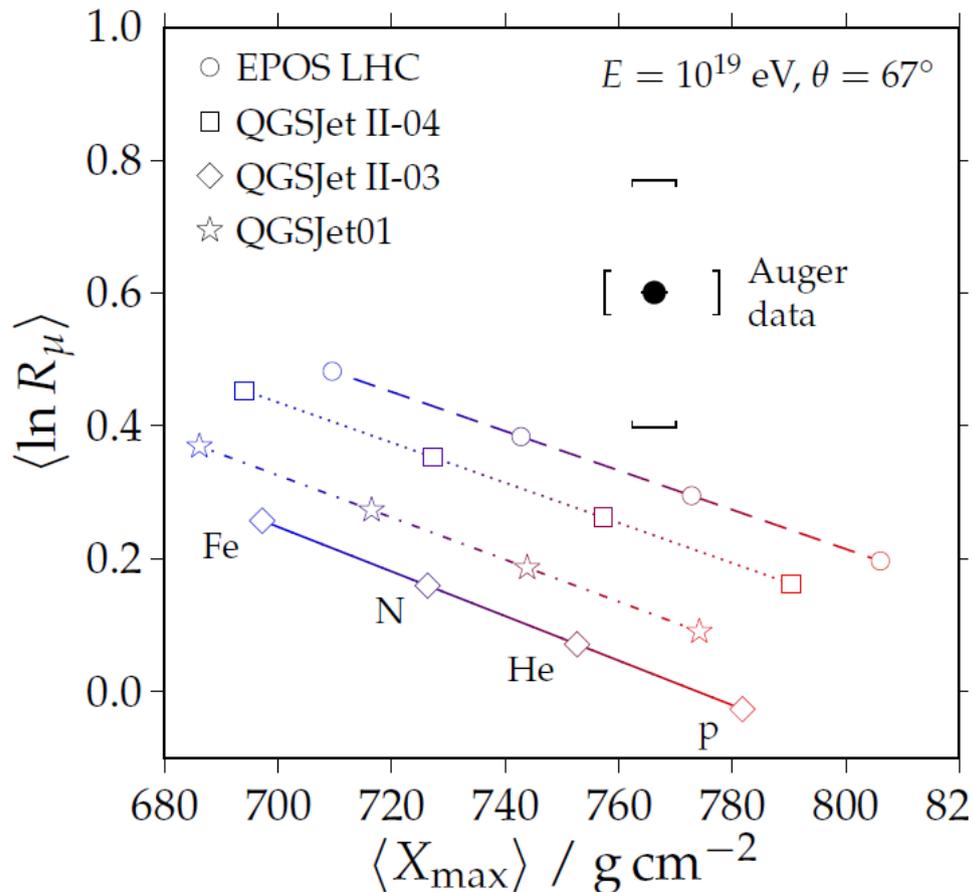# Surface muons in IceTop

Hans Dembinski[1], Javier Gonzalez[1] for the **IceCube** Collaboration

[1]Bartol Institute, University of Delaware

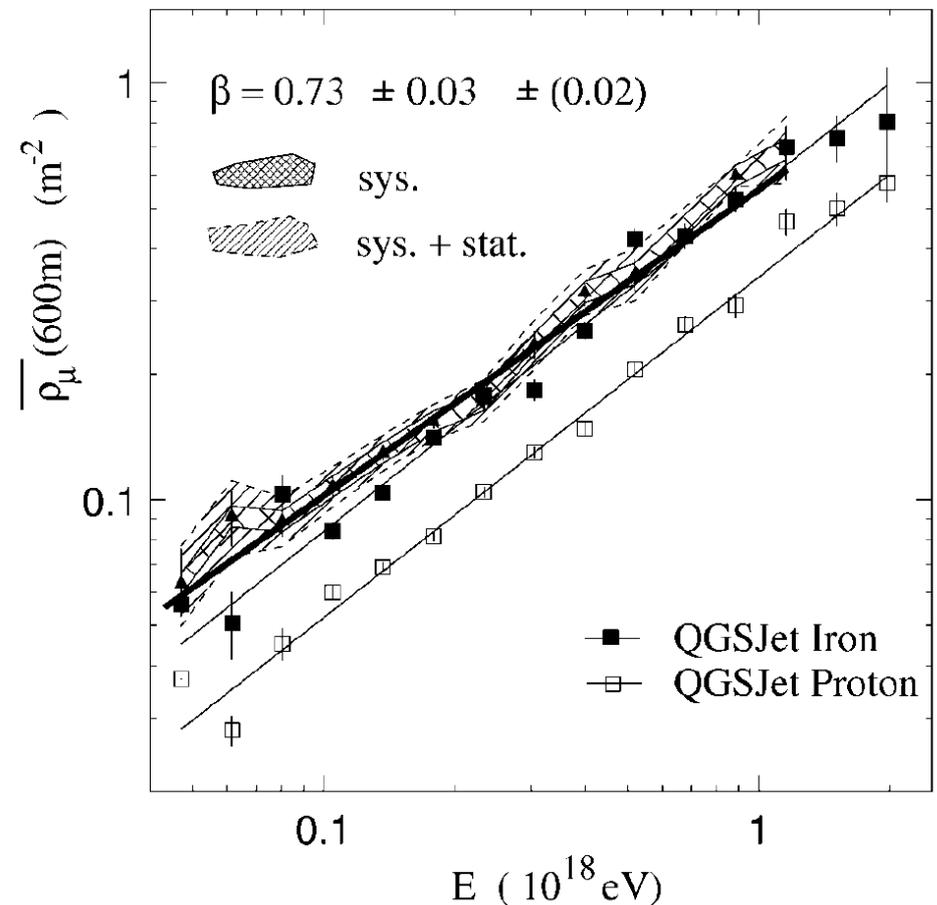*ICRC 2015, The Hague*

Too many muons in air showers?

