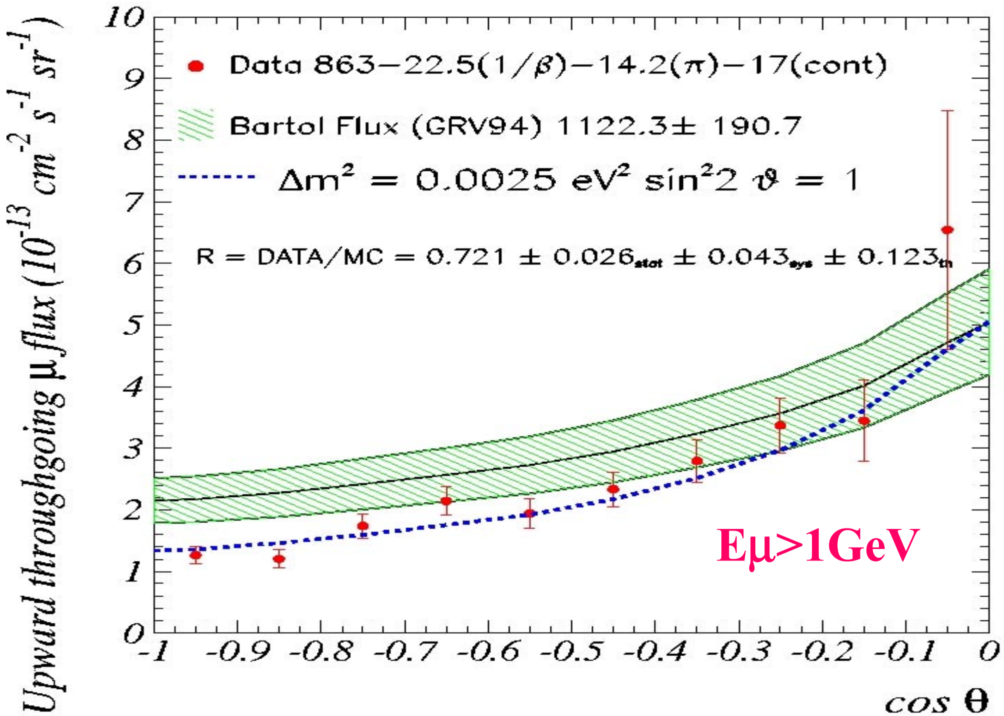
$n = -1.06 \pm 0.14$

Standard oscillation is OK.

T.Kajita Now2000

MACRO: different technique





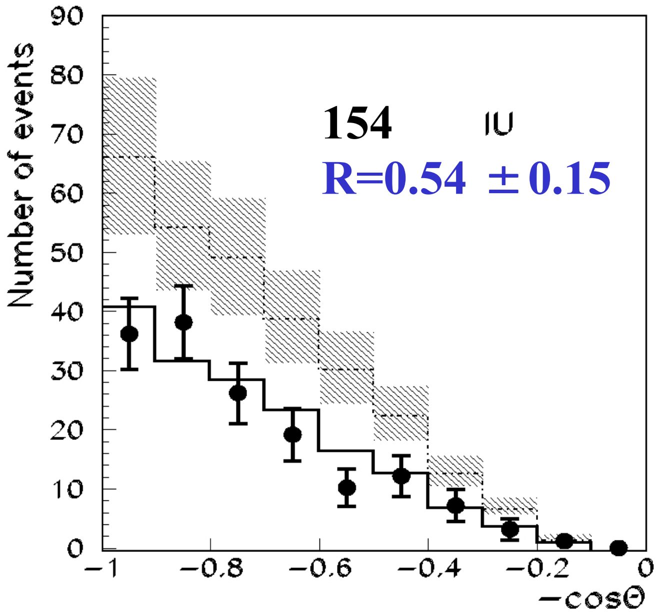
Different topologies:

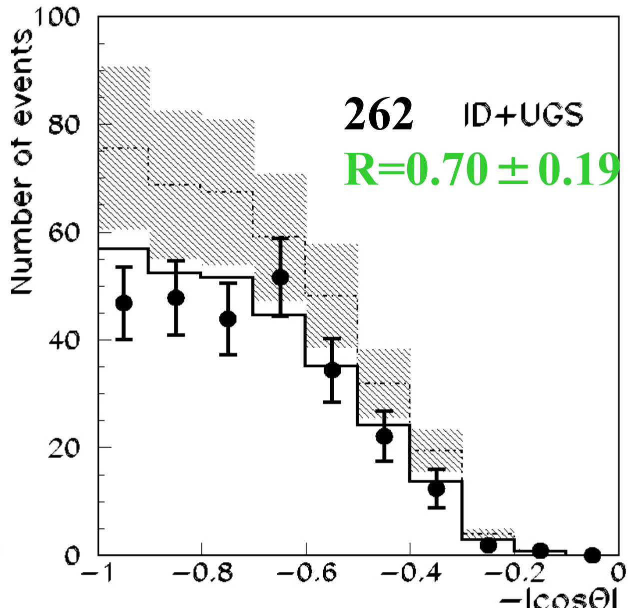
- Through-going (<Eν> ~50 GeV, 180/yr)
- Internal Up (<Eν> ~ 4 GeV, 50/yr)
- μ Stop+Internal Down (<Eν> ~ 4 GeV, 35+35/yr)

} contamination from NC + CC νe ~ 10%

Vertical/horizontal through-going μs exclude $\nu_\mu \rightarrow \nu_{sterile}$ @ 99% c.l.

MACRO favors $\nu_\mu \rightarrow \nu_\tau$

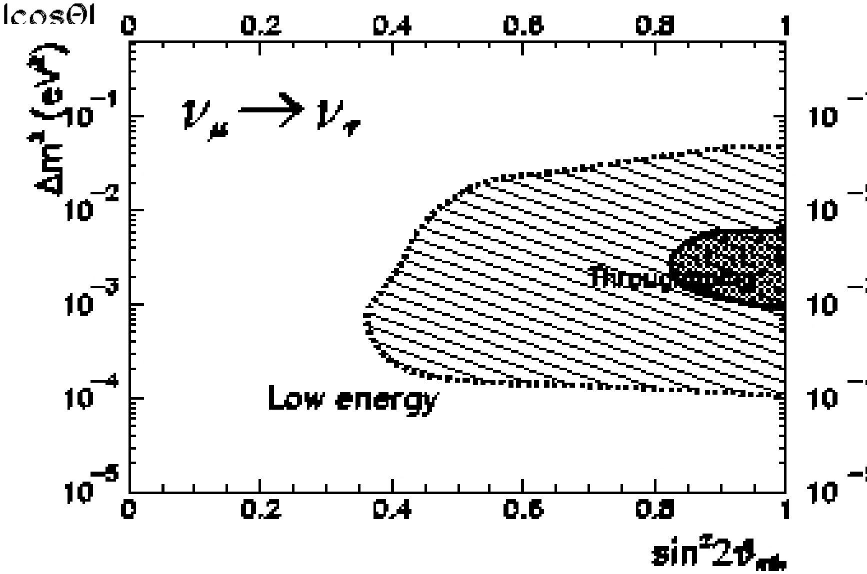




(ID+UGS/IU)meas=
0.59 ±0.06stat
(ID+UGS/IU)no osc=
0.76 ±0.06 sys+theor
(sys = 5% theor = 5%)
Probability of obtaining a ratio so far from expected 2.2%

Low energy events: max probability 87% (max mixing)

Through-going upμ: max probability of 66% at $\Delta m^2 = 0.0024\ eV^2$ and $\sin^2 2\theta = 1$ for $\nu_\mu \rightarrow \nu_\tau$



Montecarlo and analytical calculations

Montecarlo (all details can be included):

- HKKM: M. Honda, T. Kajita, K. Kasahara & Midorikawa, Phys. Rev D52 (1995)
- Bartol: **G. Barr**, T.K. Gaisser and T. Stanev, Phys. Rev. D39 (1989) and ICRC95, V. Agrawal, T.K. Gaisser, P. Lipari, T. Stanev, Phys. Rev. D53 (1996)

"Standard references" used in Super-Kamiokande, MACRO, Soudan2,...

New calculations (under development):

3D:

- G. Battistoni, A. Ferrari, P. Lipari, T. Montaruli, P.R. Sala & T. Rancati, Astrop. Phys. 12 (2000) [Updated results in http://www.mi.infn.it/~battist/neutrino.html]
- Y. Tserkovnyak, R. Komar, C. Nally, C. Waltham, hep-ph/9907450
- P. Lipari, Astropart.Phys.14:153-170,2000
- M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, hep-ph/0103328
- V. Plyaskin, hep-ph/0103286

1D:

- G. Fiorentini, V. A. Naumov, F. L. Villante, hep-ph/0103322

NOT ALL MENTIONED HERE!

Analytical (fast and for tests to understand processes)

T.K. Gaisser, astro-ph/0104327, P. Lipari, Astropart. Phys.1 (1993)

Some comments

"Standard references" very close to final result: improvements/checks are going to be presented

New calculations can be validated through comparison to existing data; results from a set of calculations which are converging (HKKM, Bartol, Fluka,...) should be taken into account

Improvements are motivated by understanding that agreement (~10%) between HKKM and Bartol comes from compensation of errors

1. Bartol uses a primary flux closer to LEAP and recent measurements but seems to produce higher multiplicities of pions, kaons and different momentum distributions than FLUKA
2. HKKM uses a primary flux closer to Webber et al., higher than more recent measurements

Calculations are checked comparing each "ingredient" by changing them inside calculations under comparisons

<u>Fundamental benchmark: muons</u>

Calculation inputs

1. Primary spectra (fits to recent measurements, isotropy, superposition model, solar modulation)

2. Hadronic interactions (multiplicities, energy distributions, cross-sections)

3. Shower modeling (particle trasport, energy losses, decays including polarization)

3. Geometry: 3D/1D

4. Geomagnetic effects: E-W asymmetry, under cut-off fluxes, bending of shower particles

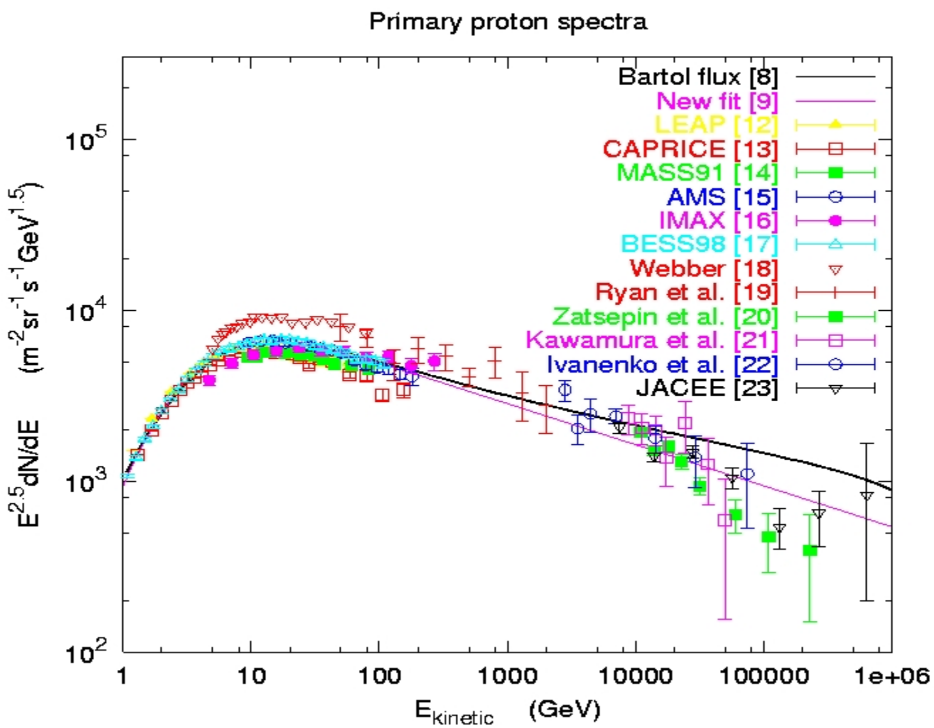
5. Atmosphere profiles and seasonal effects

6. Neutrino interaction cross sections: from neutrinos to leptons

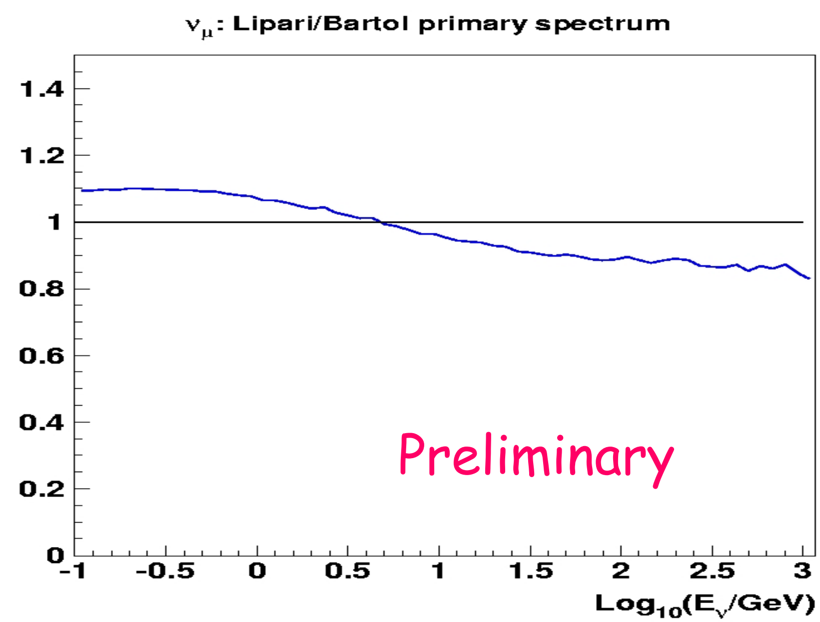
7. Minor effects: detector altitude, mountain profiles

Primary spectrum

Before 1990 primary spectrum ⩽ 100 GeV ambiguous due to 50% discrepancy between Webber et al. (1987) and LEAP (1991)
Recent data (CAPRICE, AMS, BESS) agree with lower LEAP normalization
Determination with systematic uncertainty ~±5% (agreement AMS-BESS98)
For E ⩽ 1 TeV uncertainty ~10% (important for upward muons)
At E ≳ 1 TeV uncertainty ≳ 25% but small contribution to observed fluxes

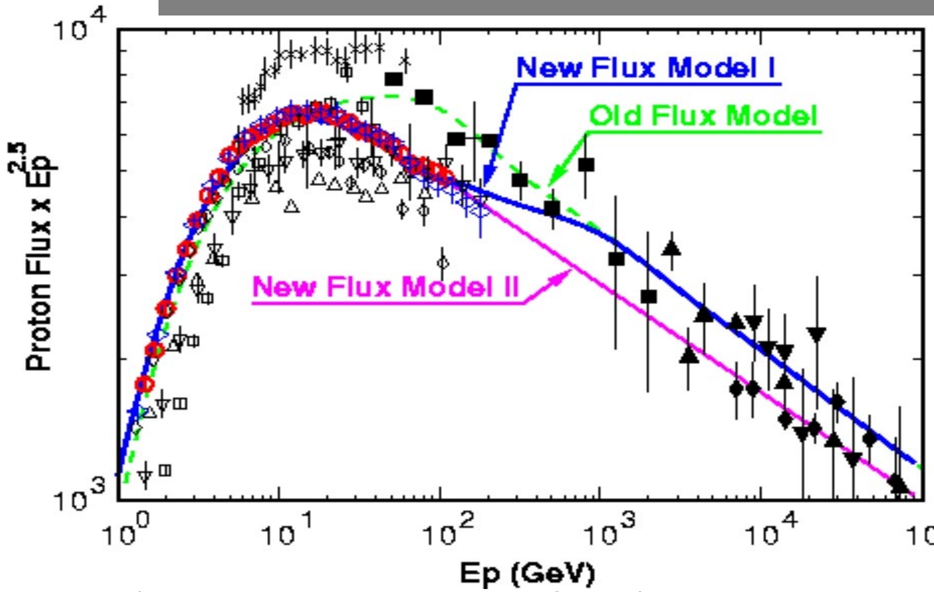


A new fit will be presented at ICRC by Bartol Group:



Larger effect in the upward μ region

Primary spectrum



HKKM are studying 2 new models differing at HE energy

Neutrino flux difference < 2-3% @1 GeV ~10% @ 10 GeV

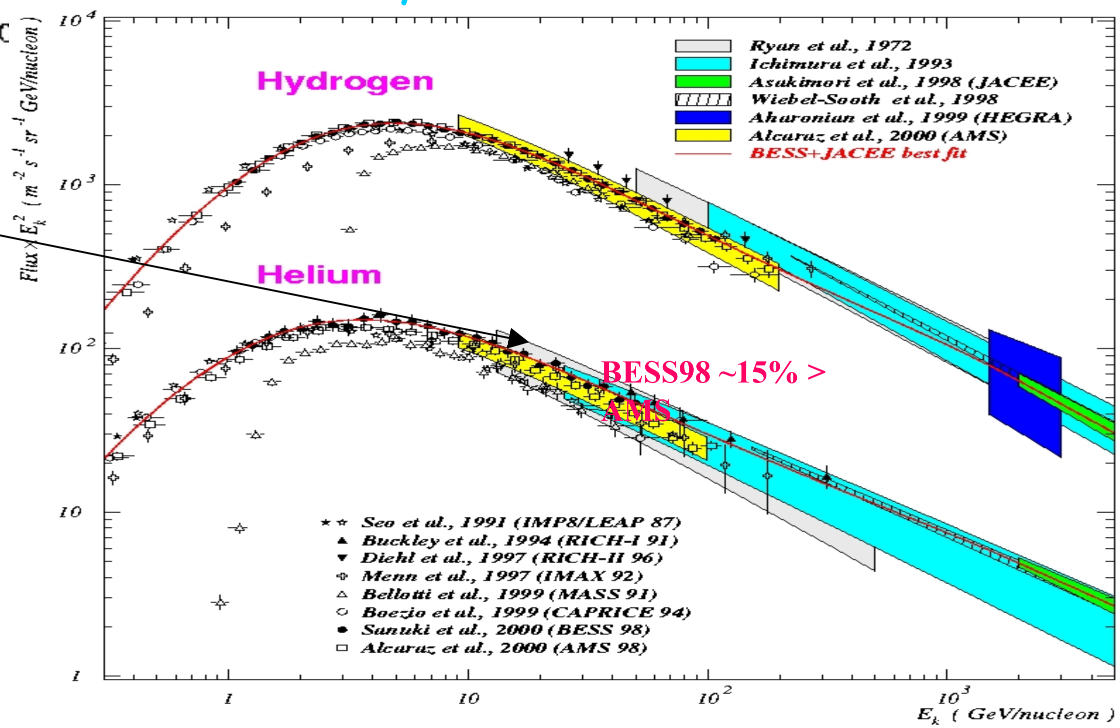
Old-New Model I: lower flux by 8-12 % @ 1 GeV, ~20% @ 8 GeV

Higher uncertainty for heavier components (~20% of total flux);

He flux still some disagreement

Future: Bess, Pamela (~200 GeV/n from H-C)

Other fit by Fiorentini et al.



