Tau Neutrino Appearance in Atmospheric Neutrinos

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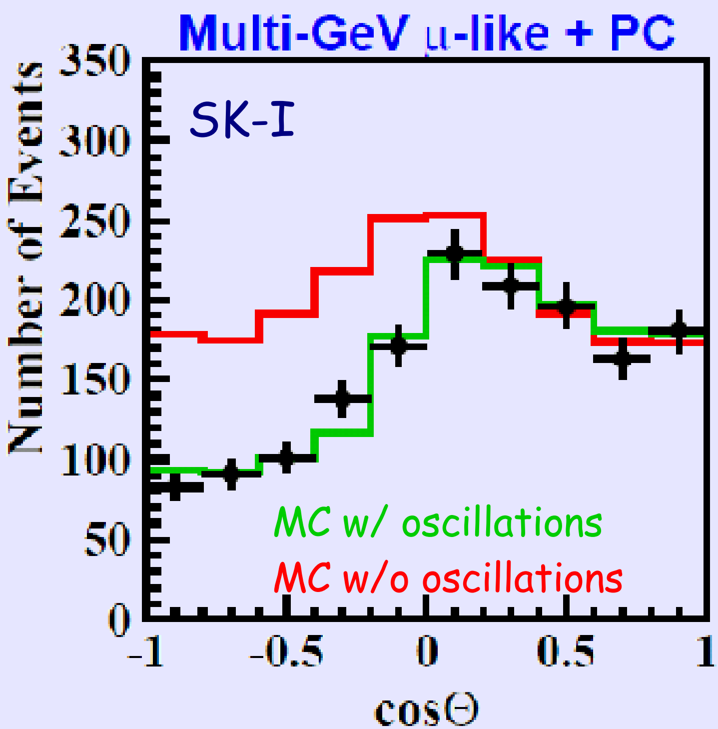
Search for ν_τ Appearance

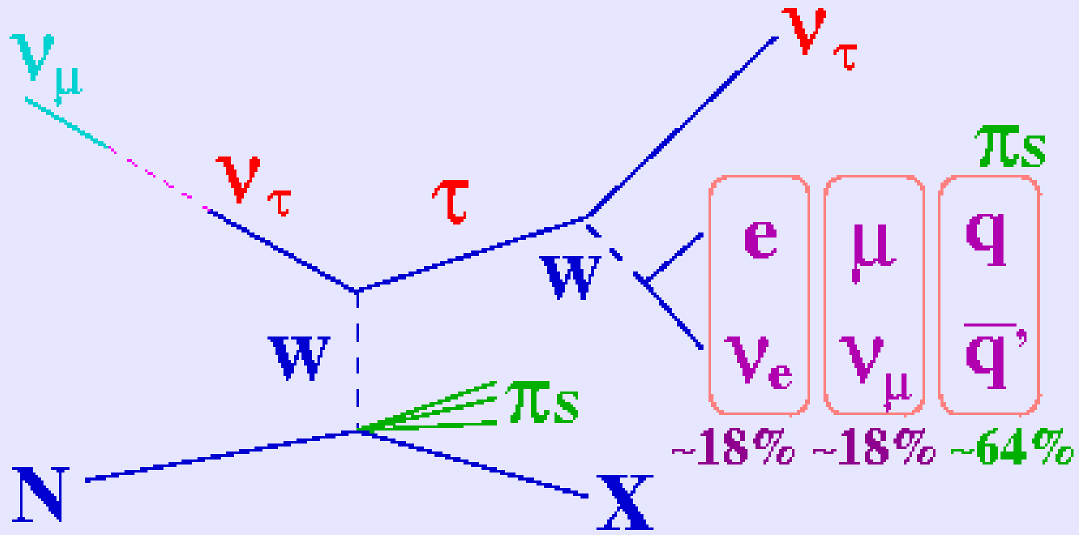
Motivation: $\nu_\mu \leftrightarrow \nu_\tau$ oscillation scenario of atmospheric neutrinos well-established via ν_μ disappearance (*See Okumura's talk*). However, no direct evidence for **ν_τ appearance** observed yet. Look for tau leptons produced in ν_τ CC interactions in Super-Kamiokande detector.



- 78 ν_τ CC events expected in SK-I (1489.2 days) for $\Delta m^2 = 2.4\times10^{-3}$ eV^2 with maximal mixing.
- Signal/Noise: ~ 0.7%

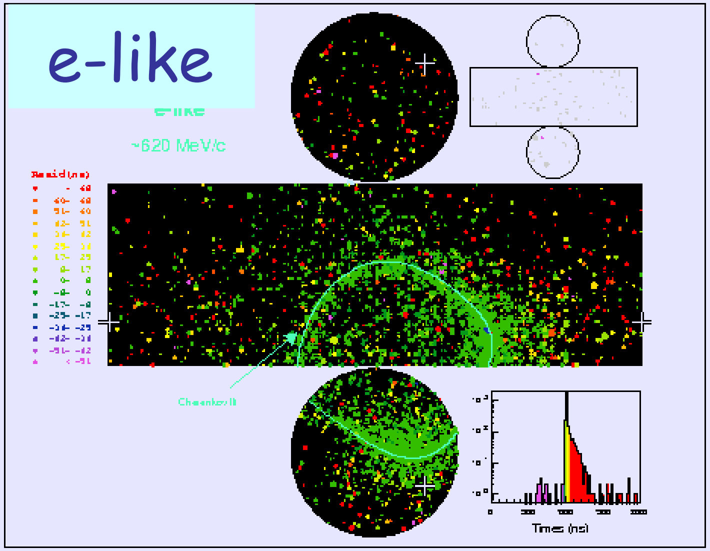
Signature of Tau events

- Signal events: ν_τ
  - Energy threshold for ν_τ to produce τ: 3.5 GeV.
  - Many Pions (high multiplicity).
  - More isotropic events than BKGs.
- Background events: ν_e , ν_μ
  - DIS events with pions.
  - Lower multiplicity.

