Random Walk in Superspace:
from Grassmannian Algebra to Gravity and Dark Matter

Dmitri Kazakov
Joint Institute for Nuclear Research
Dubna, Russia

Symposium on «Exciting Physics», Makutsi, 13-20 November 2011

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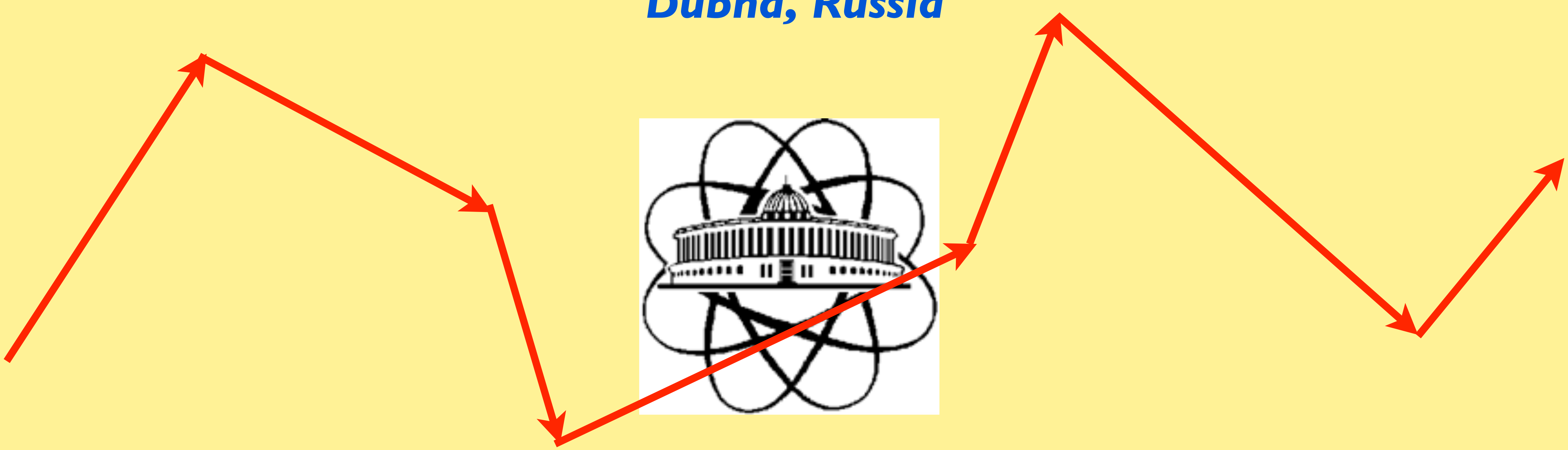

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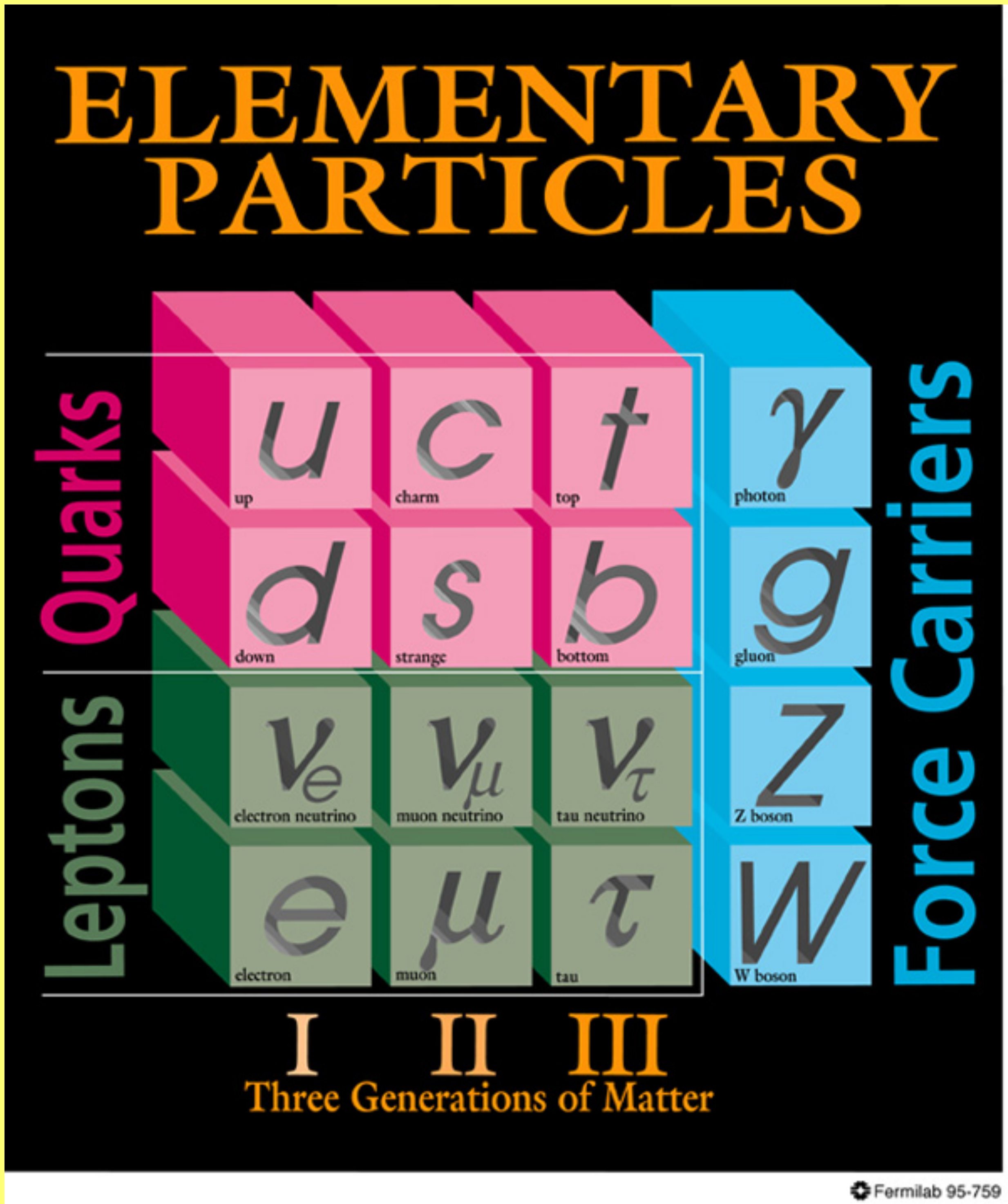
The Standard Model

SU(3)

SU(2)

U(1)

Particles



The Higgs boson

Forces

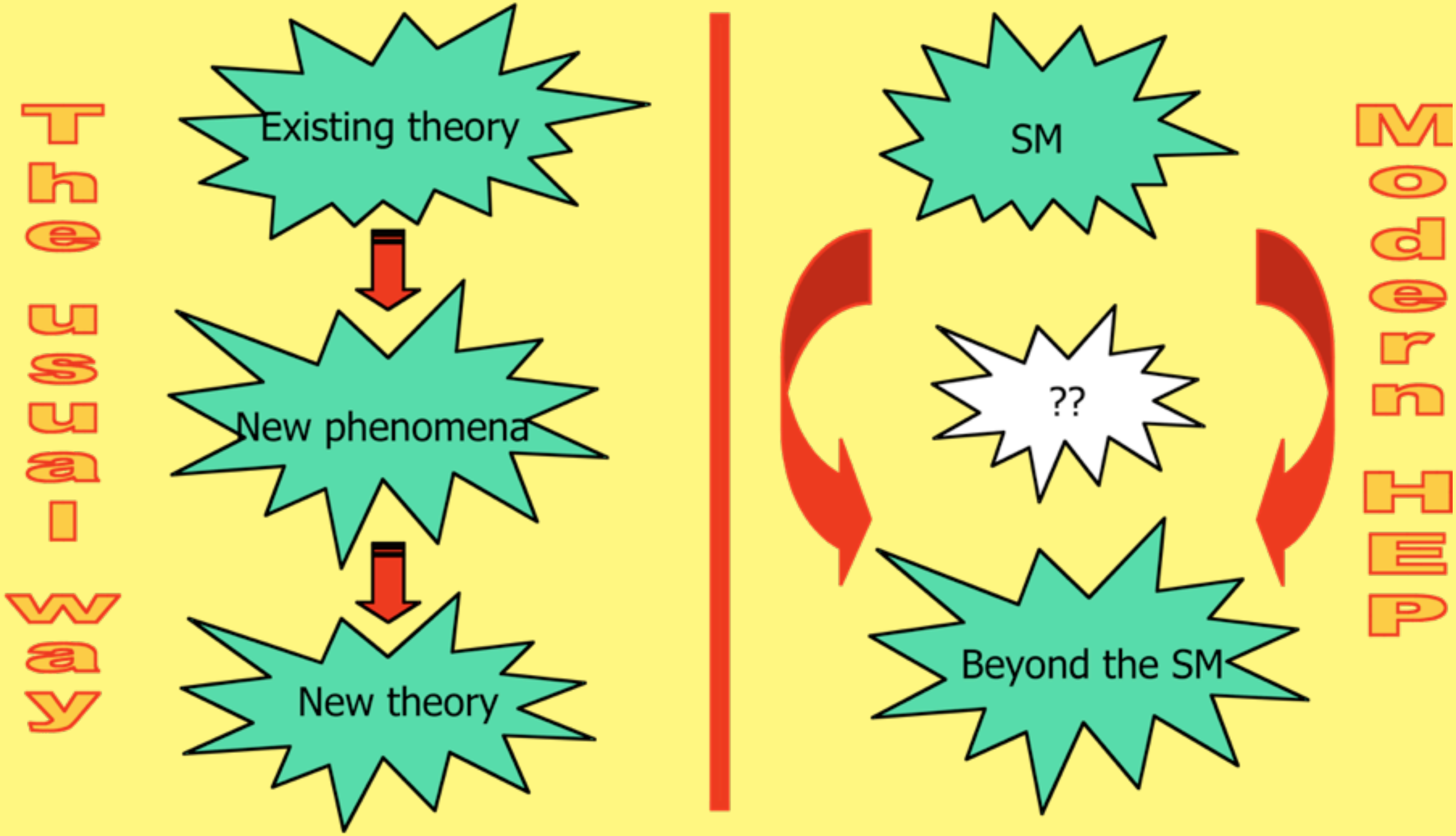
Electromagnetic

Strong

Weak

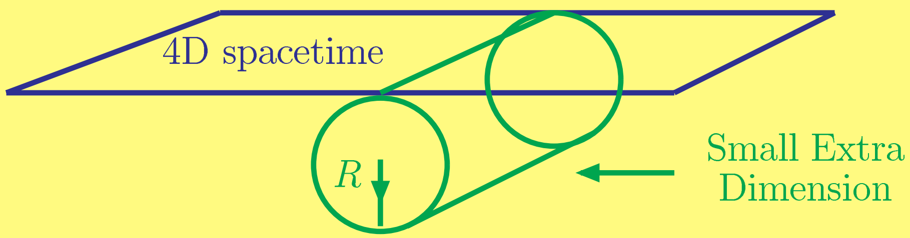
Gravity

HEP Paradox

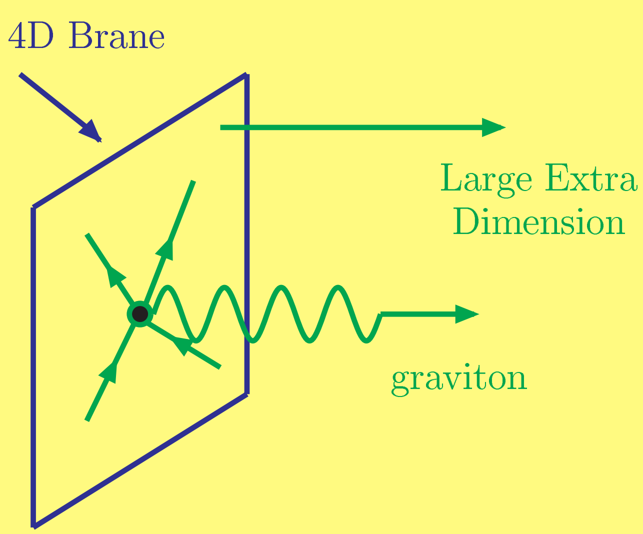


The usual way
Existing theory
New phenomena
New theory
SM
??
Beyond the SM
Modern HEP

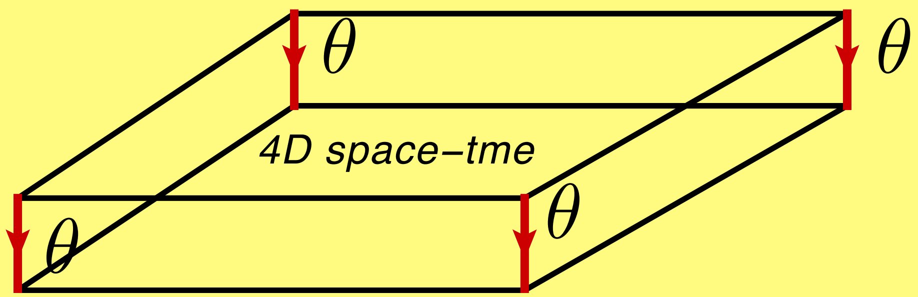
Extra Dimensions



Kaluza-Klein Picture

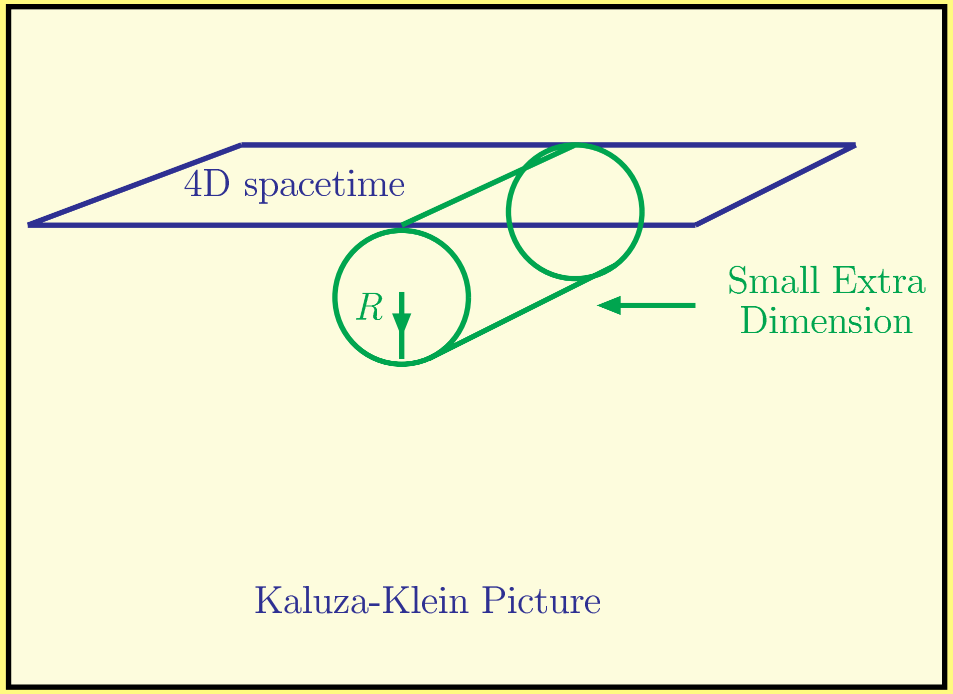


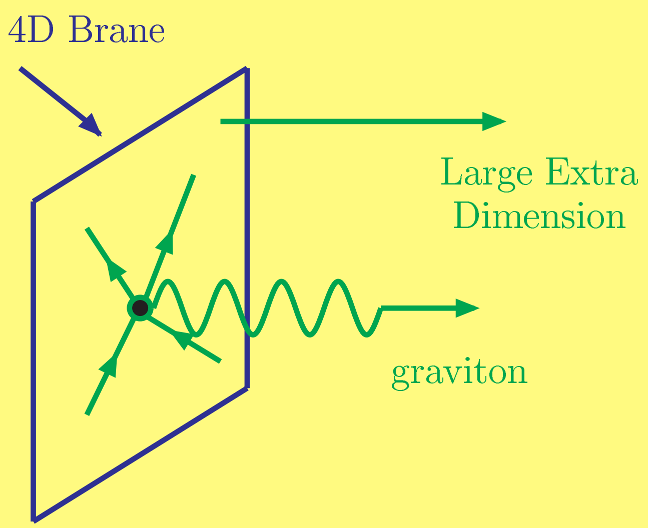
Brane-world Picture



Grassmannian extra dim

Extra Dimensions





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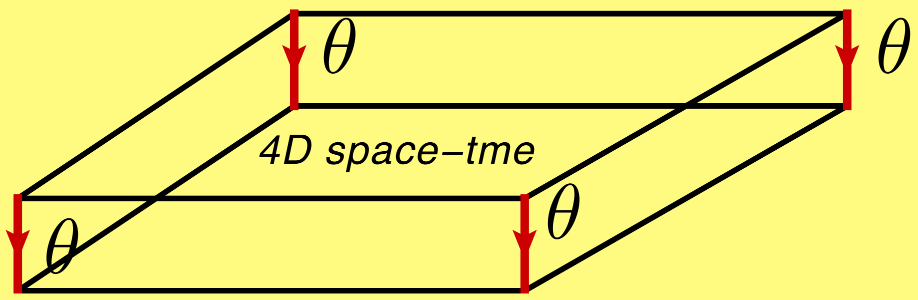

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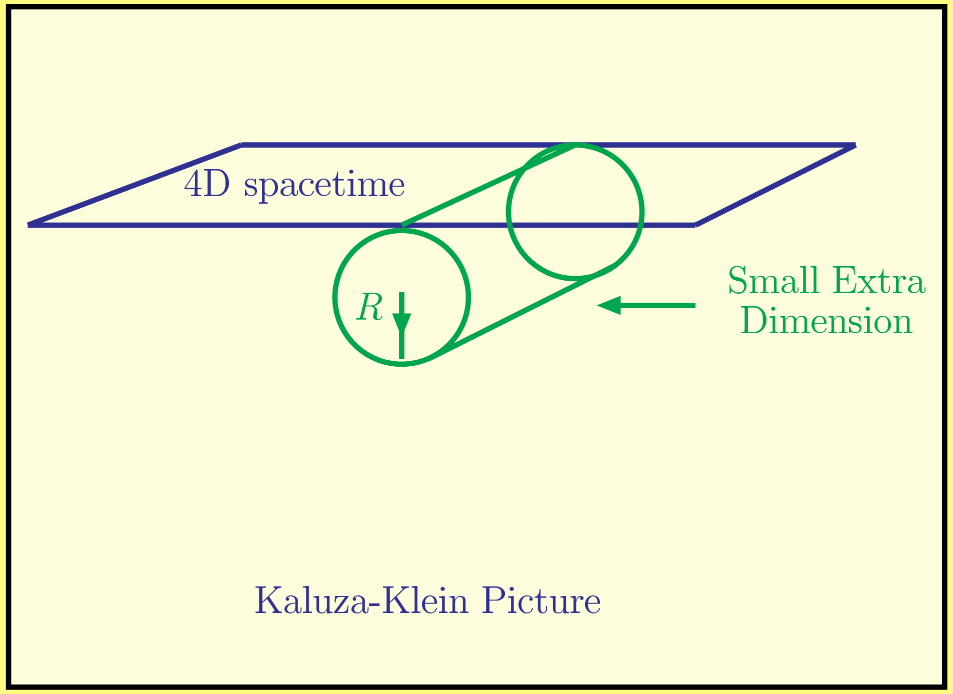

