Impact of Z' Boson on Pure Annihilation B Meson Decays

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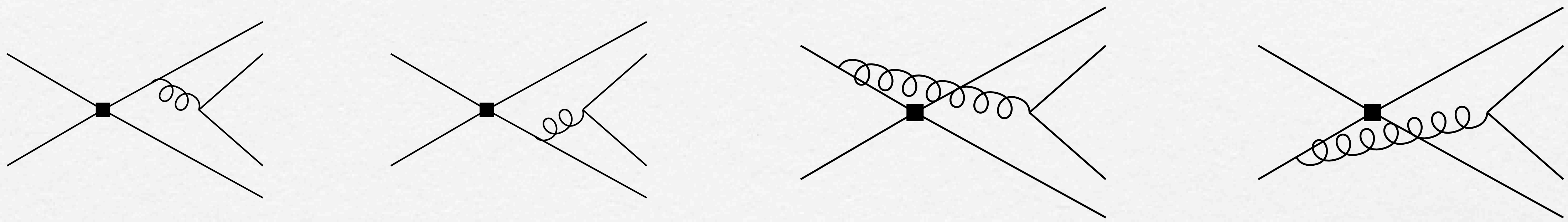
Motivation

- B meson two-body charmless non-leptonic decays have played important roles in testing SM and searching for possible effects of new physics.
- In the experimental side, not only the branching fractions but CP asymmetries have been measured in two B-factories and LHCb. More new results are expected in Belle-II experiment.
- In the theoretical side, based on the factorization hypothesis, many approaches have been proposed for studying B meson decays, such as naive factorization, QCD factorization, perturbative QCD, soft-collinear effective theory, and topological approaches.
- Currently, we cannot conclude which approach is the best one, as each one has its own faults.

$B_s^0 \to \pi^+\pi^-$ and $B_d^0 \to K^+K^-$

- None of the quarks in the final states is same as the initial quarks, these decay modes can occur only via power-suppressed annihilation diagrams.



CDF $\mathcal{B}(B_s \to \pi^+\pi^-) = (0.57 \pm 0.15 \pm 0.10) \times 10^{-6}$

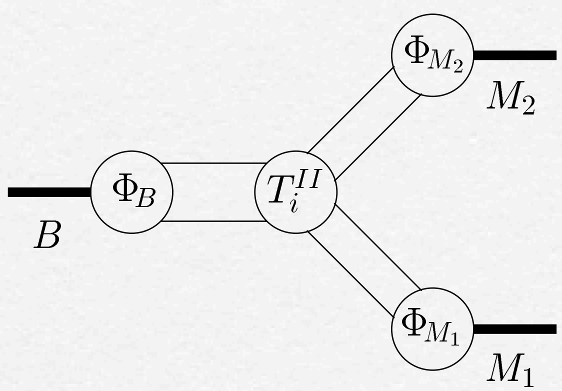
LHCb $\mathcal{B}(B_s \to \pi^+\pi^-) = (0.95^{+0.21}_{-0.17} \pm 0.13) \times 10^{-6}$

HFAG

$$\mathcal{B}(B_s \to \pi^+\pi^-) = (0.73 \pm 0.14) \times 10^{-6}.$$

$$\mathcal{B}(B_d \to K^+K^-) = (0.12 \pm 0.06) \times 10^{-6}$$

Theoretical Studies



- These decays cannot be calculated in QCDF approach due to the endpoint singularities.

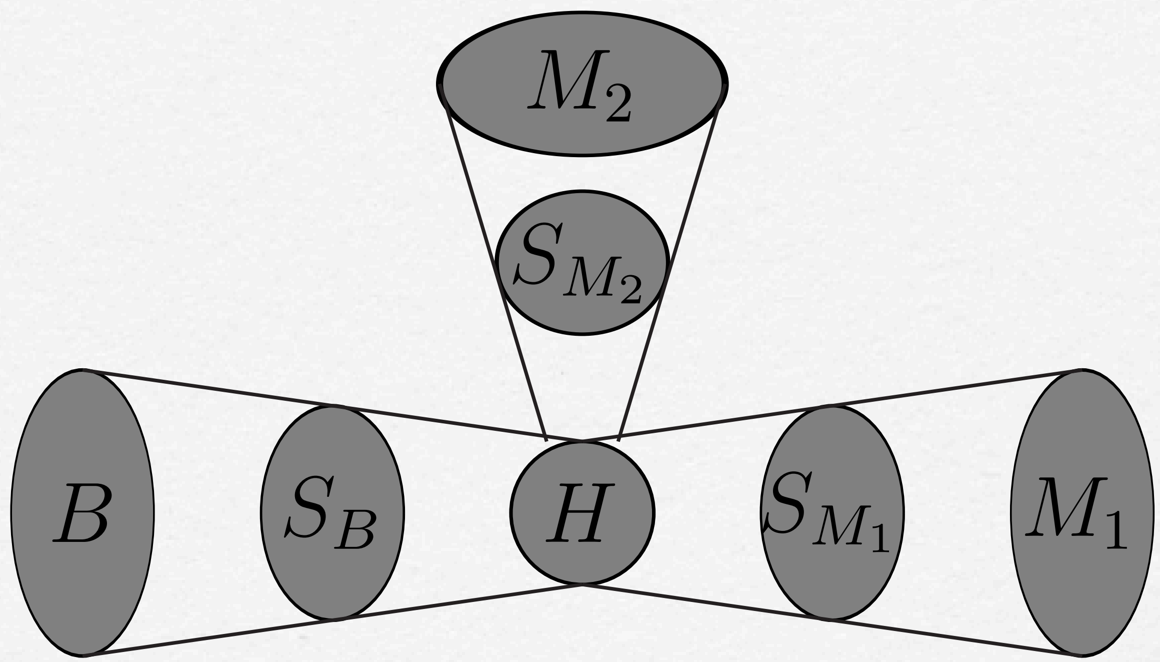
$$\int_0^1 \frac{dy}{y} \to X_A^{M_1}\,, \qquad \int_0^1 dy\, \frac{\ln y}{y} \to -\frac{1}{2}\,(X_A^{M_1})^2\,,$$

$$X_A = \left(1 + \varrho_A\, e^{i\varphi_A}\right) \ln \frac{m_B}{\Lambda_h}\,;$$

