超対称性とフレーバー混合

山口　昌弘(東北大)

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科研費特定領域第3回研究会

「質量起源と超対称性物理の研究」

Introduction

- 質量起源：
  - W/Z bosonの質量
  - quark/leptonの質量
    - hadronの質量は議論しない

- Electroweak Symmetry Breakdown (EWSB)

  would-be Nambu-Goldstone bosons

  → eaten by W/Z bosons

  → W/Z massive

Standard Model (SM)

- Two Roles of Higgs Fields:
    - Higgs: elementary scalar with SU(2)L doublet
  - Generates masses to W/Z bosons
    - 4 degrees of freedom
    - 3 are eaten by W/Z bosons to give their masses
    - 1 remains as physical Higgs

    → target of search at collider experiments
  - Geneates masses to quarks/leptons
    - Yukawa interaction

- very economical approach

Naturalness Problem in SM

- Scalar Mass:
  - unstable against radiative corrections
  - Quadratic divergence
- Fine-tuning needed to keep EW scale small

- Probably this is a real problem.

  (cf. Cosmological Constant Problem)

Theories/Models/Scenarios of EWSB

- Supersymmetry
- Extra-Dimensions
- Higgs as Pseudo NG boson
- Technicolor
- Composite Higgs
- Higgsless

  …..

- Dynamical EWSB
  - very attractive: Many people hate elementary scalar
  - symmetry breakdown →NG bosons →W/Z boson masses
  - Difficulty to generate q/l masses
    - FCNC/large top mass

- Elementary Higgs: easy to generate q/l masses Yukawa couplings

- SUSY: Minimal version (MSSM) is compatible with gauge coupling unification.
  - This is not the case for LED.

- SUSY: still the prime candidate for Beyond-SM (since '90)

Supersymmetry

- A solution to naturalness problem
  - “how” problem: how is EW scale protected from huge radiative corrections?
  - “why” problem: why is EW scale so small?
- SUSY gives an answer to the “how” problem.
  - cancellation of quadratic divergence between bosons and fermions “technically natural”
- Approach to the “why” problem
  - dynamical SUSY breaking?
  - Still a big mystery (fine tuning in string landscape !?)

SUSY phenomenology

- superparticles not far from EW scale
- light Higgs <~130 GeV
- gauge coupling unification
- dark matter candidate (neutralino LSP)
- possible effects in FCNC processes (B/D/K and leptons)
- possible effects in CP violation: EDMs

- solid framework
  - experimental study for more than 10 yrs
  - properties well-known by simulation, though not discovered yet
  - advantage to discuss FCNC as well

Talk Plan

- Introduction
- Where is SUSY?
  - naturalness
  - dark matter argument
  - split SUSY
- SUSY around the corner !?
  - Higgs
  - g-2 of muon
  - B-physics

Where is SUSY?

Where are Superpartners?

- Lower bounds
  - charginos/sleptons >100 GeV (LEP)
  - gluinos/squarks >300 GeV (Tevatron)
  - Higgs >114GeV

    → stop typically heavier than 500 GeV (MSSM)

- Upper bounds on superpartners?
  - difficult to answer
  - Let's discuss a bit more (though no clear answer).

naturalness

- naturalness/fine-tuning
  - difficult to address quantitatively
  - Usual statement: they are not far away from EW scale
  - typically(!?) within reach of LEP/ Tevatron/ LHC…. time dependent statement

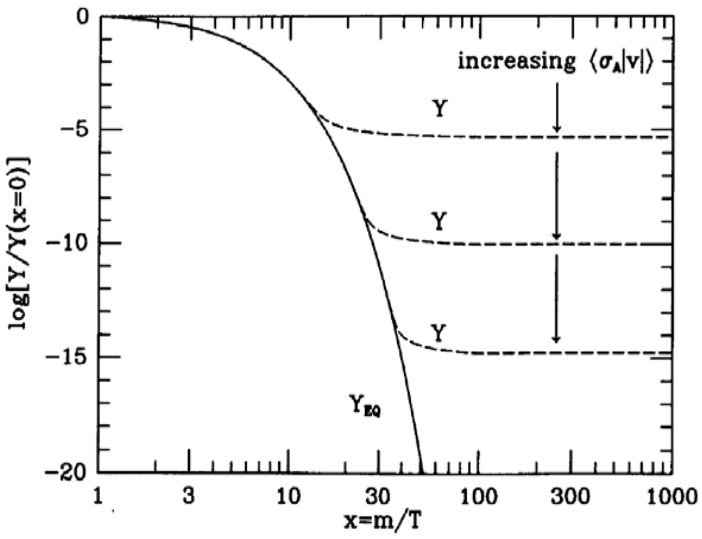
- Fine-tuning may not be a criterion at all. (e.g. split SUSY) see below

Dark Matter Argument

- SUSY provides an excellent candidate for cold dark matter: neutralino dark matter

- Assumptions:
  - Neutralino LSP:
    - A neutralino (a combination of neutral gauginos and neutral higgsinos) is lightest superparticle (LSP).
  - R-parity conservation → LSP is stable
  - Thermal Relic under Standard Thermal History
    - The Universe gradually cools down from very hot universe (T>100GeV) as the Universe expands. Nothing special (such as huge entropy production) happens.

