Flavour Physics and CP Violation III

AEPSHEP 2012 at Fukuoka
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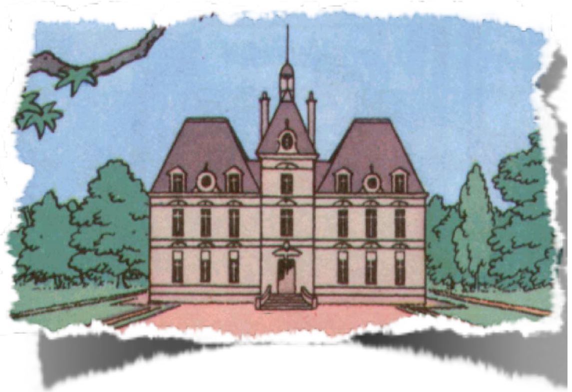
Plan

- 3rd lecture: Searching new physics with flavour physics
  - ★ Flavour constraints on models beyond SM
  - ★ Some examples: 2HDM, 4th generation, SUSY
  - ★ New proposition using angular distribution measurement

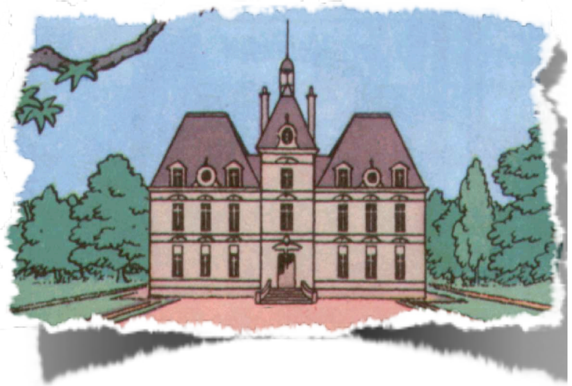
The Standard Model



- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge theory
- Very concise: 19 fundamental parameters:
  - ✓3 gauge coupling (g, g', g_s)
  - ✓1 Strong CP phase
  - ✓9 fermion masses (6 quarks, 3 leptons)
  - ✓4 in CKM matrix (3 mixing, 1 phase)
  - ✓2 in Higgs potential (μ, λ)

Hundreds of, thousands of measurements can be consistently predicted by these small numbers of parameters !

The Standard Model



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    - ✓ 1 Strong CP phase
    - ✓ 9 fermion masses (6 qu
    - ✓ 4 in CKM matrix (3 mixin
    - ✓ 2 in Higgs potential (μ, λ)

There is
nothing outside of the
SM castle?!

Hundreds of, thousands of measurements can be consistently predicted by these small numbers of parameters !

Many propositions!

In this lecture, we learn how to reliably extend the SM and some examples of new physics searches.

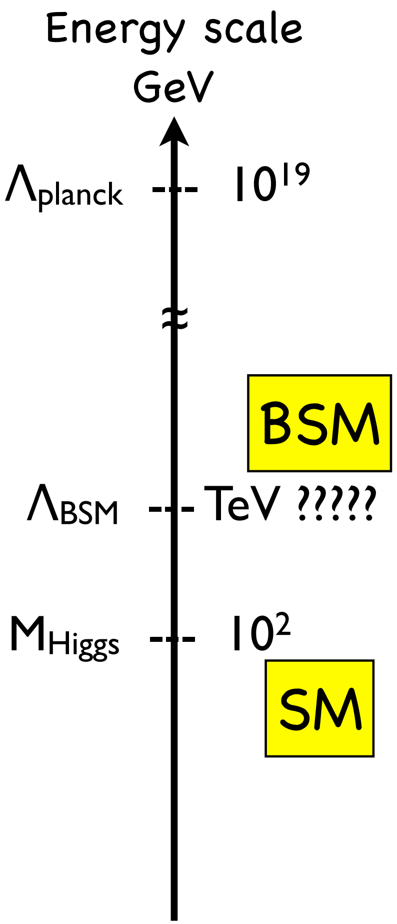
Extending the SM

$$\boxed{\mathcal{L} = \mathcal{L}^{\rm SM}_{SU(3)\times SU(2)\times U(1)} + \mathcal{L}^{\rm BSM}???}$$

- Extending the SM: introduce new fields and new interactions according to certain rules (most fundamental: Lorentz invariance).
- We have to make sure that adding these new fields and interactions would not break the agreement of the experimental observations to the SM predictions.

SM must be the effective theory of the new theory.

SM as an effective Theory



As long as the new physics enters at a "much" higher scale than the electroweak scale, the SM could be still valid as an effective theory.

Renormalizability

$\int dk\, k^{D-1}$
D=0 log-div
D=1 linear-div
D=2 quad.-div

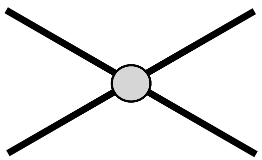
Counting rule of the level of divergence

$$D=4-\sum_f E_f\,(s_f+1)-\sum_i N_i\Delta_i\ ;\qquad \Delta_i=4-d_i-\sum_f n_{if}(s_f+1)$$

SM is constructed by including only interactions which satisfy the renormalizability condition:

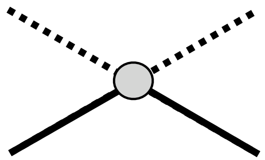
$$\boldsymbol{\Delta_i \geq 0}$$

Otherwise, SM Lagrangian could have included terms like:



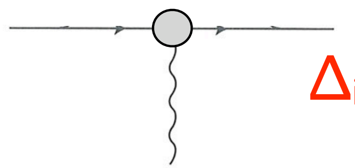
$\Delta_i=-2$

$\frac{c_i}{M^2}\,\overline{\psi}\psi\overline{\psi}\psi$



$\Delta_i=-1$

$\frac{c_i}{M}\,\overline{\psi}\psi\phi^2$



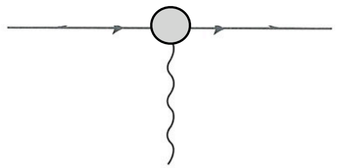
$\Delta_i=-1$

$\frac{c_i}{M}\,\overline{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$

Where is the scale of new physics??

Example of 5 dimensional operator (dipole operator)

$$\frac{e}{M}\,\overline{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$$



This kind of operator induces
anomalous magnetic moment of electron and muon, $a_{e/\mu}$

Precession measurement in the magnetic field

a_e=0.00115965218073(28)

a_μ=0.00116592089(54)(33)

One of the most precisely
measured quantities

Theoretical prediction within SM

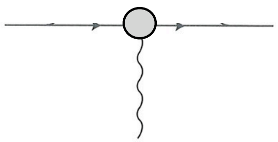
✓ a_e agrees relatively well (up to $\Delta\alpha$)

✓ a_μ is slightly smaller

$a_\mu^{exp}-a_\mu^{SM}=(28.7\pm8.0)\,10^{-10}$

Where is the scale of new physics??

Example of 5 dimensional operator (dipole operator)



$$\frac{e}{M}\,\overline{\psi}\sigma_{\mu\nu}\psi F^{\mu\nu}$$

This interaction induces an extra contribution

4e/M

$a_\mu = 0.00116592089(54)(33)$

SM loop contribution agrees within the term

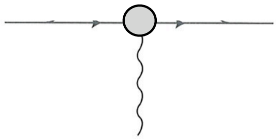
$\delta_\mu \sim 10^{-9} e/2m_\mu$

$M \sim 10^6$ TeV

The indirect search of new physics through quantum loop effect: the higher precision one measure, the higher scale one can probe!

Where is the scale of new physics??

Example of 5 dimensional operator (dipole operator)



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$4e/M$

$M\sim10^6$ TeV

a_μ=0.00116592089(54)(33)

SM loop contribution agrees within the term

$\delta_\mu\sim10^{-9}e/2m_\mu$

But if the new operator obeys a symmetry $\psi\rightarrow\gamma_5\psi,\ m\rightarrow -m$

This interaction induces an extra contribution

$4em_\mu/M^2$

$M\sim10$ TeV

SM loop contribution agrees within the term

$\delta_\mu\sim10^{-9}e/2m_\mu$

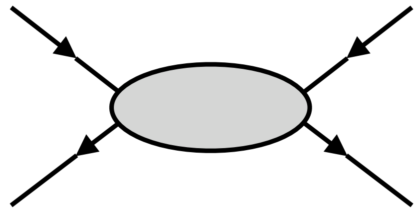
Interplay with direct/indirect searches

Where is the scale of new physics??

Example of 6 dimensional operator (four Fermi operator)

ij=generation
Γ: Dirac matrix

$$\frac{(\delta_{ij})^2}{M^2}\;\overline{\psi}_i\Gamma_\mu\psi_i\;\overline{\psi}_j\Gamma^\mu\psi_j$$



This kind of operator induces K/D/Bd/Bs mixing.
Furthermore, it could be at tree level (strong constraint on M)!

Precession measurement in the magnetic field

$\Delta M_d=(0.507\pm0.004)\ \mathrm{ps}^{-1}$
$\Delta M_s=(17.69\pm0.08)\mathrm{ps}^{-1}$
$\Delta M_K=(5.292\pm0.009)\times10^{-3}\ \mathrm{ps}^{-1}$
$\sin2\Phi_1=0.676\pm0.020$
$\Phi_s=-0.14^{+0.16}_{-0.11}$
$\varepsilon_K=(2.228\pm0.001)\times10^{-3}$

Theoretical prediction within SM

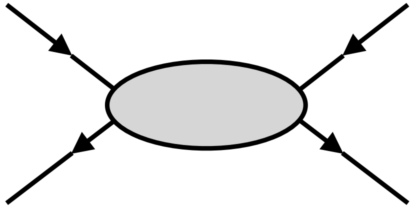
- ✓ *Agreement is relatively good, although the prediction heavily depend on lattice input CKM parameter input. A new physics contribution is still possible within those errors.*

Where is the scale of new physics??

Example of K mixing (ΔM_K, ε_K)

$i=2, j=1$

$$\frac{(\delta_{ij})^2}{M^2}\ \overline{\psi}_i \Gamma_\mu \psi_i\ \overline{\psi}_j \Gamma^\mu \psi_j$$



This interaction induces an extra contribution

δ_{21}/M^2

$M \sim 10^4$ TeV

SM loop contribution agrees within 10-15% error

Where is the scale of new physics??

Example of K mixing (ΔM_K, ε_K)

i=2, j=1

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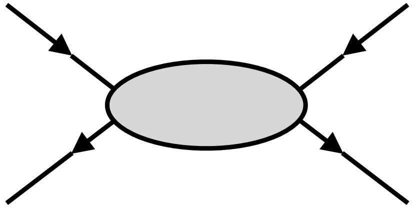


This interaction induces an extra contribution **δ_{21}/M^2**

$M \sim 10^4$ TeV

SM loop contribution agrees within 10-15% error

But if the coupling is CKM like (minimal flavour violation)

This interaction induces an extra contribution **$(V_{td}V_{ts}^*)^2/M^2$**

M~a few TeV

SM loop contribution agrees within 10-15% error

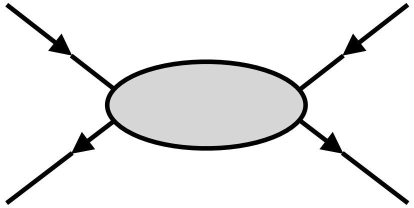
Interplay with direct/indirect searches

Where is the scale of new physics??

Example of K mixing (ΔM_K, ε_K)

$i=2, j=1$

$$\frac{(\delta_{ij})^2}{M^2}\ \overline{\psi}_i\Gamma_\mu\psi_i\ \overline{\psi}_j\Gamma^\mu\psi_j$$



This interaction induces an extra contribution δ_{21}/M^2

M~10⁴ TeV

SM loop contribution agrees within 10-15% error

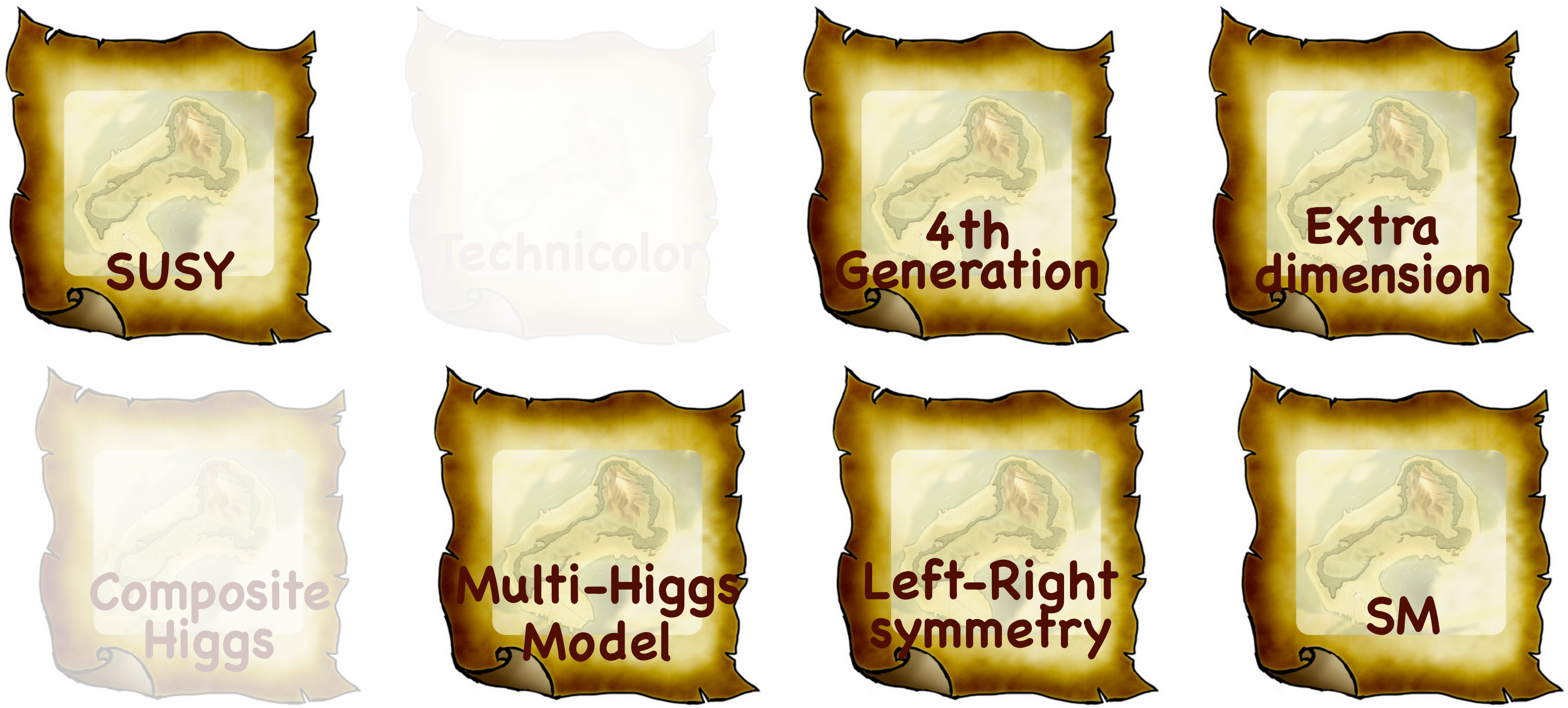
But if the couplin ... lation)

Thi ... on ... %

... ect/indirect searches

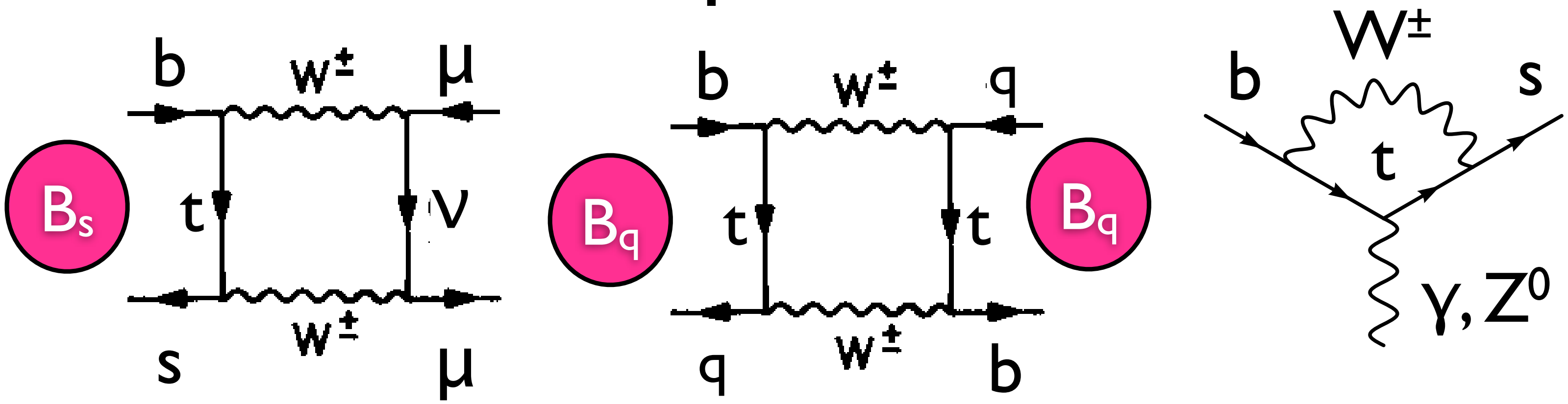
Flavour physics provides very important guides for building a new models beyond SM!

Indirect Search of new physics effects

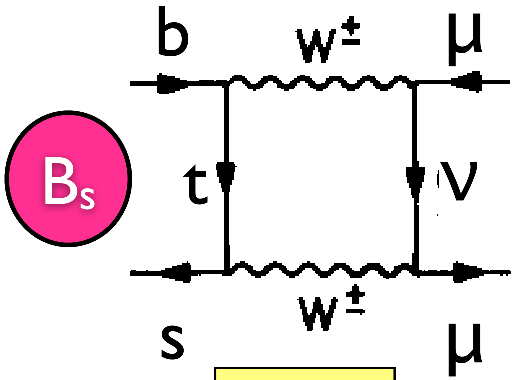


It is just for the matter of the time constraint, I focus on these models...