- With keeping the transverse momenta of the inner quarks, the endpoint singularities can be smeared in the pQCD, so the pure annihilation decays can be calculated directly.

$$\frac{1}{xm_B^2 - k_T^2 + i\epsilon} = \frac{P}{xm_B^2 - k_T^2} - i\pi\delta(xm_B^2 - k_T^2).$$

Perturbative QCD Approach



Threshold Resummation

Hard kernel

$$\mathcal{A} \sim \int dx_1 dx_2 dx_3 \int b_1 db_1 b_2 db_2 b_3 db_3 \mathrm{Tr}\Big[C(t)\underbrace{\Phi_B(x_1,b_1)\Phi_2(x_2,b_2)\Phi_3(x_3,b_3)}_{\text{Distribution Amplitude}} H(x_i,b_i,t) S_t(x_i) e^{-S(t)}\Big],$$

Sudakov Factor

$$\mathcal{B}(B_s \to \pi^+\pi^-) = (5.5^{+1.1}_{-0.9}) \times 10^{-7},$$
$$\mathcal{B}(B_d \to K^+K^-) = (1.9^{+0.3}_{-0.3}) \times 10^{-7}.$$

QCDF(10^{-6}) BBNS'0308039

Mode	Theory
$\bar{B}_s \to \pi^+\pi^-$	$0.024^{+0.003}_{-0.003}{}^{+0.025}_{-0.012}{}^{+0.000}_{-0.000}{}^{+0.163}_{-0.021}$
$\bar{B}_s \to \pi^0\pi^0$	$0.012^{+0.001}_{-0.001}{}^{+0.013}_{-0.006}{}^{+0.000}_{-0.000}{}^{+0.082}_{-0.011}$

CDF $\mathcal{B}(B_s \to \pi^+\pi^-) = (0.57 \pm 0.15 \pm 0.10) \times 10^{-6}$

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$$\begin{cases} \mathcal{A}_{CP}^{dir}(B_s \to \pi^+\pi^-) = (-1.5 \pm 0.2)\%, \\ \mathcal{S}_f(B_s \to \pi^+\pi^-) = 0.11 \pm 0.01, \\ \mathcal{H}_f(B_s \to \pi^+\pi^-) = 0.99; \end{cases}$$

$$\begin{cases} \mathcal{A}_{CP}^{dir}(B_d \to K^+K^-) = (37^{+5}_{-7})\%, \\ \mathcal{S}_f(B_d \to K^+K^-) = -0.81 \pm 0.05, \\ \mathcal{H}_f(B_d \to K^+K^-) = -0.45 \pm 0.05, \end{cases}$$

Why Do We Need NP ?

- It is accepted by most of us that the SM is not a final theory, and it should be an effective one of a more fundamental theory at higher scale, although the SM Higgs boson has been discovered.

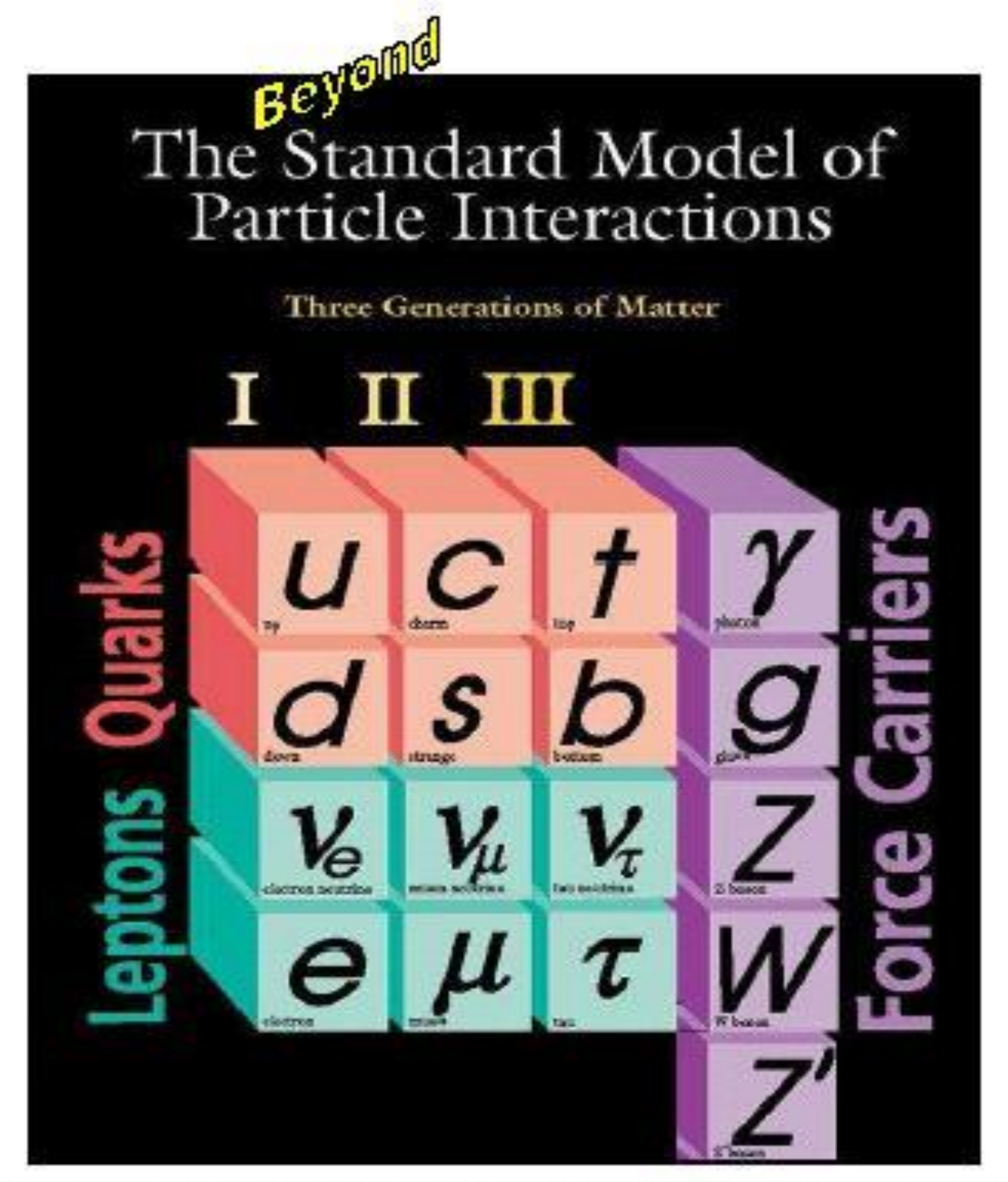
- Fine Tuning --> SUSY, XD, LH
- CP Violation --> Neutrino, Heavy Flavor
- Dark Matter --> SUSY, XD, Z_2, et.al
- Grand Unitary Theory --> String, et al.

