LHCb: Run I Results & Future Prospects

Tim Gershon
University of Warwick

MIAPP workshop on Indirect Searches for New Physics in the LHC and Flavour Precision Era

24th June 2015
The LHCb detector

- In high energy collisions, $b\bar{b}$ pairs produced predominantly in forward or backward directions
- LHCb is a forward spectrometer
  - a new concept for HEP experiments

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CPV and rare decays

Precision primary and secondary vertex measurements

Excellent $K/\pi$ separation capability
The LHCb Run 1 trigger

Challenge is
- to efficiently select most interesting B decays
- while maintaining manageable data rates

Main backgrounds
- “minimum bias” inelastic pp scattering
- other charm and beauty decays

Handles
- high $p_T$ signals (muons)
- displaced vertices
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Towards New SM
In 12 Steps

Content of this talk

Focus on areas with recent experimental progress

LHCb top observation

B → X_s ν̅ν
B → K^*(K)ν̅ν
K → πν̅ν

B → X_s l^+l^−
B → K^*(K)l^+l^−
B^0 → K*μμ
&B^− → φμμ

B^- → τ^+ ντ
B → D^{(*)}τν

Lattice

ΔF=2 Obsevables

γ & V_{ub}

δ'/δ

B_{s,d} → μ^+μ^−
B_{s,d} → τ^+τ^−
B_{d,s} → μμ

Will end with future perspectives

ΔF=2

γ & V_{ub}

δ'/δ

B_{s,d} → μ^+μ^−
B_{s,d} → τ^+τ^−
B_{d,s} → μμ

B → X_s γ
B → K^* γ

B, B^0 → K*μμ

Clock from Buras & Girrbach, RPP 77 (2014) 086201
D → π⁺π⁻π⁰ – a quasi-CP eigenstate

- Seminal Dalitz plot analysis from BaBar
  - Gives the parameter $x_0 = 0.850$ (without uncertainty)
  - Relation to fractional CP-even content: $x_0 = 2F_+ - 1$

- Exploit CLEOc $\Psi(3770) \rightarrow D\bar{D}$ data for direct measurement of CP content: $F_+ = 0.973 \pm 0.017$
New decay modes for $\gamma$

arXiv:1504.05442

$B \to DK$, $D \to \pi^+\pi^-\pi^0$

$F_+ = 0.973 \pm 0.017$

$B \to DK$, $D \to K^+K^-\pi^0$

$F_+ = 0.734 \pm 0.119$

$B \to DK$, $D \to K^+\pi^-\pi^0$

More precise than BaBar or Belle

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New decay modes for $\gamma$

**arXiv:1505.07044**

\[ B \to D K \pi^+ \pi^-, \]

\[ D \to K^+ \pi^-, K^+ K^-, \pi^+ \pi^- \]

**LHCb**

\[ B^+ \to [K^+ \pi^+]_{D} K^+ \pi^+ \pi^+ \]

\[ B^- \to [K^+ \pi^+]_{D} K^- \pi^+ \pi^- \]

\[ B^- \to [\pi^+ \pi^-]_{D} K^+ \pi^+ \pi^- \]

\[ B^+ \to [\pi^+ \pi^-]_{D} K^+ \pi^+ \pi^+ \]

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CPV and rare decays
γ status

- Most precise channel is $D_{CP} K$ (awaiting LHCb update with full Run I sample)
- New LHCb results with competitive sensitivity
- LHCb only combination, without latest results (but including measurements not shown in plot to right), gives $\gamma = (73^{+9}_{-10})^\circ$
Extension to $B \to D\pi K$ decays

- Extension of the method to exploit additional sources of interference that occur in multibody decays
  - $B^0 \to D(\pi^- K^+)$ decays can have CP violation
  - $B^0 \to (D\pi^-)K^+$ decays have no CP violation
- Provides ideal reference amplitude from which to determine relative phases via interference between different resonances on the Dalitz plot

Toy example containing $K^*(892)^0$, $K_2^*(1430)^0$, $D_2^*(2460)^-$

Effects of spin clearly visible

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Extension to $B \to D\pi K$ decays

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Toy example containing
- $K^*(892)^0$
- $K_2^*(1430)^0$
- $D_2^*(2460)^-$

Effects of spin clearly visible
B → DπK Dalitz plot

- Use D → Kπ decays to determine Dalitz plot model for favoured b → c amplitude

\[ m^2(\bar{D}^0\pi^-) \text{ [GeV}^2] \]
\[ m^2(K^+\pi^-) \text{ [GeV}^2] \]

LHCb
(a)

n.b. axes flipped c.f. previous slides
\[ |V_{ub}/V_{cb}| \text{ from } \Lambda_b \rightarrow p\mu\nu/\Lambda_b \rightarrow \Lambda_c \mu\nu \]

- Long standing discrepancy between exclusive and inclusive determinations of both $V_{ub}$ and $V_{cb}$

\[
|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \quad |V_{ub}| = (4.41 \pm 0.15 \pm 0.15) \times 10^{-3} \text{ (inclusive)},
\]
\[
|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \quad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \text{ (exclusive)}.\]
\[ |V_{ub}|/|V_{cb}| \text{ from } \Lambda_b \rightarrow p\mu\nu/\Lambda_b \rightarrow \Lambda_c \mu\nu \]

- Long standing discrepancy between exclusive and inclusive determinations of both $V_{ub}$ and $V_{cb}$

\[
|V_{cb}| = (42.4 \pm 0.9) \times 10^{-3} \text{ (inclusive)} \quad |V_{ub}| = (4.41 \pm 0.15 \pm 0.15) \times 10^{-3} \text{ (inclusive)},
\]

\[
|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3} \text{ (exclusive)} \quad |V_{ub}| = (3.23 \pm 0.31) \times 10^{-3} \text{ (exclusive)}.\]

- Use of $b$ baryon decays provides complementary alternative to $B$ mesons

- At LHCb, exploit displaced vertex to reconstruct corrected mass

\[
M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp
\]
\[ |V_{ub}/V_{cb}| \text{ from } \Lambda_b \to p\mu\nu/\Lambda_b \to \Lambda_c \mu\nu \]

- Can then reconstruct \( q^2 = m(\mu\nu)^2 \)
  - Select events with \( q^2 > 15 \text{ GeV}^2 \) (\( p\mu\nu \))/ 7 GeV\(^2\) (\( \Lambda_c\mu\nu \))
  - Highest rate, best resolution & most reliable theory (lattice) predictions

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\[ |\mathcal{N}_{ub}/\mathcal{N}_{cb}| \text{ from } \Lambda_b \rightarrow p\mu\nu/\Lambda_b \rightarrow \Lambda_c\mu\nu \]

- Use isolation MVA to suppress background
- Fit \(M_{\text{corr}}\) to obtain signal yields

\[ N(\Lambda_b \rightarrow p\mu\nu) = 17687 \pm 733 \]
\[ N(\Lambda_b \rightarrow \Lambda_c\mu\nu) = 34255 \pm 571 \]
$|V_{ub}/V_{cb}|$ from $\Lambda_b \rightarrow p\mu\nu/\Lambda_b \rightarrow \Lambda_c \mu\nu$

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(\Lambda_c^+ \rightarrow pK^+\pi^-)$</td>
<td>$+4.7$ $-5.3$</td>
</tr>
<tr>
<td>Trigger</td>
<td>3.2</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Lambda_c^+$ selection efficiency</td>
<td>3.0</td>
</tr>
<tr>
<td>$N^*$ shapes</td>
<td>2.3</td>
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<tr>
<td>$\Lambda_b^0$ lifetime</td>
<td>1.5</td>
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<tr>
<td>Isolation</td>
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<tr>
<td>Form factor</td>
<td>1.0</td>
</tr>
<tr>
<td>$\Lambda_b^0$ kinematics</td>
<td>0.5</td>
</tr>
<tr>
<td>$q^2$ migration</td>
<td>0.4</td>
</tr>
<tr>
<td>PID</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$+7.8$ $-8.2$</td>
</tr>
</tbody>
</table>
$|V_{ub}|/|V_{cb}|$ from $\Lambda_b \rightarrow p\mu\nu/\Lambda_b \rightarrow \Lambda_c \mu\nu$

- Rules out models with RH currents
- Compatible with UT fit ($\beta,\gamma$)

$$\frac{B(\Lambda_b \rightarrow p\mu^-\bar{\nu}_\mu)_{q^2>15 \text{ GeV}^2/c^4}}{B(\Lambda_b \rightarrow \Lambda_c\mu\nu)_{q^2>7 \text{ GeV}^2/c^4}} = (1.00 \pm 0.04(\text{stat}) \pm 0.08(\text{syst})) \times 10^{-2}$$

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(\text{expt}) \pm 0.004(\text{lattice})$$

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Unitarity Triangle
not including latest results
sin(2\beta)

Decay-time dependent CP asymmetry in $B^0 \rightarrow J/\psi K_S$ → golden mode to measure sin(2\beta)

Previously measured by BaBar & Belle … now LHCb becomes competitive

$41\ 560 \pm 270$
tagged $B^0 \rightarrow J/\psi K_S$ decays

$S = 0.731 \pm 0.035 \pm 0.020$
$C = -0.038 \pm 0.032 \pm 0.005$

Effective tagging efficiency: $3.02 \pm 0.05 \%$
sin(2β)

Decay-time dependent CP asymmetry in $B^0 \rightarrow J/\psi K_S$ → golden mode to measure sin(2β)
Previously measured by BaBar & Belle … now LHCb becomes competitive

World average:
$sin(2\beta) = 0.691 \pm 0.017$
φ_s from B_s → J/ψφ (etc.)

Latest LHCb results
PRL 114 (2015) 041801
$B_s \rightarrow \mu^+\mu^-$

Killer app. for new physics discovery

Very rare in Standard Model due to
- absence of tree-level FCNC
- helicity suppression
- CKM suppression
... all features which are not necessarily reproduced in extended models

$$B(B_s \rightarrow \mu^+\mu^-)^{\text{SM}} = (3.66 \pm 0.23) \times 10^{-9}$$

$$B(B_s \rightarrow \mu^+\mu^-)^{\text{MSSM}} \sim \tan^6 \beta/M^4$$

Intensively searched for over 30 years!

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Combination of CMS and LHCb data results in first observation of $B_s \rightarrow \mu^+ \mu^-$ and first evidence for $B^0 \rightarrow \mu^+ \mu^-$

Results consistent with SM at $2\sigma$ level
\[ \text{B} \to \text{D}^{(*)}\tau\nu \]

- Powerful channel to test lepton universality
  - ratios \( R(D^{(*)}) = \frac{B(\text{B} \to \text{D}^{(*)}\tau\nu)}{B(\text{B} \to \text{D}^{(*)}\mu\nu)} \) could deviate from SM values, e.g. in models with charged Higgs

- Heightened interest in this area
  - anomalous results from BaBar
  - other hints of lepton universality violation, e.g. \( R_K, H \to \tau\mu \)

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\[ \text{B} \rightarrow \text{D}^*\tau\nu \text{ at LHCb} \]

- Identify \( \text{B} \rightarrow \text{D}^*\tau\nu, \text{D}^* \rightarrow \text{D}\pi, \text{D} \rightarrow \text{K}\pi, \tau \rightarrow \mu\nu\bar{\nu} \)
  - Similar kinematic reconstruction to \( \Lambda_b \rightarrow p\mu\nu \)
    - Assume \( p_{B,z} = (p_{D^*} + p_\mu)_z \) to calculate \( M_{\text{miss}}^2 = (p_B - p_{D^*} - p_\mu)^2 \)
    - Require significant \( B, D, \tau \) flight distances & use isolation MVA

- Separate signal from background by fitting in \( M_{\text{miss}}^2, q^2 \) and \( E_\mu \)
  - Shown below high \( q^2 \) region only (best signal sensitivity)

\[ R(D^*) = 0.336 \pm 0.027 \pm 0.030 \]
**B → D*τν at LHCb – all q^2 bins**

**Results of simultaneous fit to M_{miss}^2, q^2 and E_\mu**

q^2 distribution is an input to, not an output of, the fit
B → D*τν at LHCb – systematics

R(D*) = 0.336 ± 0.027 ± 0.030

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size (×10⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified μ template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors</td>
<td>0.6</td>
</tr>
</tbody>
</table>
| $\bar{B} \to D^{*+}H_c(\to \mu
u X')X$ shape corrections                                   | 0.5                   |
| $\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$ | 0.5                   |
| $\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections                                   | 0.4                   |
| Corrections to simulation                              | 0.4                   |
| Combinatorial background shape                         | 0.3                   |
| $\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors                                   | 0.3                   |
| $\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction                                              | 0.1                   |
| **Total model uncertainty**                            | **2.8**               |

<table>
<thead>
<tr>
<th>Normalization uncertainties</th>
<th>Absolute size (×10⁻²)</th>
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</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
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<tr>
<td>Hardware trigger efficiency</td>
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<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
</tr>
<tr>
<td>Form-factors</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}<em>\mu\nu</em>\tau)$</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td><strong>Total normalization uncertainty</strong></td>
<td><strong>0.9</strong></td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>3.0</strong></td>
</tr>
</tbody>
</table>

Largest sources scale with statistics
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B → D(⋆)τν

Careful averaging needed to account for statistical and systematic correlations

SM predictions from PRD 85 (2012) 094025

Very preliminary & unofficial average including new LHCb & Belle results

Tension with SM seems to persist

Δχ² = 1.0

R(D*) = 0.390 ± 0.047
R(D) = 0.322 ± 0.021

Thanks to M. Rotondo
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ provides superb laboratory to search for new physics in $b \rightarrow s l^+ l^-$ FCNC processes
  - rates, angular distributions and asymmetries sensitive to NP
  - experimentally clean signature
  - many kinematic variables … with clean theoretical predictions
- Full set of CP conserving observables measured
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

- Example of fits, in $1.1 < q^2 < 6.0$ GeV$^2$ bin

Angle and $m(K\pi)$ projections in ± 50 MeV around B peak
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
Full angular analysis of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$

LHCb-CONF-2015-002

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Tension in $P'_5$

LHCb-CONF-2015-002

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$B_s \rightarrow \phi \mu^+ \mu^-$

- Full angular analysis performed
- Not self-tagging $\rightarrow$ complementarity to $K^{*0}\mu^+ \mu^-$
  - Measure also differential branching fraction

Tension with SM prediction – consistent picture in $b \rightarrow s l^+ l^-$ branching fractions
$B_s \rightarrow \phi \mu^+ \mu^-$

All angular observables consistent with SM
All angular observables consistent with SM
$$\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$$

Similar tension with SM prediction for branching fraction at low $q^2$
Statistics still low for angular analysis
Baryonic system provides sensitivity to additional observables

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Lepton universality – $R_K$ (reminder)

Deficit of $B \to K\mu^+\mu^-$ compared to expectation
also seen in $K\mu^+\mu^-/K\mu^+\mu^-$ ratio ($R_K$)

$$R_K(1 < q^2 < 6 \text{ GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$$

<3σ from SM but suggestive
Top observation at LHCb

- Top production in the forward region is sensitive to the low-x part of the gluon PDF; also potentially more sensitive to asymmetries than in central region

- Challenge is to be able to see signal with low $\bar{t}t$ production cross-section (at $\sqrt{s} = 7,8$ TeV) and low luminosity (1,2/fb)
  - Cannot get full final state in LHCb acceptance
  - Use highest yield mode: ($W\rightarrow \mu$) + b-jet
  - Need high $p_T$ b-jet, excellent b-tagging and good control of (non-t) Wb background
    - Jets reconstructed (anti-kT with $R = 0.5$) as in JHEP01 (2014) 033 (Z+jet)
    - b- & c-tagging described in arXiv:1504.07670

Exploits LHCb's excellent vertexing capability
W+b,c-jet observation at LHCb

Separate signal from background using $p_T(\mu)/p_T(\mu)$

7 TeV

8 TeV

μ + c-jet

μ + b-jet

arXiv:1505.04051

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Top observation at LHCb

- $W+b$-jet sample contains top. To determine relative amount:
  - tighten fiducial requirements ($p_T(\mu)>25$ GeV; $50 < p_T(b\text{-jet}) < 100$ GeV)
  - control rate of non-t $W+b$-jet from precise prediction for $\sigma(W+b\text{-jet})/\sigma(W+\text{jet})$ & measured $\sigma(W+\text{jet})$
  - validate method using $W+c$-jet (no top contribution)

5.4σ observation of top production in the forward region
Run II data taking

- LHCb is ready! Will gain from higher $\sqrt{s}$ (increased production) and 25 ns bunch spacing (lower pile up)
- During LS1: some subdetector consolidation; new HERSCHEL forward shower counters; change of data flow in trigger
First signals from Run II

\[ D \rightarrow K\pi \]

\[ D \rightarrow K\pi\pi \]

\[ D^* \rightarrow D\pi; D \rightarrow K\pi \]

LHCb preliminary 
\( \sqrt{s} = 13 \text{ TeV} \)

It works!

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Beyond Run II – the LHCb Upgrade

- Beyond LHC Run II, the data-doubling time for LHCb becomes too long
  - Due to 1 MHz readout limitation and associated hardware (L0) trigger
- However, there is an excellent physics case to push for improved precision and an ever-broader range of observables
- Will upgrade the LHCb detector in the LHC LS2 (2018-20)
  - Upgrade subdetector electronics to 40 MHz readout
  - Make all trigger decisions in software
  - Operation at much higher luminosity with improved efficiency
    - order of magnitude improvement in precision (compared to today)
- Upgrade will be performed during LSII (now expected to be 2019-20)
  - Restart data taking in 2021 at instantaneous luminosity up to 2 \(10^{33}/cm^2/s\)
  - Upgrade detector qualified to accumulate 50/fb
LHC upgrade and the all important trigger

- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at $L_{\text{inst}}$ up to $2 \times 10^{33}/\text{cm}^2/\text{s}$
LHC upgrade and the all important trigger

- readout detector at 40 MHz
- implement trigger fully in software → efficiency gains
- run at $L_{\text{inst}}$ up to $2 \times 10^{33} \text{cm}^{-2}/\text{s}$
LHCb detector upgrade

- RICH 1 redesigned; new photodetectors for RICH 1 and RICH 2
- Replacement of full tracking system
- Calorimetry and muons: - Redundant components of system removed; new electronics added; more shielding included
- Novel trigger and offline data management strategies
Table 28: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the expected sensitivity is given for the integrated luminosity accumulated by the end of LHC Run 1, by 2018 (assuming 5 fb\(^{-1}\) recorded during Run 2) and for the LHCb Upgrade (50 fb\(^{-1}\)). An estimate of the theoretical uncertainty is also given – this and the potential sources of systematic uncertainty are discussed in the text.

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_s^0 ) mixing</td>
<td>( \phi_s(B_s^0 \rightarrow J/\psi \phi) ) (rad)</td>
<td>0.050</td>
<td>0.025</td>
<td>0.009</td>
<td>( \sim 0.003 )</td>
</tr>
<tr>
<td></td>
<td>( \phi_s(B_s^0 \rightarrow J/\psi f_0(980)) ) (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>( \sim 0.01 )</td>
</tr>
<tr>
<td></td>
<td>( A_{s}(B_s^0) ) (10(^{-3}))</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
</tr>
<tr>
<td>Gluonic penguin</td>
<td>( \phi_s^{\text{eff}}(B_s^0 \rightarrow \phi \phi) ) (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.023</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>( \phi_s^{\text{eff}}(B_s^0 \rightarrow K^{*0}K^{*0}) ) (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.029</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>( 2\beta^{\text{eff}}(B_s^0 \rightarrow \phi K_s^0) ) (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.04</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>( \phi_s^{\text{eff}}(B_s^0 \rightarrow \phi \gamma) )</td>
<td>0.20</td>
<td>0.13</td>
<td>0.030</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>( \tau^{\text{eff}}(B_s^0 \rightarrow \phi \gamma)/\tau_{B_s^0} )</td>
<td>5%</td>
<td>3.2%</td>
<td>0.8%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguin</td>
<td>( S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4) )</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>( q_0^2 A_{FB}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) )</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>( \sim 7% )</td>
</tr>
<tr>
<td></td>
<td>( A_1(K^{+}\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4) )</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>( \sim 0.02 )</td>
</tr>
<tr>
<td></td>
<td>( B(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/B(B^+ \rightarrow K^+ \mu^+ \mu^-) )</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>( \sim 10% )</td>
</tr>
<tr>
<td>Higgs penguin</td>
<td>( B(B_s^0 \rightarrow \mu^+ \mu^-) ) (10(^{-9}))</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>( B(B_s^0 \rightarrow \mu^+ \mu^-)/B(B_s^0 \rightarrow \mu^+ \mu^-) )</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>( \sim 5% )</td>
</tr>
<tr>
<td>Unitarity triangle</td>
<td>( \gamma(B \rightarrow D^{(<em>)}K^{(</em>)}) )</td>
<td>7(^{\circ})</td>
<td>4(^{\circ})</td>
<td>1.1(^{\circ})</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>( \gamma(B_s^0 \rightarrow D \pm K \mp) )</td>
<td>17(^{\circ})</td>
<td>11(^{\circ})</td>
<td>2.4(^{\circ})</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>( \beta(B_s^0 \rightarrow J/\psi K_s^0) )</td>
<td>1.7(^{\circ})</td>
<td>0.8(^{\circ})</td>
<td>0.31(^{\circ})</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>( A_T(D^0 \rightarrow K^+K^-) ) (10(^{-4}))</td>
<td>3.4</td>
<td>2.2</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>( \Delta A_{CP} ) (10(^{-3}))</td>
<td>0.8</td>
<td>0.5</td>
<td>0.12</td>
<td>–</td>
</tr>
</tbody>
</table>
Studies for ECFA HL-LHC workshop

Table 2: Expected sensitivities that can be achieved on key heavy flavour physics observables, using the total integrated luminosity recorded until the end of each LHC run period. Discussion of systematic uncertainties is given in the text. Uncertainties on $\phi_s$ are given in radians. The values for flavour-changing neutral-current top decays are expected 95% confidence level upper limits in the absence of signal.

<table>
<thead>
<tr>
<th>$B(B^{0}\rightarrow \mu^{+}\mu^{-})$</th>
<th>$B(B^{0}_{s}\rightarrow \mu^{+}\mu^{-})$</th>
<th>$q_0^2 A_{FB}(K^{*0}\mu^{+}\mu^{-})$</th>
<th>$\phi_s(B^{0}_{s}\rightarrow J/\psi\phi)$</th>
<th>$\phi_s(B^{0}_{s}\rightarrow \phi\phi)$</th>
<th>$\gamma$</th>
<th>$A_{\Gamma}(D^{0}\rightarrow K^{+}K^{-})$</th>
<th>$t\rightarrow qZ$</th>
<th>$t\rightarrow q\gamma$</th>
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</tr>
<tr>
<td>CMS</td>
<td>&gt; 100%</td>
<td>71%</td>
<td>47%</td>
<td>...</td>
<td>21%</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>LHCb</td>
<td>220%</td>
<td>110%</td>
<td>60%</td>
<td>40%</td>
<td>28%</td>
<td>3/fb</td>
<td>8/fb</td>
<td>23/fb</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10%</td>
<td>5%</td>
<td>2.8%</td>
<td>1.9%</td>
<td>1.3%</td>
<td>3/fb</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25/fb</td>
<td>100/fb</td>
<td>300/fb</td>
<td>46/fb</td>
<td>70/fb (?)</td>
<td>70/fb (?)</td>
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<tr>
<td>LHCb</td>
<td>10%</td>
<td>5%</td>
<td>2.8%</td>
<td>1.9%</td>
<td>5%</td>
<td>3/fb</td>
<td>8/fb</td>
<td>23/fb</td>
</tr>
<tr>
<td>Belle II</td>
<td>—</td>
<td>50%</td>
<td>7%</td>
<td>5%</td>
<td>—</td>
<td>3/fb</td>
<td>8/fb</td>
<td>23/fb</td>
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<tr>
<td>ATLAS</td>
<td>0.11</td>
<td>0.05-0.07</td>
<td>0.04-0.05</td>
<td>...</td>
<td>0.020</td>
<td>3/fb</td>
<td>8/fb</td>
<td>23/fb</td>
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<td>0.025</td>
<td>0.013</td>
<td>0.009</td>
<td>0.006</td>
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<td>8/fb</td>
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<td>0.18</td>
<td>0.12</td>
<td>0.04</td>
<td>0.026</td>
<td>0.017</td>
<td>3/fb</td>
<td>8/fb</td>
<td>23/fb</td>
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<tr>
<td></td>
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<td>4°</td>
<td>1.7°</td>
<td>1.1°</td>
<td>0.7°</td>
<td>3/fb</td>
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<tr>
<td></td>
<td>1°</td>
<td>11°</td>
<td>2°</td>
<td>1.5°</td>
<td>—</td>
<td>3/fb</td>
<td>8/fb</td>
<td>23/fb</td>
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<tr>
<td></td>
<td>3.4 x 10^{-3}</td>
<td>2.2 x 10^{-4}</td>
<td>0.9 x 10^{-4}</td>
<td>0.5 x 10^{-4}</td>
<td>0.3 x 10^{-4}</td>
<td>3/fb</td>
<td>8/fb</td>
<td>23/fb</td>
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<td></td>
<td></td>
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<td>4-6 x 10^{-4}</td>
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<td>3/fb</td>
<td>8/fb</td>
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<td>7.8 x 10^{-5}</td>
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</tr>
</tbody>
</table>

LHCb ∫ L dt 3/fb 8/fb 23/fb 46/fb 70/fb (?)
ATLAS/CMS ∫ L dt 25/fb 100/fb 300/fb ...

Tim Gershon
CPV and rare decays
Beyond the LHCb Upgrade

• LHCb upgrade is qualified for 50/fb
  - Anticipate to accumulate this data set approximately by LS4
  - Essential to prove that 40 MHz readout works

• The HL-LHC will run well beyond LS4
  - It will be the most copious source of heavy flavoured particles (inter alia) for many years

• Is there a physics case to operate a forward spectrometer at $O(10^{34}/\text{cm}^2/\text{s})$, and accumulate $O(500/fb)$?
  - ECFA HL-LHC studies give a mandate to think about this
  - Many conventional flavour observables become systematics or theory limited
  - Need to think “out of the box”. Possible ideas:
    • $B_s \rightarrow \mu\mu$ effective lifetime, $H \rightarrow c\bar{c}$, … your thoughts welcome!
Summary

• A great harvest of physics from LHC Run I
• LHCb expanding from its core physics programme
  – results on modes with electrons, photons, neutral pions and neutrinos
  – also top, heavy ion physics, central exclusive production, lots of baryons, charm ... (not enough time to cover everything today, or any day)
  – in some cases doing things previously thought impossible
• Several hints of BSM effects
  – $R(D^*)$, $R_K$, $B(B_s \rightarrow \phi \mu \mu)$, $B(\Lambda_b \rightarrow \Lambda \mu \mu)$, $P_5$' ... does a consistent picture emerge?
• Run II is starting, and prospects look good
• Excellent progress on the LHCb upgrade
  – We are just getting started ...