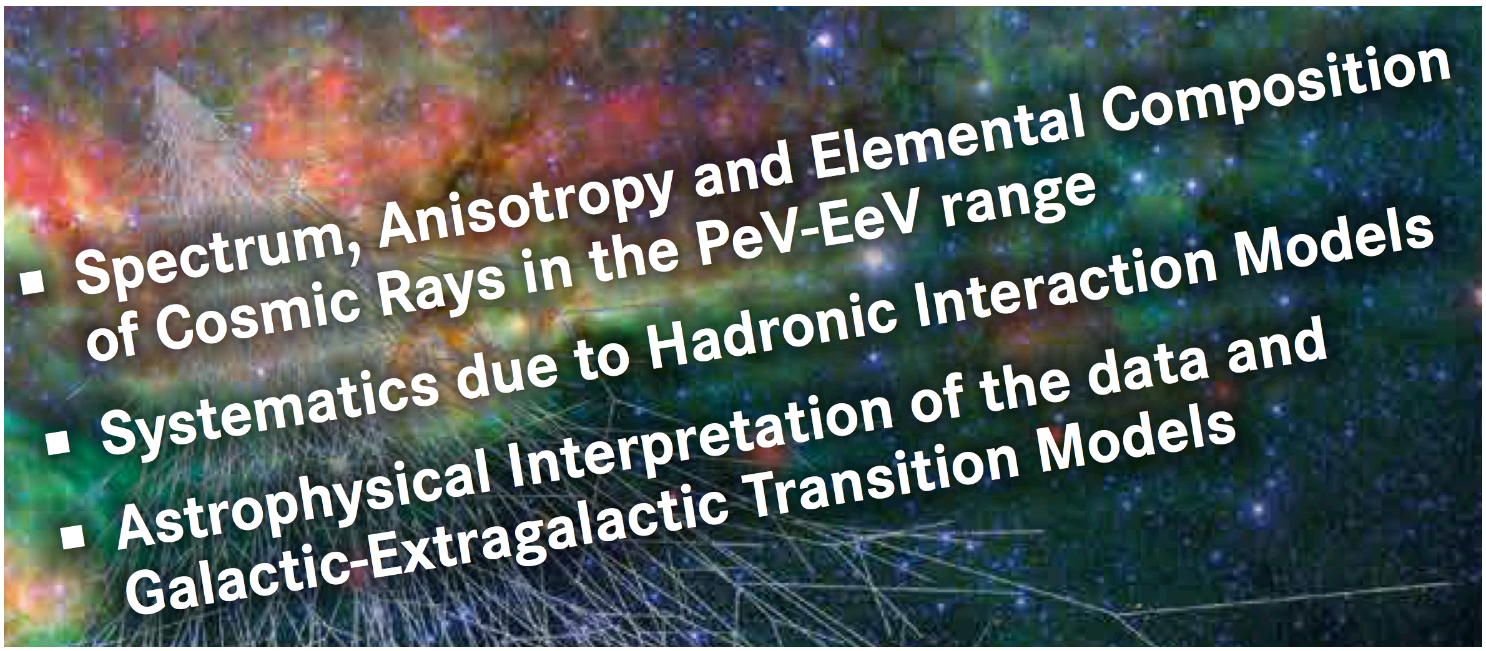
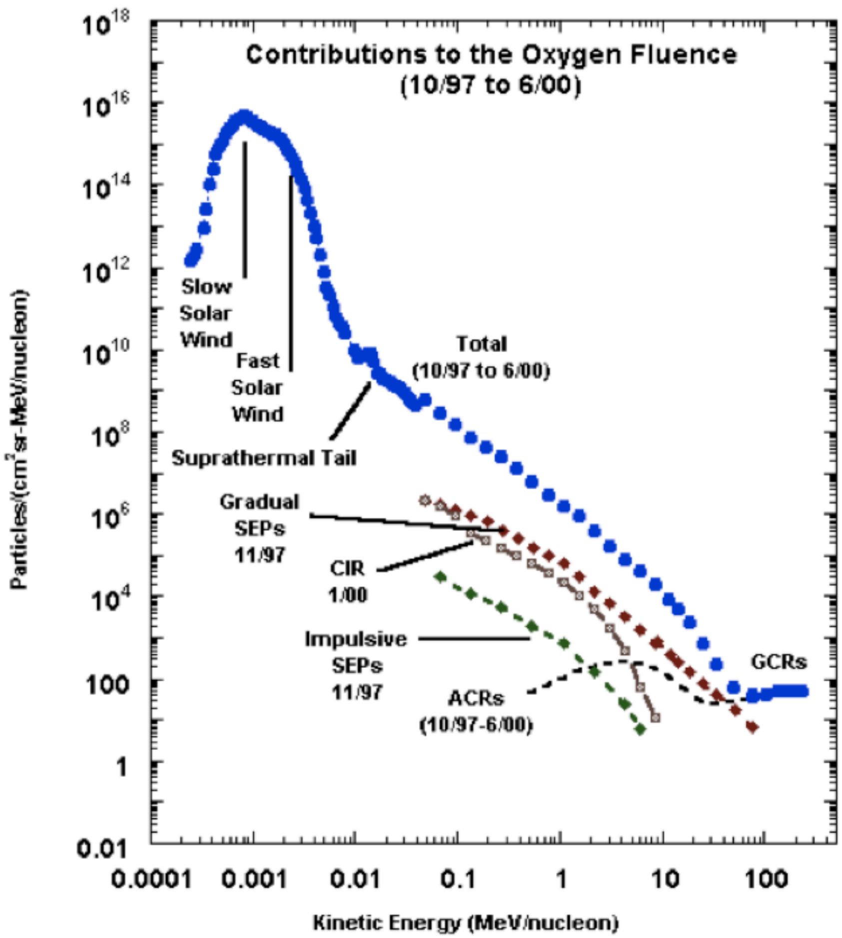
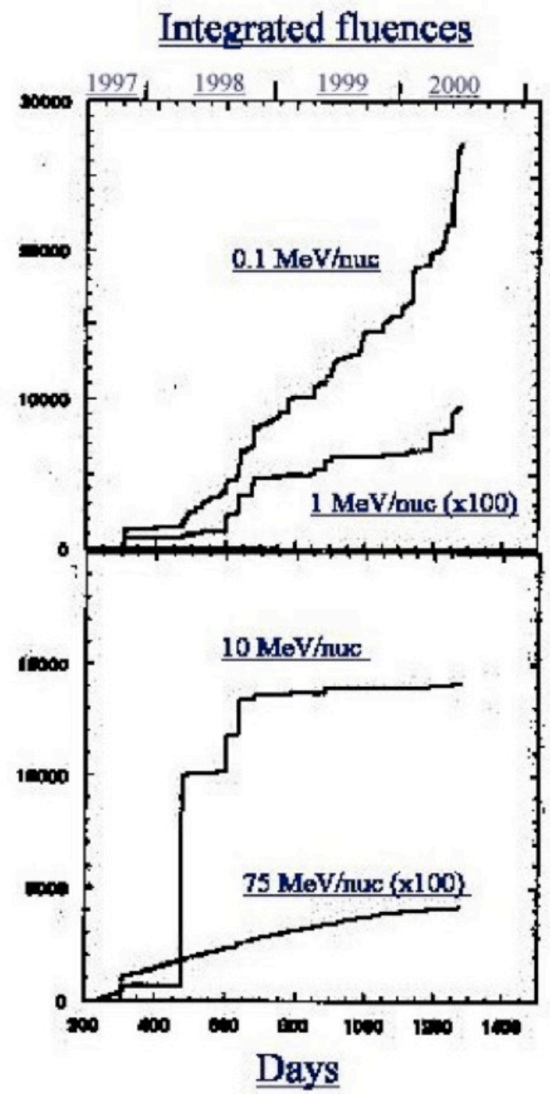

HAP Workshop 2015
COMPOSITION in the galactic to extragalactic transition range

Comments


Spectrum, Anisotropy and Elemental Composition of Cosmic Rays in the PeV-EeV range
Systematics due to Hadronic Interaction Models
Astrophysical Interpretation of the data and Galactic-Extragalactic Transition Models

Lessons from the heliosphere: Fluence of oxygen from ACE 1997-2000

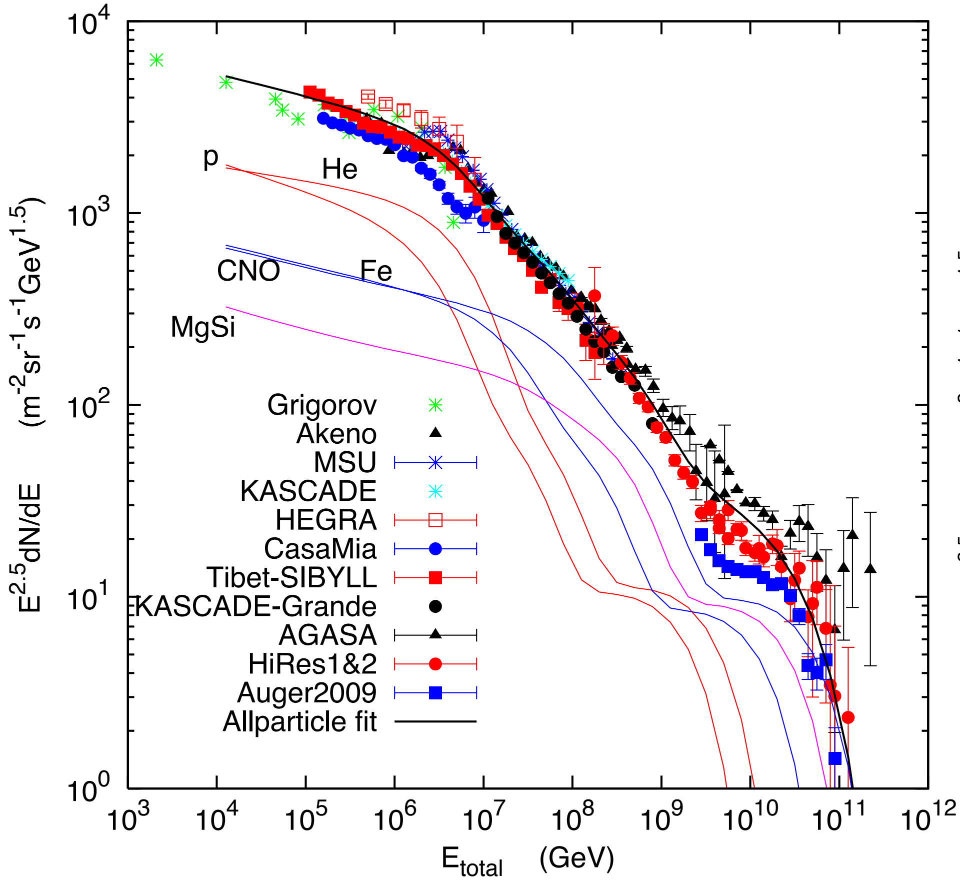




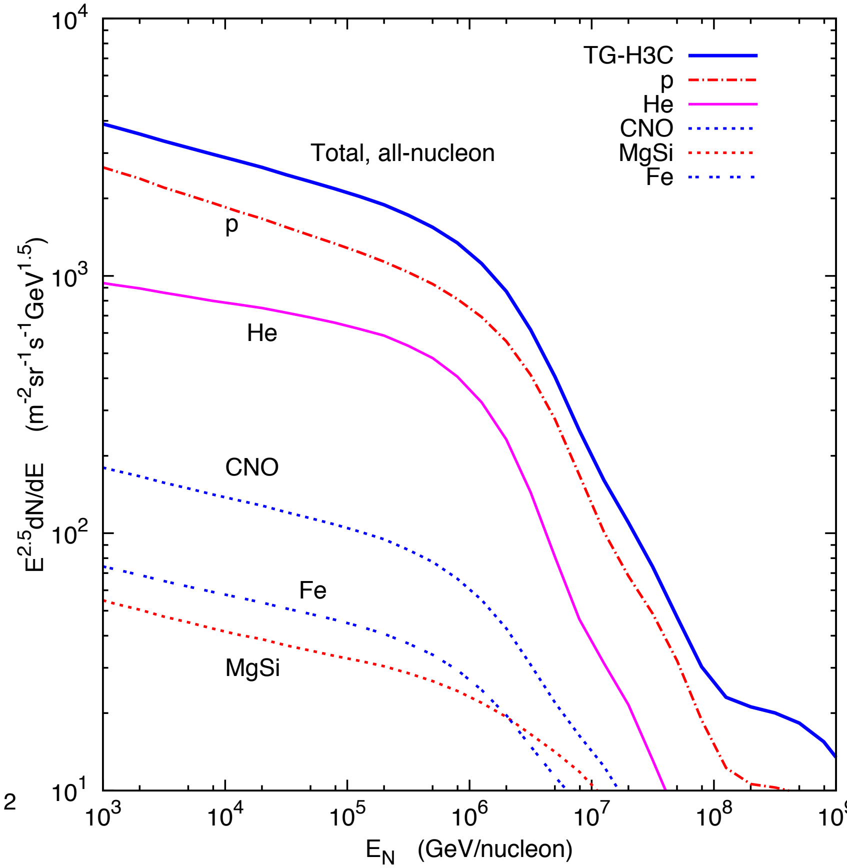
Heliosphere II

- Several kinds of events contribute
  - Typically power law with exponential cutoff
  - Different values of E_{max}
  - High energy events less frequent
- Overall spectrum is a power-law with a knee
- Galactic cosmic rays
  - High-energy population
  - Steady rate
- Expect a similar situation with cosmic rays:
  - Several types of sources with various E_{max}
  - Smoothed over Galactic propagation time
  - High energy extra-galactic population, also with multiple contributions
- Kachelriess, Lipari: anisotropy, connectivity, stochasticity …

All-particle spectrum (left) spectrum of nucleons (right)

