Detection of tau neutrino by Cherenkov telescopes

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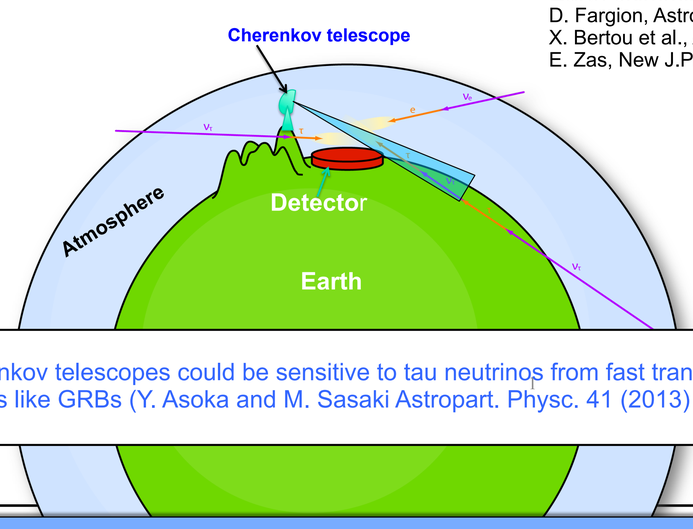
1) Earth-Skimming method

> Pointing MAGIC down from Roque de Los Muchachos (altitude 2200 a.s.l) the Sea surface is ~165 km away, yielding a large volume in viewed

Earth skimming technique:
D. Fargion, Astrophys.J. 570, 909 (2002).
X. Bertou et al., Astropart.Phys. 17, 183 (2002).
E. Zas, New J.Phys. 7, 130



Cherenkov telescopes could be sensitive to tau neutrinos from fast transient objects like GRBs (Y. Asoka and M. Sasaki Astropart. Physc. 41 (2013) 7).

2) Monte Carlo simulation chain

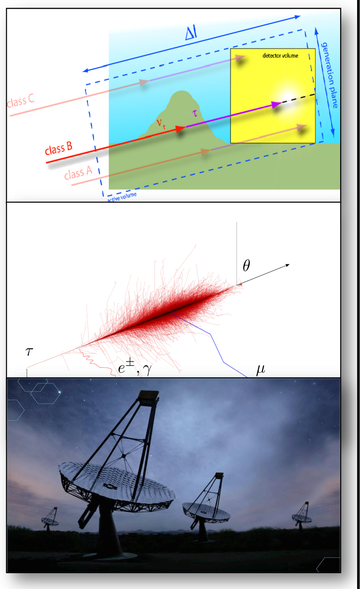
(1) Neutrino propagation in Earth: ANIS
A. Gazizov and M. Kowalski, Comput. Phys. Commun. 172 (2005) 203.

We included local topography of deterctor site
D.G. et al, Astropart. Physics 26 (2007) 402.

(2) Extensive Air shower Simulations: CORSIKA
T. Pierog and D.Heck CORSIKA website: https://web.ikp.kit.edu/corsika

Compiled with option:
- **TAULEP** – tau decay by PYTHIA
- **IACT** (Bernloehr package) – cherenkov photon distribution for any defined array geometry
- **CURVED EARTH, CERENKOV, THIN, QGSJET II, VOLUMEDET, SLANT**

(3) Detector simulation for IACTs: sim_telarray
K. Bernlohr. Astropart. Physics 30 (2008)149
http://www.mpi-hd.mpg.de/hfm/~bernlohr/sim_telarray/

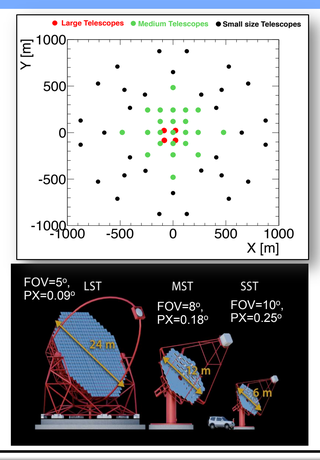


3) MC simulations

> For zenith angle (θ): 88, 87, 84, 80 deg; 10 bins in azimuth
- Shower are used several times (100 shower shifted 10 times around center of detector) in total 1000 showers for each injection depth (X_{inj})
- X_{inj} from detector level to the top of the atmosphere, at least every 50 g/cm^2

