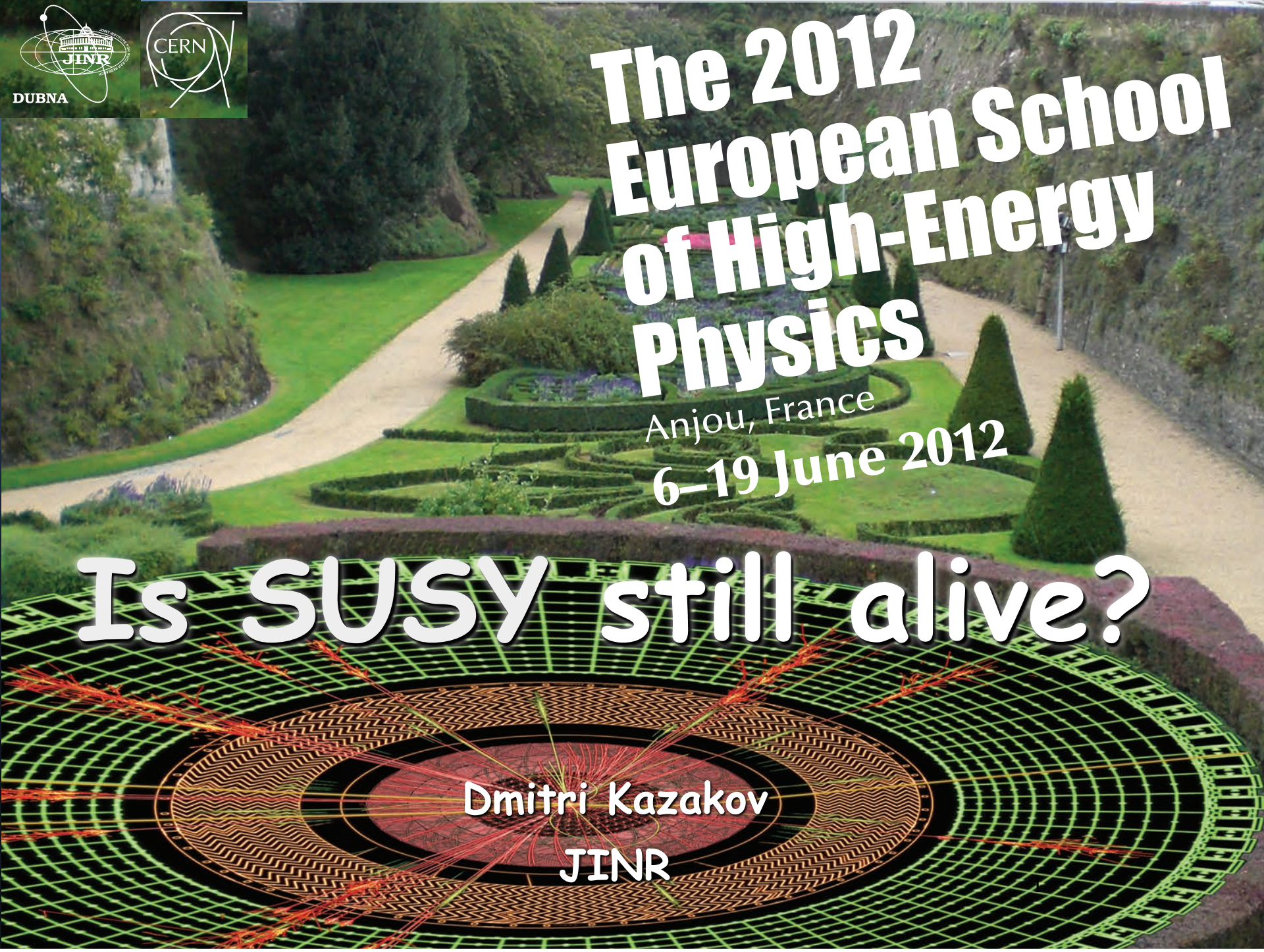
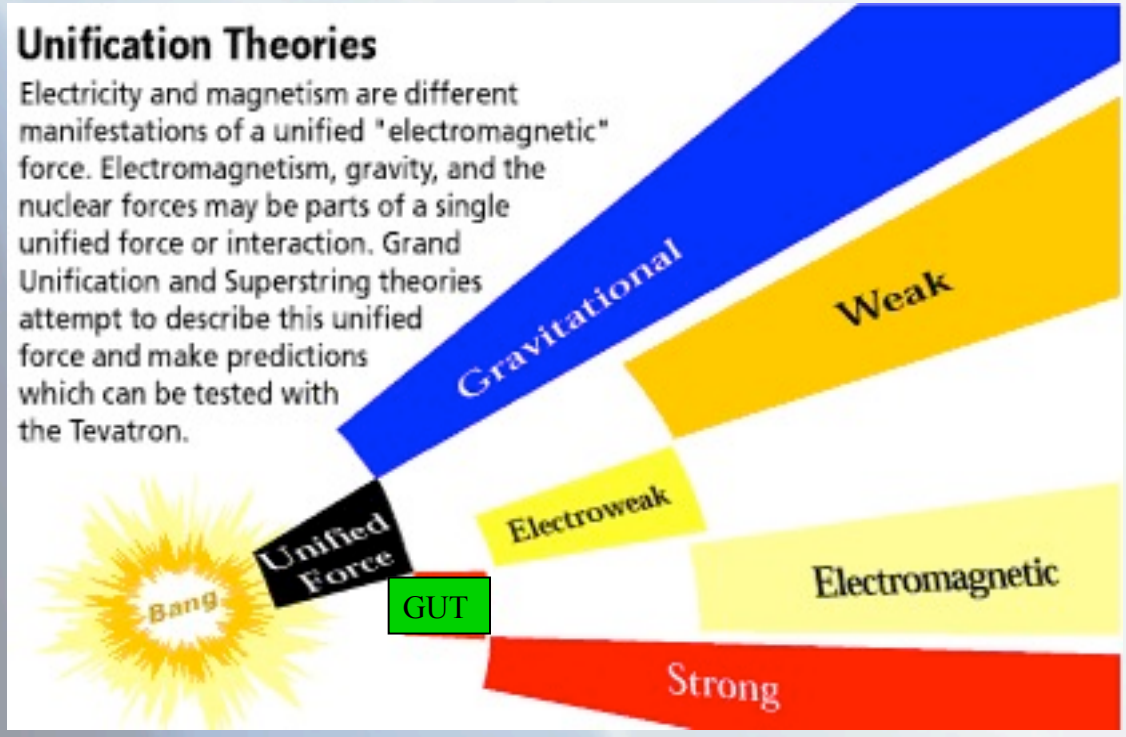