Thermal Relic Abundance

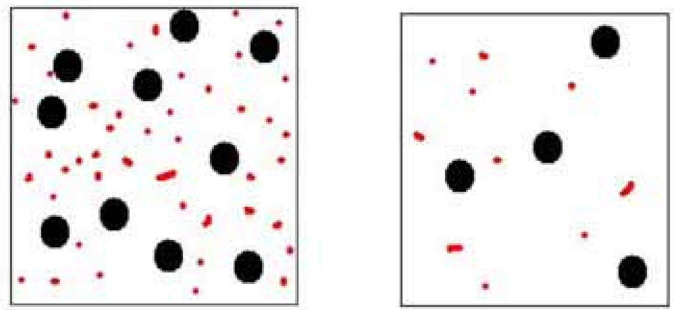


From
Text Book by
Kolb & Turner

At high T, the neutralinos are in thermal equilibrium. As Universe cools down, the neutralinos get non-relativistic and their abundance is Boltzmann suppressed.

Eventually one neutralino LSP cannot find another neutralino to annihilate each other.

→Freeze-out !

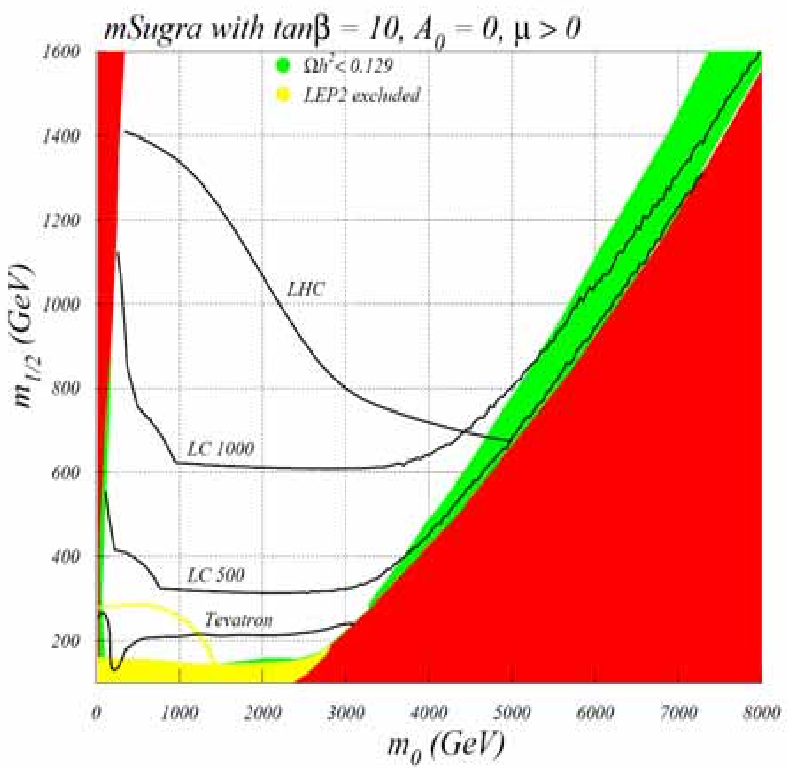


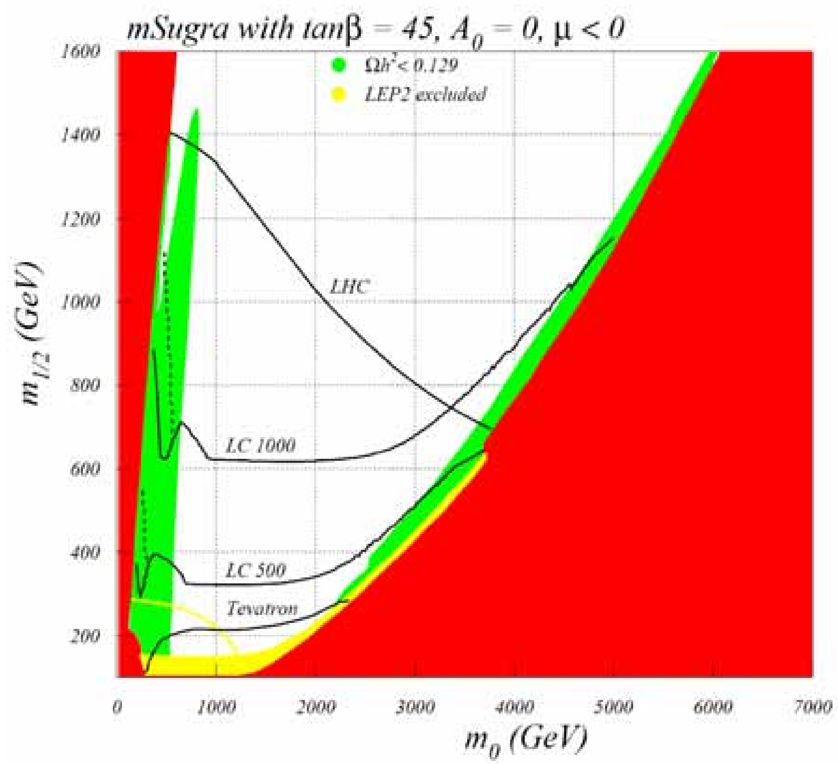
High Temp. Low Temp.

