Measurement of the diffuse neutrino flux by a global fit to multiple IceCube results

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TAUP 2013
High Energy Astrophysics II

Asilomar, California – September 10, 2013

HELMHOLTZ | ASSOCIATION

DESY

ICECUBE

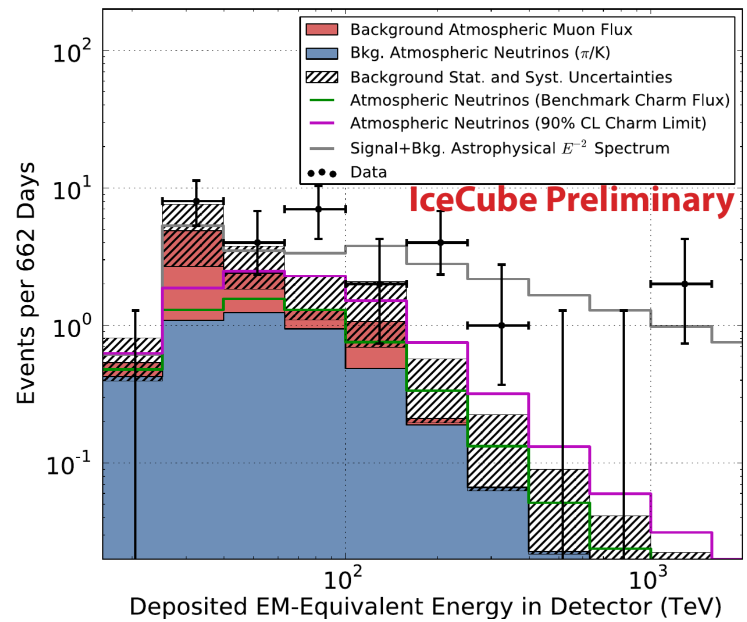
You may have heard the news...

PRL **111,** 021103 (2013) PHYSICAL REVIEW LETTERS week ending 12 JULY 2013

First Observation of PeV-Energy Neutrinos with IceCube

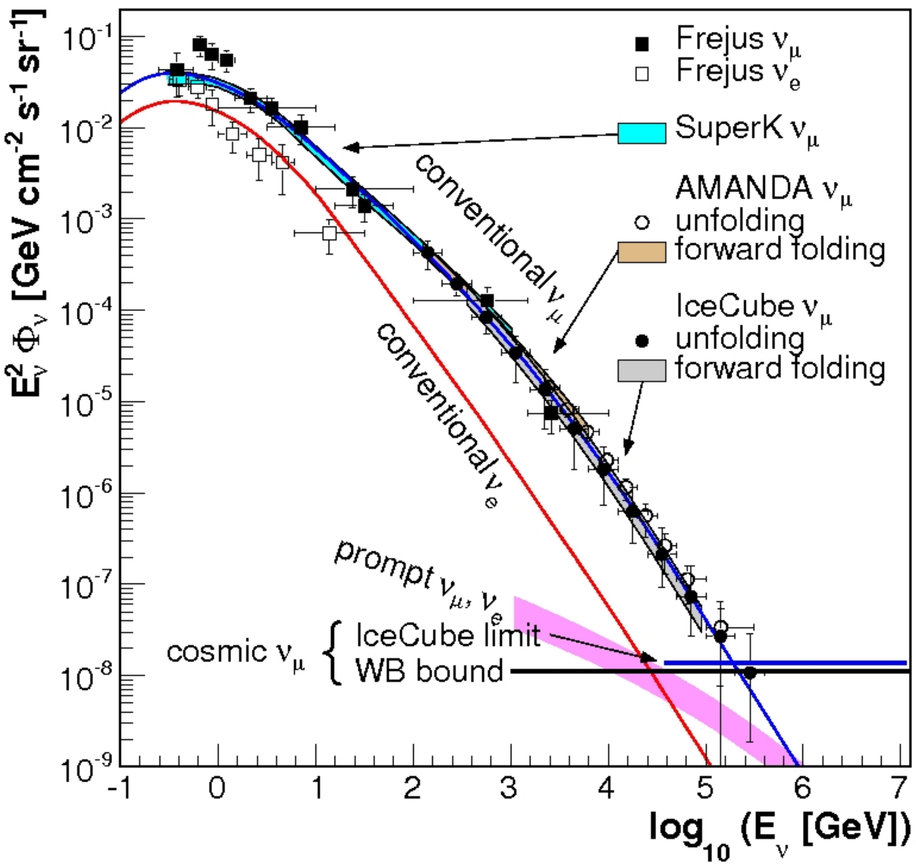
Observation of PeV Neutrinos in IceCube

Very high energy events in the 2010/2011 IceCube data



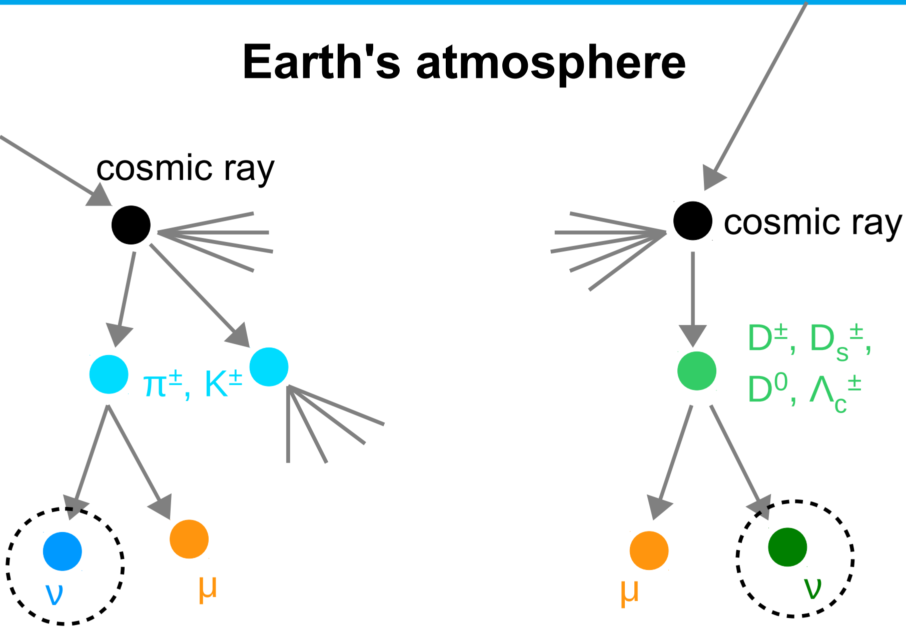
Why are high-energy neutrinos so interesting?

- Atmospheric neutrino spectrum is steeply falling
- Any excess at high energies is a sign for a new source of neutrinos
- Aim of this study: Characterize the excess measured by IceCube



What are the possible sources of high-energy neutrinos?

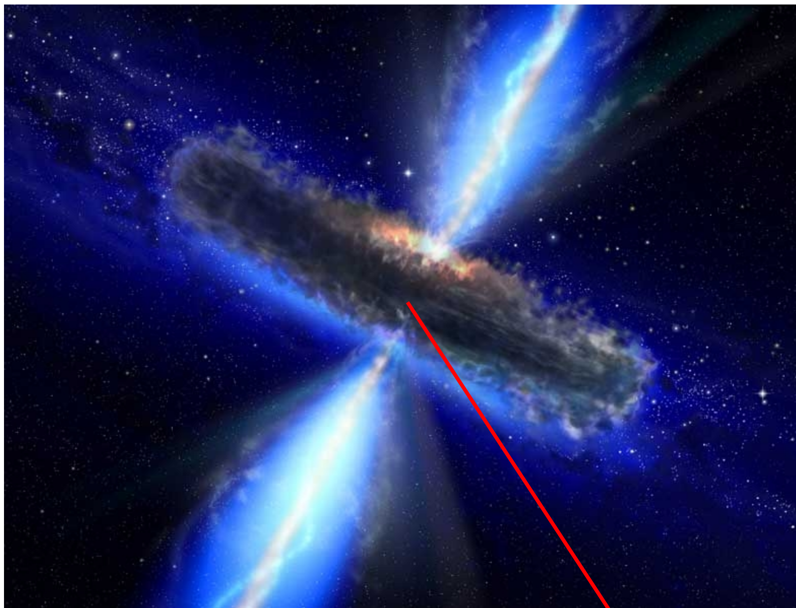
Earth's atmosphere



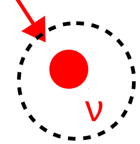
- **“Conventional”**
- From π / K decay
- dN/dE ~ $E^{-3.7}$

- **“Prompt”**
- From charmed meson decay
- dN/dE ~ $E^{-2.7}$
- Undetected so far

Astrophysical sources



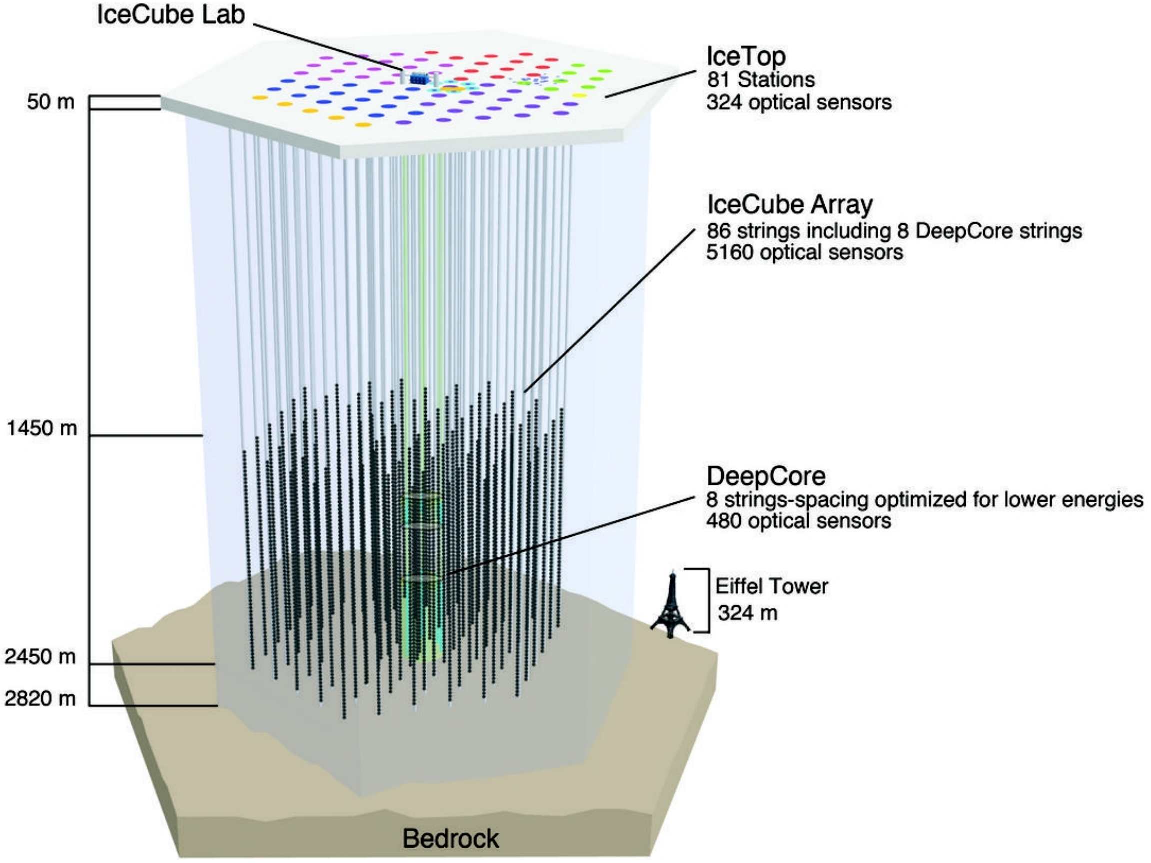
http://www.nasa.gov



- **Astrophysical**
- Fermi acceleration
- dN/dE ~ E^{-2}
- Flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ = 1 : 1 : 1
- No astrophysical sources yet

The IceCube Neutrino Observatory

- **1 km^3** of South Pole Ice instrumented with **5160 PMTs**
- Detect neutrino interactions via **Cherenkov radiation** of secondary particles
- Full detector with **86 strings** completed in **2010** → **IC86**
- Previous configurations:
  - **IC79**
  - **IC59**
  - **IC40**

