PARTICLES and INTERACTIONS

where do we stand ?

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Particle Physics and Cosmology, Rencontres de Blois, 7 June 2018

4 types of interactions are known

can they be unified, at least partly ?
are there others ?

The **Standard Model** offers a good description of
strong, electromagnetic and weak interactions of quarks and leptons
(up to, maybe, a few “anomalies”, which remain to be understood)

Nature involves a $SU(3) \times SU(2) \times U(1)$ gauge symmetry
(gluons, $W^{\pm}$, Z, photon)
with a spontaneously broken electroweak symmetry

It comes with a new particle,

the spin-0 **Brout-Englert-Higgs boson**

(Weinberg 1967 – found at CERN in 2012)

The Standard Model is now complete Great achivement , but certainly not the end of the story ...

Many questions remain unanswered, like

- Why $SU(3) \times SU(2) \times U(1)$ gauge group ?

- Why quark and lepton representations

with left-handed doublets $\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ + right-handed singlets (u_R), (d_R), (e_R) ?

- Why 3 families, and why do they mix ?

- Why is CP (slightly) broken by weak interactions

but still conserved by strong ones ($\theta_{QCD} \simeq 0$) ?

(no electric dipole moment for the neutron)

- Origin of the BEH ***"mexican hat" potential*** associated with the electroweak breaking ?

$$V = \lambda_{\rm SM}\, (\varphi^\dagger \varphi)^2 - \mu^2_{\rm SM}\, \varphi^\dagger \varphi$$

$$\Rightarrow\; m_H^2 = 2\,\mu^2_{\rm SM} = 2\,\lambda_{\rm SM}\, v^2 = \frac{\lambda_{\rm SM}}{(g^2+g'^2)/8}\, m_Z^2$$

(where is $\lambda_{\rm SM}$ coming from ?)

- What about **neutrino masses**, and why are they so small ?

of "Dirac" or "Majorana" type ?

$\downarrow$

($\Delta L = \pm 2$ processes expected)

Origin of neutrino masses ?

("see-saw" mechanism from very large Majorana masses for ν_R fields ?)

- Why so many arbitrary parameters (already $\simeq 20$ in the SM with massless ν's ...) ?

more with ν masses and mixing angles

Can we hope to compute or get relations between some of them ?

- It would be nice to be able to determine λ_{SM}

$$\lambda_{\mathrm{SM}} = \frac{g^2 + g'^2}{8} \quad \text{would imply} \quad m_H \simeq m_Z \simeq 91 \text{ GeV !}$$

$\rightarrow$ *in supersymmetric theories:*

quartic coupling $\dfrac{g^2 + g'^2}{8}\ (\times \cos^2 2\beta) \;\Rightarrow\;$ BEH masses $\lesssim m_Z\ (|\cos 2\beta|)$ in MSSM

would even lead to $m_H = m_Z$ *, if supersymmetry were conserved*

(nMSSM, 1975) more later ...

... enlarging our horizon to **gravitation**, and to the whole **Universe**:

- Up to which energy can the SM description be valid ?

stability or instability or metastability of the vacuum,

for large values of fields ...

- What about gravitation, and how can one get a consistent theory of ***quantum gravity*** ?

(a necessity, at some point the question can no longer be ignored)

($\rightarrow$ string theories ? other approaches ?)

- Can interactions, or some of them at least, be ***unified*** ?

(not a necessity, but a wish, or a dream ...)

- What is responsible for the *very small* ***excess of matter over antimatter***

that should have been present in the early Universe ?

Generated from an initially symmetric Universe ?

Requires $\not{P}$, $C\!\!\not{P}$, $\not{B}$ (Sakharov, 1967)

(necessitates new interactions)

• What is dark matter made of ?

most of it seems formed of a new substance, presumably particles of a new type

"**dark matter particles**"

(keeping in mind that the laws of gravity might be modified ...)

but there are no such dark matter candidates within the SM ...

• Why is the expansion of the Universe accelerating ?

