B decay anomalies at LHCb

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Outline

• Introduction
• The LHCb experiment
• Rare B decays
• Semileptonic B decays
• Conclusions
Introduction

• In the Standard Model of Particle Physics, transitions between different quarks are governed by the CKM mechanism:

\[ V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \]

• The amplitude of a hadron decay process can be described using Effective Field Theories: Operator Product Expansion (OPE)

\[ A(M \to F) = \langle F | \mathcal{H}_{\text{eff}} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V_{\text{CKM}}^i C_i(\mu) \langle F | O_i(\mu) | M \rangle \]
\[ A(M \rightarrow F) = \langle F | H_{\text{eff}} | M \rangle = \frac{G_F}{\sqrt{2}} \sum_i V^{i}_{CKM} C_i(\mu) \langle F | O_i(\mu) | M \rangle \]

CKM couplings
Wilson Coefficients 
(\( \mu = \text{scale} \))
Hadronic Matrix Elements

\( \rightarrow \) OPE: a series of effective vertices multiplied by effective coupling constants \( C_i \).

\[ q \quad q' \quad g \quad \ell \quad \ell' \quad O_7 \quad O_{9,10} \quad O_8 \quad O_{1\ldots6} \]

Electroweak scale \( \sim 1/M_W \)
New Physics scale \( \sim 1/M_{NP} \)

\[ C_i = C_i^{SM} + C_i^{NP} \]

\[ C'_i = C'_i^{SM} + C'_i^{NP} \]

Primed \( C'_i \rightarrow \) right handed currents: suppressed in SM
Why B decays?

- The $b$-quark is the heaviest quark forming hadronic bound states ($m \approx 4.7$ GeV)
- Must decay outside the 3rd family
  - Long lifetime (~1.6 ps)
  - Many accessible decay channels (small BR’s)
- Type of processes:
  - Dominant: $b \rightarrow c$ (favoured) and $b \rightarrow u$ (suppressed)
  - Rare: Flavour Changing Neutral Current (FCNC): $b \rightarrow s, d$
  - Flavour oscillations and CP violation

Ideal place to probe New Physics effects!

Good for experimentalists!

Good for theorists!
The LHCb experiment
The LHCb experiment

- The $b\bar{b}$ cross section in pp collisions is large, mainly from gluon fusion:
  $\sim 300 \mu$b @ $\sqrt{s}=7$ TeV
  $\sim 600 \mu$b @ $\sqrt{s}=13$ TeV

- The LHCb idea: to build a single-arm forward spectrometer:
  $\sim 4\%$ of the solid angle ($2 < \eta < 5$),
  $\sim 30\%$ of the $b$ hadron production

- The $b$ quarks hadronize in $B$, $B_s$, $B^{*}$, $b$-baryons...
  $\rightarrow$ average $B$ meson momentum $\sim 80$ GeV

Letter of Intent, 1995
The LHCb experiment

LHCb, ATLAS & CMS

$|\eta| < 2.4$
$\sigma_{P_T} \sim 0.7 - 1.5\%$
$\sigma_{IP_{\perp}} \sim 25 - 100 \mu m$
Very good PID (fake < 0.1%)

$2 < \eta < 5$
$\sigma_{P} \sim 0.5 - 1\%$
$\sigma_{IP_{\perp}} \sim 15 - 50 \mu m$
Good PID (fake < 3%)

$|\eta| < 2.5$
$\sigma_{P_T} \sim 1.3 - 3.8\%$
$\sigma_{IP_{\perp}} \sim 25 - 100 \mu m$
Rare B decays

- $b \to s, d$ quark transitions are Flavor Changing Neutral Currents (FCNCs), 
- in the SM they only can occur through loops (penguin and box diagrams),
- excellent probe for physics beyond the SM

\begin{itemize}
  \item **leptonic**
    \[
    \text{BR} \sim 10^{-9}
    \]
  \item **semileptonic**
    \[
    \text{BR} \sim 10^{-7}
    \]
  \item **radiative**
    \[
    \text{BR} \sim 10^{-5}
    \]
\end{itemize}

Experimentally → leptons/photons with high transverse momenta
Theoretically → observables can be calculated in terms of Wilson coefficients

\[\Gamma\left(B_s^0 \to \mu^+ \mu^\text{-}\right) \sim \frac{\alpha^2}{64\pi^3} \frac{m_{B_s}^2 f_{B_s}^2}{2} \left|V_{tb} V_{ts}\right|^2 \left|2m_\mu C_{10}\right|^2\]

