IceTop
PeV Cosmic Rays at the South Pole

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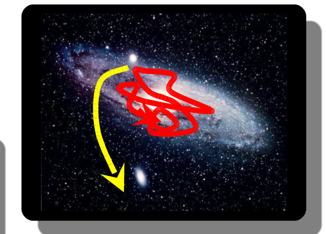
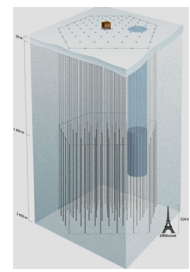
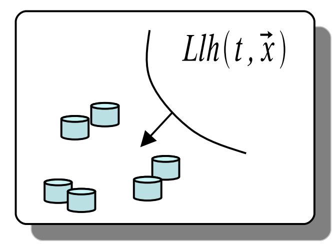
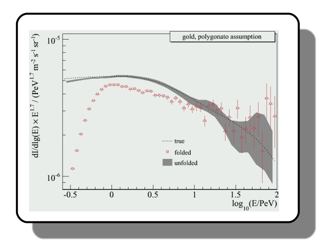
Outline

- **Prelude: Cosmic Ray Physics**
- **Extensive Air Showers**
- **IceTop and IceCube**
- **Air Shower Reconstruction**
- **Energy Assignment & Spectrum Deconvolution**

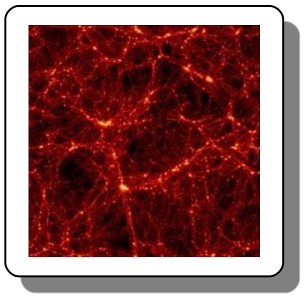


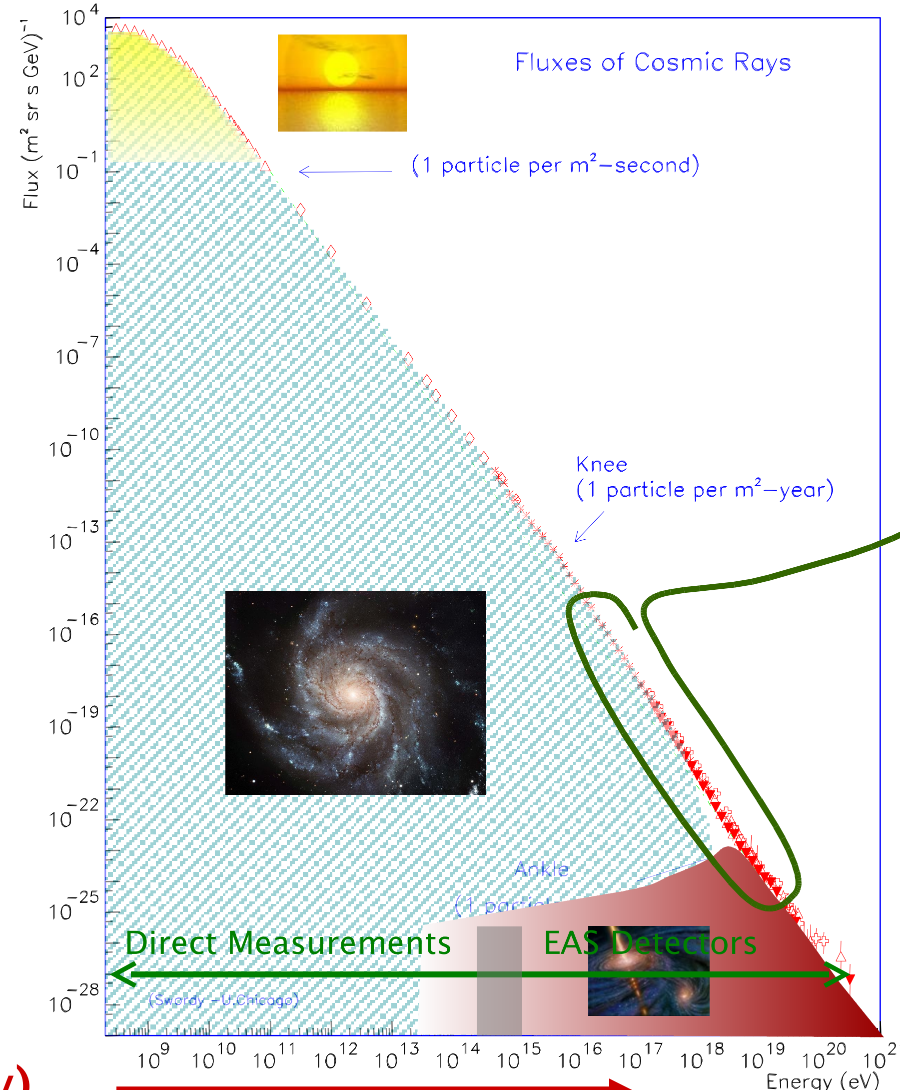


Cosmic Rays

solar physics



antimatter ratios
→ DM annih.

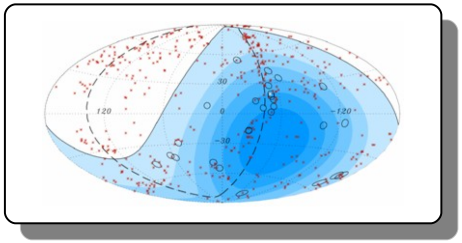


LHC (COG equiv)

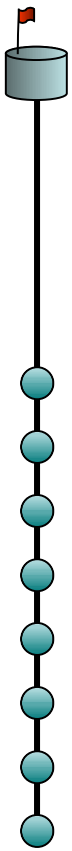
transition:

- only indirect (air shower) measurements
- important to understand

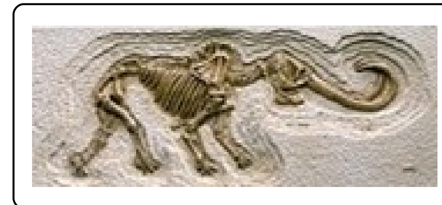
extragalactic point sources



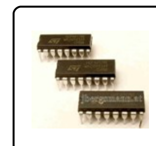
Galactic Cosmic Rays in Real Life



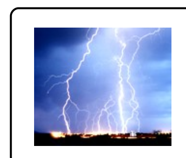
- Part of Natural Radiation (13%)



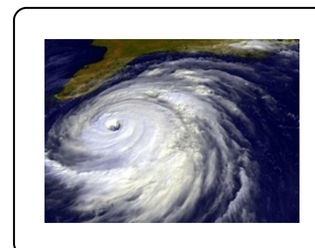
- Kept ^{14}C fraction on Earth constant (until the 1950s...)



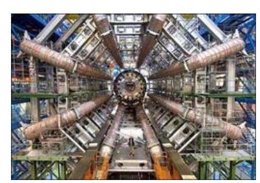
- Impact on electronic devices, increases with decreasing transistor size



- May be the trigger of lightnings



- Impact on climate change through cloud formation under discussion

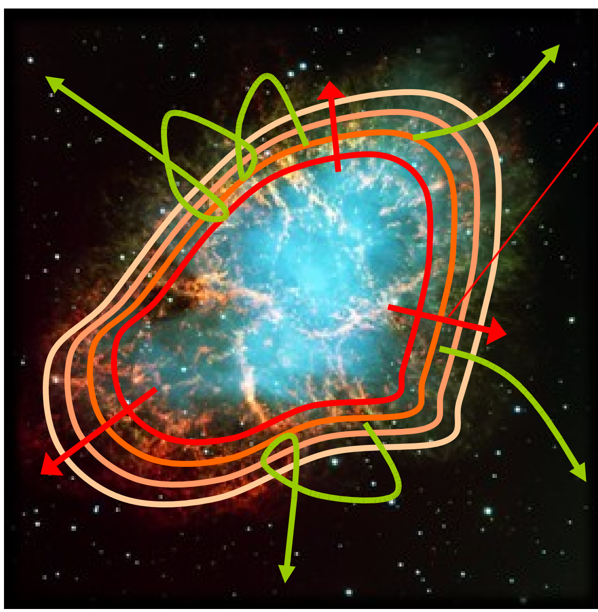


- Put down Killer-Black-Hole objections against LHC

Galactic Sources of CRs

- ~85% of visible matter is bound to stars
- Stars are most brutal when they die

→ CR believed to be from Supernovae and their remnants (SNR)



some 100 yr Shock front at ~0.1 c

→ Successive Acceleration

→ Fermi acceleration

→ $dI/dE \sim E^{-2.3}$

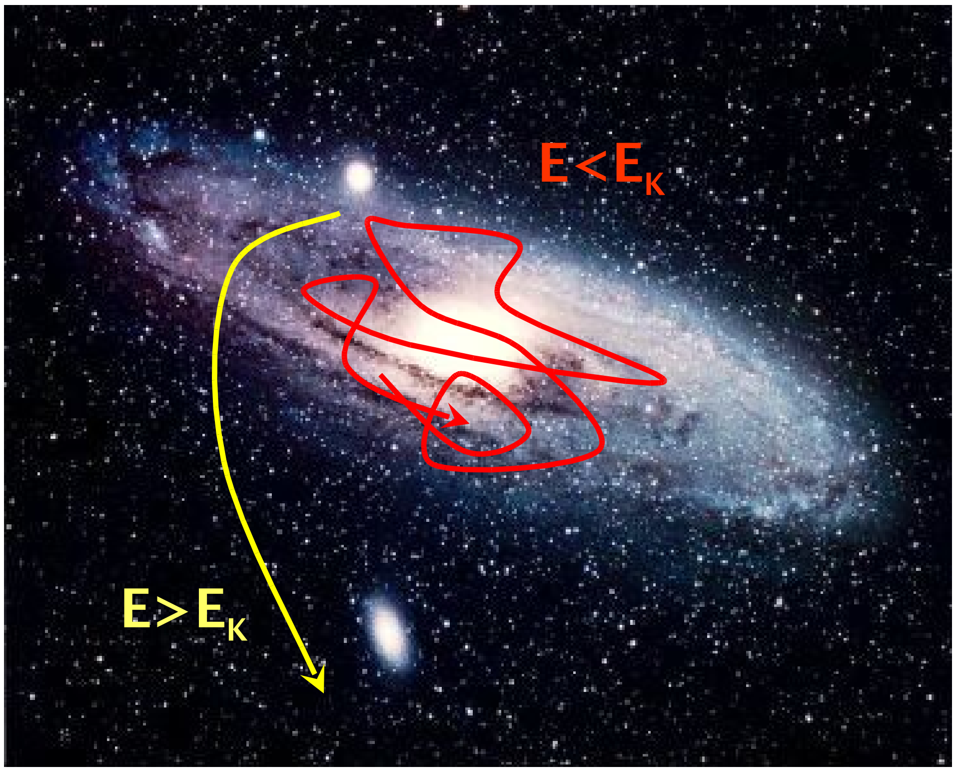
→ Absorption, Interaction

→ $dI/dE \sim E^{-2.7}$

Minor additional components from microquasars or other objects possible, but not needed.

The Knee – Upper End of Galactic CRs?

A simple knee model (leaky box):



Magnetic Fields O(μG) capture particles below knee energy

→ Rigidity-dependent knee?

$$\rho = p/ZeB = \mathbf{R}/cB$$

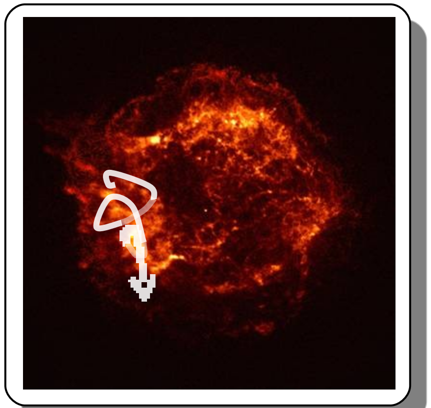
$$R_{Knee} = pc/Ze = \text{const.}$$

$$\rightarrow E_{Knee}(Z) = Z \cdot E_{Knee}(p)$$

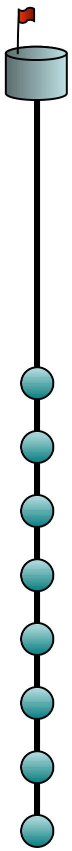
The Knee – Upper End of Galactic CRs?

- **Diffusion Equations** (leaky box 2.0)
  - Cosmic Rays = relativistic gas
  - Propagation equation describes spallation, decay, leakage, etc.
  - Also leads to Z-dependent knee

- **Upper Acceleration Limit of Galactic Sources?**
  - Local magnetic fields of SNR capture accelerated particles
  - $\rightarrow E_{knee}$ = local escape energy
  - $\rightarrow$ Z-dependent knee



Exotic Knee Models

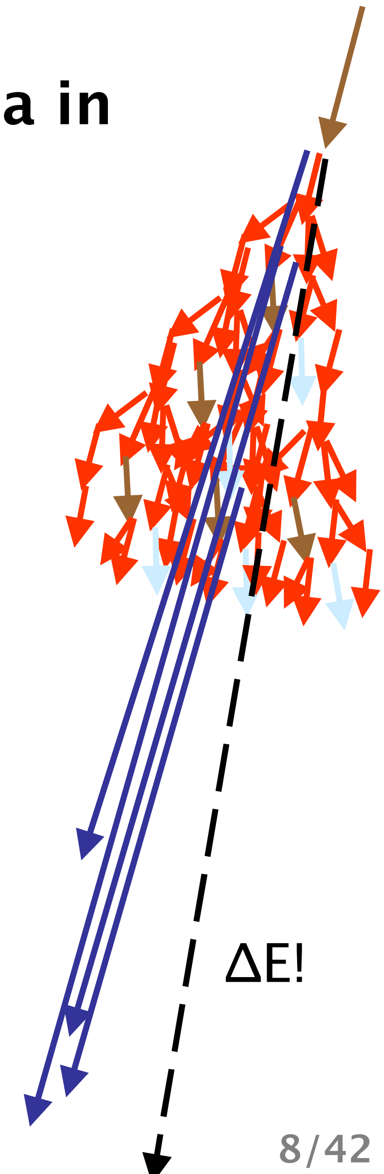


- **Knee = Effect of unexpected phenomena in the air shower production?**
- **Examples:**
  - Enhanced multi-hadron production
  - Production of undetected exotic particles

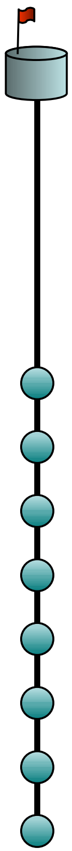
  → Undetected energy loss

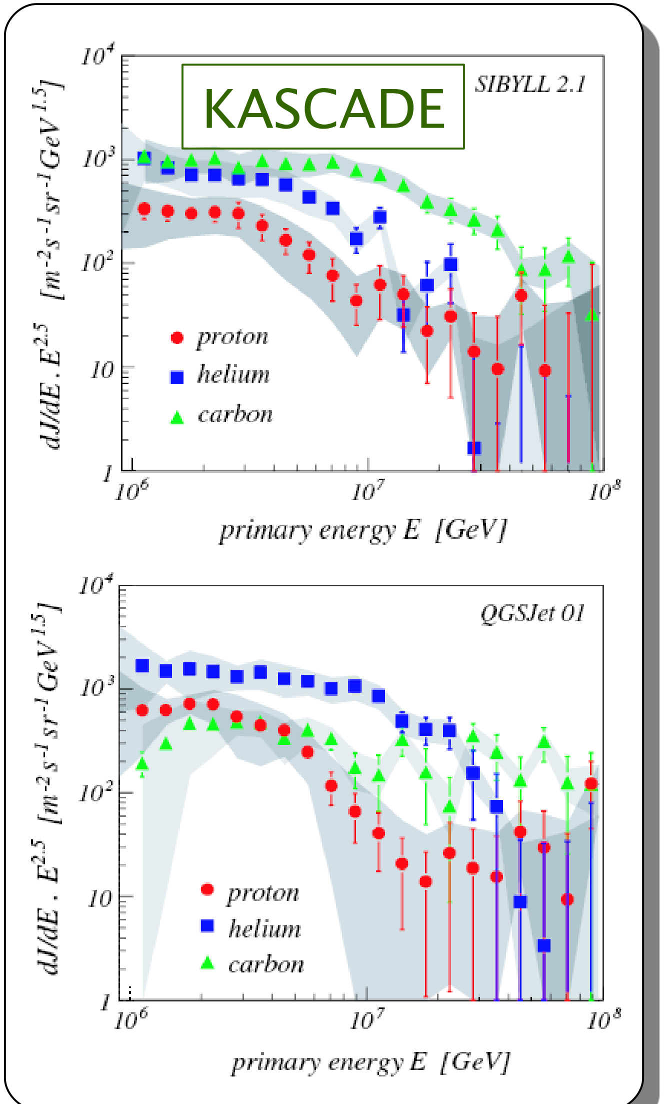
  → Wrong energy assignment
- **Production rates scale with A**

  → A-dependent knee position!

