Supersymmetry at Future Precision Frontiers

Takeo Moroi (Tohoku)

Outline

1. Introduction
2. CP / Flavor Physics
3. Muon Anomalous Magnetic Moment
4. Cosmic Microwave Background
5. Discussion

1. Introduction

LEP (and other) experiments tought us:

- Standard model (SM) well describes particle interactions up to the electroweak scale
  - $SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Three generations of fermions
- Light Higgs boson is preferred
  - $m_h < 205$ GeV
    [See, for e.g., Erler]
- SUSY is needed, if we require gauge coupling unification

Next question: Physics beyond the standard model

⇒ Current status (or my prejudice ?):

- SUSY GUT is a well-motivated candidate of the physics beyond the SM
  - Light Higgs
  - Coupling unification
  - (Solution to the naturalness problem)
- Neutrino physics is also important
  - Neutrino osc.: First evidence of new physics beyond the SM

If SUSY, what can happen next, in particular at future experiments?

- Direct detections of the superparticles are very important!
- Non-standard (but indirect) signals may exist

In this talk, I consider the second possibility

- Signal of the new physics may show up in a future precision experiment (on something)
- For this purpose, precise measurements of various quantities are needed

Fortunately, we expect various precision measurements

- Lepton flavor violations
- CP violations
- Muon anomalous magnetic moment
- Cosmic microwave background radiation

These precision measurements may see non-standard signals

- Hint of the new physics beyond the standard model
- Hint of the energy scale to look for SUSY
- Even after the discovery of SUSY, they provide very important informations

2. CP / Flavor Physics

In MSSM, new sources of CP / flavor violations exist

- Off diagonal elements in the sfermion mass matrices

$$
\begin{aligned}
V_{\text{soft}} = & (\tilde{e}\ \tilde{\mu}\ \tilde{\tau})^* \begin{pmatrix} m^2_{\tilde{E},11} & m^2_{\tilde{E},12} & m^2_{\tilde{E},13} \\ m^2_{\tilde{E},21} & m^2_{\tilde{E},22} & m^2_{\tilde{E},23} \\ m^2_{\tilde{E},31} & m^2_{\tilde{E},32} & m^2_{\tilde{E},33} \end{pmatrix} \begin{pmatrix} \tilde{e} \\ \tilde{\mu} \\ \tilde{\tau} \end{pmatrix} \\
& +(\tilde{d}\ \tilde{s}\ \tilde{b})^* \begin{pmatrix} m^2_{\tilde{D},11} & m^2_{\tilde{D},12} & m^2_{\tilde{D},13} \\ m^2_{\tilde{D},21} & m^2_{\tilde{D},22} & m^2_{\tilde{D},23} \\ m^2_{\tilde{D},31} & m^2_{\tilde{D},32} & m^2_{\tilde{D},33} \end{pmatrix} \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix} \\
& + \cdots
\end{aligned}
$$

- Gaugino masses, Higgsino mass, $\cdots$

In general, off diagonal elements of the sfermion mass matrices are <u>not</u> controled by any symmetry

- Off diagonal elements may exist at the tree level
- Radiative correction may induce them

  ⇒ In gravity mediated SUSY breaking scenario, off diagonal elements may be sizable

- In some models of SUSY breaking, they may be small
  - Gauge mediation
  - Anomaly mediation
  - Gaugino mediation

Effect of the renormalization group flow

In the gravity-mediated SUSY breaking scenario, the off-diagonal elements are radiatively induced:

⇒ Even if the diagonality is realized at the cut-off scale, off diagonal elements show up
[Barbieri & Hall]

E.g.: Model with seesaw-induced neutrino masses

$$W(\mu < M_{\mathrm{GUT}}) = N_i [\hat{Y}_N V_{\mathrm{MNS}}]_{ij} L_j H_u + \cdots$$

$$W(\mu > M_{\mathrm{GUT}}) = \cdots + N_i [\hat{Y}_N V_{\mathrm{MNS}}]_{ij} \bar{D}_j H_C + \cdots$$

N_i: Right-handed neutrino in i-th generation
H_C: Colored Higgs
$\hat{Y}_N$: Neutrino Yukawa matrix (diagonalized)
V_{MNS}: Maki-Nakagawa-Sakata matrix

Neutrino mass matrix:

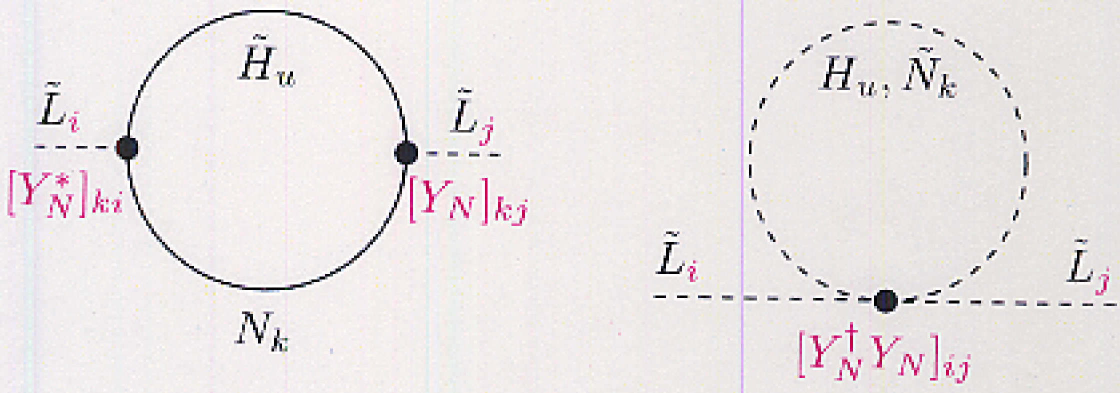
$$[m_{\nu_L}]_{ij} = \frac{\langle H_u \rangle^2}{M_N} \left[V_{\mathrm{MNS}}^T \hat{Y}_N^2 V_{\mathrm{MNS}} \right]_{ij}$$

