

# Charged-particle multiplicity measurement in proton–proton collisions at $\sqrt{s} = 7$ TeV with ALICE at LHC

The ALICE Collaboration

K. Aamodt<sup>78</sup>, N. Abel<sup>43</sup>, U. Abeysekera<sup>76</sup>, A. Abrahantes Quintana<sup>42</sup>, A. Abramyan<sup>112</sup>, D. Adamová<sup>86</sup>, M.M. Aggarwal<sup>25</sup>, G. Aglieri Rinella<sup>40</sup>, A.G. Agocs<sup>18</sup>, S. Aguilar Salazar<sup>64</sup>, Z. Ahammed<sup>53</sup>, A. Ahmad<sup>2</sup>, N. Ahmad<sup>2</sup>, S.U. Ahn<sup>38,b</sup>, R. Akimoto<sup>100</sup>, A. Akindinov<sup>67</sup>, D. Aleksandrov<sup>69</sup>, B. Alessandro<sup>105</sup>, R. Alfaro Molina<sup>64</sup>, A. Alici<sup>13</sup>, E. Almaráz Aviña<sup>64</sup>, J. Alme<sup>8</sup>, T. Alt<sup>43,c</sup>, V. Altini<sup>5</sup>, S. Altinpinar<sup>31</sup>, C. Andrei<sup>17</sup>, A. Andronic<sup>31</sup>, G. Anelli<sup>40</sup>, V. Angelov<sup>43,c</sup>, C. Anson<sup>27</sup>, T. Antičić<sup>113</sup>, F. Antinori<sup>40,d</sup>, S. Antinori<sup>13</sup>, K. Antipin<sup>36</sup>, D. Antończyk<sup>36</sup>, P. Antonioli<sup>14</sup>, A. Anzo<sup>64</sup>, L. Aphecetche<sup>72</sup>, H. Appelshäuser<sup>36</sup>, S. Arcelli<sup>13</sup>, R. Arceo<sup>64</sup>, A. Arend<sup>36</sup>, N. Armesto<sup>92</sup>, R. Arnaldi<sup>105</sup>, T. Aronsson<sup>73</sup>, I.C. Arsene<sup>78,c</sup>, A. Asryan<sup>98</sup>, A. Augustinus<sup>40</sup>, R. Averbeck<sup>31</sup>, T.C. Awes<sup>75</sup>, J. Äystö<sup>49</sup>, M.D. Azmi<sup>2</sup>, S. Bablok<sup>8</sup>, M. Bach<sup>35</sup>, A. Badalà<sup>24</sup>, Y.W. Baek<sup>38,b</sup>, S. Bagnasco<sup>105</sup>, R. Bailhache<sup>31,f</sup>, R. Bala<sup>104</sup>, A. Baldisseri<sup>89</sup>, A. Baldit<sup>26</sup>, J. Bán<sup>56</sup>, R. Barbera<sup>23</sup>, G.G. Barnaföldi<sup>18</sup>, L. Barnby<sup>12</sup>, V. Barret<sup>26</sup>, J. Bartke<sup>29</sup>, F. Barile<sup>5</sup>, M. Basile<sup>13</sup>, V. Basmanov<sup>94</sup>, N. Bastid<sup>26</sup>, B. Bathen<sup>71</sup>, G. Batigne<sup>72</sup>, B. Batyunya<sup>34</sup>, C. Baumann<sup>71,f</sup>, I.G. Bearden<sup>28</sup>, B. Becker<sup>20,g</sup>, I. Belikov<sup>99</sup>, R. Bellwied<sup>33</sup>, E. Belmont-Moreno<sup>64</sup>, A. Belogianni<sup>4</sup>, L. Benhabib<sup>72</sup>, S. Beole<sup>104</sup>, I. Berceau<sup>17</sup>, A. Bercuci<sup>31,h</sup>, E. Berdermann<sup>31</sup>, Y. Berdnikov<sup>39</sup>, L. Betev<sup>40</sup>, A. Bhasin<sup>48</sup>, A.K. Bhati<sup>25</sup>, L. Bianchi<sup>104</sup>, N. Bianchi<sup>37</sup>, C. Bianchin<sup>79</sup>, J. Bielčik<sup>81</sup>, J. Bielčíková<sup>86</sup>, A. Bilandžić<sup>3</sup>, L. Bimbot<sup>77</sup>, E. Biolcati<sup>104</sup>, A. Blanc<sup>26</sup>, F. Blanco<sup>23,i</sup>, F. Blanco<sup>62</sup>, D. Blau<sup>69</sup>, C. Blume<sup>36</sup>, M. Boccioni<sup>40</sup>, N. Bock<sup>27</sup>, A. Bogdanov<sup>68</sup>, H. Bøggild<sup>28</sup>, M. Bogolyubsky<sup>83</sup>, J. Bohm<sup>96</sup>, L. Boldizsár<sup>18</sup>, M. Bombara<sup>55</sup>, C. Bombonati<sup>79,k</sup>, M. Bondila<sup>49</sup>, H. Borel<sup>89</sup>, A. Borisov<sup>50</sup>, C. Bortolin<sup>79,ao</sup>, S. Bose<sup>52</sup>, L. Bosisio<sup>101</sup>, F. Bossú<sup>104</sup>, M. Botje<sup>3</sup>, S. Böttger<sup>43</sup>, G. Bourdaud<sup>72</sup>, B. Boyer<sup>77</sup>, M. Braun<sup>98</sup>, P. Braun-Munzinger<sup>31,32,c</sup>, L. Bravina<sup>78</sup>, M. Bregant<sup>101,l</sup>, T. Breitner<sup>43</sup>, G. Bruckner<sup>40</sup>, R. Brun<sup>40</sup>, E. Bruna<sup>73</sup>, G.E. Bruno<sup>5</sup>, D. Budnikov<sup>94</sup>, H. Buesching<sup>36</sup>, P. Buncic<sup>40</sup>, O. Busch<sup>44</sup>, Z. Buthelezi<sup>22</sup>, D. Caffarri<sup>79</sup>, X. Cai<sup>111</sup>, H. Caines<sup>73</sup>, E. Camacho<sup>65</sup>, P. Camerini<sup>101</sup>, M. Campbell<sup>40</sup>, V. Canoa Roman<sup>40</sup>, G.P. Capitani<sup>37</sup>, G. Cara Romeo<sup>14</sup>, F. Carena<sup>40</sup>, W. Carena<sup>40</sup>, F. Carminati<sup>40</sup>, A. Casanova Díaz<sup>37</sup>, M. Caselle<sup>40</sup>, J. Castillo Castellanos<sup>89</sup>, J.F. Castillo Hernandez<sup>31</sup>, V. Catanescu<sup>17</sup>, E. Cattaruzza<sup>101</sup>, C. Cavicchioli<sup>40</sup>, P. Cerello<sup>105</sup>, V. Chambert<sup>77</sup>, B. Chang<sup>96</sup>, S. Chapeland<sup>40</sup>, A. Charpy<sup>77</sup>, J.L. Charvet<sup>89</sup>, S. Chattopadhyay<sup>52</sup>, S. Chattopadhyay<sup>53</sup>, M. Cherney<sup>76</sup>, C. Cheshkov<sup>40</sup>, B. Cheynis<sup>61</sup>, E. Chiavassa<sup>104</sup>, V. Chibante Barroso<sup>40</sup>, D.D. Chinellato<sup>21</sup>, P. Chochula<sup>40</sup>, K. Choi<sup>85</sup>, M. Chojnacki<sup>106</sup>, P. Christakoglou<sup>106</sup>, C.H. Christensen<sup>28</sup>, P. Christiansen<sup>60</sup>, T. Chujo<sup>103</sup>, F. Chuman<sup>45</sup>, C. Cicalo<sup>20</sup>, L. Cifarelli<sup>13</sup>, F. Cindolo<sup>14</sup>, J. Cleymans<sup>22</sup>, O. Cobanoglu<sup>104</sup>, J.-P. Coffin<sup>99</sup>, S. Coli<sup>105</sup>, A. Colla<sup>40</sup>, G. Conesa Balbastre<sup>37</sup>, Z. Conesa del Valle<sup>72,m</sup>, E.S. Conner<sup>110</sup>, P. Constantin<sup>44</sup>, G. Contin<sup>101,k</sup>, J.G. Contreras<sup>65</sup>, Y. Corrales Morales<sup>104</sup>, T.M. Cormier<sup>33</sup>, P. Cortese<sup>1</sup>, I. Cortés Maldonado<sup>84</sup>, M.R. Cosentino<sup>21</sup>, F. Costa<sup>40</sup>, M.E. Cotallo<sup>62</sup>, E. Crescio<sup>65</sup>, P. Crochet<sup>26</sup>, E. Cuautle<sup>63</sup>, L. Cunqueiro<sup>37</sup>, J. Cussonneau<sup>72</sup>, A. Dainese<sup>80</sup>, H.H. Dalsgaard<sup>28</sup>, A. Danu<sup>16</sup>, I. Das<sup>52</sup>, A. Dash<sup>11</sup>, S. Dash<sup>11</sup>, G.O.V. de Barros<sup>93</sup>, A. De Caro<sup>90</sup>, G. de Cataldo<sup>6</sup>, J. de Cuveland<sup>43,c</sup>, A. De Falco<sup>19</sup>, M. De Gaspari<sup>44</sup>, J. de Groot<sup>40</sup>, D. De Gruttola<sup>90</sup>, N. De Marco<sup>105</sup>, S. De Pasquale<sup>90</sup>, R. De Remigis<sup>105</sup>, R. de Rooij<sup>106</sup>, G. de Vaux<sup>22</sup>, H. Delagrange<sup>72</sup>, G. Dellacasa<sup>1</sup>, A. Deloff<sup>107</sup>, V. Demanov<sup>94</sup>, E. Dénes<sup>18</sup>, A. Deppman<sup>93</sup>, G. D’Erasmus<sup>5</sup>, D. Derkach<sup>98</sup>, A. Devaux<sup>26</sup>, D. Di Bari<sup>5</sup>, C. Di Giglio<sup>5,k</sup>, S. Di Liberto<sup>88</sup>, A. Di Mauro<sup>40</sup>, P. Di Nezza<sup>37</sup>, M. Dialinas<sup>72</sup>, L. Díaz<sup>63</sup>, R. Díaz<sup>49</sup>, T. Dietel<sup>71</sup>, R. Divià<sup>40</sup>, Ø. Djuvsland<sup>8</sup>, V. Dobretsov<sup>69</sup>, A. Dobrin<sup>60</sup>, T. Dobrowolski<sup>107</sup>, B. Dönigus<sup>31</sup>, I. Domínguez<sup>63</sup>, D.M.M. Don<sup>46</sup>, O. Dordic<sup>78</sup>, A.K. Dubey<sup>53</sup>, J. Dubuisson<sup>40</sup>, L. Ducroux<sup>61</sup>, P. Dupieux<sup>26</sup>, A.K. Dutta Majumdar<sup>52</sup>, M.R. Dutta Majumdar<sup>53</sup>, D. Elia<sup>6</sup>, D. Emschermann<sup>44,o</sup>, A. Enokizono<sup>75</sup>, B. Espagnon<sup>77</sup>, M. Estienne<sup>72</sup>, S. Esumi<sup>103</sup>, D. Evans<sup>12</sup>, S. Evrard<sup>40</sup>, G. Eyyubova<sup>78</sup>, C.W. Fabjan<sup>40,p</sup>, D. Fabris<sup>80</sup>, J. Faivre<sup>41</sup>, D. Falchieri<sup>13</sup>, A. Fantoni<sup>37</sup>, M. Fasel<sup>31</sup>, O. Fateev<sup>34</sup>, R. Fearick<sup>22</sup>, A. Fedunov<sup>34</sup>, D. Fehler<sup>8</sup>, V. Fekete<sup>15</sup>, D. Felea<sup>16</sup>, B. Fenton-Olsen<sup>28,q</sup>, G. Feofilov<sup>98</sup>, A. Fernández Téllez<sup>84</sup>, E.G. Ferreira<sup>92</sup>, A. Ferretti<sup>104</sup>, R. Ferretti<sup>1,r</sup>, M.A.S. Figueredo<sup>93</sup>, S. Filchagin<sup>94</sup>, R. Fini<sup>6</sup>, F.M. Fionda<sup>5</sup>, E.M. Fiore<sup>5</sup>, M. Floris<sup>19,k</sup>, Z. Fodor<sup>18</sup>, S. Foertsch<sup>22</sup>, P. Foka<sup>31</sup>, S. Fokin<sup>69</sup>, F. Formenti<sup>40</sup>, E. Fragiaco<sup>102</sup>, M. Fragkiadakis<sup>4</sup>, U. Frankenfeld<sup>31</sup>, A. Frolov<sup>74</sup>, U. Fuchs<sup>40</sup>, F. Furano<sup>40</sup>, C. Furget<sup>41</sup>, M. Fusco Girard<sup>90</sup>, J.J. Gaardhøje<sup>28</sup>, S. Gadrat<sup>41</sup>, M. Gagliardi<sup>104</sup>, A. Gago<sup>58</sup>, M. Gallio<sup>104</sup>, P. Ganoti<sup>4</sup>, M.S. Ganti<sup>53</sup>, C. Garabatos<sup>31</sup>, C. García Trapaga<sup>104</sup>, J. Gebelein<sup>43</sup>, R. Gemme<sup>1</sup>,