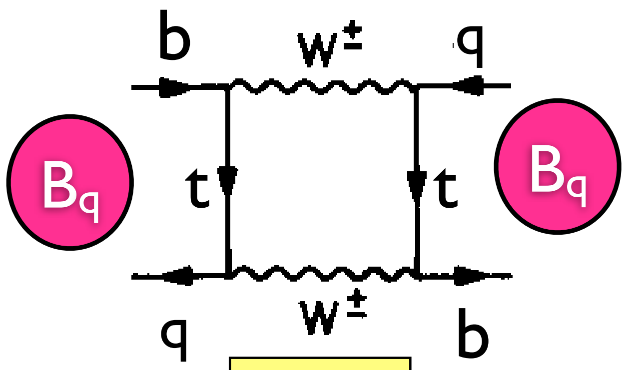
Searching new particle with loop process



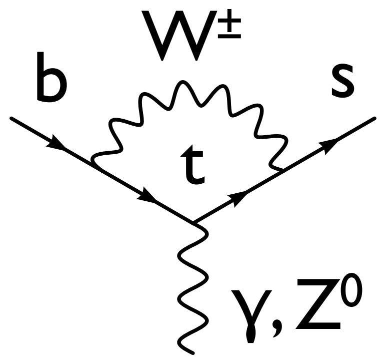
Searching new particle with loop process



$B_0(x_t)$



$C_0(x_t)$

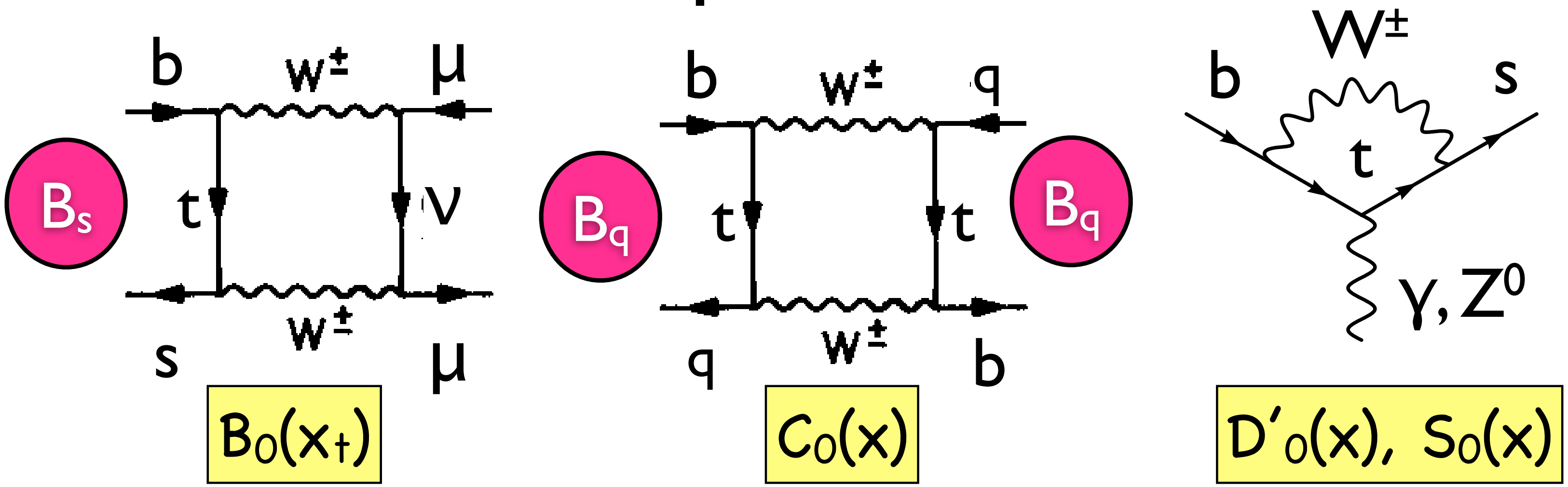


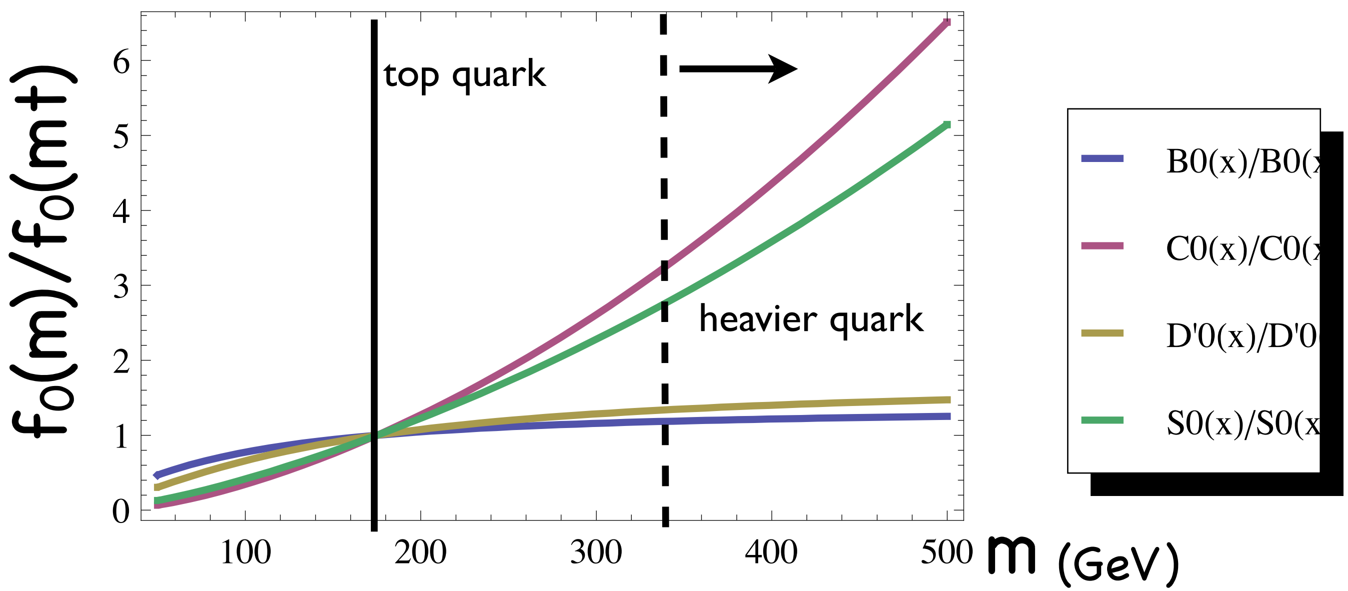
$D'_0(x_t)$, $S_0(x_t)$

loop function
$x = m_t^2/m_W^2$

Indeed, the top quark mass was predicted to be around >100 GeV after the first measurement of ΔM_d (1987 by ARGUS Experiment)

Searching new particle with loop process





Two Higgs doublet model (2HDM)

in nutshell...

✓The number of the Higgs particle is not restricted.

✓Therefore, an extension of the Higgs sector is certainly an interesting possibility to go beyond SM. → The Two Higgs Doublet Model (2HDM)

✓2HDM : 3 neutral and 2 charged scalar Higgs.

✓In order to avoid the overproduction of the CP violation and the FCNC due to the neutral Higgs, a discrete symmetry is often imposed (according to the Weinberg-Glashow Natural Flavour Conservation).

✓Three types of 2HDM are proposed according to the different coupling of the two Higgs doublets to the quarks and leptons.

Multi-Higgs Model

Two Higgs doublet model (2HDM)

In flavour physics, a large contribution from the charged Higgs is expected.

$$\mathcal{L} = \frac{g}{2\sqrt{2}M_W} H^{\pm} \left[V_{ij} m_{u_i} A_u \bar{u}_i (1-\gamma_5) d_j + V_{ij} m_{d_j} A_d \bar{u}_i (1+\gamma_5) d_j \right]$$

$\Phi_1=(\Phi_0,\Phi^+)_1 \rightarrow v_1$; $\Phi_2=(\Phi_0,\Phi^+)_2 \rightarrow v_2$

$\tan\beta = v_2/v_1$, $v_1{}^2 + v_1{}^2 = v^2$

Type I: $A_u=\cot\beta, A_d=-\cot\beta$

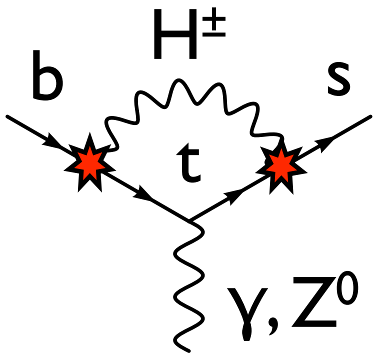
Type II: $A_u=\cot\beta, A_d=\tan\beta$

In particular, we study:

- $B \rightarrow X_s\, \gamma$
- $B \rightarrow \tau\, \nu$

The b → s γ process in 2HDM

Indirect probe of charged Higgs!



$$\mathcal{L} = \frac{g}{2\sqrt{2}M_W} H^{\pm} \left[V_{ij} m_{u_i} A_u \bar{u}_i (1-\gamma_5) d_j + V_{ij} m_{d_j} A_d \bar{u}_i (1+\gamma_5) d_j \right]$$

Type II: $A_u = \cot\beta, A_d = \tan\beta$

Now the loop function looks like...

$$C_{7,8}(M_W) = G_{7,8}^{\mathrm{SM}} \left(\frac{m_t^2}{m_{W^\pm}^2} \right) + \frac{1}{3\tan^2\beta} G_{7,8} \left(\frac{m_t^2}{m_{H^\pm}^2} \right) - F_{7,8} \left(\frac{m_t^2}{m_{H^\pm}^2} \right)$$

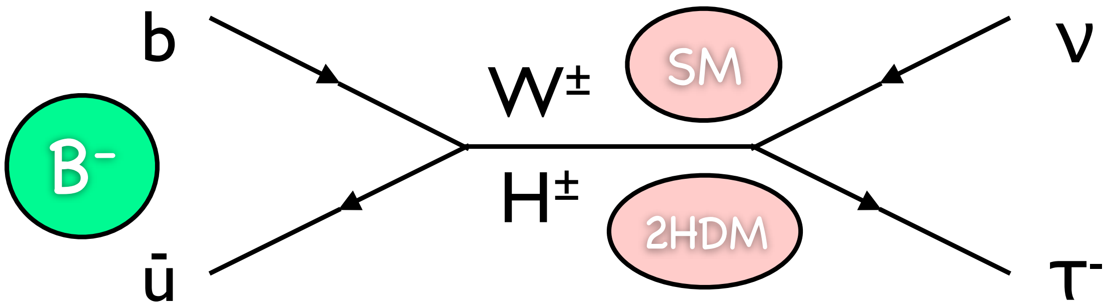
So far, a large deviation from SM is not observed in branching ratio measurement of the b → s γ.

$m_H > 295$ GeV

Multi-Higgs Model

The B→τν process in 2HDM

Indirect probe of charged Higgs!



SM

$$Br(B \to \tau\nu)_{\rm SM} = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

2HDM

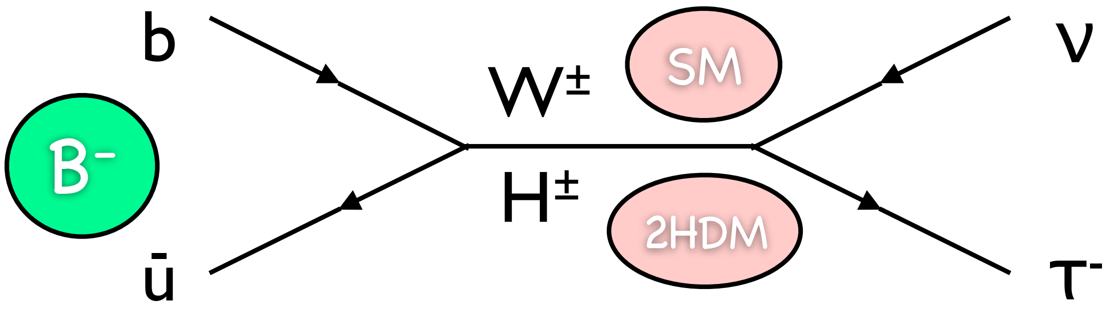
$$Br(B \to \tau\nu) = Br(B \to \tau\nu)_{\rm SM}\left(1 - \tan^2\beta \frac{m_B^2}{m_{H^\pm}^2}\right)^2$$

A small deviation from SM has been seen though the significance is not very high so far.

Multi-Higgs Model

The B→τν process in 2HDM

Indirect probe of charged Higgs!



SM

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2HDM

$$Br(B \to \tau\nu) = Br(B \to \tau\nu)_{\rm SM}\left(1 - \tan^2\beta\,\frac{m_B^2}{m_{H^\pm}^2}\right)^2$$

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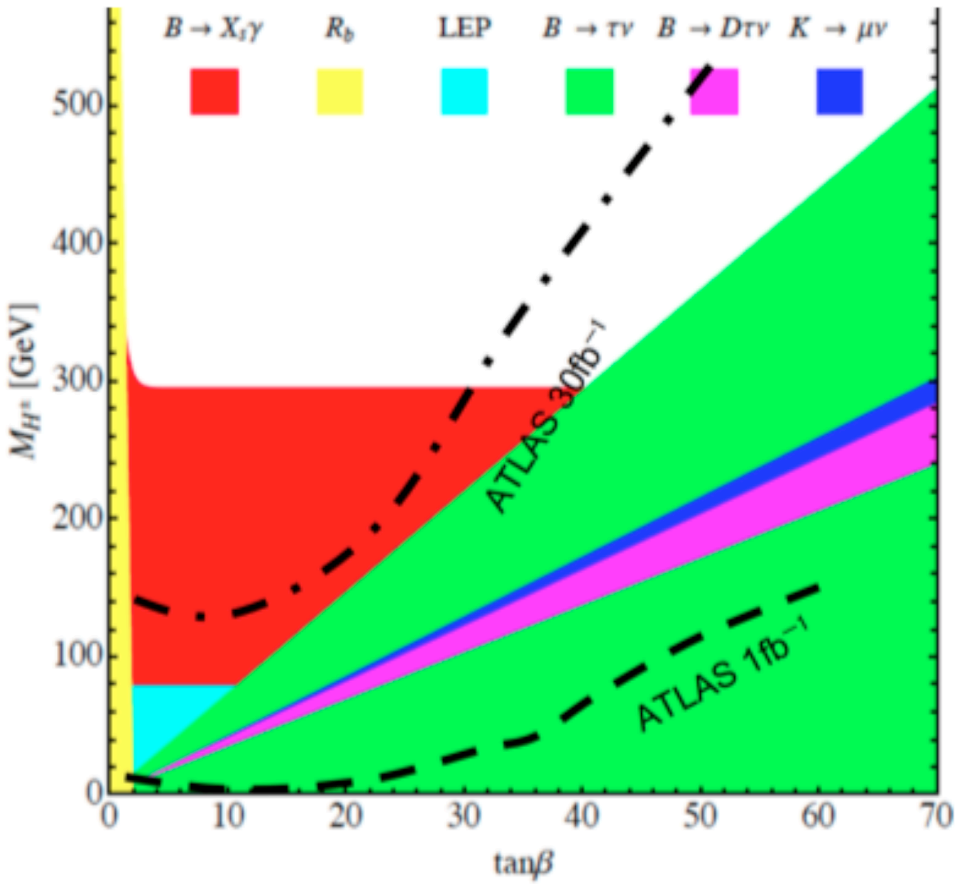
SuperB factories!

Constraints on m_H vs $\tan\beta$



Models with extra fermions

in nutshell...

- ✓Various models beyond SM require extra fermions.
- ✓The new fermions may appear as the 4th generation type (sequential quarks, left(right)-handed t′ and b′ being SU(2) doublet (singlet)), or vector like type (one or two of t′ b′ are added as both left- and right-handed being SU(2) singlet).
- ✓In these models, the unitarity of the 3x3 CKM matrix can be broken since the 3x3 part is only a part of the full matrix (4x4 for sequential and 4x3 or 3x4 with one vector-like case)

The unitarity of the 3x3 CKM matrix can be broken.

$$\left(\begin{array}{ccc|c} & & & * \\ & 3\times 3 & & * \\ & & & * \\ \hline * & * & * & * \end{array}\right)$$

4th generation model

In flavour physics, a large contribution from the heavy b′ and t′ quarks are expected!

4th generation type

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L, \begin{pmatrix} t' \\ b' \end{pmatrix}_L; \quad u_R, d_R, s_R, c_R, b_R, t_R, t'_R, b'_R,$$

Vector-like quark type

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L t'_L \qquad u_R, d_R, s_R, c_R, b_R, t_R\, t'_R$$

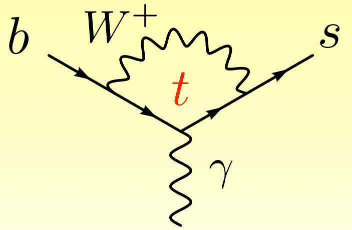
$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L b'_L \qquad u_R, d_R, s_R, c_R, b_R, t_R\, b'_R$$

In particular, we study:

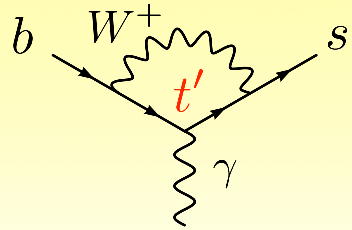
- B → Xs γ
- B_d mixing

4th generation model

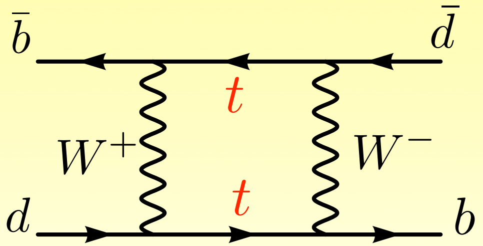
Indirect probe of heavy top quark!