JINR
DUBNA
CERN
The 2012 European School of High-Energy Physics
Anjou, France
6–19 June 2012
Is SUSY still alive?
Dmitri Kazakov
JINR

Why do we love SUSY?

✓ Unifying various spins SUSY opens the road toward unification with gravity
Local SUSY = Theory of (super)gravity



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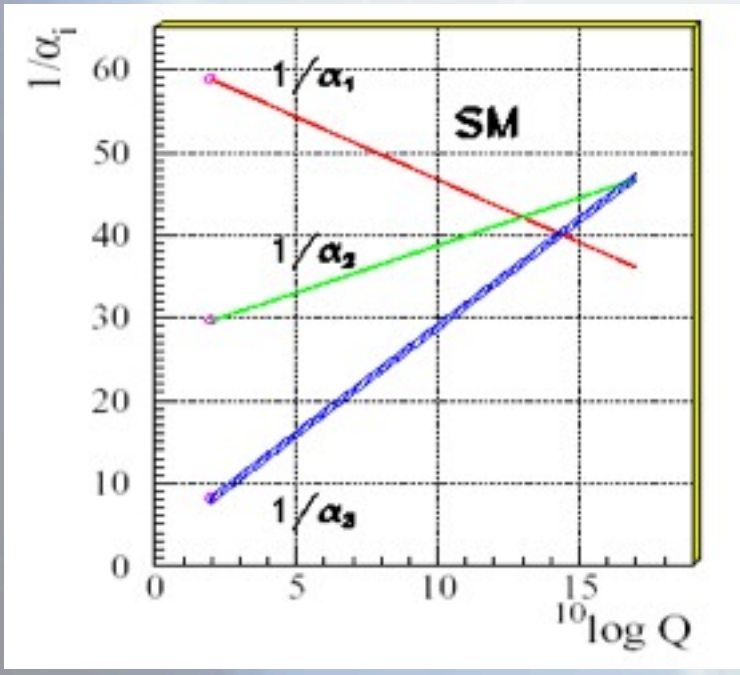

