BEYOND THE STANDARD MODEL

Dmitri Kazakov
JINR/ITEP

Outline

Part I Supersymmetry

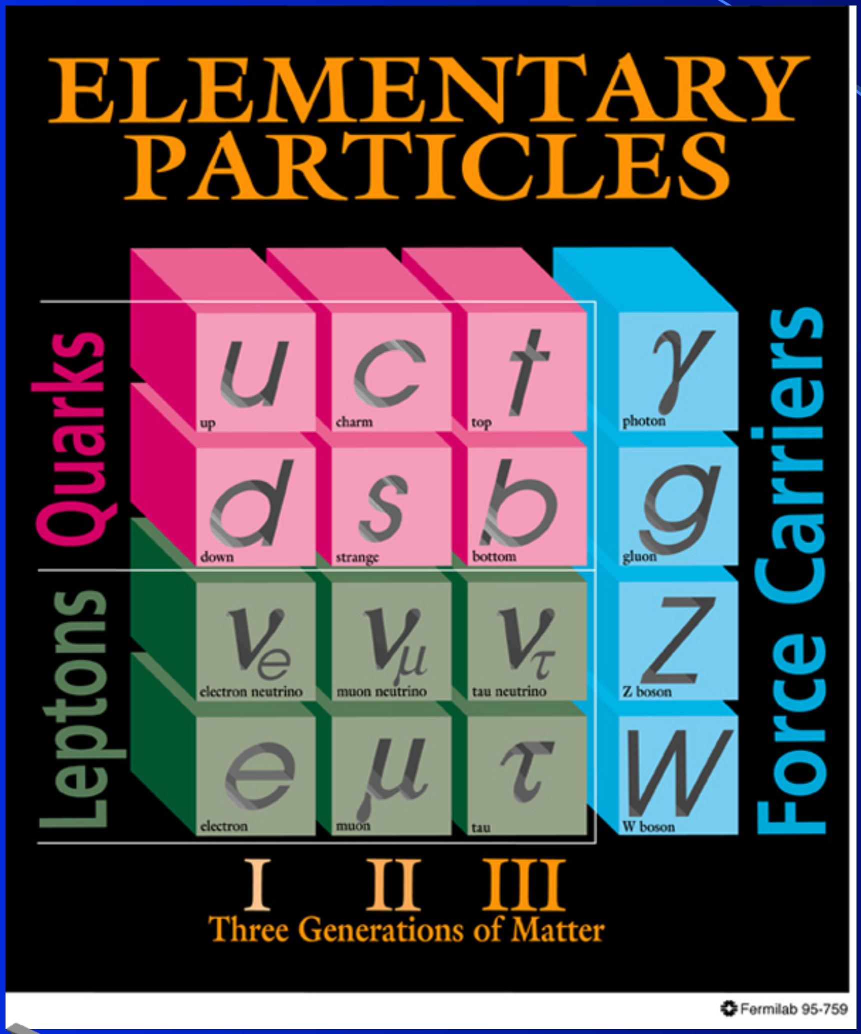
1. What is SUSY
2. Basics of SUSY
3. The MSSM
4. Constrained MSSM
5. SUSY searches
6. SUSY DM

Part II Extra Dimensions

1. The main idea
2. Kaluza-Klein Approach
3. Brane-world models
4. Possible experimental signatures of ED

The Standard Model

Particles



H

The Higgs boson

Forces

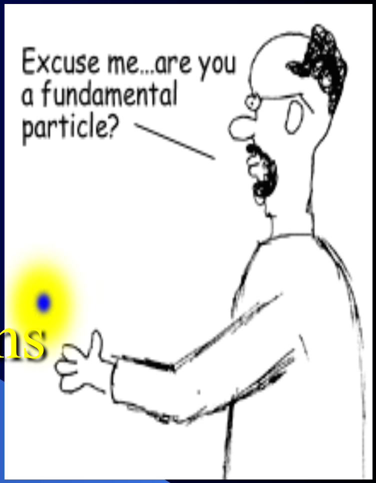
Electromagnetic

Strong

Weak

Gravity

The SM and Beyond



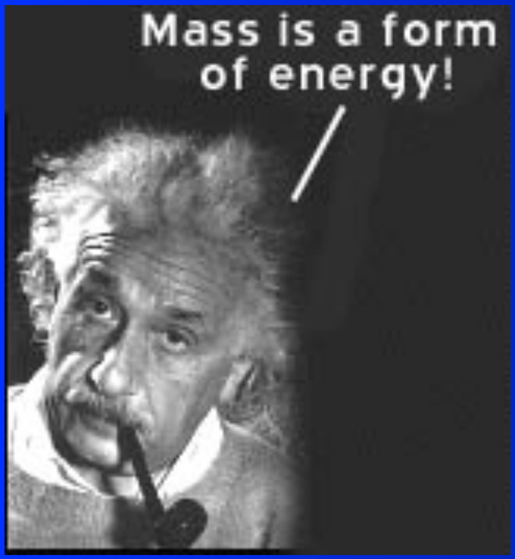
The problems of the SM:

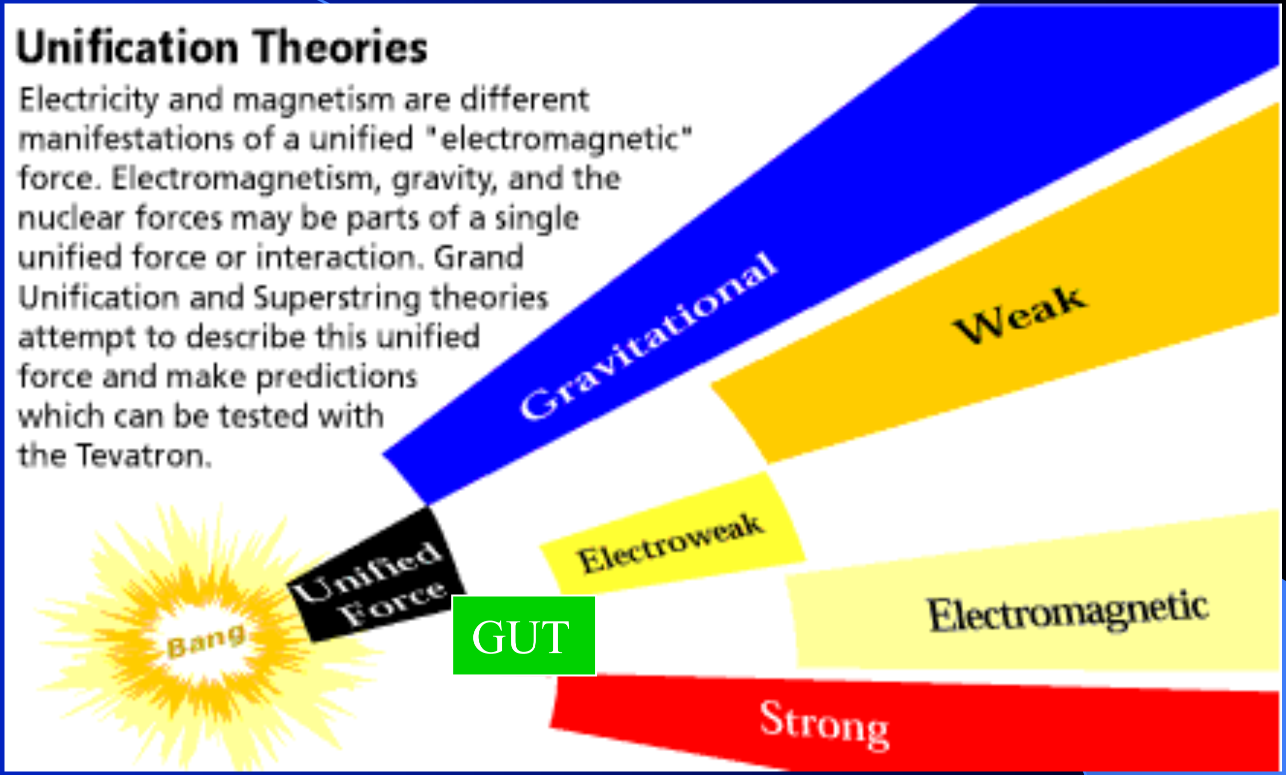
- Inconsistency at high energies due to Landau pole
- Large number of free parameters
- Formal unification of strong and electroweak interactions
- Still unclear mechanism of EW symmetry breaking
- CP-violation is not understood
- Flavour mixing and the number of generations is arbitrary
- The origin of the mass spectrum is unclear

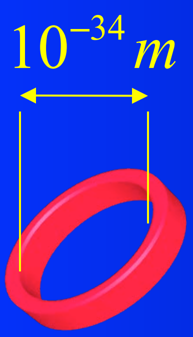
The ways beyond the SM:

- The SAME fields with NEW interactions ➡ GUT, SUSY, String
- NEW fields with NEW interactions ➡ Compositeness, Technicolour, preons

Grand Unified Theories







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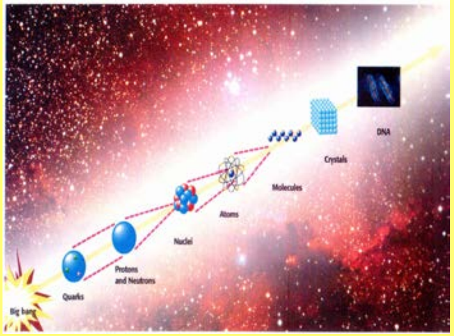
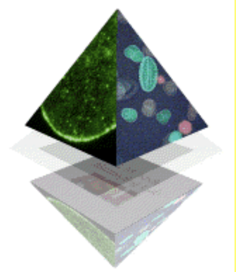
- Unification of strong, weak and electromagnetic interactions within Grand Unified Theories is the new step in unification of all forces of Nature
- Creation of a unified theory of everything based on string paradigm seems to be possible



What is SUSY?



- **Supersymmetry** is a boson-fermion sy… y that is aimed to unify all forces in N… …ing gravity within a singe fram…

$Q\,|\,boson>=|\,fe$ … $on>$

$[b,b]$ … $2\delta^{ij}(\sigma^{\mu})_{\alpha\dot\beta}P_{\mu}$

First papers in 1971-1972

No evidence in particle physics yet

- Moder… …ry in particle physics are based… …gin, though low energy manifestat… …SY can be found (?) at modern colliders and… …n non-accelerator experiments

Motivation of SUSY in Particle Physics

- Unification with Gravity
- Unification of gauge couplings
- Solution of the hierarchy problem
- Dark matter in the Universe
- Superstrings

Superalgebra

(Super) Algebra

Lorentz Algebra

$$[P_\mu, P_\nu] = 0,\ [P_\mu, M_{\rho\sigma}] = i(g_{\mu\rho}P_\sigma - g_{\mu\sigma}P_\rho),$$

$$[M_{\mu\nu}, M_{\rho\sigma}] = i(g_{\nu\rho}M_{\mu\sigma} - g_{\nu\sigma}M_{\mu\rho} - g_{\mu\rho}M_{\nu\sigma} + g_{\mu\sigma}M_{\nu\rho}),$$

SUSY Algebra

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,$$

$$[Q^i_\alpha, M_{\mu\nu}] = \tfrac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta,\ [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\tfrac{1}{2}\bar{Q}^i_{\dot\beta}(\bar\sigma_{\mu\nu})^{\dot\beta}_{\dot\alpha},$$