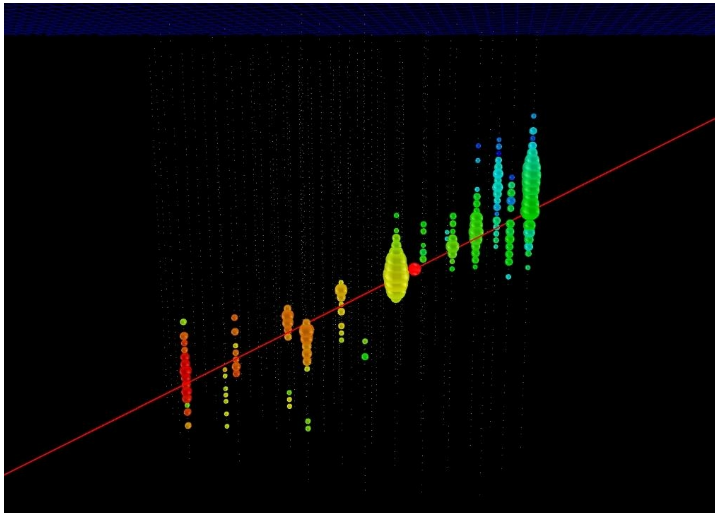


Neutrino event signatures in IceCube

Tracks

- ν_μ charged-current interaction

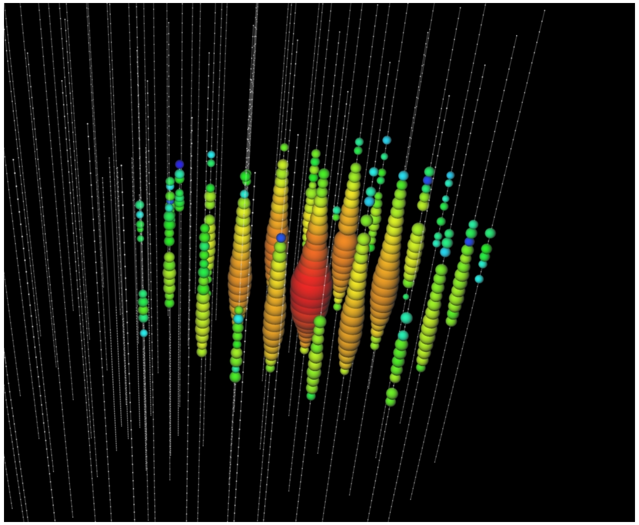
- Angular resolution < 1°
- Can measure muon dE/dx only



Showers

- ν_e + ν_τ charged-current interaction +
  ν_e + ν_μ + ν_τ neutral-current interaction

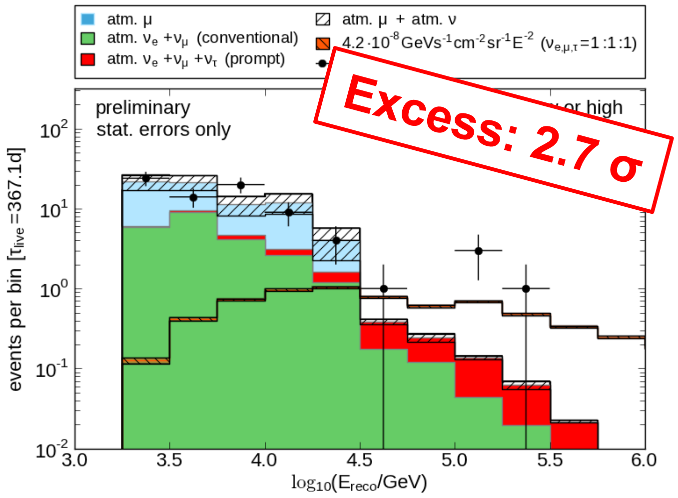
- Angular resolution > 10°
- Energy resolution ≥ 15%
  (on deposited energy)



Searches for a diffuse neutrino flux in IceCube

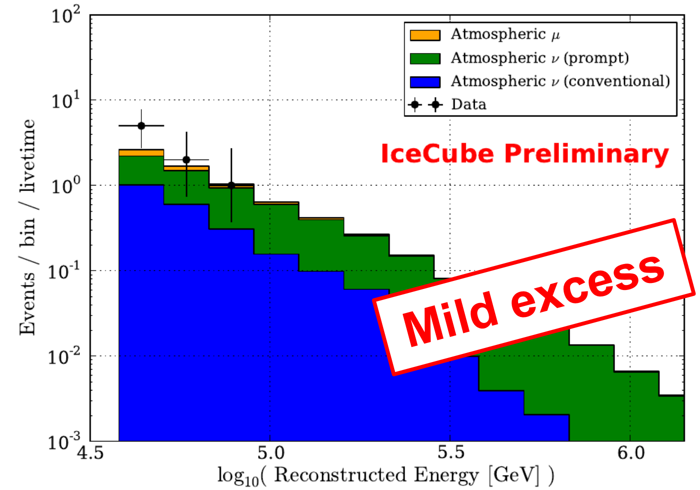
IC40 – contained showers

IceCube Collaboration, in preparation



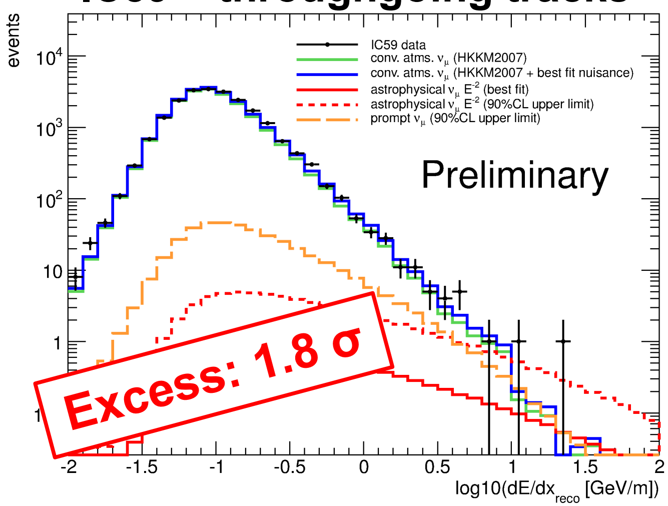
IC59 – contained showers

A. Schönwald et al., ICRC 2013



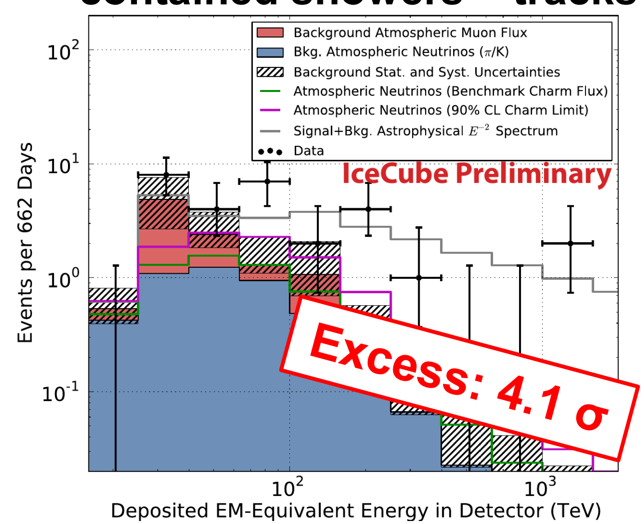
IC59 – throughgoing tracks

A. Schukraft, Nucl. Phys. B (Proc. Suppl.) 237-238, 266 (2013)



IC79 + IC86 contained showers + tracks

IceCube Collaboration, submitted to Science



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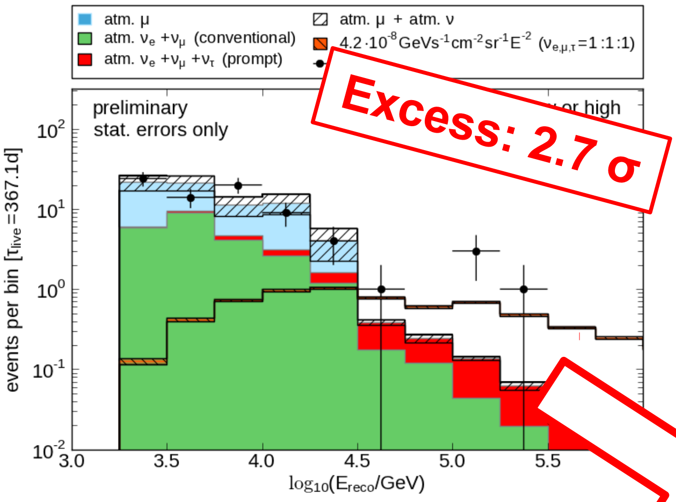

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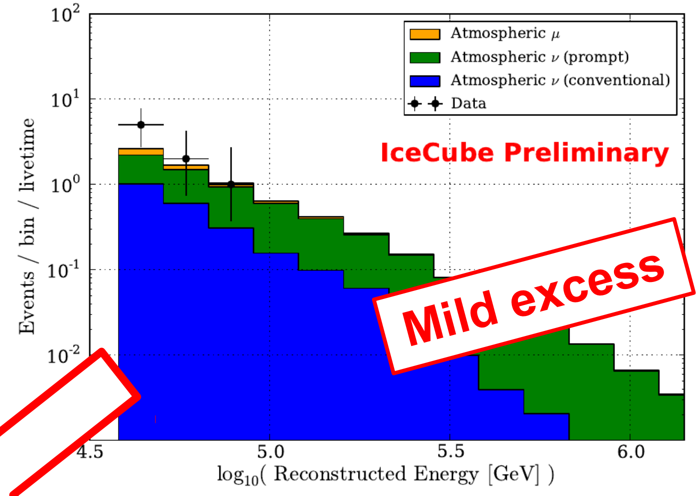

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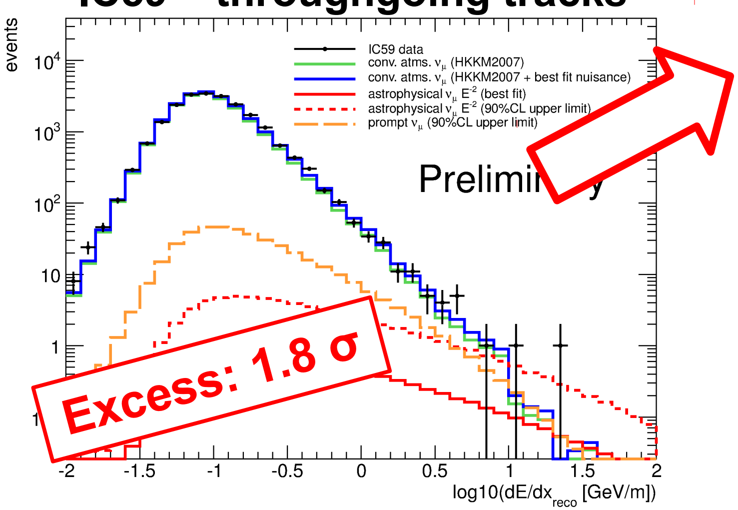

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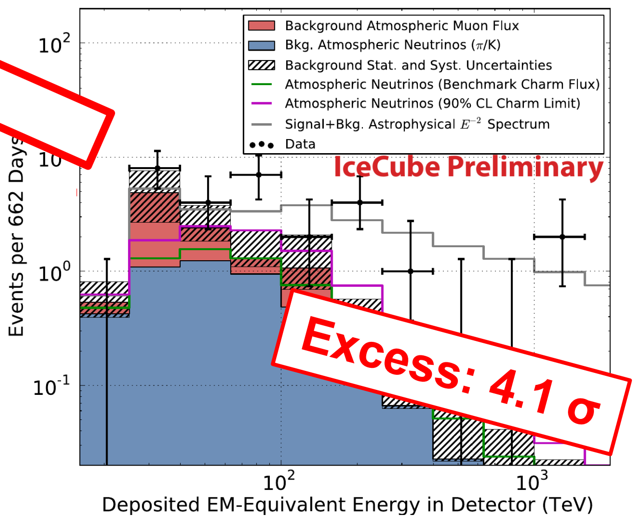

Global likelihood fit

- **Goal:** Characterize the excess by using information from all analyses at the same time
- **Method:** Global Poisson-likelihood fit of energy distributions

