UNIVERSITEIT GENT

FACULTY OF **SCIENCES**

Cosmic ray composition with muon bundles in IceCube

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(Work from Tom F., Dennis S. and myself)

ICECUBE

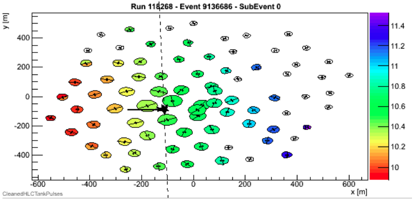
Collaboration Meeting
Madison - Spring 2015
Muon workshop

Introduction

Cosmic ray composition and energy spectrum between 1 PeV and 1 EeV.

- **Tom Feusels' analysis on IT73/IC79**.
  → Presented on ICRC 2013.
  https://wiki.icecube.wisc.edu/index.php/IT73-IC79_Composition_Analysis
- **3 year analysis: (Tom F, S. De Ridder)**
  → Add IC86-I, IC86-II.
  → Retrigger to IT73/IC79 (no IC86 simulation).
  → Discovery of "Observation level bug" in simulation.
  https://wiki.icecube.wisc.edu/index.php/IceTop_3year_update

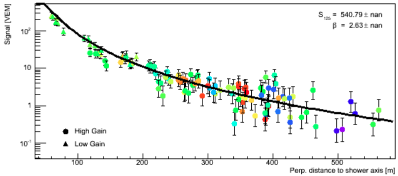
Cosmic ray reconstruction with IceTop

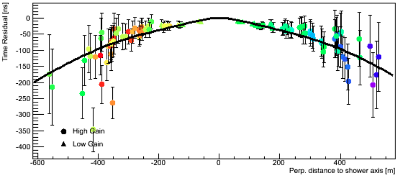


- **Lateral distribution function:**

$$S(r) = S_{125}\cdot\left(\frac{r}{125\ m}\right)^{-\beta-\kappa\log\left(\frac{r}{125\ m}\right)}$$

- **Time curvature (residuals) fit**

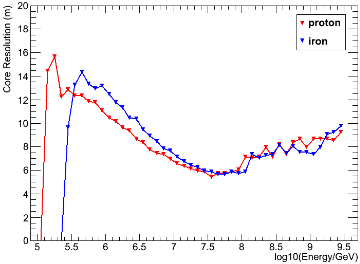


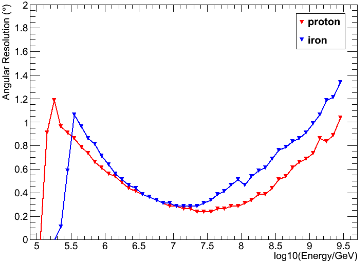


S_{125} (=shower size) sensitive to CR E_{prim}

Cosmic ray reconstruction with IceTop

Reconstruction quality:

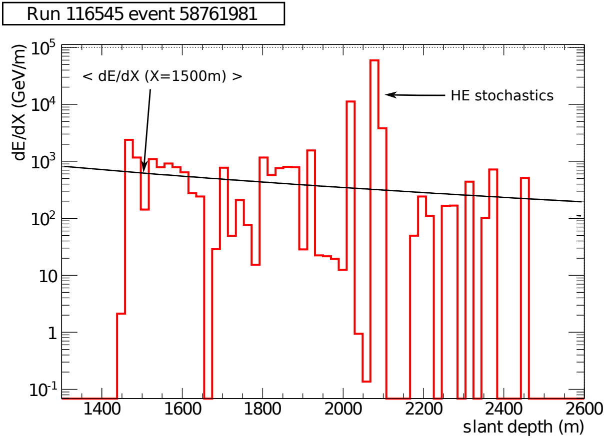




→ Direction and position used from IceTop.

Muon bundle reconstruction with IceCube

Use track reconstruction from IceTop, reconstruct energy loss pattern along track using millipede (20 m track segments).

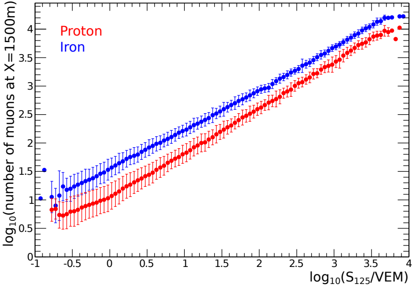


+ remove segments in dust layer and edge of detector.

