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# Upper limit on the diffuse flux of UHE tau neutrinos from the Pierre Auger Observatory

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## The Pierre Auger Collaboration

J. Abraham<sup>14</sup>, P. Abreu<sup>69</sup>, M. Aglietta<sup>55</sup>, C. Aguirre<sup>17</sup>, D. Allard<sup>33</sup>, I. Allekotte<sup>7</sup>,  
 J. Allen<sup>89</sup>, P. Allison<sup>91</sup>, J. Alvarez-Muñiz<sup>76</sup>, M. Ambrosio<sup>58</sup>, L. Anchordoqui<sup>103, 90</sup>,  
 S. Andringa<sup>69</sup>, A. Anzalone<sup>54</sup>, C. Aramo<sup>58</sup>, S. Argirò<sup>52</sup>, K. Arisaka<sup>94</sup>, E. Armengaud<sup>33</sup>,  
 F. Arneodo<sup>56</sup>, F. Arqueros<sup>73</sup>, T. Asch<sup>39</sup>, H. Asorey<sup>5</sup>, P. Assis<sup>69</sup>, B.S. Atulugama<sup>92</sup>,  
 J. Aublin<sup>35</sup>, M. Ave<sup>95</sup>, G. Avila<sup>13</sup>, T. Bäcker<sup>43</sup>, D. Badagnani<sup>10</sup>, A.F. Barbosa<sup>19</sup>,  
 D. Barnhill<sup>94</sup>, S.L.C. Barroso<sup>25</sup>, P. Bauleo<sup>83</sup>, J.J. Beatty<sup>91</sup>, T. Beau<sup>33</sup>, B.R. Becker<sup>100</sup>,  
 K.H. Becker<sup>37</sup>, J.A. Bellido<sup>92</sup>, S. BenZvi<sup>102</sup>, C. Berat<sup>36</sup>, T. Bergmann<sup>42</sup>, P. Bernardini<sup>48</sup>,  
 X. Bertou<sup>5</sup>, P.L. Biermann<sup>40</sup>, P. Billoir<sup>35</sup>, O. Blanch-Bigas<sup>35</sup>, F. Blanco<sup>73</sup>, P. Blasi<sup>86, 46, 57</sup>,  
 C. Bleve<sup>79</sup>, H. Blümer<sup>42, 38</sup>, M. Boháčová<sup>31</sup>, C. Bonifazi<sup>35, 19</sup>, R. Bonino<sup>55</sup>, M. Boratav<sup>35</sup>,  
 J. Brack<sup>83, 96</sup>, P. Brogueira<sup>69</sup>, W.C. Brown<sup>84</sup>, P. Buchholz<sup>43</sup>, A. Bueno<sup>75</sup>, R.E. Burton<sup>81</sup>,  
 N.G. Busca<sup>33</sup>, K.S. Caballero-Mora<sup>42</sup>, B. Cai<sup>98</sup>, D.V. Camin<sup>47</sup>, L. Caramete<sup>40</sup>, R. Caruso<sup>51</sup>,  
 W. Carvalho<sup>21</sup>, A. Castellina<sup>55</sup>, O. Catalano<sup>54</sup>, G. Cataldi<sup>48</sup>, L. Cazon<sup>95</sup>, R. Cester<sup>52</sup>,  
 J. Chauvin<sup>36</sup>, A. Chiavassa<sup>55</sup>, J.A. Chinellato<sup>23</sup>, A. Chou<sup>89, 86</sup>, J. Chye<sup>88</sup>, P.D.J. Clark<sup>78</sup>,  
 R.W. Clay<sup>16</sup>, E. Colombo<sup>2</sup>, R. Conceição<sup>69</sup>, B. Connolly<sup>100</sup>, F. Contreras<sup>12</sup>, J. Coppens<sup>63, 65</sup>,  
 A. Cordier<sup>34</sup>, U. Cotti<sup>61</sup>, S. Coutu<sup>92</sup>, C.E. Covault<sup>81</sup>, A. Creusot<sup>71</sup>, A. Criss<sup>92</sup>, J. Cronin<sup>95</sup>,  
 A. Curutiu<sup>40</sup>, S. Dagoret-Campagne<sup>34</sup>, K. Daumiller<sup>38</sup>, B.R. Dawson<sup>16</sup>, R.M. de Almeida<sup>23</sup>,  
 C. De Donato<sup>47</sup>, S.J. de Jong<sup>63</sup>, G. De La Vega<sup>15</sup>, W.J.M. de Mello Junior<sup>23</sup>, J.R.T. de  
 Mello Neto<sup>95, 28</sup>, I. De Mitri<sup>48</sup>, V. de Souza<sup>42</sup>, L. del Peral<sup>74</sup>, O. Deligny<sup>32</sup>, A. Della  
 Selva<sup>49</sup>, C. Delle Fratte<sup>50</sup>, H. Dembinski<sup>41</sup>, C. Di Giulio<sup>50</sup>, J.C. Diaz<sup>88</sup>, C. Dobrigkeit<sup>23</sup>,  
 J.C. D'Olivo<sup>62</sup>, D. Dornic<sup>32</sup>, A. Dorofeev<sup>87</sup>, J.C. dos Anjos<sup>19</sup>, M.T. Dova<sup>10</sup>, D. D'Urso<sup>49</sup>,  
 I. Dutan<sup>40</sup>, M.A. DuVernois<sup>97, 98</sup>, R. Engel<sup>38</sup>, L. Epele<sup>10</sup>, M. Erdmann<sup>41</sup>, C.O. Escobar<sup>23</sup>,  
 A. Etchegoyen<sup>3</sup>, P. Facal San Luis<sup>76</sup>, H. Falcke<sup>63, 66</sup>, G. Farrar<sup>89</sup>, A.C. Fauth<sup>23</sup>, N. Fazzini<sup>86</sup>,  
 F. Ferrer<sup>81</sup>, S. Ferry<sup>71</sup>, B. Fick<sup>88</sup>, A. Filevich<sup>2</sup>, A. Filipčič<sup>70</sup>, I. Fleck<sup>43</sup>, R. Fonte<sup>51</sup>,  
 C.E. Fracchiolla<sup>20</sup>, W. Fulgione<sup>55</sup>, B. García<sup>14</sup>, D. García Gámez<sup>75</sup>, D. Garcia-Pinto<sup>73</sup>,  
 X. Garrido<sup>34</sup>, H. Geenen<sup>37</sup>, G. Gelmini<sup>94</sup>, H. Gemmeke<sup>39</sup>, P.L. Ghia<sup>32, 55</sup>, M. Giller<sup>68</sup>,  
 H. Glass<sup>86</sup>, M.S. Gold<sup>100</sup>, G. Golup<sup>6</sup>, F. Gomez Albarracin<sup>10</sup>, M. Gómez Berisso<sup>6</sup>,  
 R. Gómez Herrero<sup>74</sup>, P. Gonçalves<sup>69</sup>, M. Gonçalves do Amaral<sup>29</sup>, D. Gonzalez<sup>42</sup>,  
 J.G. Gonzalez<sup>87</sup>, M. González<sup>60</sup>, D. Góra<sup>42, 67</sup>, A. Gorgi<sup>55</sup>, P. Gouffon<sup>21</sup>, V. Grassi<sup>47</sup>,  
 A.F. Grillo<sup>56</sup>, C. Grunfeld<sup>10</sup>, Y. Guardincerri<sup>8</sup>, F. Guarino<sup>49</sup>, G.P. Guedes<sup>24</sup>, J. Gutiérrez<sup>74</sup>,  
 J.D. Hague<sup>100</sup>, J.C. Hamilton<sup>33</sup>, P. Hansen<sup>76</sup>, D. Harari<sup>6</sup>, S. Harmsma<sup>64</sup>, J.L. Harton<sup>32, 83</sup>,

