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 $\overline{\text{MS}}$. 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.

Starting with this edition of the *Review*, we have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of $\mu = 2$ GeV. Results quoted in the literature at $\mu = 1$ GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.5 to 5 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9±1.1	[1] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
3.0±0.7	[2] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme
	[3] CHOI	92B	THEO	
4.3	[4] BARDUCCI	88	THEO	
3.8±1.1	[5] GASSER	82	THEO	

[1] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_u(1 GeV) = 5.3 ± 1.5 to $\mu = 2$ GeV.

[2] For NARISON 95C, we have rescaled m_u(1 GeV) = 4 ± 1 to $\mu = 2$ 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 uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$. We have rescaled m_u(1 GeV) = 5.8 to $\mu = 2$ GeV.

[5] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. We have rescaled m_u(1 GeV) = 5.1 ± 1.5 to $\mu = 2$ GeV.

d-QUARK MASS

See the comment for the u quark above.

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VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
3 to 9 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			

7.0±1.1	[6] JAMIN	95	THEO	$\overline{\rm MS}$ scheme
7.4±0.7	[7] NARISON	95C	THEO	$\overline{\rm MS}$ scheme
	[8] ADAMI	93	THEO	
	[9] NEFKENS	92	THEO	
6.2	[10] BARDUCCI	88	THEO	
	[11] DOMINGUEZ	87	THEO	
	[12] KREMER	84	THEO	
6.6±1.9	[13] GASSER	82	THEO	

[6] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_d(1 GeV) = 9.4 ± 1.5 to $\mu = 2$ GeV.
[7] For NARISON 95C, we have rescaled m_d(1 GeV) = 10 ± 1 to $\mu = 2$ GeV.
[8] ADAMI 93 obtain $m_d - m_u$=3 ± 1 MeV at μ=0.5 GeV using isospin-violating effects in QCD sum rules.
[9] 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.
[10] BARDUCCI 88 uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$. We have rescaled m_d(1 GeV) = 8.4 to $\mu = 2$ GeV.
[11] 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.
[12] 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.
[13] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. We have rescaled m_d(1 GeV) = 8.9 ± 2.6 to $\mu = 2$ GeV.

$\overline{m} = (m_u + m_d)/2$

See the comments for the *u* quark above.

Starting with this edition of the *Review*, we have normalized the $\overline{\rm MS}$ masses at a renormalization scale of $\mu = 2$ GeV. Results quoted in the literature at $\mu = 1$ GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2 to 6 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
4.6±1.2	[14] DOSCH	98	THEO	$\overline{\rm MS}$ scheme
2.7±0.2	[15] EICKER	97	LATT	$\overline{\rm MS}$ scheme
3.6±0.6	[16] GOUGH	97	LATT	$\overline{\rm MS}$ scheme
3.4±0.4±0.3	[17] GUPTA	97	LATT	$\overline{\rm MS}$ scheme
>1.5	[18] LELLOUCH	97	THEO	$\overline{\rm MS}$ scheme
4.5±1.0	[19] BIJNENS	95		

[14] DOSCH 98 use sum rule determinations of the quark condensate and chiral perturbation theory to obtain 9.4 ≤ (m_u+m_d)(1 GeV) ≤ 15.7 MeV. We have converted to result to μ=2 GeV.
[15] EICKER 97 use lattice gauge computations with two dynamical light flavors.
[16] GOUGH 97 use lattice gauge computations in the quenched approximation. Correcting for quenching gives $2.1 < \overline{m} < 3.5$ MeV at μ=2 GeV.
[17] GUPTA 97 use Lattice Monte Carlo computations in the quenched approximation. The value for two light dynamic flavors at $\mu = 2$ GeV is 2.7 ± 0.3 ± 0.3 MeV.
[18] LELLOUCH 97 obtain lower bounds on quark masses using hadronic spectral functions.
[19] BIJNENS 95 determines m_u+m_d (1 GeV) = 12 ± 2.5 MeV using finite energy sum rules. We have rescaled this to 2 GeV.