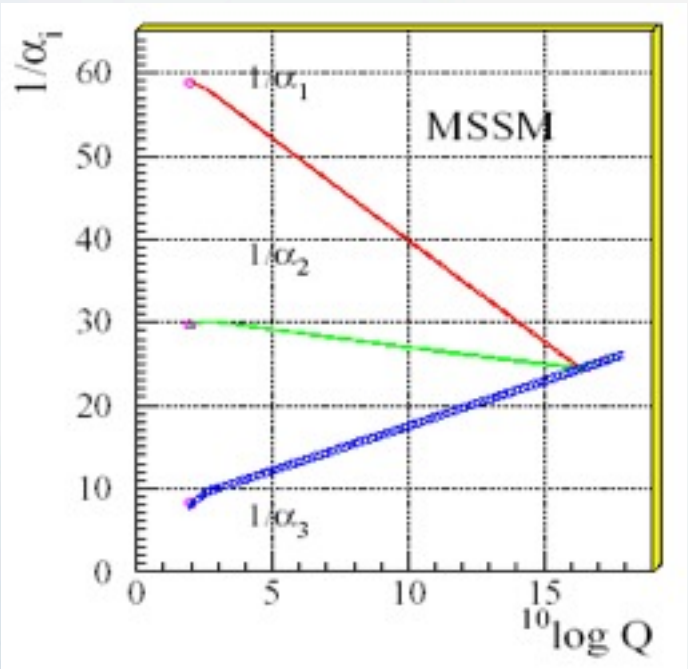

3

Why do we love SUSY?

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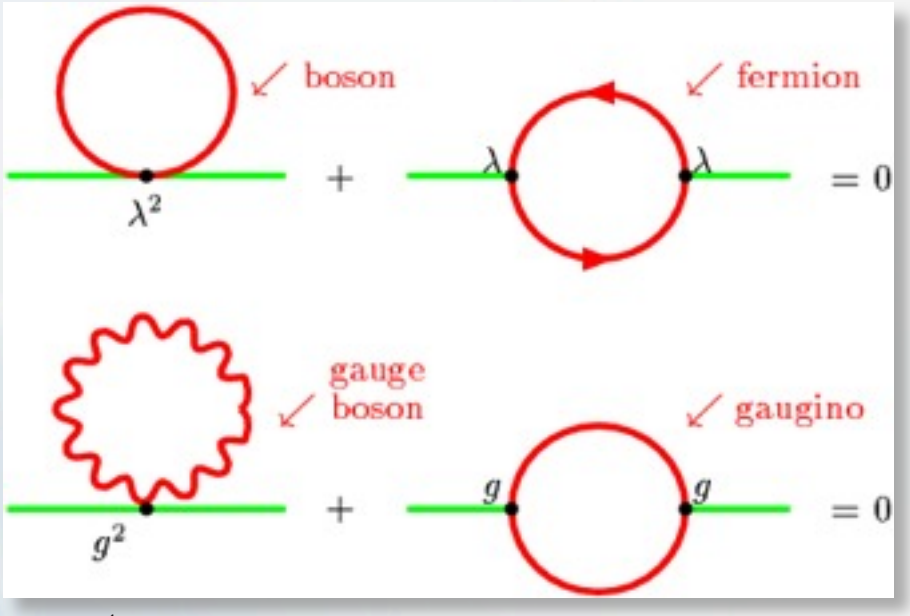
Local SUSY = Theory of (super)gravity
✓ Unifyes the gauge couplings of the SM towards Grand Unified Theory (GUT)
✓ Stabilizes the GUT theory (hierarchy problem)

Cancellation of quadratic terms (divergences)

$$\delta m_H^2 \sim g^2 M_{SUSY}^2$$



Why do we love SUSY?

✓ Unifying various spins SUSY opens the road toward unification with gravity
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✓ Unifyes the gauge couplings of the SM towards Grand Unified Theory (GUT)
✓ Stabilizes the GUT theory (hierarchy problem)
✓ Provides the Dark Matter particle (WIMP)

Dark Matter in the Universe:

Hot DM (not favoured by galaxy formation)

Cold DM (rotation curves of Galaxies)

SUSY

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Why do we love SUSY?

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Local SUSY = Theory of (super)gravity
✓ Unifyes the gauge couplings of the SM towards Grand Unified Theory (GUT)
✓ Stabilizes the GUT theory (hierarchy problem)
✓ Provides the dark Matter particle (WIMP)
✓ Provides the first integrable 4-dim quantum theory (N=4 SYM)

N=4 maximally Supersymmetric Yang-Mills theory shows all the features and seems to provide the first integrable model in 4 space-time dimensions

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Why do we love SUSY?

