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# Measurements of groomed-jet substructure of charm jets tagged by $D^0$ mesons in proton–proton collisions at $\sqrt{s}$ = 13 TeV

## Supplemental material

ALICE Collaboration*

**Abstract**

Understanding the role of parton mass and Casimir colour factors in the quantum chromodynamics parton shower represents an important step in characterising the emission properties of heavy quarks. Recent experimental advances in jet substructure techniques have provided the opportunity to isolate and characterise gluon emissions from heavy quarks. In this work, the first direct experimental constraint on the charm-quark splitting function is presented, obtained via the measurement of the groomed shared momentum fraction of the first splitting in charm jets, tagged by a reconstructed $D^0$ meson. The measurement is made in proton–proton collisions at $\sqrt{s}$ = 13 TeV, in the low jet transverse-momentum interval of $15 \leq p_{\mathrm{T}}^{\mathrm{jet\ ch}} < 30$ GeV/$c$ where the emission properties are sensitive to parton mass effects. In addition, the opening angle of the first perturbative emission of the charm quark, as well as the number of perturbative emissions it undergoes, are reported. Comparisons to measurements of an inclusive-jet sample show a steeper splitting function for charm quarks compared to gluons and light quarks. Charm quarks also undergo fewer perturbative emissions in the parton shower, with a reduced probability of large-angle emissions.



*See Appendix A for the list of collaboration members

The measured $z_g$ distribution is also compared to analytical calculations performed in the soft-collinear effective theory (SCET) framework with resummation to modified leading-logarithmic accuracy (MLL) [1, 2], presented in Fig. 1, which are consistent with the data. The calculations do not include hadronisation effects and are performed utilising a leading-order evaluation of the charm cross section, which experimentally corresponds to jets with both charged and neutral information. It is expected that the low-$z_g$ region of the calculations are affected by non-perturbative effects. For comparison with the SCET predictions, the measurement is normalised to the number of jets passing the Soft Drop condition in each sample, as the calculations are provided for $z_g \geq 0.1$ and do not include an untagged fraction.

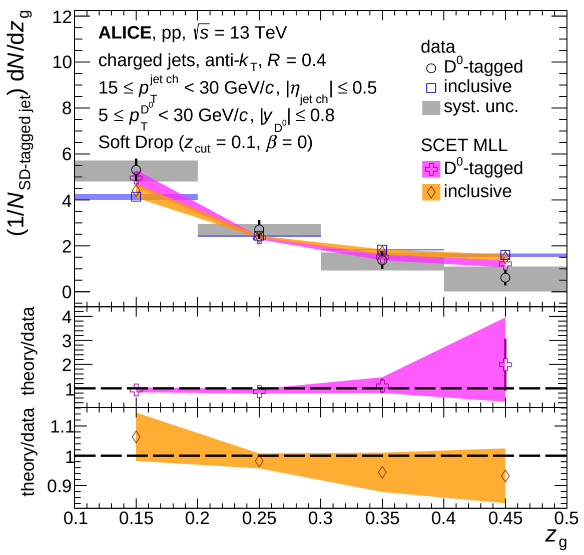


**Figure 1:** The $z_g$ distribution of prompt D$^0$-tagged jets compared to that of inclusive jets for $15 \leq p_T^{\text{jet ch}} < 30\,\text{GeV}/c$ in pp collisions at $\sqrt{s} = 13\,\text{TeV}$, normalised to the number of jets passing the Soft Drop condition. Model/data ratios are shown in the bottom panels for soft-collinear effective theory calculations [1, 2].

Comparisons of distributions of D$^0$-tagged jets, quark-initiated jets and gluon-initiated jets, obtained with PYTHIA 8 simulations, are shown in Figs. 2, 3 and 4 for the $z_g$, $R_g$ and $n_{SD}$ observables, respectively. The distributions are all normalised to the total number of jets in the kinematic range, regardless of whether they had a splitting which successfully passed the Soft Drop condition. Quark (gluon)-initiated jets are tagged by requiring an outgoing quark (gluon) from the initial hard scatter to be within $\Delta R < 0.4$ of the jet axis. Differences between the quark-initiated jet distributions and the gluon-initiated jet distributions highlight the role of Casimir colour effects in the observables, whilst differences between the quark-initiated jet distributions and the D$^0$-tagged jet distributions are sensitive to mass effects. We observe that the $z_g$ observable is not very sensitive to the different Casimir colour factors of quarks and gluons, but shows a heightened sensitivity to mass effects. The $R_g$ distribution on the other hand is sensitive to both effects, with the larger Casimir colour factor of gluons compared to quarks resulting in broader opening angles for gluon-initiated jets. The large mass of the charm quark also results in fewer small-angle emissions, compared to the quark-initiated jet sample, as expected from the presence of a large dead-cone region around the charm quark within which emissions are suppressed. The $n_{SD}$ distribution shows sensitivity to both Casimir and mass effects, with the impact of the latter being much more significant in this kinematic range. However, it is worth noting that flavour of emissions in the quark-tagged and gluon-tagged jets is only well defined for the first emission, whereas in the case of the D$^0$-tagged jets the flavour is controlled all the way through the shower.

