Coincident Event Analysis in IceCube

Tom Feusels

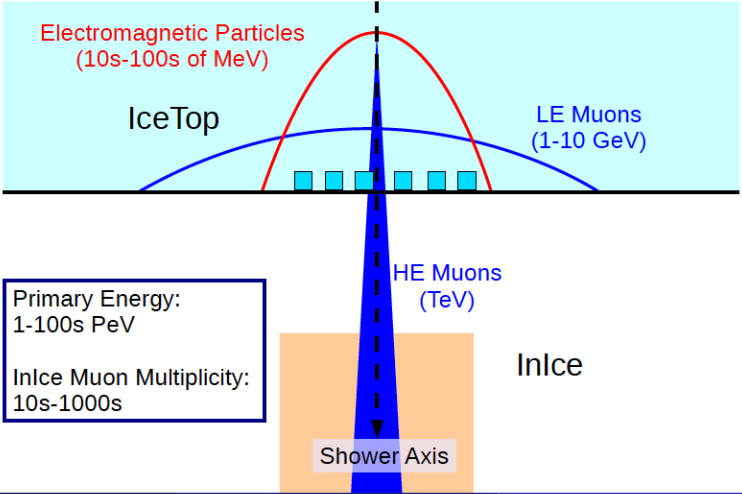
UGent

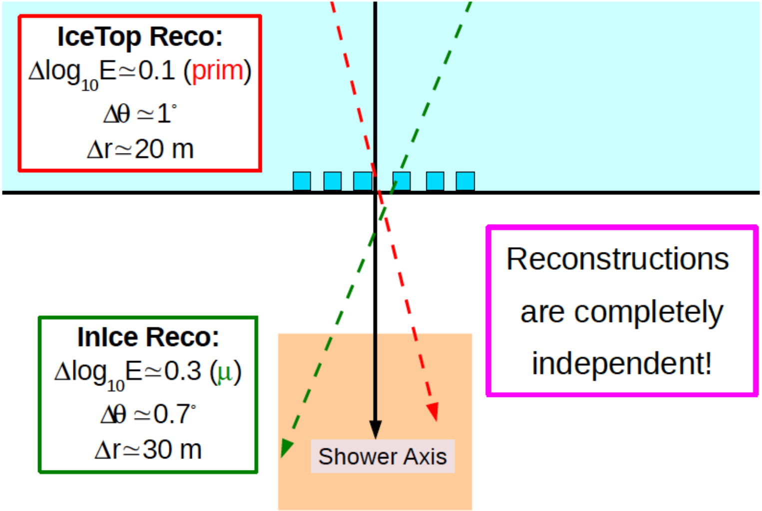
CR Workshop Zeuthen, 23/02/2010

Overview

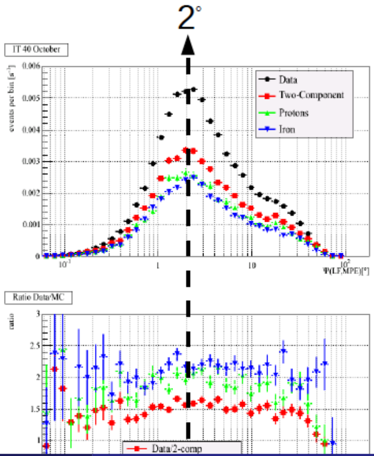
1. Coincident direction reconstruction
   - Independent reconstruction
   - Combined iterative reconstruction
2. Neural Net Analysis
3. Muon Bundle Energy Loss reconstruction

Coincident measurements with IceCube




IceTop Reco:
Δlog10E≃0.1 (prim)
Δθ ≃1°
Δr≃20 m
InIce Reco:
Δlog10E≃0.3 (μ)
Δθ ≃0.7°
Δr≃30 m
Shower Axis
Reconstructions are completely independent!