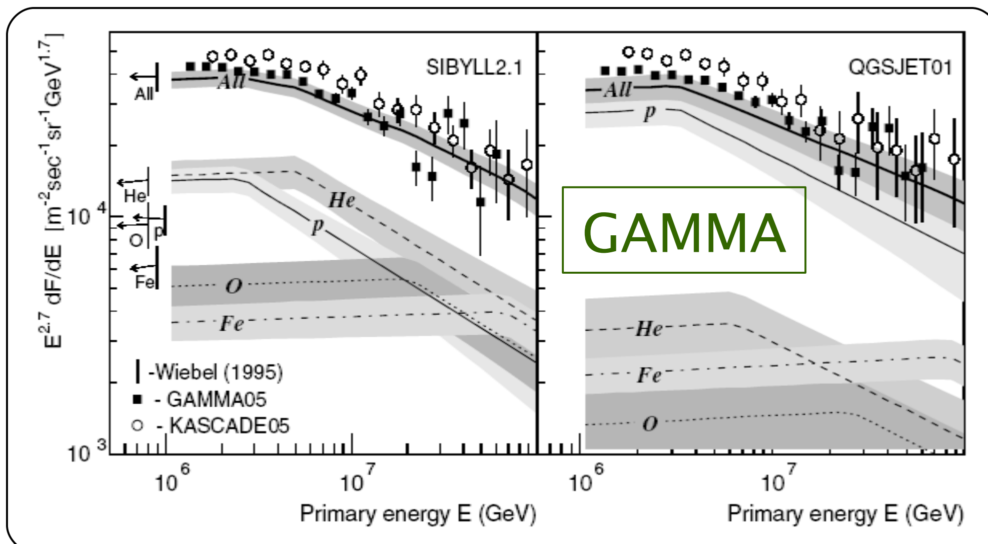


Present Data

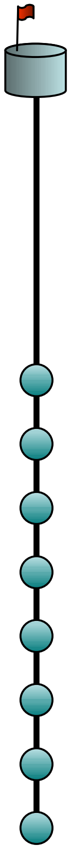




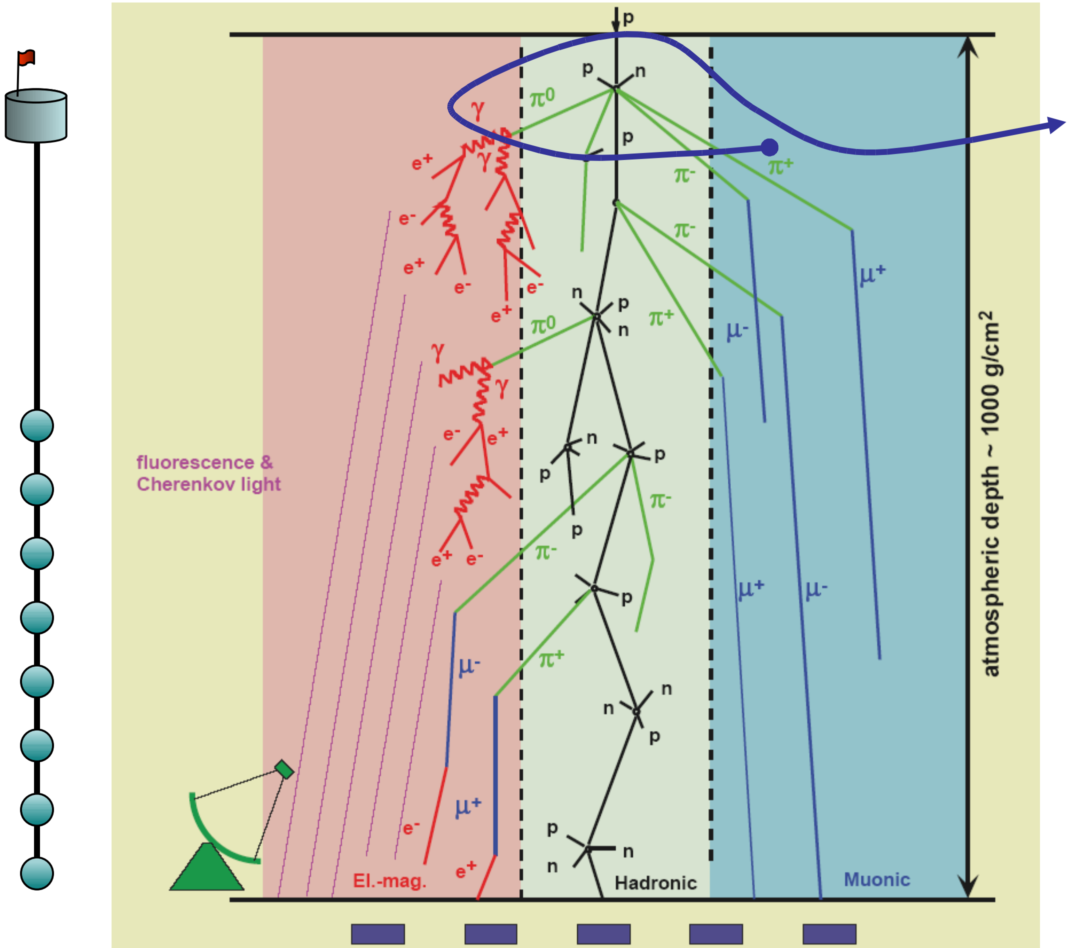
- **Published spectra indicate or support Z-dependent knee**
- **Still: Large systematic uncertainties**
- **Indications of increasing mean mass from most other experiments**



Capturing PeV Cosmic Rays: Extensive Air Showers



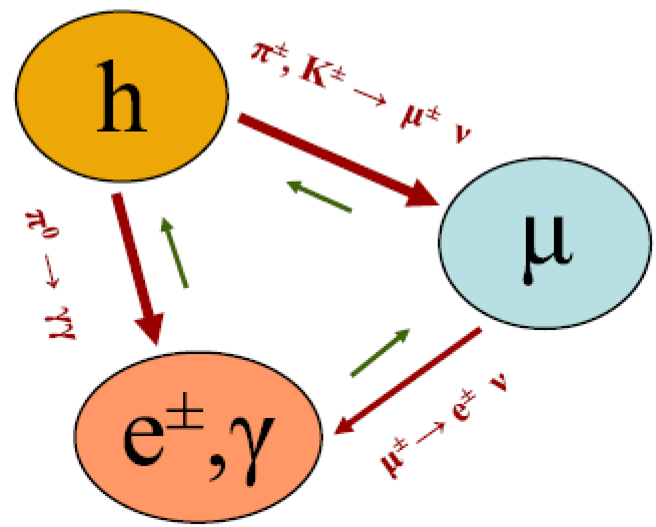
Extensive Air Showers



@ 1 PeV: O(10^6) particles

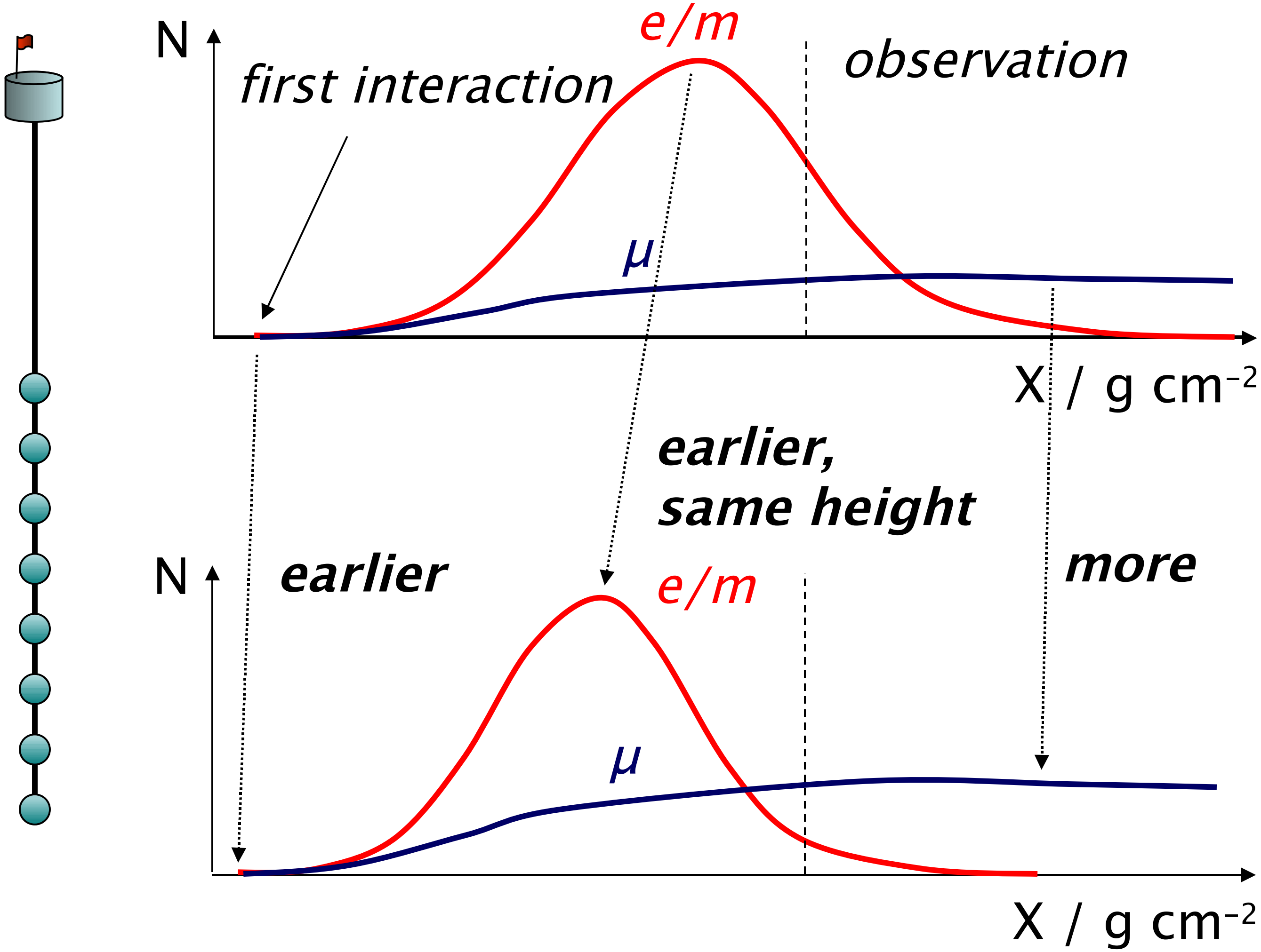
π Decay/Interaction Ratio
→ μ rate ↔ Atm. Pressure

Energy flow:



only way to access CR above some 100 TeV

Shower Development for Different Nuclei



proton

X = atmospheric depth
= column depth
= trav. mass integral

heavier nucleus

(same E/nucleus)

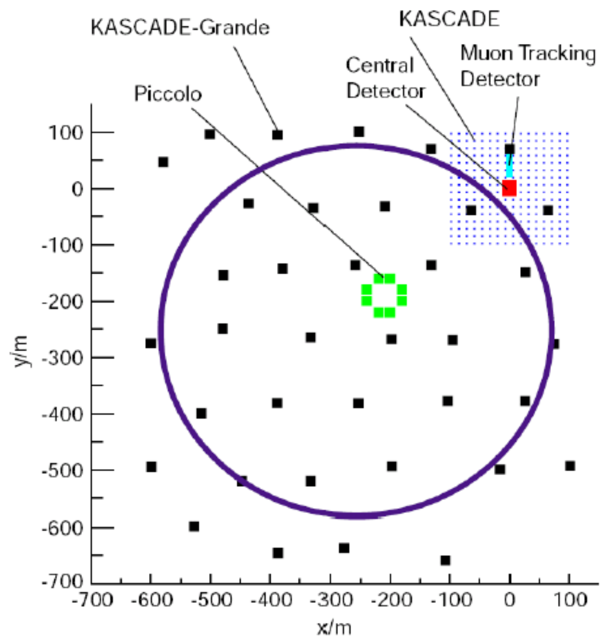
- earlier maximum
- more muons

Differences between Experiments

- **Size** (→ energy regime)
- **Altitude**
  (→ shower stage, i.e. muon ratio, model dependency)
- **Detector Type**
  - Scintillator
  - Cherenkov tanks
  - Cherenkov telescope
  - Muon detectors
- **Measured shower component(s)**
  - e/m
  - muon (high or low energy, high or low transverse momentum)
- **Analysis Techniques**

→ **Large systematics need orthogonal approaches!**

Some Experiments I
KASCADE-Grande



Multi-Component Detector:

- scintillators (137m grid size)
- some muon detectors
- one hadron calorimeter

→ high sophistication

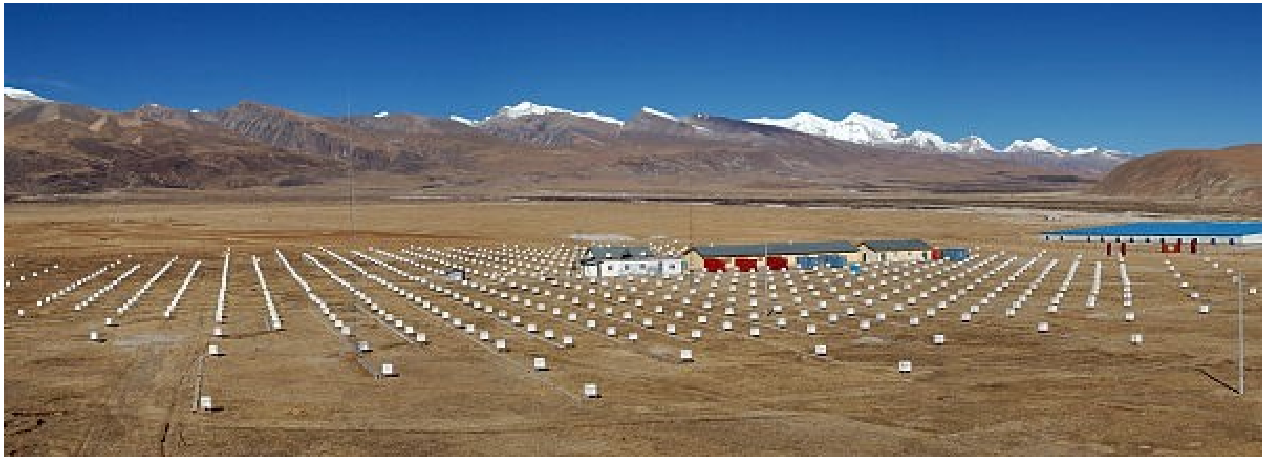
Almost Sea level (115 m)

→ late shower stage

→ large muon fraction

→ strong model dependency

Some Experiments II
Tibet-III



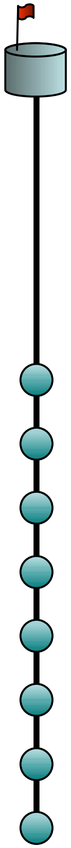
- **Scintillator array**
- **Very dense (7.5 m grid size)**
- **Very high (4300 m)**
  - → e/m dominated showers
  - → Low model dependency
- **Surface-Only**
  - → No muon measurement
  - → Composition hardly accessible
- **Upgrade expected soon**

} down to ~ 100 TeV !

