

## 51. Plots of Cross Sections and Related Quantities

Updated in 2019. See various sections for details.

51.1	Pseudorapidity Distributions in $pp$ and $p\bar{p}$ Interactions . . . . .	1
51.2	Average Hadron Multiplicities in Hadronic $e^+e^-$ Annihilation Events . . . . .	2
51.3	$\sigma$ and $R$ in $e^+e^-$ Collisions . . . . .	5
51.4	Annihilation Cross Section Near $M_Z$ . . . . .	7
51.5	Total Hadronic Cross Sections . . . . .	8

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

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

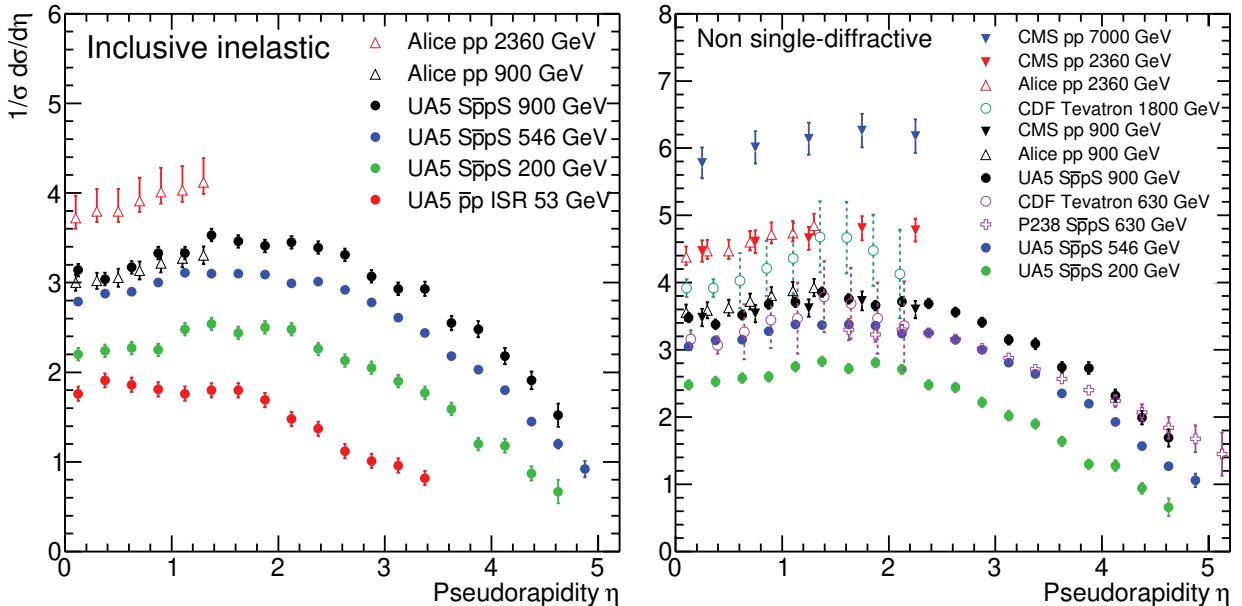
Pseudorapidity Distributions in  $pp$  and  $p\bar{p}$  Interactions

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  $Spp\bar{S}$  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  $Spp\bar{S}$  [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)

## 51.2 Average Hadron Multiplicities in Hadronic $e^+e^-$ Annihilation Events

Revised August 2019 by O. Biebel (Ludwig-Maximilians U.).

**Table 51.1:** Average hadron multiplicities per hadronic  $e^+e^-$  annihilation event at  $\sqrt{s} \approx 10, 29\text{--}35, 91,$  and  $130\text{--}200$  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	$\sqrt{s} = 29\text{--}35$ GeV	$\sqrt{s} = 91$ GeV	$\sqrt{s} = 130\text{--}200$ GeV	References
<b>Pseudoscalar mesons:</b>					
$\pi^+$	$6.52 \pm 0.11$	$10.3 \pm 0.4$	$17.02 \pm 0.19$	$21.24 \pm 0.39$	[8–17]
$\pi^0$	$3.2 \pm 0.3$	$5.83 \pm 0.28$	$9.42 \pm 0.32$		[12, 18–23]
$K^+$	$0.953 \pm 0.018$	$1.48 \pm 0.09$	$2.228 \pm 0.059$	$2.82 \pm 0.19$	[9–17, 24, 25]
$K^0$	$0.91 \pm 0.05$	$1.48 \pm 0.07$	$2.049 \pm 0.026$	$2.10 \pm 0.12$	[12, 17, 20, 26–36]
$\eta$	$0.20 \pm 0.04$	$0.61 \pm 0.07$	$1.049 \pm 0.080$		[12, 18, 19, 22, 23, 37–40]
$\eta(958)$	$0.03 \pm 0.01$	$0.26 \pm 0.10$	$0.152 \pm 0.020$		[20, 39, 41–43]
$D^+$	$0.194 \pm 0.019^{(a)}$	$0.17 \pm 0.03$	$0.175 \pm 0.016$		[12, 44–47]
$D^0$	$0.446 \pm 0.032^{(a)}$	$0.45 \pm 0.07$	$0.454 \pm 0.030$		[12, 44–47]
$D_s^+$	$0.063 \pm 0.014^{(a)}$	$0.45 \pm 0.20^{(b)}$	$0.131 \pm 0.021$		[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]
<b>Scalar mesons:</b>					
$f_0(980)$	$0.024 \pm 0.006$	$0.05 \pm 0.02^{(e)}$	$0.146 \pm 0.012$		[41, 54–56]
$a_0(980)^\pm$	—	—	$0.27 \pm 0.11^{(f)}$		[43]
<b>Vector mesons:</b>					
$\rho(770)^0$	$0.35 \pm 0.04$	$0.81 \pm 0.08$	$1.231 \pm 0.098$		[9, 12, 55, 57, 58]
$\rho(770)^\pm$	—	—	$2.40 \pm 0.43^{(f)}$		[43]
$\omega(782)$	$0.30 \pm 0.08$	—	$1.016 \pm 0.065$		[40, 42, 43, 57]
$K^*(892)^+$	$0.27 \pm 0.03$	$0.64 \pm 0.05$	$0.714 \pm 0.055$		[9, 12, 33, 57, 59, 60]
$K^*(892)^0$	$0.29 \pm 0.03$	$0.56 \pm 0.06$	$0.738 \pm 0.024$		[9, 12, 36, 57, 58, 61, 62]
$\phi(1020)$	$0.044 \pm 0.003$	$0.085 \pm 0.011$	$0.0963 \pm 0.0032$		[12, 36, 56–58, 61]
$D^*(2010)^+$	$0.177 \pm 0.022^{(a)}$	$0.43 \pm 0.07$	$0.1937 \pm 0.0057^{(g)}$		[12, 44–46, 63, 64]
$D^*(2007)^0$	$0.168 \pm 0.019^{(a)}$	$0.27 \pm 0.11$	—		[12, 44, 45]
$D_s^*(2112)^+$	$0.048 \pm 0.014^{(a)}$	—	$0.101 \pm 0.048^{(h)}$		[48, 65]
$B^*(i)$	—	—	$0.288 \pm 0.026$		[66, 67]

