BROKEN $U(1)$ SYMMETRY

and new LIGHT neutral BOSONS

in ψ and Υ decays

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One usually expects new physics at **very high energies :**

B-E-Higgs bosons / origin of mass ...

supersymmetry, grand unification,

new spacetime dimensions ...

$\Longrightarrow$

Explore the high-energy frontier

at

(LEP) FermiLab, LHC , ILC ...

But another frontier exists at lower energies !

Search for relatively light

weakly (or very weakly) coupled new particles

ψ and Υ decays offer great possibilities

to search for new light particles,

which would have stayed unobserved

due to their (very) weak couplings.

Under which circumstances should we expect new light particles ?

Would they have anything to do with

other constructions discussed for higher energies (Susy, etc.) ?

Discuss :

new neutral spin-1 or spin-0 particles

coupled to quarks and leptons.

in a general way, but also **within the context of a larger framework**

But why should / how could such particles be light ??

A **spin-1 gauge boson** *(massless from gauge invariance)*

may be light if spont. broken gauge symmetry,

with small gauge coupling *(or symmetry breaking scale)*

A **spin-0 boson**

(massless from Goldstone theorem, if spontaneously broken global symmetry)

may acquire a small mass if small explicit breaking of global symmetry

$$\Longrightarrow$$

Consider *(spontaneously or explicitly)*

broken *local or global* $U(1)$ **symmetries**

(for the moment, independently of supersymmetry)

What could be such broken $U(1)$ symmetries ?

$\boldsymbol{B}$? $\boldsymbol{L}$? $\boldsymbol{B-L}$? $\boldsymbol{Y}$? *(or a combination)* **?**

Other $\boldsymbol{U(1)}$ symmetries ? *(none in SM ...)*

$\Longrightarrow$

Extend the Standard Model, to allow for new particles, and

new (broken) $\boldsymbol{U(1)}$ SYMMETRIES ...

(local or global ...)

Starting point: *Nucl. Phys. B 90, 104, 1975*

electroweak symmetry breaking in SUSY, with

$\boxed{\textbf{two}}$ **Brout-Englert-Higgs doublets**

$$\varphi_{SM} \ \rightarrow \ \{\, \varphi'', \ \varphi' \,\}$$

$\rightarrow$ $\boldsymbol{h_1}$ **and** $\boldsymbol{h_2}$ **of** **SUSY extensions of the standard model**

$$\boxed{\boldsymbol{h_1} \ = \ \begin{pmatrix} \boldsymbol{h_1^\circ} \\ \boldsymbol{h_1^-} \end{pmatrix} \ , \quad \boldsymbol{h_2^c} \ = \ \begin{pmatrix} -\,\boldsymbol{h_2^{\circ *}} \\ \boldsymbol{h_2^-} \end{pmatrix} \rightarrow \ \boldsymbol{h_2} \ = \ \begin{pmatrix} \boldsymbol{h_2^+} \\ \boldsymbol{h_2^\circ} \end{pmatrix}}$$

allows for the possibility of *rotating independently the two doublets*, *i.e. :*

$\rightarrow$ *a possible* *new $U(1)$ symmetry* *acting on the two doublets as*

$$\boxed{\boldsymbol{h_1 \longrightarrow e^{i\alpha}\, h_1\,,\quad h_2^c \to e^{-i\alpha}\, h_2^c \;\to\; h_2 \longrightarrow e^{i\alpha}\, h_2}}$$

introduced in 2-higgs-doublet model in Nucl. Phys. B 78, 14 (1974)

(often known as 'PQ-symmetry')

constraining **interaction potential** *and* **Yukawa couplings**

Not all terms compatible with Lorentz and gauge symmetries are allowed

further restrictions due to additional symmetry ...

also reminiscent of

R-symmetry

of supersymmetric theories,

and actually was at the origin of R *symmetry ...*

$U(1)$ *symmetry*, *called* Q, *decomposed as*

$$\boxed{Q \;=\; R\; U}$$

the continuous R*-symmetry* *does not act on* h_1 *and* h_2

so that it can survive electroweak breaking, while Q *and* U *get broken*

(R *will later act on superpartners)*

under U *:* $$\boxed{h_1 \rightarrow e^{i\alpha}\, h_1\,, \quad h_2 \rightarrow e^{i\alpha}\, h_2}$$