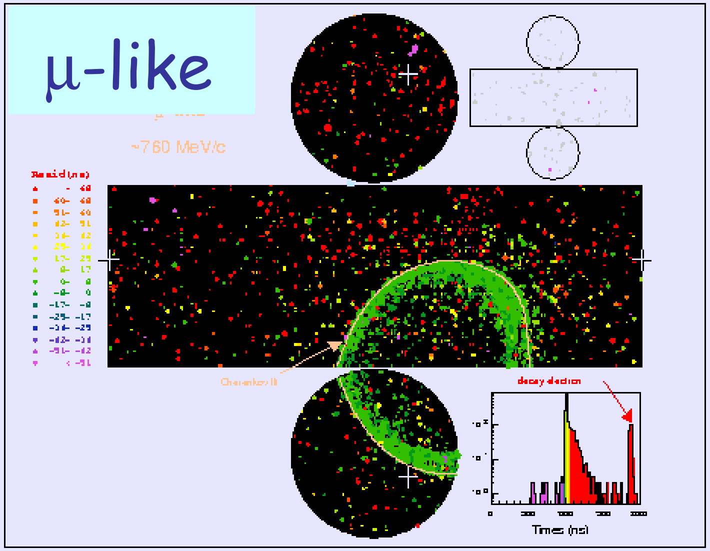


Tau event in Super-K

e-like

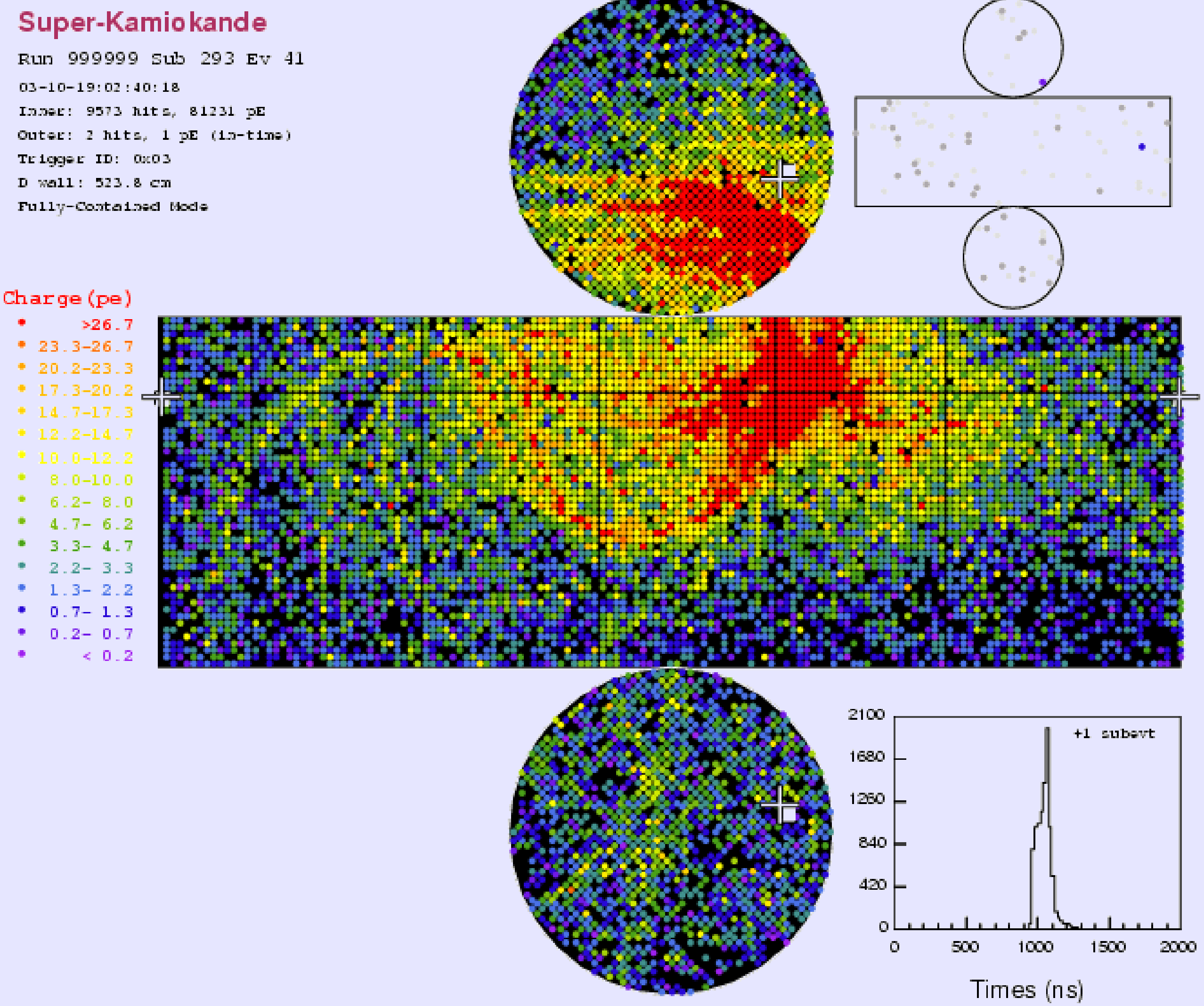


μ-like



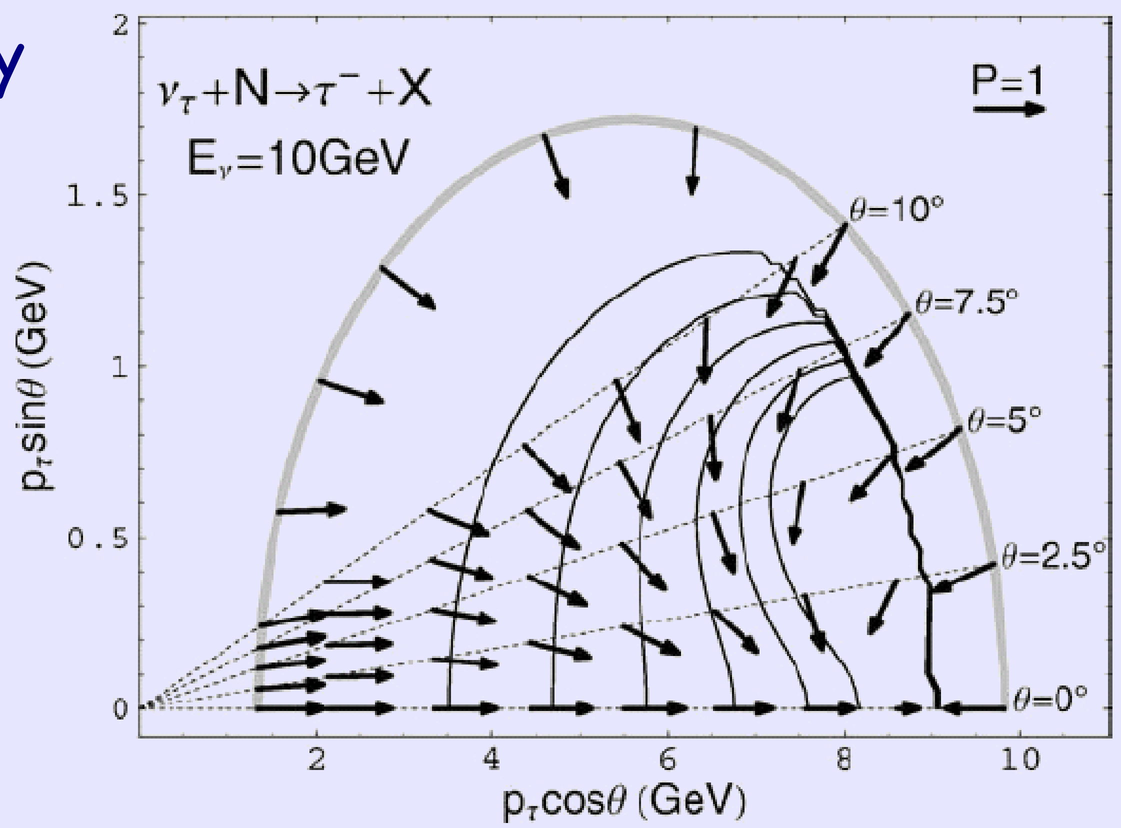
MC τ event

High energy - DIS events dominate



Tau Polarization

- The distributions of decay particles from tau leptons depend on the spin.
- In our Tau MC, the polarization of tau leptons is implemented, based on the calculations by Hagiwara et. al.



