## *u*

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 2$ to 8 MeV  Charge $= \frac{2}{3}\ e$  $I_z = +\frac{1}{2}$

$m_u/m_d = 0.25$ to 0.70

## *d*

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 5$ to 15 MeV  Charge $= -\frac{1}{3}\ e$  $I_z = -\frac{1}{2}$

$m_s/m_d = 17$ to 25

## *s*

$I(J^P) = 0(\frac{1}{2}^+)$

Mass $m = 100$ to 300 MeV  Charge $= -\frac{1}{3}\ e$  Strangeness $= -1$

$(m_s - (m_u + m_d)/2)/(m_d - m_u) = 34$ to 51

# LIGHT QUARKS ($u$, $d$, $s$)

OMITTED FROM SUMMARY TABLE

### *u*-QUARK MASS

The *u*-, *d*-, and *s*-quark masses are estimates of so-called "current-quark masses," in a mass-independent subtraction scheme such as $\overline{\text{MS}}$ at a scale $\mu \approx 1$ GeV. The ratios $m_u/m_d$ and $m_s/m_d$ are extracted from pion and kaon masses using chiral symmetry. The estimates of *d* and *u* masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the *u* quark could be essentially massless. The *s*-quark mass is estimated from SU(3) splittings in hadron masses.

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **2 to 8 OUR EVALUATION** | | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 5.3±1.5 | [1] JAMIN | 95 | THEO | Assumes $\overline{\text{MS}}$ scheme |
| 4 ±1 | [2] NARISON | 95C | THEO | Assumes $\overline{\text{MS}}$ scheme |
| | [3] CHOI | 92B | THEO | |
| 5.8 | [4] BARDUCCI | 88 | THEO | |
| 5.1±1.5 | [5] GASSER | 82 | THEO | |
| 1.8±0.7 | [6] PAGELS | 80 | THEO | |
| 5.6±2.9 | [7] PAGELS | 80 | THEO | |
| 4.2 | [8] WEINBERG | 77 | THEO | |
| 4 | [9] GASSER | 75 | THEO | |

[1] JAMIN 95 uses QCD sum rules at next-to-leading order.
[2] NARISON 95C determines the $\overline{\text{MS}}$ mass at 1 GeV.
[3] CHOI 92B argues that $m_u = 0$ is okay based on instanton contributions to the chiral coefficients. Disagrees with DONOGHUE 92 and DONOGHUE 92B.
[4] BARDUCCI 88 renormalized quark mass at 1 GeV. Uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$.
[5] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. The renormalization scale is 1 GeV.
[6] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle \overline{q}q \rangle$.
[7] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle \overline{q}q\,\overline{q}q \rangle$ correlation function.
[8] WEINBERG 77 assumes that the baryon SU(3) splittings are equal to $m_s$.
[9] GASSER 75 uses inelastic electron scattering and SU(6).

## *d*-QUARK MASS

See the comment for the *u* quark above.

| VALUE (MeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **5 to 15 OUR EVALUATION** | | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| | [10] BIJNENS | 95 | THEO | |
| 9.4±1.5 | [11] JAMIN | 95 | THEO | Assumes $\overline{\text{MS}}$ scheme |
| 10 ±1 | [12] NARISON | 95C | THEO | Assumes $\overline{\text{MS}}$ scheme |
| | [13] ADAMI | 93 | THEO | |
| | [14] NEFKENS | 92 | THEO | |
| 8.4 | [15] BARDUCCI | 88 | THEO | |
| | [16] DOMINGUEZ | 87 | THEO | |
| | [17] KREMER | 84 | THEO | |
| 8.9±2.6 | [18] GASSER | 82 | THEO | |
| 4.3±0.7 | [19] PAGELS | 80 | THEO | |
| 14.6±5.7 | [20] PAGELS | 80 | THEO | |
| 7.5 | [21] WEINBERG | 77 | THEO | |
| 6 | [22] GASSER | 75 | THEO | |