Particle	$\sqrt{s} \approx 10 \text{ GeV}$	$\sqrt{s} = 29\text{--}35 \text{ GeV}$	$\sqrt{s} = 91 \text{ GeV}$	$\sqrt{s} = 130\text{--}200 \text{ GeV}$	
$J/\psi(1S)$	$0.00050 \pm 0.00005^{(a)}$	—	$0.0052 \pm 0.0004^{(j)}$		[68–73]
$\psi(2S)$	—	—	$0.0023 \pm 0.0004^{(j)}$		[71, 73, 74]
$\Upsilon(1S)$	—	—	$0.00014 \pm 0.00007^{(j)}$		[75]
<b>Pseudovector mesons:</b>					
$f_1(1285)$	—	—	$0.165 \pm 0.051$		[76]
$f_1(1420)$	—	—	$0.056 \pm 0.012$		[76]
$\chi_{c1}(3510)$	—	—	$0.0041 \pm 0.0011^{(j)}$		[71, 74]
<b>Tensor mesons:</b>					
$f_2(1270)$	$0.09 \pm 0.02$	$0.14 \pm 0.04$	$0.166 \pm 0.020$		[54–56, 77]
$f_2'(1525)$	—	—	$0.012 \pm 0.006$		[55]
$K_2^*(1430)^+$	—	$0.09 \pm 0.03$	—		[55, 78]
$K_2^*(1430)^0$	—	$0.12 \pm 0.06$	$0.084 \pm 0.022$		[54, 55, 79]
$B^{**}(k)$	—	—	$0.118 \pm 0.024$		[80]
$D_{s1}^\pm$	—	—	$0.0052 \pm 0.0011^{(\ell)}$		[81]
$D_{s2}^{*\pm}$	—	—	$0.0083 \pm 0.0031^{(\ell)}$		[81]
<b>Baryons:</b>					
$p$	$0.266 \pm 0.008$	$0.640 \pm 0.050$	$1.050 \pm 0.032$	$1.41 \pm 0.18$	[10, 13–17, 24, 25, 77]
$\Lambda$	$0.093 \pm 0.006^{(a)}$	$0.205 \pm 0.010$	$0.3915 \pm 0.0065$	$0.39 \pm 0.03$	[17, 20, 34, 36, 77, 82–85]
$\Sigma^0$	$0.0221 \pm 0.0018^{(a)}$	—	$0.078 \pm 0.010$		[10, 59, 82, 86–88]
$\Sigma^-$	—	—	$0.081 \pm 0.010$		[88, 89]
$\Sigma^+$	—	—	$0.107 \pm 0.011$		[87, 88]
$\Sigma^\pm$	—	—	$0.174 \pm 0.009$		[84, 88]
$\Xi^-$	$0.0055 \pm 0.0004^{(a)}$	$0.0176 \pm 0.0027$	$0.0262 \pm 0.0009$		[9, 59, 77, 82–85]
$\Delta(1232)^{++}$	$0.040 \pm 0.010$	—	$0.085 \pm 0.014$		[90–92]
$\Sigma(1385)^-$	$0.006 \pm 0.002$	$0.017 \pm 0.004$	$0.0240 \pm 0.0017$		[59, 82, 84, 85, 93]
$\Sigma(1385)^+$	$0.0062 \pm 0.0011^{(a)}$	$0.017 \pm 0.004$	$0.0239 \pm 0.0015$		[59, 82–85, 93]
$\Sigma(1385)^\pm$	$0.0106 \pm 0.0020$	$0.033 \pm 0.008$	$0.0472 \pm 0.0027$		[59, 82, 84, 85, 93]
$\Xi(1530)^0$	$0.00130 \pm 0.00010^{(a)}$	—	$0.00694 \pm 0.00049$		[59, 82, 83, 85, 94]
$\Omega^-$	$0.00060 \pm 0.00033^{(a)}$	$0.014 \pm 0.007$	$0.00124 \pm 0.00018$		[59, 77, 82, 83, 85, 86]
$\Lambda_c^+$	$0.0479 \pm 0.0038^{(a,m)}$	$0.110 \pm 0.050$	$0.078 \pm 0.017$		[47, 49, 77, 83, 95]
$\Lambda_b^0$	—	—	$0.031 \pm 0.016$		[96]
$\Sigma_c^0$	$0.0025 \pm 0.0004^{(a)}$	—	—		[83]
$\Lambda(1520)$	$0.0046 \pm 0.0004^{(a)}$	—	$0.0222 \pm 0.0027$		[83, 85, 89, 97]

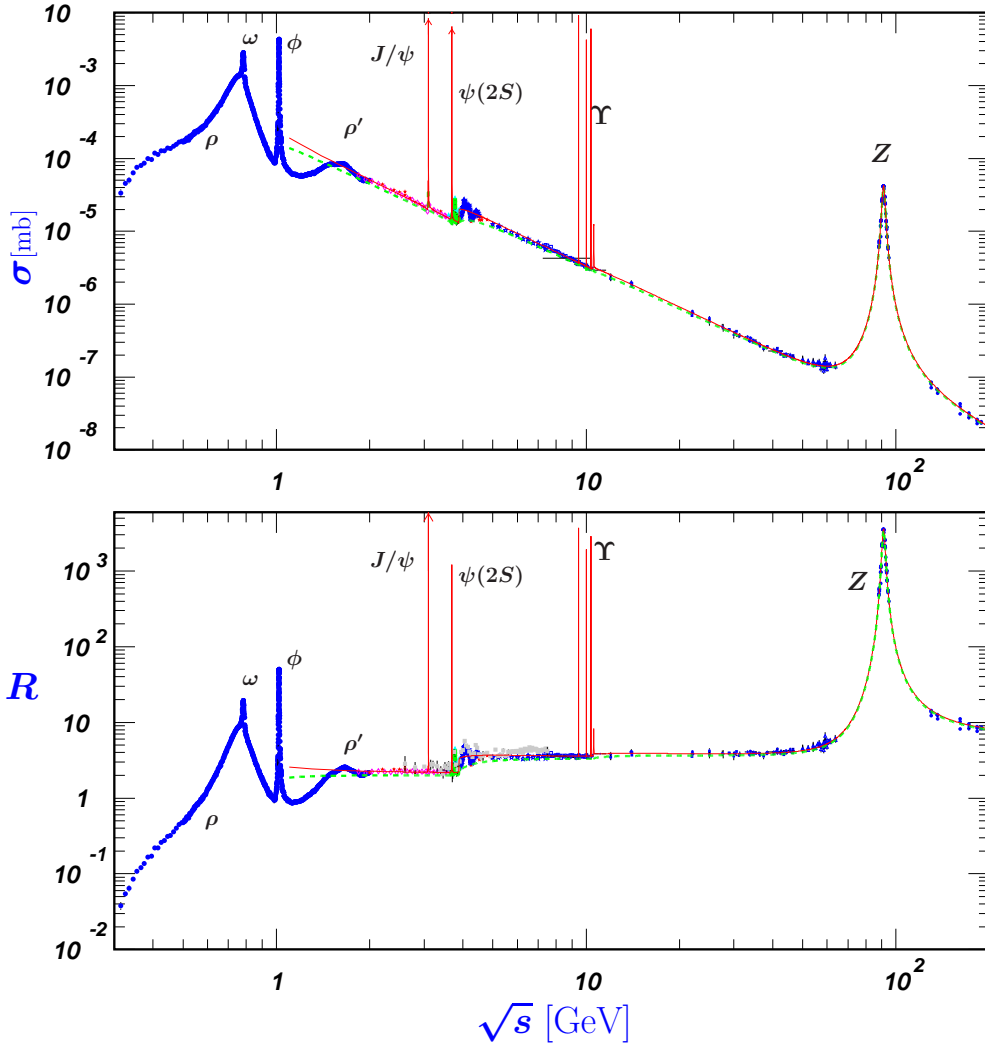
- (a)  $\sigma_{\text{had}} = 3.33 \pm 0.05 \pm 0.21$  nb (**CLEO**: [98]) has been used in converting the measured cross sections to average hadron multiplicities.
- (b)  $B(D_s \rightarrow \eta\pi, \eta'\pi)$  was used (RPP 1994).
- (c) Comprises both charged and neutral  $B$  meson states.
- (d) The Standard Model  $B(Z \rightarrow b\bar{b}) = 0.217$  was used.
- (e)  $x_p = p/p_{\text{beam}} > 0.1$  only.
- (f) Both charge states.
- (g)  $B(D^*(2010)^+ \rightarrow D^0\pi^+) \times B(D^0 \rightarrow K^-\pi^+)$  has been used (RPP 2000).
- (h)  $B(D_s^* \rightarrow D_S^+\gamma)$ ,  $B(D_s^+ \rightarrow \phi\pi^+)$ ,  $B(\phi \rightarrow K^+K^-)$  have been used (RPP 1998).
- (i) Any charge state (*i.e.*,  $B_d^*$ ,  $B_u^*$ , or  $B_s^*$ ).
- (j)  $B(Z \rightarrow \text{hadrons}) = 0.699$  was used (RPP 1994).
- (k) Any charge state (*i.e.*,  $B_d^{**}$ ,  $B_u^{**}$ , or  $B_s^{**}$ ).
- (l) Assumes  $B(D_{s1}^+ \rightarrow D^{*+}K^0 + D^{*0}K^+) = 100\%$  and  $B(D_{s2}^+ \rightarrow D^0K^+) = 45\%$ .
- (m) The value was derived from the cross section of  $\Lambda_c^+ \rightarrow p\pi K$  using (a) and assuming the branching fraction to be  $(5.0 \pm 1.3)\%$  (RPP 2004).

