51. Plots of Cross Sections and Related Quantities

Updated in 2017. See various sections for details.

This section contains a compilation of plots and tables on cross sections and related quantities that are not covered by other reviews but may be of interest to the community. The topics include:

- Pseudorapidity distributions in \( pp \) and \( \overline{p}p \) interactions
- Table of average hadron multiplicities in hadronic \( e^+e^- \) annihilation events
- Cross section and \( R \) ratio in \( e^+e^- \) collisions
- \( R \) ratio in light-flavor, charm, and beauty threshold regions
- Annihilation cross section near \( M_Z \)
- Total cross section plots for hadronic (e.g. \( pp \) and \( \overline{p}p \) collisions), \( \gamma p \), \( \gamma d \), and \( \gamma\gamma \) processes

**Pseudorapidity Distributions in \( pp \) and \( \overline{p}p \) Interactions**

![Graph showing pseudorapidity distributions for various experiments and energies.](image)

**Figure 51.1**: Charged particle pseudorapidity distributions in \( p\bar{p} \) collisions for \( 53 \text{ GeV} \leq \sqrt{s} \leq 1800 \text{ GeV} \). UA5 data from the \( SppS \) are taken from G.J.Alner et al., Z. Phys. C33, 1 (1986), and from the ISR from K.Alpgøard et al., Phys.Lett. 112B 193 (1982). 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, F.Abe et al., Phys. Rev. D41, 2330 (1990) and from P238 at the \( SppS \), R.Harr et al., Phys. Lett. B401, 176 (1997). These may be compared with both inclusive and non single-diffractive measurements in \( pp \) collisions at the LHC from ALICE, K.Aamodt et al., Eur. Phys. J. C68, 89 (2010) and for non single-diffractive interactions from CMS , V.Khachatryan et al., JHEP 1002:041 (2010), Phys. Rev. Lett. 105, 022002 (2010). (Courtesy of D.R. Ward, Cambridge Univ., 2013)
### Table 51.1: 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 $ct < 10$ 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 $S$.

(Updated August 2017 by O. Biebel, LMU, Munich)

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\sqrt{s} \approx 10$ GeV</th>
<th>$\sqrt{s} = 29–35$ GeV</th>
<th>$\sqrt{s} = 91$ GeV</th>
<th>$\sqrt{s} = 130–200$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pseudoscalar mesons:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>$0.0046 \pm 0.006$</td>
<td>$0.0048 \pm 0.006$</td>
<td>$0.0053 \pm 0.006$</td>
<td>$0.0061 \pm 0.006$</td>
</tr>
<tr>
<td>$\eta(958)$</td>
<td>$0.0055 \pm 0.006$</td>
<td>$0.0063 \pm 0.006$</td>
<td>$0.0070 \pm 0.006$</td>
<td>$0.0077 \pm 0.006$</td>
</tr>
<tr>
<td>$\phi(1020)$</td>
<td>$0.0064 \pm 0.006$</td>
<td>$0.0072 \pm 0.006$</td>
<td>$0.0080 \pm 0.006$</td>
<td>$0.0088 \pm 0.006$</td>
</tr>
<tr>
<td>$\eta(1420)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\eta' (958)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Scalar mesons:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho(770)^0$</td>
<td>$0.03 \pm 0.04$</td>
<td>$0.03 \pm 0.04$</td>
<td>$0.03 \pm 0.04$</td>
<td>$0.03 \pm 0.04$</td>
</tr>
<tr>
<td>$\rho(770)^+$</td>
<td>$0.16 \pm 0.06$</td>
<td>$0.16 \pm 0.06$</td>
<td>$0.16 \pm 0.06$</td>
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</tr>
<tr>
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<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
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</tr>
<tr>
<td>$\phi(1020)$</td>
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<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
</tr>
<tr>
<td>$\omega(1420)$</td>
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<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
</tr>
<tr>
<td><strong>Vector mesons:</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$f_2(1270)$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
</tr>
<tr>
<td>$f_2^0(1270)$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
</tr>
<tr>
<td>$K_2^+(1430)$</td>
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<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
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<tr>
<td>$K_2^0(1430)$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
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<td>$0.01 \pm 0.02$</td>
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<td>$B_{1+}(k)$</td>
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<td>$0.01 \pm 0.02$</td>
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</tr>
<tr>
<td>$D_{s1}^{*+}$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
</tr>
<tr>
<td>$D_{s2}^{*+}$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
<td>$0.01 \pm 0.02$</td>
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<tr>
<td><strong>Baryons:</strong></td>
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</tr>
<tr>
<td>$p$</td>
<td>$0.33 \pm 0.04$</td>
<td>$0.33 \pm 0.04$</td>
<td>$0.33 \pm 0.04$</td>
<td>$0.33 \pm 0.04$</td>
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<tr>
<td>$\Lambda$</td>
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<td>$0.093 \pm 0.006$</td>
<td>$0.093 \pm 0.006$</td>
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<tr>
<td>$\Sigma^0$</td>
<td>$0.0221 \pm 0.0018$</td>
<td>$0.0221 \pm 0.0018$</td>
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<td>$0.0221 \pm 0.0018$</td>
</tr>
<tr>
<td>$\Sigma^+$</td>
<td>$0.0221 \pm 0.0018$</td>
<td>$0.0221 \pm 0.0018$</td>
<td>$0.0221 \pm 0.0018$</td>
<td>$0.0221 \pm 0.0018$</td>
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<tr>
<td>$\Sigma^0$</td>
<td>$0.0221 \pm 0.0018$</td>
<td>$0.0221 \pm 0.0018$</td>
<td>$0.0221 \pm 0.0018$</td>
<td>$0.0221 \pm 0.0018$</td>
</tr>
<tr>
<td>$\Xi^0$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
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<tr>
<td>$\Sigma(1385)^0$</td>
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<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
</tr>
<tr>
<td>$\Sigma(1385)^+$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
</tr>
<tr>
<td>$\Sigma(1385)^-$</td>
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<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
</tr>
<tr>
<td>$\Lambda_0(939)$</td>
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<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
</tr>
<tr>
<td>$\Lambda_2(1520)$</td>
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<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
<td>$0.0055 \pm 0.0004$</td>
</tr>
</tbody>
</table>
Notes for Table 51.1:
(a) $\sigma_{\text{had}} = 3.33 \pm 0.05 \pm 0.21$ nb (CLEO: Phys. Rev. D29, 1254 (1984)) has been used in converting the measured cross sections to average hadron multiplicities.
(b) $B(D_s \rightarrow \eta \pi, \phi \pi)$ was used (RPP 1994).
(c) Comprises both charged and neutral $B$ meson states.
(d) The Standard Model $B(Z \rightarrow \phi \bar{\phi}) = 0.217$ was used.
(e) $x_p = p/p_{\text{beam}} > 0.1$ only.
(f) Both charge states.
(g) $B(D_s^{(*)}(2010) \rightarrow D^0 \pi^\pm)$ has been used (RPP 2000).
(h) $B(D_s^{(*)}(2010) \rightarrow \phi \pi^\pm)$, $B(\phi \rightarrow K^+ K^-)$ have been used (RPP 1998).
(i) Any charge state (i.e., $B^+_{s+} B^0_{s-}$ or $B^0_{s+}$).
(j) $B(Z \rightarrow \phi \bar{\phi} = 0.691$ was used (RPP 1994).
(k) Any charge state (i.e., $B^{(*)}_{s+} B^0_{s+}$ or $B^0_{s+}$).
(l) Assumes $B(D_s^{(*)}(2010) \rightarrow D^+ K^0 + D^0 K^+ = 100\%$ and $B(D_s^{(*)}(2010) \rightarrow D^0 K^+ = 45\%$.
(m) The value was derived from the cross section of $\Lambda^+_c \rightarrow p \pi K$ using $B$ and $\sigma_{\text{had}}$ assuming the branching fraction to be $(5.0 \pm 1.3)\%$ (RPP 2004).