U *symmetry* *will act* **axially** **on quarks and leptons**

(axial $U(1)$, *also known as* $U(1)_{PQ}$ *)*

It commutes with the Susy generator

while R *and* Q *do not commute with Susy*

Allowed quartic interactions in $V(h_1, h_2)$:

$$(h_1^\dagger h_1)^2, \quad (h_2^\dagger h_2)^2, \quad (h_1^\dagger h_1)\,(h_2^\dagger h_2), \quad |\, h_1 h_2\,|^2$$

if only one Higgs v.e.v., we get an "inert doublet model"

but we are interested in **2-Higgs v.e.v.'s :**

$$< h_1^\circ > = \frac{v_1}{\sqrt{2}} \;, \quad < h_2^\circ > = \frac{v_2}{\sqrt{2}} \;, \; \textit{with} \;\; \tan\beta = \frac{v_2}{v_1}$$

(mixing angle β initially called δ in 74)

With SUSY these (already restricted) quartic Higgs interactions

appear as **electroweak gauge interactions,** *with*

$$\boxed{V_{\text{quartic}} = \frac{g^2+g'^2}{8}\,(h_1^\dagger h_1 - h_2^\dagger h_2)^2 + \frac{g^2}{2}\,|h_1^\dagger h_2|^2}$$

$=$ **quartic Higgs potential of the MSSM**

Quartic Higgs couplings fixed by electroweak gauge couplings !

at the origin of mass inequality

m *(lightest Higgs)* $\leq$ m_Z + **rad. corr.** *in MSSM*

(potentially problematic, as it requires radiative correction effects to be rather large)

The “ μ problem”, in 1974

There is also a μ *term :* $\mu\, H_1 H_2$ **mass term in superpotential**

$$\Longrightarrow \quad \mu^2 \, (\, |h_1|^2 \, + \, |h_2^2| \,) \, , \quad or \quad \sum_{1,2} \left| \, \boldsymbol{\mu^2 \, \pm \, \xi \, \frac{g'}{2}} \, \right| \, | \, \boldsymbol{h_i^2} \, |$$

$\boldsymbol{\mu}$ term a problem to get correct electroweak breaking with 2-Higgs doublet v.e.v.’s !

(at classical level)

Get rid of the μ term by making it dynamical

generates extra term $\boldsymbol{\propto \; m_3^2 \; \Re \, (h_1 \, h_2)}$ *in the potential at the origin* $\Longrightarrow$

$$< h_1^\circ > \; = \; \frac{v_1}{\sqrt{2}} \neq 0 \, , \quad < h_2^\circ > \; = \; \frac{v_2}{\sqrt{2}} \neq 0 \; ,$$

(both μ and m_3^2 terms break explicitly the U symmetry $\Longrightarrow$ no massless axionlike particle (A) here:

it gets its mass from m_3^2 i.e. from trilinear λ coupling)

Make μ parameter of MSSM dynamical, taken to be superfield $\mu(x,\theta)$:

superpotential: $$\boxed{\mu\ H_1\, H_2 \ \longrightarrow\ \lambda\ H_1\, H_2\, S}$$

trilinear coupling with extra singlet superfield S

(Nucl. Phys. B 90, 104, 1975)

(+ possible $f(S)$ superpotential terms,

depending on the other $U(1)$ symmetries imposed)

$\longrightarrow$ **N/nMSSM, or USSM if an extra $U(1)$ symmetry is gauged**

(Phys.Lett. B 69, 489, 1977)

$$\boxed{\begin{aligned}\mathcal{W} \ =\ & \lambda_e\, H_1.\bar{E}\, L \ +\ \lambda_d\, H_1.\bar{D}\, Q \ -\ \lambda_u\, H_2.\bar{U}\, Q \\ & + \lambda\, H_1 H_2\, S \ +\ \underbrace{\frac{\kappa}{3}\, S^3 \ +\ \frac{\mu_S}{2}\, S^2 \ +\ \sigma\ S}_{f(S)}\end{aligned}}$$

