BROKEN $U(1)$ SYMMETRY

and new LIGHT neutral BOSONS

in ψ and Υ decays

Pierre FAYET

LLR, Ecole polytechnique

27-03-2009

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 78, 14,* **1974** **;** *B 90, 104,* **1975.**

electroweak symmetry breaking with

two	**Brout-Englert-Higgs doublets**

$$\varphi_{SM} \;\longrightarrow\; \{\, \varphi'',\; \varphi' \,\}$$

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

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

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*

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

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

Not all terms compatible with Lorentz and gauge symmetries are allowed

further restrictions due to additional symmetry ...

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 $V(h_1, h_2)$:

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

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*

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

= **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**

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

μ 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 $\propto\; m_3^2\; \Re\,(h_1\, h_2)$ *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:

$$\mu \; H_1 \, H_2 \;\; \longrightarrow \;\; \lambda \; H_1 \, H_2 \, S$$

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)

$$\mathcal{W} \; = \; \lambda_e \, H_1.\bar{E} \, L \; + \; \lambda_d \, H_1.\bar{D} \, Q \; - \; \lambda_u \, H_2.\bar{U} \, Q$$

$$+ \, \lambda \, H_1 H_2 \, S \; + \underbrace{\frac{\kappa}{3} \, S^3 \; + \; \frac{\mu_S}{2} \, S^2 \; + \; \sigma \; S}_{f(S)}$$

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

$$H_1 \xrightarrow{U} e^{i\alpha} H_1\,, \quad H_2 \xrightarrow{U} e^{i\alpha} H_2\,, \quad S \xrightarrow{U} e^{-2i\alpha} S$$

$$(Q, \bar{U}, \bar{D};\ L, \bar{E}) \xrightarrow{U} e^{-i\frac{\alpha}{2}} (Q, \bar{U}, \bar{D};\ L, \bar{E})$$

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. ?

New neutral gauge boson (Z' or U boson)

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

or new light spin-0 axionlike quasiGoldstone boson,

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

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

orthogonal combination:

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

(cf. standard axion, or A of MSSM)

In the presence of a (possibly large) singlet v.e.v.:
pseudoscalar Goldstone or quasi-Goldstone boson a :

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

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

The would-be “axion” a is a mixing of doublet and singlet components

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

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"

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

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 $g" \longrightarrow 0$ **, as** $m_U \propto g" \ldots \longrightarrow 0$ **as well !**

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

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

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:

$$f_{q,l\;P} \;=\; f_{q,l\;A}\,\frac{2\,m_{q,l}}{m_U}$$

A light spin-1 gauge boson behaves very much as a quasi-massless spin-0 particle, i.e. as the corresponding spin-0 Goldstone boson ...

"Equivalence theorem"

similar to the "Equivalence theorem of supersymmetry"

according to which a very light spin-$\frac{3}{2}$ gravitino behaves like the spin-$\frac{1}{2}$ massless goldstino of sp. broken global susy.

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

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

pseudoscalar couplings of A:

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

pseudoscalar couplings of standard axion (or A of the MSSM)

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

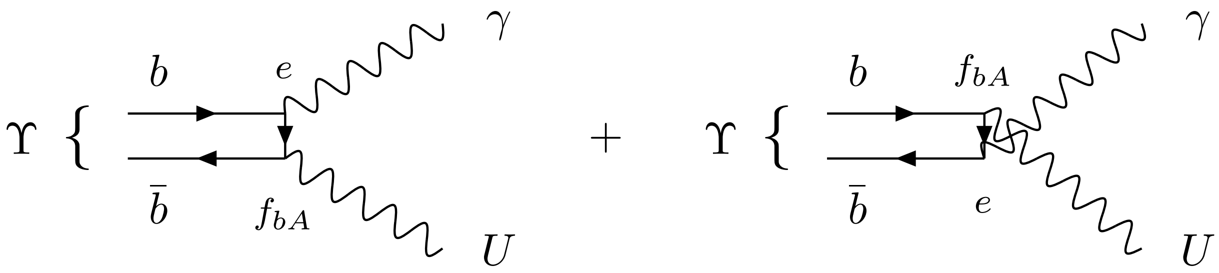
When A mixes with Im s into doublet/singlet pseudoscalar combination a
associated with extra-$U(1)$ breaking,
we get the pseudoscalar (or effective pseudoscalar) couplings,
now also proportional the invisibility parameter $r = \cos\zeta$,

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

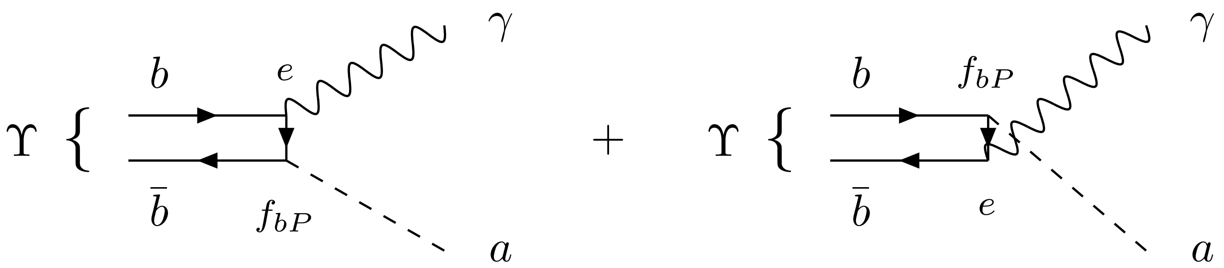
$$f_{q,l\;A} \simeq \underbrace{2^{-\frac{3}{4}}\ G_F{}^{\frac{1}{2}}\ m_U}_{2\;10^{-6}\, m_U(\mathrm{MeV})} \times \begin{cases} r\,x = \cos\zeta\ \cot\beta & (u,\ c,\ t) \\ r/x = \cos\zeta\ \tan\beta & (d,\ s,\ b;\ e,\ \mu,\ \tau) \end{cases}$$

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

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 $\Upsilon \to \gamma\, a$.

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

$$\Longrightarrow$$

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

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

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

$$\Longrightarrow$$

$$B\,(\,\psi\;\to\;\gamma\;\;U/a\,) \simeq\;\; 5\;\; 10^{-5}\;\;\; \cos^2\zeta\; \cot^2\beta\;\;\; C_\psi\, F_\psi$$

$$B\,(\,\Upsilon\;\to\;\gamma\;\;U/a\,) \simeq\;\; 2\;\; 10^{-4}\;\;\; \cos^2\zeta\; \tan^2\beta\;\;\; C_\Upsilon\, F_\Upsilon$$

ψ DECAYS

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

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

$$\begin{cases} |f_{cA}| < 1.5\;10^{-6}\; m_U(\textbf{MeV})/\sqrt{B_{\rm inv}} \\ |f_{cP}| < 5\;10^{-3}/\sqrt{B_{\rm inv}}\;, \quad |f_{cS}| < 10^{-2}/\sqrt{B_{\rm inv}} \end{cases}$$

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.*

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

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

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

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

The limit on the pseudoscalar (or effective pseudoscalar) coupling f_{bP} is 5 times smaller than the standard Higgs coupling to b, $m_b/v \simeq 2\,10^{-2}$, for an invisibly decaying boson.

For a scalar coupling,

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

Υ *limit* $\Longrightarrow$

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

(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* $\Longrightarrow$

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

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 $e,\ \mu$ *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)*

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

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

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

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

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

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

As scalar couplings are 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.*

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

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

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

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

Υ DECAYS $\rightarrow \gamma + (\mu^+ \mu^-)$

BABAR: arXiv:hep-ex/0902.2176

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

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

$$|f_{bA}| \;\lesssim\; 3\;10^{-7}\; m_U(\text{MeV})/\sqrt{B_{\mu\mu}}$$

$$|f_{bP}| \;\lesssim\; 3\;10^{-3}/\sqrt{B_{\mu\mu}}\;, \quad \text{or} \quad |f_{bS}| \;\lesssim\; 5\;10^{-3}/\sqrt{B_{\mu\mu}}$$

(slightly relaxed with a more conservative limit $\lesssim 4\;10^{-6}$*)*

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

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

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

$B_{\mu\mu}$ *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*

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

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:

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

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

SEARCHING for LIGHT DARK MATTER in Υ DECAYS

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

Search for the decays

$$\begin{cases} \Upsilon \to \ \chi\,\chi \\ \Upsilon \to \gamma\ \chi\,\chi \end{cases}$$

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

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

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

$c_\chi\, f_{bA}$ **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

$$e^+ e^- \to \gamma U$$

$$g - 2$$

ν scatterings

Supernovae explosions

...

CONCLUSIONS