10000 PeV **Auger Collab.,** Aab et al.
PRD 91, 032003 (2015)

Muon content above simulations
(1.4 σ_{sys} above EPOS-LHC)

100 PeV **HiRes-MIA Collab.,** Abu-Zayyad et al.
PRL 84, 4276 (2000)

Muon content above simulations
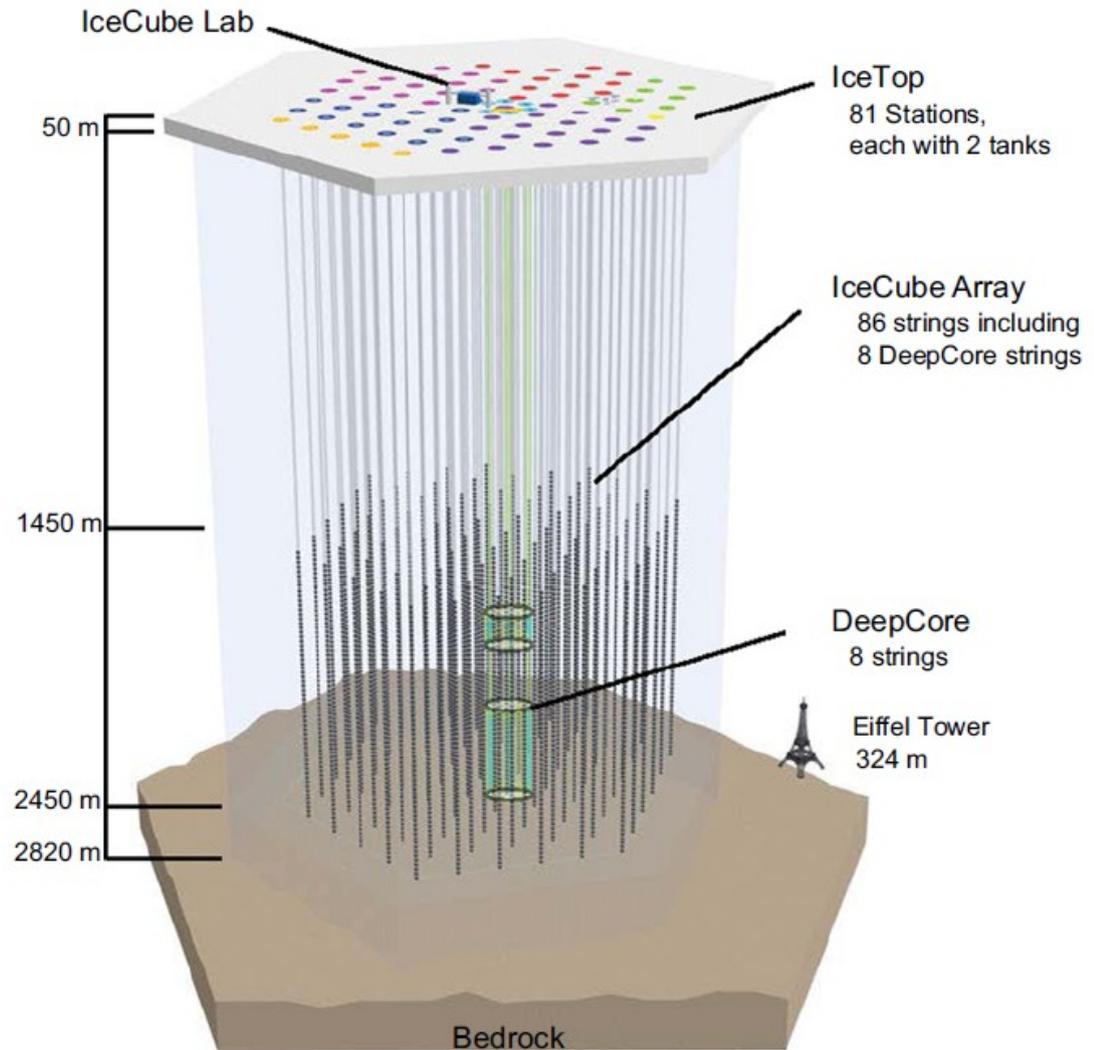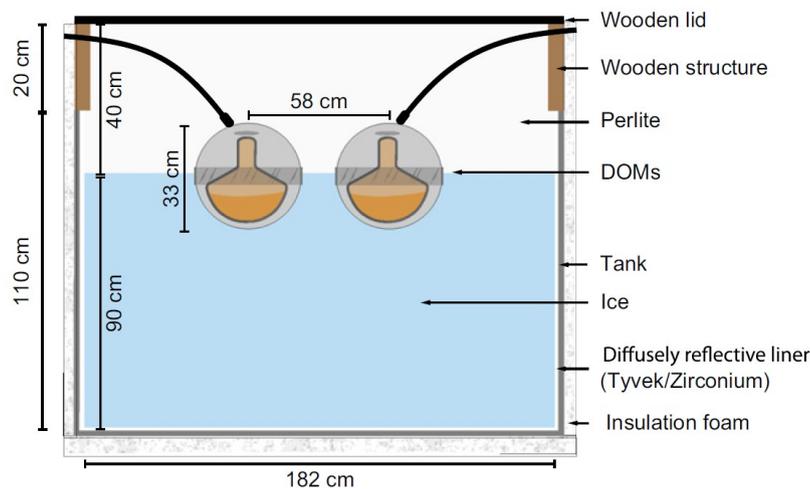(Compared to Sibyll-2.1, QGSJet01)

IceCube Neutrino Observatory

‣ CR energies 1 PeV to 1000 PeV

‣ DAQ since 2005, completed 2011

‣ IceTop

		KASCADE
‣ 1 km² ice-Cherenkov		0.04 km²
‣ 125 m spacing		13 m
‣ Coverage 3 x 10⁻⁴		1.5 x 10⁻²
‣ 2835 m a.s.l. 680 gcm⁻²		1000 gcm⁻²

$$\text{Coverage} = \frac{\text{instrumented area}}{\text{total area}}$$

IceCube Lab

IceTop
81 Stations,
each with 2 tanks

50 m

1450 m

IceCube Array
86 strings including
8 DeepCore strings

DeepCore
8 strings

2450 m

2820 m

Eiffel Tower
324 m

Bedrock

20 cm
40 cm
110 cm
33 cm
90 cm
58 cm
182 cm

Wooden lid
Wooden structure
Perlite
DOMs
Tank
Ice
Diffusely reflective liner
(Tyvek/Zirconium)
Insulation foam