This extra-$U(1)$ symmetry acts as

$$\boxed{\begin{array}{c} H_1 \xrightarrow{U} e^{i\alpha} H_1\,, \quad H_2 \xrightarrow{U} e^{i\alpha} H_2\,, \quad S \xrightarrow{U} e^{-2i\alpha} S \\[2ex] (Q, \bar{U}, \bar{D};\; L, \bar{E}) \xrightarrow{U} e^{-i\frac{\alpha}{2}} (Q, \bar{U}, \bar{D};\; L, \bar{E}) \end{array}}$$

for the superpotential to be invariant.

(acts axially on quarks and leptons, as a PQ symmetry)

What is the fate of this extra-$U(1)$ symmetry, global or local,

broken explicitly

(by small superpotential terms and/or small soft susy-breaking terms)

or spontaneously

through the 2 Higgs doublets and possibly a large Higgs singlet v.e.v. ?

It may be gauged, or not ...

New neutral gauge boson U

possibly light if the extra-$U(1)$ gauge coupling is small

or new **light spin-0 'axionlike' pseudoscalar quasiGoldstone boson a**

associated with small explicit breaking of extra-$U(1)$ symmetry

Goldstone eaten by Z*:* *Im* $(\cos\beta\, h_1^\circ - \sin\beta\, h_2^\circ)$

$\perp$ *combination:*

$$\boxed{A \;=\; \sqrt{2}\;\mathrm{Im}\,(\,\sin\beta\, h_1^\circ + \cos\beta\, h_2^\circ\,)}$$

(cf. standard axion, or (light) A of MSSM)

In the presence of a (possibly large) singlet v.e.v.:
pseudoscalar Goldstone or quasi-Goldstone boson $\boldsymbol{a}$ *:*

$$\boxed{a \;=\; \cos\zeta\;\left(\sqrt{2}\;\mathrm{Im}\,(\sin\beta\, h_1^\circ + \cos\beta\, h_2^\circ\right) + \;\sin\zeta\;(\,\sqrt{2}\;\mathrm{Im}\; s\,)}$$

$r \;=\; \cos\zeta$ **= invisibility parameter**

would-be "axion" $a \;=\;$ **mixing of doublet and singlet components**

PLB 95, 285, 1980; NPB 187, 184, 1981

(allows to reduce strength or effective strength of U *or* a *interactions, cf. "invisible axion")*

It may either acquire a small mass if extra-$U(1)$ symmetry gets explicitly broken

or gets eaten into the third degree of freedom of a new neutral gauge boson U,

if extra-$U(1)$ symmetry is local and spontaneously broken.

SEARCHING FOR A NEW LIGHT GAUGE BOSON

NPB 187, 184, 1981, ... , PRD 74, 054034 (2006); 75, 115017 (2007); PLB 675, 267 (2009)

The amplitude for producing a new gauge boson (U) is proportional

to the new gauge coupling constant, g"

$$\mathcal{A}\,(\,A\ \rightarrow\ B\ +\ U_{\text{long}}\,)\ \propto\ g\text{"}\ \ldots$$

g" may be very small !!

Is such a gauge boson unobservable,

if its gauge coupling is extremely small ?

NO !