✓ Unifying various spins SUSY opens the road toward unification with gravity
Local SUSY = Theory of (super)gravity
✓ Unifyes the gauge couplings of the SM towards Grand Unified Theory (GUT)
✓ Stabilizes the GUT theory (hierarchy problem)
✓ Provides the dark Matter particle (WIMP)
✓ Provides the first integrable 4-dim quantum theory (N=4 SYM)
✓ Stabilizes the string as an origin of a unified superstring theory → No tachions

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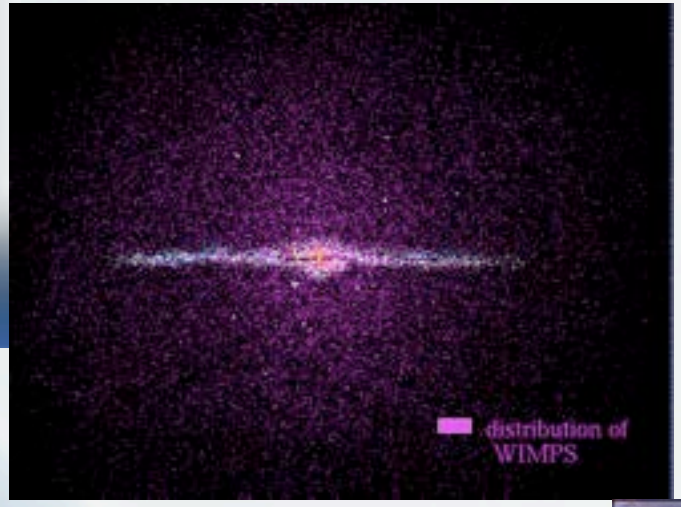
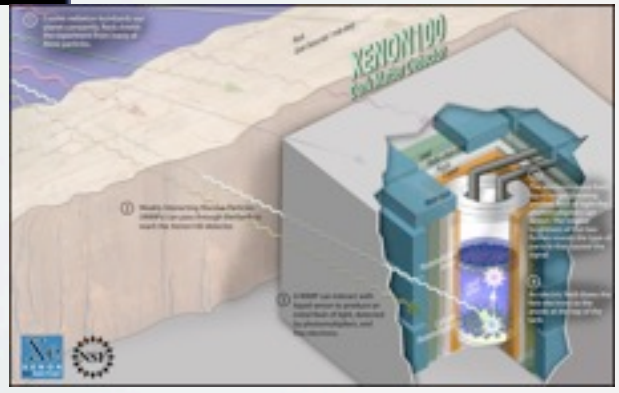
Where is SUSY?

Accelerators

Telescopes



Underground facilities



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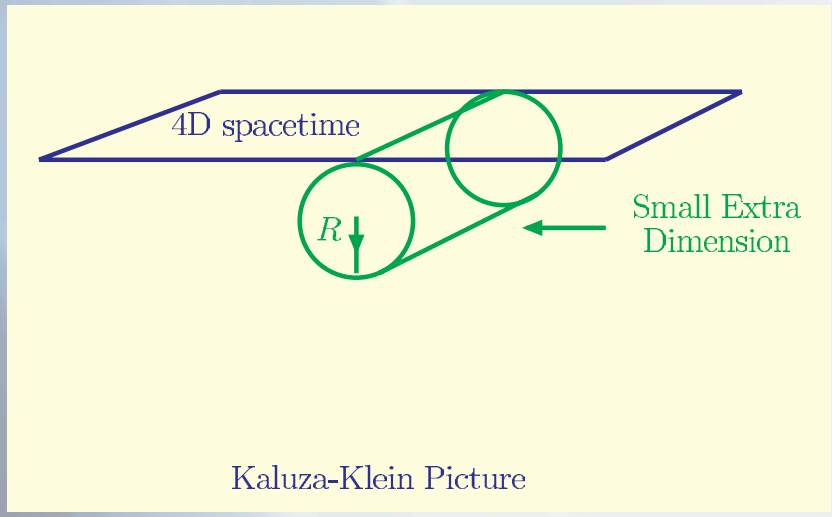
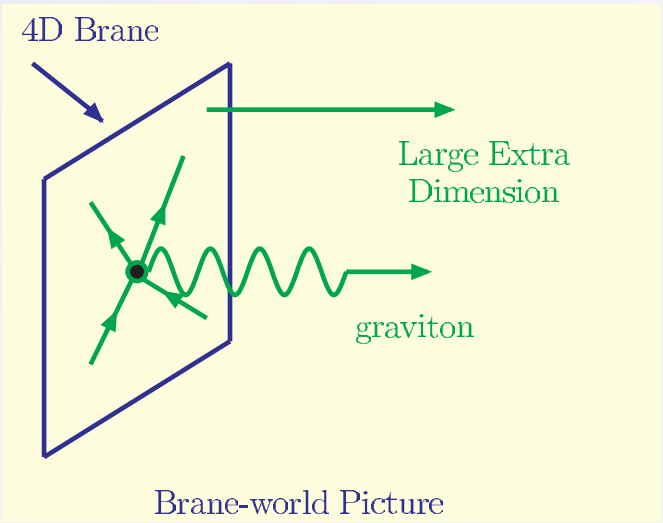
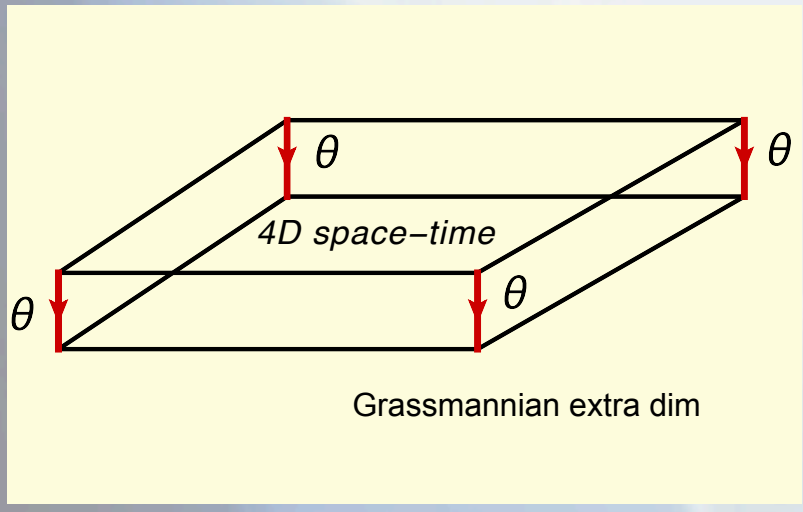
New Dimensions