H. Dembinski, J.G. Gonzalez | Bartol institute, University of Delaware | Aug 2015

IT Event reconstruction

IceCube Collab., M.G. Aartsen et al., PRD 88 (2013) 042004

- **Cosmic ray direction**
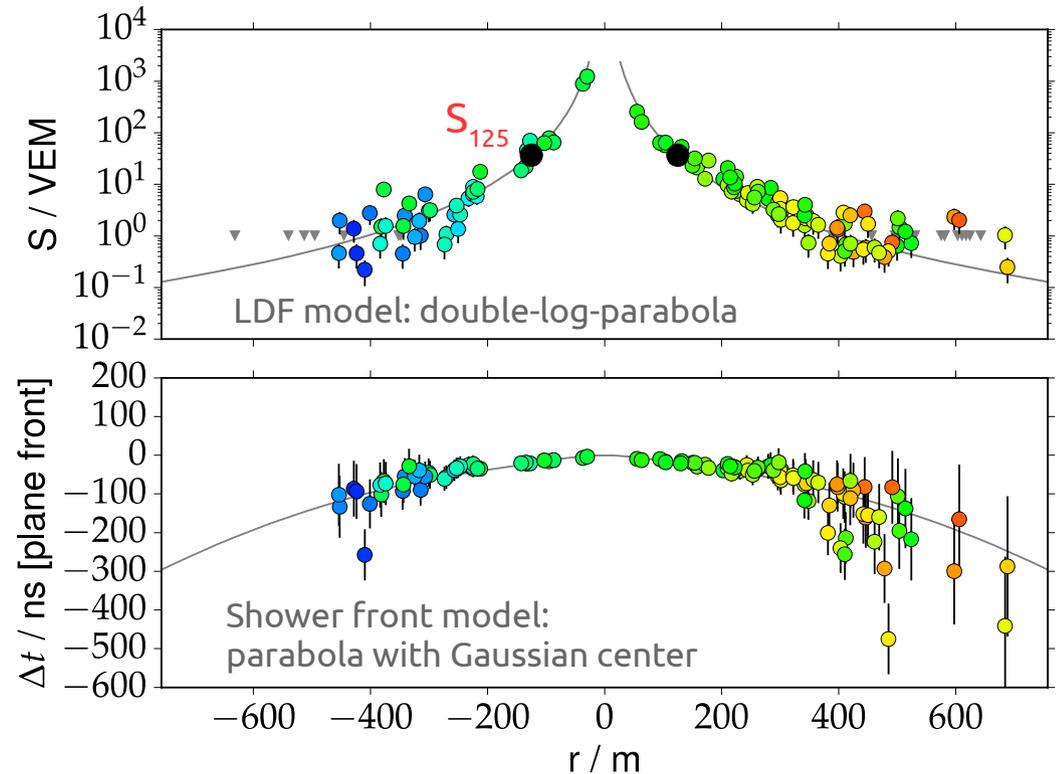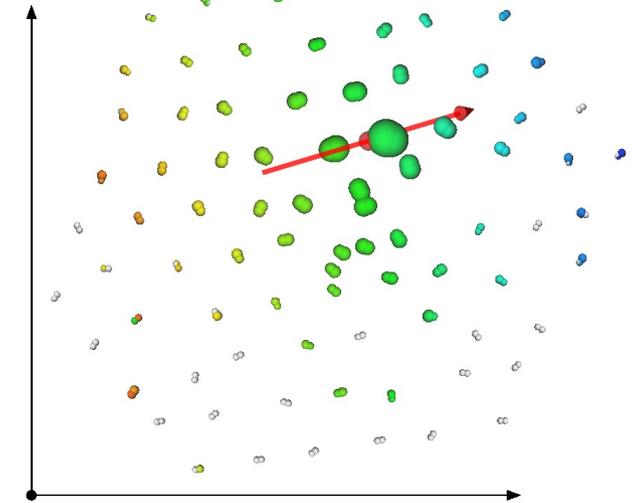 - Timing resolution 3 ns
  - Angular resolution ~1°

- **Cosmic ray energy**
  - Energy proxy S_{125} in VEM $\left\{ \begin{array}{l} \text{Vertical} \\ \text{Equivalent} \\ \text{Muon} \end{array} \right.$
  - Simulated-based energy calibration
    - Mixed-composition model H4a
  - Energy resolution <25 %
  - Systematic uncertainty ~10 %
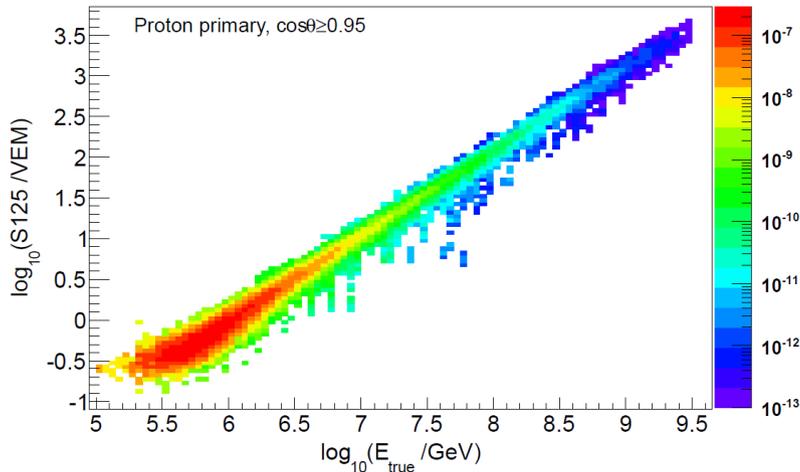
Event 120401/2498463-0
Time 2012-07-01 03:43:27 UTC
Duration 30819.2 ns

