Free Quark Searches

FREE QUARK SEARCHES

Quarks are fractionally charged particles, the constituents of hadrons, with charges 1/3 e or 2/3 e. The charge of every known charged system is an integer multiple of 1/3 e. Quantum Chromodynamics predicts that quarks cannot be observed as freely propagating particles, being confined inside hadrons or deconfined in quark-gluon plasma (QGP). We observe the top quark decaying as still free, because its lifetime is too short to allow its hadronization. Experiments have produced no evidence for free propagating quarks.

Reviews can be found in Refs. 1–5.

References

1. M.L. Perl, E.R. Lee, and D. Lomba, Mod. Phys. Lett. **A19**, 2595 (2004).
2. P.F. Smith, Ann. Rev. Nucl. and Part. Sci. **39**, 73 (1989).
3. L. Lyons, Phys. Reports **129**, 225 (1985).
4. M. Marinelli and G. Morpurgo, Phys. Reports **85**, 161 (1982).
5. L.W. Jones, Rev. Mod. Phys. **49**, 717 (1977).

Quark Production Cross Section — Accelerator Searches

X-SECT (cm^2)	CHG (e/3)	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<1.7-2.3E−39	±2	100–600	7000	pp	0	[1] CHATRCHYAN	13AR	CMS
<14-5.4E−39	±1	100–600	7000	pp	0	[1] CHATRCHYAN	13AR	CMS
<1.3E−36	±2	45–84	130–172	e^+e^-	0	ABREU	97D	DLPH
<2.E−35	+2	250	1800	$p\overline{p}$	0	[2] ABE	92J	CDF
<1.E−35	+4	250	1800	$p\overline{p}$	0	[2] ABE	92J	CDF
<3.8E−28			14.5A	^{28}Si–Pb	0	[3] HE	91	PLAS
<3.2E−28			14.5A	^{28}Si–Cu	0	[3] HE	91	PLAS
<1.E−40	±1,2	<10		$p,\nu,\overline{\nu}$	0	BERGSMA	84B	CHRM
<1.E−36	±1,2	<9	200	μ	0	AUBERT	83C	SPEC
<2.E−10	±2,4	1–3	200	p	0	[4] BUSSIERE	80	CNTR
<5.E−38	+1,2	>5	300	p	0	[5,6] STEVENSON	79	CNTR
<1.E−33	±1	<20	52	pp	0	BASILE	78	SPEC

<9.E−39	±1,2	<6	400	*p*	0	[5] ANTREASYAN	77	SPEC
<8.E−35	+1,2	<20	52	*p p*	0	[7] FABJAN	75	CNTR
<5.E−38	−1,2	4–9	200	*p*	0	NASH	74	CNTR
<1.E−32	+2,4	4–24	52	*p p*	0	ALPER	73	SPEC
<5.E−31	+1,2,4	<12	300	*p*	0	LEIPUNER	73	CNTR
<6.E−34	±1,2	<13	52	*p p*	0	BOTT	72	CNTR
<1.E−36	−4	4	70	*p*	0	ANTIPOV	71	CNTR
<1.E−35	±1,2	2	28	*p*	0	[8] ALLABY	69B	CNTR
<4.E−37	−2	<5	70	*p*	0	[4] ANTIPOV	69	CNTR
<3.E−37	−1,2	2–5	70	*p*	0	[8] ANTIPOV	69B	CNTR
<1.E−35	+1,2	<7	30	*p*	0	DORFAN	65	CNTR
<2.E−35	−2	< 2.5–5	30	*p*	0	[9] FRANZINI	65B	CNTR
<5.E−35	+1,2	<2.2	21	*p*	0	BINGHAM	64	HLBC
<1.E−32	+1,2	<4.0	28	*p*	0	BLUM	64	HBC
<1.E−35	+1,2	<2.5	31	*p*	0	[9] HAGOPIAN	64	HBC
<1.E−34	+1	<2	28	*p*	0	LEIPUNER	64	CNTR
<1.E−33	+1,2	<2.4	24	*p*	0	MORRISON	64	HBC

[1] CHATRCHYAN 13AR limits assume pair-produced long-lived spin-1/2 particles neutral under $SU(3)_C$ and $SU(2)_L$.
[2] ABE 92J flux limits decrease as the mass increases from 50 to 500 GeV.
[3] HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3.
[4] Hadronic or leptonic quarks.
[5] Cross section cm^2/GeV^2.
[6] 3×10^{-5} <lifetime $< 1 \times 10^{-3}$ s.
[7] Includes BOTT 72 results.
[8] Assumes isotropic cm production.
[9] Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

X-SECT ($cm^2 sr^{-1} GeV^{-1}$)	*CHG* *e*/3	*MASS* (GeV)	*ENERGY* (GeV)	*BEAM*	*EVTS*	*DOCUMENT ID*		*TECN*
<4.E−36	−2,4	1.5–6	70	*p*	0	BALDIN	76	CNTR
<2.E−33	±4	5–20	52	*p p*	0	ALBROW	75	SPEC
<5.E−34	<7	7–15	44	*p p*	0	JOVANOV...	75	CNTR
<5.E−35			20	γ	0	[1] GALIK	74	CNTR
<9.E−35	−1,2		200	*p*	0	NASH	74	CNTR
<4.E−36	−4	2.3–2.7	70	*p*	0	ANTIPOV	71	CNTR
<3.E−35	±1,2	<2.7	27	*p*	0	ALLABY	69B	CNTR
<7.E−38	−1,2	<2.5	70	*p*	0	ANTIPOV	69B	CNTR

[1] Cross section in cm^2/sr/equivalent quanta.

