Rare decays in quark flavour physics

Johannes Albrecht
(TU Dortmund)

On behalf of the LHCb collaboration

including results from ATLAS, CMS, Babar & Belle
Indirect searches for New Physics

- High **energy**: "real" new particles can be produced and discovered via their decays

- High **precision**: "virtual" new particles can be discovered in loop processes

Direct and indirect searches are both needed, both equally important, and complement each other

- This talk discusses precision tests with rare heavy quark decays
  - Tom Browder will discuss CP violation measurements
  - Gino Isidori will discuss the interpretation in terms of New Physics models
Searches for New Physics in flavour

Contribution of NP as correction to the SM

What is the scale of $\Lambda_{NP}$? What is its coupling $c_{NP}$?
Experimental overview of $b \rightarrow s \ell^+\ell^-$

- $b \rightarrow s \ell^+\ell^-$ decays allow precise tests of Lorentz structure
  - Sensitive to new phenomena via non-standard couplings
  - Best described with effective field theory

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \sum_{i} \left[ \begin{array}{c} C_i(\mu) O_i(\mu) \quad C_i'(\mu) O_i'(\mu) \end{array} \right]$$

- $i = 1,2$ 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

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b → s ℓ⁺ ℓ⁻ decays allow precise tests of Lorentz structure
- Sensitive to new phenomena via non-standard couplings
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\[ H_{\text{eff}} = - \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[ C_i(\mu) O_i(\mu) + C'_i(\mu) O'_i(\mu) \right] \]

- \( i = 1,2 \) 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

Experimental overview of \( b \rightarrow s \ell ^+ \ell ^- \)
Heavy quark flavour physics experiments
Quark flavour at the LHC

- The LHC is a flavour factory
  - Large $b\bar{b}$ production rate: $\sigma_{b\bar{b}} \sim 75 \, \text{µb}$ for both ATLAS/CMS and LHCb

- ATLAS and CMS collect large samples of beauty events
  - Good trigger & PID for hard muons
  - No hadron PID
  - Total dataset: $5 \, \text{fb}^{-1} @ 7\text{TeV}$ and $25 \, \text{fb}^{-1} @ 8\text{TeV}$

- LHCb: the LHC flavour experiment
  - Very efficient and flexible trigger
  - Good muon & hadron PID
  - Luminosity leveling at $4 \times 10^{32}$
    -> Constant luminosity for entire fill
  - Total dataset: $1 \, \text{fb}^{-1} @ 7\text{TeV}$ and $2.1 \, \text{fb}^{-1} @ 8\text{TeV}$
B-factories: BaBar and Belle

- BaBar/Belle: record asymmetric $e^+e^-$ collisions at Y(4S) resonance
  - Very clean sample of entangled BB pairs (dominantly $B^0$ and $B^\pm$)
  - Boost of $B^0$ allows time dependent measurements
  - Experimentally clean environment

- Data taking 1999- 2008 / 2010 (BaBar / Belle)
  - Total dataset at Y(4S): 530fb$^{-1}$ / 1000fb$^{-1}$
Search for $B_{s,d} \rightarrow \mu^+\mu^-$
Theory prediction: $B_{s,d} \rightarrow \mu^+\mu^-$

Theory prediction: Standard Model

<table>
<thead>
<tr>
<th>decay</th>
<th>SM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \mu^+\mu^-$</td>
<td>$3.65\pm0.23 \times 10^{-9}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+\mu^-$</td>
<td>$1.1\pm0.1 \times 10^{-10}$</td>
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</tbody>
</table>


Discovery channel for New Phenomena

Example: MSSM (with R-parity conservation)

$$BR(B_S \rightarrow \mu^+\mu^-) \propto \frac{\tan^6 \beta}{m_A^4}$$

$\Rightarrow B_{s,d} \rightarrow \mu^+\mu^-$ strongly constrains SUSY parameter space

$\Rightarrow$ Ratio $B_s/B^0$: Stringent test of minimal flavour violation hypothesis
Classifcation of events

