

# Searching for Supersymmetry through UHECR

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## Contents – Summarize two works:

- *Neutrino Telescopes as a Direct Probe of Supersymmetry Breaking*, Ivone. F. M. Albuquerque, Gustavo Burdman and Z. Chacko, Physical Review Letters, 92, 221802 (2004);
- *Direct detection of supersymmetric particles in neutrino telescopes*, Ivone. F. M. Albuquerque, Gustavo Burdman and Z. Chacko, Physical Review D 75, 035006 (2007);

Goal – extend the results for ultrahigh energy cosmic rays

## Introduction

- One of the most pressing questions in particle physics is the origin and stability of the hierarchy between the weak and the Planck energy scales;
- Natural solutions of this so called hierarchy problem require new physics at the TeV scale;
- There are several models for physics beyond the Standard Model of particle physics;
- One of the most attractive candidate theories is the weak scale supersymmetry (SUSY).

## Minimal Supersymmetric Standard Model – MSSM

MSSM chiral supermultiplets – the spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions.

Names		spin 0	spin 1/2	$SU(3)_C \times SU(2)_L \times U(1)_Y$
(s)quarks ( $\times 3$ families)	$Q$	$(\tilde{u}_L \ \tilde{d}_L)$	$(u_L \ d_L)$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$
(s)leptons ( $\times 3$ families)	$L$	$(\tilde{\nu} \ \tilde{e}_L)$	$(\nu \ e_L)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$
	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs(inos)	$H_u$	$(H_u^+ \ H_u^0)$	$(H_u^+ \ H_u^0)$	$(\mathbf{1}, \mathbf{2}, +\frac{1}{2})$
	$H_d$	$(H_d^0 \ H_d^-)$	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$

MSSM gauge supermultiplets

Names	spin 1/2	spin 1	$SU(3)_C \times SU(2)_L \times U(1)_Y$
gluino, gluon	$\tilde{g}$	$g$	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W bosons	$\tilde{W}^\pm \tilde{W}^0$	$W^\pm W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B boson	$\tilde{B}^0$	$B^0$	$(\mathbf{1}, \mathbf{1}, 0)$

R-parity  $\rightarrow$  neutral and stable  
lightest supersymmetric particle (LSP)

The supersymmetry must be broken  $\rightarrow \sqrt{F}$

If  $\sqrt{F} \lesssim 10^{10} \text{ GeV} \rightarrow$  Gravitino LSP

If  $\sqrt{F} \gtrsim 10^{10} \text{ GeV} \rightarrow$  Neutralino LSP

## Gravitino LSP Scenarios

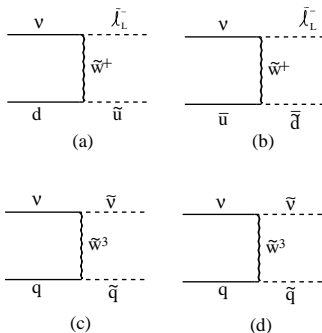
- Next to lightest supersymmetric particle (NLSP):  
→  $\tilde{l}_R$ , typically is the  $\tilde{\tau}_R$ ;
- If  $\sqrt{F} < 10^7 \text{ GeV}$  →  $\tilde{\tau}_R$  can decay to gravitino inside the Earth;
- The  $\tilde{\tau}_R$  lifetime can be very large → can travel very long distances before decaying:

$$c\tau = \left( \frac{\sqrt{F}}{10^7 \text{ GeV}} \right)^4 \left( \frac{100 \text{ GeV}}{m_{\tilde{\tau}_R}} \right)^5 10 \text{ km}$$