Hagiwara et.al: Nucl. Phys. B668, 364-384 (hep-ph/0305324)

ν_τ Event Selection

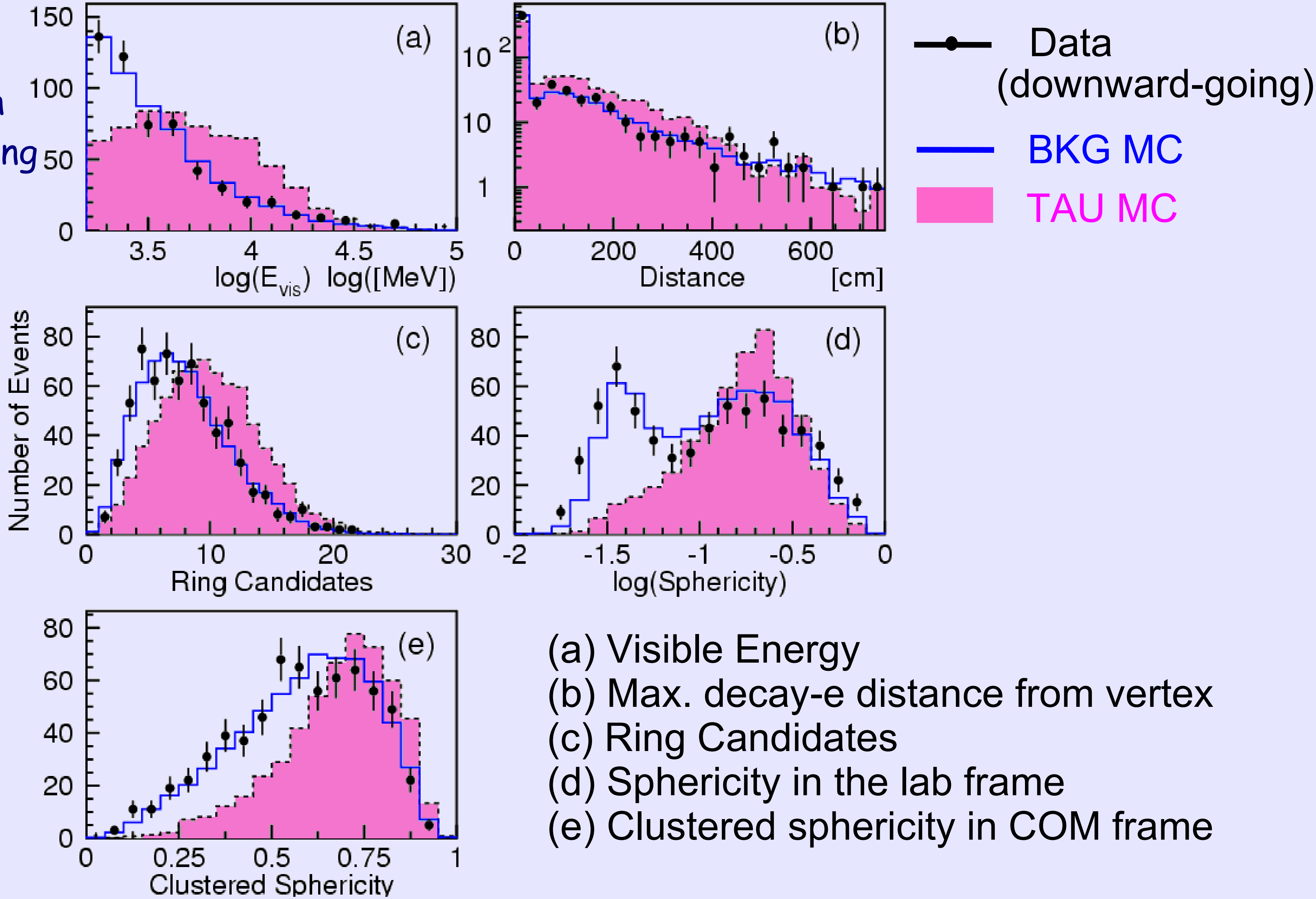
- Tau neutrino event selection criteria:
  - Fiducial Volume: 2m from the ID PMTs (Fully-Contained)
  - Visible Energy (Evis) > 1.33 GeV (Multi-GeV)
  - Most energetic ring is electron-like. (Showering events)

These 3 cuts reject approximately 90% of the backgrounds.