Final Abundance is proportional to the inverse of the annihilation cross section.
A crude estimate:
$\Omega h^2 \sim 1 \times (\langle\sigma_{ann} v\rangle / 10^{-10}\,\mathrm{GeV}^{-2})^{-1}$
motivation for WIMPs

Discovery Reach at Tevatron/ LHC/ ILC

Baer, Belyaev, Krupovnickas & Tata '03





Even LHC may not be able to cover the whole region.

- No practical upper bound on supreparticle masses from the dark matter argument
  - co-annihilation with stau: very effective to reduce the relic abundance
  - (Annihilation into W is also effective in higgsino LSP.)

- Remember that the argument relies on the three assumptions.

Split Supersymmetry

Arkani-Hamed,
Dimopoulos 04

- New scenario motivated by string landscape
  - landscape:

この世はfine tuning**でできた　終末思想**?

- scalar mass**の**fine tuning **は気にしない！**

開き直り!?

Split Supersymmetry (cont.)

- scalar masses >> gaugino masses, higgisino masses

  - ✕ naturalness
  - ○ Higgs mass ~150-160 GeV
  - ○ No SUSY FCNC
  - ○ No SUSY CP
  - ○ dark matter
  - ○ gauge coupling unification

- phenomenology
  - long-lived (practically stable) gluinos

- will be (dis)proved in future collider experiments

SUSY around the corner !?

Some Hints on New Physics

- Higgs Mass
- (g-2) of muon
- B-physics: CP asymmetry in B→phi K, eta' K

Higgs Mass

(although Higgs is a part of SM)

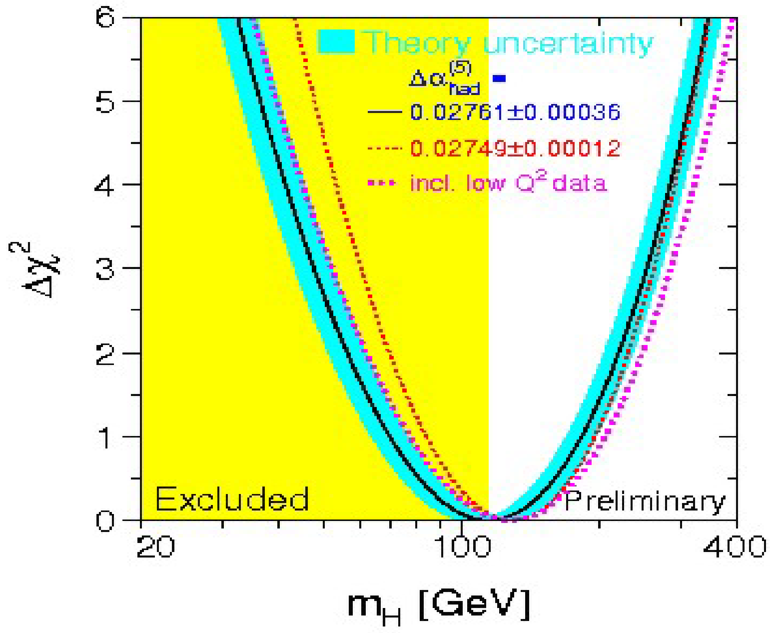
Current limit from direct search

m_h (MSM)>114 GeV

(Smoking Gun Events at LEP II !?)

Global fit prefers light Higgs (in minimal SM)

$m_h(MSM)=114^{+69}_{-45}$ GeV



Higgs in MSSM

$m_h < m_Z = 91$ GeV at tree-level

← quartic coupling given by gauge coupling

Top-stop loop→raises m_h significantly

Large radiation correction needed to raise m_h above 114 GeV (especially for low m_t): Heavy SUSY mass spectrum preferred

"little hierarchy problem in SUSY"

Higgs is waiting to be descovered in MSSM.

We expect Tevatron to tell us crucial information on Higgs.

Note: Higgs mass is very sensitive to top mass

– m_t=174 GeV→178 GeV pushes up m_h by 2 GeV or so.

$(g - 2)_\mu$: Current Status

Values of $a_\mu = (g-2)_\mu/2$

Experiment : 0.0011659203(7) (μ^- included) PDG2004

SM prediction: 0.00116591763(74)

e.g. Hagiwara et al 2004 based on $e^+e^- \to \pi^+\pi^-$

$$\delta a_\mu \sim 26(10) \times 10^{-10}$$

still more than 2-sigma deviation

cf. situation in year 2001:

Exp. 0.0011659202(14)(6)

