

Free Quark Searches

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Quark Production Cross Section — Accelerator Searches

<i>X-SECT</i> (cm ²)	<i>CHG</i> (e/3)	<i>MASS</i> (GeV)	<i>ENERGY</i> (GeV)	<i>BEAM</i>	<i>EVTS</i>	<i>DOCUMENT ID</i>	<i>TECN</i>
<1.3E-36	±2	45-84	130-172	e ⁺ e ⁻	0	ABREU	97D DLPH
<2.E-35	+2	250	1800	p \bar{p}	0	¹ ABE	92J CDF
<1.E-35	+4	250	1800	p \bar{p}	0	¹ ABE	92J CDF
<3.8E-28			14.5A	²⁸ Si-Pb	0	² HE	91 PLAS
<3.2E-28			14.5A	²⁸ Si-Cu	0	² HE	91 PLAS
<1.E-40	±1,2	<10		p,ν, $\bar{\nu}$	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	³ BUSSIERE	80 CNTR
<5.E-38	+1,2	>5	300	p	0	^{4,5} STEVENSON	79 CNTR
<1.E-33	±1	<20	52	pp	0	BASILE	78 SPEC
<9.E-39	±1,2	<6	400	p	0	⁴ ANTREASYAN	77 SPEC
<8.E-35	+1,2	<20	52	pp	0	⁶ FABJAN	75 CNTR
<5.E-38	-1,2	4-9	200	p	0	NASH	74 CNTR
<1.E-32	+2,4	4-24	52	pp	0	ALPER	73 SPEC
<5.E-31	+1,2,4	<12	300	p	0	LEIPUNER	73 CNTR
<6.E-34	±1,2	<13	52	pp	0	BOTT	72 CNTR
<1.E-36	-4	4	70	p	0	ANTIPOV	71 CNTR
<1.E-35	±1,2	2	28	p	0	⁷ ALLABY	69B CNTR
<4.E-37	-2	<5	70	p	0	³ ANTIPOV	69 CNTR
<3.E-37	-1,2	2-5	70	p	0	⁷ 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	⁸ 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	⁸ 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 ABE 92J flux limits decrease as the mass increases from 50 to 500 GeV.

² HE 91 limits are for charges of the form $N \pm 1/3$ from 23/3 to 38/3.

³ Hadronic or leptonic quarks.

⁴ Cross section cm²/GeV².

⁵ $3 \times 10^{-5} < \text{lifetime} < 1 \times 10^{-3}$ s.

⁶ Includes BOTT 72 results.

⁷ Assumes isotropic cm production.

⁸ Cross section inferred from flux.

Quark Differential Production Cross Section — Accelerator Searches

X -SECT ($\text{cm}^2\text{sr}^{-1}\text{GeV}^{-1}$)	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	pp	0	ALBROW	75 SPEC
<5.E-34	<7	7-15	44	pp	0	JOVANOVA...	75 CNTR
<5.E-35			20	γ	0	⁹ 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	$\pm 1,2$	<2.7	27	p	0	ALLABY	69B CNTR
<7.E-38	-1,2	<2.5	70	p	0	ANTIPOV	69B CNTR

⁹ 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 $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.
- (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 $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$.

FLUX		CHG ($e/3$)	MASS (GeV)	ENERGY (GeV)	BEAM	EVTS	DOCUMENT ID	TECN
<1.6E-3	b	see note		200	$^{32}\text{S-Pb}$	0	¹⁰ HUENTRUP	96 PLAS
<6.2E-4	b	see note		10.6	$^{32}\text{S-Pb}$	0	¹⁰ 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	¹¹ BUSKULIC	93C ALEP
<6.E-4	e	+2	5-30	88-94	e^+e^-	0	¹¹ BUSKULIC	93C ALEP
<1.2E-3	e	+4	15-40	88-94	e^+e^-	0	¹¹ 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	¹² CECCHINI	93 PLAS
	b	4,5,7,8		2.1A	^{16}O	0,2,0,6	¹³ GHOSH	92 EMUL
<6.4E-5	g	1			$\nu, \bar{\nu}$	1	¹⁴ BASILE	91 CNTR
<3.7E-5	g	2			$\nu, \bar{\nu}$	0	¹⁴ BASILE	91 CNTR
<3.9E-5	g	1			$\nu, \bar{\nu}$	1	¹⁵ BASILE	91 CNTR