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s-QUARK MASS

See the comment for the *u* quark above.

Starting with this edition of the *Review*, we have normalized the $\overline{\text{MS}}$ masses at a renormalization scale of $\mu = 2$ GeV. Results quoted in the literature at $\mu = 1$ GeV have been rescaled by dividing by 1.35.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
60 to 170 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
148 ±48	[20] CHETYRKIN	98	THEO	$\overline{\text{MS}}$ scheme
103 ±10	[21] CUCCHIERI	98	LATT	$\overline{\text{MS}}$ scheme
115 ±19	[22] DOMINGUEZ	98	THEO	$\overline{\text{MS}}$ scheme
> 90 ± 9	[23] DOSCH	98	THEO	$\overline{\text{MS}}$ scheme
> 30	[24] LEBED	98	THEO	$\overline{\text{MS}}$ scheme
84 ±80	[25] MALTMAN	98	THEO	$\overline{\text{MS}}$ scheme
<163 ±81	[26] MALTMAN	98B	THEO	$\overline{\text{MS}}$ scheme
152.4±14.1	[27] CHETYRKIN	97	THEO	$\overline{\text{MS}}$ scheme
≥ 89	[28] COLANGELO	97	THEO	$\overline{\text{MS}}$ scheme
140 ±20	[29] EICKER	97	LATT	$\overline{\text{MS}}$ scheme
95 ±16	[30] GOUGH	97	LATT	$\overline{\text{MS}}$ scheme
100 ±21 ±10	[31] GUPTA	97	LATT	$\overline{\text{MS}}$ scheme
> 37	[32] LELLOUCH	97	THEO	$\overline{\text{MS}}$ scheme
127 ±11	[33] CHETYRKIN	95	THEO	$\overline{\text{MS}}$ scheme
140 ±24	[34] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
146 ±22	[35] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme
	[36] NEFKENS	92	THEO	
144 ± 3	[37] DOMINGUEZ	91	THEO	
88	[38] BARDUCCI	88	THEO	
	[39] KREMER	84	THEO	
130 ±41	[40] GASSER	82	THEO	

[20] CHETYRKIN 98 uses spectral moments of hadronic τ decays to determine m_s(1 GeV)=200 ± 70 MeV. We have rescaled the result to μ=2 GeV.

[21] CUCCHIERI 98 obtains the quark mass using a quenched lattice computation of the hadronic spectrum.

[22] DOMINGUEZ 98 uses hadronic spectral function sum rules (to four loops, and including dimension six operators) to determine m_s(1 GeV)< 155 ± 25 MeV. We have rescaled the result to μ=2 GeV.

[23] DOSCH 98 use sum rule determinations of the quark condensate and chiral perturbation theory to obtain m_s(1 GeV)> 121 ± 12 MeV. We have converted the result to μ=2 GeV.

[24] LEBED 98 obtain lower bounds of 41, 90, and 139 MeV for m_s(1 GeV) using dispersion relations and chiral perturbation theory. The numbers assume the chiral perturbation theory form factor is accurate to 5%, 1%, and 0.05%, respectively. We have used the first number converted to μ=2.

[25] MALTMAN 98 uses τ decay sum rules to determine m_s(1 GeV)=113 ± 107 MeV. We have rescaled the result to μ=2 GeV.

[26] MALTMAN 98B uses spectral moments of hadronic τ decays to determine m_s(1 GeV)< 220 ± 110 MeV. We have rescaled the result to μ=2 GeV.

[27] CHETYRKIN 97 obtains 205.5 ± 19.1 MeV at μ=1 GeV from QCD sum rules including fourth-order QCD corrections. We have rescaled the result to 2 GeV.

[28] COLANGELO 97 is QCD sum rule computation. We have rescaled m_s(1 GeV) > 120 to μ = 2 GeV.

[29] EICKER 97 use lattice gauge computations with two dynamical light flavors.

[30] GOUGH 97 use lattice gauge computations in the quenched approximation. Correcting for quenching gives 54 $< m_s <$ 92 MeV at μ=2 GeV.

