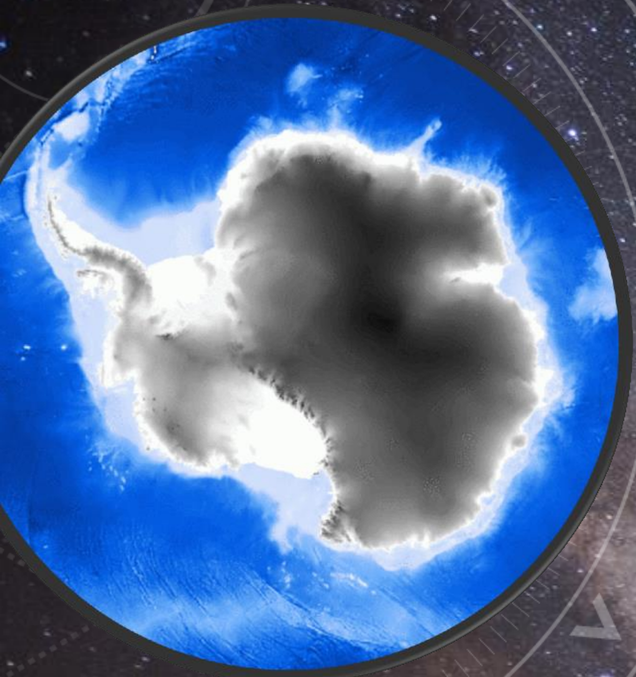


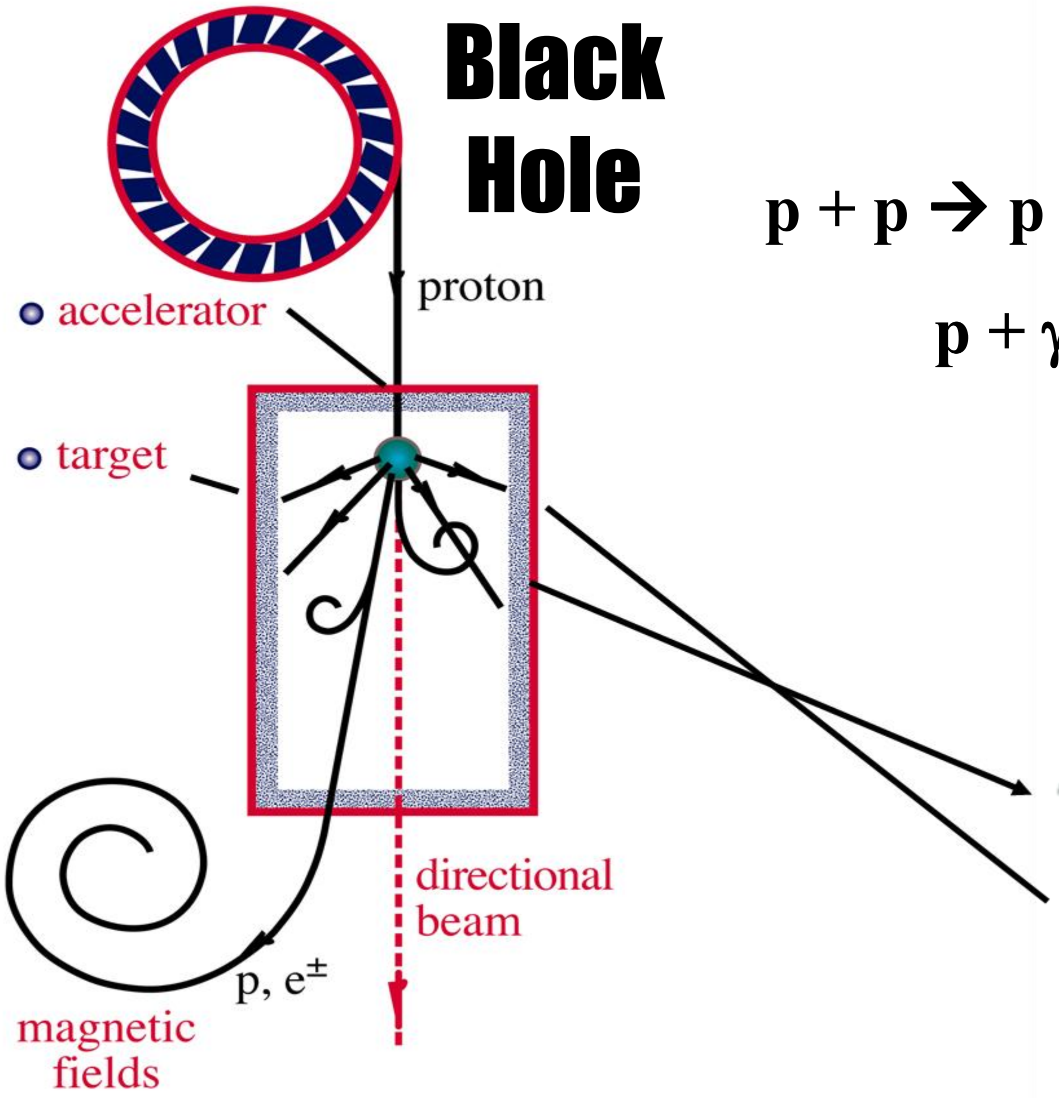
AIR SHOWERS IN ICECUBE/ICETOP

LU LU

CHIBA UNIVERSITY

11/09/2015

NEUTRINO BEAMS: HEAVEN & EARTH

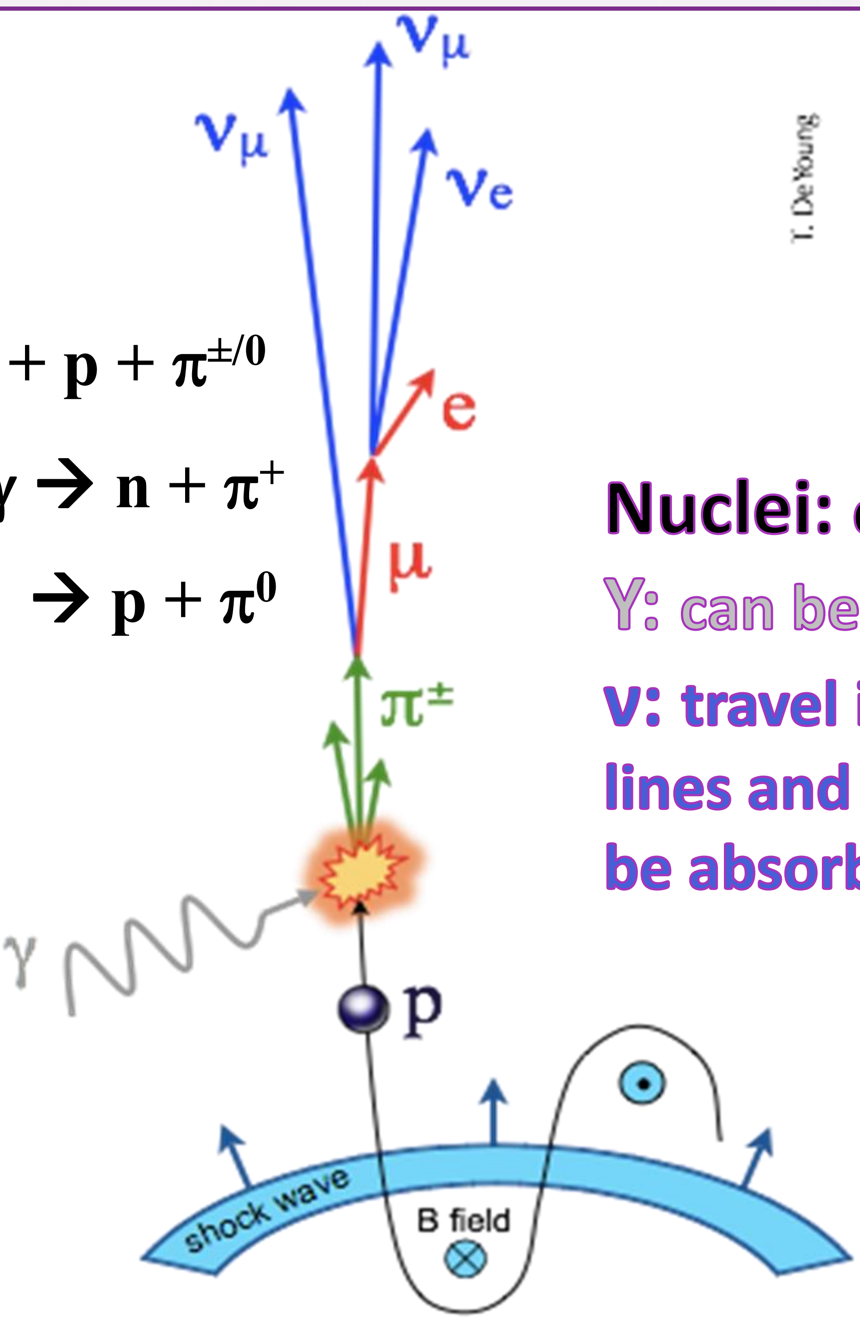


Black Hole

$p + p \rightarrow p + p + \pi^{\pm/0}$

$p + \gamma \rightarrow n + \pi^+$

$\rightarrow p + \pi^0$



T. DeYoung

Nuclei: deflected

Y: can be absorbed

ν: travel in straight lines and difficult to be absorbed

The IceCube Collaboration

USA
- Clark Atlanta University
- Drexel University
- Georgia Institute of Technology
- Lawrence Berkeley National Laboratory
- Massachusetts Institute of Technology
- Michigan State University
- Ohio State University
- Pennsylvania State University
- South Dakota School of Mines & Technology
- Southern University and A&M College
- Stony Brook University
- University of Alabama
- University of Alaska Anchorage
- University of California, Berkeley
- University of California, Irvine
- University of Delaware
- University of Kansas
- University of Maryland
- University of Wisconsin–Madison
- University of Wisconsin–River Falls
- Yale University

Canada
- University of Alberta–Edmonton
- University of Toronto

Niels Bohr Institutet, **Denmark**

Sweden
- Stockholms universitet
- Uppsala universitet

Chiba University, **Japan**

Sungkyunkwan University, **Korea**

University of Oxford, **UK**

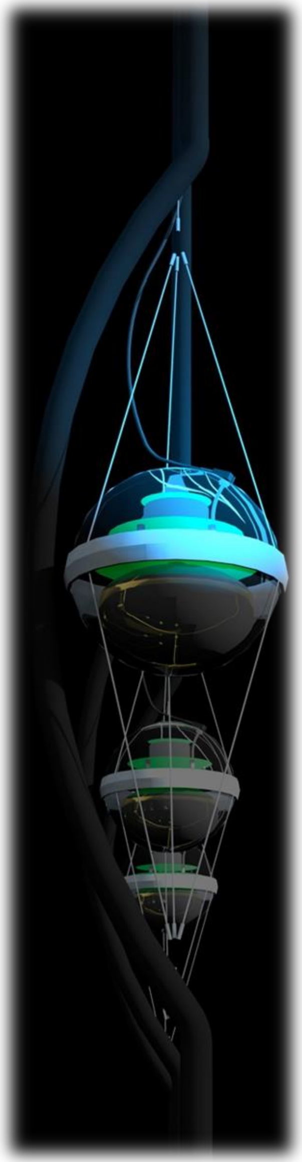
Germany
- Deutsches Elektronen-Synchrotron
- Friedrich-Alexander-Universität Erlangen-Nürnberg
- Humboldt-Universität zu Berlin
- Ruhr-Universität Bochum
- RWTH Aachen
- Technische Universität München
- Technische Universität Dortmund
- Universität Mainz
- Universität Wuppertal

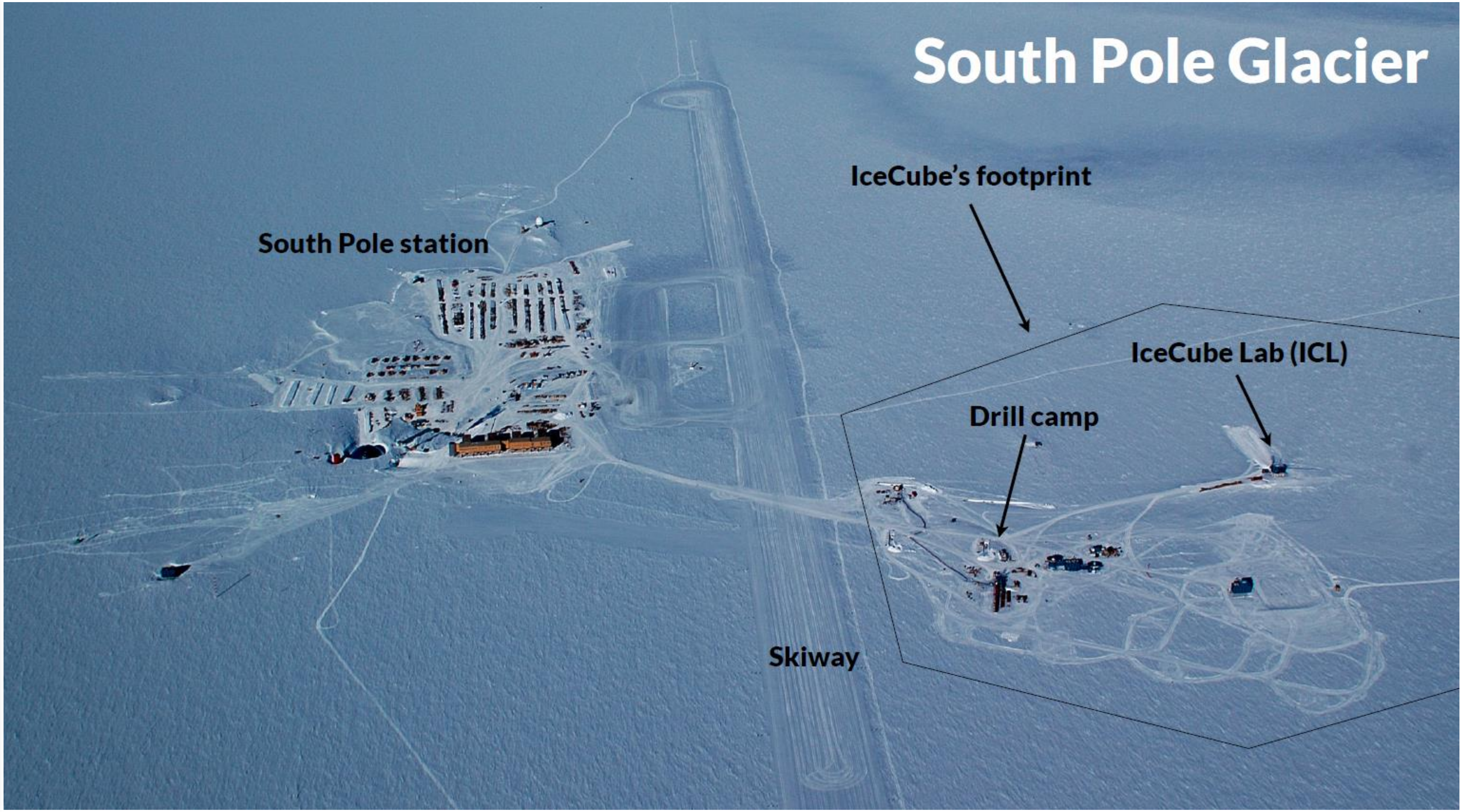
Belgium
- Université Libre de Bruxelles
- Université de Mons
- Universiteit Gent
- Vrije Universiteit Brussel