Processes that have to be considered:

$$\nu N \rightarrow \tilde{l}_L \tilde{q}$$

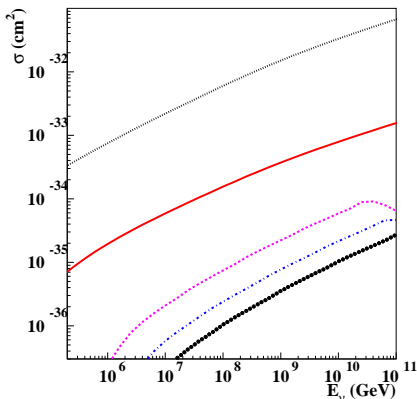
$\tilde{l}_L \tilde{q}$  promptly decay to  $2\tilde{l}_R + SM$  particles

$\nu$ -nucleon interactions

Feynman diagrams for supersymmetric particle production in  $\nu N$  collisions Charged current (chargino) interactions:

(a) Left-left interaction requiring the insertion of the gaugino mass in the t-channel line. (b) Left-right interaction.

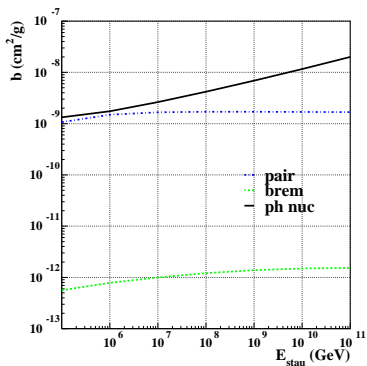
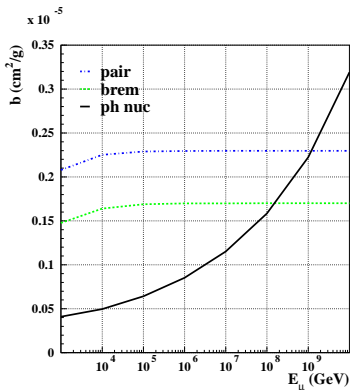
Neutral current: (c), (d). There are analogous diagrams for anti-neutrinos as well as for strange and charm initial quarks.

$\nu$ -nucleon cross-sections

The three lower curves correspond to  $m_{\tilde{\ell}_L} = 250$  GeV,  $m_{\tilde{W}} = 250$  GeV; and for squark masses  $m_{\tilde{q}} = 300$  GeV (dashed) , 600 GeV (dot-dashed) and 900 GeV (dotted). The top curve corresponds to the SM charged current interactions and the middle one to the di-muon background.

## Energy loss for muon and stau

Three main contributions – bremsstrahlung, pair production and photonuclear



## Neutrino flux

Waxman and Bahcall (WB) limit – the observed cosmic ray flux implies an upper bound on the high energy astrophysical neutrino flux.

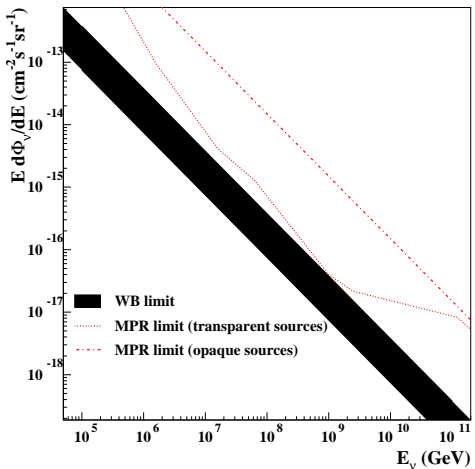
Requires that the sources be optically “thin”, meaning that most of the protons escape and only a fraction of them interact inside the source.

$$\left(\frac{d\phi_\nu}{dE}\right)_{\text{WB}} = \frac{(1-4) \times 10^{-8}}{E^2} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

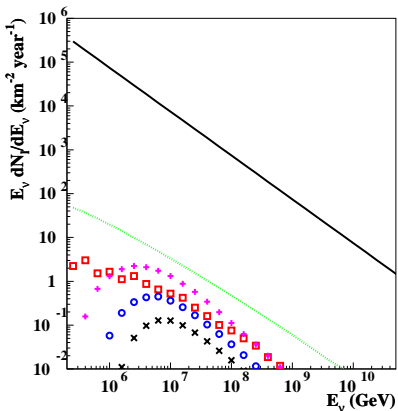
Mannheim, Protheroe and Rachen (MPR) limit – upper limit on the diffuse neutrino sources. Determine the spectrum directly from data at each energy.

