Ultra-High Energy neutrinos at the Pierre Auger Observatory

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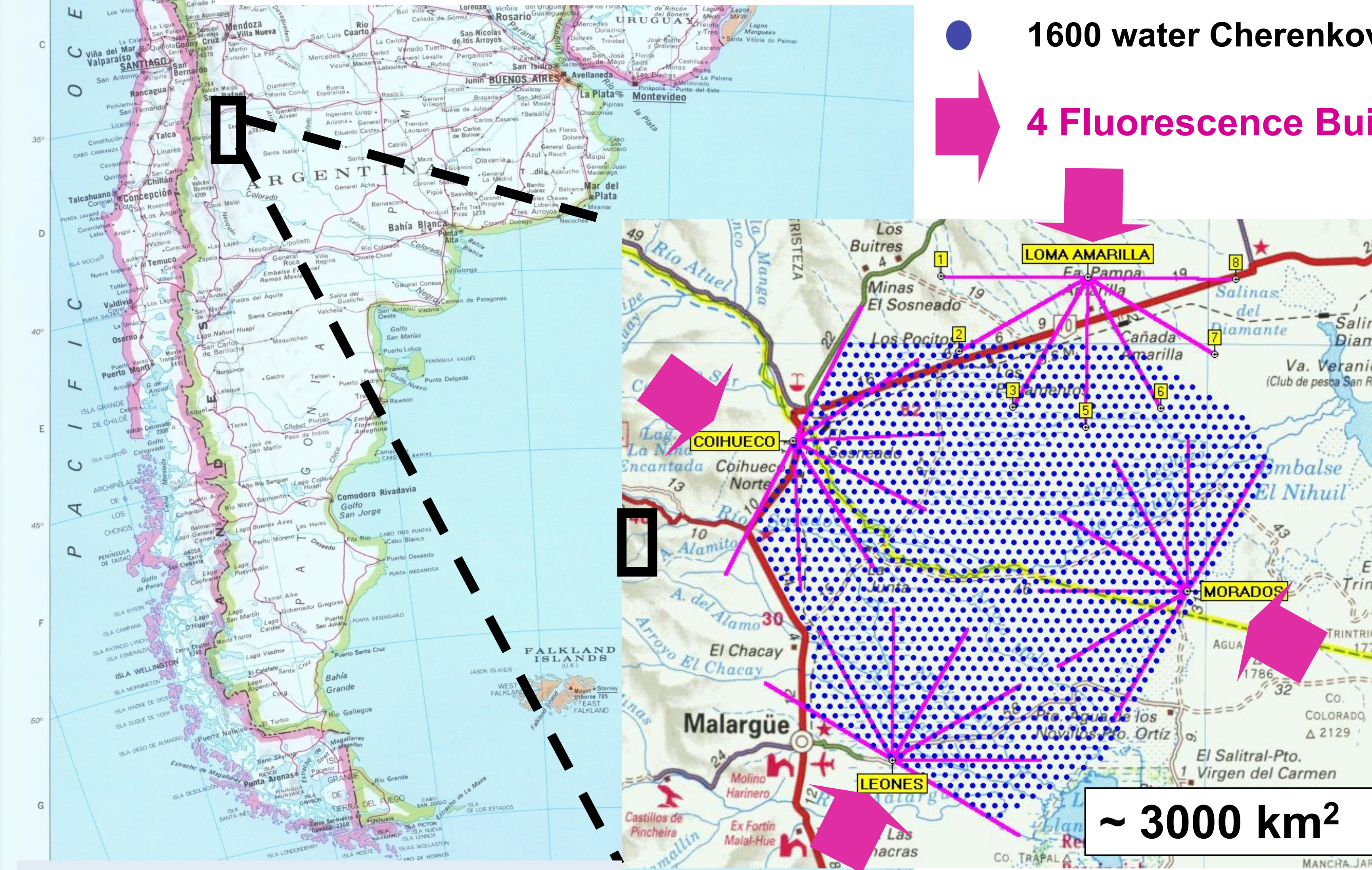
for the Pierre Auger Collaboration

Very High Energy Particle Astronomy
Kashiwa, Japan, 19 February 2014

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

1600 water Cherenkov tanks

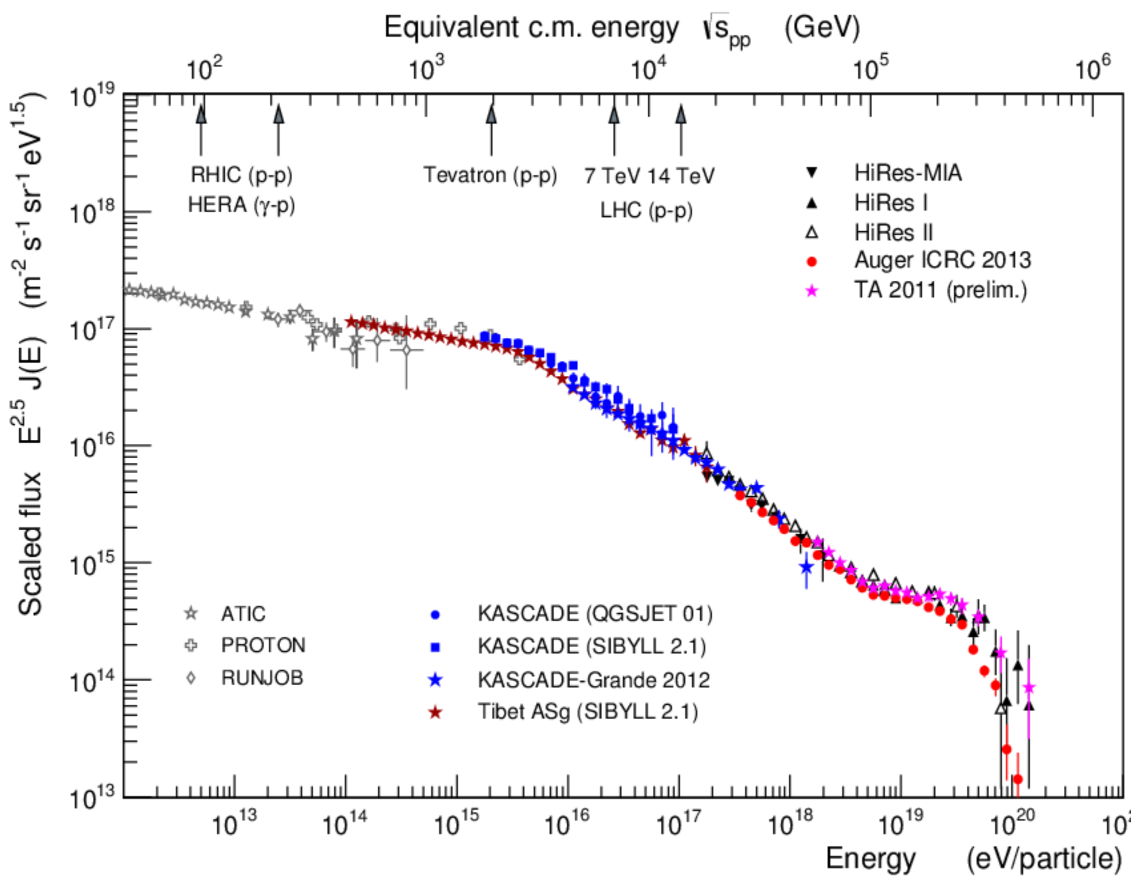
4 Fluorescence Buildings



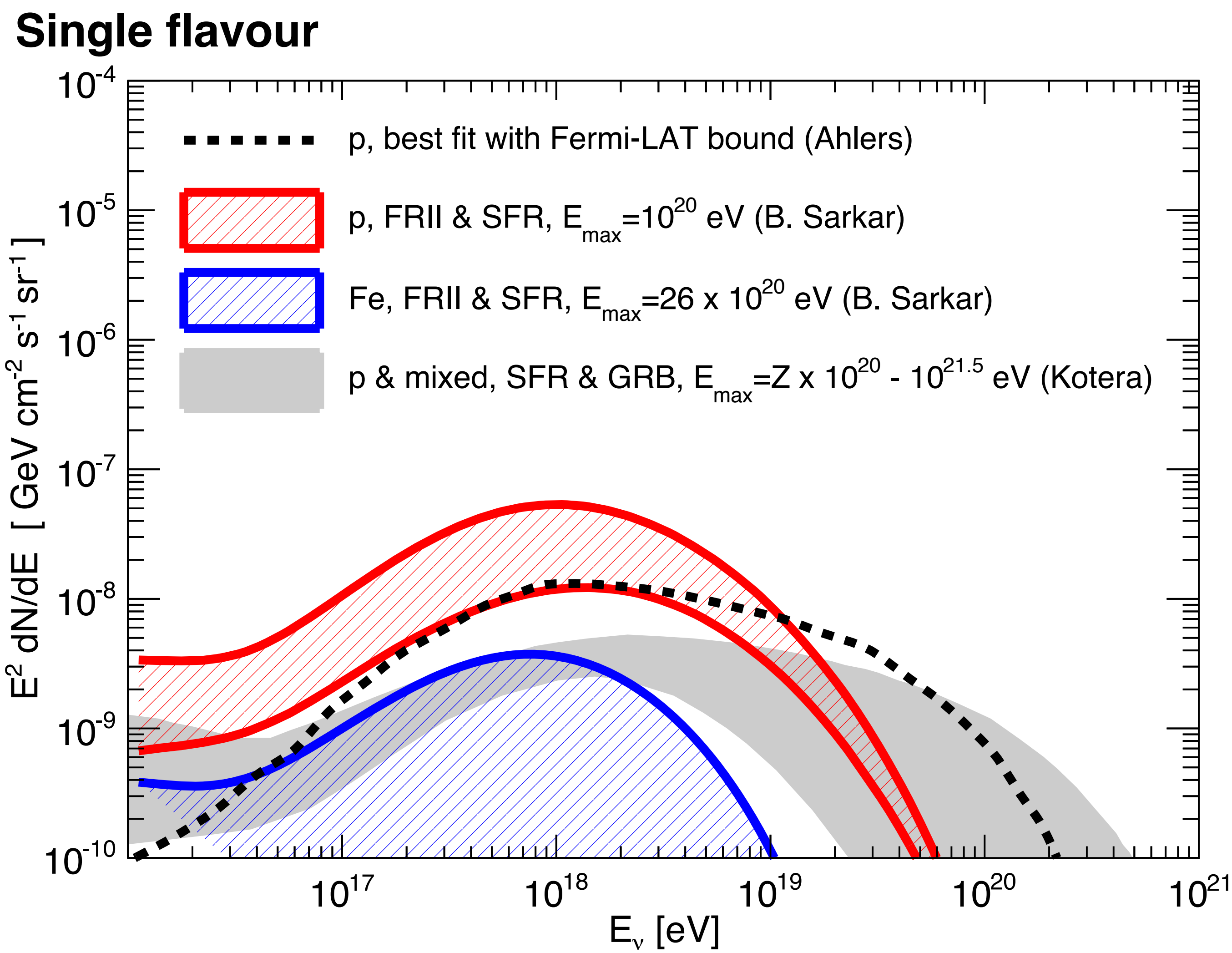
35.5º S, 69.3º W
1400 m a.s.l. (880 g cm^{-2})

Main aim of the Pierre Auger Observatory

- Characterization of energetic cosmic rays:
  - arrival directions
  - energy spectrum
  - nature of primaries: light, heavy?
- Information crucial to:
  - disentangle scenarios of UHECR origin
  - determine reason for "End of spectrum":
    a. maximum energy of CR sources?
    b. propagation effects?
       a. GZK ?
       b. Photodisintegration ?
    c. a & b acting together?



Cosmogenic neutrinos



Detection in EeV range may provide complementary information to direct UHECR detection on: UHECR nature (p, mixed, Fe), origin (evolution of the sources, maximum energy attainable,…)

Auger sensitivity to UHE neutrinos

- Auger is not a dedicated neutrino observatory but …

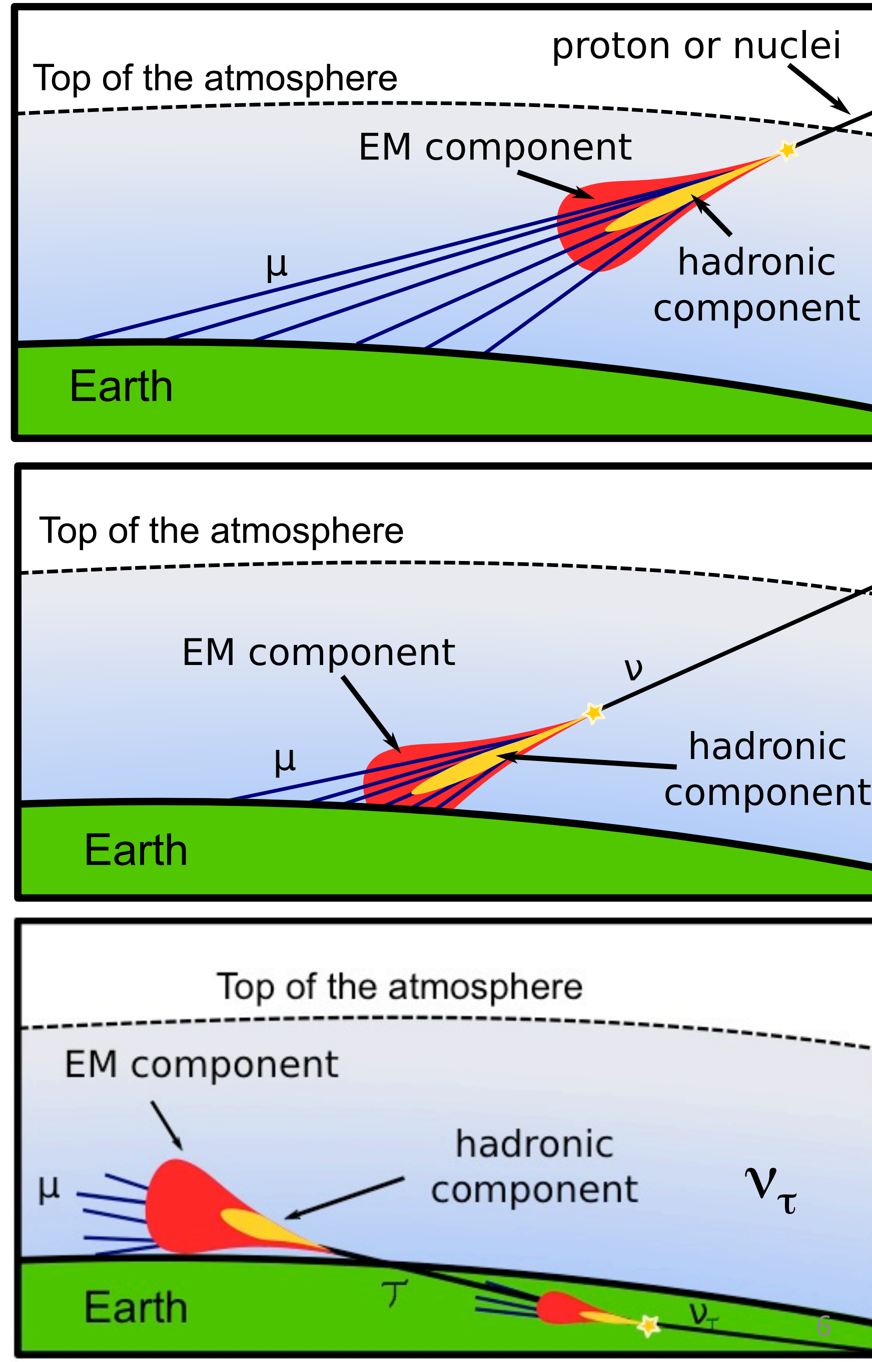
with the **surface detector** we have good sensitivity to UHE neutrinos at EeV energies and above.

- Challenge: Identifying **neutrino-induced showers** in the dominant background of showers induced by cosmic rays (p & nuclei).