- Mass eigenvalues: $y_{\nu_i}^2 v^2 \sin^2 \beta / 2M_N$
- M_N: Right-handed neutrino mass

Experimentally:

$$m_\nu \simeq (\, 0,\ 0.004\ \mathrm{eV},\ 0.06\ \mathrm{eV}\,)$$
$$V_{\mathrm{MNS}} \simeq \begin{pmatrix} 0.91 & -0.30 & 0.30 \\ 0.42 & 0.64 & -0.64 \\ \sim 0 & 0.71 & 0.70 \end{pmatrix}$$

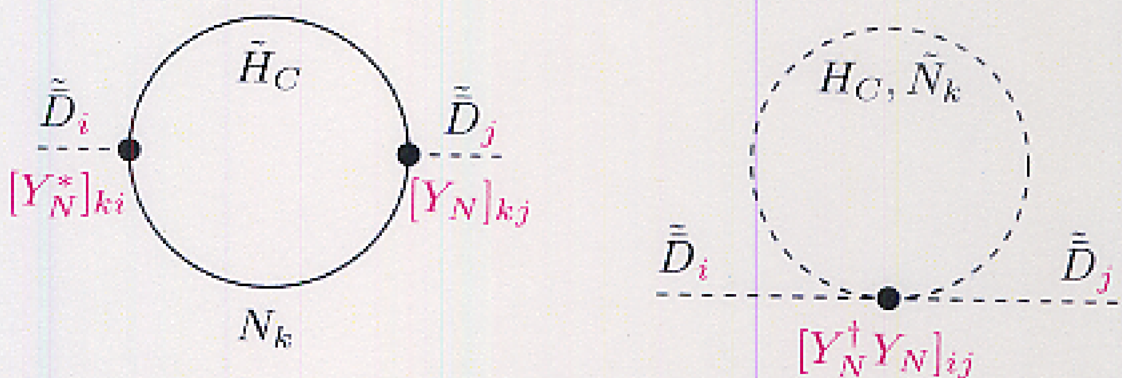
Off-diagonal elements of slepton mass matrix



$$[m_{\tilde{L}}^2]_{ij}^{(\mathrm{RG})} \sim -\frac{3}{8\pi^2}\left[V_{\mathrm{MNS}}^\dagger \hat{Y}_N^2 V_{\mathrm{MNS}}\right]_{ij} m_{\mathrm{soft}}^2 \log\frac{M_{\mathrm{pl}}}{M_N}$$

Off-diagonal elements of sdown mass matrix

[TM; Baek, Goto, Okada & Okumura]



$$[m_{\tilde{\bar{D}}}^2]_{ij}^{(\mathrm{RG})} \sim -\frac{3}{8\pi^2}\left[V_{\mathrm{MNS}}^\dagger \hat{Y}_N^2 V_{\mathrm{MNS}}\right]_{ij} m_{\mathrm{soft}}^2 \log\frac{M_{\mathrm{pl}}}{M_{\mathrm{GUT}}}$$

They affect:

- Lepton flavor violations ($\mu \to e\gamma$, $\mu \to 3e$, $\tau \to \mu\gamma$, $\cdots$)
- CP violations in B / K systems
- $\cdots$

Signal in B decay

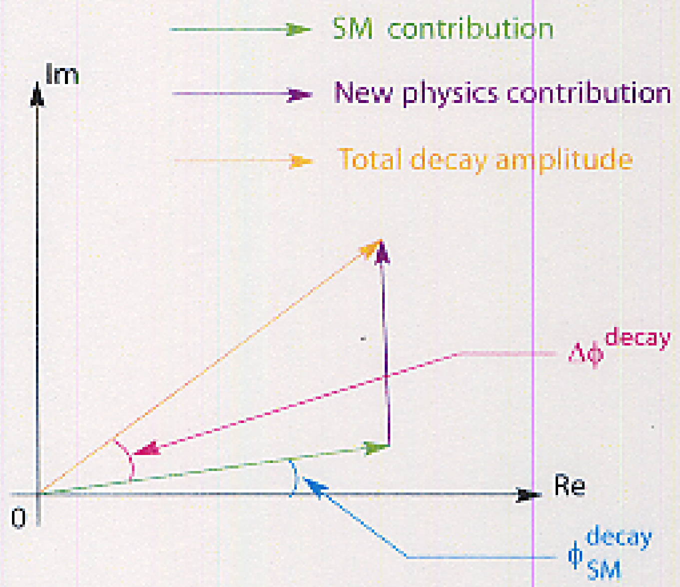
Important observable at asymmetric B-factories:
Time-dependent CP asymmetry

$$A(t) \equiv \frac{\Gamma[\bar{B}(t) \to f_{CP}] - \Gamma[B(t) \to f_{CP}]}{\Gamma[\bar{B}(t) \to f_{CP}] + \Gamma[B(t) \to f_{CP}]}$$
$$= -\xi_f \sin\left[2\left(\phi^{\text{mix}} + \phi^{\text{decay}}\right)\right] \sin \Delta m_B t$$

f_{CP}: CP eigenstate (like ψK^0, ϕK^0, $\cdots$)

- $2\phi^{\text{mix}} = \text{Arg}(\mathcal{M}_{B\to\bar{B}})$: phase in the mixing amplitude
- $\phi^{\text{decay}} = \text{Arg}(\mathcal{M}_{\bar{B}\to f_{CP}})$: phase in the decay amplitude

$\Rightarrow$ ϕ^{decay} depends on the decay processes



Typical size of $\Delta\phi^{\text{decay}}$ (assuming $O(1)$ phase):