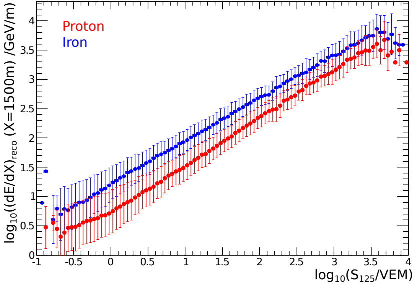
Fit profile to obtain average loss, select extremes.

Muon bundle reconstruction with IceCube: variables

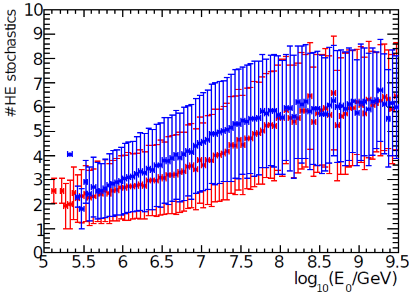
Number of HE muons



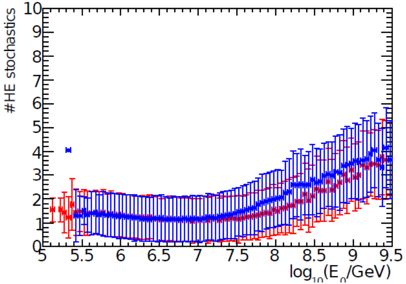
dE/dX(X=1500m)



#HE stoch: standard selection

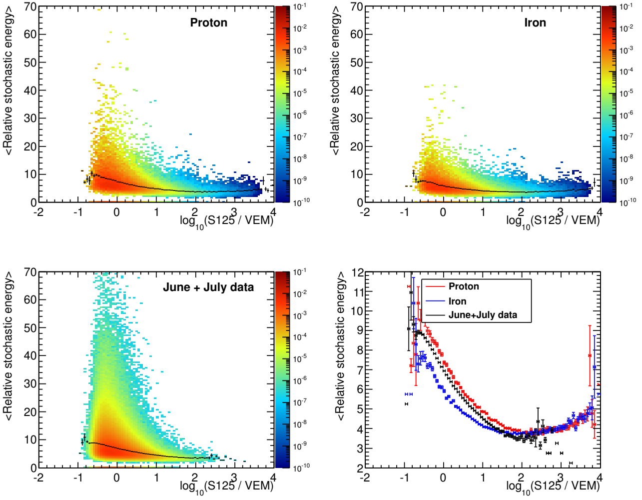


#HE stoch: Strong selection



Muon bundle reconstruction with IceCube: variables

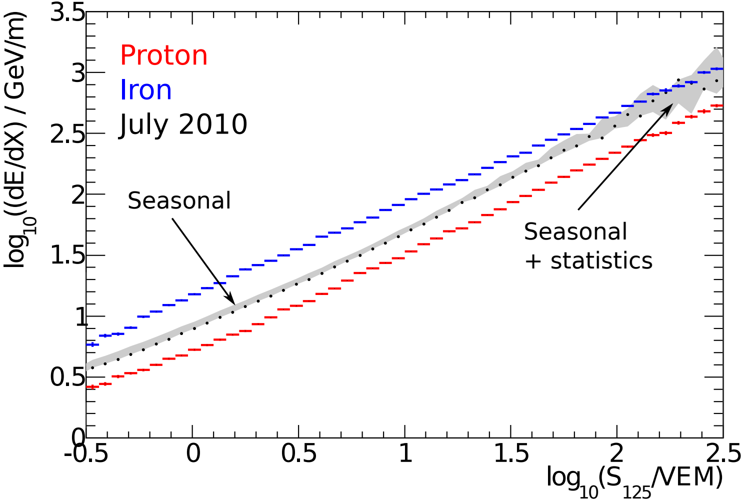
Relative energy loss in peaks (compared to average).



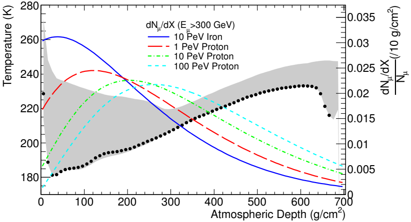
Not used in analysis.

