Search for a cosmic neutrino flux with showers in 6 years of ANTARES data

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Shower Reconstruction Strategy

All recorded PMT signals in event

Identification of shower signal hits

Separation of background and signal hits

Shower signal hits

Reconstruction of interaction vertex and time

Reconstruction of shower properties

Shower signal hits, vertex

Reconstruction of shower energy and neutrino direction

Shower Reconstruction Strategy

All recorded PMT signals in event

Identification of shower signal hits

Separation of background and signal hits

Shower signal hits

Reconstruction of shower properties

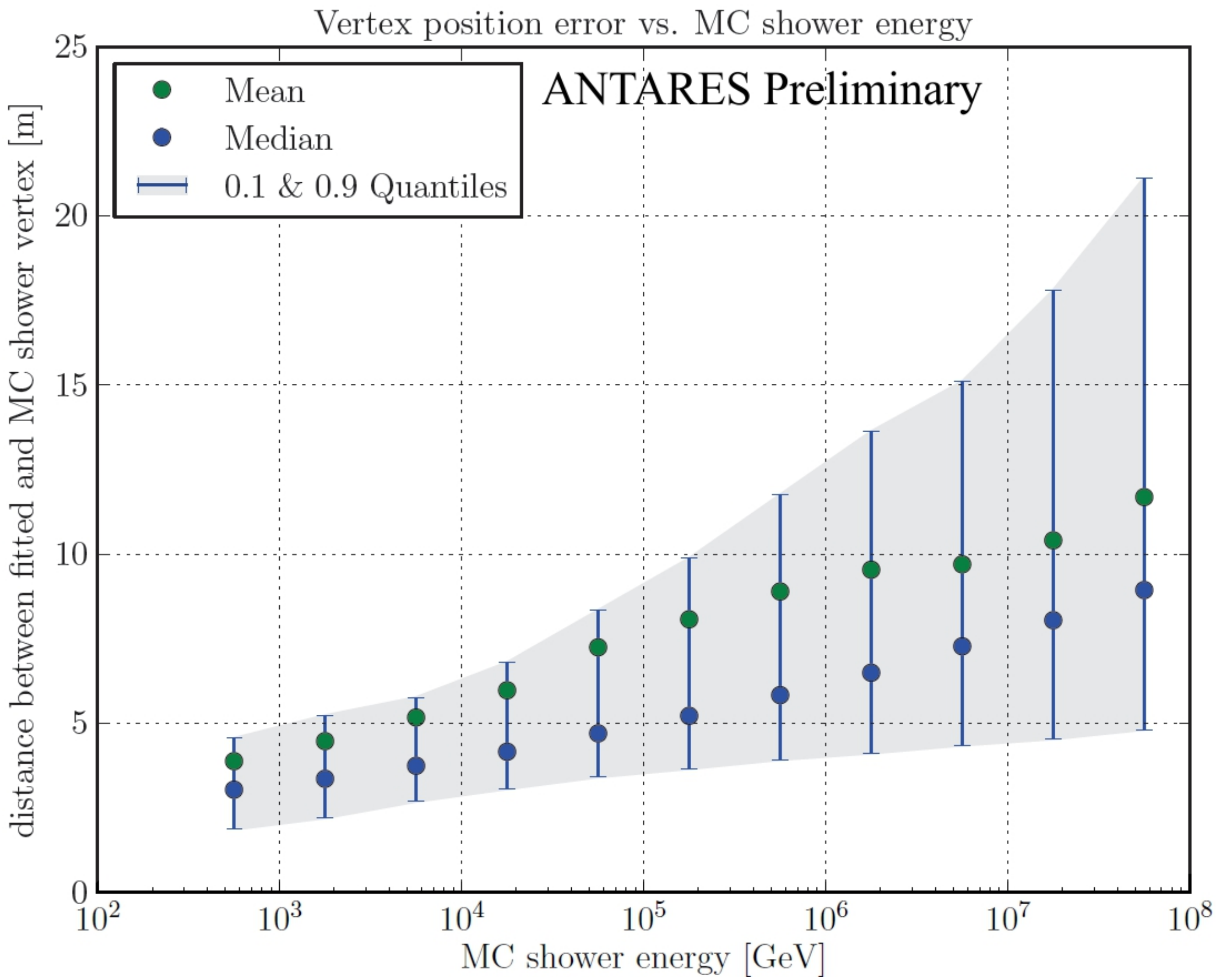
Maximum Likelihood Reconstructions:

