SUPERSYMMETRY,

DARK MATTER

and

NEW PARTICLES

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In honor of *Chris Quigg*

Chris was Visiting Professor

at Ecole Normale (Supérieure) in Paris

some time ago ...

He knows very well

le cinquième arrondissement

PARIS

....

THE WORLD

so the remaining thing to do, maybe,

is to go together and try to visit

THE SUPERWORLD !

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	**EXTRA DIMENSIONS**
$(x^\mu,\ \theta)$ ...	$(x^\mu,\ x^5,\ x^6)$ ...

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** $\boxed{V(\varphi) \;=\; \lambda\,|\varphi|^4 \;-\; \mu^2\,|\varphi|^2}$?

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

what fixes $\boxed{\mu\ ?}$ **what fixes coupling constant** $\boxed{\lambda\ ?}$

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. $SU(5)$, ...

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

  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 <u>real world</u>

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 :

$$\left\{ \begin{array}{lcl} \{\, Q\,,\, \bar{Q}\,\} & = & -\,2\,\gamma_\mu\, P^\mu \\ [\, Q,\, P^\mu\,] & = & 0 \end{array} \right.$$

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*

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

$$P^\mu \quad \longrightarrow \quad \textbf{space-time translations}$$

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

$$\boxed{\textbf{spacetime} \quad x^\mu = \begin{pmatrix} ct \\ \vec{x} \end{pmatrix} \quad \textbf{extended to} \quad \textbf{superspace} \quad (x^\mu,\ \theta\ )}$$

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

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

$$\boxed{\textbf{SUPERFIELDS} \quad \Phi(\,x,\ \theta) \quad \textbf{describe both} \quad \textbf{BOSONS and FERMIONS}}$$

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 :**

$\rightarrow$ *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

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

$\rightarrow$ **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 $\longrightarrow$ gravitino + photon *depending on* $m_{3/2}$

(cf. "GMSB" models ...)

- **Which bosons and fermions relate ?**

$$\begin{cases} photon & \overset{?}{\longleftrightarrow} & neutrino \\ W^{\pm} & \overset{?}{\longleftrightarrow} & e^{\pm} \\ gluons & \overset{?}{\longleftrightarrow} & quarks \\ & \cdots & \end{cases}$$

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

conserved quantum numbers (B, L) ?

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

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

seemed to make supersymmetry irrelevant to the real world !!

Solution:

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

photon not associated with ν_e, ν_μ or ν_τ

but with new "photonic neutrino" called in 1977 PHOTINO

and gluons with GLUINOS ...

Majorana fermions of SUSY $\rightarrow$ **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*
	...	

$\longrightarrow$

"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 $\quad U(1)_R$

(before susy breaking)

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*

$$\boxed{R\text{-parity} \;\Rightarrow\; \text{LSP stable}}$$

usually a neutralino

combination of superpartners of neutral gauge and Higgs bosons,

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

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

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

$$\boxed{\textit{neutralino} \;=\; \textit{natural WIMP candidate}}$$

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 (neutralino)

in SUSY extension of Standard Model

$\longrightarrow$

DARK MATTER related with

mediators of ELECTROWEAK INTERACTIONS

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

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

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

neutralinos interact $\sim$ *weakly with matter through* $\tilde{q}$ *etc. exchanges*

lightest neutralino became natural DM candidate

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

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

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

$+$ *additional ingredients needed* *for*

$$\boxed{\underline{SU(2) \times U(1) \text{ electroweak theory}}}$$

Nucl. Phys. B 90, 104 (1975)

electroweak breaking

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

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

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

mixing angle β, $\boxed{\tan \beta = \frac{v_2}{v_1}.}$

WHY ?

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

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

with only one Brout-Englert-Higgs doublet

one charged chiral fermion $(\tilde{W}^-_L)$ *massless*

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

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** *[$\times$ 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** **even function** **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 $\longrightarrow$ ***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"

Nice features of Higgs interactions

in supersymmetric theories :

(and not so nice ones ...)

SUSY quartic Higgs interactions

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

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

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

Quartic Higgs couplings fixed by electroweak gauge couplings !

at the origin of mass inequality

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

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

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

$\rightarrow$ **"Beyond MSSM"**

EXTRA SINGLET S *(NPB 75)*

in the old days : start with h_1, h_2, *but* $\mu \rightarrow \mu^2 (h_1^\dagger h_1 + h_2^\dagger h_2)$ $(\pm \xi g'/2$ *term)*

obstacle for satisfactory EW breaking with v_1 *and* $v_2 \neq 0$ *at tree level*

without terms breaking explicitly susy

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

$$\mu H_1 H_2 \rightarrow$$

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

(generates effectively an $h_1 h_2$ *soft term ...)*

$$\boxed{\lambda H_1 H_2 S + f(S) \text{ superpotential}}$$

N/nMSSM

with $f(S) = \frac{\kappa}{3} S^3 + \frac{\mu_S}{2} S^2 + \sigma S$

$$\mathcal{W} = \lambda_e \, H_1.\bar{E} \, L + \lambda_d \, H_1.\bar{D} \, Q - \lambda_u \, H_2.\bar{U} \, Q$$
$$+ \lambda \, H_1 H_2 \, S + \underbrace{\frac{\kappa}{3} \, S^3 + \frac{\mu_S}{2} \, S^2 + \sigma \, S}_{f(S)}$$

