Biased Review of Supersymmetry Phenomenology

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Workshop on EWSB on Mar. 12th, YITP

Motivations for New Physics

Is the Standard Model consistent with experiments?

Yes, it explains results of collider experiments consistently.

How about dark matter?

Just add some new stable particles.

How about dark matter abundance?

Just add some weak interaction between the new particles and the SM particles.

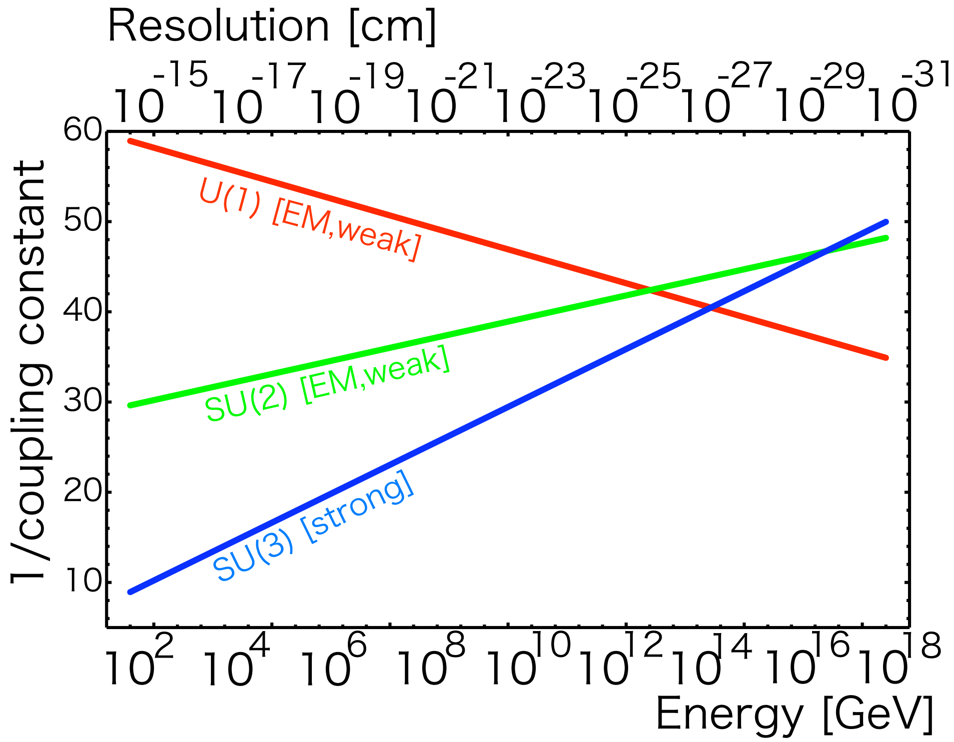
How about neutrino masses?

Why not introducing right handed neutrinos with tiny Yukawa couplings?
(Majorana neutrino mass requires "new physics", though.)

Do I really think this pessimistic picture is the most likely possibility?

Introduction

The important hint...



The observed three gauge coupling constants suggest perturbative grand unification at the very high energy scale.

↕

If perturbative unification at the very high energy, we are afraid of "hierarchy problem".

$$m_H^2 = m_{\rm bare}^2 + O(M_{\rm unif}^2/16\pi^2) = O(m_Z^2) \ll O(M_{\rm unif}^2)$$

We need symmetries or dynamics which suppress

$$\mathcal{L}_{\rm mass} = m_H^2 |H|^2$$

[Note : Hierarchy problem itself exists even at the lower scale...]

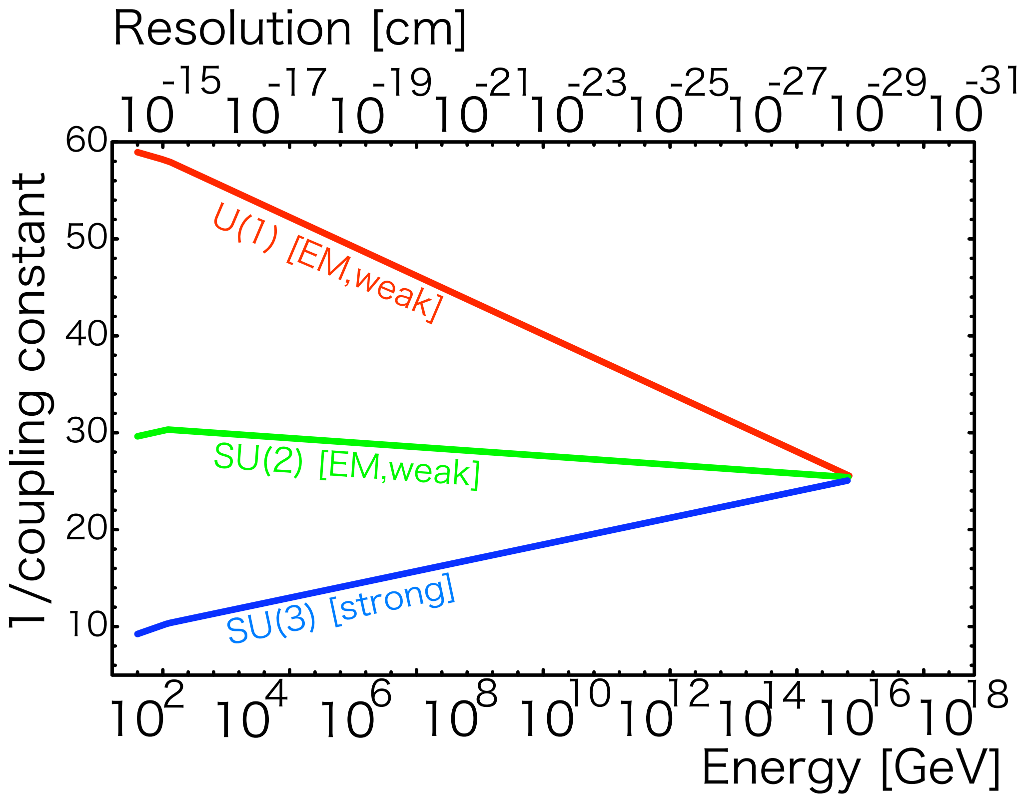
Introduction

Can we have perturbative models of the extension of the Standard Model up to the unification scale?

Introduction

Low energy supersymmetry does the very good job in this sense.

1. It tames the radiative corrections to the mass term.
2. It makes the degree of unification much better than the Standard Model.



Supersymmetry is the most motivated theory when we take the perturbative unified theory seriously.

Introduction

Are the SUSY models better than Glashow model?

It includes the Standard Model.

It allows the model to be perturbative up to the unification scale. [No other models]

Validity? We can construct consistent and calculable models!

Predictive? Perturbative SUSY models predict the upper bound on the Higgs mass.

→ Higgs search will exclude most of the parameter space if we do not see any hints on higgs by the end of 2012!

Quick review of supersymmetric theory

The Language of SUSY

Chiral Superfield : $\Phi(x^\mu, \theta_\alpha, \bar\theta_{\dot\alpha}) = \phi(y^\mu) + \sqrt{2}\theta\psi(y^\mu) + \theta^2 F(y^\mu)$

$(y^\mu = x^\mu - i\theta\sigma^\mu\bar\theta)$

(cf. quark supermultiplet : ψ~q (quark), Φ~$\tilde{q}$(squark))

Gauge Superfield : $V = \theta\sigma^\mu\bar\theta A_\mu + i\theta^2\bar\theta\bar\lambda - i\bar\theta^2\theta\lambda + \frac{1}{2}\theta^2\bar\theta^2 D$

(in Wess-Zumino gauge)

(cf. λ gaugino)

SUSY invariants:

F-components of chiral multiplets

[cf. (chiral)x(chiral)=(chiral)]

D-components of general multiplets

[cf. $(\text{chiral})^\dagger$x(chiral)=(general)]

Quick review of supersymmetric theory

Matter kinetic terms

$$\begin{aligned}\mathcal{L}_{kin} &= \int d\theta^2 d\bar{\theta}^2 K(\Phi^\dagger, e^{2gV}\Phi)\\ &= (\mathcal{D}_\mu\phi_i)^\dagger(\mathcal{D}^\mu\phi_i) + \psi^\dagger i\sigma\mathcal{D}_\mu\psi_i + \underline{F_i^\dagger F_i} - \phi_i^* D\phi_i\end{aligned}$$

Gauge kinetic terms

$$\begin{aligned}\mathcal{L}_{\rm kin} &= \int d\theta^2 \frac{1}{2g^2}\mathcal{W}^a\mathcal{W}_a + h.c.\\ &= -\frac{1}{4g^2}F_{\mu\nu}F^{\mu\nu} + \frac{1}{g^2}\lambda^\dagger i\sigma^\mu\mathcal{D}_\mu\lambda + \underline{\frac{1}{2g^2}D^2}\end{aligned}$$

$$\left(W_\alpha = -\frac{1}{8}\bar{D}^2 e^{2V} D_{\dot{\alpha}} e^{-2V}\right)$$

F, D : auxiliary fields

Order parameters of SUSY

Quick review of supersymmetric theory

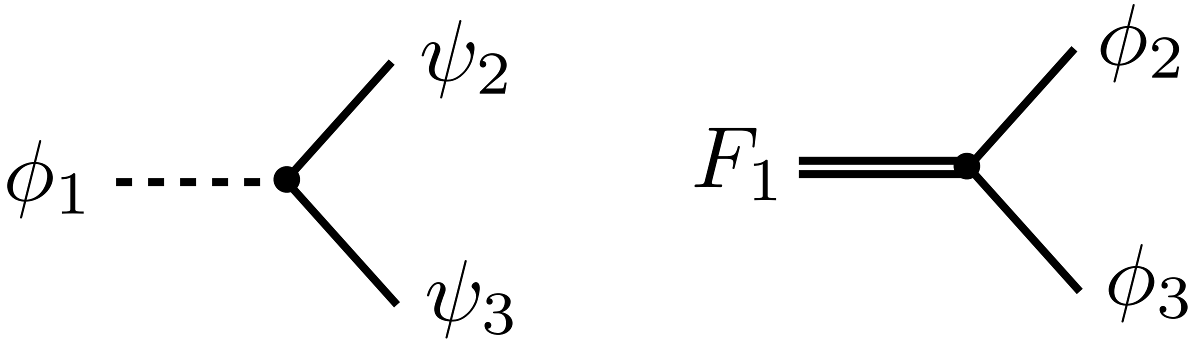
Matter interactions

$$\mathcal{L}_{int} = \int d\theta^2 W(\Phi_i) + h.c.$$
$$= -\frac{1}{2}\frac{\partial^2 W(\phi)}{\partial\phi_i\partial\phi_j}\psi_i\psi_j + \frac{\partial W(\phi)}{\partial\phi_i}F_i + h.c.$$

ex) $W = y\phi_1\phi_2\phi_3$

$\mathcal{L}_{int} = y\phi_1\psi_2\psi_3 + y\phi_2\psi_1\psi_3 + y\phi_3\psi_2\psi_1$ [Yukawa-interaction]

$+yF_1\phi_2\phi_3 + yF_2\phi_1\phi_3 + yF_3\phi_1\phi_2$ [scalar interactions]



Quick review of supersymmetric theory

Scalar potential (after integrate the auxiliary fields out)

$$V = \sum_i |F_i|^2 + \sum_{a=1,2,3} \frac{1}{2g_a^2} D_a^2$$

$$= \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 + \sum_{a=1,2,3} \underline{\frac{g_a^2}{2} \left(\sum_i \phi_i^* t^a \phi_i \right)^2}$$

$$\left(F_i^* = -\partial W / \partial \phi_i, \quad D_a = \sum_i \phi_i^* t_a \phi_a \right)$$

The quartic scalar interactions of Higgs play very important role in electroweak symmetry breaking.

