CP Violation from New Physics in Radiative B Decays

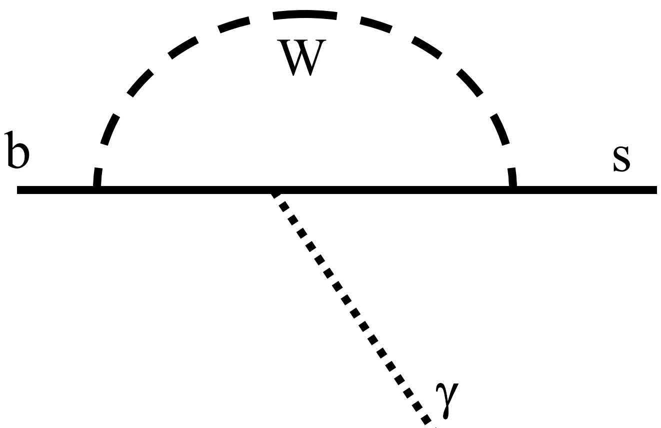
Outline

- Motivation
- Oscillation in radiative B decays Part I
- Oscillation in radiative B decays Part II
- Angular analysis in $B \to \gamma\phi K$
- Conclusions

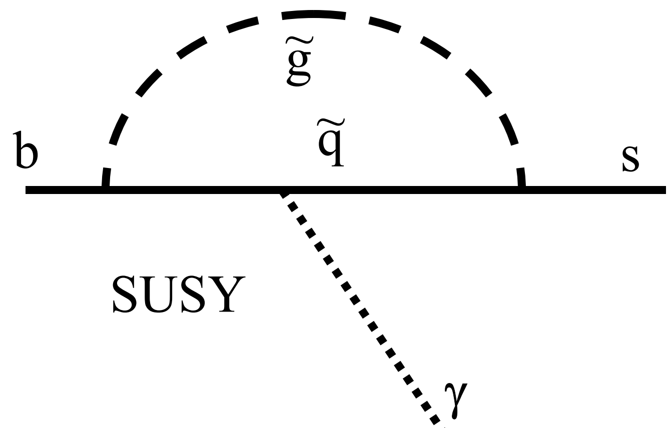
Motivation

- $b \to s\gamma$ is an important probe for new physics
- Inclusive measurements can give 2 parameters
  - Total rate $(3.55 \pm 0.24) \times 10^{-4}$ [HFAG]
  - CP asymmetry (0.00 ± 0.04) [HFAG]
- In exclusive decays it is possible to construct observables which are sensitive to all aspects of the polarization of the photon.
- This allows reasonably good null tests of the SM.

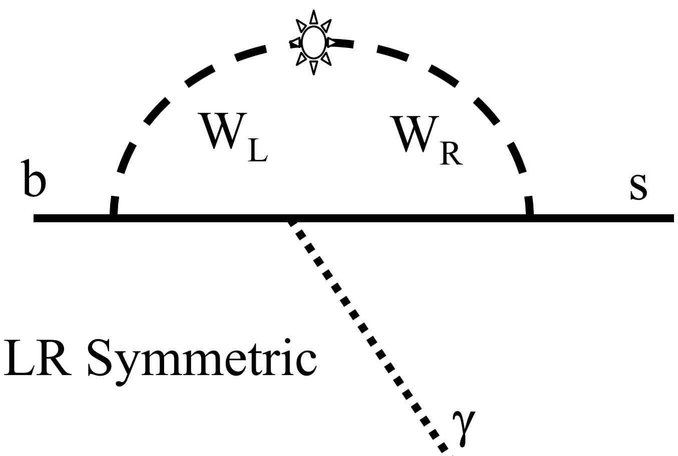
Radiative Penguins in Various Models



Basic SM Penguin

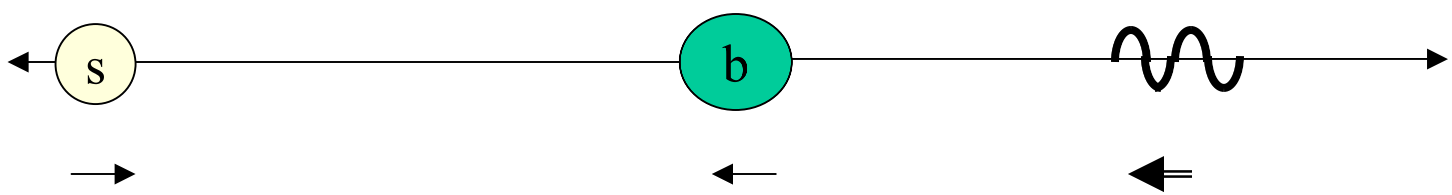


SUSY



LR Symmetric

SM Quark Level Helicity Argument



Must be left handed because it is touched by the W.

Initial b must have this spin otherwise photon has 0 helicity.

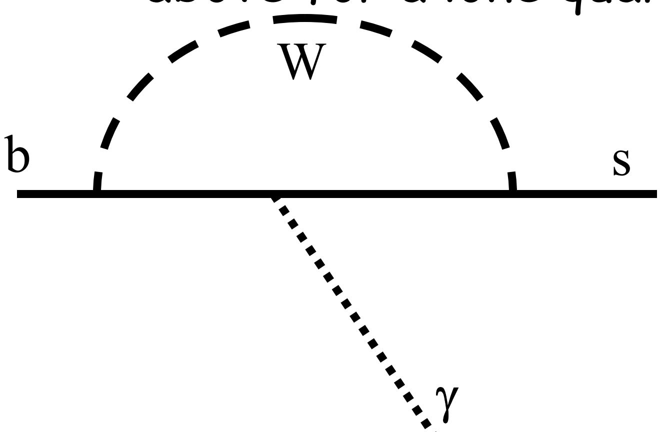
Must be left handed by helicity conservation

A Null Test of the SM?

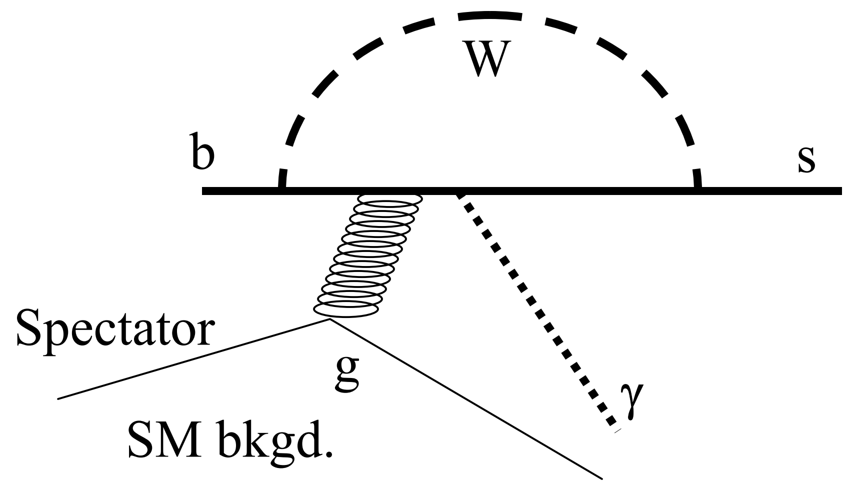
- On the quark level in the SM, the radiative decay $b \to s\gamma$ produces left polarized photons: right/left=m_s/m_b.

- If there is a significant right handed content, it may indicate New Physics: SUSY, LR symmetric etc.

- Consideration must be given to the SM contributions to right photons, in a meson decay it could be larger than the SM result above for a lone quark.

