Atmospheric Muons Measured with IceCube

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Outline

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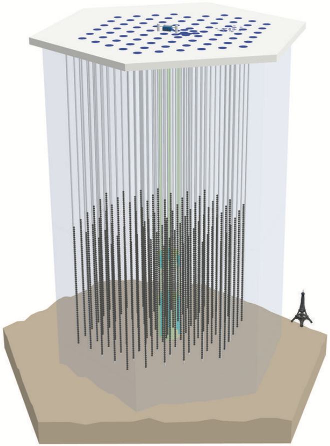
4. Summary



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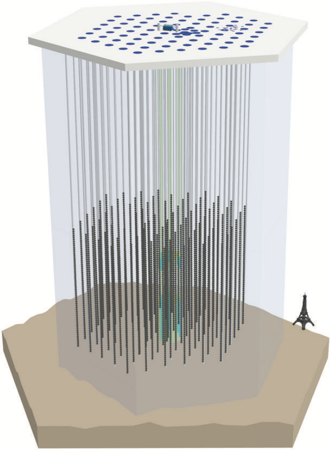
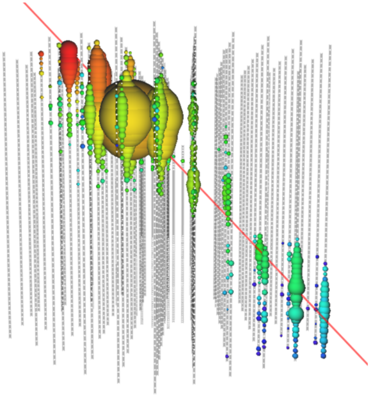
Introduction

- **IceCube** (this talk)
  - Geographic South Pole
  - $\sim 1\,\text{km}^3$ instrumented volume
  - Between 1450 – 2450 m deep
  - 5160 optical modules, 86 strings
  - Trigger rate of $\sim 2.1\,\text{kHz}$
    (> 8 hits in $5\,\mu$s)
  - Mainly atmospheric muons
    ($E_\mu >$ few 100GeV)
  - **Air shower measurements**
- **IceTop**
  - $\sim 1\,\text{km}^2$ surface array
  - 162 tanks in 81 stations
  - **Air shower measurements**
    → see talk by K. Andeen



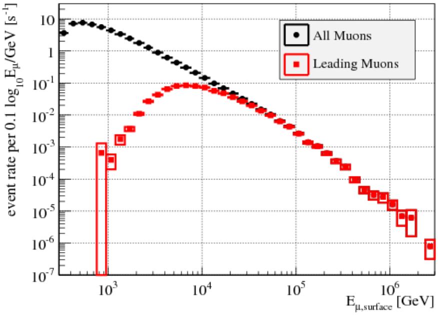
High-Energy Muons

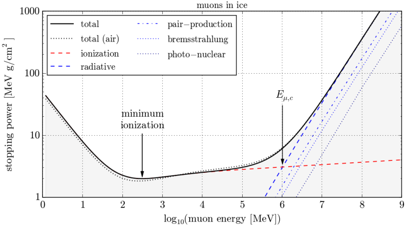
- High-energy (HE) muons ($E_\mu > 10\,\text{TeV}$) are produced during air shower development
- They trigger IceCube together with *'low-energy'* bundle muons ($\sim$ few $100\,\text{GeV}$)
- HE (*'leading'*) muons generate *catastrophic energy losses* along the track
- Energy losses are used to isolate HE muon events and for energy reconstruction

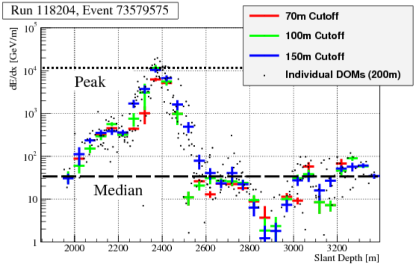


High-Energy Muons

- Radiative (catastrophic) energy losses at high muon energies
- Event selection based on peak over median of energy losses