Supersymmetric Standard Model

Chiral Matter Multiplets

	$SU(3)$	$SU(2)$	$U(1)$
Q_L	3	2	1/6
$\overline{U}_R$	3	1	-2/3
$\overline{D}_R$	3	1	1/3
L_L	1	2	-1/2
$\overline{E}_R$	1	1	1
H_u	1	2	1/2
H_d	1	2	-1/2

x3-generations

Why 2-Higgs doublets?

U(1)-SU(2) anomaly cancelation

Holomorphic realization of Yukawa interactions

$$W = y_u H_u Q_L \bar{U}_R + y_d H_d Q \bar{D}_R + y_e H_d L_L \bar{E}_R$$

All the Yukawa interactions in the SM are extended in a supersymmetric way.

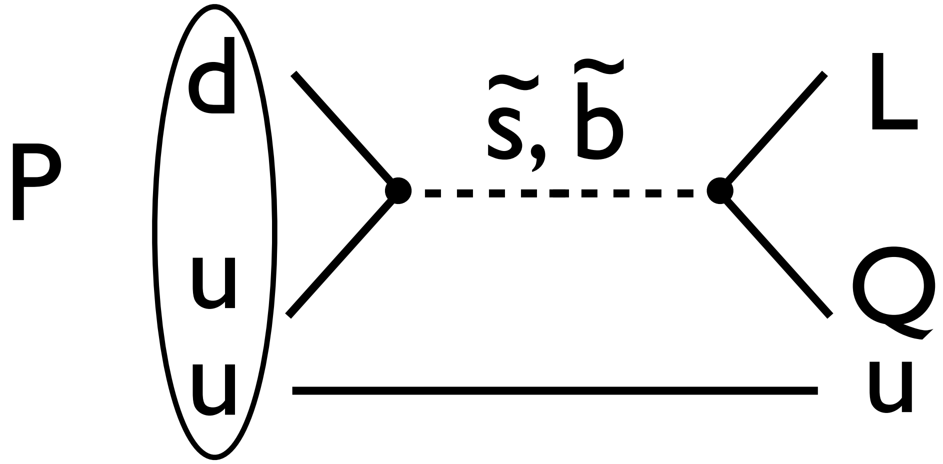
Supersymmetric Standard Model

R-parity

ΔB = 1

$$W_{RPV} = \alpha Q_L L_L \bar{D}_R + \beta L_L L_L \bar{E}_R + \delta \bar{D}_R \bar{D}_R \bar{U}_R + \mu' L_L H_u$$

ΔL = 1



Too fast proton decay...

p→ eπ, νπ, eK,νK,...

These operators can be suppressed by imposing R-parity
(~ a discrete subgroup of L and B symmetry)

$$R_p = (-)^{3(B-L)+F}$$

Rp[SM particles] = +1

Rp[Non-SM particles] = -1

Supersymmetric Standard Model

LSP : Lightest supersymmetric particle (Rp= -1)

LSP is stable in R-parity preserving MSSM.
It provides the candidate of dark matter.

ex) The neutral LSP candidates

- The lightest neutralino (Zino, Bino, 2 neutral Higgsino)
- Gravitino (The superpartner of gravitino)

The actual LSP depends on how SUSY is broken!
[I'm not going to talk about Cosmological Aspect today...]

Supersymmetric Standard Model

μ-term : Supersymmetric Higgs mixing term

$$\boxed{W = \mu_H H_u H_d}$$

This term gives masses to Higgs and Higgsino in a supersymmetric way.

$$\mathcal{L}_{\rm mass} = |\mu_H|^2(|H_u|^2 + |H_d|^2) + (\mu_H \psi_{H_u} \psi_{H_d} + h.c.)$$

μ_H has a mass dimension and it will turn out to be within O($10^{2\text{-}3}$)GeV range.

Why it's not $M_{\rm unif}$ but in the weak scale?

⟶ μ-problem

[We may postpone the origin of μ]

Supersymmetric Standard Model

Now we have Supersymmetric Standard Model.
[In particular, we have built the MSSM.]

Parameters :	Gauge coupling constants Yukawa coupling constants μ_H parameter

⟶ Of course it's far from realistic!

Why?

Particles in the same supermultiplets will have the same mass.

We need to carefully break supersymmetry, so that we can make unobserved superparticles heavy enough.

Supersymmetric Standard Model

Soft supersymmetry breaking in the MSSM

$$
\begin{aligned}
\mathcal{L}_{\rm soft} = -\frac{1}{2}\Big(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B}\Big) \\
-\Big(a_u H_u \tilde{Q}_L \tilde{\bar{U}}_R + a_d H_d \tilde{Q}_L \tilde{\bar{D}}_R + a_e H_d \tilde{L}_L \tilde{\bar{E}}_R\Big) + c.c. \\
-m_Q^2|\tilde{Q}_L|^2 - m_{\bar{U}}^2|\tilde{\bar{U}}_R|^2 - m_{\bar{D}}^2|\tilde{\bar{D}}_R|^2 - m_L^2|\tilde{L}_L|^2 - m_{\bar{E}}^2|\tilde{\bar{E}}_R|^2 \\
-m_{H_u}^2|H_u|^2 - m_{H_d}^2|H_d|^2 - (B\mu_H H_u H_d + c.c.)
\end{aligned}
$$

$$
M_{1,2,3},\, a_{u,d,e},\, m_{Q,U,D,E,L,H_u,H_d},\, B = O(10^{2-3})\ {\rm GeV}
$$

Here, we are assuming that these soft breaking parameters are generated as a result of spontaneously SUSY breaking outside of the MSSM.

Supersymmetric Standard Model

Soft supersymmetry breaking in the MSSM

$$
\begin{aligned}
\mathcal{L}_{\text{soft}} = &-\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B}\right)\\
&-\left(a_u H_u \tilde{Q}_L \tilde{\bar{U}}_R + a_d H_d \tilde{Q}_L \tilde{\bar{D}}_R + a_e H_d \tilde{L}_L \tilde{\bar{E}}_R\right) + c.c.\\
&-m_Q^2|\tilde{Q}_L|^2 - m_{\bar{U}}^2|\tilde{\bar{U}}_R|^2 - m_{\bar{D}}^2|\tilde{\bar{D}}_R|^2 - m_L^2|\tilde{L}_L|^2 - m_{\bar{E}}^2|\tilde{\bar{E}}_R|^2\\
&-m_{H_u}^2|H_u|^2 - m_{H_d}^2|H_d|^2 - (B\mu_H H_u H_d + c.c.)
\end{aligned}
$$

Eventually, if supersymmetry is correct, these coefficients are experimentally determined and use these to infer the underlying model of supersymmetry breaking.

Supersymmetric Standard Model

crude MSSM spectrum

squark masses ~ $M_{Q,\bar{U},\bar{D}}$

slepton masses ~ $M_{L,\bar{E}}$ [for large a-terms, LR-mixing]

gluino mass ~ M_3

neutralino ⟵ $(\tilde{B}, \tilde{W}^0, \tilde{H}^0_d, \tilde{H}^0_u)$

$$\mathbf{M}_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -c_\beta\, s_W\, m_Z & s_\beta\, s_W\, m_Z \\ 0 & M_2 & c_\beta\, c_W\, m_Z & -s_\beta\, c_W\, m_Z \\ -c_\beta\, s_W\, m_Z & c_\beta\, c_W\, m_Z & 0 & -\mu \\ s_\beta\, s_W\, m_Z & -s_\beta\, c_W\, m_Z & -\mu & 0 \end{pmatrix}$$

chargino ⟵ $(\tilde{W}^+(\tilde{W}^-), \tilde{H}^+_u(\tilde{H}^-_d))$

$$\mathbf{M}_{\tilde{C}} = \begin{pmatrix} M_2 & \sqrt{2} s_\beta\, m_W \\ \sqrt{2} c_\beta\, m_W & \mu \end{pmatrix}$$

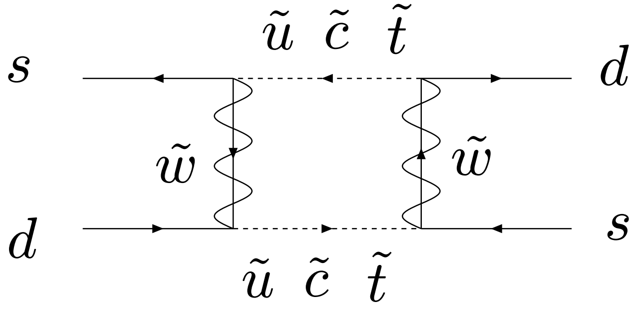
$(s_W = \sin\theta_W,\ c_W = \cos\theta_W)$ $(s_\beta = \sin\beta,\ c_\beta = \cos\beta,\ \tan\beta = \langle H_u\rangle / \langle H_d\rangle)$

Supersymmetric Standard Model

Although we have no experimental evidence of supersymmetry, there are already good clues to restrict the model parameters.

