[185] Limit is for m_{X^0} around 60 GeV.

[186] ADRIANI 92F give $\sigma_Z \cdot$ B($Z \rightarrow q\overline{q}X^0$) $\cdot$ B($X^0 \rightarrow \gamma\gamma$)<(0.75–1.5) pb (95%CL) for m_{X^0} = 10–70 GeV. The limit is 1 pb at 60 GeV.

Heavy Particle Production in Quarkonium Decays

Limits are for branching ratios to modes shown.

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<5.6 \times 10^{-5}$	90	[187] ANTREASYAN	90C	CBAL	$\Upsilon(1S) \rightarrow X^0\gamma$, $m_{X^0} < 7.2$ GeV
		[188] ALBRECHT	89	ARG	

[187] ANTREASYAN 90C assume that X^0 does not decay in the detector.

[188] ALBRECHT 89 give limits for B($\Upsilon(1S), \Upsilon(2S) \rightarrow X^0\gamma$)$\cdot$B($X^0 \rightarrow \pi^+\pi^-, K^+K^-, p\overline{p}$) for $m_{X^0} < 3.5$ GeV.

REFERENCES FOR Searches for Heavy Bosons Other Than Higgs Bosons

ABACHI 94B PRL 72 965 +Abbott, Abolins, Acharya, Adam+ (D0 Collab.)
BUSKULIC 94 ZPHY C62 539 +Casper, De Bonis, Decamp, Ghez, Goy+ (ALEPH Collab.)
ABE 93C PL B302 119 +Amako, Arai, Arima, Asano, Chiba+ (VENUS Collab.)
ABE 93D PL B304 373 +Adachi, Awa, Aoki, Belusevic, Emi+ (TOPAZ Collab.)
ABE 93G PRL 71 2542 +Albrow, Akimoto, Amidei, Anway-Wiese+ (CDF Collab.)
ABE 93I PR D48 R3939 +Albrow, Amidei, Anway-Wiese, Apollinari+ (CDF Collab.)
ABREU 93J PL B316 620 +Adam, Adye, Agasi, Aleksan, Alekseev+ (DELPHI Collab.)
ABT 93 NP B396 3 +Andreev, Andrieu, Appuhn, Arpagaus+ (H1 Collab.)
ACTON 93E PL B311 391 +Akers, Alexander+ (OPAL Collab.)
ADRIANI 93D PL B306 187 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
ADRIANI 93M PRPL 236 1 +Aguilar-Benitez, Ahlen, Alcaraz, Aloisio+ (L3 Collab.)
ALITTI 93 NP B400 3 +Ambrosini, Ansari, Autiero, Bareyre+ (UA2 Collab.)
ALLEN 93 PR D47 11 +Chen, Doe, Hausammann+ (UCI, LANL, ANL, UMD)
ALTARELLI 93B PL B318 139 +Casalbuoni+ (CERN, FIRZ, GEVA, PADO)
BHATTACH... 93 PR D47 R3693 Bhattacharyya+ (CALC, JADA, ICTP, AHMED, BOSE)
BUSKULIC 93F PL B308 425 +De Bonis, Decamp, Chez, Goy, Lees+ (ALEPH Collab.)
DERRICK 93 PL B306 173 +Krakauer, Magill, Musgrave, Repond+ (ZEUS Collab.)
LEURER 93 PRL 71 1324 (REHO)
RIZZO 93 PR D48 4470 (ANL)
SEVERIJNS 93 PRL 70 4047 +Gimeno-Nogues+ (LVLN, WISC, LEUV, ETH, MASA)
STERNER 93 PL B303 385 +Abashian, Gotow, Haim, Mattson, Morgan+(AMY Collab.)
ABE 92B PRL 68 1463 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABREU 92D ZPHY C53 555 +Adam, Adami, Adye, Akesson, Alekseev+(DELPHI Collab.)
ABREU 92F PL B275 222 +Adam, Adami, Adye, Akesson, Alekseev+(DELPHI Collab.)
ADRIANI 92F PL B292 472 +Aguilar-Benitez, Ahlen, Akbari, Alcarez+ (L3 Collab.)
ALITTI 92E PL B274 507 +Ambrosini, Ansari, Autiero, Bareyre+ (UA2 Collab.)
DECAMP 92 PRPL 216 253 +Deschizeaux, Goy, Lees, Minard+ (ALEPH Collab.)
DELAGUILA 92 NP B372 3 del Aguila+ (CERN, GRAN, MPIM, BRUXT, MADE)
Also 91C NP B361 45 del Aguila, Moreno, Quiros (BARC, MADE)
IMAZATO 92 PRL 69 877 +Kawashima, Tanaka+ (KEK, INUS, TOKY, TOKMS)
LANGACKER 92B PR D45 278 +Luo (PENN)