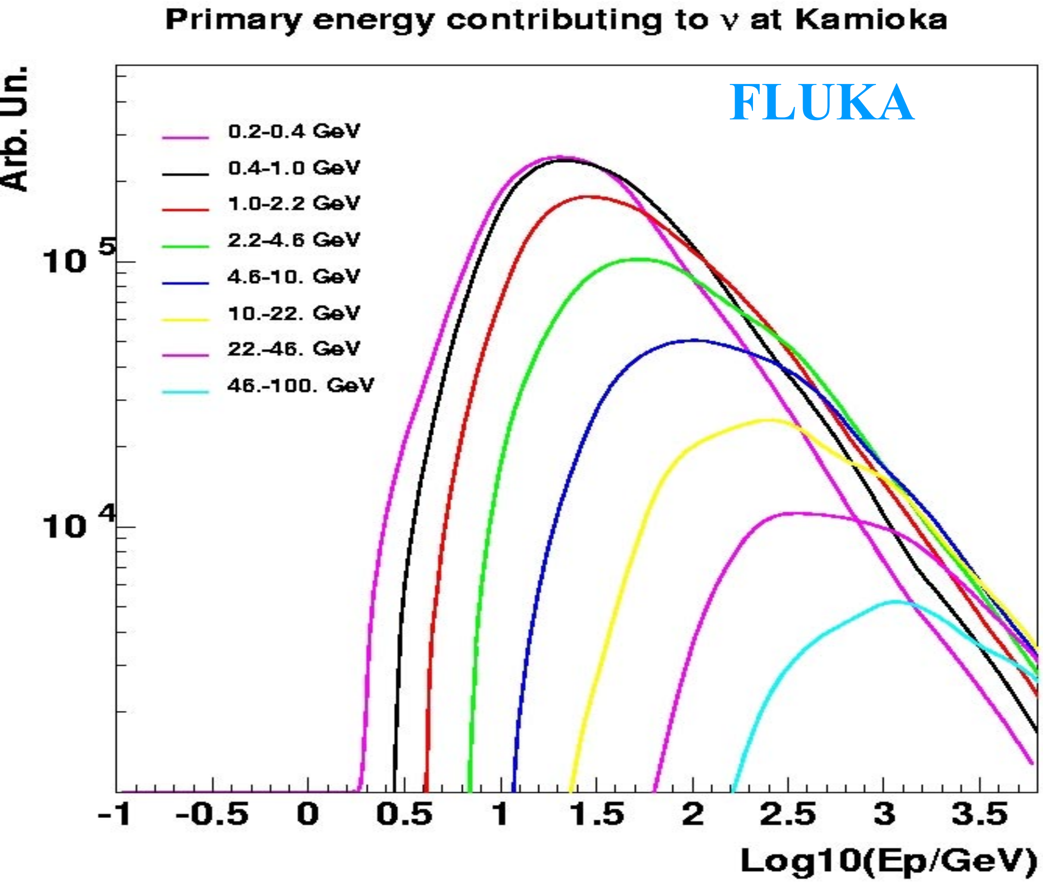
Important: converge towards a certified reference spectrum common to all calculations + algorithm for solar modulation

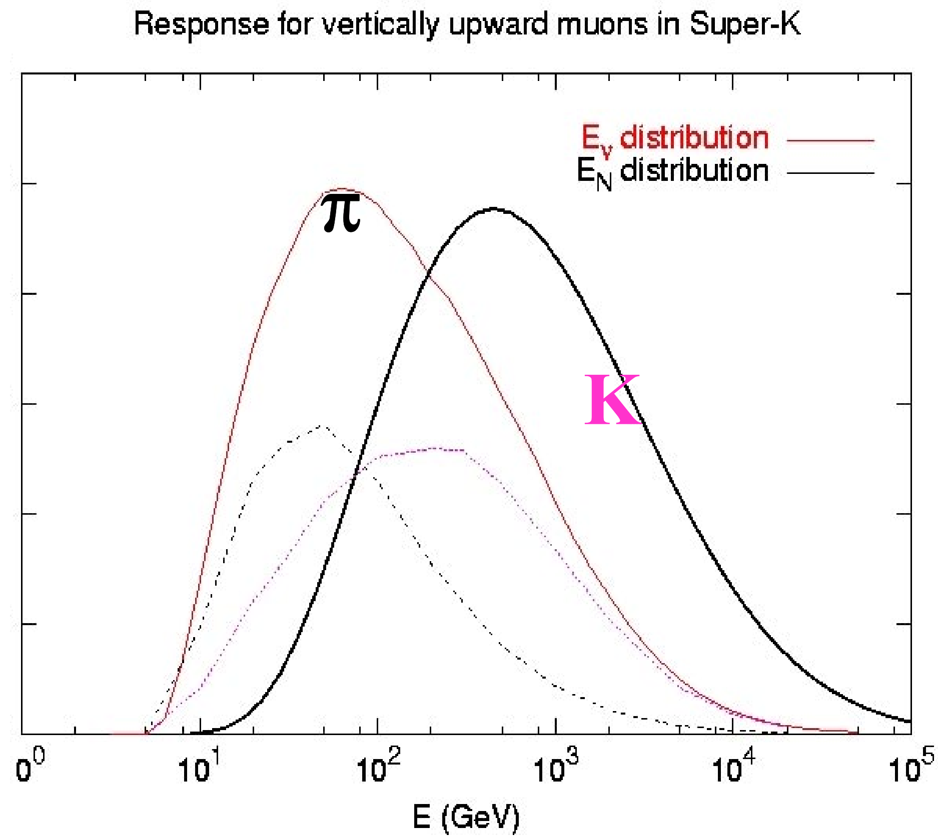
Primary and neutrino energies

Estimated uncertainties have implications on atmospheric νs:

Sub-GeV $E_N \lesssim$1-200 GeV, Multi-GeV E_N ~10-1000 GeV, μ stop E_N ~20-2000 GeV

Up-through μ E_N ~100-50000 GeV





Analytical: TKGaisser, astro-ph/ 0104327

Solar Modulation

Time dependence for Eν≤10 GeV more relevant @ low cut-off sites (Soudan)
Solar wind plasma+e.m. fields ⇨ heliosphere semi-transparent to opaque medium for low energy CRs correlated with 11 yr-cycle (exact periodicity in 22 yr due to IMF polarity)
Sunspot monitoring by n monitors @ Earth (1-20 GeV): measure hadronic component through secondary interactions in lead+proportional counters

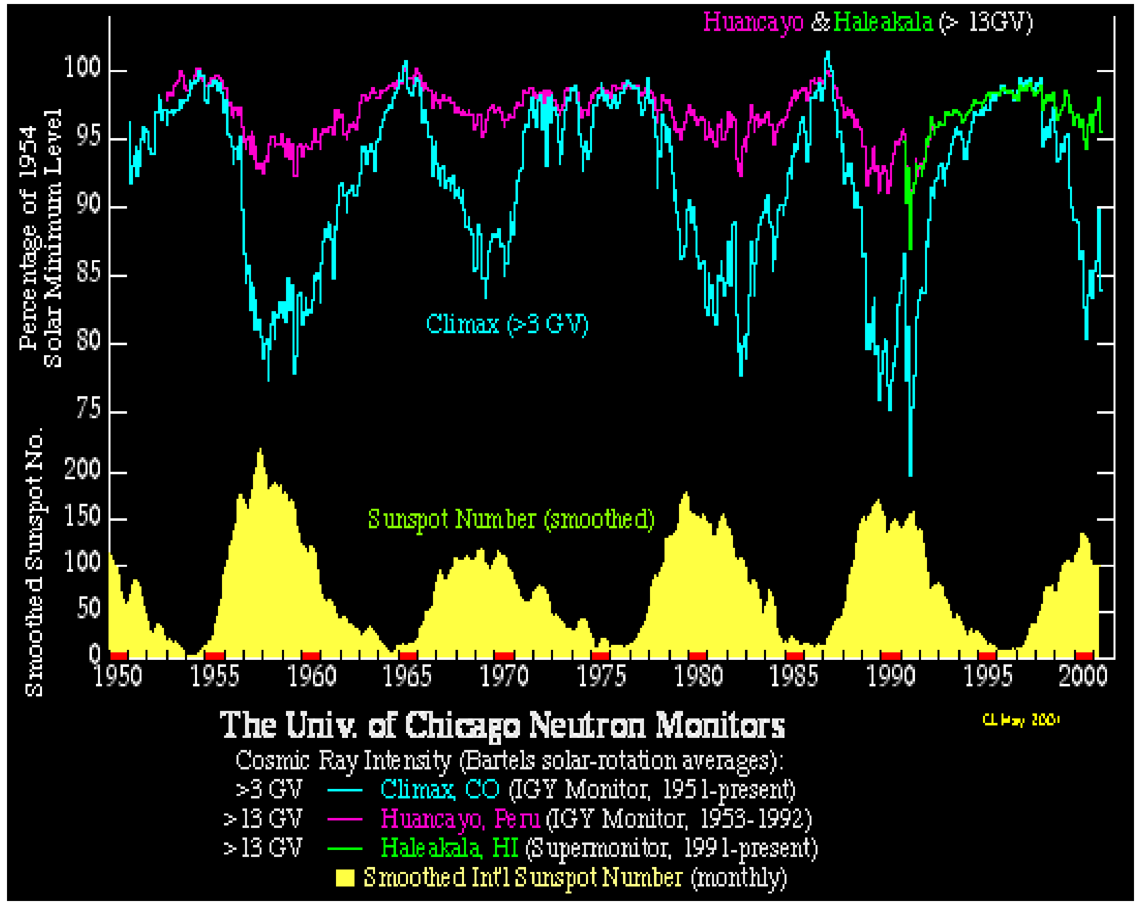
Depends on detector λ+altitude

Badhwar & O'Neill (used by FLUKA): Φ(MV) estimated from fits to Climax n counting rates+ sunspot numbers (> 4 cycles) to predict modulation at later times

Predict galactic CR intensity inside ±10% for 3 month variations

Φν solar min/Φν solar max ~5%

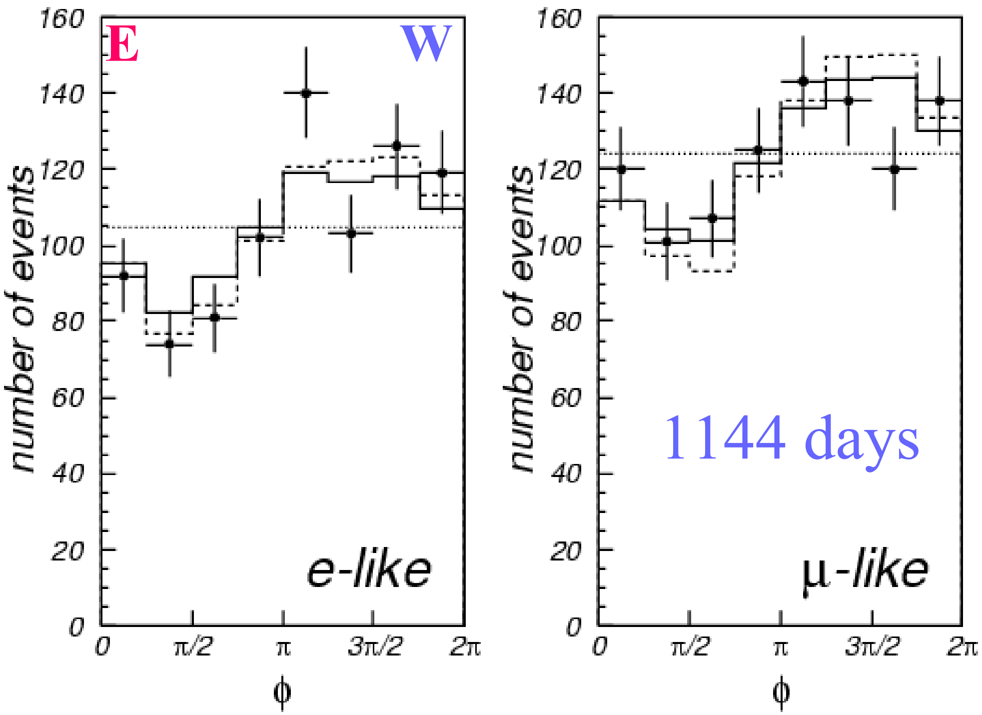
@1 GeV for SK site

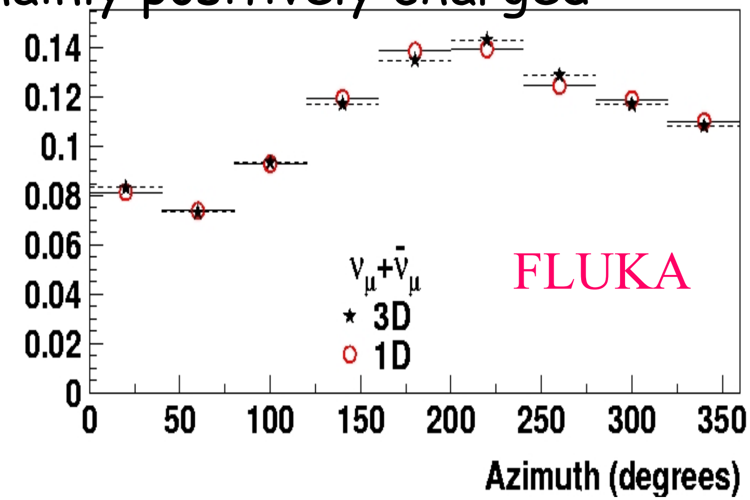


CR flux isotropy: geomagnetic effects

Geomagnetic field prevents low rigidity CRs from reaching atmosphere
Dependence on detector location (higher flux at Poles) + CR direction
Most important source of asymmetry breaking at $E\nu \lesssim 2$ GeV
Test: Super-Kamiokande East-West asymmetry in azimuth

Secondary flux > for W directions due to CR mainly positively charged

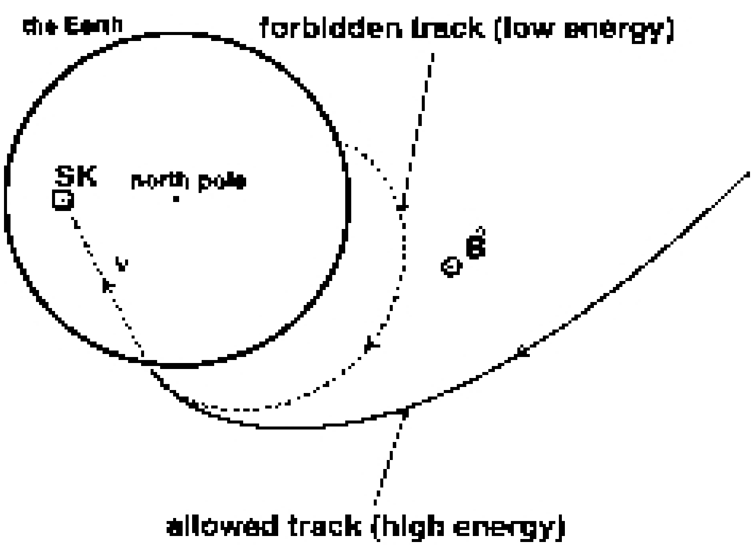




3D/1D small effect, but here no field in shower development: μ bending can improve agreement (measured Ae=(E-W)/(E+W) >Aμ)

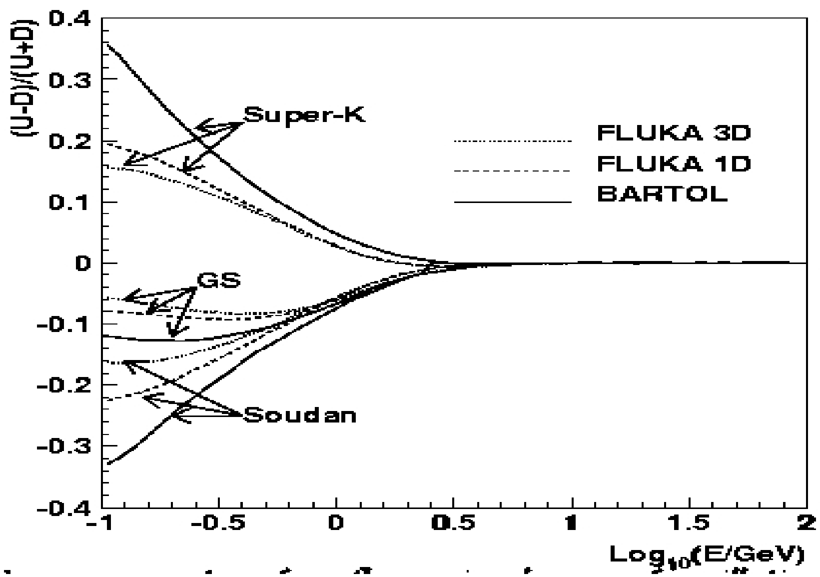
Ref.: P. Lipari: hep-ph/9905506, hep-ph/0003013, P. Lipari, T. Stanev & T.K. Gaisser, PRD58 (1998), HKKM, hep-ph/0103328, http://nssdc.gsfc.nasa.gov/space

CR flux isotropy: geomagnetic effects



Offset dipolar model not precise enough

International Geomagnetic Reference Field employs spherical harmonic expansion of scalar potential (coefficients slightly vary with time)
Dipolar models can differ ~30% from IGRF
Back-tracing technique: backward path for CR with same A and E but opposite charge
(allowed = out of geomagnetic sphere to ∞)



AMS measurement of CR fluxes at different latitudes CR isotropy at 10% level
Asymmetry breaking: Up Sub-GeV flux > Down @ SK due to high cut-off, < @ Soudan due to low cut-off

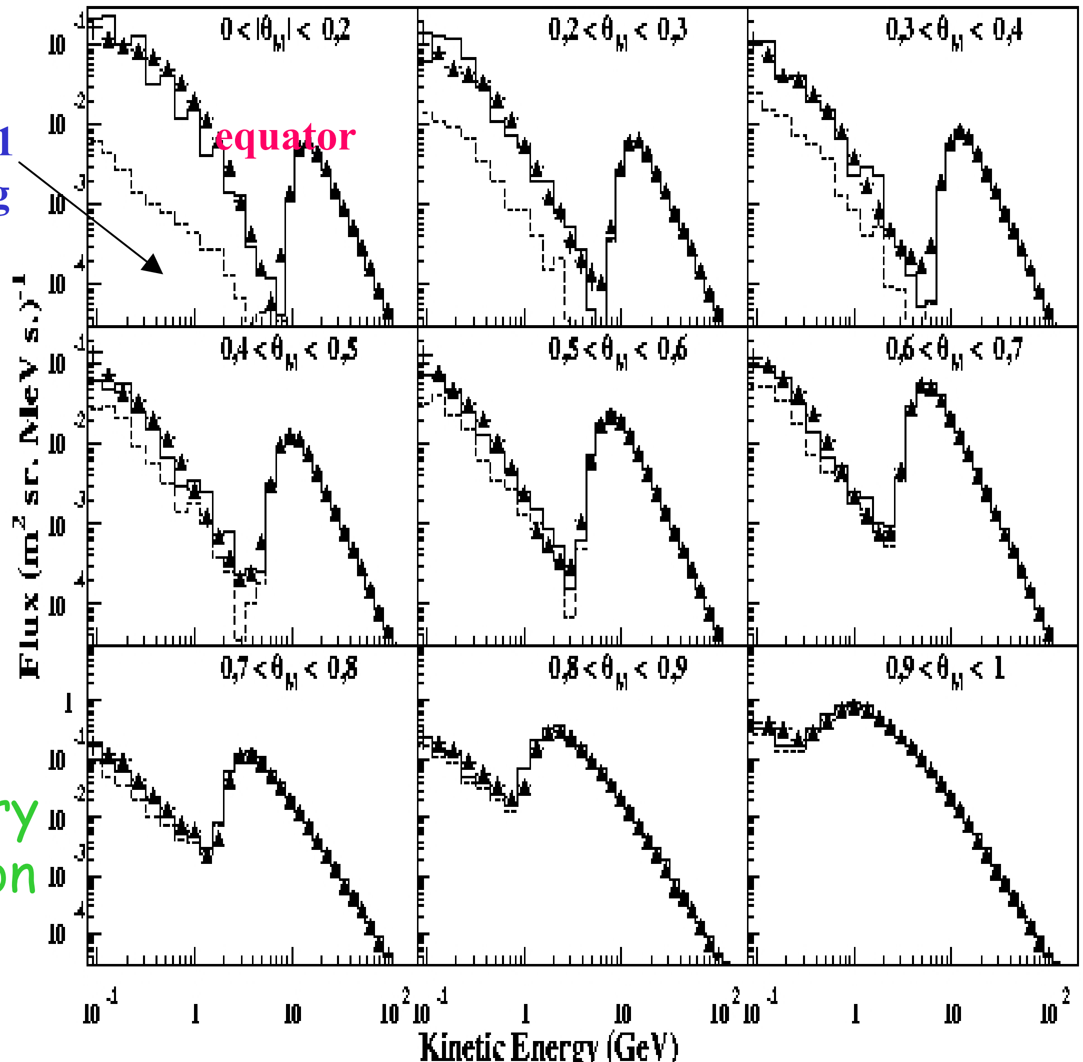
FLUKA < Bartol asymmetry due to lower ν yield

Sub-cutoff fluxes

AMS PLB472 (2000) @ ~400 km in ±51.7° latitude interval: sub-cutoff secondary fluxes produced by CR in upper atmosphere, bent by geomagnetic field toward higher altitudes; trapped at lower altitudes for seconds

FLUKA 3D (Zuccon et al.): internal +external magnetic fields, p back-tracing
Detector: spherical surface @ 400 km, F.o.V.+acceptance
Very good agreement of upgoing/downgoing p, $e^{\pm}$
Some particles have large probability to cross many times detector mostly in equatorial region (high cut-off)

Downgoing p fluxes



Considering largest equatorial secondary flux⇨ 0.06 (kton yr)$^{-1}$ ≲ 1% contribution
(P. Lipari, astro-ph/0101559)

Atmosphere models

Atmosphere density profile depends on geographical position and seasonal temperature variations: affect competition between interaction-decay

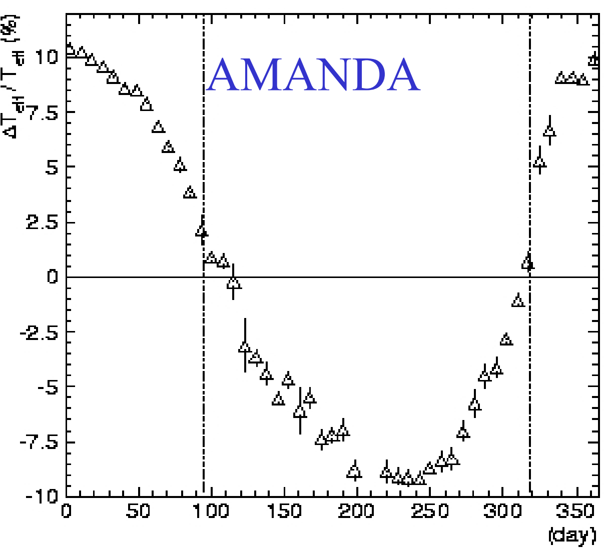
If T increases ρ decreases ⇨ mesons have decay prob. > interaction prob.