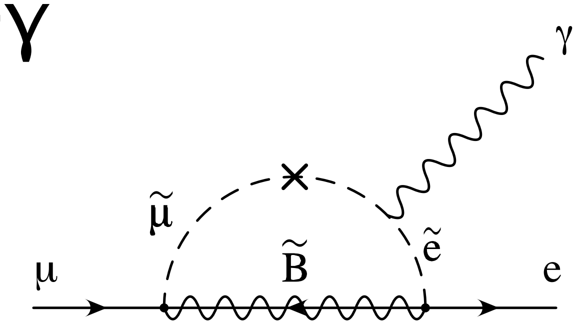
SUSY FCNC contributions
⟶ Flavor-violating soft masses must be suppressed!

K0-$\overline{\text{K0}}$ mixing



$$\frac{m^2_{\tilde{s}\tilde{d}}}{m^2_{\text{soft}}} \sim 10^{-(2-3)} \left(\frac{m_{\text{soft}}}{500\,\text{GeV}}\right)$$

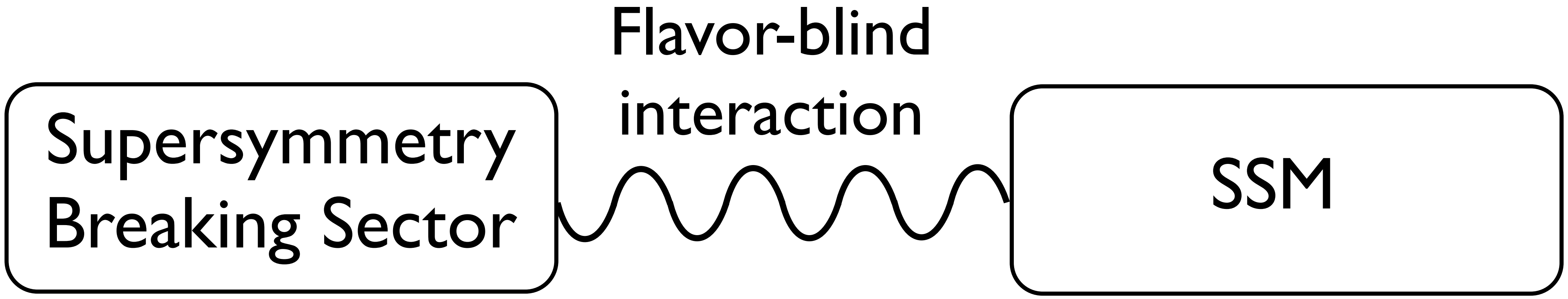
μ→e+γ



$$\frac{m^2_{\tilde{e}\tilde{\mu}}}{m^2_{\text{soft}}} \sim 10^{-(2-3)} \left(\frac{m_{\text{soft}}}{100\,\text{GeV}}\right)^2$$

Models with flavor-blind soft parameters are preferred!

Supersymmetric Standard Model



Supersymmetry Breaking Sector

Flavor-blind interaction

SSM

Proposals

mSUGRA (default)

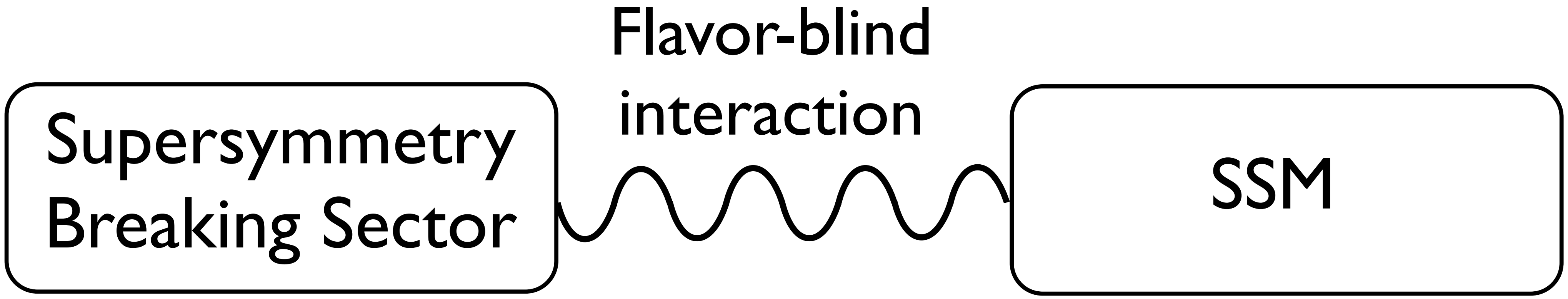
Gravity is flavor-blind, so if the SSM is connected to SUSY breaking sector via supergravity, the resultant soft parameters should be flavor-blind.

Caution! This very attractive idea turns out to be wrong. In supergravity, flavor-violating soft terms are unsuppressed, and no successful mechanisms found, which naturally lead to "mSUGRA".

$$m^2_{\rm scalar} = m^2_0, \;\; m_{\rm gaugino} = m_{1/2}, \; a_{u,d,e} = y_{y,d,e} \times A_0$$

at the Planck scale.

Supersymmetric Standard Model



Supersymmetry Breaking Sector

Flavor-blind interaction

SSM

Proposals

Gauge Mediation

Gauge interactions are flavor-blind, so if the SUSY breaking effects are mediated via gauge interactions, the resultant soft parameters should be flavor-blind.

This works, but model building is more complicated.

$$m_{\mathrm{gaugino}} = \frac{\alpha_a}{4\pi}\Lambda_{\mathrm{SUSY}} \qquad m^2_{\mathrm{scalar}} = 2\left(\frac{\alpha_a}{4\pi}\right)^2 C_a \Lambda^2_{\mathrm{SUSY}}$$

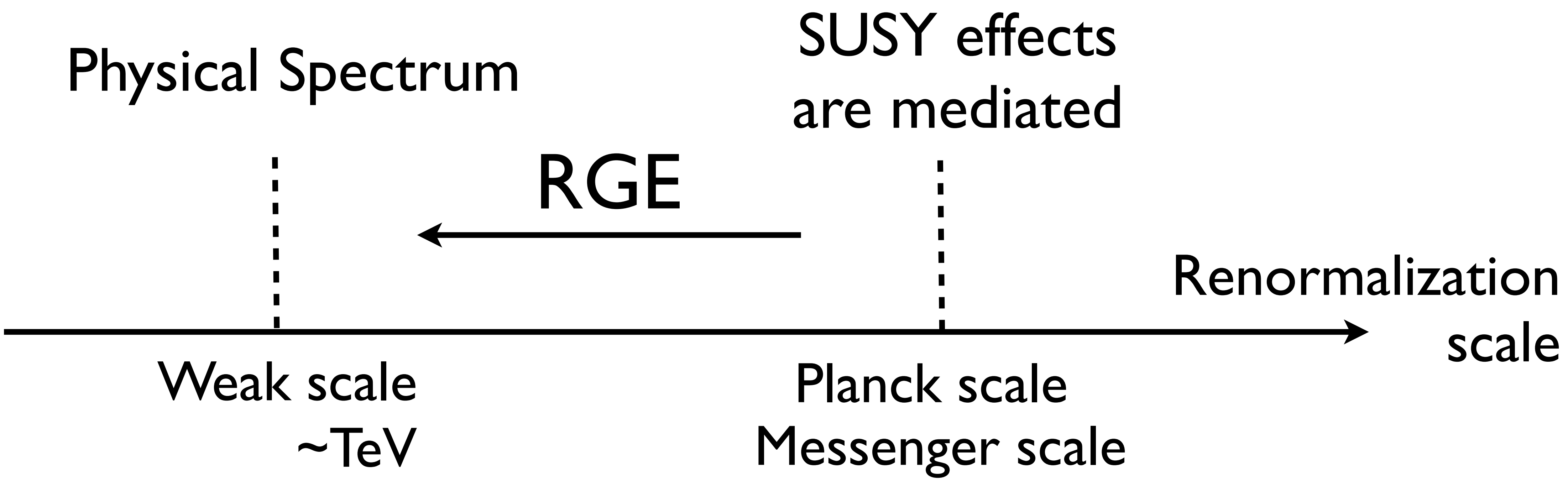
$\Lambda_{\mathrm{SUSY}} = \dfrac{F}{M}$ F : SUSY parameter M: Messenger scale

at the Messenger scale.

Supersymmetric Standard Model

In those proposals, the soft parameters are given at the high energy scale.

⟶ We need to evolve the mass parameters down to around TeV scale to know the spectrum.



Physical Spectrum

SUSY effects
are mediated

RGE

Renormalization
scale

Weak scale
~TeV

Planck scale
Messenger scale

Supersymmetric Standard Model

Gaugino Masses

The RG equation of gaugino masses

$$\frac{d}{dt}M_a = \frac{1}{8\pi^2} b_a g_a^2 M_a \qquad (b_a = 33/5, 1, -3)$$

$$\left(\frac{d}{dt}\alpha_a^{-1} = -\frac{b_a}{2\pi} \right)$$

$$\frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2}$$ at any RG scale

↓

$$M_1 : M_2 : M_3 = \underbrace{0.5 : 1 : 3.5}$$ at the TeV range

This ratio of the gaugino mass is the prediction of the universal gaugino mass!

[Realized in both the mSUGRA and gauge mediation]

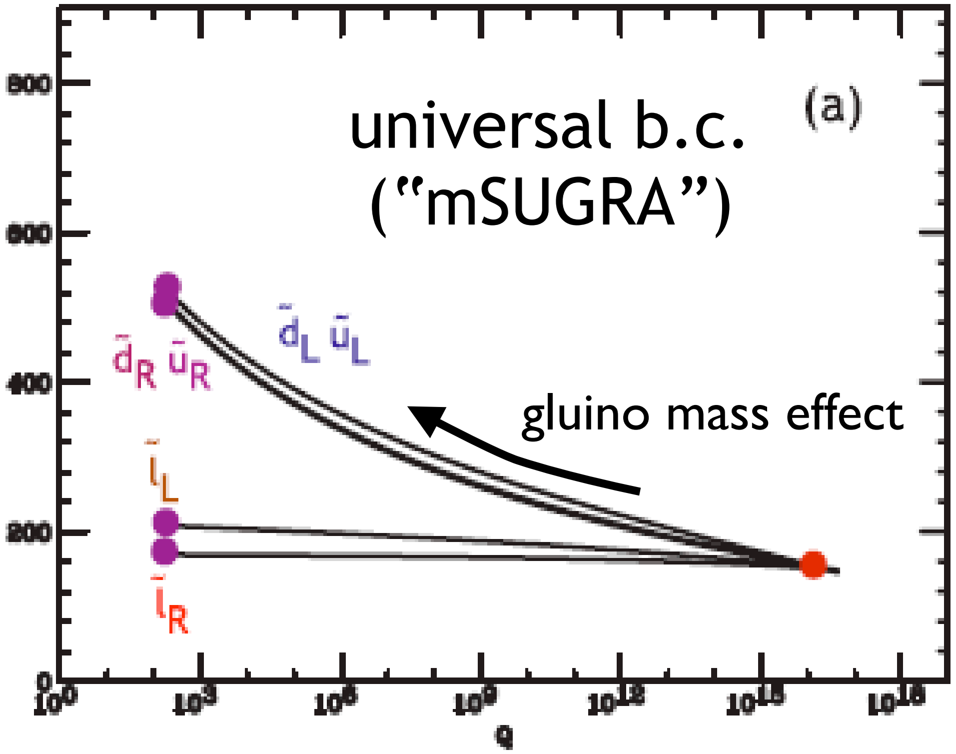
Checking the gaugino mass universality provides us very important hints on the origin of SUSY breaking.

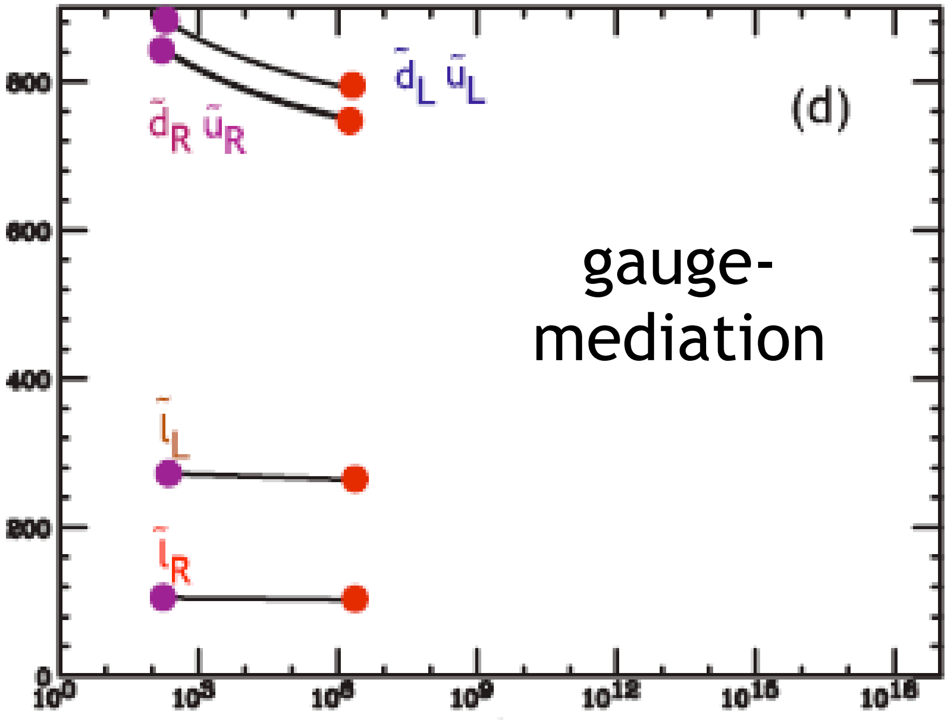
Supersymmetric Standard Model

squark/slepton Masses
(first 2 generations)

$$16\pi^2 \frac{d}{dt} m_\phi^2 = -\sum_{a=1,2,3} 8 g_a^2 C_a^\phi |M_a|^2$$

Gaugino mass effects raise the scalar masses at the low energy!





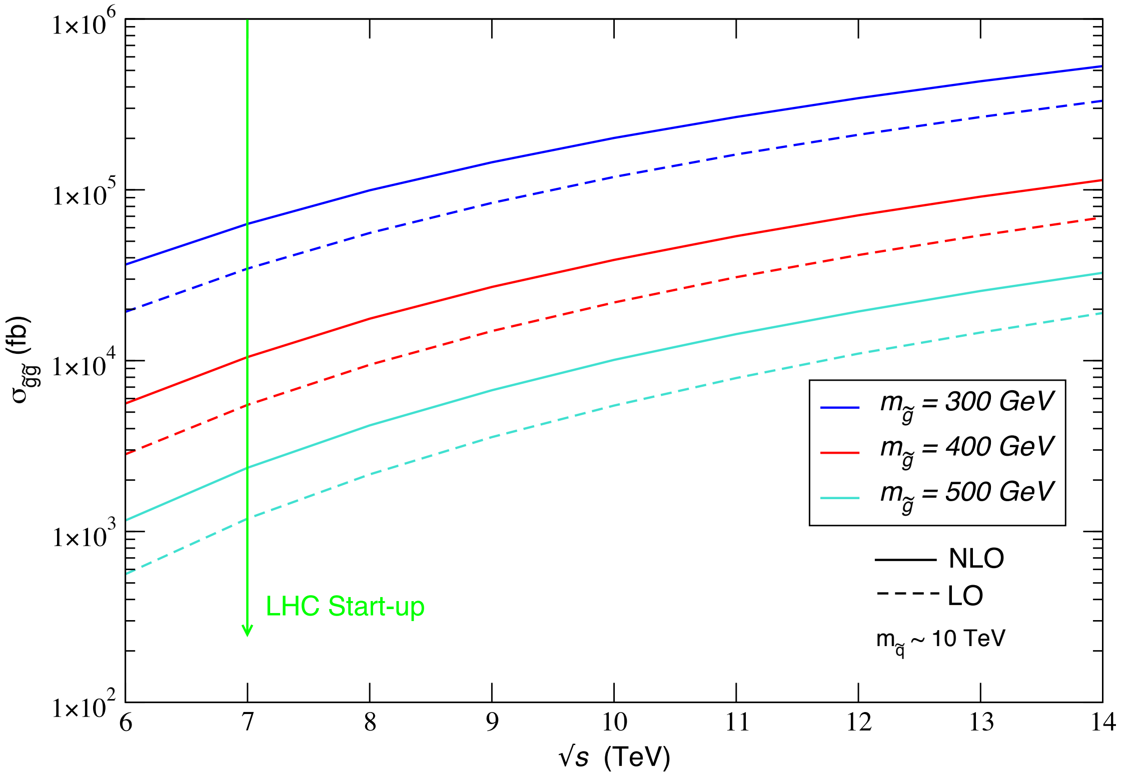
[borrowed from M.Peskin's lecture]

Typically, squarks are much heavier than sleptons.

Typically, squarks are degenerated compared with leptons due to large gluino contributions

SUSY @ LHC

Production cross section of superparticles @ LHC



Baer et al.

For colored superparticle < 1TeV

The SUSY production is dominated by squarks and gluinos (pair production).

$$\begin{aligned} gg &\longrightarrow \tilde{g}\tilde{g}, \quad \tilde{q}_i\tilde{q}_j^*, \\ gq &\longrightarrow \tilde{g}\tilde{q}_i, \\ q\bar{q} &\longrightarrow \tilde{g}\tilde{g}, \quad \tilde{q}_i\tilde{q}_j^*, \\ qq &\longrightarrow \tilde{q}_i\tilde{q}_j, \end{aligned}$$

σ < 1-10 pb (LHC7TeV)

The integrated luminosity will reach to 7-8fb^{-1} by the end of 2012.

The colored superparticles will be copiously produced!

SUSY @ LHC

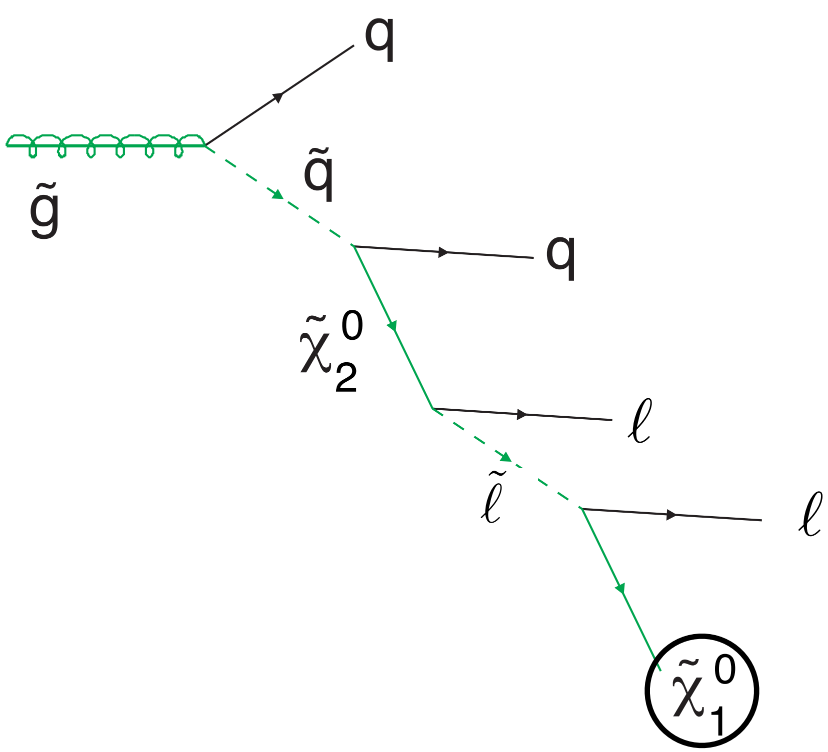
How do the SUSY events look?

It depends on what is the LSP...

In the models with neutralino LSP (e.g. mSUGRA), the decays of the produced superparticles result in final state with two LSPs which escape the detector.

SUSY events : n jets + m leptons + missing E_T ($n \geq 0, m \geq 0$)

ex)



LSP escape the detector and results in the missing ET.

