Flavour Physics and the LHCb Experiment

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John Ellis Fest - October 2 2012
Outline

- The LHCb detector and running conditions

- Selected results
  - Mainly focus on new physics measurements from LHCb. Most examples based on 1 fb\(^{-1}\) of 2011 pp collision data.
  - A couple of anecdotes from John’s distinguished career along the way

- Summary
LHCb - forward spectrometer

- Forward-peaked production $\rightarrow$ LHCb is a forward spectrometer (operating in collider mode)
- $b\bar{b}$ cross-section $= 284 \pm 53 \ \mu b$ at the LHC (pp collisions at $\sqrt{s} = 7$ TeV) [PLB 694 209]
- $\rightarrow$ $\sim 100,000 \ b\bar{b}$ pairs produced/second ($10^4 \times B$ factories)

[Diagram of LHCb-Forward Spectrometer]

- $10 - 300 \ mrad$
What the doomsayers said

• “Hadron colliders are too dirty an environment for flavour-physics”

• “Impossible to trigger efficiently on non-leptonic final states”

• “It will take a long time to understand detector performance, and so physics output will take years to emerge”
Indeed, a Google search yields:

John Ellis, Executioner
Englishman Famous for Hanging Notorious Criminals

Oct 15, 2008  Kevin Guthrie

John Ellis's career as an executioner spanned more than two decades, but his profession took a heavy toll on him.

Ellis's Early Life and First Executions

John Ellis was born in the Balderstone district of Rochdale, England, on October 4th, 1874. In his early life he worked at the Eagle Mill, until suffering a back injury there in 1898. After trying to find less
But if anyone was still left in any doubt...

\[ D^+, D_s \rightarrow K K \pi \]

\[ B^+ \rightarrow (K \pi)_D \pi^+ \]

...and even with photons

\[ B^0 \rightarrow K^*\gamma \]
Nominal luminosity = $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ : however, LHCb has learned to run at >2 times this.

Continuous (automatic) adjustment of offset of colliding beams allows luminosity to be levelled

- 37 pb$^{-1}$ collected in 2010
- 1 fb$^{-1}$ in 2011
- So far 1.4 fb$^{-1}$ in 2012 – hope for 2.5 fb$^{-1}$ before the long shutdown
Selected highlights from early running

- Parameters of the CKM matrix
- Flavour changing neutral currents: searches & studies
- Studies of CPV in the $B_s$ system
- CP violation in charm
The CKM describes all the flavour-changing processes in the SM

Amazing progress in the last 20 years; the SM remains intact, but still a whole lot still to learn
Spectacular results from $e^+e^-$ B factories on CP violation

Large CP violation effects: $\sin(2\beta)$ from $B^0 \to J/\psi K^0_{S/L}$

**Babar**

PRD 79 (2009) 072009

**Belle**

PRL 108 (2012) 171802

World average: $\sin(2\beta) = 0.667 \pm 0.023 \pm 0.012$
And now LHCb in the game ...

\[ A_{J/\psi K_S^0}(t) \equiv \frac{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) - \Gamma(B^0(t) \rightarrow J/\psi K_S^0)}{\Gamma(\bar{B}^0(t) \rightarrow J/\psi K_S^0) + \Gamma(B^0(t) \rightarrow J/\psi K_S^0)} = S_{J/\psi K_S^0} \sin(\Delta m_d t) - C_{J/\psi K_S^0} \cos(\Delta m_d t). \]

\[ S_{J/\psi K_S^0} = 0.73 \pm 0.07 \text{ (stat)} \pm 0.04 \text{ (syst)}, \]
\[ C_{J/\psi K_S^0} = 0.030 \pm 0.089 \text{ (stat)} \pm 0.012 \text{ (syst)}, \]
\[ \rho(S_{J/\psi K_S^0}, C_{J/\psi K_S^0}) = 0.416 \]
A measurement of $\gamma$ from $B^\pm \to DK^\pm$ and $D\pi^\pm$

- Three LHCb analyses, comprising 16 B decays included in a combined fit

- $B^\pm \to DK^\pm$, $D \to Ks^0\pi^+\pi^-$ and $D \to Ks^0K^+K^-$
  "GGSZ": LHCb-paper-2012-027

