Searching for BSM physics in heavy flavor loop decays at LHCb

Tomasz Skwarnicki
Syracuse University

In this talk
(BSM = Beyond Standard Model = New Physics = NP)
Evidence for Beyond Standard Model physics

- Unknown particles and forces exist, likely hiding at higher energy scales

Visible

Dark Matter?

Mass of the dark matter in galaxies is ~6 times the mass of visible matter

Visible Dark Matter?

~3 times energy of everything else in the universe

Baryogensis?

Holographic? What? How does gravity fit in?

Hierarchical problem?

M_H << M_{Planck}

GUT? How does gravity fit in?

end of 19th century → atoms, QED

mid 20th century → quarks, QCD

Generation problem?

now → ?

big bang → Lepton Quarks, Force Carriers

M_{H} << M_{Planck}
Two complementary ways of advancing “energy frontier” at accelerator-based experiments

**Collision energy**

**Tree diagrams**, for example

- Standard Model (SM)
- New Physics (NP)

Want high CM energy to exceed the production threshold

**Loop diagrams**, for example

- SM
- NP

Want high precision since NP particles are highly virtual here, thus probabilities small

Heisenberg’s uncertainty principle:

\[ \Delta E \Delta t = \frac{\hbar}{2} \]

i.e. \[ \Delta m \Delta t = \frac{\hbar}{2} \]
LHCb Physics Program

Not enough time to cover entire scope of the LHCb experiment - selection of topics has been unavoidable.
Loops as low energy windows to high energy physics

- Some spectacular successes in the past:
  - Lack of tree level FCNC, suppression of $K^0_L \rightarrow \mu^+\mu^-$ and GIM mechanism (1970):
    - prediction of charm quark 4 years before its discovery

\[
\frac{\Delta E}{\Delta t} = \frac{\hbar}{2}
\]

FCNC at loop level

- $V_{us}^*$
- $V_{ud}$
- $V_{cs}^*$
- $V_{cd}$

\[BR \sim 10^{-4}\] (rare decay!)
Not detected at expected rate

\[
\begin{array}{c}
\text{NEGATIVE INTERFERENCE} \\
\text{BR} \ll 10^{-4}
\end{array}
\]

Observed in 1973 with $BR \sim 10^{-8}$
Loops as low energy windows to high energy physics

- CPV in $K^0_L \rightarrow \pi^+\pi^-$ decays (1964) + Kobayashi-Maskawa hypotheses (1972):
  - prediction of 3\textsuperscript{rd} quark generation 5 years before its discovery
  - first glimpse of top quark 31 years before its discovery

- Large $B^0\overline{B^0}$ mixing at ARGUS (1987):
  - lower limit on top mass puts 5 higher energy colliders (PETRA,PEP,TRISTRAN,SLC,LEP) out of business in quest for top discovery,
  - but makes CPV measurements in $B^0$ easier
Colliders and $b\bar{b}$ rates

- The past decade has been a golden age of 10 GeV $e^+e^-$ b-factories
- Super b-factories are being pursued in Japan and Italy, with luminosity upgrade by almost 2 orders of magnitude
Colliders and $b\bar{b}$ rates

- Tremendous rate potential at hadron colliders
  - physics reach determined by the detector capabilities not by the machine
- Collect all $b$-hadron species at the same time:
  - additional gain by a factor of $\sim 10$ to $100$ in integrated $B_s$ rates at hadronic colliders
  - time dependent CPV studies of $B_s$ possible
  - also get $\Lambda_b$, $B_c$ which are out of reach of the 10 GeV $e^+e^-$ factories
- Charm rates factor of 10 higher than beauty rates:
  - nuisance and great physics opportunity at the same time
LHCb vs central detectors

Advantages of LHCb (forward spectrometer):

- comparable b cross-section in much smaller solid angle; smaller number of electronic channels; smaller event size; much larger trigger bandwidth to tape (~3.5 kHz)
- b and c physics dominate the trigger bandwidth (e.g. CMS b-trigger rate ~25 Hz; 2 orders of magnitude less than LHCb)
- large p for small $p_T$ (in central region $p \sim p_T$); can identify muons to lower $p_T$ values
- large bandwidth important for triggering on purely hadronic final states (GDPs limited to dimuon trigger)
- large bandwidth important for collecting very large charm samples
- space for RICH detectors: $K/\pi$ separation; crucial for background suppression in many channels; increased flavor tagging

Limitation of LHCb:

- luminosity limited by the detector readout capabilities (see next)
LHCb luminosity at its upgrade

- Maximal value of luminosity for safe LHCb operations ~ $4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Beams are intentionally misaligned at LHCb to stay below this limit.
- Luminosity is “leveled” over run duration.

