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Reference pp cross sections for J/ψ and ψ(2S) production studies in p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

ALICE Collaboration*

Abstract

The values of the J/ψ and ψ(2S) production cross sections in pp collisions at a centre-of-mass energy of $\sqrt{s} = 8.16$ TeV are reported. These values are obtained from the existing measurements at $\sqrt{s} = 8$ TeV using an energy interpolation combined with an extrapolation in rapidity. They are used as reference for the measurements of J/ψ and ψ(2S) nuclear modification factors and double ratios, and for the J/ψ average transverse momentum ($\langle p_{\mathrm{T}} \rangle$) and average squared transverse momentum ($\langle p_{\mathrm{T}}^2 \rangle$) determination at the same center-of-mass-energy.

*See Appendix A for the list of collaboration members

1 Introduction

The production of J/ψ and ψ(2S) mesons in p–Pb collisions at the centre-of-mass energy per nucleon pair of $\sqrt{s_{\rm NN}} = 8.16$ TeV is reported in Ref. [1, 2]. The measurements performed by the ALICE Collaboration are reported in the centre-of-mass rapidity intervals $2.03 < y < 3.53$ (forward rapidity, p-going direction) and $-4.46 < y < -2.96$ (backward rapidity, Pb-going direction) as a function of the centrality of the collision, integrated or differential as a function of the quarkonium transverse momentum ($p_{\rm T}$) and rapidity (y). The measurements in p–Pb collisions are compared with the corresponding quantities in pp collisions at the same energy and in the same kinematic domain. The results in pp collisions, which are used as a reference, are reported in this note and their numerical values are also available in HEPData [3].

2 Cross section in proton–proton collisions at $\sqrt{s} = 8.16$ TeV

2.1 Cross section integrated over $p_{\rm T}$

Both ALICE and LHCb collaborations measured the J/ψ production cross section in pp collisions at $\sqrt{s} = 8$ TeV [4, 5]. However, these measurements cannot directly be used as a reference for the ALICE proton–nucleus results. First, an energy interpolation that takes into account the small increase in energy from $\sqrt{s} = 8$ TeV to 8.16 TeV was performed. Then the J/ψ production cross section was extrapolated from the rapidity interval $2.5 < y < 4$ (i.e. the rapidity range covered by the muon spectrometer in pp collisions) to the ones covered in p–Pb, namely $2.03 < y < 3.53$ and $-4.46 < y < -2.96$. The approach followed to perform the energy interpolation and the rapidity extrapolation is discussed in detail in Ref. [1]

The resulting values of the J/ψ production cross section for $p_{\rm T} > 0$ and in the two rapidity intervals are given in Table 1.

Table 1: Extrapolated J/ψ cross sections per unit of rapidity and for $p_{\rm T} > 0$ in pp collisions at $\sqrt{s}$ = 8.16 TeV [1]. The first quoted uncertainty is the total systematic uncertainty, whose size is provided in percentage in parenthesis. The uncorrelated contribution for a given rapidity region, and the correlated contribution common to both forward and backward rapidities are quoted in square brackets.

	$\mathrm{d}\sigma^{\mathrm{J}/\psi}/\mathrm{d}y$ (μb) (pp) ($0 < p_{\rm T} < 20$ GeV/c)
$-4.46 < y < -2.96$	4.472 ± 0.327 (7.3%) [0.081 (unc 1.8%) ± 0.316 (cor 7.1%)]
$2.03 < y < 3.53$	5.798 ± 0.419 (7.2%) [0.086 (unc 1.5%) ± 0.410 (cor 7.1%)]

The $\psi(2S)$ proton–proton reference is calculated at backward and forward rapidity by multiplying the J/ψ production cross sections in Table 1 by the corresponding ratio $\psi(2S)/J/\psi$ evaluated at $\sqrt{s} = 8.16$ TeV as

$$\mathrm{d}\sigma^{\psi(2S)}/\mathrm{d}y\Big|^{\rm Extr.}_{\sqrt{s}=8.16\rm TeV} = \mathrm{d}\sigma^{\mathrm{J}/\psi}/\mathrm{d}y\Big|_{\sqrt{s}=8.16\rm TeV} \times \left[\frac{\mathrm{d}\sigma^{\psi(2S)}/\mathrm{d}y}{\mathrm{d}\sigma^{\mathrm{J}/\psi}/\mathrm{d}y}\right]^{\rm Extr.}_{\sqrt{s}=8.16\rm TeV}. \quad (1)$$