BDT (topology, kinematics)

Invariant mass

Fits to mass in categories of BDT
Branching fraction normalized to $B^{+}\rightarrow J/\psi K^+$ (LHCb: and $B^0\rightarrow K^+\pi$)
Summary: Results for $B \rightarrow \mu^+ \mu^-$

- **Nov 2012:**
  LHCb found the first evidence for $B_s \rightarrow \mu^+ \mu^-$ using 2.1 fb$^{-1}$

- **Update:** full dataset: 3 fb$^{-1}$
  - Improved BDT
  - Expected sensitivity: 5.0$\sigma$

- **Update to 25 fb$^{-1}$**
  - Cut based → BDT based
  - Improved variables
  - Expected sensitivity: 4.8$\sigma$

\[ BR(B_s \rightarrow \mu^+ \mu^-) = (2.9^{+1.1}_{-1.0}) \times 10^{-9} \]
\[ BR(B^0 \rightarrow \mu^+ \mu^-) = (3.7^{+2.4}_{-2.1}) \times 10^{-10} \]
\[ BR(B^0 \rightarrow \mu^+ \mu^-) < 7 \times 10^{-10} \text{ @ } 95\% CL \]

\[ BR(B_s \rightarrow \mu^+ \mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9} \]
\[ BR(B^0 \rightarrow \mu^+ \mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10} \]
\[ BR(B^0 \rightarrow \mu^+ \mu^-) < 11 \times 10^{-10} \text{ @ } 95\% CL \]
Combined LHCb + CMS result

- Preliminary combination of results

\[ \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9} \]
\[ \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.6 \pm 1.6) \times 10^{-10} \]

- \( B^0_s \rightarrow \mu^+ \mu^- \) is observed at more than 5\( \sigma \)

- Full combination of likelihoods in preparation

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Electroweak penguins: $b \rightarrow s \ell^+ \ell^-$

All LHC experiments see clear signals of $B^0 \rightarrow K^{*0} \mu^+ \mu^-$.
Experimental overview of $b \to s \ (d) \ell^+\ell^-$

- **FCNC decays** $b \to s \ (d) \ell^+\ell^-$: large variety of final states
  - Allows detailed test of the structure of the underlying interaction
  - Effects in one decay can be cross checked in others

<table>
<thead>
<tr>
<th># of events</th>
<th>BaBar 433fb$^{-1}$</th>
<th>Belle 605fb$^{-1}$</th>
<th>CDF 9.6fb$^{-1}$</th>
<th>LHCb 1/3 fb$^{-1}$</th>
<th>ATLAS 5fb$^{-1}$</th>
<th>CMS 5fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to K^*\ell^+\ell^-$</td>
<td>137±44*</td>
<td>247±54*</td>
<td>288±20</td>
<td>2361±56</td>
<td>466±34</td>
<td>415±29</td>
</tr>
<tr>
<td>$B^+ \to K^{*+} \ell^+\ell^-$</td>
<td>24±6</td>
<td>162±16</td>
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<tr>
<td>$B^+ \to K^+ \ell^+\ell^-$</td>
<td>153±41*</td>
<td>162±38*</td>
<td>319±23</td>
<td>4746±81</td>
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<tr>
<td>$B^0 \to K^0_s \ell^+\ell^-$</td>
<td>32±8</td>
<td>176±17</td>
<td></td>
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<tr>
<td>$B_s \to \phi \ell^+\ell^-$</td>
<td>62±9</td>
<td>174±15</td>
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<tr>
<td>$\Lambda_b \to \Lambda \ell^+\ell^-$</td>
<td>51±7</td>
<td>78±12</td>
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</tr>
<tr>
<td>$B^+ \to \pi^+ \ell^+\ell^-$</td>
<td>limit</td>
<td></td>
<td></td>
<td>25±7</td>
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</table>

*B*mixture of $B^0$ and $B^\pm$ and $\ell = e, \mu$ only

Other experiments: $\ell = \mu$ only

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B^0 \to K^{*0} \mu^+\mu^- \text{ angular distribution}

- Characterize decay in three angles:

- Angular distribution depends on 11 terms

\[
\frac{d^4\Gamma[B^0 \to K^{*0} \mu^+\mu^-]}{d \cos \theta_\ell \ d \cos \theta_K \ d\phi \ dq^2} = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

- Angular terms are powerful tool to separate SM from NP
\[ B^0 \to K^{*0} \mu^+ \mu^- \text{ angular distribution} \]

- Angular distribution depends on 11 terms

\[
\frac{d^4 \Gamma[B^0 \to K^{*0} \mu^+ \mu^-]}{d \cos \theta_\ell \, d \cos \theta_K \, d \phi \, dq^2} = \frac{9}{32\pi} \left[ J_1^s \sin^2 \theta_K + J_1^c \cos^2 \theta_K + J_2^s \sin^2 \theta_K \cos 2\theta_\ell + J_2^c \cos^2 \theta_K \cos 2\theta_\ell + J_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + J_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + J_5 \sin 2\theta_K \sin \theta_\ell \cos \phi + J_6 \cos^2 \theta_K \cos \theta_\ell + J_7 \sin 2\theta_K \sin \theta_\ell \sin \phi + J_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + J_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \right]
\]

- Large number of terms, simplified by angular folding
  - E.g. \( \phi \to \phi + \pi \) for \( \phi < 0 \) (LHCb)

- Alternative: integrate over two of the three angles (ATLAS, CMS)

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d\phi} = \frac{1}{2\pi} \left( 1 + S_3 \cos 2\phi + A_9 \sin 2\phi \right) ,
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_K} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K) ,
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_\ell} = \frac{3}{4} F_L (1 - \cos^2 \theta_\ell) + \frac{3}{8} (1 - F_L)(1 + \cos^2 \theta_\ell) + A_{FB} \cos \theta_\ell
\]
$B^0 \rightarrow K^{*0} \mu^+\mu^-$ angular distribution

ATLAS (prelim.) [ATLAS-CONF-2013-038], CMS 5.2 fb$^{-1}$ [PLB 727 (2013) 77], LHCb 1 fb$^{-1}$ [JHEP 08 (2013) 131]

Theory prediction from Bobeth et al. [JHEP 07 (2011)] and references therein.
Apply different angular folding to access remaining terms

Observables designed that leading form factor uncertainties cancel, e.g. \( P'_{4,5} = S_{4,5} / F_L (1 - F_L) \)

LHCb observes a local discrepancy on 3.7\( \sigma \) in \( P_{5}' \)
(probability that at least one bin varies by this much: 0.5%)
$B^0 \rightarrow K^{*0} \mu^+\mu^-$ interpretation

- Global fits to electroweak penguin data: 2-4$\sigma$ tension
- Views from theory community (detailed discussion follows by G. Isidori)
  - Theory errors underestimated?  
    $\rightarrow$ better understanding of QCD [3,5]
  - $P_5'$ tension correlated with other (smaller) tensions and NP explanation consistent with all data possible [1,2]  
    $\rightarrow$ difficult to explain with SUSY [1]  
    $\rightarrow$ consistent with a 7TeV $Z'$ [4]
- Check with more data / channels
  - Expect suppression of $\text{BR}(B \rightarrow K^{(*)} \mu^+\mu^-)$

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Differential branching fraction of $B \rightarrow K^{(*)} \mu^+ \mu^-$

- LHCb reconstructs the $K^{(*)}$ as $K^+$, $K^0_s$, $K^{*+}(\rightarrow K^0_s \pi^+)$ or $K^{*0}$
  - $K^0_s$ final states experimental challenging due to long $K^0_s$ lifetime
  - Large signals in all four modes observed
  - Differential branching fraction normalized to $B \rightarrow J/\psi \; K^{(*)}$

- Measurements consistently below SM, but SM calculation currently revisited (scalar modes might go $\sim 10\%$ down)

- Isospin asymmetries consistent with SM
  - Detailed discussion by Jibo He (flavour parallel)
Semi-inclusive $B \to X_s \ell^+\ell^-$

- Sum of 20 exclusive $B \to X_s \ell^+\ell^-$ decays

- Measured partial BR and CP asymmetry

- High-$q^2$ measurement above prediction.
Test of lepton universality

- In the SM, couplings to all leptons are universal

- Test lepton universality in $B^+ \to K^+ \mu^+\mu^- / B^+ \to K^+ e^+e^-$

  $$R_K = \frac{\int_{q^2=6 \text{ GeV}^2/c^4}^{q^2=1 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \to K^+ \mu^+\mu^-]/dq^2)\,dq^2}{\int_{q^2=6 \text{ GeV}^2/c^4}^{q^2=1 \text{ GeV}^2/c^4} (d\mathcal{B}[B^+ \to K^+ e^+e^-]/dq^2)\,dq^2} = 1 \pm \mathcal{O}(10^{-3})$$

  SM: JHEP 12 (2007) 040

- Selection of the $B^+ \to K^+ e^+e^-$ decay experimentally challenging due to bremsstrahlung emission from $e^\pm$

Candidate triggered by the $e^\pm$
Test of lepton universality

• Correct for bremsstrahlung using calorimeter photons ($E_T > 75$ MeV)

• Migration of events into/out of the $1 < q^2 < 6$ GeV$^2$ region corrected using MC

• Double ratio with resonant decay $B^+ \rightarrow J/\psi(e^+e^-) K^+$ measured

• In $3 \text{fb}^{-1}$ LHCb determines

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

(consistent with SM at $2.6\sigma$)

LHCb-PAPER-2014-024 [Preliminary],
Belle [PRL 103 (2009) 171801],
BaBar [PRD 86 (2012) 032012]
Photon polarisation in $b \to s \gamma$

In the SM, photons from $b \to s$ decays are predominantly left-handed ($C_7 / C_0 \approx m_b / m_s$) due to the charged-current interaction. 

$b_{R(L)} \to W^- \to s_{L(R)}$ 

Can test $C_7 / C_0$ using:

- Mixing-induced CP violation [Atwood et al PRL 79 (1997) 185-188],
- $\bar{b}$ baryons [Hiller & Kagan PRD 65 (2002) 074038]
Photon polarization in $b \to s \gamma$ decays

- First penguin decay ever observed: $B^0 \to K^* \gamma$
  
  CLEO, PRL 71 (1993) 674

- Inclusive and exclusive $\text{BR}(b \to s \gamma)$ compatible with SM (B-factories)

- Yet untested: photon polarization in $b \to s \gamma$
  - SM: photons predominantly left-handed
    
    $(C_7 / C_7' \sim m_b / m_s)$

- Can test $C_7 / C_7'$ using
  - Mixing induced CPV [Altwood, PRL79 (1997) 185]
  - $B \to K^{**} \gamma$ decays such as $B^+ \to K(1270)^+ \gamma$
    
Semi-inclusive $B \rightarrow X_s \gamma$

- **Inclusive $B \rightarrow X_s$**: SM prediction more precise than exclusive
  - Sum-of exclusives: reconstruct, 38 final states (16 for $A_{CP}$)

- **New observable**: isospin difference of $A_{CP}$
  - In SM, $\Delta A_{CP}=0$

\[
\Delta A_{CP} = A_{CP}(B^\pm) - A_{CP}(B^0 / \overline{B}^0) \propto \text{Im} \frac{C_8}{C_7}
\]

**Result for all $B$ mesons:**

$A_{CP} = (1.7 \pm 1.9 \pm 1.0)\%$

Simultaneous fit to charged and neutral $B$ samples:

$\Delta A_{CP} = + (5.0 \pm 3.9_{\text{stat}} \pm 1.5_{\text{syst}})\%$

**Constraints on $C_8$:**

\[
0.07 \leq \text{Im} \frac{C_8}{C_7} \leq 4.48, \quad 68\% \text{ CL}
\]

\[-1.64 \leq \text{Im} \frac{C_8}{C_7} \leq 6.52, \quad 90\% \text{ CL}
\]

\[C_7 \text{ constrained by BR measurements} \rightarrow \text{first information on } C_8\]
(Semi-) inclusive $B \rightarrow X_s \gamma$

- Inclusive $B \rightarrow X_s \gamma$: SM prediction more precise than exclusive
- Sum-of exclusives: reconstruct 38 final states
  - Measured partial BF
    \[ B(B \rightarrow X_s \gamma) = (3.74 \pm 0.18 \pm 0.35) \times 10^{-4} \]

- Fully inclusive: tag other $B$
  - $A_{CP}(B \rightarrow X_{s+d} \gamma)$
  - SM: $A_{CP}(B \rightarrow X_{s+d} \gamma) = 0$
  - Using lepton charge tag
    \[ A_{CP} = (2.2 \pm 4.0 \pm 0.8) \times 10^{-2} \]
Photon polarization from $B^+ \to K^+\pi^+\pi^-\gamma$

- Photon polarization measured from up-down asymmetry
  - Asymmetry of photon direction in $K\pi\pi$ rest frame
  - Analogously to the Wu experiment

- Reconstruct $B^+ \to K^+\pi^+\pi^-\gamma$
  - ~13000 signal candidates in 3fb$^{-1}$
  - Several overlapping resonances in $m(K^+\pi^+\pi^-)$
    - data divided in 4 bins in $m(K^+\pi^+\pi^-)$

- Combining the 4 bins, the photon is observed to be polarized at 5.2$\sigma$
  - First observation of photon polarization in $b\to s\gamma$ decays
Flavour changing neutral currents in strange, charm & top decays

Not covered in detail here
Rare Kaon decays

The ratio of kaon leptonic modes is extremely well predicted in the SM:
- Helicity suppression;
- Hadronic uncertainties cancel in \( R_K \) ratio;
- Radiative correction are included in the RK definition and well computed in SM;

\[
R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2} \left( \frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2} \right)^2 \left( 1 + \delta R_K^{\text{rad.corr.}} \right)
\]

\[
R_K = (2.477 \pm 0.001) \times 10^{-5}
\]


A precise measurement of RK is a stringent test of the SM!

See G. Lamanna, parallels
Effective GIM cancellation due to presence of b, s, d quarks in loop

→ FCNC charm decays are very rare

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32/33
Summary

• Rare quark decays play an important role in the search for New Physics

• No striking hint yet, but several tensions emerge
  – $P_5'$ in $B^0 \rightarrow K^{*0} \mu^+\mu^-$ (LHCb)
  – Lepton-universality in $B^+ \rightarrow K^+ \ell^+\ell^-$ (LHCb)

• More data and further theoretical developments will clarify these tensions

• Many updates coming soon
  – $B^0 \rightarrow K^{*0} \mu^+\mu^-$ (LHCb, ATLAS, CMS), $B_s \rightarrow \mu^+\mu^-$ (LHCb+CMS), …
Questions?
Discussion:

\( B \rightarrow K^{(*)} \ell^+ \ell^- \) SM predictions

- High \( q^2 \) = low recoil
- Low \( q^2 \) = large recoil

**Effective Wilson coefficients**

- Perturbative uncertainties are small
- \( C_{7,9}^{\text{eff}} \): important to include two-loop virtual corrections!
  - Lead to a \( O(10\%) \) suppression of the BRs
  - **Not** included in [Bouchard et al. 1306.0434]!
  - Included in [Bobeth et al., Beaujean et al., Altmannshofer et al., Horgan et al.]
  - Apparently **not** included in today’s LHCb paper . . .

Search for \(D^0 \rightarrow \mu^+\mu^-\)

- Only Higgs penguin sensitive to up-type quarks
- SM is dominated by long distance contribution
  \[10^{-13} < B(D^0 \rightarrow \mu^+\mu^-) < 6 \times 10^{-11}\]
  [G. Burdman et al., PR D66 (2002)]
- NP up to \(10^{-9}\), e.g. RPV SUSY
- LHCb analysis:
  - \(D^*\) tagged sample of \(D^{*-} \rightarrow D^0( \rightarrow \mu^+\mu^-) \pi^+\)
  - BDT used to reduce combinatorial bkg from b and c decays
  - Yield from 2D fit to \(m(D0)\), \(\Delta m(D^{*-}-D^0)\)
  - Normalization to \(D^0 \rightarrow \pi^+\pi^-\)

- **Upper exclusion limit**
  \[6.8 \times 10^{-9} @ 95\% \text{ CL}\]
Search for $D^+_{(s)} \rightarrow \pi^+ \mu^+ \mu^-$

Can also look at other $c \rightarrow u$ decays, e.g. $D^+_{(s)} \rightarrow \pi^+ \mu^+ \mu^-$. Background from light resonances.

Background from $D^+ \rightarrow \pi^+ \pi^- \pi^+$ and $D_s^+ \rightarrow \pi^+ \pi^- \pi^+$

Set limits in 1 fb$^{-1}$ of

- $\mathcal{B}(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 8.3 \times 10^{-8}$
- $\mathcal{B}(D_s^+ \rightarrow \pi^+ \mu^+ \mu^-) < 4.1 \times 10^{-7}$

at 95% CL

Improving existing limits by 50x.
Search for $D^+_s \rightarrow \pi^+\pi^+\mu^+\mu^-$

\begin{align*}
\text{low } m(\mu^+\mu^-) & \quad \rho/\omega \\
\text{high } m(\mu^+\mu^-) & \quad \phi
\end{align*}

Signal, $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ background

- Using 1 fb$^{-1}$ of integrated luminosity, LHCb sets a limit of:

\[
\mathcal{B}(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 5.5 \times 10^{-7} \text{ at } 90\%
\]

\text{c.f. SM predictions of } \mathcal{O}(10^{-9}), \text{ improving on previous limits by 50x.}
Isospin Asymmetries in $B \rightarrow K^{(*)} \mu^+\mu^-$

- Isospin asymmetry expected to be close to zero in SM

- LHCb measured $A_\text{I}$ in two modes:
  - $B^0 \rightarrow K^0 \mu^+\mu^-$ vs $B^+ \rightarrow K^+ \mu^+\mu^-$
  - $B^0 \rightarrow K^{0*} (K^+\pi^-) \mu^+\mu^-$ vs $B^+ \rightarrow K^{*+} (K^{0}\pi^+) \mu^+\mu^-$

$A_\text{I} = \frac{B(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) - \tau_0 B(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}{B(B^0 \rightarrow K^{(*)0}\mu^+\mu^-) + \tau_0 B(B^+ \rightarrow K^{(*)+}\mu^+\mu^-)}$

$A_\text{I}$ consistent with 0 as expected from SM prediction (tension in 1fb$^{-1}$ analysis of $B \rightarrow K \mu^+\mu^-$ reduced)
Isospin asymmetry of $B \to K \mu^+ \mu^-$ decays (II)

- What changed in the meantime?
  - LHCb added another 2 fb$^{-1}$ of data.
  - Previously assumption that equal amounts of $B^+$ and $B^0$ are produced at $\Upsilon(4S)$. Now assume isospin symmetry for $B \to J/\psi K^{(*)}$.
  - All these effects reduce the discrepancy.
Decay angle definition

(a) $\theta_K$ and $\theta_\ell$ definitions for the $B^0$ decay

(b) $\phi$ definition for the $B^0$ decay

(c) $\phi$ definition for the $\bar{B}^0$ decay