SUSY @ LHC

In the models with gravitino LSP (e.g. gauge mediation), the NLSP can have a long lifetime.
[NLSP : The lightest SUSY particle in the MSSM]

Decay length of the NLSP (decaying into gravitino)

$$d/\beta\gamma_{\mathrm{NLSP}} \sim 6\,\mathrm{m} \times \left(\frac{m_{\chi^0}}{100\,\mathrm{GeV}}\right)^{-5} \left(\frac{m_{3/2}}{1\,\mathrm{keV}}\right)^{2}$$

Prompt decaying NLSP

SUSY events : n jets + m leptons + missing E_T ($n \geq 0, m \geq 0$)
(+ photons)

Escaping neutralino NLSP

SUSY events : n jets + m leptons + missing E_T ($n \geq 0, m \geq 0$)

Escaping charged NLSP

SUSY events : n jets + m leptons + new charged tracks

SUSY @ LHC

SM backgrounds

SUSY events : n jets + m leptons + missing E_T

QCD multi-jets (ET>100GeV) ~1μb

Suppressed by large missing ET.

W/Z + jets ~ 10nb [$W \to \tau\nu, l\nu$, $Z \to \nu\nu$]

Top pair + jets ~ 800pb

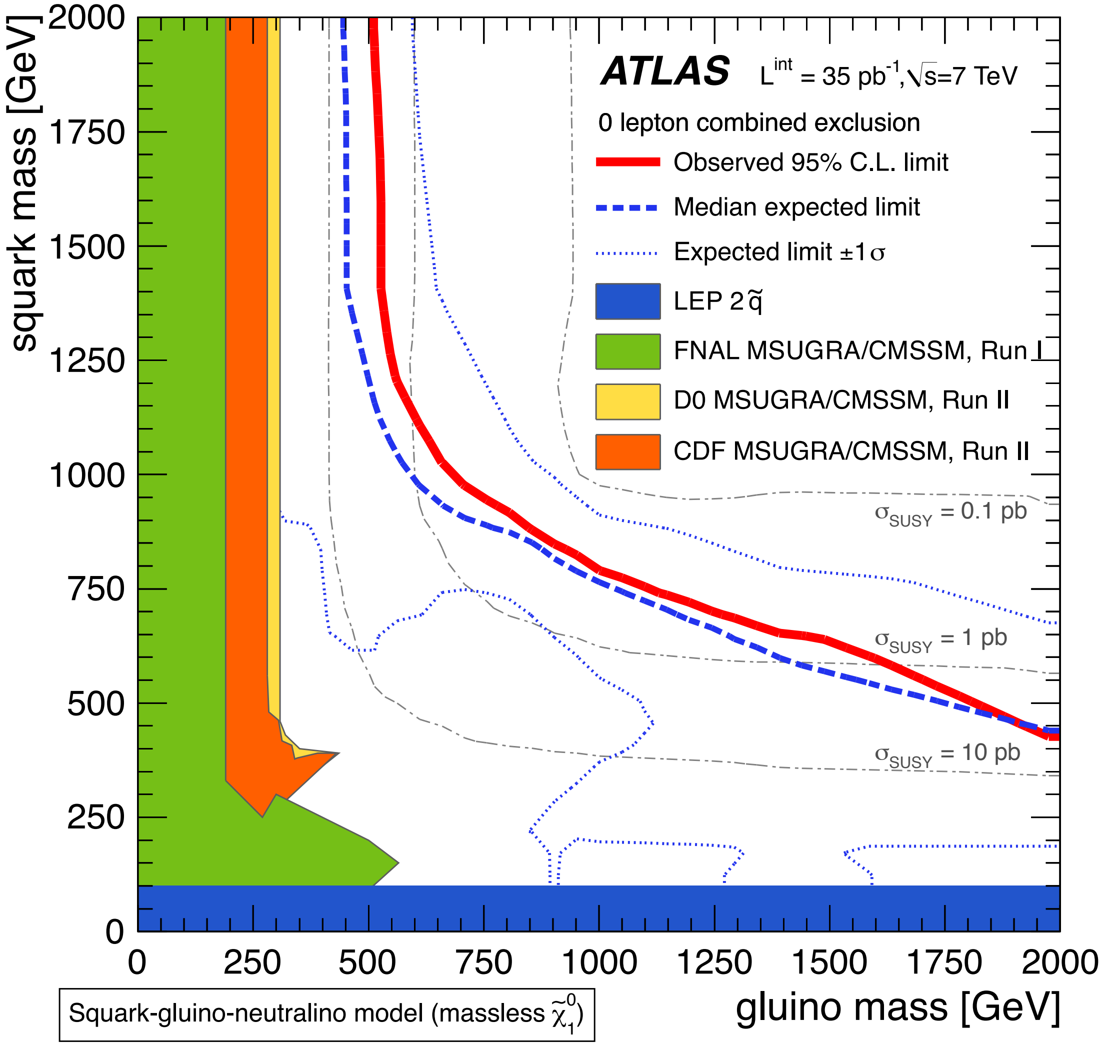
SUSY events can win with larger ET, more jets

SUSY events : n jets + m leptons + new charged tracks

Collect slow tracks to distinguish the charged tracks from the muon tracks.

SUSY @ LHC

Results of ATLAS detector in 2010 (7TeV, 35pb^{-1})



ATLAS searched for the deviation in jets + missing ET.

No deviation from the SM

95% exclusion limit

gluino mass > 500GeV
[mgluino << msquark]

gluino mass > 870GeV
[mgluino = msquark]

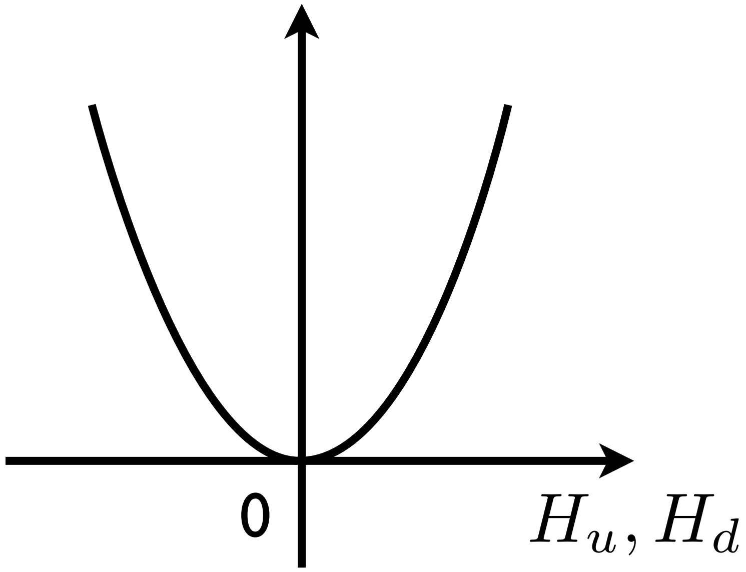
Rather light mass regions are getting excluded...

Higgs Mechanism in SSM

Higgs potential in the supersymmetric limit.

$$\boxed{W = \mu_H H_u H_d}$$

$$V = |\mu_H H_u|^2 + |\mu_H H_u|^2 + \frac{g^2}{2}(D - \mathrm{term})^2 + \cdots$$



No EWSB in the supersymmetric limit with only μ-term.

Deformation by SUSY breaking effects (well-studied)

Extended superpotential (rather exotic...)

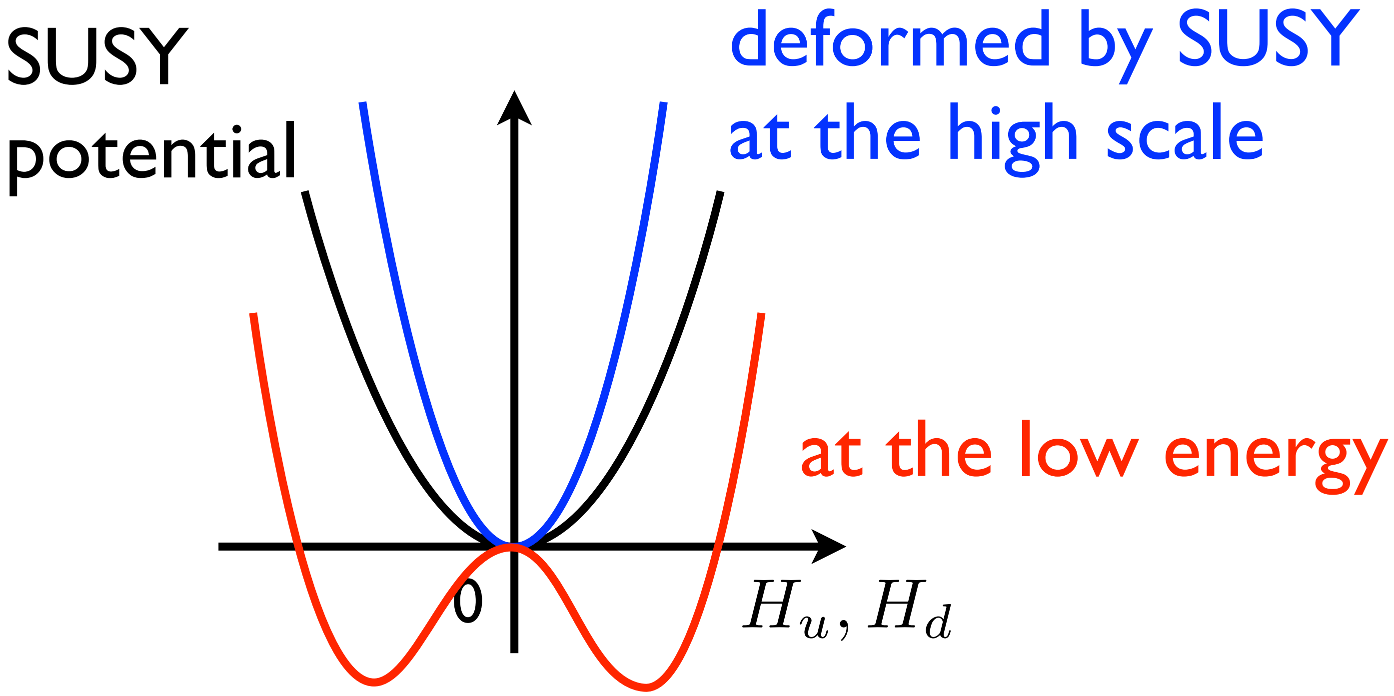
Higgs Mechanism in SSM

Radiative Electroweak Symmetry Breaking

A very nice feature of the MSSM!

