BOSONS U et PHOTONS CACHÉS

extra $U(1)$ *s et NOUVELLES FORCES*

Pierre FAYET

LAL, Orsay

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we are used to discuss the

VERY HIGH-ENERGY FRONTIER :

searching for new particles, new interactions, at very high energies

LHC **has just discovered** **a new particle**

with a mass close to 125 GeV

which may well be a, or the

Brout-Englert-Higgs boson

associated with **electroweak symmetry breaking** **in the standard model**

(the only missing part in SM)

Is it really the BEH boson of the standard Model ?

or has it some different properties, that could signal **new physics** ?

we should know soon ...

In any case:

SM cannot be the end of the story, there must be

NEW PHYSICS beyond the Standard Model

What kind of new physics ?

New PARTICLES, new INTERACTIONS, maybe new SPACETIME DIMENSIONS ...

searched for at very high-energies, now **LHC**, to explore **TeV** scale ...

One of the main questions:

Is there a "SUPERWORLD" of new particles ?

Could half of the particles *(at least)* have escaped direct observations ?

$\rightarrow$ *new matter ... ?* $\rightarrow$ *dark matter ... ?*

but supersymmetric particles did not show up yet !!

Most mass limits now close to TeV

thanks to ATLAS and CMS

(after negative results from PETRA, PEP, LEP and FermiLab ...)

is this something to worry about ?

What about supersymmetry breaking ?

Is it fixed by a **compactification scale** ?

R-odd particles having large masses $\approx \pi/L$ from compactification

with boundary conditions involving R-parity ?

Is there a relation with electroweak or TeV scales ??

(not the subject of this talk ...)

Charged and neutral spin-0 bosons

associated with electroweak breaking within SUSY ?

(not found yet ...)

"MSSM" very strongly (too strongly!) constrained

Spin-0 boson at $\simeq \mathbf{125}$ GeV (significantly above m_Z)

tends to require (within susy) additional quartic couplings

as from $\lambda\, H_1 H_2\, S$ *superpotential coupling to singlet* S

as in N/nMSSM or USSM ...

waiting for more experimental results ...

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

Simplest possibility

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

which extra $U(1)$'s may be gauged ?

which masses for new gauge bosons ?

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

maybe light, even very light, or massless ?

which couplings ?

gauge coupling $\leftrightarrow$ intensity of new interaction

$\Rightarrow$ **possibility of new forces**

next to gravitation, electromagnetism, weak NC force ...

a long time ago ...

SEARCHING FOR A NEW SPIN-1 BOSON

NPB 187 (1981) 184

a very light and very weakly coupled U boson

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

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, ψ and Υ decays

beam dump experiments ...

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

results depend crucially on BE-Higgs sector responsible for mixing

important for phenomenology

general discussion, results:

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

1) *general features of extra $\boldsymbol{U(1)}$ symmetries ($\boldsymbol{F}$) that may be gauged*

from gauge invariance of Yukawa couplings

if **1 doublet only (+ possible singlets) :**

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

if **2 doublets as in SUSY SM** *with 2 doublet BE-Higgs (super)fields* $\begin{pmatrix} h_1^0 \\ h_1^- \end{pmatrix}, \begin{pmatrix} h_2^+ \\ h_2^0 \end{pmatrix}$

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 in SUSY (or non-SUSY) theories

possibly combined with B, L *and* Y *symmetries*

$$F = \alpha B + \beta L + \gamma Y + \delta F_{ax}$$

further constraints in GUTs (with $SU(5)$ quintuplets and decuplets), usually involve

$$\left[\tfrac{5}{2}(B-L)-Y\right] \quad \textit{and} \quad F_{ax} \qquad \textit{(at GUT scale)}$$

2,3) mixing effects between neutral gauge bosons

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

with light or even massless U

write mixing matrix, depends on BE-Higgs sector, usually 1 or 2 ... doublets + singlet(s))

$$J_U^\mu \;=\; \underbrace{\text{extra-}U(1)\text{ current } J_C^\mu}_{\text{involves } B,\, L \text{ and } Y} \;+\; \text{term} \propto \underbrace{J_Z^\mu}_{J_3^\mu - \sin^2\theta\, J_{em}^\mu} \qquad \textit{from mixing}$$

(usually) family-universal (for simple BE-Higgs sectors)

4) Vector part of current = linear combination of $B,\ L,\ Q$ currents

U Current pure V if only 1 doublet (+ singlets)

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

Special case: $J_C^\mu \propto J_Y^\mu$ *(for matter fermions, not BE-Higgs singlet(s)* $\longrightarrow$ ...