LAYSSAC 92 ZPHY C53 97 +Renard, Verzegnassi (MONP, LAPP)
LAYSSAC 92B PL B287 267 +Renard, Verzegnassi (MONP, TRSTT)
LEIKE 92 PL B291 187 +Riemann, Riemann (BERL, CERN)
LEP 92 PL B276 247 +ALEPH, DELPHI, L3, OPAL (LEP Collabs.)
MISHRA 92 PRL 68 3499 +Leung, Arroyo+ (COLU, CHIC, FNAL, ROCH, WISC)
POLAK 92 PL B276 492 +Zralek (SILES)
POLAK 92B PR D46 3871 +Zralek (SILES)
RENTON 92 ZPHY C56 355 (OXF)
ABE 91D PRL 67 2418 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ABE 91F PRL 67 2609 +Amidei, Apollinari, Atac, Auchincloss+ (CDF Collab.)
ACTON 91 PL B268 122 +Alexander, Allison, Allport+ (OPAL Collab.)
ACTON 91B PL B273 338 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ADEVA 91B PL B261 169 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ADEVA 91D PL B262 155 +Adriani, Aguilar-Benitez, Akbari, Alcaraz+ (L3 Collab.)
ALEXANDER 91 PL B263 123 +Allison, Allport, Anderson, Arcelli+ (OPAL Collab.)
ALITTI 91 ZPHY C49 17 +Ansari, Ansorge, Autiero, Bareyre+ (UA2 Collab.)
ALTARELLI 91 PL B261 146 +Casalbuoni, De Curtis+ (CERN, FIRZ, GEVA)
ALTARELLI 91B PL B263 459 +Casalbuoni, De Curtis+ (CERN, FIRZ, GEVA)
Also 90 PL B245 669 Altarelli, Casalbuoni, Feruglio, Gatto(CERN, LECE, GEVA)
AQUINO 91 PL B261 280 +Fernandez, Garcia (CINV, PUEB)
BUCHMUEL... 91 PL B267 395 Buchmueller, Greub, Minkowski (DESY, BERN)
COLANGELO 91 PL B253 154 +Nardulli (BARI)
CUYPERS 91 PL B259 173 +Falk, Frampton (DURH, HARV, UNCCH)
DELAGUILA 91 PL B254 497 del Aguila, Moreno, Quiros (BARC, MADE, CERN)
FARAGGI 91 MPL A6 61 +Nanopoulos (TAMU)
GEIREGAT 91 PL B259 499 +Vilain, Wilquet, Binder, Burkard+ (CHARM II Collab.)
GONZALEZ-G... 91 PL B259 365 Gonzalez-Garcia, Valle (VALE)
Also 90C NP B345 312 Gonzalez-Garcia, Valle (VALE)
MAHANTHAP... 91 PR D43 3093 Mahanthappa, Mohapatra (COLO)
Also 91B PR D44 1616 erratum Mahanthappa, Mohapatra (COLO)
POLAK 91 NP B363 385 +Zralek (SILES)
RIZZO 91 PR D44 202 (WISC, ISU)
WALKER 91 APJ 376 51 +Steigman, Schramm, Olive+ (HSCA, OSU, CHIC, MINN)
ABE 90F PL B246 297 +Amako, Arai, Asano, Chiba+ (VENUS Collab.)
ABE 90G PRL 65 2243 +Amidei, Apollinari, Atac+ (CDF Collab.)
ABE 90H PR D41 1722 +Amidei, Apollinari, Ascoli, Atac+ (CDF Collab.)
AKRAWY 90J PL B246 285 +Alexander, Allison, Allport, Anderson+ (OPAL Collab.)
ALLEN 90 PRL 64 1330 +Chen, Doe+ (UCI, LASL, UMD)
ANTREASYAN 90C PL B251 204 +Bartels, Besset, Bieler, Bienlein+ (Crystal Ball Collab.)
BARGER 90B PR D42 152 +Hewett, Rizzo (WISC, ISU)
GLASHOW 90 PR D42 3224 +Sarid (HARV)
GLASHOW 90B PRL 64 725 +Sarid (HARV)
GONZALEZ-G... 90D PL B240 163 Gonzalez-Garcia, Valle (VALE)
GRIFOLS 90 NP B331 244 +Masso (BARC)
GRIFOLS 90C MPL A5 2657 (BARC)
GRIFOLS 90D PR D42 3293 +Masso, Rizzo (BARC, CERN, WISC, ISU)
HAGIWARA 90 PR D41 815 +Najima, Sakuda, Terunuma (KEK, DURH, YCC, HIRO)
HE 90B PL B240 441 +Joshi, Volkas (MELB)
Also 90C PL B244 580 erratum He, Joshi, Volkas (MELB)
KIM 90 PL B240 243 +Breedon, Ko, Lander, Maeshima, Malchow+(AMY Collab.)
