Ultra-High Energy neutrinos at the Pierre Auger Observatory

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for the Pierre Auger Collaboration

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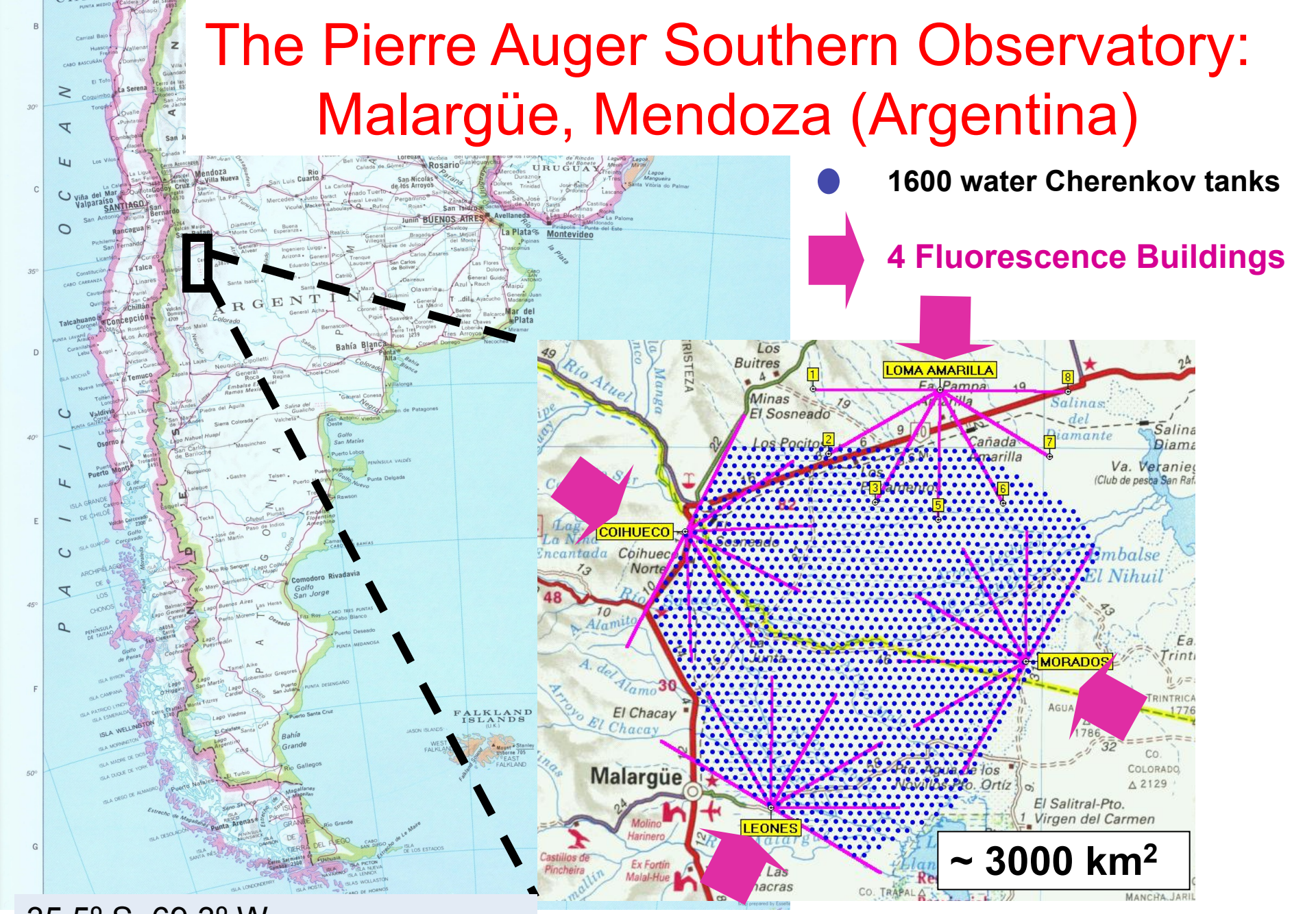
Boston, USA, 2 June 2014

The Pierre Auger Southern Observatory: Malargüe, Mendoza (Argentina)



35.5º S, 69.3º W
1400 m a.s.l. (880 g cm^{-2})

Auger sensitivity to UHE neutrinos

- **Auger is not a dedicated neutrino observatory**

(main aim is characterizing the poperties of Ultra-High Energy Cosmic Rays – UHECRs) but …

…with the **surface detector (SD)** we have a good sensitivity to UHE neutrinos at $\gtrsim$ EeV (10^{18} eV) energies.

- Challenge: Identifying **neutrino-induced showers** in the dominant background of showers induced by UHECRs (protons & nuclei).

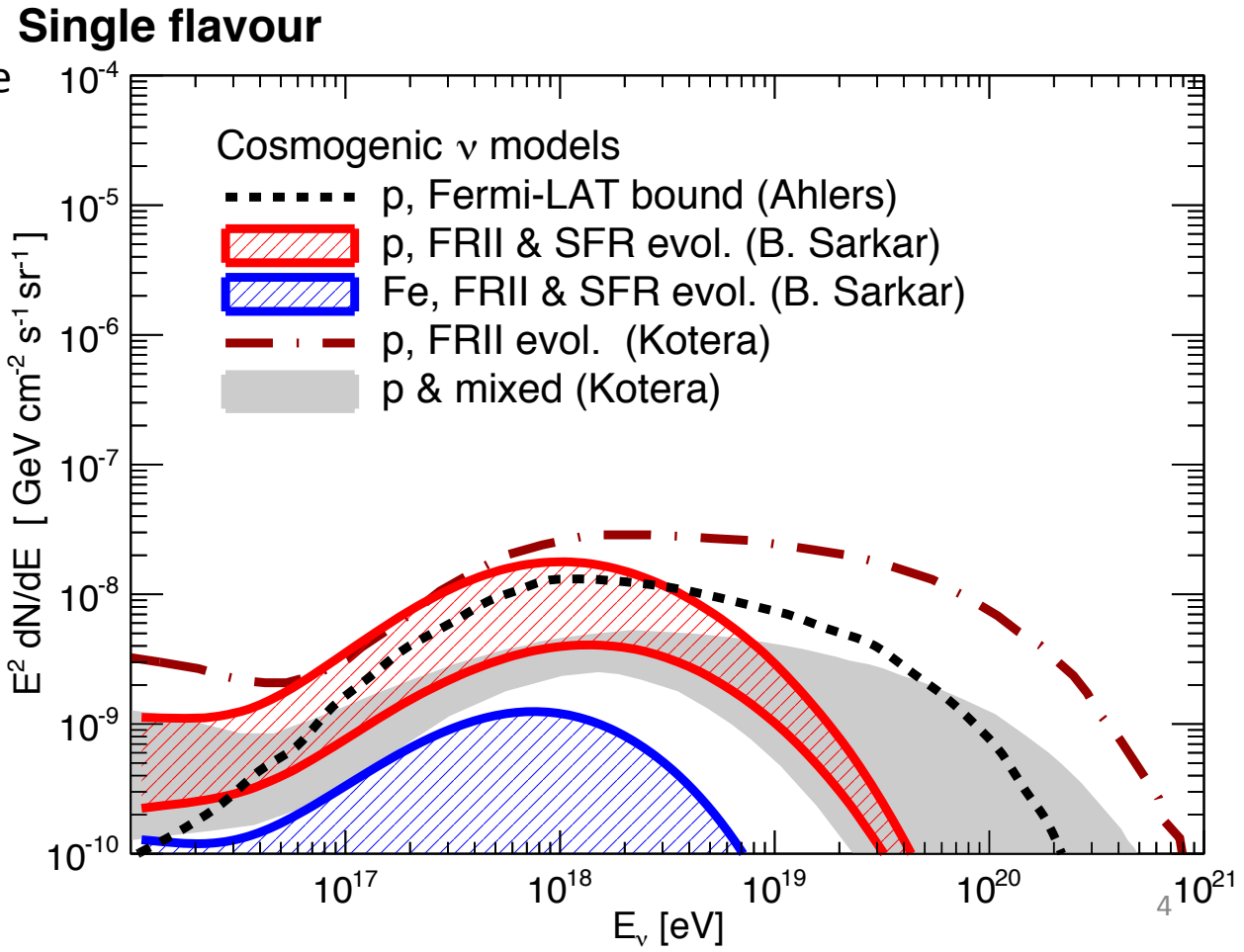
Cosmogenic neutrinos

Produced in interactions of UHECRs with the CMB

$$p + \gamma_{2.7K} \rightarrow \Delta(1232) \rightarrow n + \pi^+ \nearrow \mu^+ + \nu_\mu \searrow e^+ + \bar{\nu}_\mu + \nu_e$$
$$\searrow p + \pi^0 \searrow \gamma + \gamma$$

Detection in EeV energy range may provide complementary information to direct UHECR detection on:

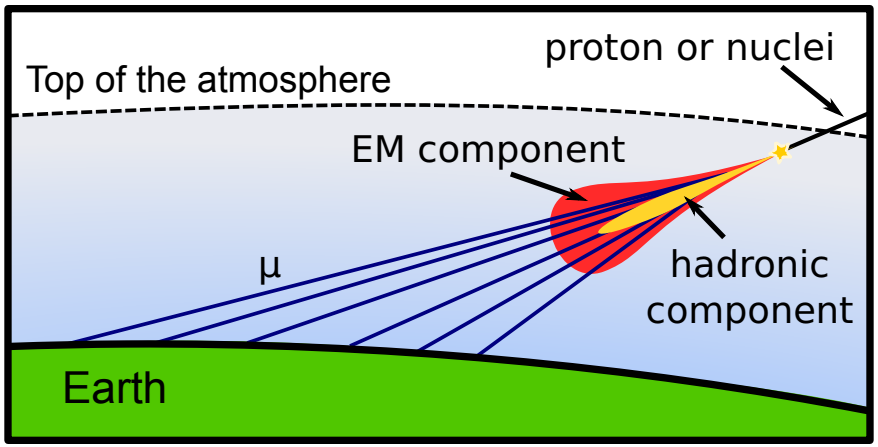
- **UHECR nature:**
  - p or Fe-dominated ?
  - mixed composition ?
- **origin:**
  - evolution of sources with redshift
  - max. energy attainable in sources

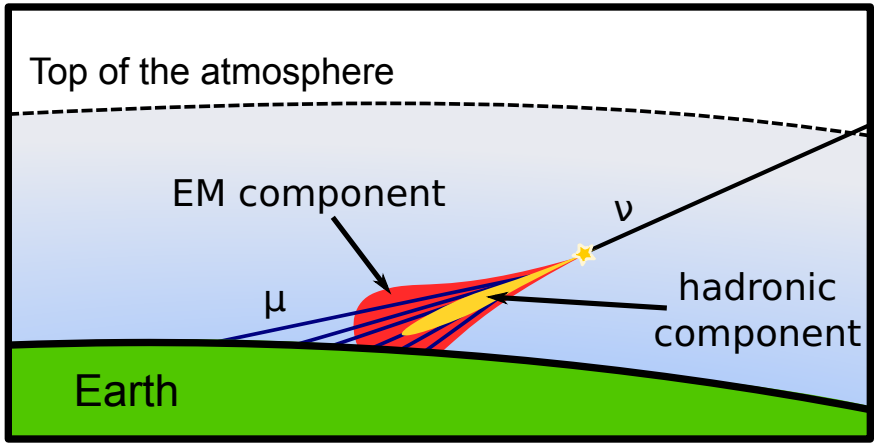


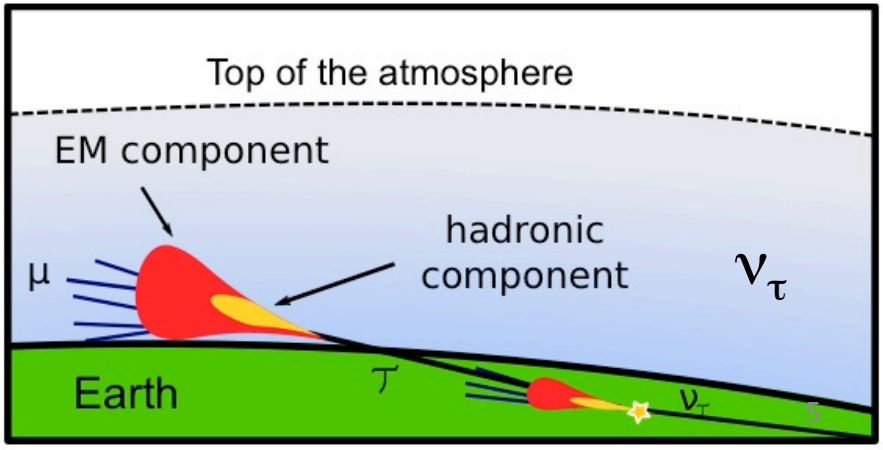
Inclined showers & UHE neutrinos

- Protons & nuclei initiate inclined showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate “deep” showers close to ground.
  - Shower front at ground: electromagnetic + muonic components

Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

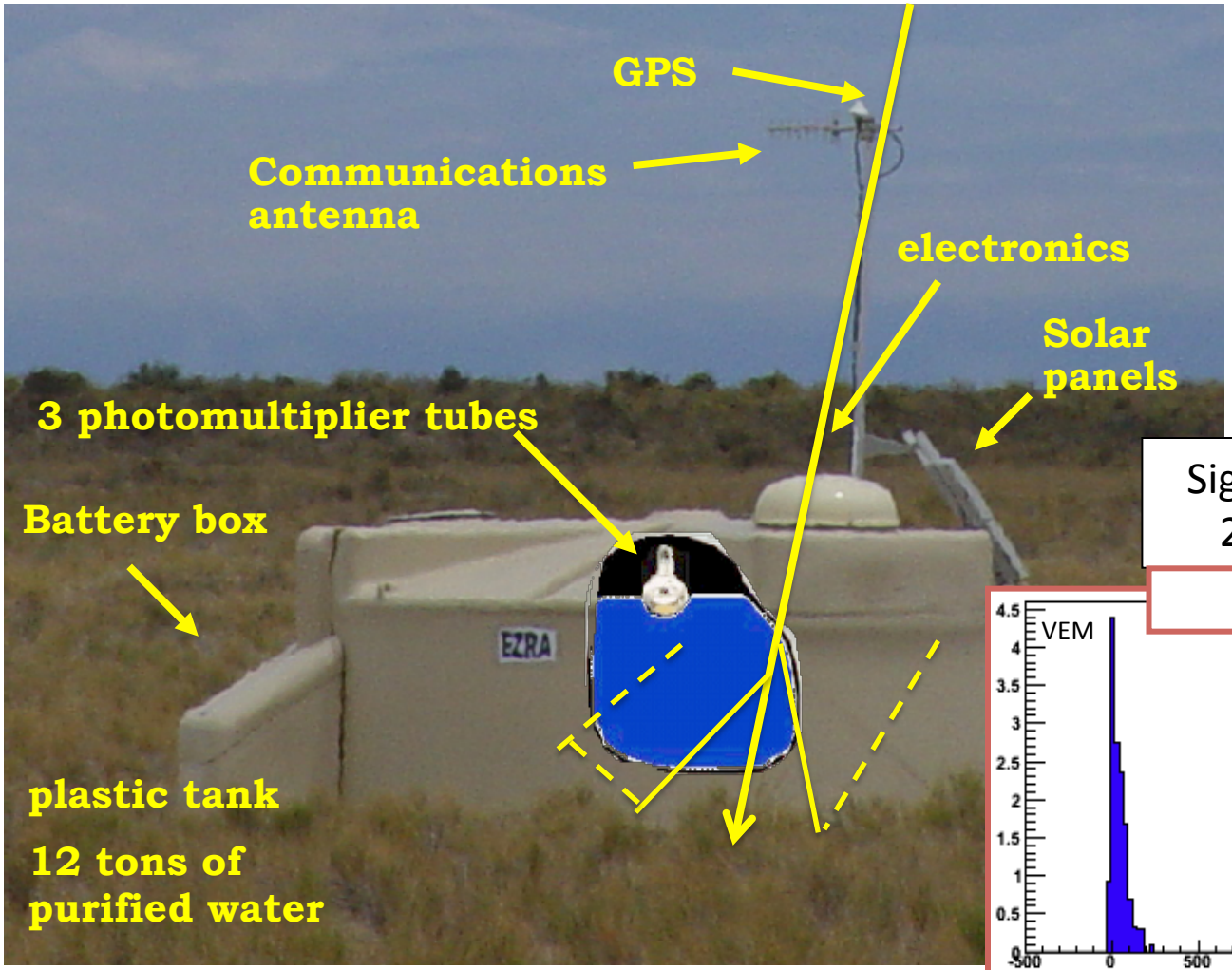






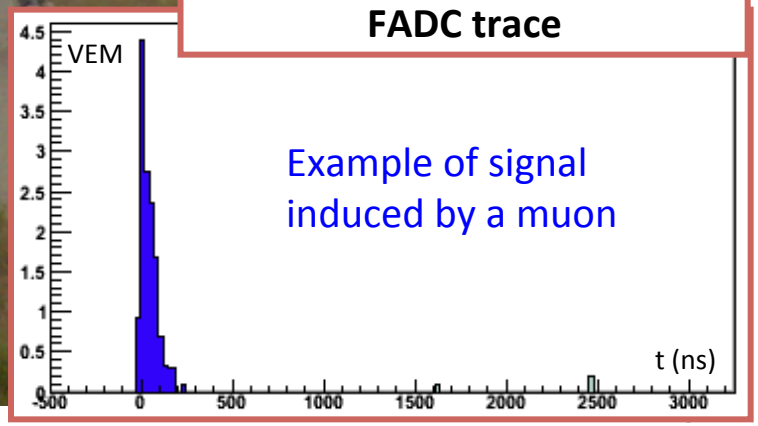
Surface Detector (SD) stations

- ✓ Sensitive to inclined showers.
- x Not directly sensitive to electromagnetic and muonic components.
- ✓ Can measure the time structure of the signals induced by electrons and muons



Signals are digitized with 25 ns time resolution

FADC trace

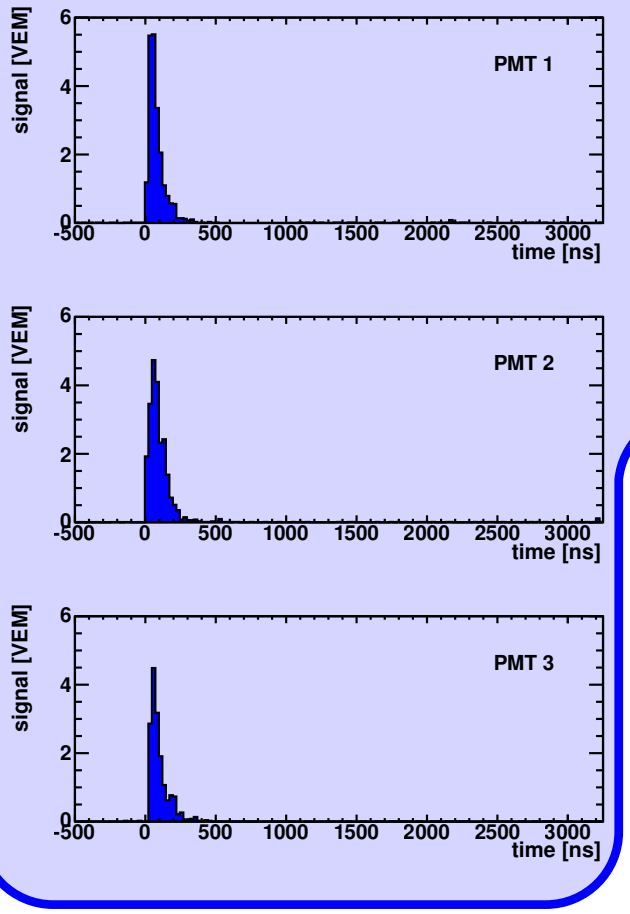


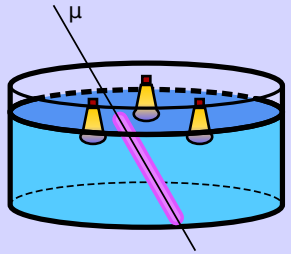
Example of signal induced by a muon

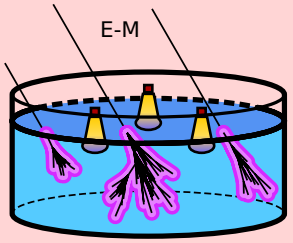
Identifying νs in data collected at SD

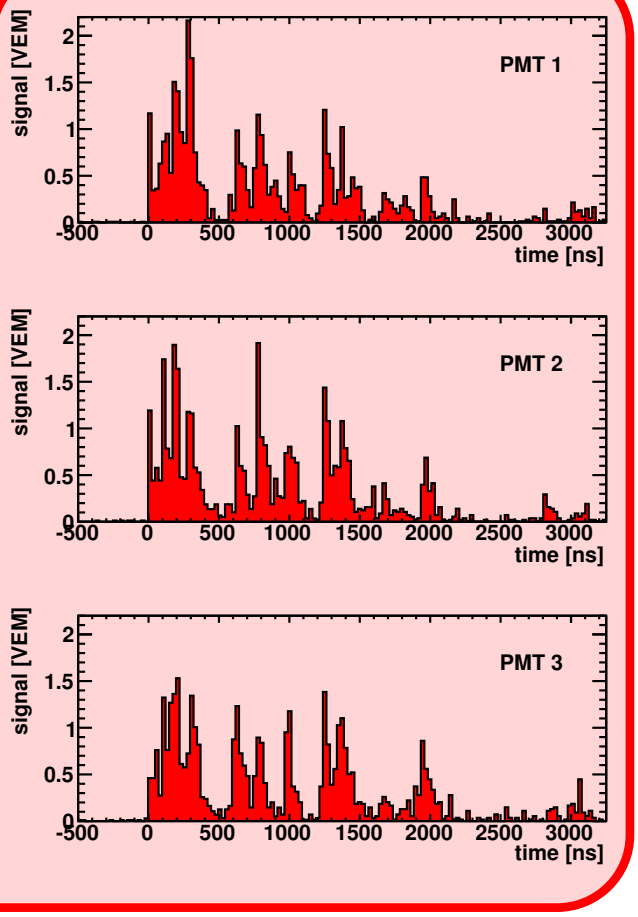
With the SD, we can distinguish muonic from electromagnetic shower fronts (using the time structure of the signals in the water Cherenkov stations).

Muonic shower front: narrow signals









EM shower front: broad signals

Identifying νs in data collected at SD

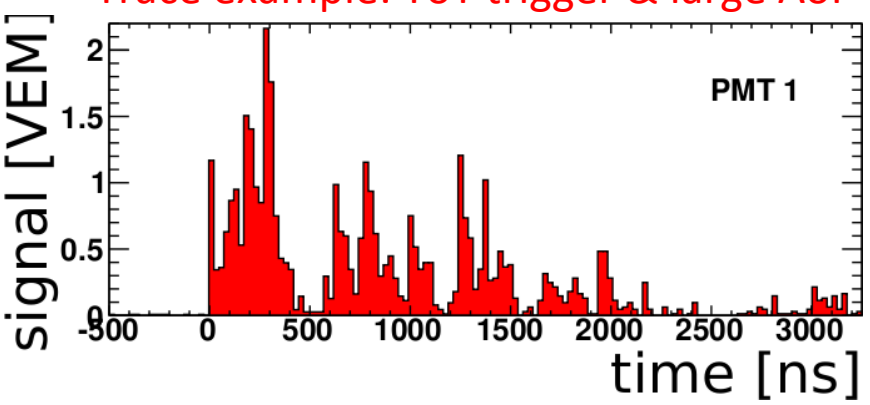
From the observational point of view, signals extended in time:

- Induce Time-over-Threshold (ToT) triggers in the SD stations

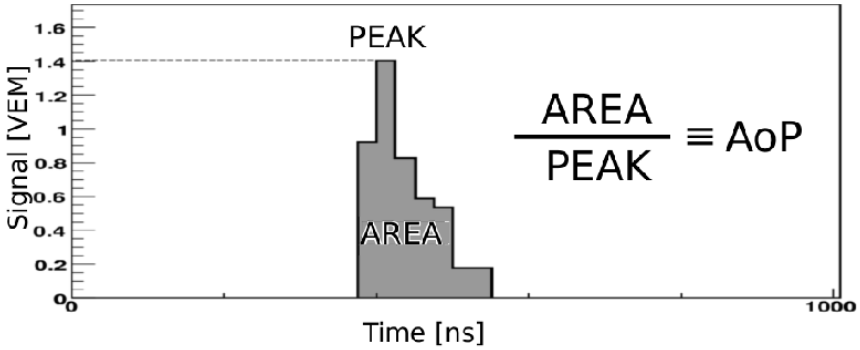
and/or

- Have large Area-over-Peak value (AoP ∼ 1 muonic front)

Trace example: ToT trigger & large AoP

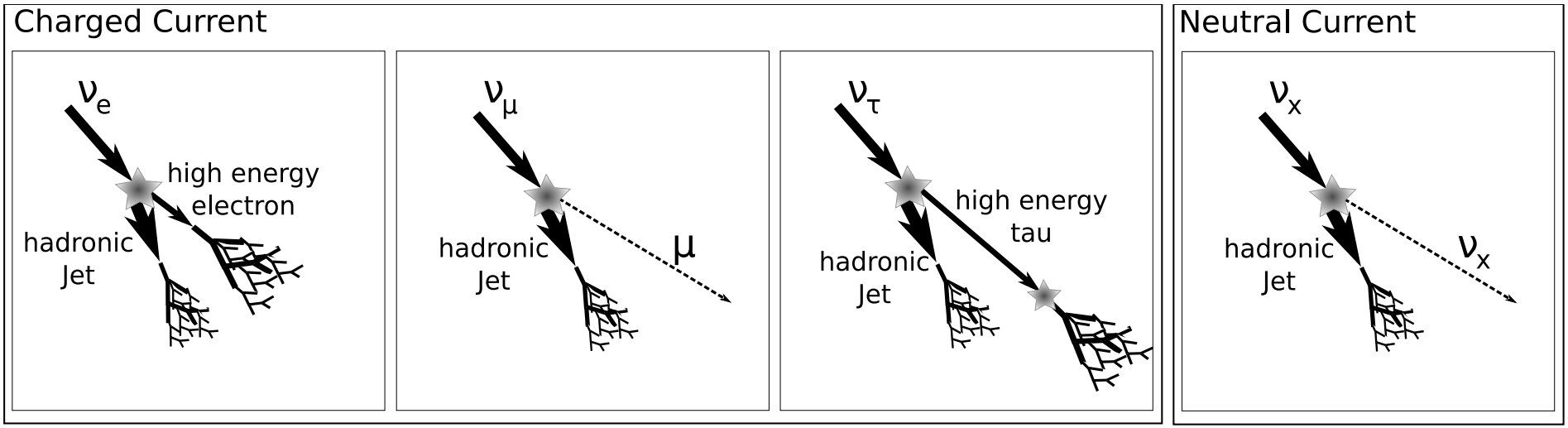


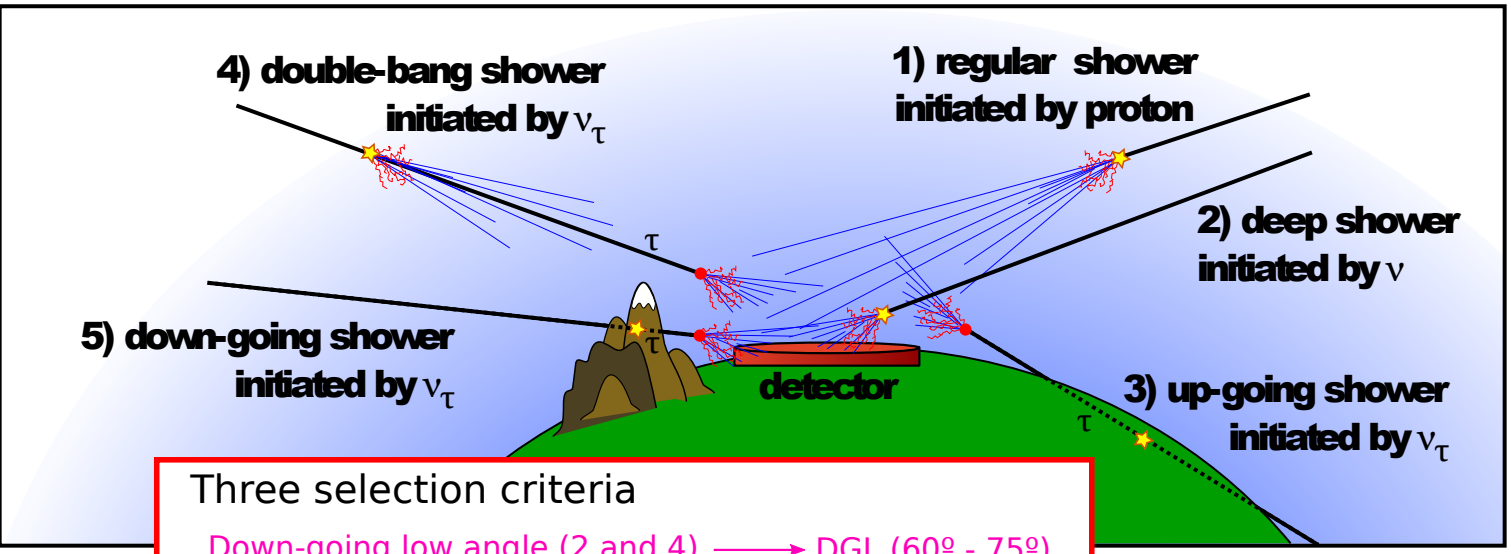
Definition of Area-over-Peak (AoP)

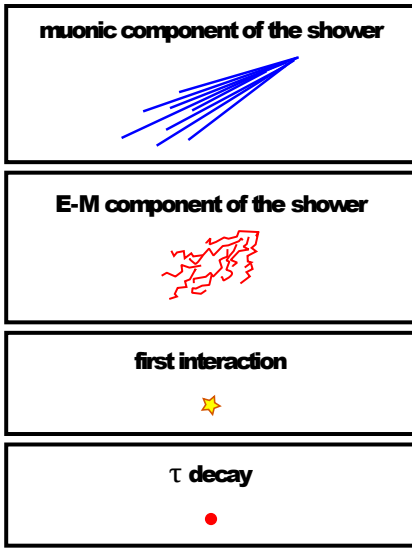


Searching for neutrinos ⇒
Searching for inclined showers with stations with ToT triggers and/or large AoP