<2.8E-5	g	2		$\nu, \bar{\nu}$	0	15	BASILE	91	CNTR
<1.9E-4	c		14.5A	$^{28}\text{Si-Pb}$	0	16	HE	91	PLAS
<3.9E-4	c		14.5A	$^{28}\text{Si-Cu}$	0	16	HE	91	PLAS
<1.E-9	c	$\pm 1,2,4$	14.5A	$^{16}\text{O-Ar}$	0		MATIS	91	MDRP
<5.1E-10	c	$\pm 1,2,4$	14.5A	$^{16}\text{O-Hg}$	0		MATIS	91	MDRP
<8.1E-9	c	$\pm 1,2,4$	14.5A	Si-Hg	0		MATIS	91	MDRP
<1.7E-6	c	$\pm 1,2,4$	60A	$^{16}\text{O-Hg}$	0		MATIS	91	MDRP
<3.5E-7	c	$\pm 1,2,4$	200A	$^{16}\text{O-Hg}$	0		MATIS	91	MDRP
<1.3E-6	c	$\pm 1,2,4$	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	$\pm 1,2$		60 $^{16}\text{O-Hg}$	0		CALLOWAY	89	MDRP
<3.5E-7	d	$\pm 1,2$		200 $^{16}\text{O-Hg}$	0		CALLOWAY	89	MDRP
<1.3E-6	d	$\pm 1,2$		200 S-Hg	0		CALLOWAY	89	MDRP
<1.2E-10	d	± 1	1	800 $p\text{-Hg}$	0		MATIS	89	MDRP
<1.1E-10	d	± 2	1	800 $p\text{-Hg}$	0		MATIS	89	MDRP
<1.2E-10	d	± 1	1	800 $p\text{-N}_2$	0		MATIS	89	MDRP
<7.7E-11	d	± 2	1	800 $p\text{-N}_2$	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	$\nu, \bar{\nu} d$	0		ALLASIA	88	BEBC
<3.E-4	b	See note		14.5 $^{16}\text{O-Pb}$	0	17	HOFFMANN	88	PLAS
<2.E-4	b	See note		200 $^{16}\text{O-Pb}$	0	18	HOFFMANN	88	PLAS
<8E-5	b	19,20,22,23		200A			GERBIER	87	PLAS
<2.E-4	a	$\pm 1,2$	<300	320 $\bar{p}p$	0		LYONS	87	MLEV
<1.E-9	c	$\pm 1,2,4,5$		14.5 $^{16}\text{O-Hg}$	0		SHAW	87	MDRP
<3.E-3	d	-1,2,3,4,6	<5	2 Si-Si	0	19	ABACHI	86C	CNTR
<1.E-4	e	$\pm 1,2,4$	<4	10 $e^+ e^-$	0		ALBRECHT	85G	ARG
<6.E-5	b	$\pm 1,2$	1	540 $p\bar{p}$	0		BANNER	85	UA2
<5.E-3	e	-4	1-8	29 $e^+ e^-$	0		AIHARA	84	TPC
<1.E-2	e	$\pm 1,2$	1-13	29 $e^+ e^-$	0		AIHARA	84B	TPC
<2.E-4	b	± 1		72 ^{40}Ar	0	20	BARWICK	84	CNTR
<1.E-4	e	± 2	<0.4	1.4 $e^+ e^-$	0		BONDAR	84	OLYA
<5.E-1	e	$\pm 1,2$	<13	29 $e^+ e^-$	0		GURYN	84	CNTR
<3.E-3	b	$\pm 1,2$	<2	540 $p\bar{p}$	0		BANNER	83	CNTR
<1.E-4	b	$\pm 1,2$		106 ^{56}Fe	0		LINDGREN	83	CNTR
<3.E-3	b	$> \pm 0.1 $		74 ^{40}Ar	0	20	PRICE	83	PLAS
<1.E-2	e	$\pm 1,2$	<14	29 $e^+ e^-$	0		MARINI	82B	CNTR
<8.E-2	e	$\pm 1,2$	<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	14,15	BASILE	80	CNTR
<3.E-10	f	$\pm 2,4$	1-3	200 p	0	21	BOZZOLI	79	CNTR
<6.E-11	f	± 1	<21	52 pp	0		BASILE	78	SPEC
<5.E-3	g			$\nu\mu$	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	22	FABJAN	75	CNTR
		+1,2	>4.5	γ	0	14,15	GALIK	74	CNTR

+1,2	>1.5	12	e^-	0	14,15	BELLAMY	68	CNTR
+1,2	>0.9		γ	0	15	BATHOW	67	CNTR
+1,2	>0.9	6	γ	0	15	FOSS	67	CNTR

- ¹⁰ HUENTRUP 96 quote 95% CL limits for production of fragments with charge differing by as much as $\pm 1/3$ (in units of e) for charge $6 \leq Z \leq 10$.
- ¹¹ BUSKULIC 93C limits for inclusive quark production are more conservative if the ALEPH hadronic fragmentation function is assumed.
- ¹² 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 $20/3 \leq Z \leq 23/3$.
- ¹³ 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 $7e/3$.
- ¹⁴ Hadronic quark.
- ¹⁵ Leptonic quark.
- ¹⁶ HE 91 limits are for charges of the form $N \pm 1/3$ from $23/3$ to $38/3$, and correspond to cross-section limits of $380 \mu\text{b}$ (Pb) and $320 \mu\text{b}$ (Cu).
- ¹⁷ The limits apply to projectile fragment charges of 17, 19, 20, 22, 23 in units of $e/3$.
- ¹⁸ The limits apply to projectile fragment charges of 16, 17, 19, 20, 22, 23 in units of $e/3$.
- ¹⁹ Flux limits and mass range depend on charge.
- ²⁰ Bound to nuclei.
- ²¹ Quark lifetimes $> 1 \times 10^{-8}$ s.
- ²² 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 .

$FLUX$ ($\text{cm}^{-2}\text{sr}^{-1}\text{s}^{-1}$)	CHG ($e/3$)	$MASS$ (GeV)	$SHIELDING$	$EVTS$	$DOCUMENT ID$	$TECN$
$< 9.2\text{E}-15$	± 1		3800	0	²³ AMBROSIO	00C MCRO
$< 2.1\text{E}-15$	± 1			0	MORI	91 KAM2
$< 2.3\text{E}-15$	± 2			0	MORI	91 KAM2
$< 2.\text{E}-10$	$\pm 1,2$		0.3	0	WADA	88 CNTR
	± 4		0.3	12	²⁴ WADA	88 CNTR
	± 4		0.3	9	²⁵ WADA	86 CNTR
$< 1.\text{E}-12$	$\pm 2,3/2$		-70.	0	²⁶ KAWAGOE	84B PLAS
$< 9.\text{E}-10$	$\pm 1,2$		0.3	0	WADA	84B CNTR
$< 4.\text{E}-9$	± 4		0.3	7	WADA	84B CNTR
$< 2.\text{E}-12$	$\pm 1,2,3$		-0.3 *	0	MASHIMO	83 CNTR
$< 3.\text{E}-10$	$\pm 1,2$		0.3	0	MARINI	82 CNTR
$< 2.\text{E}-11$	$\pm 1,2$			0	MASHIMO	82 CNTR
$< 8.\text{E}-10$	$\pm 1,2$		0.3	0	²⁶ NAPOLITANO	82 CNTR
				3	²⁷ YOCK	78 CNTR
$< 1.\text{E}-9$				0	²⁸ BRIATORE	76 ELEC
$< 2.\text{E}-11$	+1			0	²⁹ HAZEN	75 CC
$< 2.\text{E}-10$	+1,2			0	KRISOR	75 CNTR
$< 1.\text{E}-7$	+1,2			0	^{29,30} CLARK	74B CC
$< 3.\text{E}-10$	+1	>20		0	KIFUNE	74 CNTR
$< 8.\text{E}-11$	+1			0	²⁹ ASHTON	73 CNTR
$< 2.\text{E}-8$	+1,2			0	HICKS	73B CNTR
$< 5.\text{E}-10$	+4		2.8 *	0	BEAUCHAMP	72 CNTR
$< 1.\text{E}-10$	+1,2			0	²⁹ BOHM	72B CNTR