What is Z' Boson

- SUSY
- String Models
- E_6 Models
- U Boson Model
- Grand Unitary Theory

The effect of Z' on flavor physics have been discussed for many years.

G.Valencia, X.G He, C.W Chiang, T. Liu, C.S Kim, …..



Tree-Level FCNC Z'

- In the gauge eigenbasis, the Z' neutral current Lagrangian is given by

$$\mathscr{L}^{Z'} = -g_2 J'_\mu Z'^\mu$$

the standard model chiral couplings

$$J_Z^\mu = \sum_\psi \sum_i \overline{\psi}_i \gamma^\mu \left[\epsilon_i^{\psi_L} P_L + \epsilon_i^{\psi_R} P_R\right] \psi_i,$$

$$J_{Z'}^\mu = \sum_\psi \sum_{i,j} \overline{\psi}_i \gamma^\mu \left[\tilde{\epsilon}_{ij}^{\psi_L} P_L + \tilde{\epsilon}_{ij}^{\psi_R} P_R\right] \psi_j,$$

the chiral couplings of the new gauge boson

- When we turn to the mass eigenstates, the chiral Z' coupling matrices in the physical basis of up-type and down-type quarks are, respectively,

$$B_u^X \equiv V_{u_X} \varepsilon_{u_X} V_{u_X}^\dagger \;,\;\; B_d^X \equiv V_{d_X} \varepsilon_{d_X} V_{d_X}^\dagger \quad (X = L, R).$$

- If ε is not proportional to the identity matrix, $B^{L,R}$ will have nonzero off-diagonal elements, which will induce FCNC interactions.

Tree-Level FCNC Z’ -Simplification

- Neglecting the Z-Z’ mixing, which have been proved to be vey tiny by the Z-pole measurements at LEP.
- Assuming the right-handed couplings are flavor-diagonal.
- No significant RG running effect between Z’ and W scales.
- Negligible Z’ effect on the QCD penguins so that the new physics is manifestly isospin violating.
- We set $B_{ss}=B_{dd}$ with assumptions of universality for the first two families, as required by K and muon decays constraints.

Tree-Level FCNC Z′

- The effective Hamiltonian of the *b*→ *s q qbar* transitions mediated by the *Z′* is

$$\mathcal{H}_{\rm eff}^{Z'} = \frac{2G_F}{\sqrt{2}}\left(\frac{g_2 M_Z}{g_1 M_{Z'}}\right)^2 B_{sb}^{L*}(bs)_{V-A}\sum_q \left(B_{qq}^L (qq)_{V-A} + B_{qq}^R (qq)_{V+A}\right) + \text{h.c.}$$

This structure is similar to the effective operators of SM,

$$\mathcal{H}_{\rm eff}^{Z'} = -\frac{G_F}{\sqrt{2}} V_{tb}^* V_{ts} \sum_q \left(\Delta C_3 O_3^{(q)} + \Delta C_5 O_5^{(q)} + \Delta C_7 O_7^{(q)} + \Delta C_9 O_9^{(q)}\right) + \text{h.c.},$$

QCD Penguin

$$\Delta C_{3(5)} = -\frac{2}{3V_{tb}^* V_{ts}}\left(\frac{g_2 M_Z}{g_1 M_{Z'}}\right)^2 B_{sb}^{L*}\left(B_{uu}^{L(R)} + 2B_{dd}^{L(R)}\right)$$

EW Penguin

$$\Delta C_{9(7)} = -\frac{4}{3V_{tb}^* V_{ts}}\left(\frac{g_2 M_Z}{g_1 M_{Z'}}\right)^2 B_{sb}^{L*}\left(B_{uu}^{L(R)} - B_{dd}^{L(R)}\right).$$

- In order to show that the new physics is primarily manifest in the EW penguins, we assume $B^{L(R)} \simeq -2^{\mathrm{BL(R)}}$.

Tree-Level FCNC Z'

- As a result, the Z' contributions to the Wilson coefficients at the weak scale are

$$\Delta C_{3(5)} = 0 \,,$$
$$\Delta C_{9(7)} = 4 \frac{|V_{tb}^* V_{ts}|}{V_{tb}^* V_{ts}} \xi^{LL(R)} e^{-i\phi_L} \,,$$

where

$$\xi^{LX} \equiv \left(\frac{g_2 M_Z}{g_1 M_{Z'}}\right)^2 \left|\frac{B_{sb}^{L*} B_{dd}^{X}}{V_{tb}^* V_{ts}}\right| \quad (X = L, R) \,,$$
$$\phi_L \equiv \mathrm{Arg}[B_{sb}^{L}] \,.$$

- Due to the Hermiticity of the effective Hamiltonian, the diagonal elements of the effective coupling matrix are real. However, the off-diagonal elements generally may contain new weak phases.

Constrain of the Parameters – Strategy

- Up to now, there are only three free parameters left in this model. The left work is to constraint these parameters with rich data. But it is not an easy work due to large uncertainties in theoretical framework and experimental data.

b-s-Z', l-l-Z' $B_s \to \mu\mu$	b-s-Z', l-l-Z' $B \to X_S\mu\mu$	b-s-Z', l-l-Z' $B \to K^{(*)}\mu\mu$	b-s-Z' Bs Mixing

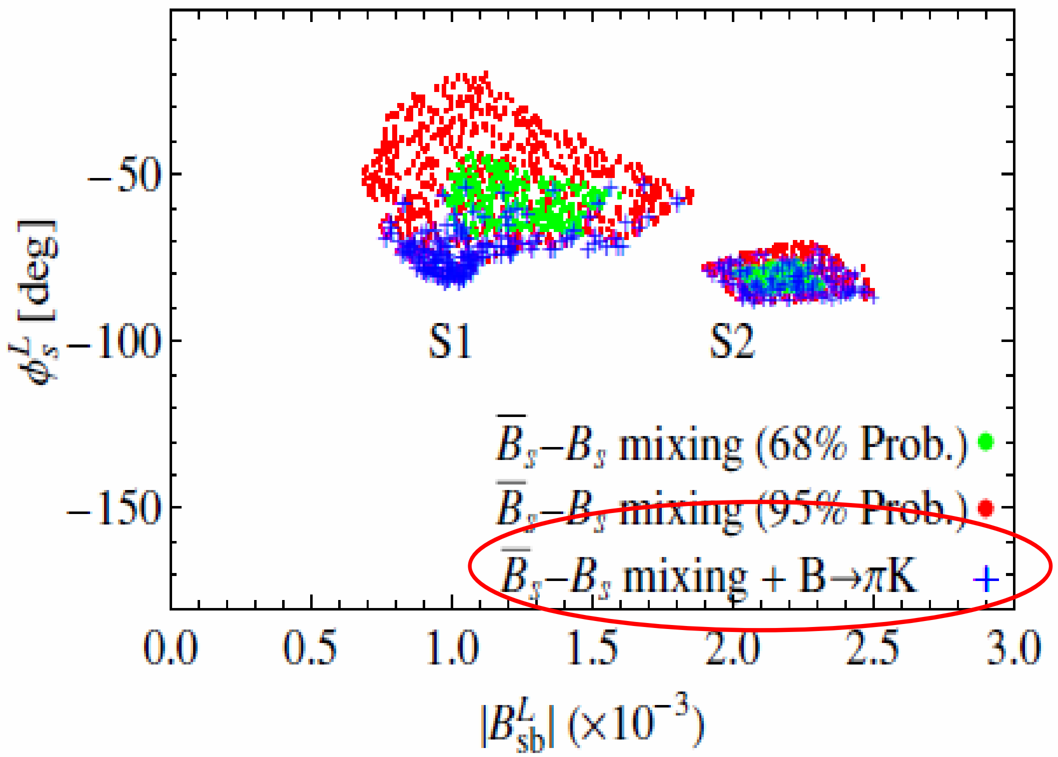
$$
\begin{aligned}
\xi^{LX} &\equiv \left(\frac{g_2 M_Z}{g_1 M_{Z'}}\right)^2 \left|\frac{B_{sb}^{L*} B_{dd}^{X}}{V_{tb}^{*} V_{ts}}\right| \quad (X = L, R) \,, \\
\phi_L &\equiv \mathrm{Arg}[B_{sb}^{L}] \,.
\end{aligned}
$$

b-s-Z', s-s-Z' $B \to K\Phi, K^*\Phi$	b-s-Z', d-d-Z' $B \to K\pi$	b-s-Z', d-d-Z' $B \to \rho K$	b-d-Z', d-d-Z' $B \to \pi\pi$

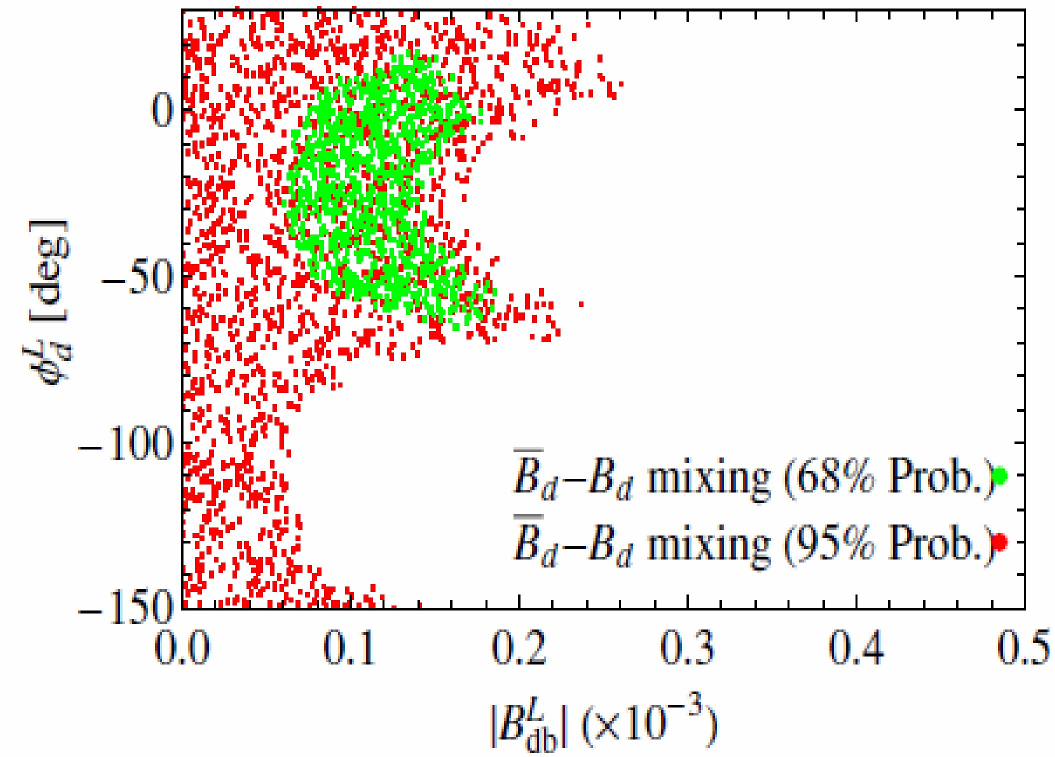
b-s-Z' coupling

constraint results

b-d-Z' coupling



(a)



(b)

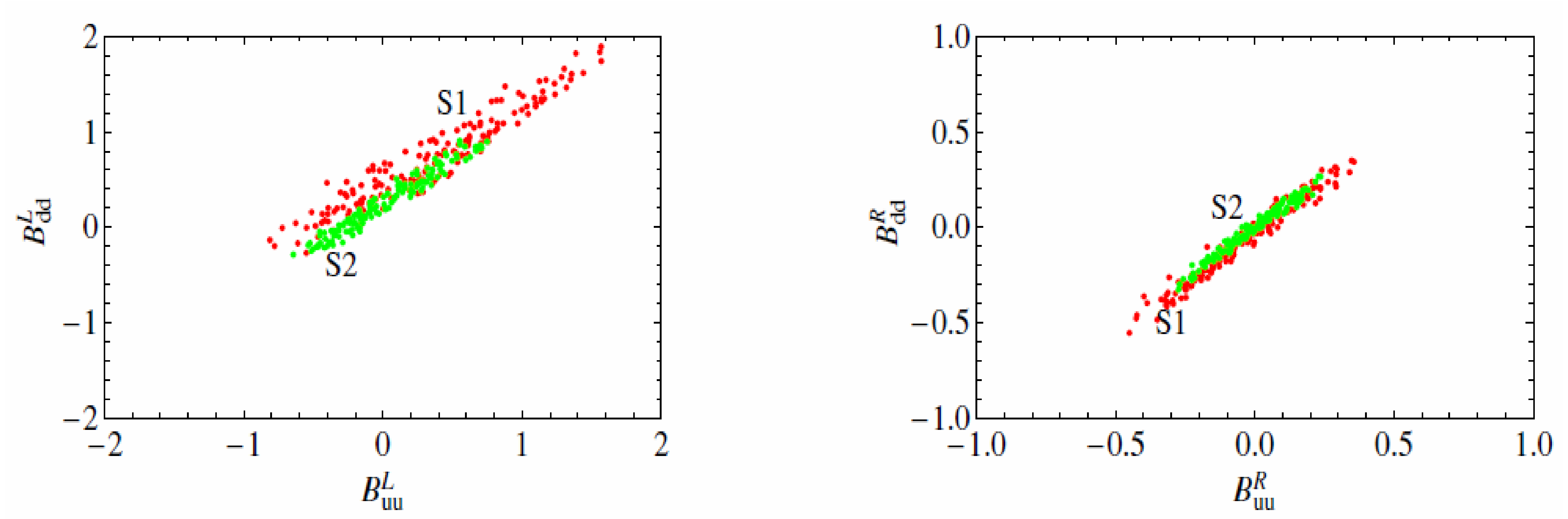
CKM-like Hierarchy:

$$|B_{db}/B_{sb}| \lesssim 0.2 \sim |V^*_{td}V_{tb}/V^*_{ts}V_{tb}|$$

Numerically,

Solutions	$\lvert B^L_{sb}\rvert (\times 10^{-3})$	$\phi^L_s [^\circ]$	$\lvert B^L_{db}\rvert (\times 10^{-3})$	$\phi^L_d [^\circ]$	
S1	1.24 ± 0.16	-58 ± 6	0.12 ± 0.03	-23 ± 21	68% prob.
	1.18 ± 0.29	-52 ± 13	$\lesssim 0.26$	arbitrary	95% prob.
S2	2.17 ± 0.07	-80 ± 2	—	—	
	2.19 ± 0.14	-80 ± 4	—	—	

u-u-Z' and d-d-Z' couplings



$\overline{B}_s - B_s$ mixing + B→πK

Solutions	$\lvert B^L_{sb}\rvert(\times 10^{-3})$	$\phi^L_s[°]$	B^L_{uu}	B^R_{uu}	B^L_{dd}	B^R_{dd}
S1	1.18 ± 0.16	-62 ± 5	0.66 ± 0.38	-0.13 ± 0.12	0.88 ± 0.36	-0.18 ± 0.14
	1.09 ± 0.22	-72 ± 7	0.34 ± 0.55	-0.04 ± 0.18	0.70 ± 0.48	-0.07 ± 0.20
S2	2.19 ± 0.06	-81 ± 2	-0.02 ± 0.34	0.01 ± 0.12	0.22 ± 0.32	0.01 ± 0.12
	2.20 ± 0.15	-82 ± 4	0.02 ± 0.34	-0.01 ± 0.12	0.27 ± 0.32	-0.04 ± 0.24

nonzero

Crucial to resolve such two puzzles

Constrain of the Parameters－Summary

$$\xi^{LX} \equiv \left(\frac{g_2 M_Z}{g_1 M_{Z'}}\right)^2 \left|\frac{B_{sb}^{L*} B_{dd}^{X}}{V_{tb}^* V_{ts}}\right| \quad (X = L, R) ,$$

$$\phi_L \equiv \mathrm{Arg}[B_{sb}^L] .$$

- Generally, we always expect $g_2/g_1 \sim\sim 1$, if both the U(1) gauge groups have the same origin from some grand unified theories.

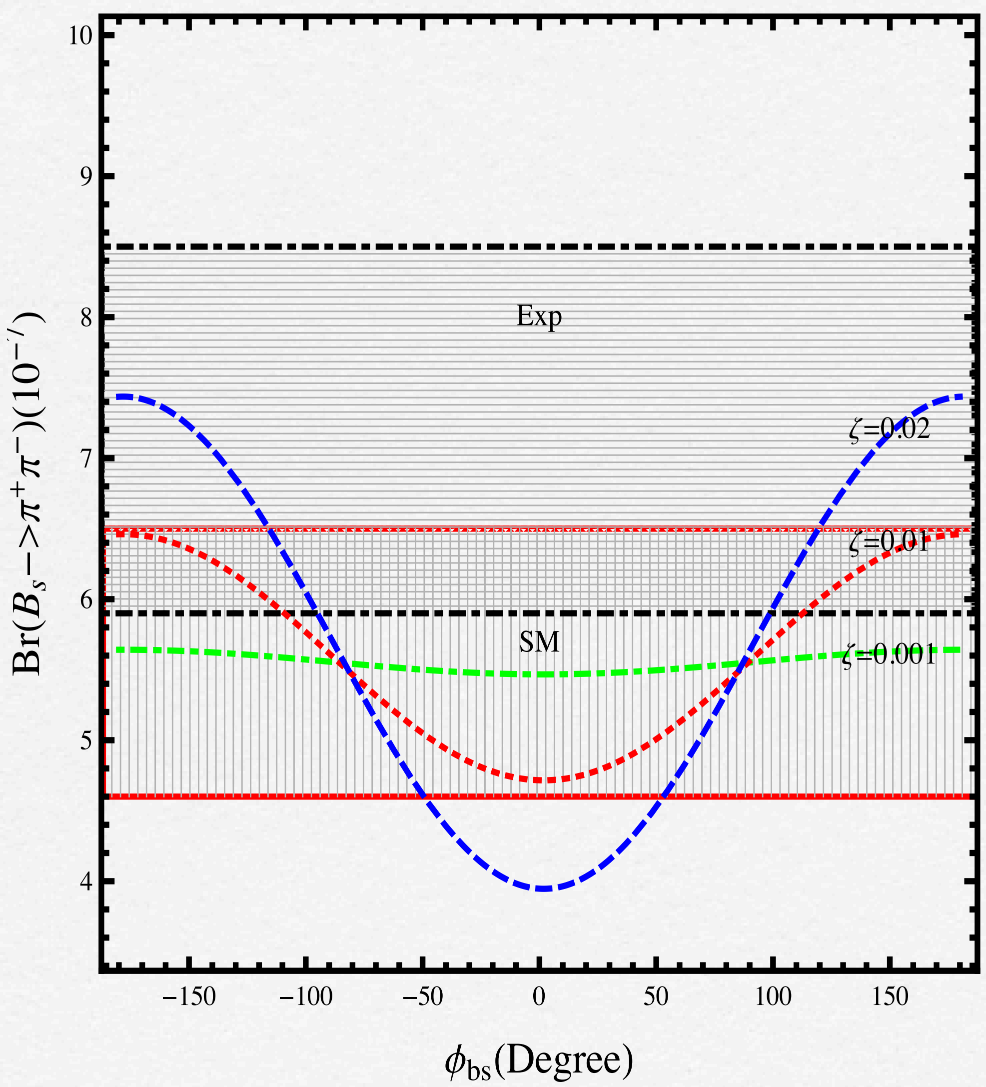
- We set $M_Z/M_{Z'} \sim 0.1$, thus the Z' could be detected in the running LHC.