Sensitivity to all flavours & channels



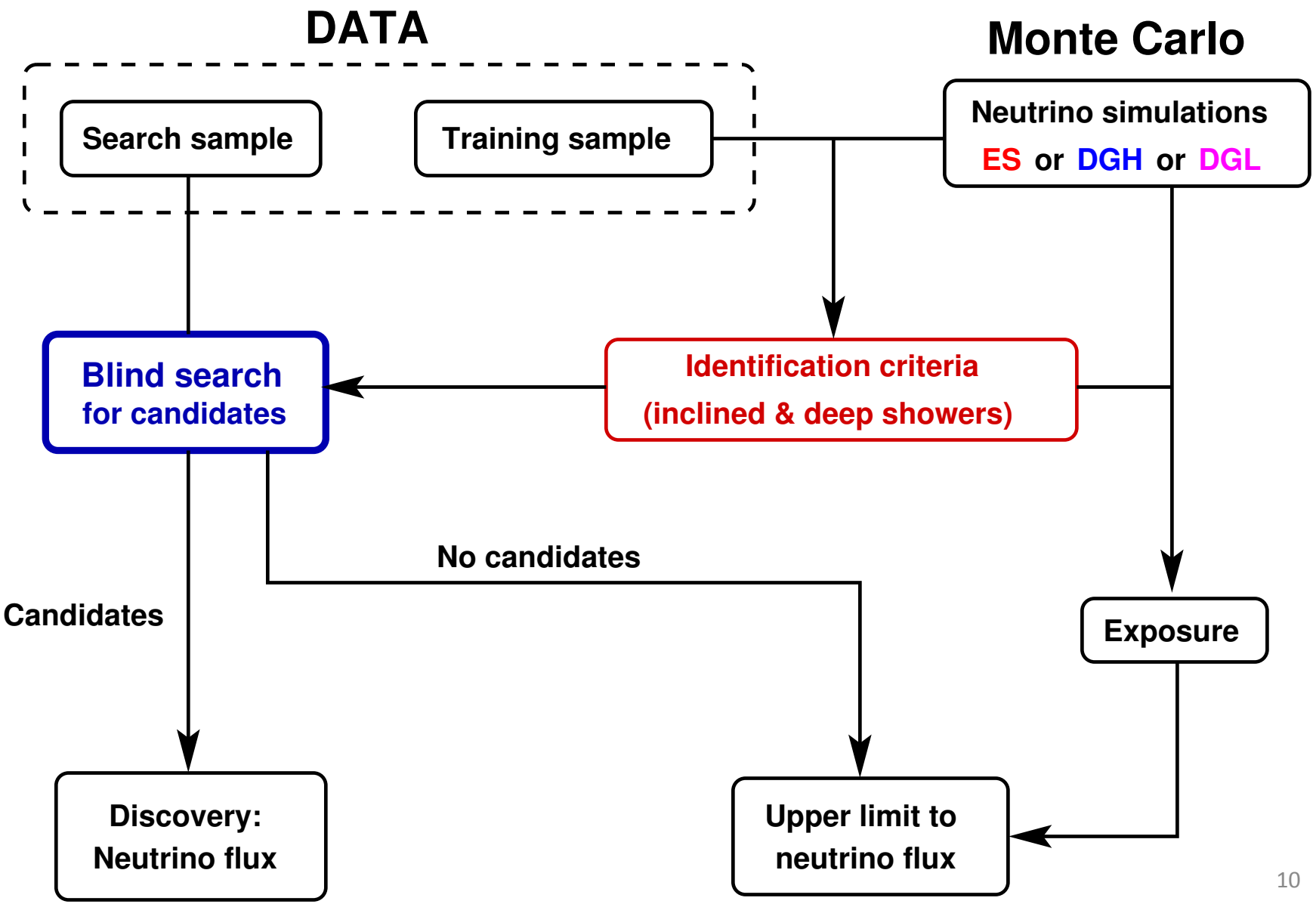




Three selection criteria

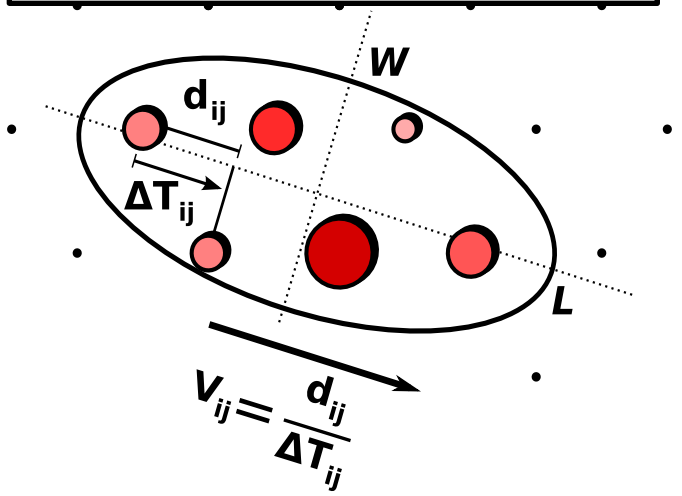
Down-going low angle (2 and 4) → DGL (60º - 75º)
Down-going high angle (2, 4 and 5) → DGH (75º - 90º)
Earth-skimming (3) → ES (90º - 95º)

Methodology: general “strategy”

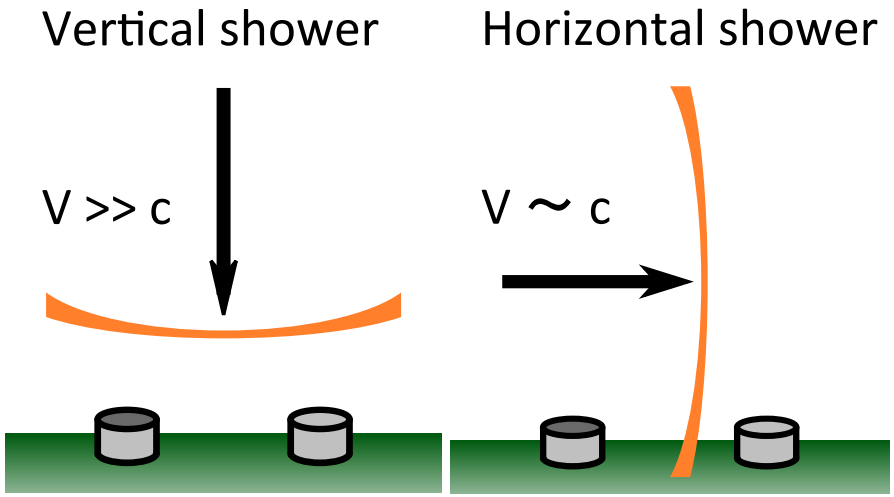


Selection of inclined showers

(1) Elongated footprint



(2) Apparent velocity V of propagation of shower front at ground along major axis L

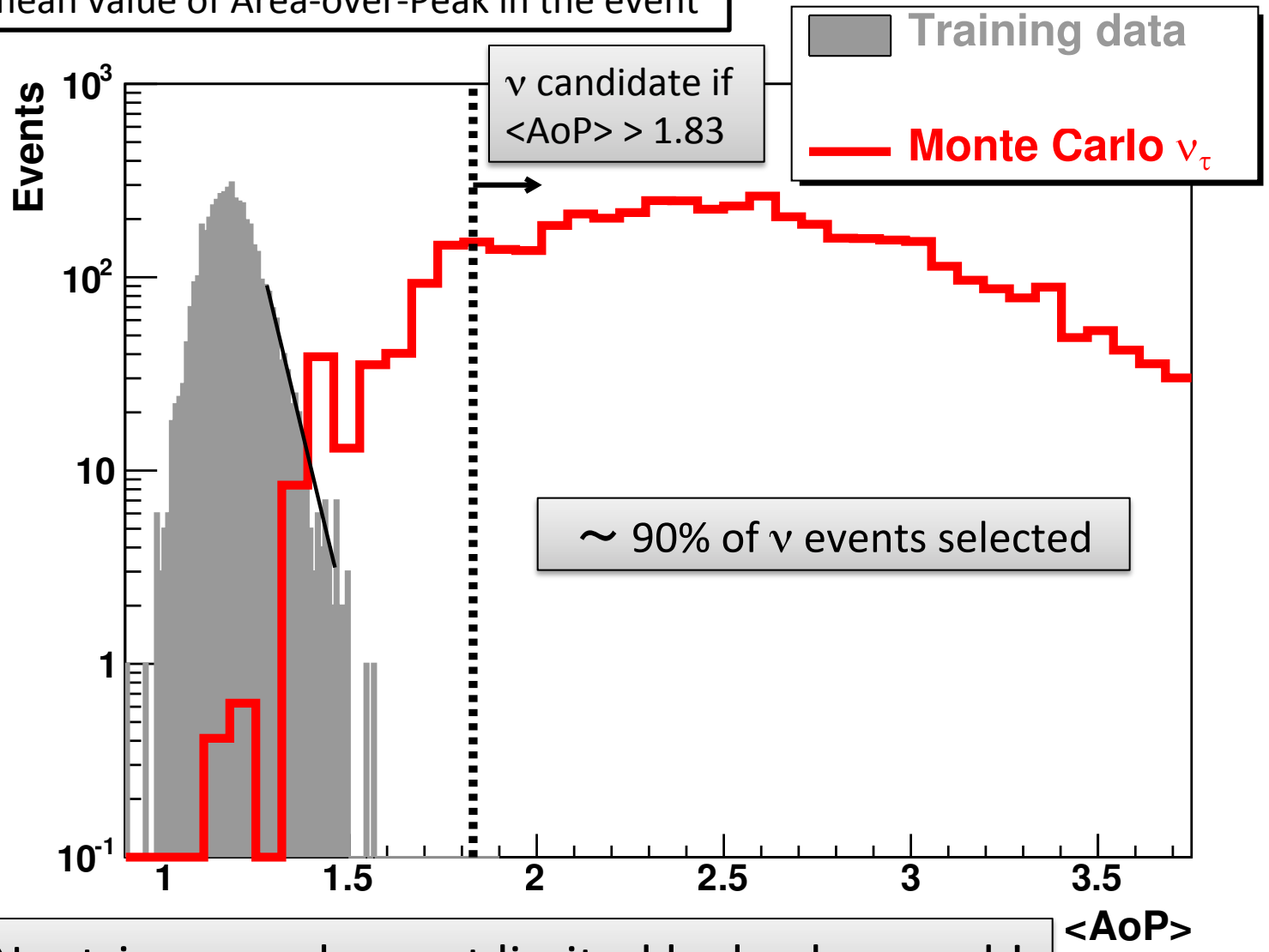


(3) Reconstructed θ

Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
$L/W > 5$	$L/W > 3$	–
$\langle V \rangle \in (0.29,\ 0.31)$ m ns^{-1}	$\langle V \rangle < 0.313$ m ns^{-1}	–
RMS$(V) < 0.08$ m ns^{-1}	RMS$(V)/\langle V \rangle < 0.08$	–
–	$\theta_{\rm rec} > 75°$	$\theta_{\rm rec} \in (58.5°,\ 76.5°)$

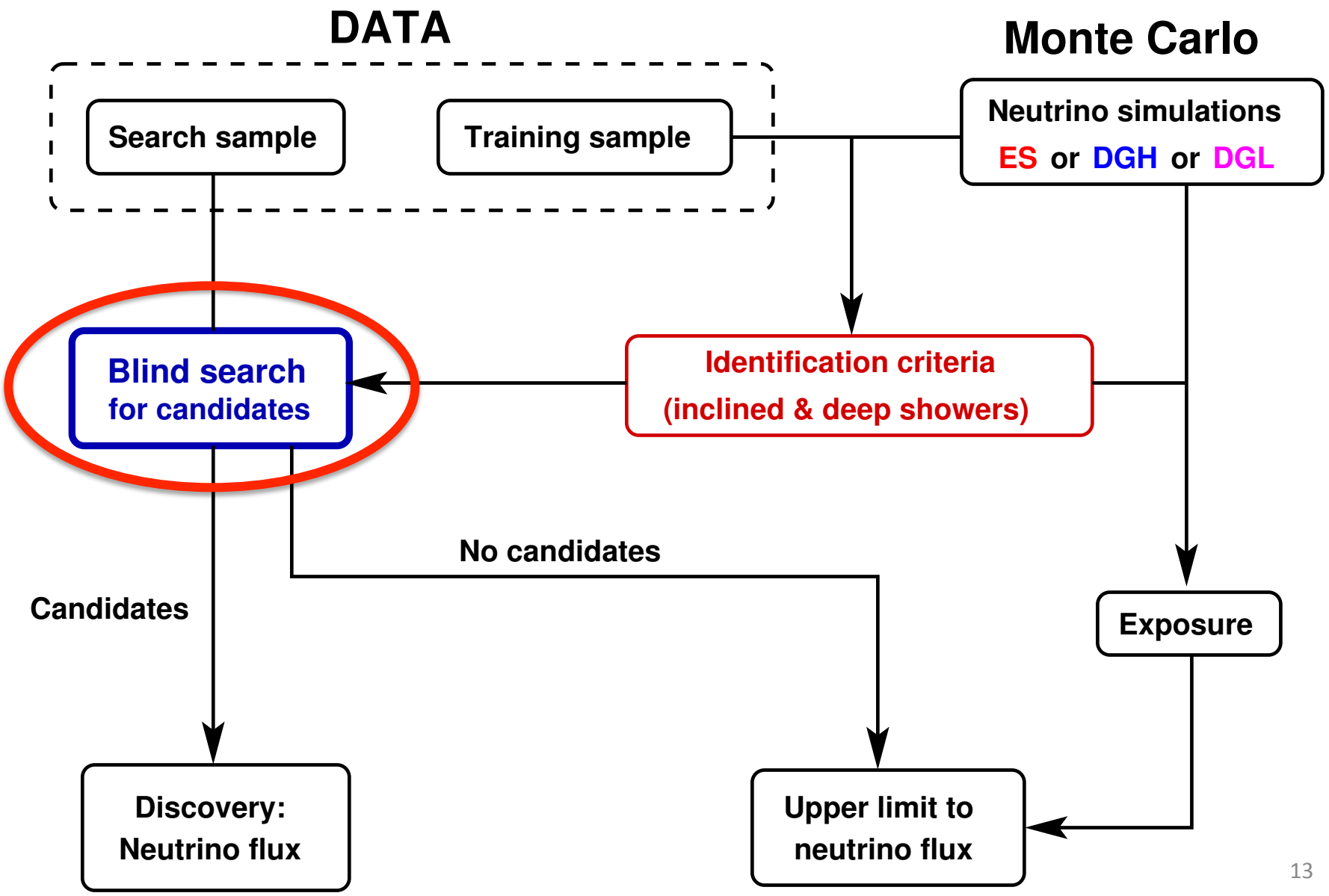
ν identification: Earth-Skimming

<AoP> = mean value of Area-over-Peak in the event



Neutrino searches not limited by background !