Figure from I. F. M. Albuquerque et. al., arXiv:0803.3479v1 [hep-ph]:

The WB limit ranges from the limit with no cosmological evolution (upper edge) and with cosmological evolution (lower edge). The MPR limit is shown for optically thin sources (red dotted line) and optically thick sources (red dot-dashed line).



## Energy distribution



Energy distribution of  $\tilde{l}_R$  pair events per  $\text{km}^2$ , per year, at the detector. Curves that do not reach y axis; from top to bottom:  $m_{\tilde{q}} = 300, 600$  and  $900$  GeV. Here,  $m_{\tilde{l}_R} = 150$  GeV and  $m_{\tilde{w}} = 250$  GeV. Also shown are the neutrino flux at earth and the  $\mu$  and the di-muon flux through the detector (curves that reach y axis; from top to bottom respectively). In all cases we make use of the WB limit for the neutrino flux.

## Number of events

Number of events per  $\text{km}^2$  per year for different neutrino fluxes at the Earth. The  $\tilde{\ell}_R$  mass is 150 GeV and squark masses are 300, 600 and 900 GeV respectively. The signal events are integrated from threshold ( $E_\nu > 1.6 \times 10^5$  GeV), whereas the number of di-muon events are given for neutrino energies above  $10^3$  GeV. The column  $\mu^+\mu^-$  corresponds to the di-muon background before track separation cuts are applied.

	$\mu^+\mu^-$	(300)	$\tilde{\ell}_R\tilde{\ell}_R$ (600)	(900)
WB	30	6	1	0.3
MPR	1412	21	3	1

The di-muon background results in a number of events larger than the signal, even for the case of a 300 GeV squark mass.

## Track separation

- The NLSPs are produced in pairs very far from the detector and with a very large boost.
- The angle between the two NLSP tracks is small but the large range guarantees a significant separation between the tracks.
- The angular separation in the signal is always well below a degree (the typical angular resolution of neutrino telescopes)  
⇒ the tracks will appear parallel to each other.

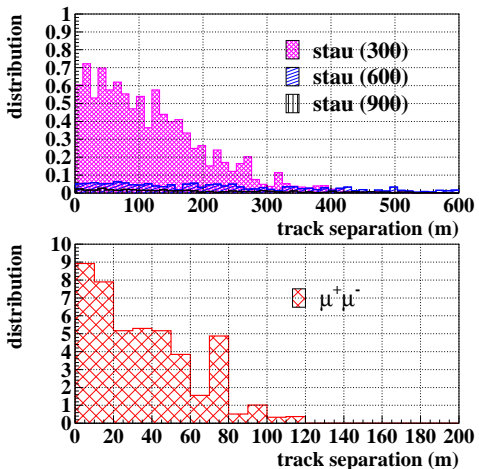
## Backgrounds

- Muons produced by upgoing neutrinos  $\rightarrow$  eliminated by asking for two tracks in the events.
- Two coincident muons tracks  $\rightarrow$  becomes negligible by requiring that the tracks be almost parallel.
- Direct di-muon production  $\rightarrow$  main source: we consider the process:

$$\nu N \rightarrow \mu^- H_c \rightarrow \mu^- \mu^+ H_x \nu$$

where the charm hadron  $H_c$  decays according to  $H_c \rightarrow H_x \mu^+ \nu$ , and  $H_x$  can be a strange or non-strange hadron.

For track separations above 100 m there should not be any significant contribution from the di-muon background.

