Testing SUSY Flavour Models at Super$B$

based on arXiv:0909.1333 [hep-ph]

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in collaboration with
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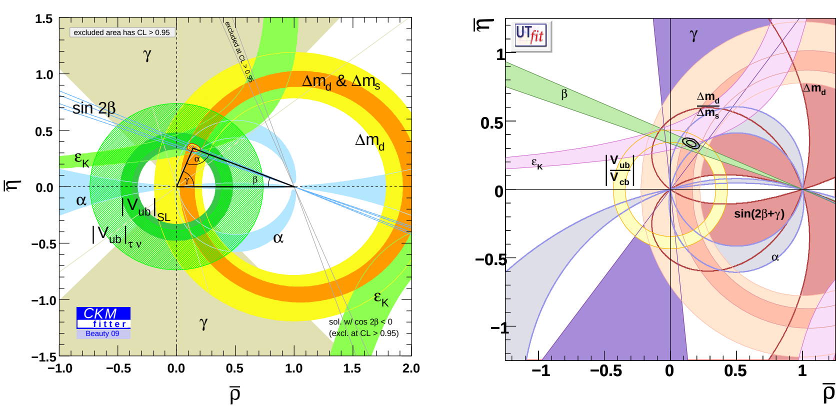
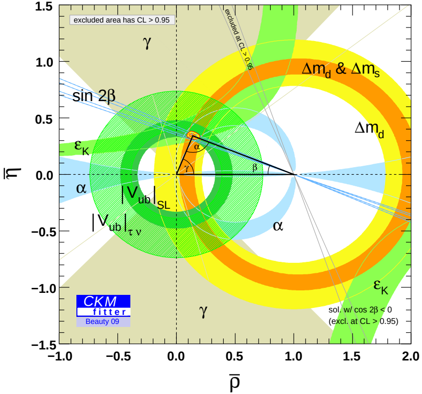
Outline

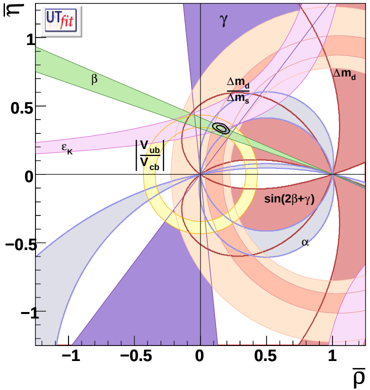
1. Hints for New Physics?
2. The SUSY flavour problem & flavour models
3. Flavour models & *B* decays: numerical results
4. Summary

Status of CKM fits



Impressive confirmation of the CKM mechanism of CP violation!

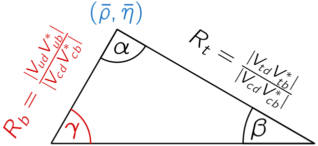


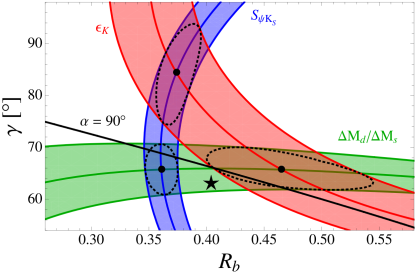


Impressive confirmation of the CKM mechanism of CP violation!

With some small tensions . . .

- Recent theoretical improvements in ϵ_K expose some tensions in the UT analysis [Lunghi & Soni, Buras & Guadagnoli]
- Look at ϵ_K, $S_{\psi K_S}$ ($\sin 2\beta$), $\Delta M_d/\Delta M_s$ in the R_b-γ plane
- R_b, γ can be obtained from tree-level processes





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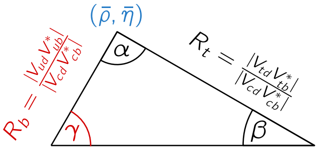

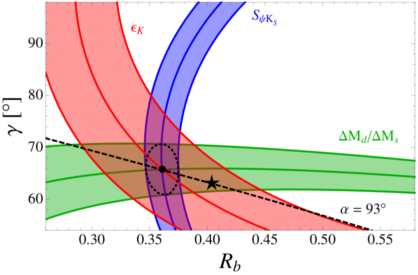

Possible solutions:

1. $+24\%$ NP effect in ϵ_K

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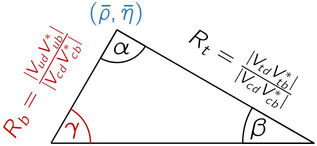

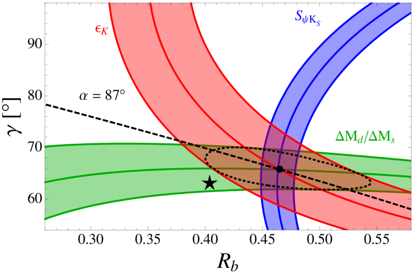

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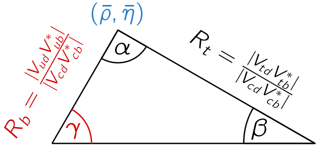

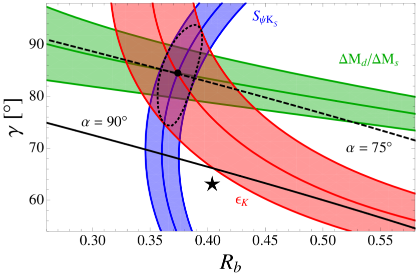

Possible solutions:

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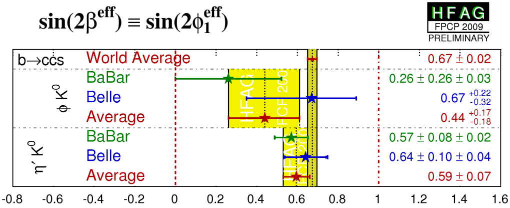
2. $-6.5°$ NP phase in B_d mixing
3. -22% NP effect in $\Delta M_d / \Delta M_s$ (requiring $\alpha \sim 74°$)

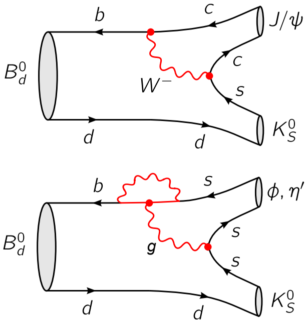
$\sin 2\beta_{\text{eff}}$ tensions

- In the SM, mixing-induced CP asymmetries in $B_d \to \psi K_S$, ϕK_S, $\eta' K_S$ all $\approx \sin 2\beta$
- $B_d \to \psi K_S$ dominated by tree level, ϕK_S and $\eta' K_S$ are loop-induced

Data indicate $S_{\phi K_S} < S_{\eta' K_S} < S_{\psi K_S}$



[adapted from HFAG]



New physics in the decay amplitudes?

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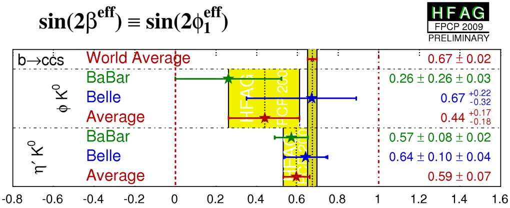

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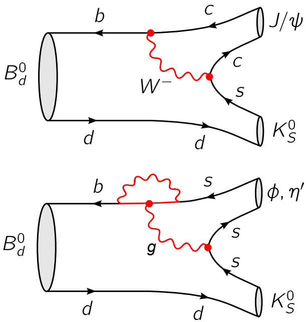
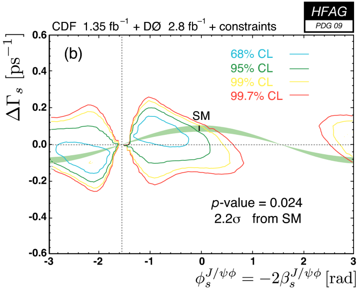


New physics in the decay amplitudes?

