53. Plots of Cross Sections and Related Quantities

Updated in 2023. See various sections for details. For additional cross section results, please see earlier editions of the *Review of Particle Physics* (https://pdg.lbl.gov/rpp-archive/).

53.1 Pseudorapidity Distributions in pp and $\overline{p}p$ Interactions

Revised August 2013 by D.R. Ward (Cavendish Lab.).

Pseudorapidity Distributions in pp and $\bar{p}p$ Interactions

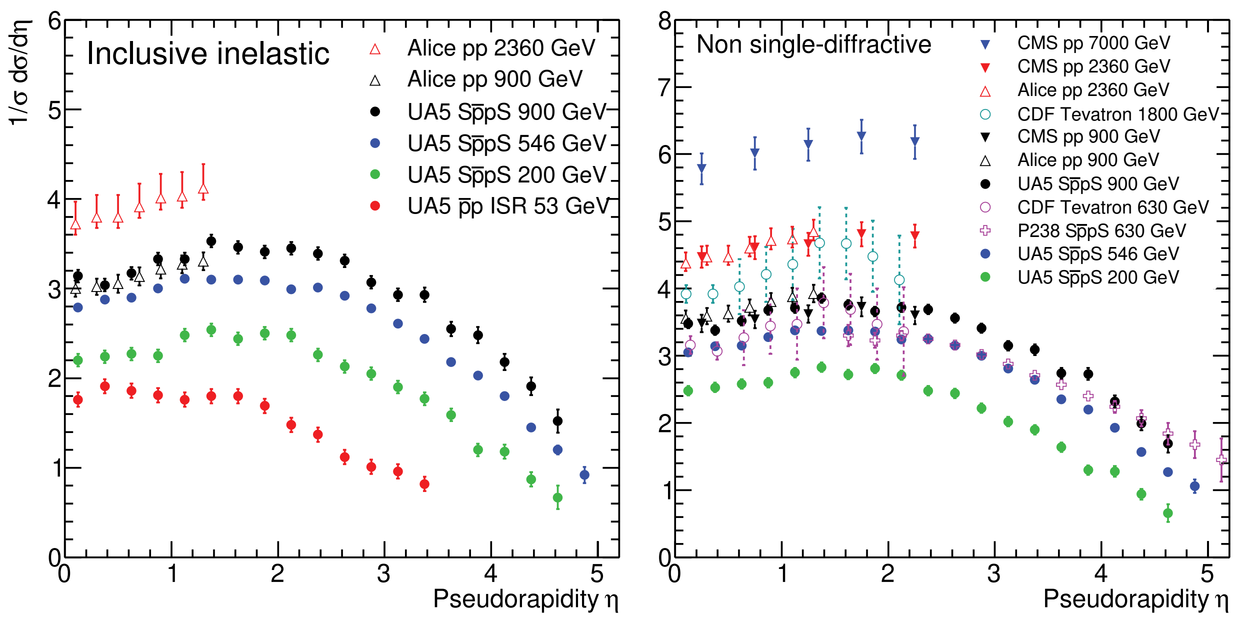

Figure 53.1: Charged particle pseudorapidity distributions in $p\overline{p}$ collisions for 53 GeV $\leq \sqrt{s} \leq$ 1800 GeV. UA5 data from the S$p\overline{p}$S are taken from [1], and from the ISR from [2]. The UA5 data are shown for both the full inelastic cross-section and with singly diffractive events excluded. Additional non single-diffractive measurements are available from CDF at the Tevatron [3] and from P238 at the S$p\overline{p}$S [4]. These may be compared with both inclusive and non single-diffractive measurements in pp collisions at the LHC from ALICE [5] and for non single-diffractive interactions from CMS [6,7]. (Courtesy of D.R. Ward, Cambridge Univ., 2013)

53.2 Average Hadron Multiplicities in Hadronic e^+e^- Annihilation Events

Revised August 2023 by O. Biebel (Ludwig-Maximilians U.).

Table 53.1: Average hadron multiplicities per hadronic e^+e^- annihilation event at $\sqrt{s} \approx 10$, 29–35, 91, and 130–200 GeV. The rates given include decay products from resonances with $c\tau < 10$ cm, and include the corresponding anti-particle state. Correlations of the systematic uncertainties were considered for the calculation of the averages. Quoted errors are not increased by scale factor S.

Particle	$\sqrt{s} \approx 10$ **GeV**	$\sqrt{s} = 29$–35 **GeV**	$\sqrt{s} = 91$ **GeV**	$\sqrt{s} = 130$–200 **GeV**	**References**
Pseudoscalar mesons:					
π^+	6.52 ± 0.11	0.3 ± 0.4	17.02 ± 0.19	21.24 ± 0.39	[8–17]
π^0	3.2 ± 0.3	5.83 ± 0.28	9.42 ± 0.32		[12, 18–23]
K^+	0.953 ± 0.018	1.48 ± 0.09	2.228 ± 0.059	2.82 ± 0.19	[9–17, 24, 25]
K^0	0.91 ± 0.05	1.48 ± 0.07	2.049 ± 0.026	2.10 ± 0.12	[12, 17, 20, 26–36]
η	0.20 ± 0.04	0.61 ± 0.07	1.049 ± 0.080		[12, 18, 19, 22, 23, 37–40]
$\eta\prime(958)$	0.03 ± 0.01	0.26 ± 0.10	0.152 ± 0.020		[20, 39, 41–43]
D^+	$0.194 \pm 0.019^{(a)}$	0.17 ± 0.03	0.175 ± 0.016		[12, 44–47]
D^0	$0.446 \pm 0.032^{(a)}$	0.45 ± 0.07	0.454 ± 0.030		[12, 44–47]
D_s^+	$0.063 \pm 0.014^{(a)}$	$0.45 \pm 0.20^{(b)}$	0.131 ± 0.021		[8, 39, 44, 47–49]
$B^{(c)}$	—	—	$0.134 \pm 0.016^{(d)}$		[46, 50]
B^+	—	—	$0.141 \pm 0.004^{(d)}$		[51]
B_s^0	—	—	$0.054 \pm 0.011^{(d)}$		[52, 53]
Scalar mesons:					
$f_0(980)$	0.024 ± 0.006	$0.05 \pm 0.02^{(e)}$	0.146 ± 0.012		[41, 54–56]
$a_0(980)^\pm$	—	—	$0.27 \pm 0.11^{(f)}$		[43]
Vector mesons:					
$\rho(770)^0$	0.35 ± 0.04	0.81 ± 0.08	1.231 ± 0.098		[9, 12, 55, 57, 58]
$\rho(770)^\pm$	—	—	$2.40 \pm 0.43^{(f)}$		[43]
$\omega(782)$	0.30 ± 0.08	—	1.016 ± 0.065		[40, 42, 43, 57]
$K^*(892)^+$	0.27 ± 0.03	0.64 ± 0.05	0.714 ± 0.055		[9, 12, 33, 57, 59, 60]
$K^*(892)^0$	0.29 ± 0.03	0.56 ± 0.06	0.738 ± 0.024		[9, 12, 36, 57, 58, 61, 62]
$\phi(1020)$	0.044 ± 0.003	0.085 ± 0.011	0.0963 ± 0.0032		[12, 36, 56–58, 61]
$D^*(2010)^+$	$0.177 \pm 0.022^{(a)}$	0.43 ± 0.07	$0.1937 \pm 0.0057^{(g)}$		[12, 44–46, 63, 64]
$D^*(2007)^0$	$0.168 \pm 0.019^{(a)}$	0.27 ± 0.11	—		[12, 44, 45]
$D_s^*(2112)^+$	$0.048 \pm 0.014^{(a)}$	—	$0.101 \pm 0.048^{(h)}$		[48, 65]
$B^{*\ (i)}$	—	—	0.288 ± 0.026		[66, 67]
$J/\psi(1S)$	$0.00050 \pm 0.00005^{(a)}$	—	$0.0052 \pm 0.0004^{(j)}$		[68–73]
$\psi(2S)$	—	—	$0.0023 \pm 0.0004^{(j)}$		[71, 73, 74]
$\Upsilon(1S)$	—	—	$0.00014 \pm 0.00007^{(j)}$		[75]
Pseudovector mesons:					
$f_1(1285)$	—	—	0.165 ± 0.051		[76]
$f_1(1420)$	—	—	0.056 ± 0.012		[76]
$\chi_{c1}(3510)$	—	—	$0.0041 \pm 0.0011^{(j)}$		[71, 74]
Tensor mesons:					
$f_2(1270)$	0.09 ± 0.02	0.14 ± 0.04	0.166 ± 0.020		[54–56, 77]
$f_2'(1525)$	—	—	0.012 ± 0.006		[55]
$K_2^*(1430)^+$	—	0.09 ± 0.03	—		[55, 78]
$K_2^*(1430)^0$	—	0.12 ± 0.06	0.084 ± 0.022		[54, 55, 79]

