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	$\overline{\text{MS}}$ scheme
7.4±0.7	[7] NARISON	95C	THEO	$\overline{\text{MS}}$ 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 $m_d(1\,\text{GeV}) = 9.4 \pm 1.5$ to $\mu = 2$ GeV.

[7] For NARISON 95C, we have rescaled $m_d(1\,\text{GeV}) = 10 \pm 1$ 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 $m_d(1\,\text{GeV}) = 8.4$ to $\mu = 2$ GeV.

[11] 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.

[12] KREMER 84 obtain m_u+m_d=21 ± 2 MeV at $Q^2 = 1\,\text{GeV}^2$ using SVZ values for quark condensates; they obtain m_u+m_d=35 ± 3 MeV at $Q^2 = 1\,\text{GeV}^2$ 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 $m_d(1\,\text{GeV}) = 8.9 \pm 2.6$ 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 $\overline{\text{MS}}$ 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*
2 to 6 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.7±0.2	[14] EICKER	97	LATT	$\overline{\text{MS}}$ scheme
3.6±0.6	[15] GOUGH	97	LATT	$\overline{\text{MS}}$ scheme
3.4±0.4±0.3	[16] GUPTA	97	LATT	$\overline{\text{MS}}$ scheme
4.5±1.0	[17] BIJNENS	95		

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

[15] 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.

[16] 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.

[17] 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.

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. • • •				
152.4±14.1	[18] CHETYRKIN	97	THEO	$\overline{\text{MS}}$ scheme
$\geq$ 89	[19] COLANGELO	97	THEO	$\overline{\text{MS}}$ scheme
140 ±20	[20] EICKER	97	LATT	$\overline{\text{MS}}$ scheme
95 ±16	[21] GOUGH	97	LATT	$\overline{\text{MS}}$ scheme
100 ±21 ±10	[22] GUPTA	97	LATT	$\overline{\text{MS}}$ scheme
127 ±11	[23] CHETYRKIN	95	THEO	$\overline{\text{MS}}$ scheme
140 ±24	[24] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
146 ±22	[25] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme
	[26] NEFKENS	92	THEO	
144 ± 3	[27] DOMINGUEZ	91	THEO	
88	[28] BARDUCCI	88	THEO	
	[29] KREMER	84	THEO	
130 ±41	[30] GASSER	82	THEO	

[18] 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.

[19] COLANGELO 97 is QCD sum rule computation. We have rescaled m_s(1 GeV) $>$ 120 to $\mu = 2$ GeV.

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

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

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

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

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

[25] For NARISON 95C, we have rescaled m_s(1 GeV) = 197 ± 29 to $\mu = 2$ 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 Λ_{QCD} = 100–200 MeV and the SVZ value for the gluon condensate. We have rescaled m_s(1 GeV) = 194 ± 9 to $\mu = 2$ GeV.

[28] 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.

[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. We have rescaled m_s(1 GeV) = 175 ± 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	[31] GAO	97	THEO	$\overline{\rm MS}$ scheme
0.553±0.043	[32] LEUTWYLER	96	THEO	Compilation
<0.3	[33] CHOI	92	THEO	
0.26	[34] DONOGHUE	92	THEO	
0.30 ±0.07	[35] DONOGHUE	92B	THEO	
0.66	[36] GERARD	90	THEO	
0.4 to 0.65	[37] LEUTWYLER	90B	THEO	
0.05 to 0.78	[38] MALTMAN	90	THEO	
0.0 to 0.56	[39] CHOI	89B	THEO	
0.0 to 0.8	[40] KAPLAN	86	THEO	
0.57 ±0.04	[41] GASSER	82	THEO	
0.38 ±0.13	[42] LANGACKER	79	THEO	
0.47 ±0.11	[43] LANGACKER	79B	THEO	
0.56	[44] WEINBERG	77	THEO	

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

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

[33] 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.

[34] 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 $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.

[35] 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.

[36] GERARD 90 uses large N and η-η' mixing.

[37] 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.

[38] 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.

[39] CHOI 89 uses second-order chiral perturbation theory and a dilute instanton gas estimate of second-order coefficients in the chiral lagrangian.

[40] 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.

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

[42] 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.

[43] LANGACKER 79B result uses LANGACKER 79 and also ρ-ω mixing.

[44] 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	[45] GAO	97	THEO	$\overline{MS}$ scheme
18.9±0.8	[46] LEUTWYLER	96	THEO	Compilation
21	[47] DONOGHUE	92	THEO	
18	[48] GERARD	90	THEO	
18 to 23	[49] LEUTWYLER	90B	THEO	
15 to 26	[50] KAPLAN	86	THEO	
19.6±1.5	[51] GASSER	82	THEO	
22 ±5	[52] LANGACKER	79	THEO	
24 ±4	[53] LANGACKER	79B	THEO	
20	[54] WEINBERG	77	THEO	

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

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

[47] 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 $(\psi(2S) \rightarrow J/\psi(1S)\pi)/(\psi(2S) \rightarrow J/\psi(1S)\eta)$.

[48] GERARD 90 uses large N and η-η' mixing.

[49] 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.

[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 $\eta \rightarrow 3\pi$. 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.

$(m_s - \overline{m})/(m_d - m_u)$ 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. • • •			
	[55] ANISOVICH	96	THEO
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

[55] 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.

[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

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	
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)