

The U BOSON as a generalized DARK PHOTON

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CERN, SHiP collaboration meeting

June 8th, 2017

4 kinds of interactions

Strong, electromagnetic, weak and gravitational

with different properties

Are there other kinds of interactions ?

it would be presumptuous 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 = {
 Matter particles:
 quarks, leptons + antimatter + dark matter ... ?
 Mediators of interactions:
 gluons, γ , W^\pm , Z , graviton, Higgs bosons ... ?

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 new symmetries and new interactions ...

new bosons expected to mediate new interactions

New spin-1 bosons \leftrightarrow

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

Simplest possibility

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

which masses for the new gauge bosons ?

$\sim m_Z ? \quad \gtrsim \text{TeV scale ?} \quad (\rightarrow \text{LHC ...}) \quad \gg \text{TeV ?}$

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)

$$- eA^\mu J_{\mu em} \rightarrow - (eA^\mu + \epsilon eA'^\mu) J_{\mu em} + \frac{1}{2} m_{A'}^2 A'^\mu A'_\mu$$

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 ?

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

→ 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** ?
(→ ”new” features, with axionlike behavior of U ...)
and possibly also to (**Light**) **Dark Matter** ...

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

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

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

SEARCHING FOR A NEW SPIN-1 BOSON

NPB 187 (1981) 184

a very light and very weakly coupled U boson

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

effects could show up in neutral current phenomenology

but not if *light and very weakly coupled*

(at least not easily visible ...)

NC amplitudes typically $\propto \frac{G_F m_U^2}{m_U^2 - q^2} (\times r^2)$ (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)

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

130 years at 1 eV \rightarrow $4 \cdot 10^{-9}$ s at 1 MeV

(“invisible”, decaying into $\nu\bar{\nu}$)

$2.4 \cdot 10^{-12}$ s at 10 MeV \rightarrow $2.4 \cdot 10^{-15}$ s at 100 MeV

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

From (old) (hadronic) **beam dump experiments** :

(Brookhaven, 1979)

and absence of observed $U \rightarrow e^+e^-$ decays

$m_U = 1 \rightarrow 7$ MeV mass excluded

(but an extra singlet with a large v.e.v.

could make the 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

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

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 $\left\{ \begin{array}{l} V \text{ part only} \\ \text{or } V \text{ part} + A \text{ part} \end{array} \right.$

*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) :**

$$\boxed{F = \alpha B + \beta_i L_i + \gamma Y} \quad (\gamma = 1)$$

(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) $h_1 \rightarrow e^{i\alpha} h_1$, $h_2 \rightarrow e^{i\alpha} h_2$

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

$$\boxed{F = \alpha B + \beta L + \gamma Y + \delta F_A} \quad \text{with } \underline{\text{extra axial generator}}$$

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

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

Mixings between neutral gauge bosons: $W_3^\mu, B^\mu, C^\mu \rightarrow Z, \gamma, U$

with light or even massless U

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

$$\begin{cases} Z = \cos \xi Z_{sm} - \sin \xi C, \\ U = \sin \xi Z_{sm} + \cos \xi C, \end{cases} \quad \text{with } \tan \xi \simeq \frac{g''}{\sqrt{g^2 + g'^2}}$$

$$\begin{cases} A = \frac{g' W_3 + g B}{\sqrt{g^2 + g'^2}} = \sin \theta W_3 + \cos \theta B, \\ Z \simeq \frac{g W_3 - g' B - g'' C}{\sqrt{g^2 + g'^2 + g''^2}}, \\ U \simeq \frac{g''(g W_3 - g' B) + (g^2 + g'^2) C}{\sqrt{g^2 + g'^2} \sqrt{g^2 + g'^2 + g''^2}}. \end{cases}$$

(Mixing with Z , the photon stays apart ... !)