$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$

$$\alpha, \dot\alpha, \beta, \beta = 1,2;\ i,j = 1,2,\ldots,N.$$

Superspace

$$x_\mu \to x_\mu, \theta_\alpha, \bar\theta_{\dot\alpha}$$

$\alpha, \dot\alpha = 1,2$

Grassmannian parameters

$$\vartheta^2_\alpha = 0,\ \bar\vartheta^2_{\dot\alpha} = 0$$

SUSY Generators

$$Q_\alpha = \frac{\partial}{\partial\vartheta_\alpha} - i\sigma^\mu_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}\partial_\mu$$

$$\bar{Q}_{\dot\alpha} = -\frac{\partial}{\partial\bar\vartheta_{\dot\alpha}} + i\theta_\alpha\sigma^\mu_{\alpha\dot\alpha}\partial_\mu$$

$$Q^2_\alpha = 0,\ \bar{Q}^2_{\dot\alpha} = 0$$

This is the only possible graded Lie algebra that mixes integer and half-integer spins and changes statistics

Quantum States

Quantum states: Vacuum = $|E,\lambda>$ $\qquad Q|E,\lambda>=0$

Energy helicity

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot{\alpha}}, P_\mu] = 0$$

State	Expression	# of states
vacuum	$\vert E,\lambda>$	1
1-particle	$\bar{Q}_i \vert E,\lambda> = \vert E,\lambda+1/2>$	$\binom{N}{1} = N$
2-particle	$\bar{Q}_i \bar{Q}_j \vert E,\lambda> = \vert E,\lambda+1>$	$\binom{N}{2} = \frac{N(N-1)}{2}$
…	…	…
N-particle	$\bar{Q}_1 \bar{Q}_2 \ldots \bar{Q}_N \vert E,\lambda> = \vert E,\lambda+N/2>$	$\binom{N}{N} = 1$

Total # of states: $\sum_{k=0}^{N} \binom{N}{k} = 2^N = 2^{N-1}\, bosons + 2^{N-1}\, fermions$

SUSY Multiplets

Chiral multiplet $N=1,\ \lambda=0$

helicity	-1/2	0	1/2
# of states	1	2	1

(φ, ψ) — scalar, spinor

Vector multiplet $N=1,\ \lambda=1/2$

helicity	-1	-1/2	1/2	1
# of states	1	1	1	1

(λ, A_μ) — spinor, vector

Members of a supermultiplet are called **superpartners**

N=4	SUSY YM	helicity			-1	–1/2	0	1/2	1		
	λ = -1	# of states			1	4	6	4	1		
N=8	SUGRA	helicity	-2	–3/2	–1	–1/2	0	1/2	1	3/2	2
	λ = -2	# of states	1	8	28	56	70	56	28	8	1

$N \leq 4S$ ← spin

$N \leq 4$ For renormalizable theories (YM)

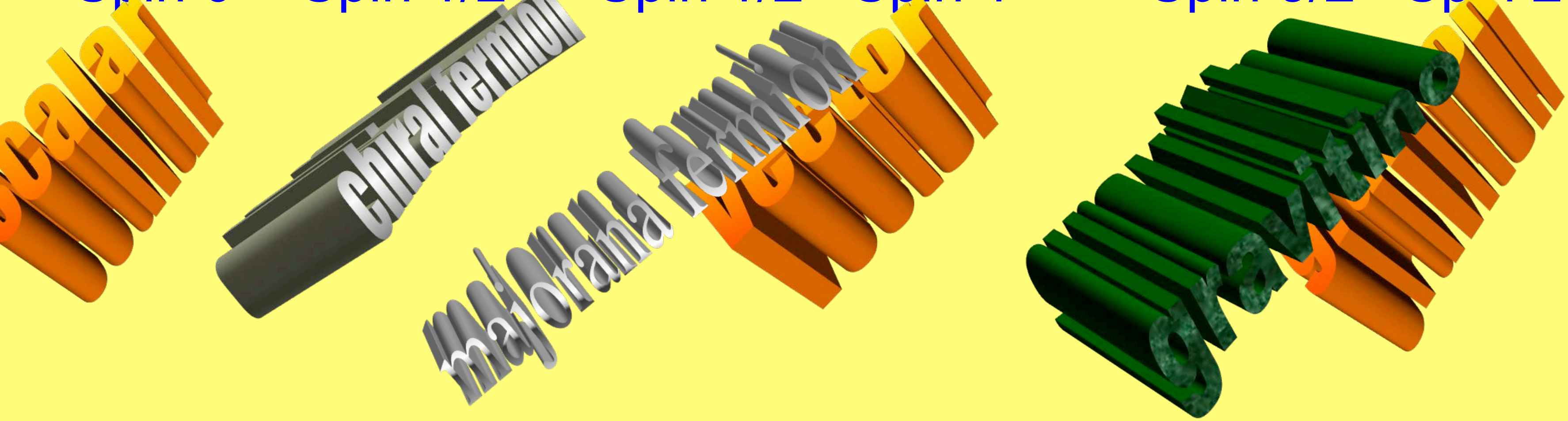
$N \leq 8$ For (super)gravity

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

(φ,ψ) (λ, A_μ) $(\tilde{g}, g)$

Spin 0 Spin 1/2 Spin 1/2 Spin 1 Spin 3/2 Spin 2



SUSY Transformation

N=1 SUSY Chiral supermultiplet:

spin=0 → $\delta_\varepsilon A = \sqrt{2}\varepsilon\psi,$

spin=1/2 → $\delta_\varepsilon \psi = i\sqrt{2}\sigma^\mu \bar{\varepsilon}\partial_\mu A + \sqrt{2}\varepsilon F,$

$\delta_\varepsilon F = i\sqrt{2}\bar{\varepsilon}\sigma^\mu \partial_\mu \psi$

parameter of SUSY transformation (spinor)

Auxiliary field

(unphysical d.o.f. needed to close SYSY algebra)

SUSY multiplets → Superfiled in Superspace

$(y = x + i\theta\sigma\bar{\theta})$

superfield

$$\Phi(y,\theta) = A(y) + \sqrt{2}\theta\psi(y) + \theta\theta F(y)$$

$$= A(x) + i\theta\sigma^\mu\bar{\theta}\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar{\theta}\bar{\theta}\Box A(x)$$

$$+ \sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar{\theta} + \theta\theta F(x)$$