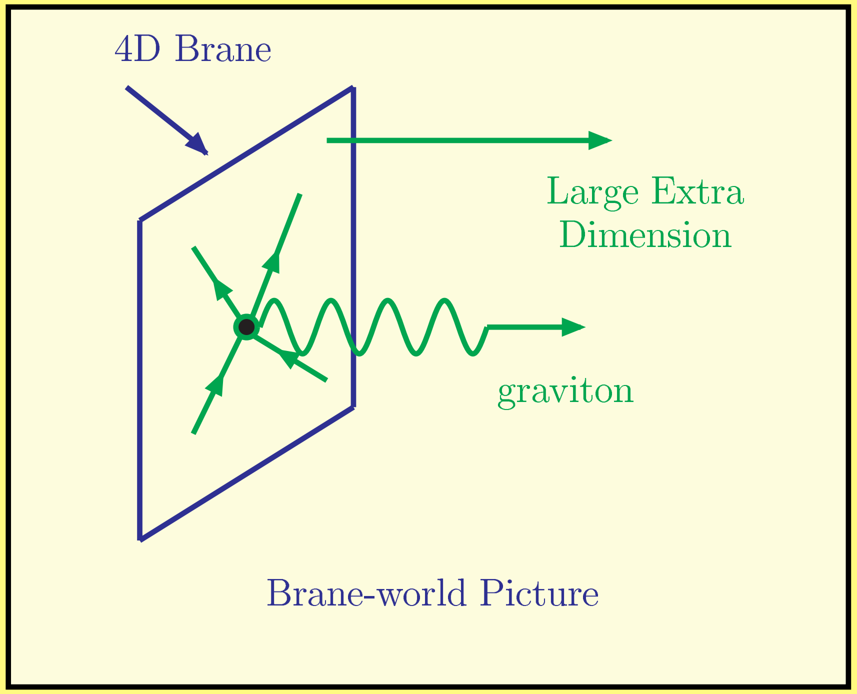

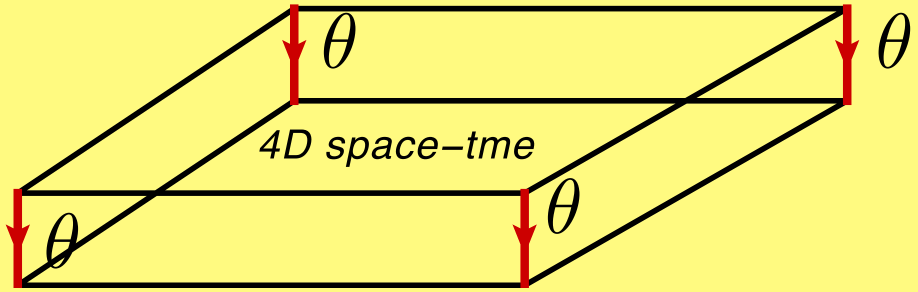

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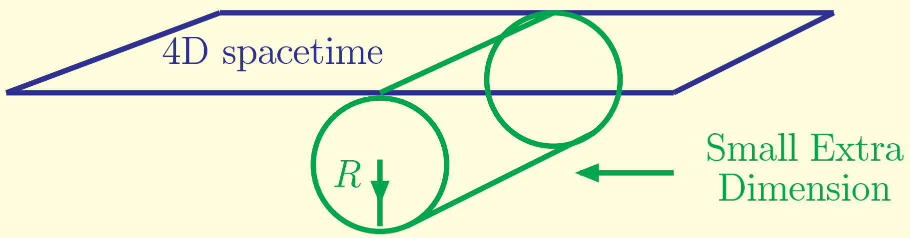

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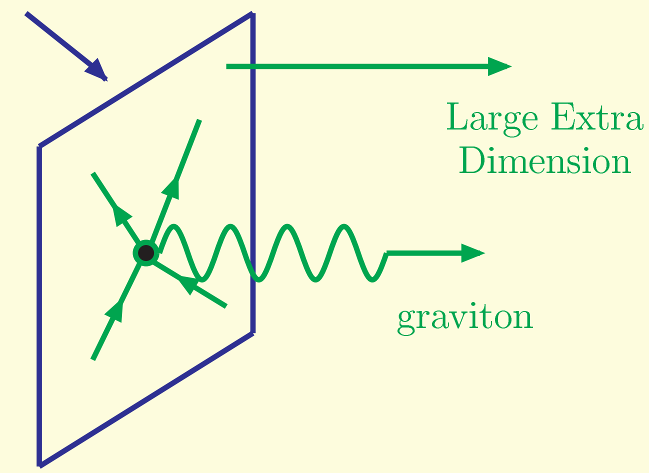

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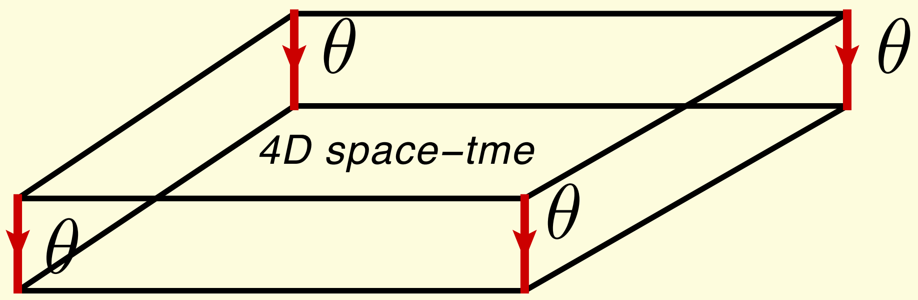

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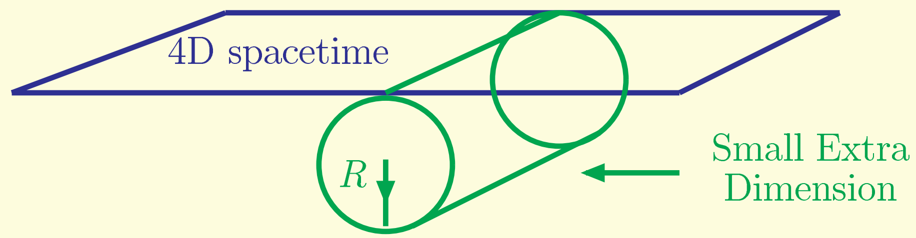

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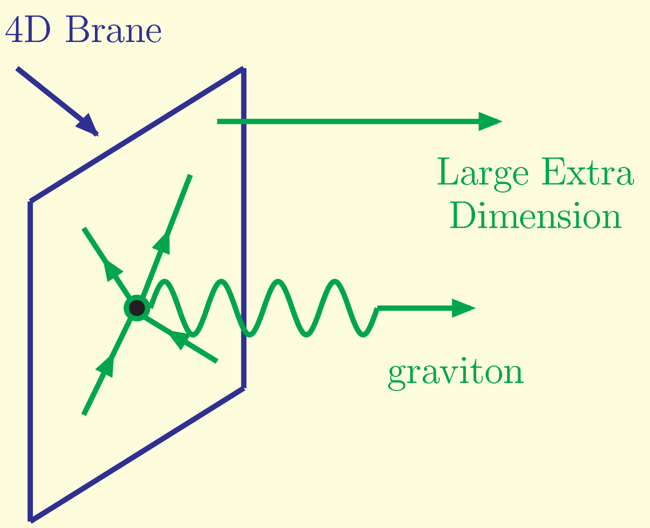

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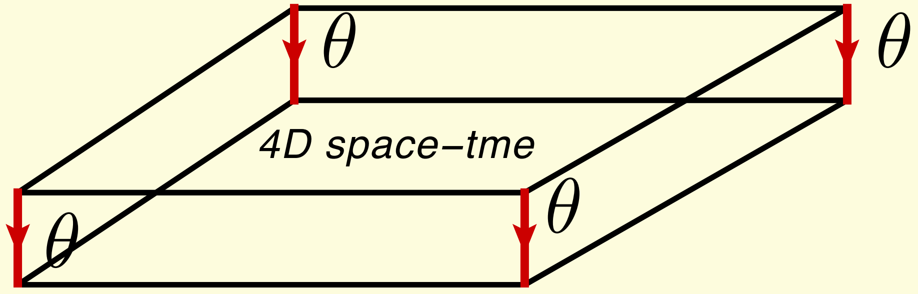


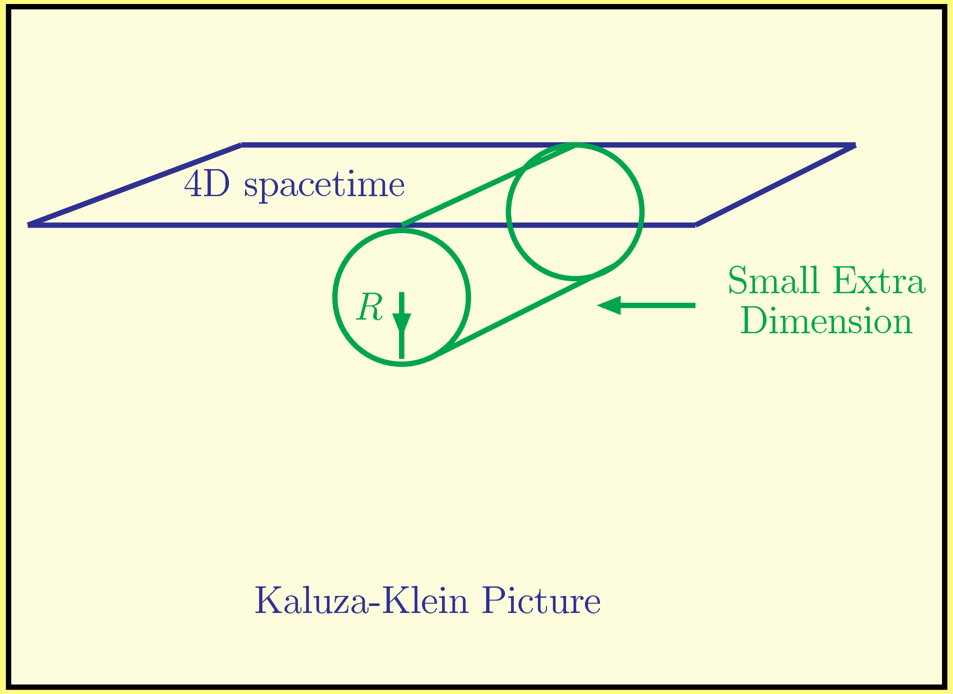
Grassmannian extra dim

Superspace

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

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

Extra Dimensions



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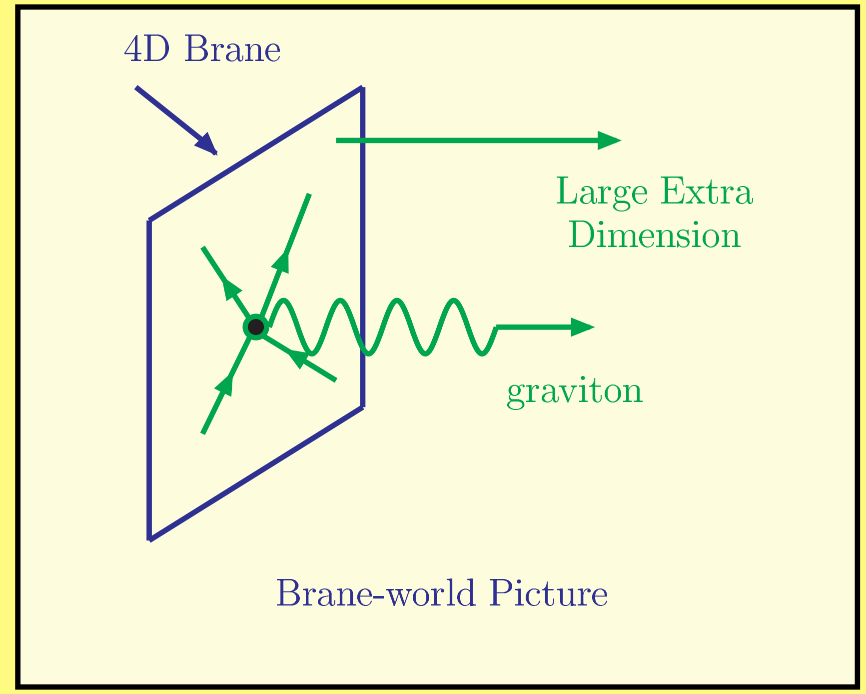

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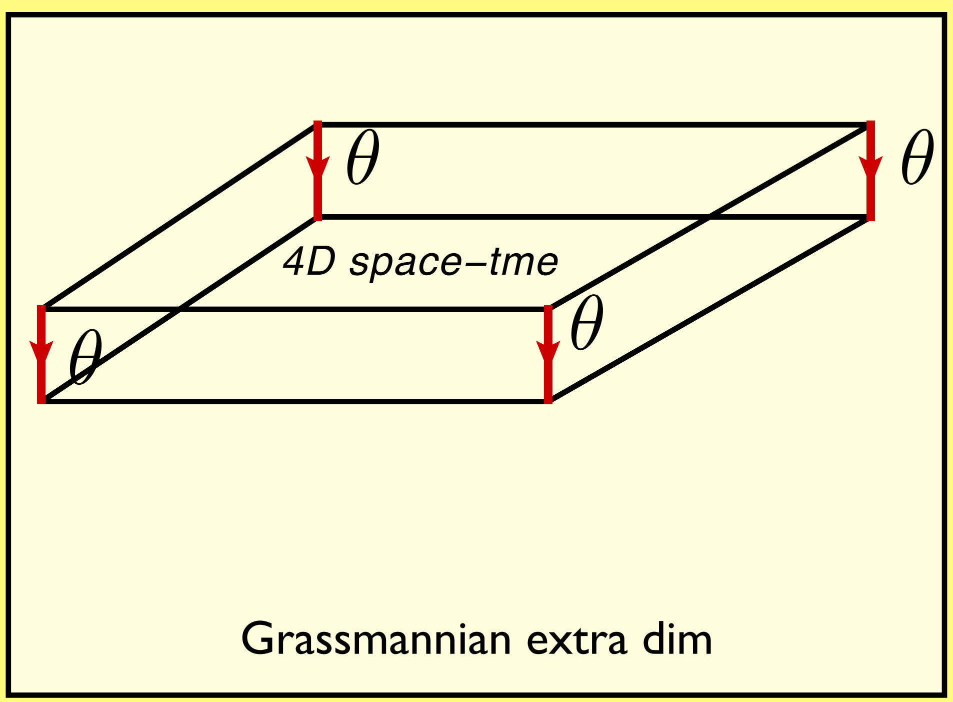

Grassmannian extra dim

Superspace

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

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

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

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

Superalgebra

Superalgebra

$$(Super)\ Algebra$$

Lorentz Algebra

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

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

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SUSY Algebra

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

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

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

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

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Superalgebra

Superspace

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

Grassmannian parameters

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

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

(Super) Algebra

Lorentz Algebra

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

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

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

SUSY Generators

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

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

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

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Superspace

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

Grassmannian parameters $\quad \alpha, \dot\alpha = 1,2$

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SUSY Generators

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

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

Supertranslation

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

Unification with Gravity

Unification with Gravity

SUSY transformation

$$Q\,|\,boson> = |\,fermion> \qquad Q\,|\,fermion> = |\,boson>$$

$$spin\ 2 \Rightarrow spin\ 3/2 \Rightarrow spin\ 1 \Rightarrow spin\ 1/2 \Rightarrow spin\ 0$$

Unification with Gravity

SUSY transformation

$$Q \,|\, boson >=|\, fermion > \qquad Q \,|\, fermion >=|\, boson >$$

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Unification of matter (fermions) with forces (bosons) naturally arises from an attempt to unify gravity with the other interactions

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

$$\varepsilon = \varepsilon(x) \ \ \text{local coordinate transf.} \ \Rightarrow \ \text{(super)gravity}$$

Unification with Gravity

SUSY transformation

$Q|boson> = |fermion> \qquad Q|fermion> = |boson>$

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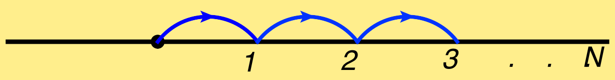
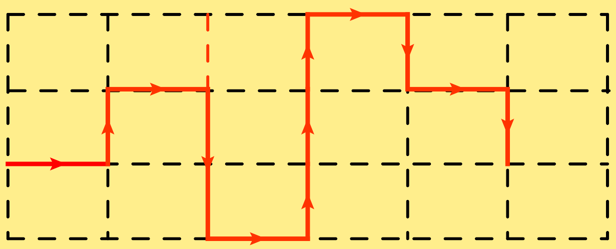
$\varepsilon = \varepsilon(x)$ local coordinate transf. $\Rightarrow$ (super)gravity

Local supersymmetry = general relativity !