[10] BIJNENS 95 determines $m_{\overline{u}}+m_{\overline{d}}$ (1 GeV) = 12 ± 2.5 MeV using finite energy sum rules.
[11] JAMIN 95 uses QCD sum rules at next-to-leading order.
[12] NARISON 95C determines the $\overline{\text{MS}}$ mass at 1 GeV.
[13] ADAMI 93 obtain $m_d - m_u$=3 ± 1 MeV at $\mu$=0.5 GeV using isospin-violating effects in QCD sum rules.
[14] NEFKENS 92 results for $m_d - m_u$ are 3.1 ± 0.4 MeV from meson masses and 3.6 ± 0.4 MeV from baryon masses.
[15] BARDUCCI 88 renormalized quark mass at 1 GeV. Uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$.
[16] DOMINGUEZ 87 uses QCD sum rules to obtain $m_u+m_d$ = 15.5 ± 2.0 MeV and $m_d - m_u$ = 6 ± 1.5 MeV.
[17] KREMER 84 obtain $m_u+m_d$=21 ± 2 MeV at $Q^2$ = 1 GeV$^2$ using SVZ values for quark condensates; they obtain $m_u+m_d$=35 ± 3 MeV at $Q^2$ = 1 GeV$^2$ using factorization values for quark condensates.
[18] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. The renormalization scale is 1 GeV.
[19] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\rangle$.
[20] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\,\overline{q}q\rangle$ correlation function.
[21] WEINBERG 77 assumes that the baryon SU(3) splittings are equal to $m_s$.
[22] GASSER 75 uses inelastic electron scattering and SU(6).

## *s*-QUARK MASS

See the comment for the *u* quark above.

| VALUE (MeV) | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **100 to 300 OUR EVALUATION** | | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 171± 15 | [23] CHETYRKIN | 95 | THEO | Assumes $\overline{\text{MS}}$ scheme |
| 189± 32 | [24] JAMIN | 95 | THEO | Assumes $\overline{\text{MS}}$ scheme |
| 197± 29 | [25] NARISON | 95C | THEO | Assumes $\overline{\text{MS}}$ scheme |
| | [26] NEFKENS | 92 | THEO | |
| 194± 4 | [27] DOMINGUEZ | 91 | THEO | |
| 118 | [28] BARDUCCI | 88 | THEO | |
| | [29] KREMER | 84 | THEO | |
| 175± 55 | [30] GASSER | 82 | THEO | |
| >300 | [31] PENSO | 82B | THEO | |
| 112± 66 | [32] PAGELS | 80 | THEO | |
| 378±220 | [33] PAGELS | 80 | THEO | |
| 150 | [34] WEINBERG | 77 | THEO | |
| 135 | [35] GASSER | 75 | THEO | |

[23] $\overline{\text{MS}}$ mass at 1 GeV. CHETYRKIN 95 uses QCD sum rules at next-to-leading order.
[24] JAMIN 95 uses QCD sum rules at next-to-leading order.
[25] NARISON 95C determines the $\overline{\text{MS}}$ mass at 1 GeV.
[26] NEFKENS 92 results for $m_s-(m_u+m_d)/2$ are 111 ± 10 MeV from meson masses and 163 ± 15 MeV from baryon masses.
[27] DOMINGUEZ 91 uses QCD sum rules with $\Lambda_{\text{QCD}}$ = 100–200 MeV and the SVZ value for the gluon condensate. The renormalization point is 1 GeV.

[28] BARDUCCI 88 renormalized quark mass at 1 GeV. Uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$.
[29] KREMER 84 obtain $m_u+m_s$=245 ± 10 MeV at $Q^2 = 1$ GeV$^2$ using SVZ values for quark condensates; they obtain $m_u+m_s$=270 ± 10 MeV at $Q^2 = 1$ GeV$^2$ using factorization values for quark condensates.
[30] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. The renormalization scale is 1 GeV.
[31] PENSO 82 uses SVZ sum rules to put a lower bound on the strange quark mass.
[32] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\rangle$.
[33] PAGELS 80 uses lowest-order chiral perturbation theory plus an estimate of $\langle\overline{q}q\,\overline{q}q\rangle$ correlation function.
[34] WEINBERG 77 assumes that the baryon SU(3) splittings are equal to $m_s$.
[35] GASSER 75 is based on SU(6).