vertex

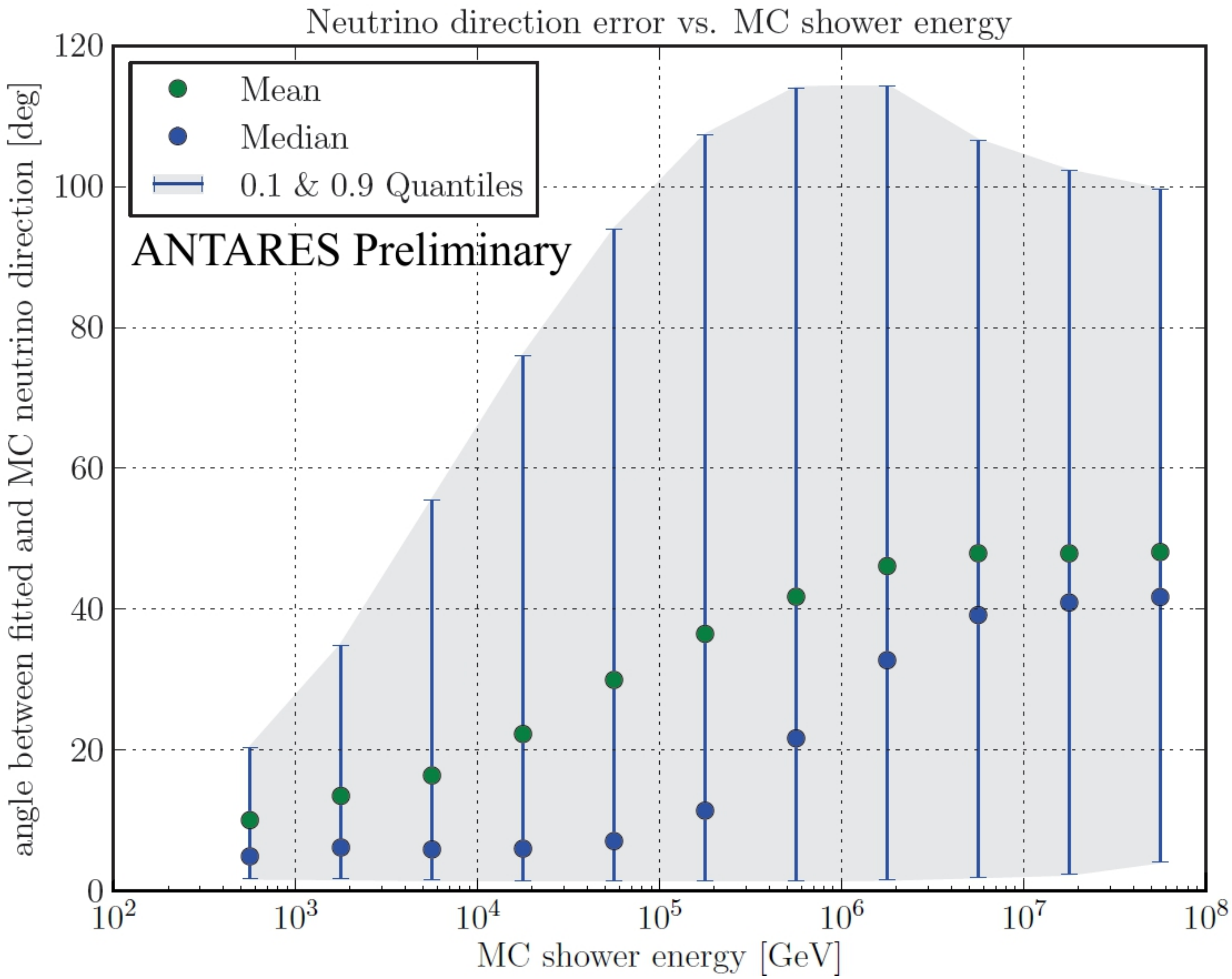
and

energy + direction

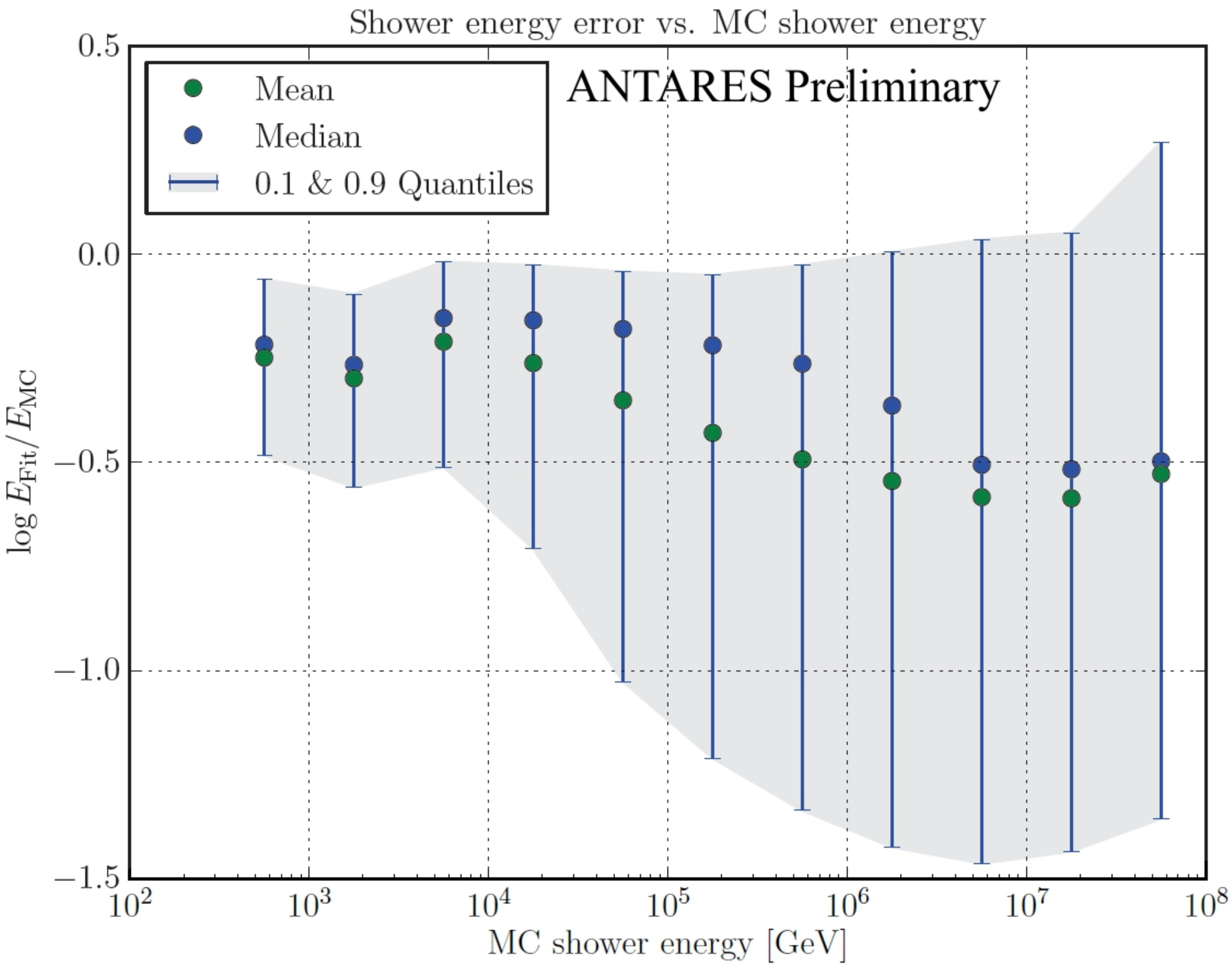
Vertex resolution



Direction resolution



Shower energy resolution



Shower reconstruction performance

- Reconstruction errors for 10 TeV showers *after muon suppression cut* on vertex likelihood:

	Median	Mean	RMS
Vertex error :	**4 meters**	**6 meters**	**14 meters**
Logarithmic Energy error:	**-0.16**	**-0.26**	**0.31**
Direction error :	**6 deg**	**22 deg**	**31 deg**

- Efficiency: 40% (@ 10 TeV) up to 90% (@ 10 PeV) of all simulated showers pass.
- Atmospheric muon rejection power ~10^5 on this level.

Data analysis

Data selection:
1382 days
(years 2007 – 2012)

Data analysis

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(years 2007 – 2012)**

↓

**Reconstruction with
shower algorithm**

Data analysis

Data selection:
1382 days
(years 2007 – 2012)

Reconstruction with
shower algorithm

Muon
filter

Data analysis

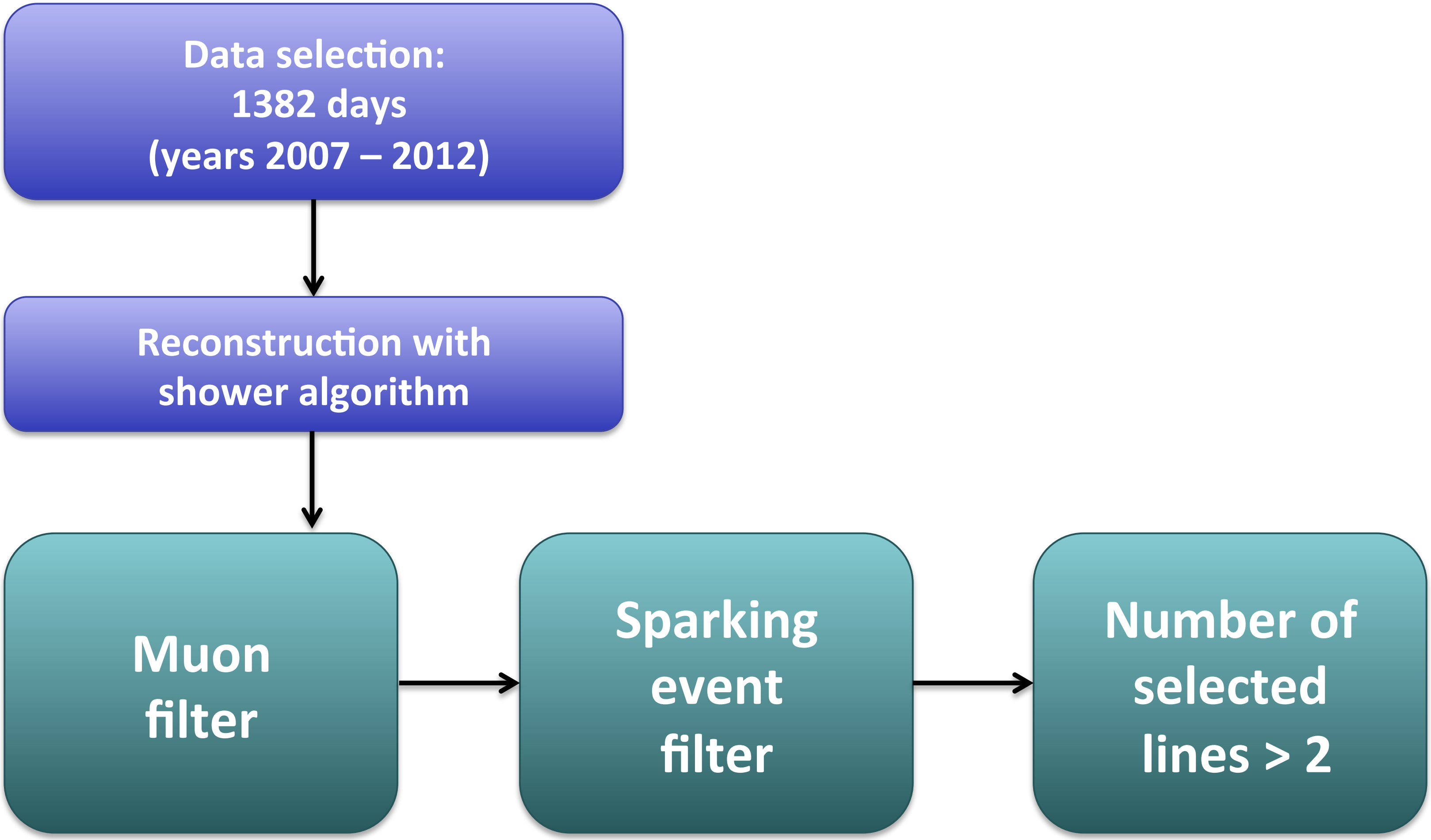
Data selection:
1382 days
(years 2007 – 2012)

Reconstruction with shower algorithm

Muon filter

Sparking event filter

Data analysis



Data selection:
1382 days
(years 2007 – 2012)

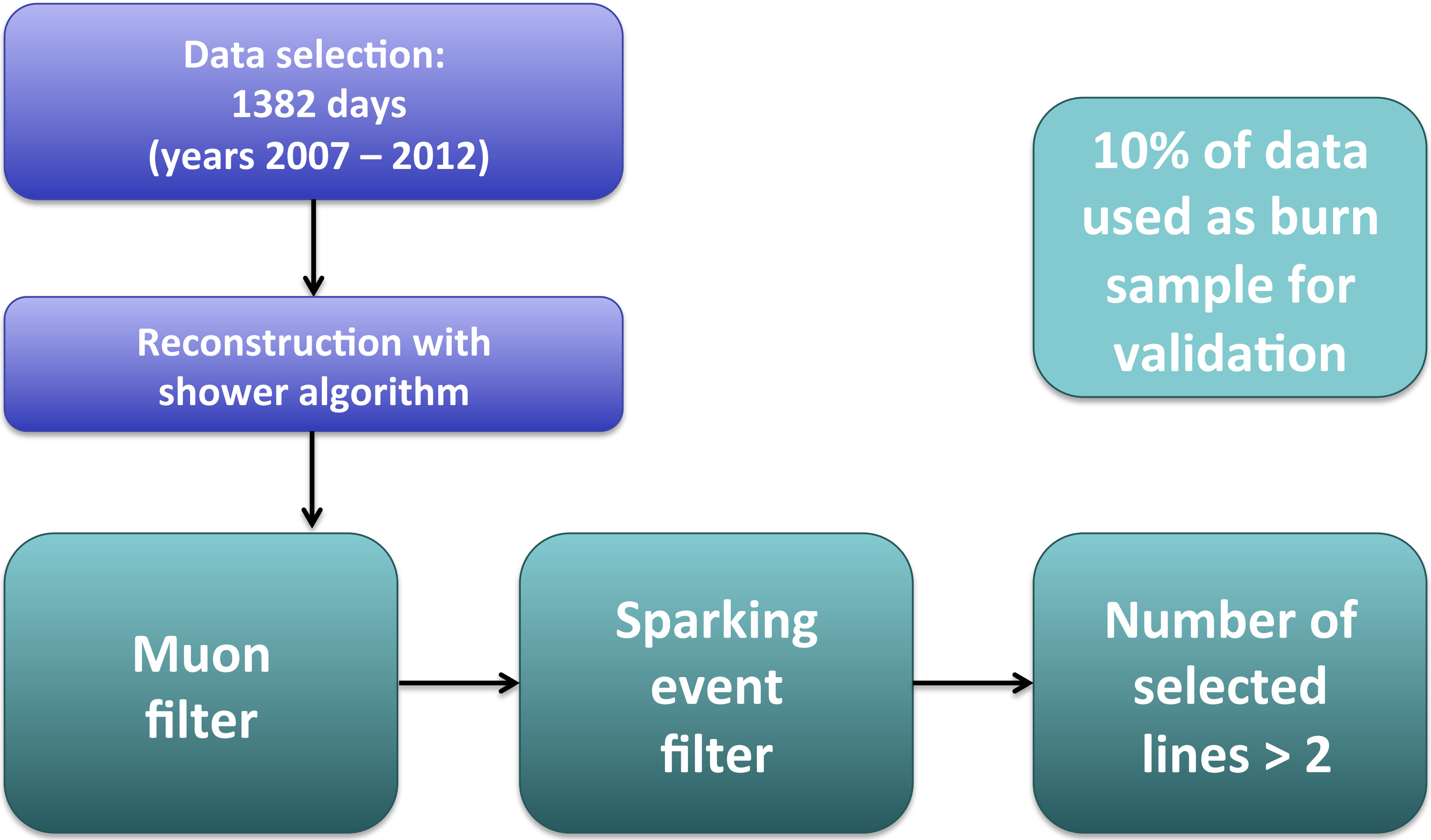
Reconstruction with shower algorithm

Muon filter

Sparking event filter

Number of selected lines > 2

Data analysis



Data selection:
1382 days
(years 2007 – 2012)

Reconstruction with
shower algorithm

Muon
filter

Sparking
event
filter

Number of
selected
lines > 2

10% of data
used as burn
sample for
validation

After vertex quality cut for 1247 days

Simulated Atmospheric Muons:

1430^{+529}_{-537}

Simulated Atmospheric Neutrinos:

84 +/- 40

Simulated Cosmic Neutrinos:

$9.4^{+2.0}_{-3.1}$

test flux:

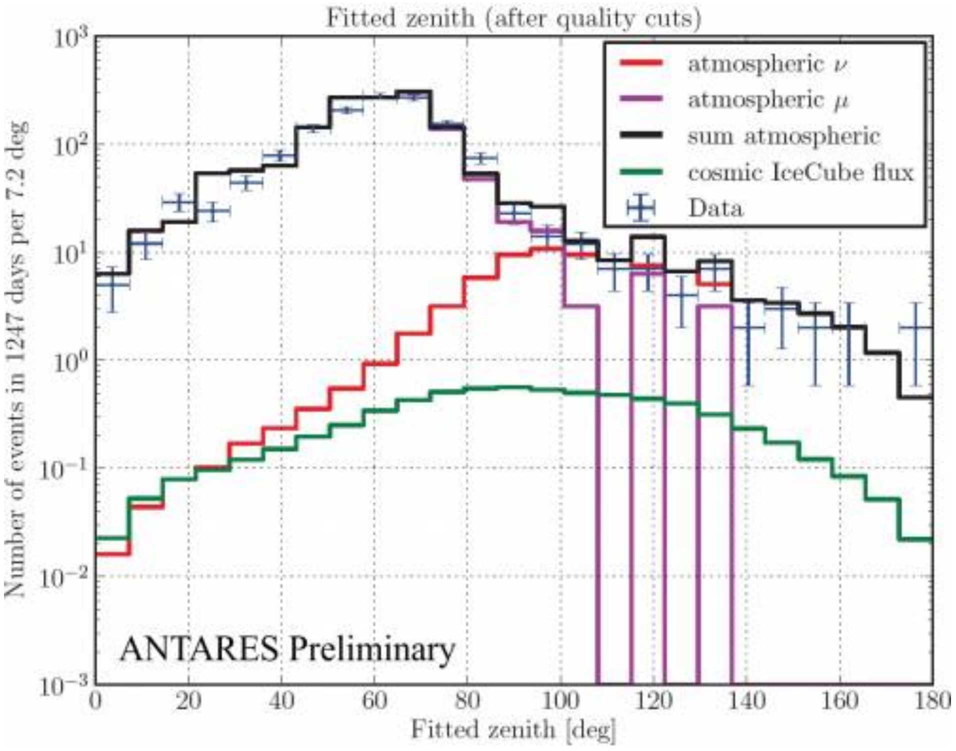
$E^{2}\,\Theta(E) = 1.2 * 10^{-8}$ GeV / s cm^{2} sr

Note: Each run simulated individually, taking into account environmental noise, calibrations and detector status on OM level.

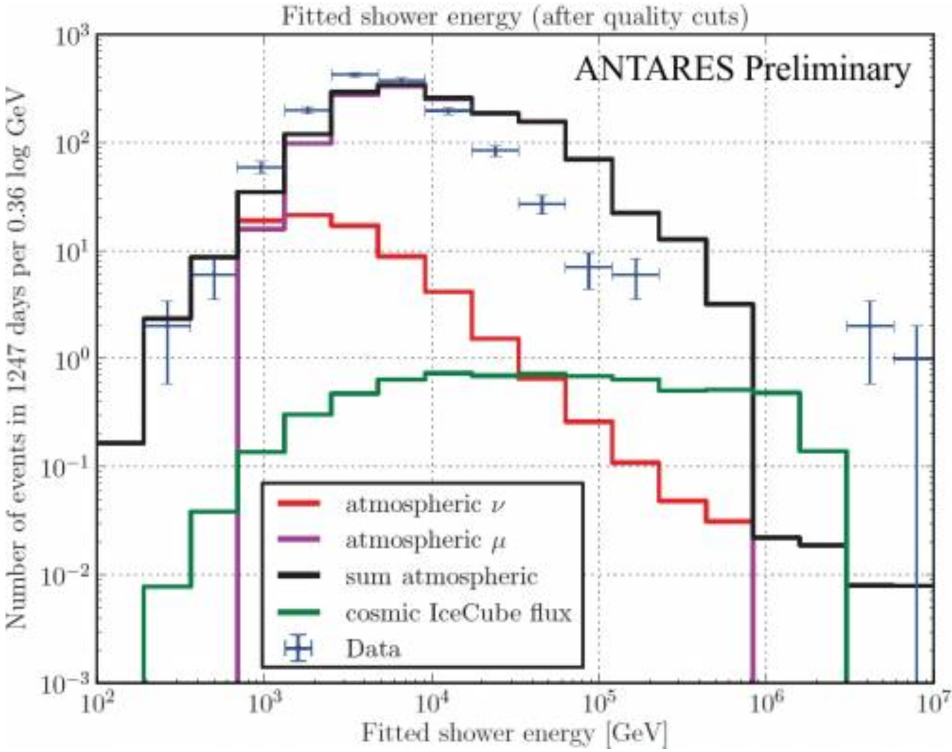
Systematic uncertainties

	Background contribution		Signal contribution	
Uncertainty on conventional atmospheric neutrino flux	+ 30 %	- 30 %		
Uncertainty on prompt atmospheric neutrino flux	+ 27 %	- 41 %		
Uncertainty on simulation parameters (10% variation on absorption, scattering and PMT efficiency)	+ 6-54 %	- 19-36%	+ 7-17 %	- 6-11 %
Errors due to simplifying assumptions in simulation (no scattering for light from hadronic shower particles)		- 31 %		- 31 %