HE muons: seasonal variations

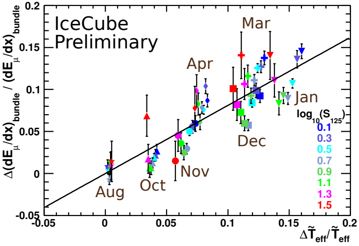
Due to density change in atmosphere, change in muon multiplicity.

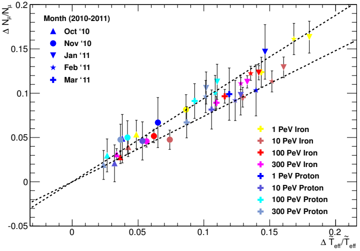


HE muons: seasonal variations



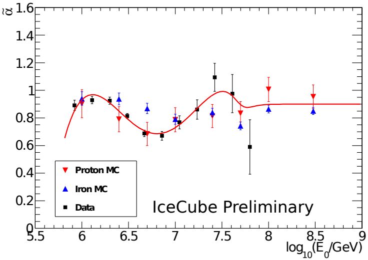
- Weight atm. T with μ prod depth $\rightarrow \tilde{T}_{eff}$
- Find correlation with N_μ (sim) or dE/dX (data)

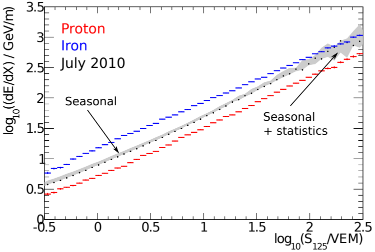


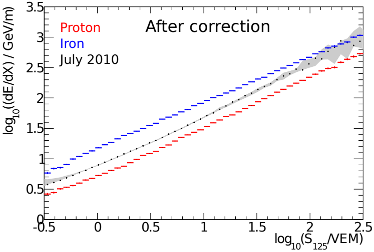


HE muons: seasonal variations

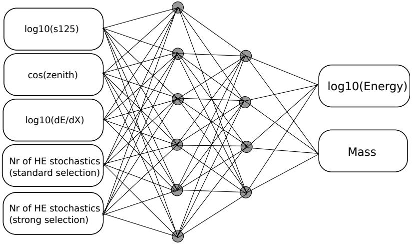
- Not understood energy dependence of correlation.
- Not understood hysteresis.
- Final result: 3% remaining variation (compared to 15% before), symm. around simulation (=smearing).

