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.

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. The values of "Our Evaluation" were determined in part via Figures 1 and 2.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
1.5 to 4.5 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
2.3 ± 0.4	[1] NARISON	99	THEO	$\overline{\text{MS}}$ scheme
3.9 ± 1.1	[2] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
3.0 ± 0.7	[3] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme

[1] NARISON 99 uses sum rules to order α_s^3 for ϕ meson decays to get m_s, and finds m_u by combining with sum rule estimates of $m_u + m_d$ and Dashen's formula.

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

[3] For NARISON 95C, we have rescaled m_u(1 GeV) $= 4 \pm 1$ to $\mu = 2$ GeV.

d-QUARK MASS

See the comment for the u quark above.

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. The values of "Our Evaluation" were determined in part via Figures 1 and 2.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
5 to 8.5 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
6.4 ± 1.1	[4] NARISON	99	THEO	$\overline{\text{MS}}$ scheme
7.0 ± 1.1	[5] JAMIN	95	THEO	$\overline{\text{MS}}$ scheme
7.4 ± 0.7	[6] NARISON	95C	THEO	$\overline{\text{MS}}$ scheme

[4] NARISON 99 uses sum rules to order α_s^3 for ϕ meson decays to get m_s, and finds m_d by combining with sum rule estimates of $m_u + m_d$ and Dashen's formula.

[5] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_d(1 GeV) $= 9.4 \pm 1.5$ to $\mu = 2$ GeV.

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

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

See the comments for the u quark above.

We have normalized the $\overline{\mathrm{MS}}$ 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. The values of "Our Evaluation" were determined in part via Figures 1 and 2.

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
2.5 to 5.5 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.9 ±0.6	[7] MALTMAN	01	THEO	$\overline{\mathrm{MS}}$ scheme
4.57±0.18	[8] AOKI	00	LATT	$\overline{\mathrm{MS}}$ scheme
4.4 ±2	[9] GOECKELER	00	LATT	$\overline{\mathrm{MS}}$ scheme
4.23±0.29	[10] AOKI	99	LATT	$\overline{\mathrm{MS}}$ scheme
$\geq$ 2.1	[11] STEELE	99	THEO	$\overline{\mathrm{MS}}$ scheme
4.5 ±0.4	[12] BECIREVIC	98	LATT	$\overline{\mathrm{MS}}$ scheme
4.6 ±1.2	[13] DOSCH	98	THEO	$\overline{\mathrm{MS}}$ scheme
4.7 ±0.9	[14] PRADES	98	THEO	$\overline{\mathrm{MS}}$ scheme
2.7 ±0.2	[15] EICKER	97	LATT	$\overline{\mathrm{MS}}$ scheme
3.6 ±0.6	[16] GOUGH	97	LATT	$\overline{\mathrm{MS}}$ scheme
3.4 ±0.4 ±0.3	[17] GUPTA	97	LATT	$\overline{\mathrm{MS}}$ scheme
>3.8	[18] LELLOUCH	97	THEO	$\overline{\mathrm{MS}}$ scheme
4.5 ±1.0	[19] BIJNENS	95	THEO	$\overline{\mathrm{MS}}$ scheme

[7] MALTMAN 01 uses Borel transformed and finite energy sum rules.

[8] AOKI 00 obtain the light quark masses from a quenched lattice simulation of the meson and baryon spectrum with the Wilson quark action.

[9] GOECKELER 00 obtained from a quenched lattice computation of the pseudoscalar meson masses using $\mathcal{O}(a)$ improved Wilson fermions and nonperturbative renormalization.

[10] AOKI 99 obtain the light quark masses from a quenched lattice simulation of the meson spectrum with the staggered quark action employing the regularization independent scheme.

[11] STEELE 99 obtain a bound on the light quark masses by applying the Holder inequality to a sum rule. We have converted their bound of $(m_u+m_d)/2 \geq 3$ MeV at μ=1 GeV to μ=2 GeV.

[12] BECIREVIC 98 compute the quark mass using the Alpha action in the quenched approximation. The conversion from the regularization independent scheme to the $\overline{\mathrm{MS}}$ scheme is at NNLO.

[13] DOSCH 98 use sum rule determinations of the quark condensate and chiral perturbation theory to obtain $9.4 \leq (m_u+m_d)(1\ \mathrm{GeV}) \leq 15.7$ MeV. We have converted to result to μ=2 GeV.

[14] PRADES 98 uses finte energy sum rules for the axial current correlator.

[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.

s-QUARK MASS

See the comment for the *u* quark above.

