The \textit{U} \textsc{Boson} as a generalized \textsc{Dark Photon}

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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

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

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

\[
\begin{cases} 
\text{(spin-1) } U \text{ bosons (including “hidden” or “dark” photons), ...} \\
\text{(spin-0) } \text{axions (or axionlike particles), ...} \\
\text{DARK MATTER particles, ...}
\end{cases}
\]

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?

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

maybe light, even very light, or massless?

which couplings? : $g_s, g, g', g''$

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 focuses 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, $\epsilon e$ (in the visible sector)

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

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 $C^\mu$ mixes with $W_3^\mu$ and $B^\mu$?

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

$\rightarrow$ 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 $SU(3) \times SU(2) \times U(1)_Y \rightarrow SU(5)$, 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 $C^\mu$ still mix with the electroweak $A^\mu$ and $Z^\mu$?

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 \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

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

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 \( \rightarrow \) \( 4 \times 10^{-9} \) s at 1 MeV

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

\[
2.4 \times 10^{-12} \text{ s at 10 MeV} \rightarrow 2.4 \times 10^{-15} \text{ s at 100 MeV}
\]

(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

\[
m_U = 1 \rightarrow 7 \text{ MeV mass excluded}
\]

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

(\textit{but an extra singlet with a large v.e.v. could make the U almost \textit{“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 $J_U^\mu$ to which $U$ couples

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

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

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):

$$F = \alpha B + \beta_i L_i + \gamma Y$$

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

(or $Y$, $B - L$ and $L_i - L_j$ for an anomaly-free theory, including $\nu_R$’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 $B$, $L$, $Y$

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

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 \(Y\)

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

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 \(C^\mu\) mixes with \(Z^\mu_{\text{sm}}\):

\[
\begin{align*}
Z &= \cos \xi \ Z_{\text{sm}} - \sin \xi \ C, \\
U &= \sin \xi \ Z_{\text{sm}} + \cos \xi \ C, \quad \text{with} \quad \tan \xi \approx \frac{g''}{\sqrt{g^2 + g'^2}}
\end{align*}
\]

\[
\begin{align*}
A &= g' W_3 + g B \\
&= \frac{g' W_3 + g B}{\sqrt{g^2 + g'^2}}, \quad = \sin \theta W_3 + \cos \theta B, \\
Z &\approx \frac{g W_3 - g' B - g'' C}{\sqrt{g^2 + g'^2 + g''^2}} \approx \cos \theta W_3 - \sin \theta B, \\
U &\approx \frac{g''(g W_3 - g' B) + (g^2 + g'^2) C}{\sqrt{g^2 + g'^2 \sqrt{g^2 + g'^2 + g''^2}}} \approx C.
\end{align*}
\]

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

\[ J^{\mu}_U = \cos \xi \left( \frac{g''}{2} J^{\mu}_F \right) + \sin \xi \sqrt{g^2 + g'^2} \left( J^{\mu}_3 - \sin^2 \theta J^{\mu}_{em} \right) \]

\[ J^{\mu}_F, \text{ involves } B, L \text{ and } Y \]

(usually) family-universal

Both parts parity-violating, combine into

\[ U \text{ Current (almost) pure } V \text{ (if only 1 doublet + singlet)} \]

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

Vector current \quad \text{linear combination of } B, L, Q \text{ currents}

\[ J^{\mu}_U = g'' \cos \xi \left( \cos^2 \theta J^{\mu}_{em} + \frac{1}{2} \left( \alpha_B J^{\mu}_B + \beta_i J^{\mu}_{L_i} + J^{\mu}_d \right) \right) \]

\[ = e \tan \chi \left( J^{\mu}_{em} + \frac{1}{2 \cos^2 \theta} \left( \alpha_B J^{\mu}_B + \beta_i J^{\mu}_{L_i} + J^{\mu}_d \right) \right). \]

with \( \epsilon_Q = \tan \chi = \frac{g''}{g'} \frac{g}{\sqrt{g^2 + g'^2 + g''^2}} \approx \frac{g''}{g'} \cos \theta, \)
In general: coupling to 

\[(\epsilon_Q Q + \epsilon_B B + \epsilon_L L) e\]

(not just to \(\epsilon_Q e\) !)

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

After mixing, \(J_Y^\mu\) and \(J_Z^\mu\) combine so as to reconstruct \(J_{em}^\mu\)

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**

\(U = \) very light "**dark photon""

leading to short-range modifications to electromagnetism

(NPB 347 (1990) 743)

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In general:

\[ U = \text{generalized "dark photon" coupled to } (\epsilon_Q Q + \epsilon_B B + \epsilon_L L) \]

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

**Within GRAND-UNIFICATION:**

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

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

\[ \epsilon_Q = - \frac{4}{5} \cos^2 \theta \epsilon_{B-L} \simeq -0.61 \epsilon_{B-L} \]

\[ \epsilon_{B-L} \left[ (B - L) - \frac{4}{5} \cos^2 \theta Q \right] e = \epsilon_{B-L} (B - L - 0.61 Q) e \]

equivalently expressed as

\[ \epsilon_Q \left[ Q - \frac{5}{4 \cos^2 \theta} (B - L) \right] e = \epsilon_Q \left[ Q - 1.64 (B - L) \right] e \]
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 $\chi$ 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** $\chi$

by allowing for sufficient LDM annihilations into SM particles
LIGHT DARK MATTER

(in ~ MeV to GeV range)

quite unconventional, at least for lower masses

*How can it be possible??*
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 $\sigma_{\text{ann}}$ at lower energies
NEW INTERACTION induced by spin-1 $U$ boson

sufficiently strong at lower energies

$\chi \xrightarrow{U} e^+ \xleftarrow{e^-}$

or

$\varphi \xrightarrow{U} e^+ \xleftarrow{e^-}$

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

\[ \text{propagator} \quad \frac{1}{q^2 - m_U^2} : \begin{cases} 
\frac{-1}{m_U^2} & \text{for } |q| \ll m_U \\
\frac{1}{q^2} & \text{for } |q| \gg m_U \\
\end{cases} \]

- (local limit at lower energies)
- $\sigma \nearrow$ with $E$ (as for weak int.)
- “stronger-than-weak” at lower energies

- (ignore $m_U$ at higher energies)
- $\sigma \searrow$ with $E$ (as in QED)
- “weaker-than-weak” at higher energies

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, \( \nu \bar{\nu} \ldots \), depending on \( m_\chi \))

\[
\sigma_{\text{ann}}^{ee} v_{\text{rel}} \approx \frac{v_\chi^2}{0.16} \left( \frac{c_\chi f_e}{10^{-6}} \right)^2 \left( \frac{m_\chi \times 1.8 \ \text{MeV}}{m_U^2 - 4 m_\chi^2} \right)^2 (4 \ \text{pb})
\]

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

\[
\sigma_{\text{ann}} \text{ OK for } |c_\chi f_e| \approx (B_{\text{ann}}^{ee})^{\frac{1}{2}} 10^{-3} \frac{|m_U^2 - 4 m_\chi^2|}{m_\chi (1.8 \ \text{GeV})}
\]

\[
\approx (B_{\text{ann}}^{ee})^{\frac{1}{2}} 10^{-6} \frac{|m_U^2 - 4 m_\chi^2|}{m_\chi (1.8 \ \text{MeV})}
\]
LIGHT DARK MATTER in $\Upsilon$ DECAYS

$$\Upsilon \left\{ \begin{array}{c} b \\ \bar{b} \end{array} \right\} \rightarrow U \rightarrow \begin{array}{c} \chi \\ \chi \end{array} \{ \text{invisible} \}$$

*Invisible $\Upsilon$ decay into LDM particles*

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

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

$$\Upsilon \rightarrow \chi\chi \text{ and } \gamma\chi\chi \text{ test vector and axial couplings to } b$$

*(no decay $\Upsilon \rightarrow \text{invisible} \text{ mediated by spin-0 exchanges})*

*What may be the expected rates?*
For Light DM particles

Invisible $\Upsilon$ 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 $\Upsilon$ decay forbidden)

For invisible $\Upsilon$ decays mediated by a light $U$,

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

and from $\psi$ decays,

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

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

\[ r = \cos \theta_A \text{ (depending on } \tan \beta) \]

\[ f_{eA} f_{qV} \text{ from atomic physics exp.} \]

...
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 $a = \frac{\cos \theta_A}{r \leq 1} A + \sin \theta_A$ singlet

In many circumstances, $U$ behaves as “poorly-visible” (down to “invisible”) axionlike pseudoscalar $a$.

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

$\psi, \Upsilon$ ... decays ... provide limits on $r = \cos \theta_A$
SEARCHING FOR A LIGHT U in quarkonium decays

\[ \Upsilon \rightarrow \gamma U, \; \psi \rightarrow \gamma U \]

\[ \Upsilon \{ b \rightarrow e \gamma U \} + \Upsilon \{ b \rightarrow \bar{b} f_{bA} \gamma U \} \]

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)

\[ \Upsilon \{ b \rightarrow e \gamma U \} + \Upsilon \{ b \rightarrow \bar{b} f_{bP} \gamma U \} \]
Amplitude for producing $U$ proportional to gauge coupling 

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

↑

may be very small!!

but longitudinal polarisation $\epsilon_{L}^{\mu} \simeq \frac{k_{\mu}}{m_{U}}$ singular when $g'' \rightarrow 0$, as $m_{U} \propto g'' \ldots \rightarrow 0$!

$$\mathcal{A} ( A \rightarrow B + U_{\text{long}} ) \propto g'' \frac{k_{\mu}^{U}}{m_{U}} <B | J_{\mu U} | A> = \frac{1}{F_{U}} k_{\mu}^{U} <B | J_{\mu U} | A>$$

$F_{U} = $ symmetry-breaking scale $k_{\mu}^{U} \bar{\psi} \gamma_{\mu} \gamma_{5} \psi \rightarrow 2m_{q} \psi \gamma_{5} \psi$

Interaction proportional to $\frac{2m_{q}}{F_{U}}$

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

behaves as “eaten-away” pseudoscalar Goldstone boson $a$

effective pseudoscalar coupling: $f_{q,l}^{P} = f_{q,l}^{A} \frac{2m_{q,l}}{m_{U}}$
same experiments can search for light spin-1 gauge boson, or spin-0 pseudoscalar, or scalar decay:

- $U \rightarrow \nu \bar{\nu}$ (or light dark matter particles)
- $U \rightarrow e^+e^-, \mu^+\mu^-, q\bar{q}, \tau^+\tau^-$ (depending on $m_U$)

⇒ search for

- $\Upsilon \rightarrow \gamma + invisible$
- $\Upsilon \rightarrow \gamma + e^+e^-$ (or $\mu^+\mu^-, \tau^+\tau^-$), ...
Light $U$ behaves very much as spin-0 “axionlike” (eaten-away) pseudoscalar $a$

$$\psi(\Upsilon) \rightarrow \gamma + \text{inv.} \text{ excluded standard axion in the 80's ...}$$

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 $a$

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

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

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

$$\psi \rightarrow \gamma U, \ \Upsilon \rightarrow \gamma U \text{ decay rates } \propto r^2 = \cos^2 \theta_A$$
ψ and Υ decays provide strong limits on axial couplings $f_A$ of $U$ to $c$ or $b$

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

or equivalent pseudoscalar couplings $f_p$ of $a$

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

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

$$rx = \cos \theta_A \cot \beta < .75 \iff |f_{cA}| < 1.5 \times 10^{-6} m_U(\text{MeV}) \iff |f_{cP}| < 5 \times 10^{-3}$$

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

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

requires $a$ to be mostly singlet

doublet fraction $r^2 = \cos^2 \theta_A < 15\% / B_{\text{inv}}$

or: $\Upsilon$ limit $\Rightarrow$ doublet fraction $r^2 = \cos^2 \theta_A < 4\% / (\tan^2 \beta B_{\text{inv}})$
if large $\tan \beta$, $\Upsilon$ limit $\Rightarrow$ not much chance to see $\psi \rightarrow \gamma U_{inv}$ ...

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

independently of $B_{inv}$
Furthermore, with \( f_{eA} = f_{bA} \) from universality constraints,

\[
\Upsilon \to \gamma + U_{\text{inv}} \text{ decays constrain } \text{axial } U \text{ couplings to electron}
\]

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

For invisible decays:

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

(\text{also limits for } U \to e^+e^-, \mu^+\mu^-, ...)

(not discussed here)
Other processes (and constraints)

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

- $U$ boson may have **visible** ($\rightarrow e^+ e^-$, ...) 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, $g_e \rightarrow 2$, $g_{\mu} \rightarrow 2$, $\nu$ scatterings, ...

- Constraints from $\psi$, $\Upsilon$, $K^+$, $\pi^0$, $\eta$, $\eta'$ ... decays, ...

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

\[ \ldots \]
Parity violations in atomic physics

\[
\begin{array}{c}
\text{e}^-
\quad \quad f_{eA}
\quad \quad e^-
\quad \quad U
\quad \quad q
\quad \quad f_{qV}
\quad \quad q
\end{array}
\]

**strong limit:** \[ \sqrt{|f_{eA} f_{qV}|} < 10^{-7} m_U(\text{MeV}) \]

*With constraints from \(\psi, \Upsilon, K^+, \pi^0, \eta, \eta'\) ... decays,*

*may favor vector \(U\) coupling to SM particles through*

\[
(\epsilon e) \quad Q - \lambda (B - L)
\]

*(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:

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

\[ \left[ = \frac{Q - 2 (B - L)}{2} \right] \text{ at the GUT scale } \]

commutes with $SU(4)$ electrostrong symmetry

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

\[ \epsilon = \tan \chi \text{ is already present at the GUT scale}! \]

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

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

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

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

[ 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 $\alpha$

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

Experiments such as SHiP may reveal NEW FUNDAMENTAL PHYSICS