For the longitudinal polarisation state of a light gauge boson

$$\epsilon_L^\mu \simeq \frac{k^\mu}{m_U}$$

gets singular when $g" \to 0$ **, as** $m_U \propto g"$ **...** $\to 0$ **as well !**

$$\boxed{\mathcal{A}\,(\,A \to B + U_{\rm long}\,) \;\propto\; g"\,\frac{k_U^\mu}{m_U} < B\,|J_{\mu\,U}|\,A > \;=\; \frac{1}{F_U}\;k_U^\mu\; < B\,|J_{\mu\,U}|\,A >}$$

$$k^\mu\,\bar\psi\,\gamma_\mu\gamma_5\,\psi \;\to\; 2\,m_q\,\psi\,\gamma_5\,\psi$$

A very light U boson does not decouple in the limit of very small gauge coupling !

behaves as "eaten-away" pseudoscalar Golstone boson a associated with the sp. breaking of the global $U(1)$.

effective pseudoscalar coupling:
$$\boxed{f_{q,l\;P} \;=\; f_{q,l\;A}\;\frac{2\,m_{q,l}}{m_U}}$$

in the low mass and low coupling regime:

A light spin-1 gauge boson behaves very much

as a quasi-massless spin-0 particle,

i.e. as corresponding spin-0 Goldstone boson ...

with pseudoscalar couplings to quarks and leptons

"Equivalence theorem"

similar to "Equivalence theorem of supersymmetry"

very light spin-$\frac{3}{2}$ *gravitino behaves as spin-*$\frac{1}{2}$ *goldstino of sp. broken global susy*

(cf. "GMSB" models ...)

Consequence:

$$\boxed{B(\Upsilon \to \gamma\, U) \;\simeq\; B(\Upsilon \to \gamma\, a)}$$

The same experiment may be used to search for

light spin-1 neutral gauge bosons,

as well as light spin-0 pseudoscalars.

(but remember: standard axion excluded ...)

Decay modes:

$$\boxed{\left\{ \begin{array}{l} U \;\to\; \nu\bar\nu \;\text{ (or light dark matter particles)} \\ U \;\to\; e^+e^-,\;\; \mu^+\mu^-,\; \dots \text{ (depending on } m_U) \end{array} \right.}$$

$\Rightarrow$ **search for**

$$\left\{ \begin{array}{l} \Upsilon \to \gamma + \textit{invisible} \\ \Upsilon \to \gamma + e^+e^- \\ \Upsilon \to \gamma + \mu^+\mu^- \\ \quad \ldots \end{array} \right.$$

as possible signal for either

spin-1 U boson,

or spin-0 pseudoscalar particle a

(or also scalar)

Determining the couplings:

couplings of h_1° *and* h_2° *to* $q,\ l$ *:* $\dfrac{m\sqrt{2}}{v\ \cos\beta}\,,\quad \dfrac{m\sqrt{2}}{v\ \sin\beta}$

with $v = 2^{-1/4}\,G_F^{-1/2} \simeq 246$ *GeV*

Pseudoscalar couplings of $A \;=\; \sqrt{2}\,\mathbf{Im}\,(\,\sin\beta\,h_1^\circ + \cos\beta\,h_2^\circ\,)$

$$\begin{cases} (m/v)\times(\tan\beta = 1/x) & \textbf{(charged leptons and } d \textbf{ quarks)} \\ (m/v)\times(\cot\beta = x) & \textbf{(u quarks)} \end{cases}$$

i.e. pseudoscalar couplings of standard axion (or A **of MSSM)**

$$\boxed{2^{\frac{1}{4}}\,G_F{}^{\frac{1}{2}}\,m_{q,l}\ \times\ (\tan\beta\ \ \textbf{or}\ \ \cot\beta).}$$

When A *mixes with Im* s *into doublet/singlet pseudoscalar combination* a
associated with extra-$U(1)$ *breaking,*
we get the pseudoscalar (or effective pseudoscalar) couplings,
now also proportional the invisibility parameter $r = \cos\zeta$.