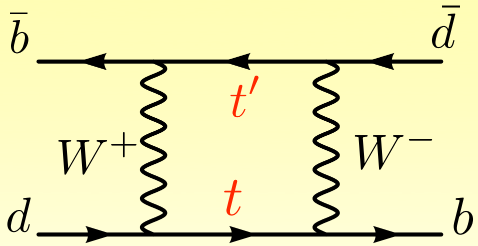
$V_{tb}V_{ts}^{*}\, D_0'(m_t)$



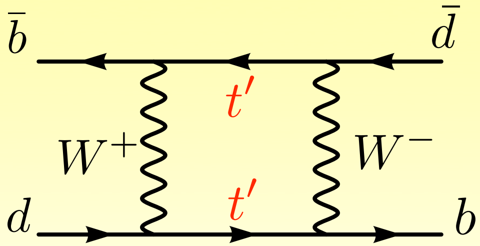
$V_{t'b}V_{t's}^{*}\, D_0'(m_{t'})$



$(V_{tb}V_{td}^{*})^2\, S_0(m_t)$



$(V_{tb}V_{td}^{*})(V_{t'b}V_{t'd}^{*})\, S_0(m_t, m_{t'})$

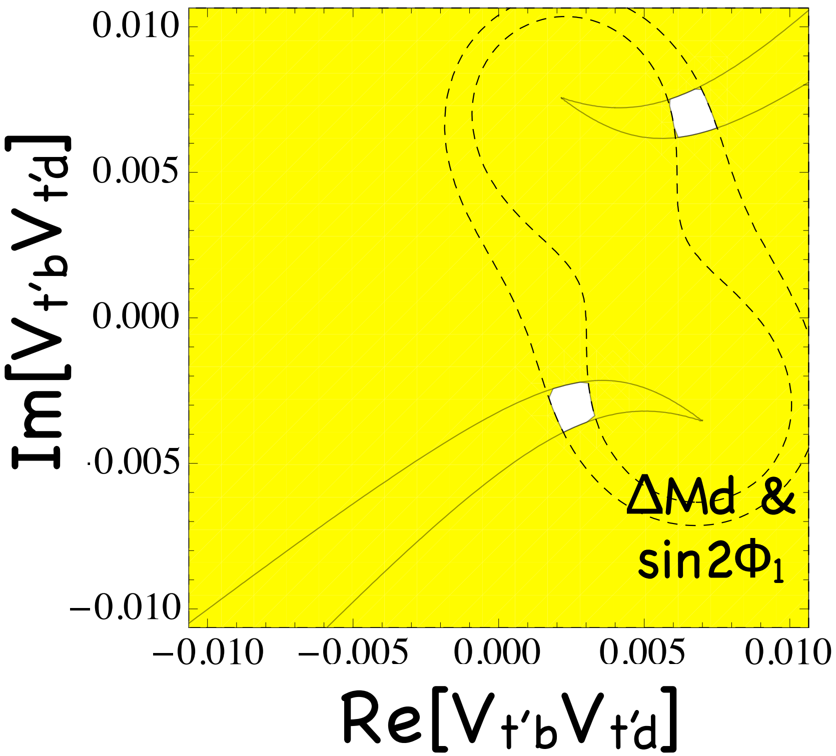


$(V_{t'b}V_{t'd}^{*})^2\, S_0(m_{t'})$

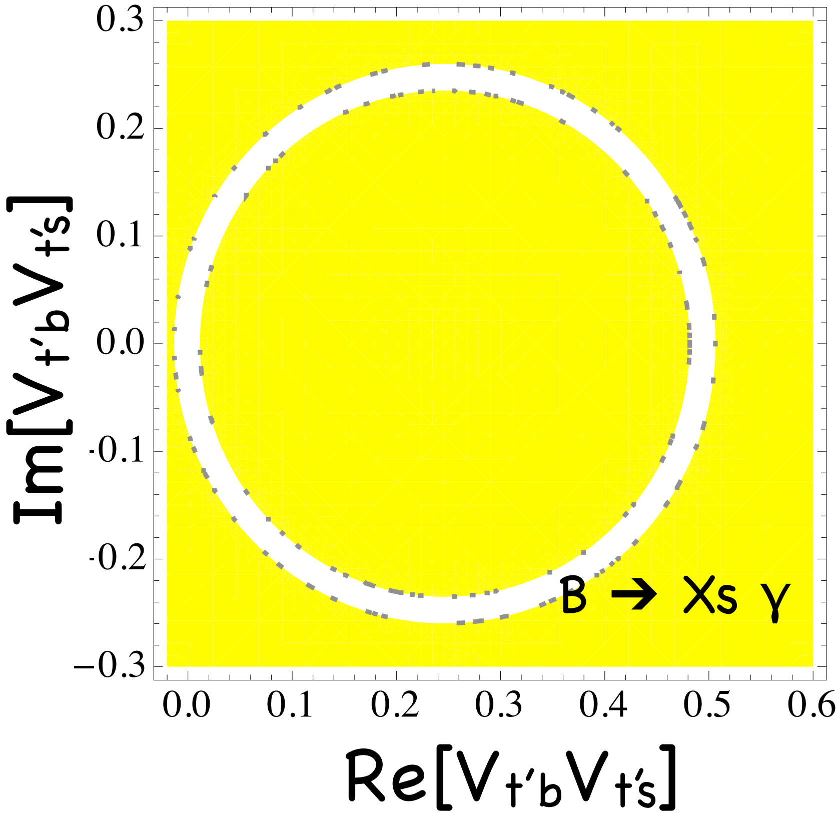
Extra fermions

4th generation model

Constraint on the 4x4 CKM matrix

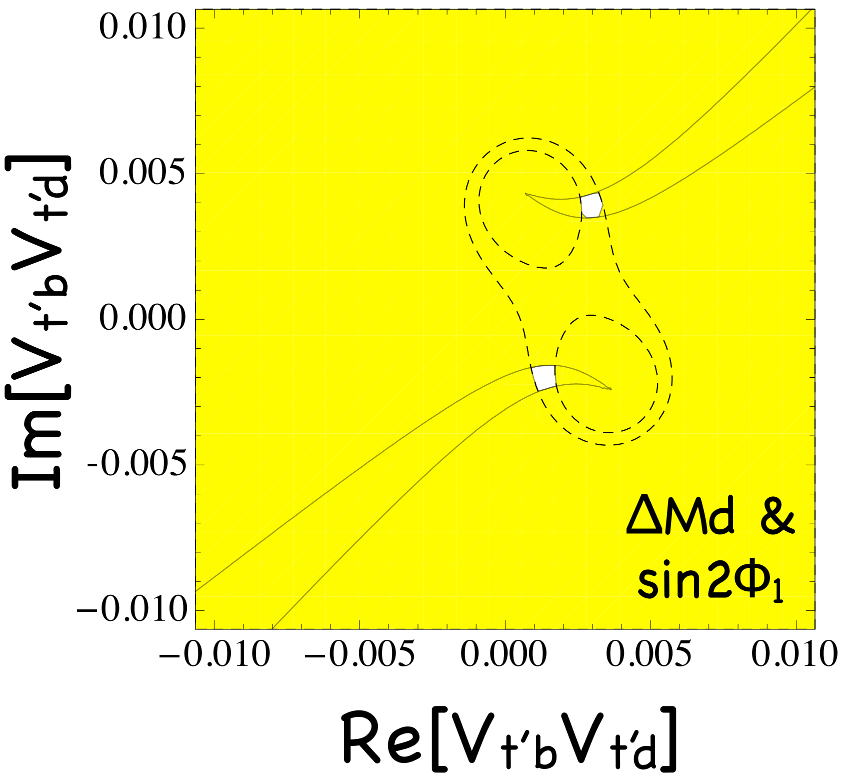


For mt'=400 GeV

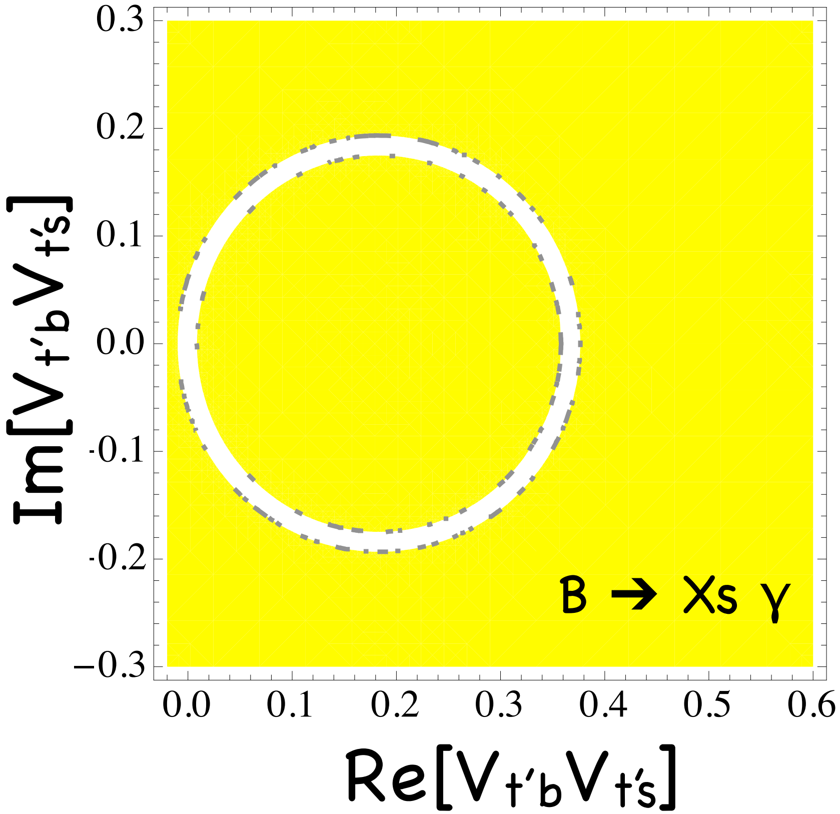


4th generation model

Constraint on the 4x4 CKM matrix



For mt'=600 GeV



SUSY

in nutshell...

✓SUSY relates the particles with spin n to those with spin n ±1/2 (eg. the gauge bosons have their fermion superpartners and fermions have their scalar superpartners).

✓SUSY has an ability to solve the so-called hierarchy problem of the SM (strong motivation for SUSY).

✓If supersymmetry is exact, the masses of the SUSY particles should be the same as their partners'.

✓ However, no candidate for SUSY particle has been detected by experiments so far. This indicates that a more realistic model should contain the SUSY breaking terms.

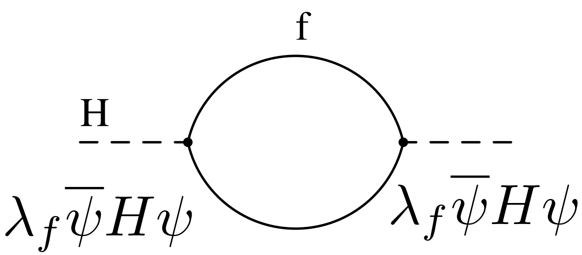
✓The SUSY breaking term introduces a number of free parameters corresponding to the masses and mixings of the superpartners to this model. Even in the MSSM, the number of these new parameters is more than a hundred.

SUSY breaking

Adding the soft SUSY breaking contribution, we find

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SUSY} + \mathcal{L}_{\rm soft\ \ breaking}}$$

$\boxed{[g_{soft}]=[M]^{\Delta_i} \text{ with } \Delta_i>0}$



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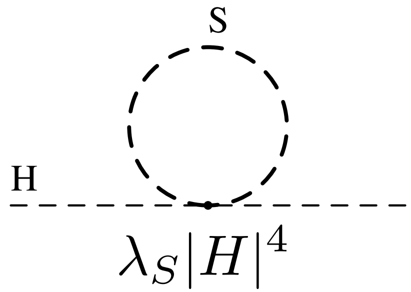


+ …

$$\delta\mu^2 = \cancel{\frac{1}{8\pi^2}(\lambda_S - |\lambda_f|^2)\Lambda_{\rm UV}^2} + m_{\rm soft}^2 \left[\frac{\lambda}{16\pi^2}\ln(\Lambda_{\rm UV}/m_{\rm soft}) + \cdots\right]$$

$\boxed{\begin{array}{c}\lambda=1 \\ \Lambda_{UV}=10^{18}\text{ GeV}\end{array}}$ $\longleftrightarrow$ $\boxed{m_{soft}=O(1\text{ TeV})}$

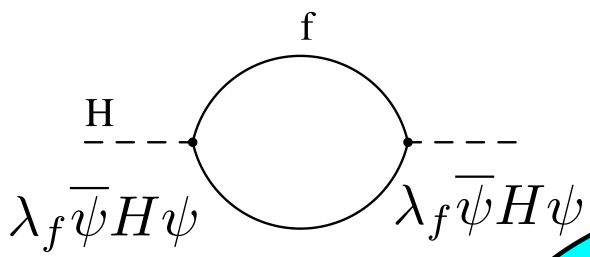
$$\delta\mu^2 = (100\ \mathrm{GeV})^2$$

SUSY breaking

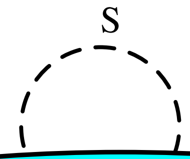
Adding the soft SUSY breaking contribution, we find

$$\mathcal{L} = \mathcal{L}_{\rm SUSY} + \mathcal{L}_{\rm soft\ \ breaking}$$

$[g_{soft}]=[M]^{\Delta i}$ with $\Delta_i>0$



+



$$\delta\mu^2 = \frac{1}{8\pi^2}(\lambda_S - |\lambda_f|^2$$

GOOD NEWS:
The SUSY particles should be around 1 TeV!!!

$\lambda=1$
$\Lambda_{UV}=10^{18}$ GeV

$\longleftrightarrow$ $m_{soft}=O(1\ \text{TeV})$

$$\delta\mu^2 = (100\ \text{GeV})^2$$

SUSY breaking

Adding the soft SUSY breaking contribution, we find

$$\boxed{\mathcal{L} = \mathcal{L}_{\rm SUSY} + \mathcal{L}_{\rm soft\ \ breaking}}$$

$[g_{soft}]=[M]^{\Delta i}$ with $\Delta_i>0$

$$\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} = & -\frac{1}{2}\left(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B}\right) + c.c. \\
& -\left(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{d}}\mathbf{a_d}\tilde{L}H_d\right) + c.c. \\
& -m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + c.c) \\
& -\tilde{Q}^\dagger\mathbf{m^2_Q}\tilde{Q} - \tilde{L}^\dagger\mathbf{m^2_L}\tilde{L} - \tilde{\bar{u}}\mathbf{m^2_{\bar{u}}}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m^2_{\bar{d}}}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m^2_{\bar{e}}}\tilde{\bar{e}}^\dagger
\end{aligned}$$

The SUSY breaking term introduces total of 105 new masses, mixings and phases. These new terms can generate new phenomena which may be seen in experiments.

SUSY CP/flavour problem

SM	SUSY
☑ There is only one source of CP violation. ☑ FCNC is suppressed naturally by the GIM mechanism.	☑ There is too many sources of CP violation (large EDM expected). ☑ FCNC can occur since there is, a priori, no GIM mechanism.

Avoiding SUSY CP/flavour problem

$$\mathcal{L}_{\rm soft}^{\rm MSSM} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B}) + c.c.$$
$$-(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{d}}\mathbf{a_d}\tilde{L}H_d) + c.c.$$
$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + c.c)$$
$$-\tilde{Q}^\dagger \mathbf{m_Q^2}\tilde{Q} - \tilde{L}^\dagger \mathbf{m_L^2}\tilde{L} - \tilde{\bar{u}}\mathbf{m_{\bar{u}}^2}\tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\mathbf{m_{\bar{d}}^2}\tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\mathbf{m_{\bar{e}}^2}\tilde{\bar{e}}^\dagger$$

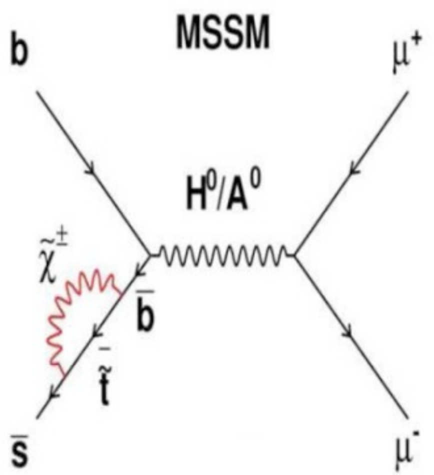
Assumption

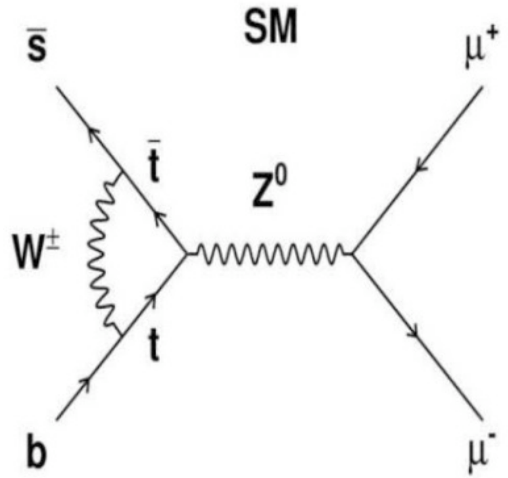
$$\mathbf{m_Q^2} = m_Q^2\mathbf{1}, \mathbf{m_L^2} = m_L^2\mathbf{1}, \mathbf{m_{\bar{u}}^2} = m_{\bar{u}}^2\mathbf{1}, \mathbf{m_{\bar{d}}^2} = m_{\bar{d}}^2\mathbf{1}, \mathbf{m_{\bar{e}}^2} = m_{\bar{e}}^2\mathbf{1}$$
$$\mathbf{a_u} = A_{u0}\mathbf{y_u}, \quad \mathbf{a_d} = A_{u0}\mathbf{y_d}, \quad \mathbf{a_e} = A_{u0}\mathbf{y_e}$$
$$\arg(M_{1\sim 3}), \arg(A_{u0}), \arg(A_{d0}), \arg(A_{e0}) = 0, \text{or } \pi$$

We often work on a simplified model e.g. mSUGRA → **m_0, $m_{1/2}$, A_0, μ, $\tan\beta$**

SUSY contributions may still appear through
- Renormalization running
- Large $\tan\beta$ case (e.g. $B \to \mu^+\mu^-$)

SUSY indirect search





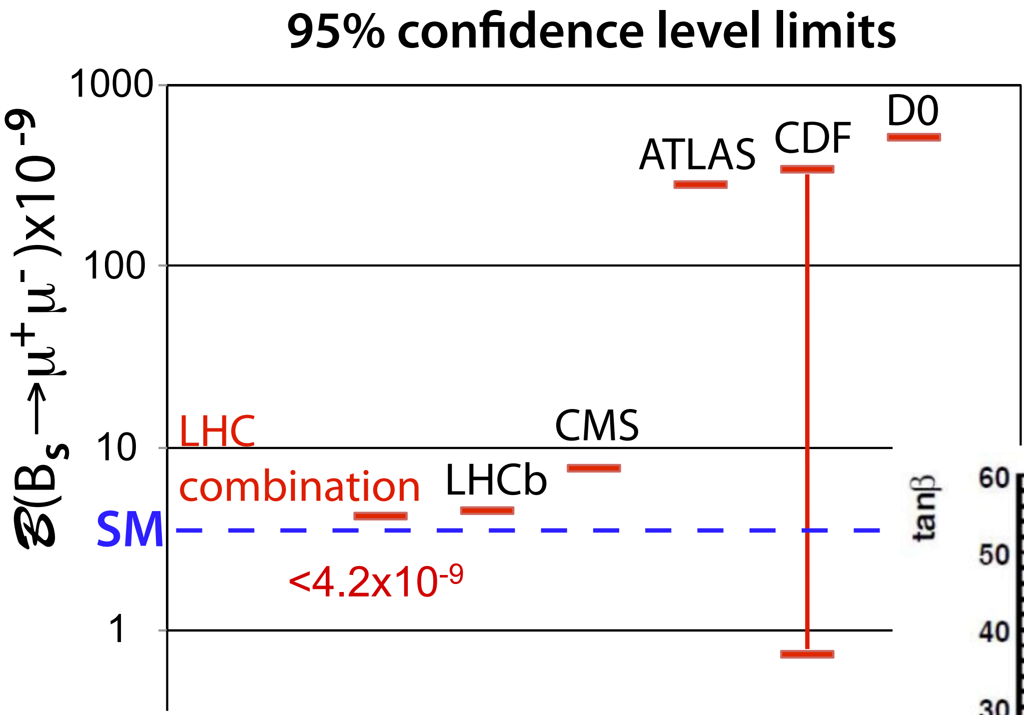
$$Br(B_s \to \mu^+\mu^-)_{\mathrm{MSSM}} = \frac{m_b^2 m_\mu^2 \tan^6\beta}{M_{A_0}^4}$$

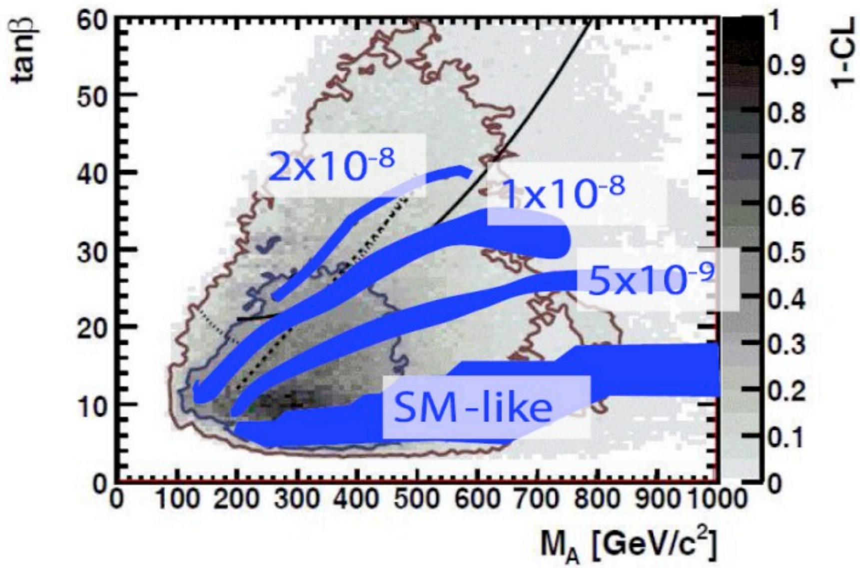
$$Br(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.2 \pm 0.2) \times 10^{-9}$$

It could be large if tanβ is large

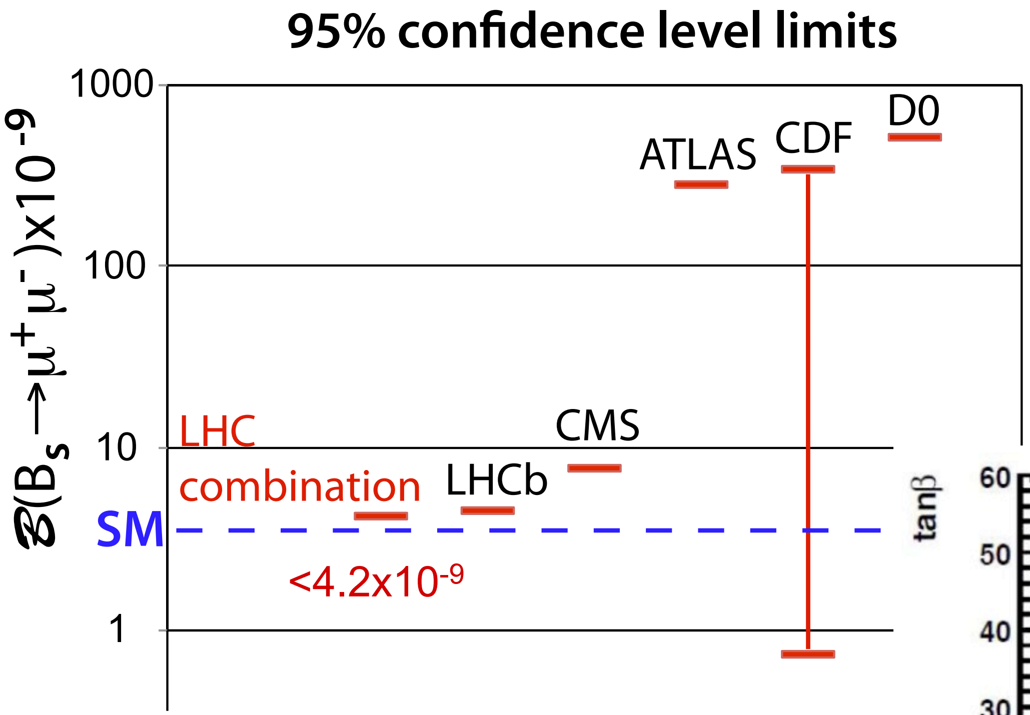
extremely small!!