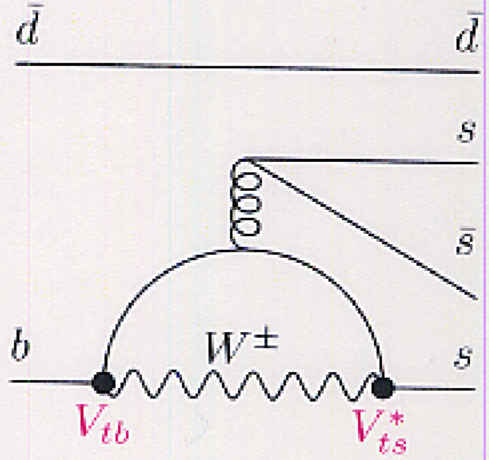
$$\Delta\phi^{\text{decay}} \sim \Delta\mathcal{M}^{\text{decay}} / \mathcal{M}^{\text{decay}}_{\text{SM}}$$

$\Rightarrow$ ϕ^{decay} is more affected as the SM contribution to the decay amplitude is smaller

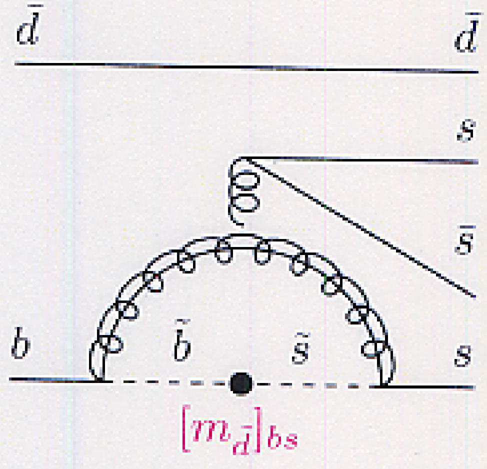
SUSY contribution is minor for $B_d \to \psi K^0$

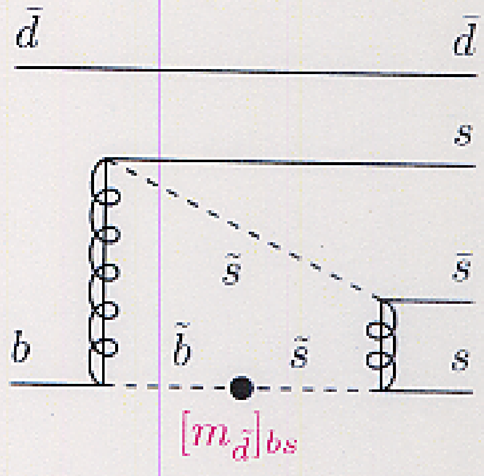
- In the SM, $B_d \to \psi K^0$ occurs at the tree level, while the SUSY effect is at the one-loop level

In SM, $B_d \to \phi K^0$ is via loop diagram



⇒ SUSY contribution can be sizable!





- The SUSY contribution is $O(\alpha_s^2)$, while the SM contribution is $O(\alpha_W \alpha_s)$
- SUSY breaking terms may have large phases

In SM, $A(B_d \to \psi K^0) \simeq A(B_d \to \phi K^0)$ up to a few % correction

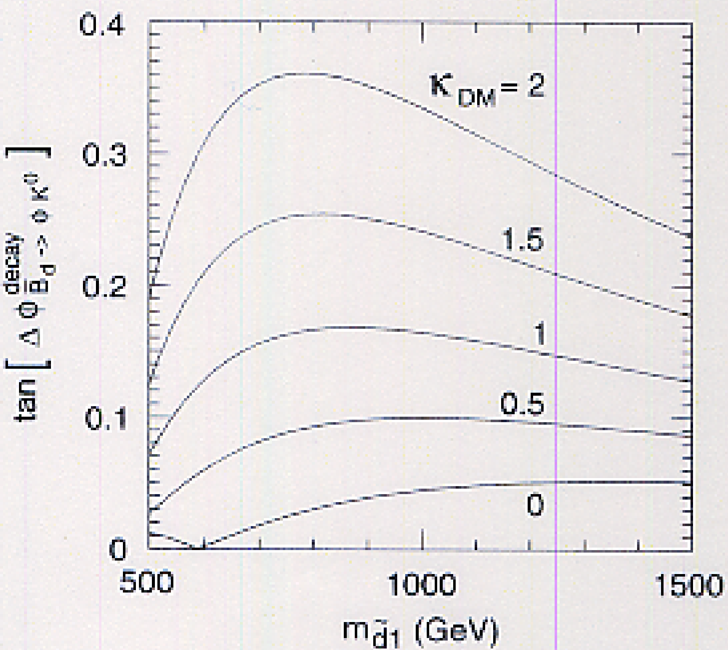
$\Rightarrow$ $\Delta\phi^{\rm decay}_{\bar{B}_d\to\phi K^0} \sim O(0.1)$ is a striking signal of the physics beyond the SM (if observed)

$\Rightarrow$ $A(B_d \to \phi K^0) \sim A(B_d \to \psi K^0) + 2\Delta\phi^{\rm decay}_{\bar{B}_d\to\phi K^0} \cos 2\phi_1$

Numerical result

[TM]

- $M_{\nu_R} \simeq 10^{15}$ GeV to realize $y_{\nu_3} \sim 1$
- Maximum CP violating phase assumed



$$\kappa_{\rm DM} = \frac{3}{4g_3} \frac{\langle \phi K^0 | m_b T^A_{ab} \bar{s}^a [\gamma^\mu, \gamma^\nu] P_L b^b G^A_{\mu\nu} | \bar{B}_d \rangle}{\langle \phi K^0 | (\bar{s}^a \gamma^\mu P_R b^a)(\bar{s}^b \gamma^\mu P_L s^b) | \bar{B}_d \rangle}$$

