Event-by-event reconstruction of air-shower events with IceCube using a two component lateral distribution function

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Two Component LDF - Motivation

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- **“Muon Puzzle”**
  - **Mismatch between data and simulations** in low energy muon content

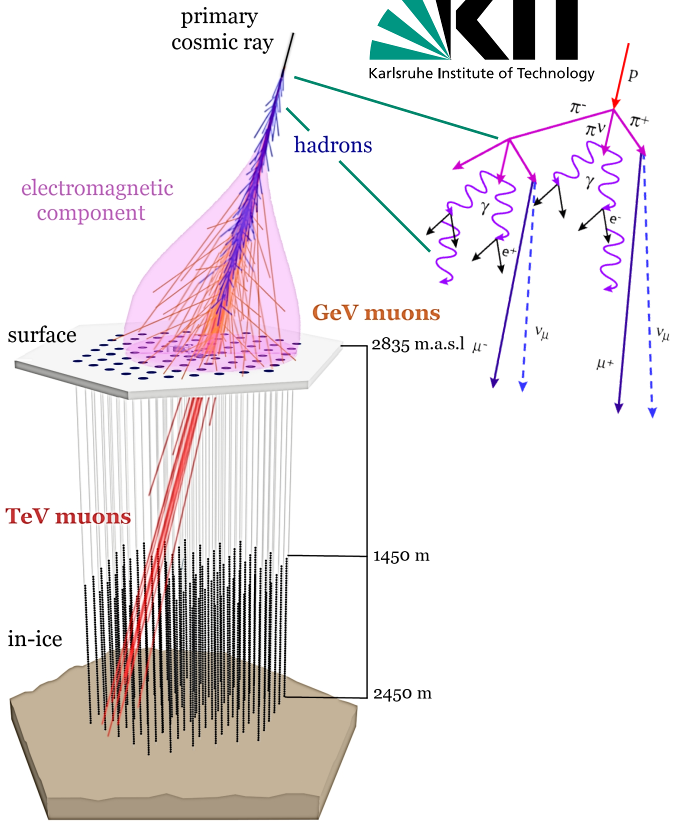
→ **Constraints necessary** for future model improvements

- **Unique role of IceCube**
  - Coincident measurement of low-energy (**~GeV**) **muons** & high-energy (**~TeV***) **muons**

  → Ideal for **tests of hadronic interaction models**

  - **Missing piece:** event-by-event based GeV muon estimator

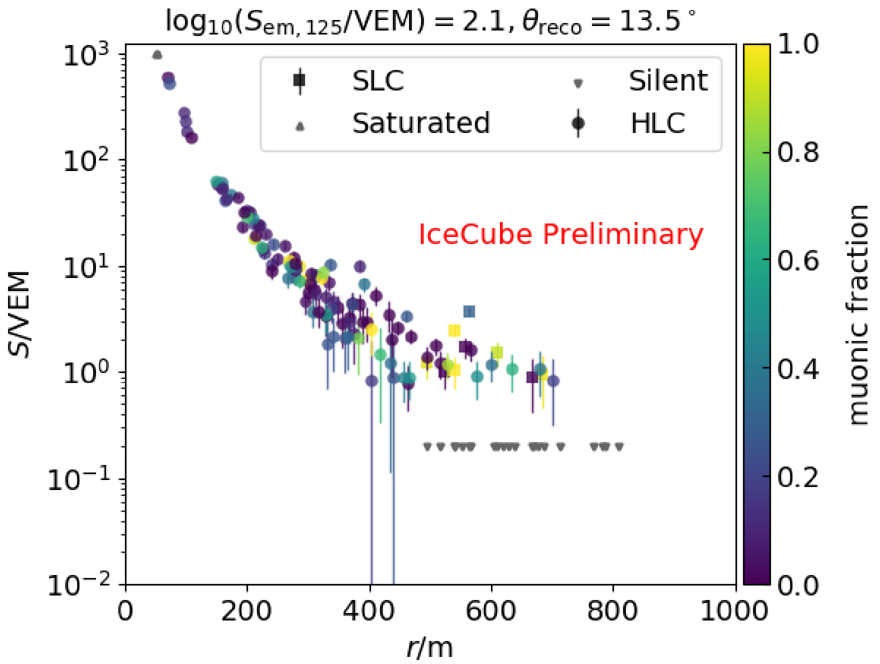
    → **emLDF + muLDF = Two Component LDF**