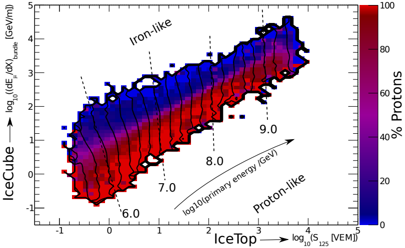




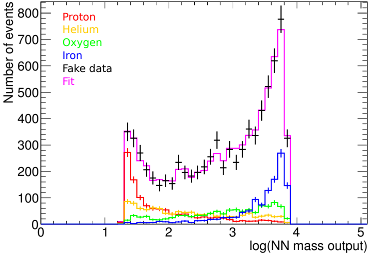


Analysis: Neural network

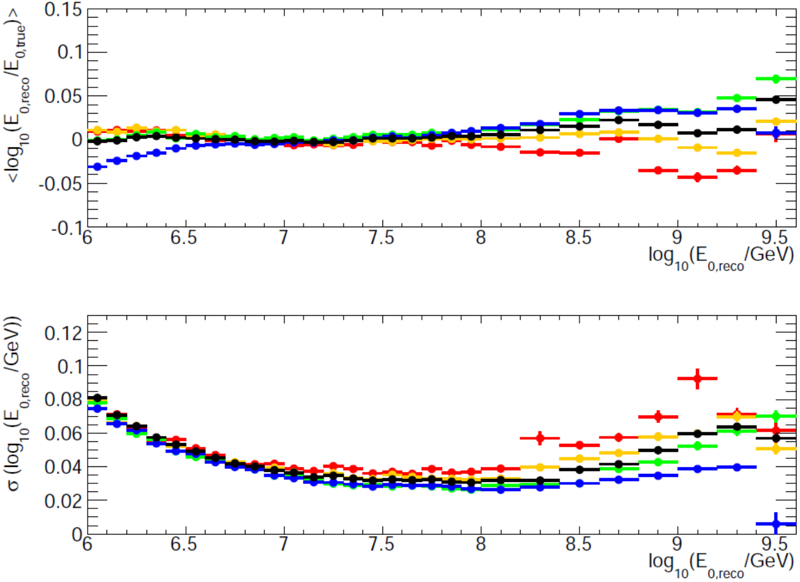




- Relation between inputs and outputs is unknown, non-linear mapping.
- Energy direct output, mass in energy bin reconstructed from template fitting.
- Reoptimization after obs. level. bug.