M. Germain<sup>72</sup>, A. Gheata<sup>40</sup>, M. Gheata<sup>40</sup>, B. Ghidini<sup>5</sup>, P. Ghosh<sup>53</sup>, G. Giraudo<sup>105</sup>, P. Giubellino<sup>105</sup>, E. Gladysz-Dziadus<sup>29</sup>, R. Glasow<sup>71,t</sup>, P. Glässel<sup>44</sup>, A. Glenn<sup>59</sup>, R. Gómez Jiménez<sup>30</sup>, H. González Santos<sup>84</sup>, L.H. González-Trueba<sup>64</sup>, P. González-Zamora<sup>62</sup>, S. Gorbunov<sup>43,c</sup>, Y. Gorbunov<sup>76</sup>, S. Gotovac<sup>97</sup>, H. Gottschlag<sup>71</sup>, V. Grabski<sup>64</sup>, R. Grajcarek<sup>44</sup>, A. Grelli<sup>106</sup>, A. Grigoras<sup>40</sup>, C. Grigoras<sup>40</sup>, V. Grigoriev<sup>68</sup>, A. Grigoryan<sup>112</sup>, S. Grigoryan<sup>34</sup>, B. Grinyov<sup>50</sup>, N. Grion<sup>102</sup>, P. Gros<sup>60</sup>, J.F. Grosse-Oetringhaus<sup>40</sup>, J.-Y. Grossiord<sup>61</sup>, R. Grosso<sup>80</sup>, F. Guber<sup>66</sup>, R. Guernane<sup>41</sup>, B. Guerzoni<sup>13</sup>, K. Gulbrandsen<sup>28</sup>, H. Gulkanyan<sup>112</sup>, T. Gunji<sup>100</sup>, A. Gupta<sup>48</sup>, R. Gupta<sup>48</sup>, H.-A. Gustafsson<sup>60,t</sup>, H. Gutbrod<sup>31</sup>, Ø. Haaland<sup>8</sup>, C. Hadjidakis<sup>77</sup>, M. Haiduc<sup>16</sup>, H. Hamagaki<sup>100</sup>, G. Hamar<sup>18</sup>, J. Hamblen<sup>51</sup>, B.H. Han<sup>95</sup>, J.W. Harris<sup>73</sup>, M. Hartig<sup>36</sup>, A. Harutyunyan<sup>112</sup>, D. Hasch<sup>37</sup>, D. Hasegan<sup>16</sup>, D. Hatzifotiadou<sup>14</sup>, A. Hayrapetyan<sup>112</sup>, M. Heide<sup>71</sup>, M. Heinz<sup>73</sup>, H. Helstrup<sup>9</sup>, A. Herghelegiu<sup>17</sup>, C. Hernández<sup>31</sup>, G. Herrera Corral<sup>65</sup>, N. Herrmann<sup>44</sup>, K.F. Hetland<sup>9</sup>, B. Hicks<sup>73</sup>, A. Hiei<sup>45</sup>, P.T. Hille<sup>78,u</sup>, B. Hippolyte<sup>99</sup>, T. Horaguchi<sup>45,v</sup>, Y. Hori<sup>100</sup>, P. Hristov<sup>40</sup>, I. Hřivnáčová<sup>77</sup>, S. Hu<sup>7</sup>, M. Huang<sup>8</sup>, S. Huber<sup>31</sup>, T.J. Humanic<sup>27</sup>, D. Hutter<sup>35</sup>, D.S. Hwang<sup>95</sup>, R. Ichou<sup>72</sup>, R. Ilkaev<sup>94</sup>, I. Ilkiv<sup>107</sup>, M. Inaba<sup>103</sup>, P.G. Innocenti<sup>40</sup>, M. Ippolitov<sup>69</sup>, M. Irfan<sup>2</sup>, C. Ivan<sup>106</sup>, A. Ivanov<sup>98</sup>, M. Ivanov<sup>31</sup>, V. Ivanov<sup>39</sup>, T. Iwasaki<sup>45</sup>, A. Jacholkowski<sup>40</sup>, P. Jacobs<sup>10</sup>, L. Jančurová<sup>34</sup>, S. Jangal<sup>99</sup>, R. Janik<sup>15</sup>, C. Jena<sup>11</sup>, S. Jena<sup>70</sup>, L. Jirdeh<sup>40</sup>, G.T. Jones<sup>12</sup>, P.G. Jones<sup>12</sup>, P. Jovanović<sup>12</sup>, H. Jung<sup>38</sup>, W. Jung<sup>38</sup>, A. Jusko<sup>12</sup>, A.B. Kaidalov<sup>67</sup>, S. Kalcher<sup>43,c</sup>, P. Kaliňák<sup>56</sup>, M. Kalisky<sup>71</sup>, T. Kalliokoski<sup>49</sup>, A. Kalweit<sup>32</sup>, A. Kamal<sup>2</sup>, R. Kamermans<sup>106</sup>, K. Kanaki<sup>8</sup>, E. Kang<sup>38</sup>, J.H. Kang<sup>96</sup>, J. Kapitan<sup>86</sup>, V. Kaplin<sup>68</sup>, S. Kapusta<sup>40</sup>, O. Karavichev<sup>66</sup>, T. Karavicheva<sup>66</sup>, E. Karpechev<sup>66</sup>, A. Kazantsev<sup>69</sup>, U. Keschull<sup>43</sup>, R. Keidel<sup>110</sup>, M.M. Khan<sup>2</sup>, S.A. Khan<sup>53</sup>, A. Khanzadeev<sup>39</sup>, Y. Kharlov<sup>83</sup>, D. Kikola<sup>108</sup>, B. Kileng<sup>9</sup>, D.J. Kim<sup>49</sup>, D.S. Kim<sup>38</sup>, D.W. Kim<sup>38</sup>, H.N. Kim<sup>38</sup>, J. Kim<sup>83</sup>, J.H. Kim<sup>95</sup>, J.S. Kim<sup>38</sup>, M. Kim<sup>38</sup>, M. Kim<sup>96</sup>, S.H. Kim<sup>38</sup>, S. Kim<sup>95</sup>, Y. Kim<sup>96</sup>, S. Kirsch<sup>40</sup>, I. Kisel<sup>43,e</sup>, S. Kiselev<sup>67</sup>, A. Kisel<sup>27,k</sup>, J.L. Klay<sup>91</sup>, J. Klein<sup>44</sup>, C. Klein-Bösing<sup>40,o</sup>, M. Kliemant<sup>36</sup>, A. Klovning<sup>8</sup>, A. Kluge<sup>40</sup>, M.L. Knichel<sup>31</sup>, S. Kniese<sup>36</sup>, K. Koch<sup>44</sup>, R. Kolevatov<sup>78</sup>, A. Kolojvari<sup>98</sup>, V. Kondratiev<sup>98</sup>, N. Kondratyeva<sup>68</sup>, A. Konevskih<sup>66</sup>, E. Kornas<sup>29</sup>, R. Kour<sup>12</sup>, M. Kowalski<sup>29</sup>, S. Kox<sup>41</sup>, K. Kozlov<sup>69</sup>, J. Kral<sup>81,i</sup>, I. Králik<sup>56</sup>, F. Kramer<sup>36</sup>, I. Kraus<sup>32,e</sup>, A. Kravčáková<sup>55</sup>, T. Krawutschke<sup>54</sup>, M. Krivda<sup>12</sup>, D. Krumbhorn<sup>44</sup>, M. Krus<sup>81</sup>, E. Kryshen<sup>39</sup>, M. Krzewicki<sup>3</sup>, Y. Kucheriaev<sup>69</sup>, C. Kuhn<sup>99</sup>, P.G. Kuijter<sup>3</sup>, L. Kumar<sup>25</sup>, N. Kumar<sup>25</sup>, R. Kupczak<sup>108</sup>, P. Kurashvili<sup>107</sup>, A. Kurepin<sup>66</sup>, A.N. Kurepin<sup>66</sup>, A. Kuryakin<sup>94</sup>, S. Kushpil<sup>86</sup>, V. Kushpil<sup>86</sup>, M. Kutouski<sup>34</sup>, H. Kvaerno<sup>78</sup>, M.J. Kweon<sup>44</sup>, Y. Kwon<sup>96</sup>, P. La