IceTop-IceCube Space Angle Difference



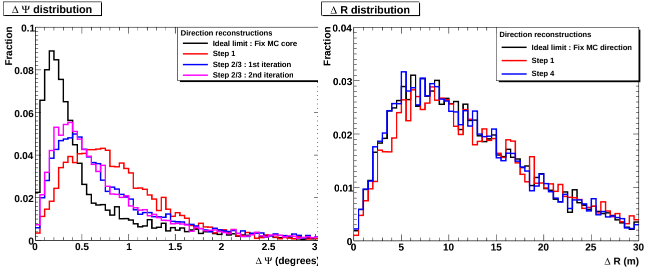
Direction reconstruction of muon bundles

Method :

1. $(t_i, N_{\mathrm{PE}_i})_{\mathrm{IceTop}} \rightarrow \theta, \phi, (X, Y)_{\mathrm{core}}$: Through a lateral signal distribution fit.
2. Fix $(X, Y)_{\mathrm{core}}$ & create a large lever arm.
3. $(N_{\mathrm{PE}_i})_{\mathrm{IceCube}} \rightarrow \theta', \phi'$: Using a simple muon bundle reconstruction which also describes range-out.
4. Fix $\theta', \phi' \rightarrow (X', Y')_{\mathrm{core}}$: With the IceTop lateral distribution fit.

Resolution

Fe:



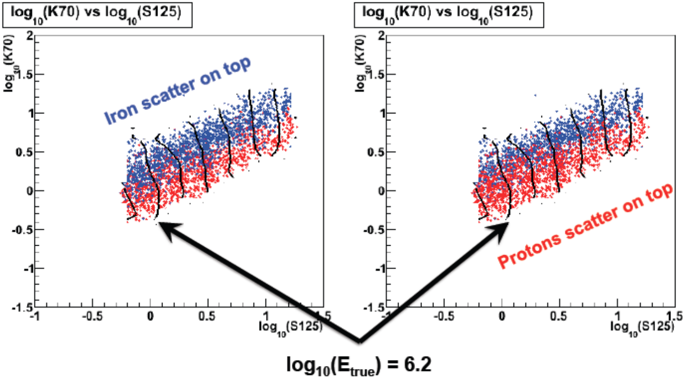
- Ideal limit for core/direction reconstruction → fix MC direction/core position.
- After 2 iterations of IceTop - IceCube algorithms → no more improvement.
- Core resolution limits angular resolution.

68.3% resolution	p	Fe
$\sigma(\Delta R)$	12.5 m	14.0 m
$\sigma(\Delta\Psi)$	0.8°	0.9°

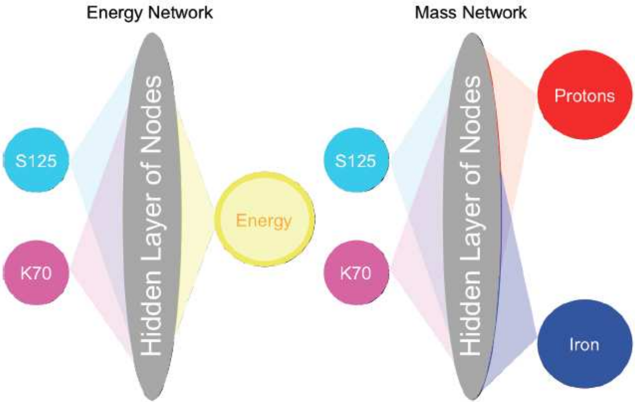
Neural Net Analysis (Karen Andeen)

- Goal : E0, A.
- Needed : Observables sensitive to E0 and A.
- S125 from IceTop Lateral Distribution function, sensitive to E0 and A.
- K70, average light intensity at 70m from bundle in center of IceCube detector, sensitive to E0 and A.
- K70 : obtained from older(AMANDA-era), simple parametrization, which takes into account light propagation, range-out and ice model.