- The interaction probability & discrimination power is enhanced when looking at **inclined showers:** $\theta > 60^{o}$

Inclined showers & UHE neutrinos

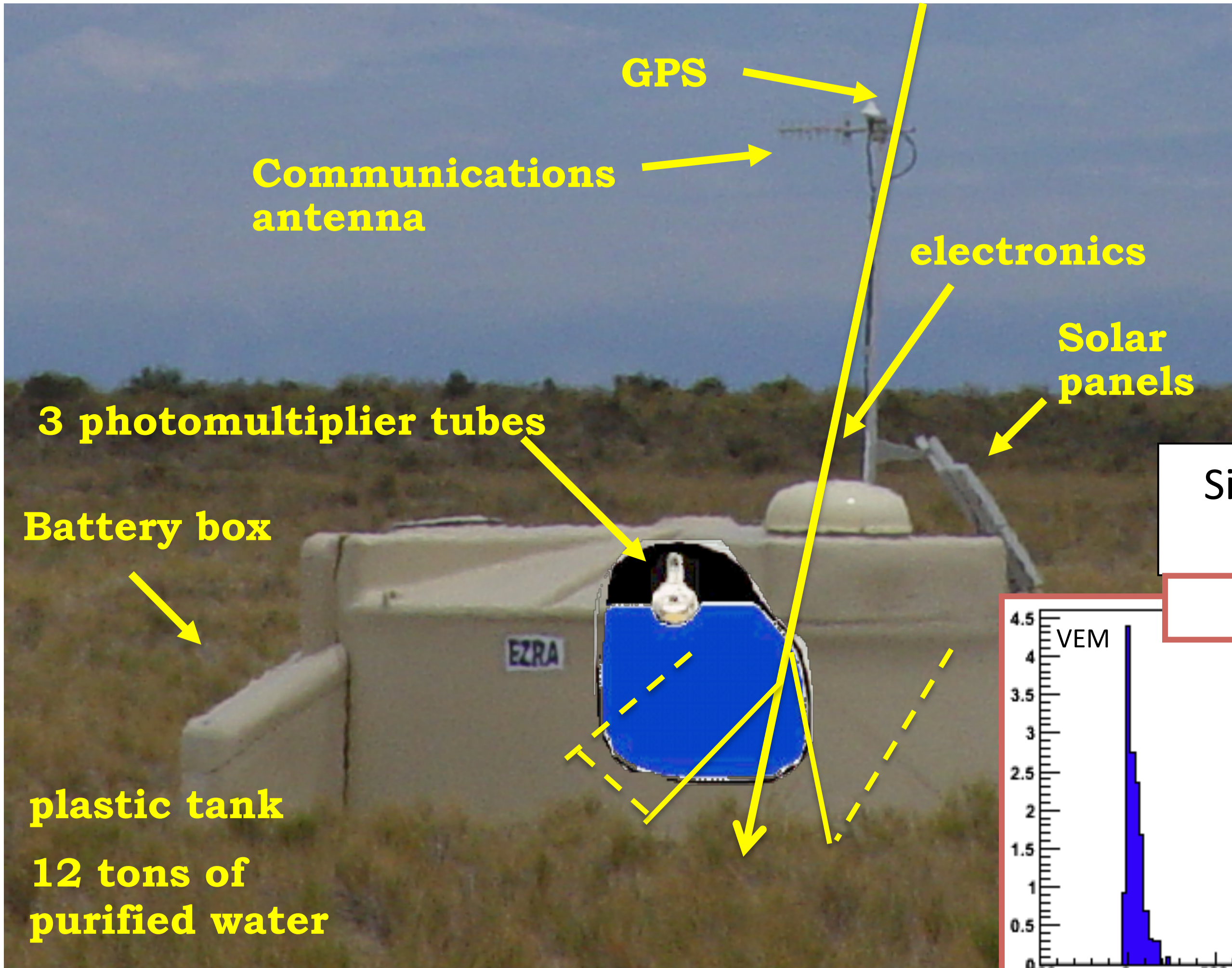
- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate “deep” showers close to ground.
  - Shower front at ground: electromagnetic + muonic components



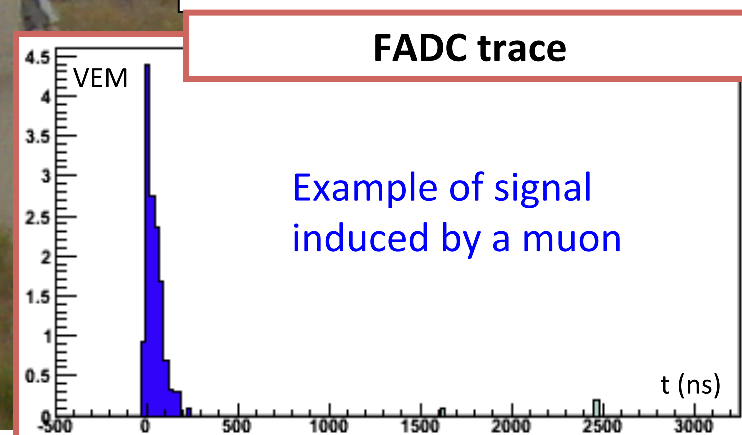
Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

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



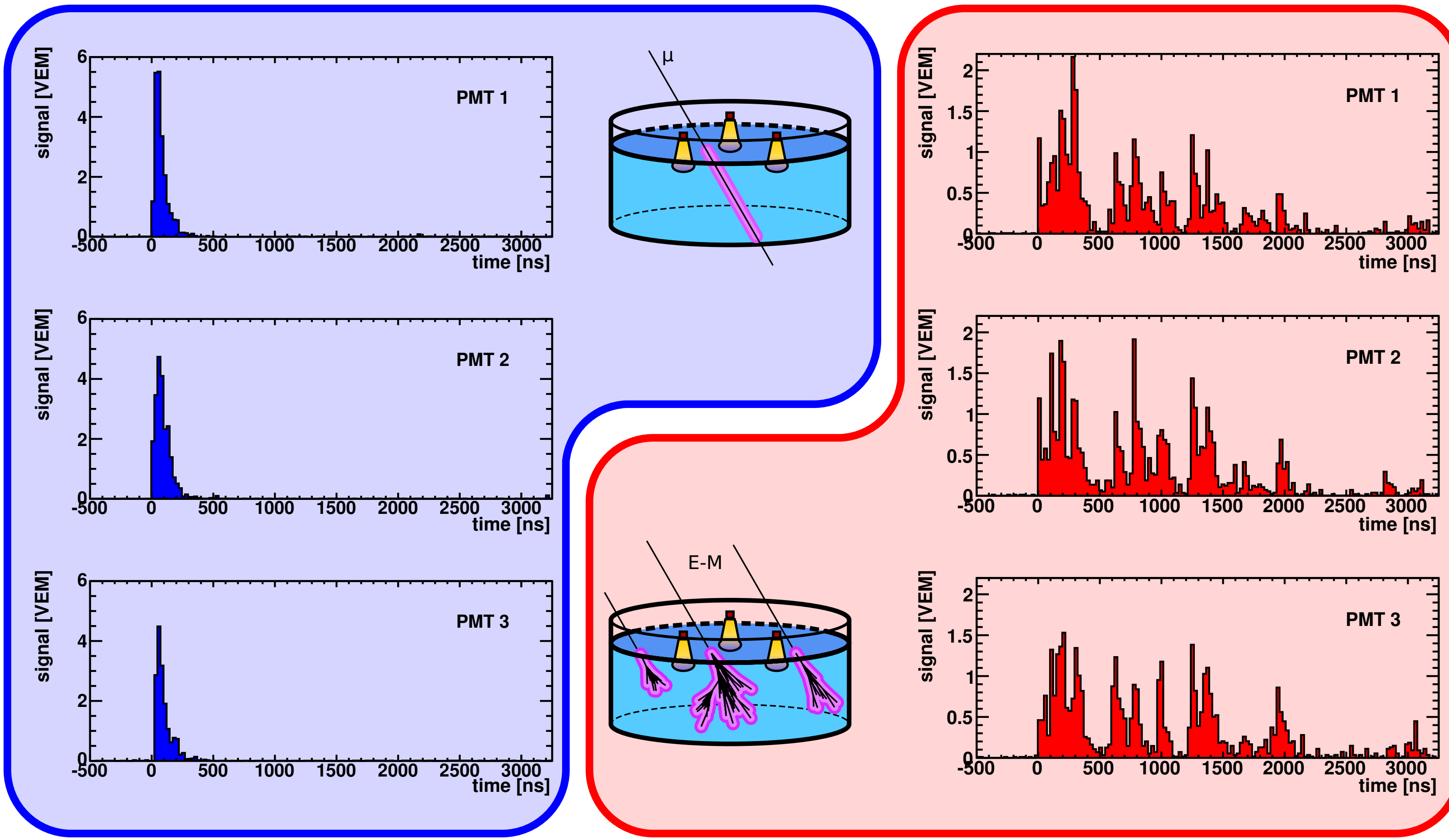
Signals are digitized with 25 ns time resolution



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

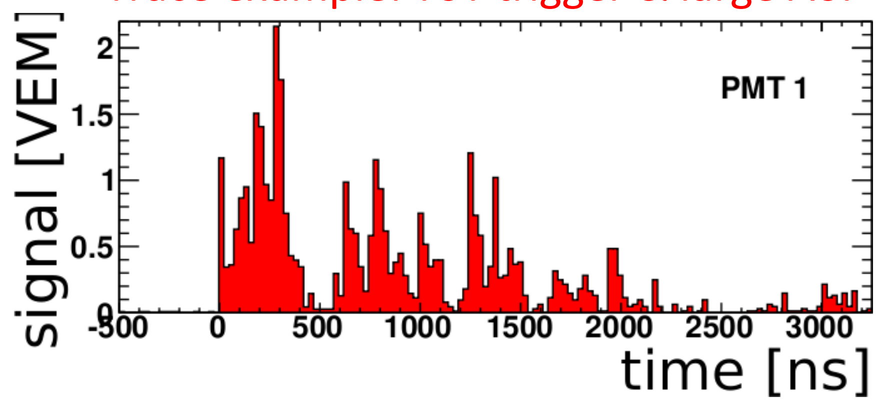
From the observational point of view, signals extended in time:

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

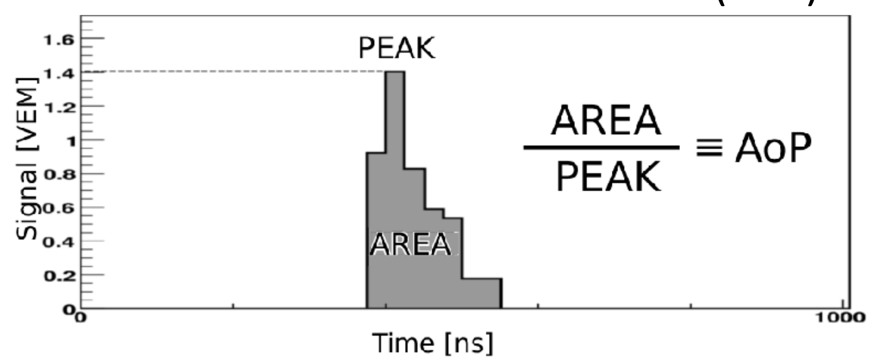
and/or

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

Trace example: ToT trigger & large AoP

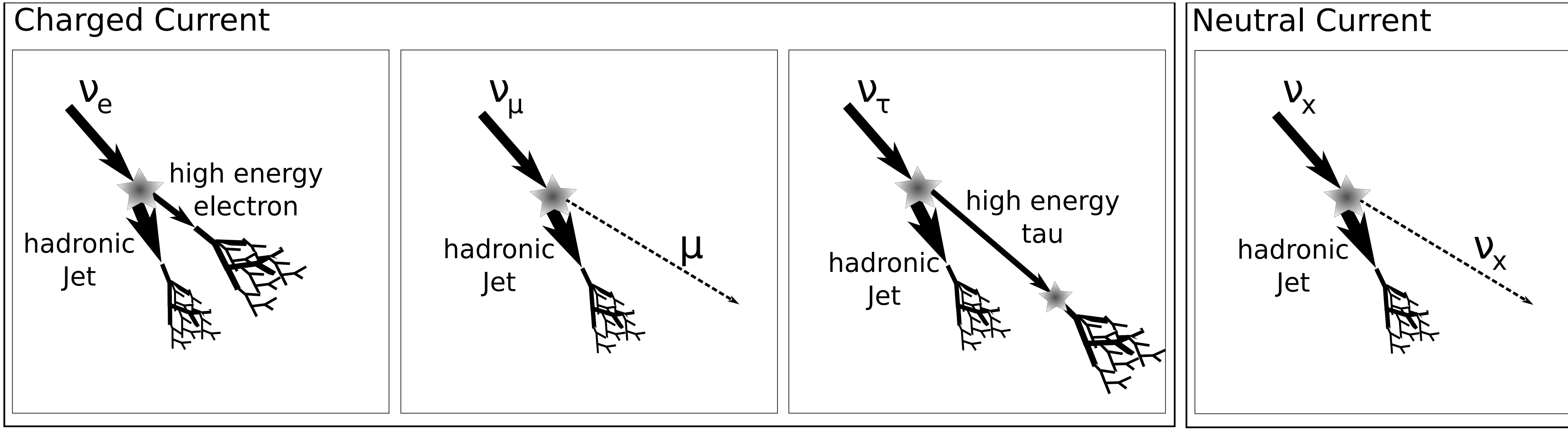


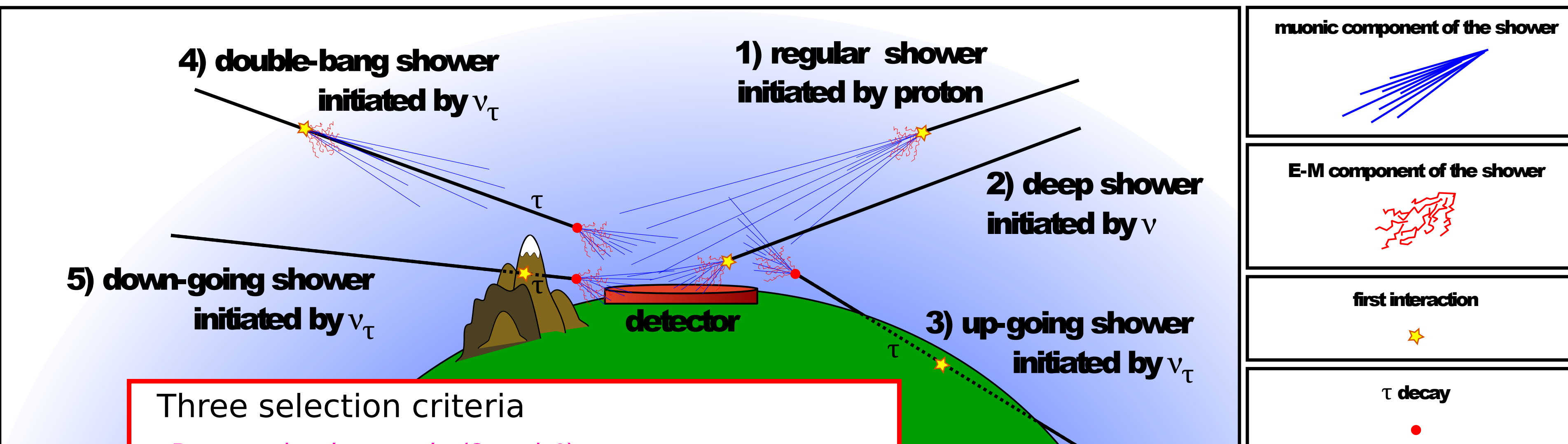
Definition of Area-over-Peak (AoP)