General “strategy”



Unblinding: "Opening the box"

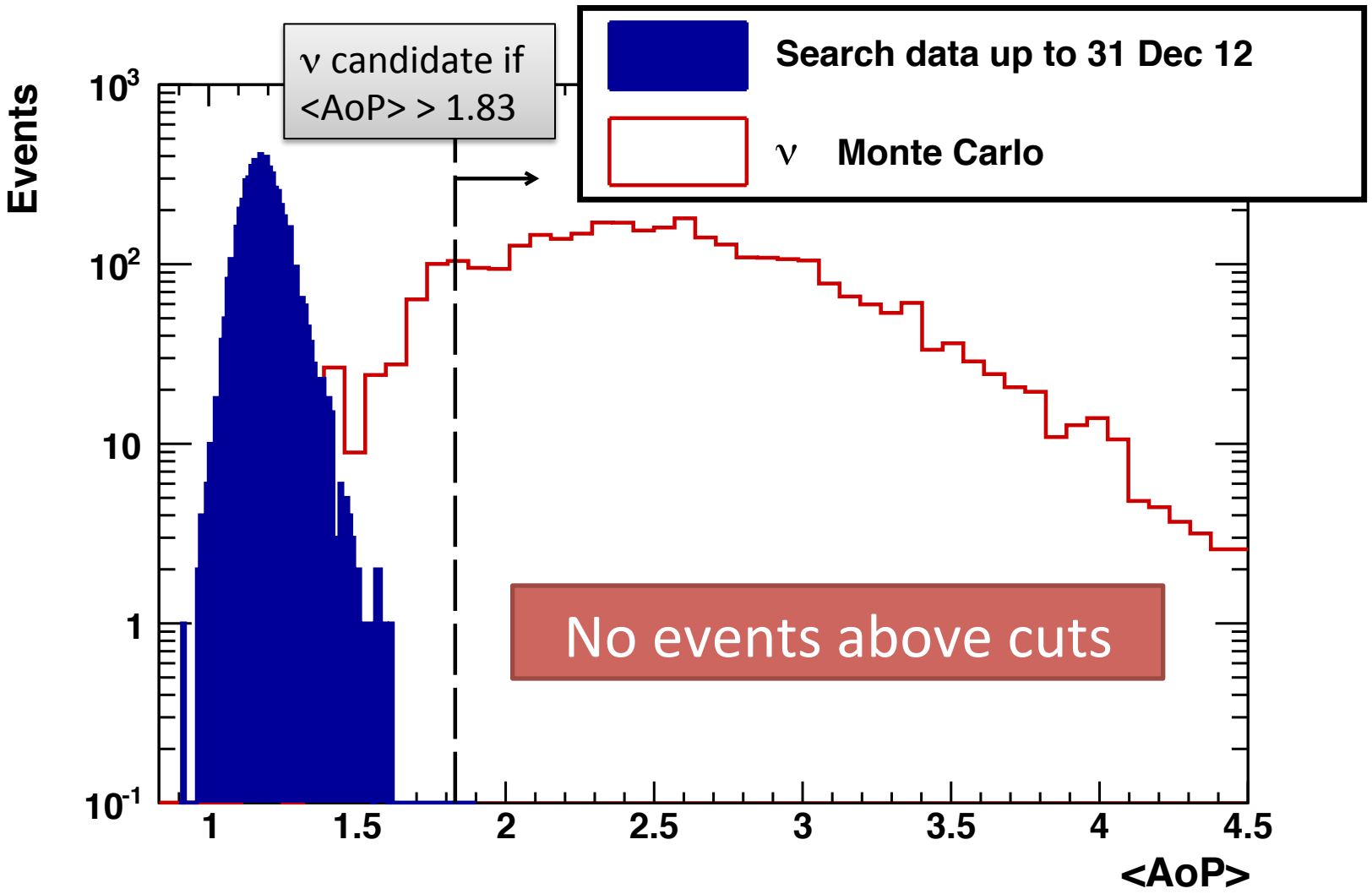
Overview of ν identification criteria

Earth-Skimming $(90°, 95°)$	Down-going High $(75°, 90°)$	Down-going Low $(65°, 75°)$
Data: 1 January 04 - 31 May 10 $\geq 60\%$ of stations with ToT trigger & AoP > 1.4	Fisher discriminant based on AoP of *early* stations	$\geq 75\%$ of stations close to shower core with ToT trigger & Fisher discriminant based on AoP of *early* stations close to shower core
Data: 1 June 10 - 31 December 12 $\langle \text{AoP} \rangle > 1.83$ $\text{AoP}_{\text{min}} > 1.4$ if Nst=3		

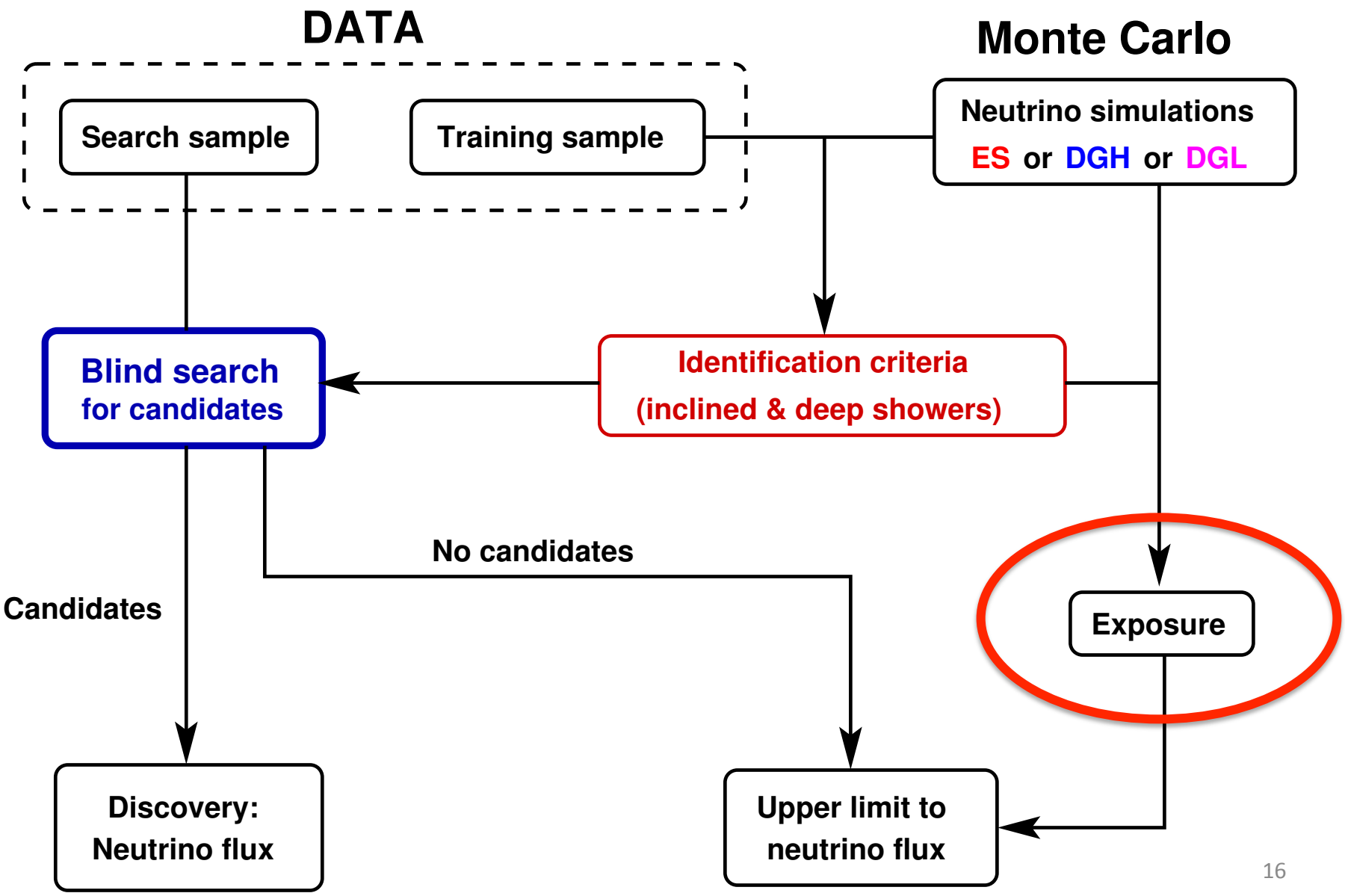
ν identification cuts applied "blindly" to data:
1 Jan 04 – 31 Dec 12 (excluding training data periods)

No candidates found
in Earth Skimming or Downward-going

ν search: Earth-Skimming analysis

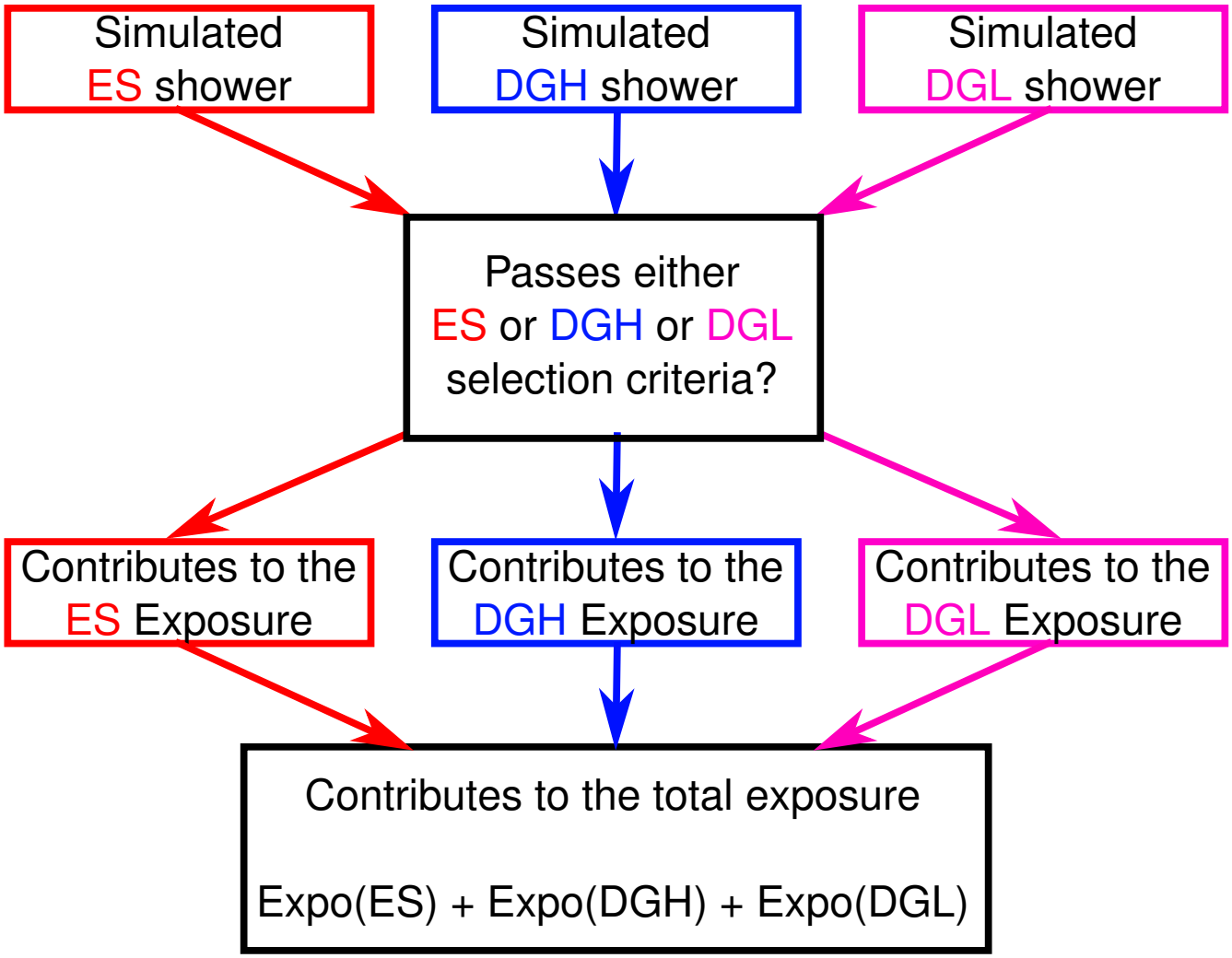


General “strategy”



"Combined" exposure calculation:

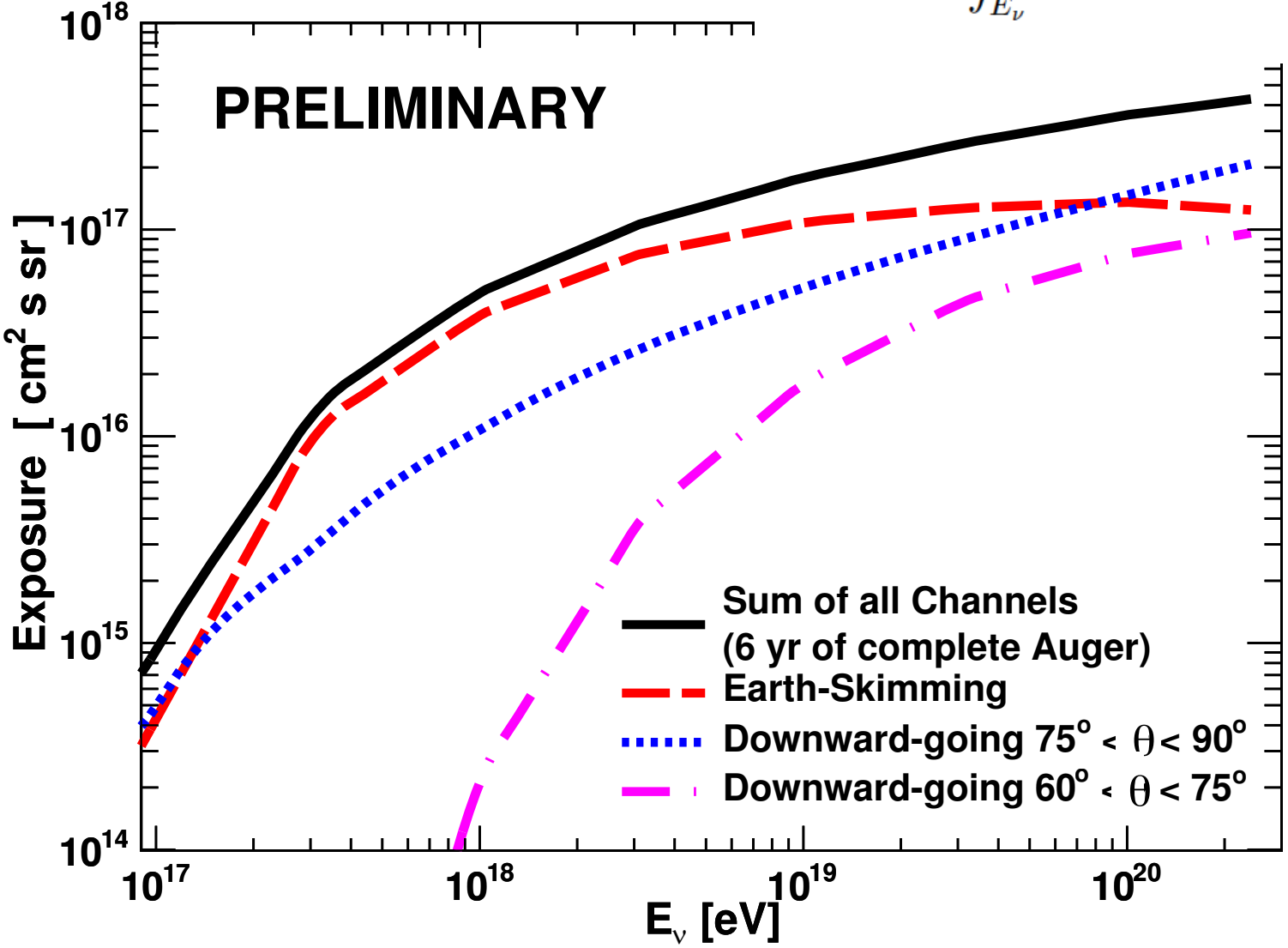
Earth-Skimming + Downgoing (60°, 75°) & (75°, 90°)