"answer" is called " **dark energy** "

Negative pressure that may be associated with a ***cosmological constant***

possibly induced by a vacuum energy density

$$\Lambda = \frac{8\pi\, G_N}{c^4}\,\rho_{\rm vac} \quad \text{with} \quad p_{\rm vac} = -\rho_{\rm vac}$$

or with something else ("quintessence" ...)

- Why should the corresponding cosmological constant **Λ** be **so incredibly small** ?

($\Lambda \approx$ intrinsic space-time curvature of an empty Universe)

$$\Lambda = \frac{8\pi\, G_N}{c^4}\, \rho_{\rm vac} \;\approx\; 10^{-56}\ {\rm cm}^{-2} \;\approx\; 10^{-122}\ L_{\rm Planck}^{-2} \quad !!$$

($\rho_{\rm vac}$ smaller by ~ 54 orders of magnitude than typical energy density associated with EW breaking)

$$\text{energy scale associated with} \begin{cases} \Lambda : & \approx 2\ \text{meV} \\ \text{weak interactions :} & \propto m_W \simeq 80\ \text{GeV} \qquad !! \\ \text{(quantum) gravity :} & \approx m_{\rm Planck} \approx 10^{19}\ \text{GeV} \end{cases}$$

how can so different energy scales possibly coexist ?

In particular, how can electroweak scale remain moderate compared

to very large scales such as m_{GUT} (hypothetical, $\approx 10^{16}$ GeV ?) or $m_{\rm Planck}$?

"Hierarchy problem (s)"

- Origin of the huge energy density held responsible for

  for very rapid inflation of early Universe ?

  (seems to involve a very large scale, possibly $\approx$ **10^{16} GeV**)

• • Very large list of questions, and not so many answers yet ...

All this shows that we have to go and look for physics

Beyond the Standard Model ...

One of the best way may be to search for ***new symmetries***

almost by definition well-hidden (or would have been noticed already)

Left-right symmetry, **Grand-unification**, Family symmetry,
$U(1)_{PQ}$ symmetry, extra-$U(1)$ gauge symmetries ...

Along the way we may be led to consider
new additional dimensions for space-time ...
bosonic or fermionic
$\downarrow$
Supersymmetry

Great ideas, but which still remain hypothetical, after more than ~40 years ...

NEW SYMMETRIES ...

Can one relate ELECTROWEAK with STRONG interactions

by relating their mediators,

$$\boxed{\begin{array}{ccc} (W^\pm,\ Z,\ \gamma) & \leftrightarrow & \text{gluons} \\ & \text{and} & \\ \text{leptons} & \leftrightarrow & \text{quarks} \end{array}} \quad ?$$

Approach of **GRAND-UNIFICATION**

Within $\boldsymbol{SU(5)}$, no new quarks and leptons required ☺ !

(Georgi-Glashow, 1974)

(not even ν_R, possibly useful for massive ν's)

But number of gauge bosons must be doubled ! ☹

$$\underbrace{(W^\pm,\ Z,\ \gamma\ ,\ \text{gluons})}_{\text{12 SM gauge bosons}} \quad \stackrel{GUT}{\longleftrightarrow} \quad \underbrace{(\,X^{\pm 4/3},\ Y^{\pm 1/3}\,)}_{\text{12 new gauge bosons}}$$

$\downarrow$

Unseen, supposed to be very heavy (initially thought $\approx 10^{14}$ GeV)

would mediate <u>proton decay</u> (τ_p initially thought $\lesssim 10^{30}$ years, still unseen) ☹

Other questions and problems

How does the GUT symmetry get spontaneously broken ?

Many new spin-0 fields needed ... ($\underline{\mathbf{24}}$ + $\underline{\mathbf{5}}$ + ...)

How do they interact ? Many arbitrary parameters in scalar potential ☹

Structure of spin-0 sector responsible for gauge symmetry breaking remains unclear

No surprise that problems appear ...

need to adjust for doublet vev to be (and remain) small compared to GUT scale ... ☹

"Hierarchy problem"

most famous; but only a signal that we do not have yet a satisfactory theory ...