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

Sensitivity to all flavours & channels

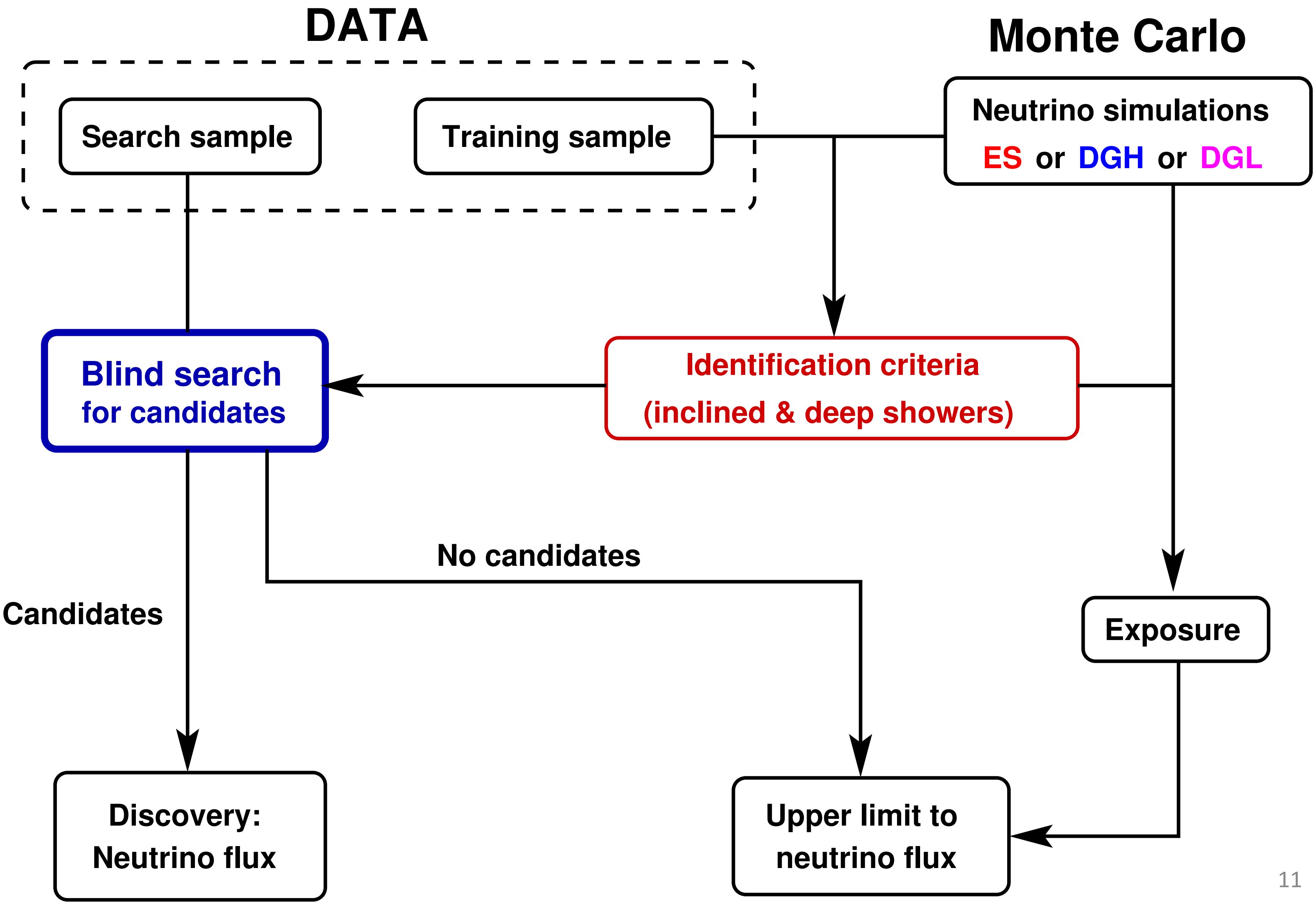




Three selection criteria

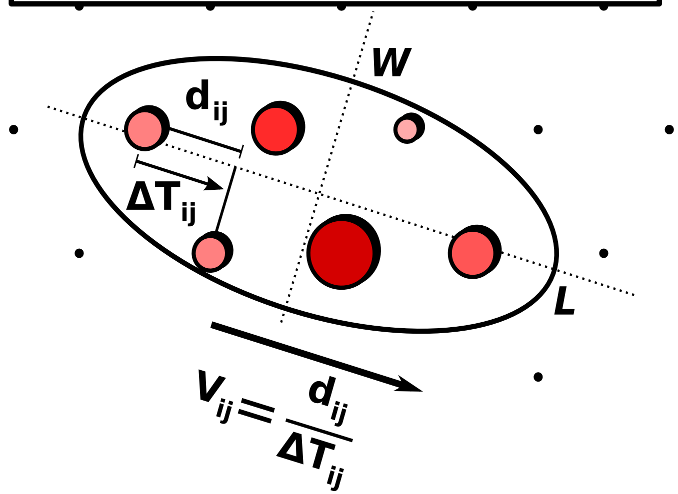
Down-going low angle (2 and 4) → DGL (60º - 75º)
Down-going high angle (2, 4 and 5) → DGH (75º - 90º)
Earth-skimming (3) → ES (90º - 95º)

Methodology: general "strategy"

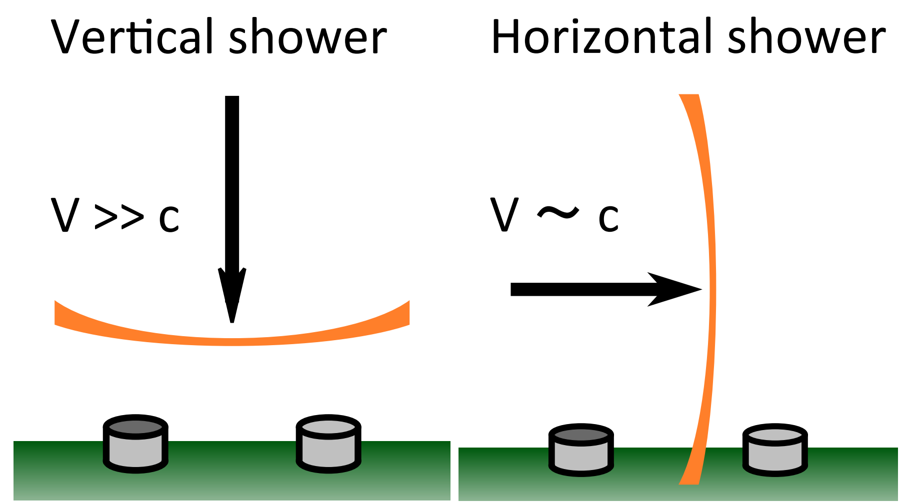


Selection of inclined showers: 3 observables

(1) Elongated footprint



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

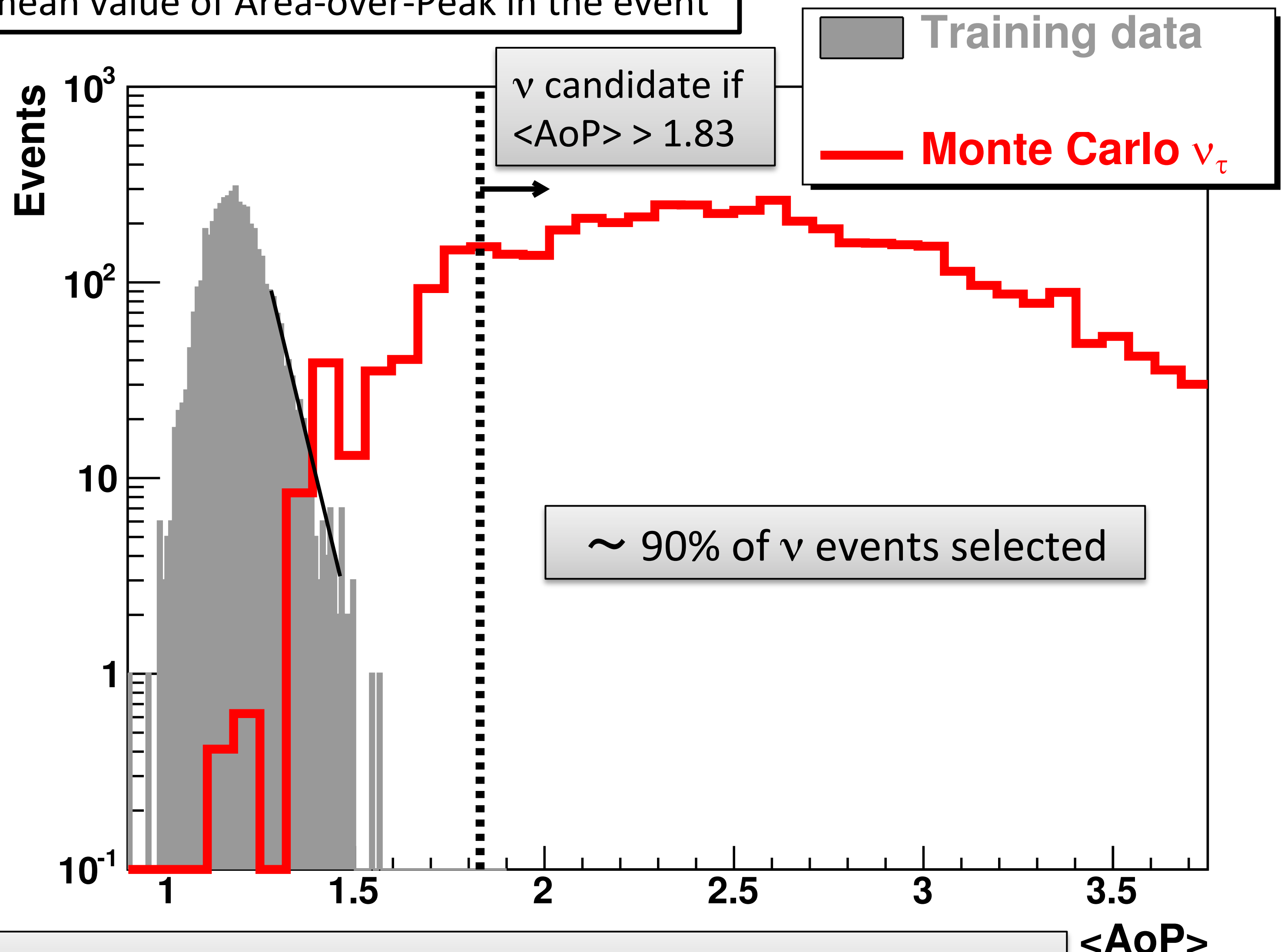


(3) Reconstructed θ

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$(V)/\langle V \rangle < 0.08$	–
–	$\theta_{rec} > 75°$	$\theta_{rec} \in (58.5°,\ 76.5°)$

ν identification: Earth-Skimming

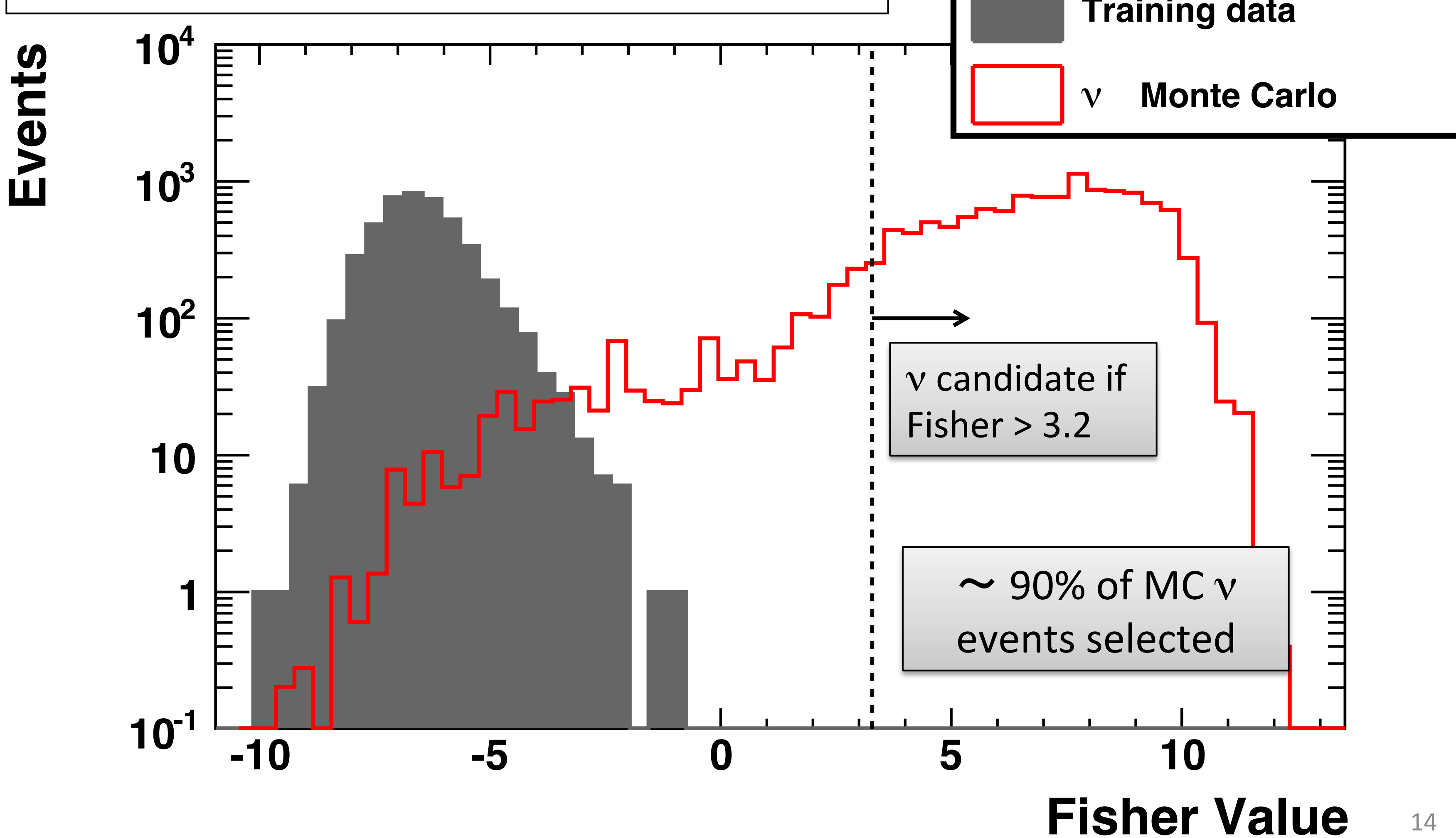
<AoP> = mean value of Area-over-Peak in the event



Neutrino searches not limited by background !

