Entangled B_s-B_s States at The Upsilon (5s)

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Outline

- Motivation
- Upsilon(5s): Bs menu
- Experimental Scenario
- Categories of B_s Decays
- Oscillation Formalism
- Basic (qualitative) Idea
- Correlations
- Asymmetries
- Conclusions

Motivation

- The SM predicts that CP violating phases in the c will be small. We should check that.

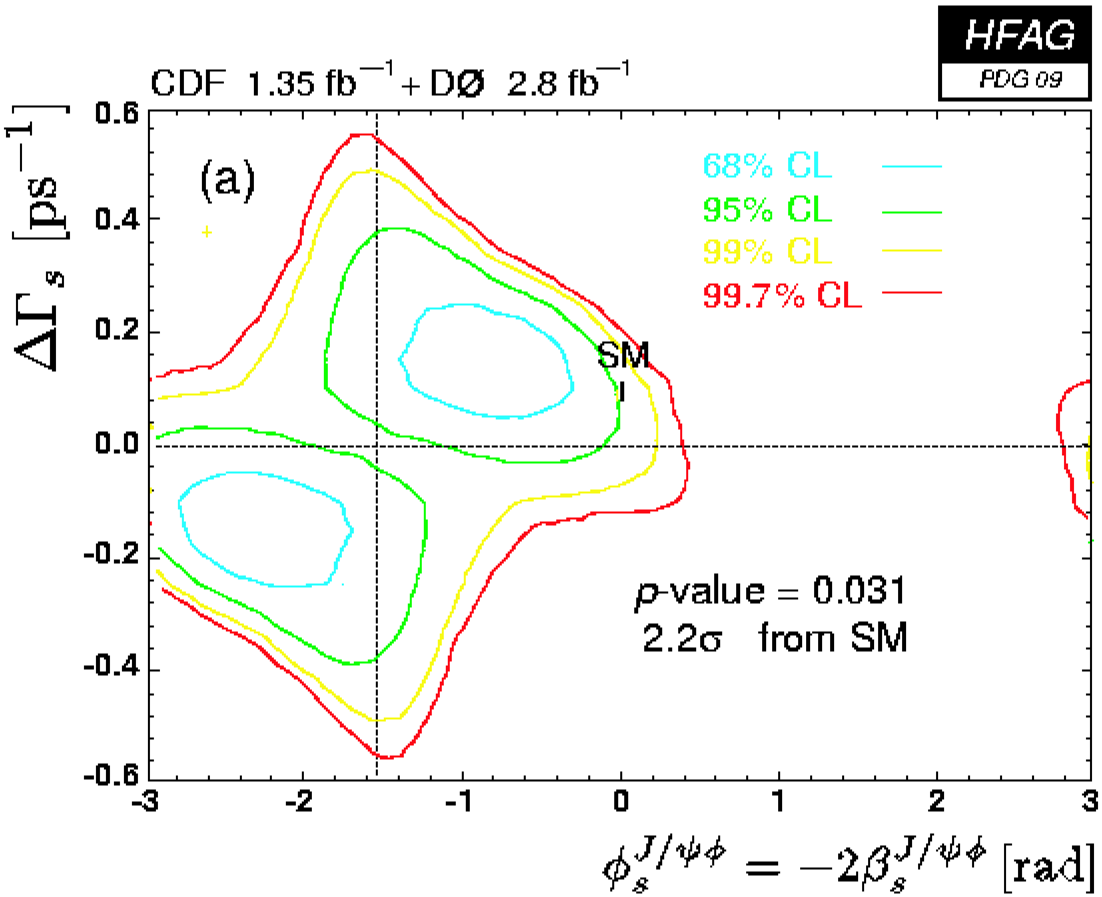
- Theory now gives a better prediction for $\Delta\Gamma_s$, We therefore want a better measurement of this.

  Nierst and Lenz JHEP 0706:072 (2007)
  Badin, Gabbiani and Petrov Phys.Lett.B653:230-240 (2007)

- In contrast to hadron colliders, electron-positron B-factories produce B_s in a unique entangled state.

- In this talk, I will consider how to make use of this correlated initial state to address these two issues.

Current knowledge (from HFAG 2009)



Results from CDF and DO:

CDF, Phys.Rev.Lett.100:121803 (2008)

DO, Phys.Rev.Lett.95:171801 (2005)

Phys.Rev.Lett.98:121801 (2007)

$$|\Delta\Gamma_s| = .154^{+0.054}_{-0.070}\ \mathrm{ps}^{-1}$$

$$\tau_s = 1.412 \pm 0.042\ \mathrm{ps}$$

$$y = \tfrac{1}{2}\tau_s\ \Delta\Gamma_s = 0.109^{+.038}_{-.050}$$

$\varphi_s = -2\ \beta_s$ (90% CL range)	[−1.47 ; −0.29] ∪ [−2.85 ; −1.65]

Upsilon(5s): B_s Menu

- Constraints we will try to live with:
  - 10^7-10^8 $b\bar{b}$ events (σ_{bb}=0.3nb→L=30-300 fb^{-1})
  - Limited time resolution (cannot see Δm_s oscillations)

- Using this, what will we do?
  - Measure $\Delta\Gamma_s$ using time independent correlations of inclusive states
  - Measure mixing/decay phases correlating inclusive with exclusive decays
  - Measure $\Delta\Gamma_s$ using time asymmetry of inclusive states (much better)
  - Constrain tan(ϕ_s) (i.e. mixing phase) using time asymmetry of inclusive states

B factories at Upsilon(5s)

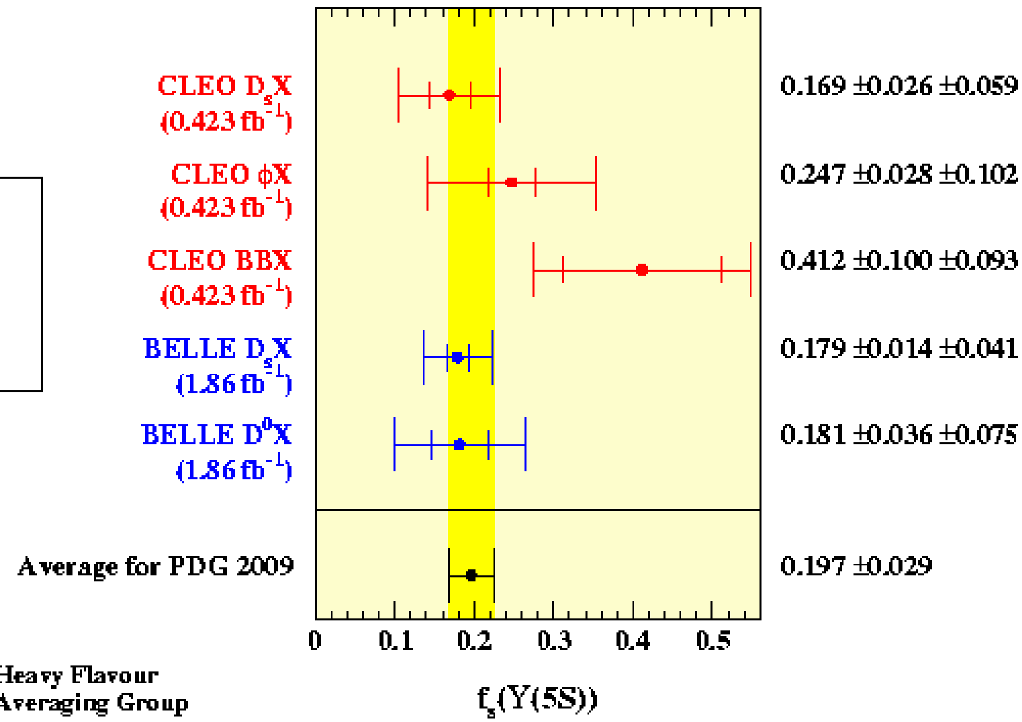
- CLEO has run at the Upsilon(5s) for $0.4fb^{-1}$
- More recently BELLE has run at Upsilon(5s)

  BELLE Collab.. PRL 102, 021801 (2009)

- BELLE has now gathered $\sim 100fb^{-1}$ [$=3\times10^7$ bb events]

Basics of B_sB_s Production at Upsilon(5s)

Fractions of Upsilon(5s) events going to each BsBs mode (from HFAG 2009)



b hadron species	fraction in Y(5S) decay	ratio
$B_s^{(*)}$ anti-$B_s^{(*)}$	$f_s^{(*)(*)} = f_s(Y(5S)) = 0.197 \pm 0.029$	
B_s^* anti-B_s^*	f_s^{**}	$f_s^{**}/f_s^{(*)(*)} = 0.901 +0.038-0.040$

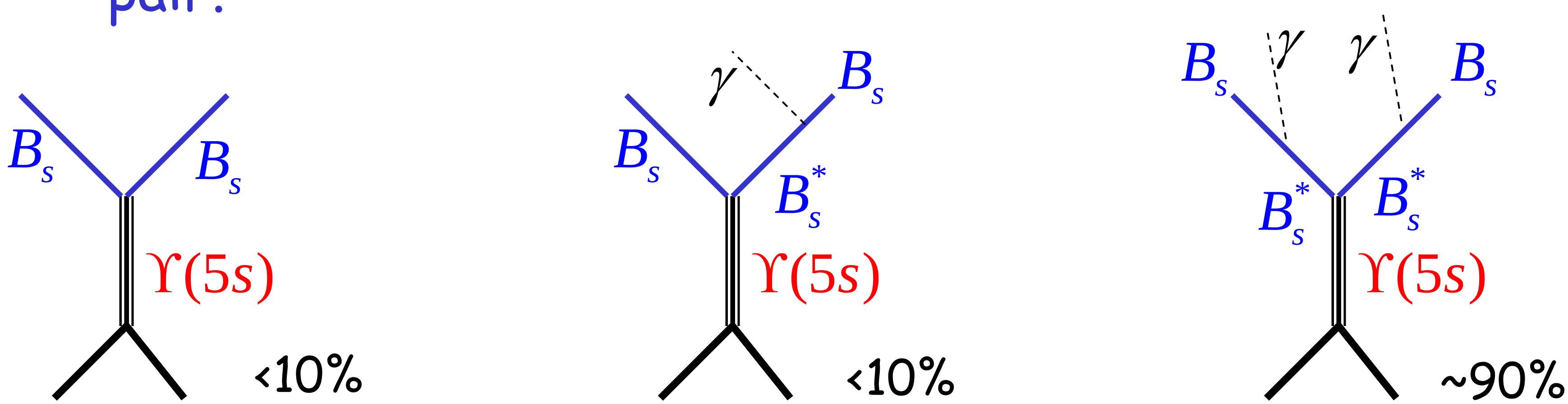
Experimental Scenario

- A $\bar{B}_s B_s$ pair is produced in about 20% of the e+e- $\rightarrow \bar{b}b$ events at the Upsilon(5s).
  - $B_s B_s$
  - $B^*_s B_s$
  - $B^*_s B^*_s$ $\rightarrow$90% of the time!

Define

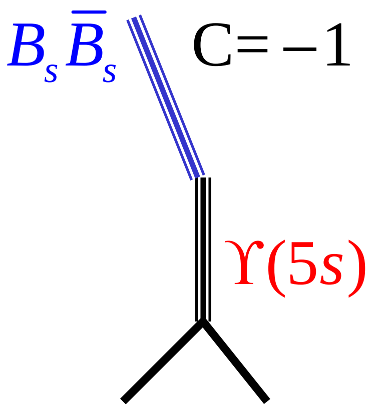
$$r^* = \frac{B_s^{(*)}\overline{B}_s + B_s\overline{B}_s^{(*)}}{B_s^{(*)}\overline{B}_s^{(*)}} \leq 10\%$$

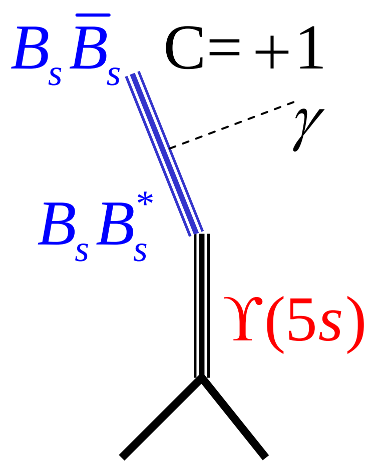
- In all cases the system decays radiatively to a $B_s B_s$ pair.

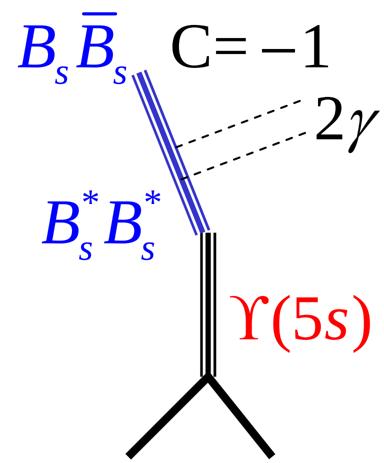


Properties of Meson Pairs

- In asymmetric B-factories, the system is in motion wrt the lab frame
- This allows us to get time information from the position of the decay (as in the Upsilon(4s)).
- I will assume time resolution not fine enough to see Δm_s oscillations.
- Unlike the Upsilon(4s), there are a variety of initial states







Initial State

- C=-1 implies L=odd and P=-1 (>90% of the time)

$$\Psi^{C=-1} = \frac{1}{\sqrt{2}}\left(\left|B_s\right\rangle\left|\overline{B}_s\right\rangle - \left|\overline{B}_s\right\rangle\left|B_s\right\rangle\right)$$

- C=+1 implies L=even and P=+1

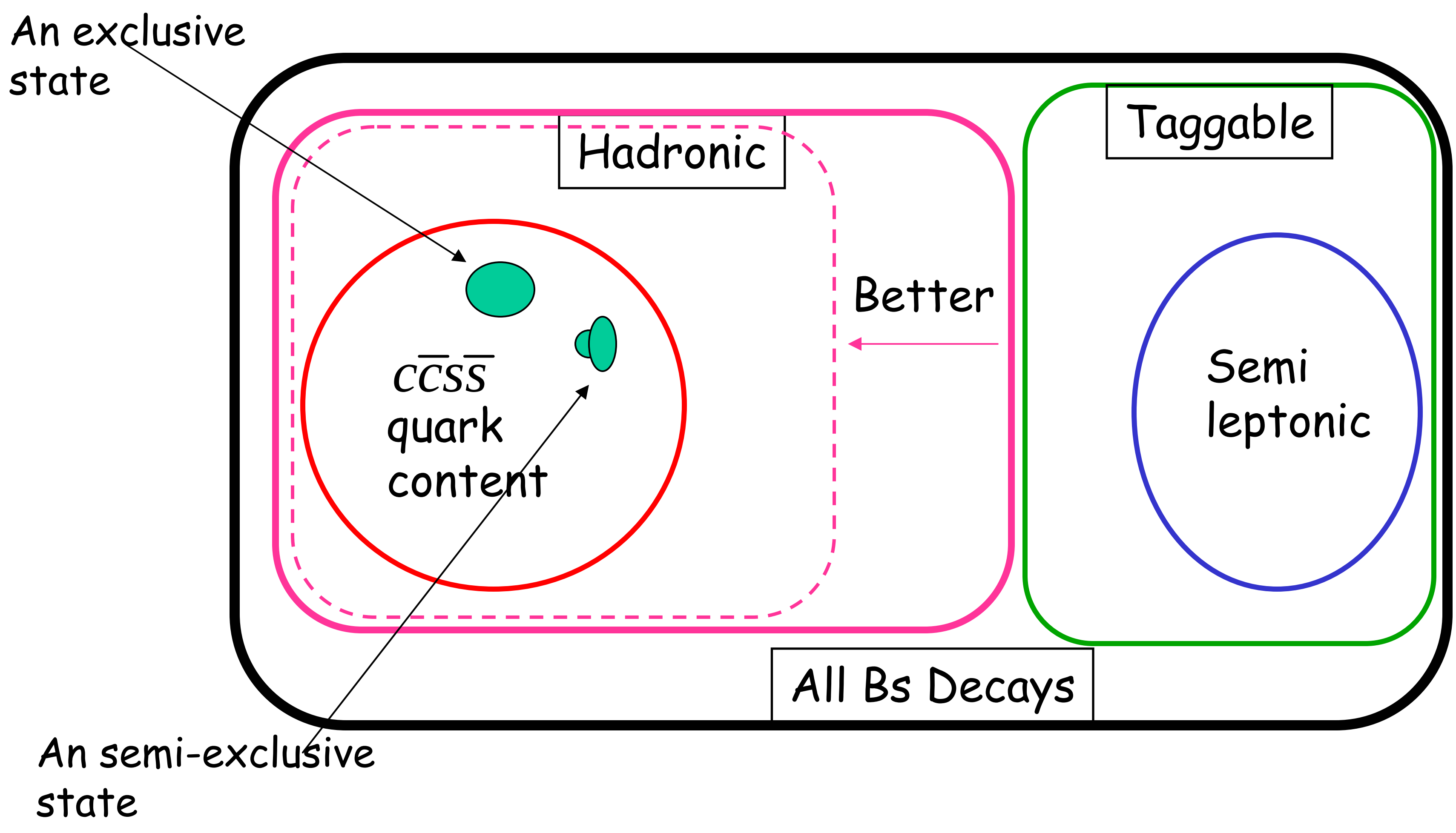
$$\Psi^{C=+1} = \frac{1}{\sqrt{2}}\left(\left|B_s\right\rangle\left|\overline{B}_s\right\rangle + \left|\overline{B}_s\right\rangle\left|B_s\right\rangle\right)$$

Categories of B_s Decays

- Given limited # of mesons, we want to consider final states with as much BR as possible.
- Use inclusive states composed of many exclusive states.
- Taggable Decays (t)
  - This includes semileptonic decays as well as hadronic decays which give the flavor of the B_s meson.
  - Usually we won't actually care whether it tags a B_s meson (t+) or a B_s meson (t-) [i.e. due to rapid oscillations].
- Hadronic Decays (h)
  - This includes all decays that are not taggable
  - Decays with quark content $c\bar{c}s\bar{s}$ should be included in this sample.
  - It is advantageous to cut away as many non-ccss states as possible.
  - The width difference is entirely due to a difference in the decay rate of the eigenstates to hadronic states

- Exclusive final state
  - A single quantum amplitude (e.g. $D_s^+ D_S^-$)
- Semi-exclusive state
  - A set of related amplitudes (e.g. $D_s^{+*} D_S^{-*}$: three polarization amplitudes; $D_s^+ D_S^- \eta'$: s-wave vs p-wave)
  - It is generally possible to separate out the components from the decay distribution.

Map of States



Oscillation Formalism: Decay Matrix for a General State

- For a single state, let
  - A=amplitude($B_s \to f$)
  - $\overline{A}$=amplitude($\overline{B}_s \to f$)

$$R_f = \begin{bmatrix} A^* A & A^* \overline{A} \\ \overline{A}^* A & \overline{A}^* \overline{A} \end{bmatrix} = \begin{bmatrix} u_f + v_f & w_f e^{i\theta_f} \\ w_f e^{-i\theta_f} & u_f - v_f \end{bmatrix} \quad \text{for a single quantum state } u^2 = v^2 + w^2$$

- For a set of states F={f}

$$R_F = \sum_f R_f = \begin{bmatrix} u_F + v_F & w_F e^{i\theta_F} \\ w_F e^{-i\theta_F} & u_F - v_F \end{bmatrix} \quad \text{for a set of quantum states } u^2 \ge v^2 + w^2$$

Oscillation of a Single Meson

- At time t, $\left|\psi(t)\right\rangle = a(t)\left|B_s\right\rangle + \overline{a}(t)\left|\overline{B}_s\right\rangle \equiv \begin{bmatrix} a(t) \\ \overline{a}(t) \end{bmatrix}$
- The time evolution is given by
  $\left|\psi(t)\right\rangle = U(t)\left|\psi(0)\right\rangle$

$$g_\pm(t) = \tfrac{1}{2}\left(e^{-im_1 t} e^{-\frac{1}{2}\Gamma_1 t} \pm e^{-im_2 t} e^{-\frac{1}{2}\Gamma_2 t}\right)$$

$$U(t) = \begin{bmatrix} g_+(t) & e^{-i\phi} g_-(t) \\ e^{+i\phi} g_-(t) & g_+(t) \end{bmatrix}$$

- Thus the time dependent decay rate is

$$\Gamma(F,t) = Tr\left[U^\dagger(t) R_F U(t) \rho_0\right]$$

ρ_0=Initial state density Matrix

General Result
Single Meson

- Define

$$x = \frac{\Delta m}{\Gamma} \quad S_x = \sin(x\Gamma t) \quad C_x = \cos(x\Gamma t)$$

$$y = \frac{\Delta\Gamma}{2\Gamma} \quad S_y = \sinh(y\Gamma t) \quad C_y = \cosh(y\Gamma t)$$

$$C_\theta^\phi = \cos(\phi+\theta) \quad S_\theta^\phi = \sin(\phi+\theta)$$

- Result

$$\Gamma(B_s \to F, t) = e^{-\Gamma t}\left[u_F C_y + v_F C_x - w_F S_y C_\theta^\phi + w_F S_x S_\theta^\phi\right] \leftrightarrow \rho_0 = \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

$$\Gamma(\bar{B}_s \to F, t) = e^{-\Gamma t}\left[u_F C_y - v_F C_x - w_F S_y C_\theta^\phi - w_F S_x S_\theta^\phi\right] \leftrightarrow \rho_0 = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\Gamma(\{B_s \bar{B}_s\} \to F, t) = e^{-\Gamma t}\left[u_F C_y - w_F S_y C_\theta^\phi\right] \leftrightarrow \rho_0 = \frac{1}{2}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

- Average Branching Ratio (as measured e.g. at a collider)

$$\hat{\Gamma}(F) = \int \Gamma(\{B_s \bar{B}_s\} \to F, t)\ dt = \frac{1}{\Gamma}\left[\frac{u_F - y w_F C_\theta^\phi}{1-y^2}\right]$$

Oscillation of Entangled Mesons

- For the C=±1 state, the time dependent decay to a final state F_1 F_2 is:

$$\Gamma^{\pm}(F_1 F_2, t_1 t_2) = s_{12}\, Tr\left(\left[U^{\dagger}(t_1) R_1 U(t_1)\right] T_{\pm} \left[U^{\dagger}(t_2) R_2 U(t_2)\right]^T T_{\pm}^{\dagger}\right)$$

$$T_{\pm} = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 1 \\ \pm 1 & 0 \end{bmatrix}$$

  - s_{12}=statistical factor=1/2 for F_1 =F_2 or 1 otherwise.

General Result: Entangled Mesons

$$S_y^{\pm} = \sinh(y\Gamma(t_1 \pm t_2)) \quad C_y^{\pm} = \cosh(y\Gamma(t_1 \pm t_2))$$

$$S_x^{\pm} = \sin(x\Gamma(t_1 \pm t_2)) \quad C_x^{\pm} = \cos(x\Gamma(t_1 \pm t_2))$$

$$\Gamma^-(F_1F_2,t_1t_2) = 2s_{12}\, e^{-\Gamma(t_1+t_2)}\Big[\left(u_1u_2 - w_1w_2C_1^\phi C_2^\phi\right)C_y^- + \left(u_1w_2C_2^\phi - u_2w_1C_1^\phi\right)S_y^- - \left(v_1w_2S_2^\phi - v_2w_1S_1^\phi\right)S_x^- - \left(v_1v_2 + w_1w_2S_1^\phi S_2^\phi\right)C_x^-\Big]$$

Only depends on time difference

$$\Gamma^+(F_1F_2,t_1t_2) = 2s_{12}\, e^{-\Gamma(t_1+t_2)}\Big[\left(u_1u_2 + w_1w_2C_1^\phi C_2^\phi\right)C_y^+ - \left(u_1w_2C_2^\phi + u_2w_1C_1^\phi\right)S_y^+ + \left(v_1w_2S_2^\phi + v_2w_1S_1^\phi\right)S_x^+ - \left(v_1v_2 - w_1w_2S_1^\phi S_2^\phi\right)C_x^+\Big]$$

$$B^- = \int \Gamma^-(F_1F_2,t_1t_2)\, dt_1dt_2 = \frac{2s_{12}}{\Gamma^2}\left[\left(u_1u_2 - w_1w_2C_1^\phi C_2^\phi\right)\frac{1}{1-y^2} - \left(v_1v_2 + w_1w_2S_1^\phi S_2^\phi\right)\frac{1}{1-x^2}\right]$$

$$B^+ = \int \Gamma^+(F_1F_2,t_1t_2)\, dt_1dt_2 = \frac{2s_{12}}{\Gamma^2}\Big[\left(u_1u_2 + w_1w_2C_1^\phi C_2^\phi\right)C_y^+\frac{1+y^2}{(1-y^2)^2} - \left(u_1w_2C_2^\phi + u_2w_1C_1^\phi\right)S_y^+\frac{2y}{(1-y^2)^2} + \left(v_1w_2S_2^\phi + v_2w_1S_1^\phi\right)\frac{2x}{(1+x^2)^2} - \left(v_1v_2 - w_1w_2S_1^\phi S_2^\phi\right)\frac{1-x^2}{(1+x^2)^2}\Big]$$

Basic (qualitative) Idea:
What happens if CP is conserved?

- The eigenstates are CP eigenstates

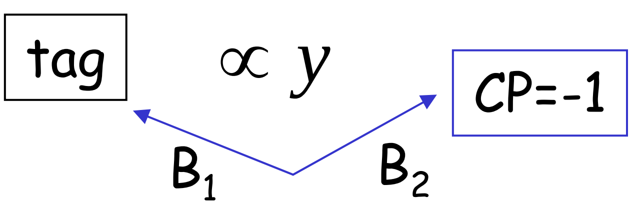
$$\left|B_1\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|B_s\right\rangle + \left|\bar{B}_s\right\rangle\right) \qquad \left|B_2\right\rangle = \tfrac{1}{\sqrt{2}}\left(\left|B_s\right\rangle - \left|\bar{B}_s\right\rangle\right)$$

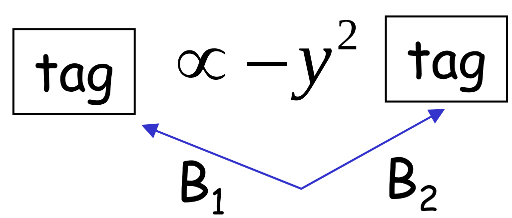
- The decay rate of B_1 and B_2 to taggable states is the same.
- The branching ratio of B_1 to taggable states will therefore be smaller because it has a larger total width.
- Just one catch:
  - there is no easy way to get a pure B_i sample.

e.g. DA and Petrov PRD 71 054032 (2005)

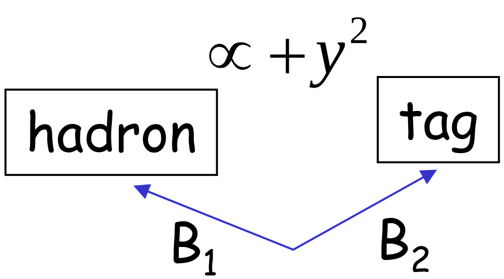
Measuring y
If CP is conserved

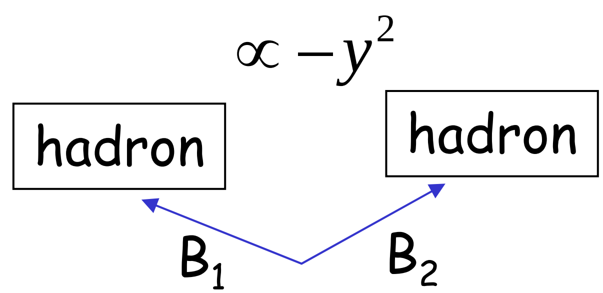
- This leads to a couple of ways to find y at B-factories (e.g. starting from a C=-1 pair):
  - You can find the BR of B_1 to taggable states by correlating with a CP=-1 eigenstate; this in effect gives a sample of B_2 states
  - If you observe one of the mesons decaying to a taggable state, it is more likely to be a B_2.
    - The other meson is thus more likely to be a B_1 and thus less likely to decay itself to taggable states.
    - There will be an effect proportional to y^2.





- By the same argument, B_1 has a larger branching ratio to hadronic states since they account for the width difference.
- Thus tt th and hh correlations will all show effects proportional to y^2.
- The correlation of t or h states with a CP eigenstate will show an effect proportional to y





Correlations of Inclusive States

- Define $$a = \left[\frac{e^+e^- \to B_s^{(*)}\overline{B}_s^{(*)}}{e^+e^- \to b\overline{b}}\right]_{\Upsilon(5s)} \approx 20\%$$

$$B_{5s}(F_1F_2) = \left[\frac{e^+e^- \to F_1F_2}{e^+e^- \to b\overline{b}}\right]_{\Upsilon(5s)}$$

- The correlated branching ratios are

$$B_{5s}(tt) = a\hat{B}_t^2\left[1-(1-2r^*)y^2\right]$$

$$B_{5s}(hh) = a\hat{B}_h^2\left[1-(1-2r^*)\left[\frac{1-\hat{B}_h}{\hat{B}_h}\right]^2 y^2\right]$$

$$B_{5s}(ht) = 2a\hat{B}_h\hat{B}_t\left[1+(1-2r^*)\left[\frac{1-\hat{B}_h}{\hat{B}_h}\right]y^2\right]$$

These are all sensitive to y^2

How Well Can y be measured?

- Assume that
  - B_t=0.3
  - B_h=0.7 (loose cuts) or 0.5 (tight cuts)
  - y=0.1
  - r*=0.1
  - I assume that taggable states are not contaminated by ccss states
  - Likewise all ccss states are designated hadronic
- How many ee→bb events do you need to get a 5σ effect just including statistical errors?
  - tt correlation: $N=21\times10^6$.
  - hh correlation: $N=120\times10^6$ (loose cuts) $N=8\times10^6$ (tight cuts)
  - ht correlation $N=25\times10^6$ (loose cuts) $N=7\times10^6$ (tight cuts)
- Note, the number increases like y^{-4} as y decreases.

Inclusive / Semi-exclusive Correlations

- For a state Y, define

$$P_Y = \frac{w_Y C_Y^{\phi}}{u_Y}$$

$$\hat{P}_Y = \frac{P_Y - y}{1 - yP_Y} = \frac{Br(B_1 \to Y) - Br(B_2 \to Y)}{Br(B_1 \to Y) + Br(B_2 \to Y)}$$

- Measuring this will give us information about $\theta+\phi$,
  - if Y is a single quantum state w=u so $\cos(\theta+\phi)$ is determined by P_Y.

$$B_{5s}(tY) = 2a\hat{B}_t \hat{B}_Y \left[1 + (1-2r^*) y\hat{P}_Y\right]$$

$$B_{5s}(hY) = 2a\hat{B}_h \hat{B}_Y \left[1 - (1-2r^*)\left[\frac{1-\hat{B}_h}{\hat{B}_h}\right] y\hat{P}_Y\right]$$

How Well can P_Y be Measured?

- Consider a final state like Y=DsDs with Br~1%.
- We expect P~1 since this a CP eigenstate.
- If the acceptance is about 10%, in effect the Br is 0.1%
- How many $ee \rightarrow bb$ events do you need to get a 5σ effect?
  - tY correlation $N=33\times10^6$.
  - hY correlation $N=76\times10^6$ (loose cuts); $N=20\times10^6$ (tight cuts)

Problem with This Approach

- For hh, ht and tt correlations, the deviation from the product branching ratios is $O(y^2)$~1%.

- To use this method the input branching ratios, $\hat{B}_h$ and $\hat{B}_t$ must be known to better than 1%

- In the tY and hY correlations the deviations are O(y)~10%

- Likewise the input branching ratios must be known to this precision.

- How do we get around this?

Better yet: Time Asymmetry

- Recall the time dependent rate

$$\Gamma^-(F_1F_2,t_1t_2) = 2s_{12}\, e^{-\Gamma(t_1+t_2)}\Big[\Big(u_1u_2 - w_1w_2C_1^\phi C_2^\phi\Big)C_y^- + \Big(u_1w_2C_2^\phi - u_2w_1C_1^\phi\Big)S_y^- - \Big(v_1w_2S_2^\phi - v_2w_1S_1^\phi\Big)S_x^- - \Big(v_1v_2 + w_1w_2S_1^\phi S_2^\phi\Big)C_x^-\Big]$$

- The colored terms are the only ones anti-symmetric under $t_1 \leftrightarrow t_2$
- Consider the asymmetry

$$A(F_1F_2) = \frac{(F_2 \text{ decays first}) - (F_1 \text{ decays first})}{\text{Total } F_1F_2}$$

- In general this will be sensitive to the red term

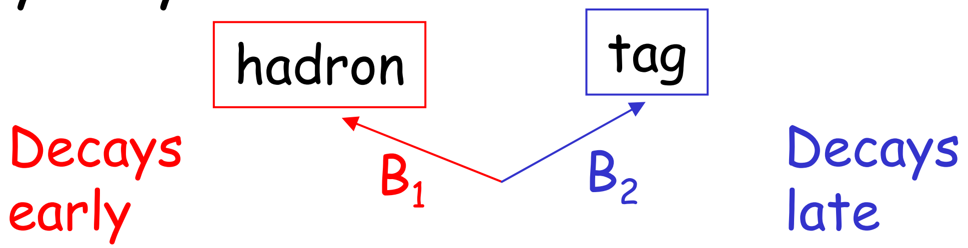
$$A(F_1F_2) = (1-r^*)(\hat{P}_2 - \hat{P}_1)y + O(1/x)$$

Time Asymmetry for ht Correlations

- For the ht correlation

$$A(ht) = (1-r^*)\frac{y^2}{\hat{B}_h} \approx 1.5\%$$

- How many $ee \to bb$ events do you need to get a 5σ effect?
  - A(ht) correlation $N=1.8\times10^6$ (loose cuts)
  - A(ht) correlation $N=1.3\times10^6$ (tight cuts)
- Why do you do so well???



- Further advantage of an asymmetry: <u>null experiment</u>, don't need to subtract another measurement to find the signal

Charge/Time Asymmetry

$$\Gamma^-(F_1F_2,t_1t_2)=2s_{12}\,e^{-\Gamma(t_1+t_2)}\Big[\left(u_1u_2-w_1w_2C_1^\phi C_2^\phi\right)C_y^- + \left(u_1w_2C_2^\phi - u_2w_1C_1^\phi\right)S_y^-$$

$\sim 1/x$

not

$\sim 1/x^2$

$$-\left(v_1w_2S_2^\phi - v_2w_1S_1^\phi\right)S_x^- - \left(v_1v_2 + w_1w_2S_1^\phi S_2^\phi\right)C_x^-\Big]$$

- We can look for the blue term by considering the asymmetry taking into account the sign of the taggable decay.

$$A' = A(ht^+) - A(ht^-) = \frac{(1-r^*)}{\hat{B}_h}\left[\frac{x^2(1-y^2)}{(1+x^2)}\right]\frac{y}{x}\tan(\phi+\theta_h)$$

- For tan=1, A'~0.5%
- This asymmetry therefore gives us tan(phase).

Charge/Time Asymmetry

- How many ee→bb events do you need to get a 5σ effect for A′ (ht) if tan($\phi+\theta$)=1?
  - A′(ht) correlation

    N=7.0x10^6 (loose cuts)   N=6.0x10^6 (tight cuts)

Summary

- At the Upsilon(5s), 90% of the time, B_s pairs are produced in the *C*=-1 correlated state.
- The correlation between the product branching ratio and the correlated branching ratio tells us about mixing
  - Two inclusive states: $|y|$
  - Inclusive/exclusive $y \cos(\phi+\theta)$
- Time taggable/hadronic time asymmetry gives us y^2 and $\tan(\phi+\theta)$.
- This method is better because it is a null experiment
- All this may be done with existing or soon to be acquired data