S_{125}

LDF model: double-log-parabola

Shower front model:
parabola with Gaussian center

Proton primary, $\cos\theta \geq 0.95$

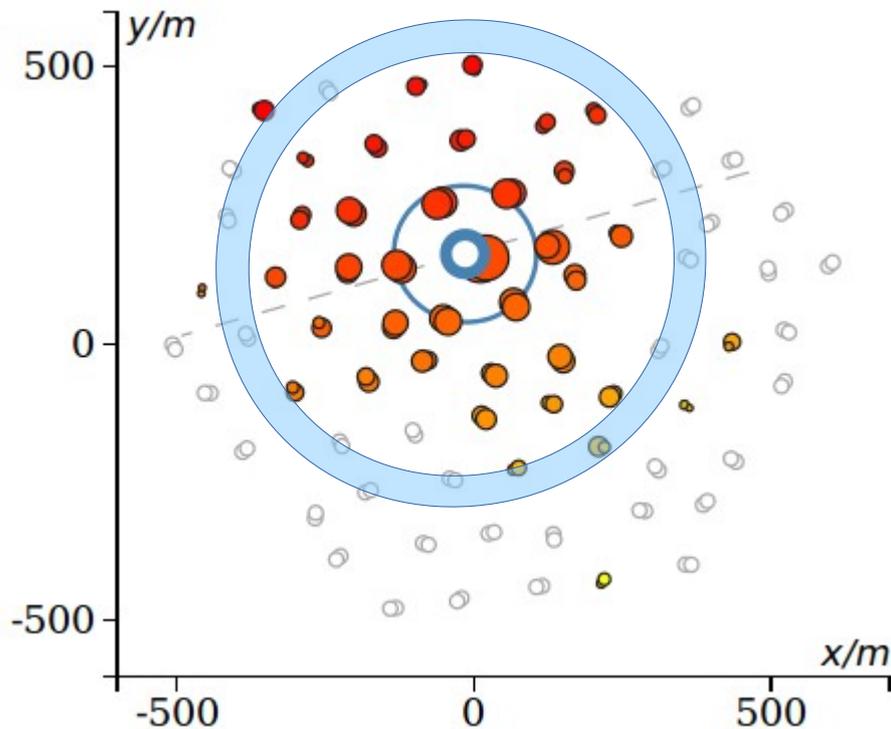$\log_{10}(S125 / VEM)$

$\log_{10}(E_{true} / GeV)$

Peripheral muons in IceTop

Peripheral muons ~ 10 GeV

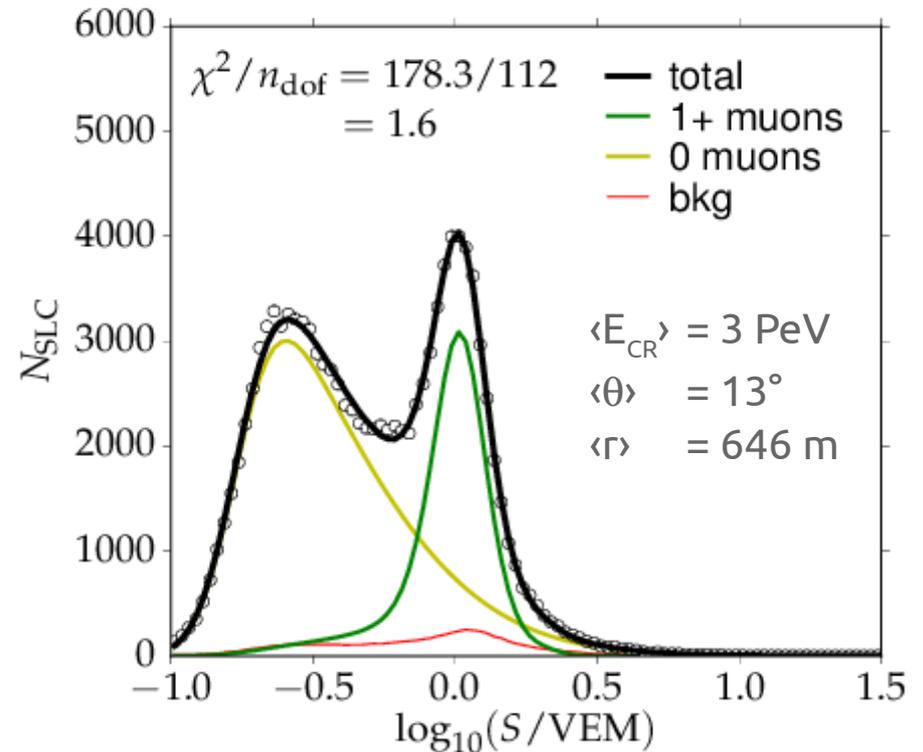Minimum-ionizing through-going particles
IceTop threshold ~ 0.2 VEM (Auger: > 1 VEM)

Collect pulse charges in lateral bins
> 250 m from core **over many events**

Charge histograms

Binned in energy, zenith, lateral distance

$\chi^2/n_{dof} = 178.3/112 = 1.6$

total
1+ muons
0 muons
bkg

$\langle E_{CR} \rangle = 3$ PeV
$\langle \theta \rangle = 13°$
$\langle r \rangle = 646$ m

Statistically identify tanks with
at least one muon through fits of
charge histograms

Analysis outline (simplified)

▸ **Peripheral muons**

  ‣ Low density at large lateral distances

  ‣ Tanks usually get one or zero muons

$$\rho_\mu \approx \frac{N_{\text{tanks with muon}}}{N_{\text{all tanks}}} \frac{1}{A_{\text{tank}}}$$

But: $N_{\text{tanks with trigger}} > N_{\text{tanks with muon}}$

Need to sort out triggered tanks **without muon hits**

  ‣ Muon signal ~ 1 VEM / cosθ   VEM = Vertical Equivalent Muon

  ‣ EM signal contribution usually smaller, smooth distribution
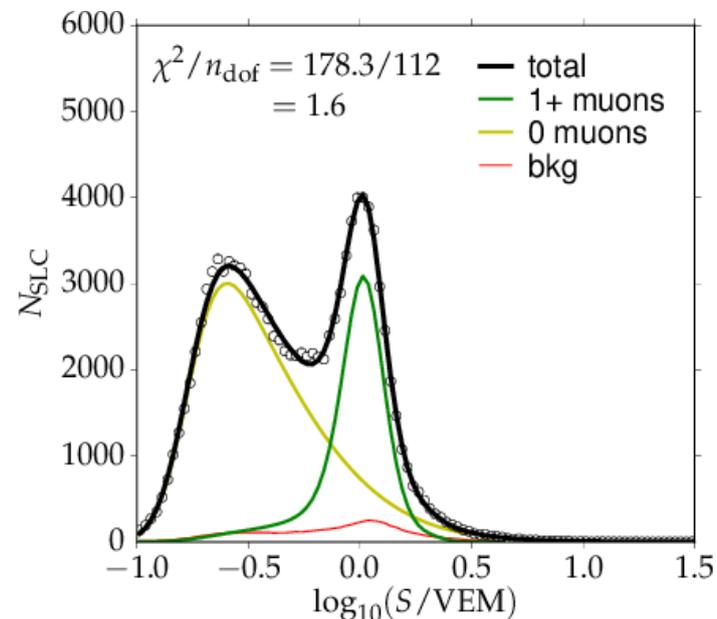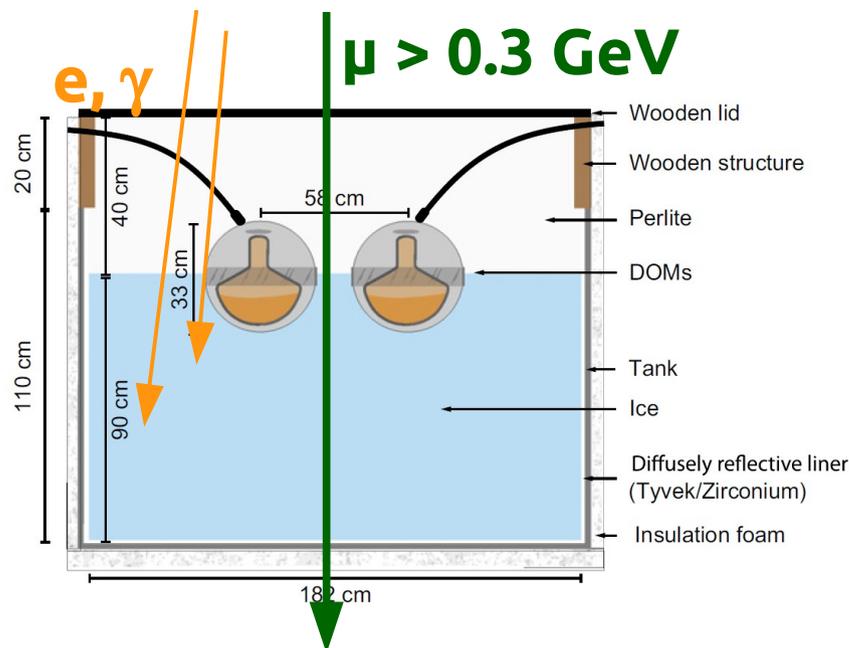
Muon response model