A. Haungs<sup>38</sup>, T. Hauschildt<sup>55</sup>, M.D. Healy<sup>94</sup>, T. Hebbeker<sup>41</sup>, G. Hebrero<sup>74</sup>, D. Heck<sup>38</sup>,  
 C. Hojvat<sup>86</sup>, V.C. Holmes<sup>16</sup>, P. Homola<sup>67</sup>, J. Hörandel<sup>63</sup>, A. Horneffer<sup>63</sup>, M. Horvat<sup>71</sup>,  
 M. Hrabovský<sup>31</sup>, T. Huege<sup>38</sup>, M. Hussain<sup>71</sup>, M. Iarlori<sup>46</sup>, A. Insolia<sup>51</sup>, F. Ionita<sup>95</sup>,  
 A. Italiano<sup>51</sup>, M. Kaducak<sup>86</sup>, K.H. Kampert<sup>37</sup>, T. Karova<sup>31</sup>, B. Kégl<sup>34</sup>, B. Keilhauer<sup>42</sup>,  
 E. Kemp<sup>23</sup>, R.M. Kieckhafer<sup>88</sup>, H.O. Klages<sup>38</sup>, M. Kleifges<sup>39</sup>, J. Kleinfeller<sup>38</sup>, R. Knapik<sup>83</sup>,  
 J. Knapp<sup>79</sup>, D.-H. Koang<sup>36</sup>, A. Krieger<sup>2</sup>, O. Krömer<sup>39</sup>, D. Kuempel<sup>37</sup>, N. Kunka<sup>39</sup>,  
 A. Kusenko<sup>94</sup>, G. La Rosa<sup>54</sup>, C. Lachaud<sup>33</sup>, B.L. Lago<sup>28</sup>, D. Lebrun<sup>36</sup>, P. LeBrun<sup>86</sup>,  
 J. Lee<sup>94</sup>, M.A. Leigui de Oliveira<sup>27</sup>, A. Letessier-Selvon<sup>35</sup>, M. Leuthold<sup>41</sup>, I. Lhenry-  
 Yvon<sup>32</sup>, R. López<sup>59</sup>, A. Lopez Agüera<sup>76</sup>, J. Lozano Bahilo<sup>75</sup>, R. Luna García<sup>60</sup>, M.C. Maccarone<sup>54</sup>,  
 C. Macolino<sup>46</sup>, S. Maldera<sup>55</sup>, G. Mancarella<sup>48</sup>, M.E. Manceñido<sup>10</sup>, D. Mandat<sup>31</sup>,  
 P. Mantsch<sup>86</sup>, A.G. Mariuzzi<sup>10</sup>, I.C. Maris<sup>42</sup>, H.R. Marquez Falcon<sup>61</sup>, D. Martello<sup>48</sup>,  
 J. Martínez<sup>60</sup>, O. Martínez Bravo<sup>59</sup>, H.J. Mathes<sup>38</sup>, J. Matthews<sup>87, 93</sup>, J.A.J. Matthews<sup>100</sup>,  
 G. Matthiae<sup>50</sup>, D. Maurizio<sup>52</sup>, P.O. Mazur<sup>86</sup>, T. McCauley<sup>90</sup>, M. McEwen<sup>74, 87</sup>, R.R. McNeil<sup>87</sup>,  
 M.C. Medina<sup>3</sup>, G. Medina-Tanco<sup>62</sup>, A. Meli<sup>40</sup>, D. Melo<sup>2</sup>, E. Menichetti<sup>52</sup>, A. Menschikov<sup>39</sup>,  
 Chr. Meurer<sup>38</sup>, R. Meyhandan<sup>64</sup>, M.I. Micheletti<sup>3</sup>, G. Miele<sup>49</sup>, W. Miller<sup>100</sup>, S. Mollerach<sup>6</sup>,  
 M. Monasar<sup>73, 74</sup>, D. Monnier Ragaigine<sup>34</sup>, F. Montanet<sup>36</sup>, B. Morales<sup>62</sup>, C. Morello<sup>55</sup>,  
 J.C. Moreno<sup>10</sup>, C. Morris<sup>91</sup>, M. Mostafá<sup>101</sup>, M.A. Muller<sup>23</sup>, R. Mussa<sup>52</sup>, G. Navarra<sup>55</sup>,  
 J.L. Navarro<sup>75</sup>, S. Navas<sup>75</sup>, P. Necesar<sup>31</sup>, L. Nellen<sup>62</sup>, C. Newman-Holmes<sup>86</sup>, D. Newton<sup>79, 76</sup>,  
 T. Nguyen Thi<sup>104</sup>, N. Nierstenhoefer<sup>37</sup>, D. Nitz<sup>88</sup>, D. Nosek<sup>30</sup>, L. Nožka<sup>31</sup>, J. Oehlschläger<sup>38</sup>,  
 T. Ohnuki<sup>94</sup>, A. Olinto<sup>33, 95</sup>, V.M. Olmos-Gilbaja<sup>76</sup>, M. Ortiz<sup>73</sup>, F. Ortolani<sup>50</sup>, S. Ostapchenko<sup>42</sup>,  
 L. Otero<sup>14</sup>, N. Pacheco<sup>74</sup>, D. Pakk Selmi-Dei<sup>23</sup>, M. Palatka<sup>31</sup>, J. Pallotta<sup>1</sup>, G. Parente<sup>76</sup>,  
 E. Parizot<sup>33</sup>, S. Parlati<sup>56</sup>, S. Pastor<sup>72</sup>, M. Patel<sup>79</sup>, T. Paul<sup>90</sup>, V. Pavlidou<sup>95</sup>, K. Payet<sup>36</sup>,  
 M. Pech<sup>31</sup>, J. Pękala<sup>67</sup>, R. Pelayo<sup>60</sup>, I.M. Pepe<sup>26</sup>, L. Perrone<sup>53</sup>, S. Petrerá<sup>46</sup>, P. Petrinca<sup>50</sup>,  