Mixing \Rightarrow

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

(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

$$\begin{aligned} \mathcal{J}_U^\mu &= g'' \cos \xi \left(\cos^2 \theta J_{\text{em}}^\mu + \frac{1}{2} (\alpha_B J_B^\mu + \beta_i J_{L_i}^\mu + J_d^\mu) \right) \\ &= e \tan \chi \left(J_{\text{em}}^\mu + \frac{1}{2 \cos^2 \theta} (\alpha_B J_B^\mu + \beta_i J_{L_i}^\mu + J_d^\mu) \right). \end{aligned}$$

$$\text{with } \epsilon = \tan \chi = \frac{g''}{g'} \frac{g}{\sqrt{g^2 + g'^2 + g''^2}} \simeq \frac{g''}{g'} \cos \theta,$$

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 “hidden photon”

leading to **short-range modifications to electromagnetism**

Returning to the more general case:

many possible consequences, and constraints

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

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

In any case, 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. Boehm

NPB 683(2004)219 ...

Too light dark matter particles

(say in MeV to GeV range)

normally forbidden, as could not annihilate sufficiently

→ relic abundance (much) too large ... !! ??

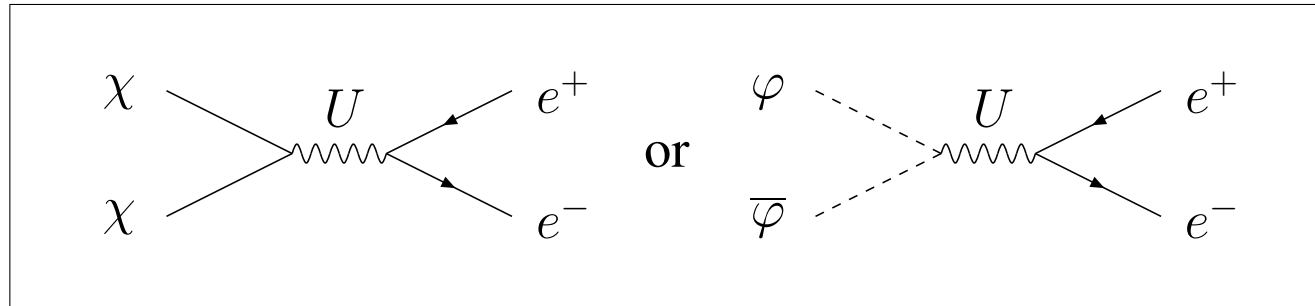
may be possible only with a new interaction, but ...

New interaction should be
significantly stronger than weak interactions ... !

to get sufficiently large σ_{ann} at lower energies

→ **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 ...

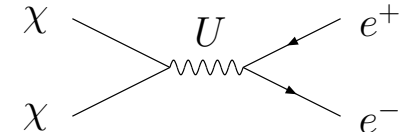
$$\text{propagator } \frac{1}{q^2 - m_U^2} : \left\{ \begin{array}{ll}
 \frac{-1}{m_U^2} \text{ for } |q| \ll m_U & \begin{array}{l} \text{(local limit at lower energies)} \\ \sigma \nearrow \text{ with } E \text{ (as for weak int.)} \\ \text{“stronger-than-weak” at lower energies} \end{array} \\
 \frac{1}{q^2} \text{ for } |q| \gg m_U & \begin{array}{l} \text{(ignore } m_U \text{ at higher energies)} \\ \sigma \searrow \text{ with } E \text{ (as in QED)} \\ \text{“weaker-than-weak” at higher energies} \end{array}
 \end{array} \right.$$

change of behavior at $|q| \sim m_U \ll m_Z$,

light U required ...

Relic density of light dark matter

$$\chi \chi \rightarrow e^+ e^-$$



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

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

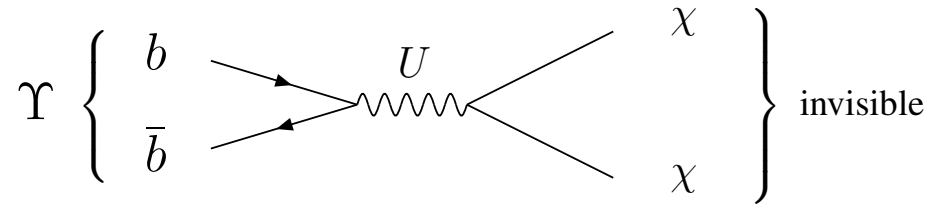
required $c_\chi f_e$ for correct total annihilation c.s. ($\sigma_{\text{ann}} = \sigma_{\text{ann}}^{ee} / B_{\text{ann}}^{ee}$) at freeze out