Rocca<sup>23,w</sup>, F. Lackner<sup>40</sup>, P. Ladrón de Guevara<sup>62</sup>, V. Lafage<sup>77</sup>, C. Lal<sup>48</sup>, C. Lara<sup>43</sup>, D.T. Larsen<sup>8</sup>, G. Laurenti<sup>14</sup>, C. Lazzeroni<sup>12</sup>, Y. Le Bornec<sup>77</sup>, N. Le Bris<sup>72</sup>, H. Lee<sup>85</sup>, K.S. Lee<sup>38</sup>, S.C. Lee<sup>38</sup>, F. Lefèvre<sup>72</sup>, M. Lenhardt<sup>72</sup>, L. Leistam<sup>40</sup>, J. Lehnert<sup>36</sup>, V. Lenti<sup>6</sup>, H. León<sup>64</sup>, I. León Monzón<sup>30</sup>, H. León Vargas<sup>36</sup>, P. Lévai<sup>18</sup>, X. Li<sup>7</sup>, Y. Li<sup>7</sup>, R. Lietava<sup>12</sup>, S. Lindal<sup>78</sup>, V. Lindenstruth<sup>43,c</sup>, C. Lippmann<sup>40</sup>, M.A. Lisa<sup>27</sup>, L. Liu<sup>8</sup>, V. Loginov<sup>68</sup>, S. Lohn<sup>40</sup>, X. Lopez<sup>26</sup>, M. López Noriega<sup>77</sup>, R. López-Ramírez<sup>84</sup>, E. López Torres<sup>42</sup>, G. Løvholden<sup>78</sup>, A. Lozea Feijo Soares<sup>93</sup>, S. Lu<sup>7</sup>, M. Lunardon<sup>79</sup>, G. Luparello<sup>104</sup>, L. Luquin<sup>72</sup>, J.-R. Lutz<sup>99</sup>, K. Ma<sup>111</sup>, R. Ma<sup>73</sup>, D.M. Madagodahettige-Don<sup>46</sup>, A. Maevskaya<sup>66</sup>, M. Mager<sup>32,k</sup>, D.P. Mahapatra<sup>11</sup>, A. Maire<sup>99</sup>, I. Makhlyueva<sup>40</sup>, D. Mal'Kevich<sup>67</sup>, M. Malaev<sup>39</sup>, K.J. Malagalage<sup>76</sup>, I. Maldonado Cervantes<sup>63</sup>, M. Malek<sup>77</sup>, T. Malkiewicz<sup>49</sup>, P. Malzacher<sup>31</sup>, A. Mamonov<sup>94</sup>, L. Manceau<sup>26</sup>, L. Mangotra<sup>48</sup>, V. Manko<sup>69</sup>, F. Manso<sup>26</sup>, V. Manzari<sup>6</sup>, Y. Mao<sup>111,y</sup>, J. Mareš<sup>82</sup>, G.V. Margagliotti<sup>101</sup>, A. Margotti<sup>14</sup>, A. Marín<sup>31</sup>, I. Martashvili<sup>51</sup>, P. Martinengo<sup>40</sup>, M.I. Martínez Hernández<sup>84</sup>, A. Martínez Davalos<sup>64</sup>, G. Martínez García<sup>72</sup>, Y. Maruyama<sup>45</sup>, A. Marzari Chiesa<sup>104</sup>, S. Masciocchi<sup>31</sup>, M. Masera<sup>104</sup>, M. Masetti<sup>13</sup>, A. Masoni<sup>20</sup>, L. Massacrier<sup>61</sup>, M. Mastroianni<sup>6</sup>, A. Mastroserio<sup>5,k</sup>, Z.L. Matthews<sup>12</sup>, A. Matyja<sup>29,ai</sup>, D. Mayani<sup>63</sup>, G. Mazza<sup>105</sup>, M.A. Mazzoni<sup>88</sup>, F. Meddi<sup>87</sup>, A. Menchaca-Rocha<sup>64</sup>, P. Mendez Lorenzo<sup>40</sup>, M. Meoni<sup>40</sup>, J. Mercado Pérez<sup>44</sup>, P. Mereu<sup>105</sup>, Y. Miake<sup>103</sup>, A. Michalon<sup>99</sup>, N. Miftakhov<sup>39</sup>, J. Milosevic<sup>78</sup>, F. Minafra<sup>5</sup>, A. Mischke<sup>106</sup>, D. Miśkowiec<sup>31</sup>, C. Mitu<sup>16</sup>, K. Mizoguchi<sup>45</sup>, J. Mlynarz<sup>33</sup>, B. Mohanty<sup>53</sup>, L. Molnar<sup>18,k</sup>, M.M. Mondal<sup>53</sup>, L. Montaña Zetina<sup>65,z</sup>, M. Monteno<sup>105</sup>, E. Montes<sup>62</sup>, M. Morando<sup>79</sup>, S. Moretto<sup>79</sup>, A. Morsch<sup>40</sup>, T. Moukhanova<sup>69</sup>, V. Muccifora<sup>37</sup>, E. Mudnic<sup>97</sup>, S. Muhuri<sup>53</sup>, H. Müller<sup>40</sup>, M.G. Munhoz<sup>93</sup>, J. Muñoz<sup>84</sup>, L. Musa<sup>40</sup>, A. Musso<sup>105</sup>, B.K. Nandi<sup>70</sup>, R. Nania<sup>14</sup>, E. Nappi<sup>6</sup>, F. Navach<sup>5</sup>, S. Navin<sup>12</sup>, T.K. Nayak<sup>53</sup>, S. Nazarenko<sup>94</sup>, G. Nazarov<sup>94</sup>, A. Nedosekin<sup>67</sup>, F. Nendaz<sup>61</sup>, J. Newby<sup>59</sup>, A. Nianine<sup>69</sup>, M. Nicassio<sup>6,k</sup>, B.S. Nielsen<sup>28</sup>, S. Nikolaev<sup>69</sup>, V. Nikolic<sup>113</sup>, S. Nikulin<sup>69</sup>, V. Nikulin<sup>39</sup>, B.S. Nilsen<sup>76</sup>, M.S. Nilsson<sup>78</sup>, F. Noferini<sup>14</sup>, P. Nomokonov<sup>34</sup>, G. Nooren<sup>106</sup>, N. Novitzky<sup>49</sup>, A. Nyatha<sup>70</sup>, C. Nygaard<sup>28</sup>, A. Nyiri<sup>78</sup>, J. Nystrand<sup>8</sup>, A. Ochirov<sup>98</sup>, G. Odyniec<sup>10</sup>, H. Oeschler<sup>32</sup>, M. Oinonen<sup>49</sup>, K. Okada<sup>100</sup>, Y. Okada<sup>45</sup>, M. Oldenburg<sup>40</sup>, J. Oleniacz<sup>108</sup>, C. Oppedisano<sup>105</sup>, F. Orsini<sup>89</sup>, A. Ortiz Velasquez<sup>63</sup>, G. Ortona<sup>104</sup>, A. Oskarsson<sup>60</sup>, F. Osmic<sup>40</sup>, L. Österman<sup>60</sup>, P. Ostrowski<sup>108</sup>, I. Otterlund<sup>60</sup>, J. Otwinowski<sup>31</sup>, G. Øvrebekk<sup>8</sup>, K. Oyama<sup>44</sup>, K. Ozawa<sup>100</sup>, Y. Pachmayer<sup>44</sup>, M. Pachr<sup>81</sup>, F. Padilla<sup>104</sup>, P. Pagano<sup>90</sup>, G. Paic<sup>63</sup>, F. Painke<sup>43</sup>, C. Pajares<sup>92</sup>, S. Pal<sup>52,ab</sup>, S.K. Pal<sup>53</sup>, A. Palaha<sup>12</sup>, A. Palmeri<sup>24</sup>, R. Panse<sup>43</sup>, V. Papikyan<sup>112</sup>, G.S. Pappalardo<sup>24</sup>, W.J. Park<sup>31</sup>, B. Pastirčák<sup>56</sup>, C. Pastore<sup>6</sup>, V. Paticchio<sup>6</sup>, A. Pavlinov<sup>33</sup>, T. Pawlak<sup>108</sup>,