[31] GUPTA 97 use Lattice Monte Carlo computations in the quenched approximation. The value for two light dynamical flavors at $\mu = 2$ GeV is 68 $\pm$ 12 $\pm$ 7 MeV.

[32] LELLOUCH 97 obtain lower bounds on quark masses using hadronic spectral functions.

[33] CHETYRKIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_s(1 GeV) = 171 $\pm$ 15 to $\mu = 2$ GeV.

[34] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_s(1 GeV) = 189 $\pm$ 32 to $\mu = 2$ GeV.

[35] For NARISON 95C, we have rescaled m_s(1 GeV) = 197 $\pm$ 29 to $\mu = 2$ GeV.

[36] NEFKENS 92 results for $m_s - (m_u + m_d)/2$ are 111 $\pm$ 10 MeV from meson masses and 163 $\pm$ 15 MeV from baryon masses.

[37] DOMINGUEZ 91 uses QCD sum rules with Λ_{QCD} = 100–200 MeV and the SVZ value for the gluon condensate. We have rescaled m_s(1 GeV) = 194 $\pm$ 9 to $\mu = 2$ GeV.

[38] BARDUCCI 88 uses a calculation of the effective potential for $\overline{\psi}\psi$ in QCD, and estimates for $\Sigma(p^2)$. We have rescaled m_s(1 GeV) = 118 to $\mu = 2$ GeV.

[39] KREMER 84 obtain $m_u + m_s$=245$\pm$10 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.

[40] GASSER 82 uses chiral perturbation theory for the mass ratios, and uses QCD sum rules to extract the absolute values. We have rescaled m_s(1 GeV) = 175 $\pm$ 55 to $\mu = 2$ GeV.

LIGHT QUARK MASS RATIOS

u/d MASS RATIO

VALUE	DOCUMENT ID		TECN	COMMENT
0.2 to 0.7 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
0.44	[41] GAO	97	THEO	$\overline{\rm MS}$ scheme
0.553$\pm$0.043	[42] LEUTWYLER	96	THEO	Compilation
<0.3	[43] CHOI	92	THEO	
0.26	[44] DONOGHUE	92	THEO	
0.30 $\pm$0.07	[45] DONOGHUE	92B	THEO	
0.66	[46] GERARD	90	THEO	
0.4 to 0.65	[47] LEUTWYLER	90B	THEO	
0.05 to 0.78	[48] MALTMAN	90	THEO	
0.0 to 0.56	[49] CHOI	89B	THEO	
0.0 to 0.8	[50] KAPLAN	86	THEO	
0.57 $\pm$0.04	[51] GASSER	82	THEO	
0.38 $\pm$0.13	[52] LANGACKER	79	THEO	
0.47 $\pm$0.11	[53] LANGACKER	79B	THEO	
0.56	[54] WEINBERG	77	THEO	

[41] GAO 97 uses electromagnetic mass splittings of light mesons.

[42] LEUTWYLER 96 uses a combined fit to $\eta \to 3\pi$ and $\psi' \to J/\psi\ (\pi,\eta)$ decay rates, and the electromagnetic mass differences of the π and K.

[43] 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.

[44] 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 $(\psi(2S) \to J/\psi(1S)\pi)/(\psi(2S) \to J/\psi(1S)\eta)$.

[45] 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.
[46] GERARD 90 uses large N and η-η' mixing.
[47] 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.
[48] 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.
[49] CHOI 89 uses second-order chiral perturbation theory and a dilute instanton gas estimate of second-order coefficients in the chiral lagrangian.
[50] 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.
[51] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.
[52] 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.
[53] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω mixing.
[54] 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*	*COMMENT*
17 to 25 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20.0	[55] GAO	97	THEO	$\overline{\text{MS}}$ scheme
18.9±0.8	[56] LEUTWYLER	96	THEO	Compilation
21	[57] DONOGHUE	92	THEO	
18	[58] GERARD	90	THEO	
18 to 23	[59] LEUTWYLER	90B	THEO	
15 to 26	[60] KAPLAN	86	THEO	
19.6±1.5	[61] GASSER	82	THEO	
22 ±5	[62] LANGACKER	79	THEO	
24 ±4	[63] LANGACKER	79B	THEO	
20	[64] WEINBERG	77	THEO	