The systematic uncertainties of the measured $z_g$, $R_g$ and $n_{SD}$ distributions of prompt D$^0$-tagged jets are presented in Figs. 5 and 6 for each individual uncertainty category considered (signal extraction,

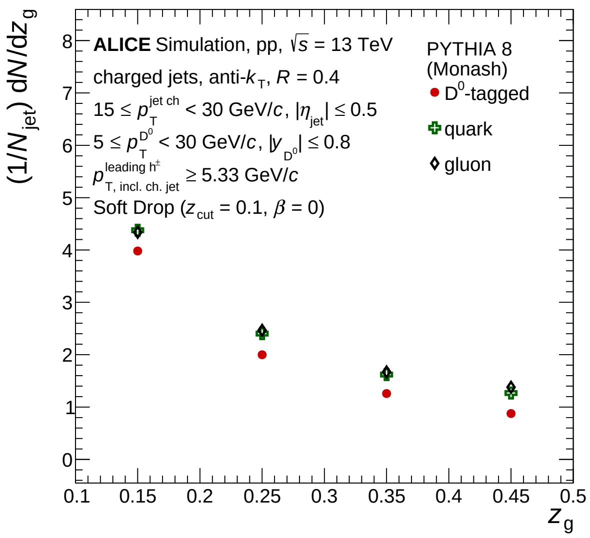


**Figure 2:** PYTHIA 8 $z_g$ distributions of prompt $D^0$-tagged jets, quark-initiated and gluon-initiated jets are compared, for $15 \leq p_T^{\text{jet ch}} < 30\,\text{GeV}/c$ in pp collisions at $\sqrt{s} = 13$ TeV.

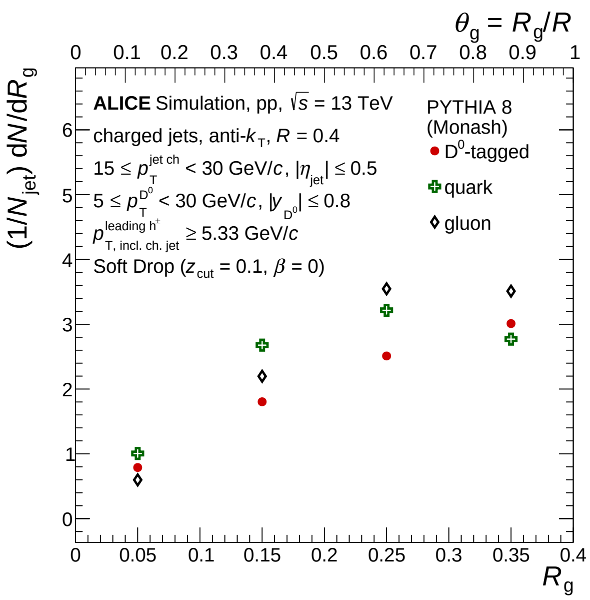


**Figure 3:** PYTHIA 8 $R_g$ distributions of prompt $D^0$-tagged jets, quark-initiated and gluon-initiated jets are compared, for $15 \leq p_T^{\text{jet ch}} < 30\,\text{GeV}/c$ in pp collisions at $\sqrt{s} = 13$ TeV.

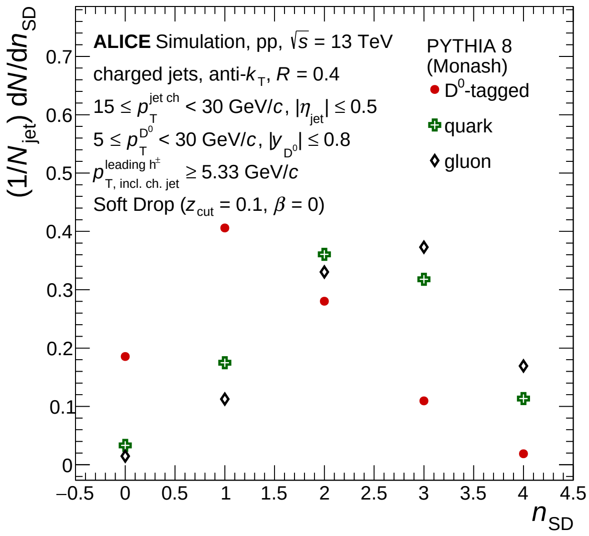


**Figure 4:** PYTHIA 8 $n_{\mathrm{SD}}$ distributions of prompt D$^0$-tagged jets, quark-initiated and gluon-initiated jets are compared, for $15 \leq p_{\mathrm{T}}^{\mathrm{jet\ ch}} < 30\,\mathrm{GeV}/c$ in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$.