Likelihood ⇐ ⇒ Neural Network

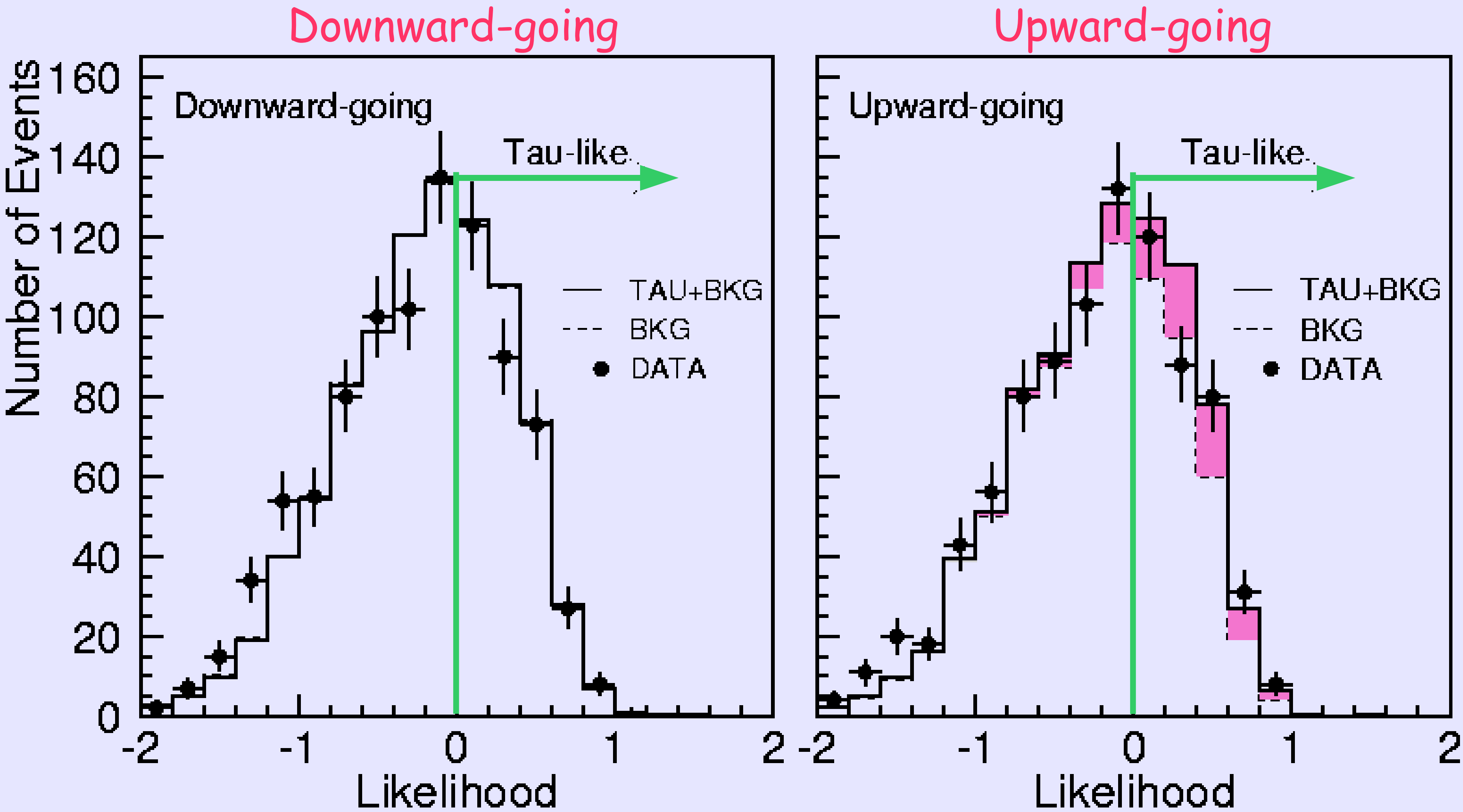
Likelihood Variables

Compare the variables with downward-going data (no tau events).



(a) Visible Energy
(b) Max. decay-e distance from vertex
(c) Ring Candidates
(d) Sphericity in the lab frame
(e) Clustered sphericity in COM frame