Expansion over grassmannian parameter

component fields

$\theta^2 = \theta_1\theta_2, \quad \theta_1^2 = \theta_2^2 = 0!$

Gauge superfields

Gauge superfield

$$V(x,\theta,\bar\theta) = C(x) + i\theta\chi(x) - i\bar\theta\bar\chi(x) + i\theta\theta M(x) - i\bar\theta\bar\theta M^{+}(x)$$

$$-\theta\sigma^{\mu}\bar\theta v_{\mu}(x) + i\theta\theta\bar\theta[\bar\lambda(x) + i\bar\sigma^{\mu}\partial_{\mu}\chi(x)] - i\bar\theta\bar\theta\theta[\lambda(x) + i\sigma^{\mu}\partial_{\mu}\bar\chi(x)]$$

$$+\tfrac{1}{2}\theta\theta\bar\theta\bar\theta[D(x) + \tfrac{1}{2}\mathrm{W}C(x)]$$

Gauge transformation

$$V \to V + \Phi + \bar\Phi$$

$$C \to C + A + A^{*}$$

$$\chi \to \chi - i\sqrt{2}\psi$$

$$M \to M - 2iF$$

$$v_{\mu} \to v_{\mu} - i\partial_{\mu}(A - A^{*})$$

$$\lambda \to \lambda$$

$$D \to D$$

Wess-Zumino gauge

$$C = \chi = M = 0$$

physical fields

Field strength tensor

$$W_{\alpha} = -\tfrac{1}{4}\bar D^{2} e^{V} D_{\alpha} e^{-V}$$

Covariant derivatives

$$D_{\alpha} = \frac{\partial}{\partial\vartheta_{\alpha}} + i\sigma^{\mu}_{\alpha\dot\alpha}\bar\vartheta^{\dot\alpha}\partial_{\mu}$$

$$\bar D_{\dot\alpha} = -\frac{\partial}{\partial\bar\theta_{\alpha}} - i\theta_{\dot\alpha}\sigma^{\mu}_{\alpha\dot\alpha}\partial_{\mu}$$

$$W_{\alpha} = -i\lambda_{\alpha} + \theta_{\alpha}D - \tfrac{i}{2}(\sigma^{\mu}\bar\sigma^{\nu}\theta)_{\alpha}F_{\mu\nu} + \theta^{2}\sigma^{\mu}D_{\mu}\bar\lambda$$

How to write SUSY Lagrangians

1st step

Take your favorite Lagrangian written in terms of fields

2nd step

Replace $$Field\ (\varphi, \psi, A_\mu) \Rightarrow Superfield\ (\Phi, V)$$

3rd step

Replace

$$Action = \int d^4x\, L(x) \quad \Rightarrow \quad \int d^4x\, d^4\theta\, L(x, \theta, \bar{\theta})$$

Grassmannian integration in superspace $\int d\theta_\alpha = 0, \ \int \theta_\beta d\theta_\alpha = \delta_{\alpha\beta}$

Minimal Supersymmetric Standard Model (MSSM)

- SUSY: # of fermions = # of bosons N=1 SUSY: (φ, ψ) (λ, A_μ)
- SM: 28 bosonic d.o.f. & 90 (96) fermionic d.o.f.

There are no particles in the SM that can be superpartners

SUSY associates **known** bosons with **new** fermions and **known** fermions with **new** bosons

- Even number of the Higgs doublets – min = 2

Cancellation of axial anomalies (in each generation)

$$Tr\ Y^3 = 3\left(\tfrac{1}{27}+\tfrac{1}{27}-\tfrac{64}{27}+\tfrac{8}{27}\right)-1-1+8=0$$

colour u_L d_L u_R d_R ν_L e_L e_R

Higgsinos

-1+1=0

Particle Content of the MSSM

Superfield	*Bosons*	*Fermions*	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	*gluon* g^a	*gluino* $\tilde{g}^a$	8	1	0
V^k	*Weak* $W^k(W^{\pm},Z)$	*wino, zino* $\tilde{w}^k(\tilde{w}^{\pm},\tilde{z})$	1	3	0
V'	*Hypercharge* $B(\gamma)$	*bino* $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i=(\tilde{\nu},\tilde{e})_L$	leptons $L_i=(\nu,e)_L$	1	2	–1
E_i	sleptons $\tilde{E}_i=\tilde{e}_R$	leptons $E_i=e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i=(\tilde{u},\tilde{d})_L$	quarks $Q_i=(u,d)_L$	3	2	1/3
U_i	squarks $\tilde{U}_i=\tilde{u}_R$	quarks $U_i=u_R^c$	3^*	1	–4/3
D_i	squarks $\tilde{D}_i=\tilde{d}_R$	quarks $D_i=d_R^c$	3^*	1	2/3
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	–1
H_2	Higgses H_2	higgsinos $\tilde{H}_2$	1	2	1

The MSSM Lagrangian

$$L = L_{gauge} + L_{Yukawa} + L_{SoftBreaking}$$

The Yukawa Superpotential

Superfields

$$W_R = y_U Q_L H_2 U_R + y_D Q_L H_1 D_R + y_L L_L H_1 E_R + \mu H_1 H_2$$

Yukawa couplings

Higgs mixing term

$$W_{NR} = \lambda_L L_L L_L E_R + \lambda_L^{'} L_L Q_L D_R + \mu^{'} L_L H_2 + \lambda_B U_R D_R D_R$$