AMANDA ±10%, MACRO ±1.5%

For atm. μ easier calculation than for ν coming from all over the Earth

T is very different for downgoing/upgoing νs

US-standard model widely used in calculations; comparisons with balloon measurements show differences (MACRO estimates effect ~1% for upμs)



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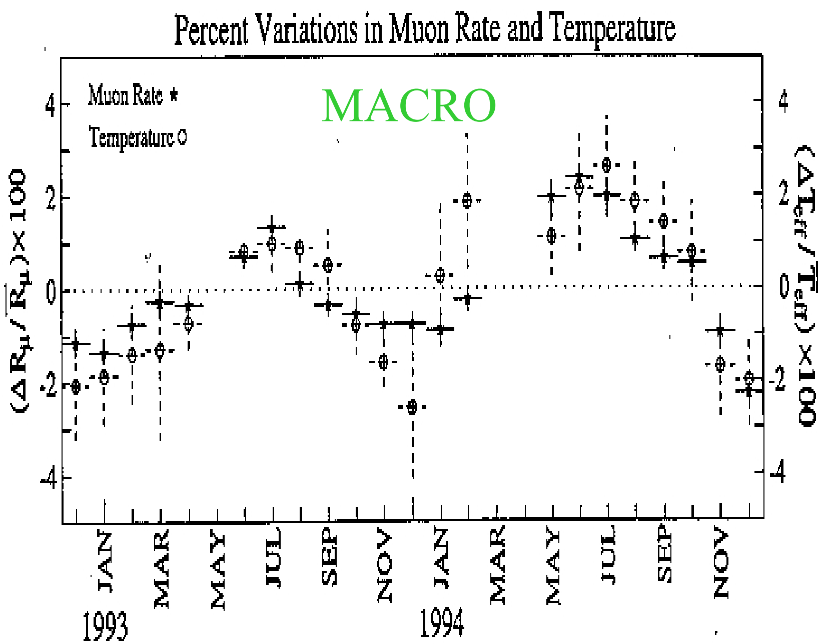
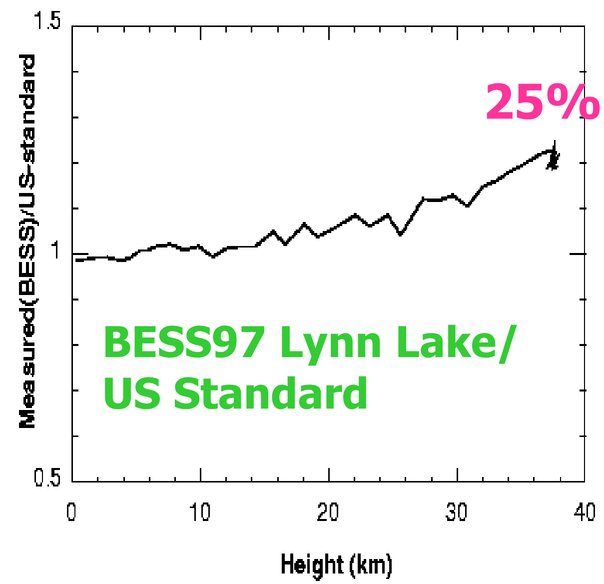




Seasonal effects

Seasonal effects: additional source of uncertainty in vertical/horizontal to discriminate $\nu_{sterile}/\nu_{\tau}$ oscillations (SK, MACRO)

MACRO estimates 3% error on K/π, 2% from ν cross sections due to different energy distributions and (analytical calculation) 1.3% due to seasonal effects, 1% to different atmospheres than US standard

MACRO throughgoing μs: R= $(-1<\cos\theta < -0.7)/(-0.4<\cos\theta <0)$ divided in "winter" (Nov.-Apr.) and "summer" ⇨ winter-summer variation of vertical/horizontal 19±17% (stat)

Honda: estimates variation on muon neutrino fluxes from winter to summer ~6% @ 100 GeV at vertical (max effect)

FLUKA group is preparing setup for 4 different atmospheres

Primary-ν directions

$\theta_{N\nu} = \theta_{N\pi} \oplus \theta_{\pi\nu}$ (when μ decay: $\theta_{N\nu} = \theta_{N\pi} \oplus \theta_{\pi\mu} \oplus \theta_{\mu B} \oplus \theta_{\mu\nu}$)

$\langle\theta_{N\pi}\rangle \sim \langle p_T\rangle/p_\pi \sim$ 0.35 GeV/c/4Eν ~5°/Eν (GeV)

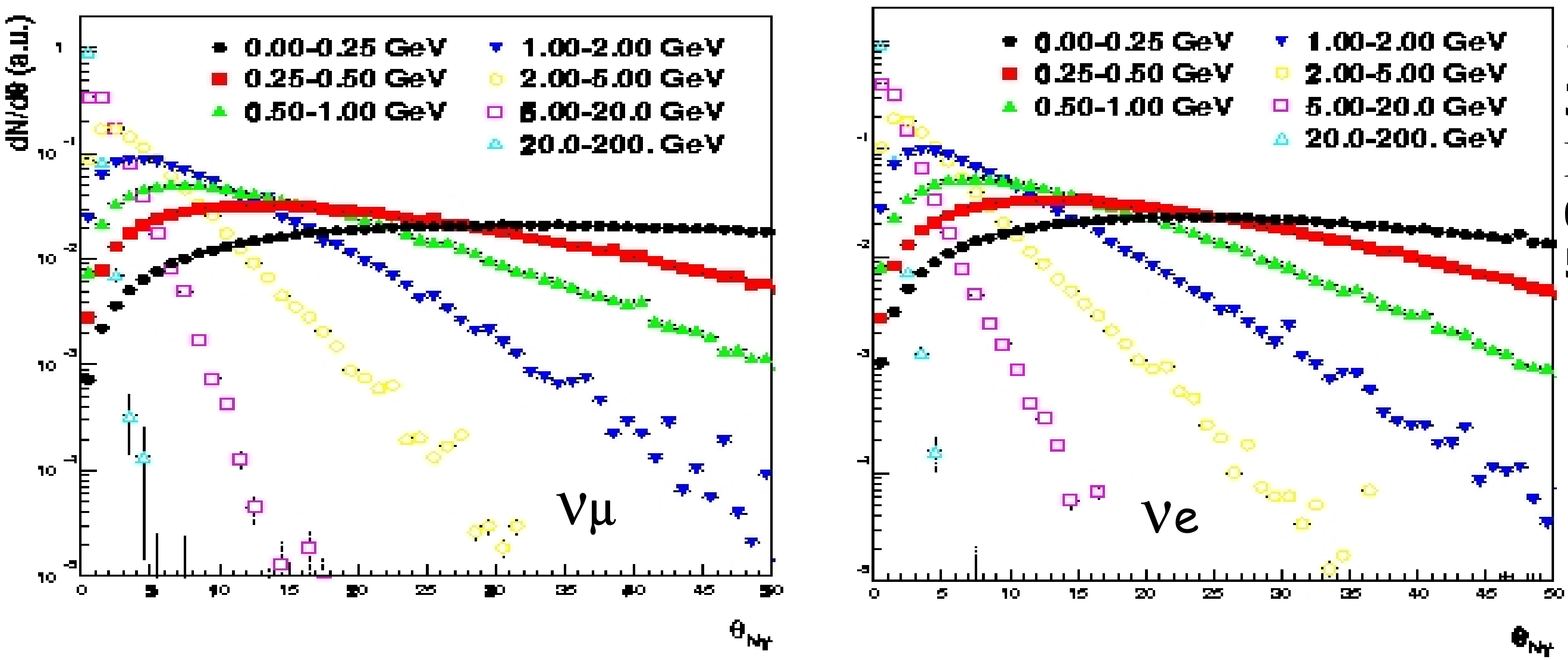
Negligible contributions:

$\pi\rightarrow\mu\nu$: **$\theta_{\pi\nu} \sim p_{CM}/p_\nu \sim 1.7°/E_\nu$** **$\theta_{\pi\mu} \sim p_{CM}/p_\mu \sim p_{CM}/3p_\nu \sim 0.6°/E_\nu$**

$\mu\rightarrow\mu\nu\nu$: **$\theta_{\mu\nu} \sim m_\mu/3E_\nu \sim 2°/E_\nu$(GeV)**

μ bending: **$\theta_{\mu B} \sim L_\mu/R_\mu \sim (\tau_\mu p_\mu/m_\mu)(eB/p_\mu) \sim 10.7°B$(Gauss)**

high pμ ⇨ bend less but live longer ⇨ B acts longer



$\langle\theta_{N\nu e}\rangle \gtrsim \langle\theta_{N\nu\mu}\rangle$

3rd generation

Eν(GeV)	νμ	νe
0.25-0.5	**24°**	**28°**
5-20	**1.8°**	**1.8°**

No μ bending

3D/1D effects

Differences between 1D/3D calculations have been investigated

1D: p_T of secondaries in int./decay+multiple scatt. neglected ⇨ ν collinear to primary) based on 2 hypotheses:

1) isotropy of primary CRs

2) spherical geometry of Earth+atmosphere

Valid approx. for Multi-GeV: $\theta_{N\nu}$ increases for decreasing Eν

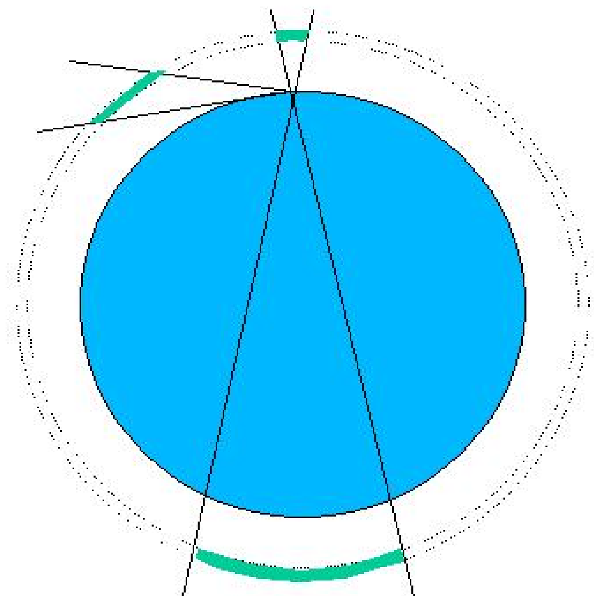
Differences in Sub-GeV angular distribution due to large θNν :
3D enhancement @ horizon

Geometrical effect: νs between θ-θ+dθ produced by atmosphere patch of area

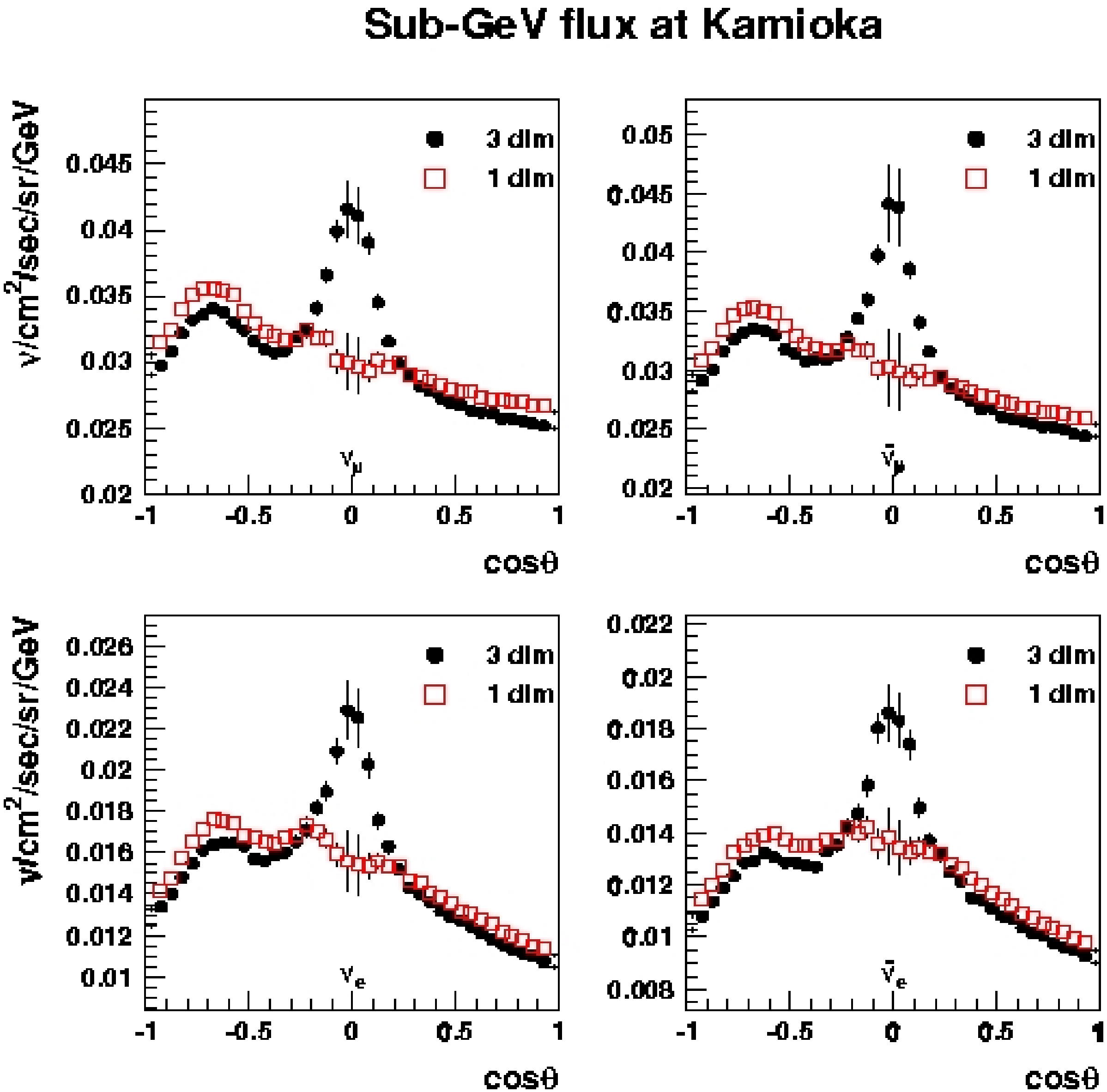
$dA = L^2(\theta) d\theta / \cos\theta_e$

L= distance to detector θe= ν emission angle

1/cosθe responsible of horizontal enhancement



3D/1D: horizontal enhancement

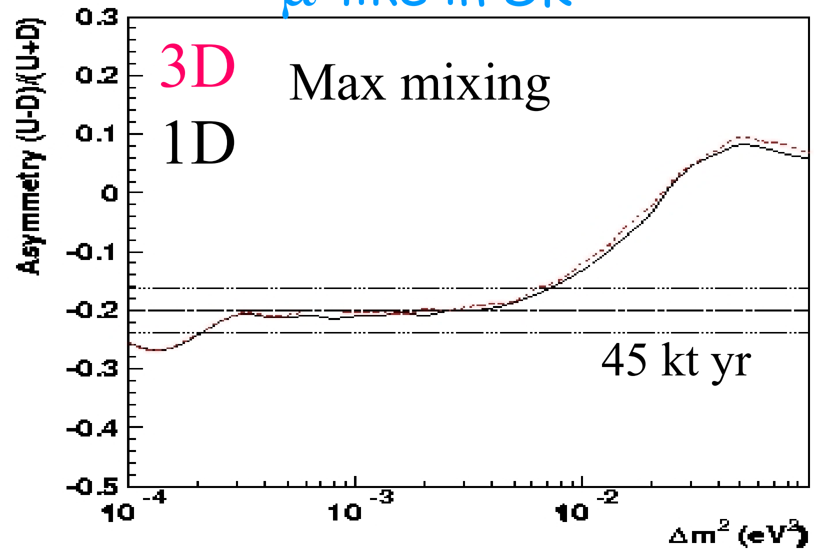


FLUKA 1D/3D

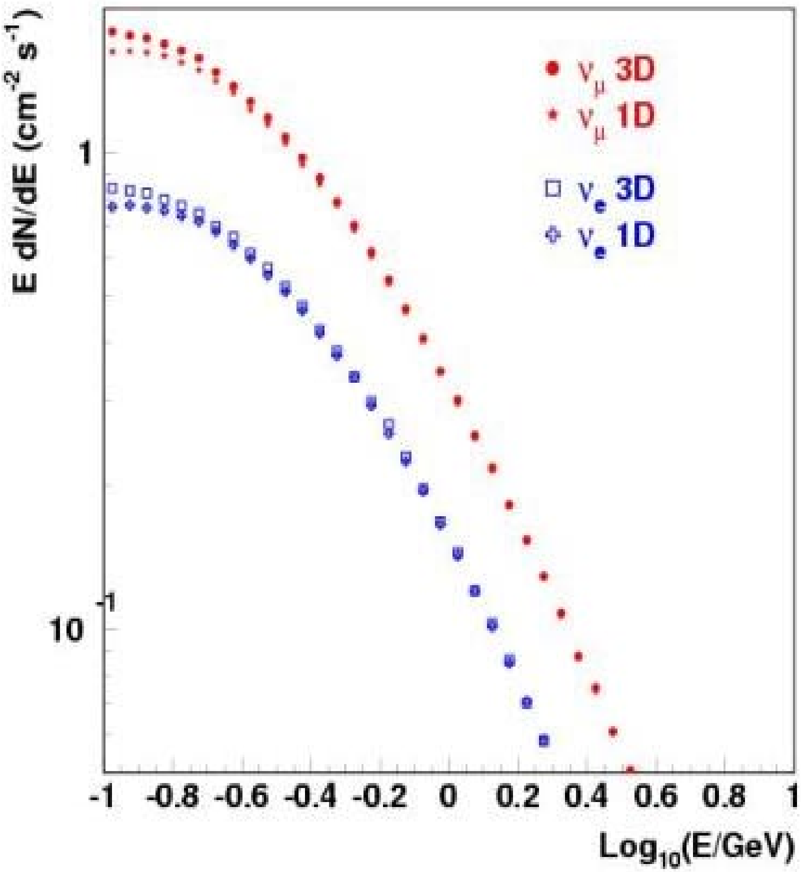
Battistoni et al., Astrop. Phys. 12 (2000)
Similar results in P. Lipari, Astrop. Phys. 14 (2000)

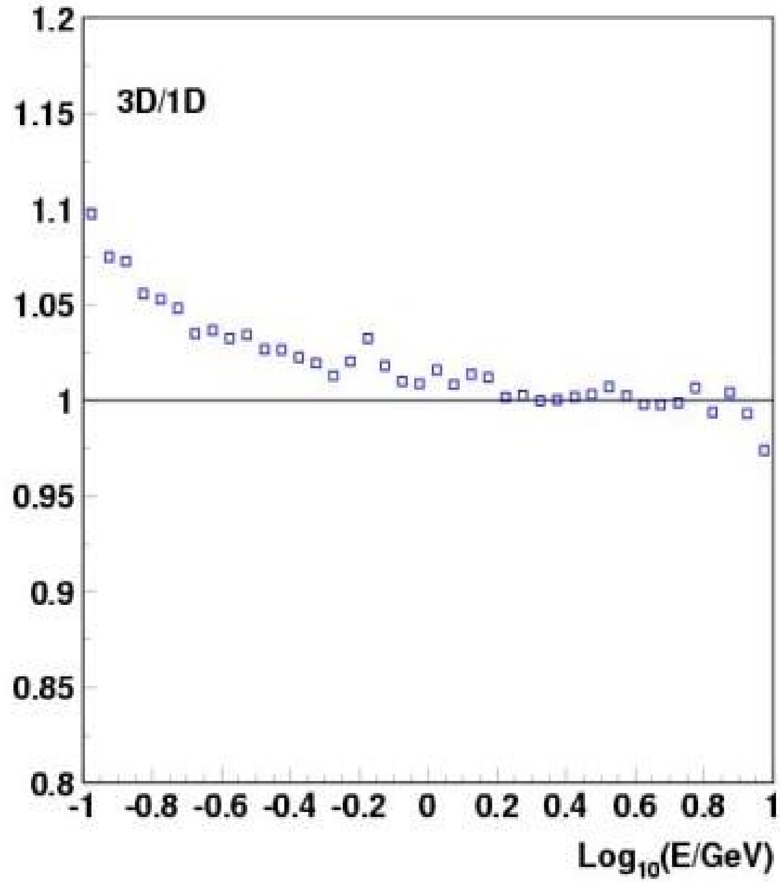
Asymmetry not affected
Modest contribution in Δm^2 evaluation