Some Experiments III
TUNKA (near Lake Baikal)

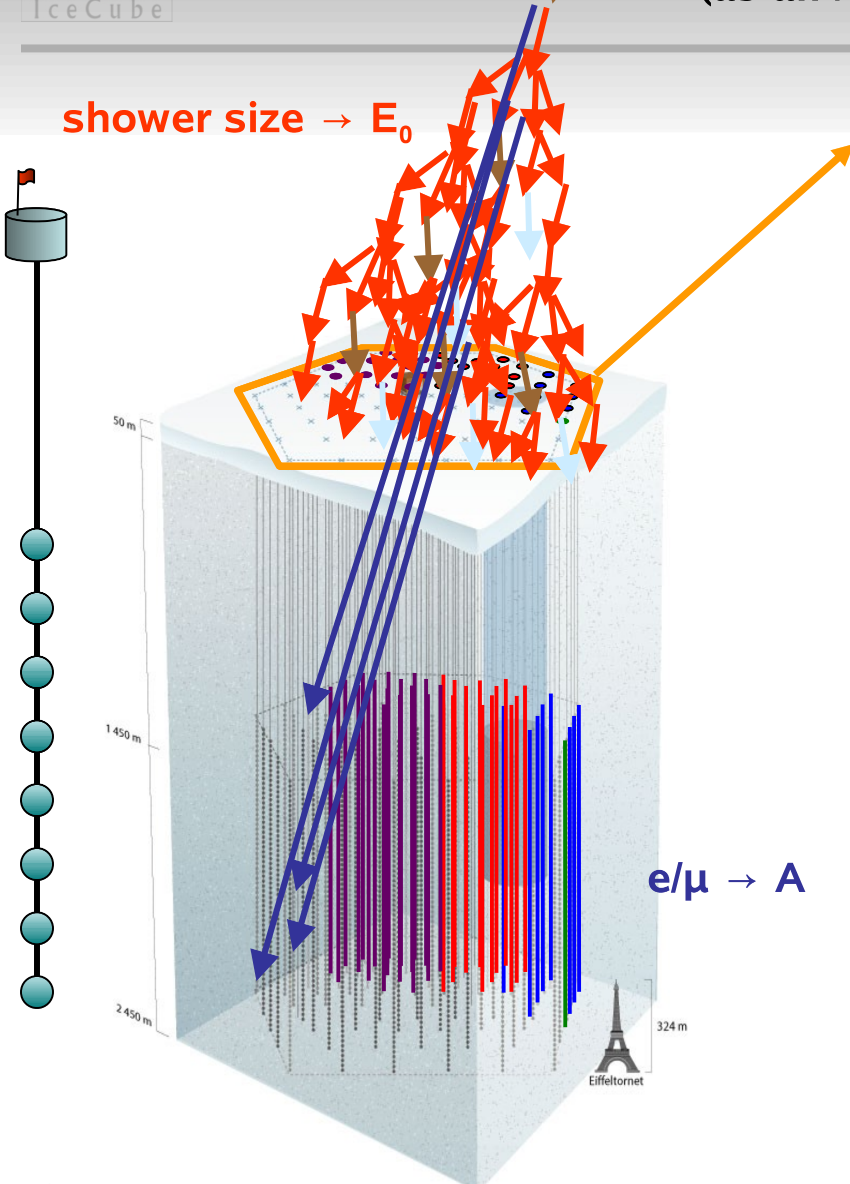
- **Cherenkov Detectors (85 m grid size)**
  - measuring e/m component in the air
- **Medium Altitude (675m)**
- **Mean mass evolution from depth of shower maximum**
  → complementary approach
- **Tunka-133 is being built**

IceTop/IceCube



The IceCube Observatory

(as an Air Shower Detector)



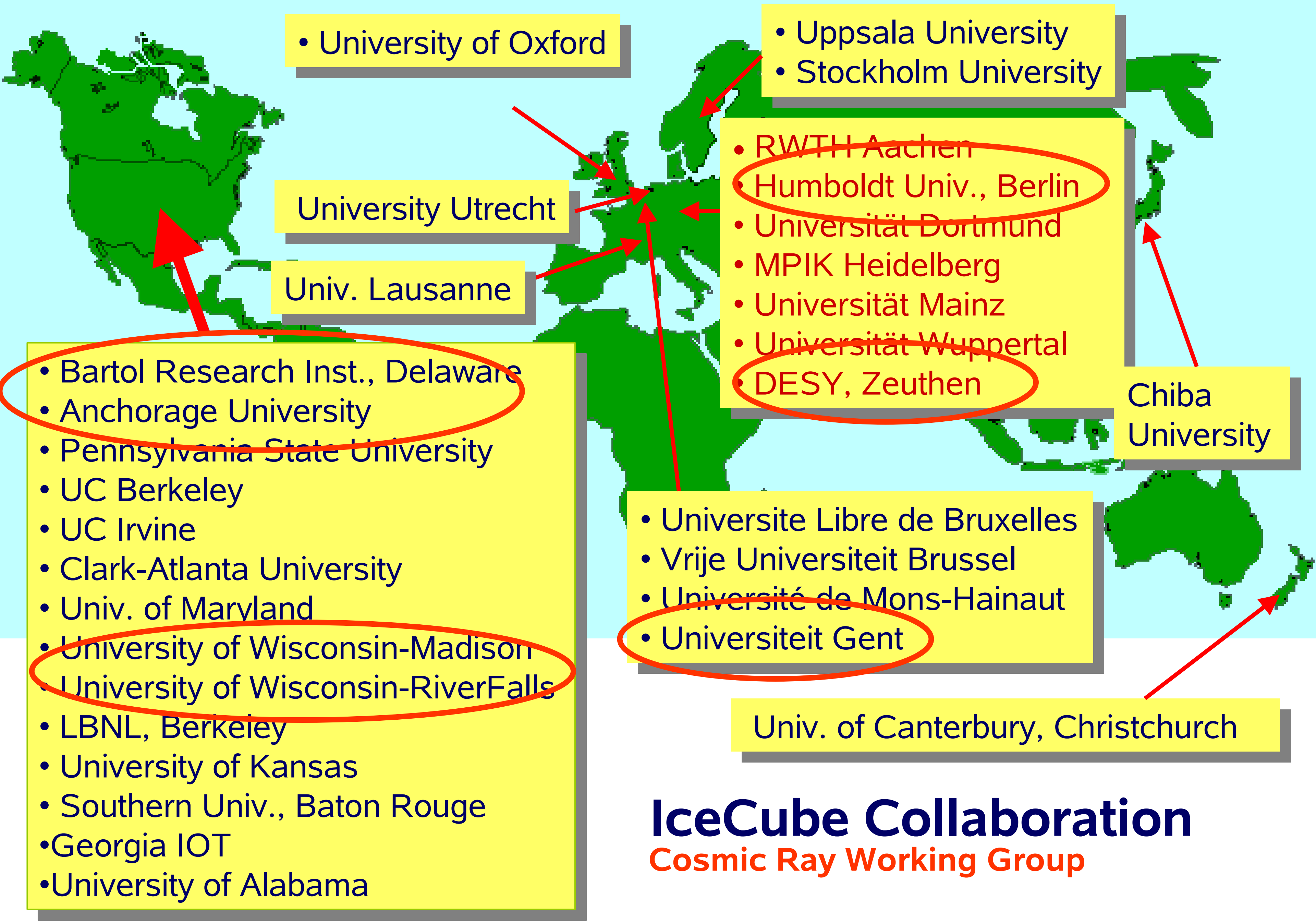
IceTop → Shower Detection

- 80 Stations à 2 Ice–Č–Tanks (40 in 2008!)
- 2830 m altitude
- 125 m spacing
- $3 \cdot 10^{14} < E < 10^{18}$ eV
- $A_{tot} \sim 1\ km^2$

IceCu

-
- 4800 DOMs
- Muon bundle detector
- $E_{muon} >$ TeV
- Neutrino Astronomy

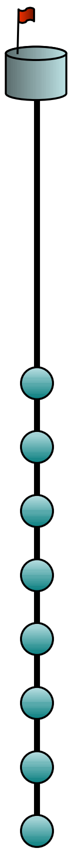
Most Important Special Feature of IceTop

