The Standard Model and Beyond

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The status of particle physics

Lecture 1

1. The Standard Model (SM) is the best theory of describing the nature of particle physics, which is in excellent agreement with almost of all current experiments
2. However, there are some theoretical problems & recent experimental results, which strongly suggest New Physics beyond the SM

Lecture 2

3. Many well-motivated New Physics models have been proposed
4. Many planned and on-going (collider) experiments may reveal New Physics in the near future

Lecture 2

Beyond the Standard Model

---- Supersymmetric Models ----

TeV scale New Physics

(1) motivated to solve the hierarchy problem

(2) suitable for WIMP Dark Matter

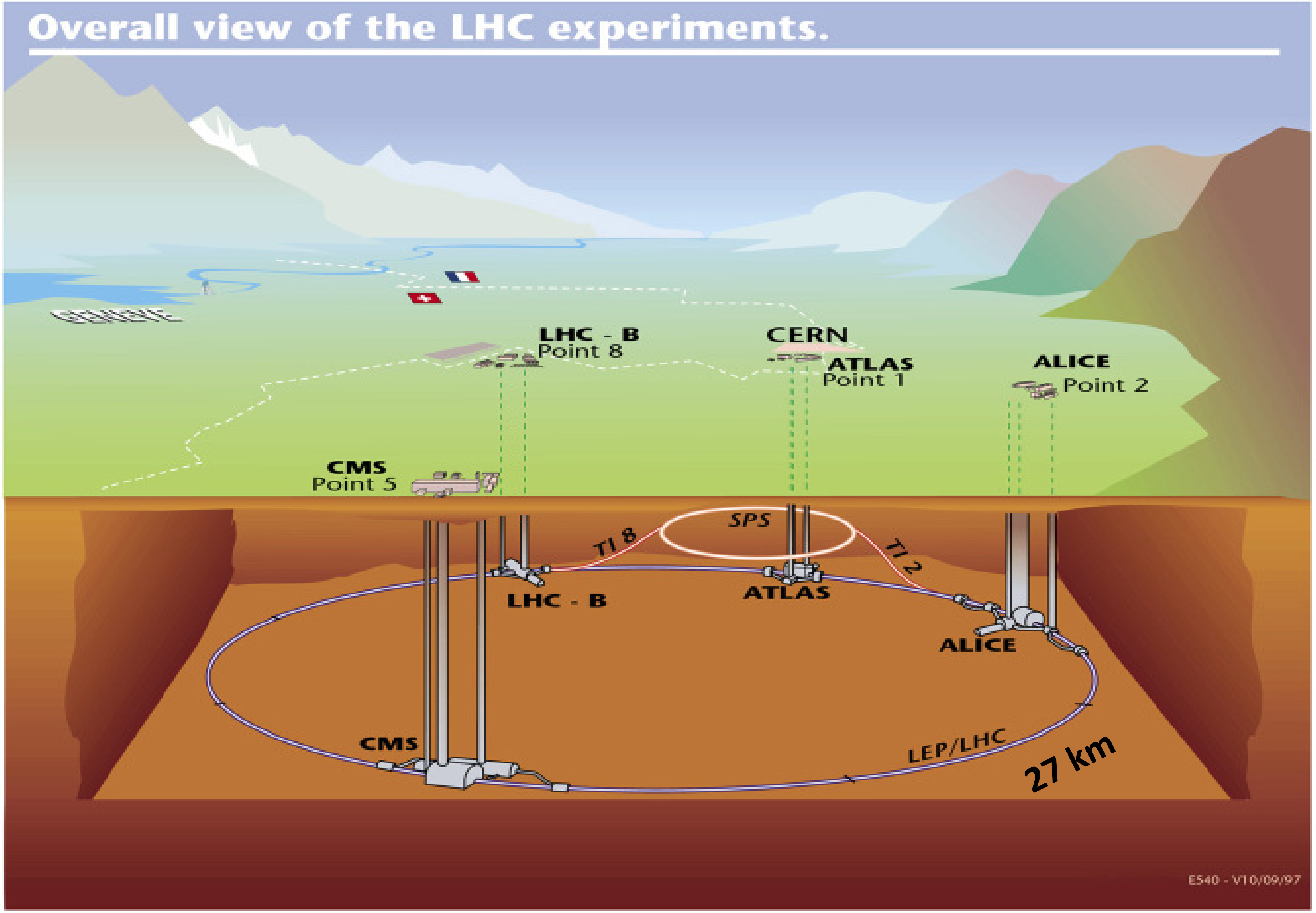
TeV scale

→ Accessible at future collider experiments!

Large Hadron Collider (LHC)

International Linear Collider (ILC)

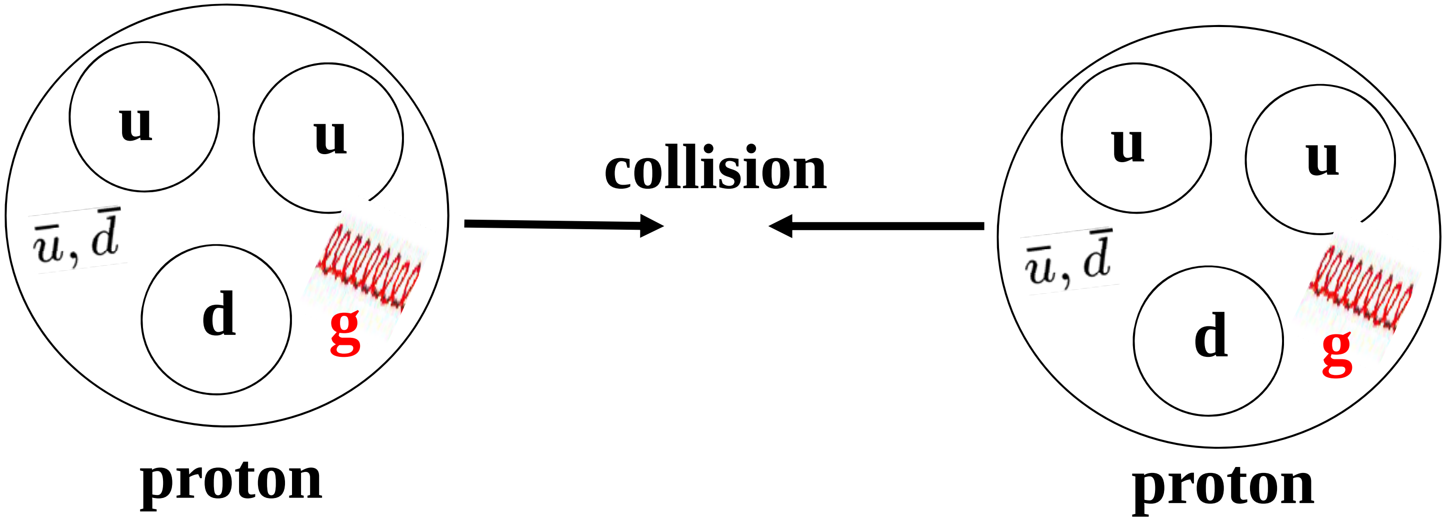
Large Hadron Collider (LHC) in operation!



LHC: hadron collider

Initial state: pp (not elementary particles)

$\sqrt{s} = 10 - 14$ TeV



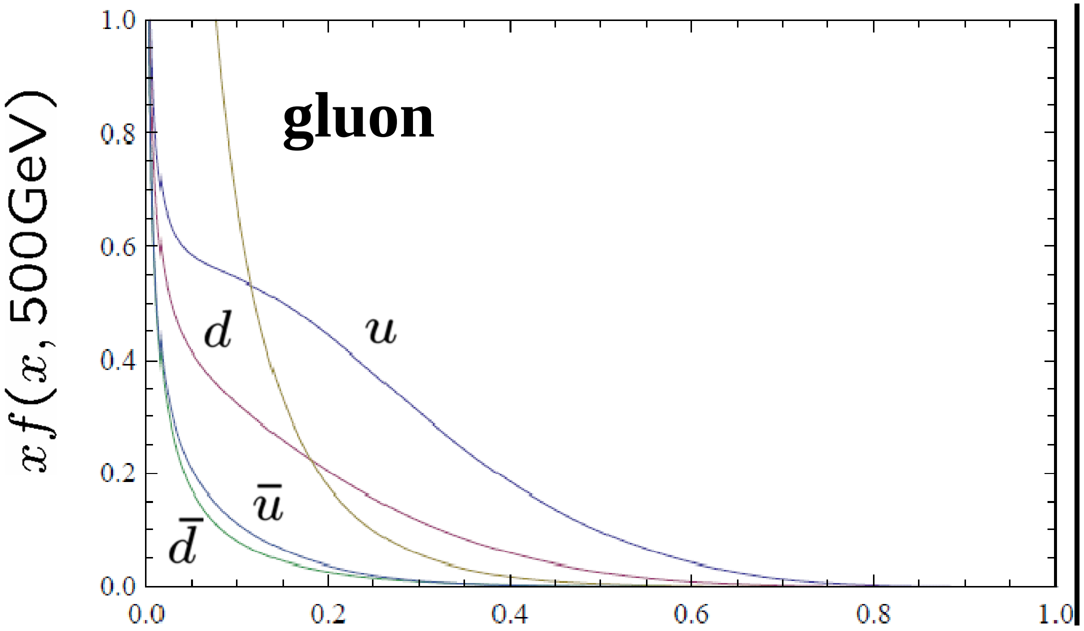
Initial states: $gg,\ gq(\bar{q}),\ q\bar{q},\ qq'$

Parton distribution function (pdf)

A **parton distribution function** is defined as the probability density for finding a particle with a certain longitudinal momentum fraction x at momentum transfer Q^2.