μ-like in SK



3D/1D: normalization





FLUKA 1D/3D

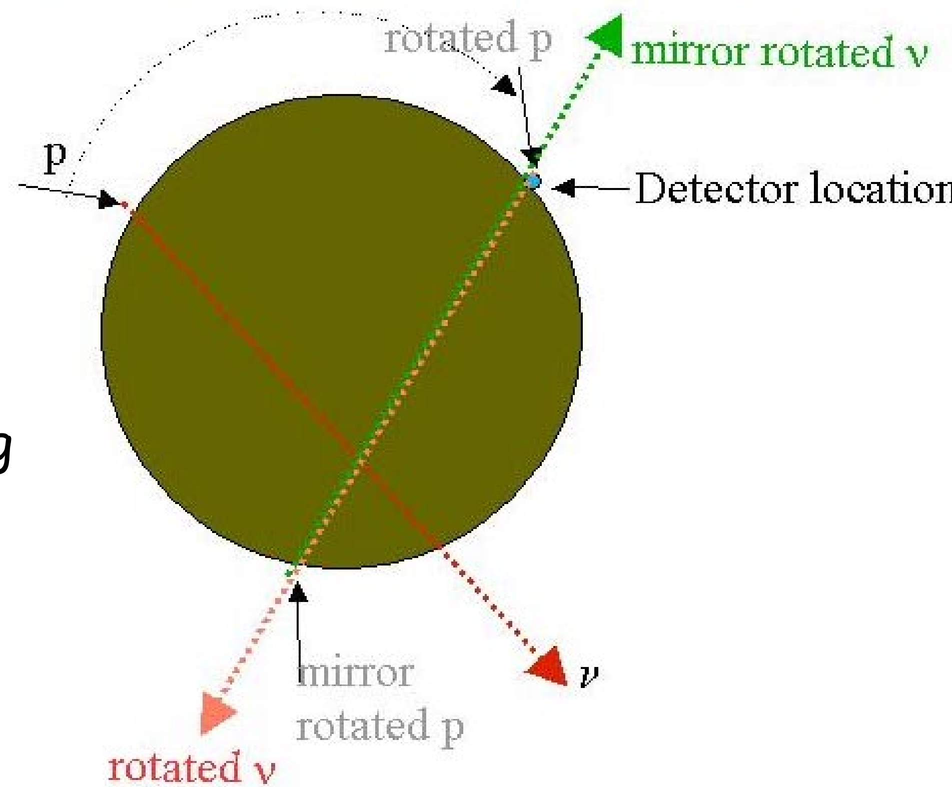
Superkamiokande site

Small effect on normalization ~5% for Eν<1GeV

1D/3D and geomagnetic field

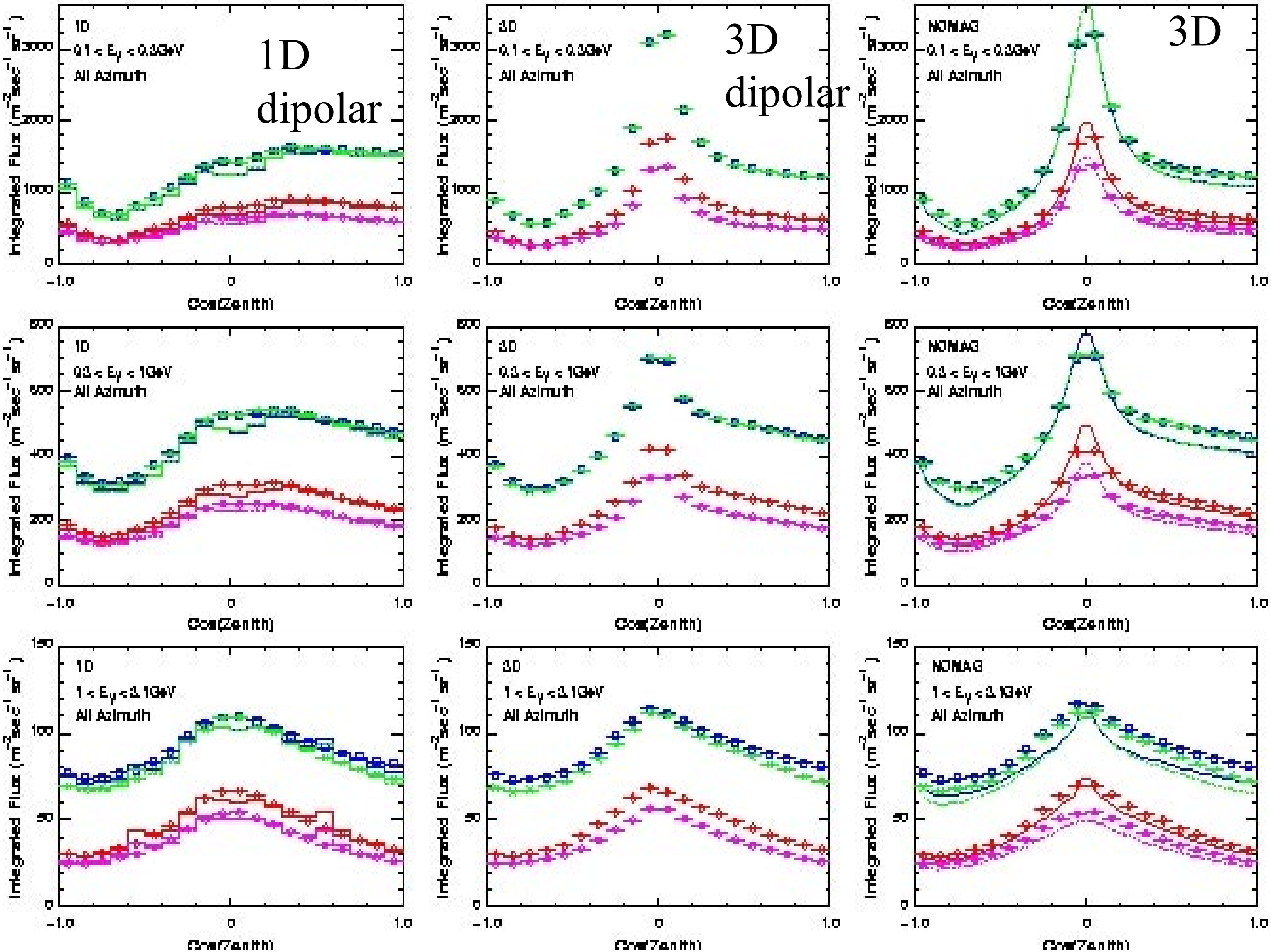
Next step: introduce geomagnetic field in shower development
Loss of rotational symmetry ⇨ high inefficiency (calculations must be performed at detector site)

No B in shower development (FLUKA):
ν generated on sphere with B=0
ν reaching surface can be rotated with its parent to detector site for cut-off calculations
For each upcoming ν a "mirror" downcoming ν is created (there is up-down symmetry because ν is generated with B=0)
FLUKA(next future): weighting towards detector location
HKKM: dipolar field (axial symmetry)
Tservkovnyak et al., huge detector size



1D/3D zenith angular distributions

HKKM: confirm horizontal enhancement



Soudan site

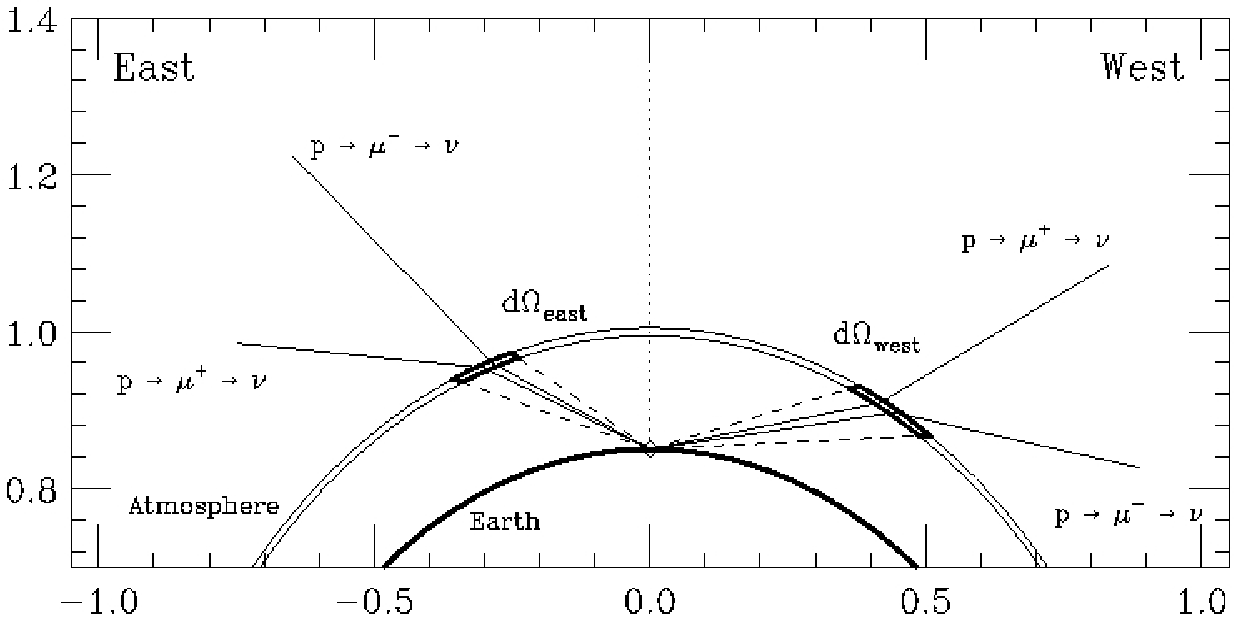
1D no cut-off:
average int. point ~100 gr/cm^2
Horiz. CR produce π at higher altitude than vert. ⇨
π–μ decay at lower density ⇨int. prob. +μ energy loss increase with air density

Horiz. ν > vert. ν

Cut-off modifies zenith dependence (@ high magnetic lat. downward>upgoing flux)

1D/3D: μ bending

Effect on E-W asymmetry (predicted in P. Lipari,astro-ph/0003013):



enhancement of asymm. effect for ν_e, ν_μ from μ^+

suppression for $\bar{\nu}_e, \nu_\mu$ from μ^-

3D with geomagnetic cut-off can reconcile SK observation $Ae > A\mu$ (while 1D: $Ae = A\mu$)

From W: for $p \to \pi^+ \to \mu^+ \to \nu$ $\langle\theta p\nu\rangle = \theta p\pi + \theta\mu B < \theta p\pi$

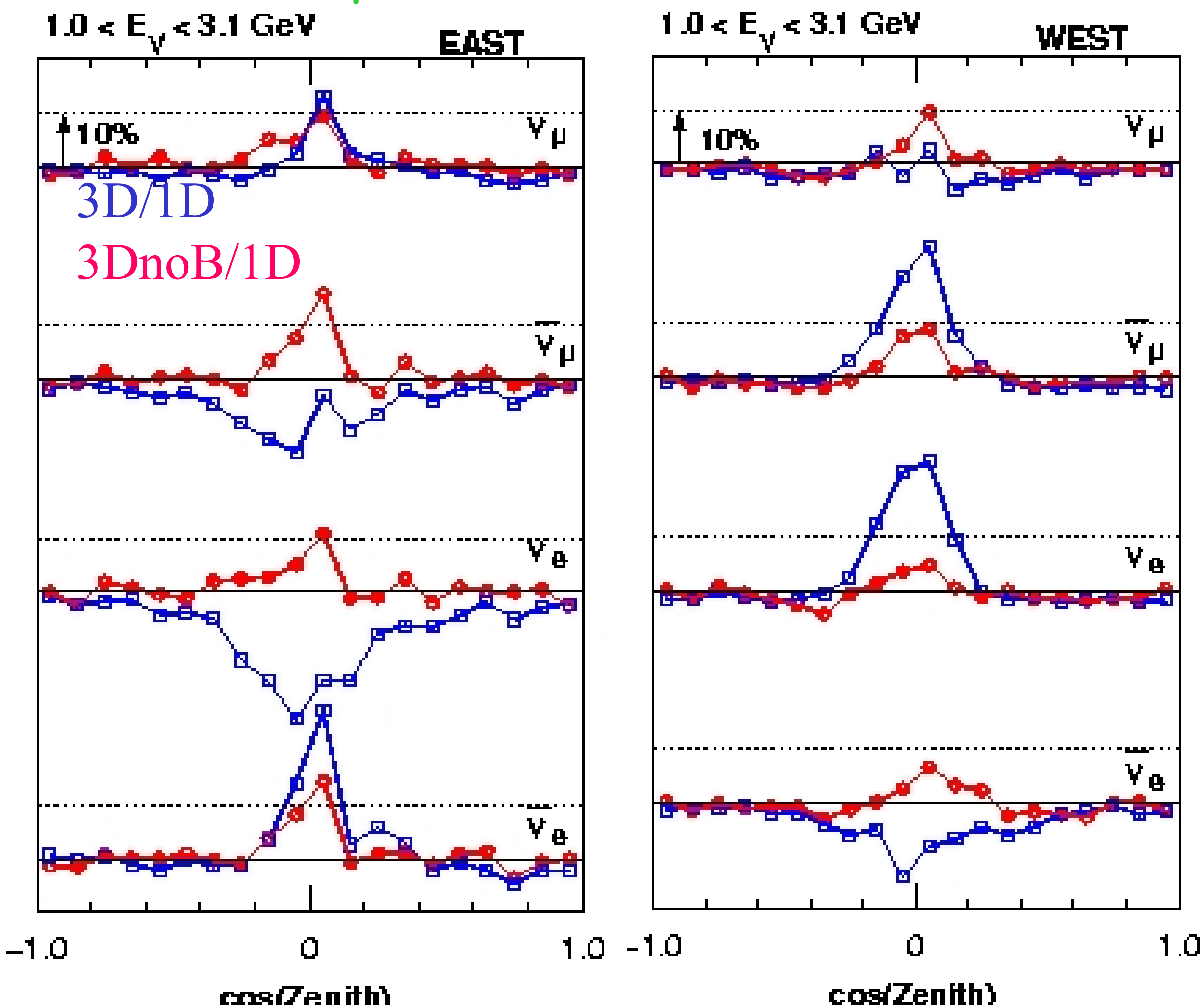
for $p \to \pi^- \to \mu^- \to \nu$ $\langle\theta p\nu\rangle = \theta p\pi + \theta\mu B > \theta p\pi$

From E: opposite effect

$d\Omega \propto \cos\theta p\nu$ and $\Phi_\nu \approx \Phi_{\bar{\nu}} + \sigma_\nu > \sigma_{\bar{\nu}}$

Effect of geomagnetic field in shower development

HKKM: Super-Kamiokande site



3D: shows horizontal increase due to geometry

Geomagnetic field in shower development: effects ~10-20% up to ~10 GeV almost independent on Eν (when μ decay)

It is a precision check on geomagnetic treatment

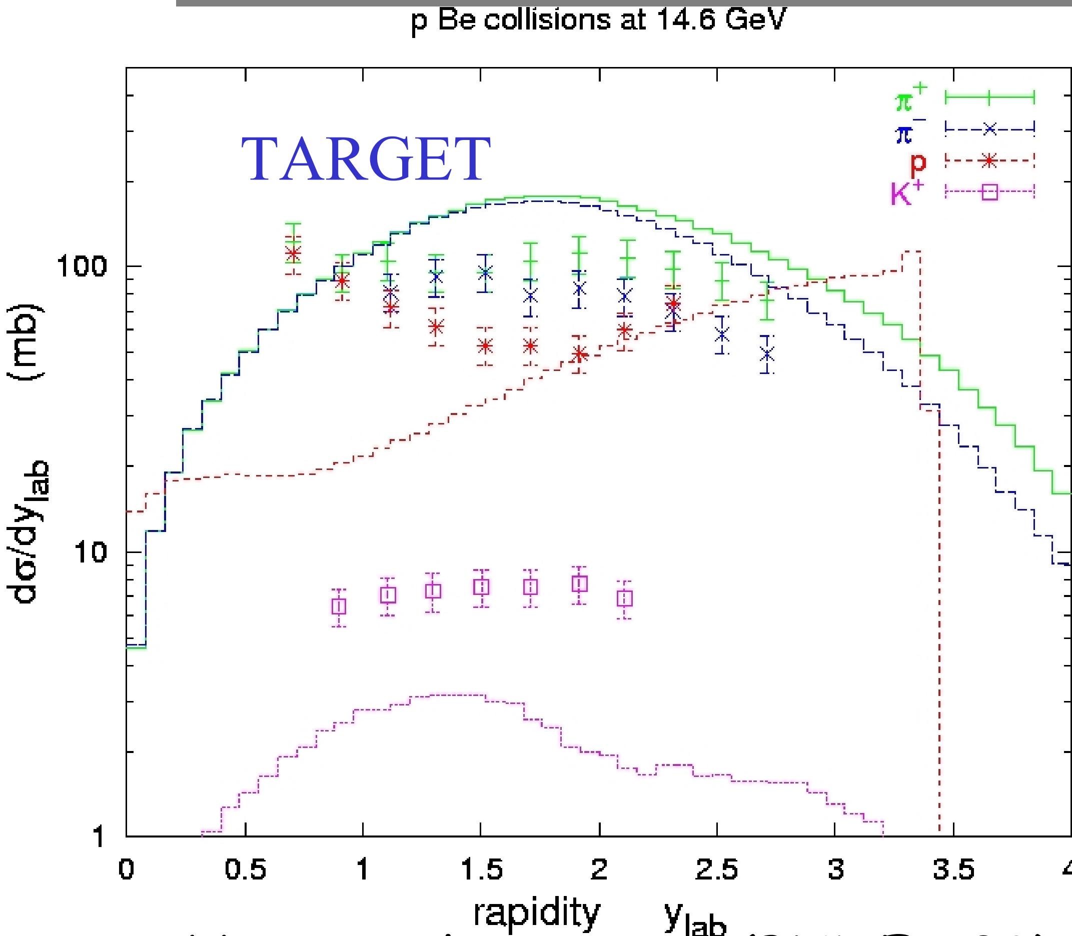
These effects have small Impact on Δm^2

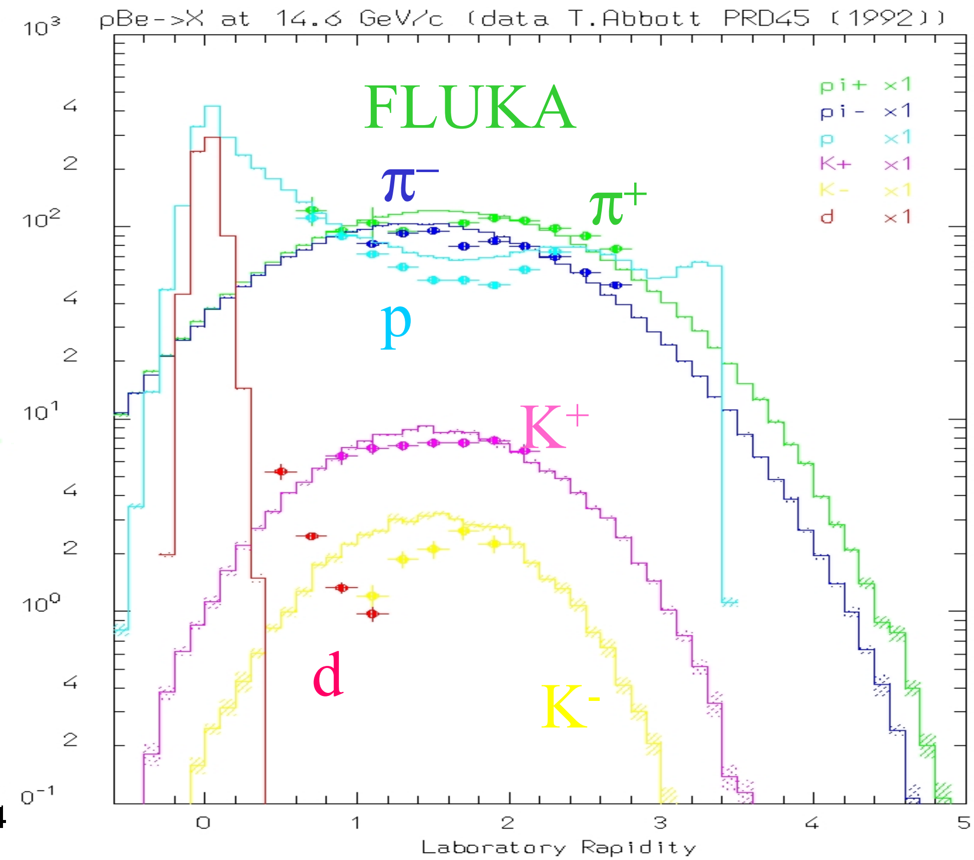
FLUKA setup

FLUKA2000 interaction and transport code
(A. Ferrari et al., Proc. of CALOR2000):
theory driven approach not phenomenological/tuned on experimental data
Conservation laws fulfilled *a priori* Extensive benchmark against data
h-A interactions based on resonance production and decay below few GeV
and on Dual Parton Model and h-A+A-A Glauber model to tens of TeV