Hadronic uncertainties in decay constants or form factors
Rare B decays: $B_s \rightarrow \mu^+\mu^-$

- Very rare decay:
  FCNC and helicity suppressed
  $BR_{SM} = 3.66(23) \times 10^{-9}$

- Searched for over the last 30 years, observed by LHCb and CMS

- Updated analysis by LHCb, including Run2 data
  [PRL 118 (2017) 191801]

- $B_s \rightarrow \tau^+\tau^-$ also searched for at LHCb:
  $\mathcal{B}(B_s^0 \rightarrow \tau^+\tau^-) < 6.8 \times 10^{-3}$ at 95%
  [PRL 118 (2017) 251802]
**Rare B decays: $B_s \rightarrow \mu^+ \mu^-$**

- New result from ATLAS!
  - ATLAS-CONF-2018-046
- Run II data (2015+2016):
  - 26.3 fb\(^{-1}\) at 13 TeV
- Combined with the Run I result:
  - [ATLAS, EPJ C76 (2016) 513]

\[ \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9} \]

\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 2.1 \times 10^{-10} \]

- Measurements in agreement with the SM
- Theoretical uncertainties ($f_{B(s)}, V_{\text{CKM}}$) well below statistical uncertainty
Rare $B$ decays: $B_s \rightarrow \mu^+\mu^-$

We are here!
Rare B decays: $B \to K(\ast)\mu^+\mu^-$

Differential decay width: $d\Gamma/dq^2$

Each $q^2$ region probes different processes

$q^2 = (p_{\ell^+} + p_{\ell^-})^2$

Photon pole

$J/\psi (1S)$

$\psi (2S)$

charmonium resonances $c\bar{c} \to \ell^-\ell^+$

$C_7^{(r)}$

$C_9^{(r)}$

$C_7^{(i)}$, $C_9^{(i)}$

$C_9^{(r)}$, $C_10^{(r)}$

$C_9^{(i)}$, $C_10^{(i)}$

$C_7^{(i)}$

$C_7^{(r)}$, $C_9^{(r)}$

$C_9^{(i)}$, $C_10^{(i)}$

$\mu=m_b$:

$C_7 \sim 0.33$

$C_9 \sim 4.27$

$C_{10} \sim -4.17$

(Everything else small or negligible)

$C_i = C_i^{SM} + C_i^{NP}$

(Primed $C_i \to$ right handed currents: suppressed in SM)
Rare B decays: $B \to K^{(*)} \mu^+ \mu^-$

$B_0 \to K^{*0} \mu^+ \mu^-$

$\psi(2S)$

$J/\psi$

$\psi(1S)$

$J/\psi(1S)$

$\psi(2S)$

$C_7^{(0)}, C_1^{(0)}$

$C_9^{(0)}, C_{10}^{(0)}$

$J^P = 0^-$

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

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$B^0 \to K^0 \mu^+ \mu^-
Rare B decays: $B \to K(\ast)\mu^+\mu^-$

- Differential decay width as function of $q^2 = m_{\mu\mu}^2$ at LHCb, using 3fb$^{-1}$

→ Smaller branching fractions than the SM predictions
Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

- Also measured by CMS in the $B \to K^*\mu^+\mu^-$ channel [PLB 753 (2016) 424]
- 20.5 fb$^{-1}$, 1430 signal decays

$\rightarrow$ Smaller branching fractions than the SM predictions?
$\rightarrow$ Compatible with other experiments, competitive accuracy with LHCb

$\rightarrow$ Results dominated by statistical uncertainties (including the BR of the normalization channels)
$\rightarrow$ Caveat: theory affected by hadronic uncertainties (LQCD + LCSR)
Rare B decays: $B \rightarrow K^{(*)} \mu^+ \mu^-$

- Angular distribution in $B \rightarrow K^* \ell^- \ell^+$: $q^2$ and three angles

$$
\frac{1}{d\Gamma/dq^2} \frac{d^4\Gamma}{d\cos\theta_{\ell} \ d\cos\theta_K \ d\phi \ dq^2} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_{\ell}
- F_L \cos^2 \theta_K \cos 2\theta_{\ell} + S_3 \sin^2 \theta_K \sin^2 \theta_{\ell} \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_{\ell} \cos \phi
+ S_5 \sin 2\theta_K \sin \theta_{\ell} \cos \phi + S_6 \sin^2 \theta_K \cos \theta_{\ell} + S_7 \sin 2\theta_K \sin \theta_{\ell} \sin \phi
+ S_8 \sin 2\theta_K \sin 2\theta_{\ell} \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_{\ell} \sin 2\phi \right]
$$