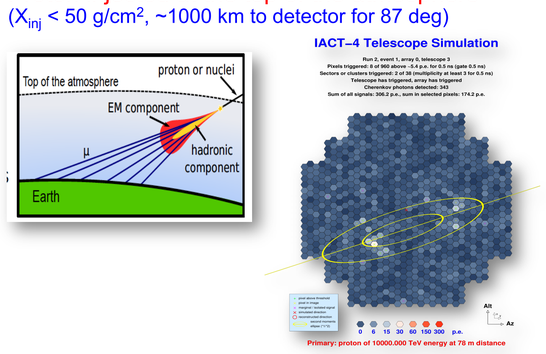
Energy	1	2.15	4.64	10	21.5	46.5	100	215	465
	[PeV]	[PeV]	[PeV]	[PeV]	[PeV]	[PeV]	[PeV]	[PeV]	[PeV]
tau	✔	✔	✔	✔	✔	✔	✔	✔	✔
proton	✔	✔	✔	✔	✔	✔	✔	✔	✔
gamma	✔			✔			✔		

- for H.E.S.S. like two/four telescops (IACT-2/IACT-4) and for a few CTAs array considered in K. Bernlohr et al., Astropart. Physc. 43 (2013) 171 with so-called *Production-1* settings

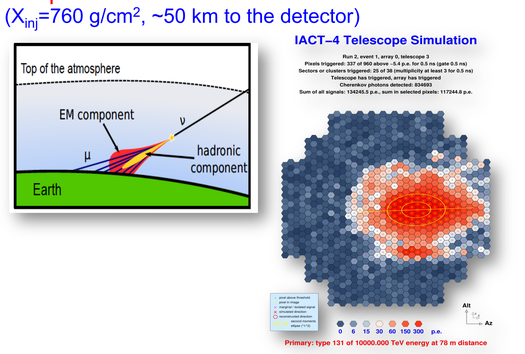


4) Example of shower images on camera

Proton injected at the top of the atmosphere
(X_{inj} < 50 g/cm^2, ~1000 km to detector for 87 deg)



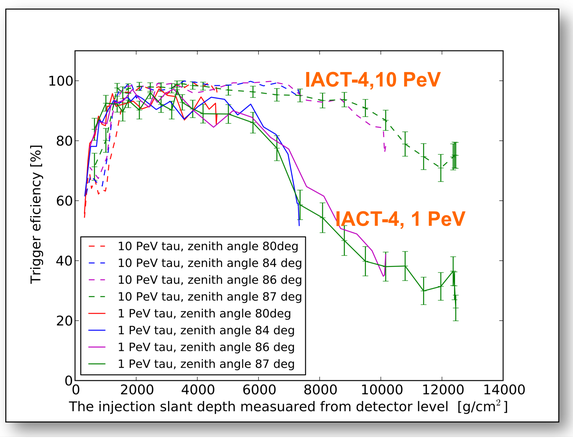
Deep tau-induced shower
(X_{inj}=760 g/cm^2, ~50 km to the detector)

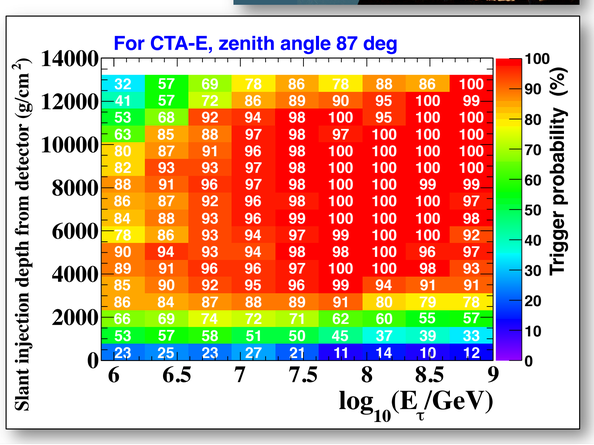


5) Trigger efficiency

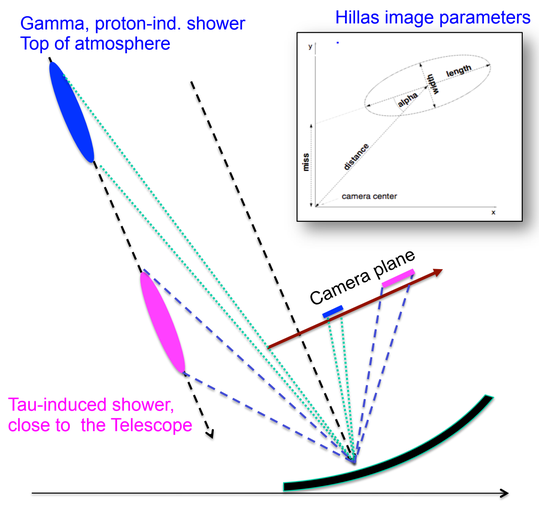
> **Trigger efficiency:** number of simulated showers with a positive trigger decision over the total number of shower generated for fixed energy and zenith angle.