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**



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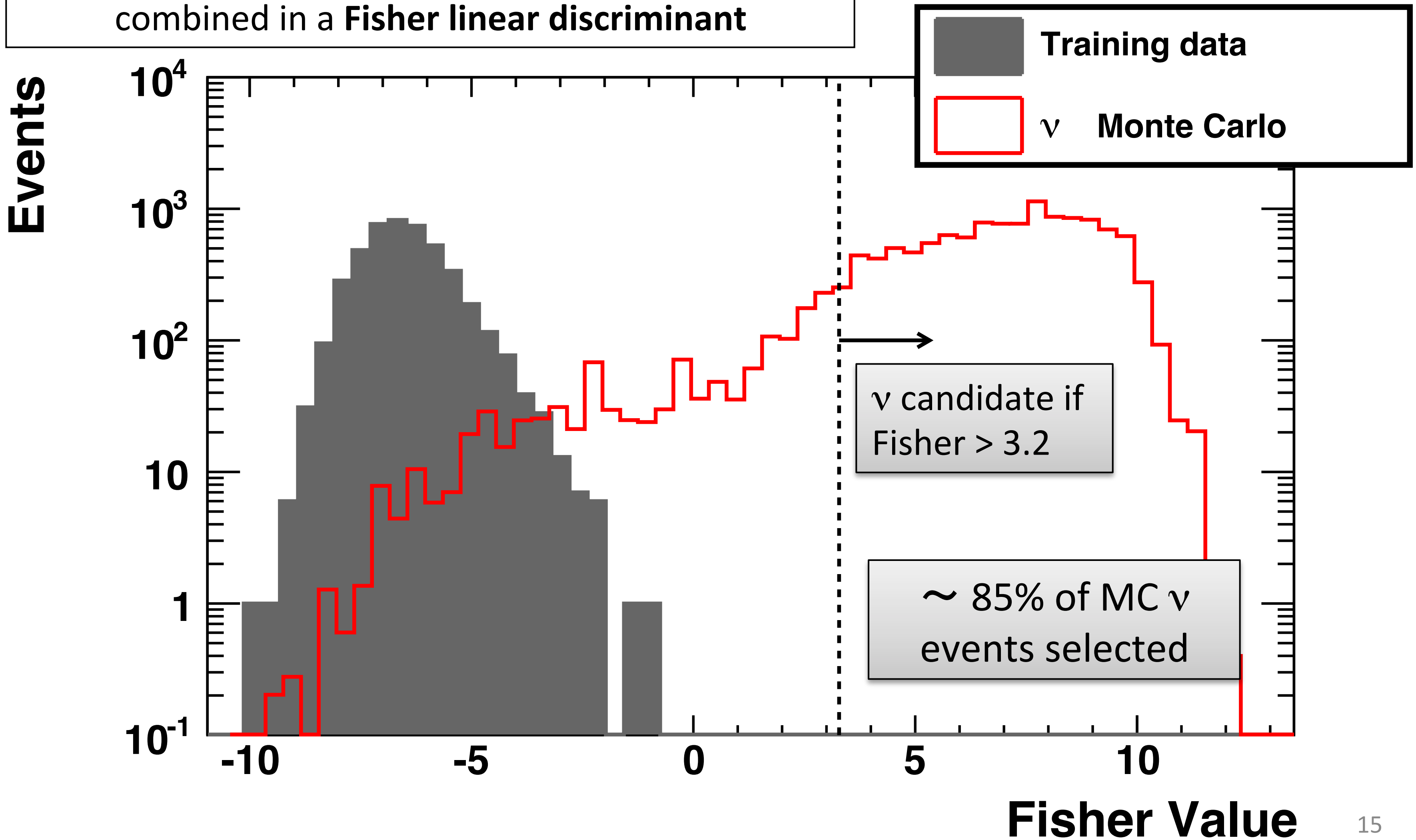
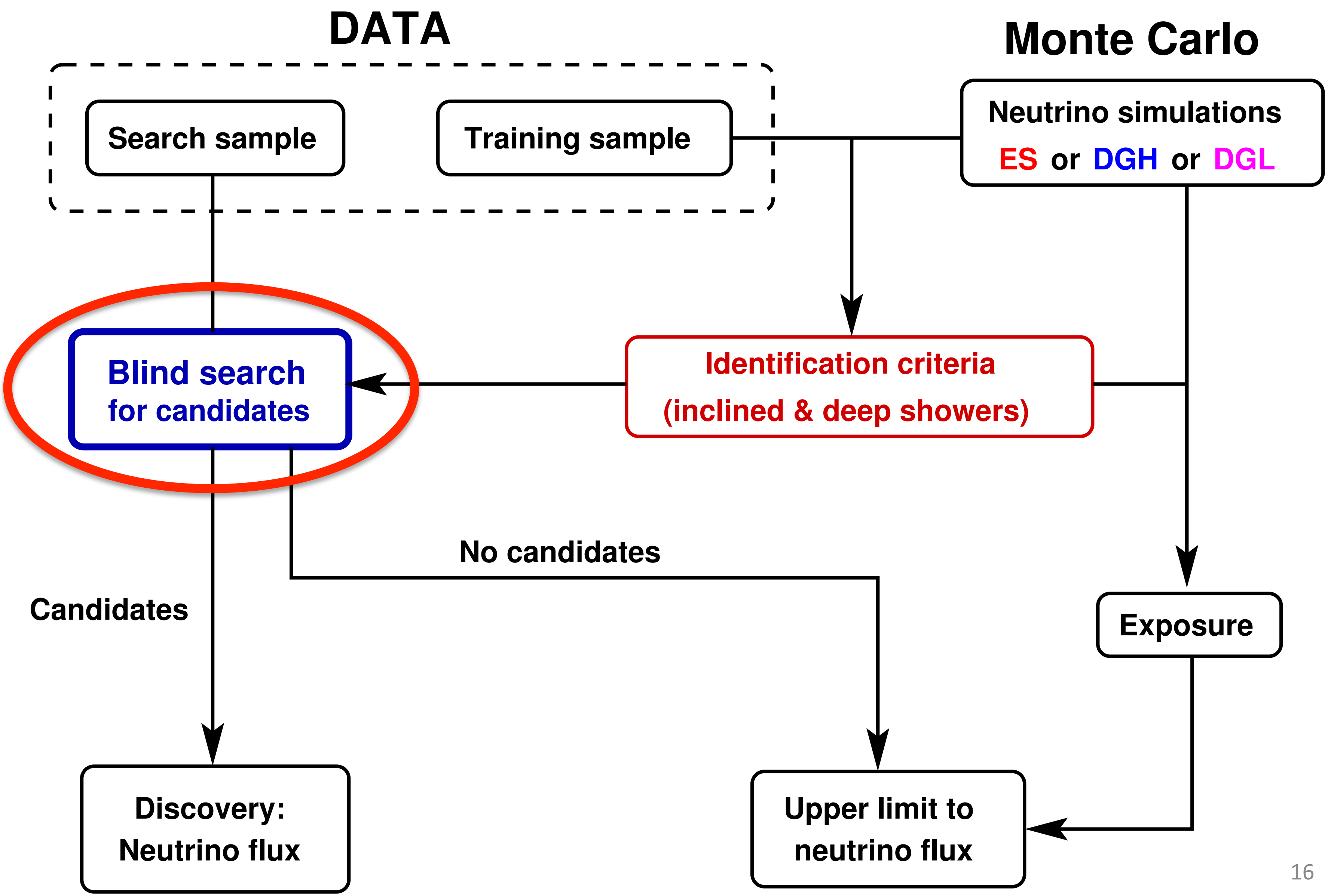
Area-over-Peak of various stations along with other observables constructed from AoP combined in a **Fisher linear discriminant**



General “strategy”



Unblinding: "Opening the box"

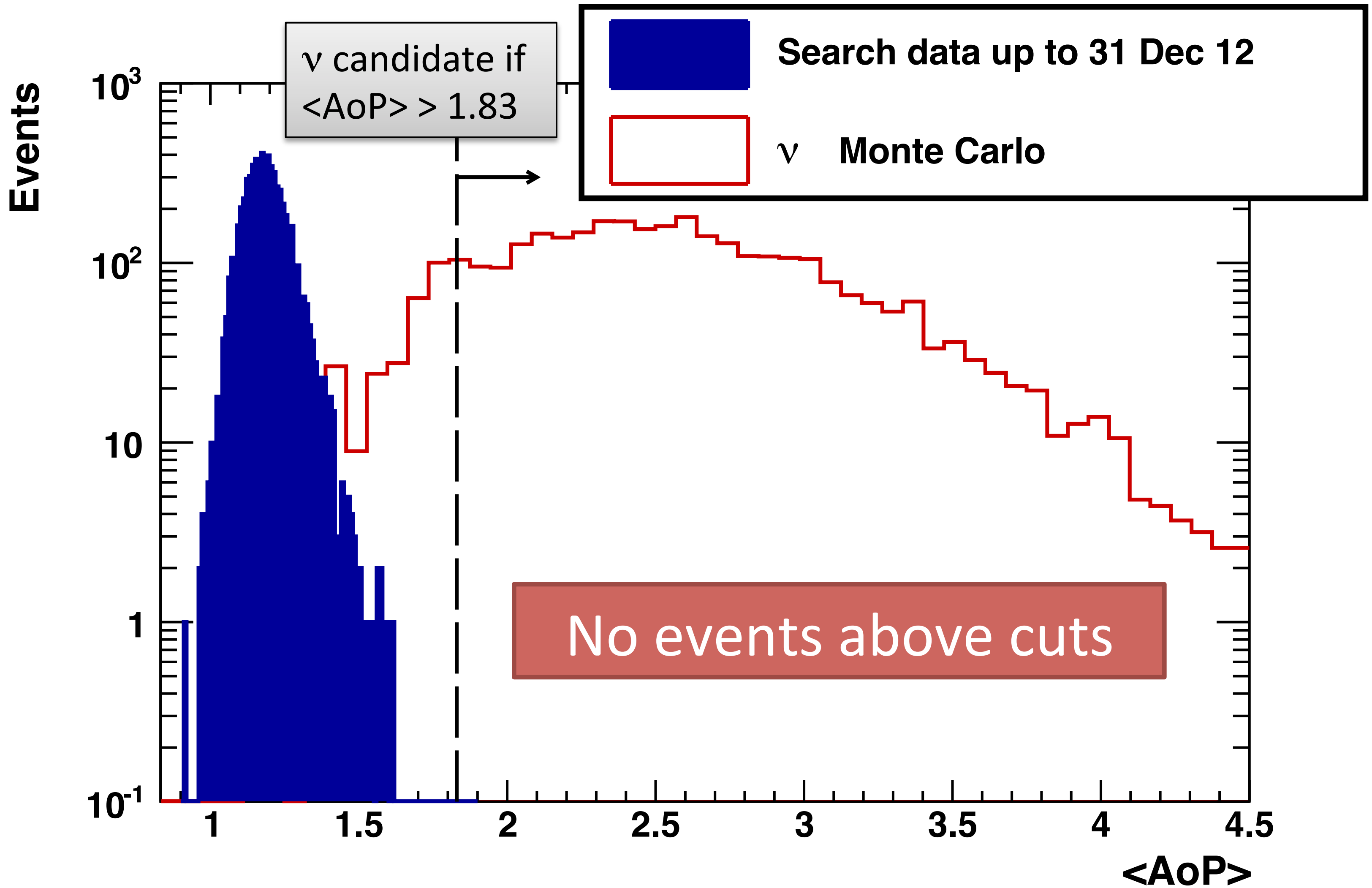
Summary of ν identification cuts

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 $\langle \mathrm{AoP} \rangle > 1.83$ $\mathrm{AoP_{min}} > 1.4$ if Nst=3		

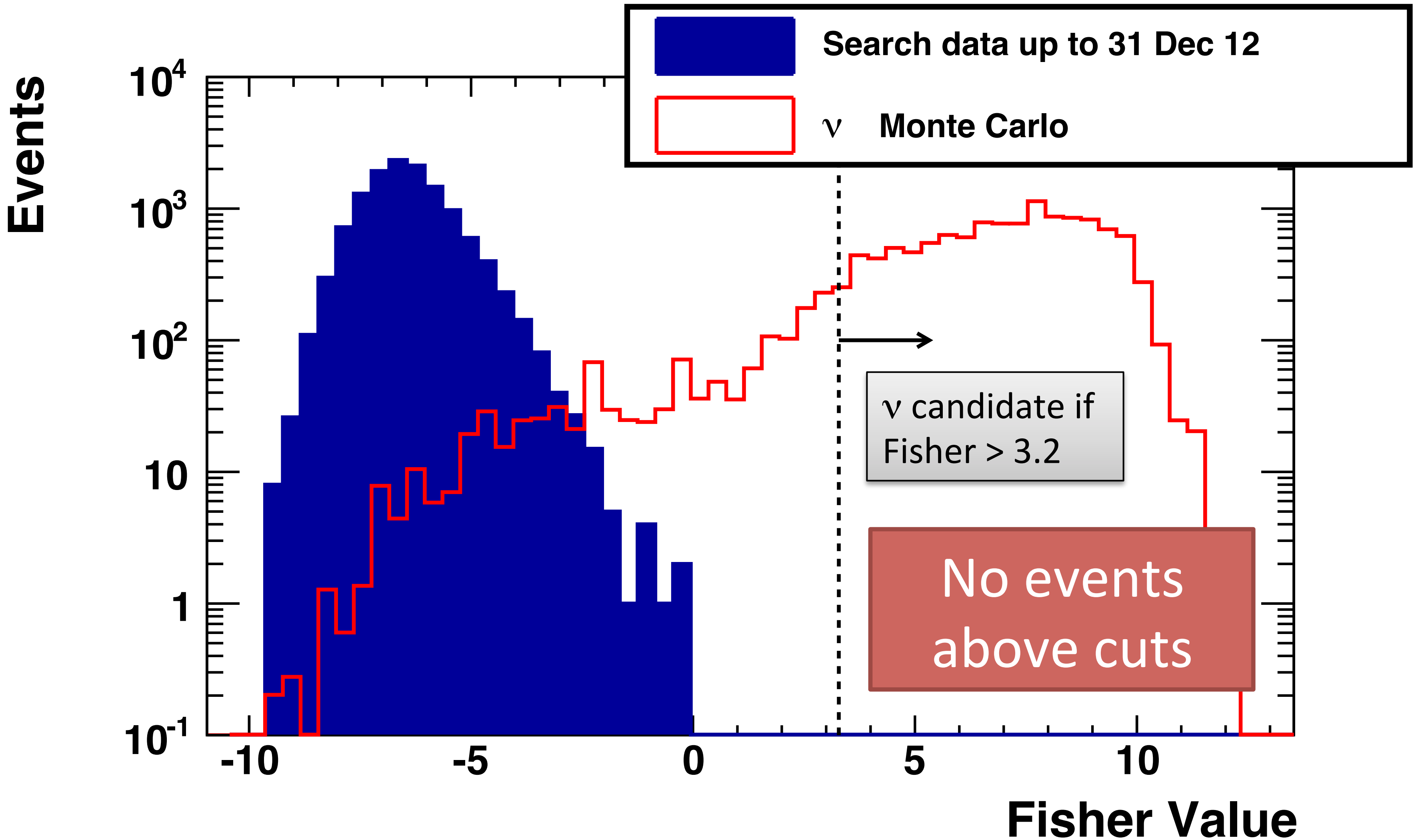
ν identification cuts applied "blindly" to data:
1 Jan 04 – 31 Dec 12 (excluding training data periods)

No candidates found
in Earth Skimming or Downward-going

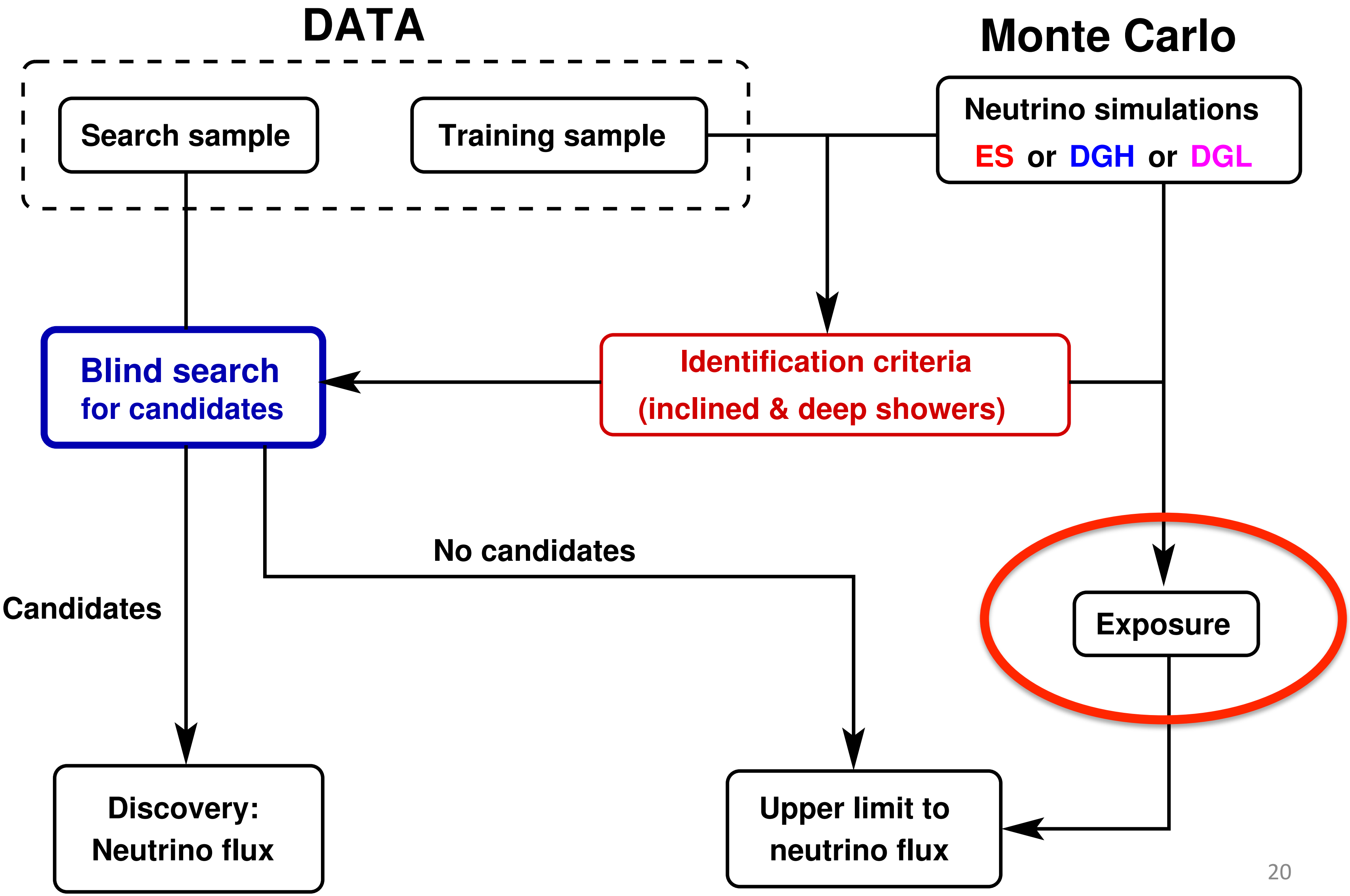
ν search: Earth-Skimming analysis



ν search: Down-going (75º, 90º)