Also see **IceCube** Collab., J.G. Gonzalez et al., arXiv:1501.03415 (2014)

Generated Cherenkov light proportional to track length: $\quad S \propto l$

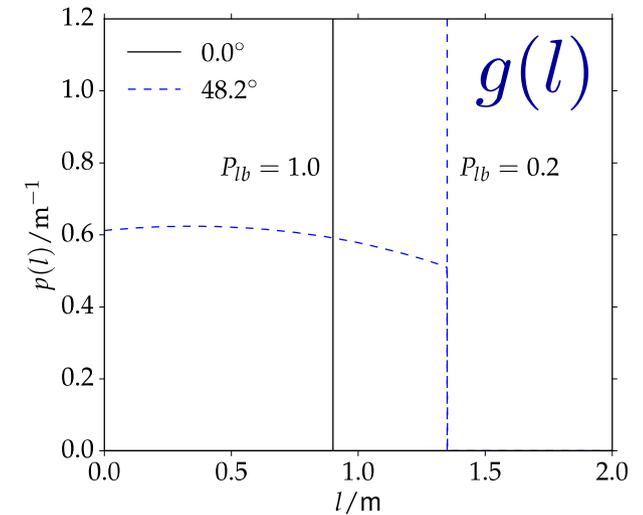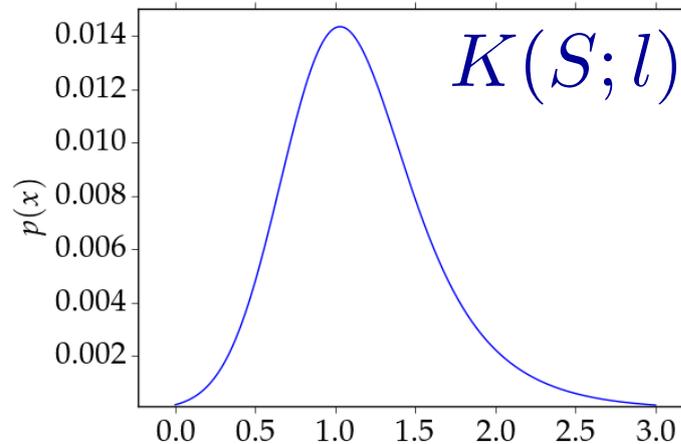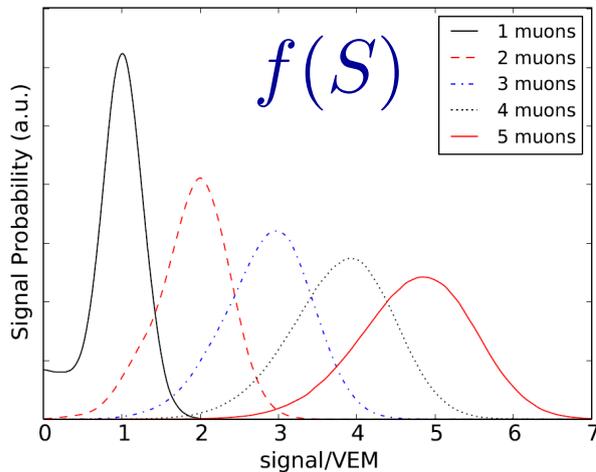$$f(S) = \int \mathrm{d}l\, K(S; l)\, g(l)$$

Signal distribution to one muon (k=1)

Detector response model: Exponentially-modified Gaussian

Track length distribution for through-going particles (pure geometry)

