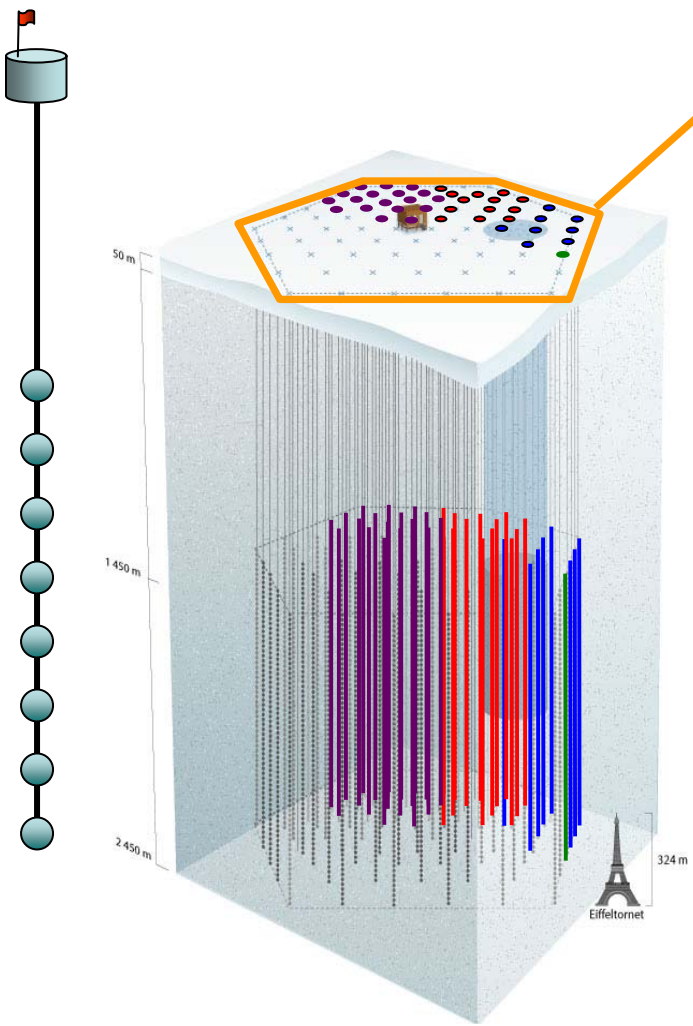
First Results from the IceTop Air Shower Array

Stefan Klepser
for the IceCube Collaboration
(see www.icecube.wisc.edu)

ECRS,
September 2008

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
- $A_{tot} \sim 1\ km^2$

IceCube → Muon Detection

- 4800 DOMs
- Muon bundle detector
- $E_{muon} > 100$ GeV

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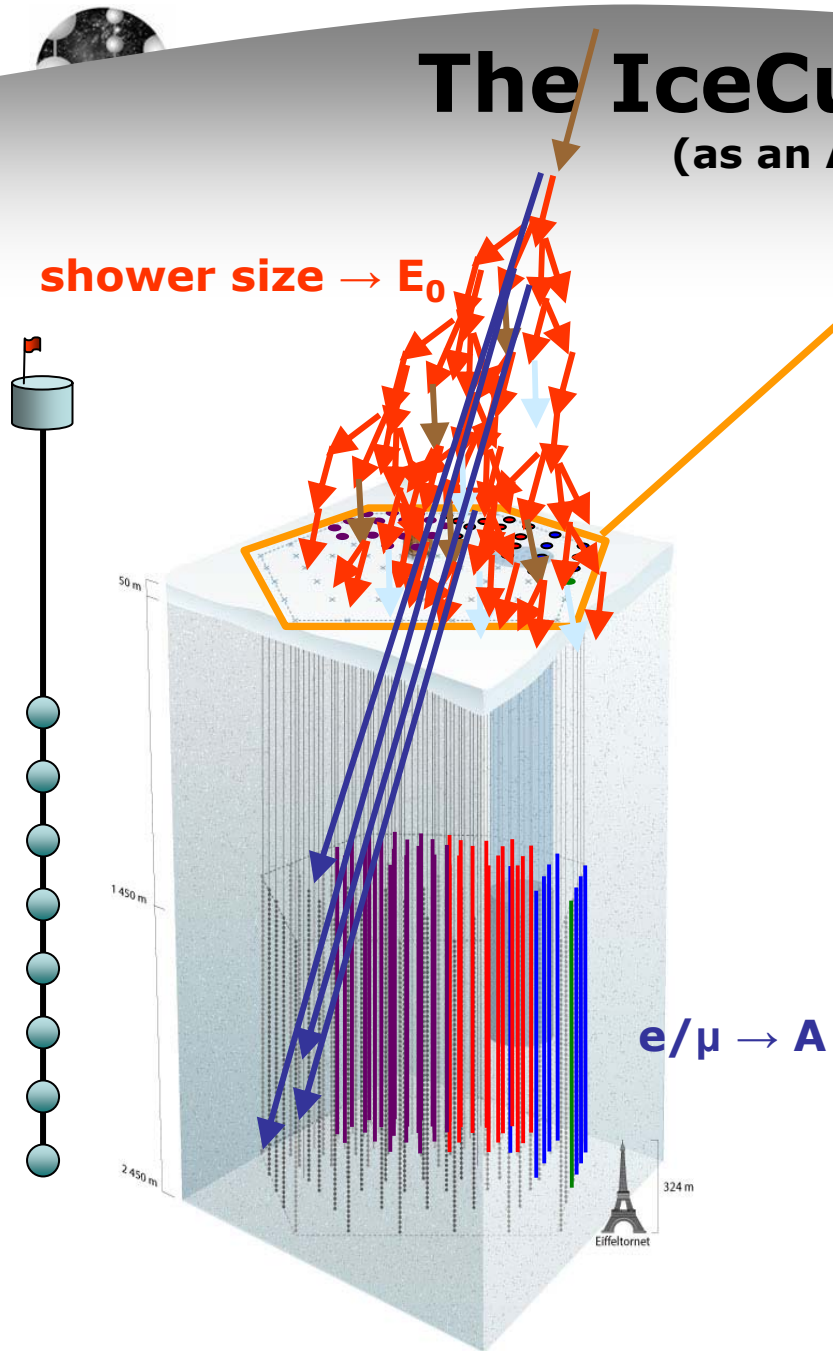

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IceCube → Muon Detection

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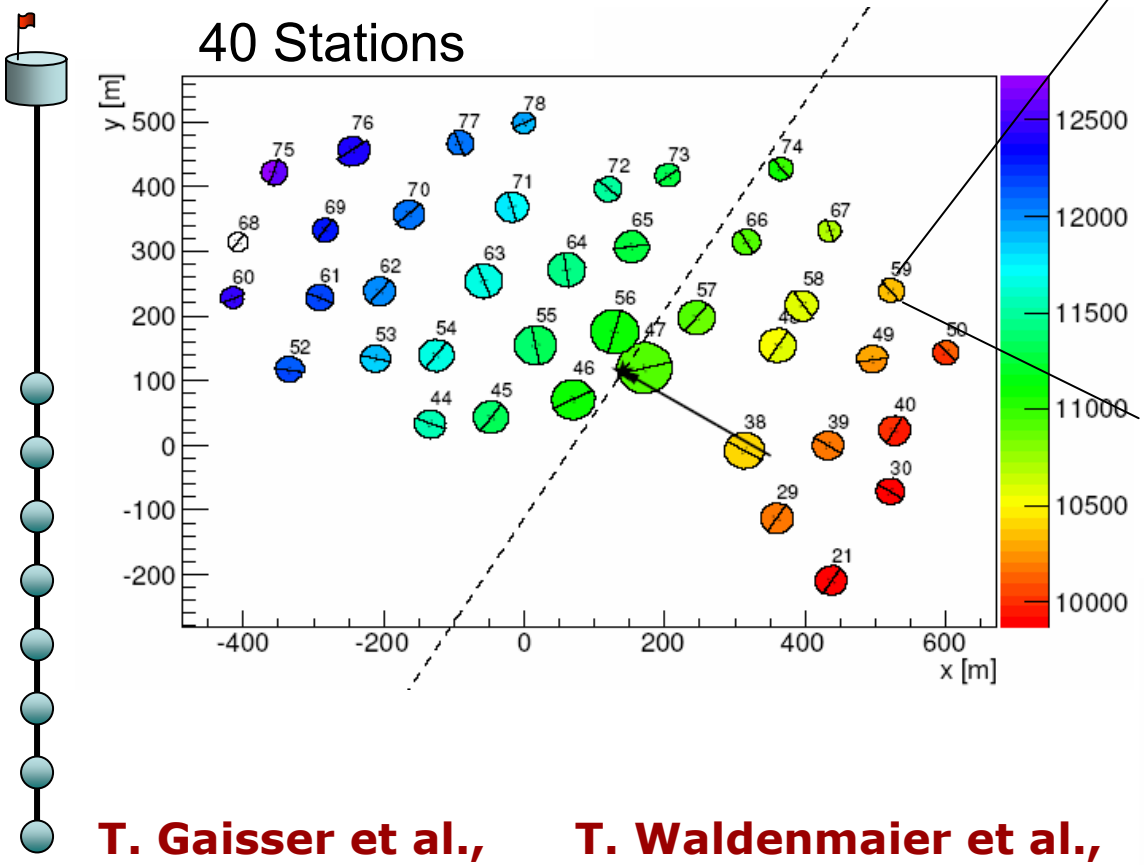
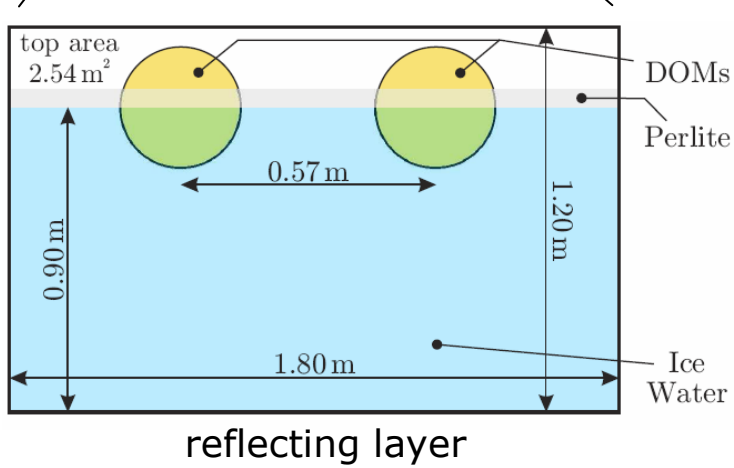
The IceTop Detector 2008

(present analysis)