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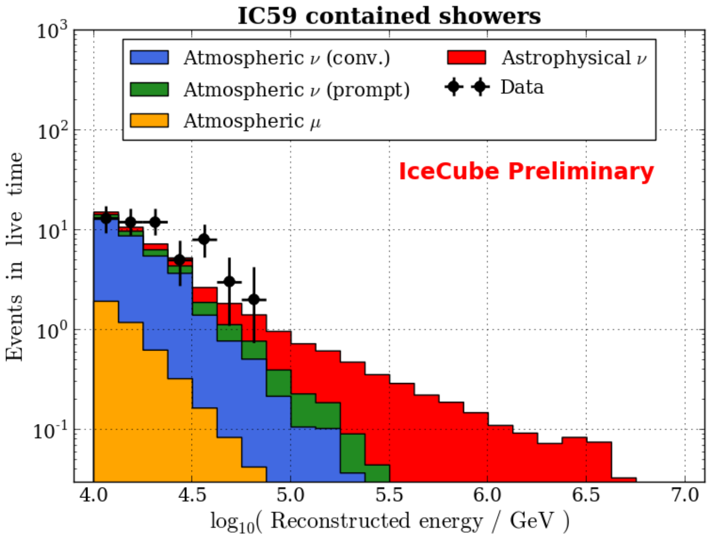
- **Components:**
  - **Atmospheric μ** – **CORSIKA simulation / from data**
  - **Atmospheric ν (conventional)** – **Honda et al.[1] + Gaisser[3] (H3a)**
  - **Atmospheric ν (prompt)** – **Enberg et al.[2] + Gaisser[3] (H3a)**
  - **Astrophysical ν** – **$E^2\Phi = 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}**



[1]Honda et al., Phys. Rev. D 75, 043006 (2007)
[2]Enberg et al., Phys. Rev. D 78, 043005 (2008)
[3]Gaisser, Astropart. Phys. 35, 801-806 (2012)

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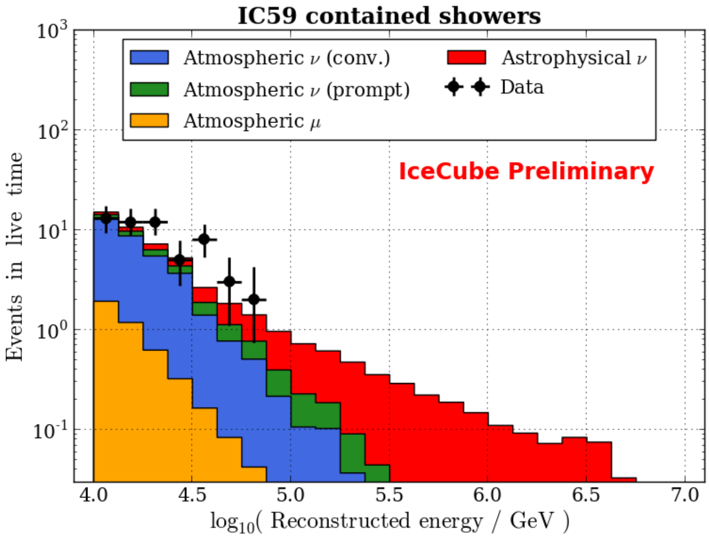

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  - * Nuisance parameters
    → absorb systematic effects

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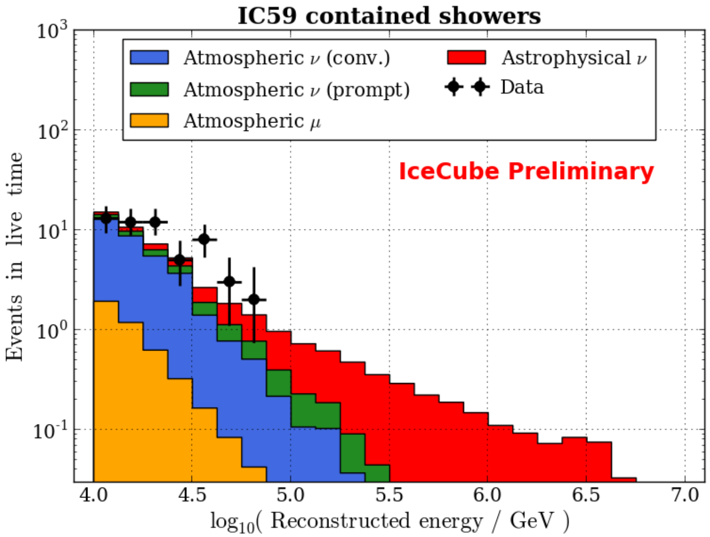

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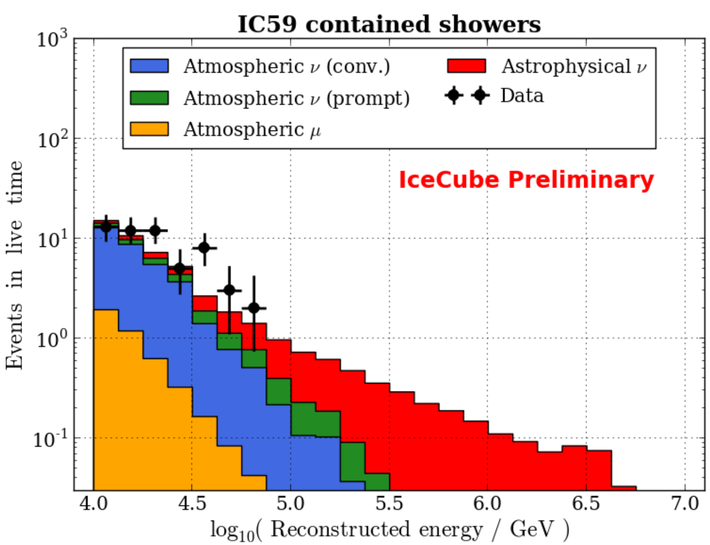

- **Parameters:**
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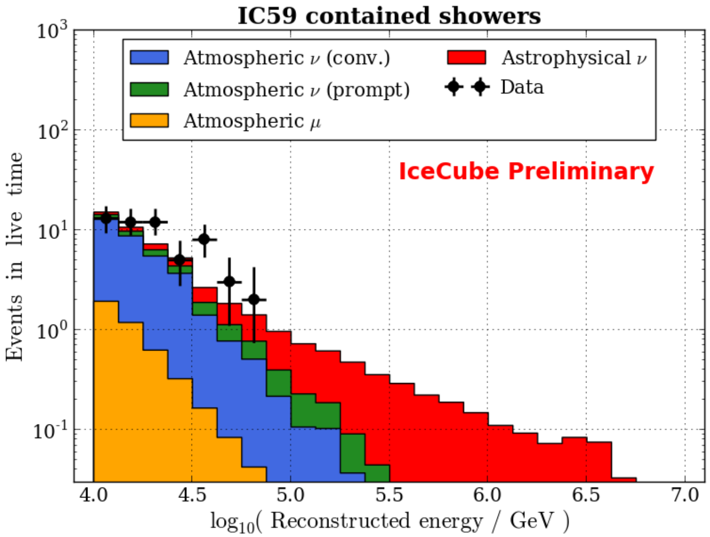

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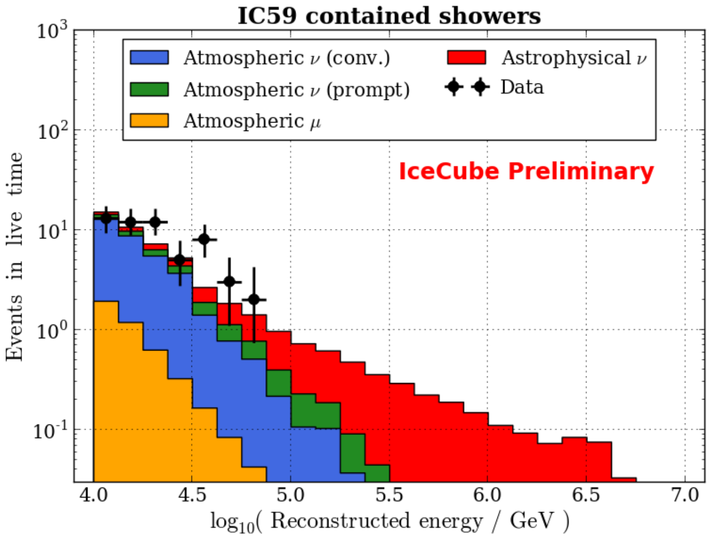

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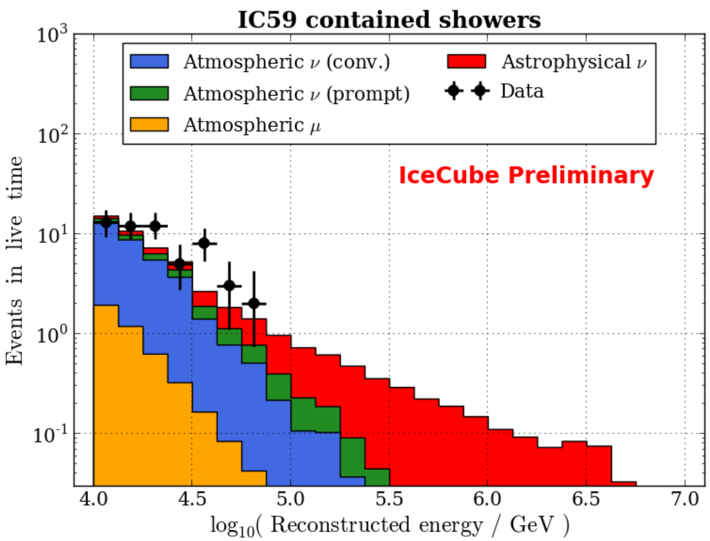

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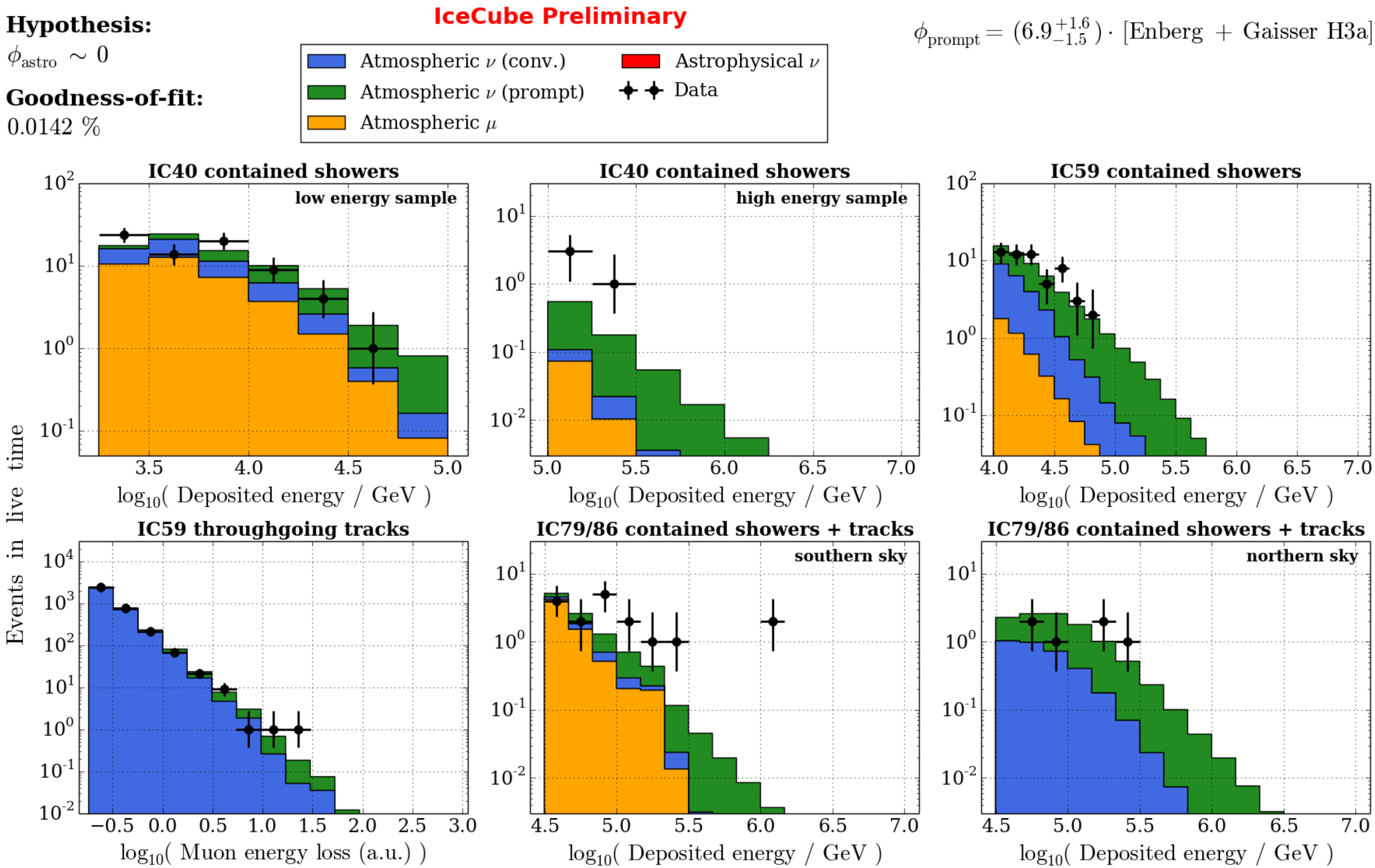
  - Cosmic ray spectral index (μ, ν, ν)*
  - Kaon-to-pion ratio (ν)*
  - Energy scale (μ, ν, ν, ν)*
  - Power law index (ν)
  - Exponential cut-off (ν)
  - * Nuisance parameters → absorb systematic effects