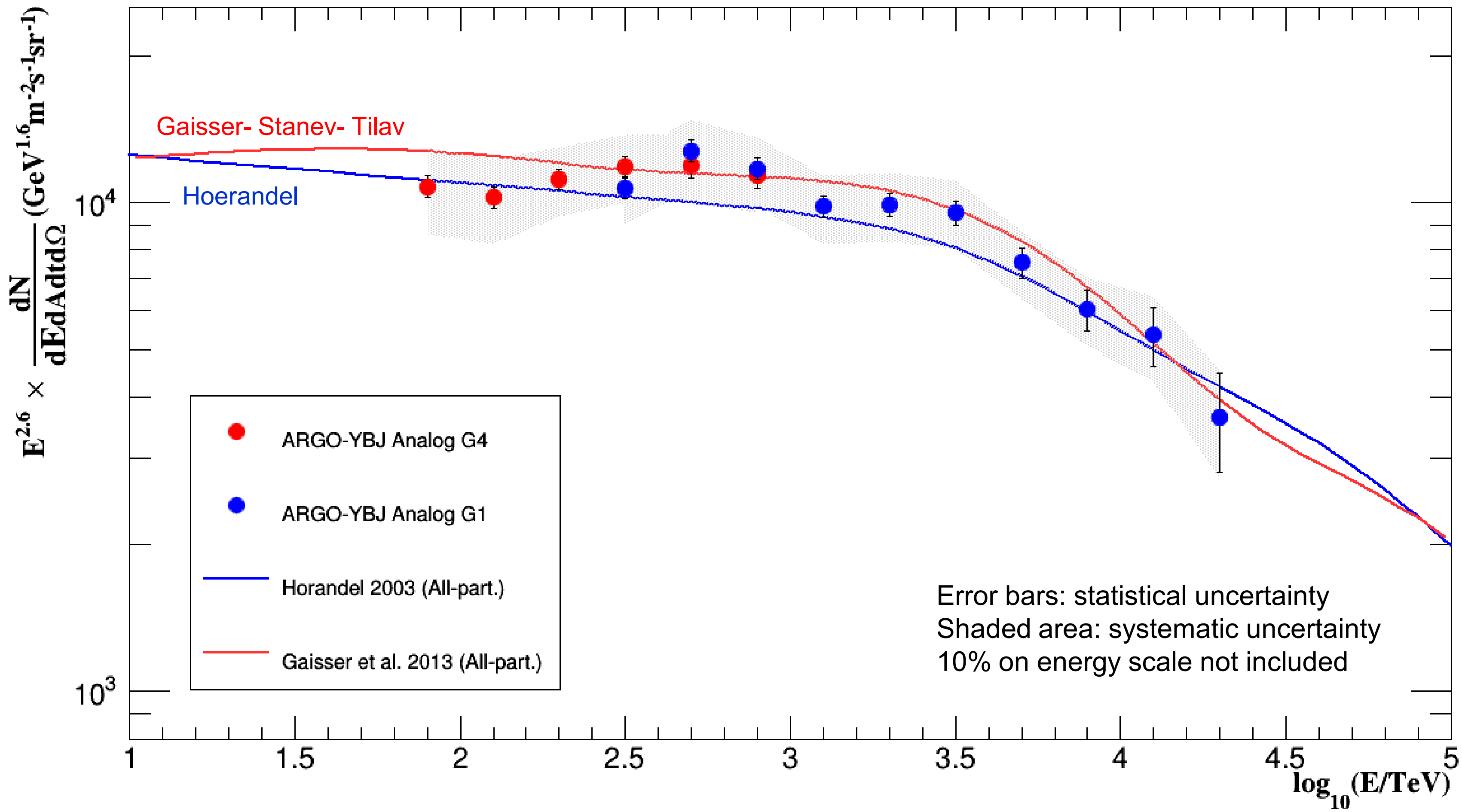


All-particle spectrum



Spectrum of nucleons

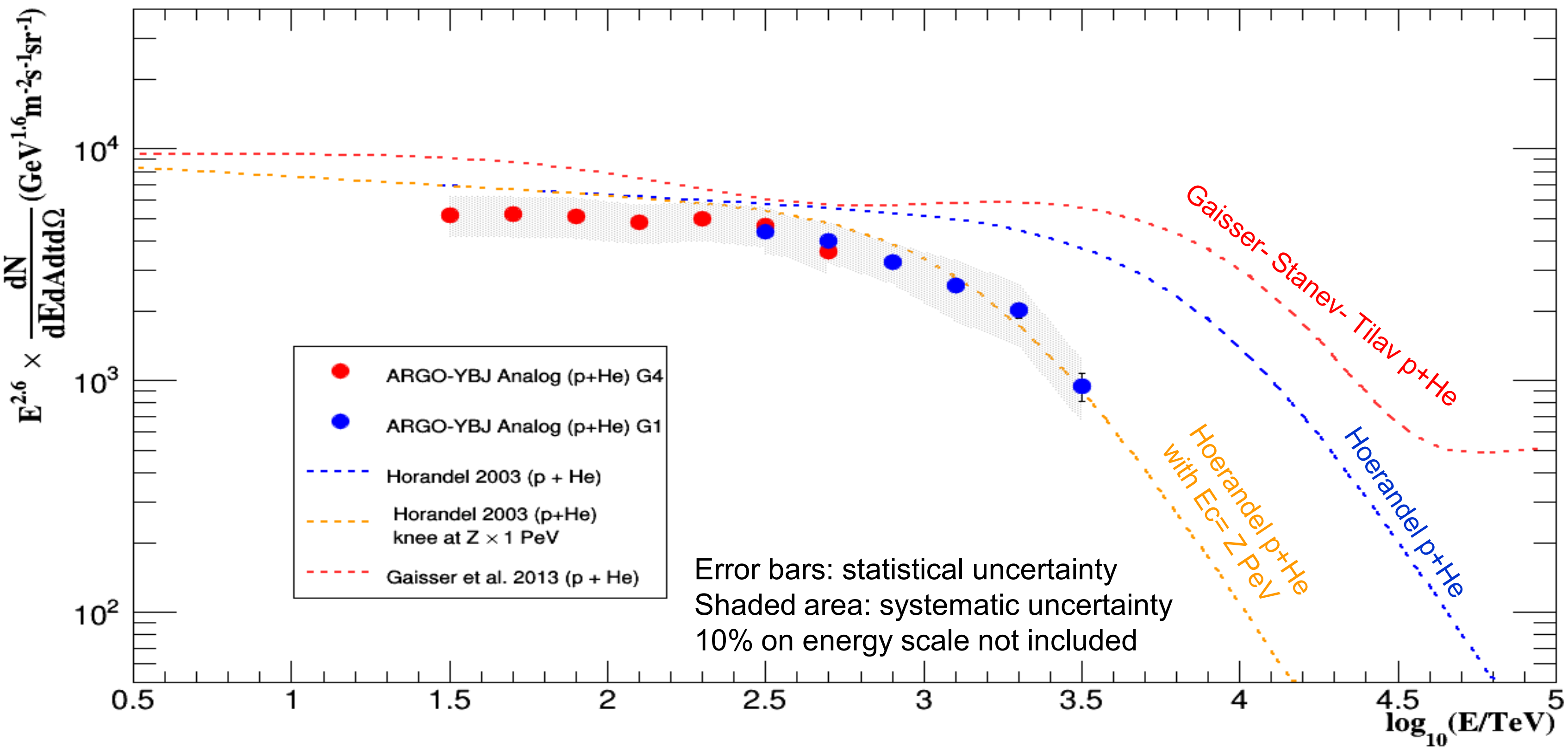
ARGO YBJ all-particle



ICRC - 2015

I. De Mitri: All particle and p+He energy spectra with ARGO-YBJ

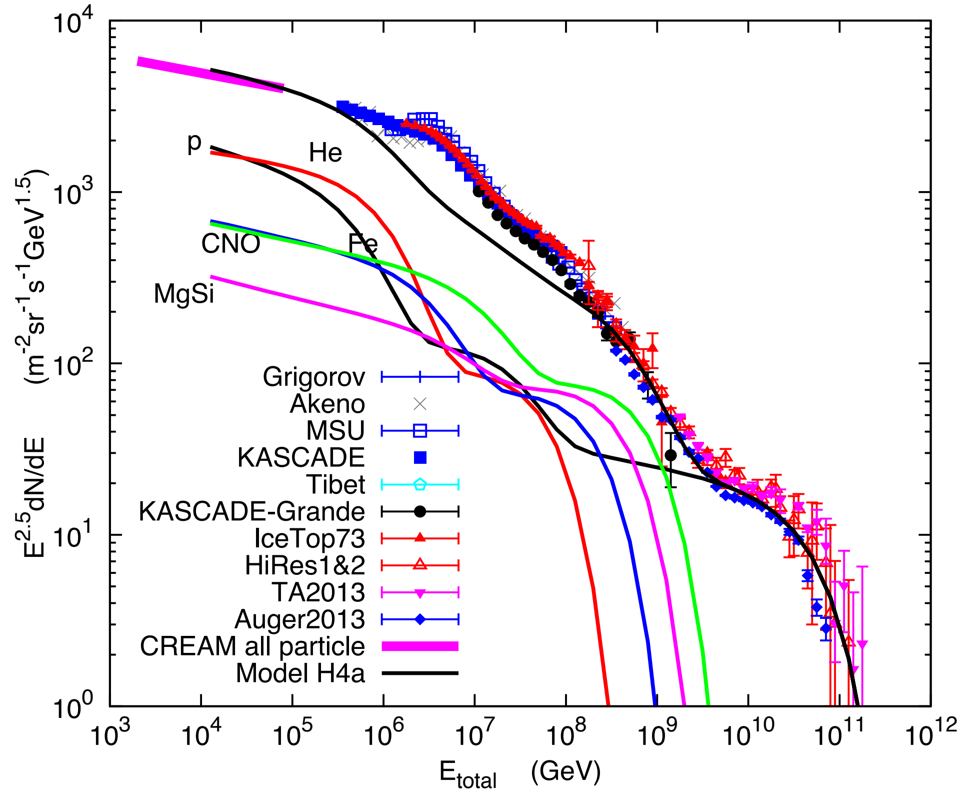
ARGO-YBJ p + He



ICRC - 2015

I. De Mitri: All particle and p+He energy spectra with ARGO-YBJ

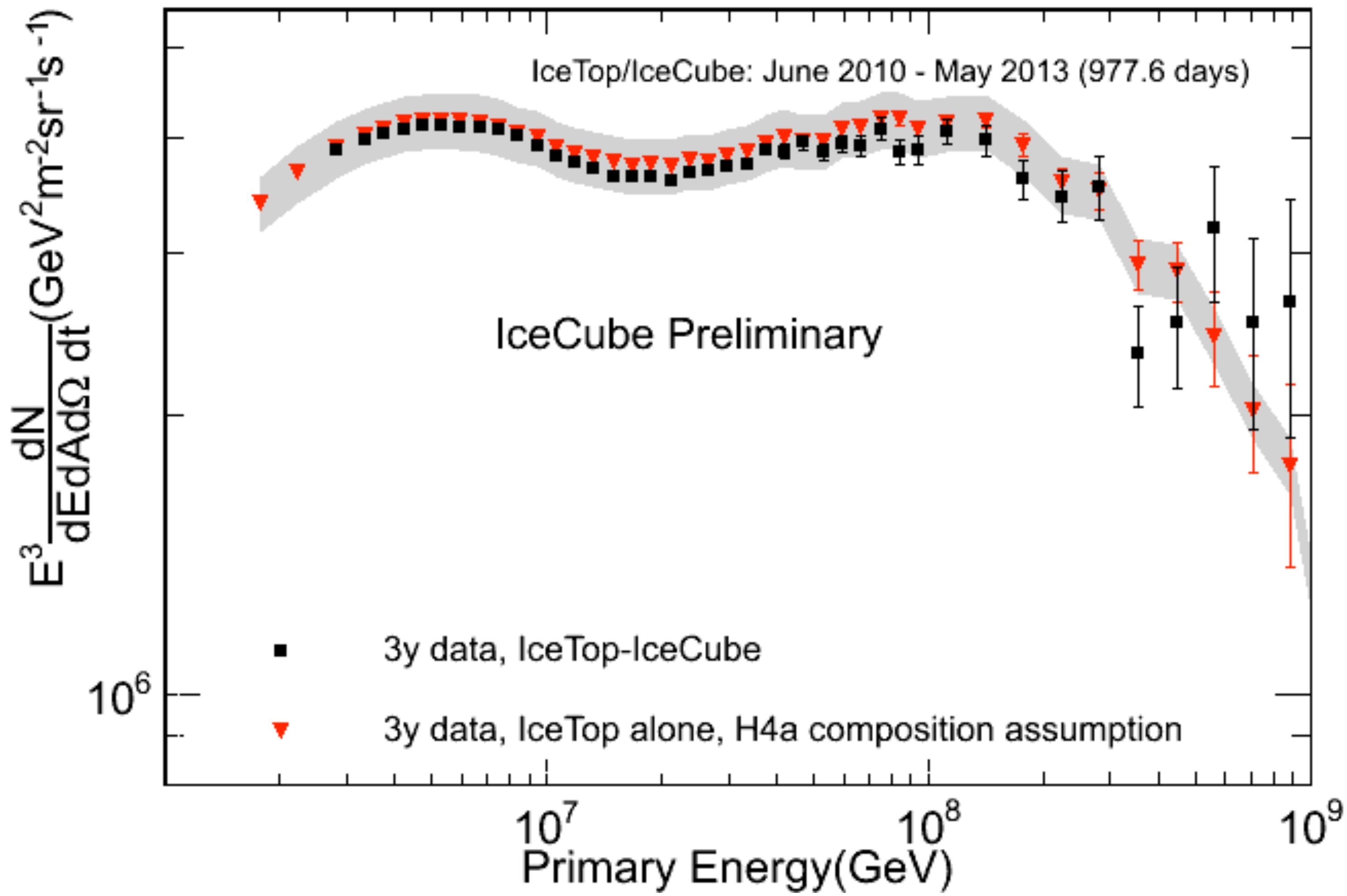
Change 1st knee from 4 to 0.7 PV



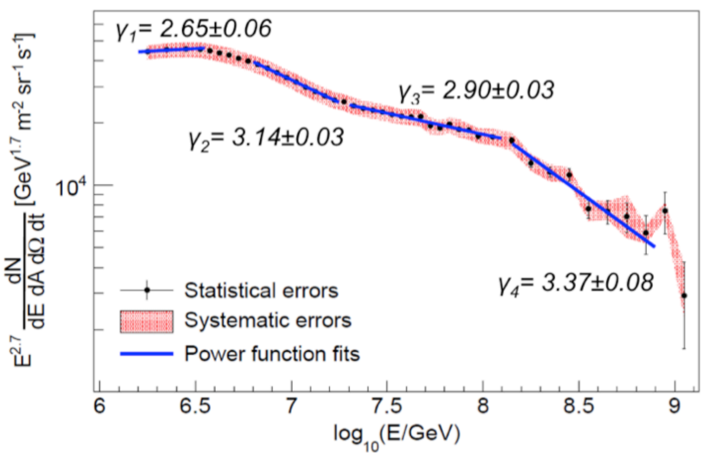
To do:

1) Try to fit by adding another population
2) Calculate corresponding spectrum of nucleons and check muon flux

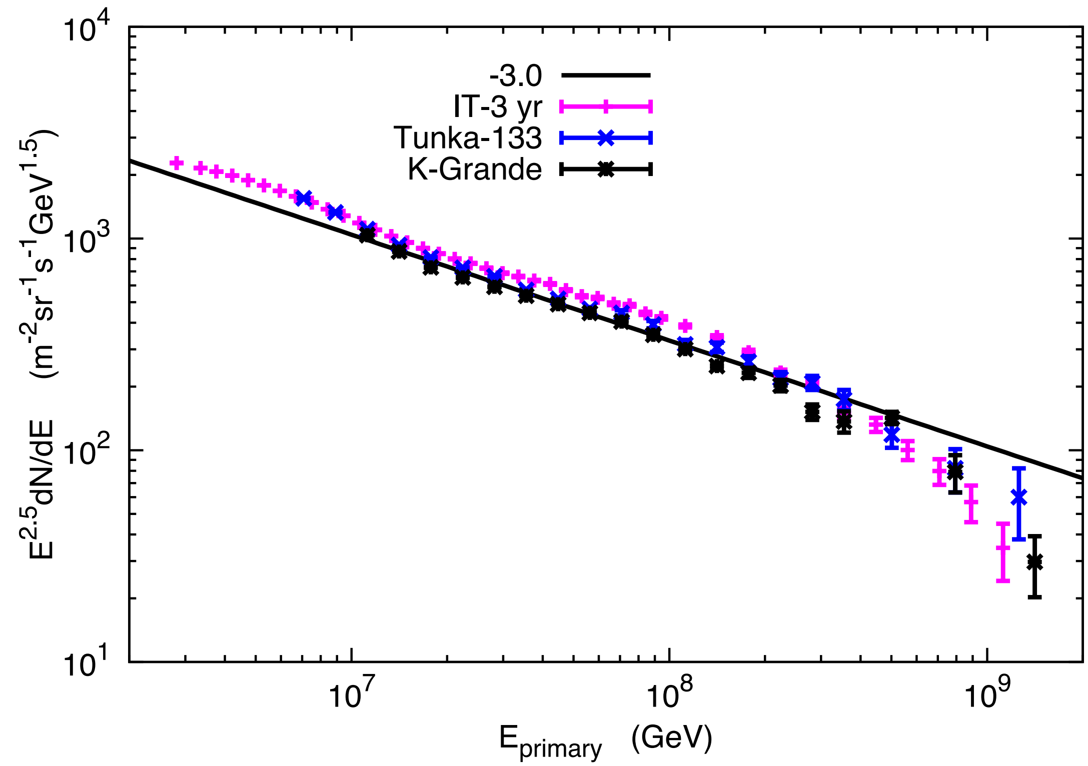
IceTop spectrum: two analyses



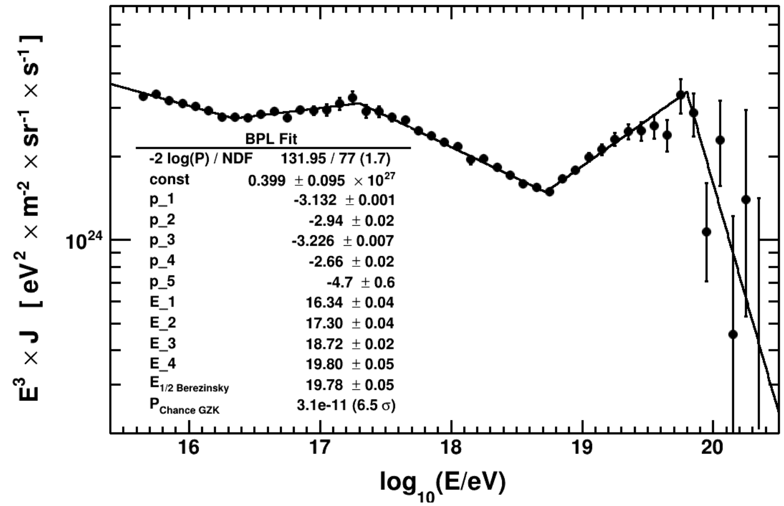
Structure in spectrum between knee and ankle