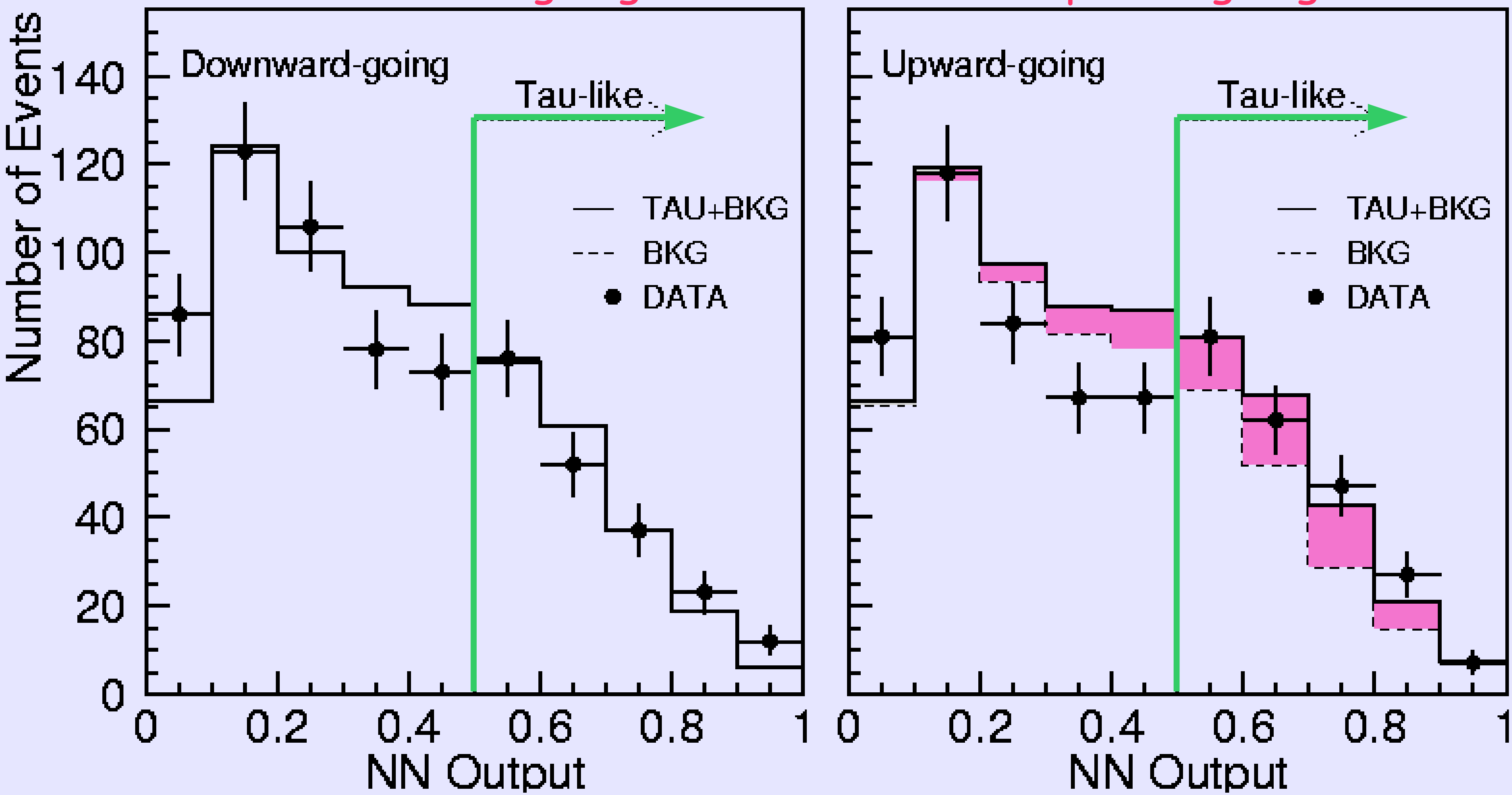
Likelihood Analysis



Likelihood > 0 is defined to be tau-like.

Neural Network Analysis

Downward-going | Upward-going



NN output > 0.5 is defined to be tau-like.

Event Summary

	Data	BKG MC	Tau MC
Generated in fiducial volume	-	17135 (100%)	78.4 (100%)
Evis > 1.33 GeV	2888	2943 (17.2%)	51.5 (65.7%)
Most Energetic ring e-like	1803	1765 (10.3%)	47.1 (60.1%)
Likelihood > 0.0	649	647 (3.79%)	33.8 (43.1%)
Neural network > 0.5	603	577 (3.36%)	30.6 (39.0%)

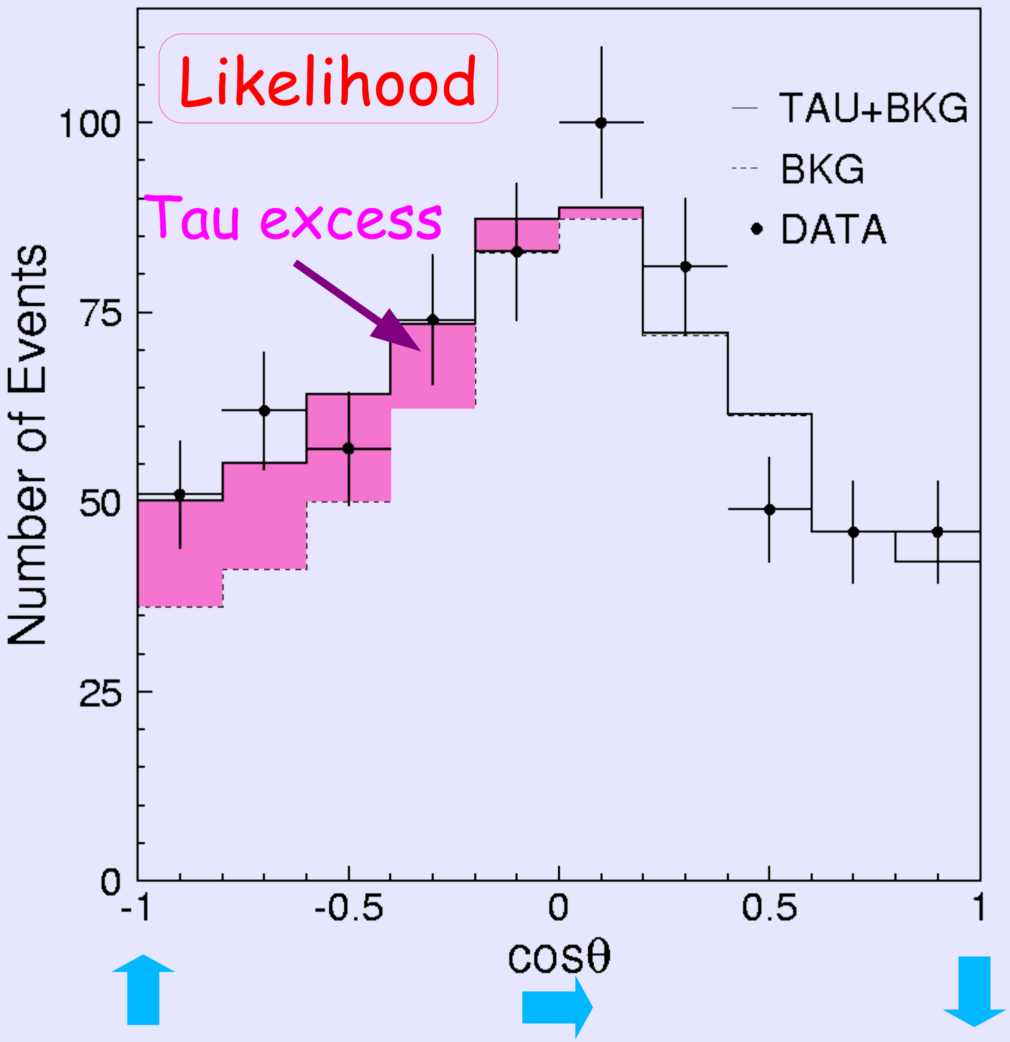
After all of tau neutrino event selection cuts and the likelihood cut (neural network cut):