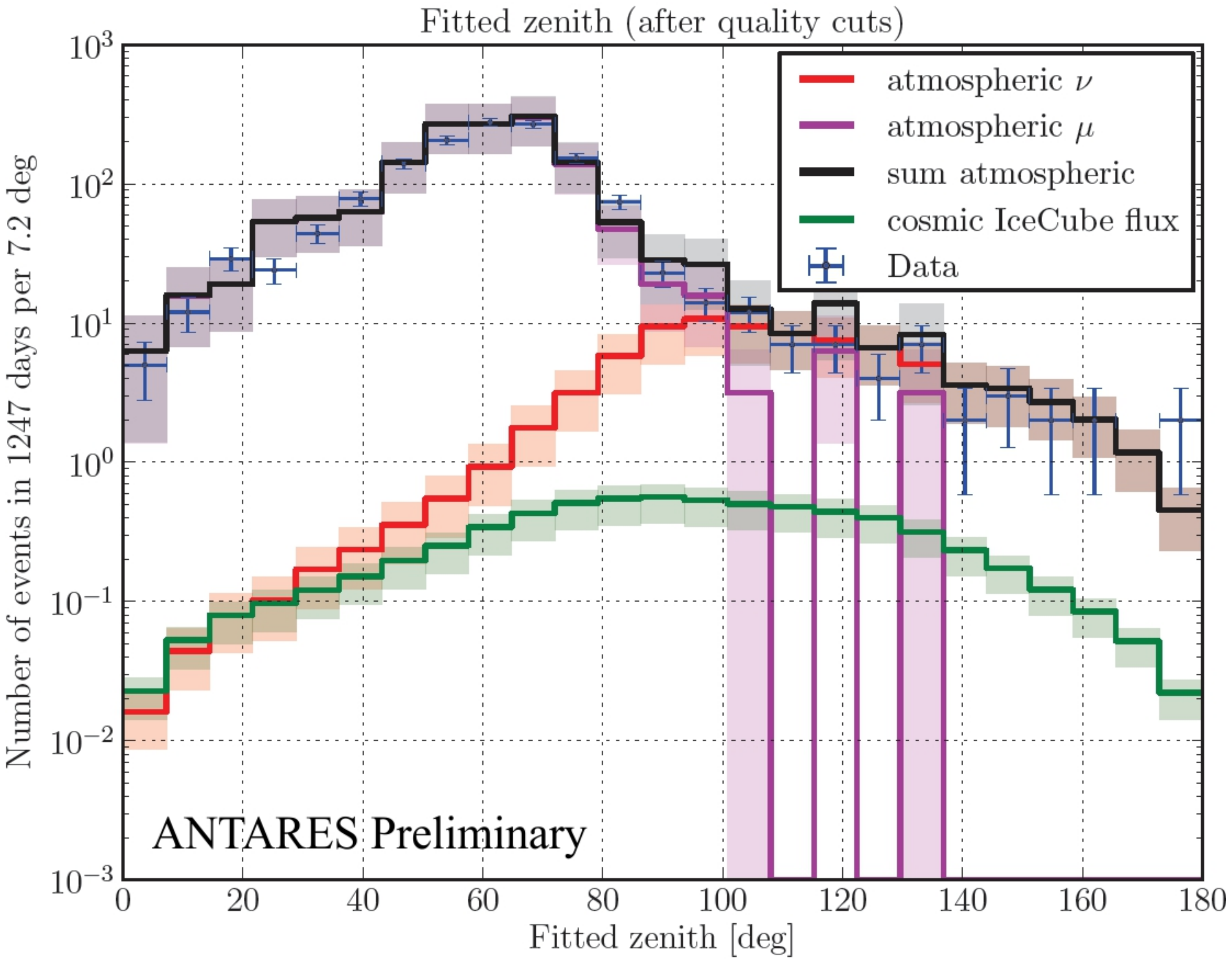
Data – MC comparison (after vertex cut, 1247 days)



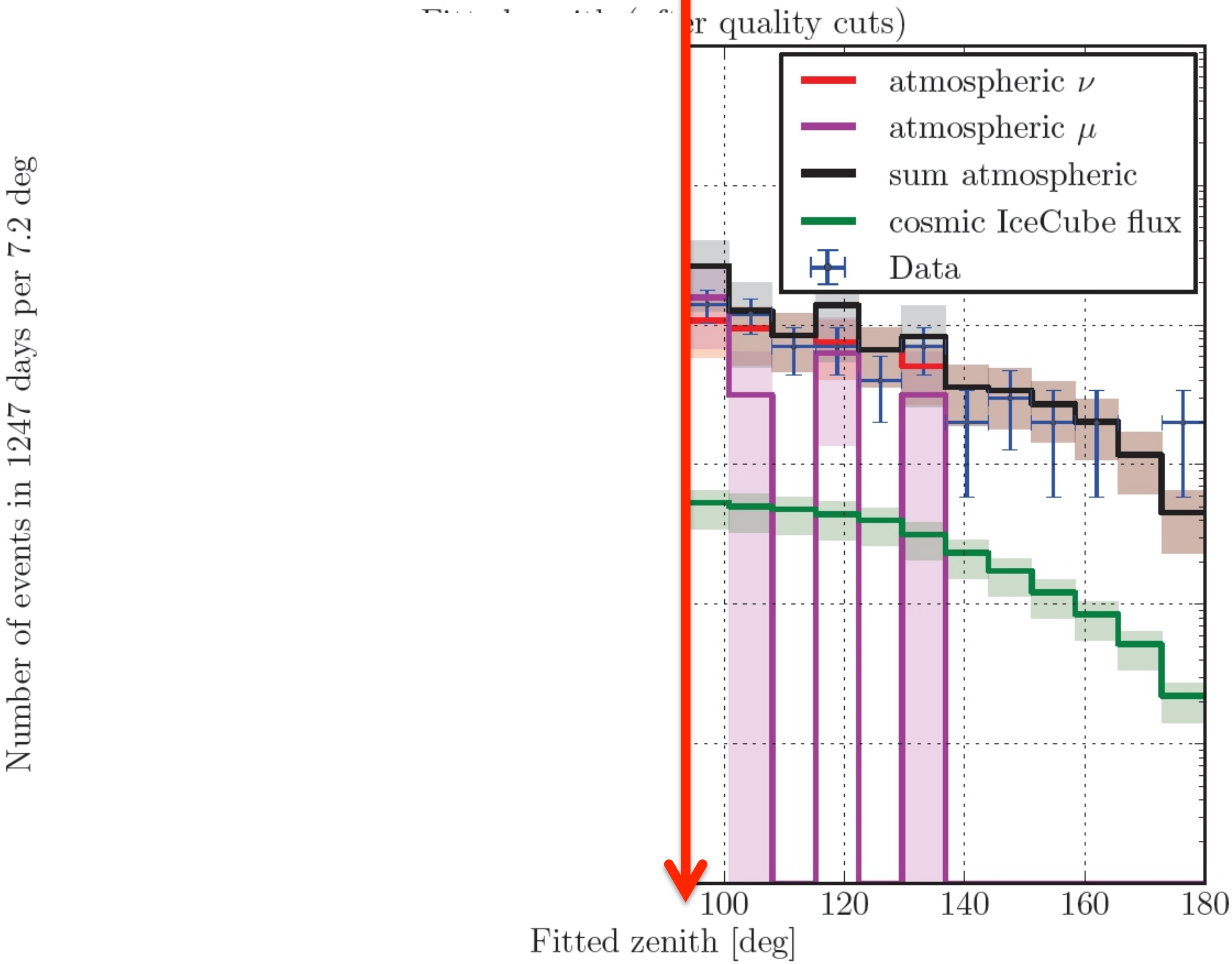
Reconstructed zenith [deg]

