Heavy Flavor Physics
What is it?

- 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

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<table>
<thead>
<tr>
<th>u, d, ν’s</th>
<th>s, μ</th>
<th>c &amp; b, τ; ν_M’s</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>too light</td>
<td>maybe</td>
<td>just right</td>
<td>too heavy</td>
</tr>
</tbody>
</table>
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DPF, Aug. 13, 2011
Physics Beyond the Standard Model

- Baryogenesis: From current measurements can only generate $(n_B-n_{\bar{B}})/n_\gamma = \sim 10^{-20}$ but $\sim 6 \times 10^{-10}$ is needed. Thus New Physics must exist.

- Dark Matter

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

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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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Limits on New Physics

- 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 ν are mixed)

$$V_{(2-1/3)} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}$$

$$V = \begin{pmatrix}
1 - \lambda^2 / 2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2 / 2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)$$

- λ=0.225, A=0.8, constraints on ρ & η
- These are fundamental constants in SM

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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 a Tree diagram – For NP both rare & CPV processes are important.
Absorptive (Imaginary) of mixing diagram should be sensitive to New Physics. Let's compare.
They are Consistent

- But consistency is only at the 5% level
- Same for $B_s$ – CP violation in $J/\psi \phi$ (not including D0 $A_{sl}$) $\Rightarrow$ limits on NP are not so strong
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 $b \rightarrow u \ell \nu$, & exclusive $B \rightarrow \pi \ell \nu$,

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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Use of Exclusive would increase $\tau \nu \sin 2\beta$ discrepancy, use of Inclusive would not solve the problem
A $V_{ub}$ fix?

- 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 Crivellian
New 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

+ New particles in loops

- 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 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.

$$B_d \rightarrow D^- K^+/B_s \rightarrow D_s^- \pi^+, \quad \& \quad B_d \rightarrow D^- \pi^+/B_s \rightarrow D_s^- \pi^+$$

- Using Semileptonics: $b \rightarrow (D^0, D^+, D_s, \Lambda_b) \chi \mu \nu$

$$f_s/f_d = 0.268 \pm 0.008^{+0.022}_{-0.020}$$

独立于 $\eta$ & $p_t$.

$$f_s/f_d = 0.267^{+0.021}_{-0.020}$$

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LHCb-CONF-2011-028
$B_s \rightarrow \mu^+ \mu^-$

- SM branching ratio is $(3.2\pm0.2) \times 10^{-9}$ [Buras arXiv: 1012.1447], NP can make large contributions.

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

- Select same topology as $B \rightarrow h^+ h^-$, 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 $B \rightarrow h^+ h^-$ to tune cuts or form a multivariate analysis, used by CDF & LHCb
Set a “two sided limit @ 90% CL”  
4.6 \times 10^{-9} < B(B_s^0 \rightarrow \mu^+ \mu^-) < 3.9 \times 10^{-8}

This means to me that there isn’t a statistically significant result
Table 1: Expected numbers of background and signal events

<table>
<thead>
<tr>
<th></th>
<th>BDT&lt;1/4</th>
<th>1/4&lt;BDT&lt;1/2</th>
<th>½&lt;BDT&lt;3/4</th>
<th>¾&lt;BDT&lt;1</th>
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</thead>
<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>
</tr>
<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>

LHCb preliminary, 300 pb⁻¹
LHCb

- LHCb does not observe any excess
- In the two BDT signal bins expect 5.1 events if $\mathcal{B}$ is at SM level, see 5
- Expected limit @95% (90%) $1.5(1.2) \times 10^{-8}$
- Observed limit @95% (90%) $1.6(1.3) \times 10^{-8}$
- $p$-value of background only hypothesis $14\%$
- Observed limit with 2010 data $1.5(1.2) \times 10^{-8}$

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Cut based analysis

<table>
<thead>
<tr>
<th># expected bkgrd</th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td></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>
</tr>
<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

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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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1st Observation of $B_s \rightarrow J/\psi f_0(980)$

- In $B_s \rightarrow J/\psi \phi$ there is the possibility of an S-wave contamination under the $\phi$. If this existed it could manifest itself as a $0^+ \pi^+\pi^-$ system. [Stone & Zhang PRD 79, 074024 (2009)]. As a CP eigenstate could be used to measure $\phi_s$ without angular analysis.

- Found by LHCb. 

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

$m(J/\psi \pi^+\pi^-)$ within 90 MeV of 980 MeV \hspace{1cm} m(\pi^+\pi^-) within 30 MeV of $B_s$ mass 

- $162 \text{ pb}^{-1}$
Confirmations

- Belle, CDF & D0
- CDF measures $\tau$ also, ignoring CP violation, in this CP odd eigenstate. $<\tau_{Bs}> = 1.43\pm0.04$ ps (PDG)

$$\tau_{J/\psi f_0} = 1.70^{+0.12}_{-0.11} \pm 0.03 \text{ ps}$$
1st Observation of $B_s \rightarrow J/\psi \ f'_2(1525)$

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

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

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

CDF $\Xi_{b}^{0}$ 1st observation
mass $5787.8\pm5.0$ MeV

$\Lambda_{b}^{0} \rightarrow \Lambda\mu^{+}\mu^{-}$

$\Lambda_{b}^{0} \rightarrow D^{0}pK^{-}$ observed for first time with significance of 6.3$\sigma$

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

CDF

115 events
6 fb$^{-1}$

CDF

~6 fb$^{-1}$

LHCb preliminary
376 pb$^{-1}$

expected signal scaled from CDF 39±9±6

fit 7±5 events

No signal evident in LHCb data

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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

- LHCb $B^- \rightarrow \pi^+ \mu^- \mu^-$, u.l < 4.5x10^{-8}

See A. Atre, T. Han, S. Pascoli, & B. Zhang
[arXiv:0901.3589]

<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>

[arXiv:1107.064]

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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....
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)

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Future Acts

- LHCb Upgrade: run at $10^{33}\text{ cm}^{-2}/\text{s} (x5)$, & 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

**BESIII Preliminary**

$\psi''$

420 pb$^{-1}$

$D^0 \rightarrow K\pi$

58.2±9.6 events

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

$LHCb$ 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 1st measurements of flavor physics. They are ready!
- Heavy Flavor experiments are ready to search for and limit New Physics, especially in b & c decays at the LHC with the 2011 data and beyond.
- Many other interesting flavor results have not been mentioned – apologies.
The End
Is there NP in $B^0$-$\bar{B}^0$ mixing?

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

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

Assume NP in tree decays is negligible, so no NP in $|V_{ij}|$, $\gamma$ from $B^- \rightarrow D^0K^-$. Allow NP in $\Delta m$, weak phases, $A_{SL}$, & $\Delta \Gamma$.

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

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Limits on New Physics From $B_S$ Mixing

- Similarly for $B_S$
  - One CP Violation measurement using $B_S \rightarrow J/\psi \phi$
- Here again SM is only at 5% c.l.
- Much more room for NP due to less precise measurements

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Exp: $\mathcal{B}(B_S \rightarrow \mu^+\mu^-)$ in NUHM1

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

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

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

This can only be done with the LHCb Upgrade.

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ATLAS B $\sigma$’s

CMS Preliminary, $\sqrt{s}$=7 TeV

Spring 2011

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 PDF, $\mu=\langle m_b^2 + p_T^2 \rangle^{1/2}$, $m_b=4.75$ GeV

B-Meson Production Cross Section [\mu b]

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Also $D^+$, $D_s^-$, $\Lambda_b$.

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

$D_f = 9406 \pm 110$

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

$D_f = 2446 \pm 60$
Extract $B_s$ fractions

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

$$f_s / (f_u + f_d) = 0.136 \pm 0.004^{+0.012}_{-0.011}$$

**Graphs**

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

- Also can use hadronic decays + theory $\sim 35 \text{ pb}^{-1}$

$\sqrt{s} = 7 \text{ TeV}$
LHCb Preliminary

$\frac{f_s}{f_d} = 0.249 \pm 0.013^{\text{stat}} \pm 0.020^{\text{syst}} \pm 0.025^{\text{theor}}$

$\frac{f_s}{f_d} = 0.242 \pm 0.024^{\text{stat}} \pm 0.018^{\text{syst}} \pm 0.016^{\text{theor}}$

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

- Significant $p_t$ dependence

- In general agreement with CDF measured at $<p_t>\sim 10$ GeV/c

\[ \frac{f_{\Lambda_b}}{f_u + f_d} = 0.281 \pm 0.012^{+0.011+0.128}_{-0.056-0.086} \]
\[ \sigma(pp \rightarrow b\bar{b}X) \text{ using } 15 \text{ nb}^{-1} \]

- \( b \rightarrow D^0X\mu^-\nu \), \( D^0 \rightarrow K^-\pi^+ \), \( \sim 280 \text{ events} \)

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

- In \( 2<\eta<6 \), \( (75.3 \pm 5.4 \pm 13.0) \) \( \mu b \) LEP frag \( \Rightarrow \) \( 284 \pm 20 \pm 49 \) \( \mu b \)
- In \( 2<\eta<6 \), \( 89.6 \) \( \mu b \) Tevatron frag \( \Rightarrow \) \( 338 \pm 24 \pm 58 \) \( \mu b \)
- Also measured charm cross-section, \( \sim 20x \) \( b \)

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Here use 5.2 pb$^{-1}$

$\sigma = 288\pm4\pm48 \mu$b

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

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CMS $\sigma$ from $b \to X \mu\nu$

- In all cases generally good agreement with NLO calculations, within large errors.

$\sigma = 1.32 \pm 0.01{\text{(stat)}} \pm 0.30{\text{(syst)}} \pm 0.15{\text{(lumi)}} \mu b$

$\sigma_{MC@NLO} = 0.84^{+0.36}_{-0.19}{\text{(scale)}} \pm 0.08{\text{(mb)}} \pm 0.04{\text{(pdf)}} \mu b$

$\sigma_{PYTHIA} = 1.8 \mu b$
Other Bs Decays

CDF Run II Preliminary L = 2.9 fb^{-1}

Candidates per 10 MeV/c^2

Mass(K⁺K⁺K⁺K⁻) (GeV/c^2)

Candidates per 5 MeV/c^2

M(μ⁺μ⁻μ⁻) (GeV/c^2)

CDF II Preliminary L=6.8fb^{-1}

B_s^0 → φμ⁺μ⁻

Data

Total Fit

Signal

Background
B_s Semileptonic Decays

- First Observation of $B_s \rightarrow D_{s2}^{**} X \mu^- \nu$ Decays
- Look at $D^0 K^+$ mass in $\mu^-$ events

$$\frac{\mathcal{B}(B_s^0 \rightarrow D_{s2}^{*+} X \mu^- \nu)}{\mathcal{B}(B_s^0 \rightarrow X \mu^- \nu)} = (3.3 \pm 1.0 \pm 0.4)\%$$

$$\frac{\mathcal{B}(B_s^0 \rightarrow D_{s1}^{+} X \mu^- \nu)}{\mathcal{B}(B_s^0 \rightarrow X \mu^- \nu)} = (5.4 \pm 1.2 \pm 0.5)\%$$

- First step in measuring structure of $B_s$ semileptonic decays, fractions to $D_s$, $D_s^*$, $D_{sJ}$, etc..

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Measurement of $\Delta m_s$

- Amplitude Scan
  - $A_{\text{mix}}$ vs time

- Use $\sim 1400$ fully hadronic $B_s$ decays
- LHCb: $\Delta m_s = 17.63 \pm 0.11 \pm 0.04$ ps$^{-1}$
- CDF: $\Delta m_s = 17.77 \pm 0.10 \pm 0.07$ ps$^{-1}$
  (PRL 97, 242003)
- Now ready for time-dependent CPV in $B_s$