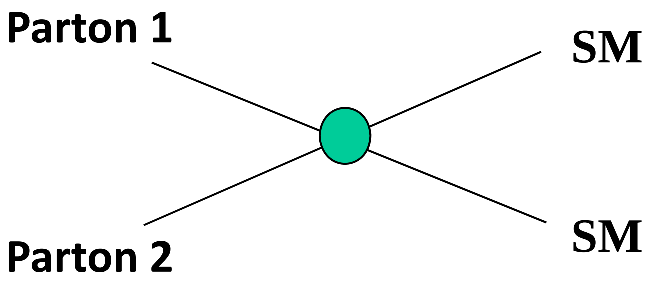
Parton: $u, d, g, \bar{u}, \bar{d}, \ldots$ **in proton**

$$\int_0^1 dx\,[f_u(x) - f_{\bar{u}}(x)] = 2, \qquad \int_0^1 dx\,[f_d(x) - f_{\bar{d}}(x)] = 1.$$



CTEQ collaborations

Fundamental process



$$\sigma(p_1, p_2, p_3, p_4)$$

$$p_{1,2} = x_{1,2}\sqrt{s}/2$$

$$\sigma_{LHC} = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{ij} f_i(x_1, Q) f_j(x_2, Q) \sigma(x_1\sqrt{s}/2, x_2\sqrt{s}/2, p_3, p_4)$$

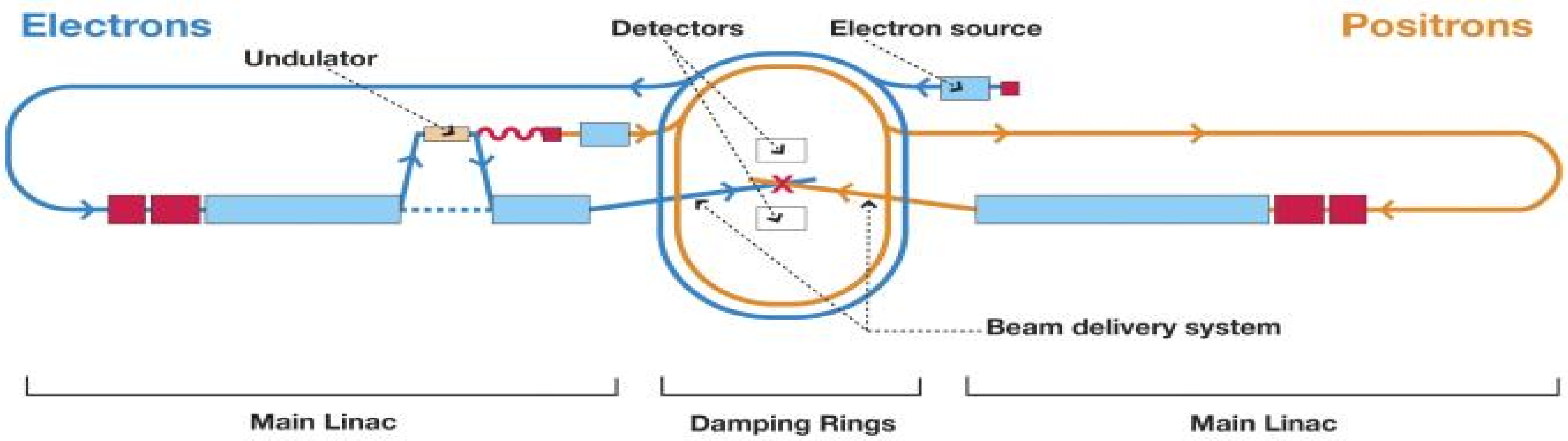
Colliding parton energy is not fixed

PDF has a peak at x << 1 → full 14 TeV cannot be used

Lots of QCD background

LHC: high energy machine
→ high New Particle discovery potential

International Linear Collider (ILC) from 20XX ?



Lepton collider

Initial states: e^+e^- elementary particle

colliding particle energy is fixed and tunable

$\sqrt{s} = 500\ \mathrm{GeV} - 1\ \mathrm{TeV}$

polarized beam option

ILC: more precise measurements

→ discriminate New Physics Models

Many TeV scale New Physics Models have been proposed

Examples :

Supersymmetric models: MSSM, GUT, SUSY breaking,

Extra-dimension models: large Xdim, Warped Xdim, Universal Xdm,
gauge-Higgs model, Higgs-less model,….

non-SUSY models in 4D: Technicolor, Little Higgs models,….

Unexpected: unparticle, hidden valley, quirk models, ….

Common feature of New Physics Models

- New Particles → ``partners'' of SM particles
- New interactions between New & SM particles

Supersymmetric models: one of promissing candidate of BSM

Supersymmetry → symmetry between bosons and fermions

Supersymmetry trans.: boson ←→ fermion

$$\phi \leftrightarrow \psi$$

$$V_\mu \leftrightarrow \lambda$$

``superpartner’’

No quadratic divergence for scalar self energy corrections

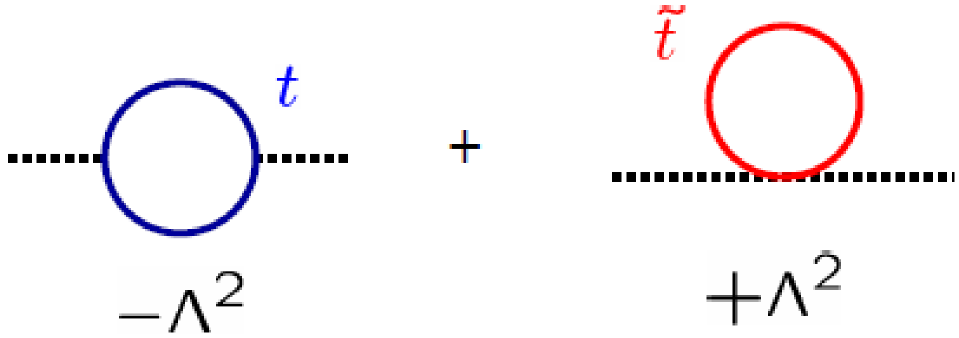
$$\begin{tikzcd}
\Delta m_f \sim m_f \log(\Lambda_{new}) \arrow[d, leftrightarrow, "\text{SUSY}"] \\
\Delta m_s^2 \sim \cancel{\Lambda_{new}^2} + m^2 \log(\Lambda_{new}) + \cdots
\end{tikzcd}$$

Scalar self energy corrections are UV insensitive!

More technically,

No quadratic divergence

$\Delta m_H^2 =$



Cancellation by New Particle (superpartner) contributions

SUSY algebra

$$\{Q_\alpha,\ \overline{Q}_{\dot\alpha}\} = -2(\sigma^\mu)_{\alpha\dot\alpha}\ P_\mu,$$

$$\{Q_\alpha,\ Q_\beta\} = \{\overline{Q}_{\dot\alpha},\ \overline{Q}_{\dot\beta}\} = 0,$$

$$[P_\mu, Q_\alpha] = [P_\mu, \overline{Q}_{\dot\alpha}] = 0,$$

$$[P_\mu, P_\nu] = 0,$$

Weyl spinor index

Left-handed: $\alpha = 1, 2$
Right-handed: $\dot\alpha = \dot1, \dot2$

Mass dim. Q = 1/2

$$Q_\alpha \phi \sim \psi_\alpha$$

Dim: ½ 1 3/2

$$\begin{aligned} \bar{Q}_{\dot\alpha} Q_\alpha \phi &\sim \bar{Q}_{\dot\alpha} \psi_\alpha \\ &\sim \sigma^\mu_{\alpha\dot\alpha} P_\mu \phi \end{aligned}$$

$$'' a Q^{2}'' \phi(x^\mu) \sim \phi(x^\mu + a^\mu)$$

Superfield formalism

4D spacetime → "superspace"

$$\{x^\mu\} \to \left\{x^\mu, \theta_\alpha, \bar{\theta}_{\dot{\alpha}}\right\}$$

fermionic coordinate (dim: -1/2)

$$\{\theta_\alpha, \theta_\beta\} = \{\bar{\theta}_{\dot{\alpha}}, \bar{\theta}_{\dot{\alpha}}\} = \{\bar{\theta}_{\dot{\alpha}}, \theta_\alpha\} = 0$$

Define SUSY trans as translation on superspace

$$e^{i(x^\mu P_\mu + \epsilon Q + \bar{\epsilon}\bar{Q})}\Phi(y^\mu, \theta, \bar{\theta}) = \Phi(x^\mu + y^\mu + i\theta\sigma\bar{\epsilon} - i\epsilon\sigma\bar{\theta}, \epsilon + \theta, \bar{\epsilon} + \bar{\theta})$$

Superfield: $\Phi(x^\mu, \theta, \bar{\theta})$

Expression as differential operators

$$\begin{cases} iQ_\alpha = \dfrac{\partial}{\partial\theta^\alpha} - i(\sigma^\mu)_{\alpha\dot\alpha}\bar\theta^{\dot\alpha}\partial_\mu \\ i\bar Q_{\dot\alpha} = -\dfrac{\partial}{\partial\bar\theta^{\dot\alpha}} + i\theta^\alpha(\sigma^\mu)_{\alpha\dot\alpha}\partial_\mu \end{cases}$$

$$\{Q_\alpha, \bar Q_{\dot\alpha}\} = -2i(\sigma^\mu)_{\alpha\dot\alpha}\,\partial_\mu$$

$$\{Q_\alpha, Q_\beta\} = \{\bar Q_{\dot\alpha}, \bar Q_{\dot\beta}\} = 0$$

General superfield: $\Phi(x^\mu, \theta, \bar\theta)$

$$\begin{aligned} \phi(x,\theta,\bar\theta) \quad &= \quad C(x) + \theta\chi(x) + \bar\theta\bar\chi'(x) + \theta\theta M(x) + \bar\theta\bar\theta N(x) \\ &+ \quad \theta\sigma^\mu\bar\theta V_\mu(x) + \theta\theta\bar\theta\bar\lambda(x) + \bar\theta\bar\theta\theta\psi(x) + \theta\theta\bar\theta\bar\theta D(x) \end{aligned}$$

Many bosons and fermions are included
This is reducible in fact.