Soft SUSY breaking mass term of Higgs doublets are generated at the mediation scale (e.g. Planck scale, Messenger scale).

Then, the soft mass mH >0 at this scale is driven to negative at the lower energies in the course of the RG flow.



EWSB is realized by the radiative correction!

Higgs Mechanism in SSM

Why only higgs gets negative mass squared?

$$\begin{aligned}
16\pi^2 \frac{d}{dt} m_{H_u}^2 &= \underline{3X_t} - \underline{6g_2^2|M_2|^2} - \frac{6}{5}\underline{g_1^2|M_1|^2}, \\
16\pi^2 \frac{d}{dt} m_{H_d}^2 &= \underline{3X_b} + \underline{X_\tau} - \underline{6g_2^2|M_2|^2} - \frac{6}{5}\underline{g_1^2|M_1|^2}.
\end{aligned}$$

$$\begin{aligned}
16\pi^2 \frac{d}{dt} m_{Q_3}^2 &= \underline{X_t} + \underline{X_b} - \frac{32}{3}\underline{g_3^2|M_3|^2} - \underline{6g_2^2|M_2|^2} - \frac{2}{15}\underline{g_1^2|M_1|^2} \\
16\pi^2 \frac{d}{dt} m_{\bar{u}_3}^2 &= \underline{2X_t} - \frac{32}{3}\underline{g_3^2|M_3|^2} - \frac{32}{15}\underline{g_1^2|M_1|^2} \\
16\pi^2 \frac{d}{dt} m_{\bar{d}_3}^2 &= \underline{2X_b} - \frac{32}{3}\underline{g_3^2|M_3|^2} - \frac{8}{15}\underline{g_1^2|M_1|^2}
\end{aligned}$$

$$\begin{aligned}
X_t &= 2|y_t|^2(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 2|a_t|^2, \\
X_b &= 2|y_b|^2(m_{H_d}^2 + m_{Q_3}^2 + m_{\bar{d}_3}^2) + 2|a_b|^2, \\
X_\tau &= 2|y_\tau|^2(m_{H_d}^2 + m_{L_3}^2 + m_{\bar{e}_3}^2) + 2|a_\tau|^2.
\end{aligned}$$

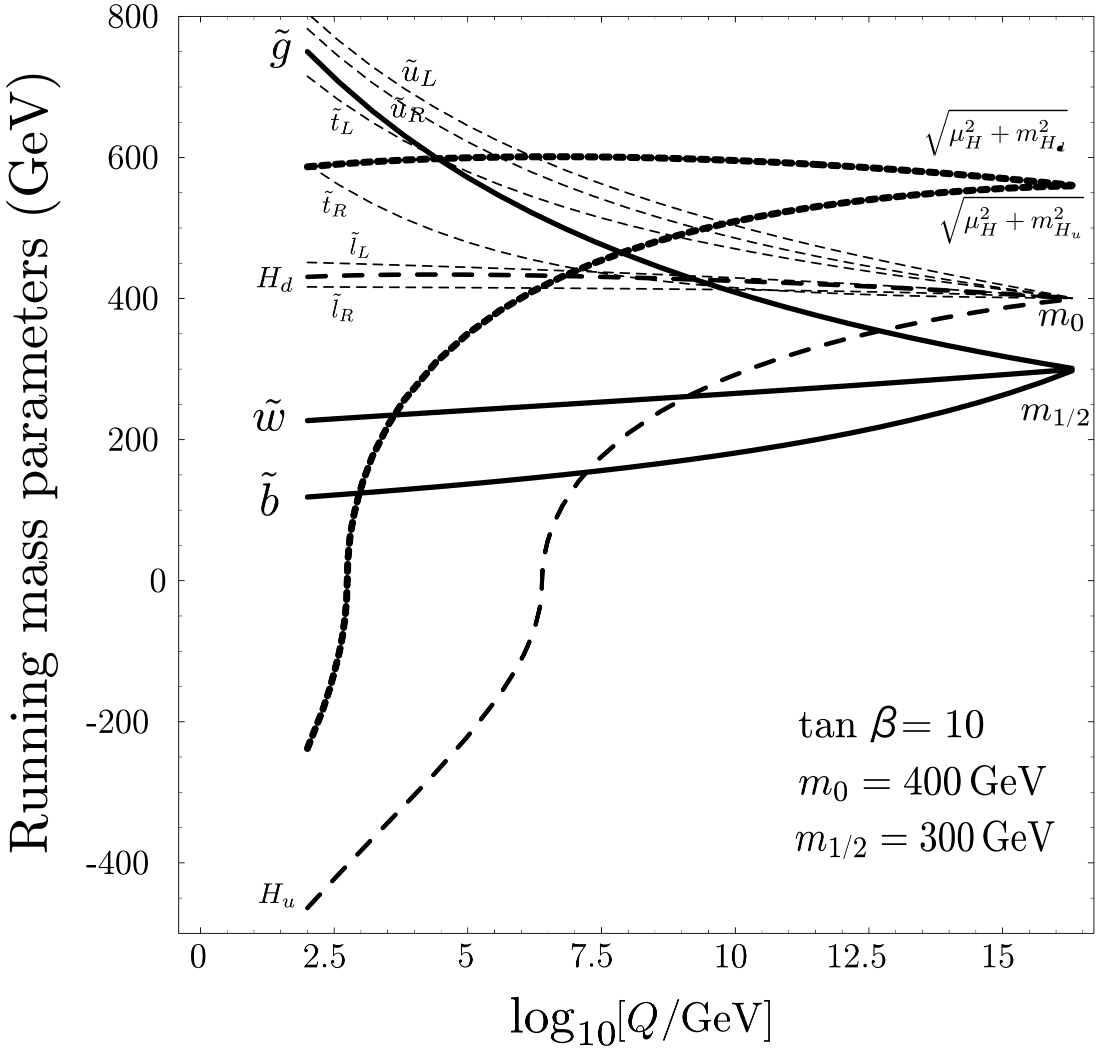
$$y_t = \frac{g m_t}{\sqrt{2} m_W \sin\beta};$$

$$y_{b,\tau} = \frac{g m_{b,\tau}}{\sqrt{2} m_W \cos\beta};$$

The color factor and the gluino contribution to the squarks makes it possible to have negative Higgs but positive squark squared masses.

Higgs Mechanism in SSM

Ex.



Typically, only Hu gets negative mass squared.

3rd generation squarks/sleptons are lighter than the first two generations.

The radiative EWSB is remarkable nature of the MSSM!

Higgs Mechanism in SSM

Higgs potential

$$\begin{aligned} V \;=\; & (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\ & + b\,(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.} \\ & + \frac{1}{8}\underline{(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2} \\ & + \frac{1}{2}\underline{g^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2}. \end{aligned}$$

[D-term contributions]

$$H_d = (H_d^0,\ H_d^-) \qquad H_u = (H_u^+,\ H_u^0)$$

We can always make $H_u^+ = 0$ at the minimum by rotating SU(2).

$$\left.\frac{\partial V}{\partial H_u^+}\right|_{H_u^+ = 0} = \left(b + \frac{g^2}{2}(H_d^0 H_u^0)^* \right) H_d^-$$

At the vacuum, $H_u^+ = H_d^- = 0$, i.e. the U(1)EM is automatically unbroken at the vacuum!

Higgs Mechanism in SSM

Potential of neutral Higgs

$$\begin{aligned} V &= (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) \\ &\quad + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2 . \end{aligned}$$

At the vacuum, $\left\langle H_{u,d}^0 \right\rangle = v_{u,d}.$

$$\begin{aligned} \frac{1}{2}\frac{\partial V}{\partial H_u^0} &= (m_{H_u}^2 + |\mu_H|^2)v_u^2 - B\mu_H v_d + \frac{g^2 + g'^2}{4}(v_u^2 - v_d^2)v_u = 0, \\ \frac{1}{2}\frac{\partial V}{\partial H_d^0} &= (m_{H_d}^2 + |\mu_H|^2)v_d^2 - B\mu_H v_u + \frac{g^2 + g'^2}{4}(v_d^2 - v_u^2)v_d = 0, \end{aligned}$$

$$\begin{aligned} \frac{1}{2}m_Z^2 &= \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu_H|^2, \\ B\mu_H &= \frac{\sin 2\beta}{2}(m_{H_u}^2 + m_{H_d}^2 + 2|\mu_H|^2). \end{aligned}$$

The model parameters (m_{Hu}, m_{Hd}, $B\mu_H$, $|\mu_H|$) are related to the model predictions (m_Z, $\tan\beta$).

Higgs Mechanism in SSM

Higgs mass spectrum

Two Higgs doublets = 8 real scalars

2 CP-even : h^0, H^0 2 CP-odd : G^0, A^0 2 CP-charged : $G^\pm, H^\pm$

absorbed by Z/W

Mixing angles

$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \sqrt{2} \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}[H_u^0] - v_u \\ \mathrm{Re}[H_d^0] - v_d \end{pmatrix}.$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \sqrt{2} \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} \mathrm{Im}[H_u^0] \\ \mathrm{Im}[H_d^0] \end{pmatrix}, \quad \begin{pmatrix} G^+ \\ H^+ \end{pmatrix} = \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix},$$

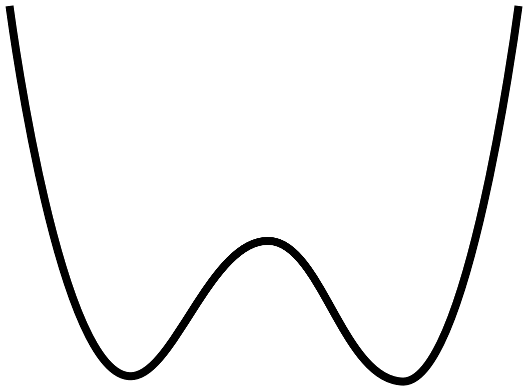
$$\frac{\sin 2\alpha}{\sin 2\beta} = -\frac{m_{A^0}^2 + m_Z^2}{m_{H^0}^2 - m_{h^0}^2}; \qquad \frac{\cos 2\alpha}{\cos 2\beta} = -\frac{m_{A^0}^2 - m_Z^2}{m_{H^0}^2 - m_{h^0}^2}.$$

$$\begin{aligned} m_{A^0}^2 &= 2b/\sin 2\beta \\ m_{H^\pm}^2 &= m_{A^0}^2 + m_W^2 \\ m_{h^0,H^0}^2 &= \frac{1}{2}\Big(m_{A^0}^2 + m_Z^2 \mp \sqrt{(m_{A^0}^2 + m_Z^2)^2 - 4 m_Z^2 m_{A^0}^2 \cos^2 2\beta}\Big). \end{aligned}$$

$$\alpha = \beta - \pi/2\ , \quad (m_{A^0} \gg m_Z)$$

Higgs Mechanism in SSM

The MSSM is highly predictive on the lightest Higgs Mass!