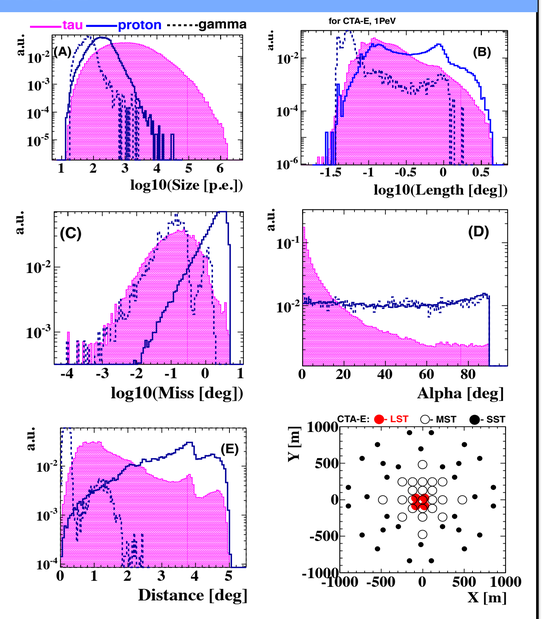
Trigger conditions:
L1: 3 pixels on camera above 4 p.e; **L2**: at least 2 neighboring triggered telescopes





6) Identification performance





> **Clear separation between shower interacting a the top of the atmosphere and deep tau induced shower**

> **Signature**: looking for inclined bright events with small value of Alpha/Miss parameter
> Size, Length and Width distribution depend on energy of primary tau lepton (more bright event leads to larger image size).
> Distance, Miss and Alpha distribution almost the same for 1-1000 PeV
> the shape of distributions is almost independent of array configuration, due to large size (> 1km) Cherenkov pool distributions at detector level

7) Identification efficiency

> Multi-parameter analysis (genetic algorithms)

$$\vec{x} = (\text{size}, \text{length}, \text{distance}, \text{miss}, \text{alpha})^T$$

Maximize cost function: $F(S(\vec{x}_{cut}), B(\vec{x}_{cut})) = \frac{S(\vec{x}_{cut})}{\sqrt{B(\vec{x}_{cut})}} \equiv max$

$S(\vec{x}_{cut}) = \int_{\vec{x}>\vec{x}_{cut}} P_S(\vec{x})d\vec{x}$ Signal from distributions of neutrino showers

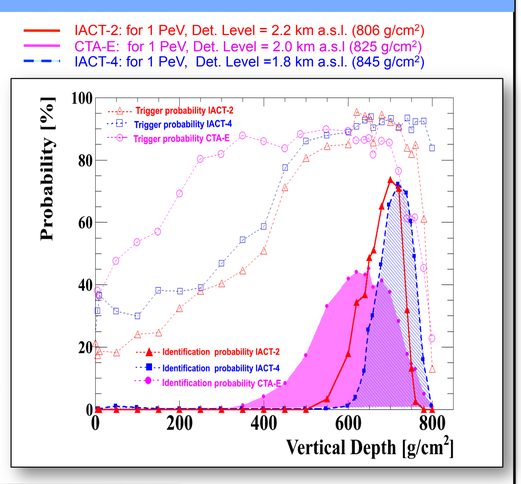
$B(\vec{x}_{cut}) = \int_{\vec{x}>\vec{x}_{cut}} P_B(\vec{x})d\vec{x}$ Background from distributions of hadronic showers (or real events)

$\vec{x}^0_{cut}$ vector of optimal cuts parameters which lead to maximum efficiency

Abdulin et al., "GARCON: Genetic Algorithm for Rectangular Cuts Optimization", hep-ph/0605143

SIGNAL: tau-induced shower with injection veritical depth X_{inj} > 600 g/cm^2
BACKGROUND: inclined proton showers with θ=87° and X_{inj} < 100 g/cm^2

Optimal scenario: 100 % signal, 0% background



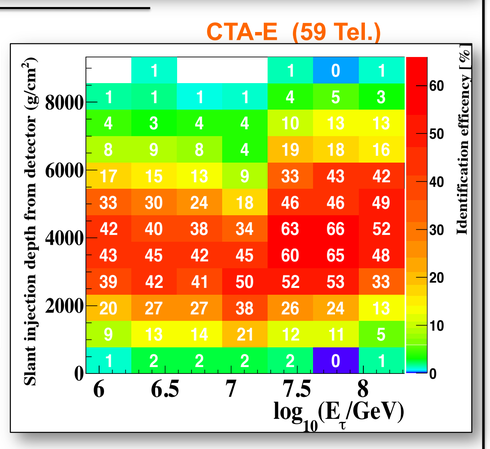
> Selection criterion:

array type	E_i^τ [PeV]	*Size* [p.e.]	*Length* [deg]	*Distance* [deg]	*Miss* [deg]	*Alpha* [deg]	$S(\vec{x}^{cut})$ [%]	$B(\vec{x}^{cut})$ [%]
IACT-2		> 2290	< 0.57	< 1.29	< 0.09	< 80.9	33	0
IACT-4	1	> 3110	< 0.46	< 1.09	< 0.18	< 45.1	33	0
CTA-E		> 791	< 0.27	< 2.91	< 2.12	< 13.8	24	0
IACT-2		> 1.35$E4$	< 0.34	< 1.94	< 0.23	< 79.4	38	0
IACT-4	10	> 3.55$E3$	< 0.70	< 2.19	< 0.30	< 48.7	31	0
CTA-E		> 3.51$E3$	< 0.26	< 2.97	< 0.56	< 41.4	34	0
IACT-2		> 2.52$E4$	< 0.62	< 1.90	< 2.04	< 29.7	44	0
IACT-4	100	> 4.31$E4$	< 0.78	< 1.89	< 1.81	< 12.7	30	0
CTA-E		> 1.81$E4$	< 0.33	< 2.93	< 0.22	< 13.5	33	0

Remark: cuts leads to 0 proton events and of about 30% signal efficiency

> Large active volume seen by present IACT and CTA-E up to 6000 g/cm^2 (~ 100 km away from detector for θ=87°)

CTA-E (59 Tel.)



8) Event rate prediction

> At energy larger than *O*(10) PeV detection of earth-skimming tau neutrinos with IACTs becomes promising for (short) transient signals (D.G. and E. Bernardini, A. Kappes, Astropart. Physc. 61 (2015) 12)

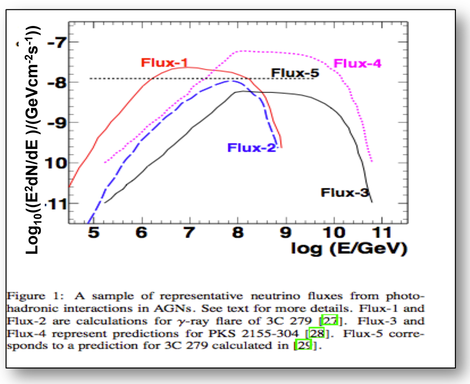
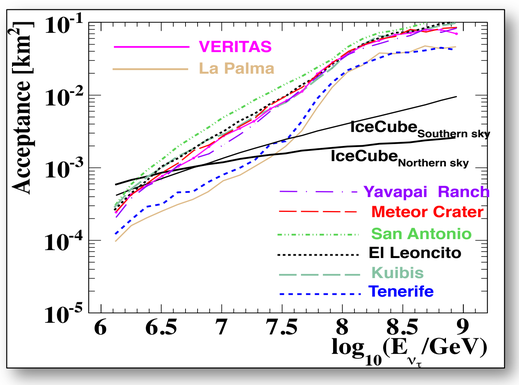


Figure 1: A sample of representative neutrino fluxes from photo-hadronic interactions in AGNs. See text for more details. Flux-1 and Flux-2 are calculations for γ-ray flare of 3C 279 [27]. Flux-3 and Flux-4 represent predictions for PKS 2155-304 [28]. Flux-5 corresponds to a prediction for 3C 279 calculated in [29].



> In recent paper results for ideal detector with 10% trigger efficiency for lepton tau induced showers.
> This simulation will increase the trigger efficiency and calculated rate at least of about factor 3 to our previous calculation

Expected event rate for a detector located at La Palma/VERITAS compared with what expected for IceCube

	Flux-1 [$\times10^{-4}$/3 hours]	Flux-2 [$\times10^{-4}$/3 hours]	Flux-3 [$\times10^{-4}$/3 hours]	Flux-4 [$\times10^{-4}$/3 hours]	Flux-5 [$\times10^{-4}$/3 h
N_{LaPalma}	**8.4**	**4.5**	**2.6**	**26**	**7.8**
N_{VERITAS}	24.6	11.7	4.8	48	20.7
$N_{\text{IceCube}}^{\text{Northern Sky}}$	**6.8**	**2.5**	**0.46**	**4.6**	**8.8**
$N_{\text{IceCube}}^{\text{Southern Sky}}$	11.0	3.2	0.76	7.6	8.8

> For all models studied in this work which predict neutrino fluxes, the event rate can be comparable to IceCube or even better
> In case of sites surrounded by mountains results shown higher event rate (by at least factor 2).