⊕ *Risk of unwanted mass relations between quarks and leptons* ☹

GUTs: elegant in spin-1 and spin-1/2 sectors

problems mostly from spin-0 sector responsible for symmetry breaking

- Possible solution, away from SM: try to

$\boxed{\textbf{Avoid fundamental spin-0 fields}}$

spin-0 fields, possibly composite, long viewed as gimmick to trigger sp. symmetry breaking

$\Rightarrow$ ***Technicolor attempts***, in late 70's,

Introduce additional fundamental, confining, interaction, $\boldsymbol{SU(4)_{TC}}$,

within Extended Technicolor gauge group ...

Fundamental SM spin-0 doublet φ replaced by *bilinear forms in "techniquark" fields*

$<\bar{Q}\,Q>$ breaks spontaneously electroweak symmetry

Quite a heavy price for trying to avoid fundamental spin-0 fields

did not survive experimental tests and results ...

or

$\boxed{\textbf{Take fundamental spin-0 fields seriously}}$

as for spin-1/2 fermion fields and spin-1 gauge fields

This is the approach of $\boxed{\textbf{SUPERSYMMETRY}}$ (... Wess-Zumino (1973) ...)

No fundamental difference between spin-0 and spin-1/2 fields

partners under supersymmetry

2 types of fundamental entities:

$\underline{\text{(spin-1} \oplus \text{spin-1/2)}}$ and $\underline{\text{(spin-1/2} \oplus \text{spin-0)}}$ fields

Relate bosonic to fermionic sectors

Natural framework to discuss spin-0 fields and associated problems

$$\boxed{\text{Space-time } (x^\mu) \;\Rightarrow\; \textbf{\textit{Superspace}} \;\; (x^\mu,\ \theta)}$$

$\downarrow$

4 anticommuting Grassman coordinates: $\theta_i\theta_j = -\,\theta_j\theta_i$

(Salam-Strathdee, 1974)

New fundamental concept $\{\, Q\,,\ \bar{Q}\,\} \;=\; -\,2\,\not{P}$

Susy transformations generate translations

Natural introduction of gravitational interactions through supergravity (1976)

Great, but what can we do with this ?

Can Nature be supersymmetric ?

It does not look like it !!

Where are the bosons and fermions that might be related ?

bosons, messengers of interactions	$\overset{??}{\longleftrightarrow}$	fermions, constituants of matter
($W^{\pm}$, Z, γ, gluons)		(leptons, quarks)

This would be very attractive, but things don't work out that way !! ...

Although supersymmetry is often presented as unifying forces with matter ...

this is wrong (at least at the moment)

How can the world be supersymmetric ?

Many problems:

- *bosons* $\leftrightarrow$ *fermions, but which ones ?*

(or transforms elementary fields into composite ones ?)

- How to deal with (self-conjugate) ***Majorana fermions*** of SUSY theories ?

How to construct Dirac fermions carrying ***conserved B and L*** ?

$\downarrow$

supposed to be fermionic numbers ...

(should B and L also be carried by bosons ? appeared as non-sense !)

- Can one get ***spontaneous supersymmetry breaking*** ?

(apparently forbidden, as algebra requires a supersymmetric vacuum state to be stable)

- Where is the Goldstone fermion of spontaneously broken supersymmetry ?

(unseen ...)

- How to avoid unwanted spin-0 exchanges ?

(*that might spoil B and L conservation laws*)

Solution:

Introduce new particles

Accept attributing ***B*** *and* ***L*** *(previously "fermionic numbers") also to bosons* ...

photon associated, not with ν_e, ν_μ (ν_τ)

but with its own "photonic neutrino" called the *PHOTINO*

gluons associated with *GLUINOS* ... (named so in 1977)

↓

(but at the time, fermionic color octets were supposed not to exist, as violating the "triality principle")

→ $\boxed{\text{All particles get associated with new superpartners}}$ (PF, 1975-76)

photon	↔	photino
gluons	↔	gluinos
leptons	↔	spin-0 sleptons
quarks	↔	spin-0 squarks
	...	

→ *charginos, neutralinos, new Brout-Englert-Higgs bosons*

Thus

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

$\Rightarrow$ ***SUPERPARTNERS***

Many new particles, still unseen (even now at LHC ...)