## LIGHT QUARK MASS RATIOS

### *u/d* MASS RATIO

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| **0.25 to 0.70 OUR EVALUATION** | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| <0.3 | [36] CHOI | 92 | THEO |
| 0.26 | [37] DONOGHUE | 92 | THEO |
| 0.30±0.07 | [38] DONOGHUE | 92B | THEO |
| 0.66 | [39] GERARD | 90 | THEO |
| 0.4 to 0.65 | [40] LEUTWYLER | 90B | THEO |
| 0.05 to 0.78 | [41] MALTMAN | 90 | THEO |
| 0.0 to 0.56 | [42] CHOI | 89B | THEO |
| 0.0 to 0.8 | [43] KAPLAN | 86 | THEO |
| 0.57±0.04 | [44] GASSER | 82 | THEO |
| 0.38±0.13 | [45] LANGACKER | 79 | THEO |
| 0.47±0.11 | [46] LANGACKER | 79B | THEO |
| 0.56 | [47] WEINBERG | 77 | THEO |

[36] CHOI 92 result obtained from the decays $\psi(2S) \to J/\psi(1S)\pi$ and $\psi(2S) \to J/\psi(1S)\eta$, and a dilute instanton gas estimate of some unknown matrix elements.
[37] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \to 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \to J/\psi(1S)\pi)/(\psi(2S) \to J/\psi(1S)\eta)$.
[38] DONOGHUE 92B computes quark mass ratios using $(\psi(2S) \to J/\psi(1S)\pi)/(\psi(2S) \to J/\psi(1S)\eta)$, and an estimate of $L_{14}$ using Weinberg sum rules.
[39] GERARD 90 uses large $N$ and $\eta$-$\eta'$ mixing.
[40] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine $L_7$.
[41] MALTMAN 90 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Uses a criterion of "maximum reasonableness" that certain coefficients which are expected to be of order one are $\leq 3$.
[42] CHOI 89 uses second-order chiral perturbation theory and a dilute instanton gas estimate of second-order coefficients in the chiral lagrangian.
[43] KAPLAN 86 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Assumes that less than 30% of the mass squared of the pion is due to second-order corrections.
[44] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.
[45] LANGACKER 79 result is from a fit to the meson and baryon mass spectrum, and the decay $\eta \to 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.
[46] LANGACKER 79B result uses LANGACKER 79 and also $\rho$-$\omega$ mixing.
[47] WEINBERG 77 uses lowest-order chiral perturbation theory for the meson and baryon masses and Dashen's formula for the electromagnetic mass differences.

### *s/d* MASS RATIO

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| **17 to 25 OUR EVALUATION** | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| 21 | [48] DONOGHUE | 92 | THEO |
| 18 | [49] GERARD | 90 | THEO |
| 18 to 23 | [50] LEUTWYLER | 90B | THEO |
| 15 to 26 | [51] KAPLAN | 86 | THEO |
| 19.6±1.5 | [52] GASSER | 82 | THEO |
| 22 ±5 | [53] LANGACKER | 79 | THEO |
| 24 ±4 | [54] LANGACKER | 79B | THEO |
| 20 | [55] WEINBERG | 77 | THEO |

[48] DONOGHUE 92 result is from a combined analysis of meson masses, $\eta \to 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \to J/\psi(1S)\pi)/(\psi(2S) \to J/\psi(1S)\eta)$.

[49] GERARD 90 uses large $N$ and $\eta$-$\eta'$ mixing.

[50] LEUTWYLER 90B determines quark mass ratios using second-order chiral perturbation theory for the meson and baryon masses, including nonanalytic corrections. Also uses Weinberg sum rules to determine $L_7$.

[51] KAPLAN 86 uses second-order chiral perturbation theory including nonanalytic terms for the meson masses. Assumes that less than 30% of the mass squared of the pion is due to second-order corrections.

[52] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.

[53] LANGACKER 79 result is from a fit to the meson and baryon mass spectrum, and the decay $\eta \to 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.

[54] LANGACKER 79B result uses LANGACKER 79 and also $\rho$-$\omega$ mixing.

[55] WEINBERG 77 uses lowest-order chiral perturbation theory for the meson and baryon masses and Dashen's formula for the electromagnetic mass differences.