 Y. Petrov<sup>83</sup>, Diep Pham Ngoc<sup>104</sup>, Dong Pham Ngoc<sup>104</sup>, T.N. Pham Thi<sup>104</sup>, A. Pichel<sup>11</sup>,  
 R. Piegaia<sup>8</sup>, T. Pierog<sup>38</sup>, M. Pimenta<sup>69</sup>, T. Pinto<sup>72</sup>, V. Pirronello<sup>51</sup>, O. Pisanti<sup>49</sup>, M. Platino<sup>2</sup>,  
 J. Pochon<sup>5</sup>, P. Privitera<sup>50</sup>, M. Prouza<sup>31</sup>, E.J. Quel<sup>1</sup>, J. Rautenberg<sup>37</sup>, A. Redondo<sup>74</sup>,  
 S. Reucroft<sup>90</sup>, B. Revenu<sup>33</sup>, F.A.S. Rezende<sup>19</sup>, J. Ridky<sup>31</sup>, S. Riggi<sup>51</sup>, M. Risse<sup>37</sup>,  
 C. Rivière<sup>36</sup>, V. Rizi<sup>46</sup>, M. Roberts<sup>92</sup>, C. Robledo<sup>59</sup>, G. Rodriguez<sup>76</sup>, D. Rodríguez  
 Frias<sup>74</sup>, J. Rodríguez Martino<sup>51</sup>, J. Rodríguez Rojo<sup>12</sup>, I. Rodríguez-Cabo<sup>76</sup>, G. Ros<sup>73, 74</sup>,  
 J. Rosado<sup>73</sup>, M. Roth<sup>38</sup>, B. Rouillé-d'Orfeuill<sup>33</sup>, E. Roulet<sup>6</sup>, A.C. Rovero<sup>11</sup>, F. Salamida<sup>46</sup>,  
 H. Salazar<sup>59</sup>, G. Salina<sup>50</sup>, F. Sánchez<sup>62</sup>, M. Santander<sup>12</sup>, C.E. Santo<sup>69</sup>, E.M. Santos<sup>35, 19</sup>,  
 F. Sarazin<sup>82</sup>, S. Sarkar<sup>77</sup>, R. Sato<sup>12</sup>, V. Scherini<sup>37</sup>, H. Schieler<sup>38</sup>, A. Schmidt<sup>39</sup>, F. Schmidt<sup>95</sup>,  
 T. Schmidt<sup>42</sup>, O. Scholten<sup>64</sup>, P. Schovánek<sup>31</sup>, F. Schüssler<sup>38</sup>, S.J. Sciutto<sup>10</sup>, M. Scuderi<sup>51</sup>,  
 A. Segreto<sup>54</sup>, D. Semikoz<sup>33</sup>, M. Settimo<sup>48</sup>, R.C. Shellard<sup>19, 20</sup>, I. Sidelnik<sup>3</sup>, B.B. Siffert<sup>28</sup>,  
 G. Sigl<sup>33</sup>, N. Smetniansky De Grande<sup>2</sup>, A. Smialkowski<sup>68</sup>, R. Šmída<sup>31</sup>, A.G.K. Smith<sup>16</sup>,  
 B.E. Smith<sup>79</sup>, G.R. Snow<sup>99</sup>, P. Sokolsky<sup>101</sup>, P. Sommers<sup>92</sup>, J. Sorokin<sup>16</sup>, H. Spinka<sup>80, 86</sup>,  
 R. Squartini<sup>12</sup>, E. Strazzeri<sup>50</sup>, A. Stutz<sup>36</sup>, F. Suarez<sup>55</sup>, T. Suomijärvi<sup>32</sup>, A.D. Supanitsky<sup>62</sup>,  
 M.S. Sutherland<sup>91</sup>, J. Swain<sup>90</sup>, Z. Szadkowski<sup>68</sup>, J. Takahashi<sup>23</sup>, A. Tamashiro<sup>11</sup>,  
 A. Tamburro<sup>42</sup>, O. Taşcau<sup>37</sup>, R. Tcaciuc<sup>43</sup>, D. Thomas<sup>101</sup>, R. Ticona<sup>18</sup>, J. Tiffenberg<sup>8</sup>,  
 C. Timmermans<sup>65, 63</sup>, W. Tkaczyk<sup>68</sup>, C.J. Todero Peixoto<sup>23</sup>, B. Tomé<sup>69</sup>, A. Tonachini<sup>52</sup>,  
 I. Torres<sup>59</sup>, D. Torresi<sup>54</sup>, P. Travnicek<sup>31</sup>, A. Tripathi<sup>94</sup>, G. Tristram<sup>33</sup>, D. Tscherniakhovski<sup>39</sup>,  
 M. Tueros<sup>9</sup>, V. Tunnicliffe<sup>78</sup>, R. Ulrich<sup>38</sup>, M. Unger<sup>38</sup>, M. Urban<sup>34</sup>, J.F. Valdés Galicia<sup>62</sup>,  
 I. Valiño<sup>76</sup>, L. Valore<sup>49</sup>, A.M. van den Berg<sup>64</sup>, V. van Elewyck<sup>32</sup>, R.A. Vázquez<sup>76</sup>,  
 D. Veberić<sup>71</sup>, A. Veiga<sup>10</sup>, A. Velarde<sup>18</sup>, T. Venters<sup>95, 33</sup>, V. Verzi<sup>50</sup>, M. Videla<sup>15</sup>,  
 L. Villaseñor<sup>61</sup>, S. Vorobiov<sup>71</sup>, L. Voyvodic<sup>86</sup>, H. Wahlberg<sup>10</sup>, O. Wainberg<sup>4</sup>, P. Walker<sup>78</sup>,  
 D. Warner<sup>83</sup>, A.A. Watson<sup>79</sup>, S. Westerhoff<sup>102</sup>, G. Wieczorek<sup>68</sup>, L. Wiencke<sup>82</sup>, B. Wilczyńska<sup>67</sup>,