T. Peitzmann<sup>106</sup>, A. Pepato<sup>80</sup>, H. Pereira<sup>89</sup>, D. Peressouko<sup>69</sup>, C. Pérez<sup>58</sup>, D. Perini<sup>40</sup>, D. Perrino<sup>5,k</sup>, W. Peryt<sup>108</sup>, J. Peschek<sup>43,c</sup>, A. Pesci<sup>14</sup>, V. Peskov<sup>63,k</sup>, Y. Pestov<sup>74</sup>, A.J. Peters<sup>40</sup>, V. Petráček<sup>81</sup>, A. Petridis<sup>4,t</sup>, M. Petris<sup>17</sup>, P. Petrov<sup>12</sup>, M. Petrovici<sup>17</sup>, C. Petta<sup>23</sup>, J. Peyré<sup>77</sup>, S. Piano<sup>102</sup>, A. Piccotti<sup>105</sup>, M. Pikna<sup>15</sup>, P. Pillot<sup>72</sup>, O. Pinazza<sup>14,k</sup>, L. Pinsky<sup>46</sup>, N. Pitz<sup>36</sup>, F. Piuze<sup>40</sup>, R. Platt<sup>12</sup>, M. Płoskoń<sup>10</sup>, J. Pluta<sup>108</sup>, T. Pocheptsov<sup>34,ac</sup>, S. Pochybova<sup>18</sup>, P.L.M. Podesta Lerma<sup>30</sup>, F. Poggio<sup>104</sup>, M.G. Poghosyan<sup>104</sup>, K. Polák<sup>82</sup>, B. Polichtchouk<sup>83</sup>, P. Polozov<sup>67</sup>, V. Polyakov<sup>39</sup>, B. Pommeresch<sup>8</sup>, A. Pop<sup>17</sup>, F. Posa<sup>5</sup>, V. Pospišil<sup>81</sup>, B. Potukuchi<sup>48</sup>, J. Pouthas<sup>77</sup>, S.K. Prasad<sup>53</sup>, R. Preghenella<sup>13,w</sup>, F. Prino<sup>105</sup>, C.A. Pruneau<sup>33</sup>, I. Pshenichnov<sup>66</sup>, G. Puddu<sup>19</sup>, P. Pujahari<sup>70</sup>, A. Pulvirenti<sup>23</sup>, A. Punin<sup>94</sup>, V. Punin<sup>94</sup>, M. Putiš<sup>55</sup>, J. Putschke<sup>73</sup>, E. Quercigh<sup>40</sup>, A. Rachevski<sup>102</sup>, A. Rademakers<sup>40</sup>, S. Radomski<sup>44</sup>, T.S. Rähkä<sup>49</sup>, J. Rak<sup>49</sup>, A. Rakotozafindrabe<sup>89</sup>, L. Ramello<sup>1</sup>, A. Ramírez Reyes<sup>65</sup>, M. Rammler<sup>71</sup>, R. Raniwala<sup>47</sup>, S. Raniwala<sup>47</sup>, S.S. Räsänen<sup>49</sup>, I. Rashevskaya<sup>102</sup>, S. Rath<sup>11</sup>, K.F. Read<sup>51</sup>, J.S. Real<sup>41</sup>, K. Redlich<sup>107,ap</sup>, R. Renfordt<sup>36</sup>, A.R. Reolon<sup>37</sup>, A. Reshetin<sup>66</sup>, F. Rettig<sup>43,c</sup>, J.-P. Revol<sup>40</sup>, K. Reygers<sup>71,ad</sup>, H. Ricard<sup>32</sup>, L. Riccati<sup>105</sup>, R.A. Ricci<sup>57</sup>, M. Richter<sup>8</sup>, P. Riedler<sup>40</sup>, W. Riegler<sup>40</sup>, F. Riggi<sup>23</sup>, A. Rivetti<sup>105</sup>, M. Rodriguez Cahuantzi<sup>84</sup>, K. Røed<sup>9</sup>, D. Röhrich<sup>40,af</sup>, S. Román López<sup>84</sup>, R. Romita<sup>5,e</sup>, F. Ronchetti<sup>37</sup>, P. Rosinsky<sup>40</sup>, P. Rosnet<sup>26</sup>, S. Rossegger<sup>40</sup>, A. Rossi<sup>101</sup>, F. Roukoutakis<sup>40,ag</sup>, S. Rousseau<sup>77</sup>, C. Roy<sup>72,m</sup>, P. Roy<sup>52</sup>, A.J. Rubio-Montero<sup>62</sup>, R. Rui<sup>101</sup>, I. Rusanov<sup>44</sup>, G. Russo<sup>90</sup>, E. Ryabinkin<sup>69</sup>, A. Rybicki<sup>29</sup>, S. Sadovsky<sup>83</sup>, K. Šafařík<sup>40</sup>, R. Sahoo<sup>79</sup>, J. Saini<sup>53</sup>, P. Saiz<sup>40</sup>, D. Sakata<sup>103</sup>, C.A. Salgado<sup>92</sup>, R. Salgueiro Domingues da Silva<sup>40</sup>, S. Salur<sup>10</sup>, T. Samanta<sup>53</sup>, S. Sambyal<sup>48</sup>, V. Samsonov<sup>39</sup>, L. Šándor<sup>56</sup>, A. Sandoval<sup>64</sup>, M. Sano<sup>103</sup>, S. Sano<sup>100</sup>, R. Santo<sup>71</sup>, R. Santoro<sup>5</sup>, J. Sarkamo<sup>49</sup>, P. Saturnini<sup>26</sup>, E. Scapparone<sup>14</sup>, F. Scarlassara<sup>79</sup>, R.P. Scharenberg<sup>109</sup>, C. Schiaua<sup>17</sup>, R. Schicker<sup>44</sup>, H. Schindler<sup>40</sup>, C. Schmidt<sup>31</sup>, H.R. Schmidt<sup>31</sup>, K. Schossmaier<sup>40</sup>, S. Schreiner<sup>40</sup>, S. Schuchmann<sup>36</sup>, J. Schukraft<sup>40,a</sup>, Y. Schutz<sup>72</sup>, K. Schwarz<sup>31</sup>, K. Schweda<sup>44</sup>, G. Scioli<sup>13</sup>, E. Scomparin<sup>105</sup>, G. Segato<sup>79</sup>, D. Semenov<sup>98</sup>, S. Senyukov<sup>1</sup>, J. Seo<sup>38</sup>, S. Serçi<sup>19</sup>, L. Serkin<sup>63</sup>, E. Serradilla<sup>62</sup>, A. Sevcenco<sup>16</sup>, I. Sgura<sup>5</sup>, G. Shabratova<sup>34</sup>, R. Shahoyan<sup>40</sup>, G. Sharkov<sup>67</sup>, N. Sharma<sup>25</sup>, S. Sharma<sup>48</sup>, K. Shigaki<sup>45</sup>, M. Shimomura<sup>103</sup>, K. Shtejer<sup>42</sup>, Y. Sibiraki<sup>69</sup>, M. Siciliano<sup>104</sup>, E. Sicking<sup>40,ah</sup>, E. Siddi<sup>20</sup>, T. Siemiarczuk<sup>107</sup>, A. Silenzi<sup>13</sup>, D. Silvermyr<sup>75</sup>, E. Simili<sup>106</sup>, G. Simonetti<sup>5,k</sup>, R. Singaraju<sup>53</sup>, R. Singh<sup>48</sup>, V. Singhal<sup>53</sup>, B.C. Sinha<sup>53</sup>, T. Sinha<sup>52</sup>, B. Sitar<sup>15</sup>, M. Sitta<sup>1</sup>, T.B. Skaali<sup>78</sup>, K. Skjerdal<sup>8</sup>, R. Smakal<sup>81</sup>, N. Smirnov<sup>73</sup>, R. Snellings<sup>3</sup>, H. Snow<sup>12</sup>, C. Søgaard<sup>28</sup>, A. Soloviev<sup>83</sup>, H.K. Soltveit<sup>44</sup>, R. Soltz<sup>59</sup>, W. Sommer<sup>36</sup>, C.W. Son<sup>85</sup>, H. Son<sup>95</sup>, M. Song<sup>96</sup>, C. Soos<sup>40</sup>, F. Soramel<sup>79</sup>, D. Soyk<sup>31</sup>, M. Spyropoulou-Stassinaki<sup>4</sup>, B.K. Srivastava<sup>109</sup>, J. Stachel<sup>44</sup>, F. Staley<sup>89</sup>, E. Stan<sup>16</sup>, G. Stefanek<sup>107</sup>, G. Stefanini<sup>40</sup>, T. Steinbeck<sup>43,c</sup>, E. Stenlund<sup>60</sup>, G. Steyn<sup>22</sup>, D. Stocco<sup>104,ai</sup>, R. Stock<sup>36</sup>, P. Stolpovsky<sup>83</sup>, P. Strmen<sup>15</sup>, A.A.P. Suaide<sup>93</sup>, M.A. Subieta Vásquez<sup>104</sup>, T. Sugitate<sup>45</sup>, C. Suire<sup>77</sup>, M. Šumbera<sup>86</sup>, T. Susa<sup>113</sup>, D. Swoboda<sup>40</sup>, J. Symons<sup>10</sup>, A. Szanto de Toledo<sup>93</sup>, I. Szarka<sup>15</sup>, A. Szostak<sup>20</sup>, M. Szuba<sup>108</sup>, M. Tadel<sup>40</sup>, C. Tagridis<sup>4</sup>, A. Takahara<sup>100</sup>, J. Takahashi<sup>21</sup>, R. Tanabe<sup>103</sup>, D.J. Tapia Takaki<sup>77</sup>, H. Taureg<sup>40</sup>, A. Tauro<sup>40</sup>, M. Tavlet<sup>40</sup>, G. Tejada Muñoz<sup>84</sup>, A. Telesca<sup>40</sup>, C. Terrevoli<sup>5</sup>, J. Thäder<sup>43,c</sup>, R. Tieulent<sup>61</sup>, D. Tlusty<sup>81</sup>, A. Toia<sup>40</sup>, T. Tolyhy<sup>18</sup>, C. Torcato de Matos<sup>40</sup>, H. Torii<sup>45</sup>, G. Torralba<sup>43</sup>, L. Toscano<sup>105</sup>, F. Tosello<sup>105</sup>, A. Tournaire<sup>72,aj</sup>, T. Traczyk<sup>108</sup>, P. Tribedy<sup>53</sup>, G. Tröger<sup>43</sup>, D. Triesdale<sup>27</sup>, W.H. Trzaska<sup>49</sup>, G. Tsileidakis<sup>44</sup>, E. Tsilis<sup>4</sup>, T. Tsuji<sup>100</sup>, A. Tumkin<sup>94</sup>, R. Turrisi<sup>80</sup>, A. Turvey<sup>76</sup>, T.S. Tveter<sup>78</sup>, H. Tydesjö<sup>40</sup>, K. Tywoniuk<sup>78</sup>, J. Ulery<sup>36</sup>, K. Ullaland<sup>8</sup>, A. Uras<sup>19</sup>, J. Urbán<sup>55</sup>, G.M. Urciuoli<sup>88</sup>, G.L. Usai<sup>19</sup>, A. Vacchi<sup>102</sup>, M. Vala<sup>34,j</sup>, L. Valencia Palomo<sup>64</sup>, S. Vallero<sup>44</sup>, N. van der Kolk<sup>3</sup>, P. Vande Vyvre<sup>40</sup>, M. van Leeuwen<sup>106</sup>, L. Vannucci<sup>57</sup>, A. Vargas<sup>84</sup>, R. Varma<sup>70</sup>, A. Vasiliev<sup>69</sup>, I. Vassiliev<sup>43,ag</sup>, M. Vasileiou<sup>4</sup>, V. Vechernin<sup>98</sup>, M. Venaruzzo<sup>101</sup>, E. Vercellin<sup>104</sup>, S. Vergara<sup>84</sup>, R. Vernet<sup>23,ak</sup>, M. Verweij<sup>106</sup>, I. Vetlitskiy<sup>67</sup>, L. Vickovic<sup>97</sup>, G. Viesti<sup>79</sup>, O. Vikhlyantsev<sup>94</sup>, Z. Vilakazi<sup>22</sup>, O. Villalobos Baillie<sup>12</sup>, A. Vinogradov<sup>69</sup>, L. Vinogradov<sup>98</sup>, Y. Vinogradov<sup>94</sup>, T. Virgili<sup>90</sup>, Y.P. Viyogi<sup>53</sup>, A. Vodopianov<sup>34</sup>, K. Voloshin<sup>67</sup>, S. Voloshin<sup>33</sup>, G. Volpe<sup>5</sup>, B. von Haller<sup>40</sup>, D. Vranic<sup>31</sup>, J. Vrláková<sup>55</sup>, B. Vulpescu<sup>26</sup>, B. Wagner<sup>8</sup>, V. Wagner<sup>81</sup>, L. Wallet<sup>40</sup>, R. Wan<sup>111,m</sup>, D. Wang<sup>111</sup>, Y. Wang<sup>44</sup>, K. Watanabe<sup>103</sup>, Q. Wen<sup>7</sup>, J. Wessels<sup>71</sup>, U. Westerhoff<sup>71</sup>, J. Wiechula<sup>44</sup>, J. Wikne<sup>78</sup>, A. Wilk<sup>71</sup>, G. Wilk<sup>107</sup>, M.C.S. Williams<sup>14</sup>, N. Willis<sup>77</sup>, B. Windelband<sup>44</sup>, C. Xu<sup>111</sup>, C. Yang<sup>111</sup>, H. Yang<sup>44</sup>, S. Yasnopolskiy<sup>69</sup>, F. Yermia<sup>72</sup>, J. Yi<sup>85</sup>, Z. Yin<sup>111</sup>, H. Yokoyama<sup>103</sup>, I.-K. Yoo<sup>85</sup>, X. Yuan<sup>111,am</sup>, V. Yurevich<sup>34</sup>, I. Yushmanov<sup>69</sup>, E. Zabrodin<sup>78</sup>, B. Zagreev<sup>67</sup>, A. Zalite<sup>39</sup>, C. Zampolli<sup>40,an</sup>, Yu. Zanevsky<sup>34</sup>, S. Zaporozhets<sup>34</sup>, A. Zarochentsev<sup>98</sup>, P. Závada<sup>82</sup>, H. Zbroszczyk<sup>108</sup>, P. Zelniczek<sup>43</sup>, A. Zenin<sup>83</sup>, A. Zepeda<sup>65</sup>, I. Zgura<sup>16</sup>, M. Zhalov<sup>39</sup>, X. Zhang<sup>111,b</sup>, D. Zhou<sup>111</sup>, S. Zhou<sup>7</sup>, J. Zhu<sup>111</sup>, A. Zichichi<sup>13,w</sup>, A. Zinchenko<sup>34</sup>, G. Zinoviev<sup>50</sup>, Y. Zoccarato<sup>61</sup>, V. Zycháček<sup>81</sup>, M. Zynovyev<sup>50</sup>