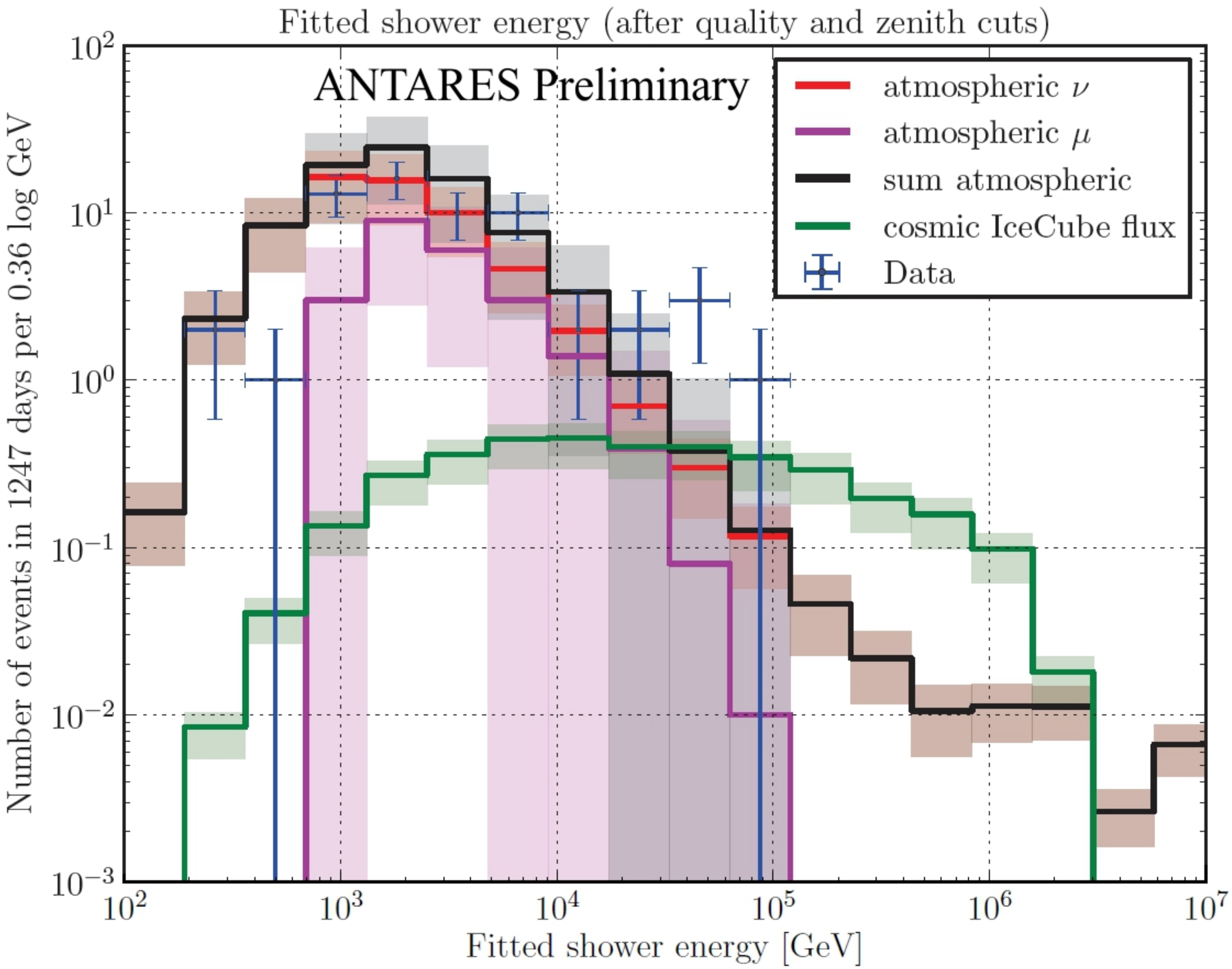


Reconstructed shower energy [GeV]

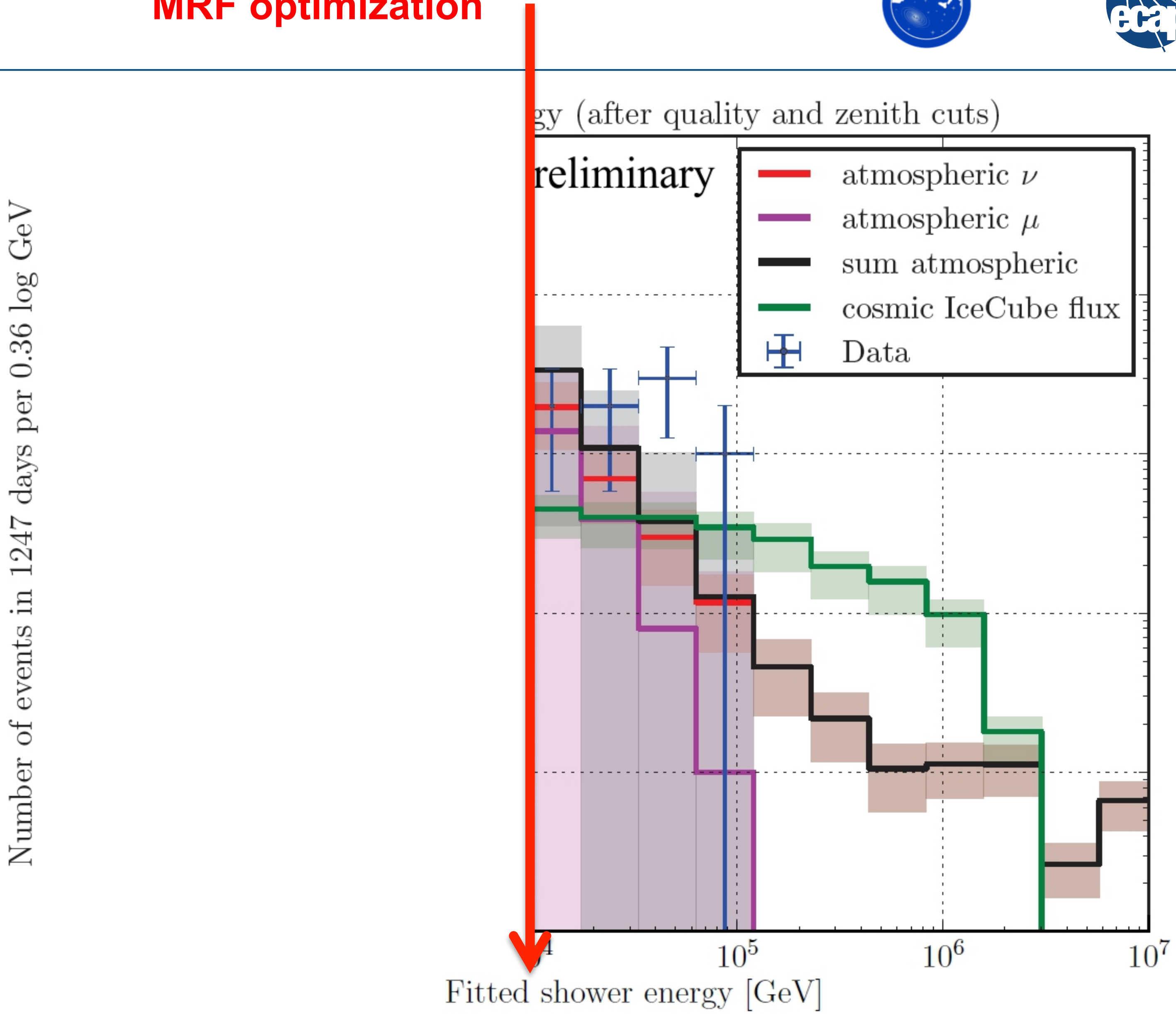

Fitted zenith (after quality cuts)
atmospheric ν
atmospheric μ
sum atmospheric
cosmic IceCube flux
Data
ANTARES Preliminary
Number of events in 1247 days per 7.2 deg
Fitted zenith [deg]
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
0
20
40
60
80
100
120
140
160
180

MRF optimization




Fitted shower energy (after quality and zenith cuts)
ANTARES Preliminary
atmospheric ν
atmospheric μ
sum atmospheric
cosmic IceCube flux
Data
Number of events in 1247 days per 0.36 log GeV
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Fitted shower energy [GeV]

MRF optimization

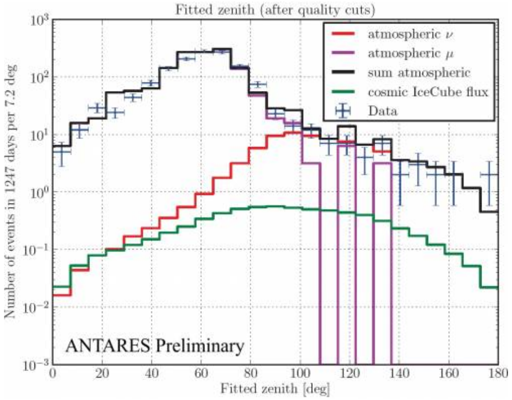


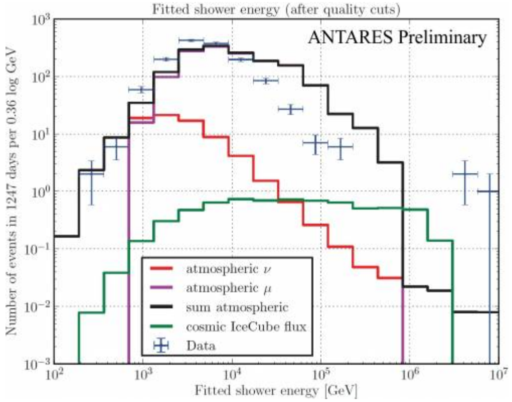
Remaining simulated events for 1247 days after vertex quality cut