Université de Genève, **Switzerland**

University of Adelaide, **Australia**

University of Canterbury, **New Zealand**





South Pole Glacier

ICECUBE

5160 PMTs

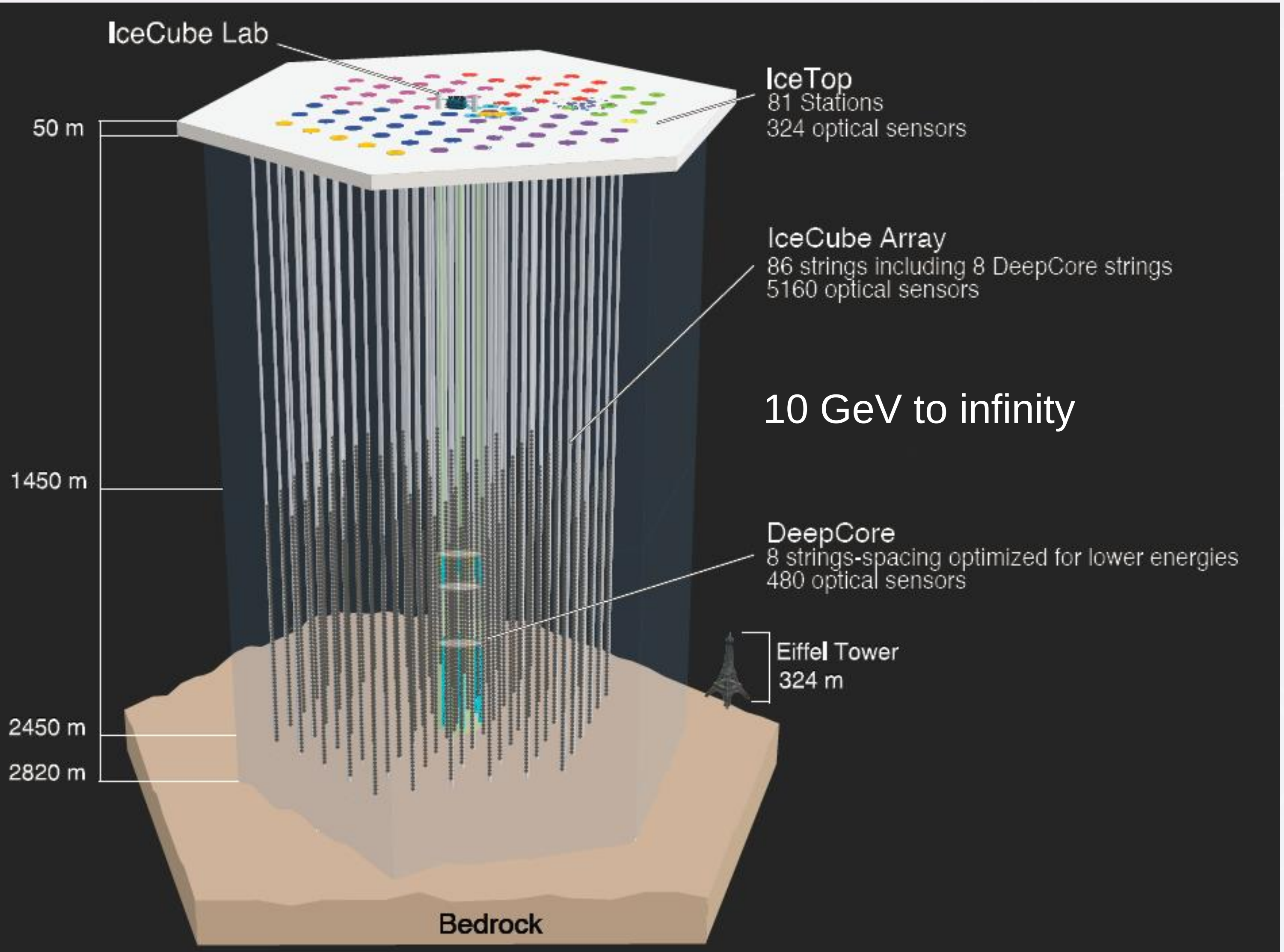
1 km^3 volume

86 strings

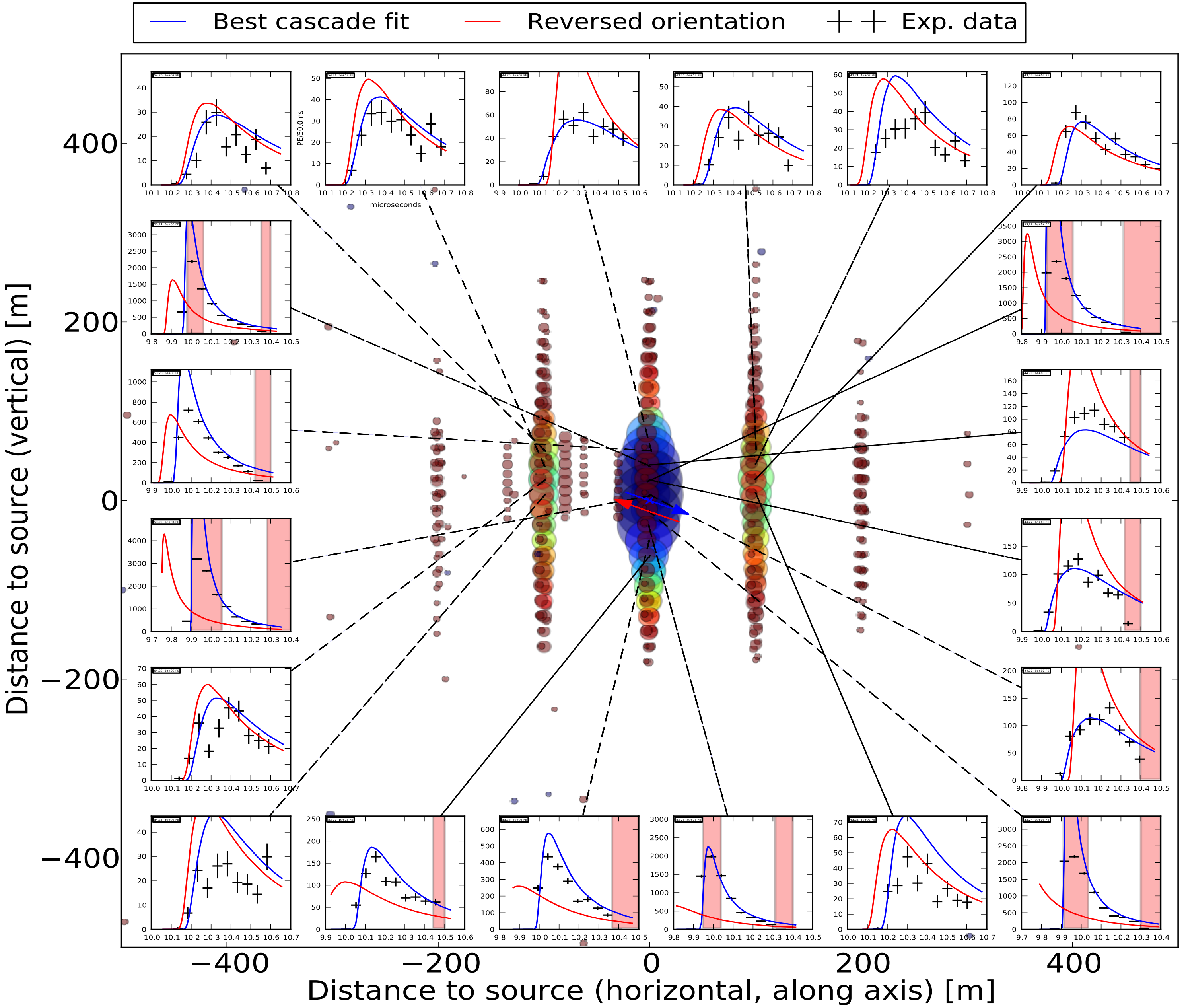
17 m vertical spacing

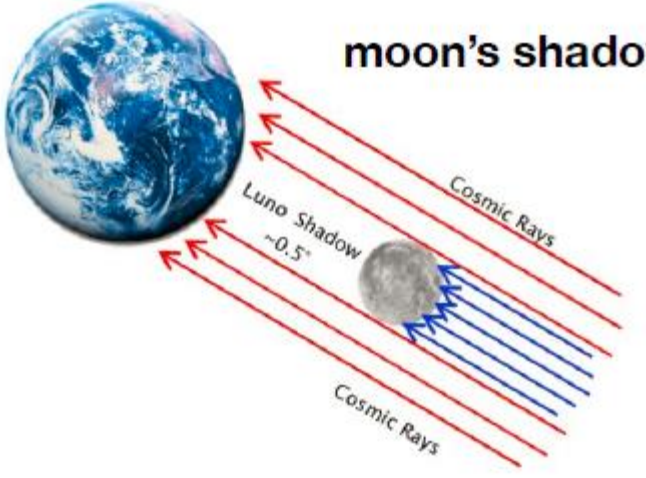
125 m string spacing

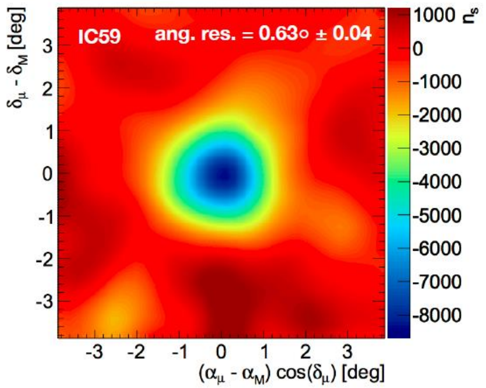
Completed **2010**



10 GeV to infinity



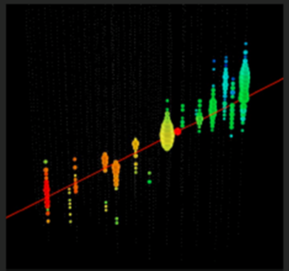




- < 0.5 degree online
- < 0.3 degree offline for muon tracks
- 10~15 degrees for showers
- < 15% energy resolution

Main-stream analyses

CC Muon Neutrino

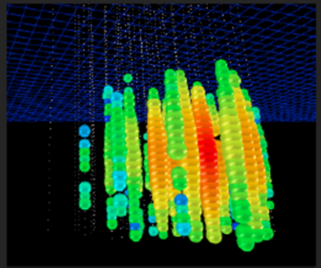


$$\nu_\mu + N \to \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino

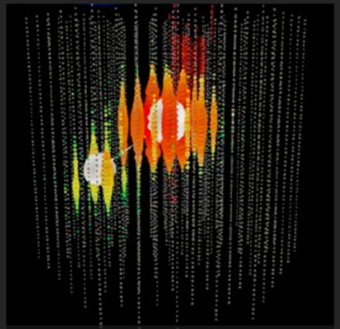


$$\nu_e + N \to e + X$$
$$\nu_x + N \to \nu_x + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ≳ 100 TeV)

CC Tau Neutrino

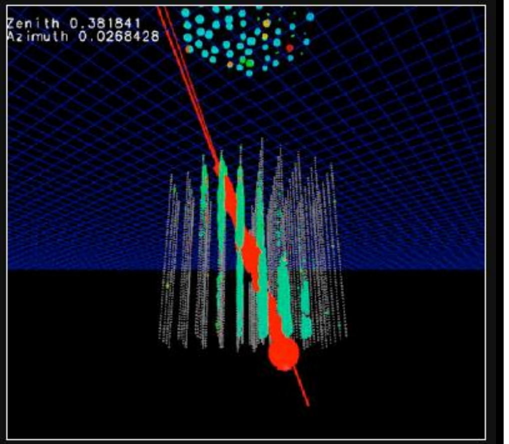


$$\nu_\tau + N \to \tau + X$$

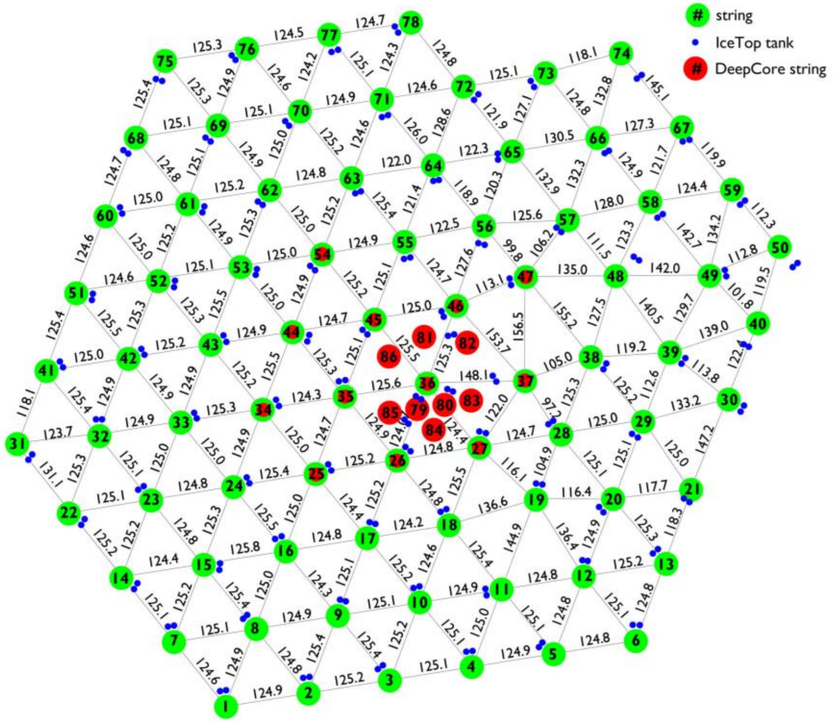
“double-bang” (≳10PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)

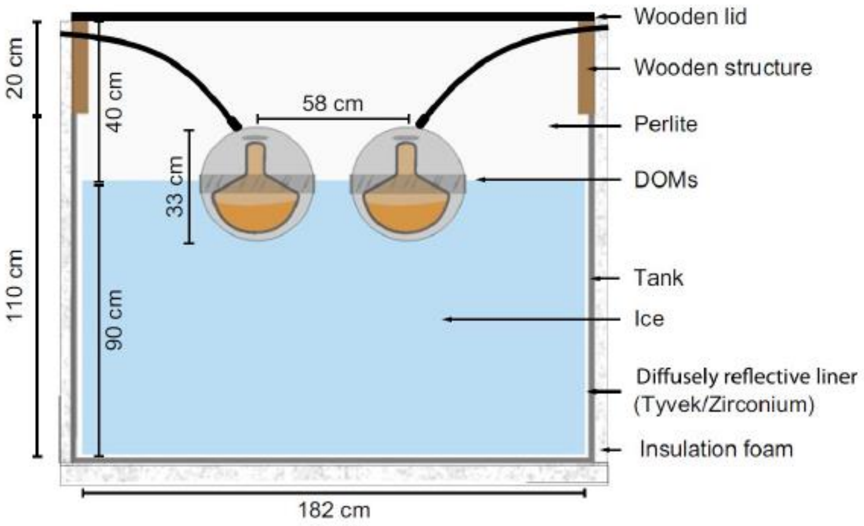
+



Another way of FD… we go below and 3D

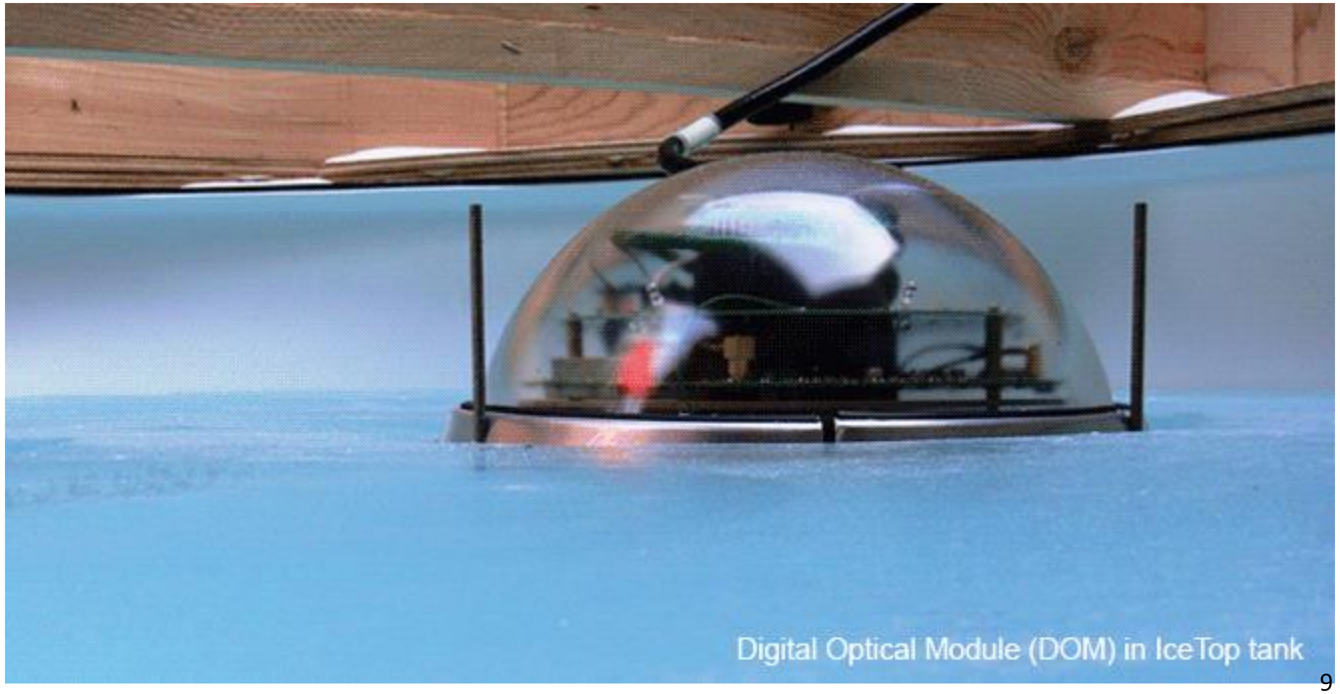


ICETOP



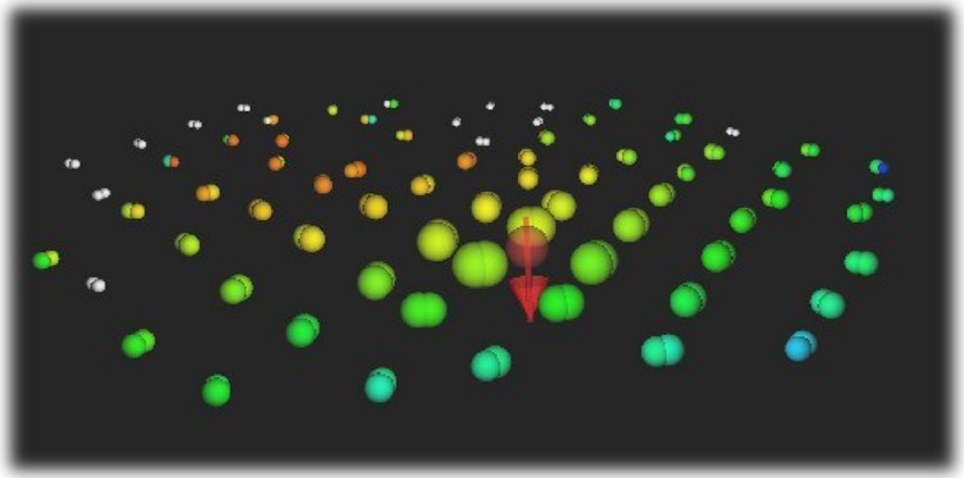
IceTop	KASCADE
1 km^2 ice-Cherenkov	**0.04 km^2**
125 m spacing	13 m spacing
2835 m a.s.l. 680 gcm^{-2}	**1000 gcm^{-2}**
Coverage 3 x 10^{-4}	Coverage 1.5 x 10^{-2}

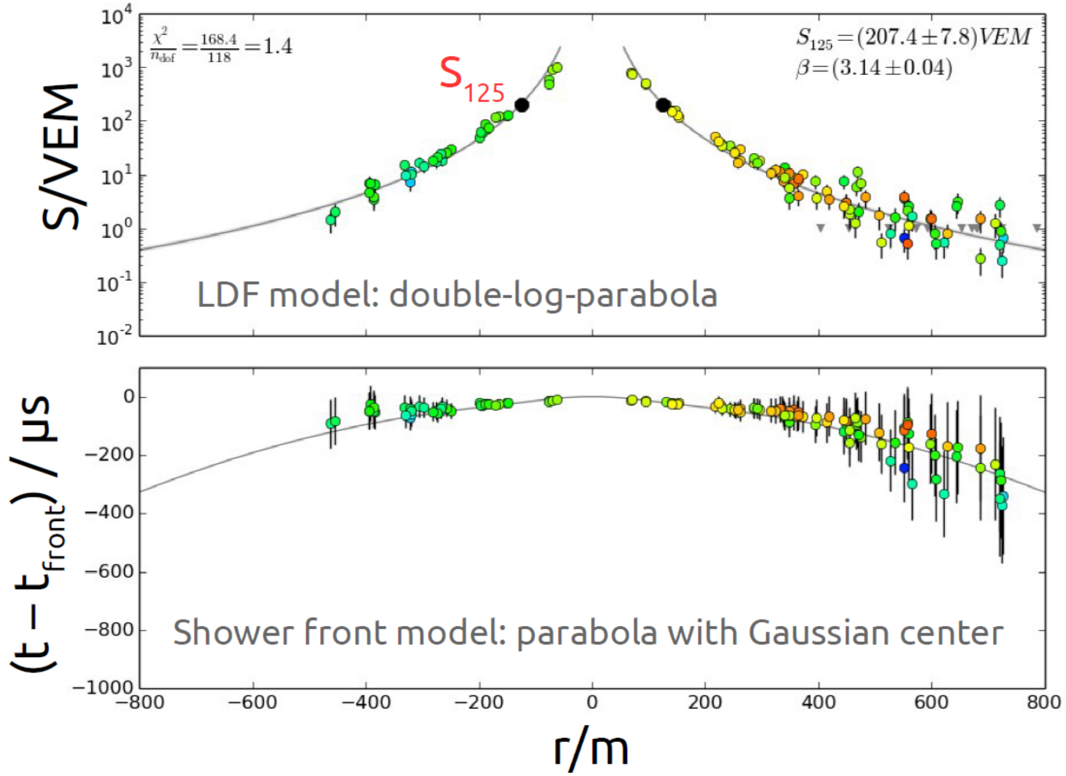
$$\text{Coverage} = \frac{\text{instrumented area}}{\text{total area}}$$

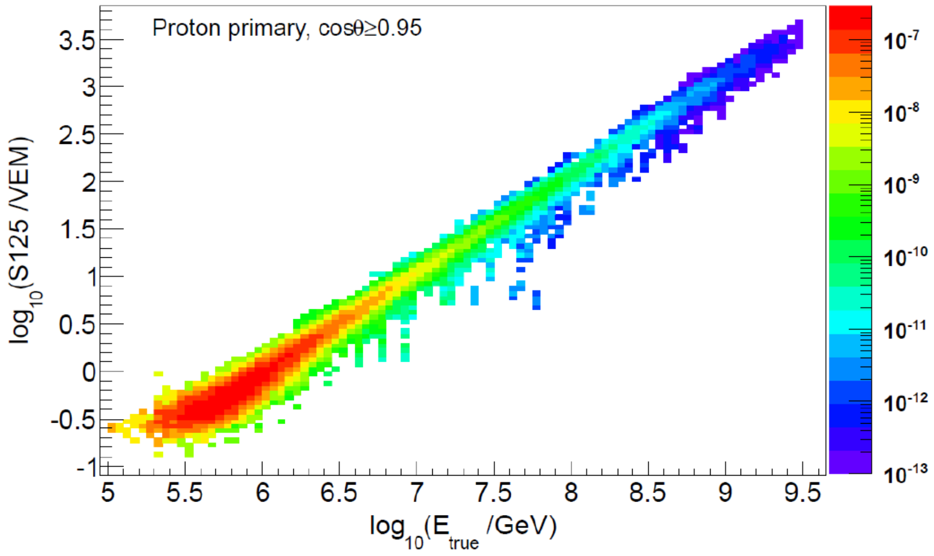


Digital Optical Module (DOM) in IceTop tank

- Angular resolution: ~1°
- Timing resolution: 3 ns
- Energy proxy S_{125} in VEM (vertical equivalent muon)
- Energy calibration based on MC (mixed-composition model H4a)
  - Energy resolution < 25%
  - Systematic uncertainty ~10%.





