SUPERSYMÉTRIE,

MATIÈRE SOMBRE

et

NOUVELLES PARTICULES

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Is there a

" SUPERWORLD " ?

of new particles ?

Could half of the particles (at least)

have escaped our direct observations ?

→ *new matter ... ?*

→ *dark matter ... ?*

moreover ...

Could there exist

new LIGHT PARTICLES ?

NEUTRAL, and VERY WEAKLY COUPLED ?

among which ...

a new light gauge boson *U* ?

axionlike ... particles ?

light dark matter particles ?

...

new forces beyond strong, electro + weak, gravity ... ?

New *particles*, *new* *forces*, *and also new* *space-time* ...

Should the notion of space-time be extended to

new (fermionic or bosonic) coordinates ?

$\longrightarrow$

SUPERSPACE

$(\boldsymbol{x^\mu},\ \boldsymbol{\theta})$ ...

EXTRA DIMENSIONS

$(\boldsymbol{x^\mu},\ \boldsymbol{x^5},\ \boldsymbol{x^6})$ ...

furthermore:

extended supersymmetric theories naturally formulated

with extra (compact) space dimensions

starting point:

STANDARD MODEL

describes

strong, electromagnetic and weak interactions of quarks and leptons

$SU(3) \times SU(2) \times U(1)$ **gauge group**

spin-1 gauge bosons:	**gluons,** $\underbrace{W^+, W^-, Z, \text{photon}}$
spin-$\frac{1}{2}$ fermions:	**quarks and leptons**

+ 1 (still unobserved) spin-0 **Englert-Brout-Higgs boson**

associated with **spontaneous electroweak symmetry breaking**

– *remarkably successful*

– *but leaves many questions unanswered:* *(a long list ...)*

- **fundamental Higgs fields ?** (**do they actually exist ?**)

many physicists long reluctant to accept fundamental spin-0 fields

- **why a potential** $V(\varphi) \;=\; \lambda\,|\varphi|^4 \;-\; \mu^2\,|\varphi|^2$ **?**

what is the mass of the B-E-Higgs boson ? ($m_H \;=\; \mu\,\sqrt{2} \;=\; v\,\sqrt{2\,\lambda}\ldots$)

what fixes μ **?** **what fixes coupling constant** λ **?**

is B-E-Higgs sector as in SM, or more complicated ... ?

- **do new particles exist ? maybe also new forces ?**

after LEP, we think we know all (sequential) quarks and leptons

now essential, in view of growing evidence for

non-baryonic dark matter

Other interrogations :

- **role of gravity** (related to **spacetime** through general relativity)

  can it be more closely connected with particle physics ?

  can one get a consistent theory of quantum gravity ?

  question of cosmological constant Λ ...

- **can interactions be unified ?** approach of **grand-unification :**

  $SU(3) \times SU(2) \times U(1) \subset$ e.g. $SU(5)$, ...

$$\begin{cases} \text{gluons} \longleftrightarrow W^{\pm},\ Z,\ \gamma & \text{(+ other gauge bosons)} \\ \text{quarks} \longleftrightarrow \text{leptons} & \end{cases}$$

with its own questions: *Higgs potential and symmetry breaking, origin of hierarchy of mass scales, many coupling constants, relations between* q *and* l *masses ...*

- can one **relate particles of different spins ?** etc. ...

We have a “new” tool, **SUPERSYMMETRY**

BOSONS $\longleftrightarrow$ **FERMIONS**

(integer spins) *(half-integer spins)*

What to do with supersymmetry ?

Can it be of any help in the real world
of fundamental particles and interactions ?

(according to common wisdom)

BOSONS	$\overset{\textit{SUPERSYMMETRY}}{\longleftrightarrow}$	**FERMIONS**

could one relate Fermions constituants of matter

to Bosons, messengers of interactions ?

and arrive to some sort of

Unification FORCES $\leftrightarrow$ MATTER ??

This would be very attractive, but unfortunately,

things don't work out that way !! ...

SUSY ALGEBRA :

$$\begin{cases} \{\, Q\,,\, \bar{Q}\,\} &= \; -\,2\,\gamma_\mu\, P^\mu \\ [\, Q,\, P^\mu\,] &= \; 0 \end{cases}$$

Gol'fand-Likhtman, Volkov-Akulov, Wess-Zumino, 1970-73

Initial motivations ?