Backgrounds: 96% (97%) rejected

Signals: 43% (39%) survived

Zenith Angle Distribution

Fit to Distribution: $N_{total}(\cos(\theta)) = \alpha N_{TAU} + \beta N_{BKG}$



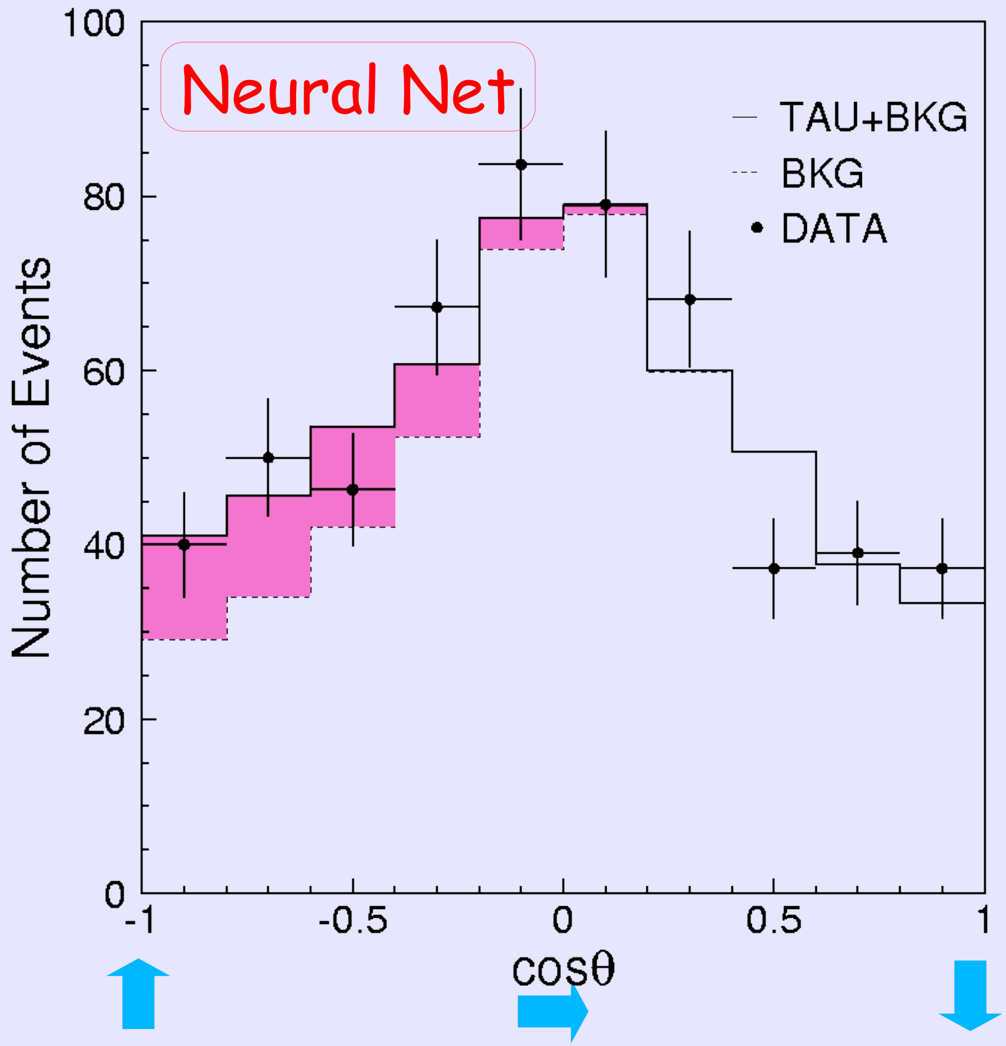
- Tau Normalization (α) = 1.76
- Bkg Normalization (β) = 0.90
- χ^2/DOF = 7.6/8
  (χ^2/DOF = 16.3/9 assuming no tau appearance)

Result:

- Fitted τ excess: 59.6 ± 20.7
- Total τ excess: 138 ± 48(stat.)
  (signal efficiency: 43.1%)

Zenith Angle Distribution

Fit to Distribution: $N_{total}(\cos(\theta)) = \alpha N_{TAU} + \beta N_{BKG}$



- Tau Normalization (α) = 1.71
- Bkg Normalization (β) = 0.99
- χ^2/DOF = 9.8/8
  (χ^2/DOF = 18.2/9 assuming no tau appearance)

Result:

- Fitted τ excess: 52.3 ± 18.7
- Total τ excess: 134 ± 48(stat.)
  (signal efficiency: 39.0%)

Systematic uncertainty

- Sys. Error: Expected # of Tau:
  - SK atm ν osc. analysis (23 terms): standard uncertainties
  - Tau related: cross section, polarization, tau likelihood eff. etc.
- Sys. Error: Observed (fitted) # of Tau:
  - Up/Down asymmetry (Flux:Up/Down, Horizontal/Vertical etc.)
  - Oscillation parameters: Δm^2, $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{13}$

Systematic Uncertainty	Likelihood	Neural Network
Expected # of Tau	± 32.6%	± 34.4%
Observed # of Tau	+10.7% / -22.9%	+12.0% / -20.3%

Systematic uncertainty

Errors on the expected # of taus.

Systematic uncertainties for expected tau	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis (23 error terms)	21.6	20.2
Tau related:		
Tau neutrino cross section	25.0	25.0
Tau lepton polarization	7.2	11.8
Tau neutrino selection efficiency	0.4	0.5
LH selection efficiency	4.8	-
NN selection efficiency	-	3.0
Total:	32.6	34.4

Errors on the observed # of taus.

Systematic uncertainties for observed tau	LH (%)	NN (%)
Super-K atmospheric ν oscillation analysis:		
Flux up/down ratio	6.5	5.7
Flux horizontal/vertical ratio	3.6	3.2
Flux K/π ratio	2.4	2.8
NC/CC ratio	4.3	3.8
Up/down asym. from energy calib.	1.4	< 0.1
Oscillation parameters:		
$0.0020 < \Delta m^2 < 0.0027$ eV^2	+5.8/-2.6	+8.8/-3.3
$0.93 < \sin^2 2\theta_{23} < 1.00$	-3.3	-3.9
$0.00 < \sin^2 2\theta_{13} < 0.15$	-20.6	-17.9
Total:	+10.7/-22.9	+12.0/-20.3

Results

- **Likelihood analysis:**
  - Observed ν_τ excess: 138 ± 48(stat.) + (+14.8/-31.6)(sys.)
  - Expected ν_τ excess: 78.4 ± 26(sys.)
- **Neural Net analysis:**
  - Observed ν_τ excess: 134 ± 48(stat.) + (+16/-27.2)(sys.)
  - Expected ν_τ excess: 78.4 ± 27(sys.)

Super-Kamiokande observed ν_τ excess events consistent with expected number of ν_τ events. This disfavors the no tau appearance hypothesis with a significance of 2.4σ.