Quark Flux — Accelerator Searches

The definition of FLUX depends on the experiment

(a) is the ratio of measured free quarks to predicted free quarks if there is no “confinement.”
(b) is the probability of fractional charge on nuclear fragments. Energy is in GeV/nucleon.
(c) is the 90%CL upper limit on fractionally-charged particles produced per interaction.

(d) is quarks per collision.
(e) is inclusive quark-production cross-section ratio to $\sigma(e^+e^- \to \mu^+\mu^-)$.
(f) is quark flux per charged particle.
(g) is the flux per ν-event.
(h) is quark yield per π^- yield.
(i) is 2-body exclusive quark-production cross-section ratio to $\sigma(e^+e^- \to \mu^+\mu^-)$.

FLUX		CHG (e/3)	MASS (GeV)	ENRGY (GeV)	BEAM	EVTS	DOCUMENT ID		TECN
<1.6E−3	b	see note		200	^{32}S–Pb	0	[1] HUENTRUP	96	PLAS
<6.2E−4	b	see note		10.6	^{32}S–Pb	0	[1] HUENTRUP	96	PLAS
<0.94E−4	e	±2	2–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.7E−4	e	±2	30–40	88–94	e^+e^-	0	AKERS	95R	OPAL
<3.6E−4	e	±4	5–30	88–94	e^+e^-	0	AKERS	95R	OPAL
<1.9E−4	e	±4	30–45	88–94	e^+e^-	0	AKERS	95R	OPAL
<2.E−3	e	+1	5–40	88–94	e^+e^-	0	[2] BUSKULIC	93C	ALEP
<6.E−4	e	+2	5–30	88–94	e^+e^-	0	[2] BUSKULIC	93C	ALEP
<1.2E−3	e	+4	15–40	88–94	e^+e^-	0	[2] BUSKULIC	93C	ALEP
<3.6E−4	i	+4	5.0–10.2	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<3.6E−4	i	+4	16.5–26.0	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<6.9E−4	i	+4	26.0–33.3	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<9.1E−4	i	+4	33.3–38.6	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<1.1E−3	i	+4	38.6–44.9	88–94	e^+e^-	0	BUSKULIC	93C	ALEP
<1.6E−4	b	see note		see note		0	[3] CECCHINI	93	PLAS
	b	4,5,7,8		2.1A	^{16}O	0,2,0,6	[4] GHOSH	92	EMUL
<6.4E−5	g	1			$\nu,\overline{\nu}$	1	[5] BASILE	91	CNTR
<3.7E−5	g	2			$\nu,\overline{\nu}$	0	[5] BASILE	91	CNTR
<3.9E−5	g	1			$\nu,\overline{\nu}$	1	[6] BASILE	91	CNTR
<2.8E−5	g	2			$\nu,\overline{\nu}$	0	[6] BASILE	91	CNTR
<1.9E−4	c			14.5A	^{28}Si–Pb	0	[7] HE	91	PLAS
<3.9E−4	c			14.5A	^{28}Si–Cu	0	[7] HE	91	PLAS
<1.E−9	c	±1,2,4		14.5A	^{16}O–Ar	0	MATIS	91	MDRP
<5.1E−10	c	±1,2,4		14.5A	^{16}O–Hg	0	MATIS	91	MDRP
<8.1E−9	c	±1,2,4		14.5A	Si–Hg	0	MATIS	91	MDRP
<1.7E−6	c	±1,2,4		60A	^{16}O–Hg	0	MATIS	91	MDRP
<3.5E−7	c	±1,2,4		200A	^{16}O–Hg	0	MATIS	91	MDRP
<1.3E−6	c	±1,2,4		200A	S–Hg	0	MATIS	91	MDRP
<5E−2	e	2	19–27	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<5E−2	e	4	<24	52–60	e^+e^-	0	ADACHI	90C	TOPZ
<1.E−4	e	+2	<3.5	10	e^+e^-	0	BOWCOCK	89B	CLEO
<1.E−6	d	±1,2		60	^{16}O–Hg	0	CALLOWAY	89	MDRP
<3.5E−7	d	±1,2		200	^{16}O–Hg	0	CALLOWAY	89	MDRP
<1.3E−6	d	±1,2		200	S–Hg	0	CALLOWAY	89	MDRP
<1.2E−10	d	±1	1	800	p–Hg	0	MATIS	89	MDRP
<1.1E−10	d	±2	1	800	p–Hg	0	MATIS	89	MDRP
<1.2E−10	d	±1	1	800	p–N_2	0	MATIS	89	MDRP
<7.7E−11	d	±2	1	800	p–N_2	0	MATIS	89	MDRP
<6.E−9	h	−5	0.9–2.3	12	p	0	NAKAMURA	89	SPEC
<5.E−5	g	1,2	<0.5		$\nu,\overline{\nu}\, d$	0	ALLASIA	88	BEBC

