Interpreting new CPV Signals in B physics:

Alakabha Datta

University of Mississippi

July 27 , 2009

OUTLINE

- I will discuss various measurements of CP violation
- Time independent:

1)Direct CP violation.

2) Triple product asymmetries.

- Time dependent:

1)Mixing induced CP violation.

2) Time dependent angular analysis for $B \to V_1 V_2$ decays.

- Measurements in penguin modes $B \to \phi K_s, \eta' K_s$... Hints of new physics in the $b \to s\bar{s}s$ decays.

- Measurements in the $B \to K\pi$ system. Hints of new physics in the $b \to s\bar{q}q$ decays ($q = u, d$).

- Measurement of the B_s mixing phase. How should we interpret the result. New physics in $b \to s\bar{c}c$ decay.

- Conclusions.

Direct CP Violation and NP

- Consider the decay $B \to f$ and the CP conjugate process $\bar{B} \to \bar{f}$

Define **direct** CP asymmetry:

$$a_{dir}^{CP} \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} \sim \sin\phi \; ,$$

where ϕ is the CP violating weak phase

- Suppose we have a decay $B \to f$:

$$\begin{aligned} A(B \to f) &= Ae^{i\phi} \\ A(\bar{B} \to \bar{f}) &= Ae^{-i\phi}. \end{aligned}$$

$a_{dir}^{CP} \sim |A(B \to f)|^2 - |A(\bar{B} \to \bar{f})|^2 = 0$

- Many decays in SM are dominated by a single amplitude and hence a measurement of non zero a_{dir}^{CP} violation is a clear signal of new physics. No hadronic uncertainty involved!

Direct CP Violation

Non zero direct CP violation requires interference of 2 amplitudes. Consider the decay $B \to f$. Suppose

$$\begin{aligned} A(B \to f) &= A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} \ , \\ A(\bar{B} \to \bar{f}) &= A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2} \ . \end{aligned}$$

Hence **direct** CP asymmetry:

$$a_{dir}^{CP} \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = -\frac{2 A_1 A_2 \sin\Phi \sin\Delta}{A_1^2 + A_2^2 + 2 A_1 A_2 \cos\Phi \cos\Delta} \ ,$$

where $\Phi \equiv \phi_1 - \phi_2$ and $\Delta \equiv \delta_1 - \delta_2$.

Note: direct CP asymmetry depends on unknown hadronic parameters. Cannot extract weak phase information (Φ) without hadronic input.

Triple Products

- If CPT is conserved (local and Lorentz invariant field theory) then CP violation implies T violation .

- T-odd CPV in B decays can be measured via Triple Product Correlations(TP)(Valencia).

- Triple Products are products of vectors of the type
T.P = $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$
$\vec{v}_i$ are spin or momentum vectors.

- Under(naive) time reversal T: $t \rightarrow -t$
T.P $\rightarrow$ -T.P : Hence they are T-odd.

- In $B \rightarrow V_1 V_2$ decays we can construct the T.P

T.P =$\vec{p} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_2)$

Triple Products

- We can define a T-odd asymmetry

$$A_T = \frac{\Gamma[T.P > 0] - \Gamma[T.P < 0]}{\Gamma[T.P > 0] + \Gamma[T.P < 0]}$$

- A_T is not a measure of true T-odd CP violation: $A_T \neq 0$ with strong phases and no weak phase.

- For true T-odd CPviolation we need to compare A_T and $\overline{A}_T$(T-odd asymmetry for the C.P conjugate process)

$B \to V_1 V_2$ Decays

- $B(p) \to V_1(k_1, \epsilon_1) V_2(k_2, \epsilon_2)$

$$
\begin{aligned}
M &= a\, \varepsilon_1^* \cdot \varepsilon_2^* + \frac{b}{m_B^2} (p \cdot \varepsilon_1^*)(p \cdot \varepsilon_2^*) \\
&+ i \frac{c}{m_B^2} \epsilon_{\mu\nu\rho\sigma} p^\mu q^\nu \varepsilon_1^{*\rho} \varepsilon_2^{*\sigma} \\
q &= k_1 - k_2
\end{aligned}
$$

- Three partial waves: c is P wave, a and b are combination of S and D.

- In rest frame of the B
$\epsilon_{\mu\nu\rho\sigma} p^\mu q^\nu \varepsilon_1^{*\rho} \varepsilon_2^{*\sigma} \to \vec{q} \cdot (\vec{\varepsilon}_1 \times \vec{\varepsilon}_2) \to$ T.P

Measuring Triple Products

T.P can be measured via an angular analysis.

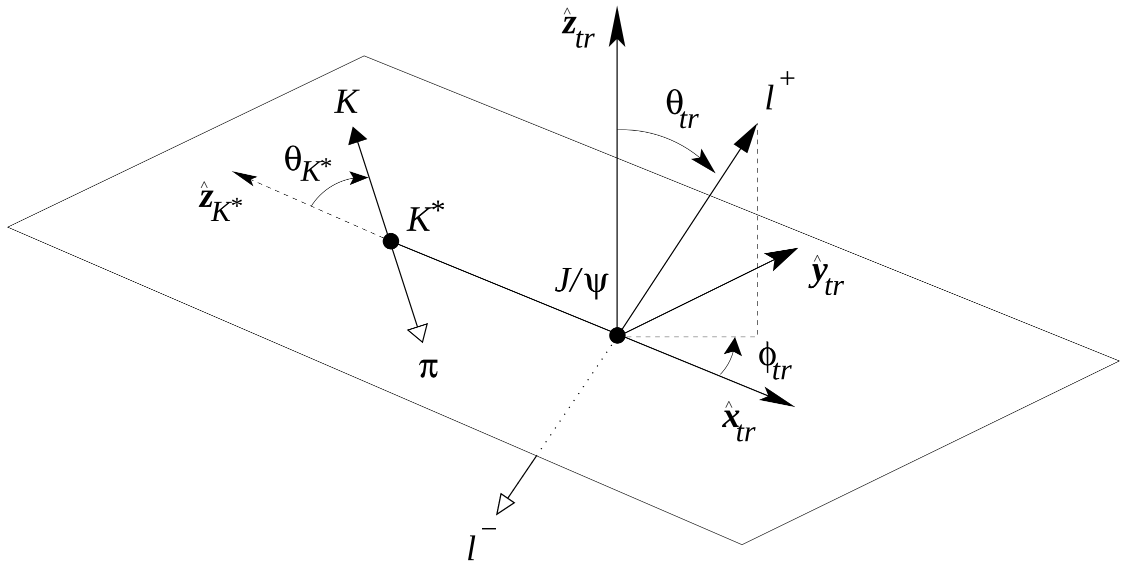
- Define linear polarization amplitudes A_0, $A_\|$ and $A_\perp$.

$$
\begin{aligned}
A_\| &= \sqrt{2}a \\
A_0 &= -ax - \frac{m_1 m_2}{m_B^2}(x^2-1)b \\
A_\perp &= 2\sqrt{2}\frac{m_1 m_2}{m_B^2}\sqrt{(x^2-1)}c \\
x &= \frac{k_1.k_2}{m_1 m_2}
\end{aligned}
$$

- $B(p) \to V_1(k_1, \epsilon_1) V_2(k_2, \epsilon_2)$

$$
M = A_0 \varepsilon_1^{*L} \cdot \varepsilon_2^{*L} - \frac{1}{\sqrt{2}} A_\| \vec{\varepsilon}_1^{*T} \cdot \vec{\varepsilon}_2^{*T} - \frac{i}{\sqrt{2}} A_\perp \vec{\varepsilon}_1^{*T} \times \vec{\varepsilon}_2^{*T} \cdot \hat{q} \ ,
$$