This hypothesis was long mocked as a sign of the irrelevance of supersymmetry !!

(now often presented as "obvious" consequence of susy algebra !)

[open question : at which scale should susy particles be present ?

m_W (LEP) ? ~ TeV scale (LHC) ? compactification scale ?]

Many interesting consequences

Also requires $\boxed{\text{two spin-0 BEH doublets}}$ for EW breaking and quark and lepton masses

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}, \quad \tan\beta = v_2/v_1$$

$\Rightarrow$ charginos, neutralinos, additional spin-0 BEH bosons ... (1975)

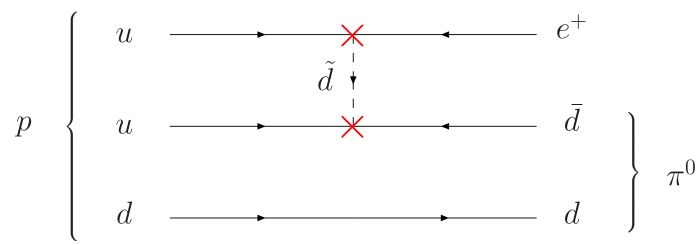
$\downarrow$

(very unpopular at the time)

We may still have to take care of a potential problem ...

$\boxed{\text{Avoid unwanted } \underline{\text{spin-0 exchanges}}}$

especially with spin-0 bosons $\tilde{q}$, $\tilde{l}$ carrying B or L)



proton decay that might be induced by $\tilde{d}$ *exchange*

Exchanges automatically forbidden by R-parity

R-PARITY

Z_2 remnant of $\boldsymbol{U(1)_R}$ symmetry acting chirally on SUSY generator

$\downarrow$

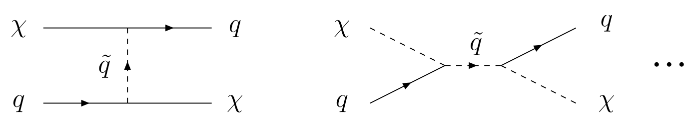
(would require (Majorana) gluinos massless)

$$\left\{ \begin{array}{l} \boldsymbol{R_p = (-1)^R} = \begin{cases} +1 : & \textit{ordinary particles} \\ -1 : & \textit{superpartners} \end{cases} \\ \\ \qquad \textit{identified as } \boldsymbol{(-1)^{2S}\,(-1)^{3B+L}} \end{array} \right.$$

(conserved as soon as $B - L$ conserved, even only modulo 2)

$\rightarrow$ *pair production of SUSY particles*

$\rightarrow$ *lightest SUSY particle (LSP) stable*



interactions of dark matter with quarks

typically a neutralino, natural WIMP candidate

for non-baryonic ***dark matter*** *of Universe*

also: gaugino and higgsino mass parameters $(m_3, m_2, m_1,\, \mu)$ may be naturally $\approx$ gravitino mass $m_{3/2}$

Minimal content of **Supersymmetric Standard Model** (MSSM)

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 $\tilde{h}^0$	$\left.\begin{matrix} H^{\pm} \\ H \\ h,\ A \end{matrix}\right\}$ Higgs bosons
	leptons l quarks q	sleptons $\tilde{l}$ squarks $\tilde{q}$

+ possible extra $U(1)$ gauge groupe and/or extra singlet superfield S

USSM N/nMSSM

$$\{W_3,\, W';\; h_1^\circ,\, h_2^\circ;\; \ldots\} \overset{SUSY}{\longleftrightarrow} \underbrace{\{\tilde{W}_3,\, \tilde{W}';\; \tilde{h}_1^\circ,\, \tilde{h}_2^\circ;\; \ldots\}}_{\to \text{ 4 neutralinos}}$$

LSP neutralino, Dark matter candidate

$\to$ possible relation between FORCES and DARK MATTER !

Searches for Dark Matter at colliders (unseen yet.) Is this serious ?

BEH interactions in susy theories

SUSY quartic BE-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 BE-Higgs potential of MSSM

Quartic couplings from electroweak interactions, fixed by EW gauge couplings !