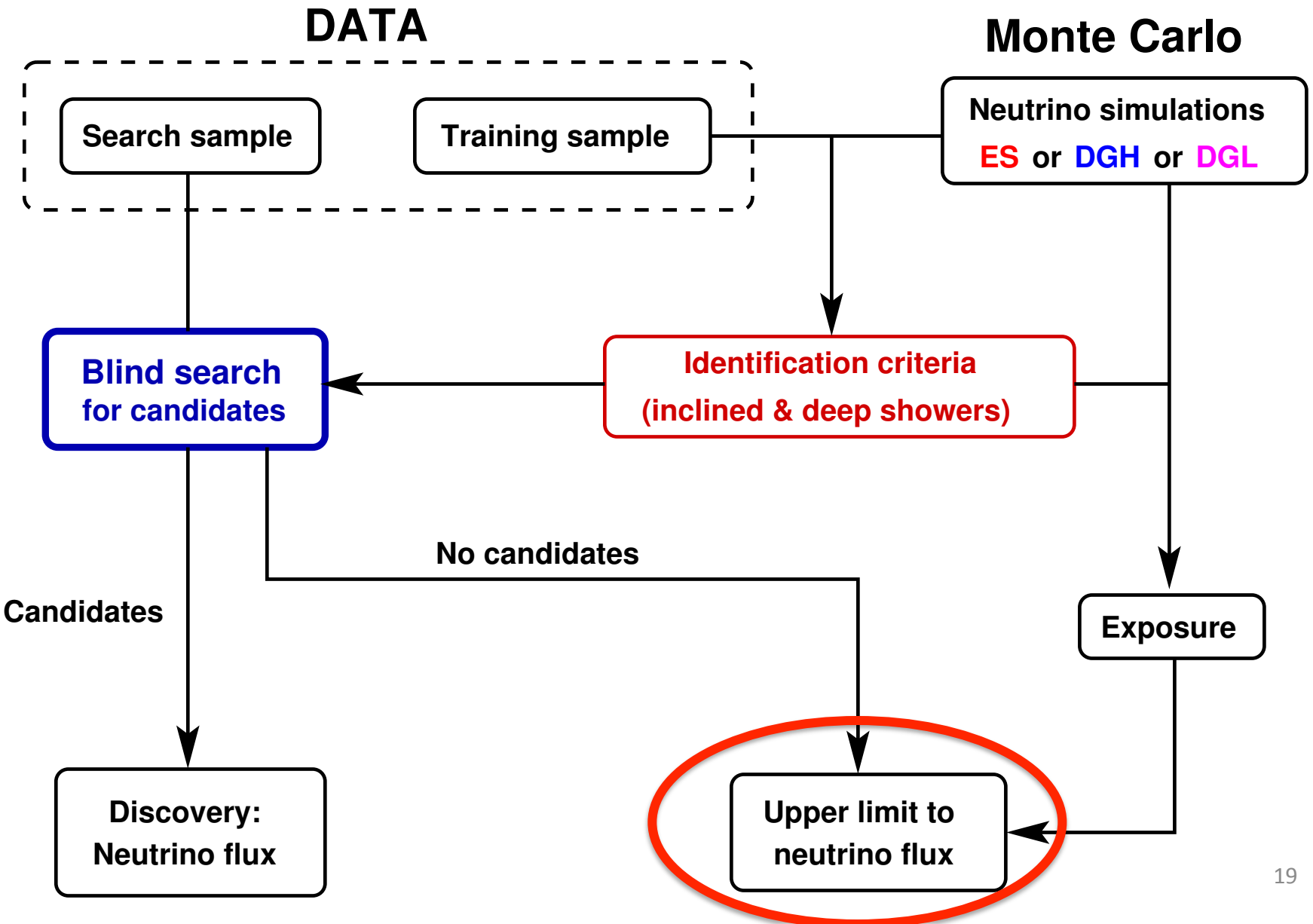
Exposure: 1 Jan 04 – 31 Dec 12

(excluding training data periods)

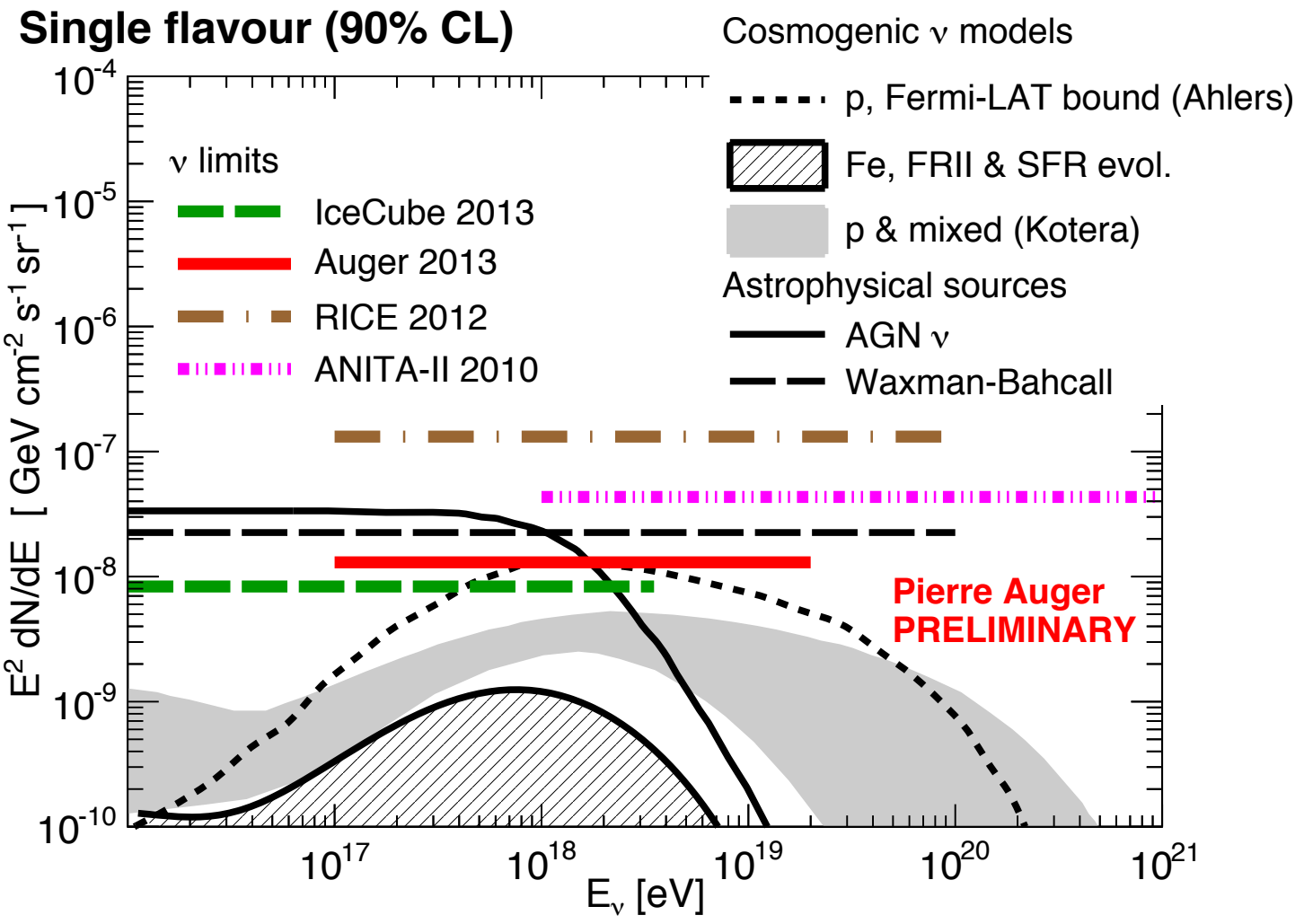
$$N_{\text{events}} = \int_{E_\nu} \Phi(E_\nu)\ \varepsilon_{\text{tot}}(E_\nu)\ \mathrm{d}E_\nu$$



General “strategy”

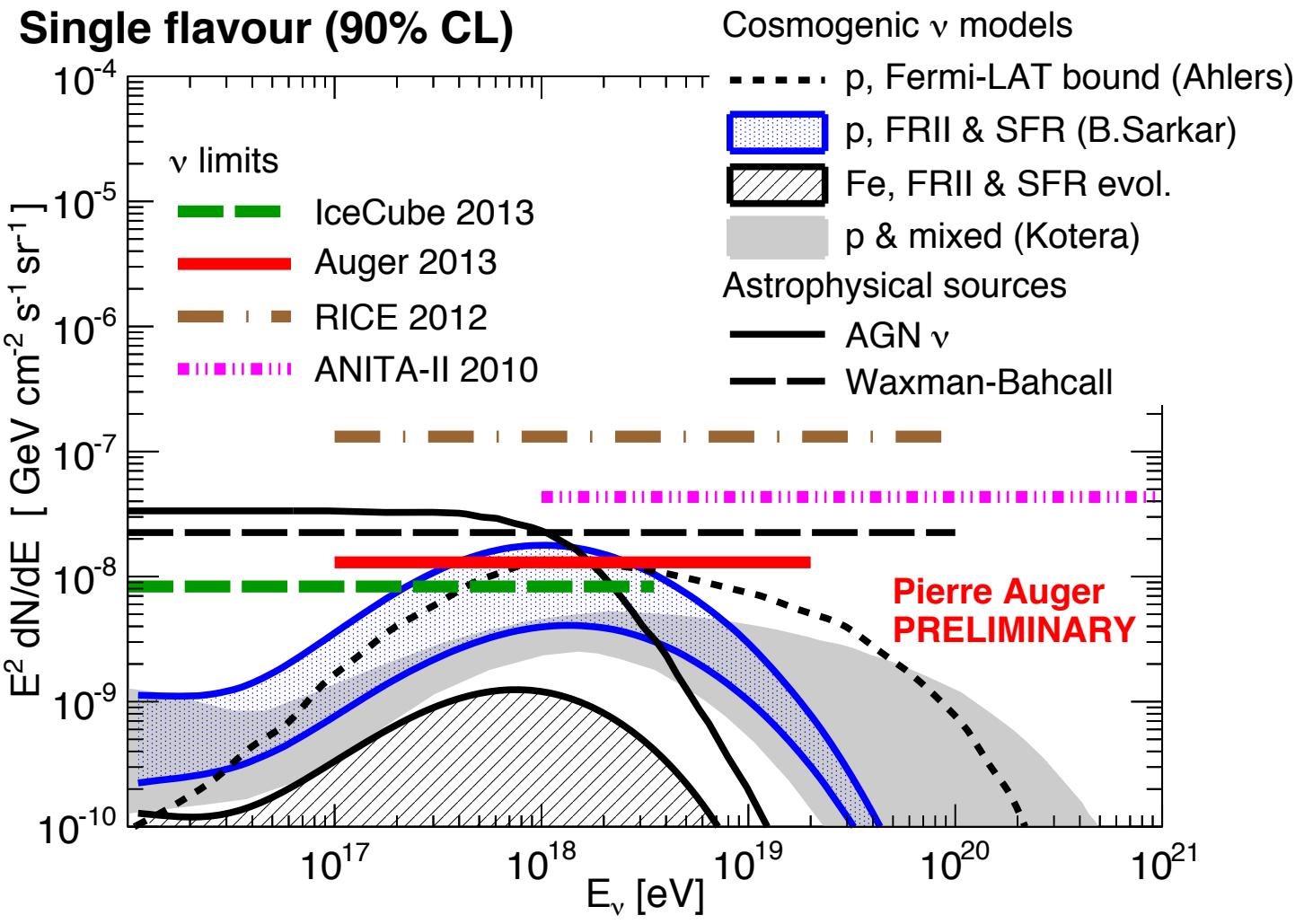


Integral limits to diffuse flux of UHEν



$dN/dE = k\,E^{-2} \longrightarrow k \sim 1.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} - 90% C.L. - 10^{17} eV < E < $2\,10^{19}$ eV

Integral limits to diffuse flux of UHEν

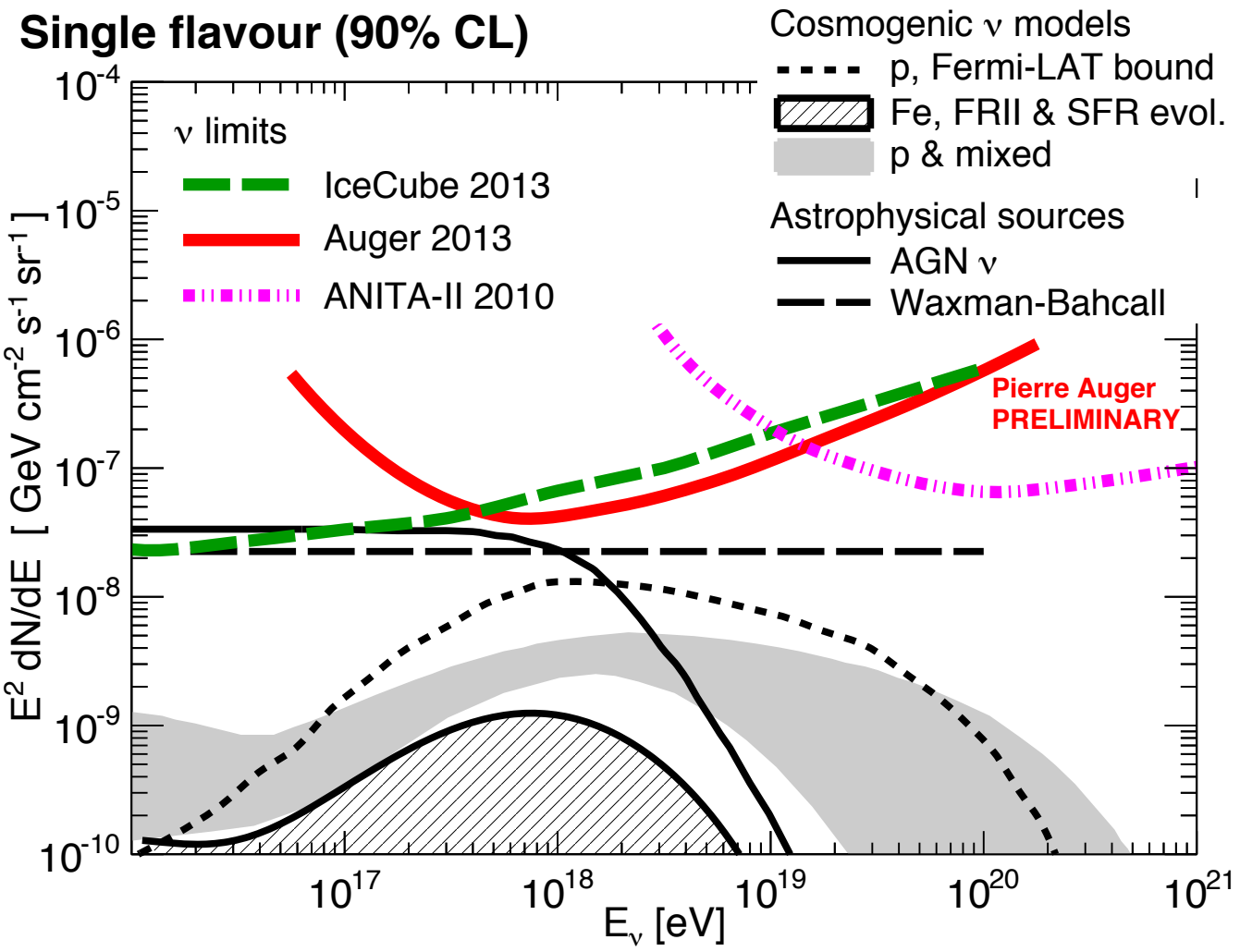


Auger limit constrains models with proton primaries & strong evolution with redshift

Expected number of events
PRELIMINARY

Diffuse flux Neutrino Model	Expected number of events (1 Jan 04 - 31 Dec 12)
Cosmogenic (Kotera *et al.*) - proton, FRII	~ 4.0
Cosmogenic (Kampert *et al.*) - proton, FRII	~ 2.0
Cosmogenic (Kampert *et al.*) - proton, SFR	~ 0.5
Cosmogenic (Ahlers *et al.*) - proton, Fermi-LAT	~ 1.4
Cosmogenic (Kotera *et al.*) - band	$\sim 0.2 - 0.6$
Cosmogenic (Kampert *et al.*) - iron, FRII	~ 0.1
AGN (Becker *et al.*)	~ 3.0
IceCube $E^{-2.3}$ flux no-cutoff (consistent with observed events)	~ 0.2

Differential limits to diffuse flux of UHEν



All limits converted to single flavour and given per half a decade of energy

Conclusions I

- SD of Auger sensitivity to UHE neutrinos:
  - Easy to identify: inclined showers with broad fronts.
  - Search NOT limited by background but by exposure.
  - Sensitivity peaks @∼EeV (peak of cosmogenic ν).