Violate: Lepton number Baryon number

These terms are forbidden in the SM

$$\lambda_L, \lambda_L^{'} < 10^{-6}, \quad \lambda_B < 10^{-9}$$

R-parity

$$R = (-)^{3(B-L)+2S}$$

The Usual Particle : R = + 1

SUSY Particle : R = - 1

B - Baryon Number

L - Lepton Number

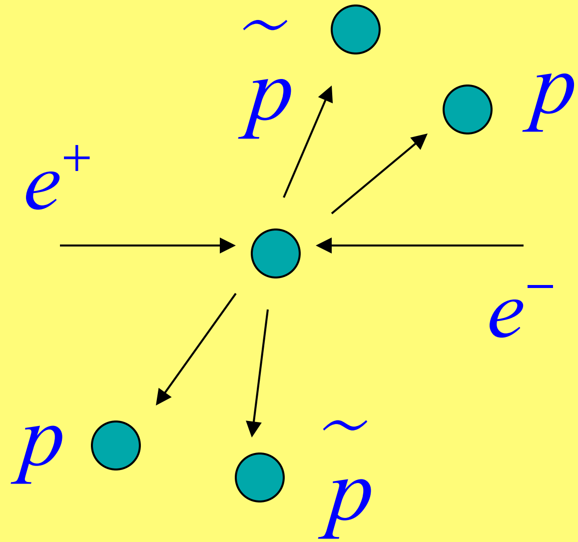
S - Spin

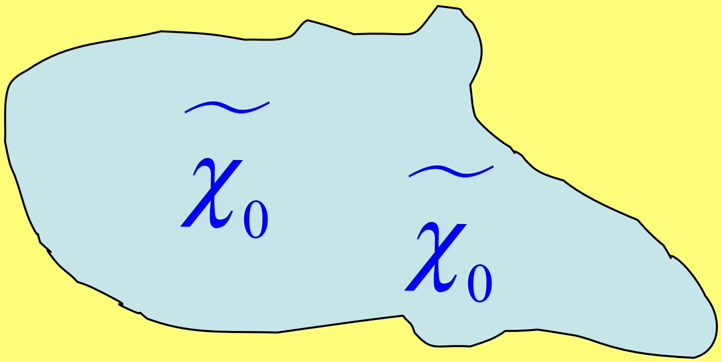
The consequences:

- The superpartners are created in pairs
- The lightest superparticle is stable

⇩

- The lightest superparticle (LSP) should be neutral - the best candidate is neutralino (photino or higgsino) $\tilde{\chi}_0$
- It can survive from the Big Bang and form the Dark matter in the Universe