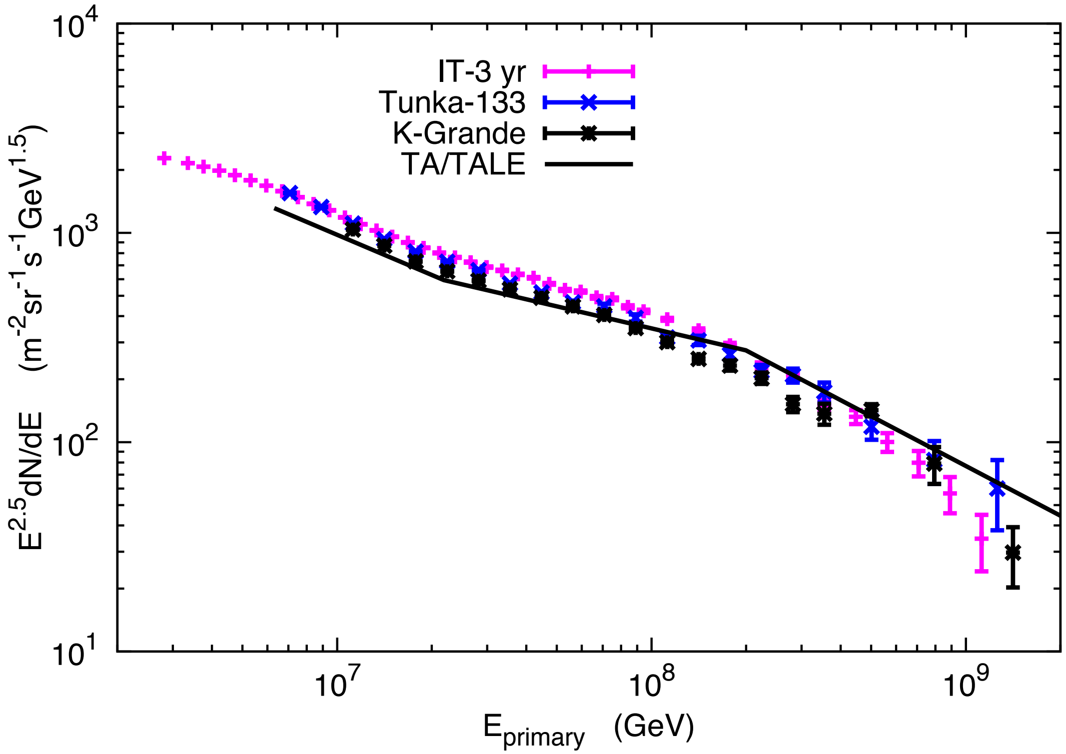
IceTop, 1 year
PR DD88 (2013) 042004



TALE/TA

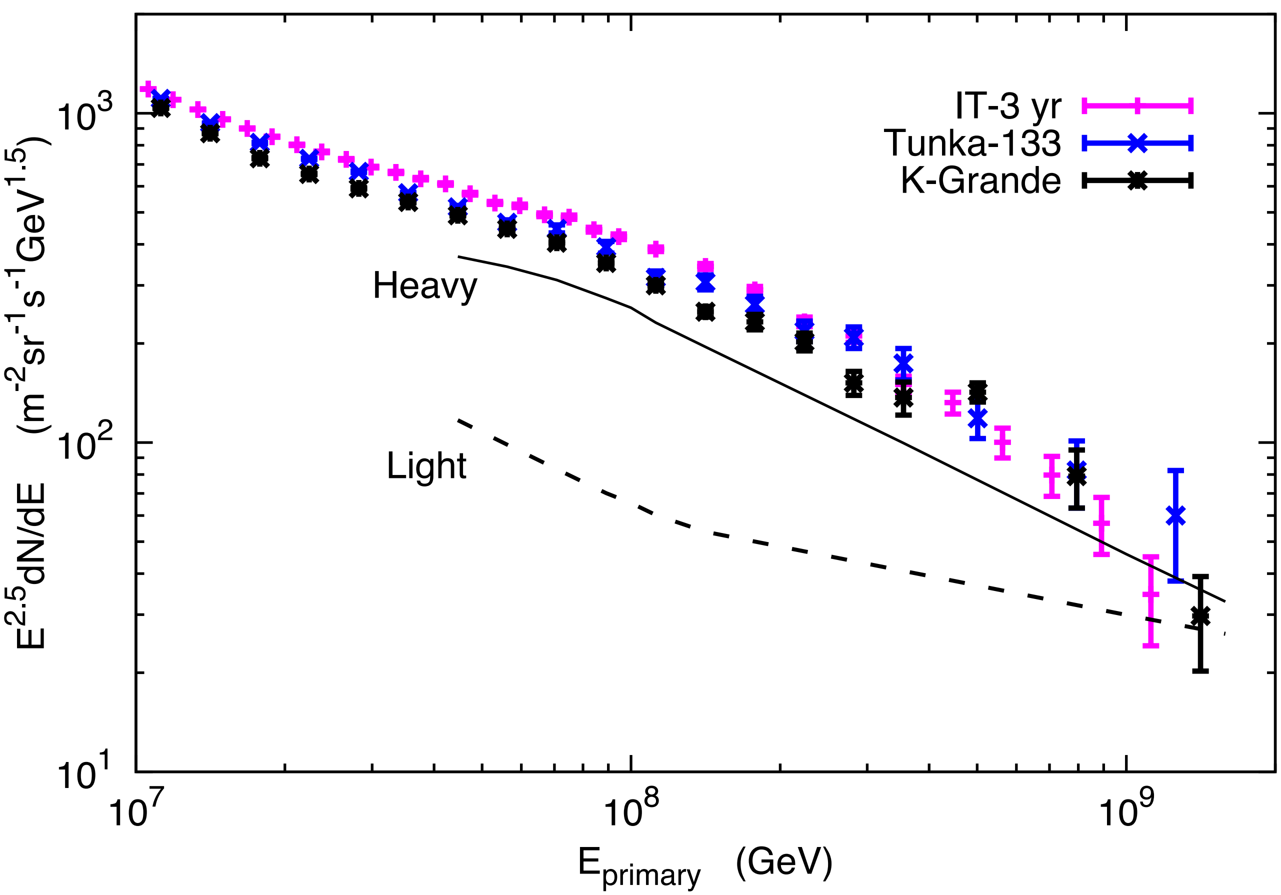


BPL Fit
-2 log(P) / NDF 131.95 / 77 (1.7)
const 0.399 ± 0.095 × 10^27
p_1 -3.132 ± 0.001
p_2 -2.94 ± 0.02
p_3 -3.226 ± 0.007
p_4 -2.66 ± 0.02
p_5 -4.7 ± 0.6
E_1 16.34 ± 0.04
E_2 17.30 ± 0.04
E_3 18.72 ± 0.02
E_4 19.80 ± 0.05
E_1/2 Berezinsky 19.78 ± 0.05
P_Chance GZK 3.1e-11 (6.5 σ)
E^3 × J [eV^2 × m^-2 × sr^-1 × s^-1]
log10(E/eV)

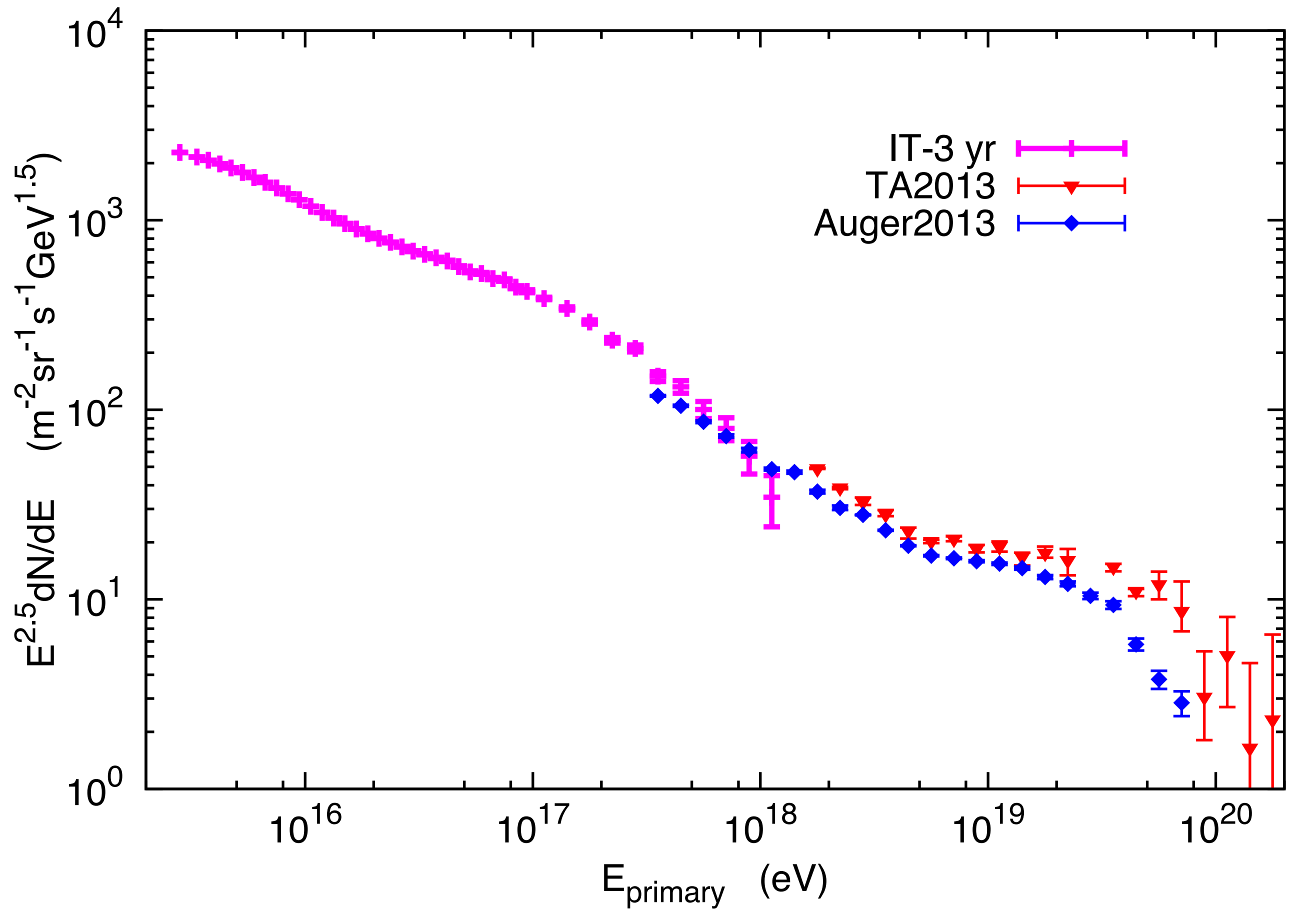


IT-3 yr
Tunka-133
K-Grande
TA/TALE
E^2.5 dN/dE (m^-2 sr^-1 s^-1 GeV^1.5)
E_primary (GeV)

KASCADE-Grande: heavy knee, light ankle

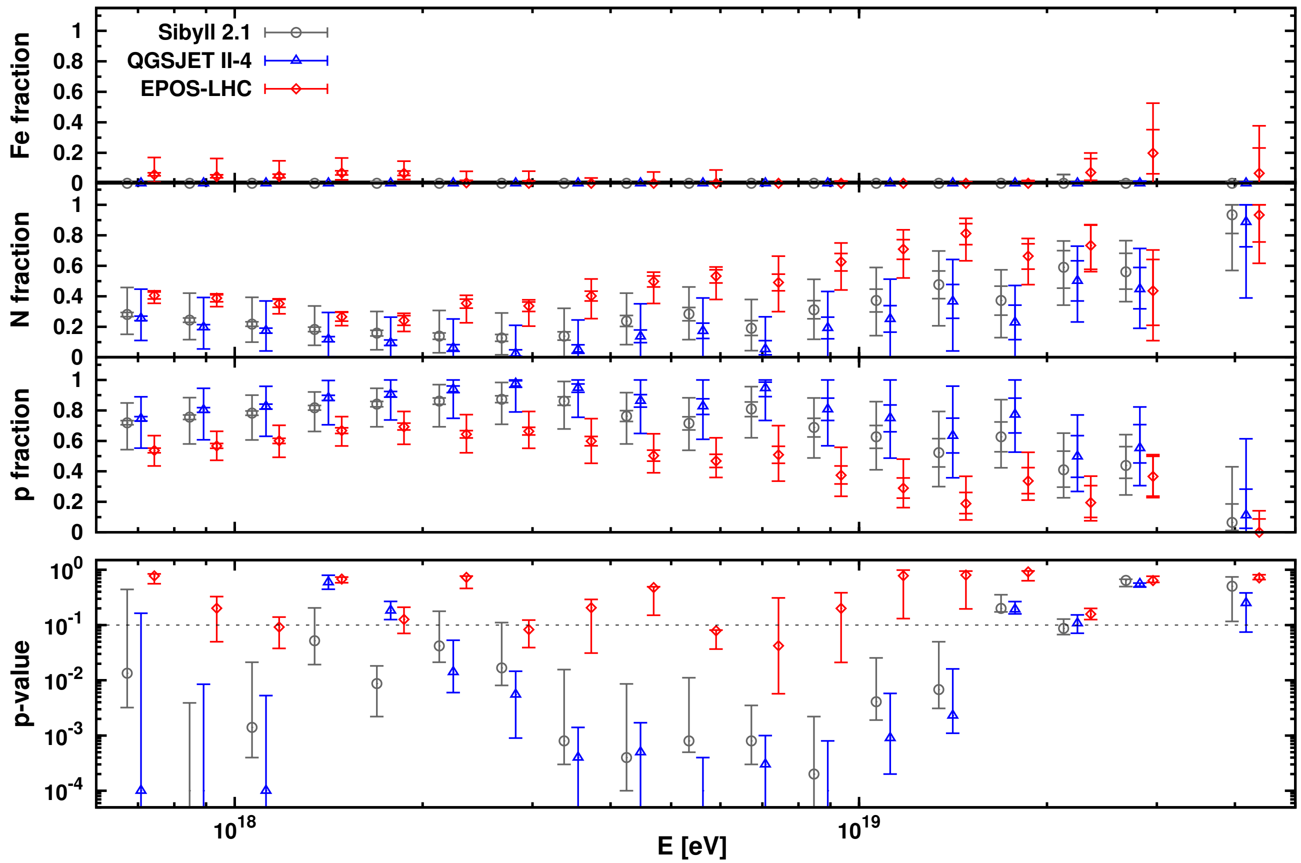


Global view



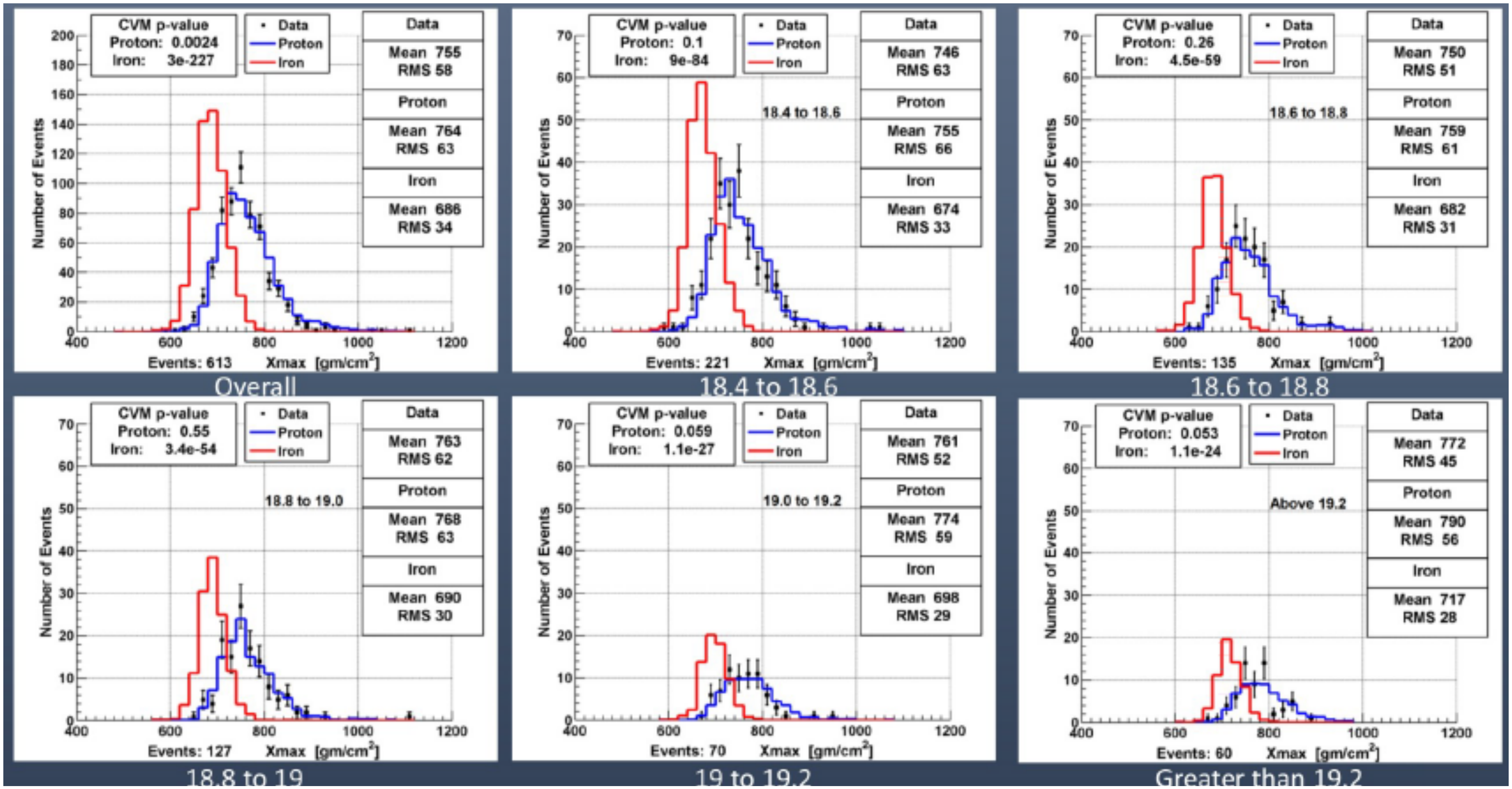
IT-3 yr
TA2013
Auger2013
$E^{2.5}dN/dE$ $(m^{-2}sr^{-1}s^{-1}GeV^{1.5})$
$E_{primary}$ (eV)
10^0
10^1
10^2
10^3
10^4
10^{16}
10^{17}
10^{18}
10^{19}
10^{20}