T.P from Angular distribution



$$
\begin{aligned}
\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_{K^*}\,\mathrm{d}\cos\theta_{tr}\,\mathrm{d}\phi_{tr}} &= f_1(\boldsymbol{\omega})|A_0|^2 + f_2(\boldsymbol{\omega})|A_\parallel|^2 + f_3(\boldsymbol{\omega})|A_\perp|^2 + \\
& f_4(\boldsymbol{\omega})Im(A_\parallel^* A_\perp) + f_5(\boldsymbol{\omega})Re(A_\parallel A_0^*) + \\
& f_6(\boldsymbol{\omega})Im(A_\perp A_0^*),
\end{aligned}
$$

$f_i(\boldsymbol{\omega})$ are known angular functions of $\boldsymbol{\omega} \equiv (\theta_{K^*}, \theta_{tr}, \phi_{tr})$

$$\frac{1}{\Gamma}\frac{\mathrm{d}^3\Gamma}{\mathrm{d}\cos\theta_{K^*}\mathrm{d}\cos\theta_{tr}\mathrm{d}\phi_{tr}} = N\left[...Im(A_\perp A_0^*)f_4 + Im(A_\perp A_\parallel^*)f_5 + ..\right]$$

$$f_4 \sim \sim (\varepsilon_1\cdot\hat{p}\varepsilon_2\cdot\hat{p})\underline{\vec{q}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)}$$

$$f_5 \sim (\varepsilon_1\cdot\varepsilon_2)\underline{\vec{q}\cdot(\vec{\varepsilon}_1\times\vec{\varepsilon}_2)}$$

$$A_T^1 = \frac{Im(A_\perp A_0^*)}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$

$$A_T^2 = \frac{Im(A_\perp A_\parallel^*)}{|A_0|^2+|A_\parallel|^2+|A_\perp|^2}$$

Triple Products-Properties

- True T-odd CP violating asymmetries are (Datta-London).

$$\tilde{A}_T^1 = (A_T^1 - \overline{A}_T^2)/2$$
$$\tilde{A}_T^2 = (A_T^2 - \overline{A}_T^2)/2$$

- $A_0 = |A_0|e^{i\delta_0}e^{i\phi_0} \quad A_\perp = |A_\perp|e^{i\delta_\perp}e^{i\phi_\perp}$

$$A_T = Im(A_0^* A_\perp) \sim |A_0||A_\perp|\sin(\phi+\delta) \quad \phi = \phi_\perp - \phi_0, \delta = \delta_\perp - \delta_0$$

- $A_T \neq 0$ if $\phi = 0$ and $\delta \neq 0$: fake signal
- $\overline{A}_T = \sin(-\phi+\delta) = -\sin(\phi-\delta)$
- $\tilde{A}_T = A_T - \overline{A}_T = \sin(\phi+\delta) + \sin(\phi-\delta)$

$= \sin\phi\cos\delta$!

Triple Products-Properties

• T.P CPV does not require strong phase unlike direct CP violation $\sim \sin\phi \sin\delta$. This is important as in (certain) B decays strong phases are small ($10^0 - 20^0$)

• T.P CPV require two kinematically distinct amplitude. Two amplitudes not kinematically different may generate a direct CP violation(if strong phase is non zero) but will not generate T.P CP violation.

•As an example, if the new physics has the same structure as the SM then there is no T.P asymmetry even with new non SM weak phases. Hence non zero T.P asymmetries will indicate non SM type new physics.

Mixing Induced CP Violation

There is another signal of CP violation. Use B^0–$\bar{B}^0$ mixing. Choose final state f accessible to both B^0 and $\bar{B}^0$. (Simplest is CP eigenstate.) Then $B^0 \to f$ and $B^0 \to \bar{B}^0 \to f$ interfere. This leads to indirect or mixing induced CP violation.

Aside: requires large B^0–$\bar{B}^0$ mixing. Large mixing measured in 1987. One of the most important discovery in particle physics in the last 20 years.

Size of mixing was great surprise. $\Delta M_d \sim m_t^2$, as it was expected that $m_t \sim 10$ GeV! Experiment: $m_t/M_W \sim 2$.

Large B^0–$\bar{B}^0$ mixing: get **indirect** CP asymmetry:

$$\Gamma(B^0(t) \to f) \sim B + a_{dir} \cos(\Delta M t) + a_{mix} \sin(\Delta M t)$$

with

$$B \equiv \frac{1}{2}\left(|A|^2 + |\bar{A}|^2\right) \ , \ a_{dir} \equiv \frac{1}{2}\left(|A|^2 - |\bar{A}|^2\right) \ , \ a_{mix} \equiv \mathrm{Im}\left(e^{-2i\beta} A^* \bar{A}\right) \ .$$

Point: $\Gamma(B^0(t) \to f)$ gives 3 measurements.

Note: if there is only a single decay amplitude in $B^0 \to f$, i.e. $A_2 = 0$, then $a_{dir} = 0$, but $a_{mix} \neq 0$. This is the most interesting case, since all dependence on hadronic physics cancel.

Idea: measure $\sin 2\beta$ in ways independent of strong phases.

$B(t) \to V_1 V_2$ Decays

•The decay amplitude for each of the three possible helicity states in $B \to V_1 V_2$ decays may be written as,

$$
\begin{aligned}
A_\lambda \equiv Amp(B \to V_1 V_2)_\lambda &= a_\lambda e^{i\delta_\lambda^a} + b_\lambda e^{i\phi} e^{i\delta_\lambda^b} ~, \\
\bar{A}_\lambda \equiv Amp(\bar{B} \to (V_1 V_2)_\lambda &= a_\lambda e^{i\delta_\lambda^a} + b_\lambda e^{-i\phi} e^{i\delta_\lambda^b} ~,
\end{aligned}
$$

Here a_λ and b_λ represent two amplitudes which may be the SM and NP amplitudes, respectively, ϕ is the new-physics weak phase, the $\delta_\lambda^{a,b}$ are the strong phases, and the helicity index λ takes the values $\{0, \|, \perp\}$. Using CPT invariance, the full decay amplitudes can be written as

$$
\begin{aligned}
\mathcal{A} &= Amp(B \to V_1 V_2) = A_0 g_0 + A_\| g_\| + i\, A_\perp g_\perp ~, \\
\bar{\mathcal{A}} &= Amp(\bar{B} \to V_1 V_2) = \bar{A}_0 g_0 + \bar{A}_\| g_\| - i\, \bar{A}_\perp g_\perp ~,
\end{aligned}
$$

The $g's$ are angular functions.