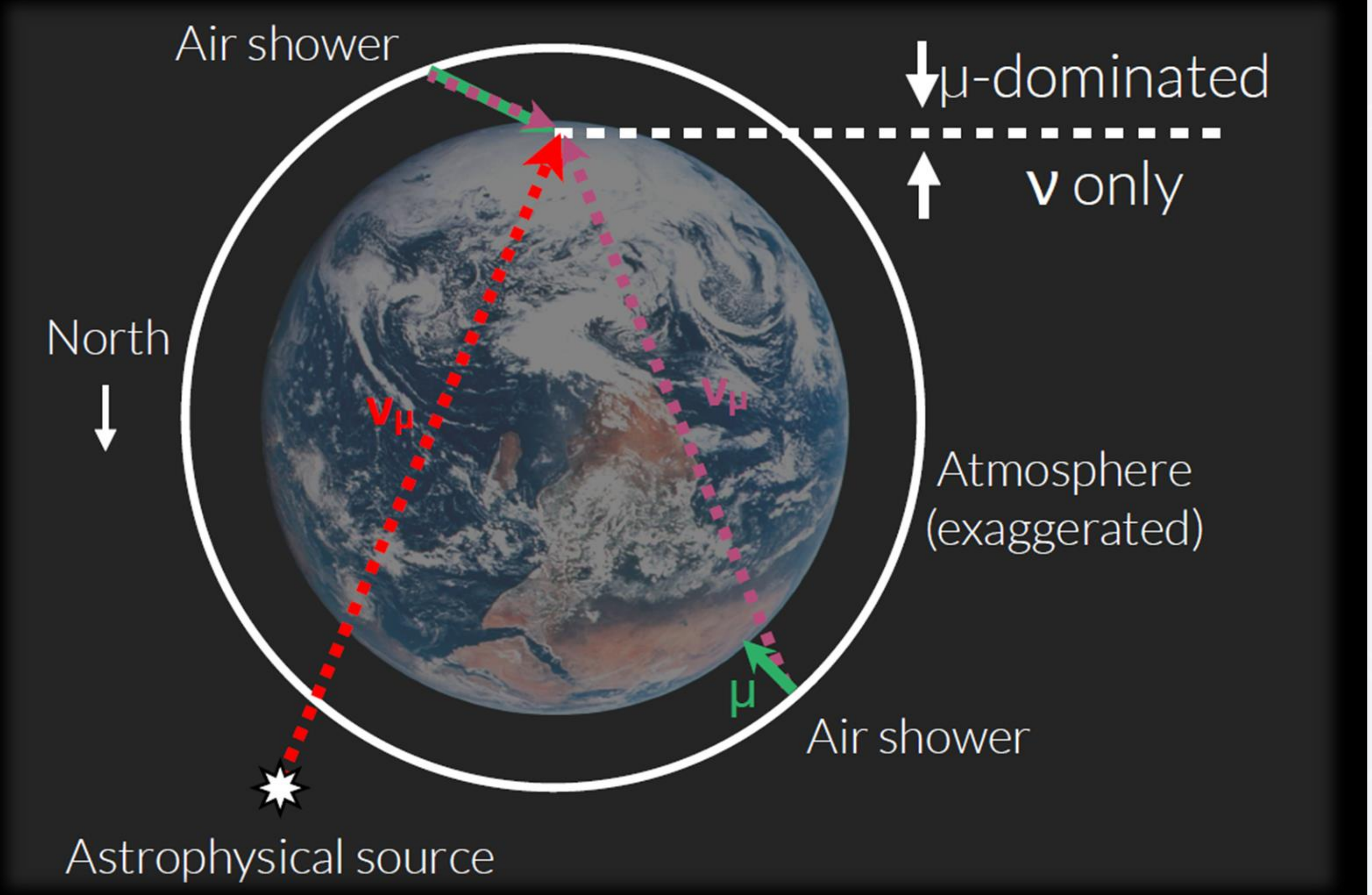


Muons detected per year:

- atmospheric* μ
  7×10^{10}

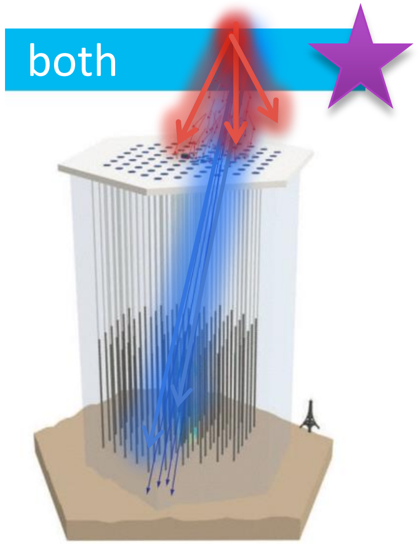
- atmospheric** ν → μ
  > 8×10^4

- cosmic ν → μ
  ~ 10

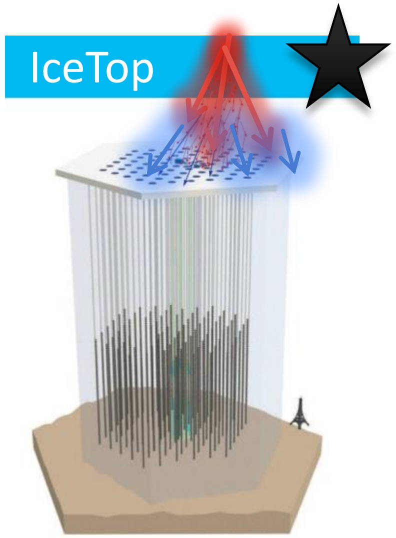


* ~ 3000 per second
** 1 every 6 minutes

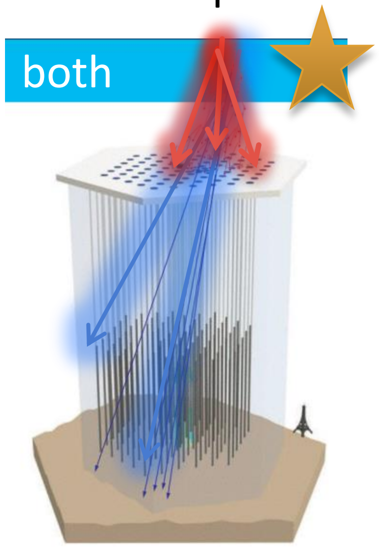
Analyses of interest



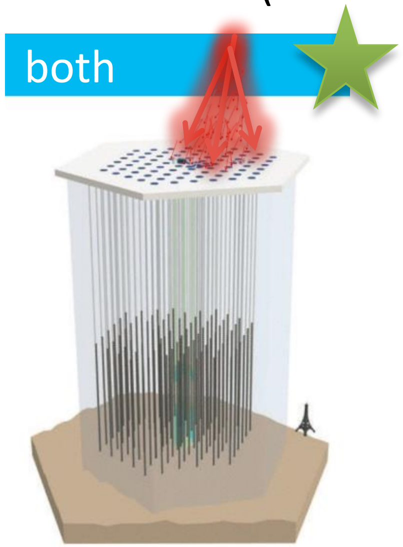
Mass composition



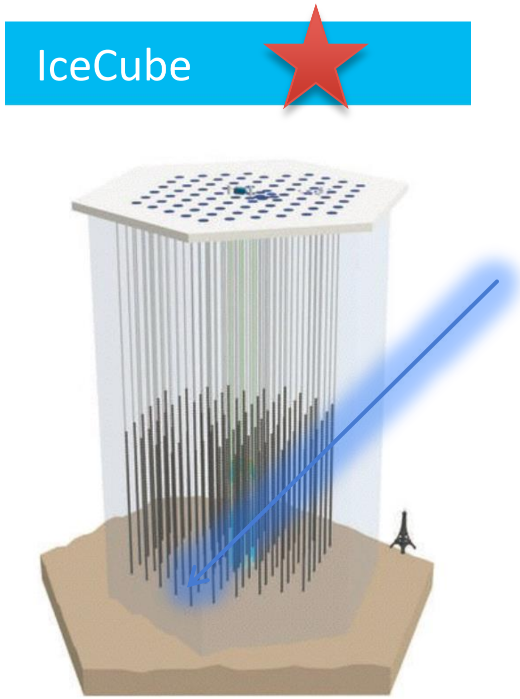
Peripheral muons (1-10 GeV)



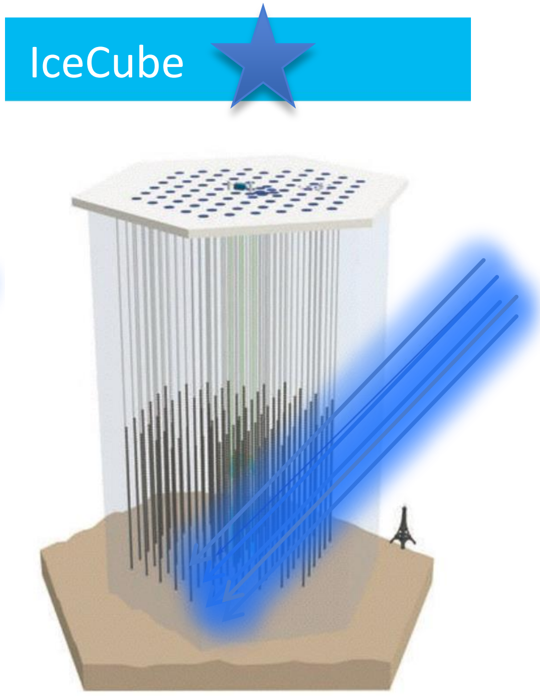
High PT muons



Photon search



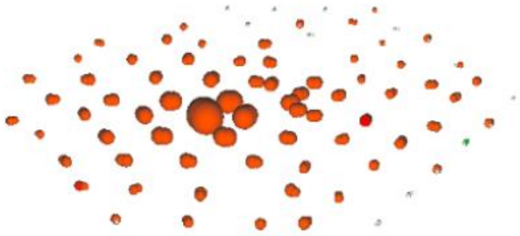
High energy muons
Prompt component
(hadronic interaction models)

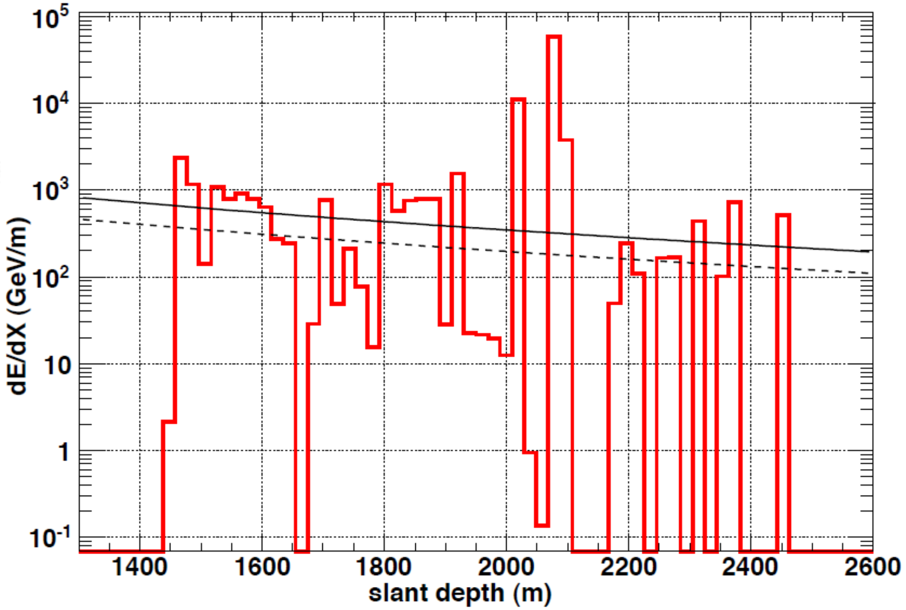


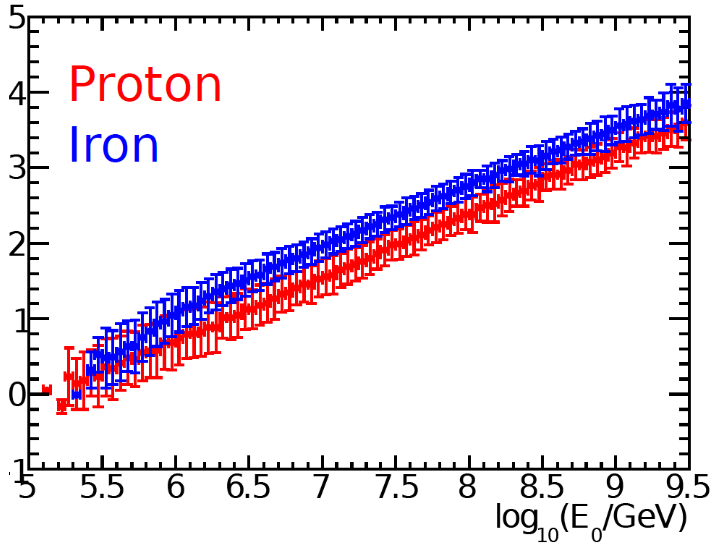
Muon bundle
Muon multiplicity and mass composition

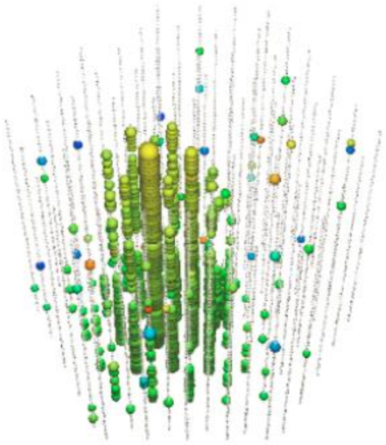
ICRC 2015
Sam DE RIDDER
Tom FEUSELS
Katherine RAWLINS
Serap TILAV

Coincidence and mass composition (I/2)





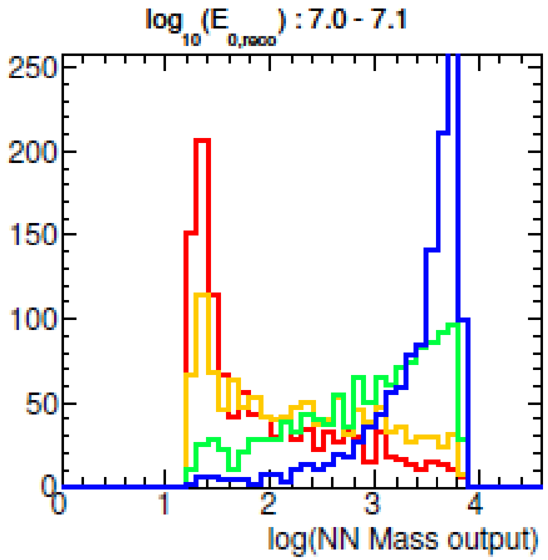


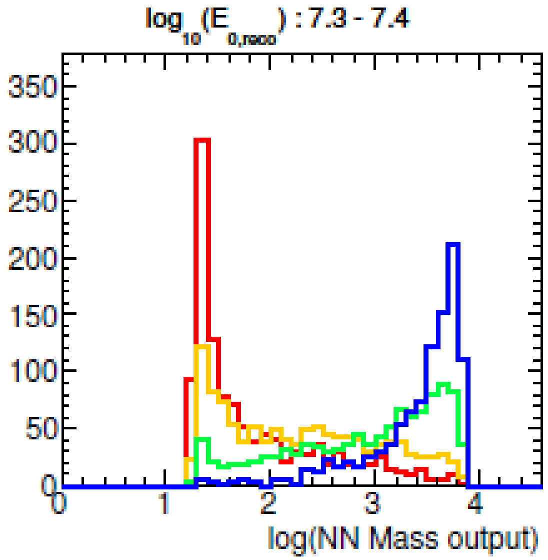


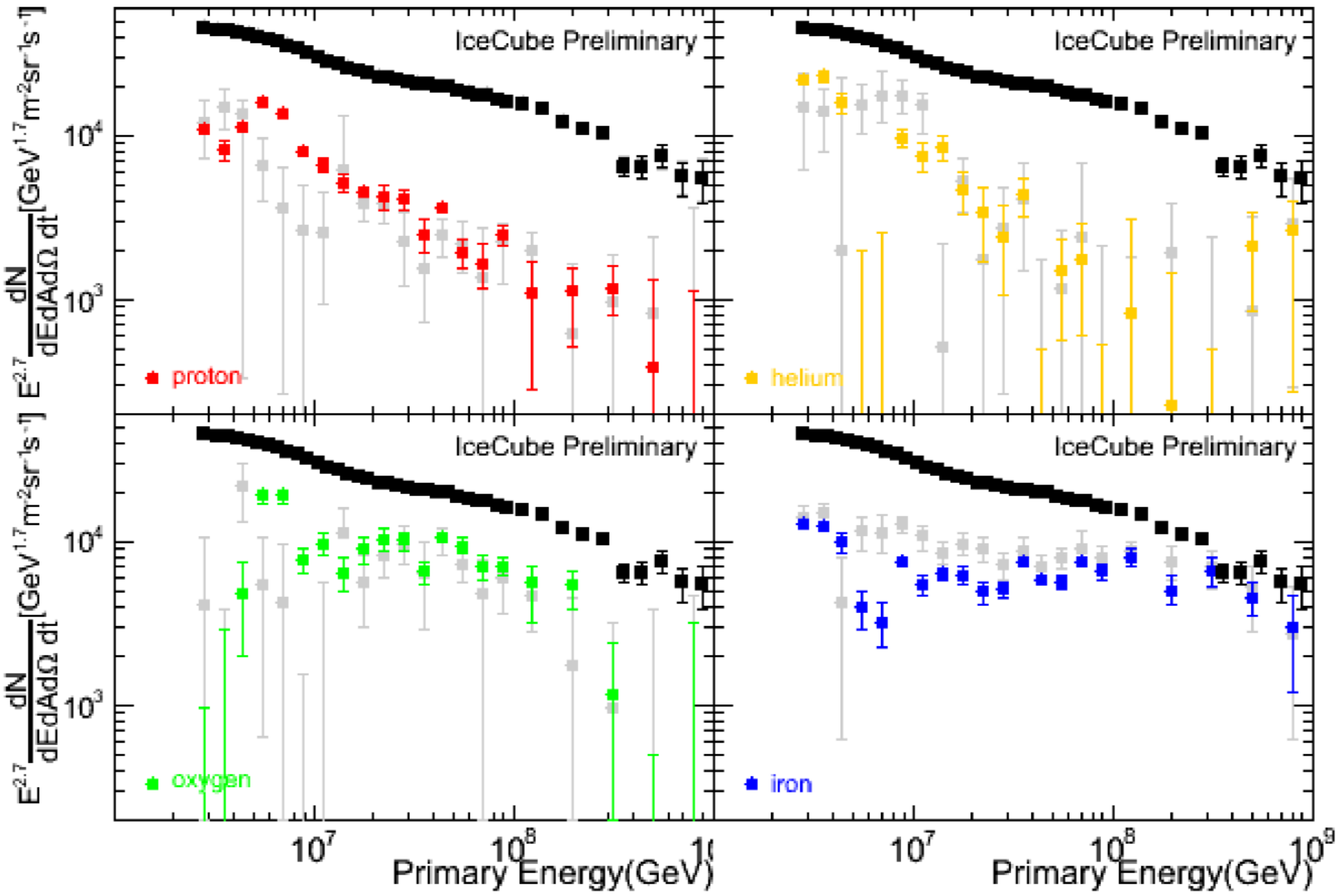
Neural network of variables both from IceTop & IceCube

- Signal at 125 m on the ground
- Zenith angle
- dE/dX at 1500 m (slant depth)
- The number of large stochastic energy losses at two threshold values

Coincidence and mass composition (2/2)