<sup>1</sup>Dipartimento di Scienze e Tecnologie Avanzate dell'Università del Piemonte Orientale and Gruppo Collegato INFN, Alessandria, Italy

<sup>2</sup>Department of Physics Aligarh Muslim University, Aligarh, India

<sup>3</sup>National Institute for Nuclear and High Energy Physics (NIKHEF), Amsterdam, Netherlands

<sup>4</sup>Physics Department, University of Athens, Athens, Greece

<sup>5</sup>Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy

<sup>6</sup>Sezione INFN, Bari, Italy

- <sup>7</sup>China Institute of Atomic Energy, Beijing, China
- <sup>8</sup>Department of Physics and Technology, University of Bergen, Bergen, Norway
- <sup>9</sup>Faculty of Engineering, Bergen University College, Bergen, Norway
- <sup>10</sup>Lawrence Berkeley National Laboratory, Berkeley, CA, USA
- <sup>11</sup>Institute of Physics, Bhubaneswar, India
- <sup>12</sup>School of Physics and Astronomy, University of Birmingham, Birmingham, UK
- <sup>13</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Bologna, Italy
- <sup>14</sup>Sezione INFN, Bologna, Italy
- <sup>15</sup>Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia
- <sup>16</sup>Institute of Space Sciences (ISS), Bucharest, Romania
- <sup>17</sup>National Institute for Physics and Nuclear Engineering, Bucharest, Romania
- <sup>18</sup>KFKI Research Institute for Particle and Nuclear Physics, Hungarian Academy of Sciences, Budapest, Hungary
- <sup>19</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
- <sup>20</sup>Sezione INFN, Cagliari, Italy
- <sup>21</sup>Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
- <sup>22</sup>Physics Department, University of Cape Town, iThemba Laboratories, Cape Town, South Africa
- <sup>23</sup>Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
- <sup>24</sup>Sezione INFN, Catania, Italy
- <sup>25</sup>Physics Department, Panjab University, Chandigarh, India
- <sup>26</sup>Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France
- <sup>27</sup>Department of Physics, Ohio State University, Columbus, OH, USA
- <sup>28</sup>Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- <sup>29</sup>The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
- <sup>30</sup>Universidad Autónoma de Sinaloa, Culiacán, Mexico
- <sup>31</sup>Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany
- <sup>32</sup>Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany
- <sup>33</sup>Wayne State University, Detroit, MI, USA
- <sup>34</sup>Joint Institute for Nuclear Research (JINR), Dubna, Russia
- <sup>35</sup>Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- <sup>36</sup>Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
- <sup>37</sup>Laboratori Nazionali di Frascati, INFN, Frascati, Italy
- <sup>38</sup>Gangneung-Wonju National University, Gangneung, South Korea
- <sup>39</sup>Petersburg Nuclear Physics Institute, Gatchina, Russia
- <sup>40</sup>European Organization for Nuclear Research (CERN), Geneva, Switzerland
- <sup>41</sup>Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France
- <sup>42</sup>Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
- <sup>43</sup>Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>44</sup>Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- <sup>45</sup>Hiroshima University, Hiroshima, Japan
- <sup>46</sup>University of Houston, Houston, TX, USA
- <sup>47</sup>Physics Department, University of Rajasthan, Jaipur, India
- <sup>48</sup>Physics Department, University of Jammu, Jammu, India
- <sup>49</sup>Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland
- <sup>50</sup>Bogolyubov Institute for Theoretical Physics, Kiev, Ukraine
- <sup>51</sup>University of Tennessee, Knoxville, TN, USA
- <sup>52</sup>Saha Institute of Nuclear Physics, Kolkata, India
- <sup>53</sup>Variable Energy Cyclotron Centre, Kolkata, India
- <sup>54</sup>Fachhochschule Köln, Köln, Germany
- <sup>55</sup>Faculty of Science, P.J. Šafárik University, Košice, Slovakia
- <sup>56</sup>Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
- <sup>57</sup>Laboratori Nazionali di Legnaro, INFN, Legnaro, Italy
- <sup>58</sup>Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
- <sup>59</sup>Lawrence Livermore National Laboratory, Livermore, CA, USA
- <sup>60</sup>Division of Experimental High Energy Physics, University of Lund, Lund, Sweden
- <sup>61</sup>Institut de Physique Nucléaire de Lyon, Université de Lyon 1, CNRS/IN2P3, Lyon, France
- <sup>62</sup>Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- <sup>63</sup>Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
- <sup>64</sup>Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
- <sup>65</sup>Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
- <sup>66</sup>Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
- <sup>67</sup>Institute for Theoretical and Experimental Physics, Moscow, Russia
- <sup>68</sup>Moscow Engineering Physics Institute, Moscow, Russia
- <sup>69</sup>Russian Research Centre Kurchatov Institute, Moscow, Russia
- <sup>70</sup>Indian Institute of Technology, Mumbai, India