We have normalized the $\overline{\mathrm{MS}}$ 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*
80 to 155 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$116\ ^{+20}_{-25}$	[20] CHEN	01B	THEO	$\overline{\mathrm{MS}}$ scheme
$125\ \pm27$	[21] KOERNER	01	THEO	$\overline{\mathrm{MS}}$ scheme
$130\ \pm15$	[22] AOKI	00	LATT	$\overline{\mathrm{MS}}$ scheme
$105\ \pm\ 4$	[23] GOECKELER	00	LATT	$\overline{\mathrm{MS}}$ scheme
$118\ \pm14$	[24] AOKI	99	LATT	$\overline{\mathrm{MS}}$ scheme
$170\ ^{+44}_{-55}$	[25] BARATE	99R	ALEP	$\overline{\mathrm{MS}}$ scheme
$115\ \pm\ 8$	[26] MALTMAN	99	THEO	$\overline{\mathrm{MS}}$ scheme
$129\ \pm24$	[27] NARISON	99	THEO	$\overline{\mathrm{MS}}$ scheme
$114\ \pm23$	[28] PICH	99	THEO	$\overline{\mathrm{MS}}$ scheme
$111\ \pm12$	[29] BECIREVIC	98	LATT	$\overline{\mathrm{MS}}$ scheme
$148\ \pm48$	[30] CHETYRKIN	98	THEO	$\overline{\mathrm{MS}}$ scheme
$103\ \pm10$	[31] CUCCHIERI	98	LATT	$\overline{\mathrm{MS}}$ scheme
$115\ \pm19$	[32] DOMINGUEZ	98	THEO	$\overline{\mathrm{MS}}$ scheme
152.4 ± 14.1	[33] CHETYRKIN	97	THEO	$\overline{\mathrm{MS}}$ scheme
≥ 89	[34] COLANGELO	97	THEO	$\overline{\mathrm{MS}}$ scheme
$140\ \pm20$	[35] EICKER	97	LATT	$\overline{\mathrm{MS}}$ scheme
$95\ \pm16$	[36] GOUGH	97	LATT	$\overline{\mathrm{MS}}$ scheme
$100\ \pm21\ \pm10$	[37] GUPTA	97	LATT	$\overline{\mathrm{MS}}$ scheme
>100	[38] LELLOUCH	97	THEO	$\overline{\mathrm{MS}}$ scheme
$140\ \pm24$	[39] JAMIN	95	THEO	$\overline{\mathrm{MS}}$ scheme

[20] CHEN 01B uses an anlysis of the hadronic spectral function in τ decay.

[21] KOERNER 01 obtain the *s* quark mass of $m_s(m_\tau) = 130 \pm 27(\mathrm{exp}) \pm 9(\mathrm{thy})$ MeV from an analysis of Cabibbo suppressed τ decays. We have converted this to $\mu = 2$ GeV.

[22] AOKI 00 obtain the light quark masses from a quenched lattice simulation of the meson and baryon spectrum with the Wilson quark action. We have averaged their results of $m_s = 115.6 \pm 2.3$ and $m_s = 143.7 \pm 5.8$ obtained using m_K and m_ϕ, respectively, to normalize the spectrum.

[23] GOECKELER 00 obtained from a quenched lattice computation of the pseudoscalar meson masses using $\mathcal{O}(a)$ improved Wilson fermions and nonperturbative renormalization.

[24] AOKI 99 obtain the light quark masses from a quenched lattice simulation of the meson spectrum with the Staggered quark action employing the regularization independent scheme. We have averaged their results of m_s=106.0 $\pm$ 7.1 and m_s=129 $\pm$ 12 obtained using m_K and m_ϕ, respectively, to normalize the spectrum.

[25] BARATE 99R obtain the strange quark mass from an analysis of the observed mass spectra in τ decay. We have converted their value of $m_s(m_\tau) = 176^{+46}_{-57}$ MeV to μ=2 GeV.

[26] MALTMAN 99 determines the strange quark mass using finite energy sum rules.

[27] NARISON 99 uses sum rules to order α_s^3 for ϕ meson decays.

[28] PICH 99 obtain the *s*-quark mass from an analysis of the moments of the invariant mass distribution in τ decays.

[29] BECIREVIC 98 compute the quark mass using the Alpha action in the quenched approximation. The conversion from the regularization independent scheme to the $\overline{\mathrm{MS}}$ scheme is at NNLO.

