Beyond the SM in B decays

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- Give examples of experimental observables that can be used to find NP
- Point to the theoretical issues
- Cover (partial) only $\not{C}\!\not{P}$ and meson mixing
- Do not discuss any NP scenario in details

Outline

- Models
  - What NP can (and cannot) do
  - Example: Z'
- How to find NP
  - Global fit
  - Discrete ambiguities
  - "Zero prediction" observables – a_{sl}
  - $\Delta\Gamma(B_s)$
  - $D - \bar{D}$ mixing

NP models

What NP can do?

Modify the low energy effective Hamiltonian

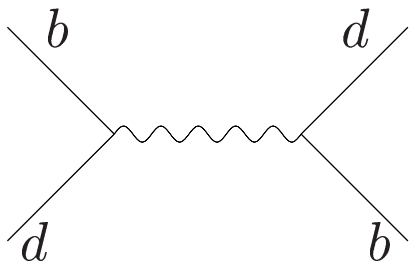
- New contributions to the SM operators
- Generate new operators
- New $\not{C}\not{P}$ phases

What NP cannot do?

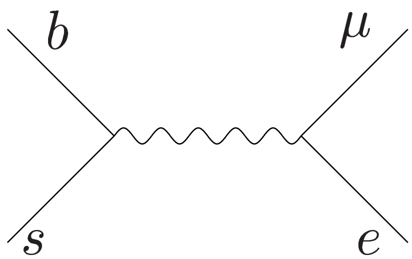
- Cannot change things we "know":
  $a_{CP}(\psi K_S) = -a_{CP}(\psi K_L)$
- Unlikely to compete with "large" SM contributions:
  BR$(b \to c\bar{u}d)$ is mainly SM

In general we expect that NP can affect observables that are at least 1 loop in the SM:
$B - \bar{B}$ mixing, 1 loop B decays, double Cabbibo B decays

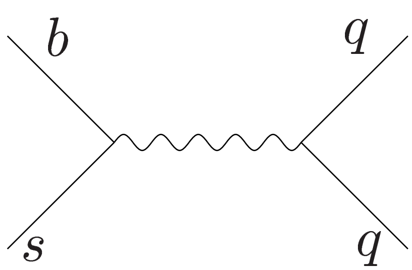
Example Z' exchange



$$\propto \quad \kappa_{bd}^{*}\kappa_{db}/m_{Z'}^{2}$$



$$\propto \quad \kappa_{bs}^{*}\kappa_{\mu e}/m_{Z'}^{2}$$



$$\propto \quad \kappa_{bs}^{*}\kappa_{qq}/m_{Z'}^{2}$$

Similar contributions exist in a large number of NP scenarios: SUSY, LRS, MHDM...

How to find NP

We like to find observables that are

1. "Easy" to measure
2. Have small SM uncertainties
3. Likely to be sensitive to NP

"Wrong" examples:

- Check if $\alpha(\pi\pi) + \beta(\psi K_S) + \gamma(DK) \neq \pi$
- Check if $\sin 2\alpha$ is in the SM allowed range

Global fit

Measure an angle, α, β or γ and check if its value is in the SM allowed range.

At present the SM allowed range is determined from V_{ub}, ϵ_K, Δm_d and Δm_s

The problem: How well do we know the hadronic parameters?

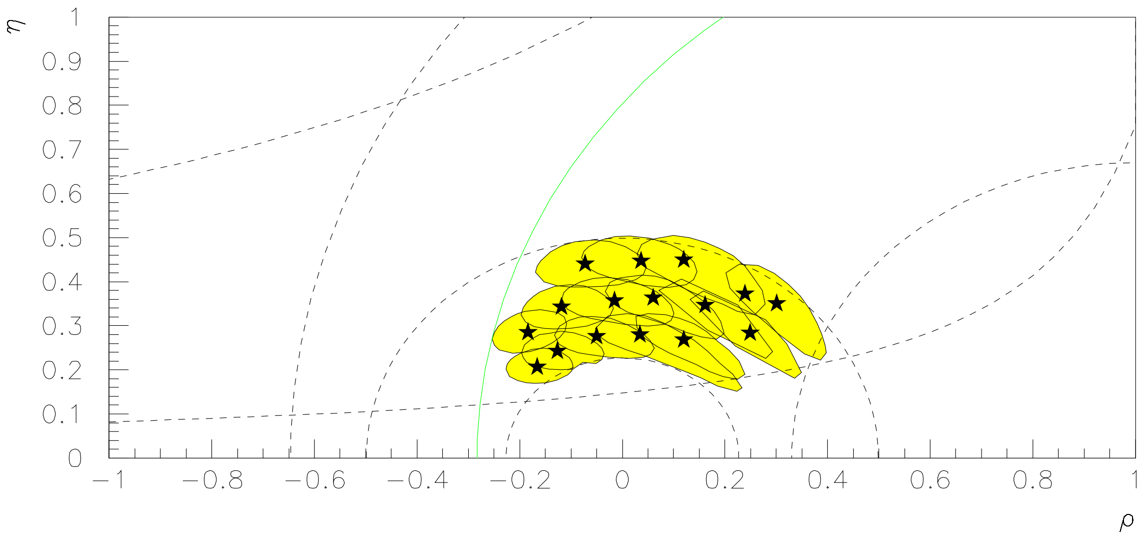
$$|V_{ub}/V_{cb}|$$

$$f_{B_d}\sqrt{B_{B_d}}$$

$$B_K$$

$$R_{SU(3)} = \left(\frac{m_{B_s}}{m_{B_d}}\right)\left(\frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2}\right)$$

The SM allowed range: ρ–η plane



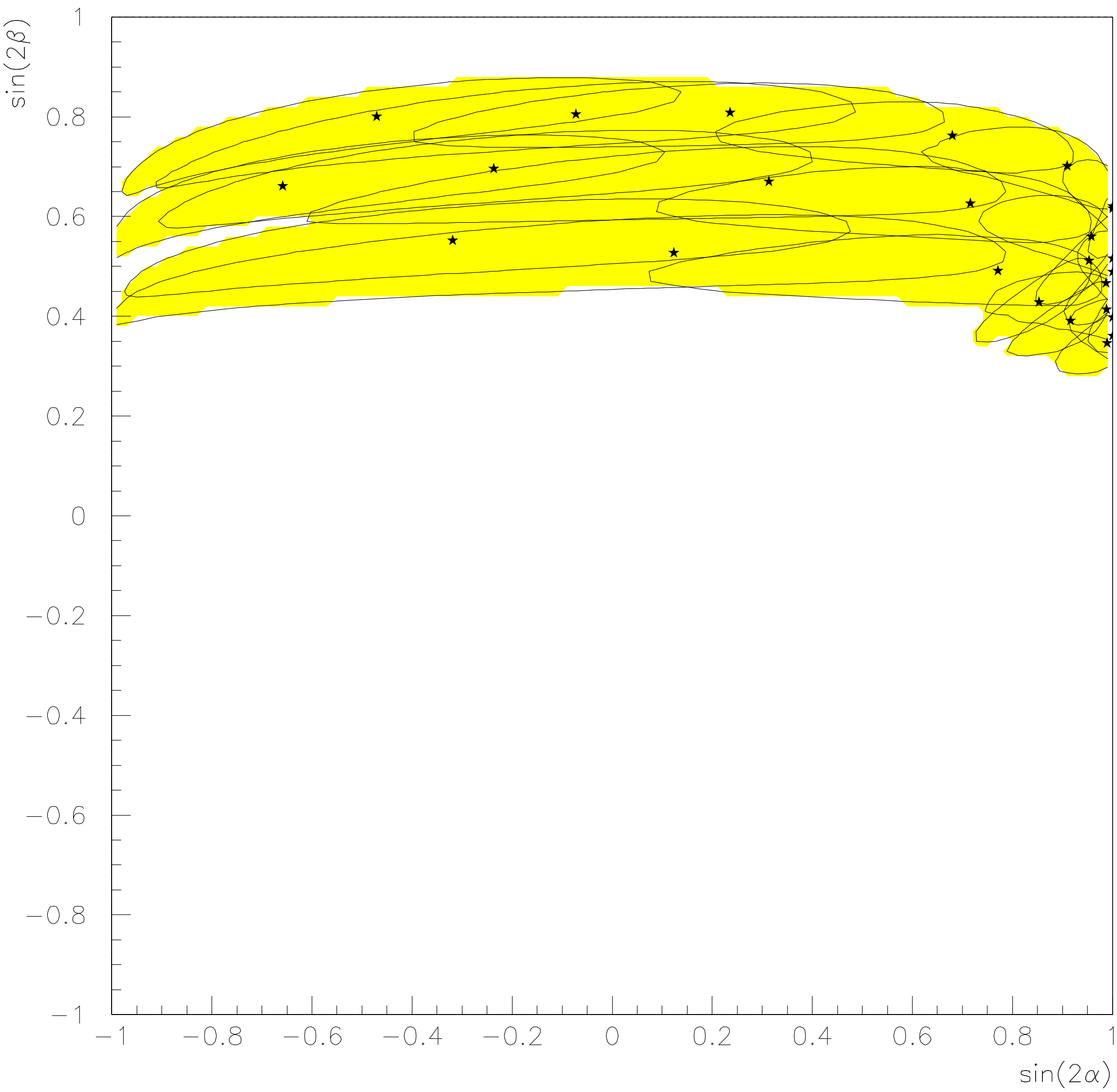
$$0.06 \leq |V_{ub}/V_{cb}| \leq 0.10$$

$$160 \leq f_{B_d}\sqrt{B_{B_d}} \leq 240 \text{ MeV}$$

$$0.6 \leq B_K \leq 1.0$$

$$R_{SU(3)} = \left(\frac{m_{B_s}}{m_{B_d}}\right)\left(\frac{B_{B_s}f^2_{B_s}}{B_{B_d}f^2_{B_d}}\right) < 1.5$$

The SM allowed range: $\sin 2\alpha$–$\sin 2\beta$ plane



In the SM

$$0.3 \lesssim \sin 2\beta \lesssim 0.9 \qquad -1 \leq \sin 2\alpha \leq 1$$

$$10^o \lesssim \beta \lesssim 35^o \qquad 20^o \lesssim \alpha \lesssim 160^o$$

With some correlations

The "problem": The SM allowed range in the $\sin 2\alpha$–$\sin 2\beta$ plane is about 30%, while in the α–β plane it is 3%
$\Longrightarrow$ The NP can "hide"

A possible scenario is to have $\tilde{\alpha}$ and $\tilde{\beta}$ out of the SM range but $\sin 2\tilde{\alpha}$ and $\sin 2\tilde{\beta}$ within it

With NP
$$a_{\rm CP}(\psi K_S) = \sin 2\tilde{\beta}$$
$$a_{\rm CP}(\pi^+\pi^-) = \sin 2\tilde{\alpha}$$

To find such NP we need to resolve discrete ambiguities

Resolving discrete ambiguities

Wolfenstein; Grossman and Quinn

α and β are defined in the range $\{0, 2\pi\}$. However, $a_{\rm CP}(\pi^+\pi^-)$ and $a_{\rm CP}(\psi K_S)$ measure $\sin 2\alpha$ and $\sin 2\beta$. $\sin 2\phi$ determines ϕ up to a four fold ambiguity

$$\{\phi,\ \pi/2-\phi,\ \pi+\phi,\ 3\pi/2-\phi\}$$

Total of 16 fold ambiguity.

In the SM β has no ambiguity and α has at most two fold ambiguity $\Longrightarrow$ sensitive to NP

The ambiguities can be resolved by measuring other functions of the angle

- sign$(\cos 2\phi)$ resolves $\phi \to \pi/2 - \phi$
- sign$(\sin \phi)$ resolves $\phi \to \pi + \phi$

Example: $\sin 2\beta = 0.5$

β	15^o	75^o	195^o	255^o
$\cos 2\beta$	0.87	-0.87	0.87	-0.87
$\sin \beta$	0.26	0.96	-0.26	-0.96

Only a sign is needed

- "Impossible" methods may become useful
- We should ask: What angles and what functions can we measure?

Many ideas, but with many theoretical or experimental difficulties

$a_{\rm CP}(\psi K_S)$ vs $a_{\rm CP}(D^+D^-)$

Without penguins both $B \to \psi K_S$ and $B \to D^+D^-$ measure $\sin 2\beta$. However, $B \to D^+D^-$ has "large", $O(10\%)$, $b \to d$ penguins

$$a_{\rm CP}(D^+D^-) + a_{\rm CP}(\psi K_S) = -2r \cos\delta \cos 2\beta \sin\beta + O(r^2)$$

where

$$r \equiv \frac{A_P}{A_T} \qquad \delta \equiv \delta_T - \delta_P$$

In order to know $r\cos\delta$ we must rely on models. Factorization predicts $r\cos\delta < 0$. Therefore, in the SM

$$|a_{\rm CP}(\psi K_S)| < |a_{\rm CP}(D^+D^-)|$$

- Large r is needed
- We use factorization only in a color allowed process, and only to know the sign of $r\cos\delta$

How reliably can we calculate the sign of $r\cos\delta$?

“Zero prediction” observables

A non vanishing value for an observable that is zero in the SM indicates NP

- $a_{CP}(B_s \to \psi\phi)$, $a_{CP}(B_s \to D_s^+ D_s^-)$
- $a_{dir}(B^\pm \to \psi K^\pm)$
- $a_{dir}(b \to s\gamma)$
- $a_{CP}(B \to \psi K_S) - a_{CP}(B \to \phi K_S)$
- a_{sl}

How reliable are the predictions that these observables vanish in the SM?

Semileptonic asymmetry: a_{sl}

Sanda and Xing; Randall and Su; Cahn and Worah

$$a_{sl} = \frac{\Gamma(\bar{B}^0 \to X\ell^+) - \Gamma(B^0 \to X\ell^-)}{\Gamma(\bar{B}^0 \to X\ell^+) + \Gamma(B^0 \to X\ell^-)}$$

It is given by

$$a_{sl} = \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) = \left|\frac{\Gamma_{12}}{M_{12}}\right| \arg(\Gamma_{12} M_{12}^*)$$

Assuming local duality

$$\left|\frac{\Gamma_{12}}{M_{12}}\right| \approx O(m_b^2/m_t^2) \sim 10^{-2}$$

$$\sin\phi_{12} \equiv \arg(\Gamma_{12} M_{12}^*) \approx O(m_c^2/m_b^2) \sim 10^{-1}$$

In the SM we expect $a_{sl} \sim 10^{-3}$

How NP can affect a_{sl} ?

- Change $|\Gamma_{12}|$ unlikely
- Change $|M_{12}|$ NP in mixing, $O(1)$
- Change $\sin\phi_{12}$ new $\not{C}\not{P}$ in mixing, $O(10)$

Assuming local duality, a_{sl} is a very good probe of new CP violating contributions to $B - \bar{B}$ mixing

How accurate are the local duality SM predictions?

Altomari, Wolfenstein and Bjorken

Im(Γ_{12}/M_{12}) is a long distance quantity and we cannot trust the quark level computation

What value of a_{sl} should be taken as an evidence for NP?

- For B_s a robust SM prediction is $\sin\phi_{12} \ll 1$ and thus also $a_{sl} \ll 10^{-2}$.

The B_s width difference, $\Delta\Gamma(B_s)$

Dunietz; Beneke, Buchalla and Dunietz; Grossman

- In the SM, $\Delta\Gamma$ is generated by the unsuppressed $b \to c\bar{c}s$ decay
- We expect $\Delta\Gamma/\Gamma \sim 15\%$
- We can use untagged B_s data to find $\not{C}\not{P}$

In general for $\Gamma_{12} \ll M_{12}$

$$\Delta M = 2|M_{12}| \qquad \Delta\Gamma = 2|\Gamma_{12}|\cos\phi_{12}$$

In the SM $\cos\phi_{12} = 1$. Therefore, NP in $B_s - \bar{B}_s$ mixing can only reduce $\Delta\Gamma$.

How can we measure $\Delta\Gamma$?

- Semileptonic decays

$$\Gamma(t) \propto e^{-\Gamma_L t} + e^{-\Gamma_S t}$$

- CP even final state $(D_s^+ D_s^-)$

$$\Gamma(t) \propto e^{-\Gamma_S t}$$

The latter assumes SM. With NP it is

$$\Gamma(t) \propto \cos^2 \phi_{12} e^{-\Gamma_S t} + \sin^2 \phi_{12} e^{-\Gamma_L t}$$

- We should be aware when we make SM assumptions in a measurement
- If the untagged decay $B_s \to D_s^+ D_s^-$ can only be fitted with two lifetimes, it is a clear evidence for NP
- The relative size of the two components measures the $\not{C}\!\!\not{P}$ phase in the mixing

$D - \bar{D}$ mixing

Experimentally, $x \equiv \Delta M/\Gamma$ and $y \equiv \Delta\Gamma/2\Gamma < 0.08$

In the SM $D - \bar{D}$ mixing is small

- SD is suppressed by $m_s^2/m_W^2 \times m_s^2/m_c^2$
- Estimates for LD: $x, y \sim \lambda^2 \times$ (SU(3) breaking)$^2 \lesssim 1\%$
- NP can give x at the experimental bound, but cannot enhance y

What are the uncertainties in the SM expectation?

- It is hard to estimate the LD contributions. $x_{SM} < 1\%$ seems to be a reliable upper bound
- For y it is somewhat harder. Probably $y_{SM} > x_{SM}$

We can conclude that we have NP if $x > 1\%$ and $x \gg y$

It is important to try to measure both x and y

Conclusions

- If non–SM scenarios have significant effects in B physics, we would like to find them
- The way to do it is to perform many measurements that are redundant in the SM