<1.E-10	+1,2		2.8 *	0	COX	72	ELEC
<3.E-10	+2			0	CROUCH	72	CNTR
<3.E-8			7	0	²⁸ DARDO	72	CNTR
<4.E-9	+1			0	²⁹ EVANS	72	CC
<2.E-9		>10		0	²⁸ TONWAR	72	CNTR
<2.E-10	+1		2.8 *	0	CHIN	71	CNTR
<3.E-10	+1,2			0	²⁹ CLARK	71B	CC
<1.E-10	+1,2			0	²⁹ HAZEN	71	CC
<5.E-10	+1,2		3.5 *	0	BOSIA	70	CNTR
	+1,2	<6.5		1	²⁹ CHU	70	HLBC
<2.E-9	+1			0	FAISSNER	70B	CNTR
<2.E-10	+1,2		0.8 *	0	KRIDER	70	CNTR
<5.E-11	+2			4	CAIRNS	69	CC
<8.E-10	+1,2	<10		0	FUKUSHIMA	69	CNTR
	+2			1	^{29,31} MCCUSKER	69	CC
<1.E-10		>5	1.7,3.6	0	²⁸ BJORNBOE	68	CNTR
<1.E-8	±1,2,4		6.3,.2 *	0	²⁶ BRIATORE	68	CNTR
<3.E-8		>2		0	FRANZINI	68	CNTR
<9.E-11	±1,2			0	GARMIRE	68	CNTR
<4.E-10	±1			0	HANAYAMA	68	CNTR
<3.E-8		>15		0	KASHA	68	OSPK
<2.E-10	+2			0	KASHA	68B	CNTR
<2.E-10	+4			0	KASHA	68C	CNTR
<2.E-10	+2		6	0	BARTON	67	CNTR
<2.E-7	+4		0.008,0.5 *	0	BUHLER	67	CNTR
<5.E-10	1,2		0.008,0.5 *	0	BUHLER	67B	CNTR
<4.E-10	+1,2			0	GOMEZ	67	CNTR
<2.E-9	+2			0	KASHA	67	CNTR
<2.E-10	+2		220	0	BARTON	66	CNTR
<2.E-9	+1,2		0.5 *	0	BUHLER	66	CNTR
<3.E-9	+1,2			0	KASHA	66	CNTR
<2.E-9	+1,2			0	LAMB	66	CNTR
<2.E-8	+1,2	>7	2.8 *	0	DELISE	65	CNTR
<5.E-8	+2	>2.5	0.5 *	0	MASSAM	65	CNTR
<2.E-8	+1		2.5 *	0	BOWEN	64	CNTR
<2.E-7	+1		0.8	0	SUNYAR	64	CNTR

²³ 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} .

²⁴ Distribution in celestial sphere was described as anisotropic.

²⁵ With telescope axis at zenith angle 40° to the south.

²⁶ Leptonic quarks.

²⁷ Lifetime $> 10^{-8}$ s; charge $\pm 0.70, 0.68, 0.42$; and mass $> 4.4, 4.8, \text{ and } 20$ GeV, respectively.

²⁸ Time delayed air shower search.

²⁹ Prompt air shower search.

³⁰ Also $e/4$ and $e/6$ charges.

³¹ No events in subsequent experiments.

Quark Density — Matter Searches

For a review, see SMITH 89.

<u>QUARKS/ NUCLEON</u>	<u>CHG (e/3)</u>	<u>MASS (GeV)</u>	<u>MATERIAL/METHOD</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>
<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	³² HODGES 81
1.E-20	+1		levitated niobium	4	³³ LARUE 81
1.E-20	-1		levitated niobium	4	³³ 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	³³ 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	³³ LARUE 77
4.E-21	+1		levitated niobium	2	³³ 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	³⁴ 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

³² Also set limits for $Q = \pm e/6$.

³³ Note that in PHILLIPS 88 these authors report a subtle magnetic effect which could account for the apparent fractional charges.

³⁴ Limit inferred by JONES 77B.

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