The full time dependent angular analysis for $B(t) \to V_1 V_2$ decays is given as:

$$\Gamma(\overset{(-)}{B}(t) \to V_1 V_2) = e^{-\Gamma t} \sum_{\lambda \leq \sigma} \Big(\Lambda_{\lambda\sigma} \pm \Sigma_{\lambda\sigma} \cos(\Delta M t) \mp \rho_{\lambda\sigma} \sin(\Delta M t) \Big) g_\lambda g_\sigma \, .$$

$$\Lambda_{\lambda\lambda} = \frac{1}{2}(|A_\lambda|^2 + |\bar{A}_\lambda|^2), \qquad \Sigma_{\lambda\lambda} = \frac{1}{2}(|A_\lambda|^2 - |\bar{A}_\lambda|^2),$$

$$\Lambda_{\perp i} = -\mathrm{Im}(A_\perp A_i^* - \bar{A}_\perp \bar{A}_i^*), \qquad \Lambda_{\parallel 0} = \mathrm{Re}(A_\parallel A_0^* + \bar{A}_\parallel \bar{A}_0^*),$$

$$\Sigma_{\perp i} = -\mathrm{Im}(A_\perp A_i^* + \bar{A}_\perp \bar{A}_i^*), \qquad \Sigma_{\parallel 0} = \mathrm{Re}(A_\parallel A_0^* - \bar{A}_\parallel \bar{A}_0^*),$$

$$\rho_{\perp i} = \mathrm{Re}\Big(e^{-i\phi_M^q} [A_\perp^* \bar{A}_i + A_i^* \bar{A}_\perp] \Big), \qquad \rho_{\perp\perp} = \mathrm{Im}\Big(e^{-i\phi_M^q} A_\perp^* \bar{A}_\perp \Big),$$

$$\rho_{\parallel 0} = -\mathrm{Im}\Big(e^{-i\phi_M^q} [A_\parallel^* \bar{A}_0 + A_0^* \bar{A}_\parallel] \Big), \qquad \rho_{ii} = -\mathrm{Im}\Big(e^{-i\phi_M^q} A_i^* \bar{A}_i \Big),$$

where $i = \{0, \|\}$ and ϕ_M^q is the B_q mixing weak phase.

Triple Products

- One set of observables are the Triple Product Asymmetries (TPA)

$$\Lambda_{\perp i} \quad = \quad -\mathrm{Im}(A_\perp A_i^* - \bar{A}_\perp \bar{A}_i^*),$$

- These are T-odd CP violating quantities.

- TPA vanish if a decay is dominated by a single amplitude like $B \to (J/\psi K^*, \phi K^*$ and $B_s \to (J/\psi\phi, \phi\phi$).

Testing for New Physics

• In the absence of the second amplitude, the b_λ are zero (e.g $B_s^0 \to J/\psi\phi$, $B_d \to J/\psi K^*$, $B_s \to \phi\phi$, $B_d \to \phi K^*$ etc in the SM).

• There exist 12 relations among the observables with $b_\lambda = 0$. These are:

$$\Sigma_{\lambda\lambda} = \Lambda_{\perp i} = \Sigma_{\|0} = 0 \ ,$$

$$\frac{\rho_{ii}}{\Lambda_{ii}} = -\frac{\rho_{\perp\perp}}{\Lambda_{\perp\perp}} = \frac{\rho_{\|0}}{\Lambda_{\|0}} \ ,$$

$$\Lambda_{\|0} = \frac{1}{2\Lambda_{\perp\perp}} \Big[\frac{\Lambda_{\lambda\lambda}^2 \rho_{\perp 0} \rho_{\perp \|} + \Sigma_{\perp 0} \Sigma_{\perp \|} (\Lambda_{\lambda\lambda}^2 - \rho_{\lambda\lambda}^2)}{\Lambda_{\lambda\lambda}^2 - \rho_{\lambda\lambda}^2} \Big] \ ,$$

$$\frac{\rho_{\perp i}^2}{4\Lambda_{\perp\perp}\Lambda_{ii} - \Sigma_{\perp i}^2} = \frac{\Lambda_{\perp\perp}^2 - \rho_{\perp\perp}^2}{\Lambda_{\perp\perp}^2} \ .$$

• *The violation of any of the above relations will be a smoking-gun signal of NP*.

• The extraction of β_s via time dependent angular analysis of $B_s^0 \to J/\psi\phi$ assumes the SM and hence the relations above.

Testing for New Physics

•I will focus on two conditions: With only one decay amplitude (e.g $B_s^0 \to J/\psi\phi$, $B_d \to J/\psi K^*$, $B_s \to \phi\phi$, $B_d \to \phi K^*$ etc in the SM).

$$\Sigma_{\lambda\lambda} = \Lambda_{\perp i} = 0 \ , \qquad \frac{\rho_{ii}}{\Lambda_{ii}} = -\frac{\rho_{\perp\perp}}{\Lambda_{\perp\perp}} \ .$$

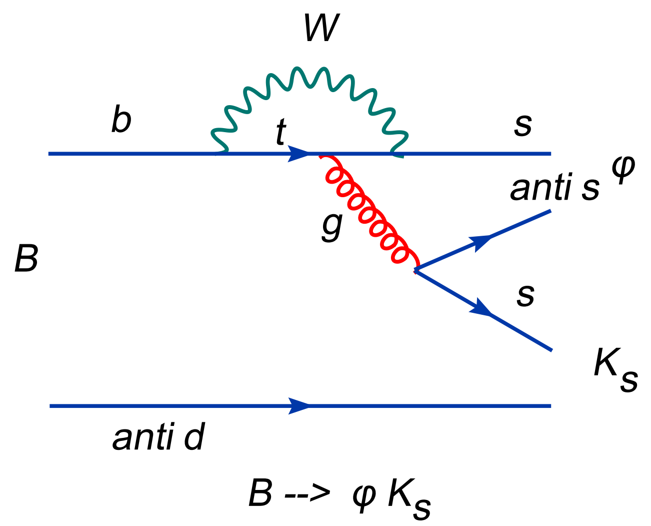
Hence
a) All Triple Products are zero. All direct CPV=0.(First Equation)

b) $\sin 2\beta$ measured for the three helicity are the same. Or the mixing induced CP asymmetry for the three helicities are the same expect for a sign.(Second Equation)

If there is NP in the decay amplitude then in general the angular distribution changes and the extraction of mixing phase is impacted.