The ratio $\psi(2S)/J/\psi$ is not available at $\sqrt{s} = 8.16$ TeV, therefore it is extracted by interpolating the ratio at $\sqrt{s} = 5$, 7, 8 and 13 TeV [6] with a constant function. The total uncertainty is the quadratic sum of the uncertainty from the fitting procedure and a 1% contribution due to the rapidity shift from pp to p–Pb collisions. An additional 1% uncertainty is added in quadrature to account for deviations from the constant dependence of the ratio with $\sqrt{s}$ as suggested by the NRQCD+CGC calculations [7, 8]. The

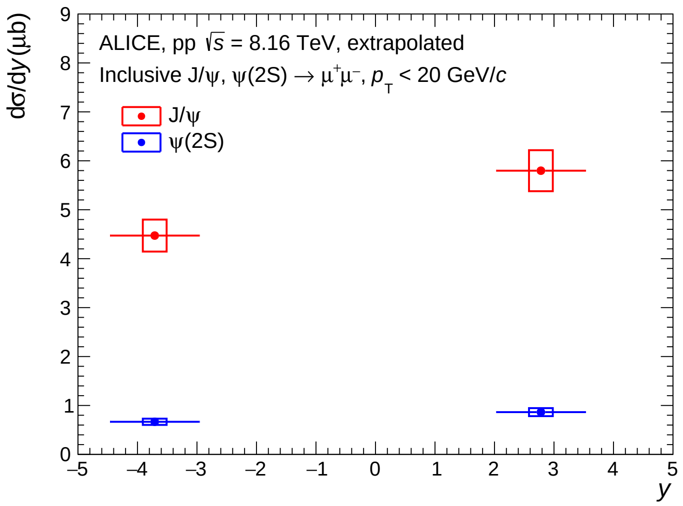

Fig. 1: Extrapolated J/ψ and ψ(2S) production cross section in pp collisions at $\sqrt{s} = 8.16$ TeV as a function of rapidity. The boxes represent the total systematic uncertainty. The horizontal error bars indicate the rapidity interval.

resulting ratio is

$$\left.\frac{\mathrm{d}\sigma^{\psi(2S)}/\mathrm{d}y}{\mathrm{d}\sigma^{J/\psi}/\mathrm{d}y}\right|^{\rm Extr.}_{\sqrt{s}=8.16\rm TeV} = 0.149 \pm 0.009 (6.2\%), \tag{2}$$

where the systematic uncertainty is considered as correlated over centrality, $p_{\rm T}$ and rapidity. The resulting values of the ψ(2S) production cross section for the two rapidity intervals are given in Table 2.

Table 2: Extrapolated ψ(2S) cross sections per unit of rapidity and for $p_{\rm T} > 0$ in pp collisions at $\sqrt{s} = 8.16$ TeV. The first quoted uncertainty is the total systematic uncertainty, whose size is provided in percentage in parenthesis. The uncorrelated contribution for a given rapidity region, and the correlated contribution common to both forward and backward rapidities are quoted in square brackets.

	$\mathrm{d}\sigma^{\psi(2S)}/\mathrm{d}y$ (μb) (pp) ($0 < p_{\rm T} < 20$ GeV/c)
$-4.46 < y < -2.96$	0.666 ± 0.064 (9.6%) [0.012 (unc 1.8%) $\pm$ 0.062 (cor 9.4%)]
$2.03 < y < 3.53$	0.864 ± 0.082 (9.5%) [0.013 (unc 1.5%) $\pm$ 0.081 (cor 9.4%)]

The J/ψ and ψ(2S) production cross sections in pp collisions at $\sqrt{s} = 8.16$ TeV are shown in Fig. 1 as a function of rapidity.

2.2 y-differential cross section

The extrapolated values of the J/ψ production cross section in pp collisions at $\sqrt{s} = 8.16$ TeV as a function of rapidity for the backward and forward rapidity intervals of the p–Pb measurements are reported in Tables 3 and 4 and shown in Fig. 2.

