LIGHT DARK MATTER

and

U BOSONS

in QUARKONIUM DECAYS

Pierre FAYET

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1974: $\psi\ (c\bar{c})$ **discovery** *SLAC (Richter ...), MIT (Ting ...)*

1977: $\Upsilon\ (b\bar{b})$ **discovery** *FermiLab (Lederman ...)*

NOT A NEW SUBJECT !

1977-78: Search for light Higgs bosons or axions in $\psi(\Upsilon) \rightarrow \gamma\, h$ *or* $\gamma\, a$;

and more exotic particles, already $\sim$ *30 years ago :*

1979: **gravitinos** and **photinos** in $\psi \rightarrow$ *invisible*

PLB 84 (1979) 421

1980: **light U bosons** in $\psi \rightarrow \gamma\, U \quad (\Upsilon \rightarrow \gamma\, U)$

NPB 187 (1981) 184

1991: **light dark matter** in $\Upsilon \rightarrow \chi\chi$ *or* $\gamma\, \chi\chi$

PLB 269 (1991) 213

experimental limits not very good yet ... *(→ much better now !)*

we are used to discuss **very high energy frontier :**

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

Waiting for LHC to (presumably) discover the

Brout-Englert-Higgs ... boson

(practically constrained to 114 $\leftrightarrow$ 145 GeV)

only missing part in Standard Model

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 ... ?*

What is (non-baryonic) **DARK MATTER ?**

In the late 70's, one did not talk so much about dark matter

mostly considered it could be made of

(massive but light) neutrinos ν_e, ν_μ or ν_τ

now referred to as "hot dark matter"

(... seems in disagreement with data ...)

At the same time (70's)

SUPERSYMMETRIC extensions of STANDARD MODEL

SM particles $\leftrightarrow$ SUPERPARTNERS

gluinos, squarks, selectrons, smuons ...

spin-$\frac{1}{2}$ **NEUTRALINOS**, spin-$\frac{3}{2}$ **GRAVITINO** (spin-0 sneutrinos)

Pair-production of new particles

Lightest (LSP) expected **stable** thanks to ***R*-parity**

and (usually) **"weakly-interacting"** $\longrightarrow$ natural dark matter candidate

as soon as one was needed, other than neutrinos ...

What is R-PARITY ? *PLB69(1977)489;B76(1978)575*

Continuous $U(1)_R$ *acts chirally on SUSY generator* *(not SM particles)*

but would require gluinos and photino to stay massless ...

In any case broken by **gravitino mass term** $m_{3/2}$ *in supergravity*

$U(1)_R$ *broken (by gravitino and gluino ... mass terms ...)*

$(m_{3/2},\ m_i,\ \mu, \dots)$

$U(1)_R$ *reduced to discrete symmetry* R_p

$$R_p = (-1)^R = \begin{cases} +1 : & \text{ordinary particles} \\ -1 : & \text{superpartners} \end{cases}$$

R*-parity then identified as* $(-1)^{2S}\,(-1)^{3B+L}$

related to B *and* L*, prevents exchanges of* $\tilde{q},\ \tilde{l}$ *between quarks and leptons ...*

pair production of SUSY particles

R-parity $\Rightarrow$ LSP stable, non-baryonic DM candidate

NEUTRALINO

combination of superpartners of neutral gauge and Higgs bosons

naturally "weakly-interacting" *through* $\tilde{q},\ \tilde{l},\ Z$ *or Higgs exchanges*

PLB 86(1979)272 ...

$$\{W_3,\ W';\ h_1^\circ,\ h_2^\circ;\ \dots\} \stackrel{SUSY}{\longleftrightarrow} \underbrace{\{\tilde{W}_3,\ \tilde{W}';\ \tilde{h}_1^\circ,\ \tilde{h}_2^\circ;\ \dots\}}_{\text{neutralinos}}.$$

possible alternative:

[LSP less-than-weakly-interacting for very-weakly coupled gravitino LSP

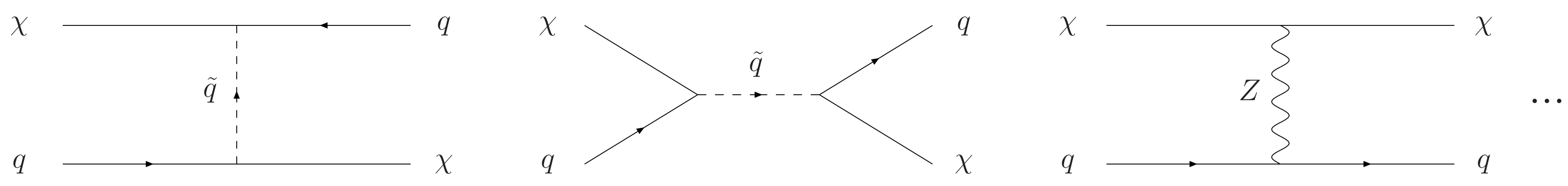
decoupling very early, also possible DM candidate]

$$\textit{graviton} \stackrel{SUSY}{\longleftrightarrow} \textit{gravitino}$$

DM relic density evaluated from annihilation cross-sections at freeze-out

(relic density $\propto\ 1/(\sigma_{ann})_{FO}$)

with $\boldsymbol{\sigma_{ann}}$ $\approx$ weak cross sections **from squark, slepton, Z or Higgs exchanges**



(DM interactions with quarks) $\longleftrightarrow$ *(DM annihilations* $\rightarrow$ $q\bar{q}$*)*

neutralino $=$ natural WIMP candidate

precise relic density depends on $\tilde{q}$ and $\tilde{l}$ masses ($\gtrsim$ TeV ?? from LHC ?), mixing angles, ...

No SUSY relation between known particles and forces ....

but ...

DM candidate from lightest neutralino in SUSY SM

relation of dark matter with gauge ($\gamma, Z, ...$) and Higgs bosons

(graviton if gravitino DM)

$\longrightarrow$

DARK MATTER related with

mediators of (ELECTROWEAK) INTERACTIONS

Relation

DARK MATTER $\leftrightarrow$ FORCE(S)

Can we produce directly DARK MATTER

at particle colliders ?

most notably LHC ...

or quarkonium decays ...

Producing NEUTRALINOS (or DARK MATTER) *at colliders*

pair-production of neutralinos *(or DM candidates)*

stable from R-parity *(or similar)*

$p\,p \;\longrightarrow$ *pair of* **squarks** *or* **gluinos** ... $\longrightarrow$ **2 neutralinos** $+\;\ldots$

Missing energy-momentum signature of SUSY ... *(1977 ...)*

PLB69(1977)489 ...

interact $\sim$ *"weakly" through* $\tilde q$ *etc. exchanges* *PLB86(1979)272 ...*

or directly $e^+\,e^- \;\longrightarrow\; \ldots \;\longrightarrow$ **2 neutralinos** $+\;\ldots$ *(1977 ...)*

through $\tilde e$ *... production or exchanges* *PLB69(1977)489;B117(1982)460 ...*

or, for unstable neutralinos (NLSP) → (photon + gravitino):

as in "GMSB" models with very light gravitino LSP PLB70(1977)461 ...

$$\left\{ \begin{array}{llllll} e^+e^- & \longrightarrow & \textbf{2 neutralinos} + \ldots & \longrightarrow & \gamma\,\gamma + \textbf{2 gravitinos} + \ldots \\ p\,p & \longrightarrow & \textbf{2 neutralinos} + \ldots & \longrightarrow & \gamma\,\gamma + \textbf{2 gravitinos} + \ldots \end{array} \right.$$

search for photons + missing energy-momentum

Accelerators can look for Dark Matter ...

NEUTRALINOS and DM in quarkonium decays

invisible ψ and Υ decays

$$\begin{cases} \psi(2S) & \longrightarrow \; \pi^+\pi^- \, \psi\,(1S)\; (\longrightarrow \textit{inv.}) \\ \Upsilon(3S\,(2S)) & \longrightarrow \; \pi^+\pi^- \, \Upsilon\,(1S)\; (\longrightarrow \textit{inv.}) \end{cases}$$

$\psi \longrightarrow$ ***inv.*** *(1979)*: *search for* **(light) photinos** *and* **(ultralight) gravitinos**

PLB84(1979)421

$\Upsilon \longrightarrow$ ***inv.*** *(1991): search for* **light dark matter particles** **("cosmions")**

PLB269(1991)213

given that $\Upsilon \rightarrow \nu\bar{\nu} \simeq 10^{-5}$ $\quad (\psi \rightarrow \nu\bar{\nu} \simeq (2 \text{ to } 3)\, 10^{-8})$

$\Upsilon \longrightarrow$ ***inv.*** or $\gamma +$ ***inv.*** *may restrict production of* **light DM particles**

(discussed later)

"Expected" BR ?? can it be "predicted" from DM annihilation cross sections ??