$\rightarrow$

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

reaching 125 GeV problematic, as requires radiative correction effects to be large !

(from squarks $\tilde{t}$ sufficiently above TeV scale, recreates ("little") hierarchy problem ...)

A larger quartic coupling would be much appreciated ...

fortunately, already present in the N/nMSSM ... !

$\Rightarrow$ $\boxed{\text{N/nMSSM}}$

introduce extra singlet S with trilinear $\boldsymbol{\lambda H_2 H_1 S}$ superpotential coupling (NPB 90 (1975) 104)

μ parameter of MSSM promoted to dynamical variable $\mu(x,\theta) = \lambda\, S(x,\theta)$

$\lambda < S >$ can recreate effective μ ...

$$\boxed{\rightarrow \quad \mu\, H_2 H_1 \,+\, \lambda\, H_2\, H_1\, S \,+\, \tfrac{\kappa}{3}\, S^3 \,+\, \tfrac{\mu_S}{2}\, S^2 \,+\, \sigma\, S \quad \text{superpotential}}$$

$$V \;=\; \frac{g^2+g'^2}{8}\;(h_1^\dagger\, h_1 - h_2^\dagger\, h_2)^2 \;+\; \frac{g^2}{2}\;|h_1^\dagger\, h_2|^2 + |\,\boldsymbol{\lambda}\, h_1 h_2 + \frac{\partial f(s)}{\partial s}\,|^2 \;+\; \lambda^2\,|s|^2\;(h_1^\dagger h_1 + h_2^\dagger h_2) \;\; + \text{SU}\!\!\!/\text{SY} \;\text{ terms .}$$

$$\downarrow$$

λ allows to get all BE-Higgs bosons sufficiently heavy

without having to rely so much, as in the MSSM,

on large radiative corrections from very heavy squarks $\tilde t$

spin-0 BEH boson at $\simeq$ **125** GeV 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 ...

(possibly pointing in the direction of extended supersymmetry, and extra dimensions ...)

Susy particles did not show up yet !! ☹

Most mass limits now $\gtrsim$ TeV (ATLAS, CMS)

Charged and neutral spin-0 bosons associated with EW breaking within SUSY *also not found yet ..* ☹

MSSM very strongly (too strongly!) constrained. Is this something to worry about ?

consider extensions with an extra singlet, and/or an extra-$U(1)$ gauge group,

and/or a light gravitino LSP, and/or Dirac gluinos, and/or R-parity breaking, and/or extra dimensions ...

What about ***SUPERSYMMETRY BREAKING*** *?*

Which mechanism ? ... hidden sector, e.g. from supergravity ?

- Is it fixed by a **compactification scale** ? (possibly but not necessarily very large) ?

  R-odd particles having large masses $\approx m_{3/2} \approx \pi/L_6$ from compactification

  with ***boundary conditions involving R-parity ?*** (1984-85 ...)

  (Is there a relation with electroweak or ~ TeV scales ?)

- Are grand-unification particles also at a compactification scale $m_X \approx \pi/L_5$

  Can GUT and SUSY-breaking scales be comparable ? ...

  ... Phys.Scripta T15 (1987) 46 ... Adv.Ser. Dir. High-En. Phys. 26 (2016) 397

Where are the SUSY particles to be found ??? *(if they do exist ... big questions ...)*

Unconventional possibilities for dark matter, and additional interactions :

LIGHT DARK MATTER

U BOSONS and ***DARK PHOTONS***

we know Strong, electromagnetic, weak and gravitational interactions

Are there others ?

New interactions may exist and even probably should ...

what could be their properties ?

how could we know ?

Particles, Interactions and Symmetries *are intimately related*

New spin-1 bosons $\leftrightarrow$ *new gauge symmetries*

Simplest possibility: $\boxed{SU(3) \times SU(2) \times U(1) \times \text{ extra } U(1)}$ as e.g. in USSM (1977)

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

which mass for the new gauge boson ?

$\sim m_Z$? $\gtrsim$ TeV ? $\gg$ TeV ? light, very light, or massless ?

which couplings ? gauge coupling (g") $\leftrightarrow$ intensity of new interaction

$\Rightarrow$ possibility of new (very weak ?) forces next to gravitation, electromagnetism, ...