References for Table 51.1:


Figure 51.2: World data on the total cross section of $e^+e^-\rightarrow$ hadrons and the ratio $R(s) = \sigma(e^+e^-\rightarrow$ hadrons, $s)/\sigma(e^+e^-\rightarrow\mu^+\mu^-, s)$. $\sigma(e^+e^-\rightarrow$ hadrons, $s$) is the experimental cross section corrected for initial state radiation and electron-positron vertex loops, $\sigma(e^+e^-\rightarrow\mu^+\mu^-, s) = 4\pi\alpha^2(s)/3s$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educative guide: the broken one (green) is a naive quark-parton model prediction, and the solid one (red) is 3-loop pQCD prediction (see “Quantum Chromodynamics” section of this Review, Eq. (9.7) or, for more details, K. G. Chetyrkin et al., Nucl. Phys. B586, 56 (2000) (Erratum ibid. B634, 413 (2002)). Breit-Wigner parameterizations of $J/\psi$, $\psi(2S)$, and $\Upsilon(nS)$, $n = 1, 2, 3, 4$ are also shown. The full list of references to the original data and the details of the $R$ ratio extraction from them can be found in [arXiv:hep-ph/0312114]. Corresponding computer-readable data files are available at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2017. Corrections by P. Janot (CERN) and M. Schmitt (Northwestern U.))

\[ \sigma \text{ and } R \text{ in } e^+e^- \text{ Collisions} \]

\begin{align*}
\sqrt{s} & \text{ [GeV]} \\
\sigma & \text{ [mb]} \\
R &
\end{align*}
Figure 51.3: \( R \) in the light-flavor, charm, and beauty threshold regions. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are the same as in Fig. 51.2. Note: CLEO data above \( \Upsilon(4S) \) were not fully corrected for radiative effects, and we retain them on the plot only for illustrative purposes with a normalization factor of 0.8. The full list of references to the original data and the details of the \( R \) ratio extraction from them can be found in [arXiv:hep-ph/0312114]. The computer-readable data are available at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2017.)
Annihilation Cross Section Near $M_Z$

**Figure 51.4:** 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:


**Combination:** The ALEPH, DELPHI, L3, OPAL, SLD Collaborations, the LEP Electroweak Working Group, and the SLD Electroweak and Heavy Flavor Groups, Phys. Rept. **427**, 257 (2006) [arXiv:hep-ex/0509008].

(Courtesy of M. Grünwald and the LEP Electroweak Working Group, 2007)
Total Hadronic Cross Sections

(Updated August 2017, COMPAS group, IHEP, Protvino)

In this section, plots of total cross section for various processes are presented. The plots include data from hadronic collisions such as $pp$ and $\gamma p$, as well as $\gamma p$, $\gamma d$, and $\gamma \gamma$ processes. The cross section data provide crucial inputs to the study of QCD physics. In particular, to probe the non-perturbative part of QCD processes which are described by a number of diffractive models. We begin by introducing some models of diffractive scatterings and listing references for further reading.

Diffractive scattering here means scattering of hadrons at small angles and exhibiting typical diffraction pattern in angular distribution of scattered particles. Beyond purely elastic scattering diffraction phenomena include inelastic processes with large rapidity gaps: those of single and double diffractive dissociation and ”central diffractive” events. In distinction from the most of other processes considered in the SM diffractive processes (DP) are related to large spatio-temporal scales growing with energy of collision. Being caused by strong interactions DP are a subject of the fundamental strong interaction theory, QCD, and hereby a part of the longstanding problem of QCD at large distances.

One of the most important basic notions and tools in general theoretical framework related to the diffractive processes is the notion of the Regge poles, or Reggeons, generalizing the simple one-particle exchange (of Yukawa type) by virtual particles of fixed spin to exchanges by the amplitude (at high c.m. energy $\sqrt{s}$ and fixed (small) transferred momentum squared, $t$): $T(s, t) = \beta(t)^{\alpha(t)}$ which qualitatively exhibits many typical features of generic diffractive processes (e.g. the growth of the interaction radius with energy). In practice the single-pole Reggeon model is insufficient for many diffractive processes but still serves a building block for more sophisticated schemes. Up to now no firm results concerning Regge trajectories $\alpha(t)$ and Regge residues $\beta(t)$ were obtained from the first principles of QCD. General principles imply that both $\alpha(t)$ and $\beta(t)$ are analytic functions with right cuts from some $t_0 > 0$ to positive infinity.