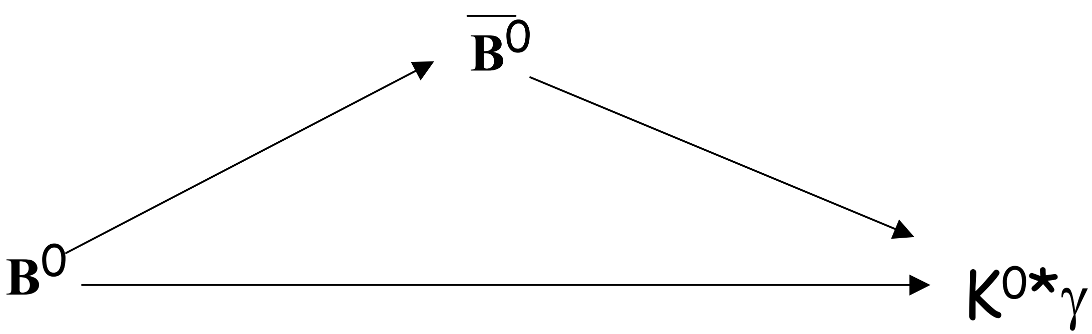


Basic SM Penguin



Oscillation in Radiative B Decays
Part I: $B \to K^*\gamma$

- The first proposed signal (Atwood Gronau Soni 1997) for right polarized photons in B decay was to look for oscillations in $B \to K^*\gamma$.
- To have oscillation in $B^0 \to K^{0*}\gamma$, both B and $\overline{B}$ need to decay to a common final state:



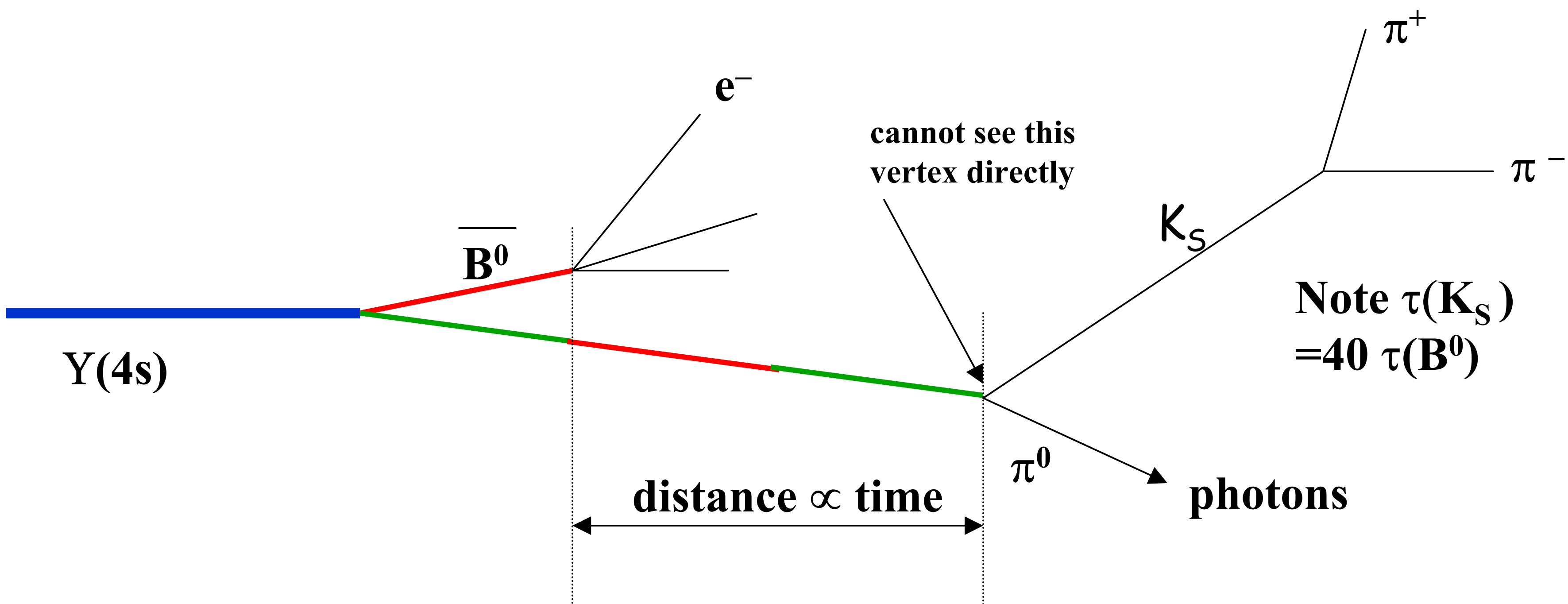
In the Standard Model $\overline{B}$ likes to decay to left photons while B likes to decay to right photons so no oscillations

The following things must therefore happen:

1) K^{0*} must decay in a flavor non-specific way, $K^{0*} \to K_S \pi^0$.
2) Both B^0 and B^0 must produce both left and right polarized photons..

The Experiment: $B^0 \rightarrow K^{0*}\gamma$ Oscillation

- The B factory experiment is similar to ψK_S except that the decay vertex is a little more challenging to detect.
- In addition one needs to trace back $K_S$the decay to the vertex
- This seems very challenging but none the less…



hep-ex/0405082(BaBaR)

Measurement of Time-dependent *CP*-violating Asymmetries in $B^0 \rightarrow K^{*0}\gamma(K^{*0} \rightarrow K^0_s\pi^0)$ Decays

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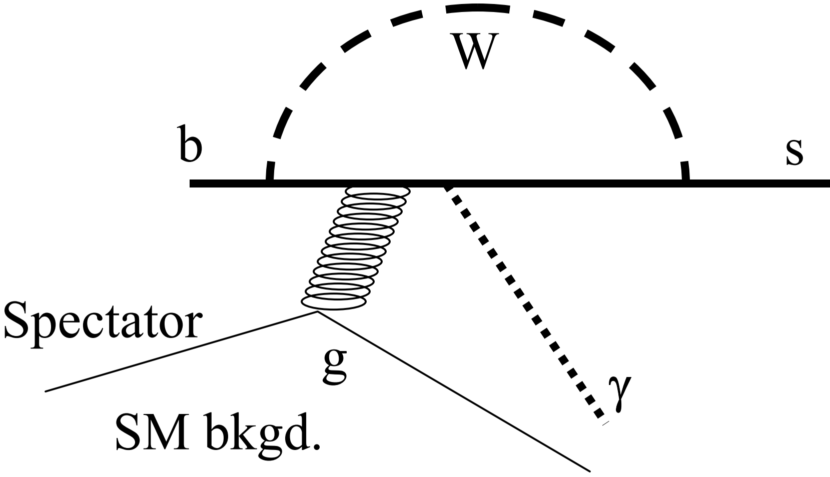
We present a measurement of the time-dependent *CP*-violating asymmetries in $B^0 \rightarrow K^{*0}\gamma(K^{*0} \rightarrow K^0_S\pi^0)$ decays based on 124 million $\Upsilon(4S) \rightarrow B\overline{B}$ decays collected with the BABAR detector at the PEP-II asymmetric-energy B Factory at the Stanford Linear Accelerator Center. In a sample containing 105 ± 14 signal decays, we measure $S_{K^*\gamma} = 0.25 \pm 0.63 \pm 0.14$ and $C_{K^*\gamma} = -0.57 \pm 0.32 \pm 0.09$, where the first error is statistical and the second systematic.

OK for the first try I guess

How good a null test?

- Higher order graphs could ruin the two body helicity argument which works on the quark level.
- How bad is this contamination?
- Clearly it would be good to ultimately have more control over SM contamination.

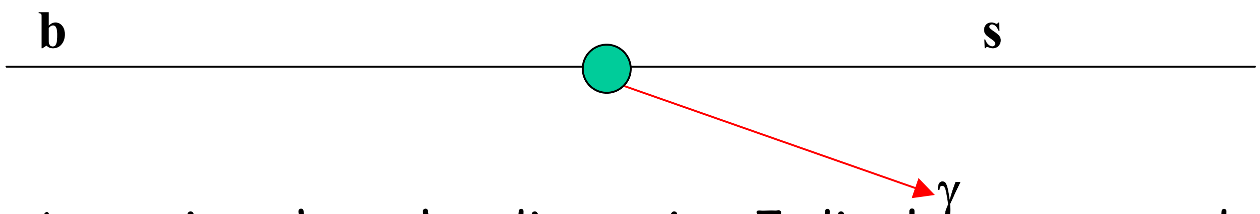
Paper	$S_{K^*\gamma}(SM)$
Ball and Zwicky hep-ph/0609037	-2.2±1.5%
Matsumori and Sanda PRD73:114022(2006)	-3.5±1.7%
Grinstein and Pirjol PRD73:014013(2006)	$\|\| \leq 10\%$
Grinstein, Grossman, Ligeti, Pirjol PRD71:011504(2005)	$\|\| \leq 10\%$



Oscillation in Radiative B Decays Part II: $B \to X_s \gamma$

- In (Atwood Gershon Hazumi Soni 2005) it was pointed out that the K* can be replaced by any X_s of definite charge conjugation.
- The simplest such generalization is to $X_s = K_s \pi^0$
  - That is you can throw together all $K_s \pi^0$, not just at the K* peek.
- The sign of the oscillation depends only on the *C* eigenvalue of X_s.
- This approach gives potentially more statistics
- The dependence on X_s gives a handle on the degree of SM contamination.

H_{eff} for New Physics



- Assuming that the dimension 5 dipole operator dominates, the effective Hamiltonian is:

$$H_{eff} = -\sqrt{8}\, G_F \frac{e m_b}{16\pi^2} \quad F_{\mu\nu} \left[F_L \ \bar{q}\sigma^{\mu\nu}\frac{1+\gamma_5}{2} b + F_R \ \bar{q}\sigma^{\mu\nu}\frac{1-\gamma_5}{2} b \right]$$

$b \to s\gamma_L$ $\qquad$ $b \to s\gamma_R$

- If this model is true, then the photon polarization should not depend on the invariant mass or composition of the hadrons. An important point to test.

- In the SM F_L dominates because of the left coupling of the W

- New physics will contribute to both F_L and F_R.

NP versus SM Contamination

- If radiative decays are controlled by this H_{eff}, then the amplitude, S, of the oscillations will not depend on X_s.
- SM contamination will depend on the kinematics of X_s.
- To check for SM contamination, look for variations in S as a function of:
  - The particles in X_s.
  - The invariant mass of X_s.
  - Other kinematic variables inside X_s
    - e.g. Dalitz plot variables in $B \to \pi^0 K_s \gamma$.

Angular Analysis in $B\to\gamma\phi K$

- Let us now consider the decay $B\to\gamma\phi K$ as a probe of photon polarization in $b \to s\gamma$. (WIP Atwood Gershon Hazumi and Soni).
- The following points make it particularly desirable (the same methods can be applied more generally to any γPV final state):
  - The large branching ratio measured at BABAR and BELLE

$$B(B^- \to \phi K^- \gamma) = (3.46 \pm 0.6)\times 10^{-6} \qquad \text{(HFAG)}$$

  - The neutral version of this final state makes an excellent choice for the time dependent analysis: the prompt ϕ decay allows the vertex to be better located.
  - The time independent angular distribution of the ϕ decay allows the measurement of additional polarization dependent observables, some of which are even more suppressed in the SM than the oscillation amplitude.
  - An easy decay mode to reconstruct even at hadronic machines (LHCB)
- This is somewhat similar to the analysis of $B\to\gamma[K^{**} \to K\pi\pi]$ considered by (Gronau Pirjol PRD 054008(02) and Gronau Grossman, Pirjol and Ryd PRL88 0510802(02))

Features of $B \to \gamma\phi K$

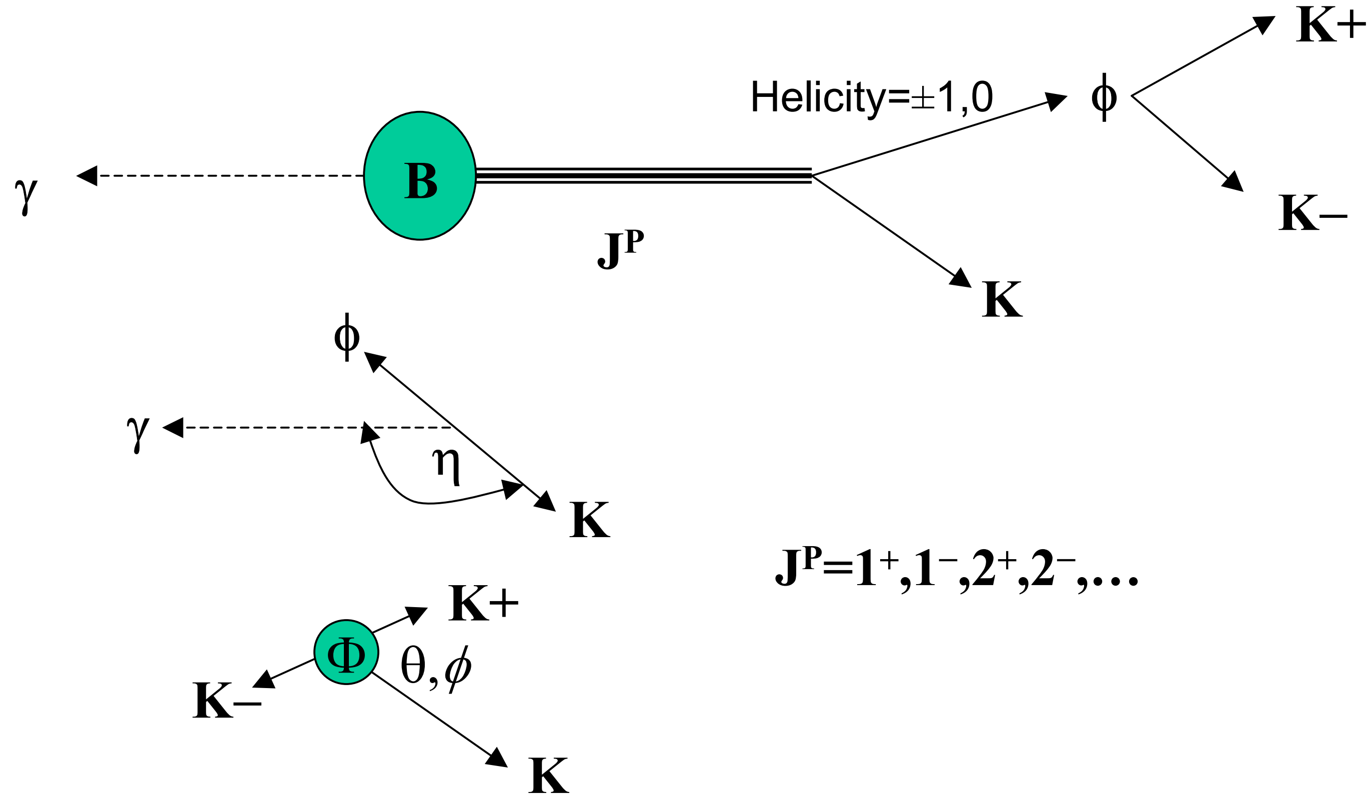
- Time Dependent analysis
  - Only applies in neutral case
  - Requires tagging and time measurement
  - Can integrate over angular variables
  - Extracts only one observable (oscillation amplitude)
  - Subject to an unknown amount of SM contamination; can check Dalitz variable dependence.
- Angular Analysis
  - Neutral and charged cases can be used
  - No time measurement
  - No tagging for C-even P-odd observables
  - Charged case self tagging.
  - Extracts 4 observables
  - Some observables (ie C-even P-odd) have reduced [O(1%)] SM contamination.
  - Complicated angular distributions require lots of data to untangle (super B or LHCB)

Angular Distribution

B frame

Kϕ frame

ϕ frame



What can we learn from angular distributions

- If there are 2 different J^P partial waves, then the left photon can interfere with the right photon.
- Components of the angular distribution will be proportional to:

$$\mathrm{Re}(F_R F_L^*) \quad \mathrm{Im}(F_R F_L^*) \quad \mathrm{Re}(F_\perp F_\parallel^*) = |F_R|^2 - |F_L|^2$$

NB: 2x sign ambiguity

- This is separately true for the B^+ and B^-.
- In general, you can take the components of the angular distribution and solve for the magnitude and phase of F_R/F_L, both for B^+ and B^-.
- Here I would like to highlight the part of the distribution proportional to $\mathrm{Im}(F_R F_L^*)$

C-even P-odd

- Generally you will get a parity odd distribution proportional to $Im(F_R F_L^*)$.
- If you add this coeficient of B and anti-B distributions, the result is C-even P-odd ($\therefore$ CP-odd).
- P-odd means it is proportional to $\sin\phi$ (ie triple product).
- It is small in the SM for two reasons:
  - It is proportional to F_R/F_L: to produce an non-zero result the SM must make photons of the suppressed helicity.
  - It is proportional to $\sin(\arg(F_R F_L^*))$, the wrong handed photons must have a different CP phase ($O(\lambda^2)$)
- Signals of this type will therefore be O(1%) in the SM.

Key Points

- For the C-even P-odd distribution, no tagging is required: particle and anti-particle distributions are added together.
- If a C-odd P-even distribution is found, there must be new physics.

Toy Model

- As a toy model, I will assume that only the two channels $J^P=1^+$ and 1^- participate and that that the 1^+ happens to decay in such a way that the ϕ has only helicity=±1.

- The angular distribution in this case is

$$\Gamma^{+}(\eta,\theta,\phi)=\sin^2\theta\,[\lambda_0+\lambda_1\cos^2\eta+\lambda_2\cos\eta$$
$$+\lambda_3\cos(2\phi)+\boxed{\lambda_4\sin(2\phi)}+\lambda_5\cos\eta\cos(2\phi)$$
$$\boxed{+\lambda_6\cos\eta\sin(2\phi)}+\lambda_7\cos^2\eta\cos(2\phi)+\boxed{\lambda_8\cos^2\eta\sin(2\phi)}]$$

C-even P-odd

$\lambda_4+\overline{\lambda}_4$

$\lambda_6+\overline{\lambda}_6$

$\lambda_8+\overline{\lambda}_8$

- The following information may be extracted from these parameters:

$$\frac{\mathrm{Re}(F_R F_L^*)}{|F_R|^2+|F_L|^2}=\frac{1}{2}\left(\frac{\lambda_0-\lambda_1}{\lambda_7+\lambda_3}\right)$$

$$\frac{|F_R|^2-|F_L|^2}{|F_R|^2+|F_L|^2}=\pm\frac{(\lambda_8-\lambda_4)}{\sqrt{(\lambda_0+\lambda_1)^2-(\lambda_7+\lambda_3)^2-\lambda_2^2}}$$

$$\frac{\mathrm{Im}(F_R F_L^*)}{|F_R|^2+|F_L|^2}=\frac{1}{2}\left(\frac{\lambda_6}{\lambda_0+\lambda_1}\right)$$

(note: 2× ambiguity)

Inventory of polarization observables

In B^0 decay there are 4 rates and 3 phases

① $b \to s\gamma_R$ Angular

② $b \to s\gamma_L$

③ $\bar{b} \to \bar{s}\gamma_L$ Angular

④ $\bar{b} \to \bar{s}\gamma_R$

[1] Angular (① ↔ ②)

[2] Oscillation (② ↔ ③)

[3] Angular (③ ↔ ④)

In $B^{\pm}$ decay there are 4 rates and 2 phases

① $b \to s\gamma_R$ Angular

② $b \to s\gamma_L$

③ $\bar{b} \to \bar{s}\gamma_L$ Angular

④ $\bar{b} \to \bar{s}\gamma_R$

[1] Angular (① ↔ ②)

[2] Angular (③ ↔ ④)

Conclusions

- Oscillations in $B \to K^*\gamma$ and more generally $B \to X_s\gamma$ provide a good ($\leq$10%) null test for New Physics beyond the SM.
- The consistency of a NP signal versus SM contamination can be tested by checking the variation with X_s and Dalitz variables.
- The decay $B \to \phi K\gamma$ is an excellent choice for oscillation studies
- Angular distributions in $B \to \phi K\gamma$ can elucidate all the polarization observables of the photon.
- In particular, C-even P-odd observables are an excellent null test of the SM, only O(1%) SM contamination.