A^0, H^0, $H^\pm$ can be arbitrarily heavy ~ 2b/sin2β

The lightest higgs is not, since the quartic term is given by gauge coupling constants.

At the tree-level, the lightest Higgs mass is below LEP2 limit.

$$m_{h^0} < |\cos 2\beta| m_Z$$

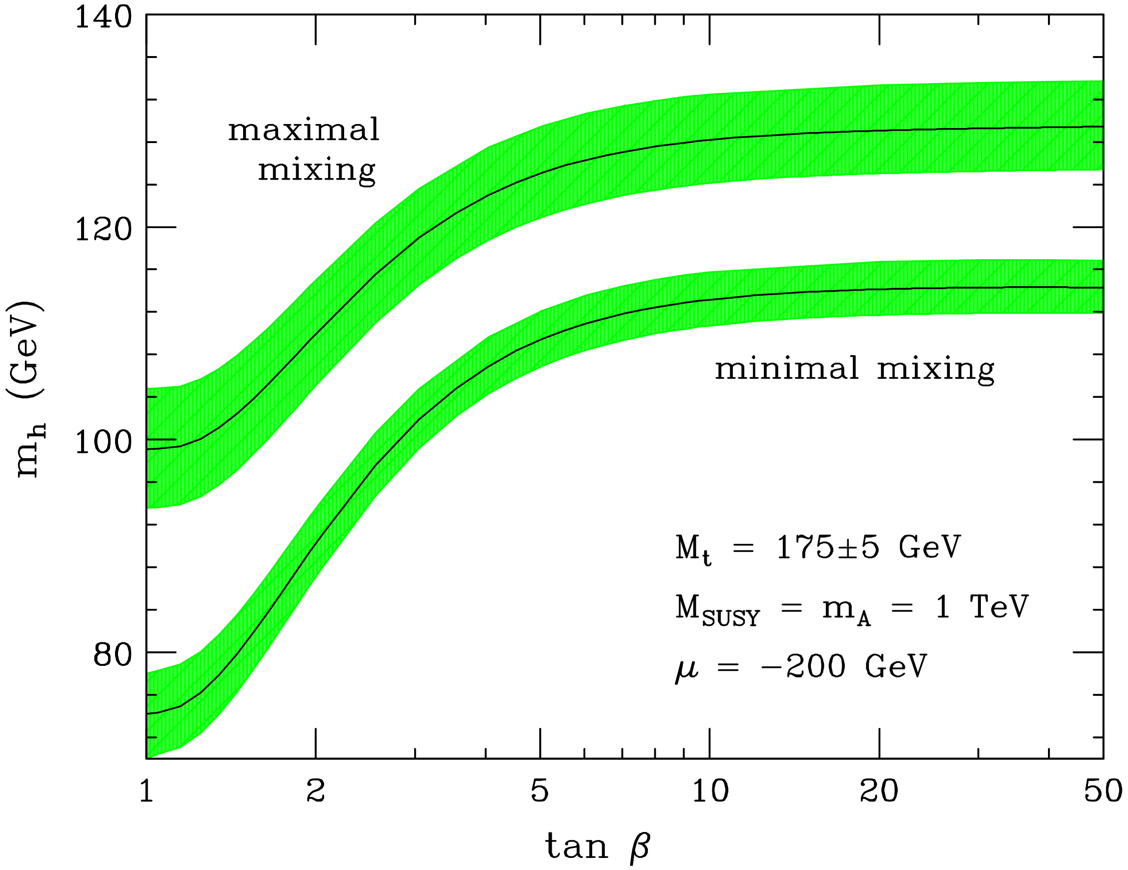
[The inequality saturates for $m_{A0} > m_Z$]

Fortunately, the above mass gets rather drastic contribution from the radiative correction, and can exceed the LEP2 limit!

$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2} v^2 y_t^4 \sin^4\beta \; \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right). \quad (m_{\tilde{t}} \gg m_t)$$

Higgs Mechanism in SSM

[Quiros,Wagner, Haber]



In the decoupling limit, i.e. mA0 >> mZ

$$m_{h^0} = |\cos 2\beta| m_Z + \Delta(m_{h^0})$$

For MSUSY<1TeV, the predicted lightest higgs mass

$$m_{h^0} < 130\,\mathrm{GeV}$$

The MSSM is still highly predictive on the lightest Higgs Mass although the higgs gets rather important radiative collection!

Higgs Mechanism in SSM

NMSSM

$$W = \underline{\lambda N} H_u H_d + \frac{1}{3}\underline{\kappa N^3}$$

effective μ-term

PQ-breaking

Soft mass terms

$$\mathcal{L}_{\rm soft} = -m_N^2 |N|^2 - \underline{\lambda A_\lambda} N H_u H_d + \frac{1}{3}\kappa A_\kappa N^3$$

effective b-term

Two Higgs doublets + a singlet = 10 real scalars

3 CP-even : h^0, H^0, H_2^0 3 CP-odd : G^0, A^0, a

2 CP-charged : $G^{\pm}, H^{\pm}$

[MSSM limit : $\lambda \to 0,\ \kappa \to 0$ keeping κ/λ , $\mu_{\rm eff}$ fixed]

Higgs Mechanism in SSM

Approximated NMSSM Higgs spectrum

CP-odd Higgs : $m_{A^0}^2 = \frac{2\mu_{\rm eff}A_\lambda}{\sin 2\beta}\left(1+\frac{\kappa v_s}{\sqrt{2}A_\lambda}\right)$ $m_a^2 = \frac{3}{\sqrt{2}}\kappa v_s A_\kappa$

massless in PQ-symmetric limit

CP-even Higgs : $m_{H^0}^2 = m_{A^0}^2$ $m_{H_2^0}^2 = \frac{1}{2}\kappa v_s(4\kappa v_s + \sqrt{2}A_\kappa)$

$$m_{h^0}^2 \leq m_Z^2\cos^2 2\beta + \underline{\frac{1}{2}(\lambda v)^2}\sin^2 2\beta + \frac{3}{4\pi^2}v^2 y_t^4 \sin^4\beta \ln\left(\frac{m_{\tilde{t}_1}m_{\tilde{t}_2}}{m_t^2}\right)$$

contribution from the new quartic term

Charged Higgs : $m_{H^\pm}^2 = m_{A^0}^2 + m_W^2 - \frac{1}{2}(\lambda v)^2$

Although the SM-like higgs gets additional contribution,
λ cannot be very large, since RG makes m_N^2 positive...

$$m_{h^0} < 140\,\mathrm{GeV}$$

Higgs Mechanism in SSM

Little tuning μ-problem

$$\frac{1}{2}m_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - |\mu_H|^2 \sim |m_{H_u}^2| - |\mu_H|^2$$

If m_{Hu} is huge, we require fine-tuning between m_{Hu} and μ_H.

Is m_{Hu} huge? ... almost yes in the allowed parameter space.

RGE effects on m_{Hu} : $\Delta m_{H_u}^2 \sim -12\frac{y_t^2}{16\pi^2}m_{\tilde{t}}^2 \log\frac{M_{UV}}{\mu_{IR}}$

(1) squark mass > 500GeV (ATLAS)

For m_{stop} ~ m_{squark} : $\frac{m_Z^2/2}{|\Delta m_{H_u}^2|} < O(1)\%$ for M_{UV} > 100TeV

(2) SM-like higgs mass > 115GeV(LEP2) → stop mass > 500GeV

Again, the fine-tuning finer than O(1)% is required.

Higgs Mechanism in SSM

Answers

(1) Don't complain!

SUSY gave us a perturbative model up to the unification scale at the price of just O(1)%.

(2) Light stop → small m_{H_u}.

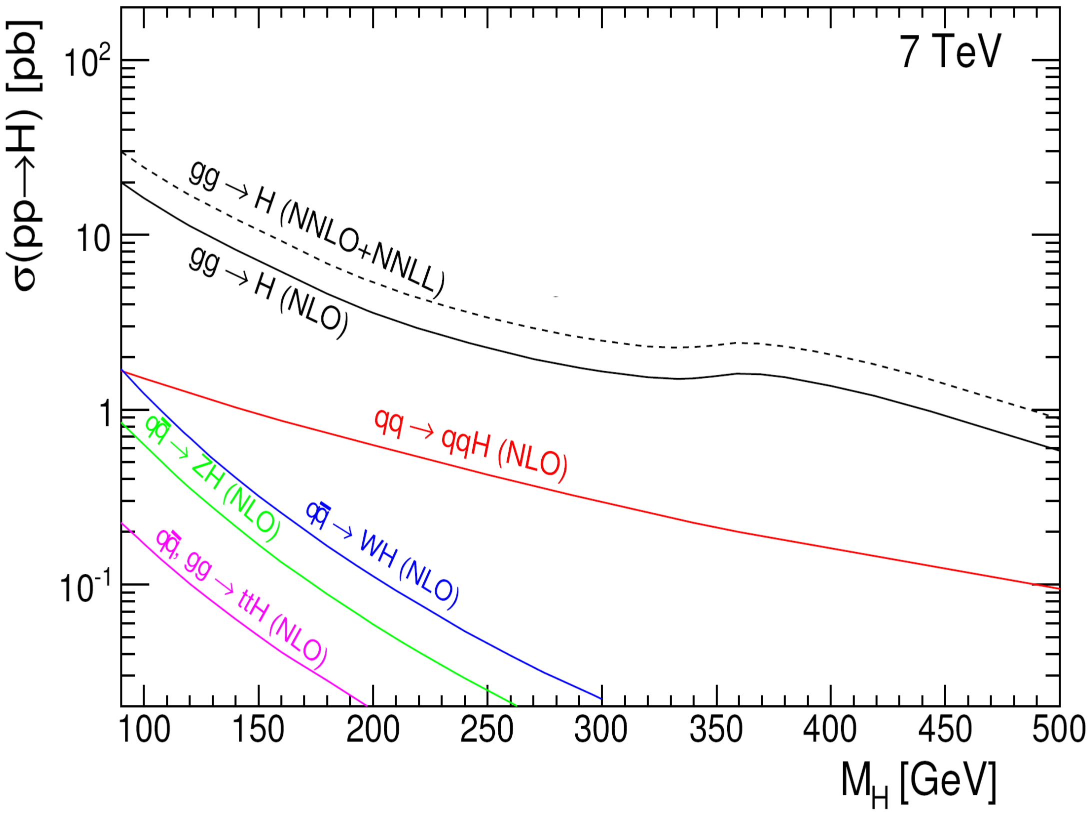
How about light higgs mass?