– *SUSY algebra at origin of parity non-conservation ?* *(no ...)*

– *is the neutrino a Goldstone particle ?* *(no ...)*

V-A model: SUSY without bosons !!! $\longrightarrow$ *SUSY algebra does not require superpartners ... !*

– *extend to 4 dim. supergauge transformations on* $2d$ *string worldsheet*

$\longrightarrow$ **SUSY gauge theories in 4 dim.**

$P^\mu \quad \longrightarrow$ **space-time translations**

relation with spacetime, general relativity $\longrightarrow$ *supergravity*

spacetime $x^\mu = \begin{pmatrix} ct \\ \vec{x} \end{pmatrix}$ **extended to superspace** (x^μ, θ)

$$\theta = \begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{pmatrix} = \text{spin-}\tfrac{1}{2} \text{ Majorana anticommuting coordinate}$$

$$\theta_1\,\theta_2 = -\,\theta_2\,\theta_1\,, \quad (\theta_1)^2 = 0\ \ldots$$

SUPERFIELDS $\Phi(x, \theta)$ **describe both BOSONS and FERMIONS**

Can SUSY apply to fundamental laws of Nature ?

(*what would be the consequences ... ?)*

Nature is "obviously" not supersymmetric !

it seems

1 *(Unbroken)* **SUSY** $\Rightarrow$ **Bosons and fermions should have EQUAL MASSES :**

$\longrightarrow$ *break (spontaneously (?)) susy ??*

But: spontaneous susy breaking did not seem possible !

(*SUSY vacuum has* $E = 0$, *always stable ...* **)**

still it turns out possible, but very constrained

($\longrightarrow$ *easier to use soft susy-breaking terms: price to pay : many arbitrary parameters ...)*

$\longrightarrow$ **predict existence of new particles, but difficult to predict their masses**

2 **Spontaneous SUSY breaking** $\longrightarrow$ *massless spin-$\frac{1}{2}$ Goldstone fermion*

where is the spin-$\frac{1}{2}$ Goldstone fermion of SUSY ?

it cannot be a neutrino, why has not it been observed ?

present answer: eliminated in favor of

$\longrightarrow$ **massive** *spin-$\frac{3}{2}$* *GRAVITINO*

warning:

this one may still behave very much as a spin-$\frac{1}{2}$ goldstino, if very light ... !!

... which could be *observable* **... !**

e.g. through decays of SUSY particles, like

neutralino $\rightarrow$ gravitino + photon

• **Which bosons and fermions relate ?**

$$\left\{ \begin{array}{ccc} photon & \stackrel{\textbf{?}}{\longleftrightarrow} & neutrino \\ W^{\pm} & \stackrel{\textbf{?}}{\longleftrightarrow} & e^{\pm} \\ gluons & \stackrel{\textbf{?}}{\longleftrightarrow} & quarks \\ & \cdots & \end{array} \right.$$

does not work ...

• **How to deal with Majorana fermions ?**

SUSY theories systematically involve (self-conjugate) Majorana fermions

while Nature only knows Dirac fermions !

• **How to construct Dirac fermions ?**

How to give fermions

<u>**conserved**</u> **quantum numbers** **(** $\boldsymbol{B}$**,** $\boldsymbol{L}$ **) ?**

B **and** L **carried by** <u>**fermions**</u> **only** *(quarks and leptons),* **not bosons !**

this cannot be, in a supersymmetric theory ... !!

seemed to make supersymmetry <u>*irrelevant*</u> *to the real world !!*

Solution:

1) keep Majorana fermions $\longrightarrow$ new class of particles:

photon not associated with $\nu_e, \ \nu_\mu$ or ν_τ

but with new "photonic neutrino" called PHOTINO

and gluons with GLUINOS ...

Majorana fermions of SUSY $\longrightarrow$ **NEUTRALINOS, GLUINOS ....**

2) Introduce new BOSONS carrying baryon and lepton numbers

SQUARKS, SLEPTONS

(still you are not safe yet ... see later ...)

$\Longrightarrow$ *all particles should be associated with* **new superpartners**

$photon$	$\longleftrightarrow$	spin-$\frac{1}{2}$ $photino$
$gluons$	$\longleftrightarrow$	spin-$\frac{1}{2}$ $gluinos$
$leptons$	$\longleftrightarrow$	spin-0 $sleptons$
$quarks$	$\longleftrightarrow$	spin-0 $squarks$
	$\ldots$	

$\rightarrow$

"doubling the number of degrees of freedom" **in susy theories**

(within "linear realisations" of susy)

SUSY does not relate directly known bosons and fermions !! **but:**

Known bosons	$\longleftrightarrow$	**New fermions**
Known fermions	$\longleftrightarrow$	**New bosons**

(long mocked as a sign of irrelevance of supersymmetry ...)

