The U BOSON as a generalized DARK PHOTON

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Journée SHiP / Physique du secteur caché LPNHE-Paris, October 11$^{\rm th}$, 2017

4 kinds of interactions

Strong, electromagnetic, weak and gravitational

with different properties

Are there other kinds of interactions ?

it would be presomptuous to pretend that we know all of them !

NEW INTERACTIONS MAY EXIST

and remain unknown to us ...

what could be their properties ?

how could we know about that ?

Particles, Interactions and Symmetries

are intimately related

Particles $=$ $\begin{cases} \textbf{Matter particles:} \\ \quad \textbf{quarks, leptons + antimatter + dark matter ... ?} \\ \textbf{Mediators of interactions:} \\ \quad \textbf{gluons, } \gamma, W^{\pm}, Z, \textbf{ graviton, } \text{Higgs bosons } \textbf{... ?} \end{cases}$

NEW PARTICLES MAY EXIST (and probably should) ... , like

(spin-1) ***U*** **bosons** (including **"hidden" or "dark" photons), ...**

(spin-0) **axions** (or axionlike particles), ...

DARK MATTER particles, ...

and be associated with <u>new symmetries</u> and <u>new interactions</u> ...

New bosons expected to mediate new interactions

New spin-1 bosons $\leftrightarrow$

new gauge symmetries beyond $\boldsymbol{SU(3) \times SU(2) \times U(1)}$

Simplest possibility

$\boldsymbol{SU(3) \times SU(2) \times U(1) \times}$ **extra** $\boldsymbol{U(1)}$

which masses for the new gauge bosons ?

$\sim m_Z$? $\gtrsim$ TeV scale ? ($\rightarrow$ LHC ...) $\gg$ TeV ?

maybe light, even very light, or massless ?

which couplings ? : $g_s,\ g,\ g',\ \boxed{g''}$

new gauge coupling (g'') $\leftrightarrow$ intensity of new interaction $(\propto g''^2)$

$\Rightarrow$ **possibility of new very weak forces** next to gravitation, electromagnetism, weak NC force ...

*Nowadays one often focusses on the simple situation of a " **dark photon**"*

coupled to SM particles through the electromagnetic current

(and maybe also coupled to dark matter, with dark matter staying neutral)

owing to the simplicity of the experimental discussion

in terms of the mass of the new boson,

and the strength of its interactions, ϵe (in the visible sector)

$$- \, e A^\mu \, J_{\mu\, em} \to - \, (e A^\mu + \epsilon e A'^\mu) \, J_{\mu\, em} + \tfrac{1}{2} \, m_{A'}^2 \, A'^\mu A'_\mu$$

Easy to understand and discuss !

But is there any good reason to focus on such a situation ?

What is the general situation which ought to be discussed ?

What is the general situation which ought to be discussed ?

1. Identify the extra $U(1)$'s which may be gauged

(already in the "visible" sector, even before thinking about DM)

2. How the gauge symmetries get spontaneously broken ?

How does extra-$U(1)$ gauge field C^μ mixes with W_3^μ and B^μ ?

$$\begin{pmatrix} W_3^\mu \\ B^\mu \\ C^\mu \end{pmatrix} \rightarrow \begin{pmatrix} Z^\mu \\ A^\mu \\ U^\mu \end{pmatrix}$$

$\rightarrow$ neutral gauge boson U, may be very light (or even remain massless)

3. What are the U boson couplings ?

to the electric charge in the visible sector, or more general ?

to a ***vector current*** *? or possibly also to an* ***axial current*** *?*

($\rightarrow$ "new" features, with axionlike behavior of U ...)

and possibly also to ***(Light) Dark Matter ...***

4. What to expect when $\boldsymbol{SU(3) \times SU(2) \times U(1)_Y \;\rightarrow\; SU(5)}$, i.e.

$\boldsymbol{SU(3) \times SU(2) \times U(1)_Y}$ $\times$ extra-$\boldsymbol{U(1)} \rightarrow$ $\boldsymbol{SU(5)} \times$ extra-$\boldsymbol{U(1)}$?

Can the extra-$U(1)$ gauge field C^μ still mix with the electroweak A^μ and Z^μ ?

already at the tree approximation ?? or through loop effects ... ??

Consequences for experimental searches, and the way of discussing the results ...