Can only be resolved at Super*B*

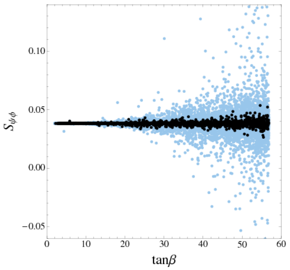
CP violation in B_s mixing

- $S_{\psi\phi}$: mixing-induced CP asymmetry in $B_s \to J/\psi\phi$
- $S_{\psi\phi} = \sin 2(\beta_s + \phi^{NP}_{B_s})$
- $S^{SM}_{\psi\phi} \approx 0.035$

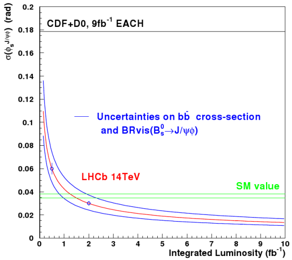


Recent Tevatron data favour
$0.20 \le S_{\psi\phi} \le 0.98$

New physics in the B_s mixing phase?



- Sizable $S_{\psi\phi}$ impossible in MFV MSSM
- Will be measured at LHCb



Main goals

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1. Find well-motivated SUSY models which can generate large effets in $S_{\psi\phi}$
2. Check whether $S_{\phi K_S}$ anomaly and UT tensions can be solved as well

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3. How can Super*B* help distinguish between these models?

Outline

SUSY vs. flavour

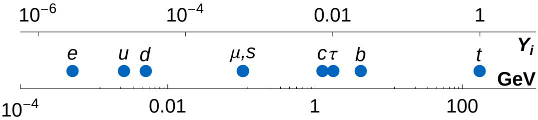
The SUSY flavour problem

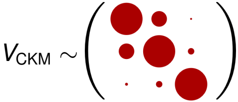
- Most of the 105 additional parameters in the MSSM violate flavour
- $O(1)$ values are strongly disfavoured by the excellent agreement of the SM with the flavour data

Possible solutions

1. Decoupling
   - Sfermion mass scale very high
   - Clashes with the gauge hierarchy problem
2. Degeneracy
   - Sfermion masses nearly degenerate
   - Arises in models with low-scale SUSY breaking
   - Partly spoiled by RG evolution
3. Alignment
   - Quark and squark mass matrices aligned

Flavour violation is highly non-generic already in the SM!





The two problems should be related!

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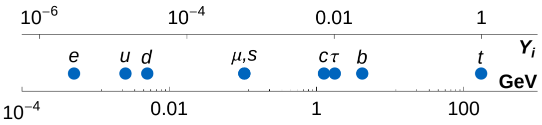
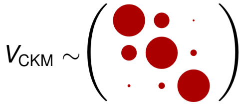




The two problems should be related!

Minimal Flavour Violation (MFV)

- Yukawa couplings are the only sources of flavour violation
- Effective theory
- Pragmatic approach
- Pessimistic phenomenology

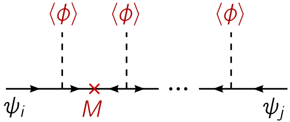
Flavour Models

- Flavour structure of Yukawa couplings and soft terms generated by spontaneous breaking of a flavour symmetry
- Ambitious approach
- Diverse phenomenology

Main idea: hierarchies in Yukawa couplings generated by spontaneous breakdown of flavour symmetry (horizontal symmetry, family symmetry)

- Generalization of the Froggat-Nielsen mechanism
- Yukawa hierarchies explained by different powers of small ϵ:

$$\Rightarrow Y_{ij} \propto \left(\frac{\langle\phi\rangle}{M}\right)^{(a_i+b_j)} = \epsilon^{(a_i+b_j)}$$



- Possible to relate Yukawa matrices and sfermion mass matrices/trilinear couplings

SUSY flavour models can explain the origin of the hierarchies in the Yukawa couplings *and* solve the SUSY flavour problem

- Many different viable models exist, with abelian or non-abelian flavour symmetries

The SUSY CP problem

$O(1)$ values for many of the $O(50)$ phases in the MSSM are strongly disfavoured by experimental bounds, in particular EDMs