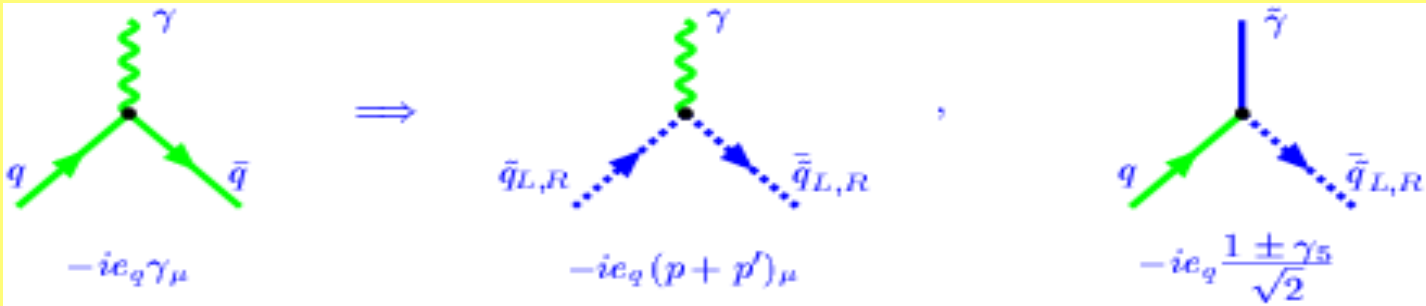


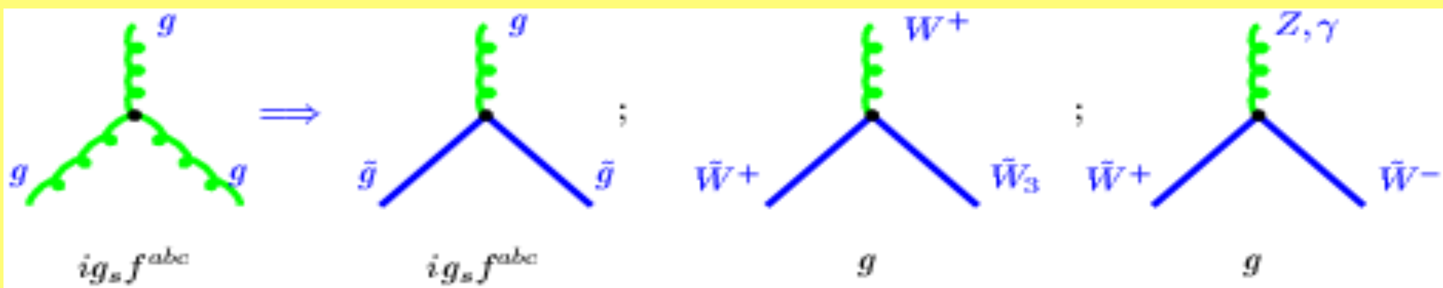


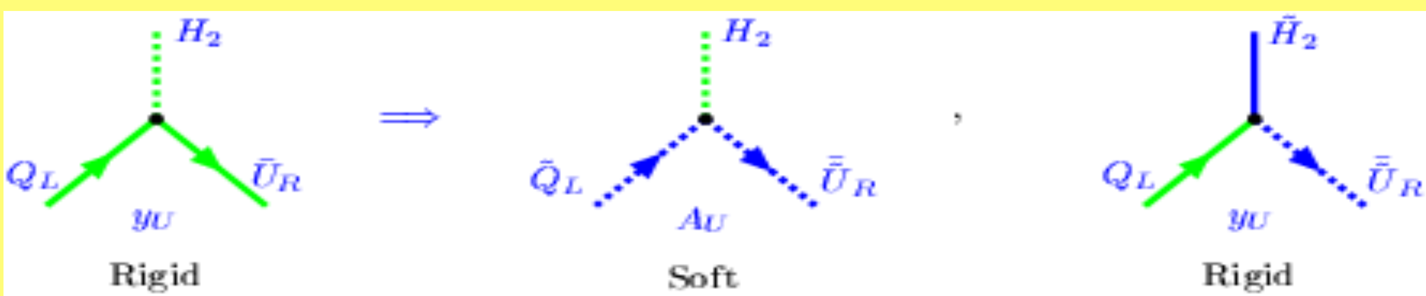
Interactions in the MSSM

SM → MSSM

Vertices

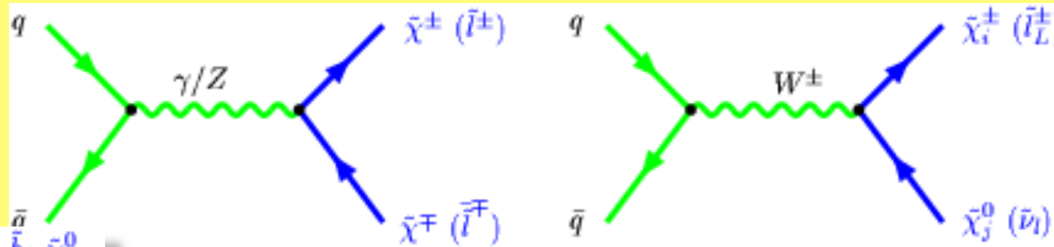


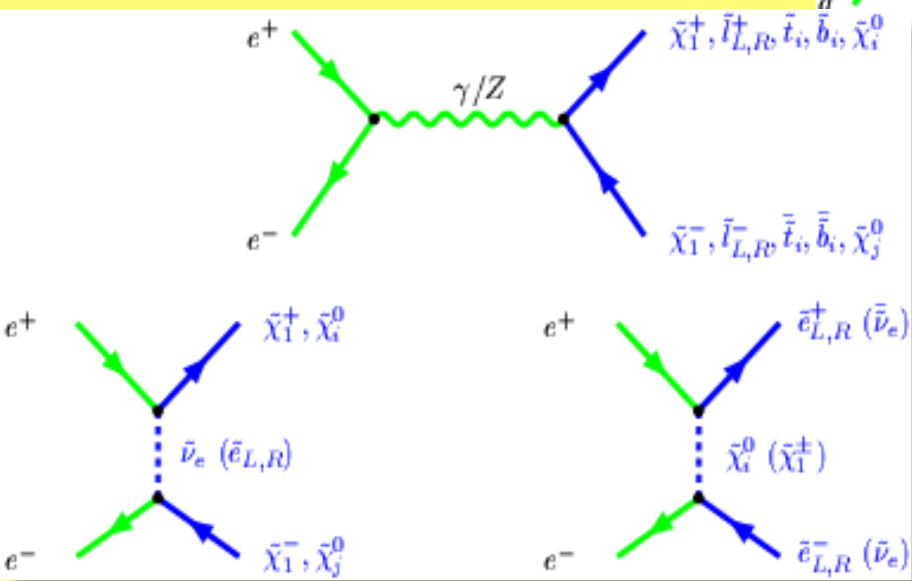


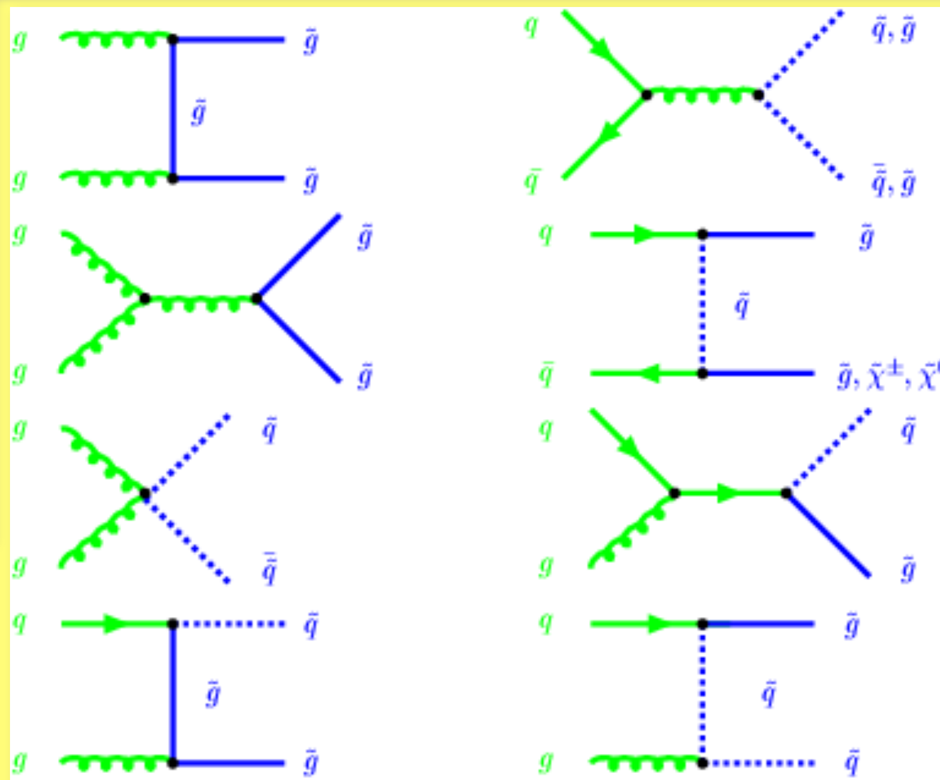


Creation of Superpartners at colliders

Annihilation channel







Gluon fusion, ee, qq scattering and qg scattering channels

Decay of Superpartners

squarks

$$\tilde{q}_{L,R} \to q + \tilde{\chi}_i^0$$

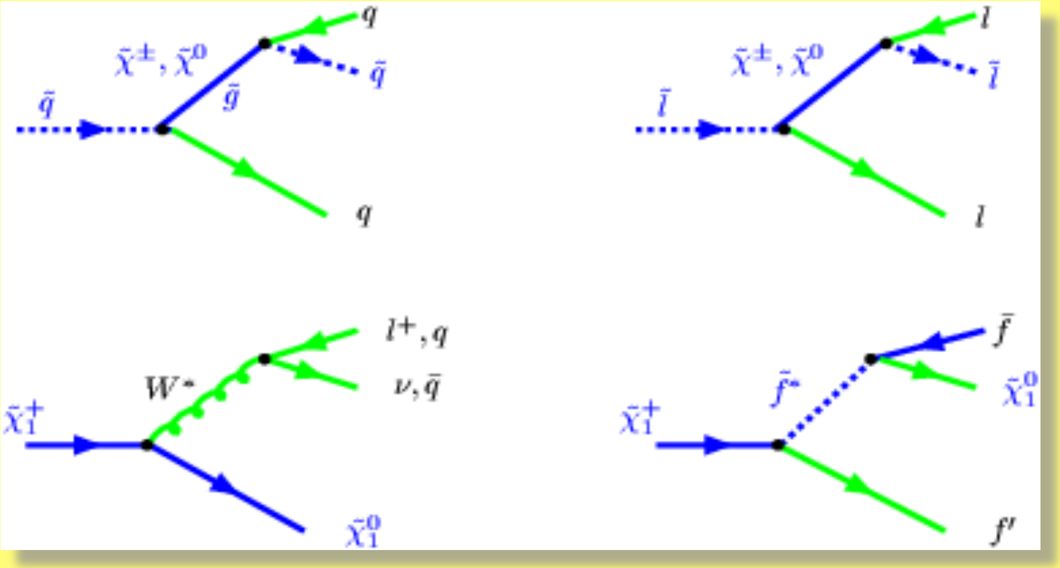
$$\tilde{q}_L \to q' + \tilde{\chi}_i^\pm$$

$$\tilde{q}_{L,R} \to q + \tilde{g}$$

sleptons

$$\tilde{l} \to l + \tilde{\chi}_i^0$$

$$\tilde{l}_L \to \nu_l + \tilde{\chi}_i^\pm$$



chargino

$$\tilde{\chi}_i^\pm \to e + \nu_e + \tilde{\chi}_i^0$$

$$\tilde{\chi}_i^\pm \to q + \bar{q}' + \tilde{\chi}_i^0$$

gluino

$$\tilde{g} \to q + \bar{q} + \tilde{\gamma}$$

$$\tilde{g} \to g + \tilde{\gamma}$$

neutralino