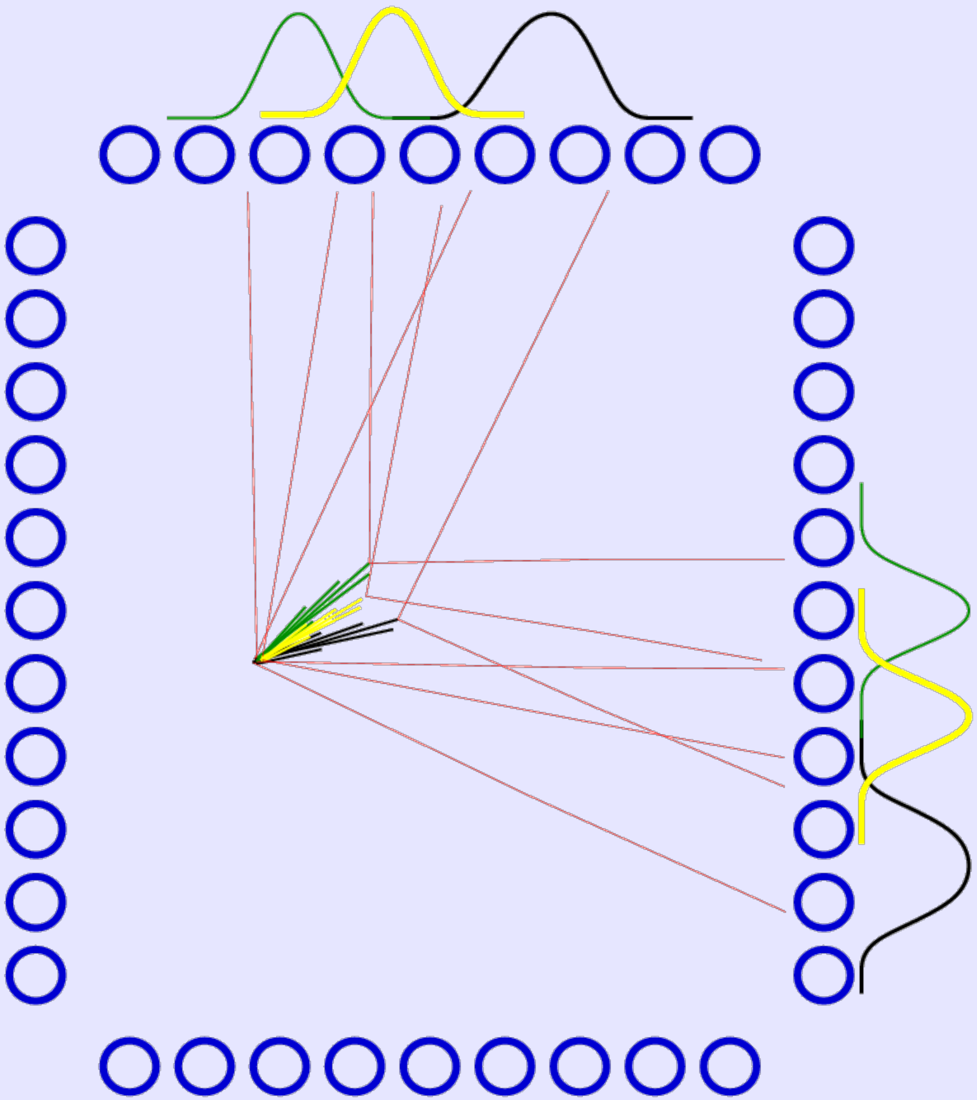
Conclusions

- ν_τ appearance search in Super-K finds that SK-I data are consistent with the expectation from neutrino oscillations with a significance of 2.4σ.
- Paper has been recently published in Physical Review Letters: Vol 97 Issue 17, Page 171801.

Happy Halloween!!!

Supplement

Energy Flow Analysis



- Energy flow is deconvolved with Cherenkov patterns observed.
- Energy Flow in each direction is assigned to a "pseudo-particle" and jets are reconstructed.
- Using "jets", the event shape variable, i.e. sphericity is obtained.

Sphericity

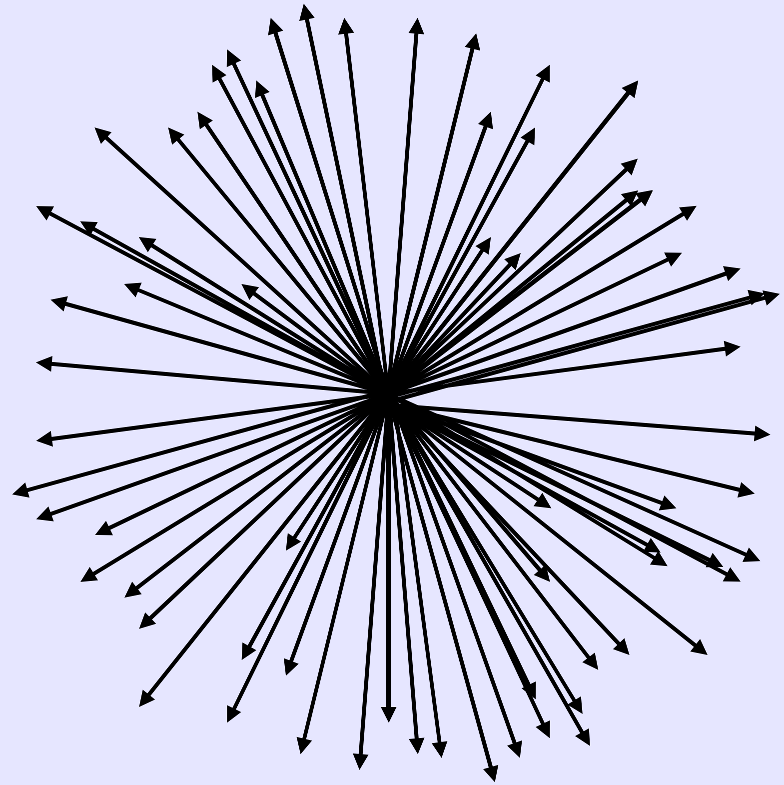
Describes isotropy of energy flow

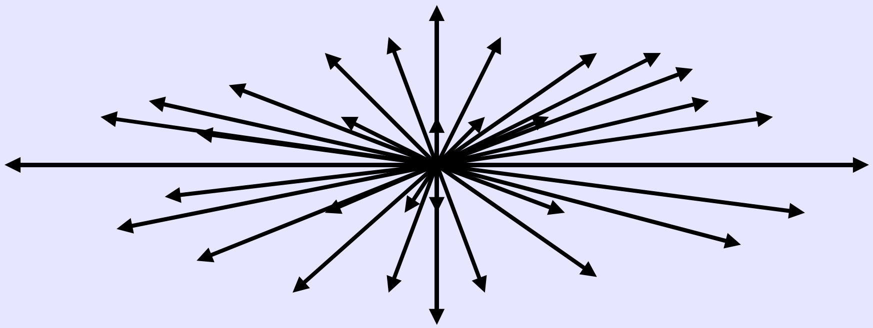
- Measure of the summed p^2_T wrt. Sphericity axis