The setup for atmospheric νs:
3D representation of Earth and atmosphere (50-100 shell) to ~100 km (0.1 gr/cm^2)
with Shibata "standard atm" profile; all secondaries can be scored
Primary particles injected at ~100 km sampled from Bartol flux at solar min
Solar modulation from NASA tables and algorithms using Climax data
For μ benchmarks: cut-off+shower development through back-tracing
For νs: cut-off only (to be improved)
Superposition model will be replaced by DPMJET using nuclear projectiles
Change in primary spectrum can be obtained just through weighting
All relevant physics: polarization in decays, energy losses, multiple scatter.
FLUKA atm. ν simulation will be used by ICARUS
Used for CNGS beam project, tested in Nomad and comparison with SPY

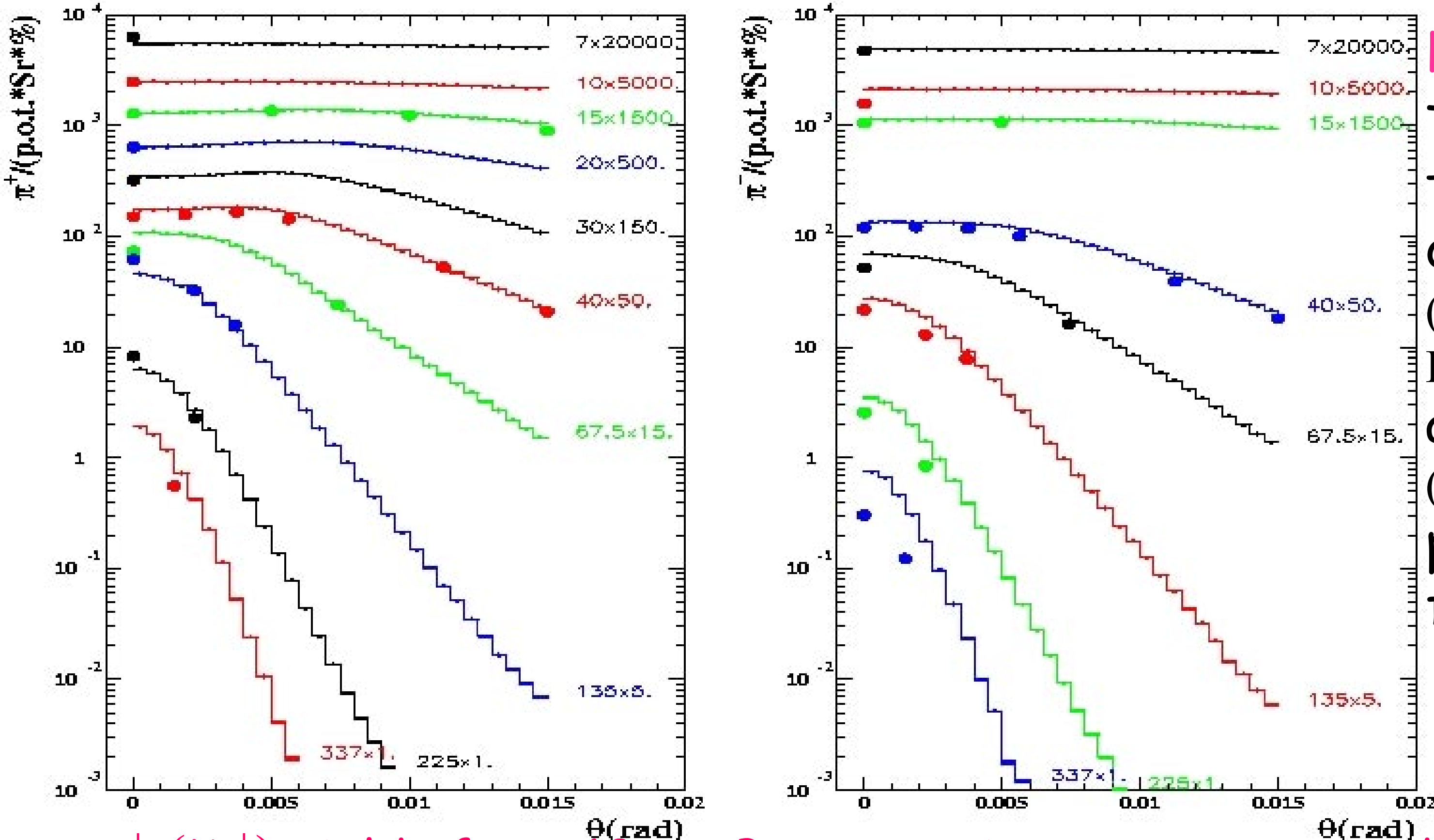
Interaction models: FLUKA/TARGET





T. Abbott et al. PRD45(1992) (BNL E-802): explored different targets (Be, Al, Cu, Au) at single lab energy, lab angle 5°-58°, Xlab ⇨ 0.1 where most differences between atm. calculations but extrapolations needed to obtain dN/dx_{lab} from rapidity distributions

FLUKA: benchmarks



FLUKA compared to SPY: p(450 GeV/c) +Be with 3% precision on K/π for p<40 GeV/c (Ambrosini et al., Eur Phys JC10(1999) and Atherton et al. (CERN rep80-07) p(400 GeV/c)+Be for p>67.5 GeV

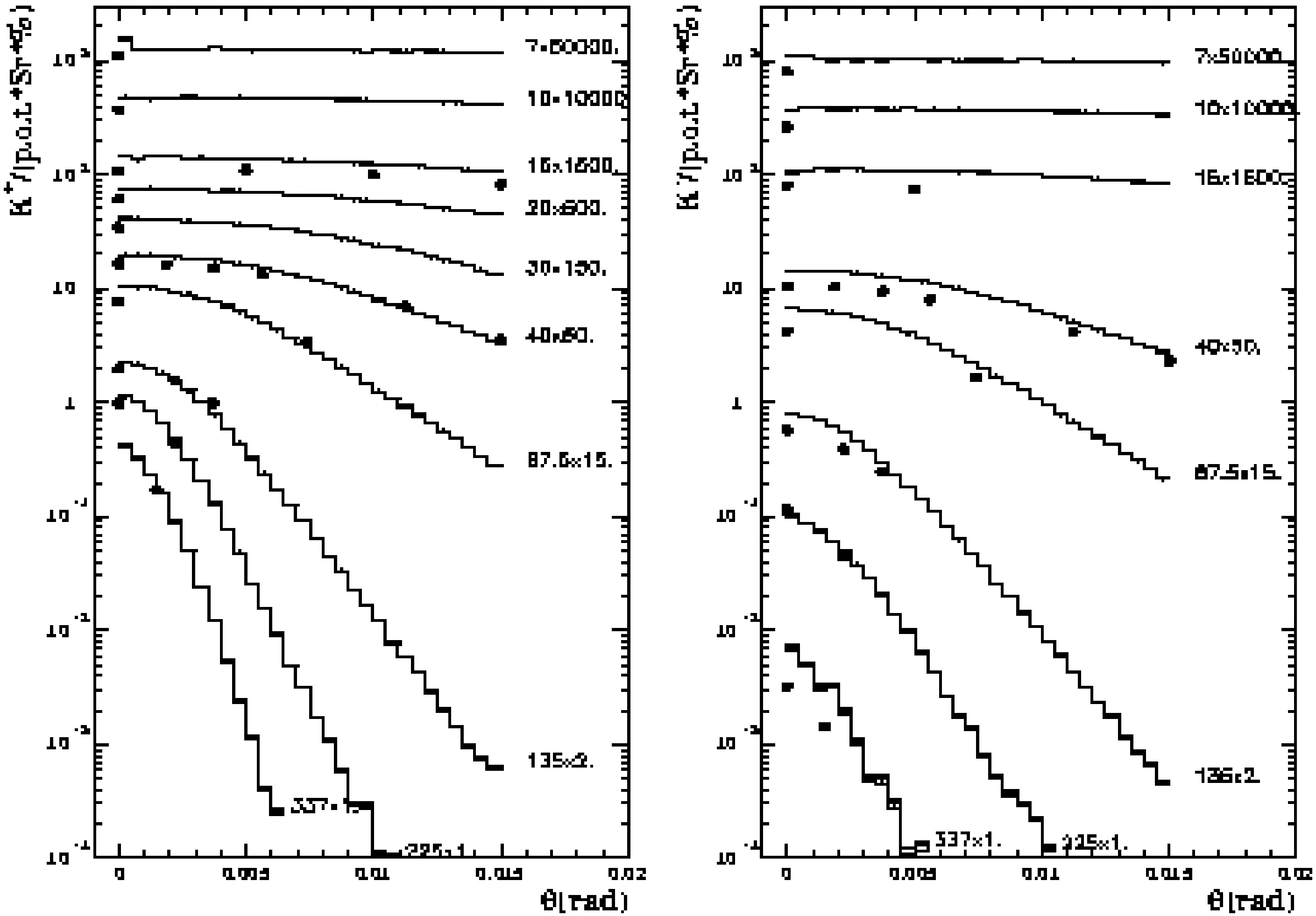
$\pi^{\pm}$ ($K^{\pm}$) yields from 10 cm Be target in p ranges vs production angle

Agreement at 20% (except for few points for K^{-}) and K/π at 10% @ 30-100 GeV/c Important comparison for atm νs but small angle and large Ep

HARP: Ep~2-15 GeV on thin and thick different targets, $d^2\sigma/dp_T dp_L$

2% precision large solid angle (previous meas. have ~15% uncertainty)

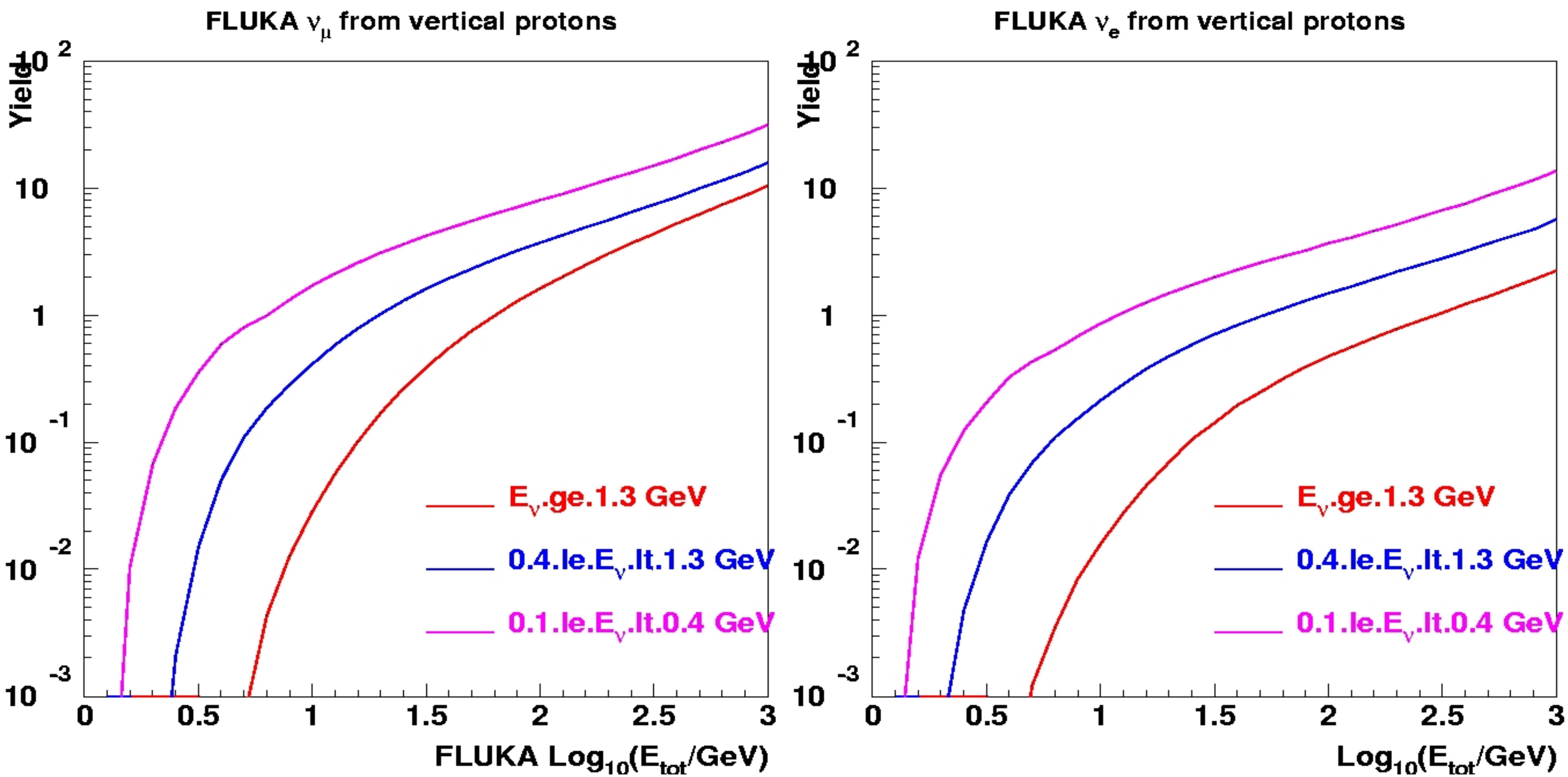
FLUKA: benchmarks



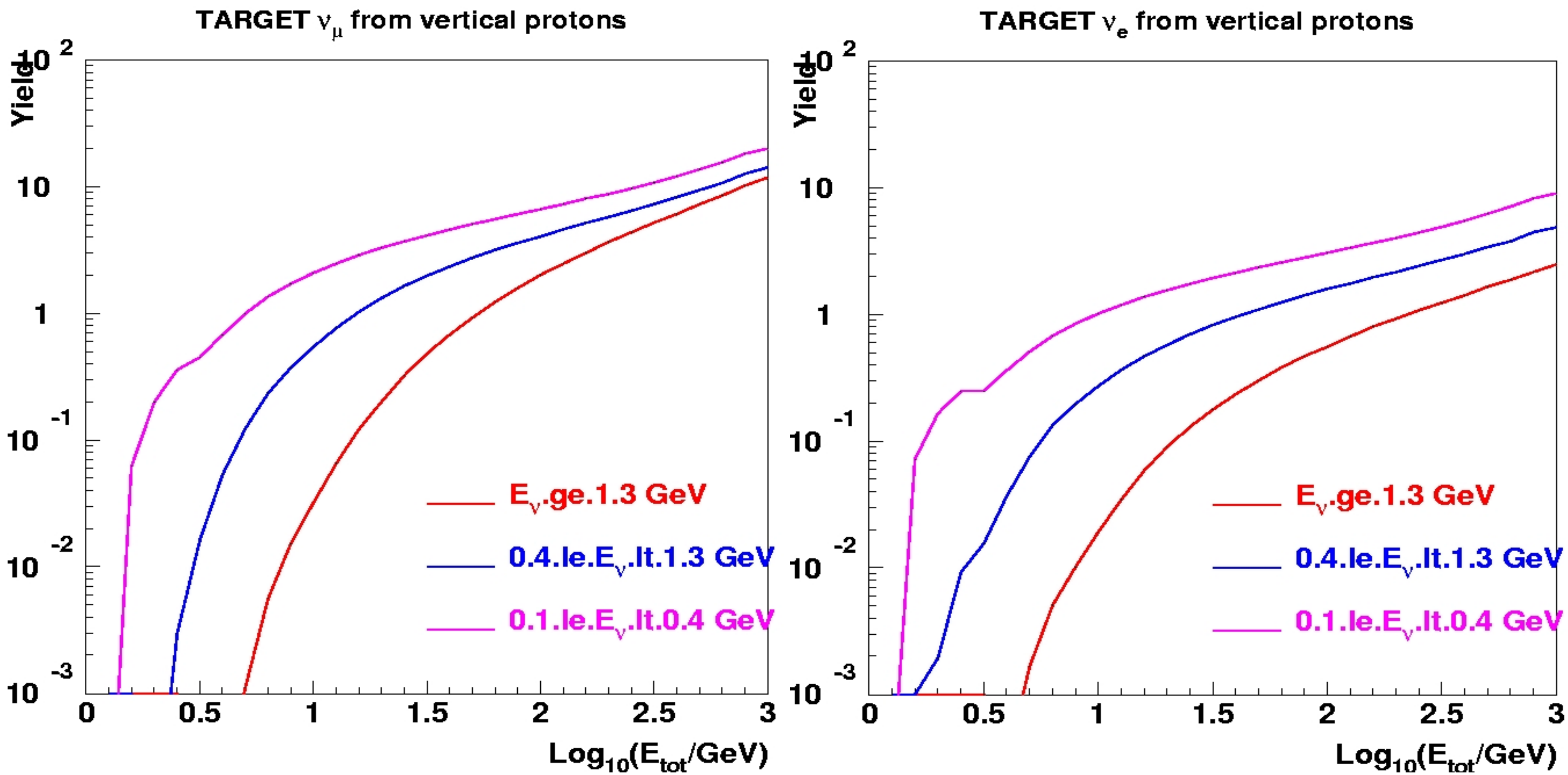
FLUKA compared to SPY p(450GeV/c)+Be with 3% precision on K/π for p<40 GeV/c (Ambrosini et al., Eur Phys JC10(1999) and Atherton et al. (CERN rep80-07) p(400 GeV/c)+Be for p>67.5 GeV

$K^{\pm}$ yields from 10 cm Be target in momentum ranges vs production angle

FLUKA/TARGET: ν yields



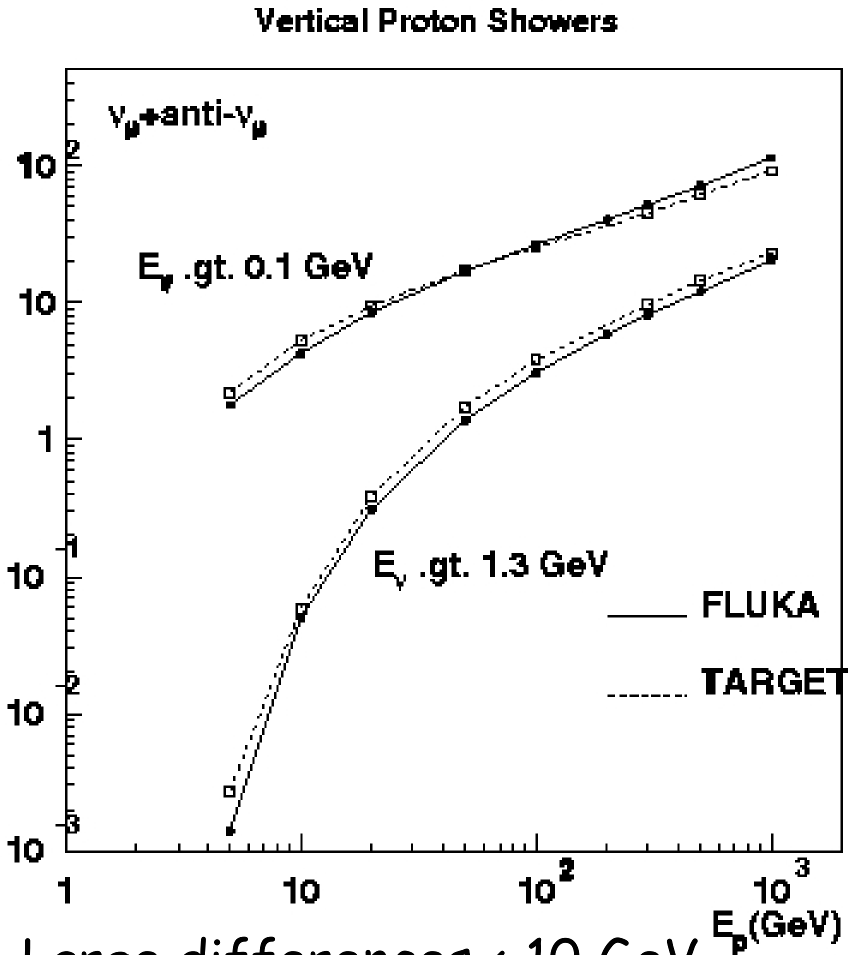
FLUKA/TARGET: ν yields



From extensive comparison we learnt: TARGET gives too high π multiplicity @ small x = E/E_0. Next future: new 3D TARGET (ICRC)