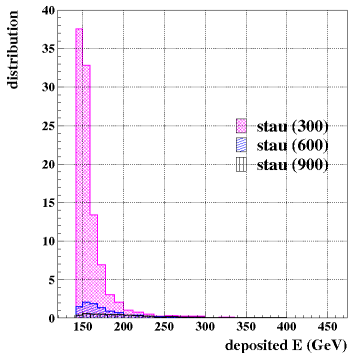
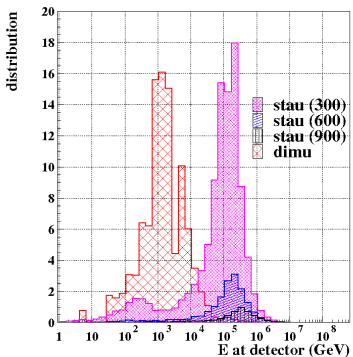


The relative normalization corresponds to the relative number of events for signal and background. Note the different horizontal scales, as well as different binning between the two figures.

## Di-muon background reduction:

- Angular separation between di-muon tracks is also very small  
⇒ tracks will also appear to be parallel.
- However, muons need to be much closer to the detector to range into it  
⇒ di-muon events have a smaller separation between the two tracks.
- Statistical significance:  $S/\sqrt{B}$ , with  $S$  and  $B$  the number of signal and background events, respectively.
- Cutting events with less than 106 m separation results in 3 detectable NLSPs and 0.25 di-muons, yielding a  $5\sigma$  significance.

## Arrival energy at detector and its loss



Left – arrival energy distribution of the  $\tilde{\tau}_R$  at the detector for  $m_{\tilde{q}} = 300, 600$  and  $900$  GeV. Here,  $m_{\tilde{\tau}_R} = 150$  GeV and  $m_{\tilde{W}} = 250$  GeV. Also shown is the arrival distribution for the di-muon background. Right – energy deposited in the detector by a  $\tilde{\tau}_R$  traveling the average track length of 800 m.

Additional reduction of the di-muon background by making use of the energy deposition of the events

Example: a muon with an arrival energy of  $3 \times 10^3$  GeV, transversing 800 m of ice (the average through-detector length) will deposit  $\sim 450$  GeV in its path.

Thus, excluding events with deposited energies above a few hundred GeV, we can eliminate the high energy tail of the di-muon background.

## Conclusions

- Neutrinos telescopes are potentially sensitive to relatively long-lived charged NLSPs;
- Our goal is extend these results to ultrahigh energy cosmic rays;
- However, we are still facing the problem :-)

## References

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- [2] Ivone F. M. Albuquerque, Gustavo Burdman and Z. Chacko, *Physical Review D* **75**, 035006 (2007);
- [3] S. Martin, arXiv:9709356 [hep-ph];
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- [6] K. Mannheim, R.J.Protheroe and J. P. Rachen, *Physical Review D* **63**, 023003 (2001);
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Thank you!

## Cosmic rays difficulties:

- proton primary: squark pair production should be larger than the slepton production via neutrino interactions, because it goes through a larger coupling.
- However, this cannot compete with the soft, forward cross section of cosmic rays with air, which is large enough to stop primaries in the atmosphere.
- cross sections for cosmic ray primaries in the earth's atmosphere are around 10 – 100 mb. But, supersymmetric production cross sections at the energies of interest are in the order of 10 – 100 pb, or  $10^{-9}$  times smaller.
- Thus, the probability of producing supersymmetric events with proton or other cosmic ray primaries is very small. Neutrinos, on the other hand, will always go through the atmosphere.
- Since the neutrino flux is not expected to be that much smaller than the cosmic ray flux, using neutrinos is advantageous.

Additional potential source of di-muons:

- source of di-muons from  $\nu\gamma \rightarrow W^\pm\mu$  scattering  
→  $\gamma$  is emitted off the parton in the nucleon and  $W^\pm$  decays to  $\mu\nu_\mu$ .
- Is a smaller source of di-muons and its track separation is very similar to the di-muons' coming from charm production. Is equally eliminated by the same cut in track separation.