2.3 $p_{\rm T}$-differential cross section

The extrapolated values of the J/ψ production cross section in pp collisions at $\sqrt{s} = 8.16$ TeV as a function of $p_{\rm T}$ for the backward and forward rapidity intervals of the p–Pb measurements are obtained by combining the cross sections evaluated in Ref. [1], and are reported in Tables 5 and 6 and shown in Fig. 3.

Table 3: Extrapolated J/ψ production cross section as a function of rapidity in pp collisions at $\sqrt{s} = 8.16$ TeV for the backward rapidity interval ($-4.46 < y < -2.96$) of the p–Pb measurement. The first uncertainty is the total uncertainty. The size of this uncertainty is also provided in percentage in parenthesis. The uncorrelated and rapidity-correlated contributions are quoted in brackets.

y	$\mathrm{d}\sigma^{\mathrm{J}/\psi}/\mathrm{d}y$ (μb) ($0 < p_{\mathrm{T}} < 20$ GeV/c)
$-4.46 < y < -4.21$	3.363 ± 0.310 (9.2%) [0.199 (unc 5.9%) ± 0.238 (cor 7.1%)]
$-4.21 < y < -3.96$	3.814 ± 0.281 (7.4%) [0.078 (unc 2.0%) ± 0.270 (cor 7.1%)]
$-3.96 < y < -3.71$	4.391 ± 0.327 (7.4%) [0.102 (unc 2.3%) ± 0.311 (cor 7.1%)]
$-3.71 < y < -3.46$	5.077 ± 0.374 (7.4%) [0.106 (unc 2.1%) ± 0.359 (cor 7.1%)]
$-3.46 < y < -3.21$	5.562 ± 0.409 (7.4%) [0.113 (unc 3.0%) ± 0.393 (cor 7.1%)]
$-3.21 < y < -2.96$	5.891 ± 0.429 (7.3%) [0.104 (unc 1.8%) ± 0.417 (cor 7.1%)]

Table 4: Extrapolated J/ψ production cross section as a function of rapidity in pp collisions at $\sqrt{s} = 8.16$ TeV for the forward rapidity interval ($2.03 < y < 3.53$) of the p–Pb measurement. The first uncertainty is the total uncertainty. The size of this uncertainty is also provided in percentage in parenthesis. The uncorrelated and rapidity-correlated contributions are quoted in brackets.

y	$\mathrm{d}\sigma^{\mathrm{J}/\psi}/\mathrm{d}y$ (μb) ($0 < p_{\mathrm{T}} < 20$ GeV/c)
$2.03 < y < 2.28$	6.395 ± 0.506 (7.9%) [0.227 (unc 3.5%) ± 0.452 (cor 7.1%)]
$2.28 < y < 2.53$	6.206 ± 0.464 (7.5%) [0.149 (unc 2.4%) ± 0.439 (cor 7.1%)]
$2.53 < y < 2.78$	5.982 ± 0.434 (7.2%) [0.095 (unc 1.6%) ± 0.423 (cor 7.1%)]
$2.78 < y < 3.03$	5.918 ± 0.429 (7.2%) [0.094 (unc 1.6%) ± 0.419 (cor 7.1%)]
$3.03 < y < 3.28$	5.822 ± 0.426 (7.3%) [0.108 (unc 1.9%) ± 0.412 (cor 7.1%)]
$3.28 < y < 3.53$	5.444 ± 0.401 (7.4%) [0.112 (unc 2.1%) ± 0.385 (cor 7.1%)]

Table 5: Extrapolated J/ψ production cross section as a function of p_{T} in pp collisions at $\sqrt{s} = 8.16$ TeV for the backward rapidity interval ($-4.46 < y < -2.96$). The first uncertainty is the total uncertainty. The size of this uncertainty is also provided in percentage in parenthesis. The uncorrelated and y and p_{T}-correlated contributions are quoted in brackets.