Fit result – background-only hypothesis

Hypothesis:
$\phi_{\text{astro}} \sim 0$

Goodness-of-fit:
0.0142 %

$\phi_{\text{prompt}} = (6.9^{+1.6}_{-1.5}) \cdot$ [Enberg + Gaisser H3a]



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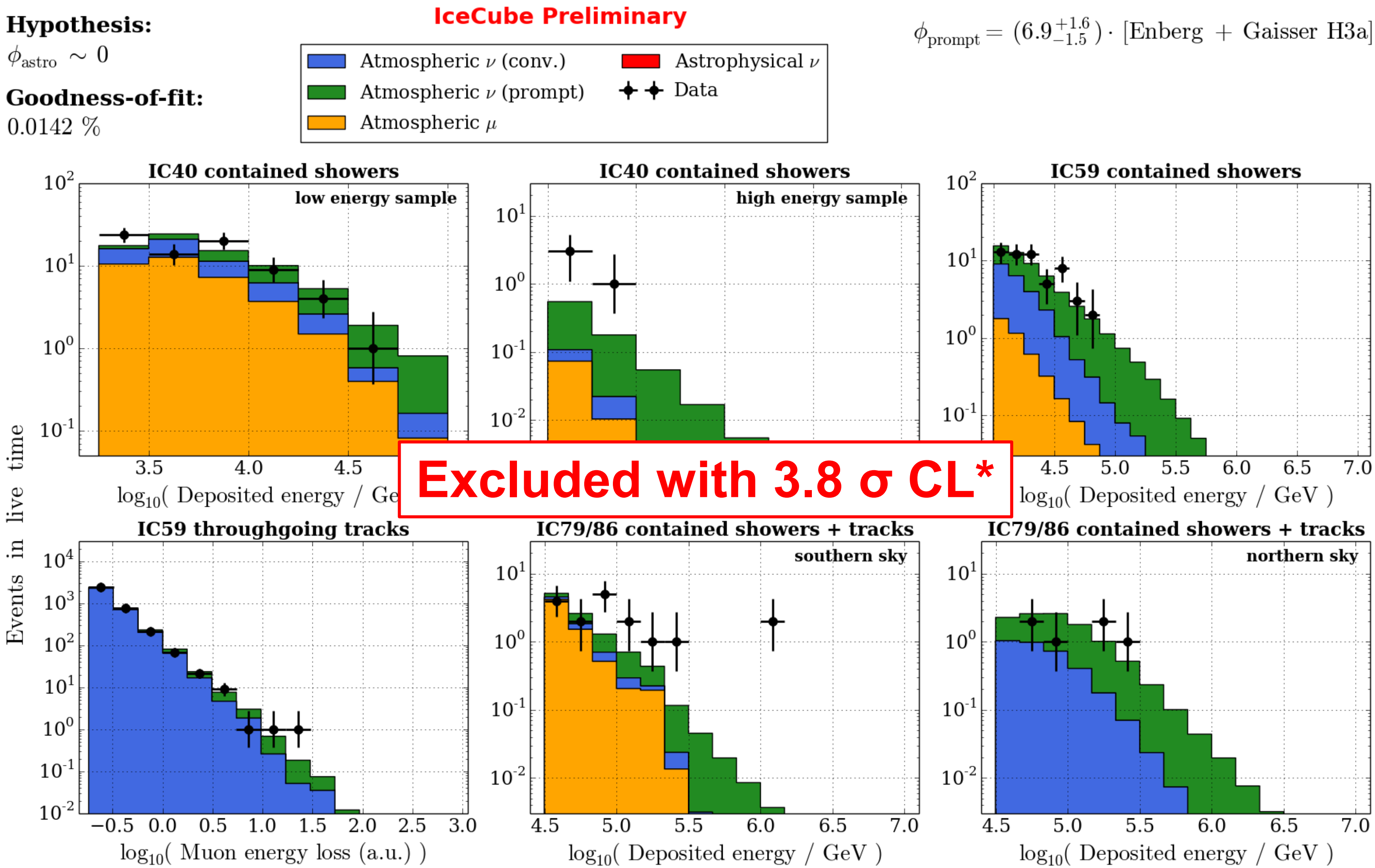


Excluded with 3.8 σ CL*

*** based on a comparison with simulated experiments**

Fit result – with astrophysical signal ($\Phi_{astro} \sim E^{-2}$)

Hypothesis:

$\phi_{astro} \sim E^{-2}$

Goodness-of-fit:

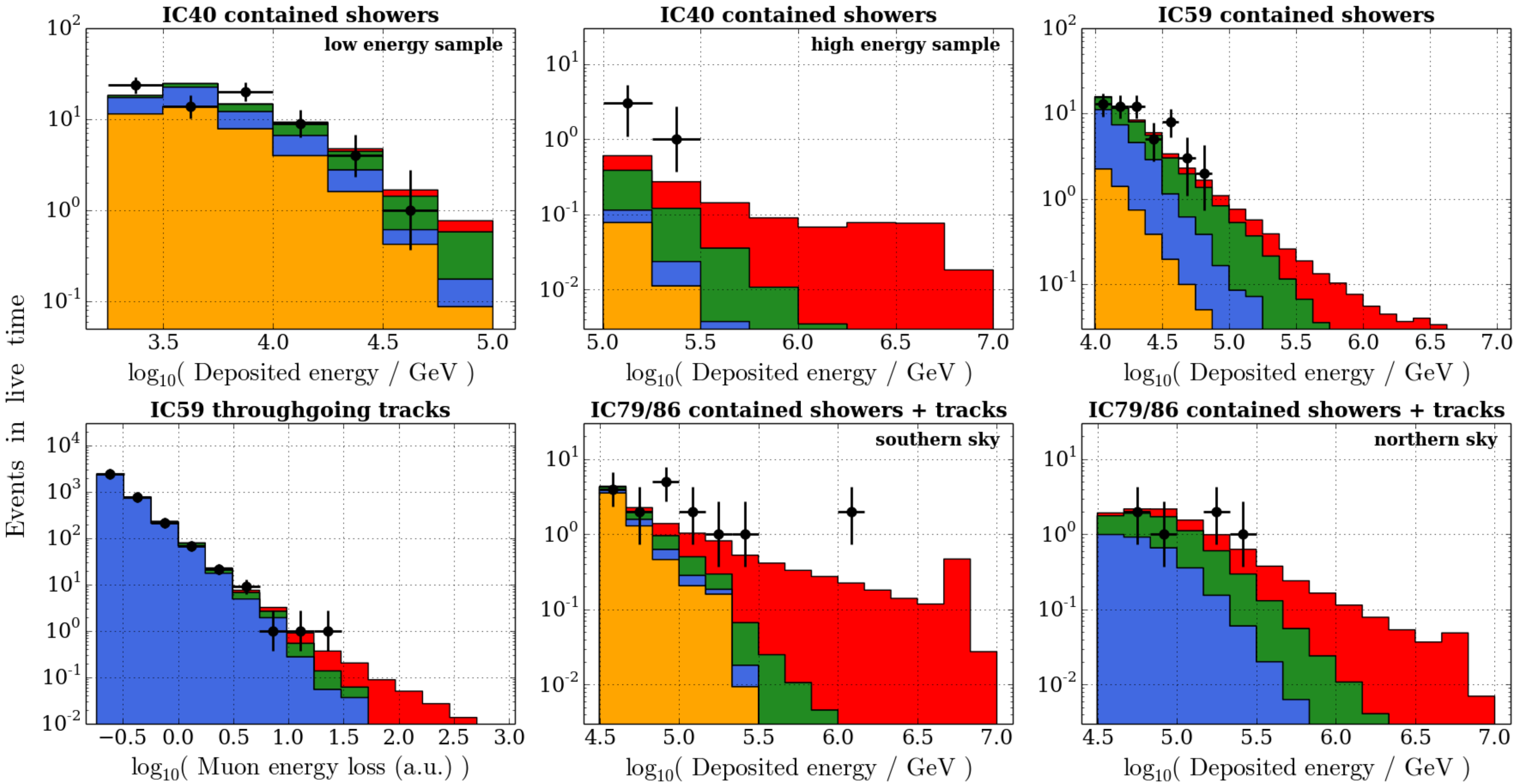
13.2 %

IceCube Preliminary

- Atmospheric ν (conv.)
- Atmospheric ν (prompt)
- Atmospheric μ
- Astrophysical ν
- Data

$$\phi_{prompt} = (4.2^{+1.8}_{-1.7}) \cdot [\text{Enberg + Gaisser H3a}]$$

$$E^2\,\phi_{astro} = (0.47^{+0.24}_{-0.20}) \cdot 10^{-8}\ \text{GeV s}^{-1}\ \text{sr}^{-1}\ \text{cm}^{-2}$$



Fit result – with astrophysical signal ($\Phi_{astro} \sim E^{-2} \cdot e^{E/Ecut}$)

Hypothesis:

$\phi_{astro} \sim E^{-2} \cdot \exp(E/E_{cut})$

Goodness-of-fit:

7.8 %

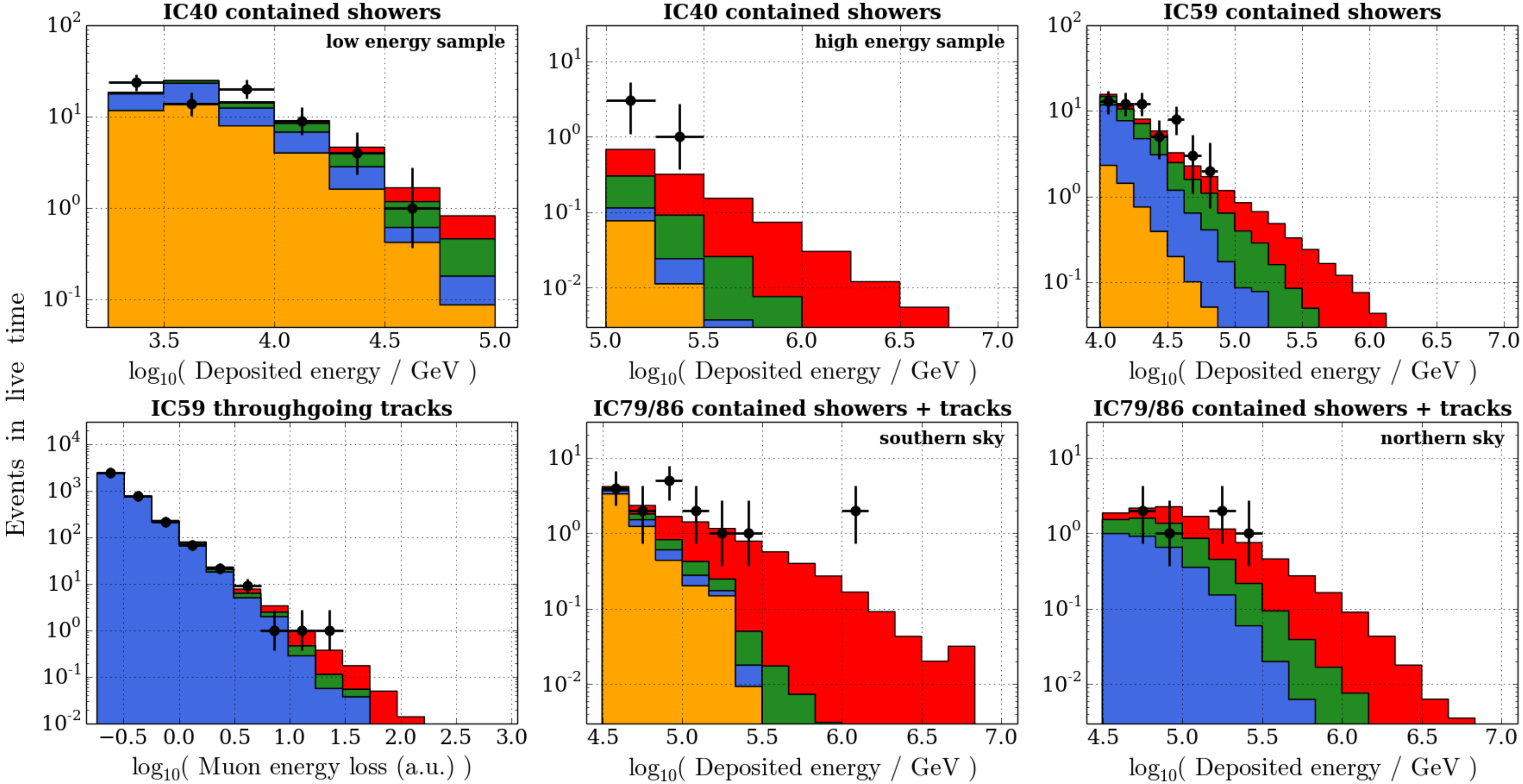
IceCube Preliminary

- Atmospheric ν (conv.)
- Atmospheric ν (prompt)
- Atmospheric μ
- Astrophysical ν
- Data