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + l^+ + l^-$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + q + \bar{q}'$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^\pm + l^\pm + \nu_l$$

$$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 + \nu_l + \bar{\nu}_l$$

Final sates

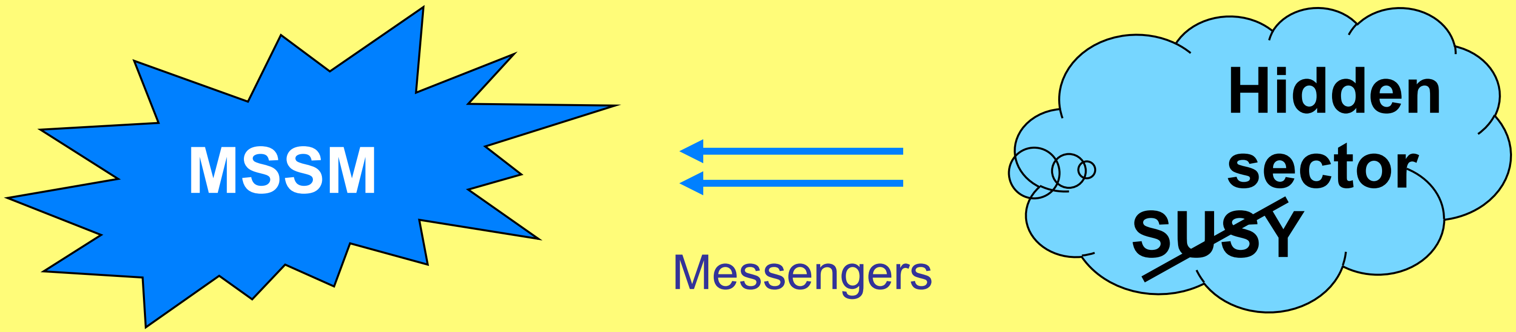
$l^+l^- + \not{E}_T$

2 jets $+ \not{E}_T$

$\gamma + \not{E}_T$

$\not{E}_T$

Soft SUSY Breaking



Gravitons, gauge, gauginos, etc

Breaking via F and D terms in a hidden sector

$$-L_{Soft} = \sum_{\alpha} M_i \tilde{\lambda}_i \tilde{\lambda}_i + \sum_i m_{0i}^2 \, |A_i|^2 + + \sum_{ijk} \mathrm{A}_{ijk} A_i A_j A_k + \sum_{ij} \mathrm{B}_{ij} A_i A_j$$

gauginos

scalar fields

Over 100 of free parameters !

MSSM Parameter Space

- Three gauge couplings
- Three (four) Yukawa matrices
- The Higgs mixing parameter
- Soft SUSY breaking terms

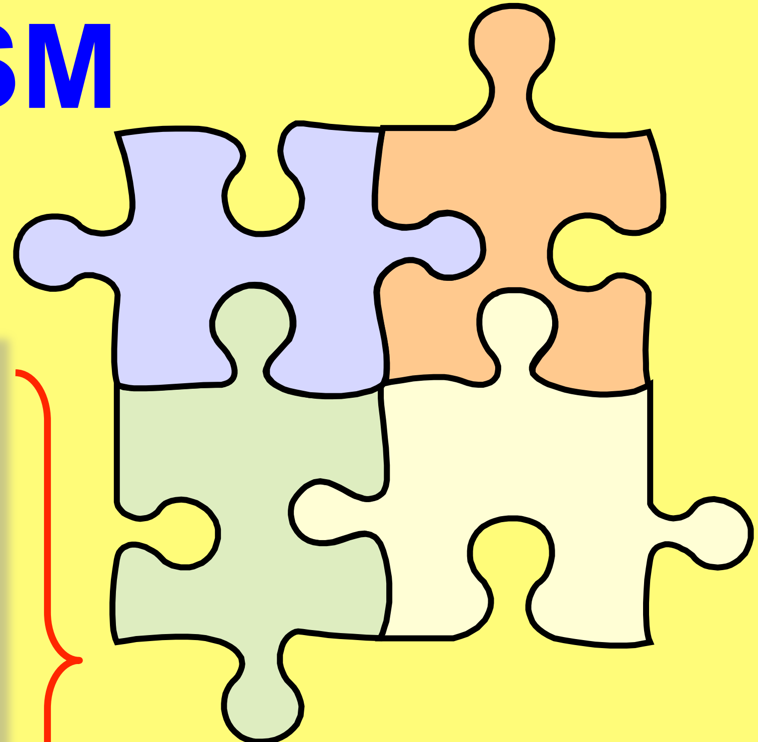
mSUGRA Universality hypothesis (gravity is colour and flavour blind):
Soft parameters are equal at Planck (GUT) scale