p_{T} (GeV/c)	$\mathrm{d}^2\sigma^{\mathrm{J}/\psi}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}$ (μb/(GeV/c)) ($-4.46 < y < -2.96$)
0–1	0.751 ± 0.063 (8%) [0.034 (unc 4.5%) ± 0.053 (cor 7.1%)]
1–2	1.374 ± 0.115 (8%) [0.061 (unc 4.5%) ± 0.097 (cor 7.1%)]
2–3	1.074 ± 0.090 (8%) [0.048 (unc 4.5%) ± 0.076 (cor 7.1%)]
3–4	0.635 ± 0.053 (8%) [0.028 (unc 4.5%) ± 0.045 (cor 7.1%)]
4–5	0.339 ± 0.028 (8%) [0.015 (unc 4.5%) ± 0.024 (cor 7.1%)]
5–6	0.172 ± 0.014 (8%) [0.008 (unc 4.6%) ± 0.012 (cor 7.1%)]
6–8	0.069 ± 0.006 (8%) [0.003 (unc 3.6%) ± 0.005 (cor 7.1%)]
8–10	0.0201 ± 0.0016 (8%) [0.0008 (unc 3.9%) ± 0.0014 (cor 7.1%)]
10–16	0.0033 ± 0.0003 (8.0%) [0.0001 (unc 3.0%) ± 0.0002 (cor 7.1%)]

2.4 $\langle p_{\mathrm{T}} \rangle$ and $\langle p_{\mathrm{T}}^2 \rangle$ of inclusive J/ψ

The reference $\langle p_{\mathrm{T}} \rangle$ and $\langle p_{\mathrm{T}}^2 \rangle$ are evaluated from the p_{T}-differential cross section in pp collisions at $\sqrt{s} = 8.16$ TeV shown in Fig. 3, which are obtained using the extrapolation procedure described above. Table 7 shows the values of $\langle p_{\mathrm{T}} \rangle$ and $\langle p_{\mathrm{T}}^2 \rangle$ of inclusive J/ψ, which are obtained with the same fitting procedure as described in [2] and in the same p_{T} range $0 < p_{\mathrm{T}} < 16$ GeV/c as for the p–Pb results published in Ref. [1].

Figure 4 shows the obtained values of inclusive J/ψ $\langle p_{\mathrm{T}} \rangle$ and $\langle p_{\mathrm{T}}^2 \rangle$ as a function of rapidity for pp collisions at $\sqrt{s} = 8.16$ TeV.

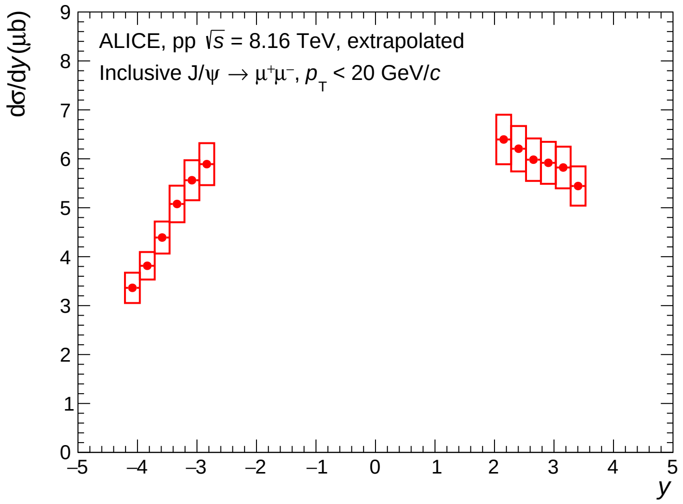

Fig. 2: Extrapolated J/ψ production cross section in pp collisions at $\sqrt{s} = 8.16$ TeV as a function of rapidity. The boxes represent the total systematic uncertainty.

Table 6: Extrapolated J/ψ production cross section as a function of $p_{\rm T}$ in pp collisions at $\sqrt{s} = 8.16$ TeV for the forward rapidity interval ($2.03 < y < 3.53$). The first uncertainty is the total uncertainty. The size of this uncertainty is also provided in percentage in parenthesis. The uncorrelated and y- and $p_{\rm T}$-correlated contributions are quoted in brackets.