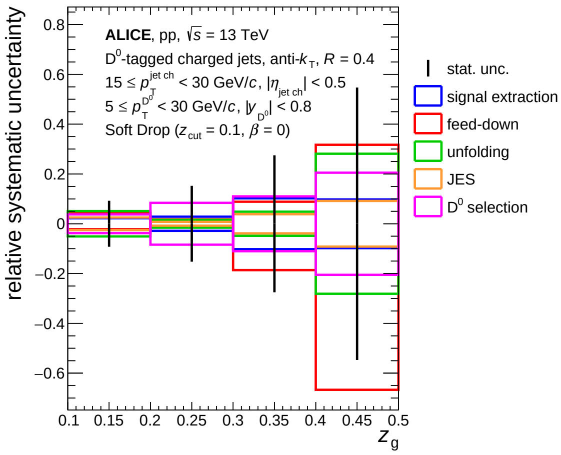


**Figure 5:** The systematic uncertainties of the measured $z_{\mathrm{g}}$ distribution of prompt D$^0$-tagged jets for each uncertainty category, relative to the central value of the measurement in each interval, are presented. The statistical uncertainty relative to the central value is also shown.

feed-down subtraction, unfolding, jet energy scale (JES), D$^0$ selection). The results are shown relative to the central values of the measured distributions in each interval. The statistical uncertainty relative to the central value is also shown for comparison.

The systematic uncertainties of the measured $z_{\mathrm{g}}$, $R_{\mathrm{g}}$ and $n_{\mathrm{SD}}$ distributions of inclusive jets are presented in Figs. 7 and 8 for each individual uncertainty category considered (unfolding, JES and $p_{\mathrm{T}}$ selection on the leading track). The results are shown relative to the central values of the measured distributions in each interval. The statistical uncertainty relative to the central value is also shown for comparison.

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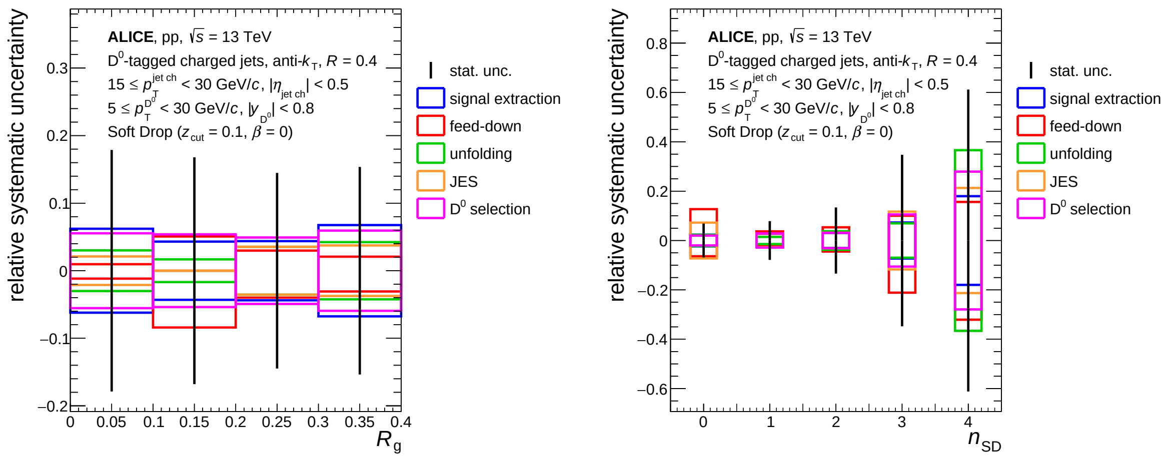


**Figure 6:** The systematic uncertainties of the measured $R_g$ (left) and $n_{SD}$ (right) distributions of prompt $D^0$-tagged jets for each uncertainty category, relative to the central value of the measurement in each interval, are presented. The statistical uncertainty relative to the central value is also shown.

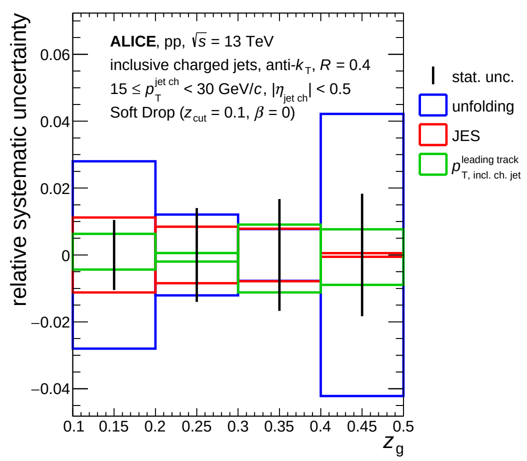


**Figure 7:** The systematic uncertainties of the measured $z_g$ distribution of inclusive jets for each uncertainty category, relative to the central value of the measurement in each interval, are presented. The statistical uncertainty relative to the central value is also shown.