The main luminosity limitation comes from 1MHz L0 bandwidth imposed by the readout speed.

**upgrade: (2018-)**  instantenous luminosity up to ~ $20 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Readout all detectors at 40 MHz. Do all triggering in the computer farm. Increase output bandwidth to 20-30 kHz to cope with the increased physics rate
- Factor of ~2 improvement in hadronic trigger efficiencies. Muon trigger efficiencies stay the same.
LHCb data samples

- Statistically, 2010 data are insignificant (~0.04 fb\textsuperscript{-1}), but some analyses published only on this statistics so far.
- Most of 2011 results were based on “summer” statistics (~0.4 fb\textsuperscript{-1}). Still being published.
- Many new results at winter conferences 2012 (~1 fb\textsuperscript{-1}). More to come in summer.
### Expected future data samples

<table>
<thead>
<tr>
<th>Run</th>
<th>CM Energy [TeV]</th>
<th>Integrated luminosity (all data together) [fb⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>LHCb</strong></td>
</tr>
<tr>
<td>2011</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>2012</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>2015-17</td>
<td>14</td>
<td>5</td>
</tr>
<tr>
<td>2019-...</td>
<td>14</td>
<td>50</td>
</tr>
</tbody>
</table>

- LHCb will collect ~1fb⁻¹ a year until upgrade
- LHCb upgrade

~50% higher bb cross section at 14 TeV
2012 run so far

LHC 2012 RUN (4 TeV/beam)

LHC ~70x10^{32} cm^{-2}s^{-1}

LHCb 4x10^{32} cm^{-2}s^{-1}

(generated 2012-05-26 01:10 including fill 2663)
Quark flavor transitions – CKM matrix

- Described by CKM matrix in SM
- A complex phase in 3-generation matrix gives a rise to CPV
- Wolfensteins’s parameterization depicts the measured structure of CKM well

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

Complex phase \(\eta\) mostly in \(V_{td}, V_{ub}\) \(\lambda^3 = 0.012\)
- then a bit in \(V_{ts}\) \(\lambda^4 = 0.0026\)
- even less in \(V_{cd}\) \(\lambda^5 = 0.0006\)

\[\lambda = 0.226 \pm 0.001 (\sin \theta_C)\]
\[A = 0.81 \pm 0.02\]
\[\lambda^0 = 1\]
\[\lambda^1 = 0.23\]
\[\lambda^2 = 0.051\]

\[\rho, \eta\] see next

\[
\delta V = \begin{pmatrix}
0 & 0 & 0 \\
-iA^2\lambda^5\eta & 0 & 0 \\
A\lambda^5(\rho + i\eta)/2 & -A\lambda^4(1/2 - \rho - i\eta) & 0
\end{pmatrix}
\]
Quark flavor transitions – unitarity triangle

- After a decade of $e^+e^-$ B-factory experiments the KM hypothesis is well verified.

\[ \rho = \rho(1-\lambda^2/2) \]
\[ \eta = \eta(1-\lambda^2/2) \]

- The game now is looking for NP in corrections to CKM picture.

Kobayashi & Maskawa
Nobel Prize 2008

Note: $\bar{\rho} = \rho(1-\lambda^2/2)$
$\bar{\eta} = \eta(1-\lambda^2/2)$

Trees: $\gamma, V_{ub}$
Loops: everything else
Importance of $B_s$ physics: example indirect CPV

- **Super fast mixing, very small CPV**
  - $-A\lambda^2$
  - $A\lambda^3(1-\rho-i\eta)$
  - $B_s$
  - $B_\bar{s}$
  - Good place to look for non-SM CPV

- **Slow mixing, small CPV**
  - $A\lambda^2$
  - $A\lambda^3(\rho-i\eta)$
  - $K^0$ to $\bar{K}^0$
  - CPV discovery
  - KM hypothesis

- **Super slow mixing, very small CPV**
  - $A\lambda^3(1-\rho-i\eta)$
  - Long distance diagrams can come into play
  - Good place to look for non-SM CPV, but SM background not well predicted

- **Large mixing, large CPV**
  - $A\lambda^2$
  - Good place to test SM CPV

- **Dominant decay (lifetime)**
  - $V_{us}$ to $V_{sc}$
  - $\lambda^0 = 1$
  - $\lambda^3 = 0.23$
  - $\lambda^2 = 0.051$
  - $\lambda^3 = 0.012$
  - $\lambda^4 = 0.0026$
  - $\lambda^5 = 0.0006$
• First measured by CDF in 2006