<3.E−4	b	See note		14.5	^{16}O–Pb	0	[8]	HOFFMANN	88	PLAS
<2.E−4	b	See note		200	^{16}O–Pb	0	[9]	HOFFMANN	88	PLAS
<8E−5	b	19,20,22,23		200A				GERBIER	87	PLAS
<2.E−4	a	±1,2	<300	320	$\overline{p}p$	0		LYONS	87	MLEV
<1.E−9	c	±1,2,4,5		14.5	^{16}O–Hg	0		SHAW	87	MDRP
<3.E−3	d	−1,2,3,4,6	<5	2	Si–Si	0	[10]	ABACHI	86C	CNTR
<1.E−4	e	±1,2,4	<4	10	e^+e^-	0		ALBRECHT	85G	ARG
<6.E−5	b	±1,2	1	540	$p\overline{p}$	0		BANNER	85	UA2
<5.E−3	e	−4	1–8	29	e^+e^-	0		AIHARA	84	TPC
<1.E−2	e	±1,2	1–13	29	e^+e^-	0		AIHARA	84B	TPC
<2.E−4	b	±1		72	^{40}Ar	0	[11]	BARWICK	84	CNTR
<1.E−4	e	±2	<0.4	1.4	e^+e^-	0		BONDAR	84	OLYA
<5.E−1	e	±1,2	<13	29	e^+e^-	0		GURYN	84	CNTR
<3.E−3	b	±1,2	<2	540	$p\overline{p}$	0		BANNER	83	CNTR
<1.E−4	b	±1,2		106	^{56}Fe	0		LINDGREN	83	CNTR
<3.E−3	b	$>\vert\pm 0.1\vert$		74	^{40}Ar	0	[11]	PRICE	83	PLAS
<1.E−2	e	±1,2	<14	29	e^+e^-	0		MARINI	82B	CNTR
<8.E−2	e	±1,2	<12	29	e^+e^-	0		ROSS	82	CNTR
<3.E−4	e	±2	1.8–2	7	e^+e^-	0		WEISS	81	MRK2
<5.E−2	e	+1,2,4,5	2–12	27	e^+e^-	0		BARTEL	80	JADE
<2.E−5	g	1,2			ν	0	[5,6]	BASILE	80	CNTR
<3.E−10	f	±2,4	1–3	200	p	0	[12]	BOZZOLI	79	CNTR
<6.E−11	f	±1	<21	52	pp	0		BASILE	78	SPEC
<5.E−3	g				ν_μ	0		BASILE	78B	CNTR
<2.E−9	f	±1	<26	62	pp	0		BASILE	77	SPEC
<7.E−10	f	+1,2	<20	52	p	0	[13]	FABJAN	75	CNTR
		+1,2	>4.5		γ	0	[5,6]	GALIK	74	CNTR
		+1,2	>1.5	12	e^-	0	[5,6]	BELLAMY	68	CNTR
		+1,2	>0.9		γ	0	[6]	BATHOW	67	CNTR
		+1,2	>0.9	6	γ	0	[6]	FOSS	67	CNTR

[1] HUENTRUP 96 quote 95% CL limits for production of fragments with charge differing by as much as $\pm1/3$ (in units of e) for charge $6 \leq Z \leq 10$.

[2] BUSKULIC 93C limits for inclusive quark production are more conservative if the ALEPH hadronic fragmentation function is assumed.

[3] CECCHINI 93 limit at 90%CL for $23/3 \leq Z \leq 40/3$, for 16A GeV O, 14.5A Si, and 200A S incident on Cu target. Other limits are 2.3×10^{-4} for $17/3 \leq Z \leq 20/3$ and 1.2×10^{-4} for $20/3 \leq Z \leq 23/3$.

[4] GHOSH 92 reports measurement of spallation fragment charge based on ionization in emulsion. Out of 650 measured tracks, 2 were consistent with charge $5e/3$, and 4 with $7e/3$.

[5] Hadronic quark.

[6] Leptonic quark.

[7] HE 91 limits are for charges of the form $N\pm1/3$ from 23/3 to 38/3, and correspond to cross-section limits of 380μb (Pb) and 320μb (Cu).

[8] The limits apply to projectile fragment charges of 17, 19, 20, 22, 23 in units of $e/3$.

[9] The limits apply to projectile fragment charges of 16, 17, 19, 20, 22, 23 in units of $e/3$.

[10] Flux limits and mass range depend on charge.

[11] Bound to nuclei.

[12] Quark lifetimes $> 1 \times 10^{-8}$ s.

[13] One candidate m <0.17 GeV.

Quark Flux — Cosmic Ray Searches

Shielding values followed with an asterisk indicate altitude in km. Shielding values not followed with an asterisk indicate sea level in kg/cm^2.

FLUX ($cm^{-2}sr^{-1}s^{-1}$)	*CHG* ($e/3$)	*MASS* (GeV)	*SHIELDING*	*DOCUMENT ID*		*TECN*
$<$ 6.2E−10	±2			[1] ALEMANNO	22	DAMP
$<$ 1.E−8	±1/6–1/10			[2] AGNESE	15	CDMS
$<$ 9.2E−15	±1		3800	[3] AMBROSIO	00C	MCRO
$<$2.1E−15	±1			MORI	91	KAM2
$<$2.3E−15	±2			MORI	91	KAM2
$<$2.E−10	±1, 2		0.3	WADA	88	CNTR
	±4		0.3	[4] WADA	88	CNTR
	±4		0.3	[5] WADA	86	CNTR
$<$1.E−12	±2,3/2		−70.	[6] KAWAGOE	84B	PLAS
$<$9.E−10	±1,2		0.3	WADA	84B	CNTR
$<$4.E−9	±4		0.3	WADA	84B	CNTR
$<$2.E−12	±1,2,3		−0.3 *	MASHIMO	83	CNTR
$<$3.E−10	±1,2		0.3	MARINI	82	CNTR
$<$2.E−11	±1,2			MASHIMO	82	CNTR
$<$8.E−10	±1,2		0.3	[6] NAPOLITANO	82	CNTR
				[7] YOCK	78	CNTR
$<$1.E−9				[8] BRIATORE	76	ELEC
$<$2.E−11	+1			[9] HAZEN	75	CC
$<$2.E−10	+1,2			KRISOR	75	CNTR
$<$1.E−7	+1,2			[9,10] CLARK	74B	CC
$<$3.E−10	+1	$>$20		KIFUNE	74	CNTR
$<$8.E−11	+1			[9] ASHTON	73	CNTR
$<$2.E−8	+1,2			HICKS	73B	CNTR
$<$5.E−10	+4		2.8 *	BEAUCHAMP	72	CNTR
$<$1.E−10	+1,2			[9] BOHM	72B	CNTR
$<$1.E−10	+1,2		2.8 *	COX	72	ELEC
$<$3.E−10	+2			CROUCH	72	CNTR
$<$3.E−8			7	[8] DARDO	72	CNTR
$<$4.E−9	+1			[9] EVANS	72	CC
$<$2.E−9		$>$10		[8] TONWAR	72	CNTR
$<$2.E−10	+1		2.8 *	CHIN	71	CNTR
$<$3.E−10	+1,2			[9] CLARK	71B	CC
$<$1.E−10	+1,2			[9] HAZEN	71	CC
$<$5.E−10	+1,2		3.5 *	BOSIA	70	CNTR
	+1,2	$<$6.5		[9] CHU	70	HLBC
$<$2.E−9	+1			FAISSNER	70B	CNTR
$<$2.E−10	+1,2		0.8 *	KRIDER	70	CNTR
$<$5.E−11	+2			CAIRNS	69	CC
$<$8.E−10	+1,2	$<$10		FUKUSHIMA	69	CNTR
	+2			[9,11] MCCUSKER	69	CC
$<$1.E−10		$>$5	1.7,3.6	[8] BJORNBOE	68	CNTR
$<$1.E−8	±1,2,4		6.3,.2 *	[6] BRIATORE	68	CNTR
$<$3.E−8		$>$2		FRANZINI	68	CNTR
$<$9.E−11	±1,2			GARMIRE	68	CNTR
$<$4.E−10	±1			HANAYAMA	68	CNTR
$<$3.E−8		$>$15		KASHA	68	OSPK

<2.E−10	+2			KASHA	68B	CNTR
<2.E−10	+4			KASHA	68C	CNTR
<2.E−10	+2		6	BARTON	67	CNTR
<2.E−7	+4		0.008,0.5 *	BUHLER	67	CNTR
<5.E−10	1,2		0.008,0.5 *	BUHLER	67B	CNTR
<4.E−10	+1,2			GOMEZ	67	CNTR
<2.E−9	+2			KASHA	67	CNTR
<2.E−10	+2		220	BARTON	66	CNTR
<2.E−9	+1,2		0.5 *	BUHLER	66	CNTR
<3.E−9	+1,2			KASHA	66	CNTR
<2.E−9	+1,2			LAMB	66	CNTR
<2.E−8	+1,2	>7	2.8 *	DELISE	65	CNTR
<5.E−8	+2	>2.5	0.5 *	MASSAM	65	CNTR
<2.E−8	+1		2.5 *	BOWEN	64	CNTR
<2.E−7	+1		0.8	SUNYAR	64	CNTR

[1] ALEMANNO 22 uses data from the DAMPE satellite, with calorimetry and tracking to search for fractionally charged particles with $q = \pm 2/3e$ with a exposure time of 2.3×10^{7} s.
[2] See AGNESE 15 Fig.6 for limits on vertical density as function of charge extending to $|q|/e < 1/10$.
[3] AMBROSIO 00C limit is below 11×10^{-15} for $0.25 < q/e < 0.5$, and is changing rapidly near q/e=2/3, where it is 2×10^{-14}.
[4] Distribution in celestial sphere was described as anisotropic.
[5] With telescope axis at zenith angle 40° to the south.
[6] Leptonic quarks.
[7] Lifetime $> 10^{-8}$ s; charge ±0.70, 0.68, 0.42; and mass >4.4, 4.8, and 20 GeV, respectively.
[8] Time delayed air shower search.
[9] Prompt air shower search.
[10] Also $e/4$ and $e/6$ charges.
[11] No events in subsequent experiments.

Quark Density — Matter Searches

QUARKS/ NUCLEON	CHG (e/3)	MASS (GeV)	MATERIAL/METHOD	EVTS	DOCUMENT ID	
<1.17E−22			silicone oil drops	0	[1] LEE	02
<4.71E−22			silicone oil drops	1	[2] HALYO	00
<4.7E−21	±1,2		silicone oil drops	0	MAR	96
<8.E−22	+2		Si/infrared photoionization	0	PERERA	93
<5.E−27	±1,2		sea water/levitation	0	HOMER	92
<4.E−20	±1,2		meteorites/mag. levitation	0	JONES	89
<1.E−19	±1,2		various/spectrometer	0	MILNER	87
<5.E−22	±1,2		W/levitation	0	SMITH	87
<3.E−20	+1,2		org liq/droplet tower	0	VANPOLEN	87
<6.E−20	−1,2		org liq/droplet tower	0	VANPOLEN	87
<3.E−21	±1		Hg drops-untreated	0	SAVAGE	86
<3.E−22	±1,2		levitated niobium	0	SMITH	86
<2.E−26	±1,2		^{4}He/levitation	0	SMITH	86B
<2.E−20	>±1	0.2–250	niobium+tungs/ion	0	MILNER	85
<1.E−21	±1		levitated niobium	0	SMITH	85
	+1,2	<100	niobium/mass spec	0	KUTSCHERA	84