A new LIGHT GAUGE BOSON U

with a small or very small gauge coupling g" to SM particles

(discussed since 1980 : Searching for a new spin-1 boson PL95B (1980) 285, NPB 187 (1981) 184, ...)

opens up the unconventional possibility of ***light dark matter particles***

(if extremely light or massless, and extremely weakly coupled,

might also lead to apparent deviations from the Equivalence Principle)

LIGHT DARK MATTER

with C. Bœhm

NPB 683 (2004) 219 ...

(in ~ MeV to GeV range)

unconventional, at least for lower masses

How can it be possible ??

Too light DM particles normally forbidden, as could not annihilate sufficiently

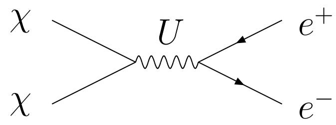
→ relic abundance (much) too large ... !! ??

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

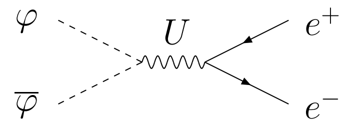
New interaction should be
significantly stronger than weak interactions ... !

to get sufficiently large σ_{ann}

New interaction induced by spin-1 U boson must be sufficiently strong at lower energies



or



DM annihilations, for spin-$\frac{1}{2}$ or spin-0 particles

to ensure for sufficient annihilations of light dark matter particles

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)

how is it possible ??

Interaction mediated by <u>LIGHT</u> 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

$\rightarrow$

$\frac{1}{q^2}$ *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 $|\boldsymbol{q}| \sim \boldsymbol{m_U} \ll \boldsymbol{m_Z}$,

light $\boldsymbol{U}$ *required ...*

*Nowadays one often focusses on a " **dark photon** "*

coupled to SM particles through electromagnetic current

(and maybe also coupled to dark matter, with dark matter staying neutral)

owing to simplicity of experimental discussion

in terms of mass of new boson,

and strength of its interactions, ϵe (in visible sector)

$$- eA^\mu J_{\mu\, em} \to -(eA^\mu + \epsilon e A'^\mu)\, J_{\mu\, em} + \frac{1}{2}\, m_{A'}^2\, A'^\mu A'_\mu$$

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 ?

A long time ago ... *PLB 95 (1980) 285, NPB 187 (1981) 184*

SEARCHING FOR A NEW SPIN 1 BOSON
a very light and very weakly coupled U boson

$SU(3)\times SU(2)\times U(1)\times$ extra $U(1)$ → 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 $\propto \dfrac{G_F\, m_U^2}{m_U^2 - q^2}\ (\times r^2)$ (compared to G_F for Z exchanges)

(r =≤ 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, $K^+ \to \pi^+ U$, $\psi \to \gamma U$, $\Upsilon \to \gamma U$ decays

From (old) (hadronic) ***beam dump experiments*** *(Brookhaven, 1979)*

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

$m_U = 1 \to 7$ MeV mass interval excluded, in simplest situation

A new light spin-1 boson with a small or very small small gauge coupling ?

(in early 80's)

Reactions from experimentalists:

why do you want such a thing to exist ?

Reactions from theoreticians:

it cannot be grand-unified (implying it is bad ...)

Still, more than 30 years later, many experiments are now looking for "such a thing"

a new light gauge mediator ...

General discussion

Extra $U(1)$'s and new forces, NPB 347 (1990) 743

- with *one BE-Higgs doublet only* [or several with the same gauge quantum numbers], (+ singlet)

extra-$U(1)$ gauged involves combination of $\boldsymbol{Y}$ with $\boldsymbol{B}$, $\boldsymbol{L_i}$ + possible DM contribution

After mixing effects: resulting $\boldsymbol{U}$ boson (mixing of extra-$U(1)$ boson C with SM Z boson)

coupled to a *purely* ***vectorial current***,

linear combination to electromagnetic with B and L_i currents

U boson coupled, not just proportionally to Q, but to linear combination

$$\boxed{(\epsilon_Q\, Q + \epsilon_B\, B + \epsilon_L\, L)\, e \quad (\,+\,\text{Dark Matter}\,)}$$

(*not just to* $\epsilon_Q\, Q\, e$ (+ DM) as for a pure "dark photon" !!)

- with two BEH doublets [or more], (+ singlet)

axial $\boldsymbol{U(1)_A}$ symmetry generator may contribute

$\boldsymbol{U}$ current involves also an ***axial part***

$\Rightarrow$ pssibility of $\not{P}$ + ***(invisible) axionlike behavior*** of a light $\boldsymbol{U}$ ($f_p = f_A\, \frac{2m_{l,q}}{m_U}$)

(already pointed out in 1980)

$\boxed{U = \textit{generalized} \ \textbf{“dark photon”} \ \textit{coupled to} \ (\epsilon_Q\, Q + \epsilon_B\, B + \epsilon_L\, L)}$

(could have provided a possible explanation of the ≈ 3σ effect observed in $\boldsymbol{g_\mu - 2}$*)*

Within **GRAND-UNIFICATION** : $\rightarrow \ SU(5) \times U(1)$

extra-$U(1)$ generator: $\boxed{\boldsymbol{F = \left[\, Y - \frac{5}{2}\,(B-L)\,\right]} \quad \textit{(at GUT scale)}}$

After mixing effects, coupling to $[\,\epsilon_Q\ Q\ + \epsilon_{B-L}\,(B-L)\,]\,e$

involving a specific linear combination

$$\epsilon_Q\,[\,Q - \frac{5}{4\,\cos^2\theta}\ (B-L)\,]\,e \quad = \quad \boxed{\boldsymbol{\epsilon\,[\,Q\ -\ 1.64\,(B-L)\,]\,e}}$$

(would be $\epsilon\,[\,\underbrace{Q - 2\,(B-L)}\,]\,e$ at GUT scale)

$\downarrow$

invariant under $SU(4)$ ***electrostrong*** symmetry

connecting directly photons with gluons

In addition to visible decay modes, $U \rightarrow e^+ e^-$ ... *(depending on mass)*

the U can also have ***invisible decay modes into neutrinos*** $\boldsymbol{U \rightarrow \nu \bar{\nu}}$

independently of other possible decays into Light Dark Matter particles , $U \rightarrow \chi \chi$

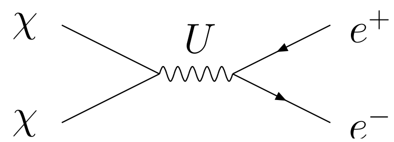
(in contrast with ordinary "dark photon")

Possibility of LIGHT DARK MATTER particles χ

by allowing for sufficient LDM annihilations into SM particles

Relic density of light dark matter

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



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

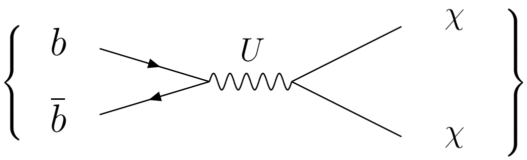
$$\sigma^{ee}_{\rm ann}\, v_{\rm rel} \;\simeq\; \frac{v_\chi^2}{.16}\left(\frac{c_\chi\, f_e}{10^{-6}}\right)^2 \left(\frac{m_\chi \times 1.8\ \ \mathrm{MeV}}{m_U^2 - 4\,m_\chi^2}\right)^2 \;(4\ \mathrm{pb})$$

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*

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

LIGHT DARK MATTER in $\psi\,(\Upsilon)$ DECAYS

Invisible Υ decay into LDM particles : Υ



invisible

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

could be sizeable, for DM particles with relatively large cross sections:

invisible and monophoton searches in $q\bar{q}$ annihilations *(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)

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

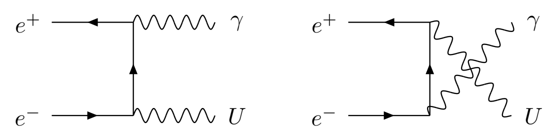
$$\psi \to \underbrace{\chi\,\chi}_{\text{inv}} \;<\; 7.2\;10^{-4} \;\textit{(BES II)}\;\Rightarrow\quad |c_\chi\, f_{cV}| \;<\; .95\;10^{-2}$$

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

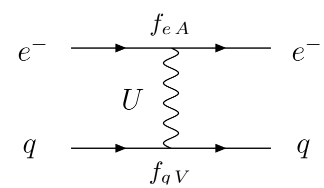
Other possible effects of a new light gauge boson

DM 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 on f_{qA} *from* ψ, Υ *and* K^+ *decays,*

may favor vector U coupling to SM particles *through* $\epsilon_Q + \epsilon_{B-L}\,(B-L)$

or, within grand-unification, to $\boxed{\epsilon\,[Q - 1.64\,\alpha\,(B-L)]\; e}$

(instead of just $\epsilon\, Q\, e$)

Many different experiments + many projects

If extremely small coupling + extremely small mass

$\rightarrow$ extremely small new force, with very large range $\lambda = \dfrac{\hbar}{mc}$

Might lead to ***apparent violations of the Equivalence Principle***

MICROSCOPE experiment now testing it at the $\mathbf{2\ 10^{-14}}$ level PRL 119 (2017) 231101

Extremely small coupling $\boldsymbol{g"} \lesssim \mathbf{10^{-24}}$ may be related to

huge energy density $\propto \dfrac{1}{g"^2}$ responsible for ***inflation***

$\rightarrow$ hierarchy in mass scales by a factor $\gtrsim \mathbf{1/\sqrt{g"}} \gtrsim \mathbf{10^{12}}$

$(\sim \text{TeV} \times 10^{13} \rightarrow \sim 10^{16}\ \text{GeV} \ \ldots)$ PRD 97 (2018) 055039

(very short summary)

U may be viewed as spin-1 boson interpolating between extreme cases of ***"dark photon"*** and *("invisible")* ***axionlike particle***

CONCLUSIONS

- ***Great discoveries from the observation of the Universe***

CMB, acceleration of expansion

direct detection of gravitational waves from the merging of two black holes, ...

- Discovery in 2012 of ***spin-0 BEH boson***

great step forward, confirming again the track of sp. broken gauge theories

with a new sort of particle

- No reason to think that 125 GeV spin-0 ***H*** boson should be alone

The Standard Model cannot be the end of the story

Many open questions point towards "new physics"

- But what ? Many ideas ... (too many ... ?)

Experiments deeply needed to progress and clarify the situation

- Supersymmetry enlarges space-time (x^μ) to new spinorial coordinates (θ)

provides connection with gravity + natural place for fundamental spin-0 bosons

- Leads to introduce new superpartners

many attractive aspects, including a possible DM candidate

- In spite of hopes associated with possible solution for hierarchy problem

Still waiting for SUSY particles, new spin-0 BEH bosons (e.g. from second doublet) ... detection of ***dark matter*** particles (or maybe a whole new "dark sector")

or any direct evidence for new physics beyond the SM

- ***Such discoveries may occur at any moment*** ☺

  but we have learned to be patient ! ☹

- Supersymmetry might also be broken at a (large ?) compactification scale

Possibly 125 GeV H boson ≈ spin-0 partner of Z under two susy transformations:

$$\boxed{\boldsymbol{Z} \overset{\text{SUSY}}{\longleftrightarrow} \overset{\text{SUSY}}{\longleftrightarrow} \boldsymbol{H}} \quad \text{with} \quad W^{\pm} \overset{\text{SUSY}}{\longleftrightarrow} \overset{\text{SUSY}}{\longleftrightarrow} H^{\pm}$$

(first susy relation between fundamental particles of different spins ?)

Other approaches, new ideas ...

- *Next to observation of Universe + high-energy frontier at LHC (NLC, ...)*

another frontier, at much lower energies:

(weakly → extremely-weakly) coupled light new particles

U boson *(= generalized* ***dark photon****),* ***light dark matter,*** ***axion*** *or axionlike particles,* ...

Room for very weak new interactions ... *and* $\boxed{\textbf{\textit{unsuspected possibilities !}}}$