U Current pure V if only 1 doublet (+ singlets)

Special case: $J_C^\mu \propto J_Y^\mu$ *(for matter fermions, not BE-Higgs singlet(s))*

Then after mixing, **combining J_Y^μ and J_Z^μ so as to reconstruct J_{em}^μ**

(equivalent to "kinetic mixing")

$J_U^\mu \propto J_{em}^\mu$ *(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)

$U =$ **"hidden photon"**

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

many possible consequences, and constraints

including a possible explanation of the $\approx 3\sigma$ *effect observed in* $g_\mu - 2$

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

but no axionlike particle has been found ...

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

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

...

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

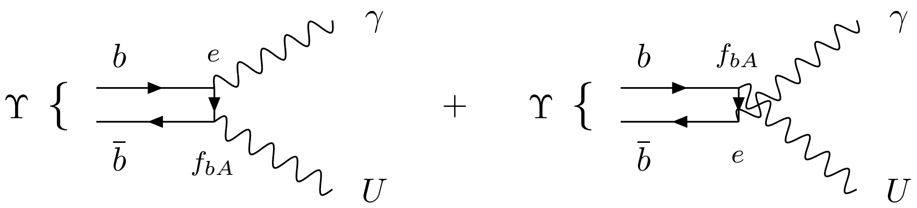
amplitudes $\mathcal{A} \propto (r = \cos\theta_A)$ **rates** $\propto (r^2 = \cos^2\theta_A)$

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

($\cos\theta_A$ *also called* $\cos\zeta$ *in later slides)*

SEARCHING FOR A LIGHT U in quarkonium decays

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

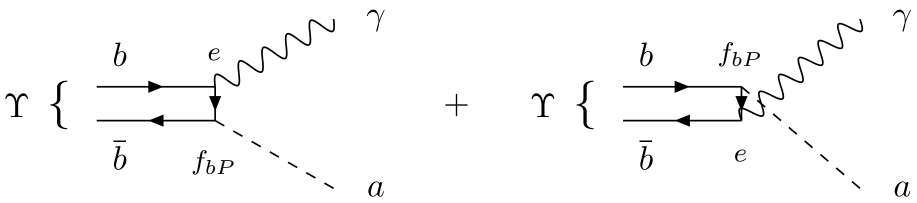


does not vanish even if U *couplings to* b (f_{bA} *and* f_{bV}) $\to 0$ *!!*

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 $\epsilon_L^\mu \simeq \dfrac{k^\mu}{m_U}$ *singular when* $g" \to 0$, *as* $m_U \propto g" \ldots \to 0$ *!*

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

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

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 $\boldsymbol{a}$

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

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

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

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)

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

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

U behaves as almost "invisible" axionlike pseudoscalar a

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

$r \;=\; \cos\zeta$ = *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* $\propto\ r^2 = \cos^2\zeta$

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

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

or equivalent pseudoscalar couplings f_p of a

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

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

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

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

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

requires a to be mostly singlet

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

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***

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

For invisible decays:

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

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

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

(not discussed here)

From (old) (hadronic) beam dump experiments:

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

$m_U = 1 \to 7$ **MeV mass excluded**

in simplest situation *(1981)*

(EW breaking induced by 2 Brout-Englert-Higgs doublets without extra singlet)

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

Additional part in U current

involving **(Light) DARK MATTER particle** χ may also be present

the DM particle remaining neutral (unless one decides otherwise)

$\rightarrow$ dark forces, dark photon, ...

U may be **"dark photon"**

couples (very weakly) to SM particles (and dark matter particles)

But U is more general as just "dark photon"

coupling to SM through electromagnetic current

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. Bœhm
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 ... !! ??