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 (2003)

NPB683(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 ...

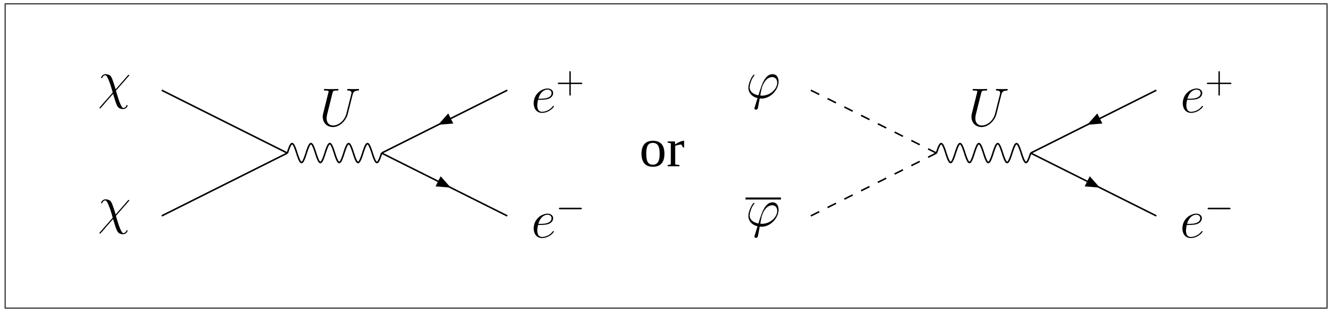
New interaction should be

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 ...)

le deuxième truc (since 1980 ...)

Interaction mediated by LIGHT spin-1 U boson

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

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

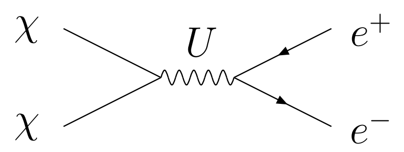
$$\begin{cases} \dfrac{-1}{m_U^2} \quad \textit{for} \;\; |q| \ll m_U & \textit{(local limit at lower energies)} \\ & \sigma \nearrow \textit{ with } E \textit{ (as for weak int.)} \\ & \textbf{“stronger-than-weak” at lower energies} \\ \longrightarrow & \\ \dfrac{1}{q^2} \quad \textit{for} \;\; |q| \gg m_U & \textit{(ignore } m_U \textit{ at higher energies)} \\ & \sigma \searrow \textit{ with } E \textit{ (as in QED)} \\ \longrightarrow & \textbf{“weaker-than-weak” at higher energies} \end{cases}$$

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)

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

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*

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

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

Where can **extra-$U(1)$ come from ?**

how a light U could be detected ?

Light $U \sim$ (MeV to GeV) *discussed since 1980*

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

allowing for possible **extra-$U(1)_A$ symmetry**

$h_1 \to e^{i\alpha}\, h_1, \;\; h_2 \to e^{i\alpha}\, h_2$ *of 2 HD models (1974)*

watch out for a possible **spin-0 "axion" (if $U(1)_A$ global,** *1976*) **!**

gets **"eaten away" when U acquires mass** *(PLB69(1977)489)* $\longrightarrow$ *now USSM*

Still it may **"resurrect"** *as we shall see*, **if U is light**

A light U with axial couplings is very reminiscent of a spin-0 axion ... *(1980)*

general discussion, under simple hypothesis *NPB 347 (1990) 743*

extra-$U(1)$ acts *(on SM particles) as*

combination of $B, L, Y,$ with $U(1)_A$ generator *(if 2 Higgs doublets as in SUSY)*

After mixing between neutral gauge bosons: U *current* =

AXIAL part *(depending on Higgs sector, 2 doublets + possible singlet ...)*

+ **VECTOR part** *c.l. of* B, L *(or* $B - L$*)* *and* **electromagnetic** *currents*