H. Wilczyński<sup>67</sup>, C. Wileman<sup>79</sup>, M.G. Winnick<sup>16</sup>, H. Wu<sup>34</sup>, B. Wundheiler<sup>2</sup>, T. Yamamoto<sup>95</sup>,  
P. Younk<sup>101</sup>, E. Zas<sup>76</sup>, D. Zavrtnik<sup>71</sup>, M. Zavrtnik<sup>70</sup>, A. Zech<sup>35</sup>, A. Zepeda<sup>60</sup>, M. Ziolkowski<sup>43</sup>

<sup>1</sup> Centro de Investigaciones en Láseres y Aplicaciones, CITEFA and CONICET, Argentina

<sup>2</sup> Centro Atómico Constituyentes, CNEA, Buenos Aires, Argentina

<sup>3</sup> Centro Atómico Constituyentes, Comisión Nacional de Energía Atómica and CONICET, Argentina

<sup>4</sup> Centro Atómico Constituyentes, Comisión Nacional de Energía Atómica and UTN-FRBA, Argentina

<sup>5</sup> Centro Atómico Bariloche, Comisión Nacional de Energía Atómica, San Carlos de Bariloche, Argentina

<sup>6</sup> Departamento de Física, Centro Atómico Bariloche, Comisión Nacional de Energía Atómica and CONICET, Argentina

<sup>7</sup> Centro Atómico Bariloche, Comisión Nacional de Energía Atómica and Instituto Balseiro (CNEA-UNC), San Carlos de Bariloche, Argentina

<sup>8</sup> Departamento de Física, FCEyN, Universidad de Buenos Aires y CONICET, Argentina

<sup>9</sup> Departamento de Física, Universidad Nacional de La Plata and Fundación Universidad Tecnológica Nacional, Argentina

<sup>10</sup> IFLP, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

<sup>11</sup> Instituto de Astronomía y Física del Espacio (CONICET), Buenos Aires, Argentina

<sup>12</sup> Pierre Auger Southern Observatory, Malargüe, Argentina

<sup>13</sup> Pierre Auger Southern Observatory and Comisión Nacional de Energía Atómica, Malargüe, Argentina

<sup>14</sup> Universidad Tecnológica Nacional, FR-Mendoza, Argentina

<sup>15</sup> Universidad Tecnológica Nacional, FR-Mendoza and Fundación Universidad Tecnológica Nacional, Argentina

<sup>16</sup> University of Adelaide, Adelaide, S.A., Australia

<sup>17</sup> Universidad Católica de Bolivia, La Paz, Bolivia

<sup>18</sup> Universidad Mayor de San Andrés, Bolivia

<sup>19</sup> Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, RJ, Brazil

<sup>20</sup> Pontificia Universidade Católica, Rio de Janeiro, RJ, Brazil

<sup>21</sup> Universidade de Sao Paulo, Inst. de Física, Sao Paulo, SP, Brazil

<sup>22</sup> Universidade Estadual de Campinas, IFGW, Campinas, SP, Brazil

<sup>23</sup> Univ. Estadual de Feira de Santana, Brazil

<sup>24</sup> Universidade Estadual do Sudoeste da Bahia, Vitoria da Conquista, BA, Brazil

<sup>25</sup> Universidade Federal da Bahia, Salvador, BA, Brazil

<sup>26</sup> Universidade Federal do ABC, Santo André, SP, Brazil

<sup>27</sup> Univ. Federal do Rio de Janeiro, Instituto de Física, Rio de Janeiro, RJ, Brazil

<sup>28</sup> Univ. Federal Fluminense, Inst. de Física, Niterói, RJ, Brazil

<sup>29</sup> Charles University, Institute of Particle & Nuclear Physics, Prague, Czech Republic

<sup>30</sup> Institute of Physics of the Academy of Sciences of the Czech Republic, Prague, Czech Republic

<sup>31</sup> Institut de Physique Nucléaire, Université Paris-Sud, IN2P3/CNRS, Orsay, France