#### References grouped by collaboration for Table-51.1:

- **RPP**: [12]
- **ALEPH**: [13, 20, 40, 58, 59, 63, 70, 81],
- **ARGUS**: [8, 24, 37, 41, 57, 82, 90, 97],
- **BaBar**: [10, 48, 68, 95],
- **Belle**: [44, 69, 83],
- **CELLO**: [19, 26],
- **CLEO**: [9, 45, 49, 98],
- **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, 96],
- **PLUTO**: [30]
- **SLD**: [16, 36],
- **TASSO**: [31]
- **TPC**: [32].

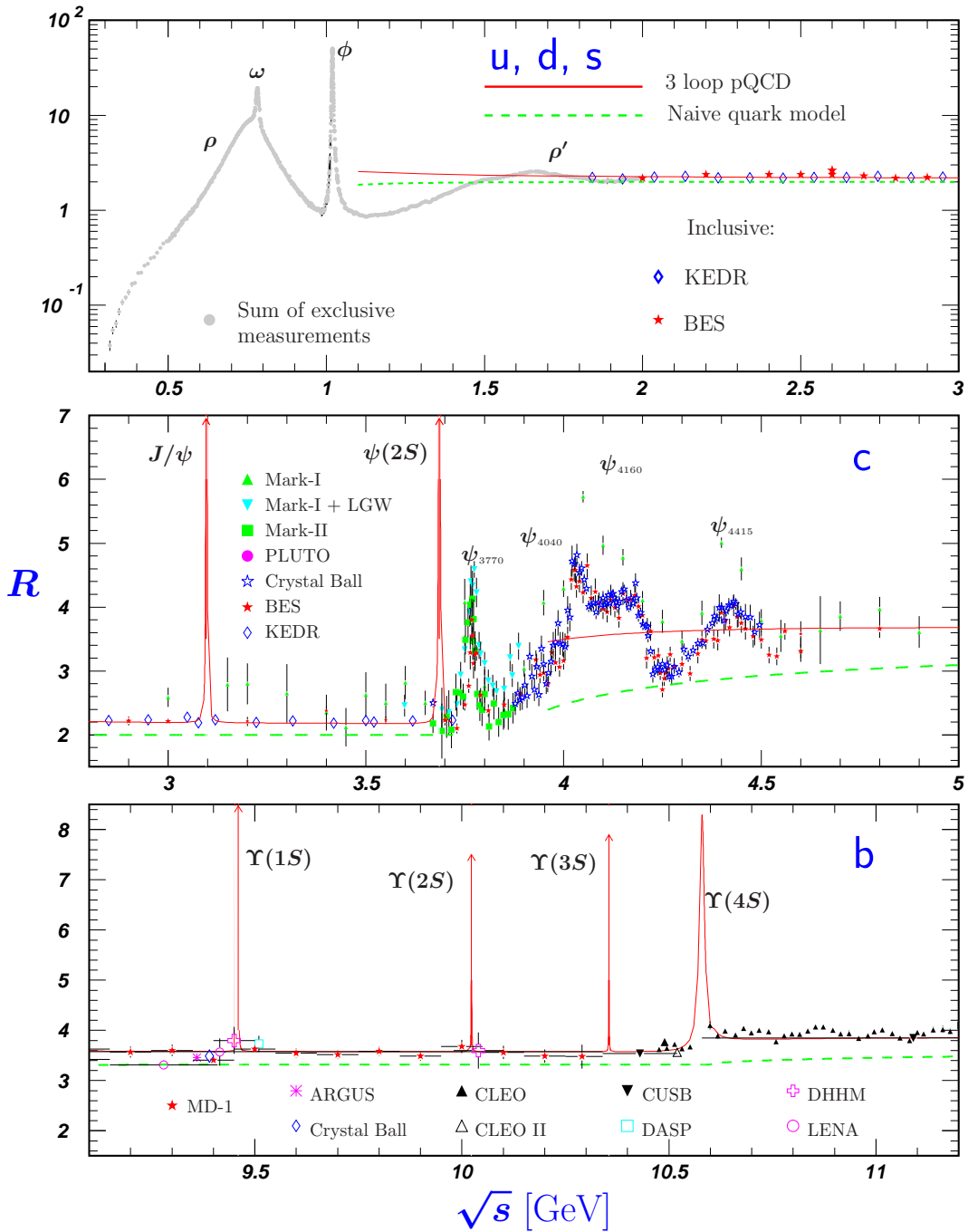
51.3  $\sigma$  and  $R$  in  $e^+e^-$  Collisions

revised August 2019 by V.I. Belousov (COMPAS Group, IHEP), V.V. Ezhela (COMPAS Group, IHEP), A.A. Odizov (COMPAS Group, IHEP), V.A. Petrov (COMPAS Group, IHEP), R.A. Ryutin (COMPAS Group, IHEP), N.P. Tkachenko (COMPAS Group, IHEP) and O.V. Zenin (COMPAS Group, IHEP; MIPT Moscow)

 $\sigma$  and  $R$  in  $e^+e^-$  Collisions

**Figure 51.2:** World data on the total cross section of  $e^+e^- \rightarrow \text{hadrons}$  and the ratio  $R(s) = \sigma(e^+e^- \rightarrow \text{hadrons}, s) / \sigma(e^+e^- \rightarrow \mu^+\mu^-, s)$ .  $\sigma(e^+e^- \rightarrow \text{hadrons}, s)$  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 [99], 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 [100]. Corresponding computer-readable data files are available at <http://pdg.lbl.gov/current/xsect/>. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2019. Corrections by P. Janot (CERN) and M. Schmitt (Northwestern U.))