Pseudoscalar coupling

$$f_{q,l\ P} \simeq \underbrace{2^{\frac{1}{4}}\, G_F{}^{\frac{1}{2}}\, m_{q,l}}_{4\ 10^{-6}\, m_{q,l}(\mathrm{MeV})} \times \begin{cases} r\, x = \cos\zeta\ \cot\beta & (u,\ c,\ t) \\ r/x = \cos\zeta\ \tan\beta & (d,\ s,\ b;\ e,\ \mu,\ \tau) \end{cases}$$

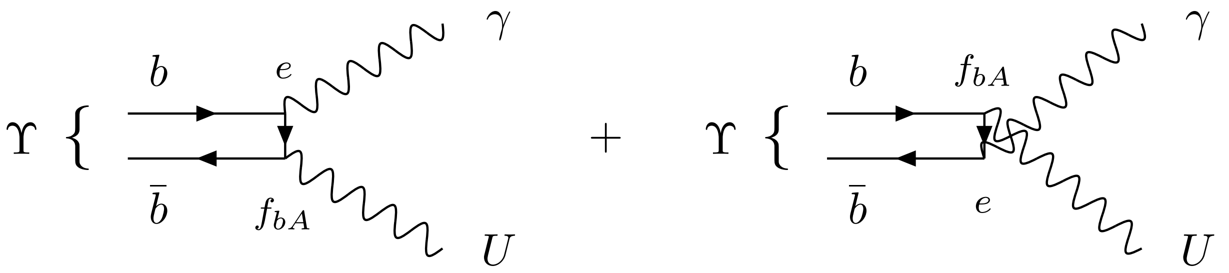
Equivalent axial coupling

$$f_{q,l\ A} \simeq \underbrace{2^{-\frac{3}{4}}\ G_F{}^{\frac{1}{2}}\ m_U}_{2\ 10^{-6}\, m_U(\mathrm{MeV})} \times \begin{cases} r\, x = \cos\zeta\ \cot\beta & (u,\ c,\ t) \\ r/x = \cos\zeta\ \tan\beta & (d,\ s,\ b;\ e,\ \mu,\ \tau) \end{cases}$$

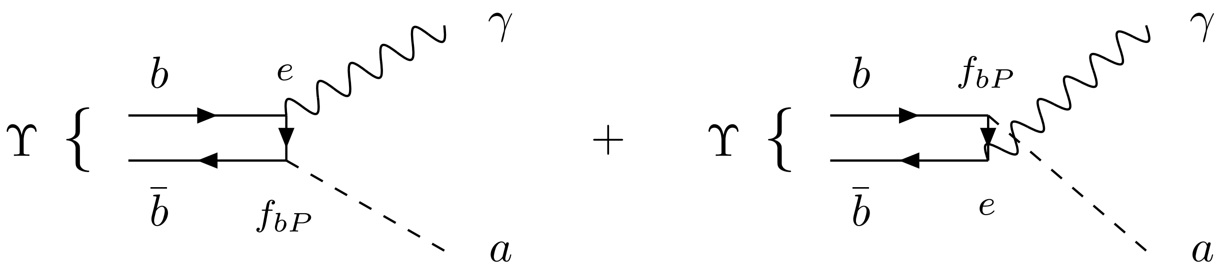
ratio: $2\ \dfrac{m_{q,l}}{m_U}$

$r = \cos\zeta =$ *invisibility parameter* $\qquad \tan\beta = \frac{v_2}{v_1}$

ψ and Υ DECAYS



$\Upsilon \to \gamma\, U$ induced by the axial coupling f_{bA}. For a light U the amplitude is essentially the same as for a spin-0 a with pseudoscalar coupling $f_{bP} = f_{bA}\, \frac{2\, m_b}{m_U}$.



Production of a spin-0 pseudoscalar in $\Upsilon \to \gamma\, a$.

$$\frac{B(\text{onium} \to \gamma\, U/a)}{B(\text{onium} \to \mu^+\mu^-)} = \frac{2\, f_{qP}^{\,2}}{e^2} = \frac{G_F\, m_q^2}{\sqrt{2}\,\pi\,\alpha} \left(r^2 x^2 \;\; \text{or} \;\; \frac{r^2}{x^2} \right)$$

$$\Longrightarrow$$

$$\boxed{\begin{aligned} \frac{B(\psi \to \gamma\, U/a)}{B(\psi \to \mu^+\mu^-)} &= \frac{G_F\, m_c^2}{\sqrt{2}\,\pi\alpha}\; r^2\, x^2\;\, C_\psi\, F_\psi \;\simeq\; 8\; 10^{-4}\;\, r^2\, x^2\;\, C_\psi\, F_\psi \\ \frac{B(\Upsilon \to \gamma\, U/a)}{B(\Upsilon \to \mu^+\mu^-)} &= \frac{G_F\, m_b^2}{\sqrt{2}\,\pi\alpha}\; \frac{r^2}{x^2}\;\, C_\Upsilon\, F_\Upsilon \;\simeq\; 8\; 10^{-3}\; \frac{r^2}{x^2}\;\, C_\Upsilon\, F_\Upsilon \end{aligned}}$$

(F phase space factor; $C \gtrsim \frac{1}{2}$ for QCD radiative and rel. corrections)

$$\Longrightarrow$$

$$\boxed{\begin{aligned} B\,(\,\psi \;\to\; \gamma\;\, U/a\,) &\simeq\;\; 5\;\; 10^{-5}\;\;\; \cos^2\zeta\; \cot^2\beta\;\;\; C_\psi\, F_\psi \\ B\,(\,\Upsilon \;\to\; \gamma\;\, U/a\,) &\simeq\;\; 2\;\; 10^{-4}\;\;\; \cos^2\zeta\; \tan^2\beta\;\;\; C_\Upsilon\, F_\Upsilon \end{aligned}}$$

ψ DECAYS

$$B\,(\,\psi \to \gamma + \textbf{invisible}\,) < 1.4\;10^{-5} \quad \textit{(1982)} \quad \Longrightarrow$$

$$rx = \cos\zeta\ \cot\beta\ <\ .75/\sqrt{B_{\rm inv}} \quad \Longleftrightarrow$$

$$\boxed{\left\{ \begin{array}{c} |f_{cA}| < 1.5\;10^{-6}\; m_U(\textbf{MeV})/\sqrt{B_{\rm inv}} \\[2ex] |f_{cP}| < 5\;10^{-3}/\sqrt{B_{\rm inv}}\;, \quad |f_{cS}| < 10^{-2}/\sqrt{B_{\rm inv}} \end{array} \right.}$$

Υ DECAYS

PLB 675, 267 (2009)

CLEO, BABAR

BABAR: *hep-ex/0808.0017*

Limit on $\Upsilon \to \gamma +$ invisible improved with $\Upsilon(3S)$ by more than 4

prel. limit from 3.2 *to* $3.5\ 10^{-6}$ *for neutral mass 0 to 1 GeV, down to* $.7\ 10^{-6}$ *for 3 GeV,*

and $< 4\ 10^{-6}$ *up to 6 GeV.*

$$r/x = \cos\zeta\ \tan\beta\ <\ .2/\sqrt{B_{\rm inv}} \quad \Longleftrightarrow$$

$$\boxed{|f_{bA}| < 4\ 10^{-7}\ m_U(\mathit{MeV})/\sqrt{B_{\rm inv}}\ , \quad \mathit{or}\ \ |f_{bP}| < 4\ 10^{-3}/\sqrt{B_{\rm inv}}}$$

takes into account invisible B.R. of the new boson

valid up to $\simeq$ 5 GeV *(as long as invisible decay modes are present)*

For an invisibly decaying boson:

limit on pseudoscalar (or effective pseudoscalar) coupling

$$f_{bP} < 4\,10^{-3}$$

5 times smaller than standard Higgs coupling to b**,** $m_b/v \simeq 2\,10^{-2}$

For a scalar coupling,

$$|f_{bS}| < 6\,10^{-3}/\sqrt{B_{\rm inv}}$$

Υ *limit* $\Longrightarrow$

$$\boxed{\textit{doublet fraction:} \quad \boldsymbol{r^2 = \cos^2\zeta \; < \; 4\,\% \,/\, (\tan^2\beta\, B_{\rm inv}) \;\; ,}}$$

(stronger than ψ *limit for* $\tan\beta > .5$*), requires*

a *(*$< 4\,\%$ *doublet,* $> 96\,\%$ *singlet) for* $\tan\beta > 1$*; and* $< .5\,\%$ *doublet for* $\tan\beta > 3$*, for invisible decays of the new boson.*