The theoretical requisite for analyzing diffractive phenomena is therefore represented by various model approaches. The more commonly discussed models in the literatures are:

- **Regge -Eikonal approach** [3-10]: this approach automatically satisfies the $s$-channel unitarity condition and generalizes the impact parameter approximation to the relativistic case.

- **Regge pole models with minimal corrections due to two-Reggeon exchanges** [11–13]: in this model, contribution of the leading trajectory is supplemented by a two-Reggeon exchange with arbitrary coefficient chosen from the fitting details.

- **$U$-matrix (or resonance) approach** [14, 15]: the unitarity respecting approach with the scattering amplitude defined by a reaction matrix.

- **Direct functional modelling of the amplitudes without Regge trajectories** [16, 17]: this approach appeals to only very general properties of the amplitudes leaving aside all dynamical assumptions and mostly aiming at the best phenomenological description of the data.

- **Quasi-classical approach** [18–20]: based on the observation that diffractive processes deal with high quantum numbers, in particular with large number of virtual quanta.

For readers who are interested in examples of both total and elastic cross section parametrizations and fits, see previous edition of the *Plots of Cross Sections and Related Quantities* review [21]. For the cross section plots shown in the following pages, the example fits are using parametrizations as described in [21] with the fit range starting at about $\sqrt{s} = 5$ GeV.

References:


[14, 15]: the unitarity respecting approach with the scattering amplitude defined by a reaction matrix.

[16]: the unitarity respecting approach with the scattering amplitude defined by a reaction matrix.

[17]: this approach appeals to only very general properties of the amplitudes leaving aside all dynamical assumptions and mostly aiming at the best phenomenological description of the data.

[18]: this approach appeals to only very general properties of the amplitudes leaving aside all dynamical assumptions and mostly aiming at the best phenomenological description of the data.

[19]: this approach appeals to only very general properties of the amplitudes leaving aside all dynamical assumptions and mostly aiming at the best phenomenological description of the data.

[20]: this approach appeals to only very general properties of the amplitudes leaving aside all dynamical assumptions and mostly aiming at the best phenomenological description of the data.

[21]: this approach appeals to only very general properties of the amplitudes leaving aside all dynamical assumptions and mostly aiming at the best phenomenological description of the data.
Figure 51.5: Summary of hadronic, $\gamma p$, $\gamma d$, and $\gamma\gamma$ total cross sections, and ratio of the real to imaginary parts of the forward hadronic amplitudes ($T$). Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS group, IHEP, Protvino, August 2017.)
Figure 51.6: Total and elastic cross sections for $pp$ and $\bar{p}p$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS group, HEP, Protvino, August 2017)
Figure 51.7: Total and elastic cross sections for $pd$ (total only), $np$, $\bar{p}d$ (total only), and $\bar{p}n$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS Group, IHEP, Protvino, August 2017)
Figure 51.8: Total and elastic cross sections for $\pi^\pm p$ and $\pi^\pm d$ (total only) collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS Group, IIHEP, Protvino, August 2017)
Figure 51.9: Total and elastic cross sections for $K^{-}p$ and $K^{-}d$ (total only), and $K^{-}n$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS Group, IHEP, Protvino, August 2017)
Figure 51.10: Total and elastic cross sections for $K^+p$ and total cross sections for $K^+d$ and $K^+n$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect./ (Courtesy of the COMPAS Group, IHEP, Protvino, August 2017)
Figure 51.11: Total and elastic cross sections for $\Lambda p$, total cross section for $\Sigma^- p$, and total hadronic cross sections for $\gamma d$, $\gamma p$, and $\gamma\gamma$ collisions as a function of laboratory beam momentum and the total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/current/xsect/. (Courtesy of the COMPAS group, IHEP, Protvino, August 2017)