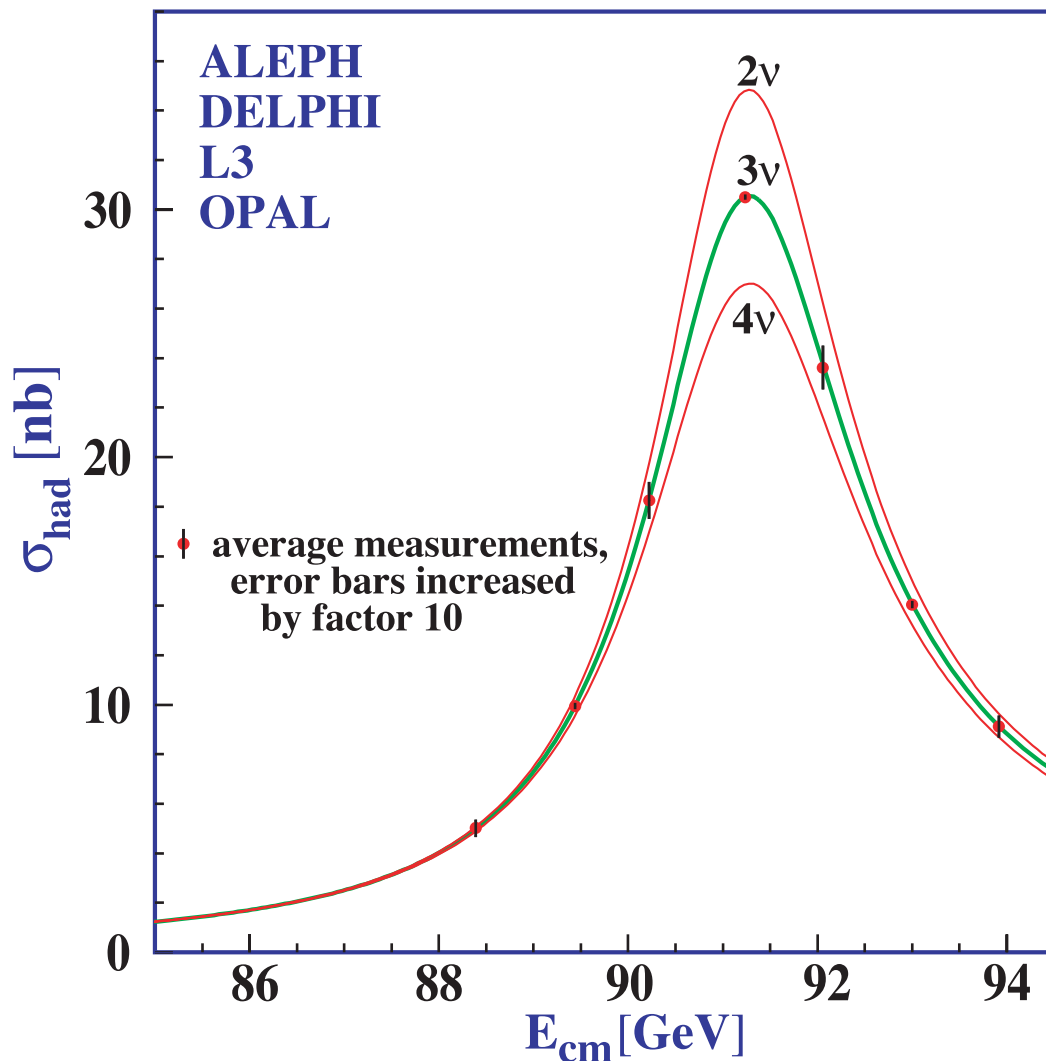
### $R$ in Light-Flavor, Charm, and Beauty Threshold Regions



**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 [100]. The computer-readable data are available at <http://pdg.lbl.gov/current/xsect/>. (Courtesy of the COMPAS (Protvino) and HEPDATA (Durham) Groups, August 2019.)

51.4 Annihilation Cross Section Near  $M_Z$ 

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



**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: ALEPH [101], DELPHI [102], L3 [103], OPAL [104], Combination [105],

## 51.5 Total Hadronic Cross Sections

revised August 2019 by COMPAS Group (NRC KI – 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  $\bar{p}p$ , 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 diffraction 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.

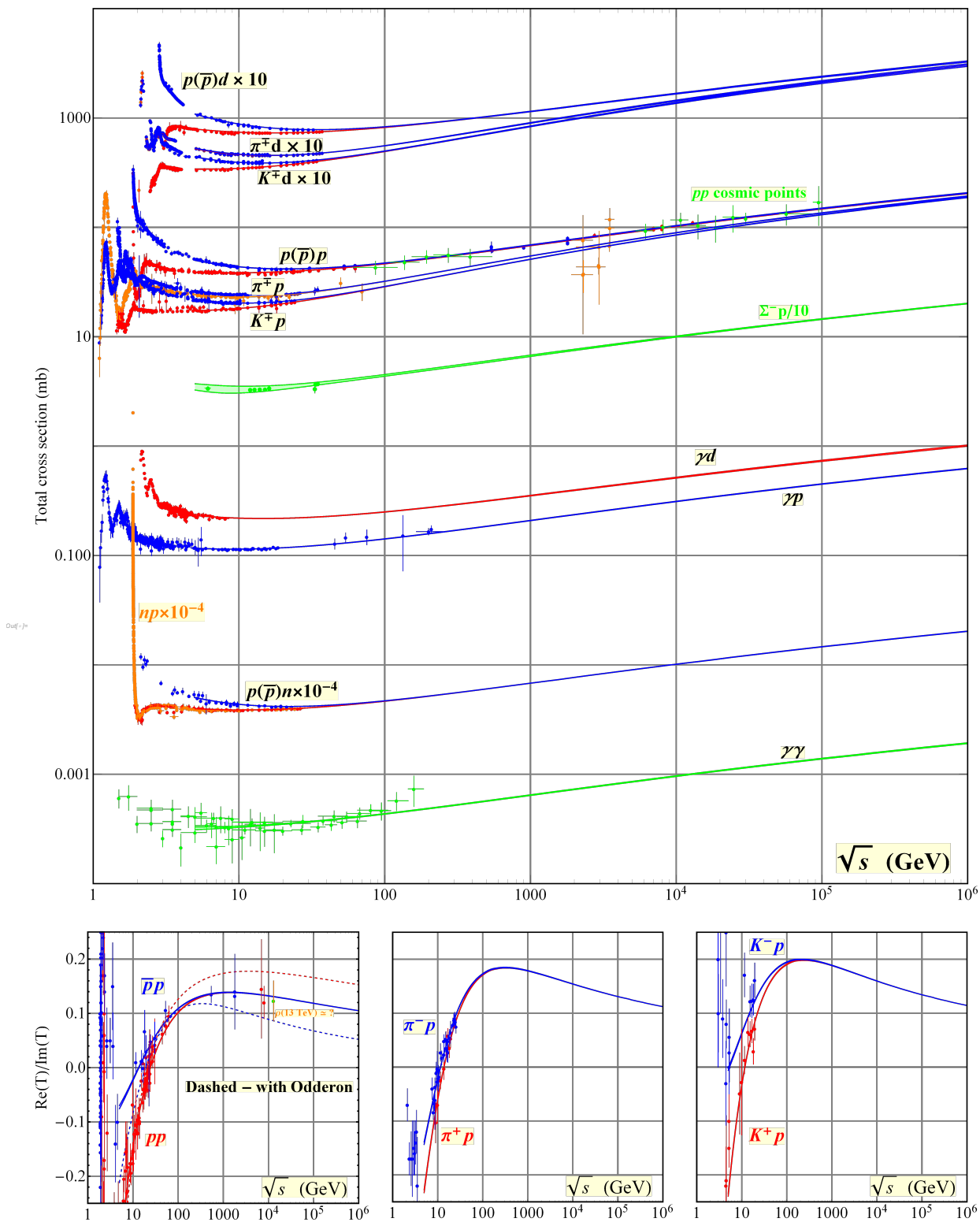
One of the most important basic notions and tools in general theoretical framework related to the diffractive processes is the notion of the Regge poles, or Reggeons, generalizing the simple one-particle exchange (on Yukawa type) by virtual particles of fixed spin to exchanges by states with “running spin” dependent on the transferred momenta [106, 107]. The simplest case of the one-Reggeon exchange amplitude is given by the amplitude (at high c.m. energy  $\sqrt{s}$  and fixed (small) transferred momentum squared,  $t$ ):  $T(s, t) = \beta(t)s^{\alpha(t)}$  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:

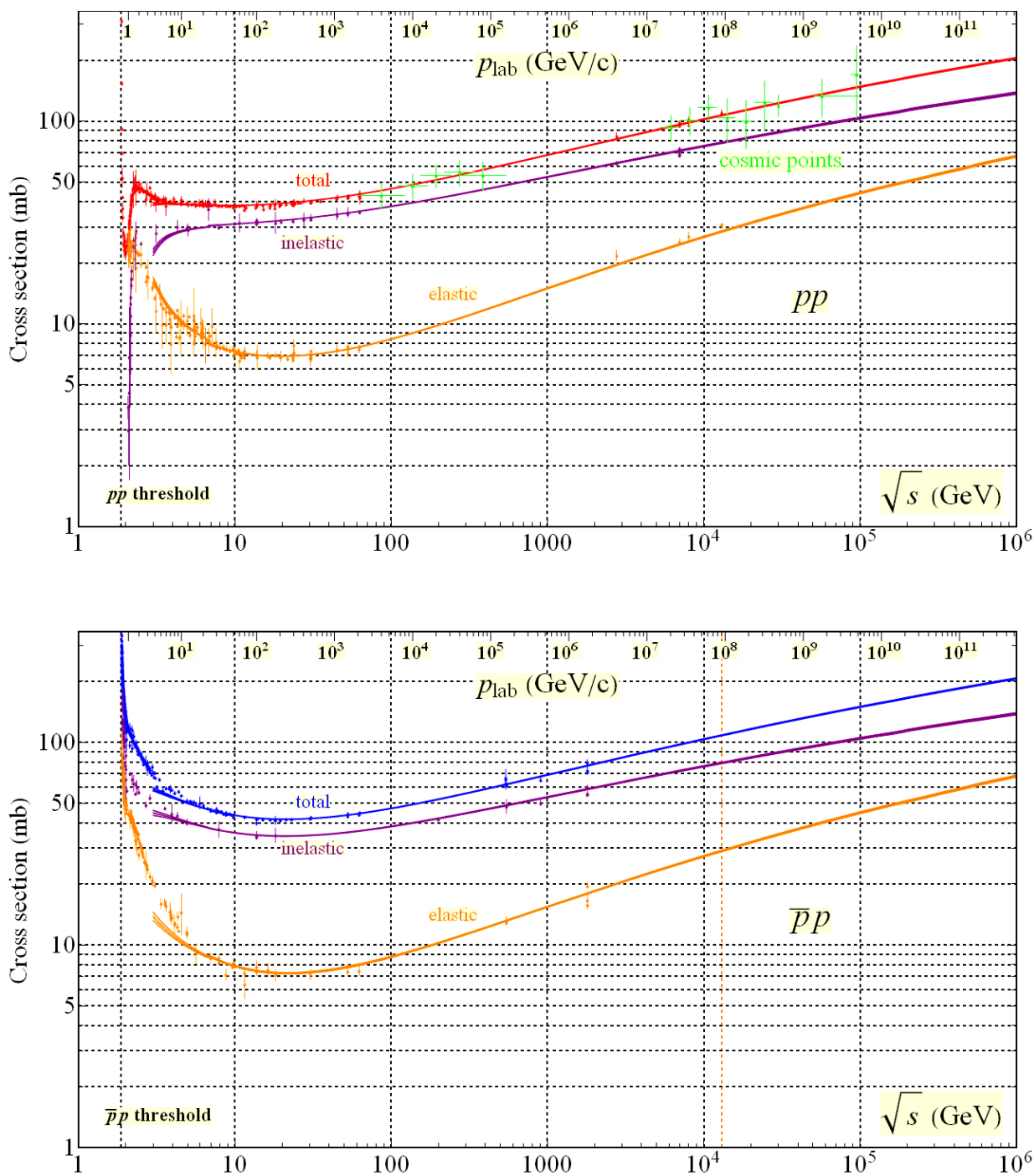
- **Regge -Eikonal approach** [108–115]: this approach automatically satisfy the  $s$ -channel unitarity condition and generalizes the impact parameter approximation to the relativistic case.
- **Regge pole models with minimal corrections due to two-Reggeon exchanges** [116–118]: in this model, contribution of the leading trajectory is supplemented by a two-Reggeon exchange with arbitrary coefficient chosen from the fitting details.
- **$U$ -matrix (or resonance) approach** [119, 120]: the unitarity respecting approach with the scattering amplitude defined by a reaction matrix.
- **Direct functional modelling of the amplitudes without Regge trajectories** [121, 122]: 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** [123–126]: 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 the previous edition of the *Plots of Cross Sections and Related Quantities* review [127]. For the cross section plots shown in the following pages, the example fits are using parametrizations as described in [127] with the  $t$  range starting at about  $\sqrt{s} = 5$  GeV.