$\phi_{prompt} = (2.8^{+2.0}_{-2.0}) \cdot$ [Enberg + Gaisser H3a]

$E^2 \phi_{astro} = (1.0^{+0.8}_{-0.5}) \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

$E_{cut} = (1.8^{+5.0}_{-1.0})$ PeV



Fit result – with astrophysical signal ($\Phi_{astro} \sim E^{-\gamma}$)

IceCube Preliminary

Hypothesis:
$\phi_{astro} \sim E^{-\gamma}$

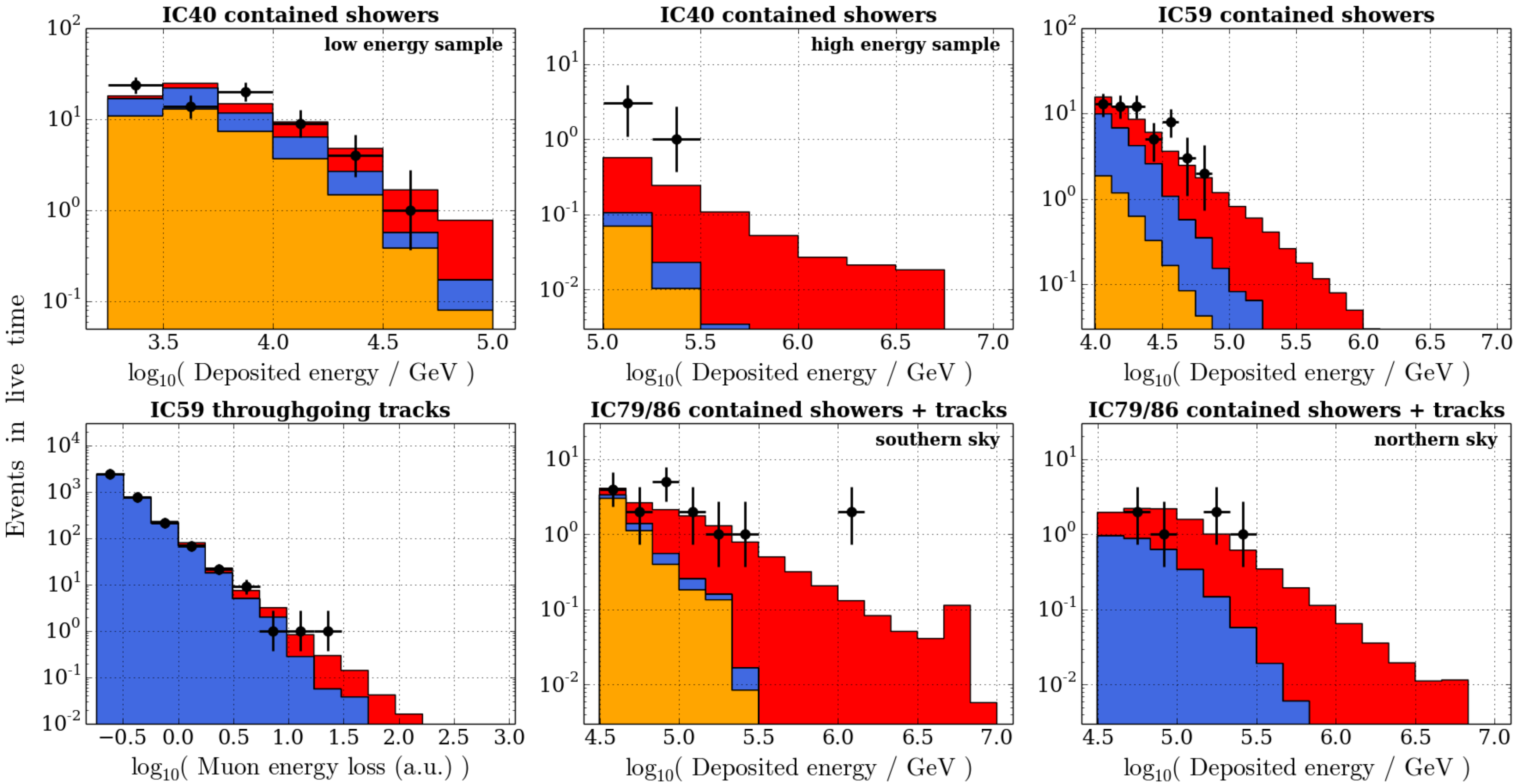
Goodness-of-fit:
10.0 %

Legend: Atmospheric ν (conv.) · Atmospheric ν (prompt) · Atmospheric μ · Astrophysical ν · Data

$$\phi_{prompt} = (0^{+1.6}_{-0.0}) \cdot \text{[Enberg + Gaisser H3a]}$$

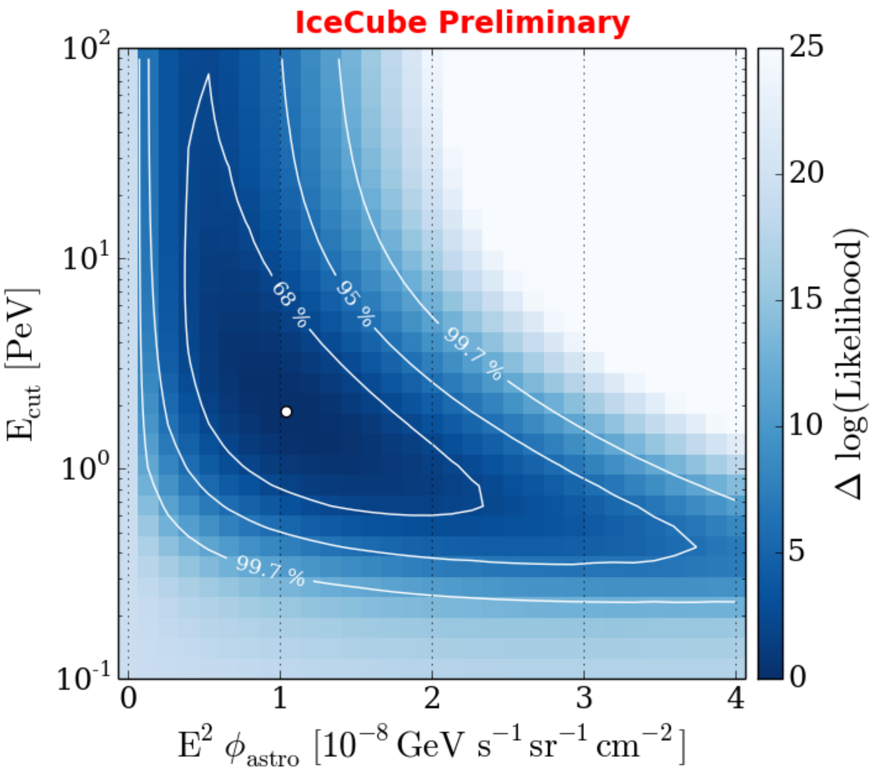
$$E^{2.7}\phi_{astro} = (6.8^{+1.8}_{-1.8}) \cdot 10^{-5}\,\text{GeV}^{1.7}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{cm}^{-2}$$

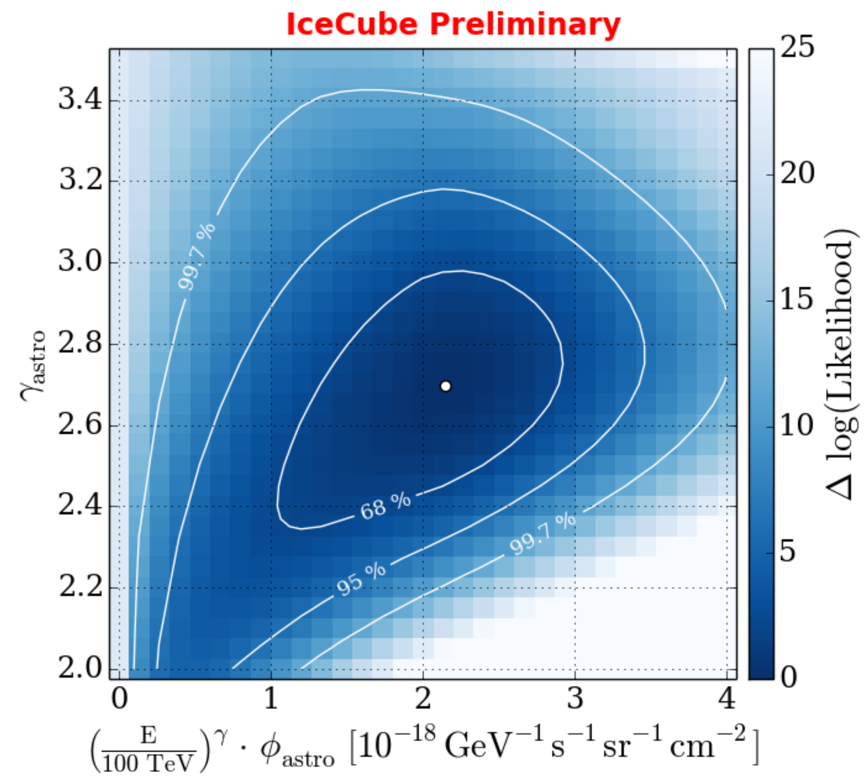
$$\gamma_{astro} = (2.7^{+0.2}_{-0.2})$$



Likelihood landscapes

- Scan of **likelihood landscape** shows **correlation of parameters**
- **Normalization** of astrophysical spectrum is **correlated with index / cut-off parameter**





Conclusion

- **IceCube** measures an **excess of high-energy neutrino events**

- Presented **first global interpretation** of IceCube results
  - Results of individual analyses are **consistent**
  - The **prompt component** of the atmospheric neutrino flux is **not well constrained**
  - However, an **astrophysical component is needed** to explain the excess
  - **Different hypotheses** for the astrophysical flux yield **similar results**

- Results of **new analyses** expected soon
  → **global analysis** will become more powerful