Particle	$\sqrt{s} \approx 10$ **GeV**	$\sqrt{s} = 29$–35 **GeV**	$\sqrt{s} = 91$ **GeV**	$\sqrt{s} = 130$–200 **GeV**	
$B^{**\ (k)}$	—	—	0.118 ± 0.024		[80]
$D_{s1}^{\pm}$	—	—	$0.0052 \pm 0.0011^{(\ell)}$		[81]
$D_{s2}^{*\pm}$	—	—	$0.0083 \pm 0.0031^{(\ell)}$		[81]
Baryons:					
p	0.266 ± 0.008	0.640 ± 0.050	1.050 ± 0.032	1.41 ± 0.18	[10, 13–17, 24, 25, 77]
Λ	$0.093 \pm 0.006^{(a)}$	0.205 ± 0.010	0.3915 ± 0.0065	0.39 ± 0.03	[17, 20, 34, 36, 77, 82–85]
Σ^0	$0.0221 \pm 0.0018^{(a)}$	—	0.078 ± 0.010		[10,59,82,86–88]
Σ^-	—	—	0.081 ± 0.010		[88,89]
Σ^+	—	—	0.107 ± 0.011		[87,88]
$\Sigma^{\pm}$	—	—	0.174 ± 0.009		[84,88]
Ξ^-	$0.0055 \pm 0.0004^{(a)}$	0.0176 ± 0.0027	0.0262 ± 0.0009		[9,59,77,82–85]
$\Delta(1232)^{++}$	0.040 ± 0.010	—	0.085 ± 0.014		[90–92]
$\Sigma(1385)^-$	0.006 ± 0.002	0.017 ± 0.004	0.0240 ± 0.0017		[59,82,84,85,93]
$\Sigma(1385)^+$	$0.0062 \pm 0.0011^{(a)}$	0.017 ± 0.004	0.0239 ± 0.0015		[59,82–85,93]
$\Sigma(1385)^{\pm}$	0.0106 ± 0.0020	0.033 ± 0.008	0.0472 ± 0.0027		[59,82,84,85,93]
$\Xi(1530)^0$	$0.00130 \pm 0.00010^{(a)}$	—	0.00694 ± 0.00049		[59,82,83,85,94]
Ω^-	$0.00060 \pm 0.00033^{(a)}$	0.014 ± 0.007	0.00124 ± 0.00018		[59, 77, 82, 83, 85, 86]
Λ_c^+	$0.0480 \pm 0.0036^{(a,m)}$	0.110 ± 0.050	$0.0591 \pm 0.0047^{(n)}$		[47, 49, 77, 83, 95, 96]
Λ_b^0	—	—	0.031 ± 0.016		[97]
Σ_c^0	$0.0025 \pm 0.0004^{(a)}$	—	—		[83]
$\Lambda(1520)$	$0.0046 \pm 0.0004^{(a)}$	—	0.0222 ± 0.0027		[83,85,89,98]

(a) $\sigma_{\text{had}} = 3.33 \pm 0.05 \pm 0.21$ nb (**CLEO**: [99]) has been used in converting the measured cross sections to average hadron multiplicities.