Composition > EeV

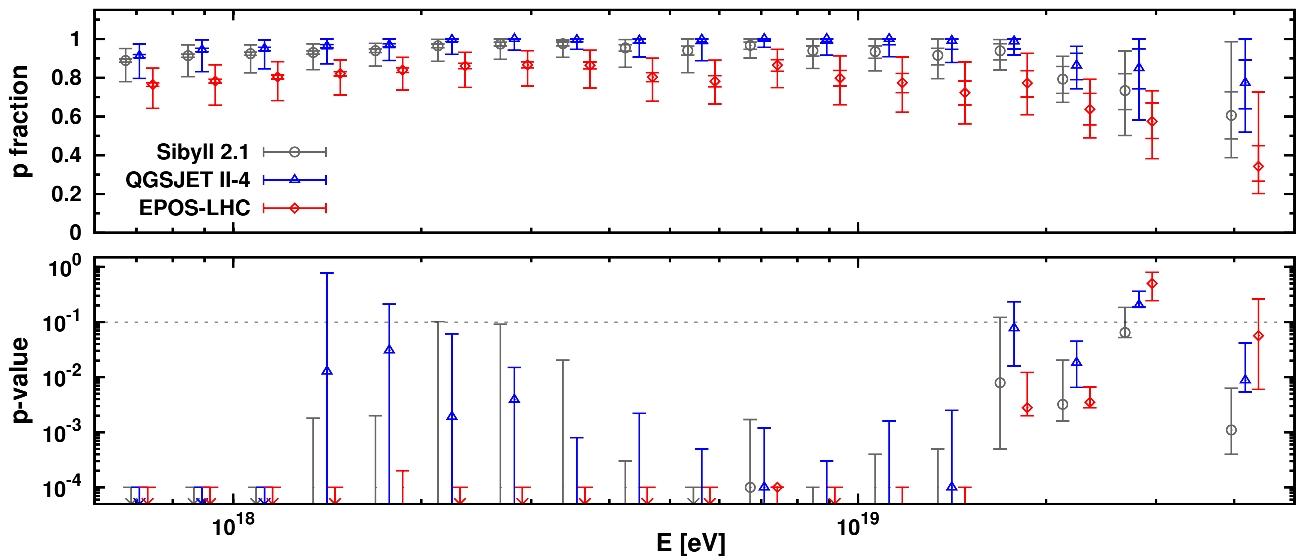


Auger: Phys. Rev. D90 (2014) 122006, arXiv:1409.5083 [astro-ph.HE].

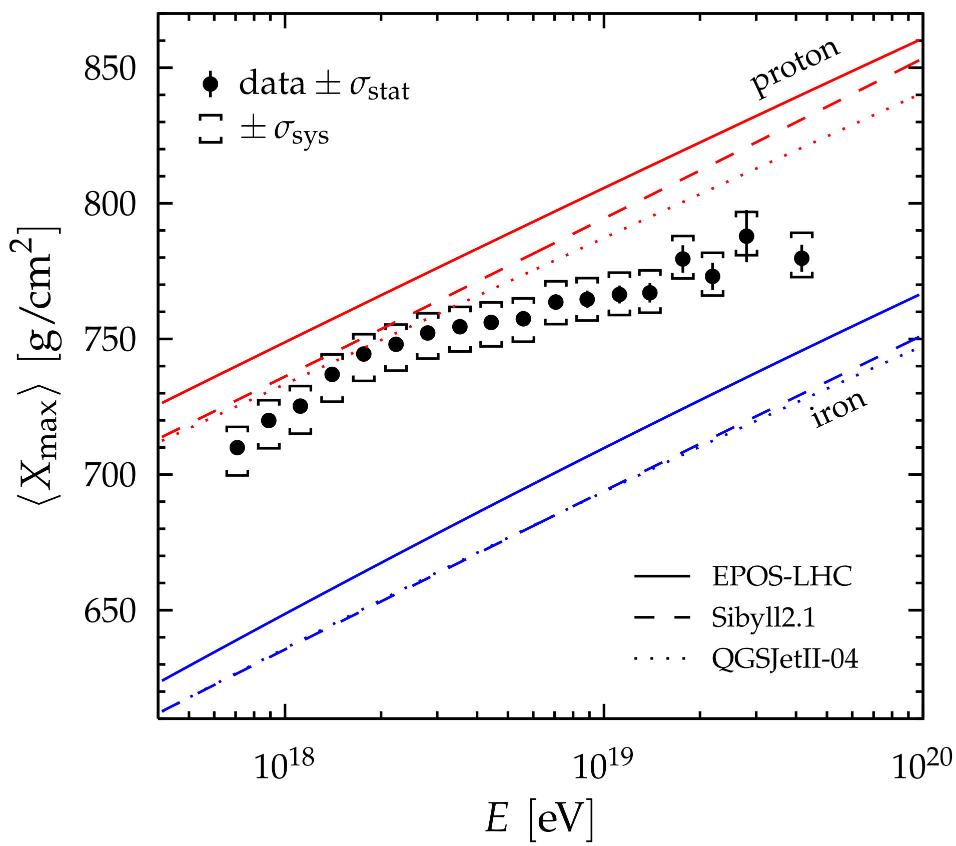
Telescope array

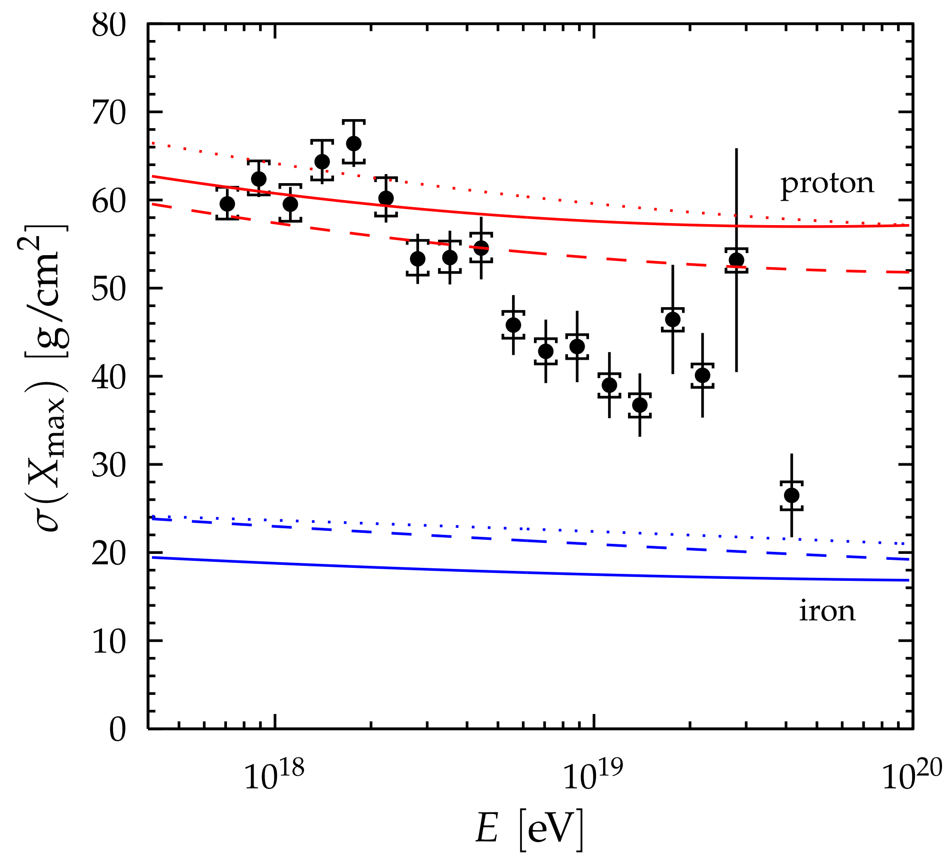


Auger, p, Fe only



Average Shower Maximum



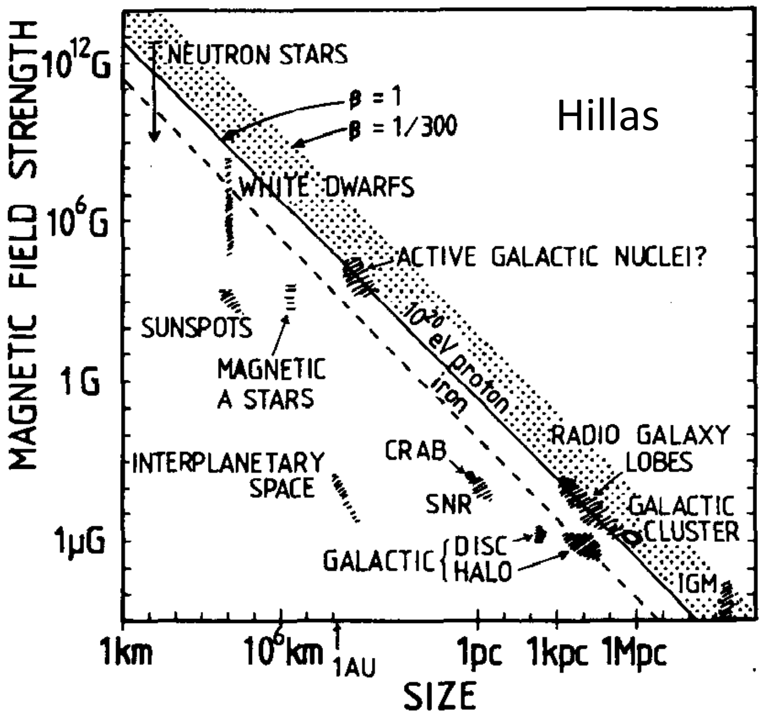


Markus Roth

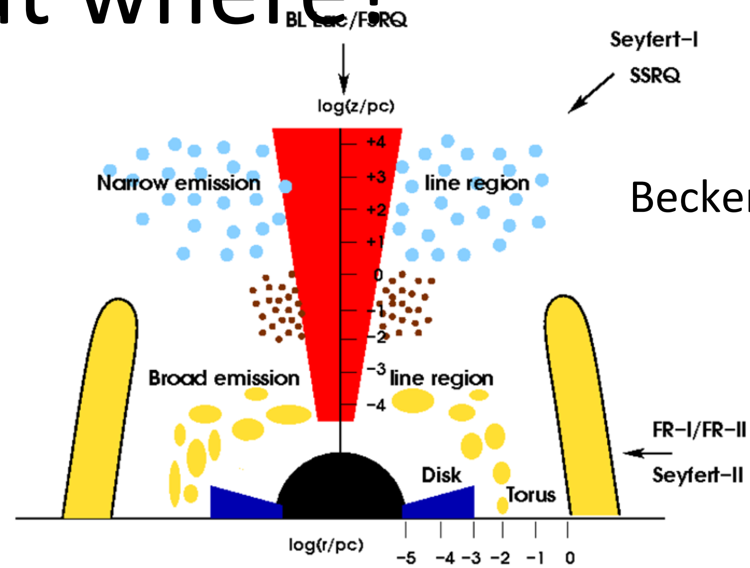
Pierre Auger Collaboration, PRD 90 (2014) 12, 122005

Are active galaxies sources of UHECR? Probably, but where?

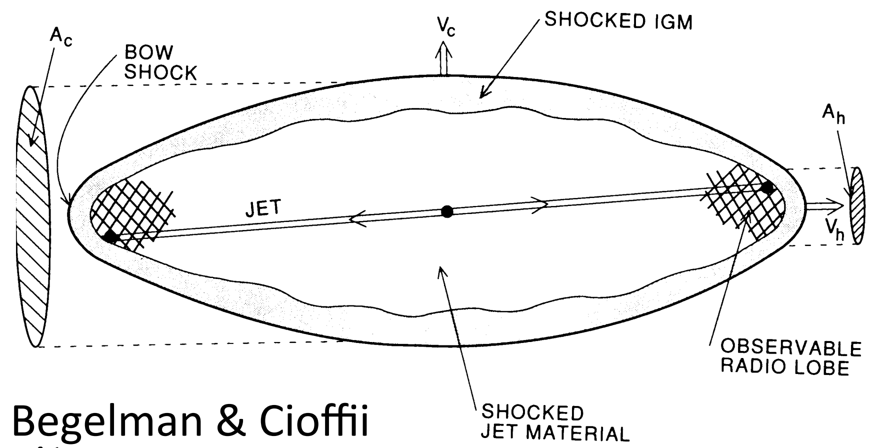
Near central BH or at termination shock?



Recall Martin Pohl's talk



Becker-Tjus



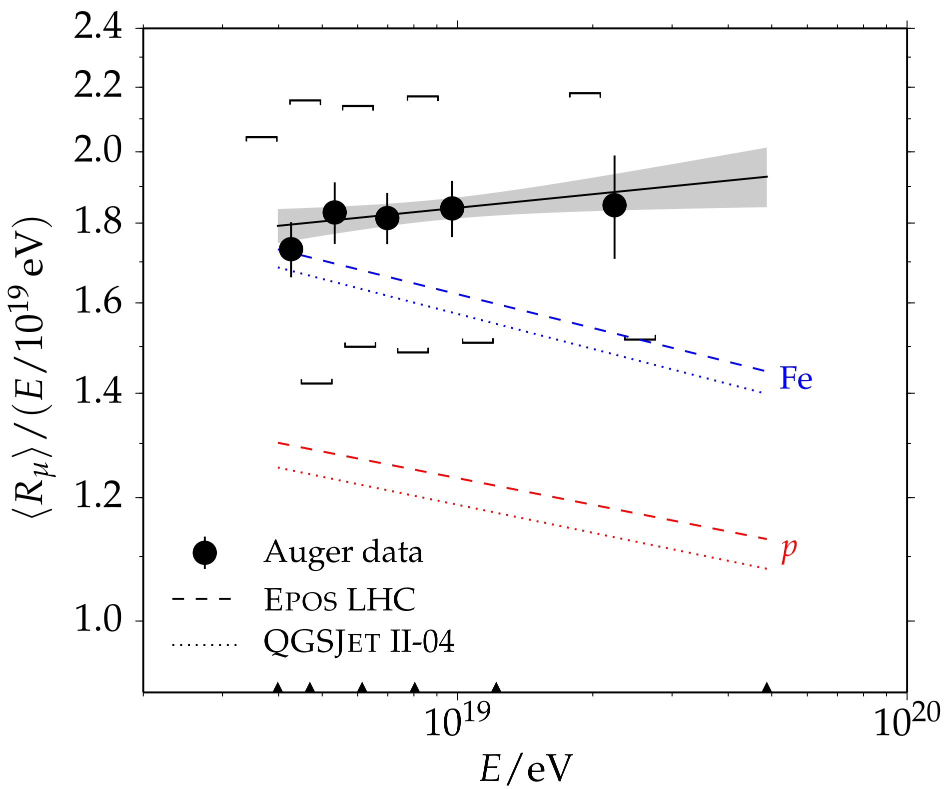
Begelman & Cioffi

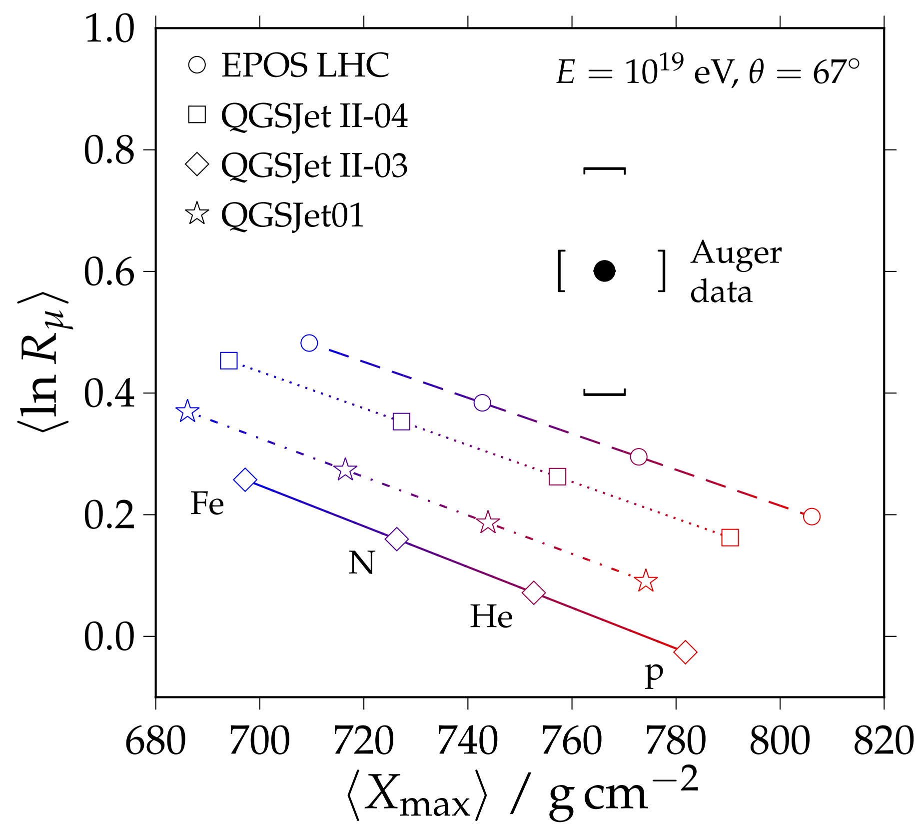
Muons in air shower

- $E \sim N_e$ + "25" x N_μ (Jim Matthews)
- Should be simple
- Apparently not so
- Too many muons at Auger (compared to sims)
- Differences between event generators
- Tension between IceCube coincident analysis and light composition approaching EeV