Common solution in Flavour Models:

- CP is conserved in the "underlying" theory
- CP broken spontaneously by flavon VEVs
- Flavour-blind CP violation suppressed

Parenthesis: the SUSY CP problem

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Applying the same approach to MFV: [Paradisi & DS, 0906.4551]

- The MFV principle does not forbid new phases beyond the CKM
- Assume CP conservation in the limit of flavour blindness
- CP violated by MFV-compatible terms breaking the flavour blindness
- Viable but interesting CP-phenomenology

Classes of flavour models

Abelian vs. Non-abelian

- In most non-abelian models, 1st & 2nd generatio sfermions are approximately degenerate
  - Suppressed contributions to $1 \leftrightarrow 2$ transitions, in particular D^0-$\bar{D}^0$ mixing
- In abelian models, sfermions of different generations need not be degenerate
  - $O(1)$ 1-2 mass splitting leads to $O(\lambda)$ $(\delta_u^{LL})_{12}$ in the SCKM basis
  - Large effects in D^0-$\bar{D}^0$ mixing

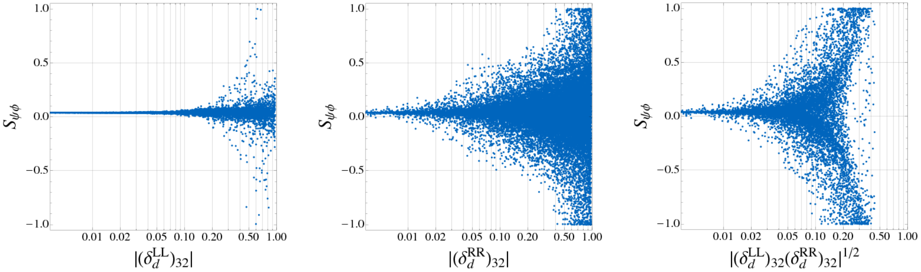
Chirality structure of flavour violating terms

- Different flavour symmetries lead to different patterns of flavour violation
- Mass insertions: $M_{\tilde{d}}^2 = \mathrm{diag}(\tilde{m}^2) + \tilde{m}^2 \begin{pmatrix} \delta_d^{LL} & \delta_d^{LR} \\ \delta_d^{RL} & \delta_d^{RR} \end{pmatrix}$
- δ^{LL}, δ^{RR}, δ^{LR} fixed by the flavour symmetry (up to $O(1)$ factors)

$S_{\psi\phi}$ vs. mass insertions

How to generate large NP effects in $S_{\psi\phi}$?

- LR MIs strongly constrained by $b \to s\gamma$
- Sizable effects in $S_{\psi\phi}$ possible in particular with simultaneous LL and RR MIs
- LL MIs are always generated by RG effects even if vanishing at the GUT scale



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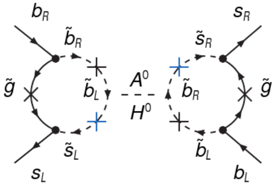
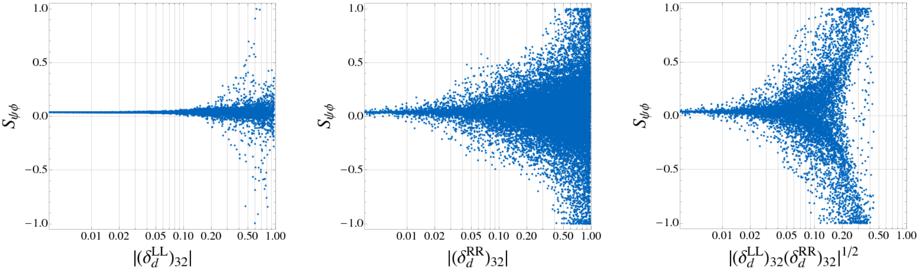




Models

4 representative flavour models with different chirality structures in the $\tilde{d}$ sector:

AC model [Agashe, Carone]	AKM model [Antusch, King, Malinsky]	RVV model [Ross, Velasco-Sevilla, Vives]	δLL model [e.g. Hall, Murayama]
$U(1)$	$SU(3)$	$SU(3)$	$(S_3)^3$
Large, $O(1)$ RR mass insertions	Only CKM-like RR mass insertions	CKM-like LL & RR mass insertions	Only CKM-like LL mass insertions

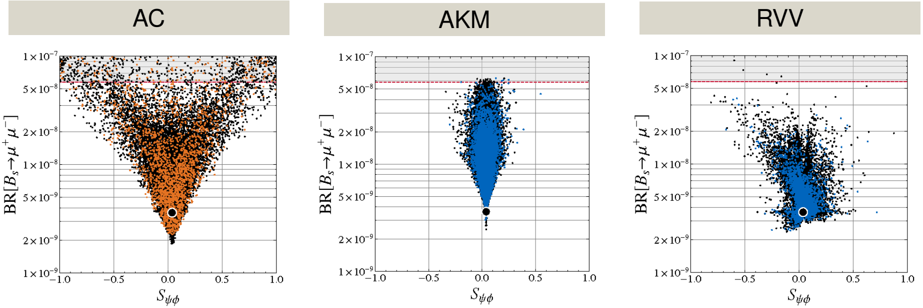
$$\delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & \lambda^2 \\ 0 & \lambda^2 & \cdot \end{pmatrix} \quad \delta_d^{LL} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix} \quad \delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix} \quad \delta_d^{LL} \sim \begin{pmatrix} \cdot & \lambda^5 & \lambda^3 \\ \lambda^5 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix}$$

$$\delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 1 \\ 0 & 1 & \cdot \end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^3 \\ \lambda^3 & \cdot & \lambda^2 \\ \lambda^3 & \lambda^2 & \cdot \end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix} \cdot & \lambda^3 & \lambda^2 \\ \lambda^3 & \cdot & \lambda \\ \lambda^2 & \lambda & \cdot \end{pmatrix} \quad \delta_d^{RR} \sim \begin{pmatrix} \cdot & 0 & 0 \\ 0 & \cdot & 0 \\ 0 & 0 & \cdot \end{pmatrix}$$

[cf. also Calibbi et al. (2009)]

Outline

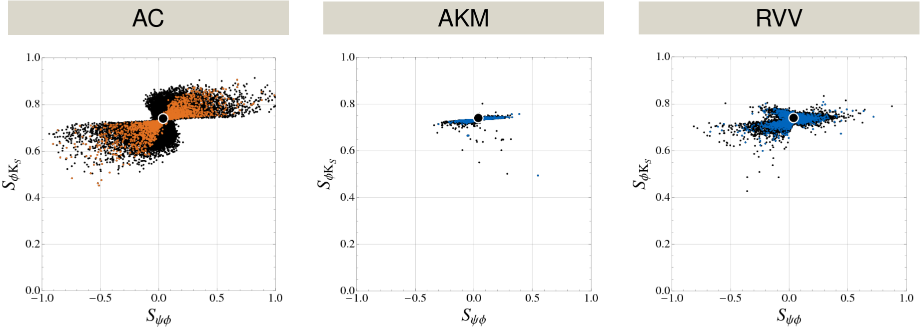
- Both observables can deviate significantly from the SM in all 3 models
- large $S_{\psi\phi}$ $\Rightarrow$ large BR($B_s \to \mu^+\mu^-$) in the AC and AKM models
- Correlation arises from dominance of Higgs penguin contributions



- Orange points: UT tension solved through contribution to $\Delta M_d/\Delta M_s$
- Blue points: UT tension solved through contribution to ϵ_K
- Scan ranges: $m_0 < 2$ TeV, $M_{1/2} < 1$ TeV, $|A_0| < 3m_0$, $5 < \tan\beta < 55$, $O(1)$ parameters varied within $[\frac{1}{2}, 2]$