S125 vs K70


log10(K70) vs log10(S125)
log10(K70)
log10(S125)
Iron scatter on top
log10(K70) vs log10(S125)
log10(K70)
log10(S125)
Protons scatter on top
log10(Etrue) = 6.2

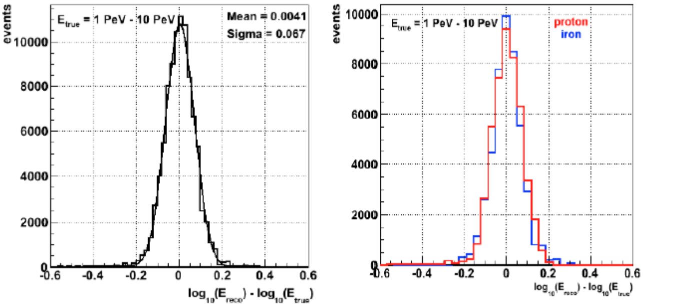
Neural Net principle



Still needs to be optimized: currently using 8 nodes for Energy, and 5 for Mass

Neural Net Energy Output

IT/IC 40

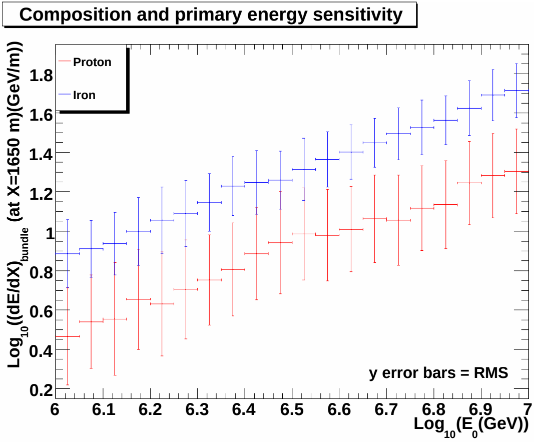


Protons: σ = 6.7% log(E), mean = 0.008
Iron: σ = 6.8% log(E), mean = 0.002

Why looking at muon bundle energy loss?

1. $\left(\frac{dE_\mu}{dX}\right)(X) = f(A, E_0)$
2. IceCube cannot separate single muons in a bundle (large string spacing).
3. IceCube detects Cherenkovlight, caused (mainly) by energy loss processes.

Muon Bundle Energy Loss in IceCube



$$\left(\frac{dE_\mu}{dX}\right)_{\text{bundle}}(X) = \int_{E_{min}}^{E_{max}} \frac{dN_\mu}{dE_\mu}\frac{dE_\mu}{dX}\, dE_\mu \text{ where } \frac{dN_\mu}{dE_\mu}(A, E_0, \theta, E_\mu, X)$$

Muon Bundle Energy Loss Reconstruction

START : single muon energy loss algorithm

- Likelihood : $\mathcal{L} = \prod^{\text{modules}} \prod^{\text{pulses}} P(\{N_{\text{PE}}(\text{t})_{\text{measured}}\}|\{N_{\text{PE}}(\text{t})_{\text{expected}}\})$
- Muon light model = infinite track of electromagnetic cascades.
- Ice properties and Čerenkov photon propagation.

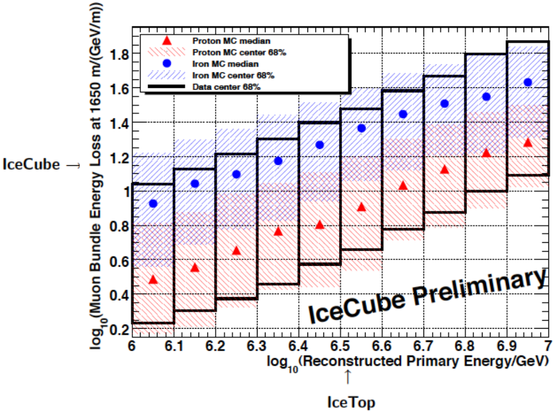
For muon bundles :

- $N_{\text{PE}}(\text{t})_{\text{measured}} \propto \left(\frac{dE_\mu}{dX}\right)_{\text{bundle}}(X) = \int_{E_{min}}^{E_{max}} \frac{dN_\mu}{dE_\mu} \frac{dE_\mu}{dX} dE_\mu$
- Approximation of Elbert formula for muon multiplicity + energy loss $\Rightarrow \left(\frac{dE_\mu}{dX}\right)_{\text{bundle}}(X)$