<5.E−22			levitated steel	0	MARINELLI	84
<9.E−20	± <13		water/oil drop	0	JOYCE	83
<2.E−21	> | ± 1/2|		levitated steel	0	LIEBOWITZ	83
<1.E−19	±1,2		photo ion spec	0	VANDESTEEG	83
<2.E−20			mercury/oil drop	0	[3] HODGES	81
1.E−20	+1		levitated niobium	4	[4] LARUE	81
1.E−20	−1		levitated niobium	4	[4] LARUE	81
<1.E−21			levitated steel	0	MARINELLI	80B
<6.E−16			helium/mass spec	0	BOYD	79
1.E−20	+1		levitated niobium	2	[4] LARUE	79
<4.E−28			earth+/ion beam	0	OGOROD...	79
<5.E−15	+1		tungs./mass spec	0	BOYD	78
<5.E−16	+3	<1.7	hydrogen/mass spec	0	BOYD	78B
<1.E−21	±2,4		water/ion beam	0	LUND	78
<6.E−15	>1/2		levitated tungsten	0	PUTT	78
<1.E−22			metals/mass spec	0	SCHIFFER	78
<5.E−15			levitated tungsten ox	0	BLAND	77
<3.E−21			levitated iron	0	GALLINARO	77
2.E−21	−1		levitated niobium	1	[4] LARUE	77
4.E−21	+1		levitated niobium	2	[4] LARUE	77
<1.E−13	+3	<7.7	hydrogen/mass spec	0	MULLER	77
<5.E−27			water+/ion beam	0	OGOROD...	77
<1.E−21			lunar+/ion spec	0	STEVENS	76
<1.E−15	+1	<60	oxygen+/ion spec	0	ELBERT	70
<5.E−19			levitated graphite	0	MORPURGO	70
<5.E−23			water+/atom beam	0	COOK	69
<1.E−17	±1,2		levitated graphite	0	BRAGINSK	68
<1.E−17			water+/uv spec	0	RANK	68
<3.E−19	±1		levitated iron	0	STOVER	67
<1.E−10			sun/uv spec	0	[5] BENNETT	66
<1.E−17	+1,2		meteorites+/ion beam	0	CHUPKA	66
<1.E−16	±1		levitated graphite	0	GALLINARO	66
<1.E−22			argon/electrometer	0	HILLAS	59
	−2		levitated oil	0	MILLIKAN	10

[1] 95% CL limit for fractional charge particles with $0.18e \leq |Q_{residual}| \leq 0.82e$ in total of 70.1 mg of silicone oil.

[2] 95% CL limit for particles with fractional charge $|Q_{residual}|$ >0.16e in total of 17.4 mg of silicone oil.

[3] Also set limits for $Q = \pm e/6$.

[4] Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.

[5] Limit inferred by JONES 77B.

REFERENCES FOR Free Quark Searches

ALEMANNO	22	PR D106 063026	F. Alemanno *et al.*	(DAMPE Collab.)
AGNESE	15	PRL 114 111302	R. Agnese *et al.*	(CDMS Collab.)
CHATRCHYAN	13AR	PR D87 092008	S. Chatrchyan *et al.*	(CMS Collab.)
Also		PR D106 099903 (errat.)	S. Chatrchyan *et al.*	(CMS Collab.)
LEE	02	PR D66 012002	I.T. Lee *et al.*	
AMBROSIO	00C	PR D62 052003	M. Ambrosio *et al.*	(MACRO Collab.)
HALYO	00	PRL 84 2576	V. Halyo *et al.*	
ABREU	97D	PL B396 315	P. Abreu *et al.*	(DELPHI Collab.)
HUENTRUP	96	PR C53 358	G. Huentrup *et al.*	(SIEG)