- <sup>33</sup> Laboratoire AstroParticule et Cosmologie, Université Paris 7, IN2P3/CNRS, Paris, France
- <sup>34</sup> Laboratoire de l'Accélérateur Linéaire, Université Paris-Sud, IN2P3/CNRS, Orsay, France
- <sup>35</sup> Laboratoire de Physique Nucléaire et de Hautes Energies, Universités Paris 6 & 7, IN2P3/CNRS, Paris Cedex 05, France
- <sup>36</sup> Laboratoire de Physique Subatomique et de Cosmologie, IN2P3/CNRS, Université Grenoble 1 et INPG, Grenoble, France
- <sup>37</sup> Bergische Universität Wuppertal, Wuppertal, Germany
- <sup>38</sup> Forschungszentrum Karlsruhe, Institut für Kernphysik, Karlsruhe, Germany
- <sup>39</sup> Forschungszentrum Karlsruhe, Institut für Prozessdatenverarbeitung und Elektronik, Germany
- <sup>40</sup> Max-Planck-Institut für Radioastronomie, Bonn, Germany
- <sup>41</sup> RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
- <sup>42</sup> Universität Karlsruhe (TH), Institut für Experimentelle Kernphysik (IEKP), Karlsruhe, Germany
- <sup>43</sup> Universität Siegen, Siegen, Germany
- <sup>46</sup> Università de l'Aquila and Sezione INFN, Aquila, Italy
- <sup>47</sup> Università di Milano and Sezione INFN, Milan, Italy
- <sup>48</sup> Università del Salento and Sezione INFN, Lecce, Italy
- <sup>49</sup> Università di Napoli "Federico II" and Sezione INFN, Napoli, Italy
- <sup>50</sup> Università di Roma II "Tor Vergata" and Sezione INFN, Roma, Italy
- <sup>51</sup> Università di Catania and Sezione INFN, Catania, Italy
- <sup>52</sup> Università di Torino and Sezione INFN, Torino, Italy
- <sup>53</sup> Università del Salento and Sezione INFN, Lecce, Italy
- <sup>54</sup> Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo (INAF), Palermo, Italy
- <sup>55</sup> Istituto di Fisica dello Spazio Interplanetario (INAF), Università di Torino and Sezione INFN, Torino, Italy
- <sup>56</sup> INFN, Laboratori Nazionali del Gran Sasso, Assergi (L'Aquila), Italy
- <sup>57</sup> Osservatorio Astrofisico di Arcetri, Florence, Italy
- <sup>58</sup> Sezione INFN di Napoli, Napoli, Italy
- <sup>59</sup> Benemérita Universidad Autónoma de Puebla, Puebla, Mexico
- <sup>60</sup> Centro de Investigación y de Estudios Avanzados del IPN (CINVESTAV), México, D.F., Mexico
- <sup>61</sup> Universidad Michoacana de San Nicolas de Hidalgo, Morelia, Michoacan, Mexico
- <sup>62</sup> Universidad Nacional Autónoma de Mexico, Mexico, D.F., Mexico
- <sup>63</sup> IMAPP, Radboud University, Nijmegen, Netherlands
- <sup>64</sup> Kernfysisch Versneller Instituut, University of Groningen, Groningen, Netherlands
- <sup>65</sup> NIKHEF, Amsterdam, Netherlands
- <sup>66</sup> ASTRON, Dwingeloo, Netherlands
- <sup>67</sup> Institute of Nuclear Physics PAN, Krakow, Poland
- <sup>68</sup> University of Łódź, Łódź, Poland
- <sup>69</sup> LIP and Instituto Superior Técnico, Lisboa, Portugal
- <sup>70</sup> J. Stefan Institute, Ljubljana, Slovenia
- <sup>71</sup> Laboratory for Astroparticle Physics, University of Nova Gorica, Slovenia
- <sup>72</sup> Instituto de Física Corpuscular, CSIC-Universitat de València, Valencia, Spain

- <sup>73</sup> Universidad Complutense de Madrid, Madrid, Spain
- <sup>74</sup> Universidad de Alcalá, Alcalá de Henares (Madrid), Spain
- <sup>75</sup> Universidad de Granada & C.A.F.P.E., Granada, Spain
- <sup>76</sup> Universidad de Santiago de Compostela, Spain
- <sup>77</sup> Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford, United Kingdom
- <sup>78</sup> Institute of Integrated Information Systems, University of Leeds, United Kingdom
- <sup>79</sup> School of Physics and Astronomy, University of Leeds, United Kingdom
- <sup>80</sup> Argonne National Laboratory, Argonne, IL, USA
- <sup>81</sup> Case Western Reserve University, Cleveland, OH, USA
- <sup>82</sup> Colorado School of Mines, Golden, CO, USA
- <sup>83</sup> Colorado State University, Fort Collins, CO, USA
- <sup>84</sup> Colorado State University, Pueblo, CO, USA
- <sup>86</sup> Fermilab, Batavia, IL, USA
- <sup>87</sup> Louisiana State University, Baton Rouge, LA, USA
- <sup>88</sup> Michigan Technological University, Houghton, MI, USA
- <sup>89</sup> New York University, New York, NY, USA
- <sup>90</sup> Northeastern University, Boston, MA, USA
- <sup>91</sup> Ohio State University, Columbus, OH, USA
- <sup>92</sup> Pennsylvania State University, University Park, PA, USA
- <sup>93</sup> Southern University, Baton Rouge, LA, USA
- <sup>94</sup> University of California, Los Angeles, CA, USA
- <sup>95</sup> University of Chicago, Enrico Fermi Institute, Chicago, IL, USA
- <sup>96</sup> University of Colorado, Boulder, CO, USA
- <sup>97</sup> University of Hawaii, Honolulu, HI, USA
- <sup>98</sup> University of Minnesota, Minneapolis, MN, USA
- <sup>99</sup> University of Nebraska, Lincoln, NE, USA
- <sup>100</sup> University of New Mexico, Albuquerque, NM, USA
- <sup>100</sup> University of Pennsylvania, Philadelphia, PA, USA
- <sup>101</sup> University of Utah, Salt Lake City, UT, USA
- <sup>102</sup> University of Wisconsin, Madison, WI, USA
- <sup>103</sup> University of Wisconsin, Milwaukee, WI, USA
- <sup>104</sup> Institute for Nuclear Science and Technology, Hanoi, Vietnam

### Abstract

The surface detector array of the Pierre Auger Observatory is sensitive to Earth-skimming tau-neutrinos  $\nu_\tau$  that interact in the Earth's crust. Tau leptons from  $\nu_\tau$  charged-current interactions can emerge and decay in the atmosphere to produce a nearly horizontal shower with a significant electromagnetic component. The data collected between 1 January 2004 and 31 August 2007 are used to place an upper limit on the diffuse flux of  $\nu_\tau$  at EeV energies. Assuming an  $E_\nu^{-2}$  differential energy spectrum the limit set at 90 % C.L. is  $E_\nu^2 dN_{\nu_\tau}/dE_\nu < 1.3 \times 10^{-7}$  GeV  $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$  in the energy range  $2 \times 10^{17} \text{ eV} < E_\nu < 2 \times 10^{19} \text{ eV}$ .

The detection of Ultra High Energy (UHE) cosmic neutrinos at EeV (1 EeV  $\equiv 10^{18}$  eV) energies and above is a long standing experimental challenge. Many experiments are searching for such neutrinos, and there are several ongoing efforts to construct dedicated experiments to detect them [Halzen et al.(2002), Halzen(2007), Falcke et al.(2004)]. Their discovery would open a new window to the universe [Becker(2007)], and provide an unique opportunity to test fundamental particle physics at energies well beyond current or planned accelerators. The observation of UHE Cosmic Rays (UHECRs) requires that there exist UHE cosmic neutrinos, even though the nature of the UHECR particles and their production mechanisms are still uncertain. All models of UHECR origin predict neutrino fluxes from the decay of charged pions which are produced either in interactions of the cosmic rays in their sources, or in their subsequent interactions with background radiation fields. For example, UHECR protons interacting with the Cosmic Microwave Background (CMB) give rise to the so-called 'cosmogenic' or GZK neutrinos [Berezinsky et al.(1969)]. The recently reported suppression of the cosmic ray flux above  $\sim 4 \times 10^{19}$  eV [Abbasi et al.(2007), Yamamoto(2007), Pierre Auger Collaboration(2007a)] as well as the observed correlation of the highest energy cosmic rays with relatively nearby extragalactic objects [Pierre Auger Collaboration(2007b)] both point to UHECR interactions on the infrared or microwave backgrounds during extragalactic propagation. These interactions must result in UHE neutrinos although their flux is somewhat uncertain since this depends on the primary UHECR composition and on the nature and cosmological evolution of the sources as well as on their spatial distribution [Engel et al.(2001), Allard et al.(2006)].

Tau neutrinos are suppressed in such production processes relative to  $\nu_e$  or  $\nu_\mu$ , because they are not an end product of the charged pion decay chain and far fewer are made through the production and decay of heavy flavours such as charm. Nevertheless, because of neutrino flavour mixing, the usual 1:2 ratio of  $\nu_e$  to  $\nu_\mu$  at production is altered to approximately equal fluxes for all flavours after travelling cosmological distances [Learned et al.(1995)]. Soon after the discovery of neutrino oscillations [Fukuda et al.(1998)] it was shown that  $\nu_\tau$  entering the Earth just below the horizon (Earth-skimming) [Fargion(2002), Letessier-Selvon(2001), Feng et al.(2002)] can undergo charged-current interactions and produce  $\tau$  leptons. Since a  $\tau$  lepton can travel tens of kilometers in the Earth at EeV energies, it can emerge into the atmosphere and decay in flight producing a nearly horizontal extensive air shower (EAS) above the detector. In this way the effective target volume for neutrinos can be rather large.

The Pierre Auger Observatory [Abraham et al.(2004)] has been designed to measure UHECRs with unprecedented precision. Detection of UHECRs is being achieved

exploiting the two available techniques to detect EAS, namely, arrays of surface particle detectors and telescopes that detect fluorescence radiation. UHE particles such as protons or heavier nuclei interact high in the atmosphere, producing showers that contain muons and an electromagnetic component of electrons, positrons and photons. This latter component reaches a maximum at an atmospheric depth of order  $800 \text{ g cm}^{-2}$ , after which it is gradually attenuated. Inclined showers that reach the ground after travelling through  $2000 \text{ g cm}^{-2}$  or more of the atmosphere are dominated by muons arriving at the detector in a thin and flat shower front.

The surface detector (SD) array of the Pierre Auger Observatory can be used to identify neutrino-induced showers [Capelle et al.(1998), Bertou et al.(2002), Zas(2005)]. The fluorescence detectors can also be used for neutrino searches [Aramo et al.(2005), Miele et al.(2006)] but the nominal 10% duty cycle of the fluorescence technique reduces the sensitivity. The electromagnetic component of neutrino-induced showers might reach the ground if the shower develops close enough to the detector, producing a signal which has a longer time duration than for an inclined shower initiated by a nucleonic primary. Thus close examination of inclined showers enables showers developing near to the ground and those produced early in the atmosphere to be distinguished. This allows the clean identification of showers induced by neutrinos, and in particular those induced by  $\nu_\tau$ , with the SD [Billoir et al.(2007), Blanch Bigas(2007), Alvarez-Muñiz(2007)].

Here we present the result of a search for deep, inclined, showers in the data collected with the SD of the Pierre Auger Observatory. Identification criteria have been developed to find EAS that are generated by  $\tau$  leptons emerging from the Earth. No candidates have been found in the data collected between 1 January 2004 and 31 August 2007 — equivalent to roughly one year of operation of the planned full array.

The construction of the Southern Pierre Auger Observatory in Mendoza, Argentina, is currently close to being completed. It consists of an array of water Cherenkov tanks arranged in a hexagonal grid of 1.5 km covering an area of  $3000 \text{ km}^2$  that is overlooked by 24 fluorescence telescopes located at four sites around the perimeter. The array comprises 1600 cylindrical tanks of  $10 \text{ m}^2$  surface containing purified water, 1.2 m deep, each instrumented with  $3 \times 9''$  photomultiplier tubes sampled by 40 MHz Flash Analog Digital Converters (FADCs)[Abraham et al.(2004)]. Each tank is regularly monitored and calibrated in units of Vertical Equivalent Muon (VEM) corresponding to the signal produced by a  $\mu$  traversing the tank vertically [Bertou et al.(2006)].

The procedure devised to identify neutrino candidate events within the data set is based on an end-to-end simulation of the whole process, from the interaction of the  $\nu_\tau$  inside the Earth to the detection of the signals in the tanks. The first step is the calculation of the  $\tau$  flux emerging from the Earth. This is done using a simulation of the coupled interplay between the  $\tau$  and the  $\nu_\tau$  fluxes through charged-current weak-interactions and  $\tau$  decay, taking into account also the energy losses due to neutral current interactions for both particles, and bremsstrahlung, pair production and nuclear interactions for the  $\tau$  lepton. The emerging  $\tau$  flux can be folded with the  $\tau$  decay probability to give the differential probability of  $\tau$  decaying in the atmosphere as a function of its energy and decay altitude,  $d^2p_\tau/dE_\tau dh_c$ .