Self-avoiding Random Walk





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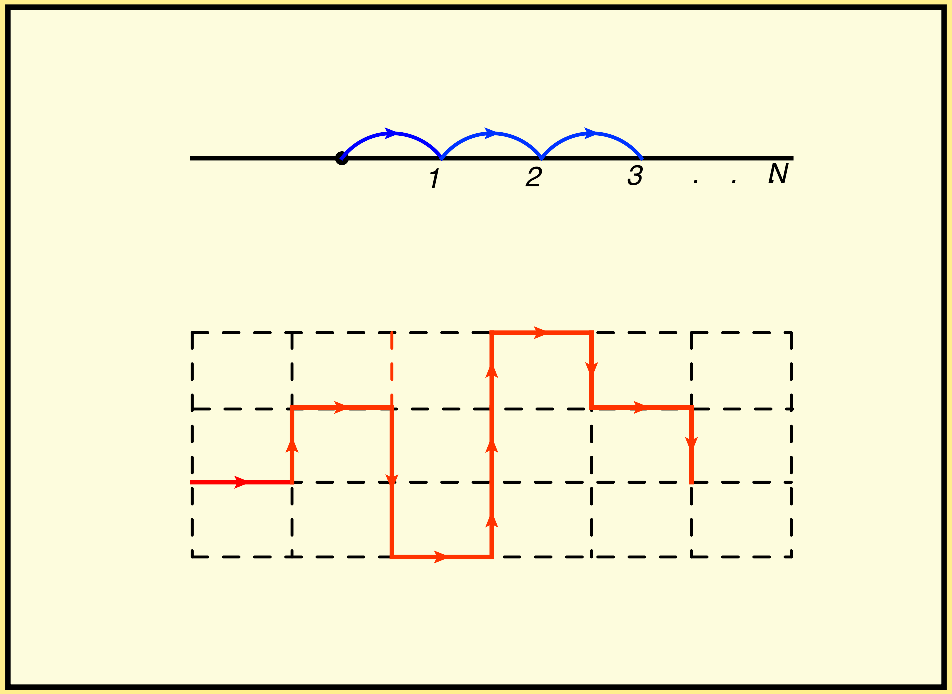

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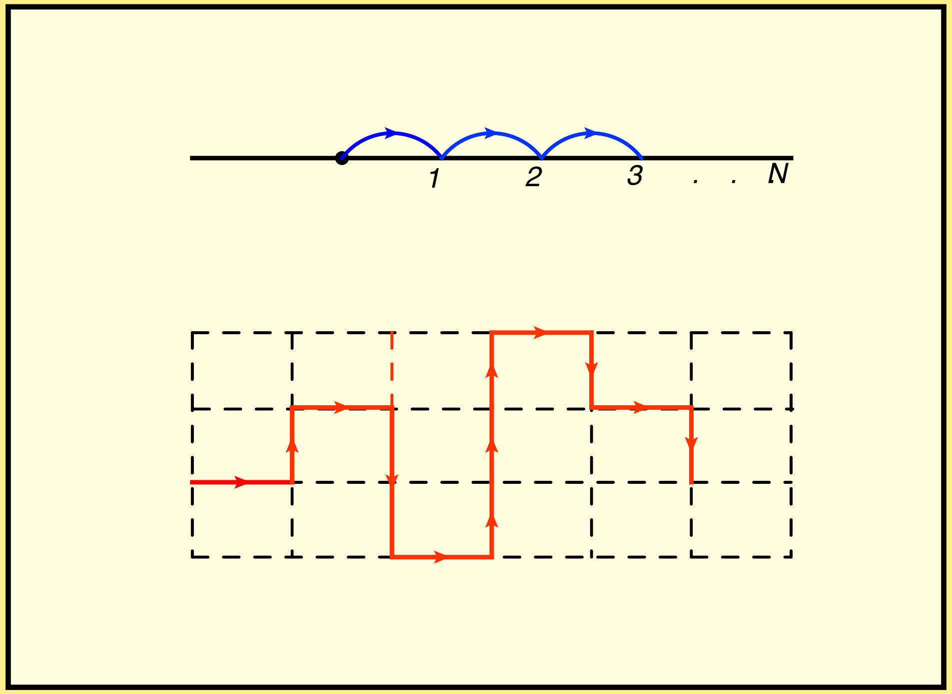
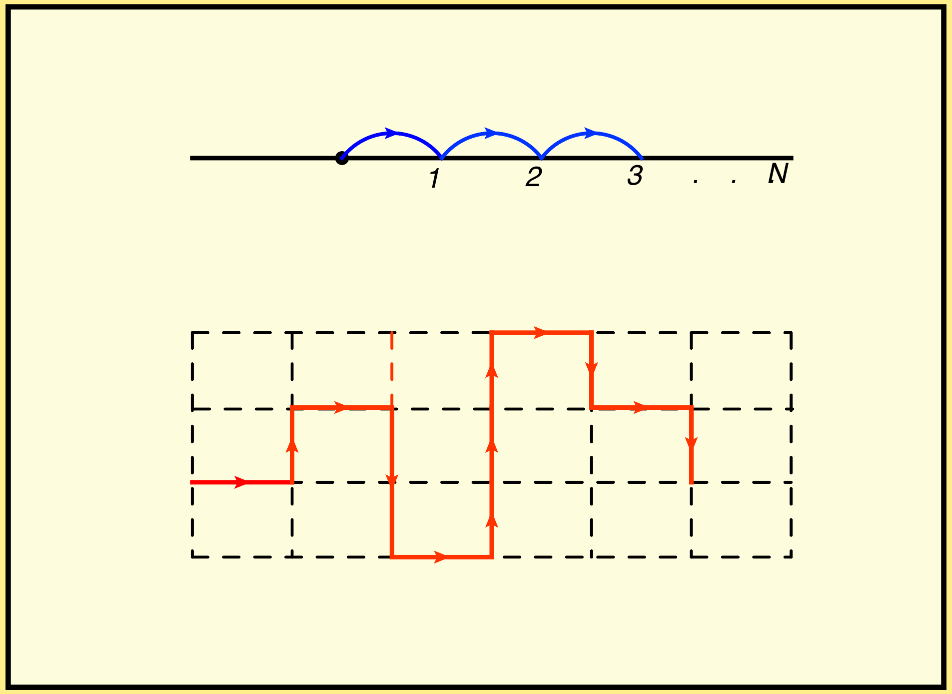


Length = N

Self-avoiding Random Walk



Length = N

Length ~ N^{ν}, $\nu < 1$

$N \to \infty$

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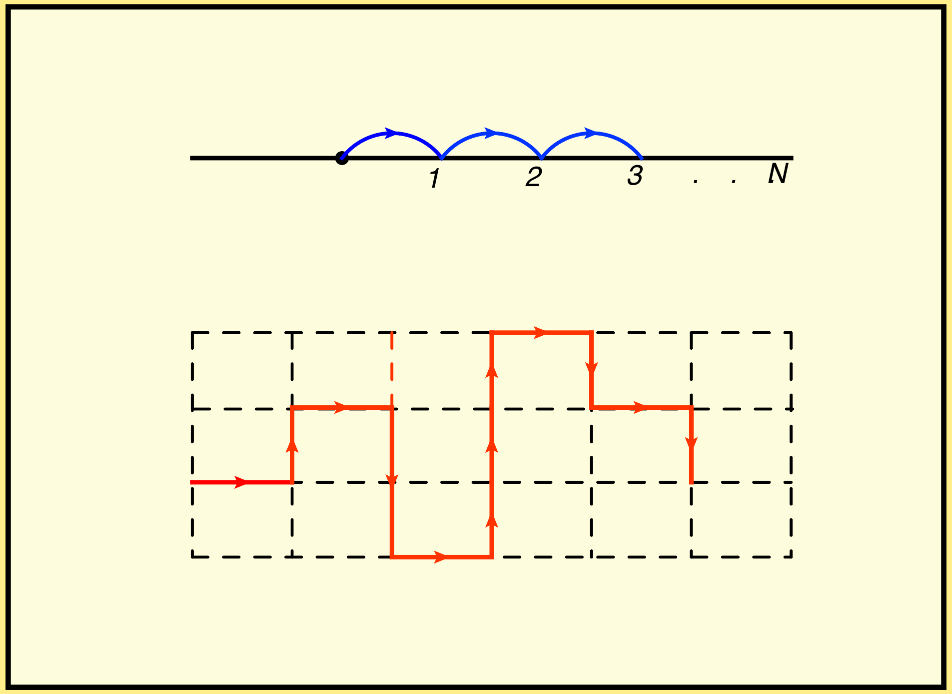

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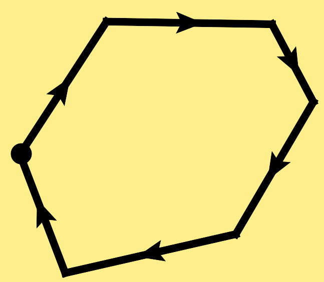
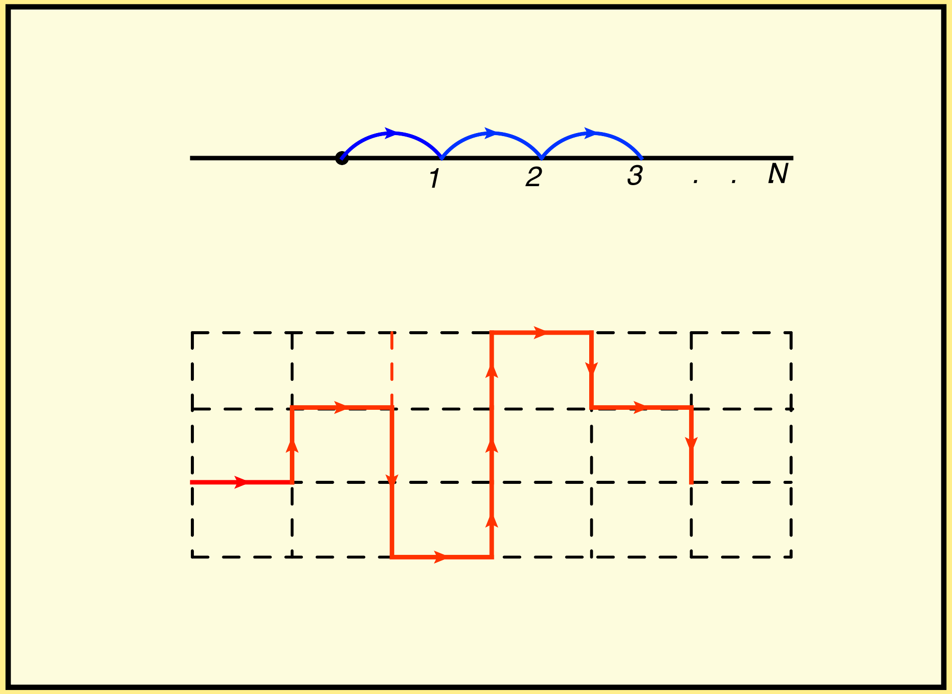


$\sim \theta^2 = 0$

Walk in superspace

Self-avoiding Random Walk



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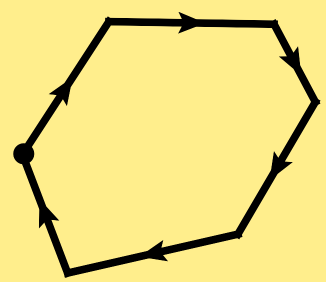
Field theory $\Rightarrow$ Anamalous dimension of the field at the critical point



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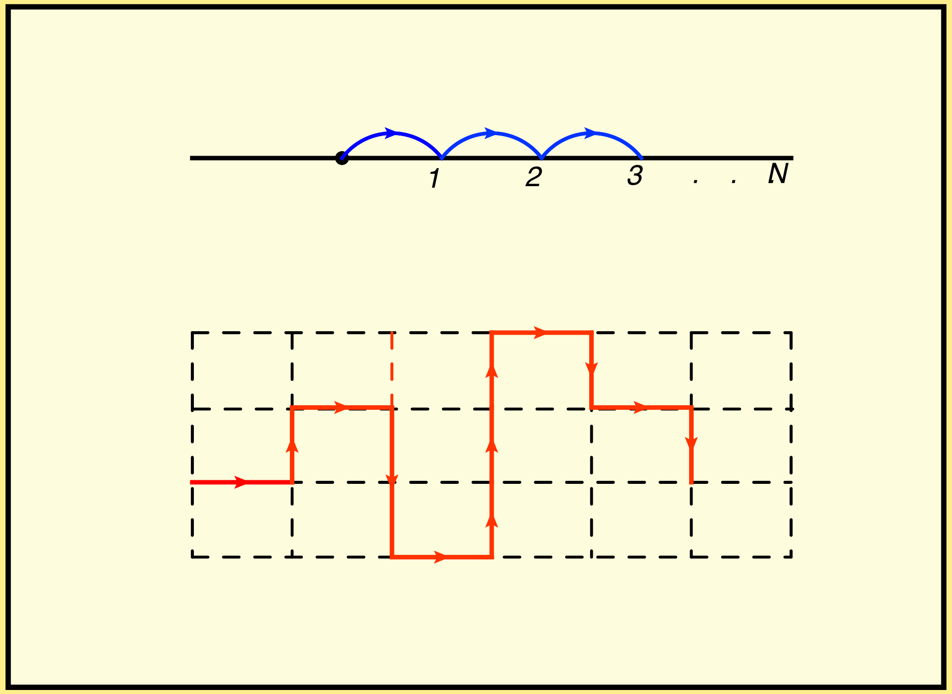

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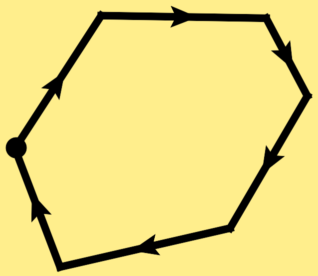

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Walk in superspace

$$Exact\ Solution: \quad \nu = \frac{3}{d+2}$$

$d = 1$	$d = 2$	$d = 3$	$d = 4$
$\nu = 1$	$\nu = \frac{3}{4}$	$\nu = \frac{3}{5}$	$\nu = \frac{1}{2}$

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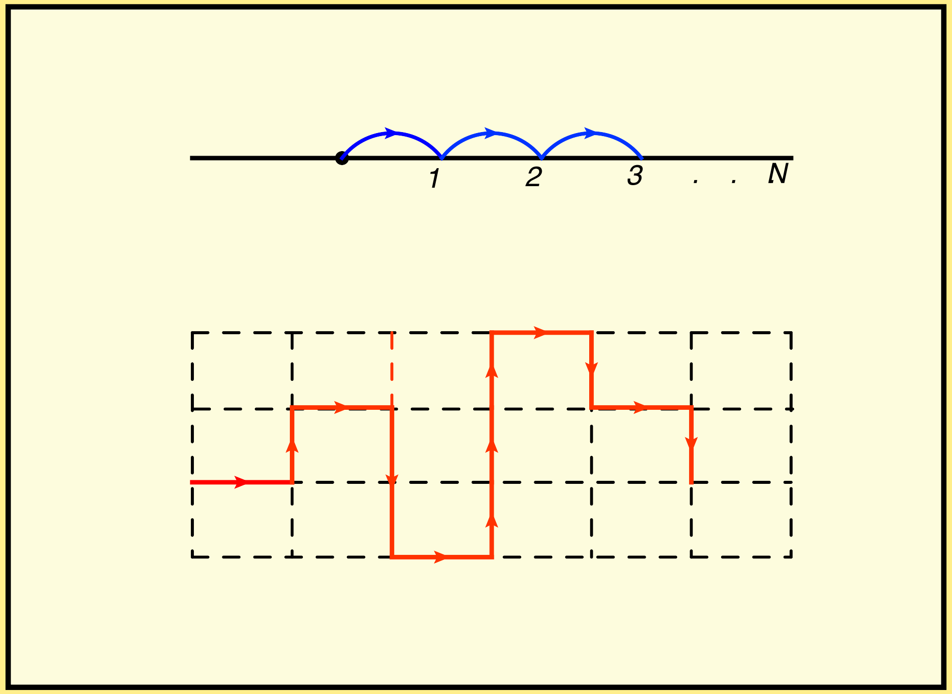

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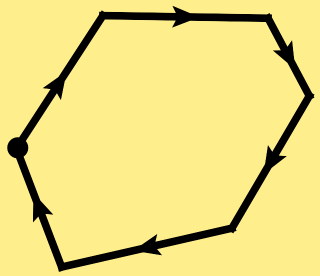

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$Experiment:$ 0.76 ± 0.03 0.589 ± 0.003

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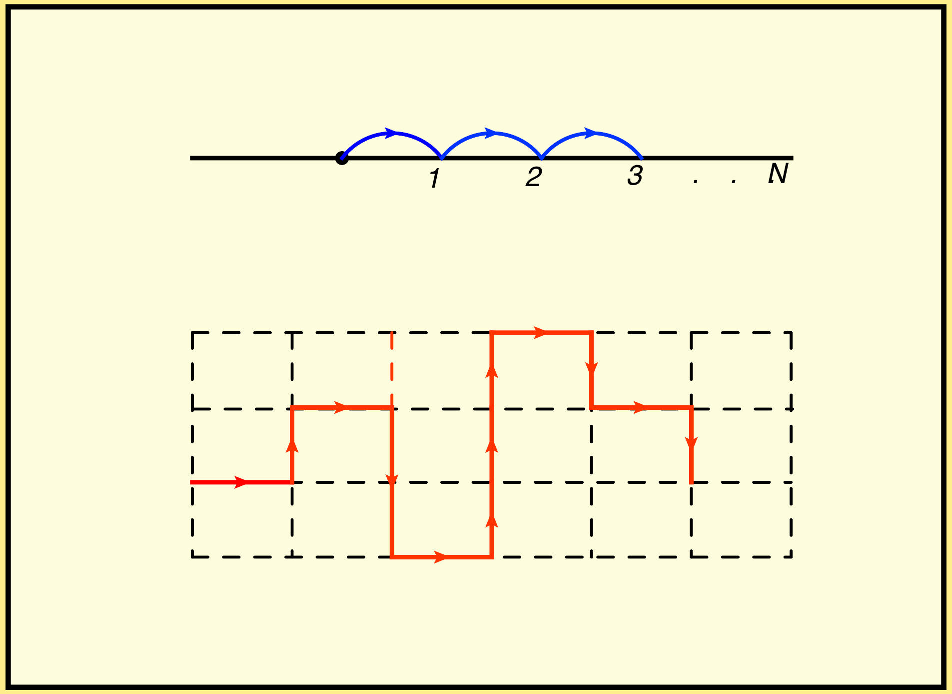

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$N \to \infty$

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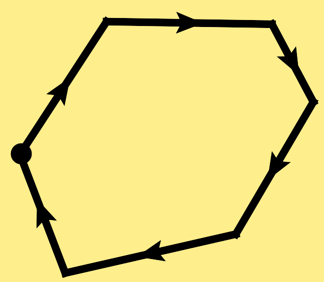

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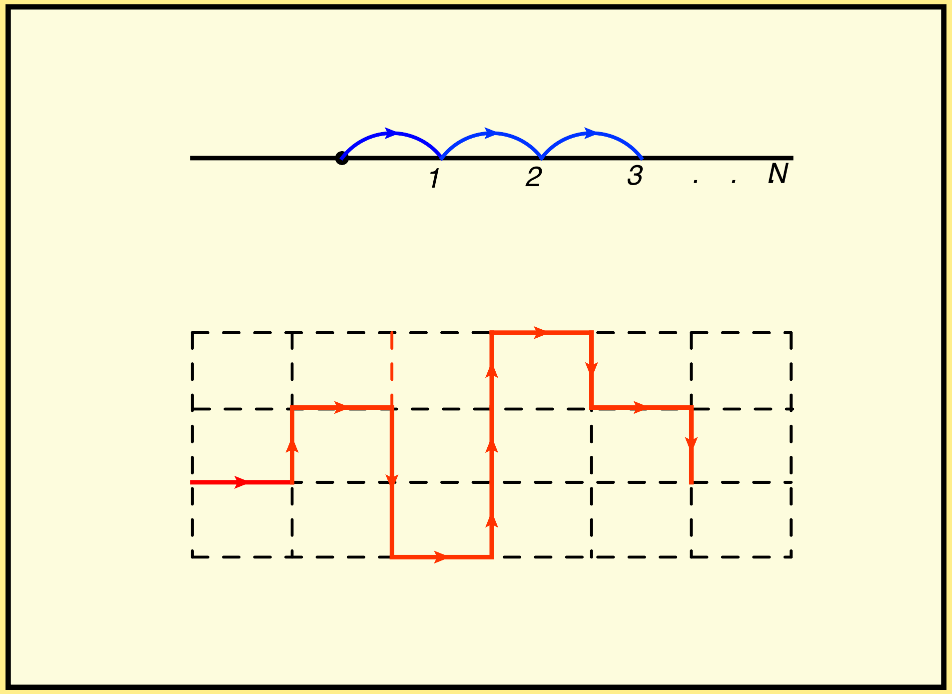

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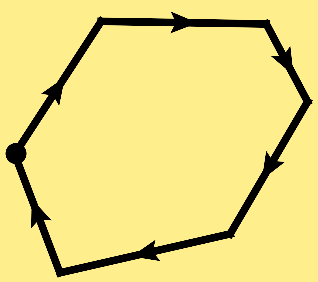
$N \rightarrow \infty$

Field theory $\Rightarrow$ Anamalous dimension of the field at the critical point



$\sim \theta^2 = 0$

Walk in superspace

$$Exact\ Solution: \quad \nu = \frac{3}{d+2}$$

$d = 1$	$d = 2$	$d = 3$	$d = 4$
$\nu = 1$	$\nu = \frac{3}{4}$	$\nu = \frac{3}{5}$	$\nu = \frac{1}{2}$

$Experiment:$ 0.76 ± 0.03 0.589 ± 0.003

Superfield in Superspace

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N=1 SUSY Chiral supermultiplet:

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

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

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Chiral multiplet $N = 1 \;\; h = 0$

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

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(φ,ψ)

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Vector multiplet $N = 1 \quad h = 1/2$

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# of states	1	1	1	1

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(λ, A_μ)

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(λ, A_μ) — λ: spinor, A_μ: vector

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N=4	SUSY YM	helicity			-1	–1/2	0	1/2	1			
	h = -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	
	h = -2	# of states	1	8	28	56	70	56	28	8	1	

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scalar spinor
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$N \leq 4S$ ← spin

$N \leq 4$ For renormalizable theories (YM)
$N \leq 8$ For (super)gravity

Mathematical Beauty of SUSY

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- N=4 SUSY: Cancellation of all divergences ~~$Log\Lambda^2$~~
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- N=8 SUGRA: Finiteness (Construction of quantum gravity)??