Chiral superfield

SUSY covariant derivative

$$\begin{aligned} D_\alpha &= \frac{\partial}{\partial\theta^\alpha} + i(\sigma^\mu)_{\alpha\dot\alpha}\,\bar\theta^{\dot\alpha}\,\partial_\mu, \\ \bar D_{\dot\alpha} &= -\frac{\partial}{\partial\bar\theta^{\dot\alpha}} - i\theta^\alpha\,(\sigma^\mu)_{\alpha\dot\alpha}\,\partial_\mu. \end{aligned}$$

$$\begin{aligned} &\{Q_\alpha, D_\beta\} = \{\overline{Q}_{\dot\alpha}, D_\alpha\} \\ &= \{Q_\alpha, \overline{D}_{\dot\alpha}\} = \{\overline{Q}_{\dot\alpha}, \overline{D}_{\dot\beta}\} = 0 \end{aligned}$$

Chiral superfield is defined as $\boxed{\bar D_{\dot\alpha}\phi = 0}$

“y-basis” $y^\mu \equiv x^\mu + i\,(\theta\sigma^\mu\bar\theta)$

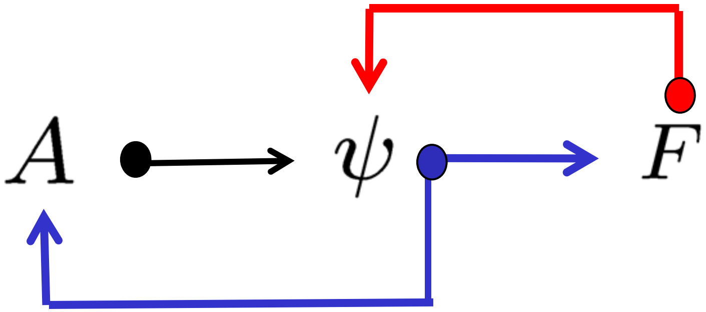
$$\boxed{\begin{aligned} \phi(y,\ \theta) &= A(y) + \sqrt{2}\,\theta\psi(y) + \theta\theta F(y) \\ &= A(x) + i\,(\theta\sigma^\mu\bar\theta)\,\partial_\mu A(x) - \frac{1}{4}\,\theta\theta\bar\theta\bar\theta\,\Box A(x) + \sqrt{2}\,\theta\psi(x) \\ &- \frac{i}{\sqrt{2}}\theta\theta\,(\partial_\mu\psi)\sigma^\mu\bar\theta + \theta\theta F(x), \end{aligned}}$$

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

dim:	**1**	**1**	**-1/2**	**3/2**	**-1**	**2**
spin:	**0**	**0**		**1/2**		**0**

Transformation law

$$\begin{aligned}\delta A &= \sqrt{2}\epsilon\psi,\\ \delta\psi &= \sqrt{2}i\sigma^{\mu}\bar{\epsilon}\partial_{\mu}A + \sqrt{2}\epsilon F,\\ \delta F &= -\sqrt{2}i\bar{\epsilon}\bar{\sigma}^{\mu}\partial_{\mu}\psi.\end{aligned}$$



The highest component transforms to total derivative of a lower component field

$$F \rightarrow \partial_{\mu}\psi$$

For general superfield

$$
\begin{aligned}
\phi(x,\theta,\bar{\theta}) &= C(x) + \theta\chi(x) + \overline{\theta\chi'}(x) + \theta\theta M(x) + \overline{\theta\theta}N(x) \\
&+ \theta\sigma^{\mu}\bar{\theta}V_{\mu}(x) + \theta\theta\overline{\theta\lambda}(x) + \overline{\theta\theta}\theta\psi(x) + \boxed{\theta\theta\overline{\theta\theta}D(x)}
\end{aligned}
$$

highest comp.

Transformation law

$$
\delta D = \frac{i}{2}(\sigma^{\mu})_{\alpha\dot{\alpha}}(\epsilon^{\alpha}\partial_{\mu}\bar{\lambda}^{\dot{\alpha}} - (\partial_{\mu}\psi^{\alpha})\bar{\epsilon}^{\dot{\alpha}}).
$$

The highest component transforms to total derivative of lower component fields

SUSY invariant action

X: general superfield **W: chiral superfield**

$$S_{SUSY} = \int d^4x \mathcal{L}_{SUSY}$$

$$\mathcal{L}_{SUSY} = \int d^4\theta \left[X + X^\dagger\right] + \left[\int d^2\theta W + \int d^2\bar{\theta} W^\dagger\right]$$

$$d^2\theta = d\theta^\alpha d\theta_\alpha$$

$$d^2\bar{\theta} = d\bar{\theta}_{\dot{\alpha}} d\bar{\theta}^{\dot{\alpha}}$$

$$d^4\theta = d^2\theta \; d^2\bar{\theta}$$

$$\int d^2\theta \; \theta\theta = \int d^2\bar{\theta} \; \bar{\theta}\bar{\theta} = 1$$

$$\int d^4\theta \; \theta\theta\bar{\theta}\bar{\theta} = 1$$

Others are zero

$$\left.\begin{aligned} \int d^4\theta X &= D_X \\ \int d^2\theta W &= F_W \end{aligned}\right\}$$

SUSY trans: $\mathcal{L}_{SUSY} \rightarrow \mathcal{L}_{SUSY} + \partial_\mu \mathcal{O}$

→ This action is SUSY invariant

Wess-Zumino model

Kahler potential: $K = \sum_i \phi_i^\dagger \phi_i$

Superpotentail: $W(\phi) = \lambda_i\phi_i + \frac{1}{2}m_{i,j}\phi_i\phi_j + \frac{1}{3}g_{i,j,k}\phi_i\phi_j\phi_k$

dim.
2
3

$$\mathcal{L}_{SUSY} = \int d^4\theta K + \left[\int d^2\theta W + \int d^2\bar\theta W^\dagger\right]$$

Canonical kinetic terms

$$\left\{\begin{array}{l} \int d^4\theta K = (\partial_\mu A_i^*)(\partial^\mu A_i) - i\bar{\psi}_i\bar{\sigma}^\mu\partial_\mu\psi_i + \boxed{F_i^* F_i} \\ \int d^2\theta W = \boxed{\frac{\partial W(A)}{\partial A_i} F_i} - \frac{1}{2}\frac{\partial^2 W(A)}{\partial A_i \partial A_j}\psi_i\,\psi_j . \end{array}\right.$$

Mass, interaction terms

***F* has no kinetic term → auxiliary field**

Scalar potential

$$V = \sum_i F_i^* F_i$$

where F_i are solutions of E.O.M.: $\boxed{F_i^* = \frac{\partial W(A)}{\partial A_i}}$

Potential energy in SUSY model is semi-positive definite

$$V = \sum_i F_i^* F_i = \sum_i \left| \frac{\partial W(A)}{\partial A_i} \right|^2 \geq 0$$

SUSY vacuum → $V_{min} = 0$

→ $\boxed{F_i^* = \frac{\partial W(A)}{\partial A_i} = 0}$

SUSY vacuum condition

(F-flat condition)

Vector superfield: $V = V^\dagger$

$$\boxed{V = -\theta\sigma^\mu\bar{\theta}V_\mu + i(\theta\theta\bar{\theta}\bar{\lambda} - \bar{\theta}\bar{\theta}\theta\lambda) + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D.}$$

in Wess-Zumino gauge

dim:	**0**	**1**	**3/2**	**3/2**	**2**
spin:	**0**	**1**	**1/2**	**1/2**	**0**

gauge boson gaugino

Field strength (chiral) superfield (U(1) gauge theory)

$$W_\alpha = -\frac{1}{4}\overline{DD}D_\alpha V.$$

$$\boxed{\begin{aligned}\mathcal{L}_{gauge-kin} &= \frac{1}{4}\int d^2\theta W^\alpha W_\alpha + h.c. \\ &= -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - i\lambda^\alpha(\sigma^\mu)_{\alpha\dot{\alpha}}\partial_\mu\bar{\lambda}^{\dot{\alpha}} + \frac{1}{2}D^2\end{aligned}}$$

SUSY QED

	U(1)
Chiral superfield: ϕ_i	Q_i

Gauge invariant mater kinetic term

$$\boxed{\begin{aligned} \mathcal{L} &= \int d^4\theta\ \phi_i^\dagger e^{2eQ_iV}\phi_i \\ &= (D_\mu A_i)^*(D^\mu A_i) - i\bar{\psi}_i\bar{\sigma}^\mu D_\mu \psi_i + |F_i|^2 \\ &- \sqrt{2}ieQ_i(A_i\bar{\lambda}\bar{\psi}_i - A_i^*\lambda\psi_i) + \boxed{eQ_iD|A_i|^2} \end{aligned}}$$

$$V = \sum_i F_i^* F_i + \frac{1}{2}D^2$$

where D is determined by E.O.M of D, $\boxed{D + eQ_i|A_i|^2}$

$$V_{min} = 0 \rightarrow \boxed{D + eQ_i|A_i|^2 = 0}$$

D-flat condition

Scalar potential of SUSY QED

$$V = \sum_i F_i^* F_i + \frac{1}{2} D^2 = \sum_i \left| \frac{\partial W(A)}{\partial A_i} \right|^2 + \frac{e^2}{2} (\sum_i Q_i |A_i|^2)^2$$