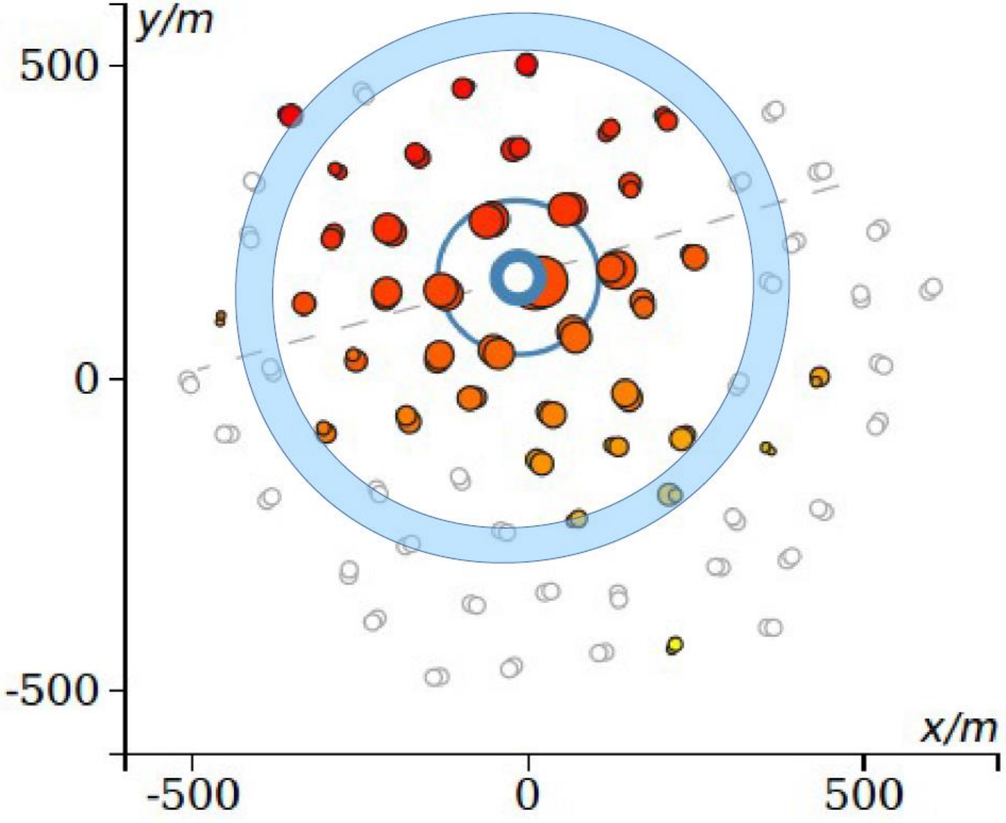


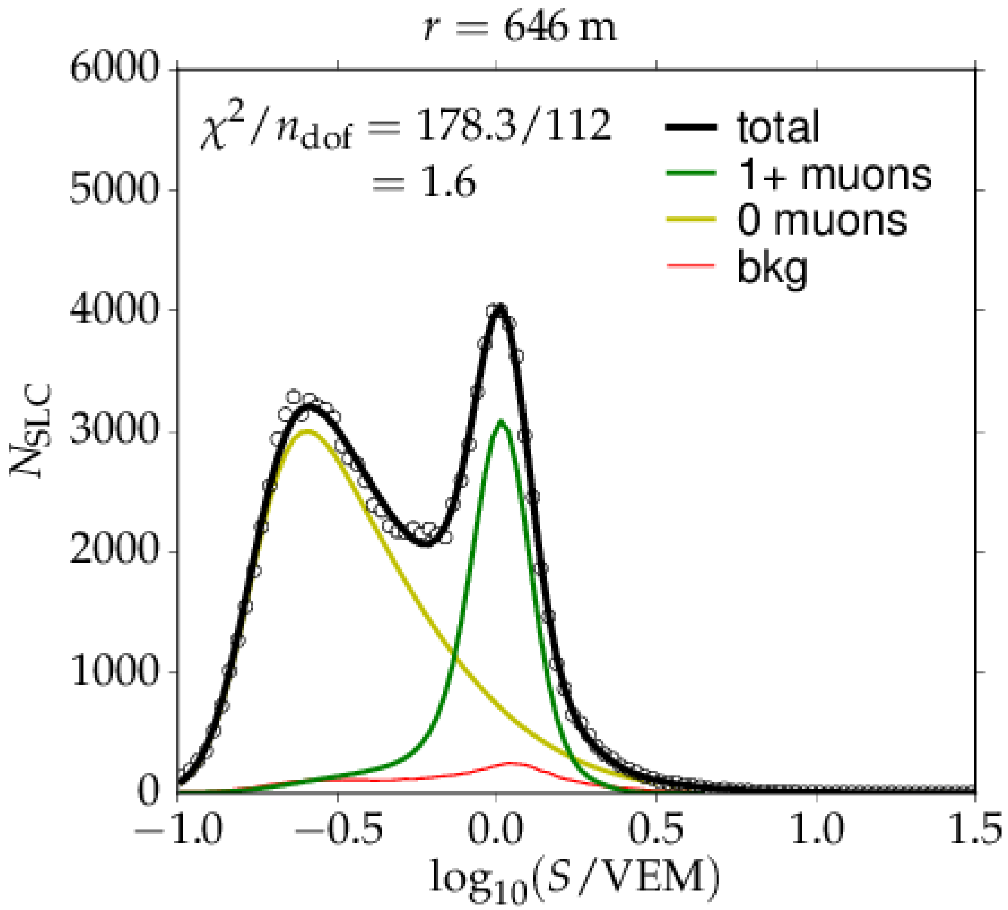


Light grey: QGSJETII-03, Coloured: Sibyll2.1

Hans DEMBINSKI: ICRC 267
Javier GONZALEZ

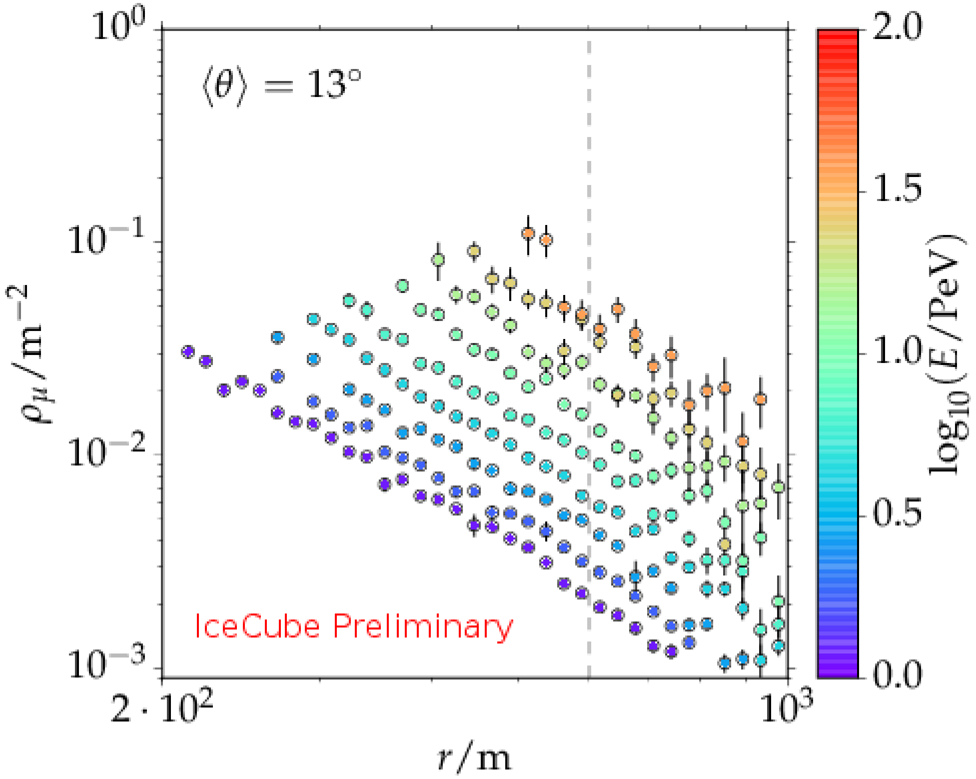
★ Peripheral muons (I/2)

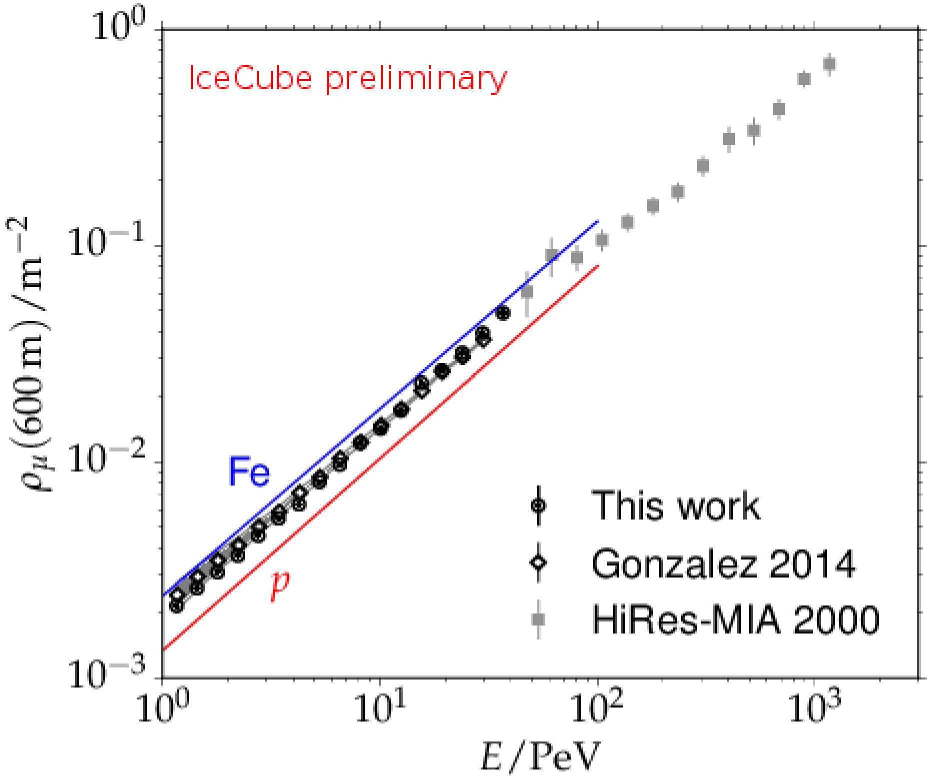




Hans DEMBINSKI: ICRC 267
Javier GONZALEZ

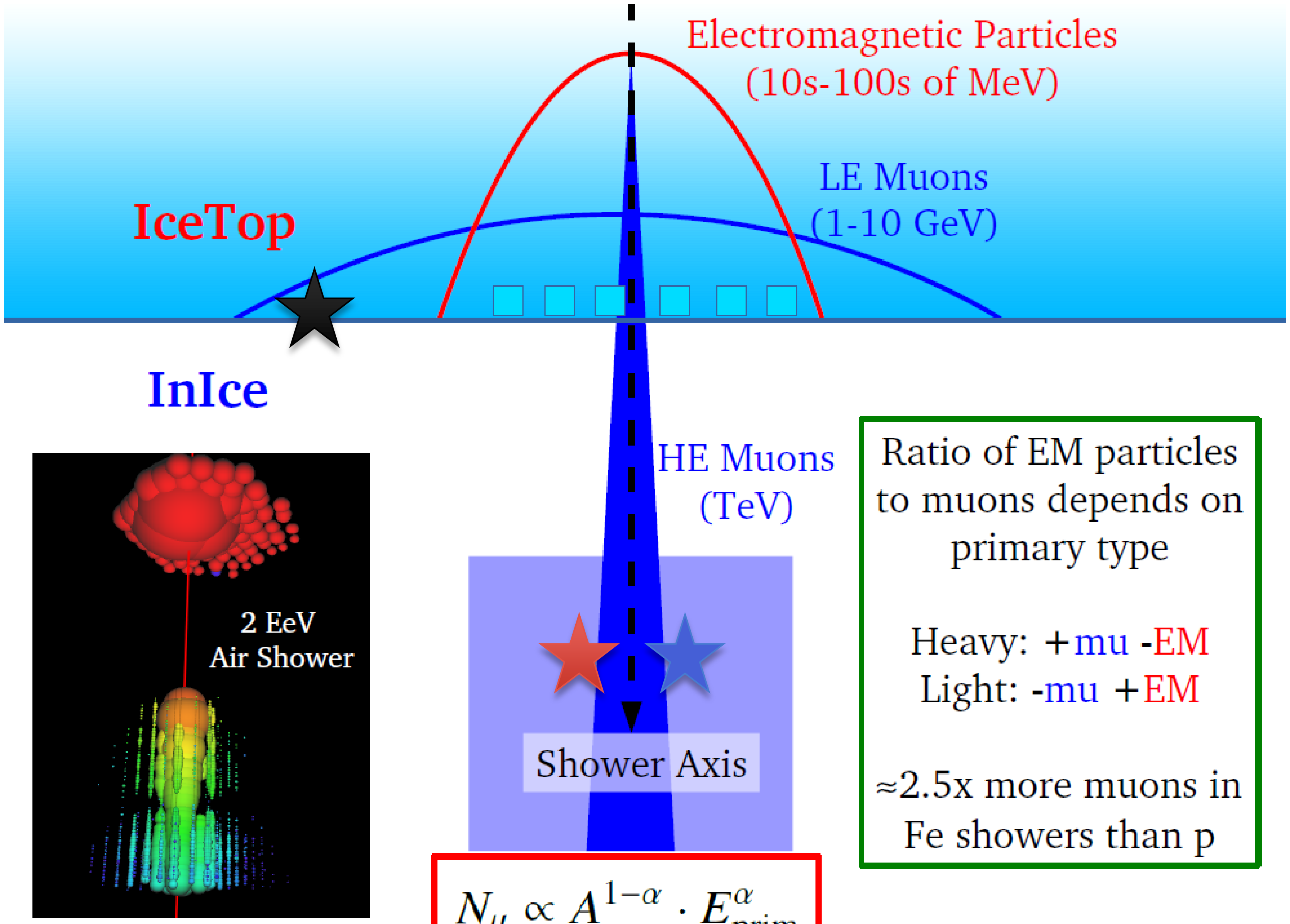
★ Peripheral muons (2/2)





CORSIKA-Sibyll2.1-Fluka, and the HiRes-MIA result at a different slant depth of 860 g cm-2 (we are at 680 g cm^{-2}).

QGSJetII-04 and EPOS-LHC results in progress



Ratio of EM particles to muons depends on primary type

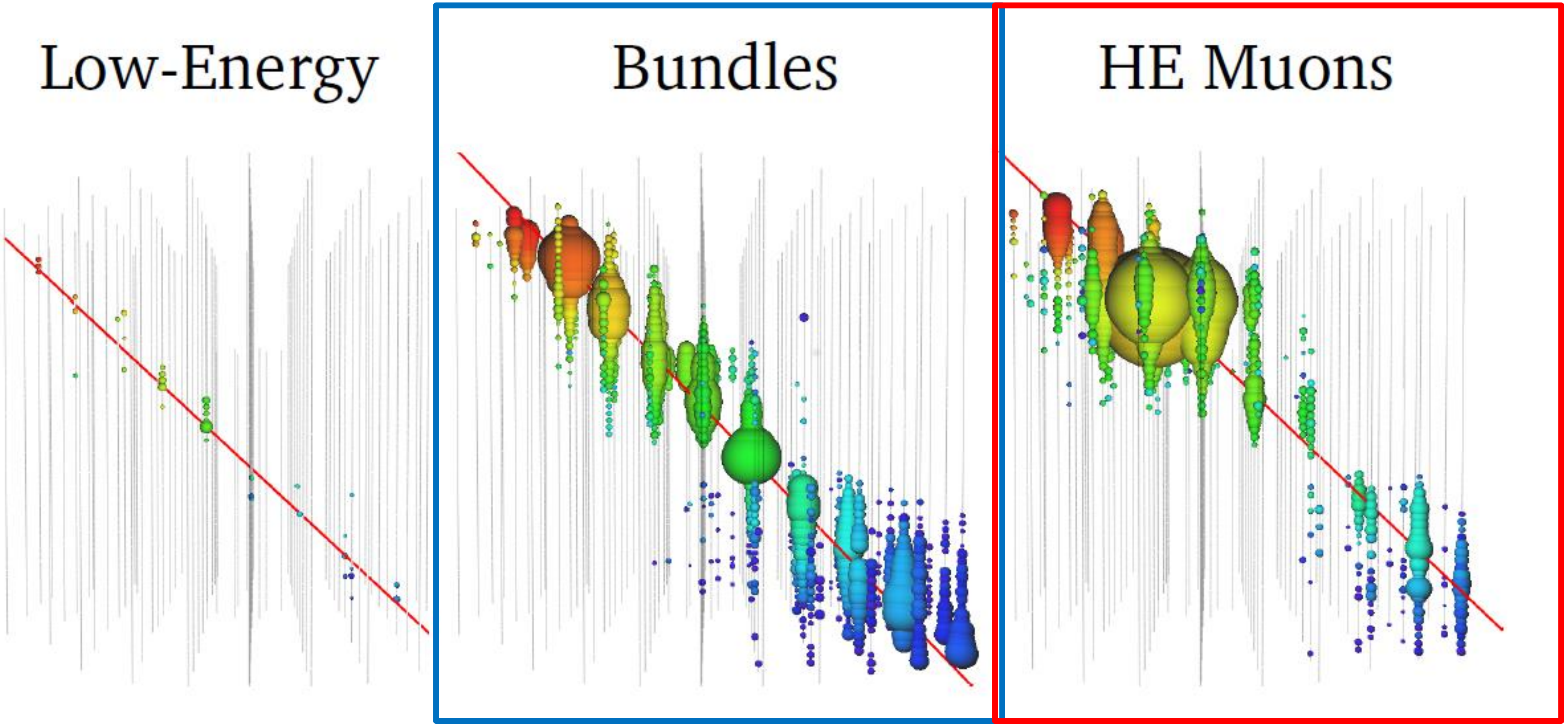
Heavy: +mu -EM
Light: -mu +EM

≈2.5x more muons in Fe showers than p

$$N_\mu \propto A^{1-\alpha} \cdot E_{\mathrm{prim}}^{\alpha}$$

arXiv:
1506.07981
(subm. to ApP)