MAR	96	PR D53 6017	N.M. Mar *et al.*	(SLAC, SCHAF, LANL, UCI)
AKERS	95R	ZPHY C67 203	R. Akers *et al.*	(OPAL Collab.)
BUSKULIC	93C	PL B303 198	D. Buskulic *et al.*	(ALEPH Collab.)
CECCHINI	93	ASP 1 369	S. Cecchini *et al.*	
PERERA	93	PRL 70 1053	A.G.U. Perera *et al.*	(PITT)
ABE	92J	PR D46 1889	F. Abe *et al.*	(CDF Collab.)
GHOSH	92	NC 105A 99	D. Ghosh *et al.*	(JADA, BANGB)
HOMER	92	ZPHY C55 549	G.J. Homer *et al.*	(RAL, SHMP, LOQM)
BASILE	91	NC 104A 405	M. Basile *et al.*	(BGNA, INFN, CERN, PLRM+)
HE	91	PR C44 1672	Y.B. He, P.B. Price	(UCB)
MATIS	91	NP A525 513	H.S. Matis *et al.*	(LBL, SFSU, UCI+)
MORI	91	PR D43 2843	M. Mori *et al.*	(Kamiokande II Collab.)
ADACHI	90C	PL B244 352	I. Adachi *et al.*	(TOPAZ Collab.)
BOWCOCK	89B	PR D40 263	T.J.V. Bowcock *et al.*	(CLEO Collab.)
CALLOWAY	89	PL B232 549	D. Calloway *et al.*	(SFSU, UCI, LBL+)
JONES	89	ZPHY C43 349	W.G. Jones *et al.*	(LOIC, RAL)
MATIS	89	PR D39 1851	H.S. Matis *et al.*	(LBL, SFSU, UCI+)
NAKAMURA	89	PR D39 1261	T.T. Nakamura *et al.*	(KYOT, TMTC)
ALLASIA	88	PR D37 219	D. Allasia *et al.*	(WA25 Collab.)
HOFFMANN	88	PL B200 583	A. Hofmann *et al.*	(SIEG, USF)
PHILLIPS	88	NIM A264 125	J.D. Phillips, W.M. Fairbank, J. Navarro	(STAN)
WADA	88	NC 11C 229	T. Wada, Y. Yamashita, I. Yamamoto	(OKAY)
GERBIER	87	PRL 59 2535	G. Gerbier *et al.*	(UCB, CERN)
LYONS	87	ZPHY C36 363	L. Lyons *et al.*	(OXF, RAL, LOIC)
MILNER	87	PR D36 37	R.E. Milner *et al.*	(CIT)
SHAW	87	PR D36 3533	G.L. Shaw *et al.*	(UCI, LBL, LANL, SFSU)
SMITH	87	PL B197 447	P.F. Smith *et al.*	(RAL, LOIC)
VANPOLEN	87	PR D36 1983	J. van Polen, R.T. Hagstrom, G. Hirsch	(ANL+)
ABACHI	86C	PR D33 2733	S. Abachi *et al.*	(UCLA, LBL, UCD)
SAVAGE	86	PL 167B 481	M.L. Savage *et al.*	(SFSU)
SMITH	86	PL B171 129	P.F. Smith *et al.*	(RAL, LOIC)
SMITH	86B	PL B181 407	P.F. Smith *et al.*	(RAL, LOIC)
WADA	86	NC 9C 358	T. Wada	(OKAY)
ALBRECHT	85G	PL 156B 134	H. Albrecht *et al.*	(ARGUS Collab.)
BANNER	85	PL 156B 129	M. Banner *et al.*	(UA2 Collab.)
MILNER	85	PRL 54 1472	R.E. Milner *et al.*	(CIT)
SMITH	85	PL 153B 188	P.F. Smith *et al.*	(RAL, LOIC)
AIHARA	84	PRL 52 168	H. Aihara *et al.*	(TPC Collab.)
AIHARA	84B	PRL 52 2332	H. Aihara *et al.*	(TPC Collab.)
BARWICK	84	PR D30 691	S.W. Barwick, J.A. Musser, J.D. Stevenson	(UCB)
BERGSMA	84B	ZPHY C24 217	F. Bergsma *et al.*	(CHARM Collab.)
BONDAR	84	JETPL 40 1265	A.E. Bondar *et al.*	(NOVO)
		Translated from ZETFP 40 440.		
GURYN	84	PL 139B 313	W. Guryn *et al.*	(FRAS, LBL, NWES, STAN+)
KAWAGOE	84B	LNC 41 604	K. Kawagoe *et al.*	(TOKY)
KUTSCHERA	84	PR D29 791	W. Kutschera *et al.*	(ANL, FNAL)
MARINELLI	84	PL 137B 439	M. Marinelli, G. Morpurgo	(GENO)
WADA	84B	LNC 40 329	T. Wada, Y. Yamashita, I. Yamamoto	(OKAY)
AUBERT	83C	PL 133B 461	J.J. Aubert *et al.*	(EMC Collab.)
BANNER	83	PL 121B 187	M. Banner *et al.*	(UA2 Collab.)
JOYCE	83	PRL 51 731	D.C. Joyce *et al.*	(SFSU)
LIEBOWITZ	83	PRL 50 1640	D. Liebowitz, M. Binder, K.O.H. Ziock	(UVA)
LINDGREN	83	PRL 51 1621	M.A. Lindgren *et al.*	(SFSU, UCR, UCI+)
MASHIMO	83	PL 128B 327	T. Mashimo *et al.*	(ICEPP)
PRICE	83	PRL 50 566	P.B. Price *et al.*	(UCB)
VANDESTEEG	83	PRL 50 1234	M.J.H. van de Steeg, H.W.H.M. Jongbloets, P. Wyder	
MARINI	82	PR D26 1777	A. Marini *et al.*	(FRAS, LBL, NWES, STAN+)
MARINI	82B	PRL 48 1649	A. Marini *et al.*	(FRAS, LBL, NWES, STAN+)
MASHIMO	82	JPSJ 51 3067	T. Mashimo, K. Kawagoe, M. Koshiba	(INUS)
NAPOLITANO	82	PR D25 2837	J. Napolitano *et al.*	(STAN, FRAS, LBL+)
ROSS	82	PL 118B 199	M.C. Ross *et al.*	(FRAS, LBL, NWES, STAN+)
HODGES	81	PRL 47 1651	C.L. Hodges *et al.*	(UCR, SFSU)
LARUE	81	PRL 46 967	G.S. Larue, J.D. Phillips, W.M. Fairbank	(STAN)
WEISS	81	PL 101B 439	J.M. Weiss *et al.*	(SLAC, LBL, UCB)
BARTEL	80	ZPHY C6 295	W. Bartel *et al.*	(JADE Collab.)
BASILE	80	LNC 29 251	M. Basile *et al.*	(BGNA, CERN, FRAS, ROMA+)
BUSSIERE	80	NP B174 1	A. Bussiere *et al.*	(BGNA, SACL, LAPP)
MARINELLI	80B	PL 94B 433	M. Marinelli, G. Morpurgo	(GENO)
Also		PL 94B 427	M. Marinelli, G. Morpurgo	(GENO)
BOYD	79	PRL 43 1288	R.N. Boyd *et al.*	(OSU)
BOZZOLI	79	NP B159 363	W. Bozzoli *et al.*	(BGNA, LAPP, SACL+)