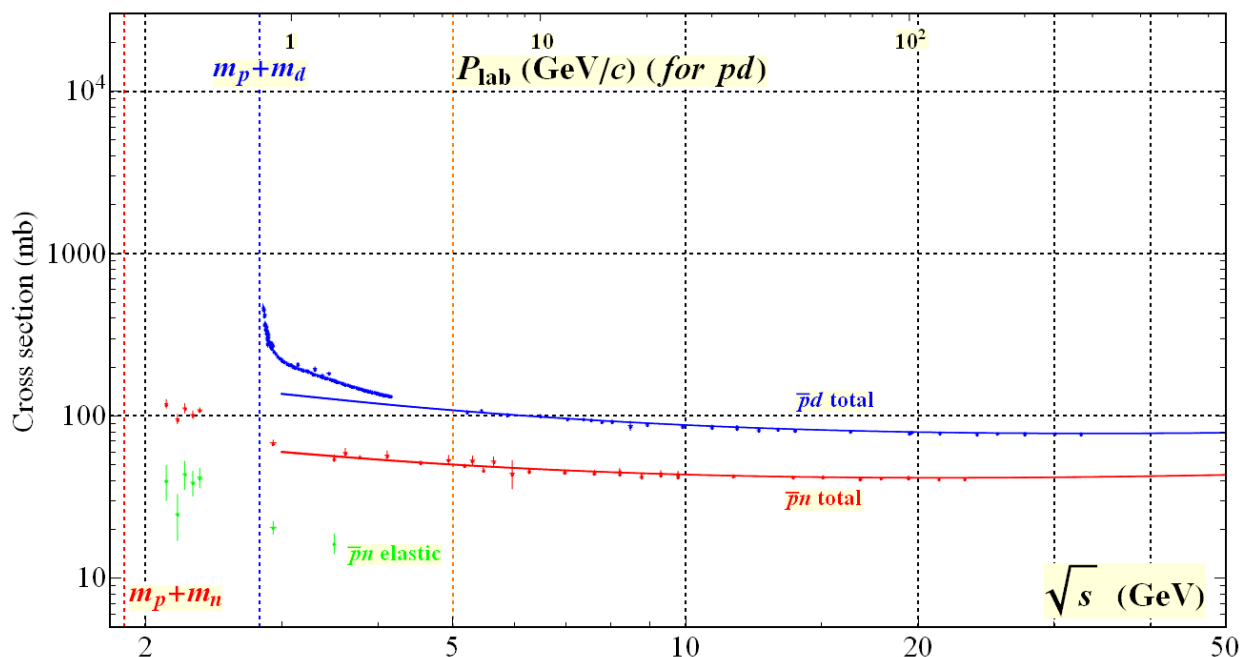
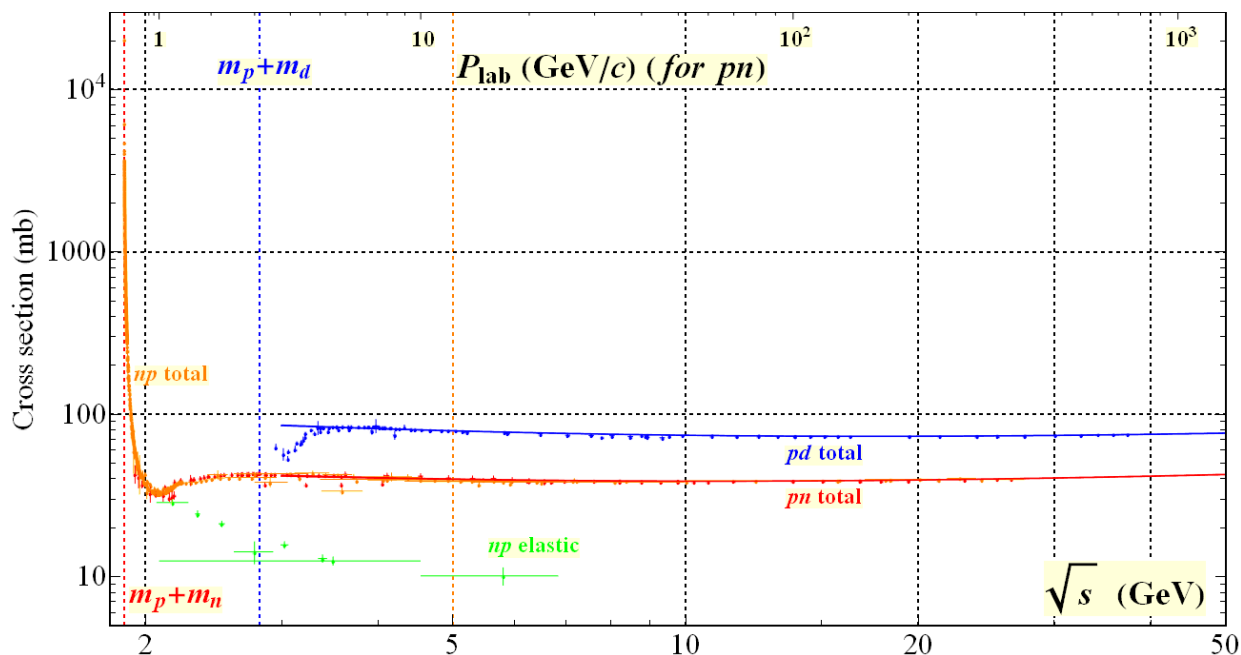




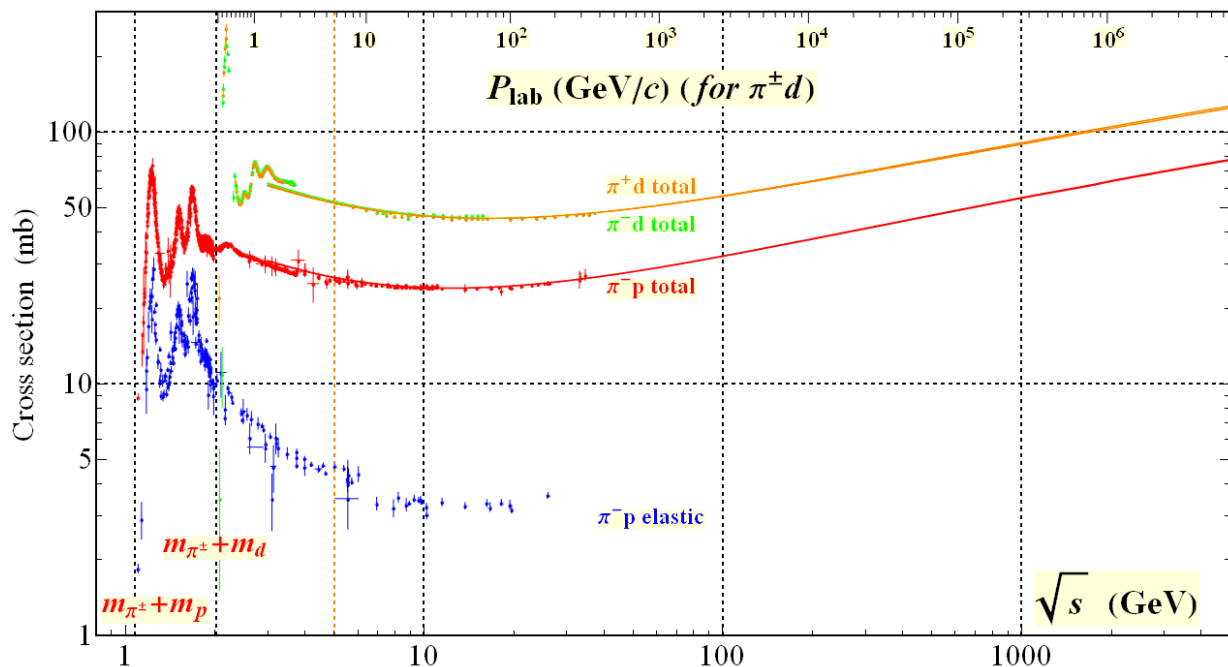
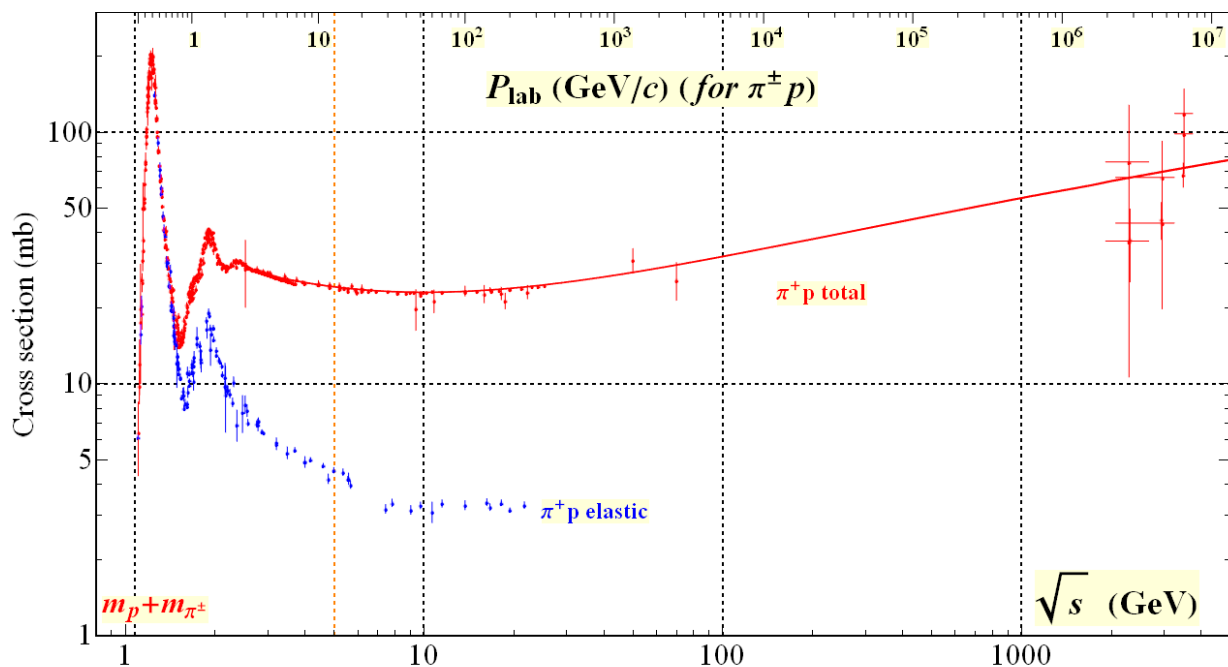
**Figure 51.5:** Summary of hadronic,  $\gamma p$ ,  $\gamma d$ , and  $\gamma\gamma$  total cross sections, and ratio of the real to imaginary parts of the forward hadronic amplitudes. Corresponding computer-readable data files may be found at <http://pdg.lbl.gov/current/xsect/>. (Courtesy of the COMPAS group, NRC KI – IHEP, Protvino, August 2019.)