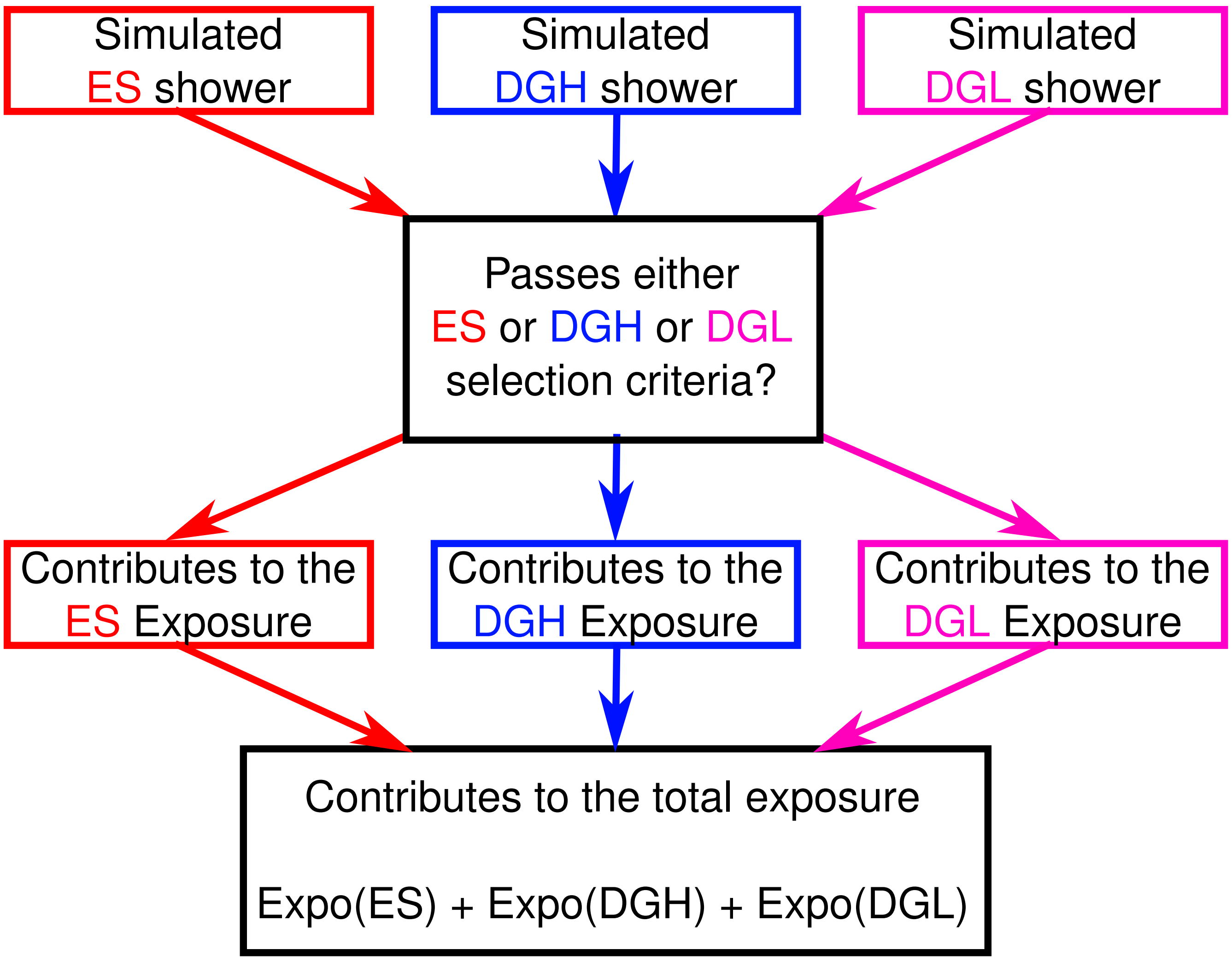


General "strategy"

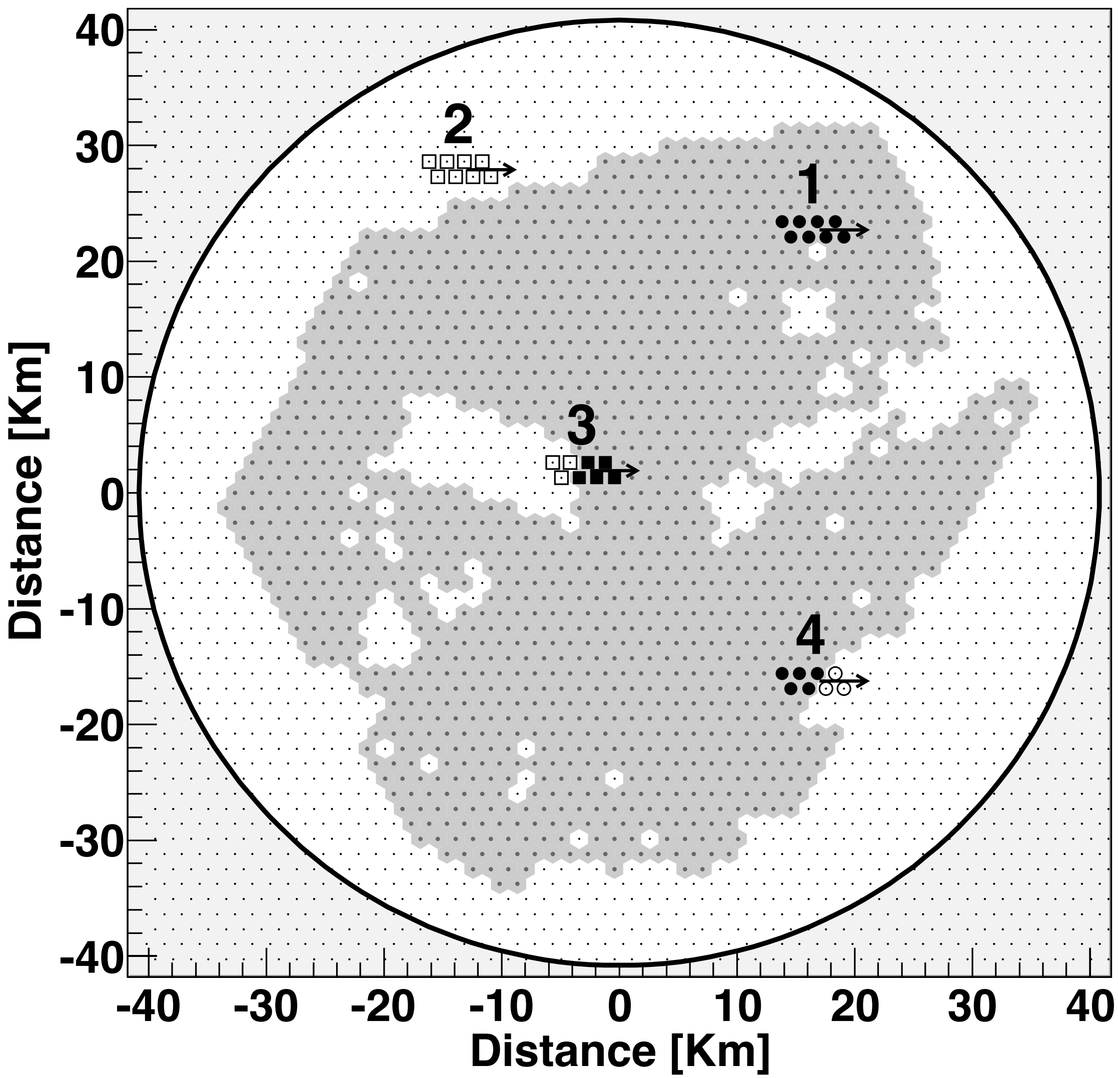


“Combined” exposure calculation:

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



Exposure calculation: accounting for a "dynamical" array



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

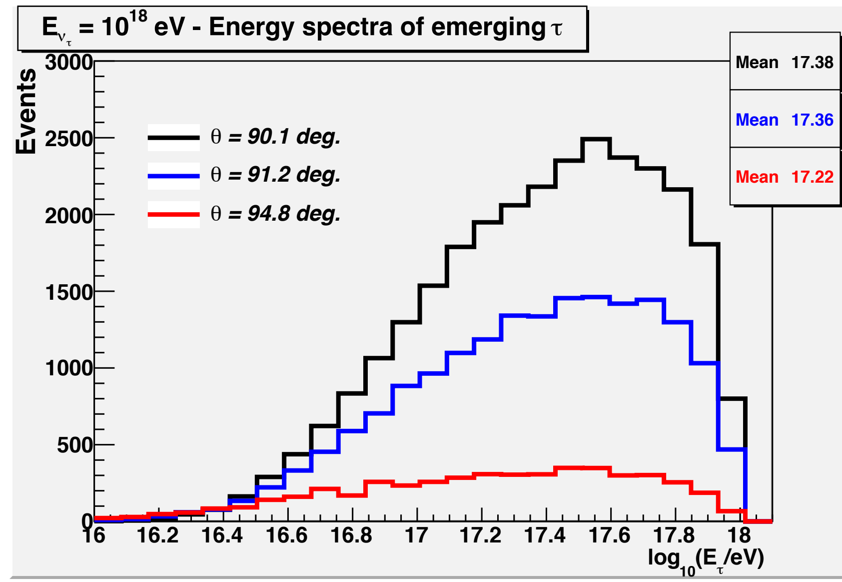
Neutrino simulated showers are "thrown" over a changing array

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

Exposure: Earth-skimming ν_τ

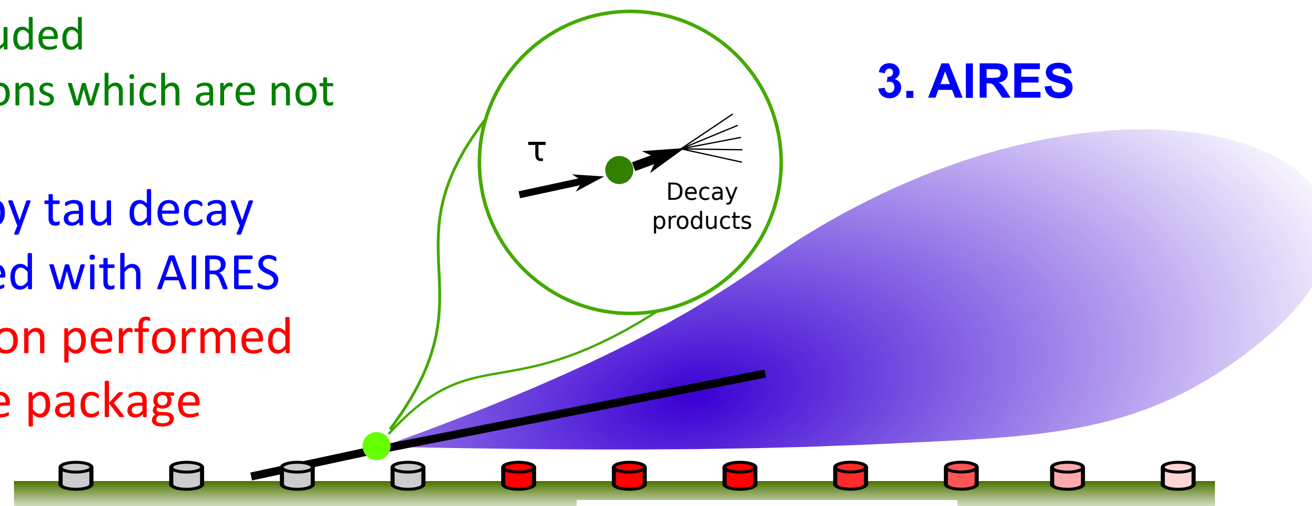
1. Tau neutrino propagation and tau production:
   - Dedicated MC for propagation of ν_τ through the Earth producing emerging tau leptons.
   - Convolute with probability of tau decay in the atmos. (exponential)
2. Tau decay products obtained with TAUOLA generator:
   - All decays included
   - 17% BR 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

