Rare b and c decays at LHCb

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Diverse physics program studying decays of $b, c, s$ hadrons

(Non-exhaustive) sampling:

- EW penguins
- Lepton flavor universality tests
- Radiative decays
- Baryonic decays
- Very rare decays
- Rare charm decays
- Searches for lepton flavor violation

Many recent results - will only cover a few in this talk!

(Diego Martinez Santos will cover recent results on LFV and rare kaon decays)
RARE DECAYS

- ‘Flavor-changing neutral current’ (FCNC) transitions
- Proceed via electroweak loops; suppressed in the SM
- New particles could also contribute at loop level

Potential effects observed via:

- Anomalies in decay rates, differential branching fraction measurements
- Analyses of angular distributions
- Tests of lepton flavor universality and lepton flavor violation
\[ B(0) \rightarrow \mu^+ \mu^- \] DECAYS

- \( b \rightarrow ll \) transitions are additionally helicity-suppressed
  - Very rare in the SM; excellent probes of NP
- Search for \( B(0) \rightarrow \mu^+ \mu^- \) carried out with 4.4 fb\(^{-1} \) of data
  - Theoretically and experimentally clean
  - First single-experiment observation of \( B_s \rightarrow \mu^+ \mu^- \) decays (at 7.8 \( \sigma \))
  - Limit set on \( B^0 \rightarrow \mu^+ \mu^- \) BF
- Measurement of effective lifetime in \( B_s \rightarrow \mu^+ \mu^- \) decays offers complementary probe of NP effects
  - In the SM, only heavy mass eigenstate decays to \( \mu^+ \mu^- \)

\[ B(B_s^0 \rightarrow \mu^+ \mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9} \]
\[ \tau(B_s^0 \rightarrow \mu^+ \mu^-) = 2.04 \pm 0.44 \pm 0.05 \text{ ps} \]
\[ B(B^0 \rightarrow \mu^+ \mu^-) < 3.4 \times 10^{-10} \ [95\% \ C.L] \]

- All results consistent with SM expectations

\[ [\text{Candidates} / (50 \text{ MeV/c}^2)] \]

\[ [\text{Total, } B^0 \rightarrow \mu^+ \mu^-, \text{ Combinatorial, } B_s^0 \rightarrow h'^+ h'] \]

\[ [\text{LHCb}, BDT > 0.5] \]

\[ [\text{Weighted } B^0 \rightarrow \mu^+ \mu^- \text{ candidates} / (1 \text{ ps})] \]

\[ [\text{LHCb, Effective lifetime fit}] \]
Consistent pattern of deviations from SM predictions

JHEP 06 (2014) 133

JHEP 06 (2015) 115

JHEP 11 (2016) 047

JHEP 09 (2015) 179
• Ratios of $B \rightarrow hll$ decays are clean probes of NP

• Hadronic uncertainties cancel

• Analysis performed with $B^0 \rightarrow K^{*0}ll$ decays (where $K^{*}(892)^0 \rightarrow K^+\pi^-$ and $l=e,\mu$) in two bins of invariant mass squared

\[
R_{K^{*0}} \left[ q^2_{\min}, q^2_{\max} \right] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{dq^2}}{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 \frac{d\Gamma(B^0 \rightarrow K^{*0} e^+ e^-)}{dq^2}}
\]

• Double ratio with $B^0 \rightarrow K^{*0} J/\psi$ reduces systematic uncertainties

\[
R_{K^{*0}} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow \mu^+ \mu^-))} \bigg/ \frac{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} J/\psi(\rightarrow e^+ e^-))}
\]

• However, extremely challenging due to differences in trigger/reconstruction for electrons and muons
• Electron reconstruction challenging due to bremsstrahlung; momentum and mass resolution degraded
• Recover by adding ECAL clusters to extrapolated upstream electron track
  • Limited by calorimeter acceptance, energy threshold ($E_T > 75$ MeV)
• Worse B mass resolution in the electron channel
• $J/\psi$ backgrounds leak into signal region
Analysis strategy:

- Keep selection as similar as possible for electron, muon channels
  - Multivariate classifier to reject combinatorial background
  - Veto for peaking backgrounds
- Signal efficiencies determined from simulation corrected using data-driven techniques
- Normalisation channel used to correct signal mass shapes
- Hardware trigger $E_T$ thresholds are higher for electrons than for muons
  - Analysis performed for three exclusive trigger categories

\[
R_{K^*0} = \begin{cases} 
0.66^{+0.11}_{-0.07} \text{ (stat)} \pm 0.03 \text{ (syst)} & \text{for } 0.045 < q^2 < 1.1 \text{ GeV}^2/c^4 \\
0.69^{+0.11}_{-0.07} \text{ (stat)} \pm 0.05 \text{ (syst)} & \text{for } 1.1 < q^2 < 6.0 \text{ GeV}^2/c^4 
\end{cases}
\]

- Compatible with the SM at 2.1$\sigma$ - 2.3$\sigma$ (2.4$\sigma$ - 2.5$\sigma$) in the low (central) $q^2$ bin
- Measurement is statistically dominated
GLOBAL FITS

Results from $b \rightarrow sll$, $b \rightarrow ll$ and $b \rightarrow s\gamma$ transitions interpreted by global fits to Wilson coefficients

- Includes ~100 observables from multiple experiments
- All fits require additional (non-SM) contribution
- NP in $C_9$-$C_{10}$ favored at ~3.5$\sigma$ from $R(K^{(*)})$ results considered alone
- Adding in other results, $C_9$ favored at ~5$\sigma$

arXiv:1705.06274
PHASE DIFFERENCE IN $B^+ \rightarrow K^+ \mu^+ \mu^-$ DECAYS

- Vector-like resonances that produce di-muon pairs could mimic NP:
  \[ C_9^{\text{eff}} = C_9 + \sum_j \eta_j e^{i\delta_j} A_j(q^2) \]
- Perform a full fit of the di-muon invariant mass spectrum:
  - Resonances described by sum of relative Breit-Wigners, short-distance contribution modeled with EFT description of decay
  - Magnitudes, relative phases between short-distance component and resonances allowed to vary in fit
  - Four ~degenerate solutions for unknown $J/\psi$ and $\psi(2S)$ phases
- Measured phases of $J/\psi$, $\psi(2S)$ indicate that interference with short-distance component in regions away from their pole masses is small
- Exclusion of $C_9=0$ hypothesis at 5 $\sigma$

![Graph showing di-muon invariant mass spectrum](image)

![Graph showing candidates per unit mass](image)
SEARCH FOR $B_s \rightarrow \bar{K}^*\mu^+\mu^-$ DECAYS

- $b \rightarrow d\ell\ell$ transitions are additionally suppressed by CKM factor
- Provide information complementary to studies of $b \rightarrow s\ell\ell$ decays
- Search for $B_s \rightarrow K^*\mu^+\mu^-$ carried out with $4.6 \text{ fb}^{-1}$ of data collected in 2011, 2012 and 2016
- $B_s \rightarrow K^*J/\psi [\rightarrow \mu^+\mu^-]$ decays used as a normalization channel
- First evidence (at 3.4 $\sigma$) for this decay, with a measured breaching fraction

$$\mathcal{B}(B_s \rightarrow \bar{K}^*\mu^+\mu^-) = (3.0 \pm 1.0(\text{stat}) \pm 0.2(\text{sys}) \pm 0.3(\text{norm})) \times 10^{-8}$$
Search for $\Lambda_c^+ \rightarrow p\mu^+\mu^+$ Decays

- Search for rare charm baryonic decay $\Lambda_c^+ \rightarrow p\mu^+\mu^+$ performed with 3 fb$^{-1}$ of data
- BR of short distance $c \rightarrow u$ll contribution expected to be $\sim 10^{-9}$ in the SM
- Expected long-distance contribution via intermediate di-muon resonance enhanced in the SM ($\sim 10^{-6}$)
- Analysis performed in three regions of di-muon invariant mass:
  - $\Lambda_c^+ \rightarrow p\phi$ decays used as a normalization channel
  - Searches performed in region around $\omega$ invariant mass region, and non-resonant region
- No significant excess seen in non-resonant channel, limits set at 90% (95%) CL:
  - $\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 7.7 \,(9.6) \times 10^{-8}$
- First observation of the $\Lambda_c^+ \rightarrow p\mu^+\mu^+$ decay at 5$\sigma$ in the $\omega/\rho$ invariant mass region:
  - $\mathcal{B}(\Lambda_c^+ \rightarrow p\omega) = (9.4 \pm 3.2 \,(\text{stat}) \pm 1.0 \,(\text{syst}) \pm 2.0 \,(\text{ext})) \times 10^{-4}$
ASYMMETRIES IN $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ DECAYS

- Total amplitude dominated by long-distance contributions from decays via intermediate resonances
- Study of decay asymmetries increases sensitivity to short-distance effects

- System can be characterized in terms of two invariant masses ($m_{hh}$ and $m_{\mu\mu}$) and three angles ($\theta_h$, $\theta_\mu$ and $\phi$)
  - Forward-backward asymmetry $A_{FB}$, charge asymmetry $A_{CP}$, and triple-product asymmetry $A_\phi$ could have high sensitivity to NP effects
ASYMMETRIES IN $D^0 \rightarrow h^+ h^- \mu^+ \mu^-$ DECAYS

• Analysis performed with 5 fb$^{-1}$ of data collected in 2011-2016

• Signal studied in regions of di-muon invariant mass defined by resonances
  • Asymmetry computed only in regions where significant yield was previously observed (arXiv: 1707.08377)

• BDT used to reject combinatorial background, peaking backgrounds from double mis-id in $D^0 \rightarrow hh\pi\pi$ decays suppressed with muon ID criteria

• Measurements consistent with SM predictions:
  $$A_{FB}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (3.3 \pm 3.7 \pm 0.6)\%,$$
  $$A_{\phi}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (-0.6 \pm 3.7 \pm 0.6)\%,$$
  $$A_{CP}(D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-) = (4.9 \pm 3.8 \pm 0.7)\%,$$
  $$A_{FB}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%,$$
  $$A_{\phi}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (9 \pm 11 \pm 1)\%,$$
  $$A_{CP}(D^0 \rightarrow K^+ K^- \mu^+ \mu^-) = (0 \pm 11 \pm 2)\%.$$
SUMMARY

- Wide variety of measurements and searches performed with the Run 1 LHCb dataset

- No direct evidence of NP (yet) from a single measurement/search

- Consistent anomalies seen in LFU measurements, BF measurements, angular analyses of $b \rightarrow sll$ transitions

- Analyses are statistically limited - LHCb Run 2 dataset will more than double existing statistics

- Enables the study of very rare baryonic decays and $b \rightarrow dll$ processes, offering complementary information on potential NP effects

- First analyses ready, more results to come soon!
BACKUP
The LHCb Detector

Single-arm spectrometer instrumented in the forward ($2 < \eta < 5$) region
Trigger system:

Initial hardware trigger (L0), using information from calorimeters and muon system

Software trigger split into two stages: fast partial event reconstruction + subsequent full reco.

Low luminosity $\rightarrow$ can trigger on relatively low pT objects
THE LHCb DETECTOR

✦ 3 fb\(^{-1}\) collected in Run 1
  ✦ Dataset used for most analyses shown today
✦ To date, a total of \(~7\ fb\(^{-1}\) has been collected
✦ Measurements/searches with Run 2 data underway

![LHCb Integrated Recorded Luminosity in pp, 2010-2018](chart.png)
Effective Hamiltonian described by an operator product expansion:

\[ H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i [C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu)] \]

- \( C_i(\mu) \) (left handed) - long-distance effects (non-perturbative)
- \( C'_i(\mu) \) (right handed) - perturbative, short-distance physics

Operators (\( O_i \)):
- \( i = 1, 2 \): Tree
- \( i = 3-6, 8 \): Gluon penguin
- \( i = 7 \): Photon penguin
- \( i = 9, 10 \): Electroweak penguin
- \( i = S \): Higgs (scalar) penguin
- \( i = P \): Pseudoscalar penguin

Different regions of \( q^2 \) probe different processes.
R(K*)

- Yields obtained from fit to the invariant mass
- Precision dominated by statistics in electron channel

**low q\(^2\)**

![Graph with data points and fit curves for candidate distributions in low q\(^2\) region.]

\((285 \pm 18)\)

**central q\(^2\)**

![Graph with data points and fit curves for candidate distributions in central q\(^2\) region.]

\((353 \pm 21)\)

**normalisation channel**

![Graph with data points and fit curves for candidate distributions in normalisation channel.]

\(~274,000~\)

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\(LHCb\)

\(\bar{B}^0 \rightarrow K^0 \mu^+\mu^-\)  

Combinatorial

\(0.045 < q^2 < 1.1\) [GeV\(^2/c^4\)]

\((89 \pm 11)\)

\(B^0 \rightarrow K^0 e^+e^-\)  

Combinatorial  

\(B \rightarrow X e^+e^-\)

\(0.045 < q^2 < 1.1\) [GeV\(^2/c^4\)]

\((111 \pm 14)\)

\(B^0 \rightarrow K^0 \Lambda^0 J/\psi\)  

Combinatorial  

\(\Lambda^0 \rightarrow K^+\pi J/\psi\)

\(B^0 \rightarrow K^0 J/\psi\)

\(~58,000~\)

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R(K*)

- Yields obtained from fit to the invariant mass
- Precision dominated by statistics in electron channel

**low q^2**

LHCb

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Combinatorial

$0.045 < q^2 < 1.1$ [GeV$^2$/c$^4$]

(285 ± 18)

**central q^2**

LHCb

- $B^0 \rightarrow K^{*0} \mu^+ \mu^-$
- Combinatorial

$1.1 < q^2 < 6.0$ [GeV$^2$/c$^4$]

(353 ± 21)

**normalisation channel**

LHCb

- $B^0 \rightarrow K^{*0} J/\psi$
- Combinatorial

$0.045 < q^2 < 1.1$ [GeV$^2$/c$^4$]

0.045 < $q^2$ < 1.1 [GeV$^2$/c$^4$]

~274,000

(89 ± 11)

LHCb

- $B^0 \rightarrow K^{*0} e^+ e^-$
- Combinatorial

1.1 < $q^2$ < 6.0 [GeV$^2$/c$^4$]

(111 ± 14)

~58,000

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• Analysis performed with 3 fb⁻¹ of data

\[ R_K = \frac{\int \frac{d\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{dq^2} dq^2}{\int \frac{d\Gamma(B^+ \to K^+ e^+ e^-)}{dq^2} dq^2} \]

• Signal in \( q^2 \) range [1,6] GeV²/c⁴

• \( R(K) \) value compatible with SM at 2.6σ