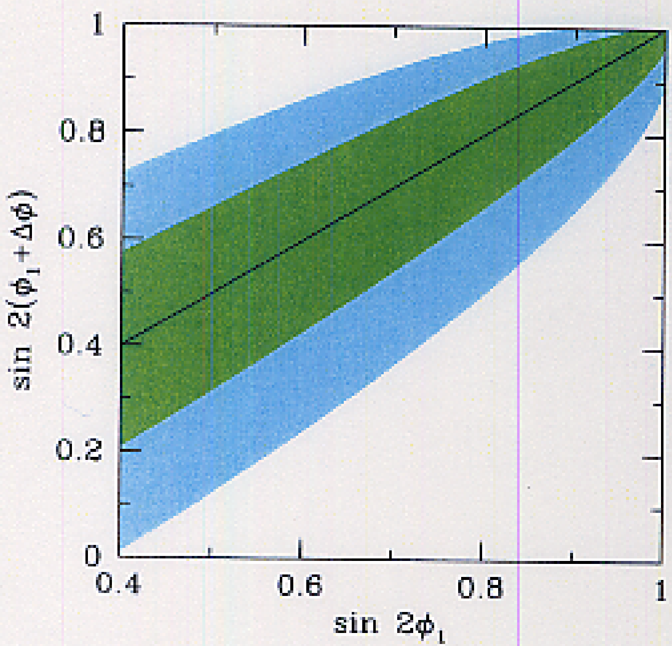
Model-independent calculation of $\kappa_{\rm DM}$ is difficult

$\kappa_{\rm DM} \simeq 1.2$ in some model, but $\cdots$

$\Delta\phi^{\rm decay}_{\bar{B}_d\to\phi K^0} \sim O(0.1)$ is possible in SUSY models

- New source of flavor / CP violations

For $\Delta\phi^{\rm decay}_{\bar{B}_d\to\phi K^0} = 0.1$ (green) and 0.2 (blue)



Disadvantage: small branching ratio

$\text{Br}(B^0 \to \phi K^0) < 1.2 \times 10^{-5}$

$\text{Br}(B^- \to \phi K^-) = (6.4^{+2.5}_{-2.9}) \times 10^{-6}$
[CLEO, at ICHEP00]

$\text{Br}(B^0 \to \psi K^0) = (9.6 \pm 0.9) \times 10^{-4}$
[PDG '01]

⇒ Large number of the event sample required

For the $B^0 \to \phi K^0$, asymmetry error less than 0.2 is possible at the high-luminosity B-factories
[Katayama (talk given at June meeting at KEK / Snowmass)]

3. Muon Anomalous Magnetic Moment

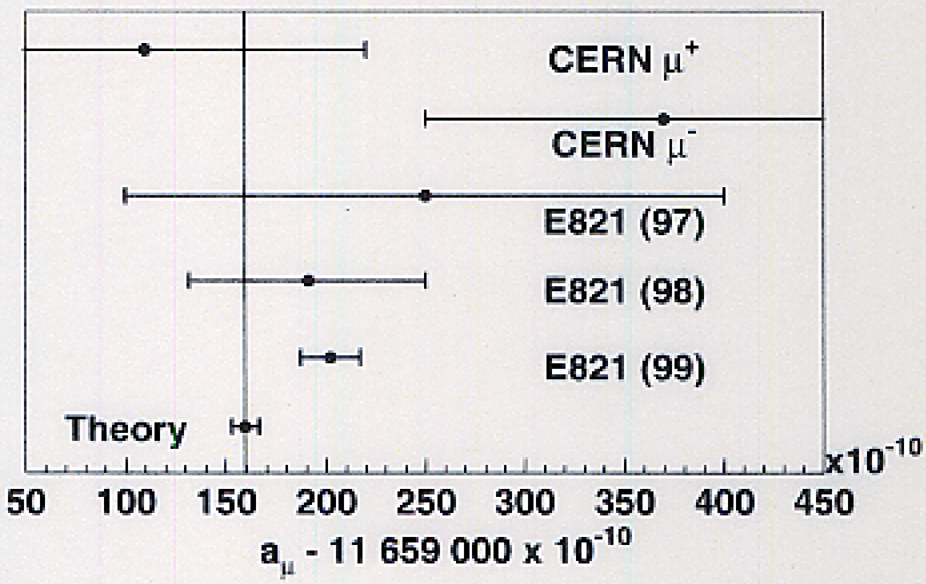
Feb. 2001, BNL E821 exp. announced their result

- Precise measurement of $a_\mu = (g-2)/2$ for muon
- Proposed accuracy: $\delta a_\mu(E821) \sim a_\mu$(W/Z loop)

$\Rightarrow$ Sensitive to contributions from new physics

Exp. result: $a_\mu(\text{E821}) = 11\ 659\ 202\ (16) \times 10^{-10}$

SM prediction: $a_\mu(\text{SM}) = 11\ 659\ 159.6\ (6.7) \times 10^{-10}$



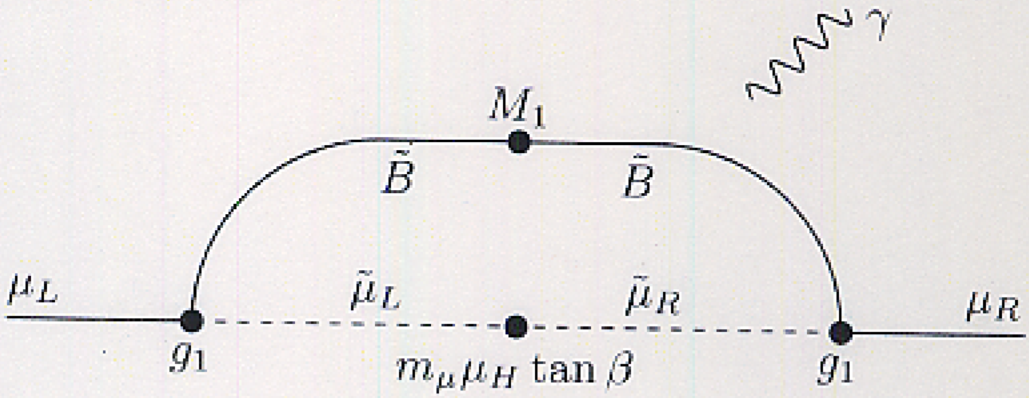
$a_\mu(\text{E821}) - a_\mu(\text{SM}) = 43\ (16) \times 10^{-10}$