Dependence on $B_{\rm inv}$ *disappears for the production, in radiative decays of the* ψ*, of a new boson decaying invisibly.*

Non-observation of a signal in $\Upsilon \to \gamma +$ *invisible neutral* $\Longrightarrow$

$$\boxed{\boldsymbol{B\,(\,\psi \to \gamma \; + \; \textit{neutral}\,) \;\; B_{\rm inv} \;\; \lesssim \;\; 10^{-6} /\, \tan^4\beta \;\; ,}}$$

i.e. $\lesssim 10^{-8}$ *for* $\tan\beta \gtrsim 3$, independently of the invisible branching ratio $B_{\rm inv}$ *(also applicable, to a scalar particle).*

Consequences for couplings to LEPTONS

implications for the couplings of the new spin-1 or spin-0 boson to e, μ *or* τ. *!!*

Universality of the axial coupling of the U

family-independent and identical for all charged leptons and d *quarks.*
(from gauge invariance of Yukawa couplings responsible for m_l, m_q *in a 2-HD model)*

$$\boxed{f_{eA} = f_{\mu A} = f_{\tau A} = f_{dA} = f_{sA} = f_{bA}}$$

It also reflects that the couplings of the corresponding pseudoscalar a *to* d *quarks and* l^- *are proportional to masses :*

$$\boxed{f_{eP} = f_{bP}\ \frac{m_e}{m_b}}$$

$\Longrightarrow$ *limit on* f_{bA} *also applies to* f_{eA} *:*

$$\boxed{|f_{eA}|\ <\ 4\ 10^{-7}\ m_U(\mathit{MeV})\,/\sqrt{B_{\rm inv}}\ ,\qquad |f_{eP}|\ <\ 4\ 10^{-7}\,/\sqrt{B_{\rm inv}}}$$

for invisible decays of the new boson:
Limit on pseudoscalar coupling f_{eP} *5 times smaller than the standard Higgs coupling to the electron,* $m_e/v \simeq 2\ 10^{-6}$,

As scalar couplings are also proportional to masses, with $f_{eS} = f_{bS}\ m_e/m_b$, *the limit on* $|f_{eP}|$, *slightly relaxed, may be applied to a scalar coupling.*

$$\boxed{|f_{eS}| \ < \ 6\ 10^{-7}/\sqrt{B_{\rm inv}}}$$

For a spin-1 U *the strong limit on* f_{eA} *agrees with atomic physics parity-violation experiments (strong limit on* $|f_{eA}\, f_{qV}|$*).*

$$\sqrt{|f_{eA}\, f_{qV}|} \ < \ 10^{-7}\, m_U(\textit{MeV})$$

$\Longrightarrow \ e^+e^- \to \gamma\, U$ *annihilation cross section, roughly* $\propto\ (f_{eV}^2 + f_{eA}^2)$,

very small for a light U, *unless* $f_{eV} \gg f_{eA}$.

$$\boxed{\Upsilon\ \textbf{DECAYS} \rightarrow\ \gamma + (\mu^+\mu^-)}$$

BABAR: arXiv:hep-ex/0902.2176

$B\,(\Upsilon \rightarrow \gamma + \textit{neutral}\,)\ B_{\mu\mu}\ \lesssim\ 2\ 10^{-6}$ *in most of the mass range considered*
(compared to $B\,(\Upsilon \rightarrow \gamma + \textit{neutral}\,)\ B_{\text{inv}}\ \lesssim\ 3.5\ 10^{-6}$*)*

$$r/x = \cos\zeta\ \tan\beta\ \lesssim\ .15/\sqrt{B_{\mu\mu}}\quad \Longrightarrow$$

$$\boxed{\begin{array}{c} |f_{bA}|\ \lesssim\ 3\ 10^{-7}\ m_U(\text{MeV})/\sqrt{B_{\mu\mu}} \\[1em] |f_{bP}|\ \lesssim\ 3\ 10^{-3}/\sqrt{B_{\mu\mu}}\,,\quad \textit{or}\quad |f_{bS}|\ \lesssim\ 5\ 10^{-3}/\sqrt{B_{\mu\mu}} \end{array}}$$