Restrictions on $f(S)$ may be obtained by using

extra-$U(1)_A$ and/or R symmetries

Potential of N/nMSSM:

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

$$+ \left|\lambda\, h_1 h_2 + \frac{\partial f(s)}{\partial s}\right|^2 + \lambda^2\,|s|^2\,(h_1^\dagger h_1 + h_2^\dagger h_2) + \ldots\,.$$

new bound on the lightest Higgs mass, λ *allows to get*

all Higgs bosons sufficiently heavy

$\longrightarrow$ **additional singlino**

effective μ **term may be regenerated through a translation of the extra singlet** S

as now needed for the two charginos both $> m_W$ *(in MSSM and N/nMSSM)*

EXTRA-$U(1)$

supersymmetric extensions of the SM

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

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

$\longrightarrow$ additional gaugino

where is such an extra $\boldsymbol{U(1)}$ *coming from ?*

a number of possibilities ...

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

electroweak breaking as in SUSY, with 2 doublets:

cf. h_1 and h_2 of <u>SUSY extensions of the standard model</u>

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

allows for possibility of *<u>rotating independently the two doublets</u>*

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

$\rightarrow$ *<u>extra- $U(1)$ symmetry</u>*

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

constraining *<u>interaction potential</u>* *and* *<u>Yukawa couplings</u>*

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

($\lambda H_1 H_2 S$ OK with $S \rightarrow e^{-2i\alpha} S$)

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)

axial $U(1)_A$

(often known as 'PQ' symmetry)

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.

BUT WHAT ABOUT A POSSIBLE "AXION" ?

Extra-$U(1)$ (*if global and unbroken in $\mathcal{L}$*)

could lead to massless (or quasimassless) Goldstone boson

now known as an "axion".

(momentarily) present in early models (1974-1976)

with $h_1 \longrightarrow e^{i\alpha}\, h_1\,,\;\; h_2 \longrightarrow e^{i\alpha}\, h_2$

before extra-$U(1)$ symmetry $U(1)_A$ was either

1) explicitly broken through $f(S) = \sigma S$ ... superpotential interactions

of singlet S $\boxed{\longrightarrow \text{ N/nMSSM}}$ **(***would-be "axion" acquires mass $\propto \lambda$***)**

(*but can sometimes "resurrect" !***)**

or 2) gauged (*assuming anomalies cancelled***) :**

would-be axion "eaten away" by new gauge boson Z' (later also called U boson)

$\boxed{\longrightarrow \text{ USSM}}$ **(1977)** **(***but can also sometimes "resurrect" !***)**

LIGHT DARK MATTER

with C. Bœhm

(just a few words)

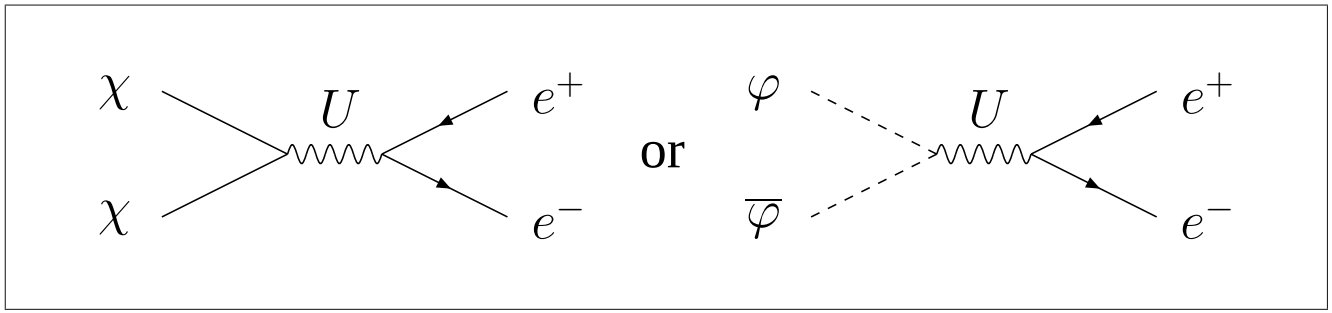
Too light dark matter particles (say in MeV to GeV range) normally forbidden

as they could not annihilate sufficiently $\longrightarrow$ *relic abundance too large ...*

unless a new interaction exists

as induced by a new light spin-1 $\boldsymbol{U}$ *boson*

sufficiently strong at lower energies,



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

extra-$\boldsymbol{U}(1)$ *symmetry ...*

how a light $\boldsymbol{U}$ *could be detected ?*

Relic density of light dark matter particles:

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

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

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

allows to estimate required $c_\chi\,f_e$

for correct annihilation cross section at freeze out time

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

or

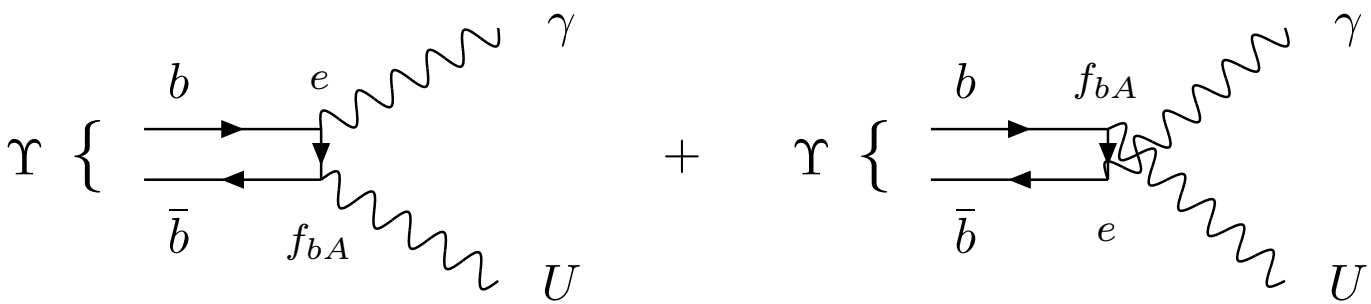
$$|\,c_\chi\,f_e\,| \;\simeq\; (B_{\rm ann}^{ee})^{\frac{1}{2}}\;10^{-6}\;\frac{|\,m_U^2-4\,m_\chi^2\,|}{m_\chi\,(1.8\ \text{MeV})}\;.$$

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*

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

$\uparrow$

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** $m_U \propto g" \ldots \to 0$ **!**

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

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

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

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

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

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.:

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

$r = \cos\zeta$ = **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

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

Equivalent pseudoscalar coupling

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

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

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

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

(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

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

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**

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

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

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

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

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

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

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

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

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, ...

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

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.)**

$$\Upsilon \to \underbrace{\chi\chi}_{\textbf{inv}} < 3\,10^{-4} \quad \Rightarrow \quad |c_\chi\, f_{bV}| < 5\,10^{-3} \qquad \textit{arXiv:0910.2587}$$

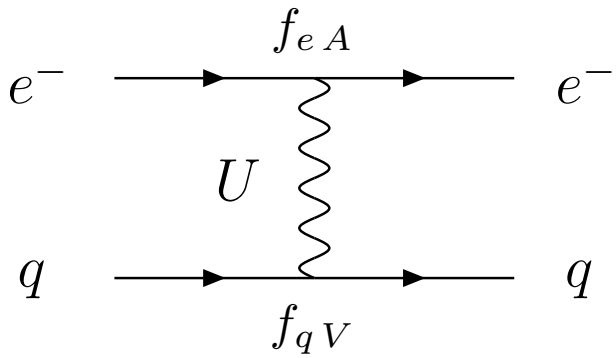
(as recently improved by Babar)

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

Many other processes ...

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

Parity violations in atomic physics



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

Other constraints from:

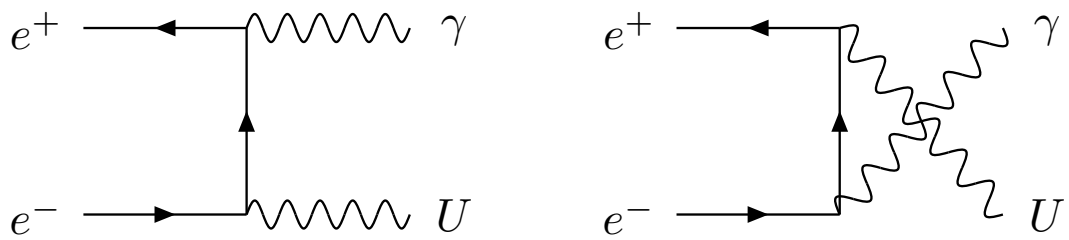
$g - 2$

ν scatterings

Supernovae explosions

...

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



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 ...

BON ANNIVERSAIRE

CHRIS !

et, comme dirait Chris, un grand merci aux gentils organisateurs de la Conférence