A long time ago ... PLB 95 (1980) 285, and

A LA RECHERCHE D'UN NOUVEAU BOSON DE SPIN 1

NPB 187 (1981) 184

a very light and very weakly coupled *U* boson

$SU(3) \times SU(2) \times U(1) \times$ **extra** $U(1) \rightarrow$ **additional ("Z'")**

effects could show up in neutral current phenomenology

but not if ***light and very weakly coupled***

(at least not easily visible ...)

NC amplitudes typically $\propto \dfrac{G_F\, m_U^2}{m_U^2 - q^2}\ (\times\, r^2)$ (compared to G_F for Z exchanges)

($r = \leq 1$, EW scale / extra-$U(1)$ breaking scale , $r \ll 1$ if large extra singlet vev, PLB 95(1980)285)

discussed how it could appear in

e^+e^- **annihilations,** $K^+ \rightarrow \pi^+ U$, $\psi \rightarrow \gamma U$, $\Upsilon \rightarrow \gamma U$ **decays**

beam dump experiments

U lifetime depends strongly on m_U

In simplest situation *(1981)*

(EW breaking induced by 2 Higgs doublets without extra singlet yet)

(extra-$U(1)$ broken at EW scale, $r = 1$)

130 years *at* 1 eV $\to$ 4 $\mathbf{10^{-9}}$ s *at* 1 MeV

("***invisible***", decaying into $\boldsymbol{\nu\bar{\nu}}$)

2.4 $\mathbf{10^{-12}}$ s *at* 10 MeV $\to$ 2.4 $\mathbf{10^{-15}}$ s *at* 100 MeV

(decaying into $\boldsymbol{e^+e^-}$ and $\boldsymbol{\nu\bar{\nu}}$)

From (old) (hadronic) beam dump experiments :

(Brookhaven, 1979)

and absence of observed $\boldsymbol{U \to e^+e^-}$ decays

$\boldsymbol{m_U = 1 \to 7}$ MeV mass excluded

(if above 7 MeV, lifetime too short, decays too early)

(but an extra singlet with a large v.e.v.
could make the $\boldsymbol{U}$ *almost "invisible", as for the axion ...)*

general discussion

EXTRA $U(1)$'s and NEW FORCES

NPB 347 (1990) 743

1) general features of extra-$U(1)$ symmetries that may be gauged

(depending on BE-Higgs structure of theory
1 doublet or 2 doublets as in SUSY or ...)

2) take into account mixing effects between neutral gauge bosons

$$W_3^\mu,\ B^\mu,\ C^\mu \quad \rightarrow \quad Z,\ \gamma,\ U$$

3) deduce the current J_U^μ to which U couples

(extra-$U(1)$ current, with possible additional part $\propto J_Z$, due to mixing

4) discuss if $\begin{cases} V \text{ part only} \\ \text{or } V \text{ part} + A \text{ part} \end{cases}$

results depend crucially on BE-Higgs sector responsible for mixing

important for phenomenology

Extra $U(1)$ symmetries (F) that may be gauged

(first considering the visible sector)

result depends on the Higgs sector: from gauge invariance of Yukawa couplings:

if **1 doublet only** *(or several with same quantum numbers)* **(+ possible singlet) :**

$$\boldsymbol{F = \alpha B + \beta_i L_i + \gamma Y}$$

(normalized to $\gamma = 1$, if $\gamma \neq 0$)

(or Y, $B - L$ and $L_i - L_j$ for an anomaly-free theory, including ν_R's)

---

if **2 doublets as in SUSY SM,** *with* $\begin{pmatrix} h_1^0 \\ h_1^- \end{pmatrix}, \begin{pmatrix} h_2^+ \\ h_2^0 \end{pmatrix}$

possibility of rotating independently the two doublets, thanks to

extra-$U(1)_A$ (axial) $h_1 \to e^{i\alpha}\, h_1, \;\; h_2 \to e^{i\alpha}\, h_2$

may get gauged, possibly in combination with B, L, Y

$$F = \alpha B + \beta L + \gamma Y + \delta F_A$$

with *extra axial generator*

but let us ignore for the moment this possibility

Further constraints in GUTs *(with $SU(5)$ quintuplets and decuplets)*

With quarks and leptons in the same multiplets,

B and L_i occur through $B-L$, together with Y

$$\boldsymbol{F \;=\; \Big[\,Y - \frac{5}{2}\,(B-L)\Big]} \qquad \textit{(at the GUT scale)}$$

Mixings between neutral gauge bosons: $\boldsymbol{W_3^\mu,\ B^\mu,\ C^\mu \quad \to \quad Z,\ \gamma,\ U}$

with light or even massless U

Extra-$U(1)$ gauge field C^μ mixes with Z^μ_{sm} :

$$\left\{ \begin{array}{lcl} Z &=& \cos\xi\ Z_{\rm sm} - \sin\xi\ C\,, \\ U &=& \sin\xi\ Z_{\rm sm} + \cos\xi\ C\,, \end{array} \right. \qquad \textit{with} \quad \tan\xi \simeq \frac{g''}{\sqrt{g^2+g'^2}}$$

$$\left\{ \begin{array}{lcll} A &=& \dfrac{g'\,W_3 + g\,B}{\sqrt{g^2+g'^2}} & = \sin\theta\,W_3 + \cos\theta\,B\,, \\[2ex] Z &\simeq& \dfrac{g\,W_3 - g'B - g''C}{\sqrt{g^2+g'^2+g''^2}} & \simeq \cos\theta\,W_3 - \sin\theta\,B\,, \\[2ex] U &\simeq& \dfrac{g''(g\,W_3 - g'B) + (g^2+g'^2)\,C}{\sqrt{g^2+g'^2}\,\sqrt{g^2+g'^2+g''^2}} & \simeq \qquad C\,. \end{array} \right.$$

(Mixing with $\boldsymbol{Z}$, the photon stays apart ... !)

Mixing $\Rightarrow$

$$\mathcal{J}_U^\mu \;=\; \cos\xi \quad \underbrace{\left(\frac{g''}{2}\,J_F^\mu\right)}_{\mathcal{J}_F^\mu,\ \text{involves } B,\,L \text{ and } Y} \quad +\;\sin\xi\;\underbrace{\sqrt{g^2+g'^2}\,(J_3^\mu - \sin^2\theta\,J_{\rm em}^\mu)}_{\mathcal{J}_{Z_{\rm sm}}^\mu}$$

(usually) family-universal

Both parts parity-violating, combine into

U Current (almost) pure V (if only 1 doublet + singlet)

involves $B,\ L$ (or $B-L$) *and* Q

Vector current | linear combination of $B,\ L,\ Q$ currents

$$\mathcal{J}_U^\mu = g''\cos\xi\,\left(\cos^2\theta\,J_{\rm em}^\mu + \tfrac{1}{2}\,(\alpha_B J_B^\mu + \beta_i\,J_{L_i}^\mu + J_d^\mu)\right)$$

$$= e\tan\chi\,\left(J_{\rm em}^\mu + \frac{1}{2\,\cos^2\theta}\,(\alpha_B\,J_B^\mu + \beta_i\,J_{L_i}^\mu + J_d^\mu)\right).$$

with $\epsilon_Q \;=\; \tan\chi \;=\; \dfrac{g''}{g'}\,\dfrac{g}{\sqrt{g^2+g'^2+g''^2}} \;\simeq\; \dfrac{g''}{g'}\,\cos\theta\,,$

In general: coupling to

$$\boxed{(\,\epsilon_Q\, Q + \epsilon_B\, B + \epsilon_L\, L)\, e}$$

(not just to $\epsilon_Q\, Q\, e$!!)

Special case: $J_F^\mu = J_Y^\mu$ *(for matter fermions, not for Higgs singlet, with $Y = 0$)*

After mixing, **J_Y^μ and J_Z^μ combine so as to reconstruct J_{em}^μ**

no need to consider the so-called "kinetic mixing"

essentially irrelevant as it simply corresponds, not to a new phenomenon,

but to the choice of a description in a non-orthogonal field basis

$J_U^\mu \propto J_{em}^\mu$ *(for usual matter fermions, not (L)DM if coupled to extra $U(1)$)*

U coupled to SM particles through electromagnetic current

(NPB 347 (1990) 743)

$U =$ *very light* **"dark photon"**

leading to short-range modifications to electromagnetism

In general:

U = *generalized* **"dark photon"** *coupled to* $(\epsilon_Q\, Q + \epsilon_B\, B + \epsilon_L\, L)$

(could have provided a possible explanation of the $\approx 3\sigma$ *effect observed in* $g_\mu - 2$*)*

Within GRAND-UNIFICATION :

$$F\ =\ \left[Y - \frac{5}{2}\,(B-L) \right] \qquad \text{(at the GUT scale)}$$

Coupling to $[\, \epsilon_{B-L}\,(B-L) + \epsilon_Q\, Q\,]\, e$

$$\epsilon_Q\ =\ -\,\frac{4}{5}\,\cos^2\theta\ \epsilon_{B-L}\ \simeq\ -\,.61\,\epsilon_{B-L}$$

$$\epsilon_{B-L}\left[(B-L) - \frac{4}{5}\,\cos^2\theta\, Q \right] e\ =\ \epsilon_{B-L}\,(B-L-.61\,Q)\, e$$

equivalently expressed as

$$\epsilon_Q\,[\, Q - \frac{5}{4\,\cos^2\theta}\,(B-L)\,]\, e\quad =\ \epsilon_Q\,[\, Q\ -\ 1.64\,(B-L)\,]\, e$$

In addition to ordinary visible decay modes

$$U \rightarrow e^+ e^- \ \ldots$$

(depending on its mass)

the U boson can also have

invisible decay modes into neutrinos

$$U \rightarrow \nu \bar{\nu}$$

even without taking into account (yet) the possibility of decays into

Light Dark Matter particles

$$U \rightarrow \chi \chi$$

(in contrast with an ordinary "dark photon")

Additional part involving (Light) Dark Matter particle χ may also be present

the DM particle remaining neutral (unless one decides otherwise)

U **couples SM particles to dark matter particles**

U *leads to the possibility of*

LIGHT DARK MATTER particles χ

by allowing for sufficient LDM annihilations into SM particles

LIGHT DARK MATTER

(in $\sim$ MeV to GeV range)

quite unconventional, at least for lower masses

How can it be possible ??

LIGHT DARK MATTER

with C. Bœhm

NPB 683(2004)219 ...

Too light dark matter particles

(say in MeV to GeV range)

normally forbidden, as could not annihilate sufficiently

$\rightarrow$ *relic abundance (much) too large ... !! ??*

may be possible only with a new interaction, but ...

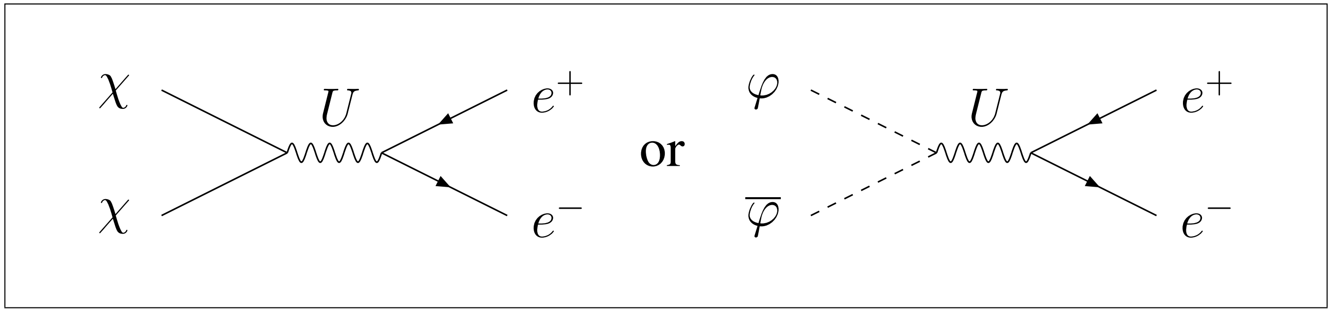
New interaction should be

significantly stronger than weak interactions ... !

to get sufficiently large σ_{ann} *at lower energies*

$\rightarrow$ NEW INTERACTION induced by spin-1 ***U*** boson

sufficiently strong at lower energies



DM annihilations, for spin-$\frac{1}{2}$ or spin-0 particles

[other possibility (not favored ...):

light spin-0 DM annihilations through heavy (mirror) fermion exchanges]

but how can it be unobserved, if stronger than weak interactions ... ??

does not seem to make sense ... !!

the trick : **new interaction**

much stronger than weak interactions **at lower energies**
(where weak interactions are very weak)
but much weaker at higher energies ...
(at which weak interactions become stronger)

again, how is it possible ??

(il y a encore un truc, bien sûr ...)

Interaction mediated by LIGHT spin-1 U boson

PLB 95(1980)285, NPB 187(1981)184, PRD 70(2004) 023514 ...

propagator $\frac{1}{q^2 - m_U^2}$ **:**

$\frac{-1}{m_U^2}$ *for* $|q| \ll m_U$ *(local limit at lower energies)*

$\sigma \nearrow$ *with* E *(as for weak int.)*

$\rightarrow$ **"stronger-than-weak" at lower energies**

$\frac{1}{q^2}$ *for* $|q| \gg m_U$ *(ignore* m_U *at higher energies)*

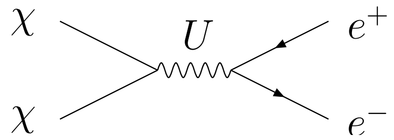
$\sigma \searrow$ *with* E *(as in QED)*

$\rightarrow$ **"weaker-than-weak" at higher energies**

change of behavior at $|\boldsymbol{q}| \sim m_U \ll m_Z$, ***light U* required ...**

Relic density of light dark matter

$$\chi\,\chi \;\to\; e^+\,e^-$$



(other modes possible, $\nu\bar\nu$ ... , depending on m_χ)

$$\sigma^{ee}_{\rm ann}\, v_{\rm rel} \;\simeq\; \frac{v_\chi^{\,2}}{.16}\left(\frac{c_\chi\, f_e}{10^{-6}}\right)^2 \left(\frac{m_\chi \times 1.8\ \text{MeV}}{m_U^2 - 4\, m_\chi^{\,2}}\right)^2\ (4\ \text{pb})$$

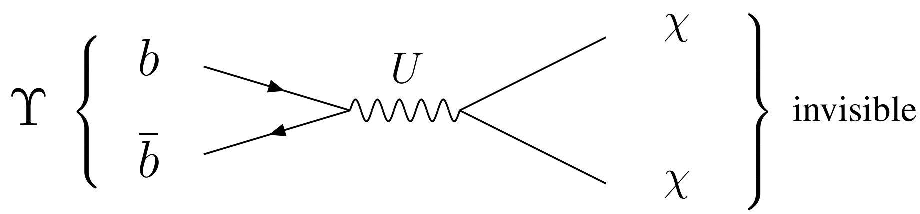
required $c_\chi\, f_e$ *for correct total annihilation c.s.* ($\sigma_{\rm ann} = \sigma^{ee}_{\rm ann}/B^{ee}_{\rm ann}$) *at freeze out*

$\sigma_{\rm ann}$ *OK for*

$$|\,c_\chi\, f_e\,| \;\simeq\; (B^{ee}_{\rm ann})^{\frac12}\ 10^{-3}\ \frac{|\,m_U^2 - 4\, m_\chi^{\,2}\,|}{m_\chi\ (1.8\ \text{GeV})}$$

$$\simeq\; (B^{ee}_{\rm ann})^{\frac12}\ 10^{-6}\ \frac{|\,m_U^2 - 4\, m_\chi^{\,2}\,|}{m_\chi\ (1.8\ \text{MeV})}$$

LIGHT DARK MATTER in Υ DECAYS



Invisible Υ decay into LDM particles

$$\begin{cases} \Upsilon \to \chi\chi = \textbf{invisible} & (V\ coupling) \\ \Upsilon \to \gamma\ \chi\chi = \gamma + \textbf{invisible} & (A\ coupling) \end{cases}$$

could be sizeable, for DM particles with relatively large cross sections: *PLB 269 (1991) 213*

$\Upsilon \to \chi\chi$ and $\gamma\ \chi\chi$ test vector and axial couplings to b

(no decay $\Upsilon \to$ invisible mediated by spin-0 exchanges)

What may be the expected rates ?

For Light DM particles

Invisible Υ BR cannot be "predicted" from DM annihilation cross section !

different processes involved, $b\bar{b} \to \chi\chi$ and $\chi\chi \to f\bar{f}$, *at different energies* ....

(and if LDM interactions due to spin-0 exchanges, invisible Υ decay forbidden)

For invisible Υ decays mediated by a light U,

$$\Upsilon \to \underbrace{\chi\,\chi}_{inv} < 3\;10^{-4} \text{ (BABAR)} \Rightarrow \quad |c_\chi\, f_{bV}| < 5\;10^{-3}$$

and from ψ decays,

$$\psi \to \underbrace{\chi\,\chi}_{inv} < 7.2\;10^{-4} \text{ (BES II)} \Rightarrow \quad |c_\chi\, f_{cV}| < .95\;10^{-2}$$

PRD 74(2006)054034, ... , PRD 81(2010)054025

Let us return to U couplings to SM particles

Axial part may be present if more than 1 BE-Higgs doublet

as in 2HD (SUSY) models

"Axionlike" behavior and parity-violating effects may then occur

limits on $r = \cos\theta_A$ *(depending on* $\tan\beta$*)*

limits on $f_{eA}\, f_{qV}$ *from atomic physics exp.*

...

Furthermore, in a general way, due to **axial** couplings (when present)

U tends to be produced somewhat like **pseudoscalar axion**

This may require a large-enough singlet v.e.v. to make

pseudoscalar a mostly singlet rather than doublet

(PLB 95 (1980) 285)

cf. "invisible axion" mechanism

U *then behaves as* $a = \underbrace{\cos\theta_A}_{r \leq 1} A + \sin\theta_A$ *singlet*

In many circumstances, U behaves as

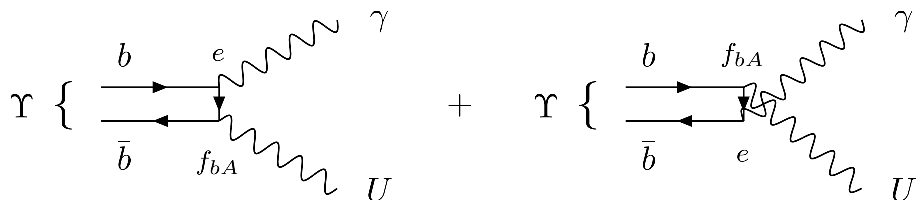
"poorly-visible" (down to "invisible") axionlike pseudoscalar a

amplitudes $\mathcal{A} \propto (r = \cos\theta_A)$ **rates** $\propto (r^2 = \cos^2\theta_A)$

ψ, Υ **... decays ... provide limits on** $r = \cos\theta_A$

SEARCHING FOR A LIGHT U in quarkonium decays

$$\Upsilon \to \gamma\, U\,,\ \psi \to \gamma\, U$$

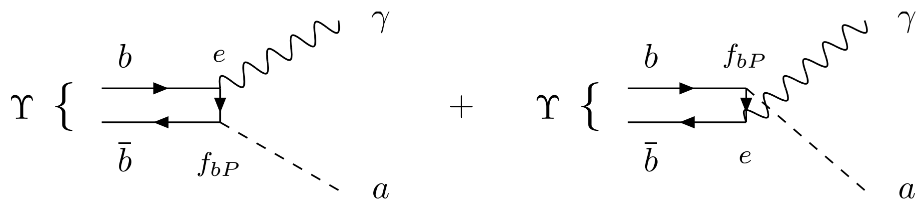


does not vanish even if U *couplings to* b (f_{bA} *and* f_{bV}) $\to 0$ *!!*

very light U *behaves as spin-0 pseudoscalar with* **effective pseudoscalar coupling:**

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

(*equivalence theorem* , *as in SUSY where very light spin-*$\frac{3}{2}$ *gravitino* $\leftrightarrow$ *spin-*$\frac{1}{2}$ *goldstino*)



Amplitude for producing U proportional to gauge coupling

$$\mathcal{A}\,(\,A \to B + U_{\rm long}\,) \;\propto\; g" \;\ldots$$

$\uparrow$

may be very small !!

but longitudinal polarisation $\epsilon^\mu_L \simeq \dfrac{k^\mu}{m_U}$ *singular when* $g" \to 0$, *as* $m_U \propto g" \ldots \to 0$ *!*

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

F_U = *symmetry-breaking scale* $\qquad k^\mu\, \bar\psi\, \gamma_\mu \gamma_5\, \psi \;\to 2\, m_q\, \psi\, \gamma_5\, \psi$

Interaction proportional to $\dfrac{2\, m_q}{F_U}$

A very light U does not decouple for very small gauge coupling !

behaves as "eaten-away" pseudoscalar Goldstone boson a

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

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

same experiments can search for light spin-1 gauge boson, or spin-0 pseudoscalar, or scalar

$$\textit{decays:}\ \begin{cases} U \ \to\ \nu\bar\nu \ \ \textit{(or light dark matter particles)} \\ U \ \to\ e^+e^-,\ \mu^+\mu^-,\ q\bar q,\ \tau^+\tau^- \ \ \textit{(depending on } m_U\textit{)} \end{cases}$$

$$\Rightarrow \textit{search for} \quad \boxed{\begin{cases} \Upsilon \ \to\ \gamma\ +\ \textit{invisible} \\ \Upsilon \ \to\ \gamma\ +\ \ e^+e^- \ \ (\textit{or}\ \ \mu^+\mu^-,\ \tau^+\tau^-),\ \ldots) \end{cases}}$$

Light U behaves very much as spin-0 "axionlike" (eaten-away) pseudoscalar a

$\psi(\Upsilon) \to \gamma + inv.$ *excluded standard axion in the 80's* ...

to avoid excluding a U *with invisible decays having "eaten away" an axionlike pseudoscalar*

break $U(1)_A$ symmetry through 2 doublets $h_1,\ h_2$ + extra singlet with much larger v.e.v.

(as in U(N)MSSM with $\lambda\, H_1 H_2 S$ *superpotential)*

$$h_1 \to e^{i\alpha} h_1,\ \ h_2 \to e^{i\alpha} h_2,\ \ s \to e^{-2i\alpha} s$$

A *gets mixed with "almost inert" singlet* s

U behaves as almost "invisible" axionlike pseudoscalar a

$$a\ =\ \boxed{\cos\theta_A}\ \underbrace{\left(\sqrt{2}\ \mathit{Im}\,(\sin\beta\, h_1^\circ\ +\ \cos\beta\, h_2^\circ)\right)}_{A}\ +\ \sin\theta_A\ \underbrace{(\sqrt{2}\ \mathit{Im}\ s\,)}_{singlet}$$

$r\ =\ \cos\theta_A$ = *INVISIBILITY PARAMETER*

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

$\psi \to \gamma\, U,\ \ \Upsilon \to \gamma\, U$ *decay rates* $\ \propto\ r^2 = \cos^2\theta_A$

ψ and Υ decays provide strong limits on axial couplings f_A of U to c or b

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

or equivalent pseudoscalar couplings f_p of a

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

For invisibly decaying U (with $B_{inv} \simeq 1$): $\psi \to \gamma U < 1.4\ 10^{-5}$, $\Upsilon \to \gamma U < 4\ 10^{-6}$

$$r x = \cos\theta_A\ \cot\beta < .75 \ \Leftrightarrow\ |f_{cA}| < 1.5\ 10^{-6}\ m_U(MeV) \ \Leftrightarrow\ |f_{cP}| < 5\ 10^{-3}$$

$$r/x = \cos\theta_A\ \tan\beta < .2 \ \Leftrightarrow\ |f_{bA}| < 4\ 10^{-7}\ m_U(MeV) \ \Leftrightarrow\ |f_{bP}| < 4\ 10^{-3}$$

(limits to be divided by $\sqrt{B_{inv}}$)

requires a to be **mostly singlet**

doublet fraction	$r^2 = \cos^2\theta_A < 15\% \,/ B_{inv}$
or: Υ limit $\Rightarrow$ doublet fraction	$r^2 = \cos^2\theta_A < 4\% \,/ (\tan^2\beta\ B_{inv})$

if large $\tan\beta$, Υ *limit* $\Rightarrow$ *not much chance to see* $\psi \to \gamma U_{inv}$ ...

$$B(\psi \to \gamma U)\, B_{inv} \lesssim 10^{-6}/\tan^4\beta$$

independently of B_{inv}

Furthermore, with $f_{eA} = f_{bA}$ *from universality constraints,*

$\Upsilon \to \gamma + U_{inv}$ *decays constrain* ***axial U couplings to electron***

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

For invisible decays:

$$|f_{eP}| \; < \; \frac{1}{5} \; \text{[standard Higgs coupling to electron } (\, 2 \; 10^{-6} \,)]$$

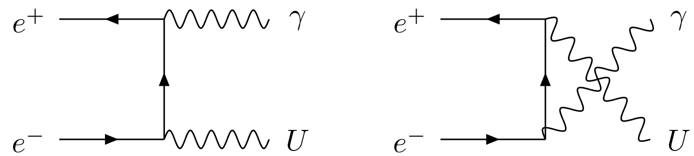
PRD 75, 115017 (2007);PLB 675, 267 (2009); PRD 81, 054025 (2010)

(also limits for $U \to e^+e^-, \; \mu^+\mu^-, ...$*)*

(not discussed here)

Other processes (and constraints)

- **Production in $e^+ e^- \to \gamma U$**



- *U boson may have **visible** ($\to e^+e^-$, ...) or **invisible** ($\to \nu\bar{\nu}$, or $\chi\chi$) decay modes*

  the latter ($\to \chi\chi$) possibly dominant

- *Production mechanisms and effects depend on whether the U boson has*

  V and/or A couplings

  *(With **enhanced effects of the A couplings** in the low m_U limit)*

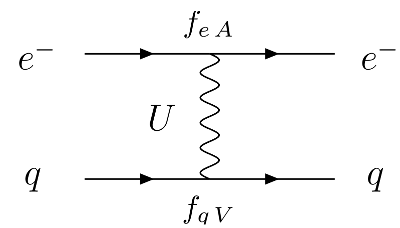
- *Dark Matter annihilations, $g_e - 2$, $g_\mu - 2$, ν scatterings, ...*

- *Constraints from ψ, Υ, K^+, π^0, η, η' ... decays, ...*

- Many recent experimental results, not recalled here ...

. . .

Parity violations in atomic physics



strong limit : $\sqrt{|f_{eA}\, f_{qV}|} \;<\; 10^{-7}\, m_U(\text{MeV})$

With constraints from ψ, Υ, K^+, π^0, η, η' *... decays,*

may favor **vector** ***U*** **coupling to SM particles** *through*

$$(\epsilon e) \quad \boxed{Q - \lambda\,(B - L)}$$

(possibly through electromagnetic current, with $U = A'$*)*

Within GRAND-UNIFICATION : $\boldsymbol{SU(5) \times U(1)_F}$

$F = Y - \frac{5}{2}\,(B-L) + F_{\rm dark}$ commutes with $SU(5)$

After mixing :

$$(\epsilon e) \qquad \boxed{\;\rightarrow\; Q_U = Q - \frac{5}{4\,\cos^2\theta}\,(B-L) \,+\, Q_{U\ \rm dark}\;}$$

$$[\;= \underbrace{Q - 2\,(B-L)}_{\text{commutes with } SU(4) \text{ electrostrong symmetry}} \quad \text{at the GUT scale}\;]$$

$(Q_U = 1$ for antiquartet $(e^-,\ \bar d)$; 0 for sextet $(u,\ \bar u\,)\,)$

$\epsilon = \tan\chi$ is already present at the GUT scale !

no need to be generated by radiative corrections ...

CONCLUSION

a new frontier: **light** **(very) weakly coupled new particles**

U **boson** *appears as a* **generalized dark photon**

very weakly coupled to SM particles, possibly to (light) dark matter

visible $(e^+e^-, \dots)$ *and* **invisible** *(dm, neutrinos) decays*

"preferred" coupling to $\boldsymbol{e \, \tan\chi \, [\, Q_U = Q - \lambda\,(B-L) + Q_{U\,\text{dark}}\,]}$

$(\boldsymbol{\lambda} = 5/(4\cos^2\theta)) \simeq \mathbf{1.64}$ ***in GUT;*** $\epsilon = \tan\chi$ *already present at GUT scale*

Experimental limits on $\boldsymbol{\epsilon}$ *should be expressed as a function of* $\boldsymbol{m_U}$ *and* $\boldsymbol{\lambda}$

[could mediate new long-range force next to gravity; $\rightarrow$ *possible "EP-violations"]*

could also have ***axial*** *couplings*

could then be produced like *light pseudoscalar* $\boldsymbol{a}$

(reminiscent of "invisible axion" , with extra $U(1)$ *broken by large singlet vev)*

Experiments such as ***SHiP*** *may reveal* ***NEW FUNDAMENTAL PHYSICS***