QUARKS

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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 $= -1$

$(m_s - (m_u + m_d)/2)\big/(m_d - m_u) = 34$ 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 $\overline{\mathrm{MS}}$ 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 $\overline{\mathrm{MS}}$ scheme
4 ± 1	[2] NARISON	95C	THEO	Assumes $\overline{\mathrm{MS}}$ 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 $\overline{\mathrm{MS}}$ 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) $= 12 \pm 2.5$ 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 $m_d - m_u = 3 \pm 1$ 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 $m_u+m_d = 15.5 \pm 2.0$ MeV and $m_d - m_u = 6 \pm 1.5$ MeV.
[17] KREMER 84 obtain $m_u+m_d=21 \pm 2$ MeV at $Q^2 = 1$ GeV^2 using SVZ values for quark condensates; they obtain $m_u+m_d=35 \pm 3$ 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 $\overline{\rm MS}$ scheme
189 ± 32	[24] JAMIN	95	THEO	Assumes $\overline{\rm MS}$ scheme
197 ± 29	[25] NARISON	95C	THEO	Assumes $\overline{\rm MS}$ 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] $\overline{\rm MS}$ 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 $\overline{\rm MS}$ 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 $\Lambda_{\rm QCD} = 100$–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 $m_u+m_s=245\pm10$ MeV at $Q^2 = 1$ GeV^2 using SVZ values for quark condensates; they obtain $m_u+m_s=270 \pm 10$ 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 $\psi(2S) \rightarrow J/\psi(1S)\pi$ and $\psi(2S) \rightarrow J/\psi(1S)\eta$, and a dilute instanton gas estimate of some unknown matrix elements.

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

[38] DONOGHUE 92B computes quark mass ratios using $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$, and an estimate of L_{14} using Weinberg sum rules.

[39] GERARD 90 uses large N and η-η' 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 ≤ 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 $\eta \rightarrow 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.

[46] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω 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, $\eta \rightarrow 3\pi$ using second-order chiral perturbation theory including nonanalytic terms, and $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.

[49] GERARD 90 uses large N and η-η' 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 $\eta \rightarrow 3\pi$. The electromagnetic contribution is taken from Socolow rather than from Dashen's formula.

[54] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω 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 $\eta \rightarrow \pi^+ \pi^- \pi^0$ and ρ 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)