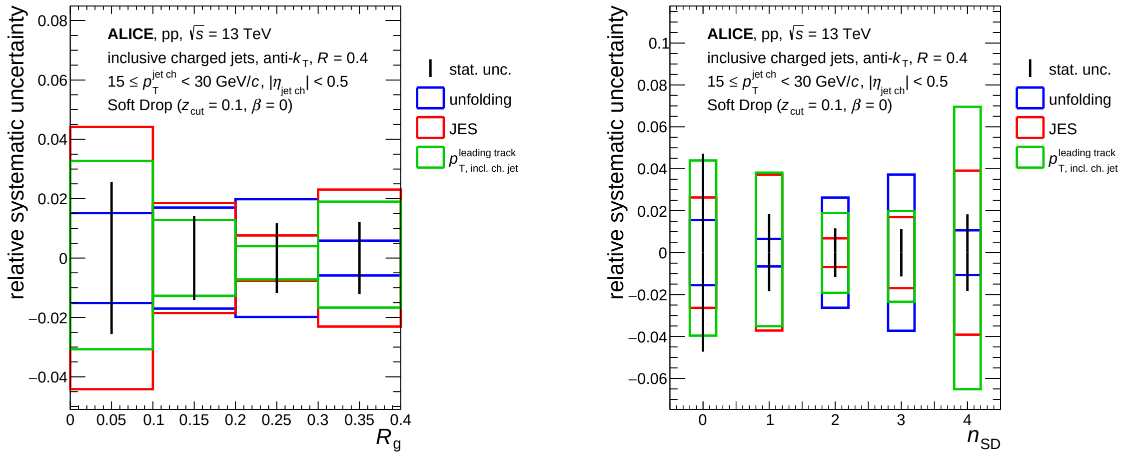


**Figure 8:** The systematic uncertainties of the measured $R_g$ (left) and $n_{SD}$ (right) distributions of inclusive jets for each uncertainty category, relative to the central value of the measurement in each interval, are presented. The statistical uncertainty relative to the central value is also shown.

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## A The ALICE Collaboration