LOPEZ 90 PL B241 392 +Nanopoulos (TAMU)
ALBAJAR 89 ZPHY C44 15 +Albrow, Allkofer, Arnison, Astbury+ (UA1 Collab.)
ALBRECHT 89 ZPHY C42 349 +Boeckmann, Glaeser, Harder+ (ARGUS Collab.)
BARBIERI 89B PR D39 1229 +Mohapatra (PISA, UMD)
DELAGUILA 89 PR D40 2481 del Aguila, Moreno, Quiros (BARC, MADE)
Also 90B PR D41 134 del Aguila, Moreno, Quiros (BARC, MADE)
Also 90C PR D42 262 erratum del Aguila, Moreno, Quiros (BARC, MADE)
DORENBOS... 89 ZPHY C41 567 Dorenbosch, Udo, Allaby, Amaldi+ (CHARM Collab.)
GEIREGAT 89 PL B232 539 +Vilain, Wilquet, Bergsma, Binder+ (CHARM II Collab.)
LANGACKER 89B PR D40 1569 +Uma Sankar (PENN)
ODAKA 89 JPSJ 58 3037 +Kondo, Abe, Amako+ (VENUS Collab.)
ROBINETT 89 PR D39 834 (PSU)
ALBAJAR 88B PL B209 127 +Albrow, Allkofer, Astbury, Aubert+ (UA1 Collab.)
BAGGER 88 PR D37 1188 +Schmidt, King (HARV, BOST)
BALKE 88 PR D37 587 +Gidal, Jodidio+ (LBL, UCB, COLO, NWES, TRIU)
BERGSTROM 88 PL B212 386 (STOH)
COSTA 88 NP B297 244 +Ellis, Fogli+ (PADO, CERN, BARI, WISC, LBL)
CUYPERS 88 PRL 60 1237 +Frampton (UNCCH)
DONCHESKI 88 PL B206 137 +Grotch, Robinett (PSU)
DONCHESKI 88B PR D38 412 +Grotch, Robinett (PSU)
ELLIS 88 PL B202 417 Ellis, Franzini, Zwirner (CERN, UCB, LBL)
RAFFELT 88 PRL 60 1793 +Seckel (UCB, LLL, UCSC)
AMALDI 87 PR D36 1385 +Bohm, Durkin, Langacker+ (CERN, AACH3, OSU+)
ANSARI 87D PL B195 613 +Bagnaia, Banner+ (UA2 Collab.)
BARTEL 87B ZPHY C36 15 +Becker, Felst+ (JADE Collab.)
MARCIANO 87 PR D35 1672 +Sirlin (BNL, NYU)
ARNISON 86B EPL 1 327 +Albrow, Allkofer+ (UA1 Collab.)
BARGER 86B PRL 56 30 +Deshpande, Whisnant (WISC, OREG, FSU)
BEHREND 86B PL B178 452 +Buerger, Criegee, Fenner, Field+ (CELLO Collab.)
DERRICK 86 PL 166B 463 +Gan, Kooijman, Loos+ (HRS Collab.)
Also 86B PR D34 3286 Derrick, Gan, Kooijman, Loos, Musgrave+ (HRS Collab.)
DURKIN 86 PL 166B 436 +Langacker (PENN)
ELLIS 86 PL 167B 457 +Enqvist, Nanopoulos, Sarkar (CERN, OXFTP)
JODIDIO 86 PR D34 1967 +Balke, Carr, Gidal, Shinsky+ (LBL, NWES, TRIU)
Also 88 PR D37 237 erratum Jodidio, Balke, Carr+ (LBL, NWES, TRIU)
MOHAPATRA 86 PR D34 909 (UMD)
STEIGMAN 86 PL B176 33 +Olive, Schramm, Turner (BART, MINN+)
ADEVA 85 PL 152B 439 +Becker, Becker-Szendy+ (Mark-J Collab.)
ADEVA 85B PRL 55 665 +Becker, Becker-Szendy+ (Mark-J Collab.)
BERGER 85B ZPHY C27 341 +Deuter, Genzel, Lackas, Pielorz+ (PLUTO Collab.)
STOKER 85 PRL 54 1887 +Balke, Carr, Gidal+ (LBL, NWES, TRIU)
ADEVA 84 PRL 53 134 +Barber, Becker, Berdugo+ (Mark-J Collab.)
BEHREND 84C PL 140B 130 +Burger, Criegee, Fenner+ (CELLO Collab.)
ARNISON 83D PL 129B 273 +Astbury, Aubert, Bacci+ (UA1 Collab.)
BERGSMA 83 PL 122B 465 +Dorenbosch, Jonker+ (CHARM Collab.)
CARR 83 PRL 51 627 +Gidal, Gobbi, Jodidio, Oram+ (LBL, NWES, TRIU)
DESHPANDE 83 PR D27 1193 +Johnson (OREG)
BEALL 82 PRL 48 848 +Bander, Soni (UCI, UCLA)
SHANKER 82 NP B204 375 (TRIU)
DIMOPOUL... 81 NP B182 77 Dimopoulos, Raby, Kane (STAN, MICH)
RIZZO 81 PR D24 704 +Senjanovic (BNL)
STEIGMAN 79 PRL 43 239 +Olive, Schramm (BART, EFI)