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

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

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

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

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

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

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

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

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

[39] JAMIN 95 uses QCD sum rules at next-to-leading order. We have rescaled m_s(1 GeV) = 189 $\pm$ 32 to μ = 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	[40] GAO	97	THEO	$\overline{\mathrm{MS}}$ scheme
0.553$\pm$0.043	[41] LEUTWYLER	96	THEO	Compilation
$<$0.3	[42] CHOI	92	THEO	
0.26	[43] DONOGHUE	92	THEO	
0.30 $\pm$0.07	[44] DONOGHUE	92B	THEO	
0.66	[45] GERARD	90	THEO	
0.4 to 0.65	[46] LEUTWYLER	90B	THEO	
0.05 to 0.78	[47] MALTMAN	90	THEO	

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

[41] 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.

[42] 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.

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

[44] 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.

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

[46] 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.

[47] 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.

s/*d* MASS RATIO

VALUE	DOCUMENT ID		TECN	COMMENT
17 to 22 OUR EVALUATION				
• • • We do not use the following data for averages, fits, limits, etc. • • •				
20.0	[48] GAO	97	THEO	$\overline{MS}$ scheme
18.9±0.8	[49] LEUTWYLER	96	THEO	Compilation
21	[50] DONOGHUE	92	THEO	
18	[51] GERARD	90	THEO	
18 to 23	[52] LEUTWYLER	90B	THEO	

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

[49] 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.

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

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

[52] 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.

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

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

VALUE	DOCUMENT ID		TECN
30 to 50 OUR EVALUATION			
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	[53] ANISOVICH	96	THEO
36±5	[54] NEFKENS	92	THEO
45±3	[55] NEFKENS	92	THEO

[53] 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.

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

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

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

CHEN	01B	EPJ C22 31	S. Chen *et al.*	
KOERNER	01	EPJ C20 259	J.G. Koerner, F. Krajewski, A.A. Pivovarov	
MALTMAN	01	PL B517 332	K. Maltman, J. Kambor	
AOKI	00	PRL 84 238	S. Aoki *et al.*	(CP-PACS Collab.)
GOECKELER	00	PR D62 054504	M. Goeckeler *et al.*	
AOKI	99	PRL 82 4392	S. Aoki *et al.*	(JLQCD Collab.)
BARATE	99R	EPJ C11 599	R. Barate *et al.*	(ALEPH Collab.)
MALTMAN	99	PL B462 195	K. Maltman	
NARISON	99	PL B466 345	S. Narison	
PICH	99	JHEP 9910 004	A. Pich, J. Prades	
STEELE	99	PL B451 201	T.G. Steele, K. Kostuik, J. Kwan	
BECIREVIC	98	PL B444 401	D. Becirevic *et al.*	
CHETYRKIN	98	NP B533 473	K.G. Chetyrkin, J.H. Kuehn, A.A. Pivovarov	
CUCCHIERI	98	PL B422 212	A. Chucchieri *et al.*	
DOMINGUEZ	98	PL B425 193	C.A. Dominguez, L. Pirovano, K. Schilcher	
DOSCH	98	PL B417 173	H.G. Dosch, S. Narison	
PRADES	98	NPBPS 64 253	J. Prades	
CHETYRKIN	97	PL B404 337	K.G. Chetyrkin, D. Pirjol, K. Schilcher	

COLANGELO	97	PL B408 340	P. Colangelo *et al.*	
EICKER	97	PL B407 290	N. Eicker *et al.*	(SESAM Collab.)
GAO	97	PR D56 4115	D.-N. Gao, B.A. Li, M.-L. Yan	
GOUGH	97	PRL 79 1622	B. Gough *et al.*	
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	J. Bijnens, J. Prades, E. de Rafael	(NORD, BOHR+)
JAMIN	95	ZPHY C66 633	M. Jamin, M. Munz	(HEIDT, MUNT)
NARISON	95C	PL B358 113	S. Narison	(MONP)
CHOI	92	PL B292 159	K.W. Choi	(UCSD)
DONOGHUE	92	PRL 69 3444	J.F. Donoghue, B.R. Holstein, D. Wyler	(MASA+)
DONOGHUE	92B	PR D45 892	J.F. Donoghue, D. Wyler	(MASA, ZURI, UCSBT)
NEFKENS	92	CNPP 20 221	B.M.K. Nefkens, G.A. Miller, I. Slaus	(UCLA+)
GERARD	90	MPL A5 391	J.M. Gerard	(MPIM)
LEUTWYLER	90B	NP B337 108	H. Leutwyler	(BERN)
MALTMAN	90	PL B234 158	K. Maltman, T. Goldman, Stephenson Jr.	(YORKC+)