S. Acharya[125], D. Adamová[86], A. Adler[69], G. Aglieri Rinella[32], M. Agnello[29], N. Agrawal[50], Z. Ahammed[132], S. Ahmad[15], S.U. Ahn[70], I. Ahuja[37], A. Akindinov[140], M. Al-Turany[98], D. Aleksandrov[140], B. Alessandro[55], H.M. Alfanda[6], R. Alfaro Molina[66], B. Ali[15], Y. Ali[13], A. Alici[25], N. Alizadehvandchali[114], A. Alkin[32], J. Alme[20], G. Alocco[51], T. Alt[63], I. Altsybeev[140], M.N. Anaam[6], C. Andrei[45], A. Andronic[135], V. Anguelov[95], F. Antinori[53], P. Antonioli[50], C. Anuj[15], N. Apadula[74], L. Aphecetche[104], H. Appelshäuser[63], C. Arata[73], S. Arcelli[25], M. Aresti[51], R. Arnaldi[55], I.C. Arsene[19], M. Arslandok[137], A. Augustinus[32], R. Averbeck[98], M.D. Azmi[15], A. Badalà[52], Y.W. Baek[40], X. Bai[118], R. Bailhache[63], Y. Bailung[47], R. Bala[91], A. Balbino[29], A. Baldisseri[128], B. Balis[2], D. Banerjee[4], Z. Banoo[91], R. Barbera[26], F. Barile[31], L. Barioglio[96], M. Barlou[78], G.G. Barnaföldi[136], L.S. 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Ivanov [140], V. Izucheev[140], M. Jablonski [2], B. Jacak [74], N. Jacazio [32], P.M. Jacobs [74], S. Jadlovska[106], J. Jadlovsky[106], S. Jaelani [82], L. Jaffe[38], C. Jahnke [111], M.J. Jakubowska [133], M.A. Janik [133], T. Janson[69], M. Jercic[89], O. Jevons[101], A.A.P. Jimenez [64], F. Jonas [87], P.G. Jones[101], J.M. Jowett [32,98], J. Jung [63], M. Jung [63], A. Junique [32], A. Jusko [101], M.J. Kabus [32,133], J. Kaewjai[105], P. Kalinak [59], A.S. Kalteyer [98], A. Kalweit [32], V. Kaplin [140], A. Karasu Uysal [71], D. Karatovic [89], O. Karavichev [140], T. Karavicheva [140], P. Karczmarczyk [133], E. Karpechev [140], V. Kashyap[80], U. Kebschull [69], R. Keidel [139], D.L.D. Keijdener[58], M. Keil [32], B. Ketzer [42], A.M. Khan [6], S. Khan [15], A. Khanzadeev [140], Y. Kharlov [140], A. Khatun [15], A. Khuntia [107], B. Kileng [34], B. Kim [16], C. Kim [16], D.J. Kim [115], E.J. Kim [68], J. Kim [138], J.S. Kim [40], J. Kim [95], J. Kim [68], M. Kim [95], S. Kim [17], T. Kim [138], K. Kimura [93], S. Kirsch [63], I. Kisel [38], S. Kiselev [140], A. Kisiel [133], J.P. Kitowski [2], J.L. Klay [5], J. Klein [32], S. Klein [74], C. Klein-Bösing [135], M. Kleiner [63], T. Klemenz [96], A. Kluge [32], A.G. Knospe [114], C. Kobdaj [105], T. Kollegger[98], A. Kondratyev [141], E. Kondratyuk [140], J. Konig [63], S.A. Konigstorfer [96], P.J. Konopka [32], G. Kornakov [133], S.D. Koryciak [2], A. Kotliarov [86], O. Kovalenko [79], V. Kovalenko [140], M. Kowalski [107], I. Králik [59], A. Kravčáková [37], L. Kreis[98], M. Krivda [101,59], F. Krizek [86], K. Krizkova Gajdosova [35], M. Kroesen [95], M. Krüger [63], D.M. Krupova [35], E. Kryshen [140], V. Kučera [32], C. Kuhn [127], P.G. Kuijer [84], T. Kumaoka[123], D. Kumar[132], L. Kumar [90], N. Kumar[90], S. Kumar [31], S. Kundu [32], P. Kurashvili [79], A. Kurepin [140], A.B. Kurepin [140], S. Kushpil [86], J. Kvapil [101], M.J. Kweon [57], J.Y. Kwon [57], Y. Kwon [138], S.L. La Pointe [38], P. La Rocca [26], Y.S. Lai[74], A. Lakrathok[105], M. Lamanna [32], R. Langoy [119], P. Larionov [32], E. Laudi [32], L. Lautner [32,96], R. Lavicka [103], T. Lazareva [140], R. Lea [131,54], G. Legras [135], J. Lehrbach [38], R.C. Lemmon [85], I. León Monzón [109], M.M. Lesch [96], E.D. Lesser [18], M. Lettrich[96], P. Lévai [136], X. Li[10], X.L. Li[6], J. Lien [119], R. Lietava [101], B. Lim [16], S.H. Lim [16], V. Lindenstruth [38], A. Lindner[45], C. Lippmann [98], A. Liu [18], D.H. Liu [6], J. Liu [117], I.M. Lofnes [20], C. Loizides [87], P. Loncar [33], J.A. Lopez [95], X. Lopez [125], E. López Torres [7], P. Lu [98,118], J.R. Luhder [135], M. Lunardon [27], G. Luparello [56], Y.G. Ma [39], A. Maevskaya[140], M. Mager [32], T. Mahmoud[42], A. Maire [127], M. Malaev [140], G. Malfattore [25], N.M. Malik [91], Q.W. Malik[19], S.K. Malik [91], L. Malinina [VII,141], D. Mal'Kevich [140], D. Mallick [80], N. Mallick [47], G. Mandaglio [30,52], V. Manko [140], F. Manso [125], V. Manzari [49], Y. Mao [6], G.V. Margagliotti [23], A. Margotti [50], A. Marín [98], C. Markert [108], P. Martinengo [32], J.L. Martinez[114], M.I. Martínez [44], G. Martínez García [104], S. Masciocchi [98], M. Masera [24], A. Masoni [51], L. Massacrier [72], A. Mastroserio [129,49], A.M. Mathis [96], O. Matonoha [75], P.F.T. Matuoka[110], A. Matyja [107], C. Mayer [107], A.L. Mazuecos [32], F. Mazzaschi [24], M. Mazzilli [32], J.E. Mdhluli [121], A.F. Mechler[63], Y. Melikyan [140], A. Menchaca-Rocha [66], E. Meninno [103,28], A.S. Menon [114], M. Meres [12], S. Mhlanga[113,67], Y. Miake[123], L. Micheletti [55], L.C. Migliorin[126], D.L. Mihaylov [96], K. Mikhaylov [141,140], A.N. Mishra [136], D. Miśkowiec [98], A. Modak [4], A.P. Mohanty [58], B. Mohanty[80], M. Mohisin Khan [V,15], M.A. Molander [43], Z. Moravcova [83], C. Mordasini [96], D.A. Moreira De Godoy [135], I. Morozov [140], A. Morsch [32], T. Mrnjavac [32], V. Muccifora [48], S. Muhuri [132], J.D. Mulligan [74], A. Mulliri[22], M.G. Munhoz [110], R.H. Munzer [63], H. Murakami [122], S. Murray [113], L. Musa [32], J. Musinsky [59], J.W. Myrcha [133], B. Naik [121], R. Nair [79], A.I. Nambrath [18], B.K. Nandi [46], R. Nania [50], E. Nappi [49], A.F. Nassirpour [75], A. Nath [95], C. Nattrass [120], A. Neagu[19], A. Negru[124], L. Nellen [64], S.V. Nesbo[34], G. Neskovic [38], D. Nesterov [140], B.S. Nielsen [83], E.G. Nielsen [83], S. Nikolaev [140], S. Nikulin [140], V. Nikulin [140], F. Noferini [50], S. Noh [11], P. Nomokonov [141], J. Norman [117], N. Novitzky [123], P. Nowakowski [133], A. Nyanin [140], J. Nystrand [20], M. Ogino [76], A. Ohlson [75], V.A. Okorokov [140], J. Oleniacz [133], A.C. Oliveira Da Silva [120], M.H. Oliver [137], A. Onnerstad [115], C. Oppedisano [55], A. Ortiz Velasquez [64], A. Oskarsson[75], J. Otwinowski [107], M. Oya[93], K. Oyama [76], Y. Pachmayer [95], S. Padhan [46], D. Pagano [131,54], G. Paić [64], A. Palasciano [49], S. Panebianco [128], H. Park [123], J. Park [57], J.E. Parkkila [32], R.N. Patra[91], B. Paul [22], H. Pei [6], T. Peitzmann [58], X. Peng [6],