- <sup>71</sup>Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany  
<sup>72</sup>SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France  
<sup>73</sup>Yale University, New Haven, CT, USA  
<sup>74</sup>Budker Institute for Nuclear Physics, Novosibirsk, Russia  
<sup>75</sup>Oak Ridge National Laboratory, Oak Ridge, TN, USA  
<sup>76</sup>Physics Department, Creighton University, Omaha, NE, USA  
<sup>77</sup>Institut de Physique Nucléaire d'Orsay (IPNO), Université Paris-Sud, CNRS-IN2P3, Orsay, France  
<sup>78</sup>Department of Physics, University of Oslo, Oslo, Norway  
<sup>79</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Padova, Italy  
<sup>80</sup>Sezione INFN, Padova, Italy  
<sup>81</sup>Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic  
<sup>82</sup>Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic  
<sup>83</sup>Institute for High Energy Physics, Protvino, Russia  
<sup>84</sup>Benemérita Universidad Autónoma de Puebla, Puebla, Mexico  
<sup>85</sup>Pusan National University, Pusan, South Korea  
<sup>86</sup>Nuclear Physics Institute, Academy of Sciences of the Czech Republic, Řež u Prahy, Czech Republic  
<sup>87</sup>Dipartimento di Fisica dell'Università 'La Sapienza' and Sezione INFN, Rome, Italy  
<sup>88</sup>Sezione INFN, Rome, Italy  
<sup>89</sup>Commissariat à l'Energie Atomique, IRFU, Saclay, France  
<sup>90</sup>Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Sezione INFN, Salerno, Italy  
<sup>91</sup>California Polytechnic State University, San Luis Obispo, CA, USA  
<sup>92</sup>Departamento de Física de Partículas and IGFAE, Universidad de Santiago de Compostela, Santiago de Compostela, Spain  
<sup>93</sup>Universidade de São Paulo (USP), São Paulo, Brazil  
<sup>94</sup>Russian Federal Nuclear Center (VNIIEF), Sarov, Russia  
<sup>95</sup>Department of Physics, Sejong University, Seoul, South Korea  
<sup>96</sup>Yonsei University, Seoul, South Korea  
<sup>97</sup>Technical University of Split FESB, Split, Croatia  
<sup>98</sup>V. Fock Institute for Physics, St. Petersburg State University, St. Petersburg, Russia  
<sup>99</sup>Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France  
<sup>100</sup>University of Tokyo, Tokyo, Japan  
<sup>101</sup>Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy  
<sup>102</sup>Sezione INFN, Trieste, Italy  
<sup>103</sup>University of Tsukuba, Tsukuba, Japan  
<sup>104</sup>Dipartimento di Fisica Sperimentale dell'Università and Sezione INFN, Turin, Italy  
<sup>105</sup>Sezione INFN, Turin, Italy  
<sup>106</sup>Institute for Subatomic Physics, Utrecht University, Utrecht, Netherlands  
<sup>107</sup>Soltan Institute for Nuclear Studies, Warsaw, Poland  
<sup>108</sup>Warsaw University of Technology, Warsaw, Poland  
<sup>109</sup>Purdue University, West Lafayette, IN, USA  
<sup>110</sup>Zentrum für Technologietransfer und Telekommunikation (ZTT), Fachhochschule Worms, Worms, Germany  
<sup>111</sup>Hua-Zhong Normal University, Wuhan, China  
<sup>112</sup>Yerevan Physics Institute, Yerevan, Armenia  
<sup>113</sup>Rudjer Bošković Institute, Zagreb, Croatia

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<sup>a</sup> e-mail: [jurgen.schukraft@cern.ch](mailto:jurgen.schukraft@cern.ch)

<sup>b</sup> Also at Laboratoire de Physique Corpusculaire (LPC), Clermont Université, Université Blaise Pascal, CNRS-IN2P3, Clermont-Ferrand, France.

<sup>c</sup> Also at Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany.

<sup>d</sup> Now at Sezione INFN, Padova, Italy.

<sup>e</sup> Now at Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany.

<sup>f</sup> Now at Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany.

<sup>g</sup> Now at Physics Department, University of Cape Town, iThemba Laboratories, Cape Town, South Africa.

<sup>h</sup> Now at National Institute for Physics and Nuclear Engineering, Bucharest, Romania.

<sup>i</sup> Also at University of Houston, Houston, TX, USA.

<sup>j</sup> Now at Faculty of Science, P.J. Šafárik University, Košice, Slovakia.

<sup>k</sup> Now at European Organization for Nuclear Research (CERN), Geneva, Switzerland.

<sup>l</sup> Now at Helsinki Institute of Physics (HIP) and University of Jyväskylä, Jyväskylä, Finland.

<sup>m</sup> Now at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, Strasbourg, France.

<sup>n</sup> Now at Sezione INFN, Bari, Italy.

<sup>o</sup> Now at Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany.

<sup>p</sup> Now at University of Technology and Austrian Academy of Sciences, Vienna, Austria.

<sup>q</sup> Also at Lawrence Livermore National Laboratory, Livermore, CA, USA.

**Abstract** The pseudorapidity density and multiplicity distribution of charged particles produced in proton–proton collisions at the LHC, at a centre-of-mass energy  $\sqrt{s} = 7$  TeV, were measured in the central pseudorapidity region  $|\eta| < 1$ . Comparisons are made with previous measurements at  $\sqrt{s} = 0.9$  TeV and 2.36 TeV. At  $\sqrt{s} = 7$  TeV, for events with at least one charged particle in  $|\eta| < 1$ , we obtain  $dN_{\text{ch}}/d\eta = 6.01 \pm 0.01$  (stat.) $_{-0.12}^{+0.20}$  (syst.). This corresponds to an increase of  $57.6\% \pm 0.4\%$  (stat.) $_{-1.8}^{+3.6}\%$  (syst.) relative to collisions at 0.9 TeV, significantly higher than calculations from commonly used models. The multiplicity distribution at 7 TeV is described fairly well by the negative binomial distribution.

<sup>r</sup>Also at European Organization for Nuclear Research (CERN), Geneva, Switzerland.

<sup>s</sup>Now at Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru.

<sup>t</sup>Deceased.

<sup>u</sup>Now at Yale University, New Haven, CT, USA.

<sup>v</sup>Now at University of Tsukuba, Tsukuba, Japan.

<sup>w</sup>Also at Centro Fermi – Centro Studi e Ricerche e Museo Storico della Fisica “Enrico Fermi”, Rome, Italy.

<sup>x</sup>Now at Dipartimento Interateneo di Fisica ‘M. Merlin’ and Sezione INFN, Bari, Italy.

<sup>y</sup>Also at Laboratoire de Physique Subatomique et de Cosmologie (LPSC), Université Joseph Fourier, CNRS-IN2P3, Institut Polytechnique de Grenoble, Grenoble, France.

<sup>z</sup>Now at Dipartimento di Fisica Sperimentale dell’Università and Sezione INFN, Turin, Italy.

<sup>aa</sup>Now at Physics Department, Creighton University, Omaha, NE, USA.

<sup>ab</sup>Now at Commissariat à l’Energie Atomique, IRFU, Saclay, France.

<sup>ac</sup>Also at Department of Physics, University of Oslo, Oslo, Norway.

<sup>ad</sup>Now at Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany.

<sup>ae</sup>Now at Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany.

<sup>af</sup>Now at Department of Physics and Technology, University of Bergen, Bergen, Norway.

<sup>ag</sup>Now at Physics Department, University of Athens, Athens, Greece.

<sup>ah</sup>Also at Institut für Kernphysik, Westfälische Wilhelms-Universität Münster, Münster, Germany.

<sup>ai</sup>Now at SUBATECH, Ecole des Mines de Nantes, Université de Nantes, CNRS-IN2P3, Nantes, France.

<sup>aj</sup>Now at Université de Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Lyon, France.

<sup>ak</sup>Now at Centre de Calcul IN2P3, Lyon, France.

<sup>al</sup>Now at Variable Energy Cyclotron Centre, Kolkata, India.