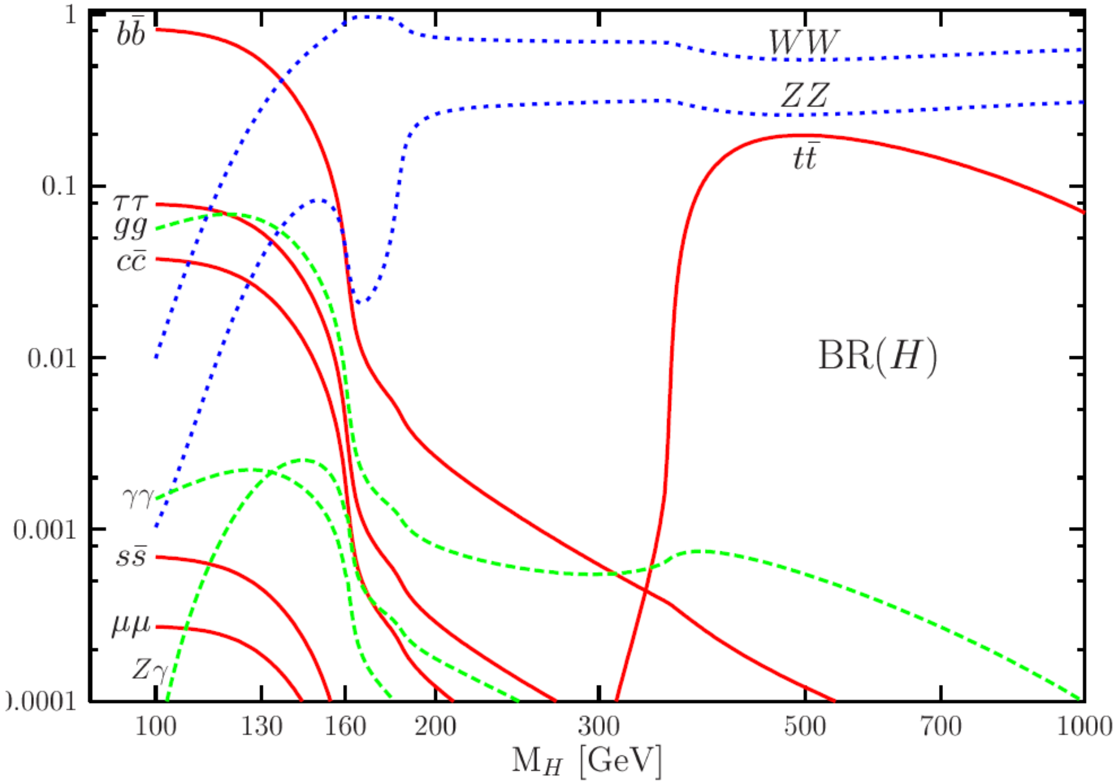
(i) Rather large A-term will help to push the higgs mass with rather light stop (ask Asano san and Kitano san!)

(ii) Hide SM-like higgs with mass below the LEP2 bound by adding new decay modes.

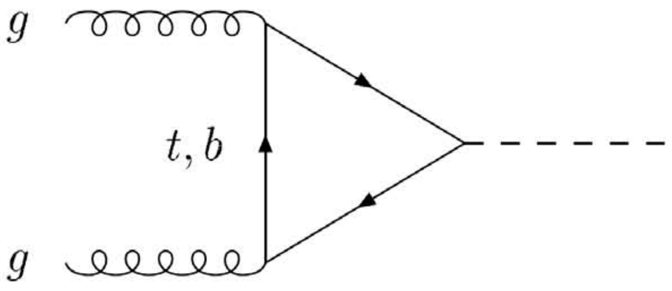
Higgs Search @ LHC

SM-like Higgs search @ LHC

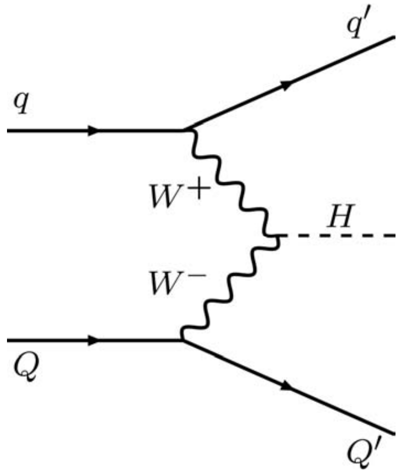




For m_{h^0}=110-140GeV



$h^0 \to \gamma\gamma$



$h^0 \to \tau\tau$

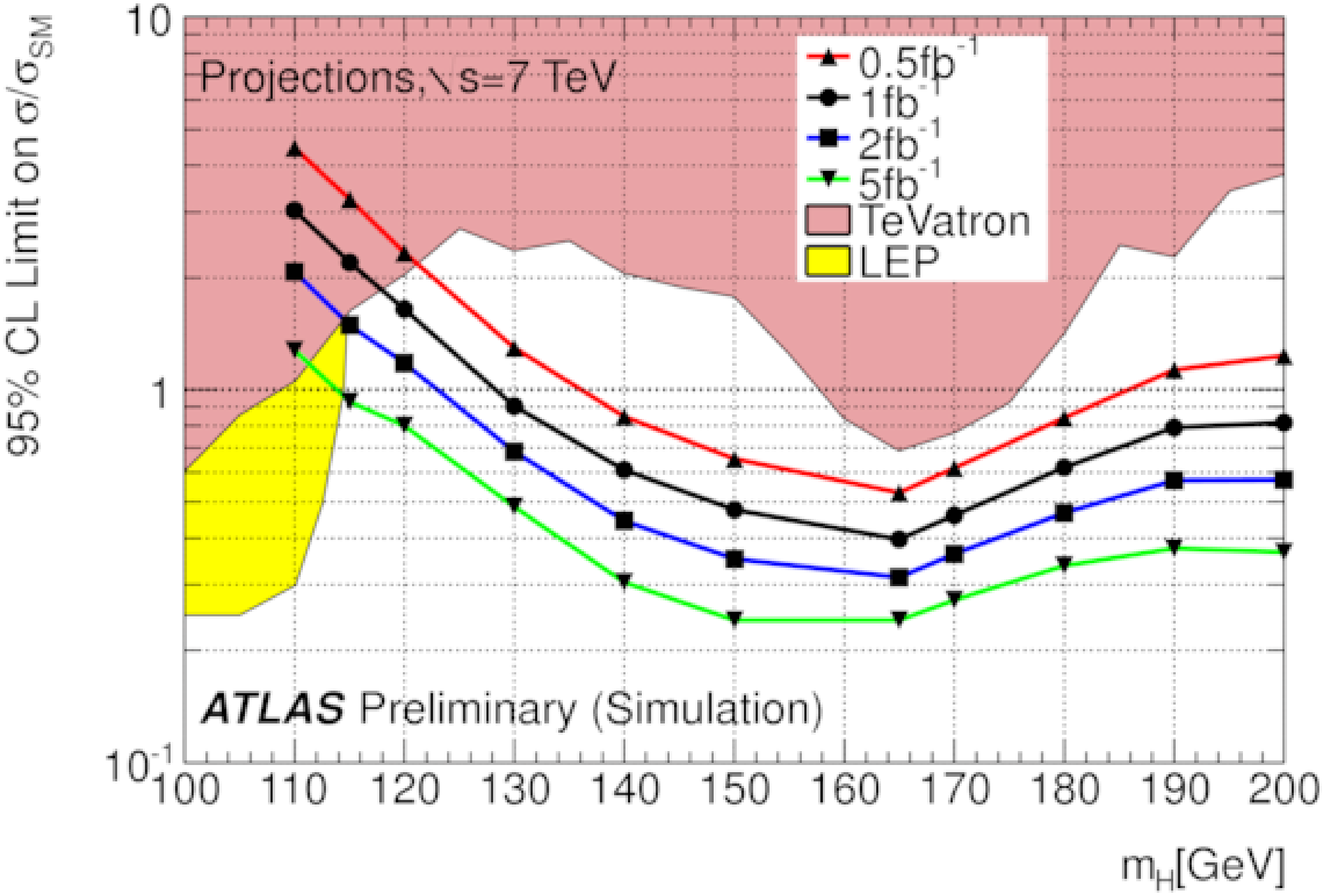
[Backgrounds: irreducible photons jet misidentification]

[Backgrounds: Z+jets, W+jets...]

Higgs Search @ LHC

When do we give up SUSY?

No Higgs signal gives the finishing blow to SUSY....



MSSM

$$m_{h^0} < 130\,\mathrm{GeV}$$

NMSSM

$$m_{h^0} < 140\,\mathrm{GeV}$$

Other perturbative extensions?

$$m_{h^0} < 200\,\mathrm{GeV?}$$

By the end of 2012, the integrated luminosity, we must see some hints (i.e. 3σ) on Higgs.

Summary

Perturbative GUT strongly motivates the perturbative SUSY to stabilize the scale of the Higgs mass.

It allows the model to be perturbative up to the unification scale at the price of just O(1)% tuning in Higgs sector.

Coupling unification looks better than the SM!

Perturbative SUSY models predict the upper bound on the Higgs mass.

Higgs search will exclude most of the parameter space if we do not see any hints on higgs by the end of 2012!