Heavy Flavor Highlights
What is Heavy Flavor Physics?

- Define Heavy Flavor Physics
  - Flavor Physics: Study of interactions that differ among flavors
  - Heavy: Not SM neutrino’s or u or d quarks, maybe s quarks, concentrate here on c & b quarks, t too heavy

u, d, ν’s
  - too light

s, μ
  - maybe

c & b, τ; ν_M’s
  - just right

t
  - too heavy

BF11, Oct. 20, 2011
Physics Beyond the Standard Model

- **Baryogenesis:** From current measurements can only generate \((n_B - \bar{n}_B)/n_\gamma \approx 10^{-20}\) but \(\approx 6 \times 10^{-10}\) is needed. Thus, New Physics must exist to generate needed CP Violation.

- **Dark Matter**

- **Hierarchy Problem:** We don’t understand how we get from the Planck scale of Energy \(\approx 10^{19}\) GeV to the Electroweak Scale \(\approx 100\) GeV without “fine tuning” quantum corrections.
Seeking New Physics

- HFP as a tool for NP discovery
  - While measurements of fundamental constants are fun, the main purpose of HFP is to find and/or define the properties of physics beyond the SM
  - HFP probes large mass scales via virtual quantum loops. An example, of the importance of such loops is extracting the Higgs mass
  - $M_W$ changes due to $m_t$: $\frac{dM_W}{dm_t} \alpha \frac{m_t}{M_W}$
  - $M_W$ changes due to $m_H$: $\frac{dM_W}{dm_H} \alpha - \frac{dm_H}{M_H}$
Flavor as a High Mass Probe

- Already excluded ranges
  - $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{c_i}{\Lambda_i} O_i$, take $c_i = 1$

Ways out
1. New particles have large masses $>> 1$ TeV
2. New particles have degenerate masses
3. Mixing angles in new sector are small, same as in SM (MFV)
4. The above already implies strong constrains on NP

Ex. of Strong Constraints on NP

- Inclusive $b \rightarrow s \gamma$, $(E_\gamma > 1.6$ GeV)
  - Measured $(3.55 \pm 0.26) \times 10^{-4}$ (HFAG)
  - Theory $(3.15 \pm 0.23) \times 10^{-4}$ (NNLL) Misiak arXiv:1010.4896
  - Ratio = $1.13 \pm 0.11$, Limits most NP models
- Example 2HDM
  - $m(H^+) < 316$ GeV

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It is oft said that we have not seen New Physics, yet what we observe is the sum of Standard Model + New Physics. How to set limits on NP?

One hypothesis: assume that tree level diagrams are dominated by SM and loop diagrams could contain NP.
Quark Mixing & CKM Matrix

- In SM charge -1/3 quarks (d, s, b) are mixed
- Described by CKM matrix (also v are mixed)

\[
V(\frac{2}{3}, -\frac{1}{3}) = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

\[
= \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

- \(\lambda=0.225, A=0.8\), constraints on \(\rho\) & \(\eta\)
- These are fundamental constants in SM
What are limits on NP from quark decays?

- Tree diagrams are unlikely to be affected by physics beyond the Standard Model.

Note $\gamma$ is a CP violating angle but is measured via Tree diagrams here – For NP both rare & CPV processes are important.
Absorptive (Imaginary) part of mixing diagram should be sensitive to New Physics. Let's compare...
They are Consistent

- But consistency is only at the 5% level
- Limits on NP are not so strong
Is there NP in $B^0$-$\bar{B}^0$ mixing?

$$\langle B^0 | H_{\Delta B=2}^{\text{SM+NP}} | \bar{B}^0 \rangle = \Delta_{d}^{NP} \langle B^0 | H_{\Delta B=2}^{\text{SM}} | \bar{B}^0 \rangle$$

$$\Delta_{d}^{NP} = \text{Re} \Delta_{d} + i \text{Im} \Delta_{d}$$

Assume NP in tree decays is negligible, so no NP in $|V_{ij}|$, $\gamma$ from $B^- \rightarrow D^0 K^-$

Allow NP in $\Delta m$, weak phases, $A_{SL}$, & $\Delta \Gamma$

Room for new physics, in fact SM is only at 5% c.l.
One Clear Problem

- $B^- \rightarrow \tau^- \nu$, tree process:
- $\sin 2\beta$, CPV in e.g. $B^0 \rightarrow J/\psi K_s$: Box diagram
- Source of most of the CKM discrepancy

Can be new particles instead of $W^-$ but why not also in $D^+_S \rightarrow \ell^+ \nu$?

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An irritating problem: Lingering difference between inclusive \(b \to u \ell \nu\), & exclusive \(B \to \pi \ell \nu\),

Values \(|V_{ub}| \times 10^{-3}\)
- Inclusive: \(4.25 \pm 0.15 \pm 0.20\)
- Exclusive: \(3.25 \pm 0.12 \pm 0.28\)

New

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See Urquijo EPS 2011
Use of Exclusive would increase $\tau \nu \sin 2\beta$ discrepancy, use of Inclusive would not solve the problem
Add new physics: right handed currents with coupling $V_{ub}^R$

- $B \rightarrow \pi \ell \nu$ rate goes as $\left| V_{ub}^L + V_{ub}^R \right|^2$
- $B \rightarrow \tau \nu$ rate goes as $\left| V_{ub}^L - V_{ub}^R \right|^2$
- $B \rightarrow X_u \ell \nu$ rate goes as $\left| V_{ub}^L \right|^2 + \left| V_{ub}^R \right|^2$

Agreement with $\sim 15\%$ rhc

- Can arise in SUSY
- Not in loops
- See Crivellin

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Recent Results

- **NP must** affect every process; the amount tells us what the NP is ("DNA footprint")
- New data from CDF, D0, BaBar BES, BELLE, ATLAS, CMS & LHCb – Not nearly enough time to cover
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Similar to $K^*\gamma$, but more decay paths
- Several variables can be examined, e.g. muon forward-backward asymmetry, $A_{FB}$ is well predicted
- Situation as of July 26

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New $B^o \rightarrow K^{*0} \mu^+ \mu^-$

- New results from CDF 6.8 fb$^{-1}$ & LHCb 0.3 fb$^{-1}$

No evidence of deviation from SM so far
**b Fractions (LHCb)**

- Important to set normalization scale for $B_s$
- $f_s/f_d$ using hadronic decays

\[ B_d \rightarrow D^- K^+ / B_s \rightarrow D_s^- \pi^+, \text{ and } B_d \rightarrow D^- \pi^+ / B_s \rightarrow D_s^- \pi^+ \]

\[ N_{\text{sig}} = 253 \pm 21 \]

\[ f_s / f_d = 0.253 \pm 0.017 \pm 0.017 \pm 0.020 \]

**Using Semileptonics:**

$$b \rightarrow (D^0, D^+, D_s, \Lambda_b) \chi_{\mu\nu}$$

- $D^+ + \mu^-$ signal
- Bkgrd Prompt
- $f_s / f_d = 0.268 \pm 0.008^{+0.022}_{-0.020}$
- independent of $\eta$ & $p_t$

\[ f_s / f_d = 0.253 \pm 0.017 \pm 0.017 \pm 0.020 \]

**Theory error**
$\text{SM branching ratio is } (3.2\pm0.2)\times10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

- Many NP models possible, not just Super-Sym
Discrimination

- Select same topology as $B \to h^+ h^-$, add $\mu$ ID
- Lots of other variables to discriminate against bkgrd: B impact parameter, B lifetime, $B p_t$, B isolation, muon isolation, minimum impact parameter of muons, muon polarization...
- Can use $B \to h^+ h^-$ to tune cuts or form a multivariate analysis, used by CDF & LHCb
Set a “two sided limit @ 90% CL”

This means to me that there isn’t a statistically significant result

Example:

\[ B(B_s \rightarrow \mu^+\mu^-) = (1.8^{+1.1}_{-0.9}) \times 10^{-8} \]

5.6 x SM expectation

p value for bkgrnd + SM is 2.9%
### LHCb

**Combinatorial background**

- B→hh misid background
- 0.1 ± 0.1 events in each of 4 BDT bins

### Table:

<table>
<thead>
<tr>
<th></th>
<th>BDT&lt;1/4</th>
<th>1/4&lt;BDT&lt;1/2</th>
<th>1/2&lt;BDT&lt;3/4</th>
<th>3/4&lt;BDT&lt;1</th>
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<tbody>
<tr>
<td># expected bkgrd</td>
<td>2968±69</td>
<td>25.0±2.5</td>
<td>2.99±0.89</td>
<td>0.66±0.40</td>
</tr>
<tr>
<td># expected signal</td>
<td>1.26±0.13</td>
<td>0.61±0.06</td>
<td>0.67±0.07</td>
<td>0.72±0.07</td>
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<tr>
<td>Sum expected</td>
<td>2969±69</td>
<td>25.6±2.5</td>
<td>3.66±0.89</td>
<td>1.38±0.41</td>
</tr>
<tr>
<td>Observed</td>
<td>2872</td>
<td>26</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

**Signal with SM BR**

LHCb preliminary 300 pb⁻¹
LHCb does not observe any excess

In the two BDT signal bins expect 5.1 events if $B$ is at SM level, see 5

- Expected limit @95% (90%) $1.5(1.2)\times10^{-8}$
- Observed limit @95% (90%) $1.6(1.3)\times10^{-8}$
- $p$-value of bkgrnd only hypothesis $14\%$
- Observed limit with 2010 data $1.5(1.2)\times10^{-8}$
Cut based analysis

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<th></th>
<th>Barrel</th>
<th>Endcap</th>
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<tbody>
<tr>
<td># expected bkgrd</td>
<td>0.60±0.35</td>
<td>0.80±0.40</td>
</tr>
<tr>
<td># bkgrd B→h⁺h⁻</td>
<td>0.07±0.02</td>
<td>0.04±0.01</td>
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<tr>
<td># expected signal</td>
<td>0.80±0.16</td>
<td>0.36±0.07</td>
</tr>
<tr>
<td>Sum expected</td>
<td>1.47±0.39</td>
<td>1.20±0.41</td>
</tr>
<tr>
<td>Observed</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Upper limits:
- 1.9x10⁻⁸ @95% CL
- 1.6x10⁻⁸ @90% CL
LHC Combined

- Observed limits
  - $1.1 \times 10^{-8}$ @95% CL
  - $0.9 \times 10^{-8}$ @90% CL,
  - This is 3.4(2.8) times SM value
- LHC consistent with CDF with a probability of 0.3%
- Set serious limits in NUHM1 SUSY model
- Still lots of room for NP

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Neutral Meson Mixing

- Neutral mesons can transform into their anti-particles via 2nd order weak interactions
- Short distance transition rate depends on
  - mass of intermediate $q_i$, the heavier the better, favors s & b since t is allowed, while for c, b is the heaviest
  - CKM elements $V_{ij}$

New particles possible in loop

$D^0 \rightarrow \pi\pi,.. \rightarrow \bar{D}^0$ + “long distance” for $D^0$

Is this zero? from Van Kooten

Is this zero?

Prob[$D^0$]($t$)

Prob[$B^0_{cd}$]($t$)

Prob[$B^0_{s}$]($t$)

Prob[$\bar{B}^0_{s}$]($t$)
Some Definitions

- Weak interaction eigenstates are different than strong interaction eigenstates
  \[ |M_L\rangle = p|M^o\rangle + q|\bar{M}^o\rangle, \quad |M_H\rangle = p|M^o\rangle - q|\bar{M}^o\rangle, \]
- Since we observe the mesons via their weak decays, \( m = (M_H + M_L)/2, \quad \Delta M = M_H - M_L, \)
  \[ 1/\tau = \Gamma = (\Gamma_H + \Gamma_L)/2, \quad \Delta \Gamma = \Gamma_L - \Gamma_H, \]
- Useful quantities are \( x = \Delta M/\Gamma, \quad y = \Delta \Gamma/2\Gamma \)
- \( D^o \) mixing predictions (from Petrov 2006):

[Graph showing mixing predictions for Standard Model and New Physics]
Do^0 Mixing

- Data from BaBar, Belle, CDF, CLEO
- Result 10.1σ from no mixing, though no single measurement is better than 5σ
- Non-zero value allows for indirect CPV, as well as direct CPV in decay, or a mixture of the two

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CPV in Charm

- Expect largest effects in Cabibbo Suppressed Decays. COULD REVEAL NP (see Grossman Kagan & Nir)
- Nothing yet observed, limits at <1% level
- Experiments, in some cases, now measuring differences in CP asymmetries to cancel systematic effects
- Examples (define $A(D \rightarrow f) = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}$ ) if $f = \bar{f}$, CP eigenst

  - Belle $A(D^+\rightarrow\phi\pi^+)-A(D_s^+\rightarrow\phi\pi^+) = (-0.51\pm0.28\pm0.05)\%$ [arXiv: 1110.0694]
  - CDF $A(D^0\rightarrow\pi^+\pi^-) = (-0.22\pm0.24\pm0.11)\%$ & $A(D^o\rightarrow K^+K^-) = (-0.24\pm0.22\pm0.10)\%$ [CDF Public Note 10269]
  - BaBar using T-odd triple products in $D^+\rightarrow K^+K_S\pi^+\pi^-$ finds $A_T = (-1.21\pm1.00\pm0.46)\%$ [arXiv:1105.4410v2]
CPV Time Evolution

- Consider

$$a[f(t)] = \frac{\Gamma(\overline{M} \to f) - \Gamma(M \to f)}{\Gamma(\overline{M} \to f) + \Gamma(M \to f)}$$

- Define

$$A_f \equiv A(M \to f), \quad \bar{A}_f \equiv A(\overline{M} \to f), \quad \lambda_f = \frac{p}{q} \frac{A_f}{A_f}$$

- Only 1 \(A_f\) & \(\Delta \Gamma = 0\)

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t} \left(1 - \text{Im} \lambda_f \sin(\Delta M t)\right)$$

- Then

$$a[f(t)] = -\text{Im} \lambda_f , \quad \& \lambda_f \text{ is a function of } V_{ij} \text{ in SM}$$

- For \(B^o, \Delta \Gamma \approx 0\), but there can be multiple \(A_f\)

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t} \left(1 - \left|\frac{\lambda_f}{2}\right|^2 \cos(\Delta M t) - \text{Im} \lambda_f \sin(\Delta M t)\right)$$

- If in addition \(\Delta \Gamma \neq 0\), eg. \(B_s\)

$$\Gamma(M \to f) = N_f |A_f|^2 e^{-\Gamma t} \left(\frac{1 + |\lambda_f|^2}{2} \cosh \frac{\Delta \Gamma t}{2} + \frac{1 - |\lambda_f|^2}{2} \cos(\Delta M t) - \text{Re} \lambda_f \sinh \frac{\Delta \Gamma t}{2} - \text{Im} \lambda_f \sin(\Delta M t)\right)$$

See Nierste
CPV in $B_s \rightarrow J/\psi X$

- Interference between mixing & decay
- For $f = J/\psi \phi$ or $J/\psi f_0$
  $$\bar{B}_s^0 \{ \begin{array}{c} \bar{s} \\ \bar{b} \end{array} \} \xrightarrow{W} J/\psi \{ \begin{array}{c} c \\ \bar{c} \end{array} \}$$
  $$\pi^+ \pi^- \text{ or } K^+ K^-$$

- Small CPV expected, good place for NP to appear
- $B_s \rightarrow J/\psi \phi$ is not a CP eigenstate, as it’s a vector-vector final state, so must do an angular analysis to separate the CP+ and CP- components

$$\phi_s^{SM} \equiv -2\beta_s = -2 \arg \left( -\frac{V_{ts} V_{sb}^*}{V_{cs} V_{cb}^*} \right) = -0.04 \text{ rad}$$
\[
\frac{d^4 \Gamma(B_s^0 \to J/\psi \phi)}{dt \ d \cos \theta \ d \varphi \ d \cos \psi} \equiv \frac{d^4 \Gamma}{dt \ d \Omega} \propto \sum_{k=1}^{10} h_k(t) f_k(\Omega)
\]

<table>
<thead>
<tr>
<th>(k)</th>
<th>(h_k(t))</th>
<th>(f_k(\theta, \psi, \varphi))</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>(</td>
<td>A_0</td>
</tr>
<tr>
<td>2</td>
<td>(</td>
<td>A_\parallel(t)</td>
</tr>
<tr>
<td>3</td>
<td>(</td>
<td>A_\perp(t)</td>
</tr>
<tr>
<td>4</td>
<td>(\Im(A_\parallel(t) A_\perp(t)))</td>
<td>(-\sin^2 \psi \sin 2\theta \sin \phi)</td>
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<tr>
<td>5</td>
<td>(\Re(A_0(t) A_\parallel(t)))</td>
<td>(\frac{1}{2} \sqrt{2} \sin 2\psi \sin^2 \theta \sin 2\phi)</td>
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<tr>
<td>6</td>
<td>(\Im(A_0(t) A_\perp(t)))</td>
<td>(\frac{1}{2} \sqrt{2} \sin 2\psi \sin 2\theta \cos \phi)</td>
</tr>
<tr>
<td>7</td>
<td>(</td>
<td>A_s(t)</td>
</tr>
<tr>
<td>8</td>
<td>(\Re(A_s^*(t) A_\parallel(t)))</td>
<td>(\frac{1}{3} \sqrt{6} \sin \psi \sin^2 \theta \sin 2\phi)</td>
</tr>
<tr>
<td>9</td>
<td>(\Im(A_s^*(t) A_\perp(t)))</td>
<td>(\frac{1}{3} \sqrt{6} \sin \psi \sin 2\theta \cos \phi)</td>
</tr>
<tr>
<td>10</td>
<td>(\Re(A_s^*(t) A_0(t)))</td>
<td>(\frac{4}{3} \sqrt{3} \cos \psi (1 - \sin^2 \theta \cos^2 \phi))</td>
</tr>
</tbody>
</table>

for S-wave under \(\phi\) predicted by Stone & Zhang PRD 79, 074024 (2009)
\[ |A_0|^2(t) = |A_0|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin(\Delta m t) \right], \]

\[ |A_\parallel(t)|^2 = |A_\parallel|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin(\Delta m t) \right], \]

\[ |A_\perp(t)|^2 = |A_\perp|^2 e^{-\Gamma_s t} \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) + \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin \phi_s \sin(\Delta m t) \right], \]

\[ \Im(A_\parallel^*(t) A_\perp(t)) = |A_\parallel||A_\perp| e^{-\Gamma_s t} \left[ -\cos(\delta_\perp - \delta_\parallel) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \cos(\delta_\perp - \delta_\parallel) \cos \phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_\parallel) \cos(\Delta m t) \right], \]

\[ \Re(A_0^*(t) A_\parallel(t)) = |A_0||A_\parallel| e^{-\Gamma_s t} \cos(\delta_\parallel - \delta_0) \left[ \cosh \left( \frac{\Delta \Gamma}{2} t \right) - \cos \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) + \sin \phi_s \sin(\Delta m t) \right], \]

\[ \Im(A_0^*(t) A_\perp(t)) = |A_0||A_\perp| e^{-\Gamma_s t} \left[ -\cos(\delta_\perp - \delta_0) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \cos(\delta_\perp - \delta_0) \cos \phi_s \sin(\Delta m t) + \sin(\delta_\perp - \delta_0) \cos(\Delta m t) \right], \]

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\[ \Re(A_s^*(t) A_0(t)) = |A_s||A_0| e^{-\Gamma_s t} \left[ -\sin(\delta_0 - \delta_s) \sin \phi_s \sinh \left( \frac{\Delta \Gamma}{2} t \right) - \sin(\delta_0 - \delta_s) \cos \phi_s \sin(\Delta m t) + \cos(\delta_0 - \delta_s) \cos(\Delta m t) \right]. \]
ΔM_s

CDF 1 fb^{-1} (2006)
17.77±0.10±0.07 ps^{-1}

LHCb 0.34 fb^{-1} (2011)
17.725±0.041±0.026 ps^{-1}

Used to calibrate the flavor tagging
CPV in $B_s \rightarrow J/\psi \phi$

- Correlated constraints on $\Delta \Gamma_s$ versus CP violating phase $\phi_s$
- Ambiguous solution for $\Delta \Gamma_s \rightarrow -\Delta \Gamma_s$, $\phi_s \rightarrow \pi - \phi_s$.

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New LHCb $\phi_s$ result

$\Gamma = 0.656 \pm 0.009 \pm 0.008 \text{ (ps}^{-1})$

$\Delta \Gamma = 0.123 \pm 0.029 \pm 0.011 \text{ (ps}^{-1})$

$\phi_s = 0.13 \pm 0.18 \pm 0.07 \text{ (rad)}$

All measurements consistent with SM value
1st Observation of $B_s \rightarrow J/\psi f_0(980)$

- In $B_s \rightarrow J/\psi \phi$ the S-wave predicted (& now observed) under the $\phi$ could manifest itself as a $0^+ \pi^+\pi^-$ system, the $f_0(980)$ [Stone & Zhang PRD 79, 074024 (2009)].

As a CP eigenstate can be used to measure $\phi_s$ without angular analysis

$m(J/\psi \pi^+\pi^-)$ within 90 MeV of 980 MeV

$m(\pi^+\pi^-)$ within 30 MeV of $B_s$ mass

\[
\frac{\Gamma(J/\psi f_0; f_0 \rightarrow \pi^+\pi^-)}{\Gamma(J/\psi \phi; \phi \rightarrow K^+K^-)} \approx 0.25
\]
Confirmations

- Belle, CDF & D0
- CDF measures $\tau$ also, ignoring CP violation, in this CP odd eigenstate. $\langle \tau_{B_s}\rangle = 1.43 \pm 0.04 \text{ ps}$ (PDG)

$$
\tau_{J/\psi f_0} = 1.70_{-0.11}^{+0.12} \pm 0.03 \text{ ps}
$$
CPV in $B_s \rightarrow J/\psi f_0$

- $\phi_s = -0.44 \pm 0.44 \pm 0.02$ rad
- Combined with $J/\psi \phi$, $\phi_s = 0.03 \pm 0.16 \pm 0.07$ rad
1st Observation of $B_s \rightarrow J/\psi f'_2(1525)$

- $B_s \rightarrow J/\psi K^+K^-$

$$R_{\text{effective}}^{f'_2} \equiv \frac{\mathcal{B}(B_s^0 \rightarrow J/\psi f'_2(1525), f'_2(1525) \rightarrow K^+K^-)}{\mathcal{B}(B_s^0 \rightarrow J/\psi \phi, \phi \rightarrow K^+K^-)} = (19.4 \pm 1.8 \pm 1.1)\%$$

for $|m(K^+K^-) - 1525\text{ MeV}| < 125\text{ MeV}$. 

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CKM $B_s$ Fit

- Now even better consistency with SM than $B_d$
- However, much more room for NP than in $B_d$ system due to less precise measurements
By definition \(|q/p| = 1 - a_{sl}\)

\[
a_{sl} = \frac{\Gamma(\bar{M} \rightarrow f) - \Gamma(M \rightarrow \bar{f})}{\Gamma(\bar{M} \rightarrow f) + \Gamma(M \rightarrow \bar{f})}
\]

Here \(f\) is by construction flavor specific, \(f \neq \bar{f}\)

Can measure eg. \(\bar{B}_s \rightarrow D_s^+ \mu^- \nu\), versus \(B_s \rightarrow D_s^- \mu^+ \nu\),

Or can consider that muons from two B decays can be like-sign when one mixes and the other decays, so look at \(\mu^+ \mu^+\) vs \(\mu^- \mu^-\)

\(a_{sl}\) is expected to be very small in the SM, 
\(a_{sl} = (\Delta \Gamma / \Delta M) \tan \phi\), for \(B^o - 7.6 \times 10^{-4}\) for \(B_s + 3.4 \times 10^{-5}\)

arXiv:1008.1593 [hep-ph]
Using dimuons

\[ A_{sl}^b = (-0.787 \pm 0.172 \pm 0.093)\% \]

3.9\(\sigma\) from zero
\[ a_{sI}^s = (\Delta \Gamma / \Delta M) \tan \phi_s \]

Assume all asymmetry is due to \( B_s \)

\[ a_{sI}^s = (-0.787 \pm 0.196)\% \]
Several ways of looking for presence of heavy $\nu$’s (N) in heavy quark decays if they are Majorana (their own anti-particles) and couple to “ordinary” $\nu$’s

Analogous to $\nu$-less nuclear $\beta$ decay

$\ell$ & $\ell'$ can be e, $\mu$ or $\tau$
Current Searches

- Belle $B^- \rightarrow D^- \ell \ell'$
- Found upper limits, $ee$ mode not competitive with nuclear $\beta$ decay, others unique

<table>
<thead>
<tr>
<th>Mode</th>
<th>U.L. $[10^{-6}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow D^- e^+ e^+$</td>
<td>$&lt; 2.6$</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^- e^+ \mu^+$</td>
<td>$&lt; 1.8$</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^- \mu^+ \mu^+$</td>
<td>$&lt; 1.0$</td>
</tr>
</tbody>
</table>

LHCb $B^- \rightarrow \pi^+ \mu^- \mu^-$, u.l $< 4.5 \times 10^{-8}$
See A. Atre, T. Han, S. Pascoli, & B. Zhang
[arXiv:0901.3589]
Searches at higher masses

- CDF general search for like-sign dileptons [A. Abulencia et. al, Phys. Rev. Lett. 98, 221803 (2007)]
- CMS search for events with two isolated like-sign leptons, hadronic jets & missing $E_T$ [arXiv:1104.3168]
- ATLAS [arXiv:1108.0366]
- If seen could also be interpreted in terms of other NP, ie. supersymmetry...
New Exotic States

- Belle discovery of $Z_b(10610)$ and $Z_b(10650)$
- $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ Dalitz plots. See $\Upsilon(nS)\pi^\pm$ states
- Also seen in $h_b(1P)\pi^\pm$ & $h_b(2P)\pi^\pm$ decays arXiv:1105.4583

\[ \Upsilon(1S) \quad \Upsilon(2S) \quad \Upsilon(3S) \]
Lepton Flavor Violation

- $\mu \rightarrow e \gamma$ MEG data 2009 results (Mori EPS2011)

- Data 2010 Results

- Many limits on $\tau \rightarrow \ell hh$, $\Lambda h$, $\bar{\Lambda} h$, $\mu \gamma$, $\mu h$, $3\mu$, best limits near $10^{-8}$ (Belle, BaBar)

Note 2-sided limit

Combined $B < 2.4 \times 10^{-12}$
Future Acts

- LHCb Upgrade: run at $10^{33}$ cm$^{-2}$/s (x5), & double trigger efficiency on purely hadronic final states
- Super B factories
- Time scales are on the order of 6 years
- BES III, LHCb are happening now

$pseudovector\,420\,pb^{-1}$

$B_{c}^{+}\rightarrow J/\psi\pi^{+}\pi^{-}\pi^{+}$

58.2±9.6 events

$LHCb\,Preliminary\,0.3\,fb^{-1}$

First observation
Conclusions

- Heavy Flavor physics is now very sensitive to potential New Physics effects at high mass scales
- LHC experiments have shown their ability by already making world class 1\textsuperscript{st} measurements of flavor physics. They are ready!
- Heavy Flavor experiments are ready to search for and limit New Physics, especially in rare and CP violating $b$ & $c$ decays at the LHC with the 2011 data and beyond
- Many other interesting flavor results have not been mentioned – apologies
The End
Separate into $B_d$ and $B_s$ samples using impact parameter of muons.

Find

$$a_{s\ell}^d = (-0.12 \pm 0.52)\%,$$

$$a_{s\ell}^s = (-1.81 \pm 1.06)\%.$$
New b-Baryon Decays

CDF $\Xi_b^+$
1st observation
mass $5787.8\pm5.0$ MeV

CDF Run II Preliminary $L=6.8\text{fb}^{-1}$
Yield: $24\pm5$
Mass: $5621\pm6$ MeV/c$^2$

$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$

Data
Total Fit
Signal
Background

$\sim6\sigma$

$\Lambda_b \rightarrow D^0 p K$ observed for first time with significance of $6.3\sigma$

$B(\Lambda_b^0 \rightarrow D^0 p K^-) / B(\Lambda_b^0 \rightarrow D^0 p \pi^-) = 0.112 \pm 0.019^{+0.011}_{-0.014}$
In $B^- \rightarrow J/\psi \phi K^-$ decays, CDF reported a narrow structure in $m(J/\psi \phi)$ mass [arXiv:1101.6058].

No signal evident in LHCb data.
Exp: $\mathcal{B}(B_s \to \mu^+\mu^-)$ in NUHM1

- CMS discovery contours for $H, A \to \tau^+\tau^- \to$ jets (solid line), jet + $\mu$ (dashed), jet + $e$ (dotted) using 30-60 fb$^{-1}$

- (From O. Buchmueller et al., arXiv:0907.5568)

BF11, Oct. 20, 2011
In fact correlation between $B_d$ & $B_s$ $\mu^+\mu^-$ could be crucial.

This can only be done with the LHCb Upgrade.
CMS Preliminary, $\sqrt{s}=7$ TeV

Events / (18 MeV)

$pp \rightarrow B^+ X$
$P_T > 5$ GeV, $|y| < 2.4$

$28.3 \pm 2.4 \pm 2.0 \pm 1.1 \mu$b
(6 pb$^{-1}$)

$pp \rightarrow B^0 X$
$P_T > 5$ GeV, $|y| < 2.2$

$33.2 \pm 2.5 \pm 3.1 \pm 1.3 \mu$b
(40 pb$^{-1}$)

$pp \rightarrow B_s X \rightarrow J/\psi \phi X$
$8 < P_T < 50$ GeV, $|y| < 2.4$ (x1000)

$6.9 \pm 0.6 \pm 0.5 \pm 0.3$ nb
(40 pb$^{-1}$)

Theory: MC@NLO
CTEQ6M PDFs, $m_{B_s}=4.75$ GeV
Also $D^+$, $D_s$, $\Lambda_b$

$D^+ \rightarrow K^- \pi^+ \pi^+$

$D_{s} \rightarrow K^+ K^- \pi^+$

$D_{s}$

$D_{fb}$: $9406 \pm 110$

$D_{fb}$: $2446 \pm 60$
Extract $B_s$ fractions

- Crucial to set absolute scale for $B_s$ rates, since not given by $e^+e^-$ machines.
- Must correct for $B_s \rightarrow D^0K^+X\mu\nu$, also
  $\Lambda_b \rightarrow D^0pX\mu\nu$

\[
\frac{f_s}{f_u + f_d} = 0.136 \pm 0.004^{+0.012}_{-0.011}
\]

\[\sqrt{s} = 7 \text{ TeV} \]
LHCb Preliminary $\sim 3 \text{ pb}^{-1}$
B_s fraction - hadronic

- Also can use hadronic decays + theory ~35 pb^{-1}

\[ \sqrt{s} = 7 \text{ TeV} \]
LHCb Preliminary

Semileptonics: \( f_s / f_d = 0.272 \pm 0.008^{+0.024}_{-0.022} \)
**Λ_b Fraction**

- Significant $p_t$ dependence

\[ \sqrt{s} = 7 \text{ TeV} \]
LHCb Preliminary \( \sim 3 \text{ pb}^{-1} \)

\[
\frac{f_{\Lambda_b}}{f_u + f_d} \text{ in } \eta [2,3] = 0.401 \pm 0.019 \pm 0.106 - (0.012 \pm 0.0025 \pm 0.0012) \times p_t (\text{GeV})
\]

- In general agreement with CDF measured at \( <p_t> \sim 10 \text{ GeV/c} \)

\[
\frac{f_{\Lambda_b}}{f_u + f_d} = 0.281 \pm 0.012^{+0.011+0.128}_{-0.056-0.086}
\]

BF11, Oct. 20, 2011
\( \sigma(pp \to b\bar{b}X) \) using 15 nb\(^{-1} \)

- \( b \to D^0X\mu^-\nu \), \( D^0 \to K^-\pi^+ \), ~280 events

\[ \sigma = \frac{\text{# of detected } D^0\mu^- \& \bar{D}^0\mu^+}{L \times \text{efficiency} \times 2} \]

- In \( 2<\eta<6 \), \( (75.3\pm5.4\pm13.0) \) \( \mu b \) LEP frag \( \Rightarrow 284\pm20\pm49 \) \( \mu b \)
- In \( 2<\eta<6 \), \( 89.6 \) \( \mu b \) Tevatron frag \( \Rightarrow 338\pm24\pm58 \) \( \mu b \)
- Also measured charm cross-section, ~20x \( b \)

BF11, Oct. 20, 2011
Here use 5.2 pb^{-1}

\( \sigma = 288 \pm 4 \pm 48 \mu b \)
ATLAS $\sigma$ from $b \rightarrow J/\psi X$

- ATLAS also in agreement with FONLL for $p_t > 5$ GeV/c

BF11, Oct. 20, 2011
CMS $\sigma$ from $b \rightarrow X\mu\nu$

- In all cases generally good agreement with NLO calculations, within large errors
In general with $A_f \equiv A(M \rightarrow f)$, $\bar{A}_f \equiv A(\bar{M} \rightarrow f)$, $\lambda_f = \frac{p \bar{A}_f}{q A_f}$

$$\Gamma(M(t) \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left\{ \frac{1+|\lambda_f|^2}{2} \cosh \frac{\Delta \Gamma t}{2} + \frac{1-|\lambda_f|^2}{2} \cos(\Delta M t) \right\} ,$$

For $B^0$, $\Delta \Gamma \approx 0$

$$\Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left( \frac{1}{2} (1-|\lambda_f|) \cos(\Delta M t) - \text{Im} \lambda_f \sin(\Delta M t) \right)$$

if only 1 $A_f$

$$\Gamma(M \rightarrow f) = N_f |A_f|^2 e^{-\Gamma t} \left( 1 - \text{Im} \lambda_f \sin(\Delta M t) \right)$$

and a CP eigenstates

$$a[f_{CP}(t)] = \frac{\Gamma(\bar{M} \rightarrow f_{CP}) - \Gamma(M \rightarrow f_{CP})}{\Gamma(\bar{M} \rightarrow f_{CP}) + \Gamma(M \rightarrow f_{CP})} = -2 \text{Im} \lambda_f$$

$\lambda_f$ a function of $V_{ij}$ in SM & thus to $\alpha, \beta$ or $\gamma$