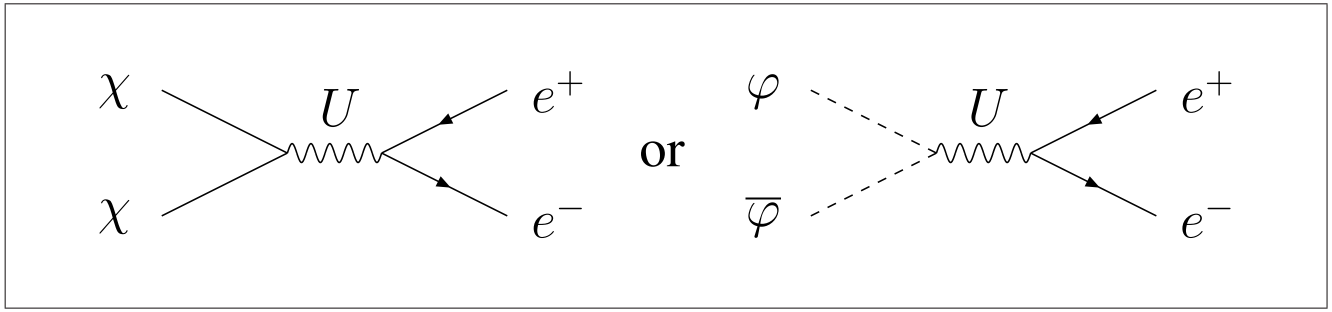
may be possible only with a new interaction, but ...

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 ...

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.)*

  → **"stronger-than-weak" at lower energies**

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

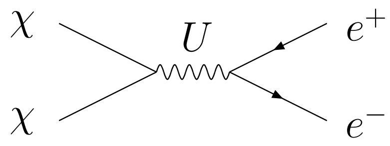
  $\sigma \searrow$ *with* E *(as in QED)*

  → **"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

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



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

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

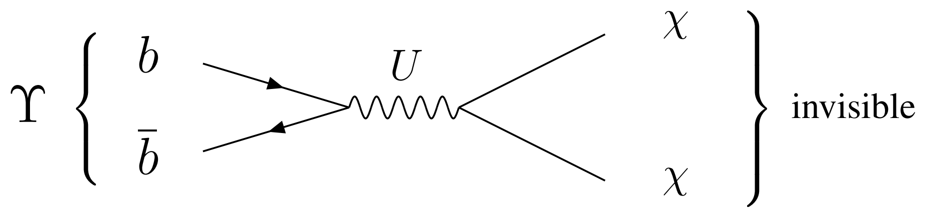
required $c_\chi\, f_e$ *for correct total annihilation c.s.* ($\sigma_{\rm ann} = \sigma_{\rm ann}^{ee}/B_{\rm ann}^{ee}$) *at freeze out*

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

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

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

LIGHT DARK MATTER in Υ DECAYS



Invisible Υ decay into LDM particles

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

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,

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

and from ψ decays,

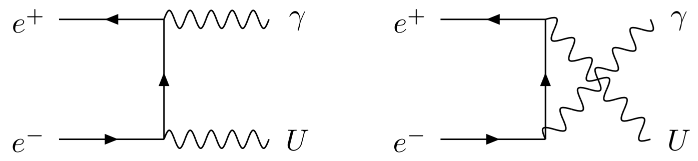
$$\psi \to \underbrace{\chi\,\chi}_{\text{inv}} < 7.2\;10^{-4} \;\textit{(BES II)} \;\Rightarrow\; |c_\chi\, f_{cV}| < .95\;10^{-2}$$

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

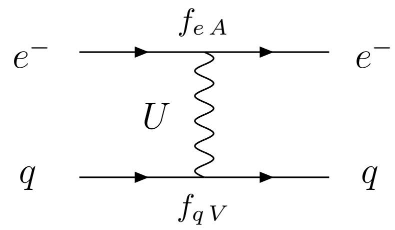
Other processes (and constraints)

Dark Matter annihilations, 511 keV annihilation line, $g_e - 2$, $g_\mu - 2$, ν scatterings, supernovae explosions, ...

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



Parity violations in atomic physics



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

With constraints from ψ, Υ *and* K^+ *decays,*

may favor **vector U coupling to SM particles** *through* $\boxed{\alpha\,(B-L) + \gamma\, Q}$

possibly through electromagnetic current (→ **"dark photon" searches, with $U \equiv A'$**)

CONCLUSION

In addition to high-energy frontier at LHC (NLC, ...)

another frontier, at much lower energies:

light **weakly (or very weakly) coupled new particles** *associated with symmetries*

U boson, light dark matter, axionlike particles, ...

U *may appear as* **'dark photon"** γ'

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

or (much more generally) coupled to combination of B, L (*or* $B-L$) *and* Q

with possibly **axial** *contribution*

could mediate extremely-weak long-ranged force next to gravity

could be produced like **light pseudoscalar a**

(reminiscent of "invisible axion" or light pseudoscalar in SUSY SM)

This may reveal **new fundamental physics**

new PARTICLES, new FORCES, new MATTER, new SYMMETRIES