<sup>am</sup>Also at Dipartimento di Fisica dell’Università and Sezione INFN, Padova, Italy.

<sup>an</sup>Also at Sezione INFN, Bologna, Italy.

<sup>ao</sup>Also at Dipartimento di Fisica dell’Università, Udine, Italy.

<sup>ap</sup>Also at Wrocław University, Wrocław, Poland.

## 1 Introduction

We present the pseudorapidity density and the multiplicity distribution for primary charged particles<sup>1</sup> from a sample of  $3 \times 10^5$  proton–proton events at a centre-of-mass energy  $\sqrt{s} = 7$  TeV collected with the ALICE detector [1] at the LHC [2], and compare them with our previous results at  $\sqrt{s} = 0.9$  TeV and  $\sqrt{s} = 2.36$  TeV [3, 4]. The present study is for the central pseudorapidity region  $|\eta| < 1$ .

In the previous measurements, the main contribution to systematic uncertainties came from the limited knowledge of cross sections and kinematics of diffractive processes. At 7 TeV, there is no experimental information available about these processes; therefore, we do not attempt to normalize our results to the classes of events used in our previous publications (inelastic events and non-single-diffractive events). Instead, we chose an event class requiring at least one charged particle in the pseudorapidity interval  $|\eta| < 1$  ( $\text{INEL} > 0_{|\eta| < 1}$ ), minimizing the model dependence of the corrections. We re-analyzed the data already published at 0.9 TeV and 2.36 TeV in order to normalize the results to this event class. These measurements have been compared to calculations with several commonly used models [5–10] which will allow a better tuning to accurately simulate minimum-bias and underlying-event effects. Currently, the expectations for 7 TeV differ significantly from one another, both for the average multiplicity and for the multiplicity distribution (see e.g. [11]).

## 2 ALICE detector and data collection

The ALICE detector is described in [1]. This analysis uses data from the Silicon Pixel Detector (SPD) and the VZERO counters, as described in [3, 4]. The SPD detector comprises two cylindrical layers (radii 3.9 and 7.6 cm) surrounding the central beam pipe, and covers the pseudorapidity ranges  $|\eta| < 2$  and  $|\eta| < 1.4$ , for the inner and outer layers, respectively. The two VZERO scintillator hodoscopes are placed on either side of the interaction region at  $z = 3.3$  m and  $z = -0.9$  m, covering the pseudorapidity regions  $2.8 < \eta < 5.1$  and  $-3.7 < \eta < -1.7$ , respectively.

Data were collected at a magnetic field of 0.5 T. The typical bunch intensity for collisions at 7 TeV was  $1.5 \times 10^{10}$  protons resulting in a luminosity around  $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ . There was only one bunch per beam colliding at the ALICE interaction point. The probability that a recorded event contains more than one collision was estimated to be around  $2 \times 10^{-3}$ . A consistent value was measured by counting the

<sup>1</sup>Primary particles are defined as prompt particles produced in the collision and all decay products, except products from weak decays of strange particles.

events where more than one distinct vertex could be reconstructed. We checked that pileup events did not introduce a significant bias using a simulation.

The data at 0.9 TeV and 7 TeV were collected with a trigger requiring a hit in the SPD or in either one of the VZERO counters; i.e. essentially at least one charged particle anywhere in the 8 units of pseudorapidity. At 2.36 TeV, the VZERO detector was turned off; the trigger required at least one hit in the SPD ( $|\eta| < 2$ ). The events were in coincidence with signals from two beam pick-up counters, one on each side of the interaction region, indicating the passage of proton bunches. Control triggers taken (with the exception of the 2.36 TeV data) for various combinations of beam and empty-beam buckets were used to measure beam-induced and accidental backgrounds. Most backgrounds were removed as described in [4]. The remaining background in the sample is of the order of  $10^{-4}$  to  $10^{-5}$  and can be neglected.

### 3 Event selection and analysis

The position of the interaction vertex was reconstructed by correlating hits in the two silicon-pixel layers. The vertex resolution achieved depends on the track multiplicity, and is typically 0.1–0.3 mm in the longitudinal ( $z$ ) and 0.2–0.5 mm in the transverse direction.

The analysis is based on using hits in the two SPD layers to form short track segments, called tracklets. A tracklet is defined by a hit combination, one hit in the inner and one in the outer SPD layer, pointing to the reconstructed vertex. The tracklet algorithm is described in [3, 4].

Events used in the analysis were required to have a reconstructed vertex and at least one SPD tracklet with  $|\eta| < 1$ . We restrict the  $z$ -vertex range to  $|z| < 5.5$  cm to ensure that the  $\eta$ -interval is entirely within the SPD acceptance. After this selection, 47 000, 35 000, and 240 000 events remain for analysis, at 0.9, 2.36, and 7 TeV, respectively. The selection efficiency was studied using two different Monte Carlo event generators, PYTHIA 6.4.21 [5, 6] tune Perugia-0 [9] and PHOJET [10], with detector simulation and reconstruction.

The number of primary charged particles is estimated by counting the number of SPD tracklets, corrected for:

- geometrical acceptance and detector and reconstruction efficiencies;
- contamination from weak-decay products of strange particles, gamma conversions, and secondary interactions;
- undetected particles below the 50 MeV/ $c$  transverse-momentum cut-off, imposed by absorption in the material;
- combinatorial background in tracklet reconstruction.

The total number of collisions corresponding to our data is obtained from the number of events selected for the analysis,

applying corrections for trigger and selection efficiencies. This leads to overall corrections of 7.8, 7.2, and 5.7% at 0.9, 2.36, and 7 TeV, respectively.

The multiplicity distributions were measured for  $|\eta| < 1$  at each energy. For the 0.9 and 2.36 TeV data we did not repeat the multiplicity-distribution analysis, we used the results from [4] while removing the zero-multiplicity bin. At 7 TeV, we used the same method as described in [4, 13] to correct the raw measured distributions for efficiency, acceptance, and other detector effects, which is based on unfolding using a detector response matrix from Monte Carlo simulations. The unfolding procedure applies  $\chi^2$  minimization with regularization [12]. Consistent results were found when changing the regularization term and the convergence criteria within reasonable limits, and when using a different unfolding method based on Bayes's theorem [14, 15].

### 4 Systematic uncertainties

Only events with at least one tracklet in  $|\eta| < 1$  have been selected for analysis in order to reduce sensitivity to model-dependent corrections. However, a fraction of diffractive reactions also falls into this event category and influences the correction factors at low multiplicities. In order to evaluate this effect, we varied the fractions of single-diffractive and double-diffractive events produced by the event generators by  $\pm 50\%$  of their nominal values at 7 TeV, and for the other energies we used the variations described in [4]. The resulting contributions to the systematic uncertainties are estimated to be 0.5, 0.3, and 1% for the data at 0.9, 2.36, and 7 TeV, respectively. For the same reason, the event selection efficiency is sensitive to the differences between models used to calculate this correction. Therefore, we used the two models which have the largest difference in their multiplicity distributions at very low multiplicities (see below): PYTHIA tune Perugia-0 and PHOJET. The first one was used to calculate the central values for all our results, and the second for asymmetric systematic uncertainties. The values obtained for this contribution are +0.8, +1.5, and +2.8% for the three energies considered.

Other sources of systematic uncertainties, e.g. the particle composition, the  $p_T$  spectrum and the detector efficiency, are described in [4], and their contributions were estimated in the same way. As a consequence of the smaller uncertainties on the event selection corrections the total systematic uncertainties are significantly smaller than in our previous analyses, which use as normalization inelastic and non-single-diffractive collisions. Many of the systematic uncertainties cancel when the ratios between the different energies are calculated, in particular the dominating ones, such as the detector efficiency and the event generator dependence. The systematic uncertainty related to diffractive cross sections was assumed to be uncorrelated between energies.

**Table 1** Charged-particle pseudorapidity densities at central pseudorapidity ( $|\eta| < 1$ ), for inelastic collisions having at least one charged particle in the same region ( $\text{INEL} > 0_{|\eta| < 1}$ ), at three centre-of-mass energies. For ALICE, the first uncertainty is statistical and the second is systematic. The relative increases between the 0.9 TeV and 2.36 TeV

data, and between the 0.9 TeV and 7 TeV data, are given in percentages. The experimental measurements are compared to the predictions from models. For PYTHIA the tune versions are given in parentheses. The correspondence is as follows: D6T tune (109), ATLAS-CSC tune (306), and Perugia-0 tune (320)

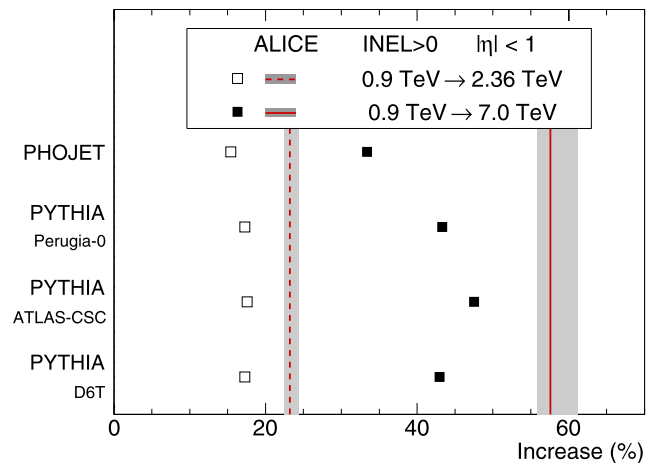
Energy (TeV)	ALICE	PYTHIA [5, 6]			PHOJET [10]
		(109) [7]	(306) [8]	(320) [9]	
Charged-particle pseudorapidity density					
0.9	$3.81 \pm 0.01^{+0.07}_{-0.07}$	3.05	3.92	3.18	3.73
2.36	$4.70 \pm 0.01^{+0.11}_{-0.08}$	3.58	4.61	3.72	4.31
7	$6.01 \pm 0.01^{+0.20}_{-0.12}$	4.37	5.78	4.55	4.98
Relative increase (%)					
0.9–2.36	$23.3 \pm 0.4^{+1.1}_{-0.7}$	17.3	17.6	17.3	15.4
0.9–7	$57.6 \pm 0.4^{+3.6}_{-1.8}$	43.0	47.6	43.3	33.4