Modelling of the showers from  $\tau$  decays in the atmosphere is performed using the AIRES code [Sciutto(2002)]. The TAUOLA package [Jadach et al.(1993)] is used



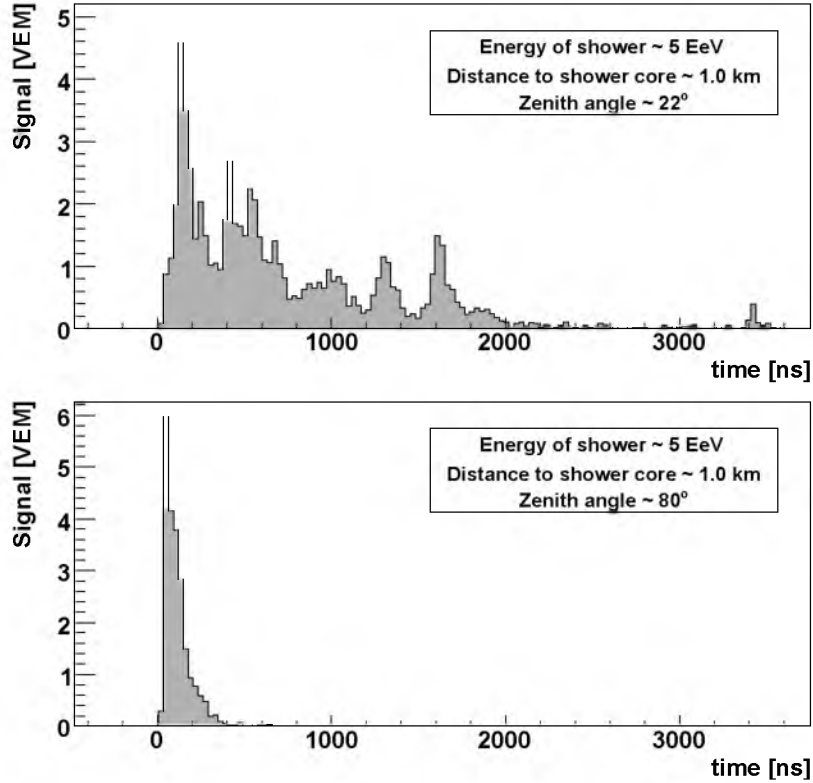


Figure 1: FADC traces of stations at 1 km from the shower core for two real showers of 5 EeV. Top panel: electromagnetic component ( $\theta \sim 22^\circ$ ); bottom: muonic signal ( $\theta \sim 80^\circ$ ).

to simulate  $\tau$  decay and obtain the secondary particles and their energies. Showers induced by the products of decaying  $\tau$ s with energies between  $10^{17}$  to  $3 \times 10^{20}$  eV are simulated at zenith angles ranging between  $90.1^\circ$  and  $95.9^\circ$  and at an altitude of the decay point above the Pierre Auger Observatory in the range 0 – 2500 m. Finally, to evaluate the response of the SD to such events, the particles reaching the ground in the simulation are stored and injected into a detailed simulation of the SD [Ghia(2007)].

A set of conditions has been designed and optimized to select showers induced by Earth-skimming  $\nu_\tau$ , rejecting those induced by UHECR. The 25 ns time resolution of the FADC traces allows unambiguous distinction between the narrow signals induced by muons and the broad signals induced by the electromagnetic component (Figure 1). For this purpose we tag the tanks for which the main segment of the FADC trace has 13 or more neighbouring bins over a threshold of 0.2 VEM, and for which the ratio of the integrated signal over the peak height exceeds 1.4. A neutrino candidate is required to have over 60% of the triggered tanks satisfying these “young shower” conditions as well as fulfilling the central trigger condition [Abraham et al.(2004)] with these tanks. In addition the triggered tanks are required to have elongated patterns on the ground

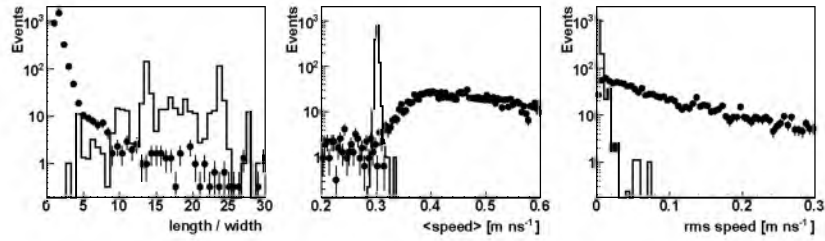


Figure 2: Distribution of discriminating variables for showers initiated by  $\tau$ s decaying in the atmosphere, generated by  $\nu_\tau$ s with energies sampled from an  $E_\nu^{-2}$  flux (histogram), and for real events passing the “young shower” selection (points). Left: length/width ratio of the footprint of the shower on the ground; middle: average speed between pairs of stations; right: r.m.s. scatter of the speeds. See text for details.

defining the azimuthal arrival direction (as expected for inclined events) by assigning a length and a width to the pattern and restricting its ratio ( $\text{length}/\text{width} > 5$ ). Finally, we calculate the apparent speed of the signal moving across the ground along the azimuthal direction, using the arrival times of the signals at ground and the projected distances between tanks. The average speed, as measured between pairs of triggered stations, is required to be compatible with that expected for an event traveling close to the horizontal direction by requiring it to be very close to the speed of light, in the range  $(0.29, 0.31) \text{ m ns}^{-1}$  with an r.m.s. scatter below  $0.08 \text{ m ns}^{-1}$ . These conditions are found to retain about 80 % of the simulated  $\tau$  showers triggering the SD. The final sample is expected to be free of background from UHECR-induced showers. In Figure 2, we show the distributions of these discriminating variables for real events and simulated  $\tau$  showers.

Over the period analyzed, no candidate events were found that fulfilled the selection criteria. Based on this, the Pierre Auger Observatory data can be used to place a limit on the diffuse flux of UHE  $\nu_\tau$ . For this purpose the exposure of the detector must be evaluated. The total exposure is the time integral of the instantaneous aperture which has changed as the detector has grown while it was being constructed and set into operation.

Calculation of the effective aperture for a fixed neutrino energy  $E_\nu$  involves folding the aperture with the conversion probability and the identification efficiency. The identification efficiency  $\epsilon_{\text{ff}}$  depends on the  $\tau$  energy  $E_\tau$ , the altitude above ground of the central part of the shower  $h_c$  (defined at 10 km after the decay point [Bertou et al.(2002)]), the position  $(x, y)$  of the shower in the surface  $S$  covered by the array, and the time  $t$  through the instantaneous configuration of the array. The expression for the exposure can be written as:

$$\text{Exp} = \int_{\Omega} d\Omega \int_0^{E_\nu} dE_\tau \int_0^\infty dh_c \frac{d^2 p_\tau}{dE_\tau dh_c} B_\tau, \quad (1)$$

where

$$B_\tau(E_\tau, h_c) = \int_T dt \int_S dx dy \cos \theta \epsilon_{\text{ff}}[E_\tau, h_c, x, y, t] \quad (2)$$

where  $\theta$  and  $\Omega$  are the zenith and solid angles.