Hadronic interactions
Data at variance with simulations

MarkusRoth





- ⟨R_μ⟩ higher than MC iron predictions
- Tension between the X_{max} and muon measurements
- Older versions of QGSJet model are at odds with data taking into account the large systematic uncertainty

History

1950-52 in a salt mine at 1574 m.w.e. in Ithaca, NY with 4 surface detectors and 1 m^2 muon counters underground. Acceptance: ~ 0.01 m^2 sr: Barrett, Bollinger, Cocconi, Eisenberg, Greisen, Revs. Mod Phys. 24 (1952) 133-178

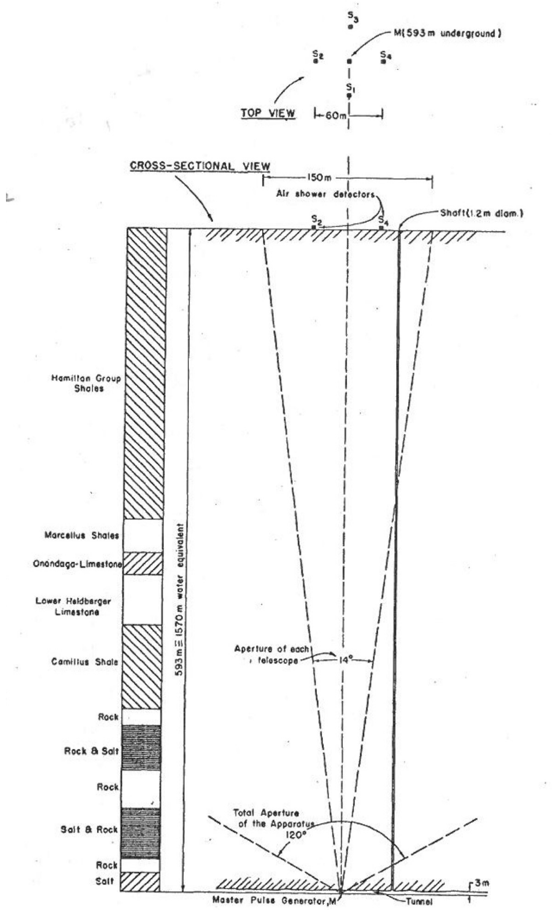
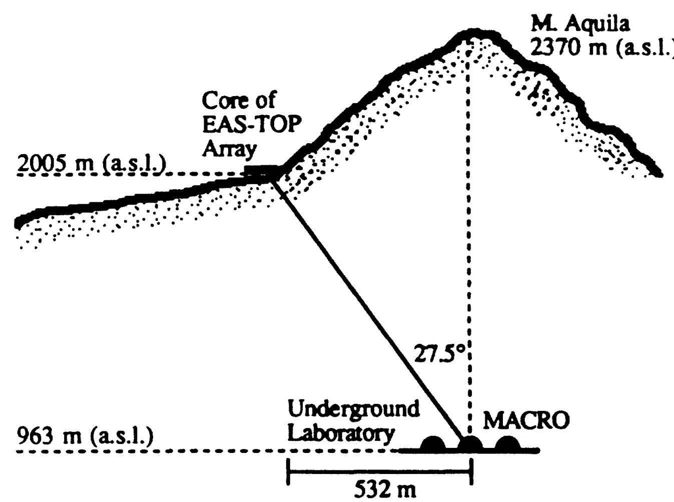
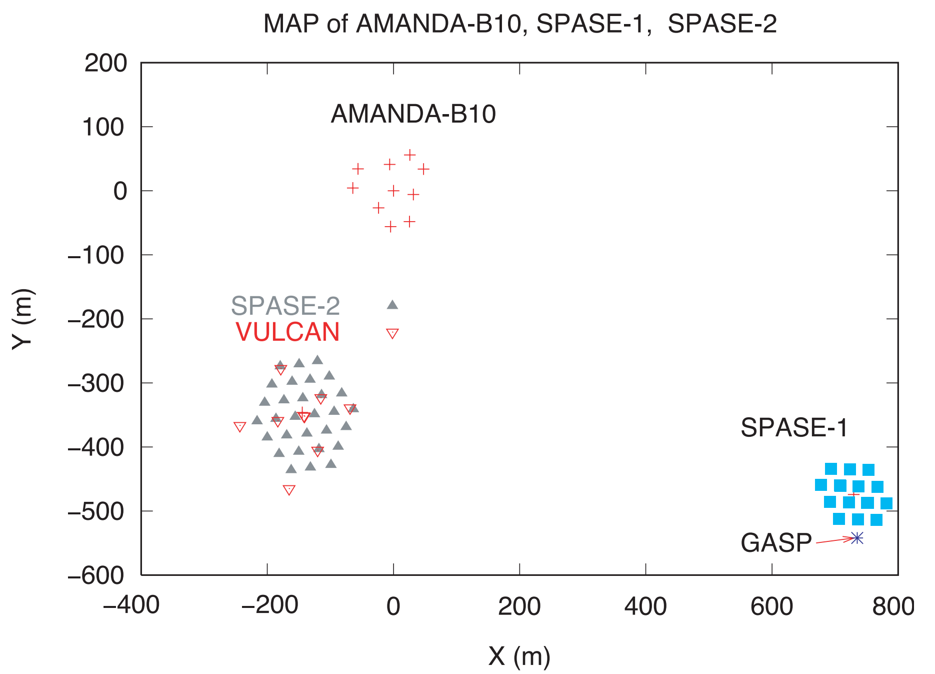


FIG. 11. Diagram showing relative positions of the counters underground and on the surface of the ground in the experiments on the association of mesons with extensive air showers. The composition of the ground is shown in the scale at the left.

EASTOP MACRO, R. Bellotti et al., PRD 42 (1990) 1396-1403
$A\Omega$ ~ 100 m^2 sr



SPASE – AMANDA: AΩ ~ 100 m^2 sr



Survey of AMANDA from SPASE-1 and SPASE-2
NIM A 522 (2004) 347-359

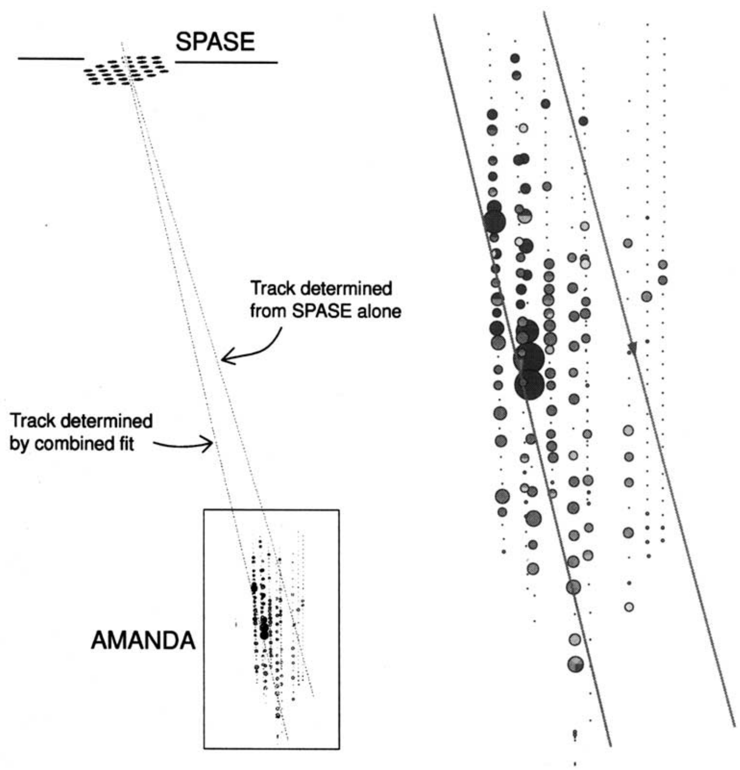
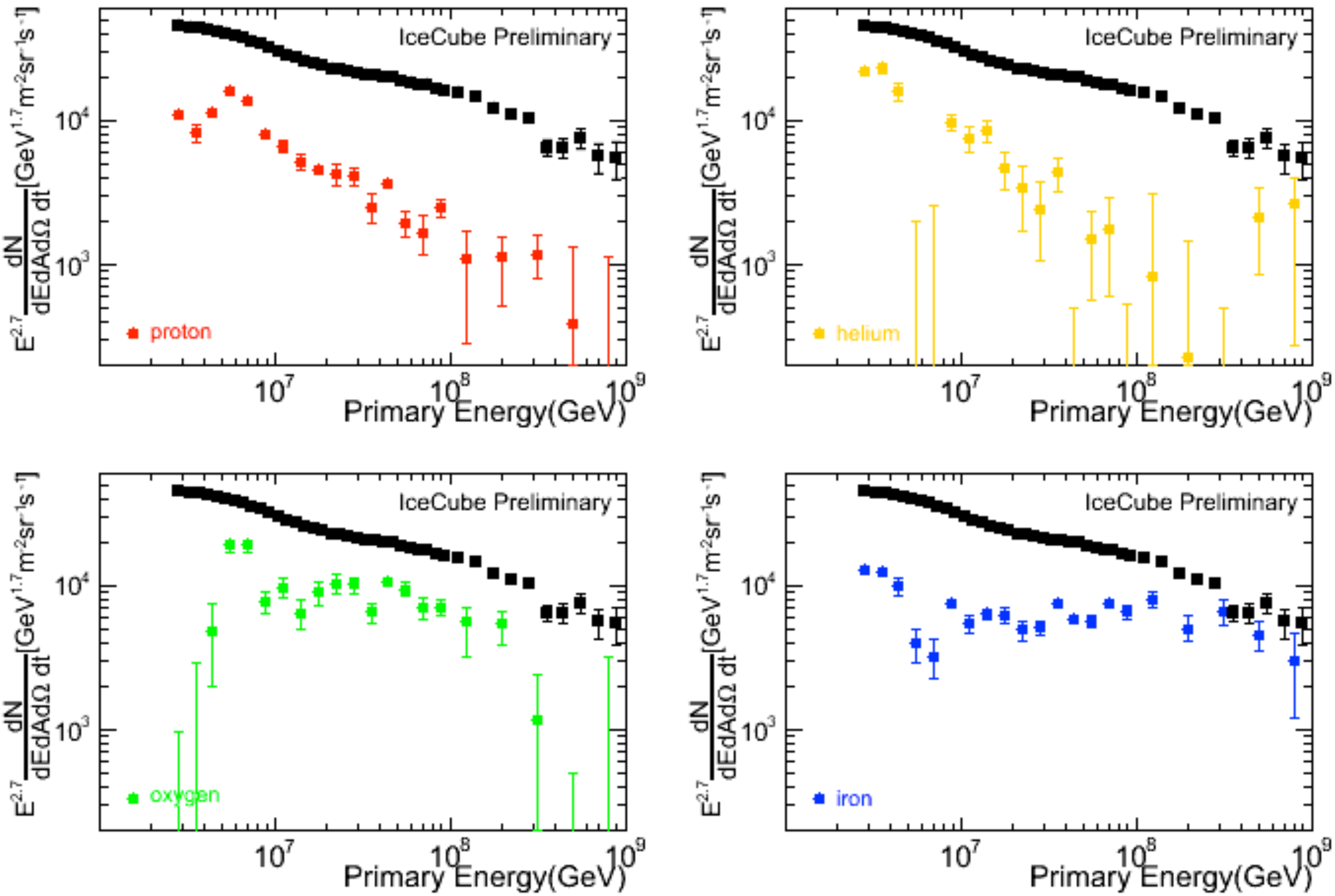


Fig. 1. SPASE/AMANDA coincidence event from 1997 data.

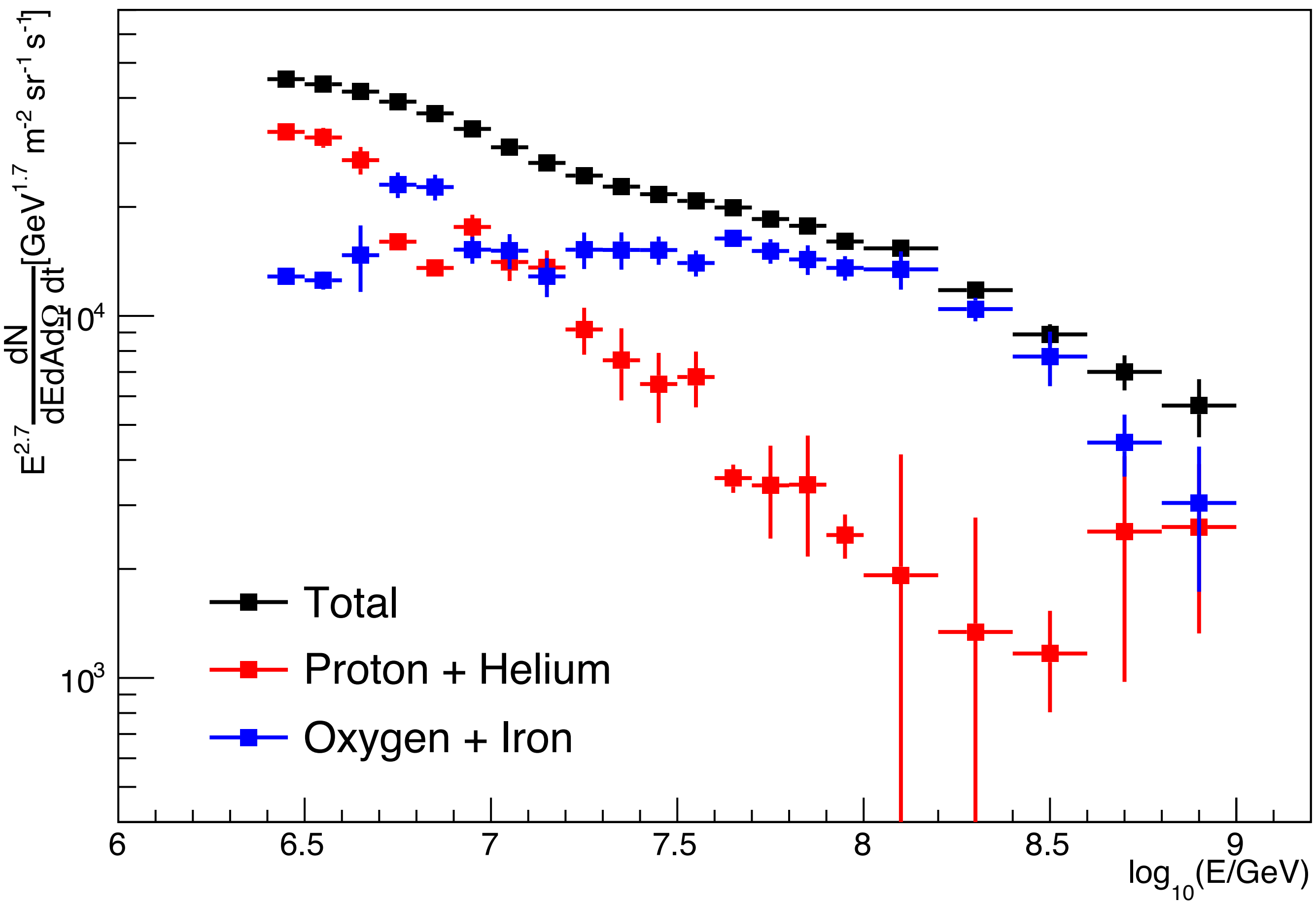
Composition at the knee with SPASE-2/AMANDA B10,
Astropart. Phys. 21 (2004) 565-581