M. Pennisi [24], L.G. Pereira [65], H. Pereira Da Costa [128], D. Peresunko [140], G.M. Perez [7], S. Perrin [128], Y. Pestov[140], V. Petráček [35], V. Petrov [140], M. Petrovici [45], R.P. Pezzi [104,65], S. Piano [56], M. Pikna [12], P. Pillot [104], O. Pinazza [50,32], L. Pinsky[114], C. Pinto [96], S. Pisano [48], M. Płoskoń [74], M. Planinic[89], F. Pliquett[63], M.G. Poghosyan [87], S. Politano [29], N. Poljak [89], A. Pop [45], S. Porteboeuf-Houssais [125], J. Porter [74], V. Pozdniakov [141], S.K. Prasad [4], S. Prasad [47], R. Preghenella [50], F. Prino [55], C.A. Pruneau [134], I. Pshenichnov [140], M. Puccio [32], S. Pucillo [24], Z. Pugelova[106], S. Qiu [84], L. Quaglia [24], R.E. Quishpe[114], S. Ragoni [14,101], A. Rakotozafindrabe [128], L. Ramello [130,55], F. Rami [127], S.A.R. Ramirez [44], T.A. Rancien[73], R. Raniwala [92], S. Raniwala[92], M. Rasa [26], S.S. Räsänen [43], R. Rath [50,47], I. Ravasenga [84], K.F. Read [87,120], C. Reckziegel [112], A.R. Redelbach [38], K. Redlich [VI,79], A. Rehman[20], F. Reidt [32], H.A. Reme-Ness [34], Z. Rescakova[37], K. Reygers [95], A. Riabov [140], V. Riabov [140], R. Ricci [28], T. Richert[75], M. Richter [19], A.A. Riedel [96], W. Riegler [32], F. Riggi [26], C. Ristea [62], M. Rodríguez Cahuantzi [44], K. Røed [19], R. Rogalev [140], E. Rogochaya [141], T.S. Rogoschinski [63], D. Rohr [32], D. Röhrich [20], P.F. Rojas[44], S. Rojas Torres [35], P.S. Rokita [133], G. Romanenko [141], F. Ronchetti [48], A. Rosano [30,52], E.D. Rosas[64], A. Rossi [53], A. Roy [47], P. Roy[100], S. Roy [46], N. Rubini [25], O.V. Rueda [75], D. Ruggiano [133], R. Rui [23], B. Rumyantsev[141], P.G. Russek [2], R. Russo [84], A. Rustamov [81], E. Ryabinkin [140], Y. Ryabov [140], A. Rybicki [107], H. Rytkonen [115], W. Rzesa [133], O.A.M. Saarimaki [43], R. Sadek [104], S. Sadhu [31], S. Sadovsky [140], J. Saetre [20], K. Šafařík [35], S.K. Saha [4], S. Saha [80], B. Sahoo [46], R. Sahoo [47], S. Sahoo[60], D. Sahu [47], P.K. Sahu [60], J. Saini [132], K. Sajdakova[37], S. Sakai [123], M.P. Salvan [98], S. Sambyal [91], T.B. Saramela[110], D. Sarkar [134], N. Sarkar[132], P. Sarma [41], V. Sarritzu [22], V.M. Sarti [96], M.H.P. Sas [137], J. Schambach [87], H.S. Scheid [63], C. Schiaua [45], R. Schicker [95], A. Schmah[95], C. Schmidt [98], H.R. Schmidt[94], M.O. Schmidt [32], M. Schmidt[94], N.V. Schmidt [87], A.R. Schmier [120], R. Schotter [127], J. Schukraft [32], K. Schwarz[98], K. Schweda [98], G. Scioli [25], E. Scomparin [55], J.E. Seger [14], Y. Sekiguchi[122], D. Sekihata [122], I. Selyuzhenkov [98,140], S. Senyukov [127], J.J. Seo [57], D. Serebryakov [140], L. Šerkšnytė [96], A. Sevcenco [62], T.J. Shaba [67], A. Shabetai [104], R. Shahoyan[32], A. Shangaraev [140], A. Sharma[90], D. Sharma [46], H. Sharma [107], M. Sharma [91], N. Sharma [90], S. Sharma [76], S. Sharma [91], U. Sharma [91], A. Shatat [72], O. Sheibani[114], K. Shigaki [93], M. Shimomura[77], S. Shirinkin [140], Q. Shou [39], Y. Sibiriak [140], S. Siddhanta [51], T. Siemiarczuk [79], T.F. Silva [110], D. Silvermyr [75], T. Simantathammakul[105], R. Simeonov [36], B. Singh[91], B. Singh [96], R. Singh [80], R. Singh [91], R. Singh [47], S. Singh [15], V.K. Singh [132], V. Singhal [132], T. Sinha [100], B. Sitar [12], M. Sitta [130,55], T.B. Skaali[19], G. Skorodumovs [95], M. Slupecki [43], N. Smirnov [137], R.J.M. Snellings [58], E.H. Solheim [19], J. Song [114], A. Songmoolnak[105], F. Soramel [27], S. Sorensen [120], R. Spijkers [84], I. Sputowska [107], J. Staa [75], J. Stachel [95], I. Stan [62], P.J. Steffanic [120], S.F. Stiefelmaier [95], D. Stocco [104], I. Storehaug [19], M.M. Storetvedt [34], P. Stratmann [135], S. Strazzi [25], C.P. Stylianidis[84], A.A.P. Suaide [110], C. Suire [72], M. Sukhanov [140], M. Suljic [32], V. Sumberia [91], S. Sumowidagdo [82], S. Swain[60], I. Szarka [12], U. Tabassam[13], S.F. Taghavi [96], G. Taillepied [98], J. Takahashi [111], G.J. Tambave [20], S. Tang [125,6], Z. Tang [118], J.D. Tapia Takaki [116], N. Tapus[124], L.A. Tarasovicova [135], M.G. Tarzila [45], G.F. Tassielli [31], A. Tauro [32], A. Telesca [32], L. Terlizzi [24], C. Terrevoli [114], G. Tersimonov[3], S. Thakur [4], D. Thomas [108], A. Tikhonov [140], A.R. Timmins [114], M. Tkacik[106], T. Tkacik [106], A. Toia [63], R. Tokumoto[93], N. Topilskaya [140], M. Toppi [48], F. Torales-Acosta[18], T. Tork [72], A.G. Torres Ramos [31], A. Trifiró [30,52], A.S. Triolo [30,52], S. Tripathy [50], T. Tripathy [46], S. Trogolo [32], V. Trubnikov [3], W.H. Trzaska [115], T.P. Trzcinski [133], R. Turrisi [53], T.S. Tveter [19], K. Ullaland [20], B. Ulukutlu [96], A. Uras [126], M. Urioni [54,131], G.L. Usai [22], M. Vala[37], N. Valle [21], S. Vallero [55], L.V.R. van Doremalen[58], M. van Leeuwen [84], C.A. van Veen [95], R.J.G. van Weelden [84], P. Vande Vyvre [32], D. Varga [136], Z. Varga [136], M. Varga-Kofarago [136], M. Vasileiou [78], A. Vasiliev [140], O. Vázquez Doce [48], V. Vechernin [140], E. Vercellin [24], S. Vergara Limón[44], L. Vermunt [98], R. Vértesi [136], M. Verweij [58], L. Vickovic[33], Z. Vilakazi[121], O. Villalobos Baillie [101], G. Vino [49], A. Vinogradov [140], T. Virgili [28], V. Vislavicius[83], A. Vodopyanov [141], B. Volkel [32], M.A. Völkl [95], K. Voloshin[140], S.A. Voloshin [134], G. Volpe [31], B. von Haller [32], I. Vorobyev [96], N. Vozniuk [140], J. Vrláková [37], B. Wagner[20], C. Wang [39], D. Wang[39], A. Wegrzynek [32], F.T. Weiglhofer[38], S.C. Wenzel [32], J.P. Wessels [135], S.L. Weyhmiller [137], J. Wiechula [63], J. Wikne [19], G. Wilk [79], J. Wilkinson [98], G.A. Willems [135], B. Windelband [95], M. Winn [128], J.R. Wright [108], W. Wu[39], Y. Wu [118], R. Xu [6], A. Yadav [42], A.K. Yadav [132], S. Yalcin [71], Y. Yamaguchi [93], K. Yamakawa[93], S. Yang[20], S. Yano [93], Z. Yin [6], I.-K. Yoo [16], J.H. Yoon [57], S. Yuan[20], A. Yuncu [95], V. Zaccolo [23], C. Zampolli [32], H.J.C. Zanoli[58], F. Zanone [95], N. Zardoshti [32,101], A. Zarochentsev [140], P. Závada [61], N. Zaviyalov[140], M. Zhalov [140], B. Zhang [6],