$p_{\rm T}$ (GeV/c)	$\mathrm{d}^2\sigma^{\mathrm{J}/\psi}/\mathrm{d}y\mathrm{d}p_{\rm T}$ (μb/(GeV/c)) ($2.03 < y < 3.53$)
0–1	0.862 ± 0.073 (8.5%) [0.040 (unc 4.6%) $\pm$ 0.061 (cor 7.1%)]
1–2	1.676 ± 0.140 (8.3%) [0.074 (unc 4.4%) $\pm$ 0.119 (cor 7.1%)]
2–3	1.394 ± 0.116 (8.3%) [0.061 (unc 4.4%) $\pm$ 0.099 (cor 7.1%)]
3–4	0.867 ± 0.073 (8.4%) [0.039 (unc 4.5%) $\pm$ 0.061 (cor 7.1%)]
4–5	0.494 ± 0.042 (8.5%) [0.023 (unc 4.7%) $\pm$ 0.035 (cor 7.1%)]
5–6	0.263 ± 0.022 (8.4%) [0.012 (unc 4.4%) $\pm$ 0.019 (cor 7.1%)]
6–8	0.111 ± 0.009 (7.9%) [0.004 (unc 3.5%) $\pm$ 0.008 (cor 7.1%)]
8–10	0.036 ± 0.003 (8.0%) [0.0014 (unc 3.8%) $\pm$ 0.0025 (cor 7.1%)]
10–16	0.0070 ± 0.0005 (8.0%) [0.0002 (unc 2.9%) $\pm$ 0.0005 (cor 7.1%)]

Table 7: Values of $\langle p_{\rm T}\rangle$ and $\langle p_{\rm T}^2\rangle$ of inclusive J/ψ in the interval $0 < p_{\rm T} < 16$ GeV/c for pp collisions at $\sqrt{s} =$ 8.16 TeV.

$-4.46 < y < -2.96$		$2.03 < y < 3.53$	
$\langle p_{\rm T}\rangle$ (GeV/c)	$\langle p_{\rm T}^2\rangle$ (GeV^2/c^2)	$\langle p_{\rm T}\rangle$ (GeV/c)	$\langle p_{\rm T}^2\rangle$ (GeV^2/c^2)
2.557 ± 0.035	9.678 ± 0.225	2.738 ± 0.037	11.242 ± 0.252

3 Summary

The inclusive J/ψ and ψ(2S) production cross sections in pp collisions at $\sqrt{s} = 8.16$ TeV have been obtained from existing measurements at $\sqrt{s} = 8$ TeV using an energy interpolation and rapidity extrapolation procedure. The $\langle p_{\rm T}\rangle$ and $\langle p_{\rm T}^2\rangle$ of inclusive J/ψ are derived from the obtained $p_{\rm T}$-differential cross section. These results were used as reference for the studies of the inclusive J/ψ and ψ(2S) production in p–Pb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV by the ALICE Collaboration.

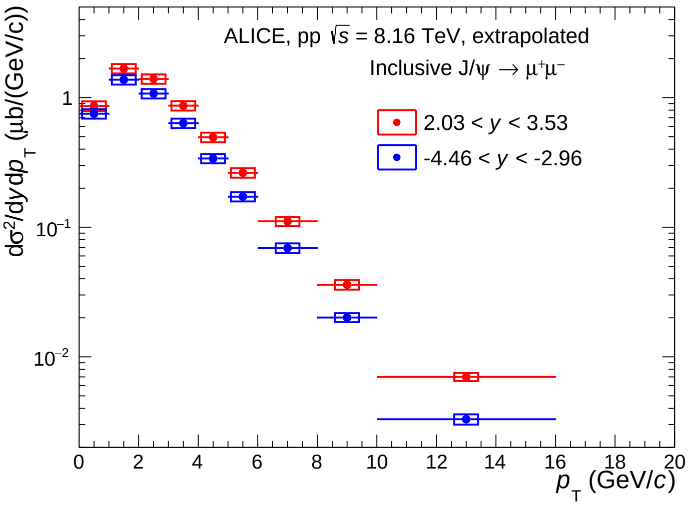

Fig. 3: Extrapolated production cross section as a function of p_{T} for inclusive J/ψ in pp collisions at $\sqrt{s} = 8.16$ TeV in the forward (red) and backward (blue) rapidity intervals. The boxes respresent the total systematic uncertainty.