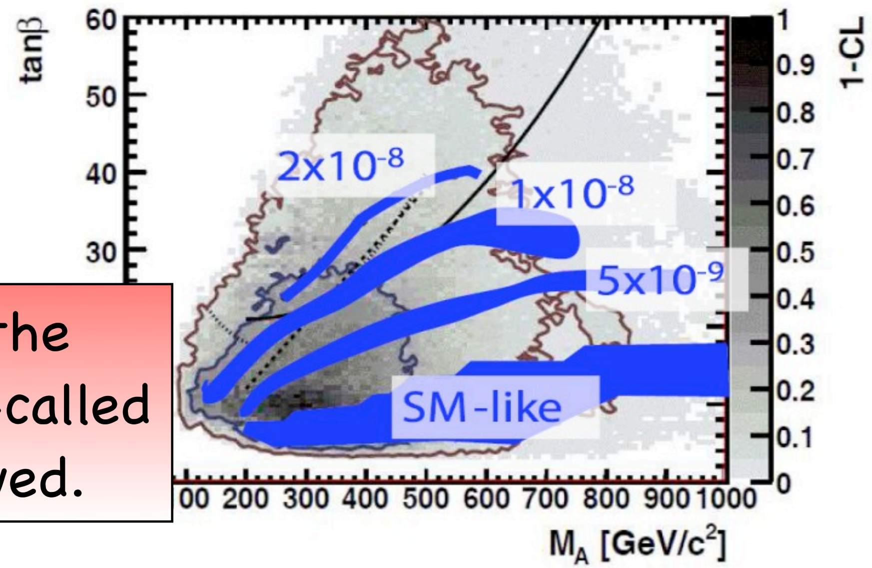
SUSY indirect search





SUSY indirect search





It is now important to see in the global-fit in which extent the so-called constrained MSSM is still allowed.

NMFV SUSY

NMFV=Non-Minimal Flavour Violating

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}(M_3\tilde{g}\tilde{g} + M_2\tilde{W}\tilde{W} + M_1\tilde{B}\tilde{B}) + c.c.$$
$$-(\tilde{\bar{u}}\mathbf{a_u}\tilde{Q}H_u - \tilde{\bar{d}}\mathbf{a_d}\tilde{Q}H_d - \tilde{\bar{d}}\mathbf{a_d}\tilde{L}H_d) + c.c.$$
$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + c.c)$$
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Less strong Assumption

$$\mathbf{m_{AB}^{2\text{SCKM}}} = \begin{pmatrix} (m_{AB}^2)_{11} & (\Delta_{AB})_{12} & (\Delta_{AB})_{13} \\ (\Delta_{AB})_{21} & (m_{AB}^2)_{22} & (\Delta_{AB})_{23} \\ (\Delta_{AB})_{31} & (\Delta_{AB})_{32} & (m_{AB}^2)_{33} \end{pmatrix}$$

Mass Insertion Parameter

$$\frac{(\Delta_{AB})_{ij}}{m_{\text{squark}}} \equiv (\delta_{AB})_{ij}$$

ij: generation
AB: L/R chirality

Instead of (artificially) choosing the parameters, why don't we constrain them?!

NMFV SUSY

NMFV=Non-Minimal Flavour Violating

$$\mathbf{m^{2\,\mathrm{SCKM}}_{AB}} = \begin{pmatrix} (m^2_{AB})_{11} & (\Delta_{AB})_{12} & (\Delta_{AB})_{13} \\ (\Delta_{AB})_{21} & (m^2_{AB})_{22} & (\Delta_{AB})_{23} \\ (\Delta_{AB})_{31} & (\Delta_{AB})_{32} & (m^2_{AB})_{33} \end{pmatrix}$$

Mass Insertion Parameter

$$\frac{(\Delta_{AB})_{ij}}{m_{\mathrm{squark}}} \equiv (\delta_{AB})_{ij}$$

ij: generation
AB: L/R chirality

$$U_d \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\mathrm{weak}} = \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\mathrm{mass}} \qquad U_d \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}_{\mathrm{weak}} = \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}_{\mathrm{mass}}$$

Squark is not on the mass eigen-basis

Flavour mixture in the propagator

NMFV SUSY

NMFV=Non-Minimal Flavour Violating

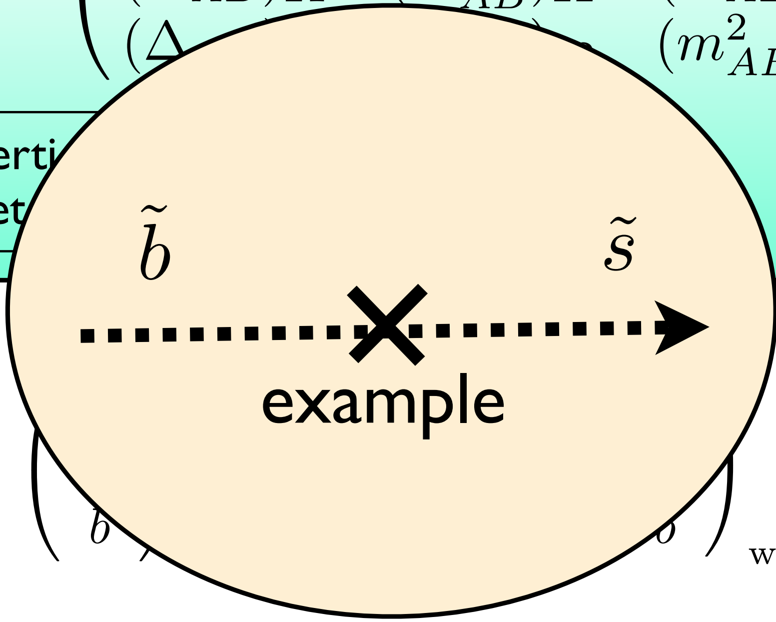
$$\mathbf{m^{2\,\mathrm{SCKM}}_{AB}} = \begin{pmatrix} (m^2_{AB})_{11} & (\Delta_{AB})_{12} & (\Delta_{AB})_{13} \\ (\Delta_{AB})_{21} & (m^2_{AB})_{22} & (\Delta_{AB})_{23} \\ (\Delta & & (m^2_{AB})_{33} \end{pmatrix}$$

Mass Inserti

Paramet

ij: generation

AB: L/R chirality



$$U_d \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\mathrm{weak}} = \begin{pmatrix} \\ \\ b \end{pmatrix} \cdots \begin{pmatrix} \\ \\ b \end{pmatrix}_{\mathrm{weak}} = \begin{pmatrix} \tilde{d} \\ \tilde{s} \\ \tilde{b} \end{pmatrix}_{\mathrm{mass}}$$

Squark is not on the mass eigen-basis

Flavour mixture in the propagator

My favorite

NMFV SUSY search in flavour

Bs oscillation phase!

- Time dependent CP violation Bs->J/ψΦ, J/ψf ..

In the following, I show some result in the case of...

New physics in penguin b->s transition:

- Time dependent CP violation of B-> KsΦ, B-> Ksη′, Bs->ΦΦ

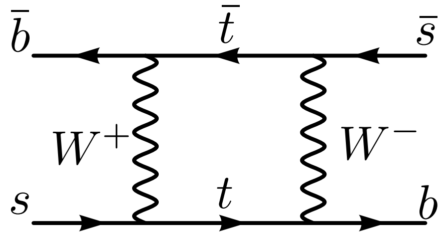
B-> sγ photon polarization

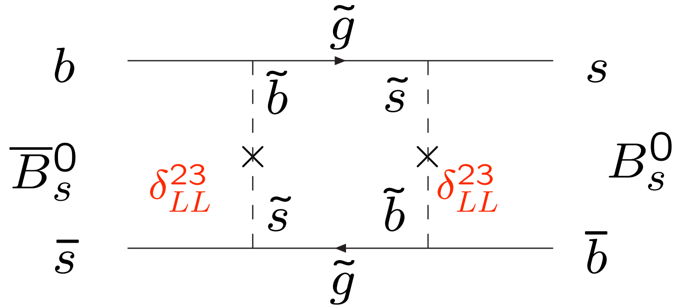
- Time dependent CP violation of B-> K*γ, ρKsγ, Ksηγ, Bs->Φγ...
- Angular distribution of B-> K*ee/K*μμ, B->K_1->γ

I am sure there are more!

Gluino contributions to Bs Oscillation

In the case of SUSY (non-MFV)





$$S_{J/\psi\phi} = Im\left[\underbrace{\frac{q}{p}}_{oscill.}\underbrace{\frac{A(\overline{B_s}\to J/\psi\phi)}{A(B_s\to J/\psi\phi)}}_{decay}\right]$$

$$= Im\left[\underbrace{\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}}_{oscill.}\underbrace{\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}}_{decay}\right]$$

$$= \sin 2\beta_s \quad (\beta$$

$\beta_s \simeq 1°$ in SM

$$S_{J/\psi\phi} = Im\left[\underbrace{\frac{q}{p}}_{oscill.}\underbrace{\frac{A(\overline{B_s}\to J/\psi\phi)}{A(B_s\to J/\psi\phi)}}_{decay}\right]$$

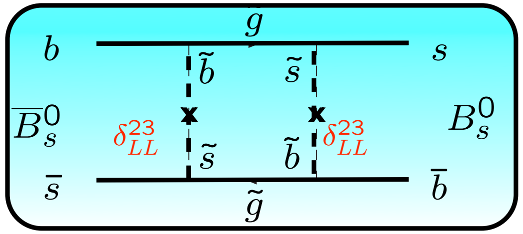
$$\simeq Im\left[\underbrace{\frac{\delta^{23}_{LL}}{\delta^{23*}_{LL}}}_{oscill.}\underbrace{\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}}_{decay}\right]$$

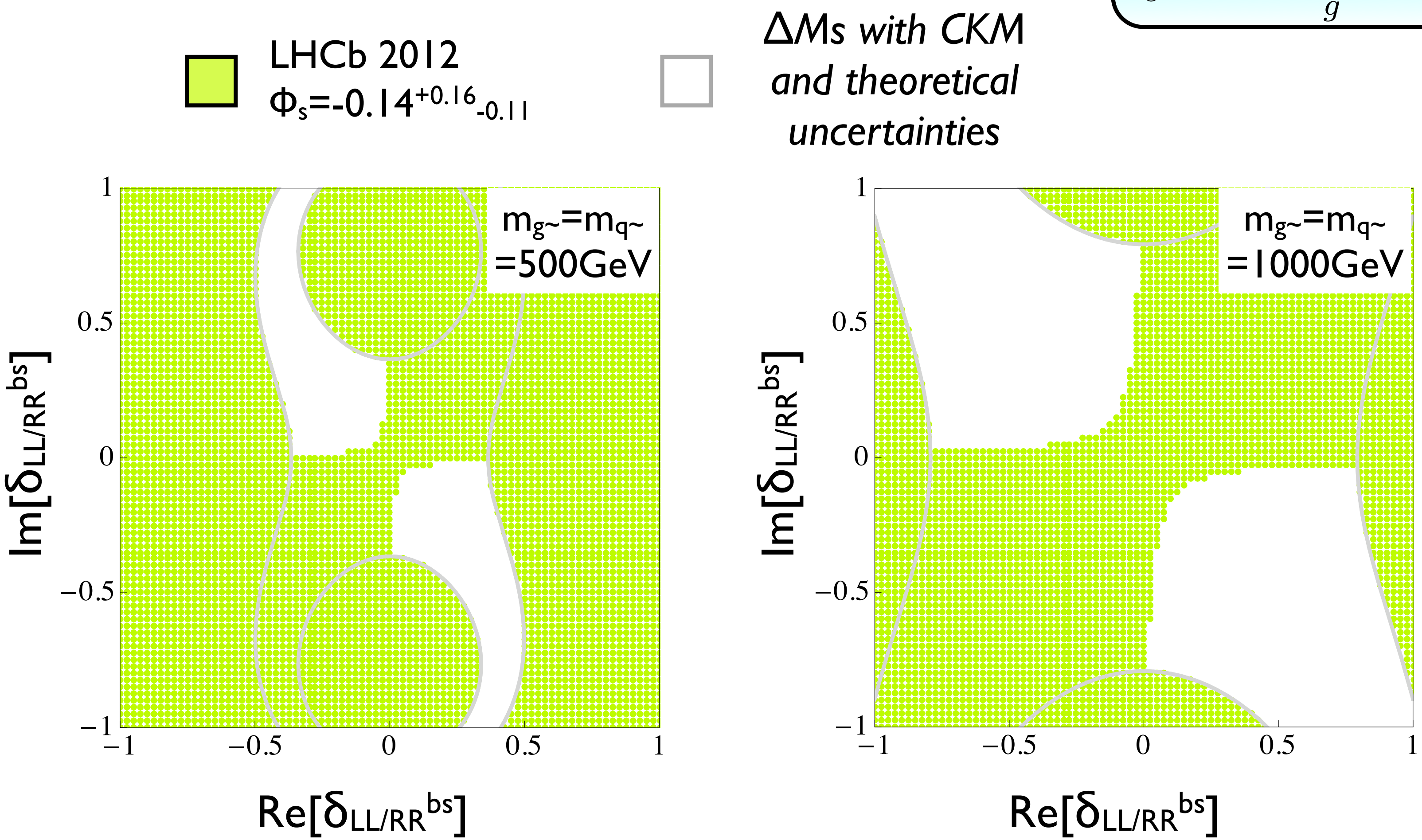
$$= \sin 2\beta_s \quad ($$

β_s can be large in BSM

Gluino contributions to Bs Oscillation

In the case of SUSY (non-MFV)





β(Φ₁) measurements with penguin decay channels

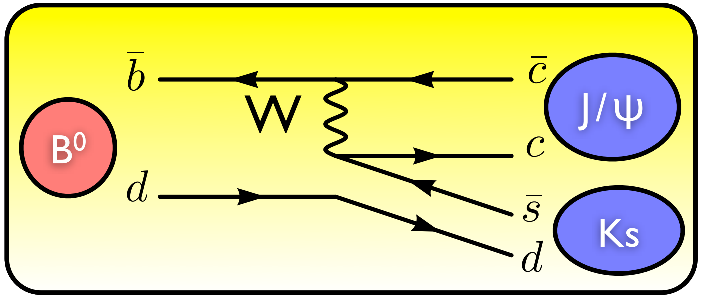
Time dependent CP asymmetry in the B_d system

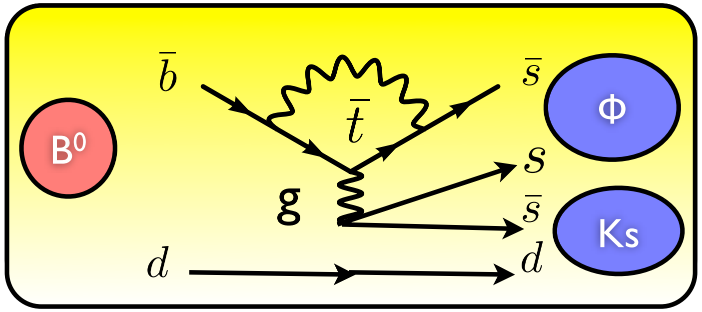
With tree process

$$\begin{aligned} S_{J/\psi K_s} &= Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to J/\psi K_S)}{A(B\to J/\psi K_S)}}_{decay}\right] \\ &= Im\left[\underbrace{\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}}_{oscill.}\underbrace{\frac{V_{cb}V_{cs}^*}{V_{cb}^*V_{cs}}}_{decay}\right] \\ &= \sin 2\beta(2\phi_1) \end{aligned}$$

With penguin process

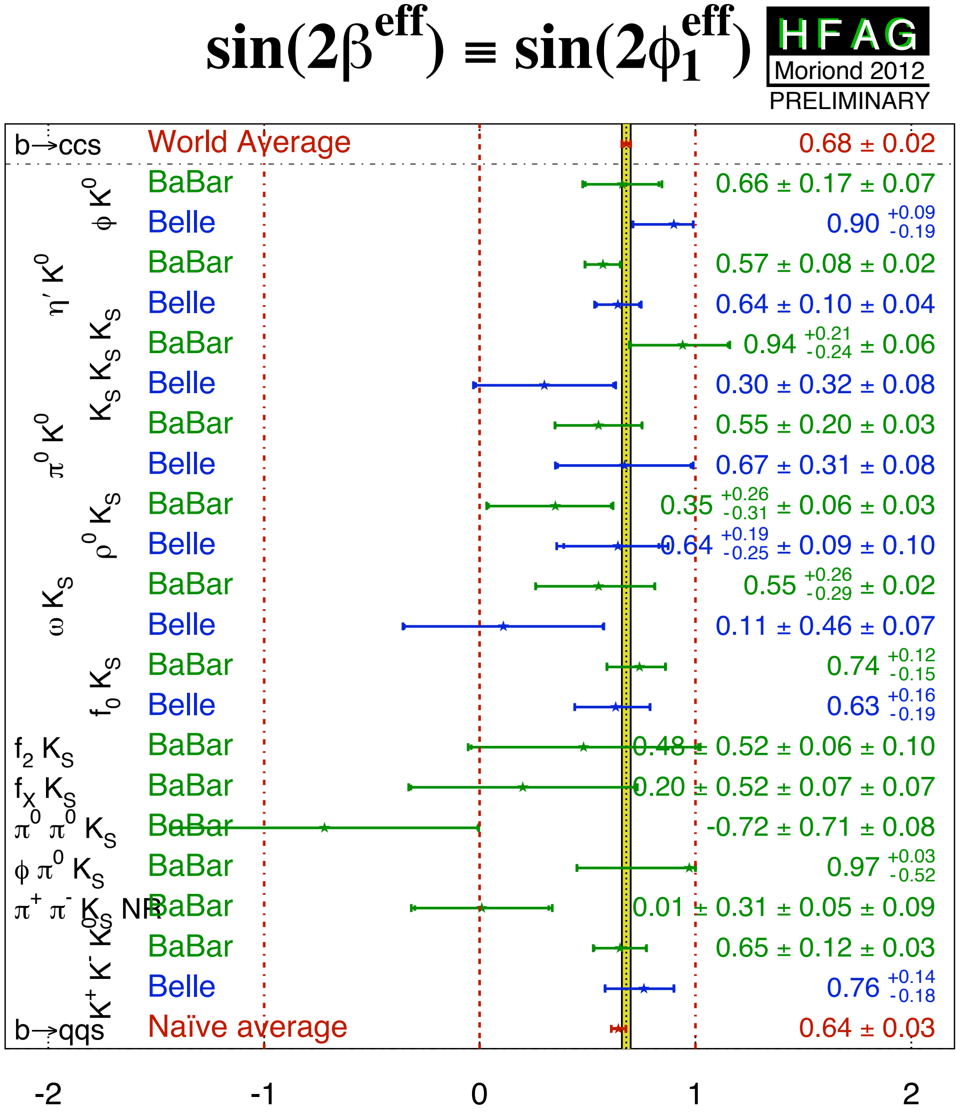
$$\begin{aligned} S_{\phi K_s} &= Im\left[\underbrace{\frac{M_{12}}{M_{12}^*}}_{oscill.}\underbrace{\frac{A(\overline{B}\to \phi K_S)}{A(B\to \phi K_S)}}_{decay}\right] \\ &= Im\left[\underbrace{\frac{V_{tb}V_{td}^*}{V_{tb}^*V_{td}}}_{oscill.}\underbrace{\frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}}_{decay}\right] \\ &= \sin 2\beta(2\phi_1) \end{aligned}$$





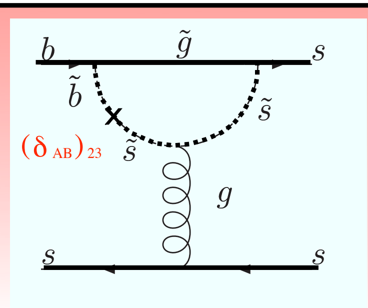
$\beta(\Phi_1)$ measurements with penguin decay channels

- B factories measured various channels.
- The experimental errors are statistics dominant. Thus, SuperB factories can improve the measurement significantly.
- Theoretical errors for some of the channels are still under discussions.
- Similar study can be done for the B_s system with, e.g. $B_s \rightarrow \Phi\Phi$, $B_s \rightarrow \eta'\Phi$ etc.
- New physics contributions for box (B_q oscillation) and penguin can be significantly different.