Further problem: get interactions from $W^\pm, Z,$ photon and gluon exchanges

avoid unwanted spin-0 exchanges ?

($\tilde{q}, \tilde{l}$ carrying B and L)

related with introduction of **R-symmetry and R-parity**

in Susy extensions of the Standard Model ,

$\longrightarrow$ *pair production of SUSY particles*

Stable LSP (usually neutralino) candidate for

non-baryonic dark matter of Universe

continuous R-symmetry $\underline{U(1)_R}$

acting "chirally" on susy generator: $Q \longrightarrow e^{-\gamma_5 \alpha}\, Q$

$\longrightarrow$

Not all possible superpotential interactions admissible ...

Continuous R-symmetry $\longrightarrow$ progenitor of R-parity ...

$U(1)_R$ **reduced to** $(-1)^R$ **to allow for gravitino and gluino masses**

R_p **first defined as discrete symmetry** $(-1)^R$

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

$\longrightarrow$ *stable dark matter candidate*

R-parity $\Rightarrow$ LSP stable

usually a neutralino

combination of superpartners of neutral gauge and Higgs bosons,

$$\{W_3,\ W';\ h_1^\circ,\ h_2^\circ;\ \ldots\} \ \stackrel{SUSY}{\longleftrightarrow}\ \underbrace{\{\tilde W_3,\ \tilde W';\ \tilde h_1^\circ,\ \tilde h_2^\circ;\ \ldots\}}_{\text{neutralinos}}.$$

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

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

neutralino = natural WIMP candidate

supersymmetry does not relate known particles together

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

but ...

DARK MATTER candidate naturally obtained

from lightest Majorana fermion

in SUSY extension of Standard Model

$\longrightarrow$

DARK MATTER related with

mediators of ELECTROWEAK INTERACTIONS

$\longrightarrow$ **possibility of** **pair-producing neutralinos**

(i.e. Dark Matter particle candidates) at particle colliders.

Missing energy -momentum signature of SUSY ...

(1977)

neutralinos interact weakly with matter

lightest neutralino became natural DM candidate

Accelerators can look for the Dark Matter of the Universe ...

$$\begin{cases} e^+ \, e^- & \longrightarrow \quad \textbf{2 neutralinos} \; + \; \ldots \\ p \;\; p & \longrightarrow \quad \textbf{2 neutralinos} \; + \; \ldots \end{cases}$$

(... , PETRA, PEP, LEP) *FNAL* , **LHC**, *ILC*, ...

$+$ *additional ingredients needed*

$SU(2) \times U(1)$ electroweak theory

Nucl. Phys. B 90, 104 (1975)

electroweak breaking

we need, also, a pair of doublet Higgs superfields,

$$\boldsymbol{H_1} = \begin{pmatrix} \boldsymbol{H_1^0} \\ \boldsymbol{H_1^-} \end{pmatrix}, \quad \boldsymbol{H_2} = \begin{pmatrix} \boldsymbol{H_2^+} \\ \boldsymbol{H_2^0} \end{pmatrix}, \text{ (left-handed)}$$

$$< h_1^0 > = \frac{v_1}{\sqrt{2}}, \quad < h_2^0 > = \frac{v_2}{\sqrt{2}}$$

mixing angle β,

$$\tan \beta = \frac{v_2}{v_1}.$$

WHY ?

- **With 1 doublet** (H_1) **:** $\left\{ \begin{array}{l} \textbf{1 charged Dirac “\underline{gaugino}”} \quad \tilde{W}^- = \tilde{W}_L^- + \tilde{W}_R^- \\ + \ \textbf{1 chiral charged “\underline{higgsino}” e.g.} \quad \tilde{h}_{1L}^- \end{array} \right.$

one massive charged Dirac fermion ($\tilde{h}_{1L}^- + \tilde{W}_R^-$ **)**

with only one Brout-Englert-Higgs doublet
one *<u>charged</u> chiral fermion* $(\tilde{W}_L^-)$ *<u>massless</u>*