Simplest (N=1) SUSY Multiplets

Bosons and Fermions come in pairs

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scalar chiral fermion majorana fermion vector gravitino graviton

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	$-4/3$
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Higgs							
H_1	Higgses	H_1	higgsinos	$\tilde{H}_1$	1	2	-1
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Creation and Decay of Superpartners @ LHC

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weak int's

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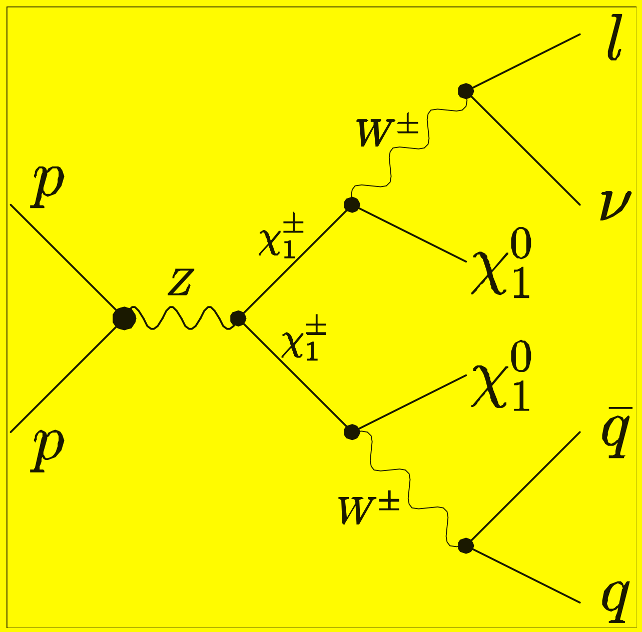

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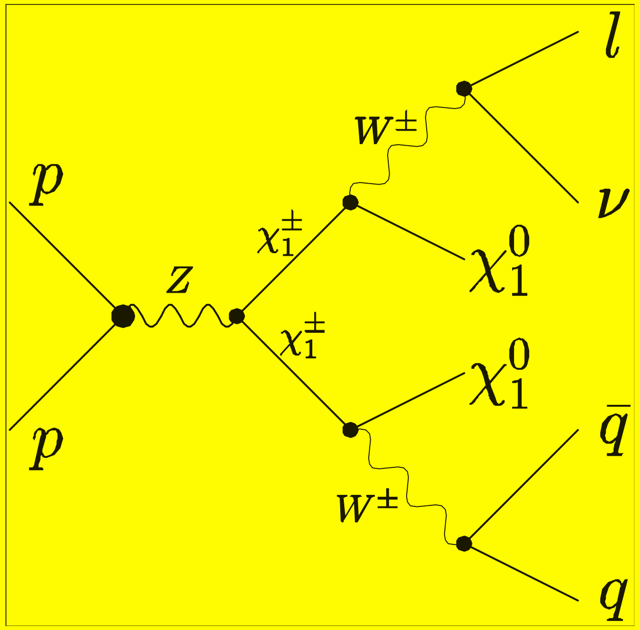

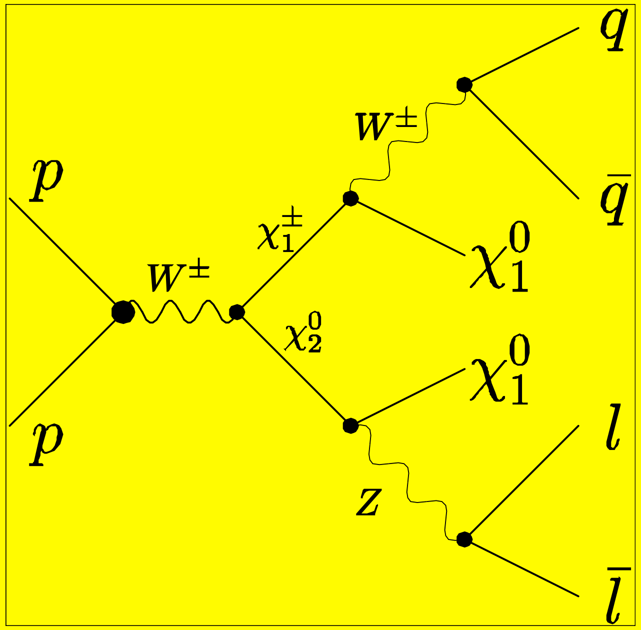

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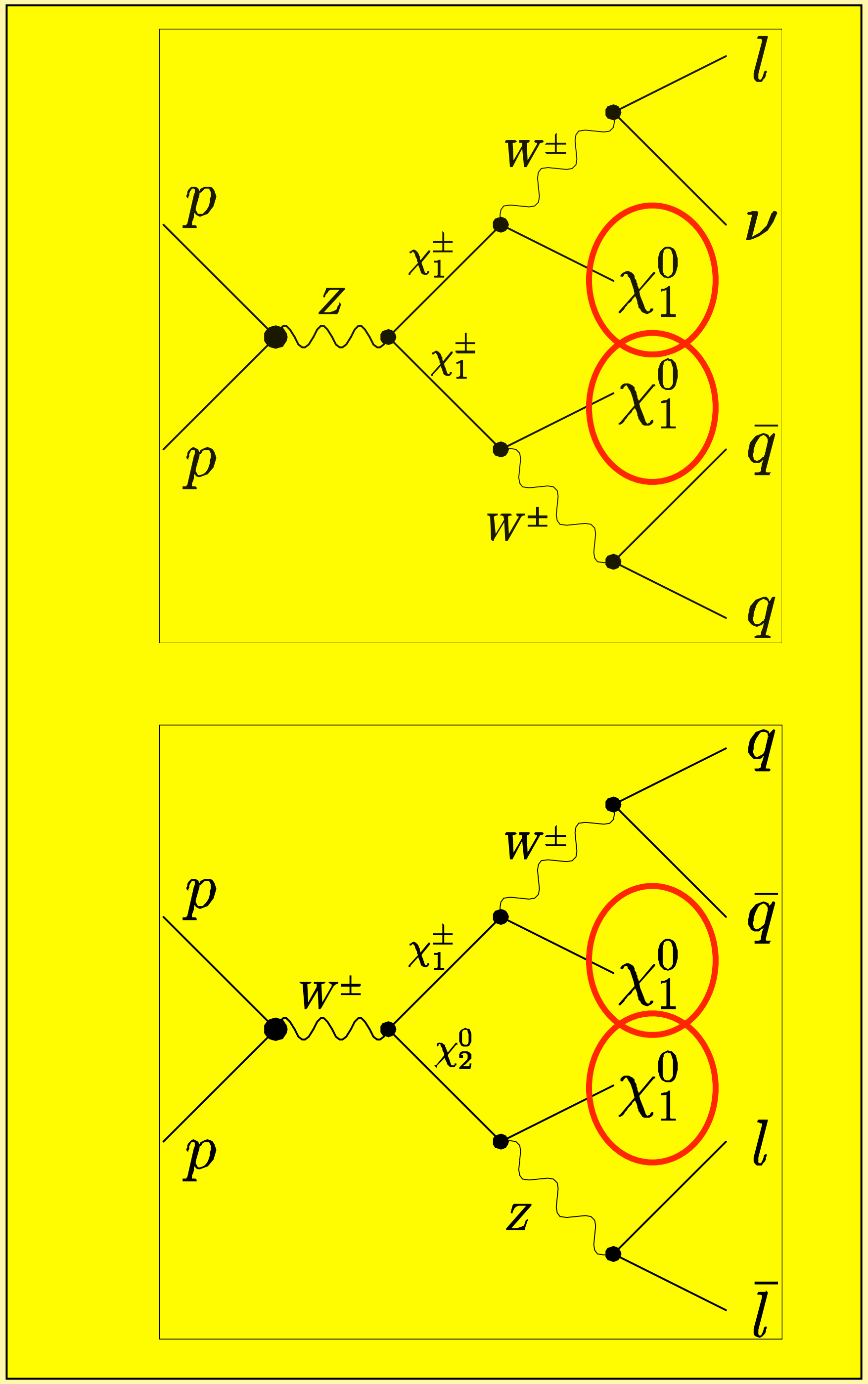

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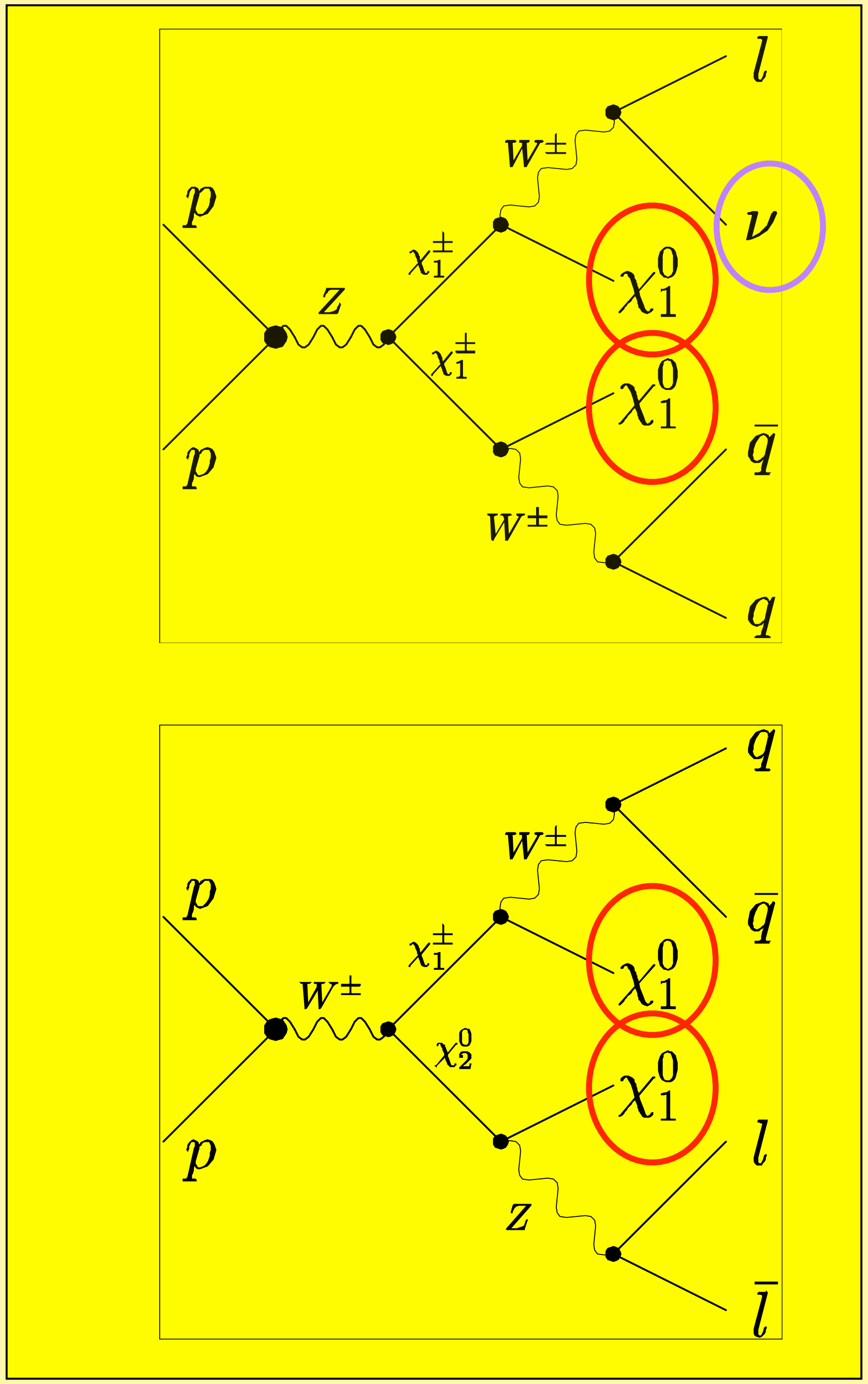
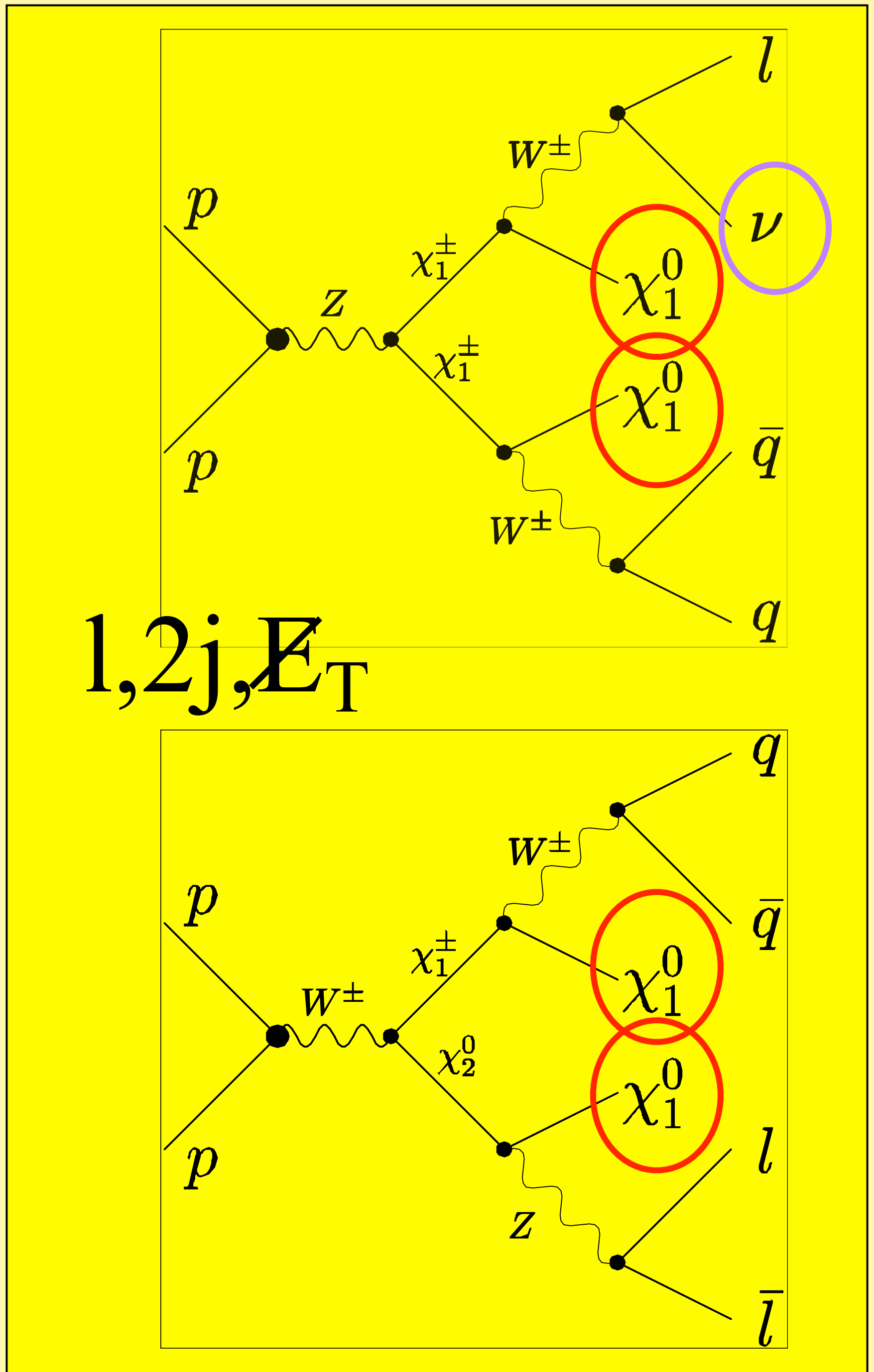