Searches for Axions (A^0) and Other Very Light Bosons

NOTE ON AXIONS

In this section we list limits for very light neutral (pseudo) scalar bosons that couple weakly to stable matter. Typical examples are pseudo-Goldstone bosons like axions (A^0) [1], familons [2], and Majorons [3], associated, respectively, with spontaneously broken Peccei-Quinn [4], family, and lepton-number symmetries.

Peccei-Quinn symmetry gives a natural solution to the strong CP-violation problem. Axion mass and its coupling to stable particles are inversely proportional to the scale of the Peccei-Quinn symmetry breaking f_A. The original axion model [1,4] assumes f_A =v, where $v = (\sqrt{2}G_F)^{-1/2} = 247$ GeV is the scale of the electroweak symmetry breaking, and has two Higgs doublets as minimal ingredients. By requiring tree-level flavor conservation, the axion mass and its couplings are completely fixed in terms of one parameter, the ratio of the vacuum expectation values of two Higgs fields. The result of extensive experimental searches for such an axion have been negative [5].

One way to avoid these experimental constraints is to make A^0 sufficiently massive. This is achieved by introducing a new strong interaction (QC$'$D) with $\Lambda_{\mathrm{QC'D}} \gg \Lambda_{\mathrm{QCD}}$, whose anomaly couples to the axion [7]. A^0 can receive significant mass from the QC$'$D sector if QC$'$D colored quarks are massive. However one needs an explanation why $|\theta_{\mathrm{QCD}} - \theta_{\mathrm{QC'D}}| < 10^{-9}$ in this scenario.

Another way to save the Peccei-Quinn idea is to introduce a new scale $f_A \gg v$. Then the A^0 mass becomes smaller and its coupling weaker, thus one can easily avoid all the existing experimental limits; such models are called invisible axion models [8,9]. Various invisible axion models can be