Spectra of 4 elemental groups



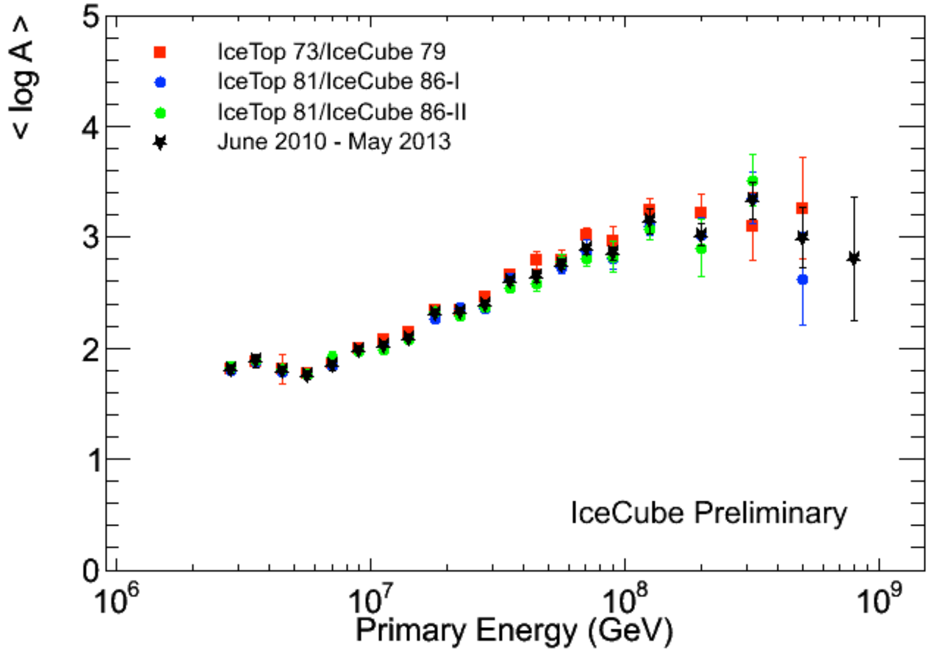
Statistical and fit uncertainties only

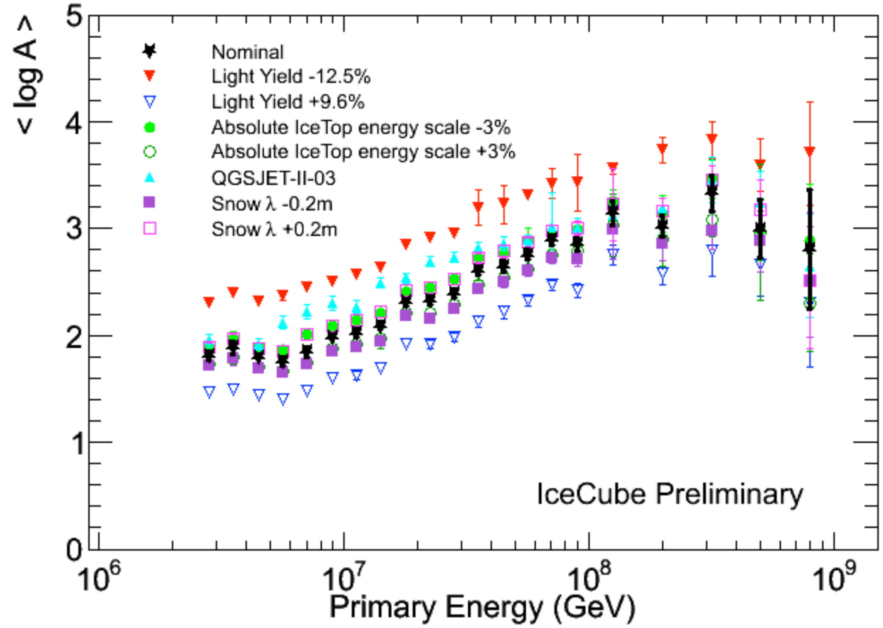
IceCube/IceTop



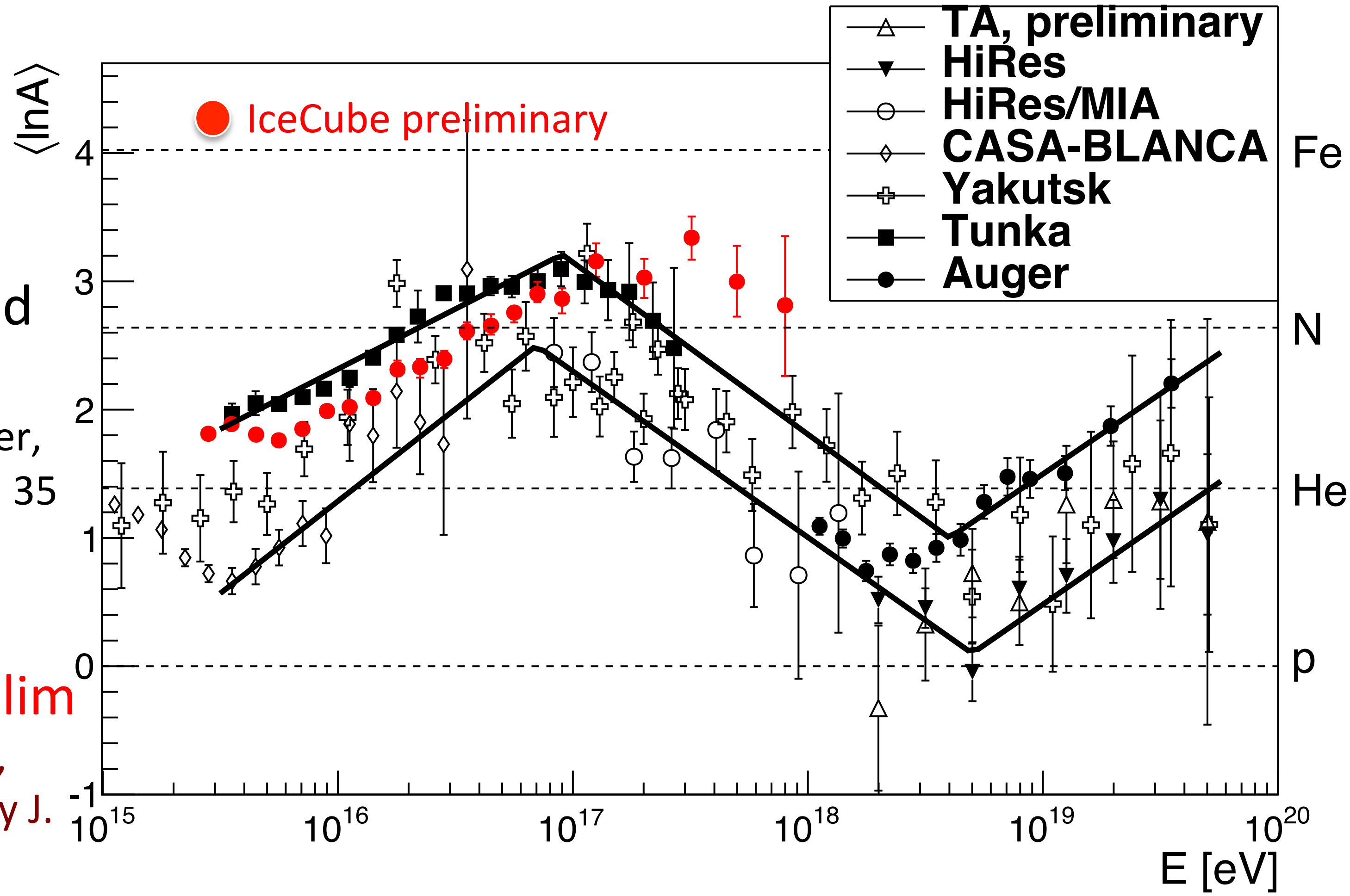
Sam De Ridder

Mean ln(A)


< log A >
5
4
3
2
1
0
IceTop 73/IceCube 79
IceTop 81/IceCube 86-I
IceTop 81/IceCube 86-II
June 2010 - May 2013
IceCube Preliminary
10^6
10^7
10^8
10^9
Primary Energy (GeV)


< log A >
5
4
3
2
1
0
Nominal
Light Yield -12.5%
Light Yield +9.6%
Absolute IceTop energy scale -3%
Absolute IceTop energy scale +3%
QGSJET-II-03
Snow λ -0.2m
Snow λ +0.2m
IceCube Preliminary
10^6
10^7
10^8
10^9
Primary Energy (GeV)

Compare < ℓn(A)>

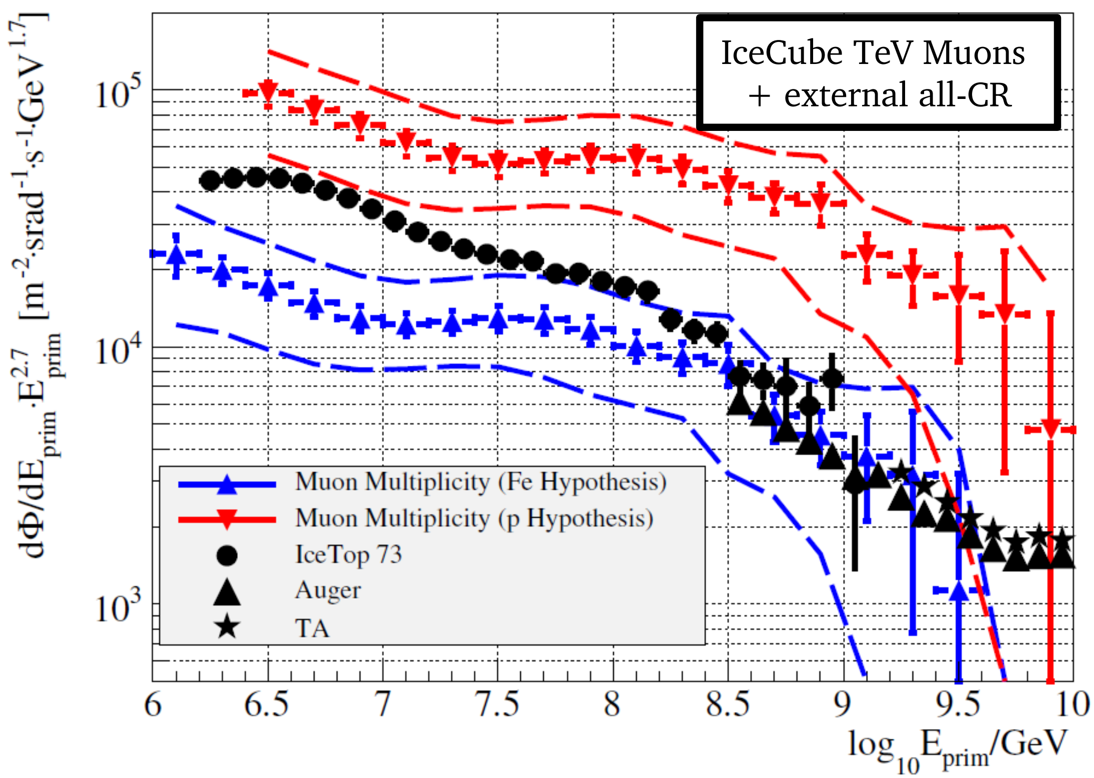


Plot: inferred from Xmax

Kampert & Unger, Astropart. Phys. 35 (2012) 660-678

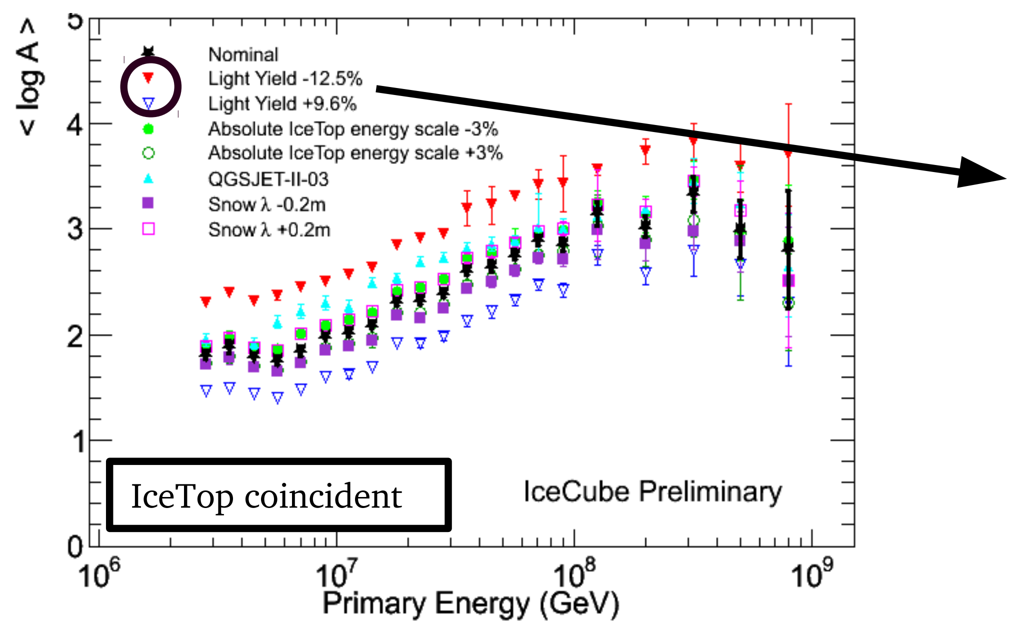
Red points: IceCube prelim

T.Feusels thesis, results shown by J. Gonzalez @ UHECR2014



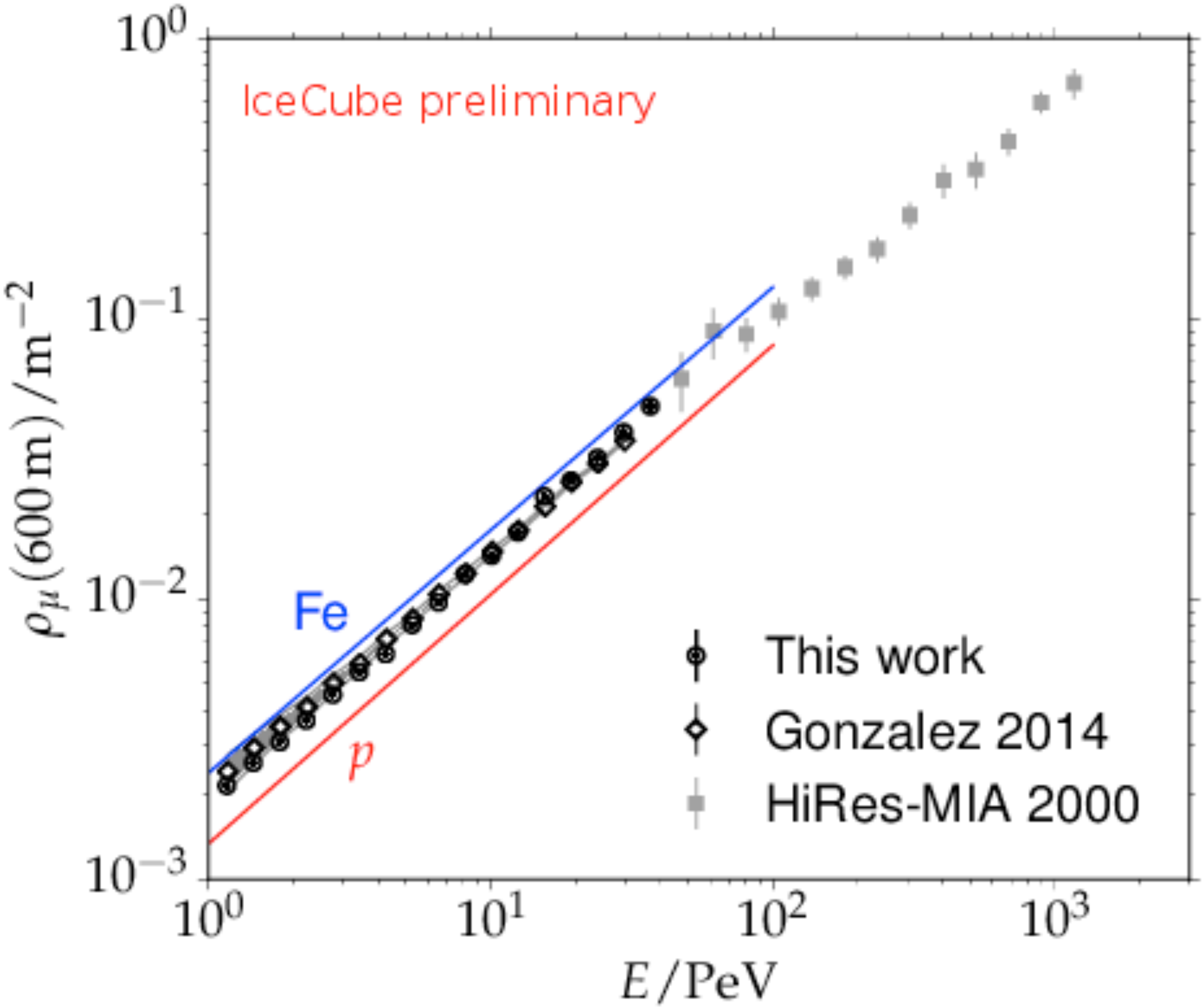
Patrick Berghaus:
Muon bundles in IceCube
to > EeV primary energy

Consistent picture:
Average mass increases up to $3{\cdot}10^{17}$ eV, stays at same level until the ankle.