- **With** $H_1,\ H_2$**:** $\left\{ \begin{array}{lcl} \tilde{W}_1^- & = & \tilde{h}_{1L}^- + \tilde{W}_R^- \\ \tilde{W}_2^- & = & \tilde{W}_L^- + (\tilde{h}_{2L}^+)^c \end{array} \right.$ **2 “<u>charginos</u>”**

mass matrix

$$\mathcal{M} = \begin{pmatrix} (\, m_2 \,) & \frac{g\, v_2}{\sqrt{2}} = m_W \sqrt{2}\, \sin\beta \\ \frac{g\, v_1}{\sqrt{2}} = m_W \sqrt{2}\, \cos\beta & \mu \end{pmatrix}$$

Ingredients of **Supersymmetric Standard Model** *(minimal or not ...)*

(Phys. Lett. 64B (1976) 159; 69B (1977) 489)

1) $SU(3) \times SU(2) \times U(1)$ **gauge superfields** *[× extra-$U(1)$]*

2) chiral quark and lepton superfields

3) two doublet Higgs superfields H_1 and H_2

4) trilinear superpotential for q and l masses

- **Superpotential <u>even function</u> of quark and lepton superfields !**

$$h_e\, H_1 . \bar{E}\, L \;+\; h_d\, H_1 . \bar{D}\, Q \;-\; h_u\, H_2 . \bar{U}\, Q \quad [\, + \mu\, H_1 H_2\,]$$

R-invariance → R-parity

Minimal content of

Supersymmetric Standard Model

Spin 1	Spin 1/2	Spin 0
gluons g photon γ	gluinos $\tilde{g}$ photino $\tilde{\gamma}$	
$W^{\pm}$ Z	winos $\widetilde{W}^{\pm}_{1,2}$ zinos $\widetilde{Z}_{1,2}$ higgsino $\tilde{h}^0$	$H^{\pm}$, H, h, A } Higgs bosons
	leptons l quarks q	sleptons $\tilde{l}$ squarks $\tilde{q}$

2 neutral gauginos + 2 higgsinos mix $\longrightarrow$ 4 neutralinos

"MSSM"

SUSY quartic Higgs interactions

appear as **electroweak gauge interactions,** *with*

$$V_{\text{quartic}} = \frac{g^2 + g'^2}{8} \, (h_1^\dagger h_1 - h_2^\dagger h_2)^2 + \frac{g^2}{2} \, |h_1^\dagger h_2|^2$$

$=$ **quartic Higgs potential of the MSSM**

Quartic Higgs couplings fixed by electroweak gauge couplings !

at the origin of mass inequality

$$m \text{ (lightest Higgs)} \leq m_Z + \underbrace{\text{rad. corr.}}_{\textit{should be large !!}} \quad \textit{in MSSM}$$

(potentially problematic, as it requires radiative correction effects to be large)

(need squark masses $\approx$ TeV scale, recreates ("little") hierarchy problem ...)

$\longrightarrow$ **“Beyond MSSM”**

EXTRA SINGLET

μ *promoted to dynamical variable* $\boldsymbol{\mu(x,\theta)}$

$$\mu\, H_1 H_2 \quad \longrightarrow$$

trilinear coupling $\boldsymbol{\lambda\, H_1 H_2\, S}$ *with extra singlet chiral superfield* $\boldsymbol{S}$ *(1975)*

$$\lambda\, H_1\, H_2\, S \; + \; f(S) \quad \textit{superpotential}$$

N/nMSSM

(λ *useful* $\longrightarrow$ *all Higgs bosons sufficiently heavy)*

EXTRA-$U(1)$

and/or gauge extra-$U(1)$ symmetry ...

extra-$U(1)$ gauge superfield (“USSM”)