Creation and Decay of Superpartners @ LHC

weak int's



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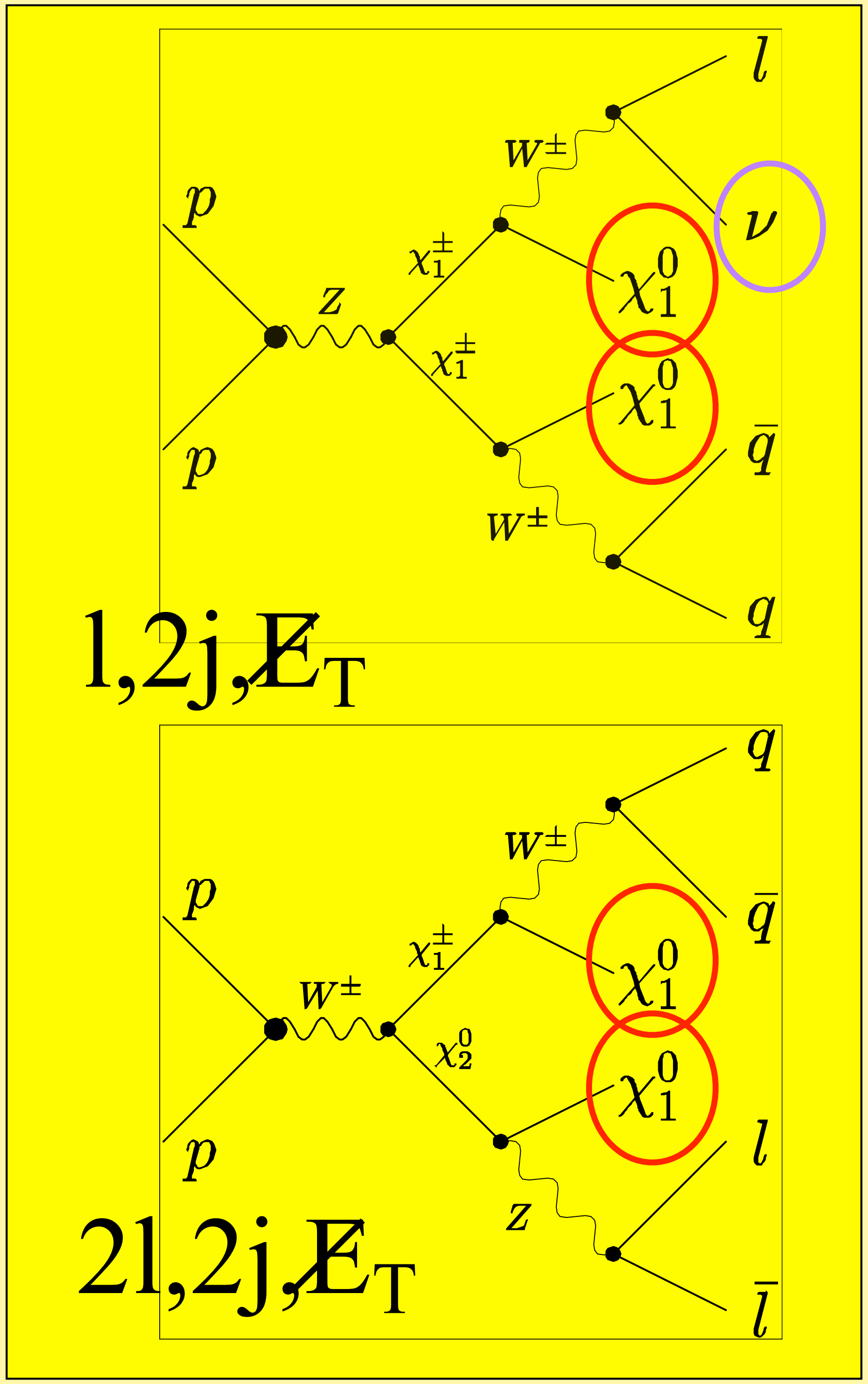

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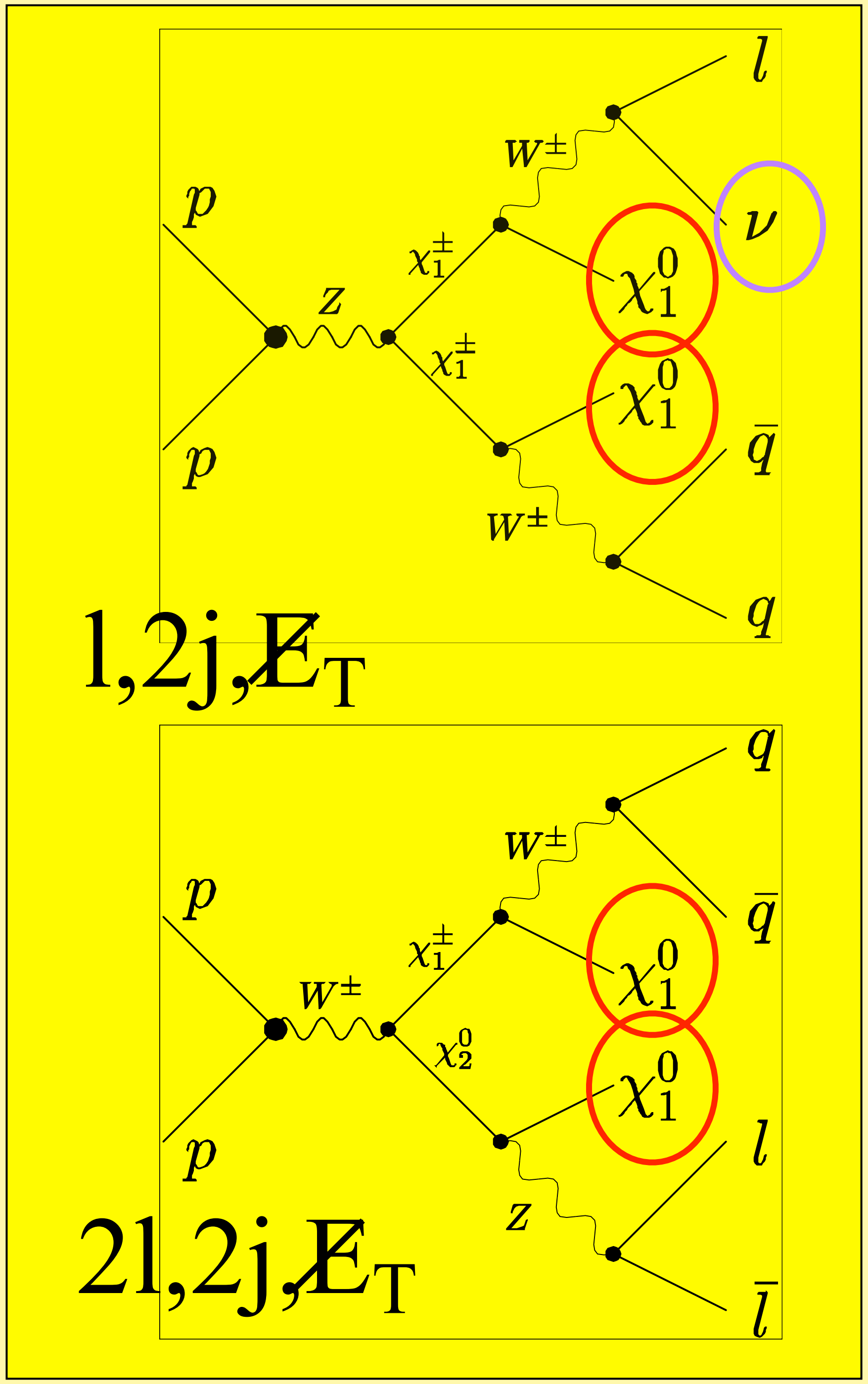

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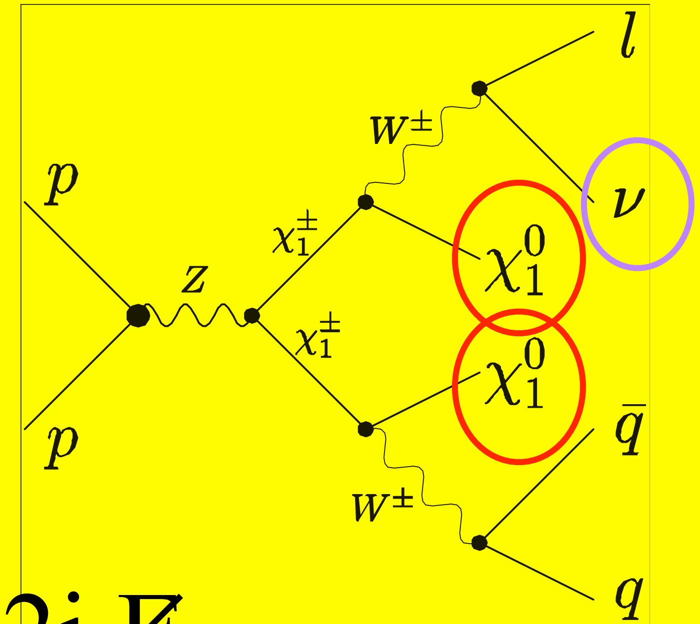
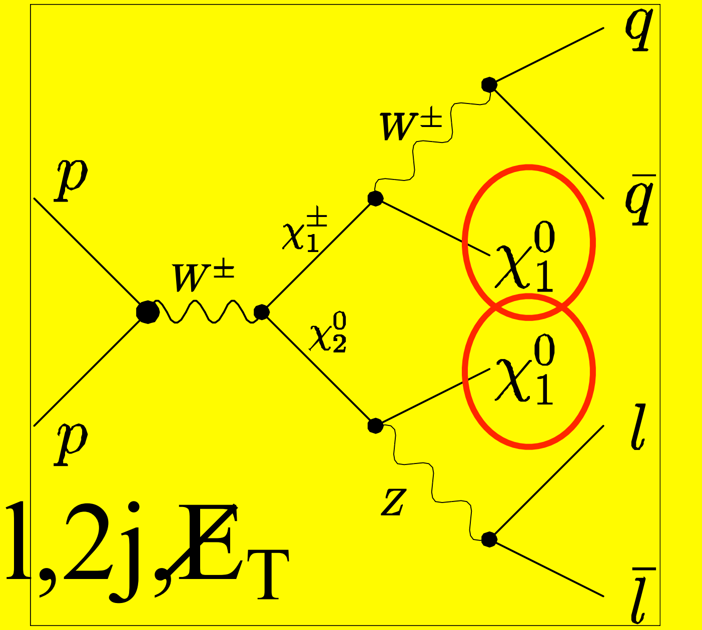


$1,2j,\not{E}_T$



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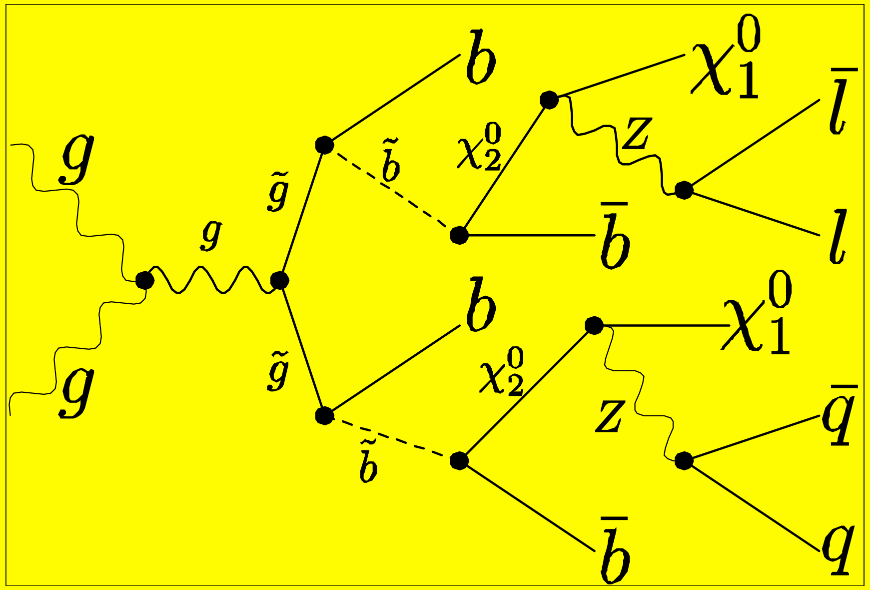

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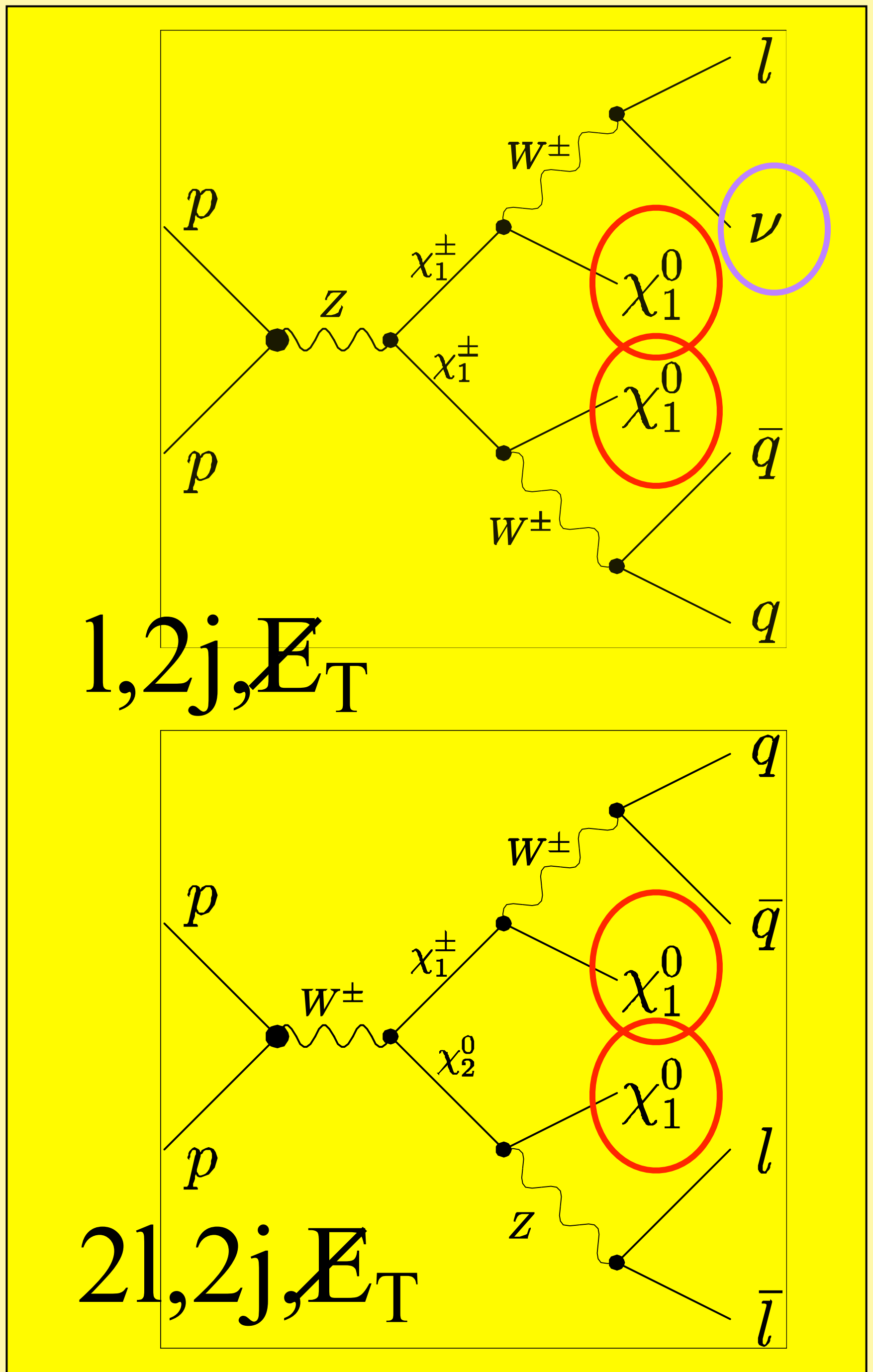