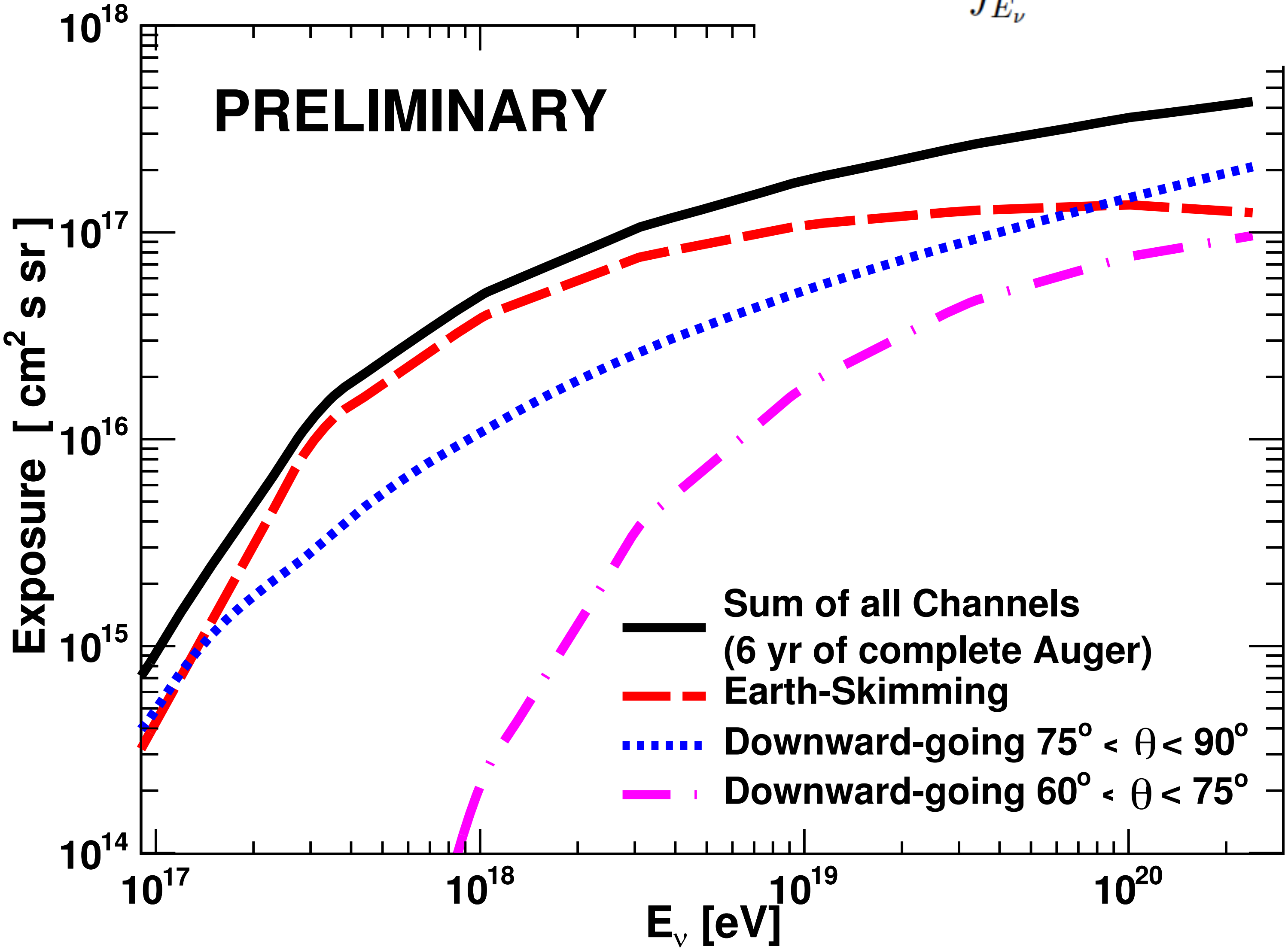


4. OFFLINE

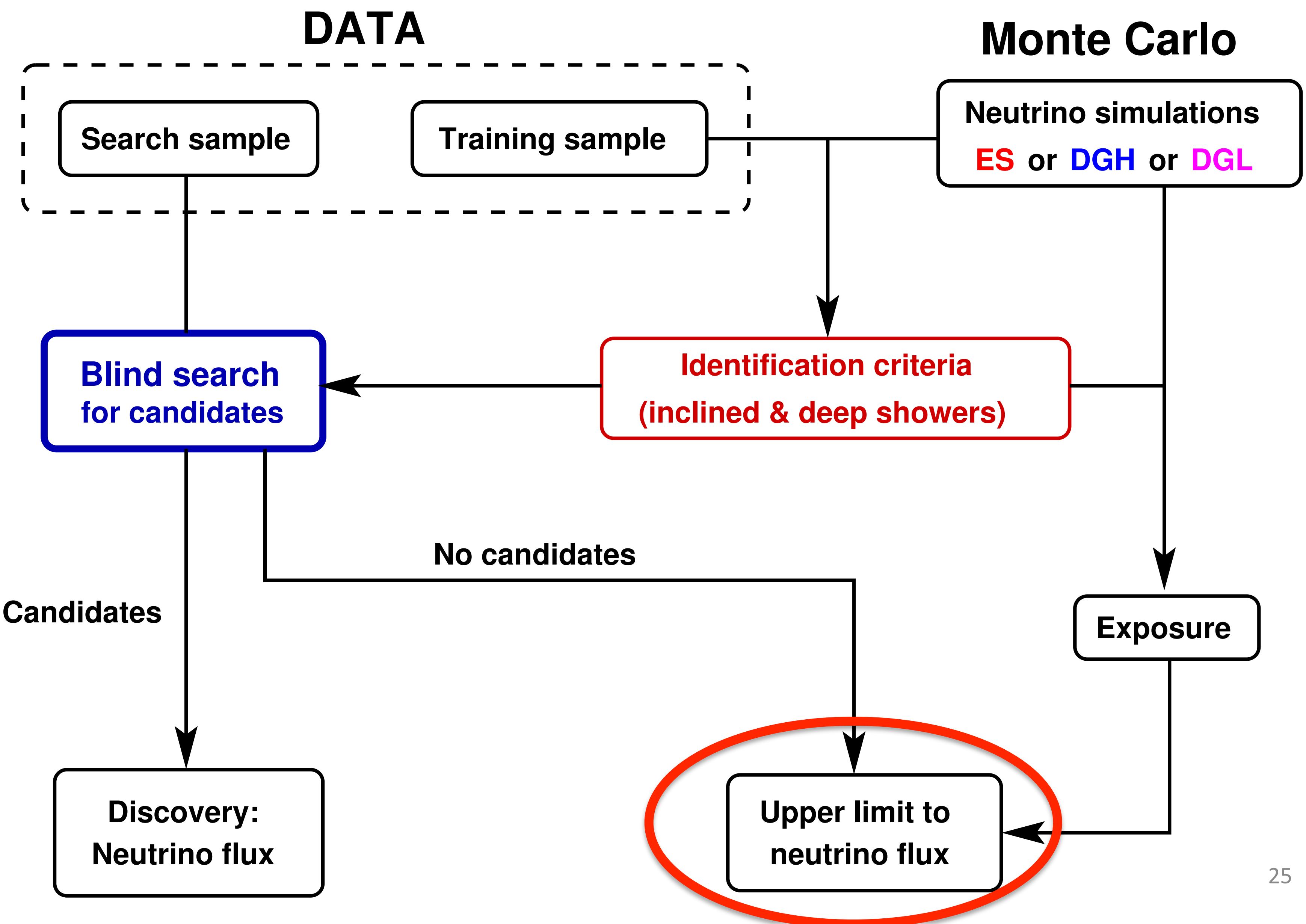
Exposure: 1 Jan 04 – 31 Dec 12

(excluding training data periods)

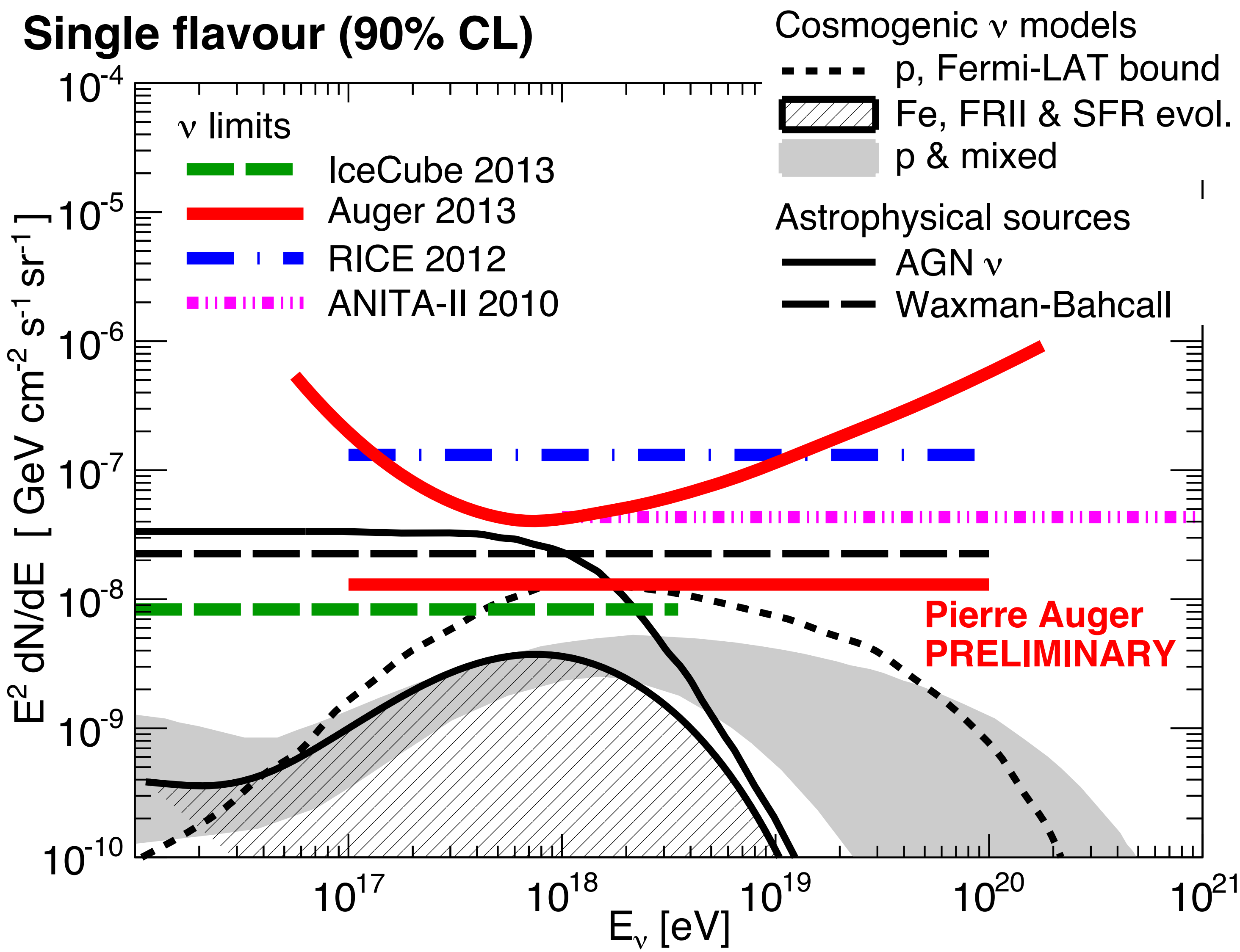
$$N_{\text{events}} = \int_{E_\nu} \Phi(E_\nu)\ \varepsilon_{\text{tot}}(E_\nu)\ \mathrm{d}E_\nu$$



General "strategy"

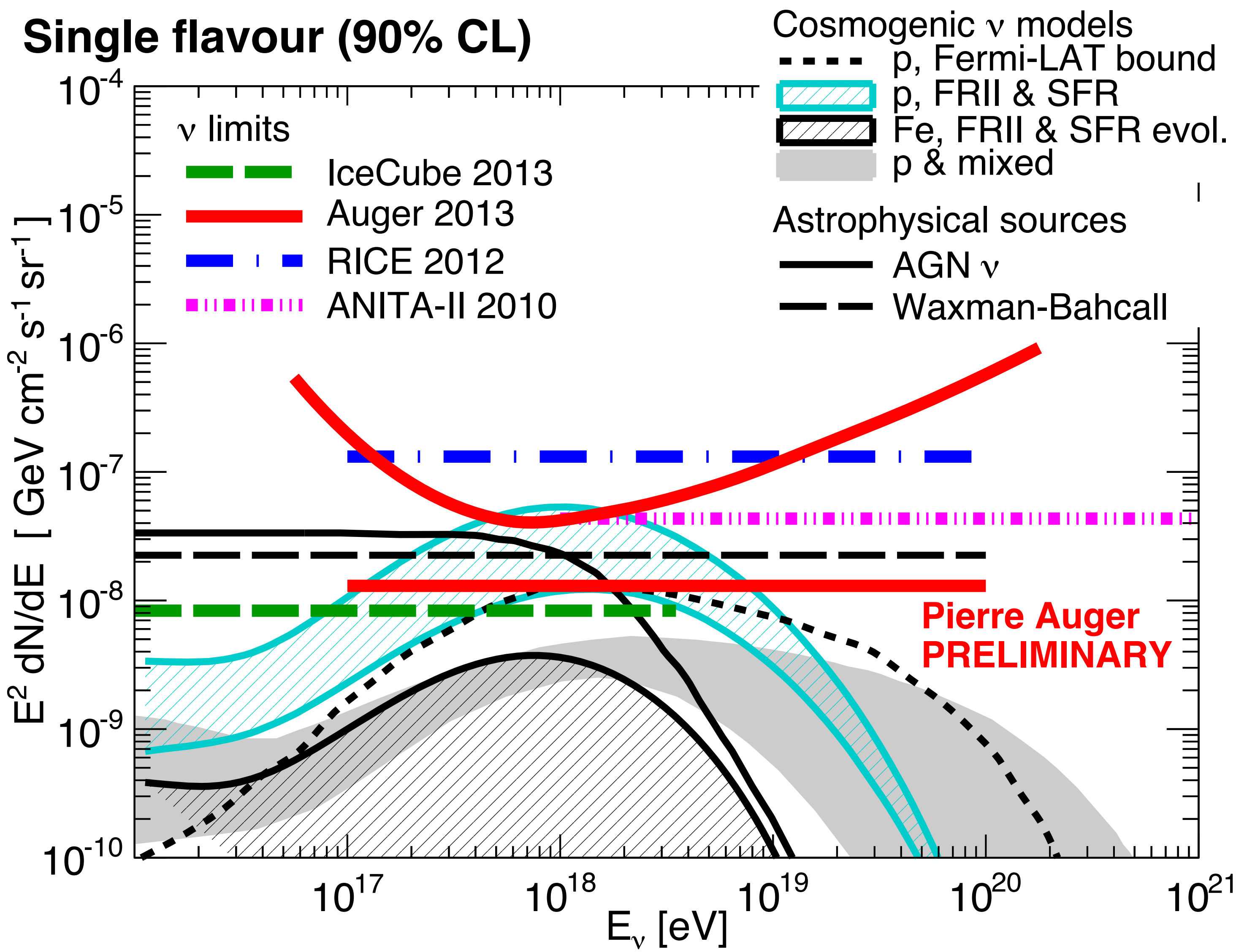


Limits to diffuse flux of UHEν



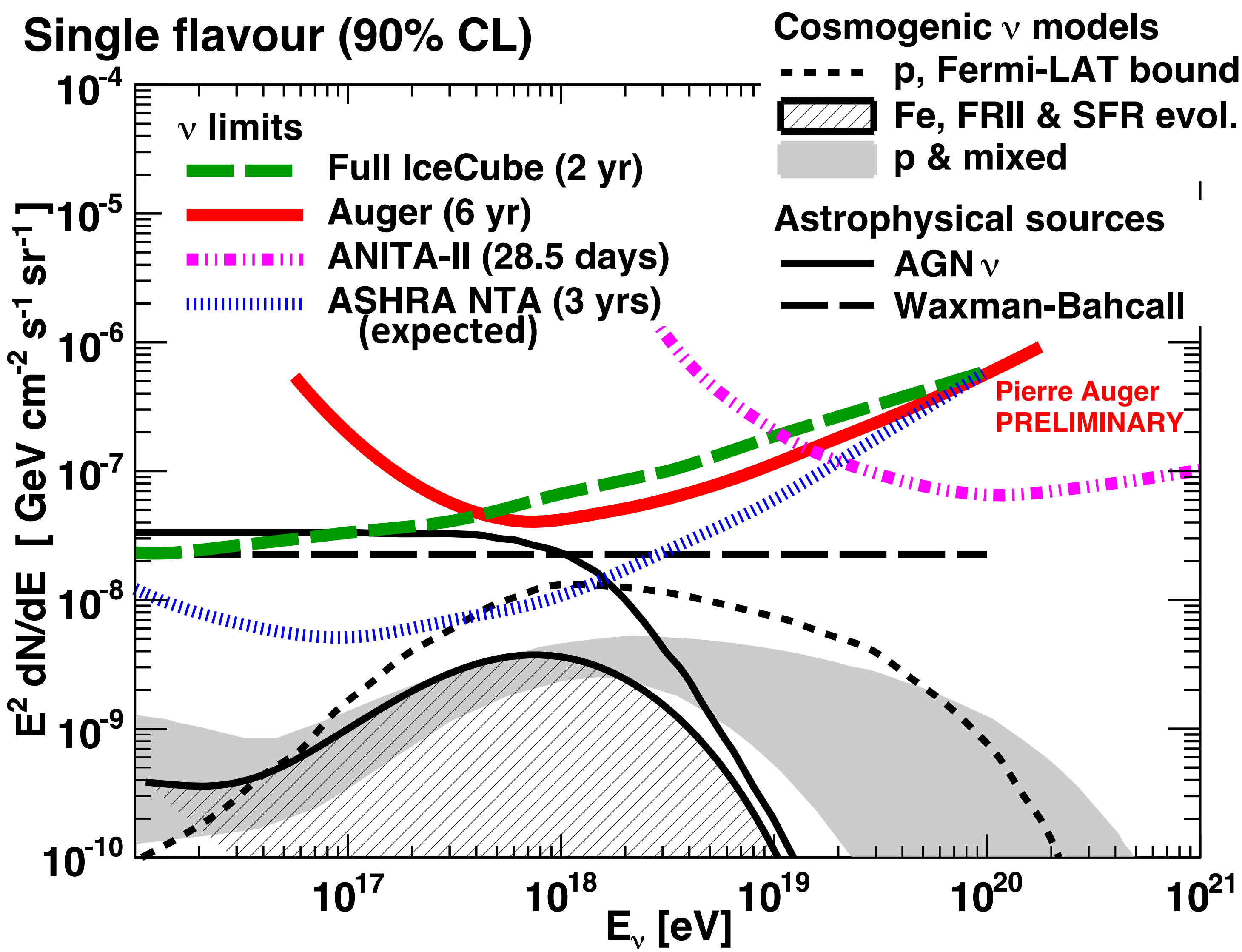
$dN/dE = k\,E^{-2} \longrightarrow k \sim 1.3 \times 10^{8}$ GeV cm^{-2} s^{-1} sr^{-1} - 90% C.L. - 10^{17} eV < E < 10^{20} eV