σ_{ann} OK for

$$|c_\chi f_e| \simeq (B_{\text{ann}}^{ee})^{\frac{1}{2}} 10^{-3} \frac{|m_U^2 - 4 m_\chi^2|}{m_\chi (1.8 \text{ GeV})}$$

$$\simeq (B_{\text{ann}}^{ee})^{\frac{1}{2}} 10^{-6} \frac{|m_U^2 - 4 m_\chi^2|}{m_\chi (1.8 \text{ MeV})}$$

LIGHT DARK MATTER in Υ DECAYS



Invisible Υ decay into LDM particles

$$\left\{ \begin{array}{l} \Upsilon \rightarrow \chi\chi = \text{invisible} \quad (V \text{ coupling}) \\ \Upsilon \rightarrow \gamma\chi\chi = \gamma + \text{invisible} \quad (A \text{ coupling}) \end{array} \right.$$

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

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

(no decay $\Upsilon \rightarrow$ 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, $b\bar{b} \rightarrow \chi\chi$ and $\chi\chi \rightarrow f\bar{f}$, 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,

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

and from ψ decays,

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

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 $a = \underbrace{\cos \theta_A}_{r \leq 1} A + \sin \theta_A \text{ singlet}$

In many circumstances, U behaves as

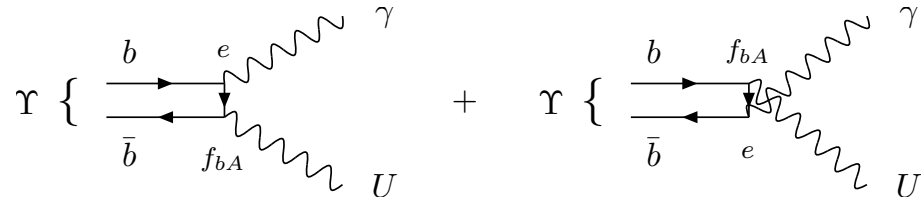
“poorly-visible” (down to “invisible”) axionlike pseudoscalar a

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

$\psi, \Upsilon \dots$ decays ... provide limits on $r = \cos \theta_A$

SEARCHING FOR A LIGHT U in quarkonium decays

$$\Upsilon \rightarrow \gamma U, \quad \psi \rightarrow \gamma U$$

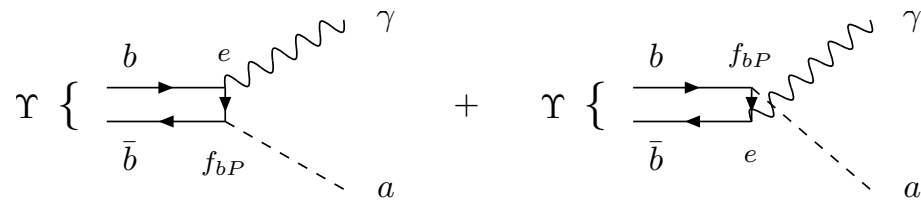


does not vanish even if U couplings to b (f_{bA} and f_{bV}) $\rightarrow 0$!!

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

$$\mathcal{A}(A \rightarrow B + U_{\text{long}}) \propto g'' \dots$$

↑
may be very small !!

but longitudinal polarisation $\epsilon_L^\mu \simeq \frac{k^\mu}{m_U}$ singular when $g'' \rightarrow 0$, as $m_U \propto g'' \dots \rightarrow 0$!

$$\mathcal{A}(A \rightarrow B + U_{\text{long}}) \propto g'' \frac{k_U^\mu}{m_U} \langle B | J_{\mu U} | A \rangle = \frac{1}{F_U} k_U^\mu \langle B | J_{\mu U} | A \rangle$$

$$F_U = \text{symmetry-breaking scale} \quad k^\mu \bar{\psi} \gamma_\mu \gamma_5 \psi \rightarrow 2 m_q \psi \gamma_5 \psi$$

Interaction proportional to $\frac{2 m_q}{F_U}$

*A very light U does not decouple for very small gauge coupling!
behaves as “eaten-away” pseudoscalar Goldstone boson a*

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

$$\Rightarrow \boxed{B(\Upsilon \rightarrow \gamma U) \simeq B(\Upsilon \rightarrow \gamma a)}$$

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

$$\text{decays: } \left\{ \begin{array}{l} U \rightarrow \nu\bar{\nu} \text{ (or light dark matter particles)} \\ U \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q}, \tau^+\tau^- \text{ (depending on } m_U) \end{array} \right.$$

$$\Rightarrow \text{search for } \boxed{\left\{ \begin{array}{l} \Upsilon \rightarrow \gamma + \text{invisible} \\ \Upsilon \rightarrow \gamma + e^+e^- \text{ (or } \mu^+\mu^-, \tau^+\tau^-), \dots \end{array} \right.}$$

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

$\psi(\Upsilon) \rightarrow \gamma + inv.$ *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)

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

A gets mixed with “almost inert” singlet s

U behaves as almost “invisible” axionlike pseudoscalar a

$$a = \cos \theta_A \underbrace{\left(\sqrt{2} \operatorname{Im} (\sin \beta h_1^\circ + \cos \beta h_2^\circ) \right)}_A + \sin \theta_A \underbrace{\left(\sqrt{2} \operatorname{Im} s \right)}_{\text{singlet}}$$

$r = \cos \theta_A = \text{INVISIBILITY PARAMETER}$

(reduces strength or effective strength of U or a interactions, cf. “invisible axion”)

$\psi \rightarrow \gamma U, \Upsilon \rightarrow \gamma U$ 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

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

or equivalent pseudoscalar couplings f_P of a

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

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

$$\begin{aligned} r x = \cos \theta_A \cot \beta < .75 & \Leftrightarrow |f_{cA}| < 1.5 \cdot 10^{-6} m_U (\text{MeV}) \Leftrightarrow |f_{cP}| < 5 \cdot 10^{-3} \\ r/x = \cos \theta_A \tan \beta < .2 & \Leftrightarrow |f_{bA}| < 4 \cdot 10^{-7} m_U (\text{MeV}) \Leftrightarrow |f_{bP}| < 4 \cdot 10^{-3} \end{aligned}$$

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

requires a to be **mostly singlet**

$$\begin{aligned} & \text{doublet fraction} & r^2 = \cos^2 \theta_A < 15\% / B_{inv} \\ \text{or: } \Upsilon \text{ limit} & \Rightarrow \text{doublet fraction} & r^2 = \cos^2 \theta_A < 4\% / (\tan^2 \beta B_{inv}) \end{aligned}$$

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

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

independently of B_{inv}

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

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

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

For invisible decays:

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

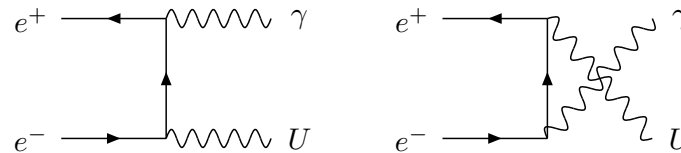
PRD 75, 115017 (2007); PLB 675, 267 (2009); PRD 81, 054025 (2010)

(also limits for $U \rightarrow e^+e^-, \mu^+\mu^-, \dots$)

(not discussed here)

Other processes (and constraints)

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



- U boson may have **visible** ($\rightarrow e^+e^-, \dots$) or **invisible** ($\rightarrow \nu\bar{\nu}$, or $\chi\chi$) decay modes
the latter ($\rightarrow \chi\chi$) possibly dominant

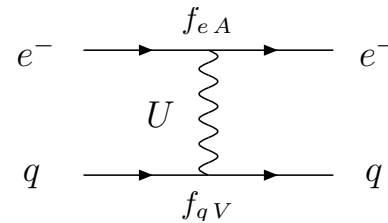
- Production mechanisms and effects depend on whether the U boson has
 V and/or A couplings

(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

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

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

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

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

After mixing :

$$(\epsilon e) \rightarrow Q_U = Q - \frac{5}{4 \cos^2 \theta} (B - L) + Q_U \text{ dark}$$

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

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

$\epsilon = \tan \chi$ 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^- , ...) and **invisible** (dm , neutrinos) decays

“preferred” coupling to

$$e \tan \chi [Q_U = Q - \lambda (B - L) + Q_{U \text{ dark}}]$$

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

Experimental limits on ϵ should be expressed as a function of m_U and λ

[*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 a

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

Experiments such as SHiP may reveal NEW FUNDAMENTAL PHYSICS