Backup slides

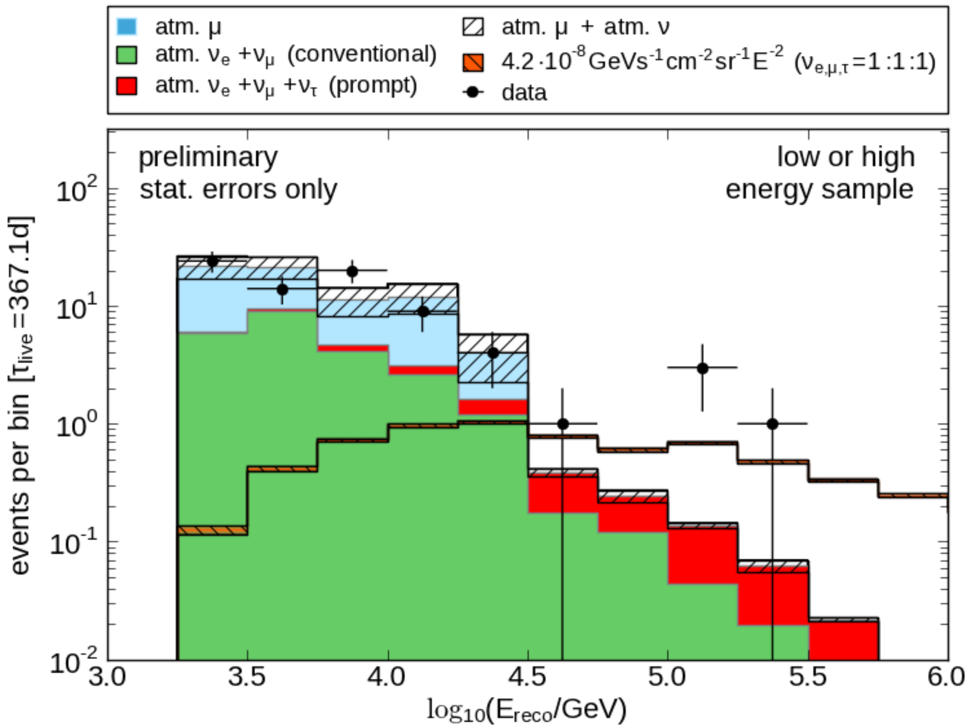
IceCube-40 – contained showers

- **Excess**
  2.7 σ

- **Prompt flux**
  - **Best fit**

  - **Upper limit (90% CL)**

- **Astrophysical flux**
  - **Best fit**
    $E^2 \Phi = 1.7 \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}
  - **Upper limit (90% CL)**
    $E^2 \Phi < 7.0 \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

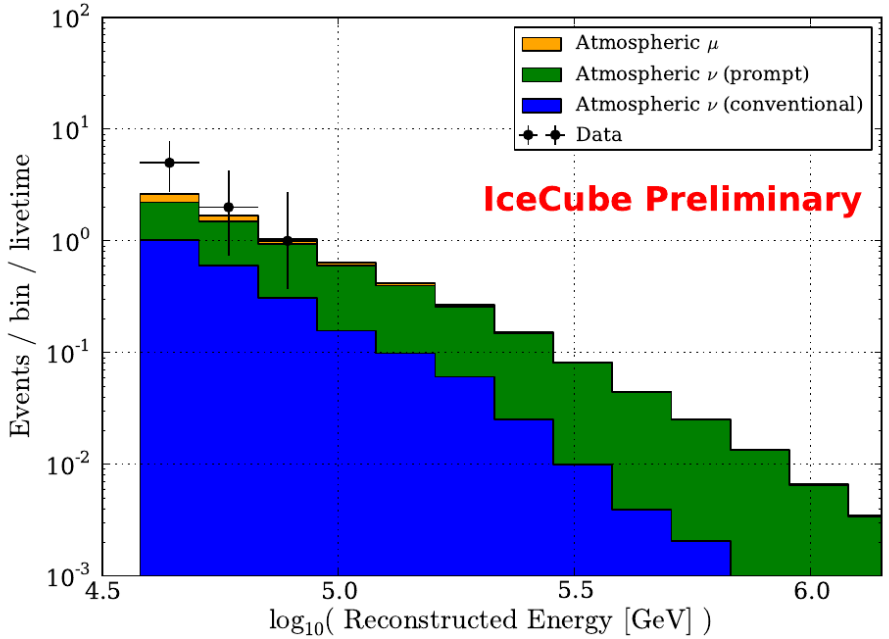


IceCube-59 – contained showers

- **Excess**
  None

- **Prompt flux**
  - **Best fit**
    $\Phi = 2.9 \cdot$ [Enberg et al. + H3a]
  - **Upper limit (90% CL)**
    $\Phi < 9.0 \cdot$ [Enberg et al. + H3a]

- **Astrophysical flux**
  - **Best fit**
    $E^2 \Phi = 0$
  - **Upper limit (90% CL)**
    $E^2 \Phi < 0.6 \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

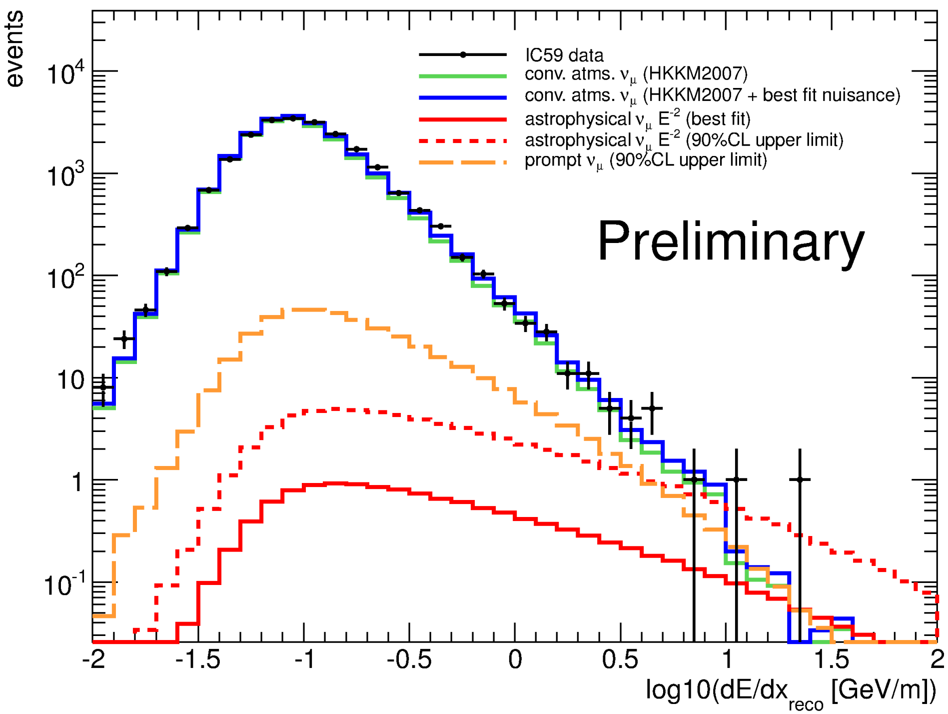


IceCube-59 – throughgoing tracks

- **Excess**
  1.8 σ

- **Prompt flux**
  - **Best fit**
    $\Phi = 0$
  - **Upper limit (90% CL)**
    $\Phi < 3.8 \cdot$ [Enberg et al. + H3a]

- **Astrophysical flux**
  - **Best fit**
    $E^2 \Phi = 0.2 \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}
  - **Upper limit (90% CL)**
    $E^2 \Phi < 1.4 \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

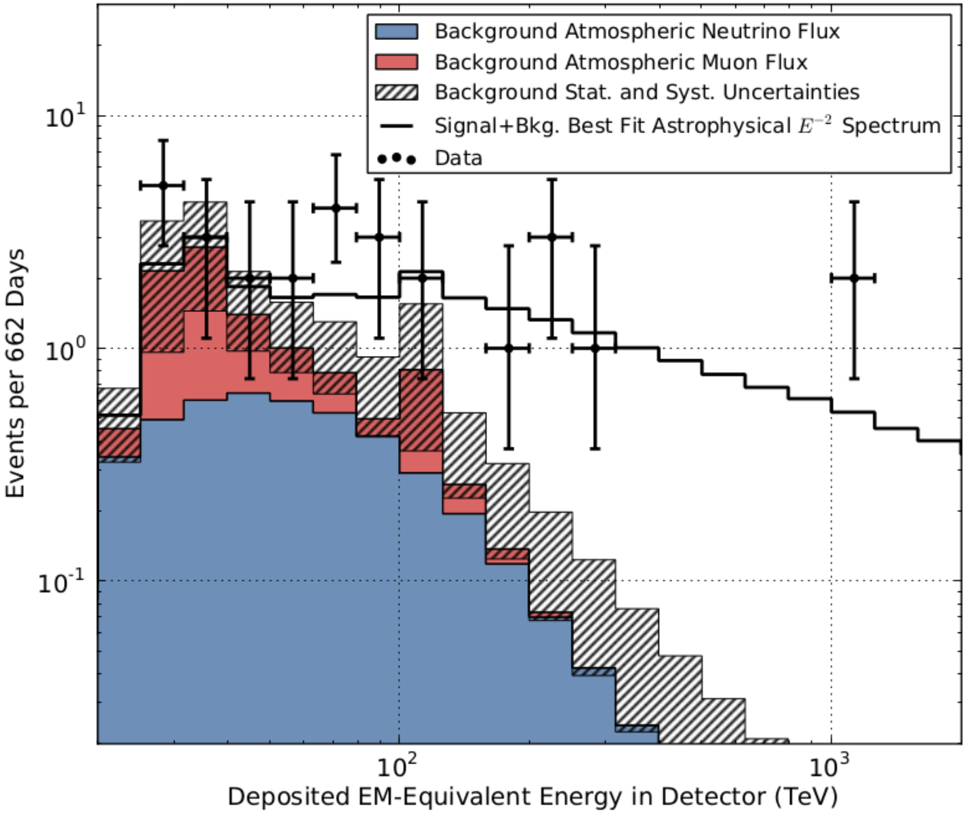


IceCube-79 + 86 – contained showers + tracks

- **Excess**
  4.1 σ

- **Prompt flux**
  - **Best fit**
    $\Phi = 0$
  - **Upper limit (90% CL)**

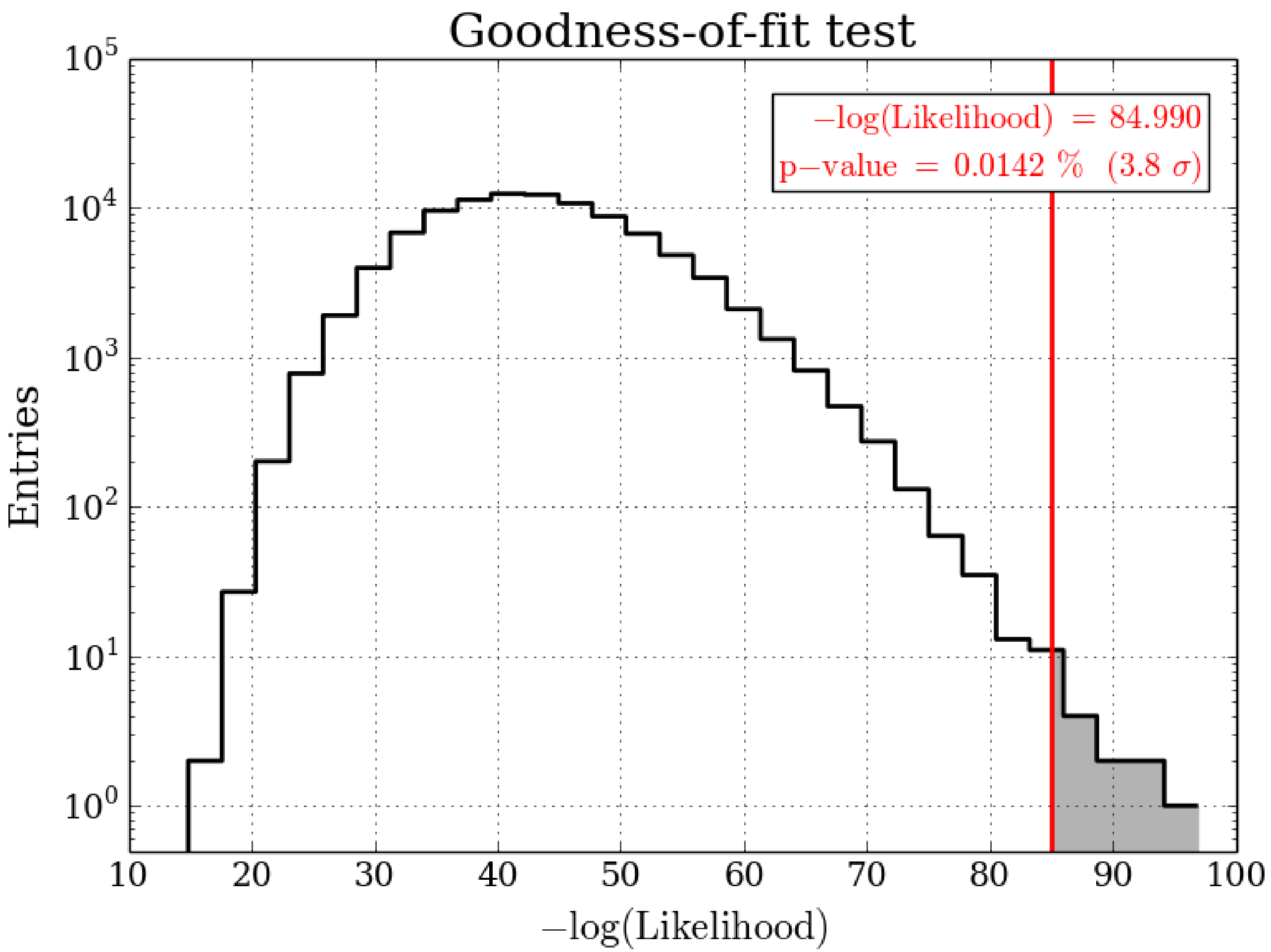
- **Astrophysical flux**
  - **Best fit (only valid up to 2 PeV)**
    $E^2 \Phi = 1.2 \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}
  - **Upper limit (90% CL)**