Kaluza-Klein Picture



Brane-world Picture



Grassmannian extra dim

Superspace

Grassmannian numbers

$$x^\mu \qquad \theta_\alpha, \bar{\theta}_{\dot{\alpha}}$$

$$\mu = 0,1,2,3 \qquad \alpha, \dot{\alpha} = 1,2$$

$$\theta_1\theta_1 = \theta_2\theta_2 = 0$$

$$\theta_1\theta_2 = -\theta_2\theta_1 \neq 0$$

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

$$[Q^i_\alpha, P_\mu] = [\bar{Q}^i_{\dot\alpha}, P_\mu] = 0,$$
$$[Q^i_\alpha, M_{\mu\nu}] = \tfrac{1}{2}(\sigma_{\mu\nu})^\beta_\alpha Q^i_\beta,\ [\bar{Q}^i_{\dot\alpha}, M_{\mu\nu}] = -\tfrac{1}{2}\bar{Q}^i_{\dot\beta}(\bar{\sigma}_{\mu\nu})^{\dot\beta}_{\dot\alpha},$$
$$\{Q^i_\alpha, \bar{Q}^j_{\dot\beta}\} = 2\delta^{ij}(\sigma^\mu)_{\alpha\dot\beta}P_\mu$$
$$\alpha, \dot\alpha, \beta, \dot\beta = 1,2;\ i, j = 1, 2, ..., N.$$

Superspace

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

Grassmannian parameters

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

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

SUSY Generators

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

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

Supertranslation

$$x_\mu \to x_\mu + i\theta\sigma_\mu\bar\xi - i\xi\sigma_\mu\bar\theta,$$
$$\theta \to \theta + \xi,$$
$$\bar\theta \to \bar\theta + \bar\xi$$

Superfield in Superspace

N=1 SUSY Chiral supermultiplet: $\Phi(y,\theta)$

Expansion over grassmannian parameter

superfield

spin=0

spin=1/2

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

Auxiliary field

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

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

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

$$= A(x) + i\theta\sigma^\mu\bar{\theta}\partial_\mu A(x) + \tfrac{1}{4}\theta\theta\bar{\theta}\bar{\theta}\Box A(x)$$
$$+\sqrt{2}\theta\psi(x) - i/\sqrt{2}\theta\theta\partial_\mu\psi(x)\sigma^\mu\bar{\theta} + \theta\theta F(x)$$

component fields

Gauge supermultiplet:

$$V(x,\theta,\bar{\theta}) = C(x) + i\theta\chi(x) - i\bar{\theta}\bar{\chi}(x) + i\theta\theta M(x) - i\bar{\theta}\bar{\theta}M^+(x)$$
$$-\theta\sigma^\mu\bar{\theta}v_\mu(x) + i\theta\theta\bar{\theta}[\bar{\lambda}(x) + i\bar{\sigma}^\mu\partial_\mu\chi(x)] - i\bar{\theta}\bar{\theta}\theta[\lambda(x) + i\sigma^\mu\partial_\mu\bar{\chi}(x)]$$
$$+\tfrac{1}{2}\theta\theta\bar{\theta}\bar{\theta}[D(x) + \tfrac{1}{2}\Box C(x)]$$

spin=1

Auxiliary fields

spin=1/2

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SUSY Multiplets

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

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

scalar spinor

(φ, ψ)