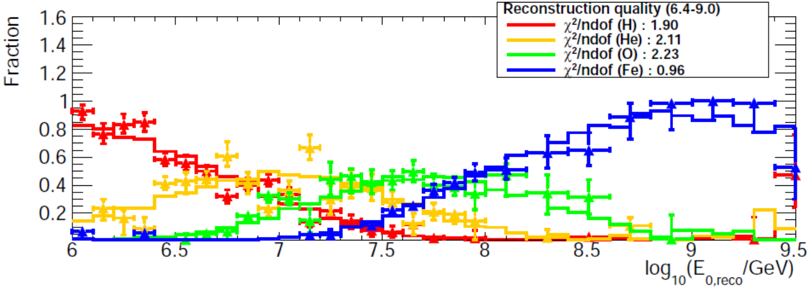


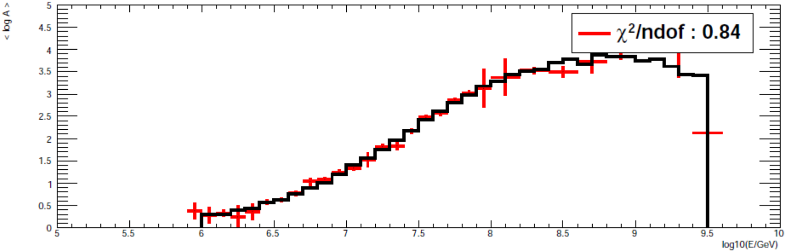
Energy bias and resolution



Composition: Blind challenges

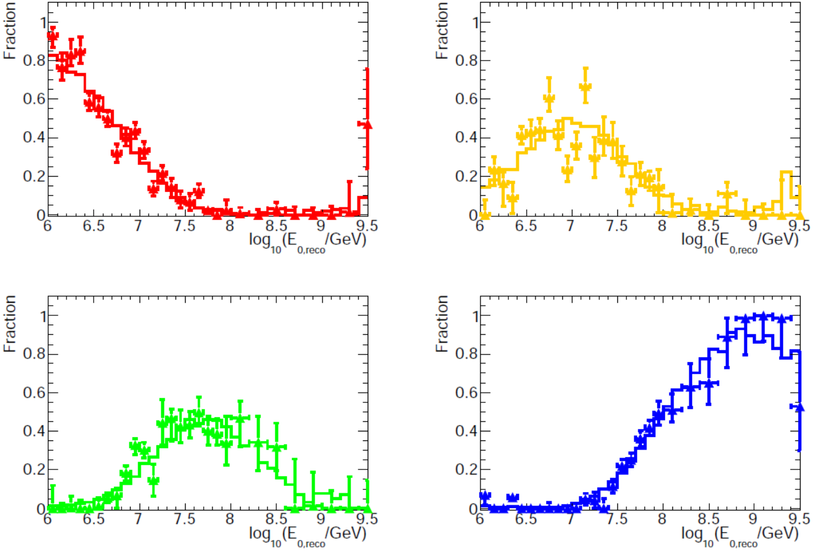
Histogram= truth; Points= reconstructed



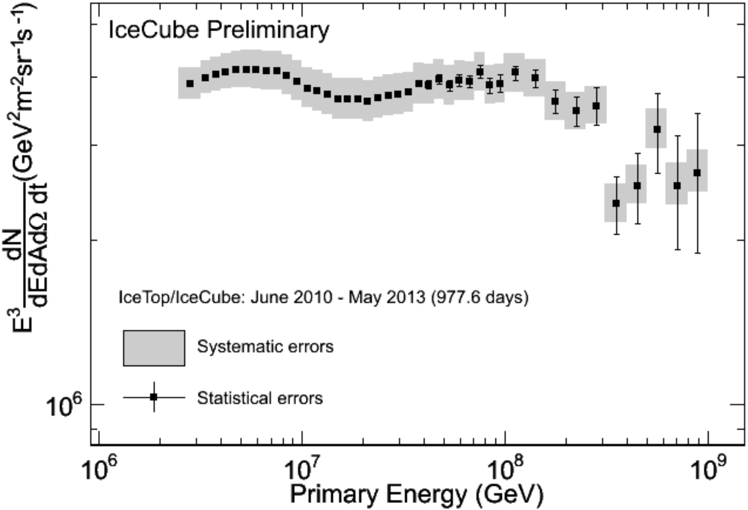


Composition: Blind challenges

Histogram= truth; Points= reconstructed

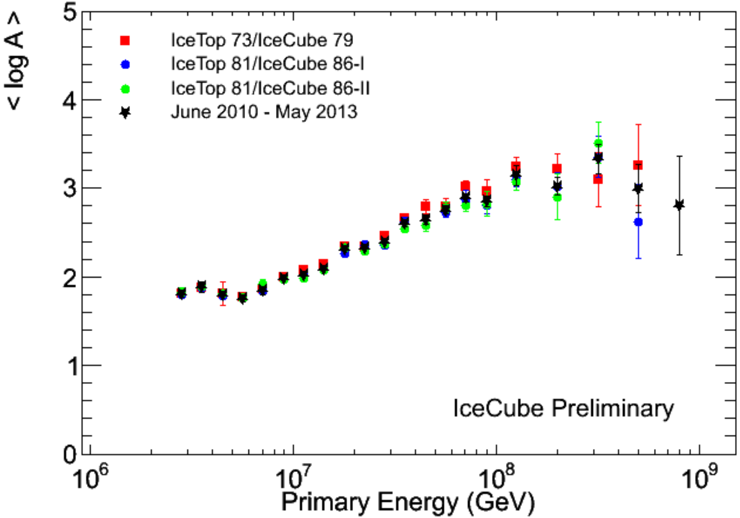


Results: Energy spectrum



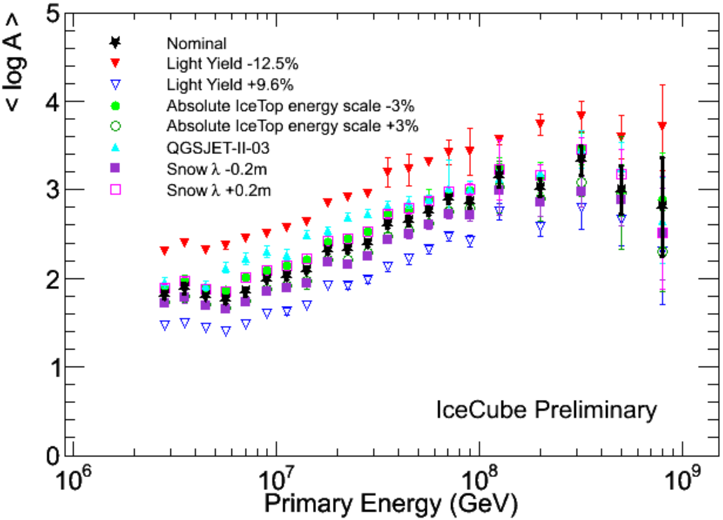
Very nice agreement with the IT-alone spectrum.