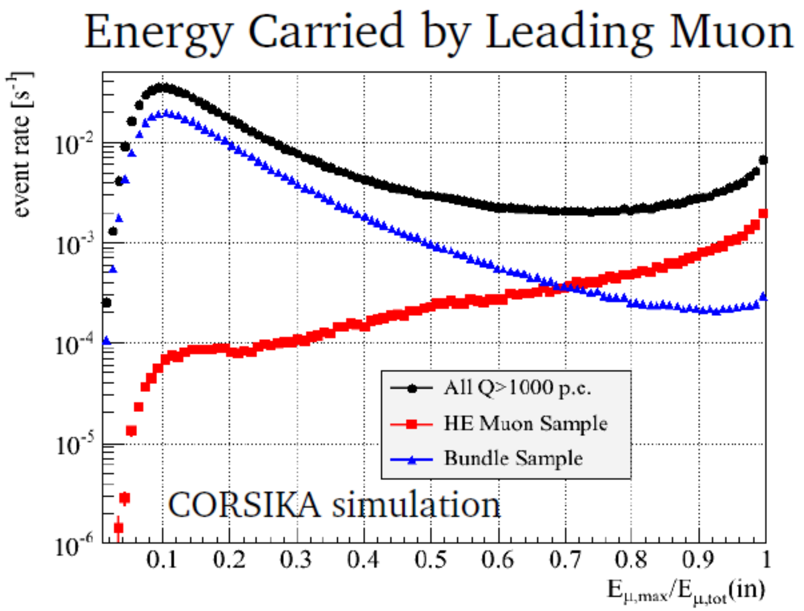
★ Muon bundle and high energy muon ★

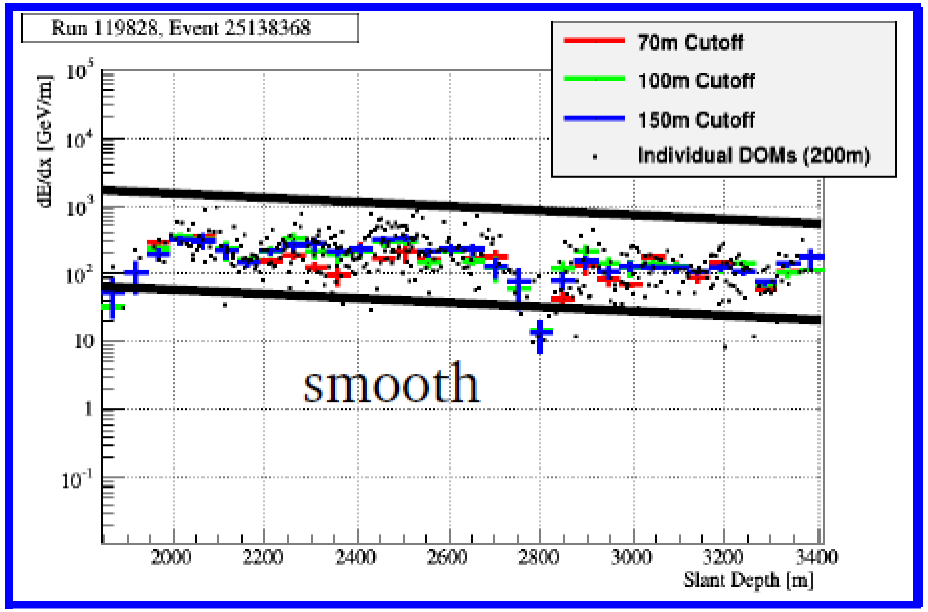


Low-Energy

Bundles

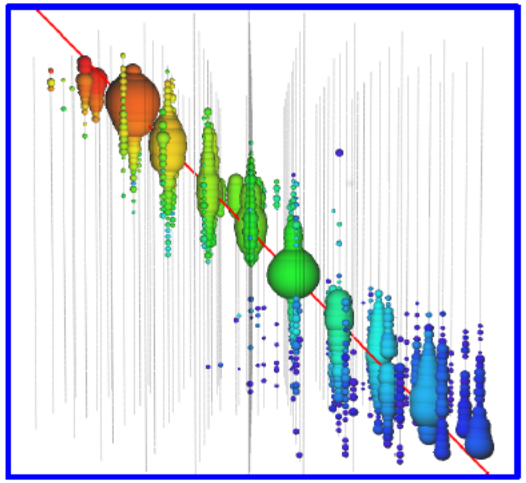
HE Muons

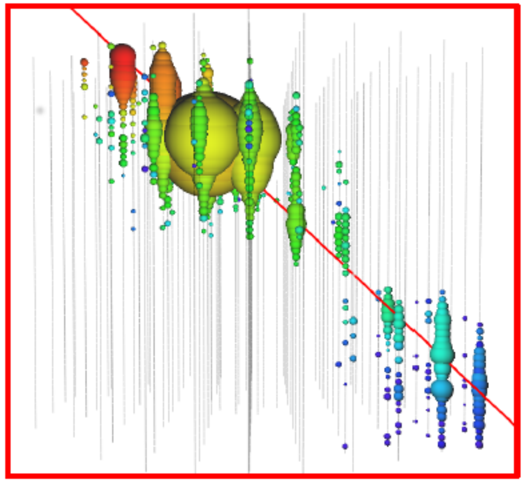

Energy Carried by Leading Muon

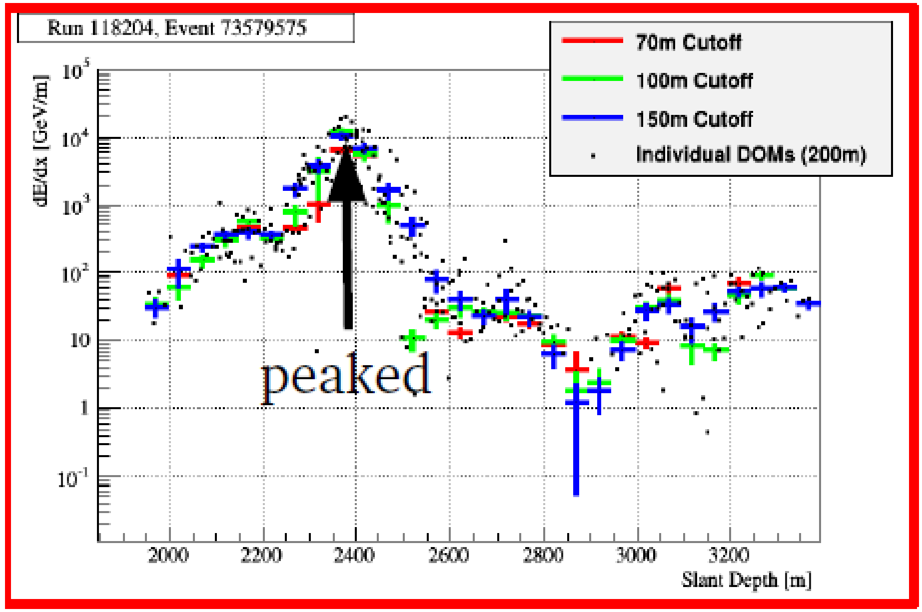


HE Muons

Bundles

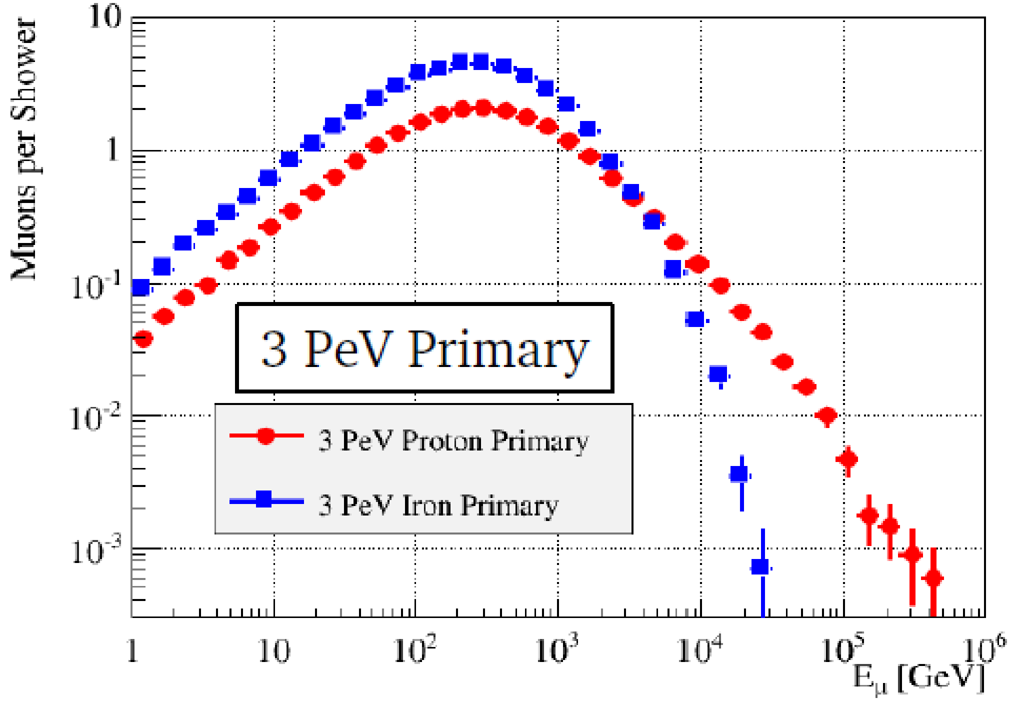


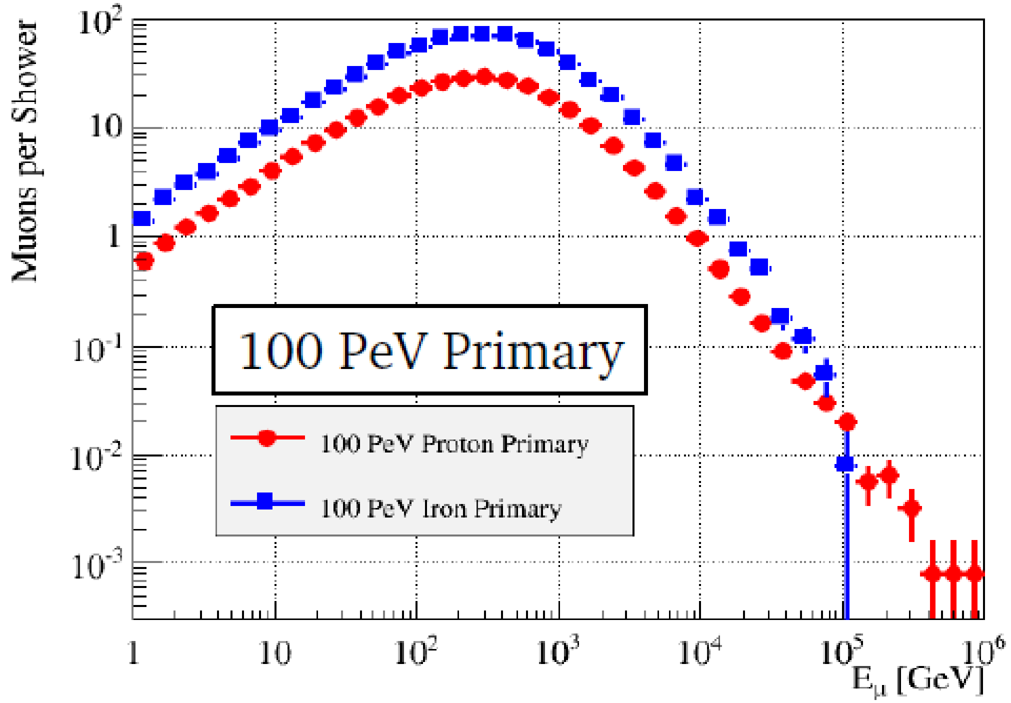




Patrick BERGHAUS

Muon energy distribution in the deep ice: Proton vs Fe

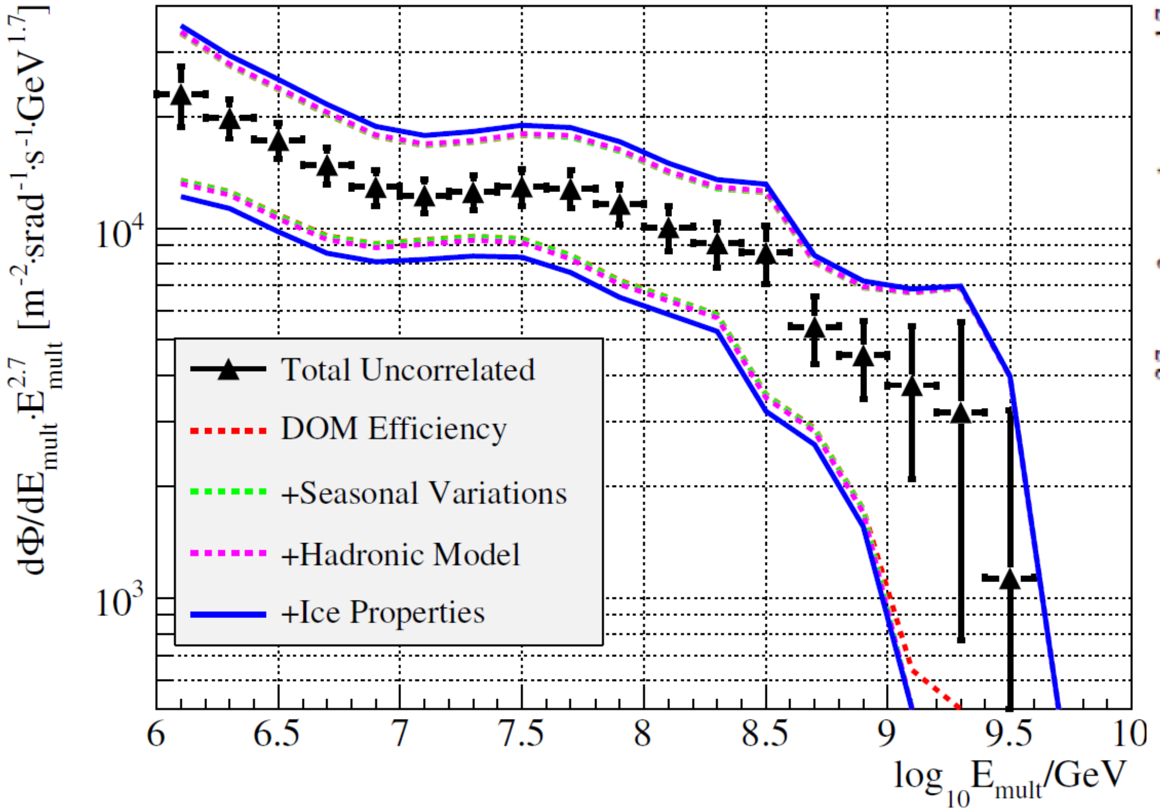


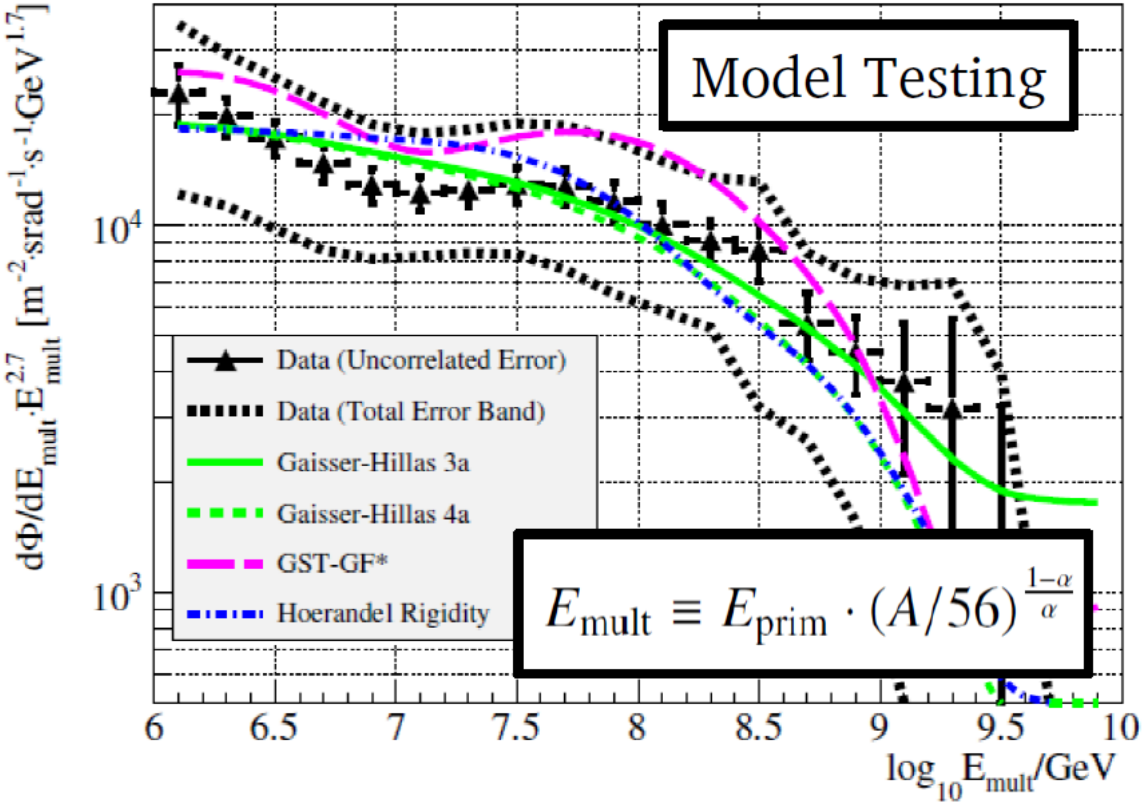


$$N_\mu(E > E_{\mu,\mathrm{min}}) = A \cdot \frac{E_0}{E_{\mu,\mathrm{min}} \cos\ \theta} \cdot \left(\frac{E_\mathrm{prim}}{AE_\mu}\right)^{\alpha \approx 0.79} \cdot \left(1 - \frac{AE_\mu}{E_\mathrm{prim}}\right)^{\beta}$$

(see e.g. T.K. Gaisser: CR&Part.Phys.)

For fixed angle θ and $E_\mathrm{prim}/A \gg E_\mu$: $\boxed{N_\mu \propto A^{1-\alpha} \cdot E_\mathrm{prim}^{\alpha}}$



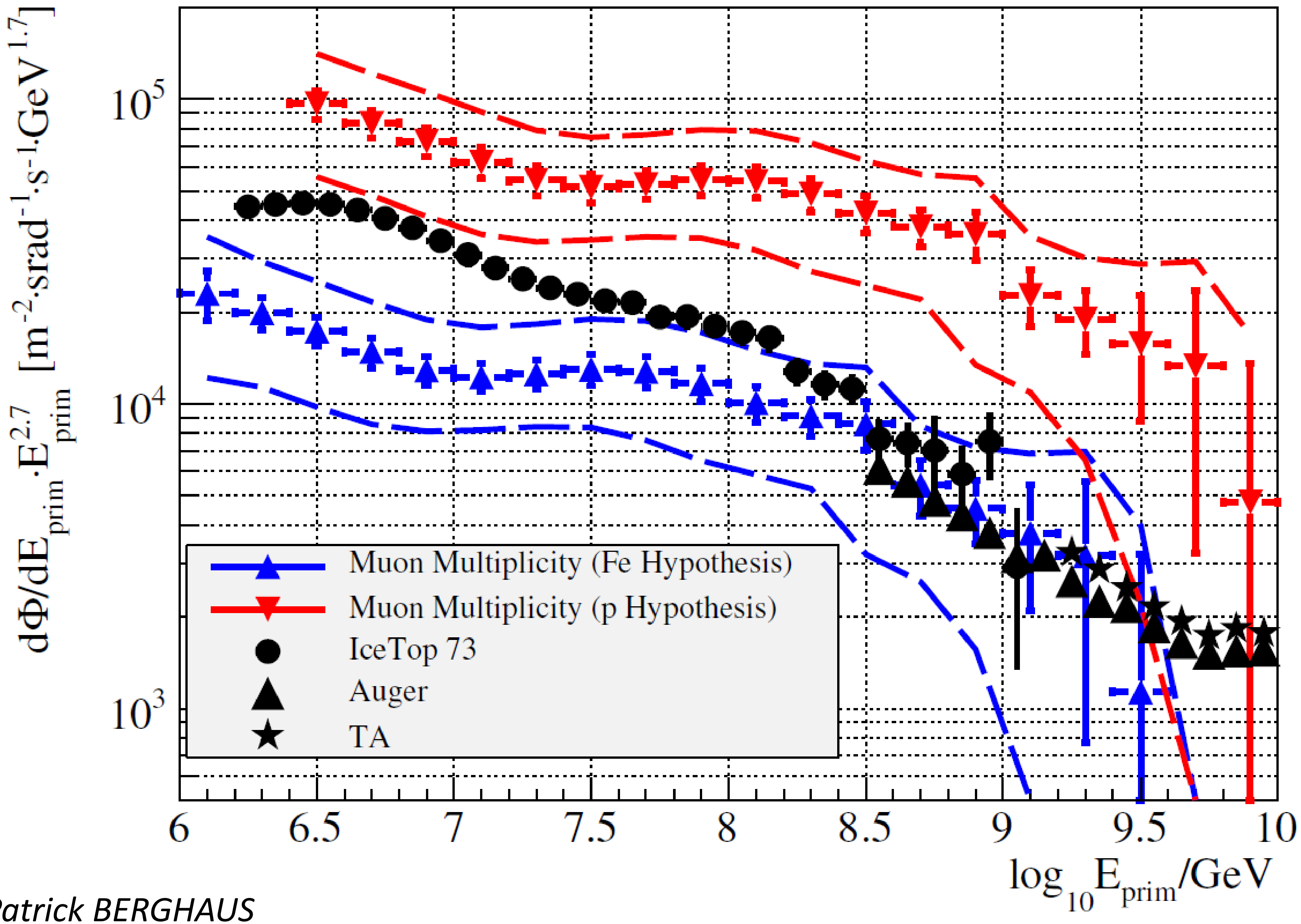


Model Testing

$$E_{\mathrm{mult}} \equiv E_{\mathrm{prim}} \cdot (A/56)^{\frac{1-\alpha}{\alpha}}$$

Source	Type	Variation	Effect	Comment
Composition	uncorrelated	Fe, protons	variable	Residual bias near threshold
Energy Estimator	uncorrelated	4 discrete values	variable	Derived from data
Angular Acceptance	uncorrelated	3 zenith regions	±10% Flux Scaling	Estimated from data
Light Yield	correlated	±10%	±13% Energy Shift	Composite Scalar Factor
Ice Optical	correlated	10% Scattering, Absorption	±25% Flux Scaling	Global variations around default model
Hadronic Model	correlated	discrete	±10% Flux Scaling	EPOS/QGSJET/SIBYLL
Seasonal Variations	correlated	Summer vs. Winter	±5% Flux Scaling	Estimated from data
Muon Energy Loss	correlated	Theoretical uncertainty [69]	±1%	Official IceCube Value