Atmospheric muons:
1430^{+529}_{-537}

Atmospheric neutrinos:
84 +/- 40

Cosmic neutrinos:
$9.4^{+2.0}_{-3.1}$


Fitted zenith (after quality cuts)


Fitted shower energy (after quality cuts)

n_b

n_s

Sensitivity

$$\Phi_{90\,\%} = \Phi_{\mathrm{Test}} \frac{\mu_{90,2}(n_{\mathrm{obs}}, n_{\mathrm{b}})}{n_{\mathrm{s}}}$$

Upper limit on neutrino flux

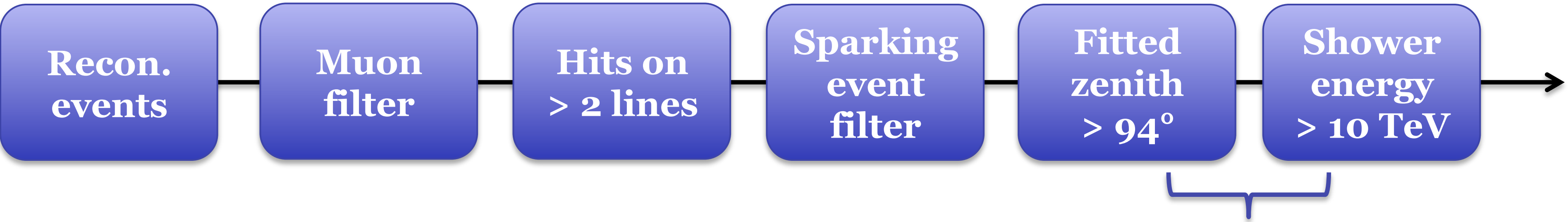
$$\bar{\Phi}_{90\,\%} = \Phi_{\mathrm{Test}} \frac{\bar{\mu}_{90,2}(n_{\mathrm{b}})}{n_{\mathrm{s}}}$$

$$\bar{\mu}_{90,2}(n_{\mathrm{b}}) = \sum_{n_{\mathrm{obs}}=0}^{\infty} \mu_{90,2}(n_{\mathrm{obs}}, n_{\mathrm{b}}) \cdot \frac{n_{\mathrm{b}}^{n_{\mathrm{obs}}}}{n_{\mathrm{obs}}!} e^{-n_{\mathrm{b}}}$$

Sensitivity
(1247 days livetime) per neutrino flavour:

$$E^2 \cdot \bar{\Phi}_{90\,\%} = 2.21^{+0.87}_{-0.73} \cdot 10^{-8}\,\mathrm{GeV/cm^2 \cdot sr \cdot s}$$

Simulations, estimations, extrapolations



Recon. events → **Muon filter** → **Hits on > 2 lines** → **Sparking event filter** → **Fitted zenith > 94°** → **Shower energy > 10 TeV** →

MRF optimization

EVENT NUMBERS AFTER FINAL OPTIMIZED CUTS	Cosmic signal events	Atmospheric background events
Cosmic signal (test flux 1.2 * 10^{-8} per flav.)	**1.75**	
Conventional atmospheric neutrinos	-	**2.32**
Prompt atmospheric neutrinos	-	**0.56**
Tau neutrino estimation	**0.78**	**0.02** ***(prompt)***
Atmospheric muon extrapolation	-	**1.85**
Correction for missing vertex showers in CC muon simulations	**0.26**	**0.16**
High multiplicity muon bundles	-	**0.01**
TOTAL	**2.79**	**4.92**

Retrieved from full run-by-run simulations

Additional estimations and extrapolations

Remaining events in 1247 days livetime

After quality cuts:

Atm. μ: 1430^{+529}_{-537}

Atm. ν: 84 +/- 40

Cosm. ν: $9.4^{+2.0}_{-3.1}$

Measured: 1394

Remaining events in 1247 days livetime

After quality cuts:

Atm. μ: 1430^{+529}_{-537}

Atm. ν: 84 +/- 40

Cosm. ν: $9.4^{+2.0}_{-3.1}$

Measured: 1394

+ Zenith > 94°

21 +/- 11

61 +/- 29

$4.3^{+0.8}_{-1.4}$

60

Remaining events in 1247 days livetime

	Atm. μ:	Atm. ν:	Cosm. ν:	Measured:
After quality cuts:	1430^{+529}_{-537}	84 +/- 40	$9.4^{+2.0}_{-3.1}$	1394
+ Zenith > 94°	21 +/- 11	61 +/- 29	$4.3^{+0.8}_{-1.4}$	60
+ Shower energy > 10 TeV	1.9 +/- 1.5	$3.1^{+1.3}_{-1.4}$	$2.8^{+0.6}_{-1.0}$	8

Result

Upper limit (1247 days livetime) on cosmic diffuse neutrino flux (90% CL) per flavour, accounting for systematic uncertainties :

$$E^2 \cdot \Phi_{90\,\%} = 4.9 \cdot 10^{-8}\,\mathrm{GeV/cm^2 \cdot sr \cdot s}$$

1.9 +/- 1.5

$3.1+^{1.3}_{-1.4}$

$2.8^{+0.6}_{-1.0}$

8

Unblinding summary (1247 days)

- After the zenith cut **60 events** are found in data, where **81^{+40}_{-40}** are expected from **background only**.
- After the final energy cut (>10 TeV) **8 events** remain in data, where the **background only** expectation is **$4.9^{+2.8}_{-2.9}$**. This is consistent with the “IceCube flux”, but note the large uncertainties.
- Following **Feldman-Cousins** the 90% confidence upper limit on the diffuse flux is (no systematic uncertainties included)

$$E^2 \cdot \Phi_{90\,\%} = 3.91 \cdot 10^{-8}\,\mathrm{GeV}/\mathrm{cm}^2 \cdot \mathrm{sr} \cdot \mathrm{s}$$

- Taking into account systematic uncertainties using **Pole 1.0** (Conrad et al., Comput. Phys. Comm. 158 (2004) with relative background uncertainty: 0.42, rel. signal uncert.: 0.29) the upper limit is:

$$E^2 \cdot \Phi_{90\,\%} = 4.91 \cdot 10^{-8}\,\mathrm{GeV}/\mathrm{cm}^2 \cdot \mathrm{sr} \cdot \mathrm{s}$$

Some remarks on the events

- For the 60 selected “up-going” events the **distance between 2 different vertex fitters** is **10** meters (mean), **2** meters (median).