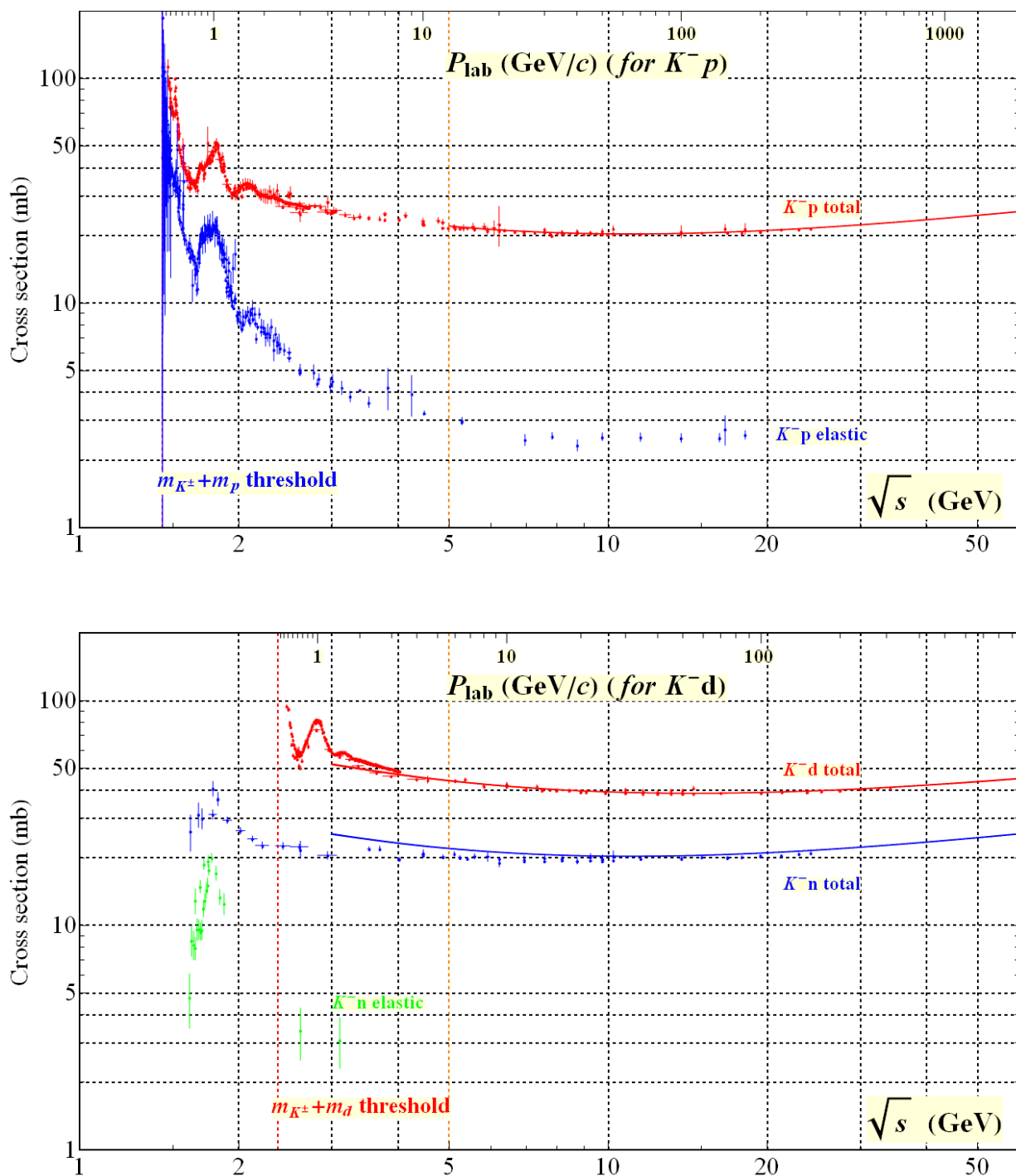
**Figure 51.6:** Total and elastic cross sections for  $pp$  and  $\bar{p}p$  collisions as a function of laboratory beam momentum and total center-of-mass energy.  $\sigma_{\text{el}}$  is computed using the nuclear part of the elastic scattering amplitude [126]. Corresponding computer-readable data files may be found at <http://pdg.lbl.gov/current/xsect/>. (Courtesy of the COMPAS group, NRC KI – IHEP, Protvino, August 2019.)



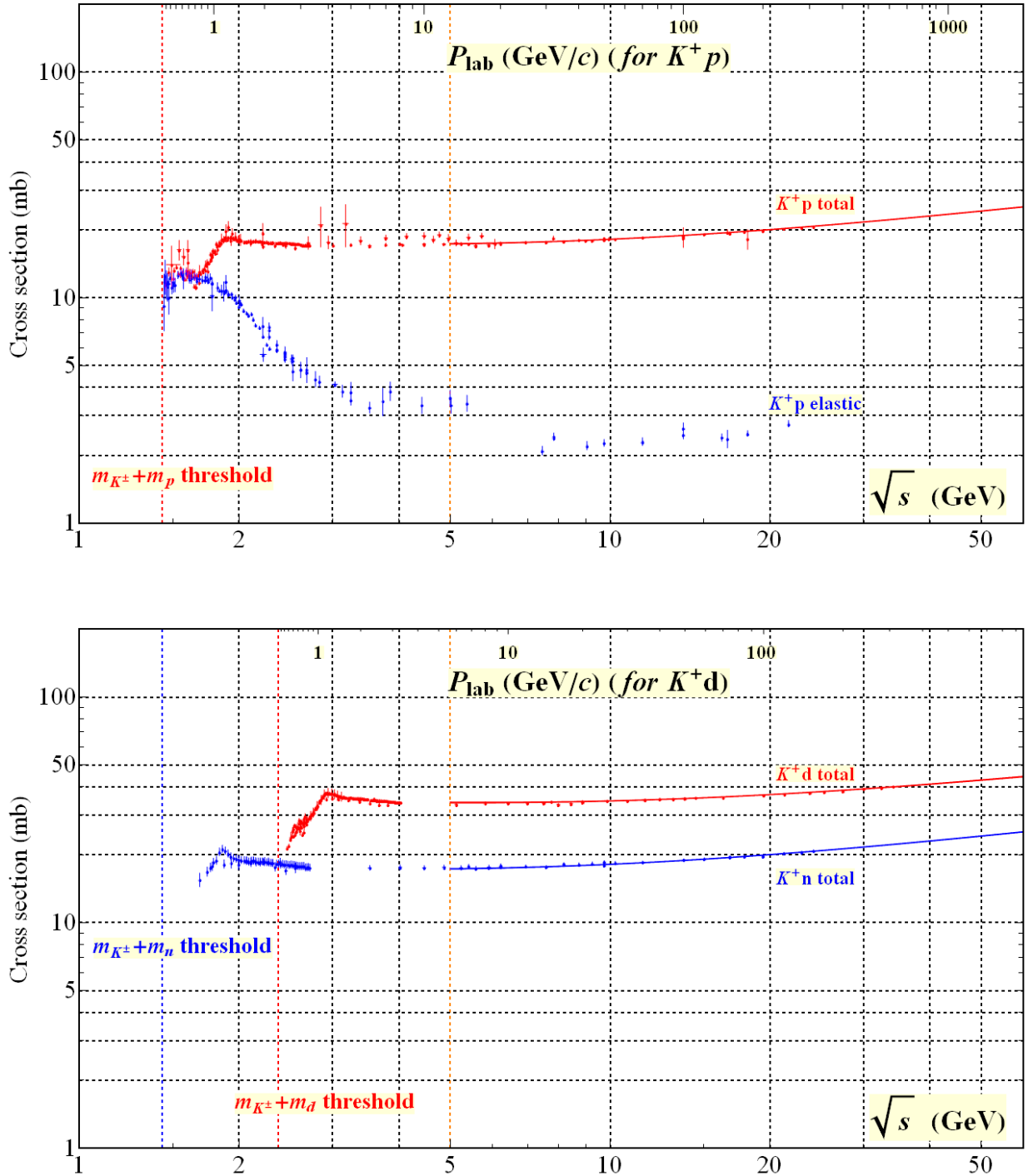
**Figure 51.7:** Total and elastic cross sections for  $pd$  (total only),  $np$ ,  $\bar{p}d$  (total only), and  $\bar{p}n$  collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at <http://pdg.lbl.gov/current/xsect/>. (Courtesy of the COMPAS Group, NRC KI – IHEP, Protvino, August 2019.)



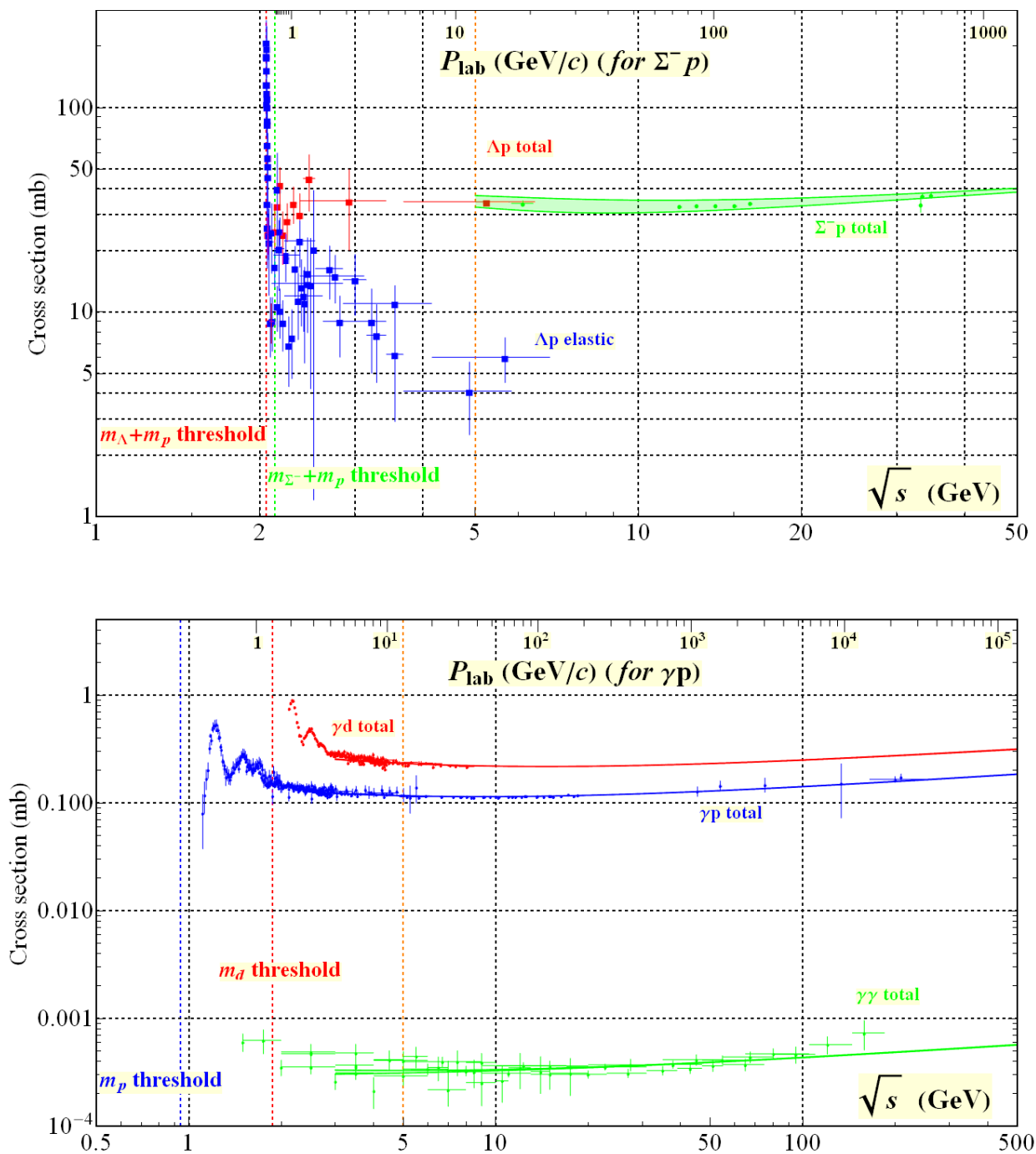
**Figure 51.8:** Total and elastic cross sections for  $\pi^\pm p$  and  $\pi^\pm d$  (total only) collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at <http://pdg.lbl.gov/current/xsect/>. (Courtesy of the COMPAS Group, NRC KI – IHEP, Protvino, August 2019.)



**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, NRC KI – IHEP, Protvino, August 2019.)



**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, NRC KI – IHEP, Protvino, August 2019.)



**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, NRC KI – IHEP, Protvino, August 2019.)

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