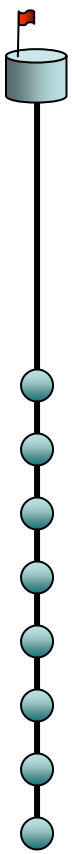


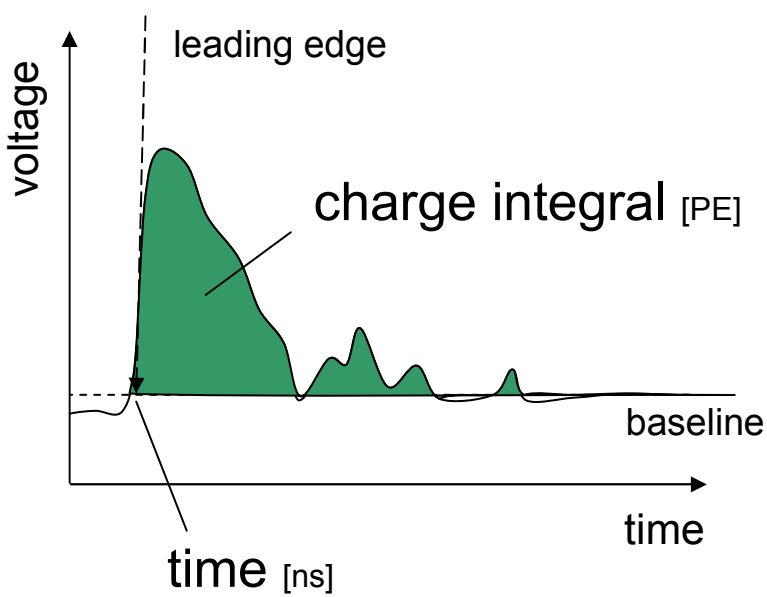


T. Gaisser et al.,
arXiv:0711.0353

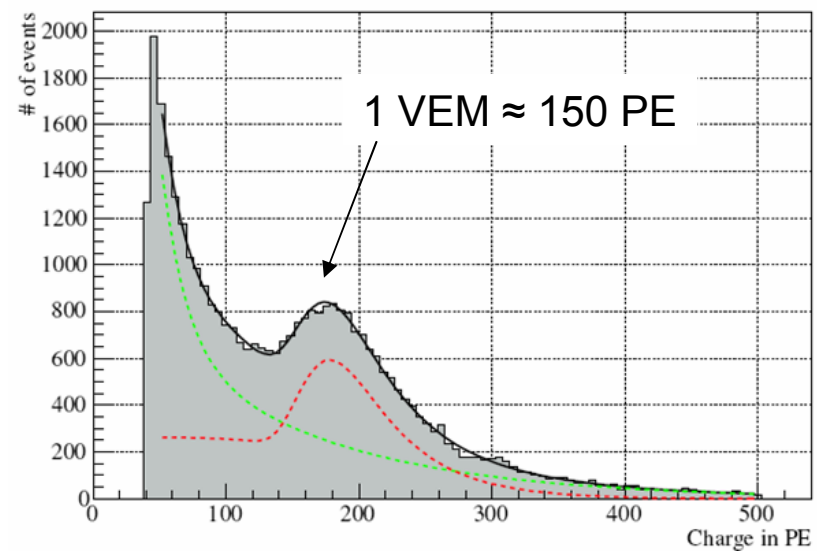
T. Waldenmaier et al.,
NIM in Ph. Res. A,
588 (2008) 130–134

Signal Processing





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

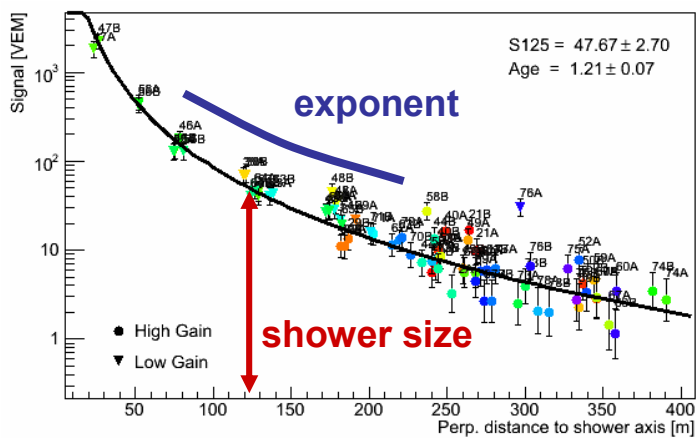


calibration run, i.e. no coincidence conditions

L. Demirörs et al.,
arXiv:0711.0353

Lateral Pulse Height Distribution

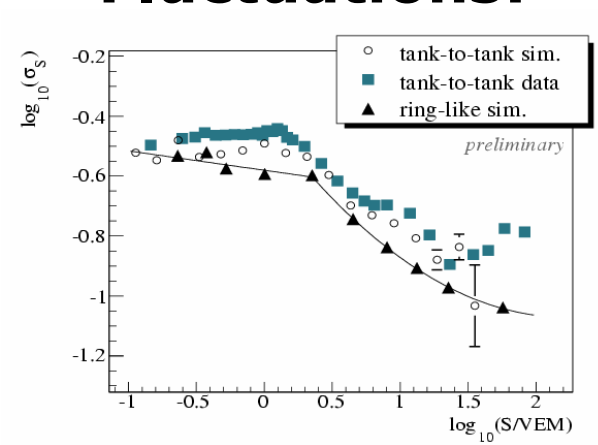
- **Lateral Function**



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

➢ charge expectation as a function of distance to shower axis

- **Fluctuations:**

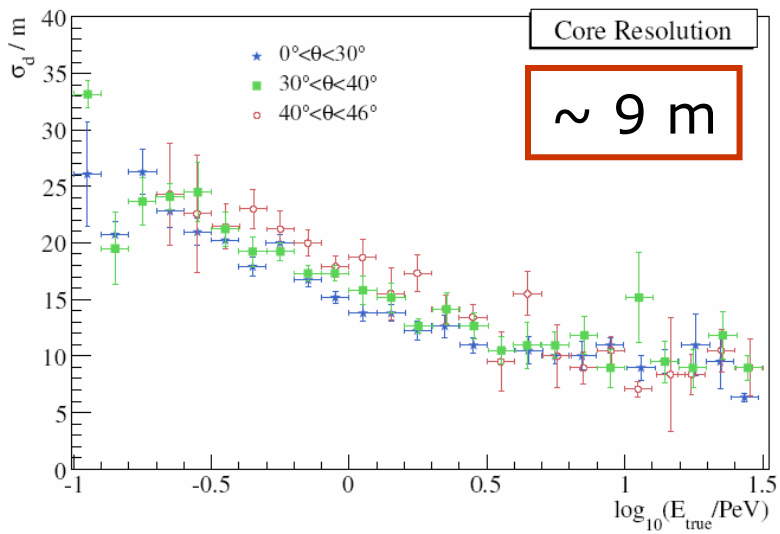


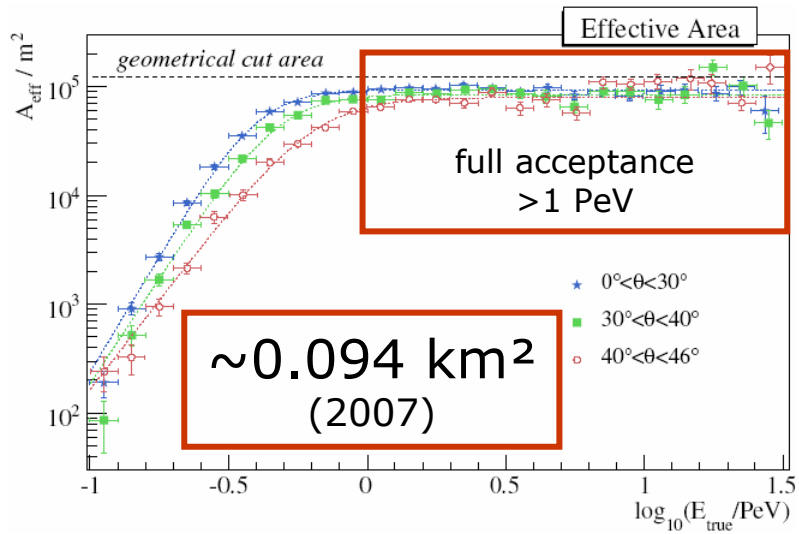
➢ Function of S

F. Kislat,
dipl. thesis, HU Berlin

S. Klepser et al.,
arXiv:0711.0353

Resolution & Efficiency





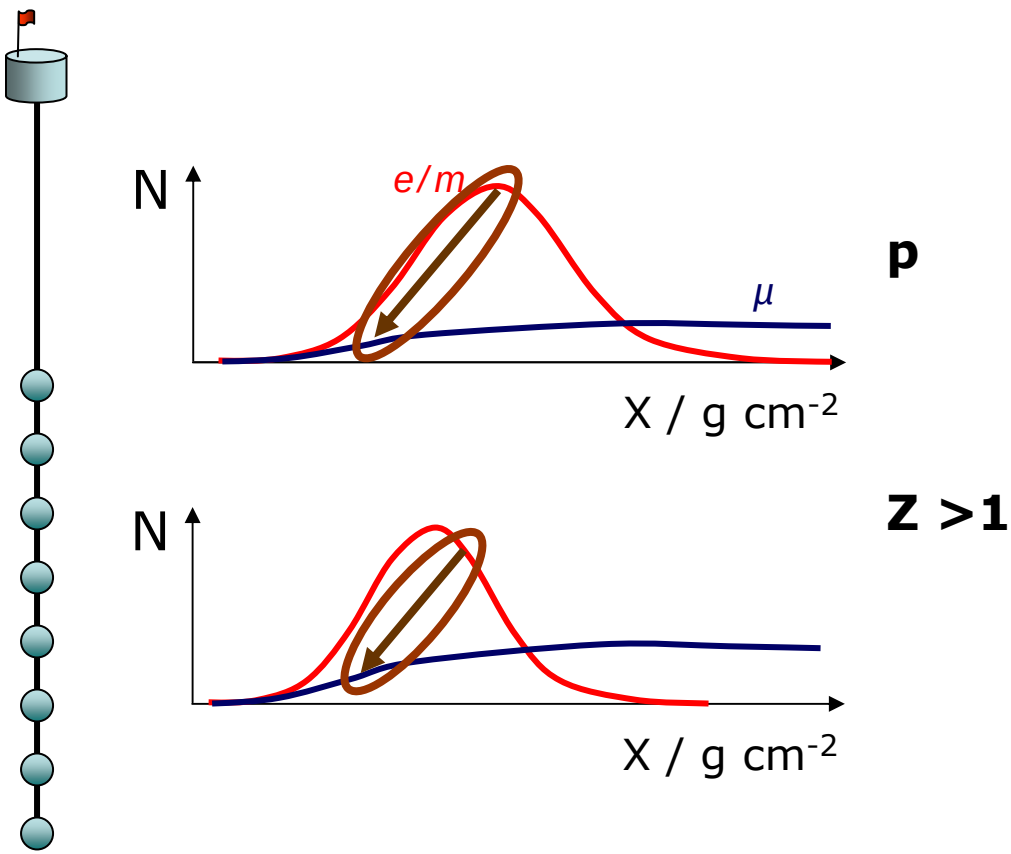
Directional Resolution ~**1.5°**

Energy Resolution (above 3 PeV) ~**16% in E**

numbers given for zenith angles 0°-30°!

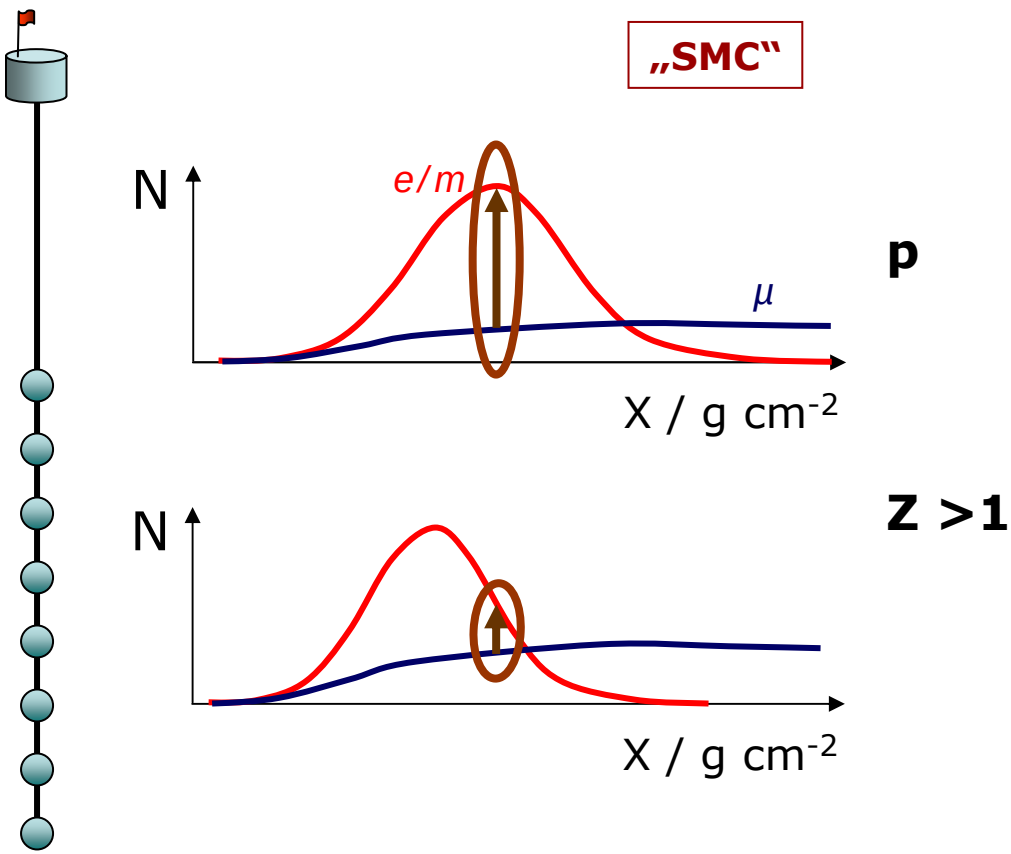
Analysis Strategies

„IceTop/IceCube"



1. **Coincident Analysis**
2. **Surface Muon Counting Analysis**
3. **IceTop-only Analysis**

Analysis Strategies



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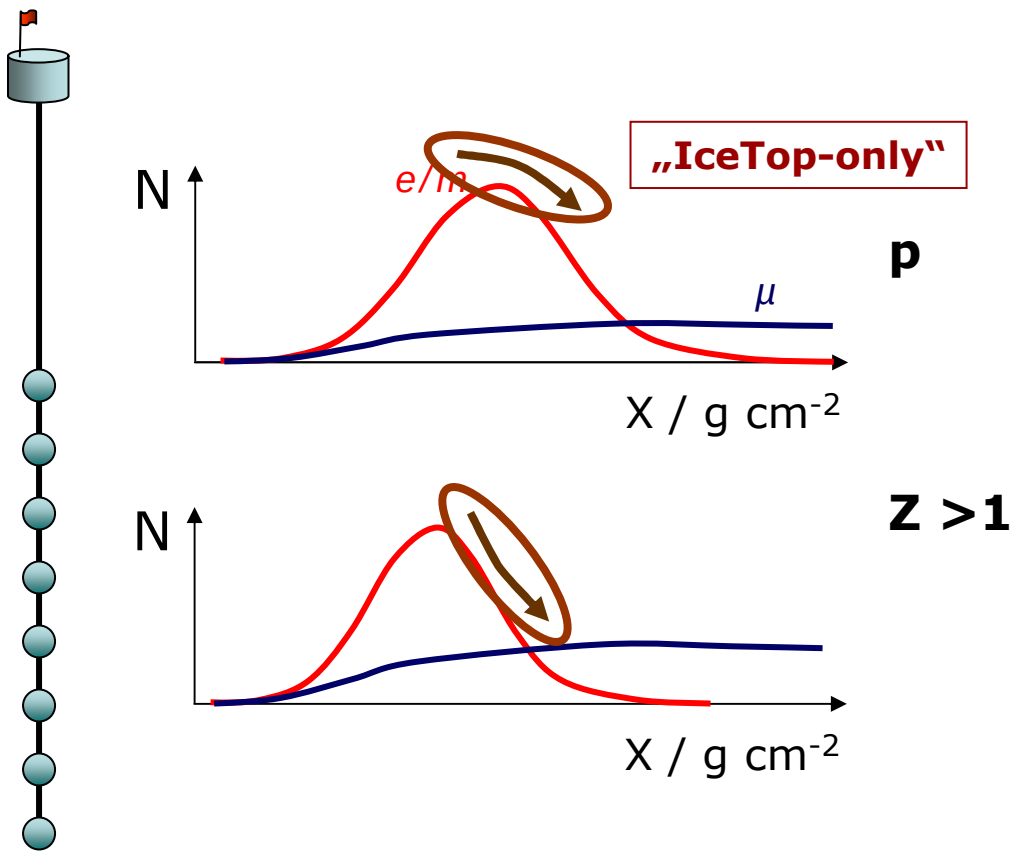


1. **Coincident Analysis**
2. **Surface Muon Counting Analysis**

following slides…

3. **IceTop-only Analysis**

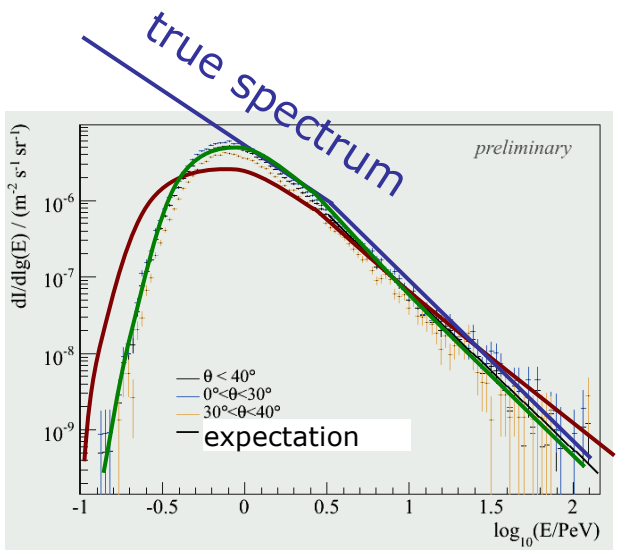
Energy Response

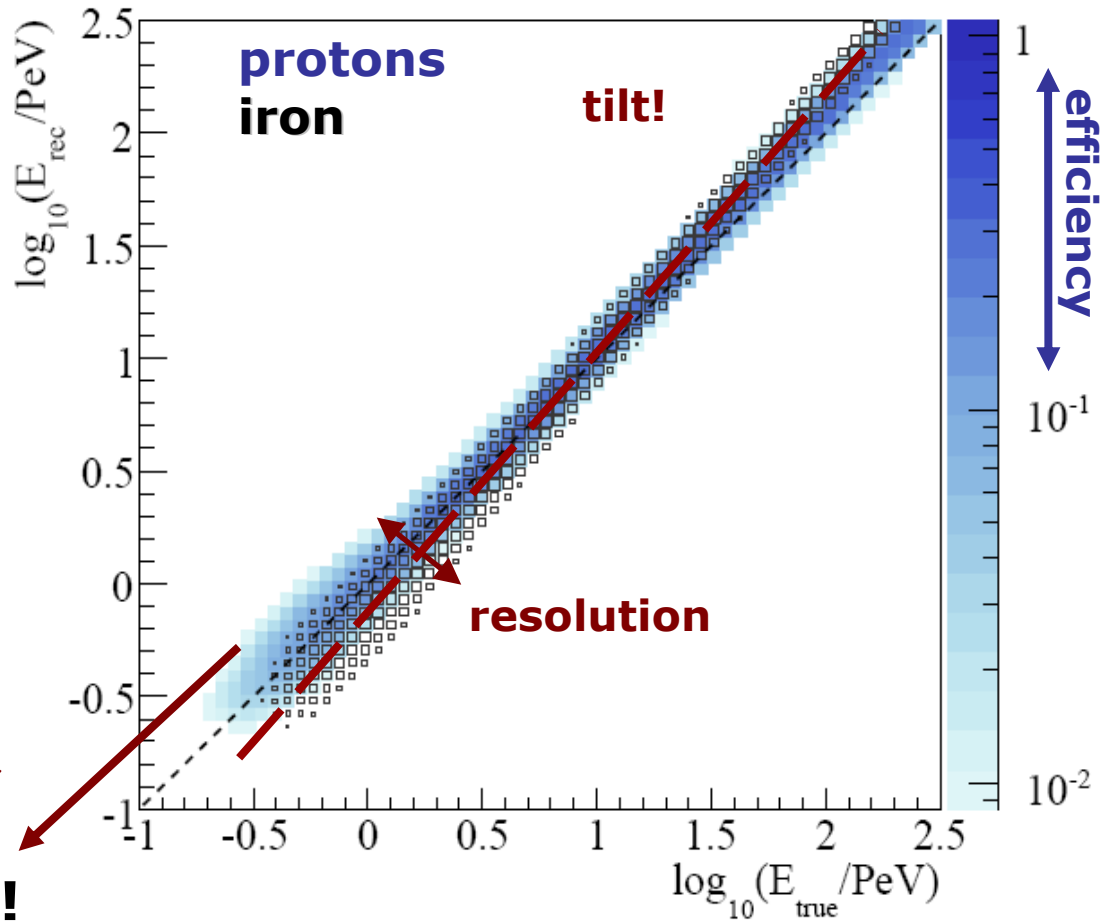
Convolution:

Response Matrix

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

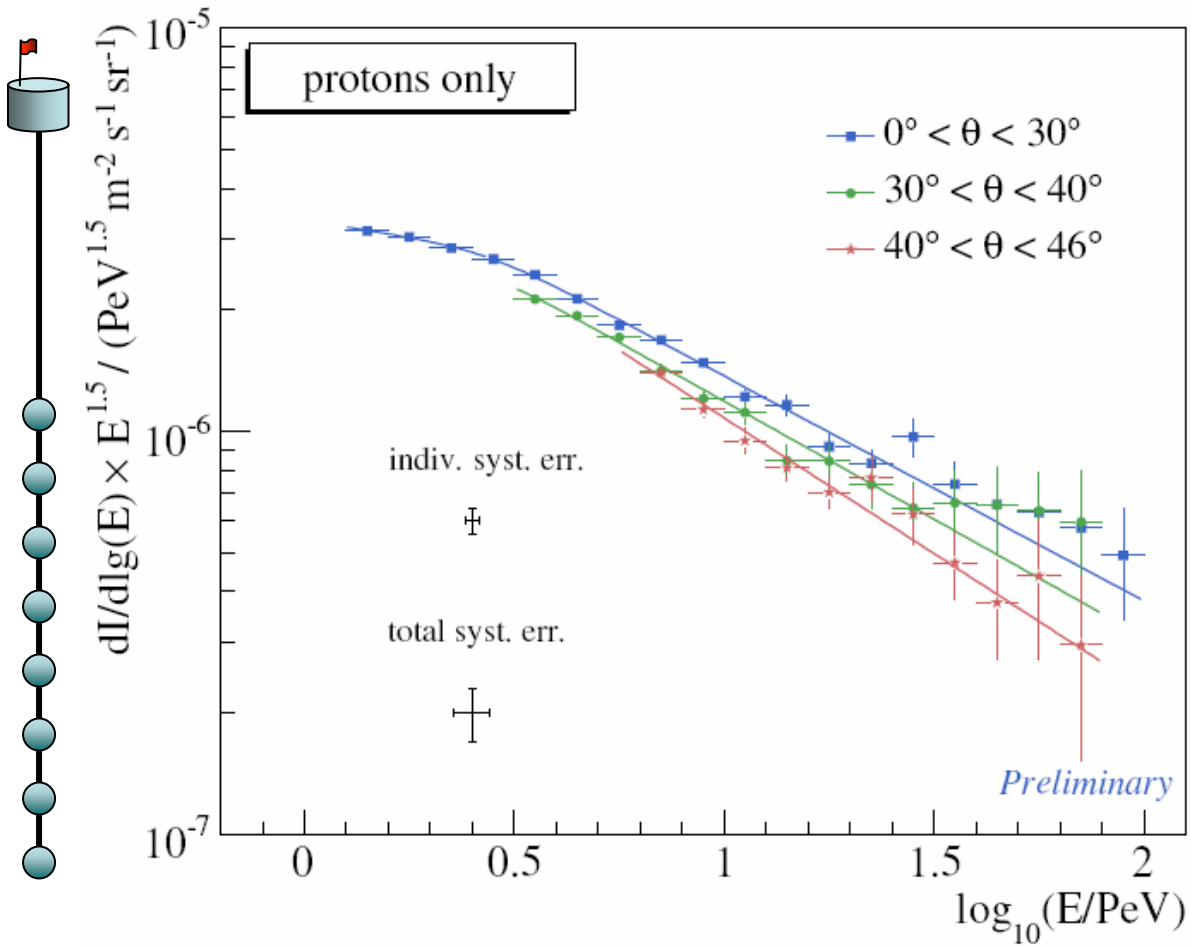
measured **true**





composition dependency!

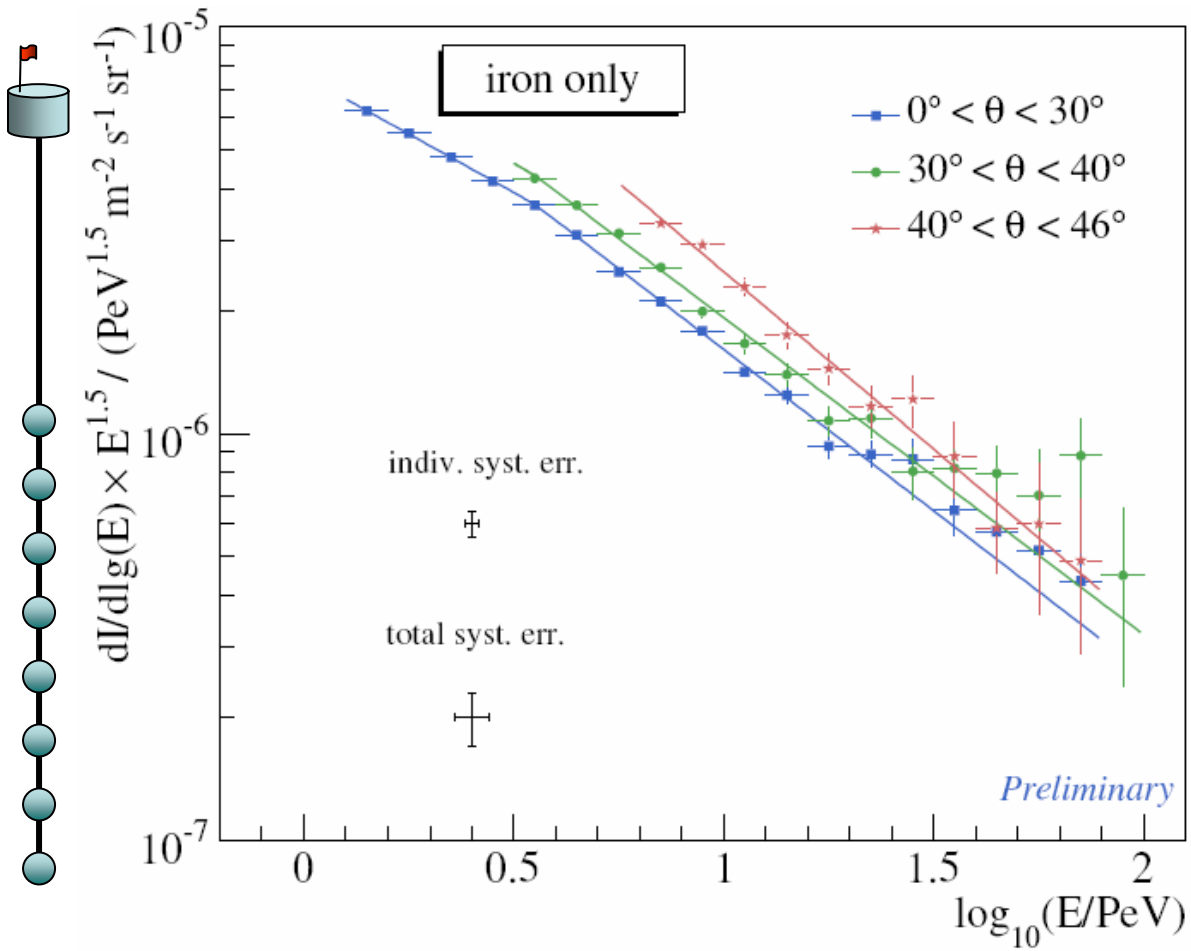
Unfolding under Composition Assumptions



- ‚Bayesian' and ‚Gold' algorithms
- 3 Zenith bins
- Inconsistency between Zenith ranges

S. Klepser,
PhD thesis, HU Berlin

Unfolding under Composition Assumptions



- **‚Bayesian' and ‚Gold' algorithms**
- **3 Zenith bins**
- **Inconsistency between Zenith ranges**

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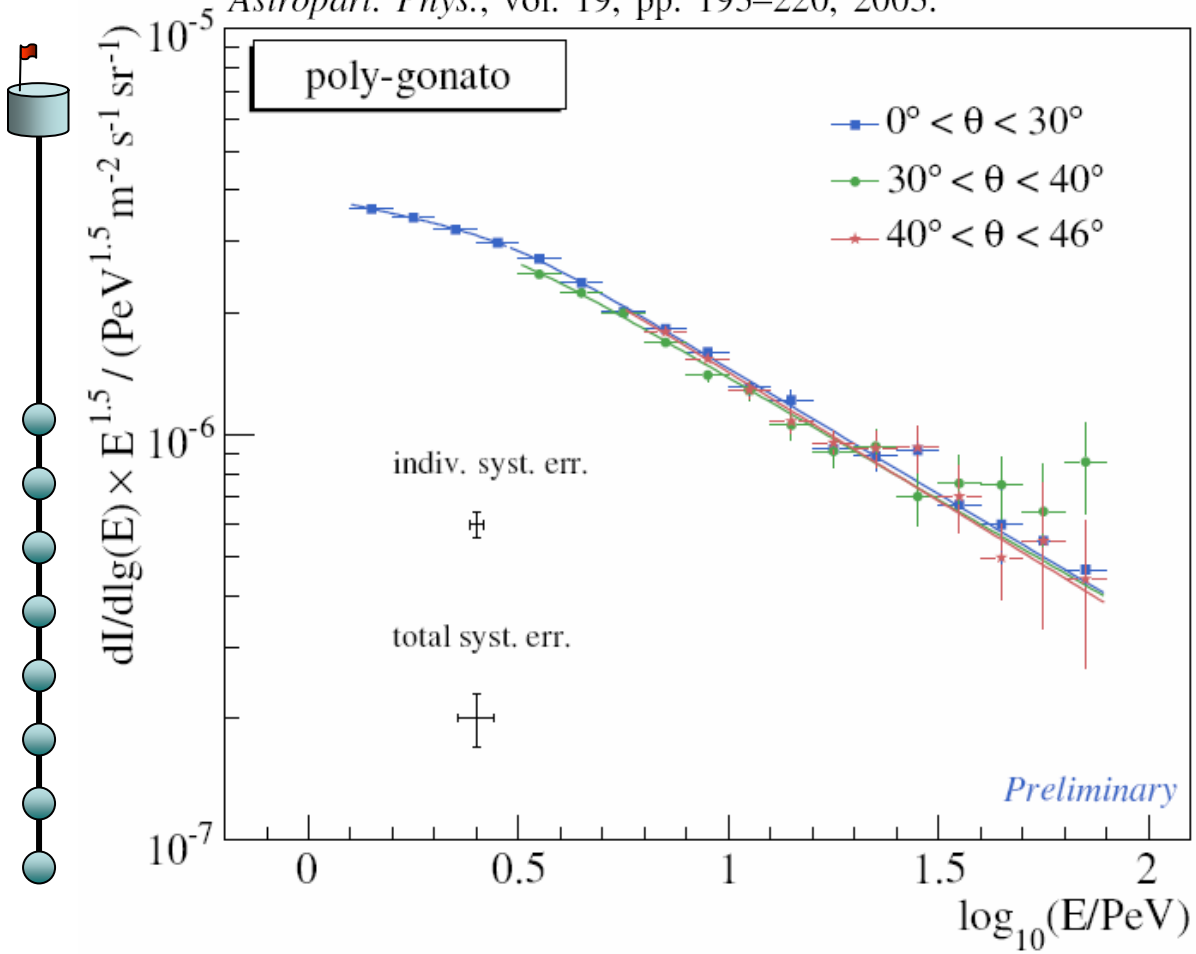
Unfolding under Composition Assumptions

J. Hoerandel, "On the knee in the energy spectrum of cosmic rays," *Astropart. Phys.*, vol. 19, pp. 193–220, 2003.



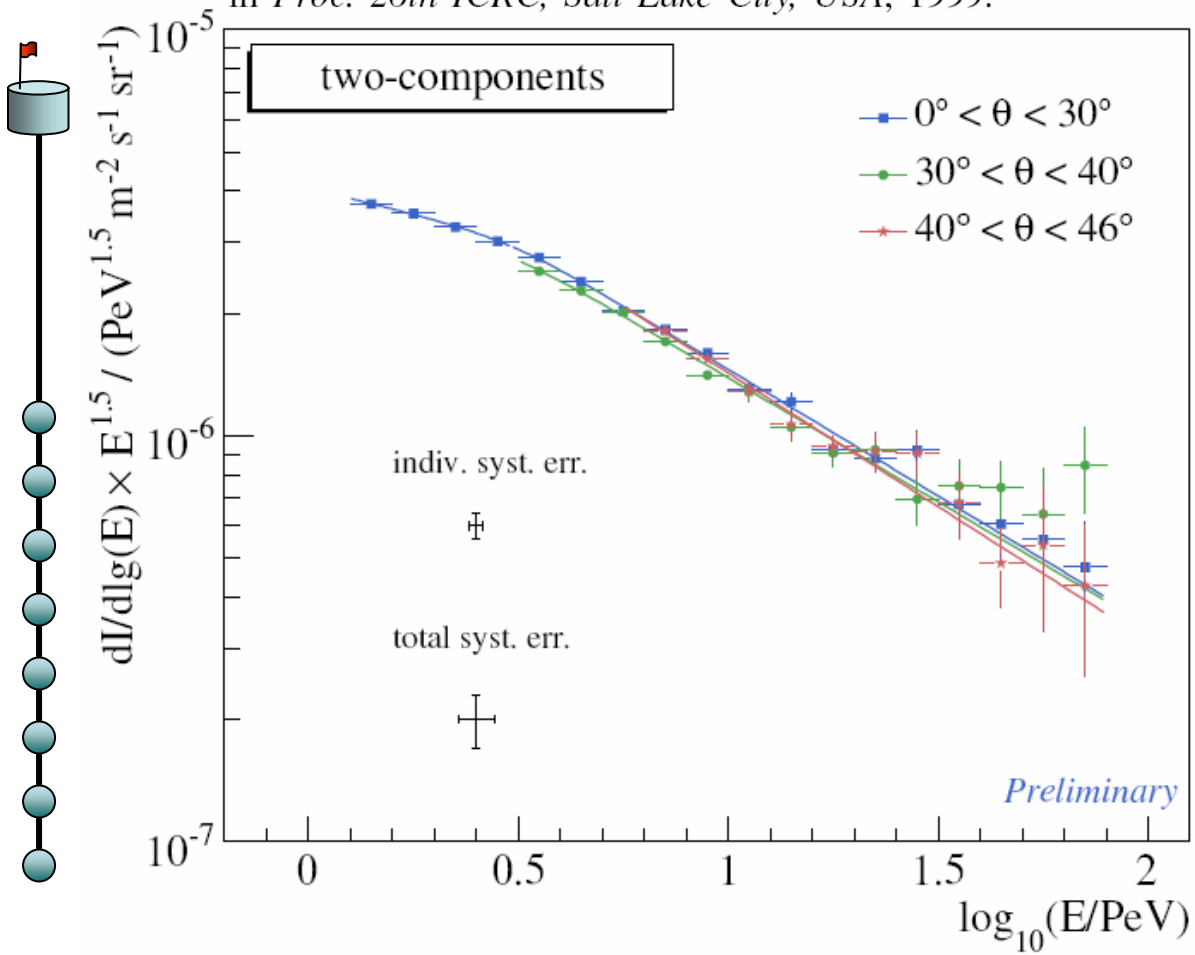
- **‚Bayesian' and ‚Gold' algorithms**
- **3 Zenith bins**
- **Inconsistency between Zenith ranges**

➢ **Sensitivity on Composition!**

S. Klepser,
PhD thesis, HU Berlin

Unfolding under Composition Assumptions

R. Glasstetter *et al.*, "Analysis of electron and muon size spectra of eas," in *Proc. 26th ICRC, Salt Lake City, USA*, 1999.



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➢ **Sensitivity on Composition!**

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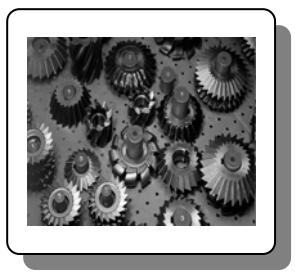
Quantitative Analysis

- **Highest compatibility: Both mixed composition models**
  - **Other Likelihood ratios:**

- Pure **proton** composition: $\mathbf{4 \cdot 10^{-8}}$

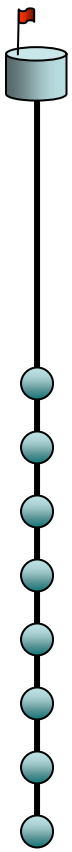


- Pure **iron** composition: $\mathbf{2 \cdot 10^{-14}}$

- **Complementary approach,**
  ~ independent of muon multiplicities in HE interactions!

Quantitative Analysis

- **Highest compatibility: Both mixed composition models**



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- Pure **iron** composition: **$2 \cdot 10^{-14}$**

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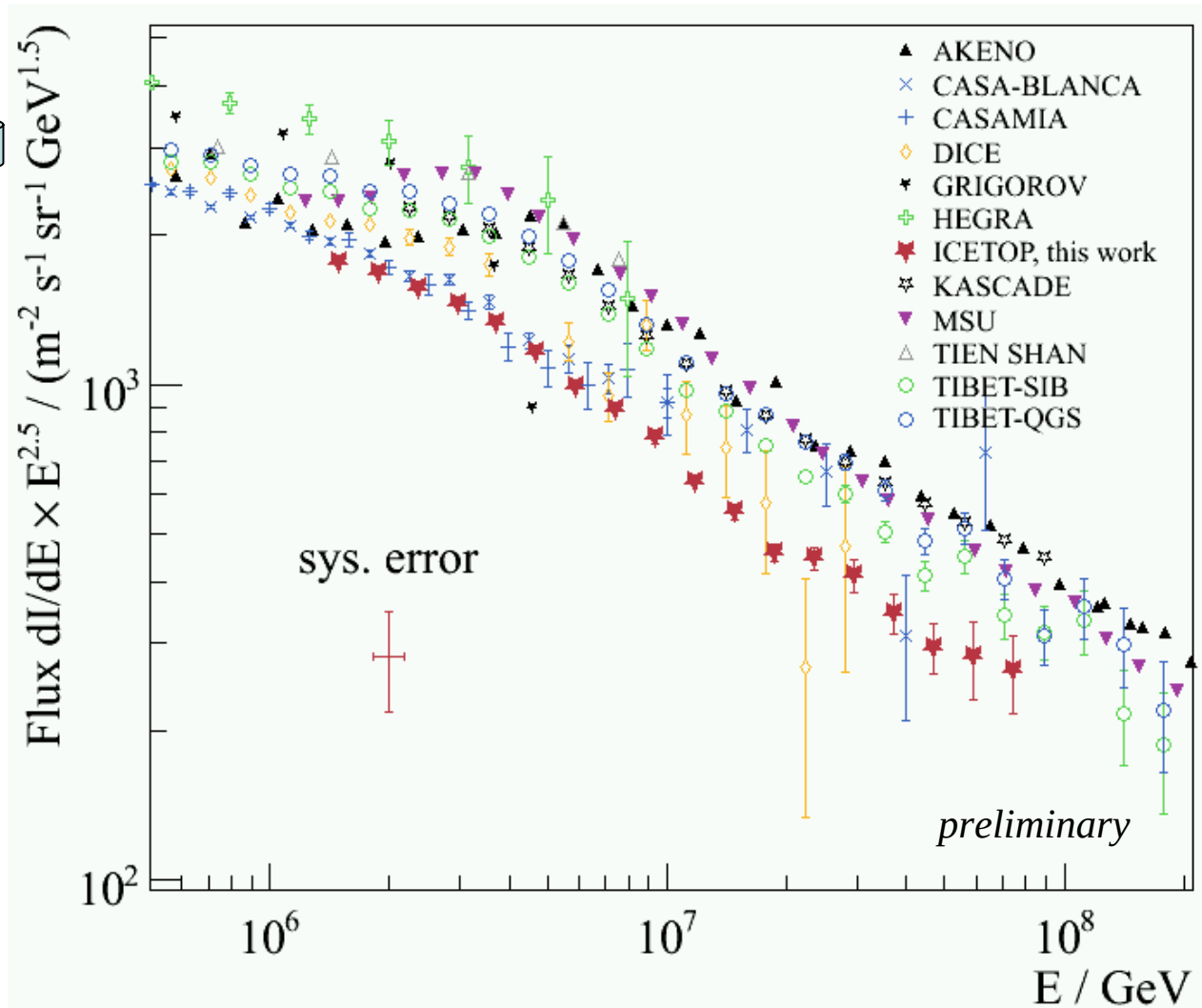
Energy Spektrum

(Polygonato Assumption)



- Data Aug. 07 (26 Stations)
- Exposure: $3.86 \cdot 10^{11} m^2$ s sr
- 734982 Events
- $\sigma_{sys} \sim 11\%$ in E
- Comparably low flux or energy ($\sim 1.5\ \sigma_{sys}$)
- $E_{knee} = 3.1(3)$ PeV
- $\gamma_1 = 2.71(7)$
- $\gamma_2 = 3.11(8)$

S. Klepser,
PhD thesis, HU Berlin

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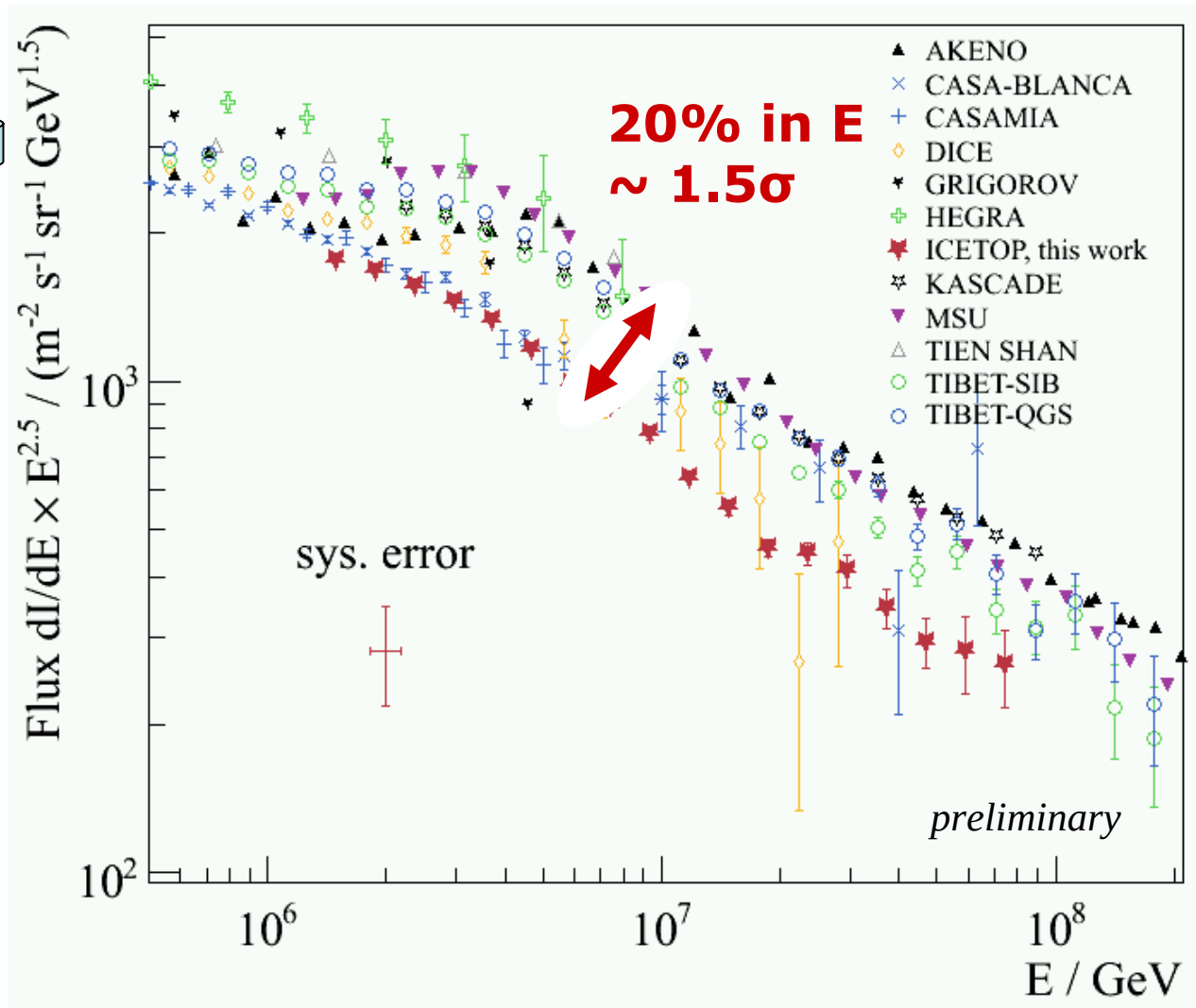

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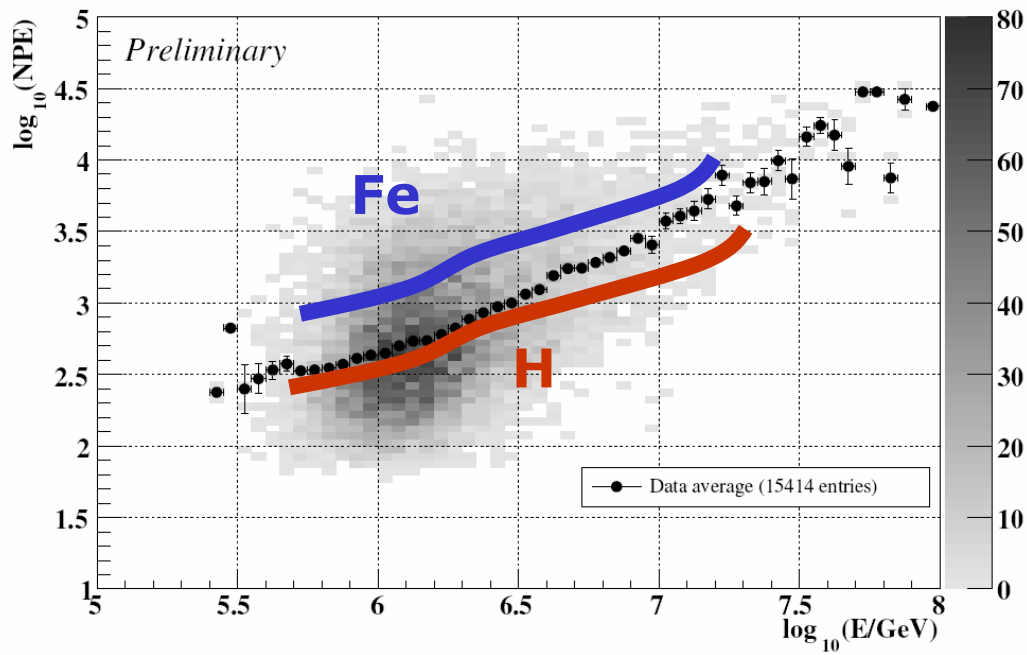
S. Klepser,
PhD thesis, HU Berlin

Outlook I: Coincident Analysis



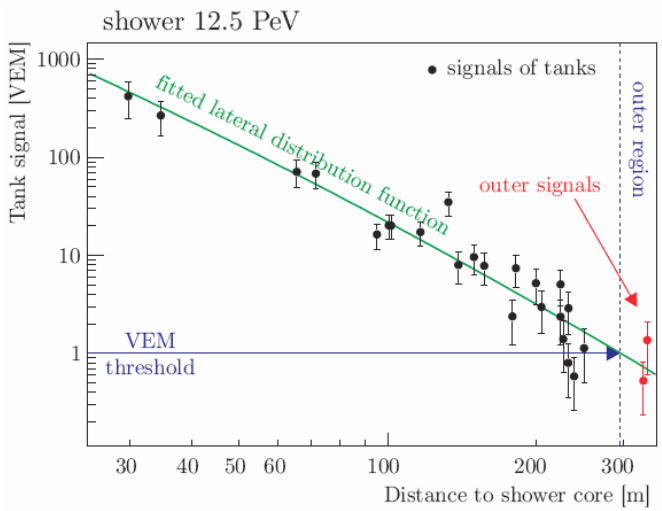
- **IceTop: e/m shower**
- **IceCube: HE muons**

More advanced:

- Size & Spread of IceTop Event
- Size & Spread of IceCube Event

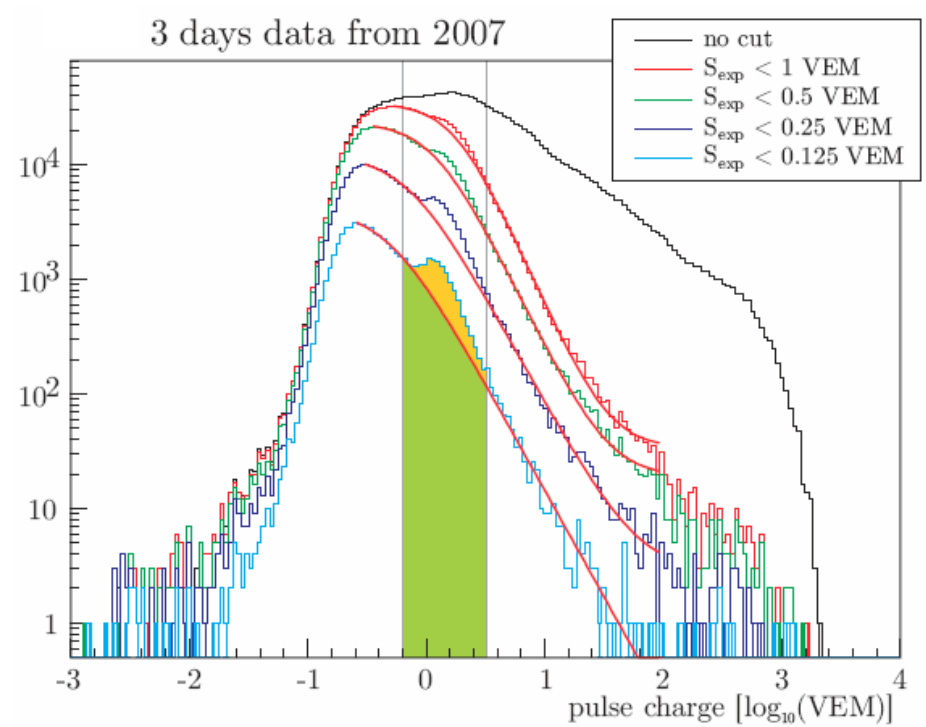
} **4 Parameters** to analyse **E** and **mass**!

Outlook II: Surface Muon Counting



- **muon peak in data and simulation!**
- **difference in p and Fe peak height!**
- **sensitivity to composition!**

- **looking for excess events in „outer region" of an event**

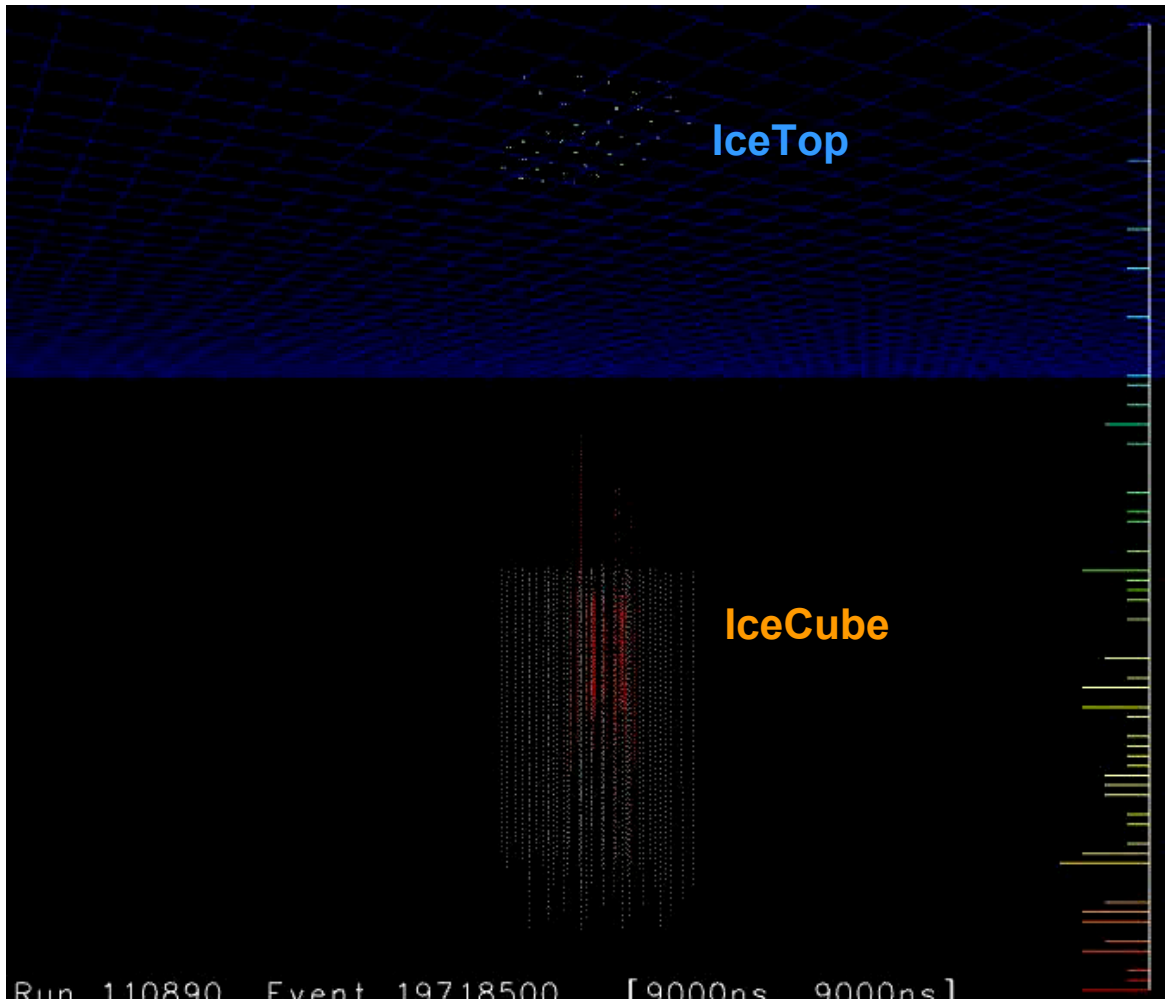


A. Lucke,
dipl. thesis, HU Berlin

Summary

- **First Energy Spectrum from 1 – 80 PeV**
- **Complementary Composition Sensitivity with IceTop only**
- **Technical Outlook:**
  - Several Reducible Sytematics
  - Completition of IceTop in 2011
- **Analysis Outlook:**
  - Main Analysis: IceTop/IceCube Coincidences
  - Yet Complementary Approach: Muon Counting

1 EeV



Spectral Parameters

(Polygonato Assumption)

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

γ_1 = 2.71 ± 0.07 (stat.)

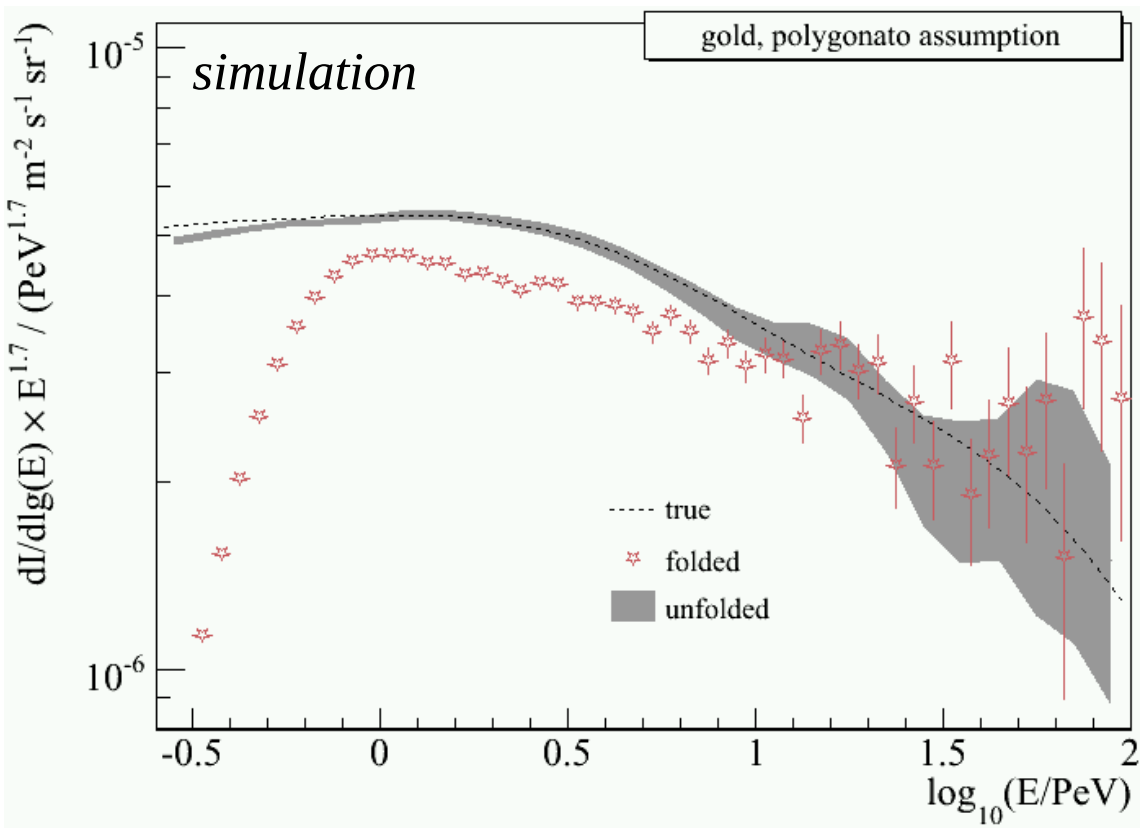
γ_2 = 3.110 ± 0.014 (stat.) ± 0.08 (sys.)

	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)

Unfolding

- **Inverts the effects of the response matrix**
  - No single solution
  - Depends on iteration or regularisation parameters

- **Used 2 iterative Algorithms:**
  - Gold
  - Bayesian, following D´Agostini



Mixed Composition Models

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

Table 6.1: Constants of the input spectrum assumptions. $I_{\mathrm{PeV,lg}}$ is given in terms of $10^{-6}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, E_{knee} in PeV.

model		A	Z	$I_{\mathrm{PeV,lg}}$	$-\gamma_1$	$-\gamma_2$	E_{knee}
only protons	H	1.0	1.0	5.47	2.66	3.08	3.08
poly-gonato	H	1.0	1.0	1.61	2.71	$-\gamma_1+2.1$	4.49
	He	4.0	2.0	1.71	2.64	$-\gamma_1+2.1$	$Z\cdot E_{\mathrm{knee,H}}$
	CNO	14.2	7.1	0.673	2.67	$-\gamma_1+2.1$	$Z\cdot E_{\mathrm{knee,H}}$
	Mg-S	27.2	13.5	0.514	2.64	$-\gamma_1+2.1$	$Z\cdot E_{\mathrm{knee,H}}$
	Mn-Fe	55.7	25.9	0.997	2.57	$-\gamma_1+2.1$	$Z\cdot E_{\mathrm{knee,H}}$
two-comp.	H	1.0	1.0	3.89	2.67	3.39	4.1
	Fe	1.0	1.0	1.95	2.66	–	–
only iron	Fe	56.0	26.0	5.47	2.66	3.08	3.08

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 issues of the simulation

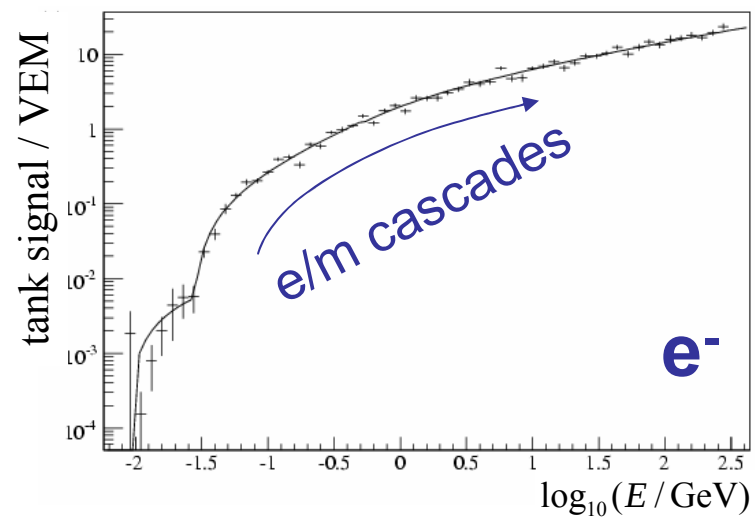
Calibration

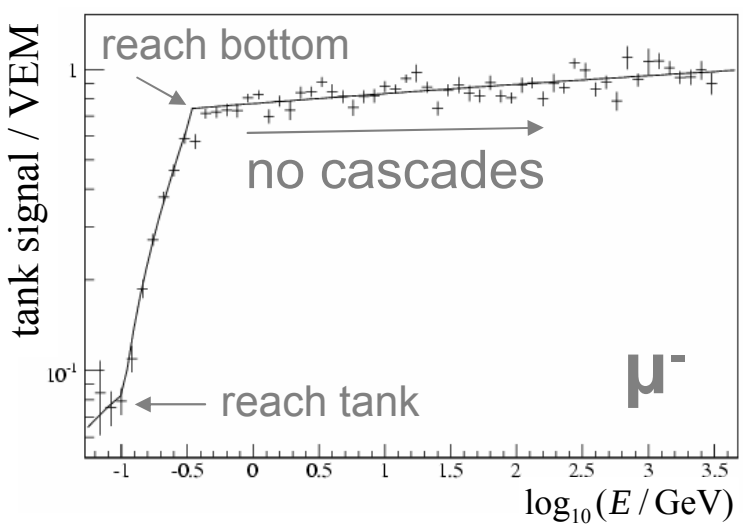
Σ: **~ 9 – 11 % in E**

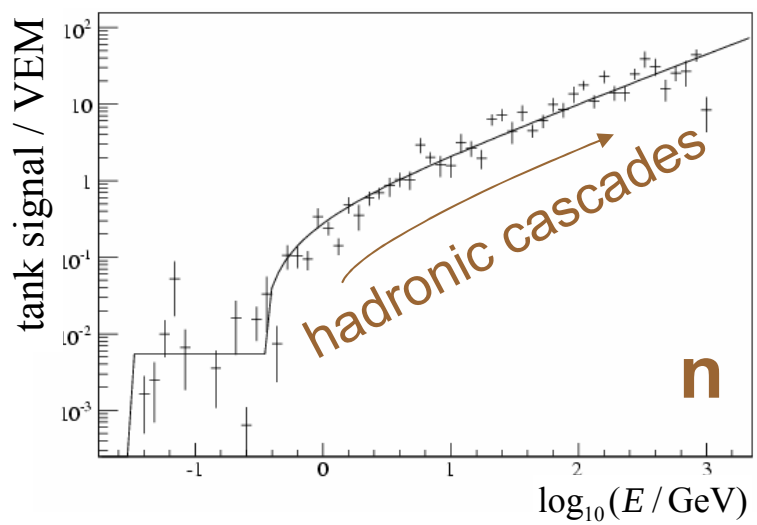
IceTop Tank Response

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







Backup: Fits on Raw Spectrum, Folded Raw Spectra

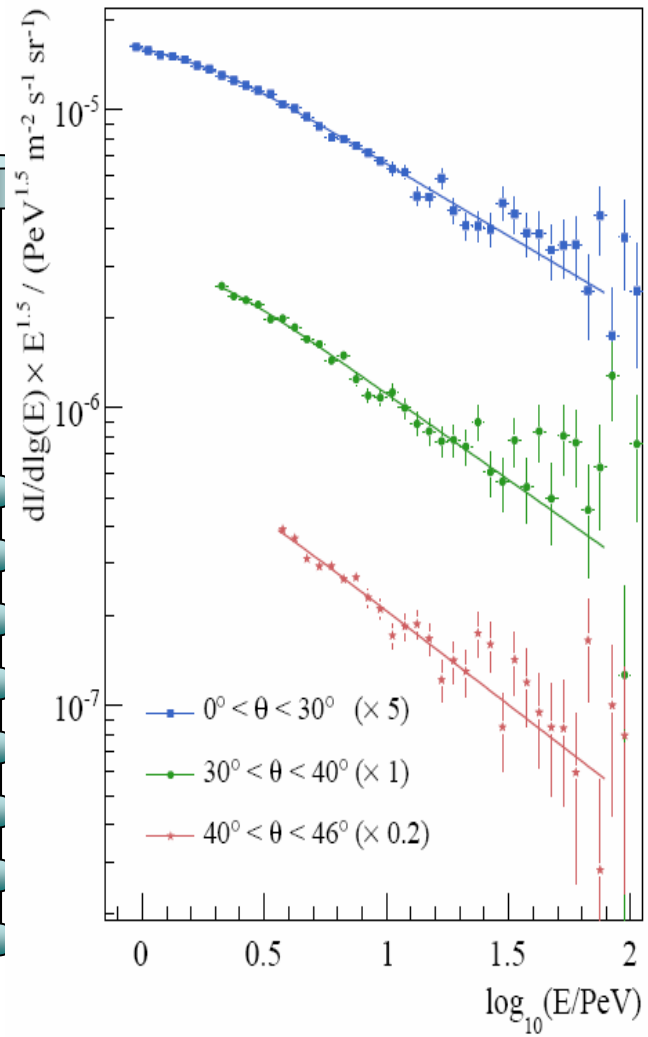
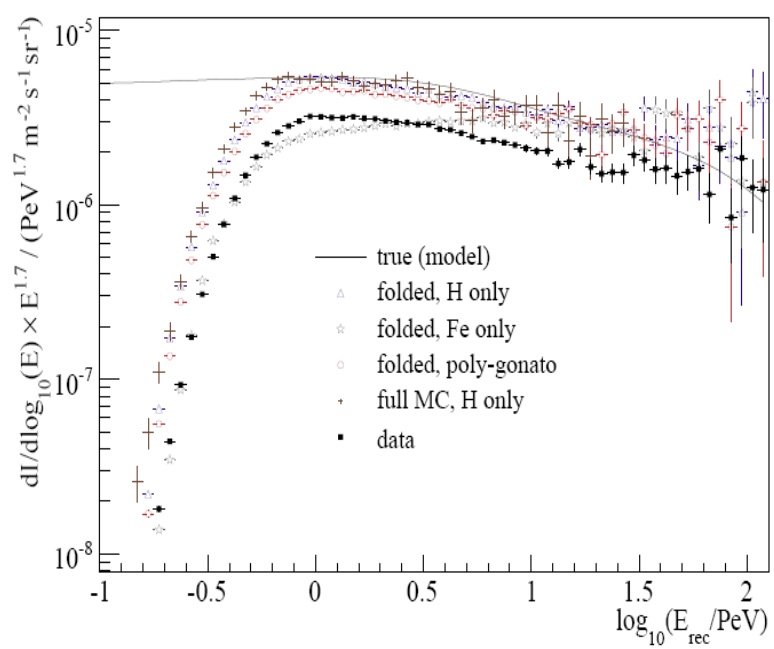
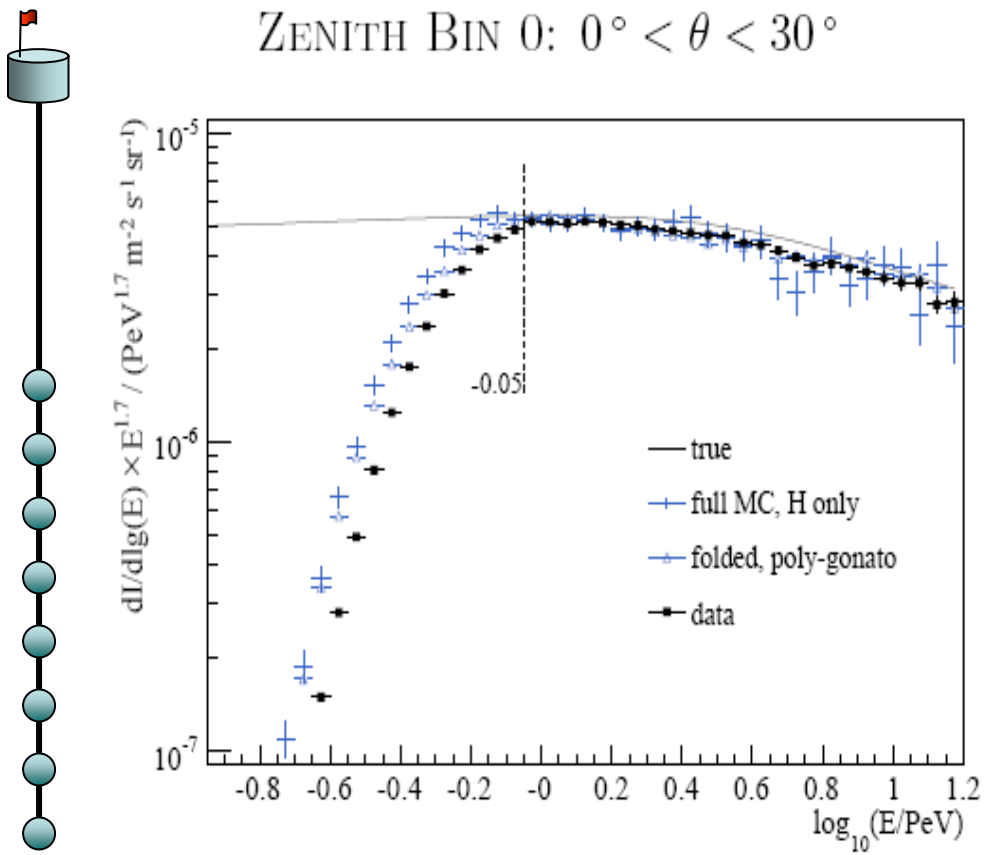


Table 6.3: Parameters of the raw spectra (see eq. 6.1). $I_{\mathrm{PeV,lg}}$ is given in terms of $10^{-6}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, E_{knee} in PeV.

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



- **Done for each Zenith bin**
- **Results:**

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

- **Additional tolerance for unfolded spectra: 2 x width of response matrix**

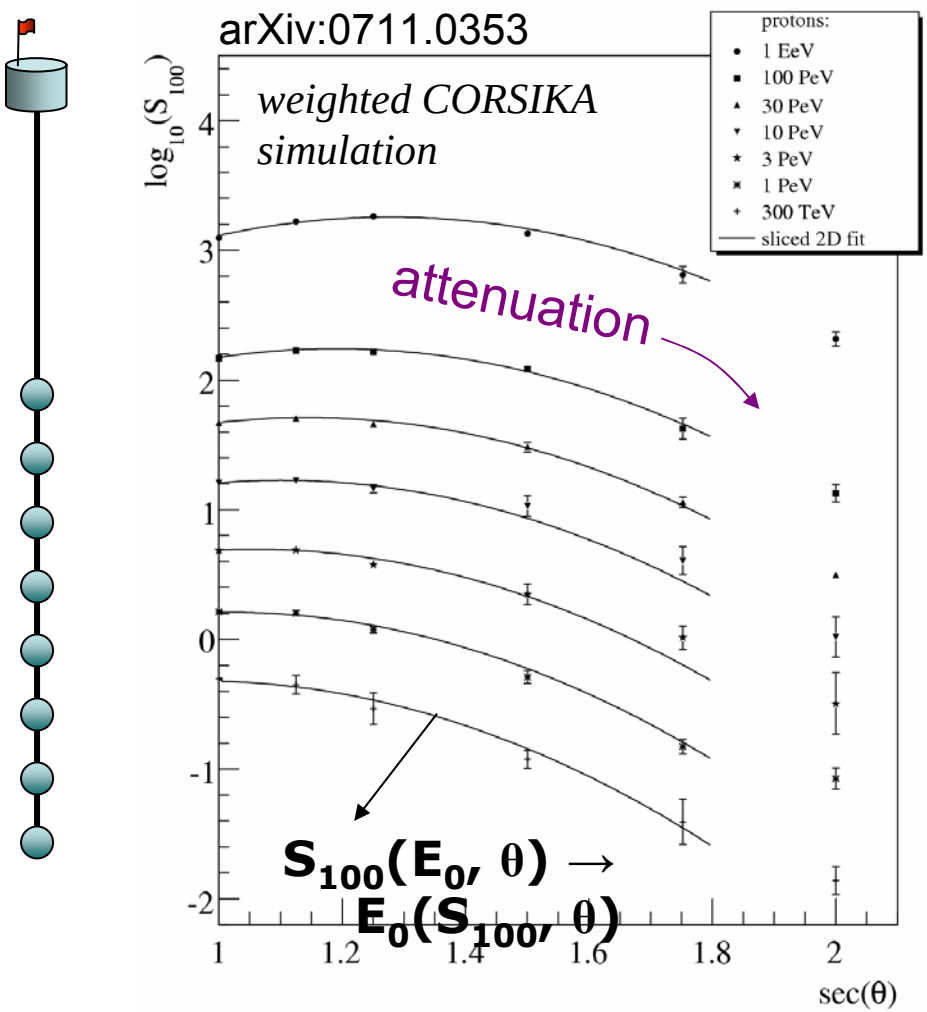
Backup: Fit Function & Parameters

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

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
only protons	Ω_0	3.61(10)	2.66(8)	3.05(2)	2.8(3)	5.8(3.4)	14.2/14
	Ω_1	3.23(5)	–	3.08(3)	–	–	11.6/12
	Ω_2	3.3(2)	–	3.17(6)	–	–	5.7/9
poly-gonato	Ω_0	4.21(9)	2.71(7)	3.12(3)	3.1(3)	4.7(2.7)	9.5/13
	Ω_1	3.92(7)	–	3.10(2)	–	–	14.2/12
	Ω_2	4.2(2)	–	3.13(4)	–	–	5.2/9
two-comp.	Ω_0	4.43(9)	2.75(6)	3.12(3)	3.1(3)	5.4(3.3)	9.7/13
	Ω_1	4.15(5)	–	3.11(2)	–	–	16.2/12
	Ω_2	4.6(2)	–	3.16(4)	–	–	5.4/9
only iron	Ω_0	8.39(4)	3.074(9)	3.29(2)	3.7(3)	2.7(7.0)	11.7/13
	Ω_1	9.91(9)	–	3.28(2)	–	–	21.7/13
	Ω_2	14.2(7)	–	3.37(4)	–	–	6.3/9

Energy Estimation



$$l_{E0}(x, l_{S100}) = p_0 + p_1 x - \sqrt{p_2 + p_3 x - p_4 l_{S100}}.$$

$$p_0 = 24.0269$$
$$p_1 = 11.3414$$
$$p_2 = 459.884$$
$$p_3 = 805.717$$
$$p_4 = 69.9528$$

$x = \sec \theta$

→ Analytical Function to assign S_{ref} and θ an energy estimator for proton assumption

S. Klepser et al., arXiv:0711.0353

Quantitative Analysis

- **Calculating Likelihood Ratios**

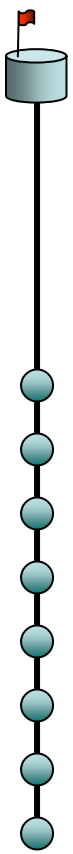
➢ **Clear Preference of mixed composition models!**

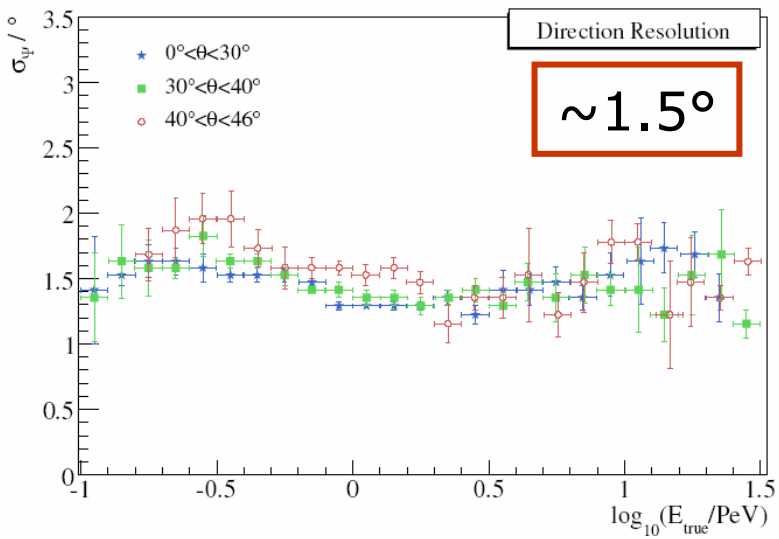
➢ **Complementary approach, ~ independent of muon multiplicities in HE interactions!**

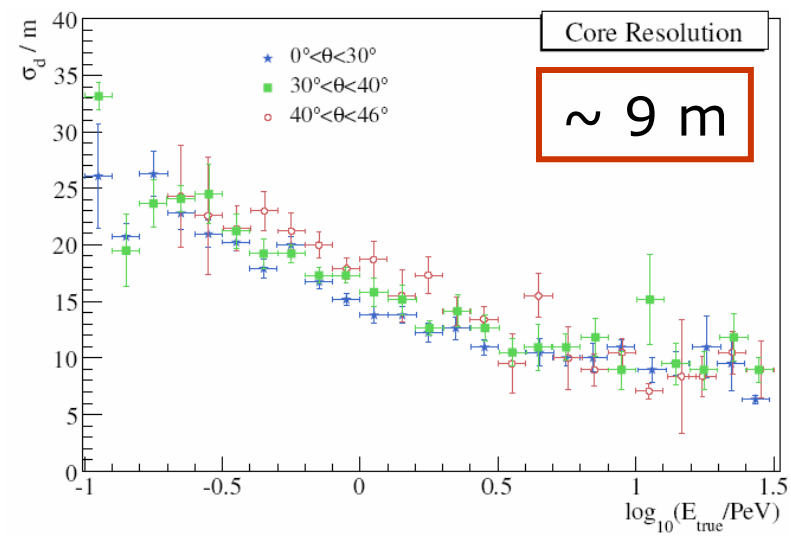
	only protons	poly-gonato	two-components	only iron
(a) fit parameter compatibility				
$I_{\mathrm{PeV,lg}}$	3.34(12)	4.05(10)	4.26(11)	8.8(5)
χ^2/ndf	10.0/2	6.9/2	8.4/2	257/2
prob.	$6.7 \cdot 10^{-3}$	$3.2 \cdot 10^{-2}$	$1.53 \cdot 10^{-3}$	$6.9 \cdot 10^{-11}$
$-\gamma_2$	3.07(2)	3.110(14)	3.120(14)	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.	$9.8 \cdot 10^{-4}$	$2.3 \cdot 10^{-2}$	$8.2 \cdot 10^{-3}$	$8.7 \cdot 10^{-12}$
(b) single bin compatibility				
prob.	$4.5 \cdot 10^{-11}$	$1.06 \cdot 10^{-3}$	$1.13 \cdot 10^{-3}$	$2.3 \cdot 10^{-17}$
(c) integral compatibility				
χ^2/ndf	20.0/2	1.9/2	1.7/2	42.4/2
prob.	$4.6 \cdot 10^{-5}$	$4.0 \cdot 10^{-1}$	$4.2 \cdot 10^{-1}$	$6.2 \cdot 10^{-10}$

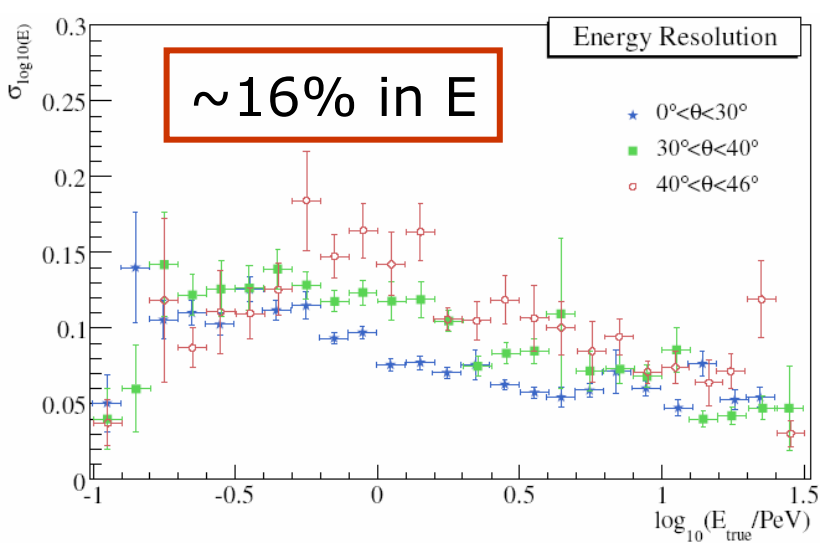
Likelihood Ratios

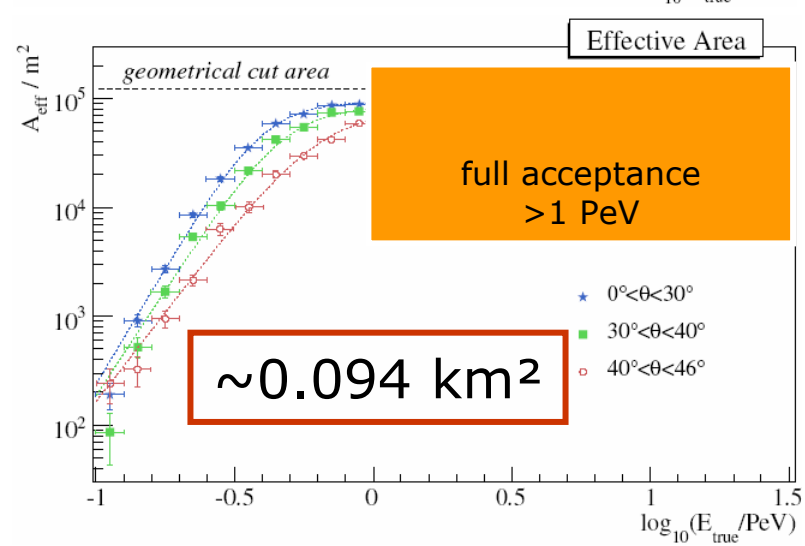
Resolution & Efficiency











numbers given for zenith angles 0°-30°!

Quantitative Analysis

- **Calculating Likelihood Ratios**

  - **Clear Preference of mixed composition models!**

  - **Complementary approach, ~ independent of muon multiplicities in HE interactions!**