LARUE	79	PRL 42 142	G.S. Larue, W.M. Fairbank, J.D. Phillips	(STAN)
Also		PRL 42 1019	G.S. Larue, W.M. Fairbank, J.D. Phillips	
OGOROD...	79	JETP 49 953	D.D. Ogorodnikov, I.M. Samoilov, A.M. Solntsev	
		Translated from ZETF 76 1881.		
STEVENSON	79	PR D20 82	M.L. Stevenson	(LBL)
BASILE	78	NC 45A 171	M. Basile *et al.*	(CERN, BGNA)
BASILE	78B	NC 45A 281	M. Basile *et al.*	(CERN, BGNA)
BOYD	78	PRL 40 216	R.N. Boyd *et al.*	(ROCH)
BOYD	78B	PL 72B 484	R.N. Boyd *et al.*	(ROCH)
LUND	78	RA 25 75	T. Lund, R. Brandt, Y. Fares	(MARB)
PUTT	78	PR D17 1466	G.D. Putt, P.C.M. Yock	(AUCK)
SCHIFFER	78	PR D17 2241	J.P. Schiffer *et al.*	(CHIC, ANL)
YOCK	78	PR D18 641	P.C.M. Yock	(AUCK)
ANTREASYAN	77	PRL 39 513	D. Antreasyan *et al.*	(EFI, PRIN)
BASILE	77	NC 40A 41	M. Basile *et al.*	(CERN, BGNA)
BLAND	77	PRL 39 369	R.W. Bland *et al.*	(SFSU)
GALLINARO	77	PRL 38 1255	G. Gallinaro, M. Marinelli, G. Morpurgo	(GENO)
JONES	77B	RMP 49 717	L.W. Jones	
LARUE	77	PRL 38 1011	G.S. Larue, W.M. Fairbank, A.F. Hebard	(STAN)
MULLER	77	SCI 196 521	R.A. Muller *et al.*	(LBL)
OGOROD...	77	JETP 45 857	D.D. Ogorodnikov, I.M. Samoilov, A.M. Solntsev	
		Translated from ZETF 72 1633.		
BALDIN	76	SJNP 22 264	B.Y. Baldin *et al.*	(JINR)
		Translated from YAF 22 512.		
BRIATORE	76	NC 31A 553	L. Briatore *et al.*	(LCGT, FRAS, FREIB)
STEVENS	76	PR D14 716	C.M. Stevens, J.P. Schiffer, W. Chupka	(ANL)
ALBROW	75	NP B97 189	M.G. Albrow *et al.*	(CERN, DARE, FOM+)
FABJAN	75	NP B101 349	C.W. Fabjan *et al.*	(CERN, MPIM)
HAZEN	75	NP B95 189	W.E. Hazen *et al.*	(MICH, LEED)
JOVANOV...	75	PL 56B 105	J.V. Jovanovich *et al.*	(MANI, AACH, CERN+)
KRISOR	75	NC 27A 132	K. Krisor	(AACH3)
CLARK	74B	PR D10 2721	A.F. Clark *et al.*	(LLL)
GALIK	74	PR D9 1856	R.S. Galik *et al.*	(SLAC, FNAL)
KIFUNE	74	JPSJ 36 629	T. Kifune *et al.*	(TOKY, KEK)
NASH	74	PRL 32 858	T. Nash *et al.*	(FNAL, CORN, NYU)
ALPER	73	PL 46B 265	B. Alper *et al.*	(CERN, LIVP, LUND, BOHR+)
ASHTON	73	JP A6 577	F. Ashton *et al.*	(DURH)
HICKS	73B	NC 14A 65	R.B. Hicks, R.W. Flint, S. Standil	(MANI)
LEIPUNER	73	PRL 31 1226	L.B. Leipuner *et al.*	(BNL, YALE)
BEAUCHAMP	72	PR D6 1211	W.T. Beauchamp *et al.*	(ARIZ)
BOHM	72B	PRL 28 326	A. Bohm *et al.*	(AACH)
BOTT	72	PL 40B 693	M. Bott-Bodenhausen *et al.*	(CERN, MPIM)
COX	72	PR D6 1203	A.J. Cox *et al.*	(ARIZ)
CROUCH	72	PR D5 2667	M.F. Crouch, K. Mori, G.R. Smith	(CASE)
DARDO	72	NC 9A 319	M. Dardo *et al.*	(TORI)
EVANS	72	PRSE A70 143	G.R. Evans *et al.*	(EDIN, LEED)
TONWAR	72	JP A5 569	S.C. Tonwar, S. Naranan, B.V. Sreekantan	(TATA)
ANTIPOV	71	NP B29 374	Y.M. Antipov *et al.*	(SERP)
CHIN	71	NC 2A 419	S. Chin *et al.*	(OSAK)
CLARK	71B	PRL 27 51	A.F. Clark *et al.*	(LLL, LBL)
HAZEN	71	PRL 26 582	W.E. Hazen	(MICH)
BOSIA	70	NC 66A 167	G.F. Bosia, L. Briatore	(TORI)
CHU	70	PRL 24 917	W.T. Chu *et al.*	(OSU, ROSE, KANS)
Also		PRL 25 550	W.W.M. Allison *et al.*	(ANL)
ELBERT	70	NP B20 217	J.W. Elbert *et al.*	(WISC)
FAISSNER	70B	PRL 24 1357	H. Faissner *et al.*	(AACH3)
KRIDER	70	PR D1 835	E.P. Krider, T. Bowen, R.M. Kalbach	(ARIZ)
MORPURGO	70	NIM 79 95	G. Morpurgo, G. Gallinaro, G. Palmieri	(GENO)
ALLABY	69B	NC 64A 75	J.V. Allaby *et al.*	(CERN)
ANTIPOV	69	PL 29B 245	Y.M. Antipov *et al.*	(SERP)
ANTIPOV	69B	PL 30B 576	Y.M. Antipov *et al.*	(SERP)
CAIRNS	69	PR 186 1394	I. Cairns *et al.*	(SYDN)
COOK	69	PR 188 2092	D.D. Cook *et al.*	(ILL)
FUKUSHIMA	69	PR 178 2058	Y. Fukushima *et al.*	(TOKY)
MCCUSKER	69	PRL 23 658	C.B.A. McCusker, I. Cairns	(SYDN)
BELLAMY	68	PR 166 1391	E.H. Bellamy *et al.*	(STAN, SLAC)
BJORNBOE	68	NC B53 241	J. Bjornboe *et al.*	(BOHR, TATA, BERN+)
BRAGINSK	68	JETP 27 51	V.B. Braginsky *et al.*	(MOSU)
		Translated from ZETF 54 91.		