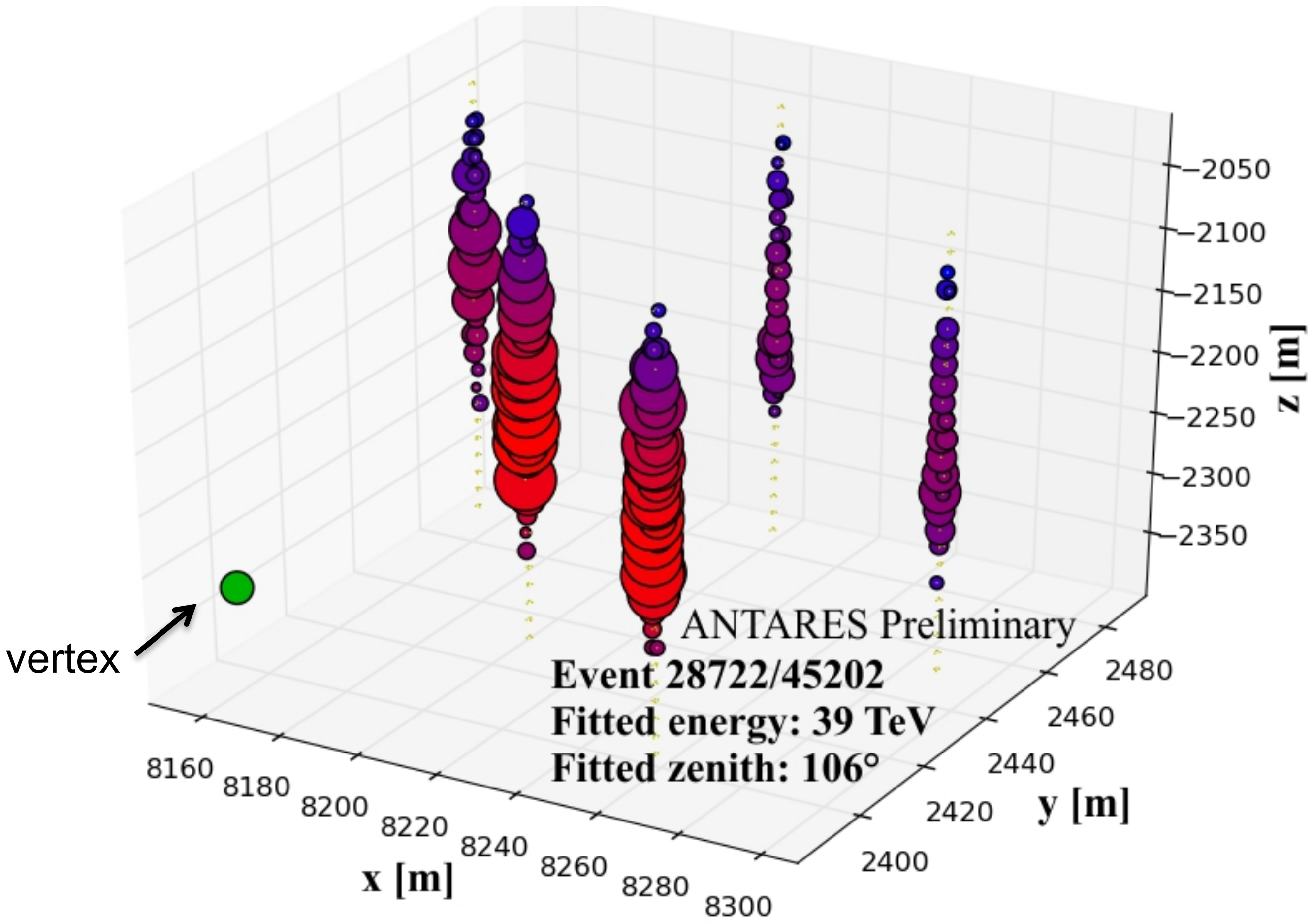
- The **angle between muon track reconstruction and shower direction** fit is **37** deg (mean), **36** deg (median).

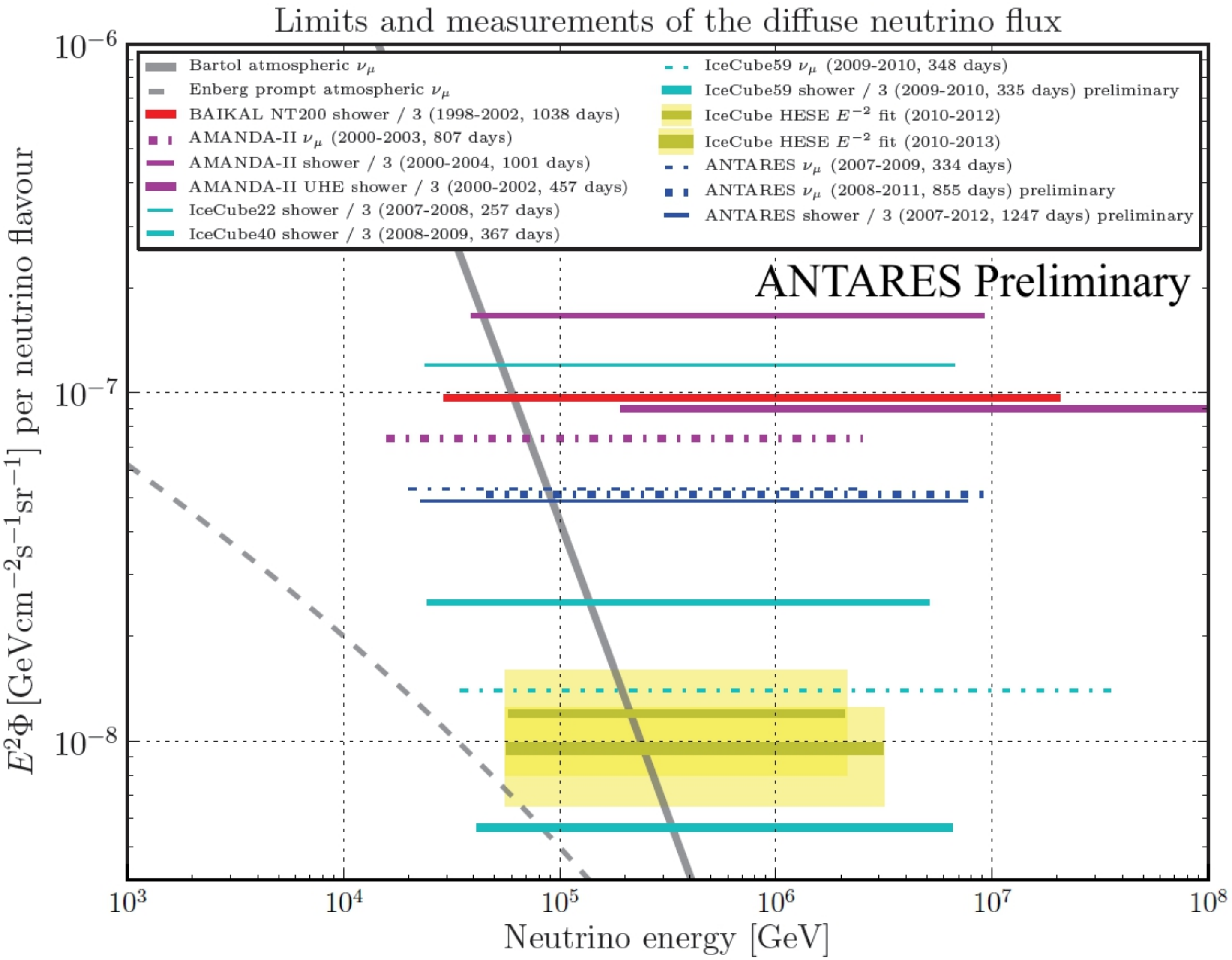
- Among the 60 events 36 have a **contained** vertex position **(60 +/- 13) %,** where from simulations about **(71 +/- 47) %** are expected.

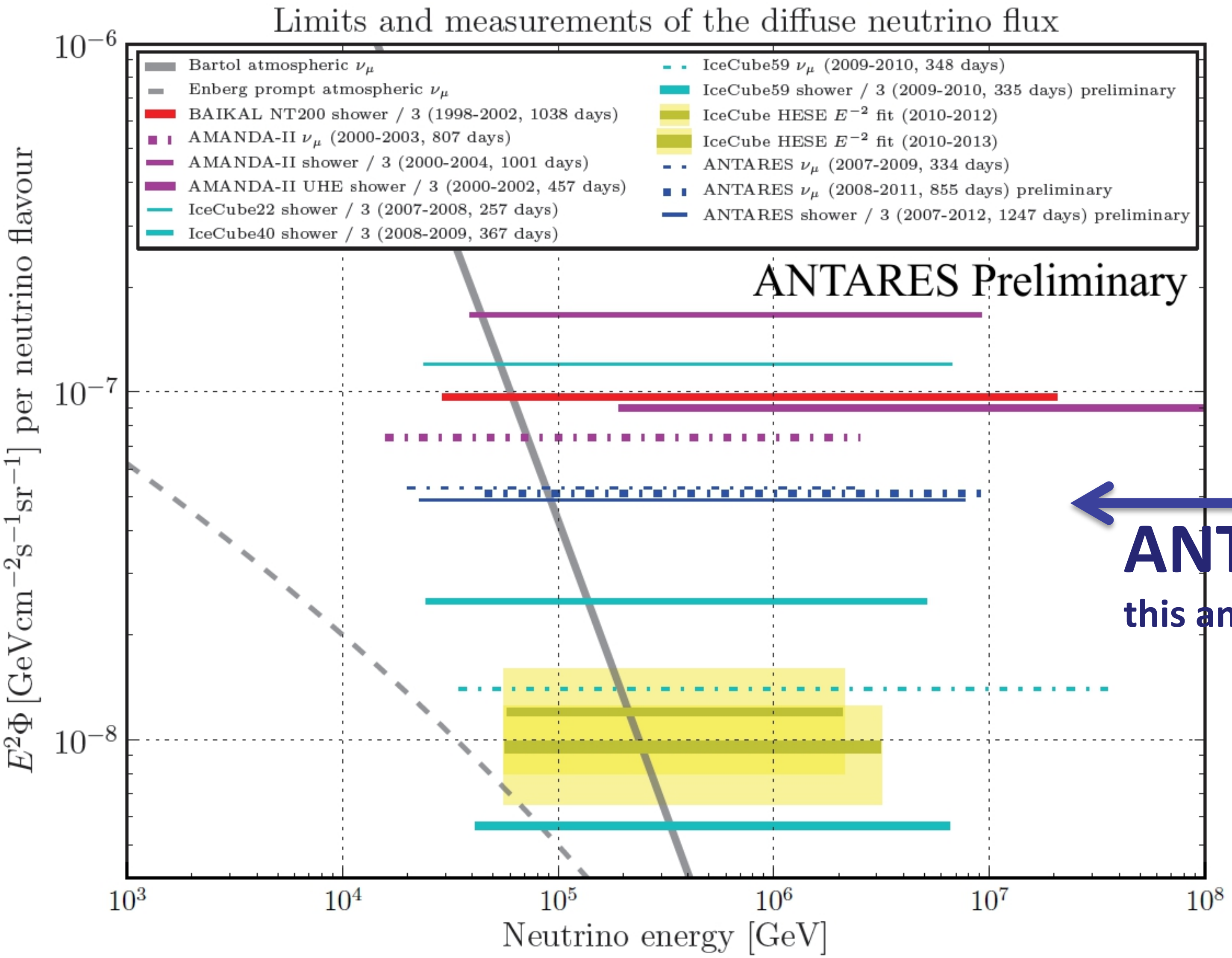
- **After the energy cut** about **(30 +/- 20) % contained events** are expected from simulations, but **none** is measured.