Response to **k** muons is **k**-fold **auto-convolution** of **k=1**
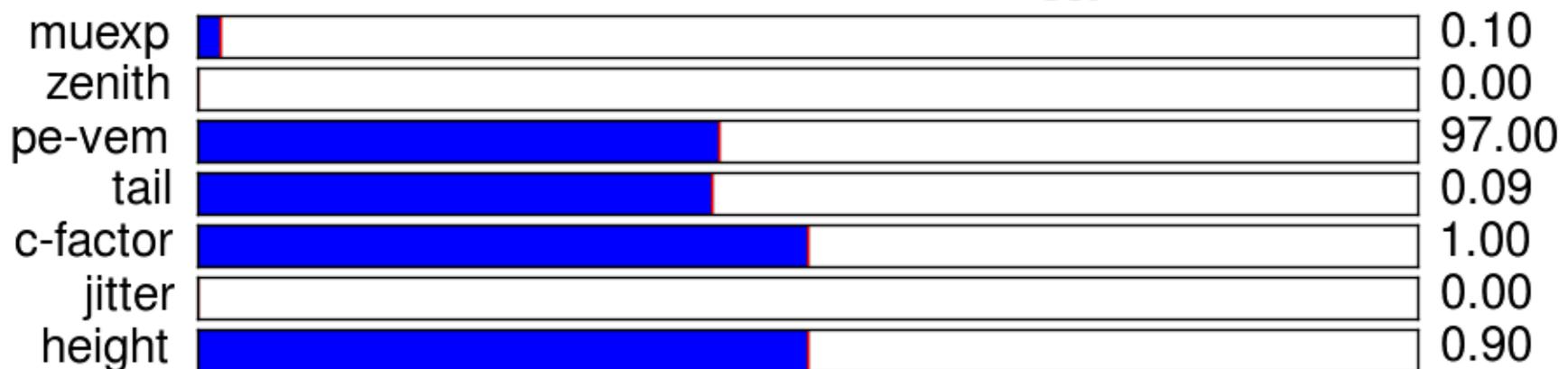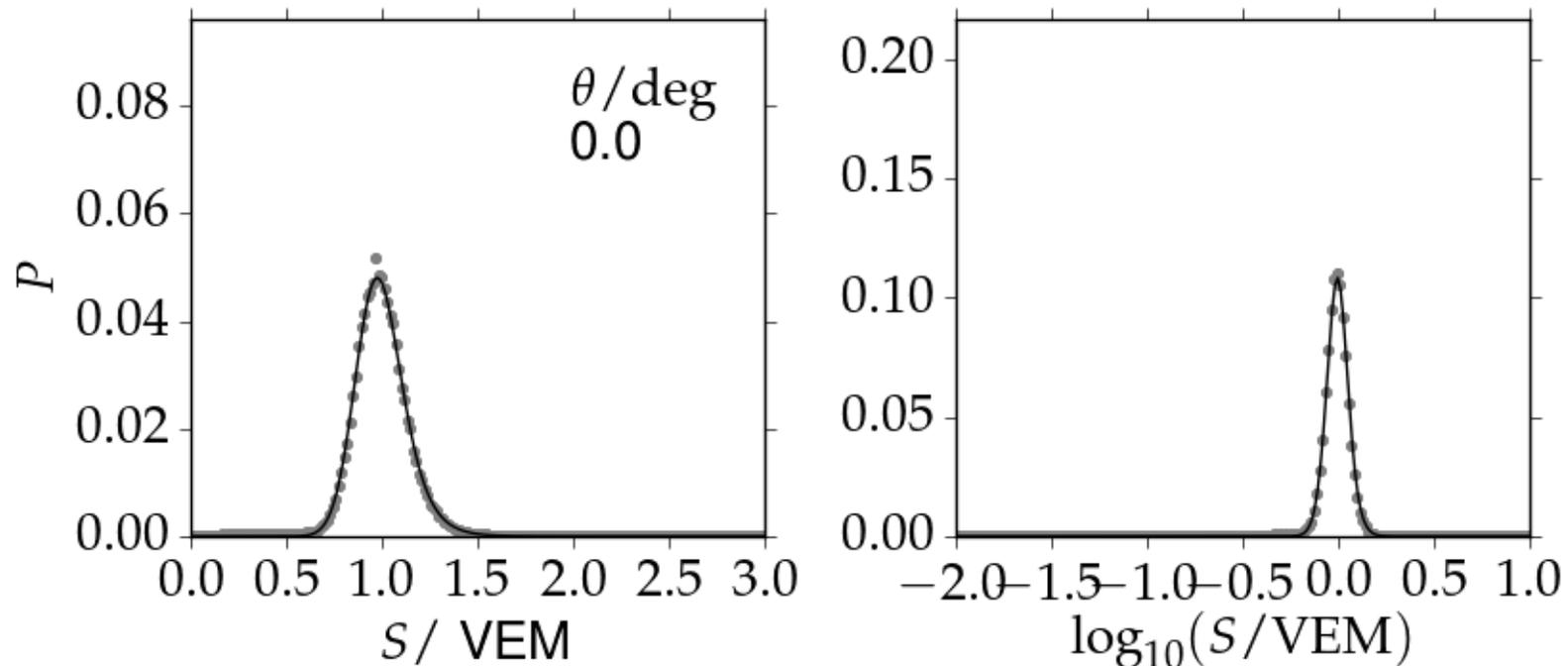
$$K(S; \mu(l), \sigma(l), \lambda) = \frac{\lambda}{2} \exp\left(\frac{\lambda}{2}(2\mu + \lambda\sigma^2 - 2x)\right)$$

$$\times \mathrm{erfc}\left(\frac{\mu + \lambda\sigma^2 - S}{\sqrt{2}\sigma}\right)$$

$f(S)$

Signal Probability (a.u.)