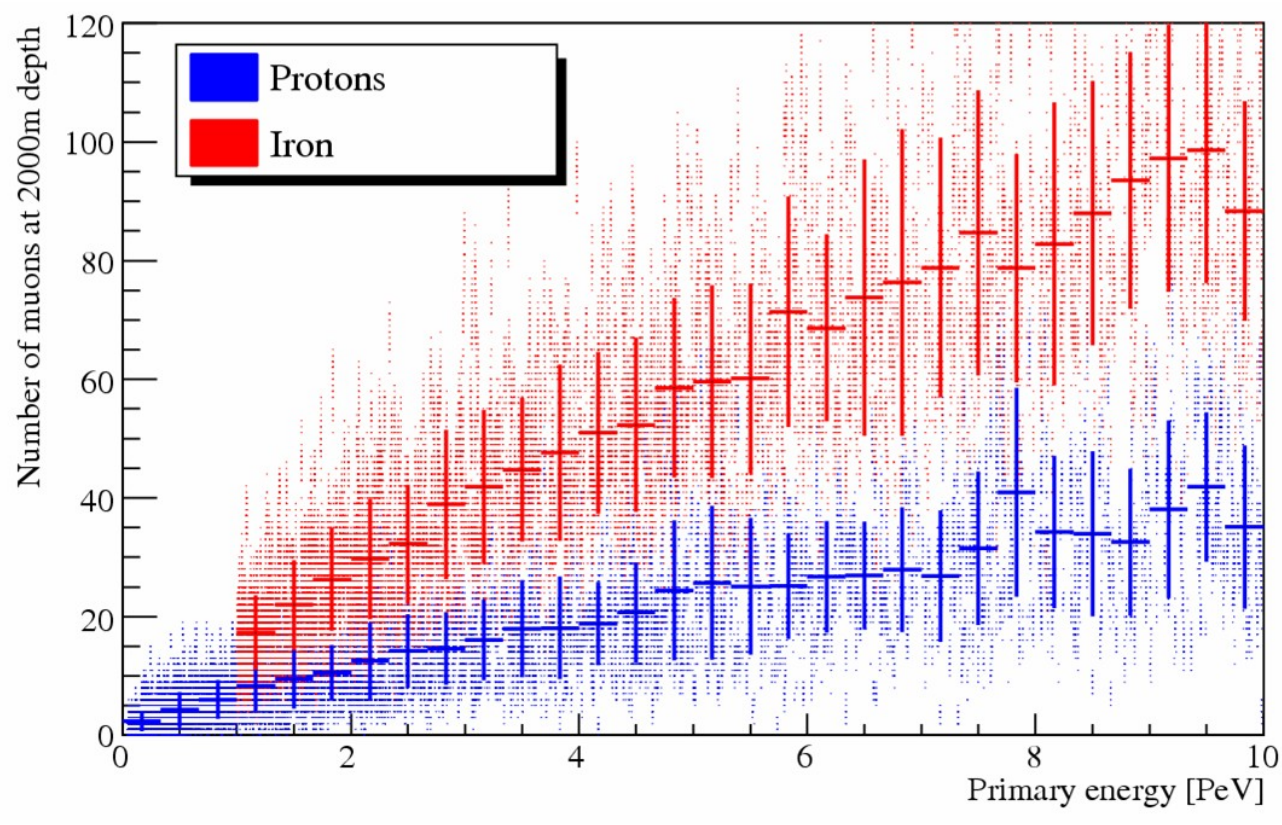


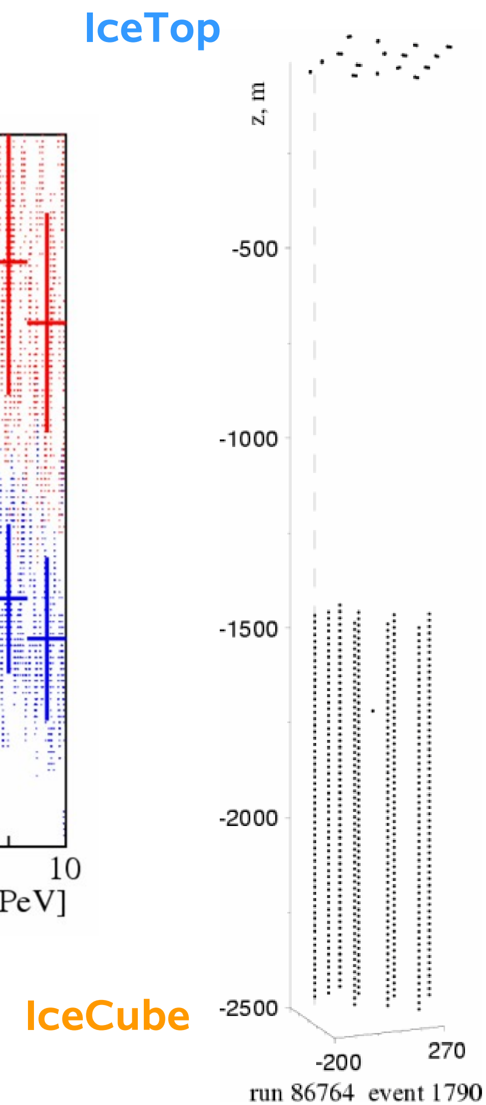
IceCube Collaboration

Cosmic Ray Working Group

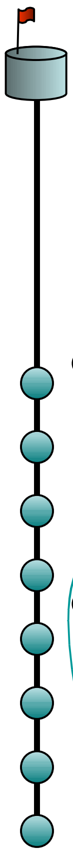
IceTop/IceCube



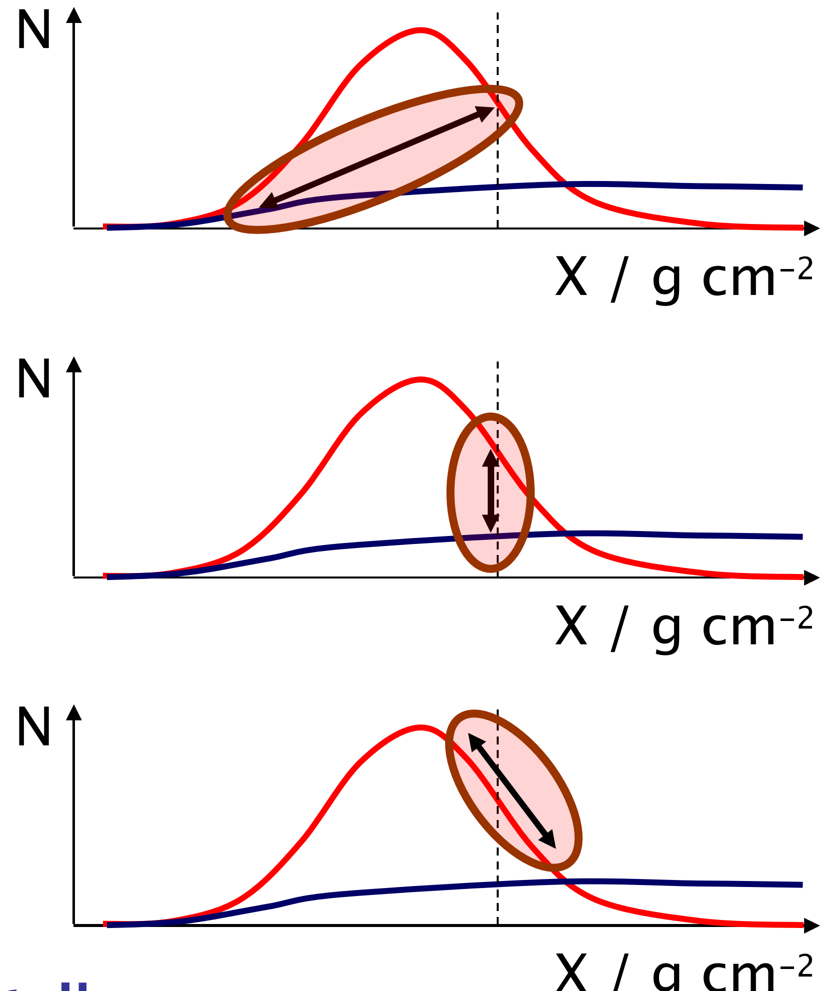




IceTop Strategies to Unravel CR Composition



- **Coincident Analysis, measuring e/m vs. high energy (early interaction) muons**
- **Single (low energy) muon counting at high radii**
- **IceTop-only analysis, measuring e/m component vs. zenith angle**

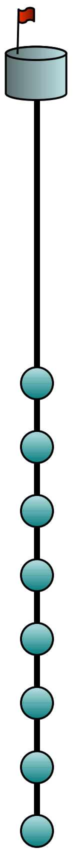


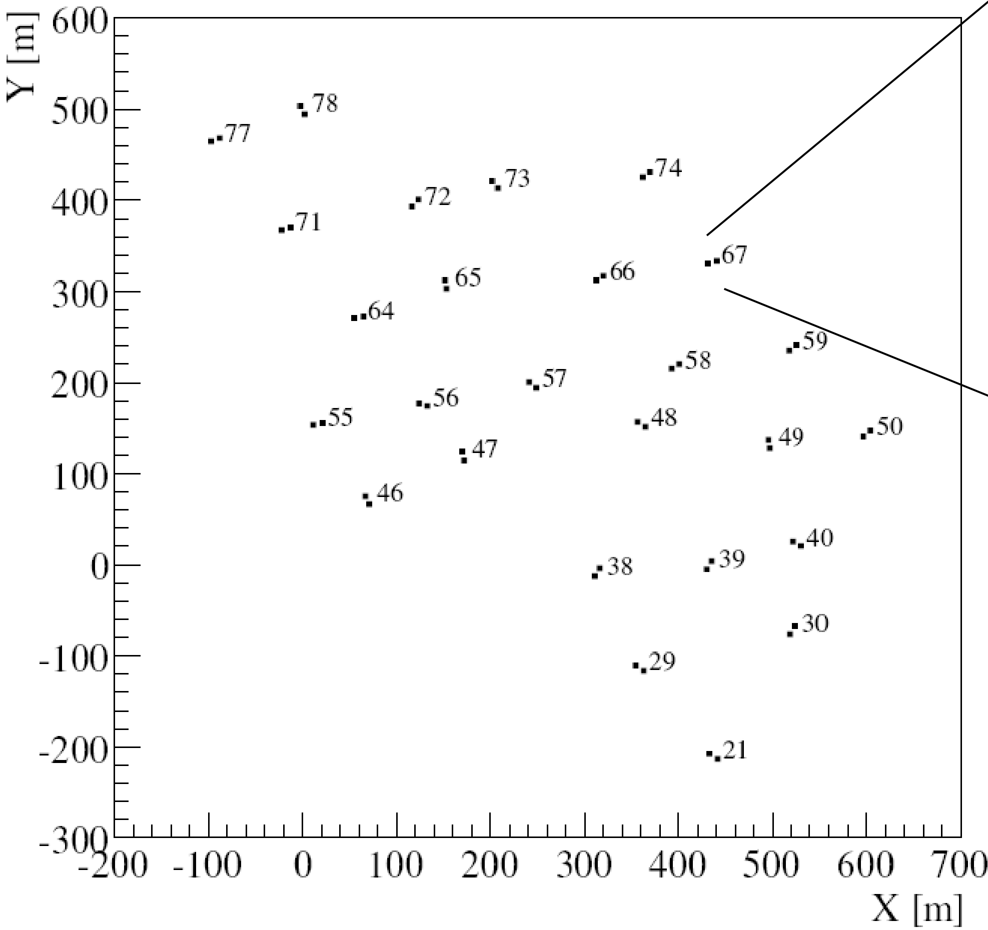
first shot → this talk

IceTop Detector Array 2007

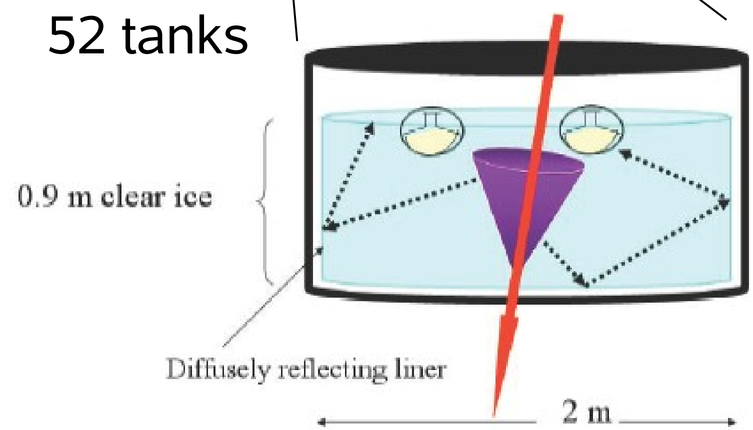
(setup of present analysis)

26 stations

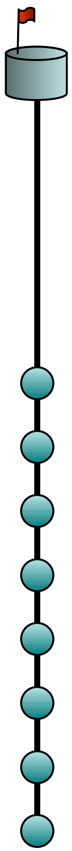


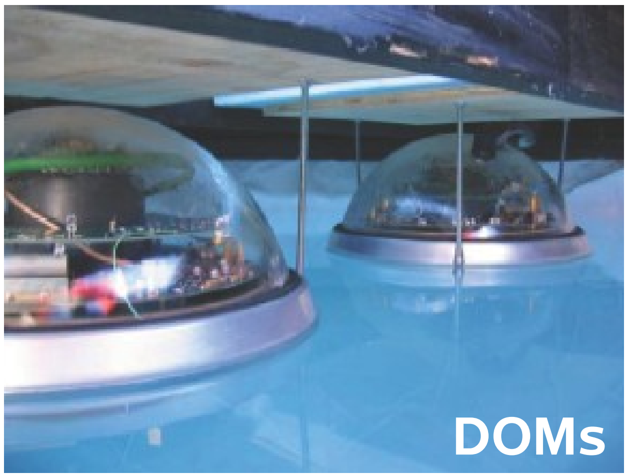


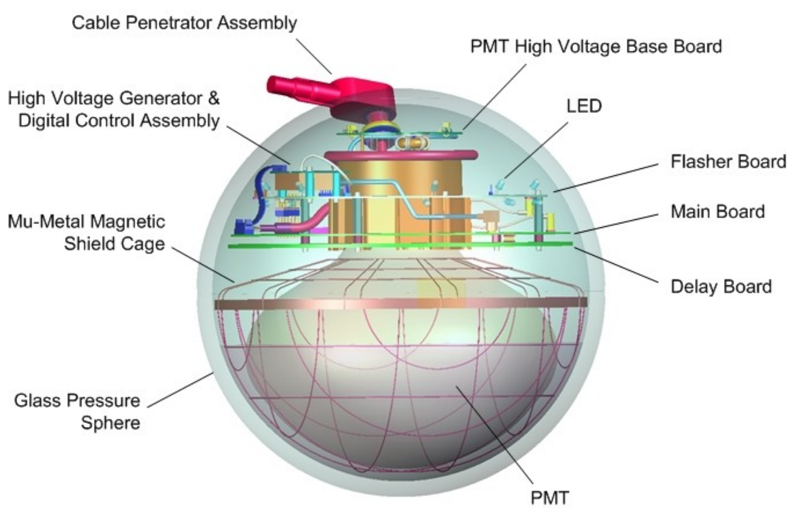
52 tanks

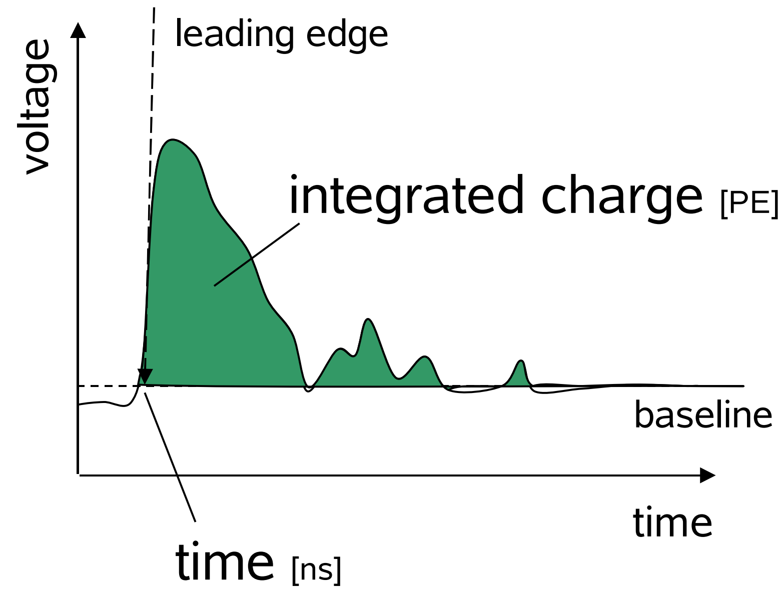


IceTop Signal Recording

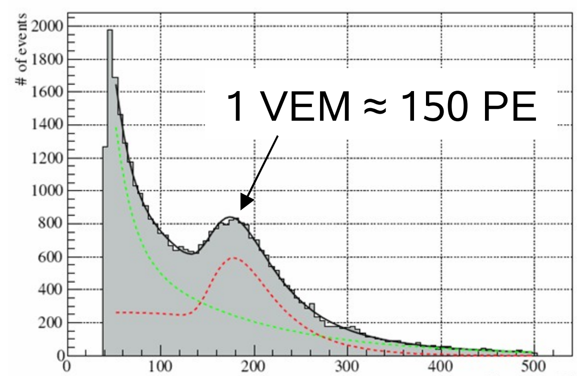








Finally: conversion to
Vertical **E**quivalent **M**uons



VEM plot from untriggered calibration run

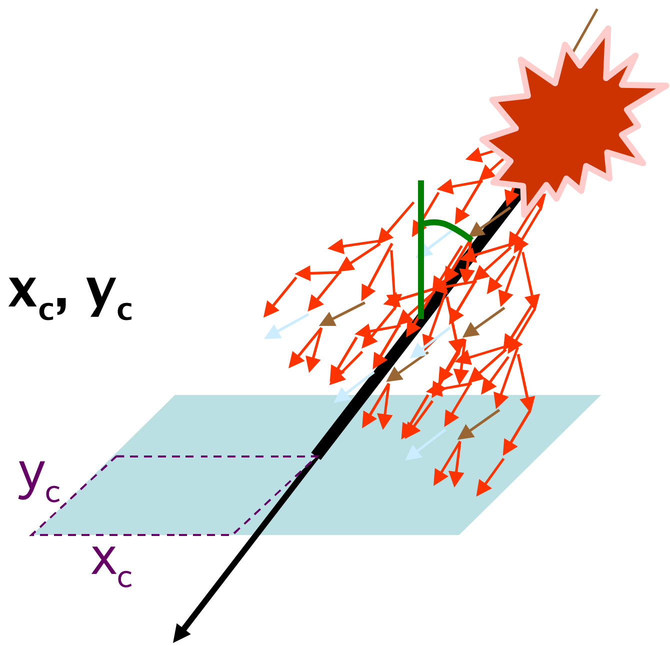
Air Shower Reconstruction

Each event = set of $(\vec{x}, q, t)$

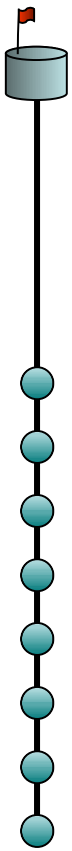
Reconstruction = making physical quantities out of this

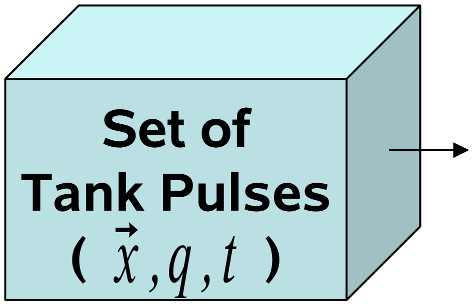
Wanted variables:

- **Shower Direction: θ, φ**
- **Shower Centre (in the array plane): x_c, y_c**
- **Primary Energy: E_0**
- **(Shower Age: a, not needed here)**



IceTop Shower Reconstruction

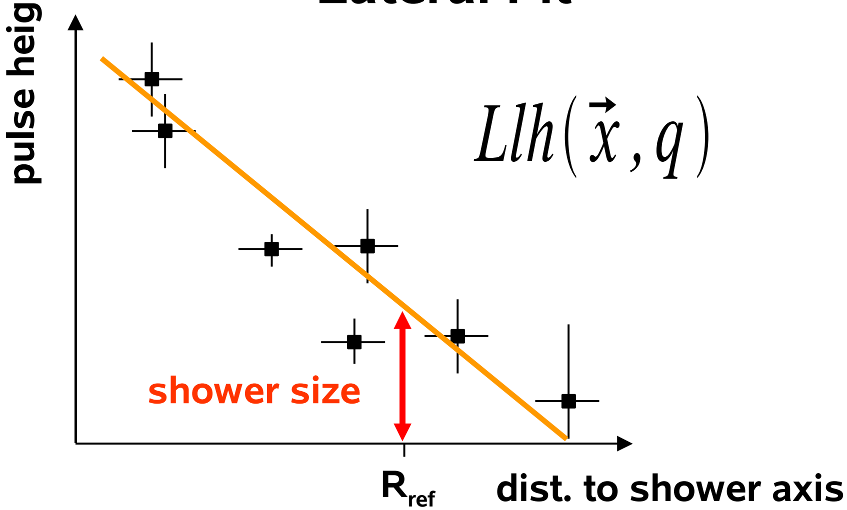




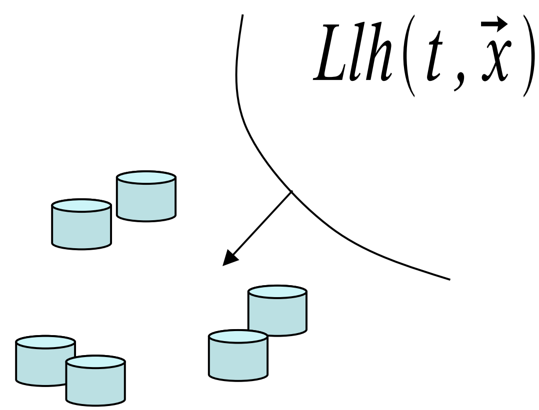
$\vec{x}, t \leftrightarrow$ direction

$\vec{x}, q \leftrightarrow$ core, shower size ($\rightarrow E_0$)

Core & Shower Size Log-Llh:
Lateral Fit

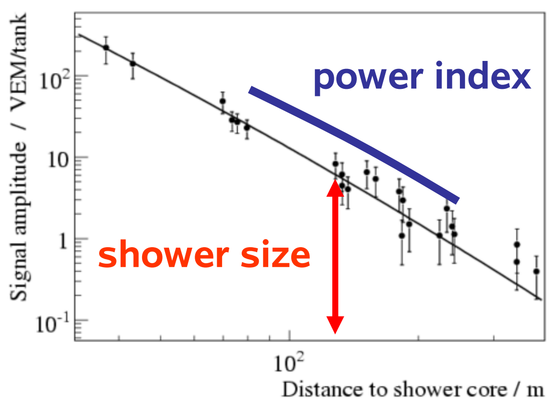


Shower Front Llh-Fit:



Pulse Height Probability Density Function

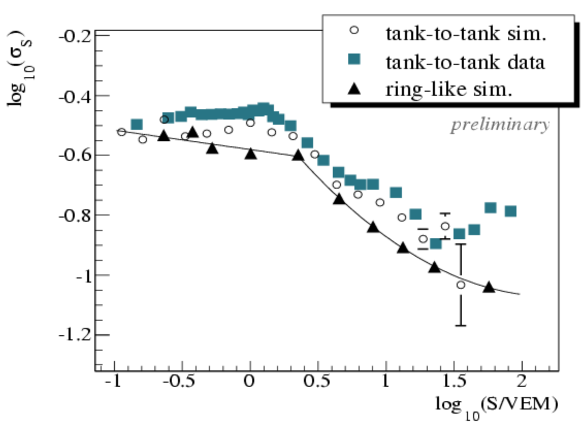
- **Expectation Value: Lateral Distribution Function**



$$S(R) = S_{R_0}\left(\frac{R}{R_0}\right)^{-\beta-\kappa\log_{10}\left(\frac{R}{R_0}\right)}$$

- Charge expectation in dependence of distance to shower axis
- Made at DESY (as everything that follows)

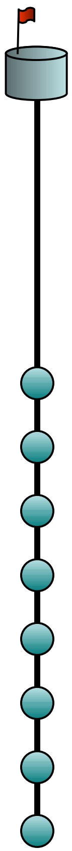
- **Fluctuations from that:**

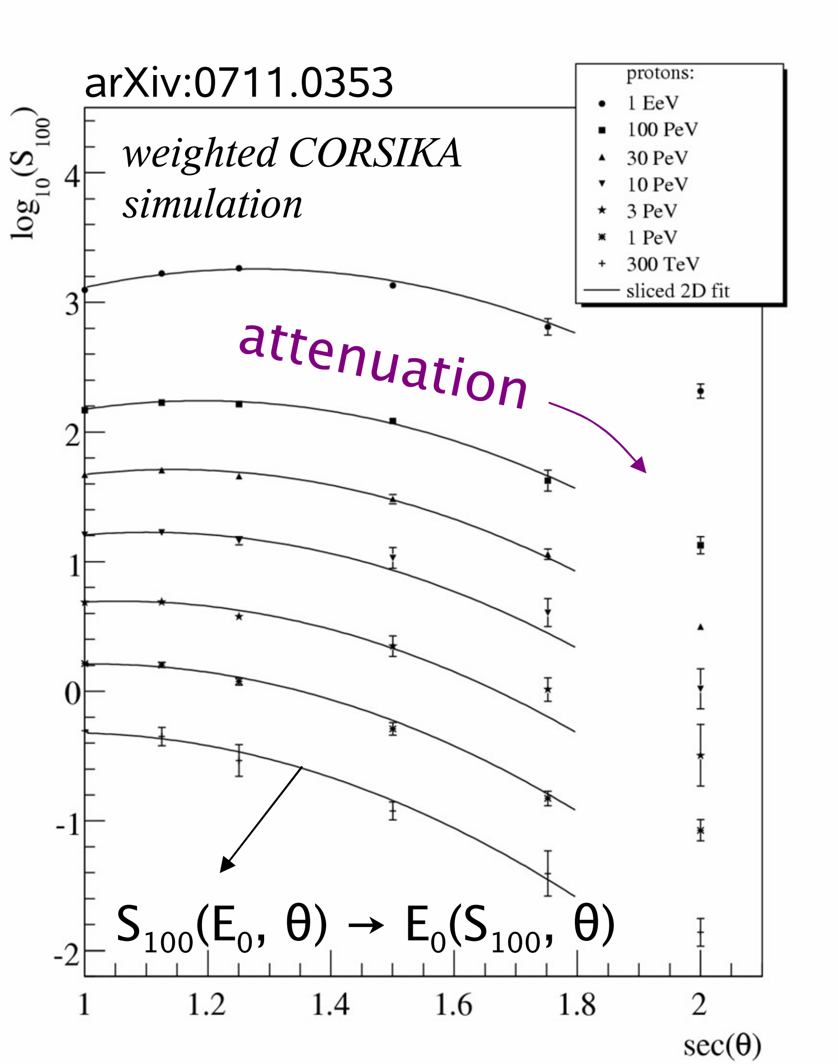


- Parametrised in dependence on S

arXiv:0711.0353

Energy Estimator

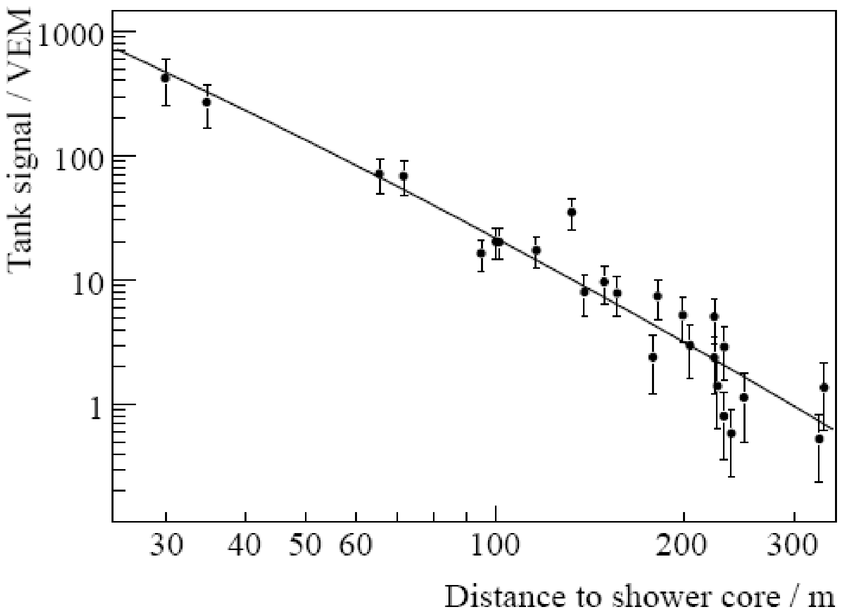




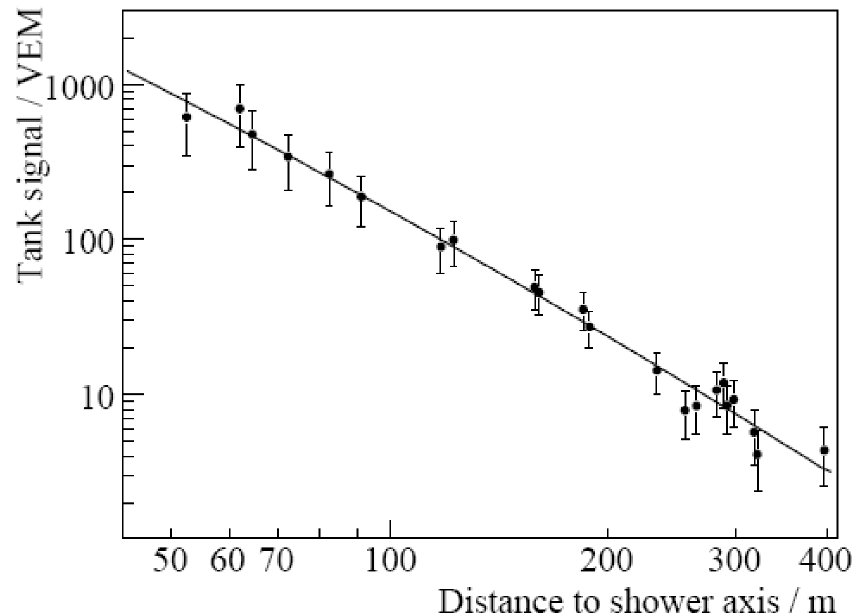
- **Analytical function for event-by-event energy estimator**
- **shower size almost proportional to energy**
- **assuming primaries were protons**

Example Lateral Fits

E_0 = 12.4 PeV

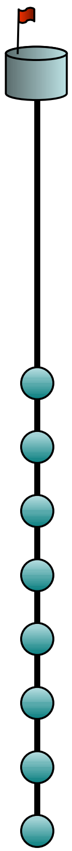


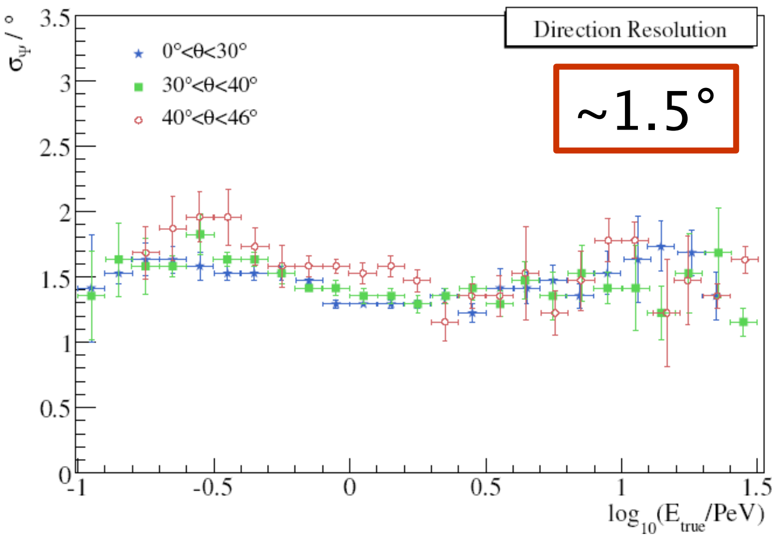
E_0 = 110 PeV

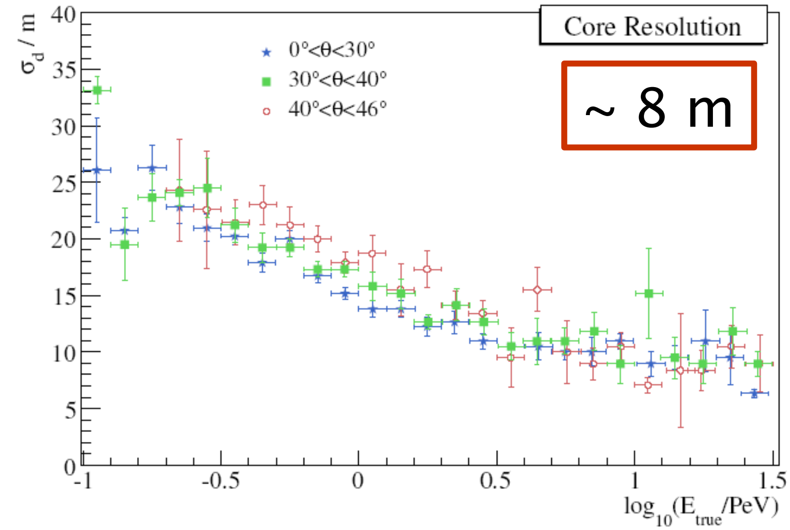


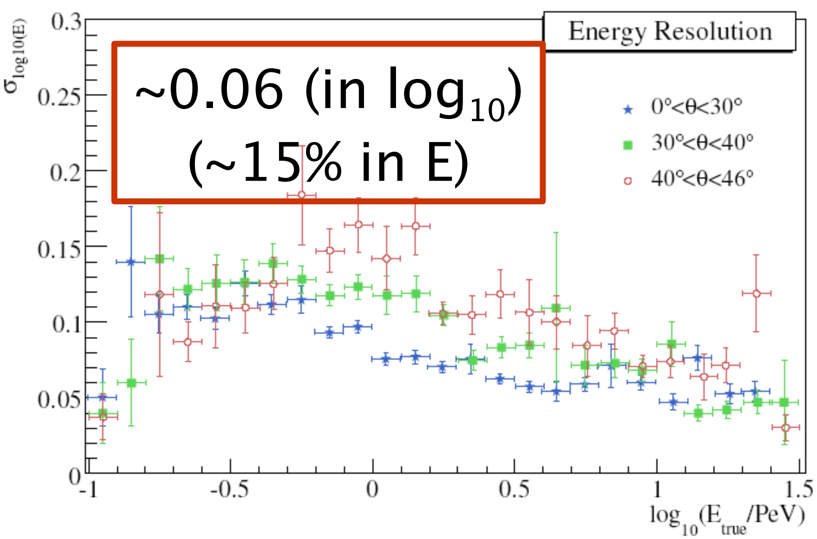
R_0 = 100m because of numerical stability (mean $\log_{10} R_{signal}$ for all events ≈ 2)

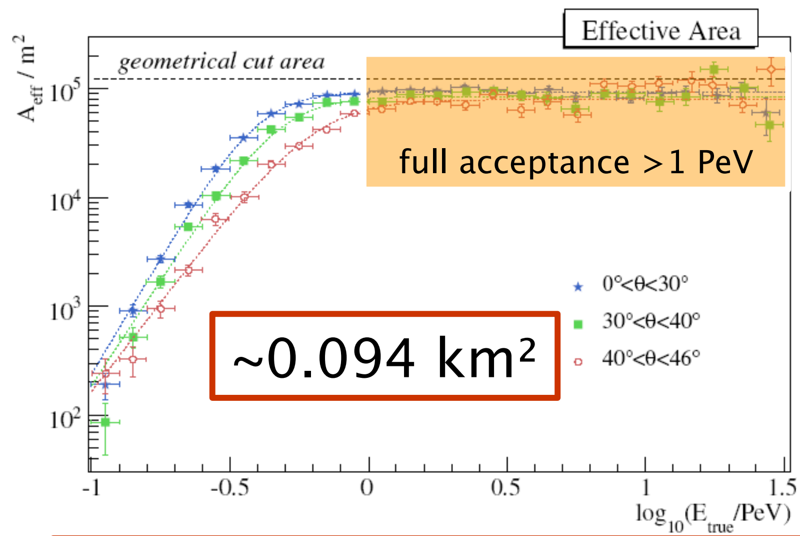
Resolution & Efficiency





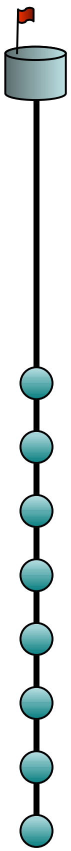






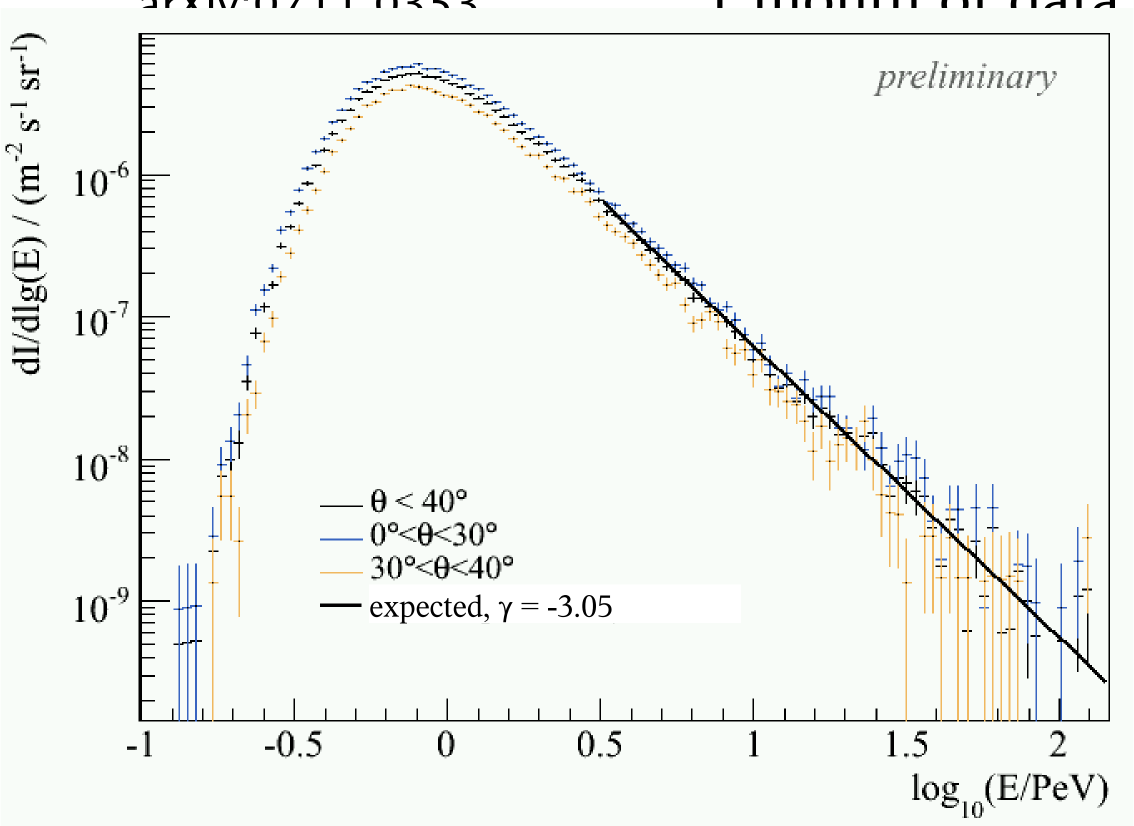
numbers for the 0°–30° zenith range only!

First Energy Spectrum Analysis



Uncorrected Energy Distribution

arXiv:0711.0353 1 month of data



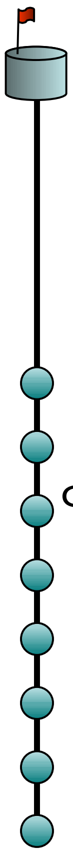
- energy extracted assuming primary was proton

→ good approximate agreements with expectation of ...

  - spectral index
  - absolute scale
  - different angular bins

→ but of course: needs response correction

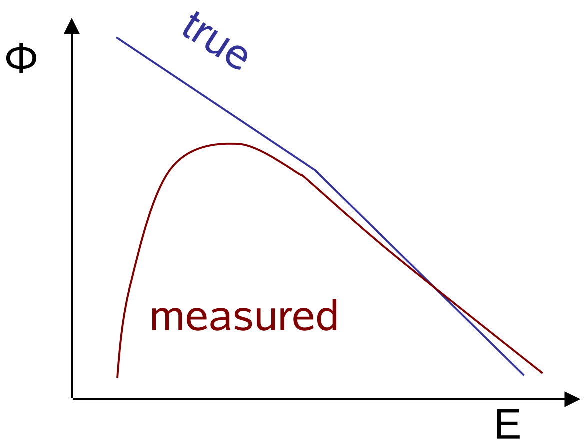
Problem (for IceTop-only Analysis): Composition Dependency

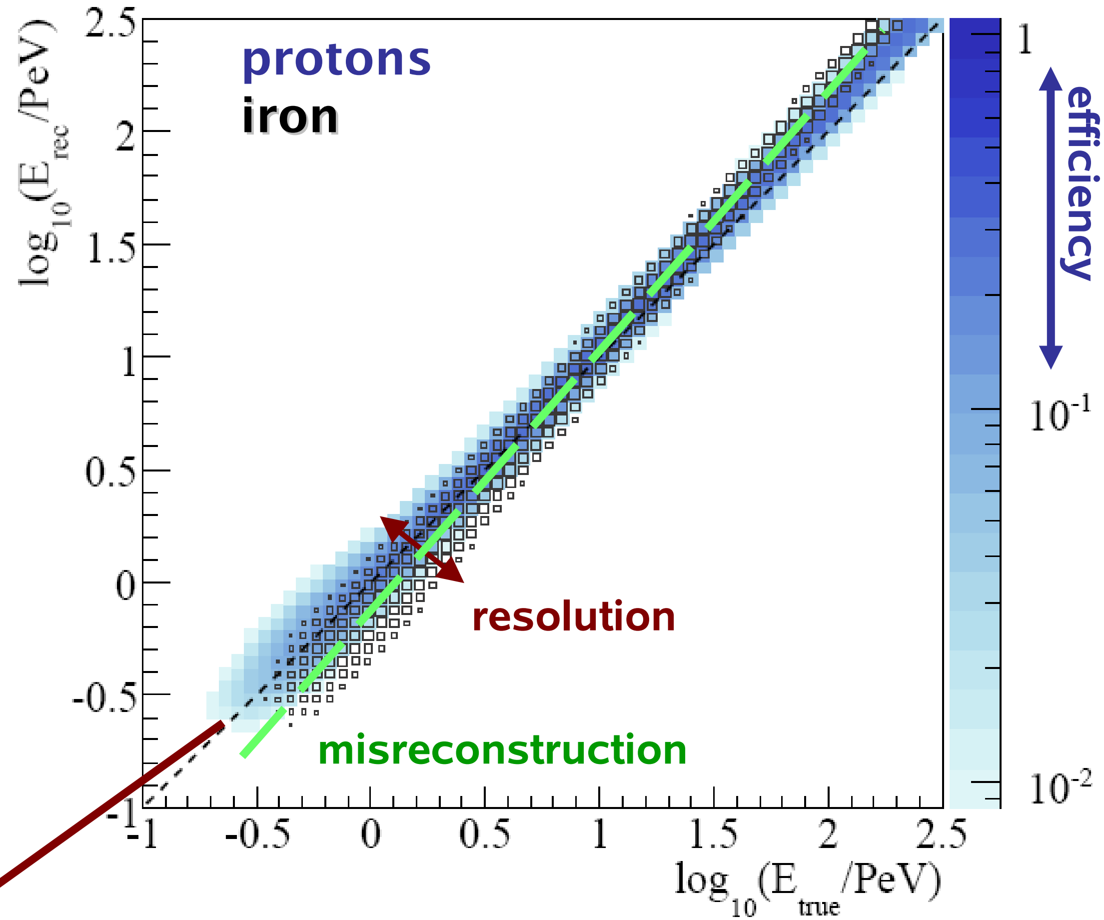


Convolution:

$$\vec{F} = \mathrm{R}\vec{C}$$

measured — true

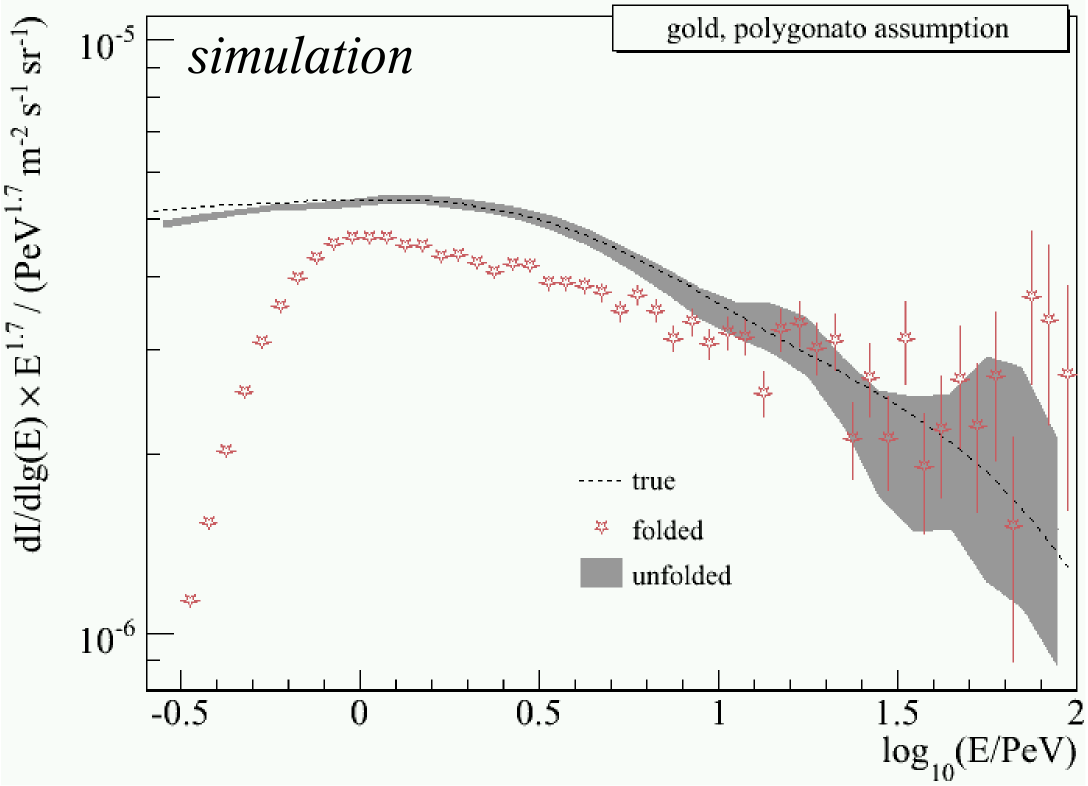




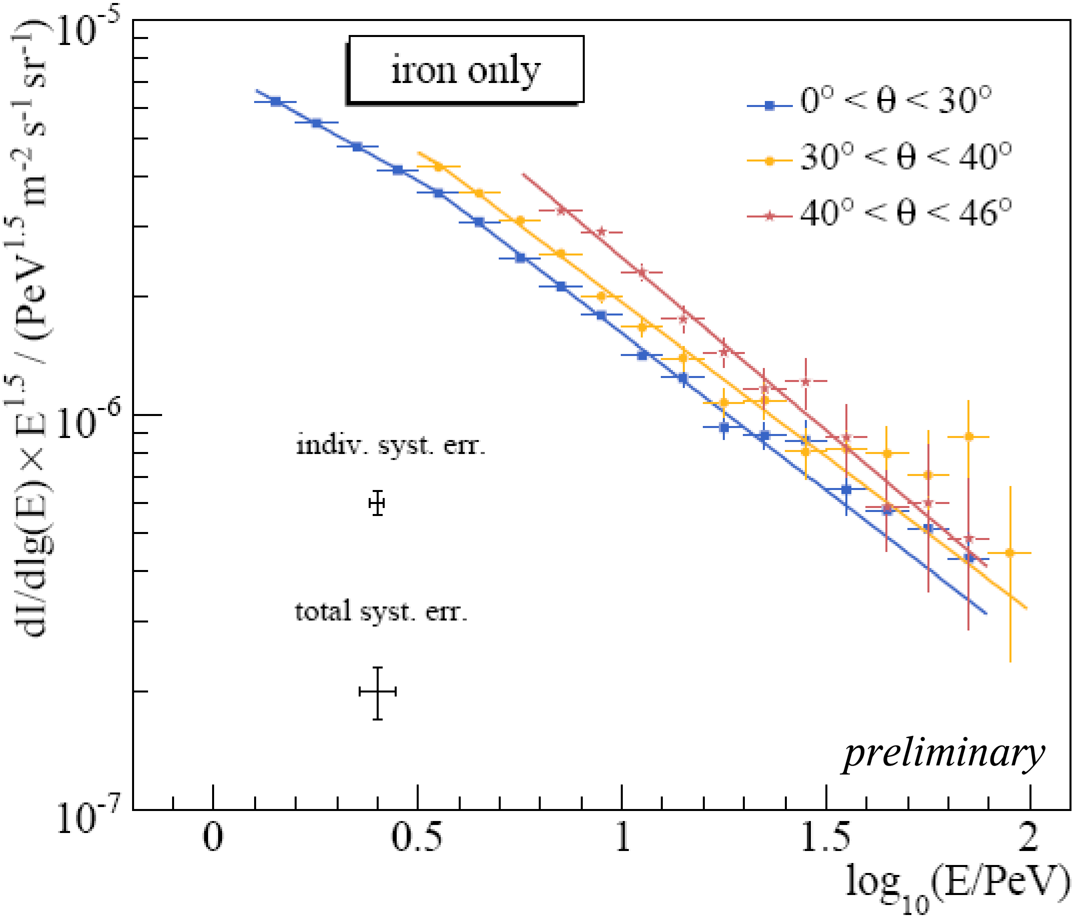
Composition dependent!