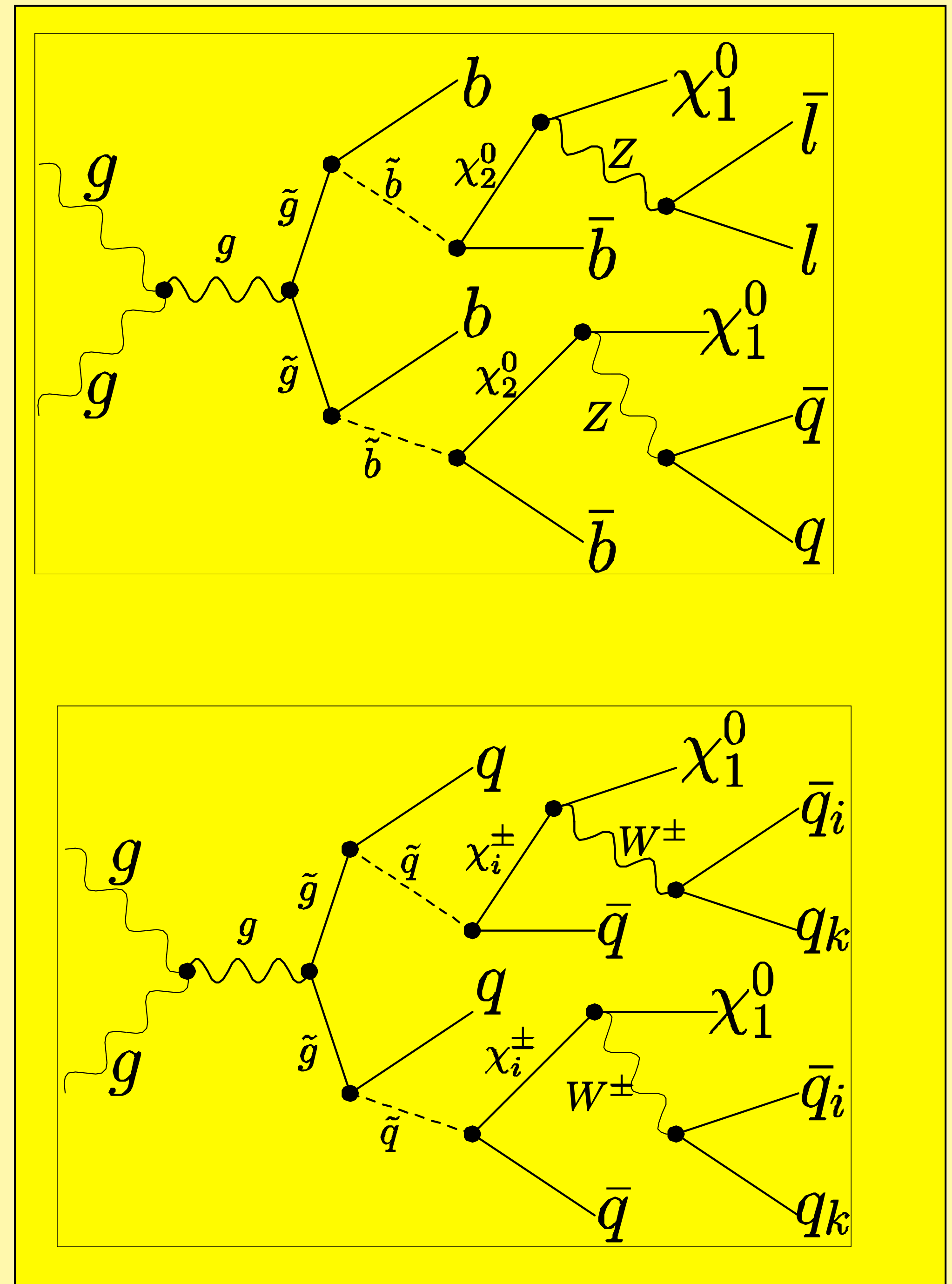

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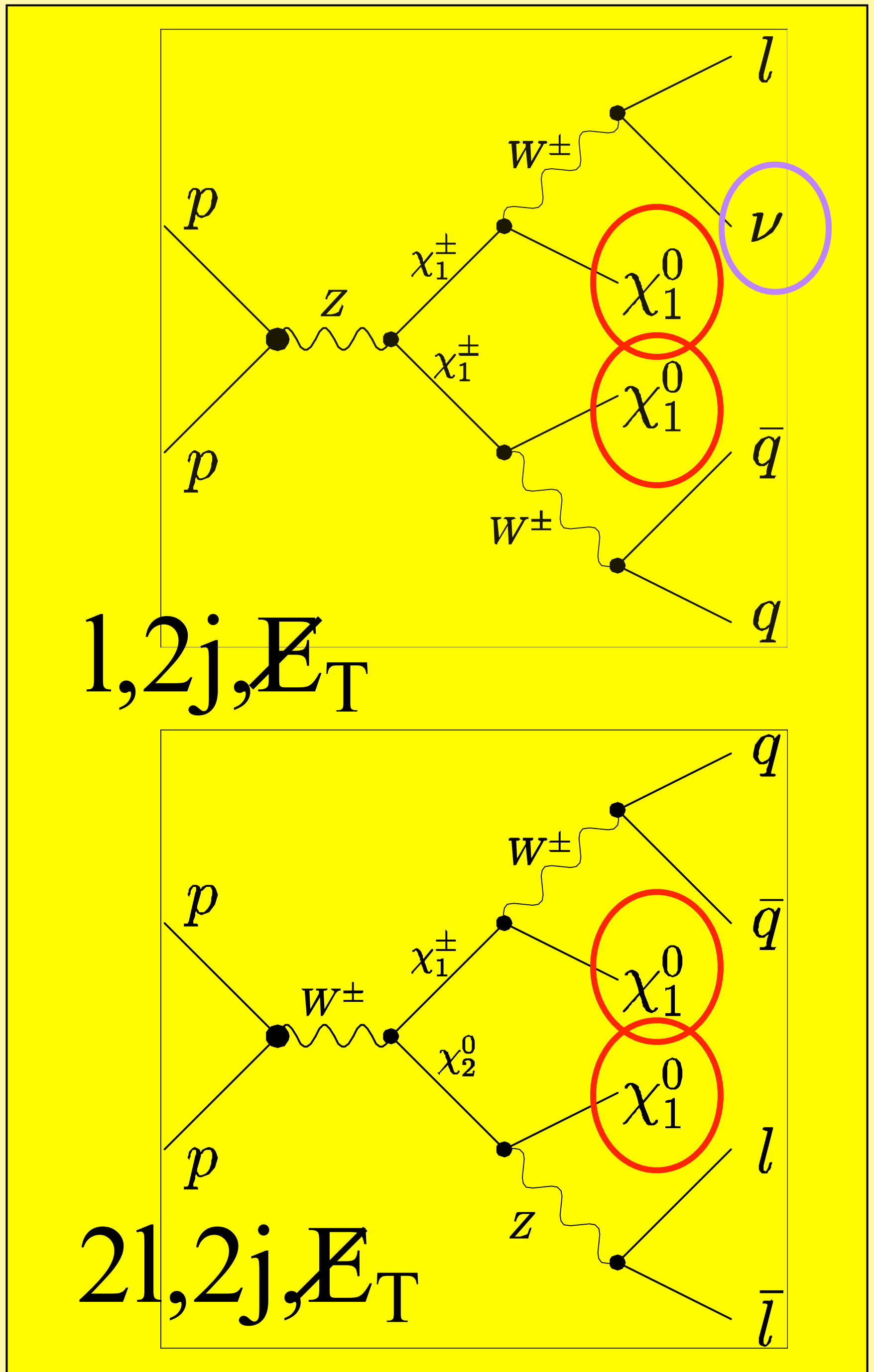

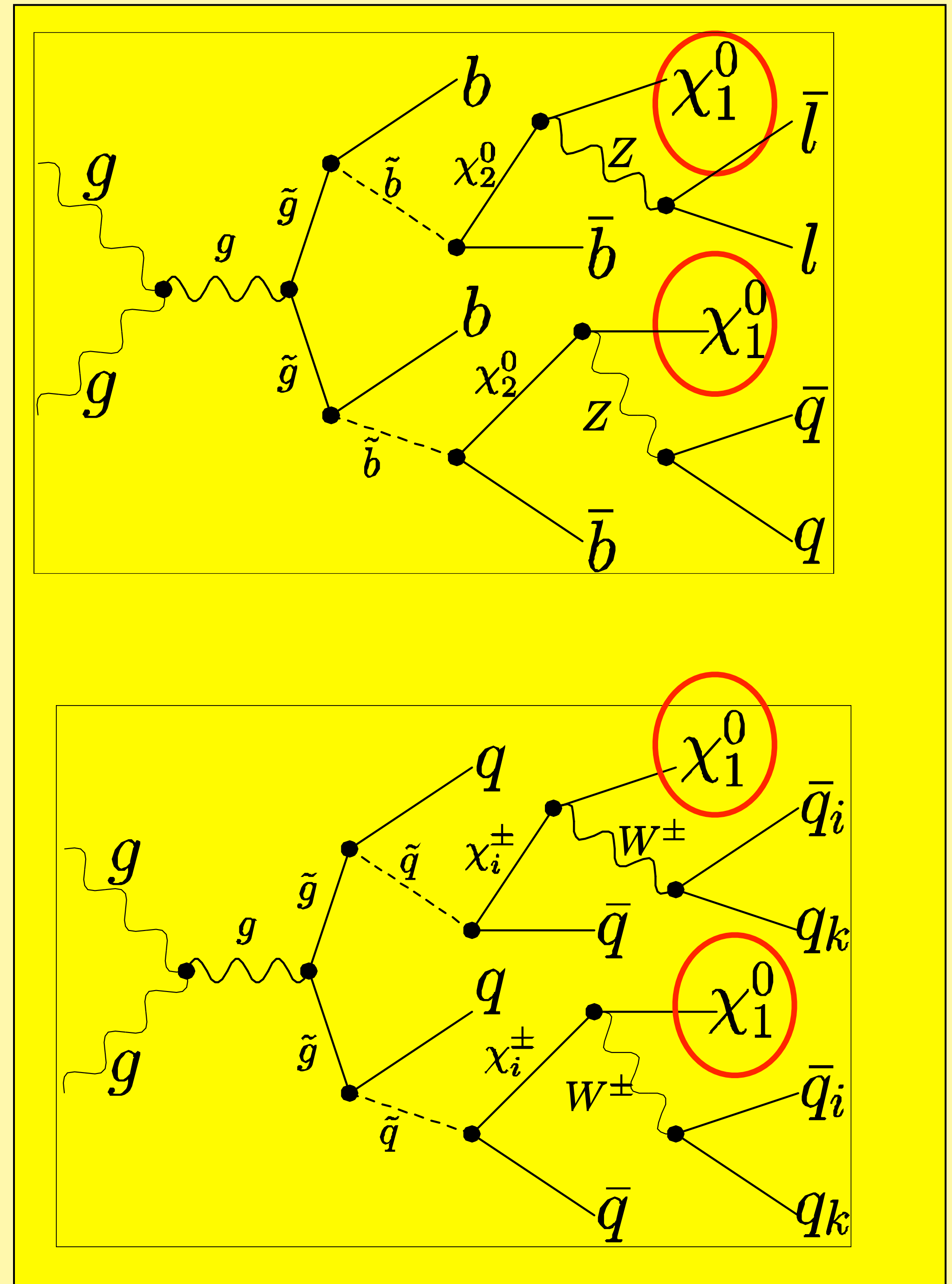

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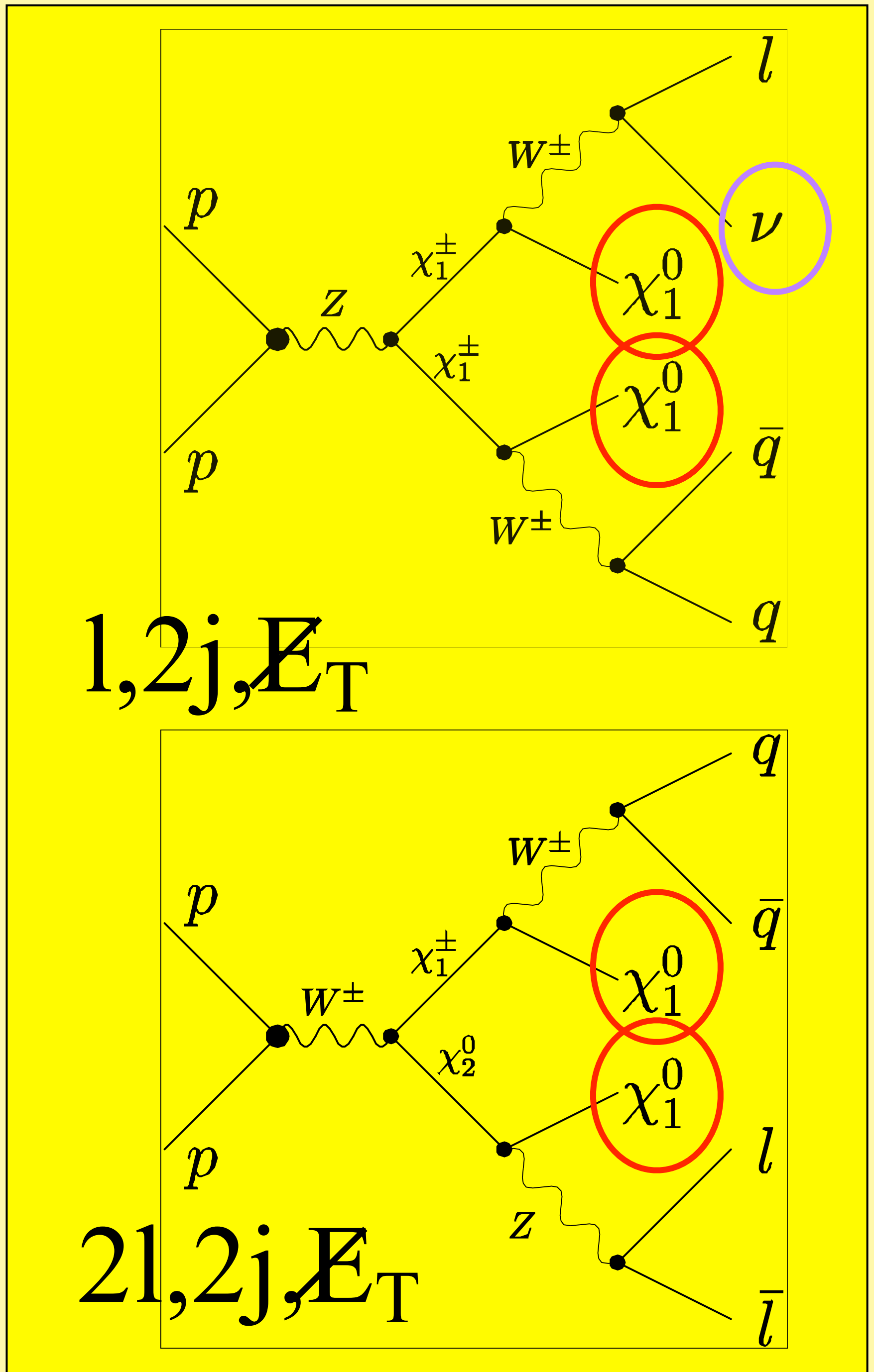

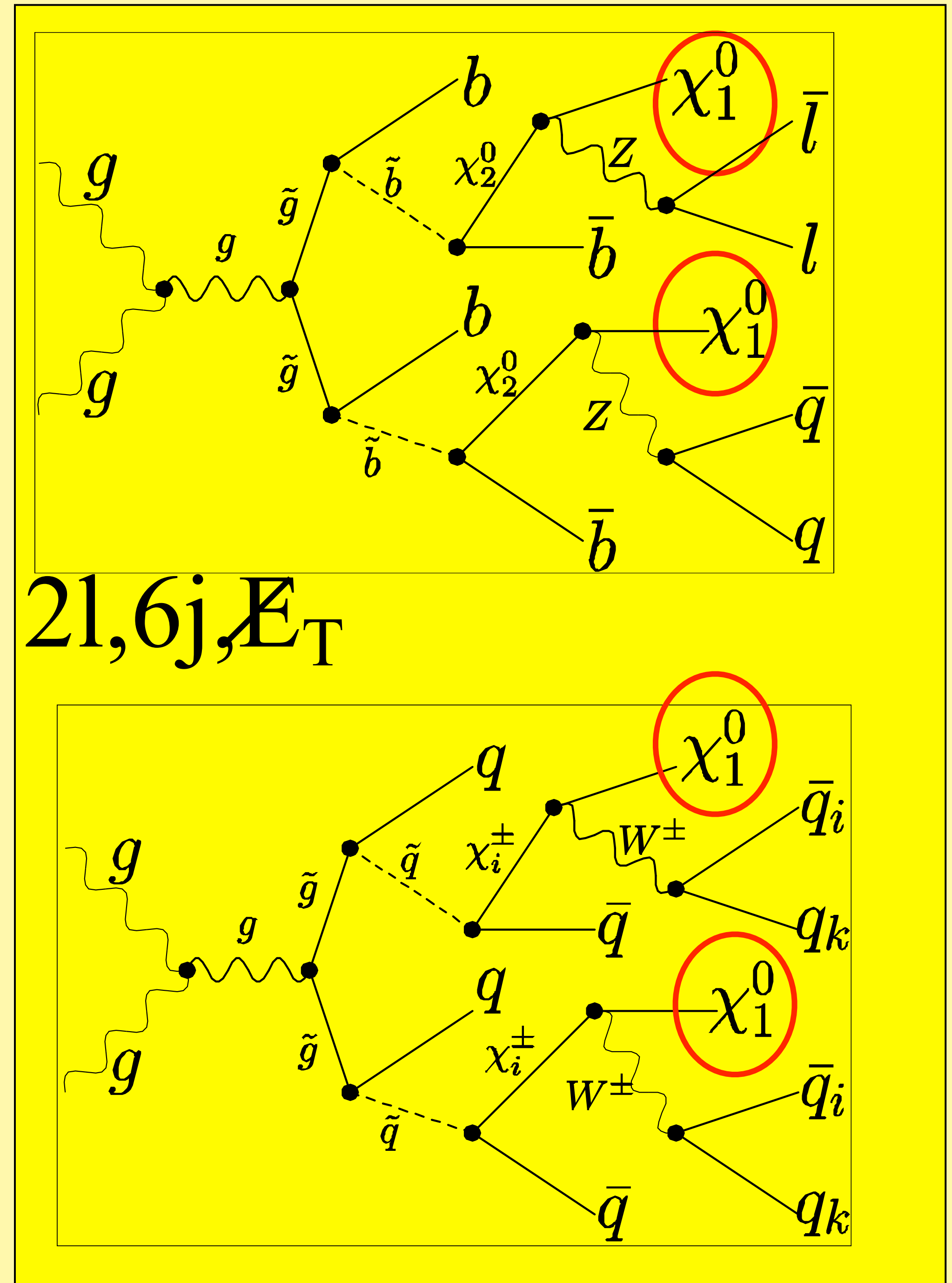

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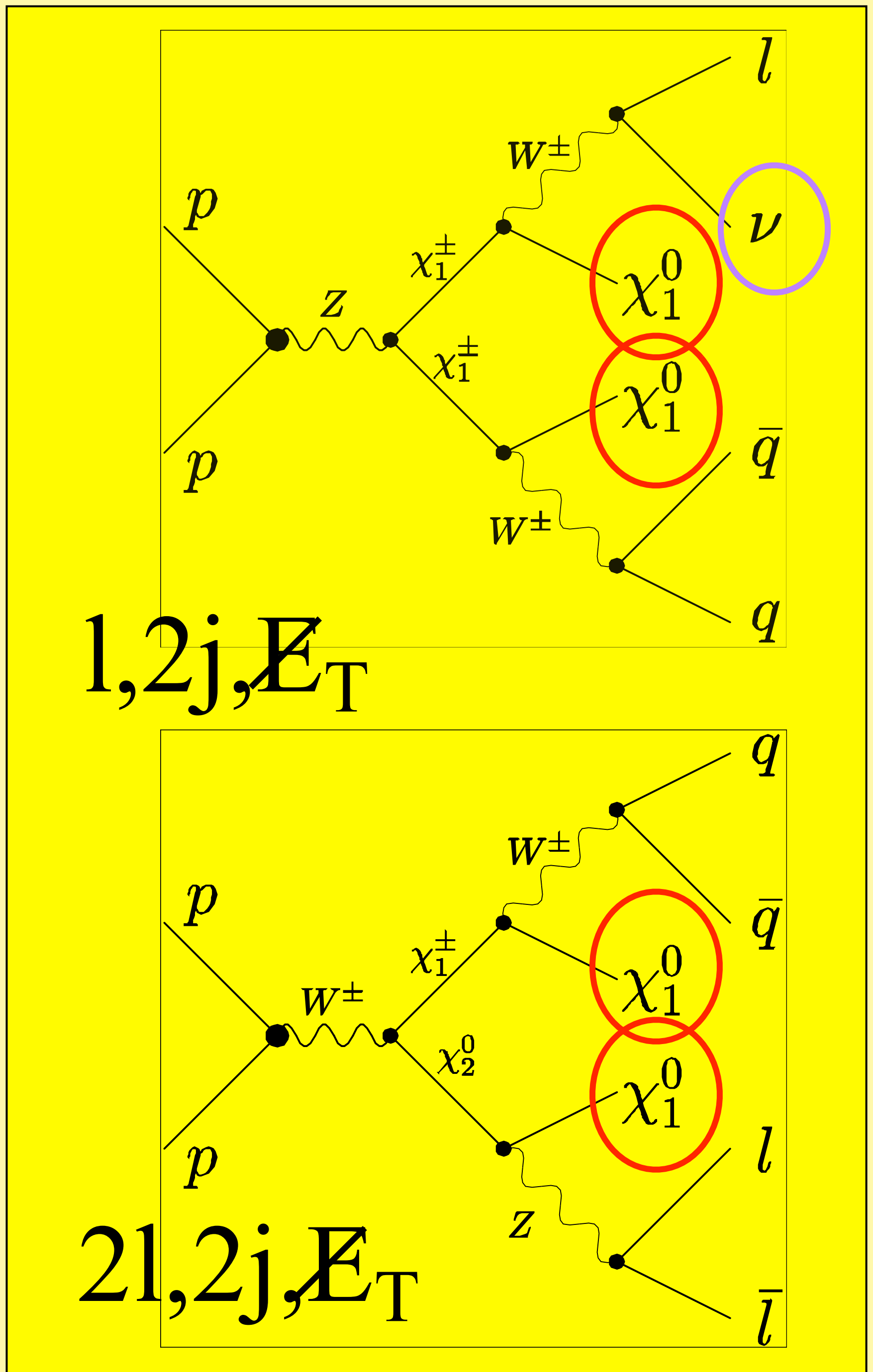