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

$N \le 4S$ ← spin

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

$N \le 8$ For (super)gravity

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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

scalar

chiral fermion

majorana fermion

vector

gravitino

graviton

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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

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Particle Content of the MSSM

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

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 $\int d\theta_\alpha = 0,\ \int \theta_\beta d\theta_\alpha = \delta_{\alpha\beta}$

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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

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

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R-parity

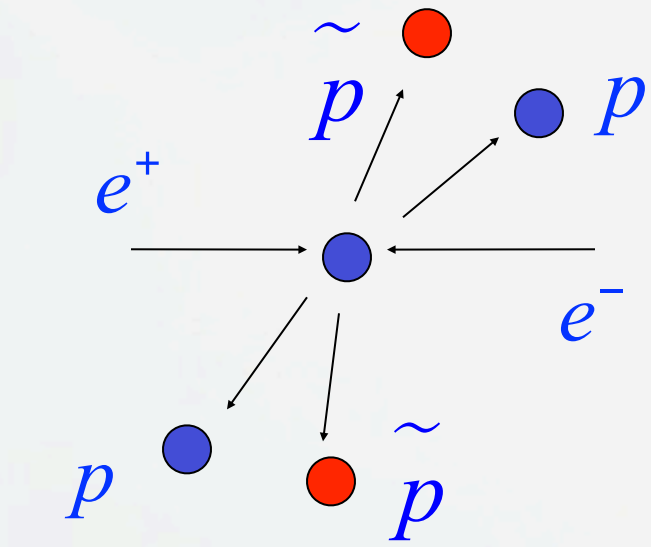
$$R = (-)^{3(B-L)+2S}$$

The Usual Particle : R = + 1
SUSY Particle : R = - 1

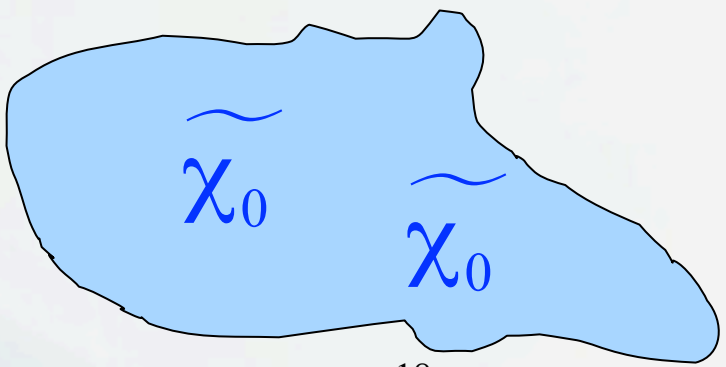
B - Baryon Number
L - Lepton Number
S - Spin