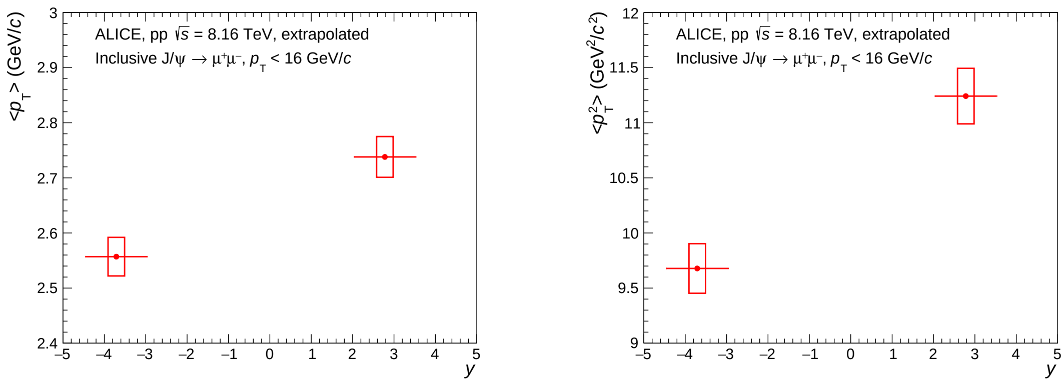

Fig. 4: Inclusive J/ψ $\langle p_{\mathrm{T}} \rangle$ (left) and $\langle p_{\mathrm{T}}^2 \rangle$ (right) as a function of rapidity for pp collisions at $\sqrt{s} = 8.16$ TeV. The results are obtained from fits to the extrapolated p_{T} differential cross sections as described in the text. The total systematic uncertainty is shown as open boxes.