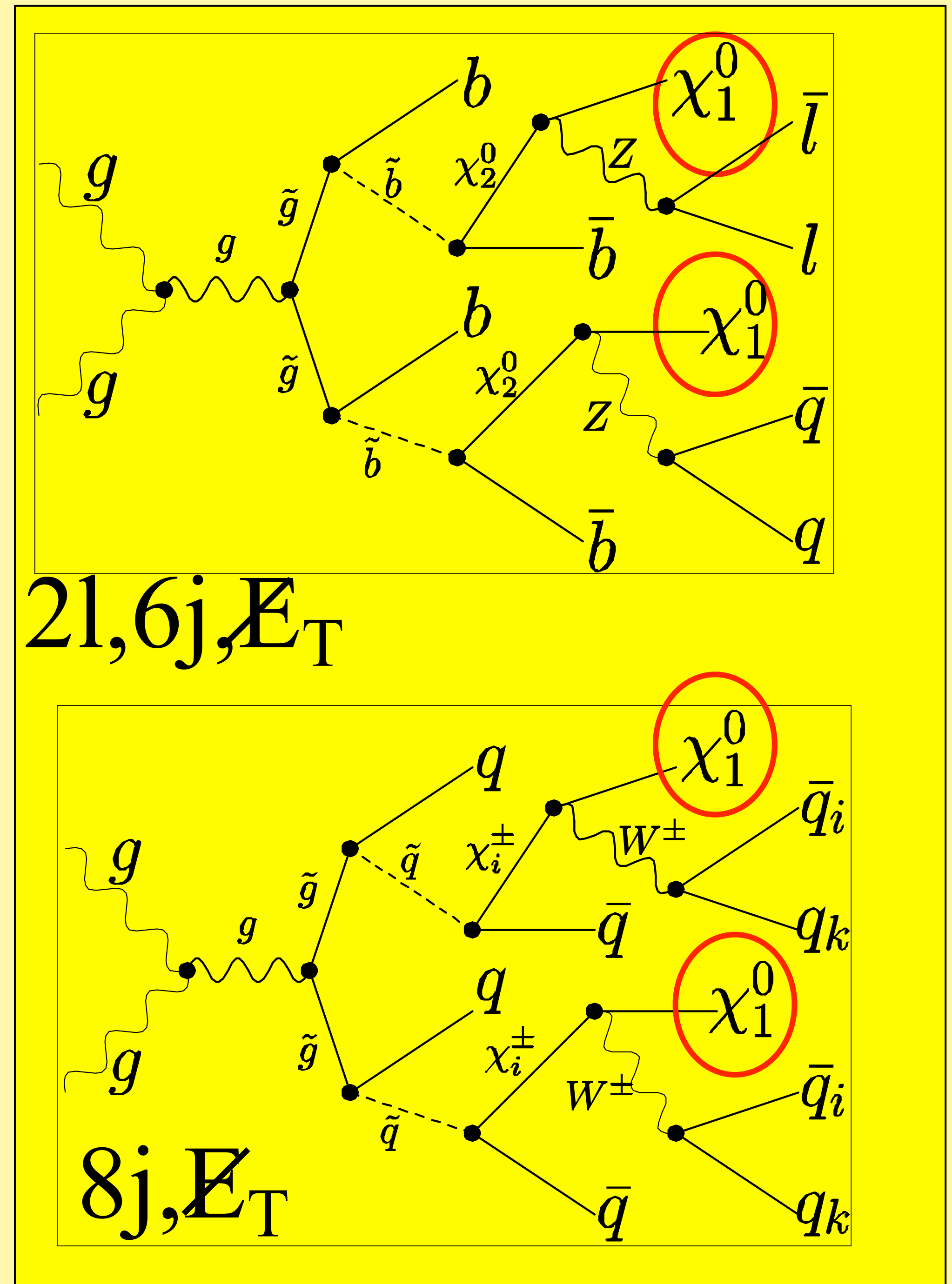

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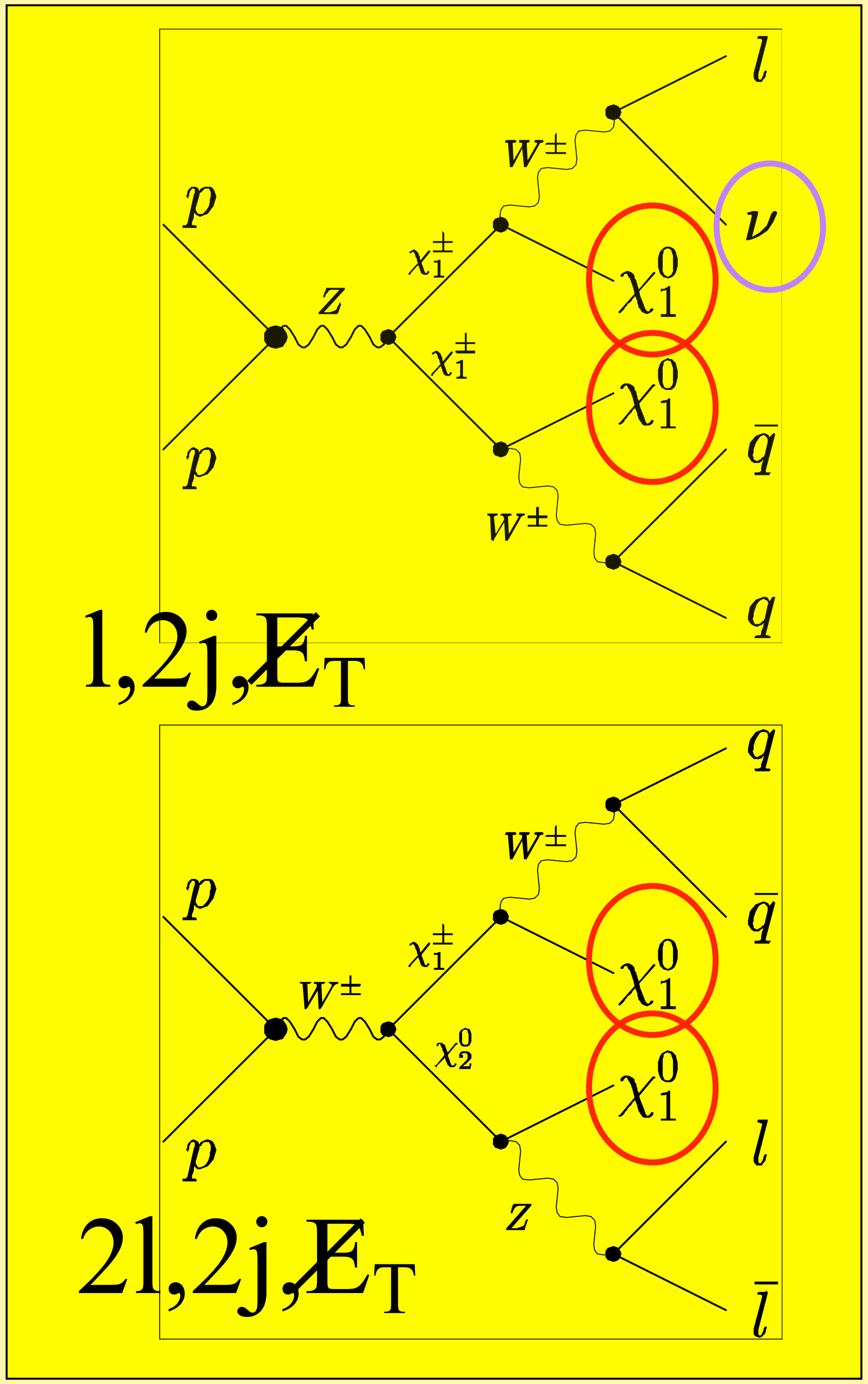
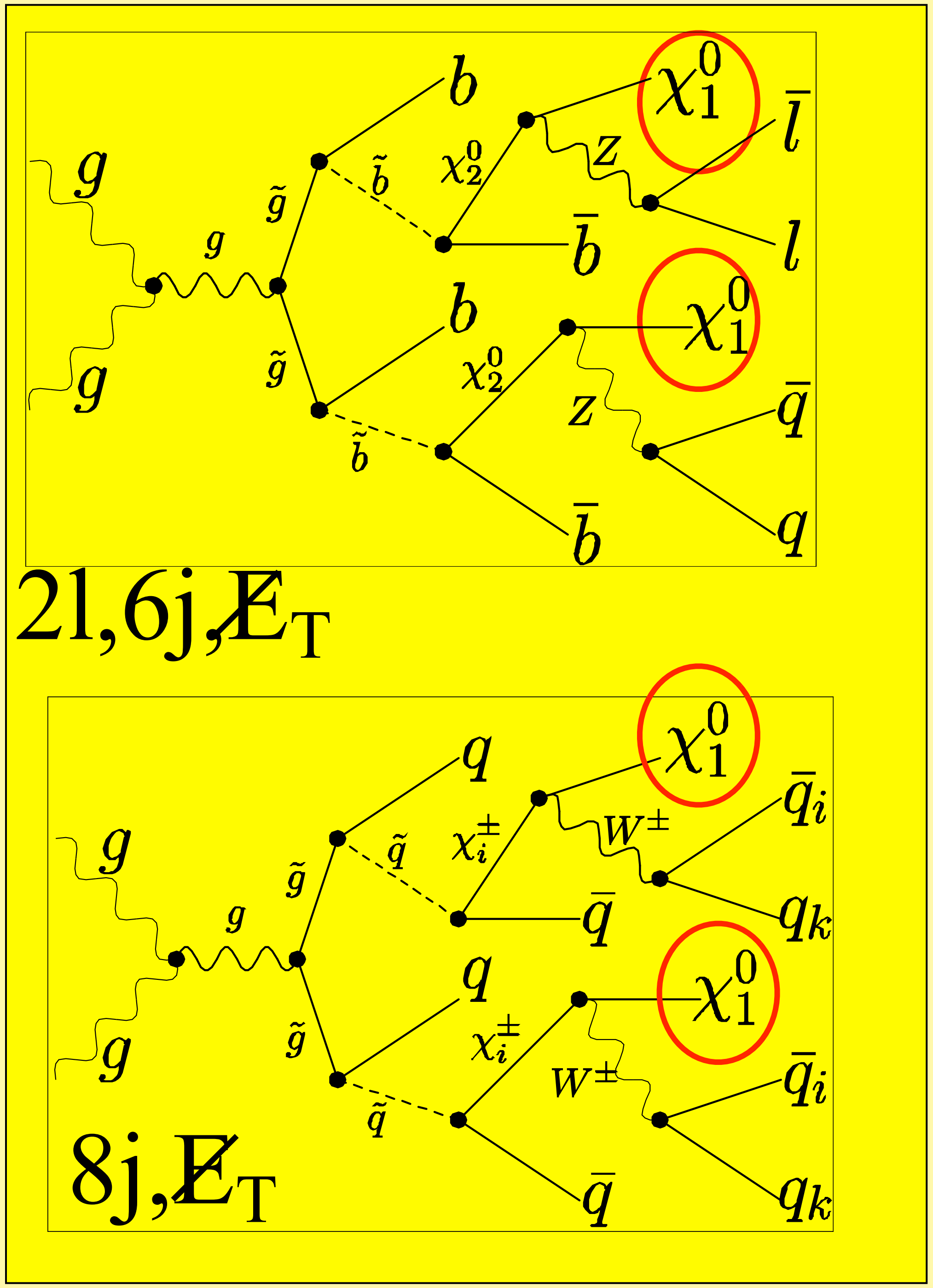




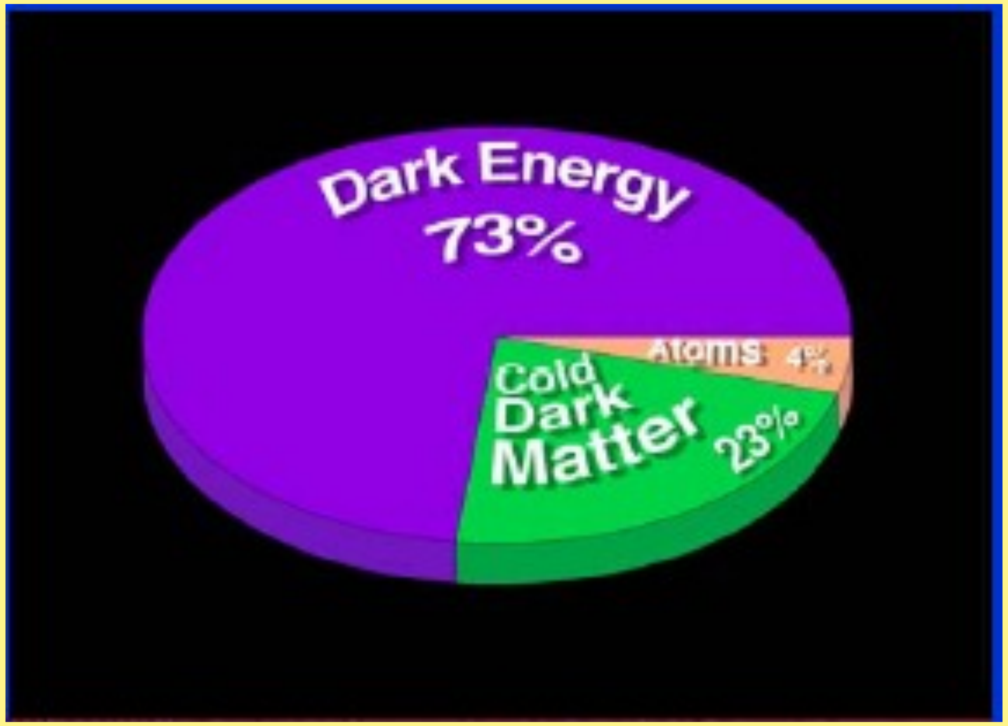
Strong int's

Typical SUSY signature: Missing Energy and Transverse Momentum

Cosmological Constraints

New precise cosmological data

$\Omega h^2 = 1 \quad \Longleftrightarrow \quad \rho = \rho_{crit}$



- Supernova Ia explosion
- CMBR thermal fluctuations

(measured by WMAP)

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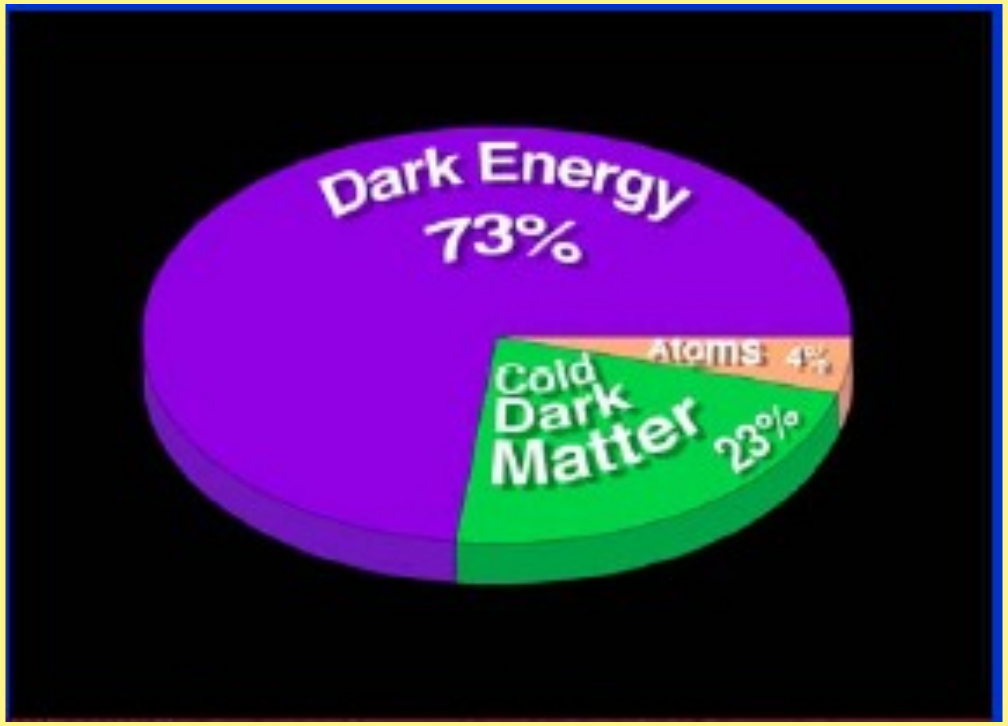

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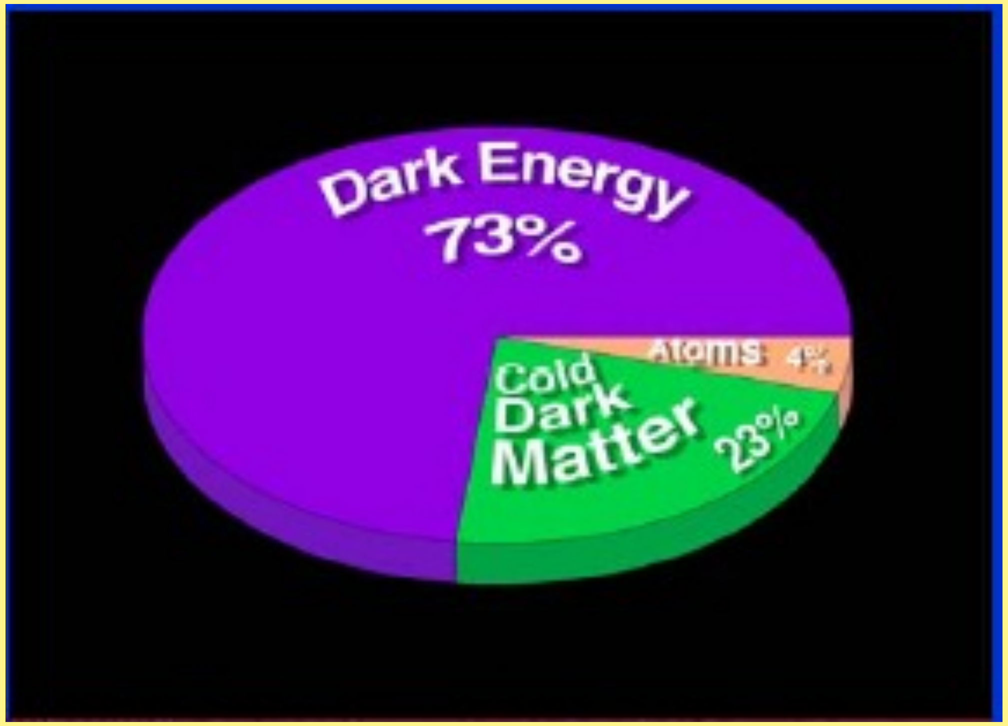