$B \to \phi K_s$- Mixing CP

$B \to \phi K_s$ is a pure penguin process dominated by single amplitude

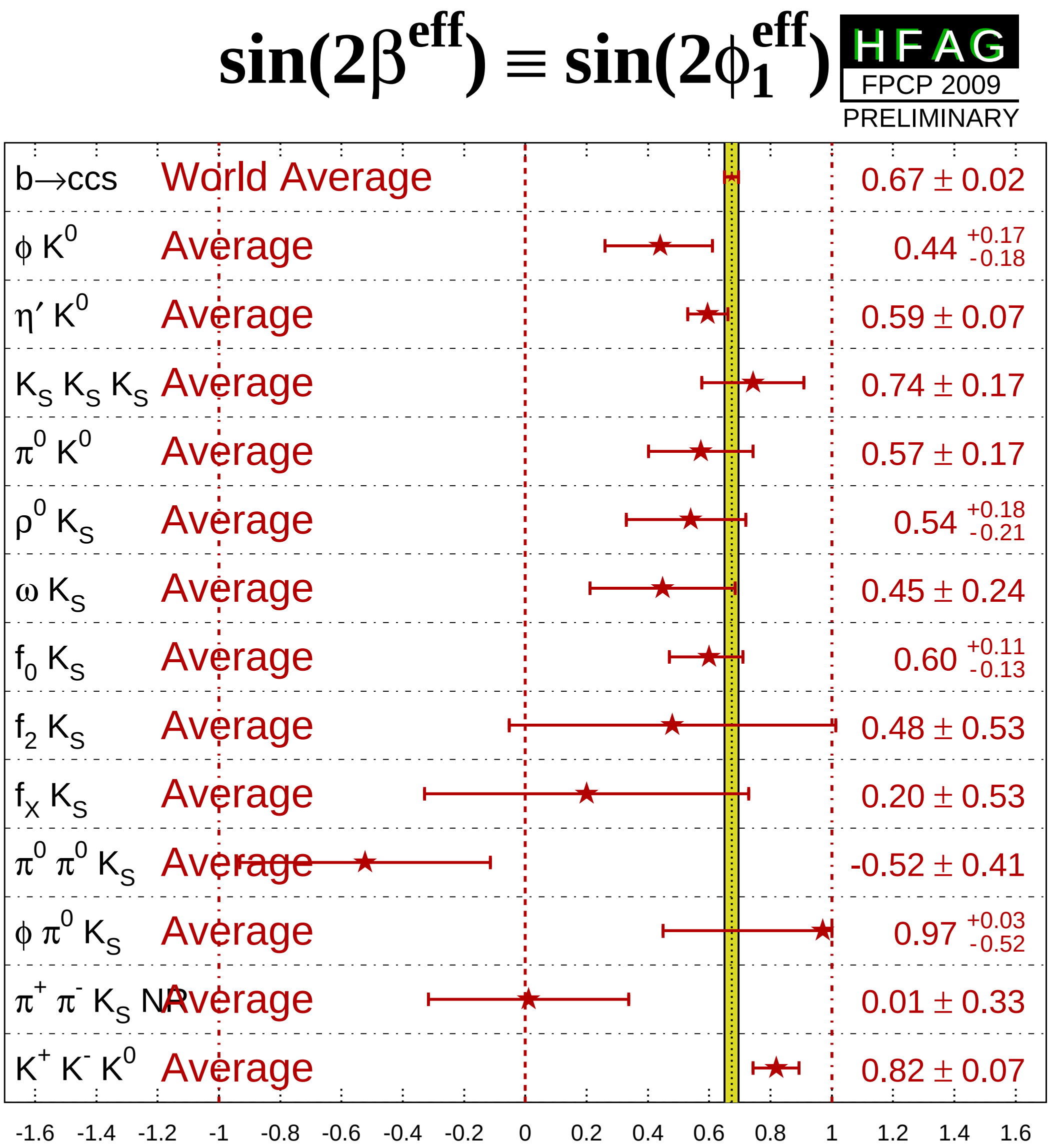


$A(B \to \phi K_s) = (P_t - P_c)V_{tb}V_{ts}^* + (P_u - P_c)V_{ub}V_{us}^* \approx (P_t - P_c)V_{tb}V_{ts}^*$
and so in SM

$$a_{mix}(B \to \phi K_s) = \sin 2\beta = 0.67 \pm 0.02 \ .$$

but Expt:$a_{mix}(B \to \phi K_s) = 0.44^{+0.17}_{-0.18}$.
There are many other final states, $\eta' K_s, \pi^0 K_s, f_0 K_s, ...$ for which $a_{mix} = \sin 2\beta$ in the SM.

a_{mix} for $b \longrightarrow s$ transitions



• Note that NP will effect different final states differently.

$$H_{NP} \sim \bar{s}\gamma_5 b \bar{s}\gamma_5 s$$

There can be a contribution to $B \to \eta' K_s$ but not to $B \to \phi K_s$ as

$$\bar{s}\gamma_5 b \to B \to K_s$$

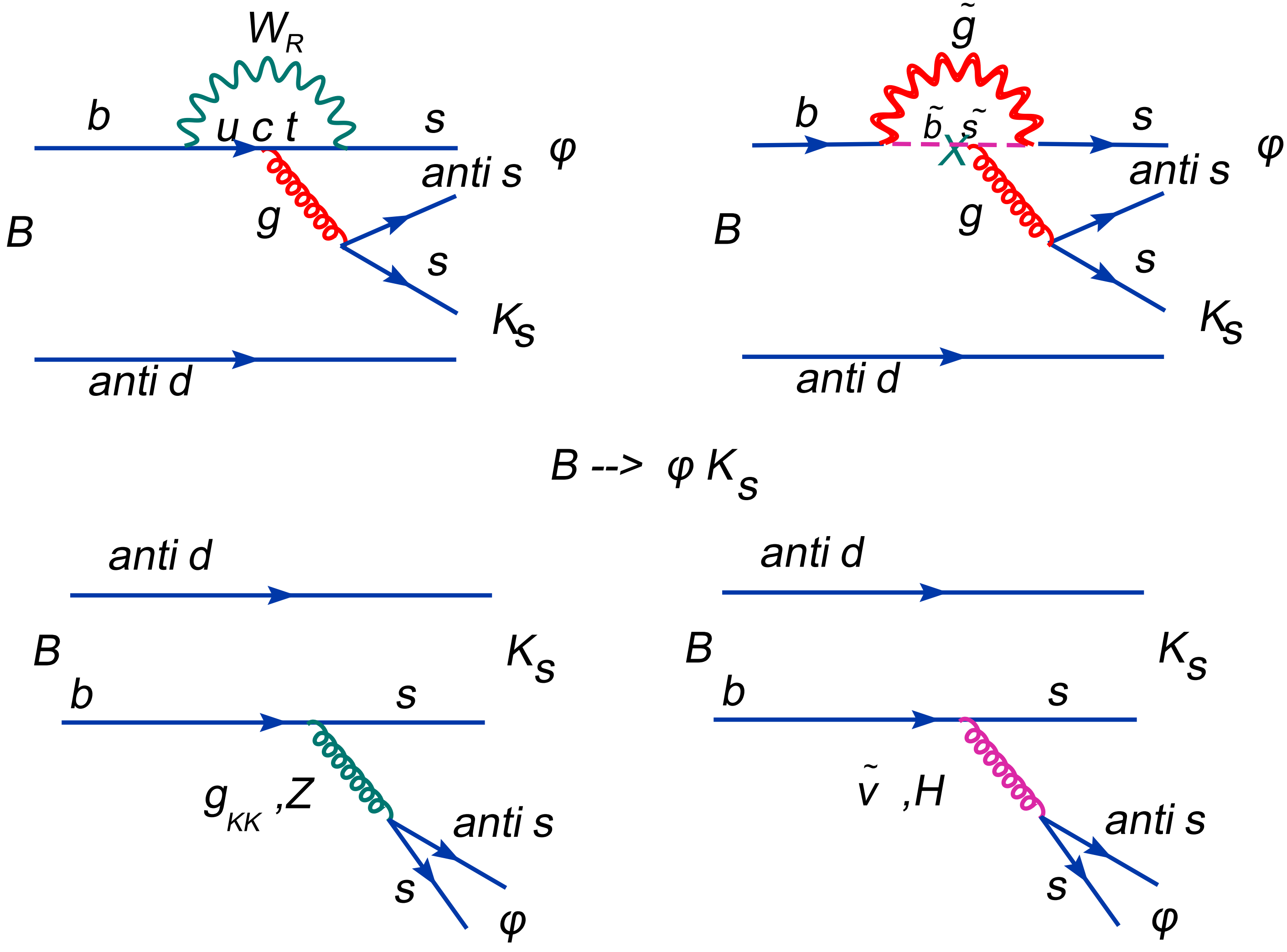
$$\bar{s}\gamma_5 s \to \eta'$$

but not ϕ.

• Hence by observing NP effects in different final states allows us to obtain information about the Lorentz structure of NP.

$B \to \phi K_s$-NP models

- Many NP models can produce deviation from the SM for $B \to \phi K_s$



$B \to K\pi$ Decays

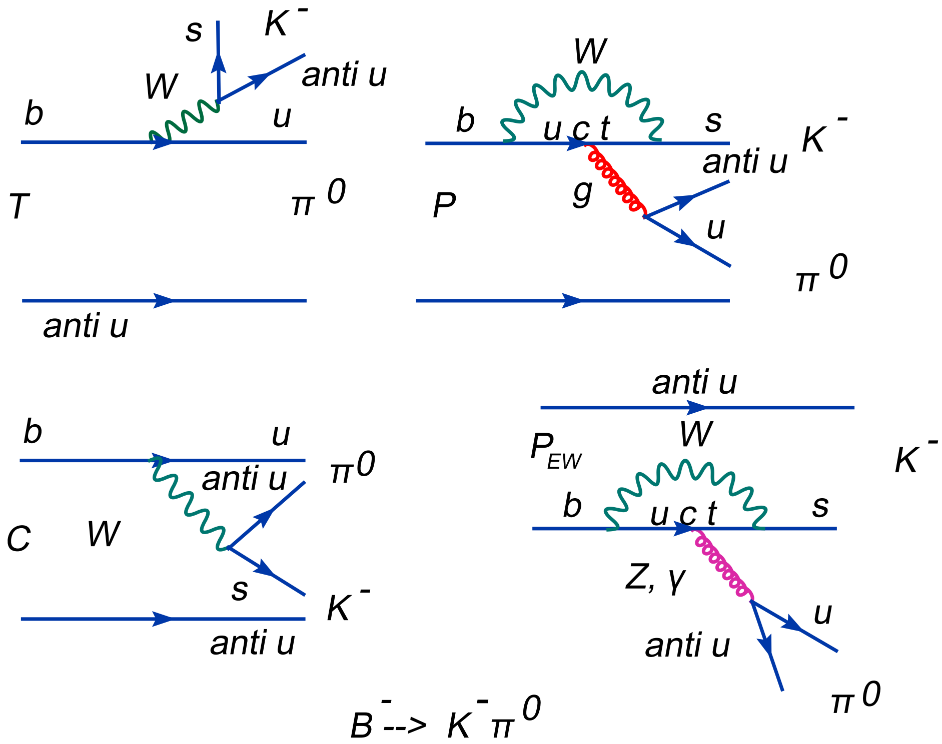
•Let $A^{i,j} = B \to K^i \pi^j =< K^I \pi^j | H_{eff} | B >$ then we have the following decays:

$B^+ \to \pi^+ K^0$ (A^{+0})
$B^+ \to \pi^0 K^+$ (A^{0+})
$B_d^0 \to \pi^- K^+$ (A^{-+})
$B_d^0 \to \pi^0 K^0$(A^{00})

$$
\begin{aligned}
A^{+0} &= -P' + P'_{uc} e^{i\gamma} - \frac{1}{3} P'^{C}_{EW} \,, \\
\sqrt{2} A^{0+} &= -T' e^{i\gamma} - C' e^{i\gamma} + P' - P'_{uc} e^{i\gamma} \\
&\qquad - P'_{EW} - \frac{2}{3} P'^{C}_{EW} \,, \\
A^{-+} &= -T' e^{i\gamma} + P' - P'_{uc} e^{i\gamma} - \frac{2}{3} P'^{C}_{EW} \,, \\
\sqrt{2} A^{00} &= -C' e^{i\gamma} - P' + P'_{uc} e^{i\gamma} - P'_{EW} - \frac{1}{3} P'^{C}_{EW} \,.
\end{aligned}
$$

$B \to K\pi$- SM

- In the SM the amplitudes for the four decays can be related by isospin.
The four decays can be represented by the following amplitudes:



- $\frac{|T|}{|P|} = \frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*}\frac{c_1}{c_t} \sim 0.2 \quad \frac{|C|}{|P|} \sim \frac{1}{N_c}\frac{|T|}{|P|} \sim 0.04 \quad \frac{|P_{EW}|}{|P|} \sim 0.14$

$B \to K\pi$ puzzle- old data

Table 1:

Mode	$BR(10^{-6})$	A_{dir}	$A_{mix}(S)$
$B^+ \to \pi^+ K^0$	23.1 ± 1.0	0.009 ± 0.025	
$B^+ \to \pi^0 K^+$	12.8 ± 0.6	0.047 ± 0.026	
$B_d^0 \to \pi^- K^+$	19.7 ± 0.6	-0.093 ± 0.015	
$B_d^0 \to \pi^0 K^0$	10.0 ± 0.06	-0.12 ± 0.11	0.31 ± 0.21

•Puzzles:

Puzzle 1: $A_{dir}(B^+ \to \pi^0 K^+) = A_{dir}(B_d^0 \to \pi^- K^+)$ using isospin if electroweak penguins(EWP) are neglected. In the SM the EWP are not big enough to explain the data. Need new EWP to explain the data.

Puzzle 2: $B_d^0 \to \pi^0 K^0$ is dominated by a single amplitude and so in SM $A_{dir} = 0$ and $A_{mix} = \sin 2\beta = 0.668 \pm 0.026$ in disagreement with data. Again need new EWP to explain the data.

$B \to K\pi$ puzzle

•BR($R_{c,n}$) of the $K\pi$ modes are consistent with SM. The puzzles are in the CP measurements

•Puzzle 1 can be resolved by an accidental equality of the strong phase in $(T + C)$ and P amplitudes(PQCD). How stable is this equality to higher order corrections?

Puzzle 1 can be resolved including $\frac{\Lambda_{QCD}}{m_b}$ corrections- General Parametrization(Silvestrini et. al).

	PQCD	GP	exp
$S_{\pi^0 K_S}$	74^{+2}_{-3}	74.3 ± 4.4	33 ± 21
$S_{\phi K_S}$	71^{+1}_{-1}	71.5 ± 8.7	39 ± 18

•Puzzle 2(central value) remains unresolved. A precise measurement of S is crucial.

$B \to K\pi$ puzzle- all data

$$
\begin{aligned}
A^{+0} &= -P' + P'_{uc}e^{i\gamma} - \frac{1}{3}P'^{C}_{EW} \,, \\
\sqrt{2}A^{0+} &= -T'e^{i\gamma} - C'e^{i\gamma} + P' - P'_{uc}e^{i\gamma} \\
&\qquad - P'_{EW} - \frac{2}{3}P'^{C}_{EW} \,, \\
A^{-+} &= -T'e^{i\gamma} + P' - P'_{uc}e^{i\gamma} - \frac{2}{3}P'^{C}_{EW} \,, \\
\sqrt{2}A^{00} &= -C'e^{i\gamma} - P' + P'_{uc}e^{i\gamma} - P'_{EW} - \frac{1}{3}P'^{C}_{EW} \,.
\end{aligned}
$$

•Keep all amplitudes- no assumption about their sizes. We now have eight theoretical parameters: $|P|$, $|P_{uc}|$, $|T|$, $|C|$, γ, and three relative strong phases. With nine pieces of experimental data, we can still perform a fit. However fit gives $|C/T| = 1.6 \pm 0.3$ about 10 times bigger than expected size. Such large $|C/T|$ are not seen in other decays including decays like $B \to \pi\pi$ which are related to $B \to K\pi$ by SU(3) symmetry.

New Physics- General

The low energy structure of new physics can have the general form(Datta-London)

$$H_{NP} = \sum_{ij} c_{ij} \mathcal{O}^{ij,q}_{NP} + \sum_{ij} d_{ij} \mathcal{O}^{ij,q}_{NPC}$$

$$\mathcal{O}^{ij,q}_{NP} \sim \bar{s}_\alpha \Gamma_i b_\alpha \, \bar{q}_\beta \Gamma_j q_\beta$$

$$\mathcal{O}^{ij,q}_{NPC} \sim \bar{s}_\alpha \Gamma_i b_\beta \, \bar{q}_\beta \Gamma_j q_\alpha$$

where the $\Gamma_{i,j}$ represent Lorentz structures. There are a total of 20 possible NP operators.