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Blau[88] , C. Blume[68] , G. Boca[139] , F. Bock[96] , A. Bogdanov[93] , S. Boi[23] , J. Bok[61] , L. Boldizsár[145] , A. Bolozdynya[93] , M. Bombara[38] , G. Bonomi[140] , H. Borel[137] , A. Borissov[93] , H. Bossi[146] , E. Botta[25] , L. Bratrud[68] , P. Braun-Munzinger[107] , M. Bregant[121] , M. Broz[37] , E. Bruna[59] , G.E. Bruno[33,106] , M.D. Buckland[127] , D. Budnikov[109] , H. Buesching[68] , S. Bufalino[30] , O. Bugnon[115] , P. Buhler[114] , P. Buncic[34] , Z. Buthelezi[72,131] , J.B. Butt[14] , S.A. Bysiak[118] , D. Caffarri[90] , A. Caliva[107] , E. Calvo Villar[112] , J.M.M. Camacho[120] , R.S. Camacho[45] , P. Camerini[24] , F.D.M. Canedo[121] , A.A. Capon[114] , F. Carnesecchi[26] , R. Caron[137] , J. Castillo Castellanos[137] , A.J. Castro[130] , E.A.R. Casula[55] , F. Catalano[30] , C. Ceballos Sanchez[75] , P. Chakraborty[49] , S. Chandra[141] , W. Chang[6] , S. Chapeland[34] , M. Chartier[127] , S. Chattopadhyay[141] , S. Chattopadhyay[110] , A. Chauvin[23] , C. Cheshkov[135] , B. Cheynis[135] , V. Chibante Barroso[34] , D.D. Chinellato[122] , S. Cho[61] , P. Chochula[34] , T. Chowdhury[134] , P. Christakoglou[90] , C.H. Christensen[89] , P. Christiansen[81] , T. Chujo[133] , C. Cicalo[55] , L. Cifarelli[10,26] , F. Cindolo[54] , M.R. Ciupek[107] , G. Clai[54,ii], J. Cleymans[124] , F. Colamaria[53] , J.S. Colburn[111] , D. Colella[53] , A. Collu[80] , M. Colocci[26] , M. Concas[59,iii], G. Conesa Balbastre[79] , Z. Conesa del Valle[78] , G. Contin[24,60] , J.G. Contreras[37] , T.M. Cormier[96] , Y. Corrales Morales[25] , P. Cortese[31] , M.R. Cosentino[123] , F. Costa[34] , S. Costanza[139] , P. Crochet[134] , E. Cuautle[69] , P. Cui[6] , L. Cunqueiro[96] , D. Dabrowski[142] , T. Dahms[105] , A. Dainese[57] , F.P.A. Damas[115,137] , M.C. Danisch[104] , A. Danu[67] , D. Das[110] , I. Das[110] , P. Das[86] , P. Das[3] , S. Das[3] , A. Dash[86] , S. Dash[49] , S. De[86] , A. De Caro[29] , G. de Cataldo[53] , L. De Cilladi[25] , J. de Cuveland[39] , A. De Falco[23] , D. De Gruttola[10] , N. De Marco[59] , C. De Martin[24] , S. De Pasquale[29] , S. Deb[50] , H.F. Degenhardt[121] , K.R. Deja[142] , A. Deloff[85] , S. Delsanto[25,131] , W. Deng[6] , P. Dhankher[49] , D. Di Bari[33] , A. Di Mauro[34] , R.A. Diaz[8] , T. Dietel[124] , P. Dillenseger[68] , Y. Ding[6] , R. Divià[34] , D.U. Dixit[19] , Ø. Djuvsland[21] , U. Dmitrieva[62] , A. Dobrin[67] , B. Dönigus[68] , O. Dordic[20] , A.K. Dubey[141] , A. Dubla[90,107] , S. Dudi[100] , M. Dukhishyam[86] , P. Dupieux[134] , R.J. Ehlers[96] , V.N. Eikeland[21] , D. Elia[53] , B. Erazmus[115] , F. Erhardt[99] , A. Erokhin[113] , M.R. Ersdal[21] , B. Espagnon[78] , G. Eulisse[34] , D. Evans[111] , S. Evdokimov[91] , L. Fabbietti[105] , M. Faggin[28] , J. Faivre[79] , F. Fan[6] , A. Fantoni[52] , M. Fasel[96] , P. Fecchio[30] , A. Feliciello[59] , G. Feofilov[113] , A. Fernández Téllez[45] , A. Ferrero[137] , A. Ferretti[25] , A. Festanti[34] , V.J.G. 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H. Hillemanns[34] , C. Hills[127] , B. Hippolyte[136] , B. Hohlweger[105] , J. Honermann[144] , D. Horak[37] , A. Hornung[68] , S. Hornung[107] , R. Hosokawa[15] , P. Hristov[34] , C. Huang[78] , C. Hughes[130] , P. Huhn[68] , T.J. Humanic[97] , H. Hushnud[110] , L.A. Husova[144] , N. Hussain[42] , S.A. Hussain[14] , D. Hutter[39] , J.P. Iddon[34,127] , R. Ilkaev[109] , H. Ilyas[14] , M. Inaba[133] , G.M. Innocenti[34] , M. Ippolitov[88] , A. Isakov[95] , M.S. Islam[110] , M. Ivanov[107] , V. Ivanov[98] , V. Izucheev[91] , B. Jacak[80] , N. Jacazio[34,54] , P.M. Jacobs[80] , S. Jadlovska[117] , J. Jadlovsky[117] , S. Jaelani[63] , C. Jahnke[121] , M.J. Jakubowska[142] , M.A. Janik[142] , T. Janson[74] , M. Jercic[99] , O. Jevons[111] , M. Jin[125] , F. Jonas[96,144] , P.G. Jones[111] , J. Jung[68] , M. Jung[68] , A. Jusko[111] , P. Kalinak[64] , A. Kalweit[34] , V. Kaplin[93] , S. Kar[6] , A. Karasu Uysal[77] , D. Karatovic[99] , O. Karavichev[62] , T. Karavicheva[62] , P. 