Legend:
— 1 muons
-- 2 muons
-·- 3 muons
··· 4 muons
— 5 muons

signal/VEM

$K(S; l)$

$p(x)$

$g(l)$

— 0.0°
-- 48.2°

$P_{lb} = 1.0$

$P_{lb} = 0.2$

$p(l)\,/\mathrm{m}^{-1}$

$l\,/\mathrm{m}$

B. Kegl, D. Veberic, Auger note (2009)
http://arxiv.org/abs/1502.03347
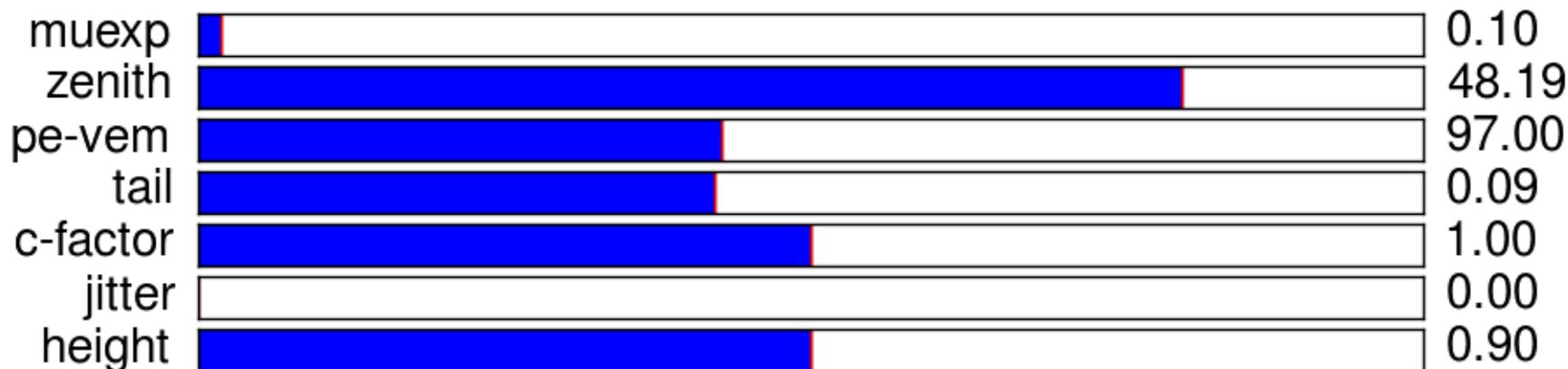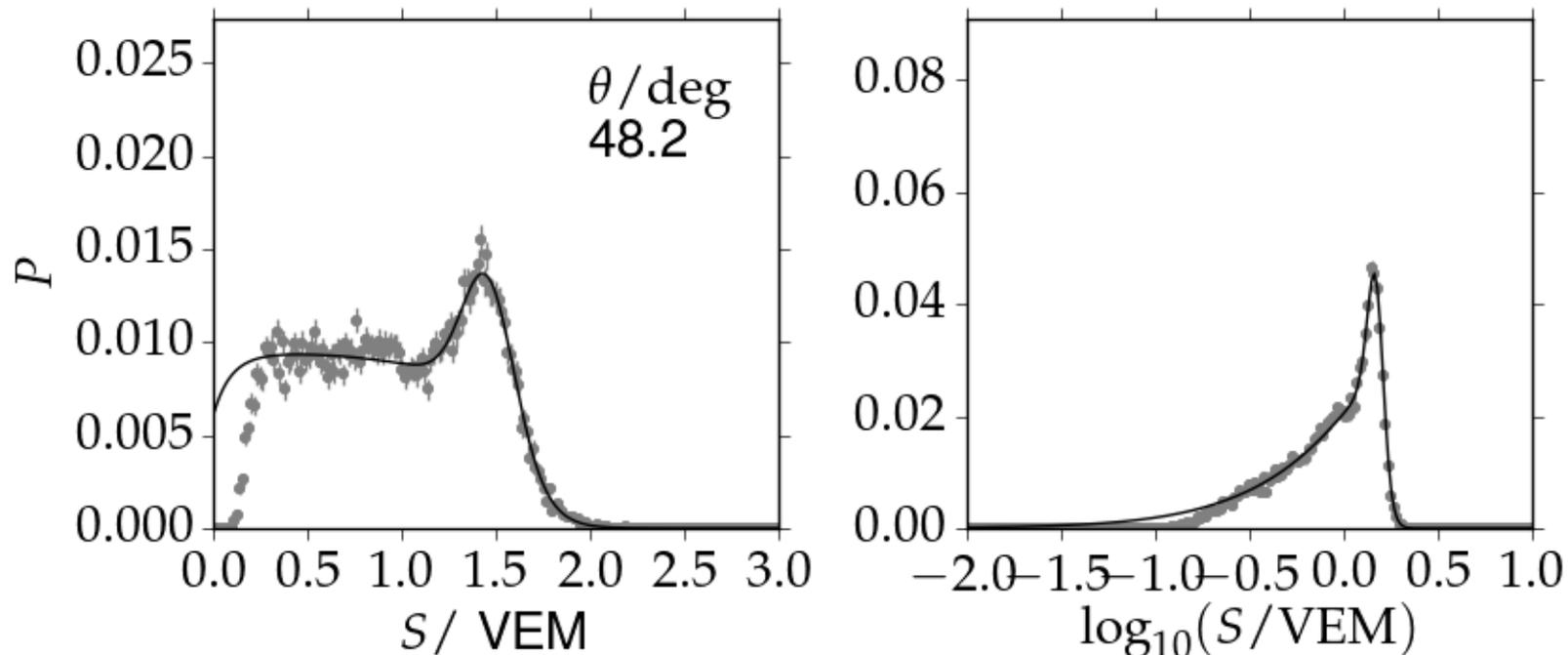
Muon model reproduces simulations

Trigger suppression included in full model, but neglected here

Data points: Tank response simulated with Geant4
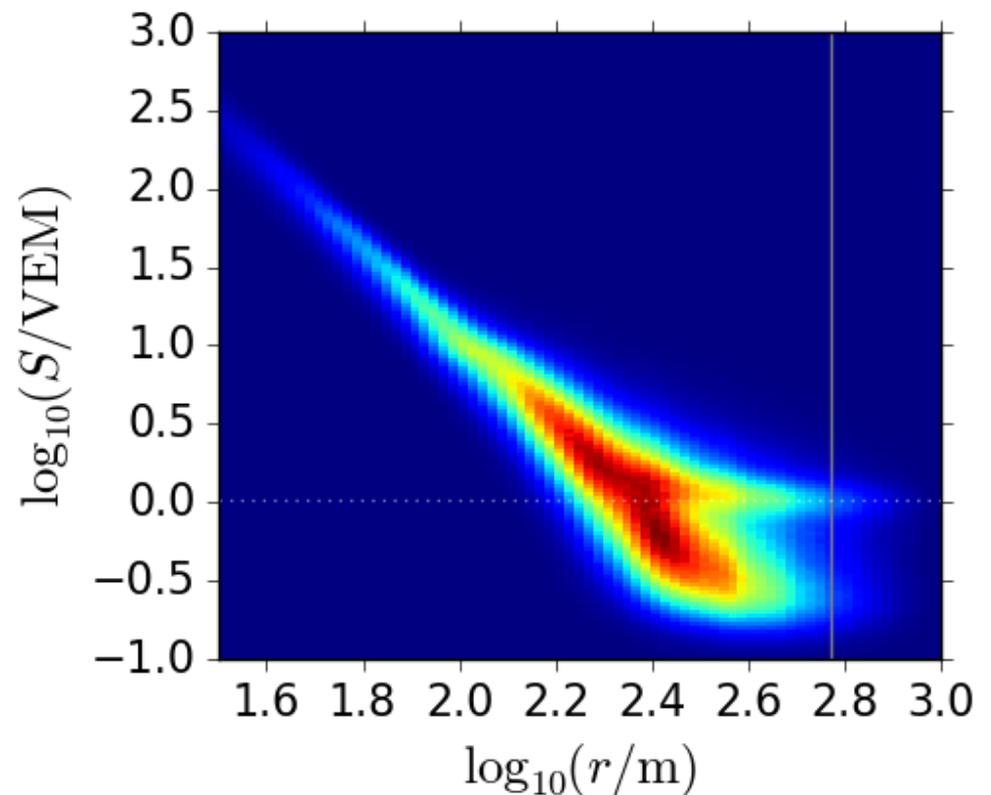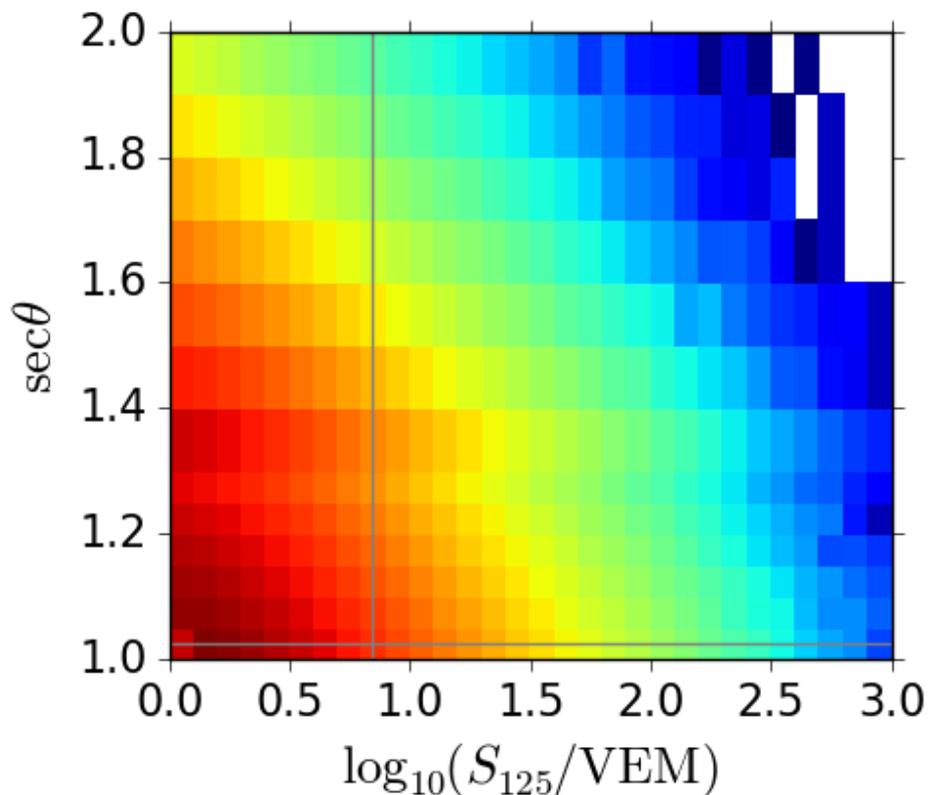
Muon model reproduces simulations