Results: Composition

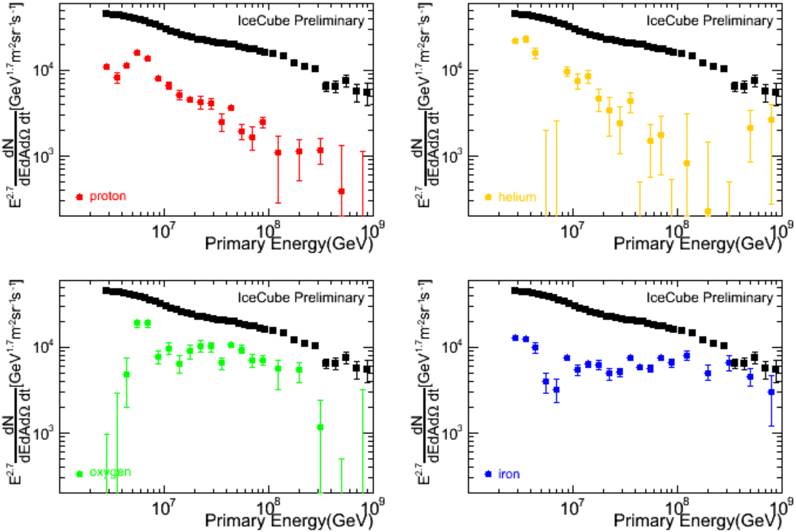


All years agree nicely.