Muon bundle



$$\sum E_\mu \propto N_\mu \propto E_{\text{prim}}^{\alpha} \cdot A^{1-\alpha}$$

$$E_{\text{mult}} \equiv E_{\text{prim}} \cdot (A/56)^{\frac{1-\alpha}{\alpha}}$$

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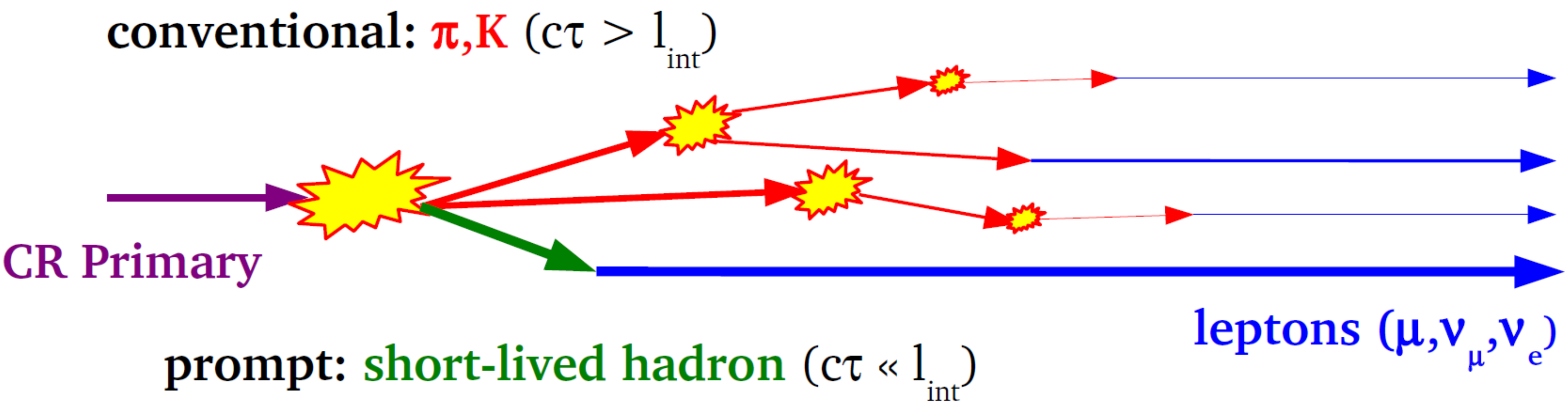


conventional: **π,K** (cτ > l_{int})

CR Primary

leptons (μ,ν_μ,ν_e)

prompt: **short-lived hadron** (cτ « l_{int})

$$\pi^\pm, K^\pm \rightarrow \mu^\pm + \nu_\mu(\overline{\nu}_\mu)$$ (63.5% for K)

$$\hookrightarrow e^\pm + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

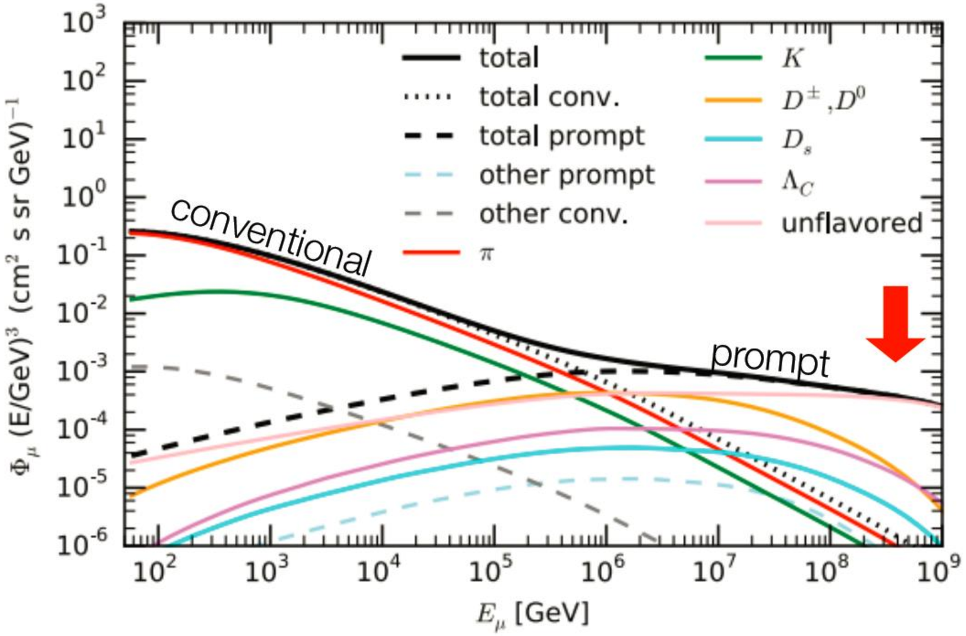
$$K^\pm \rightarrow \pi^0 e \nu_e$$ (5%)

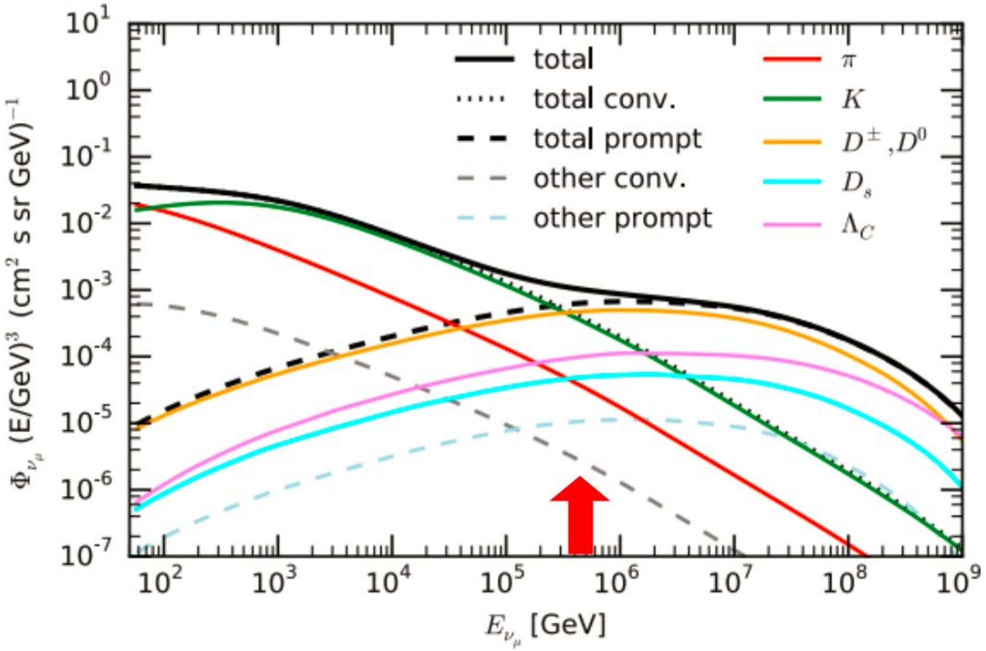
$$K_L^0 \rightarrow \pi e \nu_e$$ (40%)

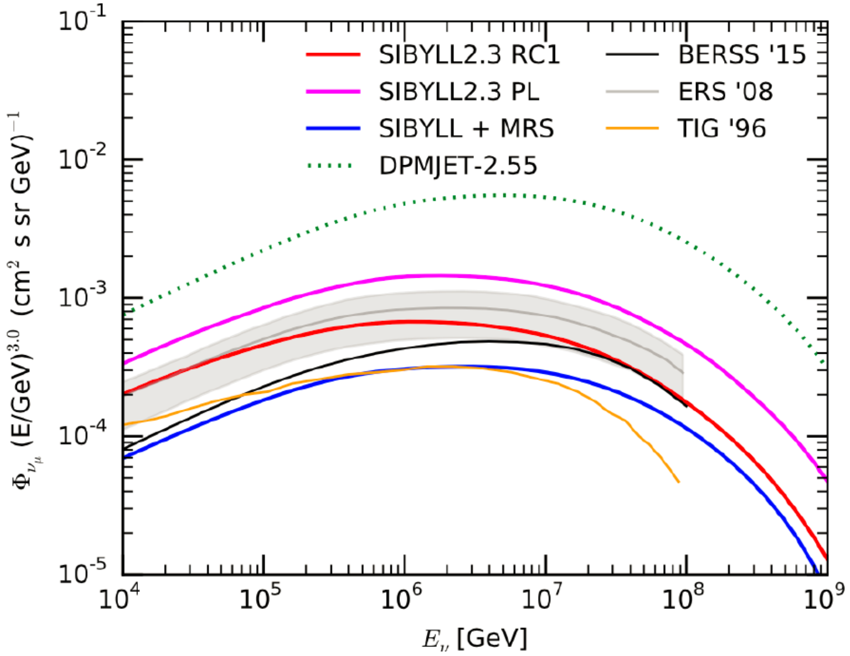
$$D, \Lambda_c \rightarrow \ell + \nu_\ell + \ldots$$ (order %)

$$K_S^0 \rightarrow \pi e \nu_e$$ (Gaisser & Klein 2014) (0.07%)

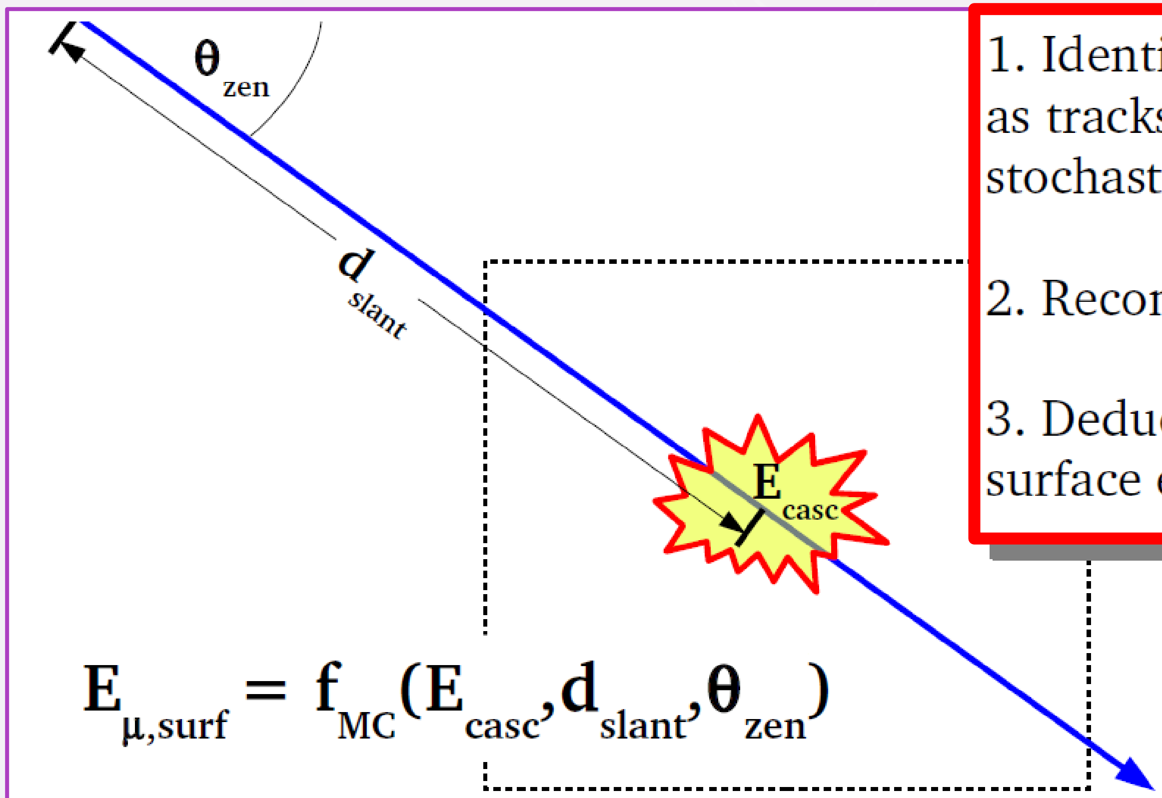
$$\eta, \eta' \rightarrow \mu^+ \mu^-$$ ‘flavourless’







Anatoli FEDYNITCH
ICRC 2015



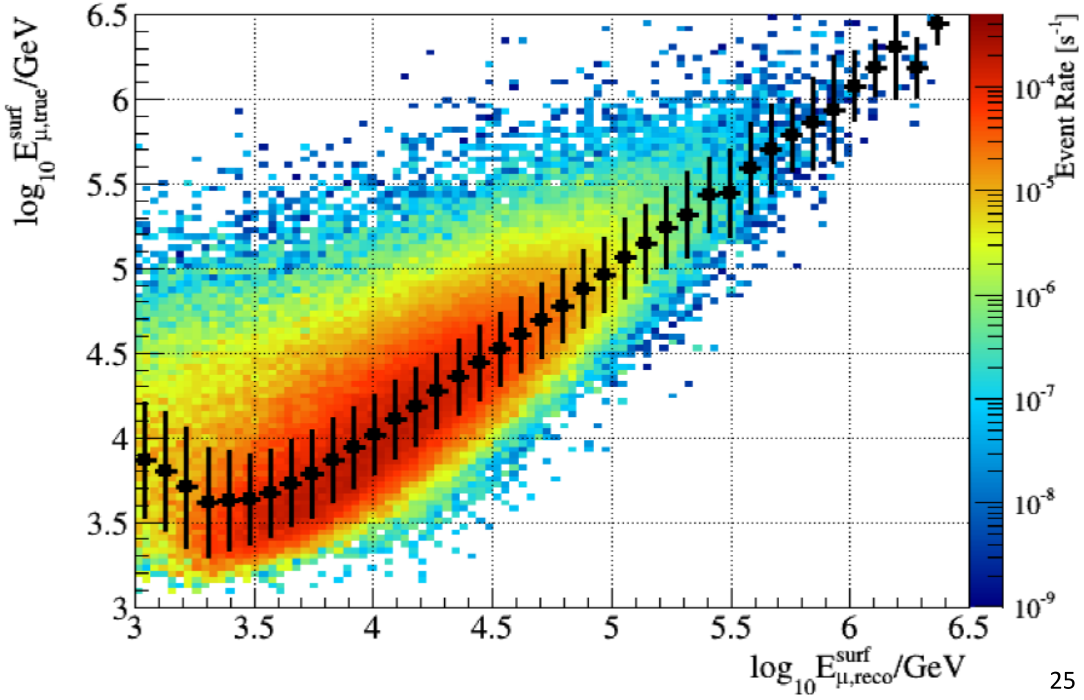
1. Identify HE muons as tracks with exceptional stochastics losses