$\longrightarrow$ additional singlino or gaugino

LIGHT DARK MATTER

with C. Bœhm

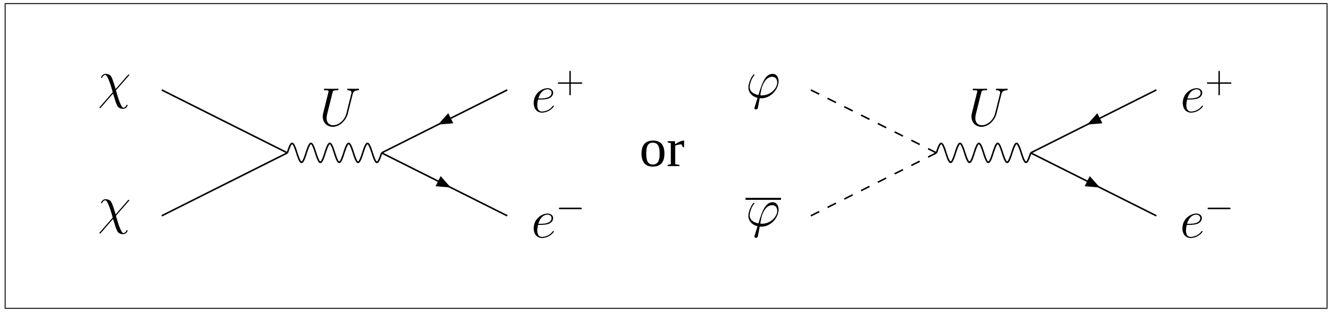
(just a few words)

Too light dark matter particles (say in MeV to GeV range) normally forbidden as they could not annihilate sufficiently $\longrightarrow$ *relic abundance too large ...*

unless a new interaction exists

as induced by a new light spin-1 U *boson*

sufficiently strong at lower energies,



DM annihilations into e^+e^-*, for spin-*$\frac{1}{2}$ *or spin-0 particles*

extra-$U(1)$ *symmetry ...*

how a light U *could be detected ?*

"New" possibility for extra-$U(1)$ symmetry :

electroweak breaking as in SUSY, with 2 doublets:

cf. h_1 and h_2 of SUSY extensions of the standard model

$$h_1 = \begin{pmatrix} h_1^\circ \\ h_1^- \end{pmatrix}, \quad h_2^c = \begin{pmatrix} -h_2^{\circ *} \\ h_2^- \end{pmatrix} \to h_2 = \begin{pmatrix} h_2^+ \\ h_2^\circ \end{pmatrix}$$

allows for possibility of rotating independently the two doublets

(Nucl. Phys. B 78, 14 (1974)) :

$\rightarrow$ *extra-* $U(1)$ *symmetry*

$$h_1 \to e^{i\alpha} h_1, \quad h_2^c \to e^{-i\alpha} h_2^c \leftrightarrow h_2 \to e^{i\alpha} h_2$$

constraining interaction potential and Yukawa couplings

constraints on superpotential from extra-$U(1)$ ...

($\lambda H_1 H_2 S$ OK)

extra-$U(1)$ acts as

$$H_1 \xrightarrow{U} e^{i\alpha} H_1 , \quad H_2 \xrightarrow{U} e^{i\alpha} H_2 , \quad S \xrightarrow{U} e^{-2i\alpha} S$$

$$(Q, \bar{U}, \bar{D};\ L, \bar{E}) \xrightarrow{U} e^{-i\frac{\alpha}{2}} (Q, \bar{U}, \bar{D};\ L, \bar{E})$$

for superpotential to be invariant.

(acts axially on quarks and leptons)

extra-$U(1)$, global or local,

broken explicitly

(by small superpotential terms and/or small soft susy-breaking terms)

or spontaneously

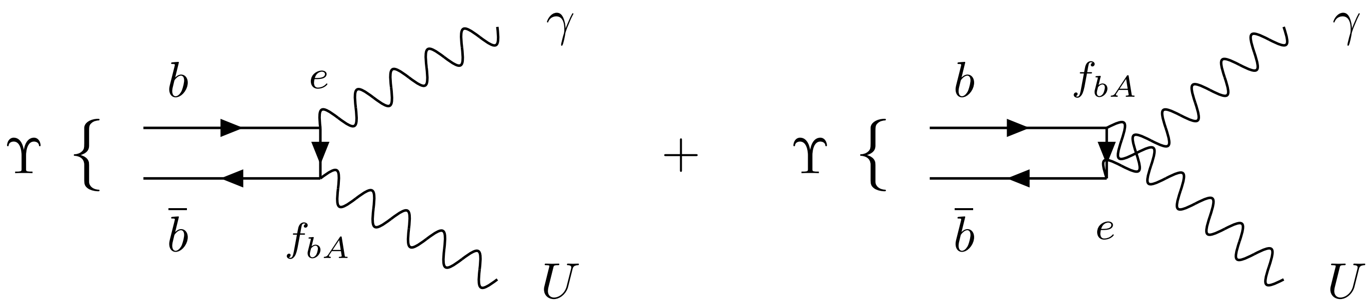
through the 2 Higgs doublets and possibly a large singlet v.e.v.