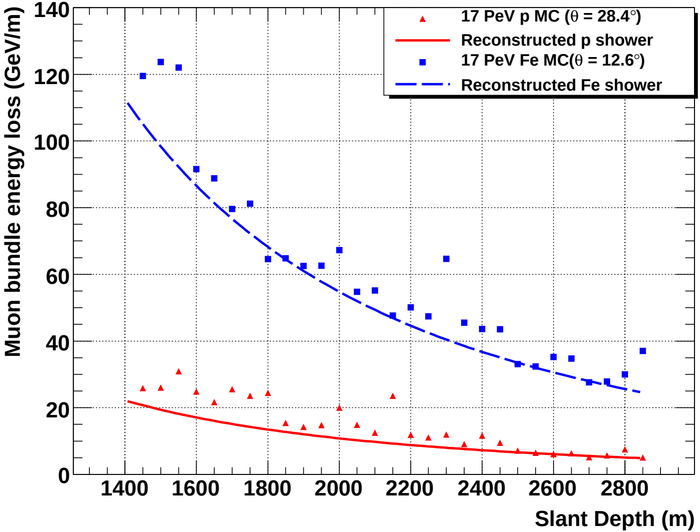
$$\downarrow$$

$$N_\mu(E_\mu > E_{\mu_{thr}}) = \kappa(A) \left(\frac{E_0}{A}\right)^{\gamma_\mu - 1} E_\mu^{-\gamma_\mu}$$

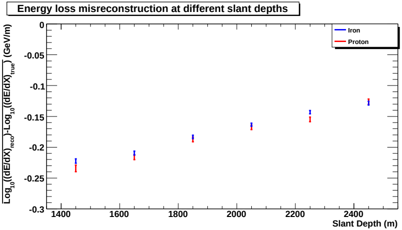
First result

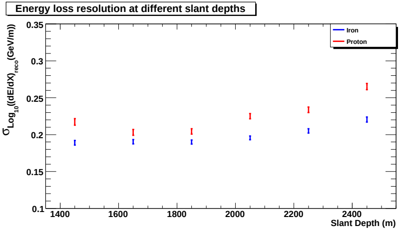


Example of two reconstructed events



Performance





Energy loss shift :

- Shift of ≈ 0.2 with a slope.
- Cause : overestimation of expected charge by MC.

Energy resolution :

- $\sigma \approx 0.2$
- larger for proton showers, since $N_\mu(Fe) > N_\mu(p)$ $\langle E_\mu(Fe)\rangle < \langle E_\mu(p)\rangle$

Summary and outlook

- With coincident events we can obtain an angular resolution ¡ 1°, and a core resolution of 12-14m.
- Neural Net analysis with current algorithms looks also promising for IceTop-IceCube.
- Muon bundle energy loss behaviour can be reconstructed in IceCube with a resolution of about 0.2 in log10(dE/dX).
- The spread in data is similar as the spread in combined p + Fe MC.
- Lot of improvements under way (to get rid of bias and get a primary mass estimate)
- Next step : studying and implementing energy loss fluctuations.

Technical Details

$\left(\frac{dE_\mu}{dX}\right)_{\text{bundle}}(X) = \int_{E_{min}}^{E_{max}} \frac{dN_\mu}{dE_\mu}\frac{dE_\mu}{dX} dE_\mu$:

- Elbert formula approximation : $N_\mu(E_\mu > E_{\mu_{thr}}) = \kappa(A)\left(\frac{E_0}{A}\right)^{\gamma_\mu - 1} E_\mu^{-\gamma_\mu}$, with $\kappa(A) = \frac{14.5\text{GeV}\,A}{\cos(\theta)}, \gamma_\mu = 1.757$
- Thus : $\frac{dN_\mu}{dE_\mu} = \gamma_\mu \kappa(A)\left(\frac{E_0}{A}\right)^{\gamma_\mu - 1} E_\mu^{-\gamma_\mu - 1}$
- The average energy loss behaviour is : $\frac{dE_\mu}{dX} = -b(E_{\mu_{\text{surf}}} + a/b)e^{-bX}$
- The integration over $dE_{\mu_{\text{surf}}}$ goes from $E_{min} = a/b(e^{bX} - 1)$ to $E_{max} = E_0/A$
- E_0/A and κ will be fitted to the data.