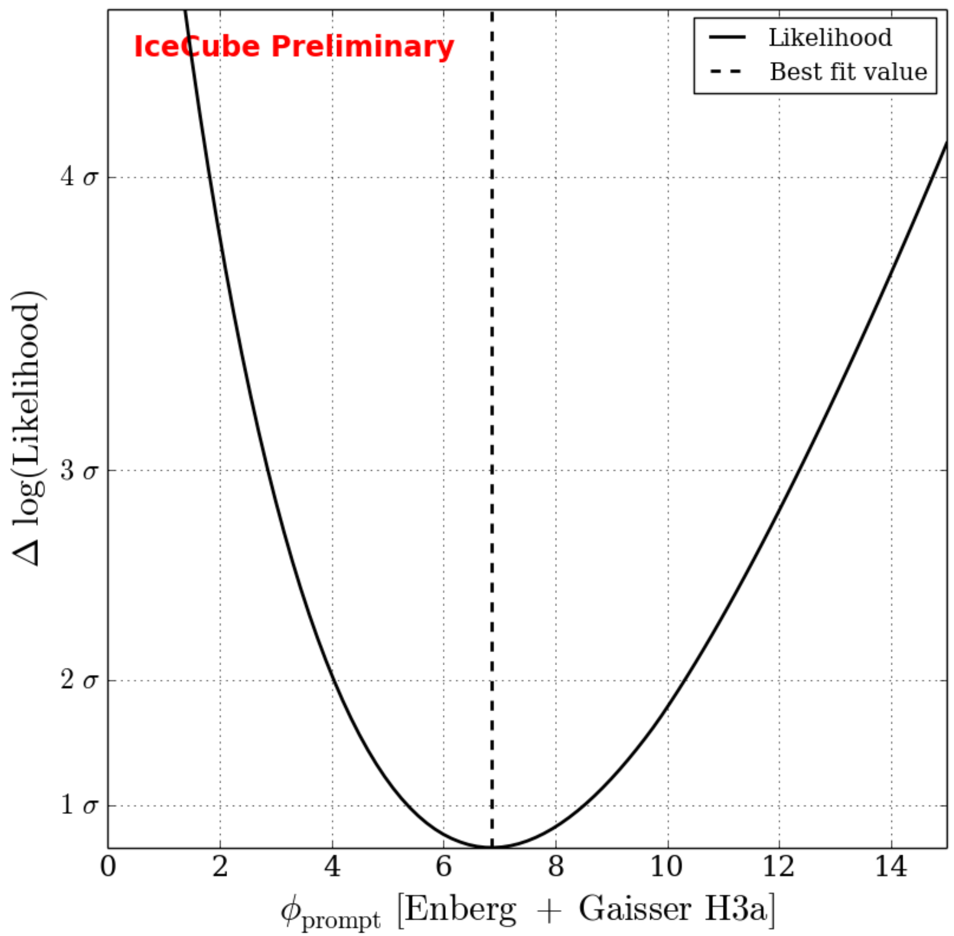
Best fit parameter values

Parameter	Background	Background + Signal	Background + Signal (Index)	Background + Signal (Cut-off)
ϕ_{conv}	$0.821^{+0.130}_{-0.118}$	$0.842^{+0.135}_{-0.122}$	$0.817^{+0.136}_{-0.134}$	$0.853^{+0.136}_{-0.126}$
ϕ_{prompt}	$6.862^{+1.645}_{-1.495}$	$4.163^{+1.794}_{-1.670}$	$0.000^{+1.556}_{-0.000}$	$2.827^{+2.006}_{-1.978}$
ϕ_{astro}	–	$0.468^{+0.243}_{-0.196}$	$2.154^{+0.500}_{-0.591}$	$1.045^{+0.750}_{-0.489}$
γ_{astro}	–	2	$2.695^{+0.186}_{-0.187}$	2
$\varepsilon_{\mathrm{astro}}$	–	–	–	$6.264^{+0.574}_{-0.365}$
ζ_{μ}	$0.367^{+0.761}_{-0.808}$	$0.498^{+0.787}_{-0.909}$	$0.216^{+0.800}_{-1.115}$	$0.448^{+0.788}_{-1.005}$
ζ_{cr}	$1.375^{+0.605}_{-0.597}$	$1.219^{+0.610}_{-0.603}$	$1.090^{+0.612}_{-0.599}$	$1.138^{+0.615}_{-0.608}$
$\zeta_{\mathrm{K}\pi}$	$-0.118^{+1.004}_{-1.005}$	$-0.074^{+1.001}_{-1.001}$	$-0.085^{+1.003}_{-1.002}$	$-0.066^{+1.001}_{-1.000}$
$\zeta_{\mathrm{E-scale\,IC40\,cascades}}$	$-0.712^{+0.645}_{-0.420}$	$-0.655^{+0.705}_{-0.441}$	$-0.531^{+0.910}_{-0.478}$	$-0.584^{+0.794}_{-0.460}$
$\zeta_{\mathrm{E-scale\,IC59\,cascades}}$	$-0.690^{+0.671}_{-0.569}$	$-0.223^{+0.777}_{-0.675}$	$-0.403^{+0.771}_{-0.687}$	$-0.077^{+0.836}_{-0.706}$
$\zeta_{\mathrm{E-scale\,IC59}\,\nu_\mu}$	$-0.050^{+0.902}_{-0.852}$	$-0.123^{+0.917}_{-0.865}$	$0.016^{+1.027}_{-0.877}$	$-0.170^{+0.927}_{-0.862}$
$\zeta_{\mathrm{E-scale IC79/86\,HESE}}$	$0.815^{+0.941}_{-0.821}$	$0.045^{+0.838}_{-0.855}$	$-0.076^{+0.885}_{-0.844}$	$-0.078^{+0.895}_{-0.834}$
Goodness-of-fit	$0.0142\,\%\,(3.8\,\sigma)$	$13.2\,\%$	$10.0\,\%$	$7.8\,\%$

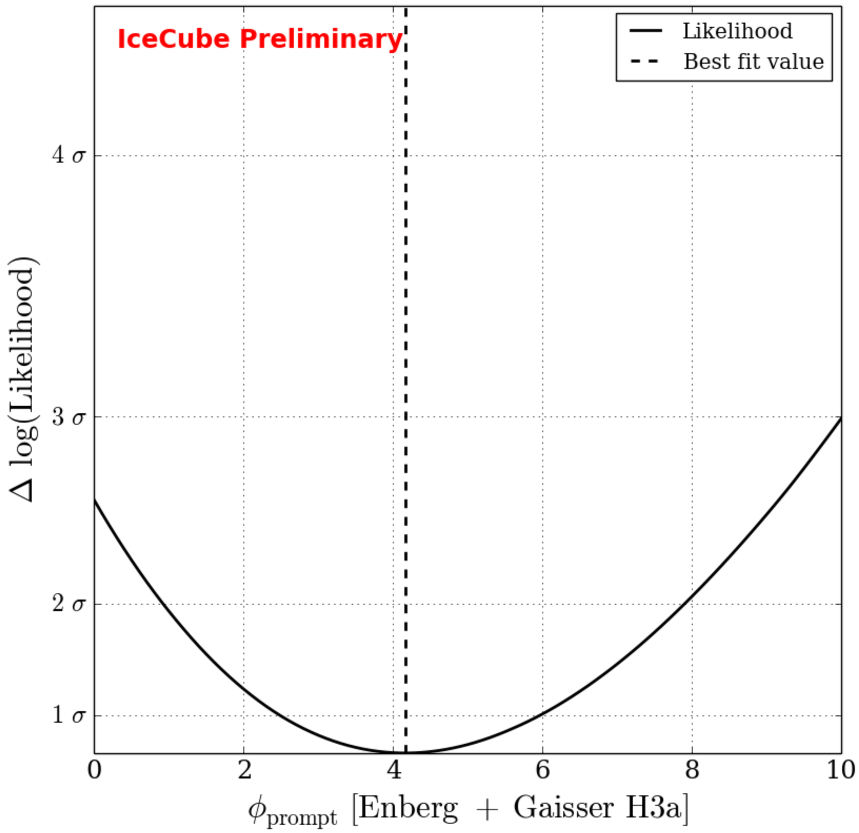
Goodness-of-fit for background-only hypothesis