$$S = \frac{3}{2}(\lambda_2 + \lambda_3)$$

$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}$$

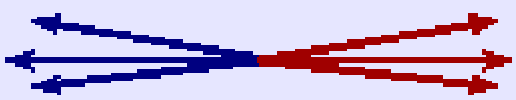
$$0 \le S \le 1$$



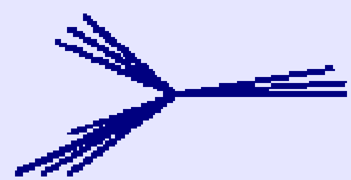


Sphericity

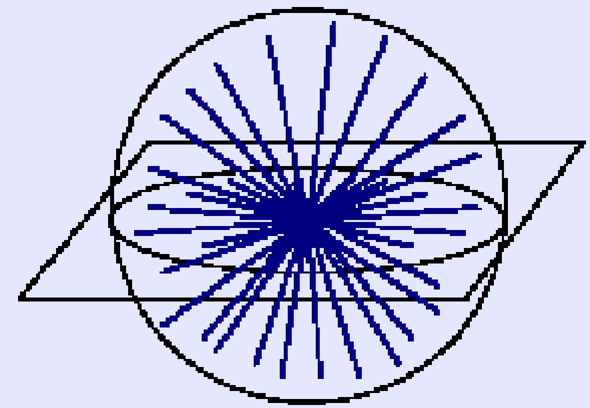
Collimated



Planar

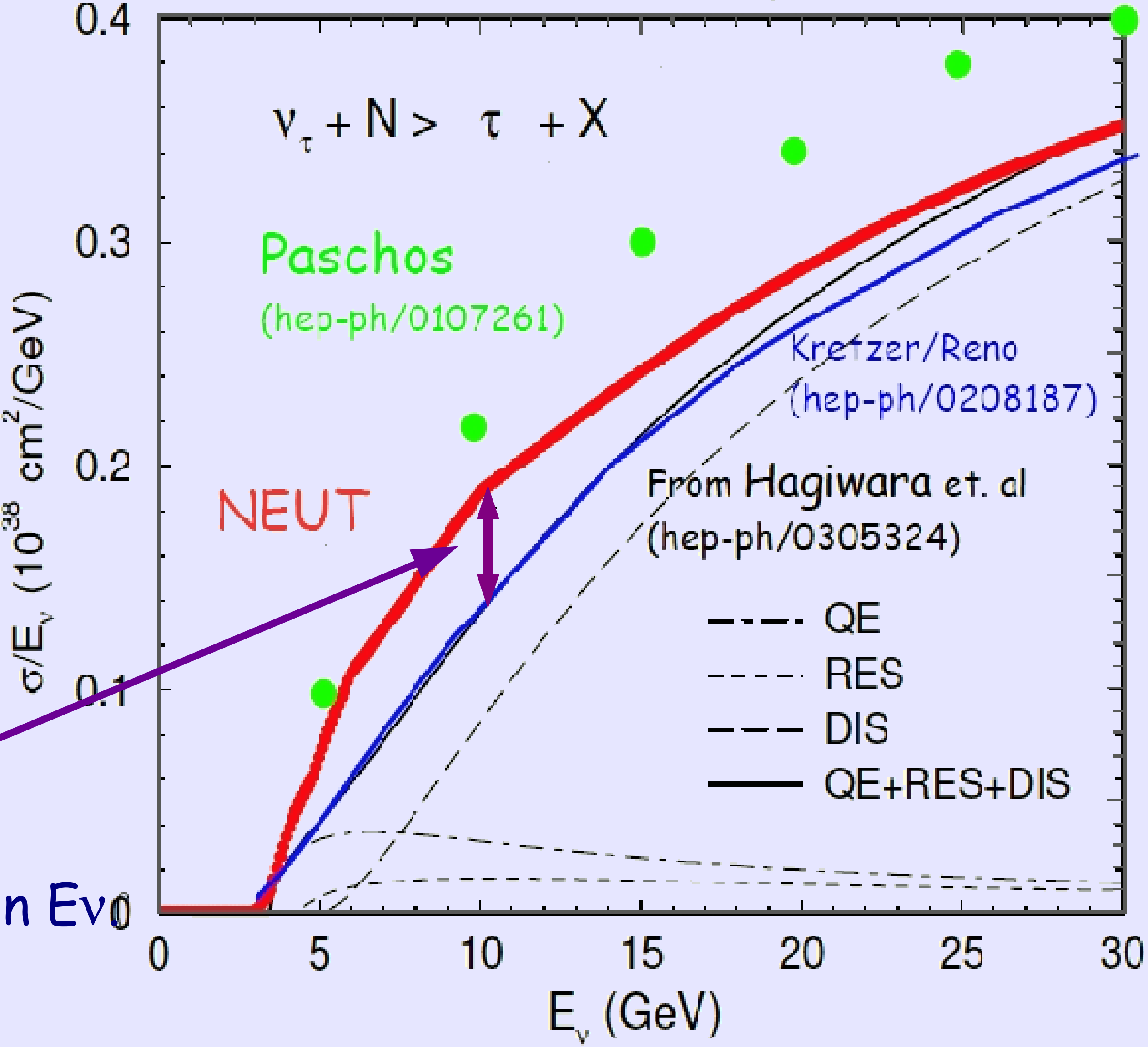


Isotropic



S = 0 → Increase → S = 1/2 → Increase → S = 1

ν_τ Cross-section



NEUT vs. Hagiwara et.al

Uncertainty depending on Eν

The consistency of the two analyses is also checked and 83% of the selected tau-like events are in common.