•Define

$$\sum \langle f | \, \mathcal{O}^{ij,q}_{NP} \, | B \rangle = \mathcal{A}^q e^{i\Phi_q}$$

$$\sum \langle f | \, \mathcal{O}^{ij,C,q}_{NPC} \, | B \rangle = \mathcal{A}^{C,q}_{NP} e^{i\Phi^C_q}$$

New Physics- $K\pi$

$$
\begin{aligned}
A^{+0} &= -P' + \mathcal{A}'^{C,d} e^{i\Phi_d'^C} \,, \\
\sqrt{2}A^{0+} &= P' - T'\, e^{i\gamma} - P'_{EW} \\
&\quad + \mathcal{A}'^{,comb} e^{i\Phi'} - \mathcal{A}'^{C,u} e^{i\Phi_u'^C} \,, \\
A^{-+} &= P' - T'\, e^{i\gamma} - \mathcal{A}'^{C,u} e^{i\Phi_u'^C} \,, \\
\sqrt{2}A^{00} &= -P' - P'_{EW} + \mathcal{A}'^{,comb} e^{i\Phi'} + \mathcal{A}'^{C,d} e^{i\Phi_d'^C} \,,
\end{aligned}
$$

$\mathcal{A}'^{,comb} e^{i\Phi'} \equiv -\mathcal{A}'^{,u} e^{i\Phi_u'} + \mathcal{A}'^{,d} e^{i\Phi_d'}$

- The best fit is obtained for models with

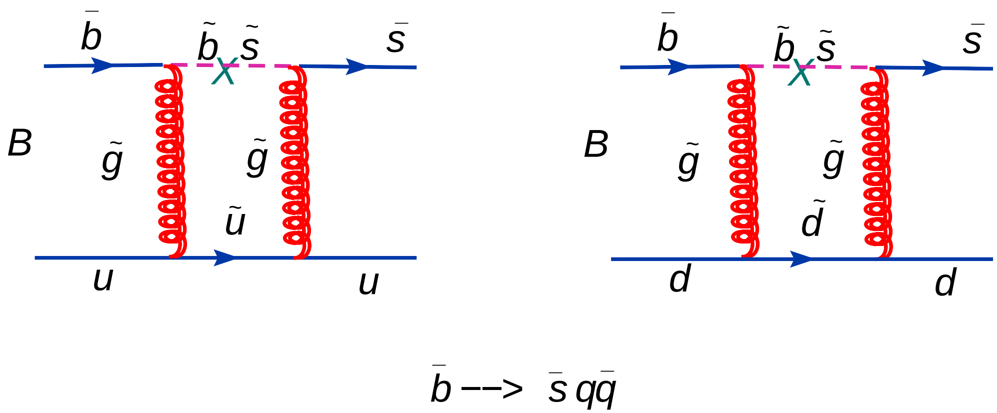
$A_{comb} = A_{NP}, \quad A_C^u \sim A_C^d \sim 0$

This can come from NP that is not isospin conserving.

This points to electroweak penguins(EWP) and to certain color structures of the NP operators- color allowed EWP ($c_{ij} \neq 0, d_{ij} \sim 0$).

NP that might work

- For models that produce new QCD penguins (LR models, SUSY with squark mixing, extra dim) the NP is isospin conserving and $A_{comb} = 0, \quad A_C^u = A_C^d = A_{NP}$- do not work but



- SUSY with different up and down squark masses(Trojan penguins) (Recent analysis rules out this possibility.)

- FCNC with Z or Z'

- FCNC through scalar exchange- colored scalars are not allowed.

$K\pi$- New data

•There is new data and fits have been done by various groups.

•Explain the data by including $\frac{\Lambda_{QCD}}{m_b}$ corrections to factorized matrix elements(QCD factorization) (M. Ciuchini et al, see also Kagan and Duraisamy)

•The $\frac{\Lambda_{QCD}}{m_b}$ corrections are assumed to be vary between (0-0.5) of the leading order factorized matrix elements.

•The $\frac{\Lambda_{QCD}}{m_b}$ corrections have to be $O(1)$ of the leading order factorized matrix elements to explain the polarization data in $B \to \rho K^*$ decays(Kagan and Duraisamy). This is inconsistent with the factorization approach.

•The same new physics needed to explain the $B \to K\pi$ data can also explain the polarization data in $B \to \rho K^*$ decays(Datta et.al)

SM with $\frac{\Lambda_{QCD}}{m_b}$ Corrections

Decay Mode	HFAG average	global fit	fit prediction
10^6 BR$(K^+\pi^-)$	19.4 ± 0.6	19.5 ± 0.5	19.7 ± 1.0
10^6 BR$(K^+\pi^0)$	12.9 ± 0.6	12.7 ± 0.5	12.4 ± 0.7
10^6 BR$(K^0\pi^+)$	23.1 ± 1.0	23.8 ± 0.8	24.9 ± 1.2
10^6 BR$(K^0\pi^0)$	9.8 ± 0.6	9.3 ± 0.4	8.7 ± 0.6
$A_{\rm CP}(K^+\pi^-)$ [%]	-9.8 ± 1.2	-9.5 ± 1.2	3.9 ± 6.8
$A_{\rm CP}(K^+\pi^0)$ [%]	5.0 ± 2.5	3.6 ± 2.4	-6.2 ± 6.0
$A_{\rm CP}(K^0\pi^+)$ [%]	0.9 ± 2.5	1.8 ± 2.1	6.2 ± 4.5
$C(K_S\pi^0)$	0.01 ± 0.10	0.09 ± 0.03	0.10 ± 0.03
$S(K_S\pi^0)$	0.57 ± 0.17	0.73 ± 0.04	0.74 ± 0.04
$\Delta A_{\rm CP}$ [%]	14.8 ± 2.8	13.1 ± 2.6	1.7 ± 6.1

•An isospin sum rule predicts $C(K_S\pi^0) = 0.15$ in the SM(Rosner et.al).

Precise measurements of $C(K_S\pi^0)$ and $S(K_S\pi^0)$ are crucial.

Experimental inputs and fit results for $B \to K\pi$. For each observable, we report the results of the fit using all the constraints (third column) and the prediction obtained using all constraints except the considered observable (fourth column).

$K\pi$- NP

There are fits to the data that indicate new physics(Fleisher et al)
This approach uses flavor symmetry- takes input from $B^+ \to \pi^+\pi^0$.
Then $S(K_S\pi^0)$ is predicted as a function of the measured $C(K_S\pi^0)$ in the SM

$$
\begin{aligned}
S(K_S\pi^0)_{predicted} &= 0.99^{+0.01}_{-0.08} \\
S(K_S\pi^0)_{exp} &= 0.57 \pm 0.17
\end{aligned}
$$

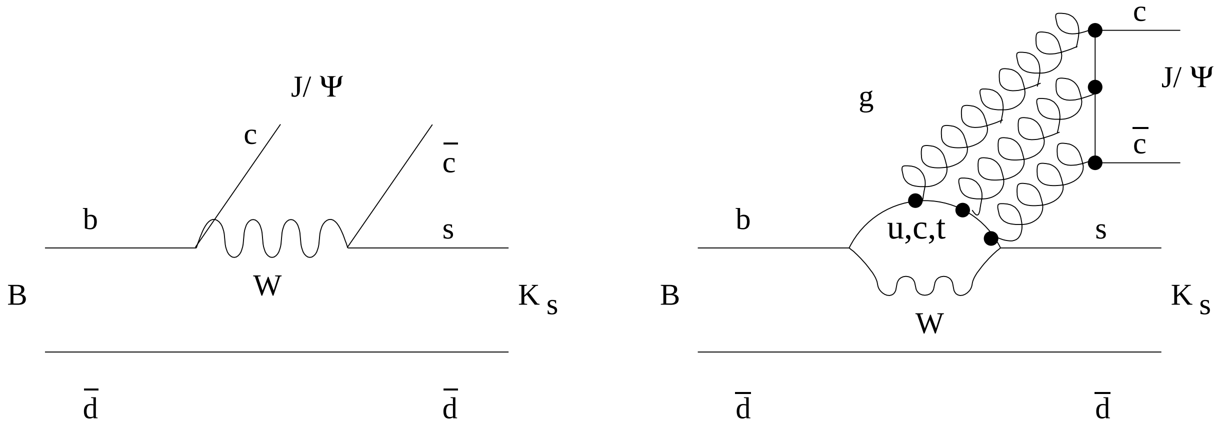
Including theory errors $S(K_S\pi^0)$ can be as low as ~ 0.8.