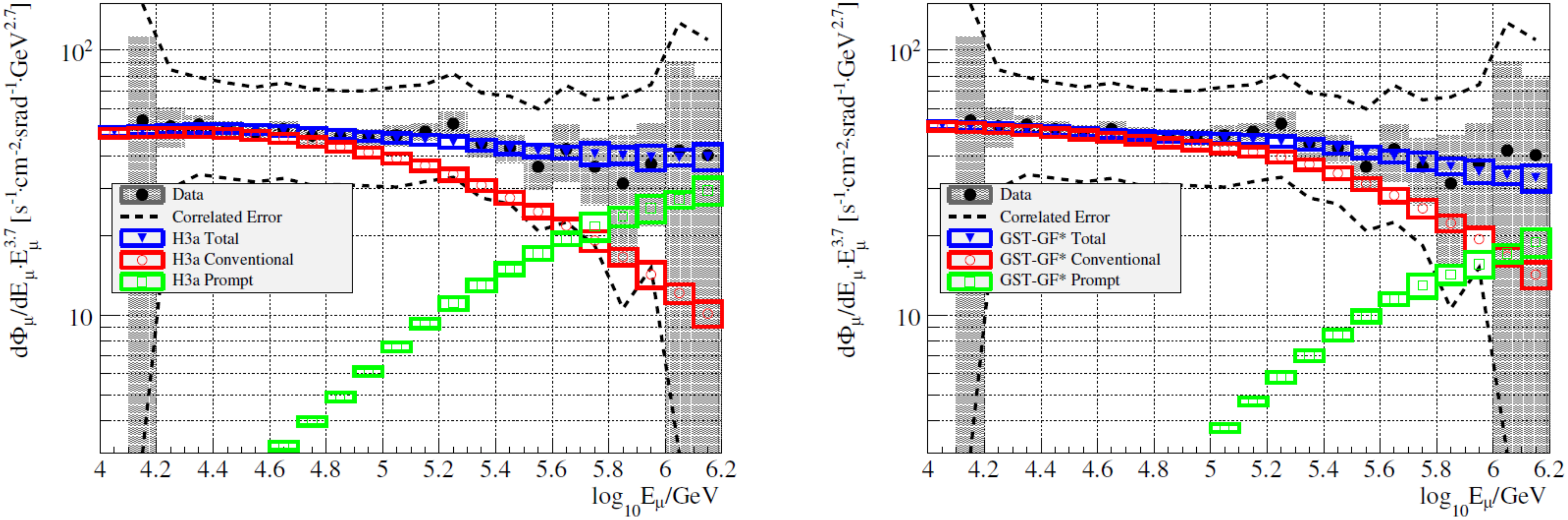
2. Reconstruct cascade energy

3. Deduce most likely muon surface energy from simulation

$$E_{\mu,surf} = f_{MC}(E_{casc}, d_{slant}, \theta_{zen})$$

high energy muon

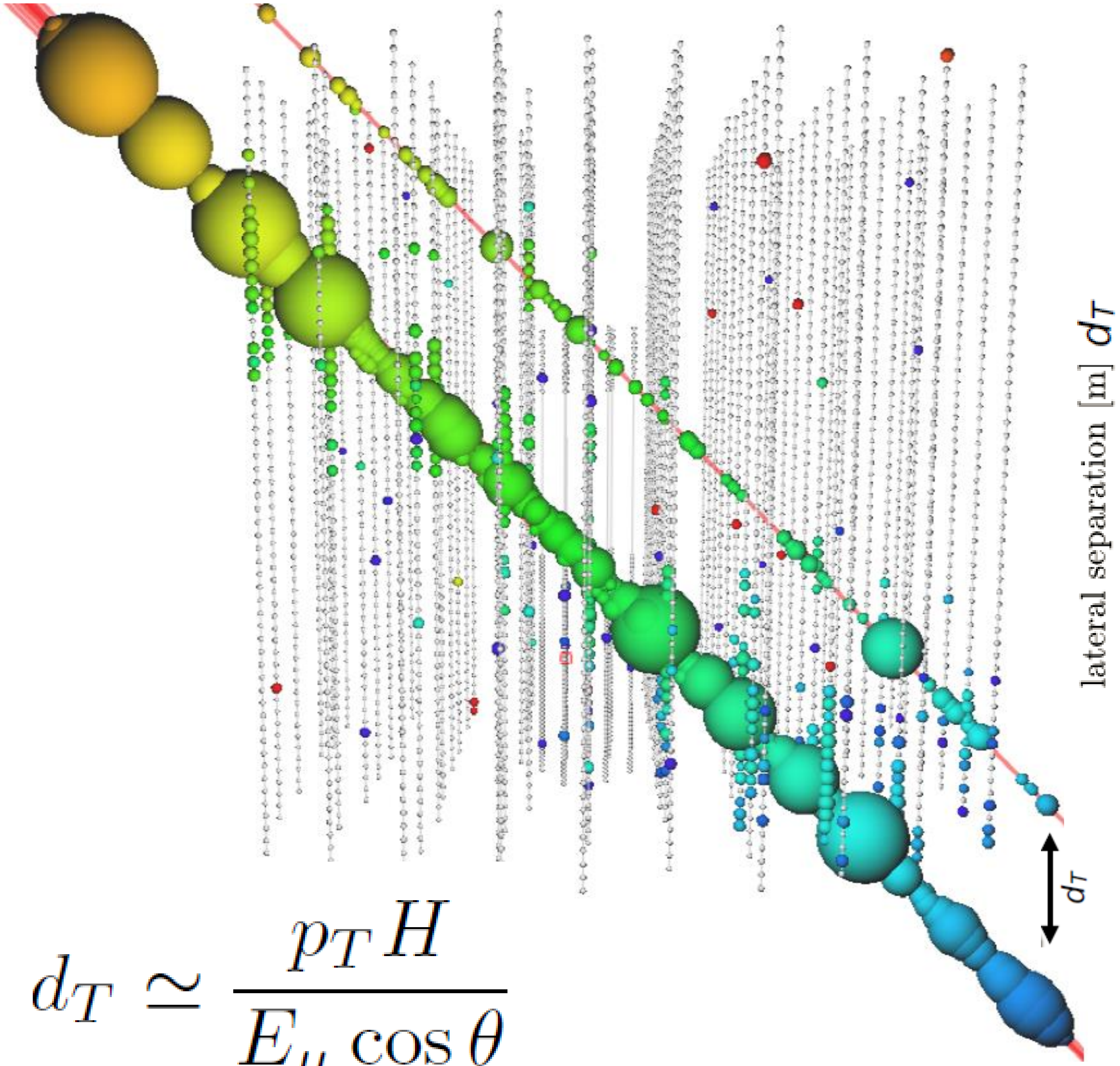




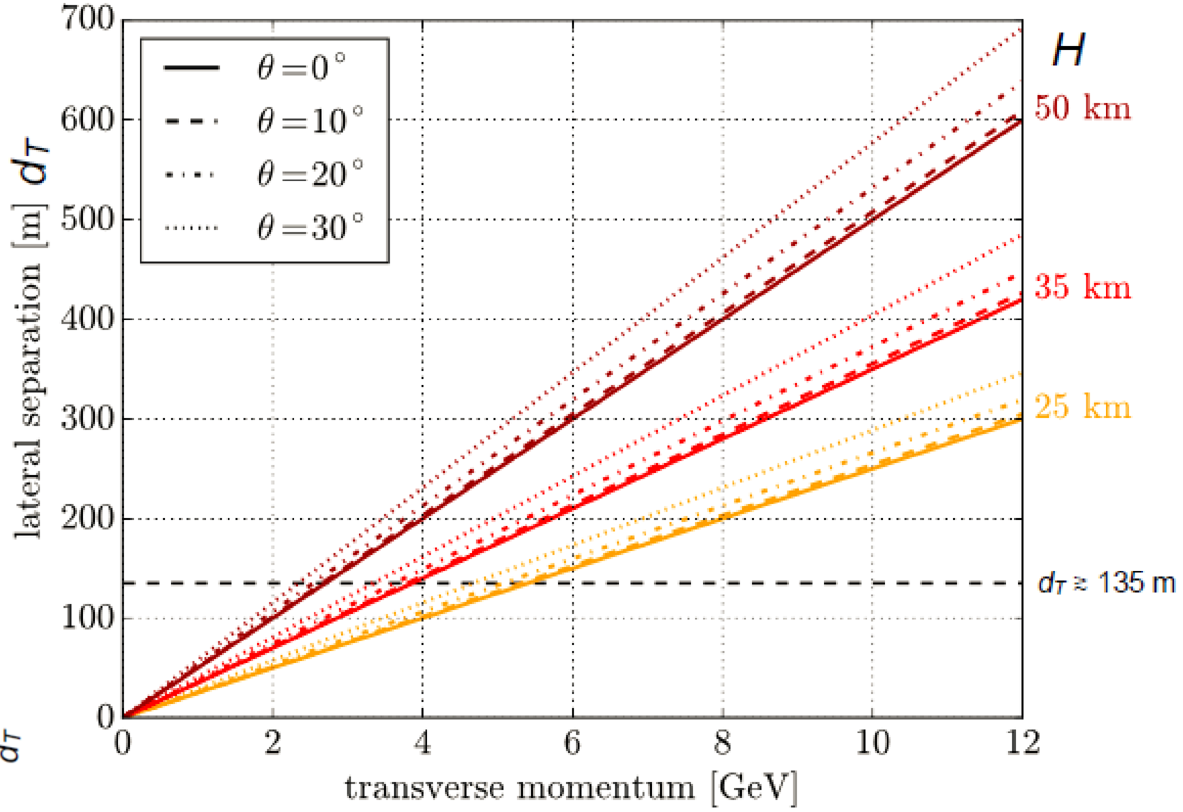
- High energy inclusive muon spectrum compatible with additional contribution at high energy
- Prompt component from charm production and unflavored η mesons

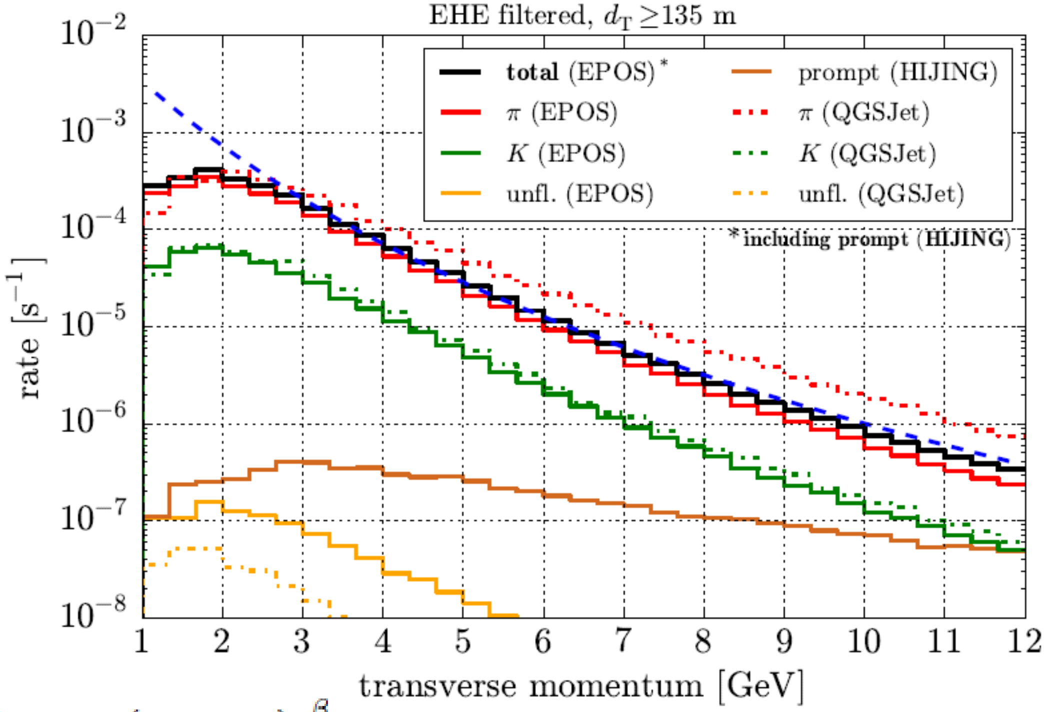
High PT Muons

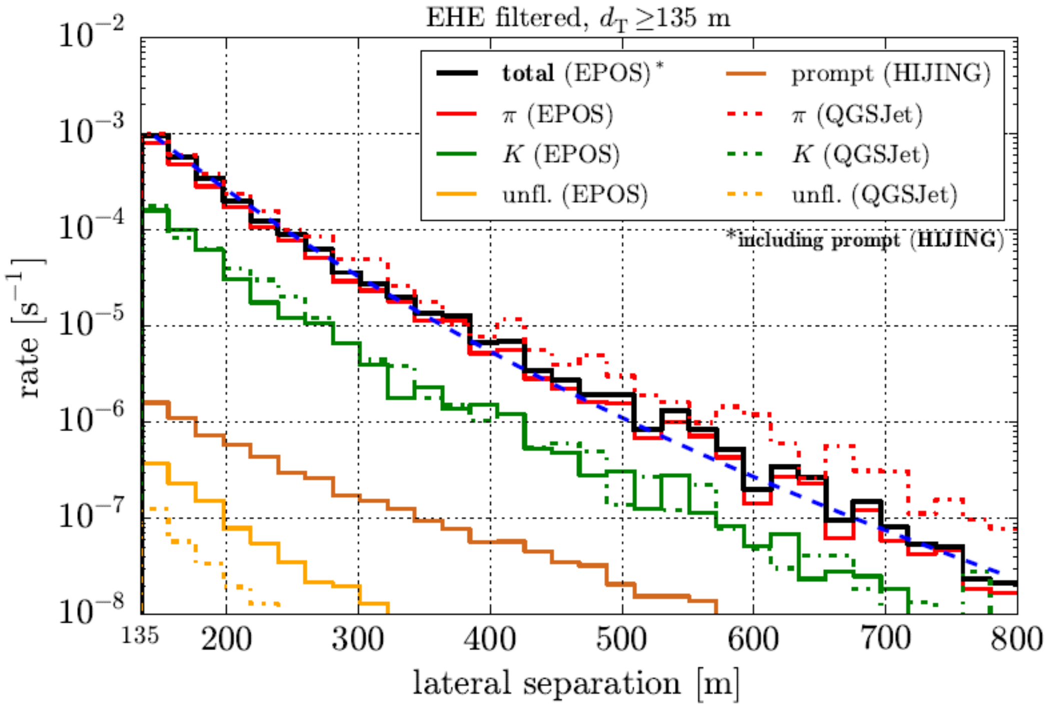
Dennis SOLDIN: ICRC 256



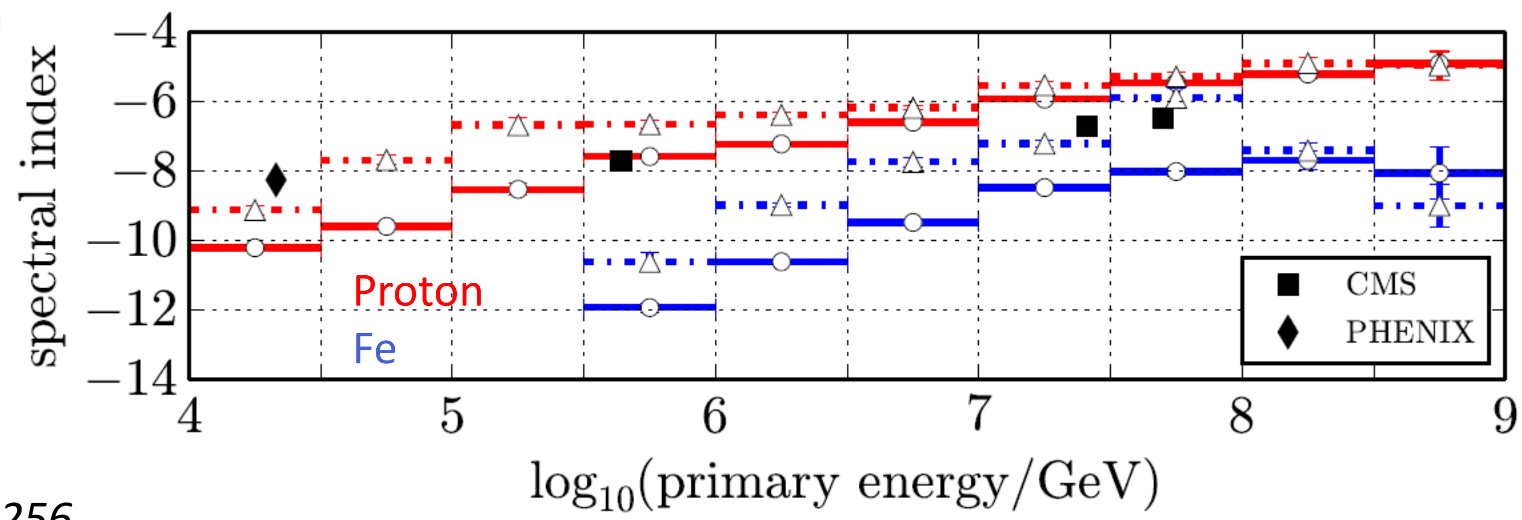
$$d_T \simeq \frac{p_T H}{E_\mu \cos\theta}$$







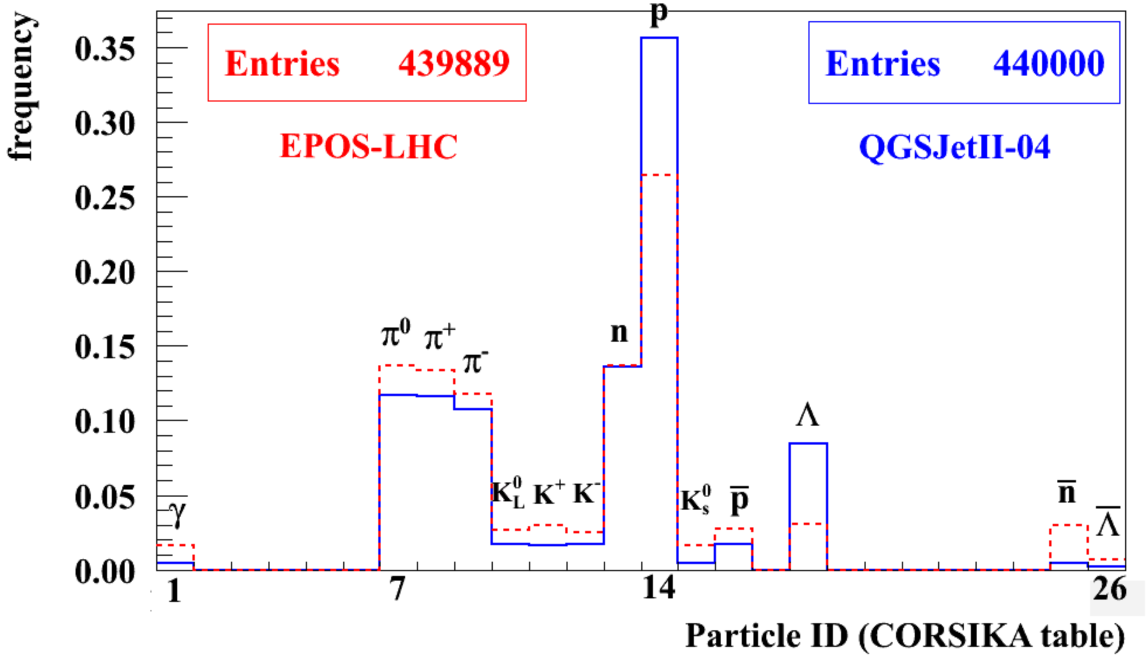
$$\frac{\mathrm{d}N}{\mathrm{d}p_T} = \alpha\left(1 + \frac{p_T}{p_0}\right)^{\beta}$$

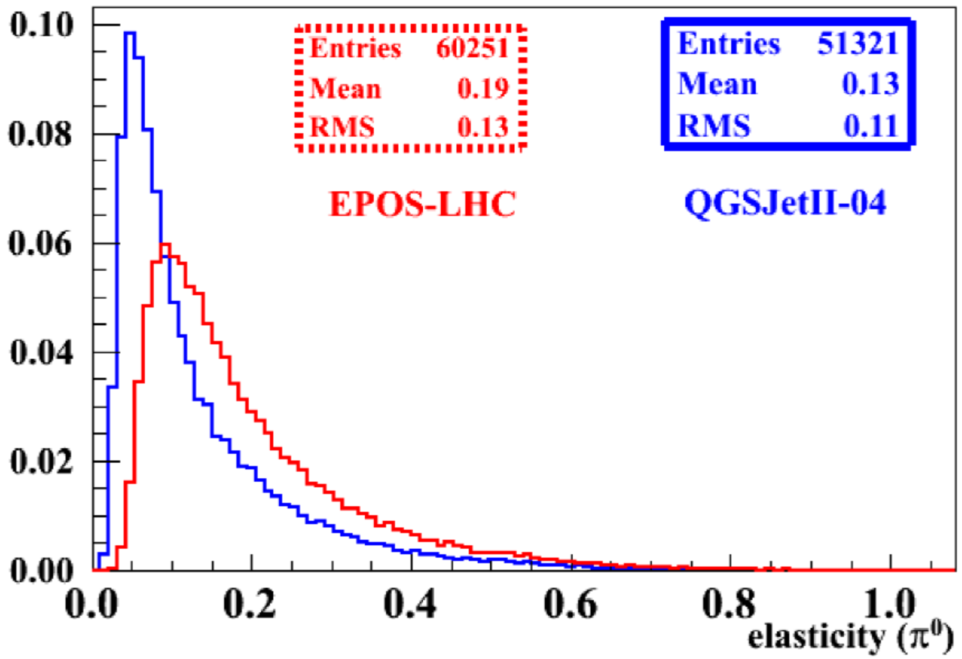


Spectrum index sensitive to mass composition and models

Dennis SOLDIN: ICRC 256

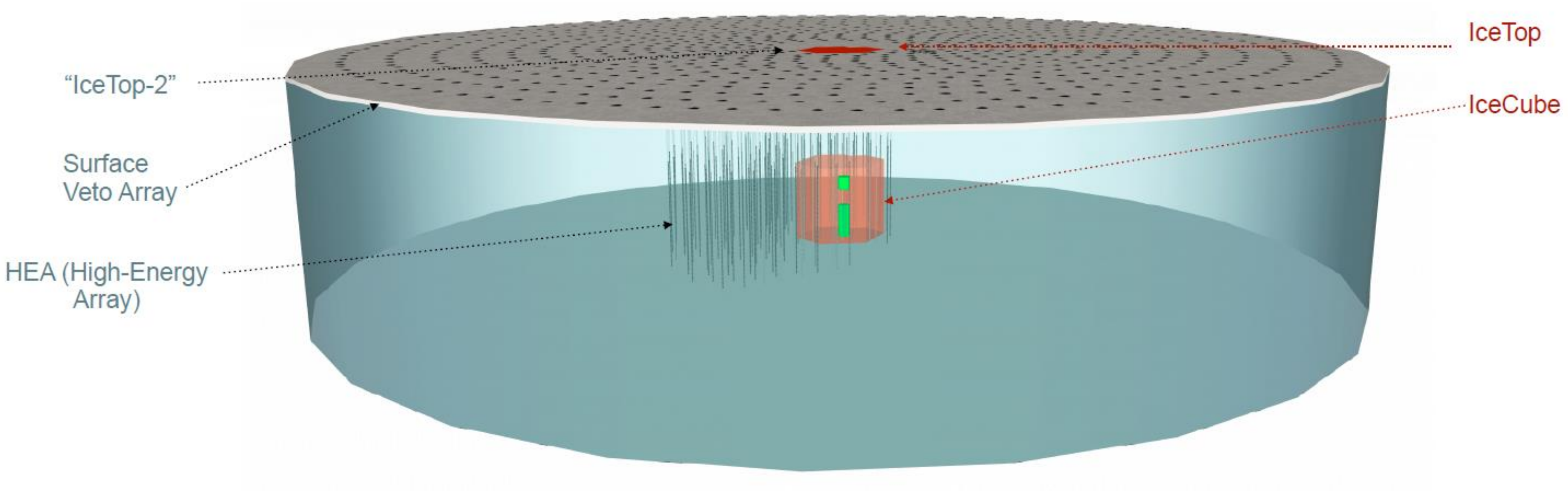
Photon search, forward muon production etc…





The plot is for Auger energy but the physics is the same… we always have proton background and seems model-dependent

Future for IceCube: Gen2!



- 10 km^3 in-ice array with 10 km^2 IceTop-like cosmic-ray array on top
    - Increase accessible cosmic-ray energy range by factor of 3
    - Increase coincident events by factor of 50 (due to increased zenith angle range)
- Surrounded by ~ 100 km^2 veto (less sophisticated air shower detectors)
    - Enable lateral muon distribution measurements on event-by-event basis.

we also have proposals such as air-Cherenkov telescopes, scintillator on surface, PINGU…

IceCube DOM

Gen2 D-Egg

CHIBA
UNIVERSITY

ICECUBE
GENERATION 2

JAMSTEC
獨立行政法人
海洋研究開發機構

CONCLUSION

IceCube has a broad science program for neutrino physics, particle physics, astrophysics and so on.