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



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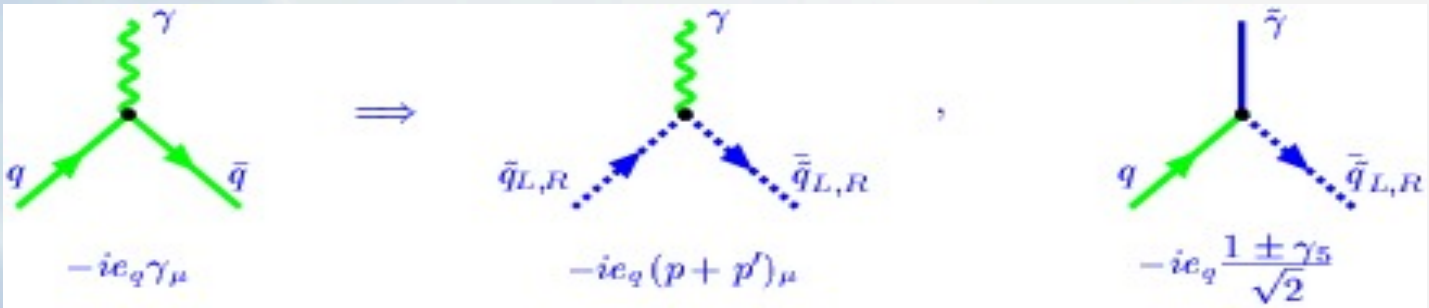
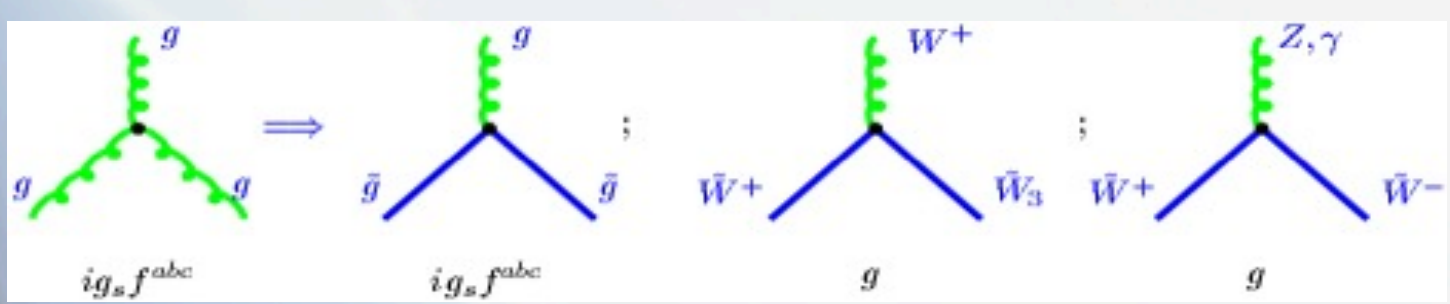
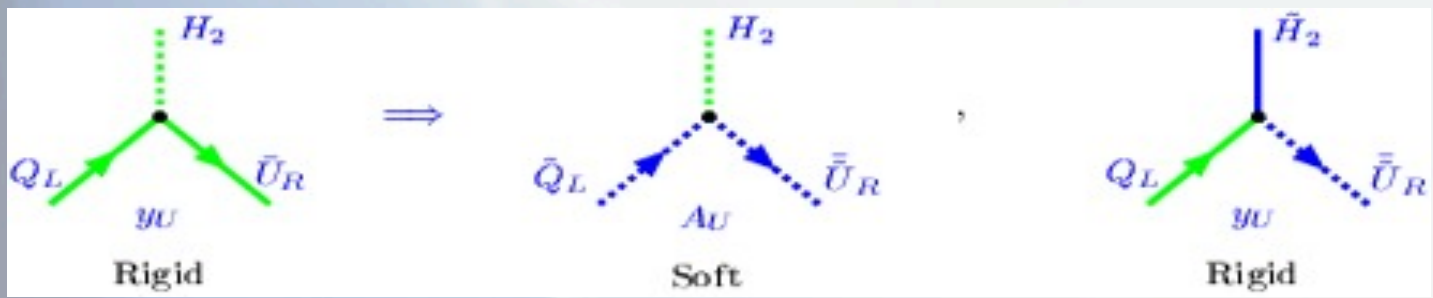
Interactions in the MSSM