*arXiv:2211.16970

IceTop Signal Classification

- "Hard Local Coincidence" (**HLC**) hits
  - Both tanks in one station hit within $1\mu s$
    - → **full station** triggers
    - → dominant **close to axis**
- "Soft Local Coincidence" (**SLC**) hits
    - → **single tank** triggers
    - → dominant **far from axis**
- "Silent" hits
    - → tanks without trigger

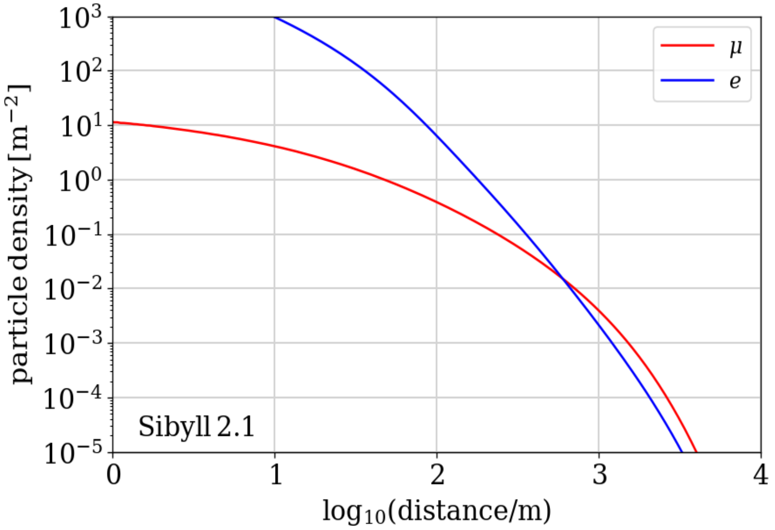


Two Component LDF – Basic Idea

$$S_{em}(r) = S_{DLP} = S_{em,125}\left(\frac{r}{125\,\mathrm{m}}\right)^{-\beta_{em}-\kappa\log\left(\frac{r}{125\,\mathrm{m}}\right)}$$

$$\kappa = 0.255\cdot\log_{10} S_{em,125} + 1.01$$

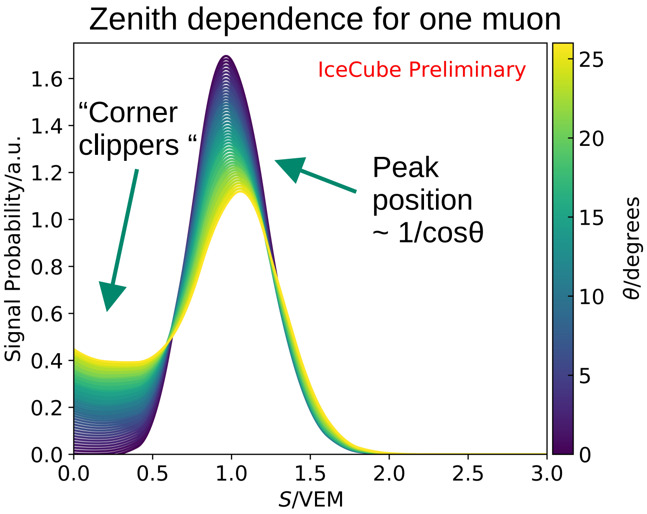
$$S_{\mu}(r) = S_{\mu,600}\left(\frac{r}{R_\mu}\right)^{-\beta_\mu}\left(\frac{r+320\,\mathrm{m}}{R_\mu+320\,\mathrm{m}}\right)^{-\gamma}$$