Event Display

run 28722, 5 lines, 2007-07-13 02:10:22




Limits and measurements of the diffuse neutrino flux
Bartol atmospheric ν_μ
Enberg prompt atmospheric ν_μ
BAIKAL NT200 shower / 3 (1998-2002, 1038 days)
AMANDA-II ν_μ (2000-2003, 807 days)
AMANDA-II shower / 3 (2000-2004, 1001 days)
AMANDA-II UHE shower / 3 (2000-2002, 457 days)
IceCube22 shower / 3 (2007-2008, 257 days)
IceCube40 shower / 3 (2008-2009, 367 days)
IceCube59 ν_μ (2009-2010, 348 days)
IceCube59 shower / 3 (2009-2010, 335 days) preliminary
IceCube HESE E^{-2} fit (2010-2012)
IceCube HESE E^{-2} fit (2010-2013)
ANTARES ν_μ (2007-2009, 334 days)
ANTARES ν_μ (2008-2011, 855 days) preliminary
ANTARES shower / 3 (2007-2012, 1247 days) preliminary
ANTARES Preliminary
10^{-6}
10^{-7}
10^{-8}
$E^2\Phi$ [GeV cm^{-2}s^{-1}sr^{-1}] per neutrino flavour
10^3
10^4
10^5
10^6
10^7
10^8
Neutrino energy [GeV]



ANTARES

this analysis

Limits for other flux assumptions

	Unbroken cosmic signal flux	**Cosmic signal flux with a cut-off at 2 PeV**
Normal Enberg prompt atmospheric flux	Signal events: **2.79** Backgr. events: **4.92** Sensitivity: **2.21 * 10^{-8}** POLE UPPER LIMIT: **4.92 * 10^{-8}**	Signal events: **2.14** Backgr. events: **4.92** Sensitivity: **2.89 * 10^{-8}** POLE UPPER LIMIT: **6.40 * 10^{-8}**
3.8 * Enberg prompt atmospheric flux	Signal events: **2.79** Backgr. events: **6.63** Sensitivity: **2.48 * 10^{-8}** POLE UPPER LIMIT: **4.05 * 10^{-8}**	Signal events: **2.14** Backgr. events: **6.63** Sensitivity: **3.22 * 10^{-8}** POLE UPPER LIMIT: **5.28 * 10^{-8}**

Unblinding result

Note: without reoptimization of cuts!

What if the observed excess is a signal?

- The Poisson probability to measure **8 events where 4.9 are expected** from background is **6.2 %**.

- The Poisson probability to measure **8 or more events** is **12.5 %**

- In a one-sided Gaussian distribution this gives a significance of **1.5 σ**.

- The **best fit of an E^{-2}-flux normalization** to measure 8 events is
  - **$1.3^{+1.8}_{-1.3}$ * 10^{-8}** GeV / cm^2*sr*s (unbroken spectrum)
  - **$1.7^{+2.3}_{-1.8}$ * 10^{-8}** GeV / cm^2*sr*s (cut-off at 2 PeV)

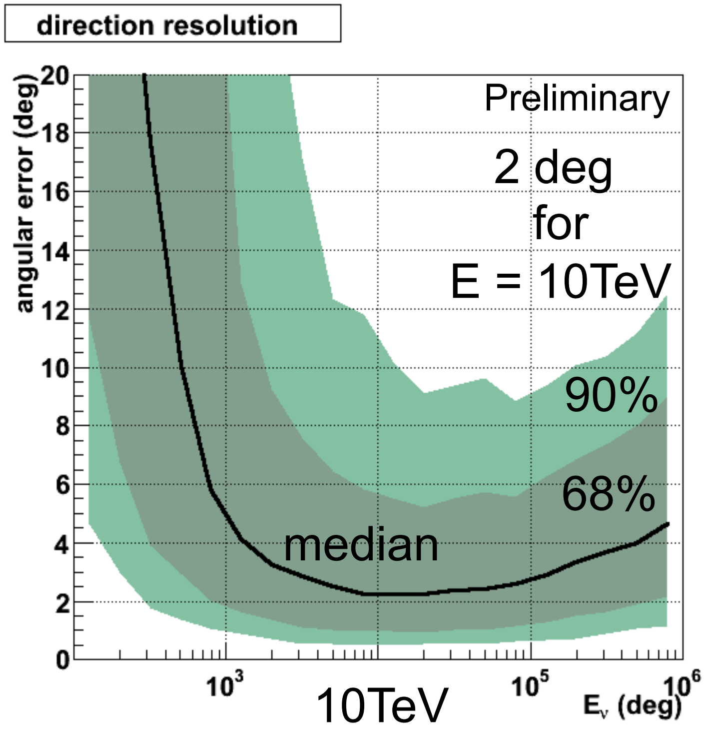
  (per neutrino flavour)

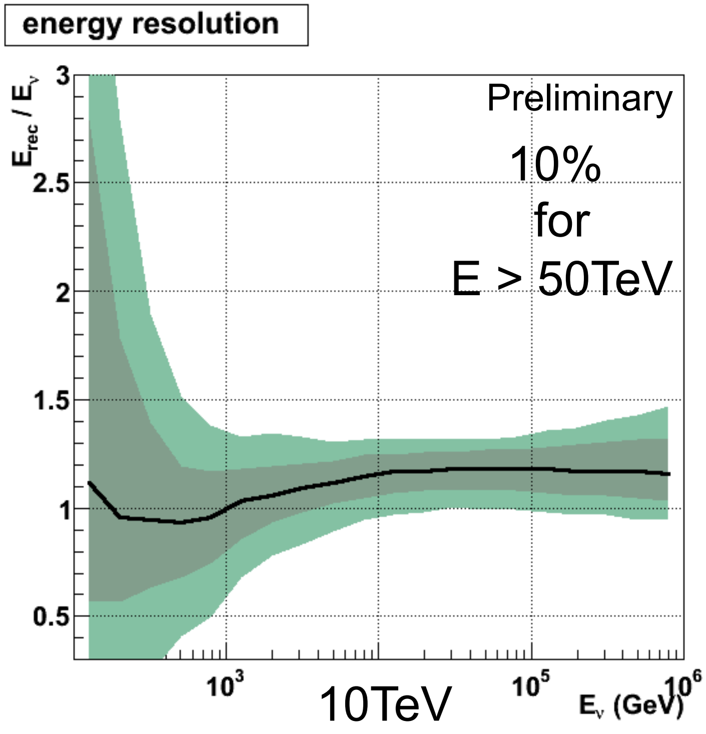
- However, the measured excess is compatible with atmospheric background when taking systematic and statistical errors into account.

Outlook

- Working on error estimates for direction and energy for each event
- Publication draft undergoing internal review process

Very recent development: new shower reconstruction (for details see next talk by A. Heijboer)





Remarks:

- Contained events only
- Monte Carlo with fully operational detector
- 60 kHz steady optical background

Backup slides

The 8 remaining data events

Run ID	Fitted energy [TeV]	Fitted zenith [°]	# hits / strings	Total charge [pe]	Containment	Run burst fraction	Run mean rate [kHz]	Quality basic
26397	42.1	125.9	42/3	169	29*	0.41	91	1
27893	16.3	98.2	75/3	321	61*	0.05	63	4
28722	39.1	106.1	286/5	1373	23*	0.04	63	4
43639	87.5	129.7	36/3	74	84*	0.09	90	4
46852	39.3	143.3	91/6	603	84*	0.13	87	1
49425	21.4	100.9	88/6	562	22*	0.36	235	1
51879	15.0	119.6	50/3	318	40*	0.16	100	4
62834	28.1	118.5	99/7	456	69*	0.16	66	4

* Distance in meters to detector edge.

- All remaining events have a fitted vertex outside the instrumented volume