SM → **MSSM**

Vertices

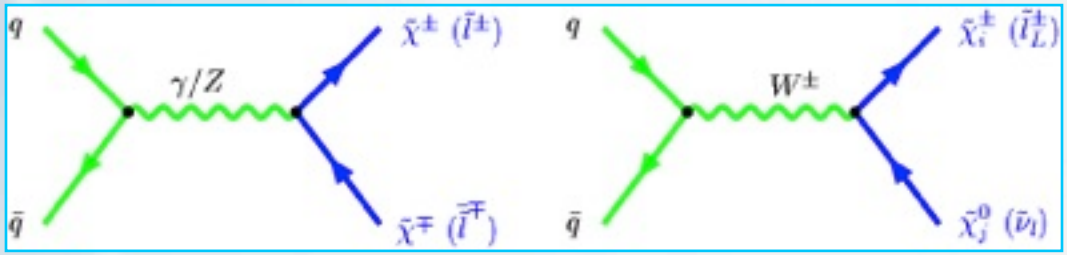




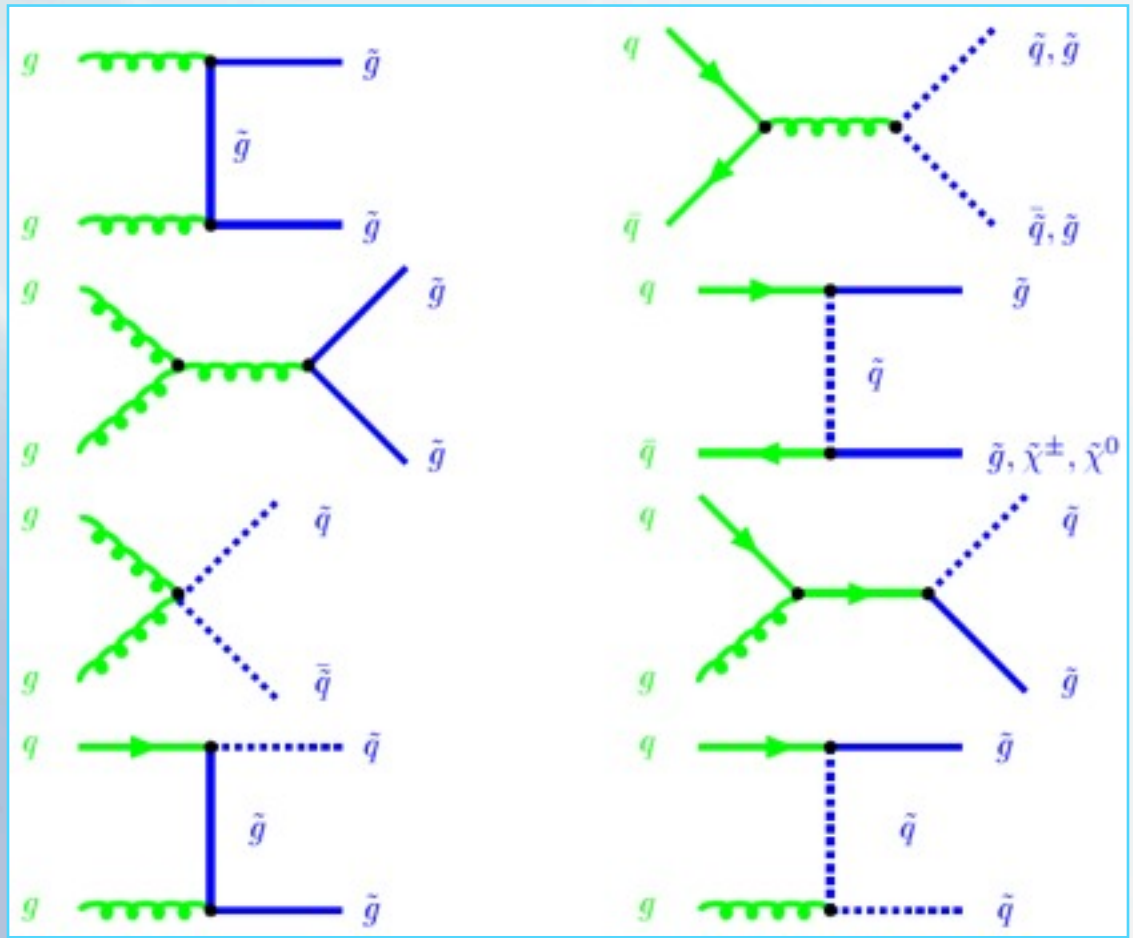


Superpartners Production at LHC

Annihilation



Quark- gluon Fusion



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

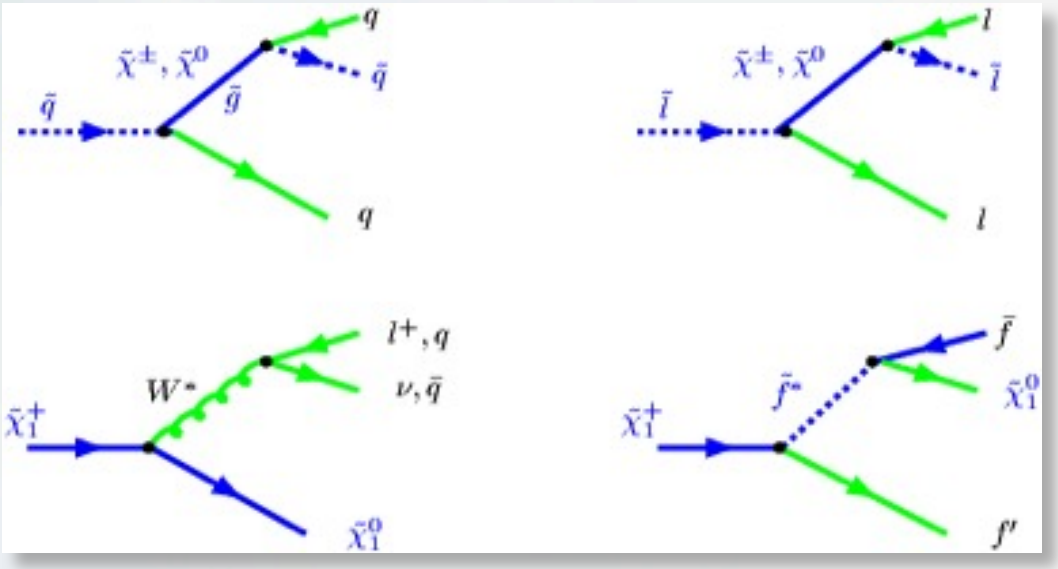
$$\tilde{\chi}_i^{\pm} \to e + \nu_e + \tilde{\chi}_i^{0}$$

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

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 states

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

2 jets $+ \not{E}_T$

$\gamma + \not{E}_T$

$\not{E}_T$

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