New Physics with $B_s \to VV$

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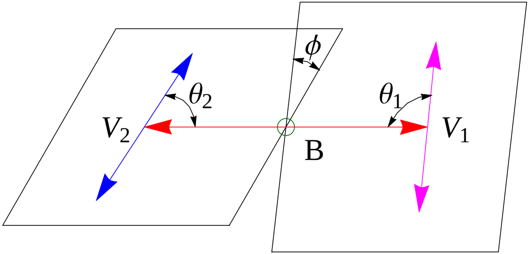
Background

- Spin 0 meson (B_s) $\rightarrow$ 2 Spin 1 mesons (Vectors)
- Relative angular momentum : $L_{VV} = 0, 1, 2$
- Vectors identified through their decay modes : Eg. $\phi \rightarrow K\bar{K}$
- Angular analysis to separate out :
  1.) Functions of helicity angles θ_1, θ_2, and ϕ
  2.) Observables that are dependent on time



The decay amplitude and angular analysis

- Penguin-dominated decays : Eg. $B_s \to \phi\phi, K^* \bar{K}^*$

  Amplitude suppressed in the SM. Good place for new-physics searches.
- Vectors detected via hadronic decay come with scalar backgrounds

  Eg. $\phi \to K^+ K^-$, Background Scalar : $K^+ K^-$ s-wave
- Additional contributions to Amplitude :

  $A(B \to V_1 V_2) \ + \ A(B \to V_1 S_2) \ + \ A(B \to S_1 V_2) \ + \ A(B \to S_1 S_2)$
- 3 helicity amplitudes in $B \to VV$: 1 Longitudinal and 2 transverse
- Scalar background adds additional helicities : (SV, VS, SS)

  Identical final-state vector mesons : 2 additional helicities ($VS = -SV$)

  Distinguishable final-state vector mesons : 3 additional helicities

The differential decay rate

- Most general amplitude has the following terms :

$$A_{VV} : A_0 \cos\theta_1 \cos\theta_2 + \frac{A_\parallel}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \cos\phi + i\frac{A_\perp}{\sqrt{2}} \sin\theta_1 \sin\theta_2 \sin\phi$$

$$A_{VS} : -\frac{A_+^{(VS)}}{\sqrt{6}}(\cos\theta_1 - \cos\theta_2) - \frac{A_-^{(VS)}}{\sqrt{6}}(\cos\theta_1 + \cos\theta_2)$$

$$A_{SS} : -\frac{A_s}{3}; \quad A_\pm^{(VS)} = (A_{VS} \pm A_{SV})/\sqrt{2} \quad \text{If } V_1 = V_2 \text{ then } A_+^{(VS)} \equiv 0$$

- The differential decay rate is then :

$$\frac{d^4\Gamma}{dt\ d\vec{\Omega}} \propto |A_{VV} + A_{VS} + A_{SS}|^2$$

(Time-dependent tagged analysis)

- Angular distribution with six helicities : $({}^6C_2 + 6 = 21)$

$$\frac{d^4\Gamma}{dt\ d\vec{\Omega}} = \frac{9}{8\pi} \sum_{i=1}^{21} K_i(t)\ X_i(\theta_1, \theta_2, \phi)$$

$$\text{where } K_i(t) = \tfrac{1}{2}\ e^{-\Gamma t} \left[a_i \cosh\left(\frac{\Delta\Gamma}{2} t\right) + c_i \cos(\Delta m t) + b_i \sinh\left(\frac{\Delta\Gamma}{2} t\right) + d_i \sin(\Delta m t) \right]$$

- Appropriately integrate over phase space to extract K_i's using :

$$\int X_i(\vec{\Omega})\ f_j(\vec{\Omega})\ d\vec{\omega} = \delta_{ij}$$

- Note: It is not possible to distinguish between $\mathrm{Re}[A_S A_0^*]$ and $|A_+^{(VS)}|^2$ - $|A_-^{(VS)}|^2$ since the angular function is the same : $X \propto \cos\theta_1 \cos\theta_2$

- Time-dependent fit to K_i's give the observables : a_i, b_i, c_i, d_i

Physics from the angular analysis

- a_i, b_i, c_i, d_i are functions of 12 magnitudes $|A_h|, |\bar{A}_h|$, 11 relative phases and the $B_s - \bar{B}_s$ mixing phase (ϕ_M) : Hence they are not all independent
- Construction of observables is model-independent. However, several CP-violating observables are expected to be small in the SM. Large values of these can indicate new physics in B_s decay
- Examples of CP-violating observables : $(\phi_M = -2\mathrm{Arg}(V_{tb}^* V_{ts}))$

  Direct CP Asymmetry (c_i, a_i) : $\mathrm{Re}[A_i A_j^* - \bar{A}_i \bar{A}_j^*] \quad i = j \Rightarrow |A|^2 - |\bar{A}|^2$

  Indirect CP Asymmetry (d_i, b_i) : $\mathrm{Im}\left[(A_i^* \bar{A}_j - \bar{A}_i A_j^*) e^{-i\phi_M}\right]$

  True triple product (a_i, c_{12}) : $\mathrm{Im}\left[A_\perp A_i^* - \bar{A}_\perp \bar{A}_i^*\right]$

  Mixing-induced triple product (b_i, d_{12}) : $\mathrm{Im}\left[(\bar{A}_\perp A_i^* + A_\perp^* \bar{A}_i) e^{-i\phi_M}\right]$

Within the Standard Model

- Amplitude within the SM : (Loosely : γ comes from phase of V_{ub}^*)

$$A_h \;=\; e^{-i\phi_M/2}\left[P'_{tc,h}\; e^{i\delta_{tc,h}} \;+\; e^{i(\gamma+\phi_M/2)}\; P'_{uc,h}\; e^{i\delta_{uc,h}}\right]$$

- Leading order in Wolfenstein Parameter λ : $P'_{tc,h} \;\propto\; |V_{tb}^* V_{ts}| \;\sim\; \mathcal{O}(\lambda^2)$
- Next-to-leading order in λ : $P'_{uc,h} \;\propto\; |V_{ub}^* V_{us}| \;\sim\; \mathcal{O}(\lambda^4)$
- $R_h \;=\; P'_{uc,h}/P'_{tc,h} \sim \mathcal{O}(\lambda^2)$: non-negligible for ϕ_M measurement
- Observables : $A_i A_j^*$ or $A_i^* \bar{A}_j e^{-i\phi_M}$
- a_i, b_i, c_i, d_i are insensitive to ϕ_M (leading order)!

  $\Rightarrow$ Tree-dominated decays (Eg. $B_s \to J/\psi\;\phi$) for NP in $B_s - \bar{B}_s$ mixing

$$\phi_s \;=\; 0.07 \pm 0.09(\mathrm{stat}) \pm 0.01(\mathrm{syst})\ \mathrm{rad}$$

LHCb in Phys. Rev. D (arXiv:1304.2600)

Flavor SU(3)

- Relate $\bar{b} \to \bar{s}$ decay modes to $\bar{b} \to \bar{d}$ decay modes using Flavor SU(3)

  Fleischer and Gronau, arXiv:0709.4013, in PLB

- $B_s \to \phi\phi$ with $B_s \to \phi \bar{K}^{*0}$; $B_s \to K^{*0} \bar{K}^{*0}$ with $B_d \to K^{*0} \bar{K}^{*0}$

- Usual SU(3) breaking corrections $\sim m_s/\Lambda_{\rm QCD}$: Large SU(3) breaking in decay rate comparisons

- Ratios of hadronic amplitudes involve cancellation of certain SU(3)-breaking corrections

- Effect of SU(3) breaking is further suppressed by the new-physics scale

- Extract NP amplitudes and strong and weak phases

NP in B_s decay

- NP may be comparable or larger than sub-dominant SM term
- Amplitude with (large) NP in the decay :

$$A_h \;=\; P_{tc,h} e^{i\delta_{tc,h}} \left(1 + R_h^{NP} e^{i\phi^{NP}} e^{i\Delta_h^{NP}}\right)$$

- Δ_h^{NP} is the difference between NP strong phase and $\delta_{tc,h}$

  NP strong phases may themselves be helicity dependent

- $R_h^{NP} = P^{NP,h}/P_{tc,h}$: $R_h^{NP} \gg R_h^{SM} \sim \mathcal{O}(\lambda^2) \Rightarrow$ New Physics
- CP violation appears due to the interference of two terms

  $\Rightarrow$ CP-violating observables are proportional to R_h!

  Look for large CPV (direct, indirect, TP) for signals of NP in B_s decay

$B_s \to \phi\phi$

- Two identical vectors in the final state :

  5 helicity amplitudes ($3VV, SS, VS_-$)

- Studied by LHCb in detail : arXiv:1303.7125 (published in PRL)

- SM form for each helicity amplitude A_h :

$$A_h \; = \; P'_{tc,h} \; e^{i\delta_{tc,h}} \left[1 + R_h \; e^{i(\gamma + \phi_M/2)} \; e^{i\Delta_h} \right]$$

- Corresponding to $|A_0(t)|^2$, to leading order in R_0 :

$$c_1 \;\approx\; -2\; R_0 \;\sin\Delta_0 \sin(\gamma + \phi_M/2)$$
$$b_1 \;\approx\; -1 \;-\; 2\; R_0 \;\cos\Delta_0 \cos(\gamma + \phi_M/2)$$
$$d_1 \;\approx\; -\; 2\; R_0 \;\cos\Delta_0 \sin(\gamma + \phi_M/2)$$

- Assuming $c_1 = 0$ from the get go $\Rightarrow$ assuming $\Delta_0 = 0$

- Strong-phase difference between $P_{uc,h}$ and $P_{tc,h}$ (SM) can be large

$B_s \to \phi\phi$

- Alternatively extract weak phase ϕ using $b_1 = -\cos\phi$ and $d_1 = \sin\phi$
- A small ϕ from b_1 and d_1 is really due to a small R_h
- In the SM $R_h \sim \mathcal{O}(\lambda^2)$
- If the measured ϕ is an order of magnitude larger than expected $\Rightarrow$ NP
- What if NP effects are tiny?

  Small deviations from SM can be due to neglect of Δ_h
- Small NP effects are best detected through individual CPV observables!

$B_s \to K^{*0}\bar{K}^{*0}$

- Final state has distinguishable vectors : 6 helicity amplitudes
- The same final state is accessible to both B_s and $\bar{B}_s$
- $K^{*0}(890)$ is identified through its decay to $K^+\pi^-$
- Scalar background : $K^{*0}(1430)$ (Large width)
- Time-dependent tagged analysis could be difficult
- Interesting physics even in untagged time-dependent analysis

$B_s \to K^{*0}\bar{K}^{*0}$

- Untagged analysis : angular distribution with same angular functions
- CP conjugate K_i's can be obtained from :

$$\overline{K}_i(t) = \frac{1}{2}\, e^{-\Gamma t} \left[\bar{a}_i \cosh\left(\frac{\Delta\Gamma}{2} t\right) + \bar{c}_i \cos(\Delta m t) + \bar{b}_i \sinh\left(\frac{\Delta\Gamma}{2} t\right) + \bar{d}_i \sin(\Delta m t)\right]$$

where $\quad \bar{a}_i = a_i, \quad \bar{b}_i = b_i, \quad \bar{c}_i = -c_i, \quad \bar{d}_i = -d_i$

- Asymmetric integration over helicity angles obtain :

$$K_i^{\rm untagged} = K_i + \overline{K}_i = e^{-\Gamma t}\left[a_i \cosh\left(\frac{\Delta\Gamma}{2} t\right) + b_i \sinh\left(\frac{\Delta\Gamma}{2} t\right)\right]$$

- Observables a_i and b_i from time-dependent fit to $K_i^{\rm untagged}$

$B_s \to K^{*0}\bar{K}^{*0}$

- Triple product ($A_\perp$) and $A_+^{(VS)}$ are CP-odd amplitudes
- CP-violating terms are the result of interference between CP-odd and CP-even amplitudes
- NP searches can measure CP-Violating observables :

Triple products : $$a_5 = \mathrm{Im}\left[A_\perp A_0^* - \bar{A}_\perp \bar{A}_0^*\right]$$

$$b_5 = \mathrm{Im}\left[(\bar{A}_\perp A_0^* + A_\perp^* \bar{A}_0) e^{-i\phi_M}\right]$$

Direct CP Asymmetries : $$a_8 = \mathrm{Re}\left[A_+^{(VS)} A_S^* - \bar{A}_+^{(VS)} \bar{A}_S^*\right]$$

Indirect CP Asymmetries : $$b_8 = \mathrm{Re}\left[(\bar{A}_+^{(VS)} A_S^* - A_+^{(VS)*} \bar{A}_S) e^{-i\phi_M}\right]$$

New-Physics Scenarios

- Typical effective NP operator :

  $H_{AB}^{NP} \sim (\overline{b}\,\gamma_A\, s)(\overline{q}\,\gamma_B\, q)$ where A, B stands for left(L) or right(R)
- Expansion parameters : Λ_{QCD}/m_B and R_h^{NP}
- RR and LL operators only contribute to $A_{\|}, A_{\perp}$, and A_{SS}

  $\Rightarrow$ Direct CPV involving $A^{(VS)+}$ and $A^{(VS)-}$ suppressed

  Reasonable triple products and mixing-induced TP's
- RL and LR operators don't contribute to VS helicities

  $\Rightarrow$ Triple products involving $A_{\|}$ and $A_{\perp}$ are small

  Other CP violating observables are reasonable, including direct CPV
- a_i, b_i, c_i, d_i can help distinguish between different NP scenarios

Conclusions and Outlook

- Interesting $B \to VV$ decay modes discussed
- Penguin-dominated decays present an excellent place to look for New Physics in B_s decay
- Large new physics in $B_s - \bar{B}_s$ mixing can be identified through weak-phase measurements in $B_s \to \phi\phi$
- Model-independent approach is better in looking for small New Physics
- Several CP-violating observables in penguin dominated $B_s \to VV$ decays discussed. These may eventually help identify certain types of effective-NP operators
- Plenty to look forward to with more data and analysis from LHCb

Amplitude construction

- $A(B \to VV) \;=\; N \sum_{j=-1}^{1} A_j^{VV}\; Y_1^{-j}(\theta_1, -\phi)\; Y_1^{j}(\pi - \theta_2, 0)$
- $A(B \to VS) \;=\; N\; A_0^{VS}\; Y_1^{0}(\theta_1, -\phi)\; Y_0^{0}(\pi - \theta_2, 0)$
- $A(B \to VS) \;=\; N\; A_0^{SV}\; Y_0^{0}(\theta_1, -\phi)\; Y_1^{0}(\pi - \theta_2, 0)$
- $A(B \to SS) \;=\; N\; A_0^{SS}\; Y_0^{0}(\theta_1, -\phi)\; Y_0^{0}(\pi - \theta_2, 0)$
- Spherical harmonics :

$$Y_1^m(\theta, \phi) \;\propto\; \cos\theta\; e^{im\phi}$$

$$Y_0^0(\theta, \phi) \;\propto\; \mathrm{constant}$$

Normalization chosen such that :

$$\frac{d\Gamma}{dt} \;=\; \sum_h |A_h|^2$$

Angular functions

Angular distribution for $B \to VV$

n	$K_n(t)$	Prefactor	$X_n(\theta_1, \theta_2, \phi)$
1	$\lvert A_0(t)\rvert^2$	1	$\cos^2\theta_1 \cos^2\theta_2$
2	$\lvert A_\parallel(t)\rvert^2$	$1/2$	$\sin^2\theta_1 \sin^2\theta_2 \cos^2\phi$
3	$\lvert A_\perp(t)\rvert^2$	$1/2$	$\sin^2\theta_1 \sin^2\theta_2 \sin^2\phi$
4	$\mathrm{Re}[A_\parallel(t)A_0^*(t)]$	$1/2\sqrt{2}$	$\sin 2\theta_1 \sin 2\theta_2 \cos\phi$
5	$\mathrm{Im}[A_\perp(t)A_0^*(t)]$	$-1/2\sqrt{2}$	$\sin 2\theta_1 \sin 2\theta_2 \sin\phi$
6	$\mathrm{Im}[A_\perp(t)A_\parallel^*(t)]$	$-1/2$	$\sin^2\theta_1 \sin^2\theta_2 \sin 2\phi$

For a complete list including scalar backgrounds : arXiv:1306.1911

Observables

Observables to be extracted from a time-dependent fit in $B \to VV$

n	a_n	c_n	b_n	d_n
			Re	Im
1	$\lvert A_0\rvert^2 + \lvert\bar{A}_0\rvert^2$	$\lvert A_0\rvert^2 - \lvert\bar{A}_0\rvert^2$	$-A_0^*\bar{A}_0 e^{-i\phi_M}$	
2	$\lvert A_\parallel\rvert^2 + \lvert\bar{A}_\parallel\rvert^2$	$\lvert A_\parallel\rvert^2 - \lvert\bar{A}_\parallel\rvert^2$	$-A_\parallel^*\bar{A}_\parallel e^{-i\phi_M}$	
3	$\lvert A_\perp\rvert^2 + \lvert\bar{A}_\perp\rvert^2$	$\lvert A_\perp\rvert^2 - \lvert\bar{A}_\perp\rvert^2$	$A_\perp^*\bar{A}_\perp e^{-i\phi_M}$	
4	$\mathrm{Re}[A_\parallel A_0^* + \bar{A}_\parallel \bar{A}_0^*]$	$\mathrm{Re}[A_\parallel A_0^* - \bar{A}_\parallel \bar{A}_0^*]$	$-(\bar{A}_\parallel A_0^* + A_\parallel^* \bar{A}_0)e^{-i\phi_M}$	
5	$\mathrm{Im}[A_\perp A_0^* - \bar{A}_\perp \bar{A}_0^*]$	$\mathrm{Im}[A_\perp A_0^* + \bar{A}_\perp \bar{A}_0^*]$	$-i(\bar{A}_\perp A_0^* + A_\perp^* \bar{A}_0)e^{-i\phi_M}$	
6	$\mathrm{Im}[A_\perp A_0^* - \bar{A}_\perp \bar{A}_0^*]$	$\mathrm{Im}[A_\perp A_0^* + \bar{A}_\perp \bar{A}_0^*]$	$-i(\bar{A}_\perp A_\parallel^* + A_\perp^* \bar{A}_\parallel)e^{-i\phi_M}$	

For a complete list including scalar backgrounds : arXiv:1306.1911