## 5 Results

The pseudorapidity densities of primary charged particles obtained in the central pseudorapidity region  $|\eta| < 1$  are presented in Table 1 and compared to models. The measured values are higher than those from the models considered, except for PYTHIA tune ATLAS-CSC for the 0.9 and 2.36 TeV data, and PHOJET for the 0.9 TeV data, which are consistent with the data. At 7 TeV, the data are significantly higher than the values from the models considered, with the exception of PYTHIA tune ATLAS-CSC, for which the data are only two standard deviations higher. We have also studied the relative increase of pseudorapidity densities of charged particles (Table 1) between the measurement at 0.9 TeV and the measurements at 2.36 and 7 TeV. We observe an increase of  $57.6\% \pm 0.4\%$  (stat.) $^{+3.6}_{-1.8}\%$  (syst.) between the 0.9 TeV and 7 TeV data, compared with an increase of 47.6% obtained from the closest model, PYTHIA tune ATLAS-CSC (Fig. 1). The 7 TeV data confirm the observation made in [4, 16] that the measured multiplicity density increases with increasing energy significantly faster than in any of the models considered.

In Fig. 2, we compare the centre-of-mass energy dependence of the pseudorapidity density of charged particles for the  $\text{INEL} > 0_{|\eta| < 1}$  class to the evolution for other event classes (inelastic and non-single-diffractive events), which have been measured at lower energies. Note that  $\text{INEL} > 0_{|\eta| < 1}$  values are higher than inelastic and non-single-diffractive values, as expected, because events with no charged particles in  $|\eta| < 1$  are removed.

The increase in multiplicity from 0.9 TeV to 2.36 TeV and 7 TeV was studied by measuring the multiplicity distributions for the event class,  $\text{INEL} > 0_{|\eta| < 1}$  (Fig. 3 left). Small wavy fluctuations are seen at multiplicities above 25. While visually they may appear to be significant, one should



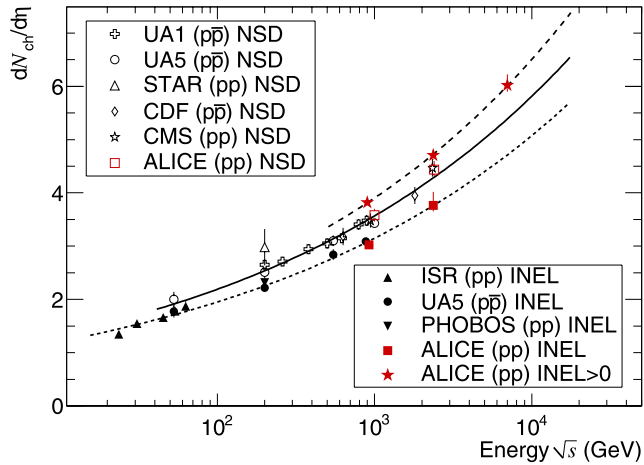
**Fig. 1** Relative increase of the charged-particle pseudorapidity density, for inelastic collisions having at least one charged particle in  $|\eta| < 1$ , between  $\sqrt{s} = 0.9$  TeV and 2.36 TeV (*open squares*) and between  $\sqrt{s} = 0.9$  TeV and 7 TeV (*full squares*), for various models. Corresponding ALICE measurements are shown with *vertical dashed and solid lines*; the width of *shaded bands* correspond to the statistical and systematic uncertainties added in quadrature

note that the errors in the deconvoluted distribution are correlated over a range comparable to the multiplicity resolution and the uncertainty bands should be seen as one-standard-deviation envelopes of the deconvoluted distributions (see also [4]). The unfolded distributions at 0.9 TeV and 2.36 TeV are described well by the Negative Binomial Distribution (NBD). At 7 TeV, the NBD fit slightly underestimates the data at low multiplicities ( $N_{\text{ch}} < 5$ ) and slightly overestimates the data at high multiplicities ( $N_{\text{ch}} > 55$ ).

A comparison of the 7 TeV data with models (Fig. 3 right) shows that only the PYTHIA tune ATLAS-CSC is close to the data at high multiplicities ( $N_{\text{ch}} > 25$ ). However, it does not reproduce the data in the intermediate multiplicity region ( $8 < N_{\text{ch}} < 25$ ). At low multiplicities, ( $N_{\text{ch}} < 5$ ),



there is a large spread of values between different models: PHOJET is the lowest and PYTHIA tune Perugia-0 the highest.



**Fig. 2** Charged-particle pseudorapidity density in the central pseudorapidity region  $|\eta| < 0.5$  for inelastic and non-single-diffractive collisions [4, 16–25], and in  $|\eta| < 1$  for inelastic collisions with at least one charged particle in that region ( $\text{INEL} > 0_{|\eta| < 1}$ ), as a function of the centre-of-mass energy. The lines indicate the fit using a power-law dependence on energy. Note that data points at the same energy have been slightly shifted horizontally for visibility

### 6 Conclusion

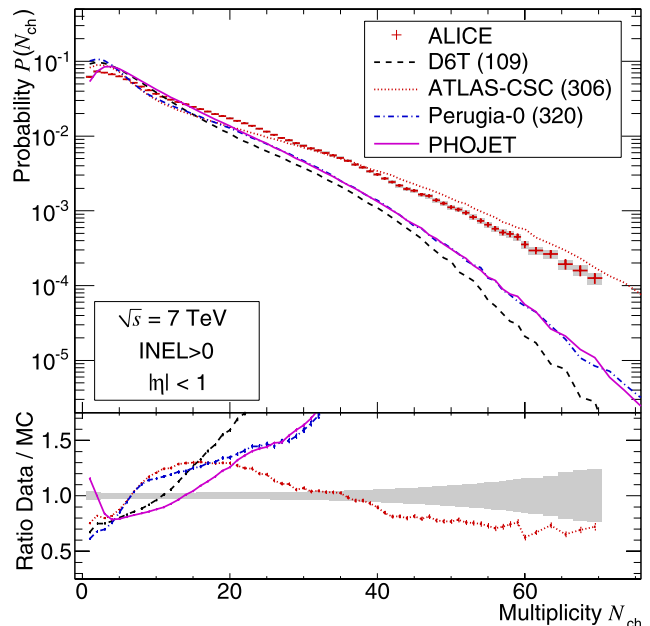
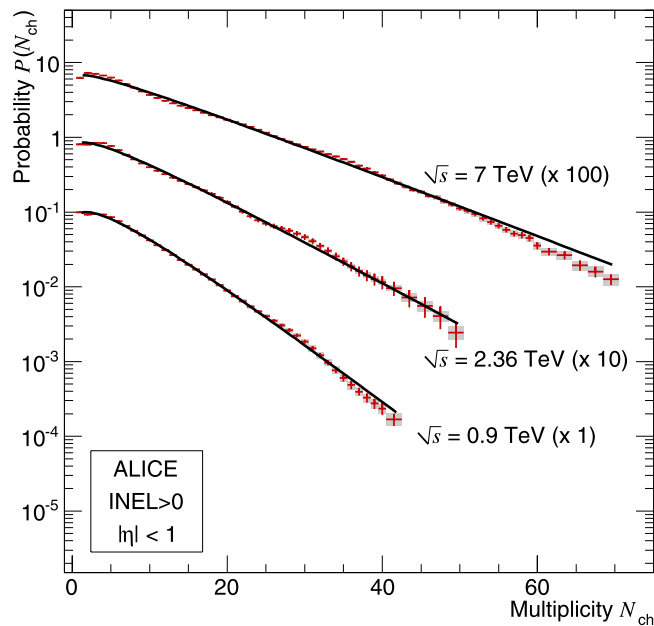
We have presented measurements of the pseudorapidity density and multiplicity distributions of primary charged particles produced in proton–proton collisions at the LHC, at a centre-of-mass energy  $\sqrt{s} = 7$  TeV. The measured value of the pseudorapidity density at this energy is significantly higher than that obtained from current models, except for PYTHIA tune ATLAS-CSC. The increase of the pseudorapidity density with increasing centre-of-mass energies is significantly higher than that obtained with any of the models and tunes used in this study.

The shape of our measured multiplicity distribution is not reproduced by any of the event generators considered. The discrepancy does not appear to be concentrated in a single region of the distribution, and varies with the model.

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**Fig. 3** Measured multiplicity distributions in  $|\eta| < 1$  for the  $\text{INEL} > 0_{|\eta| < 1}$  event class. The error bars for data points represent statistical uncertainties, the shaded areas represent systematic uncertainties. *Left:* The data at the three energies are shown with the NBD fits (lines). Note that for the 2.36 and 7 TeV data the distributions have been scaled for clarity by the factors indicated. *Right:* The data at 7 TeV

are compared to models: PHOJET (solid line), PYTHIA tunes D6T (dashed line), ATLAS-CSC (dotted line) and Perugia-0 (dash-dotted line). In the lower part, the ratios between the measured values and model calculations are shown with the same convention. The shaded area represents the combined statistical and systematic uncertainties

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