Limits to diffuse flux of UHEν



Auger constrains on models with proton primaries & strong FRII evolution

Differential limits to diffuse flux of UHEν



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

Relative contribution of different channels to Auger limit

PRELIMINARY

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

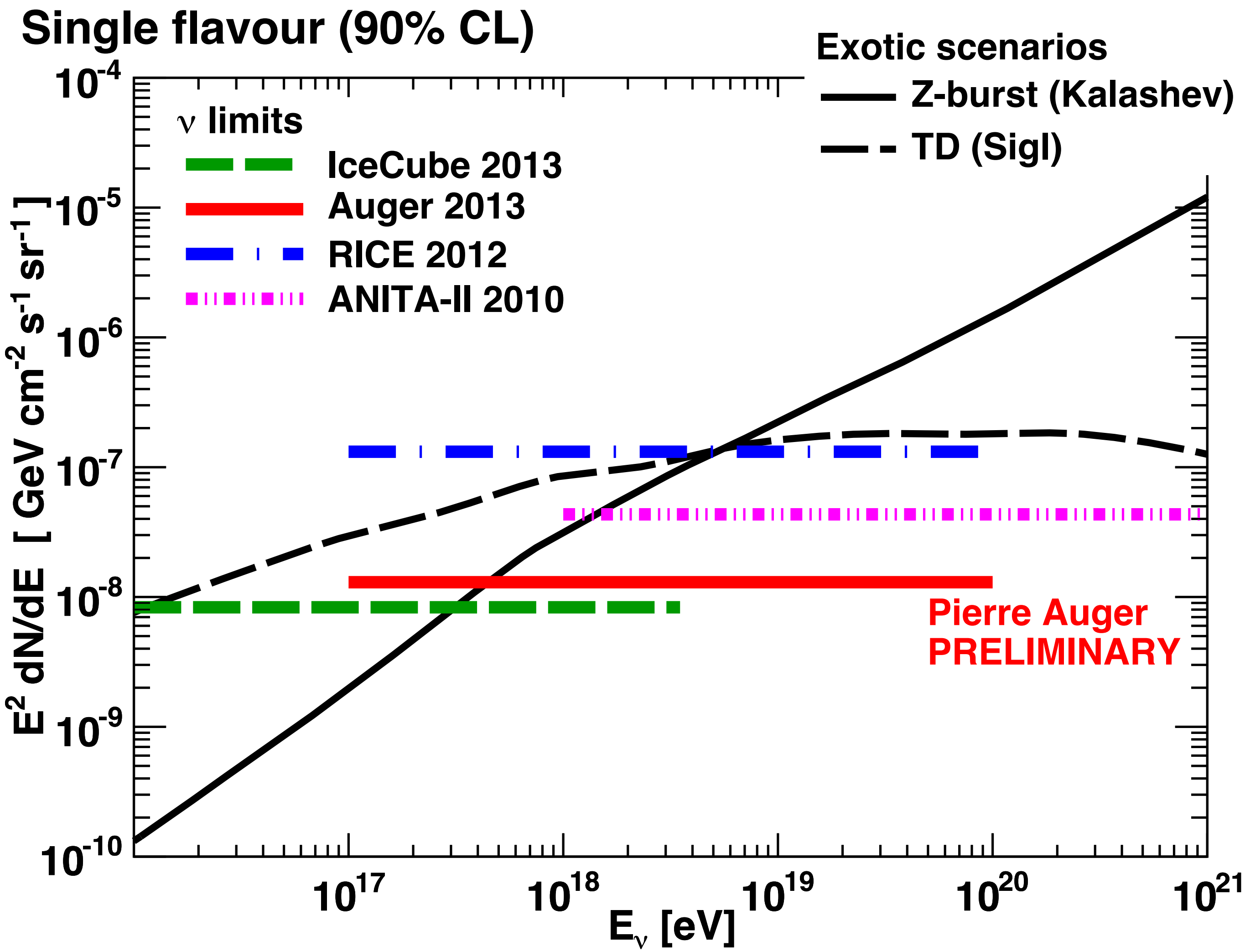
Expected number of events

PRELIMINARY

Neutrino Model	Expected number of events (1 Jan 04 - 31 Dec 12)
Cosmogenic (Ahlers *et al.*)	~ 1.4
Cosmogenic (Kotera *et al.* band)	$\sim 0.2 - 0.6$
AGN (Becker *et al.*)	~ 3.0

Exotic models of UHECR production & limits

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



Systematic uncertainties

PRELIMINARY

Source of systematic	Earth-Skimming $(90^\circ, 95^\circ)$	Down-going $(60^\circ, 90^\circ)$
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.

Conclusions I

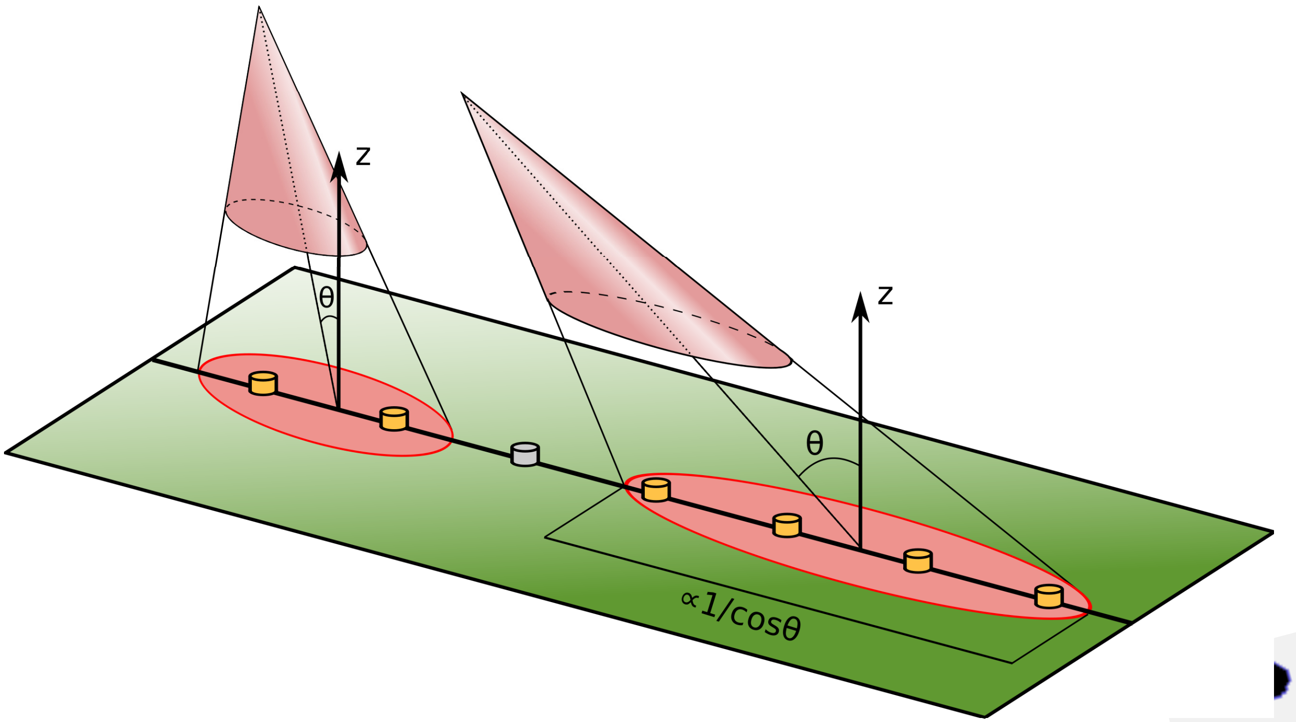
- Cosmogenic neutrinos at EeV energies provide complementary information on UHECR origin and composition at 10s of EeV.
- SD of Auger sensitive to UHE neutrinos:
  - Easy to identify: inclined showers with broad fronts.
  - Search NOT limited by background but by exposure.
  - Sensitivity peaks at ~ EeV (peak of cosmogenic neutrino fluxes).

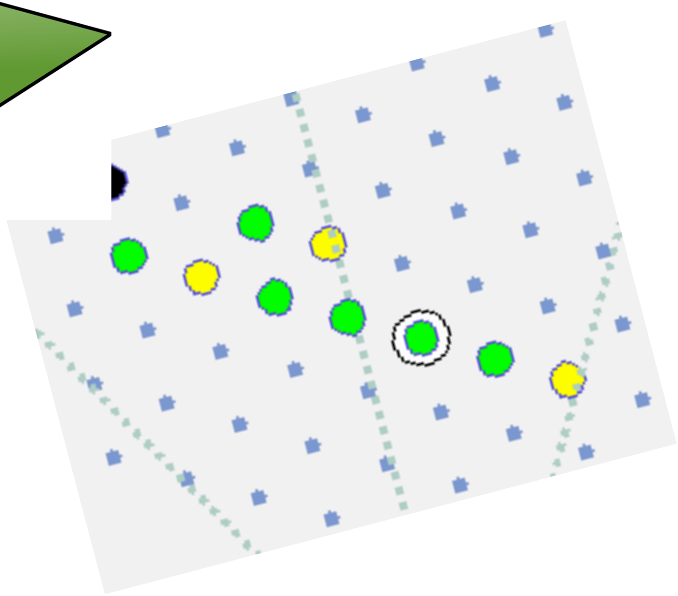
Conclusions II

- Physics results from Auger neutrino limits relevant to the origin of UHECR:
  - Limits below Waxman-Bahcall landmark.
    - First shower array to achieve this benchmark.
  - Protons from cosmological sources start to be constrained: p & FRII evolution disfavored.
  - Top-down (exotic) models strongly disfavored (when not excluded).
  - More exposure needed to constrain UHECR production at individual candidate sources.

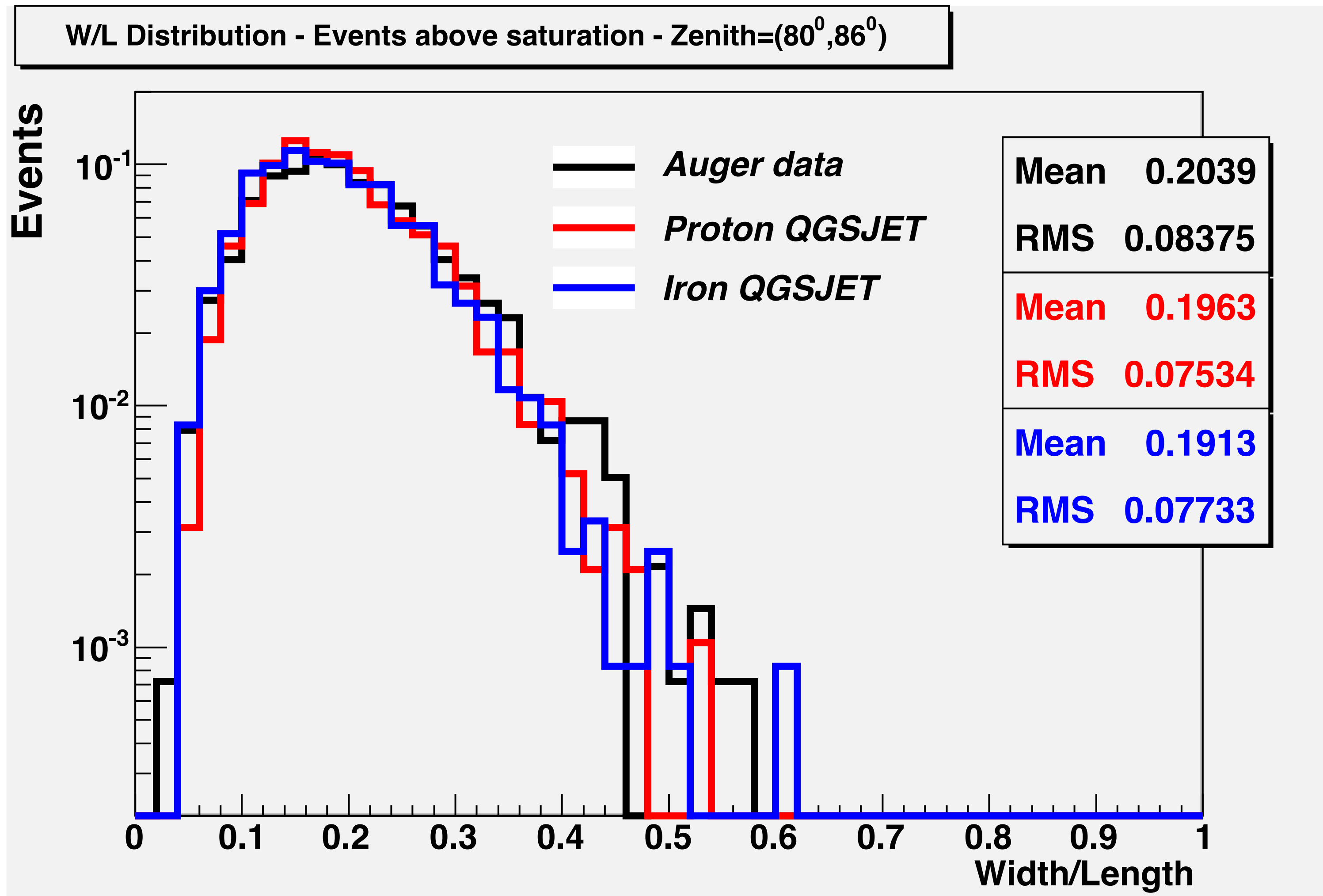
Backup

Inclined showers

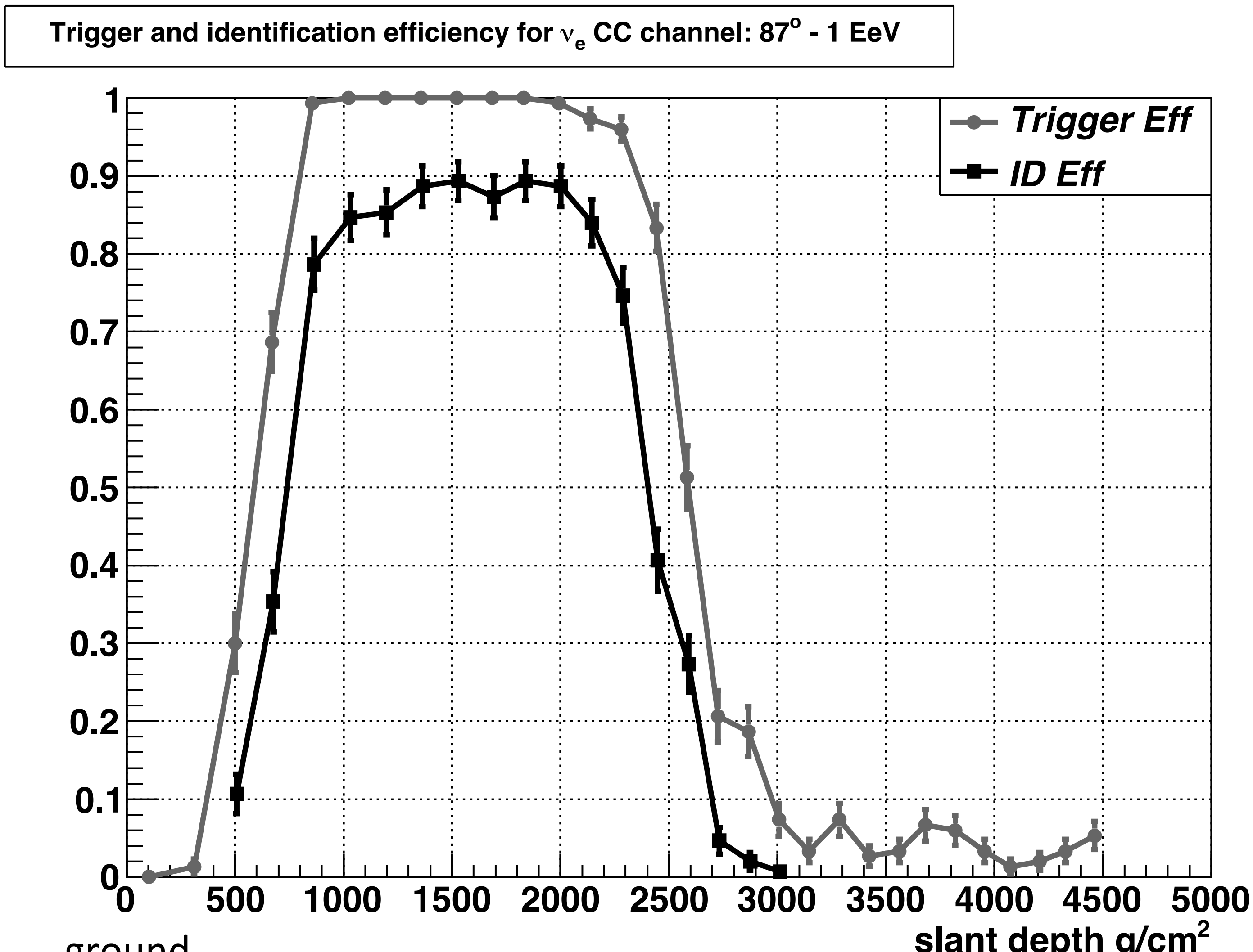




Data vs MC simulations



Efficiencies: Down-going (75°, 90°)