No model is perfect, all need continuous benchmark against data

FLUKA/TARGET



Large differences < 10 GeV

At HE FLUKA produces softer νs

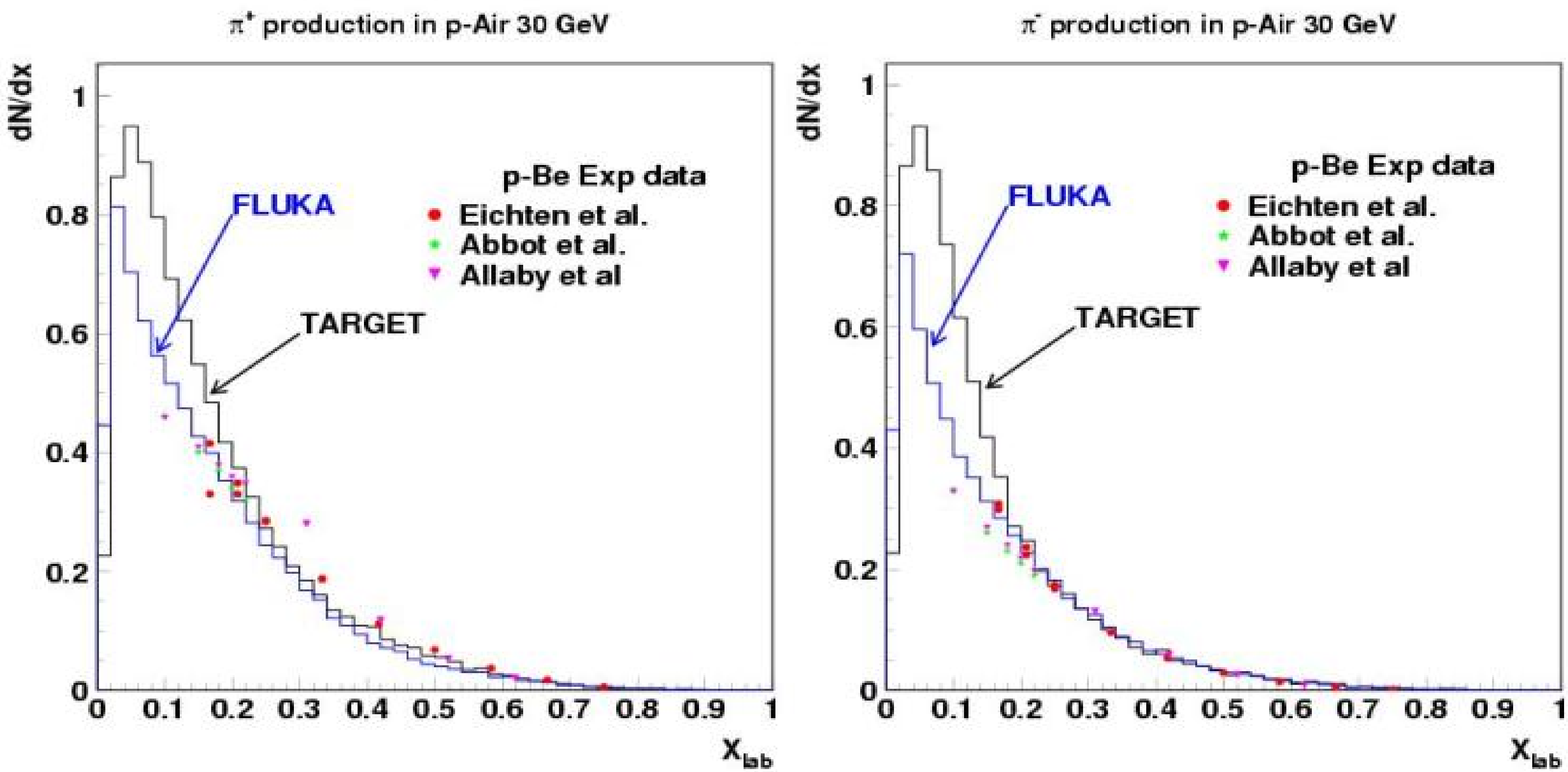
Warning: from ν fluxes to detected rates uncertainties on ν cross sections are relevant

Larger for Eν ~0.1-10 GeV (quasi-elastic interactions, resonance production, nuclear effects, transition in DIS regime)

Need of higher precision data (K2K, LBL near detectors)

Average n. of atm νμ produced by vertical protons

FLUKA/TARGET

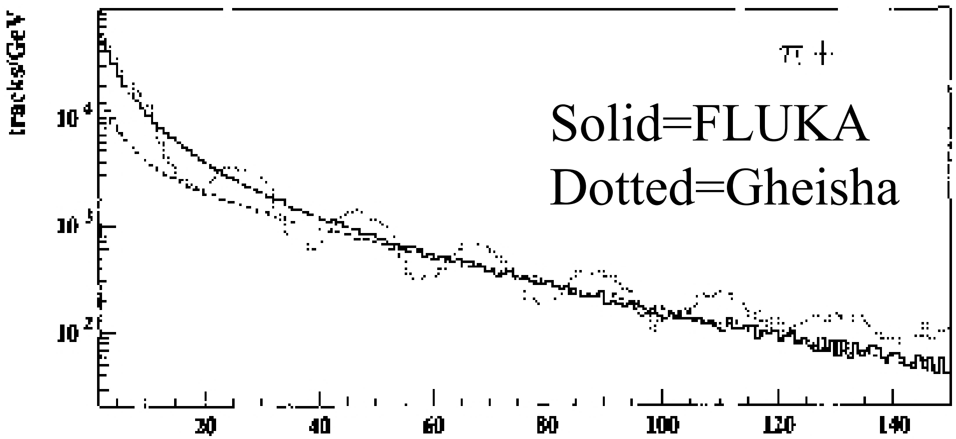


Fluka predicts that a smaller fraction of primary energy goes into charged pions ⇨ smaller ν fluxes

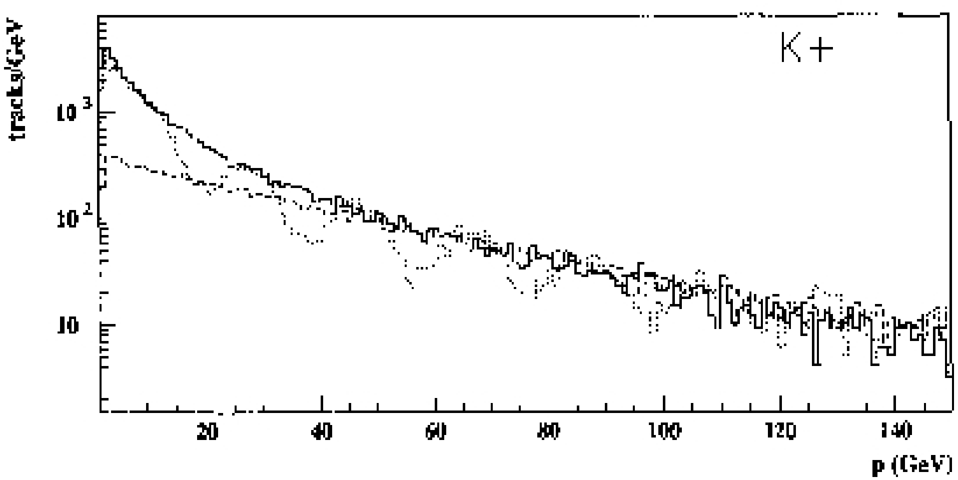
Gheisha

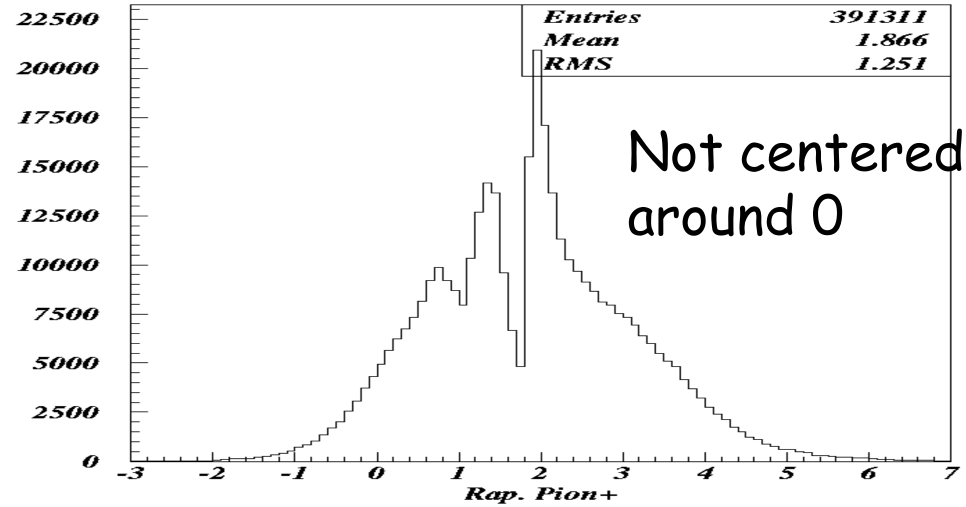
Production spectra of π^+ and K^+ for 400 GeV incident p

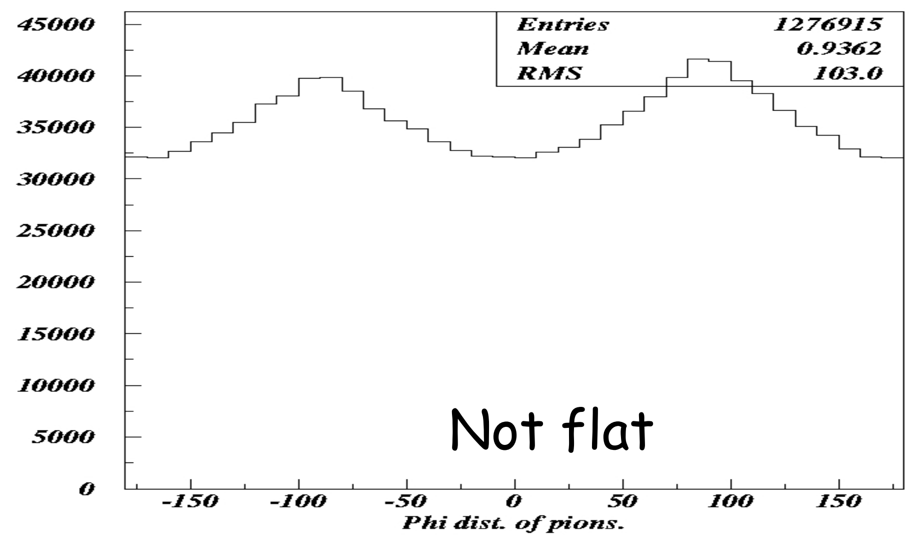
Used in Plyaskin, hep-ph/0103286



Ball et al, NIMA383 (1996)



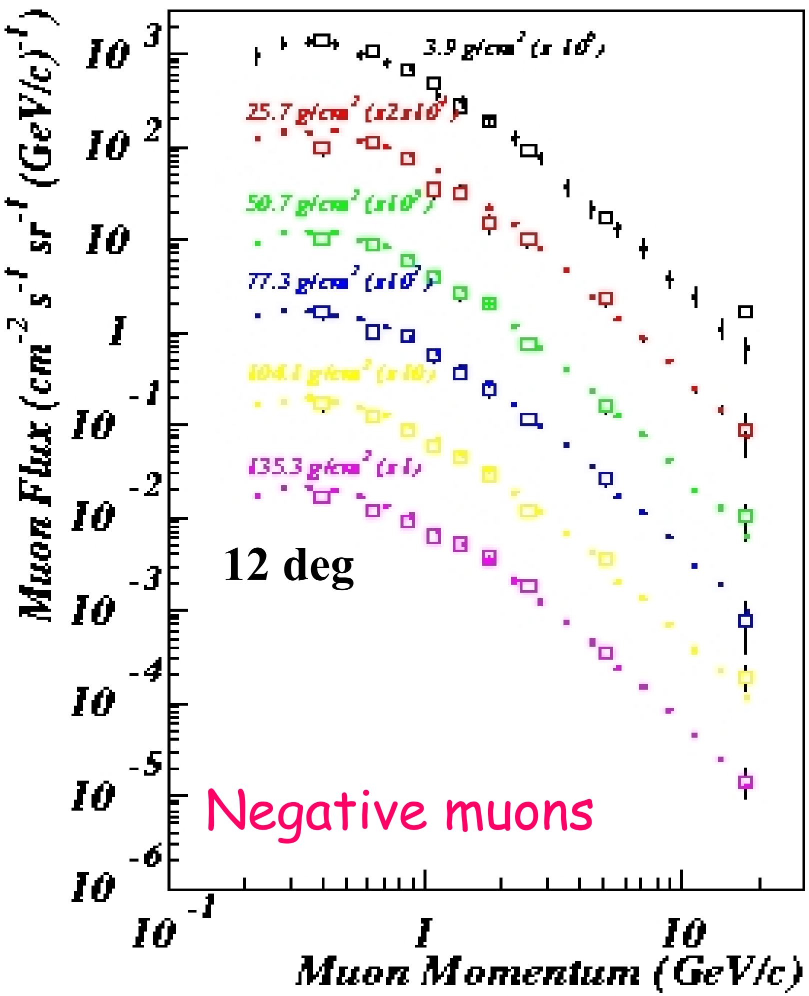


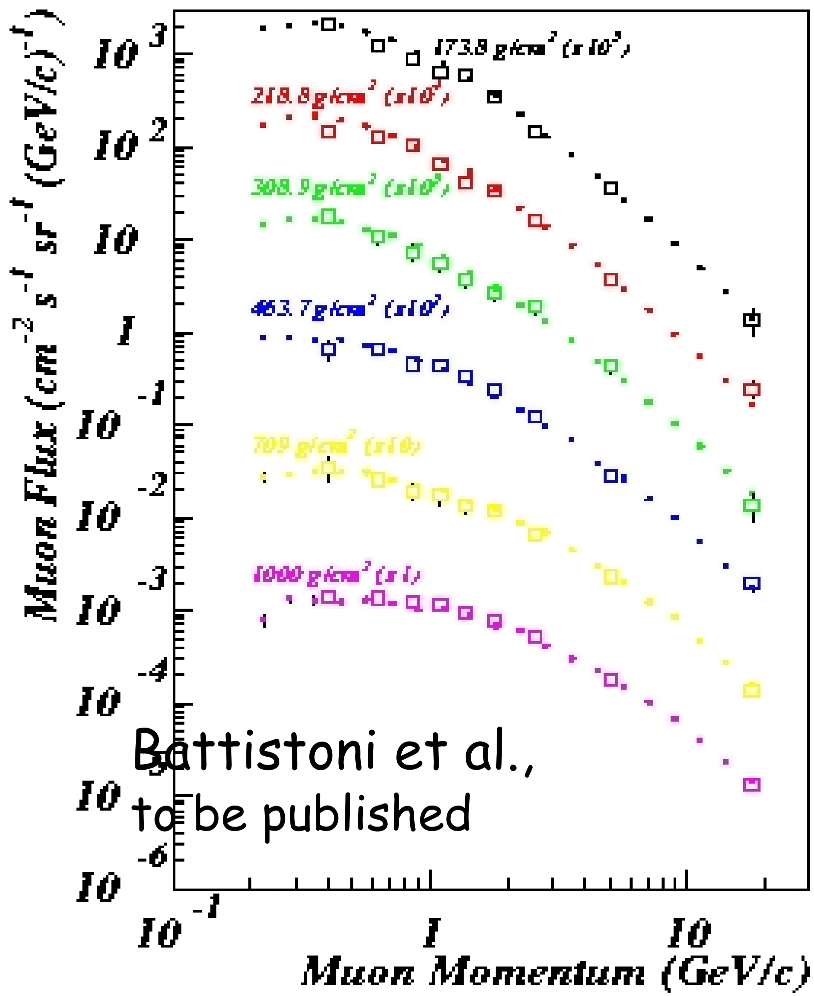


FLUKA floating muon benchmark

Important benchmark to validate ν calculations (same parents, shower development check)

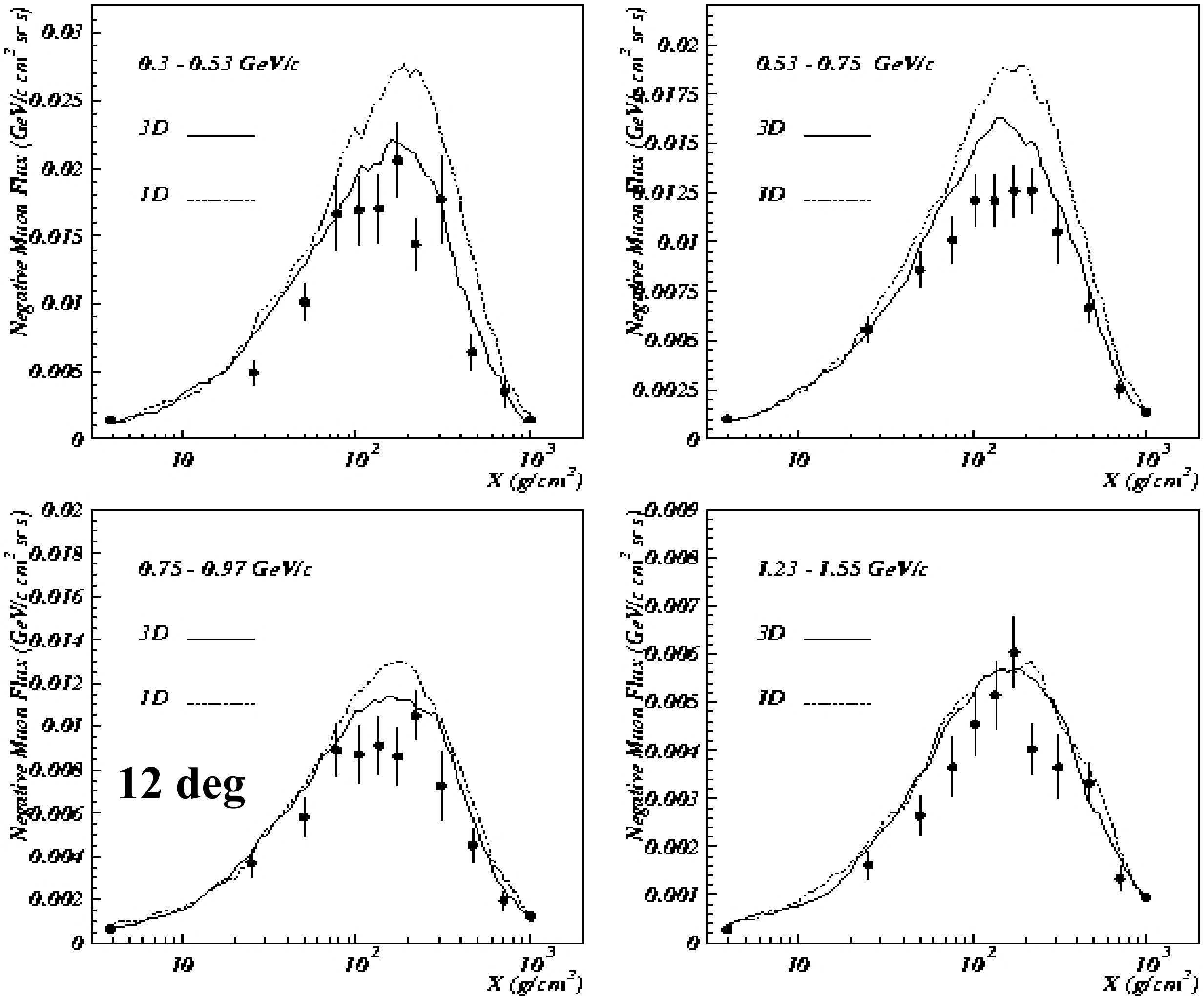
Differences TARGET/FLUKA: not due to FLUKA insufficient particle production