Unfolding

- **Inverting effects of response matrix**
- **Trying two different unfolding algorithms**
  (Gold and Bayesian after D'Agostini)

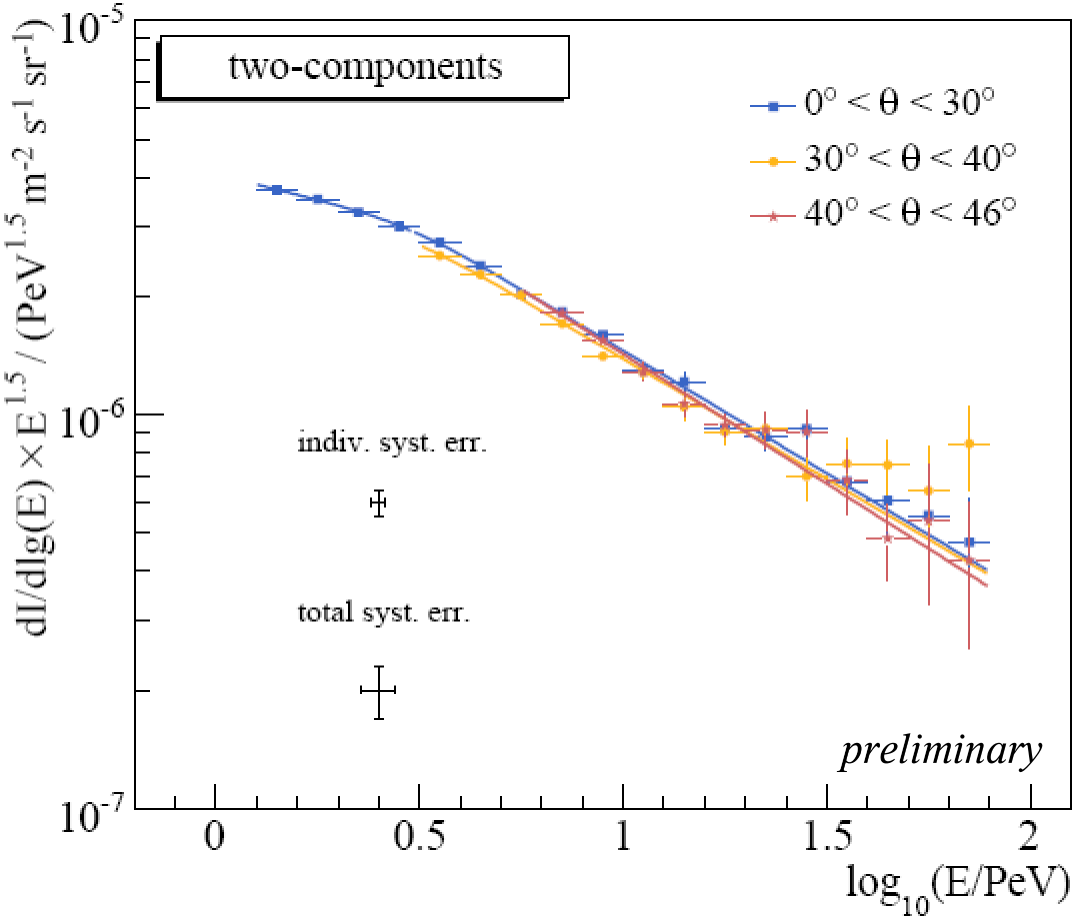


Unfolding under Pure Proton and Iron Assumptions



Angular bins disagree!

Unfolding under Mixed Composition Assumptions



Much better agreement!

Quantitative Evaluation

- Defined 3 Likelihoods to check agreement of
  - Knee Fit variables
  - All bins
  - Integral over Spectra
- Sensitivity to CR composition!
- Clear preference of mixed composition models

	only protons	poly-gonato	two-components	only iron
	NO GOOD	GOOD		NO NO GOOD
(a) fit parameter compatibility				
$I_{\mathrm{PeV,lg}}$	3.34(12)	4.05(10)	4.26(11)	8.8(5)
χ^2/ndf	10.0/2	6.9/2	8.4/2	257/2
prob.	$6.7 \cdot 10^{-3}$	$3.2 \cdot 10^{-2}$	$1.53 \cdot 10^{-3}$	$6.9 \cdot 10^{-11}$
$-\gamma_2$	3.07(2)	3.110(14)	3.120(14)	3.294(19)
χ^2/ndf	3.9/2	0.61/2	1.25/2	4.1/2
prob.	0.145	0.74	0.54	0.126
total prob.	$9.8 \cdot 10^{-4}$	$2.3 \cdot 10^{-2}$	$8.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-12}$
llh. ratio	0.04	1.0	0.35	$3.7 \cdot 10^{-10}$
(b) single bin compatibility				
prob.	$4.5 \cdot 10^{-11}$	$1.06 \cdot 10^{-3}$	$1.13 \cdot 10^{-3}$	$2.3 \cdot 10^{-17}$
llh. ratio	$4.0 \cdot 10^{-8}$	0.94	1.0	$2.0 \cdot 10^{-14}$
(c) integral compatibility				
χ^2/ndf	20.0/2	1.9/2	1.7/2	42.4/2
prob.	$4.6 \cdot 10^{-5}$	$4.0 \cdot 10^{-1}$	$4.2 \cdot 10^{-1}$	$6.2 \cdot 10^{-10}$
llh. ratio	$1.1 \cdot 10^{-4}$	0.95	1.0	$1.5 \cdot 10^{-9}$

Likelihood Ratios

Systematics

	$\log_{10} E$	$\log_{10}(dI/d\log_{10} E)$	E
threshold	0.007	–	1.6 %
snow, Ω0	0.009	–	2.1 %
snow, Ω1	0.014	–	3.2 %
snow, Ω2	0.017	–	3.9 %
saturation, $E < 30\,\mathrm{PeV}$	–	–	–
saturation, $E = 100\,\mathrm{PeV}$	0.02	–	4.6 %
atmosphere	0.014	–	3.2 %
instability	0.017	–	3.9 %
interaction model	0.004	–	0.92 %
calibration	0.03	–	6.9 %
unfolding	–	0.014	1.90 %
response matrix, Ω0	0.0015	0.007	1.01 %
response matrix, Ω1	0.003	0.011	1.6 %
response matrix, Ω2	0.004	0.015	2.2 %

technical simulation issues that might improve soon

calibration

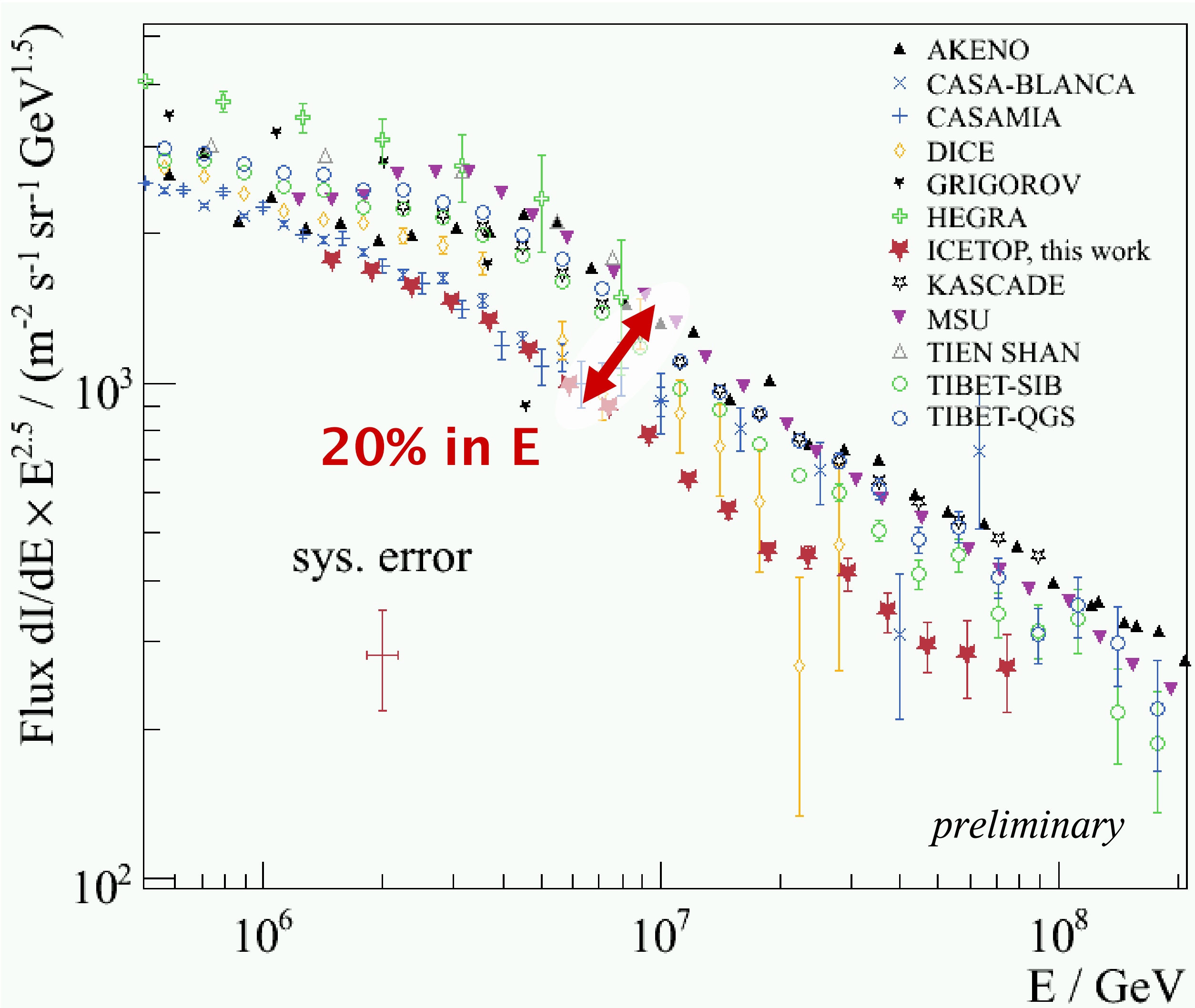
$$\sum$$

	flux	$E < 30\,\mathrm{PeV}$		$E = 100\,\mathrm{PeV}$	
zenith bin	$\sigma_{\lg I}$	$\sigma_{\lg E}$	σ_E	$\sigma_{\lg E}$	σ_E
Ω_0	0.016	0.039	9.3 %	0.044	10.3 %
Ω_1	0.018	0.041	9.7 %	0.045	10.7 %
Ω_2	0.021	0.042	10.0 %	0.046	11.0 %

~9 – 11 % in E

Preliminary Energy Spectrum

(Polygonato composition assumption)



- Data from Aug. 07 (26/80 of full IceTop)
- Exposure: $3.86 \cdot 10^{11} m^2\ s\ sr$
- 734982 events
- Comparably low Flux or Energy (~1.5 σ of syst. err)

Preliminary Spectral Features

(Polygonato composition assumption)

E_{knee} = 3.1 ± 0.3 (stat.) ± 0.3 (sys.) PeV

γ_1 = 2.71 ± 0.07 (stat.)

γ_2 = 3.110 ± 0.014 (stat.) ± 0.08 (sys.)

	E_{knee}	$-\gamma_1$	$-\gamma_2$
KASCADE	4.0(8) – 5.7(1.6)	2.70(6)	3.10(7) – 3.14(6)
TIBET	3.8(1) – 4.0(1)	2.65(1) – 2.67(1)	3.08(5) – 3.12(1)
TUNKA	—	2.71(5)	3.22(5)
this work	3.1(4)	2.71(7)	3.11(8)

Outlook

- Technical improvements in the Simulation
- Process all 2007 data (6 months)
- Main Focus Now: Understand & Develop Coincident Analysis

Summary

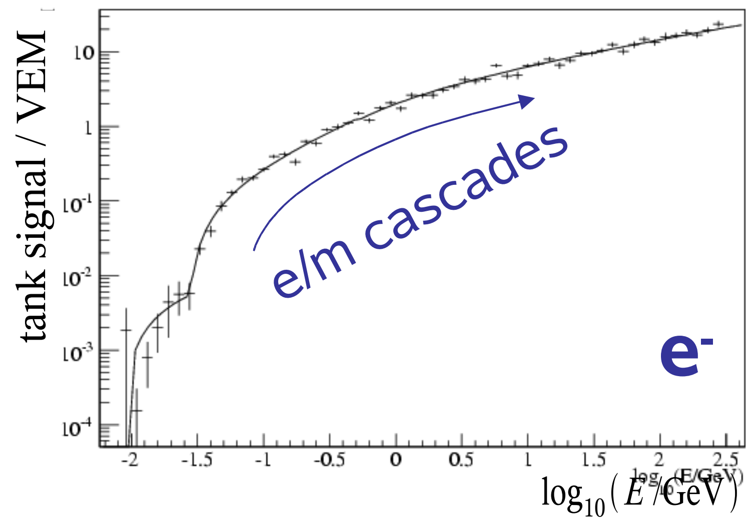
- IceTop Construction is half completed
- Shower Reconstruction, IceTop-Only analysis works well
- Requiring an isotropic flux can give a handle on composition, using deconvolution methods
- Work now focuses on coincident analyses

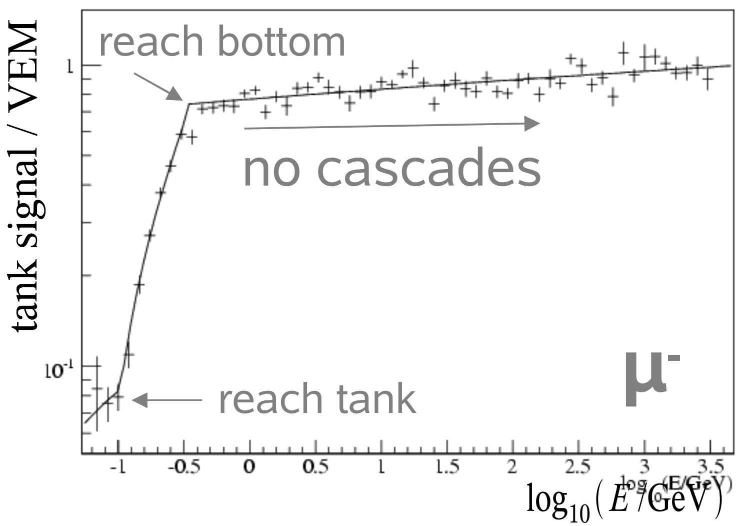

THE END

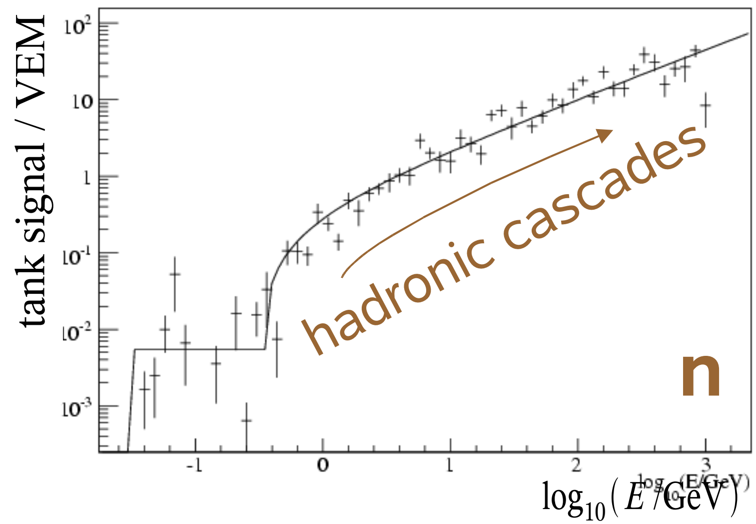
IceTop Tank Response

Tank response depends on particle type and energy

→ Average tank responses $S_j(E)$ for all particles types j abundant in air showers were parametrised

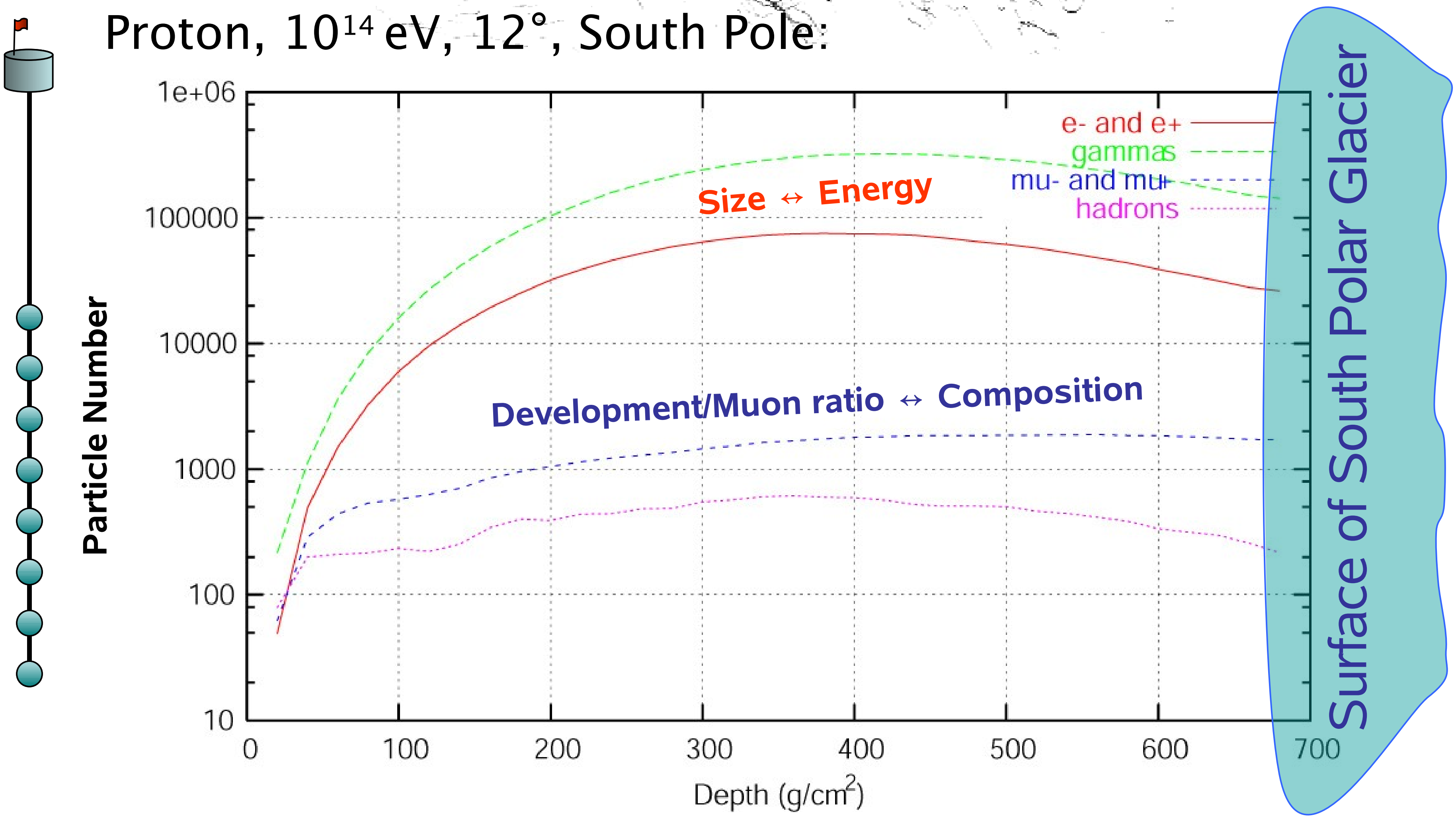






Longitudinal Development

Proton, 10^{14} eV, 12°, South Pole:



Backup: Fits on Raw Spectrum, Folded Raw Spectra

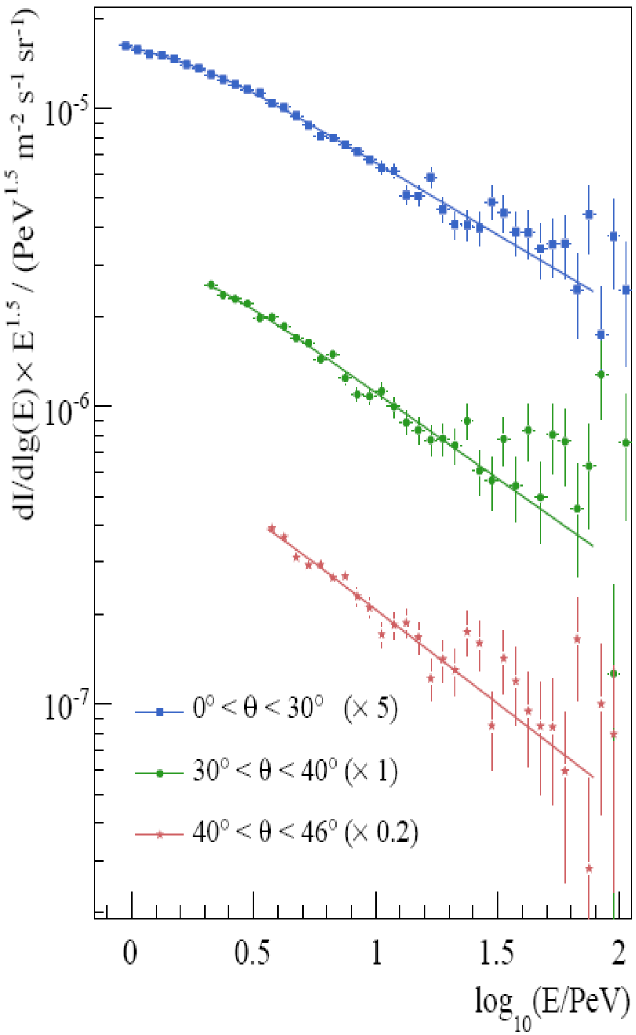
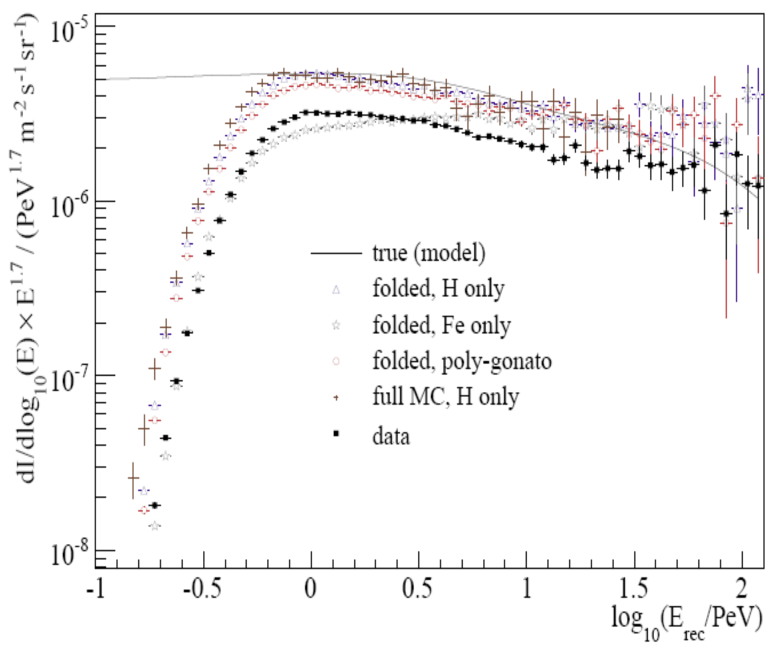


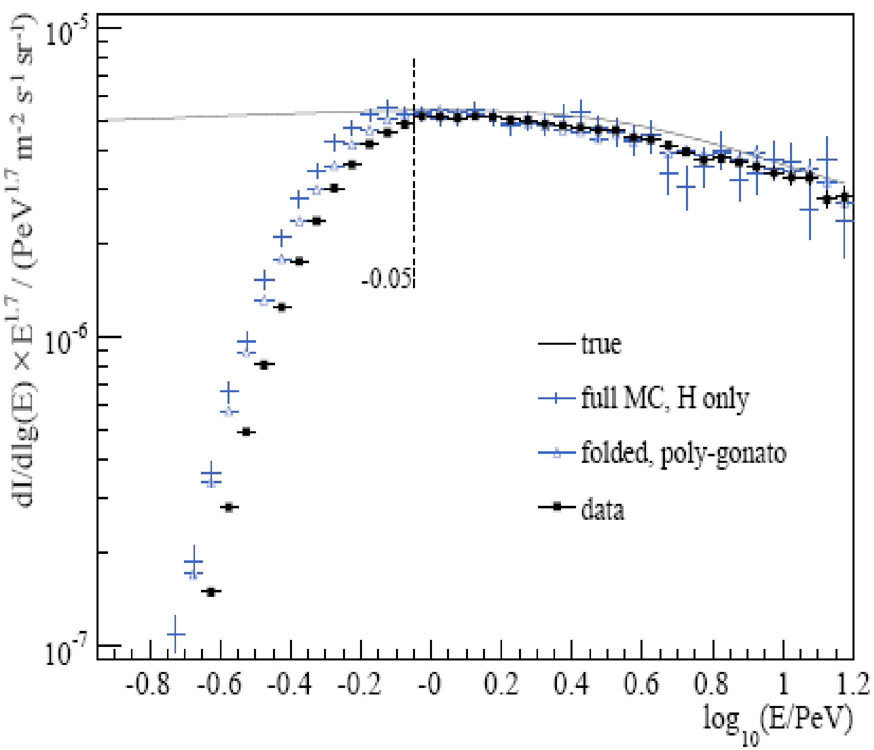
Table 6.3: Parameters of the raw spectra (see eq. 6.1). $I_{\mathrm{PeV,lg}}$ is given in terms of $10^{-6}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, E_{knee} in PeV.

zenith range	$I_{\mathrm{PeV,lg}}$	$-\gamma_1$	$-\gamma_2$	E_{knee}	ε	χ^2/ndf
$0° - 30°$	3.24(7)	2.68(9)	2.98(2)	2.0(5)	3.2(1.5)	30.1/34
$30° - 40°$	3.19(3)	–	3.079(14)	–	–	40.9/30
$40° - 46°$	3.24(12)	–	3.13(3)	–	–	27.3/25



Backup: Threshold Definition

ZENITH BIN 0: $0^\circ < \theta < 30^\circ$



- Done for each Zenith bin
- Results:

zenith range	raw	unfolded
$0^\circ - 30^\circ$	-0.05	0.10
$30^\circ - 40^\circ$	0.30	0.50
$40^\circ - 46^\circ$	0.55	0.75

- for unfolded spectra: 2 x width of response matrix

Backup: Fit Function & Parameters

$$\frac{dI}{d\log_{10} E} = I_{\mathrm{PeV,lg}} \cdot \left(\frac{E}{1\,\mathrm{PeV}}\right)^{\gamma_1+1} \cdot \left(1 + \left(\frac{E}{E_{\mathrm{knee}}}\right)^{\varepsilon}\right)^{(\gamma_2-\gamma_1)/\varepsilon}$$

Table 8.4: Knee fit parameters of all 12 unfolded spectra, as defined in eq. 6.1. $I_{\mathrm{PeV,lg}}$ is given in terms of $10^{-6}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, E_{knee} in PeV.

model	θ bin	$I_{\mathrm{PeV,lg}}$	$-\gamma_1$	$-\gamma_2$	E_{knee}	ε	χ^2/ndf
	Ω_0	3.61(10)	2.66(8)	3.05(2)	2.8(3)	5.8(3.4)	14.2/14
only protons	Ω_1	3.23(5)	–	3.08(3)	–	–	11.6/12
	Ω_2	3.3(2)	–	3.17(6)	–	–	5.7/9
	Ω_0	4.21(9)	2.71(7)	3.12(3)	3.1(3)	4.7(2.7)	9.5/13
poly-gonato	Ω_1	3.92(7)	–	3.10(2)	–	–	14.2/12
	Ω_2	4.2(2)	–	3.13(4)	–	–	5.2/9
	Ω_0	4.43(9)	2.75(6)	3.12(3)	3.1(3)	5.4(3.3)	9.7/13
two-comp.	Ω_1	4.15(5)	–	3.11(2)	–	–	16.2/12
	Ω_2	4.6(2)	–	3.16(4)	–	–	5.4/9
	Ω_0	8.39(4)	3.074(9)	3.29(2)	3.7(3)	2.7(7.0)	11.7/13
only iron	Ω_1	9.91(9)	–	3.28(2)	–	–	21.7/13
	Ω_2	14.2(7)	–	3.37(4)	–	–	6.3/9