The exposure is calculated using standard Monte Carlo techniques (MC) in two steps. The first integral deals with the detector-dependent part, including the time evolution of the array over the period  $T$  considered (eq.2). The integral in  $E_\tau$  and  $h_c$  involves only the differential conversion probability and  $B_\tau$  (eq.1). The estimated statistical uncertainty for the exposure is below 3%.

The MC simulations require some physical quantities that have not been experimentally measured in the relevant energy range, namely the  $\nu$  interaction cross-section, the  $\tau$  energy loss, and the  $\tau$  polarisation. The main uncertainty in these comes from the QCD structure functions in the relevant kinematic range. We estimate the uncertainty in the exposure due to the  $\nu$  cross-section to be 15% based on the allowed range explored in [Anchordoqui et al.(2006)]. The uncertainties in the  $\tau$  energy losses are dominated by the  $\tau$  photonuclear cross section. The 40% difference among existing calculations for the  $\tau$  energy losses [Bugaev et al.(2004), Dutta et al.(2005), Aramo et al.(2005)], which use different structure functions, is used as the systematic uncertainty. The two extreme cases of polarization give 30% difference in exposure and we take this as the corresponding uncertainty. The relevant range of the structure functions includes regions of Bjorken- $x$  and squared 4-momentum transfer,  $Q^2$ , where no experimental data exist. Only extrapolations that follow the behaviour observed in the regions with experimental data have been considered.

We also take into account uncertainties coming from neglecting the topography around the site of the Pierre Auger Observatory [Gora et al.(2007)] (18%). We adopt a 25% systematic uncertainty due to MC simulations of the EAS and the detector, dominated by differences between hadronic models (QGSJET [Kalmykov et al.(1997)] and SIBYLL [Engel et al.(1999)]).

Assuming a  $f(E_\nu) \propto E_\nu^{-2}$  differential flux of  $\nu_\tau$  we have obtained a 90% C.L. limit on the diffuse flux of UHE  $\nu_\tau$ , whose level at  $10^{18}$  eV is representative for any smooth spectral shape:

$$E_\nu^2 f(E_\nu) < 1.0_{-0.5}^{+0.3} \times 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (3)$$

The central value is computed using the  $\nu$  cross-section from Ref. [Anchordoqui et al.(2006)], the parametrisation of the energy losses from Ref. [Dutta et al.(2005)] and an uniform random distribution for the  $\tau$  polarisation. The uncertainties correspond to the combinations of systematic uncertainties in the exposure as given above that lead to the highest/lowest neutrino event rate. The limit is applicable in the energy range  $2 \times 10^{17} - 2 \times 10^{19}$  eV, with a systematic uncertainty of about 15%, over which 90% of the events are expected for  $f(E_\nu) \propto E_\nu^{-2}$ . In Figure 3, we show our limit adopting the most pessimistic scenario for systematic uncertainties. It improves by a factor  $\sim 3$  for the most optimistic one. For energies above  $10^{20}$  eV, limits are usually quoted as  $2.3/\text{Exp} \times E_\nu$  for different energy values (differential format), while at lower energies they are usually given assuming an  $E^{-2}$  flux (integrated format). We plot the differential format to demonstrate explicitly that the sensitivity of the Pierre Auger Observatory to Earth-skimming  $\nu_\tau$  peaks in a narrow energy range close to where the GZK neutrinos are expected.

The Earth-skimming technique used with data collected at the surface detector array of the Southern Pierre Auger Observatory, provide at present the most sensitive

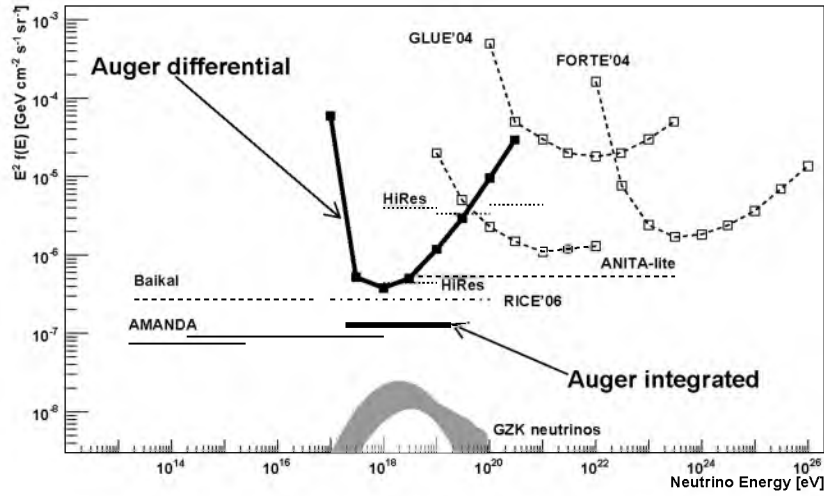


Figure 3: Limits at 90% C.L. for a diffuse flux of  $\nu_\tau$  from the Pierre Auger Observatory. Limits from other experiments [Achterberg(2007), Ackermann et al.(2007), Martens(2007), Aynutdinov et al.(2006), Kravchenko et al.(2006), Barwick et al.(2006), Gorham et al.(2004), Lehtinen et al.(2004)] are converted to a single flavour assuming a 1 : 1 : 1 ratio of the 3 neutrino flavours and scaled to 90% C.L. where needed. Two different formats are used: differential (squares) and integrated (constant lines). The shaded curve shows the range of expected fluxes of GZK neutrinos from Ref. [Engel et al.(2001), Allard et al.(2006)], although predictions almost 1 order of magnitude lower and higher exist.

bound on neutrinos at EeV energies. This is the most relevant energy to explore the predicted fluxes of GZK neutrinos. The Pierre Auger Observatory will continue to take data for about 20 years over which time the limit should improve by over an order of magnitude if no neutrino candidate is found.

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