[55] GAO 97 uses electromagnetic mass splittings of light mesons.
[56] LEUTWYLER 96 uses a combined fit to $\eta \to 3\pi$ and $\psi' \to J/\psi\ (\pi,\eta)$ decay rates, and the electromagnetic mass differences of the π and K.
[57] 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 $(\psi(2S) \to J/\psi(1S)\pi)/(\psi(2S) \to J/\psi(1S)\eta)$.
[58] GERARD 90 uses large N and η-η' mixing.
[59] 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.
[60] 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.
[61] GASSER 82 uses chiral perturbation theory for the meson and baryon masses.
[62] 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.
[63] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω mixing.
[64] WEINBERG 77 uses lowest-order chiral perturbation theory for the meson and baryon masses and Dashen's formula for the electromagnetic mass differences.

$(m_s - \overline{m})/(m_d - m_u)$ MASS RATIO

$\overline{m} \equiv (m_u + m_d)/2$

VALUE	DOCUMENT ID		TECN
34 to 51 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[65] ANISOVICH	96	THEO
36 ±5	[66] NEFKENS	92	THEO
45 ±3	[67] NEFKENS	92	THEO
38 ±9	[68] AMETLLER	84	THEO
43.5±2.2	GASSER	82	THEO
34 to 51	GASSER	81	THEO
48 ±7	MINKOWSKI	80	THEO

[65] ANISOVICH 96 find Q=22.7 ± 0.8 with $Q^2 \equiv (m_s^2 - \overline{m}^2)/(m_d^2 - m_s^2)$ from $\eta \rightarrow \pi^+ \pi^- \pi^0$ decay using dispersion relations and chiral perturbation theory.

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

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

[68] AMETLLER 84 uses $\eta \rightarrow \pi^+ \pi^- \pi^0$ and ρ dominance.

LIGHT QUARKS (*u*, *d*, *s*) REFERENCES

CHETYRKIN	98	NP B533 473	K.G. Chetyrkin, J.H. Kuehn, A.A. Pivovarov	
CUCCHIERI	98	PL B422 212	A. Chucchieri+	
DOMINGUEZ	98	PL B425 193	C.A. Dominguez, L. Pirovano, K. Schilcher	
DOSCH	98	PL B417 173	H.G. Dosch, S. Narison	
LEBED	98	PL B430 341	R.F. Lebed, K. Schilcher	
MALTMAN	98	PL B428 179	K. Maltman	
MALTMAN	98B	PR D58 093015	K. Maltman	
CHETYRKIN	97	PL B404 337	K.G. Chetyrkin, D. Pirjol, K. Schilcher	
COLANGELO	97	PL B408 340	P. Colangelo+	
EICKER	97	PL B407 290	N. Eicker+	(SESAM Collab.)
GAO	97	PR D56 4115	D.-N. Gao, B.A. Li, M.-L. Yan	
GOUGH	97	PRL 79 1622	B. Gough+	
GUPTA	97	PR D55 7203	R. Gupta, T. Bhattacharya	
LELLOUCH	97	PL B414 195	L. Lellouch, E. de Rafael, J. Taron	
ANISOVICH	96	PL B375 335	A.V. Anisovich, H. Leutwyler	
LEUTWYLER	96	PL B378 313	H. Leutwyler	
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)
GASSER	81	ANP 136 62		(BERN)
MINKOWSKI	80	NP B164 25	+Zepeda	(BERN)
LANGACKER	79	PR D19 2070	+Pagels	(DESY, PRIN)
LANGACKER	79B	PR D20 2983		(PENN)
WEINBERG	77	ANYAS 38 185		(HARV)