The $\sim 2\sigma$ discrepancy in $S(K_S\pi^0)$ can be explained with new contribution to the EW penguin with a large new weak phase($\sim (63^{+10}_{-9})^0$)

•A fit similar to one done by (Datta et.al) have been repeated by (Baek et.al). The case for new physics with new data is somewhat weaker than before but still new physics in the electroweak penguin is indicated.

$b \longrightarrow s\bar{c}c$ Decays

•We consider decays $B_d(t) \to J/\psi K_s(K^*)$, $B_s(t) \to J/\psi\phi$ via the $b \longrightarrow s\bar{c}c$ transition.
$B \to J/\psi K_s$:



(a) (b)

- $P_{u,c}$ are re scattered penguins from tree operators.

- $P_{u,c,t}$ are OZI suppressed.

$$
\begin{aligned}
A(B \to J/\psi K_s) &= V_{cb}V_{cs}^*C + V_{tb}V_{ts}^*P_t \\
&+ V_{cb}V_{cs}^*P_c + V_{ub}V_{us}^*P_u \\
&= V_{cb}V_{cs}^*(C + P_c - P_t) \\
&+ V_{ub}V_{us}^*(P_u - P_t)
\end{aligned}
$$

$$
\begin{aligned}
A &= V_{cb}V_{cs}^*(C + P_c - P_t)[1 + \chi_{J/\psi K_s}] \\
|\chi_{J/\psi K_s}| &= \frac{V_{ub}V_{cs}^*}{V_{cb}V_{cs}^*}\frac{P_{OZI}}{C} \sim 2\% \frac{P_{OZI}}{C}
\end{aligned}
$$

- To a very good approximation the decays are dominated by a single amplitude.

$b \longrightarrow s\bar{c}c$ Decays -SM

$B \to J/\psi K_s$:

$$C_{B_d \to J/\psi K_s} \approx 0$$
$$S_{B_d \to J/\psi K_s} = \sin 2\beta$$

$B \to J/\psi K^*$:

$$C^{\lambda}_{B_d \to J/\psi K^*} \approx 0$$
$$S^{\lambda}_{B_d \to J/\psi K^*} = \pm \sin 2\beta \quad A_T^{\tilde{1},2} \approx 0$$

$B \to J/\psi \phi$:

$$C^{\lambda}_{B_d \to J/\psi K^*} \approx 0$$
$$S^{\lambda}_{B_d \to J/\psi K^*} = \pm \sin 2\beta_s \quad A_T^{\tilde{1},2} \approx 0$$

$b \longrightarrow s\bar{c}c$ Decays -NP

How large can NP be in $b \to s\bar{c}c$ decay. How large is $r = \frac{A_{NP}}{A_{SM}}$

$B \to J/\psi K_s$: Experiment: $\sin 2\beta_{eff} = 0.668 \pm 0.028$ (utfit)

The value of $\sin 2\beta$ can be taken from the fit to the sides of the UT:

$\sin 2\beta = 0.731 \pm 0.038$ (utfit)

$$\sin 2\beta_{eff} = \sin 2\beta + 2r \cos 2\beta \sin \varphi \cos \delta \ .$$

$\cos \delta \simeq \pm 1$. The NP weak phase is unknown, but if $\sin \varphi \simeq \mp 1$ then $r \simeq 0.1$ is allowed with the present measurement.

$B \to J/\psi K^*$:

Experiment:

$$\sin 2\beta_{eff} = 0.16 \pm 0.28 (HFAG)$$

$$|2\tilde{A_T^1}| = 0.044 \pm 0.046 (B^0) 0.016 \pm 0.054 (B^+) - Belle$$

$$2\tilde{A_T^1} = -0.011 \pm 0.046 (B^0) 0.075 \pm 0.09, -0.051 \pm 0.12 (B^+) - Babar$$

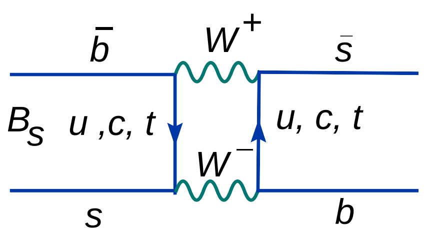
$$|2\tilde{A_T^1}| = 2r|A_0||A_\perp| \simeq 0.7r \simeq 0.07 (r = 0.1)$$

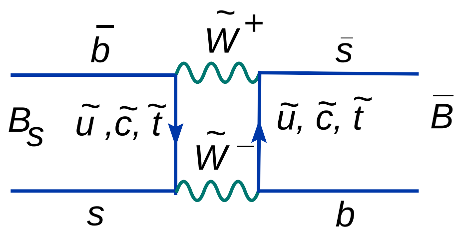
Hence $r \simeq 0.1$ is consistent with experiment

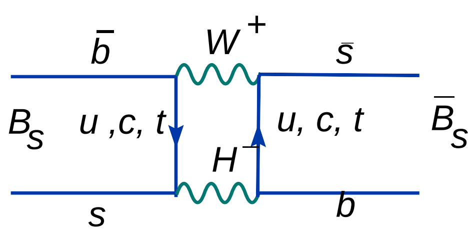
B_s mixing

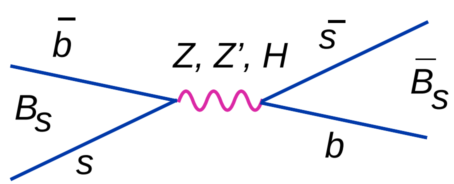
• B_s mixing in the SM arises as a loop process. Many New physics models can contribute to B_s mixing. Some at loop level and some even at tree level.

• The phase of B_s mixing in the SM comes from $V_{tb}V_{ts}^*$ and is tiny($\phi_s = -2\beta_s = -0.04$). Many New physics models can contribute to the phase of B_s mixing.