CAPRICE 94 (Lynn Lake)
FLUKA 3D, 100 standard USA atm. shells, Bartol all-nucleon spectrum modulated with Climax n data, geomagnetic field in shower development

Floating muon benchmark: 3D/1D



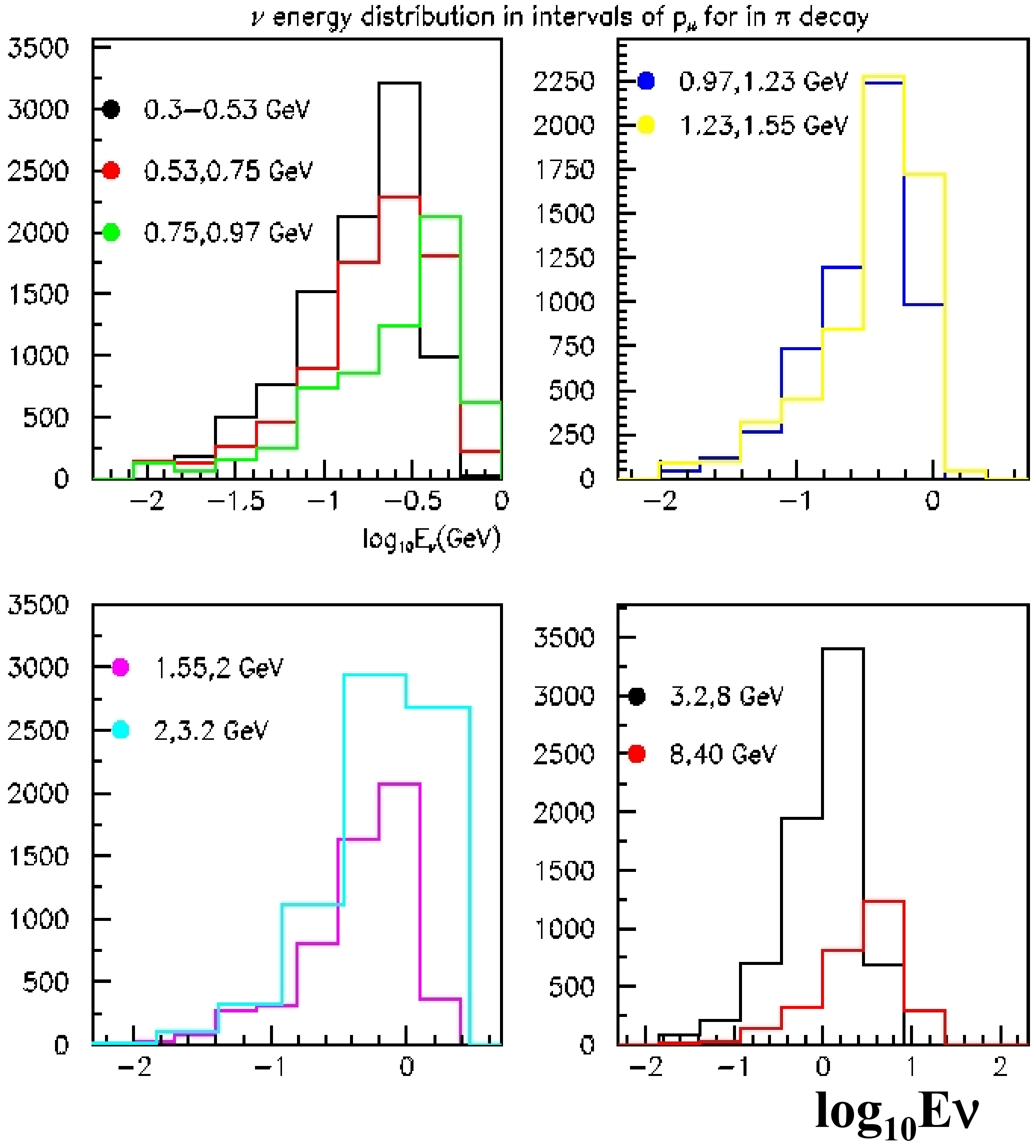
Negative muons

1D brings overestimate at low pμ: kinematic angles + bending in geomagnetic field ⇨ increase of path-length and larger decay probability

Better agreement than 1D by Fiorentini et al. (produces lower fluxes at low energies)

Warning: still Bartol CR flux

Correlation between muons and neutrinos

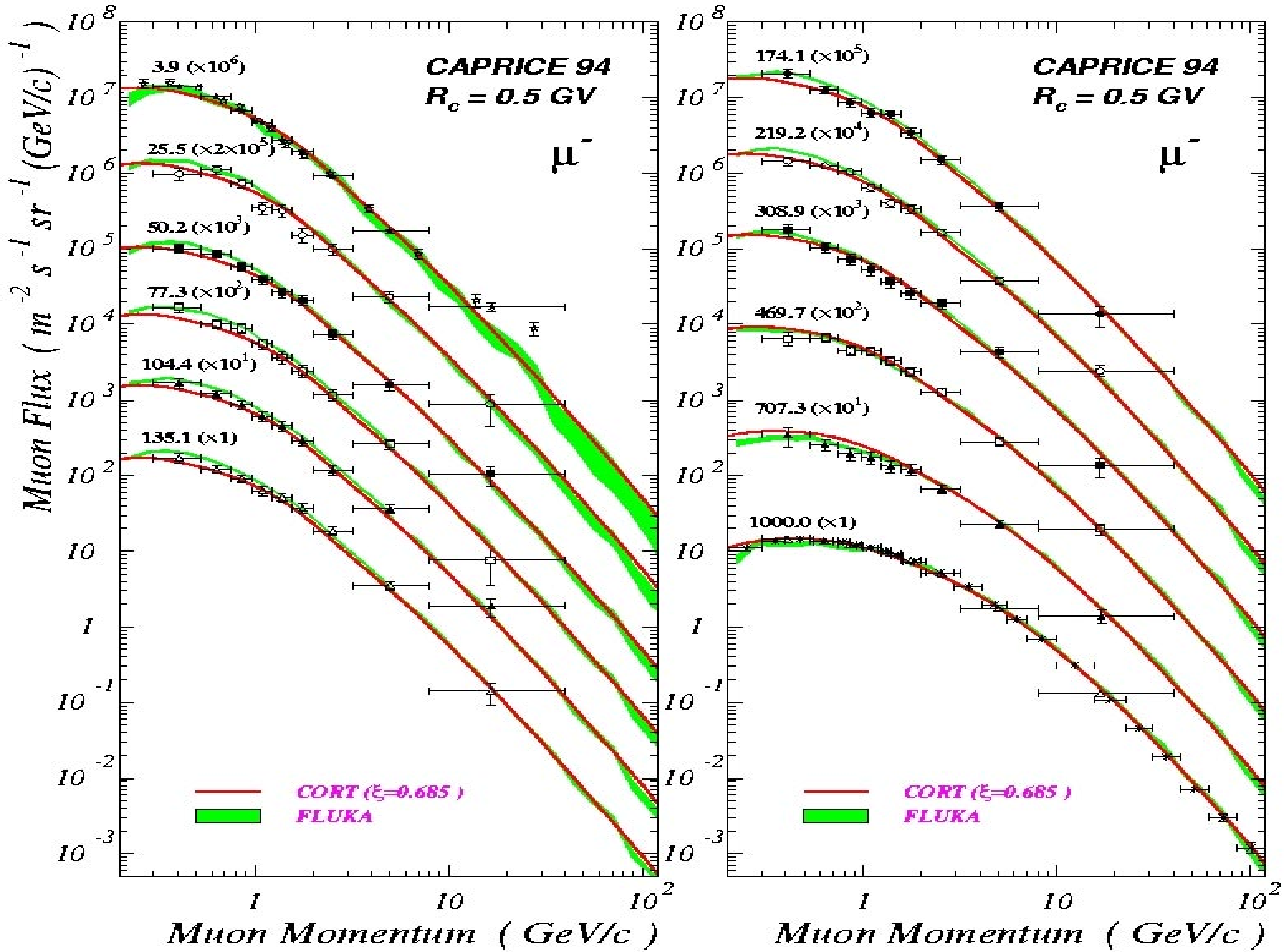


Caprice 94 μs constrain Sub-GeV events

Average ν energies in μ momentum intervals:

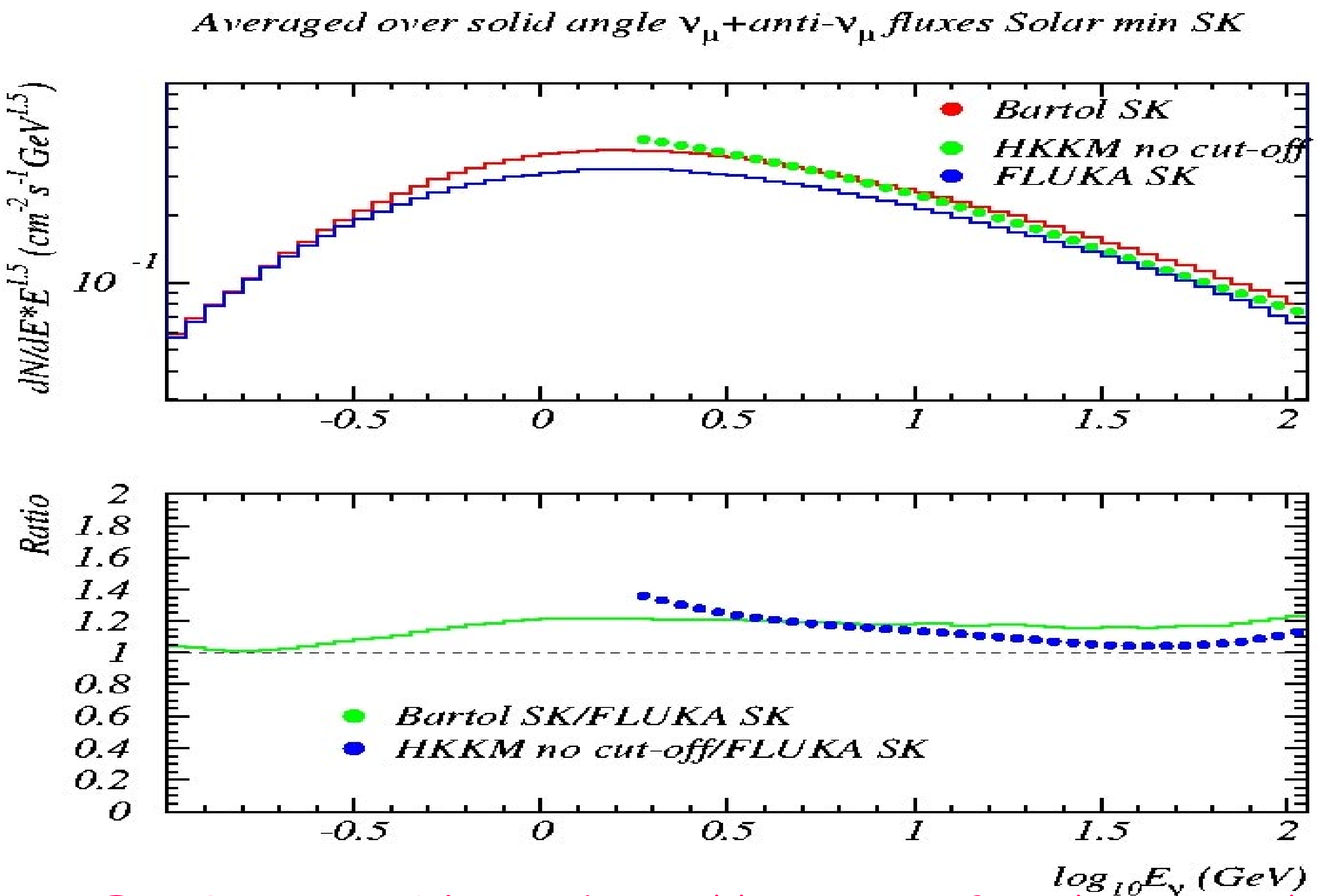
pμ GeV/c	<Eν> GeV	Frac. of primaries with E<10 GeV
0.3 - 0.53	0.19	42%
0.53 - 0.75	0.25	34%
0.75 - 0.97	0.32	28%
0.97 - 1.23	0.39	22%
1.23 - 1.55	0.48	18%
1.55 - 2	0.60	13%
2 - 3.2	0.89	5%
3.2 - 8	1.44	0.6%
8 - 40	3.28	0%

Correlation between muons and neutrinos



Thanks to
V.A. Naumov

Comparison of absolute νμ+anti-νμ fluxes



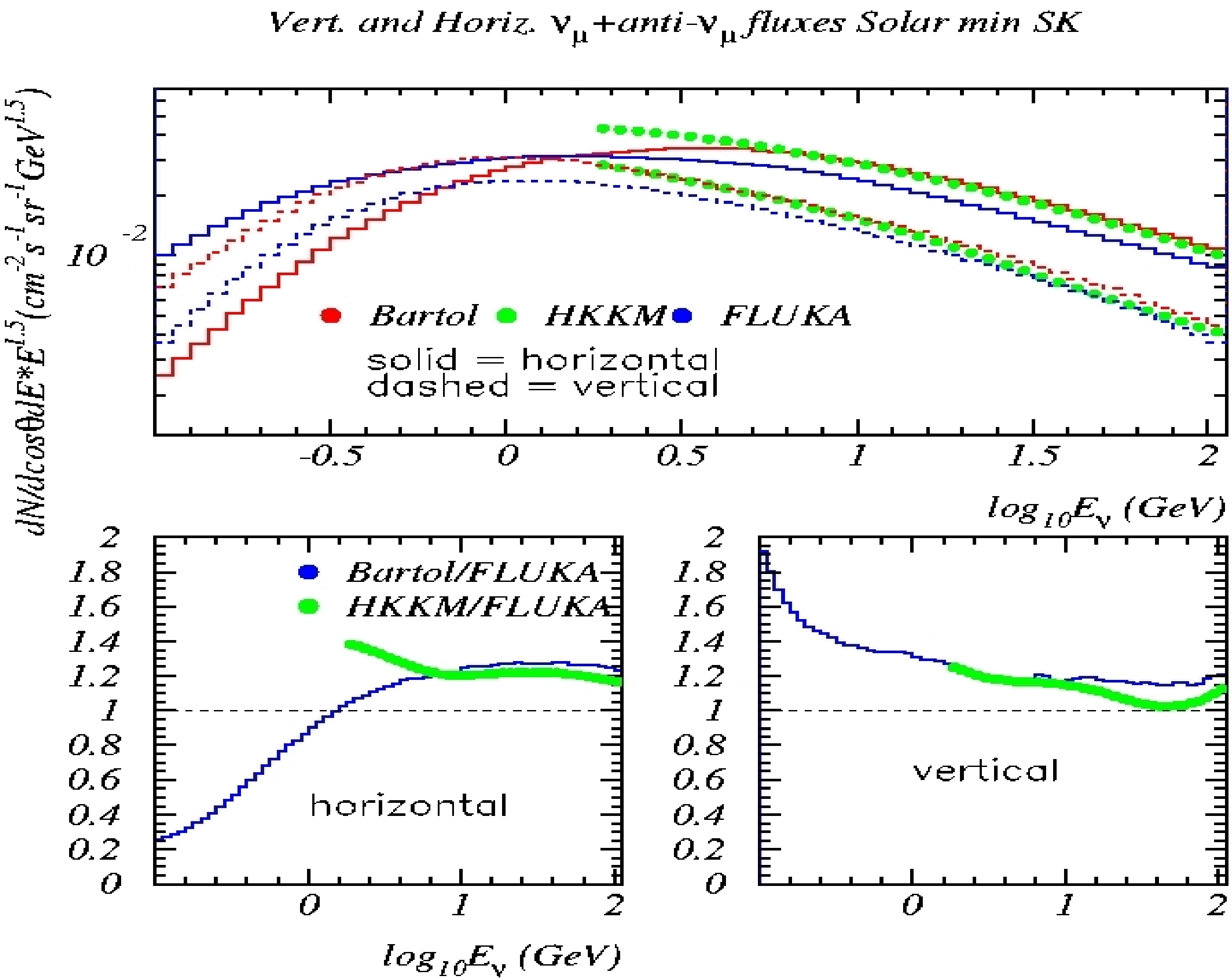
HKKM: no cut-off

Average fluxes agree inside 20%

FLUKA predicts lower fluxes than TARGET due to lower π multiplicities

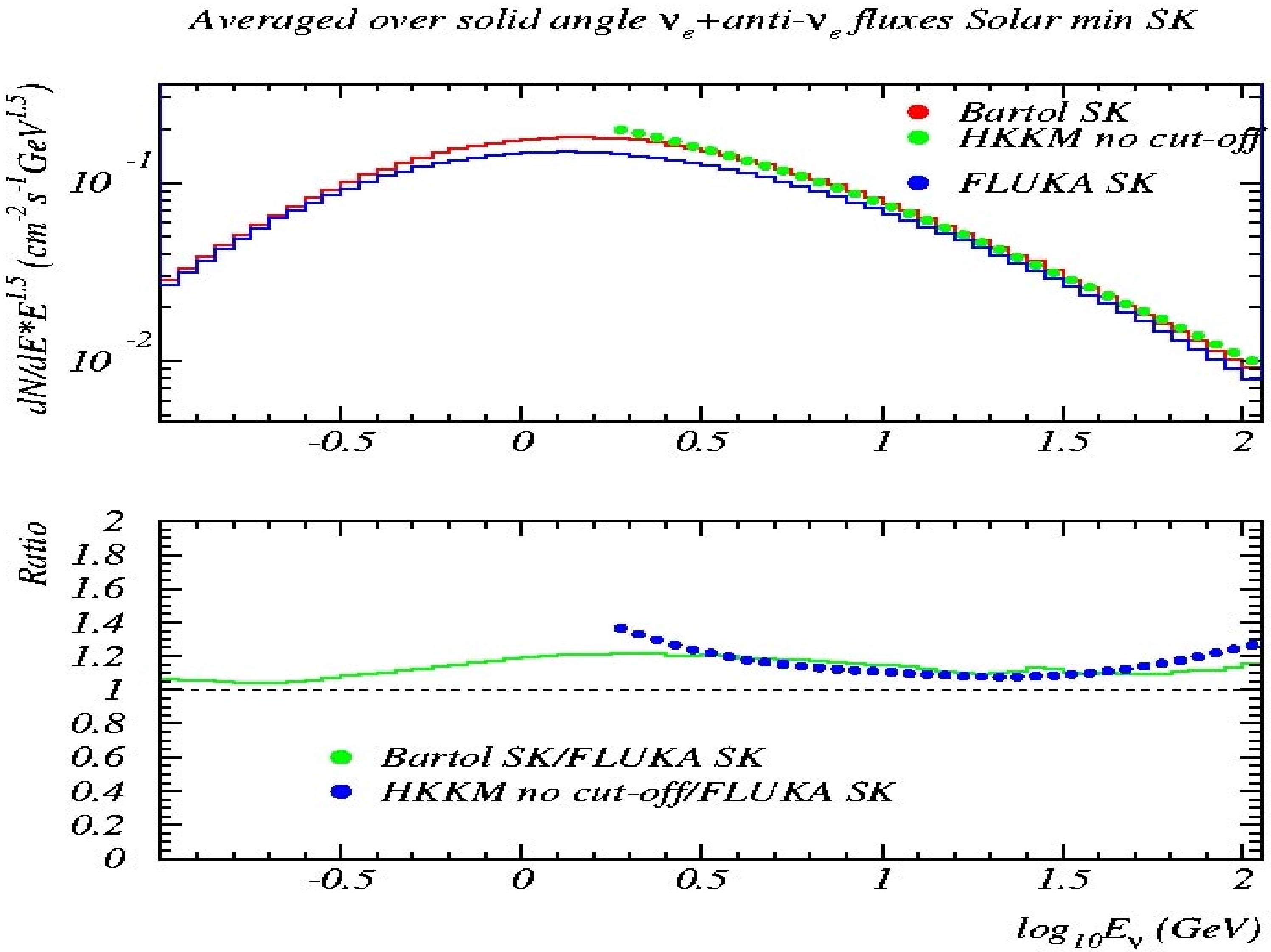
NEW FLUKA tables at http://www.mi.infn.it/~battist/neutrino.html: introduced solar mod. (new CR flux will be introduced through weights)