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Kravčáková[38] , L. Kreis[107] , M. Krivda[64,111] , F. Krizek[95] , K. Krizkova Gajdosova[37] , M. Krüger[68] , E. Kryshen[98] , M. Krzewicki[39] , V. Kučera[34,61] , C. Kuhn[136] , P.G. Kuijer[90] , L. Kumar[100] , S. Kundu[86] , P. Kurashvili[85] , A. Kurepin[62] , A.B. Kurepin[62] , A. Kuryakin[109] , S. Kushpil[95] , J. Kvapil[111] , M.J. Kweon[61] , J.Y. Kwon[61] , Y. Kwon[147] , S.L. La Pointe[39] , P. La Rocca[27] , Y.S. Lai[80] , A. Lakrathok[116] , M. Lamanna[34] , R. Langoy[129] , K. Lapidus[34] , A. Lardeux[20] , P. Larionov[52] , E. Laudi[34] , R. Lavicka[37] , T. Lazareva[113] , R. Lea[24] , L. Leardini[104] , J. Lee[133] , S. Lee[147] , S. Lehner[114] , J. Lehrbach[39] , R.C. Lemmon[94] , I. León Monzón[120] , E.D. Lesser[19] , M. Lettrich[34] , P. Lévai[145] , X. Li[12] , X.L. Li[6] , J. Lien[129] , R. Lietava[111] , B. Lim[17] , V. Lindenstruth[39] , A. Lindner[48] , C. Lippmann[107] , M.A. Lisa[97] , A. Liu[19] , J. Liu[127] , W.J. Llope[143] , I.M. Lofnes[21] , V. Loginov[93] , C. Loizides[96] , P. Loncar[35] , J.A. Lopez[104] , X. Lopez[134] , E. López Torres[8] , J.R. Luhder[144] , M. Lunardon[28] , G. Luparello[60] , Y.G. Ma[40] , A. Maevskaya[62] , M. Mager[34] , S.M. Mahmood[20] , T. Mahmoud[43] , A. Maire[136] , R.D. Majka[146,i], M. Malaev[98] , Q.W. Malik[20] , L. Malinina[75,iv], D. Mal'Kevich[92] , P. Malzacher[107] , G. Mandaglio[32,56] , V. Manko[88] , F. Manso[134] , V. Manzari[53] , Y. Mao[6] , M. Marchisone[135] , J. Mareš[66] , G.V. Margagliotti[24] , A. Margotti[54] , A. Marín[107] , C. Markert[119] , M. Marquard[68] , N.A. Martin[104] , P. Martinengo[34] , J.L. Martinez[125] , M.I. Martínez[45] , G. Martínez García[115] , S. Masciocchi[107] , M. Masera[25] , A. Masoni[55] , L. Massacrier[78] , E. Masson[115] , A. Mastroserio[53,138] , A.M. Mathis[105] , O. Matonoha[81] , P.F.T. Matuoka[121] , A. Matyja[118] , C. Mayer[118] , F. Mazzaschi[25] , M. Mazzilli[53] , M.A. Mazzoni[58] , A.F. Mechler[68] , F. Meddi[22] , Y. Melikyan[62,93] , A. Menchaca-Rocha[71] , C. Mengke[6] , E. Meninno[29,114] , A.S. Menon[125] , M. Meres[13] , S. Mhlanga[124] , Y. Miake[133] , L. Micheletti[25] , L.C. Migliorin[135] , D.L. Mihaylov[105] , K. Mikhaylov[75,92] , A.N. Mishra[69] , D. Miśkowiec[107] , A. Modak[3] , N. Mohammadi[34] , A.P. Mohanty[63] , B. Mohanty[86] , M. Mohisin Khan[16,v], Z. Moravcova[89] , C. Mordasini[105] , D.A. Moreira De Godoy[144] , L.A.P. Moreno[45] , I. Morozov[62] , A. Morsch[34] , T. Mrnjavac[34] , V. Muccifora[52] , E. Mudnic[35] , D. Mühlheim[144] , S. Muhuri[141] , J.D. Mulligan[80] , A. Mulliri[23,55] , M.G. Munhoz[121] , R.H. Munzer[68] , H. Murakami[132] , S. Murray[124] , L. Musa[34] , J. Musinsky[64] , C.J. Myers[125] , J.W. Myrcha[142] , B. Naik[49] , R. Nair[85] , B.K. Nandi[49] , R. Nania[10,54] , E. Nappi[53] , M.U. Naru[14] , A.F. Nassirpour[81] , C. Nattrass[130] , R. Nayak[49] , T.K. Nayak[86] , S. Nazarenko[109] , A. Neagu[20] , R.A. Negrao De Oliveira[68] , L. 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