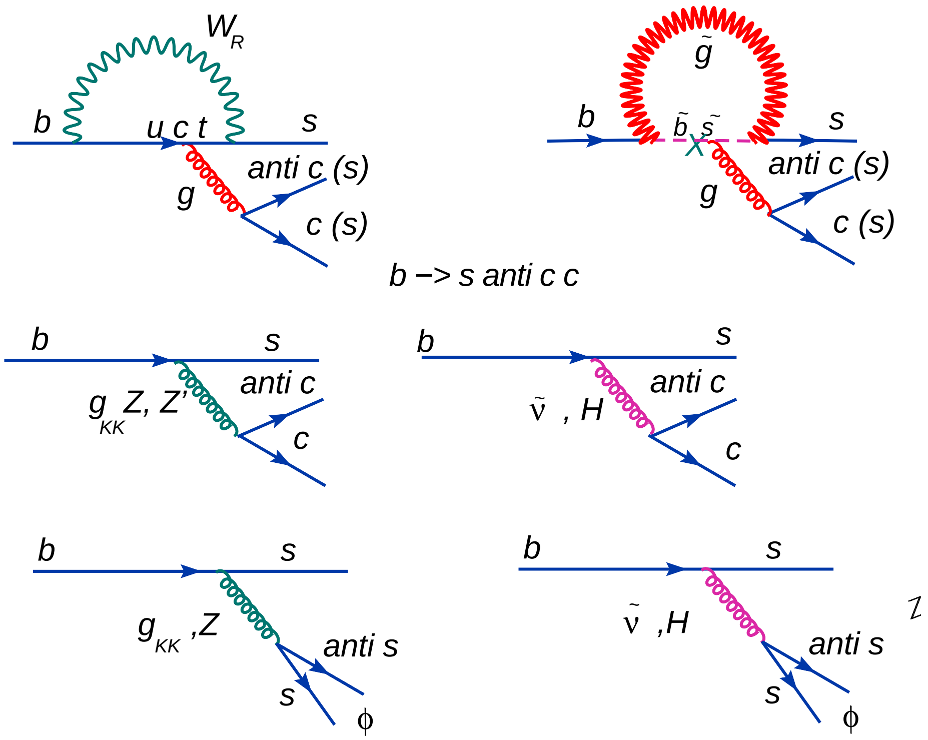


$$2\beta_s = 0.57\,^{+0.30}_{\;0.24}\ (\text{stat.})\ ^{+0.02}_{-0.07}\ (\text{syst.}) \qquad (DO),$$

$$2\beta_s \in [0.32, 2.82]\ (68\%) \qquad (CDF).$$

NP in $b \longrightarrow s\bar{c}c$ Decay

Most(if not all) new physics model that contribute to B_s mixing also contributes to the decay $b \to s\bar{c}c$ decay (Datta et.al).



This changes the angular distribution and hence the interpretation of the B_s mixing phase(ϕ_s) measured in experiment.

Hence it is important to check for signs of NP in the $b \to s\bar{c}c$ decays.

ZFCNC model

In the ZFCNC model, it is assumed that a new vector-like isosinglet down-type quark d' is present. Such quarks appear in E_6 GUT theories, for example. The ordinary quarks mix with the d'. As a result, FCNC's appear at tree level in the left-handed sector. In particular, a $Z\bar{b}s$ coupling can be generated:

$$\mathcal{L}^Z_{FCNC} = -\frac{g}{2\cos\theta_W} U_{sb}\, \bar{s}_L \gamma_\mu b_L\, Z^\mu \ .$$

This coupling leads to a NP contribution to B_s^0-$\overline{B_s^0}$ mixing at tree level. Constraints ΔM_s and $b \to s l^+ l^-$ lead to $|U_{sb}| \simeq 0.002$.
This coupling will also lead to the decay $b \to s\bar{c}c$ at tree level, mediated by a virtual Z. The amplitude is

$$\begin{aligned} H^{tot}_{eff} &= \frac{G_F}{\sqrt{2}} V_{cb} V^*_{cs}\, a_2 (1+r)\, V_{LL} \ , \\ V_{LL} &= \bar{s}\gamma_\mu (1-\gamma_5) b\, \bar{c}\gamma^\mu (1-\gamma_5) c \ , \end{aligned}$$

where $r \simeq 0.06$

Triple Products: Because the structure of the NP Hamiltonian is kinematically identical to that of the SM there are no TPs in $B_d \to J/\psi K^*$ or $B_s^0 \to J/\psi\phi$. As such, there are no constraints from the measurements of TPs in $B_d \to J/\psi K^*$.

Helicity-dependent indirect CPA in $B_s^0 \to J/\psi\phi$: In the presence of NP in the decay. the general expression for the indirect CPA is

$$\sin 2\beta_{eff}^{\lambda} \quad = \quad \sin 2\beta_s + 2r\cos 2\beta_s \sin\varphi \cos\delta_\lambda \ .$$

Experiments have measured strong-phase differences and found that $\delta_T - \delta_0 \simeq \pm 180^\circ$, $\delta_{\|} - \delta_{\perp} \simeq 21.2^\circ$. Thus, $\cos(\delta_T - \delta_0) \approx -1$. The helicity-dependent corrections to $\sin 2\beta_s$ are then

$$\frac{corr(\sin 2\beta_{eff}^T)}{corr(\sin 2\beta_{eff}^0)} = \frac{\cos\delta_T}{\cos\delta_0} = \frac{\cos(\delta_T - \delta_0 + \delta_0)}{\cos\delta_0} = \frac{\cos(\pi + \delta_0)}{\cos\delta_0} \approx -1$$

The corrections to $\sin 2\beta_s$ *are* helicity-dependent: they have opposite signs for $\lambda = 0$ and $\lambda = T$. The size is is $0.12\sin\varphi$, which could be O(10%).

$\boldsymbol{B_d \to J/\psi K_s}$: We can calculate the effective $\sin 2\beta$ in $B_d \to J/\psi K_s$ in the presence of NP in the decay. We have

$$\sin 2\beta_{eff} = \sin 2\beta + 2r \cos 2\beta \sin \varphi \cos \delta \ .$$

The value of $\sin 2\beta$ can be taken from the fit to the sides of the UT: $\sin 2\beta = 0.731 \pm 0.038$.

$$\begin{aligned} \sin 2\beta_{eff} &= \sin 2\beta + 0.12 \times 0.682 \sin \varphi \cos \delta \\ &= \sin 2\beta + 0.08 \sin \varphi \cos \delta \ . \end{aligned}$$

We have $\cos \delta \simeq \pm 1$. The NP weak phase is unknown, but if $\sin \varphi \simeq \mp 1$, we obtain

$$\sin 2\beta_{eff} = 0.731 - 0.08 \simeq 0.65 \ .$$

The experimental measurement gives $\sin 2\beta_{eff} = 0.668 \pm 0.028$. Note the result in is quite consistent with measurements.

SUSY

SUSY: There are two new physics operators. For the case $(\delta^d_{LR})_{23} = -(\delta^d_{RL})_{23}$ (Datta and Khalil)

$$
\begin{aligned}
\sin 2{\beta_s}^{\|} &= \sin(2\beta_s^{SM} + 2\theta_s) + 0.28\cos(2\beta_s^{SM} + 2\theta_s)\sin\theta_{\rm NP}^{\|}\cos\delta^{\|} \\
\sin 2{\beta_s}^{\perp} &= \sin(2\beta_s^{SM} + 2\theta_s).
\end{aligned}
$$

If we neglect the contribution from mixing then $\sin 2{\beta_s}^{\|}$ can reach a value of upto 0.3 for $\sin\theta_{\rm NP}^{\|} \sim 1$ and $\cos\delta^{\|} \sim 1$. There is no effect in $\sin 2\beta$ in $B_d \to J/\psi K_s$.

What is the point?

Theorist: Should check and calculate the effect of new physics not only on B_s mixing but also on the $b \to s\bar{c}c$ decay.

Experimentalist: Should use the full angular analysis in $B_s(t) \to J/\psi\phi$ including NP in the $b \to s\bar{c}c$ decay to fit for β_s, T.P, helicity dependent CPA etc. In particular the measurement of T.P asymmetries(TPA) will be very useful. Note TPA only require time independent angular analysis.

If there are precise measurements of not only β_s(mixing phase) but other parameters that measure NP in the decay amplitude, then NP models will be severely constrained. E.g. if a non zero TPA is established then the ZFCNC model will be ruled out even though it can explain the present B_s mixing data.

Conclusions

- There are many interesting CPV measurement in B decays.

- There are hints of new physics in $b \rightarrow s$ transitions in decays like $B \rightarrow \phi K_s$, $B \rightarrow K\pi$ etc.

- Recent measurement in B_s mixing indicate non SM phase in the mixing. However most NP models also predict new physics in $b \rightarrow s\bar{c}c$ decay. This can be searched for my measuring T.P asymmetries and helicity dependent indirect CP asymmetries among other things.