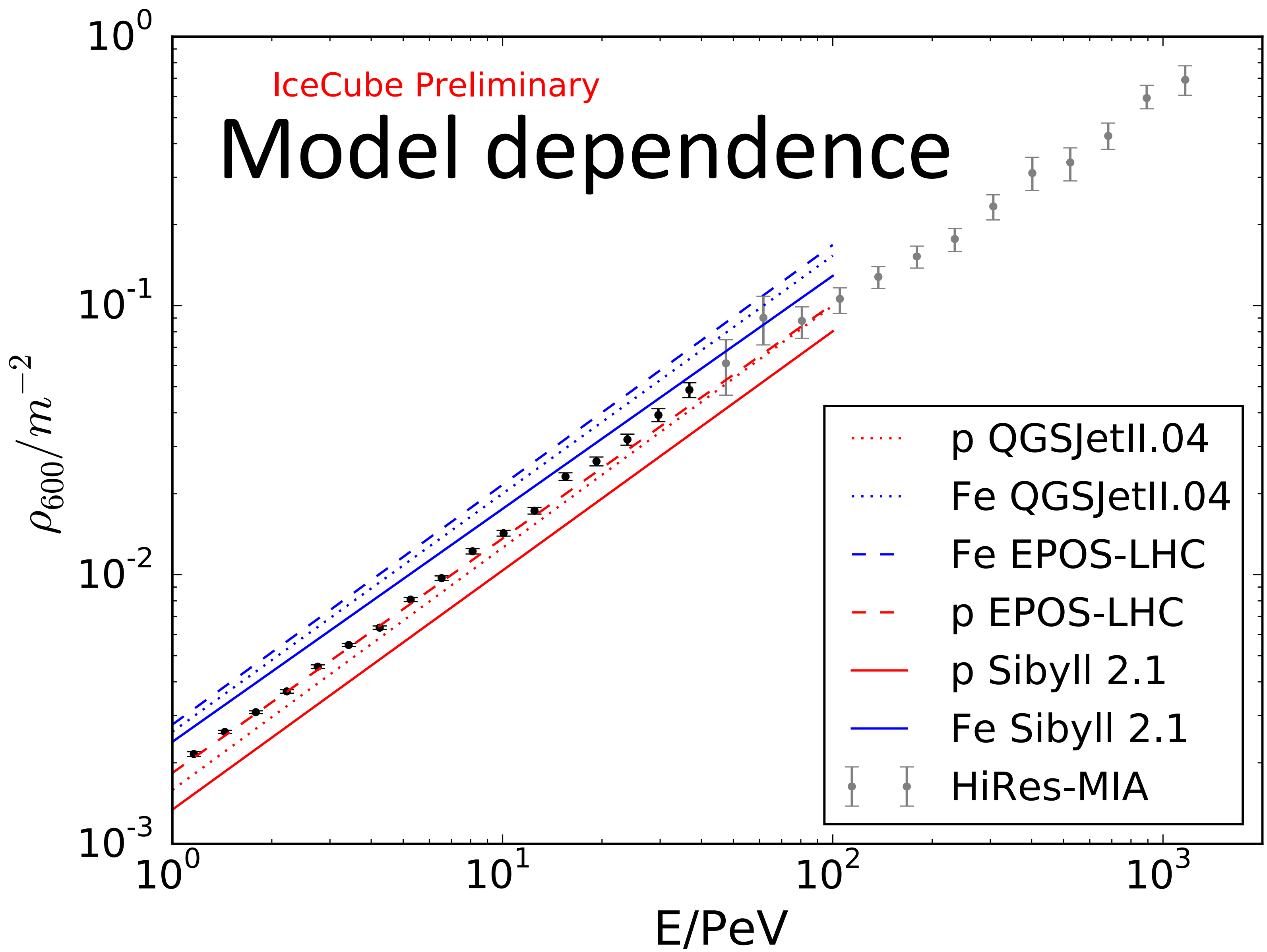


In IceTop coincident events, systematic uncertainty is dominated by deep detector effects ("Light Yield").

Muons at the surface



Model dependence



IceCube collaboration, ISVHECRI 204, arxiv:1501.03415

Abu-Zayyad et al. [HiRes-MIA Collaboration] Phys. Rev. Lett. **84**, 4276 (2000)

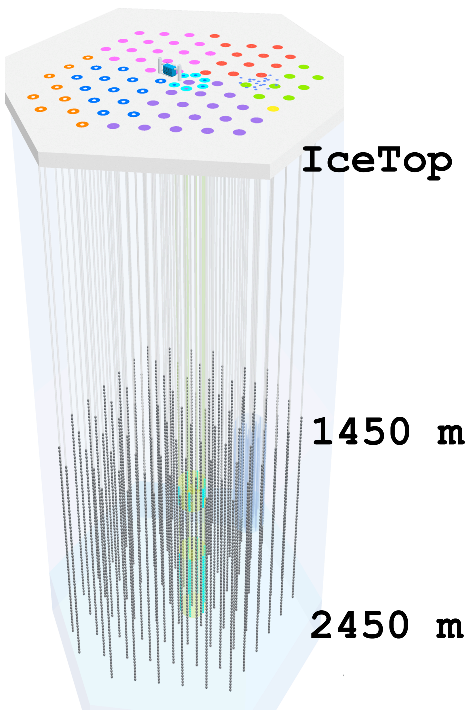
IceCube Gen2

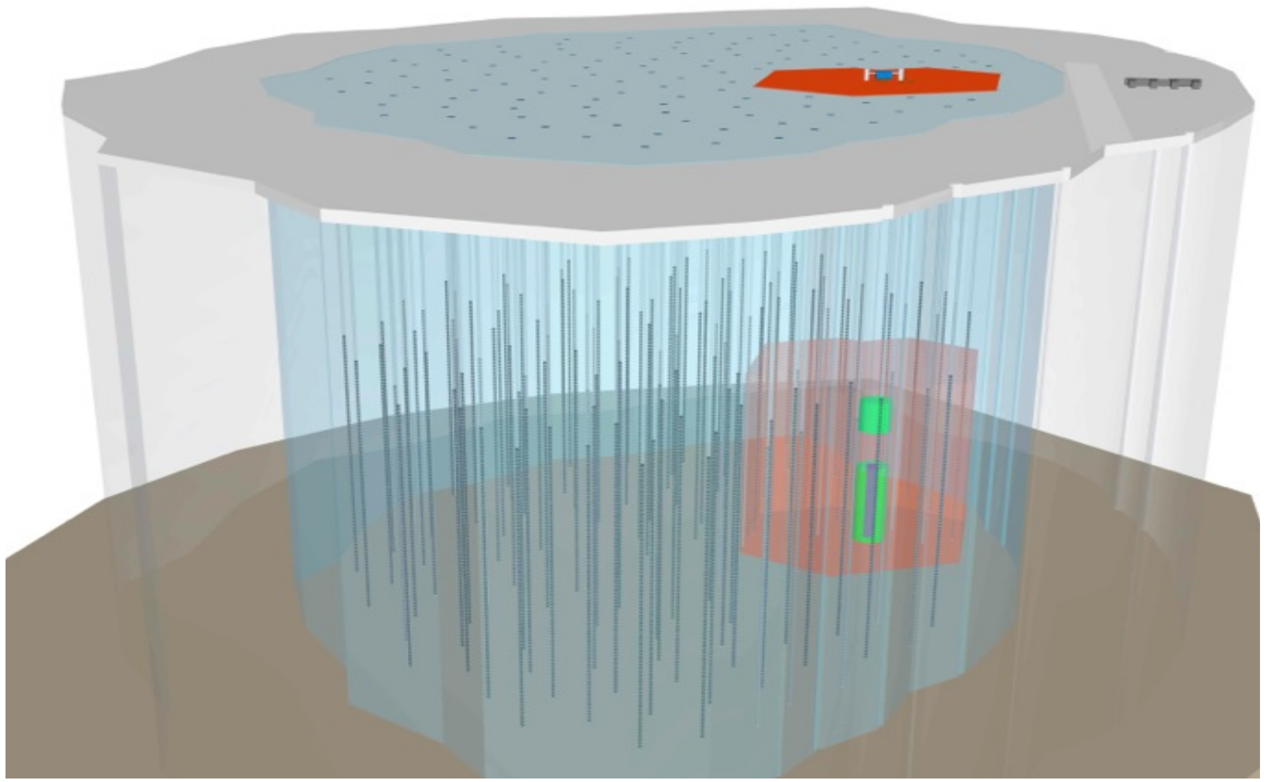
arXiv:1412.5106

125 m string spacing ⟶ 250 m

1 km^2 area ⟶ 6 km^2

Aperture: 0.26 km^2 sr ⟶ ~ 10 km^2 sr





Concluding remarks

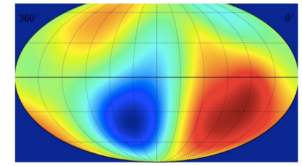
- Structure in the spectrum
  - Hardening around $10^{16.2}$ eV
  - "Second knee" steepening around $10^{17.3}$ eV
- Surface muons:
  - ρ_{600} between p and Fe to $10^{16.5}$ eV
  - TeV muons?

Extras: anisotropy if time

cosmic ray anisotropy

equatorial coordinates

Sky-map with HAWC is in progress



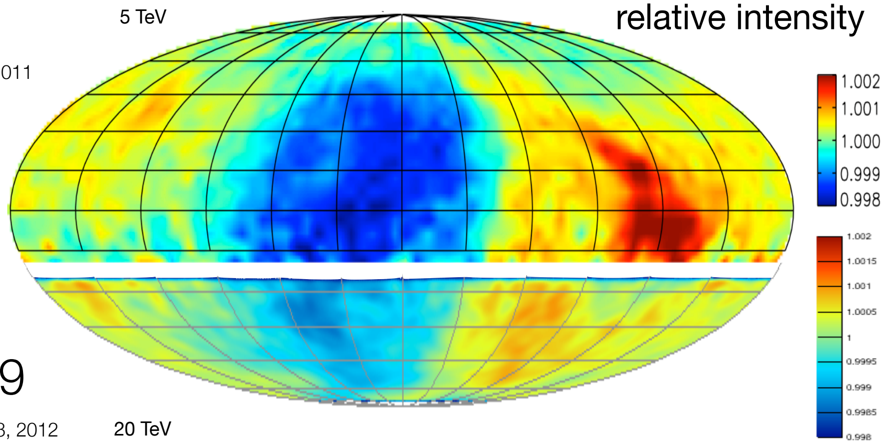
large scale anisotropy

Tibet-III

Amenomori et al., ICRC 2011

5 TeV

relative intensity



IceCube-59

Abbasi et al., ApJ, **746**, 33, 2012

20 TeV

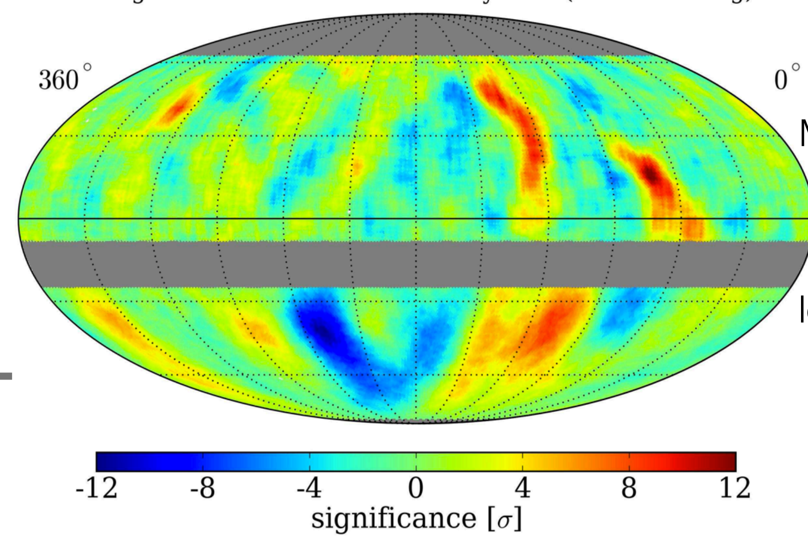
statistical significance

small scale anisotropy

2 hr = 30°

4 hr = 60°

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)