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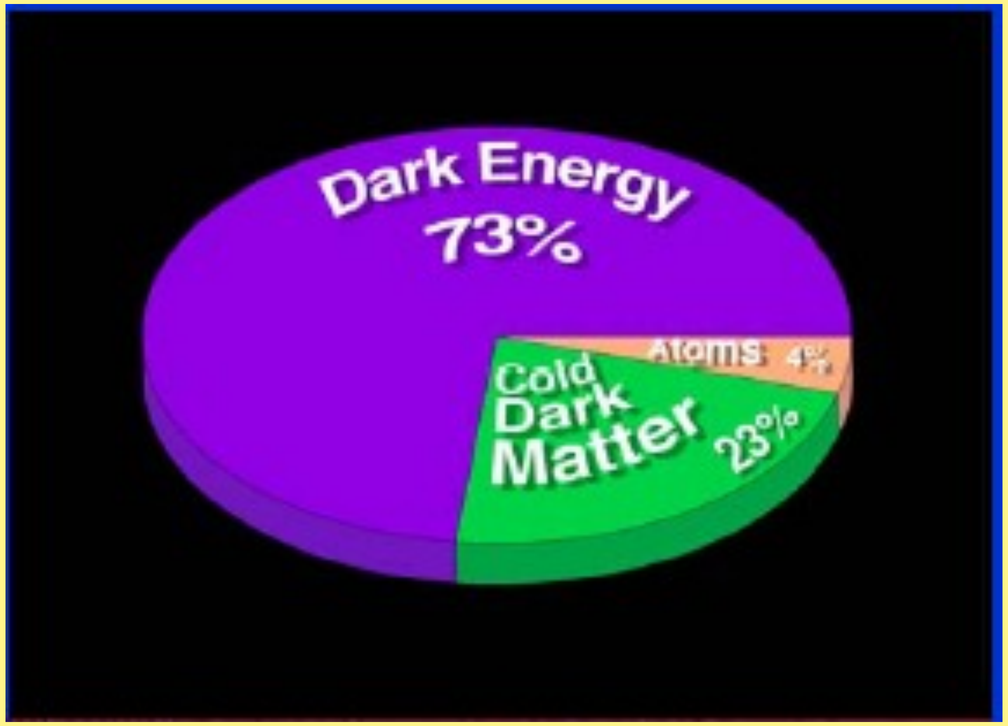

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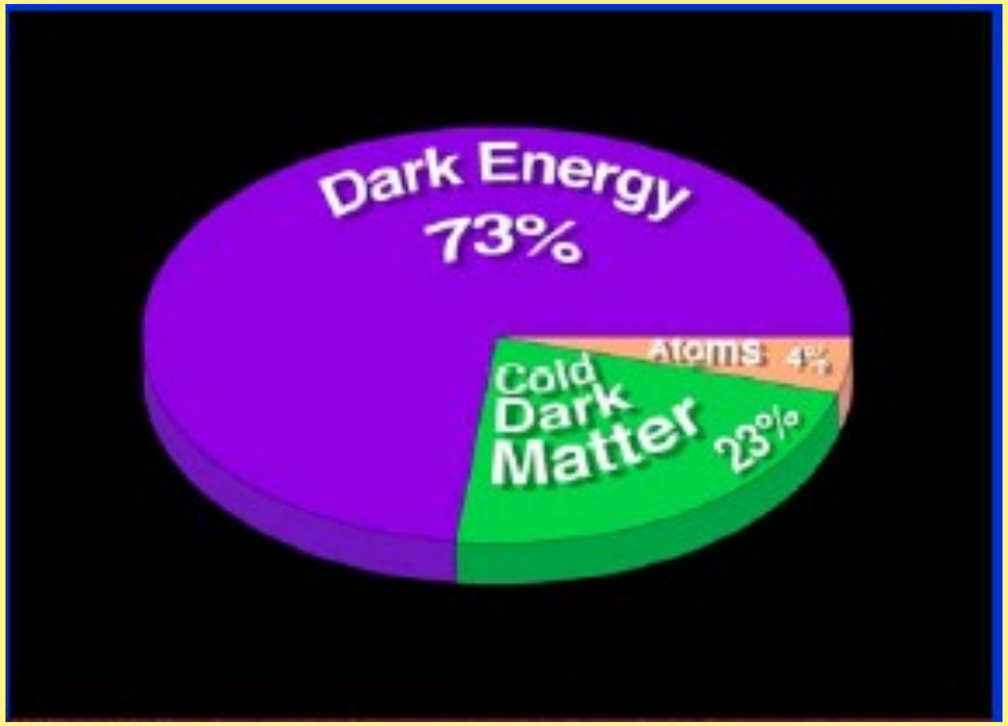

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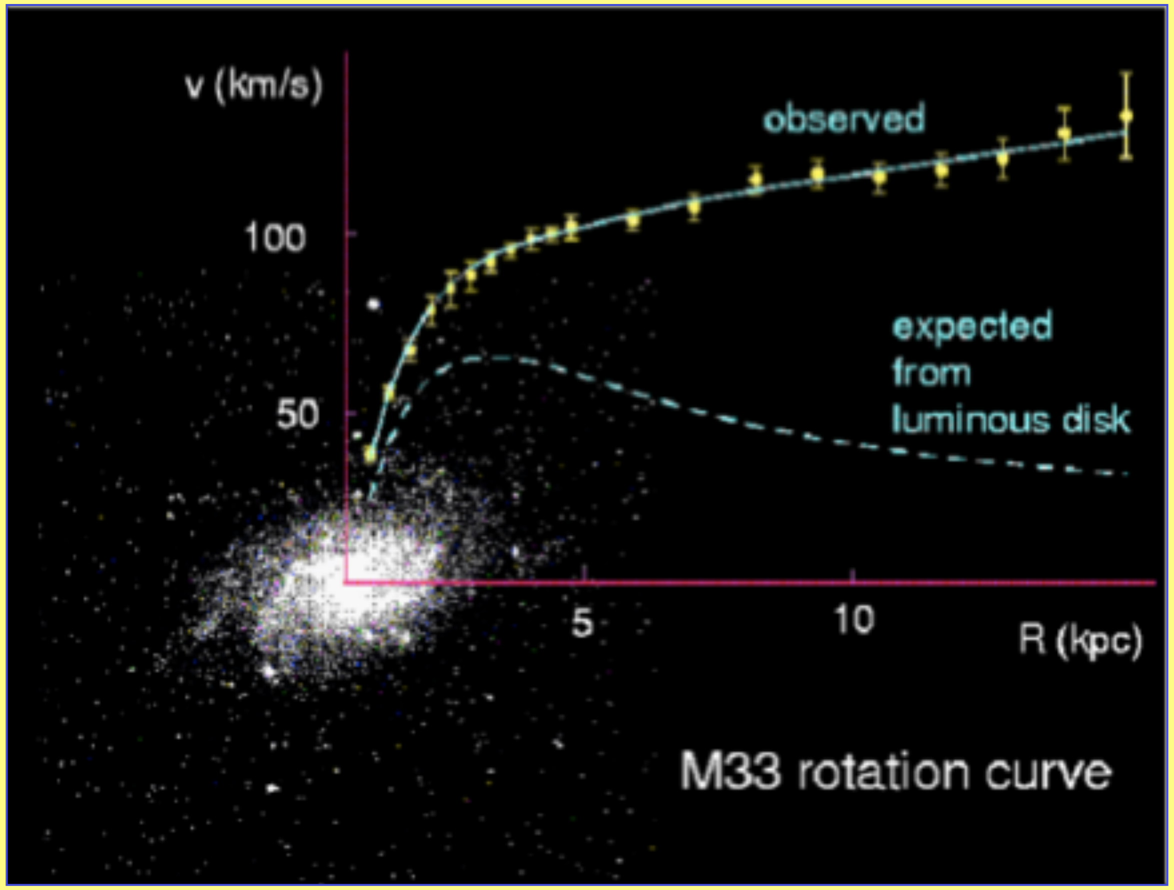
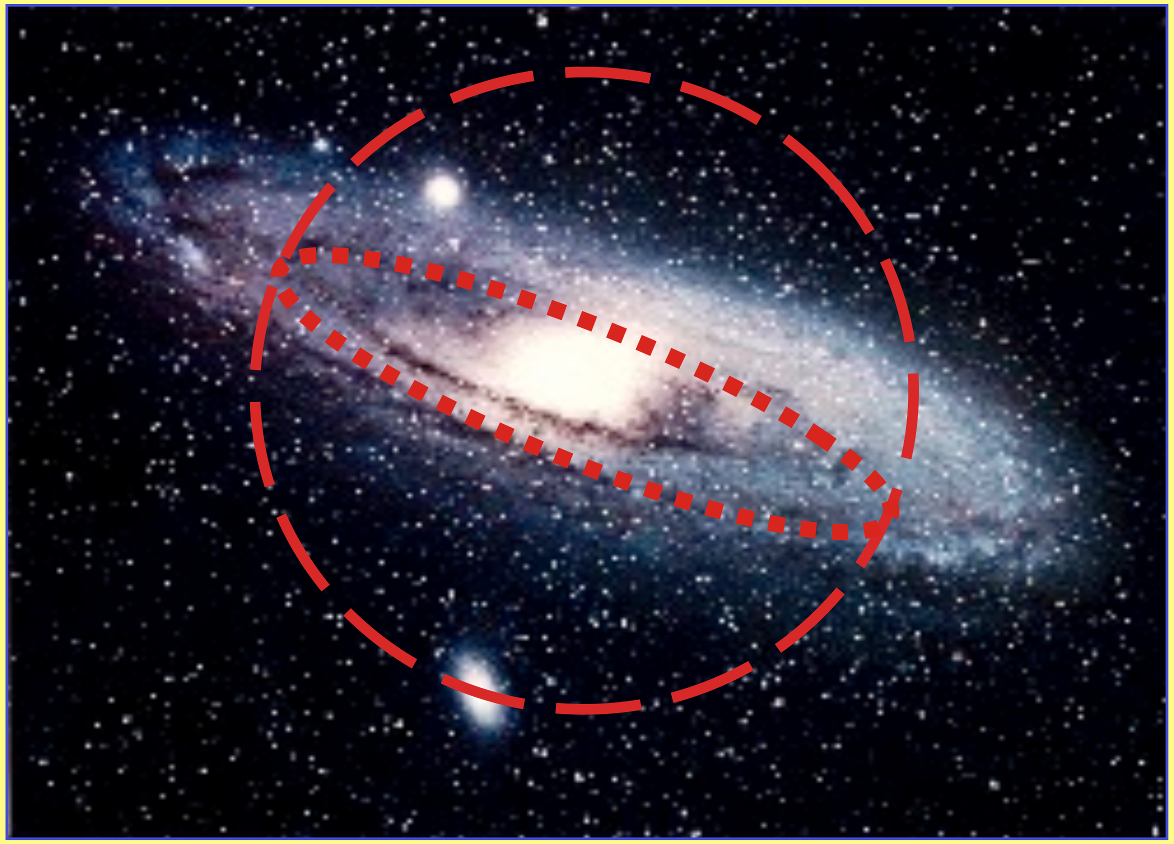
→ Cold DM (rotation curves of Galaxies) ← SUSY

Dark Matter in the Universe



The flat rotation curves of spiral galaxies provide the most direct evidence for the existence of large amount of the dark matter.

Spiral galaxies consist of a central bulge and a very thin disc, and surrounded by an approximately spherical halo of dark matter



SUSY provides a candidate for the Dark matter – a stable neutral particle

Origin of Dark Matter

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Photon ⟷ Photino

γ $\tilde{\gamma}$

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Cosmic Microwave Background

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Relic Dark Matter

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Weakly Interacting Massive Particle

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Weakly Interacting Massive Particle

$$\tilde{\chi}^0 = N_1 \tilde{\gamma} + N_2 \tilde{z} + N_3 \tilde{H}_1^0 + N_4 \tilde{H}_2^0$$

photino zino higgsino higgsino

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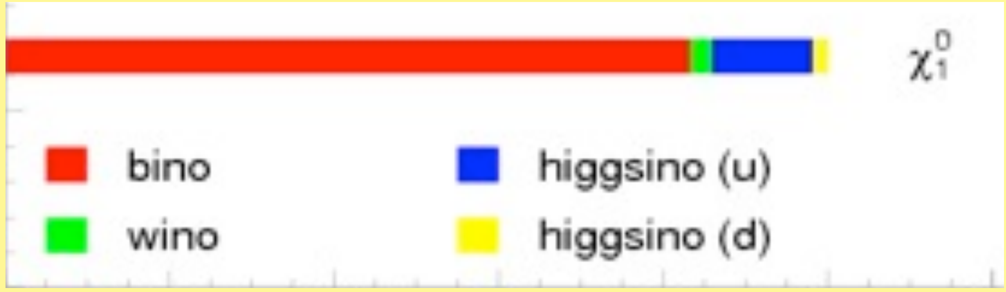

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Cosmic Microwave Background | Relic Dark Matter

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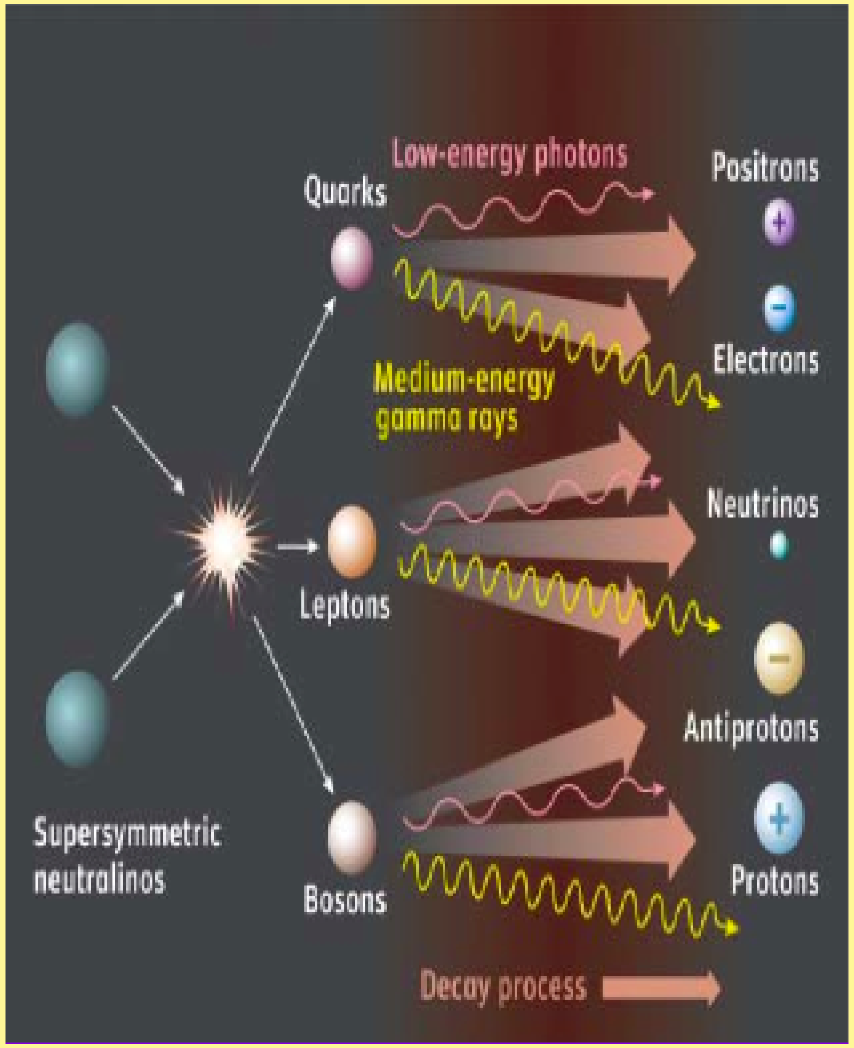

Overview

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Overview

✓

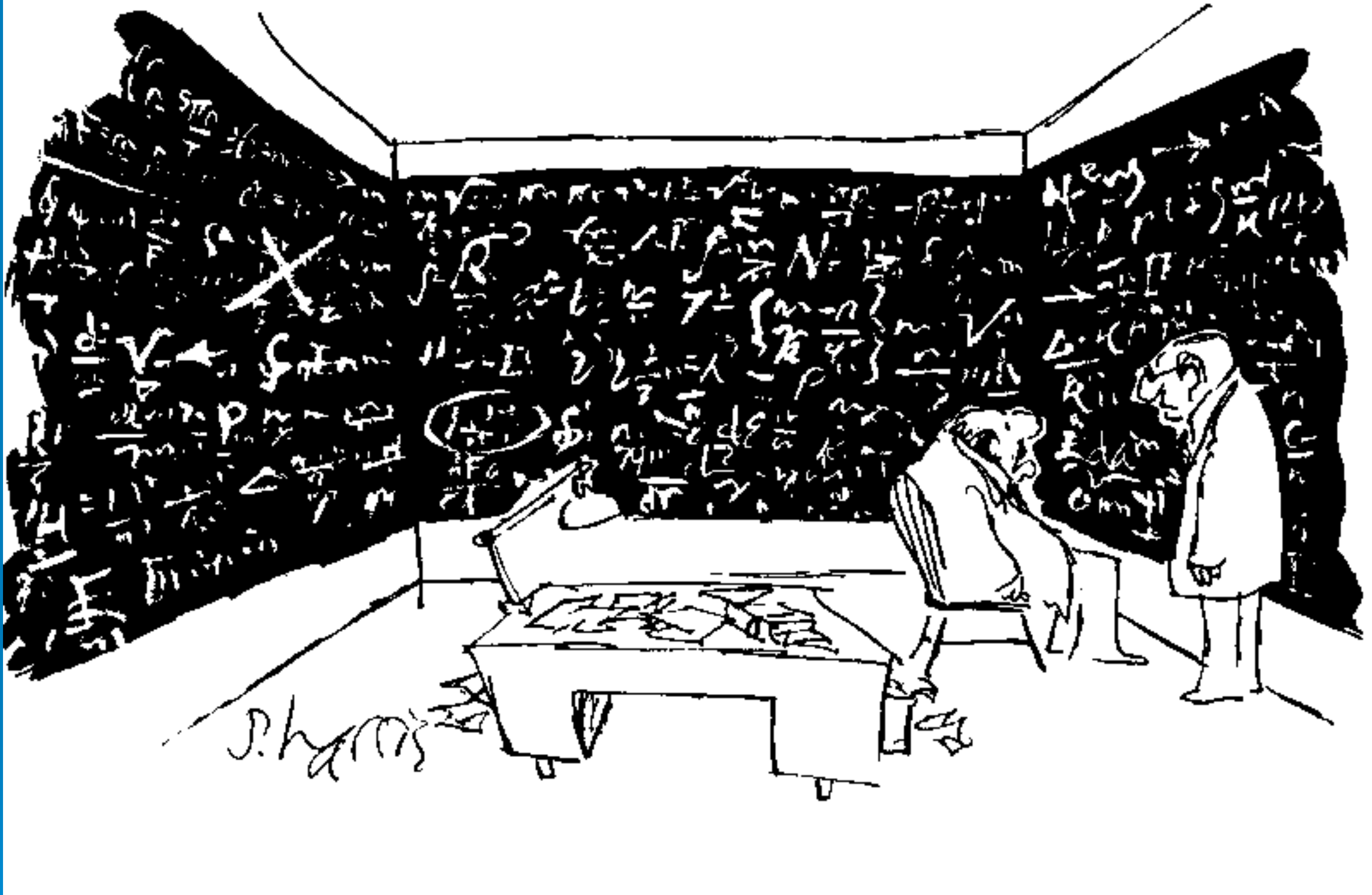
✓

✓

✓

✓

We like elegant solutions



"Whatever happened to *elegant* solutions?"