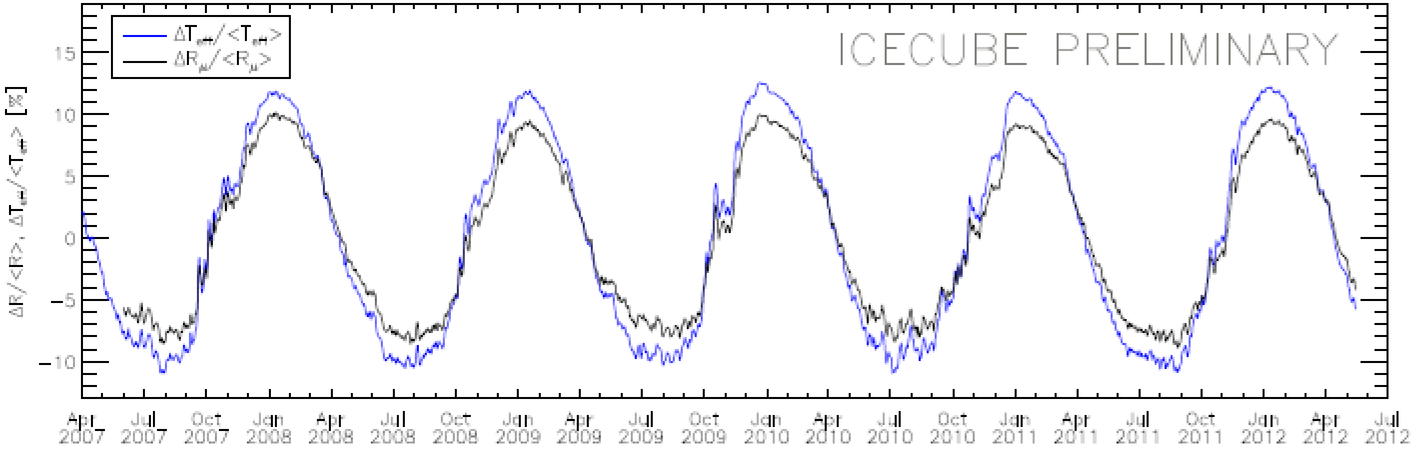
The combination of IceCube and IceTop analysis offers a unique chance to study EM component, low and high energy and high pt muons of air showers. So far most analyses based on SIBYLL, will be updated to use post-LHC models.

IceCube Gen2 is around the corner, more possibilities to do coincidence measurements for constraining hadronic interaction models.

THANK YOU VERY MUCH!

Illustration by Guy Billout

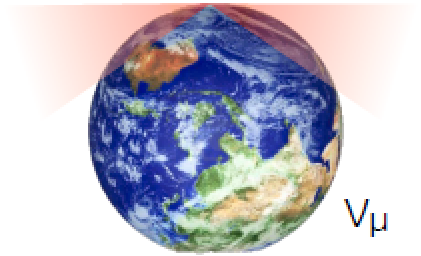
BACKUP: WEATHER EFFECT AND CHARM COMPONENT

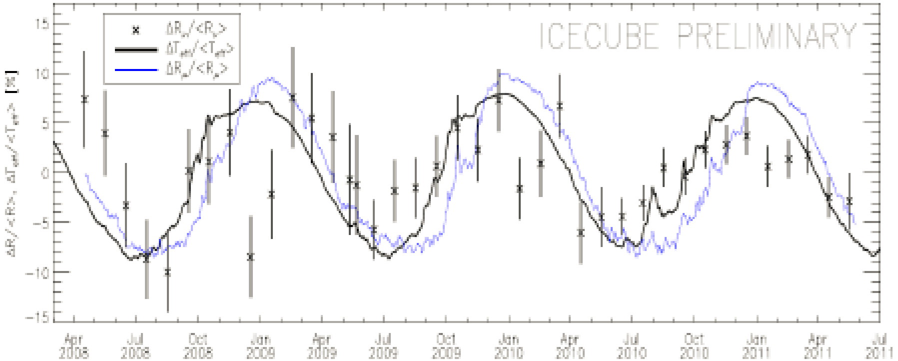


μ multiplicity - **ICRC 2013**

ICRC 2009
ICRC 2011

Takao KUWABARA

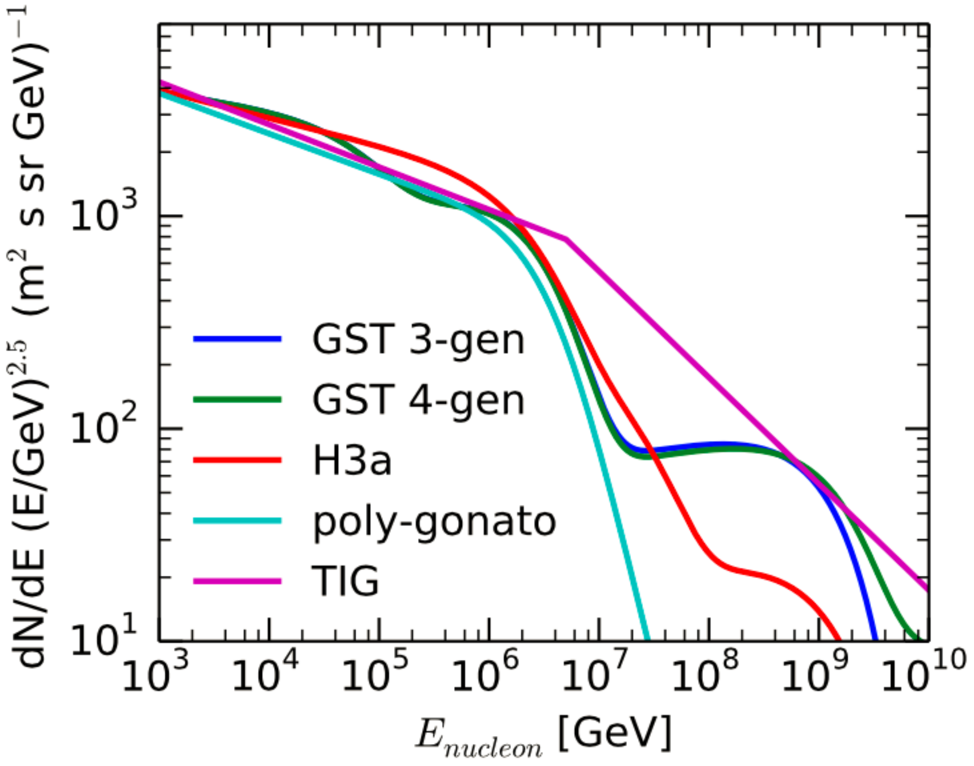




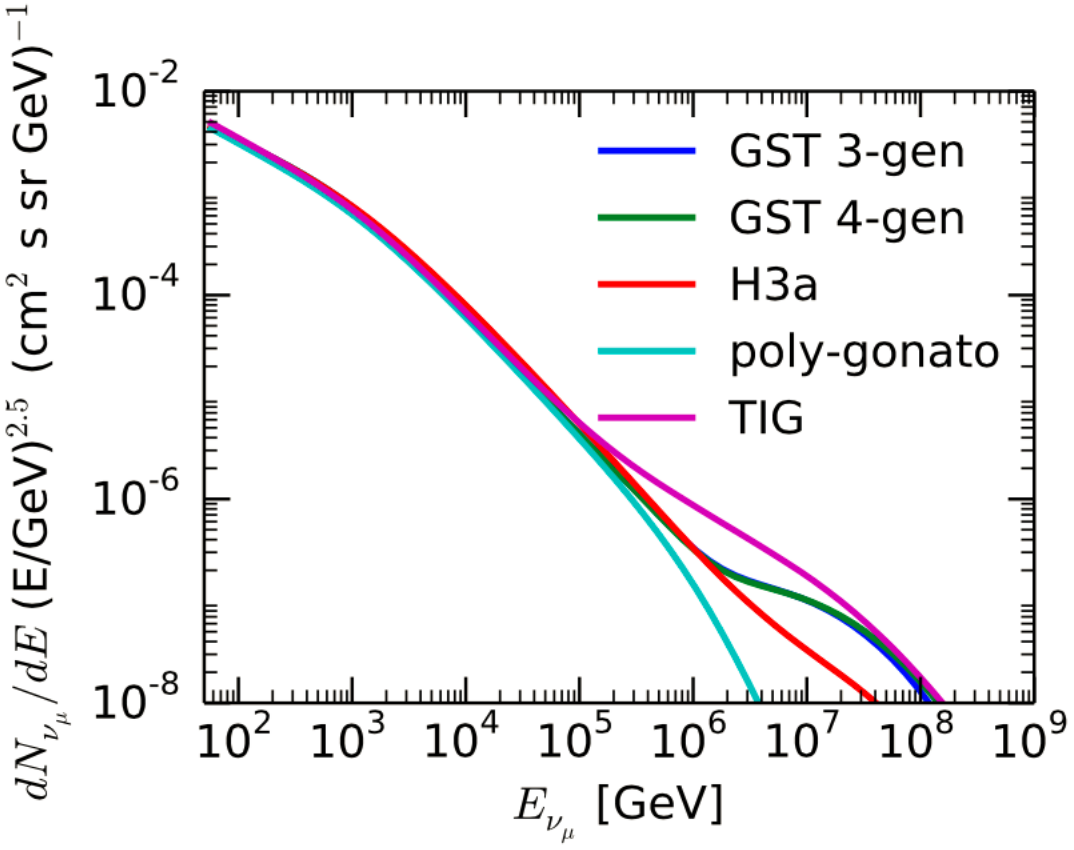
ICRC 2013

Backup

nucleon flux



muon neutrino flux



GST - T. K. Gaisser, T. Stanev, and S. Tilav, arXiv: 1303.3565, (2013).

H3a - T. K. Gaisser, Astroparticle Physics 35, 801 (2012).

TIG - M. Thunman, G. Ingelman, and P. Gondolo, Astroparticle Physics 5, 309 (1996).

poly-gonato - [1] J. R. Hörandel, Astroparticle Physics 19, 2 (2003)

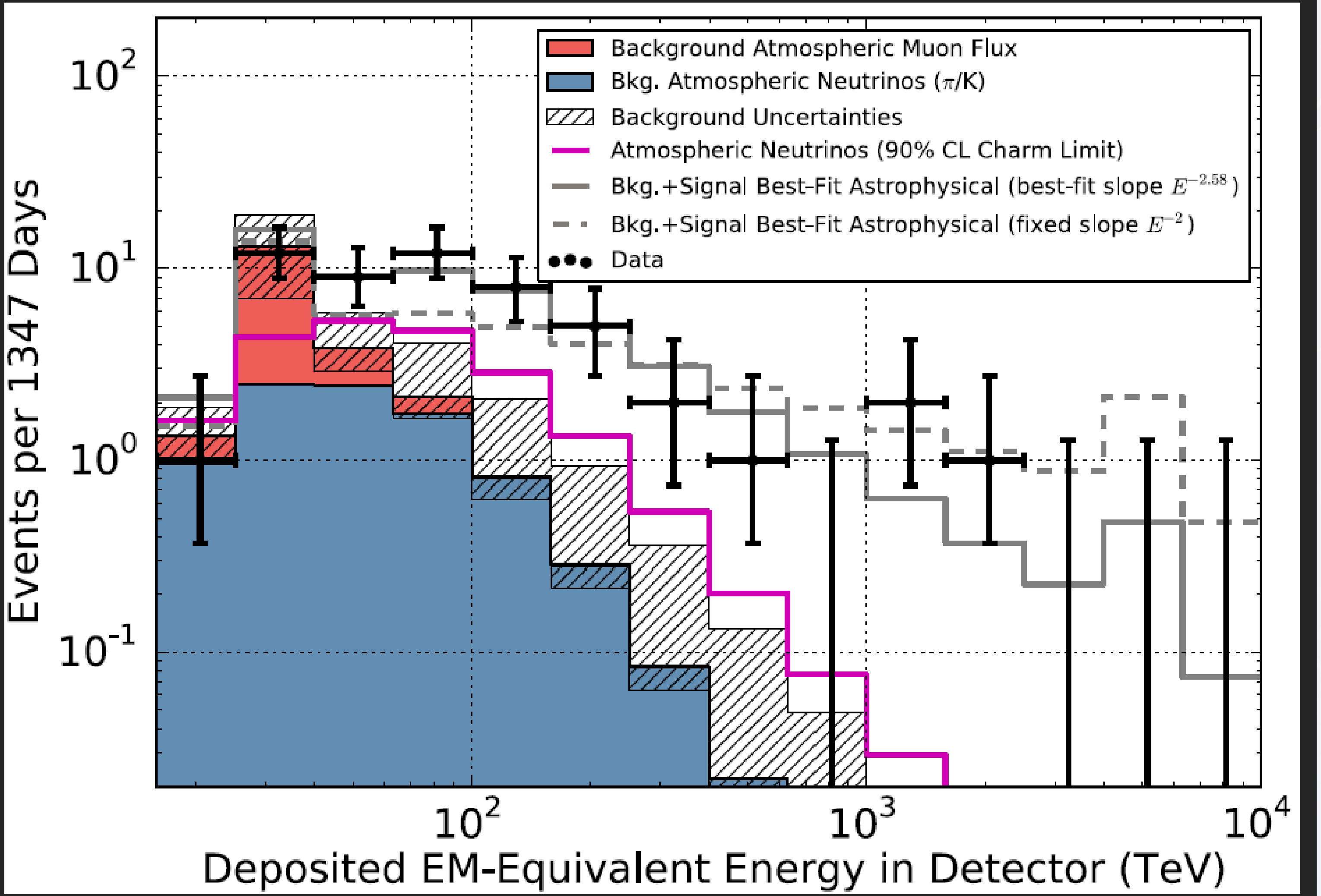
Backup

Somewhat compatible with benchmark E^{-2} astrophysical model or single power-law model, but looks like things are more complicated

Best fit assuming E^{-2} (not a very good fit anymore):

$0.84 \pm 0.3\ 10^{-8}\ E^{-2}$ GeV cm^{-2} s^{-1} sr^{-1}

Best fit spectral index: $E^{-2.58}$



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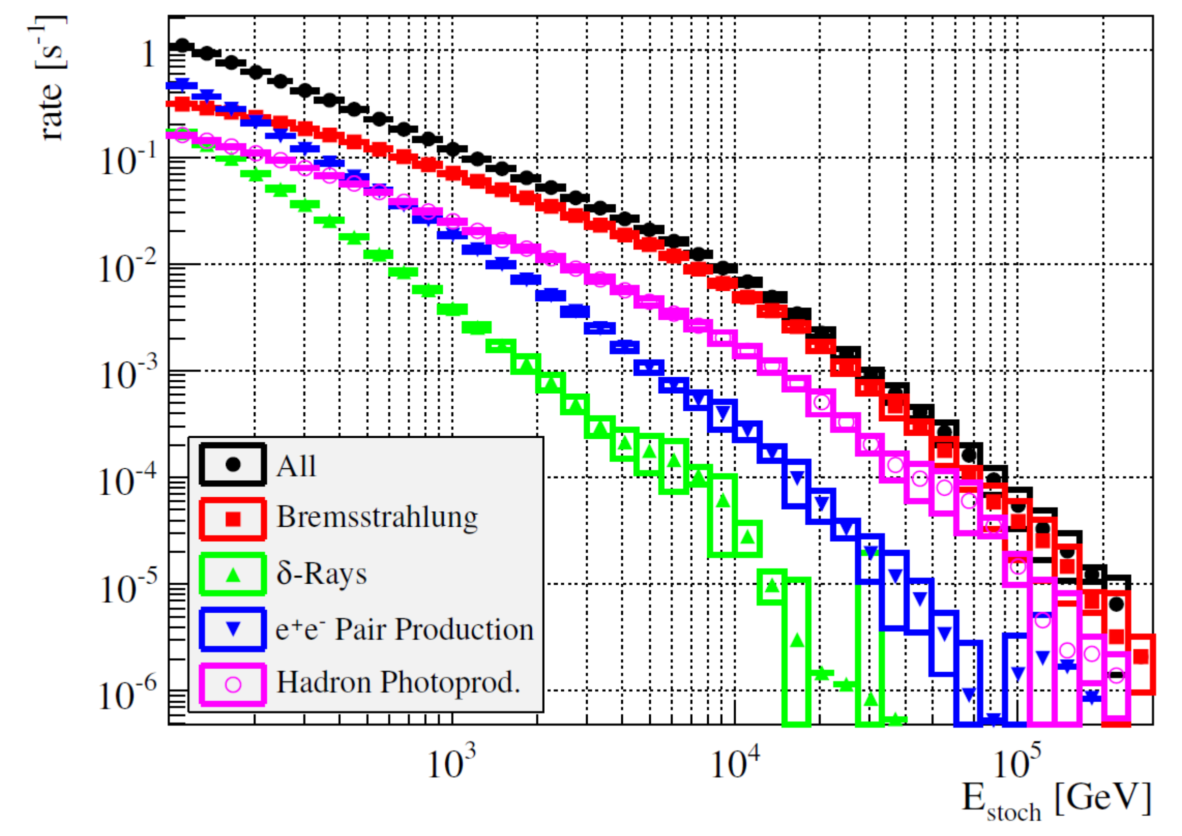
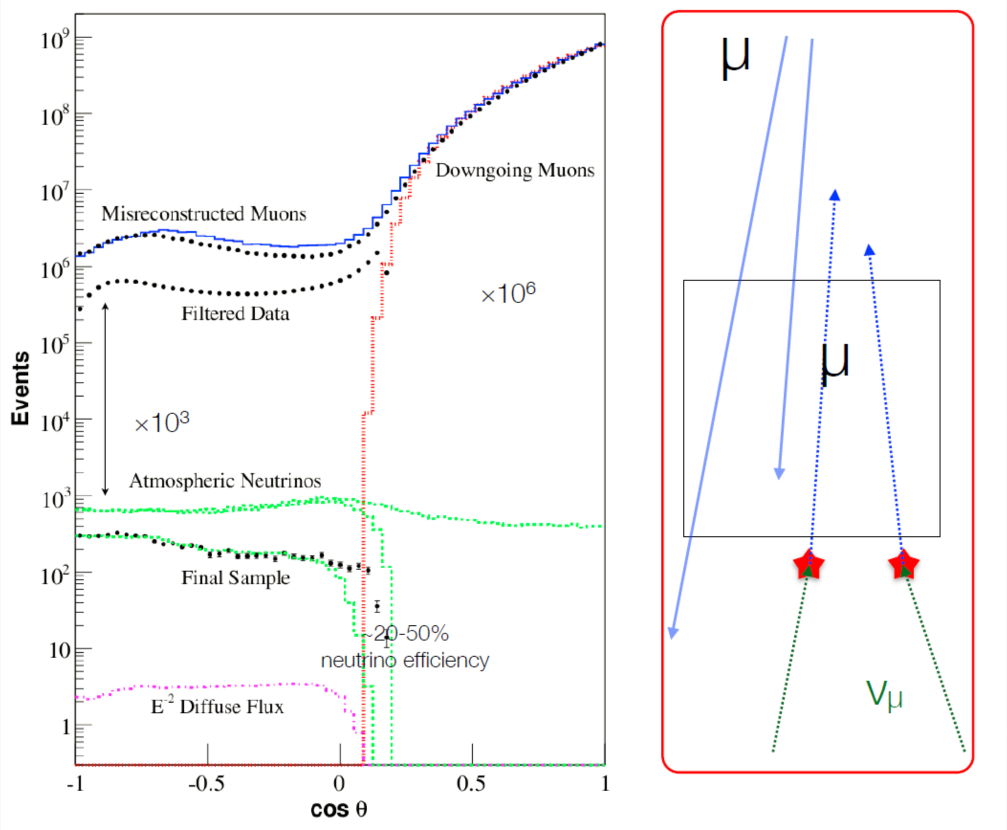

rate [s^{-1}]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^3
10^4
10^5
E_{stoch} [GeV]
● All
■ Bremsstrahlung
▲ δ-Rays
▼ e^+e^- Pair Production
○ Hadron Photoprod.


Events
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
-1
-0.5
0
0.5
1
cos θ
Downgoing Muons
Misreconstructed Muons
Filtered Data
×10^6
×10^3
Atmospheric Neutrinos
Final Sample
20-50%
neutrino efficiency
E^{-2} Diffuse Flux
μ
μ
ν_μ