Search for New Physics at LHCb

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Outline

- Introduction
  - Overview of CKM Picture & CP Violation
  - Measuring the CKM sides & angles
- A next generation B Physics experiments – LHCb
  - Detector
  - Physics opportunities
- Summary
Introduction

• SM great success, but it “cannot” be the final word

• The case for New Physics is clear
  - Particle Physics
    • Hierarchy Problem and Unification with gravity
    • GR and Quantum theory
    • Origin of EWSB
    • Why 3 generations?
    • Masses & coupling constants
  - Cosmology
    • Dark Matter
    • Dark Energy
    • Cosmological constant problem
    • Baryon Asymmetry of the Universe
    • …
The Flavor Connection

- Higgs generates mass for gauge bosons
- Higgs also generates mass for fermions through the $Hff^\dagger$ Yukawa coupling $\rightarrow$ in general $3\times3$ matrix in SM ($\hat{\gamma}_e$, $\hat{\gamma}_u$, $\hat{\gamma}_d$)
  - Diagonalize to get fermion masses
  - But, what diagonalizes $\hat{\gamma}_u$, doesn’t diagonalize $\hat{\gamma}_d$.
    - $m_u \neq m_d$, $m_c \neq m_s$, $m_t \neq m_b$ $\rightarrow$ $\hat{\gamma}_u \neq \hat{\gamma}_d$
  - $\hat{\gamma}_d$ can be diagonalized, but the cost is an additional unitary transformation.
    - $d$-type quarks are then rotated with respect to $u$-type quarks
  - Mass eigenstates $\neq$ Flavor eigenstates
  - CKM matrix ($V_{\text{CKM}}$) encompasses this misalignment.

- CKM matrix is directly tied to the origin of mass i.e., EWSB, Higgs, and its Yukawa coupling to fermions.
CKM Formalism

Mass eigenstates $\neq$ flavor eigenstates

$$L_{CC} = -\frac{g}{\sqrt{2}} \langle \bar{u}, \bar{c}, \bar{t} \rangle_L \gamma^\mu \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} W^\mu \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

3 real parameters $+$ 1 complex phase $\Rightarrow$ if complex phase $\neq 0$ $B \to f \neq \bar{B} \to \bar{f}$

Hierarchy of $|element| \Rightarrow$ Parameterize in powers $\lambda = \sin \theta_C \approx 0.22; (A \approx 0.8)$

$K^0$ mixing

$B_S$ mixing

$D_0$ mixing

$B^0$ mixing

$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

$(1 - \lambda^2/2)V_{ub}^* = \frac{\lambda |V_{cb}|}{|V_{ub}|}$
New Physics - Direct vs Indirect

New Physics likely at high mass

Direct detection of decay products
- leptons, jets, $E_T$, etc

B meson decays
- NP particles in loops
- NP could compete with SM

Complementary sensitivity to New Physics

Kersting & Hinchcliffe
hep-ph/0003090
Direct Assault on the Standard Model

Direct detection of high-mass particles at the TeV scale

CDF

D0

Tevatron: 1 TeV pp, $L \sim 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
General purpose detectors: High $p_T$, with admirable $b$ physics program
Direct Assault
The Next Generation

CMS & ATLAS: General purpose high p_T, with b\rightarrow\mu X capabilities

LHC: 7 TeV pp, L\sim10^{34} \text{ cm}^{-2} \text{ s}^{-1}
The Indirect Assault on the Standard Model

Indirect "measurements" of the top quark mass from precision EW observables

Barger et al.
PRL 1990,
4 years before top was discovered!