## $(m_s - m)/(m_d - m_u)$ MASS RATIO

$m \equiv (m_u + m_d)/2$

| VALUE | DOCUMENT ID | | TECN |
|---|---|---|---|
| **34 to 51 OUR EVALUATION** | | | |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| 36 ±5 | [56] NEFKENS | 92 | THEO |
| 45 ±3 | [57] NEFKENS | 92 | THEO |
| 38 ±9 | [58] AMETLLER | 84 | THEO |
| 43.5 ±2.2 | GASSER | 82 | THEO |
| 34 to 51 | GASSER | 81 | THEO |
| 48 ±7 | MINKOWSKI | 80 | THEO |

[56] NEFKENS 92 result is from an analysis of meson masses, mixing, and decay.

[57] NEFKENS 92 result is from an analysis of of baryon masses.

[58] AMETLLER 84 uses $\eta \to \pi^+ \pi^- \pi^0$ and $\rho$ dominance.

## LIGHT QUARKS ($u$, $d$, $s$) REFERENCES


| | | | | |
|---|---|---|---|---|
| BIJNENS | 95 | PL B348 226 | +Prades, de Rafael | (NORD, BOHR, CPPM) |
| CHETYRKIN | 95 | PR D51 5090 | +Dominguez, Pirjol, Schilcher | (INRM, CAPE, MANZ) |
| JAMIN | 95 | ZPHY C66 633 | +Munz | (HEIDT, MUNT) |
| NARISON | 95C | PL B358 113 | | (MONP) |
| ADAMI | 93 | PR D48 2304 | +Drukarev, Ioffe | (CIT, ITEP, PNPI) |
| CHOI | 92 | PL B292 159 | | (UCSD) |
| CHOI | 92B | NP B383 58 | | (UCSD) |
| DONOGHUE | 92 | PRL 69 3444 | +Holstein, Wyler | (MASA, ZURI) |
| DONOGHUE | 92B | PR D45 892 | +Wyler | (MASA, ZURI, UCSBT) |
| NEFKENS | 92 | CNPP 20 221 | +Miller, Slaus | (UCLA, WASH, ZAGR) |
| DOMINGUEZ | 91 | PL B253 241 | +van Gend, Paver | (CAPE, TRST, INFN) |
| GERARD | 90 | MPL A5 391 | | (MPIM) |
| LEUTWYLER | 90B | NP B337 108 | | (BERN) |
| MALTMAN | 90 | PL B234 158 | +Goldman, Stephenson Jr. | (YORKC, LANL) |
| CHOI | 89 | PRL 62 849 | | |
| CHOI | 89B | PR D40 890 | +Kim | (CMU, JHU) |
| BARDUCCI | 88 | PR D38 238 | +Casalbuoni, De Curtis+ | (FIRZ, INFN, LECE, GEVA) |
| Also | 87 | PL B193 305 | Barducci, Casalbuoni+ | (FIRZ, INFN, LECE, GEVA) |
| DOMINGUEZ | 87 | ANP 174 372 | +de Rafael | (ICTP, MARS, WIEN) |
| KAPLAN | 86 | PRL 56 2004 | +Manohar | (HARV) |
| AMETLLER | 84 | PR D30 674 | +Ayala, Bramon | (BARC) |
| KREMER | 84 | PL 143B 476 | +Papadopoulos, Schilcher | (MANZ) |
| GASSER | 82 | PRPL 87 77 | +Leutwyler | (BERN) |
| PENSO | 82 | NC 68A 213 | +Penso, Truong | (ROMA, EPOL) |
| PENSO | 82B | NC 72A 113 | +Verzegnassi | (ROMA, INFN, TRST, SISSA) |
| GASSER | 81 | ANP 136 62 | | (BERN) |
| MINKOWSKI | 80 | NP B164 25 | +Zepeda | (BERN) |
| PAGELS | 80 | PR D22 2876 | +Stokar | (ROCK) |
| LANGACKER | 79 | PR D19 2070 | +Pagels | (DESY, PRIN) |
| LANGACKER | 79B | PR D20 2983 | | (PENN) |
| WEINBERG | 77 | ANYAS 38 185 | | (HARV) |
| GASSER | 75 | NP B94 269 | +Leutwyler | (BERN) |