• LHCb (world best!):
Measure $\Delta m_s$ with $B_s \to D_s(KK\pi)(3)\pi$

$\sigma_{LHCb}^{LHCb} \sim 44 \ (36) \ \text{fs for } D_s(3)\pi$

Final state determines $B_s$ flavor at the decay (no interference of mixing & decay). Also need to determine (“tag”) $B_s$ flavor at the production point.

\[ \Delta m_s = \infty \]

\[ \Delta m_s = 17.63 \pm 0.11 \text{ (stat)} \pm 0.02 \text{ (syst) ps}^{-1} \]

<table>
<thead>
<tr>
<th>Tagging</th>
<th>$\varepsilon D^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposite Side</td>
<td>$2.1 \pm 0.2 %$</td>
</tr>
<tr>
<td>Same Side Kaon</td>
<td>$1.3 \pm 0.4 %$</td>
</tr>
</tbody>
</table>

$\Delta m = M_L - M_S$  frequency of oscillations sensitive to $|V_{ts}|$
Interference of mixing and decay produces indirect CPV.
No SM phase in the lowest order. Small $V_{ts}$ phase suppressed by $\lambda^2$. 

$B_S \rightarrow J/\psi \phi$ ($\phi \rightarrow K^+ K^-$)

21,200 events

$B_S \rightarrow J/\psi \pi^+ \pi^-$

7,400 events
Phase of $B_s$-$\overline{B}_s$ mixing

$B_s \rightarrow J/\psi \phi$: not an eigenstate; need angular analysis

$(\sigma_t \sim 45 \text{ fs})$

Opposite side flavor tags only:

$\epsilon D^2 = 2.3 \pm 0.3 \%$

$B_s \rightarrow J/\psi \pi^+\pi^-$: eigenstate (LHCb-PAPER-2012-005); no need for angular analysis
Resolving fit ambiguity (sign of $\Delta \Gamma_s$)

**Solution I**

\[
\begin{align*}
\delta_{||} - \delta_0 \\
\delta_{\perp} - \delta_0 \\
\delta_s - \delta_0 \\
\phi_s \\
\Delta \Gamma_s
\end{align*}
\]

**Solution II**

\[
\begin{align*}
\delta_0 - \delta_{\perp} \\
\pi + \delta_0 - \delta_{\perp} \\
\delta_0 - \delta_s \\
\pi - \phi_s \\
-\Delta \Gamma_s
\end{align*}
\]

To resolve the ambiguity look at interference of the $\phi$ resonance (P-wave) and small S-wave component

Expected for the right solution:

\[
\begin{align*}
\delta_s - \delta_{\perp}
\end{align*}
\]

Solution I chosen (4.5σ away from flat)
Phase of $B_s - \bar{B}_s$ mixing

- Profile likelihood contour in $\Delta \Gamma_s - \phi_s$ plane:

![Profile likelihood contour](attachment:image.png)

- Result, LHCb 1 fb$^{-1}$ (Preliminary)

  $\Gamma_s = 0.6580 \pm 0.0054$ (stat.) $\pm 0.0066$ (syst.) ps$^{-1}$

  $\Delta \Gamma_s = 0.116 \pm 0.018$ (stat.) $\pm 0.006$ (syst.) ps$^{-1}$

  $\phi_s = -0.001 \pm 0.101$ (stat.) $\pm 0.027$ (syst.) rad

- Simultaneous fit to both $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$, $B_s^0 \rightarrow J/\psi \phi$:

  $\phi_s = -0.002 \pm 0.083$ (stat.) $\pm 0.027$ (syst.) rad
Phase of Bs-\overline{Bs} mixing

- First significant observation of $\Delta \Gamma_s$, sign determined
- SM not challenged yet.
- Plenty of room for improved NP searches: SM uncertainty on $\phi_s \sim 0.003$
- LHCb will measure $\phi_s$ to $\pm 0.02$ with 5 fb$^{-1}$.
- Upgraded LHCb will measure $\phi_s$ to $\pm 0.006$ with 50 fb$^{-1}$.

If necessary, we can control penguin pollution in $B_s \rightarrow J/\psi \phi$ with measurement of direct-CPV in $B_s \rightarrow J/\psi K^{*0}$

Also plan to study indirect CPV in $B_s \rightarrow [\psi(2S), \eta_c, \chi_{c1}] \phi, J/\psi \eta^{(')}, D_s D_s$

Why is LHCb with 1/10th of CDF luminosity doing a factor of 4 better than CDF?

Higher $b\overline{b}$-cross section at LHC helps, but only by a factor of $\sqrt{3} = 1.7$
<table>
<thead>
<tr>
<th>B trigger happy!</th>
<th>CDF</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bunch crossing rate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bunch spacing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Interactions / crossing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Stage 1</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Output rate</strong></td>
<td>L1</td>
<td>L0</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>30 kHz</td>
<td>1 000 kHz</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>5.5 µs</td>
<td>4.0 µs</td>
</tr>
<tr>
<td><strong>Single µ</strong></td>
<td>Hardware (tracks,mu,ecal)</td>
<td>Hardware (hcal,mu,ecal)</td>
</tr>
<tr>
<td><strong>Dimoun</strong></td>
<td>Pt&gt;4 GeV</td>
<td>Pt&gt;1.3 GeV</td>
</tr>
<tr>
<td><strong>Pt1&gt;2.0 &amp; Pt2&gt;2.0 GeV</strong></td>
<td></td>
<td>Pt1+Pt2&gt;1.3 GeV</td>
</tr>
<tr>
<td><strong>Stage 2</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Output rate</strong></td>
<td>L2</td>
<td>HLT1</td>
</tr>
<tr>
<td><strong>Execution time</strong></td>
<td>1 kHz</td>
<td>30 kHz</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>20 µs</td>
<td>~5 000 µs</td>
</tr>
<tr>
<td><strong>Hardware</strong></td>
<td>Hardware (tracks, IP)</td>
<td>Computer Farm (tracks,IP)</td>
</tr>
<tr>
<td><strong>Stage 3</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Output rate</strong></td>
<td>L3</td>
<td>HLT2</td>
</tr>
<tr>
<td><strong>Event size</strong></td>
<td>150 Hz</td>
<td>3 500 Hz</td>
</tr>
<tr>
<td><strong>Type</strong></td>
<td>250 kB</td>
<td>45 kB</td>
</tr>
<tr>
<td><strong>Computer farm</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fraction of bandwidth for heavy flavors</strong></td>
<td>small</td>
<td>all</td>
</tr>
</tbody>
</table>

- LHCb is the first dedicated hadron collider b-experiment
Indirect CPV via box-gluonic penguin interference

\[ B_s \rightarrow \phi\phi \]

No SM phase in the lowest and second order: small \( V_{ts} \) phase cancels between the mixing and decay diagrams.

NP can enter also through the penguin diagram.

- Purely hadronic final states – at LHC only LHCb can trigger on them
Indirect CPV with $B_s \rightarrow \phi\phi$

- These flavor untagged asymmetries must be zero unless there is a difference between phase of CP even/odd amplitudes (not in SM!)
- LHCb results based on $801 \pm 29$ events in $1 \text{ fb}^{-1}$ consistent with the SM and with less precise measurements by the CDF (arXiv:1107.4999 $295 \pm 20$ events in $2.9 \text{ fb}^{-1}$)
- Future improvements:
  - Full angular analysis
  - Flavor-tagged time-dependent analysis with more data
- CPV phase of this process will be measured by LHCb to $\pm 0.04$ with $5 \text{ fb}^{-1}$; to $\pm 0.01$ with $50 \text{ fb}^{-1}$ and upgraded detector (improved hadronic triggers!) reaching the theoretical uncertainty
Look for interference of these SM diagrams. NP diagrams can contribute.

Need to eliminate effect of form-factors – various observables related to angular correlations. Most famous $A_{FB}$
\[ B^0 \rightarrow K^{*0} \mu^+ \mu^- \]

Before summer 2011:

**Babar, Belle and CDF**
- **Babar** 60 events with \( B/S = 0.3 \)
- **Belle** 247
- **CDF** 100 \((4.4 \text{ fb}^{-1})\) \(0.4\)

New results:
- **CDF** 164 \((6.8 \text{ fb}^{-1})\) \(0.4\)
- **LHCb** 900 \((1.0 \text{ fb}^{-1})\) \(0.25\)

- So far no challenge to SM
- LHCb already has the most sensitive measurement:
  - 5 times more data by 2018
  - 50 times more data with upgrade
- LHCb upgrade will have better sensitivity than super \(e^+e^-\) factories in this exclusive channel \((e^+e^-\) can also do inclusive measurement)
First measurement of $A_{FB}$ zero-crossing point

- The SM predicts $A_{FB}$ to change sign at a well defined point in $q^2$
- This zero-crossing point $q_0^2$ is largely free from form-factor uncertainties
- Extracted through a 2D fit to the forward- and backward-going $m_{B^0}$ and $q^2$ distributions

![Graph showing $A_{FB}$ vs $q^2$]

- The world's first measurement of $q_0^2$, at $q_0^2 = 4.9^{+1.1}_{-1.3}$ GeV$^2$/c$^4$ [preliminary]
- This is consistent with SM predictions which range from 4 - 4.3 GeV$^2$/c$^4$
Brackets BR(Bs → μ⁺μ⁻) Could be strongly enhanced. In some models negative interference with the SM.

BR_{SM}(B_s → μ⁺μ⁻) = (3.2 ± 0.2) \times 10^{-9}

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Date</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>7/12/11</td>
<td>(1.8^{+1.1}_{-0.9}) \times 10^{-8}</td>
</tr>
<tr>
<td>CDF</td>
<td>3/5/12</td>
<td>(1.3^{+0.9}_{-0.7}) \times 10^{-8}</td>
</tr>
<tr>
<td>LHCb</td>
<td>7/21/11</td>
<td>PL B707,497 (2012)</td>
</tr>
<tr>
<td>CMS</td>
<td>2/28/12</td>
<td>CMS-BPH-11-020</td>
</tr>
<tr>
<td>ATLAS</td>
<td>3/2/12</td>
<td>ATLAS-CONF-2012-010</td>
</tr>
<tr>
<td>LHCb</td>
<td>3/21/12</td>
<td>LHC-B-PAPER-2012-007</td>
</tr>
</tbody>
</table>

No excess of events over the expected background + expected SM signal

JHEP 1010, 009 (2010) Small with small theoretical error! 2.1σ evidence for NP

< 4.0 \times 10^{-8} (95% CL)
**BR(\(B_S \rightarrow \mu^+\mu^-\)) and BR(\(B^0 \rightarrow \mu^+\mu^-\))**

- Together more sensitive probe for NP

<table>
<thead>
<tr>
<th>New results in 2012</th>
<th>CDF</th>
<th>CMS</th>
<th>ATLAS</th>
<th>LHCb</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity (fb(^{-1}))</td>
<td>10</td>
<td>4.9</td>
<td>2.4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>BR((B^0 \rightarrow \mu^+\mu^-))</td>
<td>95% CL upper limit (10(^{-9}))</td>
<td>4.6</td>
<td>1.8</td>
<td>1.03</td>
<td>0.10 ± 0.01</td>
</tr>
<tr>
<td>BR((B_s \rightarrow \mu^+\mu^-))</td>
<td>95% CL upper limit (10(^{-9})) Value (10(^{-9}))</td>
<td>(31^{+9}_{-7})</td>
<td>7.7</td>
<td>22</td>
<td>(4.5^{+1.8}_{-1.3})</td>
</tr>
</tbody>
</table>

(status after CDF 7 fb\(^{-1}\) results) (now LHCb 1 fb\(^{-1}\))

SM has survived an order of magnitude improvement in experimental sensitivity room left for NP (in some models negative interference with the SM)
## Future LHC samples and $B_s \rightarrow \mu^+\mu^-$ prospects

<table>
<thead>
<tr>
<th>Run</th>
<th>CM Energy [TeV]</th>
<th>Integrated luminosity (all data together) [fb$^{-1}$]</th>
<th>LHCb</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>7</td>
<td>1</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>8</td>
<td>2</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>2015-17</td>
<td>14</td>
<td>5</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>2019-…</td>
<td>14</td>
<td><strong>50</strong></td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

At present CMS limits $\sim 1.7 \times$ LHCb limits

If CMS manages to retain present trigger and analysis efficiencies, it will lead in sensitivity for this channel until LHCb upgrade.

If no NP found earlier, the SM value will be observed during 2015-17 run.

$$\text{BR}(B^0 \rightarrow \mu^+\mu^-)/\text{BR}(B_s \rightarrow \mu^+\mu^-) \sim 1/30 \text{ in SM; } \sim 5\% \text{ theor. error will also be measured to } \sim 35\% \text{ accuracy by the upgraded LHCb}$$

After 2019-21 run the experimental errors will become comparable to the SM theoretical uncertainty (<10%), closing this window to NP.
Charm mixing

Short distance

\[ \overline{D^0} \rightarrow \bar{b}, s, d \quad \overline{D^0} \rightarrow \bar{u} \]
\[ u \rightarrow b, s, d \quad u \rightarrow c \]

b: CKM-suppressed:
\[ |A^2 \lambda^5 (\rho - i \eta)|^2 \sim 10^{-8} \]

s,d: GIM-cancellations:
\[ (m_s^2 - m_d^2)/m_c^2 \sim 10^{-5} \]

phase is CKM-suppressed: \( A^2 \lambda^5 \eta \)

Long distance

\[ \overline{D^0} \rightarrow \bar{s} \rightarrow K^+ \quad \overline{D^0} \rightarrow \bar{u} \rightarrow u \]
\[ u \rightarrow d, \pi^- \quad u \rightarrow c \]

Many intermediate states can contribute:
\( K\pi, \ K\bar{K}, \ \pi\pi, \ \pi\pi\pi, \ldots \)

with difficult to predict magnitudes & phases.
Mixing with |x|<1%, |y|<1% in SM possible.

\[ y = (\Gamma_1 - \Gamma_2)/(2\Gamma) \]
\[ \Gamma = (\Gamma_1 + \Gamma_2)/2 \]

• Mixing observed by the previous experiments at the level of the largest SM predictions. It is a bit of surprise, but can’t prove NP contributions.
• SM CPV phase is strongly CKM-suppressed. Expect indirect CPV to be tiny \( \sim 10^{-8} (<< 10^{-3}) \); good place to look for NP.
Charm mixing and CPV via effective lifetimes

Measure effective lifetimes (effective = fit simple exponential decay) for $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^+ \pi^-$

$D^0 \rightarrow K^- \pi^+$, 
$\overline{D}^0 \rightarrow K^+ \pi^-$

Cabibbo Favored
BR $\sim 0.04$

$D^0, \overline{D}^0 \rightarrow K^+ K^-$

Single Cabibbo Suppressed
BR $\sim 0.004$

Not a CP eigenstate
(averages over CP states)

CP eigenstate (CP= -1)
Sensitivity to CPV in mixing, and in interference of mixing and decay (indirect CPV)

Interference of the tree and penguin decays can produce small direct CPV

NP can enter via mixing or penguin processes
Charm mixing and CPV via effective lifetimes

Measure effective lifetimes (effective = fit simple exponential decay)

\[ y_{CP} = \frac{\tau_{K\pi}}{\tau_{KK}} - 1 \]

\[ y_{CP} \approx (1 + \frac{1}{8} A_m^2) y \cos \phi - \frac{1}{2} A_m x \sin \phi \]

\[ A_m \approx \left( \frac{q}{p} \right)^2 - 1 \quad |D_{1,2}| = p |D^0| > \pm q |\bar{D}^0| > \]

CPV in mixing itself ("indirect CPV")

\[ \phi = \arg \left( \frac{q}{p} \frac{A_{D^0 \rightarrow K^+ K^-}}{A_{\bar{D}^0 \rightarrow K^+ K^-}} \right) \]

CPV in interference of mixing and decay ("indirect CPV")

\[ A_m \rightarrow 0, \phi \rightarrow 0 \]

\[ y_{CP} \rightarrow y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \]

\[ y_{CP} \neq y \quad \text{is a sign of indirect CPV} \]

\[ A_{\Gamma} = \frac{\tau_{\bar{D}^0 \rightarrow K^+ K^-} - \tau_{D^0 \rightarrow K^+ K^-}}{\tau_{\bar{D}^0 \rightarrow K^+ K^-} + \tau_{D^0 \rightarrow K^+ K^-}} \]

\[ A_{\Gamma} \approx \frac{1}{2} (A_m + A_d) y \cos \phi - x \sin \phi \]

\[ A_d \approx \left( \frac{A_{D^0 \rightarrow K^+ K^-}}{A_{\bar{D}^0 \rightarrow K^+ K^-}} \right)^2 - 1 \quad \text{CPV in decay ("direct CPV")} \]

\[ A_m \rightarrow 0, \phi \rightarrow 0, A_d \rightarrow 0 \]

\[ A_{\Gamma} \rightarrow 0 \]

For no CPV

\[ y_{CP} \neq y \quad \text{is a sign of indirect CPV} \]

\[ A_{\Gamma} \neq 0 \quad \text{is a sign of indirect or direct CPV} \]
Charm mixing and CPV via effective lifetimes

\[ \Delta m = M(D^0\pi^\pm) - m(D^0) \]

- Charge of the (strong interactions) transition $\pi$ tags the $D^0$ flavor
- $D^{*+}$ detection also helps the background suppression
Charm mixing and CPV via effective lifetimes

\[ \tau_{K^+\pi^-} = 410.2 \pm 0.9 \, \text{(stat.) fs} \quad \text{vs} \quad 410.1 \pm 1.5 \, \text{fs PDG} \]

\[ \tau_{K^+K^-} = 408.0 \pm 2.4 \, \text{(stat.) fs} \]

\[ y_{CP} = \frac{\tau_{K^+\pi^-}}{\tau_{K^+K^-}} - 1 = (5.5 \pm 6.3 \pm 4.1) \times 10^{-3} \]

BaBar \quad (11.2 \pm 2.2 \pm 1.8) \times 10^{-3} \quad PRD78,01105(2008)

Belle \quad (13.1 \pm 3.2 \pm 2.5) \times 10^{-3} \quad PRD80,071103(2009)

HFAG \quad y = (7.5 \pm 1.2) \times 10^{-3} \]

\[ y_{CP} \approx y \quad \text{No evidence for CPV in mixing} \quad A_\Gamma \approx 0 \]

- First measurements at hadron collider.
- Not yet competitive with e^+e^-\text{. With 2011 data (1.1 fb}^{-1}\text{) statistical errors will be 1x}10^{-3}\text{. Need to improve background systematics. Most sensitive measurements expected.}
- Expected statistical errors on \( A_\Gamma \) with 5 fb\text{^{-1}} (upgraded LHCb 50 fb}^{-1}\text{) \sim 4x10^{-4} (1x10^{-4})
Direct CPV in charm decays via time integrated rates
Direct CPV in charm decays via time integrated rates

$LHCb 0.62 \text{ fb}^{-1} \text{ LHCb-PAPER-2011-023; PRL 108, 111602 (2012)}$

\[ A_{\text{CP}}(f) = \frac{\Gamma_{D^0 \to f} - \Gamma_{\bar{D}^0 \to f}}{\Gamma_{D^0 \to f} + \Gamma_{\bar{D}^0 \to f}} \]

\[ a_{\text{CP}}^{\text{dir}}(f) = \frac{|A_{D^0 \to f}|^2 - |A_{\bar{D}^0 \to f}|^2}{|A_{D^0 \to f}|^2 + |A_{\bar{D}^0 \to f}|^2} \approx -\frac{1}{2} A_d \]

\[ A_{\text{CP}}(f) \approx a_{\text{CP}}^{\text{dir}}(f) - A_{\Gamma}(f) \frac{<t>}{\tau} \]

For experimental reasons (see next) we measure:

\[ \Delta A_{\text{CP}} = A_{\text{CP}}(K^+K^-) - A_{\text{CP}}(\pi^+\pi^-) \]

For $D^0 \to \pi^+\pi^-$ also SCS, similar BR

In case of U-spin symmetry: $A_{\text{CP}}(K^+K^-) = -A_{\text{CP}}(\pi^+\pi^-)$

\[ \Delta A_{\text{CP}} \approx \Delta a_{\text{CP}}^{\text{dir}} - \Delta \left( A_{\Gamma} \frac{<t>}{\tau} \right) \]

\[ \Delta A_{\text{CP}} \approx \Delta a_{\text{CP}}^{\text{dir}} + a_{\text{CP}}^{\text{ind}} \frac{\Delta <t>}{\tau} \]

\[ \frac{\Delta <t>}{\tau} = 0.098 \pm 0.002 \pm 0.001 \] (LHCb specific)
\[ \Delta A_{CP} \]

For any \( D^* \)-tagged decay \( D^0 \to f \):

\[
A_{RAW}(f)^* \equiv \frac{N(D^{*+} \to D^0(f)\pi^+) - N(D^{*-} \to \bar{D}^0(f)\pi^-)}{N(D^{*+} \to D^0(f)\pi^+) + N(D^{*-} \to \bar{D}^0(f)\pi^-)}
\]

\[
A_{RAW}(f)^* = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^{*+})
\]

physics CP asymmetry

Detection asymmetry of \( D^0 \)

Detection asymmetry of soft pion

Production asymmetry

For a two-body decay of a spin-0 particle to a self-conjugate final state, no \( D^0 \) detector efficiency asymmetry, i.e.

\[ A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0 \]

Then:

\[
A_{RAW}(K^-K^+)^* = A_{CP}(K^-K^+) + A_D(\pi_s) + A_P(D^{*+})
\]

\[
A_{RAW}(\pi^-\pi^+)^* = A_{CP}(\pi^-\pi^+) + A_D(\pi_s) + A_P(D^{*+})
\]

\[ A_{RAW}(K^-K^+)^* - A_{RAW}(\pi^-\pi^+)^* = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \]
Δa_{CP} previous measurements

- Different measurements are sensitive to different combinations of direct and indirect asymmetries

HFAG averages:

Δa_{CP}^{dir}=(-0.42±0.27)\% 
1.6σ away from zero

a_{CP}^{ind}=(-0.03±0.23)\%
$\Delta A_{CP}$: LHCb data

- Based on 60% of 2011 data

$$\delta m = M(D^0\pi^+) - m(D^0) - M(\pi^+)$$
$\Delta A_{CP}: \text{LHCb result}$

$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (0.82 \pm 0.21 \pm 0.11)\%$

$= a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-) + (0.098 \pm 0.002 \pm 0.001)a_{CP}^{ind}$

SM $\Delta A_{CP} < \sim 0.1\%$

Our result is consistent with the previous measurements ($\sim 1.1\sigma$) but more precise

HFAG averages including LHCb:

$\Delta a_{CP}^{dir} = (-0.65 \pm 0.18)\%$

$3.6\sigma$ away from zero

$a_{CP}^{ind} = (-0.02 \pm 0.23)\%$
\[ \Delta A_{CP} \] recent developments: CDF 9.6 fb\(^{-1}\)

- CDF Public Note 10784, 2/28/12, similar analysis to LHCb

\[
\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (0.62 \pm 0.21 \pm 0.10)\% \\
= a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-) + (0.26 \pm 0.01)a_{CP}^{ind}
\]

CDF
2.7\(\sigma\) from no-CPV

HFAG averages including new CDF:
\[ \Delta a_{CP}^{dir} = (-0.66 \pm 0.15)\% \]
4.4\(\sigma\) away from zero
\[ a_{CP}^{ind} = (-0.03 \pm 0.23)\% \]
**$\Delta A_{CP}$ recent developments: theory**

- **Before the LHCb results:**
  - $\Delta A_{CP} \sim O(1\%)$ would be a sign of NP

- A large number of theoretical papers has been published since then

- **Now:**
  - It may be possible to accommodate such asymmetry within the SM via interference of decays mediated by tree and penguin diagrams; see e.g.
    - T. Feldman, S. Nandi, A. Soni arXiv: 1202.3795,

- More measurements of direct and indirect CPV in charm decays are needed to distinguish between SM and NP scenarios
\( \Delta A_{CP} \): future prospects in LHCb

- The present LHCb result is based on 0.6 fb\(^{-1} \); update to 1 fb\(^{-1} \) in preparation
- Further future:
  - LHCb 5 fb\(^{-1} \): \( \Delta A_{CP} \) to \( \pm 0.04\% \)
  - LHCb upgrade 50 fb\(^{-1} \): to \( \pm 0.005\% \)
- Related measurements:
  - Measure \( \Delta A_{CP} \) with D\(^0 \) from B semileptonic decays
  - Look for direct CPV in other SCS modes, especially 3 body ones
LHCb upgrade – opportunity to contribute

- The collaboration is of BaBar size:
  - 800 Physicists
  - 54 Institutes
  - 15 Countries

- Upgrade work is still in early stages:
  - R&D on various technologies -2012
  - TDR in 2013, prototypes
  - Production 2013-17
  - Installation 2018

- On-going and future physics program are very broad (many topics not covered in this talk)
- Cutting edge in sensitivity in many beauty and charm topics – NP discovery potential
- Opportunity for significant scientific impact
Conclusions

• LHC is a beauty and charm factory for foreseeable future:
  – Unique reach in $B_s$ physics. Best sensitivity in many $B_{d,u}$ measurements.

• LHCb is the first hadron collider experiment dedicated to heavy flavor physics
  – The recent results have proven that a broad beauty and charm physics program at a hadronic collider is possible with quality of results matching the $e^+e^-$ factories.
  – Reaching new levels of sensitivity (i.e. higher energy scales) in many key measurements:
    • No indication of NP in beauty decays yet. **Plenty of room left for NP before theoretical limitations are reached. Probing smaller deviations from SM means probing high energy scales.**
    • More data to be collected in next few years
      – Channels with many neutrals, neutrino(s) and inclusive processes will remain exclusive domain of the $e^+e^-$ factories.

• Have we just seen a glimpse of NP in charm decays?
  – More data and more measurements in charm sector soon

• Physics reach limited by the detector capabilities not the collider: