LHC

SUPERSYMMETRY

and

NEW PARTICLES

Pierre FAYET

LHC days in Split

Split, 7 october 2010

LHC is operating

a great machine *(with great physicists)*

What can we expect or hope to discover at LHC ?

What are the constituents of matter ?

What is the origin of mass ?

How do weak and electromagnetic interactions differentiate ?

Do new states of matter exist ?

What is the nature of Dark Matter ?

Are there new forces beyond the ones we know ?

Are there hidden dimensions of space-time ?

etc.

are some of the most fundamental questions

about the basic laws of our Universe

LHC should bring us answers to some of these questions ...

starting point:

STANDARD MODEL

strong, electromagnetic and weak interactions of quarks and leptons

$$SU(3) \times SU(2) \times U(1)$$

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

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

associated with **spontaneous electroweak symmetry breaking**

– *remarkably successful*

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

- **What about** **<u>fundamental Higgs-... fields</u>** **?**

(do they actually exist ?)

We heard talks about Higgs physics

We are confident that

LHC should elucidate the mechanism
by which weak and electromagnetic interactions differentiate,
and quarks and leptons acquire masses

presumably (?) through the expected discovery of one (or several) Higgs boson(s)

or possibly through some other mechanism.

Even if Higgs bosons are discovered we still have questions ....:

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

what determines the Higgs boson mass ? $(\,m_H = \mu\sqrt{2} = v\sqrt{2\,\lambda}\ldots)$

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

growing evidence for non-baryonic DARK MATTER

What is dark matter made of ??

Other interrogations :

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

  can it be more closely connected with particle physics ?

  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. $SU(5)$, ...

  $$\begin{cases} \text{gluons} \longleftrightarrow W^{\pm},\ Z,\ \gamma \quad \text{(+ other gauge bosons e.g. } X^{\pm 4/3},\ Y^{\pm 1/3},\ \ldots \text{)} \\ \text{quarks} \longleftrightarrow \text{leptons} \end{cases}$$

  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 ?** approach of **supersymmetry** $\longrightarrow$

...

a “new” tool,

SUPERSYMMETRY

BOSONS $\longleftrightarrow$ **FERMIONS**

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

what can we do with it ?

can it be of any help in the real world

of fundamental particles and interactions ?

(according to common wisdom)

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

could one relate Fermions constituants of matter

to Bosons, messengers of interactions ?

and arrive to some sort of

Unification FORCES ↔ 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

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

Fundamental connection of supersymmetry with SPACE-TIME

$\rightarrow$ *relation with general relativity, gravitation* $\rightarrow$ *supergravity*

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

$\theta = \begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{pmatrix} =$ **spin-$\frac{1}{2}$ 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**

Extension of space-time to include

new <u>fermionic</u> coordinates (or <u>bosonic</u> ones)

$\longrightarrow$

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

furthermore:

extended supersymmetric theories are naturally formulated

using extra (compact) space dimensions

($N=2$ SUSY obtained from 5 or 6 dimensions, $N=4$ SUSY from 10 dimensions)

we shall concentrate on simple ($N = 1$) supersymmetry *well, but ...*

Can SUSY apply to fundamental laws of Nature ?

(*what would this imply ... ?)*

Nature is "obviously" not supersymmetric !

it seems

1 **Bosons and fermions should have EQUAL MASSES :**

this is not the case

$\rightarrow$ *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,

in the absence of a better understanding of the susy-breaking mechanism ...)

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

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

we think we know the answer:

it is eliminated in favor of

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

which should normally have extremely small interactions with matter

and not be directly observable ...

(but there is a caveat, with the possibility of an observable gravitino ...)

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

(with effective coupling $\propto \kappa \sqrt{\frac{2}{3}} \frac{k^\mu}{m_{3/2}}$*) which could be observable ... ! depending on* $m_{3/2}$

e.g. through decays of SUSY particles, like

neutralino $\rightarrow$ gravitino + photon

gravitino "lightest susy particle", stable ...

limits on such processes, since PETRA experiments in the 80's ...

One possible SUSY signature, that should be searched for at LHC ...

interactions of the gravitino much weaker than weak interactions

decouples much before neutrinos, during evolution of Universe

a possible DM candidate

main question, if susy is to be applicable to the real world :

• **Which bosons and fermions relate ?**

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

does not work ...

and also:

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

SUSY theories involve (self-conjugate) Majorana fermions

Nature only knows Dirac fermions !

• **How to construct Dirac fermions ?**

carrying conserved quantum numbers ($\boldsymbol{B}$ and $\boldsymbol{L}$)

How to give fermions

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

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

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

problems, problems, problems ... !

Now, solutions:

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

photon not associated with ν_e, ν_μ 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

$\Longrightarrow$ *all particles get 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*
	...	

$\rightarrow$

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

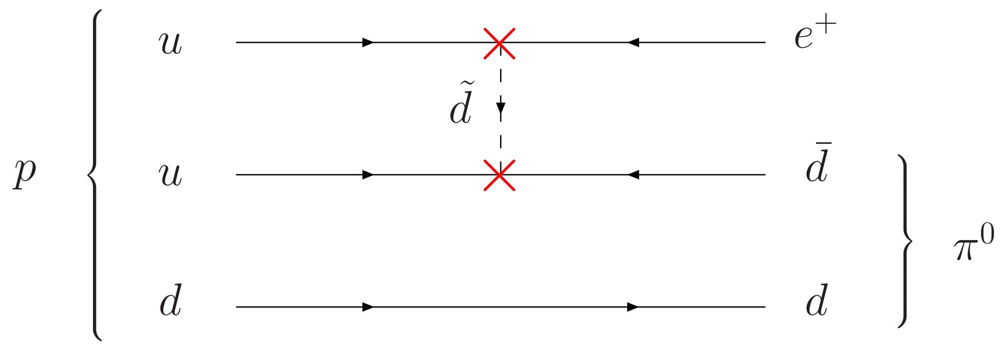
Known bosons	$\longleftrightarrow$	**New fermions**
Known fermions	$\longleftrightarrow$	**New bosons**

(this was long mocked as a sign of irrelevance of supersymmetry !)

still a problem: **get <u>interactions</u> from $W^{\pm}$, Z, <u>photon and gluon</u> exchanges**

avoid unwanted <u>spin-0 exchanges</u> ?

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



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

this exchange is forbidden by ***R*-parity**

R-PARITY

initial continuous $U(1)_R$ *symmetry acts chirally on SUSY generator*

but it would require the gluinos and photino to be massless ...

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

$$R_p = \begin{cases} +1 : & \textit{ordinary particles} \\ -1 : & \textit{superpartners} \end{cases}$$

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

$\longrightarrow$ *pair production of SUSY particles*

$\longrightarrow$ *lightest SUSY particle stable*

$\longrightarrow$ **stable dark matter candidate**

also:

gluinos and other gaugino masses may be naturally $\approx$ gravitino mass $m_{3/2}$

R-parity $\Rightarrow$ LSP stable

candidate for non-baryonic dark matter of Universe

usually a neutralino

combination of superpartners of neutral gauge and Higgs bosons,

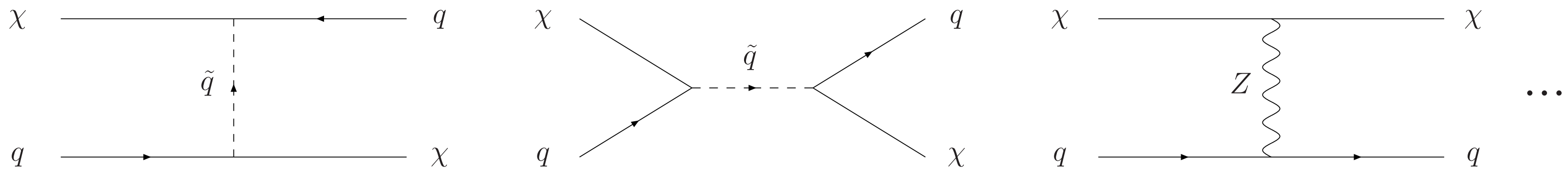
$$\{W_3,\, W';\, h_1^\circ,\, h_2^\circ;\, \dots\} \quad \overset{SUSY}{\longleftrightarrow} \quad \underbrace{\{\tilde{W}_3,\, \tilde{W}';\, \tilde{h}_1^\circ,\, \tilde{h}_2^\circ;\, \dots\}}_{\text{neutralinos}}.$$

relation of dark matter with gauge (γ, Z, ...) and Higgs bosons

Relic density of dark matter particles

evaluated from annihilation cross-sections at freeze-out time

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



interactions of dark matter with quarks

(annihilation processes of dm particles are similar)

neutralino $=$ natural WIMP candidate

precise relic density of neutralinos depends on the details of mass spectrum

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

DARK MATTER $\longleftrightarrow$ FORCES

Producing DARK MATTER at particle colliders

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

stable from R-parity *(or similar conservation law)*

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

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

lightest neutralino became natural DM candidate

$e^+ e^- \longrightarrow$ ... $\longrightarrow$ **2 neutralinos** $+$ ...

$p\ p \longrightarrow$ *pair-production of* $\tilde{q}$ *or* $\tilde{g}$ $\longrightarrow$ **2 neutralinos** $+$ ...

or e.g., for unstable neutralinos (N)LSP decaying e.g. into (photon + gravitino):

$$\begin{cases} e^+ e^- \;\rightarrow\; \textbf{2 neutralinos} + \ldots \;\rightarrow\; \gamma\,\gamma + \textbf{2 gravitinos} + \ldots \\ p\;p \;\rightarrow\; \textbf{2 neutralinos} + \ldots \;\rightarrow\; \gamma\,\gamma + \textbf{2 gravitinos} + \ldots \end{cases}$$

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

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

About Higgs-. bosons ...

we need a pair of doublet Higgs superfields,

3 reasons: $\begin{cases} \text{avoid massless chiral chargino} \\ H_1 \text{ gives masses to } d \text{ and } e\text{, } H_2 \text{ to } u \\ \text{cancel anomalies} \end{cases}$

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

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

Charged Higgs bosons $\boldsymbol{H^\pm}$

+ *3 neutral ones* $\boldsymbol{H, h, A}$ + *maybe others ...*

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

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

2) **chiral quark and lepton superfields**

3) **two doublet Higgs superfields** H_1 **and** H_2

4) **trilinear superpotential for** q **and** l **masses**

[$\times$ extra-$U(1)$]

- **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*

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

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

Quartic couplings fixed by electroweak gauge couplings !

$\longrightarrow$

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

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

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

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

introduce EXTRA SINGLET S *(1975)*

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

(cf. electron mass $m_e \rightarrow \lambda_e\, \varphi(x)$ *in SM)*

$$\mu\, H_1 H_2 \rightarrow \lambda\, H_1 H_2\, S$$

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

$\rightarrow$ $\mu\, H_1 H_2 + \lambda\, H_1\, H_2\, S + f(S)$ **superpotential**

N/nMSSM

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

tends to be required to make all Higgs bosons sufficiently heavy
without relying too much on large radiative corrections

Potential of N/nMSSM:

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

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

$\boldsymbol{\lambda}$ *allows to get*

all Higgs bosons sufficiently heavy

$\longrightarrow$ **additional singlino**

EXTRA-$U(1)$

supersymmetric extensions of the SM

gauge extra-$U(1)$ symmetry ... $\longrightarrow$ **("USSM")**

$\rightarrow$ **additional gaugino**

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

various possibilities, among which $\boldsymbol{U(1)}$*'s from groups like*
$\boldsymbol{SU(3) \times SU2)_L \times SU(2)_R \times U(1)}$ *or* $\boldsymbol{O(10)}$ *or* $\boldsymbol{E(6)}$ *GUT groups*

in SUSY extensions of the standard model

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

possibility of rotating independently the two doublets

$$\boxed{h_1 \to e^{i\alpha}\, h_1\,, \quad h_2 \to e^{i\alpha}\, h_2}$$

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

acts axially on quarks and leptons (+ possible vector coupling)

(global) or local $\rightarrow$ **new gauge boson** Z' **or** U

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.*

LIGHT DARK MATTER

with C. Bœhm

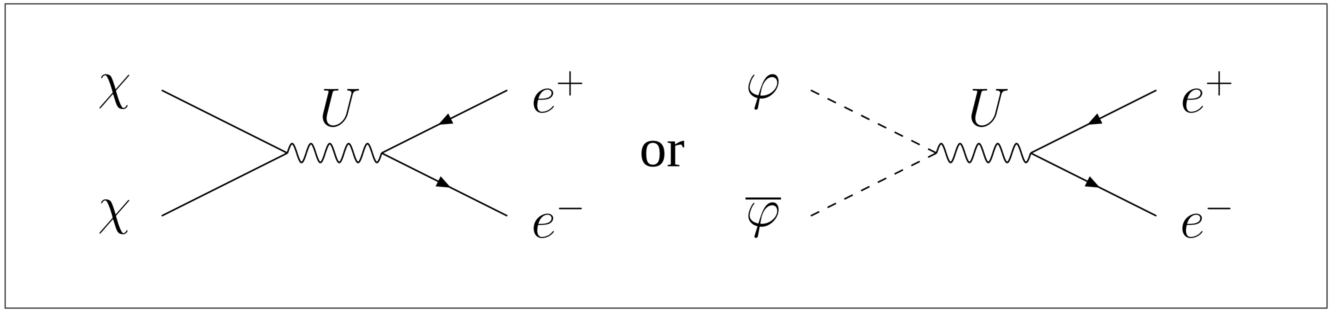
(a few words)

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 ...

