

Indirect searches of New Physics with very rare decays at LHCb

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PASCOS

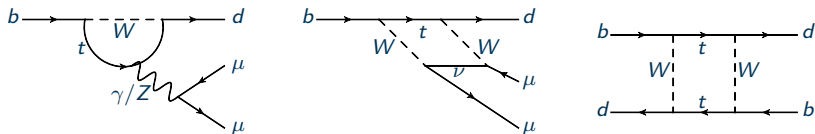
15th July, 2016

Introduction

Need new physics at the TeV-scale to protect the Higgs mass from diverging

- ▶ Flavour changing neutral currents (FCNC) are very small in the SM (loop suppressed)
- ▶ The effect of new particles should appear in FCNC: in mixing and rare decays
- ▶ FCNCs allow to search for particles at much higher energies than the CoM energy of a given collider

→ Today focus on very rare decays



Outline

- ▶ Theoretical framework
- ▶ Very rare decays
 - ▶ $B_{s,d}^0 \rightarrow \mu^+ \mu^-$
 - ▶ $B_u^+ \rightarrow \pi^+ \mu^+ \mu^-$
- ▶ $b \rightarrow s \mu \mu$ decays
 - ▶ $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$
 - ▶ $B_u^+ \rightarrow K^+ \mu^+ \mu^-$
 - ▶ $B_s^0 \rightarrow \phi \mu^+ \mu^-$
- ▶ Lepton flavour universality and lepton flavour violation
 - ▶ $R(K)$
 - ▶ search for $B_{s,d}^0 \rightarrow e^+ \mu^-$
 - ▶ search for $D^0 \rightarrow e^+ \mu^-$

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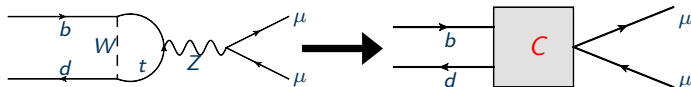
- ▶ $R(K)$
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Theoretical framework

Can integrate out heavy degrees of freedom \Rightarrow hamiltonian for rare decays becomes a sum of coefficients \times operators:

$$\mathcal{H} = \sum_i C_i O_i$$

- ▶ Wilson Coefficients C_i :
 - ▶ describe short distance physics, i.e. heavy degrees of freedom that can't be probed at the scale of the interaction μ
 - ▶ can be computed perturbatively
- ▶ Operator O_i
 - ▶ describe long-distance physics, i.e. involve particles below scale μ
 - ▶ include QCD effects, are difficult to compute precisely
- ▶ New physics may manifest itself by modifying some Wilson Coefficients



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$$B_{s,d}^0 \rightarrow \mu^+ \mu^-$$

In the standard model:

- ▶ Dominant contribution from Z-penguin (C_{10})
- ▶ Loop + helicity suppression
- ▶ Very precise theory prediction for branching fractions:

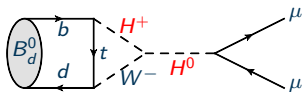
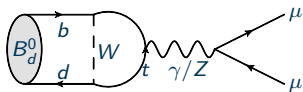
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$

$$\mathcal{B}(B_d^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

PRL 112 101801 (2014)

In New Physics models:

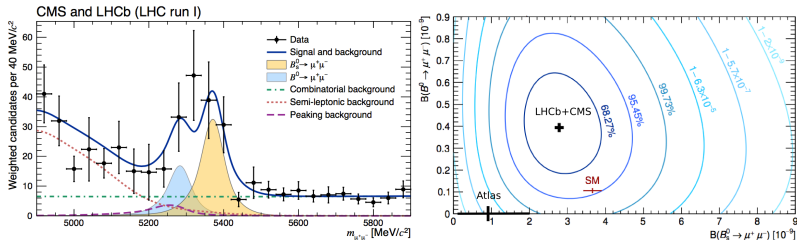
- ▶ (pseudo)scalar operators (C_S , C_P) can substantially modify \mathcal{B}
- ▶ e.g. extended higgs sector in SUSY



$B_{s,d}^0 \rightarrow \mu^+ \mu^-$: combined analysis

LHCb and CMS have searched for $B_{s,d}^0 \rightarrow \mu^+ \mu^-$ and have combined their run-1 datasets.

Separate search done at ATLAS, set limits on both $\mathcal{B}(B_{s,d}^0 \rightarrow \mu^+ \mu^-)$.



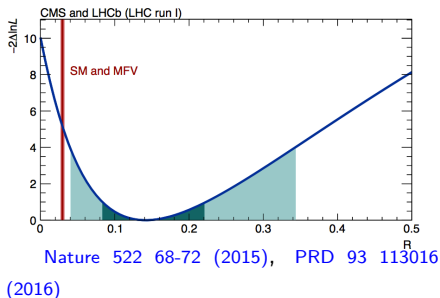
CMS+LHCb: [Nature 522, 68-72 \(2015\)](#), ATLAS: [PRB 713 387 \(2012\)](#)

- ▶ Observation of $B_s^0 \rightarrow \mu^+ \mu^-$: $\mathcal{B} = (2.8_{-0.6}^{+0.7}) \times 10^{-9}$ (6.2σ)
→ compatibility with SM at 1.2σ
- ▶ Evidence for $B_d^0 \rightarrow \mu^+ \mu^-$: $\mathcal{B} = (3.9_{-1.4}^{+1.6}) \times 10^{-10}$ (3.0σ)
→ compatibility with SM at 2.2σ

$B_{s,d}^0 \rightarrow \mu^+ \mu^-$ and minimal flavour violation

- ▶ Minimal flavour violation (MFV): flavour structure of BSM model aligned with SM flavour structure
- ▶ the ratio of the branching fractions is a test of MFV which predicts:

$$\frac{\mathcal{B}(B_d \rightarrow \mu^+ \mu^-)}{\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)} \propto \left| \frac{V_{td}}{V_{ts}} \right|^2$$

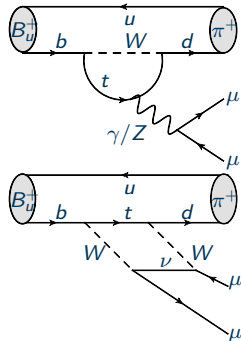


→ ratio consistent with SM or MFV at 2.3σ , but need more data to probe this better

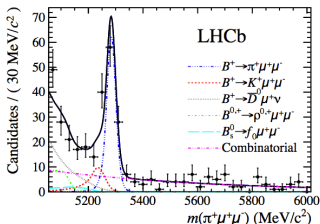
$B_u^+ \rightarrow \pi^+ \mu^+ \mu^-$: observation at LHCb

- ▶ Larger \mathcal{B} because not helicity suppressed, sensitive to $C_{7,9,10}$
- ▶ Measured at LHCb: first observation of a box or penguin-mediated $b \rightarrow dll$ transition
- ▶ Recently, \mathcal{B} measurement updated to full run 1 dataset:

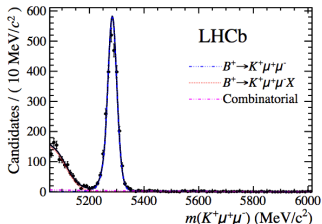
$$\mathcal{B}(B_u^+ \rightarrow \pi^+ \mu^+ \mu^-) = (1.83 \pm 0.24 \pm 0.05) \times 10^{-8}$$



Cabbibo suppressed (V_{td}):

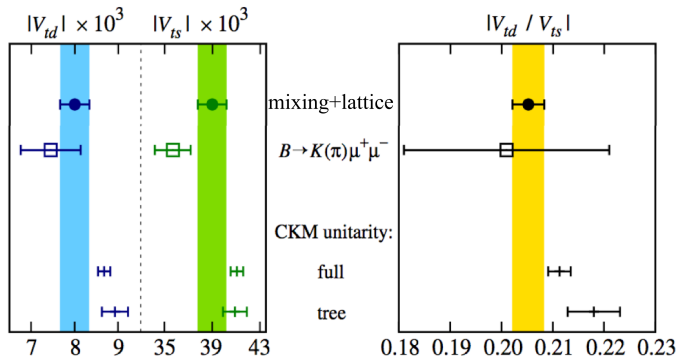


Cabbibo favoured (V_{ts}):



$B^+ \rightarrow \pi^+ \mu^+ \mu^-$: impact on V_{td}

- $\mathcal{B}(B^+ \rightarrow \pi^+(K^+)\mu^+\mu^-)$ can also be used to extract $|V_{td}|(|V_{ts}|)$



PRD 93, 113016 (2016)

- Results for $|V_{td}|$ from $B^+ \rightarrow \pi^+(K^+)\mu^+\mu^-$ competitive with expectations from *CKM* unitarity and *B* oscillations
- Need more precision to see if picture stays consistent

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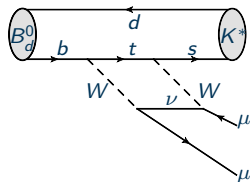
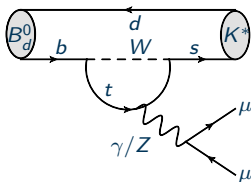
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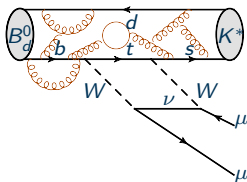
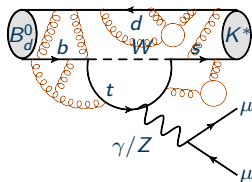
$B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$: physics interest

- ▶ FCNC, $\mathcal{B} \sim \mathcal{O}(10^{-6})$
- ▶ Try to extract observables where theoretical uncertainties cancel
- ▶ New physics might manifest itself by modifying the angular distribution
- ▶ Decay fully described by three angles (θ_L , ϕ , θ_K) and dimuon invariant mass squared q^2



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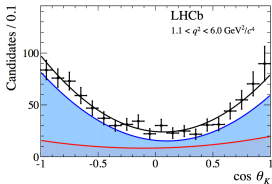
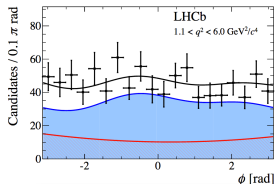


$B_d \rightarrow K^{*0} \mu^+ \mu^-$: theoretically clean observables

- ▶ At low and high q^2 relations between form factors allow variables independent on form factors at leading order to be constructed, e.g.:

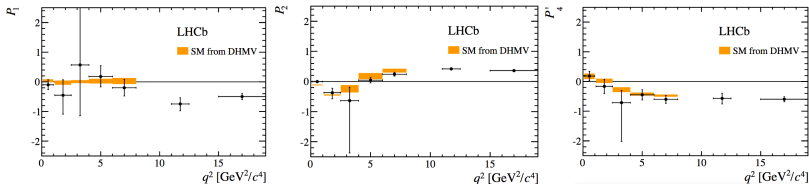
$$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

- ▶ Can rewrite angular distribution using similar $P_i^{(\prime)}$ observables: six are form factor independent, two are form factor dependent
- ▶ Recent LHCb analysis measures all of these

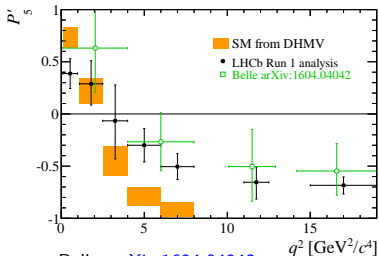


JHEP 02 (2016) 104

$B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$: P'_5 measurement



- ▶ P'_5 : local tension of 2.8σ and 3σ in bin 4 and 5
- ▶ Belle result has larger uncertainties but looks consistent with LHCb result

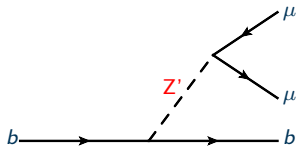
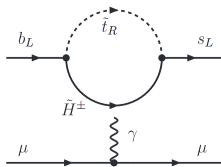


Belle: [arXiv:1604.04042](https://arxiv.org/abs/1604.04042)

LHCb: [JHEP 02 104 \(2016\)](https://arxiv.org/abs/1604.04042)

$B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ and P'_5 : NP interpretation

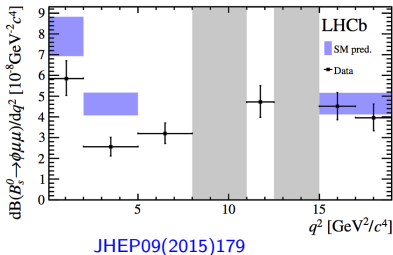
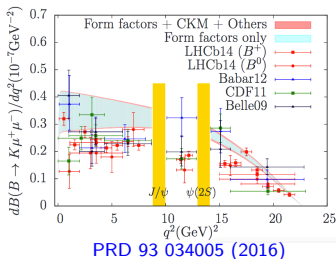
- ▶ P'_5 anomaly can be explained by modifying C_9
- ▶ Difficult to generate in SUSY models, but could be explained by a Z' or leptoquark



Eur.Phys.J. C73 (2013) 2646

→ Expect modification of C_9 to manifest itself in other $b \rightarrow s\mu\mu$ decays

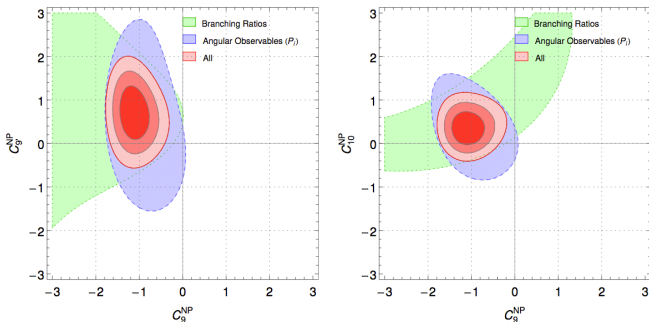
$$B_s^0 \rightarrow \phi \mu^+ \mu^- \text{ \& \ } B_{u,d}^{+,0} \rightarrow K^{+,0} \mu^+ \mu^-$$



- ▶ LHCb measured $d\mathcal{B}/dq^2$ for $B_s^0 \rightarrow \phi \mu^+ \mu^-$, $B_u^+ \rightarrow K^+ \mu^+ \mu^-$, $B_d^0 \rightarrow K_S \mu^+ \mu^-$
- ▶ As $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$, also $b \rightarrow s \mu \mu$ transition
- ▶ In $1 < q^2 < 6 \text{ GeV}^2$, data is 1.8σ below SM prediction for $B_u^+ \rightarrow K^+ \mu^+ \mu^-$ and $> 3\sigma$ below SM prediction for $B_s^0 \rightarrow \phi \mu^+ \mu^-$

Global fit to $b \rightarrow s\mu\mu$

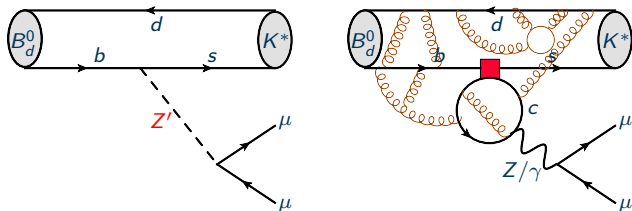
Can fit $b \rightarrow s\mu\mu$ angular observables and branching fractions together for the Wilson Coefficients:



JHEP06(2016)092

- ▶ Fit favours scenarios where C_9 and C_9' deviate from SM value with a pull $> 4\sigma$
- ▶ Scenarios with modified C_9 and C_{10} also favoured. In that case, also impact $B_{s,d}^0 \rightarrow \mu^+ \mu^-$

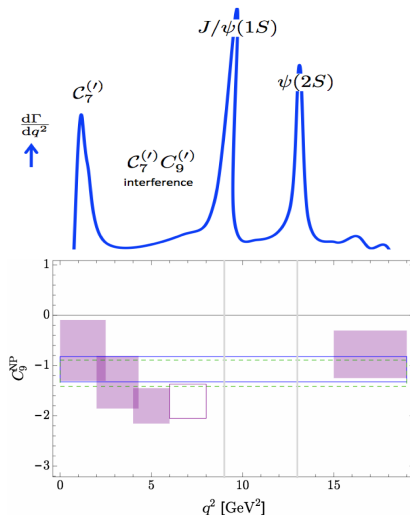
Standard model interpretation



- ▶ Modification of C_9 could indicate new vector particle...
- ▶ ... or could be problem with QCD calculations
- ▶ Vector-like charm loop contributions might be incorrectly estimated