→ In the lepton massless limit there are eight independent observables:

- $F_L =$ fraction of the longitudinal polarization of the $K^*$
- $S_6 = 4/3 \ A_{FB},$ the forward-backward asymmetry of the dimuon system
- $S_{3,4,5,7,8,9}$ are the remaining CP-averaged observables

→ They can be further reduced by folding over $\phi$ (if statistics is small)
Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

- These observables are also affected by hadronic uncertainties
- A new set of “optimized observables”, with form factor cancellations can be defined:  
  \[ P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L (1 - F_L)}} \]

- These observable are functions of $q^2$ and the Wilson coefficients $C_i$

Example: $P'_5$

3$\sigma$ local deviation
Recent results by CMS and ATLAS in the $B^0 \rightarrow K^* \mu^+ \mu^-$ decay channel


(CMS and ATLAS fit simultaneously only a subset of the amplitude parameters)
Rare B decays: $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$

→ New: results from LHCb in the $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ decay channel  
Run1 + Run2 data: 5fb$^{-1}$

$$\frac{d^5 \Gamma}{d\Omega} = \frac{3}{32\pi^2} \sum_{i}^{34} K_i(q^2) f_i(\Omega)$$

5 angles and 1 normal vector $\vec{n}$

Depends on many observables ($K_i$)

Obtained from method of moments

$$15 < q^2 < 20 \text{ GeV}^2$$

In general compatible with SM predictions

[Boër et al, JHEP 01 (2015) 155],  
Rare B decays: \( R_K \)

- In the SM all leptons are expected to behave in the same way

**Test of lepton universality:**

\[
R_K = \frac{\mathcal{B}(B^+ \rightarrow K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \rightarrow K^+e^+e^-)} = 1.000 + O(m_\mu^2/m_b^2)
\]

- Precise theory prediction due to cancellation of hadronic form factor uncertainties

- Challenge: bremsstrahlung by electrons

- Experimentally, use the \( B^+ \rightarrow K^+J/\psi(\rightarrow e^+e^-) \) and \( B^+ \rightarrow K^+J/\psi(\rightarrow \mu^+\mu^-) \) to perform a double ratio

1 GeV < \( q^2 < 6 \) GeV  \[\text{[PRL 113 (2014) 151601]}\]

\[
R_K = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}
\]

→ Consistent, but lower, than the SM at \( 2.6\sigma \)
Rare B decays: $R_{K^*}$

- Measurement in the $B \rightarrow K^* \mu^+ \mu^-$ channel, $R_{K^*}$:

$$R_{K^*0} = \frac{\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{\mathcal{B}(B^0 \rightarrow K^{*0} e^+ e^-)}$$

- Computed in two bins of $q^2$
  - $[0.045, 1.1 \text{ GeV}^2]$ avoiding the photon pole
  - $[1.1, 6.0 \text{ GeV}^2]$ avoiding the radiative tail of $J/\psi$ modes

$0.045 \text{ GeV} < q^2 < 1.1 \text{ GeV}$ 
$1.1 \text{ GeV} < q^2 < 6 \text{ GeV}$
Rare B decays: $R_{K^*}$

- Results: [JHEP 08 (2017) 055]

Low $q^2$ [0.045-1.1 GeV$^2$]: $\text{SM} \downarrow = 0.922(22)$

$$R_{K^*0} = 0.66 \pm 0.11 \pm 0.07 \text{ (stat) } \pm 0.03 \text{ (syst)}$$

Central $q^2$: [1.1-6 GeV$^2$]: $\text{SM} \downarrow = 1.000(6)$

$$R_{K^*0} = 0.69 \pm 0.11 \pm 0.07 \text{ (stat) } \pm 0.05 \text{ (syst)}$$

→ Consistent, but lower than the SM at 2.1-2.3σ (low $q^2$) and 2.4-2.5σ (central $q^2$)
Rare B decays: $B_s \to \phi \gamma$

- Time dependent distribution for $B_s \to \phi \gamma$ is sensitive to the photon polarization (predicted to be right-handed in the SM)

$|\mathcal{A}_{\text{SM}}| = 0.047 \pm 0.029$

$\Delta \mathcal{A} = -0.98^{+0.46+0.23}_{-0.52-0.20}$

→ Compatible with the SM within $2\sigma$
Rare B decays

Global fits (some cases with more than 100 observables)

New Physics hypothesis preferred over SM by more than 4 - 5σ
Main effect on the $C_{9\mu}$ coefficient: $4.27^{\text{SM}} - 1.1^{\text{NP}}$

Triggered models with $Z'$, leptoquarks (LQ), new fermions and scalars....
Semileptonic B decays
Semileptonic B decays: $R_D, R_{D^*}$

- Another test of lepton universality (now at tree level):

Ratio of semi-tauonic and semi-muonic branching fractions:

$$R(D^*) = \frac{\mathcal{B}(\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B}^0 \to D^{*+} \mu^- \bar{\nu}_\mu)}$$

Sensitive to charged Higgs bosons and leptoquarks

**SM predictions very precise:**  (V$_{cb}$ and form factors (partially) cancel)

- $R(D)_{SM} = 0.299 \pm 0.003$
- $R(D^*)_{SM} = 0.252 \pm 0.003$

Based on HQET form factors:
- [H. Na et al., PRD 92 (2015) 054510]
- and experimental measurements (HFLAV)
- [D.Bigi, Gambino, PRD 94 (2016) 094008]
Semileptonic B decays

**BaBar** measured an excess of $B^0 \to D^{(*)} \tau^- \nu_\tau$ (3\sigma away from SM!) [PRD 88 (2013) 072012] [Nature 546 (2017) 227]

### \( R(D^*) \)
- $B^0 \to D^{*+} \tau^- \bar{\nu}_\tau$, with $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ [PRL 115 (2015) 111803]
- $B^0 \to D^{*-} \tau^+ \nu$, with $\tau^+ \to \pi^+ \pi^- \pi^+(\pi^0) \bar{\nu}_\tau$ [PRL 120 (2018) 171802]

### LHCb:
- $B^{0} \to D^{*-} \tau^- \bar{\nu}_\tau$, with $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$ [PRL 120 (2018) 121801]

- Using $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

Information from the missing mass squared $m_{\text{miss}}^2 = (P_B - P_{D^* - P_\mu})^2$ and muon energy

- Using $\tau^+ \to \pi^+ \pi^- \pi^+ \bar{\nu}_\tau$

Information from the position of the pions. Normalized to $B^0 \to D^{*-} \pi^+ \pi^- \pi^+$

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**Plot:**
- **Legend:**
  - Data
  - $B \to D^{* \tau}$
  - $B \to D^{* \tau}$
  - $B \to D^{* \tau}$
  - $B \to D^{* \tau}$
  - $B \to D^{* \tau}$
  - Combinatorial
  - Misidentified $\mu$

- **Axes:**
  - $m_{\text{miss}}^2$ (GeV$^2$/c$^4$)
  - Candidates / (0.3 GeV$^2$/c$^4$)

- **Graph:**
  - 9.35 < $q^2$ < 12.60 GeV$^2$/c$^4$
  - Normalization
  - Signal

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**Plot:**
- **Legend:**
  - Data
  - $B \to D^{* \tau}$
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  - $B \to D^{* \tau}$
  - $B \to D^{* \tau}$
  - $B \to D^{* \tau}$
  - Combinatorial

- **Axes:**
  - 3\pi decay time / (0.25 ps)
  - $t_\tau$ [ps]

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Semileptonic B decays

- Global picture of $R_D$ and $R_{D^*}$

→ About 4σ deviation from SM
Conclusions

• Deviations from the Standard Model in the flavour sector have been found by LHCb and other experiments:

* **Differential branching fractions**: \( B^0 \rightarrow K(\ast)^0 \mu^+\mu^- \), \( B^+ \rightarrow K(\ast)^+ \mu^+\mu^- \), \( B_s \rightarrow \phi \mu^+\mu^- \), \( B^+ \rightarrow \pi^+ \mu^+\mu^- \) and \( \Lambda_b \rightarrow \Lambda \mu^+\mu^- \)
  → Affected by hadronic uncertainties in the theory predictions

* **Angular analyses**: \( B^0 \rightarrow K(\ast)^0 \mu^+\mu^- \), \( B_s \rightarrow \phi \mu^+\mu^- \), \( B^0 \rightarrow K^{*0} e^+e^- \) and \( \Lambda_b \rightarrow \Lambda \mu^+\mu^- \)
  → Observables with smaller theory uncertainties