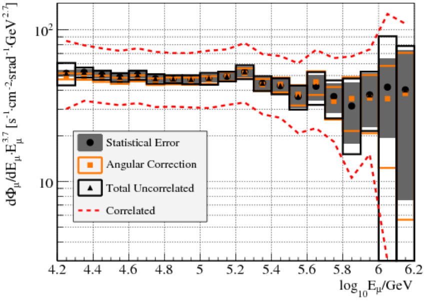






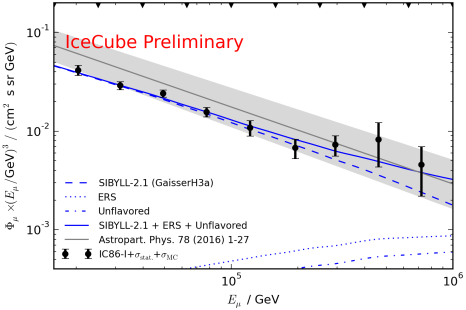
HE Muon Energy Spectrum (Surface Level)

Astropart. Phys. 78 (2016)



- Straight cuts
- Surface correction

XXV ECRS 2016 Proceedings



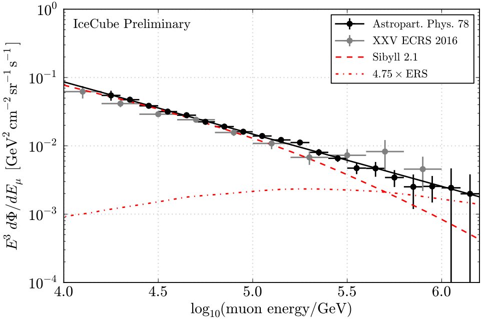
- Machine learning
- Unfolding

Prompt HE Muons

Best fit:

$$\frac{d\Phi}{dE_\mu} = (0.86 \pm 0.03) \times 10^{-10}\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\left(\frac{E_\mu}{10\,\mathrm{TeV}}\right)^{-3.76\pm0.02}$$

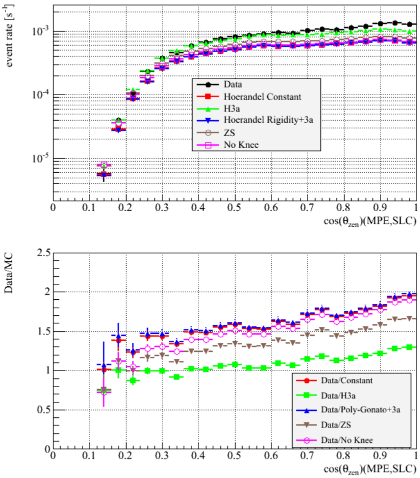
- Results agree within uncertainties
- Assuming H3a* (GST†) flux: $\Phi_{\mathrm{prompt}} = 4.75\,(2.14) \times \mathrm{ERS}^{\ddagger}$
- **Very** large sys. uncertainties!
- $\Phi_{\mathrm{prompt}} = 0$ excluded with $3.97\,(2.64)\sigma$
- Not accounting for decay of unflavored mesons



*[T. K. Gaisser, Astropart. Phys. 35 (2012)]
†[T. K. Gaisser, T. Stanev, S. Tilav, Front. Phys. 8 (2013)]
‡[R. Enberg, M. H. Reno, I. Sarcevic, Phys.Rev. D78 (2008)]

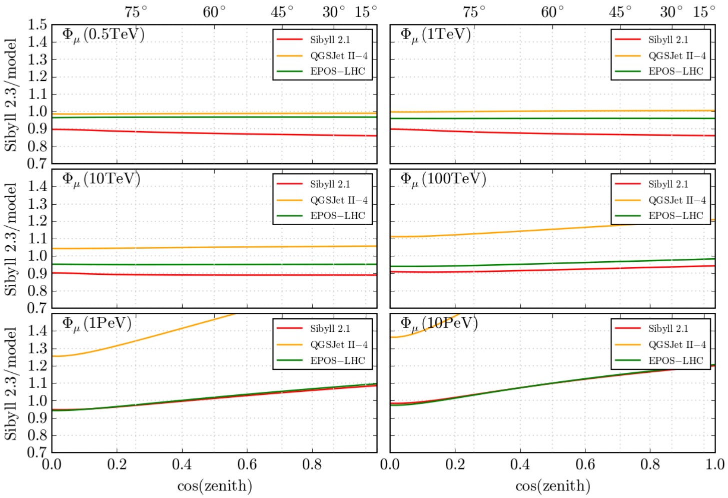
HE Muon Angular Distribution (In Ice)

- Data/MC disagreement in $\cos\theta$
- Only few percent mismatch at trigger level
- Excluded effects:
  - DOM efficiency
  - Ice model
  - Primary flux
  - In-ice photon propagation
- Present for various hadronic models (pre-LHC)
- Any other explanation?