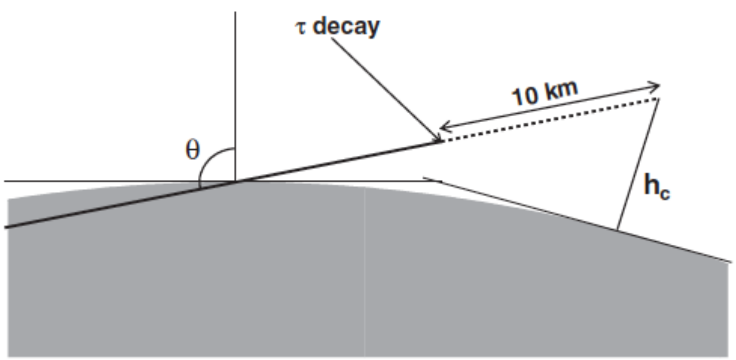


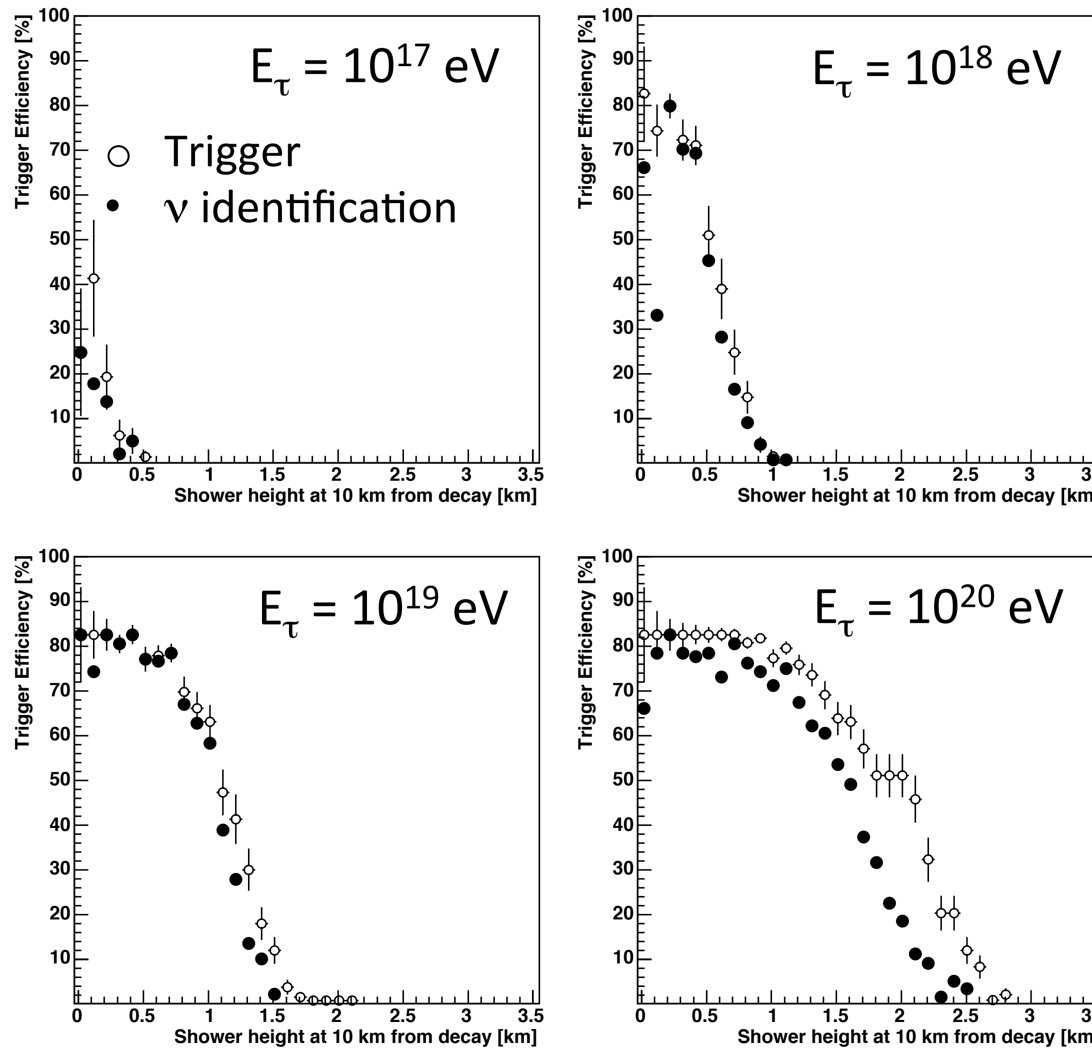
ground

top of atmosphere ⟶

Efficiencies: Earth-skimming

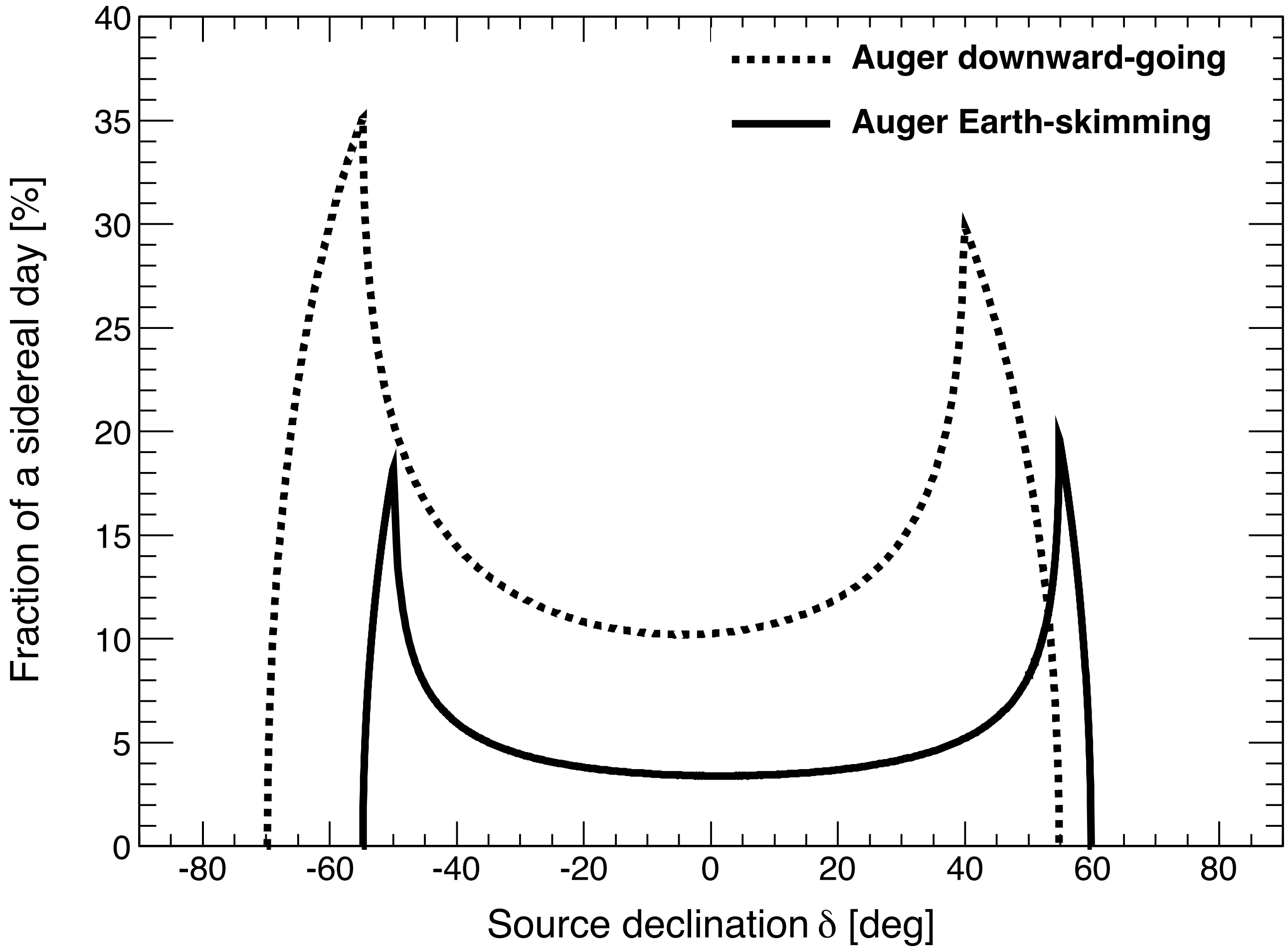
Trigger and identification probabilities as a function of shower height h_c at 10 km from tau decay point



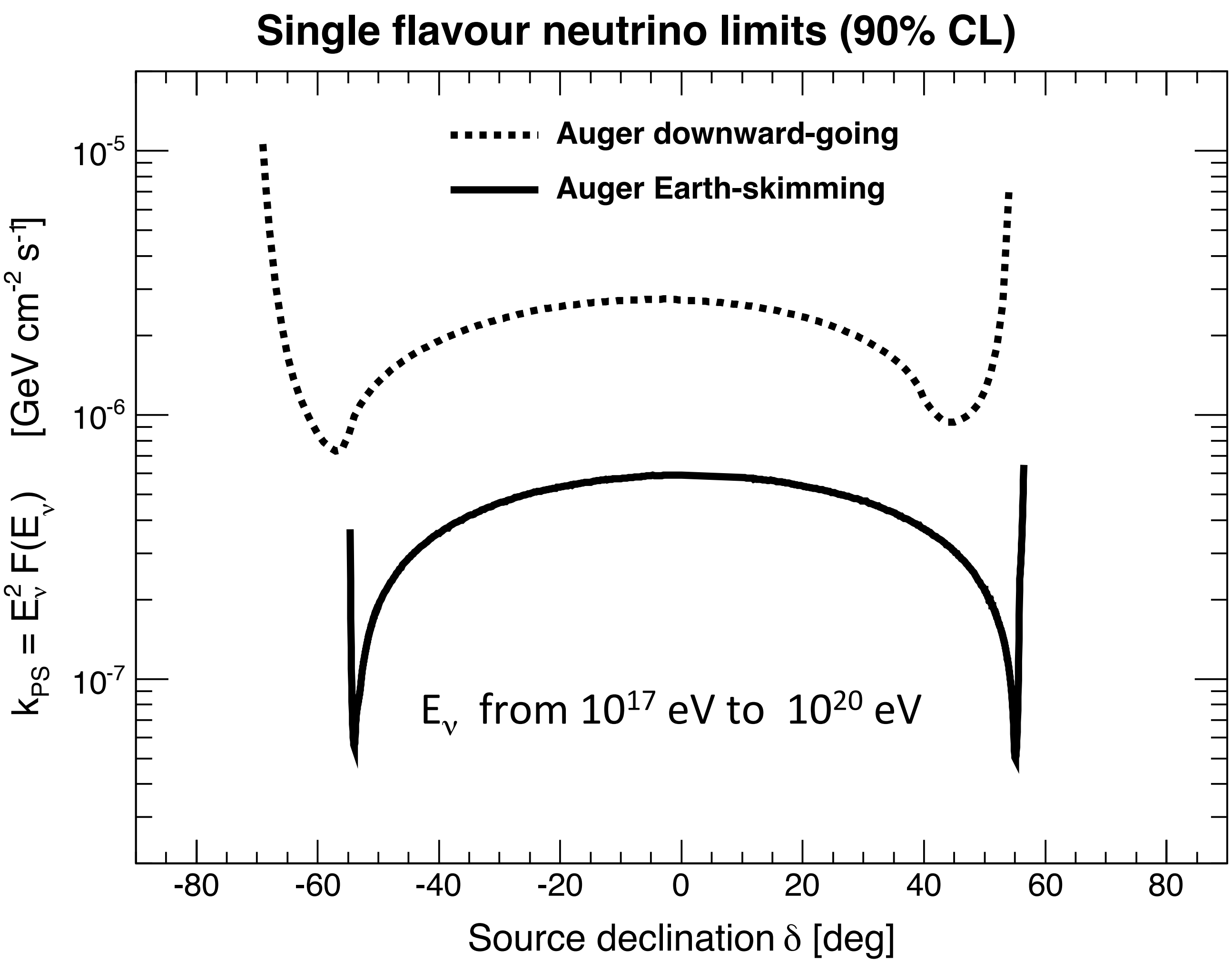


Point-like sources

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

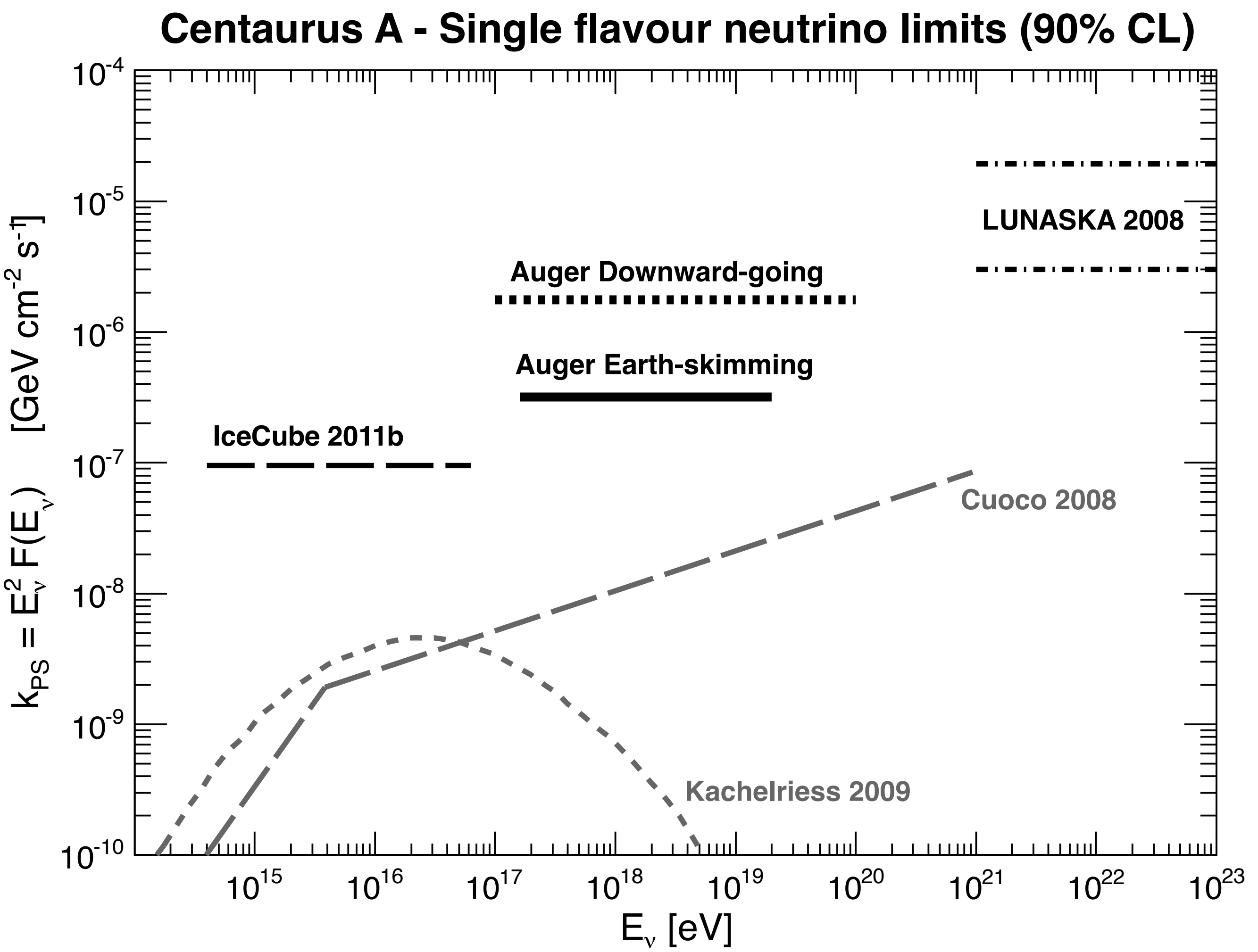


Limits to UHEν: point-like sources



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).**