Results: Composition

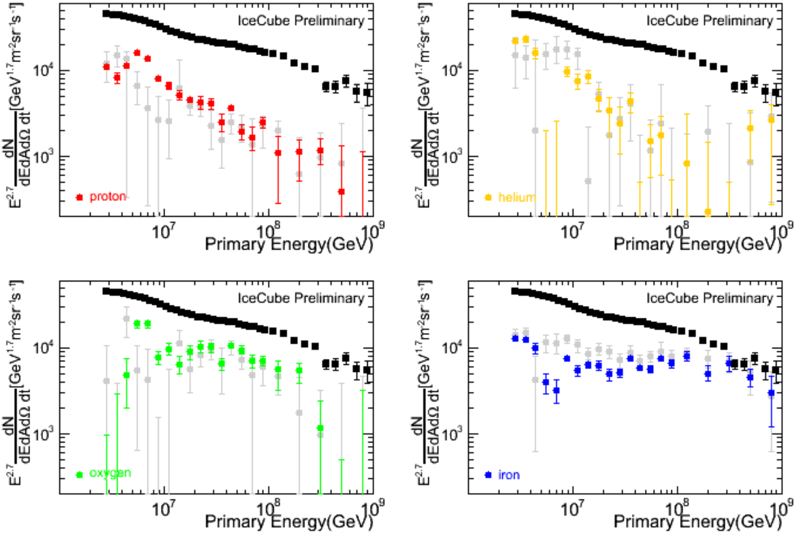


Results: Individual energy spectra



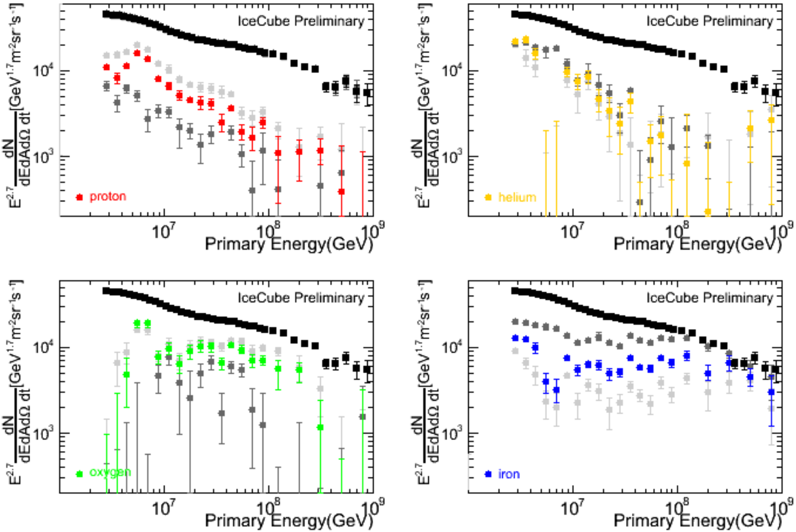
Results: Individual energy spectra

QGSJET



Results: Individual energy spectra

in-ice light yield systematic: dark gray: -12.5%, light gray: +9.6%



In-ice light yield systematics

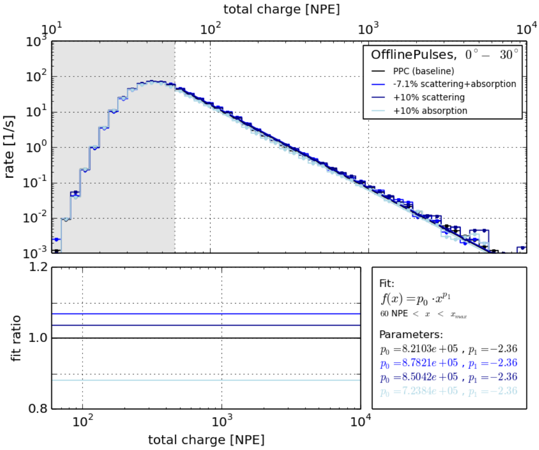
- DOM efficiency: $\pm$ 3% (Jake and Tania)
- Photonics/PPC: Photonics bug.
  - Need hybrid MC, not available
  - Derive shift in absolute light yield ($\sim$ to Jake)
  - Use as corr. factor for DOM light yield in millipede
- Ice models:
  - 3 points on error elipse
    (+10% abs, +10% scat, -7.1% scat + abs)
  - Affects timing, z dependence and light yield
  - Need 3 new photonics tables (spline fitted)
  - This analysis dominated by light yield
  - Same method as above: compare shift with baseline PPC
- Hole Ice:
  - 30 cm, 100 cm
  - Same approach as above

In-ice light yield systematics

Very extensive work by Dennis Soldin

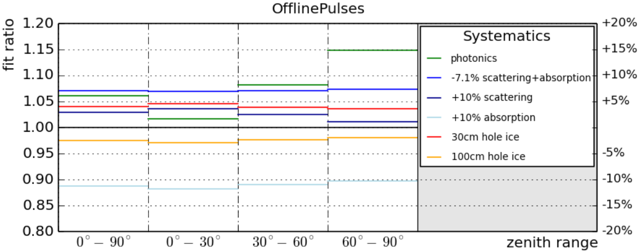
`astro.uni-wuppertal.de/~soldin/systematics.html`

One example: Ice model systematics, 0°-30°



In-ice light yield systematics

Summary:



0°-30° numbers:

	OfflinePulses (systematics/PPC)
Photonics	1.017
Hole ice 30 cm	1.045
Hole ice 100 cm	0.971
+ 10 % scattering	1.036
- 10 % scattering	0.882
-7 % scattering and absorption	1.070

In-ice light yield systematics

Correlations between Ice Model and DOM efficiency are negligible ($\sim$ Jake). No correlations are implemented.

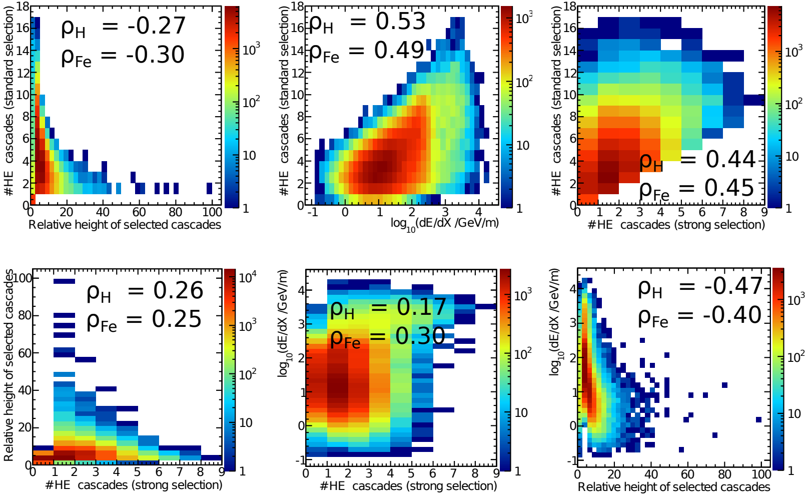
	Systematics uncertainty
DOM eff	$\pm$ 3%
Hole ice 30 cm	+ 4.5%
Hole ice 100 cm	- 2.9%
+ 10 % scattering	+ 3.6 %
- 10 % scattering	-11.8 %
-7 % scattering and absorption	+ 7%
Total	+9.6%,-12.5%

Summary

- In-ice systematic dominates composition measurement
- Shift in light yield used to account for these systematics, but appropriate simulations are needed.
- Need for verifications of low-level data

Back-up

Back-up: correlations



Back-up: closed circle in-ice systematics

After correction: