New Physics from
$B \to VV$ Decays

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Introduction:

Hints of Deviation from SM in several decays
- $B \rightarrow \phi K_s$, $B \rightarrow \phi K^*$, $B \rightarrow K\pi \pi \ldots$

Question: If effects are real
- Can we identify nature of N.P.
- Can we measure effective parameters of the N.P.

Ans: Yes - specially with $B \rightarrow \nu \nu$ Decays
• $B(p) \rightarrow V_1(k_1, \epsilon_1)V_2(k_2, \epsilon_2) (\phi K^*)$

\[
M = a \epsilon_1^* \cdot \epsilon_2^* + \frac{b}{m_B^2} (p \cdot \epsilon_1^*) (p \cdot \epsilon_2^*) \\
+ i \frac{c}{m_B^2} \epsilon_{\mu \nu \rho \sigma} p^\mu q^\nu \epsilon_1^{*\rho} \epsilon_2^{*\sigma} \\
q = k_1 - k_2
\]

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

• T.P: $A_T \sim \text{Im}(bc^*)$ and $\sim \text{Im}(ac^*)$: Interference between P-even and P-odd amplitudes

$\bar{A}_T \sim \text{Im}(\bar{b}\bar{c}^*)$ and $\sim \text{Im}(\bar{a}\bar{c}^*)$
T-violation- Another Probe of CP(T) violating phases (DaHa and London)

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

- T-violation in $B$ decays can be measured via Triple Product Correlations (TP)

- 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 time reversal $T$: $t \rightarrow -t$
  \[ T.P \rightarrow -T.P \]

- In $B \rightarrow V_1 V_2$ decays we can construct the T.P
  \[ T.P = \vec{p} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \]
  \[ B \rightarrow \text{spin } 0 \]
• 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-violation: \( A_T \neq 0 \) with strong phases and no weak phase.

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

\[ \begin{align*}
A_T & \quad (B \to \phi K^*) \\
\bar{A}_T & \quad (\bar{B} \to \bar{\phi} \bar{K}^*)
\end{align*} \]

\[ T \Rightarrow A_T \text{ and } \bar{A}_T \text{ disagree} \]

\[ \propto \cos(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \]

Note: Direct CP \( \propto \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2) \)
$B \to \phi K^0$ (Pol Puzzle)

$B \to \gamma \gamma \gamma$  3 amp  $S, P, D$

Helicity:

\begin{align*}
(0,0) & \quad (+,+) \quad (-,-) \\
\downarrow & \\
A_L & \quad A_T = A_L, A_{11} \\
& \quad A_L \sim P
\end{align*}

\begin{align*}
\text{if } m_V < m_B \\
E_L \sim P_V/m_V \\
E_T \sim O(1)
\end{align*}

SM $(V-A)$

\begin{align*}
A_L & \sim E_L^1, E_L^2 \sim \frac{P_1 \cdot P_2}{m^2} - \frac{m_B^2}{m^2} \\
A_T & \sim E_T^1, E_T^2 \sim 1 \\
\frac{f_L}{f_T} & = \frac{E_L^1}{E_T^1 + E_T^2} \sim 1
\end{align*}

\begin{align*}
A_L & = -(2a+b)E_T^2/E_{m^2} \\
A_{11} & \sim \sqrt{2} a \\
A_L & \sim \sqrt{2} c
\end{align*}

$B \to \gamma \gamma$ $(b \to d)$  $f_L \sim 1$

$B \to \phi K^0$ $(b \to c \bar{c})$  $f_L = 0.52 \pm 0.04$
Resolution of Pol Puzzle

SM: Estimation of factorization incorrect
- Large Rescattering
- Large Annihilation

Imp Question: What are the predictions for $B \to J/\psi K^*$

NP fits to KLT suggest new physics
in $PEW \Rightarrow$ NP couples to $u$ and $d$ differently
- Diff in measurement in $B^+ \to p^+ K^{*0}$
  and $B^+ \to s^0 K^{*0}$ would be interesting!
Pol Puzzle:
Can be explained by N.P which is not SM like

\[ \langle \Phi K^0 | H_{V+A} | B \rangle \sim (-)^{\frac{\|}{2}} \langle \Phi K^0 | H_{V-A} | B \rangle \]

\[ A_\perp = \frac{1}{2} \text{SM} + \text{ANP} \]

\[ A_0 = \frac{1}{2} \text{SM} - \text{ANP} \]

\[ \text{T.P.} \sim \langle \vec{E}_1 \times \vec{E}_2 \cdot \hat{p} \rangle \]

\[ \text{T.P.} (B+\Phi K^0) = 0 \quad \text{(single amp)} \]

\[ \text{T.P.} = 0.11 \pm 0.05 \pm 0.01 \quad \text{(Babar)} \]

\[ 0.07 \pm 0.11 \pm 0.04 \quad \text{(Belle)} \]

\[ \text{Av: } 0.10 \pm 0.05 \sim 2\sigma \]

Non zero TP \(\Rightarrow\) NP and new weak phase \(\Rightarrow\) non-SM like physics
New Physics in $B \rightarrow \phi K^*$

- Suppose there is a new physics contribution which is SM like- involving new left-handed coupling of the $b$ quark.

$A \sim g_\phi < K^*|V - A|B > X_{SM}$
$+ g_\phi < K^*|V - A|B > X_{NP}$

- We can combine $X_{SM}$ and $X_{NP}$- still only one phase here $X = X_{SM} + X_{NP}$ and so $A_T = 0$. In other words

$a \sim g_\phi A_1[X_{SM} + X_{NP}]$
$b \sim g_\phi A_2[X_{SM} + X_{NP}]$
$c \sim g_\phi V[X_{SM} + X_{NP}]$

$a$ and $b$ are proportional to the axial vector form factors $A_{1,2}$ while $c$ is proportional to vector form factor $V$

- $A_T \sim Im(bc^*) = Im(|X|^2) = 0 = Im(ac^*)$  

No T-violation even with N.P if N.P is SM type( LH interaction)!

Even though there is N.P it is kinematically similar to SM
New Physics in $B \rightarrow \phi K^*$

- Suppose there is a new physics contribution which is not SM like e.g involving new right-handed coupling of the $b$ quark.

$$A \sim g_\phi <K^*|V - A|B > X_{SM}$$
$$+ g_\phi <K^*|V + A|B > X_{NP}$$

$\sim (X_{SM} - X_{NP})$

- Clearly now $A_T \sim \text{Im}(X_{SM}X_{NP}^*) \neq 0$

$$A_T \sim \text{Im}(bc^*)$$

- Hence non zero measurement of $T$ violation in $B \rightarrow \phi K^*$ not only indicates presence of new physics but also yields information (partially) about the nature of new physics. — RH $b$ coupling
Parametrizing NP

Many models of NP contribute to rare $B$ decays

\[
\begin{align*}
\text{At $m_b$ scale effect of NP:} & \quad H_{\text{NP}} = \sum \bar{\psi} \gamma_\mu \psi \bar{\psi} \gamma_\mu \psi + \text{color} \\
& \quad H = H_{\text{SM}} + H_{\text{NP}}
\end{align*}
\]
- 20 new operators

For each process \( B = f \)

\[
\langle f | \Sigma O_i^{NP} | B \rangle = \sum A_i e^{i \phi_i^{NP}} e^{i \delta_i^{NP}}
\]

\( \phi_i^{NP} \) - process independent (weak phase)

\( A_i, \delta_i^{NP} \) - process dependent

Argue \( \delta_i^{NP} \sim \text{small} \)

\( \delta_i^{SM} \) may be large

\[
\langle f | \Sigma O_i^{NP} | B \rangle = \sum A_i e^{i \phi_i^{NP}} = \text{Num. ANP, \( \Theta_{NP}^{NP} \)}
\]

\[
\text{tan} \Theta_{NP}^{NP} = \frac{\sum A_i \text{Sin} \phi_i^{NP}}{\sum A_i \text{Cos} \phi_i^{NP}}
\]

\{ Delta London PLB \}

\{ Delta et al. PRD \}

Can measure ANP, \( \Theta_{NP}^{NP} \)
\[ B \to \nu_1 \nu_2 \]

Consider decays with quark level transitions:
\[ b \to c \bar{c} \bar{c}, \; b \to s \bar{s} s, \; b \to d \bar{d} d \]

In SM dominated by single amp

Weak phase \( \approx 0 \)

\[
A_\lambda (B \to \nu_1 \nu_2) = \alpha_\lambda e^{i\delta_\lambda} + A_\lambda^\text{SM} e^{i\phi_\lambda} \quad \text{NP}
\]

\[
A_\lambda (\bar{B} \to \nu_1 \nu_2) = \alpha_\lambda e^{-i\phi_\lambda} + A_\lambda^\text{SM} e^{-i\phi_\lambda} \quad \text{NP}
\]

\( \theta = \sigma \quad (\bar{B} \to \bar{s}s \bar{s} \text{ etc.}) \quad \lambda = \text{helicity} \)

Time dependent angular analysis:

\[
\Gamma [B(t) \to \nu_1 \nu_2] = e^{-\frac{\Gamma}{2} t} \sum_{\lambda} A_{\lambda} \Theta \sum_{\lambda} A_{\lambda}^\text{SM} \sin(\Delta m t) \quad \text{NP}
\]

\[ t \approx \sin(\Delta m t) \]
\[ \Lambda_i : = \text{Im} (A_\lambda A^*_\lambda - \bar{A}_\lambda \bar{A}^*_\lambda) \rightarrow \text{Top} \]
\[ i = \{0,11\} \]

- \( A (\bar{b} \rightarrow V_V \nu) \rightarrow 3 \text{ amp} \)
- \( A (\bar{b} \rightarrow V_V \nu) \rightarrow 3 \text{ amp} \)

11 independent obs - 6 amp + 5 relative phases.

(count # unknowns: \( \alpha_\lambda (3), \phi_\lambda (3) \)
\( A_\lambda^0 (3), \phi_\lambda^3 (3), \phi_{\text{mixing}} \) known = 12
12 unknowns 11 obs - cannot solve)
Many classes of NP have
- one dominant weak phase
or universal weak phase

\[ \Phi_{\theta}^\lambda = \Phi_{\theta}^\nu \] (helicity independent)

Now 10 unknowns, 11 obs
- can solve (fit)

\[ A^\Delta, \bar{A}^\Delta \text{ measured from } B \rightarrow \phi K^0 \]
\[ B_3 \rightarrow \phi \phi \]
\[ A^\lambda, \bar{A}^\lambda \text{ " } B \rightarrow K^{*+} \eta^0 \]
\[ B_3 \rightarrow K^{*+} \eta^0 \]
\[ A^\lambda, \bar{A}^\lambda \text{ " } B_3 \rightarrow D_3^+ D_3^- \]
Conclusions

- Hints of NP in several decays
- In $B\to VV$ polarization and T.P may reveal sign and nature of N.P
- Full time dependent angular analysis can be used to measure "effective" parameters of N.P