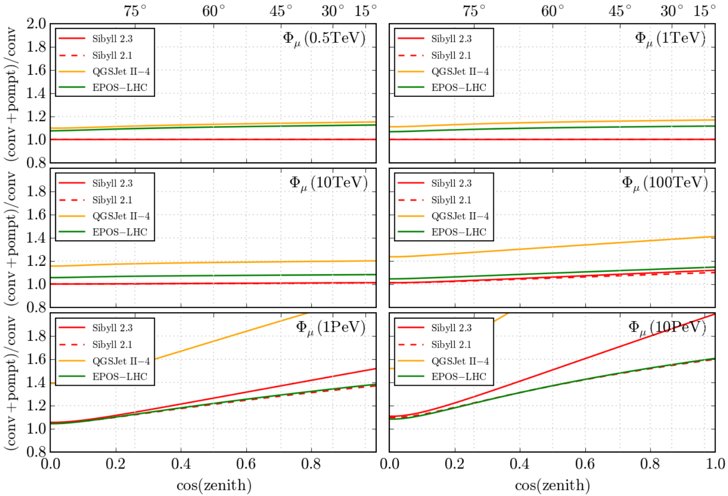
HE Muon Angular Distribution

MCEq flux calculations [A. Fedynitch et al., EPJ Web Conf. 99 (2015)]



HE Muon Angular Distribution

MCEq flux calculations [A. Fedynitch et al., EPJ Web Conf. 99 (2015)]



Here: prompt from Sibyll 2.3c!

HE Muon Angular Distribution

- Zenith angle data/MC discrepancy observed
- MCEq comparisons Sibyll 2.3c vs. other hadronic models

$\rightarrow$ **Evidence that HE muon data/MC discrepancy can be explained by missing prompt in MC simulations**

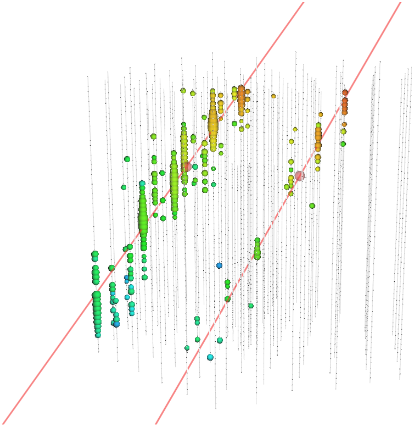
- Full Sibyll 2.3c MC needed!
- In-ice Sibyll 2.3c CORSIKA MC in preparation
- New analysis using three years of data (almost) ready to be published!
- Stay tuned..

Laterally Separated Muons

- High energy cosmic ray interaction can produce secondaries with large transverse momentum p_{T} that might decay into muons
- Isolated muons (LS muons) separate from shower core while traveling to the detector
  $\rightarrow$ **double track signature**
- **Lateral separation**:

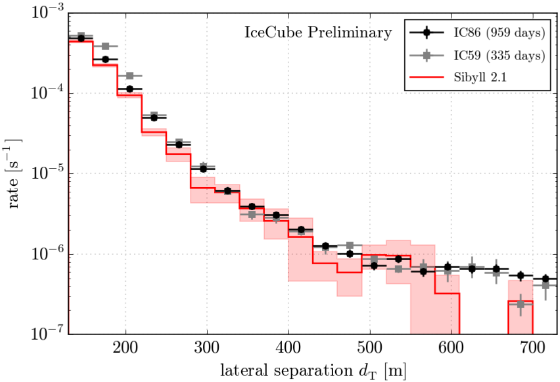
$$d_{\mathrm{T}} \simeq \frac{p_{\mathrm{T}} \cdot H}{E_{\mu} \cdot \cos(\theta)}$$

- Minimal resolvable track separation
  $\rightarrow d_{\mathrm{T}} \sim 135$ m
  $\rightarrow$ typical $p_{\mathrm{T}} > 2$ GeV/c $\rightarrow$ pQCD regime



Lateral Separation (In Ice)

- 80951 events in 960 days of data after final event selection
- Good agreement with previous IceCube results* (IC59)