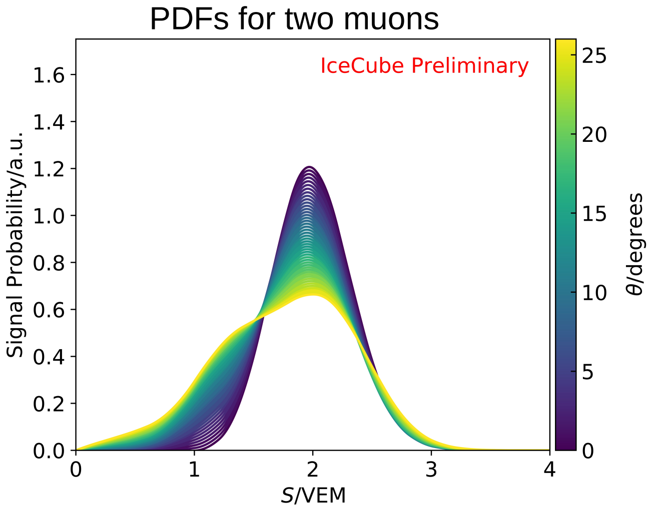


Combined fit of em & mu signal model

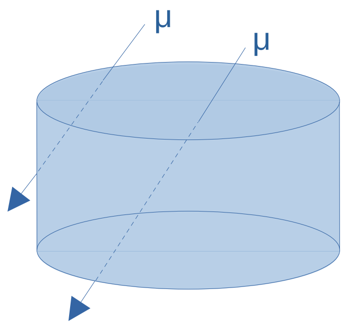
- **em contribution** dominant close to the shower axis → **HLCs**
- **μ contribution** more significant at **large distances** → **SLCs**
- This talk: **vertical** (θ<26°) **showers** produced with **Sibyll2.1**

Muon Signal PDF



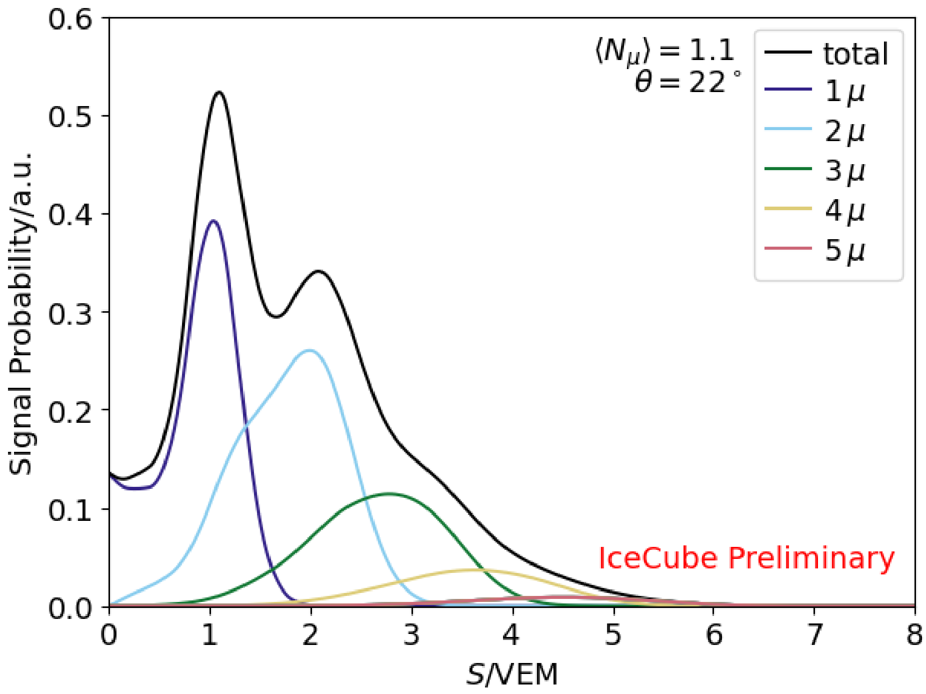


- $\mathbf{p}_{\mathrm{sig}}(\mathbf{S}|\theta, \mathbf{n})$
  - → probability to observe signal S given n muons & θ
  - → assuming **muons propagate along primary direction**



- **IceTop tank response** for different $\mathbf{n}, \theta$ **saved as spline fits**
- Muon **signal ~ track length**