BRIATORE	68	NC 57A 850	L. Briatore *et al.*	(TORI, CERN, BGNA)
FRANZINI	68	PRL 21 1013	P. Franzini, S. Shulman	(COLU)
GARMIRE	68	PR 166 1280	G. Garmire, C. Leong, V. Sreekantan	(MIT)
HANAYAMA	68	CJP 46 S734	Y. Hanayama *et al.*	(OSAK)
KASHA	68	PR 172 1297	H. Kasha, R.J. Stefanski	(BNL, YALE)
KASHA	68B	PRL 20 217	H. Kasha *et al.*	(BNL, YALE)
KASHA	68C	CJP 46 S730	H. Kasha *et al.*	(BNL, YALE)
RANK	68	PR 176 1635	D. Rank	(MICH)
BARTON	67	PRSL 90 87	J.C. Barton	(NPOL)
BATHOW	67	PL 25B 163	G. Bathow *et al.*	(DESY)
BUHLER	67	NC 49A 209	A. Buhler-Broglin *et al.*	(CERN, BGNA)
BUHLER	67B	NC 51A 837	A. Buhler-Broglin *et al.*	(CERN, BGNA+)
FOSS	67	PL 25B 166	J. Foss *et al.*	(MIT)
GOMEZ	67	PRL 18 1022	R. Gomez *et al.*	(CIT)
KASHA	67	PR 154 1263	H. Kasha *et al.*	(BNL, YALE)
STOVER	67	PR 164 1599	R.W. Stover, T.I. Moran, J.W. Trischka	(SYRA)
BARTON	66	PL 21 360	J.C. Barton, C.T. Stockel	(NPOL)
BENNETT	66	PRL 17 1196	W.R. Bennett	(YALE)
BUHLER	66	NC 45A 520	A. Buhler-Broglin *et al.*	(CERN, BGNA+)
CHUPKA	66	PRL 17 60	W.A. Chupka, J.P. Schiffer, C.M. Stevens	(ANL)
GALLINARO	66	PL 23 609	G. Gallinaro, G. Morpurgo	(GENO)
KASHA	66	PR 150 1140	H. Kasha, L.B. Leipuner, R.K. Adair	(BNL, YALE)
LAMB	66	PRL 17 1068	R.C. Lamb *et al.*	(ANL)
DELISE	65	PR 140 B458	D.A. de Lise, T. Bowen	(ARIZ)
DORFAN	65	PRL 14 999	D.E. Dorfan *et al.*	(COLU)
FRANZINI	65B	PRL 14 196	P. Franzini *et al.*	(BNL, COLU)
MASSAM	65	NC 40A 589	T. Massam, T. Muller, A. Zichichi	(CERN)
BINGHAM	64	PL 9 201	H.H. Bingham *et al.*	(CERN, EPOL)
BLUM	64	PRL 13 353A	W. Blum *et al.*	(CERN)
BOWEN	64	PRL 13 728	T. Bowen *et al.*	(ARIZ)
HAGOPIAN	64	PRL 13 280	V. Hagopian *et al.*	(PENN, BNL)
LEIPUNER	64	PRL 12 423	L.B. Leipuner *et al.*	(BNL, YALE)
MORRISON	64	PL 9 199	D.R.O. Morrison	(CERN)
SUNYAR	64	PR 136 B1157	A.W. Sunyar, A.Z. Schwarzschild, P.I. Connors	(BNL)
HILLAS	59	NAT 184 B92	A.M. Hillas, T.E. Cranshaw	(AERE)
MILLIKAN	10	Phil Mag 19 209	R.A. Millikan	(CHIC)

OTHER RELATED PAPERS

LYONS Review	85	PRPL C129 225	L. Lyons	(OXF)
MARINELLI Review	82	PRPL 85 161	M. Marinelli, G. Morpurgo	(GENO)