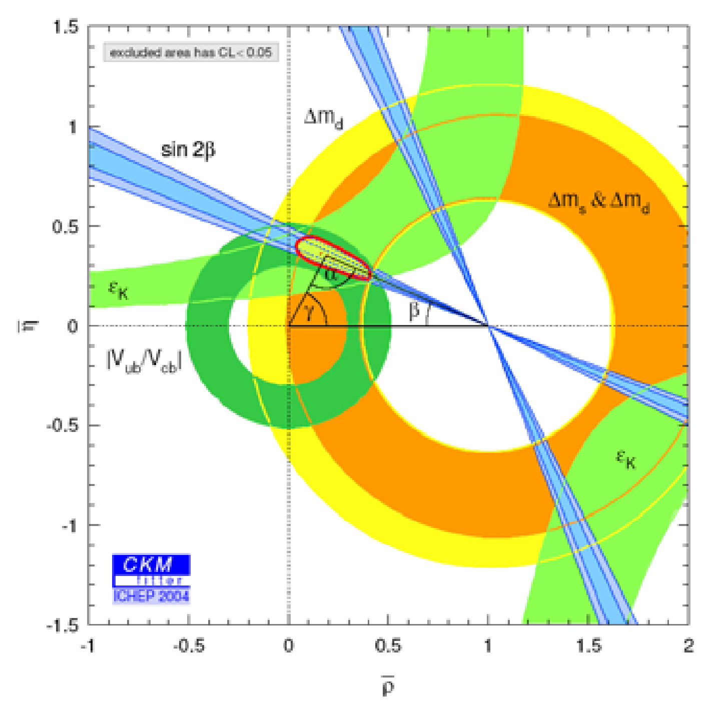
$$\delta a_\mu \sim 43(16) \times 10^{-10}$$

B physics

- CP asymmetry in b→c transition:
  - measurement of sin 2 beta (phi_1)
  - good agreement with SM.

  The Kobayashi-Maskawa framework has been established.

- b→s penguin is now a hot subject.



B→S penguin is interesting

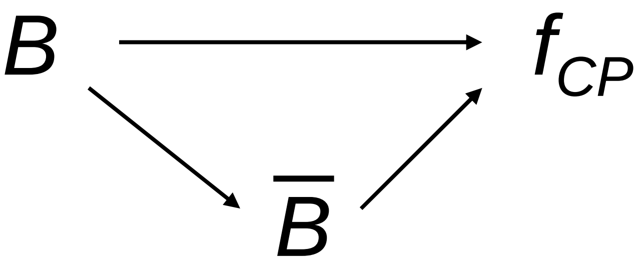
- b → c tree level in SM
- b → s loop level in SM
  - Increasing chance to see New Physics Effects
  - Not fully explored yet

- Prejudice: Mixing between 2-3 generation may be large, as suggested by atmospheric neutrino.

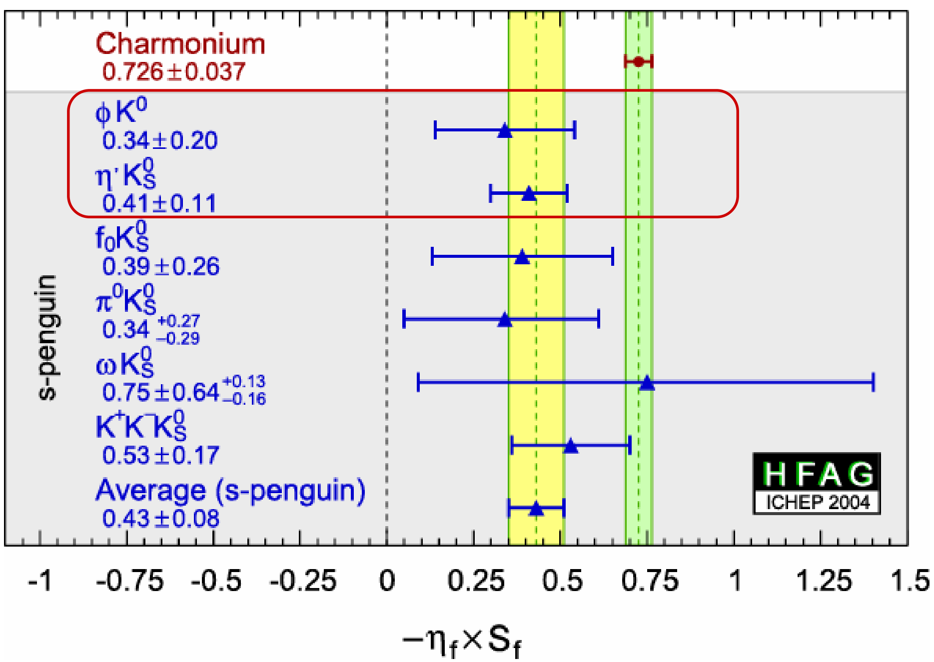
Time dependent CP asymmetry of $B \to \phi K$ & $B \to \eta' K$

○ mixing-induced CP asymmetry

$$a_{CP}(t) \equiv \frac{\Gamma(\bar{B}(t) \to f_{CP}) - \Gamma(B(t) \to f_{CP})}{\Gamma(\bar{B}(t) \to f_{CP}) + \Gamma(B(t) \to f_{CP})}$$
$$= \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \cos \Delta m t + \frac{2 \mathrm{Im} \lambda}{|\lambda|^2 + 1} \sin \Delta m t$$



○ B-factoriesの実験の現状 (summer 2004)