Data points: Tank response simulated with Geant4

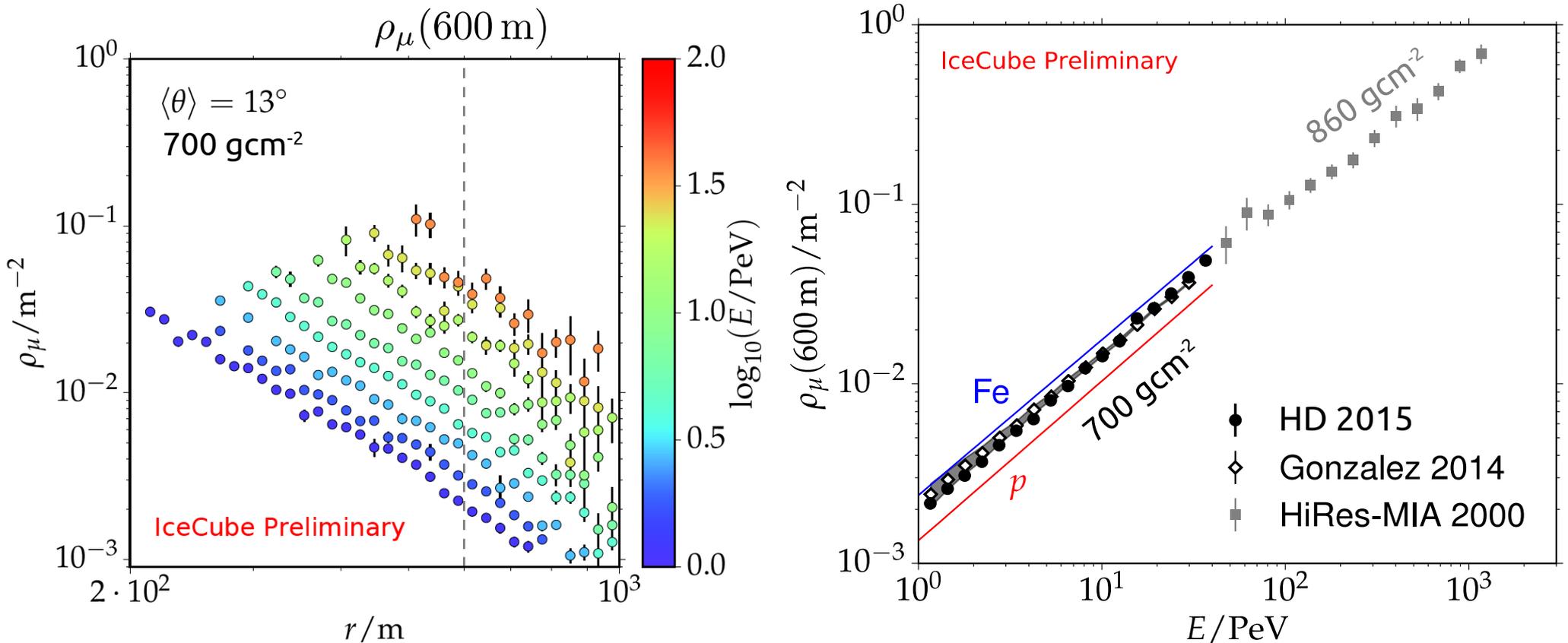# Data set

- Data from 1 June 2010 to 31 May 2013
- Standard quality cuts   **IceCube** Collab., M.G. Aartsen et al., PRD 88 (2013) 042004
- Zenith angle θ < 40°
- Shower size S_{125} > 1 VEM (~ 1 PeV)
- 47 M events

Muon-LDF

One month of data (June 2011)

More checks needed for final publication – stay tuned

Final results will have larger energy range and several zenith angles (μ attenuation!)

Summary

‣ **Analysis: Muon density from charge histograms**

  ‣ High-resolution measurement of muon density from 250 m to 1000 m

  ‣ No simulation input (except conversion S125 ↔ energy)

  ‣ Systematic uncertainties expected to be small

‣ **Preliminary results**

  ‣ Vertical showers from 1 PeV to 30 PeV from June 2011

  ‣ ρ_μ(600m) bracketed by p/Fe showers simulated with CORSIKA / Sibyll-2.1 / Fluka

‣ **Road-map towards publication**

  ‣ Analyse full data-set (statistic x 36) $E_{CR} \sim 1 - 100$ PeV, $\theta \sim 0 - 40°$

  ‣ Analyse muon attenuation with zenith angle and compare with simulations

    • Muon density + muon attenuation: Test of hadronic interaction model

  ‣ Checks needed, against MC simulated events, time dependency, etc.

  ‣ Systematic uncertainties need to be quantified