S. Zhang [39], X. Zhang [6], Y. Zhang[118], Z. Zhang [6], M. Zhao [10], V. Zherebchevskii [140], Y. Zhi[10], N. Zhigareva[140], D. Zhou [6], Y. Zhou [83], J. Zhu [98,6], Y. Zhu[6], G. Zinovjev[I,3], N. Zurlo [131,54]

## Affiliation Notes

[I] Deceased
[II] Also at: Max-Planck-Institut für Physik, Munich, Germany
[III] Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy
[IV] Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy
[V] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[VI] Also at: Institute of Theoretical Physics, University of Wroclaw, Poland
[VII] Also at: An institution covered by a cooperation agreement with CERN

## Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] AGH University of Science and Technology, Cracow, Poland
[3] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] California Polytechnic State University, San Luis Obispo, California, United States
[6] Central China Normal University, Wuhan, China
[7] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[8] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[9] Chicago State University, Chicago, Illinois, United States
[10] China Institute of Atomic Energy, Beijing, China
[11] Chungbuk National University, Cheongju, Republic of Korea
[12] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovak Republic
[13] COMSATS University Islamabad, Islamabad, Pakistan
[14] Creighton University, Omaha, Nebraska, United States
[15] Department of Physics, Aligarh Muslim University, Aligarh, India
[16] Department of Physics, Pusan National University, Pusan, Republic of Korea
[17] Department of Physics, Sejong University, Seoul, Republic of Korea
[18] Department of Physics, University of California, Berkeley, California, United States
[19] Department of Physics, University of Oslo, Oslo, Norway
[20] Department of Physics and Technology, University of Bergen, Bergen, Norway
[21] Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[22] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[25] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[28] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[29] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[30] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
[31] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[32] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[33] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[34] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[35] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[36] Faculty of Physics, Sofia University, Sofia, Bulgaria
[37] Faculty of Science, P.J. Šafárik University, Košice, Slovak Republic