- $B^\pm \to Dh^\pm$, $D \to \pi^+K^\pm\pi^+\pi^\pm$ and $D \to K^+\pi^+\pi^+\pi^\pm$
  "K3\pi": LHCb-conf-2012-030

- $B^\pm \to Dh^\pm$, $D \to \pi^+K^\pm$ and $D \to K^+\pi^\pm$
  "ADS": Phys Lett B712, 2030

- $B^\pm \to Dh^\pm$, $D \to K^\pm\bar{K}^\pm$, $D \to \pi^\pm\pi^\pm$
  "GLW": Phys Lett B712, 2030

\[ r_B \approx 0.1 \]

\[ r_D \approx 0.06 \]

\[ r_D / r_B \approx 0.6 \sim 1 \]
$B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D\pi^\pm$ modes

### Favoured modes

- $B^- \rightarrow (\pi^-K^+)DK^-$
- $B^+ \rightarrow (\pi^+K^-)D\pi^+$

### ADS modes

- $B^- \rightarrow (\pi^-K^+)D\pi^-$
- $B^+ \rightarrow (\pi^+K^-)D\pi^+$

### GLW modes

- $B^- \rightarrow (\pi^-K^+)DK^-$
- $B^+ \rightarrow (\pi^+K^-)D\pi^+$
LHCb $\gamma$ measurement

- LHCb: $B^\pm \rightarrow DK^\pm$ only $\gamma = 62.1^0 \pm 16.7$ $- 12.7$

- LHCb: including both $B^\pm \rightarrow DK^\pm$ and $B^\pm \rightarrow D\pi^\pm$ $\gamma = 86.0^0 \pm 7.1$ $- 7.8$

- [Current world average $\gamma = 66^0 \pm 12^0$]

- More data eagerly awaited
Selected highlights from early running

- Parameters of the CKM matrix
- Flavour changing neutral currents: searches & studies
- Studies of CPV in the $B_s$ system
- CP violation in charm
Digression: the history of the penguin

• John was studying CP-violation in 1976/77 and the phenomenology of the b quark.

• With Melissa Franklin and Serge Rudaz, John went to a pub and started a game of darts.

• They made a bet that if John lost he had to put the word penguin into his next paper. Oh dear, John lost!

• But in a flash it came to him that the famous diagrams look like penguins. [Source Wikipedia]
The game of darts

John & Melissa [?]
circa 1977
Rare decay $B_s \rightarrow \mu^+\mu^-$

- Decay strongly suppressed in SM
- Predicted BR
  $= (3.2 \pm 0.2) \times 10^{-9}$
- Very sensitive to new physics - MSSM
- But it's like looking for a needle in a haystack
CMS – the $\mu^+\mu^-$ spectrum

$\sim 10 \, B_s \rightarrow \mu^+\mu^-$ and $\sim 1 \, B_d \rightarrow \mu^+\mu^-$ decays expected in 1/fb (after trigger&selection) assuming SM

$B^0_s \rightarrow \mu^+\mu^-$?
LHCb $B_s \rightarrow \mu^+\mu^-$ candidate
- LHCb selection based on multivariate estimator (BDT) combining vertex and geometrical information
- No significant excess observed
\[ B_s \rightarrow \mu^+\mu^- \] Limits

**LHCb**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>at 90% CL</th>
<th>at 95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ B_s^0 \rightarrow \mu^+\mu^- ]</td>
<td>Exp. bkg + SM</td>
<td>(6.3 \times 10^{-9})</td>
<td>(7.2 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>Exp. bkg</td>
<td>(2.8 \times 10^{-9})</td>
<td>(3.4 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>(3.8 \times 10^{-9})</td>
<td>(4.5 \times 10^{-9})</td>
</tr>
<tr>
<td>[ B^0 \rightarrow \mu^+\mu^- ]</td>
<td>Exp. bkg</td>
<td>(0.91 \times 10^{-9})</td>
<td>(1.1 \times 10^{-9})</td>
</tr>
<tr>
<td></td>
<td>Observed</td>
<td>(0.81 \times 10^{-9})</td>
<td>(1.0 \times 10^{-9})</td>
</tr>
</tbody>
</table>

- **ATLAS/CMS/LHCb combined @95% CL**
  - \[ BR(B_s \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-9}\]
  - SM (\[ B_s \rightarrow \mu^+\mu^- \]) = \((3.2 \pm 0.2) \times 10^{-9}\)
  - \[ BR(B_d \rightarrow \mu^+\mu^-) < 8.1 \times 10^{-10}\]
- 95% CL \[ B_s \rightarrow \mu^+\mu^- \] upper limit already close to SM value.
- But lower BR is interesting as well!
$B_s \rightarrow \mu^+\mu^-$ constraints on new physics

CMS direct exclusion

1.1 fb$^{-1}$

4.4 fb$^{-1}$

CMS direct exclusion
St. SUSY lived every moment as if it were her last

Hang on a minute. Put your bibles and crosses away. I've got a few more breaths left in me yet.
FCNC decay $B^0 \rightarrow K^{*0}\mu^+\mu^-$

- $BR = (1.22^{+0.38}_{-0.32}) \times 10^{-6}$ agrees to within ~30% of SM
- But forward-backward asymmetry $A_{FB}(s)$ in the $\mu\mu$ rest-frame is a sensitive NP probe

SM + New physics contributions
$B^0 \to K^*\mu^+\mu^-$ continued

- Previous results hinted at discrepancy
- LHCb has largest sample in world, as clean as the B Factories!
- First measurement of zero crossing point: $q^2 = 4.9^{+1.1}_{-1.3}$ GeV$^2$
- Sadly $A_{FB}$ now consistent with Standard Model

Previous results hinted at discrepancy

- LHCb has largest sample in world, as clean as the B Factories!
- First measurement of zero crossing point: $q^2 = 4.9^{+1.1}_{-1.3}$ GeV$^2$
- Sadly $A_{FB}$ now consistent with Standard Model
But not all is quite as expected ...

- LHCb measure “isospin asymmetry”

\[
\frac{\Gamma(B^0 \rightarrow K^0 \mu^+ \mu^-) - \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\Gamma(B^0 \rightarrow K^0 \mu^+ \mu^-) + \Gamma(B^+ \rightarrow K^+ \mu^+ \mu^-)}
\]

- Expected to be \(~\text{zero}\) in SM

- Significant deviation emerging. Requires further studies and more theoretical understanding
This penguin is especially for John ...

- $B^+ \rightarrow \pi^+\mu^+\mu^-$

First observation, rarest B decay ever observed

$1 \text{ fb}^{-1}$, LHCb-CONF-2012-006

- SM prediction: $(1.96 \pm 0.21) \times 10^{-8}$
- BR measured: $(2.4 \pm 0.6 \pm 0.2) \times 10^{-8}$

LHCb Preliminary

25±6 events
5.2 σ significance
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**B_s weak mixing**

**phase $\phi_s$ in $B_s \rightarrow J/\psi \phi$**

- Analogue of $2\beta$ (phase of $B^0$ mixing) in the $B_s$ system is expected to be very small, and precisely predicted: $\phi_s = -0.036 \pm 0.002$

  (eg. Charles e.a. PRD84(2011)033005)

- **Golden mode for this study is** $B_s \rightarrow J/\psi \phi$

- First measurements from the Tevatron indicated large values for $\phi_s$ discrepancy with SM reaching $\sim 3\sigma$

Perform $B_s \rightarrow J/\Psi \phi$ angular analysis
$B_s \rightarrow J/\psi \phi :$ fit projections

- CP-even
- CP-odd
Results correlated with $\Delta \Gamma_s = \text{width difference of the } B_s \text{ mass eigenstates}$

$\rightarrow$ plotted as contours in $(\phi_s \text{ vs } \Delta \Gamma_s)$ plane

First significant direct measurement of $\phi_s$ and $\Delta \Gamma_s$

$\Delta \Gamma_s = 0.116 \pm 0.018 \pm 0.006 \text{ ps}^{-1}$

$\phi_s = -0.001 \pm 0.101 \pm 0.027 \text{ rad}$

Add in $B_s \rightarrow J/\Psi \pi\pi$

$\phi_s = -0.002 \pm 0.083 \pm 0.027$

Not much room for new physics, will continue to improve precision
**CP-violating asymmetry $a_{s l}^s$ in $B_s$ decays**

First step to resolving the issue (CPV in mixing $P(B \rightarrow \bar{B}) \neq P(\bar{B} \rightarrow B)$) of the D0 di-muon asymmetry anomaly.

- **LHCb preliminary result**

\[ a_{s l}^s = \frac{\Gamma(B_s^0 \rightarrow D_s^- \mu^+) - \Gamma(\bar{B}_s^0 \rightarrow D_s^+ \mu^-)}{\Gamma(B_s^0 \rightarrow D_s^- \mu^+) + \Gamma(\bar{B}_s^0 \rightarrow D_s^+ \mu^-)} \]

\[ a_{s l}^s = (-0.24 \pm 0.54 \pm 0.33)\% \]

- **D0 not confirmed nor ruled out. More will come soon**

**Standard Model predictions**

\[ a_{s l}^s = (1.9 \pm 0.3) \times 10^{-5} \]

\[ a_{s l}^d = (-4.1 \pm 0.6) \times 10^{-4} \]

A. Lenz

arXiv:1205.1444

Kings College London, Ellis Fest 2nd October 2012

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CP-violation in charm decays

LHC reveals hints of 'new physics' in particle decays

By Jason Palmer
Science and technology reporter, BBC News

LHC-beauty, or LHCb, is an enormous detector designed to examine CP violation.

Large Hadron Collider researchers have shown off what may be the facility's first "new physics" outside our current understanding of the Universe.

Particles called D-mesons seem to decay slightly differently from their antiparticles, LHCb physicist Matthew Charles told the HCP 2011 meeting on Monday.

The result may help explain why we see so much more matter than antimatter.

The team stresses that further analysis will be needed to shore up the result.

Related Stories

Antimatter mystery gains ground
Science ups the 'anti' on matter
New clue to anti-matter mystery
First evidence for CP violation in charm decays at LHCb

Measure $D^0/D^0(\bar{b})$ decay asymmetries - charge of $\pi$ from $D^*$ determines production state of the $D^0$

$$A_K = \frac{N(D^0 \rightarrow K^+K^-) - N(D^0 \rightarrow K^+\bar{K}^-)}{N(D^0 \rightarrow K^+K^-) + N(D^0 \rightarrow K^+\bar{K}^-)}$$

$$A_\pi = \frac{N(D^0 \rightarrow \pi^+\pi^-) - N(D^0 \rightarrow \pi^+\bar{\pi}^-)}{N(D^0 \rightarrow \pi^+\pi^-) + N(D^0 \rightarrow \pi^+\bar{\pi}^-)}$$

In the Standard Model these asymmetries should be close to zero

The quantity $\Delta A_{CP} = A_K - A_\pi$ is measured (since systematics largely cancel)

$$\Delta A_{CP} = [-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{sys})] \%$$

(Note also recent preliminary CDF result: [-0.62 + 0.21 - 0.10]% [CDF note 10784])

Predicted to be ~0 in the Standard Model 3.5$\sigma$ different from zero

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Conclusions

- LHCb has been a huge success: LHCb has now submitted/published ~65 papers - highest paper/author ratio at the LHC.

- Up to 2017 we expect 7-8 fb$^{-1}$ of data in total, and much of this at ~double the current heavy-flavour production cross-section (since $\sqrt{s}$: 8→14 TeV)

- So far all in good agreement with the Standard Model → New physics is constrained in the flavour sector → CP violation in charm may (or may not) be the first evidence of NP.

- But still much room for new physics, higher precision required...

Upgrade of LHCb detector planned for 2019 to take at least 10× more data: 50 fb$^{-1}$: Much more to come!
Should John have named the “penguin” after an uncanny resemblance slightly closer to home?
MANY CONGRATULATIONS JOHN!