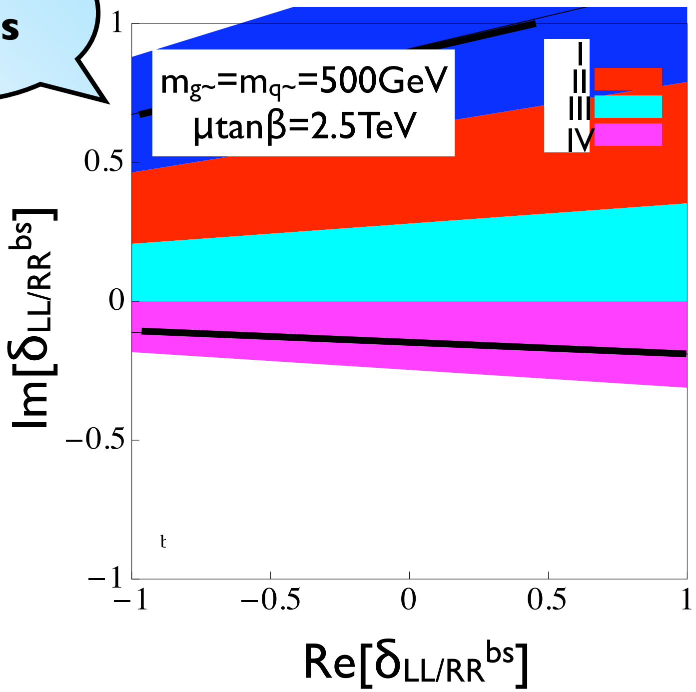


$\beta(\Phi_1)$ measurements with penguin decay channels

In the case of SUSY (non-MFV)



$S_{\phi K_s}$



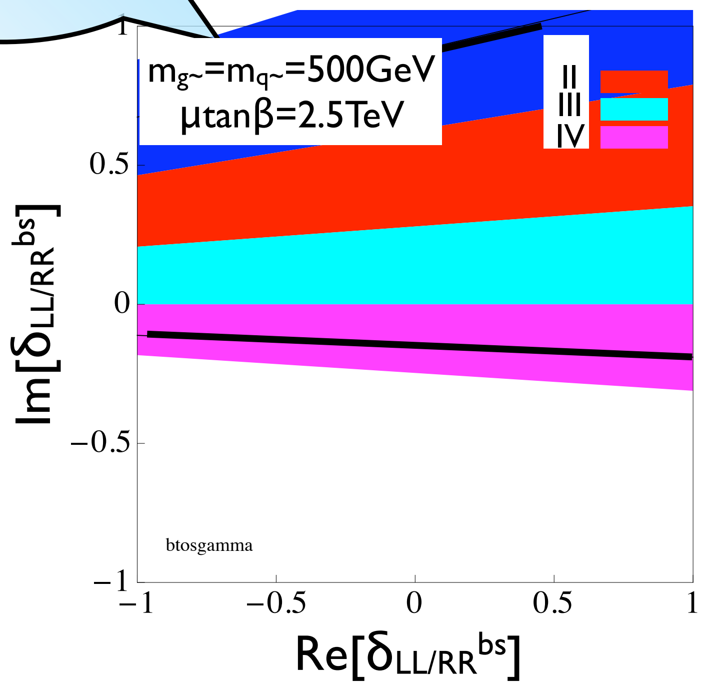
The expected precision at the SuperB factories:
I: $0.2<\Delta S_{\phi K_s}<0.3$
II: $0.1<\Delta S_{\phi K_s}<0.2$
III: $0<\Delta S_{\phi K_s}<0.1$
IV: $-0.1<\Delta S_{\phi K_s}<0$

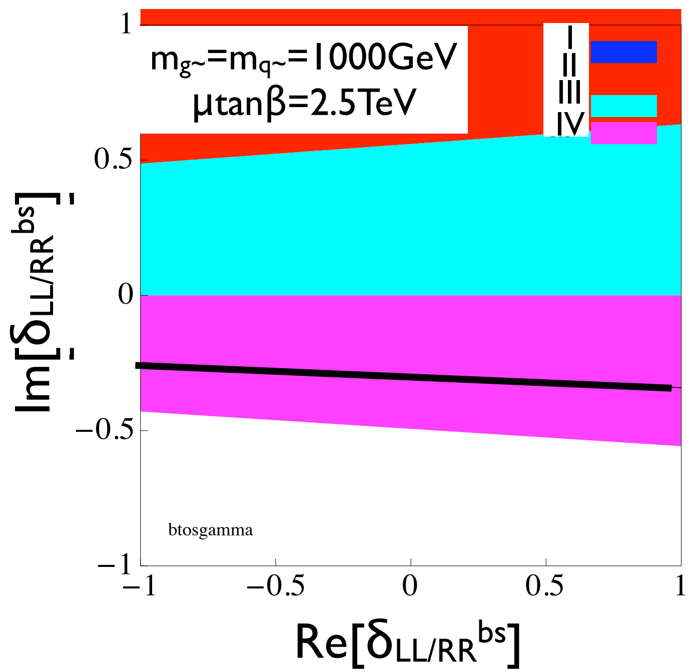
Current limit
$\Delta S_{\phi K_s}=0.1\pm0.16$

β(Φ1) measurements with penguin decay channels

In the case of SUSY (non-MFV)

$S_{\phi K_S}$ with Bs Oscillation





$\beta(\Phi_1)$ measurements with penguin decay channels

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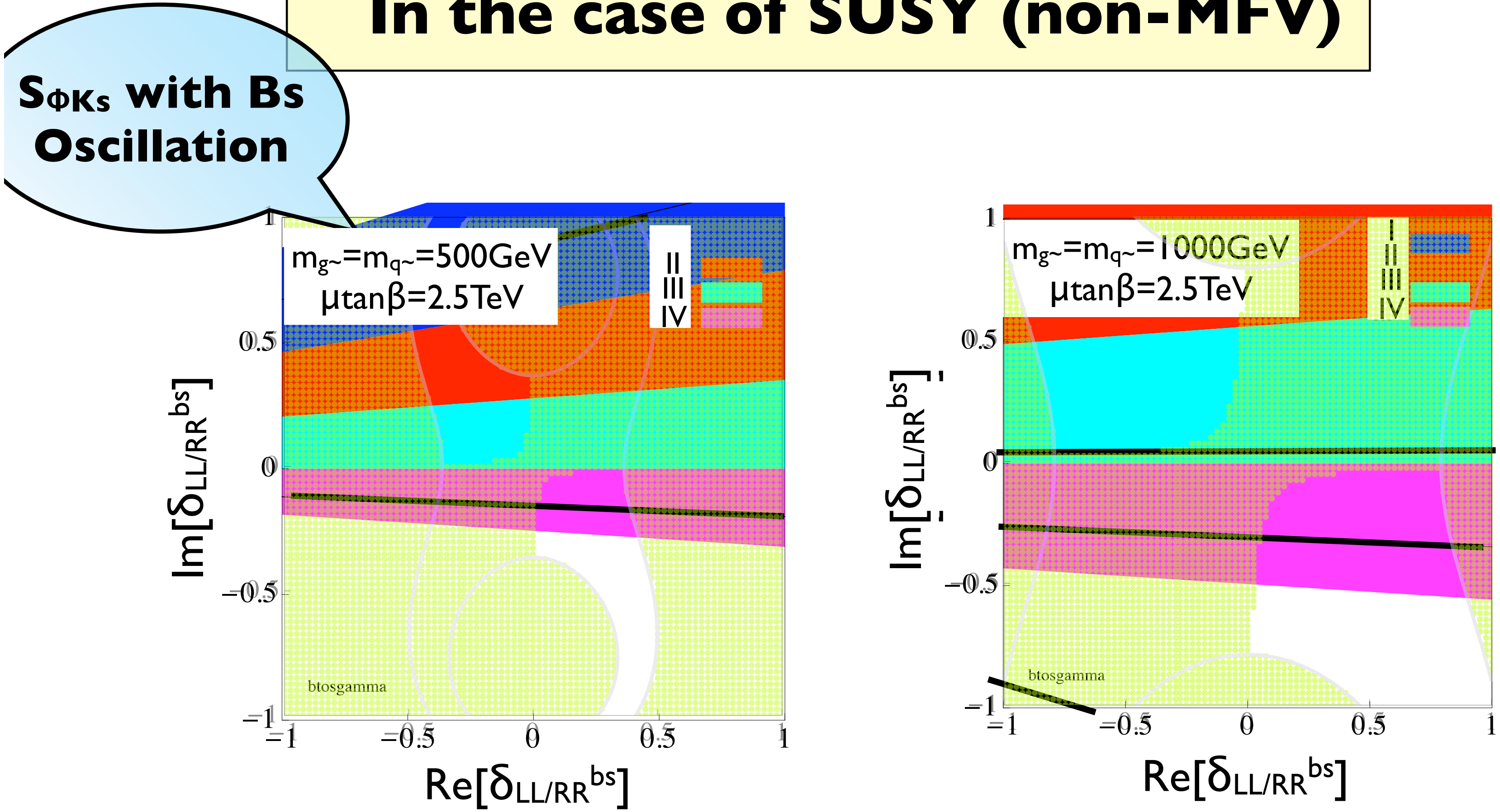
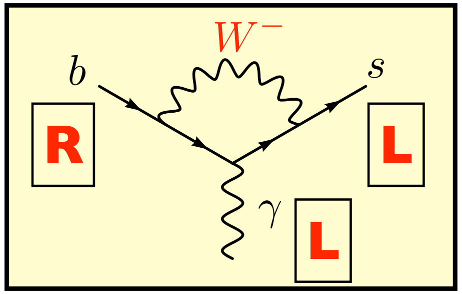


Photon polarization measurement of the $b \to s\gamma$ processes

challenge for future...

The b→sγ processes in SM

- The b →sγ process is a good probe of fundamental properties of SM as well as BSM (CKM, top mass, new particle mass etc..)
- Especially, the b→sγ process has a particular structure in SM:



$$\bar{b}A_\mu s = -iV_{tb}V_{ts}^*\frac{G_F}{\sqrt{2}}\frac{e}{8\pi^2}\left[\underbrace{E_0(x_t)\bar{s}_L(q^2\gamma_\mu - q_\mu \not{q})b_L}_{O_{9\sim10}\text{: penguin operator}} - \underbrace{m_b E_0'(x_t)\bar{s}_L\sigma_{\mu\nu}q^\nu b_R}_{O_{7\gamma,8g}\text{: magnetic operator}}\right]$$

photon off-shell
= not polarized
(e.g. semi-leptonic)

photon on-shell
and $b_R \to s_L\ \gamma_L$,

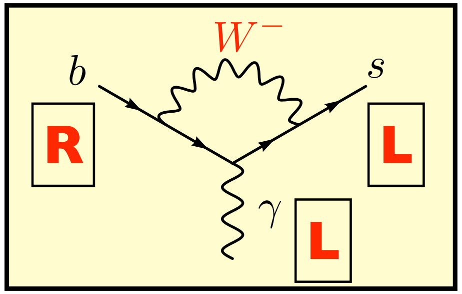
W-boson couples only left-handed ⟺ γ of b →s γ should be circularly-polarized

$m_s\bar{s}_R\sigma_{\mu\nu}q^\nu b_L$
Opposite chirality is suppressed by a factor m_s/m_b

✍ b →s γ_L (left-handed polarization)
✍ $\bar{b}$ →s γ_R (right-handed polarization)

The b→sγ processes in SM

- The b →sγ process is a good probe of fundamental properties of SM as well as BSM (CKM, top mass, new particle mass etc..)
- Especially, the b→sγ process has a particular structure in SM:



$$\bar{b}A_\mu s = -iV_{tb}V_{ts}^* \frac{G_F}{\sqrt{2}}\frac{e}{8\pi^2}\left[\underbrace{E_0(x_t)\bar{s}_L(q^2\gamma_\mu - q_\mu \not{q})b_L}_{O_{9\sim10}:\ \text{penguin operator}} - \underbrace{m_b E_0'(x_t)\bar{s}_L\sigma_{\mu\nu}q^\nu b_R}_{O_{7\gamma,8g}:\ \text{magnetic operator}}\right]$$

photon off-shell
= not polarized
(e.g. semi-leptonic)

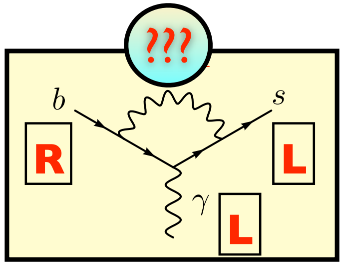
photon on-shell
and $b_R \to s_L\ \gamma_L$,

W-bo
only l

However, this left-handedness of the polarization of b →s γ has never been confirmed at a high precision yet!!

$_R\sigma_{\mu\nu}q^\nu b_L$
Opposite
hirality is
pressed by
a factor m_s/m_b

Right-handed: which NP model?



- **What types of new physics models?**
  For example, models with right-handed neutrino, or custodial symmetry in general induces the right handed current.

Left-Right symmetric model (W_R)	SUSY GUT model δ_{RR} mass insertion
Blanke et al. JHEP1203	*Girrbach et al. JHEP1106*

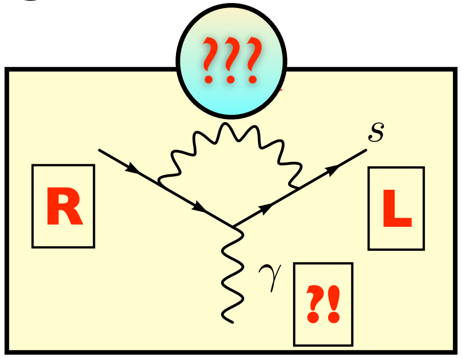
- **Which flavour structure?**
  The models that contain new particles which change the chirality inside of the $b \to s\gamma$ loop can induce a large chiral enhancement!

Left-Right symmetric model: mt/mb	SUSY with δ_{RL} mass insertions: m_{SUSY}/mb
Cho, Misiak, PRD49, '94 *Babu et al PLB333 '94*	*Gabbiani, et al. NPB477 '96* *Ball, EK, Khalil, PRD69 '04*

NP signal beyond the constraints from Bs oscillation parameters possible.

Theoretical interests in searching right-handed current using $b \to s\gamma$

- Left-Right symmetry is often required for building new physics models in order to satisfy the electroweak data of rho≃1.
- SUSY-GUT models often induces right-handed current in relation to the right-handed neutrino.
- etc...
- In addition, when there is a new particle in the loop which changes the chirality inside of the loop, there is chiral enhancement!



examples

Left-Right symmetric model: mt/mb

Babu, Fujikawa, Yamada PLB333 '94

SUSY with δ_{RL} mass insertions: m_{SUSY}/m_b

Gabbiani, Gabrielli, Masiero, Silvestrini NPB477 '96

Ball, EK, Khalil, PRD69 '04

Theoretical interests in searching right-handed current using b→sγ

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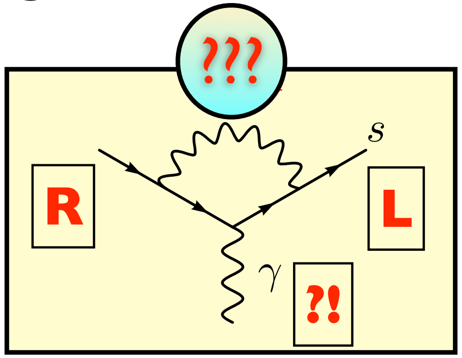

examples

Left-Right symmetric model: mt/mb

Babu, Fujikawa, Yamada PLB333 '94

SUSY with δ_{RL} mass insertions: m_{SUSY}/mb

Gabbiani, Gabrielli, Masiero, Silvestrini NPB477 '96

We can allow a large new physics enhancement in b→sγ/b →sg (on-shell s/g), despite of the strong constraints on e.g. Bs box diagram, namely ΔM_s and Φ_s.

Ball, EK, Khalil, PRD69 '04

By the way...

Is a right-handed contribution still allowed in b→sγ from experiment?

We can write the amplitude including RH contribution as:

$$\mathcal{M}(b \to s\gamma) \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\underbrace{(C_{7\gamma}^{\rm SM} + C_{7\gamma}^{\rm NP})\langle \mathcal{O}_{7\gamma} \rangle}_{\propto \mathcal{M}_L} + \underbrace{C_{7\gamma}^{\prime \rm NP} \langle \mathcal{O}_{7\gamma}^{\prime} \rangle}_{\propto \mathcal{M}_R} \right]$$

We have a constraint from inclusive branching ratio measurement

$$Br(B \to X_S\gamma) \propto |C_{7\gamma}^{\rm SM} + C_{7\gamma}^{\rm NP}|^2 + |C_{7\gamma}^{\prime \rm NP}|^2$$

HFAG $(3.55 \pm 0.24 \pm 0.09)\times 10^{-4}$

By the way...

Is a right-handed contribution still allowed in b→sγ from experiment?

We can write the amplitude including RH contribution as:

$$\mathcal{M}(b\to s\gamma)\simeq -\frac{4G_F}{\sqrt{2}}V_{ts}^*V_{tb}\left[\underbrace{(C_{7\gamma}^{\rm SM}+C_{7\gamma}^{\rm NP})\langle\mathcal{O}_{7\gamma}\rangle}_{\propto\mathcal{M}_L}+\underbrace{C_{7\gamma}^{\prime\rm NP}\langle\mathcal{O}_{7\gamma}^{\prime}\rangle}_{\propto\mathcal{M}_R}\right]$$

We have a constraint from inclusive branching ratio measurement

$$Br(B\to X_S\gamma)\propto|C_{7\gamma}^{\rm SM}+C_{7\gamma}^{\rm NP}|^2+|C_{7\gamma}^{\prime\rm NP}|^2$$

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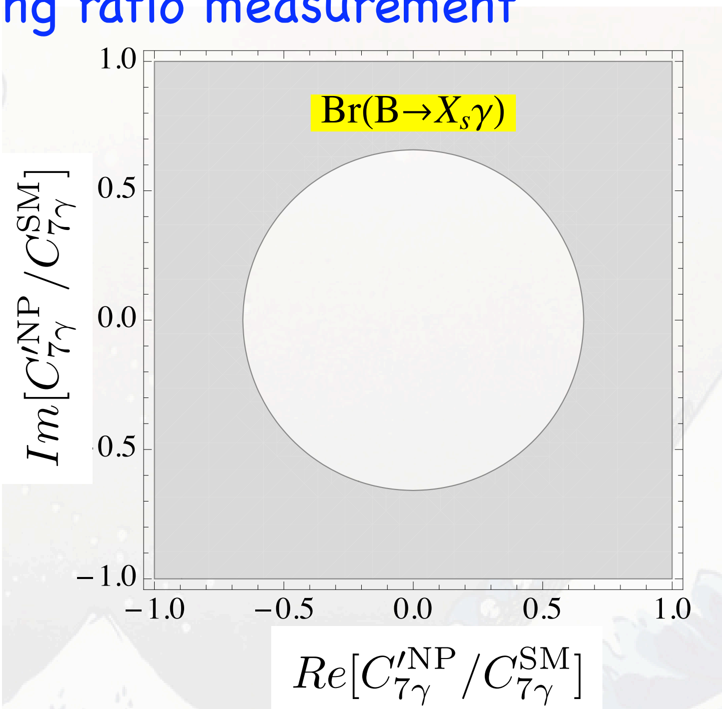

While the polarization measurement carries information on

$$\frac{\mathcal{M}_R}{\mathcal{M}_L}\simeq\frac{C_{7\gamma}^{\prime\rm NP}}{C_{7\gamma}^{\rm SM}+C_{7\gamma}^{\rm NP}}$$

Here we assume $C'^{\rm NP}_{7\gamma}\neq0$, $C_{7\gamma}^{\rm NP}=0$

-SUSY with δ_{RL} mass insertions
- SUSY-GUT models
-etc...

More general case
E.K. F. Yu in preparation

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Current situation!

We have a constraint from inclusive branching ratio measurement

$$Br(B\to X_S\gamma) \propto |C_{7\gamma}^{\rm SM} + C_{7\gamma}^{\rm NP}|^2 + |C_{7\gamma}^{\prime \rm NP}|^2$$

HFAG $(3.55 \pm 0.24 \pm 0.09)\times 10^{-4}$

Here we assume $C'^{\rm NP}_{7\gamma} \neq 0$, $C^{\rm NP}_{7\gamma} = 0$

- SUSY with δ_{RL} mass insertions
- SUSY-GUT models
- etc...

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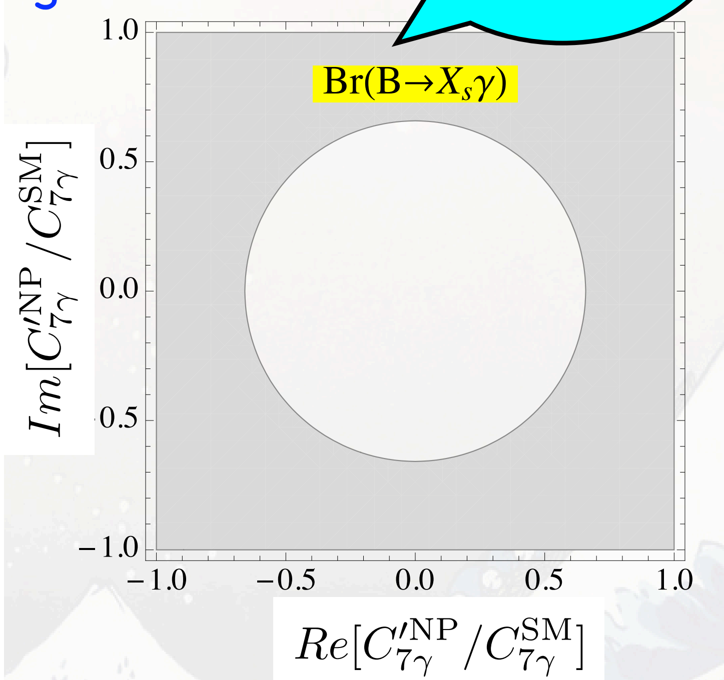
While the polarization measurement carries information on

$$\frac{\mathcal{M}_R}{\mathcal{M}_L} \simeq \frac{C_{7\gamma}^{\prime \rm NP}}{C_{7\gamma}^{\rm SM} + C_{7\gamma}^{\rm NP}}$$



How do we measure the polarization?!

proposed methods

- Method I: Time dependent CP asymmetry in $B_d \to K_S \pi^0 \gamma$ $B_s \to K^+ K^- \gamma$ (called $S_{K_S \pi^0 \gamma}$, $S_{K^+ K^- \gamma}$)
- Method II: Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)
- Method III: $B \to K_1 (\to K\pi\pi)\gamma$ (called λ_γ)
- Method IV: $\Lambda_b \to \Lambda^{(*)}\gamma$, $\Xi_b \to \Xi^* \gamma$ ...

Atwood et.al. PRL79

Kruger, Matias PRD71
Becirevic, Schneider, NPB854

Gronau et al PRL88
E.K. Le Yaouanc, Tayduganov PRD83

Gremm et al.'95, Mannel et al '97, Legger et al '07, Oliver et al '10

Polarization measurement using Time-dependent CPV of $B \to K^*(\to K_S \pi^0)\gamma$

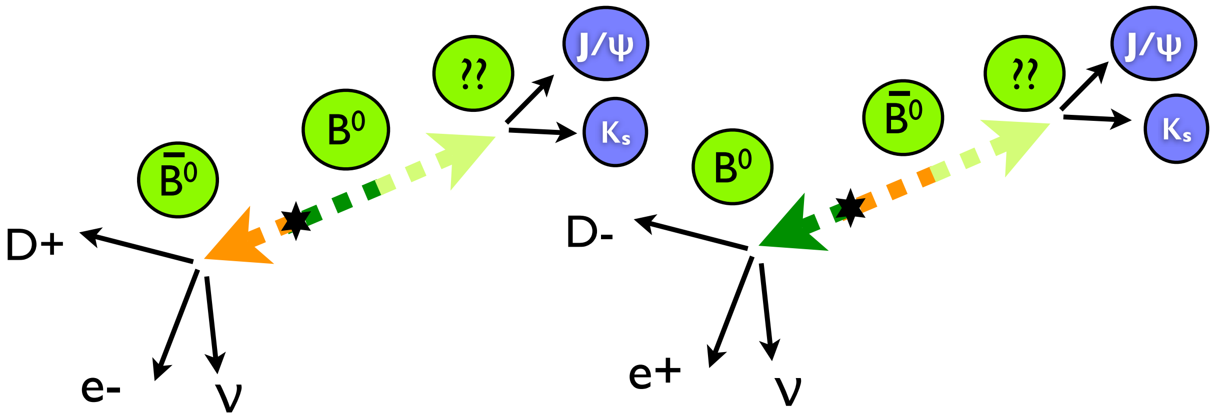
Atwood et.al. PRL79

Flavour Non-specific mixing CPV

(CP Violation in oscillation)

Choose a final state which could come both B and Bbar!

ex: $J/\psi K_s$ final state



$$|B(t)\rangle = f_+(t)|B\rangle + \frac{q}{p} f_-(t)|\overline{B}\rangle$$

$$|\overline{B}(t)\rangle = f_+(t)|\overline{B}\rangle + \frac{p}{q} f_-(t)|B\rangle$$

Polarization measurement using Time-dependent CPV of B→K*(→Ksπ^0)γ

Atwood et.al. PRL79

Flavour Non-specific mixing CPV

(CP Violation in oscillation)

Choose a final state which could come both B and Bbar!

ex: J/ΨK$_s$ final state

$$\begin{aligned} |B(t)\rangle &= f_+(t)|B\rangle + \frac{q}{p} f_-(t)|\overline{B}\rangle \\ |\overline{B}(t)\rangle &= f_+(t)|\overline{B}\rangle + \frac{p}{q} f_-(t)|B\rangle \end{aligned}$$

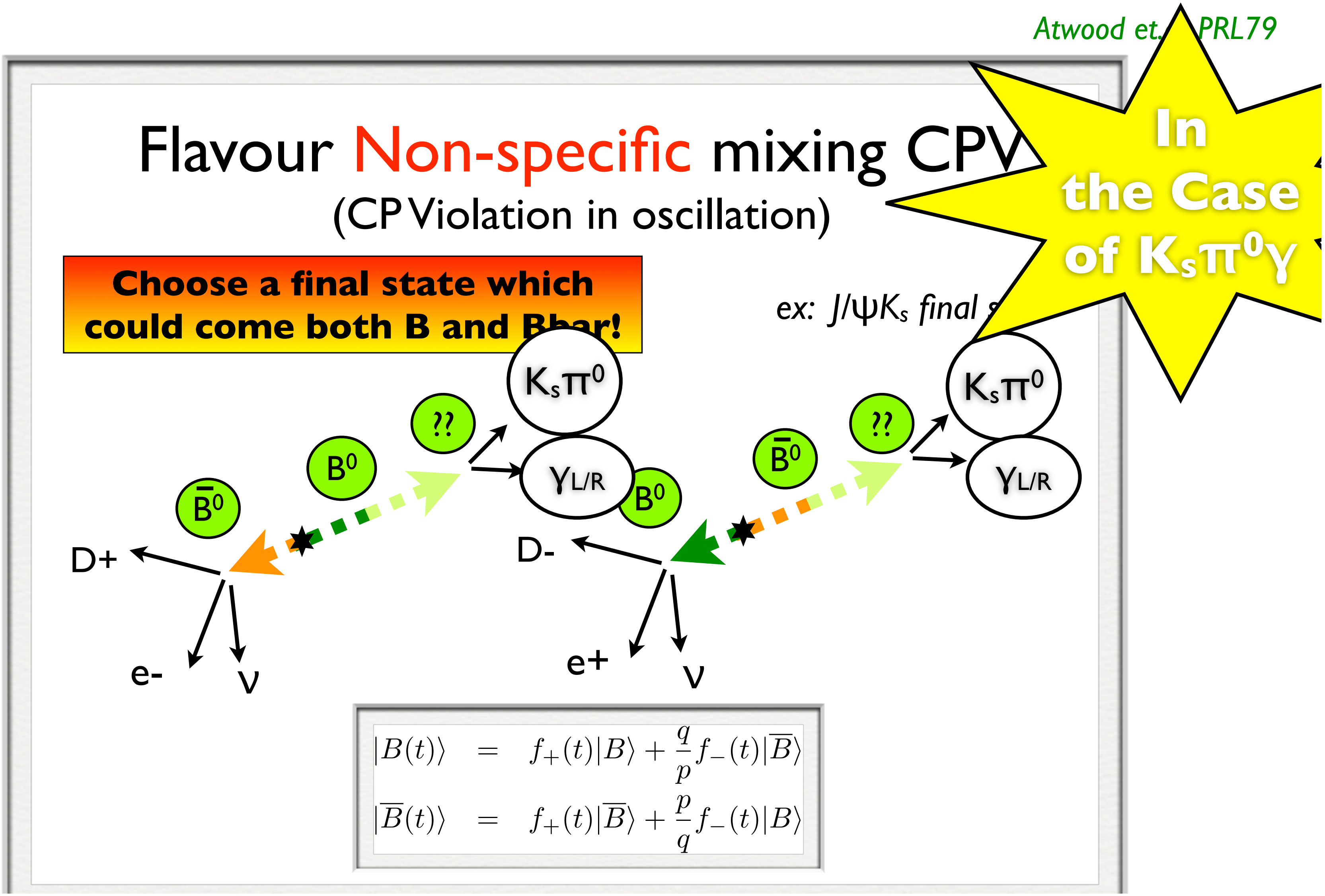
$$\begin{aligned} \langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|B(t)\rangle &= f_+(t)\langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|B\rangle + \frac{q}{p} f_-(t)\langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|\overline{B}\rangle \\ \langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|\overline{B}(t)\rangle &= f_+(t)\langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|\overline{B}\rangle + \frac{p}{q} f_-(t)\langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|B\rangle \end{aligned}$$

We assume...

$$\langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|\overline{B}\rangle = \langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|B\rangle \qquad {}_{12} << M_{12}$$

Polarization measurement using Time-dependent CPV of B→K*(→Ksπ^0)γ

Atwood et.al. PRL79



Polarization measurement using Time-dependent CPV of $B \to K^*(\to K_S \pi^0)\gamma$

Atwood et al., PRL79

Flavour Non-specific mixing CPV

(CP Violation in oscillation)

In SM

- $\bar{B} \to s\, \gamma_L$ (left-handed polarization)
- $B \to s\, \gamma_R$ (right-handed polarization)

ex: $J/\psi K_s$ final s

In the Case of $K_s\pi^0\gamma$

$$|B(t)\rangle = f_+(t)|B\rangle + \frac{q}{p} f_-(t)|\overline{B}\rangle$$

$$|\overline{B}(t)\rangle = f_+(t)|\overline{B}\rangle + \frac{p}{q} f_-(t)|B\rangle$$

$$\langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|B(t)\rangle = f_+ \cancel{\langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|B\rangle} + \frac{q}{p} f_- \langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|\overline{B}\rangle$$

$$\langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|\overline{B}(t)\rangle = f_+ \langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|\overline{B}\rangle + \frac{p}{q} f_- \cancel{\langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|B\rangle}$$

We assume...

$$\langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|\overline{B}\rangle = \langle J/\psi K_s|\mathcal{H}^{\Delta B=1}|B\rangle \qquad {}_{12} << M_{12}$$

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Atwood et al. PRL79

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- $B \to s\, \gamma_R$ (right-handed polarization)

ex: $J/\psi K_s$ final s…

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$$|B(t)\rangle = f_+(t)|B\rangle + \frac{q}{p} f_-(t)|\overline{B}\rangle$$

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$$\langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|B(t)\rangle = f_+ \cancel{\langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|B\rangle} + \frac{q}{p} f_- \langle K_s\pi^0\gamma_L|\mathcal{H}^{\Delta B=1}|\overline{B}\rangle$$

$$\mathcal{H}^{\Delta B=1}|B\rangle$$

M_{12}

If we observe non-zero CP violating phase, that would mean that a decay $B \to K_s\pi^0\gamma_L$ or $\overline{B} \to K_s\pi^0\gamma_R$ occured, which comes from a right-handed current!

Polarization measurement using Time-dependent CPV of B→K*(→Ksπ^0)γ

We can write the amplitude including RH contribution as:

$$\mathcal{M}(b \to s\gamma) \simeq -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \left[\underbrace{(C_{7\gamma}^{\rm SM} + C_{7\gamma}^{\rm NP})\langle \mathcal{O}_{7\gamma}\rangle}_{\propto \mathcal{M}_L} + \underbrace{C_{7\gamma}'^{\rm NP} \langle \mathcal{O}'_{7\gamma}\rangle}_{\propto \mathcal{M}_R} \right]$$

- Constraints from Time dependent CPV of $S_{K_S\pi^0\gamma}$

$$S_{K_S\pi^0\gamma} = \frac{2|C_{7\gamma}^{\rm SM} C_{7\gamma}'^{\rm NP}|}{|C_{7\gamma}^{\rm SM}|^2 + |C_{7\gamma}'^{\rm NP}|^2} \sin(2\phi_1 - \phi_R) \qquad \phi_R = \arg\left[\frac{C_{7\gamma}'^{\rm NP}}{C_{7\gamma}^{\rm SM}}\right]$$

HFAG $S_{K_S\pi^0\gamma}$=-0.15 ± 0.2

- Constraints from inclusive branching ratio

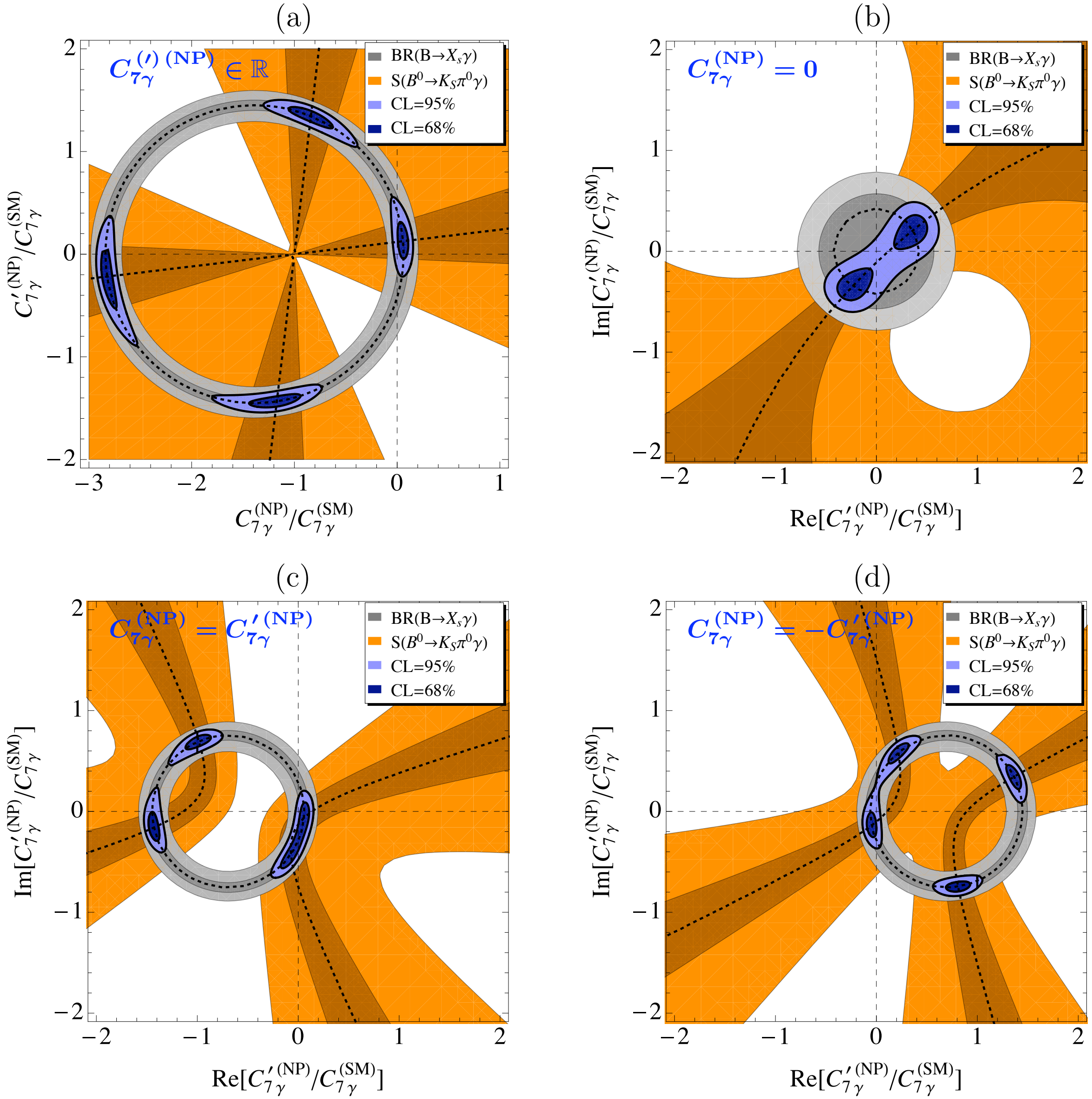
$$Br(B \to X_S\gamma) \propto |C_{7\gamma}^{\rm SM} + C_{7\gamma}^{\rm NP}|^2 + |C_{7\gamma}'^{\rm NP}|^2$$

HFAG (3.43 ± 0.21 ± 0.07)x10^{-4}

Current constraints on C_7&C_7'

New physics
real

New physics
only RH C_7'



New physics
LH=RH

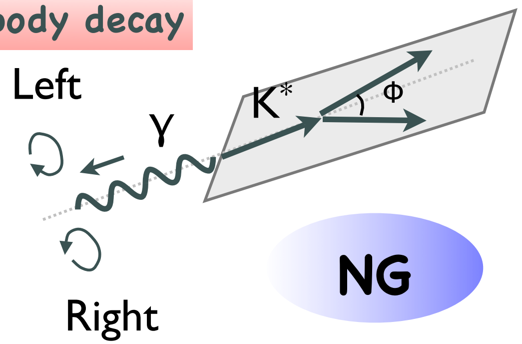
New physics
LH=-RH

Polarization measurement using $B \to K_1 (\to K\pi\pi)\gamma$: the method by Gronau et al.

Gronau, Grossman, Pirjol, Ryd hep-ph/0107254

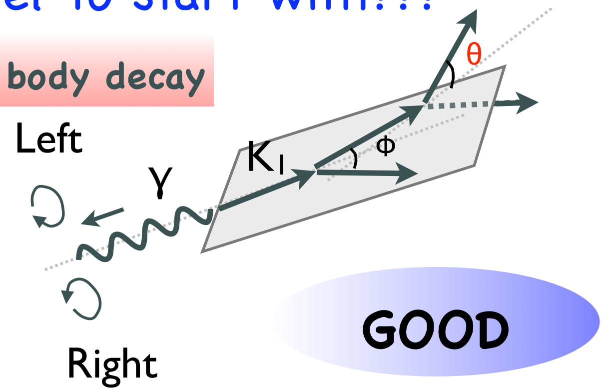
Why do we need three body channel to start with???

2 body decay



Decays are symmetric along the helicity axis. No LR distinction!

3 body decay



Three body decays can make an angle to the plane!