$S_{\phi K^0}$

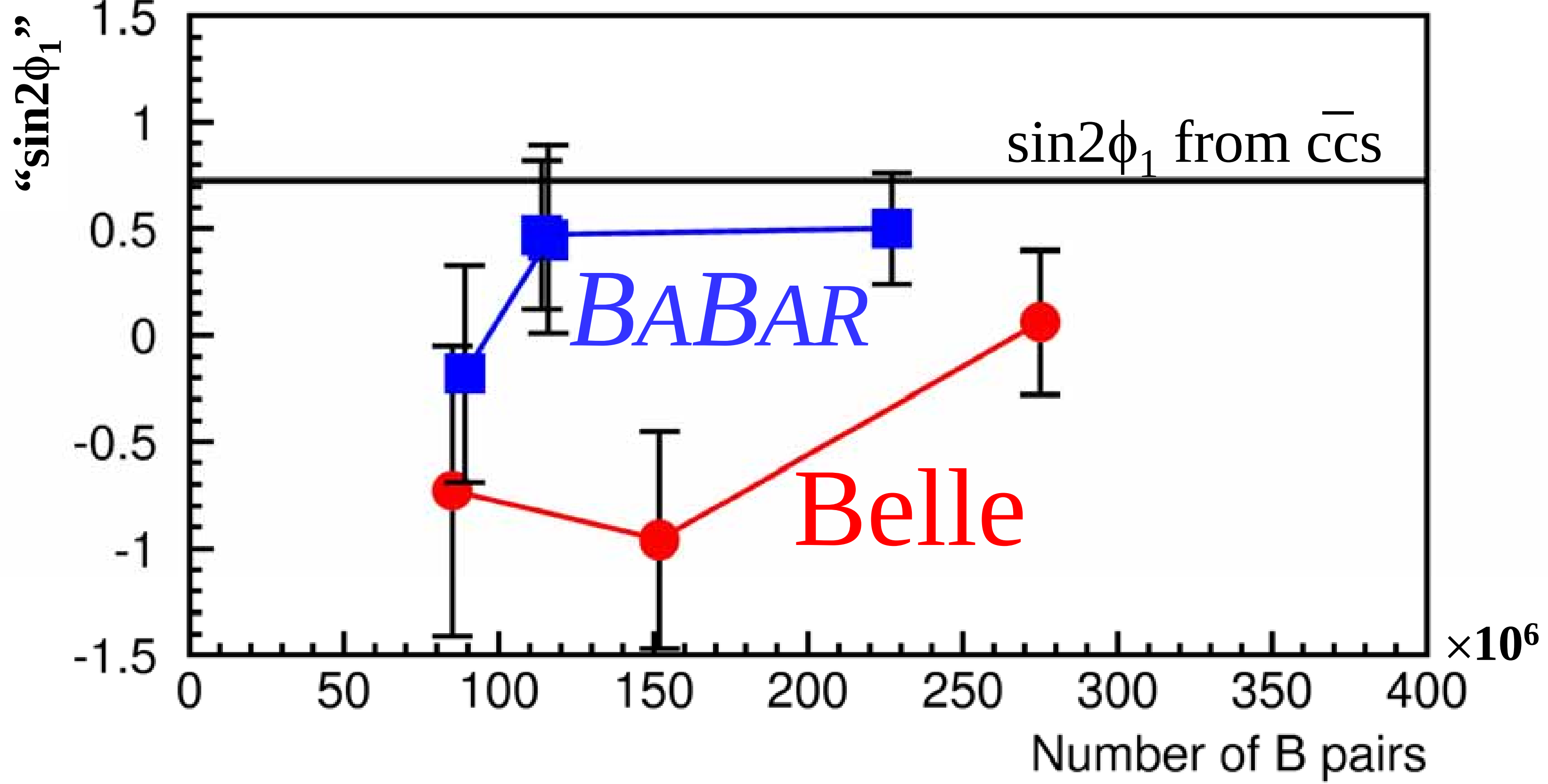
Belle	$0.06 \pm 0.33 \pm 0.09$
BaBar	$0.50 \pm 0.25^{+0.07}_{-0.04}$

$S_{\eta' K_S}$

Belle	$0.65 \pm 0.18 \pm 0.04$
BaBar	$0.27 \pm 0.14 \pm 0.03$

History of “sin2ϕ_1” with ϕK^0

Hazumi, fpcp2004



- Clearly we need more data of year 2005, 2006, 2007,... to say something definite.
- Stay tuned!

- A new feature:
  – Apparent anomalies are seen in more than one mode! ($B \to \phi K$ and $B \to \eta' K$)

-- Ken-Ichi Hikasa
talk in the same meeting
last year

How theorists behave

- Wait and see
  - 99% of 99%CL “new physics” will go away
- Play and enjoy
  - Write as much papers as you can, before it goes away
  - If real, you may hit a gold mine

Take the second approach! In fact we wrote a paper and are preparing another one.

Let us consider SUSY interpretation.

FCNC and CP in SUSY SM

New sources of flavor mixing (with CP violation):
soft SUSY breaking terms

- eg. squark masses, slepton masses (3x3 matrices, non-diagonal)

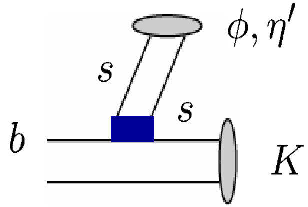
SM: FCNC is suppressed by GIM mechanism
SUSY contribution: No GIM suppression for arbitrary choice of soft masses
→ Too large FCNC for weak scale SUSY
"SUSY FCNC problem"

Sensible Choice of soft masses required:
Various proposals:

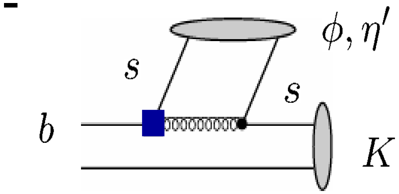
- Universal sfermion masses: mSUGRA, gauge mediation,…
- Aligned sfermion masses: flavor symmetry,…..