$\Rightarrow$ a_μ(E821) is about 2.6-σ away from the SM prediction

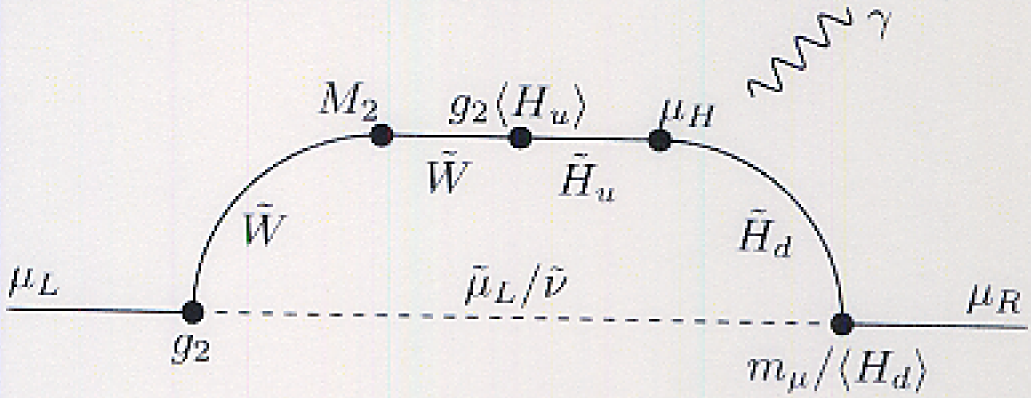
- Statistical fluctuation?
- Theoretical uncertainty underestimated?
- New Physics?

Dominant SUSY diagrams

"Gaugino diagram"



"Higgsino-Gaugino diagram"



$$\Rightarrow a_\mu(\text{SUSY}) \sim \frac{g_i^2}{16\pi^2}\frac{m_\mu^2 M_i \mu_H}{m_{\text{SUSY}}^4}\tan\beta$$

- a_μ(SUSY) ↗ as $\tan\beta$ ↗, since enhanced chiralty-flip may exist in MSSM
  [Chattopadhyay & Nath; TM]
- Sign of a_μ(SUSY) is determined by the relative sign between μ_H and the gaugino mass(es)
- a_μ(SUSY) ↘ as m_{SUSY} ↗

For small $\tan\beta$ case, Higgs mass may become too light

$$m_h^2 \sim m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{\pi^2 v^2} \ln\left(\frac{m_{\tilde{t}}}{m_t}\right)$$

- $m_h \searrow$ as $\tan\beta \searrow$
- m_h becomes larger as the stops become heavier via the loop correction
  [Okada, Yamaguchi & Yanagida; Haber & Hempfling; Ellis, Ridolfi & Zwirner]

For small $\tan\beta$ case:

- Muon $g-2$ anomaly requires relatively light smuons
- Higgs mass bound requires heavy stops
  ($m_h > 113.5$ GeV by LEP 200)

In many models, stop and smuon masses are correlated

Stops often become lighter as the smuon masses become smaller

Are two requirements consistent?

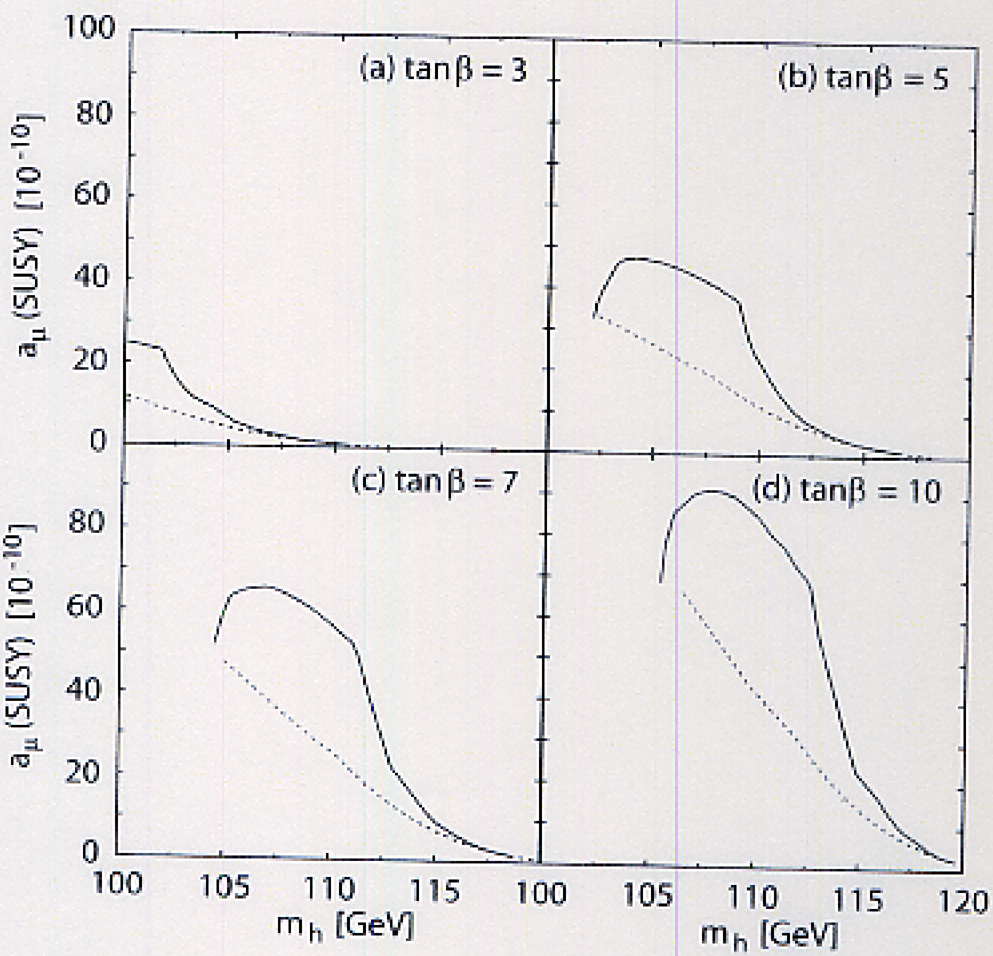
Relation between the smuon and the stop masses is model-dependent

$\Rightarrow$ The answer is model-dependent

$\Rightarrow$ Of course, in the unconstrained MSSM, there is no constraint

Maximum possible value of $a_\mu(\mathrm{SUSY})$ for $a_{\tilde{U}} = 0$ case

- General SUSY SU(5) model (Solid)
  - $M_{1/2}$, $m_{\mathbf{10}}$, $m_{\bar{\mathbf{5}}}$, $m_{H\mathbf{5}}$, $m_{H\bar{\mathbf{5}}}$, $\cdots$
- CMSSM (Dashed)
  - $M_{1/2}$, m_0, $\cdots$

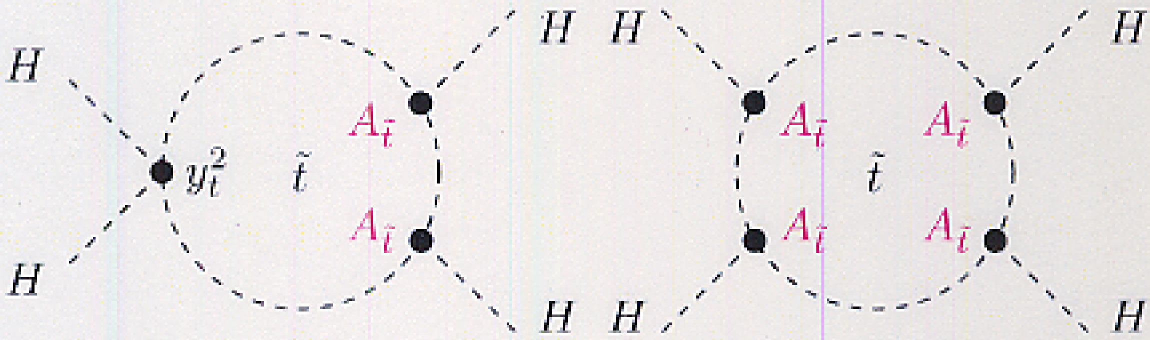


To explain the E821 anomaly at the 1-σ level:

- $\tan\beta \gtrsim 7$ for the general SU(5) model
- $\tan\beta \gtrsim 10$ for CMSSM

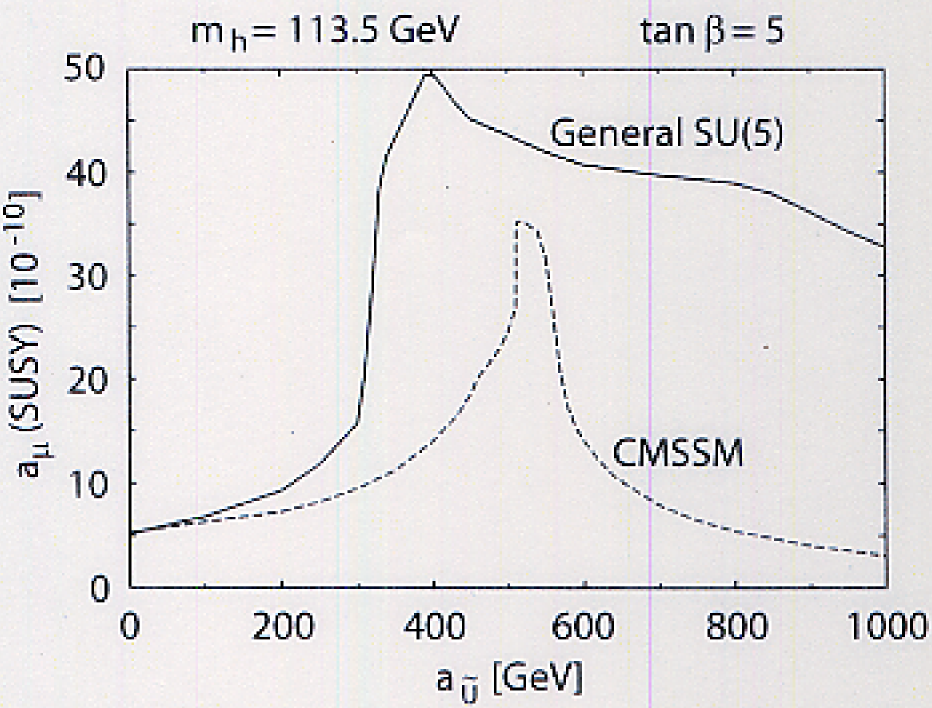
Effect of the trilinear scalar coupling is important

- Trilinear scalar coupling for stop affects the quartic coupling of the SM-like Higgs



$$\Rightarrow \quad \Delta\lambda \simeq \frac{3}{8\pi^2}\left(\frac{y_t^2 A_{\tilde{t}}^2}{m_{\tilde{t}}^2} - \frac{1}{12}\frac{A_{\tilde{t}}^4}{m_{\tilde{t}}^4}\right)\sin^4\beta.$$

A-dependence of the maximum possible value of $a_\mu(\mathrm{SUSY})$



4. Cosmic Microwave Background

SUSY plays significant roles in cosmology:

Inflation, Baryogenesis, Cold dark matter, ...

Some particles may cause cosmological difficulties:

- Gravitino problem
- Cosmological moduli problem

Modulus field ϕ: Very weakly interacting scalar field

- Mass: $m_\phi \sim m_{3/2}$
- Interaction: suppressed by $1/M_{\rm pl}$

  ⇒ For collider experiments, no significance

  ⇒ Cosmologically, it may be important

Cosmology with a modulus field:

- Its initial amplitude may be large ($\sim M_{\rm pl}$)

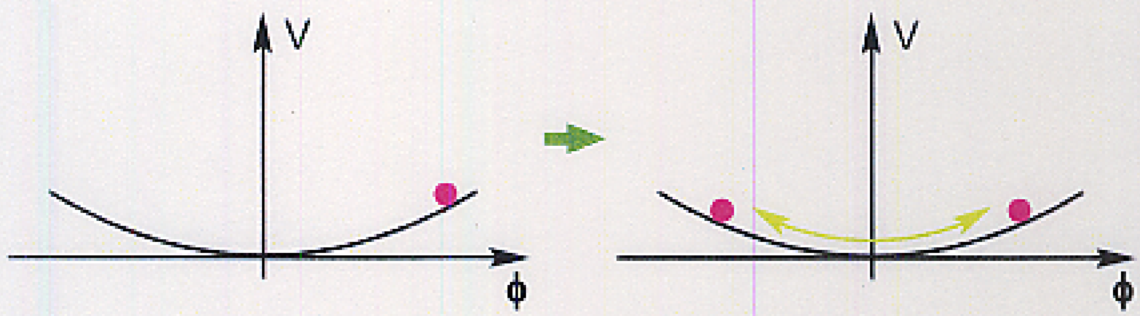
  ⇒ The energy density of ϕ may become large

- Its lifetime is very long

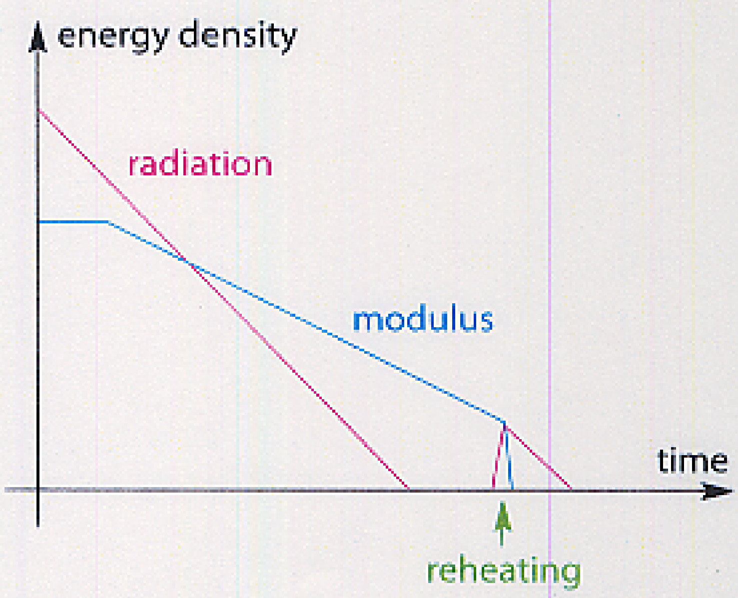
  ⇒ $\tau_\phi \sim 10^{+6}$ sec $\times (m_\phi/100\ \text{GeV})^{-3}$

  ⇒ It decays at a later stage of the evolution of the universe

Cosmological scenario with a modulus field:



1. In the early universe, $\phi \neq 0$
2. ϕ starts to oscillate as the universe expands
3. The modulus field decays and reheats the universe



$T_R \sim 10^{-4}$ MeV $\times (m_\phi/100 \text{ GeV})^{-3/2}$

⇒ For $m_\phi \lesssim O(10 \text{ TeV})$, ϕ decays after the BBN

⇒ Serious damage to the success of the BBN

One solution to this problem: Heavy moduli scenario

If $m_\phi \gtrsim O(10 \text{ TeV})$, ϕ decays before the BBN

If a cosmological modulus field exists, the CMB we observe today originates to ϕ

⇒ The modulus fluctuation affects CMB anisotropy

$$\langle \delta T(\vec{x}, \vec{\gamma}) \delta T(\vec{x}, \vec{\gamma}') \rangle_{\vec{x}} = \frac{1}{4\pi} \sum_l (2l+1) C_l P_l(\vec{\gamma}\vec{\gamma}')$$

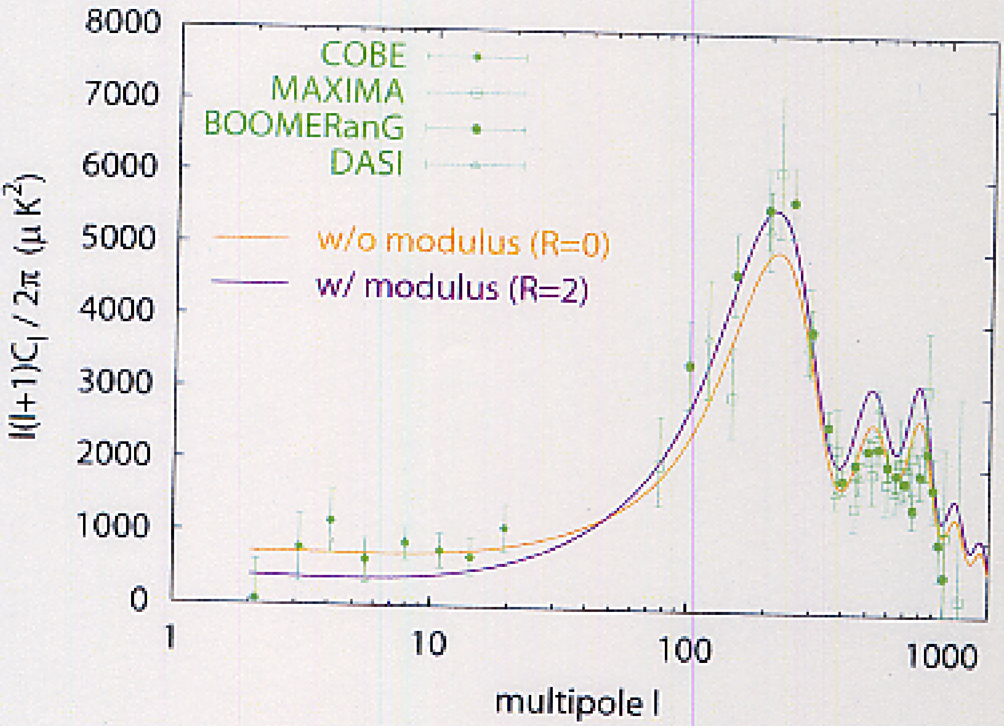
Modulus field is a scalar field: $\phi(t, \vec{x}) = \bar{\phi}(t) + \delta\phi(t, \vec{x})$

$\bar{\phi}(t)$: Zero mode / $\delta\phi(t, \vec{x})$: Fluctuation

During the inflation, $\delta\phi(t, \vec{x})$ is generated: $\delta\phi \simeq H_{\rm inf}/2\pi$

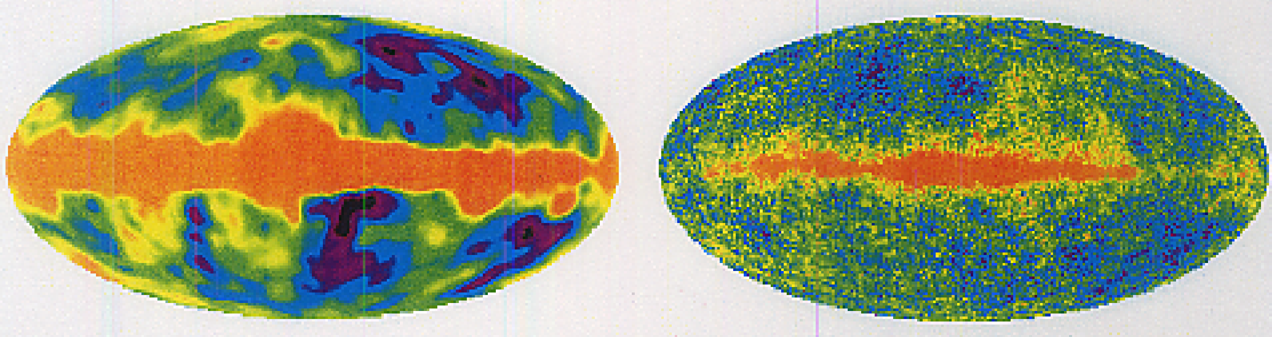
$H_{\rm inf}$: Expansion rate during the inflation

If $\delta\phi$ exists, density fluctuation in ϕ is imprinted into that of radiation (and others) when ϕ decays
[TM & Takahashi]

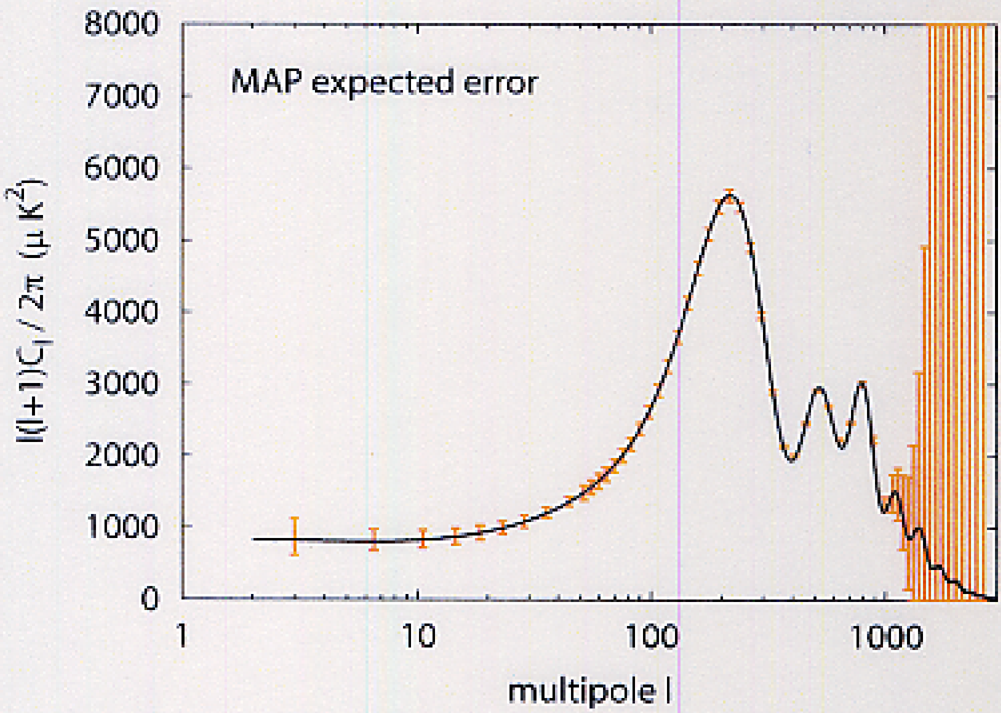


⇒ Enhancement of the first and other peaks

The CMB anisotropies will be precisely measured by future satellite experiments



Left: COBE (4years) / Right: MAP (Simulation)



⇒ The CMB angular power spectrum will be determined at % level

⇒ Cosmology is now more than an order of estimation!

Implication to the heavy moduli scenario:

Deformed angular power spectrum may be observed by MAP / PLANCK experiments!

5. Discussion

Today, I discussed several possible signals of SUSY models at future precision measurements

- CP / flavor violations
- Muon $g-2$
- (Lepton flavor violations)
- Cosmic microwave background radiation

I believe it is important to measure various quantities very precisely

⇒ Precision frontiers at flavor physics / cosmology

Before direct discoveries of the SUSY particles, precision measurements may provide:

- Evidence of the new physics beyond the standard model
- Hint of the energy scale to look for SUSY

Even after discovering the SUSY particles, they provide important informations

- Hint of the SUSY breaking mechanism
- Hint of the origin of the CP / flavor violations

⇒ Once the SUSY is discovered, just improving upper bounds have important implications