$S_{\phi K_S}$ vs. $S_{\psi\phi}$

- In the AC model, both $S_{\phi K_S}$ and $S_{\psi\phi}$ can have large effects, but a simultaneous *enhancement* of $S_{\psi\phi}$ and *suppression* of $S_{\phi K_S}$ (as indicated by the data) is impossible
- $S_{\phi K_S}$ nearly SM-like in AKM and RVV models



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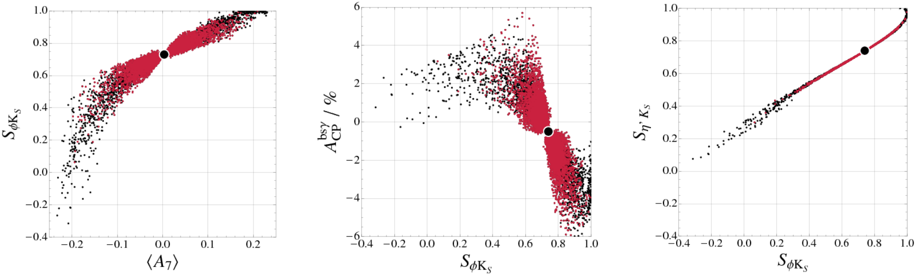
Pattern of NP effects in the δLL model:

- No large effects in $S_{\psi\phi}$
- Large, correlated effects in $S_{\phi K_S}$, $S_{\eta' K_S}$, $A_{CP}(b \to s\gamma)$, $\langle A_{7,8} \rangle$
- $\langle A_{7,8} \rangle$: T-odd CP asymmetries in $B \to K^* \ell^+ \ell^-$



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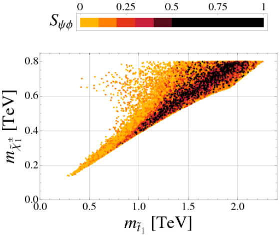
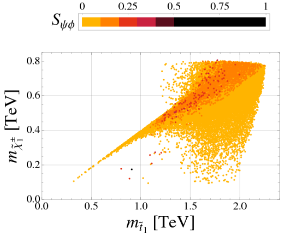
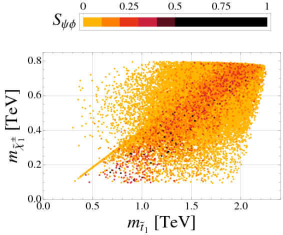
AC



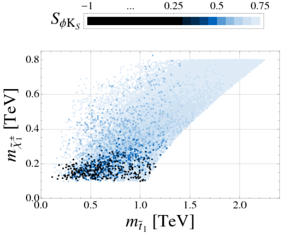
AKM



RVV



δLL



- Large effects in $S_{\psi\phi}$ even possible for spectra beyond the LHC reach in the models with RH currents
- Large effects in $S_{\phi K_S}$ not possible for spectra beyond the LHC reach in the δLL model

"DNA-Flavour Test" at Super*B*

	GMSSM	AC	RVV2	AKM	δLL	FBMSSM	
$S_{\phi K_S}$	★★★	★★★	●●	■	★★★	★★★	
$A_{CP}(B \to X_s\gamma)$	★★★	■	■	■	★★★	★★★	
$B \to K^{(*)}\nu\bar{\nu}$	●●	■	■	■	■	■	
$\tau \to \mu\gamma$	★★★	★★★	★★★	■	★★★	★★★	
$D^0 - \bar{D}^0$	★★★	★★★	■	■	■	■	
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	★★★	★★★	vs.
$A_9(B \to K^*\mu^+\mu^-)$	★★★	■	■	■	■	■	
$S_{\psi\phi}$	★★★	★★★	★★★	★★★	■	■	
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★★★	
ϵ_K	★★★	■	★★★	★★★	■	■	
$K^+ \to \pi^+\nu\bar{\nu}$	★★★	■	■	■	■	■	
$K_L \to \pi^0\nu\bar{\nu}$	★★★	■	■	■	■	■	
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	
d_n	★★★	★★★	★★★	★★★	●●	★★★	
d_e	★★★	★★★	★★★	●●	■	★★★	
$(g-2)_\mu$	★★★	★★★	★★★	●●	★★★	★★★	