(b) $\mathrm{B}(D_s \to \eta\pi,\ \eta'\pi)$ was used (RPP 1994).

(c) Comprises both charged and neutral B meson states.

(d) The Standard Model $\mathrm{B}(Z \to b\bar{b}) = 0.217$ was used.

(e) $x_p = p/p_{\text{beam}} > 0.1$ only.

(f) Both charge states.

(g) $\mathrm{B}(D^*(2010)^+ \to D^0\pi^+) \times \mathrm{B}(D^0 \to K^-\pi^+)$ has been used (RPP 2000).

(h) $\mathrm{B}(D_s^* \to D_S^+\gamma)$, $\mathrm{B}(D_s^+ \to \phi\pi^+)$, $\mathrm{B}(\phi \to K^+K^-)$ have been used (RPP 1998).

(i) Any charge state (*i.e.*, B_d^*, B_u^*, or B_s^*).

(j) $\mathrm{B}(Z \to \text{hadrons}) = 0.699$ was used (RPP 1994).

(k) Any charge state (*i.e.*, B_d^{**}, B_u^{**}, or B_s^{**}).

(ℓ) Assumes $\mathrm{B}(D_{s1}^+ \to D^{*+}K^0 + D^{*0}K^+) = 100\%$ and $\mathrm{B}(D_{s2}^+ \to D^0K^+) = 45\%$.

(m) Derived from the production cross section of $\Lambda_c^+ \to p\pi K$ using (a) and using $\mathrm{B}(\Lambda_c^+ \to p\pi K) = (6.26 \pm 0.29)\%$ (RPP 2022).

(n) Derived from [96], updated with $\mathrm{B}(\Lambda_c^+ \to p\pi K) = (6.26 \pm 0.29)\%$ (RPP 2022), and complemented by the Λ_c^+ contribution from $g \to c\bar{c}$ of [47].

References grouped by collaboration for Table-53.1:

- **RPP**: [12]
- **ALEPH**: [13, 20, 40, 58, 59, 63, 70, 81],
- **ARGUS**: [8, 24, 37, 41, 57, 82, 90, 98],
- **BaBar**: [10, 48, 68, 95],
- **Belle**: [44, 69, 83],
- **CELLO**: [19, 26],
- **CLEO**: [9, 45, 49, 99],
- **Crystal Ball**: [38],
- **DELPHI**: [14, 17, 21, 25, 33, 46, 50–52, 55, 61, 66, 71, 76, 80, 84, 86, 89, 91, 94],
- **HRS**: [27, 54, 78, 93],
- **L3**: [22, 34, 42, 67, 72, 74, 87]
- **MARK II**: [29, 39],
- **JADE**: [18, 28],
- **OPAL**: [15, 23, 35, 43, 47, 53, 56, 60, 62, 64, 65, 73, 75, 79, 85, 88, 92, 97],
- **PLUTO**: [30]
- **SLD**: [16, 36],
- **TASSO**: [31]
- **TPC**: [32].

53.3 Annihilation Cross Section Near M_Z

Courtesy of M. Grünewald and the LEP Electroweak Working Group, 2007.