- No ν candidates (1 Jan 04 – 31 Dec 12) :
  - Stringent (PRELIMINARY) limit to diffuse flux.
  - $dN/dE = k\ E^{-2} \longrightarrow k \sim 1.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} - 90% C.L. - 10^{17} eV < E < 10^{20} eV

Conclusions II

- Physics results from Auger neutrino limits relevant to origin of UHECR:
  - Limits below Waxman-Bahcall landmark.
    - First shower array to achieve this benchmark.
  - Protons from cosmological sources start to be constrained: p & strong FRII evolution disfavored.
  - Top-down (exotic) models strongly disfavored (many ruled-out).
  - More exposure needed to constrain UHECR production at individual candidate sources.

Further information

Systematic uncertainties

PRELIMINARY

Source of systematic	Earth-Skimming $(90°, 95°)$	Down-going $(60°, 90°)$
Shower simulation	$+20\%, -5\%$	$+9\%, -33\%$
ν cross section	$+5\%, -9\%$	$+7\%, -7\%$
τ energy losses	$+25\%, -10\%$	$+6\%, -6\%$
Topography	$+18\%, 0\%$	–

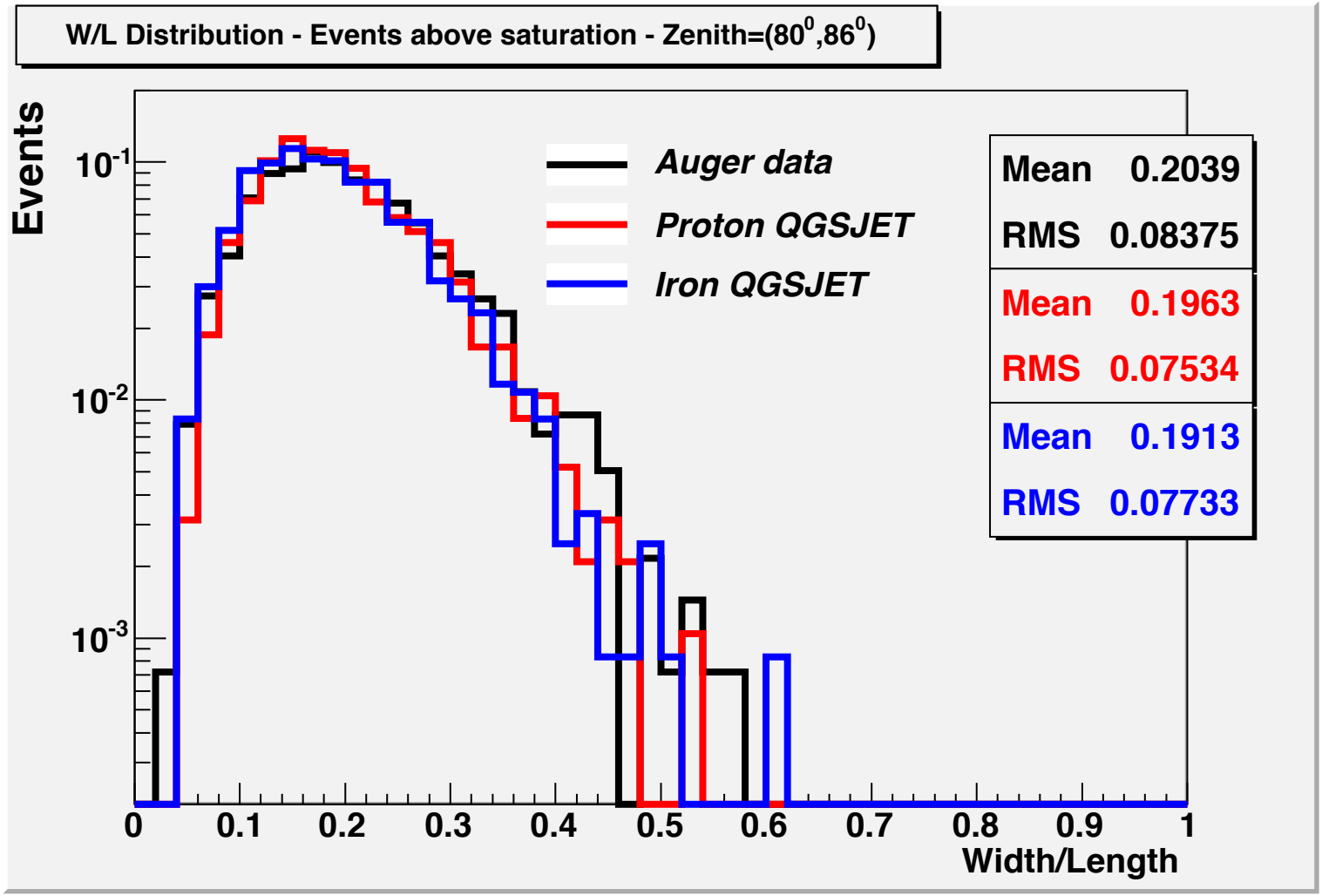
Uncertainties incorporated in the limit following the well-known Conrad approach.

Relative contribution of different channels to Auger limit

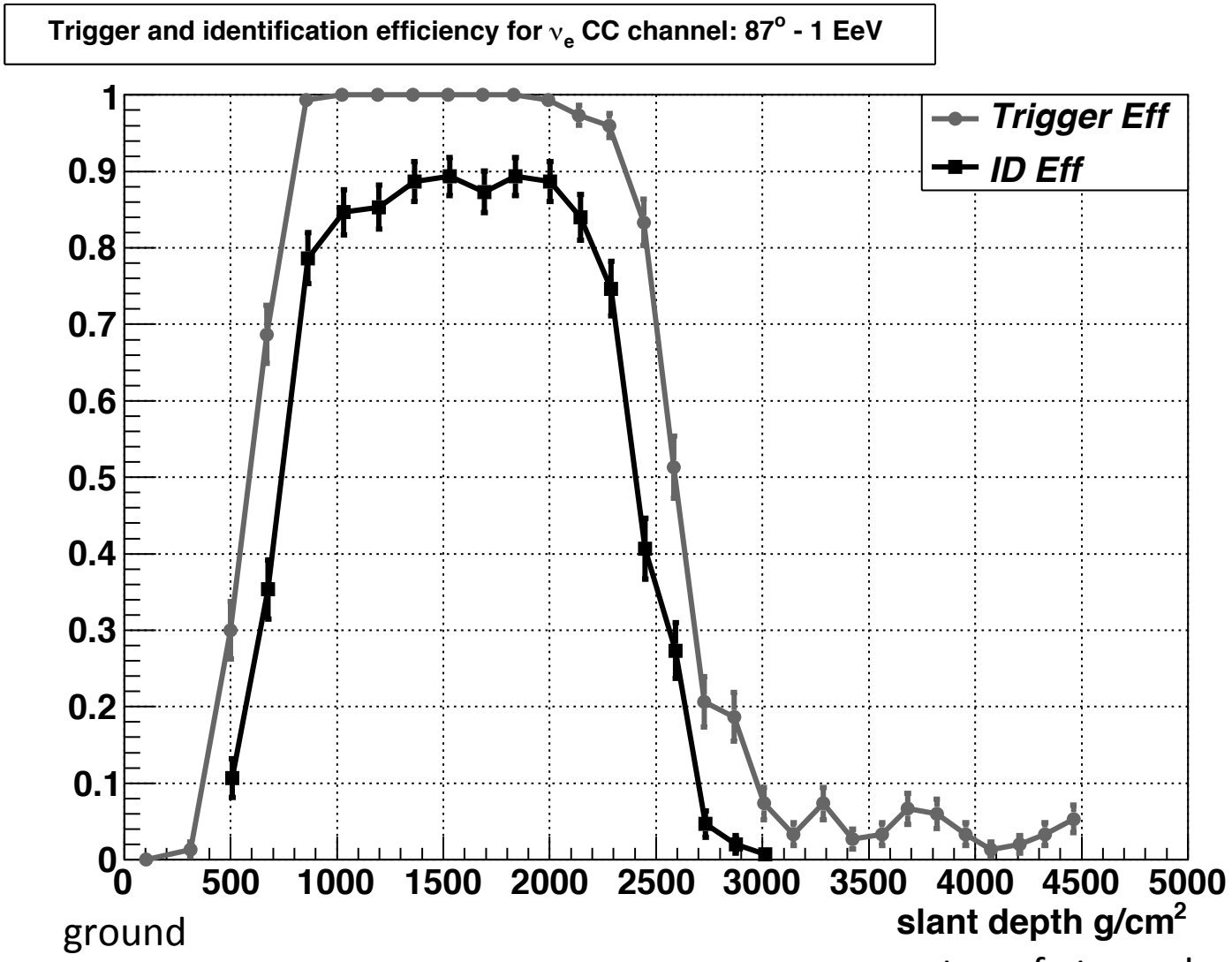
PRELIMINARY

Channel	Relative contribution
Earth-Skimming $(90°, 95°)$	$\sim 73\%$
Down-going High $(75°, 90°)$	$\sim 23\%$
Down-going Low $(65°, 75°)$	$\sim 4\%$

Data vs MC simulations

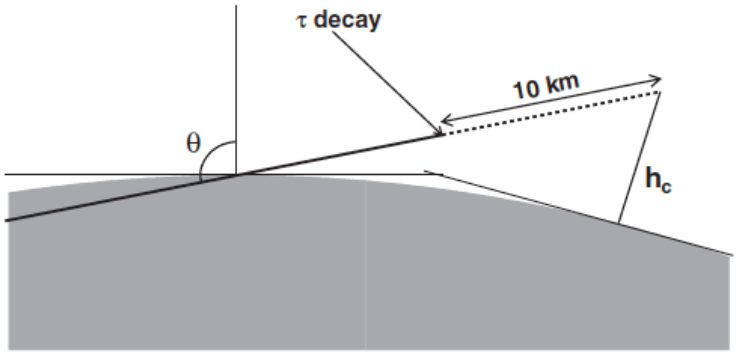


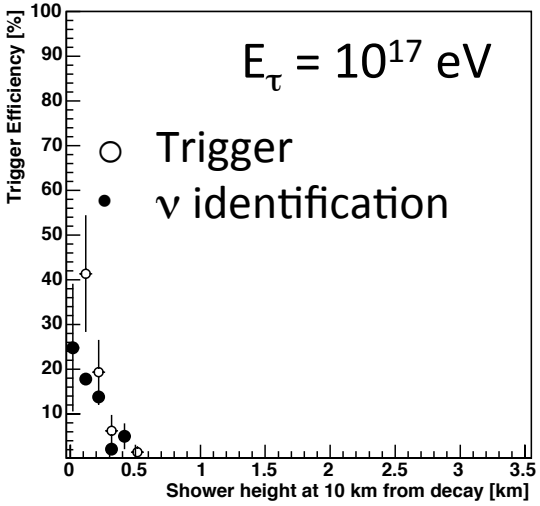
Efficiencies: Down-going (75°, 90°)

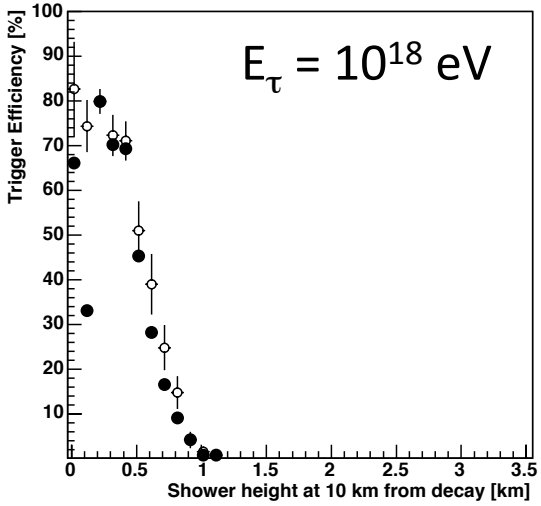


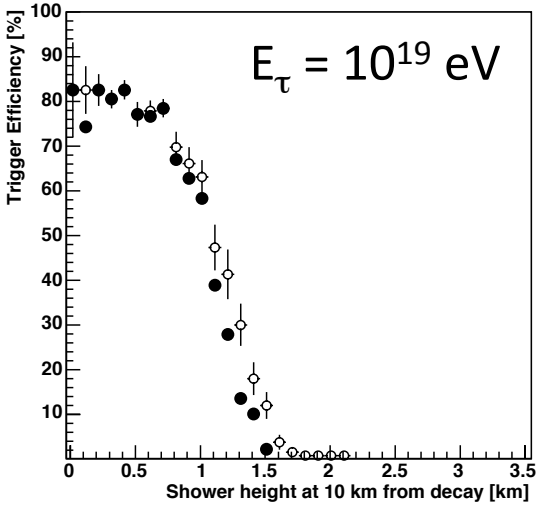
Efficiencies: Earth-skimming

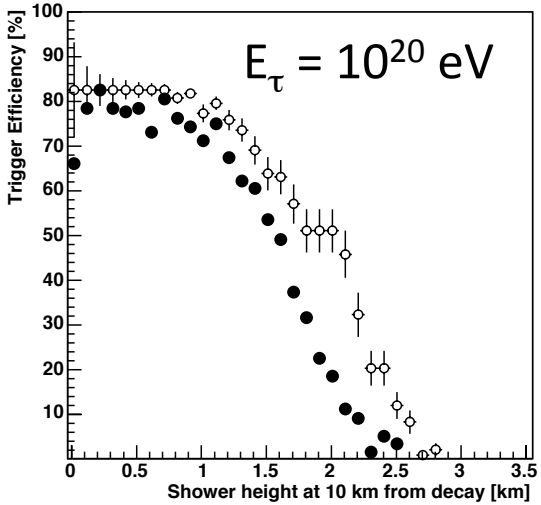
Trigger and identification probabilities as a function of shower height h_c at 10 km from tau decay point