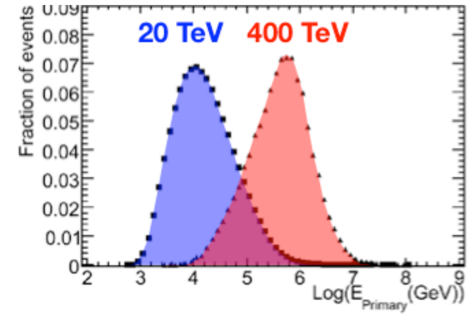
Milagro 1 TeV

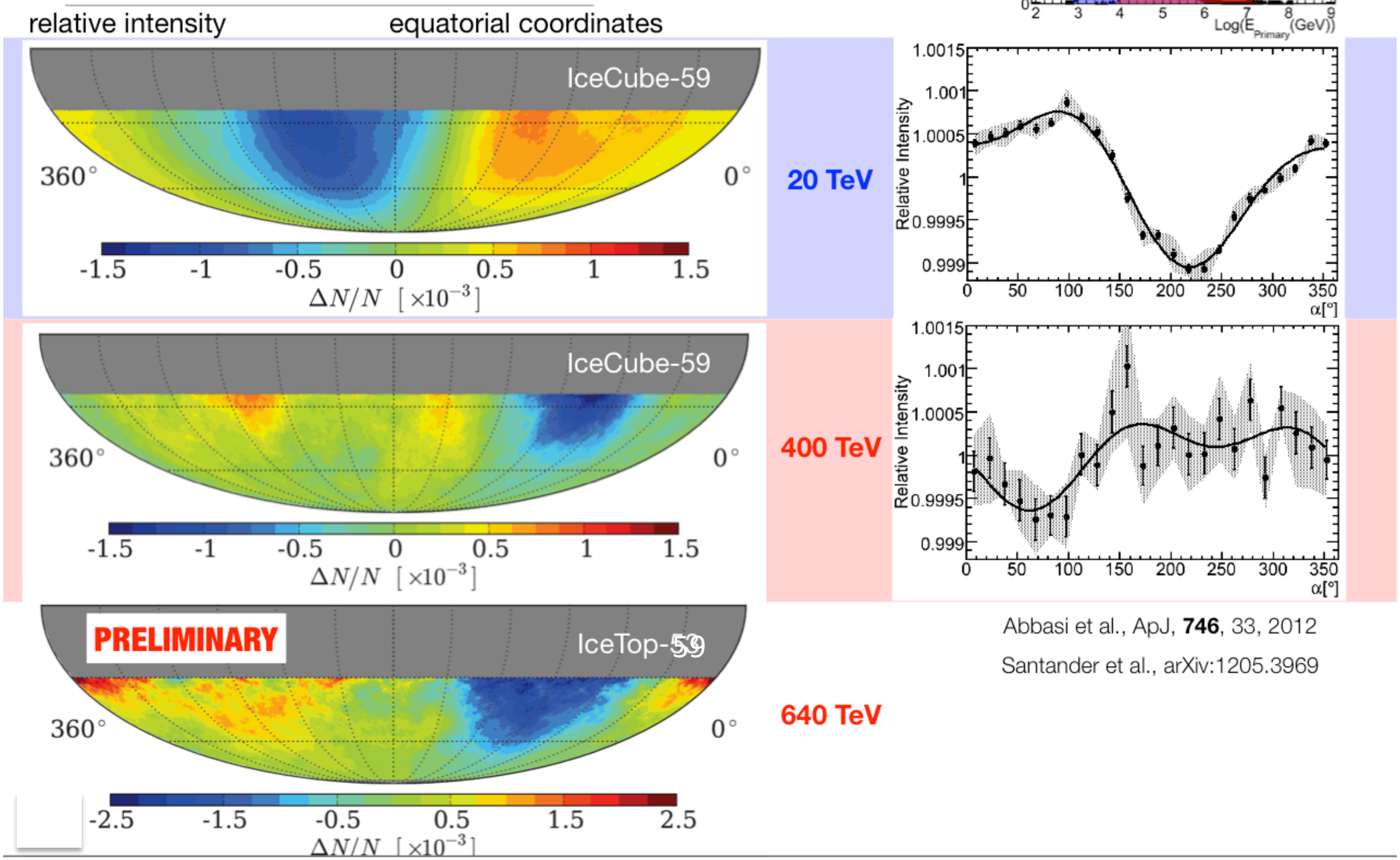
Abdo et al., PRL, **101**, 221101, 2008

IceCube 20 TeV

Abbasi et al., ApJ, **740**, 16, 2011

cosmic ray anisotropy



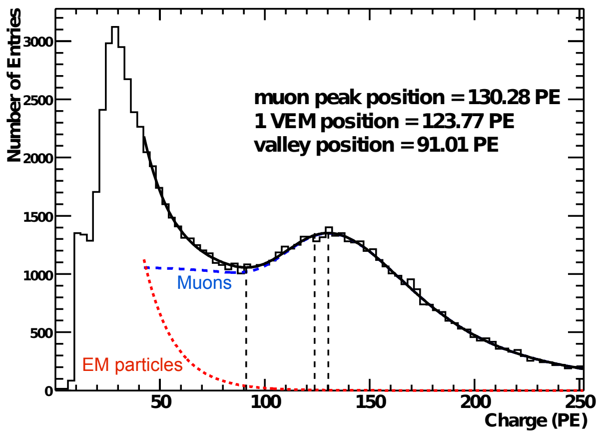


Abbasi et al., ApJ, **746**, 33, 2012

Santander et al., arXiv:1205.3969

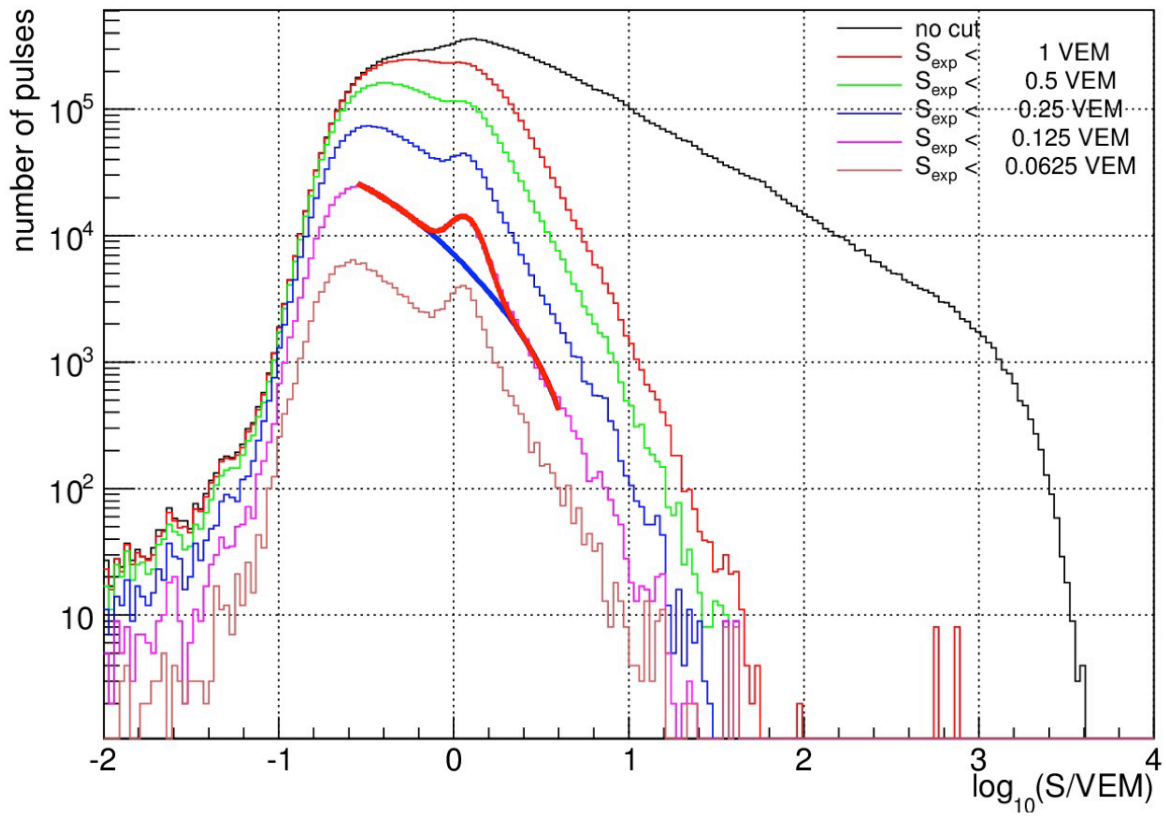
Surface muons in IceTop: the idea

Use the fact that we know very well the signal of muons in tanks from our calibration procedure.



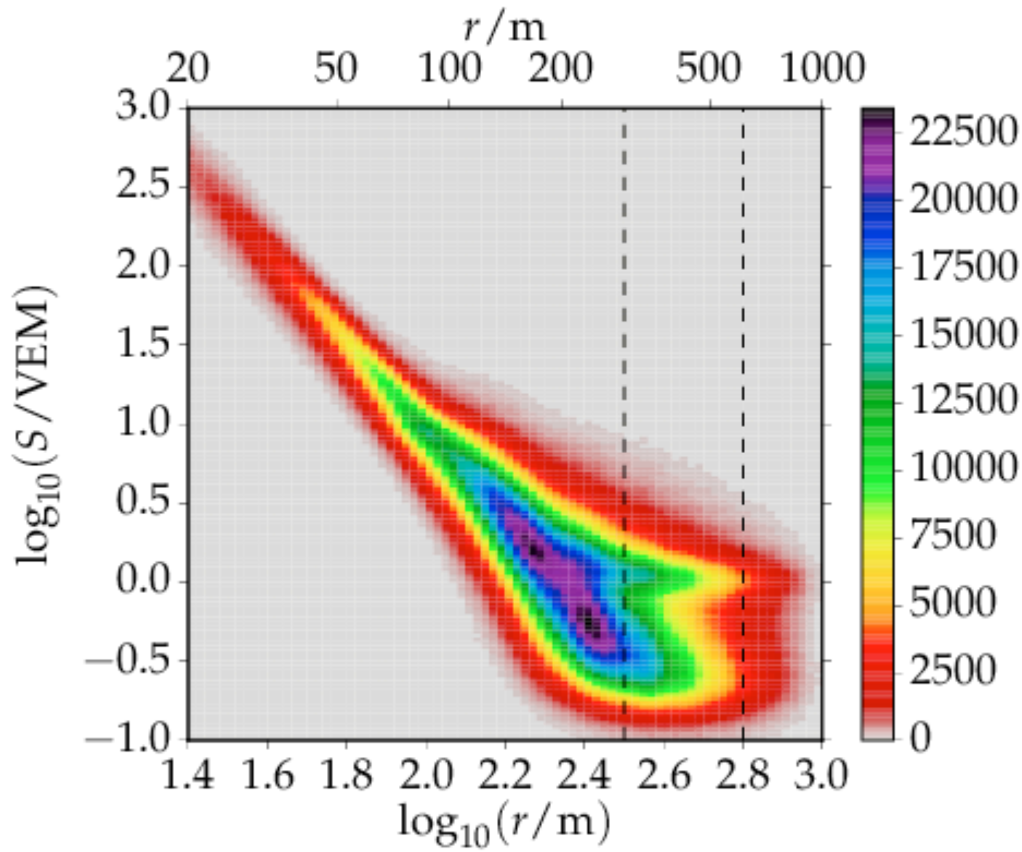
Calibration run for DOM 61-61 (ICRC 2011, arXiv:1111.2735, A van Overloop for IceCube

Look for the muon signal to appear in the periphery where the expected em signal is < 1 VEM



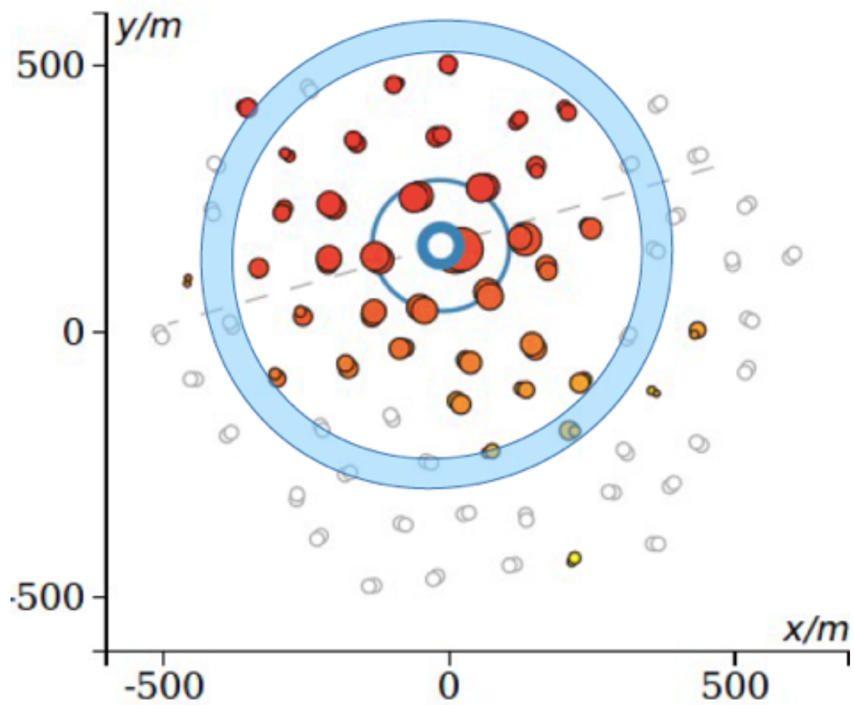
H. Kolanoski, for IceCube, ICRC Beijing, 2011

Implementation*



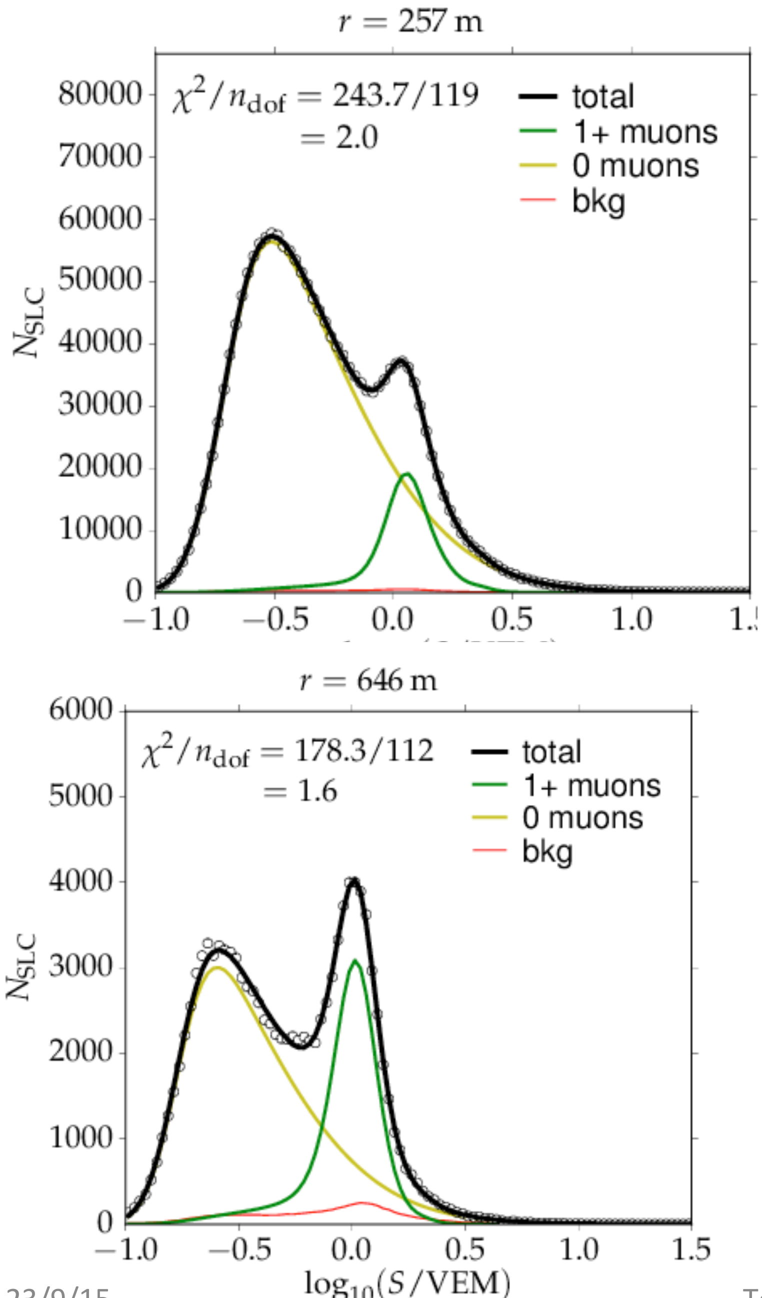
*Javier Gonzalez, ISVHECRI 2014 (arXiv:1501.03415)
Hans Dembinski, ICRC 2015

How the muon density is extracted

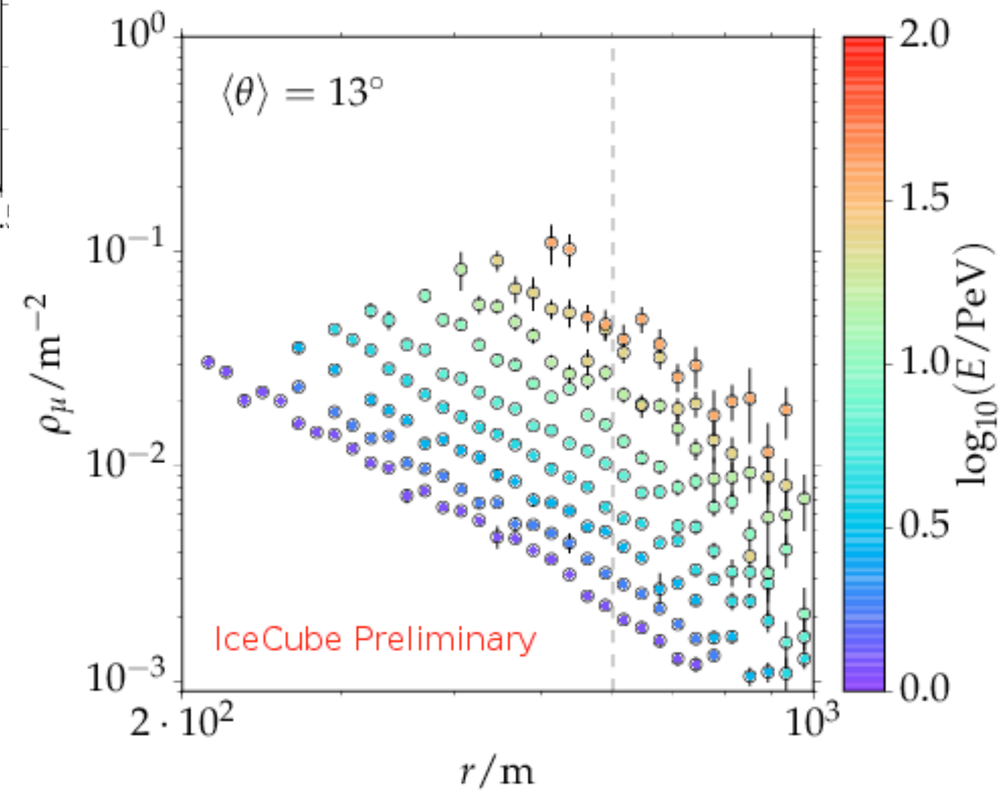


$$\rho_\mu \approx \frac{N_{\text{tanks in ring with }\mu}}{N_{\text{tanks in ring}}} \frac{1}{A_{\text{tank}}}$$

ρ_μ vs r & E



r = 257 m
χ²/n_dof = 243.7/119
= 2.0
total
1+ muons
0 muons
bkg
N_SLC
r = 646 m
χ²/n_dof = 178.3/112
= 1.6
log10(S/VEM)



⟨θ⟩ = 13°
IceCube Preliminary
ρ_μ/m^-2
r/m
log10(E/PeV)