(for $B_{\mu\mu} \simeq 1$*, lim. on* f_{bP} *is* $\simeq 15\,\%$ *of SM Higgs coupling to* b*).*

May be or not more constraining that invisible decays, depending on whether $B_{\mu\mu}$ *is larger than* $\approx B_{\text{inv}}$*.*

(e.g. $B_{\text{inv}} \approx 16\,\%$ *and* $B_{\mu\mu} \approx 10\,\%$*, for a 1 GeV* U*, ignoring light dark matter particles).*

$$\boxed{\textit{doublet fraction:}\quad \boldsymbol{r^2 = \cos^2\zeta \ \lesssim\ 2\,\%\,/\,(\tan^2\beta\ B_{\mu\mu})}\ .}$$

$B_{\mu\mu}$ *disappears for the production, in radiative decays of the* ψ*,*
of a new boson decaying into $\mu^+\mu^-$.

Non-observation of $\Upsilon \to \gamma + ($*neutral* $\to\ \mu^+\mu^-)$ *decays implies*

$$\boxed{\boldsymbol{B\,(\,\psi\ \to\ \gamma + \textit{neutral}\,)\ B_{\mu\mu}\ \lesssim\ 5\ 10^{-7}/\tan^4\beta}\ ,}$$

i.e. $\lesssim 5\,10^{-9}$ *for* $\tan\beta \gtrsim 3$, independently of $B_{\mu\mu}$.

Limits on b *couplings may be translated into limits on*
pseudovector, pseudoscalar or scalar couplings to electrons:

$$\boldsymbol{|f_{eA}|\ \lesssim\ 3\ 10^{-7}\ m_U(\textit{MeV})\,/\sqrt{B_{\mu\mu}}}$$

$$\boldsymbol{|f_{eP}|\ \lesssim\ 3\ 10^{-7}\,/\sqrt{B_{\mu\mu}}}\quad \textit{or}\quad \boldsymbol{|f_{eS}|\ \lesssim\ 5\ 10^{-7}\,/\sqrt{B_{\mu\mu}}}$$

SEARCHING for LIGHT DARK MATTER in Υ DECAYS

PF + Kaplan, PLB 269, 213 (1991); PF, PRD 74, 054034, 2006, ...

Search for the decays

$$\boxed{\left\{\begin{array}{l} \Upsilon \to \ \ \chi\,\chi \\ \Upsilon \to \gamma\ \chi\,\chi \end{array}\right.}$$

mediated by a light U boson *(or a spin-0 particle in the case of $\gamma\ \chi\chi$)*

(no decay $\Upsilon \to$ invisible mediated by the direct exchange of a spin-0 particle)

give limits on the product of couplings of the U boson

to the b quark and the light dark matter particle χ

($\Upsilon \to \chi\,\chi$ and $\gamma\ \chi\chi$ test the vector and axial couplings to the b, respectively)

From $\Upsilon \to \underbrace{\chi\,\chi}_{\textbf{inv}}$

$$\boxed{|c_\chi\, f_{bV}| \ \lesssim \left\{ \begin{array}{rl} 9\ 10^{-2} & \textbf{(spin-0)}\ , \\ 6\ 10^{-2} & \textbf{(Majorana)}\ , \\ 4.5\ 10^{-2} & \textbf{(Dirac)}\ . \end{array} \right.}$$

(Υ limits weaker than ψ ones by more than 2)

$$\boxed{c_\chi\, f_{bA}\ \textbf{ may be constrained from }\ \Upsilon \to \gamma\ \ \underbrace{\chi\,\chi}_{\textbf{inv}}}$$

Many other processes may also be discussed ...

Dark Matter

Parity violations in atomic physics

$$e^+ \, e^- \rightarrow \, \gamma \, U$$

$$g - 2$$

ν **scatterings**

Supernovae explosions

...

CONCLUSIONS