SUSY contribution to $B \to \phi K, \eta' K$

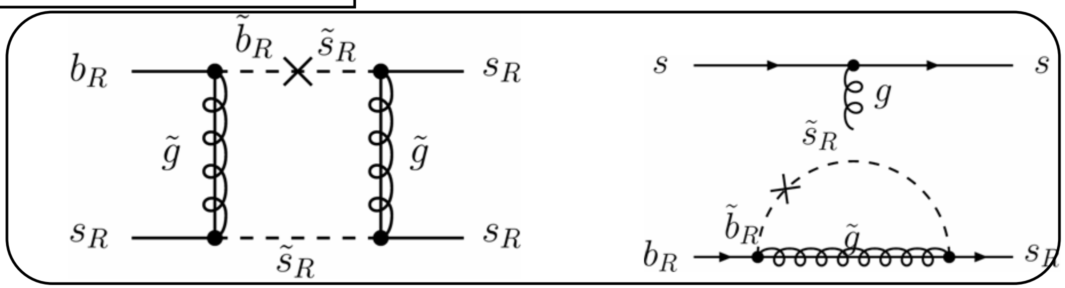
four-quark



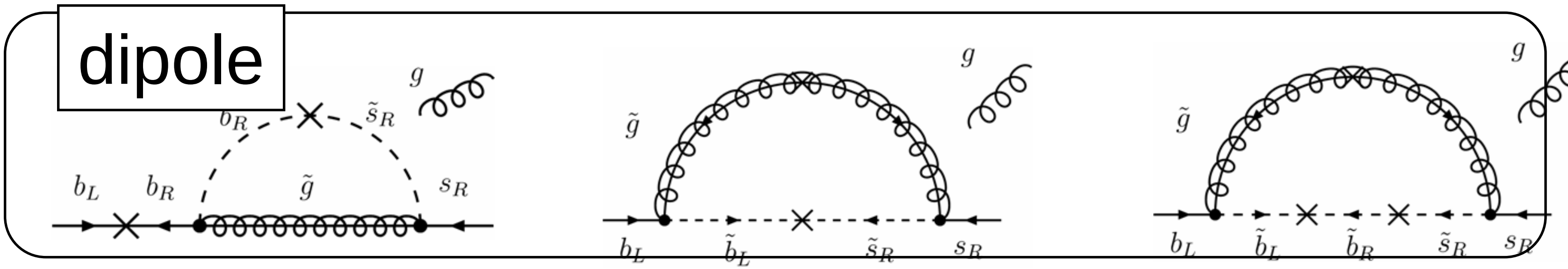
chromo-dipole



four-quark



dipole



Left-Handed (LH) VS Right-Handed (RH)

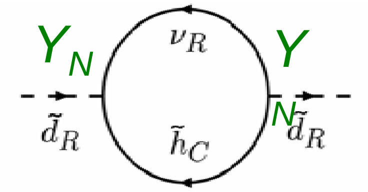
- SM: W-loop, V-A current (LH structure)

- NP: Both chiralities can arise.
  - Pattern of NP contribution depends on chirality structure of flavor violation in NP

- SUSY: Flavor mixing in squark masses
  - LH (SU(2) doublet) squarks
  - RH (SU(2) singlet) squarks

RH vs LH in "SDOWN" sector

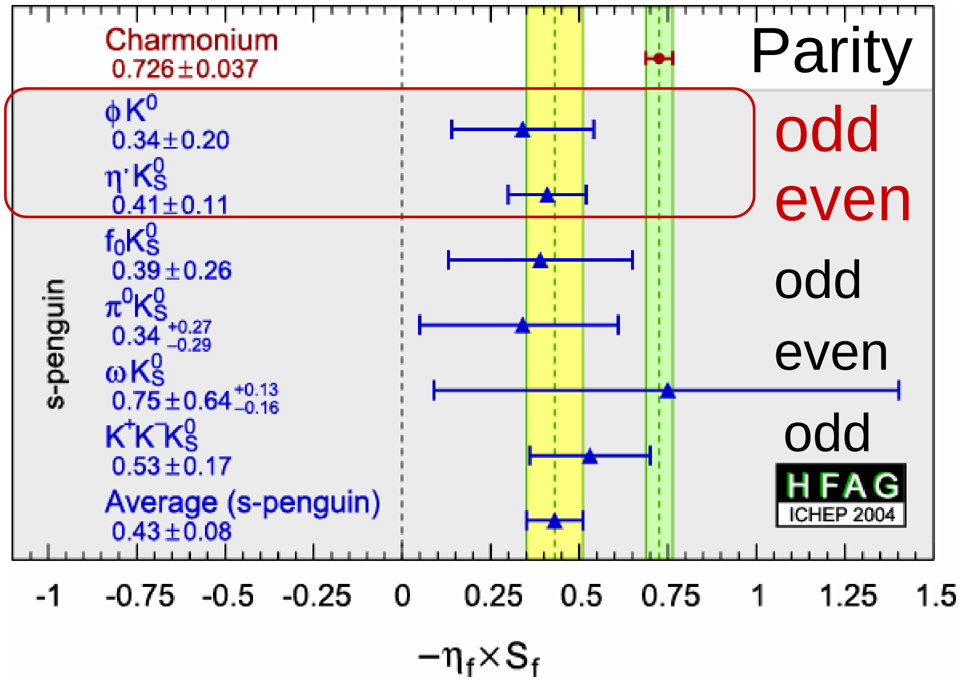
- RH:
  - Large 2-3 RH sdown mixing in SUSY GUT see-saw models (Moroi 01)
    - Atmospheric neutrino implies large 2-3 mixing in neutrino Yukawa
    - SUSY GUTs→ large 2-3 mixing in RH sdown sector
    - Large contribution to B→phi K
  - Cf. solar neutrino → Kaon physics



- LH:
  - Renormalization Group Flow: does not give significant flavor mixing with new CP phase
  - May be imprinted at Ultra-High Energy Scale
  - Flavor symmetry!?
  - Large 2-3 neutrino mixing may also give large 2-3 mixing in LH squark sector.

A SUSY Interpretation of Current Data

Endo, Mishima & MY hep-ph/0409245

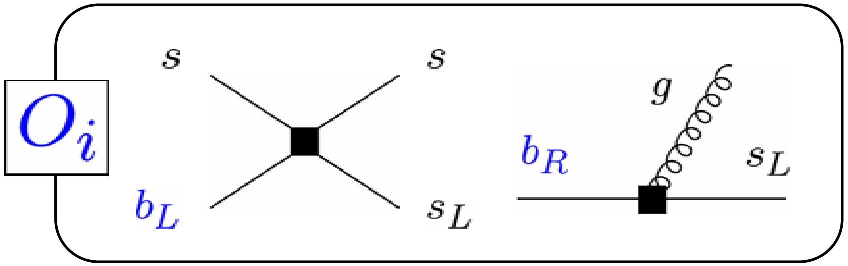


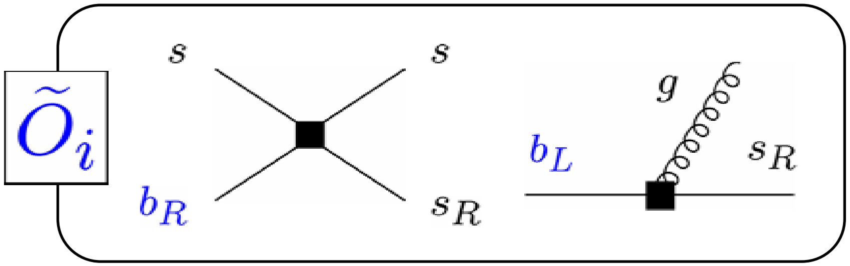
Key Points:

1. Anomalies in more than one mode $(\phi K, \eta' K)$
2. The final states have opposite parity.

Sign of Contributions by Final-state Parity

- Effective Hamiltonian $H_{\rm eff} \sim C_i O_i \;+\; (\tilde{C}, \tilde{O} : R \leftrightarrow L)$





- Decay Amplitude $\langle f|\tilde{O}_i|B_d\rangle = -(-1)^{P_f}\langle f|O_i|B_d\rangle$

$$A \sim \left[\, C_i - (-1)^{P_f}\tilde{C}_i \,\right] \langle f|O_i|B_d\rangle$$

Kagan; Khalil&Kou

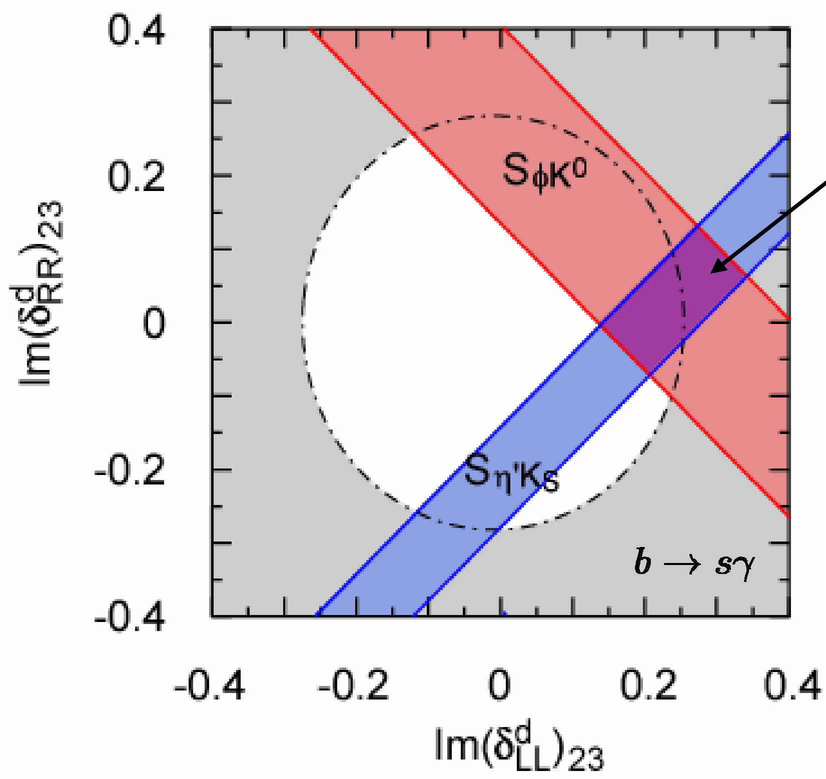
$$A_i^{\rm NP}(\phi K) \propto [\, C_i^{\rm SM} + C_i^{\rm NP} + \tilde{C}_i^{\rm NP} \,]\langle \phi K|O_i|B_d\rangle$$

$$A_i^{\rm NP}(\eta' K) \propto [\, C_i^{\rm SM} + C_i^{\rm NP} - \tilde{C}_i^{\rm NP} \,]\langle \eta' K|O_i|B_d\rangle$$

LH

Numerical Estimation of $S_{b\text{-}s}$ in MSSM

Endo, Mishima & MY 04



favored by current data from B-factories (1σ)

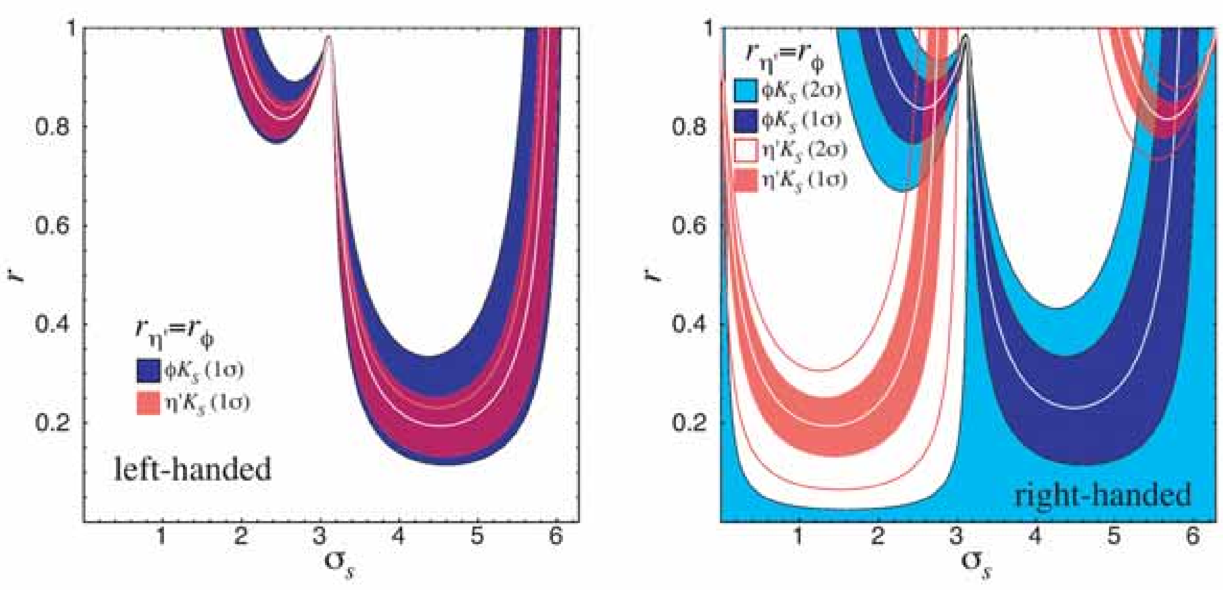
The current data prefers LH dominant case!

$$(\delta^d_{LL,RR})_{23} = (m^2_{\tilde{d}_{L,R}})_{23}/m^2_{\tilde{q}}$$

$$m_{\mathrm{soft}} = 500\ \mathrm{GeV},\ \tan\beta = 10$$

GF: $q^2 = m_b^2/2$

RH completely excluded?



Larson, Murayama & Perez 04

$$\mathcal{A}(B^0 \to \phi, \eta') = \mathcal{A}^{\rm SM}_{\phi,\eta'} \left(1 \pm r_{\phi,\eta'} e^{i\sigma_s}\right)$$

LH interpretation:

OK for generic choice of CP phase

RH interpretation:

may marginally workfor special choice of CP phase and r~1

(danger of b→s gamma etc)

← detailed study (Endo,Mishima &MY, in preparation)

Lesson from this analysis

Future confirmation of the s-penguin anomalies will tell us

- not only the existence of NP
- but also the pattern of chiral structure (and hopefully more structure) of the NP.

↑

Determination of Wilson coefficients

Usage of more than one mode is crucial!

Prospects

More Data on s-penguin: wait and watch!

Correlation with other B decay processes

e.g. $B_S - \bar{B}_S$ mixing: $\Delta m_S \geq 20 - 100\, ps^{-1}$

$Br(B \to \mu^+ \mu^-)$ can be $10^{-7} >> 10^{-9}$ (SM)

Correlation with Lepton Flavor Violation

$\tau \to \mu\gamma, \tau \to \mu\eta$ etc

$\mu \to e\gamma$ etc

Conclusions

- SUSY: **腐ってもSUSY**
  - the prime candidate for Beyond-SM
- Sparticles/Higgs Searches → Lower bounds
- No Clear Upper bounds on Sparticle Masses
- EW precision data prefers light Higgs
  - top**発見の直前の状況に似ている**
  - Expect Evidence (?) from Tevatron RUN II
- Some anomalies:
  - g-2 of muon
  - CP in b→s penguin   More data from B-factories to conclude
- We also expect
  - discovery of superparticles
  - dark matter detection
  - new events such as LFV $B_S - \overline{B}_S$ $B \to \mu^+ \mu^-$