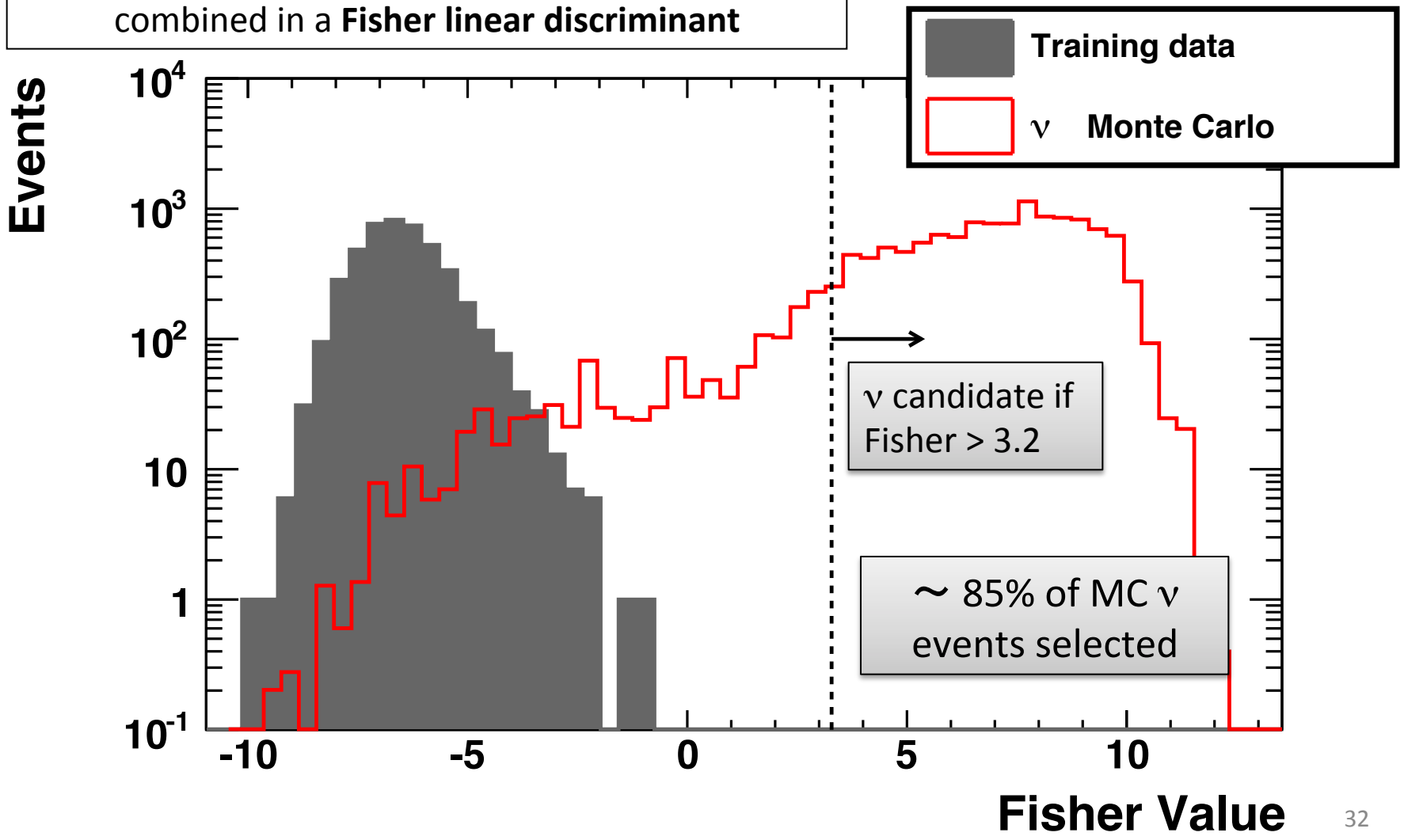




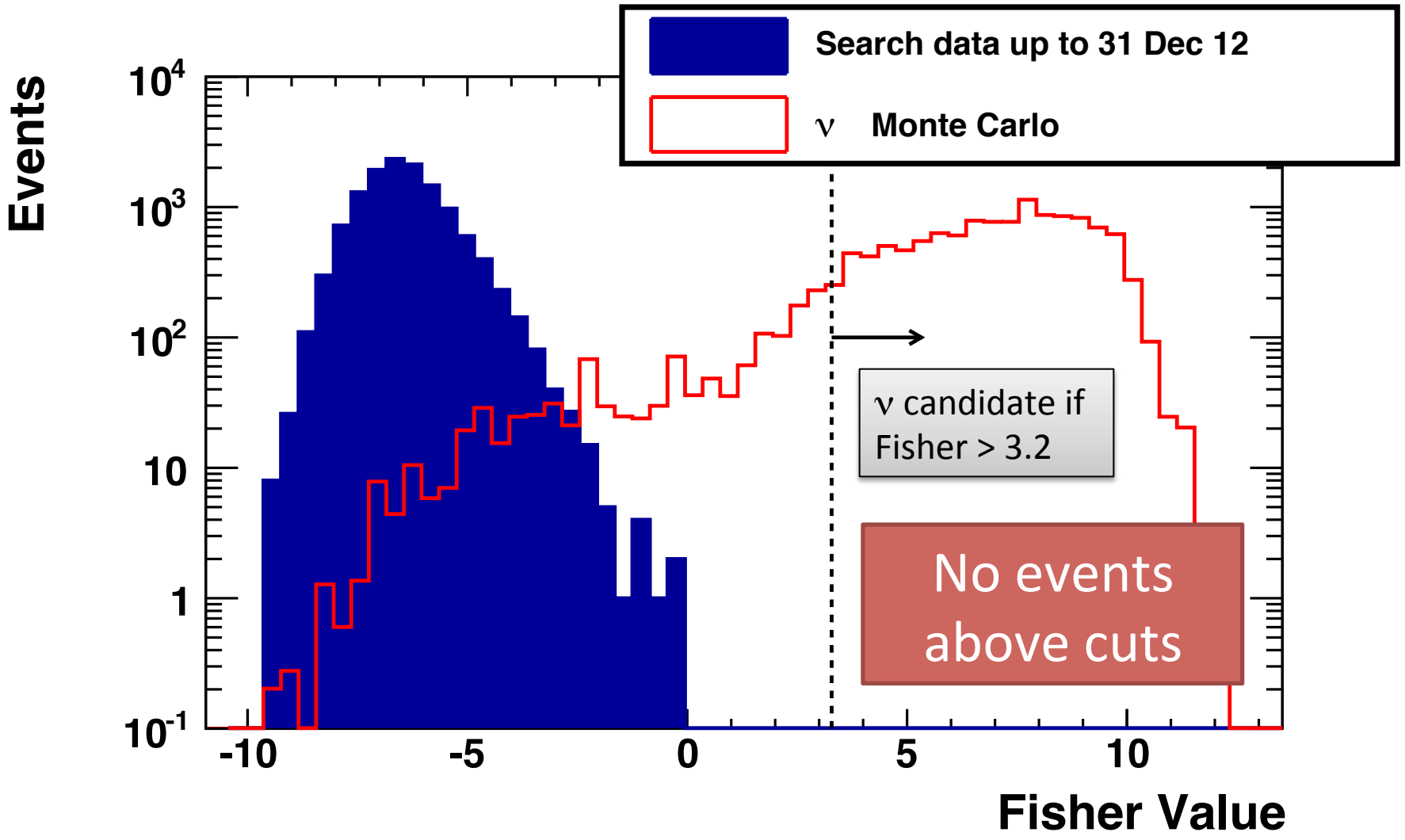


ν identification: Down-going (75°, 90°)

Area-over-Peak of various stations along with other observables constructed from AoP combined in a **Fisher linear discriminant**



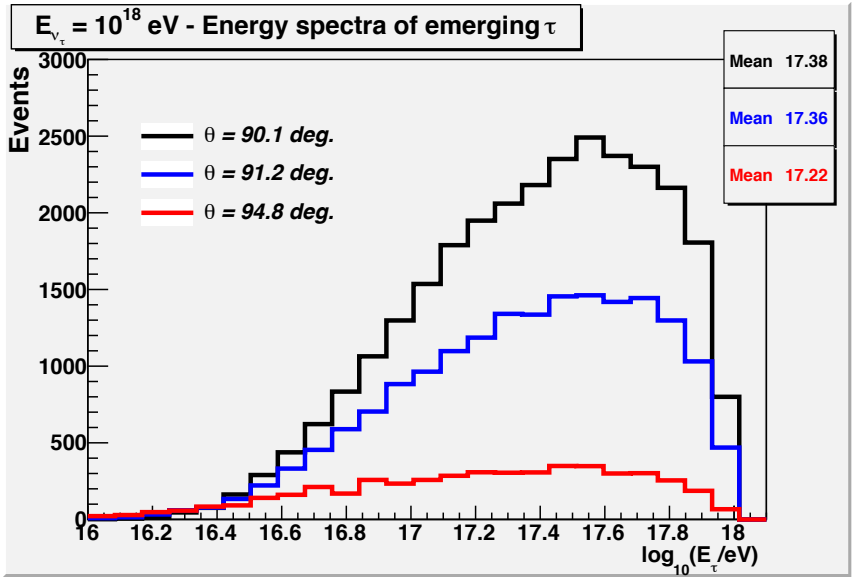
ν search: Down-going (75°, 90°)



Exposure: Earth-skimming ν_τ

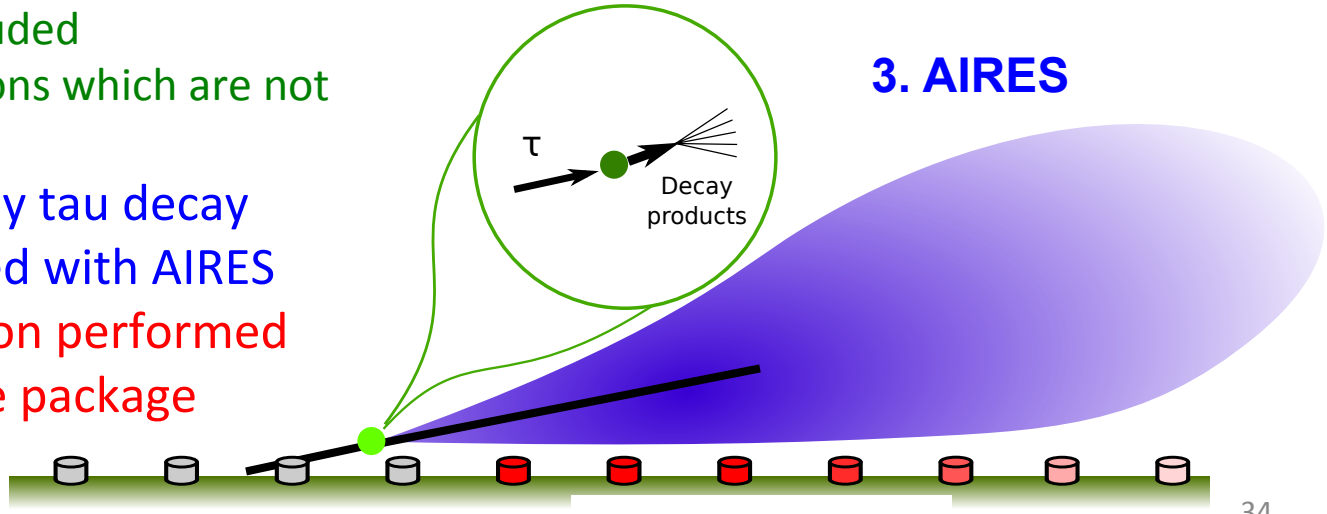
1. Tau neutrino propagation and tau production:
   - Dedicated MC for propagation of ν_τ through the Earth producing emerging tau leptons.
   - Convolute with probability of tau decay in the atmos. (exponential)
2. Tau decay products obtained with TAUOLA generator:
   - All decays included
   - 17% BR to muons which are not detected
3. Shower induced by tau decay products simulated with AIRES
4. Detector simulation performed with Auger Offline package