Direct (2006) 171.4±2.1 GeV

Indirect determination of top quark mass from B mixing (1993, before top discovery)

B°_d-B°_s mixing and the prediction of the top-quark mass in an independent particle potential

N. Barik
Physics Department, Utkal University, Bhubaneswar-751004, India

P. Das, A. R. Panda, and K. C. Roy
Physics Department, Kendrapara College, Kendrapara-754271, India
(Received 22 December 1992; revised manuscript received 30 April 1993)

Considering B°_d-B°_s mixing in a potential model of independent quarks by taking the effective interaction Hamiltonian of the standard Salam-Weinberg-Glashow model and subsequently diagonalizing the corresponding mass matrix with respect to B°_d and B°_s states, we obtain an expression for the mass difference ΔM_{B°_d} in terms of the top-quark mass m_t. Using the recent observation of the mixing parameter x_s=0.72±0.15 by the ARGUS Collaboration, we predict the lower bound on the top-quark mass as m_t≥149 GeV. Furthermore, a consideration of experimental mass difference ΔM_{B°_d}=(4.0±0.8)×10^{-3} GeV also leads to m_t=167±1 GeV which is in agreement with the recent experimental bound as well as other theoretical predictions. However, such a prediction of m_t that utilizes the experimental value of the CKM matrix element [V_{td}] may not appear convincing in view of the large uncertainties in the measurement of [V_{td}] so far reported. Therefore using the range of m_t values within its bounds predicted from other independent works, we make a reasonable estimation of [V_{td}].

 Bounds on Standard Model Higgs mass obtained using precision EW, M_W, M_{top}!

W t t W

M_W^2 = M_Z^2 (1 - sin^2 θ_W) (1 + Δρ) 

Δρ = \frac{3 G_F M_t^2}{8 \pi^2 - C ln(M_H/300 \text{ GeV})}

W W W

W W W

W H H W

W H H W
- Overconstrain the CKM triangle.
  - Measure \((\rho, \eta)\) using TREES (B, K decay rates)
  - Measure 3 CPV angles in several decay modes (LOOPS)
    - NP can affect one, but not the other…
    - Do we get a consistent picture?

- Rare or forbidden decays
  - SM-suppressed decays (loop diagrams) allow NP to compete.
  - New FC amplitudes & phases (could affect rates and/or CPV angles)
    - \(K \to \pi \nu \nu\) also provides tight constraints!
    - \(\mu \to e \gamma\), etc

- Discover NP, or constrain/interpret NP detected at CMS, ATLAS
Measuring Sides

Work ongoing to reduce both theoretical (dominant) and experimental uncertainties…
Recent advance on $B_s$ mixing – $|V_{td}/V_{ts}|$

$\mathcal{L}(A, \Delta m_s, ...) \propto \Delta m_s 
\mathcal{L}(A, \Delta m_s, ...) \propto A \cos(\Delta m_s t)$

NP in Loops?

$\Delta m_d = \frac{G_F^2 m_{B_d} f_2 (m_t^2 / m_W^2) m_t^2 \eta_B f_{B_d}^2 B_{B_d}}{6\pi^2} |V_{td}^* V_{tb}|^2$

$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 B_B}{m_{B_s} f_{B_s}^2 B_{B_s}} |V_{td}|^2 \Delta m_d = 0.507 \pm 0.005 \text{ ps}^{-1}$

$\tau_B \sim 1.5 \text{ ps}$

Consistent with SM expectations, but still significant room for NP – ehem... phase!

Period of oscillations $\sim 56 \text{ fs}$
Requires precise decay length m’ment
Measuring the CKM Angles

- Interference between 2 (or more) amplitudes with differing phases. Rate asymmetries “expose” the interference terms (which contain the CPV angles)

\[ A_f(t) = \frac{\Gamma(t) - \bar{\Gamma}(t)}{\Gamma(t) + \bar{\Gamma}(t)} = C_f \cos(\Delta mt) - S_f \sin(\Delta mt) \]

- Direct CPV Term
- Mixing induced CP Violation term

\[ C_f = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \]
\[ S_f = \frac{-2 \text{Im} \lambda}{1 + |\lambda|^2} \]
\[ \lambda = \frac{q \bar{A}}{p A} \]

CPV \((\Gamma(t) \neq \bar{\Gamma}(t))\) occurs when \(\lambda \neq 1\)

- \(q/p\) is the phase of B mixing

\[ \Delta m_d \propto |V_{td}^* V_{tb}|^2 \]

Value depends if there is one or more diagrams
- If \(|\bar{A}/A| \neq 1 \Rightarrow\) DCPV
- Weak phase flips sign under CP
- Strong phase invariant under CP
CKM Angles - $\sin(2\beta)$ in $B^0 \rightarrow J/\psi K_S$

$$A(t) = \sin(2\beta) \sin(\Delta mt)$$

$A_f(t) = \text{Im} \lambda \sin(\Delta mt)$

$|\lambda|=1 \rightarrow C_f = 0$

$$\lambda = \frac{q \bar{A}}{p A} = \left( \frac{V_{cs}^* V_{cb}}{V_{cs} V_{cb}} \right) \left( \frac{V_{tb}^* V_{td}^*}{V_{tb} V_{td}^*} \right) \left( \frac{V_{cd}^* V_{cs}}{V_{cd} V_{cs}} \right) = e^{-i2\beta}$$

$\text{Im}(\lambda) = \sin(2\beta)$

$\sin(2\beta)_{WA} = 0.675 \pm 0.026$
The State of Affairs

- $|V_{ub}/V_{cb}|$: Systematics limited, SM dominated
- $|V_{td}/V_{ts}|$: $f_B$ errors dominant, SM+NP
- $\sin(2\beta)$: Exp. error dominant (SM + NP)
- Need:
  - Accurate measurement of $\gamma$ with TREES only
  - Precise measurement of $\gamma$ in LOOPS (SM+NP)
  - Precise measurement of $\alpha$ (SM + NP)
  - Reduce theory errors.

CKM Fitter

Pins down $(\rho, \eta)_{SM}$

Pins down $(\rho, \eta)_{SM+NP}$

Summer 2007
Model independent constraints on New Physics

Parameterize NP in $B_s$ mixing as:

$$\Delta m_s = \Delta m_{s}^{SM} (1 + h_s e^{2i\sigma_s})$$

Z. Ligeti, FPCP07
arXiv.0706.0919

$\Delta m_s$(NP) $\sim$ SM if
$\sim$(180±30)$^{\circ}$ relative phase
Model Dependent Constraints on NP from $b \rightarrow s\gamma$

Constraints on 2HDM, Type II

Experiment: $\mathcal{B}(b \rightarrow s\gamma) = (3.54 \pm 0.26) \times 10^{-4}$

Theory: $\mathcal{B}(b \rightarrow s\gamma) = (3.15 \pm 0.23) \times 10^{-4}$ (Misiak *et al* hep-ph/0609232)

M($H^+$) $> 295$ GeV at 95% CL, for $\tan\beta \gtrsim 2$.

Best lower bound on M($H^+$) from any other measurement
**First Measurements of $\phi_s$**

Recent CDF and D0 measurements of CP Asymmetry in $B_s \rightarrow J/\psi \phi$

$-\phi_s = -2\beta_s$ in $[0.32, 2.82]$ at the 68% C.L.

Stronger constraints if $\Delta \Gamma_s$ is taken from theory (dominated by $b \rightarrow ccs$ tree diagrams, so ‘no’ NP)

$\phi_s = -2\beta_s$ in $[0.24, 1.36]$ or $[1.78, 2.90]$ @68%CL

$\tau_s = 1.52 \pm 0.06 \ (stat) \pm 0.01 \ (syst) \ ps$

$\Delta \Gamma_s = 0.19 \pm 0.07 \ (stat) \pm 0.02 \ (syst) \ ps^{-1}$

$\phi_s = 0.57^{+0.24}_{-0.30} \ (stat) \pm 0.07 \ (syst) \ rad$
Another mystery?

**sin(2β)** by TREE

\[ A \propto V_{cb}^* V_{cs} \]

**sin(2β)** by PENGUIN

\[ A \propto V_{tb}^* V_{ts} \approx V_{cb}^* V_{cs} \]

Should give same answer. Should perhaps even get larger sin(2β) from penguins…

\[ \sin(2\beta^{\text{eff}}) = \sin(2\phi_1^{\text{eff}}) \]


Cheng et al., PRD 73, 014017 (2006)

\[ \Delta \sin 2\beta \]
New Physics in Flavor
(a small sampling)


2. Left-right symmetric models (Nir, hep-ph/9911321)
   “Contributions compete with or even dominate over SM contributions to $B_d$ and $B_s$ mixing. This means that CP asymmetries into CP eigenstates could be substantially different from the SM prediction”

   “dramatic deviations from SM predictions for CP asymmetries in B decays are not unlikely”

   “Both the sign and magnitude of the decay leptons in $B \to K^* \ell^+ \ell^-$, carry sensitive information on new physics. Potential effects are on the order of 10%, compared to a entirely negligible SM asymmetry of $\sim 10^{-3}$”

   “If the geometry of space-time is noncommutative i.e. $[x^\mu, x^\nu] = i \theta^\mu\nu$, then CP violating effects may be manifest at low energy. For a scale $\leq 2$ TeV there are comparable effects to the SM”

   Could find an inconsistency between $\alpha, \beta$ & $\gamma$ and CKM determinations of ($\eta, \rho$) using mixing, $V_{ub}/V_{cb}$, and/or $\varepsilon_K$

7. Many papers on Extra Dimensions !!
Moving forward

- B factories have done a tremendous job on $\sin(2\beta)$
- Pioneered/implemented many methods for accessing $\alpha, \gamma$
- Tevatron has delivered on $\Delta m_s$

- But… many of the critical measurements in $B_{(s)}$ decays still remain.
  - Precise measurements of $\alpha, \gamma$ (in both trees & loops when possible)
  - Measurement of $B_s$ mixing phase, $\phi_s$, (first m’ments from Tevatron!)
  - Measurement of $B_s \rightarrow \mu^+\mu^-$ and other rare decays
  - Full exploration of CPV in $B_s$ sector
  - $B \rightarrow K*\ell\ell$ forward-backward asymmetry
  - …

- These important measurements are all stats deprived.

- Solutions:
  - B physics at a hadron machine
  - B factory at $\mathcal{L}\sim10^{36}$ cm$^{-2}$ s$^{-1}$

- Theoretical advances are also needed
  - FF’s for $V_{ub}$
  - Decay constants for $f_{B(s)}$
  - …
LHCb: B Physics at the LHC

- Large cross section
  - $\sim 5 \times 10^{11}$ bb/year.
- $L \sim 10^{32}$ cm$^{-2}$s$^{-1}$
  - prefer 1 int/Xing
  - CMS/Atlas $\sim 10^{34}$
- Harsh environment:
  - $\sim 30$ particles/B event in spectrometer

Detector Requirements
1) Precision vertexing
2) Excellent PID
3) Selective trigger
   (B/MinBias $\sim 0.001$)
4) Precision tracking / $\sigma_p$
5) Reconstruction of neutrals:
   $\pi^0$, $\eta$, $\gamma$
6) Muon ID
The LHCb Detector

Acceptance is from ~10-300 mrad
**Vertex locator** around the interaction region

Silicon strip detector with ~ 30 µm impact-parameter resolution

n⁺ in n, 300 µm R-φ strip geom 35-100 µm pitch
**LHCb Tracking**

Tracking system and dipole magnet (4 T-m) to measure angles and momenta

$\Delta p/p \sim 0.4\%$, mass resolution $\sim 14$ MeV (for $B_s \rightarrow D_s K$)
Two RICH detectors for charged hadron identification
LHCb Calorimeters

Calorimeter system to identify electrons, hadrons and neutrals
Important for the first level of the trigger
**LHCb Muon System**

Muon system to identify muons, also used in first level of trigger
**LHCb trigger**

<table>
<thead>
<tr>
<th>HLT rate</th>
<th>Event type</th>
<th>Physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 Hz</td>
<td>Exclusive B candidates</td>
<td>B (core program)</td>
</tr>
<tr>
<td>600 Hz</td>
<td>High mass di-muons</td>
<td>J/ψ, b→J/ψX</td>
</tr>
<tr>
<td>300 Hz</td>
<td>D* candidates</td>
<td>Charm (mixing &amp; CPV)</td>
</tr>
<tr>
<td>900 Hz</td>
<td>Inclusive b (e.g. b→μ)</td>
<td>B (data mining)</td>
</tr>
</tbody>
</table>

**Detector**

- **L0**: high $p_T$ (μ, e, γ, h) [hardware, 4μs]
- **HLT**: high IP, high $p_T$ tracks [software]
  then full reconstruction of event
- **Storage** (event size ~ 50 kB)

**Efficiency**

The efficiency graph shows the efficiency for various channels with different colors indicating different categories. The channels are labeled with various physics processes, such as B candidates, high mass di-muons, D* candidates, and inclusive b (e.g. b→μ), each with corresponding efficiencies for L0, HLT, and L0×HLT.
Putting it all together

- Muon
- ECAL
- HCAL
- SPD
- RICH2
- IT/OT
- RICH1
- Magnet
- TT
- Velo
Tracking Performance

Vertex detector information is used in the trigger.

Proper time Resolution for $B_s \rightarrow D_s \pi$

$\sigma_t \sim 40$ fs

For CDF

$\sim 90$ fs

Impact parameter resolution

$\delta IP = 14 \mu m + 35 \mu m / p_T$

$B$ decay tracks

$\delta p(p)$
Hadron ID performance

• Critical for B physics: reduction of background & flavor tagging
  eg $B_s^0 \rightarrow D_s^- K^+ \rightarrow K^+ K^- \pi^- K^+$
  $B \rightarrow \pi \pi$, $K \pi$; $B_s \rightarrow KK$, $\pi K$
• Wide momentum range $\rightarrow$ 2 RICHs
• $N_\pi \sim 7XN_K$ (PID critical)

CDF
$B \rightarrow hh$
Flavor Tagging

For CP Violation measurements it is critical to know the flavor of the b-hadron at production.

Can use information on the CP tag side, or from the other B.

<table>
<thead>
<tr>
<th>Method (For $B_S$)</th>
<th>$\mu^\pm$</th>
<th>$e^\pm$</th>
<th>$K^\pm_{\text{same}}$</th>
<th>$K^\pm_{\text{opp}}$</th>
<th>Jet charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon D^2(%)$</td>
<td>1.5</td>
<td>0.7</td>
<td>3.1</td>
<td>2.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Expect $\varepsilon D^2 \sim 7.5\%$ for $B_S$ & $4.3\%$ for $B_d$
Now, some expected physics performance
**$B_s$ mixing – Amplitude & Phase**

$\Delta m_s = 17.7 \pm 0.1 \text{ ps}^{-1}$ [CDF], … but still significant room for NP; need a tight constraint on phase of $\Delta m_s$.

**Trees**

\[ \begin{align*}
\bar{d} & \quad V_{cb} \quad W^- \quad V_{cs}^* \quad \bar{d} \\
\bar{d} & \quad V_{cb} \quad W^- \quad V_{cs}^* \quad \bar{d} \\
\bar{d} & \quad V_{cb} \quad W^- \quad V_{cs}^* \quad \bar{d} \\
\end{align*} \]

**Penguins**

\[ \begin{align*}
\bar{d} & \quad V_{th} \quad W^- \quad V_{ts}^* \quad \bar{d} \\
\bar{d} & \quad V_{th} \quad W^- \quad V_{ts}^* \quad \bar{d} \\
\bar{d} & \quad V_{th} \quad W^- \quad V_{ts}^* \quad \bar{d} \\
\end{align*} \]

$\Rightarrow \delta \beta_{\text{NP}}$  
$\Rightarrow \delta \phi_{s\text{NP}}$

Same $s$-penguin diagram contributes to both. If $\delta \beta$ effect persists, we might expect a difference in $\phi_s$. LHCb very well positioned to study this.
\( B_s \) Mixing Amplitude (\( \Delta m_s \))

- Example of an early physics measurement that is expected from LHCb:
  Measurement of \( B_s \) oscillations
  Use channel \( B_s \rightarrow D_s^{-} \pi^+ \)

- Plot made for 1 year of data
  \( \rightarrow 80,000 \) selected events
  for \( \Delta m_s = 20 \) ps\(^{-1}\)

- Next step: measure the *phase* of the oscillation,
  using \( B_s \rightarrow J/\psi \phi \) decays
  cleanly predicted in the SM:
  \( \phi_s = -0.04 \)
**$B_s$ mixing phase - $B_s \rightarrow J/\psi \phi$**

- $B_s \rightarrow VV \rightarrow$ mixture of CP+ and CP-
- Angular analysis to separate them.

**One year:** 2 fb$^{-1}$

**Yield for analysis:** $\sim 130K$

**Precision on $\phi_s$:** $\sigma(\phi_s) = 0.023$

From pure CP states: $B_s \rightarrow J/\psi \eta$, $\eta_c \phi$, $D_s D_s : \sigma(\phi_s) = 0.059$

Combined: $\sigma(\phi_s) = 0.021$

(UT fit value: -0.037)

**$B_s \rightarrow \phi \phi$:**

- $\sigma_{\phi_s} \sim 6^\circ$ for 2 fb$^{-1}$
- $\sim 2^\circ$ for 10 fb$^{-1}$

**Equation:**

$$A_{CP}(t) = \frac{\Gamma[\overline{B}_s(t) \rightarrow f] - \Gamma[B_s(t) \rightarrow f]}{\Gamma[\overline{B}_s(t) \rightarrow f] + \Gamma[B_s(t) \rightarrow f]}$$

$$A_{CP}(t) = \frac{\eta_f \sin \phi_s \sin(\Delta m_t) t}{\cosh(\Delta \Gamma_t t/2) - \eta_f \cos \phi_s \sinh(\Delta \Gamma_t t/2)}$$
Key Measurement - $\gamma$

CKMFitter – Moriond 2008

Constraints from Trees
Only (SM only)
$|V_{ub}/V_{cb}|$ & $\gamma$

Constraints from Loops
Only (SM + NP)
$\Delta m_d, \Delta m_s, \sin(2\beta), \varepsilon_K$

Precise measurement of $\gamma$ needed

$B^\pm \rightarrow D^0 K^\pm$: Trees only, no mix $\rightarrow \gamma_{SM}$ ★★★★★
$B_s \rightarrow D_s^+ K^+: T, \text{Mix} \rightarrow (\gamma + 2\phi_s)_{SM+NP}$ ★★★★★
$B \rightarrow \pi\pi$, $B_s \rightarrow KK$: T, P & Mixing ★★★
B\(^\pm\) ~ Counting experiment (no mixing) TREES

$\gamma$ Measurements

<table>
<thead>
<tr>
<th>B mode</th>
<th>D mode</th>
<th>Method</th>
<th>$\sigma(\gamma)$ 2 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$K\pi + KK/\pi\pi + K3\pi$</td>
<td>ADS+GLW</td>
<td>5°–15°</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^*K^+$</td>
<td>$K\pi$</td>
<td>ADS+GLW</td>
<td>Under study</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$K_S\pi\pi$</td>
<td>GGSZ</td>
<td>8°</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$KK\pi\pi$</td>
<td>ADS+4-body Dalitz</td>
<td>15°</td>
</tr>
<tr>
<td>$B^+ \rightarrow DK^+$</td>
<td>$K_S\pi\pi\pi$</td>
<td>ADS+4-body Dalitz</td>
<td>Under study</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$K\pi + KK + \pi\pi$</td>
<td>ADS+GLW</td>
<td>7°–10°</td>
</tr>
<tr>
<td>$B^0 \rightarrow DK^{*0}$</td>
<td>$K_S\pi\pi$</td>
<td>Dalitz</td>
<td>Under study</td>
</tr>
<tr>
<td>$B_s \rightarrow D_sK$</td>
<td>$K^+K^-\pi^+$</td>
<td>tagged, A(t)</td>
<td>13°</td>
</tr>
</tbody>
</table>

Interference between direct decay and mixing+decay (4 time-dep rates)

Simultaneous fit to all $\sigma_\gamma \sim 4\text{–}5\text{°} (2 \text{ fb}^{-1})$
**Bs → Ds K**

- <Decay Length>
  - ~ 6 mm for $D_s$
  - ~ 11 mm for $B_s$

- Estimated branching fraction for full $B_s$ decay: $(1.0 \pm 0.4) \times 10^{-5}$

- $B_s$ decay time resolution: 39 fs

- Effective tag eff $\varepsilon D^2 \sim 9\%$

**Observed decay times $B_s \rightarrow D_s K$**

**Expected event yields/2fb$^{-1}$ B/S**

- $B_s \rightarrow D_s \pi$: 140k <0.5
- $B_s \rightarrow D_s K$: 6.2k <0.5

- $B_s \rightarrow D_s \pi$ is also a control channel: precise $\Delta m_s$ & tagging dilution.

**Sensitivity with 2 fb$^{-1}$**

$$\sigma(\gamma) \sim 13^\circ$$
Constraints on New Physics from LHCb

Parameterize NP in Bs mixing as:

\[ \Delta m_\text{s} = \Delta m_\text{s}^{\text{SM}} \left( 1 + h_s e^{2i\sigma_s} \right) \]

Z. Ligeti, FPCP07
arXiv.0706.0919

NP can still be ~SM (or larger) if ~150-210° relative phase

If NP, expect \( h \sim (4\pi v/\Lambda_{\text{NP}})^2 \)

\( \Lambda_{\text{NP}} \sim 2 \text{ TeV for } h \sim 1 \)
\( \Lambda_{\text{NP}} \sim 7 \text{ TeV for } h < 0.1 \)

Tension with EW obs
\( \Lambda \sim \text{TeV expected} \)
NP is MFV

Very tight constraints on any theory/models which yield additional flavor changing interactions (highly restrictive!)
Additional constraints from \( B_d \) mixing
**$B_s \rightarrow \mu\mu$: 70 events for 2 fb$^{-1}$ (SM)**

**Background:**
- B to $\pi\pi$, $\pi K$, $KK$ followed by mis-id. Addressed by RICH particle identification.
- Combinatorial: B to $\mu^+X$, $\bar{B}$ to $\mu^-X$. Addressed by very good mass resolution: $18\text{ MeV}/c^2$

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G. Kane et al, hep-ph/0310042

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With $L = 2\text{ fb}^{-1}$

3$\sigma$ observation if at SM value

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**Integrated Luminosity (fb$^{-1}$)**
B_d \rightarrow K^\ast \mu\mu

Measure:
- Forward – Backward Asymmetry (FBA) as a function of the \( \mu\mu \) invariant mass (\( M_{\mu\mu}^2 \))
- Determine, \( s_0 \), the \( M_{\mu\mu}^2 \) for which FBA = 0.
- Sensitive to New Physics.

\[
\begin{array}{c}
\sigma(s_0) = 0.52 \\
\text{(For 10 fb}^{-1}, \text{expect 0.28)}
\end{array}
\]

FBA can be modified by NP

Coarse measurements beginning to emerge from B factories
### Some of the key modes

**LHCb sensitivities for 2 fb⁻¹ (~1 year)**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
<th>B/S</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to D_s^{+} K^{+}$</td>
<td>5.4k</td>
<td>&lt; 1.0</td>
<td>$\sigma(\gamma) \sim 14^\circ$</td>
</tr>
<tr>
<td>$B_s \to K^{+} K^{-}$</td>
<td>36k</td>
<td>0.46</td>
<td>$\sigma(\gamma) \sim 4^\circ$</td>
</tr>
<tr>
<td>$B_s \to D^0 (K\pi,\bar{K}K) K^{*0}$</td>
<td>3.4 k, 0.5 k, 0.6 k</td>
<td>&lt; 0.06</td>
<td>$\sigma(\gamma) \sim 7^\circ - 10^\circ$</td>
</tr>
<tr>
<td>$B_d \to D^0 (K^-\pi^+,K^+ \pi^-) K^-$</td>
<td>28k, 0.5k</td>
<td>&lt;0.3, &lt;1.7, &lt;1.4</td>
<td>$\sigma(\gamma) \sim 5^\circ - 15^\circ$</td>
</tr>
<tr>
<td>$B^- \to D^0 (K^-\pi^+,\pi^-\pi^-) K^-$</td>
<td>4.3 k</td>
<td>0.6, 4.3</td>
<td>$\sigma(\gamma) \sim 8^\circ - 16^\circ$</td>
</tr>
<tr>
<td>$B^- \to D^0 (K^-\pi^+,\pi^-\pi^-) K^-$</td>
<td>1.5 - 5k</td>
<td>2.0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>Yield</th>
<th>B/S</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_d \to \pi^+ \pi^- \pi^0$</td>
<td>14k</td>
<td>&lt; 0.8</td>
<td>$\sigma(\alpha) \sim 10^\circ$</td>
</tr>
<tr>
<td>$B \to \rho^+ \rho^-,\rho^+ \rho^-,\rho^- \rho^0$</td>
<td>9k, 2k, 1k</td>
<td>1, &lt;5, &lt;4</td>
<td></td>
</tr>
<tr>
<td>$B_d \to J/\psi(\mu\mu) K_S$</td>
<td>216k</td>
<td>0.8</td>
<td>$\sigma(\sin 2\beta) \sim 0.022$</td>
</tr>
<tr>
<td>$B_s \to D_s^{+} \pi^-$</td>
<td>80k</td>
<td>0.3</td>
<td>$\sigma(\Delta m_s) \sim 0.01 \text{ ps}^{-1}$</td>
</tr>
<tr>
<td>$B_s \to J/\psi(\mu\mu) \phi$</td>
<td>131k</td>
<td>0.12</td>
<td>$\sigma(\phi_s) \sim 1.3^\circ$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rare decays</th>
<th>Yield</th>
<th>B/S</th>
<th>Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \to \mu^+ \mu^-$</td>
<td>17</td>
<td>&lt; 5.7</td>
<td>$\sigma(C_7^{\text{eff}}/C_9^{\text{eff}}) \sim 0.13$</td>
</tr>
<tr>
<td>$B_d \to K^{*0} \mu^+ \mu^-$</td>
<td>7.7 k</td>
<td>0.4</td>
<td>$\sigma(A_{CP}) \sim 0.01$</td>
</tr>
<tr>
<td>$B_d \to K^{*0} \gamma$</td>
<td>35k</td>
<td>&lt; 0.7</td>
<td></td>
</tr>
<tr>
<td>$B_s \to \phi \gamma$</td>
<td>9.3 k</td>
<td>&lt; 2.4</td>
<td></td>
</tr>
</tbody>
</table>

| charm | $D^{*+} \to D^0 (K^-\pi^+) \pi^+$ | 100 M | |


The 5 year CKM forecast

Constraints on the Unitarity Triangle that can be expected after ~ 5 years of LHCb data (~10 fb⁻¹)

scenario after the LHCb measurement: new physics?

- γ from Bₛ → Dₛ⁺K⁻, B → DK etc
- Angle α from B⁰ → π⁺π⁻π⁰
- φₛ measured to ± 0.01, i.e. precisely enough to see SM value and therefore any new physics enhancements
Experimental results in B physics from B factories have taken a front seat in the last ~7 years due to outstanding performance of PEP-II and KEK and the ingenuity of the collaborations.

CKM has thus far escaped ~unscathed (although several tantalizing differences)

But significant room for New Physics

To uncover this New Physics will require precision measurements in B decays which are now statistically limited

LHCb is ready and poised to carry the torch into the next decade:

High rates of B, B_s, B_c, Λ_b… (all species available!)

LHCb will either provide stringent constraints on New Physics OR discover New Physics (complementary role to direct observation)

LHCb is also considering a future upgrade, with the hope of reaching 100 fb\(^{-1}\).

Faster DAQ, displaced trigger at L0

More rad hard silicon (pixels, strixels, n-on-p, etc)

etc…