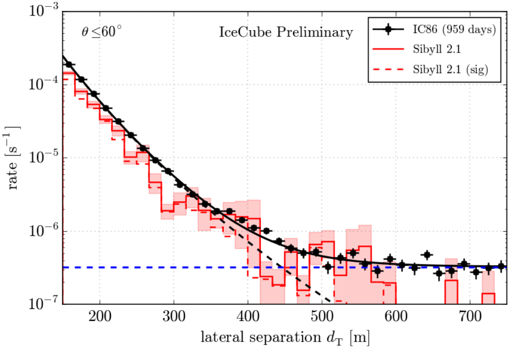
*[Phys. Rev. D 87 (2013)]

Lateral Separation (In Ice)

QCD-inspired Hagedorn fit*:

$$\alpha \cdot \left(1 + \frac{d_\mathrm{T}}{d_0}\right)^{\beta} + C$$

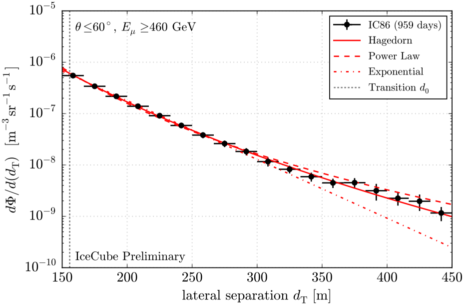
- C: constant irreducible background contribution (blue line)
- Background bin-wise subtracted for further analysis
- Sibyll 2.1 underestimates LS muon event rate (H3a flux)

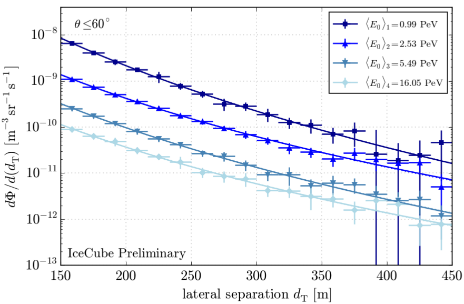


*[R. Hagedorn, Riv. Nuovo Cim. 6 N10 (1983)]

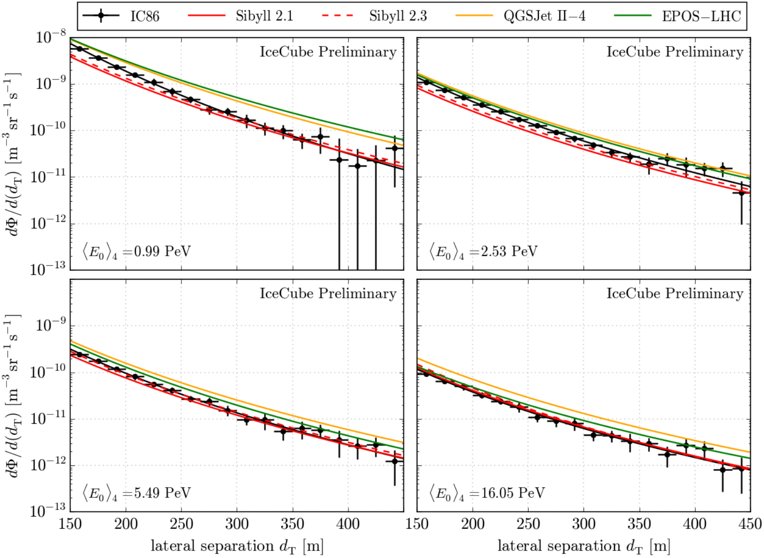
Lateral Separation (Surface Level)

- Lateral separation distribution after background subtraction (4 primary cosmic ray energy bins)
- Accounting for trigger/filter efficiencies, using effective areas
- **Hagedorn fit:** transition from soft (exponential) to hard (power law) regime at around $d_0 \simeq 160\,\mathrm{m}$ favored over pure fits

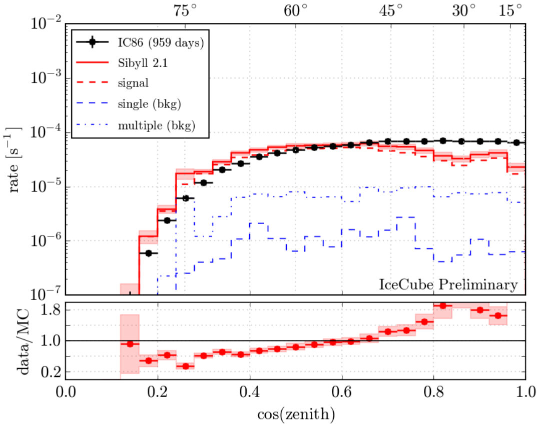




Lateral Separation (Surface Level)



LS Muon Angular Distribution



- Significant data/MC disagreement (similar in HE muon analysis)
- Known from previous IceCube IC59 analysis*

*[Phys. Rev. D 87 (2013)]

LS Muon Angular Distribution

- **Zenith angle data/MC discrepancy:**
  - Trigger level: $< 5\%$
  - HE muons: $20 - 30\%$
  - LS muons: $> 50\%$
- Evidence that HE muon discrepancy can be **explained by missing prompt**
- LS muon analysis: typical LS muon energy $\sim 1\,\text{TeV}$
  $\rightarrow$ Unlikely due to missing prompt
- Other effects of hadronic models (e.g. p_T modelling)?
- Large production heights ($\sim 30\,\text{km}$)
  $\rightarrow$ Atmospheric models?
- **Waiting for Sibyll 2.3c in-ice CORSIKA simulations...**

Summary

- **HE muon analyses:**
  - HE muon spectrum
  - Evidence for prompt component ($> 2.6\sigma$)
  - Zenith angle data/MC discrepancy
    → Likely explained by missing prompt in MC
- **LS muon analysis:**
  - Lateral separation of isolated muons between $150 - 450\,\text{m}$
  - First primary energy dependent analysis
  - Zenith angle data/MC discrepancy
    → Not yet understood... also hadronic model?

→ **Publications in preparation...** (waiting for Sibyll 2.3c MC)

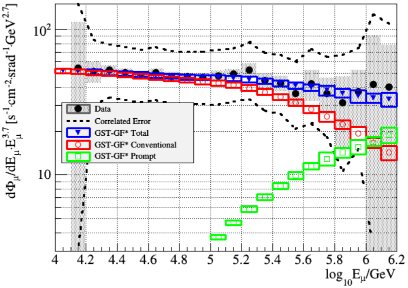
- **Not covered in this talk:**
  - Forward muons with large Feynman-x [PoS(ICRC2017)317]
  - Seasonal variations of muons [ICRC 2011 Proceedings]

Thank you!

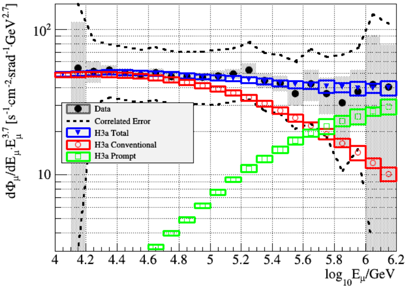
Backup

HE Muon Energy Spectrum (Surface Level)

GST primary spectrum
[Front. Phys. (Beijing) 8 (2013)]

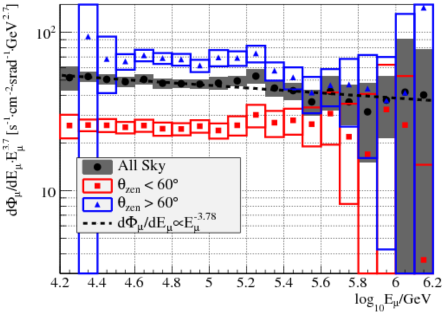


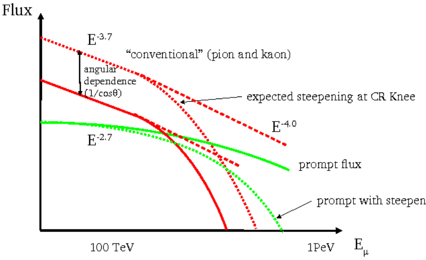
H3a primary spectrum
[Astropart. Phys. 35 (2012)]



CR Model	Best Fit (ERS)	χ^2/dof	1σ Interval (90% CL)	Pull ($\Delta\gamma$)	$\sigma(\Phi_{Prompt} > 0)$
GST-Global Fit [13]	2.14	7.96/9	1.27 - 3.35 (0.77 - 4.30)	0.01	2.64
H3a [13]	4.75	9.09/9	3.17 - 7.16 (2.33 - 9.34)	-0.03	3.97
Zats.-Sok. [35]	6.23	13.98/9	4.55 - 8.70 (3.59 - 10.68)	-0.23	5.24
PG Constant $\Delta\gamma$ [33]	0.94	9.07/9	0.36 - 1.63 (< 2.15)	0.03	1.52
PG Rigidity [33]	6.97	5.86/9	4.73 - 10.61 (3.53 - 13.83)	-0.06	4.35

HS Muon Energy Spectrum (Surface Level)



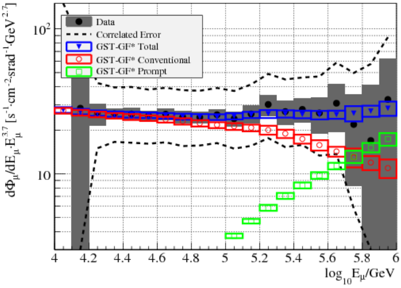


- Zenith dependence of prompt muon flux
- Experimentally measured fraction of prompt muons:

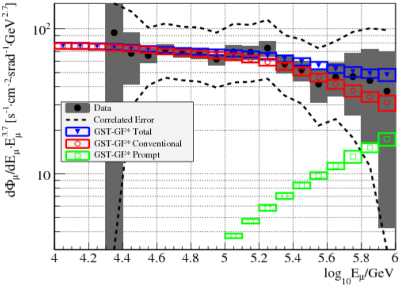
$$f_{\text{prompt}}(E_\mu, \cos(\theta)) = \frac{\Phi_{\text{prompt}}(E_\mu, \cos(\theta))}{\Phi_{\text{total}}(E_\mu, \cos(\theta))} \simeq \left(1 + \frac{E_{1/2} \cdot \cos(\theta)}{E_\mu \cdot (1 + \alpha \cdot \cos(\theta))}\right)^{-1}$$

HE Muon Energy Spectrum (Surface Level)

$0° \leq \theta < 60°$ (GST)

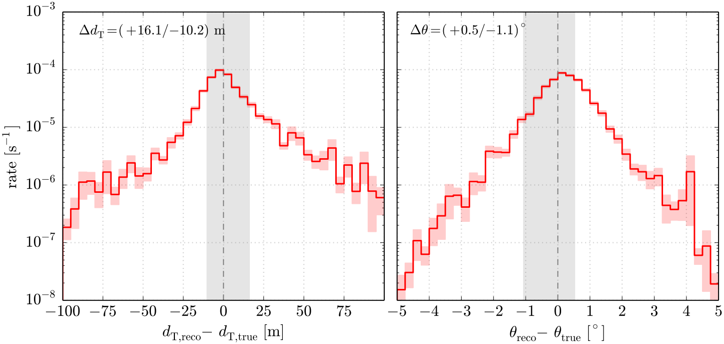


$60° \leq \theta < 84°$ (GST)

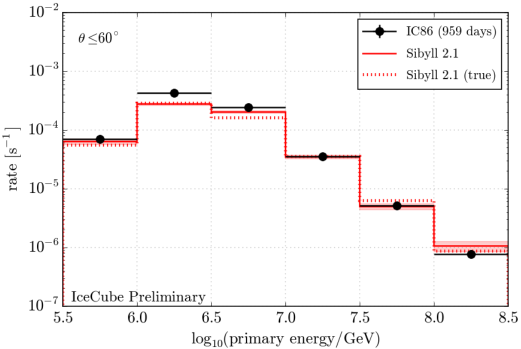


Double Track Reconstruction

- **Dedicated double track reconstruction** based on two-step hit splitting and two separate likelihood fits
- For details see [Phys. Rev. D 87 (2013)]



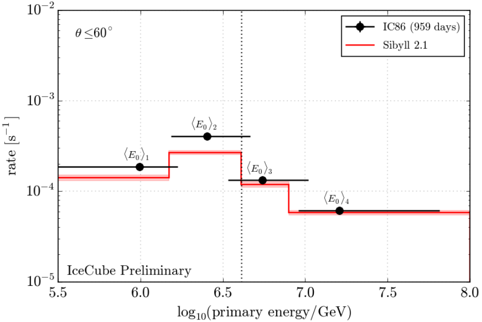
Primary Energy



Primary Energy

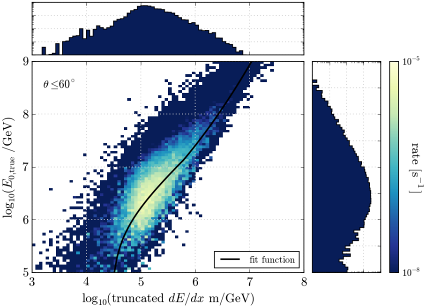
- First energy-dependent measurement of lateral separation
- Energy spectrum derived from deposited energy in the detector*