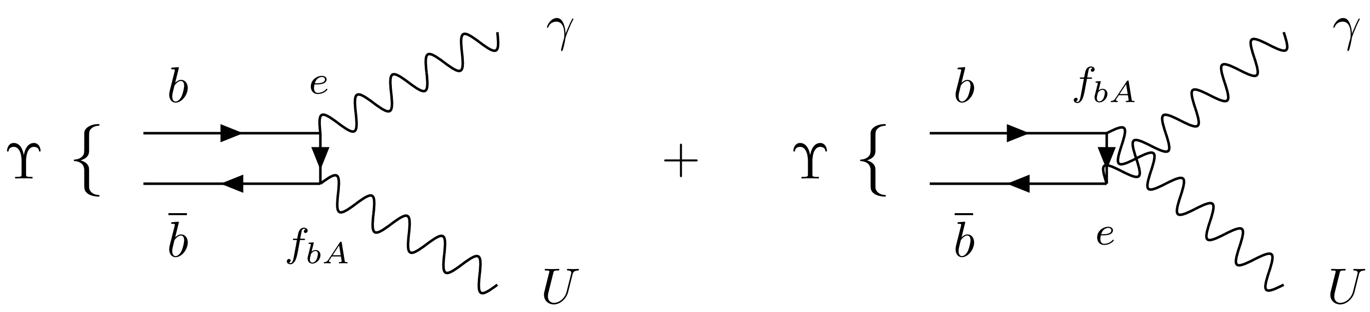
how a light U could be detected ?

SEARCHING FOR A LIGHT U

in particle physics experiments

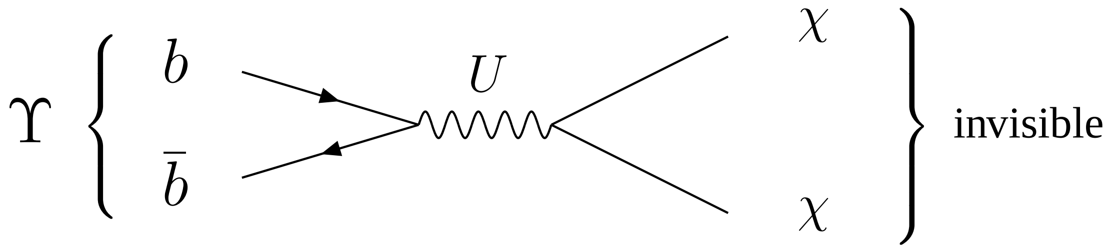
for example in ψ and Υ DECAYS :

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



Dark Matter at accelerators

waiting for LHC results, we already have information from other experiments



Invisible Υ decay into light dark matter particles

$$\Upsilon \to \underbrace{\chi\,\chi}_{\textbf{inv}} \; < \; 3\;10^{-4} \;\; \textit{(Babar)} \;\; \Rightarrow$$

$$|c_\chi \, f_{bV}| \;\; < \;\; 5\;10^{-3}$$

Searches for EXTRA SPACE DIMENSIONS

expect series of heavy copies of ordinary particles

(“KK excitations”)

expect new stable particles (presumably neutral, but might also be charged ...)

masses $\approx \dfrac{\hbar}{L\,c}$ $\quad L =$ **compactification scale**

CHAMPs $\longrightarrow$ *superheavy stable isotopes of hydrogen ... ?*

new Dark Matter candidates

(e.g. lightest excitation of photon or weak-hypercharge gauge boson,

or associated scalars ...)

what is the compactification scale (s) ?

$\sim m_{\mathrm{GUT}}$ **?** $\quad \sim m_{\mathrm{Planck}}$ **?** $\quad \sim$ **TeV ?**

also, stay attentive to unconventional scenarios

possibility of

UNEXPECTED DISCOVERIES ...

CONCLUSIONS

with LHC we expect to elucidate the mechanism responsible for

EW symmetry breaking + mass generation

presumably (?) through the discovery of **spin-0 (Higgs-..) bosons**

we hope to elucidate the nature of Dark Matter through pair-production of

new particles, decaying into stable DM particles

more specifically

we hope to discover SUPERSYMMETRY through pair-production of

Superpartners = SUSY particles

the lightest, usually a neutralino (or ...)

stable from R-parity and $\sim$ "weakly-interacting"

being a natural Dark Matter candidate

(provided SUSY particles are not too heavy, $\lesssim$ TeV scale, as usually expected)

expected Higgs sector:

2 doublets + possible singlet
with $\lambda\, H_1 H_2\, S$ trilinear coupling

singlet welcome *(possibly required)* **to make Higgs bosons sufficiently heavy**

MSSM already very tightly (too tightly ?) constrained .... $\longrightarrow$ *N/nMSSM, USSM, ...*

if superpartners too heavy, SUSY might also show up indirectly
through its characteristic Higgs sector

search for new gauge bosons Z', W_R, ...

and possible signs of extra dimensions ...

(especially if responsible for susy-breaking
through boundary conditions involving R-parity)

(+ possibility of light weakly (or very weakly) coupled particles)

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