+ *possible* **DARK MATTER** *contribution* **(if LDM particle)**

If no axial part, U **coupled to SM particles through a VECTOR current, e.g.**

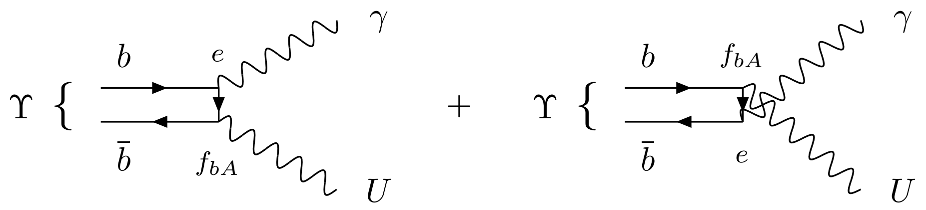
$$J_U^\mu = \alpha\, J_{B-L}^\mu + \gamma\, J_{em}^\mu + J_{dark}^\mu$$

Special case, U **coupled to SM through electromagnetic current** *(NPB 347 (1990) 743)*

$U =$ **"dark photon"**

SEARCHING FOR A LIGHT U in quarkonium decays

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



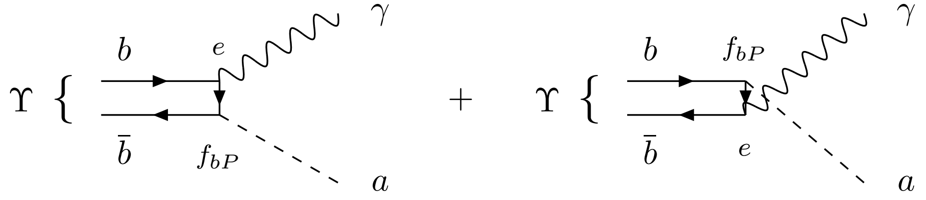
does not vanish even if U *couplings to* b *(*f_{bA} *and* f_{bV}*)* $\to 0$ *!!*

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

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

NPB 187, 184, 1981, ... ,

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

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

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

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

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)* *PF, PLB 95, 285, 1980; NPB 187, 184, 1981*

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

A gets mixed with "almost inert" singlet s

U behaves as almost "invisible" axionlike pseudoscalar a

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

$r \;=\; \cos\zeta$ = **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:

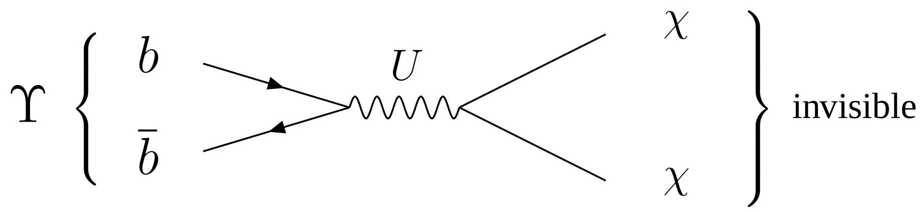
$|f_{eP}| \, < \, \frac{1}{5}$ [standard Higgs coupling to electron ($2 \; 10^{-6}$)]

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)

LIGHT DARK MATTER in Υ DECAYS



Invisible Υ decay into LDM particles

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

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,

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

and from ψ decays,

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

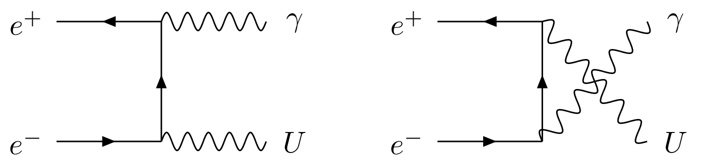
PRD 74(2006)054034, ... , PRD 81(2010)054025

Other processes (and constraints)

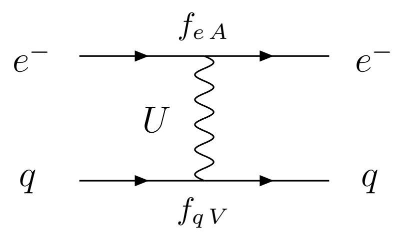
Dark Matter annihilations, 511 keV annihilation line, $g_e - 2$, $g_\mu - 2$,

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 $U \equiv A'$)**

CONCLUSIONS

familiar scenario:

- **pair-production of SUSY particles at colliders**, *with 2 doublets* h_1, h_2 *+ extra singlet*
- **stable LSP (neutralino ...)** $\rightarrow$ **dark matter**

Search for dark matter ... **Explore high-energy frontier at LHC** *(NLC, ...)*

Another frontier (at lower energies) !

light weakly (or very weakly) coupled new particles

including

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

may reveal **new fundamental physics, new FORCES** *and/or* **new MATTER**

from **quarkonium decays ...**