* **Test of Lepton Flavour Universality**: \( B^+ \rightarrow K^+ \ell^+\ell^- \) and \( B^0 \rightarrow K^{*0} \ell^+\ell^- \); \( B \rightarrow D(\ast)\tau \nu \)
  → Hadronic uncertainties in theory predictions cancel in ratios

• Deviations show a consistent pattern in global fits, pointing to new physics in the Wilson coefficient \( C_{g\mu} \), affecting differently to lepton families.
  → Difficult to be explained by just experimental effects.
  → Difficult to be explained by just QCD effects...
Thanks!
Rare B decays: $B \to K^* e^+ e^-$

- What about electrons? (sensitive to $C_7^{(')}$)

Angular observables of the $B^0 \to K^* e^- e^+$ at LHCb in the low $q^2 < 1\text{GeV}^2$

→ Virtual $\gamma$ decaying in an observable $\ell^- \ell^+$ pair
→ Requires to go very low in the $q^2$ region

$[\text{JHEP04(2015)064}]$ (3fb$^{-1}$)

$150$ events

Long radiative tail in the B mass distribution: controlled from $B \to K^* \gamma$ events ($\gamma \to e^- e^+$, with bremsstrahlung emission)

→ Compatible with the SM predictions*

$[\text{Adapted from Jäger and Camalich arXiv:1412.3183}]$

*leading order estimation, 5% accuracy for SM value
Rare B decays: $R_{K^{(*)}}$  

Quick note on experimental issues:

- LHCb is far better with muons than electrons
- Trigger, reconstruction, selection and particle identification are harder with electrons
- Mass resolution affected by $e$ bremsstrahlung → need energy recovery
- Mass shape modelled according to the number of bremsstrahlung recovered
Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

**LHCb**

[JHEP02(2016)104]

**CMS**

[PLB 753 (2016) 424]

**ATLAS**

[arXiv:1805.04000]

SM predictions based on

[Altmanshofer & Straub, EPJC 75 (2015) 382]

[LCSR f.f. from Bharucha, Straub & Zwicky, JHEP 08 (2016) 98]

Rare B decays: $B \to K^{(*)}\mu^+\mu^-$

Understanding effects from charm at LHCb:

- Phase difference between short- and long-distance amplitudes in the $B^+ \to K^+\mu^+\mu^-$ decay [LHCb, EPJ C(2017) 77]

$\frac{d\Gamma}{dm_{\mu\mu}}$ is a function of form factors and $C_i$

$C_i^{\text{eff}}$ expressed as a sum of relativistic Breit-Wigner amplitudes: magnitudes and phases extracted from data

Form factors from FNAL & MILC [PRD 93(2016)025026]

→ Small effect of hadronic resonances in Wilson coefficients
Recent measurements by CMS in the $B^+ \rightarrow K^+ \mu^+ \mu^-$ decay channel [arXiv:1806.00636], submitted to PRD

$\frac{1}{\Gamma_\ell} \frac{d\Gamma_\ell}{d\cos \theta_\ell} = \frac{3}{4} \left( 1 - F_H \right) (1 - \cos^2 \theta_\ell) + \frac{1}{2} F_H + A_{FB} \cos \theta_\ell$

$A_{FB}$ = Forward-backward asymmetry of the dimuon system
$F_H$ = contribution from the pseudoscalar, scalar and tensor amplitudes to the decay width

→ Consistent with SM predictions
Semileptonic B decays: $R_D, R_{D^*}$

**BaBar** measured an excess of $B^0 \rightarrow D(\ast) \tau^- \nu_\tau$ (3σ away from SM!) [PRD 88 (2013) 072012] [Nature 546 (2017) 227]

**Belle:**

$R(D), R(D^*)$

- $B^0 \rightarrow D(\ast)^+ \tau^- \nu_\tau$, with $\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$ [PRD92 (2015) 072014]
- $B^0 \rightarrow D^{*+} \tau^- \nu_\tau$, with $\tau^- \rightarrow \ell^- \nu_\ell \nu_\tau$ [PRD94 (2016) 072007]
- $B^0 \rightarrow D^{*+} \tau^- \nu_\tau$ and $\tau^-$ polarization [PRL118 (2017) 211801]

![Graphs and plots showing data analysis](remaining energy of e.m. calorimeter clusters)
Rare B decays: $R_K$

B mass versus $q^2$ for $B^+ \rightarrow K^+ \ell^+ \ell^-$

[References: [PRL 113 (2014) 151601]]