SEARCHING FOR A LIGHT U

NPB 187, 184, 1981, ... , PRD 75, 115017 (2007); PLB 675, 267 (2009)

ψ and Υ DECAYS:

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



Amplitude for producing $\boldsymbol{U}$ proportional to gauge coupling

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

$$\uparrow$$

may be very small !!

(at least in visible sector)

such a gauge boson will be unobservable,

if its gauge coupling is extremely small ...

it seems ...

NO !

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

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

$$k^\mu\,\bar\psi\,\gamma_\mu\gamma_5\,\psi \;\to\; 2\,m_q\,\psi\,\gamma_5\,\psi$$

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

behaves as "eaten-away" pseudoscalar Goldstone boson a

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

Equivalence theorem similar to Equivalence theorem of SUSY

according to which **very light spin-$\frac{3}{2}$ gravitino behaves as spin-$\frac{1}{2}$ goldstino**

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

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

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

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

New gauge boson U *possibly light if extra-*$U(1)$ *gauge coupling is small*

behaves very much as almost "equivalent"

spin-0 'axionlike' (eaten-away) pseudoscalar a

with a (possibly large) singlet v.e.v.:

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

$r \;=\; \cos\zeta$ = **INVISIBILITY PARAMETER**

$a \;=\;$ **mixing of doublet and singlet components**

PLB 95, 285, 1980; NPB 187, 184, 1981

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

Axial coupling

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

Equivalent pseudoscalar coupling

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

ratio: $2\ \dfrac{m_{q,l}}{m_U}$

$r\ =\ \cos\zeta = $ *invisibility parameter* $\qquad \tan\beta\ =\ \frac{v_2}{v_1}$

$$B\,(\,\psi\;\rightarrow\;\gamma\;U/a\,)\;\simeq\;5\;10^{-5}\;\cos^2\zeta\,\cot^2\beta\;\;C_\psi\,F_\psi$$
$$B\,(\,\Upsilon\;\rightarrow\;\gamma\;U/a\,)\;\simeq\;2\;10^{-4}\;\cos^2\zeta\,\tan^2\beta\;\;C_\Upsilon\,F_\Upsilon$$

(*F phase space factor;* $C\;\gtrsim\;\frac{1}{2}$ *for QCD radiative and rel. corrections)*

Υ DECAYS

PLB 675, 267 (2009)

CLEO, BABAR hep-ex/0808.0017

$$|f_{bA}|\,<\,4\;10^{-7}\;m_U(\text{MeV})/\sqrt{B_{\rm inv}}\;,\quad \text{or}\quad |f_{bP}|\,<\,4\;10^{-3}/\sqrt{B_{\rm inv}}$$

For invisibly decaying boson: $f_{bP}\;<\;4\;10^{-3}$

5 times smaller than standard Higgs coupling to b**,** $m_b/v\;\simeq\;2\;10^{-2}$

$$\Longrightarrow$$

doublet fraction: $r^2 = \cos^2\zeta\;<\;4\,\%\;/\;(\tan^2\beta\;B_{\rm inv})$

a **(**$<\,4\,\%$ **doublet,** $>\,96\,\%$ **singlet) for** $\tan\beta > 1$ **with inv. decays**

$\Rightarrow\;\;B\,(\,\psi\rightarrow\gamma\,+\,$ **neutral** $)\;B_{\rm inv}\;\lesssim\;10^{-6}/\tan^4\beta\;,$

i.e. $\lesssim\;10^{-8}$ **for** $\tan\beta\;\gtrsim\;3$**,** ***independently of*** $B_{\rm inv}$

Consequences for couplings to LEPTONS

implications for the couplings of the new spin-1 or spin-0 boson to e, μ *or* τ. *!!*

Universality of the axial coupling of the U : $f_{eA} = f_{\mu A} = f_{\tau A} = f_{dA} = f_{sA} = f_{bA}$

$\Longrightarrow$ **limit on f_{bA} applies to f_{eA} :**

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

for invisible decays: $f_{eP} < \frac{1}{5}$ **standard Higgs coupling to the electron**