[38] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[39] Fudan University, Shanghai, China
[40] Gangneung-Wonju National University, Gangneung, Republic of Korea
[41] Gauhati University, Department of Physics, Guwahati, India
[42] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[43] Helsinki Institute of Physics (HIP), Helsinki, Finland
[44] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[45] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[46] Indian Institute of Technology Bombay (IIT), Mumbai, India
[47] Indian Institute of Technology Indore, Indore, India
[48] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[49] INFN, Sezione di Bari, Bari, Italy
[50] INFN, Sezione di Bologna, Bologna, Italy
[51] INFN, Sezione di Cagliari, Cagliari, Italy
[52] INFN, Sezione di Catania, Catania, Italy
[53] INFN, Sezione di Padova, Padova, Italy
[54] INFN, Sezione di Pavia, Pavia, Italy
[55] INFN, Sezione di Torino, Turin, Italy
[56] INFN, Sezione di Trieste, Trieste, Italy
[57] Inha University, Incheon, Republic of Korea
[58] Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
[59] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovak Republic
[60] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[61] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[62] Institute of Space Science (ISS), Bucharest, Romania
[63] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[64] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[65] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[66] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[67] iThemba LABS, National Research Foundation, Somerset West, South Africa
[68] Jeonbuk National University, Jeonju, Republic of Korea
[69] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[70] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[71] KTO Karatay University, Konya, Turkey
[72] Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
[73] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[74] Lawrence Berkeley National Laboratory, Berkeley, California, United States
[75] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[76] Nagasaki Institute of Applied Science, Nagasaki, Japan
[77] Nara Women's University (NWU), Nara, Japan
[78] National and Kapodistrian University of Athens, School of Science, Department of Physics , Athens, Greece
[79] National Centre for Nuclear Research, Warsaw, Poland
[80] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[81] National Nuclear Research Center, Baku, Azerbaijan
[82] National Research and Innovation Agency - BRIN, Jakarta, Indonesia
[83] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[84] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
[85] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[86] Nuclear Physics Institute of the Czech Academy of Sciences, Husinec-Řež, Czech Republic
[87] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[88] Ohio State University, Columbus, Ohio, United States
[89] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[90] Physics Department, Panjab University, Chandigarh, India

[91] Physics Department, University of Jammu, Jammu, India
[92] Physics Department, University of Rajasthan, Jaipur, India
[93] Physics Program and International Institute for Sustainability with Knotted Chiral Meta Matter (SKCM2), Hiroshima University, Hiroshima, Japan
[94] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[95] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[96] Physik Department, Technische Universität München, Munich, Germany
[97] Politecnico di Bari and Sezione INFN, Bari, Italy
[98] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[99] Saga University, Saga, Japan
[100] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[101] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[102] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[103] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[104] SUBATECH, IMT Atlantique, Nantes Université, CNRS-IN2P3, Nantes, France
[105] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[106] Technical University of Košice, Košice, Slovak Republic
[107] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[108] The University of Texas at Austin, Austin, Texas, United States
[109] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[110] Universidade de São Paulo (USP), São Paulo, Brazil
[111] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[112] Universidade Federal do ABC, Santo Andre, Brazil
[113] University of Cape Town, Cape Town, South Africa
[114] University of Houston, Houston, Texas, United States
[115] University of Jyväskylä, Jyväskylä, Finland
[116] University of Kansas, Lawrence, Kansas, United States
[117] University of Liverpool, Liverpool, United Kingdom
[118] University of Science and Technology of China, Hefei, China
[119] University of South-Eastern Norway, Kongsberg, Norway
[120] University of Tennessee, Knoxville, Tennessee, United States
[121] University of the Witwatersrand, Johannesburg, South Africa
[122] University of Tokyo, Tokyo, Japan
[123] University of Tsukuba, Tsukuba, Japan
[124] University Politehnica of Bucharest, Bucharest, Romania
[125] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[126] Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
[127] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[128] Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[129] Università degli Studi di Foggia, Foggia, Italy
[130] Università del Piemonte Orientale, Vercelli, Italy
[131] Università di Brescia, Brescia, Italy
[132] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[133] Warsaw University of Technology, Warsaw, Poland
[134] Wayne State University, Detroit, Michigan, United States
[135] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[136] Wigner Research Centre for Physics, Budapest, Hungary
[137] Yale University, New Haven, Connecticut, United States
[138] Yonsei University, Seoul, Republic of Korea
[139] Zentrum für Technologie und Transfer (ZTT), Worms, Germany
[140] Affiliated with an institute covered by a cooperation agreement with CERN
[141] Affiliated with an international laboratory covered by a cooperation agreement with CERN.