Muon Signal PDF

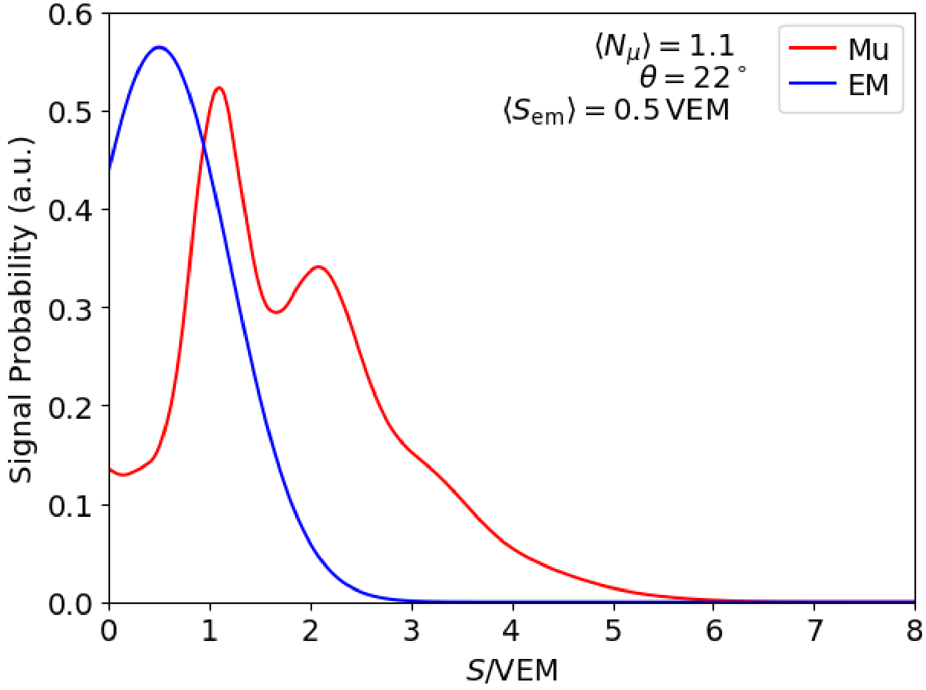


- **Total muon signal PDF** for expected average number of muons $\langle N_\mu \rangle$(given by muonLDF * tank area)

$$p_\mu(S|\theta, \langle N_\mu \rangle) = \sum_{n=1}^{\infty} \frac{\langle N_\mu \rangle^n}{n!} e^{-\langle N_\mu \rangle} p_{\text{sig}}(S|\theta, n)$$

→ $p_{\text{sig}}(S|\theta, n)$ weighted by probability to observe n muons given $\langle N_\mu \rangle$

Total Signal PDF



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→ $p_{\text{sig}}(S|\theta, n)$ weighted by probability to observe n muons given $\langle N_\mu \rangle$

- **Total signal PDF** (convolution of em and mu PDF)

$$s = s_{\text{em}} + s_\mu$$

$$p\left(S|\theta, \langle S_{\text{em}} \rangle, \langle N_\mu \rangle\right) = p_{\text{trg}} \cdot \int_0^s p_{\text{em}}(S_{\text{em}}|\theta, \langle S_{\text{em}} \rangle) p_\mu(S - S_{\text{em}}|\theta, \langle N_\mu \rangle) dS_{\text{em}}$$

Reconstruction Procedure

- **Fit regimes:**

$$p_{\mathrm{HLC}}\left(S|\theta,\langle S_{\mathrm{em}}\rangle,\langle N_{\mu}\rangle\right)=p_{\mathrm{trg}}\begin{cases} p_{\mathrm{em}}\left(\left(S-\langle S_{\mu}\rangle\right)/c_{\mathrm{snow}}|\theta,\langle S_{\mathrm{em}}\rangle\right) & ,\langle S_{\mu}\rangle<\dfrac{\langle S_{\mathrm{em}}\rangle}{2} \\ \displaystyle\int_0^s p_{\mathrm{em}}(S'_{\mathrm{em}}/c_{\mathrm{snow}}|\theta,\langle S_{\mathrm{em}}\rangle)\;p_{\mu}(S-S'_{\mathrm{em}}|\theta,\langle N_{\mu}\rangle)dS'_{\mathrm{em}} & ,\ \text{else} \end{cases}$$

$$p_{\mathrm{SLC}}\left(S|\theta,\langle S_{\mathrm{em}}\rangle,\langle N_{\mu}\rangle\right)=p_{\mathrm{trg}}\int_0^s p_{\mathrm{em}}(S'_{\mathrm{em}}/c_{\mathrm{snow}}|\theta,\langle S_{\mathrm{em}}\rangle)\;p_{\mu}(S-S'_{\mathrm{em}}|\theta,\langle N_{\mu}\rangle)dS'_{\mathrm{em}}$$

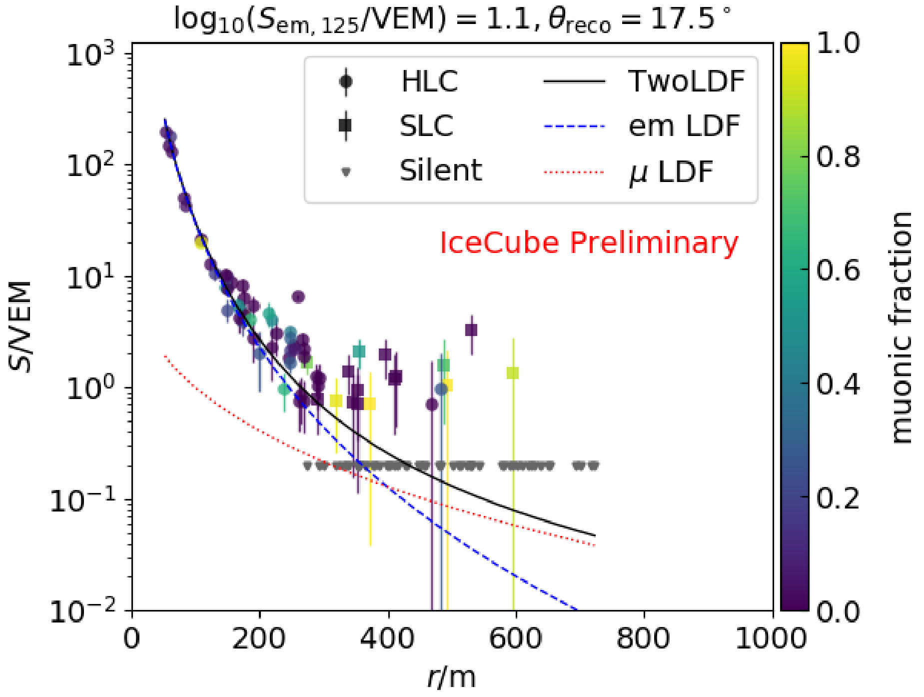
- **Full 6 Step nLLH minimization procedure**

x, y, S_{125}, β → $x, y, S_{125}, \beta, \theta, \phi$ → x, y, S_{125}, β —S_{125}→ $S_{\mathrm{em},125},\ \beta_{\mu},\ \gamma,\ S_{\mu,600}$ → $S_{\mathrm{em},125},\ \beta_{\mu},\ \beta_{\mathrm{em}},\ S_{\mu,600}$ → $\beta_{\mathrm{em}},\ \beta\mu,\ S_{\mu,600}$

Standard IceTop reconstruction
→ **HLCs** only

Two Component reconstruction
→ **HLCs + SLCs**

Two Component LDF – Single Fits



$$S_{em} = S_{em,125}\left(\frac{r}{125\,m}\right)^{-\beta_{em} - \kappa \log\left(\frac{r}{125\,m}\right)}$$

$$S_{\mu} = S_{\mu,600}\left(\frac{r}{R_\mu}\right)^{-\beta_\mu}\left(\frac{r+320\,m}{R_\mu+320\,m}\right)^{-\gamma}$$

- General behavior as expected
  - **Sem** describes em dominated **HLC hits** close the shower axis
  - **Smu** sensitive to muon dominated **SLC hits** at large lateral distances

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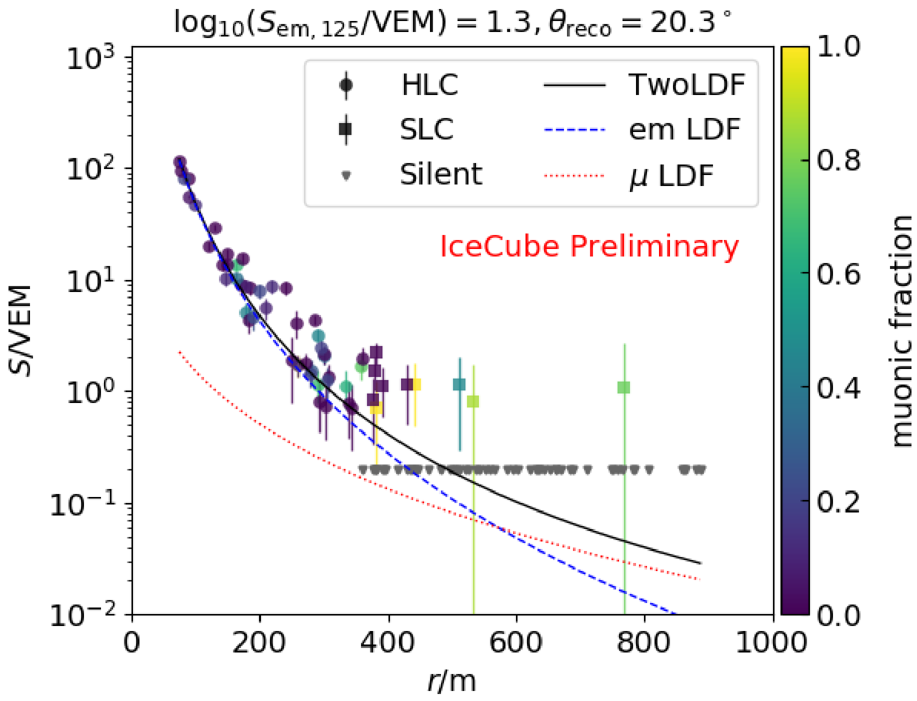

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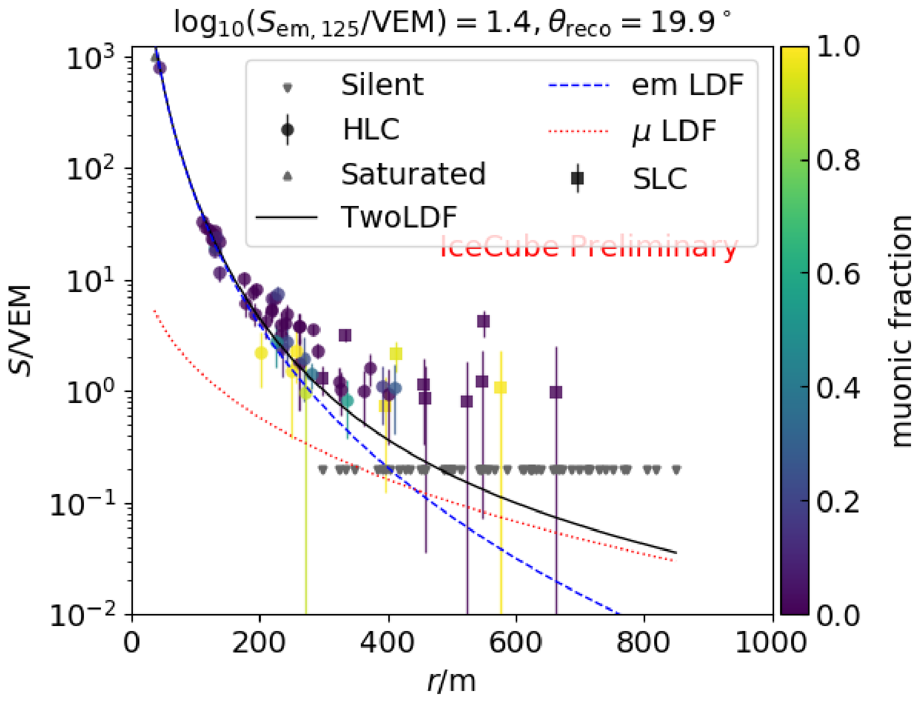

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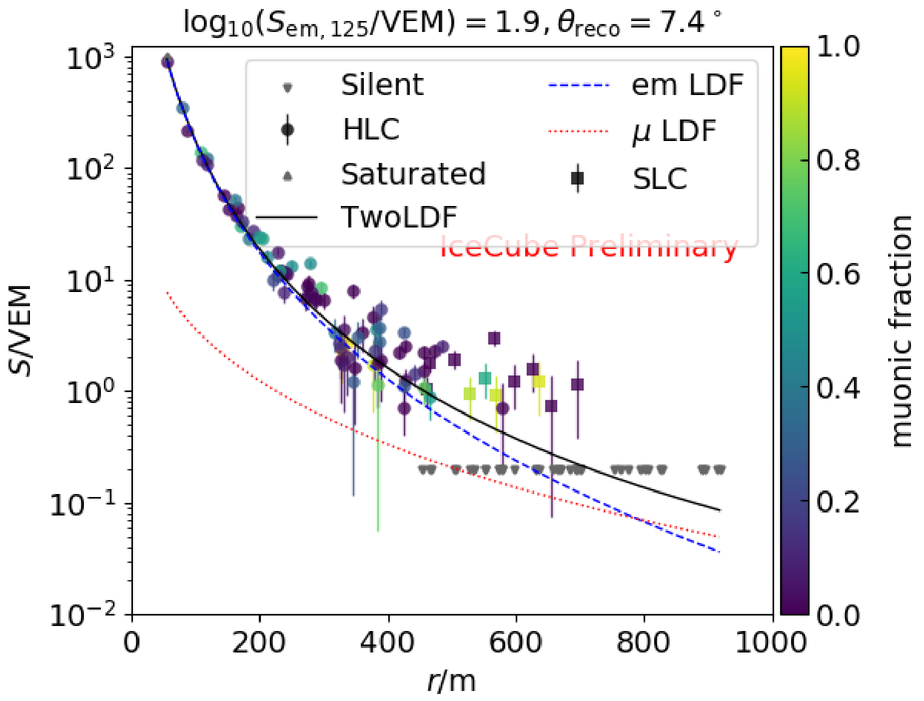

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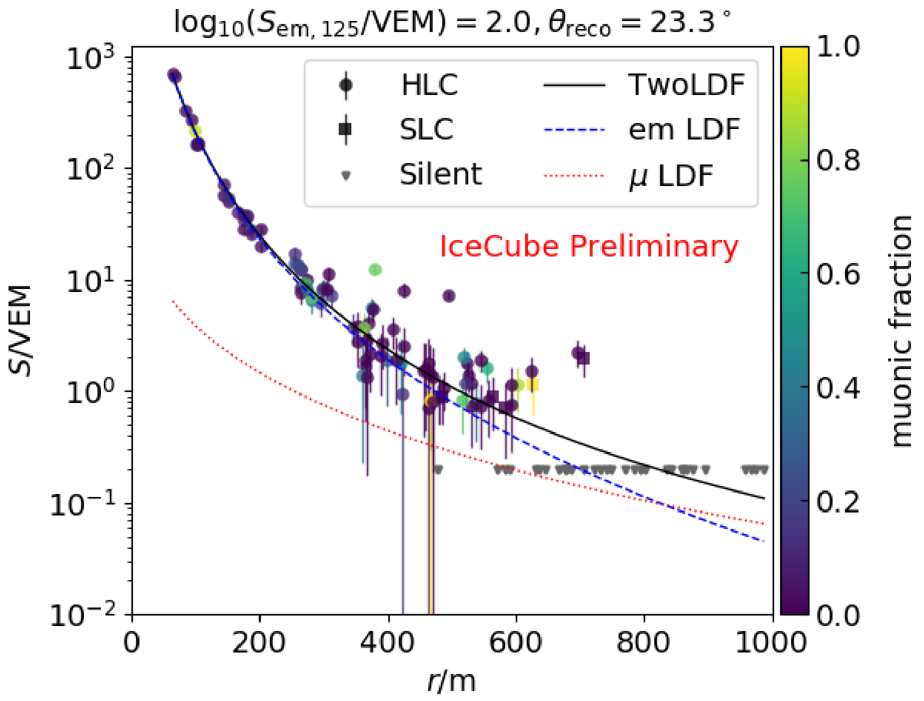

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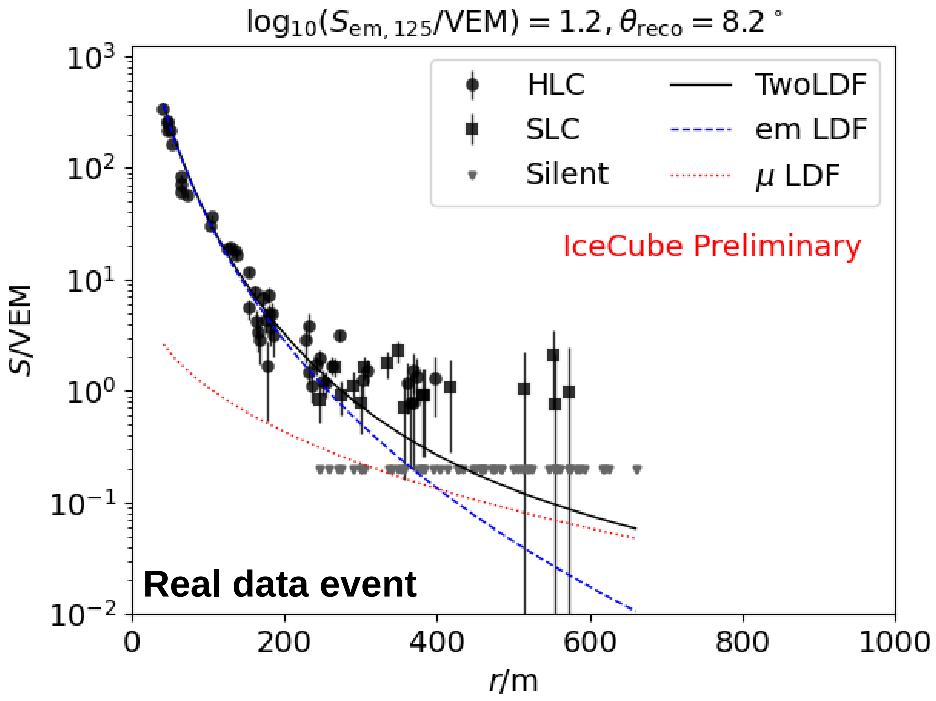

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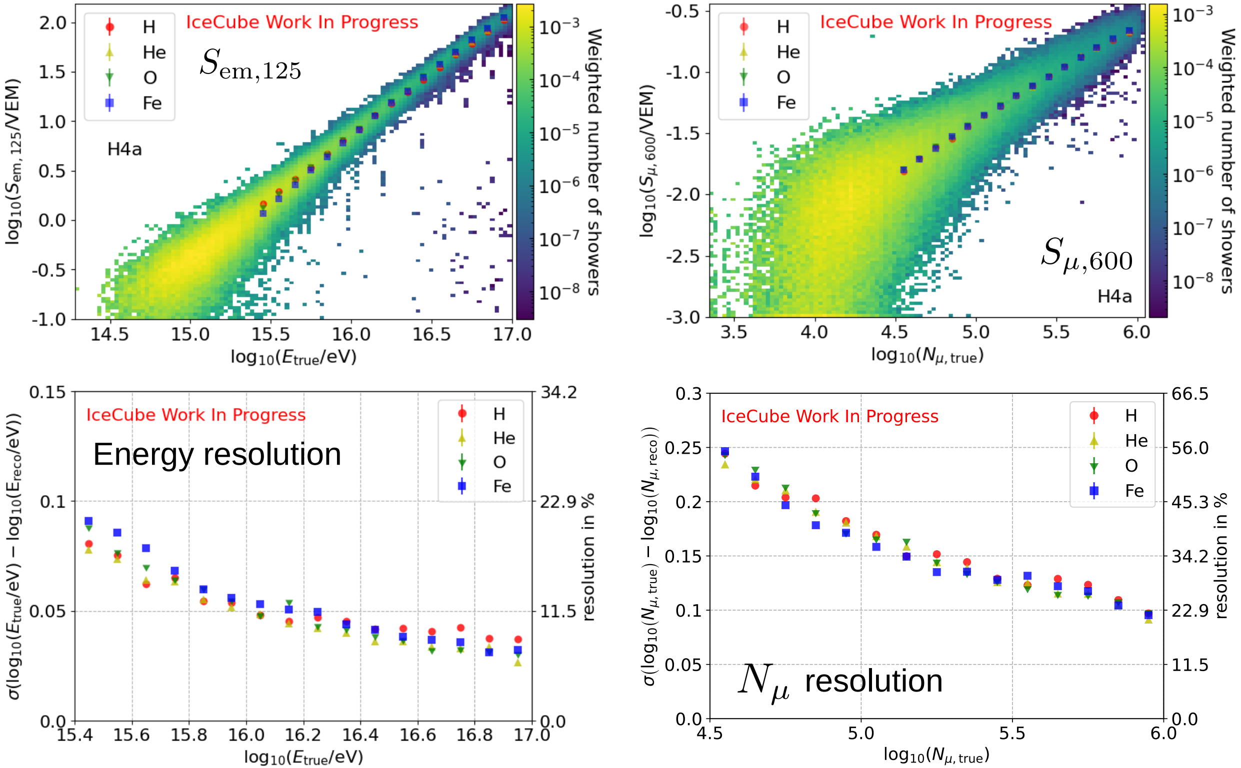
Two Component LDF – Average Distributions

- **Successful reconstruction** of **energy** and low energy **(GeV) muon number**



Summary & Outlook

- **Successful reconstruction** of **energy** and low energy **(GeV) muon number**
- **Next Steps:**
  - **Extending energy & zenith** angle range
  - Study **systematics**
  - Study **correlations of TeV & GeV muons** on event-by-event basis
  - Test **different hadronic models**