Comparison of vertical and horizontal νμ+anti-νμ fluxes



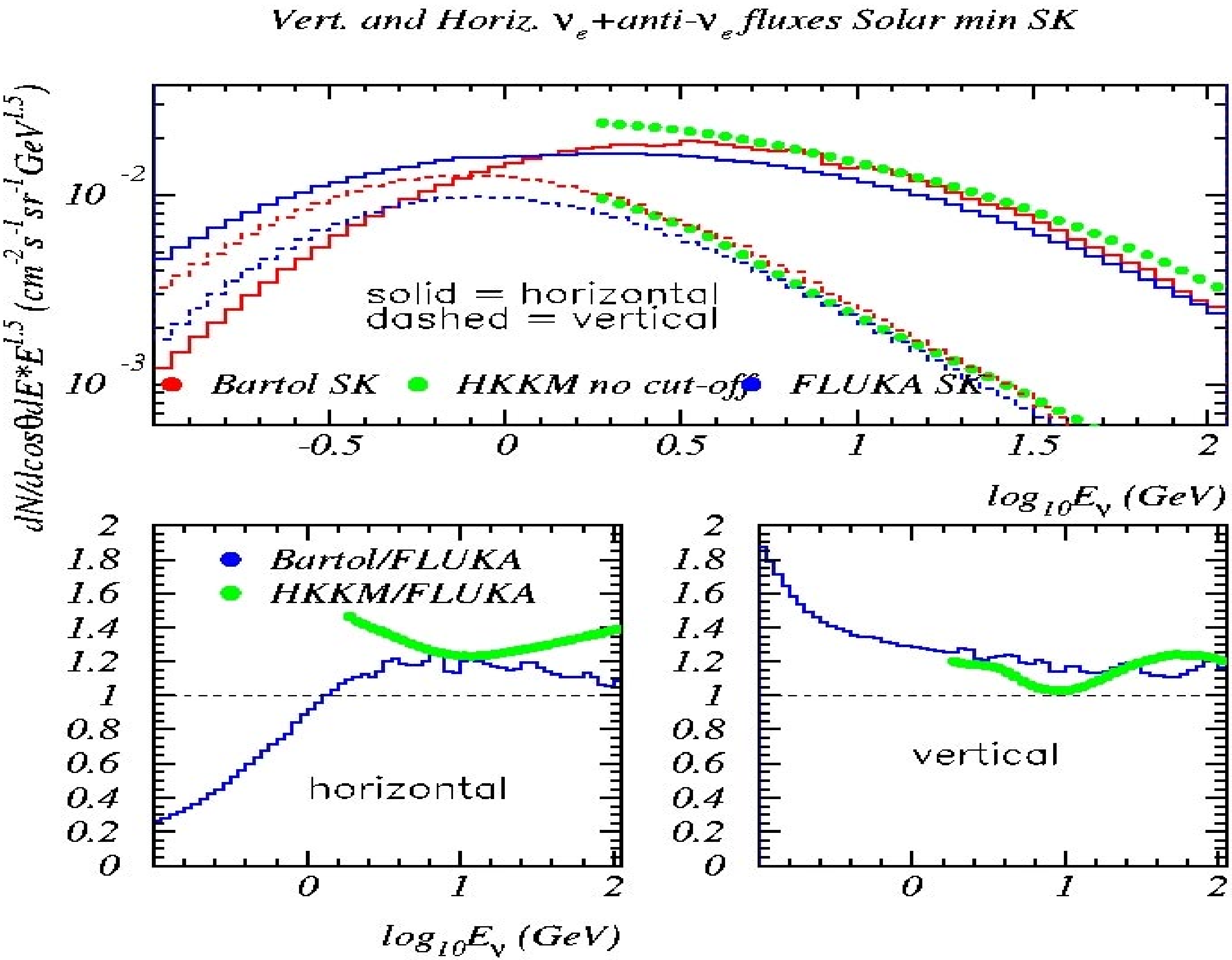
For Eν<600 MeV FLUKA 3D produces larger fluxes than Bartol at the horizon, lower at the vertical

Comparison of absolute νe+anti-νe fluxes



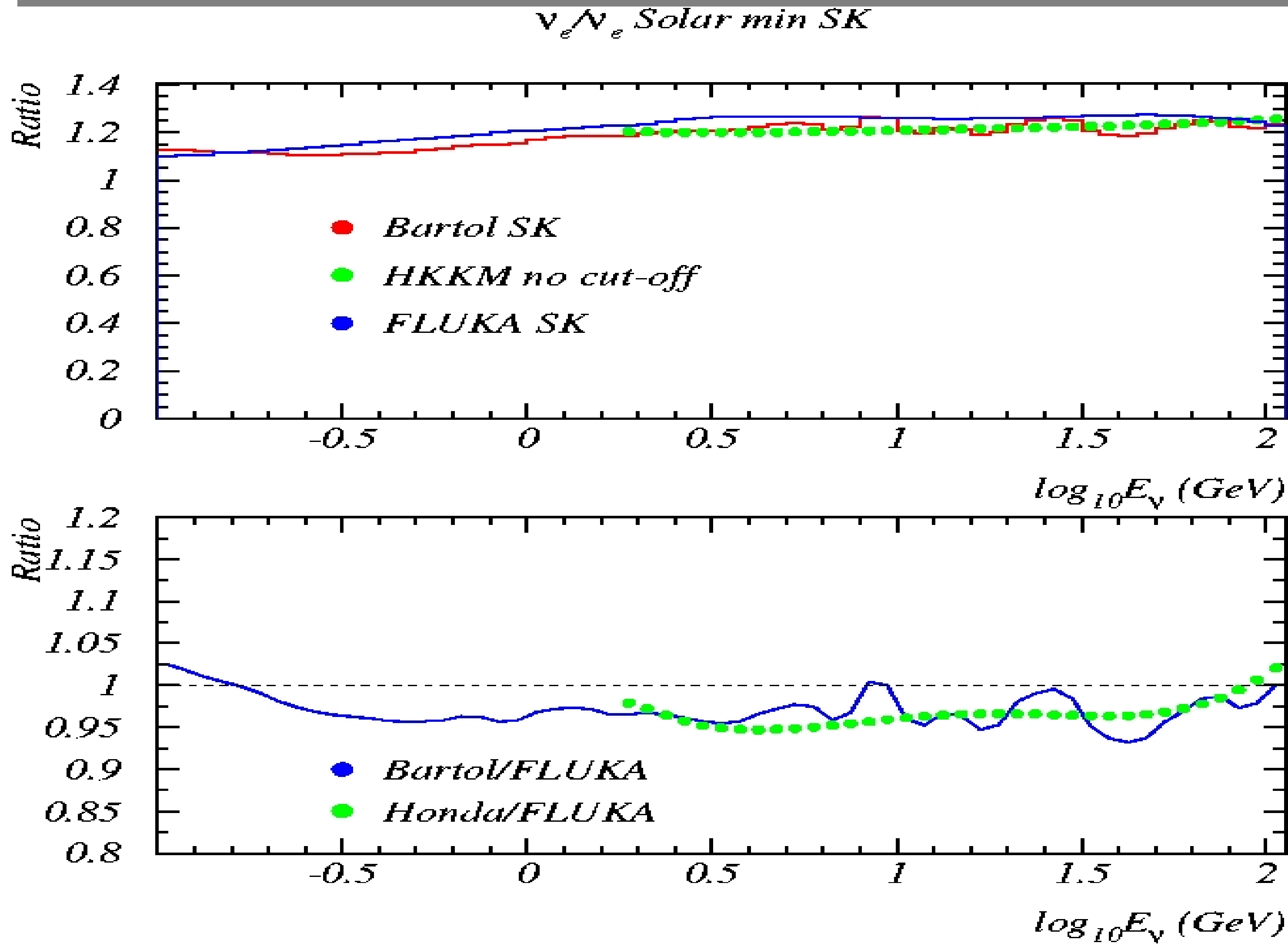
Average fluxes agree inside 10-20%

Comparison of vertical and horizontal νe+anti-νe fluxes



For Eν < 600 MeV FLUKA 3D produces larger fluxes at the horizon, lower at the vertical

Charge ratio comparison: νe/anti-νe



No experiment has measured charge ratio

Monolith: magnetic field

At $E \lesssim 2$ GeV

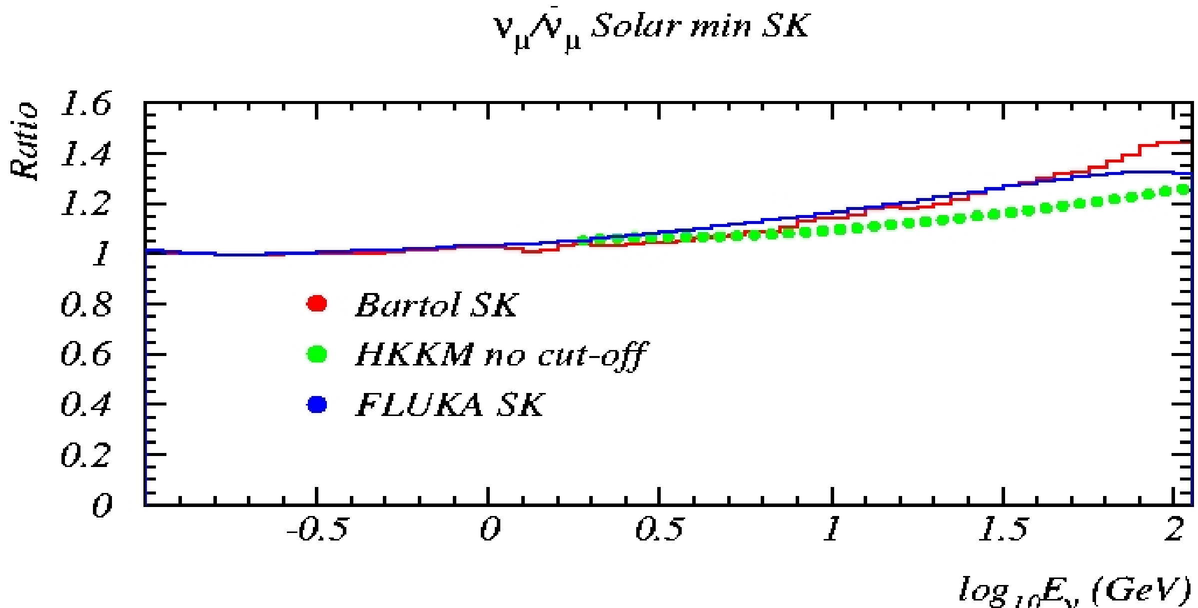
$$\frac{\nu_e}{\bar{\nu}_e} \leq \frac{\mu^+}{\mu^-}$$

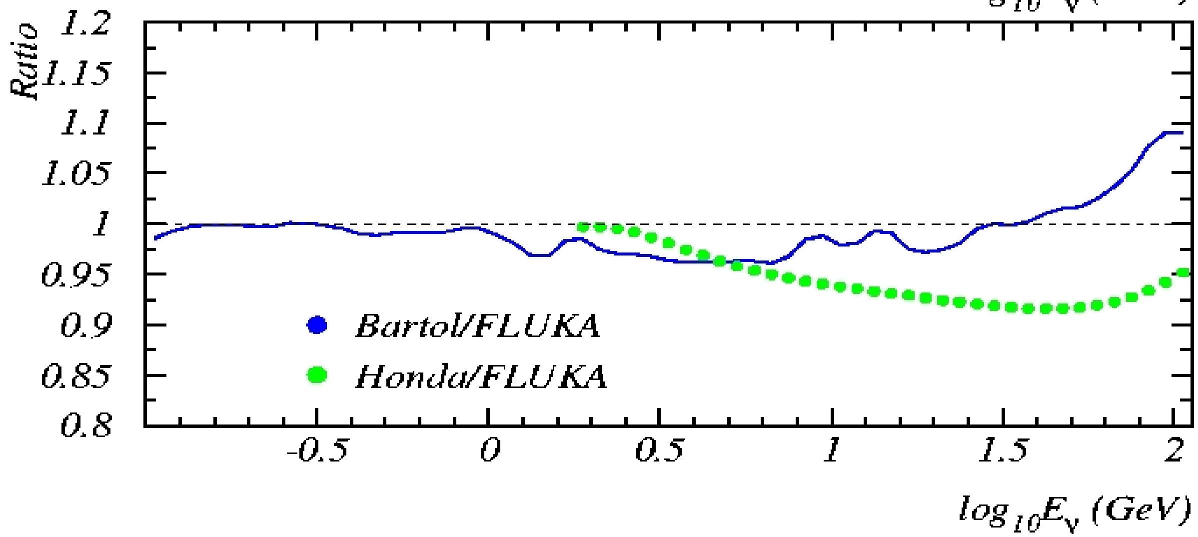
νe from μ decay + energy loss

Re reflects charge asymmetry in primary CRs proved by E-W asymmetry

At HE reflects K_L charge asymmetry

Charge ratio comparison: ν_μ/anti-ν_μ





When μ do not decay increase due to meson charge asymm.

Check for interaction models but large differences in charge ratio at HE do not affect current measurable quantities

E.g.: upgoing μ rate changes of factor 3 if $\frac{\phi_\nu}{\phi_{\bar{\nu}}} = 0 \rightarrow \infty$

Rate $= \Phi_\nu \sigma_\nu + \Phi_{\bar{\nu}} \sigma_{\bar{\nu}} =$

$(\Phi_\nu + \Phi_{\bar{\nu}})\sigma_{\bar{\nu}}\,(3r_\nu + (1 - r_\nu))$

$r_\nu = \Phi_\nu/(\Phi_\nu + \Phi_{\bar{\nu}})$ and $\sigma_{\bar{\nu}} \sim 3\sigma_\nu$

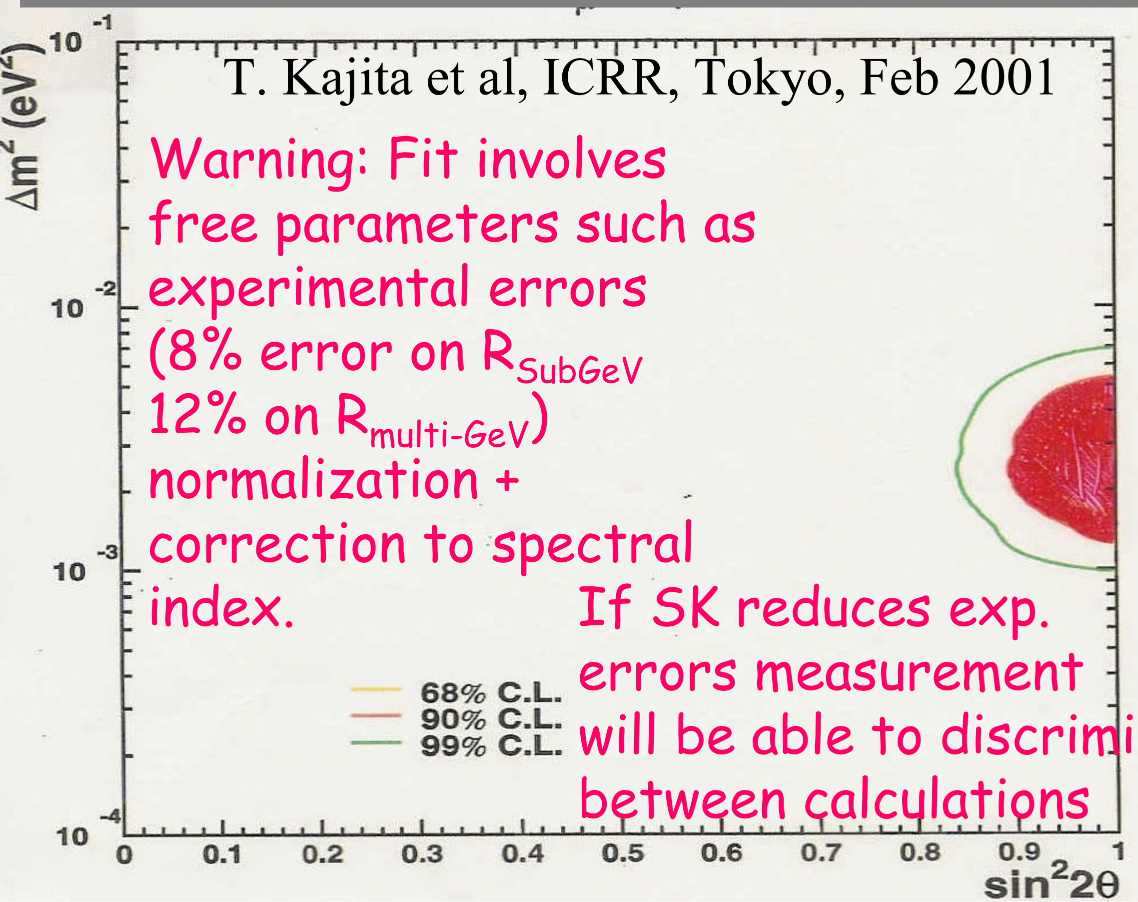
If $\Phi_\nu/\Phi_{\bar{\nu}} \rightarrow 0 \Rightarrow r_\nu \rightarrow 0 \Rightarrow$

Rate $\rightarrow (\Phi_\nu + \Phi_{\bar{\nu}})\sigma_{\bar{\nu}}$

If $\Phi_\nu/\Phi_{\bar{\nu}} \rightarrow \infty \Rightarrow r_\nu \rightarrow 1 \Rightarrow$

Rate $\rightarrow 3(\Phi_\nu + \Phi_{\bar{\nu}})\sigma_{\bar{\nu}}$

SK regions with FLUKA



T. Kajita et al, ICRR, Tokyo, Feb 2001

Warning: Fit involves free parameters such as experimental errors (8% error on R_{SubGeV} 12% on $R_{multi-GeV}$) normalization + correction to spectral index.

If SK reduces exp. errors measurement will be able to discriminate between calculations

Main differences: interaction model (Honda/Fluka) + CR spectrum

FC+PC 1290 days

Best fit $\nu_\mu \to \nu_\tau$:	FLUKA	Honda
Δm^2 (eV^2)	$2.4 \cdot 10^{-3}$	$2.4 \cdot 10^{-3}$
χ^2_{min}/dof	129.7/137	132.4/137
No oscillations		
χ^2_{min}/dof	308.5/139	229.3/139

Effect on absolute normalization

Sub-GeV	e	μ
FLUKA/Honda	0.88	1.19
FLUKA/Bartol	0.89	0.87

Effect on μ/e double ratio	Sub-GeV	Multi-GeV
	FLUKA/Honda ~4%	FLUKA/Honda ~0.7%
	FLUKA/Bartol ~3%	FLUKA/Bartol ~0.1%

Conclusions

A lot of comparison work is being done between models and data and between models themselves

Major changements for next future calculations are due to:

•Recent Precise measurements of primary CRs

•Accelerator data and atmospheric muon benchmarks (but ~10% error from experiments) which seem to favor FLUKA interaction model with respect to models producing higher π/K multiplicities

Effects at %level are investigated to reach a very good description of shower propagation, interactions, geomagnetic field, solar modulation

Normalization error will probably be decreased at 15% level but **reliable measurement are flavor ratio, asymmetry, shape of HE angular distibution (all this changements produce negligible effects for Δm^2 evaluation)**

If SK, Soudan2, MACRO will be able to reduce exp. errors measurements can be used to constrain calculations

Future experiments (HARP and hopefully others at higher energies) will provide necessary knowledge for future generation experiments towards an exact determination of Δm^2 and channel

Future experiments improving cross section knowledge are needed

Neutrinos from meson decay

M = π,K

kinematic factor

$$\frac{dN}{dE\,dE_M\,dE_N\,dX} = \frac{S(E,E_M)}{(1-r_M)E_M}\,\frac{1}{d_M} \times \int_0^X \frac{dX'}{\lambda_N}\, P_M(E_M,X,X') \times \frac{1}{E_M}\, F_{NM}(E_M,E_N)$$

$$r_M = \frac{m^2_{\mu,\nu}}{m^2_M}$$

$$\times e^{-X'/\Lambda_N}\,\phi(E_N)$$

nucleon spectrum @ depth X’

CR spectrum with int. spectral index γ

inclusive cross section p,N+Air →π+X

$\Lambda_N, \lambda_N \equiv$ nucleon attenuation / interaction length ~ 120 / 86 g/cm²

$$\frac{1}{d_M} = \frac{\varepsilon_M}{E_M X \cos\vartheta}$$ ≡ decay probability ($\varepsilon_\pi = 115$ GeV $\varepsilon_K = 850$ GeV)

$P_M(E_M, X, X') \equiv$ survival probability (decay and interaction) of meson

$$Z_{N\to\pi} = \int_0^1 dx\,(x)^{\gamma-1} F_{N\to\pi}(x)$$

scaling approximation (x =Esec/Epr)

Z -factors to compare interaction models in regions where γ is constant