F-term potential **D-term potential**

If W doesn't include triple terms of As, <u>quartic scalar coupling is nothing but the gauge coupling</u>

New SUSY interactions

$$- \quad \sqrt{2} i e Q_i (A_i \bar{\lambda} \bar{\psi}_i - A_i^* \lambda \psi_i)$$

← SUSY generalization of gauge interaction

Construction of non-Abelian SUSY gauge theory is analogous to SUSY QED

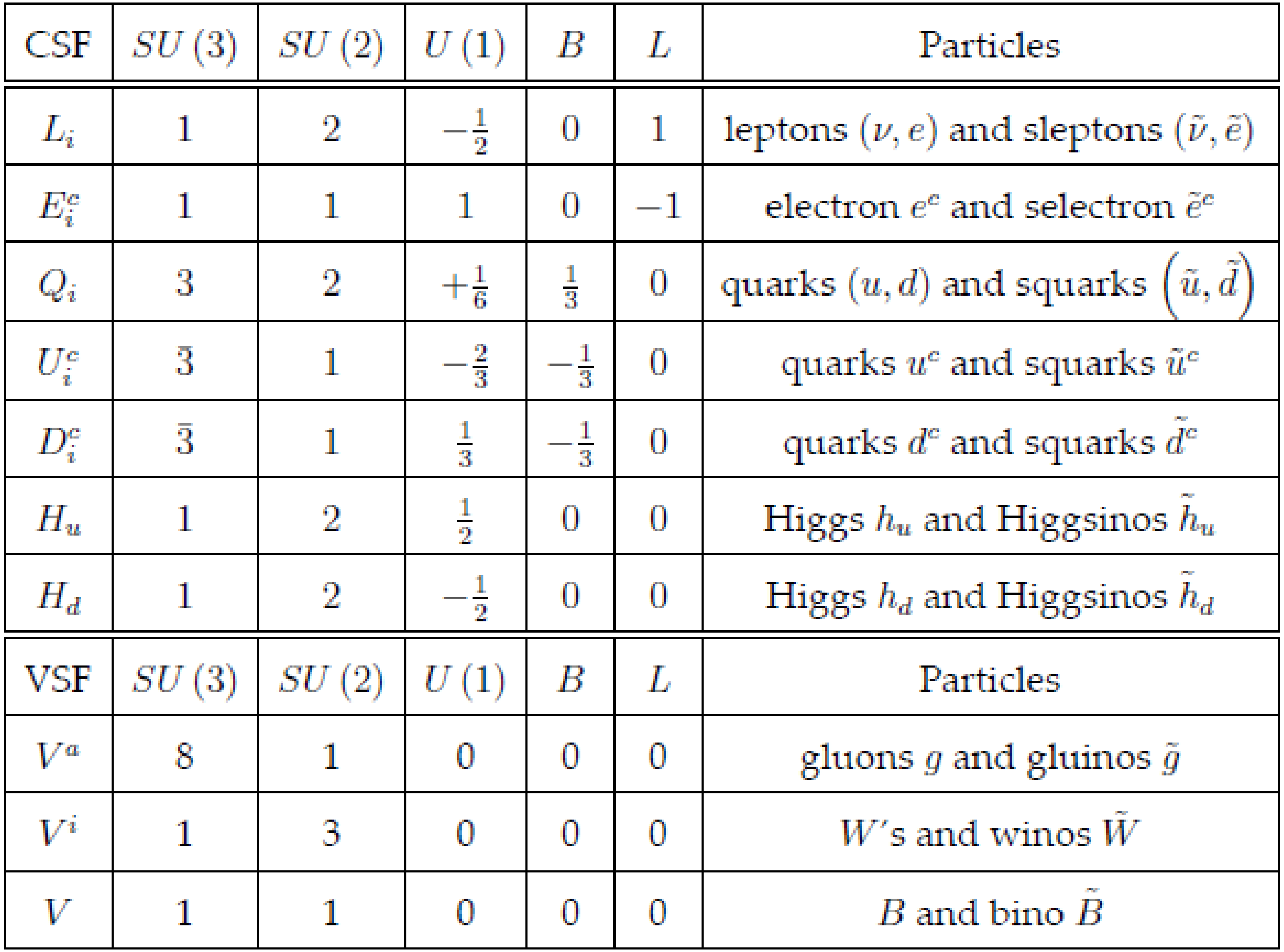
Matter multiplet: chiral superfiled of a representation

$A \& \psi$ **: sfermion & fermion**

Gauge multiplet: vector superfield

$V_\mu \& \lambda$ **: gauge boson & gaugino**

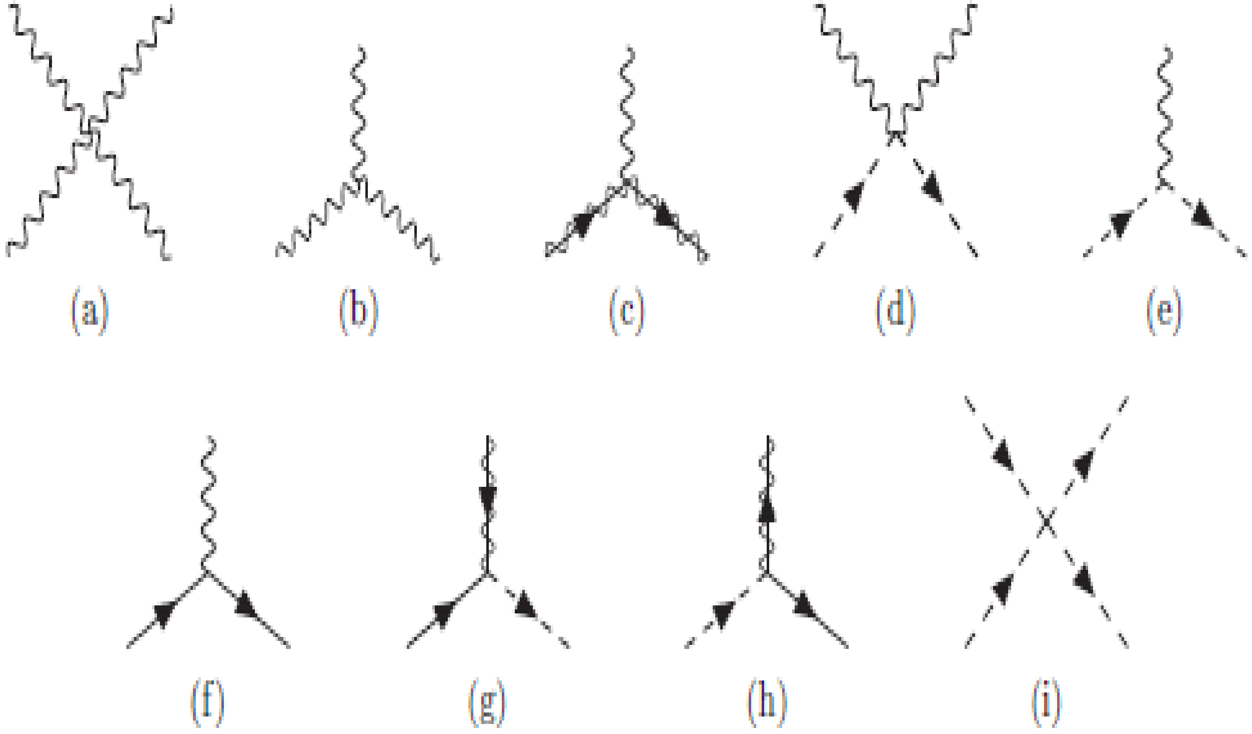
Minimal Supersymmetric Standard Model (MSSM)



CSF	$SU(3)$	$SU(2)$	$U(1)$	B	L	Particles
L_i	1	2	$-\frac{1}{2}$	0	1	leptons (ν, e) and sleptons $(\tilde{\nu}, \tilde{e})$
E_i^c	1	1	1	0	-1	electron e^c and selectron $\tilde{e}^c$
Q_i	3	2	$+\frac{1}{6}$	$\frac{1}{3}$	0	quarks (u, d) and squarks $\left(\tilde{u}, \tilde{d}\right)$
U_i^c	$\bar{3}$	1	$-\frac{2}{3}$	$-\frac{1}{3}$	0	quarks u^c and squarks $\tilde{u}^c$
D_i^c	$\bar{3}$	1	$\frac{1}{3}$	$-\frac{1}{3}$	0	quarks d^c and squarks $\tilde{d}^c$
H_u	1	2	$\frac{1}{2}$	0	0	Higgs h_u and Higgsinos $\tilde{h}_u$
H_d	1	2	$-\frac{1}{2}$	0	0	Higgs h_d and Higgsinos $\tilde{h}_d$
VSF	$SU(3)$	$SU(2)$	$U(1)$	B	L	Particles
V^a	8	1	0	0	0	gluons g and gluinos $\tilde{g}$
V^i	1	3	0	0	0	W's and winos $\tilde{W}$
V	1	1	0	0	0	B and bino $\tilde{B}$

Extended interactions

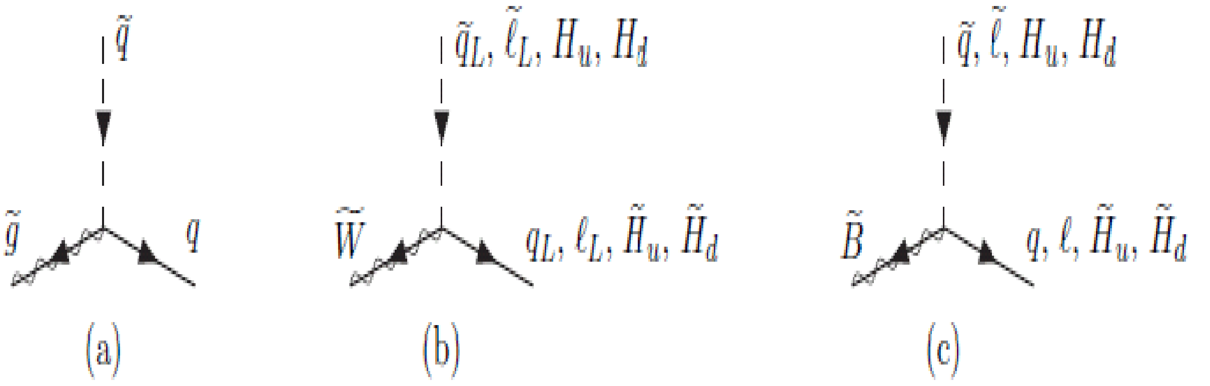
SUSY gauge int.:



SM-SM-SM

→ **SM-SP-SP**

Example:



General gauge invariant MSSM superpotential

$$\mathcal{W} = Y_u^{ij} Q^i H_u \bar{U}^j + Y_d^{ij} Q^i H_d \bar{D}^j + Y_e^{ij} L^i H_d \bar{E}^j + \mu H_d H_u + \mathcal{W}_{\not{R}_p}$$

Yukawa couplings **mu-term**

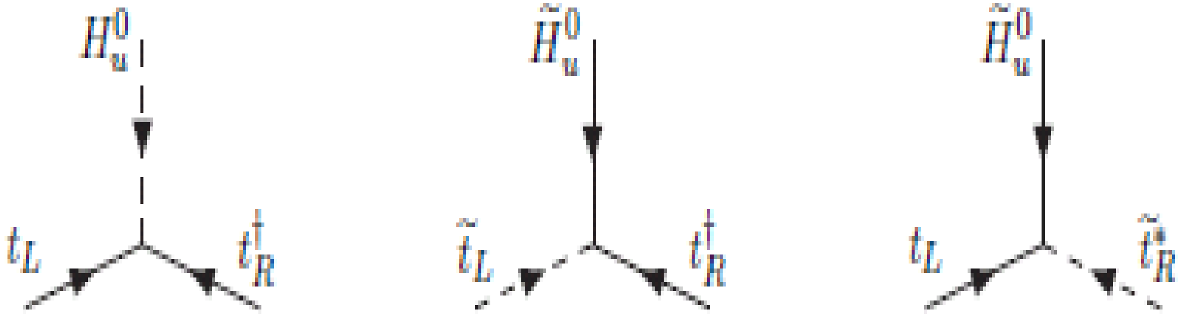
B/L number violating terms

$$\mathcal{W}_{\not{R}_p} = a_1^{ijk} Q^i L^j \bar{D}^k + a_2^{ijk} L^i L^j \bar{E}^k + a_3^i L^i H_u + a_4^{ijk} \bar{D}^i \bar{D}^j \bar{U}^k$$

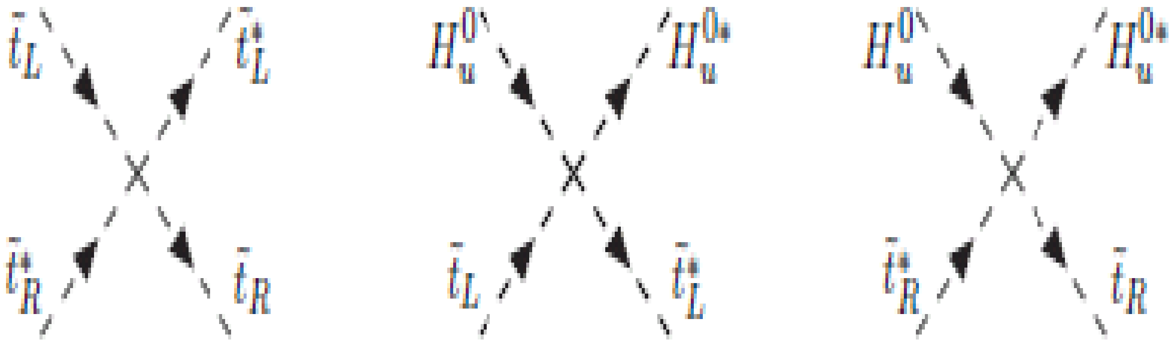
SUSY (top) Yukawa int.

SM-SM-SM

→ SM-SP-SP



(a) (b) (c)

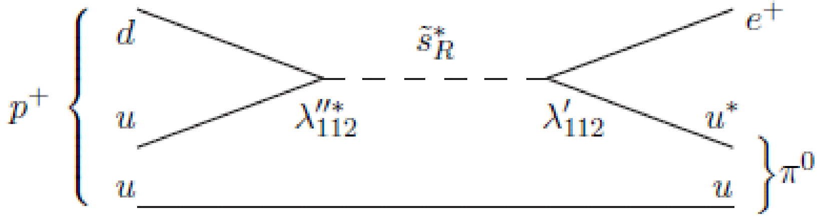


(a) (b) (c)

B/L number violating terms → dangerous in phenomenology

$$\mathcal{W}_{R\!\!\!/_p} = a_1^{ijk} Q^i L^j \bar{D}^k + a_2^{ijk} L^i L^j \bar{E}^k + a_3^i L^i H_u + a_4^{ijk} \bar{D}^i \bar{D}^j \bar{U}^k$$

Rapid proton decay



Introduction of ``R-parity'' → forbids $\mathcal{W}_{R\!\!\!/_p}$

Under R-parity

Even	Odd
SM fields	SUSY partners

Require L is R-parity even

→ interactions between SM and SM partners

$$\mathcal{L}_{int} = (SM)^m (S\tilde{M})^{2n}$$

→ Lightest Superpartner is stable → if it is neutral, DM candidate

Minimal Supersymmetric Standard Model (MSSM)

SUSY version of SM

		↔		
quark, lepton	(1/2)		squark, slepton	(0)
gauge boson	(1)		gaugino	(1/2)
Higgs	(0)		Higgsino	(1/2)
SM particles			**Superpartners**	

But, SUSY should be broken, otherwise $m_{\tilde{e}} = m_e$

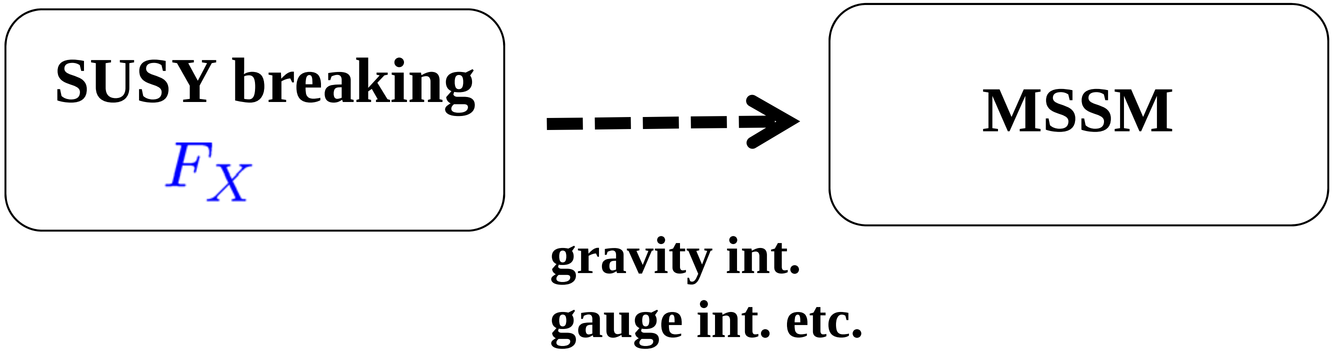
→ Superpartners have mass 100 GeV- 1 TeV

$$\boxed{\Lambda_{\mathrm{New}} \to \tilde{m}}$$

Introducing SUSY breaking term in MSSM

Hidden sector scenario

SUSY is broken in the hidden sector (singlet) by <F>
<F> is mediated to MSSM sector by some interactions



SUSY breaking
F_X

MSSM

gravity int.
gauge int. etc.

Effective interactions between hidden & MSSM

Spurion technique: $X = \theta^2 F_X$

Effective interaction between X & MSSM fields

$$\int d^4\theta \frac{X^\dagger X}{M^2} K \qquad \int d^4\theta \frac{X}{M} K + h.c. \qquad \int d^2\theta \frac{X}{M} W \qquad \int d^2\theta \frac{X}{M} W^\alpha W_\alpha$$

Ex) $\int d^4\theta c \frac{X^\dagger X}{M^2} Q^\dagger Q \to c \frac{|F_X|^2}{M^2} \tilde{Q}^\dagger \tilde{Q}$ **sfermion mass**

$\int d^2\theta c \frac{X}{M} Q H_u U^c \to c \frac{F_X}{M} \tilde{Q} H_u \tilde{U}^c$ **A-term**

$\int d^2\theta c \frac{X}{M} W^\alpha W_\alpha \to c \frac{F_X}{M} \lambda^\alpha \lambda_\alpha$ **gaugino mass**

SUSY breaking model determines M, F_X, c

gravity mediation: M= Mp

gauge mediation: Messenger mass, c given bygauge coupling

MSSM Lagrangian with soft SUSY breaking terms

$$\mathcal{L}_{total} = \mathcal{L}^{SUSY}_{MSSM} + \mathcal{L}_{soft}$$

$$-\mathcal{L}_{soft} = \sum_{i=Q_i,\bar{U}_i,\ldots} m_i^2|\phi_i|^2 + \left(\sum_{i=1,2,3} M_i\lambda_i\lambda_i - B\mu H_1 H_2 + \right.$$

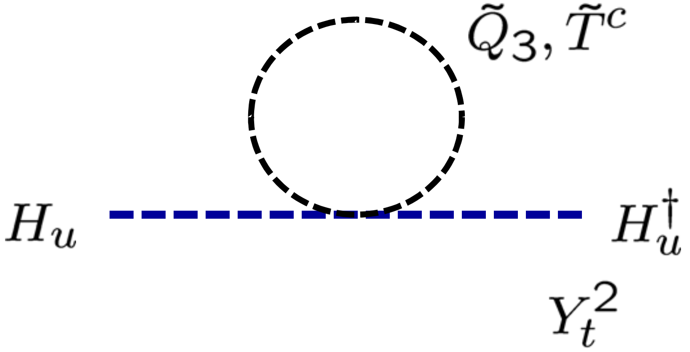
$$\left. + \sum_{ij} A_u^{ij}\lambda_u^{ij}Q^i H_2\bar{U}^j + \sum_{ij} A_d^{ij}\lambda_d^{ij}Q^i H_1\bar{D}^j + \sum_{ij} A_e^{ij}\lambda_e^{ij}L^i H_1\bar{E}^j + h.c.\right)$$

Interesting features of MSSM with soft SUSY breakings

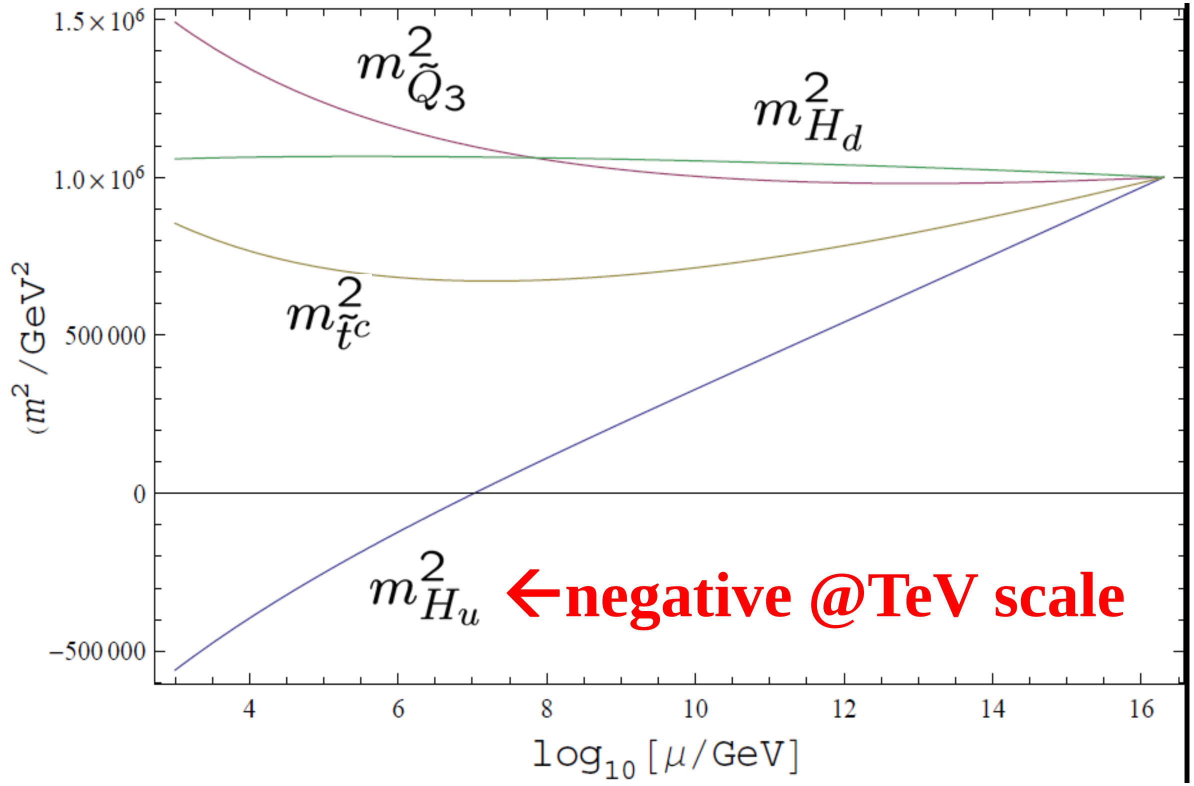
Radiative EW symmetry breaking

mass^2 correction to Higgs doublets is negative!

$$\Delta m_h^2 \sim -\frac{3Y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log\left(\frac{M_{UV}}{E_{EW}}\right) < 0$$



RGE running masses



←negative @TeV scale

$M_{1/2} = 500$ GeV

$m_0 = 1000$ GeV

$A_0 = 0$ GeV

$\tan\beta = 10$

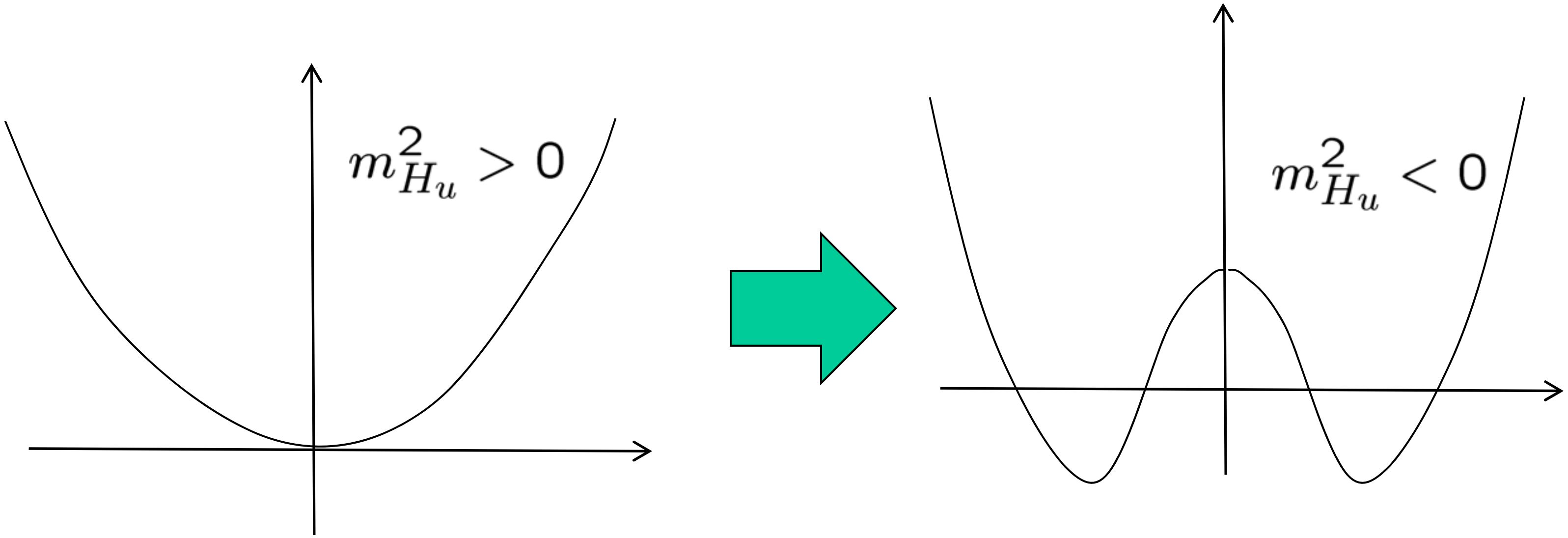
Higgs mass^2 becomes negative → EW symmetry breaking

In MSSM, EW symmetry breaking is triggered by interplay between the large top Yukawa & soft mass

Higgs potential is changing its shape according to energy

High Energy

Low Energy



Symmetric

EW symmetry breaking

$$m_{H_u}^2 \sim -m_0^2$$

Higgs VEV scale is O(sfermion mass)
→ EW scale

Higgs mass prediction

Higgs self coupling = gauge coupling by SUSY

→ **Higgs boson mass prediction**

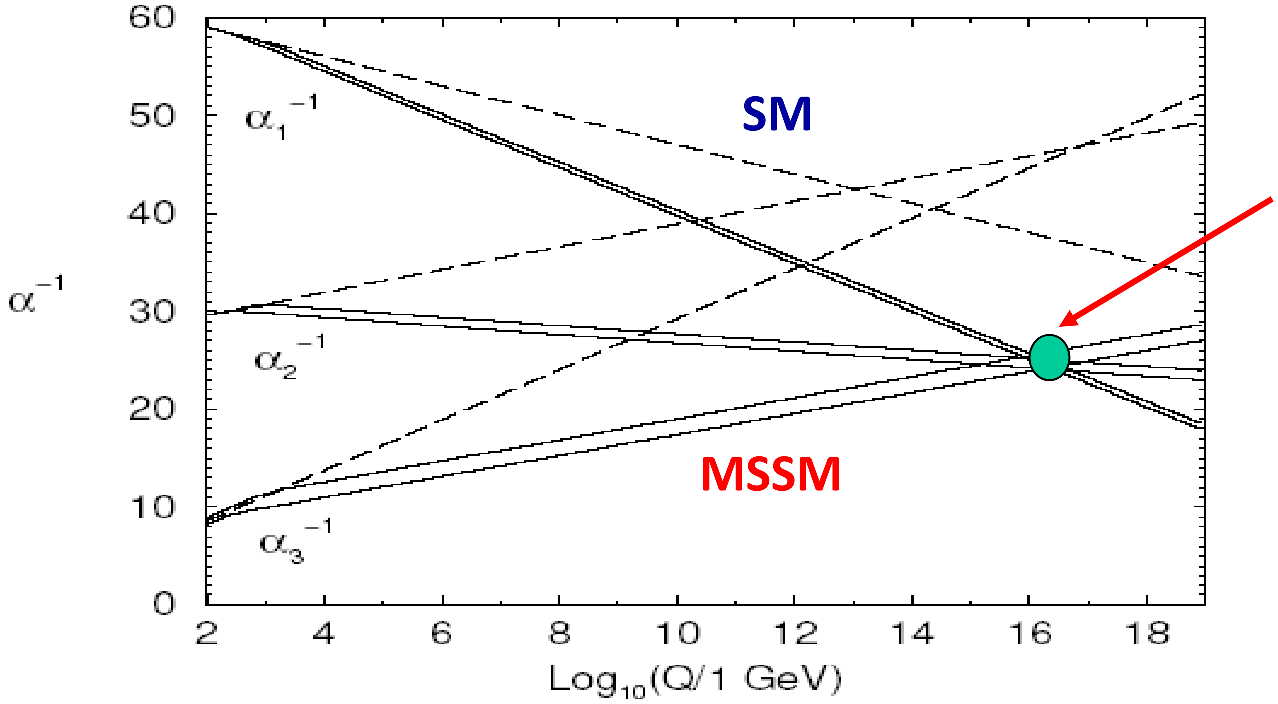
SM: $m_h^2 = \lambda v^2$

MSSM: **gauge coupling via D-term potential**

$$m_h^2 \simeq m_Z^2 + \frac{3Y_t^4 v^2}{4\pi^2}\log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right)$$

tree level **stop loop correction**

Grand Unified Theories



Gauge
Coupling
Unification

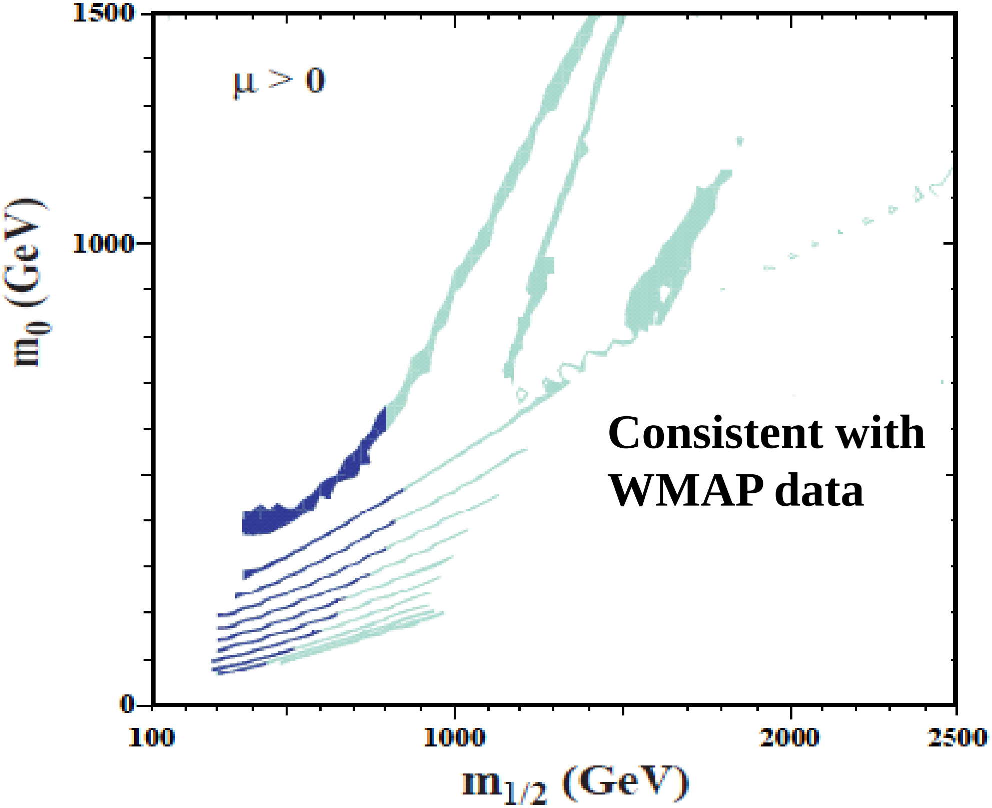
Present measurement of gauge couplings + SUSY

→ successful gauge coupling unification

→ Evidence of GUTs?

Dark Matter → LSP Neutralino

$$0.094 \leq \Omega_{DM} h^2 \leq 0.129$$



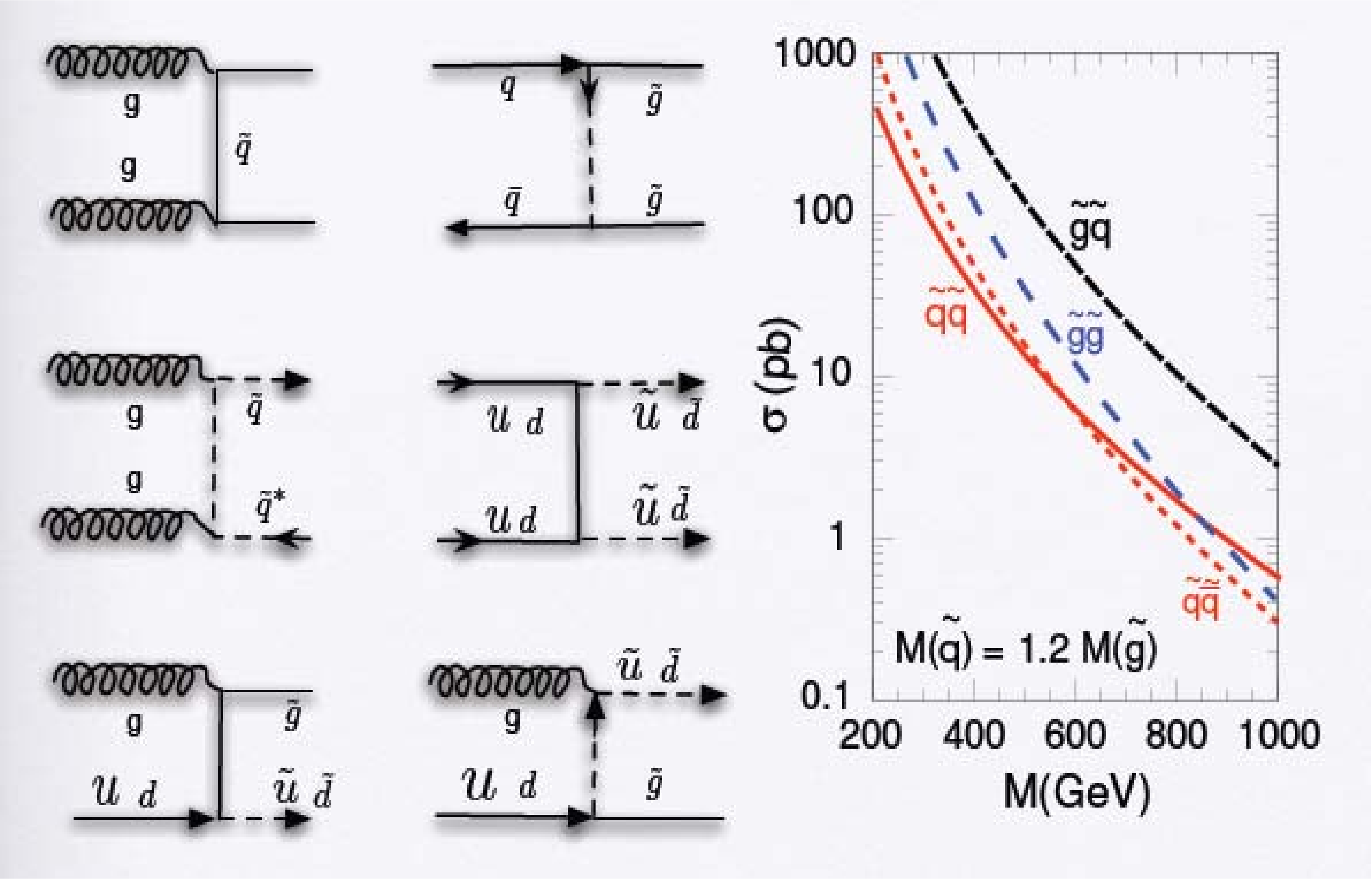
Consistent with WMAP data

Figure 2: *The strips display the regions of the* $(m_{1/2}, m_0)$ *plane that are compatible with* $0.094 < \Omega_\chi h^2 < 0.129$ *and the laboratory constraints for* $\mu > 0$ *and* $\tan\beta = 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55$. *The parts of the strips compatible with* $g_\mu - 2$ *at the 2-*σ *level have darker shading.*

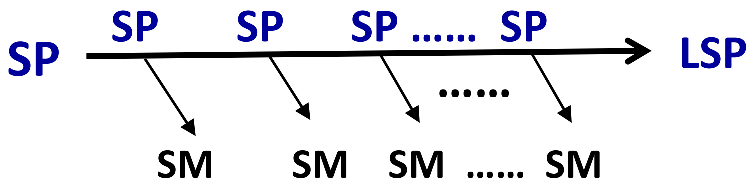
Discover SUSY at LHC

Pair production of new particles:

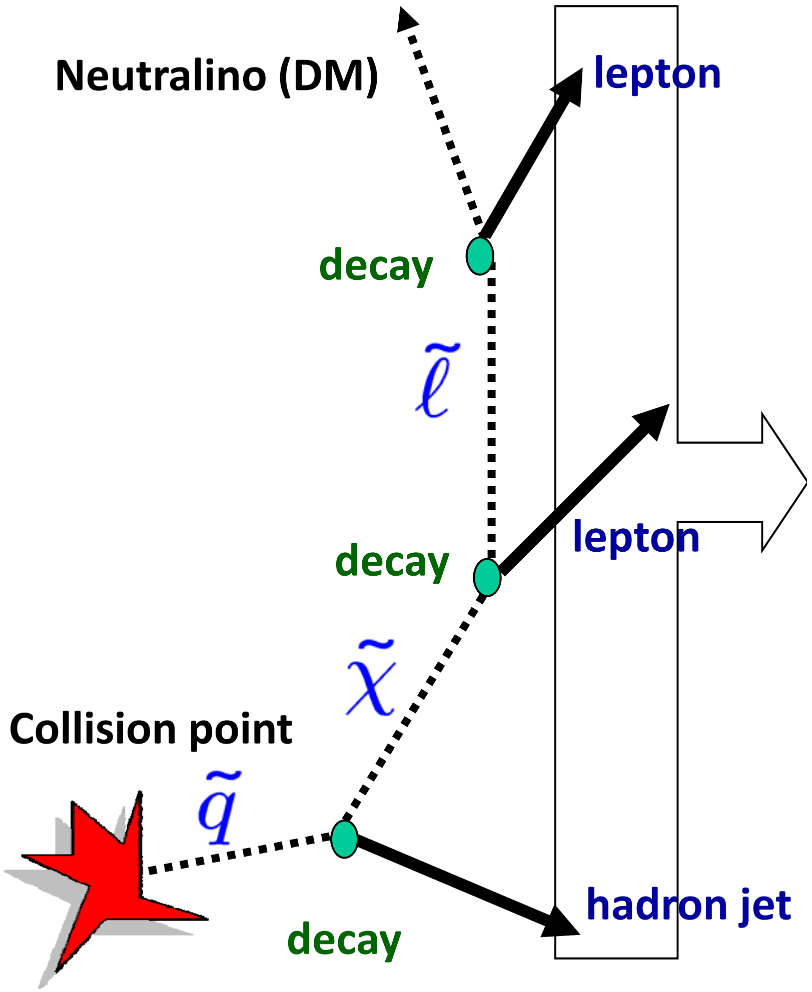
even odd odd
SM +SM → SP SP



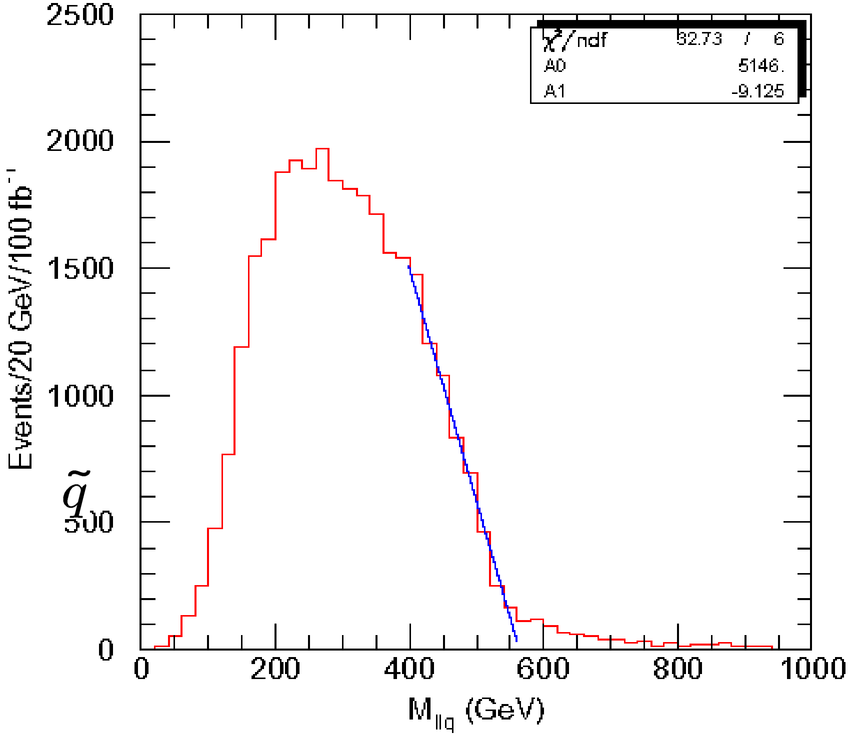
Discovery of superpartner & mass measurements



SP
SP SP SP …… SP
LSP
……
SM SM SM …… SM



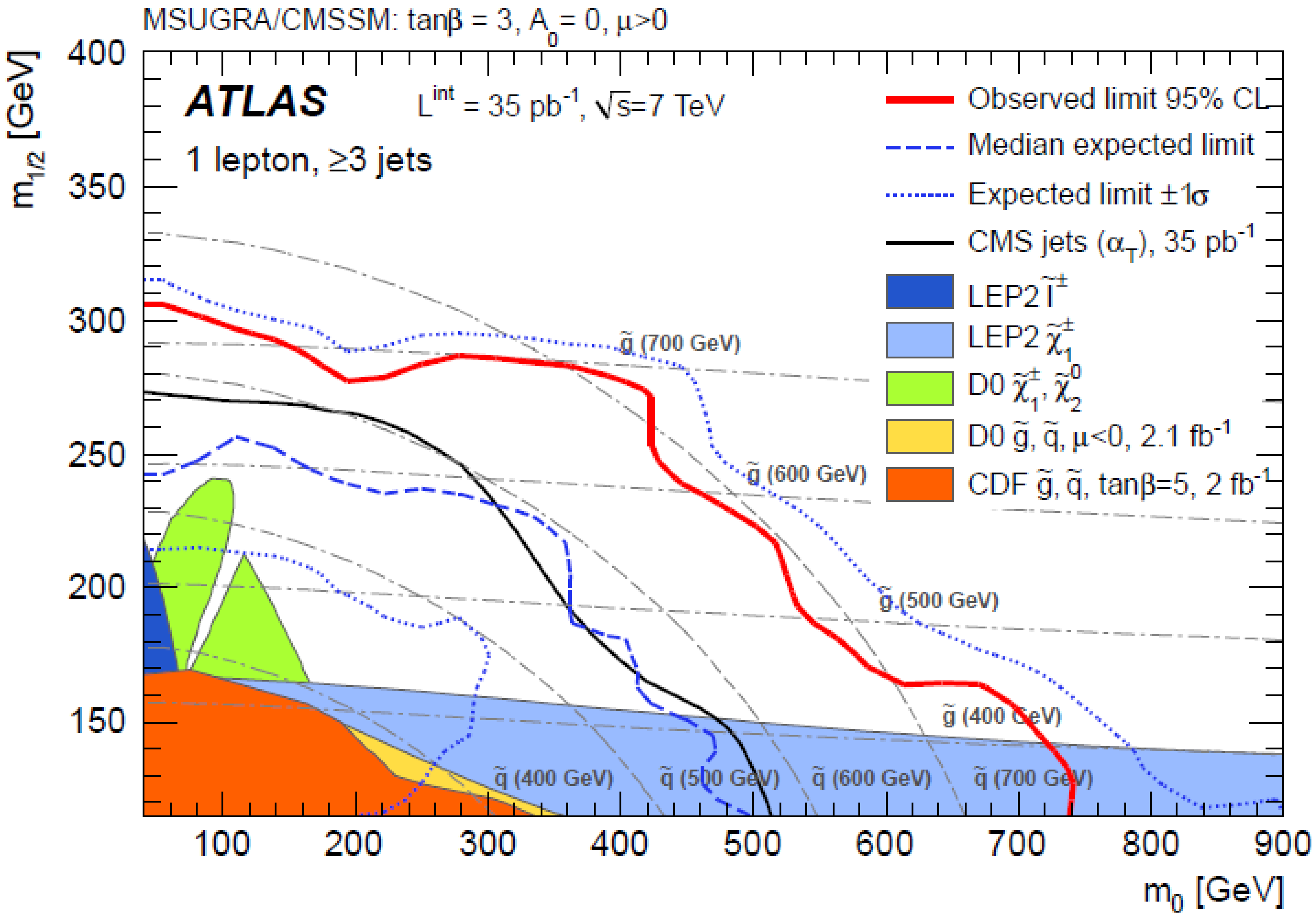
Neutralino (DM)
lepton
decay
$\tilde{\ell}$
lepton
decay
$\tilde{\chi}$
Collision point
$\tilde{q}$
hadron jet
decay



Jll invariant mass distribution

$$M_{\ell\ell q}^{\max} = \left[\frac{\left(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2\right)\left(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2\right)}{M_{\tilde{\chi}_2^0}^2}\right]^{1/2} = 552.4\,\mathrm{GeV}\,.$$

SUSY search at LHC (CMSSM parametrization)



SUSY: One of the most promissing candidates for New Phys.

MSSM

1) **SUSY breaking around 100GeV- 1TeV → No fine-tuning**
2) **Origin of EW symmetry breaking**
3) **Candidate of Dark Matter (LSP Neutralino)**
4) **Higgs boson mass prediction**
5) **GUT scenario**

LHC is testing SUSY now!

Discovery of SUSY

→ clue to understand origin of SUSY breaking
SUSY breaking mediation

New concept of space-time???

As energy goes up…..

Time + space → space-time → superspace???

Newton's theory

Theory of relativity

SUSY theory
↓
local SUSY theory
= supergravity