Standard model interpretation: C_9 in q^2 bins

- ▶ If it is a $c\bar{c}$ -loop effect, expect it to grow near charm resonances.
- ▶ Test this by fitting C_9 in bins of q^2
- ▶ Expect further investigations of these effects at LHCb



arXiv:1503.06199

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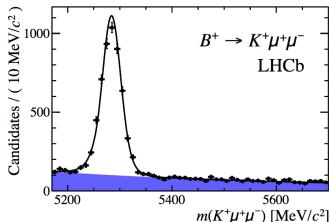
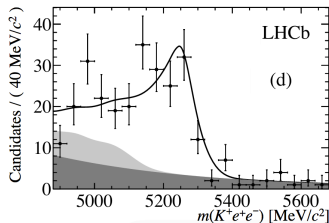
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$R(K)$: physics interest

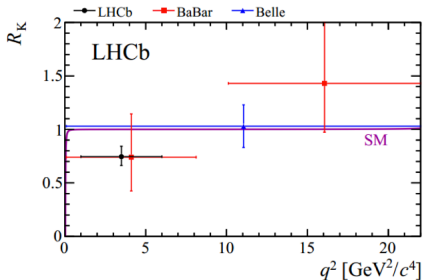
$$R(K) = \frac{\mathcal{B}(B_u^+ \rightarrow K^+ \mu^+ \mu^-)}{\mathcal{B}(B_u^+ \rightarrow K^+ e^+ e^-)}$$

- ▶ Prediction of this ratio ultra clean:
 $R(K) = 1.00030_{-0.0007}^{+0.00010}$
- ▶ No hadronic uncertainties, only deviates from 1 due to phase-space, QED
- ▶ Ideal probe for new physics coupling differently to μ and e
- ▶ Measurement challenging at LHCb because of difference in muon/electron reconstruction



[PRL 113 151601 \(2014\)](#),
[JHEP 06 133 \(2014\)](#)

$R(K)$: results



Belle: [PRL 103, 171801 \(2009\)](#)
BaBar: [PRD 86,032012 \(2012\)](#)
LHCb: [PRL 113, 151601 \(2014\)](#)

- ▶ Results from Belle, Babar, LHCb consistent with each other
- ▶ LHCb made the most precise result:

$$R(K) = 0.745_{-0.074}^{+0.090} \pm 0.036$$

- ▶ LHCb result is 2.6σ from SM prediction
- ▶ Need to improve precision and look at equivalent ratios $R(K^{*0})$, $R(\phi)$, $R(\Lambda)$...

$$B_{s,d}^0 \rightarrow e^+ \mu^- \text{ \& } D^0 \rightarrow e^+ \mu^-$$

Search for $B_{s,d}^0 \rightarrow e^+ \mu^-$ using 1 fb^{-1} of data

Limits set:

$$\mathcal{B}(B_s^0 \rightarrow e\mu) < 1.1 \times 10^{-8} \text{ 90\% C.L.}$$

$$\mathcal{B}(B_d^0 \rightarrow e\mu) < 2.8 \times 10^{-9} \text{ 90\% C.L.}$$

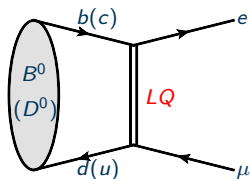
[PRL 111 141801 \(2013\)](#)

Search for $D^0 \rightarrow e^+ \mu^-$ using 3 fb^{-1} of data

Limits set:

$$\mathcal{B}(D^0 \rightarrow e\mu) < 1.3 \times 10^{-8} \text{ 90\% C.L.}$$

[PRB 754 167 \(2016\)](#)



Summary

- ▶ Rare decays can place strong constraints on BSM models.
- ▶ Several interesting tensions seen in data on $b \rightarrow s\mu\mu$ processes.
- Hints of a BSM contribution or a potential issue with the SM calculations. More data and progress from theory needed to disentangle the two.
- ▶ Many more results still to come using data from LHC run 1 and run 2, which will eventually triple the dataset

In the near future