Υ **DECAYS** $\rightarrow \ \gamma + (\mu^+ \mu^-)$

BABAR: hep-ex/0902.2176

$$r/x = \cos\zeta \ \tan\beta \ \lesssim \ .15/\sqrt{B_{\mu\mu}} \quad \Longrightarrow$$

$$|f_{bA}| \ \lesssim \ 3 \ 10^{-7} \ m_U(\mathit{MeV})/\sqrt{B_{\mu\mu}}$$

$$|f_{bP}| \ \lesssim \ 3 \ 10^{-3}/\sqrt{B_{\mu\mu}} \, , \quad \textit{or} \ \ |f_{bS}| \ \lesssim \ 5 \ 10^{-3}/\sqrt{B_{\mu\mu}}$$

(for $B_{\mu\mu} \simeq 1$*, lim. on* f_{bP} *is* $\simeq$ **15 %** *of SM Higgs coupling to* b*).*

doublet fraction: $r^2 = \cos^2\zeta \ \lesssim \ 2\,\% \ / \ (\tan^2\beta \ B_{\mu\mu})$.

$$B \ (\psi \ \rightarrow \ \gamma + \ \textit{neutral} \ ) \ B_{\mu\mu} \ \lesssim \ 5 \ 10^{-7}/\tan^4\beta \ ,$$

i.e. $\lesssim 5 \ 10^{-9}$ *for* $\tan\beta \gtrsim 3$, independently of $B_{\mu\mu}$.

LIGHT DARK MATTER in Υ DECAYS

PLB 269, 213 (1991); PRD 74, 054034, 2006, ...

$$\begin{cases} \Upsilon \to \quad \chi\,\chi \;=\; \textbf{invisible} \\ \Upsilon \to \gamma\ \chi\,\chi \;=\; \gamma + \textbf{invisible} \end{cases}$$

mediated by light U *(or a spin-0 for* $\gamma\ \chi\chi$*)*

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

($\Upsilon \to \chi\,\chi$ **and** $\gamma\ \ \chi\chi$ **test vector and axial couplings to** b**, resp.)**

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

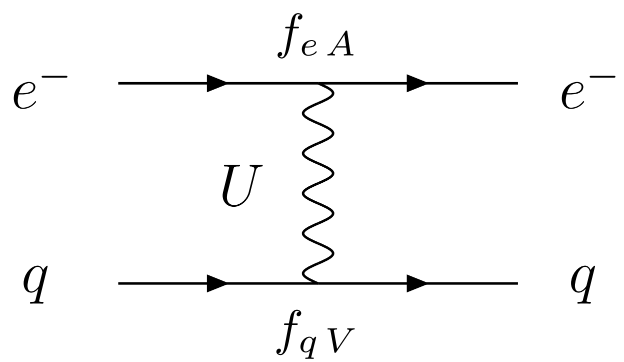
(as recently improved by Babar)

$\Upsilon \to \gamma\ \underbrace{\chi\,\chi}_{\textbf{inv}}$ **can constrain** $|c_\chi\, f_{bA}|$

Many other processes ...

(Dark Matter annihilations, 511 keV line, other signatures ...)

Parity violations in atomic physics



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

Other constraints from:

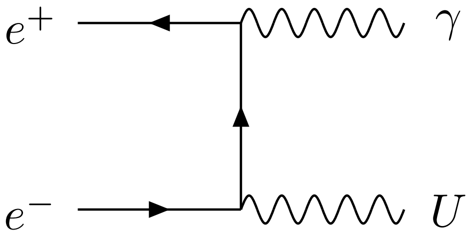
$g-2$

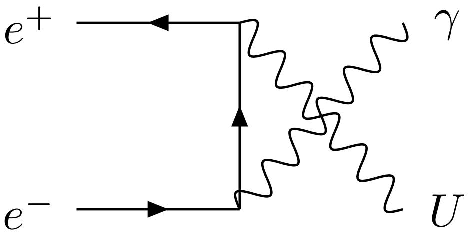
ν scatterings

Supernovae explosions

...

Direct production in $e^+ e^- \longrightarrow \gamma U$





CONCLUSIONS

complementarity:

- **pair-production of SUSY particles at colliders**
- *expected Higgs sector: 2 doublets + possible singlet*
- **stable LSP (neutralino ...) $\longrightarrow$ dark matter**

Search for dark matter ... **Explore the high-energy frontier**

waiting for more experimental data, especially from LHC ...

But another frontier exists at lower energies !

light weakly (or very weakly) coupled new particles

NEW PARTICLES, NEW FORCES, NEW (super) SPACETIME DIMENSIONS ...