1. ν_τ PROPAGATION



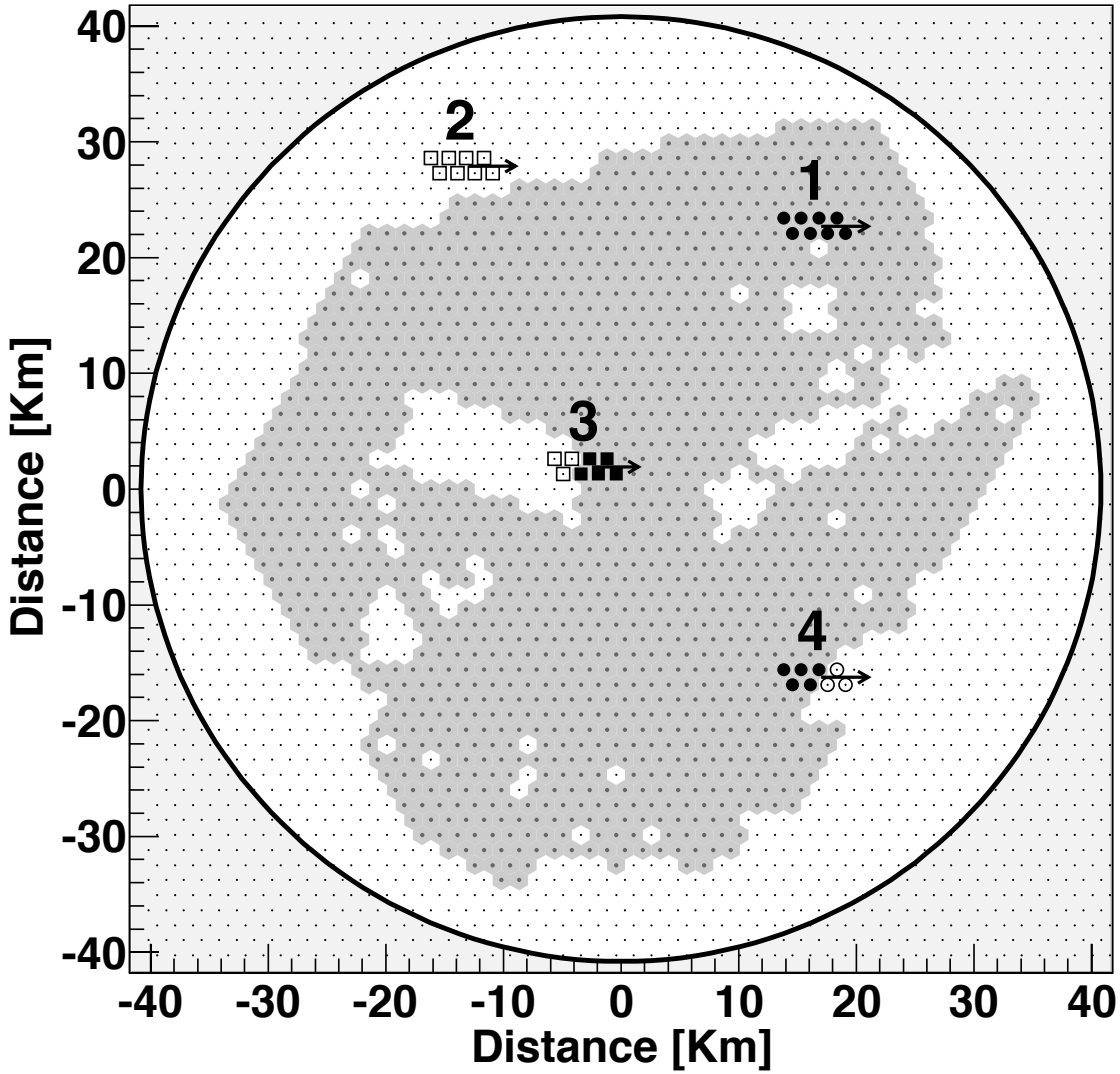
2. TAUOLA

3. AIRES



4. OFFLINE

Exposure calculation: accounting for a "dynamical" array



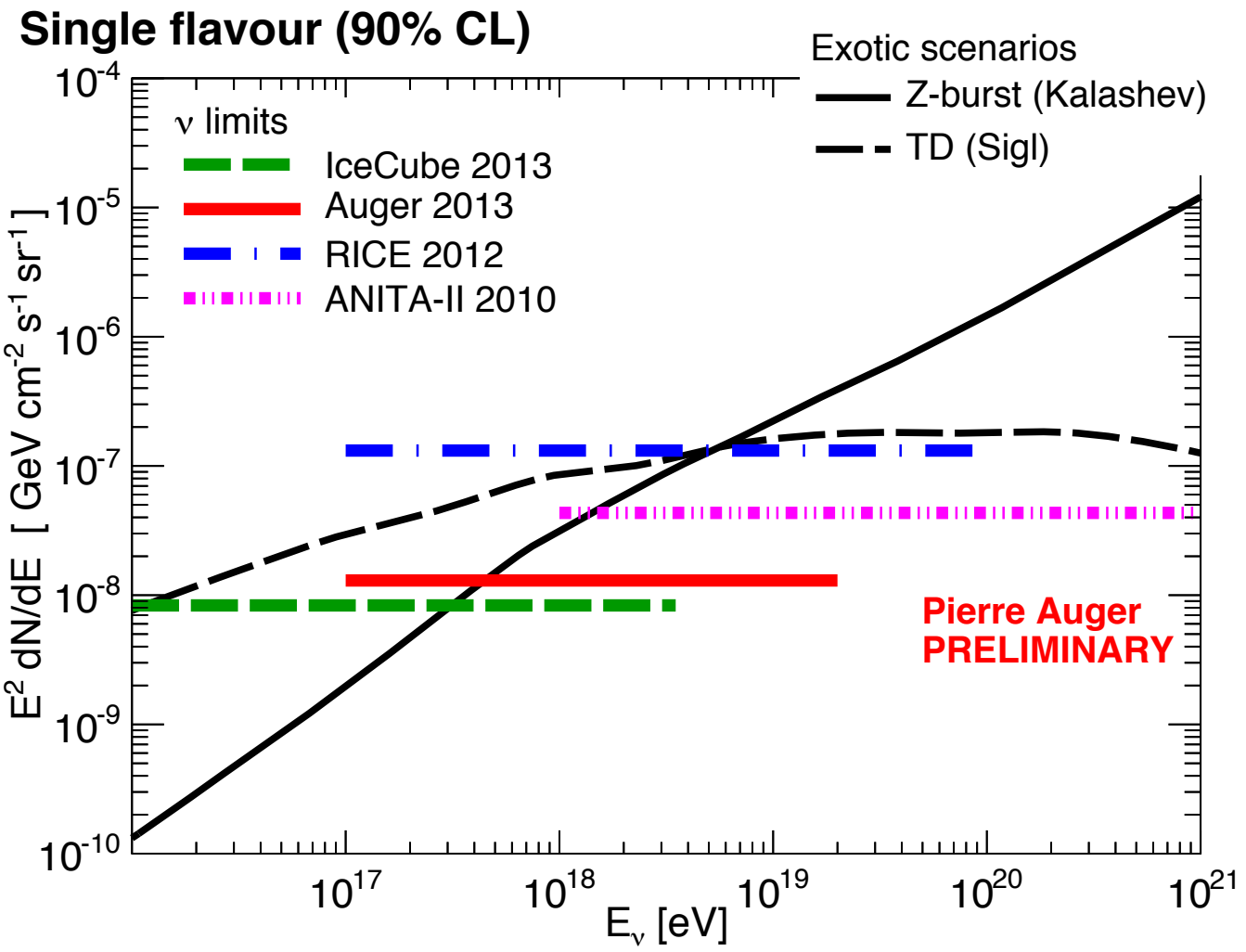
Array status in Nov. 2007 before construction ended (2008).

Neutrino simulated showers are "thrown" over a changing array

① Shower fully contained, triggering and identified as a neutrino.
② Shower outside array not triggering.
③ Shower not fully contained, triggering but not identified as a neutrino.
④ Shower not fully contained, but triggering and identified as a neutrino

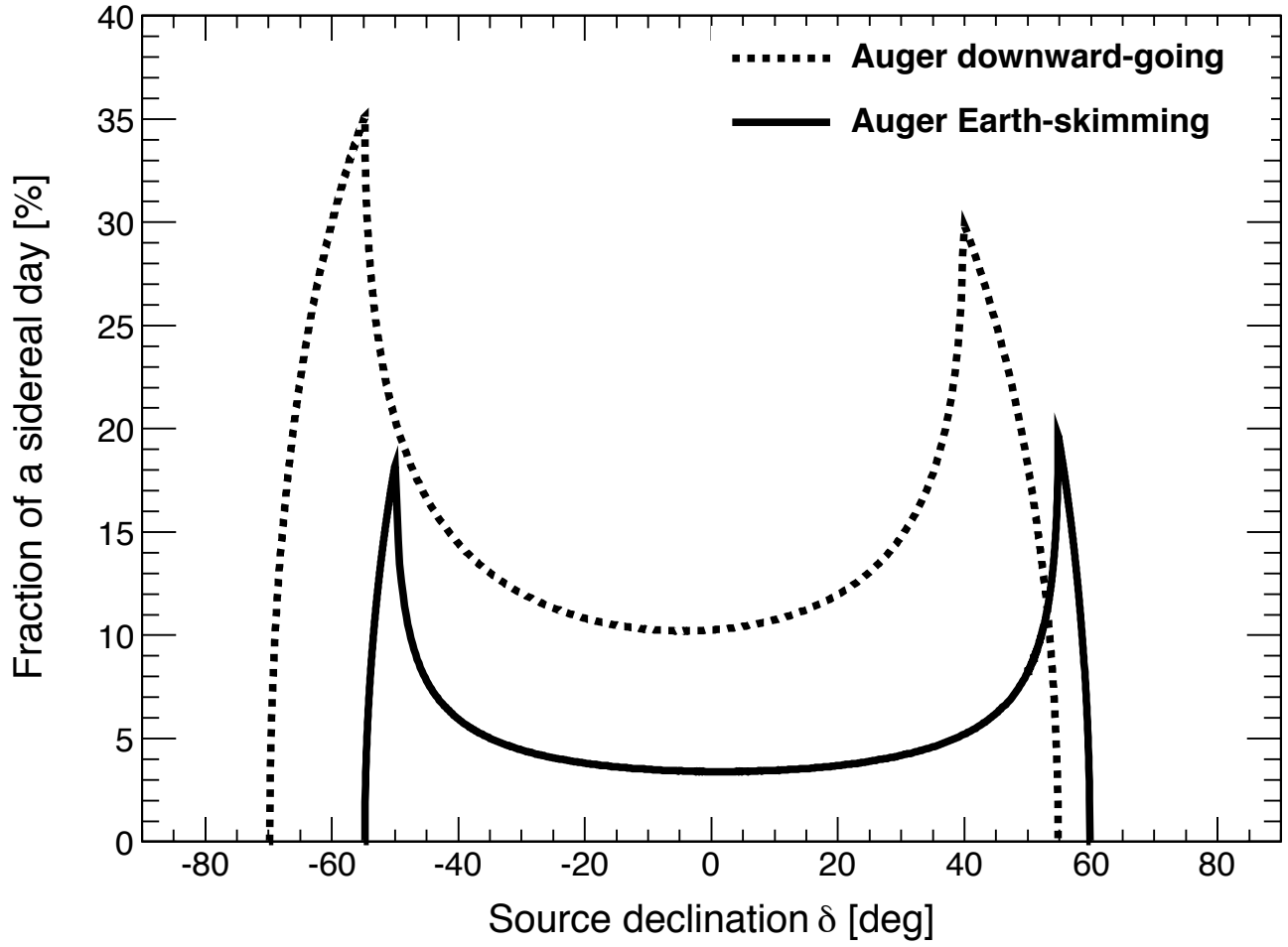
Exotic models of UHECR production & limits

Many “exotic models” ruled out by Auger limits on νs (and photons).

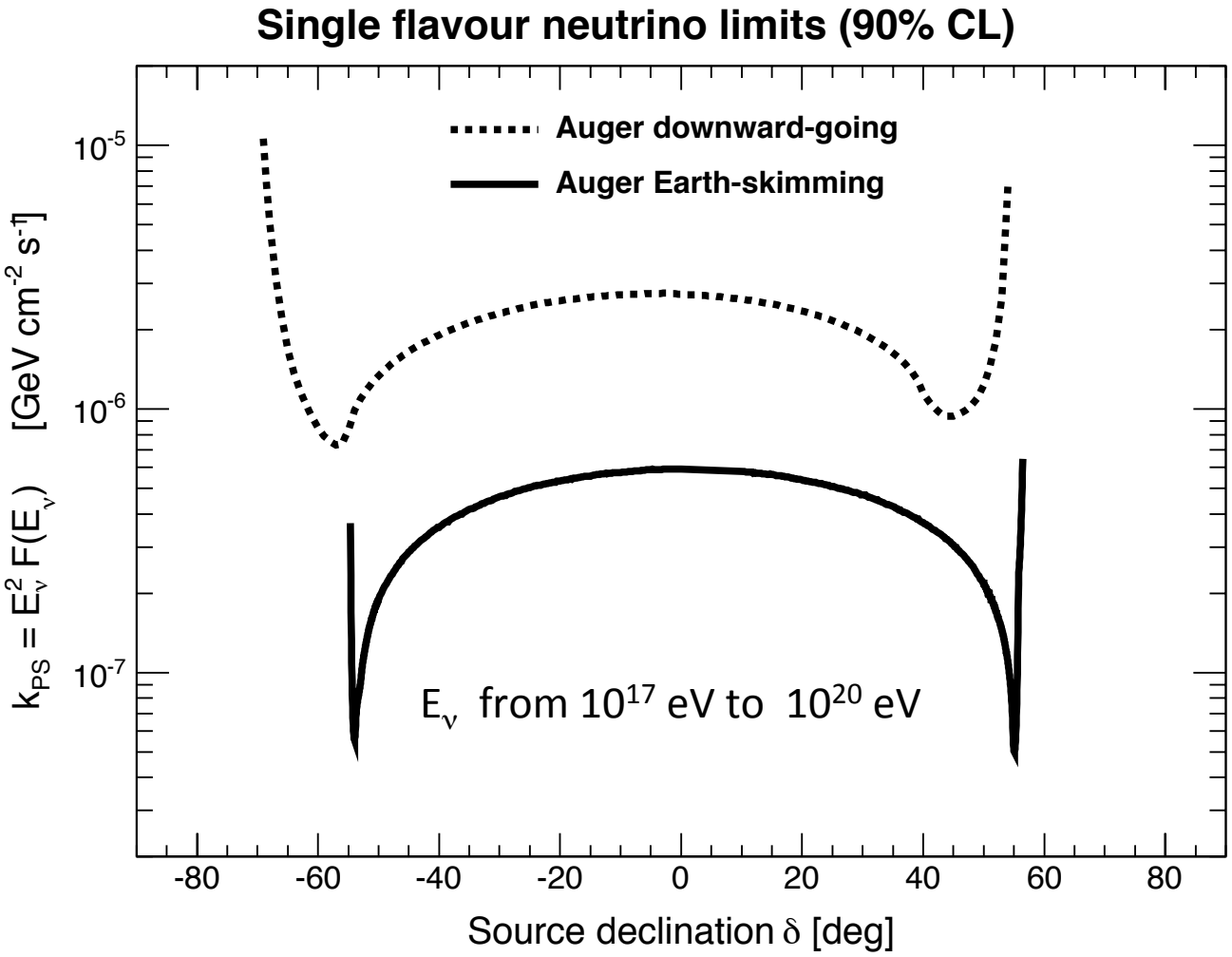


Point-like sources

Fraction of a day a source at declination δ is visible in the angular range of Earth-skimming (90°, 95°) and Down-going (75°, 90°) analysis

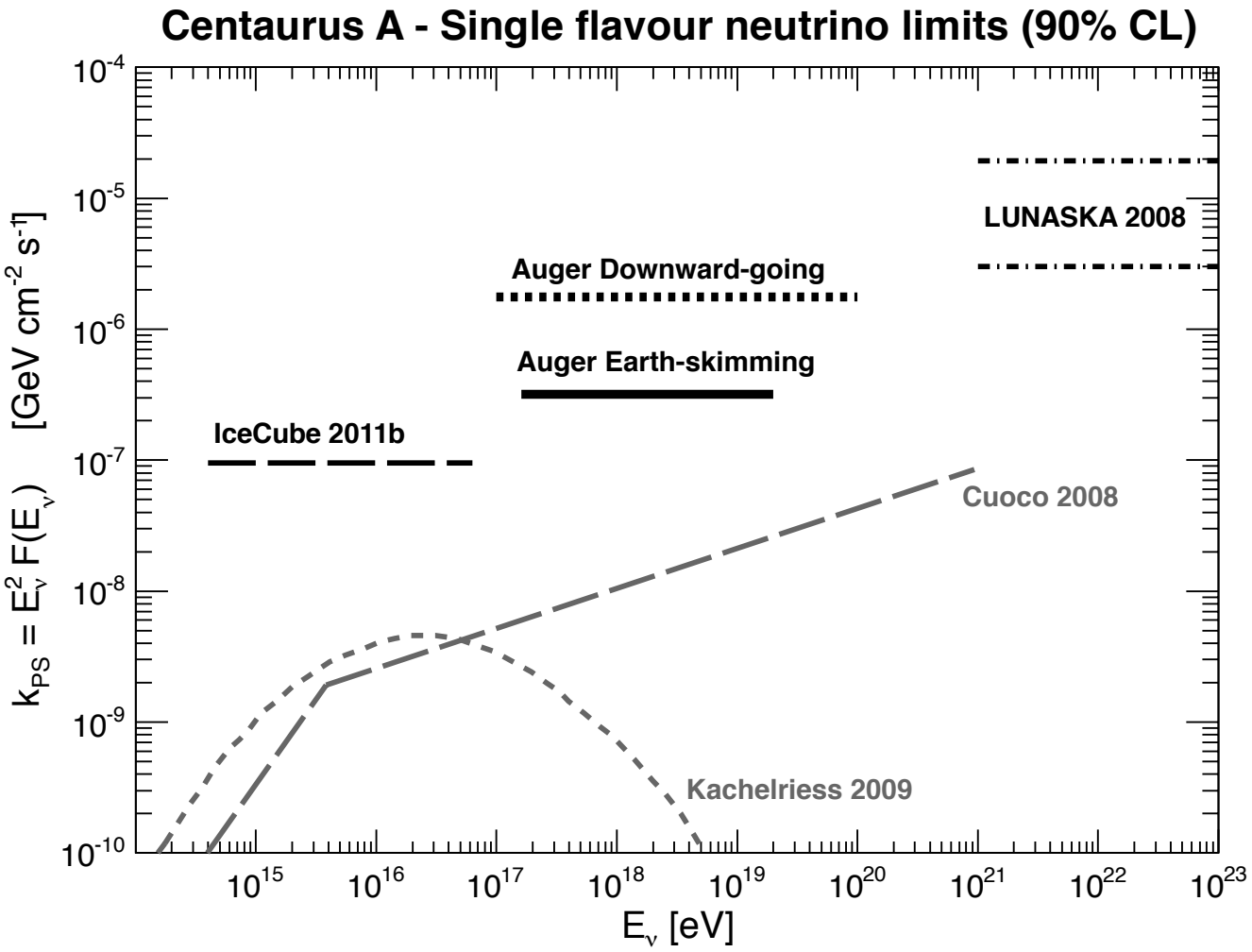


Limits to UHEν: point-like sources



NOTE: Data from 1 Jan 04 up to 31 May 10 only

Limits to UHEν from Centaurus A



NOTE: Data from 1 Jan 04 up to 31 May 10 only

What if a ν candidate appears ?

- **Energy estimate of a ν candidate:**
  - Only the energy of the ν-induced shower (E_{shower}) can be reconstructed
  - ν flavour **cannot** be determined & E_{shower} depends on flavour
  - At best a lower bound to E_ν because $E_\nu > E_{shower}$
  - ν can interact anywhere in atmosphere: E_{shower} determination should include shower age – No algorithm including age exists so far.

- **Angular reconstruction of quasi-horizontal events:**
  - Not optimized for deeply penetrating & very inclined showers (> 80 deg.). Angular resolution ~ 1-2 deg.
  - Identification of upgoing shower would indicate tau neutrino primary.

- **Auger SD = discovery experiment (a "counter" of UHE neutrinos).**