Three-body *CP* Eigenstates

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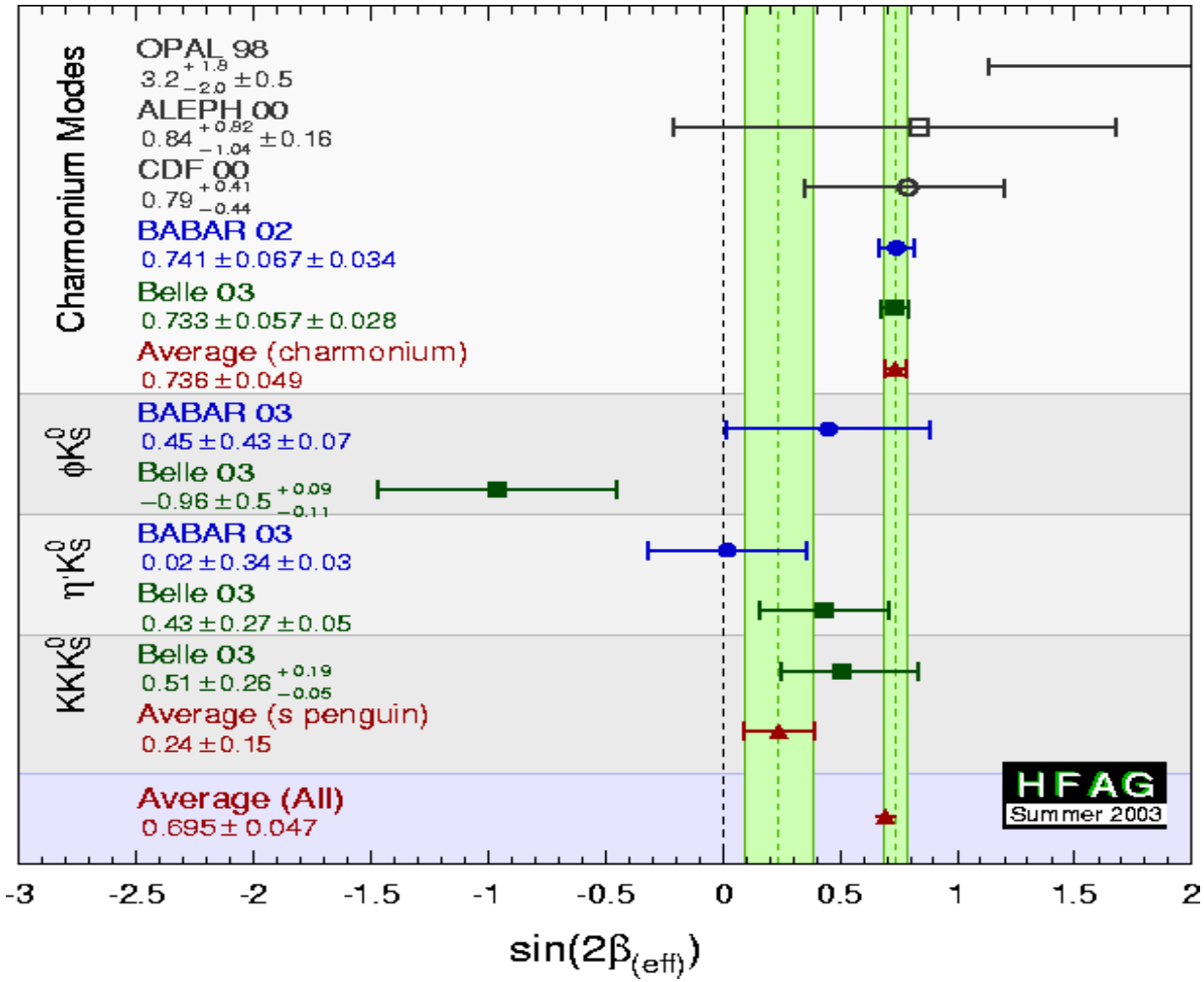
Opening Position

- *CP* violation observed in a handful of modes
- KM scheme is *elegant* and *effective*, but is it *enough*?
- Already evidence for beyond SM *CP* violation
- Desire multiple probes of *CP*V phenomena

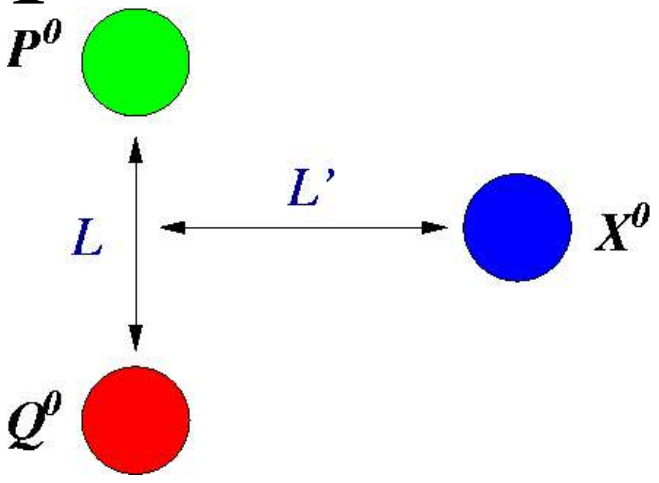
$b \to sqq$ Anomaly



CP Violation Analyses

- Time-dependent studies of $B \rightarrow CP$ eigenstates have been very successful
  - Phenomenology rather straightforward
- *CP* violation measurements from $B \rightarrow$ non-*CP* final states have more unknown parameters
  - Analysis is harder, requires more statistics
  - Their time will certainly come
- Number of two-body *CP* eigenstates is finite

$$B^0 \rightarrow P^0 Q^0 X^0$$



- B^0 is a neutral spin-0 particle
- Let P^0, Q^0, X^0 be neutral particles
- L is orbital angular momentum between $P^0 - Q^0$
- L' is orbital angular momentum between $(P^0 - Q^0)$ - X^0
- Conservation of angular momentum:

$$\boldsymbol{J}_{B^0} = \mathbf{0} = \boldsymbol{L} + \boldsymbol{L}' + \boldsymbol{S}_{P^0} + \boldsymbol{S}_{Q^0} + \boldsymbol{S}_{X^0}$$

CP of $P^0Q^0X^0$

- $CP(P^0Q^0X^0) = CP(P^0)\, CP(Q^0)\, CP(X^0)\, (-1)^L\, (-1)^{L'}$
- If P^0, Q^0, X^0 are all spin-0 particles:

  conservation of angular momentum $\longrightarrow L' = L$
- If P^0, Q^0, X^0 are all spin-0 CP eigenstates:

  final state is a CP eigenstate:

$$CP(P^0Q^0X^0) = CP(P^0)\, CP(Q^0)\, CP(X^0)$$

- P^0, Q^0, X^0 candidates:

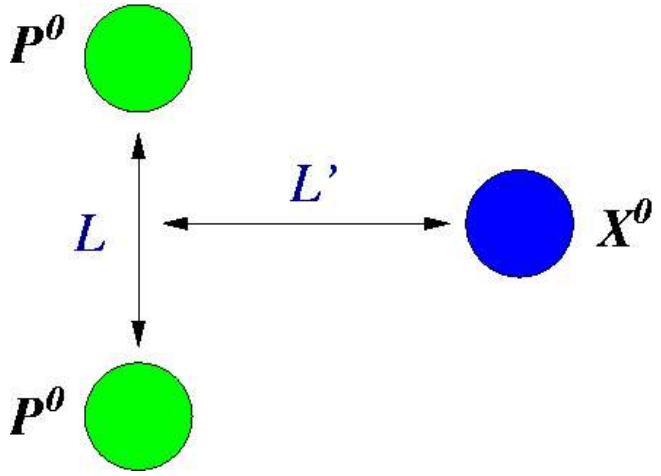
$$\pi^0,\ \eta,\ \eta',\ f_0,\ a_0,\ K_S,\ K_L,\ D_{CP},\ \eta_c,\ \chi_{c0}$$

Comments on $B^0 \to P^0 Q^0 X^0$

- Enormous number of possible final states!
- In general, more different quarks in final state

  $\to$ more amplitudes can contribute
- Concentrate on (hopefully cleaner) final states containing (at least) two identical particles

$$B^0 \rightarrow P^0 P^0 X^0$$

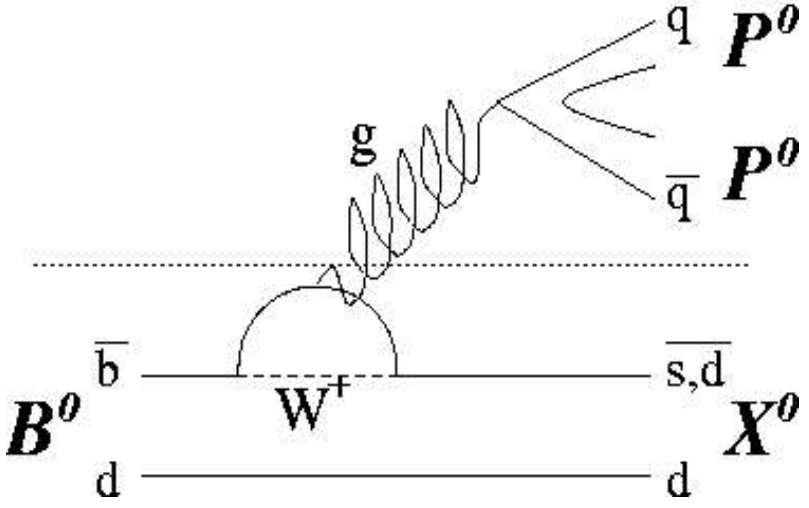


- B^0 is a neutral spin-0 particle
- Let P^0, X^0 be neutral spin-0 particles
- L is orbital angular momentum between $P^0 - P^0$
- Bose-Einstein statistics $\rightarrow L = 0, 2, 4, \ldots$
- Conservation of angular momentum: $L' = L$

$$CP(P^0 P^0 X^0) = CP(X^0)$$

Advantage of $B^0 \to P^0 P^0 X^0$ (?)

- $J^P(P^0P^0) = 0^+, 2^+, 4^+, \ldots$
- Decays to similar final states (*eg.* $B^+ \to \chi_{c(0,2)} K^+$) forbidden in factorization (although observed)
- Does this help us?
- Expert input is welcome!



Possible $B^0 \to P^0 P^0 X^0$

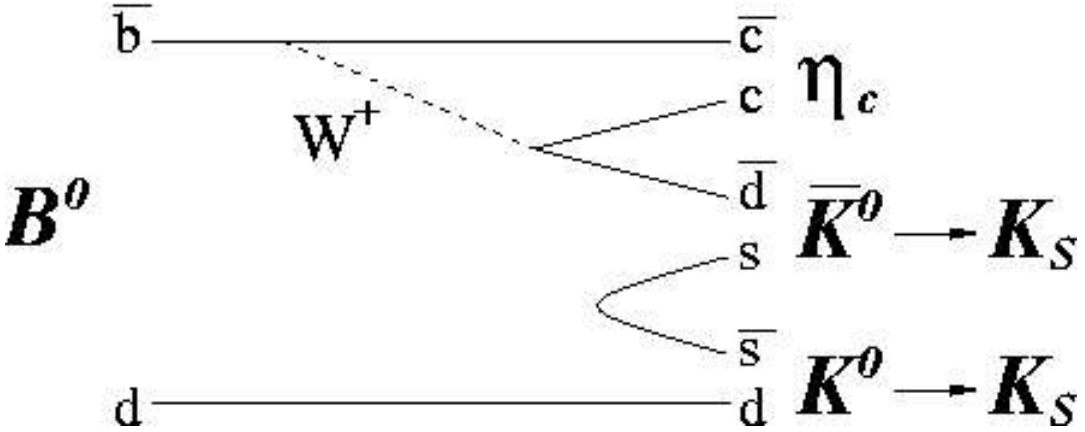
	P^0							
X^0	π^0	η	η'	f_0	a_0	K_S	K_L	D_{CP}
π^0	$\underline{\pi^0\pi^0\pi^0}$	$\eta\eta\pi^0$	$\eta'\eta'\pi^0$	$f_0 f_0 \pi^0$	$a_0 a_0 \pi^0$	$\underline{K_S K_S \pi^0}$	$K_L K_L \pi^0$	$D_{CP} D_{CP} \pi^0$
η	$\pi^0\pi^0\eta$	$\eta\eta\eta$	$\eta'\eta'\eta$	$f_0 f_0 \eta$	$a_0 a_0 \eta$	$K_S K_S \eta$	$K_L K_L \eta$	$D_{CP} D_{CP} \eta$
η'	$\pi^0\pi^0\eta'$	$\eta\eta\eta'$	$\eta'\eta'\eta'$	$f_0 f_0 \eta'$	$a_0 a_0 \eta'$	$K_S K_S \eta'$	$K_L K_L \eta'$	$D_{CP} D_{CP} \eta'$
f_0	$\pi^0\pi^0 f_0$	$\eta\eta f_0$	$\eta'\eta' f_0$	$f_0 f_0 f_0$	$a_0 a_0 f_0$	$K_S K_S f_0$	$K_L K_L f_0$	$D_{CP} D_{CP} f_0$
a_0	$\pi^0\pi^0 a_0$	$\eta\eta a_0$	$\eta'\eta' a_0$	$f_0 f_0 a_0$	$a_0 a_0 a_0$	$K_S K_S a_0$	$K_L K_L a_0$	$D_{CP} D_{CP} a_0$
K_S	$\underline{\pi^0\pi^0 K_S}$	$\underline{\eta\eta K_S}$	$\underline{\eta'\eta' K_S}$	$f_0 f_0 K_S$	$a_0 a_0 K_S$	$\underline{\underline{K_S K_S K_S}}$	$K_L K_L K_S$	$D_{CP} D_{CP} K_S$
K_L	$\pi^0\pi^0 K_L$	$\eta\eta K_L$	$\eta'\eta' K_L$	$f_0 f_0 K_L$	$a_0 a_0 K_L$	$\underline{K_S K_S K_L}$	$K_L K_L K_L$	$D_{CP} D_{CP} K_L$
D_{CP}	$\pi^0\pi^0 D_{CP}$	$\eta\eta D_{CP}$	$\eta'\eta' D_{CP}$	$f_0 f_0 D_{CP}$	$a_0 a_0 D_{CP}$	$\underline{K_S K_S D_{CP}}$	$K_L K_L D_{CP}$	
η_c	$\pi^0\pi^0\eta_c$	$\eta\eta\eta_c$	$\eta'\eta'\eta_c$	$f_0 f_0 \eta_c$	$a_0 a_0 \eta_c$	$K_S K_S \eta_c$	$K_L K_L \eta_c$	
χ_{c0}	$\pi^0\pi^0\chi_{c0}$	$\eta\eta\chi_{c0}$	$\eta'\eta'\chi_{c0}$	$f_0 f_0 \chi_{c0}$	$a_0 a_0 \chi_{c0}$	$K_S K_S \chi_{c0}$	$K_L K_L \chi_{c0}$	

Comments on $B^0 \to P^0 P^0 X^0$

- Try to judge which modes are (will be) useful now (at a Super *B* factory)
- No reliable technique to estimate three-body BFs
- Base estimates of usefulness on measured quantities, where possible
- Measurements of three-body BFs provide useful information about hadronic *B* decay

$B^0 \to K_S K_S \eta_c$

- Modes $B^0 \to P^0 P^0 (cc)$ probe $b \to ccd$ transition with additional qq production
- Consider product BFs ... not very promising

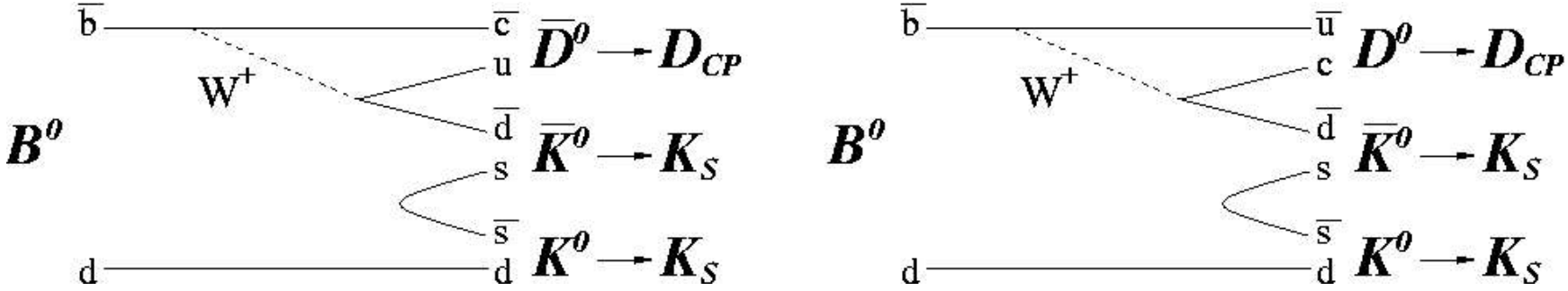


Aside: $B^0 \to K_S K_S J/\psi$

- Cleaner signal and higher efficiency for $cc = J/\psi$
- Here, X^0 has spin-1 $\to$ final state is not a CP eigenstate in general
- $J^P(K_S K_S) = \underline{0^+}, 2^+, 4^+, \ldots$
- If 0^+ is dominant, final state *is* a CP eigenstate
- Higher L states suppressed by centrifugal barrier?
- Can determine from $(K_S K_S)$ helicity distribution

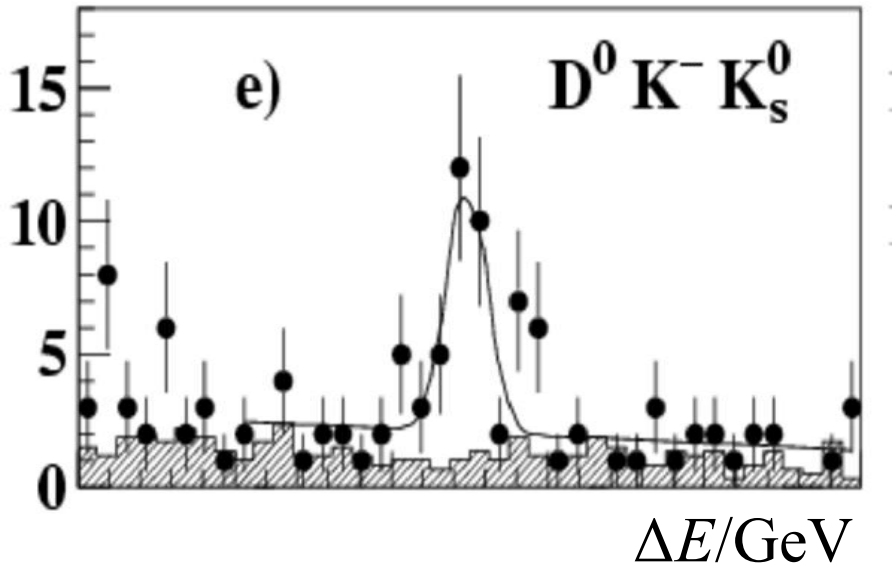
$B^0 \to K_S K_S D_{CP}$

- Can use $B^0 \to D_{CP}\pi^0$ to measure $sin(2\varphi_1)$ or probe for (*R*-parity violating) new physics
- Same diagrams with *ss* production
- Expect smaller (but cleaner) signal than $B^0 \to D_{CP}\pi^0$



$B^0 \to KKD$

- No observation of $B \to K_S K_S D$ yet, but ...
- Numerous similar $B \to KK^{(*)}D^{(*)}$ modes observed
- Eg. $B^- \to K_S K^- D^0$
  - from 29.4/fb

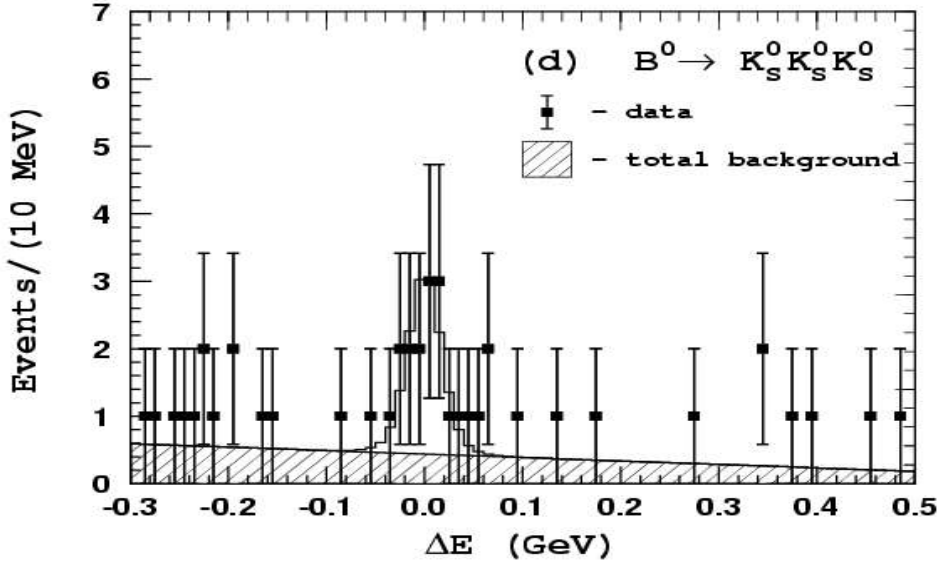


$$B^0 \to D_{CP} D_{CP} K_S / D_{CP} D_{CP} \pi^0$$

- These modes probe $b \to ccs$ / $b \to ccd$
- Negligible penguin contribution (?)
- Tiny efficiency to reconstruct $2 * (D \to D_{CP})$

$B^0 \to KKK$

- Mode $B^0 \to (K^+K^-)_{\text{non-}\varphi} K_S$ already used to probe $b \to sqq$ (found to be mainly $CP+$)
- Suggests reasonable BF for $B^0 \to K_S K_S K_S$
- Indeed observed!
  - from 78/fb



$$B^0 \to K_S K_S K_S$$

- Clean! No u quark in final state → tiny tree pollution
- Probes $b \to s$ better than $B^0 \to (K^+K^-)_{\text{non-}\varphi} K_S$ or $B^0 \to \eta' K_S$
- Clean! Good signal/background ratio.
- Little (negligible?) $b \to c$ background

K_S Vertexing

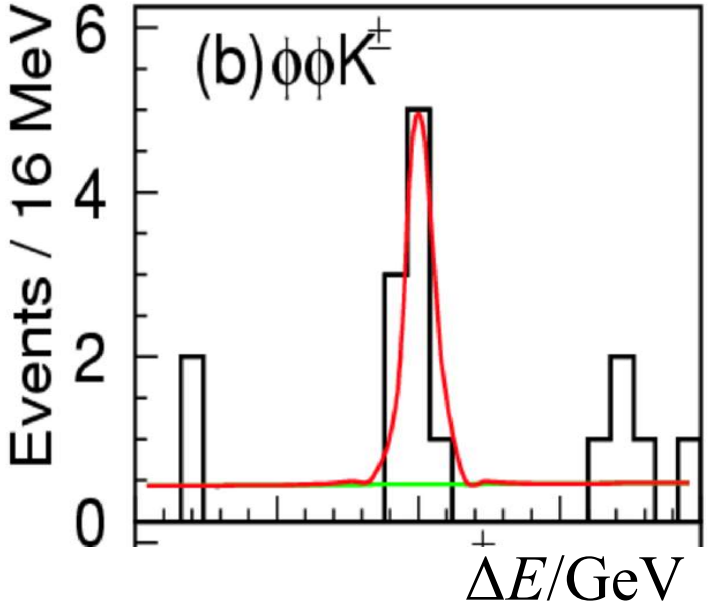
- To date, Belle has only announced results of time-dependent analyses with tracks that originate from the B vertex (*egs.* $J/\psi K_S$, $\pi^+\pi^-$, φK_S)
- BaBar has announced results on $D^{*+}D^-$, $D^{*+}D^{*-}$, $K_S\pi^0$
- It is possible to get vertex information from K_S alone, with reasonable efficiency
- High vertex efficiency for $K_S K_S K_S$

$$B^0 \to K_S K_S K_L$$

- Mode $B^0 \to (K^+K^-)_{\text{non-}\varphi} K_S$ found to be mainly $CP+$ (K^+K^- has even L)
- Suggests $B^0 \to (K_S K_L)_{\text{non-}\varphi} K_S$ should be small
- Good news! Use φ mass constraint:
  - reduce continuum background
  - remove cc background

$B^0 \to \eta'\eta' K_S$

- $B \to \varphi\varphi K$ proposed as sensitive to new physics ...
- ... and observed
  - from 78/fb



- BF$(B \to \eta' K)$ > expected
- BF$(B \to \eta' X_s)$ > expected

$B^0 \to \pi^0\pi^0 K_S$, *etc*

- $B^0 \to \pi^0 K_S$ currently a hot topic
- Add dd production $\to B^0 \to \pi^0\pi^0 K_S$
- Could also use $B^0 \to P^0 Q^0 X^0$ modes:

$$B^0 \to \pi^0 \eta K_S,\ B^0 \to \pi^0 \eta' K_S$$

- Note that, *eg.*, $B^0 \to \pi^0 \eta' K_S$ includes $B^0 \to \eta' K^{*0}$

$B^0 \to K_S K_S \pi^0$

- Time-dependence of $B^0 \to \pi^0\pi^0$ probes φ_2 in principle
- In practise cannot measure vertex position
- Add *ss* production $\to B^0 \to K_S K_S \pi^0$
- Expect this mode to be rather rare

  possibly enhanced if mediated by $B^0 \to f_0\pi^0$, $a_0\pi^0$ *(?)*

$B^0 \to \pi^0\pi^0\pi^0$

- Example of obtaining useful information without studying time-dependence
- No vertex information available
- BF can give a bound on the contribution of $B^0 \to \sigma^0\pi^0$ to $B^0 \to \pi^+\pi^-\pi^0$ (affects $B^0 \to \rho^+\pi^-$ analysis)

Aside: $B^0 \to P^0 P^0 \gamma$

- $P^0 P^0 \gamma$ is <u>not</u> a CP eigenstate
- $P^0 P^0$ *is* a CP eigenstate
- Behaves as $B^0 \to M^0 \gamma$ ... a good probe for new physics
- $P^0 P^0$ cannot form 0^+ state → suppressed (?)
- Probes $b \to d\gamma$ vertex
- No $b \to s\gamma$ background for $B^0 \to K_S K_S \gamma$

Conclusions

- Final state in $B^0 \to P^0 Q^0 X^0$ decays is a *CP* eigenstate (P^0, Q^0, X^0 are spin-0 *CP* eigenstates)
- Numerous possibilities for time-dependent studies
- Requiring $P^0 = Q^0$ adds useful (?) constraints
- Some modes which cannot be used for time-dependent analyses are still interesting
- $B^0 \to K_S K_S K_S$ may help solve the $b \to sqq$ riddle