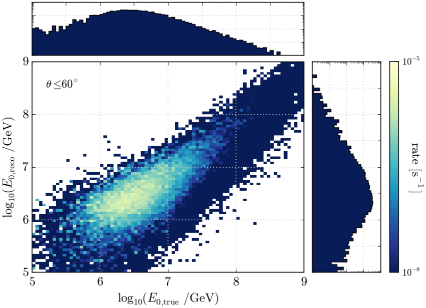
Energy bins	
$\langle E_0 \rangle_1$	0.99 PeV
$\langle E_0 \rangle_2$	2.53 PeV
$\langle E_0 \rangle_3$	5.49 PeV
$\langle E_0 \rangle_4$	16.05 PeV



*[Nucl. Instr. Meth. A703 (2013)]

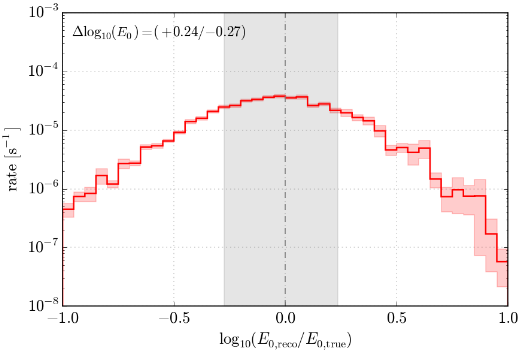
Primary Energy Estimator



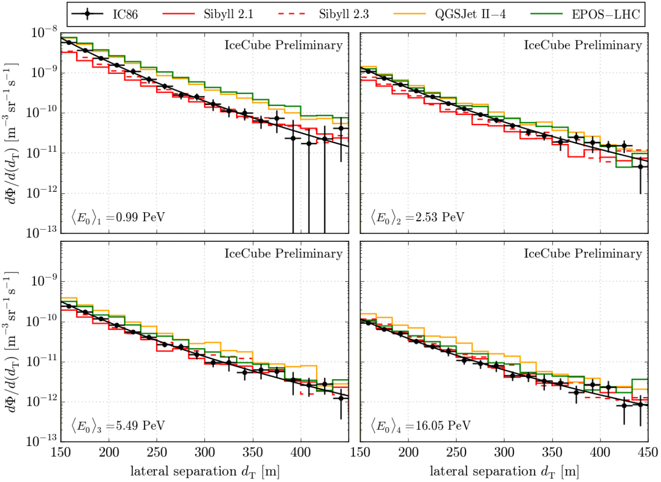


For details see [Nucl. Instr. Meth. A703 (2013)]

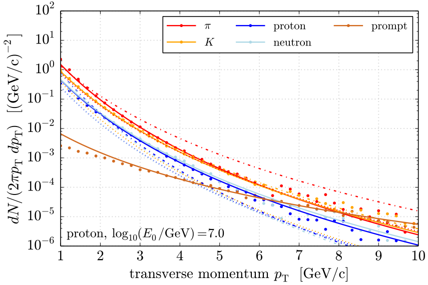
Primary Energy Estimator

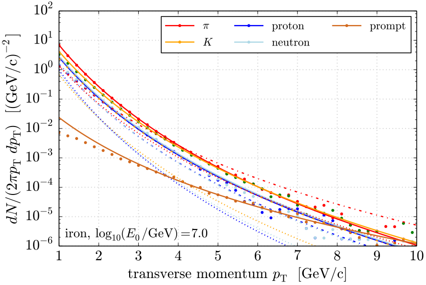


Lateral Separation (Surface Level)



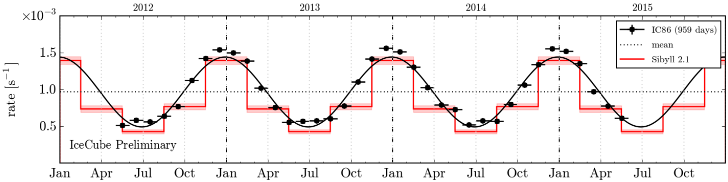
Transverse Momentum





Solid: EPOS-LHC
Dashed-dotted: QGSJet II-4
Dotted: Sibyll 2.1

LS Muon Seasonal Variations



- Very large seasonal variations on $\sim 50\%$ level
- Due to selection of muons from high altitudes (~ 35 km)
- Information about highest atmospheric layers?

LS Muon Seasonal Variations