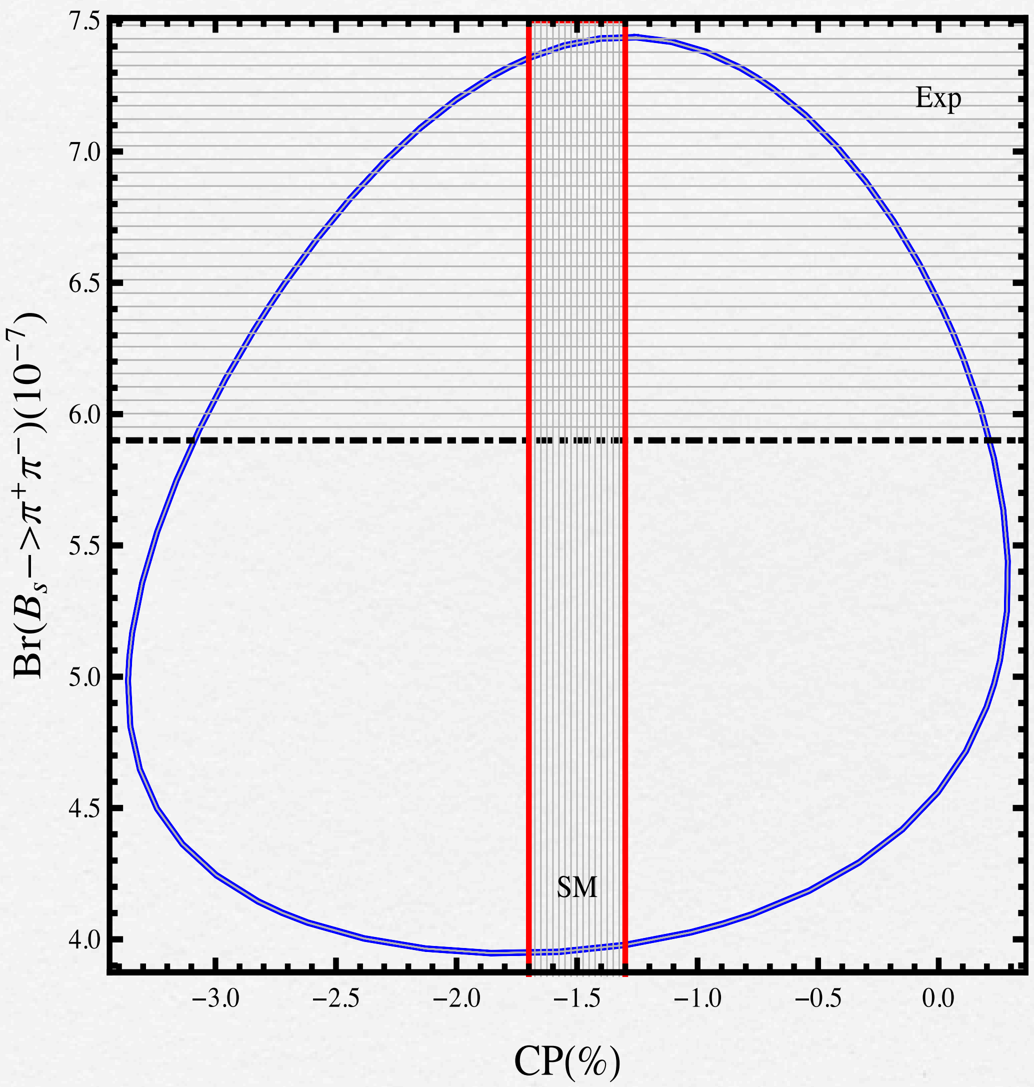
- $|B_{sb}| \sim |V_{tb} V_{ts}^*|$ is required by Bs mixing.

- From B meson rare decays stated above, we hope $|B_{qq}| \sim 1$ for both left and right couplings.

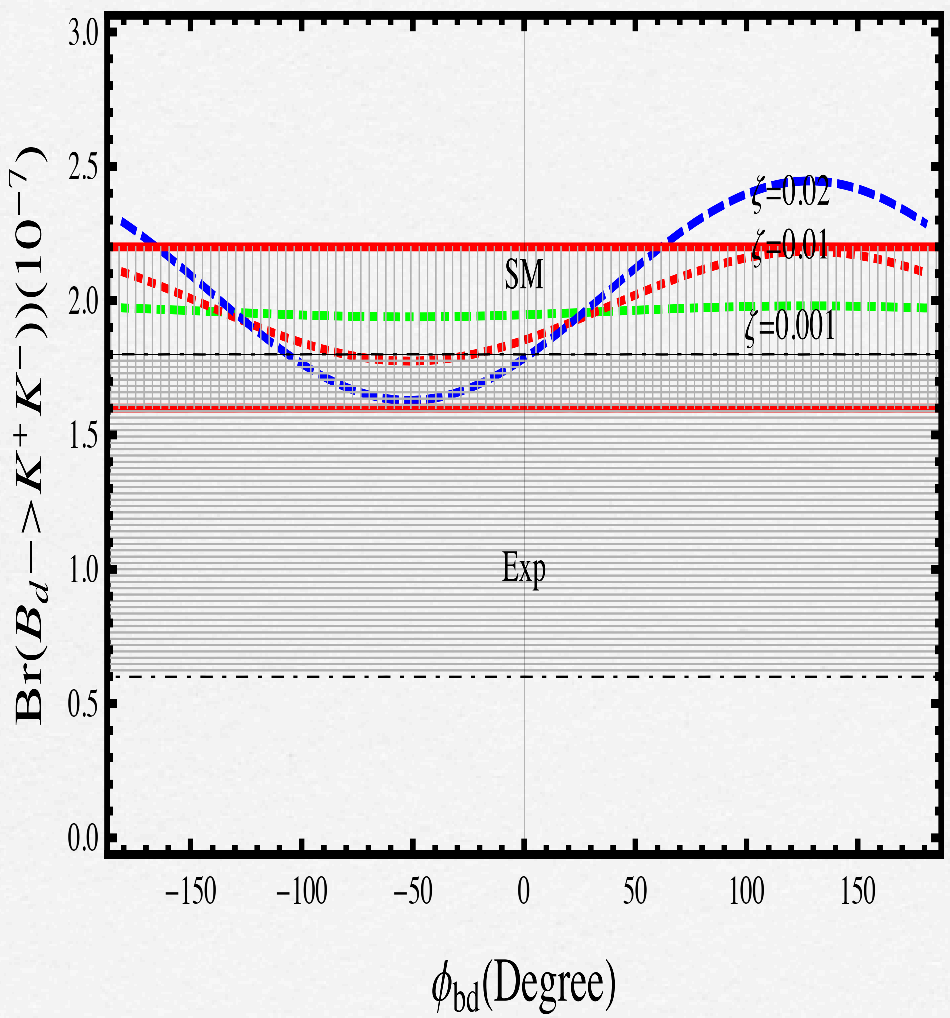
- Summing up above analysis, we thereby assume that $\xi \in [10^{-2}, 10^{-3}]$. For weak phase, though many attempts have been done to constrain it, we here left it as a free parameter.

