$B_s^0$ Decays and Leptonic $B$ Decays

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Outline

$B_s^0$ Decays  leftover pieces, assembling...
  - What we want to know about the system, $B_s^0$
  - Decay into specific CP eigenstate: $Br(B_s^0 \rightarrow D_{s(*)}D_{s(*)}^*)$
  - Implications on $B_s^0$, world averages

Leptonic $B$ Decays

- Purely leptonic $B_{d,s}^0 \rightarrow \ell^+\ell^-$
- FCNC decay $B_s^0 \rightarrow \ell^+\ell^+\ell^-$
- Purely leptonic $B_d^0 \rightarrow \ell^+\ell^-$
- Purely leptonic $B^+ \rightarrow \ell^+\ell^-$
$B_s^0$ Decays

Want to probe all the parts of:

\[
i \frac{d}{dt} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i \square}{2} & M_{12} - \frac{i \square_{12}}{2} \\ M_{12}^* - \frac{i \square_{12}^*}{2} & M - \frac{i \square}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}
\]

$|B_H\rangle = p |B_s^0\rangle + q |\bar{B}_s^0\rangle$
Heavier mass eigenstate

$|B_L\rangle = p |B_s^0\rangle - q |\bar{B}_s^0\rangle$
Lighter mass eigenstate

If CP conserved, in mixing

$|B_L\rangle = |B^{\text{CP-even}}\rangle$

$|B_H\rangle = |B^{\text{CP-odd}}\rangle$

$\square m_s = M_H \square M_L \sim 2 |M_{12}|$

$\square_s = \square_L + \square_H \sim 2 |\square_{12}| \cos \square$

$\square \sim 0.3^\circ$ in SM

Talks from
J. Piedra
G. Gomez-Ceballos
Width Difference, $\Delta \Gamma$

- $\Delta \Gamma_{12}$ dominated by decay $b \rightarrow c\bar{c}s$
  from decays into final states common to both $B_s^0 (\bar{b}s)$ and $\bar{B}_s^0 (b\bar{s})$
**Width Difference, \( B_s^0 \)**

- \( B_{12} \) dominated by decay \( b \rightarrow c\bar{c}s \) from decays into final states common to both \( B_s^0 (\bar{b}s) \) and \( \bar{B}_s^0 (b\bar{s}) \)

- \( B_{12s} \): CP-even final states, \( B_{12s} \)↑
- CP-odd final states, \( B_{12s} \)↓

For \( B_d^0 \), analogous diagram
Cabibbo suppressed, \( B_{12} \) negligible

\[
B_s^0 \rightarrow D_s^+ D_s^- \text{ is pure CP even, and under various theoretical assumptions, (Phys. Lett. B316 (1993) 567)}
\]

\[
B_s^0 \rightarrow D_s^{(*)}+D_s^{(*)} \text{ inclusive, also CP even to } \sim 5\%
\]

Likely needs re-examination!!

\[
\frac{\Delta \Gamma_{s}}{\Gamma_s} \sim \frac{2 Br(B_s^0 \rightarrow D_s^{(*)}+D_s^{(*)})}{1 Br(B_s^0 \rightarrow D_s^{(*)}+D_s^{(*)})/2} \quad (\square = 0)
\]

New measurements from CDF, DØ, and Belle
CDF $\text{Br}(B_s^0 \rightarrow D_s^+ D_s^\mp)$

- Branching ratio measured in the decay mode:
  - $B_s^0 \rightarrow D_s^+ D_s^\mp$
  - $\rightarrow K^{+}K^{\mp}$ Hadronic
  - $\rightarrow \square \square^+ (3 \square, K^{*}K)$ Hadronic

- Normalized to:
  - $B_s^0 \rightarrow D_s^+ D_s^\mp$
  - $\rightarrow \square \square^+ (3 \square, K^{*}K)$

- Plus many more channels with similar topology studied in detail with higher statistics (exclusive hadronic, two secondary resonances with 3 tracks each)
CDF Br($B^0_s \rightarrow D^+_s D^0_s$)

- Number signal $23.5 \pm 5.5$ cand.
- Very clean! Negligible backg.
- Use Br($D_s \rightarrow \phi\phi$) from PDG
  (waiting for PDG combo w/ BaBar)

\[
\frac{Br(B^0_s \rightarrow D^+_s D^0_s)}{Br(B^0_s \rightarrow D^+_s D^0_s)} = 1.67 \pm 0.41 \text{ (stat.)} \\
\pm 0.12 \text{ (syst.)} \\
\pm 0.24 (f_s/f_d) \\
\pm 0.39 (Br_\phi)
\]

- First observation of this fully reconstructed decay
- CDF working on its use to extract $\phi\phi$
  (hints for other modes there, good prospects with $1 \text{ fb}^{-1}$)
**DØ Br\( \left( B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)\overline{K}} \right) \)**

- Branching ratio measured in the decay mode:
  - **Semileptonic**: \( B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)\overline{K}} \)
  - **Hadronic**: \( \overline{K}K \)

- Normalized to:
  - **Semileptonic**: \( B_{s}^{0} \rightarrow D_{s}^{(*)} + \overline{K}K \)
  - **Hadronic**: \( \overline{K} \)

- Measure ratio:
  \[
  R = \frac{Br\left( B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)\overline{K}} \right) \cdot Br\left( D_{s} \rightarrow \overline{K}K \right)}{Br\left( B_{s}^{0} \rightarrow \overline{K}K D_{s}^{(*)} \right)}
  \]
  (many systematics cancel in the ratio)

- **Normalized to:**
  - **Semileptonic**: \( B_{s}^{0} \rightarrow D_{s}^{(*)} + \overline{K}K \)
  - **Hadronic**: \( \overline{K}K \)

**Diagram:**

**Mass (πφ)**

- **D**
- **Ds**
- 15.2k

**Events / 12 MeV/c^2**

**DØ Run II Preliminary**

**1 fb^{-1}**

**Then look for additional** \( \overline{K} \)

**Mass and width used as input parameters in following fits**
\[ D\bar{O} \quad Br(B_s^0 \rightarrow D_s^*(\star)+D_s^*(\Box)) \]

- Number found: \( N(\Box\Box D_s) = 19.3 \pm 7.8 \)
- Backgrounds:
  - \( B \rightarrow D_s^*(\star)+D_s^*(\Box) K X \) \( 0.44 \pm 0.30 \)
  - \( B_s^0 \rightarrow D_s^*(\star)+D_s^*(\Box) X \) suppressed
  - \( B_s^0 \rightarrow \Box\Box D_s^{(*)} \Box X \) \( 1.27 \pm 1.14 \)
  - \( c\bar{c} \rightarrow \Box\Box D_s^{(*)} \) lifetime cuts
- Use new \( Br(D_s \rightarrow \Box\Box) \) from BaBar, combined w/ PDG

\[ Br(B_s^0 \rightarrow D_s^*(\star)+D_s^*(\Box)) = \]
\[ = 0.071 \pm 0.032 \text{ (stat)} + 0.029 \text{ (syst)} \]
**Belle Br**\( (B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)}) \)  

- 3 day engineering run in June 2005, collected 1.86 fb\(^{-1}\)  
- (can do \( \sim 1 \) fb\(^{-1}\)/day!)  

Runs at \( \Upsilon (5S) \). Joining the party!

- First look at penguins: 
- \( B_{s} \) concerned:  
  - 2 events, \( \sim 0.14 \) backg.  
  - \( B_{s}^{0} \rightarrow K^{+}K^{-} \)  
  - \( B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)} \)  

- ...and \( Br \) concerned:
  - @ 90% C.L.  
    - \( Br(B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)}) < 7.1\% \)  
    - \( Br(B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)}) < 12.7\% \)  
    - \( Br(B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)}) < 27.3\% \)  

...and with 50 fb\(^{-1}\), expect, e.g.,  
- \( Br(B_{s}^{0} \rightarrow D_{s}^{(*)} + D_{s}^{(*)}) = (12 \pm 3)\% \)
More sensitive to certain new physics models than other penguins (e.g., 4th generation models, $R$-parity violating SUSY)

$Br(B_{s}^0 \rightarrow \gamma \gamma) = (0.5 - 1.0) \times 10^{-6}$

(but new physics can increase it by $\sim$ two orders of magnitude)

Improved limit already! (and for completeness...)

$Br(B_{s}^0 \rightarrow \gamma \gamma) < 0.56 \times 10^{-4}$ @ 90% CL

(c.f. PDG: $< 1.48 \times 10^{-4}$ factor of 3 improvement)
Putting the pieces together...
Separation of CP-even and CP-odd states from angular distributions of $J/\psi$ and $\phi$ decay products; simultaneous fit to lifetimes

(see J. Piedra's talk)

$(17 \pm 4)\%$ CP-odd at time, $t = 0$
(weighted average, CDF & DØ)
• Flavor-specific decays, e.g.,
  \[ B_s^0 \rightarrow D_s^+ K^- \]  \[ B_s^0 \rightarrow D_s^0 K^+ K^- \]

50% CP odd, 50% CP even at time, \( t = 0 \)

• Fit to single exponential,

\[
\sqrt{s}(B_s^0) = \frac{1}{\sqrt{s}} \frac{1 + (\sqrt{s}/2\sqrt{s})^2}{1 \sqrt{s}/2\sqrt{s}}
\]

• \( B_s^0 \rightarrow K^+ K^- \) is CP even (within 5%), hence lifetime measures:

\( \sqrt{L} = \frac{1}{\sqrt{L}} \)

(problems in the penguin decay?)

CDF:
\[
\sqrt{(B_s^0 \rightarrow K^+ K^-)} = 1.53 \pm 0.18 \pm 0.02 \text{ ps}
\]
1-sigma contours $pm \sqrt{\log L} = 0.5$

- Use branching ratio

\[
\frac{2 Br(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-})}{1 - Br(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-})/2}
\]

with additional 5% theory systematic added in quadrature

(caveat! possibly more CP-odd component?)

- Either compare to previous combination (consistency with SM)
- Or assume SM and include in average
1-sigma contours ($\Delta \log L = 0.5$)

- PDG 2004 (LEP) includes ALEPH measurement of $Br(B_s^0 \rightarrow D_s^{(*)+}D_s^{(*)-})$

- Theoretical prediction:
  \[
  \Box_s = 0.10 \pm 0.03 \text{ ps} [1 \left( \frac{f_{B_s}}{260 \text{ MeV}} \right)^2]
  \]


- Unofficial world average
  \[
  \Box_s = 0.097 \pm 0.041 \text{ ps} [1] \quad \Box_s = 0.042 \text{ ps} [1]
  \]
  \[
  \Box_L = \frac{1}{\Box_s} = 1.461 \pm 0.030 \text{ ps}
  \]
  \[
  \Box_H = \frac{1}{\Box_H} = 1.364 \pm 0.047 \text{ ps}
  \]
  \[
  \Box_{HL} = \frac{1}{\Box_{HL}} = 1.573 \pm 0.060 \text{ ps}
  \]
1-sigma contours ($\sqrt{\text{log} L} = 0.5$)

**Theory**

1.1

1.2

1.3

1.4

1.5

1.6

1.7

- PDG 2004 (LEP) includes ALEPH measurement of $Br(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-})$

- Theoretical prediction:
  
  $\mathcal{B}_s = 0.10 \pm 0.03 \text{ ps}^{-1} \left( \frac{f_{B_s}}{260 \text{ MeV}} \right)^2$


- Unofficial world average

  $\mathcal{B}_s = 0.097 \pm 0.041 \pm 0.042 \text{ ps}^{-1}$

  $\mathcal{B} = \frac{1}{\mathcal{B}_s} = 1.461 \pm 0.030 \text{ ps}$

  2.3 from zero,

  $\mathcal{B}_s \sim 2 \mathcal{B}_{12} \cos \theta$

  new physics tends to *reduce* the measured $\mathcal{B}_s$
**Leptonic Decay: $Br(B_d, B_s \to \ell^+\ell^-)$**

- Excellent window into new physics, enhance rates
- Forbidden at tree level, highly helicity suppressed by $(m_\ell/m_B)^2$ in SM

**Muons in "sweet spot"**

Predicted by SM:

- $Br(B_s \to \mu^+\mu^-) = (3.4 \pm 0.5) \times 10^{-9}$
- $Br(B_d \to \mu^+\mu^-)$ suppressed by another factor of $|V_{td}/V_{ts}|^2 \sim 0.04$

- $Br$ grows as $\tan^6\theta$ in the MSSM, as $\tan^4\theta$ in 2HDM models

- Very attractive probe for any new physics with extended Higgs sectors

R-Parity Violating SUSY
Leptonic Decay: $Br(B_d, B_s \rightarrow \ell^+\ell^-)$

Limits now dominated by Tevatron experiments

Backgrounds:
- Drell-Yan $J/\psi$ continuum
- Sequential semileptonic $b \rightarrow c \rightarrow s$
- Double semileptonic $b\bar{b} \rightarrow \ell^+\ell^- X$
- $b/c \rightarrow \ell^+\ell^- X + \text{fake}$
- fake + fake

Discriminating variables:
- Tranverse decay length significance or probability ($B_s$ has lifetime...)
- angle between $\ell\ell$ vector and decay length vector ("pointing consistency")
- Isolation

Both experiments similar variables

CDF
- likelihood ratio
- random grid search

DØ
- Dimuon triggers
- The challenge!
- SM Signal ($10^5$)
- $B_s \rightarrow \ell^+\ell^- \gamma$(1S, 2S, 3S)
Leptonic Decay: $Br(B_d, B_s \rightarrow K^+ \pi^+)$

- Both normalize to $B^+ \rightarrow J/\psi K^+$ (well known, high stats, muon effic. same)

- DØ: mass resolution: can’t separate $B_d$ and $B_s$
  Assume no $B_d$ contribution (conservative)

At 95% CL (Bayesian):

$Br(B_d^0 \rightarrow \pi^+ \pi^-)$

< 3.0 $\times$ 10$^{-8}$  CDF, prel., 780 pb$^{-1}$

Factor $\sim$3 more stringent than next best (BaBar)

$Br(B_s^0 \rightarrow \pi^+ \pi^-)$

< 1.0 $\times$ 10$^{-7}$  CDF, prel., 780 pb$^{-1}$

< 1.5 $\times$ 10$^{-7}$  CDF & DØ, each $\sim$300 pb$^{-1}$

< 2.3 $\times$ 10$^{-7}$  DØ, prel. exp.limit, 700 pb$^{-1}$

< 4.0 $\times$ 10$^{-7}$  DØ, prel., 300 pb$^{-1}$

Only a factor of 30 from SM prediction
e.g., Dermisek et al., hep-ph/0507233
dark matter and S0(10) with soft SUSY breaking,
other experimental constraints

Excluded at 95% CL! (CDF Limit)

Contour of equal $Br(B_s \tau \bar{\tau})$

Allowed by dark matter constraints

Excluded by CDMS II

mSUGRA model, constrain neutralino cross
sections consistent with relic density
FCNC Decay $Br(B_s \to \ell^+ \ell^-)$

- Long term goal: investigate FCNC $b \to s \ell^+ \ell^-$ transitions in $B_s^0$
  (Inclusive $B \to X_s \ell^+ \ell^-$, exclusive $B \to K(\ast)\ell^+ \ell^-$ observed @ B factories, agree with SM)

Predicted in SM:
$Br(B_s \to \ell^+ \ell^-) \sim 1.6 \times 10^{-6}$

- Potential enhancement in various SUSY and 2HDM's

- DØ: search for exclusive mode $B_s^0 \to \ell^+ \ell^-$
  - Similar to DØ $B_s^0 \to \ell^+ \ell^-$ analysis, add and vertex $\ell \to K^+ K^-$
  - Same discrimination variables: decay length significance, pointing angle, isolation; different cut optimization
  - Want non-resonant mode:
**FCNC Decay**  $\text{Br}(B_s \rightarrow J/\Psi \phi')$

- Focus on non-resonant decay, cut out $J/\Psi$ and $\phi'$.
- Normalize to resonant decay:

  Open the box, sidebands for backg.

  - Factor 10 improvement over previous limit
  - ~factor 3 more than SM prediction, should be able to observe before end of Run 2b
**Leptonic Decay: \( Br(B_d \rightarrow \tau^+ \tau^-) \)**

- First ever limit on this channel (hep-ex/0511015)
- Loophole in which theorists gleefully played
- Constrains leptoquark couplings and SUSY \( \tan \beta \) enhancements
- It's tough!
- 2 – 4 missing neutrinos

**Start with 280k fully reconstructed \( B_d^0 \rightarrow D^{(*)} X \)**

- Look for two 1-prong tau decays in rest of the event
- Remove all \( K_S, K_L, \) and \( K^\pm \)'s
- Kinematics of charged daughter momenta and residual energy in calorimeter are fed into a neural network to separate signal from backg.

**Survivors**

\[
\begin{align*}
\text{BaBar} & \quad 263 \pm 19 \text{ events} \\
\text{Expect} & \quad 281 \pm 40
\end{align*}
\]

\[
Br(B_d^0 \rightarrow \tau^+ \tau^-) < 3.4 \times 10^{-3} \text{ @ 90% C.L.}
\]

\[
\text{SM: } Br(B_d^0 \rightarrow \tau^+ \tau^-) = 1.2 \times 10^{-7}
\]
Leptonic Decay: $Br(B^+ \rightarrow \ell^+ \nu_\ell)$

- Proceeds through a $W$-annihilation diagram in the SM, but sensitive to new physics

$$Br(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 (1 - \frac{m_\ell^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

- No new results in $B^+ \rightarrow e^+ \nu_e$, or $B^+ \rightarrow \mu^+ \nu_\mu$ since 2004; excitement in $B^+ \rightarrow \tau^+ \nu_\tau$
Leptonic Decay: $\text{Br}(B^+ \rightarrow \mu^+ \nu)$

- Similar to $B_d^0 \rightarrow \pi^+ \pi^0$, fully reconstruct one $B_d^0$
- In remainder of event, look for 1- or 3-prong tau decays (5 modes), compare properties of event remainder with expected signal and background
- Demand small extra energy in calorimeter:

\[ \text{Verify with double-tag events} \]

\[
\text{Br}(B^+ \rightarrow \pi^+ \nu) = \\
(0.106 \pm 0.034 \pm 0.018)\%
\]

- Belle, hep-ex/0604108

\[
\text{< 2.6 } \times 10^3 \text{ BaBar, hep-ex/0507069} \\
[ = (0.13 \pm 0.10)\% ]
\]

\[
\int f_B |V_{ub}| = (7.73 \pm 1.24 \pm 0.66) \times 10^{14} \text{ GeV}
\]
**Leptonic Decay:** $\text{Br}(B^+ \rightarrow \pi^+ \pi^0)$

- Similar to $B_d^0 \rightarrow \pi^+ \pi^0$, fully reconstruct one $B_d^0$
- In remainder of event, look for 1- or 3-prong tau decays (5 modes), compare properties of event remainder with expected signal and background
- Demand small extra energy in calorimeter:
- Verify with double-tag events

\[
\text{Br}(B^+ \rightarrow \pi^+ \pi^0) =
\]
\[
= (0.106^{+0.034}_{-0.028}^{+0.018})\% \text{ } \text{Belle, hep-ex/0604108}
\]
\[
< 2.6 \times 10^{-4} \text{ } \text{BaBar, hep-ex/0507069}
\]
\[
[ = (0.13^{+0.10}_{-0.09})\% ]
\]
\[
\int_B |V_{ub}| = (7.73^{+1.24}_{-1.02}^{+0.66}_{-0.58}) \times 10^{-4} \text{ GeV}
\]
Leptonic Decay: $Br(B^+ \rightarrow \tau^+ \nu_\tau)$

- **Standard Model:**

- **New Physics (2HDM):**

**First Direct Measurement!**

$$f_B = 0.176 \pm 0.028 \pm 0.020 \text{ GeV}$$

(using HFAG $|V_{ub}|$)
Summary

$B_s^0$ Decays

- Being probed from all sides now: 
  \( Br's, \) lifetimes of CP states, oscillations

- World average 2.4\( \pm 0.030 \text{ ps} \) from zero, consistent with SM

  \[
  \frac{1}{\Delta s} = 0.097 \pm 0.042 \text{ ps}^{-1}
  \]

Leptonic $B$ Decays

- Purely leptonic $B_d^0, B_s^0 \rightarrow \ell^+ \ell^-$
- FCNC decay $B_s^0 \rightarrow \ell^+ \ell^-$

  Best limits from Tevatron, approaching SM, strong constraints on new physics, will improve

- Purely leptonic $B_d^0 \rightarrow \ell^+ \ell^-$

  First ever limit!

- Purely leptonic $B^+ \rightarrow \ell^+ \ell^-$

  First ever evidence!

  First direct measurement of $f_B$!
1-sigma contours ($\Delta \log L = 0.5$)

Theory

Add PDG 2004

LEP

Have come a long way!

Back-up

1/\sigma_s [ps$^{-1}$]

1.6 1.7

1/\sigma_s [ps$^{-1}$]

Flavor-Specific $\Delta \sigma_s (B_s^0)$

DØ $Br(B_s^0 \rightarrow D_s^{(*)} D_s^{(*)})$

Tevatron $B_s^0 \rightarrow J/\psi K^0$ angular

$\Delta (B_d^0)$ World Average

CDF

$B_s^0 \rightarrow K^+ K^0$
\[
\frac{\Delta \Gamma_s}{\Delta m_s} \approx \left| \frac{\Gamma_{12}}{M_{12}} \right| = \mathcal{O} \left( \frac{m_b^2}{M_W^2} \right) \approx 4 \times 10^{-3}
\]

**SM Prediction:**

\[
\frac{\Delta \Gamma_s}{\Delta m_s} = (47 \pm 8) \times 10^{-4}
\]


**Experiment:**

\[
\frac{\Delta \Gamma_s}{\Delta m_s} = \frac{0.097 \pm 0.042 \text{ ps}^{-1}}{17.33^{+0.42}_{-0.21} \pm 0.07 \text{ ps}^{-1}} = (56 \pm 24) \times 10^{-4}
\]