$$-L_{Soft} = A\{y_t Q_L H_2 U_R + y_b Q_L H_1 D_R + y_L L_L H_1 E_R\} + B\mu H_1 H_2 + m_0^2 \sum_i |\varphi_i|^2 + \tfrac{1}{2} M_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha$$

Five universal soft parameters: $A,\ m_0,\ M_{1/2},\ B \leftrightarrow \tan\beta = v_2 / v_1$ and μ

versus m and λ in the SM

Constrained MSSM



Requirements:

- Unification of the gauge couplings
- Radiative EW Symmetry Breaking
- Heavy quark and lepton masses
- Rare decays (b -> sγ)
- Anomalous magnetic moment of muon
- LSP is neutral
- Amount of the Dark Matter
- Experimental limits from direct search

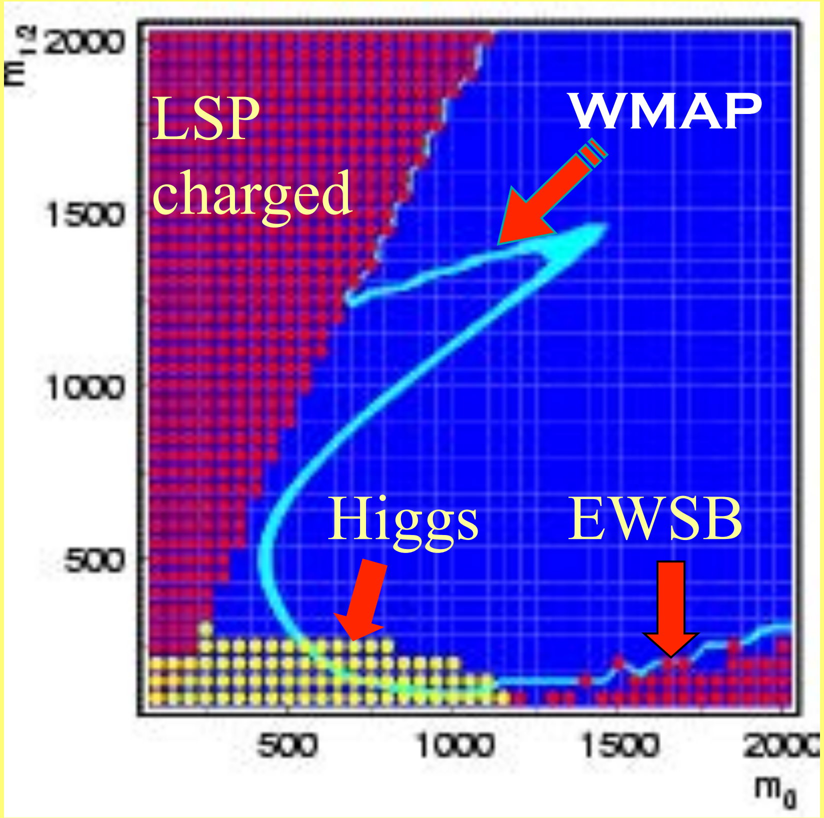
$$A_0, m_0, M_{1/2}, \mu, \tan\beta$$

Allowed region in the parameter space of the MSSM

$$100 \text{ GeV} \le m_0, M_{1/2}, \mu \le 2 \text{ TeV}$$

$$-3m_0 \le A_0 \le 3m_0, \; 1 \le \tan\beta \le 70$$

Allowed regions after WMAP



tan β =50

In allowed region one fulfills all the constraints simultaneously and has the suitable amount of the dark matter

Narrow allowed region enables one to predict the particle spectra and the main decay patterns

Phenomenology essentially depends on the region of parameter space and has direct influence on the strategy of SUSY searches

Mass Spectrum in CMSSM

(Sample)

Fitted SUSY Parameters

Symbol	Low tan β	High tan β
Tan β	1.71	35.0
m_0	200	600
$m_{1/2}$	500	400
μ(0)	1084	-558
A(0)	0	0
$1/\alpha_{GUT}$	24.8	24.8
M_{GUT}	$1.6 \cdot 10^{16}$	$1.6 \cdot 10^{16}$

SUSY Masses in GeV

Symbol	Low tan β	High tan β
$\tilde{\chi}_1^0(\tilde{B}), \tilde{\chi}_2^0(\tilde{W}^3)$	214, 413	170, 322
$\tilde{\chi}_3^0(\tilde{H}_1), \tilde{\chi}_4^0(\tilde{H}_2)$	1028, 1016	481, 498
$\tilde{\chi}_1^\pm(\tilde{W}^\pm), \tilde{\chi}_2^\pm(\tilde{H}^\pm)$	413, 1026	322, 499
$\tilde{g}$	1155	950
$\tilde{e}_L, \tilde{e}_R$	303, 270	663, 621
$\tilde{\nu}_L$	290	658
$\tilde{q}_L, \tilde{q}_R$	1028, 936	1040, 1010
$\tilde{\tau}_1, \tilde{\tau}_2$	279, 403	537, 634
$\tilde{b}_1, \tilde{b}_2$	953, 1010	835, 915
$\tilde{t}_1, \tilde{t}_2$	727, 1017	735, 906
h, H	95, 1344	119, 565
A, $H^\pm$	1340, 1344	565, 571