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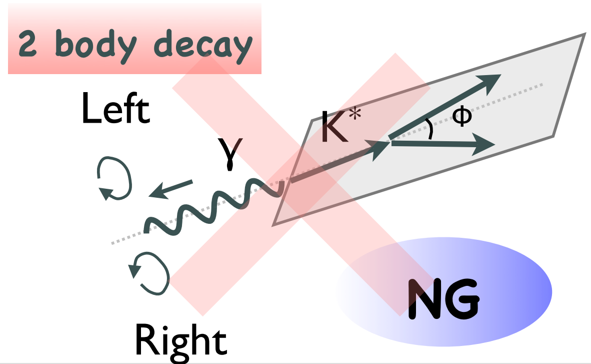

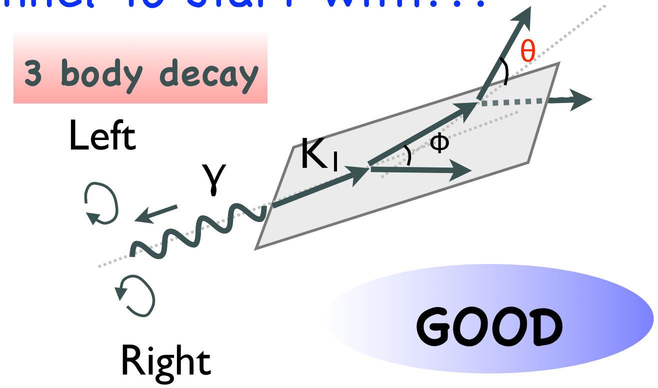

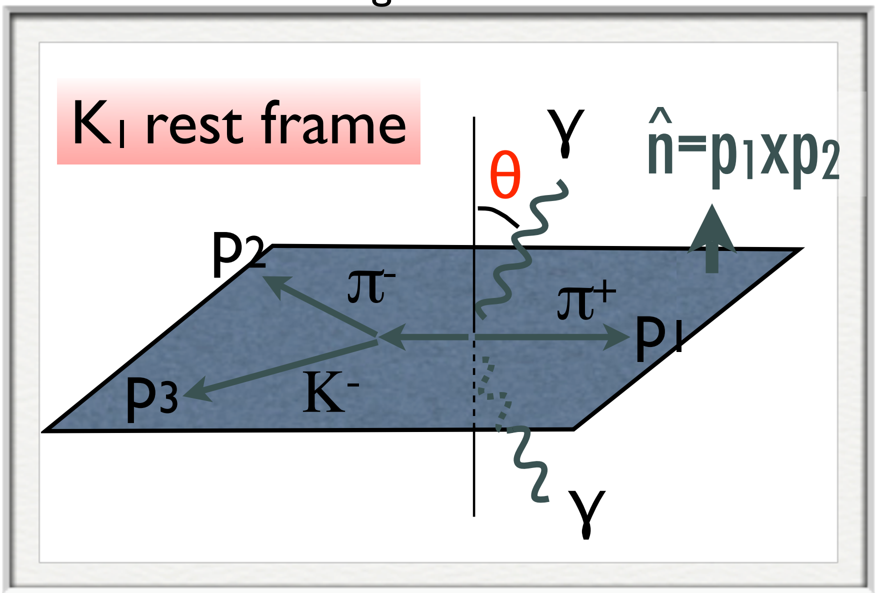

Up-Down asymmetry

Count the number of events with photon above/below the K_1 decay plane and subtract them.

$$\mathcal{A} = \frac{\int_0^{\pi/2} d|\mathcal{M}|^2 d\theta - \int_{\pi/2}^{\pi} d|\mathcal{M}|^2 d\theta}{\int_0^{\pi} d|\mathcal{M}|^2 d\theta}$$

Polarization measurement using $B \to K_1(\to K\pi\pi)\gamma$: the method by Gronau et al.

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$\vec{J}$: Helicity amplitude of $K_1 \to K\pi\pi$

λ : Polarization parameter

Angular distribution of K_1 decay ⟺ Circularly-polarization measurement of γ

Polarization measurement using $B \to K_1(\to K\pi\pi)\gamma$: the method by Gronau et al.

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$\vec{J}$: Helicity amplitude of $K_1 \to K\pi\pi$

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Angular distribution of K_1 decay ⟺ Circularly-polarization measurement of γ

Source of imaginary part ⇨ **Breit-Wigner of two resonances**

$$K_1^+(p) \to \pi^+(p_1)\pi^-(p_2)K^+(p_3)$$

K^{*0} ($\pi^-(p_2)K^+(p_3)$)

ρ^0 ($\pi^+(p_1)\pi^-(p_2)$)

Polarization measurement using $B \to K_1(\to K\pi\pi)\gamma$: the method by Gronau et al.

Gronau, Grossman, Pirjol, Ryd hep-ph/0107254

Up-Down asymmetry

$$\int_0^{\pi/2} d|\mathcal{M}|^2 d\theta - \int_{\pi/2}^{\pi} d|\mathcal{M}|^2 d\theta$$

We need detailed information on the hadronic amplitude of $K_1 \to K\pi\pi$

Angular & Dalitz distribution of K_1 decay ⇔ Circularly-polarization measurement of γ

Source of imaginary part ⇨ **Breit-Wigner of two resonances**

$$K_1^+(p) \to \underbrace{\pi^+(p_1)\overbrace{\pi^-(p_2)K^+(p_3)}^{K^{*0}}}_{\rho^0}$$

Strong decay of $K_1 \rightarrow K\pi\pi$

How to extract the hadronic information (i.e. function J)?

1. Model independent extraction i.e. from data (most ideal)

$$B \rightarrow J/\Psi K_1,\ \tau \rightarrow K_1 \nu \ldots$$

2. Model dependent extraction i.e. theoretical estimate

Modeling J function:

Assume $K_1 \rightarrow K\pi\pi$ comes from quasi-two-body decay, e.g. $K_1 \rightarrow K^*\pi$, $K_1 \rightarrow \rho K$, then, J function can be written in terms of:

- 4 form factors (S,D partial wave amplitudes)
- 2 couplings ($g_{K^*K\pi}$, $g_{\rho\pi\pi}$)
- 1 relative phase between two channel

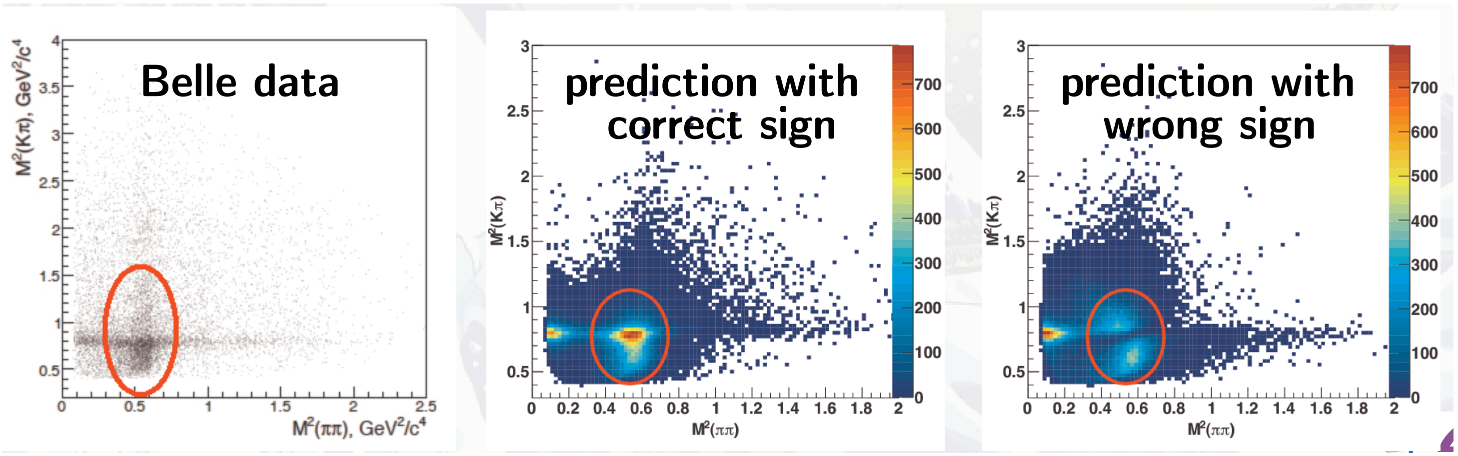
Strong decay of $K_1 \to K\pi\pi$

Model parameters are extracted by fitting to data:

✓	$Br(K_{1(1270)} \to K^*\pi)/Br(K_{1(1270)} \to \rho K) = 0.24 \pm 0.09$
✓	$Br(K_{1(1400)} \to \rho K)/Br(K_{1(1400)} \to K^*\pi) = 0.01 \pm 0.01$
✓	$Br(K_{1(1400)} \to K^*\pi)_{D\text{-wave}}/Br(K_{1(1400)} \to K^*\pi)_{S\text{-wave}} = 0.04 \pm 0.01$
✓	$Br(K_{1(1270)} \to K^*\pi)_{D\text{-wave}}/Br(K_{1(1270)} \to K^*\pi)_{S\text{-wave}} = 2.67 \pm 0.95$

Brandenburg et al,
Phys Rev Lett, 36 ('76)
Otter et al,
Nucl Phys, B106 ('77)
Daum et al,
Nucl Phys, B187 ('81)

Recent Belle measurement of $B \to J/\Psi K_1$ fixed the relative phase!!



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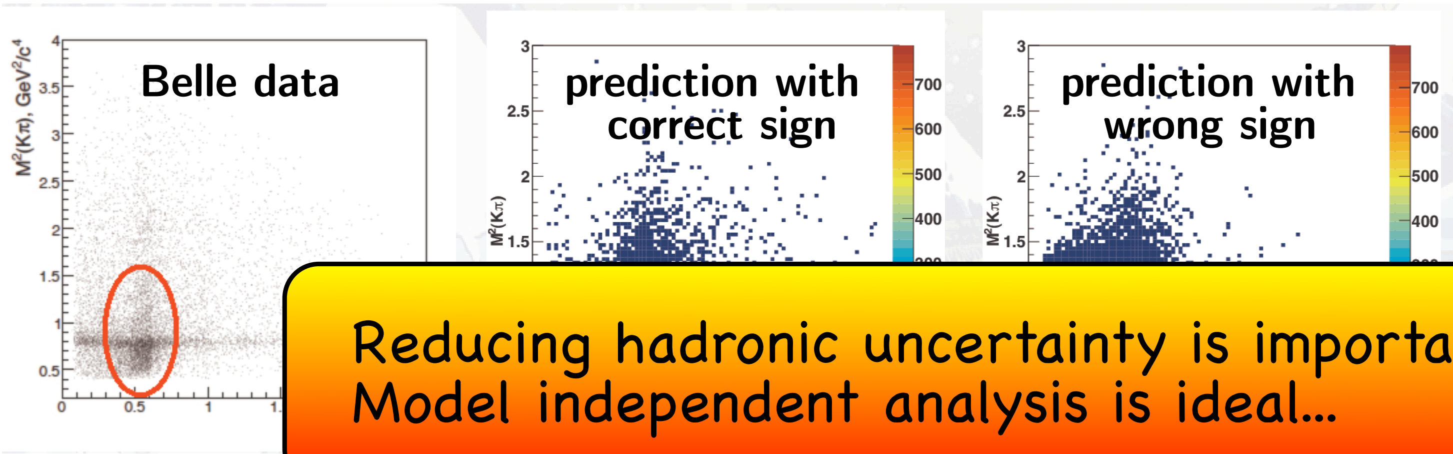


Reducing hadronic uncertainty is important.
Model independent analysis is ideal...

Comparison of the three methods

proposed methods

- **Method I**: Time dependent CP asymmetry in $B_d \to K_S\pi^0\gamma$ $B_s \to K^+K^-\gamma$ (called $S_{K_S\pi^0\gamma}$, $S_{K^+K^-\gamma}$)

$$S_{K_S\pi^0\gamma} = \frac{2|C_{7\gamma}^{\rm SM} C_{7\gamma}^{\prime\rm NP}|}{|C_{7\gamma}^{\rm SM}|^2 + |C_{7\gamma}^{\prime\rm NP}|^2}\sin(2\phi_1 - \phi_R) \qquad \phi_R = \arg\left[\frac{C_{7\gamma}^{\prime\rm NP}}{C_{7\gamma}^{\rm SM}}\right]$$

- **Method II**: Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)

$$\mathcal{A}_T^{(2)}(q^2=0) = \frac{2Re[C_{7\gamma}^{\rm SM} C_{7\gamma}^{\prime\rm NP*}]}{|C_{7\gamma}^{\rm SM}|^2 + |C_{7\gamma}^{\prime\rm NP}|^2} \qquad \mathcal{A}_T^{(im)}(q^2=0) = \frac{2Im[C_{7\gamma}^{\rm SM} C_{7\gamma}^{\prime\rm NP*}]}{|C_{7\gamma}^{\rm SM}|^2 + |C_{7\gamma}^{\prime\rm NP}|^2}$$

Assumption for γ^*/Z penguin (C_9, C_{10} contributions) necessary!

- **Method III**: $B \to K_1(\to K\pi\pi)\gamma$ (called λ_γ)

$$\lambda = \frac{|C_{7\gamma}^{\prime\rm NP}|^2 - |C_{7\gamma}^{\rm SM}|^2}{|C_{7\gamma}^{\prime\rm NP}|^2 + |C_{7\gamma}^{\rm SM}|^2}$$

Comparison of the three methods

proposed methods

- **Method I**: Time dependent CP asymmetry in $B_d \to K_S\pi^0\gamma$ $B_s \to K^+K^-\gamma$ (called $S_{K_S\pi 0\gamma}$, $S_{K+K-\gamma}$)

$$S_{K_S\pi^0\gamma} = \frac{2|C_{7\gamma}^{SM} \ldots}{|C_{7\gamma}^{SM}|^2 + \ldots} \qquad \varphi_R = \arg\left[\frac{C'^{NP}_{7\gamma}}{C^{SM}_{7\gamma}}\right]$$

Super Flavour Factories
$\sigma_{S_{K_S\pi\gamma}}(0.02)$

- **Method II**: Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)

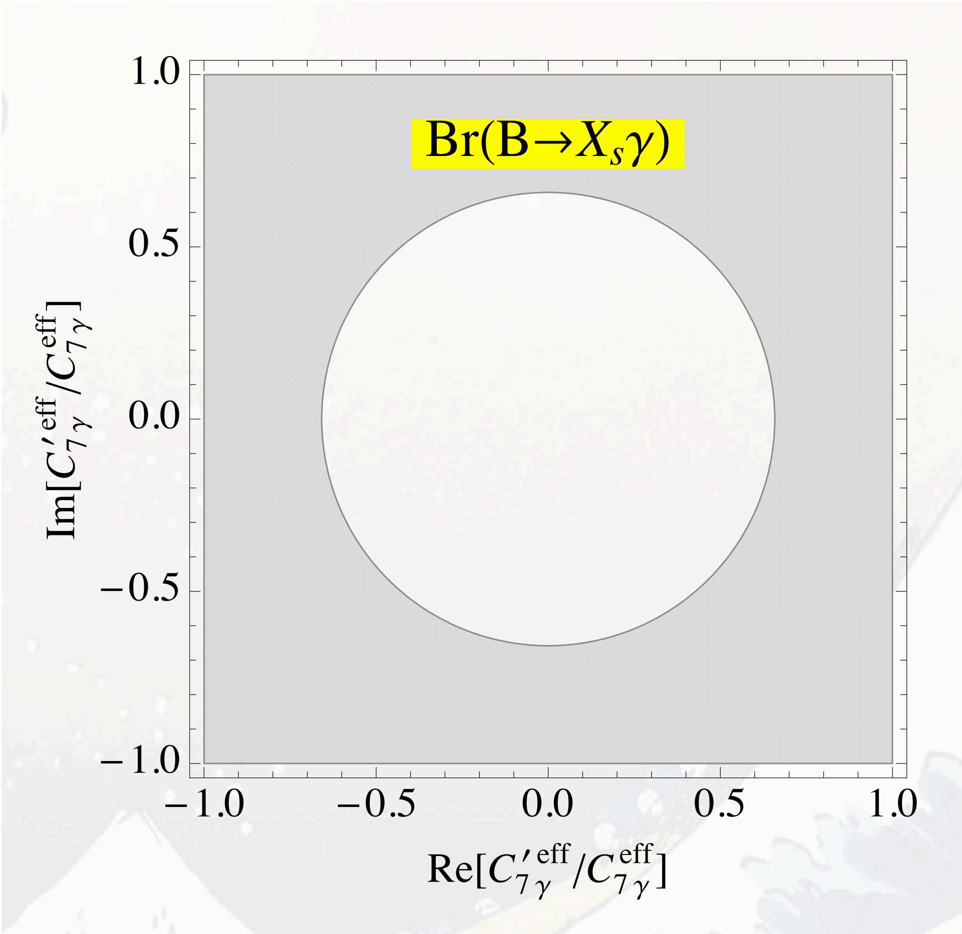
$$\mathcal{A}_T^{(2)}(q^2=0) = \frac{2Re[C_{7\gamma}^{SM} C'^{NP}_{7\gamma} \ldots}{|C_{7\gamma}^{SM}|^2 + |C'^{NP}_{7\gamma} \ldots} \qquad \ldots^2 = 0) = \frac{2Im[C_{7\gamma}^{SM} C'^{NP*}_{7\gamma}]}{|C_{7\gamma}^{SM}|^2 + |C'^{NP}_{7\gamma}|^2}$$

LHCb
$\sigma_{A_T^{2(im)}}(0.2)$

- **Method III**: $B \to K_1(\to K\pi\pi)\gamma$ (called λ_γ)

Super Flavour Factory/LHCb
$\sigma_\lambda(0.1\text{-}0.2)$

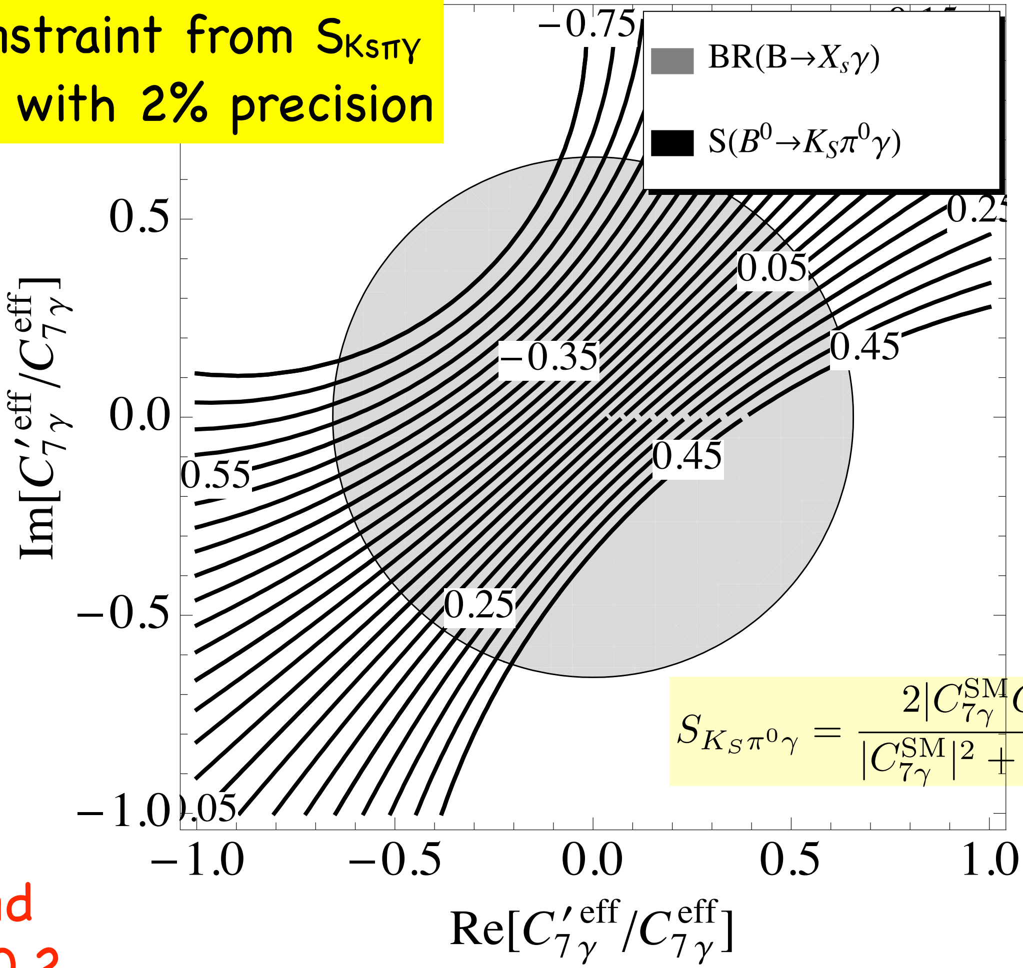
Comparison of the three methods



Comparison of the three methods

Method I

Expected constraint from $S_{K_S\pi\gamma}$ measurement with 2% precision



New physics only RH C_7'

$$S_{K_S\pi^0\gamma}=\frac{2|C^{\mathrm{SM}}_{7\gamma}C'^{\mathrm{NP}}_{7\gamma}|}{|C^{\mathrm{SM}}_{7\gamma}|^2+|C'^{\mathrm{NP}}_{7\gamma}|^2}\sin(2\phi_1-\phi_R)$$

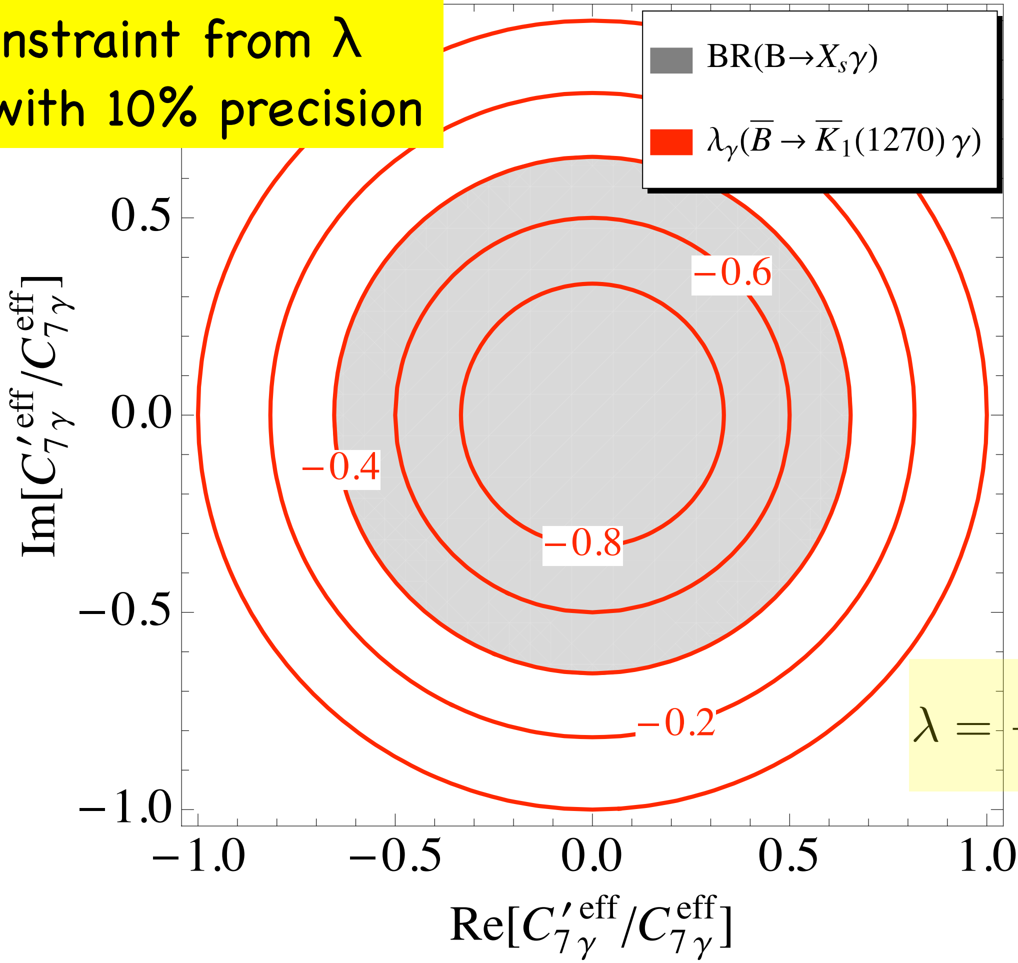
Current bound

$S_{K_S\pi^0\gamma}$ = -0.15±0.2

Comparison of the three methods

Method III

Expected constraint from λ measurement with 10% precision

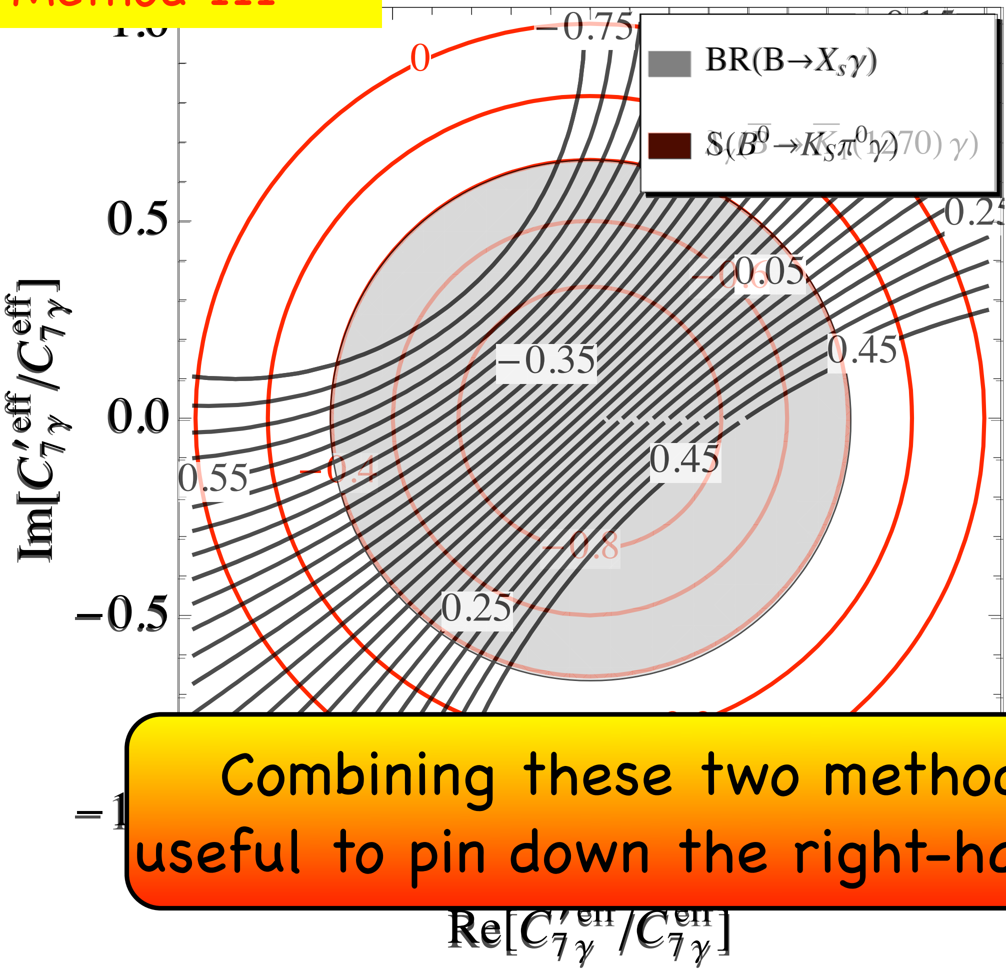


New physics only RH C_7'

$$\lambda = \frac{|C'^{\mathrm{NP}}_{7\gamma}|^2 - |C^{\mathrm{SM}}_{7\gamma}|^2}{|C'^{\mathrm{NP}}_{7\gamma}|^2 + |C^{\mathrm{SM}}_{7\gamma}|^2}$$

Comparison of the three methods

Method I & Method III



New physics only RH C_7'

Combining these two methods are very useful to pin down the right-handed current!

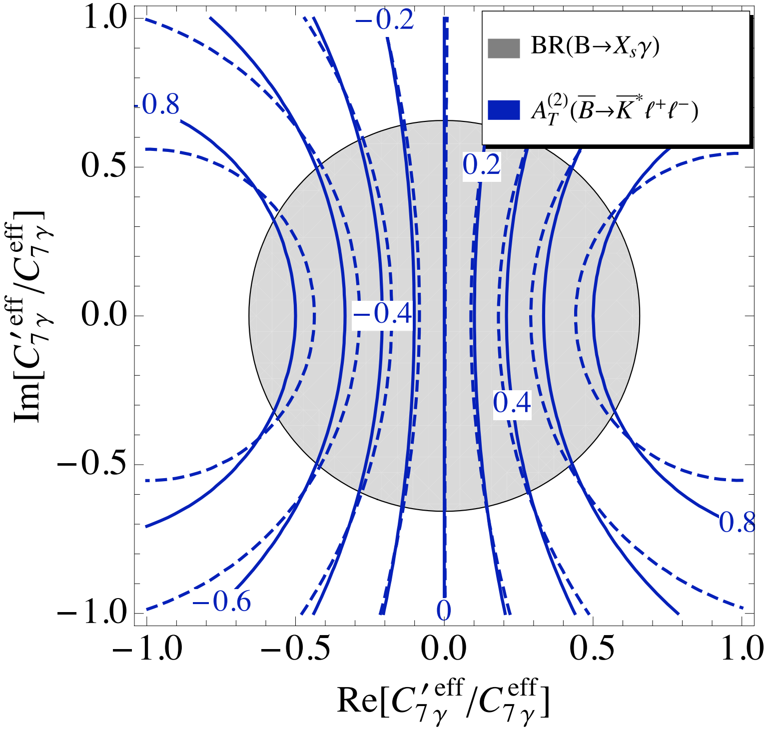
Comparison of the three methods

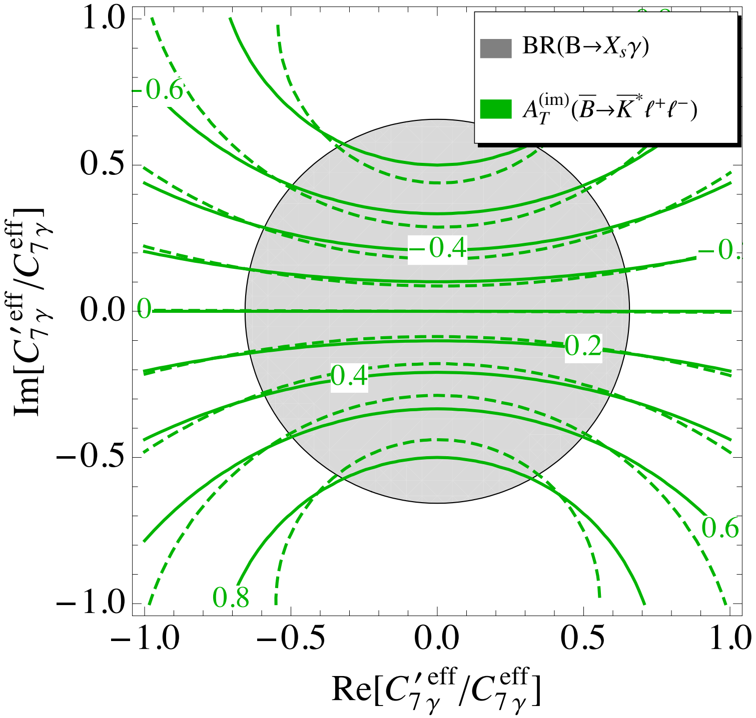
Method II

Expected constraint from

$A_T^{(2)}$, $A_T^{(im)}$ measurement with 10% precision

New physics
only RH C_7'





Assumption for γ*/Z penguin (C_9,C_{10} contributions) necessary!

Comparison of the three methods

proposed methods

- **Method I**: Time dependent CP asymmetry in $B_d \to K_S\pi^0\gamma$ $B_s \to K^+K^-\gamma$ (called $S_{K_S\pi^0\gamma}$, $S_{K^+K^-\gamma}$)

$$S_{K_S\pi^0\gamma} = \frac{2|C_{7\gamma}^{SM}|}{|C_{7\gamma}^{SM}|^2 +}$$

$$\varphi_R = \arg\left[\frac{C'^{NP}_{7\gamma}}{C^{SM}_{7\gamma}}\right]$$

Super Flavour Factories
$\sigma_{S_{K_S\pi\gamma}}(0.02)$

- **Method II**: Transverse asymmetry in $B_d \to K^* l^+ l^-$ (called $A_T^{(2)}$, $A_T^{(im)}$)

$$\mathcal{A}_T^{(2)}(q^2=0) = \frac{2Re[C_{7\gamma}^{SM} C'^{NP}_{7\gamma}}{|C_{7\gamma}^{SM}|^2 + |C'^{NP}_{7\gamma}}$$

$$(q^2=0) = \frac{2Im[C_{7\gamma}^{SM} C'^{NP*}_{7\gamma}]}{|C_{7\gamma}^{SM}|^2 + |C'^{NP}_{7\gamma}|^2}$$

LHCb
$\sigma_{A_T^{2(im)}}(0.2)$

- **Method III**: $B \to K_1(\to K\pi\pi)\gamma$ (called λ_γ)

Super Flavour Factory/LHCb
$\sigma_\lambda(0.1\text{-}0.2)$

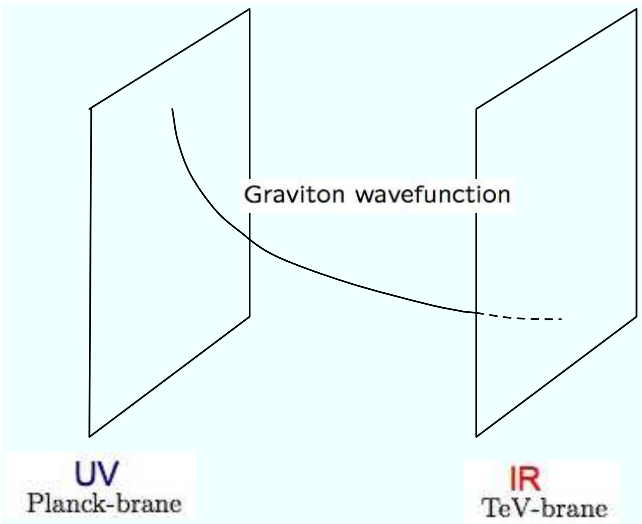
Extra-dimension

Extra-dimension model with Flavour

in nutshell...

Introduction: Randall-Sundrum model

❒ Set-up: one extra dimension (usual 4D x^μ plus one extra dimension y).



warp factor $\Omega = e^{-\pi k R}$ (k curvature, R size)

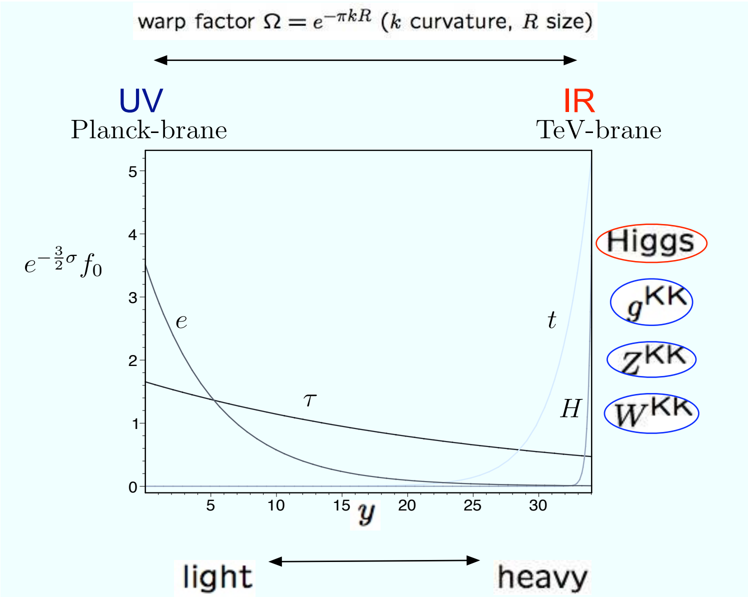
✍ Hierarchy problem is solved by the exponential factor. The Planck scale 10^{19} GeV fixes the geometric parameter $kR \simeq 11$.

Extra-dimension model with Flavour

in nutshell...

Introduction: RS model with bulk fermions

❒ Once fermions are put in the bulk, their couplings to the Higgs and KK modes are given by their distance to the TeV brane.



✍ The fermion masses hierarchy (e.g. $m_t \simeq 10^5 m_u$) can be solved by the same exponential factor.

Extra-dimension

Extra-dimension model with Flavour

in nutshell...

The coupling constants for fermions to the Higgs/KK modes

❐ The 4 dimensional Yuakawa coupling (fermion-Higgs coupling):

$$\int d^4x \int_{-\pi R}^{\pi R} \frac{dy}{2\pi R} \lambda^{5\mathrm{D}} e^{-\sigma} \underbrace{H(y)}_{\text{Higgs}} \times \underbrace{f_L^0(y)}_{\text{LHfermion}} \times \underbrace{f_R^0(y)}_{\text{RHfermion}} \times v_0 \bar{\Psi}_L^0(x) \Psi_R^0(x)$$

✍ 4D Yukawa coupling is given by the overlap of the fermion and the Higgs wavefunctions (*with some assumption for* $\lambda^{5\mathrm{D}}$).

❐ The 4 dimensional fermion-KK^1 gauge boson coupling:

$$\int d^4x \int_{-\pi R}^{\pi R} \frac{dy}{2\pi R}\, g\ e^{-\sigma} \underbrace{\chi^1(y)}_{\text{KKgauge}} \times \underbrace{f_A^0(y)}_{\text{fermion}} \times \underbrace{f_B^0(y)}_{\text{fermion}} \times \bar{\Psi}_A^0(x) \Psi_B^0(x)$$

✍ The KK coupling constant is given by the overlap of the fermion and the KK gauge boson wavefunction (with the usual g, g_s...)

$\longrightarrow$ KK gauge coupling is stronger for the heavy fermions

$\longrightarrow$ large FCNC for heavy (top/bottom) sector!

Extra-dimension

Extra-dimension model with Flavour

Breaking of GIM mechanism in the bulk flavour RS model ... nutshell...

❒ FCNC occurs *at tree level* since the fermions couple to the KK gauge bosons with different strengths.

✍ Let us define fermion eigenstates as:

$$\underbrace{\hat{\Psi}_i}_{\text{mass}-\text{eigenstate}} \equiv \underbrace{K_{ij}}_{\text{unitary matrix}} \underbrace{\Psi_j}_{\text{weak}-\text{eigenstate}}$$

✍ Then, GIM mechanism in the SM comes from $K_{ij}K^{\dagger}_{ij} = 1$

$$J^{\mu}_{\text{neutral}} \propto \overline{\Psi}_i \gamma^{\mu} \Psi_i, \quad \longrightarrow \quad \overline{\hat{\Psi}}_i \gamma^{\mu} \hat{\Psi}_i$$

✍ While in the bulk flavour RS model, the non-universal coupling C_i (larger for heavier i) leads to the non-zero off-diagonal elements (FCNC at tree level):

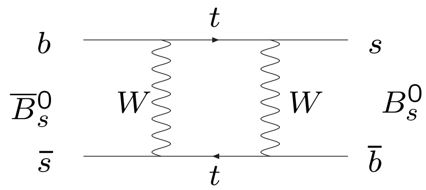
$$J^{\mu}_{\text{neutral-KK}} \propto C_i \overline{\Psi}_i \gamma^{\mu} \Psi_i, \quad \longrightarrow \quad \underbrace{K_{ji} C_i K^{\dagger}_{ik}}_{\equiv D_{ji}} \overline{\hat{\Psi}}_j \gamma^{\mu} \hat{\Psi}_k$$

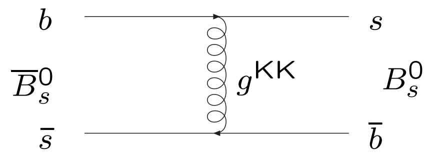
Extra-dimension model with Flavour

in nutshell...

$B_{d,s} - \overline{B}_{d,s}$ oscillation from tree level g^{KK} diagram

❒ A rough estimate predicts large effects





$$\underbrace{\frac{g_2^4}{512\pi^2 m_W^2}}_{\simeq 4.0\times 10^{-9}} \times \underbrace{(V_{tb}V_{tq}^*)^2}_{\substack{\simeq 10^{-5}(q=d) \\ \simeq 10^{-3}(q=s)}} \times \text{loop} \qquad \underbrace{\frac{2g_s^2}{9m_{g^{\mathrm{KK}}}^2}}_{\simeq 1.2\times 10^{-7}(m_{g^{\mathrm{KK}}}=2000\mathrm{GeV})} \times (\text{function of } D_{bq})$$

❒ The ΔM_d and also the recent ΔM_s measurements do not show such a large deviation: HFAG

$$\Delta M_d = 0.507 \pm 0.005\mathrm{ps}^{-1}$$
$$\Delta M_s = 17.77 \pm 0.12\mathrm{ps}^{-1}$$