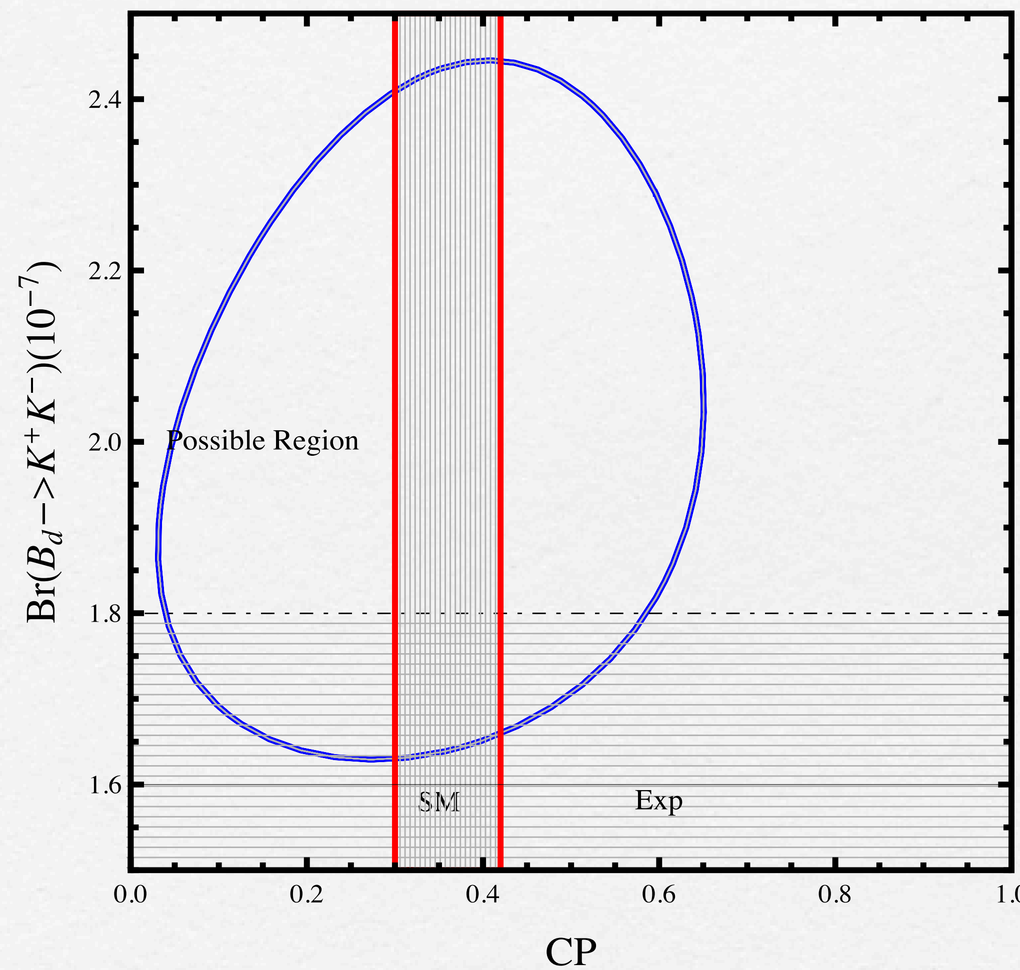
Numerical Results and Discussions





Numerical Results and Discussions





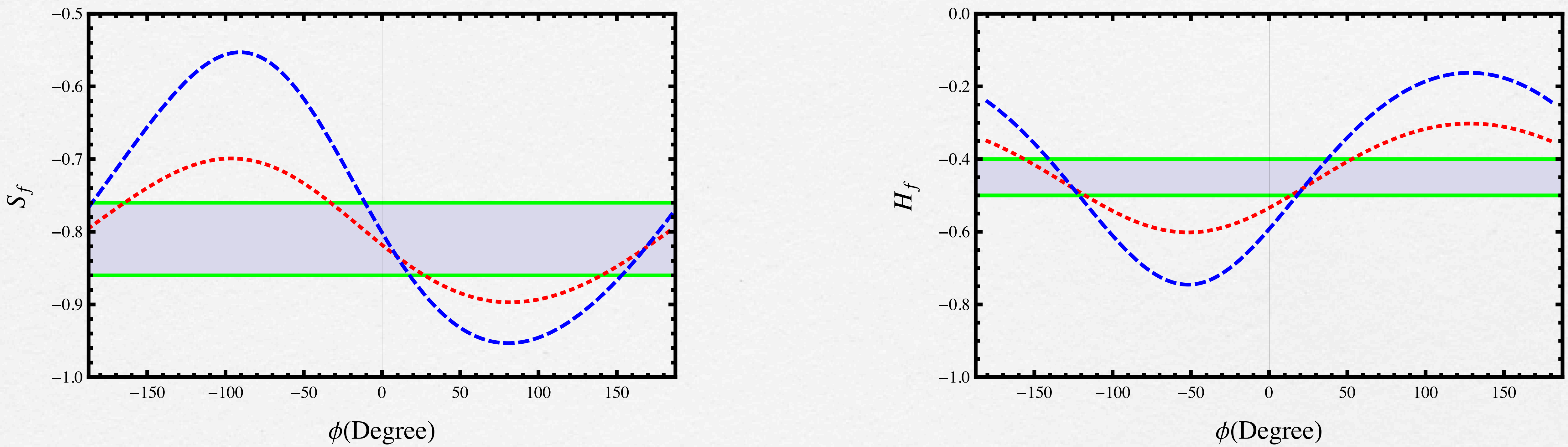


Figure 4: The CP symmetry parameters $\mathcal{S}_f$ (left panel) and $\mathcal{H}_f$ (right panel) as a function of the weak phase ϕ_{bd}, the dotted (red) and dashed (blue) lines represent results from the $\zeta = 0.01,\ 0.02$, and the regions edged by solid line (green) are the predictions of SM.

Summary

- In PQCD, the SM predictions can agree with data with large uncertainties.
- If we take the center values seriously, there is still room left for NP
- In the Z′ model, in some parameters spaces, ξ>0.2, the branching fractions and CP asymmetries can be changed remarkably.
- The CP violations of B—>KK can be used to test this model.

THANKS FOR YOUR ATTENTION !