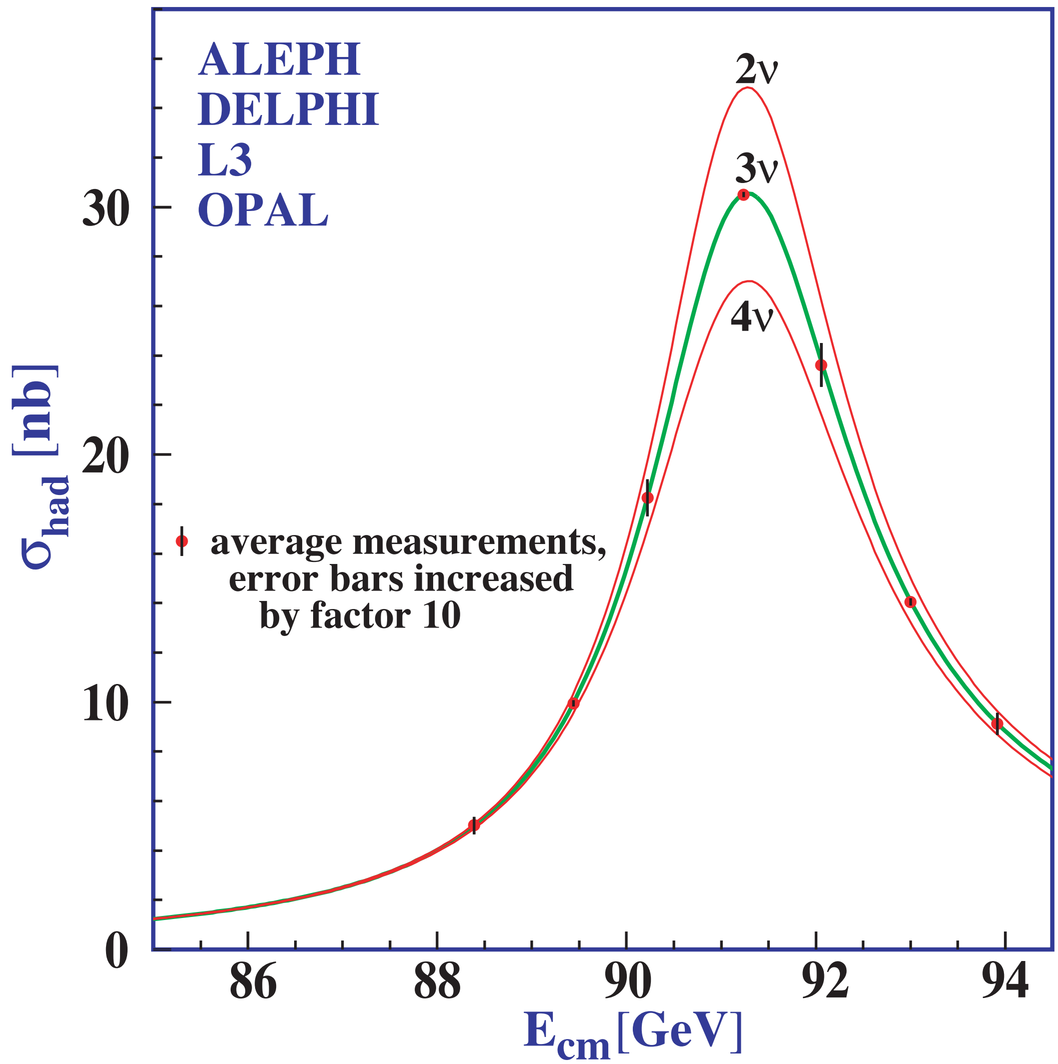

Figure 53.2: Combined data from the ALEPH, DELPHI, L3, and OPAL Collaborations for the cross section in e^+e^- annihilation into hadronic final states as a function of the center-of-mass energy near the Z pole. The curves show the predictions of the Standard Model with two, three, and four species of light neutrinos. The asymmetry of the curve is produced by initial-state radiation. Note that the error bars have been increased by a factor ten for display purposes. References: ALEPH [100], DELPHI [101], L3 [102], OPAL [103], Combination [104],

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