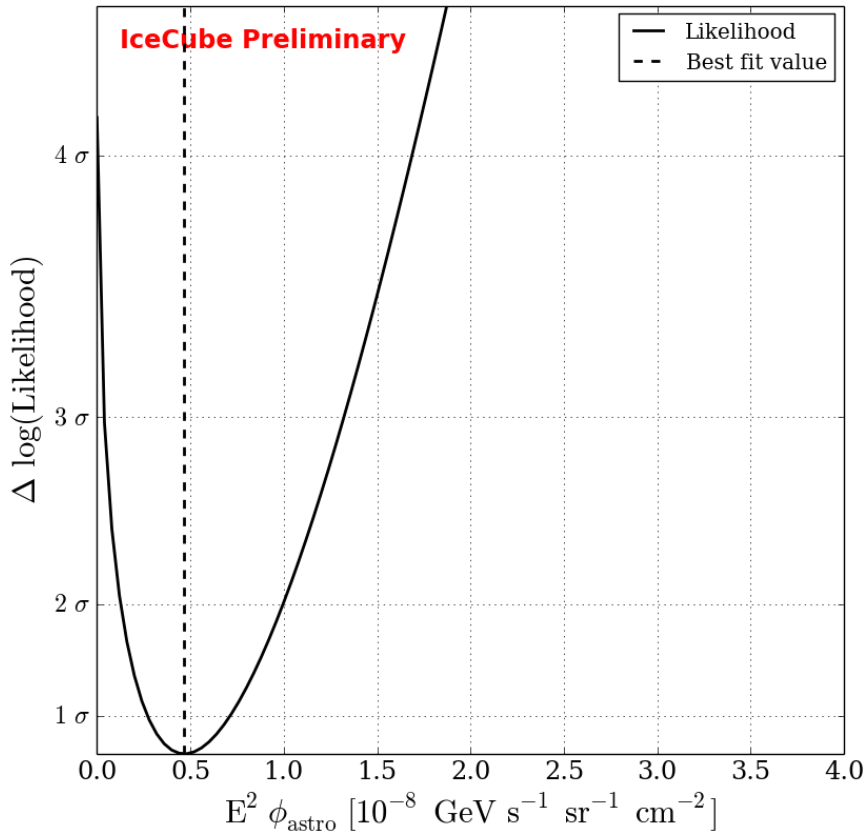


1-D profile likelihood for background-only hypothesis

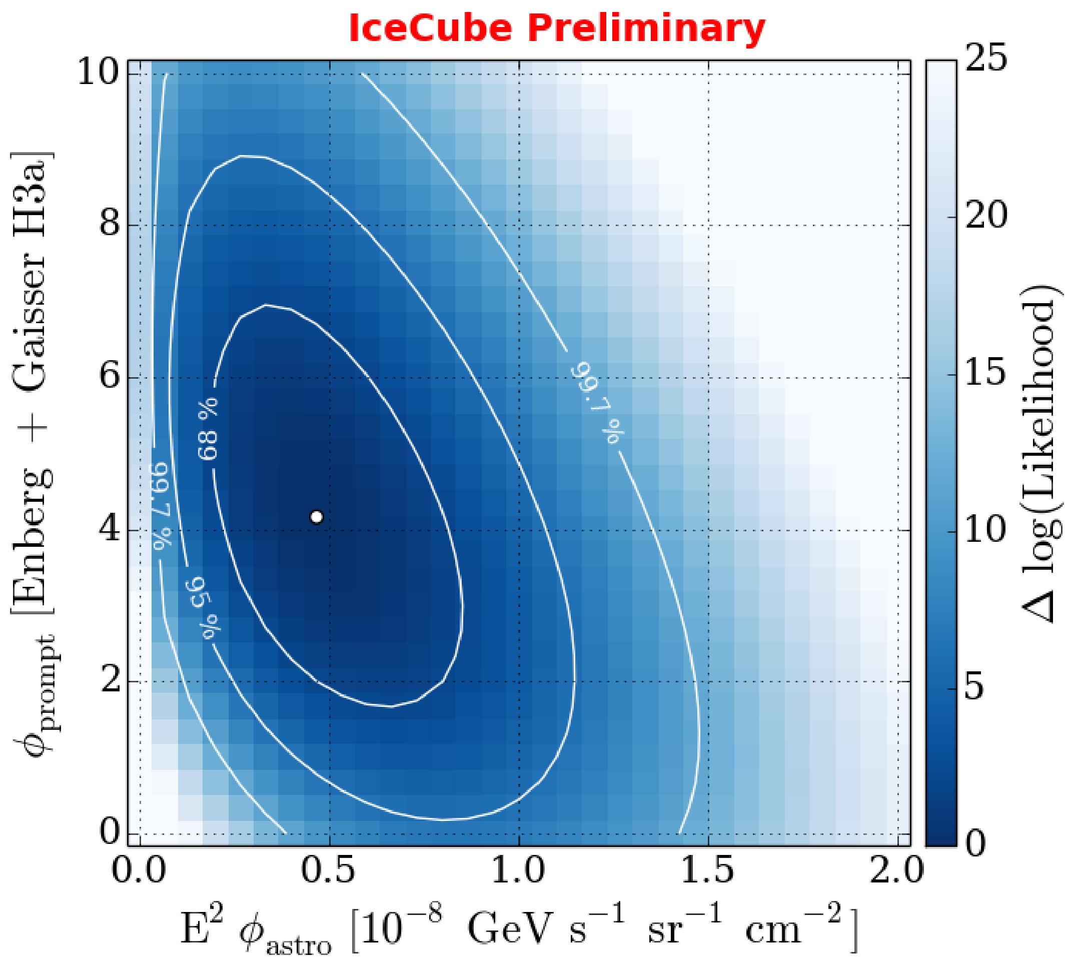


1-D profile likelihood for signal hypothesis (E^{-2})

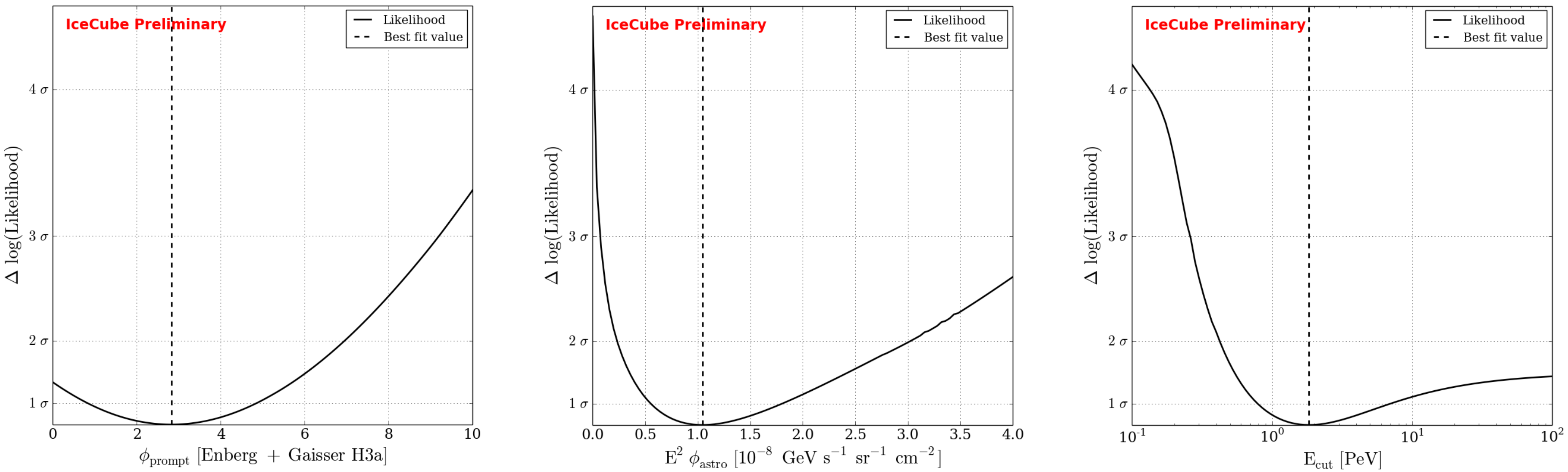




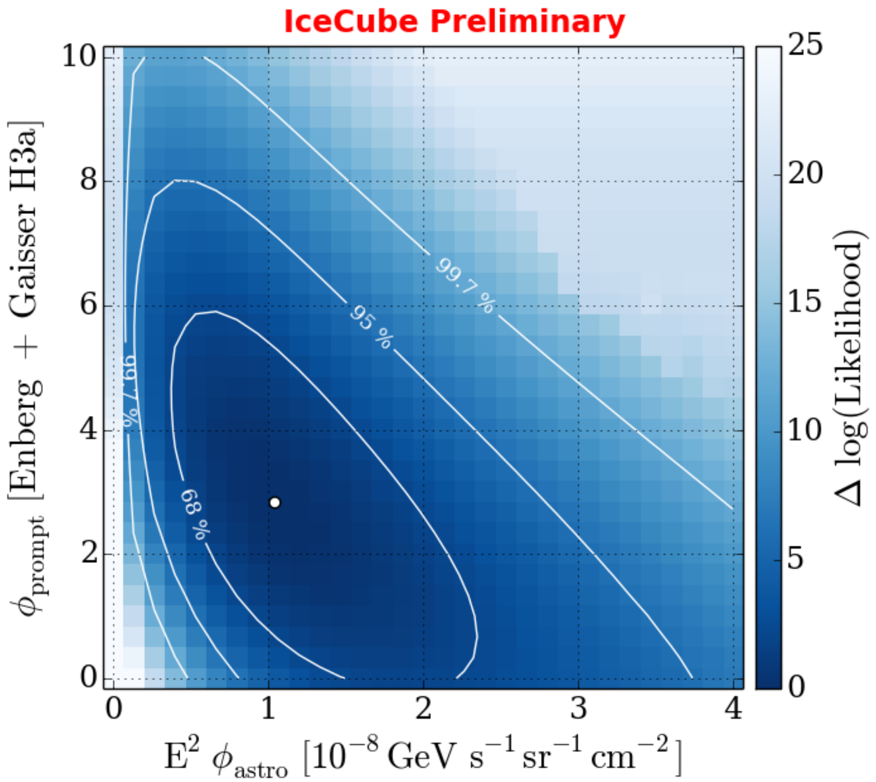
2-D profile likelihood for signal hypothesis (E^{-2})

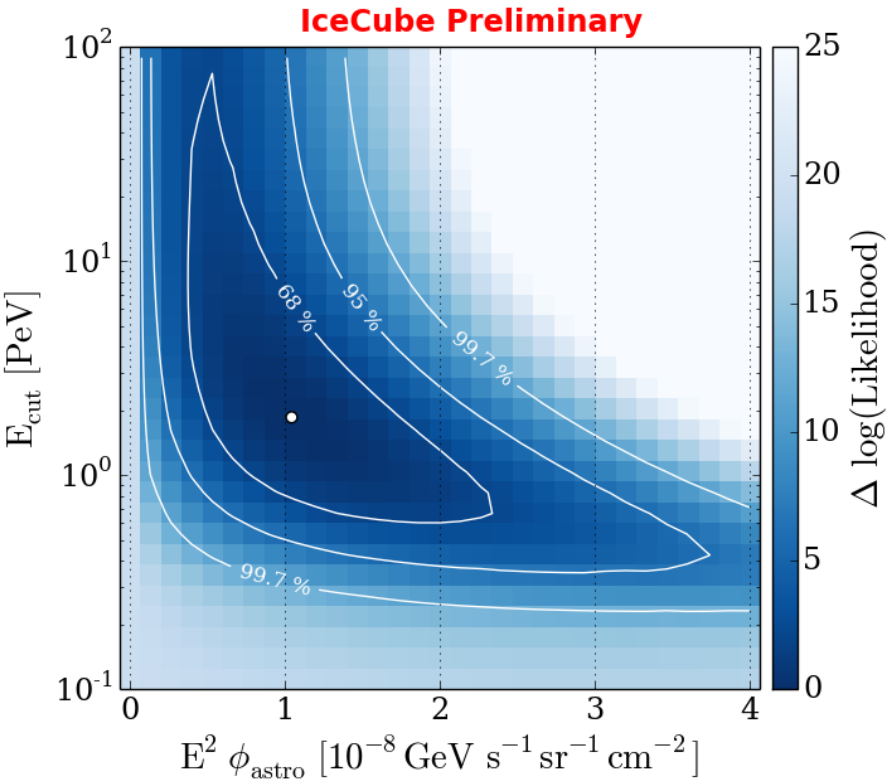


1-D profile likelihood for signal hypothesis ($E^{-2} \cdot e^{E/Ecut}$)

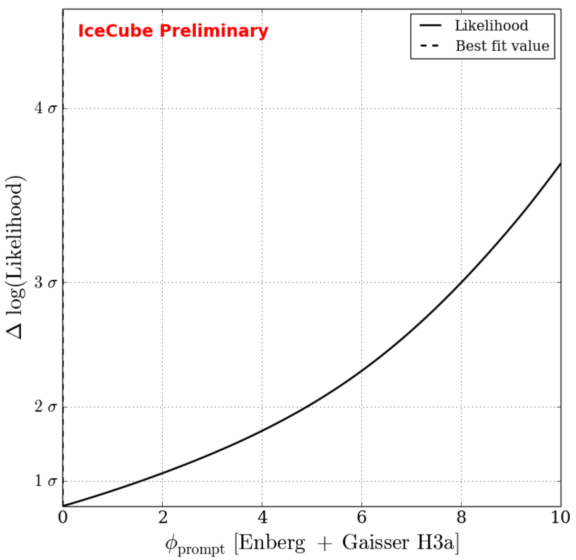


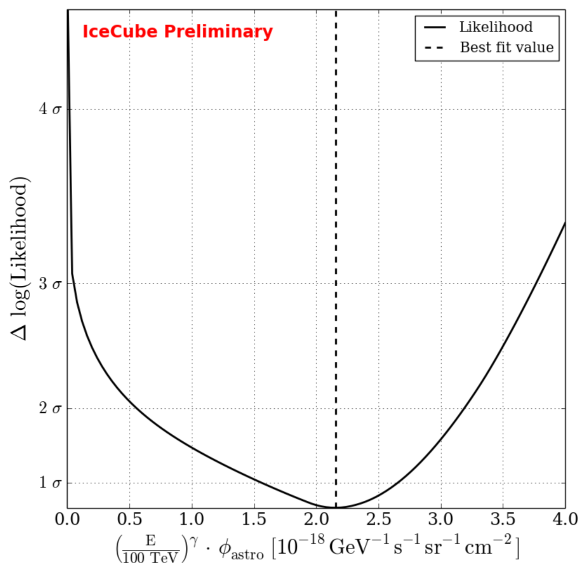
2-D profile likelihood for signal hypothesis ($E^{-2} \cdot e^{E/Ecut}$)

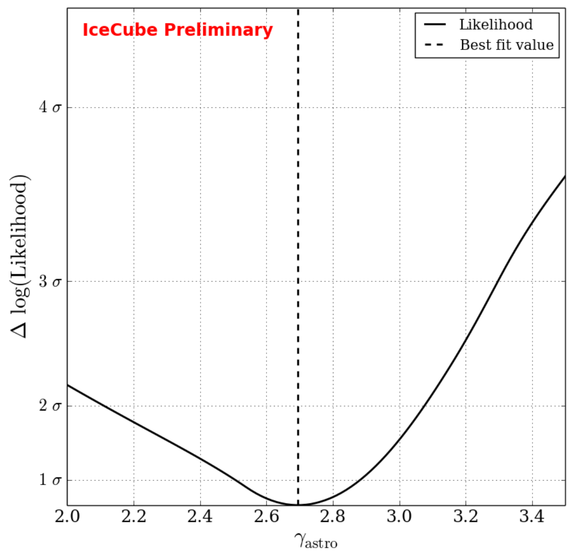




1-D profile likelihood for signal hypothesis ($E^{-\gamma}$)







2-D profile likelihood for signal hypothesis ($E^{-\gamma}$)